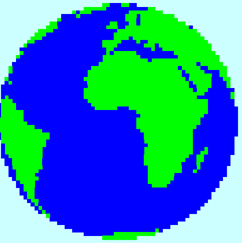

Last News of the Standard Model of the Universe : keV Dark Matter, theory and observations

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PHYSICAL CONTENTS

(0) FRAMEWORK: The Standard Cosmological Model Includes Inflation

(I) LATEST PREDICTIONS 2010: (Including primordial r Forecasts for Planck)

(II) THE CONTENT OF THE UNIVERSE: THE NATURE OF DARK MATTER

(III) PERSPECTIVE AND CONCLUSIONS

CONTENT OF THE UNIVERSE

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

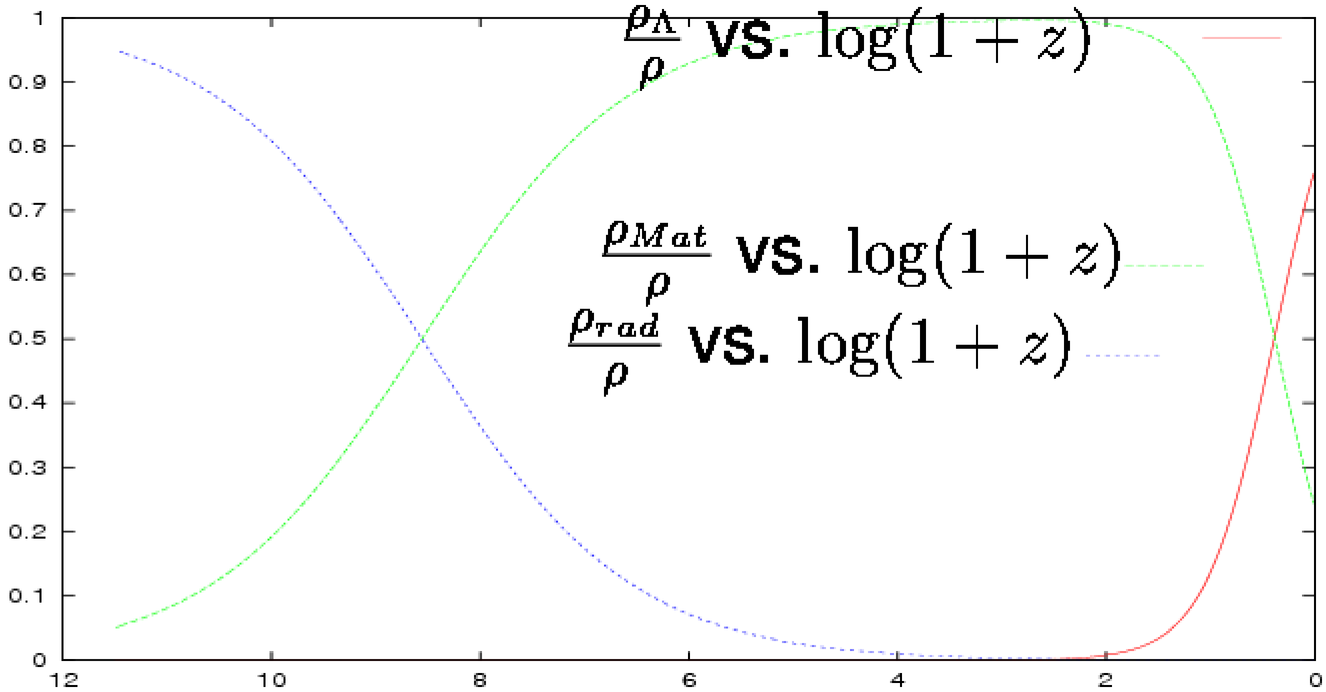
DARK MATTER comprises **23.4 %** of the universe.
This matter, different from atoms, does not emit or absorb light. It has only been detected indirectly by its gravity.

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 universe expansion, compatible with a cosmological constant

Dark Energy

$76 \pm 5\%$ of the present energy of the Universe is Dark !
Current observed value:
$\rho_\Lambda = \Omega_\Lambda \, \rho_c = (2.39 \text{ meV})^4 \quad , \quad 1 \text{ meV} = 10^{-3} \text{ eV}.$
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 !!

he Universe is made of radiation, matter and dark energ



End of inflation: $z \sim 10^{29}$, $T_{reh} \lesssim 10^{16}$ GeV, $t \sim 10^{-36}$ sec.

E-W phase transition: $z \sim 10^{15}$, $T_{\rm EW} \sim 100$ GeV, $t \sim 10^{-11}$ s.

QCD conf. transition: $z \sim 10^{12}$, $T_{\rm QCD} \sim 170$ MeV, $t \sim 10^{-5}$ s.

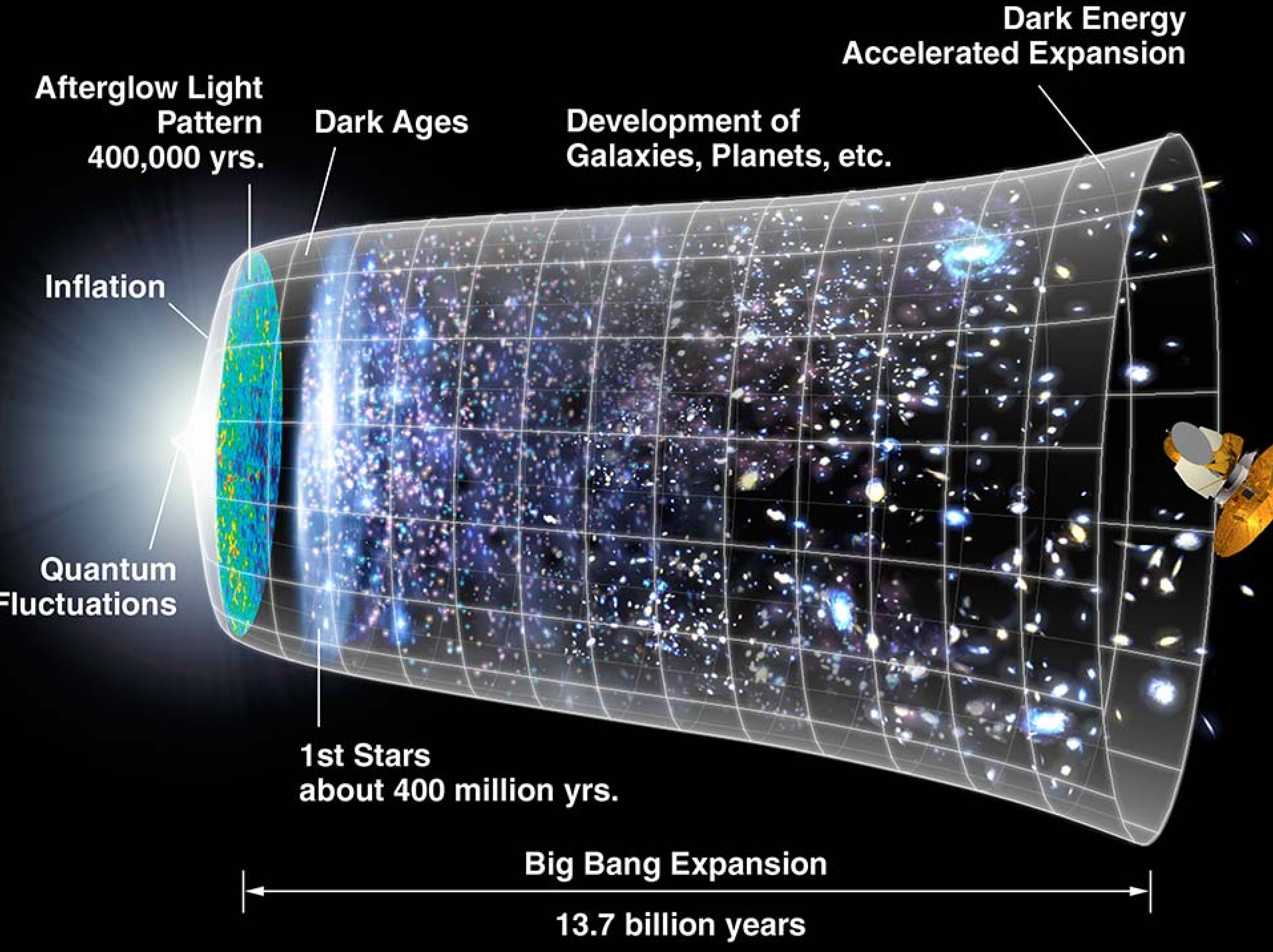
BBN: $z \sim 10^9$, $T \simeq 0.1$ MeV, $t \sim 20$ sec.

Rad-Mat equality: $z \simeq 3200$, $T \simeq 0.7$ eV, $t \sim 57000$ yr.

CMB last scattering: $z \simeq 1100$, $T \simeq 0.25$ eV , $t \sim 370000$ yr.

Mat-DE equality: $z \simeq 0.47$, $T \simeq 0.345$ meV , $t \sim 8.9$ Gyr.

Today: $z = 0$, $T = 2.725$K $= 0.2348$ meV $t = 13.72$ Gyr.


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 $= 3 \times 10^{18}$ cm $= 200000$ AU

Universe expansion classicalizes the physics: decoherence

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)

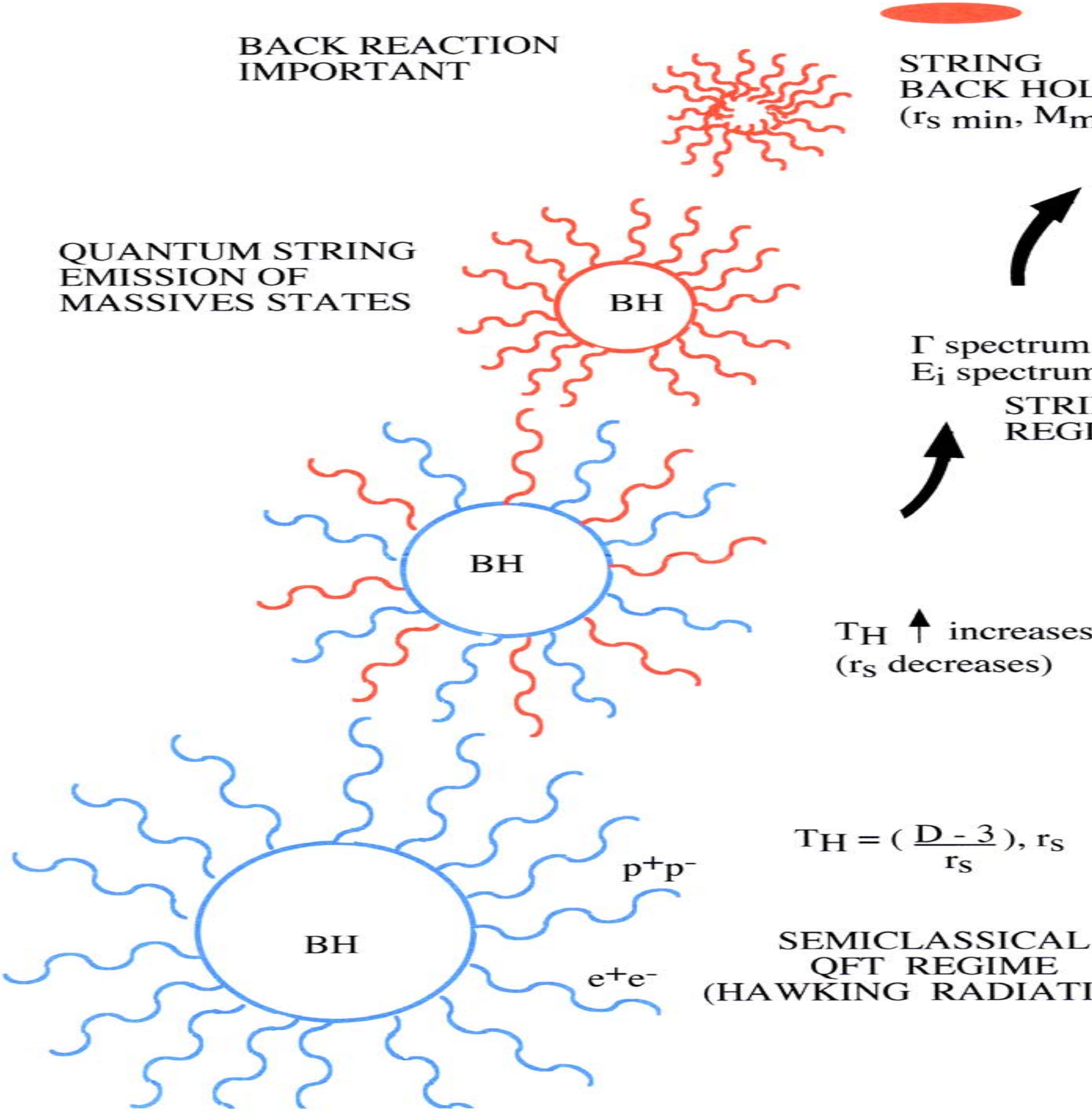
THE EXPANSION CLASSICALIZES THE UNIVERSE

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).



BACK REACTION
IMPORTANT

STRING
BACK HOLE
(r_s min, M_{min}, T_s)

QUANTUM STRING
EMISSION OF
MASSIVES STATES

Γ spectrum
E_i spectrum

STRING
REGIME

T_H ↑ increases
(r_s decreases)

$T_H = (\frac{D - 3}{r_s}), r_s$

SEMICLASSICAL
QFT REGIME
(HAWKING RADIATION)

THE ENERGY SCALE OF INFLATION IS THE

THE SCALE OF GRAVITY IN ITS SEMICLASSICAL REGIME

(OR THE SEMICLASSICAL GRAVITY TEMPERATURE) GUT SCALE

(EQUIVALENT TO THE HAWKING TEMPERATURE)

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

THE SCALE OF INFLATION IS THE SCALE OF SEMICLASSICAL GRAVITY

Δ_T and Δ_R expressed in terms of the semiclassical and quantum Gravity Temperature scales

$$T_{sem} = h\, H /(2\pi\, k_B) \quad , \quad T_{Pl} = M_{Pl}\, c^2/ (2\pi\, k_B)$$

T_{sem} is the semiclassical or Hawking-Gibbons temperature of the initial state (or Bunch-Davies vacuum) of inflation. T_{Pl} is the Planck temparature $10^{32°}$ K.

$$T_{sem} / T_{Pl} = 2\pi\, (2\, \varepsilon_V)^{1/2}\, \Delta_R, \quad T_{sem} / T_{Pl} = \pi\, (2)^{-1/2}\, \Delta_T$$

Therefore, CMB data yield for the Hawking-Gibbons Temperature of Inflation:

→ → → $T_{sem} \sim (\varepsilon_V)^{1/2}\, 10^{28\,°}$ K.

