Predictions of the Effective Theory of Inflation and keV Dark Matter in the Standard Model of the Universe

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PHYSICAL CONTENTS

(0) FRAMEWORK: The Standard Cosmological Model Includes Inflation

(I) PREDICTIONS OF INFLATION 2010:
There exists a Effective Theory of Inflation which is Predictive

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

(III) PERSPECTIVE AND CONCLUSIONS

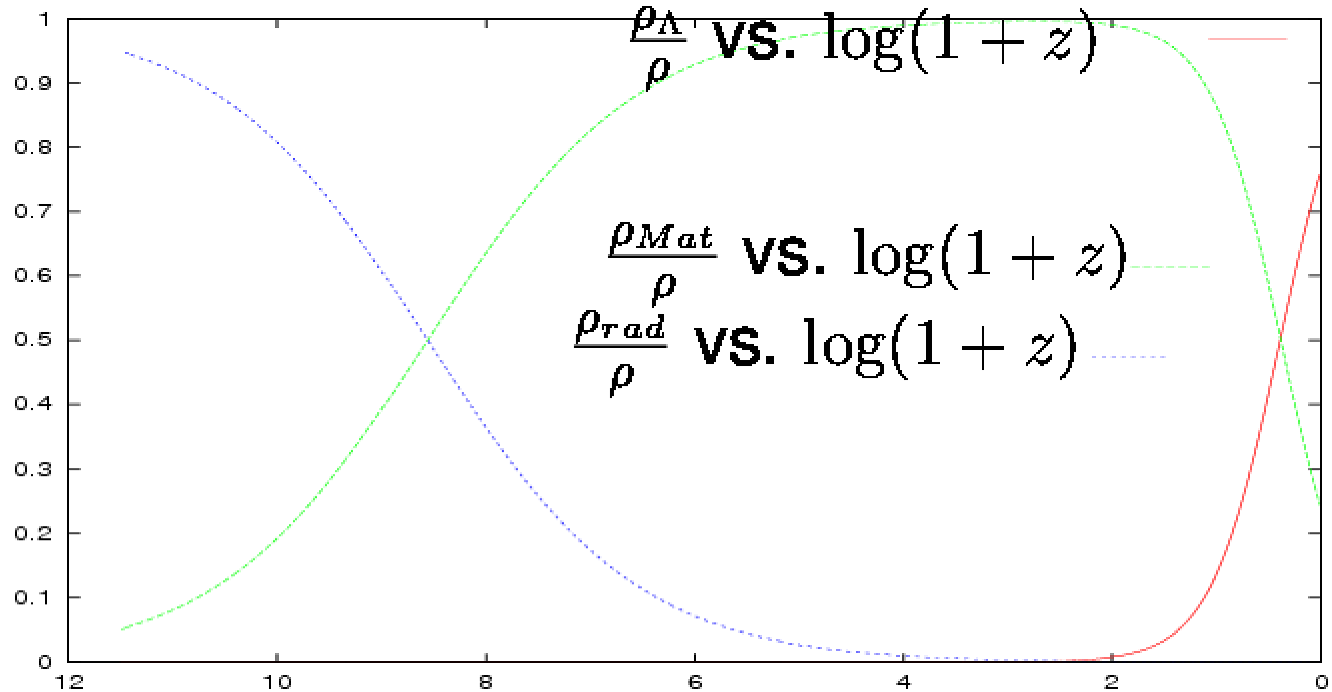
CONTENT OF THE UNIVERSE

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 universal expansion, compatible with cosmological constant

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.

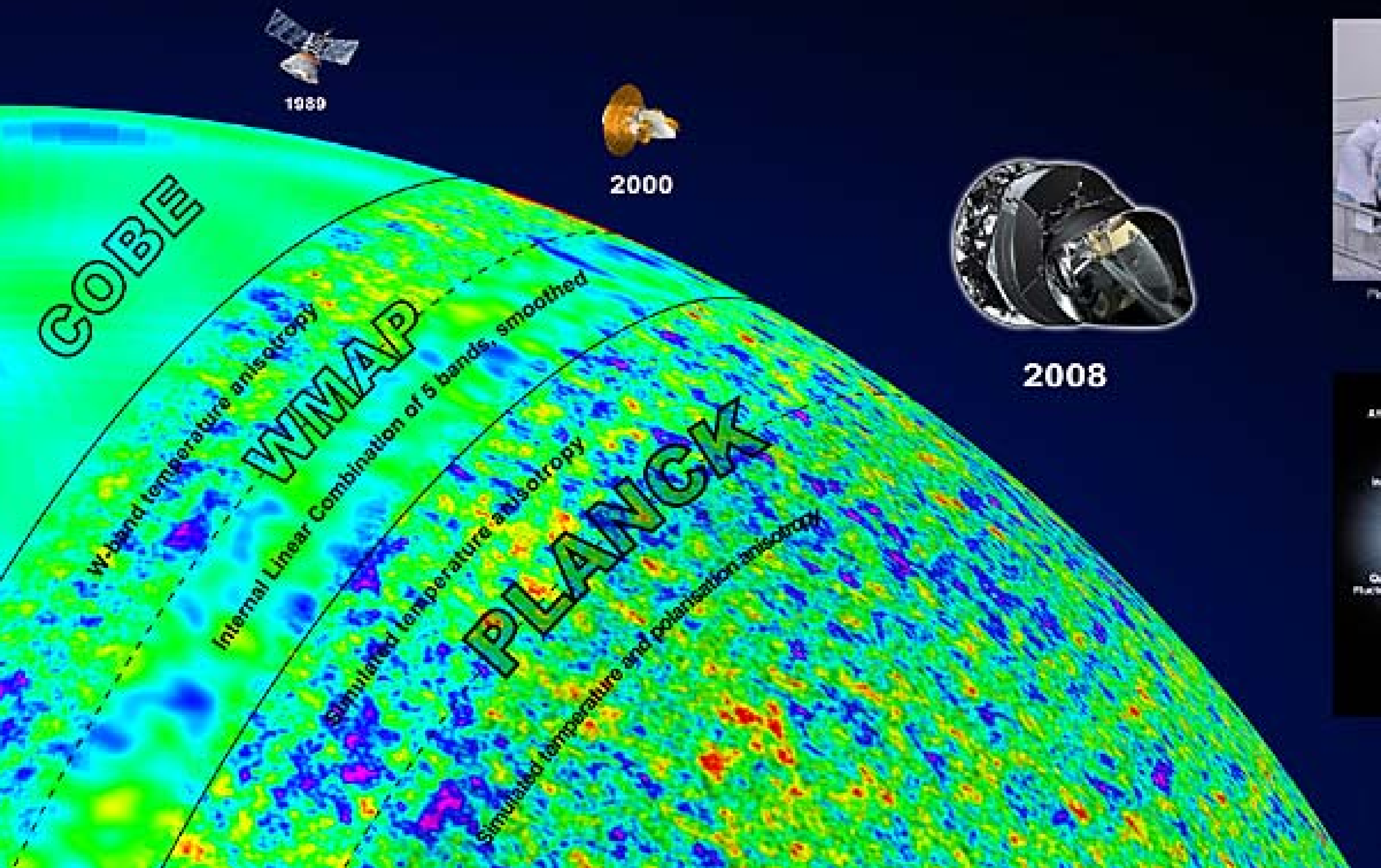
Today: $z = 0$, $T = 2.725$K $= 0.2348$ meV $t = 13.72$ Gyr.

Standard Cosmological Model: ΛCDM

ΛCDM = Cold Dark Matter + Cosmological Constant 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

