电弱相变与Higgs物理专题研讨会
IHEP, Beijing, 2020

Echoes of 1st-order Cosmological Phase Transitions in CMB

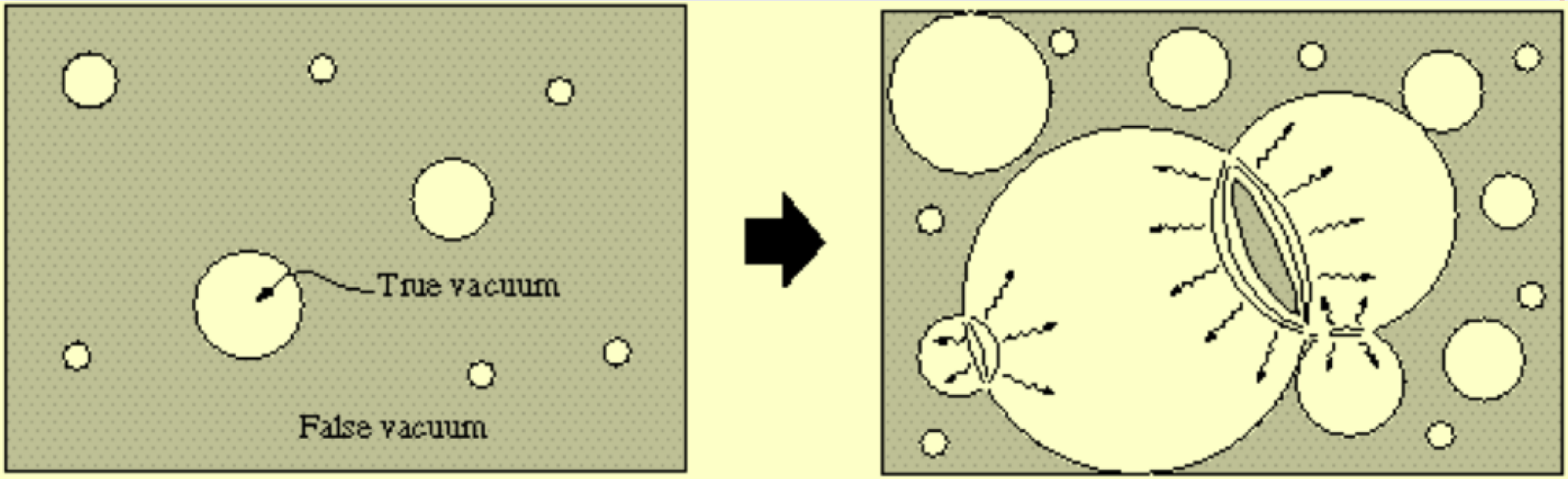
Tao Liu

The Hong Kong University of Science and Technology

Based on Phys.Lett. B765 (2017)

by H. Jiang, TL, S. Sun and Y. Wang

GWs from Bubble Dynamics



- 1st-order Cosmological Phase Transitions (CPTs): GUT, EWSB, etc.
- GWs production: bubble collisions during expansion [E. Witten, '84]; sound wave; associated motion in thermal plasma

Discovery of the GWs


nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio &

Archive > Volume 530 > Issue 7590 > News > Article

NATURE | NEWS

عربي

Gravitational waves: How LIGO forged the path to victory

Historic discovery of ripples in space-time meant ruling out the possibility of a fake signal.

