Constraining inflation with CMB : Planck (and other) results and prospects

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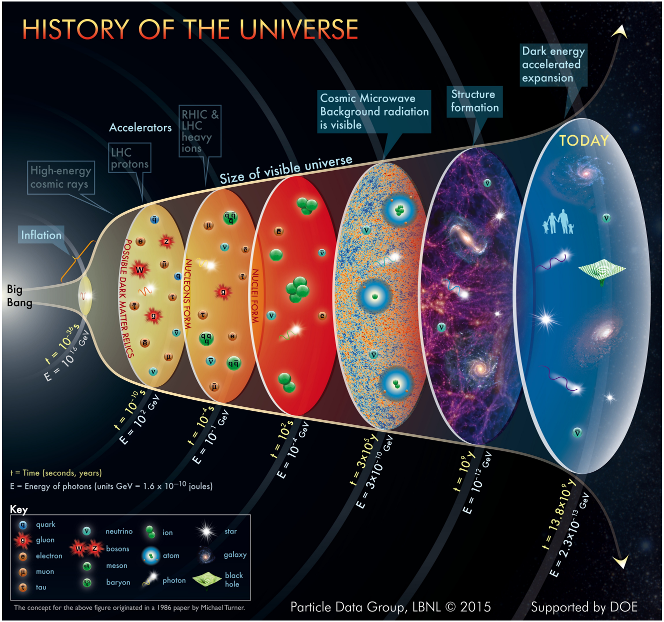


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

Cosmology basics

- general relativity description of an homogeneous+isotropic universe :
  - Geometry : FLRW metric (how to compute distances)

$$ds^2 = dt^2 - a(t)^2 \left[\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \right]$$

    $a(t)$: scale factor ; k =-1/0/+1 for open/flat/closed geometry
  - Evolution : Friedman equation (evolution of scale factor)

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2}$$

    $H(t) = \frac{\dot{a}}{a}$: Hubble parameter (expansion rate)
  - Critical density :

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

    = limit between open/flat/closed geometries ($\rho = \rho_c \Rightarrow k = 0$)

    relative densities : $\Omega_X = \rho_X / \rho_c$
- with Λ+ 5 params accounts (with standard components) for "late" history of the Universe (accelerated expansion)

Why inflation ?

Problems with classical Big-Bang model (Universe in expansion from initial space-time singularity) :

- "Flatness" : $|\Omega - 1| = (|k|/aH)^2$
  if present energy density $\Omega_0 \sim 0.1 \Rightarrow$ early on $\Omega \sim 1 - 1.10^{-6}$ (at matter-radiation equivalence)
- Horizon problem : CMB isotropic at 1/1000 but no causal relation between e.g. different hemispheres
- Relics predicted by many SM extensions but not observed
- Mechanism for structure generation ?
- ...

All these points solved in the inflationary paradigm

What's inflation ?

[A. Liddle arXiv:9901124]
Fast expansion in early universe
such that H^{-1}/a (comobile Hubble length)
decreases during inflation
Driven by out of equilibrium scalar field (inflaton, ϕ)
+ potential $V(\Phi)$ (many possibilities...)
Friedman equation :

$$H^2 = \frac{8\pi G}{3}\left[V(\phi) + 1/2\dot{\phi}^2\right]$$

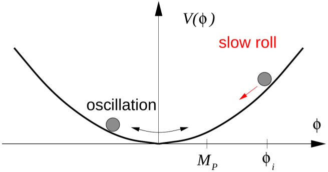
Equation of motion (conservation) :

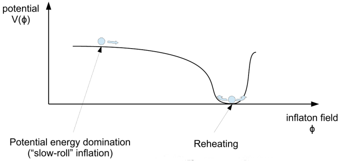
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

Generic assumptions ("slow roll") :

- $\varepsilon(\phi) = \frac{1}{16\pi G}\left(\frac{V'}{V}\right)^2 << 1$
- $\eta(\phi) = \frac{1}{8\pi G}\frac{V''}{V} << 1$