Universe Inventory

The universe is spatially flat: $ds^2 = dt^2 - a^2(t)\ d\vec{x}^2$

Dark Energy (Λ): 74 % , Dark Matter: 21 %

Baryons + electrons: 4.4 % , Radiation ($\gamma + \nu$): 0.0085%

83 % of the matter in the Universe is DARK.

$$\rho(\text{today}) = 0.974\ 10^{-29}\ \frac{\text{g}}{\text{cm}^3} = 5.46\ \frac{\text{GeV}}{\text{m}^3} = (2.36\ 10^{-3}\ \text{eV})^4$$

1 kpc = 3×10^{16} km $= 2 \times 10^8$ AU

DM dominates in the halos of galaxies (external part).

Baryons dominate around the center of galaxies.

Galaxies form out of matter collapse. Since angular momentum is conserved, when matter collapses its velocity increases. If matter can loose energy radiating, it can fall deeper than if it cannot radiate.

Standard Cosmological Model: ΛCDM or 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 (H_0) Measurements
- Properties of Clusters of Galaxies
- Measurements of the Age of the Universe

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: $\frac{d^2 a}{dt^2} > 0$.
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.

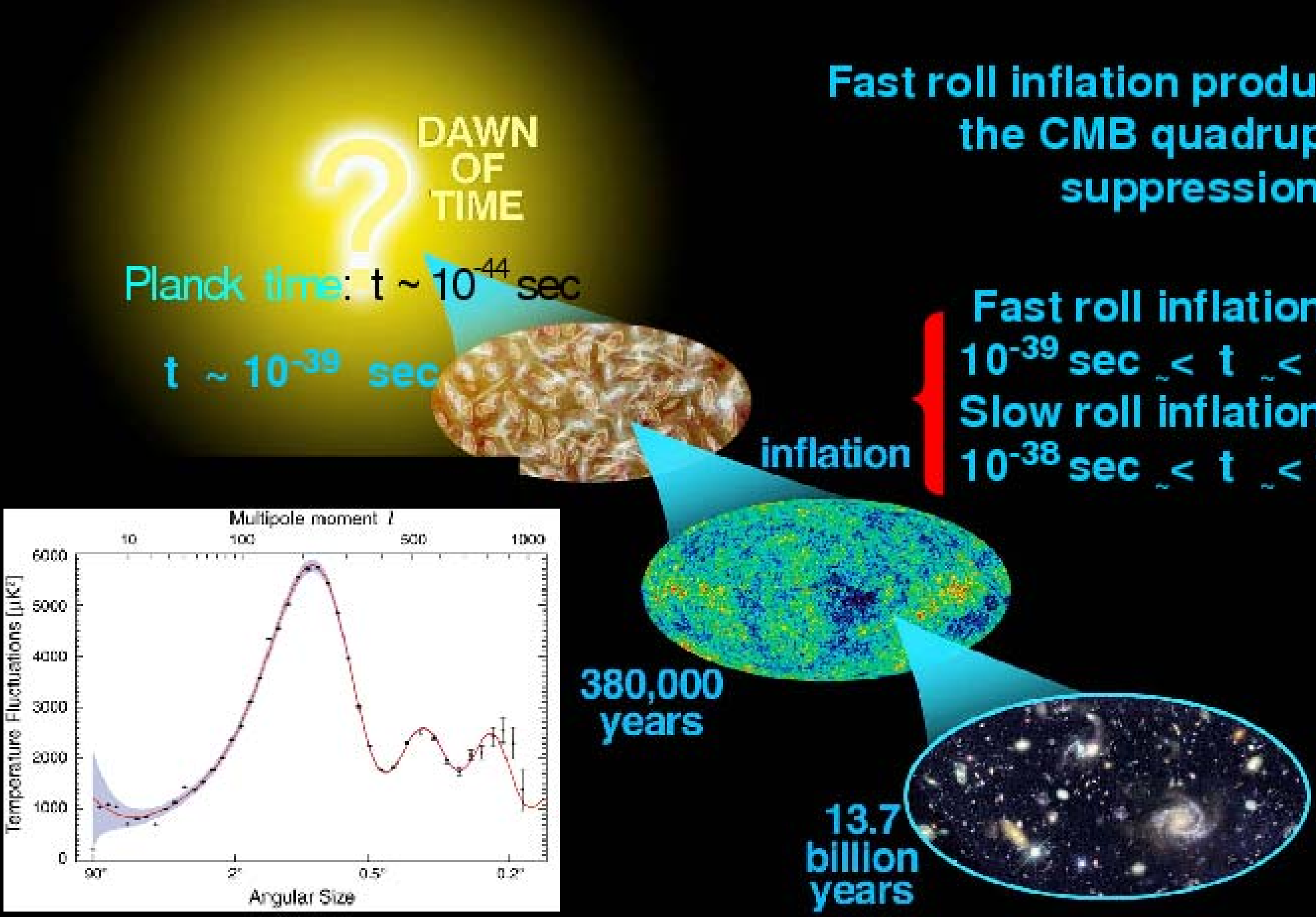
Matter can be effectively described during inflation by a Scalar Field $\phi(t, x)$: the Inflaton.

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

COSMIC HISTORY AND CMB QUADRUPOLE SUPPRESSION

Fast roll inflation produces
the CMB quadrupole
suppression



Planck time: $t \sim 10^{-44}$ sec

$t \sim 10^{-39}$ sec

inflation

380,000
years

13.7
billion
years

Fast roll inflation
10^{-39} sec $\lesssim t \lesssim 10^{-38}$ sec
Slow roll inflation
10^{-38} sec $\lesssim t \lesssim 10^{-36}$ sec

The Theory of Inflation

The inflaton is an effective field in the Ginsburg-Landau sense.

Relevant effective theories in physics:

- Ginsburg-Landau theory of superconductivity. It is an effective theory for Cooper pairs in the microscopic BCS theory of superconductivity.
- The $O(4)$ sigma model for pions, the sigma and photons at energies $\lesssim 1$ GeV. The microscopic theory is QCD: quarks and gluons. $\pi \simeq \bar{q}q$, $\sigma \simeq \bar{q}q$.
- The theory of second order phase transitions à la Landau-Kadanoff-Wilson... (ferromagnetic, antiferromagnetic, liquid-gas, Helium 3 and 4, ...)
- Fermi Theory of Weak Interactions (current-current).

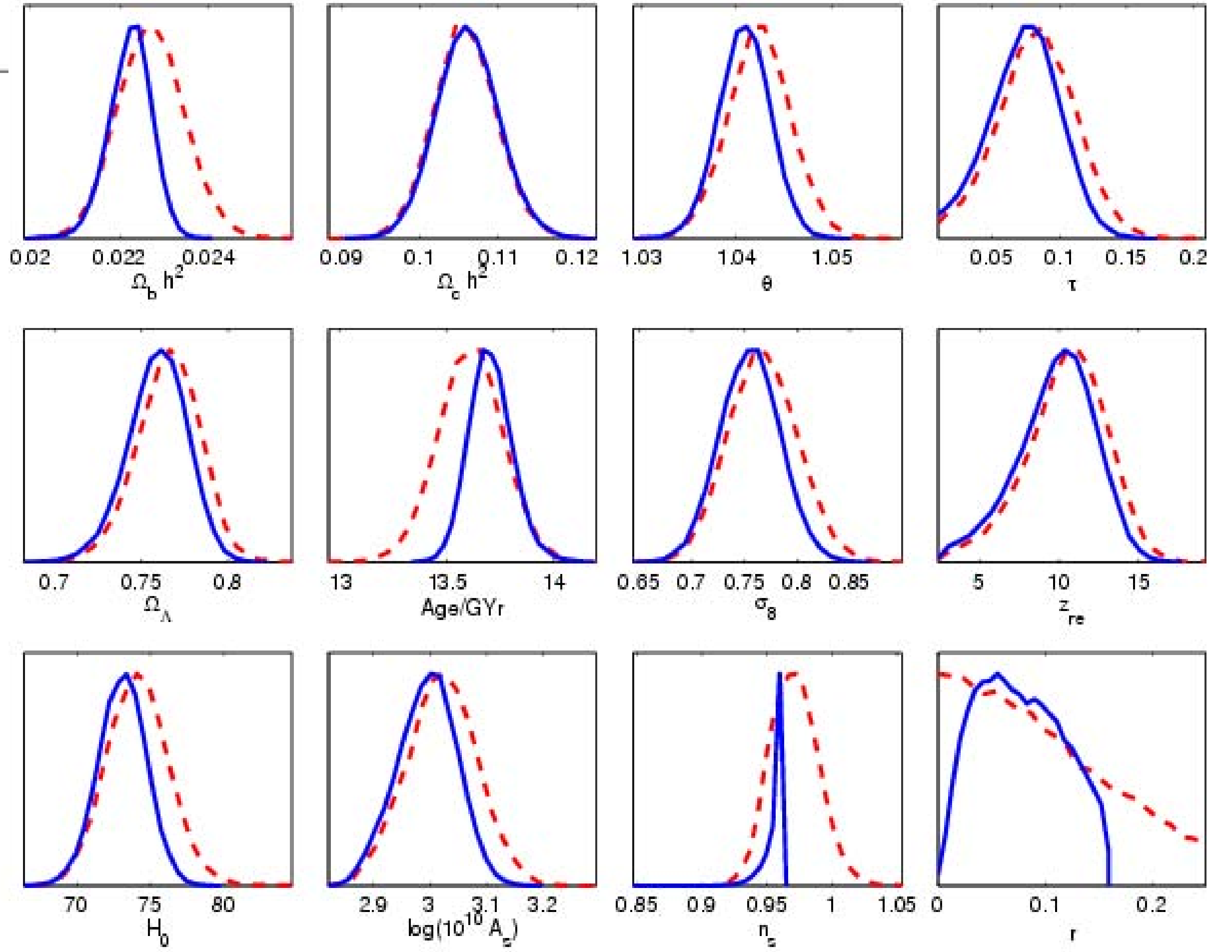
The Theory of Inflation

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: $r > 0.023 \; (95\% \text{ CL}) \quad , \quad r > 0.046 \; (68\% \text{ CL})$ 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).

Marginalized probability distributions. New Inflation.



Imposing the trinomial potential (solid blue curves) and just the ΛCDM+r model (dashed red curves).

(curves normalized to have the maxima equal to one).

LOWER BOUND on r

ON THE PRIMORDIAL GRAVITONS

Our approach (our theory input in the MCMC data analysis of WMAP5+LSS+SN data). [C. Destri, H J de Vega, N G Sanchez, Phys Rev D77, 043509 (2008)].

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

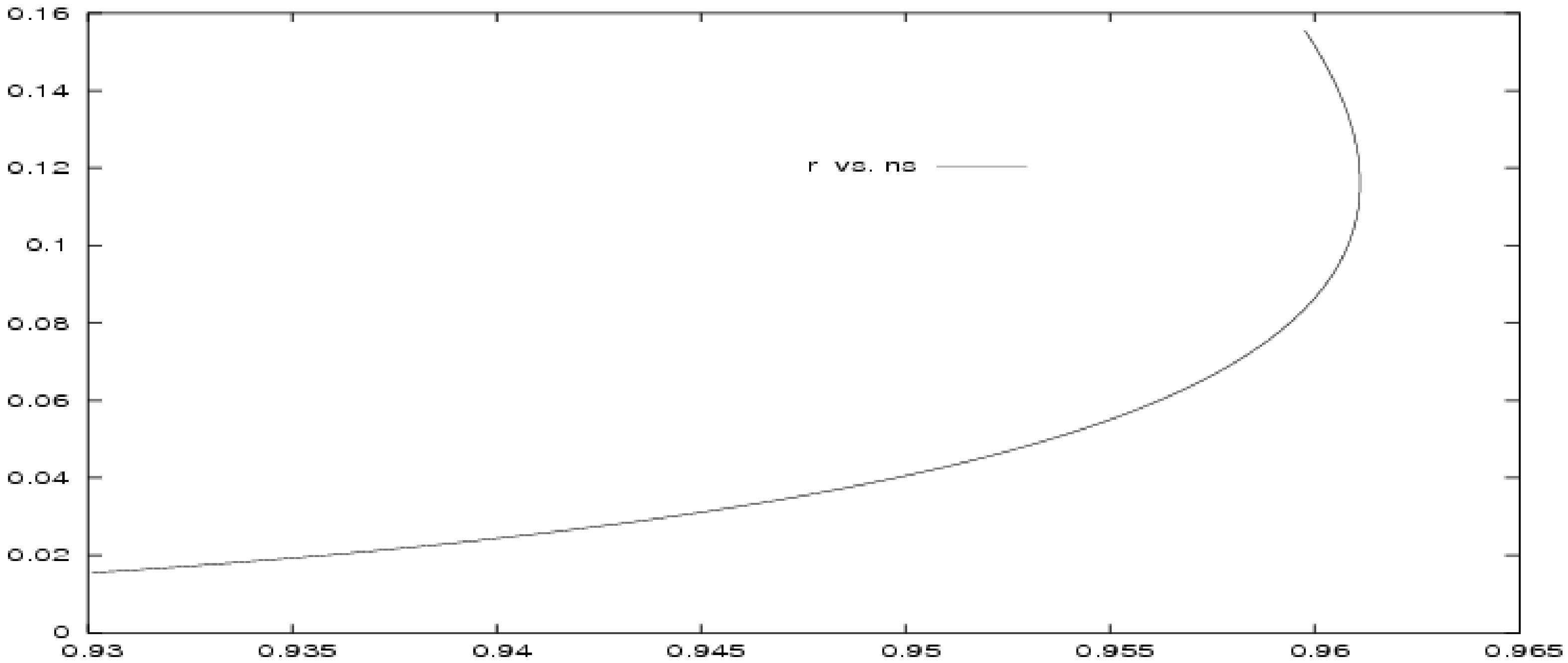
$$r > 0.023 \text{ at } 95\% \text{ CL and}$$

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

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

For the other cosmological parameters, both analysis agree.

