# Probing the Earliest Stage of Our Universe

Kavli IPMU – RIKEN iTHES – Osaka TSRP Symposium
"Frontiers of Theoretical Science – MATTER, LIFE, and COSMOS"

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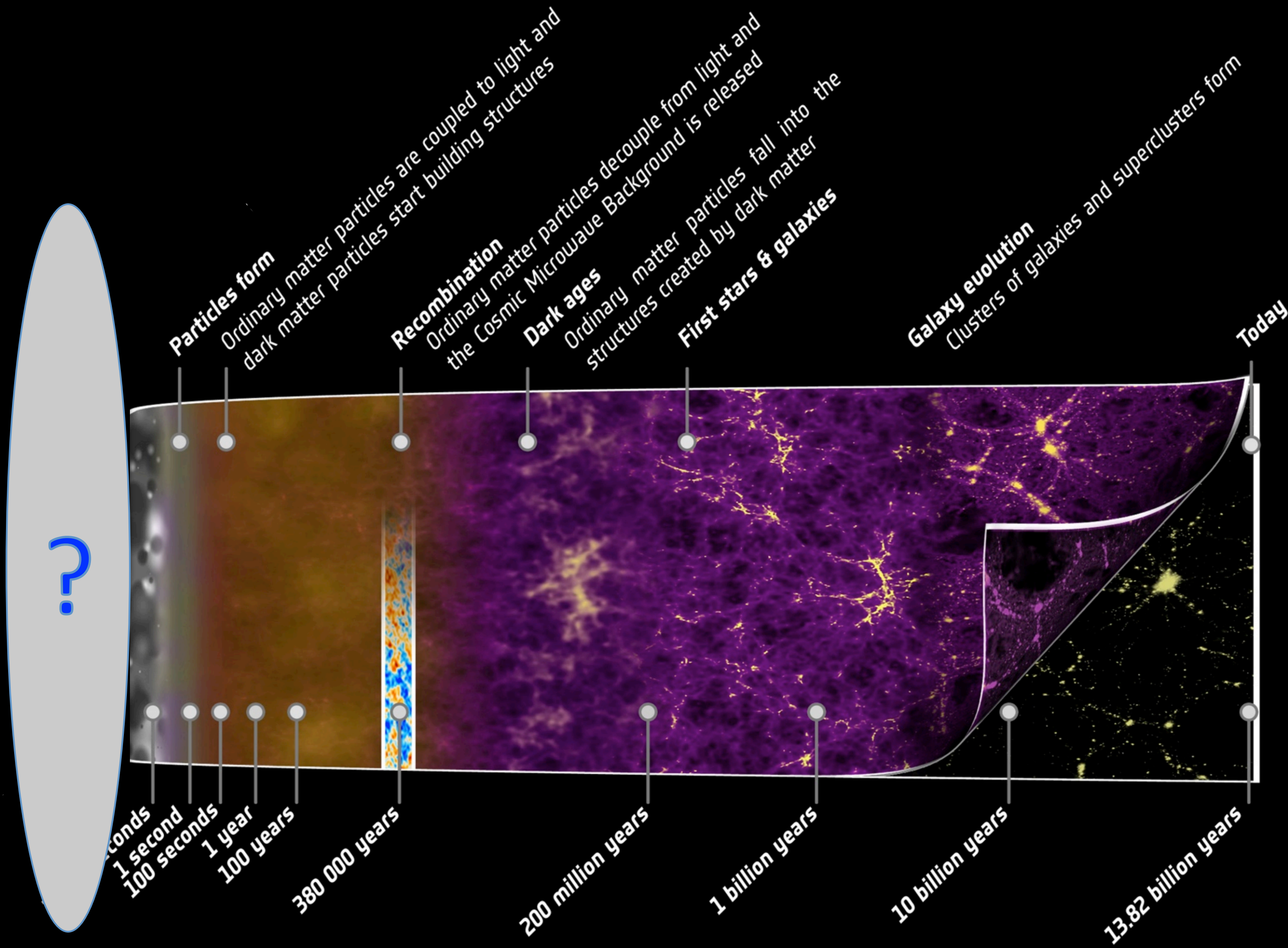
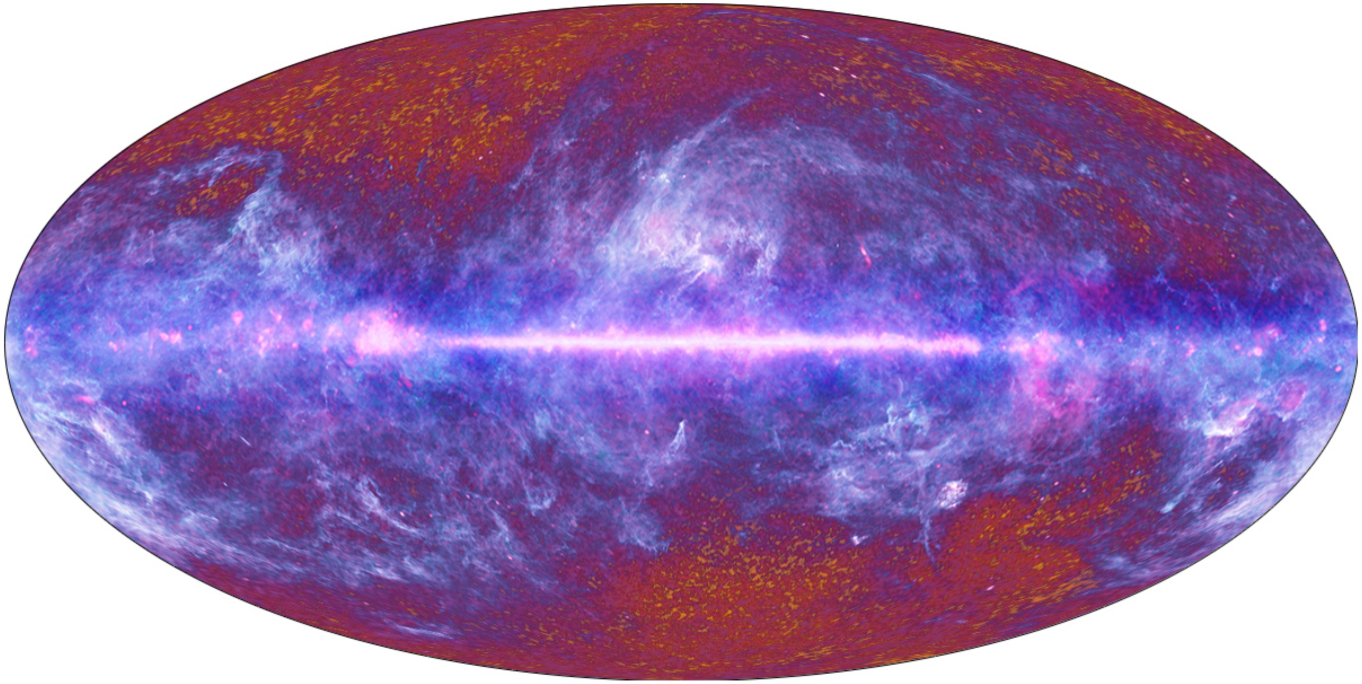
# Hot Big Bang Cosmology

