Física del Universo

El Universo desde sus Origenes Cuánticos hasta Nuestros Dias

Norma G. SANCHEZ, CNRS Paris, France

Chalonge –de Vega Int.School Center

19 November 2021

50 años Facned, Univ del Cauca, Colombia

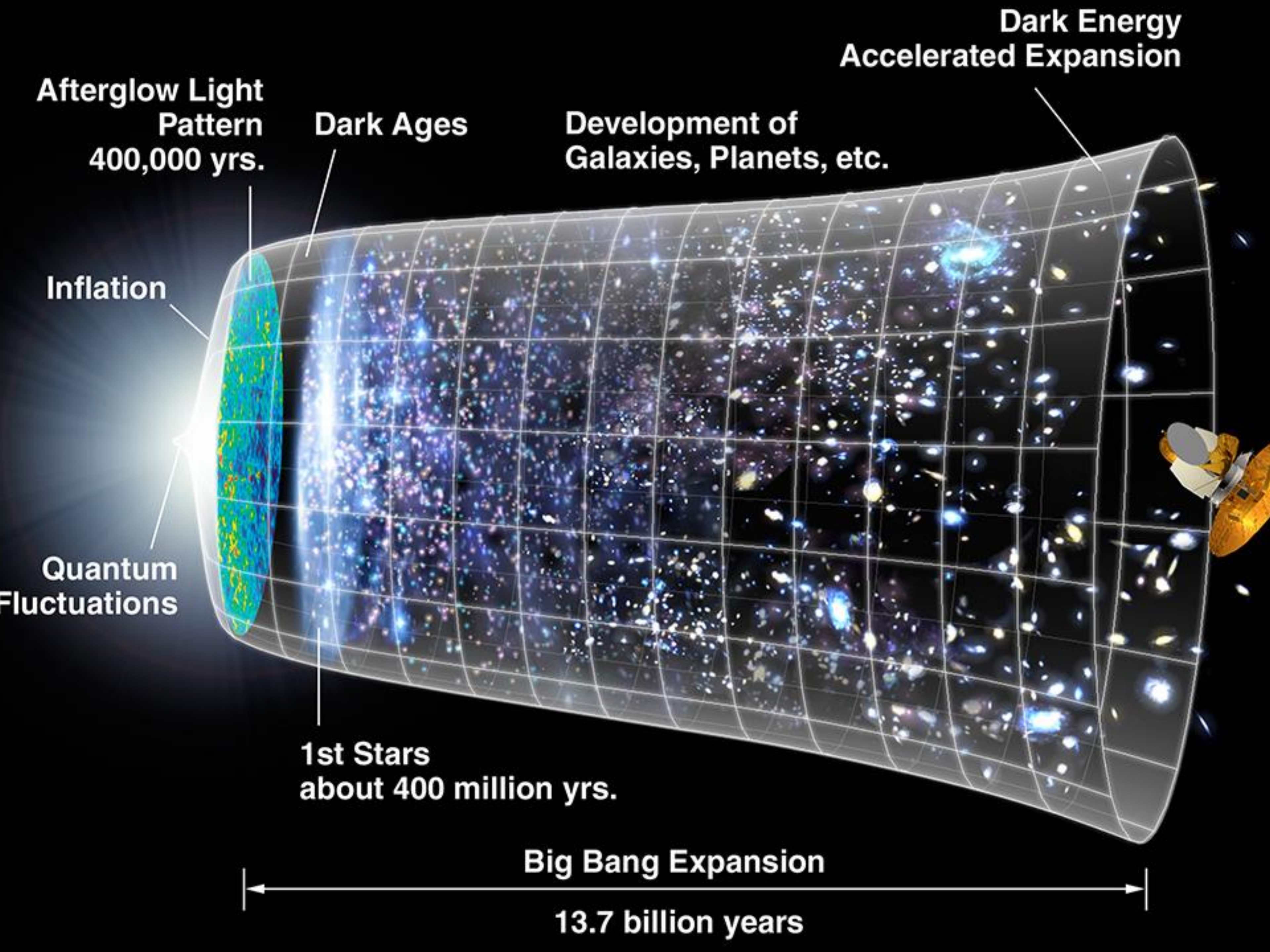
EL UNIVERSO CONOCIDO (EL VIEJO UNIVERSO)

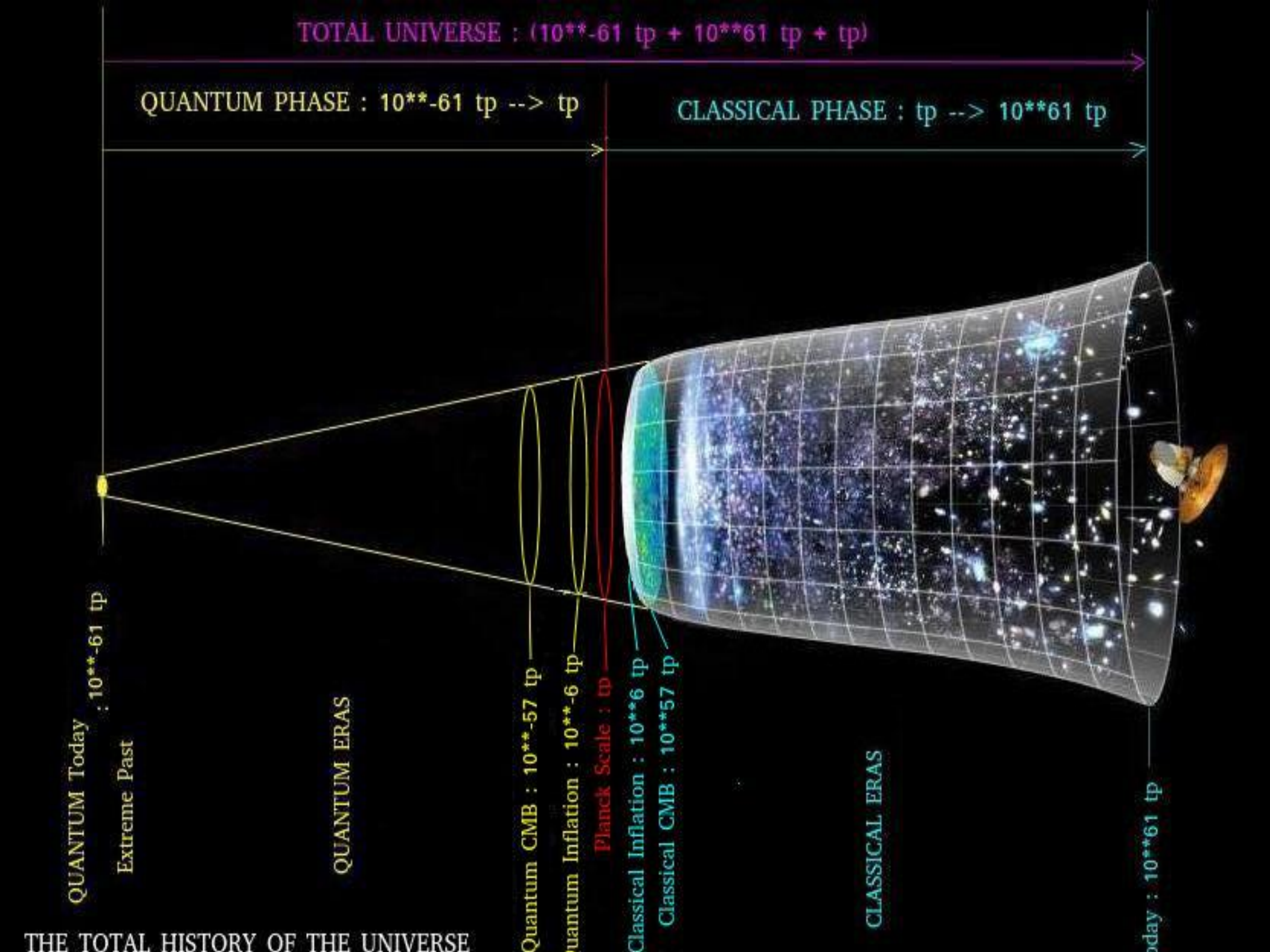
→ (i) La teoria efectiva de la Inflación cósmica compatible con las observaciones y sus predicciones .

→ (ii) La naturaleza de la materia oscura compatible con las observaciones cosmológicas y de grandes y pequeñas structuras, incluyendo los agujeros negros.

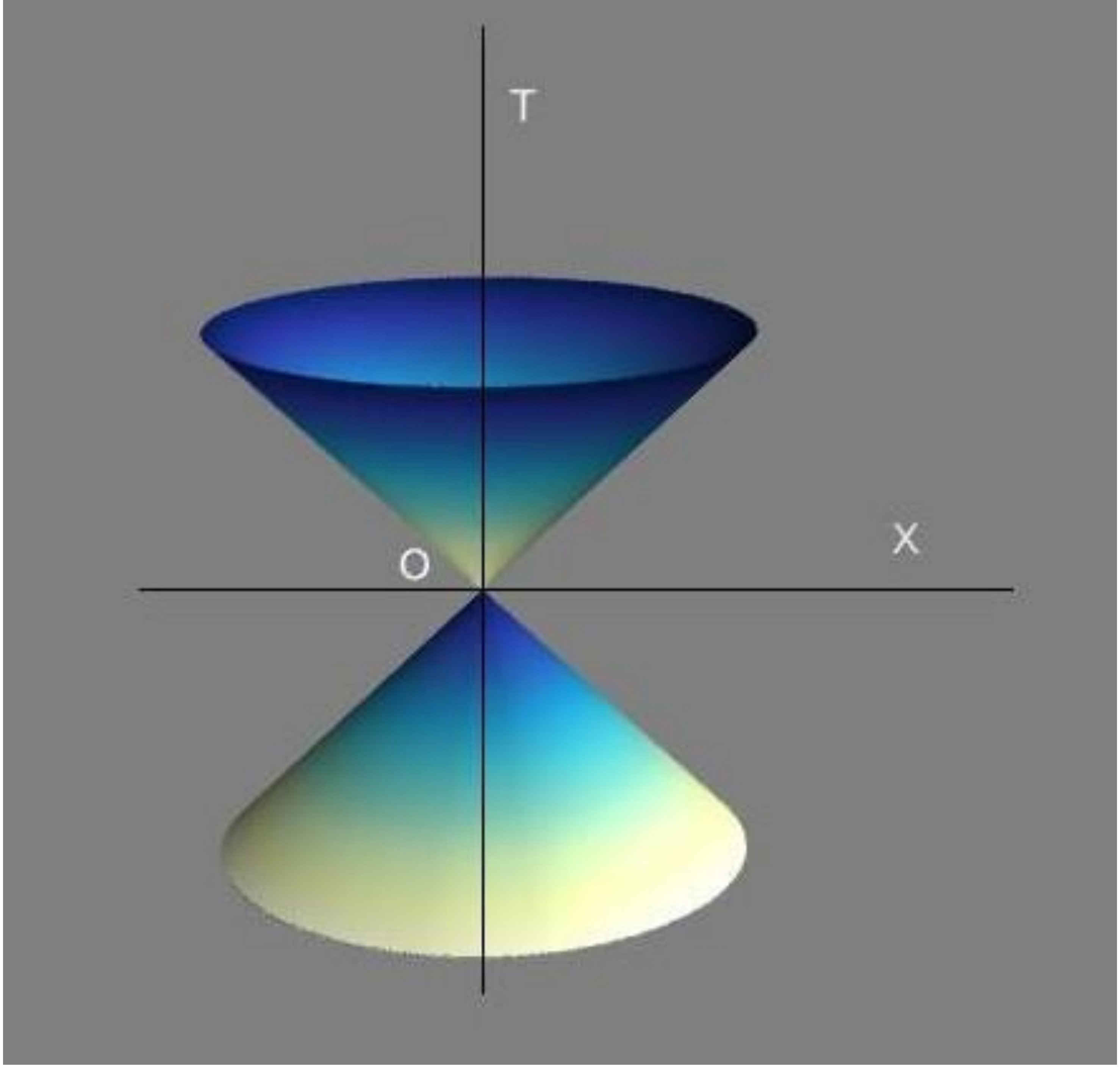
→ (iii) La naturaleza de la energía oscura compatible con la energia de vacío y su clarificación.
→(iv)Mi visión conclusiones sobre el estado actual de la investigación en el tema y las direcciones a seguir.

