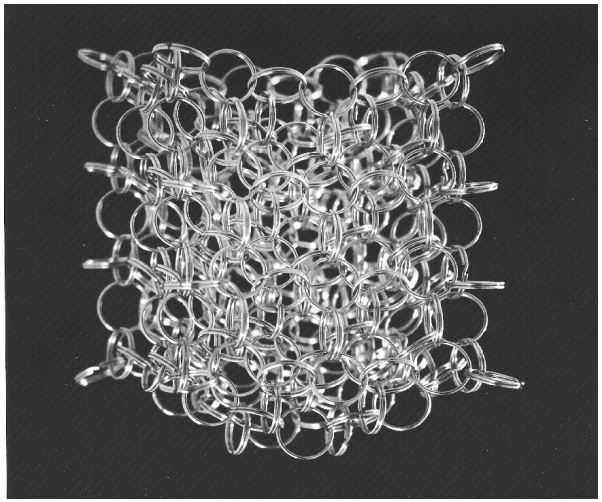
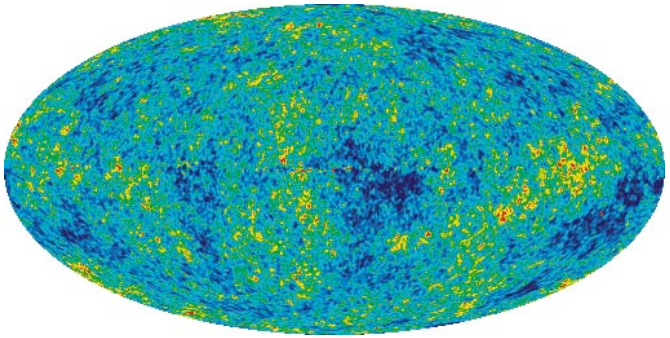
Observing Loop Quantum Cosmology with the CMB?

-J. Grain (IAS, Orsay)-
-J. Mielczarek (Cracaw University)-
-A. Barrau, A. Gorecki & T. Cailleteau (LPSC, Grenoble)-





Quantum gravity?
Theoretical question
Needs high energetic phenomena

Inflation in the very early Universe
High energetic phenomenon
Observational consequences

A bridge between tentative theory and observations

POLARIZED CMB ANISOTROPIES

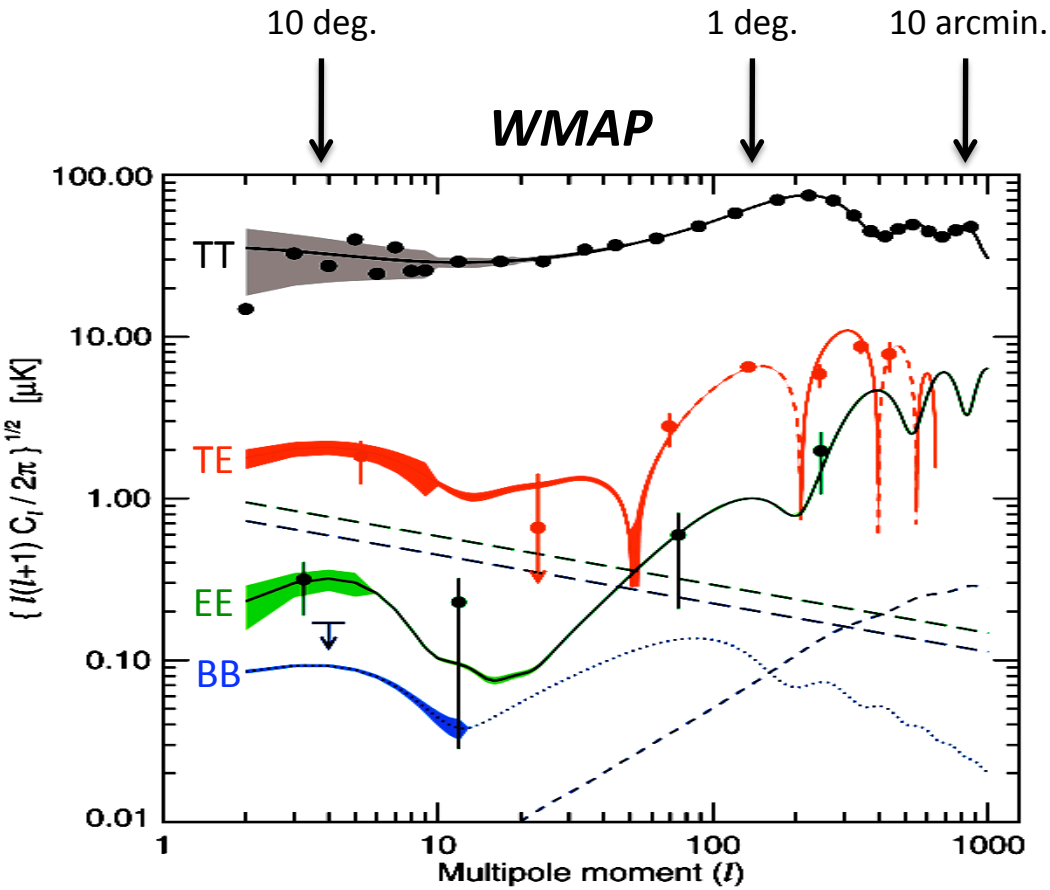
CMB plays a *keyrole* in setting cosmology in the ages of *precise science*
(geometry of the Universe, matter content, neutrinos total mass)

