The cosmological context

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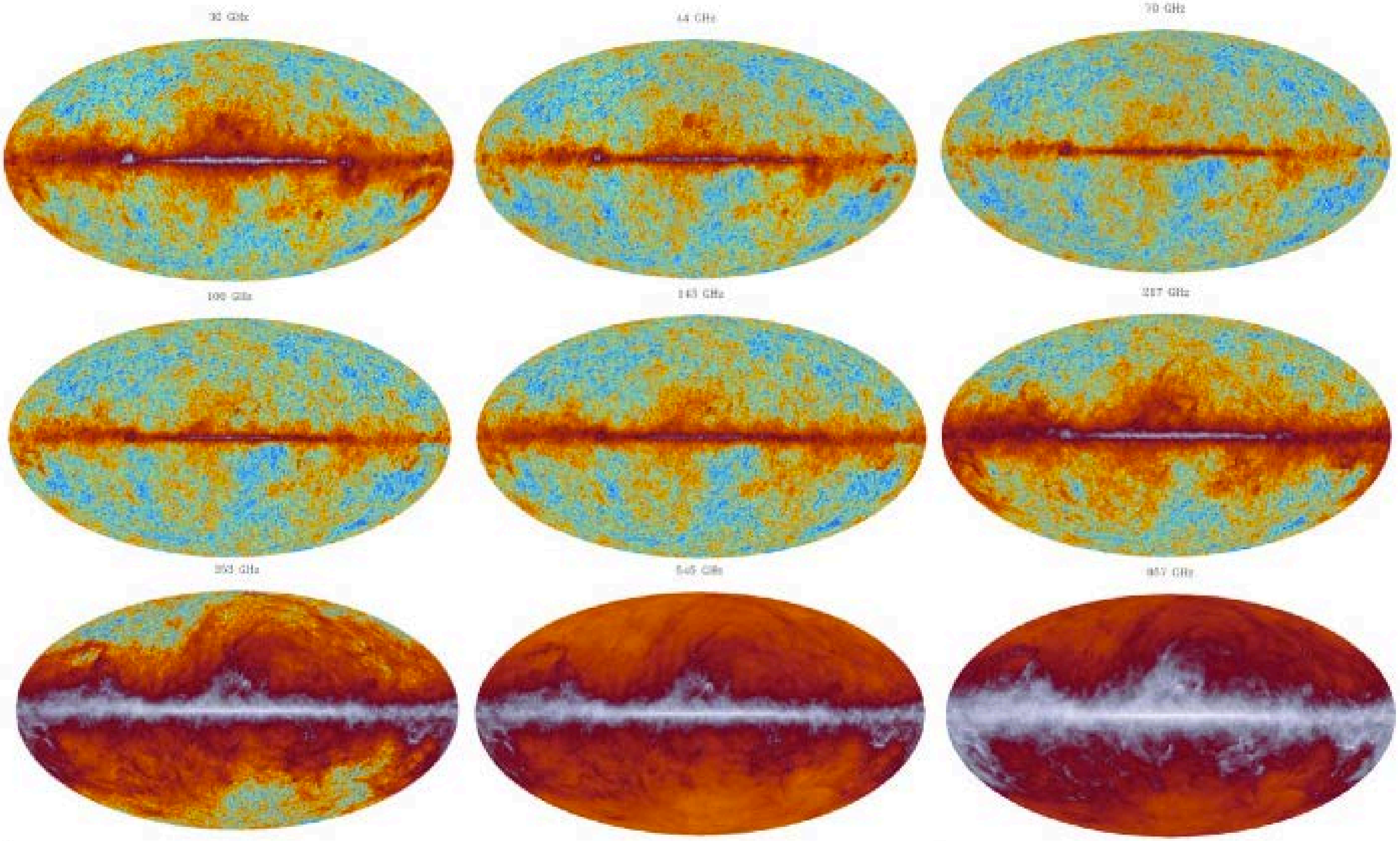
Outline

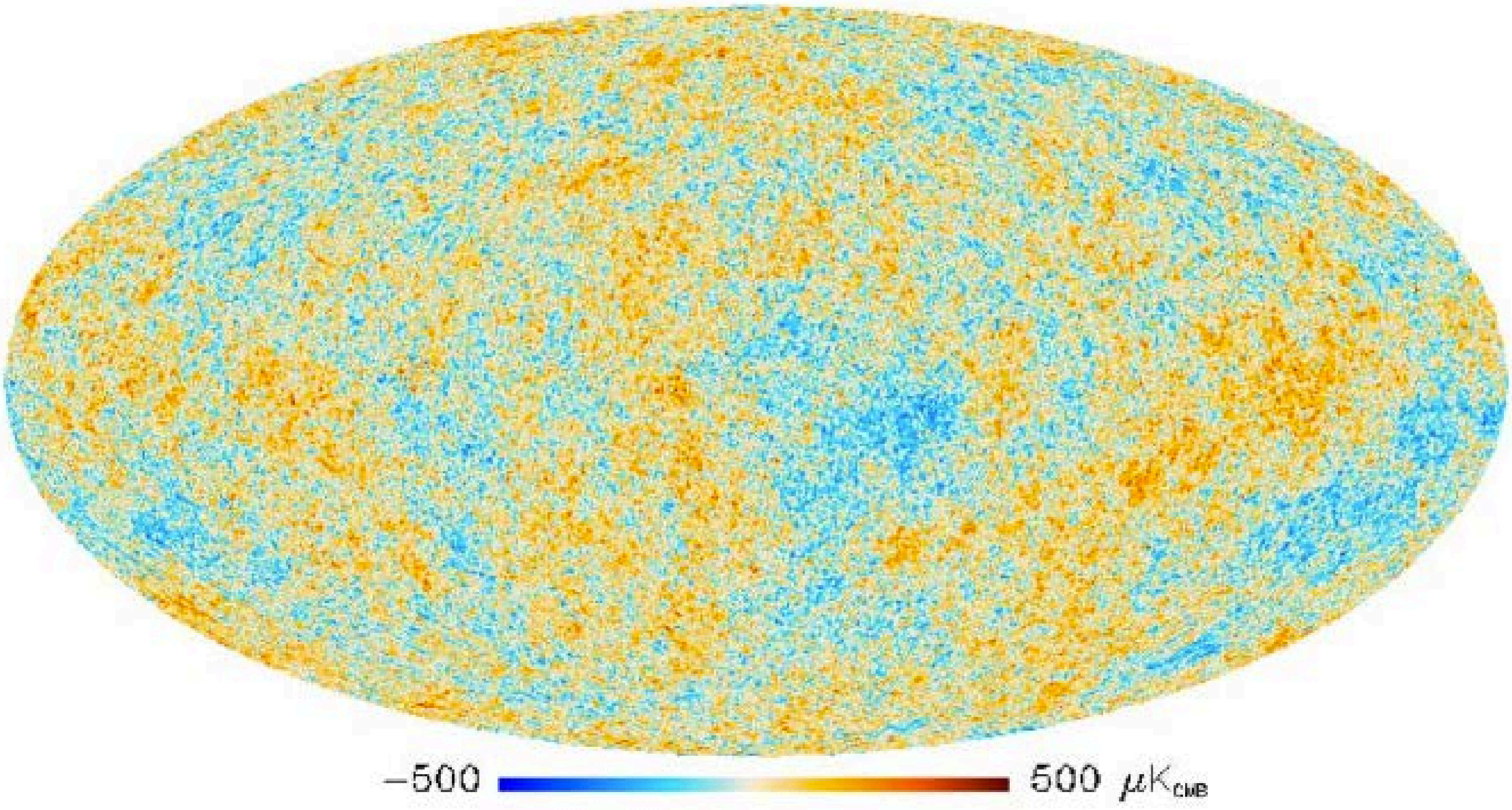
The Universe after Planck
Where quantum physics meets gravity: the vacuum energy problem
Dark energy models
Violations of the fundamental symmetries

The Universe after Planck

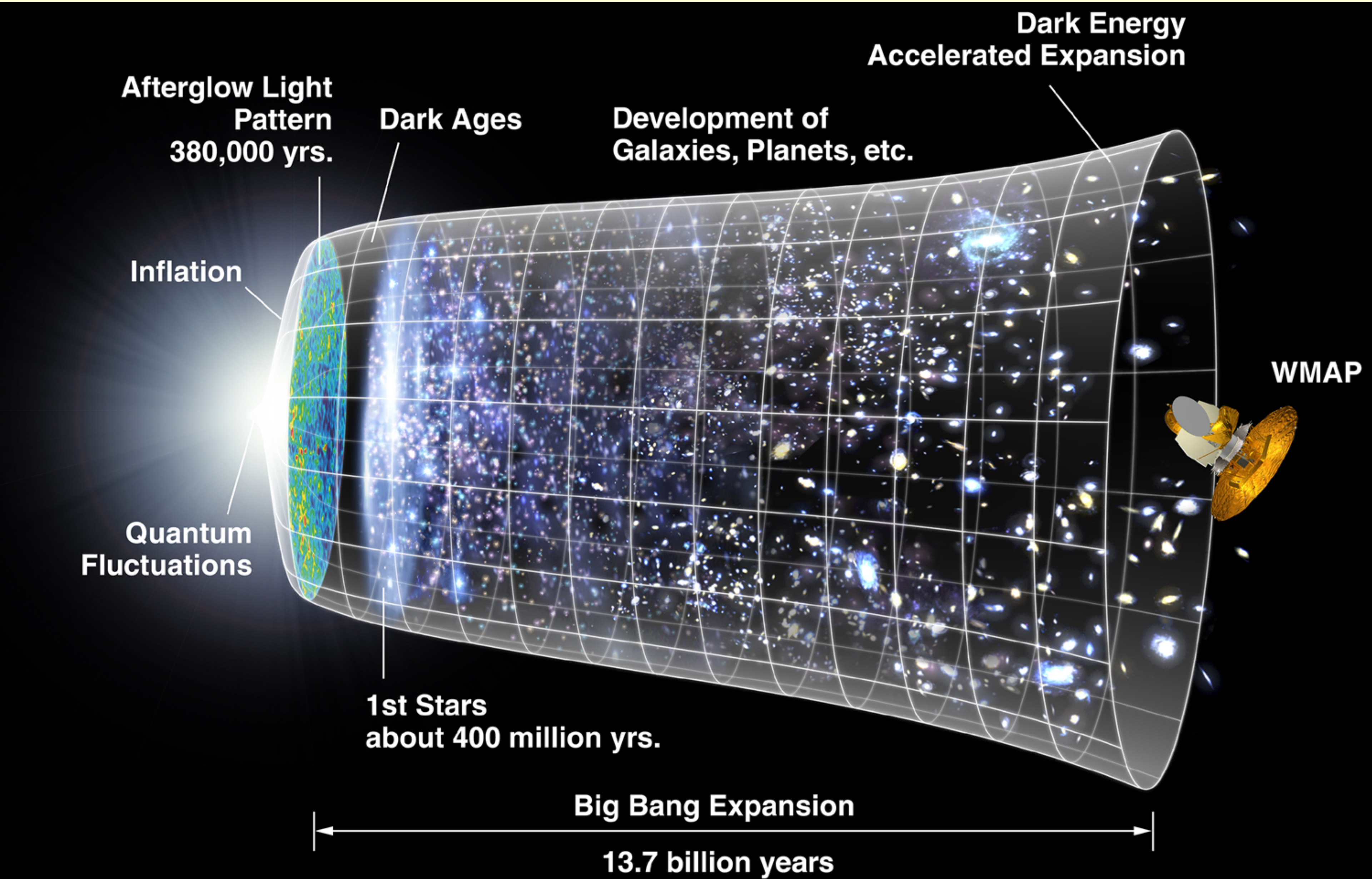
PLANCK FREQUENCYMAPS



After cleaning the foregrounds…



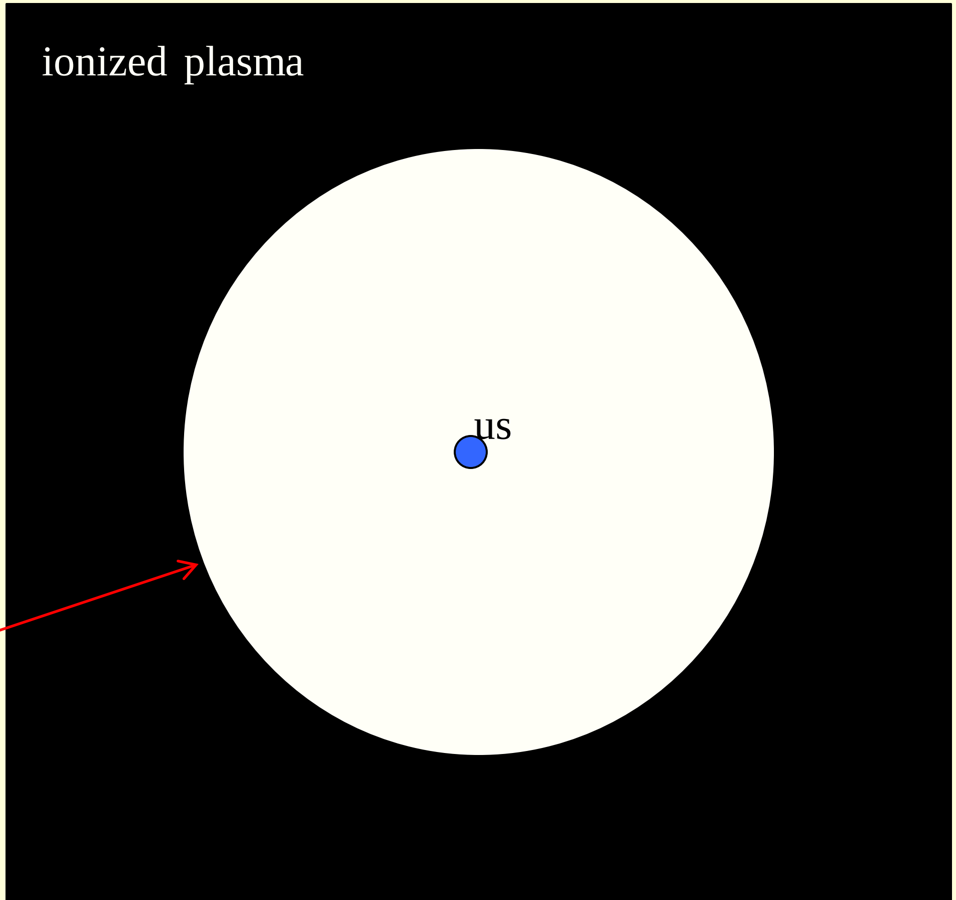
The Universe according to WMAP



The early Universe is an ionized plasma : photons interact strongly with the plasma and are absorbed before propagating: the Universe is dark.

At t ~ 400 000 yrs i.e. kT ~ 0.26 eV i.e. z ~ 1100, electrons combine with protons to form neutral hydrogen: photons can travel large distances. The universe becomes transparent to light.