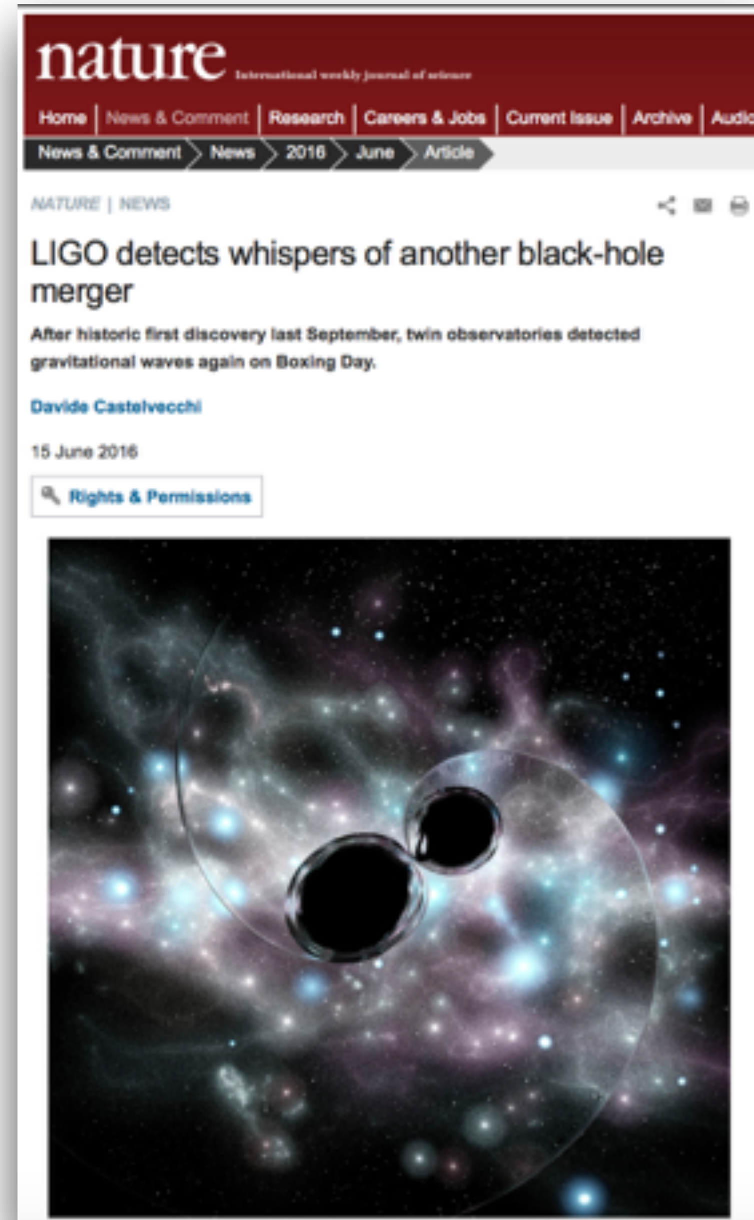
Davide Castelvecchi

16 February 2016

PDF | Rights & Permissions

S. Ossokine, A. Buonanno (Max Planck Inst. Gravitational Phys.). Scientific VisualiZation: W. Benger (Airborne Hydro Mapping)

The pair of merging black holes that LIGO detected using gravitational waves — as produced by a computer simulation.


nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio &

News & Comment > News > 2016 > June > Article

NATURE | NEWS

LIGO detects whispers of another black-hole merger

After historic first discovery last September, twin observatories detected gravitational waves again on Boxing Day.

Davide Castelvecchi

15 June 2016

Rights & Permissions

- The discovery of LIGO in 2016 started the era of GWs astronomy and implies that the time to directly detect this is coming

One of the Main Tasks of LISA

arXiv.org > astro-ph > arXiv:1512.06239

Search...

Help | Advance

Astrophysics > Cosmology and Nongalactic Astrophysics

Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions

Chiara Caprini, Mark Hindmarsh, Stephan Huber, Thomas Konstandin, Jonathan Kozaczuk, Germano Nardini, Jose Miguel No, Antoine Petiteau, Pedro Schwaller, Geraldine Servant, David J. Weir

GWs from Bubble Collision

- Consider the GWs generated by collisions of runaway bubbles in vacuum
- Parametrize the energy spectrum [S. Huber and T. Konstandin,'08]