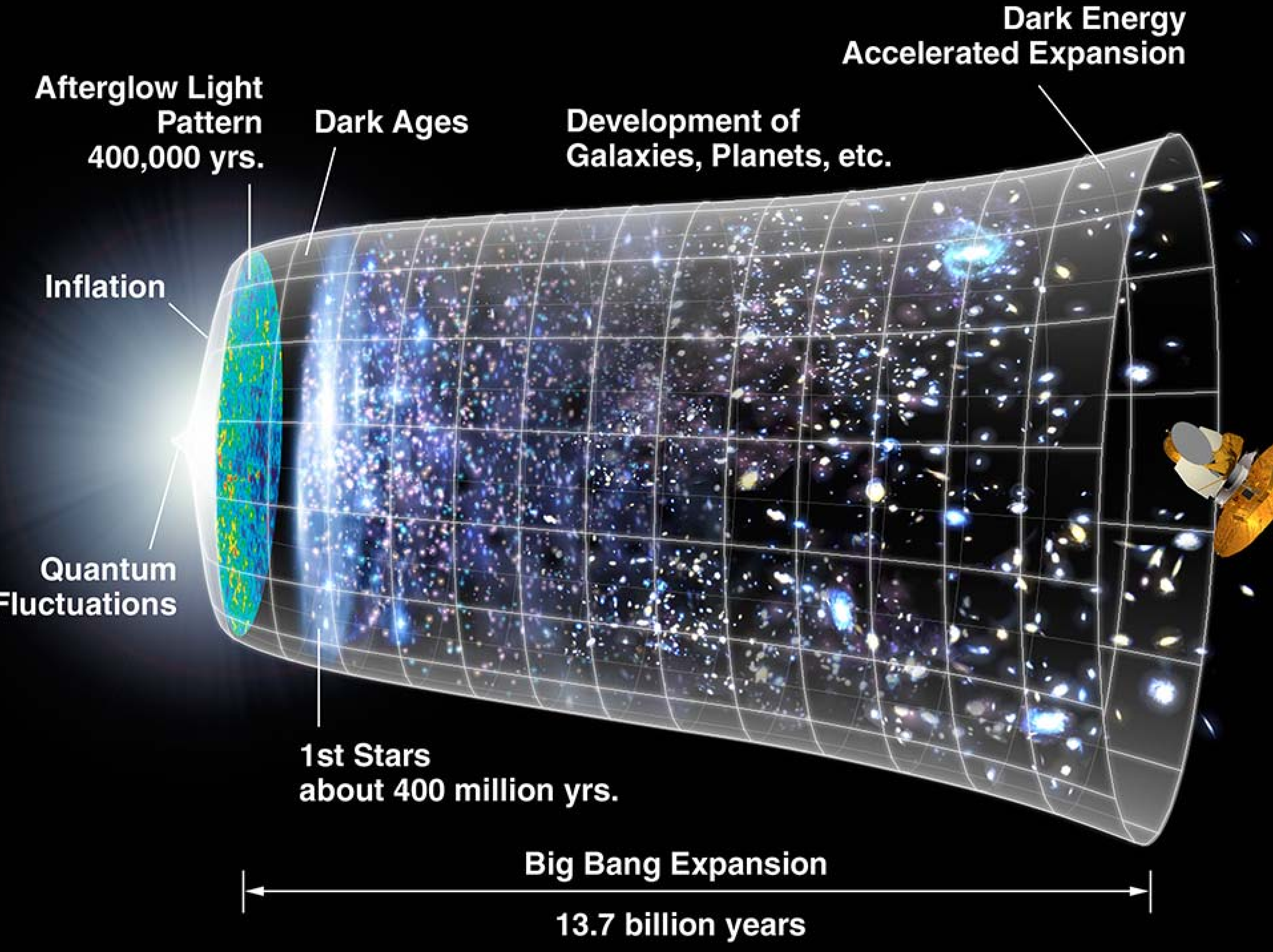
CMB Missions Revolutionise Our Understanding of the Universe



Standard Cosmological Model: ΛCDM

ΛCDM = Cold Dark Matter + Cosmological Constant

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


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

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 $\phi(t, x)$: 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

DAWN OF TIME

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

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

Fast roll inflation

10^{-39} sec $\lesssim t \lesssim 10^{-38}$ sec

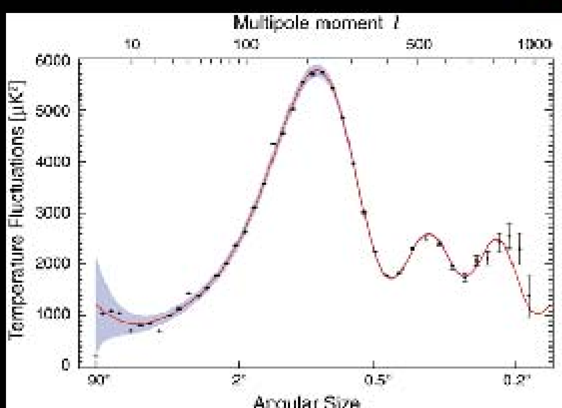
Slow roll inflation

10^{-38} sec $\lesssim t \lesssim 10^{-36}$ sec

inflation

380,000 years

13.7 billion years



Fast and Slow Roll Inflation

$$H^2 = \frac{1}{3\,M_{PL}^2}\left[\frac{1}{2}\,\dot{\Phi}^2 + V(\Phi)\right] ,$$

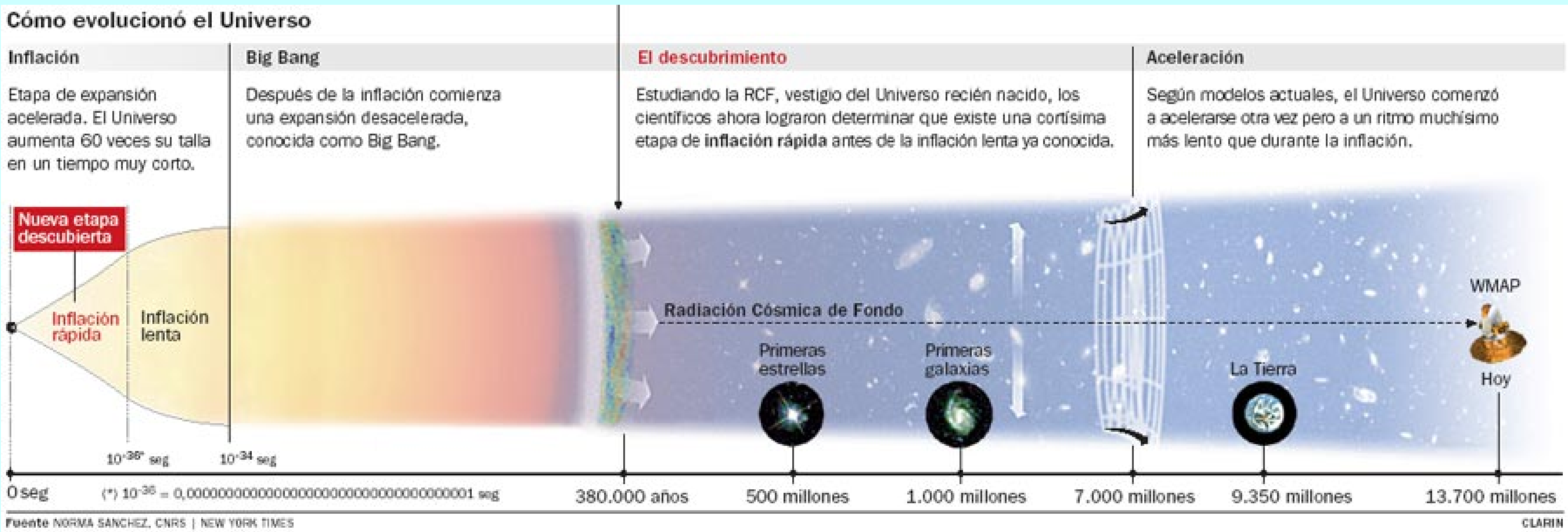
$$\ddot{\Phi} + 3\,H\,\dot{\Phi} + V'(\Phi) = 0 \,.$$

Slow-roll corresponds to $\dot{\Phi}^2 \ll V(\Phi)$.

Generically, we can have $\dot{\Phi}^2 \sim V(\Phi)$ to start.
That is, FAST ROLL inflation.

However, slow-roll is an attractor with a large basin.

Fast roll Inflation produces the Observed Quadrupole CMB Suppression

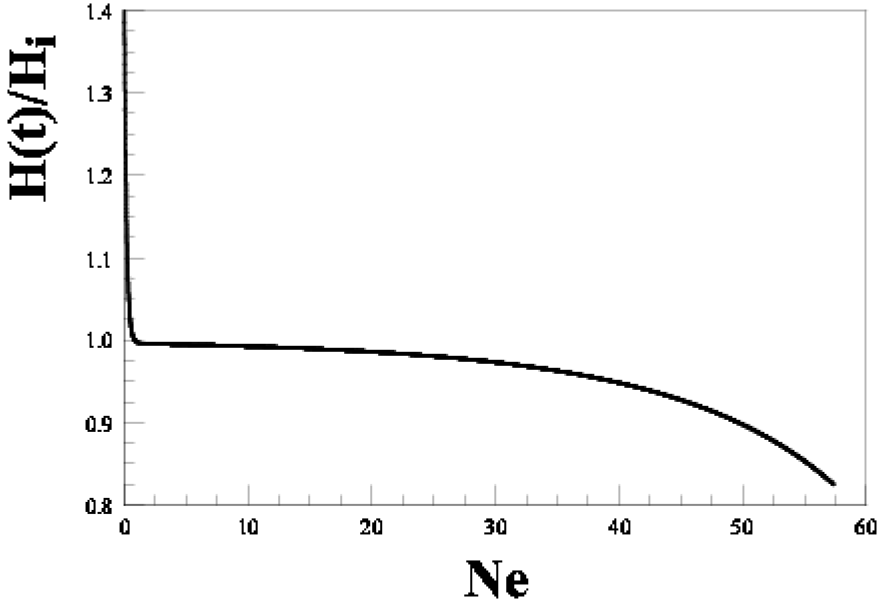


D. Boyanovsky, H. J de Vega and N. G. Sanchez,

” CMB quadrupole suppression II : The early fast roll stage ”

Phys. Rev. D74 , 123006 (2006)

Hubble vs. number of efolds



H_i = Hubble at the beginning of slow-roll.
Fast-roll lasts about one-efold.