- **Statistics of its anisotropies**
  - Temperature **T** (scalar & tensor)
  - Polarization **E** (scalar & tensor)
  - Polarization **B** (tensor)

- **B-mode**

Open window on inflation/alternatives/new theories

Gravitational lensing



A RAPID SKETCH OF LOOP QUANTUM GRAVITY (LQG)

« Can we construct a quantum theory of spacetime based only on the experimentally well confirmed principles of general relativity and quantum mechanics ? » L. Smolin, hep-th/0408048

GR classically re-written with Ashtekar variables :

densitized triad $E^a_i \equiv \left|\det(e^b_j)\right|^{-1} e^a_i$

Ashtekar connection $A^i_a = \Gamma^i_a + \gamma K^i_a$

Quantization by use of holonomies and fluxes (background independence)

$$F(E) \propto \int_S \tau^i E^a_i n_a d^2 s$$

$$h(A) \propto \exp\left(\int_C \tau_i A^i_a u^a d\lambda \right)$$

- **The area, volume and length operators have a discrete sectrum**
- **The horizon entropy is completely explained.**
- **Singularities are eliminated.**
- **Ultraviolet divergences of QFT are not present.**
- **Loop quantum cosmology is on the way….**

LQG IN THE COSMOLOGICAL FRAMEWORK : BACKGROUND

FLRW-reduced formulation of LQG : Loop Quantum Cosmology (LQC)

$$ds^2 = dt^2 - a^2(t)\delta_{ij}dx^i dx^j$$

Background equation : classical results

$$H^2 = \frac{8\pi G}{3}\rho$$

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{\delta V}{\delta \Phi} = 0$$

SEE WORKS OF: ASHTEKAR, BOJOWALD, LEWANDOWSKI, PAWLOWSKI, SINGH, CORICHI, MIELCZAREK, VANDERSLOOT, ETC.

FOR A REVIEW, SEE: CALCAGNI & HOSSAIN, ADV. SCI. LETT. 2, 184 (2009)

Background equation : quantum corrected results

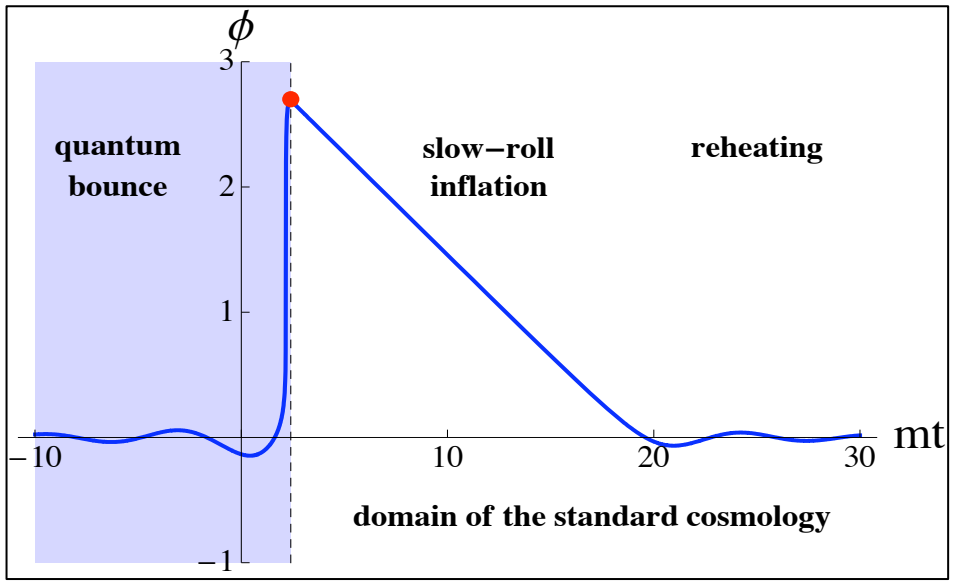
$$H^2 = \frac{8\pi G}{3}\rho \times \left[1 - \frac{\rho}{\rho_c}\right]$$