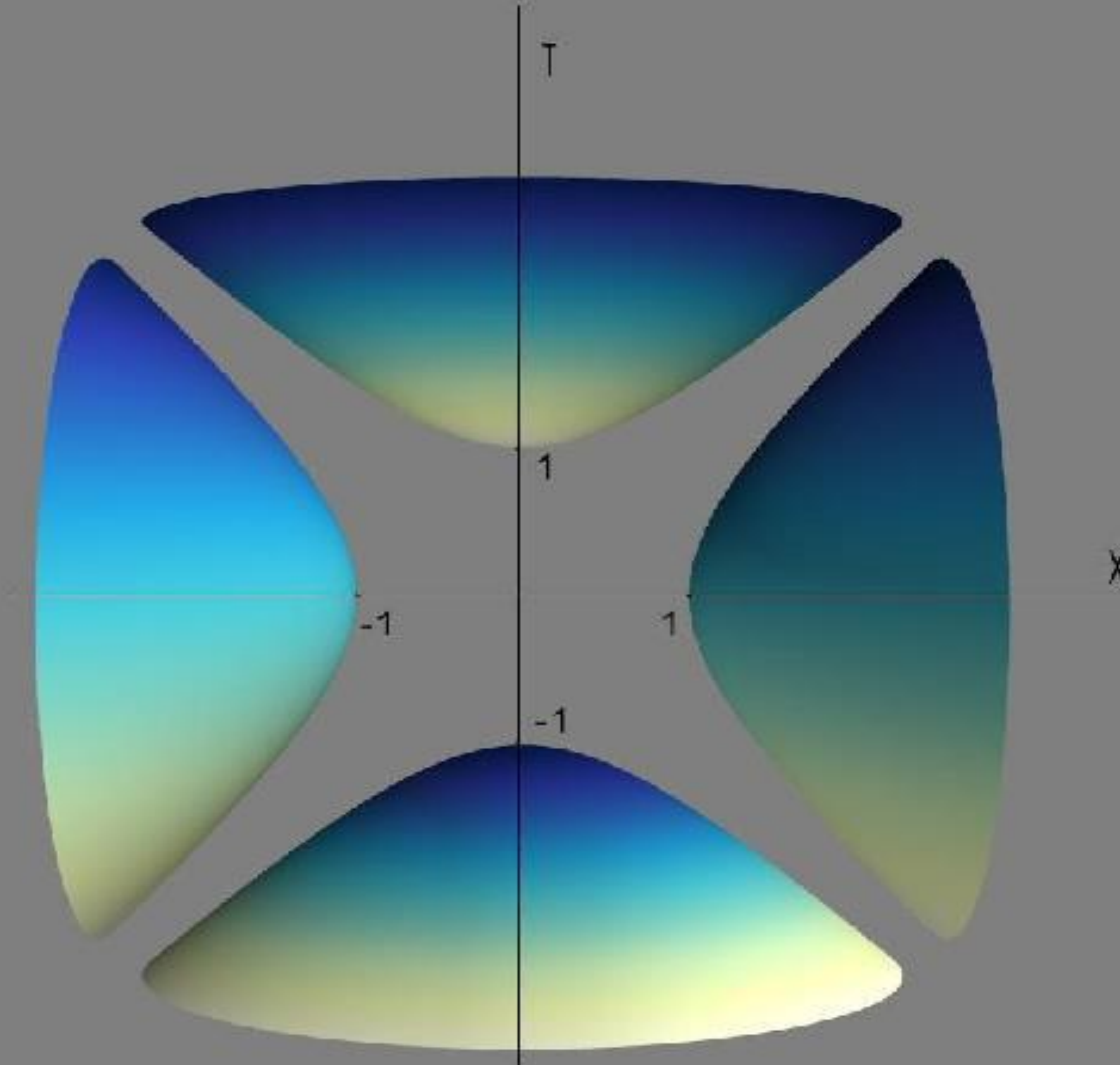
→ (iv) EL NUEVO UNIVERSO: La nueva etapa cuántica transplanckiana precursora del Universo y sus implicaciones, BHs, S-T Cuantico, Q Light-cone, NEW


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



TOTAL UNIVERSE : (10**-61 tp + 10**61 tp + tp)
QUANTUM PHASE : 10**-61 tp --> tp
CLASSICAL PHASE : tp --> 10**61 tp
QUANTUM Today : 10**-61 tp
Extreme Past
QUANTUM ERAS
Quantum CMB : 10**-57 tp
uantum Inflation : 10**-6 tp
Planck Scale : tp
Classical Inflation : 10**6 tp
Classical CMB : 10**57 tp
CLASSICAL ERAS
oday : 10**61 tp
THE TOTAL HISTORY OF THE UNIVERSE


T
X
O


T
1
X
-1
1
-1

REFERENCES

[1] N. G. Sanchez, *Quantum Discrete Levels of the Universe from the early trans-planckian vacuum to the late dark energy* (2020) ,
In press Phys Rev D (2021)

- 2019 Trilogy

- [2] N. G. Sanchez, *New Quantum Phase of the Universe before Inflation and its Cosmological and Dark Energy Implications*
  Int Journal Mod Phys A34, No.27, 1950155 (2019)

- [3] N. G. Sanchez, *The Classical-Quantum Duality of Nature: New variables for Quantum Gravity,*
  Int Journal Mod Phys D18, 1950055 (2019)

- [4] N. G. Sanchez, *The New Quantum structure of the space-time,*
  J. Grav & Cosmology 25, pp 91-102, (2019) (Springer)

https://www.researchgate.net/profile/Norma_Sanchez12

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

Standard Cosmological Model:

Ordinary Matter + Dark Matter + Cosmological Constant

- Begins by the inflationary era.
- Gravity is described by Einstein's General Relativity. Matter determines the spacetime geometry.
- Ordinary Matter described by the Standard Model of Particle Physics: $SU(3) \otimes SU(2) \otimes U(1) =$ qcd+electroweak model. Strong, electromagnetic and weak interactions involving quarks, gluons, protons, electrons, photons and neutrinos.
- Dark matter plays a crucial role in galaxy and structures formation. DM could be a sterile neutrino which does not interact through the SM and has mass $\sim$ keV.
- Dark energy uniformly distributed in space. Repulsive gravitational force. Described by the cosmological constant Λ.

Standard Cosmological Model: Concordance Model

$ds^2 = dt^2 - a^2(t)\, d\vec{x}^{\,2}$: spatially flat geometry.

The Universe starts by an **INFLATIONARY ERA**.

Inflation = Accelerated Expansion: $\frac{d^2a}{dt^2} > 0$.
During inflation the universe expands by at least sixty efolds: $e^{62} \simeq 10^{27}$. Inflation lasts $\simeq 10^{-36}$ sec and ends by $z \sim 10^{29}$ followed by a radiation dominated era.
Energy scale when inflation starts $\sim 10^{16}$ GeV ($\Longleftarrow$ CMB anisotropies) which **coincides** with the GUT scale.

Matter can be effectively described during inflation by a Scalar Field $\phi(t, \boldsymbol{x})$: the Inflaton.

Lagrangean: $\mathcal{L} = a^3(t) \left[\frac{\dot{\phi}^2}{2} - \frac{(\nabla\phi)^2}{2\, a^2(t)} - V(\phi)\right]$.

Friedmann eq.: $H^2(t) = \frac{1}{3\, M_{Pl}^2} \left[\frac{\dot{\phi}^2}{2} + V(\phi)\right]$, $H(t) \equiv \dot{a}(t)/a(t)$

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

Universe Inventory Today

The universe is spatially flat.
Curvature is present in the space-time geometry.

Today: Dark Energy (Λ): 73 % , Dark Matter: 22 %

Baryons $+$ electrons: 4.5 % , Radiation ($\gamma + \nu$): 0.0085%

83 % of the matter in the Universe is DARK.

Total average energy density today (very dilute!):

$\rho(\mathrm{today}) = 0.947\ 10^{-29}\ \frac{\mathrm{g}}{\mathrm{cm}^3} \simeq$ 5 proton masses per m^3

DM dominates in the halos of galaxies (external part).
Ordinary matter dominates around the center of galaxies.

Most galaxies exhibit a gigantic black hole in the center.
Central black hole mass ~ 0.001 galaxy mass.

Galaxies form out of matter collapse via gravitational dynamics.

The Universe Today is Essentially Empty

Inter galactic distances $\sim$ Mpc. (pc = 3.0857×10^{13} kms.)

Galaxy sizes $\sim 0.0001 - 0.1$ Mpc. (pc = 3.262 light years.)

99.9 % of the universe volume is the intergalactic space with an average energy density of 5 proton masses per m
(cosmological constant).

Galaxy masses: $10^6 - 10^{12}\ M_\odot$ from dwarf compact galaxies to (diluted) big galaxies spirals.

Galaxy density:

$\sim 4000 - 40000$ proton masses per m^3 for big galaxies.

$\sim 4 \times 10^6$ proton masses per m^3 for small compact galaxie

For comparison: air density at the atmospheric pressure and 0^o C $\sim 3.9 \times 10^{26}$ proton masses per m^3.

The Fossil Cosmic Microwave background and the Primordial Gravitons

Cosmic microwave background almost homogeneous and isotropic plus small inhomogeneities $\sim 10^{-4}$.

Inflation is the only explanation for the CMB including these small fluctuations of quantum origin $\sim 10^{-4}$.

Density CMB anisotropies first detected in 1992 by COBE.

Einstein's General Relativity predicts the existence of gravitational waves. Oscillations of the space-time itself.

Primordial gravitons are produced during inflation. They appear as tensor fluctuations in the CMB anisotropies.

This detection show two important results: a) the existence of gravitational waves, b) their existence as quantized gravitons.

How the Universe took its present aspect?

The Universe was homogeneous and isotropic after inflation thanks to the fast and gigantic expansion stretching lenghts by a factor $e^{64} \simeq 10^{28}$.

The universe by the end of inflation is a extraordinarily hot plasma at $T \sim 10^{14}$ GeV $\sim 10^{27}$ K.

However, small ($\sim 10^{-5}$) quantum fluctuations were of course present.

These inflationary quantum fluctuations are the seeds of

- the structure formation in the universe: galaxies, clusters, stars, planets (and all on them), ...
- the CMB anisotropies today.

That is, our present universe (including ourselves) was built out of inflationary quantum fluctuations.

The Theory of Inflation

Inflation can be formulated as an effective field theory in the Ginsburg-Landau sense. Main predictions:

- The inflation energy scale turns to be the grand unification energy scale: $= 0.70 \times 10^{16}$ GeV
- The MCMC analysis of the WMAP+LSS data combined with the effective theory of inflation yields: a) the inflaton potential is a double–well, b) the ratio r of tensor to scalar fluctuations. has the lower bound: $r > 0.023\ (95\%\ \mathrm{CL}) \quad , \quad r > 0.046\ (68\%\ \mathrm{CL})$ with $r \simeq 0.051$ as the most probable value.

This is borderline for the Planck satellite ($\sim 12/2012?$)
Burigana et. al. arXiv:1003.6108, ApJ to appear.
D. Boyanovsky, C. Destri, H. J. de Vega, N. G. Sánchez, (review article), arXiv:0901.0549, Int.J.Mod.Phys.**A 24**, 3669-3864 (2009).

Primordial Power Spectrum

Adiabatic Scalar Perturbations: $P(k) = |\Delta_{k\;ad}^{(S)}|^2 \; k^{n_s - 1}$.

To dominant order in slow-roll:

$$|\Delta_{k\;ad}^{(S)}|^2 = \frac{N^2}{12\,\pi^2} \; \left(\frac{M}{M_{Pl}}\right)^4 \; \frac{w^3(\chi)}{w'^2(\chi)} \; .$$

Hence, for all slow-roll inflation models:

$$|\Delta_{k\;ad}^{(S)}| \sim \frac{N}{2\,\pi\sqrt{3}} \left(\frac{M}{M_{Pl}}\right)^2$$

The WMAP result: $|\Delta_{k\;ad}^{(S)}| = (0.494 \pm 0.1) \times 10^{-4}$

determines the scale of inflation M (using $N \simeq 60$)

$$\left(\frac{M}{M_{Pl}}\right)^2 = 0.85 \times 10^{-5} \;\longrightarrow\; M = 0.70 \times 10^{16} \text{ GeV}$$

The inflation energy scale turns to be the grand unification energy scale !! We find the scale of inflation without knowing the tensor/scalar ratio r !!

The scale M is independent of the shape of $w(\chi)$.

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.

MCMC Results for double–well inflaton potential

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

Most probable values: $n_s \simeq 0.964,\ r \simeq 0.051$ ⇐measurable!!
The most probable double–well inflaton potential has a moderate nonlinearity with the quartic coupling $y \simeq 1.26\ldots$.

The $\chi \to -\chi$ symmetry is here spontaneously broken since the absolute minimum of the potential is at $\chi \neq 0$

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

MCMC analysis calls for $w''(\chi) < 0$ at horizon exit
$\Longrightarrow$ double well potential favoured.

C. Destri, H. J. de Vega, N. Sanchez, MCMC analysis of WMAP data points to broken symmetry inflaton potentials and provides a lower bound on the tensor to scalar ratio, Phys. Rev. D77, 043509 (2008), astro-ph/0703417.

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 $dn_s/dlnk$	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).

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

$r > 0.023$ at 95% CL and

Moreover,we find $r \sim 0.04$ the most probable value

For the other cosmological parameters, both analysis agree.

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:

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

$M_{Planck} \gtrsim 10^{18}$ 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

Universe expansion classicalizes the physics: decoherence

Two key observable numbers :

associated to the primordial density and primordial gravitons :