Extreme fast roll solution ($y^2 = 3$) in cosmic time:

$$H = \frac{1}{3\,t} \quad , \quad a(t) = a_0 \; t^{\frac{1}{3}} \quad , \quad \Phi = -M_{Pl} \sqrt{\frac{2}{3}} \; \log(m\;t) \; .$$

Quadrupole suppression and Fast-roll Inflation

The observed CMB-quadrupole (COBE,WMAP5) is six times smaller than the ΛCDM model value.
In the best ΛCDM fit the probability that the quadrupole is as low or lower than the observed value is 3%.
It is hence relevant to find a cosmological explanation of the quadrupole supression.

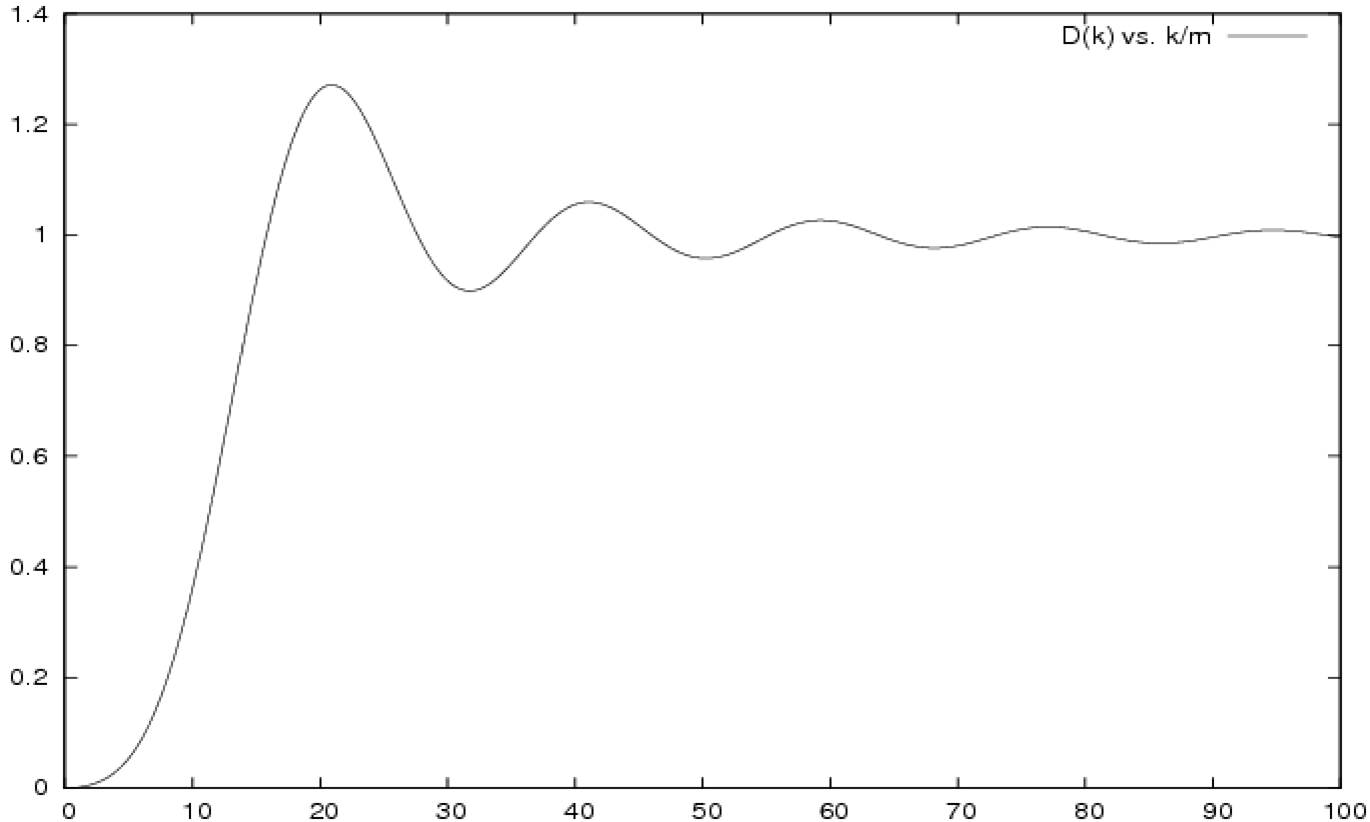
Generically, the classical evolution of the inflaton has a brief **fast-roll stage** that precedes the slow-roll regime.
In case the quadrupole CMB mode leaves the horizon during fast-roll, before slow-roll starts, we find that the quadrupole mode gets suppressed.

$$P(k) = |\Delta_{k\ ad}^{(S)}|^2 \ (k/k_0)^{n_s - 1}[1 + D(k)]$$

The transfer function $D(k)$ changes the primordial power.

$$1 + D(0) = 0, \quad D(\infty) = 0$$

The Fast-Roll Transfer Function



$k_Q = 11.5\ m,\ k_{fastroll \to slowroll} = 14\ m,\ k_{pivot} = 96.7\ m,$
$m = 1.21\,10^{13}\mathrm{GeV}, k_Q^{today} = 0.238\ \mathrm{Gpc}^{-1} \implies$ redshift at the beginning of inflation $= 0.9 \times 10^{56} \simeq e^{129}$.

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

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

THE EXPANSION OF THE UNIVERSE IS THE MOST POWERFUL REFRIGERATOR

INFLATION PRODUCES THE MOST POWERFUL STRETCHING OF LENGTHS

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

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

THE EXPANSION CLASSICALIZES THE UNIVERSE

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

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)

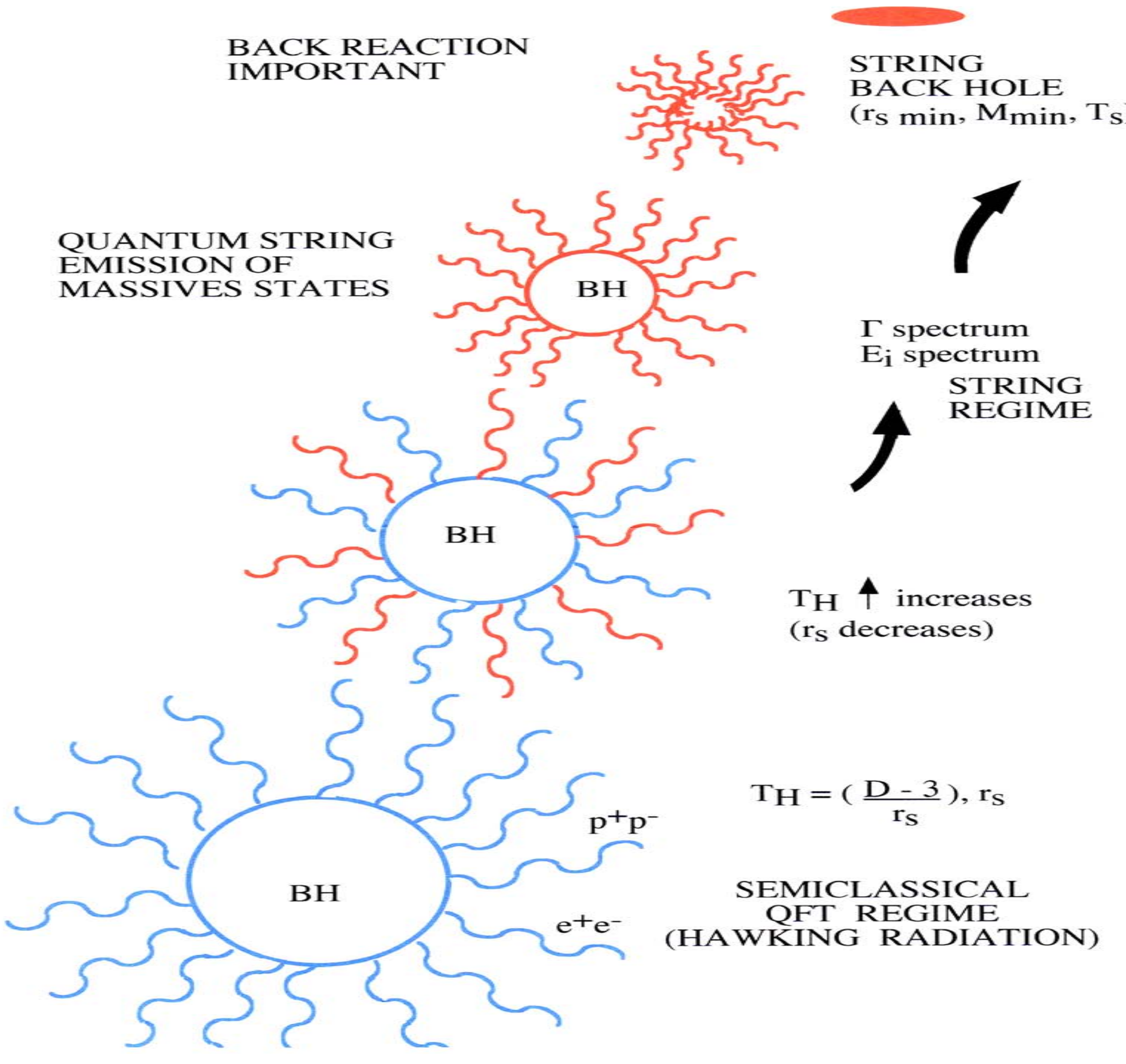
The CMB allows to observe it
(while is not possible to observe for Black Holes)

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



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)

CONCEPTUAL UNIFICATION

- Cosmological evolution goes from a quantum gravity phase to a semi-classical phase (inflation) and then to the classical (standard Friedman-Robertson-Walker) phases
- 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.