$$\ddot{\Phi} + 3H\dot{\Phi} + \frac{\delta V}{\delta \Phi} = 0$$

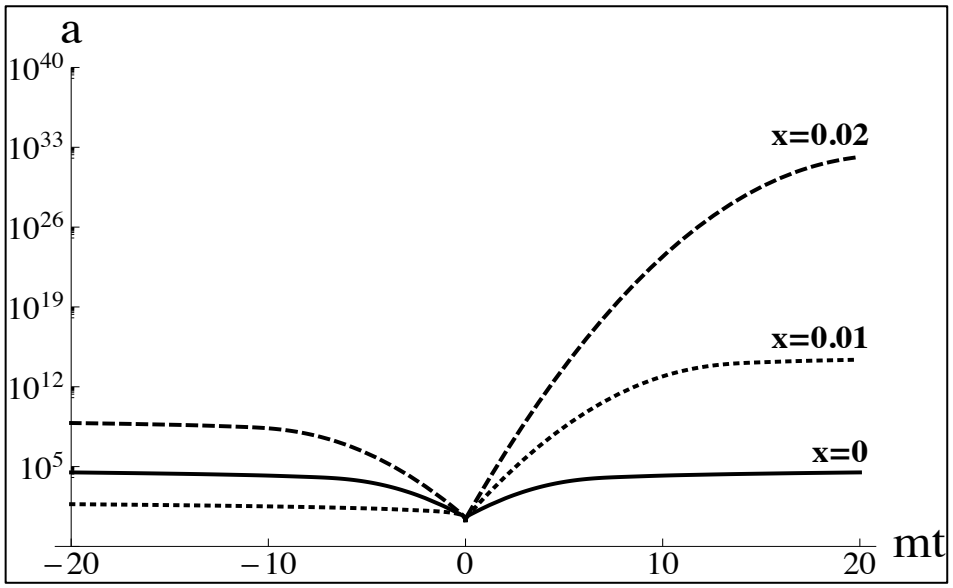
- ✓ Non-singular, bouncing Universe
- ✓ Inflation triggered by the pre-Big Bang

BACKGROUND WITH HOLONOMIES: {BOUNCING+INFLATIONNARY} UNIVERSE

Scalar field



Scale factor



✓ A sufficient amount of e-folds: $\rho_c = m_{Pl}^4$:

for $m_\Phi = 10^{-6} m_{Pl}$, $x = 0$: $\Phi_{\max} \approx 2.1 m_{Pl}$ and $N \approx 28$

for $m_\Phi = 10^{-3} m_{Pl}$, $x = 0.01$: $\Phi_{\max} \approx 3 m_{Pl}$ and $N \approx 60$

✓ A maximum amount of e-folds: $N_{\max} = \frac{4\pi\rho_c}{m_\Phi^2 m_{Pl}^2} \left(\approx 4\pi \frac{m_{Pl}^2}{m_\Phi^2} \text{ for } \rho_c \approx m_{Pl}^4 \right)$

J. MIELCZAREK, PHYS. REV. D 81 063593 (2010)

J. MIELCZAREK, T. CAILLETEAU, J. GRAIN & A. BARRAU, PHYS. REV. D 81 104049 (2010)

LQG IN THE COSMOLOGICAL FRAMEWORK : TENSOR PERTURBATIONS

Perturbed FLRW metric

$$ds^2 = a^2(\eta)\left(d\eta^2 - \left(\delta_{ij} + h_{ij}\right)dx^i dx^j\right)$$

Gravity waves equation : classical results

$$\frac{d^2\phi_k}{d\eta^2} + \left(k^2 - \frac{a''}{a}\right)\phi = 0 \quad \text{with} \quad \phi_k \equiv a(\eta)h_{ij}^{(k)}$$