- Essentially correct description of the thermal history of the universe



# CMB = Cosmic Microwave Background

**discovered by Penzias & Wilson (1965)**

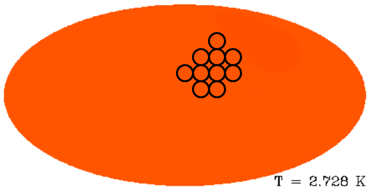


Planck/COBE collaboration

- What remains after foreground subtraction (stars, galaxies, etc)
- Photon (black-body) temperature: $T \simeq 2.73K$
- Small fluctuations: $\frac{\delta T}{T} \sim 10^{-5}$

# Puzzles in Hot BB cosmology

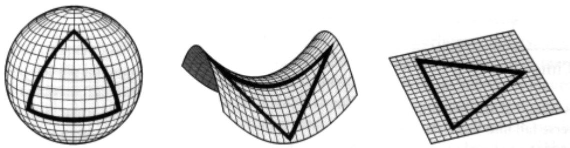
① Horizon (homogeneity) problem




- ❖Current observable universe

  ≈ $10^5$ causally disconnected regions at recombination

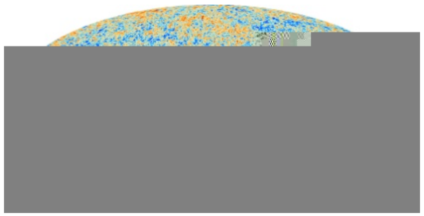
② Flatness problem



- ❖Very tiny spatial curvature

③ Unwanted relics problem

- ❖~One monopole per nucleon



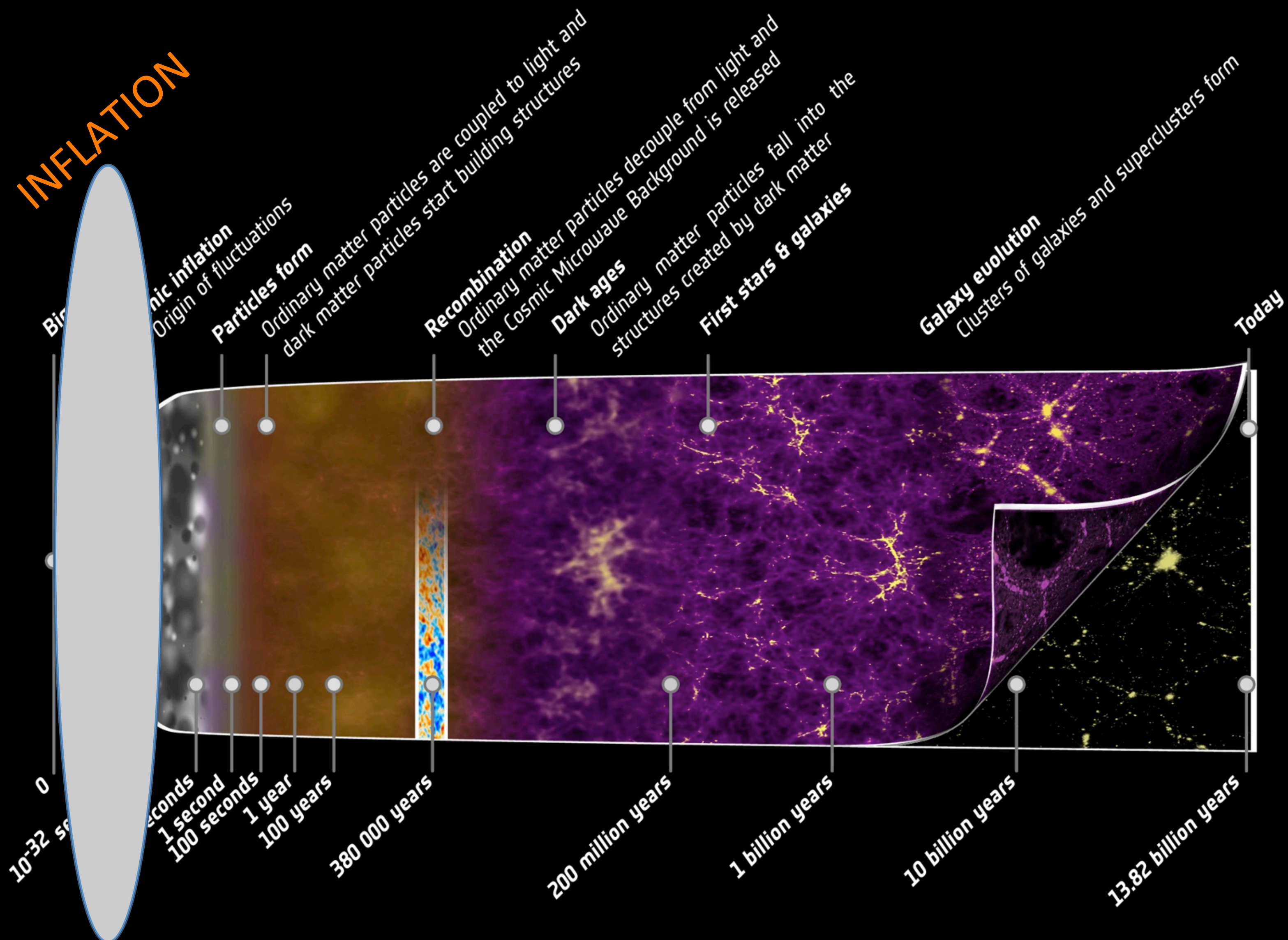
④ **Seeds of inhomogeneity**

- ❖CMB fluctuations, large-scale structure

# Inflationary cosmology

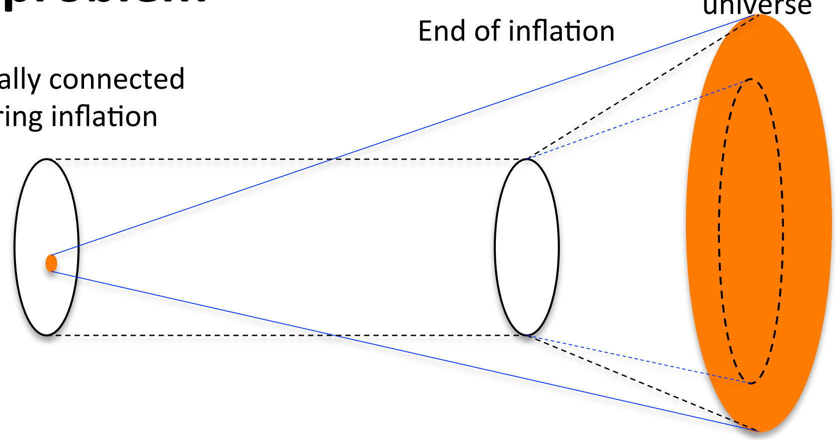
Guth 1981

= (quasi-)exponential expansion at the earliest stage of the universe



# *Inflation solves the puzzles*

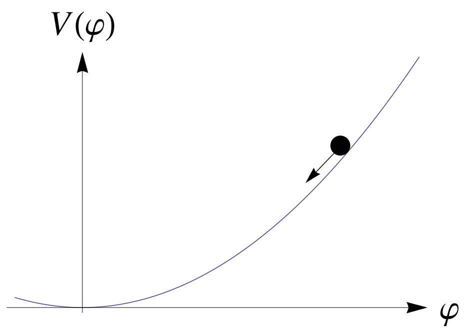
- Causally connected scales are stretched during inflation to a size larger than the horizon of the current universe
  - – solves **horizon problem**




- Spatial curvature & topological defects are diluted away by a rapid expansion
  - – solves **flatness** & **unwanted relics** problem

