What can we infer from cosmology for fundamental laws of physics ?

Three lessons

1) Fundamental "constants" are not constant
2) No conflict between quantum physics and general relativity
3) Time and space are born at the big bang

1

Fundamental “constants” are not constant

Have coupling constants in the early Universe other values than today ?

Yes !

Fundamental couplings in quantum field theory

Masses and coupling constants are determined by properties of ***vacuum*** *!*

Similar to Maxwell – equations in matter

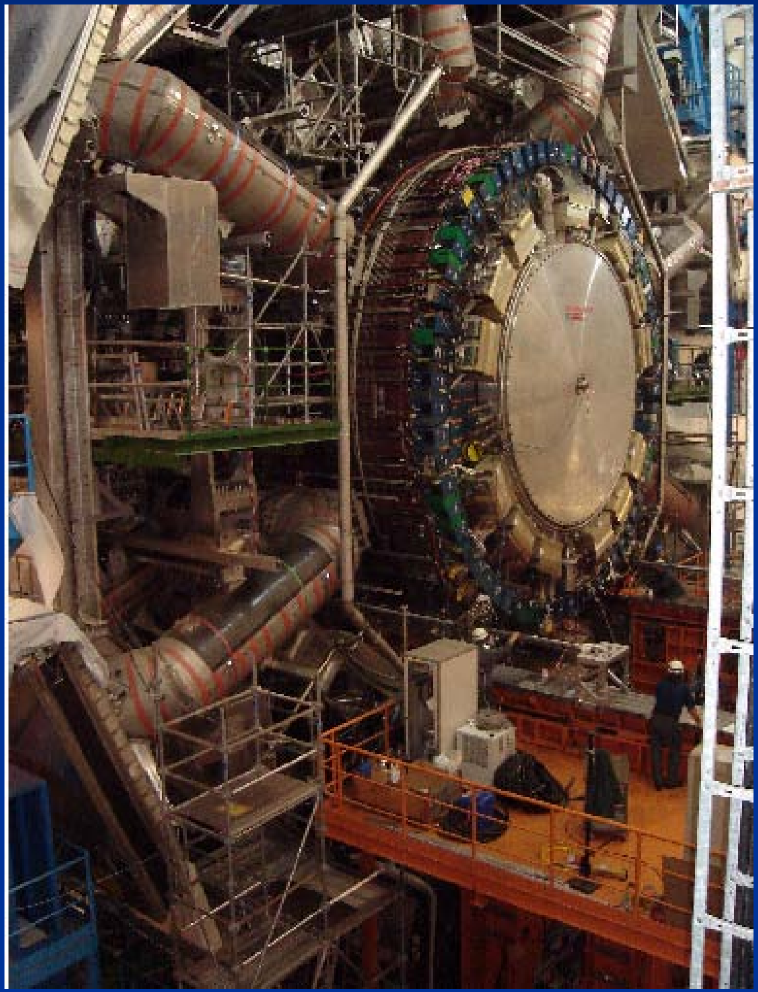
Condensed matter physics : laws depend on state of the system

- Ground state , thermal equilibrium state …
- Example : Laws of electromagnetism in superconductor are different from Maxwells' laws

Standard model of particle physics :

Electroweak gauge symmetry is spontaneously broken by expectation value of Higgs scalar

Spontaneous symmetry breaking to be confirmed at the LHC



Cosmology :

- Universe is not in one fixed state
- Dynamical evolution
- Laws are expected to depend on time

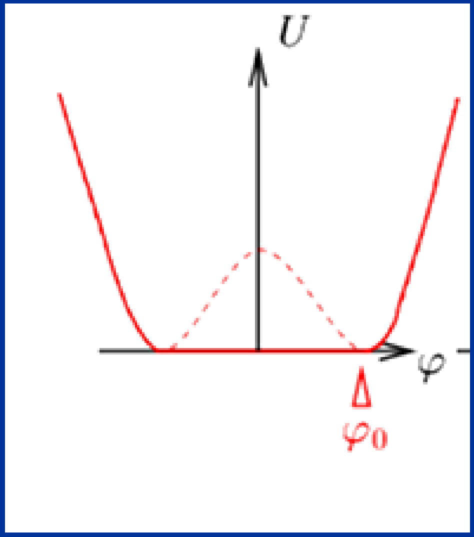
Restoration of symmetry at high temperature in the early Universe

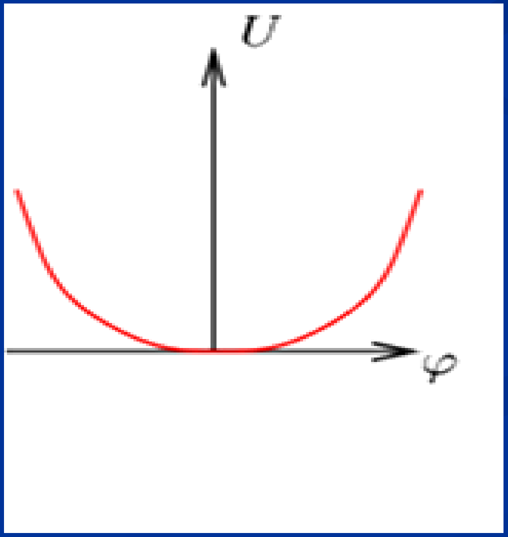
Low T
SSB
$<\varphi>=\varphi_0 \neq 0$

High T
SYM
$<\varphi>=0$

high T :
Less order
More symmetry

Example:
Magnets





In hot plasma
of early Universe :

masses of electron und muon
not different!

similar strength of electromagnetic
and weak interaction

Varying couplings

only question :

How strong is **present** variation of couplings ?

Can variation of fundamental "constants" be observed ?

Fine structure constant α (electric charge)

Ratio electron mass to proton mass

Ratio nucleon mass to Planck mass

Time evolution of couplings and scalar fields

- **Fine structure constant depends on value of cosmon field : $\alpha(\varphi)$**

in standard model: couplings depend on value of Higgs scalar field

- **Time evolution of φ ⟹ Time evolution of α**

Jordan,…

Static scalar fields

In Standard Model of particle physics :

- Higgs scalar has settled to its present value around 10^{-12} seconds after big bang.
- Chiral condensate of QCD has settled at present value after quark-hadron phase transition around 10^{-6} seconds after big bang .
- No scalar with mass below pion mass.
- No substantial change of couplings after QCD phase transition.
- Coupling constants are frozen.

