What did we learn?
How the universe begun

- it was very hot, and started with inflation

- To me, this is a milestone for mankind
Congratulations

• My congratulations and my thanks
  – to Cho-Lin Kuo and the BICEP2 Collaborations for the discovery of Primordial B-modes
  – to Linde and Guth for the formulation of Inflation
What did we measured?
Energy Scale of Inflation

• The standard story
  \[ \langle h^2 \rangle \sim \frac{H^2}{M_{Pl}^2} \]

• For a slow roll Inflationary model
  \[ V(\phi) \sim M_{Pl}^2 H^2 \quad \Rightarrow \quad \langle h^2 \rangle \sim \frac{V}{M_{Pl}^4} \]
  \[ \Rightarrow \quad \text{detection} \quad \Rightarrow \quad V(\phi) \sim 10^{16}\text{GeV} \]

• Huge energy scale probed by cosmology
  – the universe was very hot
  – The energy scale is remarkably close to the Grand Unification Scale
    • maybe further evidence of GUT and particle physics BSM implications

• Awesome!
How in detail did Inflation happened?
A Lesson

- Amplitude of signal is not associated \textit{necessarily} with $H$
  - there is possibly a larger signal that dominates the standard one
- The Gravity Waves are not \textit{necessarily} of quantum origin
- Scale invariance of the signal remains a robust prediction of Inflation
Energy Scale of Gravity Waves

- Energy of gravity waves:
  \[ \langle h^2 \rangle \sim \frac{H^2}{M_{Pl}^2} \Rightarrow \rho_h \sim M_{Pl}^2 (\partial h)^2 \left|_{\omega \sim H} \right. \sim M_{Pl}^2 H^2 \langle h^2 \rangle \sim H^4 \]

- This is minuscule

- For an harmonic oscillator with \( \omega \sim H \), vacuum energy is \( E_{\text{vac}} \sim \omega \sim H \)

- So
  \[ \rho_h \sim H^4 \Rightarrow \text{one quanta per Hubble volume} \Rightarrow \text{Minuscole!} \]

- One graviton with \( \omega \sim H \) per Hubble volume

- Consider our universe, which is accelerating. One quanta in the whole universe.
  - Good luck with detecting it!
Energy Scale of Gravity Waves

- In fact, we normally look at other sources
Available Energy

• By definition, in Inflation there is a physical clock

\[ \dot{\phi}^2 \sim \dot{H}M_{Pl}^2 \sim \epsilon H^2 M_{Pl}^2 \]

• From the temperature power spectrum \[ \langle (\delta T/T)^2 \rangle \sim \frac{H^2}{\epsilon M_{Pl}^2} \sim 10^{-10} \]

\[ \dot{\phi}^2 \sim 10^{10} H^4 \gg \gg \gg H^4 \]

• So, there is enough energy (we cannot use the potential energy, just its gradients)

• Huge possibility:

\[ \rho_h \sim H^2 M_{Pl}^2 \langle h^2 \rangle = \rho_{\dot{\phi}^2} \sim \epsilon H^2 M_{Pl}^2 \implies \langle h^2 \rangle \sim \epsilon \]

• Problem is that usually this energy sits there and does nothing

  – not converted in Gravity Waves

• It needs to be converted

• and not diluted away
Conversion and not-dilution

- A proof of principle

- Trapped Inflation
  - Consider wiggly potential
  - At each wiggle, coupling

$$V \sim \sum_{n} (\phi - \phi_n)^2 \chi_n^2$$

$$\Rightarrow m_{\chi}^2(t) \sim \dot{\phi}^2(t - t_n)^2$$

- At $t \sim t_n$, adiabaticity for $\chi$ is broken $\Rightarrow$ many particles are produced

$$\Rightarrow n_{\chi_n} \sim \dot{\phi}^{3/2}$$

- We achieved conversion of $\dot{\phi}^2$ energy in $\chi_n$, and this happens continuously:
  - $\chi_n$ dilutes away, but gets replenished by $\chi_{n+1}$
  - We now need to convert $\chi_n$ into Gravity Waves (continuously)
Conversion and not-dilution

- Conversion to Gravity Waves
- Imagine $\chi_n$ decay to $\psi_n$ (out of many)
- In this decay,
  - gravitational bremsstrahlung is produced

$$\langle h^2 \rangle \sim \frac{\rho_\chi}{\rho_{\text{total}}} \frac{HM_\chi}{M_{\text{Pl}}^2}$$

- How large can this be?
  - Detectable signal even with $H \sim 10^{-5} H_{\text{min, vacuum}}$
    - after some engineering
Lesson

• Bad:
  – Amplitude of signal is not associated \textit{necessarily} with $H$
  – Signal not \textit{necessarily} quantum

• But
  – \textit{Scale invariance} of the signal remains a robust prediction
  – \textit{Easier to produce} observable tensor modes, by several orders of magnitude
  – Possible \textit{non-Gaussian} window
Non-Gaussian Window

• In usual vacuum fluctuations, Gaussianity of the fluctuations
  – as vacuum of harmonic oscillator is Gaussian

\[ |0\rangle_{k/a \ll H} = \prod_{k_i \ll H a} \sum_{\phi_k} e^{-\frac{1}{2} \frac{1}{H^2} V_{k_i}^2} |\phi_{k_i}\rangle \]

• Here fluctuations are not vacuum, not Gaussian

• This motivates analysis of non-Gaussianity of B-modes
  – Yes, they can!

\[ \frac{\langle h^3 \rangle}{\langle h^2 \rangle^{3/2}} \lesssim \frac{1}{\sqrt{N_{\text{modes}}}} \sim \frac{l_{\text{min}}}{l_{\text{max}}} \sim \frac{50}{200} \sim 25\% \]
Scale Invariance

• Everything happens in the same way at every e-fold
  \[ \implies \] the signal is scale invariant

• It is very hard to obtain scale invariance without being in de Sitter

• Could we make it?
  \[ \implies \] Theorem: for scalar: if there is a single scalar field, this is impossible
    • but more than one field can
  \[ \implies \] Theorem: for gravity waves: only inflation can make them scale invariant

• This motivates analysis of tilt at \( n_t \sim 10\% \)
How did Inflation begun?
Seeing the beginning of Inflation

- Very mild tension with Planck
  - Maybe scalar fluctuations are smaller at large angles
  - Naturally associated with a steepening of Inflationary potential
  - Can be associated with us originating from a bubble

- Interesting to check in the data if this is possible
  - Both large angle CMB
  - and Large Scale Structures
Conclusions

• Inflation and Gravitational Waves have been discovered
  – Just beautiful

• Now, after celebrating,
  – we want to know how Inflation happened and how it started
    • this is not ungratefulness
    • As normal, any discovery allows the possibility of addressing new questions
      – in a never ending story