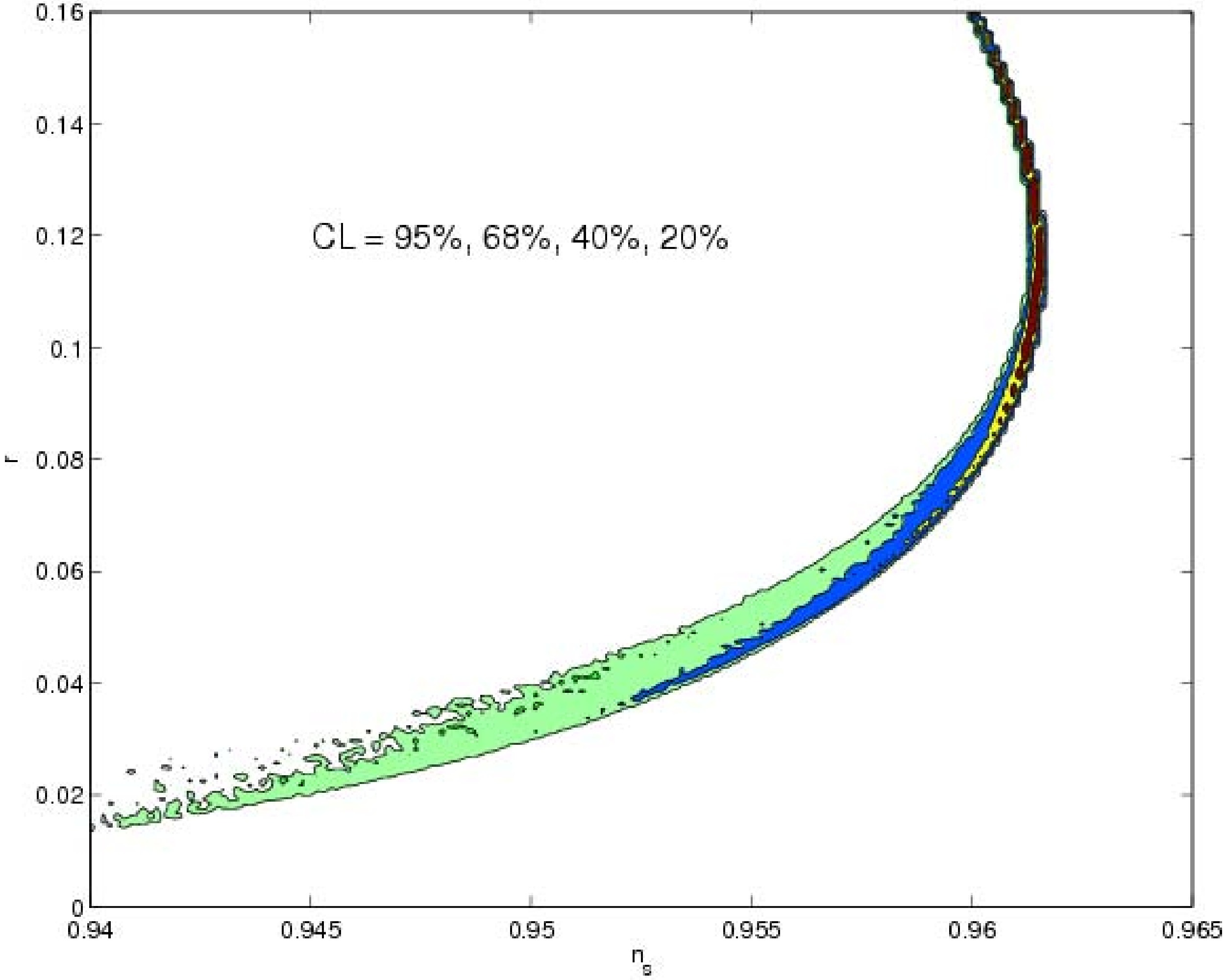
Binomial New Inflation



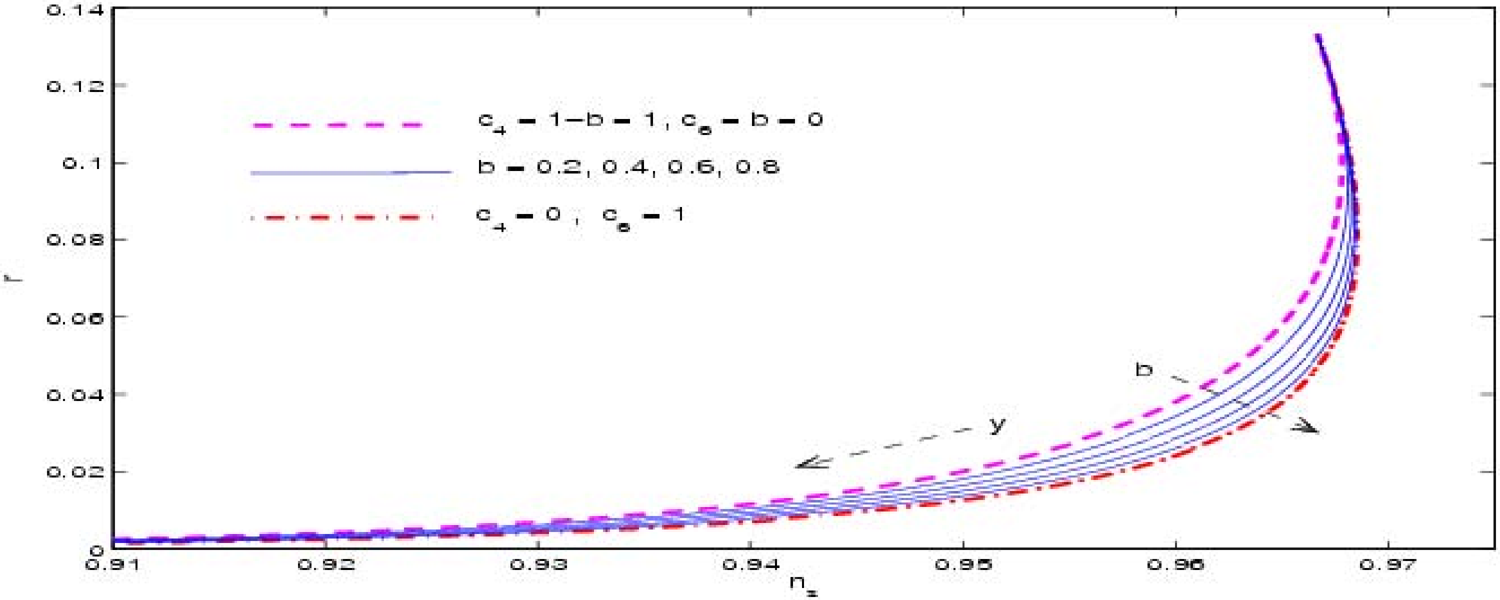
$r = \frac{8}{N} = 0.16$ and $n_s = 1 - \frac{2}{N} = 0.96$ at $y = 0$.

r is a double valued function of n_s.

r vs. n_s data within the Trinomial New Inflation Region.



The sextic double–well inflaton potential



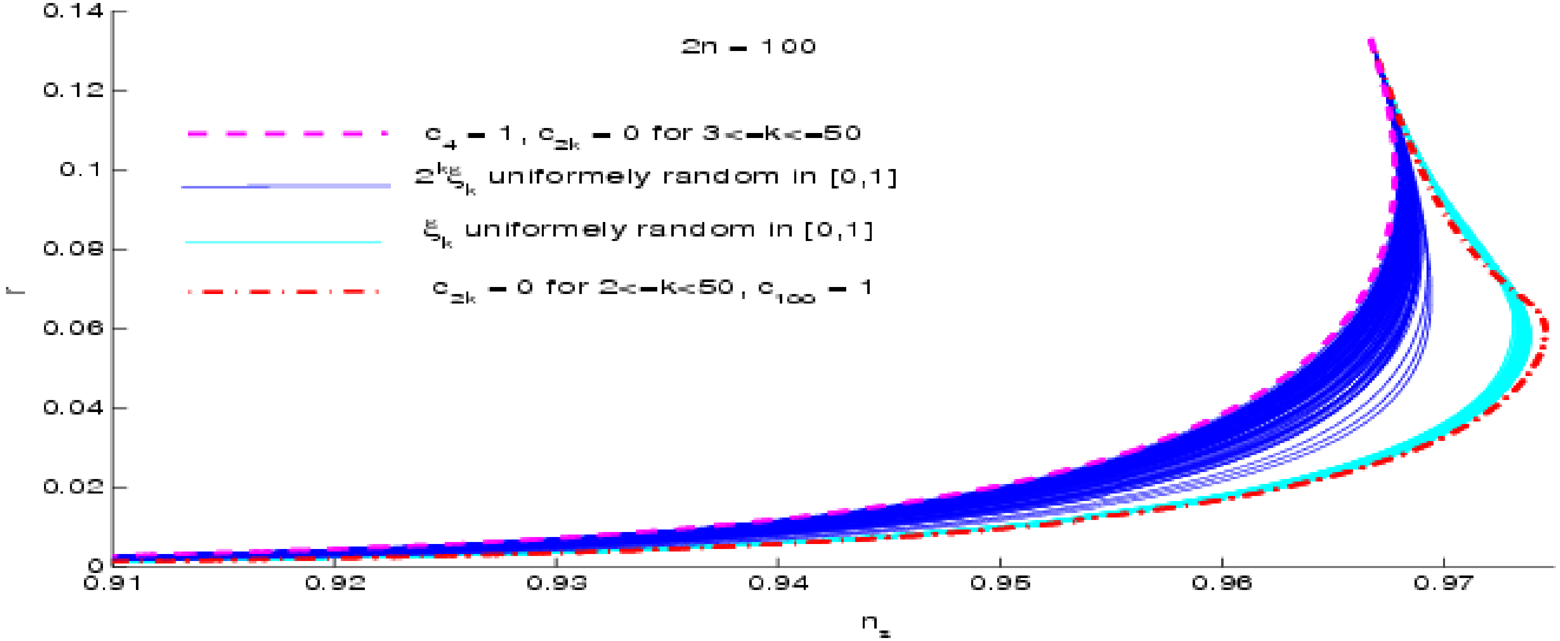
$$w_b(\chi) = \frac{y}{96}\left(\chi^2 - \frac{8}{y}\right)^2 \left(3 + b + \frac{1}{4}\, y\, b\, \chi^2\right) \ .$$

$0 < y < \infty$ coupling. $0 < b < 1$ shape-parameter.

$w_{b=0}(\chi) = \frac{y}{32}\left(\chi^2 - \frac{8}{y}\right)^2$ fourth order double–well.

$w_{b=1}(\chi) = \frac{8}{3\,y} - \frac{1}{2}\,\chi^2 + \frac{y^2}{384}\,\chi^6$ sixth order double–well.

The 100th degree polynomial inflaton potential

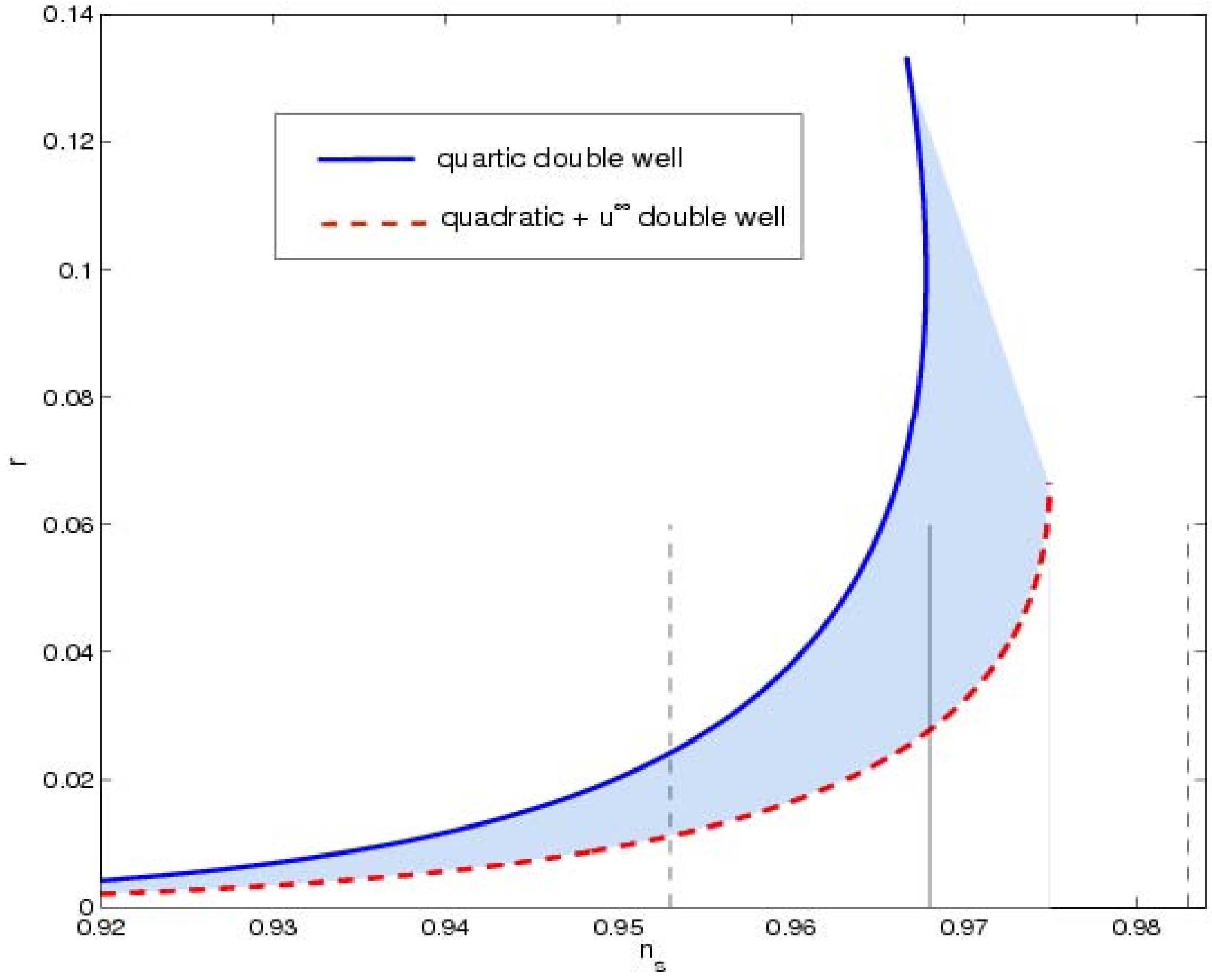


$$w(\chi) = \frac{4}{y} - \frac{1}{2}\,\chi^2 + \frac{4}{y}\sum_{k=2}^{n} \frac{c_{2k}}{k} \; \left(\frac{y^k}{8^k}\; u^{2k} - 1 \right)$$

The coefficients c_{2k} were extracted at random.