$\Rightarrow \Phi$ slowly varying and $a \sim e^t$





Structures generation

As H^{-1}/a decreases, quantum fluctuations of ϕ become classical (density field perturbations)
$\Rightarrow$ both scalar and tensor (grav. waves) energy density perturbation (analyzed in Fourier space, κ)

$A_s(\kappa) \sim \frac{(V)^{3/2}}{|V'|} \qquad (\kappa = aH)$ and

$A_t(\kappa) \sim \sqrt{V} \qquad (\kappa = aH)$

Final power spectra are gaussian and (almost) scale invariant:
$\delta_s(\kappa) \propto \kappa^{n_s - 1}$ and $\delta_t(\kappa) \propto \kappa^{n_t}$

within slow roll approximation :

$n_s = 1 - 6\varepsilon + 2\eta$

$n_t = -2\varepsilon$

And also

$$A_t/A_s == r \sim 4\pi\varepsilon(\propto V) \qquad (\kappa = 0.001)$$

$(A_t \neq 0 \Leftrightarrow r \neq 0)$

Inflation paradigm predictions

- $\sim$ flat space-time geometry
- adiabatic initial conditions (from energy density fluctuations)
- $\sim$ gaussian initial density perturbations
- Small deviation wrt scale invariance for density perturbation ($n_s < 1$)
- Small but non zero amount of grav. waves background ($r > 0$)

All these predictions may be (have been) tested using CMB anisotropies observations

Cosmological parameters from CMB (temperature) in a nutshell

- CMB temperature map → spherical harmonic decomposition ($\ell \sim 1/angle$):

$$\frac{\delta T}{T}(\theta,\phi) = \sum_\ell \sum_m a_{\ell m} Y_{\ell m}(\theta,\phi)$$

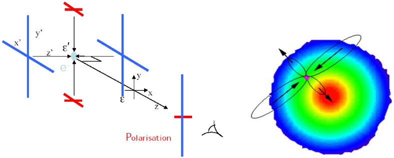
- general assumption ⇒ $a_{\ell m}$ are random variables (gaussian p.d.f.) ; $\langle a_{\ell m} \rangle_m = 0$; all information contained in their variance (=model prediction)

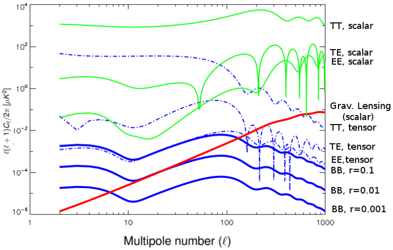
$$C_\ell^{TT} = \frac{1}{2\ell+1} \sum_m a_{\ell m} a^\dagger_{\ell m}$$

- only one realization is observable → intrinsic dispersion wrt model ("cosmic variance")
- Planck analysis : 100, 143 and 217 GHz maps cross spectra (suppression of instrumental noise) with masks (use other frequencies for foregrounds modelling/removal, special treatment for large scales)
- fit cosmological parameters (6 in ΛCDM) using a likelihood function (accounting for CMB, residual foregrounds, instrumental nuisance parameters ($\sim$ 20 parameters)

CMB polarization

- Mecanism : quadrupolar temperature anisotropies + Thomson scattering on e
- Origins :
  - primordial tensor modes (GW) → (parity odd) B modes ($\ell \lesssim 300$)
  - plasma dynamics (correlation with temp. anisotropies) → (parity even) E modes
  - late time re-ionisation ($z \sim 10$) → E modes ($\ell \lesssim 10$)
  - gravitational lensing transforms (part of) E into B modes
- very low amplitude signals ($\sim 10^{-2} - 10^{-4}$ temperature)
- amplitude of primordial B modes power spectrum measures $r = A_t/A_s$ ($\propto$ inflation energy scale)





