Lessons and challenges from PLANCK

Jinn-Ouk Gong

APCTP, Pohang 790-784, Korea

High1-2014 KIAS-NCTS Joint Workshop
High1 Resort, Korea
13rd February, 2014

Outline

Why inflation?

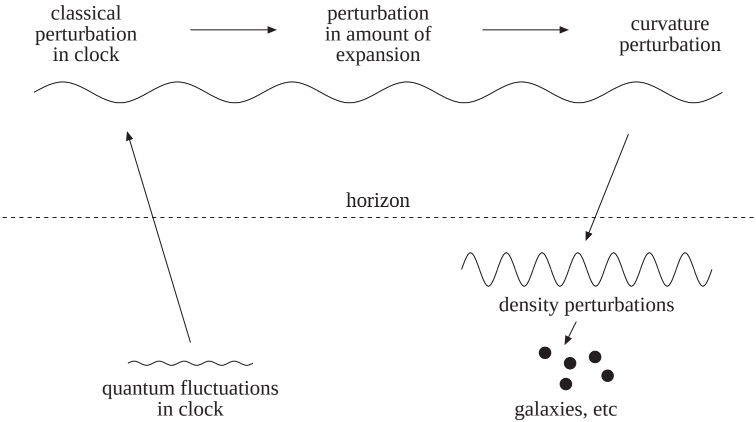
Hot big bang	Inflation
Horizon problem	Single causal patch
Flatness problem	Locally flat
Monopole problem	Diluted away
Initial perturbations	Quantum fluctuations

1. Initial conditions for hot big bang
2. A certain amount of expansion is required:

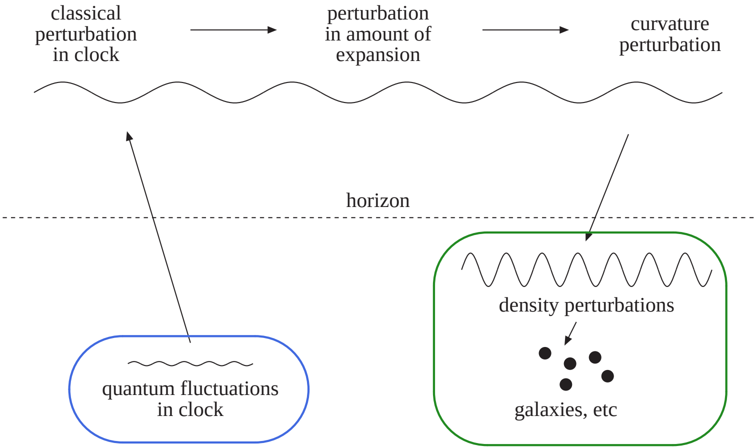
$$\text{Number of } e\text{-folds} : N = \log\left(\frac{a_e}{a_i}\right) \sim 60 \text{ is necessary}$$

3. Consistent with most recent observations
4. Typically driven by inflaton with a specific potential $V(\phi)$

Generation and evolution of perturbations



Generation and evolution of perturbations



Quantum mechanical signatures on cosmic scales!

Inside the horizon: generation of perturbation

Quantum fluctuations due to uncertainty principle

"Curvature perturbation": $\mathscr{R} = \underbrace{\varphi}_{\text{geometry}} - \frac{H}{\dot{\phi}_0}\underbrace{\delta\phi}_{\text{matter ("inflaton")}}$

$S_2 \sim \int d^4x\left[\dot{\mathscr{R}}^2 - (\nabla\mathscr{R})^2\right]$: equation of $\mathscr{R}$ = harmonic oscillator

$$\mathscr{R}_{\boldsymbol{k}} = a_{\boldsymbol{k}}\widehat{\mathscr{R}}_k + a_{\boldsymbol{k}}^\dagger\widehat{\mathscr{R}}_k^*\,, \quad \left[a_{\boldsymbol{k}}, a_{\boldsymbol{q}}^\dagger\right] = (2\pi)^3\delta^{(3)}(\boldsymbol{k}-\boldsymbol{q})\,, \quad a_{\boldsymbol{k}}|0\rangle = 0 \;\forall\; k$$

But $|0\rangle$ becomes different: ${}_{\text{before}}\langle 0|N_k(\equiv b_{\boldsymbol{k}}^\dagger b_{\boldsymbol{k}})|0\rangle_{\text{before}} \neq 0$
Observers see something out of nothing: creation of perturbation

