Last News of the Universe

from its Origins to Today

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Chalonge School Open Session

Observatoire de Paris, 15 /03/2013

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

Basement- ground Zero

Dark matter is the dominant component of Galaxies an 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

HIGHLIGHTS

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

PREDICTIONS :

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

(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

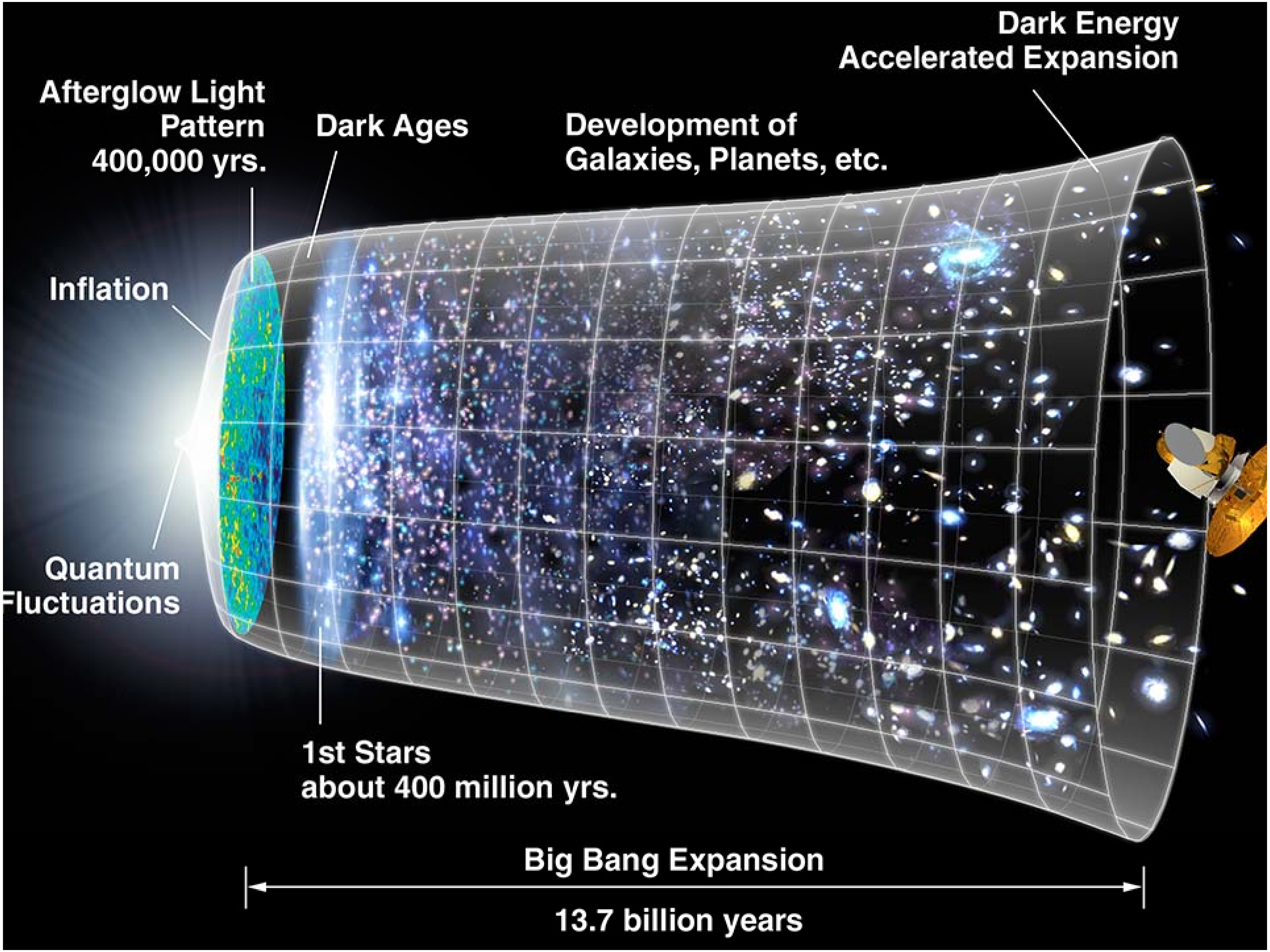
ndard Cosmological Model: DM + Λ + Baryons + Radiat

- Begins by the inflationary era. Slow-Roll inflation explains horizon and flatness.
- Gravity is described by Einstein's General Relativity.
- Particle Physics described by the Standard Model of Particle Physics: $SU(3) \otimes SU(2) \otimes U(1) =$ qcd+electroweak model.
- Dark matter is non-relativistic during the matter dominated era where structure formation happens. DM is outside the SM of particle physics.
- Dark energy described by the cosmological constant Λ.

Standard Cosmological Model: ΛCDM $\Rightarrow$ ΛWDM

Dark Matter + Λ + Baryons + Radiation
begins by the Inflationary Era. Explains the Observations:

- Seven years WMAP data and further CMB data
- Light Elements Abundances
- Large Scale Structures (LSS) Observations. BAO.
- Acceleration of the Universe expansion:
  Supernova Luminosity/Distance and Radio Galaxies.
- Gravitational Lensing Observations
- Lyman α Forest Observations
- Hubble Constant and Age of the Universe Measurements
- Properties of Clusters of Galaxies
- Galaxy structure explained by WDM



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Quantum Fluctuations During Inflation and after

The Universe is homogeneous and isotropic after inflation thanks to the fast and gigantic expansion stretching lenghts 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:

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

$M_{Planck} \gtrsim 10^{18}$ GeV $> \lambda^{-1}_{begin\, inflation} > 10^{14}$ GeV.

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

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

THE HISTORY OF THE UNIVERSE IS A HISTORY of EXPANSION and COOLING DOWN

THE EXPANSION OF THE UNIVERSE IS THE MOST POWERFUL REFRIGERATOR

INFLATION PRODUCES THE MOST POWERFUL STRETCHING OF LENGTHS

THE EVOLUTION OF THE UNIVERSE IS FROM QUANTUM TO SEMICLASSICAL TO CLASSICAL

From Very Quantum (Quantum Gravity) state to Semiclassical Gravity (Inflation) stage (Accelerated Expansion) to Classical Radiation dominated Era followed by Matter dominated Era (Deccelerated expansion) to Today Era (again Accelerated Expansion)

THE EXPANSION CLASSICALIZES THE UNIVERSE

THE EXPANSION OF THE UNIVERSE IS THE MOST POWERFUL QUANTUM DECOHERENCE MECHANISM

BLACK HOLE EVAPORATION DOES THE INVERSE EVOLUTION :

BLACK HOLE EVAPORATION GOES FROM CLASSICAL/SEMICLASSICAL STAGE TO A QUANTUM (QUANTUM GRAVITY) STATE,

Through this evolution, the Black Hole temperature goes from the semiclassical gravity temperature (Hawking Temperature) to the usual temperature (the mass) and the quantum gravity temperature (the Planck temperature).