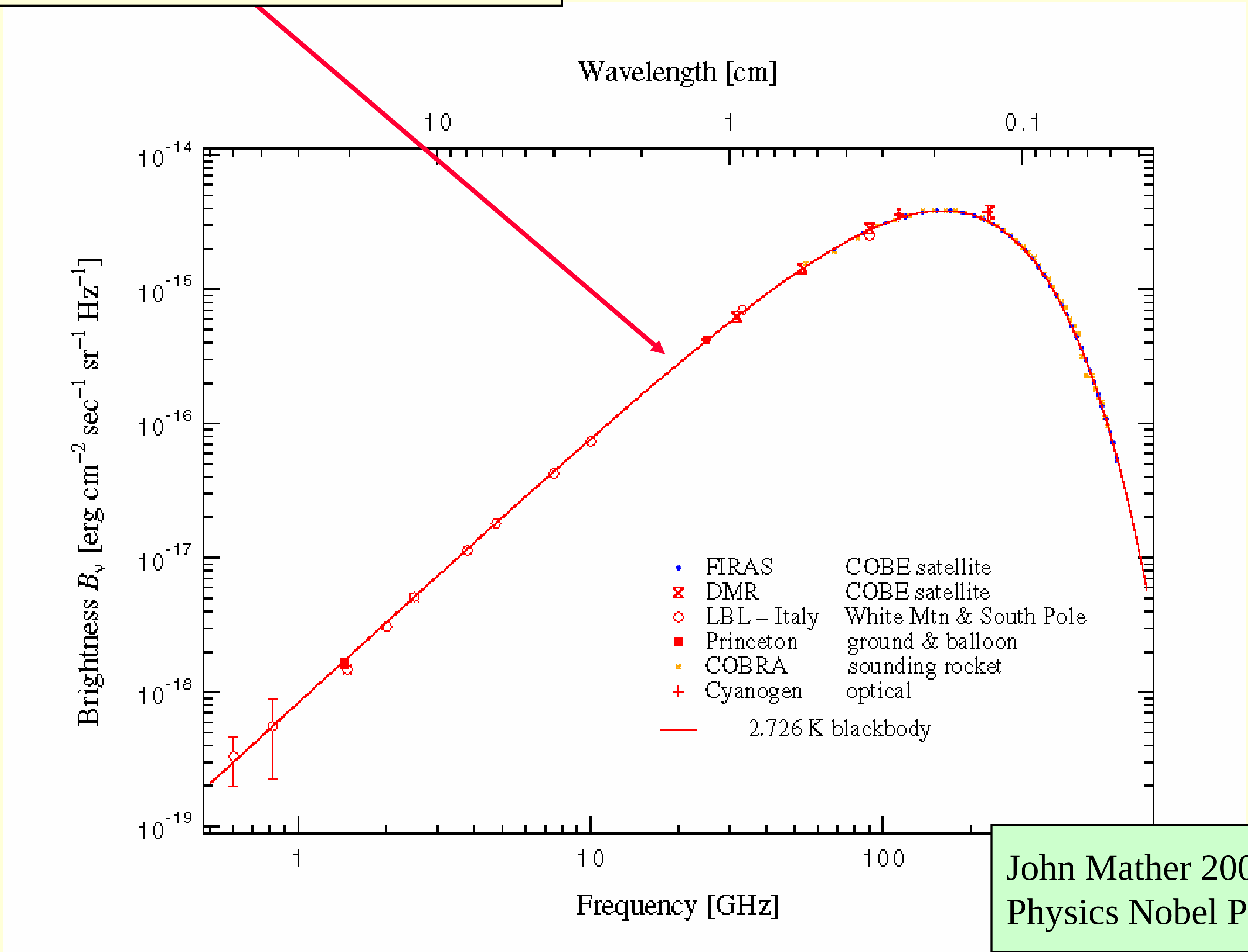
Which light?



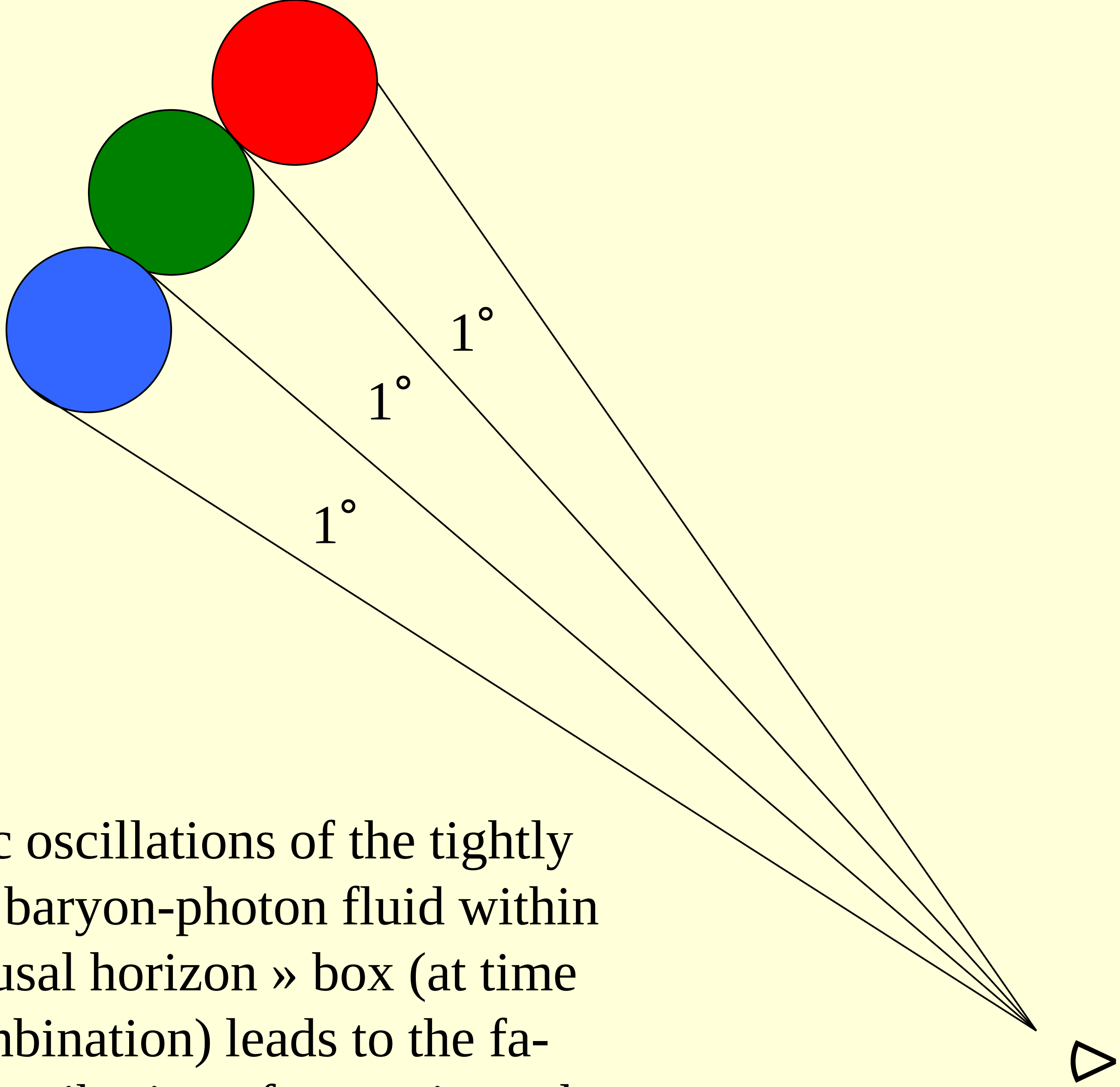
last scattering surface

Planck black body distribution at 2.7 K

$T(z) = T_o\,(1+z)$

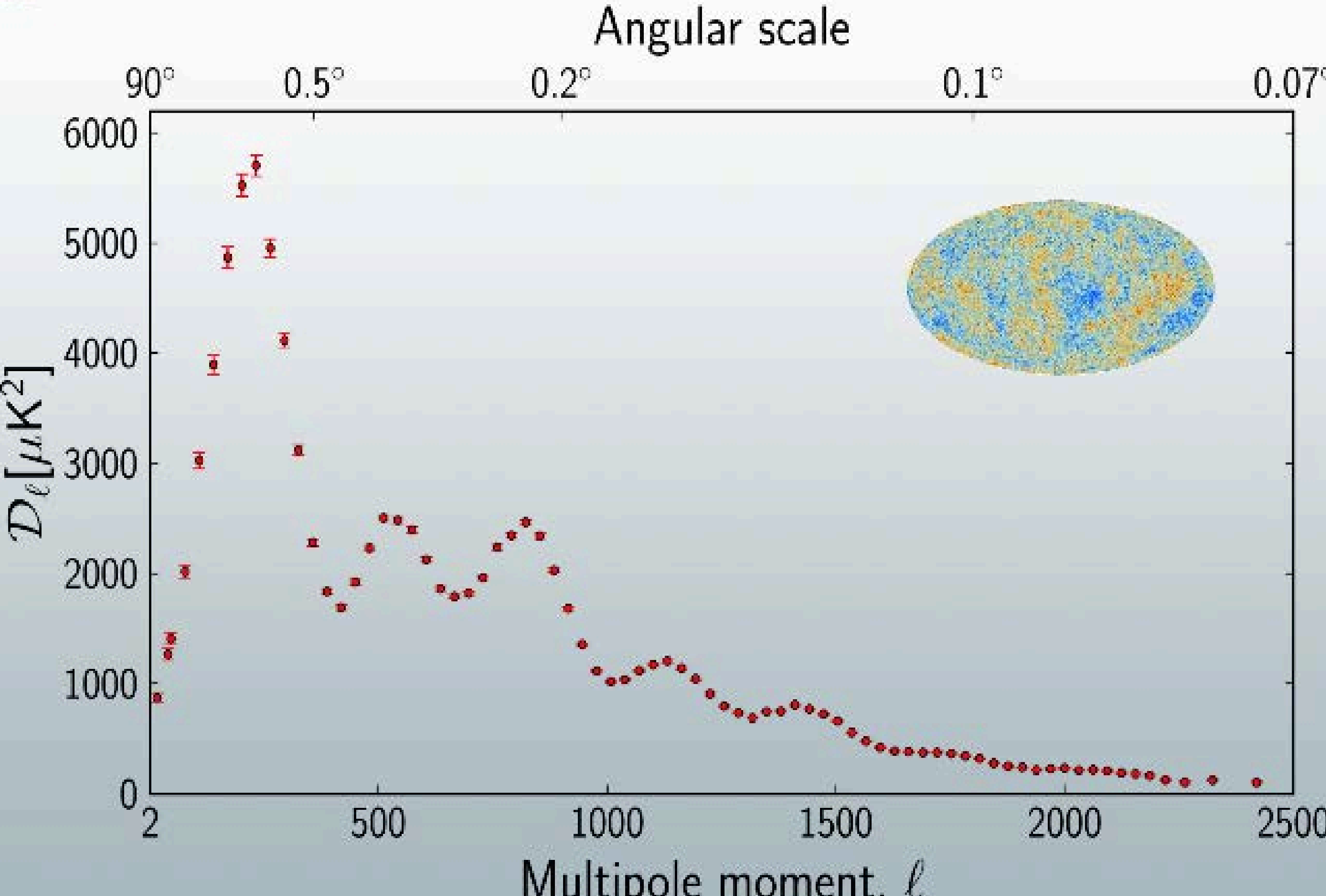


John Mather 2006
Physics Nobel Prize



Acoustic oscillations of the tightly coupled baryon-photon fluid within the « causal horizon » box (at time of recombination) leads to the famous distribution of acoustic peaks

The Planck spectrum of Temperature anisotropies

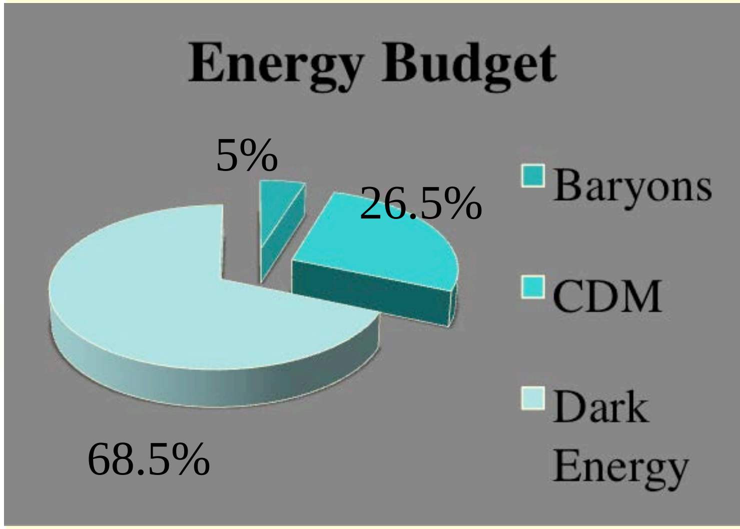


What do we learn?

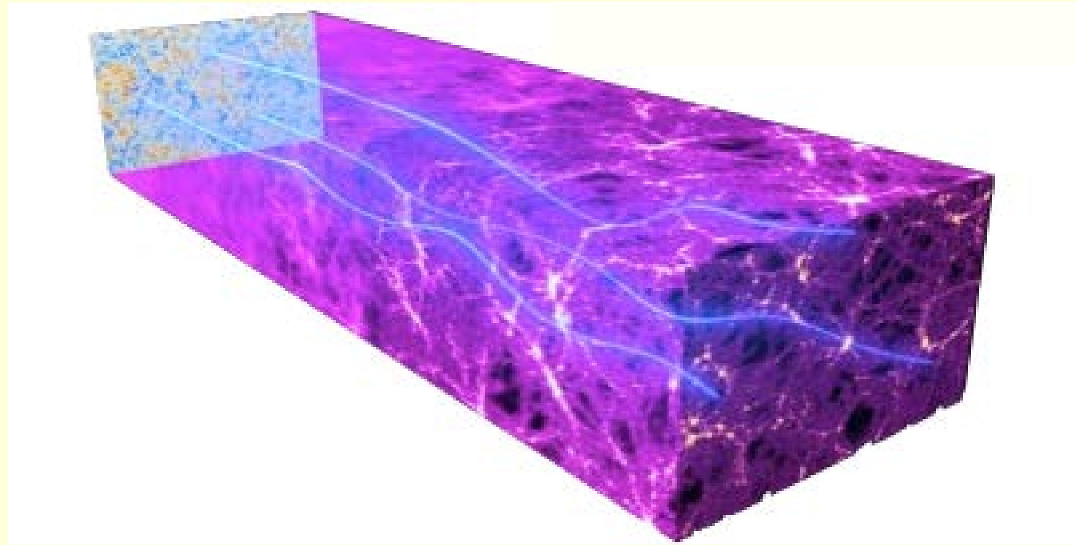
• information about recombination and the evolution of the Universe since