M. Bucher Int.J.Mod.Phys. D24 (2015)

Measuring CMB polarisation

- measured quantities : intensity (I) for temperature and Stockes parameters (Q,U) for polarization
- ideal detector measuring only one polarization direction measures at orientation ψ :

$$m = I + Q\cos 2\psi + U\sin 2\psi$$

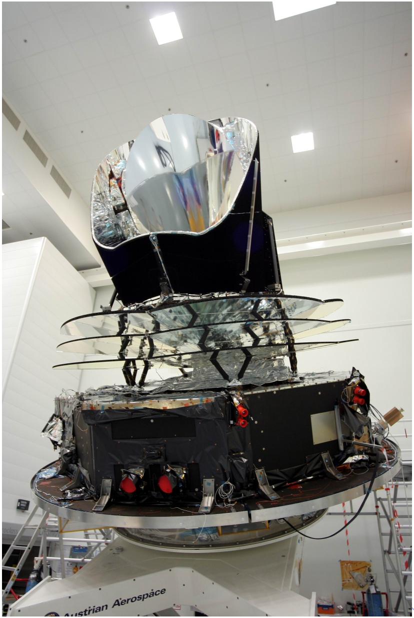
- to extract I,Q,U measurements one needs to combine several measurements : several detectors and/or different orientations
- ⇒ arrangement by orthogonal pairs, several frequencies
- examples
  - Planck (1992-2014) : O(10) detectors in pairs with ∼ orthogonal polarisation sensitivities + scan strategy to change orientation
  - Bicep :phase 2 (2010-2012) O(500) det. ; phase 3 (Keck array, 2011-2016) O(2500) detectors in pairs, rotate all focal plane
  - ...
- main systematics for Planck : I (∼ 3.3 mK CMB dipole !) to Q,U leakages (at large scales !) due to systematics : gains (needs better than 10^{-4} accuracy!), pointing, beam uncertainties, foregrounds
- main systematics for Bicep2 : foregrounds, pointing/beams

The Planck mission

ESA mission
project started 1992
launched on 15/05/2009 (with Herschel)
orbit around L2 (1.5Mkm)
guaranteed duration : 14 months (2 surveys)
extended till mid January 2012 (HFI) / mid 2013 (LFI)

1. Telescope (1.5m) - danish consortium
2. LFI (HEMTs 30-70GHz, 20 K, 15-30 arcmin beams) - consortium coordinated by Bologna Univ. (+US, Sp, It,...)
3. HFI (bolometers 100-857 GHz, 100 mK, 10-5 arcmin beam) - coordinated by Orsay+Paris ; institutes from Ca, CH, Ge, Fr, Irl, It, NL, Sp, US, UK,...

"early results" 2011
first CMB results 2013 (T only, 1/2 mission)
second release 2014/5 (T+P, full dataset)
2016 : low ℓ analysis + reionisation