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.

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**

$$r > 0.016 \quad \text{at } 95\% \text{ CL} \quad \text{and}$$

$$r > 0.049 \quad \text{at } 68\% \text{ CL.}$$

Moreover, we find **$r = 0.055$ as the most probable value.**

For the other cosmological parameters, both analysis agree.

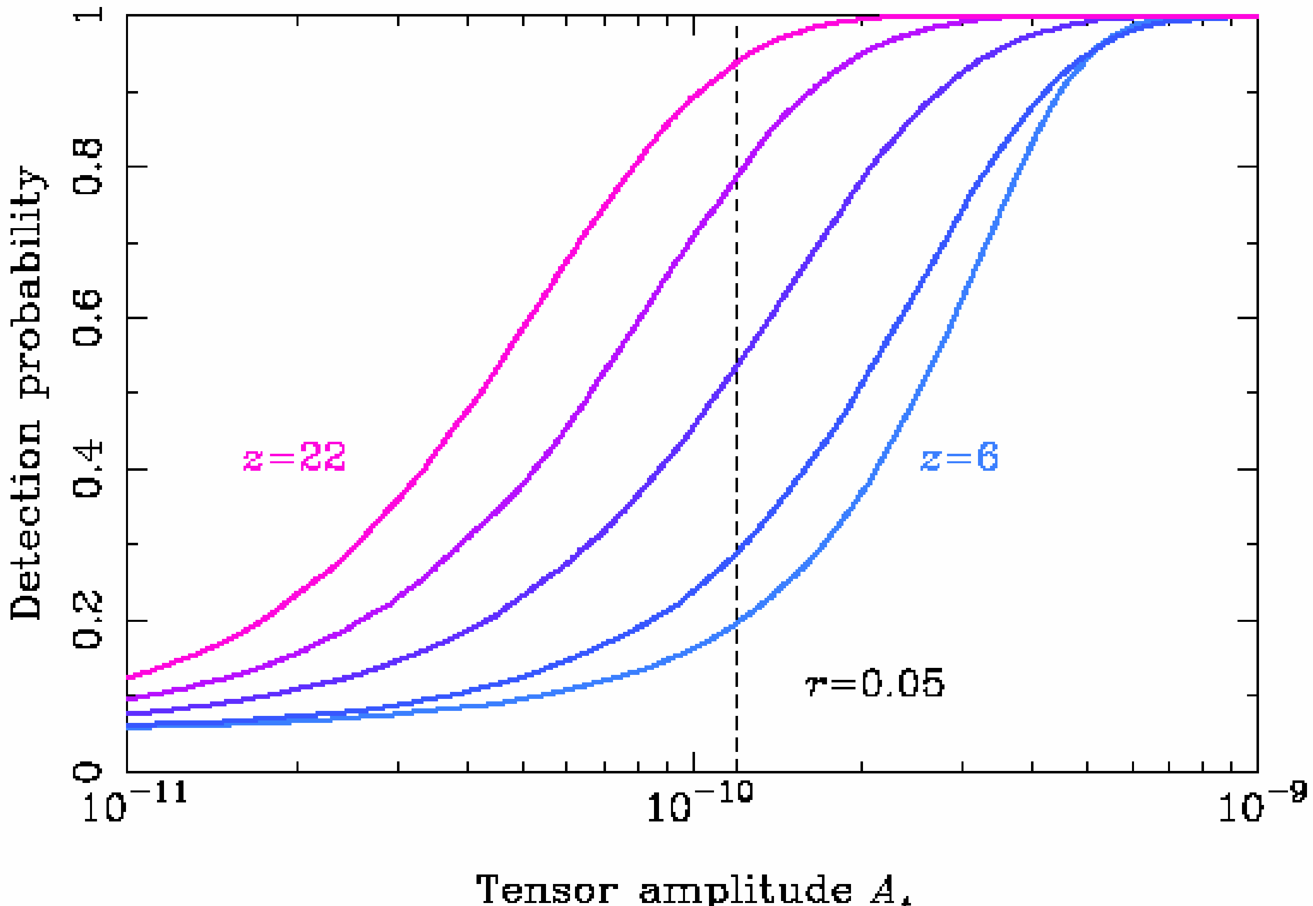


FIG 2.16.—The probability of detecting B-mode polarization at 95% confidence as a function of A_T, the amplitude of the primordial tensor power spectrum (assumed scale-invariant), for *Planck* observations using 65% of the sky. The curves correspond to different assumed epochs of (instantaneous) reionization: $z = 6$, 10, 14, 18 and 22. The dashed line corresponds to a tensor-to-scalar ratio $r = 0.05$ for the best-fit scalar normalisation, $A_S = 2.7 \times 10^{-9}$, from the one-year *WMAP* observations.

The Theory of Inflation

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

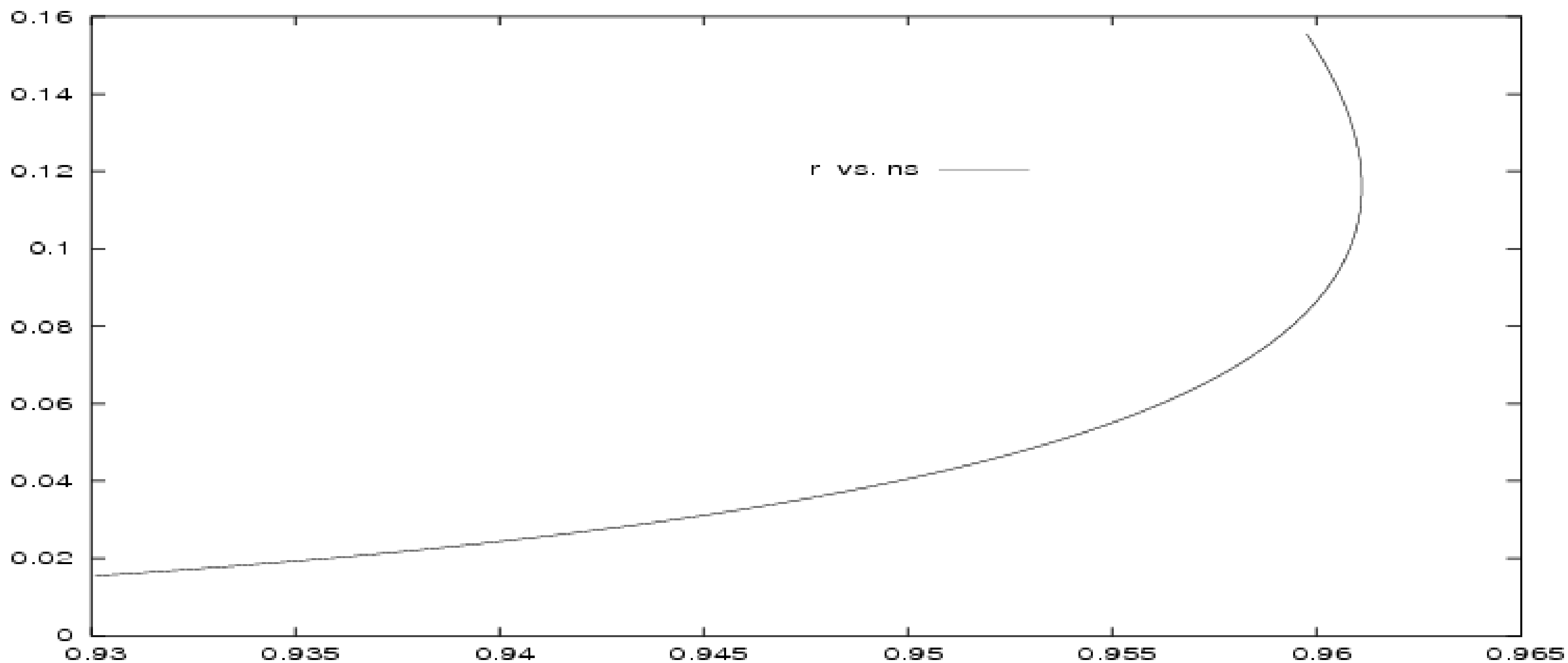
Relevant effective theories in physics:

- 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).