BASE ΛCDM MODEL

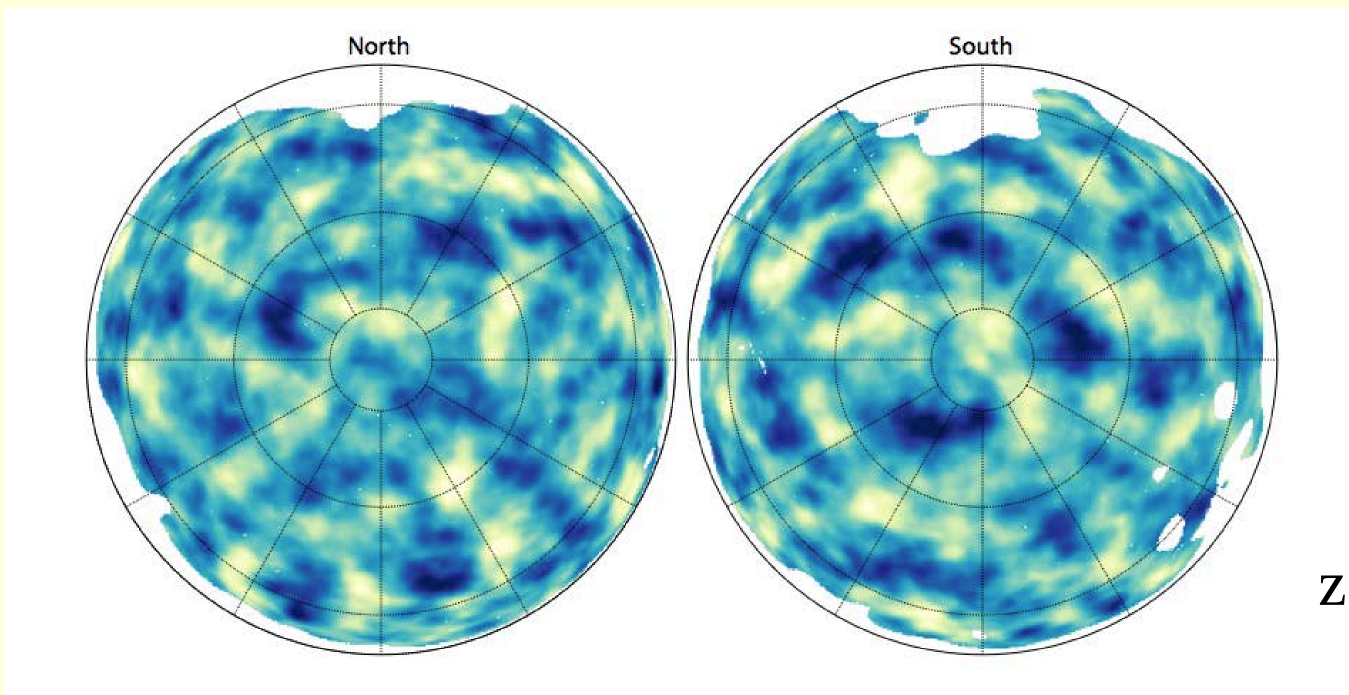
Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026
$100\theta_*$	1.04148±0.00062
τ	0.091±0.014
H_0	67.3±1.2
Ω_Λ	0.685±0.017
σ_8	0.828±0.012
z_{re}	11.1±1.1



CMB lensing

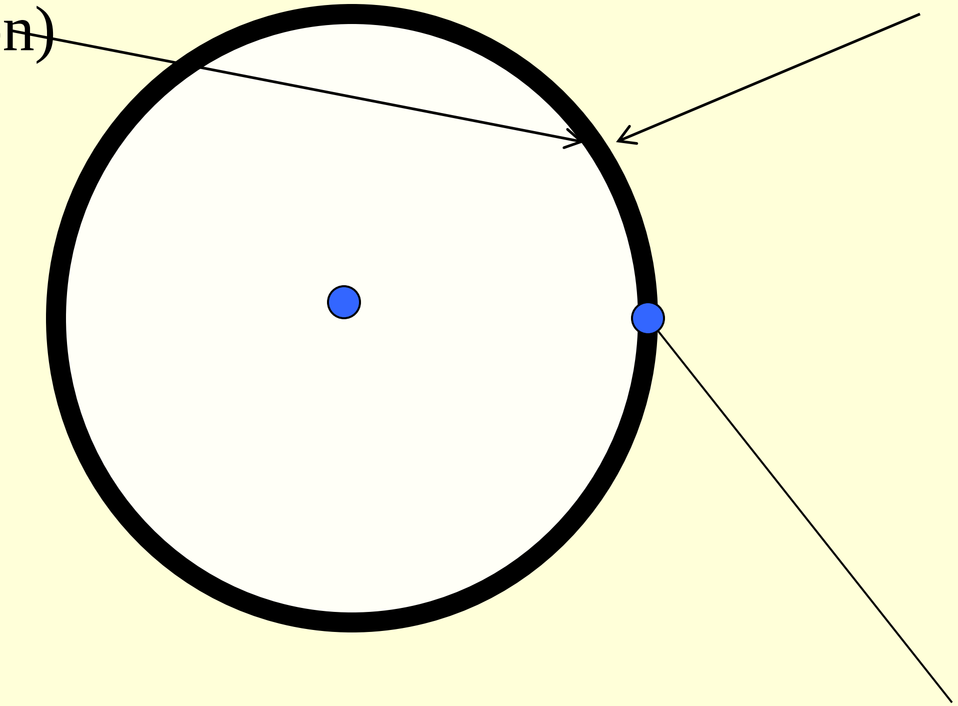


allows to reconstruct the large scale structures

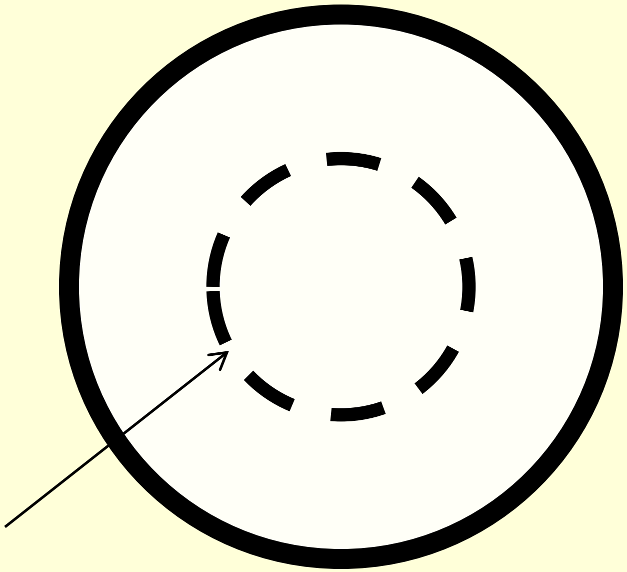


z~2

- even more importantly, information about the very early Universe



A word of caution: our observation of the Universe is very limited



slice is observed only
at given time

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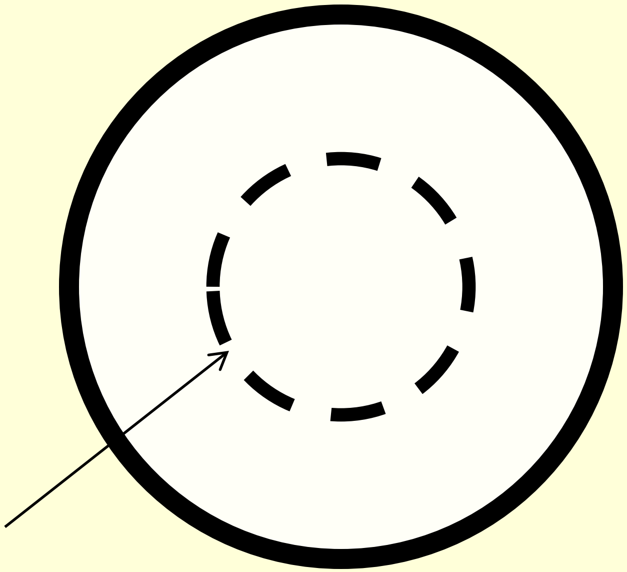

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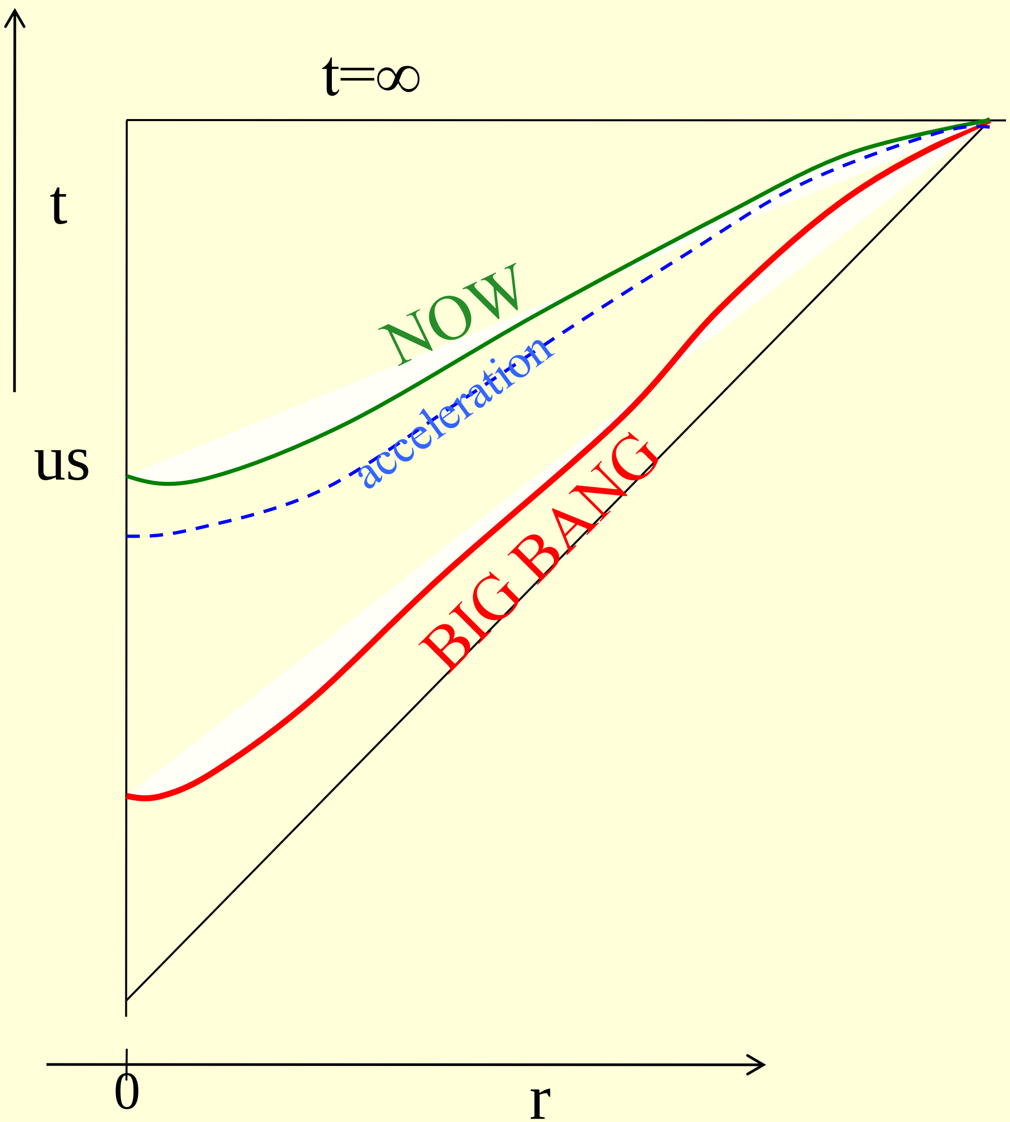

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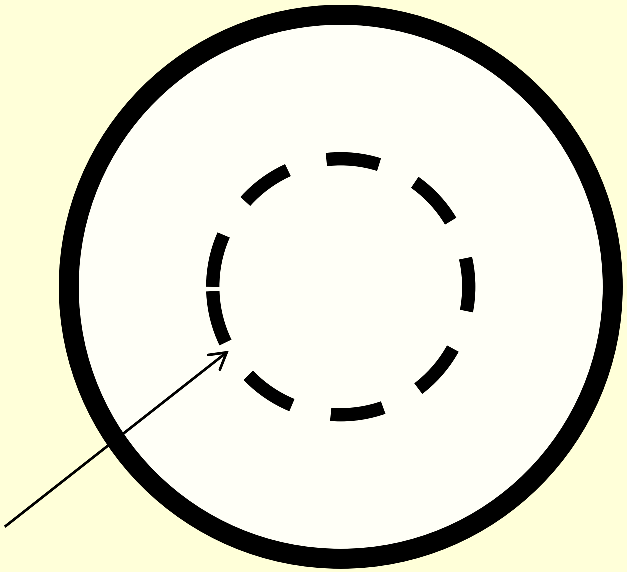

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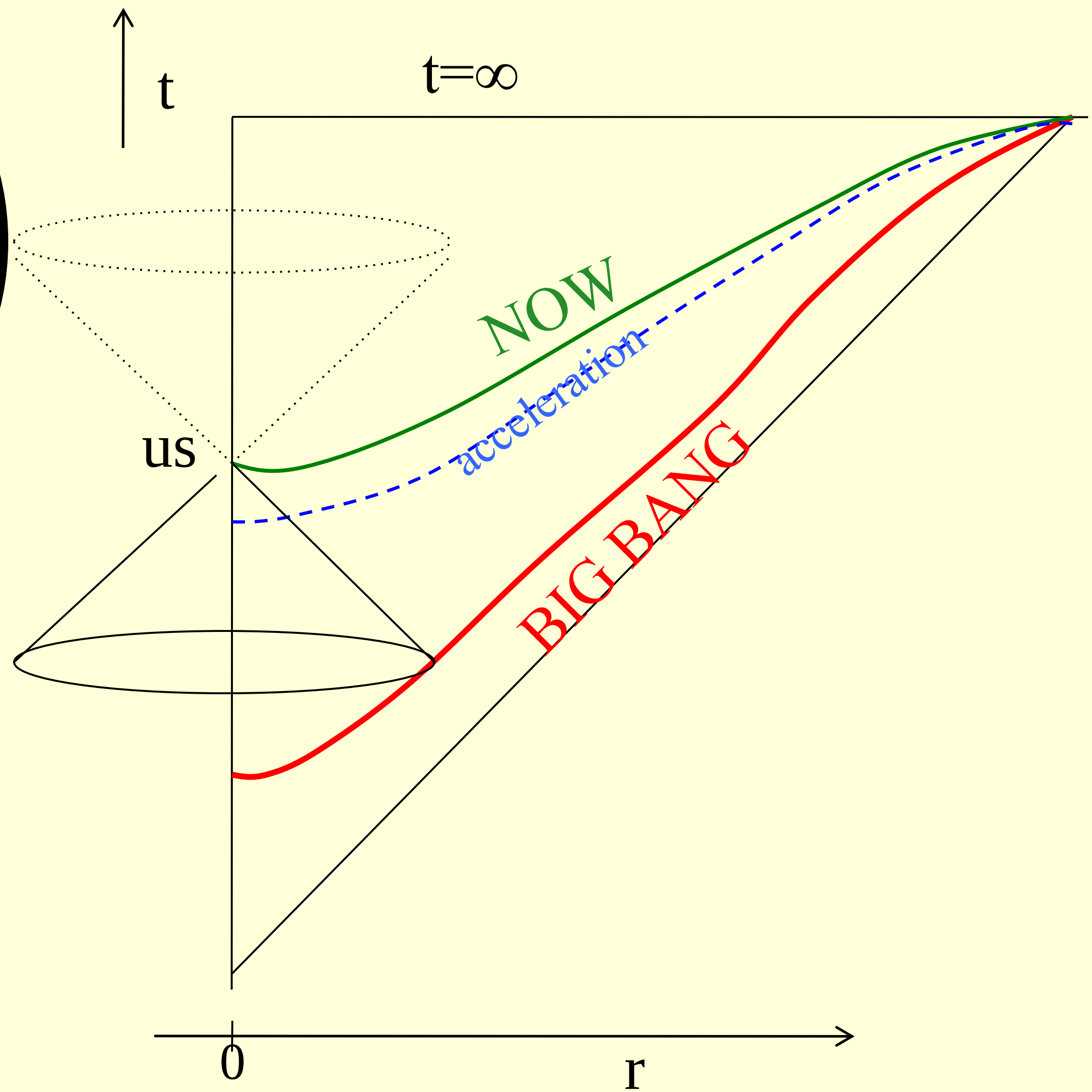
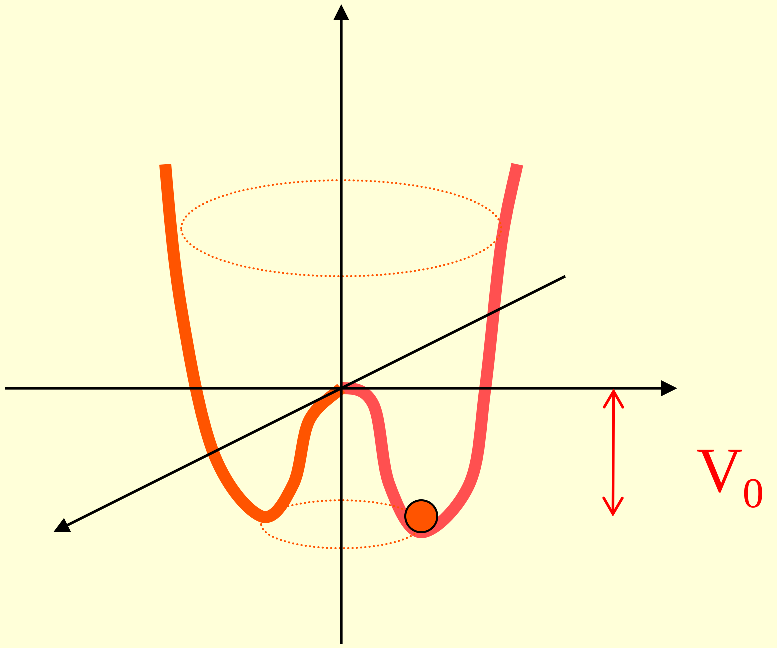