$$n_s = 0.9608\ , \quad r$$

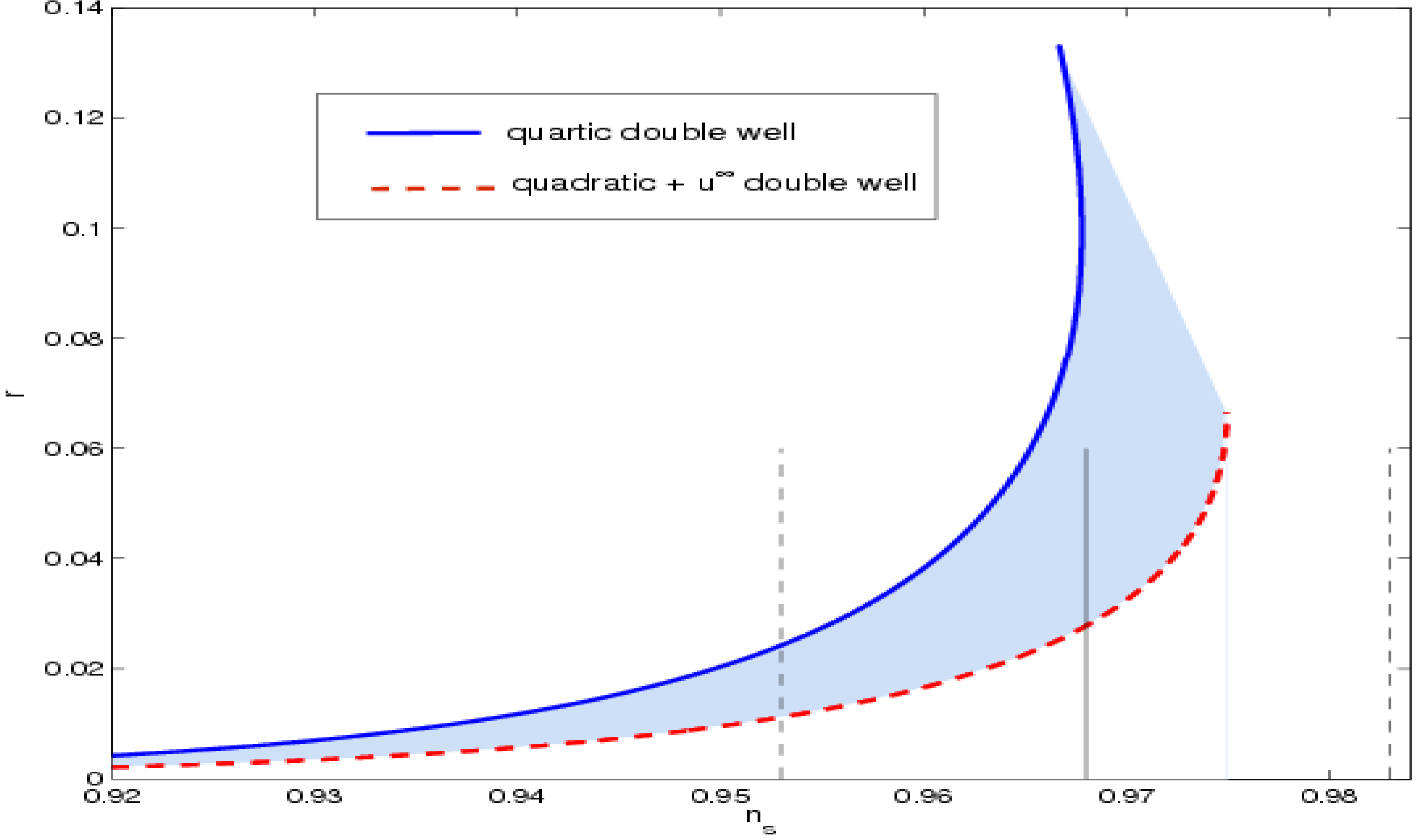
PREDICTIONS

$r < 0.04$

$r > 0.021$

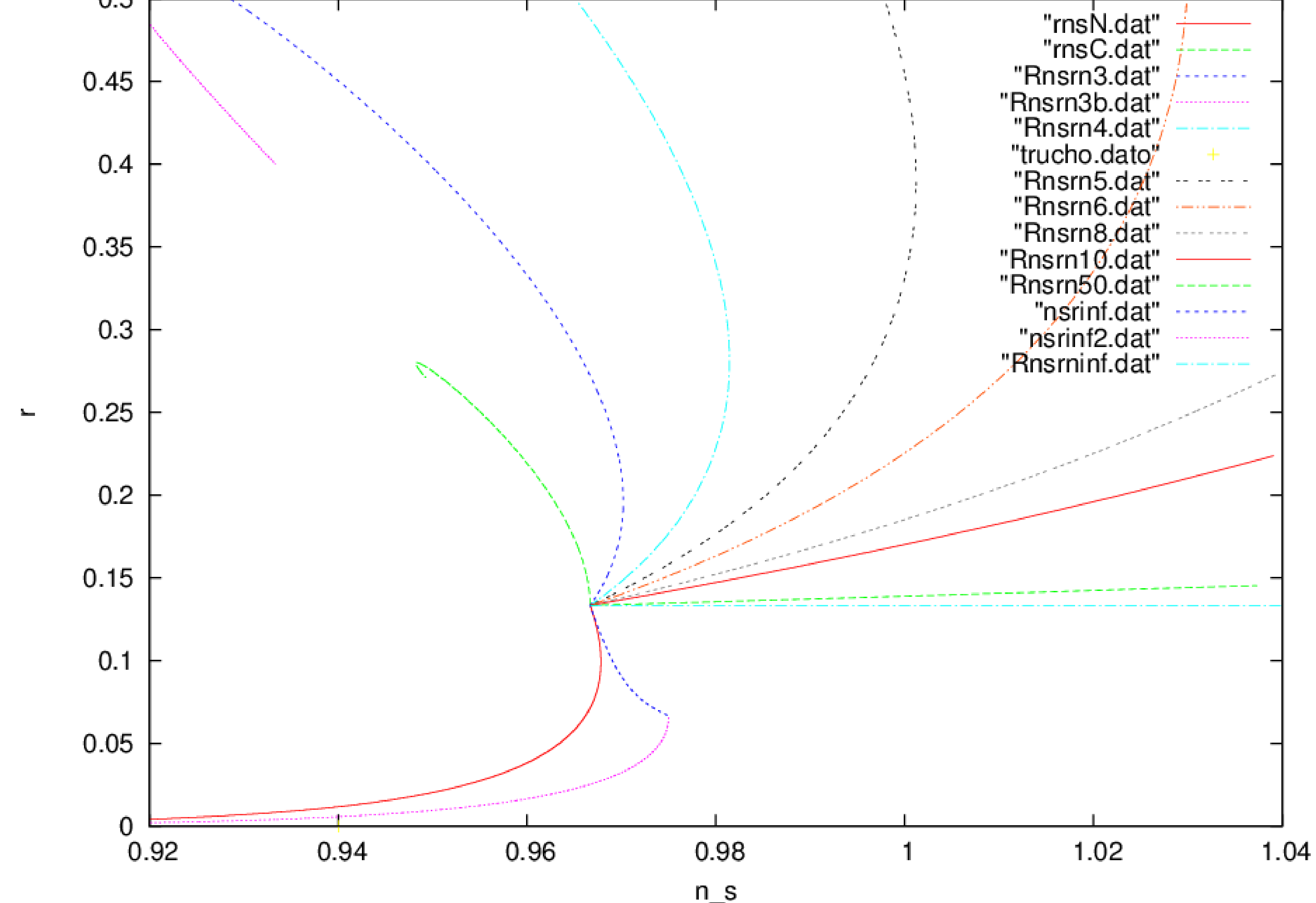
$$0.021 < r < 0.040$$

Most probable value: $r \sim 0.03,\ 0.04$



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)



"rnsN.dat"
"rnsC.dat"
"Rnsrn3.dat"
"Rnsrn3b.dat"
"Rnsrn4.dat"
"trucho.dato"
"Rnsrn5.dat"
"Rnsrn6.dat"
"Rnsrn8.dat"
"Rnsrn10.dat"
"Rnsrn50.dat"
"nsrinf.dat"
"nsrinf2.dat"
"Rnsrninf.dat"
r
n_s
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.92
0.94
0.96
0.98
1
1.02
1.04

From WMAP9 to Planck, to Next

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 : --> Besides meV active neutrinos:**
- **sterile neutrinos**
- **Would opens the sterile neutrino Family:**
- **keV sterile neutrino –WDM-**

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: $m_\nu \sim \frac{M^2_{\rm Fermi}}{M_R}$ 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: $V_{moduli} = M^4_{\rm SUSY} \; v\left(\frac{\phi}{M_{Pl}}\right)$ ressemble inflation potentials provided $M_{\rm SUSY} \sim 10^{16}$ GeV. First observation of SUSY in nature??

Predictive Physics of Inflation and GUT

Objectives: ***To focus on realistic and timely situations of inflation in connection with the CMB, dark energy, gravitational and particle physics, in the Standard model of the Universe,***

adding inter-disciplinarity and unification values, within a strongly predictive physical approach.

The formulation of inflation in the Ginsburg-Landau approach clarifies and places inflation in the setting of the succesful effective field theories of particle physics, phase transitions and superconductivity:

Recall: O(4) sigma model (for microscopic QCD), Landau-Wilson-Kadanoff (& for microscopic BCS)…

Powerful Approach: RESULTS

•***Universal*** **form** for the slow-roll inflaton potential **encodes the essential physics of the problem**:

- **$V(\varphi) = N M^4 w(\chi)$. N = number of efolds, M = scale of inflation,**
- $w(\chi)$ = dimensionless = order 1.
- **Slow-roll expansion** becomes a **explicit and *systematic* 1/N expansion. Couplings become *naturally* small:** suppression factors arising as powers of the ratio $(M/M_{Pl})^2$, $(M/M_{Pl})^4$,…., $(M/M_{Pl})^n$ **(no fine tuning).**
- **Scalar Adiabatic fluctuations:**

$|\Delta^R_k \, ad| = N (M/M_{Pl})^2$ implies using the **CMB data $\Delta T/T$**:

- **M = 0.54 10^{16} GeV = GUT SCALE** (besides the direct determination of M from tensor ratio r when detected)

- **Inflaton mass $m = M^2/M_{PL}$**

m = 1.21 x10^{13}GeV *see-saw type*

- **Small running of the scalar index:**

$$-4 \times 10^{-4} \leq dns/d\ln k \leq -2 \times 10^{-4}$$

- **Small Non-gaussianity:**

$$f_{NL} \sim (1 / N) \sim 0.02$$

- **Lower and upper Tensor r bounds**

$$0.021 \leq r \leq 0.04$$

- **$r \sim 0.03$, ns = 0.9608**
- **Universal (ns, r) banane surface**
- **Departure of scale invariance:**

$$\Delta = (½) (ns - 1) + r/8.$$

Negative concavity of the potential

$V''(\chi) < 0$ →→Symmetry breaking: double well : new inflation:

Binomial or trinomial potential

- Fast-roll stage generically precedes the Slow-roll stage and explains the low CMB multipoles: TT, TE, EE spectra and *the quadrupole supression*: Upper bound on the **Total number of inflation efolds:** Ntotal < 82 . Favoured value: Ntotal $\simeq$ 66.
- Transfert Function of Generic Initial Conditions computed: D(k) on the Power Spectra
- Quantum loop corrections to Inflation computed: small and controlled by powers of $(H/M_{Pl})^2 \sim 10^{-9}$: Validates Ginsburg-Landau Effective Theory of Inflation.
- Phases Before Inflation: planckian and trans-planckian phase: Implications for Dark energy, H_0 and CMB.
- Gravitational Entropy = Vacuum Energy of the Universe. Results: Evolution : Dark Energy Action, LSS, ESA Voyage 2050… White Paper ….

OUTLOOK AND CONCLUSIONS

- **Robust predictive physical approach** well prepared and timely: allow to extract relevant physics from the CMB+LSS data. **Paves the way with a strategy of discoveries, namely : *B-mode detection, the probe of Grand Unification scale and the hint of supersymmetry breaking* .**
- **Predicted r = 0.04-0.03 , (r, ns) banane . B mode detection : LiteBIRD, and other future CMB observations.**
- **Grand Unification Physics Scale = Scale of Inflation = Scale of Semiclassical Gravity (Semiclassical Vacuum and Connection with Hawking Temperature)**
- **GUT scale appears in: (1) Scale of particle physics coupling unification. (2) Scale in the See-saw mass neutrino oscillations .(3) Scale in the See-saw mass of the inflaton and hints to the SUSY breaking scale …A suivre . THANK YOU !!!**

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)

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).

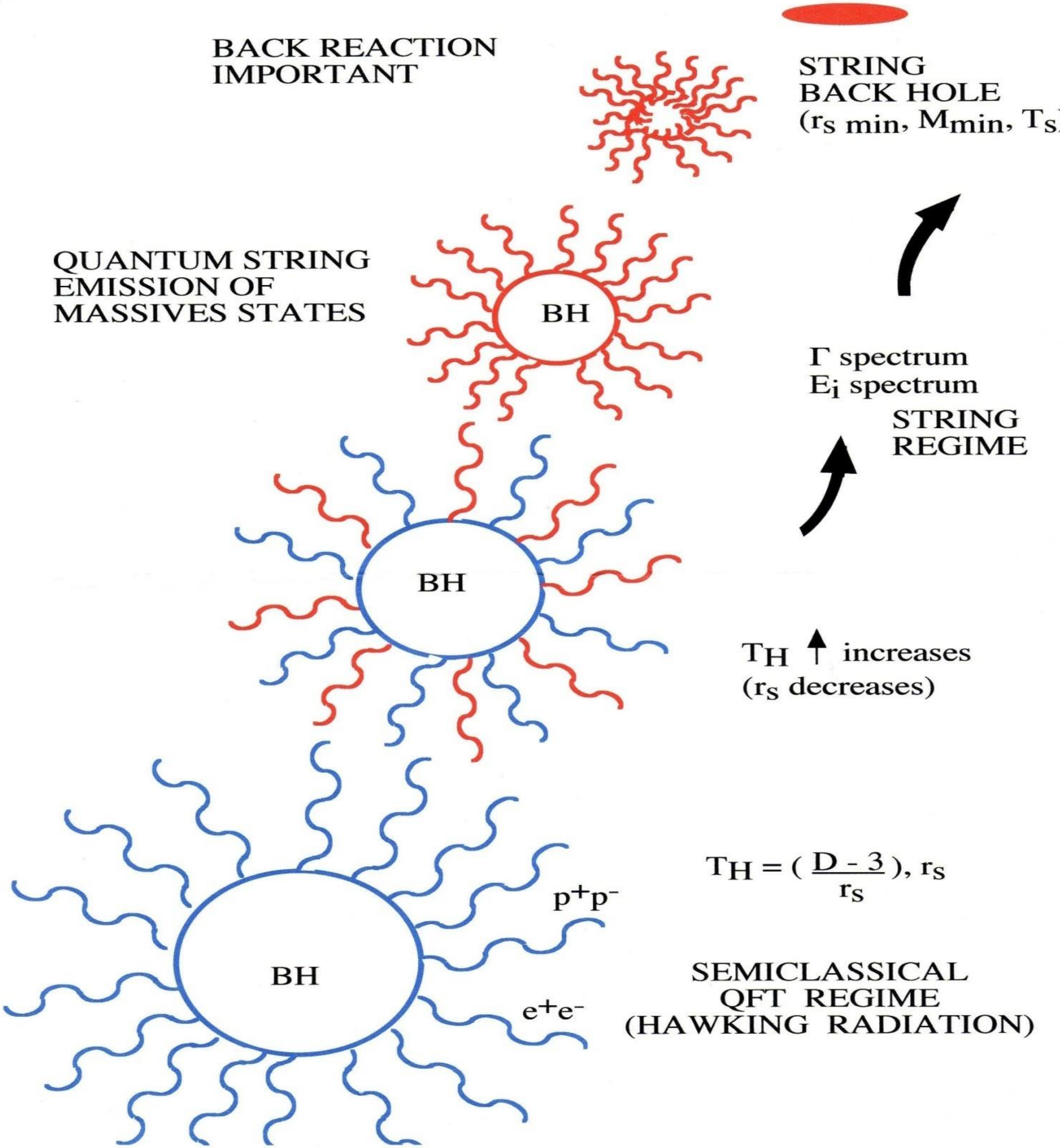
Conceptual unification of quantum black holes, elementary particles and quantum states

CONCEPTUAL UNIFICATION

- →Cosmological evolution goes from a quantum gravity phase to a semi-classical phase (inflation) and then to the classical (present cosmological) phase.

- →Black Hole Evaporation (BH hole decay rate), heavy particles and extended quantum decay rates; black hole evaporation ends as quantum extended decay into pure (non mixed) non thermal radiation.

- →The Hawking temperature, elementary particle and Hagedorn (string) temperatures are the same concept in different gravity regimes (classical, semiclassical, quantum) and turn out to be the precise classical-quantum duals of each other.



