Cospa 2017 @ Kyoto

Inflationary phase transition and gravitational waves

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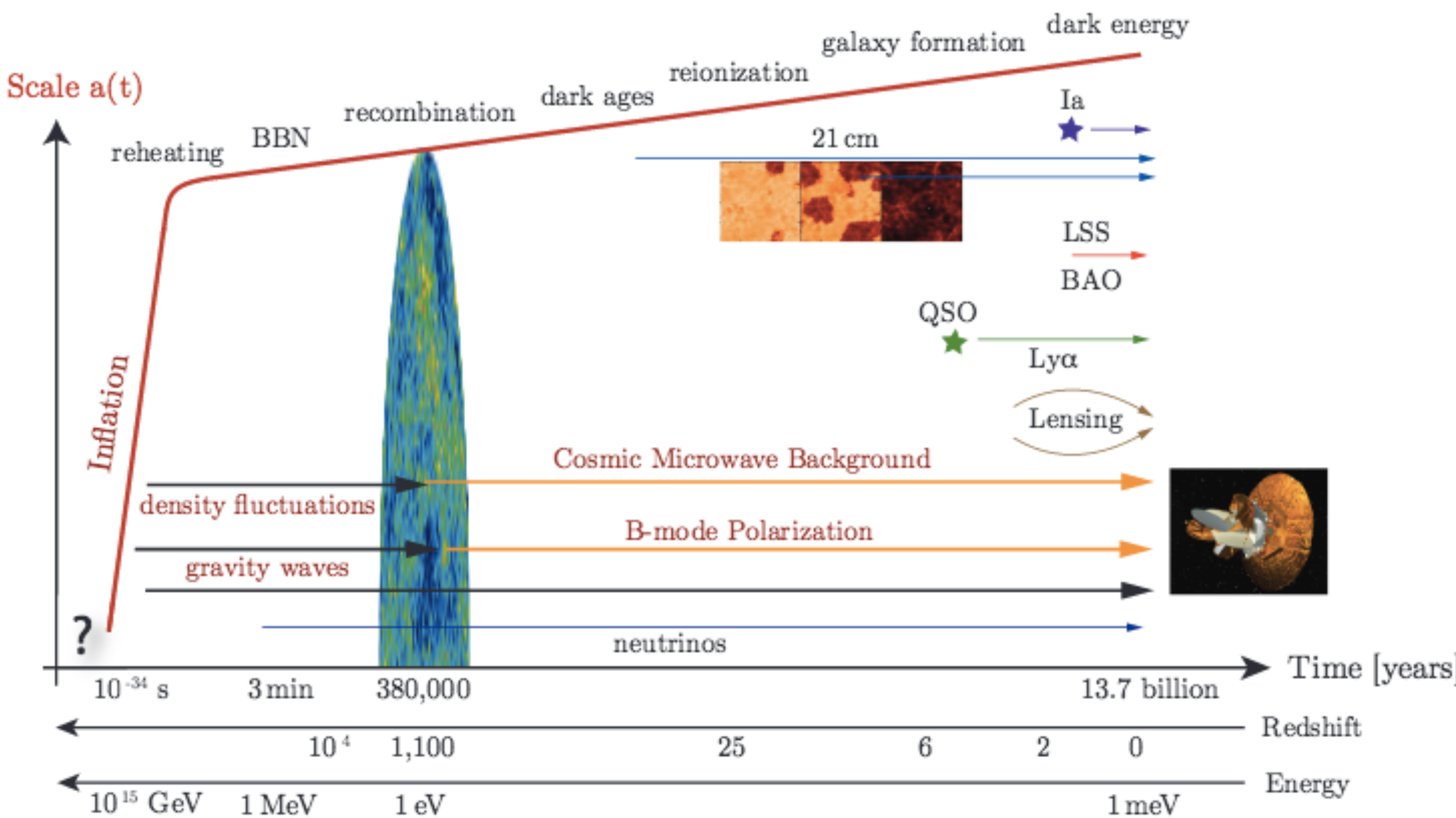
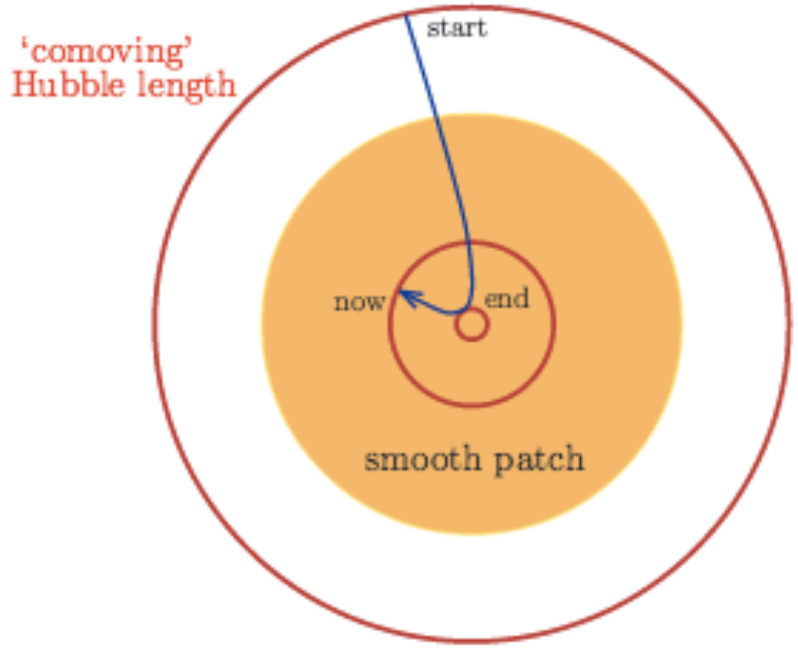
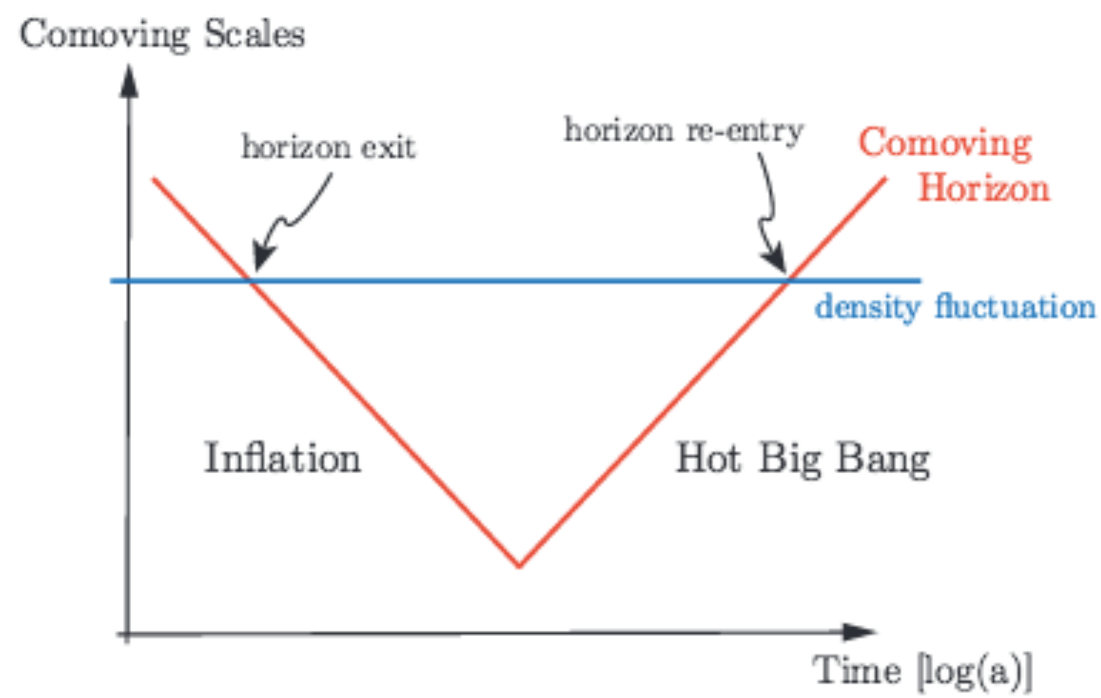
Based on
1512.07538
with Hongliang Jiang, Tao Liu, Yi Wang
and 1701.03437
with Jiunn-wei Chen, Shou-Huang Day, Debaprasad Maity and Yun-Long Zhang