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

- a: control the slope of low frequency edge of the spectrum peak

$$k < k_{\mathrm{crit}} \Rightarrow \Omega_{GW}(k) \propto k^{a}$$

- b: control the slope of high frequency edge of the spectrum peak

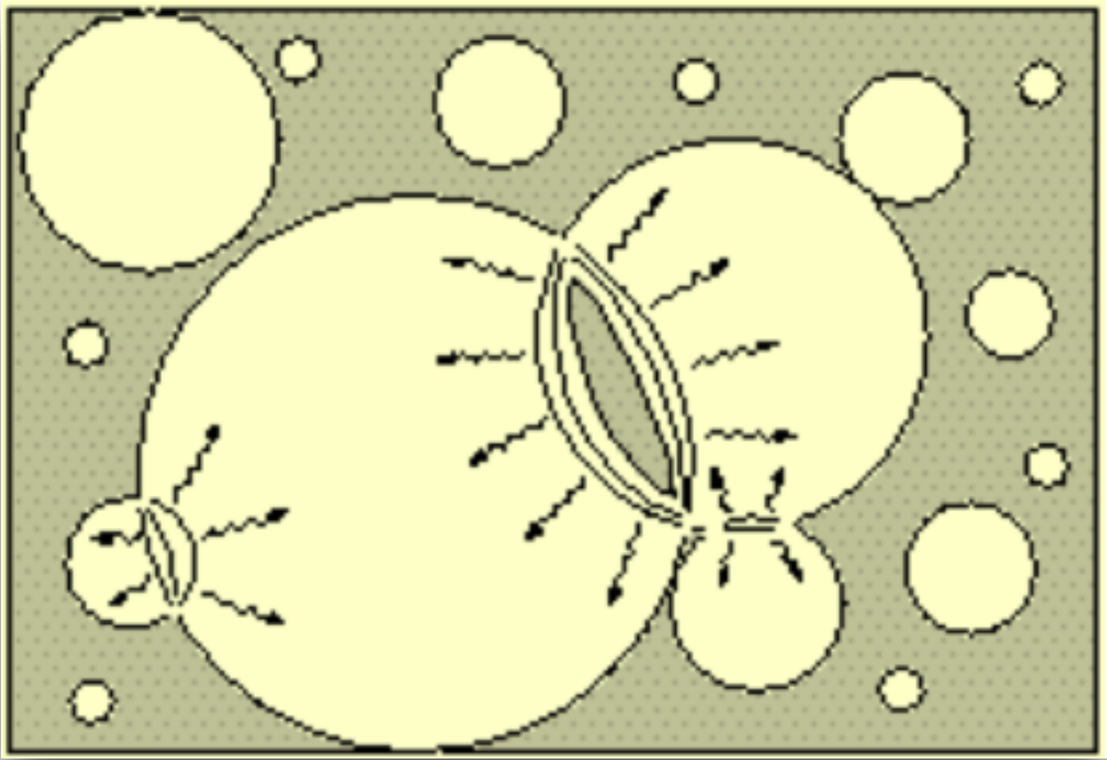
$$k > k_{\mathrm{crit}} \Rightarrow \Omega_{GW}(k) \propto k^{-b}$$

GWs from Bubble Collision

- Consider the GWs generated by collisions of runaway bubbles in vacuum
- Parametrize the energy spectrum [S. Huber and T. Konstandin,'08]

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

- a ~ 3, b ~ 1: b < a is due to nucleation of small bubbles at a late stage of the phase transition



GWs from Bubble Collision

- Consider GWs generated by collisions of runaway bubbles in vacuum
- Parametrize the energy spectrum [S. Huber and T. Konstandin,'08]

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

$$\frac{k_{\mathrm{crit}}}{2\pi} = \frac{1}{\lambda_{\mathrm{crit}}} \sim \beta \qquad \Omega_{GW}^{\mathrm{crit}} \sim \kappa^2 \left(\frac{H}{\beta}\right)^2 \left(\frac{\rho_{Higgs}}{\rho_{\mathrm{tot}}}\right)^2$$

- 1/beta: duration of the PT => characteristic size of bubbles => characteristic wavelength of GWs
- $\alpha \sim \frac{\rho_{\mathrm{higgs}}}{\rho_{\mathrm{tot}}}$: a measure of latent heat liberated => one of the most important factors to determine the strength of the GW energy spectrum