BACK REACTION
IMPORTANT
STRING
BACK HOLE
(r_S min, M_{min}, T_S)
QUANTUM STRING
EMISSION OF
MASSIVES STATES
BH
Γ spectrum
E_i spectrum
STRING
REGIME
BH
T_H ↑ increases
(r_S decreases)
$T_H = (\frac{D - 3}{r_S}), r_S$
p^+p^-
BH
e^+e^-
SEMICLASSICAL
QFT REGIME
(HAWKING RADIATION)

What is the nature of the Dark Matter?

83% of the matter in the universe is Dark.

Only the DM gravitational effects are noticed and they are necessary to explain the present structure of the Universe.

DM (dark matter) particles are neutral and so weakly interacting that no effects are so far detectable.

Theoretical analysis combined with astrophysical data from galaxy observations as:

- Observed galaxy densities and velocity dispersions.
- Observed galaxy density profiles are cored.
- Acceleration of gravity in the surface of DM dominated galaxies is universal
  $g \simeq 1.7 \times 10^{-11} \, m/s^2 \; = 540 \text{ kpc}/(\text{Gyr})^2$.

points towards a DM particle mass in the keV scale called warm dark matter (WDM). 2 keV = 1/250 electron mass.

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.

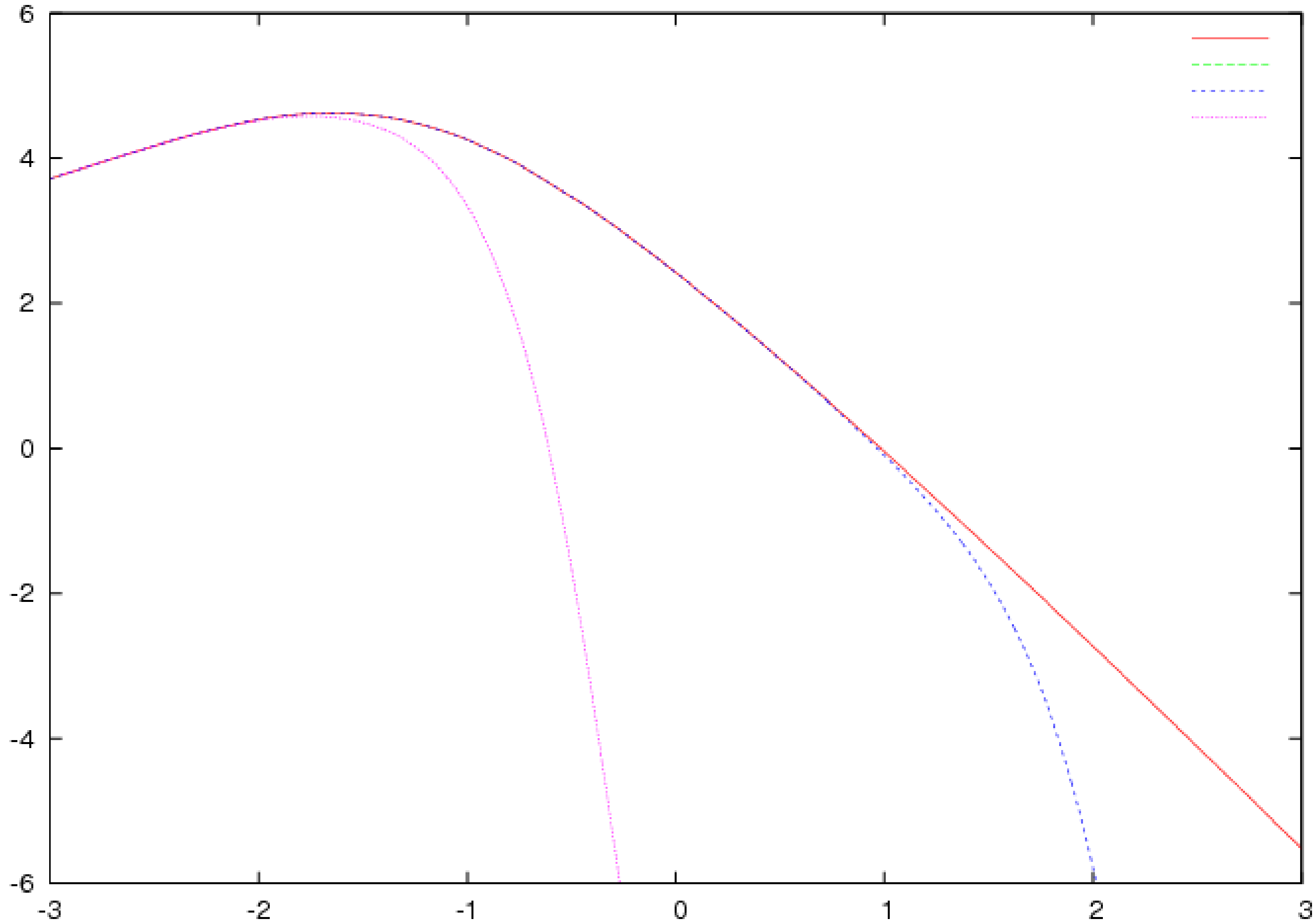
N-body CDM simulations fail to produce the observed structures for small scales less than some kpc.

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

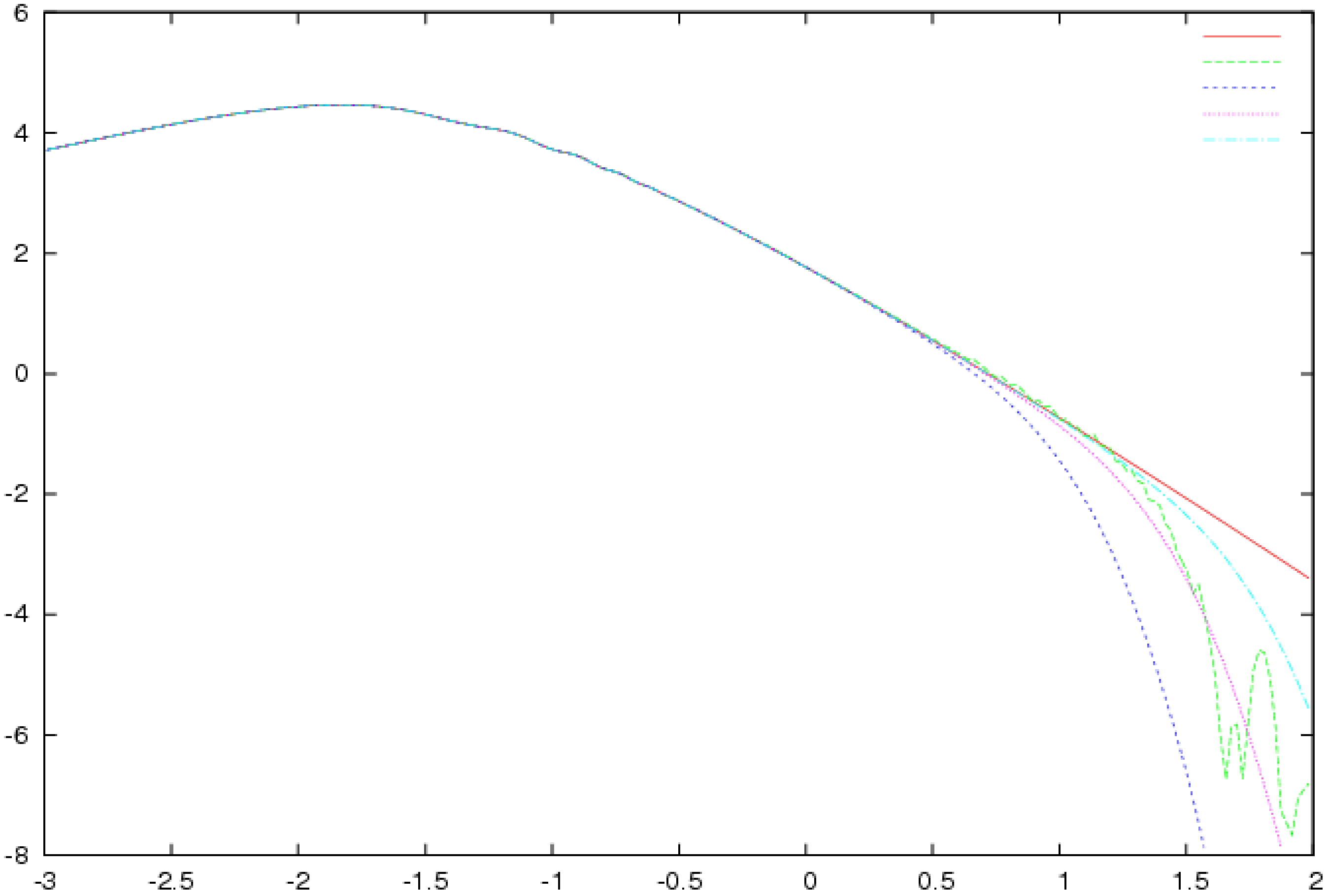


$\log_{10} P(k)$ vs. $\log_{10}[k \text{ Mpc } h]$ for WIMPS, 1 keV DM particles and 10 eV DM particles. $P(k) = P_0 \, k^{n_s} \, T^2(k)$.

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

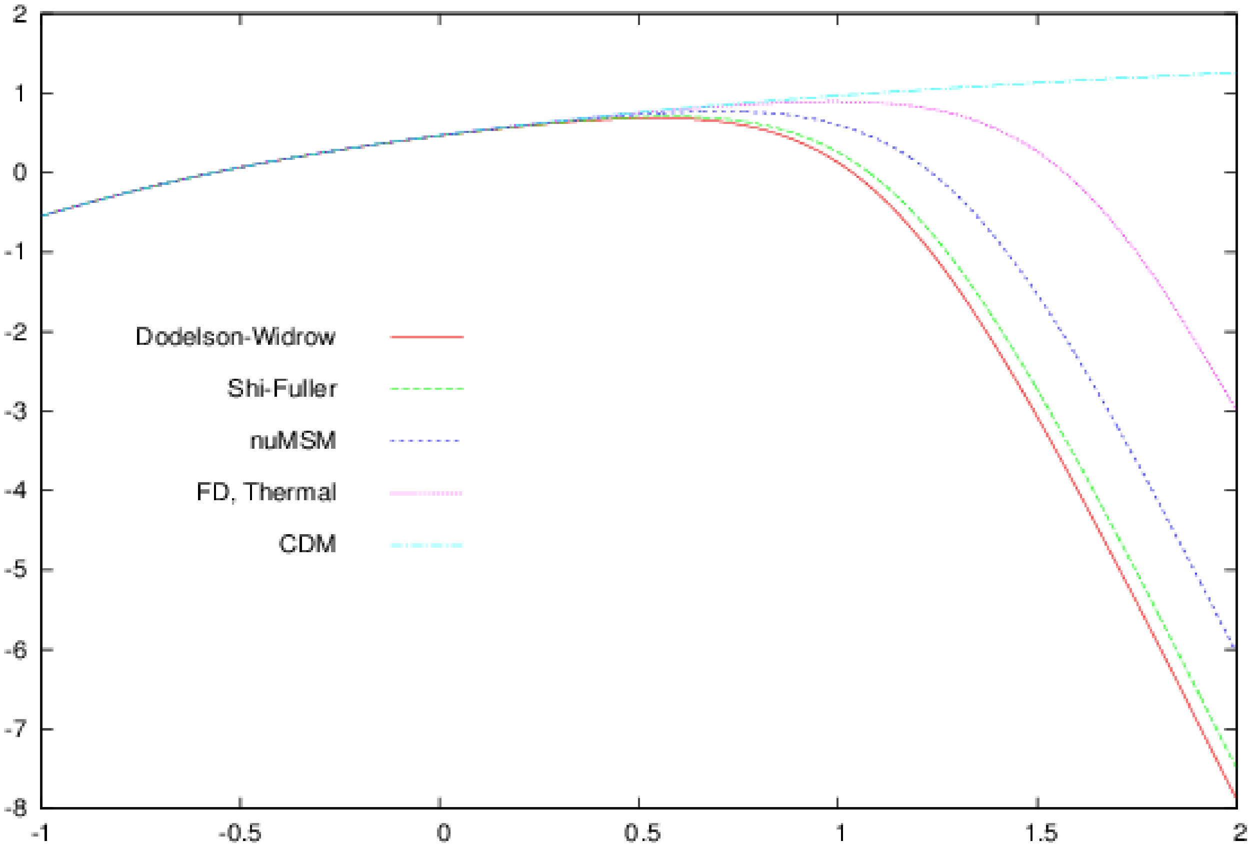
Transfer function in the MD era from Gilbert integral eq

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.

Linear primordial power spectrum $\Delta^2(k)$ vs. k Mpc $/h$



$\log_{10} \Delta^2(k)$ vs. $\log_{10}[k \text{ Mpc}/h]$ for a physical mass of 2.5 keV in four different WDM models and in CDM. WDM cuts $\Delta^2(k)$ on small scales. $r \lesssim 73 \, (\text{keV}/m)^{1.45}$ kpc/h.

CDM and WDM are identical for CMB.

Galaxies

Physical variables in galaxies:

a) Nonuniversal quantities: mass, size, luminosity, fraction of DM, DM core radius r_0, central DM density ρ_0, ...

b) Universal quantities: surface density $\mu_0 \equiv r_0\,\rho_0$ and DM density profiles. M_{BH}/M_{halo} (or the halo binding energy).

The galaxy variables are related by universal empirical relations. Only one variable remains free.

Universal quantities may be attractors in the dynamical evolution.

Universal DM density profile in Galaxies:

$$\rho(r) = \rho_0 \, F\left(\frac{r}{r_0}\right) \;,\; F(0) = 1 \;,\; x \equiv \frac{r}{r_0} \;,\; r_0 = \text{DM core radius.}$$

Empirical cored profiles: $F_{Burkert}(x) = \frac{1}{(1+x)(1+x^2)}$.

Cored profiles do reproduce the astronomical observations.

Warm Dark Matter Cosmology (LWDM)

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 within a 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

Dark Matter in the Universe

→ **81 % of the matter of the universe is DARK (DM).**
→ **DM is the dominant component of galaxies.**
→ **DM interacts through gravity.**

→ **Further DM interactions unobserved so far.**
Such couplings must be very weak: much weaker than weak interactions.
→ **DM is outside the Standard Model of Particle Physics.**

Proposed candidates:
Cold Dark Matter: CDM, WIMPS, m ~ 1 − 1000 GeV: IN BIG TROUBLE.