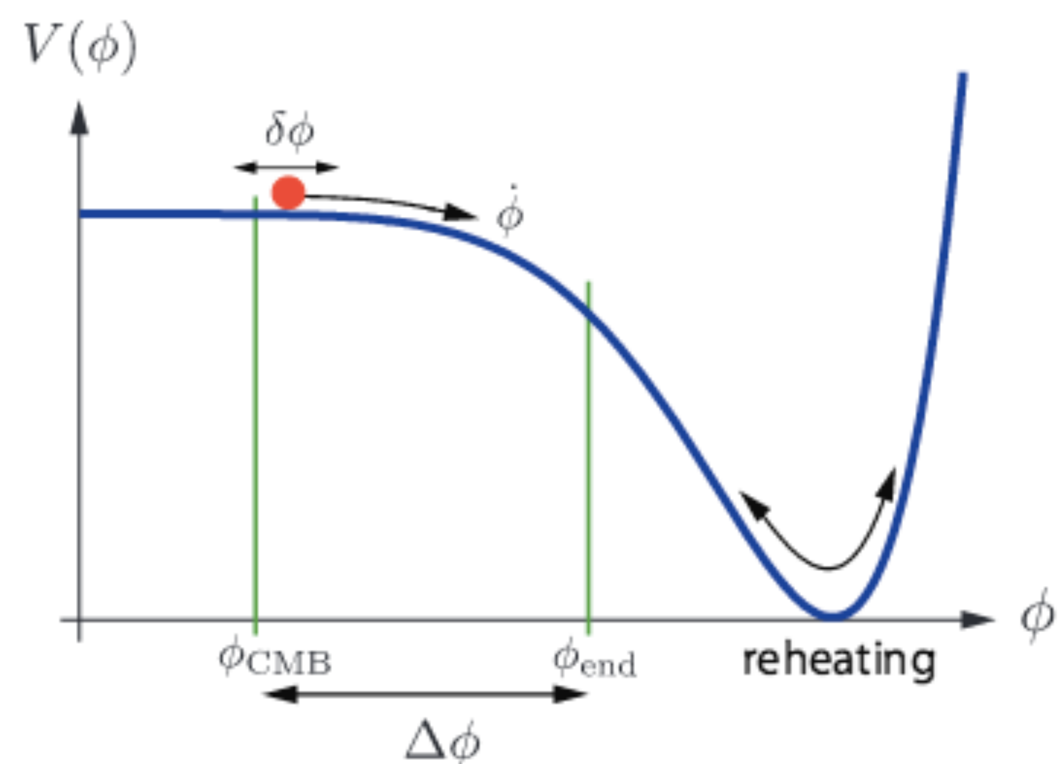
History of the Universe:







- Horizon problem
- flatness problem
- Magnetic monopole problem

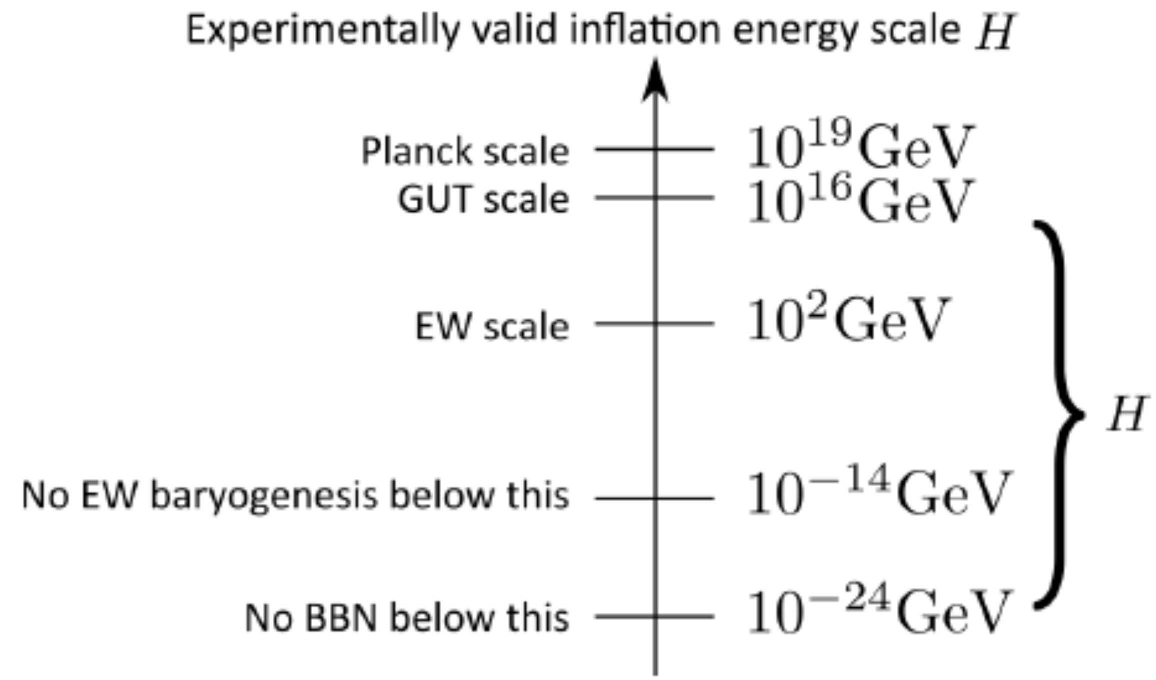


- Slow rolling instead of tunnelling
- Slow roll parameter:

$$\boxed{\varepsilon = -\frac{\dot{H}}{H^2}} = -\frac{d\ln H}{dN},$$

New inflation Andrei Linde, 1981
Old inflation Alan.Guth, 1981
Henry Tye and Alan Guth 1980

Models for inflation------ so many of them!



- Hubble constant today: 10 ^ -42 GeV

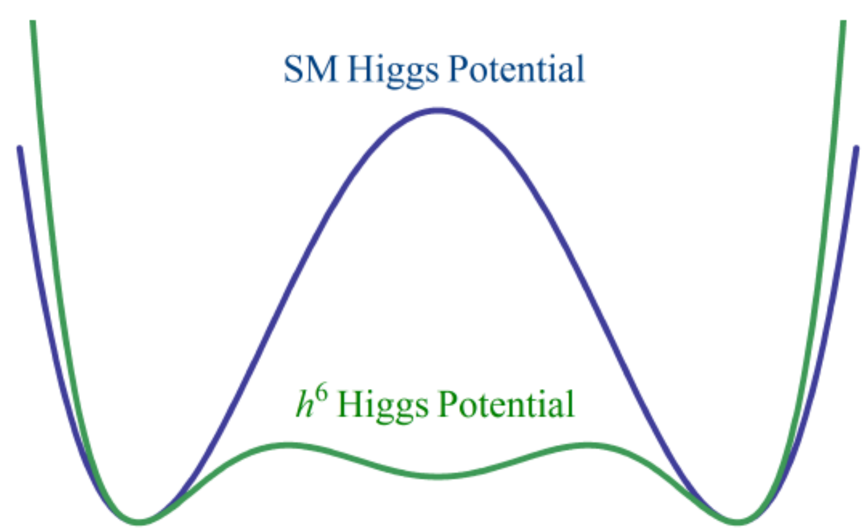
- Hubble constant stays CONSTANT during inflation

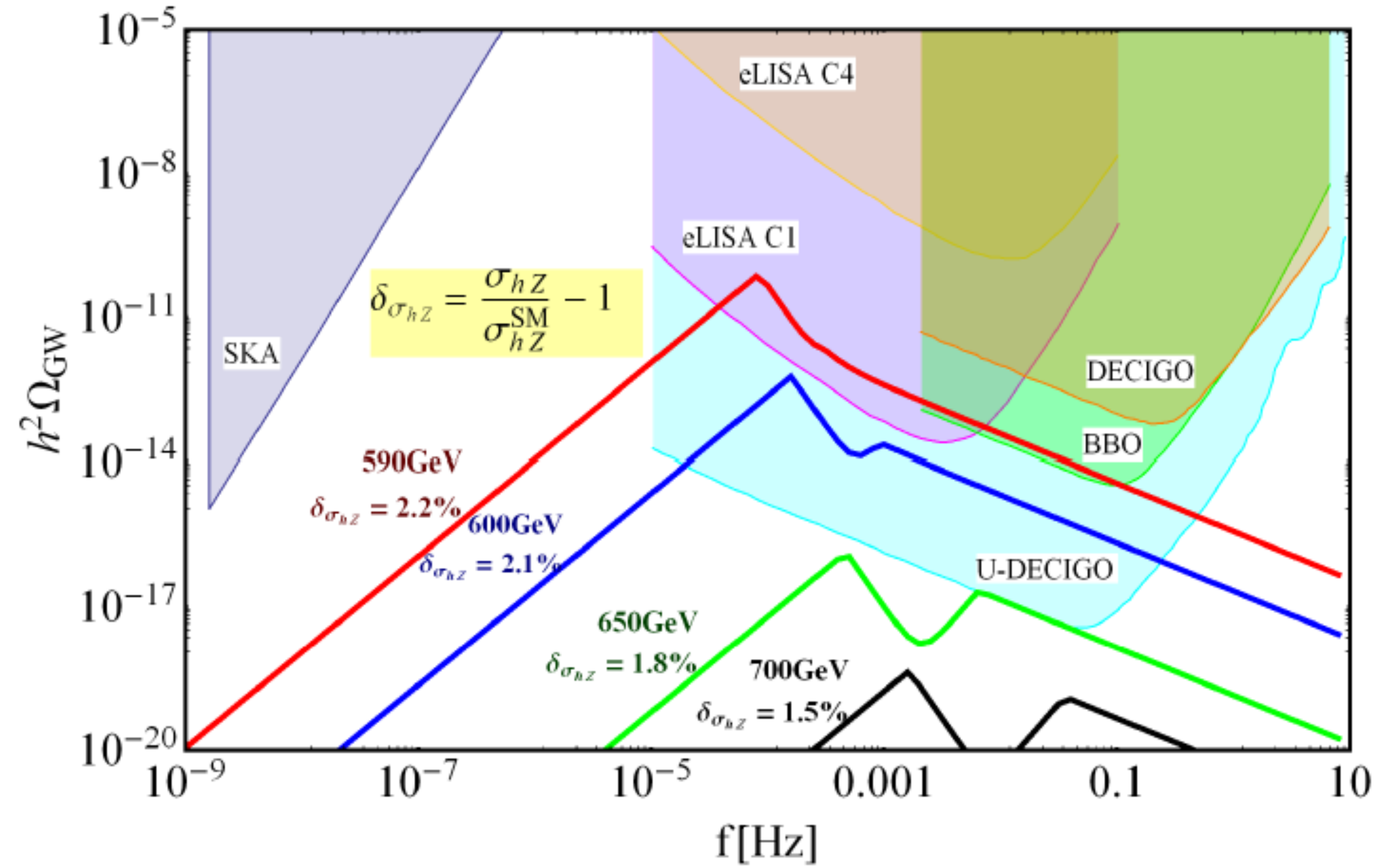
What does inflation do with Colliders?
e.g.*Cosmological Collider Physics*