**Introduce a "field"** (encodes value(s) at each point)

- Needs to end inflation
- Only need a scalar field $\varphi$ (encodes one value at each point in spacetime)
- Inflaton $\varphi$ is the *clock*
- Inflation = slow roll of $\varphi$




**Inflaton fluctuates around its spatial average** $\langle\varphi\rangle = \phi(t)$

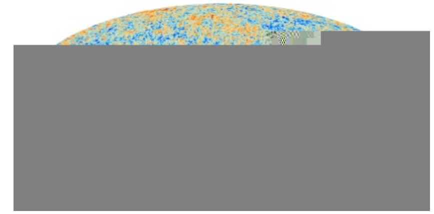
- E.g. quantum fluctuations
- Expansion stretches microscopic fluc. to macroscopic
- **Seeds of small inhomogeneities**
  - CMB fluctuations, large-scale structure of the universe

Horizon

Flatness Relics

Exponential expansion

$\phi(t)$



Inhomogeneities

$\delta\varphi(t, \vec{x})$

Statistical nature of inhomogeneities ⟷ **correlation functions**

**n-point correlation:** $\langle \delta\varphi(\vec{x}_1)\delta\varphi(\vec{x}_2)\cdots\delta\varphi(\vec{x}_n)\rangle$

Statistical average

**Qualitative features of inhomogeneities are related to spacetime symmetries during inflation**

**(at least to some extent)**

## Flat inflaton potential $V(\varphi)$ (approx. shift symmetry $\varphi \to \varphi + const.$ )

- **Small interactions = spectrum is almost Gaussian**
- Observation: deviation from Gaussian $f_{NL}^{primordial} \sim 0$ Planck 2013
- Statistical info. is encoded mostly in 2-point correlation $\langle \delta\varphi(\vec{x}_1)\delta\varphi(\vec{x}_2) \rangle$