Observation of time- or space-variation of couplings

⇒

Physics beyond Standard Model

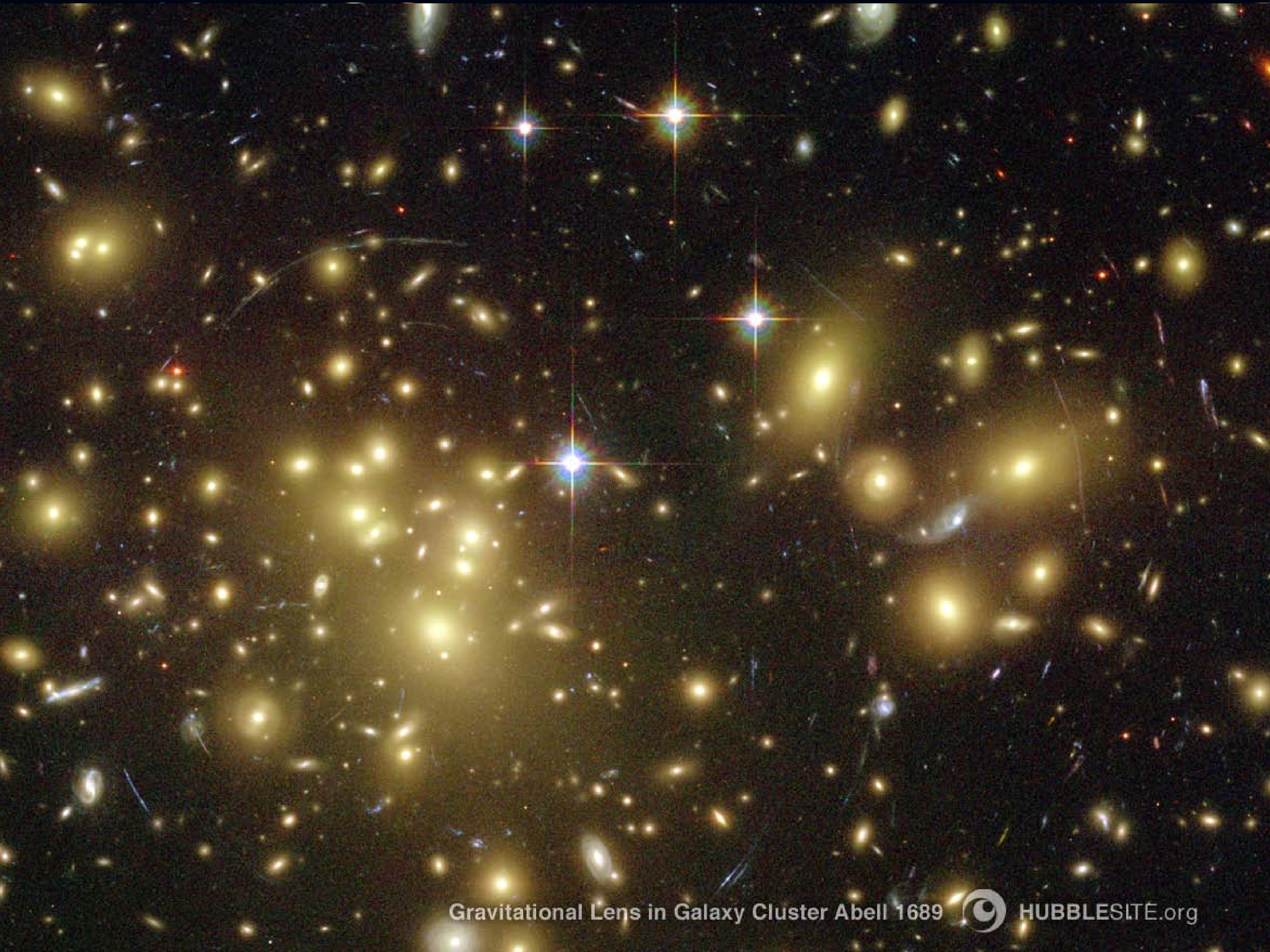
Particle masses in quintessence cosmology

can depend on value of cosmon field

similar to dependence on value of Higgs field

Dark Energy :
Energy density that does not clump

Photons , gravitons : insignificant


Gravitational Lens in Galaxy Cluster Abell 1689
HUBBLESITE.org

Space between clumps
is not empty :

Dark Energy !

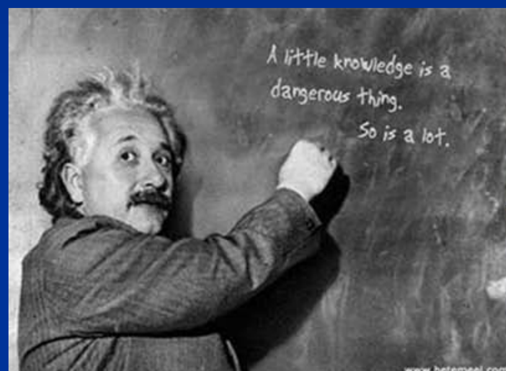
Dark Energy : Homogeneously distributed

Dark Energy density is the same at every point of space

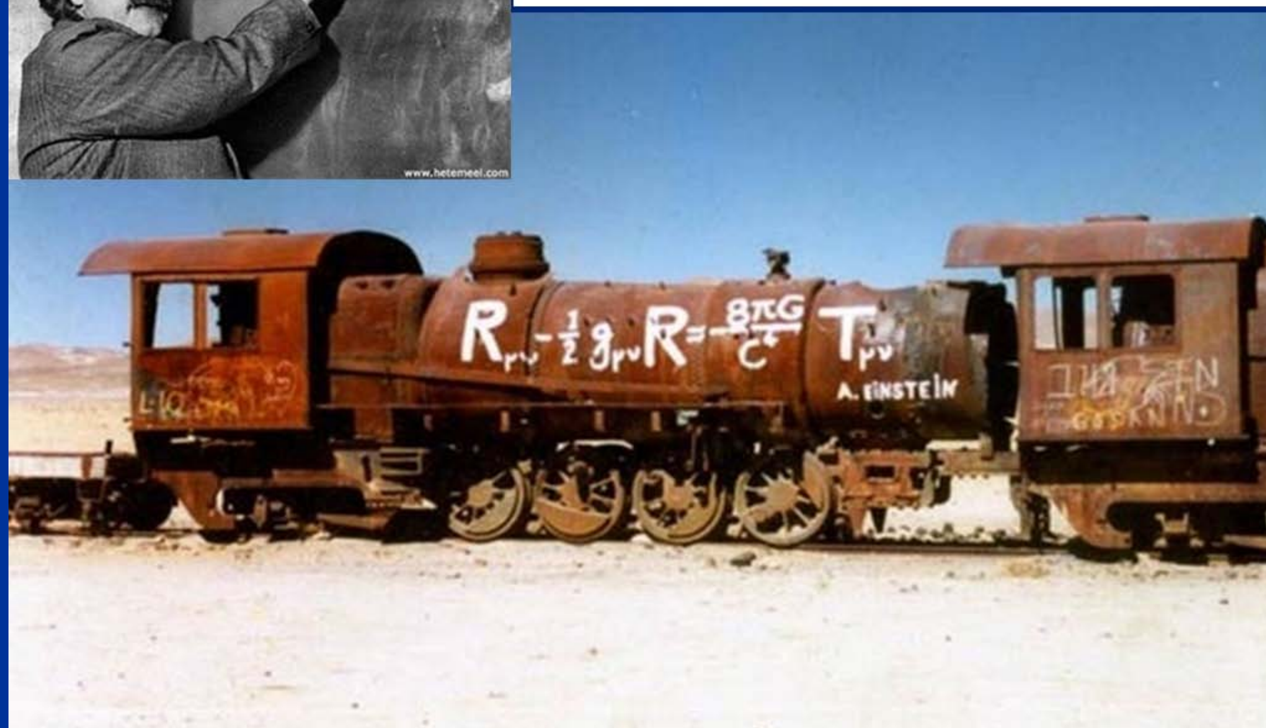
“ homogeneous “

No force in absence of matter –
“ In what direction should it draw ? “

Einstein's equations : almost static Dark Energy predicts accelerated expansion of Universe