The lower border of the banana-shaped region is given by the potential:

$$w(\chi) = \frac{4}{y} - \frac{1}{2}\,\chi^2 + \frac{4}{n\,y} \; \left(\frac{y^n}{8^n}\; u^{2n} - 1 \right)$$ with $n = 50$.


quartic double well
quadratic + u^∞ double well
r
n_s
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.92
0.93
0.94
0.95
0.96
0.97
0.98

PREDICTIONS

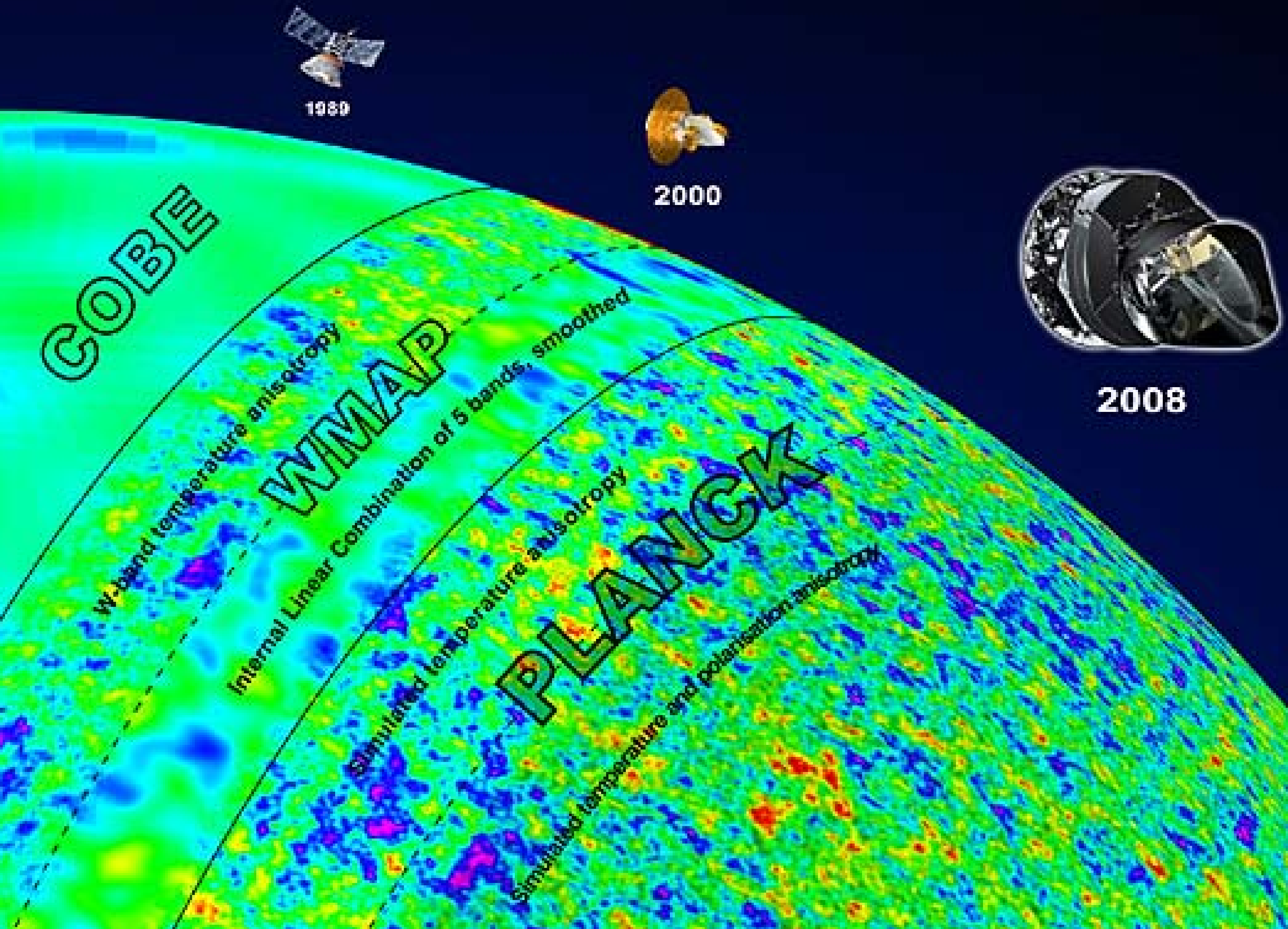
From the upper universal curve:
UPPER BOUND $r < 0.053$

From the lower universal curve:
LOWER BOUND $r > 0.021$

$$0.021 < r < 0.053$$

Most probable value: $r \sim 0.051$

CMB Missions Revolutionise Our Understanding of the Universe



FORECASTS FOR PLANCK

arXiv:1003.6108 ApJ 724, 588-607 (Nov 2010)

Forecast for the Planck precision on the tensor to scalar ratio and other cosmological parameters **C. Burigana, C. Destri, H.J. de Vega, A. Gruppuso, N. Mandolesi, P. Natoli, N. G. Sanchez**

Fiducial $r = 0.0427$

The best value for r in the presence of residuals turns to be about

$$r = 0.04$$

for both the LambdaCDMr and the LambdaCDMrT models.

- The LCDMrT model turns to be robust, it is very stable (its distributions do not change) with respect to the inclusion of residuals.We have for r at 95% CL:

$$0.028 < r < 0.116 \quad \textbf{with the best values } r = 0.04, n_s = 0.9608$$

- Better measurements for n_s will improve the prediction on r from the TT , TE and E modes even if a secure detection of B modes will be still lacking.

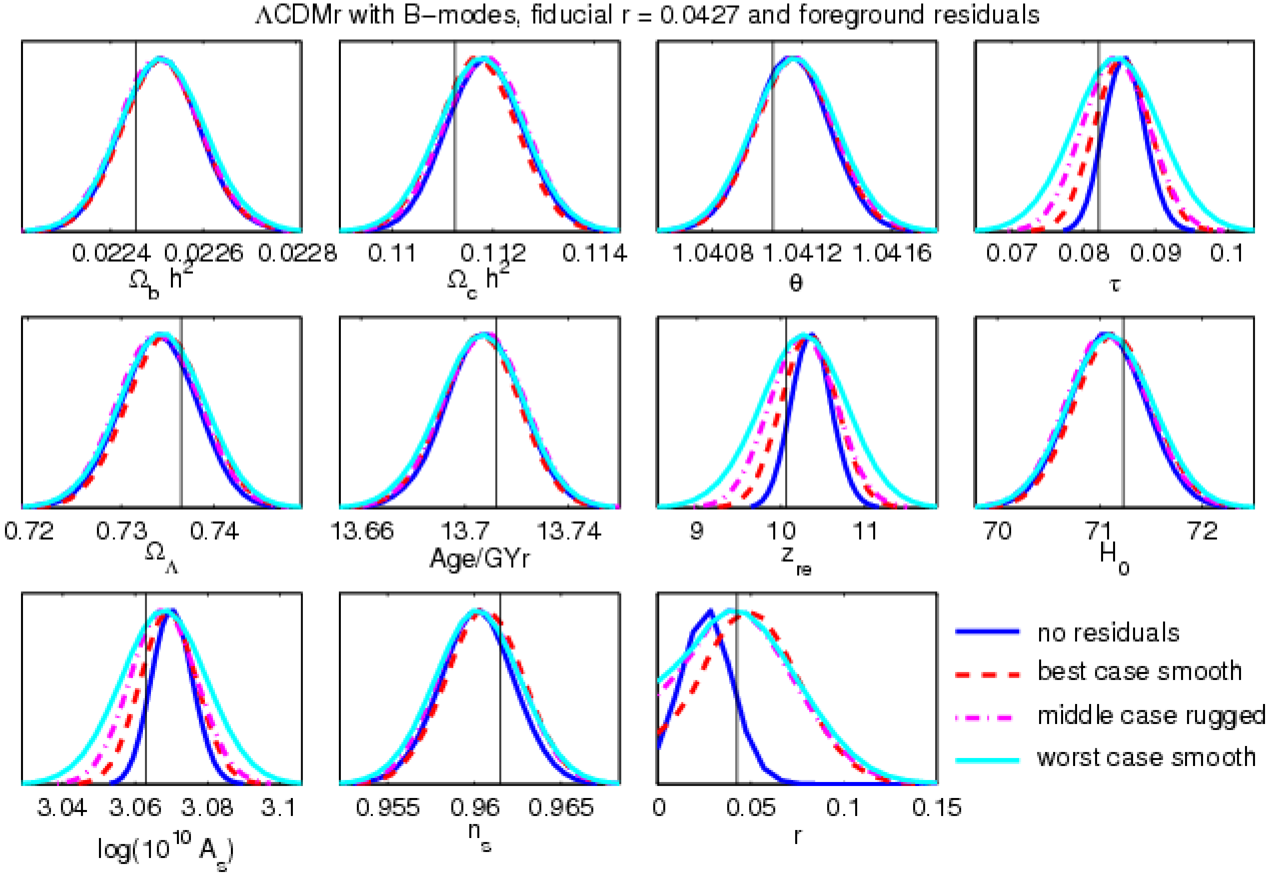


FIG. 7.— Cumulative 3—channel marginalized likelihood distributions, including B modes and foregrou
parameters for the ΛCDMr model. The fiducial ratio is $r = 0$ in the upper panel and $r = 0.0427$ in the low
four cases: (a) without residuals, (b) with 30% of the toy model residuals in the TE and E modes displaye
modes, (c) with the toy model residuals in the TE and E modes displayed in Fig. 2 and $160\mu K^2$ in the T
model residuals in the TE and E modes displayed in Fig. 2 and $88\mu K^2$ in the T modes rugged by Gauss
strength.

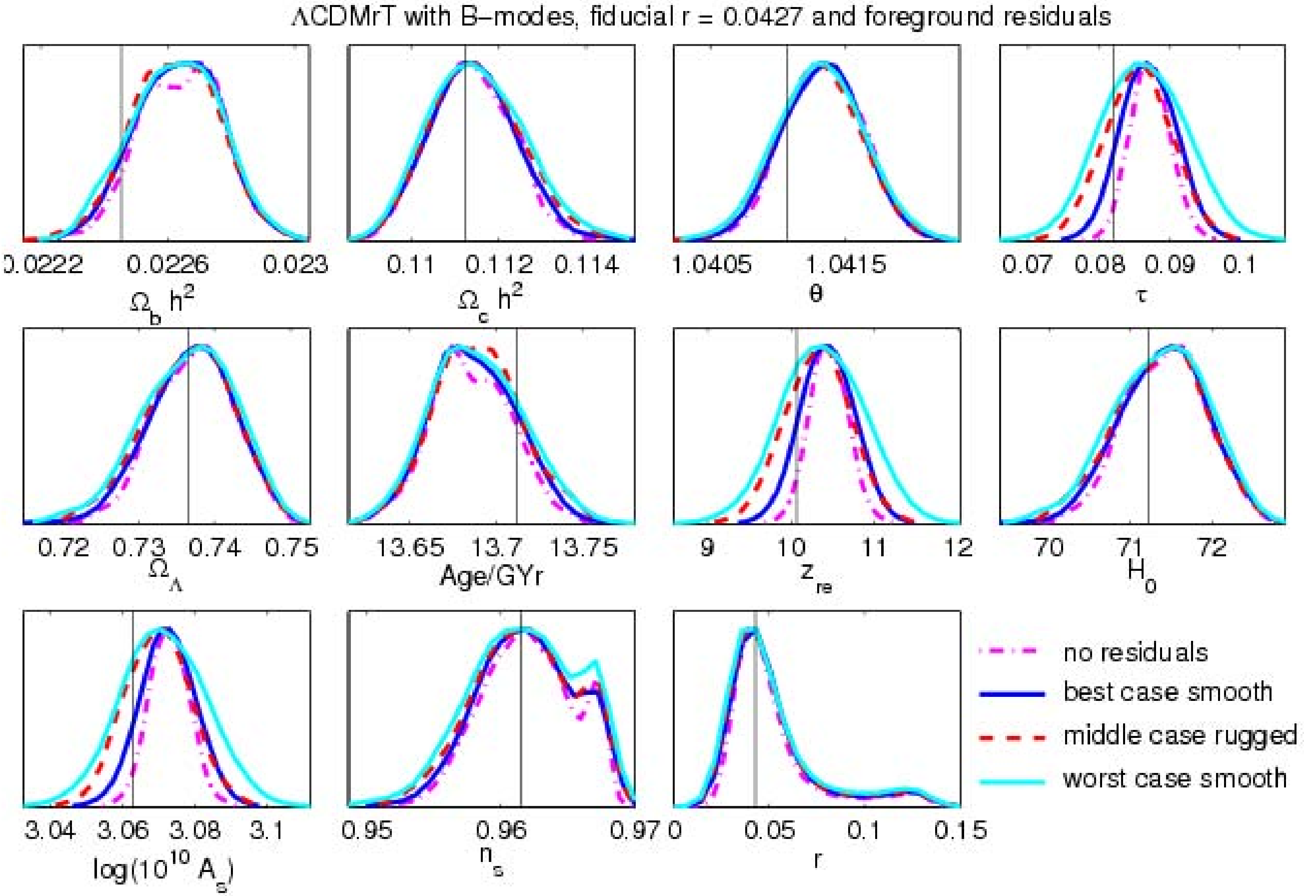


FIG. 8.— Cumulative marginalized likelihoods from the three channels for the cosmological parameters for the ΛCDMrT model including B modes and fiducial ratio $r = 0.0427$ and the foreground residuals. We plot the cumulative likelihoods in four cases: (a) without residuals, (b) with 0.3 of the worst case residuals in the TE and E modes and $16\mu K^2$ in the T modes, (c) with the worst case residuals in the TE and E modes and $160\mu K^2$ in the T modes, (d) with 65% of the toy model residuals in the TE and E modes displayed in Fig. 2 and $88\mu K^2$ in the T modes rugged by Gaussian fluctuations of 30% relative strength.