→ **Warm Dark Matter: WDM, sterile neutrinos, m ~ keV**
THE ANSWER !

→ **DM particles decouple due to the universe expansion, their distribution function freezes out at decoupling.**
→ **Early decoupling: Td ~ 100 GeV**

WDM properties

WDM is characterized by

- its initial power spectrum cutted off for scales below ~ 50 kpc. Thus, structures are not formed in WDM for scales below ~ 50 kpc.
- its initial velocity dispersion. However, this is negligible for $z < 20$ where the non-linear regime starts.
- Classical N-body simulations break down at small distances ($\sim$ pc). Need of quantum calculations to find WDM cores.

Structure formation is hierarchical in CDM.

WDM simulations show in addition top-hat structure formation at large scales and low densities but hierarchical structure formation remains dominant.

Summary Warm Dark Matter, WDM: $m \sim$ keV

- Large Scales, structures beyond ~ 100 kpc: WDM and CDM yield identical results which agree with observations
- Intermediate Scales: WDM simulations give the correct abundance of substructures.
- Inside galaxy cores, below ~ 100 pc: N-body classical physics simulations are incorrect for WDM because of important quantum effects.
- Quantum calculations (Thomas-Fermi) give galaxy cores, galaxy masses, velocity dispersions and densities in agreement with the observations.
- Direct Detection of the main WDM candidate: the sterile neutrino. Beta decay and electron capture. ^{3}H, Re, Ho.

So far, not a single valid objection arose against WDM.
Baryons (<16%DM) expected to give a correction to WDM

UPDATE and CLARIFICATIONS

→ΛCDM agrees with CMB + LSS **BUT**
ΛCDM **DOES NOT agree with SSS (GALAXIES)**

→ **ΛWDM** agrees with CMB + LSS **+ SSS (GALAXIES)**
The Standard Model of the Universe is LWDM =
{GR, Newtonian Gravity, Field Theory, QFT}

Sentences like « CMB confirms the ΛCDM model … »
Must be completed by adding: « in the large scales" »
<u>and must be updated with the sentence:</u>
→ **<u>CMB confirms the ΛWDM model in large scales</u>**

NEW: Gravity and Quantum Mechanics in Galaxies. Newton, Fermi and Dirac meet together in Galaxies because of keV WDM

→**WDM solves naturally the problems of CDM and CDM + baryons , provides the same large scale and CMB results than ΛCDM and agrees with the observations at the galactic and small scales.**

→**Warm Dark Matter Cosmology (ΛWDM) is more complete, correct and general theory than Cold Dark Matter (LCDM) because it contains CDM as a limiting case (for high particle masses), reproduces LCDM at large scales and solves the known problems of CDM at small and intermediate scales.**

→**So far, not a single valid objection arose against WDM.**

ΛWDM Cosmology

(I) The Standard Model of the Universe Includes Inflation

(II) DARK MATTER IN GALAXIES from Theory and Observations: Warm (keV scale) DM

(III) NOVEL: 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. Generalized Eddington approach to galaxies

(V) The case for the keV sterile neutrino

DARK MATTER UPDATE

- **THERE IS NO CUSP/CORE problem:**
- **Observed Galaxy density 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 CDM Wimps, NO DM annhilation,

The Total DM cannot be bosons (Axions)

WDM free streaming scale

The scale $l_{1/2}$ is where the WDM power spectrum is one-half of the CDM power spectrum:

$$l_{1/2} = 1/k_{1/2} = 207 \text{ kpc } \left(\text{keV}/m_{FD}\right)^{1.12}$$

This scale reproduces the sizes of the observed DM galaxy cores when the WDM mass is in the keV scale !!

$l_{1/2}$ is similar but more precise than the free streaming scale (or Jeans' scale):

$$r_{Jeans} = 210 \, \text{kpc} \, \frac{\text{keV}}{m_{FD}} \left(\frac{100}{g_d}\right)^{\frac{1}{3}} ,$$

$g_d =$ number of UR degrees of freedom at decoupling.

he Phase-space density $Q = \rho/\sigma^3$ and its decrease factor

The phase-space density today Q_{today} follows observing dwarf spheroidal satellite galaxies of the Milky Way (dSphs) as well as spiral galaxies. Its value is galaxy dependent.

For dSphs $Q_{today} \sim 5000 \; (0.18 \text{ keV})^4$ Gilmore et al. 07/08.

During structure formation Q decreases by a factor that we call $Z, \; (Z > 1)$: $\quad Q_{today} = \frac{1}{Z} \, Q_{prim}$

The spherical model gives $Z \simeq 41000$ and N-body simulations indicate: $10000 > Z > 1$. Z is galaxy dependent.

As a consequence m is in the keV scale:
1 keV $\lesssim m \lesssim 10$ keV.

This is true both for DM decoupling in or out of equilibrium, bosons or fermions.
It is independent of the particle physics model.

de Vega Sanchez – Theory Approach to Galaxy Structure

FERMIONIC QUANTUM WDM and GRAVITATION DETERMINE THE OBSERVED PHYSICAL GALAXY STRUCTURE

→ **Dark matter (DM): main component of galaxies. Quantum mechanics: cornerstone of physics from microscopic to macroscopic systems: quantum liquids He3, white dwarf stars, neutron stars, BHs: NOT Exotic Physics.**

→ **Quantum mechanics also responsible of galaxy structures at the kpc scales and below: near the galaxy center, below 10 - 100 pc, the DM quantum effects important for warm DM (WDM), that is for DM particles with masses in the keV scale. MNRAS 2010 , NA2013 , JAP2013, dVS PRD 2013, dVSS MNRAS 2014, EPJC 2016, IJMPA 2016,**

→ **Approach to galaxy structure with results in remarkable agreement with observations:**

Quantum Bounds on Fermionic Dark Matter

The Pauli principle gives the upper bound to the phase space distribution function of spin-$\frac{1}{2}$ particles of mass m:

$$f(\vec{r}, \vec{p}) \leq 2$$

The DM mass density is given by:

$$\rho(\vec{r}) = m \int d^3p \, \frac{f(\vec{r},\vec{p})}{(2\,\pi\,\hbar)^3} = \frac{m^4}{2\,\hbar^3}\,\sigma^3(\vec{r})\,\bar{f}(\vec{r})\,K \; ,$$

where:

$\bar{f}(\vec{r})$ is the $\vec{p}-$average of $f(\vec{r}, \vec{p})$ over a volume $m^3\,\sigma^3(\vec{r})$,

$\sigma(\vec{r})$ is the DM velocity dispersion, $\sigma^2(\vec{r}) \equiv < v^2(\vec{r}) > /3$

$K \sim 1$ a pure number.

The Pauli bound $\bar{f}(\vec{r}) \leq 2$ yields: $Q(\vec{r}) \equiv \frac{\rho(\vec{r})}{\sigma^3(\vec{r})} \leq K\,\frac{m^4}{\hbar^3}$

This is an absolute quantum upper bound on $Q(\vec{r})$ due to quantum physics, namely the Pauli principle.

$Q(\vec{r})$ can **never** take values larger than $K\,m^4/\hbar^3$.

In the classical limit $\hbar \to 0$ and the bound disappears.

Classical physics breaks down near the galaxy center

N-body simulations point to cuspy phase-space densities

$Q(r) = Q_s \left(\frac{r}{r_s}\right)^{-\beta}$, $\beta \simeq 1.9 - 2$, $r_s =$ halo radius,

$Q_s =$ mean phase space density in the halo.

$Q(r)$ derived within classical physics tends to infinity for $r \to 0$ violating the Pauli principle bound.

Classical physics breaks down near the galaxy center.

For $\beta = 2$ the quantum upper bound on $Q(r)$ is valid for

$$r \geq r_q \equiv \frac{\hbar^{\frac{3}{2}}}{m^2} \sqrt{\frac{Q_s}{K}}\, r_s \ .$$

Observations yield: $30 < \frac{r_s}{\mathrm{pc}} < 5.10^4$, $2.10^{-5} < \frac{\hbar^{\frac{3}{2}} \sqrt{Q_s}}{(\mathrm{keV})^2} < 0.6$

The larger Q_s and the smaller r_s correspond to ultra compact dwarfs

The smaller Q_s and the larger r_s correspond to spirals.

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

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

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 !

Galaxy	$\frac{r_h}{\mathrm{pc}}$	$\frac{\sigma}{\frac{\mathrm{km}}{\mathrm{s}}}$	$\frac{\hbar^{\frac{3}{2}}\sqrt{Q_h}}{(\mathrm{keV})^2}$	$\rho(0)/\frac{M_\odot}{(\mathrm{pc})^3}$	$\frac{M_h}{10^6\ M_\odot}$
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

(1) Dwarf galaxies are quantum macroscopic objects for WDM supported against gravity by the WDM fermion pressure

(2) 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.

(3) 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-

- 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 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 MINIMAL GALAXY MASS

A minimal galaxy mass and minimal velocity dispersion are found. Mmin ~ 3.1 10^4 Msun

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 O(keV).

More precise data will make this estimation more precise.

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 $\nu(0) \to +\infty$ (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 in the keV scale.

WDM THEORY OF GALAXIES
REPRODUCES THE OBSERVED GALAXY STRUCTURES
Gravity and Quantum Mechanics meet together in Galaxies

de Vega, Salucci, Sanchez 2014 reproduced, with a physical theory to 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 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 kilo 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} Msun till 5×10^{11} Msun.

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 %.

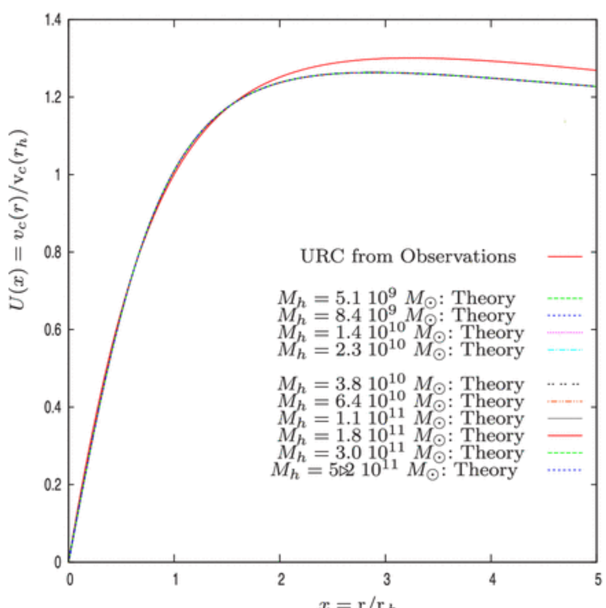
Reference:

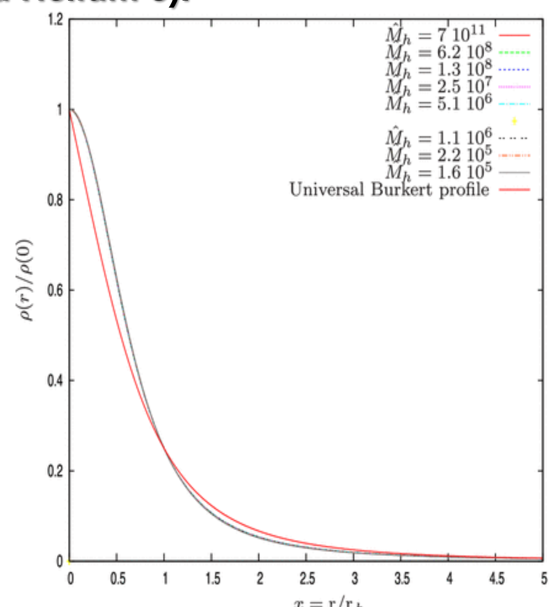
H.J. de Vega; P. Salucci; N. G.Sanchez MNRAS 442 (2): 2717-2727 (2014)

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 *radius.*

The right panel 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 observations. (Examples of other macroscopic objects in nature are dwarf stars, neutron stars and the liquid Helium 3).





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 : Two regimes for galaxies emerge : $P(r) = v^2(r)\ \rho(r)$

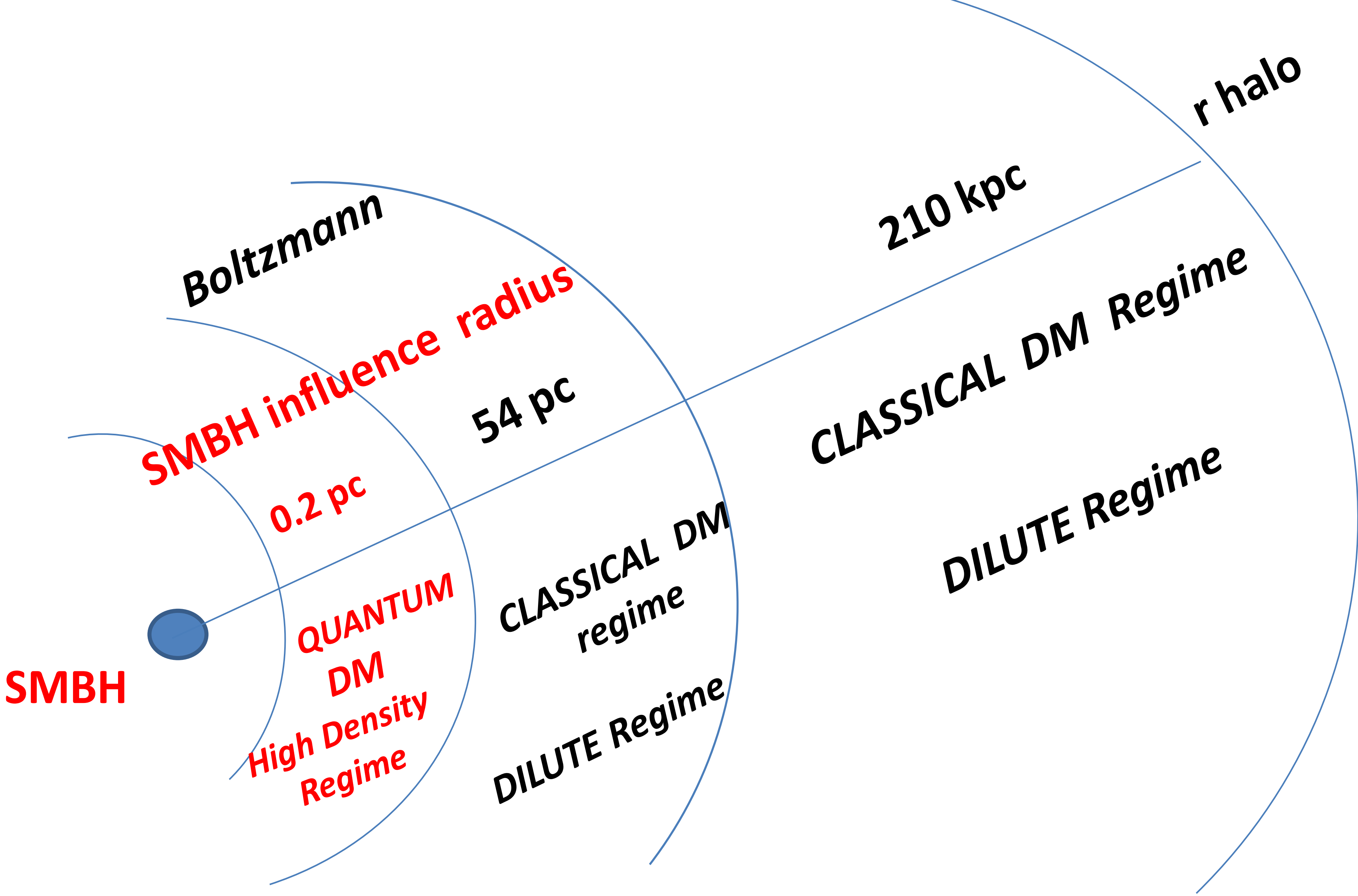
→(i) Large dilute galaxies for $M_h > 2{,}3\ 10^6$ Msun and effective températures $T_0 > 0{,}017$ K described by the classical Boltzmann gaz self-gravitational with local ideal gaz equation of state at each point (r-dependent).