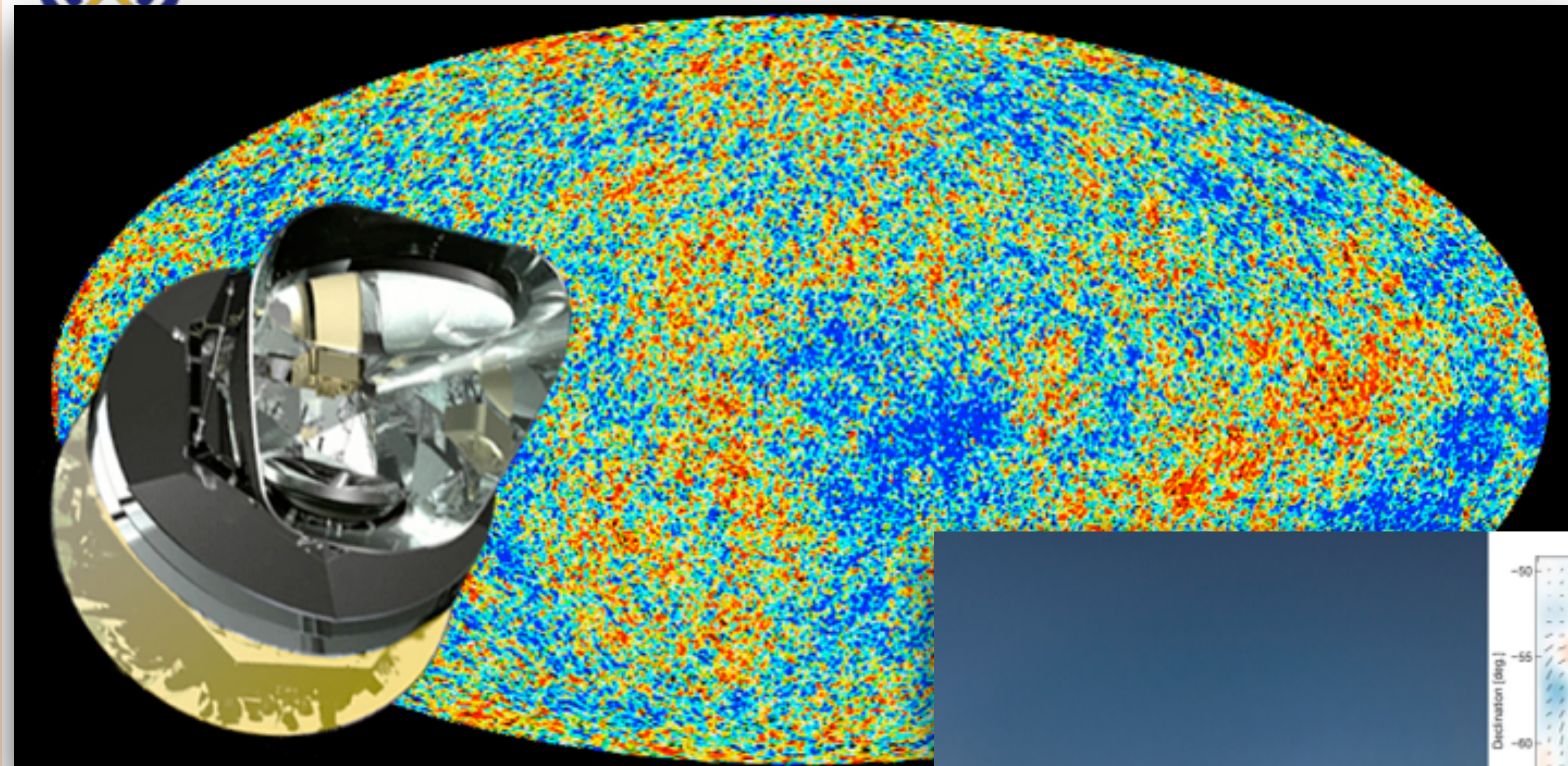
GWs Today

- Takes into account redshift effect [C. Grojean and G. Servant,'07]

$$f = f_* \frac{a_*}{a_0} \approx 6 \times 10^{-3}\mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \mathrm{GeV}} \frac{f_*}{H_*}$$