Outside the horizon: conserved classical perturbation

"Classical" in the sense that the commutation relation vanishes

$$\left[\widehat{\mathscr{R}}(t,\boldsymbol{x}),\widehat{\pi}_{\mathscr{R}}(t,\boldsymbol{x})\right]=0$$

On very large scales ($k\to 0$) $\mathscr{R}_k \to$ constant

- Once generated, $\mathscr{R}$ is conserved outside the horizon
- Good variable to deal with
  1. (Analytically) trackable evolution: CMB structure is derived
  2. Good interpretation: spatial curvature in the comoving gauge
- Harmonic oscillator → free field → Gaussian statistics

Horizon reentry: observable structure

After inflation, horizon expands faster and $\mathscr{R}_k$ enters and evolves

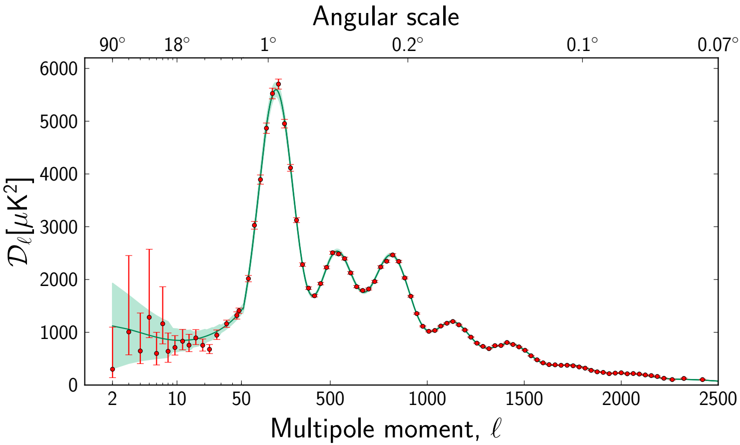
Gravitational potential $\Phi_k = \frac{3}{5}\mathscr{R}_k$ on large scales

Source of all the structure we observe today!

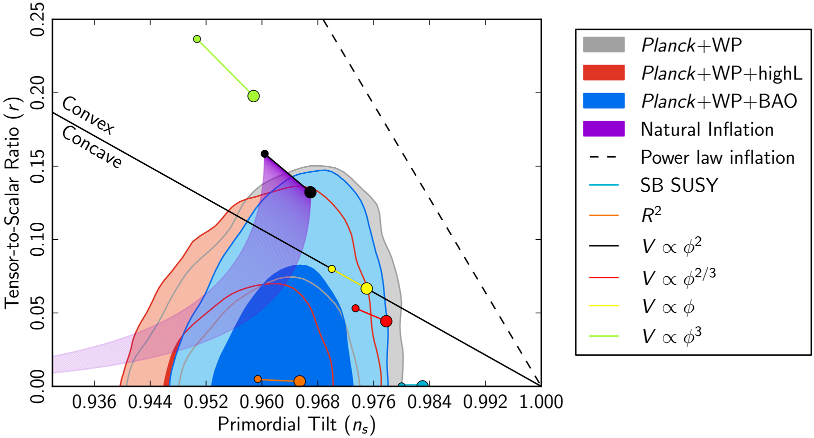
$$\text{CMB:} \quad \frac{\delta T}{T_0} = -\frac{1}{3}\Phi \qquad \text{(Sachs-Wolfe effect)}$$

$$\text{LSS:} \quad \frac{\delta\rho}{\rho_0} = \frac{2}{3}\frac{k^2 T(k)}{H_0^2\Omega_{m0}} W_R(k)\Phi \qquad \text{(Poisson equation)}$$

PLANCK 2013 data



PLANCK 2013 data



Fiducial model: single field slow-roll inflation

Lesson 1: nearly scale invariant power spectrum

$$\text{Power spectrum}: \langle \mathscr{R}_k \mathscr{R}_q \rangle \equiv (2\pi)^3 \delta^{(3)}(\boldsymbol{k}+\boldsymbol{q}) P_{\mathscr{R}}(k) = (2\pi)^3 \delta^{(3)}(\boldsymbol{k}+\boldsymbol{q}) \frac{2\pi^2}{k^3} \mathscr{P}_{\mathscr{R}}(k)$$