$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

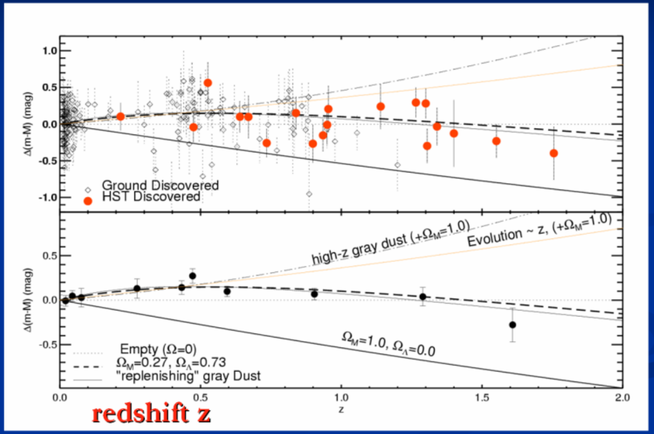


Predictions for dark energy cosmologies

The expansion of the Universe

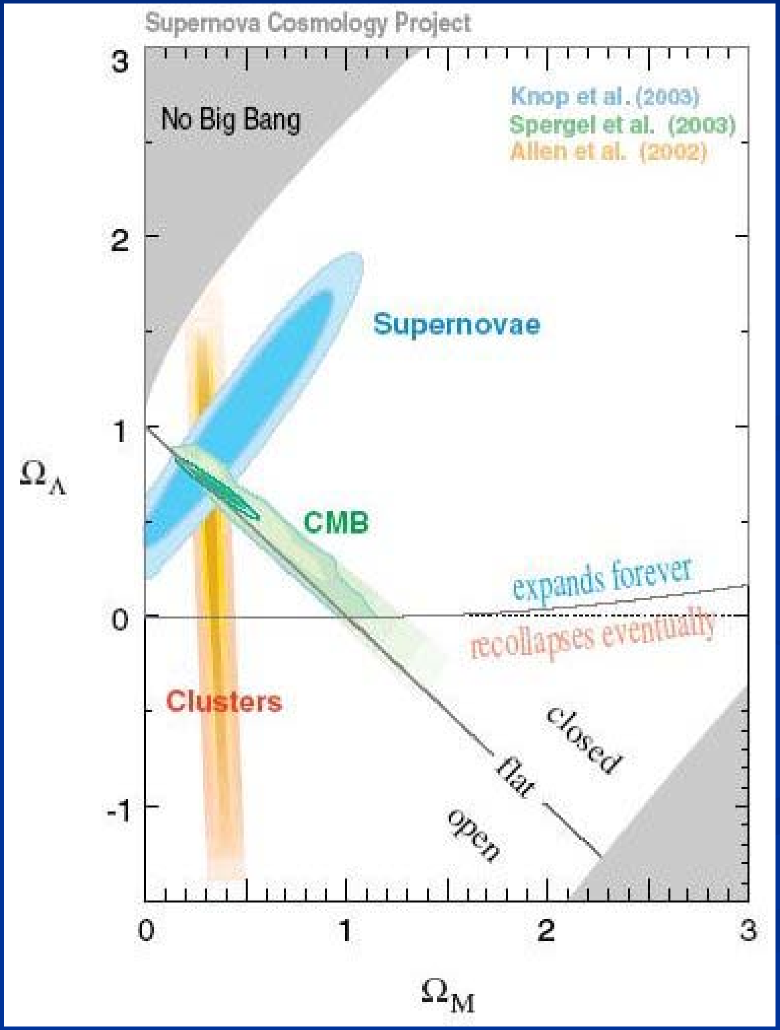
accelerates today !

Supernovae 1a Hubble diagram



Riess et al. 2004

Dark Energy : observations fit together !



Composition of the Universe

$\Omega_b = 0.045$	visible	clumping
$\Omega_{dm} = 0.2$	invisible	clumping
$\Omega_h = 0.75$	invisible	homogeneous

What is Dark Energy ?

Cosmological Constant
or
Quintessence ?

Cosmological Constant
- Einstein -

- Constant λ compatible with all symmetries
- No time variation in contribution to energy density

- Why so small ? $\lambda/M^4 = 10^{-120}$

- Why important just today ?

Cosmological mass scales

- Energy density

  $\varrho \sim (2.4 \times 10^{-3}\ \text{eV})^{-4}$

- Reduced Planck mass

  $M = 2.44 \times 10^{27}\ \text{eV}$

- Newton's constant

  $G_N = (8\pi M^2)$

Only ratios of mass scales are observable !

homogeneous dark energy: $\rho_h/M^4 = 6.5\ 10^{-121}$

matter: $\rho_m/M^4 = 3.5\ 10^{-121}$

Time evolution

- $\varrho_m/M^4 \sim a^{-3} \sim$ t^{-2} matter dominated universe; $t^{-3/2}$ radiation dominated universe

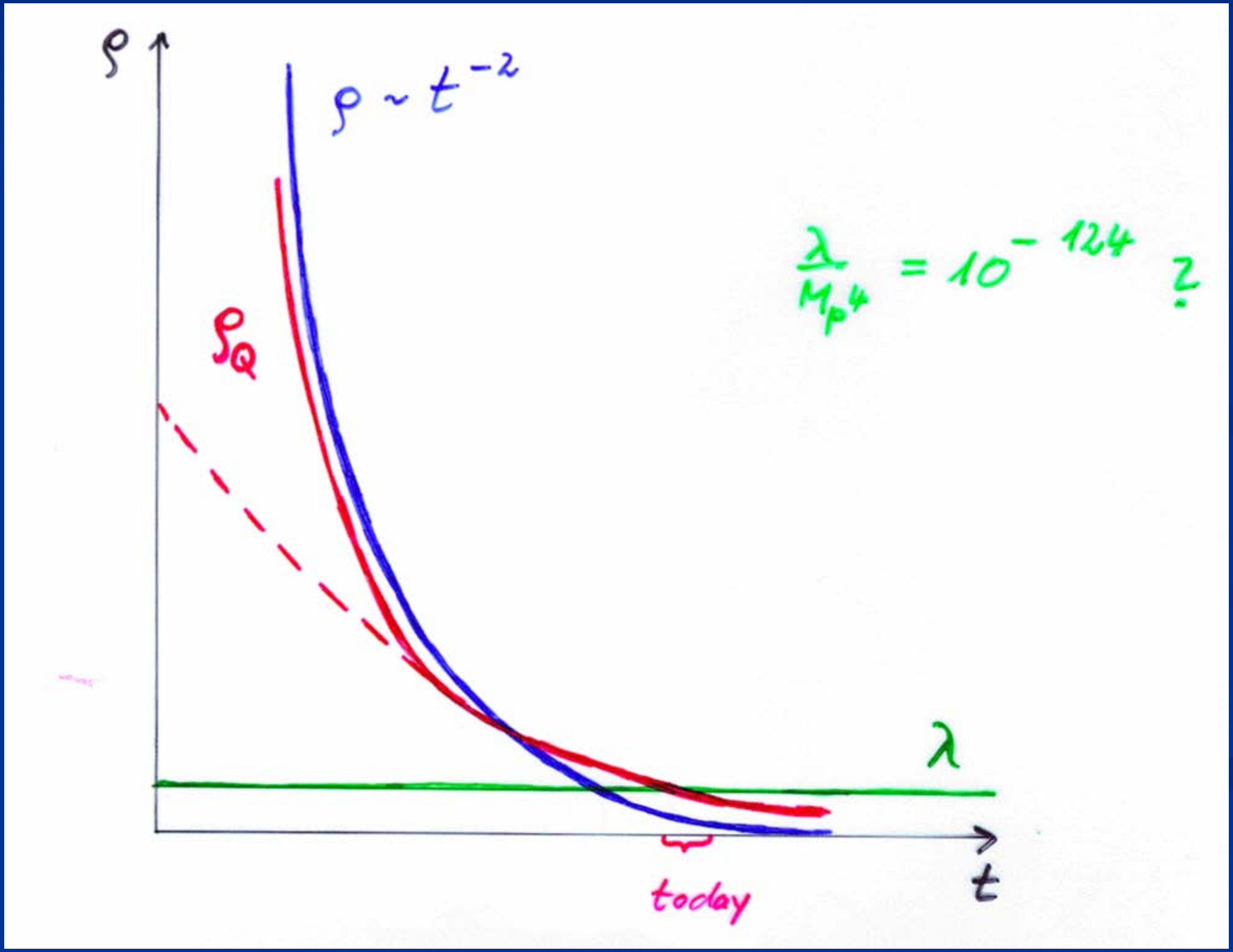
- $\varrho_r/M^4 \sim a^{-4} \sim t^{-2}$ radiation dominated universe

Huge age ⇨ small ratio

Same explanation for small dark energy?