Summary and Conclusions

- Inflation can be formulated as an effective field theory in the Ginsburg-Landau spirit with energy scale $M \sim M_{GUT} \sim 10^{16}$ GeV $\ll M_{Pl}$.
  Inflaton mass small: $m \sim H/\sqrt{N} \sim M^2/M_{Pl} \ll M$.
  Infrared regime !!
- The slow-roll approximation is a $1/N$ expansion, $N \sim 60$
- MCMC analysis of WMAP+LSS data plus the Trinomial Inflation potential indicates a spontaneously symmetry breaking potential (new inflation): $w(\chi) = \frac{y}{32}\left(\chi^2 - \frac{8}{y}\right)^2$.
- Lower Bounds: $r > 0.016\ (95\%\ \mathrm{CL})$, $r > 0.049\ (68\%\ \mathrm{CL})$.
  The most probable values are $n_s \simeq 0.956$, $r \simeq 0.055$ with a quartic coupling $y \simeq 1.3$.

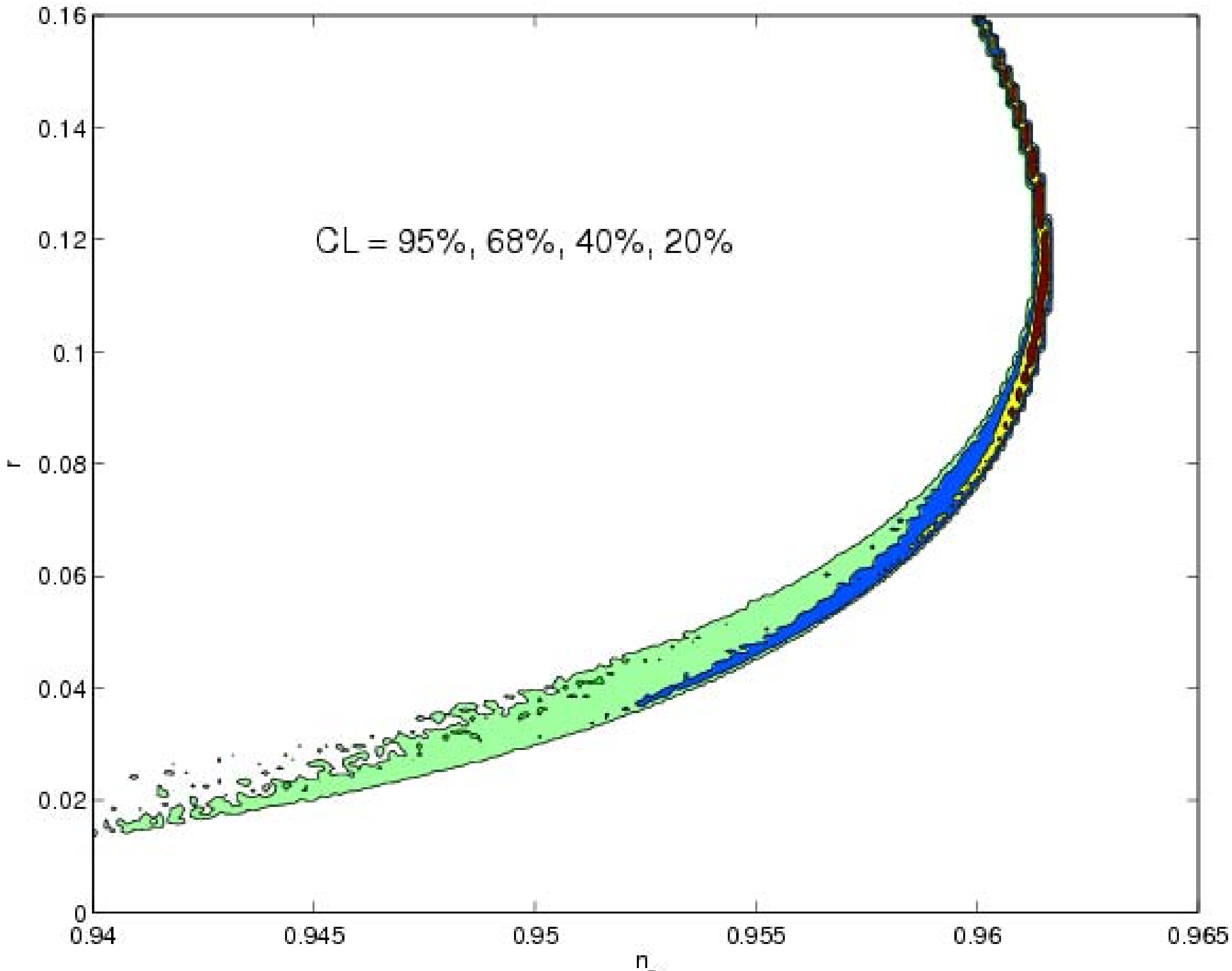
Binomial New Inflation



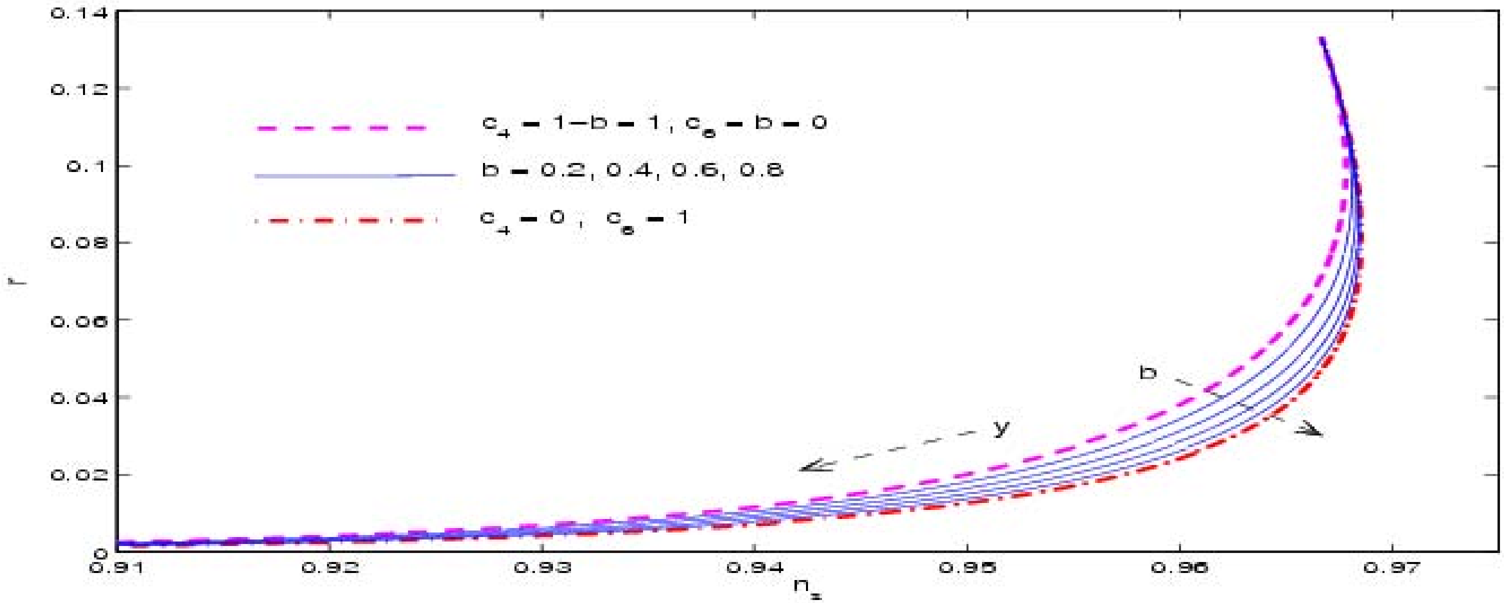
$r = \frac{8}{N} = 0.16$ and $n_s = 1 - \frac{2}{N} = 0.96$ at $y = 0$.