## Homogeneity = symmetry under spatial translation

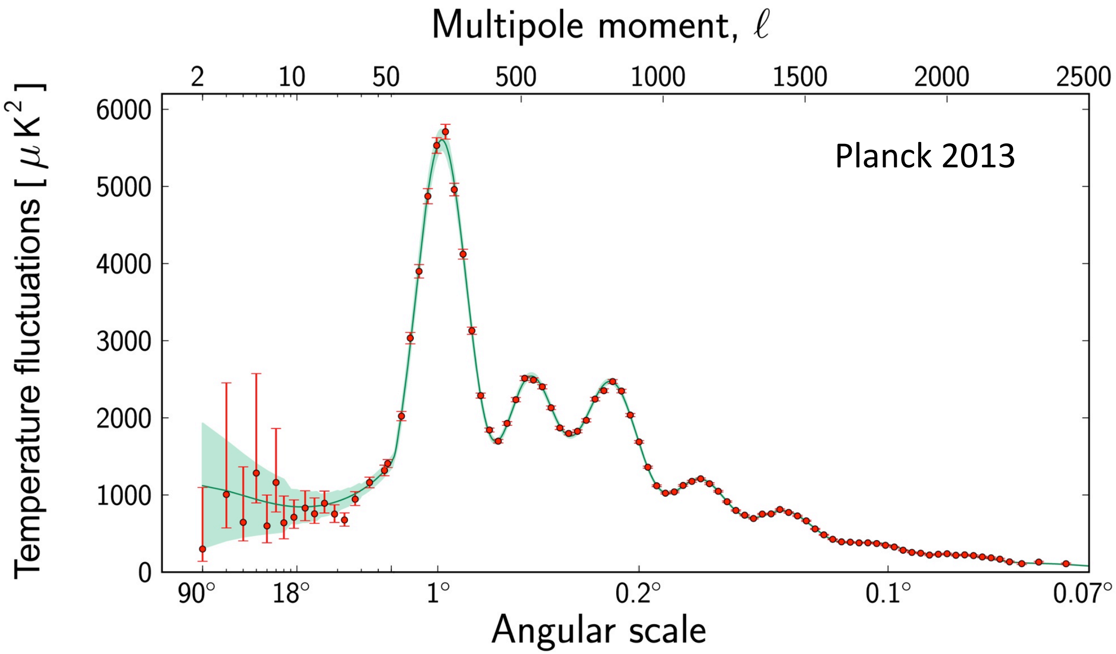
- $\langle \delta\varphi(\vec{x})\delta\varphi(\vec{x}') \rangle = f(\vec{x} - \vec{x}') \;\; \to \;\; \langle \delta\varphi(\vec{k})\delta\varphi(\vec{k}') \rangle = \delta^{(3)}(\vec{k} + \vec{k}')\, k^{-3} P(\vec{k})$

## Isotropy = symmetry under spatial rotation

- **Power spectrum only takes** $\boldsymbol{P(\vec{k}) = P(|\vec{k}|)}$
- Deviation often parameterized as $P(\vec{k}) = P_{iso}(|\vec{k}|)\left[1 + g_*(\hat{n} \cdot \hat{k})^2\right]$
- Observation: $g_* = 0.002 \pm 0.016$ Kim & Komatsu 2013

## Almost exponential expansion = quasi de Sitter universe

- **Almost scale-invariant spectrum:** $\boldsymbol{P(|\vec{k}|) \propto k^{n_s - 1} \sim \mathrm{const.}}$
- Observation: $n_s = 0.9603 \pm 0.0073$ Planck 2013