Cosm. Const. | Quintessence

static | dynamical



Quintessence

Dynamical dark energy ,

generated by scalar field

(cosmon)

C.Wetterich,Nucl.Phys.B302(1988)668, 24.9.87
P.J.E.Peebles,B.Ratra,ApJ.Lett.325(1988)L17, 20.10.87

Prediction :

homogeneous dark energy influences recent cosmology

- of same order as dark matter -

Original models do not fit the present observations

…. modifications

Quintessence

Cosmon – Field $\varphi(x,y,z,t)$

similar to electric field , but no direction (scalar field)

Homogeneous und isotropic Universe : $\varphi(x,y,z,t)=\varphi(t)$

Potential und kinetic energy of the cosmon -field contribute to a dynamical energy density of the Universe !

Cosmon

- *Scalar field changes its value even in the* **present** *cosmological epoch*
- *Potential und kinetic energy of cosmon contribute to the energy density of the Universe*
- *Time - variable dark energy :*

  $\varrho_h(t)$ *decreases with time !*

Evolution of cosmon field

Field equations

$$\ddot{\phi} + 3H\dot{\phi} = -dV/d\phi$$

$$3M^2H^2 = V + \frac{1}{2}\dot{\phi}^2 + \rho$$

Potential V(φ) determines details of the model

$$V(\varphi) = M^4 \exp(-\alpha\varphi/M)$$

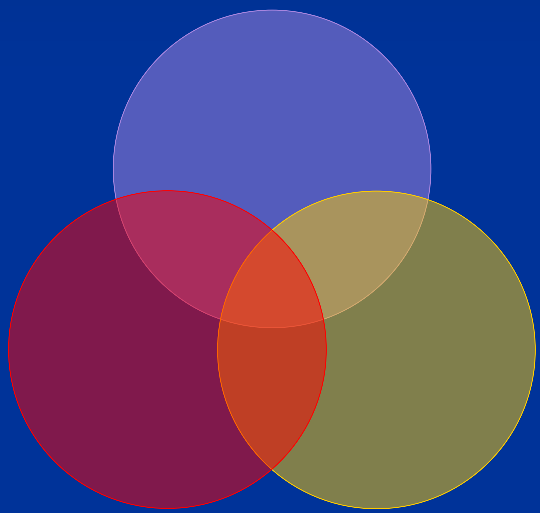
for increasing φ the potential decreases towards zero !

Cosmon

- *Tiny mass*
- $m_c \sim H$ *(depends on time !)*
- *New long - range interaction*

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation   cosmodynamics

On astronomical length scales:

graviton

+

cosmon

Time varying constants

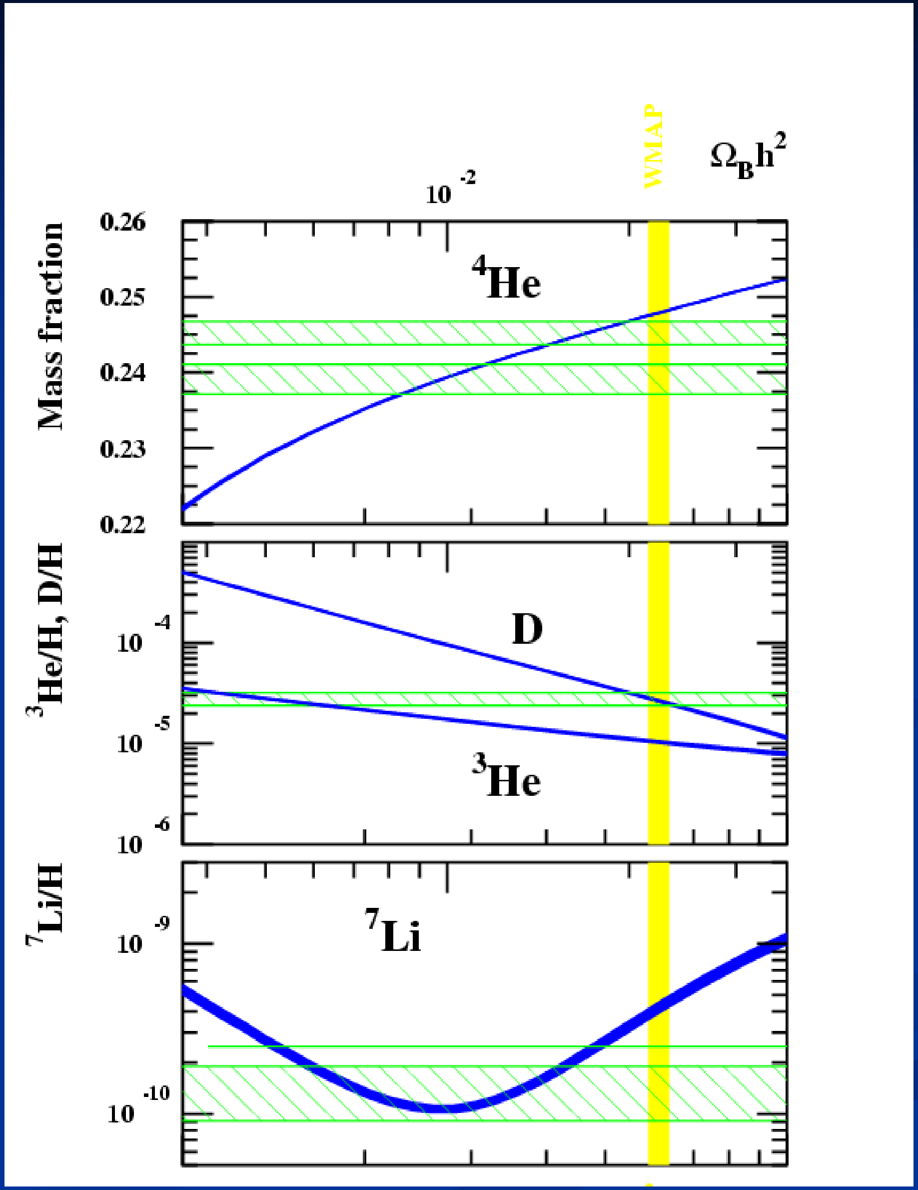
- It is not difficult to obtain quintessence potentials from higher dimensional or string theories
- Exponential form rather generic

  (after Weyl scaling)
- But most models show too strong time dependence of constants !