1503.08043 by Nima Arkani-Hamed, Juan Maldacena
Quasi-Single Field Inflation and Non-Gaussianities
0911.3380 by Xingang Chen and Yi Wang

- New particles with masses comparable to the Hubble scale produce a distinctive signature on the non-gaussianities.

Gravitational waves from particle phase transition. Direct Detection: Well-studied. *E.Witten 1984*





$$V_{\text{tree}}(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6.$$

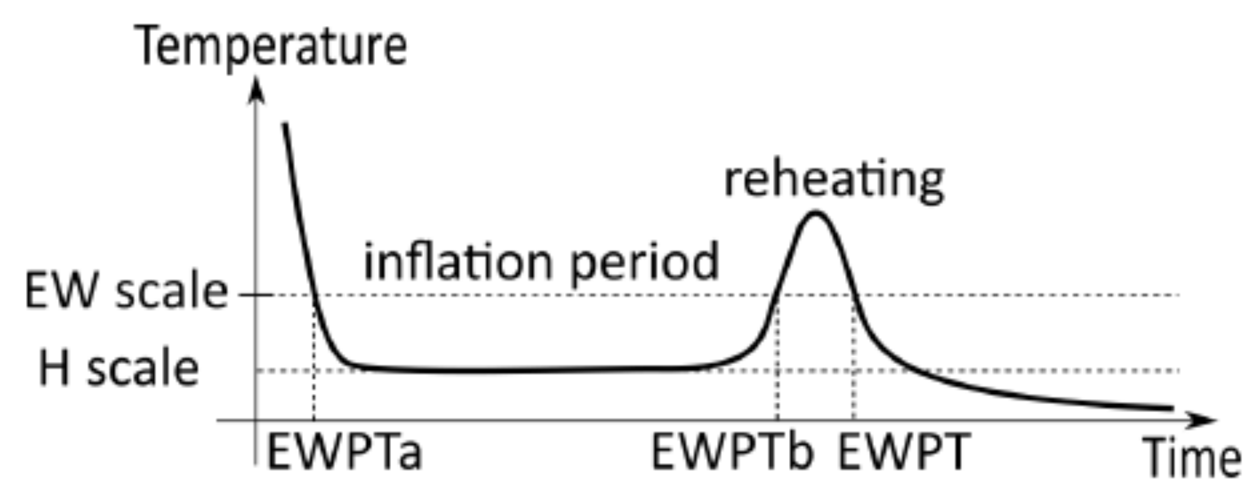
- arXiv: 1601.01640

Fa Peng Huang[1], Youping Wan[1], Dong-Gang Wang[2], Yi-Fu Cai[2], and Xinmin Zhang[1]

Thermal History of the Universe:

- Temperature drop down to Gibbons-Hawking temperature at the beginning of the inflation: $T_{GH} = H/(2\pi)$
- Energy density of the universe is very high during inflation: the vacuum energy from inflaton, Friedmann equation:

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



- EWPT: producing gravitational waves, LISA, LIGO and Virgo, Tianqin, Tai-Chi(Standard, 10^-4 Hz)
- EWPTa: gravitational waves, CMB (Our work, 10^-12 Hz)
- EWPTb: Baryogengesis

- Particle phase transition at the beginning of the inflation?

- Same temperature as the late Universe
- Vacuum energy dominant vs Radiation dominant
- Producing gravitational wave and density fluctuation

Gravitational wave spectrum@de sitter space

$$S = \frac{M_p^2}{8} \int \frac{d^3k}{(2\pi)^3} d\tau \; a^2 \left(\gamma_j^{i\prime} \gamma_i^{j\prime} - k^2 \gamma_j^i \gamma_i^j \right)$$

$$\gamma_{ij}(\mathbf{k}) = \frac{\sqrt{2}}{M_p} \left[\gamma_+(\mathbf{k}) e_{ij}^+(\mathbf{k}) + \gamma_\times(\mathbf{k}) e_{ij}^\times(\mathbf{k}) \right]$$

$$e_{ij}^+ = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & I & 0 \\ I & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} , \qquad e_{ij}^\times = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -I & 0 \\ -I & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- Second quantization:

$$S = \frac{1}{2} \int \frac{d^3k}{(2\pi)^3} d\tau \; a^2 \left[\left(\gamma_+' \gamma_+{}' - k^2 \gamma_+ \gamma_+ \right) + \left(\gamma_\times' \gamma_\times{}' - k^2 \gamma_\times \gamma_\times \right) \right]$$

$$\gamma(\mathbf{k}) = v_k(t) a_{\mathbf{k}} + v_k^*(t) a_{-\mathbf{k}}^\dagger$$

$$v_k = c_1 (1 + ik\tau) e^{-ik\tau} + c_2 (1 - ik\tau) e^{ik\tau}$$

GW@de sitter space

$$\rho_{GW} = \int \frac{dk}{k}\frac{k^3}{2\pi^2}\left(|\dot{v}_k|^2 + \frac{k^2}{a^2}|v_k|^2\right)$$

$$\Omega_{GW}(k,\tau) = k\frac{d\rho_{GW}}{dk}/\rho_{\rm tot}$$
$$= \frac{1}{3H^2M_p^2}\frac{k^3}{2\pi^2}\frac{|v_k'(\tau)|^2 + k^2|v_k(\tau)|^2}{a(\tau)^2}$$

$$P_\gamma(k,\tau) = \frac{4k^3}{\pi^2 M_p^2}|v_k(\tau)|^2$$

- Power spectrum by classical bubbles: scale dependent.
- Primordial GW by vacuum fluctuation: scale independent.