Conceptual unification of quantum black holes, elementary particles and quantum states

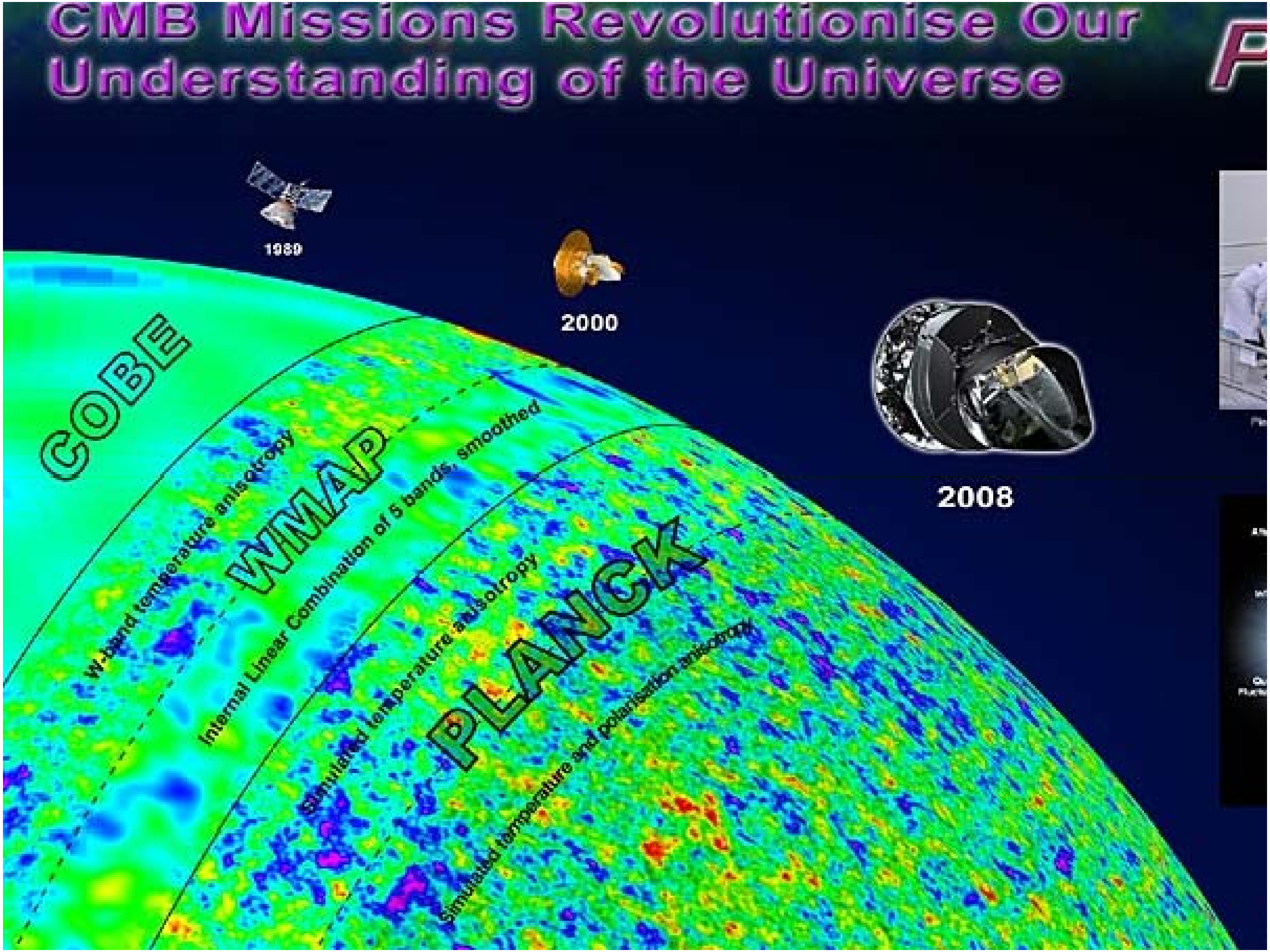
THE ENERGY SCALE OF INFLATION IS THE

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)


CMB Missions Revolutionise Our Understanding of the Universe
1989
2000
2008
COBE
WMAP
PLANCK
W-band temperature anisotropy
Internal Linear Combination of 5 bands, smoothed
Simulated temperature anisotropy
Simulated temperature and polarisation anisotropy

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 GAUSSIANITY**
- **N_{eff} neutrinos : near 4 --> Besides meV active neutrinos: 1 sterile eV neutrino**
- **Would opens the sterile neutrino Family:**
- **keV sterile neutrino –WDM-**

• Large Hadron Collider

- **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.**

- **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”.**

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: Ginsburg-Landau Approach

Universal form of the slow-roll inflaton potential:

$$V(\phi) = N\, M^4\, w\left(\frac{\phi}{\sqrt{N}\, M_{Pl}}\right) \;,\; N \sim 60 \;,\; \phi = \text{inflaton field.}$$

$n_s - 1,\; r =$ order $\frac{1}{N}$. Running $\frac{dn_s}{d\ln k} \sim \frac{1}{N^2}$.

Primordial Non-Gaussianity $f_{NL} \sim \frac{1}{N}$.

Predictions combining with WMAP+LSS data:

$M = 0.70 \times 10^{16}$ GeV, = energy scale of inflation.

MCMC analysis calls for $w''(\chi) < 0$ at horizon exit

$\Longrightarrow$ double well potential favoured.

$$w(\chi) = \frac{y}{32}\left(\chi^2 - \frac{8}{y}\right)^2$$

Bounds : $r > 0.023$ (95% CL) , $r > 0.046$ (68% CL)

Most probable values: $r \simeq 0.051 \Leftarrow$ measurable by Planck?

quartic coupling $y \simeq 1.26\ldots$ (moderate nonlinearity).

spectral index n_s, the ratio r and the running of n_s

$r \equiv$ ratio of tensor to scalar fluctuations.
tensor fluctuations = primordial gravitons.

$$n_s - 1 = -\frac{3}{N} \left[\frac{w'(\chi)}{w(\chi)}\right]^2 + \frac{2}{N} \frac{w''(\chi)}{w(\chi)} \quad , \quad r = \frac{8}{N} \left[\frac{w'(\chi)}{w(\chi)}\right]^2$$

$$\frac{dn_s}{d\ln k} = -\frac{2}{N^2} \frac{w'(\chi)\, w'''(\chi)}{w^2(\chi)} - \frac{6}{N^2} \frac{[w'(\chi)]^4}{w^4(\chi)} + \frac{8}{N^2} \frac{[w'(\chi)]^2\, w''(\chi)}{w^3(\chi)}$$

χ is the inflaton field at horizon exit.

$n_s - 1$ and r are always of order $1/N \sim 0.02$ (model indep.)

Running of n_s of order $1/N^2 \sim 0.0003$ (model independent).

Primordial Non-gaussianity $f_{NL} =$ order $1/N$

D. Boyanovsky, H. J. de Vega, N. G. Sanchez,
Phys. Rev. D 73, 023008 (2006), astro-ph/0507595.

LOWER BOUND on r

THE PRIMORDIAL GRAVITONS

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

$$r > 0.023 \text{ at } 95\% \text{ CL and}$$

$$r > 0.046 \text{ at } 68\% \text{ CL.}$$

Moreover,we find $r = 0.051$ the most probable value

For the other cosmological parameters, both analysis agree.