Bounds on time varying couplings from nucleosynthesis


baryons :
the matter of stars and humans
$\Omega_b = 0.045$

Abundancies of primordial light elements from nucleosynthesis



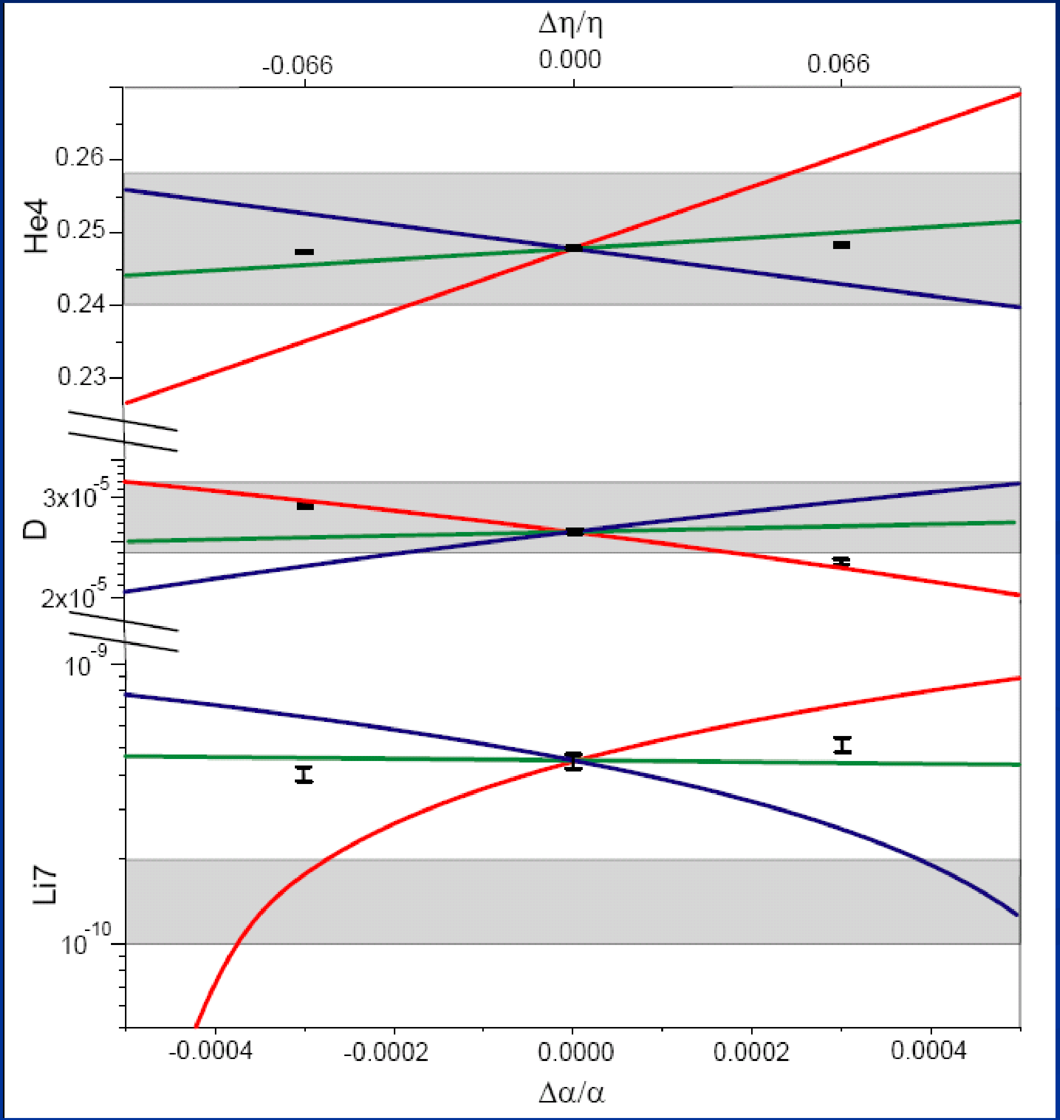
A.Coc

primordial abundances for three GUT models

He

D

Li



present observations : 1σ

T.Dent, S.Stern,…

three GUT models

- unification scale ~ Planck scale
- 1) All particle physics scales $\sim\Lambda_{QCD}$
- 2) Fermi scale and fermion masses ~ unification scale
- 3) Fermi scale varies more rapidly than Λ_{QCD}

$\Delta\alpha/\alpha \approx 4\ 10^{-4}$ allowed for GUT 1 and 3 , larger for GUT 2

$\Delta\ln(M_n/M_P) \approx 40\ \Delta\alpha/\alpha \approx 0.015$ allowed

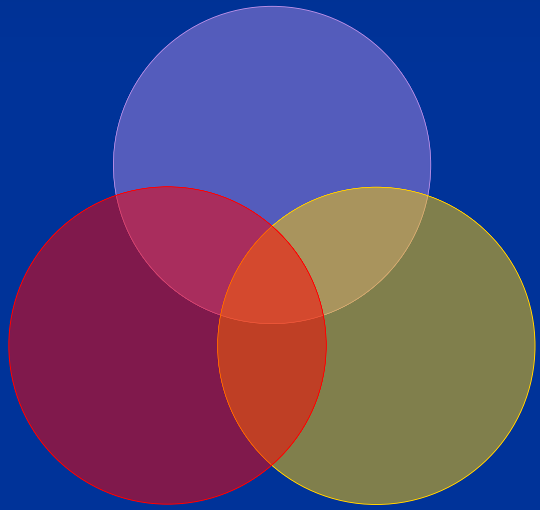
Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

“Fifth Force”

- Mediated by scalar field

R.Peccei,J.Sola,C.Wetterich,Phys.Lett.B195,183(1987)

- Coupling strength: weaker than gravity

  (nonrenormalizable interactions ~ M^{-2})

- Composition dependence

  ⇒ violation of equivalence principle

- Quintessence: connected to time variation of fundamental couplings

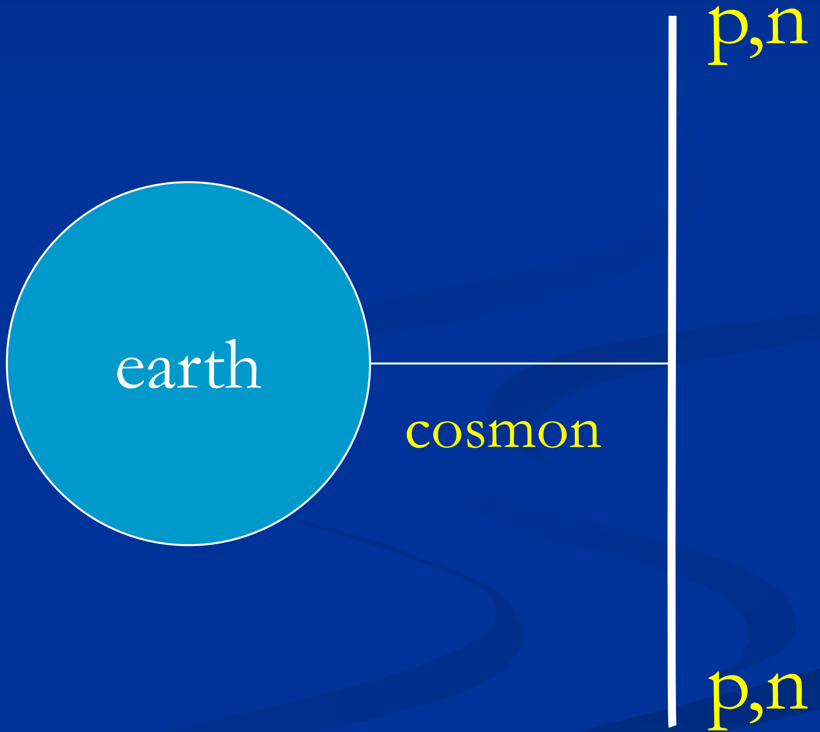
C.Wetterich , Nucl.Phys.B302,645(1988)

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

Differential acceleration

Two bodies with equal mass experience
a different acceleration !

$$\eta = (a_1 - a_2) / (a_1 + a_2)$$

bound : $\eta < 3\ 10^{-14}$

Cosmon coupling to atoms

- Tiny !!!
- Substantially weaker than gravity.
- Non-universal couplings bounded by tests of equivalence principle.
- Universal coupling bounded by tests of Brans-Dicke parameter ω in solar system.
- Only very small influence on cosmology.