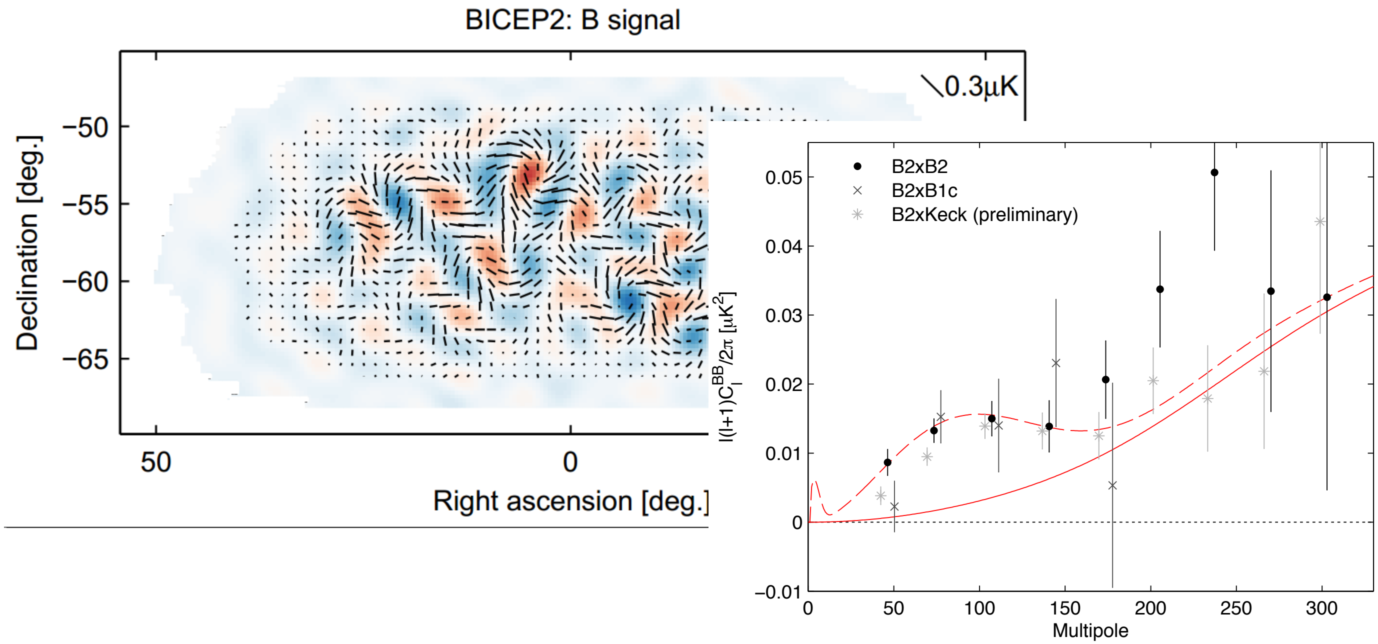



# Predictions in a good agreement with data!

Moreover…inflation predicts **gravitational waves (GW)**

- **GW** = propagating "spacetime fluctuations"
- Direct measure of the energy scale of inflation

# BICEP2 collaboration announced B-mode polarization in CMB



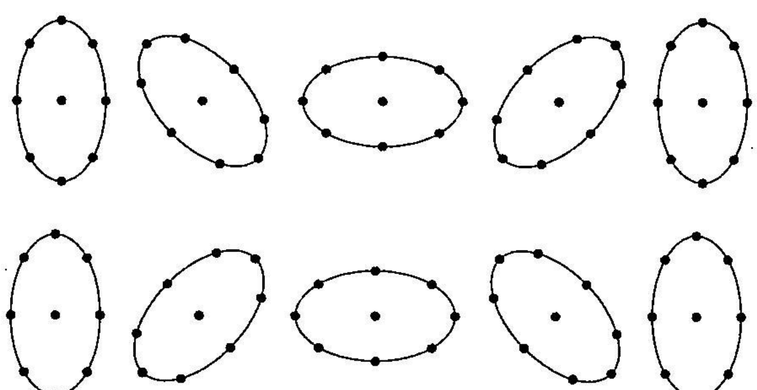

- **If primordial, B-mode polarization of CMB is a direct measure of gravitational waves**
- If discovered, it provides a strong support for inflation + other exciting implications
- Not yet clear whether the BICEP2 result is of primordial origin
  - May be significantly contaminated by polarized, galactic dust
  - Planck+BICEP2 will release their combined polarization data very soon