Two key observable numbers :

associated to the primordial density and primordial gravitons :

$$n_s = 0.9608 , \quad r$$

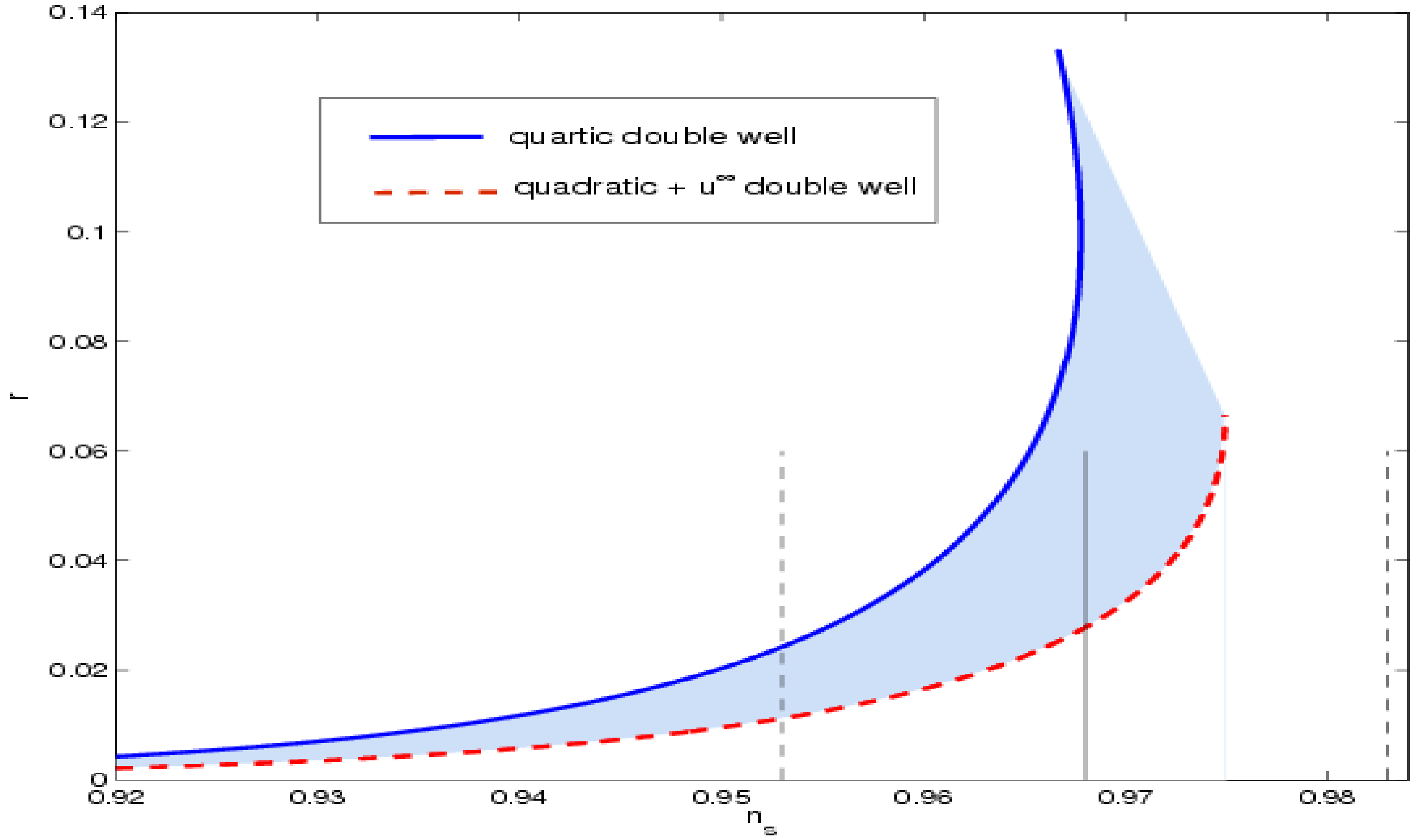
PREDICTIONS

$r < 0.053$

$r > 0.021$

$0.021 < r < 0.053$

Most probable value: $r \sim 0.051$



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)

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:

$r_{Jeans} = 57.2 \, \text{kpc} \, \frac{\text{keV}}{m} \left(\frac{100}{g_d}\right)^{\frac{1}{3}}$, 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 $m \sim$ eV HDM particles
$r_{Jeans} \sim 60$ 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…..

Structure Formation in the Universe

Structures in the Universe as galaxies and cluster of galaxies form out of the small primordial quantum fluctuations originated by inflation just after the big-bang.

These linear small primordial fluctuations grow due to gravitational unstabilities (Jeans) and then classicalize.

Structures form through non-linear gravitational evolution.

Hierarchical formation starts from small scales first.

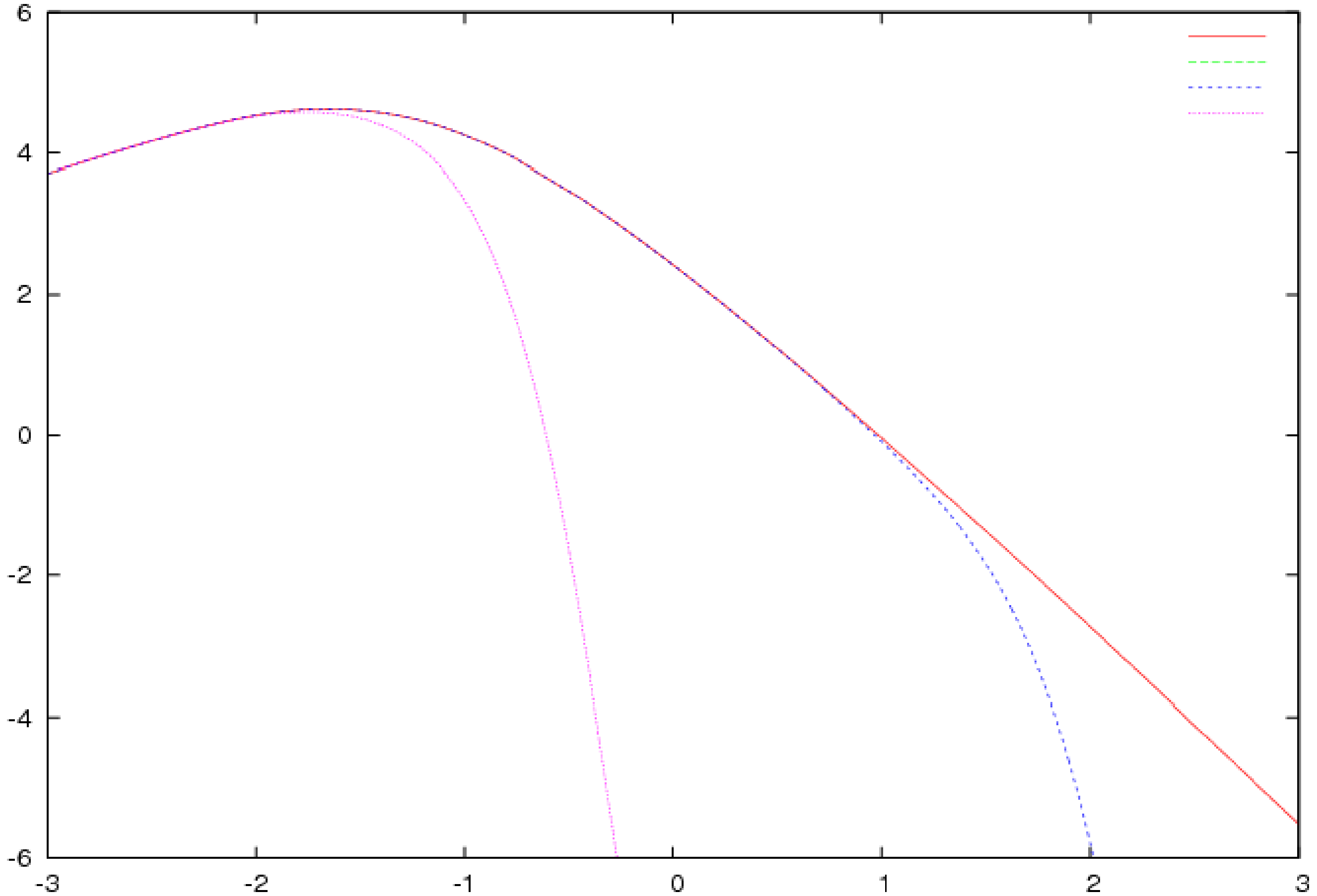
N-body CDM simulations fail to produce the observed structures for small scales less than some kpc.