- Gravitational wave power spectrum from EW phase transition:

$$\Omega_{GW}(k) = \Omega_{GW}^{\rm crit} \frac{(a+b)k_{\rm crit}^{b} k^{a}}{b k_{\rm crit}^{a+b} + a k^{a+b}} \ ,$$

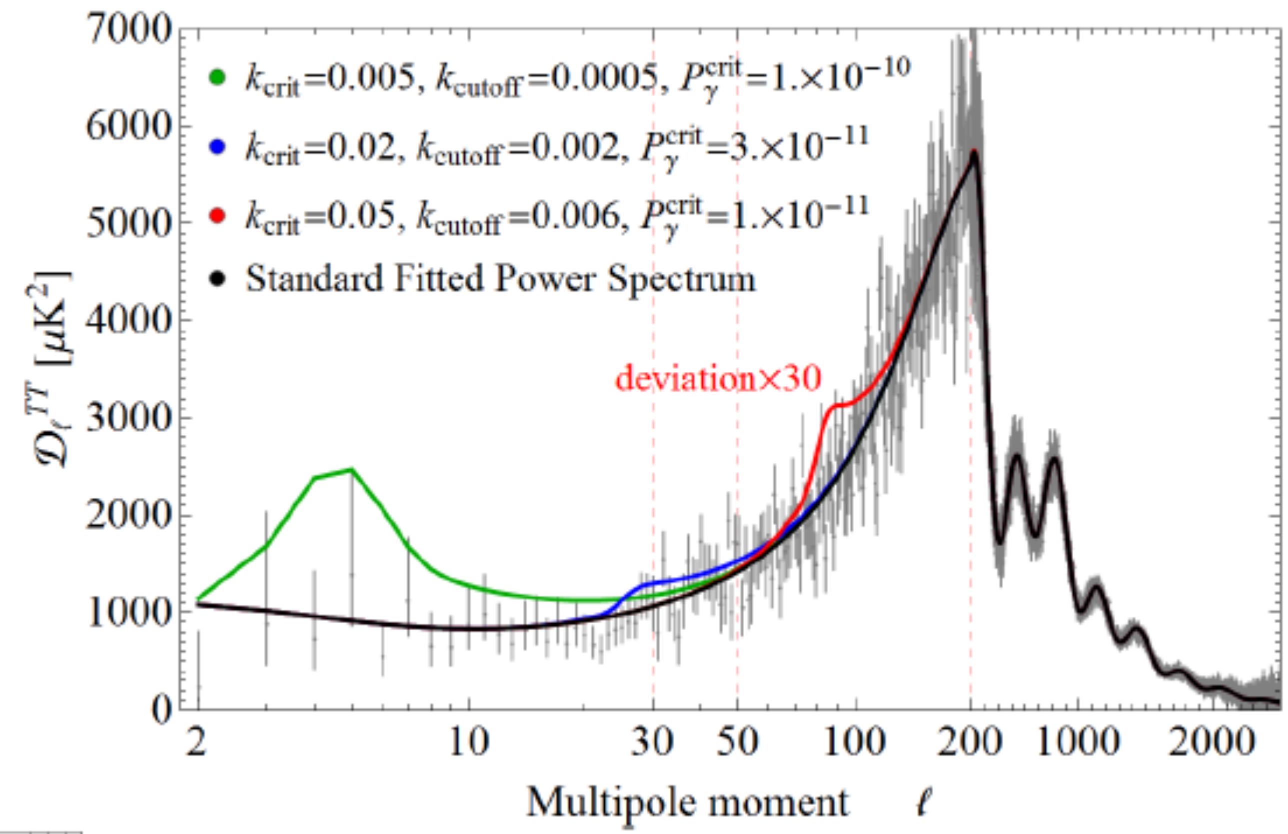
$$\Omega_{GW}^{\rm crit} = \frac{0.11 v_b^3}{0.42 + v_b^2} \kappa^2 \left(\frac{H}{\beta}\right)^2 \left(\frac{\rho_{\rm higgs}}{\rho_{\rm tot}}\right)^2$$