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



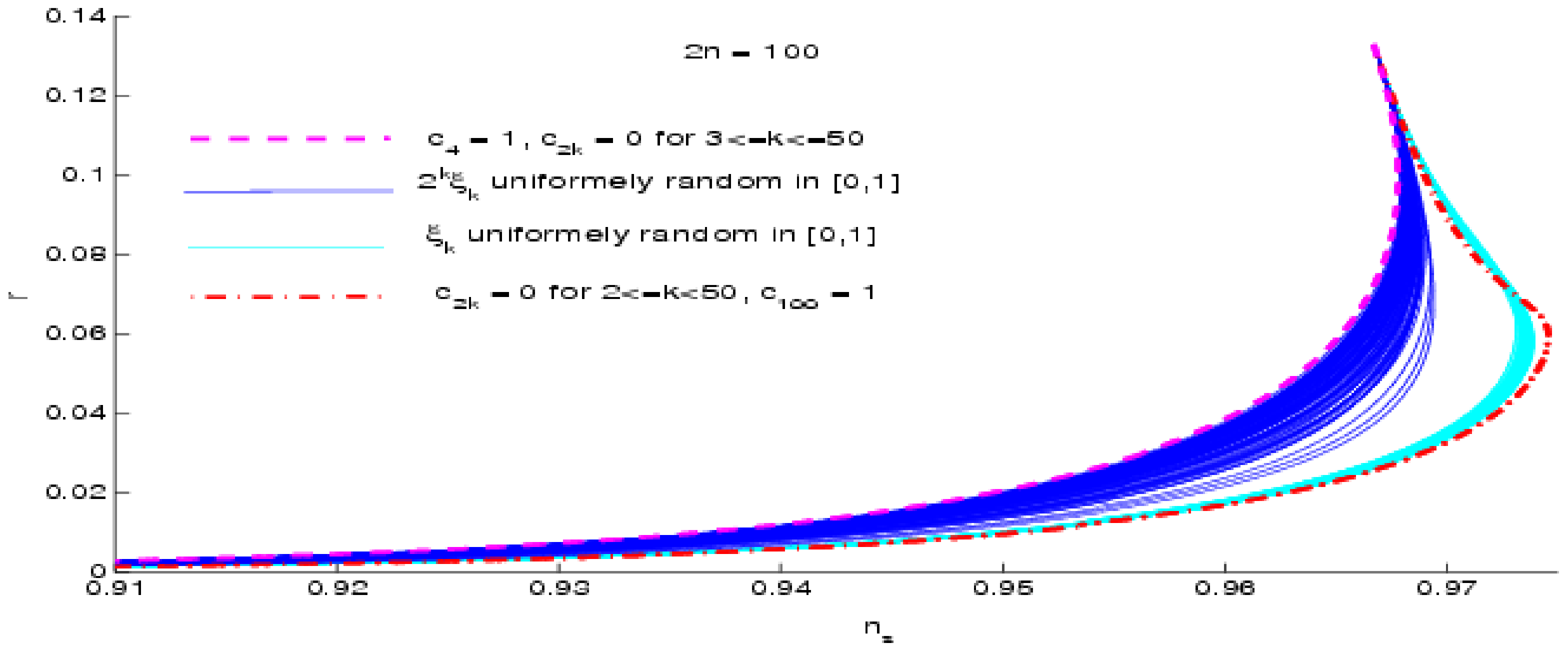
$$w_b(\chi) = \frac{y}{96}\left(\chi^2 - \frac{8}{y}\right)^2 \left(3 + b + \frac{1}{4}\, y\, b\, \chi^2\right) \; .$$

$0 < y < \infty$ 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 $n = 50$.

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

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$$r > 0.049 \quad \text{at } 68\% \text{ CL.}$$

Moreover, we find $r = 0.055$ as the most probable value.

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: $r \sim 0.051$

CONCLUSIONS

Most probable values with the fourth degree double–well inflaton potential: $n_s \simeq 0.964, \; r \simeq 0.051$

Lower bound for r for **all** potentials in the Ginsburg-Landau class: $r > 0.021$ for the current best value $n_s = 0.964$.

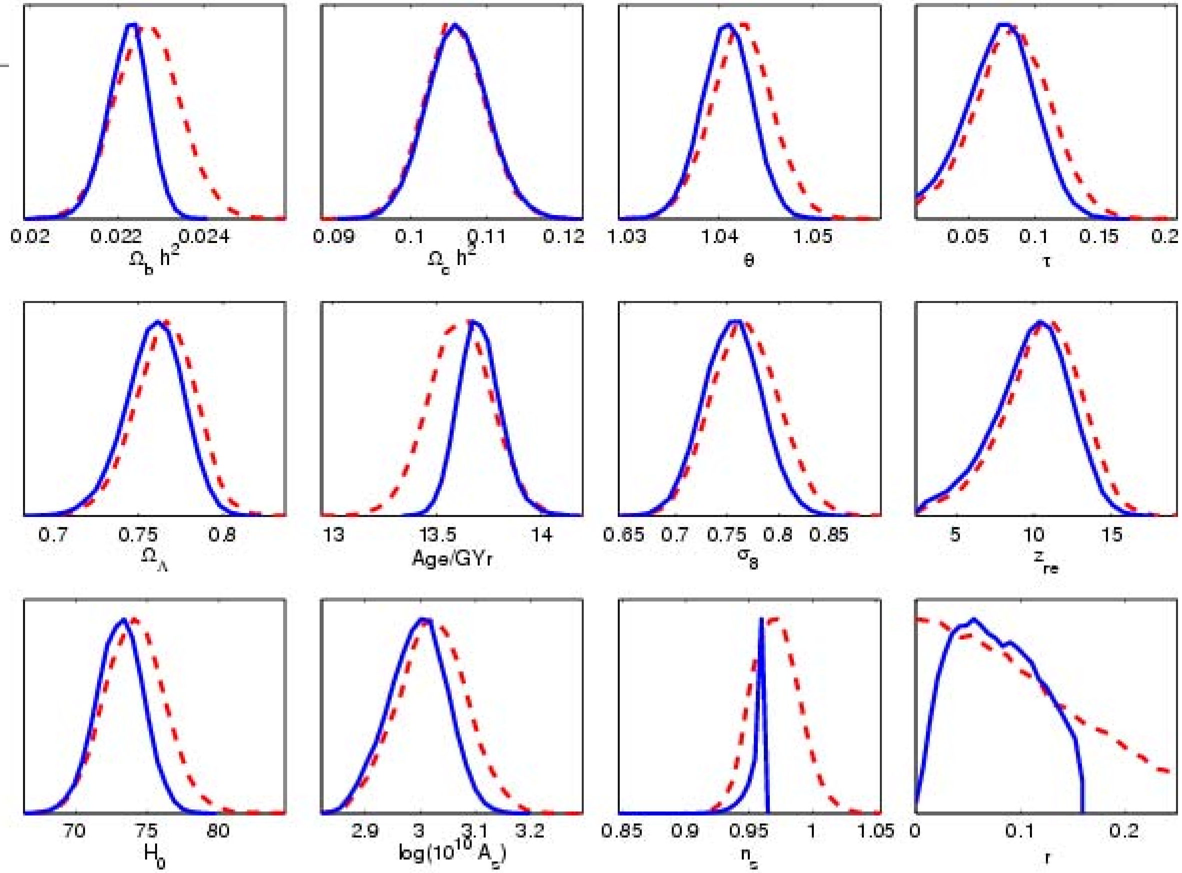
Notice that at $n_s = 0.964$:

$\frac{dr}{dn_s} = 4.9$ on the upper border of $\mathcal{B}$ (fourth degree double–well).

$\frac{dr}{dn_s} = 1.35$ on the lower border of $\mathcal{B}$.

Notice that an improvement δ on the precision of n_s implies an improvement $\simeq 5 \; \delta$ on the precision of r for the fourth degree double–well potential.

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).

FORECASTS FOR PLANCK

arXiv:1003.6108 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

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

$$r \sim 0.04$$

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:

$0.028 < r < 0.116$ with the best values $r = 0.04$, $ns = 0.9608$

.Better measurements for ns 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.