OUR FORECAST for PLANCK

$0.028 < r < 0.116$ 95 % CL ,

best value $r = 0.04$ $n_s = 0.9608$

Supports searching of CMB B-mode polarization in the current data as well as the planned CMB polarization missions

→Forecasted B mode detection probability by the most sensitive HFI-143 channel:

→For a 95% CL detection the level of foreground residual should be reduced to 10% or lower of the adopted toy model. →Borderline

El universo en una banana

(II) DARK MATTER

(I) THE MASS OF THE DARK MATTER PARTICLE

(II) THE BOLTZMAN VLASOV EQUATION: TRANSFERT FUNCTION AND ANALYTIC RESULTS

(III) UNIVERSAL PROPERTIES OF GALAXIES: DENSITY PROFILES, SURFACE DENSITY, AND THE POWER OF LINEAR APPROXIMATION

(I) MASS OF THE DARK MATTER PARTICLE

H. J. De Vega, N.G. Sanchez *Model independent analysis of dark matter points to a particle mass at the keV scale* **Mon. Not. R. Astron. Soc. 404, 885 (2010)**

D. Boyanovsky, H. J. De Vega, N.G. Sanchez *Constraints on dark matter particles from theory, galaxy observations and N-body simulations* **Phys.Rev. D77 043518, (2008)**

(II) BOLTZMAN VLASOV EQUATION, TRANSFERT FUNCTION

D. Boyanovsky, H. J. De Vega, N.G. Sanchez *The dark matter transfer function: free streaming, particle statistics and memory of gravitational clustering* **Phys. Rev. D78: 063546, (2008)**

(III) DENSITY PROFILES, SURFACE DENSITY, DARK MATTER PARTICLE MASS

H. J. De Vega, N.G. Sanchez *Gravity surface density and density profile of dark matter galaxies* **arXiv:0907.006. To appear in IJMPA**

H. J. De Vega, P. Salucci, N.G. Sanchez *Universal galaxy properties and the mass of the dark matter particle from theory and observations: the power of the linear approximation* **arXiv:1004.1908**

THE MASS OF THE

DARK MATTER PARTICLE

Dark matter was noticed seventy-five years ago (Zwicky 1933, Oort 1940). Ist nature is not yet known. DM represents about 23.4 % of the matter of the universe. DM has only been detected indirectly through its gravitational action.

The concordance standard cosmological model emerging from the CMB+LSS+Λ observations and simulations favors dark matter composed of primordial particles which are (« cold », « warm ») and collisionless.

The clustering properties of collisionless dark matter candidates in the linear regime depend on the free streaming length, which roughly corresponds to the Jeans length with the particle's velocity dispersion replacing the speed of sound in the gas. CDM candidates feature a small free streaming length favoring a bottom-up hierarchical approach to structure formation, smaller structures form first

→Compilation of observations of dwarf spheroidal galaxies dSphs, prime candidates for DM subtructure, are compatible with a core of smoother central density and a low mean mass density ~ 0.1 Msun /pc^3 rather than with a cusp.

→Dark matter particles can decouple being ultrarelativistic or non-relativistic. Dark matter must be non-relativistic during structure formation in order to reproduce the observed small structure at ~ 2 − 3 kpc.

→In addition, the decoupling can occurs at local thermal equilibrium or out of local thermal equilibrium. All these cases have been considered in our analysis.

OBSERVATIONS

The observed dark matter energy density observed today has the value $\rho_{DM} = 0.228\ (2.518\ \mathrm{meV})^4$.

In addition, compilation of dwarf spheroidal satellite galaxies observations in the Milky Way yield the one dimensional velocity dispersion σ and the radius L in the ranges

$$6.6\ \mathrm{km/s} \leq \sigma \leq 11.1\ \mathrm{km/s}\ , \qquad 0.5\ \mathrm{kpc} \leq L \leq 1.8\ \mathrm{kpc}$$

And the Phase-space Density today (with a precision of

a factor 10) has the value :

$$D(0) \sim 5 \times 10^3\ [\mathrm{keV/cm}^3]\ (\mathrm{km/s})^{-3} = (0.18\ \mathrm{keV})^4\ .$$

→ **Compute** from the distribution function of dark matter particles with their different statistics, physical magnitudes as :

-the dark matter energy density $\rho_{DM}(z)$,

-the dark matter velocity dispersion $\sigma_{DM}(z)$,

-the dark matter density in the phase space D(z)

→ **Confront** to their values observed today (z = 0).

→→ From them, the mass m of the dark matter particle and its decoupling temperature T_d are obtained.

The phase-space density today is a factor Z smaller than its primordial value. The decreasing factor Z > 1 is due to the effect of self-gravity interactions: the range of Z is computed both analytically and numerically.

Dark Matter

DM particles can decouple being ultrarelativistic (UR) at $T_d \gg m$ or non-relativistic $T_d \ll m$.

We consider particles that decouple at or out of LTE (LTE = local thermal equilibrium).

Distribution function: $F_d[p_c]$ freezes out at decoupling.

$p_c =$ comoving momentum.

$P_f(t) = p_c/a(t) =$ Physical momentum,

Velocity fluctuations: $y = P_f(t)/T_d(t) = p_c/T_d$

$$\langle \vec{V}^2(t) \rangle = \langle \frac{\vec{P}_f^2(t)}{m^2} \rangle = \left[\frac{T_d}{m\, a(t)}\right]^2 \frac{\int_0^\infty y^4 F_d(y) dy}{\int_0^\infty y^2 F_d(y) dy} .$$

Energy Density: $\rho_{DM}(t) = \frac{m\, g}{2\pi^2} \frac{T_d^3}{a^3(t)} \int_0^\infty y^2\, F_d(y)\, dy$,

g : $\#$ of internal degrees of freedom of the DM particle, $1 \leq g \leq 4$. Formula valid when DM particles are non-relativistic.

The formula for the Mass of the Dark Matter particles

Energy Density: $\rho_{DM}(t) = g \int \frac{d^3 P_f}{(2\pi)^3} \sqrt{m^2 + P_f^2} \; f_d[a(t)\, P_f]$

g : # of internal degrees of freedom of the DM particle, $1 \leq g \leq 4$. For $z \lesssim 30 \;\Rightarrow$ DM particles are non-relativistic:

$$\rho_{DM}(t) = m\; g\; \frac{T_d^3}{a^3(t)} \; \int_0^\infty y^2 \; f_d(y)\; \frac{dy}{2\pi^2} \; .$$

Using entropy conservation: $T_d = \left(\frac{2}{g_d}\right)^{\frac{1}{3}} \; T_\gamma \; (1 + z_d)$,

$g_d =$ effective # of UR degrees of freedom at decoupling, $T_\gamma = 0.2348$ meV , $1 \text{ meV} = 10^{-3}$ eV.

Today $\Omega_{DM} = \rho_{DM}(0)/\rho_c = 0.105/h^2$ and we obtain for the mass of the DM particle:

$$m = 6.986 \text{ eV} \; \frac{g_d}{g \displaystyle\int_0^\infty y^2 \; f_d(y)\; dy}$$. Goal: determine m and g_d

Dark Matter density and DM velocity dispersion

Energy Density: $\rho_{DM}(t) = g \int \frac{d^3 P_f}{(2\pi)^3} \sqrt{m^2 + P_f^2}\; F_d[a(t)\, P_f]$

g : # of internal degrees of freedom of the DM particle, $1 \leq g \leq 4$. For $z \lesssim 30 \;\Rightarrow$ DM particles are non-relativistic:

$$\rho_{DM}(t) = \frac{m\, g}{2\pi^2}\, \frac{T_d^3}{a^3(t)} \int_0^\infty y^2\, F_d(y)\, dy \;,$$

Using entropy conservation: $T_d = \left(\frac{2}{g_d}\right)^{\frac{1}{3}}\, T_{CMB}$,

$g_d =$ effective # of UR degrees of freedom at decoupling, $T_{CMB} = 0.2348\, 10^{-3}$ eV, and

$$\rho_{DM}(\text{today}) = \frac{m\, g}{\pi^2\, g_d}\, T_{CMB}^3 \int_0^\infty y^2\, F_d(y)\, dy = 1.107\, \frac{\text{keV}}{\text{cm}^3} \quad (1)$$

We obtain for the primordial velocity dispersion:

$$\sigma_{DM}(z) = \sqrt{\frac{1}{3}\, \langle \vec{V}^2 \rangle (z)} = 0.05124\, \frac{1+z}{g_d^{\frac{1}{3}}} \left[\frac{\int_0^\infty y^4\, F_d(y)\, dy}{\int_0^\infty y^2\, F_d(y)\, dy}\right]^{\frac{1}{2}} \frac{\text{keV}}{m}\, \frac{\text{km}}{\text{s}}$$

Goal: determine m and g_d. We need TWO constraints.

Phase-space density invariant under universe expansion

Using again entropy conservation to replace T_d yields for the one-dimensional velocity dispersion,

$$\sigma_{DM}(z) = \sqrt{\frac{1}{3}\,\langle\vec{V}^2\rangle(z)} = \frac{2^{\frac{1}{3}}}{\sqrt{3}}\,\frac{1+z}{g_d^{\frac{1}{3}}}\,\frac{T_\gamma}{m}\,\sqrt{\frac{\int_0^\infty y^4\,F_d(y)\,dy}{\int_0^\infty y^2\,F_d(y)\,dy}} =$$

$$= 0.05124\,\frac{1+z}{g_d^{\frac{1}{3}}}\,\frac{\mathrm{keV}}{m}\,\left[\frac{\int_0^\infty y^4\,F_d(y)\,dy}{\int_0^\infty y^2\,F_d(y)\,dy}\right]^{\frac{1}{2}}\,\frac{\mathrm{km}}{\mathrm{s}}.$$

Phase-space density: $\mathcal{D} \equiv \dfrac{n(t)}{\langle\vec{P}^2_{phys}(t)\rangle^{\frac{3}{2}}} \overset{\mathrm{non-rel}}{=} \dfrac{\rho_{DM}}{3\sqrt{3}\,m^4\,\sigma^3_{DM}}$

$\mathcal{D}$ is computed theoretically from freezed-out distributions:

$$\mathcal{D} = \frac{g}{2\,\pi^2}\,\frac{\left[\int_0^\infty y^2 F_d(y)dy\right]^{\frac{5}{2}}}{\left[\int_0^\infty y^4 F_d(y)dy\right]^{\frac{3}{2}}}$$

Theorem: The phase-space density $\mathcal{D}$ can only decrease under self-gravity interactions (gravitational clustering) [Lynden-Bell, Tremaine, Henon, 1986].

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

The phase-space density $Q \equiv \rho/\sigma^3$ is invariant under the cosmological expansion and can only decrease under self-gravity interactions (gravitational clustering).

The phase-space density today follows observing dwarf spheroidal satellite galaxies of the Milky Way (dSphs)

$\frac{\rho_s}{\sigma_s^3} \sim 5 \times 10^3 \, \frac{\mathrm{keV/cm^3}}{(\mathrm{km/s})^3} = (0.18 \, \mathrm{keV})^4$ Gilmore et al. 07 and 08.

During structure formation $(z \lesssim 30)$, $Q = \rho/\sigma^3$ decreases by a factor that we call Z:

$Q_{today} = \frac{1}{Z} \, Q_{prim}$, $Q_{prim} = \frac{\rho_{prim}}{\sigma^3_{prim}}$, (2) $Z > 1.$

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

Constraints: First $\rho_{DM}(\text{today})$, Second $Q_{today} = \rho_s/\sigma_s^3$

Mass Estimates for DM particles

Combining the previous expressions lead to general formulas for m and g_d:

$$m = 0.2504\,\mathrm{keV}\;\left(\frac{Z}{g}\right)^{\frac14}\frac{\left[\int_0^\infty y^4\;F_d(y)\;dy\right]^{\frac38}}{\left[\int_0^\infty y^2\;F_d(y)\;dy\right]^{\frac58}}$$

$$g_d = 35.96\,Z^{\frac14}\;g^{\frac34}\;\left[\int_0^\infty y^4\;F_d(y)\;dy\;\;\int_0^\infty y^2\;F_d(y)\;dy\right]^{\frac38}$$

These formulas yield for relics decoupling UR at LTE:

$$m = \left(\frac{Z}{g}\right)^{\frac14}\;\mathrm{keV}\;\left\{\begin{array}{l} 0.568 \\ 0.484 \end{array}\right.\;,\; g_d = g^{\frac34}\;Z^{\frac14}\;\left\{\begin{array}{ll} 155 & \mathrm{Fermions} \\ 180 & \mathrm{Bosons} \end{array}\right. .$$

Since $g = 1 - 4$, we see that $g_d > 100 \Rightarrow T_d > 100$ GeV.

$1 < Z^{\frac14} < 5.6$ for $1 < Z < 1000$. Example: for DM Majorana fermions $(g = 2)$ $m \simeq 0.85$ keV.

Relics decoupling non-relativistic

$$F_d^{NR}(p_c) = \frac{2^{\frac{5}{2}}\,\pi^{\frac{7}{2}}}{45}\; g_d\, Y_\infty\; \left(\frac{T_d}{m}\right)^{\frac{3}{2}}\; e^{-\frac{p_c^2}{2\,m\,T_d}} = \frac{2^{\frac{5}{2}}\,\pi^{\frac{7}{2}}}{45}\; \frac{g_d\, Y_\infty}{x^{\frac{3}{2}}}\; e^{-\frac{y^2}{2\,x}}$$

$Y(t) = n(t)/s(t)$, $n(t)$ number of DM particles per unit volume, $s(t)$ entropy per unit volume, $x \equiv m/T_d$, $T_d < m$.

$Y_\infty = \frac{1}{\pi}\sqrt{\frac{45}{8}}\;\frac{1}{\sqrt{g_d}\;T_d\;\sigma_0\;M_{Pl}}$ late time limit of Boltzmann.

σ_0: thermally averaged total annihilation cross-section times the velocity.

From our general equations for m and g_d:

$m = \frac{45}{4\,\pi^2}\;\frac{\Omega_{DM}\;\rho_c}{g\;T_\gamma^3\;Y_\infty} = \frac{0.748}{g\;Y_\infty}$ eV and $m^{\frac{5}{2}}\;T_d^{\frac{3}{2}} = \frac{45}{2\,\pi^2}\;\frac{1}{g\;g_d\;Y_\infty}\;Z\;\frac{\rho_s}{\sigma_s^3}$

Finally:

$$\sqrt{m\,T_d} = 1.47\;\left(\frac{Z}{g_d}\right)^{\frac{1}{3}}\,\mathrm{keV}. \quad m = 3.67\;\mathrm{keV}\;Z^{\frac{1}{3}}\;\frac{g_d^{\frac{1}{12}}}{\sqrt{g}}\;\sqrt{\frac{\sigma_0}{\mathrm{pb}}}$$

We used ρ_{DM} today and the decrease of the phase space density by a factor Z. 1 pb $= 10^{-36}\;\mathrm{cm}^2 = 0.257\;/(10^5\;\mathrm{GeV}^2)$.