→(ii) Compact dwarf galaxies for $1{,}6\ 10^6\ M_{sun} > M_h > M_{h,\,min} = 30000\ (2\text{keV} / m)^{16/5}\ M_{sun}$, $T_0 < 0{,}011$ 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 degenerated 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 computed too.

→ **The normalized density and velocity profiles are universal fonctions 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 remarquably 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).**



WDM Thomas-Fermi Galaxy Theory with SMBH

SMBH: Super Massive Black holes

H.J. de Vega & N.G. Sanchez

The Distribution Function of Dark Matter

→ **We developped 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 .**

MORE RESULTS

→(i) CORED density profiles $\rho(r) \to \rho(0) - Kr^2$ 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 $r < 3r_h$. (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

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

and $T(r) = m\, v^2(r) / 3$

for $3\, r_h < r < R_{virial}$,

which slowly decreases with r.

That is to say, for $r < R_{virial}$,

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 gaz can thermalize in despite of being collissionless:
- 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 are clearly understood :

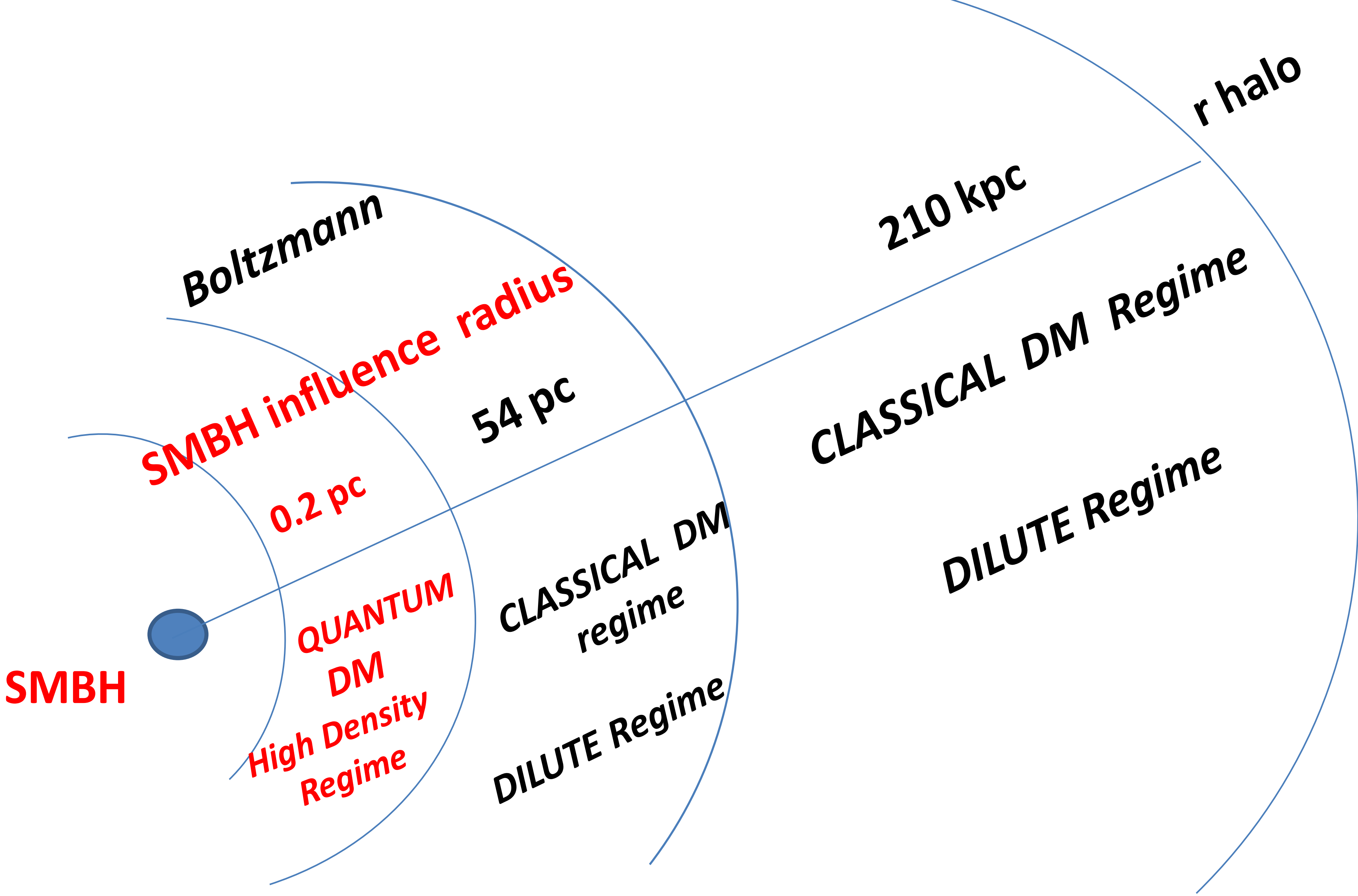
- In the inner halo region the density is higher than beyond the halo radius.

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 thermalisation is achieved.



WDM Thomas-Fermi Galaxy Theory with SMBH

SMBH: Super Massive Black holes

H.J. de Vega & N.G. Sanchez

Many Ongoing WDM Directions of Research :

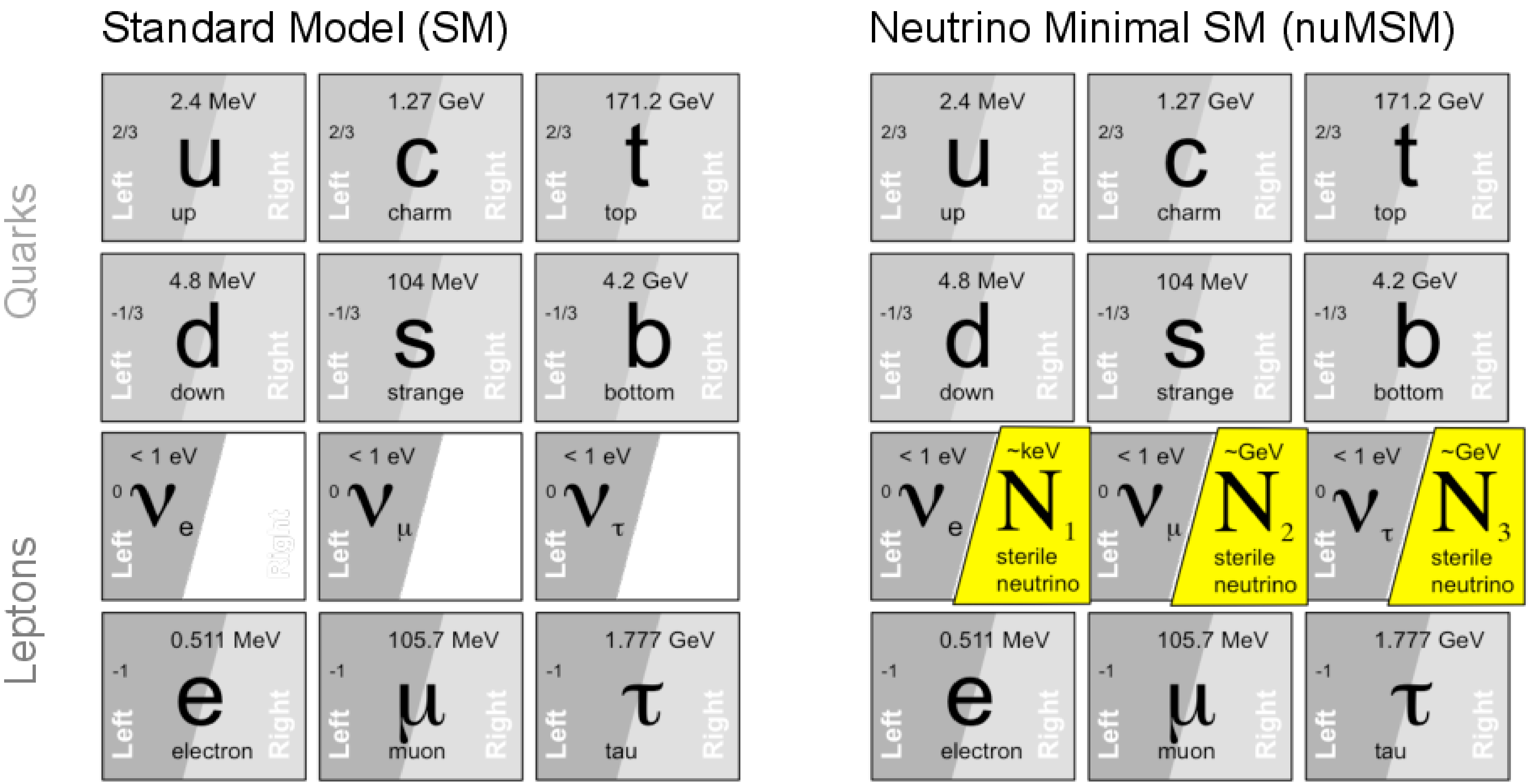
- Particle Models, Sterile neutrinos, Production mechanisms. WDM decay
- Experimental searches.

- WDM Numerical Simulations: structure formation
-Constraints on WDM m_x, mvs: Analytical, numerical, small scales, velocity dispersions

- WDM Astrophysics & Cosmological: reionization, 21 cm line, prospects for SKA. High z supernova lensing, HST, WDM Star Formation, WDM Galactic BHs

- WDM CMB: WDM decay, CMB Spectrum distortions, ….

Sterile Neutrinos



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).

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....

Sterile neutrino models

- DW: Dodelson-Widrow model (1994) sterile neutrinos produced by non-resonant mixing from active neutrinos.
- Shi-Fuller model (1998) sterile neutrinos produced by resonant mixing from active neutrinos.
- ν-MSM model (1981)-(2006) sterile neutrinos produced by a Yukawa coupling from a real scalar χ.
- DM models must reproduce $\bar{\rho}_{DM}$, galaxy and structure formation and be consistent with particle experiments.

WDM particles in different models behave just as if their masses were different (FD = thermal fermions):

$$\frac{m_{DW}}{\text{keV}} \simeq 2.85 \left(\frac{m_{FD}}{\text{keV}}\right)^{\frac{4}{3}}, \; m_{SF} \simeq 2.55 \; m_{FD}, \; m_{\nu\text{MSM}} \simeq 1.9 \; m_{FD}.$$

H J de Vega, N Sanchez,
Phys. Rev. D85, 043516 and 043517 (2012).

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 sca 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.

$$^3H_1 \Longrightarrow {}^3He_2 + e^- + \bar{\nu}_e \quad , \quad {}^{187}Re \Longrightarrow {}^{187}Os + e^- + \bar{\nu}_e .$$

The electron energy spectrum is observed.

Electron capture: $^{163}Ho + e^- \Longrightarrow {}^{163}Dy^* + \nu_e$

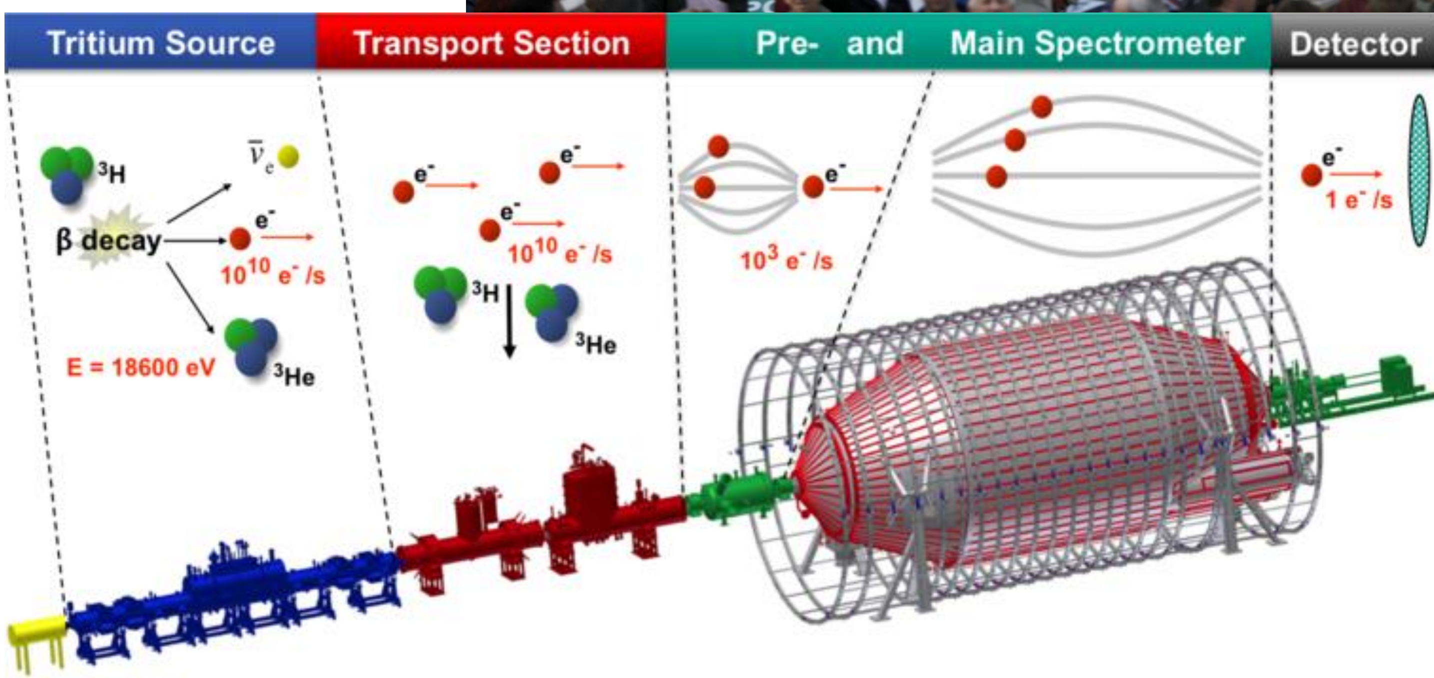
The nonradiative de-excitation of the Dy^* is observed and different for ν_s in the keV range than for active ν_e.