- Spectral index $n_{\mathscr{R}}$: $\mathscr{P}_{\mathscr{R}} \propto k^{n_{\mathscr{R}}-1}$
- Harrizon-Zeldovich spectrum: $n_{\mathscr{R}} = 1$ (const $\mathscr{P}_{\mathscr{R}}$ over all k)

For fiducial case,

- $n_{\mathscr{R}} = 1 - 6\epsilon + 2\eta$ with $\epsilon = \dfrac{m_{\rm Pl}^2}{2}\left(\dfrac{V'}{V}\right)^2$ and $\eta = m_{\rm Pl}^2 \dfrac{V''}{V}$
- If $V \sim \phi^n$, $n_{\mathscr{R}} \approx 1 - \dfrac{n/2+1}{N} \sim 0.95 - 0.97$

PLANCK found departure from HZ: $n_{\mathscr{R}} \approx 0.9635 \pm 0.0094$ at 6σ

Lesson 2: no gravity waves

Primordial gravitational waves

- Transverse ($h^i{}_{j,i} = 0$), traceless ($h^i{}_i = 0$) parts of spatial metric
- Directly related to the energy scale of inflation

$$\mathcal{P}_T = \frac{8}{m_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2 = \frac{2}{3\pi^2}\frac{\rho_{\rm inf}}{m_{\rm Pl}^4} \sim \frac{V}{m_{\rm Pl}^4}$$

Tensor-to-scalar ratio: $r \equiv \dfrac{\mathcal{P}_T}{\mathcal{P}_{\mathcal{R}}} = 16\epsilon$ for fiducial case

PLANCK found no gravity waves: $r_{0.002} < 0.11$ at $2\sigma \to \dfrac{V^{1/4}}{m_{\rm Pl}} < 0.008$

Lesson 3: almost perfect Gaussianity

$$\text{Bispectrum}: \left\langle \mathscr{R}_{k_1}\mathscr{R}_{k_2}\mathscr{R}_{k_3}\right\rangle \equiv (2\pi)^3\delta^{(3)}(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B_{\mathscr{R}}(k_1,k_2,k_3)$$

- Expanding $\mathscr{R}$ locally as $\mathscr{R} = \mathscr{R}_g + \frac{3}{5}f_{\rm NL}\mathscr{R}_g^2 + \cdots$ gives

$$B_{\mathscr{R}}(k_1,k_2,k_3) \underset{k_3\to 0}{\longrightarrow} \frac{12}{5}f_{\rm NL}P_{\mathscr{R}}(k_1)P_{\mathscr{R}}(k_3)$$

- If $\mathscr{R}$ is completely described by S_2, $f_{\rm NL}=0$

$$\text{For fiducial case,}\;\; f_{\rm NL} = \frac{5}{12}(1-n_{\mathscr{R}}) \ll 1$$

PLANCK found no nG: $f_{\rm NL} = 2.7\pm5.8$ at $2\sigma \to \mathscr{R}$ is 99.99% Gaussian

Challenge 1: nearly scale invariant power spectrum

η problem: a flat potential is difficult to obtain

- Nearly scale invariance requires $\epsilon, |\eta| \ll 1$
- When building inflation models based on particle physics...
  1. In supergravity,

$$V_F = \underbrace{e^{K/m_{\rm Pl}^2}}_{K=|\phi|^2+\cdots} V_0 \approx \left(1 + \frac{|\phi|^2}{m_{\rm Pl}^2}\right) V_0 \to \eta = 1 + m_{\rm Pl}^2 \frac{V_0''}{V_0} = \mathcal{O}(1)$$

  2. On general ground, a new scale $\Lambda(\lesssim m_{\rm Pl})$ gives

$$\Delta V = cV(\phi)\frac{\phi^2}{\Lambda^2} \to \Delta\eta = m_{\rm Pl}^2 \frac{\Delta V''}{V} \approx 2c\left(\frac{m_{\rm Pl}}{\Lambda}\right)^2 = \mathcal{O}(1)$$

- Difficult to keep flat potential against corrections

Challenge 2: no gravity waves

For $V \sim \phi^n$, $r = \dfrac{4n}{N} \gtrsim 0.1$

1. Power-law potential in a corner
2. Either hill-top inflation
   - Initially near a local maximum: how to start there?
   - Usually min > $m_{\rm Pl}$: Taylor expansion not trustable
3. ... or low-scale inflation
   - $V^{1/4}$ as low as TeV scale (N.B. $E_{\rm LHC} = 14$ TeV)
   - Possible signatures at the collider experiments?
4. ... or more perturbation from other sources
   - Curvaton, modulated reheating... multi-field effects
   - More complex