(All this assumes validity of linear approximation)

Apparent violation of equivalence principle

and

time variation of fundamental couplings

measure both the

cosmon – coupling to ordinary matter

Differential acceleration η

For unified theories (GUT) :

$$\eta = -1.75\ 10^{-2} \Delta R_z \left(\frac{\partial \ln \alpha}{\partial z}\right)^2 \frac{1+\tilde{Q}}{\Omega_h(1+w_h)}$$

$$\Delta R_z = \frac{\Delta Z}{Z+N} \approx 0.1$$

$\eta = \Delta a / 2a$

Q : time dependence of other parameters

Link between time variation of α

and violation of equivalence principle

typically : $\eta = 10^{-14}$

if time variation of α

near Oklo upper bound

to be tested (MICROSCOPE , …)

2

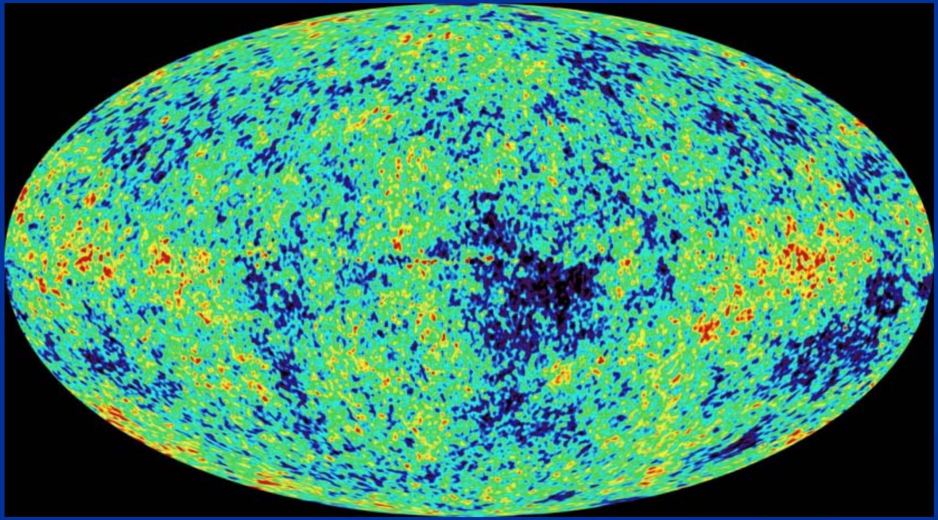
No conflict between quantum physics and general relativity

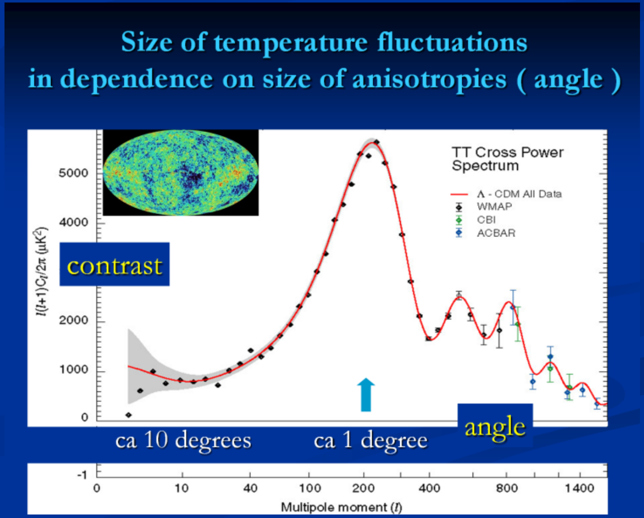
Cosmology and quantum physics

both :

Probabilistic theories

Correlations are crucial





laws are based on probabilities

determinism as special case :

probability for event = 1 or 0

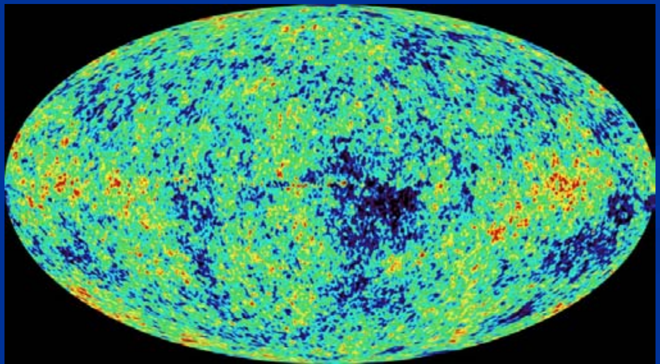
- law of big numbers
- unique ground state …

Correlations and reality

- Correlations are physical reality , not only the expectation values of certain observables

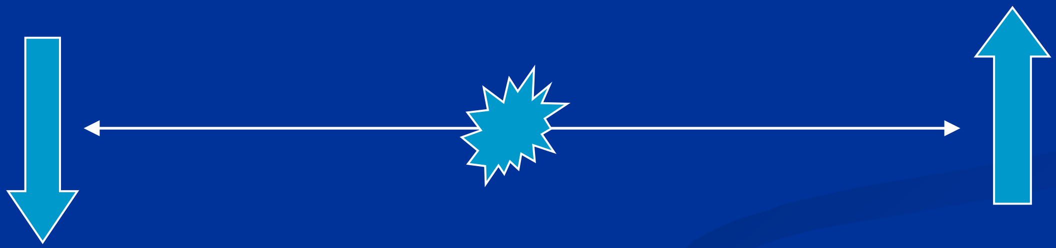
- Correlations can be non-local (also in classical statistics) ;
  causal processes needed only for preparation of non-local correlations at some time in the past

- Correlated subsystems cannot be separated –
  the whole is more that the sum of parts

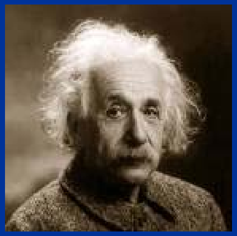


EPR - Paradoxon

Correlation between two spins is established at time of particle decay



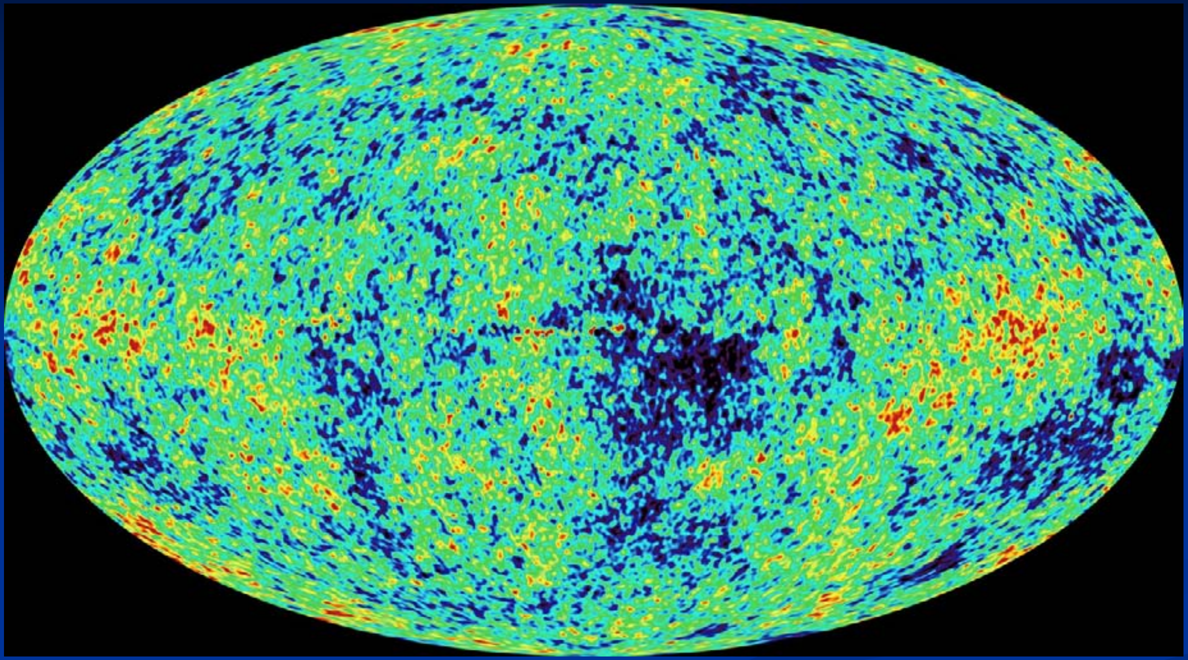
No contradiction to causality or realism if correlations are considered as genuine part of reality