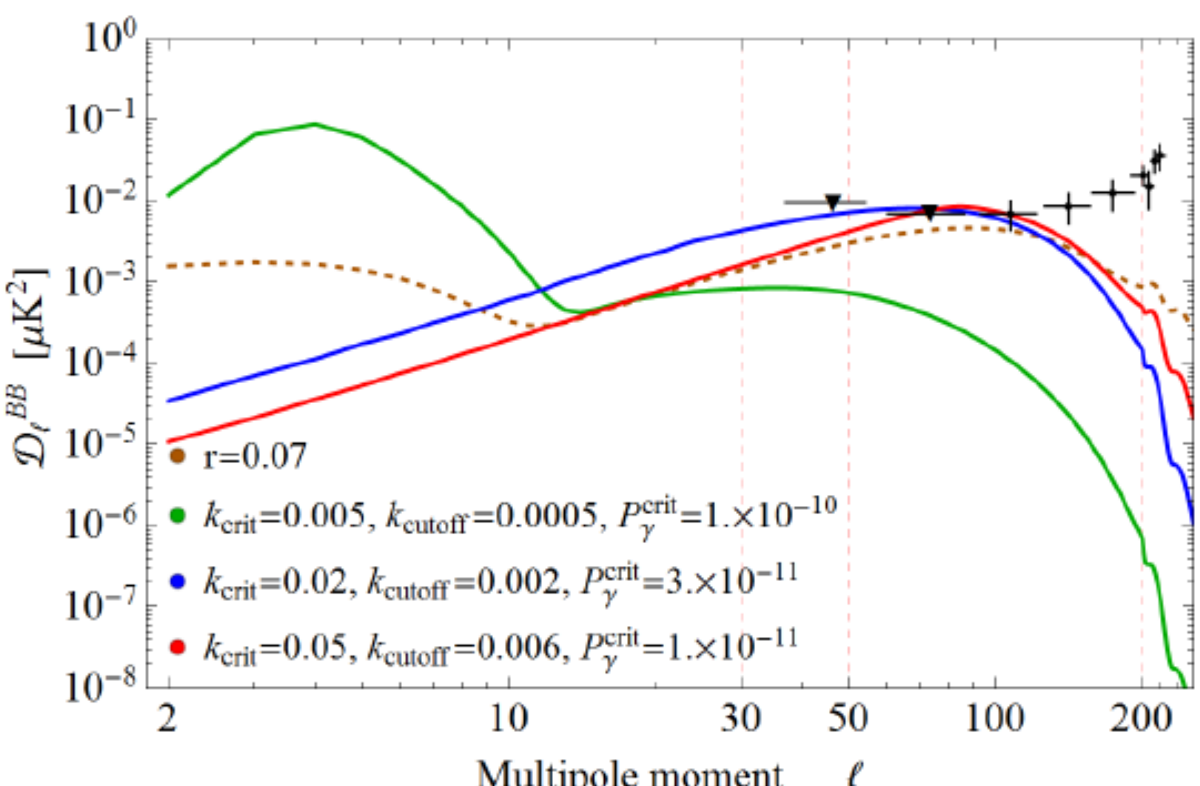
$$\kappa = \frac{1}{1+0.715\alpha}[0.715\alpha + \frac{4}{27}\sqrt{\frac{3\alpha}{2}}], \quad \alpha = \frac{\rho_{\rm particle\ vac}}{\rho_{\rm rad}}$$

- Plug into the power spectrum:

$$P_{\gamma}(\tau_{\rm obs}) = 24 H^2 \left(\frac{a(\tau_*)}{k}\right)^2 \frac{k^2 |v_k(\tau_{\rm obs})|^2}{k^2 |v_k(\tau_*)|^2 + |v_k'(\tau_*)|^2} \Omega_{GW}(\tau_*)$$

CMB spectrums:





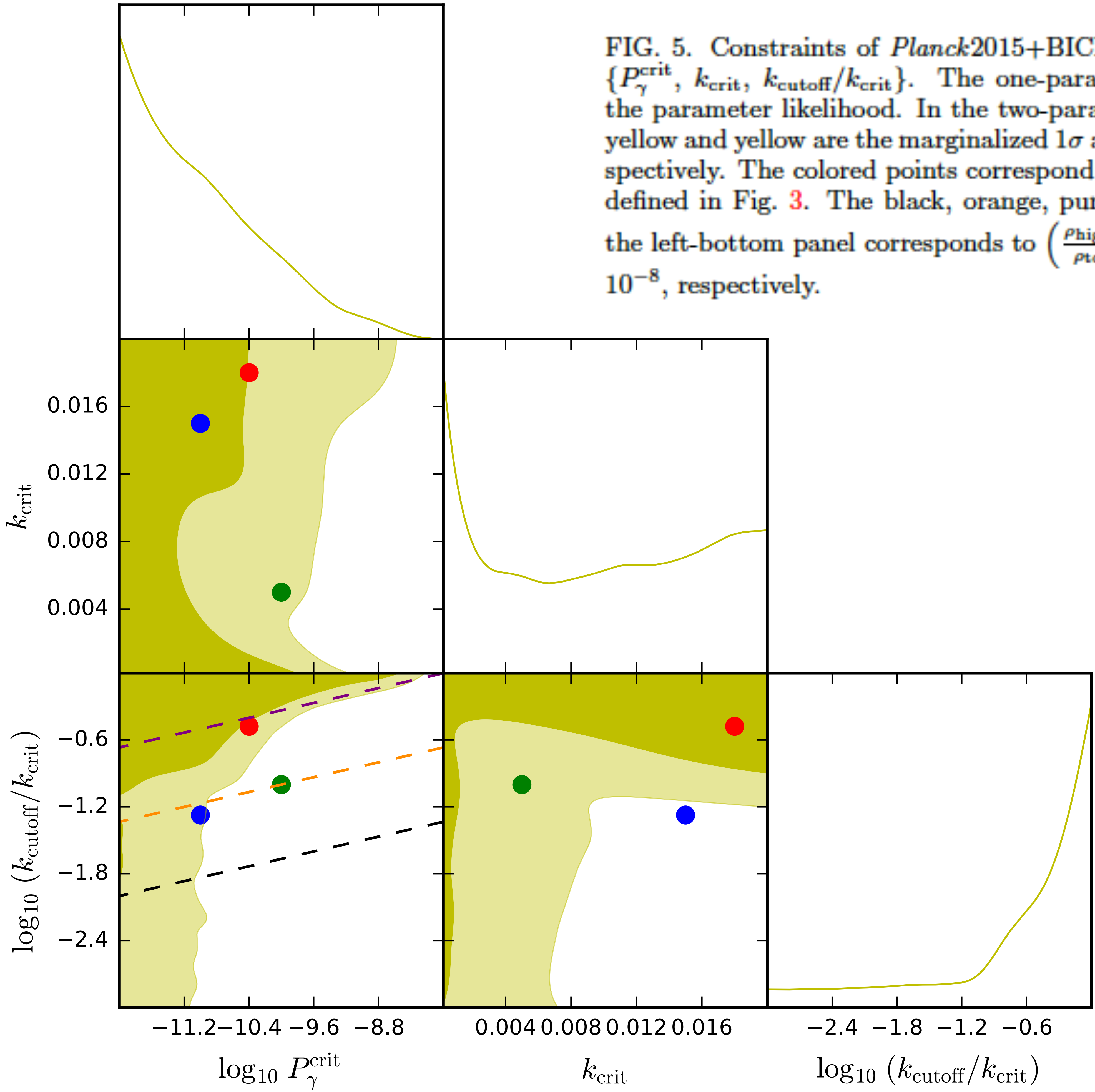


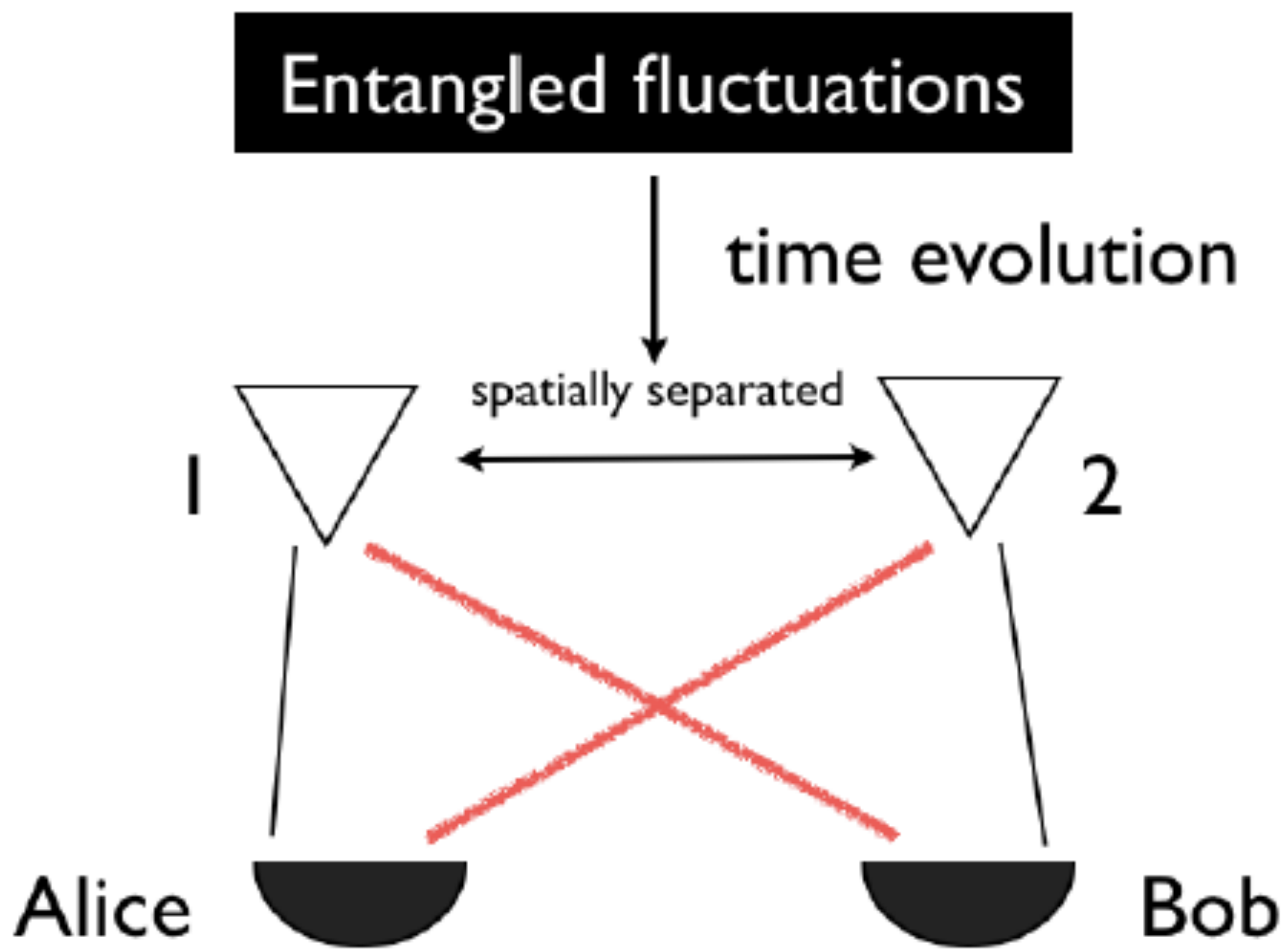
FIG. 5. Constraints of *Planck*2015+BICEP2/Keck data for $\{P_\gamma^{\rm crit},\ k_{\rm crit},\ k_{\rm cutoff}/k_{\rm crit}\}$. The one-parameter panels show the parameter likelihood. In the two-parameter panels, dark yellow and yellow are the marginalized 1σ and 2σ contours, respectively. The colored points correspond to the benchmarks defined in Fig. 3. The black, orange, purple dashed lines in the left-bottom panel corresponds to $\left(\frac{\rho_{\rm higgs}}{\rho_{\rm tot}}\right)^2 = 1, 10^{-4}$ and 10^{-8}, respectively.

Discussion

- How to have observable effect?
  - Super-horizon size vs Sub-horizon size bubbles
  - Bubble nucleation
  - First order PT phase transition
- Requiring certain range of inflation scales

Beyond:
Entanglement in CMB photons?