Relics decoupling non-relativistic 2

Allowed ranges for m and T_d.

$m > T_d > b$ eV where $b > 1$ or $b \gg 1$ for DM decoupling in the RD era

$$\left(\frac{Z}{g_d}\right)^{\frac{1}{3}} 1.47 \text{ keV} < m < \frac{2.16}{b} \text{ MeV} \left(\frac{Z}{g_d}\right)^{\frac{2}{3}}$$

$g_d \simeq 3 \quad \text{for} \quad 1 \text{ eV} < T_d < 100 \text{ keV}$ and $1 < Z < 10^3$

$1.02 \text{ keV} < m < \frac{104}{b} \text{ MeV} \quad , \quad T_d < 10.2$ keV.

Only using ρ_{DM} today (ignoring the phase space density information) gives one equation with three unknowns: m, T_d and σ_0,

$\sigma_0 = 0.16 \text{ pbarn} \, \frac{g}{\sqrt{g_d}} \, \frac{m}{T_d}$ http://pdg.lbl.gov

WIMPS with $m = 100$ GeV and $T_d = 5$ GeV require $Z \sim 10^{23}$.

- The comoving **Jeans' (free-streaming) wavelength,** ie the largest wavevector exhibiting gravitational instability , and **the Jeans' mass** (the smallest unstable mass by gravitational collapse) are obtained in the range

$$0.76 \text{ kpc} / (\sqrt{1} + z) < \lambda_{fs}(z) < 16.3 \text{ kpc} (\sqrt{1} + z)$$

$$0.45 \; 10^3 \; M_{sun} < M_J (z) \, (1 + z)^{-3/2} < 0.45 \; 10^7 \; M_{sun}$$

These values at $z = 0$ are consistent with the N-body simulations and are of the order of the small dark matter structures observed today .

By the beginning of the matter dominated era $z \sim 3200$, the masses are of the order of galactic masses 10^{12} Msun and the comoving free-streaming length is of the order of the galaxy sizes today ~ 100 kpc

- The **mass of the dark matter particle**, independent of the particle model, **is in the keV scale** and the temperature when the dark matter particles decoupled is in the 100 GeV scale at least.

No assumption about the nature of the dark matter particle.

keV DM mass much larger than temperature in matter dominated era (which is less than 1 eV)

m and T_d are mildly affected by the uncertainty in the factor Z through a power factor 1/4 of this uncertainty, namely, by a factor $10^{1/4} \sim 1.8$.

- Lower and upper bounds for the dark matter annihilation cross-section σ_0 are derived: $\sigma_0 > (0.239 - 0.956)\ 10^{-9}\ \mathrm{GeV}^{-2}$ and $\sigma_0 < 3200\ m\ \mathrm{GeV}^{-3}$. There is at least five orders of magnitude between them , the dark matter non gravitational self-interaction is therefore negligible (consistent with structure formation and observations, X-ray, optical and lensing observations of the merging of galaxy clusters).

- Typical ”wimps” (weakly interacting massive particles) with mass $m = 100$ GeV and $T_d = 5$ GeV would require a huge $Z \sim 10^{23}$, well above the upper bounds obtained and cannot reproduce the observed galaxy properties.

Wimps produce extremely short free-streaming or Jeans length λ_{fs} today λ_{fs} (0) $3.51\ 10^{-4}$ pc = 72.4 AU that would correspond to unobserved structures much smaller than the galaxy structure. Wimps result strongly disfavoured. [TOO cold]

In all cases: DM particles decoupling either ultra-relativistic or non-relativistic, LTE or OTE :

(i) the mass of the dark matter particle is in the keV scale, T_d is 100 GeV at least.

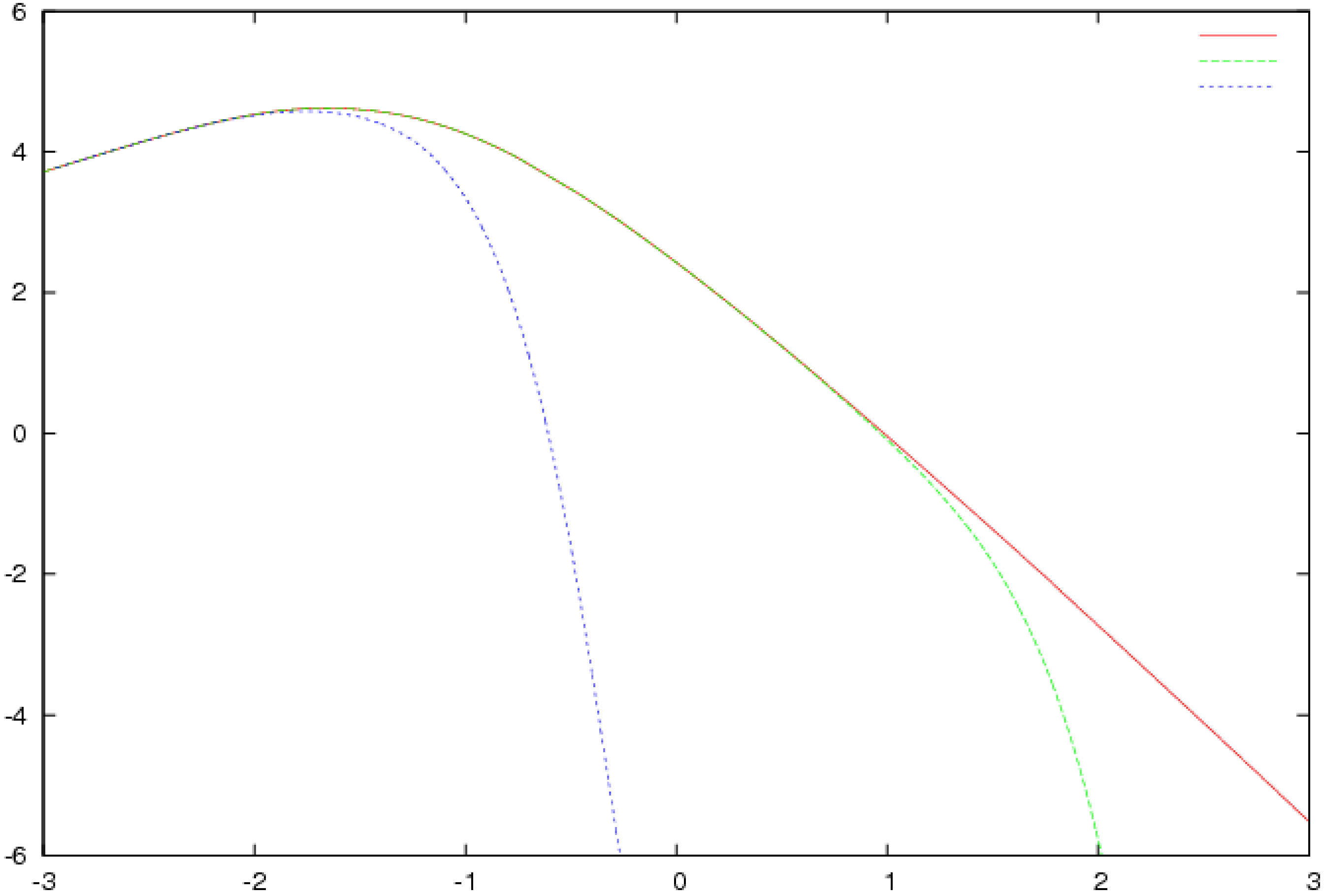
(ii) The free-streaming length today is in the kpc range, consistent with the observed small scale structure and the Jean's mass is in the range of the galactic masses, 10^{12} M_{sun}.

(iii) Dark matter self-interactions (other than grav.) are negligible.

(iv) The keV scale mass dark matter determines cored (non cusped) dark matter halos.

(v) DM candidates with typical high masses 100 GeV (”wimps”) result strongly disfavored

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 for scales < 100 kpc.

Transfer function in the MD era from Gilbert integral eq.

ΛCDM and ΛWDM simulations vs. astronomical observations

wimps

observations

1keVparticles

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.

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

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

Long distance tail reproduce galaxy rotation curves.

Cored profiles do reproduce the astronomical observations.

The constant surface density in DM and luminous galaxies

The Surface density for dark matter (DM) halos and for luminous matter galaxies defined as: $\mu_{0D} \equiv r_0 \; \rho_0,$

$r_0 =$ halo core radius, $\rho_0 =$ central density for DM galaxies

$$\mu_{0D} \simeq 120 \; \frac{M_\odot}{\text{pc}^2} = 5500 \; (\text{MeV})^3 = (17.6 \; \text{Mev})^3$$

5 kpc < r_0 < 100 kpc. For luminous galaxies $\rho_0 = \rho(r_0)$.
Donato et al. 09, Gentile et al. 09

Universal value for μ_{0D}: independent of galaxy luminosity for a large number of galactic systems (spirals, dwarf irregular and spheroidals, elliptics) spanning over 14 magnitudes in luminosity and of different Hubble types.

Similar values $\mu_{0D} \simeq 80 \; \frac{M_\odot}{\text{pc}^2}$ in interstellar molecular clouds of size r_0 of different type and composition over scales $0.001 \, \text{pc} < r_0 < 100$ pc (Larson laws, 1981).

Scaling of the energy and entropy from the surface density

Total energy using the virial and the profile $F(x)$:

$$E = \frac{1}{2} \langle U \rangle = -\frac{1}{4} G \int \frac{d^3r \, d^3r'}{|\boldsymbol{r}-\boldsymbol{r}'|} \langle \rho(r) \, \rho(r') \rangle =$$

$$= -\frac{1}{4} G \, \rho_0^2 \, r_0^5 \int \frac{d^3x \, d^3x'}{|\boldsymbol{x}-\boldsymbol{x}'|} \langle F(x) \, F(x') \rangle \quad \Rightarrow \quad E \sim G \, \mu_{0D}^2 \, r_0^3$$

The energy scales as the volume.

For consistency with the profile, the Boltzmann-Vlasov distribution function must scale as

$$f(\boldsymbol{p}, \boldsymbol{r}) = \frac{1}{m^4 \, r_0^3 \, G^{\frac{3}{2}} \, \sqrt{\rho_0}} \, \mathcal{F}\left(\frac{\boldsymbol{p}}{m \, r_0 \, \sqrt{G \, \rho_0}}, \frac{\boldsymbol{r}}{r_0} \right)$$

Hence, the entropy scales as

$$S = \int f(\boldsymbol{p}, \boldsymbol{r}) \, \log f(\boldsymbol{p}, \boldsymbol{r}) \, d^3p \, d^3r \sim r_0^3 \, \frac{\rho_0}{m} = r_0^2 \, \frac{\mu_{0D}}{m} \; .$$

The entropy scales as the surface (as for black-holes). However, very different proportionality coefficients:

$\frac{S_{BH}/A}{S_{gal}/r_0^2} \sim \frac{m}{\mathrm{keV}} \, 10^{36} \;\Rightarrow$ Much smaller coefficient for galaxies than for black-holes. Bekenstein bound satisfied.

DM surface density from linear Boltzmann-Vlasov eq

The distribution function of the decoupled DM particles:

$$f(\vec{x}, \vec{p}; t) = g \; f_0(p) + F_1(\vec{x}, \vec{p}; t)$$

$f_0(p) =$ thermal equilibrium function at temperature T_d.

We evolve the distribution function $F_1(\vec{x}, \vec{p}; t)$ according to the linearized Boltzmann-Vlasov equation since the end of inflation where the primordial inflationary fluctuations are:

$$|\phi_k| = \sqrt{2} \; \pi \; \frac{|\Delta_0|}{k^{\frac{3}{2}}} \; \left(\frac{k}{k_0}\right)^{\frac{n_s - 1}{2}}$$ where

$$|\Delta_0| \simeq 4.94 \; 10^{-5}, \; n_s \simeq 0.964, \; k_0 = 2 \; \mathrm{Gpc}^{-1}.$$

We Fourier transform over $\vec{x}$ and integrate over momentum

$$\Delta(k, t) \equiv m \; \int \frac{d^3p}{(2\pi)^3} \; \int d^3x \; e^{-i \, \vec{x} \cdot \vec{k}} \; F_1(\vec{x}, \vec{p}; t)$$

The matter density fluctuations $\rho_{lin}(r)$ are given today by

$$\rho_{lin}(r) = \frac{1}{2 \, \pi^2 \, r} \; \int_0^\infty k \; dk \; \sin(k \, r) \; \Delta(k, t_{\mathrm{today}})$$

Linear density fluctuations today

$\Delta(k,z) \overset{z\to 0}{=} \frac{3}{5}\, T(k)\,(1+z_{eq})\,\Delta(k,z_{eq}) \quad , \quad {}_{eq} =$ equilibration,

$T(k) =$ transfer function during the matter dominated era

$T(0) = 1 \quad , \quad T(k \to \infty) = 0$ and $1 + z_{eq} \simeq 3200.$

$T(k)$ decreases with k with the characteristic free streaming scale $k_{fs} = \sqrt{2}/r_{lin}$,