( for once : not right)

conditional probability

sequences of events(measurements)
are described by
conditional probabilities

both in classical statistics
and in quantum statistics

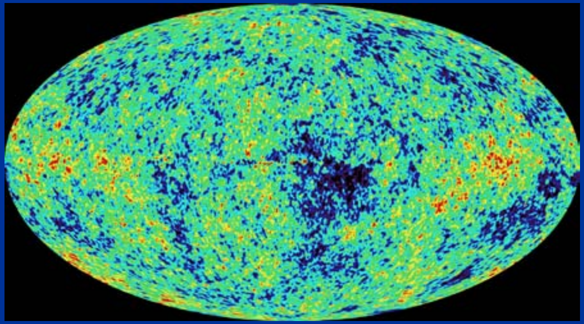
$w(t_1)$  :

not very suitable
for statement , if here and now
a pointer falls down

Schrödinger’s cat

conditional probability :
if nucleus decays
then cat dead with $w_c = 1$
(reduction of wave function)

Reduction of the wave function

- Convenient way to describe conditional probabilities
- Same in classical statistics for the Universe
- Once  realized (measured) :

new state for computation of probabilities

Metric and geometry

Quantum field theory :

- Metric is expectation value of fluctuating field
- It transforms as second rank symmetric tensor under diffeomorphisms (general coordinate transformations)
- General relativity : theory with particular symmetry – diffeomorphism symmetry
- That's all

General relativity and quantum theory

- No basic contradiction
- Metric is quantum field with same status as other fields (e.g. photon or Higgs scalar)
- Ultraviolet regularization : difficulty to implement diffeomorphism symmetry – several concepts : string theory, fixed point, lattice regularizations , lattice spinor gravity
- Metric needs not to be fundamental

Metric as collective (composite) field

Metric field could be composed from fermions

$$\tilde{g}_{\mu\nu} \sim \partial_\mu(\bar{\psi}\psi)\partial_\nu(\bar{\psi}\psi)$$

$$\bar{g}_{\mu\nu} = \langle \tilde{g}_{\mu\nu} \rangle$$

Metric as collective (composite) field

or from scalars

Metric ambiguity

given metric $g_{\mu\nu}$

collective field with expectation value

$$\tilde{g}_{\mu\nu} \sim \partial_\mu(\bar{\psi}\psi)\partial_\nu(\bar{\psi}\psi) \qquad \bar{g}_{\mu\nu} = \langle \tilde{g}_{\mu\nu} \rangle$$

new metric candidate

$$g_{2,\mu\nu} = \alpha g_{\mu\nu} + \beta \bar{g}_{\mu\nu}$$

Which one is physical metric ?

3

Time and space are born at the big bang

Which metric to choose ?

Many candidates in general relativity

$$g_{2,\mu\nu} = \alpha g_{\mu\nu} + \beta R_{\mu\nu} + \gamma R g_{\mu\nu}$$

and quantum field theory

$$\tilde{g}_{\mu\nu} \sim \partial_\mu(\bar{\psi}\psi)\partial_\nu(\bar{\psi}\psi) \qquad \bar{g}_{\mu\nu} = \langle \tilde{g}_{\mu\nu} \rangle$$

$$g_{2,\mu\nu} = \alpha g_{\mu\nu} + \beta \bar{g}_{\mu\nu}$$

It does not matter !

for distances large compared to Planck length

Ambiguity close to Planck scale !

no unique metric anymore close to Planck scale

different metrics – different definitions of distances

no unique geometry

Space and time in the usual sense , with definite geometry , emerge only after the big bang

Theories with two or several metrics

Metric potential for one metric

$$V = \lambda\sqrt{g}\ ,\ \ g = |\det g_{\mu\nu}|$$

Space-time independent metric
has to obey extremum condition

$$\frac{\partial V}{\partial g_{\mu\nu}} = \frac{1}{2}\lambda\sqrt{g}\, g^{\mu\nu} = 0\ ,\ \ g^{\mu\nu}g_{\nu\rho} = \delta^{\mu}_{\rho}$$

Metric potential for two metrics

New invariants are possible $g_{1,\mu\nu} g_2^{\mu\nu}$

Simple metric potential

$$\begin{aligned} V &= \alpha_1 \sqrt{g_1} + \alpha_2 \sqrt{g_2} \\ &\quad + (\beta_1 \sqrt{g_1} + \beta_2 \sqrt{g_2}) g_{1,\mu\nu} g_2^{\mu\nu} \\ &\quad + (\delta_1 \sqrt{g_1} + \delta_2 \sqrt{g_2}) g_{2,\mu\nu} g_1^{\mu\nu} . \end{aligned}$$

Proportionality of metrics

ansatz: $g_{1,\mu\nu} = \sigma_1 \eta_{\mu\nu}\ ,\ g_{2,\mu\nu} = \sigma_2 \eta_{\mu\nu}$.

$\gamma = \sigma_2/\sigma_1$

$$V = \sigma_1^2 \left(\sum_n s_n \gamma^n \right) = \sigma_1^2 W(\gamma).$$

Extremum of $W(\gamma)$ at γ_0 with $W(\gamma_0) = W_0$

$W_0 = 0$ → solution with

$$g_{1,\mu\nu} = \eta_{\mu\nu},\ g_{2,\mu\nu} = \gamma_0 \eta_{\mu\nu}$$

Two metrics are equivalent if

$$g_{2,\mu\nu} = \gamma g_{1,\mu\nu}$$

only units for coordinates differ

Massive tensors

expansion $$g_{1,\mu\nu} = g_{\mu\nu} \ , \ g_{2,\mu\nu} = \gamma(\delta^\rho_\mu + f_\mu{}^\rho) g_{\rho\nu}$$

tensor fields $$f = f_\mu{}^\nu \delta^\mu_\nu$$

$$\tilde{f}_\mu{}^\nu = f_\mu{}^\nu - \frac{1}{4} f \delta^\nu_\mu \ , \ \tilde{f}_\mu{}^\nu \delta^\mu_\nu = 0,$$

$$V = \sqrt{g} \left\{ \lambda + \frac{1}{2} \mu f^2 + \frac{1}{4} \nu \tilde{f}_\mu{}^\nu \tilde{f}_\nu{}^\mu \right\}$$ mass terms

$$\begin{aligned}
\lambda &= \alpha_1 + \alpha_2\gamma^2 + \frac{4}{\gamma}(\beta_1 + \beta_2\gamma^2) + 4\gamma(\delta_1 + \delta_2\gamma^2) \\
\mu &= \frac{\beta_1}{2\gamma} + \frac{\alpha_2}{8}\gamma^2 + \frac{3\delta_2}{2}\gamma^3, \\
\nu &= 4\frac{\beta_1}{\gamma} - \alpha_2\gamma^2 - 4\delta_2\gamma^3.
\end{aligned}$$

Kinetic term

$$\mathcal{L}_{\mathrm{kin}} = \sqrt{g}\Big\{-\frac{M^2}{2}R + \frac{1}{2}Z\partial^\mu f \partial_\mu f + \frac{1}{4}W_1 D^\rho \tilde{f}_\mu{}^\nu D_\rho \tilde{f}_\nu{}^\mu + \frac{1}{2}W_2 D_\rho \tilde{f}_\mu{}^\rho D_\sigma \tilde{f}_\nu{}^\sigma g^{\mu\nu} + \frac{1}{2}W_3 \partial^\nu f D_\mu \tilde{f}_\nu{}^\mu\Big\}. \quad ($$

Field equation (for W_2=0,W_3=0)

$$(W_1\partial^2 - \nu)\tilde{f}_\mu{}^\nu$$

Massive tensor field

$$(W_1 \partial^2 - \nu)\tilde{f}_\mu{}^\nu$$

Typical size of mass : Planck mass , $\nu/W_1 \sim M^2$

Yukawa type interaction , negligible for distances larger than Planck length

Relevant for distances around Planck length

No unique metric at Planck scale

$$g_{1,\mu\nu} = g_{\mu\nu} \ , \ g_{2,\mu\nu} = \gamma(\delta_\mu^\rho + f_\mu{}^\rho) g_{\rho\nu}$$

Proportionality between both metrics is no longer valid once f plays a role!