→ **The Planck satellite is right now measuring with unprecedented accuracy the primary CMB anisotropies.**

→**The Standard Model of the Universe (including inflation) provides the context to analyze the CMB and other data.**

→**The Planck performance for r, the tensor to scalar ratio Related to primordial B mode polarization, will depend on the quality of the data analysis.**

→**The Ginsburg Landau approach to inflation allows to take high benefit of the CMB data.**

→**The fourth degree double well inflaton potential gives an excellent fit to the current CMB+LSS data.**

→**We evaluate the Planck precision to the recovery of cosmological parameters within a reasonable toy model for residuals of systematic effects of instrumental and astrophysical origin based on publicly available information.**

→**We use and test two relevant models: the LambdaCDMr model, i.e. the standard LambdaCDM model augmented by r, and the LambdaCDMrT model, where the scalar spectral index, n_s, and r are related through the theoretical `banana-shaped' curve $r = r(n_s)$ coming from the double-well inflaton potential. In the latter case, $r = r\ r(n_s)$ is imposed as a hard constraint in the MCMC data analysis.**

→**We take into account the white noise sensitivity of Planck in the 70, 100 and 143 GHz channels as well as the residuals from systematics errors and foregrounds.** ***Foreground residuals turn to affect only the cosmological parameters sensitive to the B modes.***

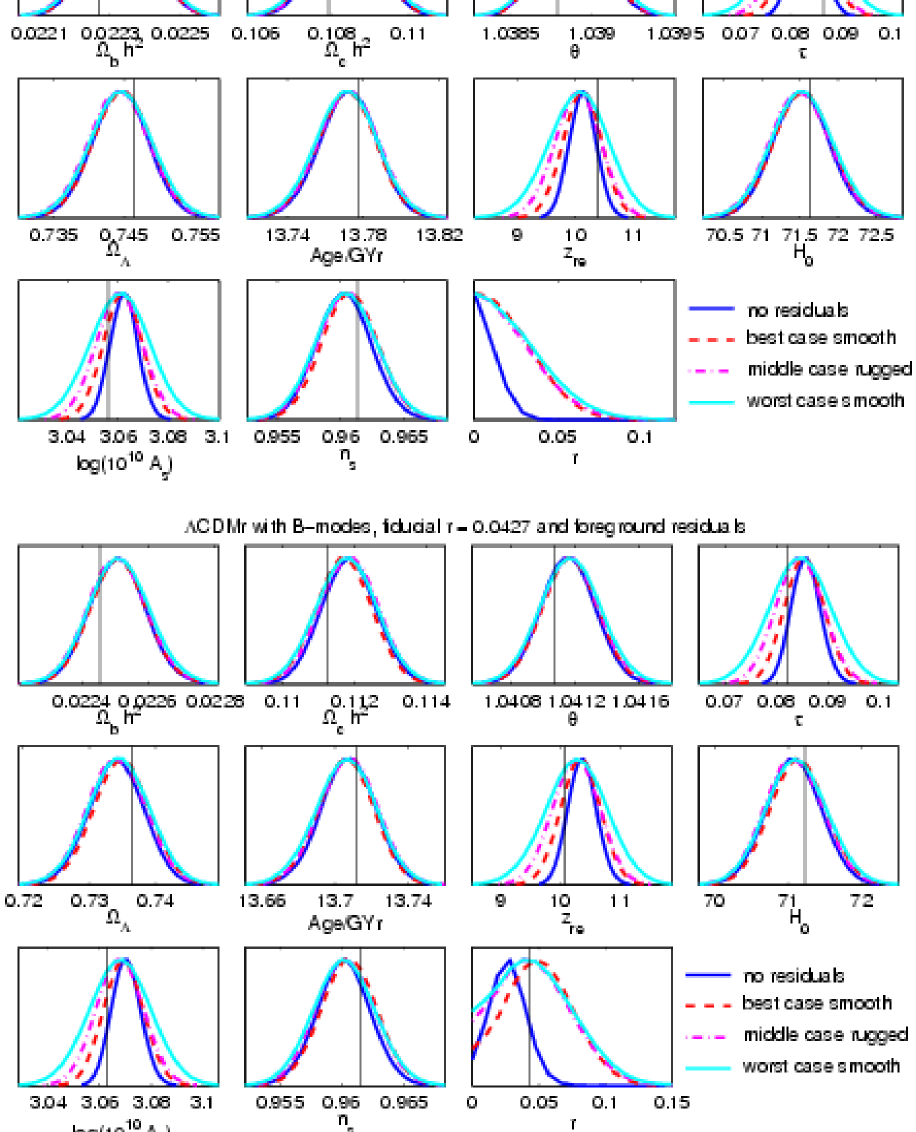


FIG. 7.— Cumulative 3−channel marginalized likelihood distributions, including B modes and foreground residuals, of the cosmological parameters for the ΛCDMr model. The fiducial ratio is $r = 0$ in the upper panel and $r = 0.0427$ in the lower. We plot the distributions in four cases: (a) without residuals, (b) with 30% of the toy model residuals in the TE and E modes displayed in Fig. 2 and $16\mu K^2$ in the T 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 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.

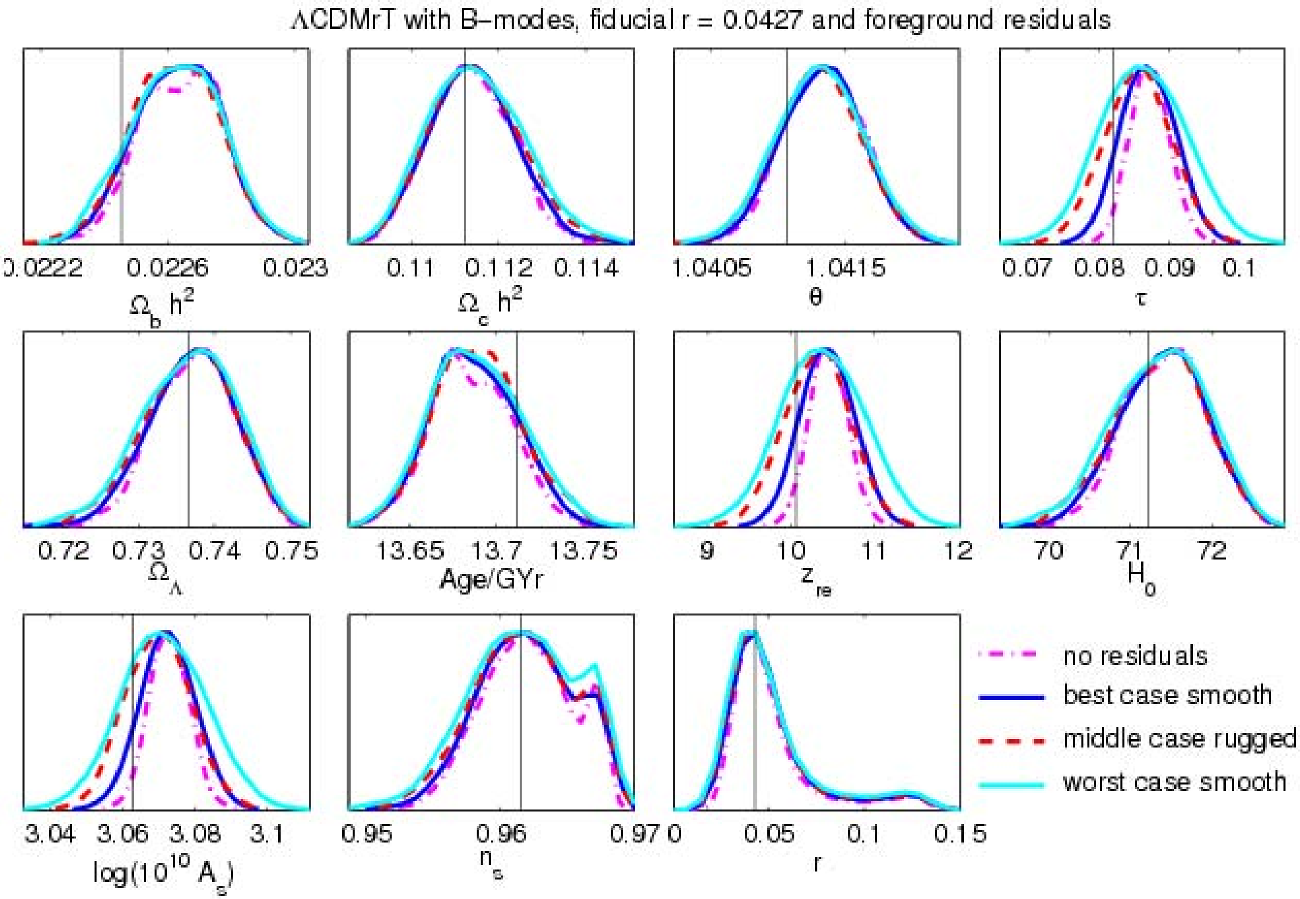


FIG. 8.— Cumulative marginalized likelihoods from the three channels for the cosmological parameters for the ΛCDMrT model including B modes and fiducial ratio $r = 0.0427$ and the foreground residuals. We plot the cumulative likelihoods in four cases: (a) without residuals, (b) with 0.3 of the worst 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.

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

→**At the level of foreground residual equal to 30% of our toy model, only a 68% CL detection of r is very likely.**

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

→**Borderline**

(II) DARK MATTER

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.

[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)]

(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 ***On the constant surface density in dark matter galaxies and interstellar molecular clouds*** **arXiv:0907.006**

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

→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 by the time of structure formation at z < 30 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.

→ **Compute 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 Td 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 non-linear self-gravity interactions: the range of Z is computed both analytically and numerically.

The formula for the Mass of the Dark Matter particles

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

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

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

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:

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

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

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

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].