Both N-body WDM and CDM simulations yield identical and correct structures for scales larger than some kpc.

WDM predicts correct structures for small scales (below kpc) when its quantum nature is taken into account.

Primordial power $P(k)$: first ingredient in galaxy formation.

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

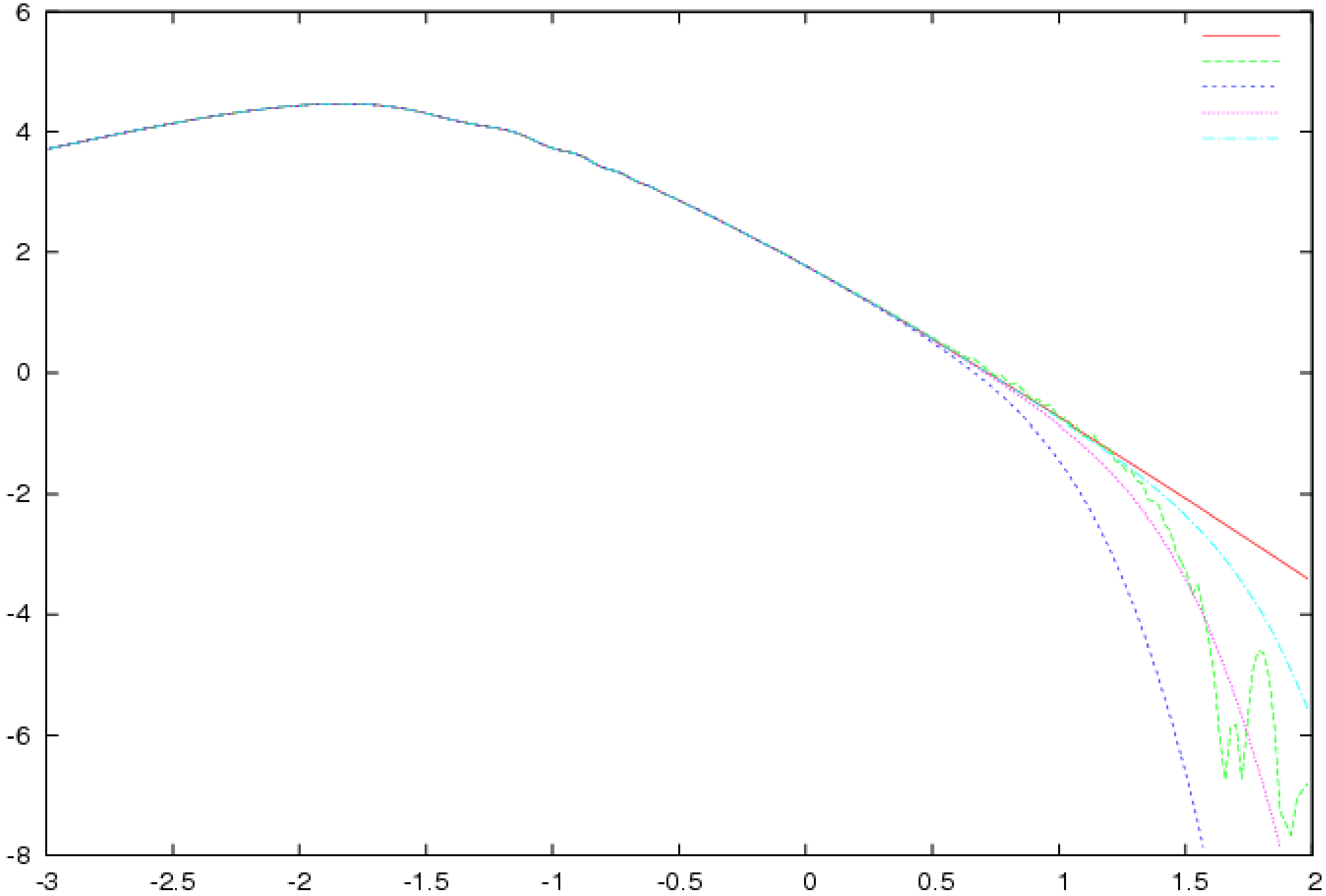


$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for WIMPS, 1 keV DM particles and 10 eV DM particles. $P(k) = P_0 \, k^{n_s} \, T^2(k)$.

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

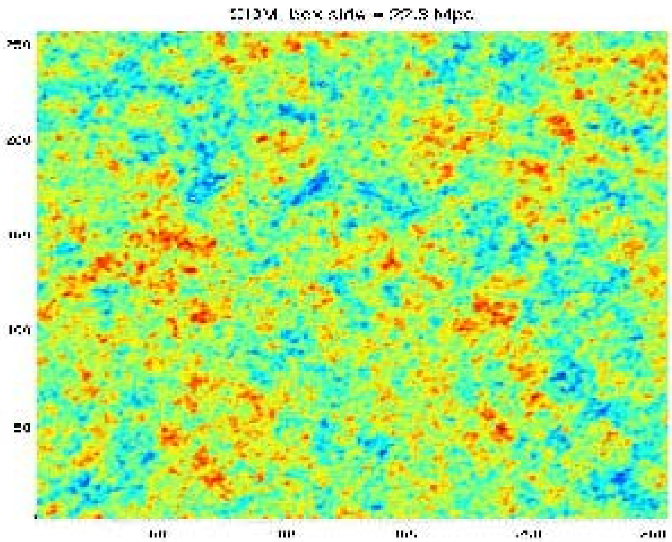
Transfer function in the MD era from Gilbert integral eq

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



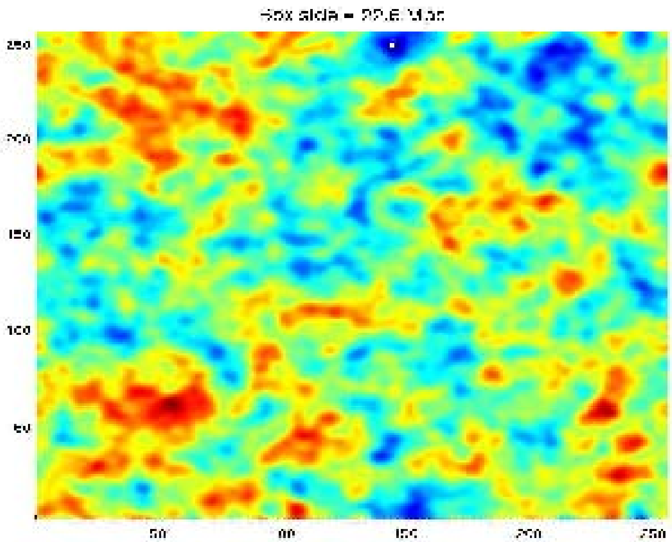
$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for CDM, 1 keV, 2 keV, light-blue 4 keV DM particles decoupling in equil, and 1 keV sterile neutrinos. WDM cuts $P(k)$ on small scales $r \lesssim 100 \, (\text{keV}/m)^{4/3}$ kpc. CDM and WDM identical for CMB.