Experiments that may detect sterile neutrinos:

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

They search the mass of the ordinary neutrino.

KATRIN
Karlsruhe Tritium Neutrino Experiment



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. $r_{Jeans} \sim 5$ 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:

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

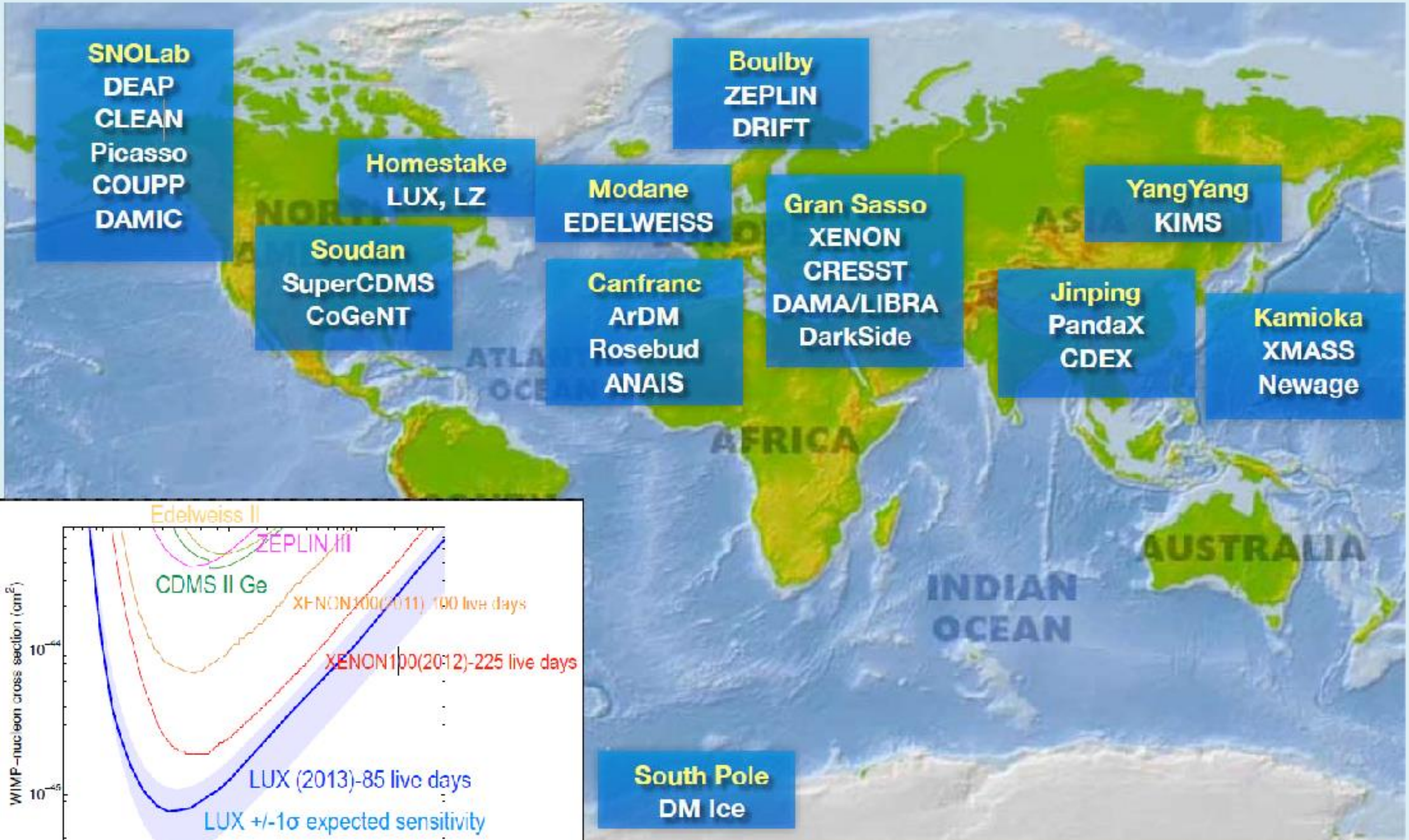
D. Boyanovsky, H. J. de Vega, N. G. Sanchez, PRD 77, 043518 (08). H. de Vega, N. Sanchez, arXiv:1401.1214

- **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 <u>cannot be due</u> 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 <u>unrelated to any DM</u> detection**

Dans le monde entier



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', MNRAS 404, 885 (2010).

Future Perspectives: Detection!

Sterile neutrino detection depends upon the particle physics model. There are sterile neutrino models where the keV sterile is stable and thus hard to detect.

Astronomical observation of steriles:
X-ray data from galaxy halos.

Direct detection of steriles in Lab:

Bounds on mixing angles from
Mare, Katrin, ECHo, Project 8 and PTOLEMY are expected.

For a particle detection a dedicated beta decay or electron capture experiment looks necessary to search sterile neutrinos with mass around 2 keV.

Calorimetric techniques seem well suited.

Best nuclei for study:

Electron capture in ^{163}Ho, beta decay in ^{187}Re and Tritium.

Dark Energy

$76 \pm 5\%$ of the present energy of the Universe is Dark !
Current observed value:
$\rho_\Lambda = \Omega_\Lambda \, \rho_c = (2.39 \text{ meV})^4 \;\; , \;\; 1 \text{ meV} = 10^{-3} \text{ eV}.$
Equation of state $p_\Lambda = -\rho_\Lambda$ within observational errors.
Quantum zero point energy. Renormalized value is finite.
Bosons (fermions) give positive (negative) contributions.
Mass of the lightest particles ~ 1 meV is in the right scale.
Spontaneous symmetry breaking of continuous symmetries produces massless scalars as Goldstone bosons. A small symmetry breaking provide light scalars: axions,majorons...
Observational Axion window $10^{-3} \text{ meV} \lesssim M_{\text{axion}} \lesssim 10 \text{ meV}$.
Dark energy can be a cosmological zero point effect. (As the Casimir effect in Minkowski with non-trivial boundaries).
We need to learn the physics of light particles (< 1 MeV), also to understand dark matter !!

The Standard Model of the Universe and its Extension

→The Standard Model of the Universe: Inflation, General Relativity, Quantum Field Theory, Dark Matter (outside of the Standard Model of Particle Physics, Warm Dark Matter), Dark Energy (Vacuum Energy).

→As in Particle Physics : The Standard Model of Cosmology needs to be Extended or Completed:

And also: Some pieces (eg CDM: recurrently do not agree with observations at galactic and smaller scales , or recurrently not detected in the dedicated energy range with the right detectors) call for a changement.

WDM It yields the same LSS results as CDM and CMB and also agree with SSS and Galaxy observations .

→ Extending / Completing the Universe History Before Inflation requires Quantum Physics at and beyond the Planck

THEORY & OBSERVATIONS

The direction in which data and Theory are pointing:

A Strategy for discoveries:

- **Standard Model of the Universe and its Quantum Precursor**

- **Standard Single field Inflation: Double Well**
  - **r ~ 0.04 - 0.02**
- **RUNNING of the Primordial Spectral Index 10^{-4}**
- **SMALL PRIMORDIAL NON GAUSSIANITY : f_NL ~ 0.02**

- **DARK ENERGY= VACUUM ENERGY = Λ, meV**

DARK MATTER = WARM DARK MATTER = keV

NO CUSP/CORE Problem, Profiles are Cored

And more in this direction….

GRACIAS

por vuestra ATENCION !!!

MERCI beaucoup pour votre ATTENTION !!

THANK YOU for your ATTENTION !!

CONTENTS

Planckian and transplanckian energies are theoretically allowed, physically motivated too

The Universe and its very early stages have all the quantum conditions for such extreme quantum gravitational regimes and energies, the black hole interiors too.

The truly quantum gravity domain is not reduced to be fixed at the planck scale or the neighborhoods of it, but extends deep beyond the planck scale in the highly quantum trans-planckian

Quantum theory is more complete than classical theory and tells us what value a classical observable should have.

The classical-quantum (or wave-particle) duality is a robust and universal concept

(It does not depend on the nature or number of space-time dimensions, compactified or not, nor on particular space-time geometries, topologies, symmetries, nor on other at priori condition.)

Moreover, the quantum trans-planckian eras in the far past universe determine the observables of the post-planckian eras

e.g. the inflation observables, CMB and the cosmological vacuum energy until today dark energy,

Namely the evolution from the quantum very early phases to the semi-classical and classical phases and the arrow of time as determined by the gravitational entropy.

REFERENCES

[1] N. G. Sanchez, *Quantum Discrete Levels of the Universe from the early trans-planckian vacuum to the late dark energy* (2020)

- ## 2019 Trilogy
- [2] N. G. Sanchez, ***New Quantum Phase of the Universe before Inflation and its Cosmological and Dark Energy Implications***
  Int Journal Mod Phys A34, No.27, 1950155 (2019)
- [3] N. G. Sanchez, ***The Classical-Quantum Duality of Nature: New variables for Quantum Gravity,***
  Int Journal Mod Phys D18, 1950055 (2019)
- [4] N. G. Sanchez, ***The New Quantum structure of the space-time,***
  J. Grav & Cosmology 25, pp 91-102, (2019)

https://www.researchgate.net/profile/Norma_Sanchez12

Nature is Quantum

That means that the real and complete laws of nature are those of quantum physics. Classical behaviours and domains are particular cases, limiting situations or approximations.

Classical gravity, and thus successful General Relativity are incomplete (non quantum) theories and must be considered as a particular approximation from a more complete theory yet to achieve.

A complete quantum theory should include and account for the physics at the Planck scale and the domain beyond it.

(i) Instead of starting from gravity, that is General Relativity and quantize it (by applying the different quantization -perturbative and non perturbative- procedures, with the by now well known shortcomings and developpements and its rich bibliography (is not our aim here to review it),

(ii) I start from Quantum theory and try to extend it to the Planck scale domain. (instead of going from classical gravity to quantum gravity, I go from quantum physics to quantum gravity). Of course, in constructing the road (ii) many of the lessons from road (i)

→ **Recall: One tractable and well posed piece of work is semiclassical gravity, in its several degrees of quantization: →** Quantum fields in classical Gen Rel. Examples are the Hawking radiation, the early universe inflation and the primordial quantum fluctuations, seeds of the structure in the Universe imprinted in the CMB temperature anisotropies and polarization.

→Moreover, as a result of quantum theory, the quantum cosmological vacuum could be the source of the present acceleration of the universe (dark energy) compatible with a cosmological constant.

The Wave-Particle Duality of Quantum Physics Including Gravity

Nature has a dual behavior of wave and corpuscle:

this *is the well known*

classical-quantum duality or wave-particle duality

of quantum physics (as the light and its photons, the microscopic world of elementary particles, ultradense plasmas, the laser, macroscopic quantum states (as compact stars, dwarfs , black holes), and many other examples).

I generalized this duality to gravity

by including its three regimes: classical, semiclassical and quantum, together with the Planck regime and the elementary particles domain: namely the

wave-particle-gravity duality* or *the classical-quantum gravity duality.