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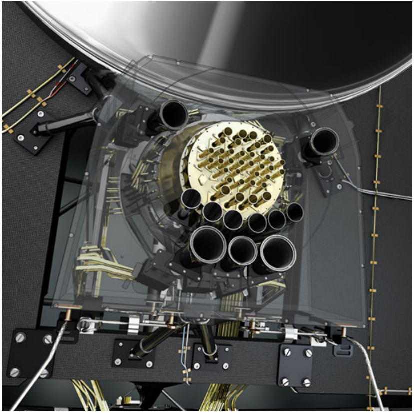
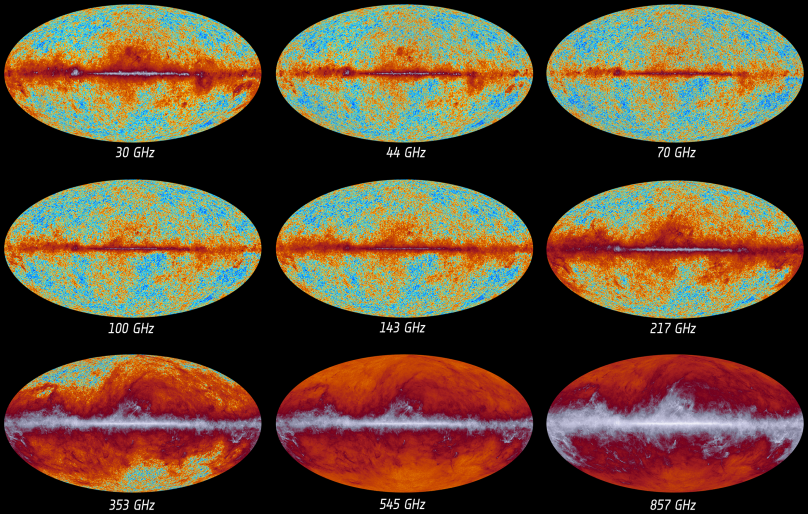
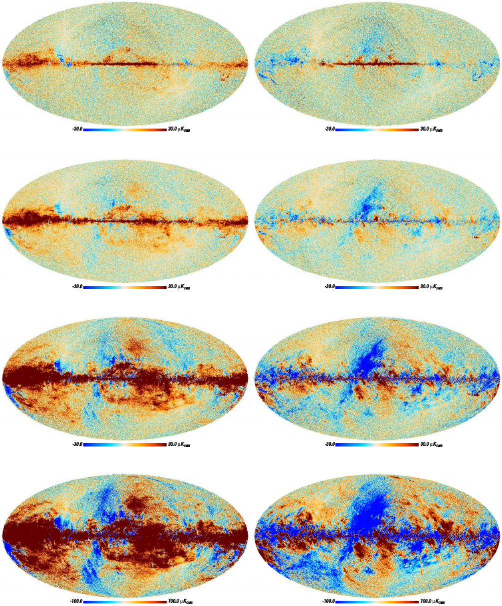


The sky as seen by Planck

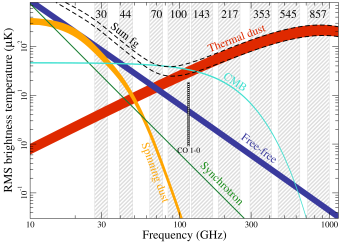


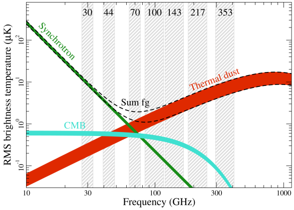
HFI polarisation maps (100 to 353 GHz)



Planck signals

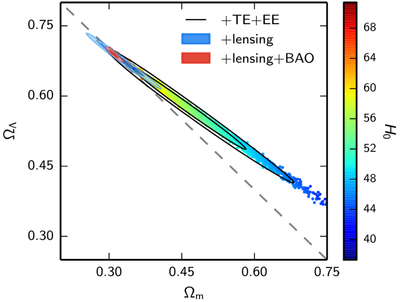
- primary objective(s) : CMB anisotropies (T and polarization) photon noise limited for T and E modes
- many astrophysical components observed together with CMB :
  - Solar system : planets, asteroids, zodiacal light ...
  - Galactic : dust, synchrotron, free-free
  - extragalactic : clusters (SZ), CIB, radio sources,...
- different frequency dependence ⇒ component separation (CMB map : check for gaussiannity, isotropy, statistics,...)
- first full sky maps at 200-800 GHz

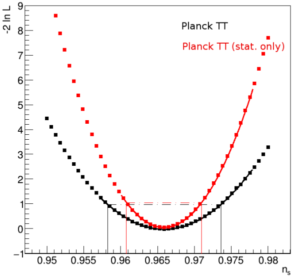




Initial conditions & geometry after Planck

- No evidence for non gaussianities ⇒ low 3-point correlation function amplitude limits e.g. $f_{NL}^{local} = 0.8 \pm 5.0$ [Planck 2015 results. XVII, arXiv:1502.01592]
- Excellent agreement with adiabatic initial conditions [Planck 2015 results. XX, arXiv:1502.02114]
- ΛCDM parameters fits ⇒ primordial spectrum index $n_s = 0.965 \pm .006$ [Planck 2015 results. XVII, arXiv:1502.01589]
- ∼ flat geometry [Planck 2015 results. XVII, arXiv:1502.01589]