Challenge 3: almost perfect Gaussianity

$\langle\mathcal{RRR}\rangle$ requires cubic order action: using in-in formalism

$$\langle\hat{\mathcal{O}}(t)\rangle = \sum_{n=1}^{\infty} i^n \int_{t_{\rm in}}^{t} dt_n \int_{t_{\rm in}}^{t_n} dt_{n-1} \cdots \int_{t_{\rm in}}^{t_2} dt_1 \left\langle 0 \left| \left[H_{\rm int}(t_1), \left[H_{\rm int}(t_2), \cdots \left[H_{\rm int}(t_n), \hat{\mathcal{O}}(t)\right] \cdots \right]\right] \right| 0 \right\rangle$$

with $H = \underbrace{H_0}_{\text{quadratic}} + \underbrace{H_{\rm int}}_{\text{cubic and higher: } S_3 = -\int dt H_{\rm int}}$

$\mathcal{R}$ = free field, thus for non-zero $\langle\mathcal{RRR}\rangle$ we need at least S_3

$$\langle\mathcal{RRR}(t)\rangle = i\int_{t_{\rm in}}^{t} dt' \left\langle 0 \left| \left[\mathcal{RRR}(t'), \mathcal{RRR}(t)\right] \right| 0 \right\rangle + \cdots$$

1. Observable [$f_{\rm NL} \gtrsim \mathcal{O}(1)$] nG when interactions are appreciable
2. New model discriminator
3. Null detection: how to probe inflationary dynamics?

Theoretical side: structure of the theory

$\mathscr{R}$ in (quasi) de Sitter expansion is highly constrained

- Time translational symm: $t \to t+\pi$ gives $\mathscr{R} = H\pi$ (Cheung et al. 2008)
- Equation follows from the Noether current conservation: $\partial_\mu \mathscr{J}^\mu{}_\nu = 0$ with $\nu = 0$ (Chung & JG)

Effective field theory approach is possible

- All the possible terms compatible with symmetry
- Independent of the model detail (Cheung et al. 2008)
- Extendable to multi-field inflation (Achcarro et al. 2011...)
- Correlated correlation functions (Achucarro et al. 2013; JG, Schalm & Shiu 2014)

CMB anomalies

The CMB spectrum is not precisely as predicted

- Outliers: if from primordial origin
  1. Features in the potential: departure from usual SR (Starobinsky 1992...)
  2. Imprints of heavy physics: non-trivial c_s (Achucarro et al. 2011...)
- Power asymmetry: if modeled as a dipole modulation

$$\frac{\delta T}{T_0}(\hat{\boldsymbol{n}}) = \left.\frac{\delta T}{T_0}\right|_{\text{iso}} \left(1 + A\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{p}}\right) \qquad A = 0.072 \pm 0.022 \text{ and } \hat{\boldsymbol{p}} = (227, -27)$$

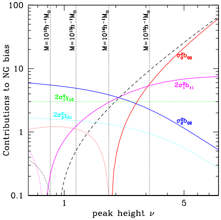
Possibly from large scale modulation and/or non-linearity (c.f. peak-background split)

Interesting windows to probe the physics of the early universe

Large scale structure perspectives

Not as precise as CMB but a number of ongoing/planned projects

- Scale dependent bias: galaxy distribution ≠ DM distribution
  k-dependence from non-linearity (Desjacques, JG & Riotto 2013)



- Compact mini haloes: DM halo that collapses at early times
  1. Constraints on small scale $\mathscr{P}_\mathscr{R}$ (Bringmann, Scott & Akrami 2012)
  2. Dependent on DM particle properties (Choi, JG & Shin)

New probes of physics relevant on large and small scales

Summary

1. Cosmology in the precision era: CMB and LSS
   - COBE, 2dFGRS in 90's, WMAP, SDSS in 00's
   - Planck, Euclid, BigBOSS, WFIRST... all in next 10 - 15 years
2. Primordial inflation and cosmological perturbations
   - Accelerated expansion: add-on to HBB for initial conditions
   - Driven by "inflaton(s)"
   - Quantum fluctuations → structure we observe today
3. PLANCK suggests both lessons and challenges
   - Not as simple as possible
   - More to come from polarization, galaxy surveys, lensing...
   - New probes of early universe physics are available

STAY TUNED!