Planck results have taught us that the source of fluctuations is *almost* of a scale-free gaussian nature

Power spectrum: $P_{\delta\rho/\rho}(k) \sim k^{n_s-1}$ $n_s \sim 1$

This is best described effectively by the theory of inflation

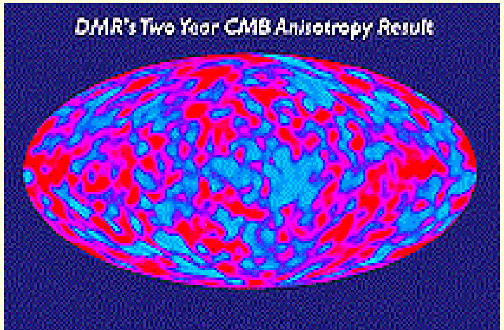
Inflation scenario proposed first in the context of the phase transition associated with grand unification (Guth, 81)



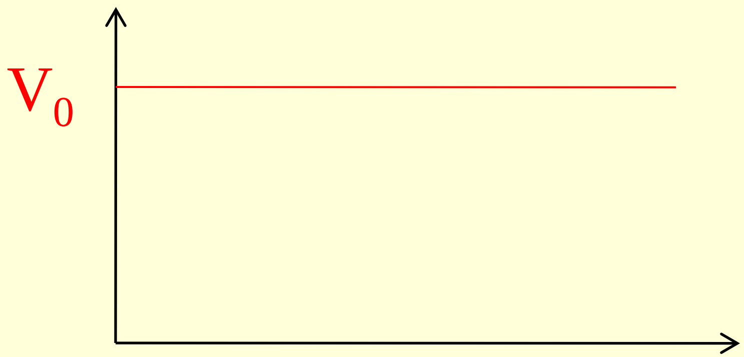
Fluctuations in CMB predicted at the level observed by the COBE satellite :

$$V_0 = \varepsilon^{1/4}\ 6.7\ 10^{16}\ \text{GeV}$$

ε slowroll parameter : $2\varepsilon=(M_P V'/V)^2 \ll 1$



If a vacuum energy V_0 dominates the energy density, the Universe has the geometry of de Sitter space time.

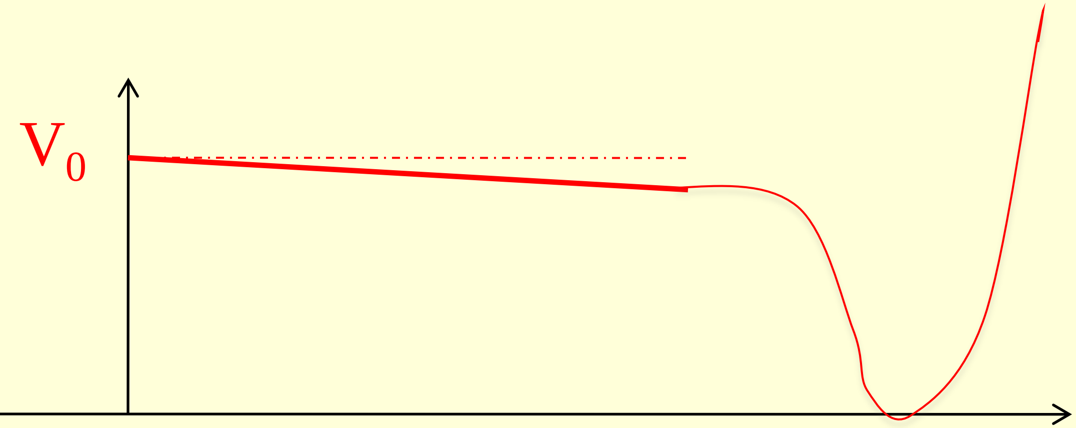


quantum fluctuations are scale-free

$n_s = 1$

Harrison-Zeldovich spectrum

But there must be an end to inflation : an instability should be built in

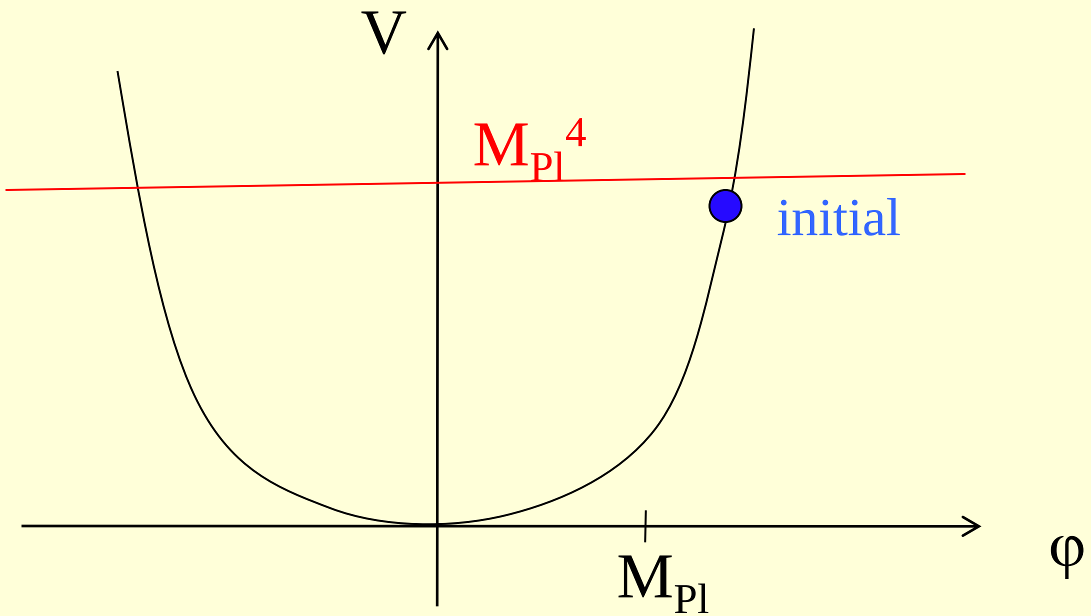


$n_s < 1$

Planck: $n_s = 0.9585 \pm 0.0070$

Two theoretical developments after the first inflation models:

• chaotic inflation: more natural initial conditions



Linde

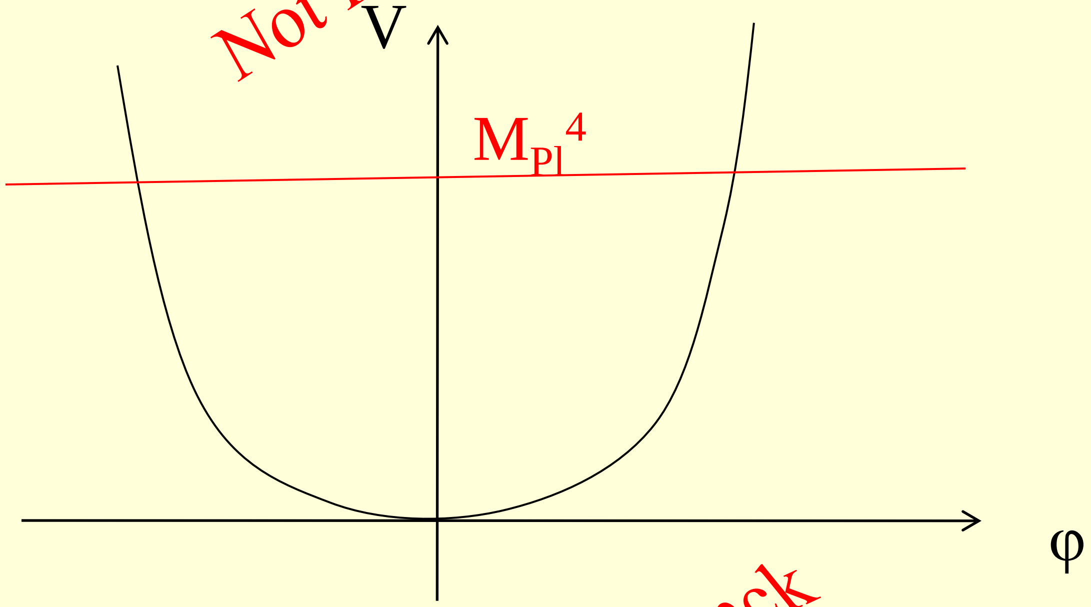
• realistic models: multi-scalar field inflation

lead to sources of non-Gaussianity (3-point function, etc…)

Two theoretical developments after the first inflation models:

Not favored by Planck

• chaotic inflation: more natural initial conditions

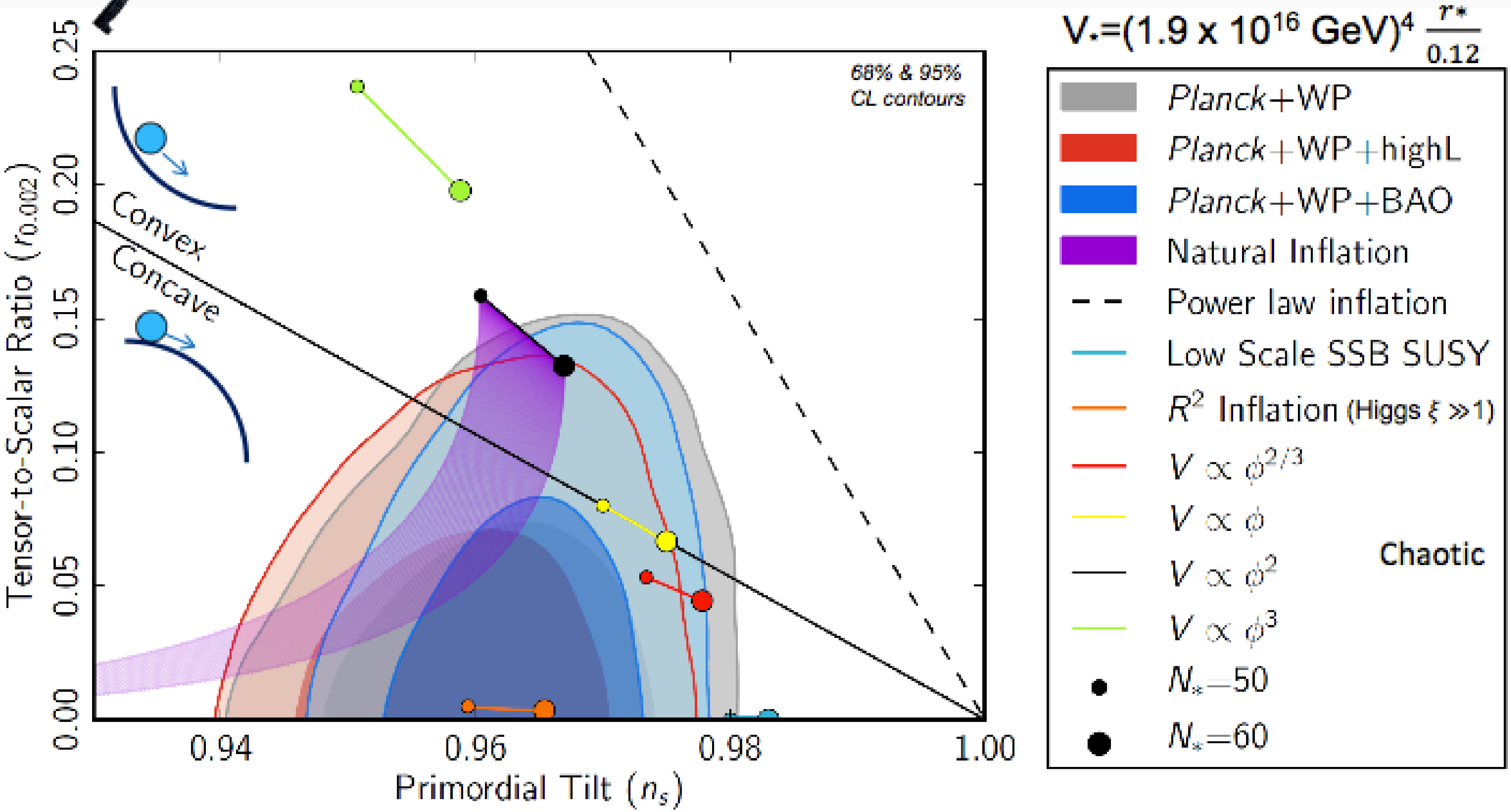


• realistic models: multi-scalar field inflation

Not favored by Planck

lead to sources of non-Gaussianity (3-point function, etc…)

Constraint on representative Inflation models

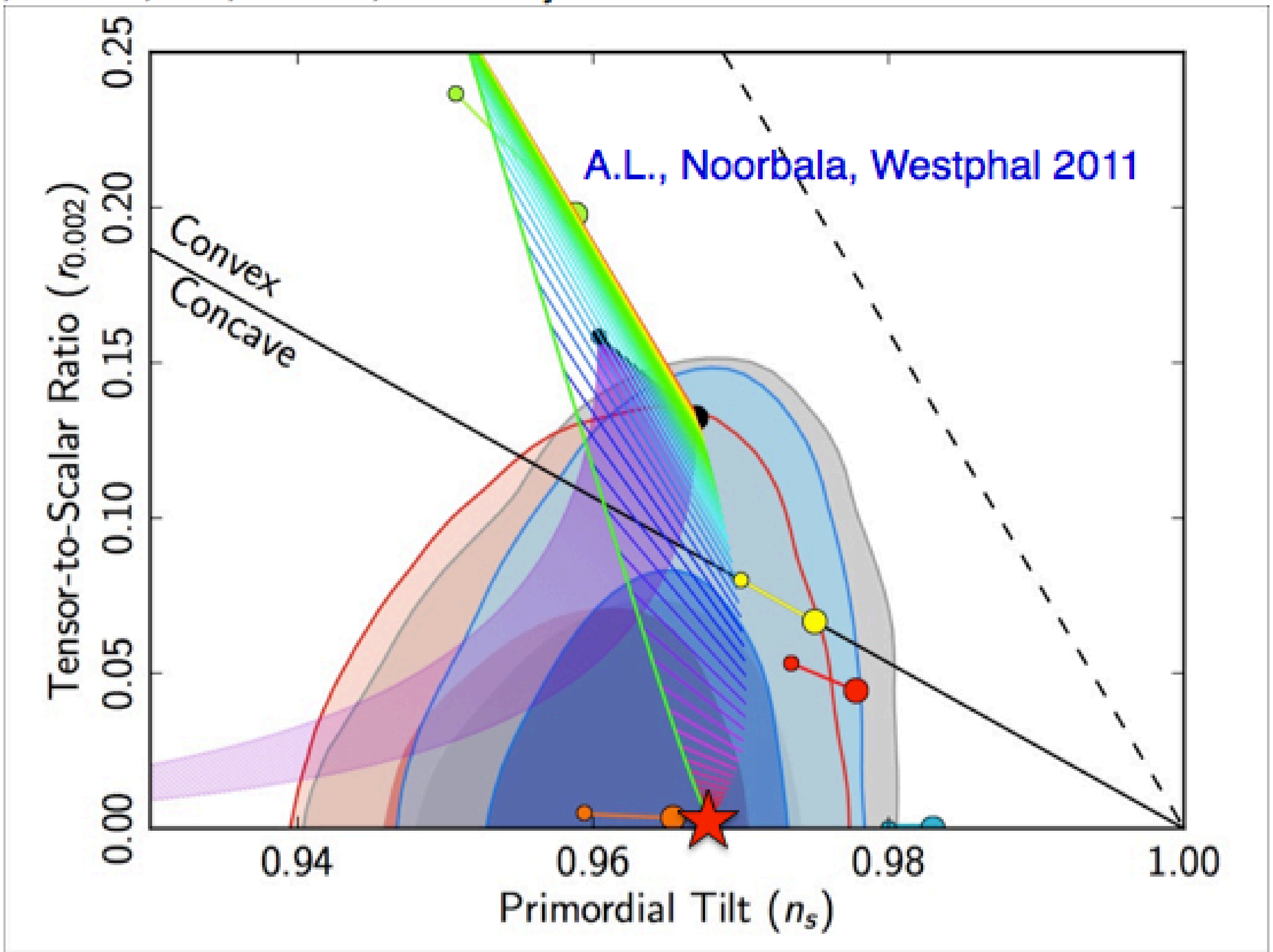


→Exponential potential models(power-law inf.), simplest hybrid inflationary models (SB SUSY), monomial potential models of degree n >2 do not provide a good fit to the data.