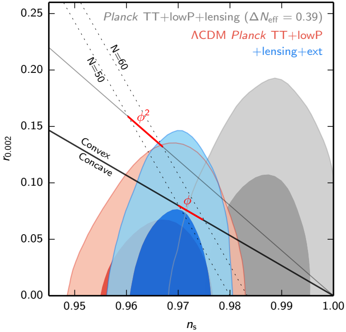
Planck intermediate results. XVI A&A 566, A54 (2014)

tools available at camel.in2p3.fr

Inflation paradigm predictions after Planck

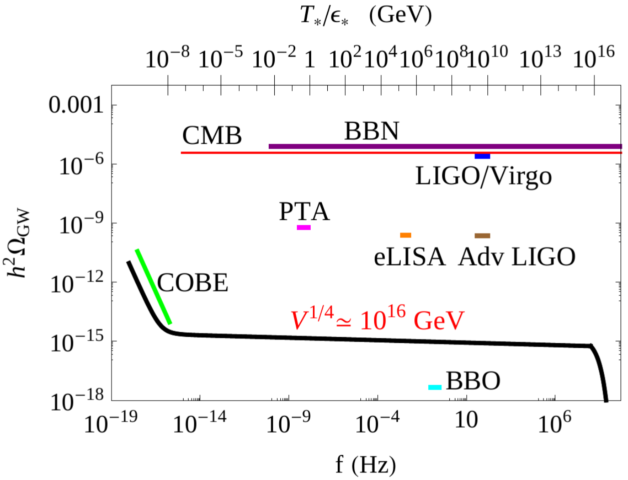
- $\sim$ flat space-time geometry ✓
- adiabatic initial conditions (from energy density fluctuations) ✓
- $\sim$ gaussian initial density perturbations ✓
- Small deviation wrt scale invariance for density perturbation ($n_s < 1$) ✓
- Small but non zero amount of GW background ($r > 0$)

- Direct limit with BB spectra ($50 < \ell < 130$):
  $r < 0.265 (95\% C.L.)$ [Hillipop team - LAL ; Planck 2015 results. XVII, arXiv:1502.01592]
- Fit for ΛCDM parameters $+r$ with TT : $r < 0.11 (95\% C.L.)$



Indirect constraints from the GW energy density

[C. Caprini, arXiv:1501.01174]

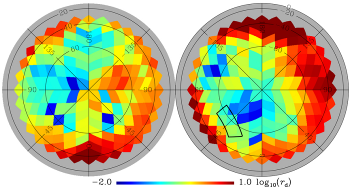


CMB → constraints on GW energy density [S. Henrot-Versillé et al 2015 Class. Quantum Grav. 32 045003]

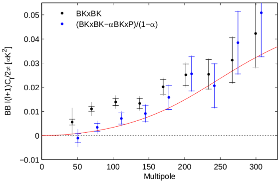
Planck & Bicep2/Keck (2015)

B modes from dust (Planck 353 GHz)

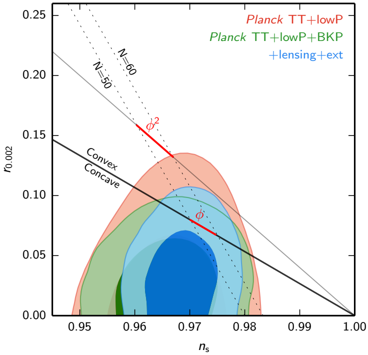
[Planck coll. A& A 586, A133 (2016)]