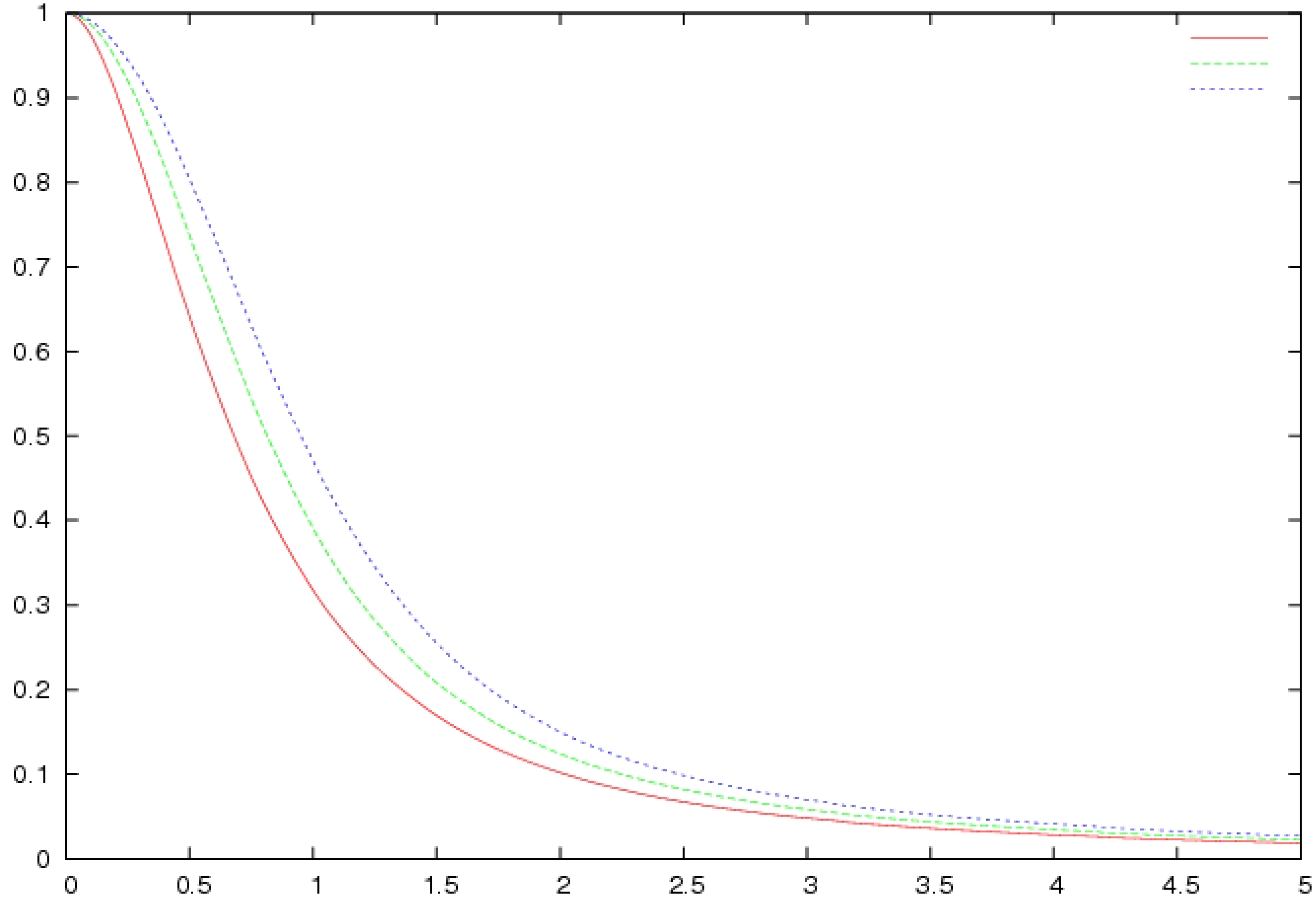
$$r_{lin} = 2\,\sqrt{1+z_{eq}}\,\left(\frac{3\,M_{Pl}^2}{H_0\,\sqrt{\Omega_{DM}}\,Q_{prim}}\right)^{\frac{1}{3}} \quad \text{and} \quad \gamma \equiv k\,r_{lin}.$$

The linear profile today results:

$$\rho_{lin}(r) = \frac{27\,\sqrt{2}}{5\,\pi}\,\frac{\Omega_M^2\,M_{Pl}^2\,H_0}{\sigma_{DM}^2}\,b_0\,b_1\,9.6\,|\Delta_0|\,(k_{eq}\,r_{lin})^{\frac{3}{2}} \times$$
$$(k_0\,r_{lin})^{\frac{1-n_s}{2}}\,\frac{1}{r}\,\int_0^\infty d\gamma\,N(\gamma)\,\sin\left(\gamma\,\frac{r}{r_{lin}}\right)$$

where $N(\gamma) \equiv \gamma^{n_s/2-1}\,\log\left(\frac{c\,\gamma}{k_{eq}\,r_{lin}}\right)\,T(\gamma) \quad , \quad c \simeq 0.11604.$

Density profiles in the linear approximation



Profiles $\rho_{lin}(r)/\rho_{lin}(0)$ vs. $x \equiv r/r_{lin}$. These are universal profiles as functions of x. r_{lin} depends on the galaxy.

Fermions and Bosons decoupling ultrarelativistically and particles decoupling non-relativistically (Maxwell-Boltzmann statistics)

atching the observed and the theoretical surface densit

Surface density: $\mu_0 \equiv r_0 \; \rho(0)$ where $r_0 =$ core radius.

Linear approximation: $r_{lin} = \alpha \; r_0$. α follows fitting the linear profile $\rho_{lin}(r)$ to the Burkert profile with core radius r_0.

$\alpha-$values: $\alpha_{BE} = 0.805 \; , \alpha_{FD} = 0.688 \; , \alpha_{MB} = 0.421$.

Theoretical result: $\mu_{0\,lin} = r_{lin} \; \rho_{lin}(0)/\alpha$.

Fermions:

$$\mu_{0\,lin} = 8261 \; \left[\frac{Q_{prim}}{(\mathrm{keV})^4}\right]^{0.161} \left[1 + 0.0489 \; \ln \frac{Q_{prim}}{(\mathrm{keV})^4}\right] \mathrm{MeV}^3$$

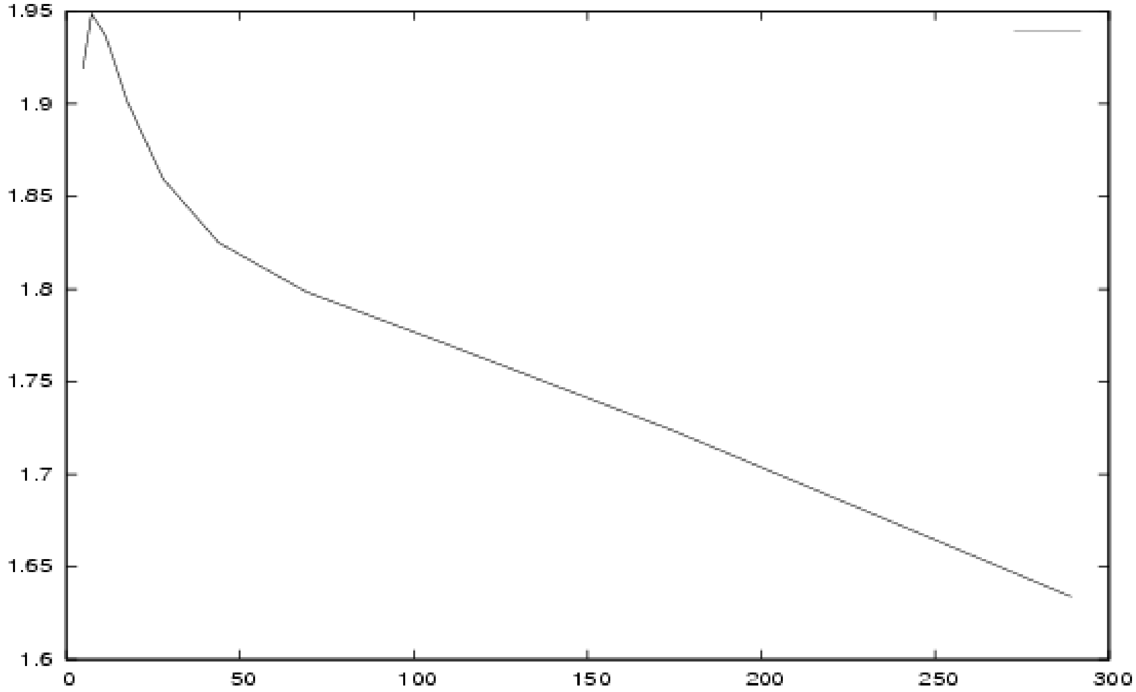
Here: $0.161 = n_s/6$

Matching the observed values $\mu_{0\,obs}$ with this $\mu_{0\,lin}$ gives $Q_{prim}/(\mathrm{keV})^4$ and the mass of the DM particle as

$$m = m_0 \; Q_{prim}^{\frac{1}{4}}/\mathrm{keV}$$

BE: $m_0 = 2.6462$ keV, FD: $m_0 = 2.6934$ keV.

The DM particle mass m from the observed surface density



m in keV vs. $M_{virial}/[10^{11} M_\odot]$

m turns to be around 1.6-1.9 keV.

Better galaxy data will be welcomed.

Linear results for μ_{0D} and the profile vs. observations

Since the surface density $r_0 \, \rho(0)$ should be universal, we can identify $r_{lin} \, \rho_{lin}(0)$ from a spherically symmetric solution of the linearized Boltzmann-Vlasov equation.

The comparison of our theoretical values for μ_{0D} and the observational value indicates that $Z \sim 10 - 1000$. Recalling the DM particle mass:

$$m = 0.568 \, \left(\frac{Z}{g}\right)^{\frac{1}{4}} \text{ keV for Fermions.}$$

This implies that the DM particle mass is in the keV range.

Remarks:

1) For larger scales nonlinear effects from small k should give the customary r^{-3} tail in the density profile.

2) The linear approximation describe the limit of very large galaxies with typical inner size $r_{lin} \sim 100$ kpc.

Density profiles in the linear approximation

Particle Statistics	$\mu_{0D} = r_{lin}\,\rho_{lin}(0)$, $n_s/6 = 0.16$
Bose-Einstein	$(18.9 \text{ Mev})^3\ (Z/100)^{0.16}$
Fermi-Dirac	$(17.7 \text{ Mev})^3\ (Z/100)^{0.16}$
Maxwell-Boltzmann	$(16.7 \text{ Mev})^3\ (Z/100)^{0.16}$

Observed value: $\mu_{0D} \simeq (17.6 \text{ Mev})^3 \Rightarrow Z \sim 10 - 1000$

The linear profiles obtained are cored at the scale r_{lin}

$\rho_{lin}(r)$ scales with the primordial spectral index n_s:

$$\rho_{lin}(r) \overset{r \gg r_{lin}}{=} r^{-1-n_s/2} = r^{-1.482} \quad ,$$

in agreement with the universal empirical behaviour $r^{-1.6\pm0.4}$: M. G. Walker et al. (2009) (observations), I. M. Vass et al. (2009) (simulations).

The agreement between the linear theory and the observations is remarkable.

Non-universal galaxy properties.

	Observed Values	Linear Theory
r_0	5 to 52 kpc	46 to 59 kpc
ρ_0	1.57 to 19.3×10^{-25} $\frac{\text{g}}{\text{cm}^3}$	1.49 to 1.91×10^{-25} $\frac{\text{g}}{\text{cm}^3}$
$\sqrt{\overline{v^2}_{halo}}$	79.3 to 261 km/sec	260 km/sec

Dark matter particle mass: $1.6 < m < 2$ keV.

The larger and less denser are the galaxies, the better are the results from the linear theory for non-universal quantities.

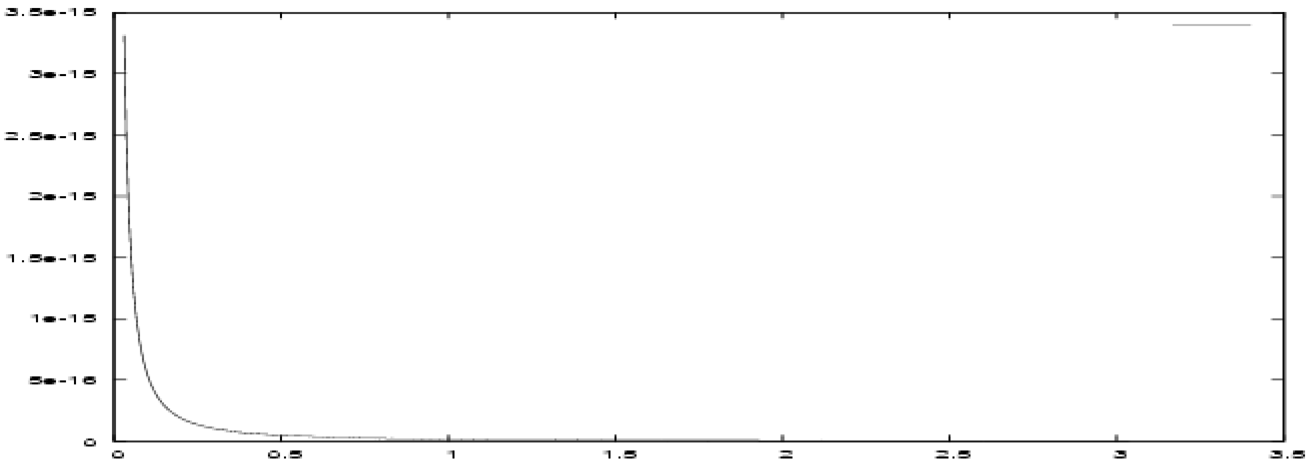
The linear approximation turns to improve for larger galaxies $r_0 > 70$ kpc (i. e. more diluted).

Therefore, universal quantities can be reproduced by the linear approximation.

Wimps vs. galaxy observations

	Observed Values	Wimps in linear theory
r_0	5 to 52 kpc	0.045 pc
ρ_0	1.57 to $19.3 \times 10^{-25}\ \frac{\mathrm{g}}{\mathrm{cm}^3}$	$0.73 \times 10^{-14}\ \frac{\mathrm{g}}{\mathrm{cm}^3}$
$\sqrt{\overline{v^2}}_{halo}$	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 $r \geq 0.03$ pc.

keV SCALE DARK MATTER PARTICLES REPRODUCE:

→OBSERVED GALAXY DENSITIES AND VELOCITY DISPERSIONS

→OBSERVED GALAXY DENSITY PROFILES

→OBSERVED SURFACE DENSITY VALUES O
DARK MATTER DOMINATED GALAXIES

Summary: keV scale DM particles

- Reproduce the phase-space density observed in dwarf satellite galaxies and spiral galaxies (dV S 2009).
- Provide cored universal galaxy profiles in agreement with observations (dV S 2009,dV S S 2010). (Review on cores vs. cusps by de Blok 2010, Salucci & Frigerio Martins 2009)
- Reproduce the universal surface density μ_0 of DM dominated galaxies (dV S S 2010). WIMPS simulations give 10^9 times the observed value of μ_0 (Hoffman et al. 2007).
- Alleviate the satellite problem which appears when wimps are used (Avila-Reese et al. 2000, Götz & Sommer-Larsen 2002)
- Alleviate the voids problem which appears when wimps are used (Tikhonov et al. 2009).