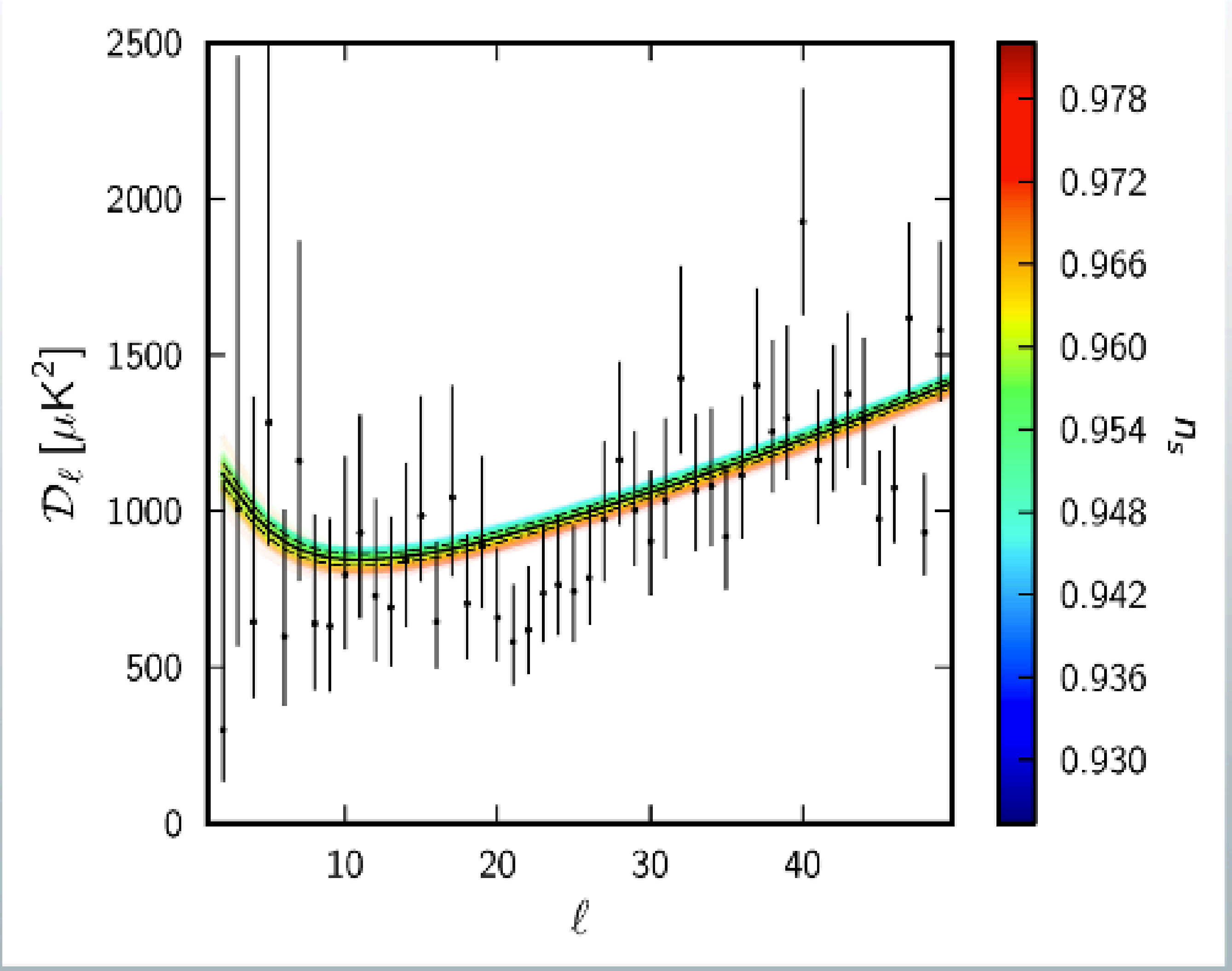
"Higgs Inflation"

$$\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}(\phi^2 - v^2)^2$$

Futamase and Maeda, 1989,
Salopek, J. R. Bond and J. M. Bardeen, 1989
Bezrukov, Shaposhnikov 2008
Ferrara, Kallosh, A.L., Marrani, Van Proeyen 2011



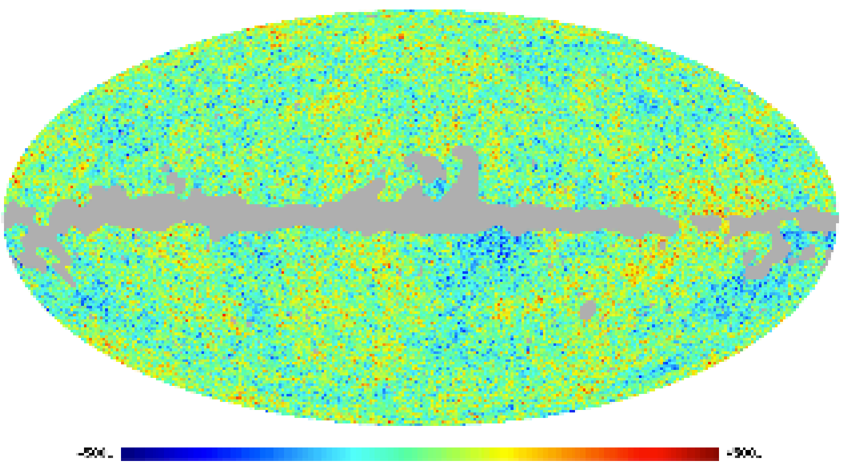
The low-multipole surprise/tension



A Paradoxical "Solution" to the Idiosyncratic Appearance of our CMB Sky

The Bianchi model **must be open** to fit the data, and cannot be merged with the overall flat cosmology that describes the observed universe

Real CMB Sky



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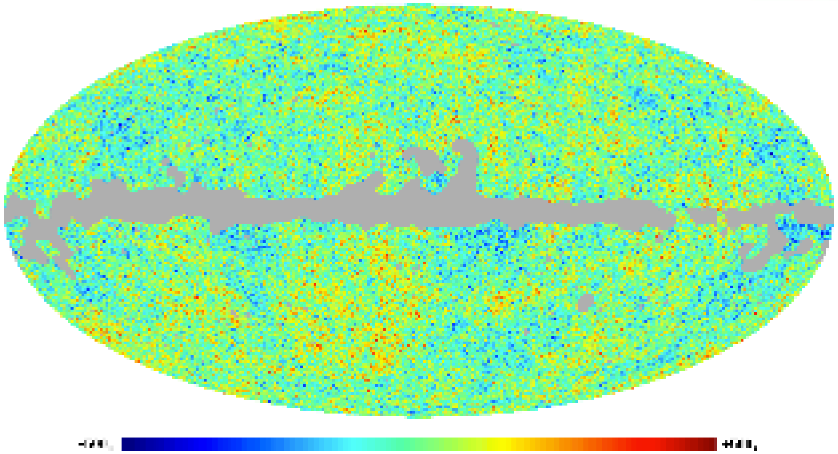
Corrected CMB Sky



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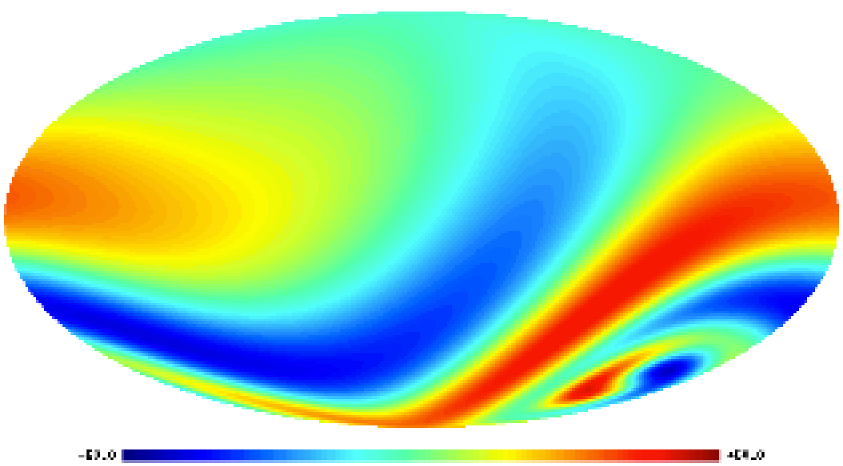


Correction that fits the sky:
a homogeneous, anisotropic Bianchi VII_h model

How to go beyond?

Key word is gravitation: the Universe is powered by gravity

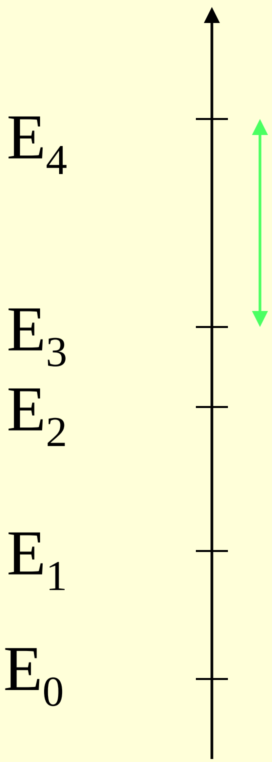
Search for primordial gravitational waves: CMB polarisation

Search for possible alternatives to inflation

Search for alternatives to general relativity

Where quantum physics meets gravity: the vacuum energy prob

Vacuum energy



Classically, only differences of energy can be measured (e.g. Casimir effect).

ground state = vacuum

The absolute energy E_0 cannot be measured experimentally

No longer true in a gravitational context!

Einstein equations: $R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu}$

geometry energy

Hence geometry may provide a way to measure absolute energies i.e. vacuum energy:

$$R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu} + 8\pi G < T_{\mu\nu} >$$ vacuum energy

similar to the cosmological term introduced by Einstein :

$$R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu} + \lambda\, g_{\mu\nu}$$

$$\boxed{\lambda \equiv \ell_\Lambda^{-2}}$$

Can we measure λ i.e. the associated scale ℓ_Λ?

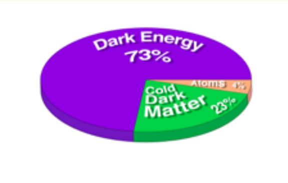
$c = 1$

Einstein equations $\rightarrow$ Friedmann equation

$H = \dot{a}/a$

$$H^2 = (8\,\pi G\,\rho + \lambda\,)\,/3 - k/a^2$$

$\rho_\Lambda = \lambda\,/\,8\pi G$ $\qquad \rho_c = 3\,H_0^{\,2}\,/\,8\pi G$ $\qquad \rho_k = -3k\,/\,8\pi G a_0^{\,2}$



$$\rho_c = \rho\; + \rho_\Lambda + \rho_k$$

$$\Omega_\Lambda \equiv \rho_\Lambda\,/\,\rho_c = \;(H_0^{-1}\,/\,\ell_\Lambda)^2\,/\,3 \;\sim 0.7 \;\Rightarrow\quad \ell_\Lambda \;\sim H_0^{-1} \sim\; 10^{26}\text{ m}$$

A very natural value for an astrophysicist: H_0^{-1} is the size of the visible Universe (our causal « horizon ») !

Introduce the quantum theory i.e. $\hbar$

Planck length $\quad \ell_P = \sqrt{8\pi G_N \hbar / c^3} = 8.1 \mathrm{x} 10^{-35}\mathrm{m}$

Planck	$\ell_P \sim 10^{-34}\,\mathrm{m}$	$m_P \sim 10^{27}\,\mathrm{eV}$
λ	$\ell_\Lambda \sim 10^{26}\,\mathrm{m}$	$m_\Lambda \sim 10^{-33}\mathrm{eV}$

$$mc^2 \equiv \frac{\hbar c}{l} = \frac{200\ \mathrm{MeV.fm}}{\ell}$$

Can we measure λ i.e. the associated scale ℓ_Λ?

Einstein equations $\rightarrow$ Friedmann equation

$H = \dot{a}/a$

$$H^2 = (8\, \pi G\, \rho + \lambda)/3 - k/a^2$$

$c = 1$

$$\rho_\Lambda = \lambda / 8\, \pi G \qquad \rho_c = 3\, H_0^2 / 8\, \pi G$$

$$\Omega_\Lambda \equiv \rho_\Lambda / \rho_c = (H_0^{-1} / l_\Lambda)^2 / 3 \sim 0.7 \Rightarrow \quad \ell_\Lambda \sim H_0^{-1} \sim 10^{26}\ \mathrm{m}$$

~~A very natural value for an astrophysicist~~ !

A very unnatural value for a Universe which presumably started as a quantum state!