NGS, IJMPD18, IJMP19, GraCosm2019

This Duality is Universal

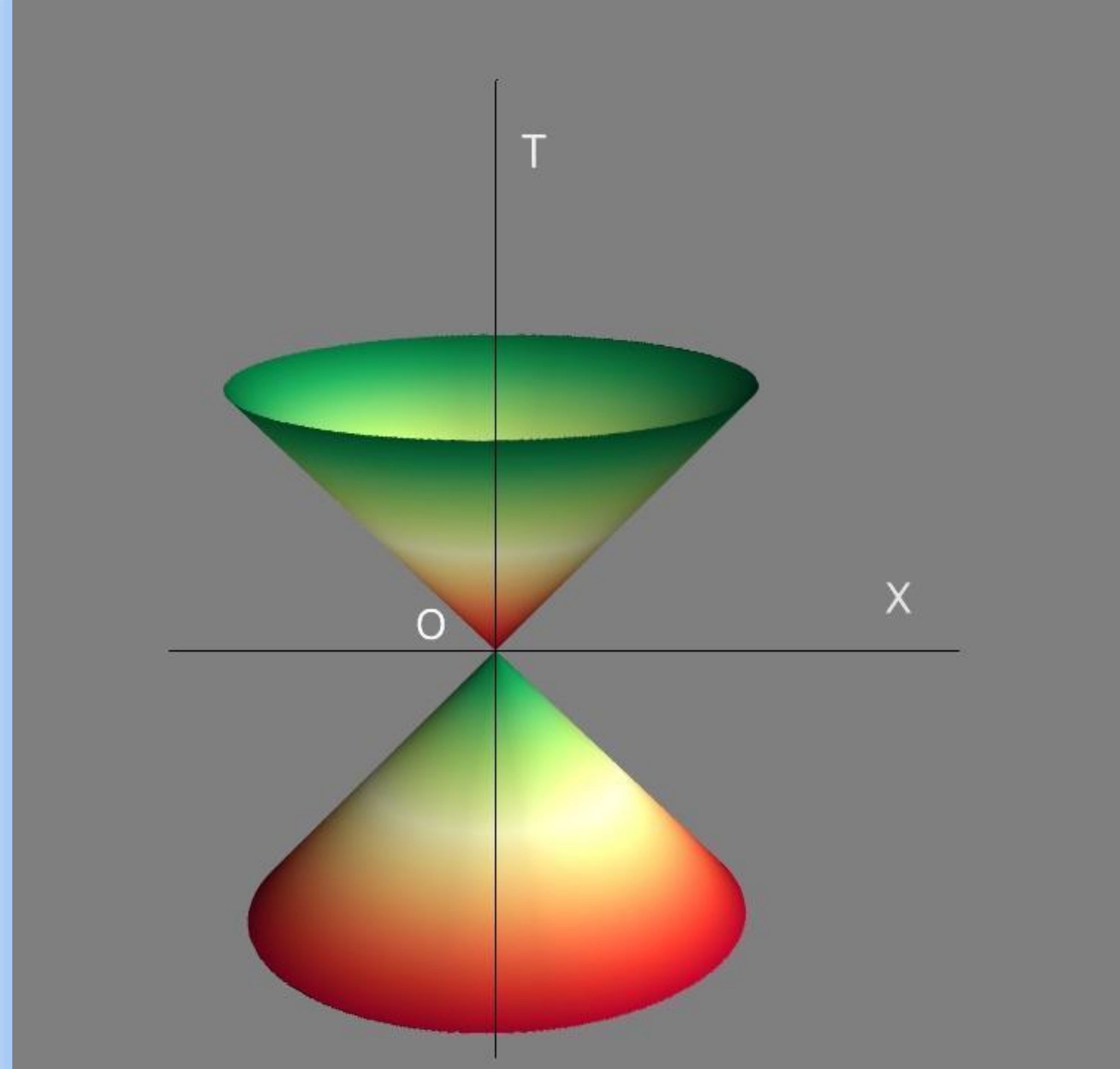
it includes the known duality and allows a general clarification and new results which reveal:

(i) The classical-quantum duality of the space-time and black holes

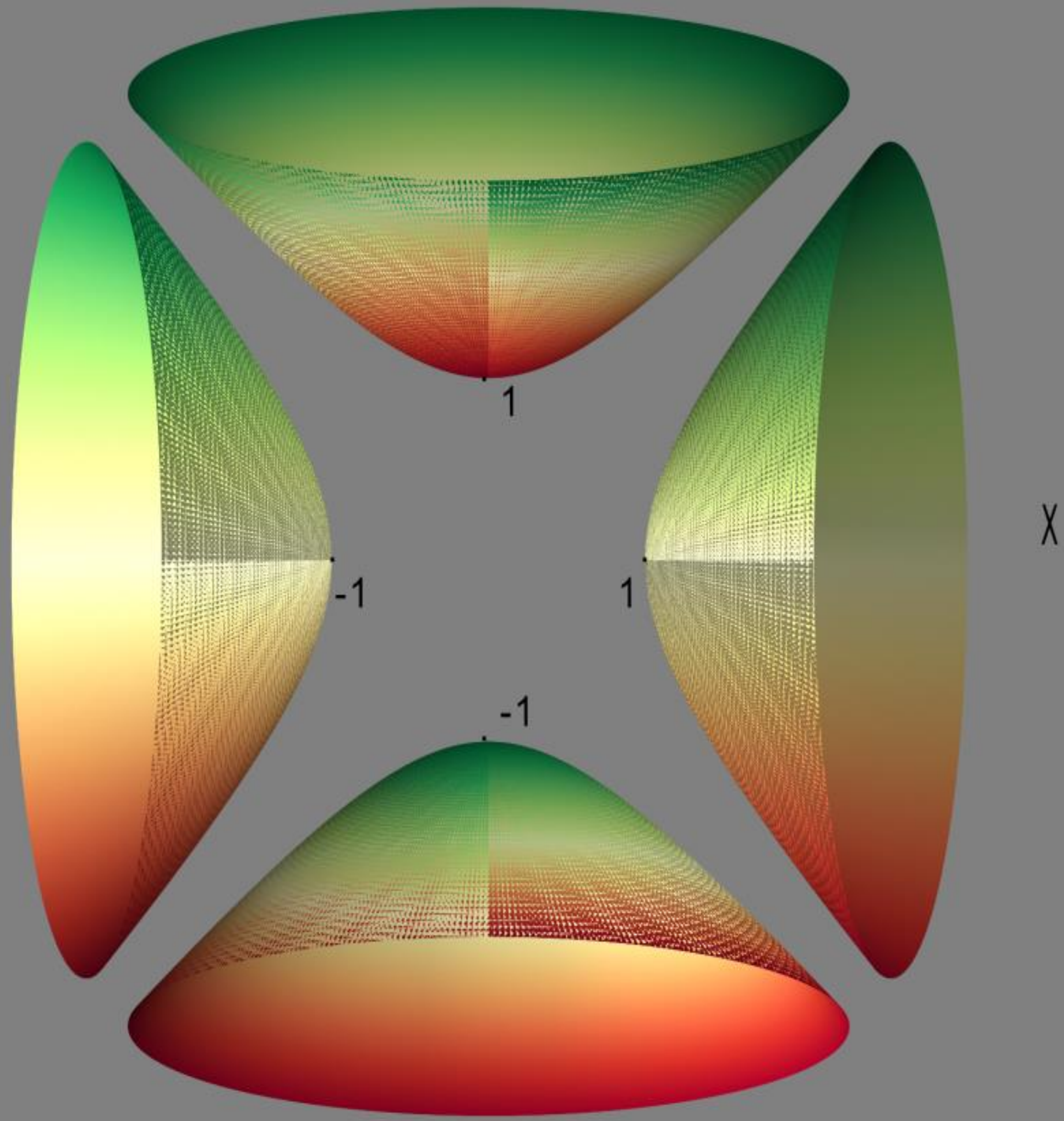
(ii) A new quantum domain not present in classical gravity does appear

(iii) The quantum light-cone from which the known classical light-cone of relativity and the classical universe are a special case.

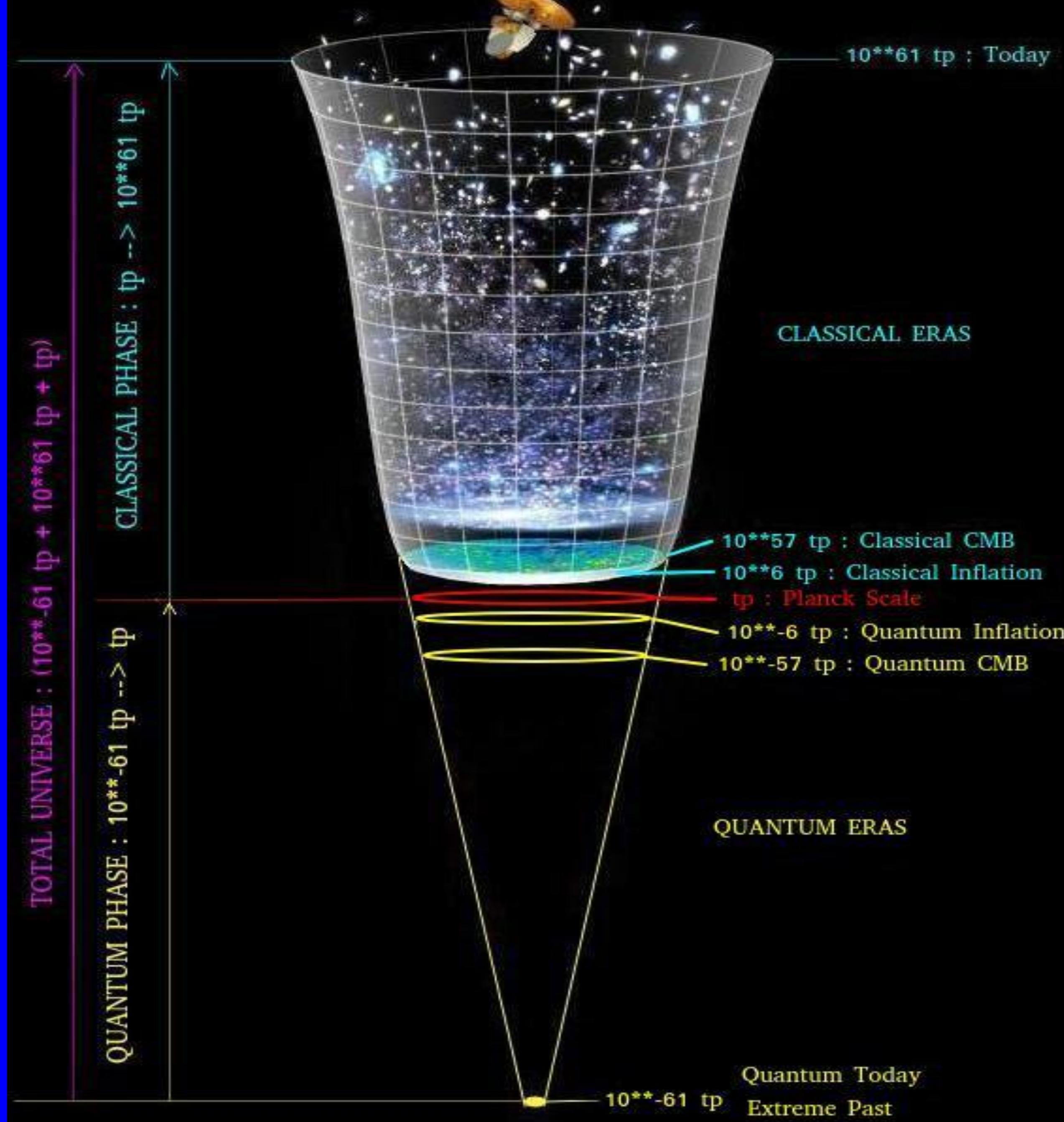
A more complete vision of space-time does



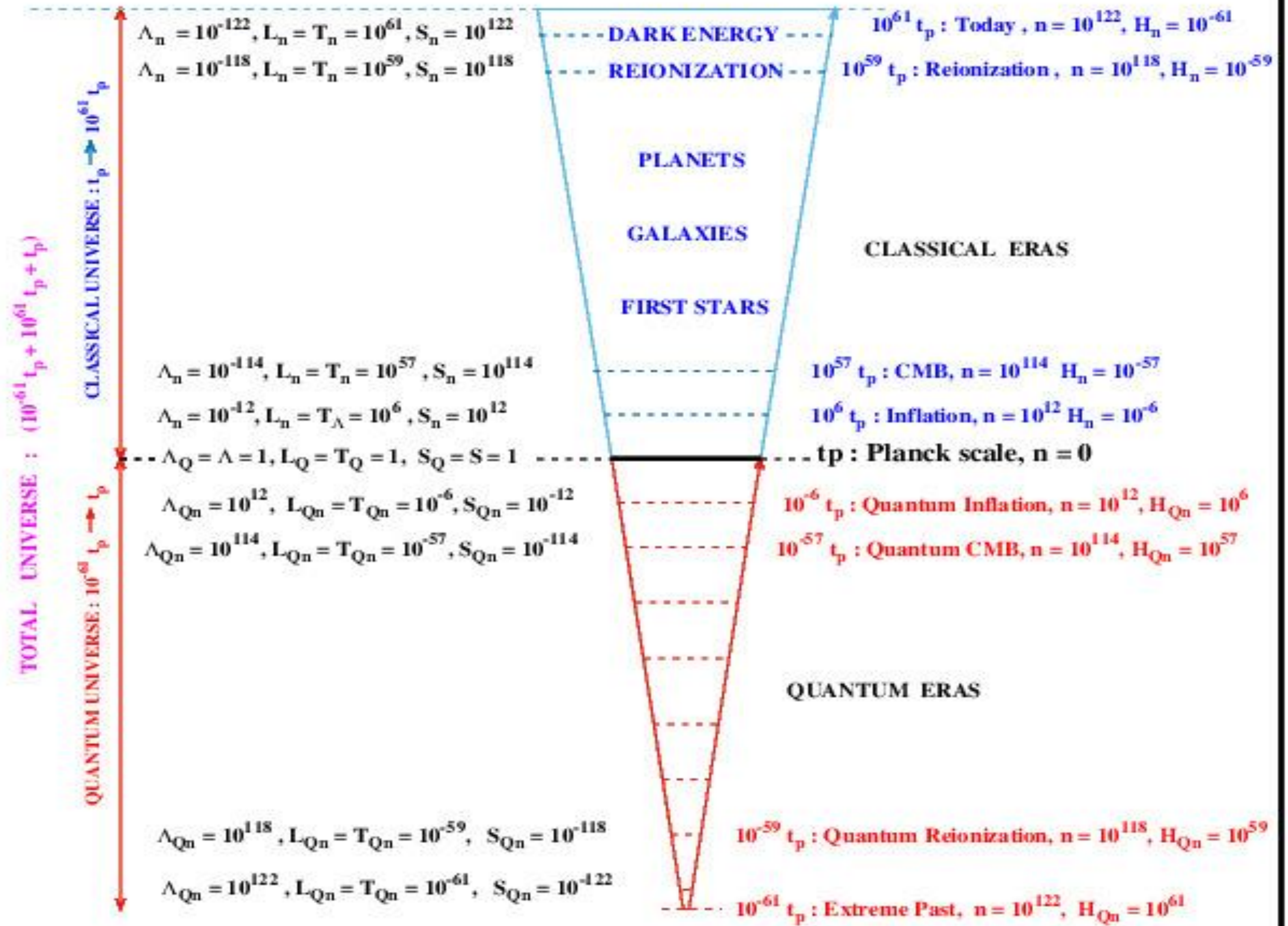
The known classical light-cone (future and past) of classical relativity in a space-time diagram is a special case of the Quantum light -cone



The quantum light-cone in a space-time diagram (time is the vertical axis).



THE TOTAL HISTORY OF THE UNIVERSE



QUANTUM DISCRETE LEVELS OF THE UNIVERSE AND THEIR TOTAL HISTORY