Gravity waves equation : quantum corrected results

$$\frac{d^2\phi_k}{d\eta^2} + \left(k^2 - \frac{a''}{a} - V_{holo}(a,\gamma)\right)\phi_k = 0 \quad \text{with} \quad \phi_k \equiv a(\eta)h_{ij}^{(k)}$$

- **Modified background**
- **Modified «Dispersion relation»**

FOR THE EQUATION: BOJOWALD & HOSSAIN, PHYS. REV. D 77 023508 (2008)

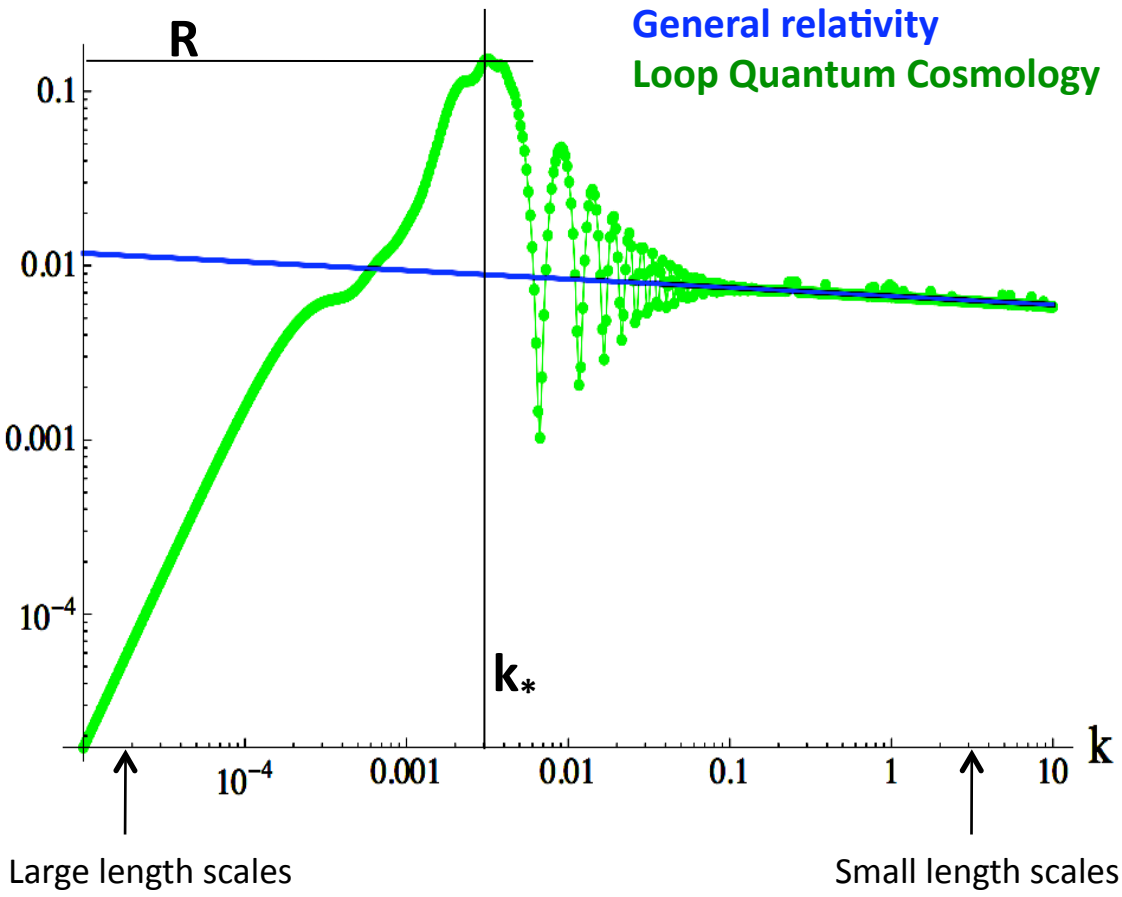
APPLIED TO INFLATION:

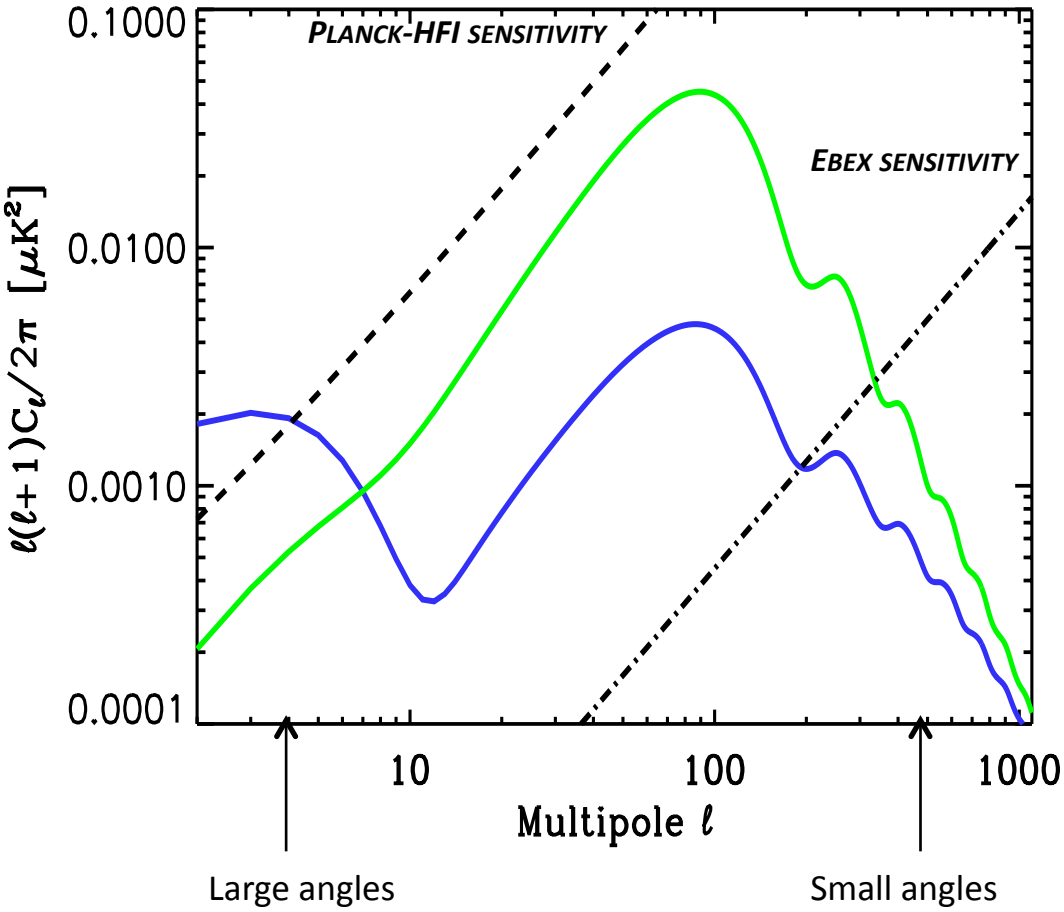
J. Grain, A. Barrau , Phys. Rev. Lett. **102** 081301 (2009)
J. Grain, A. Barrau & A. Gorecki, Phys. Rev. D **79** 084015 (2009)
J. Grain, T. Cailleteau, A. Barrau & A. Gorecki, Phys. Rev. D **81** 024040 (2010)

AND WORKS OF: MIELCZAREK, COPELAND, NUNES, MULRYNE, ETC.