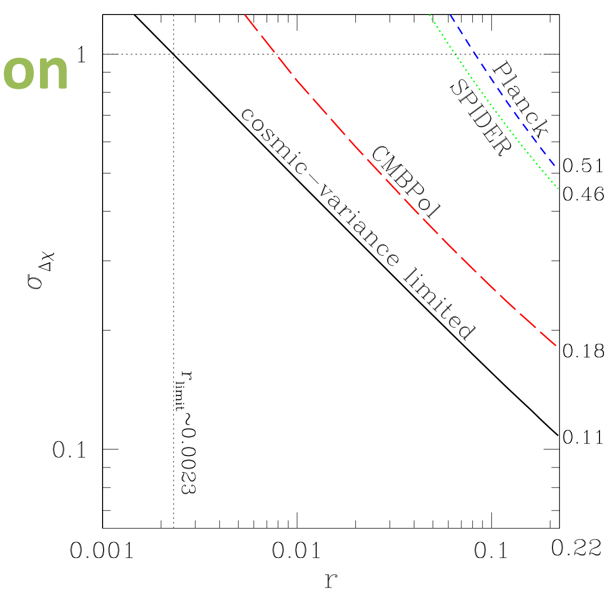
# Era of Precision cosmology

How can we test the theory of inflation or even further, the physics of the universe at its earliest stage?

One unexplored ground is **parity violation** during inflation

- Odd in **spatial inversion**
- Scalar (inflaton) perturbation is insensitive
- Can be encoded in **tensor perturbation** (**gravitational waves**)!

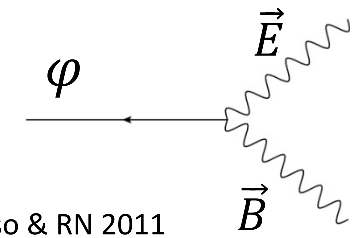





Gluscevic & Kamionkowski 2010

- One way to realize parity violation during inflation
  - **Introduce interaction** between $\varphi$ and electromagnetic field
  - Compatible with the shift symmetry
  - **Parity violating interaction induces helical EM field**
  - **Helical EM field sources helical GW**

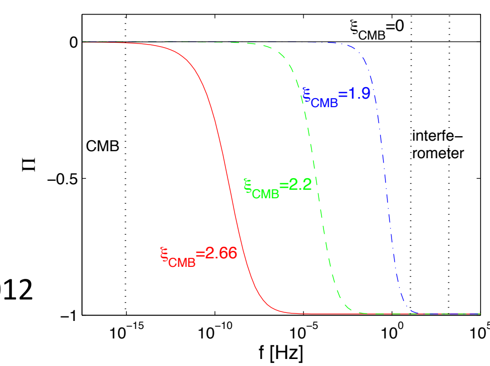
$$\mathcal{L}_{int} \sim \varphi\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$




Anber & Sorbo 2010, Barnaby, Peloso & RN 2011

- If $\varphi$ is inflaton, GW signals are too small at CMB scales
  - Due to strong bounds from scalar perturbations
  - Potentially detectable at terrestrial GW detectors (LIGO, VIRGO, KAGRA etc)

Barnaby, Pajer & Peloso 2012




Crowder et al. 2012

- If $\varphi$ is a non-inflaton field, it may be possible to produce helical GW of sufficient strength

Barnaby et al. 2012, Cook & Sorbo 2013
Mukohyama, RN, Peloso & Shiu 2014

- Other signals – primordial $\vec{B}$ field, anomaly…

# Outlook & prospects

- **Inflation complements the Hot BB cosmology**
  - Solves horizon/flatness/unwanted relic problems
- **Inflation seeds small inhomogeneities**
  - CMB fluctuations, large-scale structure
- **Prediction of gravitational waves**
  - Testing grounds of the primordial universe
- **Understanding inflation is to study ultra-high energy**
  - Symmetry structure in high energy?
- Other features/anomalies in CMB?