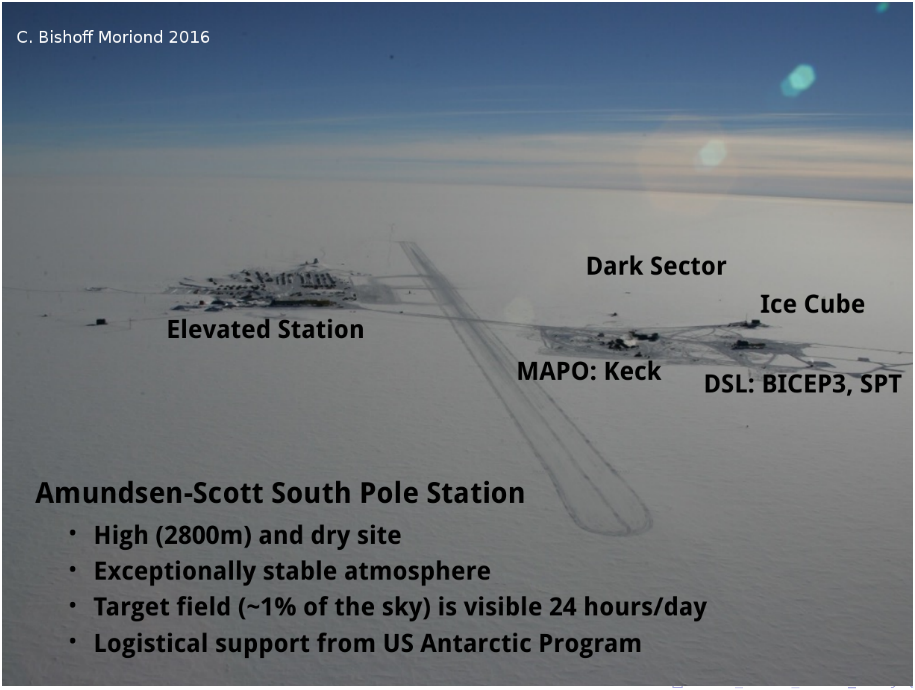
[Bicep& Planck , Phys. Rev. Lett. 114, 101301 (2015)]

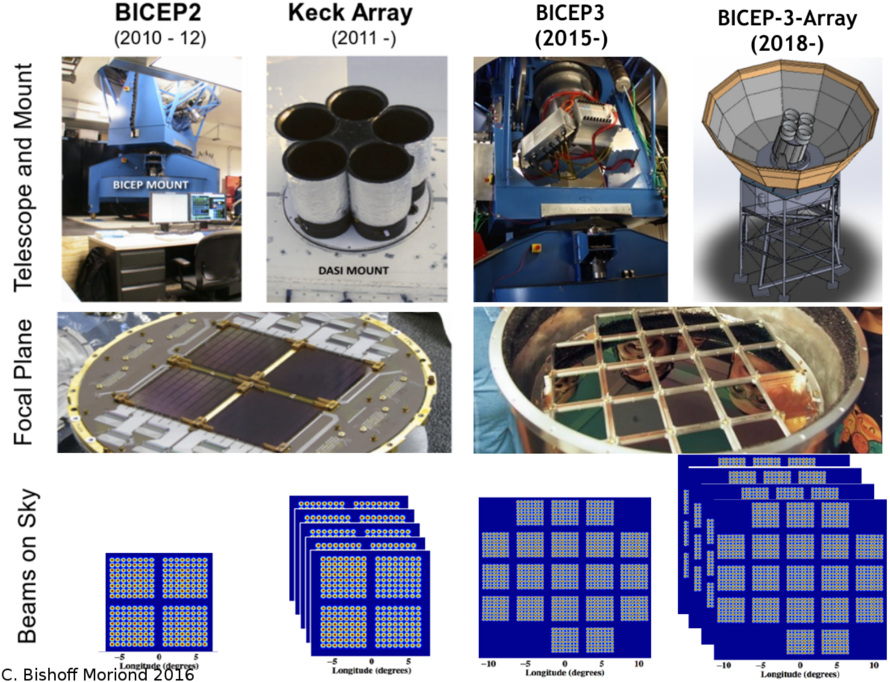


Constraints on r with B2K and Planck TT : $r < 0.09 (95\% C.L.)$



[Planck 2015 results. XVII, arXiv:1502.01589]