Indeed, if we compute the vacuum energy, we obtain typically

$$\rho_\Lambda \sim m_P{}^4 \sim 10^{120}\, \rho_{observed}$$

ħ=c=1

There should be a cancellation mechanism of most of the vacuum energy,

Or there is a selection principle for our own Universe to have a much lower vacuum energy than expected.

string vacuum

inflation

Note that,

if we write
$$\rho_\Lambda = \frac{1}{8\pi G \ell_\Lambda^2} = \frac{\hbar}{\ell_P^2 \ell_\Lambda^2} \equiv \frac{\hbar}{\ell_{DE}^4}$$

$$\boxed{\ell_{DE} = \sqrt{\ell_P \ell_\Lambda}}$$

UV cut-off

IR cut-off

Cosmological constant problem : where the two ends meet…

$$\rho_\Lambda = \frac{1}{8\pi G \ell_\Lambda^2} = \frac{\hbar}{\ell_P^2 \ell_\Lambda^2} \equiv \frac{\hbar}{\ell_{DE}^4}$$

$$\boxed{m_{DE} = \sqrt{m_P m_\Lambda}}$$

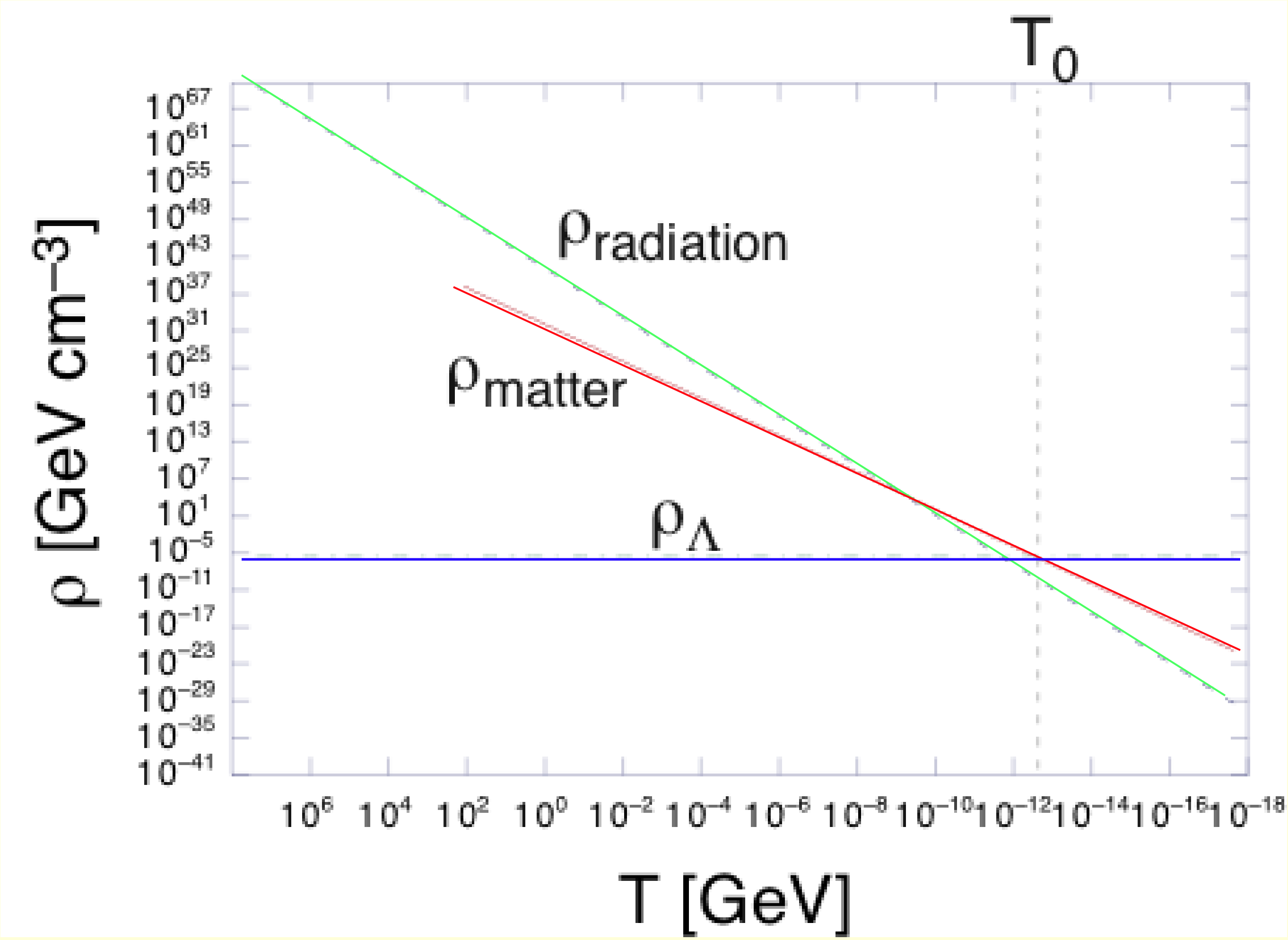
10^{-3} eV

UV cut-off

IR cut-off

Cosmological constant problem : where the two ends meet…

Central question : why now?
why is our Universe so large, so old?



Are there more general ways than a cosmological constant to account for the acceleration of the expansion?

Einstein equations: $R_{\mu\nu} - R\, g_{\mu\nu}/2 = 8\pi G\, T_{\mu\nu}$

Dark energy

geometry matter-energy

modify gravity

add new effects or a new form of energy

Friedmann equation : $H^2 = 8\,\pi G\,\rho/3 - k/a^2$

modified Friedmann equation

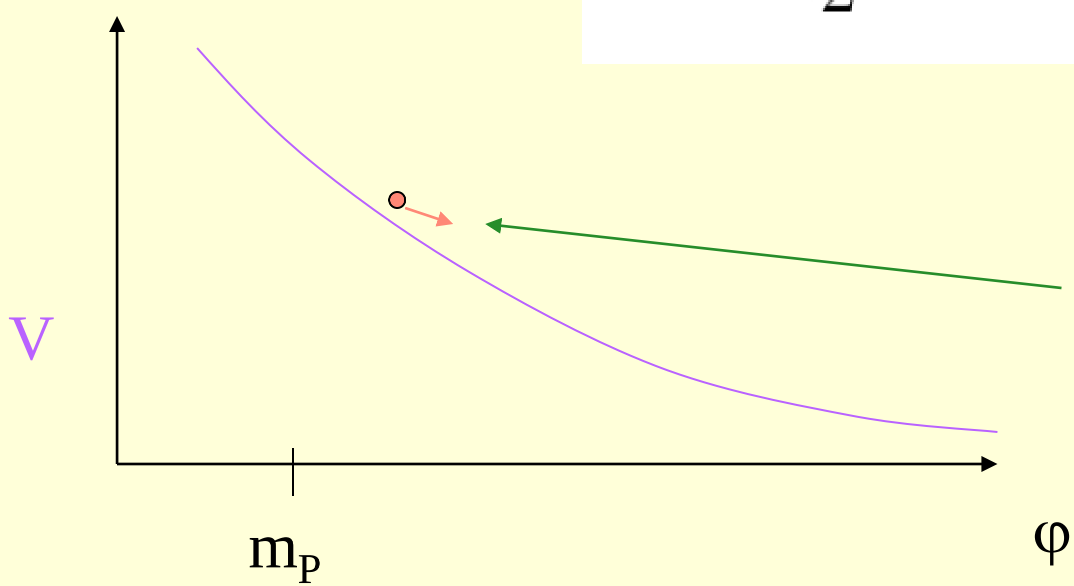
new contributions to the Friedmann equation

Are the two cases so different?

Take for illustration the simplest model using a scalar field

<u>Quintessence</u>

$$\mathcal{L} = \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - V(\phi)$$

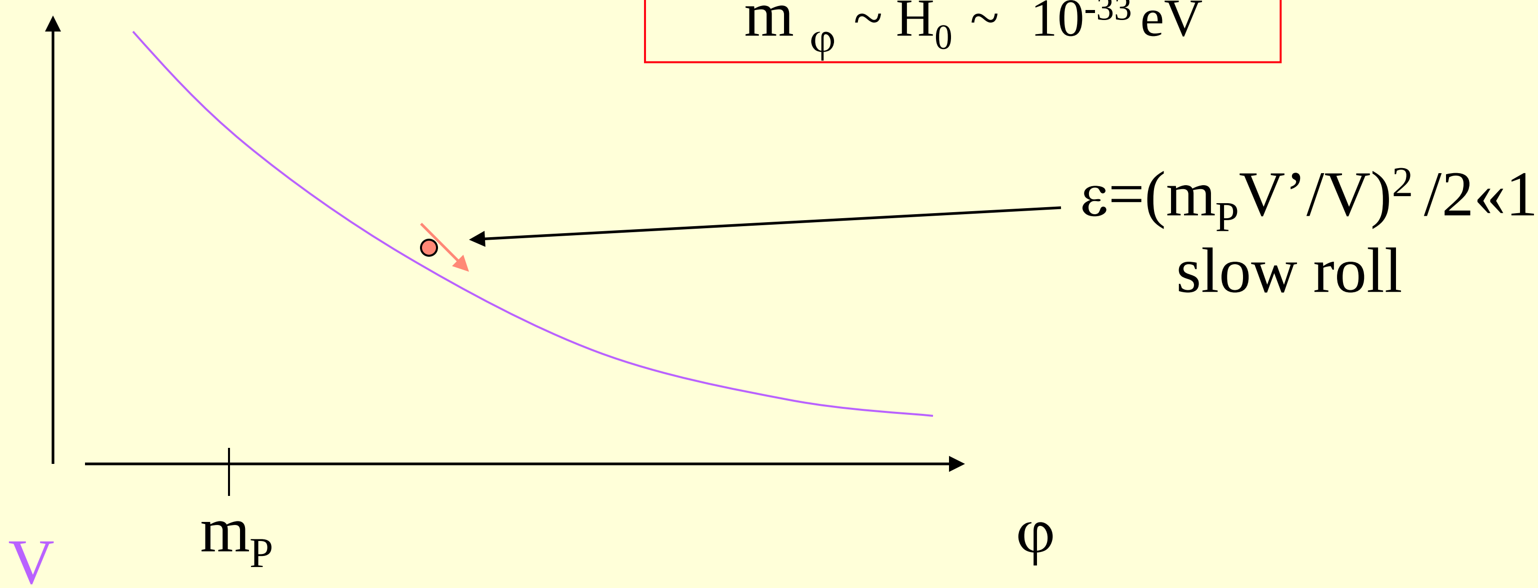


$\varepsilon = (m_P V'/V)^2/2 \ll 1$
slowroll condition

$$w = p_\varphi/\rho_\varphi = \frac{\dot{\varphi}^2/2 - V(\varphi)}{\dot{\varphi}^2/2 + V(\varphi)} > -1$$

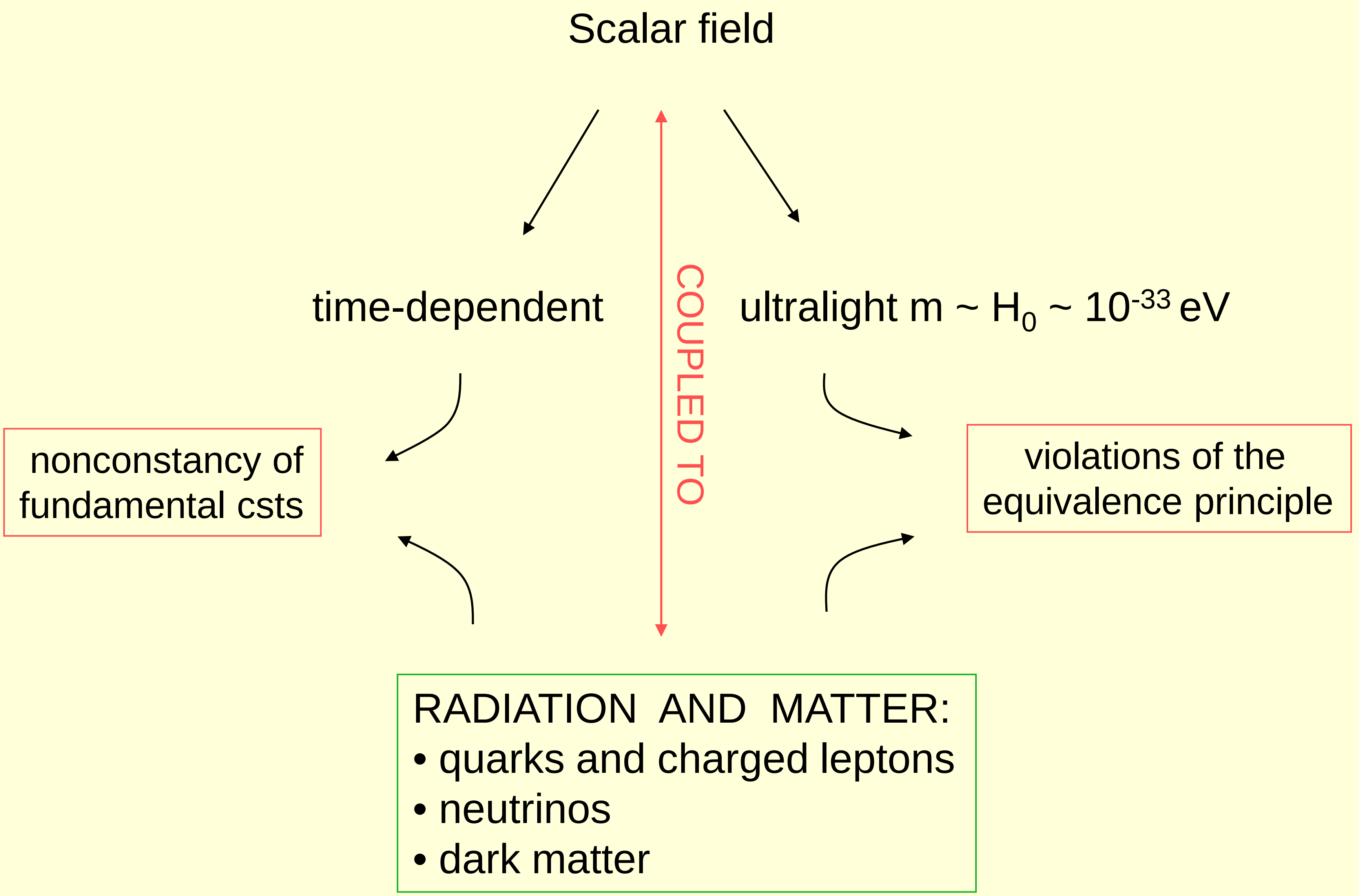
A generic problem

φ has to be very light :
$m_{\varphi} \sim H_0 \sim 10^{-33}$ eV



φ exchange between particles provides a long range force similar to gravity: φ has to be extremely weakly coupled to ordinary matter (more weakly than gravity!)