WDM vs. CDM linear fluctuations today



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

WDM:



WARM DARK MATTER REPRODUCE

→OBSERVED GALAXY DENSITIES AND VELOCITY DISPERSIONS

→SOLVES the OVERABUNDANCE (“satellite) PROBLEM

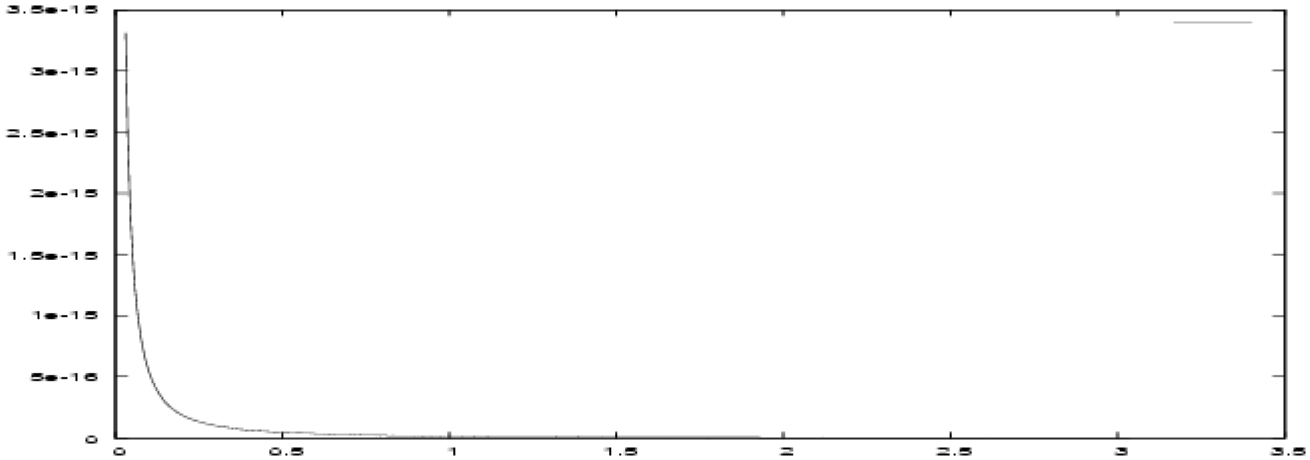
->OBSERVED SURFACE DENSITY VALUES OF DARK MATTER DOMINATED GALAXIES

→OBSERVED GALAXY CORED DENSITY PROFILES : QUANTUM MECHANICS

Wimps vs. galaxy observations

	Observed Values	Wimps in linear theory
r_0	5 to 52 kpc	0.045 pc
ρ_0	1.57 to $19.3 \times 10^{-25} \ \frac{\mathrm{g}}{\mathrm{cm}^3}$	$0.73 \times 10^{-14} \ \frac{\mathrm{g}}{\mathrm{cm}^3}$
$\sqrt{v^2}_{halo}$	79.3 to 261 km/sec	0.243 km/sec

The wimps values strongly disagree by several order of magnitude with the observations.



$\rho_{lin}(r)_{wimp}$ in g/cm^3 vs. r in pc. Exhibits a cusp behaviour for $r \gtrsim 0.03$ pc.

Galaxy Density Profiles: Cores vs. Cusps

Astronomical observations always find cored profiles for DM dominated galaxies. Selected references:

J. van Eymeren et al. A&A (2009), M. G. Walker, J. Peñarrubia, Ap J (2012). Reviews by de Blok (2010), Salucci & Frigerio Martins (2009).

Galaxy profiles in the linear regime: core size $\sim$ free streaming length (de Vega, Salucci, Sanchez, 2010)=

$$\text{halo radius } r_0 = \begin{cases} 0.05 \text{ pc cusps for CDM (m > GeV).} \\ 50 \text{ kpc cores for WDM (m} \sim \text{keV).} \end{cases}$$

N-body simulations for CDM give cusps (NFW profile).

N-body simulations for WDM :
quantum physics needed for fermionic DM !!!

CDM simulations give a precise value for the concentration $\equiv R_{virial}/r_0$. CDM concentrations disagree with observed

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 keV for the WDM particle.

- OBSERVED GALAXY CORES vs CDM CUSPS and WDM CORES-

- **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 developped 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 <u>rule out</u> the presence of galaxy cusps for WDM and <u>enlarge</u> the classical core sizes because their <u>repulsive and non-local</u> 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 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 !

Dwarf galaxies as quantum objects

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

$d =$ mean distance between particles,
$\sigma =$ DM mean velocity

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

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

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

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).

Quantum pressure vs. gravitational pressure

quantum pressure: $P_q =$ flux of momentum $= n\, v\, p$,

$v =$ mean velocity, momentum $= p \sim \hbar/\Delta x \sim \hbar\, n^{\frac{1}{3}}$,

particle number density $= n = \frac{M_q}{\frac{4}{3}\, \pi\, R_q^3\, m}$

galaxy mass $= M_q$, galaxy halo radius $= R_q$

gravitational pressure: $P_G = \frac{G\, M_q^2}{R_q^2} \times \frac{1}{4\, \pi\, R_q^2}$

Equilibrium: $P_q = P_G \Longrightarrow$

$$R_q = \frac{3^{\frac{5}{3}}}{(4\, \pi)^{\frac{2}{3}}}\, \frac{\hbar^2}{G\, m^{\frac{8}{3}}\, M_q^{\frac{1}{3}}} = 10.6 \ldots \text{pc} \left(\frac{10^6\, M_\odot}{M_q}\right)^{\frac{1}{3}} \left(\frac{\text{keV}}{m}\right)^{\frac{8}{3}}$$

$$v = \left(\frac{4\, \pi}{81}\right)^{\frac{1}{3}}\, \frac{G}{\hbar}\, m^{\frac{4}{3}}\, M_q^{\frac{2}{3}} = 11.6\, \frac{\text{km}}{\text{s}} \left(\frac{\text{keV}}{m}\right)^{\frac{4}{3}} \left(\frac{M_q}{10^6\, M_\odot}\right)^{\frac{2}{3}}$$

for WDM the values of $M_q,\ R_q$ and v are consistent with the dwarf galaxy observations !! .

Dwarf spheroidal galaxies can be supported by the fermionic quantum pressure of WDM.

Self-gravitating Fermions in the Thomas-Fermi approach

The Thomas-Fermi approach gives physical galaxy magnitudes: mass, halo radius, phase-space density and velocity dispersion fully compatible with observations from the largest spiral galaxies till the ultracompact dwarf galaxies for a WDM particle mass around 2 keV.

Compact dwarf galaxies are close to a degenerate WDM Fermi gas while large galaxies are classical WDM Boltzmann gases.

Fermionic WDM treated quantum mechanically is able to reproduce the observed galaxies.

C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:1204.3090 to appear in New Astronomy.
'Quantum WDM fermions and gravitation determine the observed galaxy structures', arXiv:1301.1864.

RESULTS

All the obtained density profiles are cored.

The Core Sizes are in agreement with the observations

from the compact galaxies where rh ~ 20 pc till the spiral and elliptical galaxies where rh ~ 0.2 - 60 kpc.