1701.03437
Jiunn-wei Chen, Shou-Huang Day, Debaprasad Maity SS, and Yun-Long Zhang



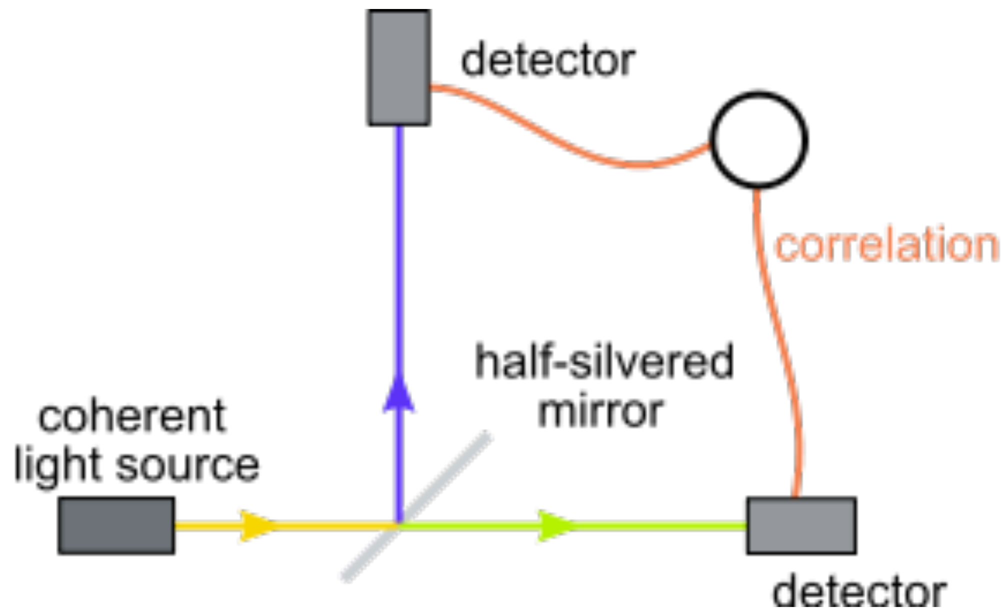
CMB measurements

- Density fluctuation: frequency (WMAP, Planck..)
- Polarization: BICEP2&Keck, Ali tibet, POLARBEAR, SPIDER, etc.

- Any entanglement information in CMB?
  1508.01082 cosmological Bell inequality by J. maldecena
    - entangled massive modes

- Entanglement between different polarization states for photons?
- Possible sources:
  - Causally disconnected sky patches.
    - Stretched by inflation.
    - Connected by wormhole.
  - Final decay product of some particles.
  - Decay of Dark Matter candidates.

A detour to quantum physics: Hanbury, Brown and Twiss (HBT) experiments :



$$\mathcal{A} = D_{1A}D_{2B} + D_{2A}D_{1B},$$

- Interference strips:

$$|\mathcal{A}|^2 = |D_{1A}|^2|D_{2B}|^2 + |D_{2A}|^2|D_{1B}|^2 + 2\mathrm{Re}D_{1A}D_{2B}D^*_{2A}D^*_{1B}.$$

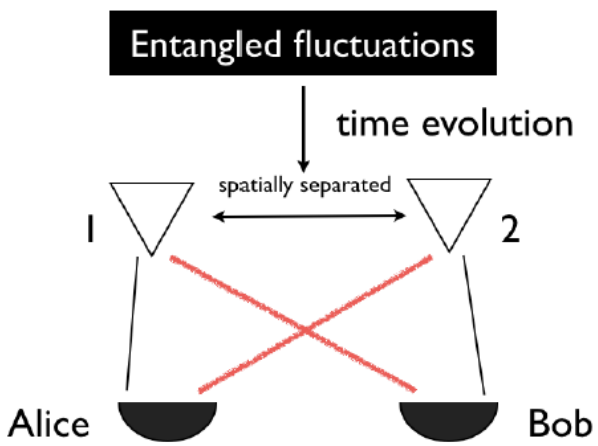
- Measure very small angles of astrophysical objects

- Entangled states:

$$|\psi_1\rangle = \frac{1}{\sqrt{2}}\left[|\epsilon_1\rangle \otimes |\epsilon_1\rangle + |\epsilon_2\rangle \otimes |\epsilon_2\rangle\right],$$

$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\left[|\epsilon_1\rangle \otimes |\epsilon_2\rangle - |\epsilon_2\rangle \otimes |\epsilon_1\rangle\right].$$

- With geometric phase:



$$\begin{aligned}|\Psi_1\rangle &= \frac{1}{\sqrt{2}}\Big(D_{1A}|\epsilon_1\rangle \otimes D_{2B}|\epsilon_1\rangle + D_{1A}|\epsilon_2\rangle \otimes D_{2B}|\epsilon_2\rangle \\ &\quad + D_{2A}|\epsilon_1\rangle \otimes D_{1B}|\epsilon_1\rangle + D_{2A}|\epsilon_2\rangle \otimes D_{1B}|\epsilon_2\rangle\Big) \\ &= |\psi_1\rangle\left(D_{1A}D_{2B} + D_{2A}D_{1B}\right),\end{aligned}$$

- Bell inequality measurements in HBT

$$C = \Pi_A\Pi_B + \Pi_{A'}\Pi_B + \Pi_A\Pi_{B'} - \Pi_{A'}\Pi_{B'},$$

$$2 < |\langle C_\gamma\rangle| \le 2\sqrt{2}$$

$$\langle\Psi_i|C|\Psi_i\rangle = \langle\psi_i|C|\psi_i\rangle\,|D_{1A}D_{2B} + D_{2A}D_{1B}|^2,$$

Signals and Noise

$$\begin{aligned}&\mathrm{Tr}\,(\Pi_A\pi_1)\,\mathrm{Tr}\,(\Pi_B\pi_2)\,|D_{1A}|^2|D_{2B}|^2\\+&\mathrm{Tr}\,(\Pi_A\pi_2)\,\mathrm{Tr}\,(\Pi_B\pi_1)\,|D_{2A}|^2|D_{1B}|^2\\+&\mathrm{Tr}\,(\Pi_A\pi_1\Pi_B\pi_2)\,D_{1A}D_{2B}D^*_{2A}D^*_{1B}\\+&\mathrm{Tr}\,(\Pi_A\pi_2\Pi_B\pi_1)\,D^*_{1A}D^*_{2B}D_{2A}D_{1B}.\end{aligned}$$

- Polarizers:

$$\Pi_A = |n_A\rangle\langle n_A| - |n_{A_\perp}\rangle\langle n_{A_\perp}|$$

- Detected states, with a net polarization α_i

$$\pi_i = (2+2\alpha_i)^{-1}((1+2\alpha_i)|n_i\rangle\langle n_i| + |n_{i_\perp}\rangle\langle n_{i_\perp}|)$$

$$\mathrm{Tr}\,(\Pi_A\pi_1)\,\mathrm{Tr}\,(\Pi_B\pi_2) = \frac{\alpha_1\alpha_2\cos 2\theta_{An_1}\cos 2\theta_{Bn_2}}{(1+\alpha_1)(1+\alpha_2)}$$

Summary

- The NEW PT phase transition at the beginning of the Universe.
- First order EW phase transition ?
- CMB B-mode can detect the phase transition GW, from EW or GUT PT.

- Potential future CMB measurements: Determine the Entanglement !…

Thank you.