NEW GRAVITATIONAL-TYPE INTERACTION


Scalar field
time-dependent
COUPLED TO
ultralight m ~ H_0 ~ 10^{-33} eV
nonconstancy of fundamental csts
violations of the equivalence principle
RADIATION AND MATTER:
• quarks and charged leptons
• neutrinos
• dark matter

A simple example

Wetterich, 02

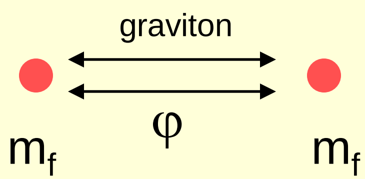
φ quintessence field

$$L_{kin} = \frac{1}{2} k^2 \, \partial^\mu \varphi \, \partial_\mu \varphi$$

Fermion masses: $m_f(\varphi)$

Quintessence charge : $\boxed{\beta_f \equiv \frac{m_{Pl}}{m_f} \frac{\partial m_f}{k \partial \varphi}}$

Damour, Esposito-Farèse, 92



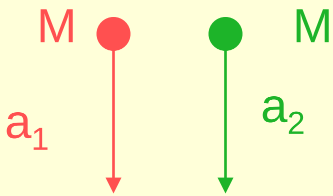
$$V_N = - \frac{G_N \, m_f^2}{r} (1 + \beta_f^2)$$

Acceleration in the Earth gravitational field :

$$a_f = \frac{G_N \, M_E}{r^2} \left[1 + \frac{m_{Pl}^2}{k^2} \left(\frac{\partial \ln M_E}{\partial \varphi} \right) \left(\frac{\partial \ln m_f}{\partial \varphi} \right) \right]$$

M_E Earth mass

For two test bodies with same mass M but different composition



$$M = N_i\, m_n + Z_i\, m_H + B_i\, \varepsilon$$

$$m_H = m_p + m_e$$
$$B_i = N_i + Z_i$$

$$\Delta N = N_1 - N_2, \ldots$$

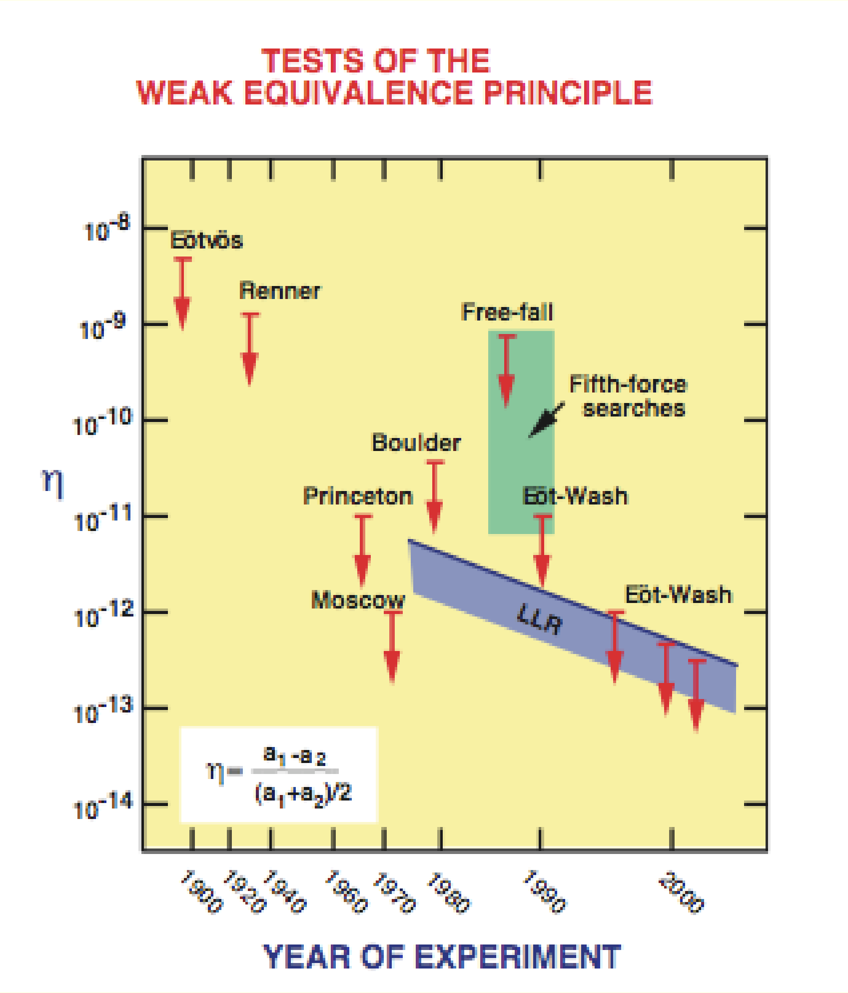
$$\eta \equiv \frac{2|a_1-a_2|}{a_1+a_2} = \frac{m_{Pl}^2}{k^2}\, \frac{\partial \ln M_E}{\partial \varphi} \left(\Delta N \frac{\partial m_n}{\partial \varphi} + \Delta Z \frac{\partial m_H}{\partial \varphi} + \Delta B \frac{\partial \varepsilon}{\partial \varphi} \right)$$

$$\Delta N\, m_n + \Delta Z\, m_H + \Delta B\, \varepsilon = 0$$

$$\eta = \frac{m_{Pl}^2}{k^2}\, \frac{\partial \ln M_E}{\partial \varphi} \left(\Delta Z\, \frac{m_H}{M}\, \frac{\partial \ln(m_H/m_n)}{\partial \varphi} + \Delta B\, \frac{\varepsilon}{M}\, \frac{\partial \ln(\varepsilon/m_n)}{\partial \varphi} \right)$$

$$\sim \frac{\partial \ln M_E/B_E}{\partial \varphi} \sim \frac{\partial \ln m_n/m_{Pl}}{\partial \varphi}$$

In most cases, difficult to reconcile with existing limits:



C. Will, Living Rev. Relativity, 2006

Modification of gravity

Extended gravity

The Einstein action $S = \int\sqrt{-g}\; R$ can be generalized into

$$S = \int\sqrt{-g}\;\; f(R)$$

Perform a redefinition of the metric $g^{(E)}_{\mu\nu} = 2\,|df/dR|\, g_{\mu\nu}$ and write

$$\phi \equiv (\sqrt{6}/2)\ \ln\,[2|df/dR|]$$

Then

$$\mathcal{L} = \frac{1}{2}R^{(E)} - D^{\mu}\phi D_{\mu}\phi - V(\phi)\ ,$$

$$V(\phi) = \epsilon e^{-2\sqrt{6}\phi/3}\left[\frac{\epsilon}{2}Re^{\sqrt{6}\phi/3} - f\right]\ , \epsilon = \text{sign of } \frac{df}{dR}\ .$$

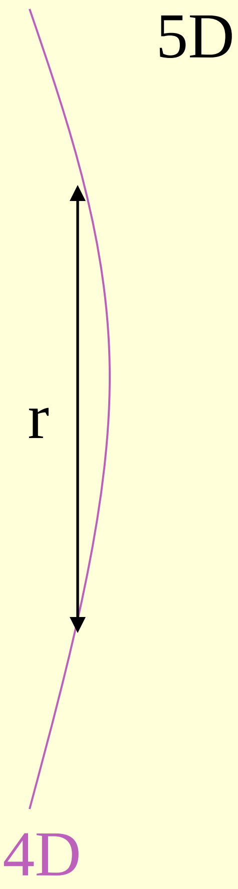
Brane world models: induced gravity à la DGP Dvali, Gabdadze, Porrattii

$$\mathcal{S} = \int d^5x\, \sqrt{-g} M_5^3 \frac{1}{2} R^{(5)} + \int_{\text{brane}} d^4x\, \sqrt{-h} M_{\text{Pl}}^2 \frac{1}{2} R^{(4)} + \int_{\text{brane}} d^4x\, \sqrt{-h}\mathcal{L}_m + \mathcal{S}_{GH}$$

For distances $r > r_c$ one recovers the 5-dim $1/r^3$ behavior:

$$r_c = M_{Pl}^2 / 2\, M_5^3$$

Gravity leakage into the 5th dimension



Cosmology

Deffayet, Dvali, Gabadadze

$$H^2 = \left(\sqrt{\frac{\rho}{3M_{\rm Pl}^2} + \frac{1}{4r_c^2}} + \frac{1}{2r_c}\right)^2 - \frac{k}{a^2}$$

Hence acceleration at late time, without a need for a cosmological constant!

More precisely, taking flat space, this may be written

$$H^2 - \frac{\epsilon}{r_c}H = \frac{\rho}{3M_{\rm Pl}^2} \ , \epsilon = \pm 1 \ .$$

As long as $H^{-1} \ll r_c$, we have the standard Friedmann equation

$$H^2 = \frac{\rho}{3M_{\rm Pl}^2} \ .$$

But when H^{-1} becomes larger than r_c,

- $\epsilon = +1$

the final regime is $H \to H_\infty = 1/r_c$. ← acceleration

- $\epsilon = -1$

the final regime is

$$H^2 = \rho^2 \frac{r_c^2}{9M_{\rm Pl}^4} = \frac{\rho^2}{36M_5^6} \ .$$

This looks like a genuine modification of gravity.

However, define the scalar field

$$\pi(\mathbf{x},t) = -\frac{H}{4r_c}|\mathbf{x}|^2 + \frac{1}{4r_c}(\dot{H}/H+H)\,t^2 + bt + c$$

Then the generalized Friedmann equation can be recast into:

$$6\,\square\,\pi - 4r_c^{\,2}(\partial_\mu\partial_\nu\,\pi)^2 + 4r_c^{\,2}(\square\,\pi)^2 = -T^\mu{}_\mu = \rho - 3p$$

Hence this can be described by an effective scalar field (a brane-bending mode)

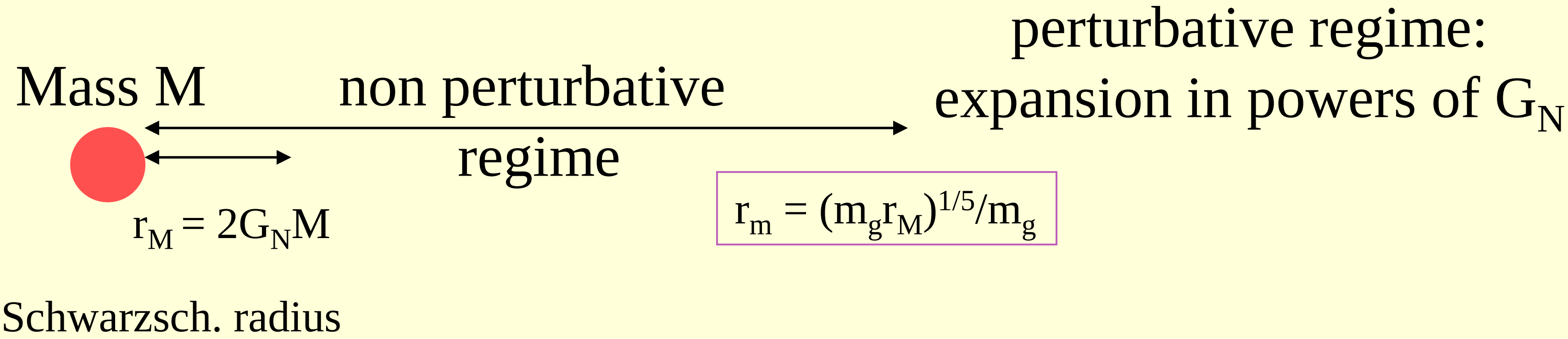
genearlized to the notion of galileon field

Nicolis, Rattazzi, Trincherini, Deffayet, Tsujikawa,, Trodden…….

Note two problems in this approach:

- one solved (Vainshtein mechanism)

$$\begin{array}{c} \text{massive graviton} \\ 5 \text{ d.o.f.} \end{array} \rightarrow \begin{array}{c} \text{massless graviton}\ _{2 \text{ d.o.f.}} \\ \text{massless graviphoton}\ _{2 \text{ d.o.f.}} \\ \text{real scalar}\ _{1 \text{ d.o.f.}} \\ \text{contributes to one} - \text{particle exchange} \end{array}$$



- one unsolved: presence of a ghost

More about the couplings of dark energy

Fundamental tests probe the most crucial part of dark energy models :
the coupling of dark energy to any form of matter

Why is it so important?

- crucial tests of the most « realistic » models of dark energy
- often connected to the « Why now? » question

Some examples…

Hung; Gu, Wang, Zhang, Fardon, Nelson, Weiner, Amendola, Baldi, Wetterich;…

Mass varying neutrino scenarios

Consider a neutrino with mass depending on scalar field ϕ: $m_\nu(\phi)$

Effective potential : $V_{eff}(\phi) = V(\phi) + n_\nu\, m_\nu(\phi)$

Dark energy is the coupled fluid neutrino-scalar: $\rho_{DE} = \rho_\phi + \rho_\nu(\phi)$

But neutrinos have a tendancy to cluster (extra force due to ϕ exchange)!

Coupled dark energy

Anderson, Carroll; Casas, Garcia-Bellido, Carroll; Farrar, Peebles; Amendola; Comelli, Pietroni, Riotto; …

φ-dependent mass for the dark matter particle χ: $M_\chi(\varphi) = M_0 \exp(-\lambda\varphi)$

If the scalar potential is $V(\varphi) = V_0 \exp(\beta\varphi)$, there is an attractor corresponding to

$$\rho_\varphi \sim \rho_\chi \sim M_\chi(\varphi)\, \underbrace{n_\chi}_{\sim a^{-3}} \sim a^{-3(1+W)} \qquad \text{with } W = -\lambda/(\lambda+\beta)$$

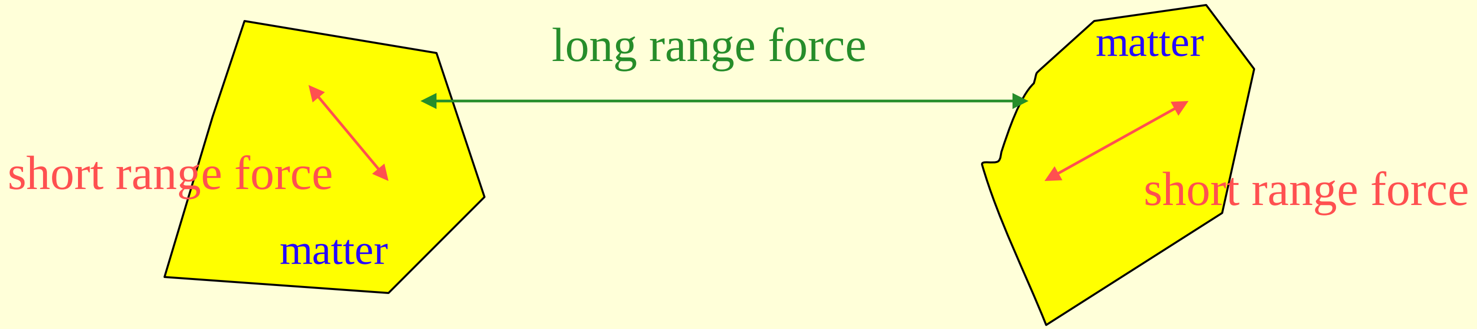
Chameleon dark energy

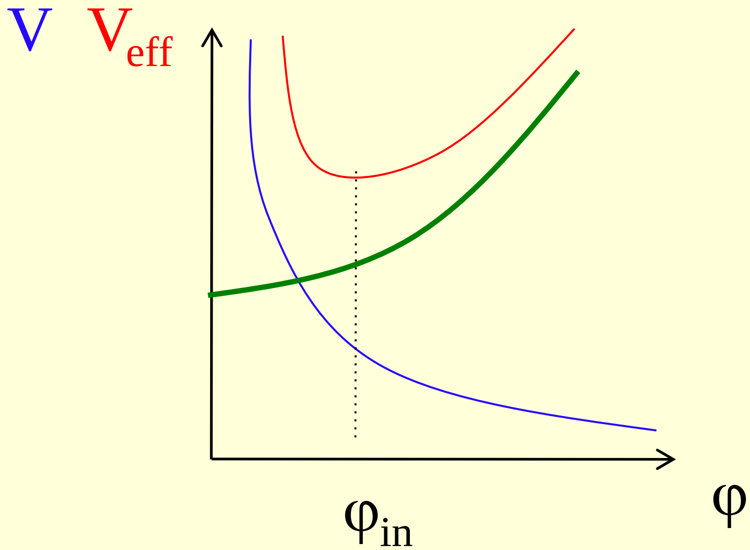
Khoury, Weltmann; Brax, van de Bruck, Davis, Khoury, Weltman;…

$$\boxed{V_{eff}(\phi) = V(\phi) + A(\phi)\, \rho_m}$$

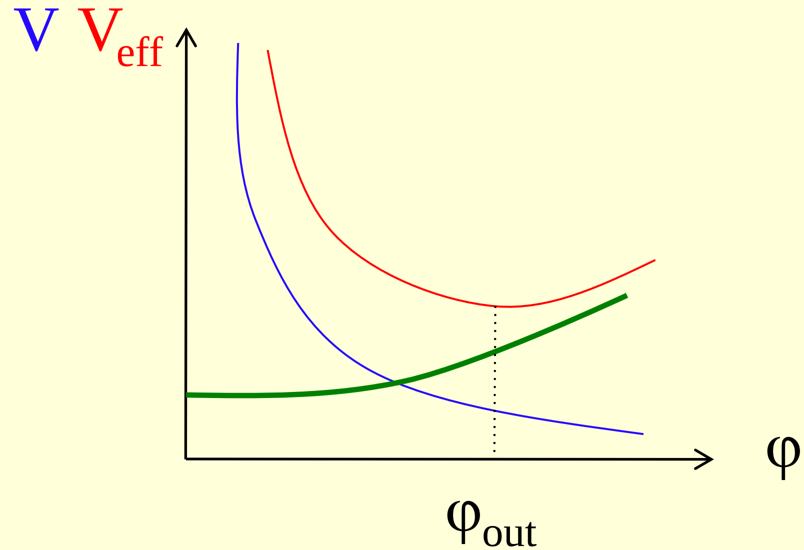
e.g. $$S = \int d^4x \sqrt{-g} \left[\frac{m_P^2}{2} R - g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + S_m \left(\psi, A^2(\phi) g_{\mu\nu} \right)$$

Then, possible to have a heavy enough scalar field ($m_\phi > 10^{-3}$ eV) in matter where constraints on the fifth force or equivalence principle apply, whereas it can be ultralight outside matter.