The larger and positive is the chemical potential ν(0), the smaller is the core. The minimal one arises in the degenerate case ν(0) --> to +infinity (compact dwarf galaxies).

And

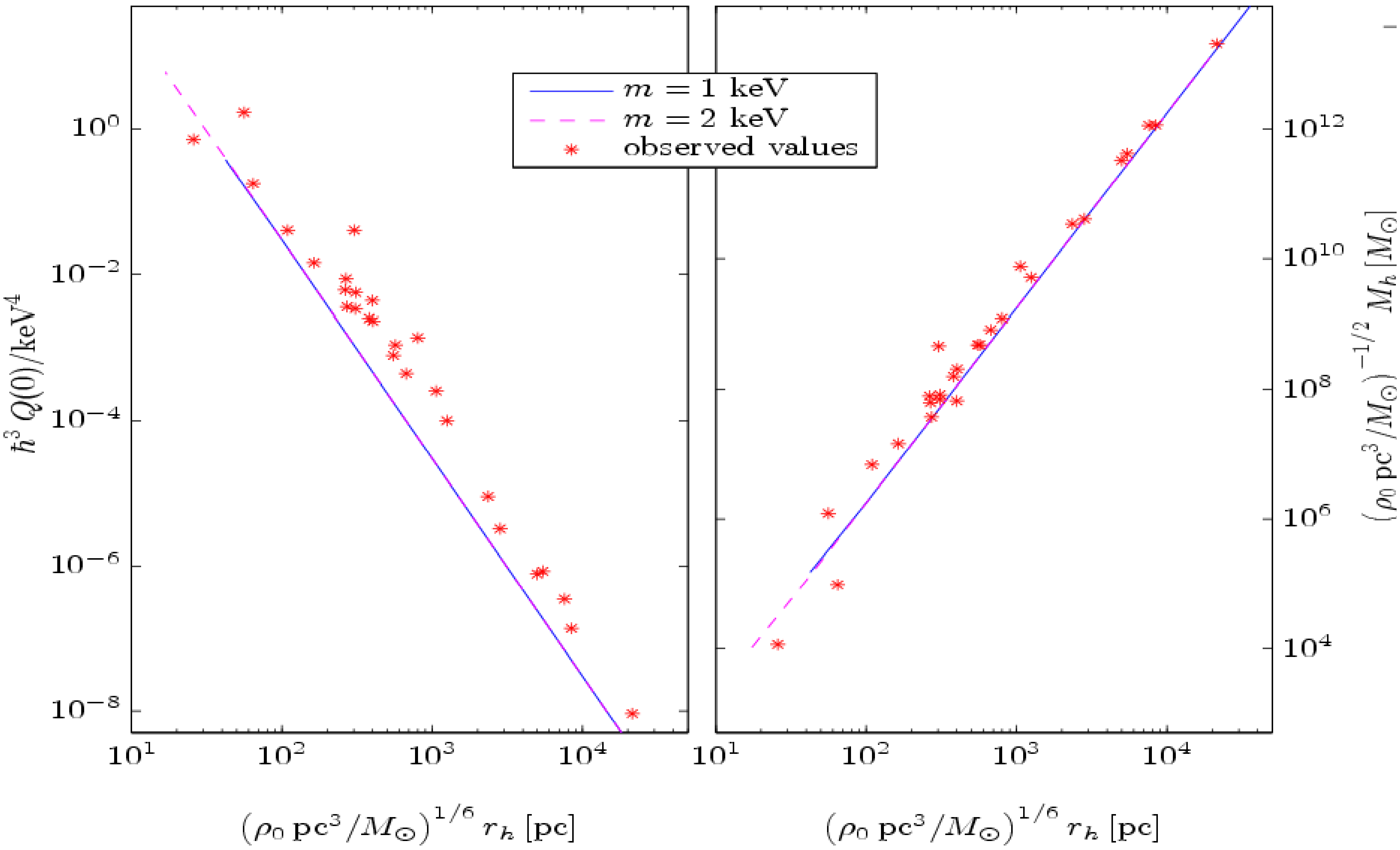
The Phase-space Density

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 %.

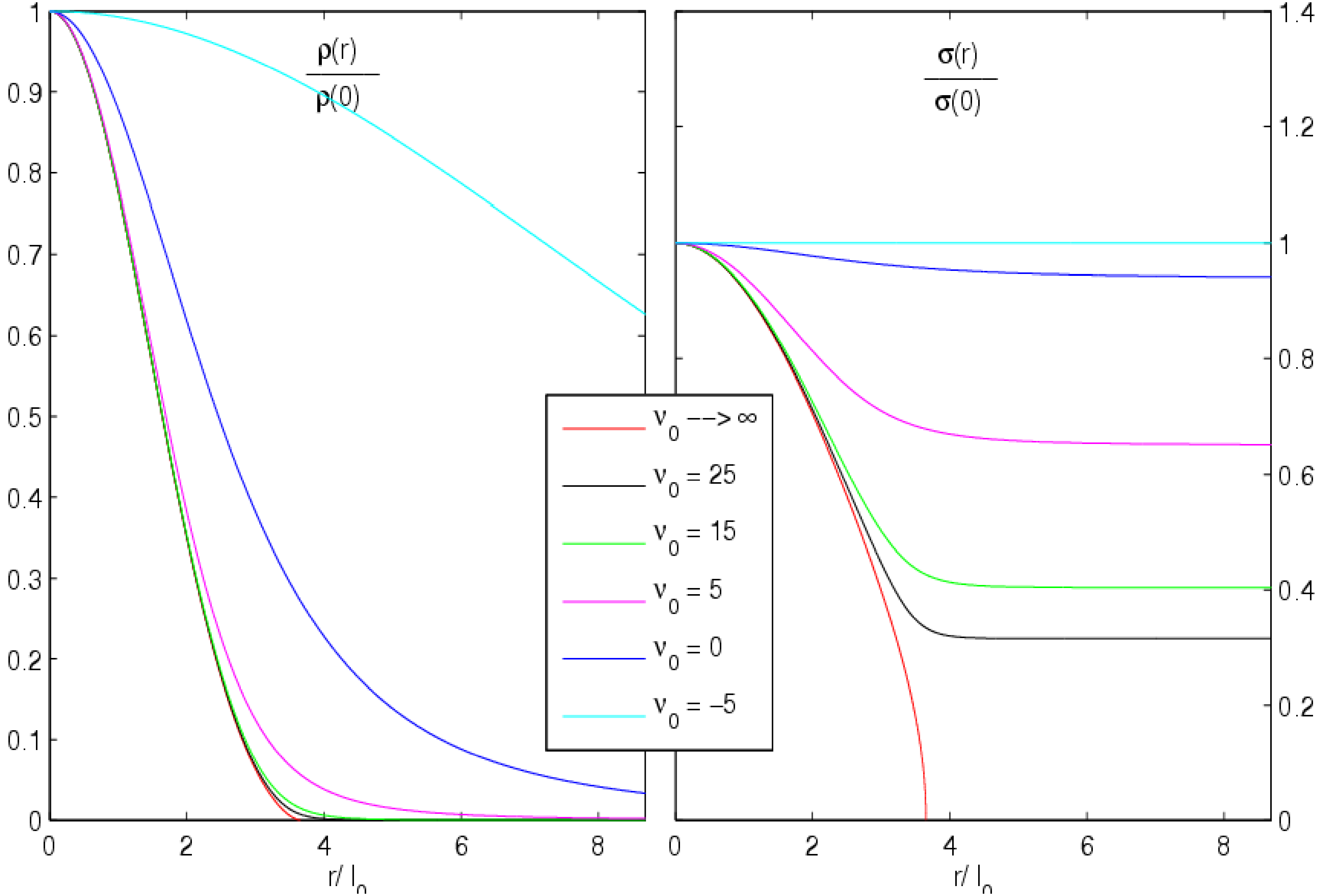
Q vs. halo radius. Galaxy observations vs. Thomas-Fermi