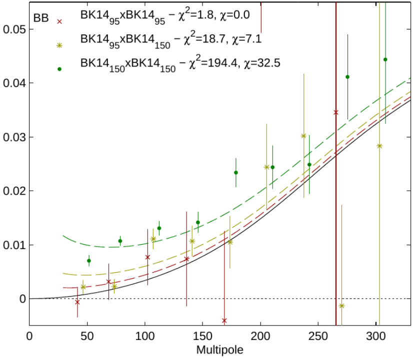

C. Bishoff Moriond 2016
Dark Sector
Ice Cube
Elevated Station
MAPO: Keck
DSL: BICEP3, SPT
Amundsen-Scott South Pole Station
• High (2800m) and dry site
• Exceptionally stable atmosphere
• Target field (~1% of the sky) is visible 24 hours/day
• Logistical support from US Antarctic Program



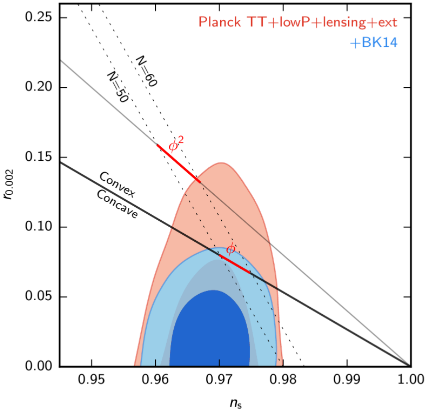
C. Bishoff Moriond 2016

Latest BICEP3 results

With BICEP3 1st year 95 GHz data [arXiv:1510.09217]



Constraints on r : $r < 0.07 (95\% C.L.)$

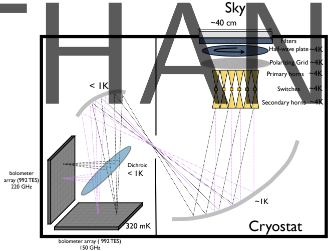


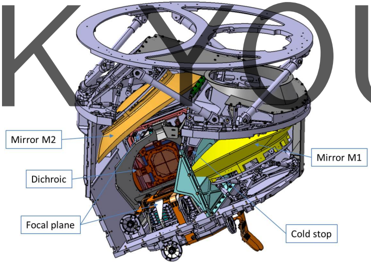
Conclusions and outlook

- Several predictions of the inflation scenario have been confirmed by CMB properties as observed by Planck (and others)
- The tensor-to-scalar ratio is the last one : the hunt continues !
- Control of systematics and foreground are essential in this game
- Current best results from BICEP & Planck (dust template!) : $r < 0.7 (95\% C.L.)$
- At this level, some models ($V(\phi) \propto \phi^2$) seem ruled out (but many are alive !)
- in addition to BICEP(3), many “stage 3” US projects are coming on line “soon” (advACT, SPTpol, Polarbear) + QUBIC (France/Italy), aiming at $r \sim 10^{-2}$ sensitivities ($\sim 2018 - 2020$)
- plus balloon projects (EBEX, Bside, SPIDER, PIPER) ...
- paving the way to the next ground based (“stage 4”) project(s) and/or space mission(s ?) (Litebird, Pixie, Core,..) ?

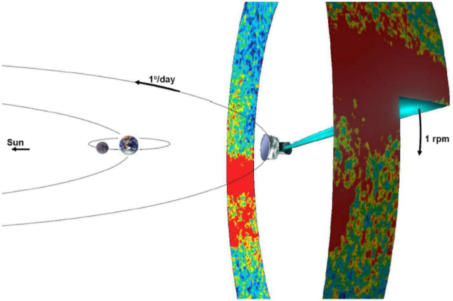
QUBIC views

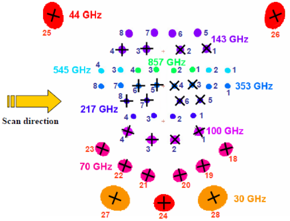
THANK YOU





Planck at L2





$\sim$ 8x8 degree field

Continuous observations (7 months → all sky)
redundancies on different timescales (systematics)

2015/6 improvements : full mission T+P data, better control of instrumental systematics, absolute & more accurate calibration