Summary: keV scale DM particles

- All direct searches of DM particles look for $m \gtrsim 1$ GeV. DM mass in the keV scale explains why nothing has been found ...
  e^+ and $\bar{p}$ excess in cosmic rays may be explained by astrophysics: P. L. Biermann et al. (2009), P. Blasi, P. D. Serpico (2009).
- Peculiar velocities in galaxy clusters. Wimp simulations give velocities below observations by factors $4 - 10$ (Kashlinsky et al. 2008, Watkins et al. 2009, Lee & Komatsu 2010). keV scale DM should alleviate this.
- Galaxies from Wimps simulations are too small (Ryan Joung et al. 2009, Holz & Perlmutter 2010). keV scale DM may alleviate this problem.

Reliable simulations with keV mass DM are needed to clarify all these issues.

Summary and Conclusions

- Combining theoretical evolution of fluctuations through the Boltzmann-Vlasov equation with galaxy data points to a DM particle mass 1 - 2 keV. T_d may be > 100 GeV. This is independent 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 : $\rho(r) \sim r^{-1-n_s/2}$.

H. J. de Vega, P. Salucci, N. G. Sanchez, 'Universal galaxy properties and the mass of the dark matter particle from theory and observations: the power of the linear approximation', arXiv:1004.1908.
H. de Vega, N. Sanchez, 'Constant surface density in dark matter galaxies', arXiv:0907.0006 and 'Model independent analysis of dark matter points to a particle mass at the keV scale', arXiv:0901.0922, MNRAS 404, 885 (2010).

END

THANK YOU FOR YOUR ATTENTION

Recent Chalonge Conferences and Workshops

Highlights and Conclusions of the Chalonge 14th Paris Cosmology Colloquium 2010: ‘The Standard Model of the Universe: Theory and Observations’. P Biermann, D Boyanovsky, A Cooray, C Destri, H de Vega, G Gilmore, S Gottlober, E Komatsu, S McGaugh, A Lasenby, R Rebolo, P Salucci, N Sanchez and A Tikhonov present their highlights of the Colloquium.
Conclusions by H. J. de Vega, M.C. Falvella, N. G. Sanchez, arXiv:1009.3494, 58 pages, 20 figures.

Highlights and Conclusions of the Chalonge Meudon Workshop Dark Matter in the Universe. P Biermann, A Cavaliere, H J. de Vega, G Gentile, C Jog, A Lapi, P Salucci, N G. Sanchez, P Serpico, R Stiele, J van Eymeren and M Weber present their highlights of the Workshop.
Conclusions by H. J. de Vega, N. G. Sanchez, arXiv:1007.2411, 41 pages, 10 figures.

[DARK MATTER : FACTS AND STATUS

→ DARK MATTER DOES EXIST

→ ASTROPHYSICAL OBSERVATIONS POINTS TO THE EXISTENCE OF DARK MATTER

→ AFTER MORE THAN TWENTY YEARS OF DEDICATED DARK MATTER PARTICLE EXPERIMENTS, THE DIRECT SEARCH OF DARK MATTER PARTICLES FULLY CONCENTRATED IN "WIMPS"REVEALED SO FAR, UNSUCCEFULL

BUT DARK MATTER DOES EXIST

IN DESPITE OF THAT: PROPOSALS TO REPLACE DARK MATTER DO APPEAR:

PROPOSING TO CHANGE THE LAWS OF PHYSICS (!!!), (???)

ADDING OVER CONFUSION, MIXING , POLLUTION

TODAY, THE DARK MATTER RESEARCH AND DIRECT SEARCH SEEMS TO SPLIT IN THREE SETS:

(1). PARTICLE PHYSICS DARK MATTER :BUILDING MODELS, DEDICATED LAB EXPERIMENTS, ANNHILATING DARK MATTER, (FULLY CONCENTRATED ON "WIMPS")

(2). ASTROPHYSICAL DARK MATTER: (ASTROPHYSICAL MODELS, ASTROPHYSICAL OBSERVATIONS)

(3). NUMERICAL SIMULATIONS RESEARCH

(1) and (2) DO NOT AGREE IN THE RESULTS

and (2) and (3) DO NOT FULLY AGREE NEITHER

SOMETHING IS GOING WRONG IN THE RESEARCH ON THE DARK MATTER SUBJECT

WHAT IS GOING WRONG ?, [AND WHY IS GOING WRONG]

"FUIT EN AVANT" ("ESCAPE TO THE FUTURE") IS NOT THE ISSUE

THE SUBJECT IS MATURE

→ THERE EXIST ASTRONOMICAL OBSERVATIONS AND FACILITIES

→ THERE EXIST MODEL/THEORETICAL ASTROPHYSICAL RESULTS WHICH FIT, AGREE WITH THE ASTRONOMICAL OBSERVATIONS

→ THERE EXISTED,THERE EXIST MANY DARK MATTER DEDICATED PARTICLE EXPERIMENTS (ALTHOUGH FULLY CONCENTRATED IN "WIMPS")

→ THERE EXIST COMPUTER AND SUPER COMPUTERS AND DIFFERENT RESEARCHER GROUPS PERFORMING WORK WITH THEM

→ THERE EXIST A CONSIDERABLE AMOUNT OF RESEARCHERS WORKING IN DARK MATTER DURING MORE THAN TWENTY YEARs

" FUITE EN AVANT" ("ESCAPE TO THE FUTURE") IS NOT THE ISSUE

WHAT IS WRONG in the present day subject of Dark Matter?,

(The Answer is Trivial and can be found in these 3 slides)]

Particle physics candidates for DM

No particle in the Standard Model of particle physics (SM) can play the role of DM.

Many extensions of the SM can be envisaged to include a DM particle with mass in the keV scale and weakly enough coupled to the Standard Model particles to fulfill all particle physics experimental constraints.

Main candidates in the keV mass scale: sterile neutrinos, gravitinos, light neutralino, majoron ...

Particle physics motivations for sterile neutrinos:

There are both left and right handed quarks
(with respect to the chirality).

It is natural to have right handed neutrinos ν_R besides the known left-handed neutrino. Quark-lepton similarity.

Sterile Neutrinos in the SM of particle physics

SM symmetry group: $SU(3)_{color} \otimes SU(2)_{weak} \otimes U(1)_{hypercharge}$

Leptons are color singlets and doublets under weak SU(2).

Sterile neutrinos ν_R do not participate to weak interactions.

Hence, they must be singlets of color, weak SU(2) and hypercharge.

Mixing (bilinear) terms appear: $\bar{\Phi}_0 \, \bar{\nu}_R \, \nu_L$ and $\bar{\nu}_L \, \nu_R \, \Phi_0$.
They produce transmutations $\nu_L \Leftrightarrow \nu_R$. $(m_D = h_Y \, |\Phi_0|)$.

Neutrino mass matrix: $(\bar{\nu}_L \; \bar{\nu}_R) \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$

Seesaw mass eigenvalues: $\frac{m_D^2}{M}$ and M, with eigenvectors:

- active neutrino: $\nu_{active} \simeq \nu_L - \frac{m_D}{M} \, \nu_R, \quad M \gg m_D.$
- sterile neutrino: $\nu_{sterile} \simeq \nu_R + \frac{m_D}{M} \, \nu_L, \quad M \gg m_D^2/M.$

Sterile Neutrinos

Choosing $M \sim 1$ keV and $m_D \sim 0.1$ eV is consistent with observations.

Mixing angle: $\theta \sim \frac{m_D}{M} \sim 10^{-4}$ is appropriate to produce enough sterile neutrinos accounting for the observed DM.

Smallness of θ makes the detection of steriles very difficult.

Precise measure of nucleus recoil in tritium beta decay:
${}^3H_1 \Longrightarrow {}^3He_2 + e^- + \bar{\nu}$ can show the presence of a sterile instead of the active $\bar{\nu}$ in the decay products.

Rhenium 187 beta decay gives $\theta < 0.095$ for 1 keV steriles [Galeazzi et al. PRL, 86, 1978 (2001)].
Available energy: $Q({}^{187}Re) = 2.47$ keV, $Q({}^3H_1) = 18.6$ keV.

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.

Future Perspectives

The Golden Age of Cosmology and Astrophysics continues.

Galaxy and Star formation. DM properties from galaxy observations. Better upper bounds on DM cross-sections.

DM in planets and the earth. Flyby and Pioneer anomalies?

Chandra, Suzaku X-ray data: keV mass DM decay?

Sun models well reproduce the sun's chemical composition but not the heliosismology (Asplund et al. 2009).
Can DM inside the Sun help to explain the discrepancy?

Nature of Dark Matter? 83% of the matter in the universe.

Light DM particles are strongly favoured $m_{DM} \sim$ keV.
Sterile neutrinos ? Other particle in the keV mass scale?

Precision determination of DM properties (mass, T_d, nature) from better galaxy data combined with theory (Boltzmann-Vlasov and simulations).

$$f(\vec{p};\vec{x};t) = f_0(p) + F_1(\vec{p};\vec{x};t) \qquad \varphi(\vec{x},t) = \varphi_0(\vec{x},t) + \varphi_1$$

Unperturbed decoupled distribution

(DM) perturbation

Unperturbed grav. Potential (FRW)

Grav. Potential perturbation

Linearized B-V Equation: $$\frac{1}{a}\frac{\partial F_1}{\partial \tau} + \frac{\vec{p}}{ma^2}\cdot\vec{\nabla}_{\vec{x}} F_1 - m\vec{\nabla}_{\vec{x}}\varphi_1\cdot\vec{\nabla}_{\vec{p}} f_0 = 0$$

Poisson Eqn: $$\varphi_1(\vec{k};s) = -\frac{4\pi G}{k^2 a(s)}\Delta(\vec{k};s) \qquad \Delta(\vec{k},s) = m\int\frac{d^3p}{(2\pi)^3}F_1(\vec{k},\vec{p};s)$$

``New'' variable s = $$s = \frac{2u}{H_0\sqrt{\Omega_{DM} a_{eq}}}; \qquad u = 1 - \left(\frac{a_{eq}}{a}\right)^{\frac{1}{2}} \longrightarrow \frac{ds}{d\tau} = \frac{1}{a}$$

Follow the steps…

- ➢ **Integrate B-V equation (in s)**
- ➢ **Use Poisson’s eqn.** → **Integral eqn: Gilbert’s**

- ➢ **Normalize at initial time (t_{eq}):**

$$\Phi(\vec{k},u)=\frac{\varphi_1(\vec{k},u)}{\varphi_1(\vec{k},0)} \qquad \delta(k,u)=\frac{\Delta(k;u)}{\Delta(k;0)}$$

$$P_f(k)=T^2(k)P_i(k)$$

$$T(k)=\frac{5}{3}\Phi(k;1)$$

- ➢ **Normalize the decoupled**
- ➢**distribution function:**

$$\tilde{f}_0(y)=\frac{f_0(y)}{\int_0^\infty y^2 f_0(y)dy}$$

→ **comoving momentum**

$$y=\frac{p}{T_{0,d}}$$

→ **decoupling temp.**

- ➢ **Take 2 derivatives w.r.t. u:** →

$$\underbrace{\ddot{\delta}(k,u) - \frac{6\,\delta(k,u)}{(1-u)^2} + 3\,\gamma^2\,\delta(k,u)} - \underbrace{\int_0^u du'\,K(u-u')\,\frac{\delta(k,u')}{(1-u')^2}} = \underbrace{S_0(k;u)}$$

Jeans' Fluid equation: replace C^2_s by $<V^2>$

Correction to fluid description: memory of gravitational clustering

Free streaming solution in absence of gravity: INITIAL CONDITIONS

$$\gamma^2 = \frac{2\,k^2}{k^2_{fs}(t_{eq})}; \quad \underbrace{k_{fs}(t_{eq}) = \frac{0.0102}{\sqrt{\overline{y^2}}}\left[\frac{g_d}{2}\right]^{\frac{1}{3}}\frac{m}{\text{keV}}[\text{kpc}]^{-1}}; \quad \overline{y^2} = \int_0^\infty dy\;y^4\;\tilde{f}_0(y)$$

Free streaming wave vector at matter-radiation equality

$$k_{fs}(t_{eq}) = \begin{cases} \dfrac{5.88}{\text{pc}}\left(\dfrac{g_d}{2}\right)^{\frac{1}{3}}\left(\dfrac{m}{100\,\text{GeV}}\right)^{\frac{1}{2}}\left(\dfrac{T_d}{10\,\text{MeV}}\right)^{\frac{1}{2}} & \text{WIMPs} \\ 0.00284\left(\dfrac{g_d}{2}\right)^{\frac{1}{3}}\dfrac{m}{\text{keV}}[\text{kpc}]^{-1} & \text{FD thermal relics} \\ 0.00317\left(\dfrac{g_d}{2}\right)^{\frac{1}{3}}\dfrac{m}{\text{keV}}[\text{kpc}]^{-1} & \text{BE thermal relics} \end{cases}$$

$$K(u-u') = 6\alpha\int_0^\infty y\,(\overline{y^2} - y^2)\;\tilde{f}_0(y)\sin[\alpha\,\dot{y}(u-u')]\,dy \qquad \alpha = \sqrt{\frac{3}{\overline{y^2}}}\gamma$$

DECOUPLED DISTRIBUTION FUNCTION: STATISTICS

Properties of K(u-u’):

- ❖ **Correction to fluid description**
- ❖**Memory of gravitational clustering** →
- ❖**f_0(y) with larger support for small y** →
- ❖**longer range of memory**
- ❖**Longer range of memory → → → larger T(k)**
- ❖**Negligible at large scales** $k << k_{fs}(t_{eq})$
- ❖**Important at small scales** $k \geq k_{fs}(t_{eq})$

Exact T(k)

$$T(k) = \frac{10}{\sqrt{3}\,\gamma^3}\int_0^1 h_2(u)\Big[\frac{I[\alpha u]}{(1-u)^2} + \frac{1}{6}S_{NB}[\delta;u]\Big]du$$

Regular solution of Jeans' Fluid eqn.

Free streaming solution In absence of gravity:INITIAL CONDITIONS

Memory of gravitational clustering: K(u-u')

Features:

- ✓ **Systematic Fredholm expansion**
- ✓**First TWO terms simple and remarkably accurate**
- ✓**Include memory of gravitational clustering**
- ✓**Arbitrary distribution function(statistics+non LTE)**
- ✓**Arbitrary initial conditions**