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:

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

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

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

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

Lightest known compact dwarf galaxy is Willman I:

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

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

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 ("satellite)
PROBLEM and the CUSPS vs CORES Problem

• 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.**

Galaxy	$\frac{r_h}{\text{pc}}$	$\frac{\sigma}{\frac{\text{km}}{\text{s}}}$	$\frac{h^{\frac{4}{2}}\sqrt{Q_h}}{(\text{keV})^2}$	$\rho(0) / \frac{M_\odot}{(\text{pc})^3}$	$\frac{M_h}{10^6\ M_\odot}$
Willman 1	19	4	0.85	6.3	0.029
Segue 1	48	4	1.3	2.5	1.93
Leo IV	400	3.3	0.2	.19	200
Canis Venatici II	245	4.6	0.2	0.49	4.8
Coma-Berenices	123	4.6	0.42	2.09	0.14
Leo II	320	6.6	0.093	0.34	36.6
Leo T	170	7.8	0.12	0.79	12.9
Hercules	387	5.1	0.078	0.1	25.1
Carina	424	6.4	0.075	0.15	32.2
Ursa Major I	504	7.6	0.066	0.25	33.2
Draco	305	10.1	0.06	0.5	26.5
Leo I	518	9	0.048	0.22	96
Sculptor	480	9	0.05	0.25	78.8
Boötes I	362	9	0.058	0.38	43.2
Canis Venatici I	1220	7.6	0.037	0.08	344
Sextans	1290	7.1	0.021	0.02	116
Ursa Minor	750	11.5	0.028	0.16	193
Fornax	1730	10.7	0.016	0.053	1750
NGC 185	450	31	0.033	4.09	975
NGC 855	1063	58	0.01	2.64	8340
Small Spiral	5100	40.7	0.0018	0.029	6900
NGC 4478	1890	147	0.003	3.7	6.55×10^4
Medium Spiral	1.9×10^4	76.2	3.7×10^{-4}	0.0076	1.01×10^5
NGC 731	6160	163	9.27×10^{-4}	0.47	2.87×10^5
NGC 3853	5220	198	8.8×10^{-4}	0.77	2.87×10^5
NGC 499	7700	274	5.9×10^{-4}	0.91	1.09×10^6
Large Spiral	5.9×10^4	125	0.96×10^{-4}	2.3×10^{-3}	$1. \times 10^6$

TABLE I: Observed values r_h, σ, $\sqrt{Q_h}$, $\rho(0)$ and M_h covering from ultracompact objects and

Summary and Conclusions

- Combining theoretical evolution of fluctuations through the Boltzmann-Vlasov equation with galaxy data points to a DM particle mass 3 - 10 keV. T_d turns to be model dependent. The keV mass scale holds independently of the DM particle physics model.
- Universal Surface density in DM galaxies $[\mu_{0D} \simeq (18 \text{ MeV})^3]$ explained by keV mass scale DM. Density profile scales and decreases for intermediate scales with the spectral index n_s : $\rho(r) \sim r^{-1-n_s/2}$ and $\rho(r) \sim r^{-2}$ for $r \gg r_0$.

H. J. de Vega, P. Salucci, N. G. Sanchez, 'The mass of the dark matter particle from theory and observations', New Astronomy, 17, 653 (2012).

H. J. de Vega, N. Sanchez, 'Model independent analysis of dark matter points to a particle mass at the keV scale',

IN PROGRESS

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 results…..

Galactic Black-Holes formed by WDM

When the Schwarzschild gravitational radius at the point r becomes larger than r, a black hole forms.

$r < 2\,G\,M(r) \quad \Rightarrow \quad$ collapse into a BH

From the self-consistent Poisson equation for degenerate WDM fermions, lower energy state:

$$M_{BH} = \frac{r_c}{G\,m^2}\,\left|\frac{d\mu}{dr}\right|(r_c) = 1.989\ldots 10^{11}\ M_\odot\ (2\ \mathrm{keV}/m)^2 =$$
$$= 0.796\ldots M_\odot\ (\mathrm{GeV}/m)^2\ ,\ 2\,G\,M_{BH} = 0.019\ \mathrm{pc}\ (2\ \mathrm{keV}/m)^2.$$

For $m = M_{neutron} = 0.9396\ldots$GeV $\Rightarrow\ M_{BH} = 0.902\ldots\ M_\odot$.

Chandrasekhar mass for galaxies and neutron stars !

When collapse into a BH happens the WDM becomes relativistic: $0 < v < 0.7\,c$ (not UR).

WDM is out of thermal equilibrium and in excited states before and during structure formation.

keV Sterile Neutrino Warm Dark Matter

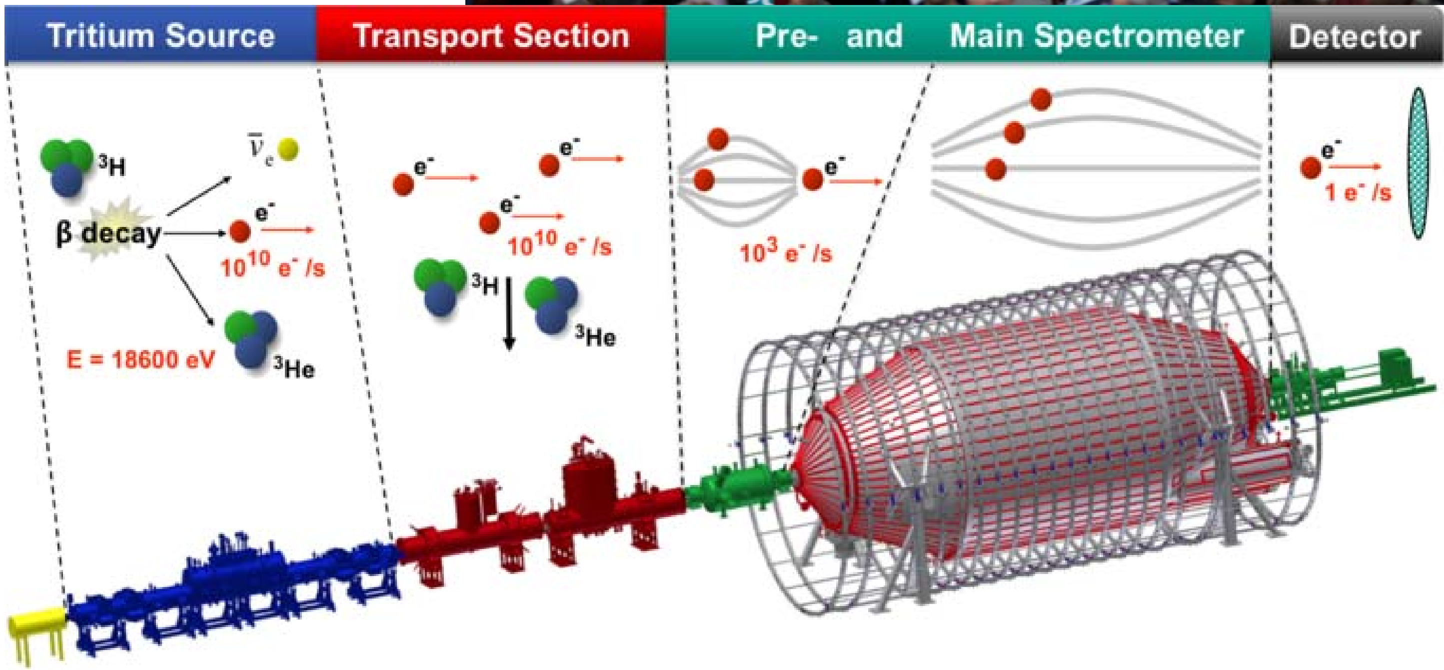
Sterile neutrinos can decay into an active-like neutrino and a monochromatic X-ray photon with an energy half the mass of the sterile neutrino. Observing the X-ray photon provides a way to observe sterile neutrinos in DM halos.