TENSOR PERTURBATIONS : PRIMORDIAL POWER SPECTRA

Tensor perturbations power spectra



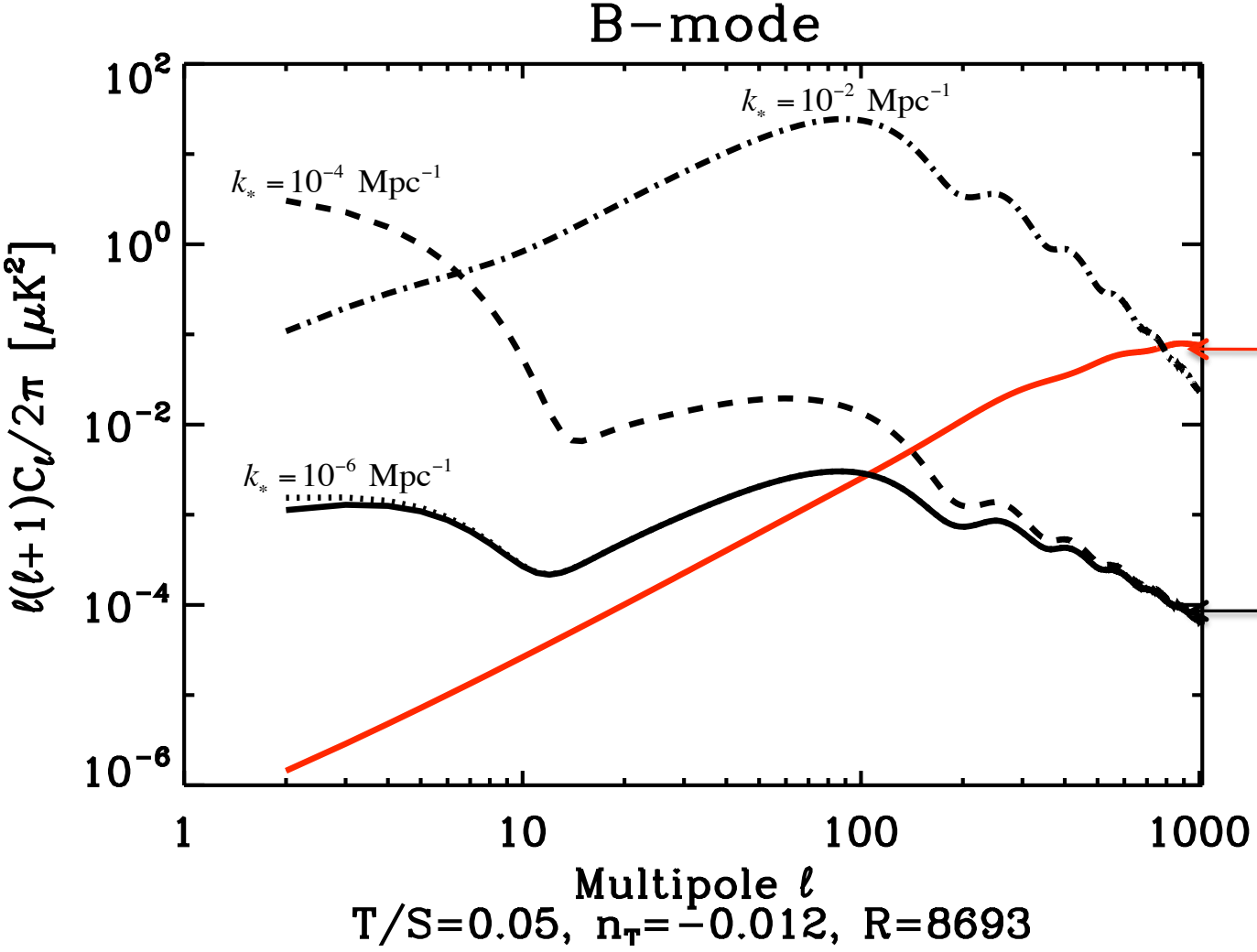


J. MIELCZAREK, T. CAILLETEAU, J. GRAIN & A. BARRAU, PHYS. REV. D 81 104049 (2010)

TENSOR PERTURBATIONS : IMPACT ON CMB B-MODES

***'Cosmological'* parameters for $P_T(k)$:**

(T/S, n_T)	Slow-roll inflation
(k_*, R)	Quantum bounce



Lensing-induced B-mode

Primordial B-mode

DETECTABILITY OF LQC USING B-MODES : PRELIMINARY RESULTS

Cosmological parameters :