Mass Estimates for DM particles

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

$$m = 0.2504\,\text{keV} \ \left(\frac{Z}{g}\right)^{\frac{1}{4}} \frac{\left[\int_0^\infty y^4 \ F_d(y)\ dy\right]^{\frac{3}{8}}}{\left[\int_0^\infty y^2 \ F_d(y)\ dy\right]^{\frac{5}{8}}}$$

$$g_d = 35.96\, Z^{\frac{1}{4}} \ g^{\frac{3}{4}} \ \left[\int_0^\infty y^4 \ F_d(y)\ dy \ \int_0^\infty y^2 \ F_d(y)\ dy\right]^{\frac{3}{8}}$$

These formulas yield for relics decoupling UR at LTE:

$$m = \left(\frac{Z}{g}\right)^{\frac{1}{4}} \ \text{keV} \left\{ \begin{array}{l} 0.568 \\ 0.484 \end{array} \right. , \ g_d = g^{\frac{3}{4}} \ Z^{\frac{1}{4}} \left\{ \begin{array}{ll} 155 & \text{Fermions} \\ 180 & \text{Bosons} \end{array} \right. .$$

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

$1 < Z^{\frac{1}{4}} < 5.6$ for $1 < Z < 1000$. Example: for DM Majorana fermions $(g = 2)$ $m \simeq 0.85$ keV.

Mass Estimates of DM particles

Our previous formulas yield for relics decoupling UR at LTE:

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Example: for DM Majorana fermions $(g = 2)$ $m \simeq 0.85$ keV.

Sterile neutrinos ν as DM decoupling out of LTE and UR.
ν is a singlet Majorana fermion with a Majorana mass m_ν coupled with a Yukawa-type coupling $Y \sim 10^{-8}$ to a real scalar field χ. χ is more strongly coupled to the particles in the Standard Model. [Chikashige,Mohapatra,Peccei (1981), Gelmini,Roncadelli (1981), Schechter, Valle (1982), Shaposhnikov, Tkachev (2006), Boyanovsky (2008)]

Relics decoupling non-relativistic

$$F_d^{NR}(p_c) = \frac{2^{\frac52}\,\pi^{\frac72}}{45}\; g_d\, Y_\infty\; \left(\frac{T_d}{m}\right)^{\frac32}\; e^{-\frac{p_c^2}{2\,m\,T_d}} = \frac{2^{\frac52}\,\pi^{\frac72}}{45}\; \frac{g_d\, Y_\infty}{x^{\frac32}}\; e^{-\frac{y^2}{2\,x}}$$

$Y(t) = n(t)/s(t)$, $n(t)$ 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:

$$m = \frac{45}{4\,\pi^2}\,\frac{\Omega_{DM}\,\rho_c}{g\,T_\gamma^3\,Y_\infty} = \frac{0.748}{g\,Y_\infty}\text{ eV} \quad \text{and} \quad m^{\frac52}\,T_d^{\frac32} = \frac{45}{2\,\pi^2}\,\frac{1}{g\,g_d\,Y_\infty}\,Z\,\frac{\rho_s}{\sigma_s^3}$$

Finally:

$$\sqrt{m\,T_d} = 1.47\,\left(\frac{Z}{g_d}\right)^{\frac13}\text{keV}. \quad m = 3.67\text{ keV}\; Z^{\frac13}\,\frac{g_d^{\frac{1}{12}}}{\sqrt{g}}\,\sqrt{\frac{\sigma_0}{\text{pb}}}$$

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

THE MASS OF THE DARK MATTER PARTICLE

A new analysis of the dark matter particle mass,

taking into account theory and astrophysical data from

galaxy observations indicates that the mass of the dark

matter particle is in the keV scale (1000 electron Volt,

equivalent to 1/511 of the electron mass) and the

temperature when the dark matter decoupled from ordinary matter and radiation, would be 100 GeV at least

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 ΛCDM standard cosmological model emerging from the CMB and LSS observations and simulations favors dark matter composed of primordial particles which are cold 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 and mergers lead to clustering on the larger scales.

OBSERVATIONS

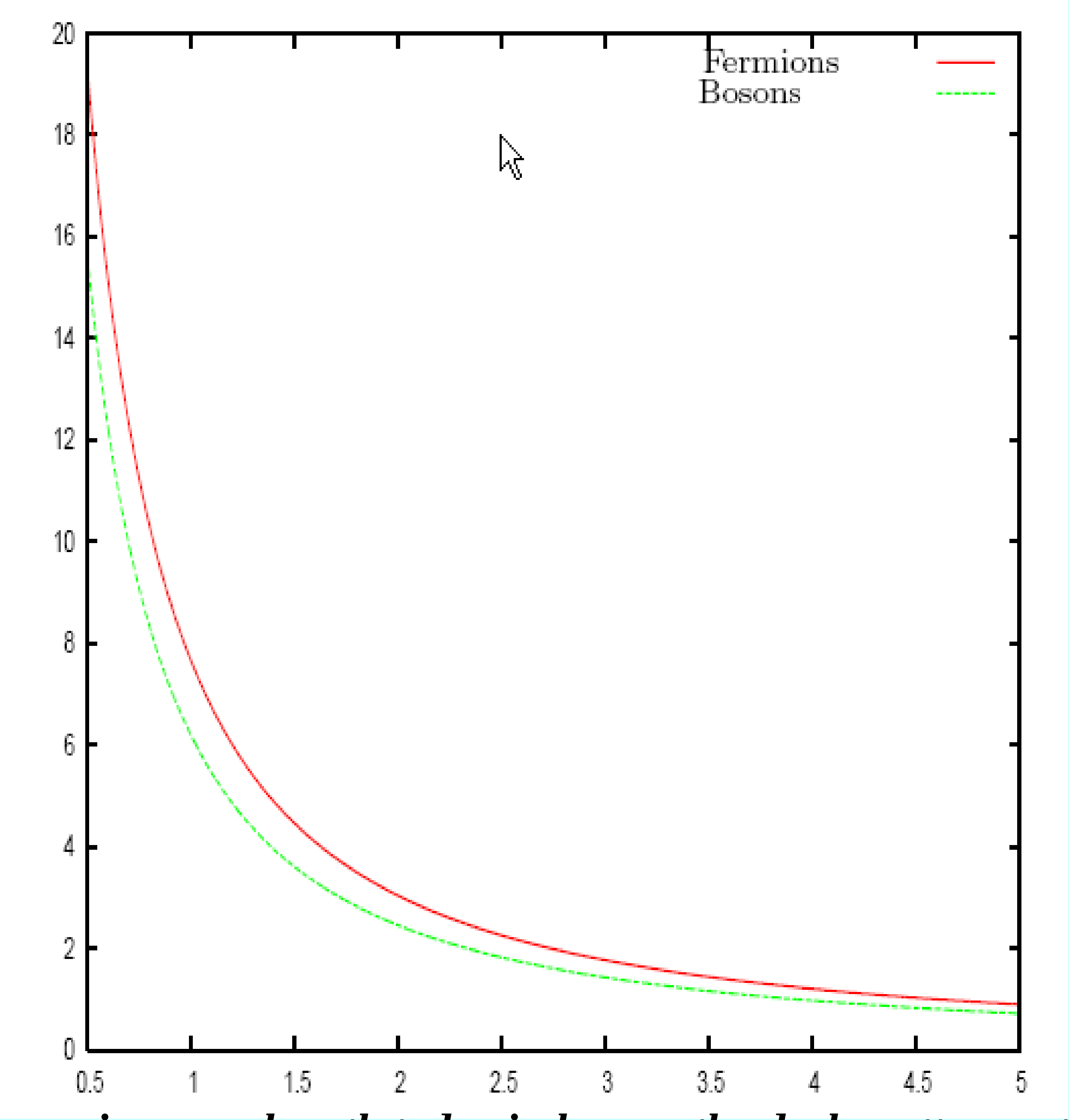
The observed dark matter energy density observed today has the value $\rho_{DM} = 0.228\ (2.518\ \text{meV})^4$.

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

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

And the Phase-space Density today (with a precision of a factor 10) has the value :

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



The free-streaming wavelength today in kpc vs. the dark matter particle mass in keV. *It decreases for increasing mass m and shows little variation with the particle*

• 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

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

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

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 ~ 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), the keV dark matter is cold (CDM).

m and Td 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, as well as by comparing X-ray, optical and lensing observations of the merging of galaxy clusters with N-body simulations).

- Typical "wimps" (weakly interacting massive particles) with mass $m = 100$ GeV and $Td = 5$ GeV would require a huge $Z \sim 10^{23}$, well above the upper bounds obtained and cannot reproduce the observed galaxy properties. They produce an extremely short free-streaming or Jeans length λ_{fs} today $\lambda_{fs}(0)\ 3.51\ 10^{-4}$ pc = 72.4 AU that would correspond to unobserved structures much smaller than the galaxy structure. Wimps result strongly disfavoured. [TOO much 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 negligable.

(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

END

THANK YOU FOR YOUR ATTENTION