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).

KATRIN

Karlsruhe Tritium Neutrino Experiment



École Internationale Daniel Chalonge

22 Years of Activity — *Calling for Understanding*

SCIENCE WITH GREAT INTELLECTUAL ENDEAVOUR AND A HUMAN FACE

LA SCIENCE QUI DONNE ENVIE : UNE GRANDE AVENTURE SCIENTIFIQUE ET HUMAINE

PROGRAMME 2013

15 MARCH 2013 : **"Présentation du Programme 2013 et des Dernières Nouvelles Scientifiques de l'Univers »** Bâtiment Perrault, Observatoire de Paris

4-7 APRIL 2013 : **"Latest News from the Universe, Dark Matter Galaxies and Particle Physics"** Palazzo de l'Università & Palazzo Graneri, Piamonte Région, Turin, Italy

16 MAY 2013 : **Spring Open Session of Scientific Culture 2013 Session Ouverte de Printemps de Culture Scientifique 2013 : "L'Homme et l'Univers"** Bâtiment Perrault, Observatoire de Paris, Paris

30 MAY 2013 : **Rencontre de Culture Scientifique "Voyage à travers l'Univers : De ses Origines à nos Jours"** Cité Internationale Universitaire de Paris, Paris

4-7 JUNE 2013 : **Chalonge Meudon Workshop 2013 "Warm Dark Matter Galaxies in Agreement with Observations : Formation, Evolution and Supermassive Black Holes"** Observatoire de Paris, Château de Meudon-CIAS, Meudon

23-26 JULY 2013 : **The 17th Paris Cosmology Colloquium Chalonge 2013: "The New Standard Model of the Universe: ΛWDM – Warm Dark Matter: "Theory and Observations"** Bâtiment Perrault, Observatoire de Paris, Paris

26 JULY 2013 : **Summer Open Session of Scientific Culture 2013 / Session Ouverte d'Eté de Culture Scientifique 2013 : A Surprise Session**

AUTOMME 2013 : **Cycle Les grandes questions posées aujourd'hui à la Science : 1ère Question : Où va la Science ?** Cité Internationale Universitaire de Paris, Paris

And Other Events...

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

http://chalonge.obspm.fr

TURIN SPECIAL SESSION

Astrophysics International School Daniel Chalonge

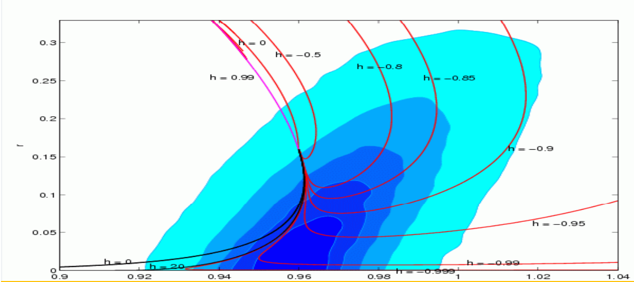
5 April 2013

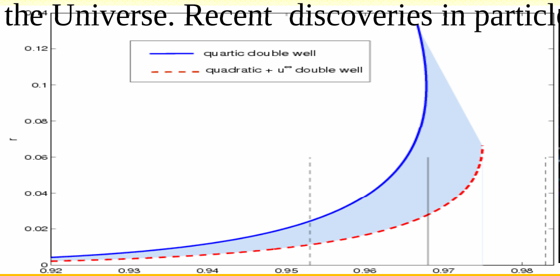
Colloquium

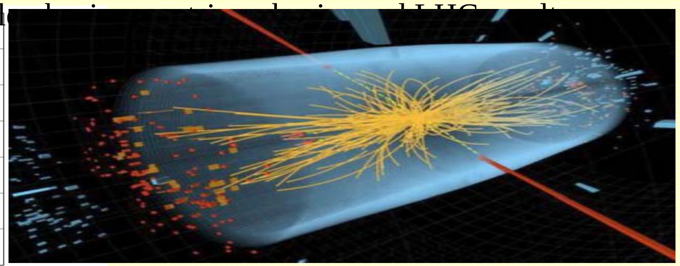
Latest News from the Universe:

Cosmology, Dark Matter, Galaxies, Astrophysics and Particle Physics

In the second Chalonge School Colloquium to be held in Torino, the highlights and recent results in advanced physics and astrophysics research are discussed, together with the future perspectives. The spirit of the Colloquium is in keeping with the Chalonge School's emphasis on astro-fundamental physics, putting together real cosmological and astrophysical data and hard theory predictive approach in ... of the Universe. Recent discoveries in particl...







Scientific Session - 5 April 2013

Palazzo Lascaris, Via Alfieri 15, Torino

http://chalonge.obspm.fr **TOPICS AND LECTURERS** http://ecolechalongetorino.oato.inaf.it

ΛWDM-The New Standard Model of the Universe	Norma Sanchez	CNRS Obs.de Paris,France
WDM-keV sterile neutrinos	Hector de Vega	CNRS UPMC Paris, France
The High-Energy Astrophysics Sky	Giovanni Bignami	INAF Roma, Italy
The AMS experiment on the ISS: a particle physics experiment in space	Roberto Battiston	Univ. e INFN Trento, Italy
High-energy astrophysics with the AGILE mission.	Attilio Ferrari	Univ.Torino e OATo, Italy

LOCATIONS

Chalonge School Torino Colloquium 4-7 April 2013

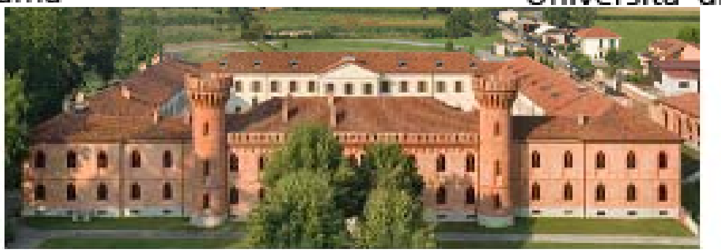
HOTEL NH S. Stefano

SCIENTIFIC SESSION
Palazzo Lascaris
Sede Regione Piemonte

OPEN SESSION
Biblioteca Archimede
Settimo Torinese

Visit and social dinner
Palazza Madama

Reception to Rettorato
Università di Torino



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THANK YOU FOR YOUR ATTENTION