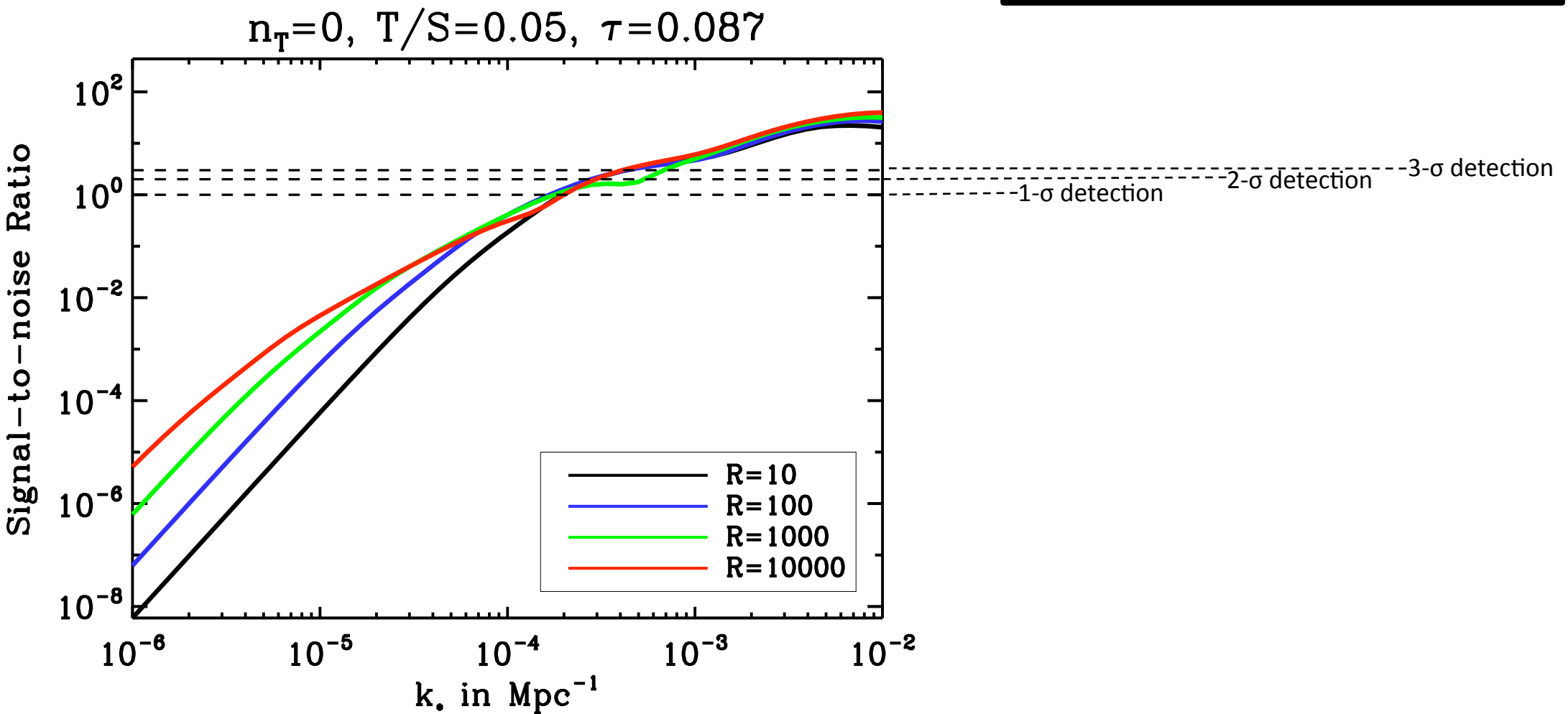
$(\Omega_b, \Omega_m, \Omega_\Lambda, A_S, n_s)$ WMAP 7-yrs fixed
(τ_{re})

***'Cosmological'* parameters for $P_T(k)$:**

$(T/S, n_T)$ Slow-roll inflation
(k_*, R) Quantum bounce

Strong prior :
Assumes scalar perturbations are not changed for intermediate and small scale

CMB-Pol/B-Pol :
- ✓ Sky coverage ~ 70 %
- ✓ Noise ~ 3 μK-arcmin.
- ✓ Resolution ~ 8 arcmin.



Still to be done…

- ✓ **Scalar perturbations : T and E in the CMB**
  - Inverse-volume
  - Holonomy

  Bojowald, Hossain, Kagan, Shankaranarayanan, Phys. Rev. D 79 043505 (2009)
  Wu, Ling, JCAP 026 05 (2010)

- ✓ **Improved dynamics at the bounce**
  - (Potential energy)>>(kinetic energy)

  Bojowald, Phys. Rev. Lett. 10 221301 (2008)

- ✓ **Beyond the effective description**
  - Perturbations at the bounce

  Bianchi, Rovelli, Vidotto, arXiv : 1003.3483
  Rovelli, Vidotto, arXiv : 0911.3097
  Rovelli, Vidotto, Class. Quantum Grav. 25 225024 (2008)

- ✓ **Comparing with other Bouncing Cosmology**
- ✓ **Realistic forecasts including T & E anisotropies**
  - Prior on scalar perturbations
- ✓ **New specific signatures**
  - Higher momentum of the CMB statistics : non-gaussianities
  - Quantum statistics

To conclude

Cosmology is now in the playground of *precision* science.

Quantum gravity (generally speaking) is in the playground of cosmology…