Energy density

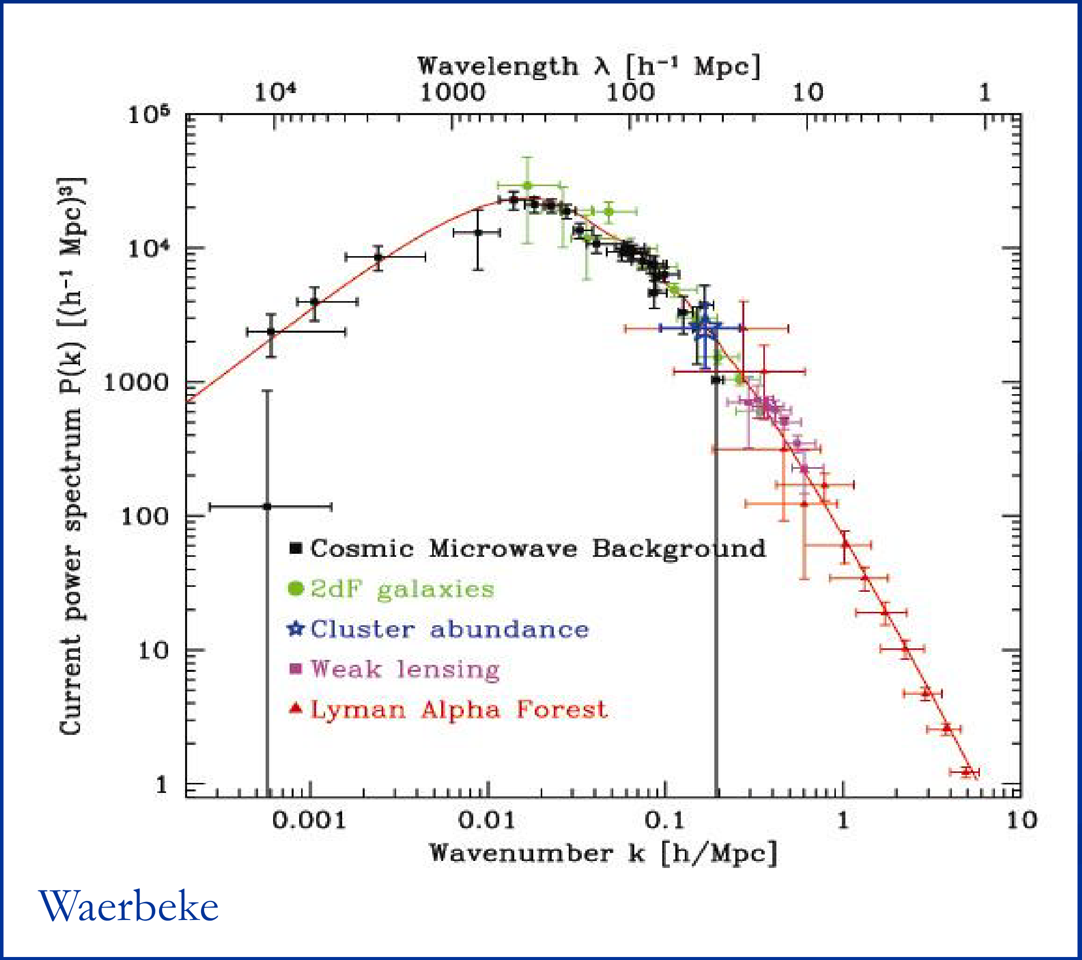
$$
\begin{aligned}
\rho \; = \; & \frac{1}{2}\mu f^2 + \frac{1}{4}\nu \left\{ \sum_k (\tilde{f}_k{}^k)^2 + \left(\sum_k \tilde{f}_k{}^k \right)^2 \right\} \\
& + \frac{1}{2}\nu \sum_k \left\{ \left(\tilde{f}_0{}^k \right)^2 + \sum_{l>k} (\tilde{f}_k{}^l)^2 \right\} \\
& + \frac{1}{2} Z (\partial_0 f)^2 + \frac{1}{2} Z \sum_i (\partial_i f)^2 \\
& + \frac{1}{4} W_1 \Bigg\{ \sum_i \Bigg[\sum_k (\partial_i \tilde{f}_k{}^k)^2 + (\partial_i \sum_k \tilde{f}_k{}^k)^2 \\
& + 2 \sum_{k,l>k} (\partial_i \tilde{f}_k{}^l)^2 + 2 \sum_k (\partial_i \tilde{f}_0{}^k)^2 \Bigg] \\
& + \sum_k (\partial_0 \tilde{f}_k{}^k)^2 + (\partial_0 \sum_k \tilde{f}_k{}^k)^2 \\
& + 2 \sum_{k,l>k} (\partial_0 \tilde{f}_k{}^l)^2 - 6 \sum_k (\partial_0 \tilde{f}_0{}^k)^2 \Bigg\} .
\end{aligned}
$$

Conclusions

1) Fundamental "constants" are not constant
2) No conflict between quantum physics and general relativity
3) Time and space are born at the big bang

End

Structure formation :
One primordial fluctuation spectrum



CMB agrees with

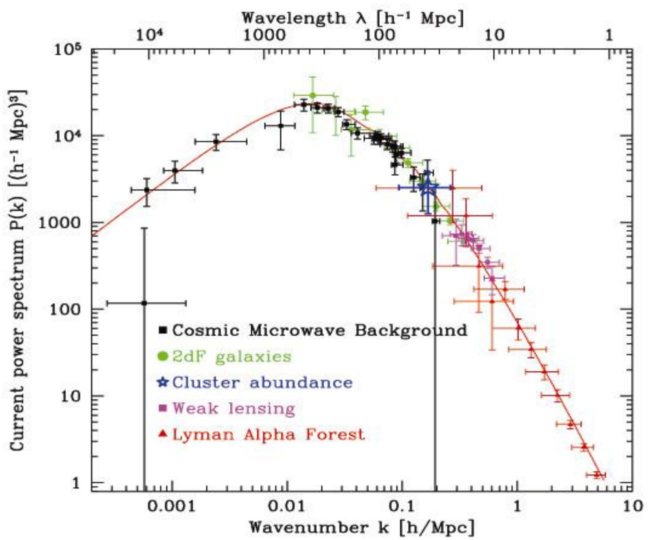
Galaxy distribution

Lyman – α

and

Gravitational Lensing !

Power spectrum



M.Tegmark + …

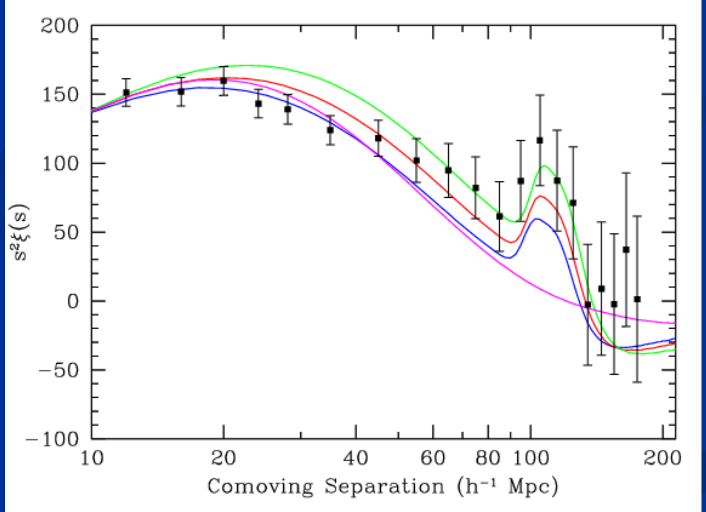
Structure formation :

One primordial

fluctuation- spectrum

Baryon - Peak

galaxy – correlation – function



SDSS