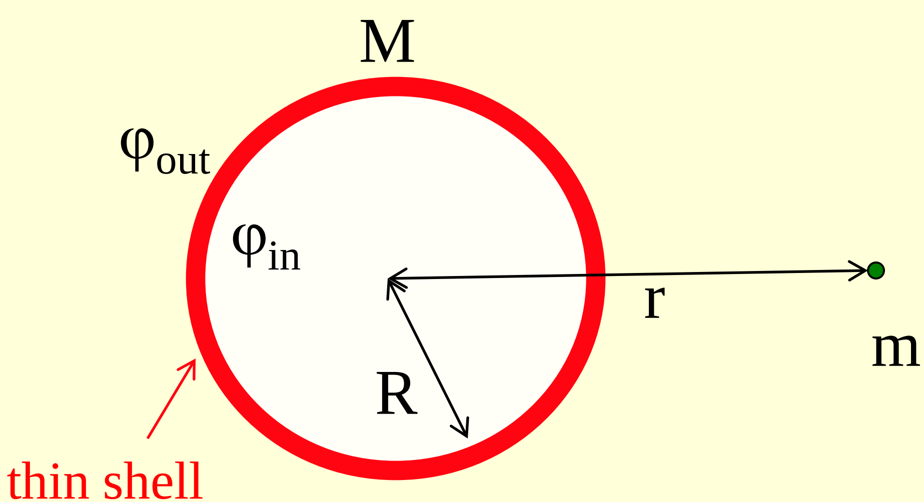


large ρ



small ρ

Thin shell effect : a tiny fraction of large objects (e.g. planets) is sensitive to the long range force. Not so for smaller objects: hence tests with satellites bring new constraints.



$$F = \frac{G_N M m}{r^2}\left[1 + \frac{\beta(\phi_{\rm out} - \phi_{\rm in})}{\Phi_N}\right]$$

$\ll 1$

$\Phi_N = GM/R$

$A(\varphi) = \exp(\beta\varphi)$

More on vacuum energy

Expanding our horizon?

Indeed, if we compute the vacuum energy, we obtain typically

$$\rho_\Lambda \sim m_P{}^4 \sim 10^{120}\,\rho_{observed}$$

$\hbar = c = 1$

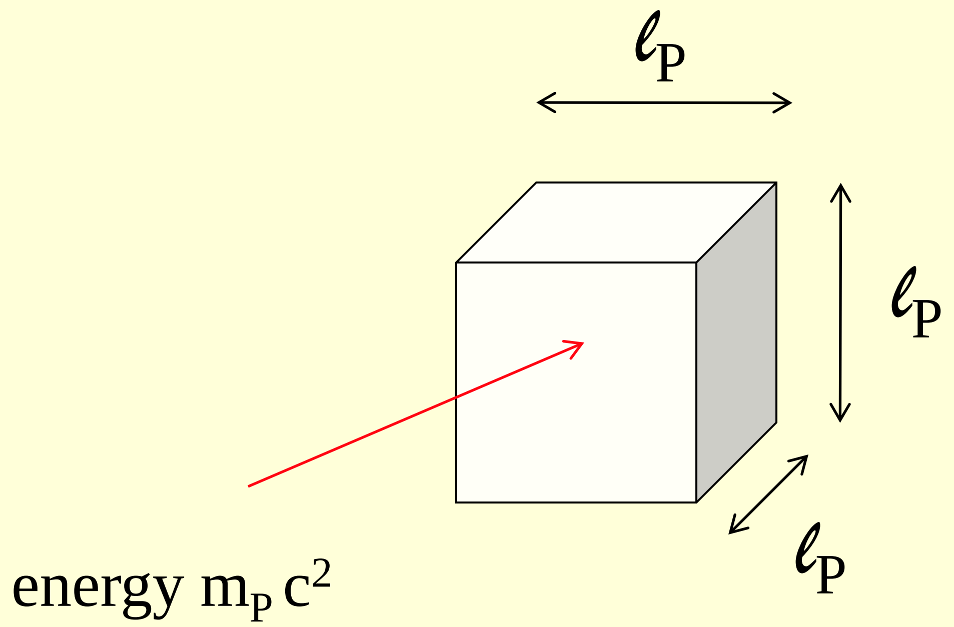
There should be a cancellation mechanism of most of the vacuum energy,

Or there is a selection principle for our Universe to have a much lower vacuum energy than expected.

string vacuum

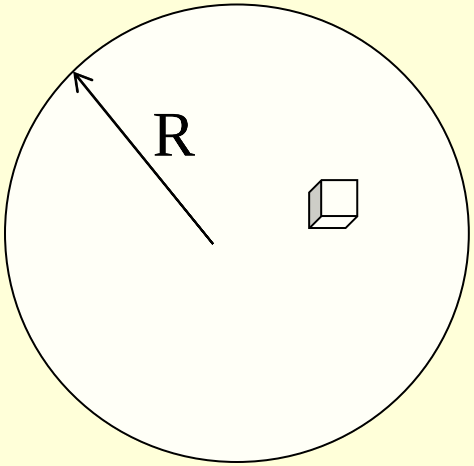
inflation

Note that the rationale behind the naive computation is as follows:



$$\rho = \frac{m_P\,c^2}{\ell_P{}^3} = m_P{}^4 \ \text{ in units } \hbar = c = 1$$

But consider a macroscopic region of size R



$$E = (4\pi R^3/3)\ \rho$$
$$= (4\pi/3)\ m_P\ (Rm_P)^3$$

But this object will undergo gravitational collapse unless

$$R > R_{schwarschild} = 2\ G_N\ E = E/(4\pi\ m_P^2) = (Rm_P)^3\ /\ 3m_P$$

i.e. $R < 1/m_P = \ell_P$

$R < R_{schwarschild} = 2\, G_N\, E$

In other words, gravitational collapse prevents us from storing in a region of macroscopic size R an energy larger than $R/2G_N$, i.e. an energy density larger than

$$\rho_{max} = E/(4\pi R^3/3) = \frac{3}{8\pi G_N R^2}$$

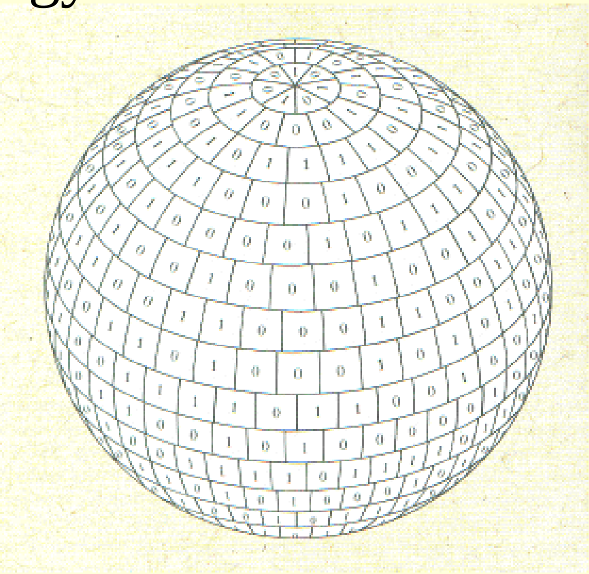
Apply this to the whole observable Universe ($R = H_0^{-1}$)

$$\rho < \frac{3\, H_0^2}{8\pi G_N} = \rho_c$$

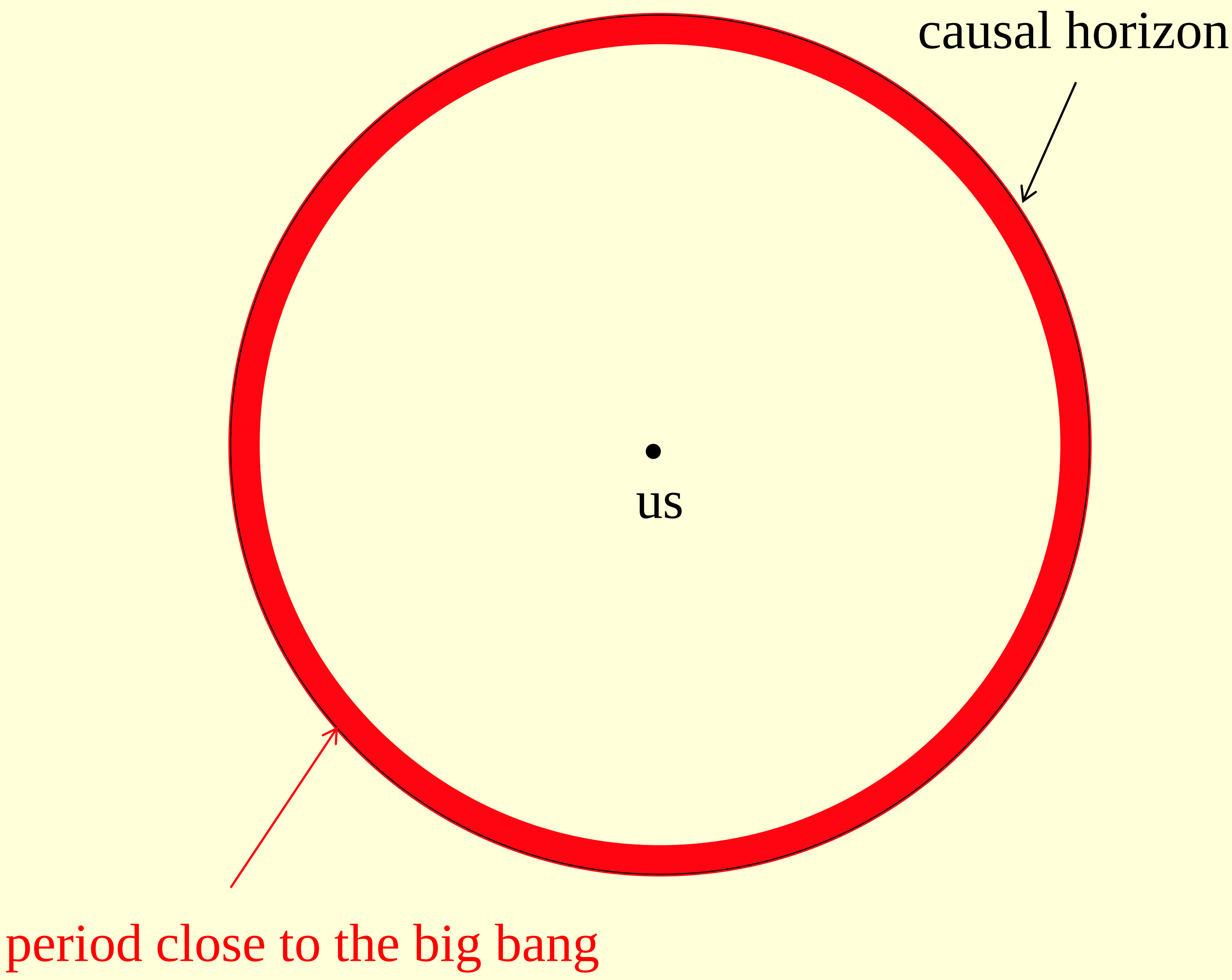
P.B. arXiv:1208.4645 [gr-qc]

Could our (causal) horizon have properties similar to the horizon of a black hole?

concept of holography in cosmology



't Hooft, Susskind, Bousso, Jacobson, Padmanabhan,…


causal horizon
us
period close to the big bang

How does the Universe look like at times close to the big bang?

Most probably, spacetime is a « long » distance notion, no longer valid at distances of order ℓ_P or times t_P.

Notion of emergent spacetime

But if spacetime is emergent, its symmetries should also be emergent!

e.g. one expects non-commutativity of the coordinates

$$[x_\mu, x_\nu] = \frac{1}{\Lambda_{LV}{}^2}\,\Theta_{\mu\nu}$$

$\Theta_{\mu\nu}$ is a constant tensor; hence Λ_{LV} is the scale of Lorentz violations.

But observational constraints on Lorentz invariance tend to give $\Lambda_{LV} \gg m_P$

Einstein's equivalence principle:

η

• Weak Equivalence Principle: universality of free fall

Nordtvedt

• Local Lorentz Invariance : independence on the velocity of the freely falling reference frame for nongravitational experiments

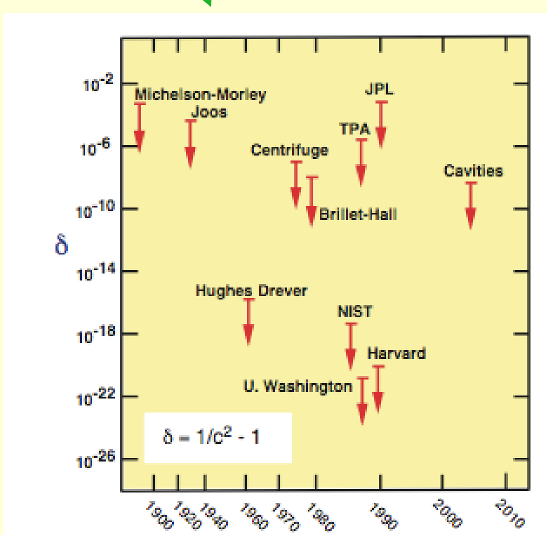
$c^2 \neq 1$

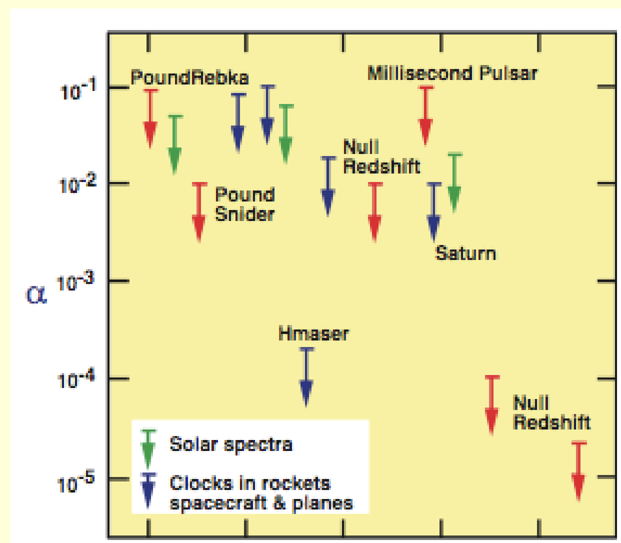
• Local Position Invariance : independence on the location in time and space where the nongravitational experiment is performed

nonconstancy of csts

grav. redshift

$\delta = |c^{-2}-1|$





$\Delta\nu/\nu=(1+\alpha)\Delta U$

Conclusions

The Universe is powered by gravity.

It may very well be that significant information will be obtained on vacuum/dark energy by testing the laws of gravity. If no violation is found, this is a very precious and constraining information.

In many instances, tests of the laws of gravity are the only way to go beyond the very efficient but very limited models that we have at hand (Standard Model of high energy physics or of cosmology). The XXIst century will be gravitational.

THE END