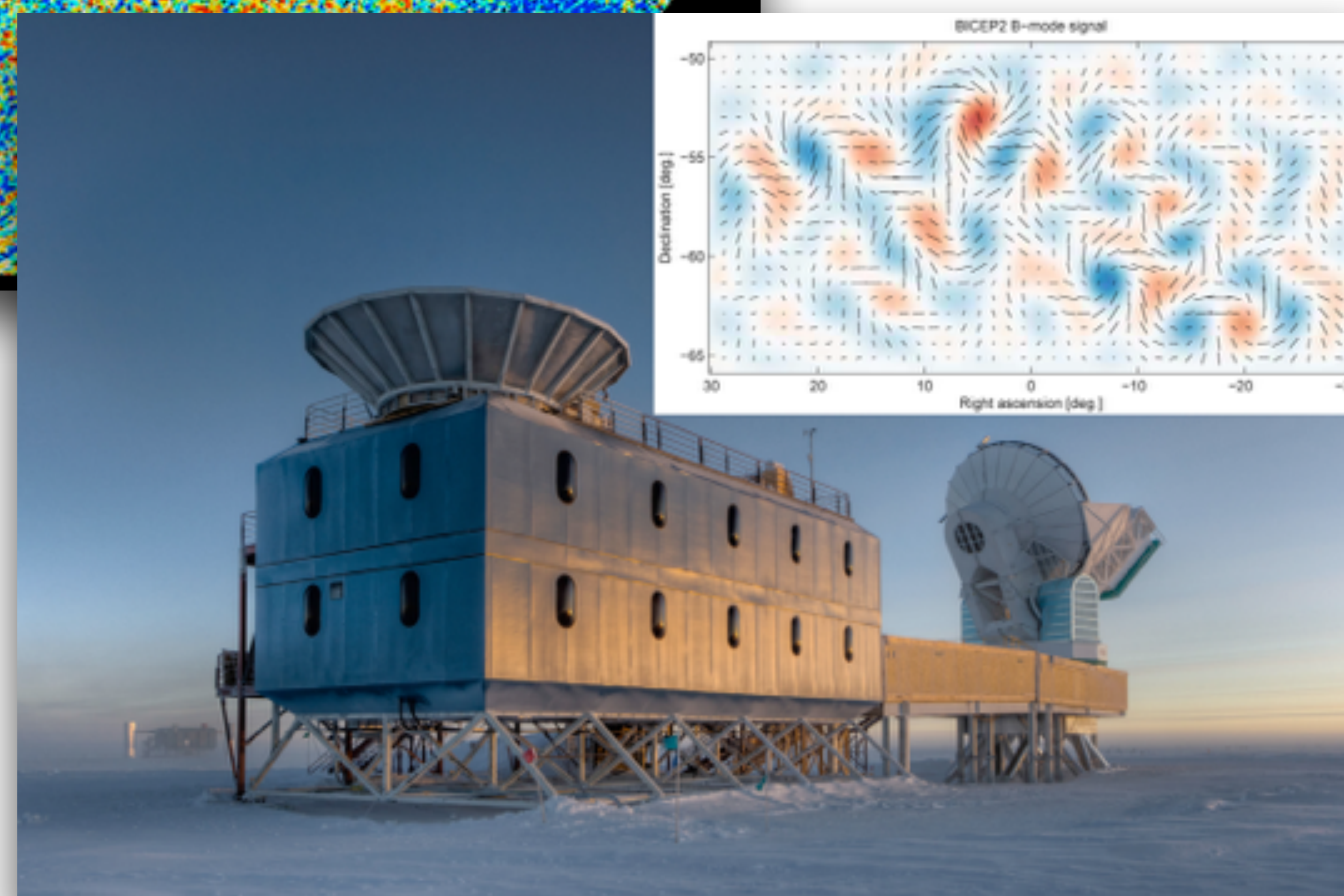
- For $T_* \sim 100\mathrm{GeV}$ and $\frac{f_*}{H_*} \sim \frac{\beta}{H_*} \sim 100$ the peak frequency falls into the LISA frequency band of milliHertz

Can We Hear the Echoes of 1st-order CPTs in CMB?



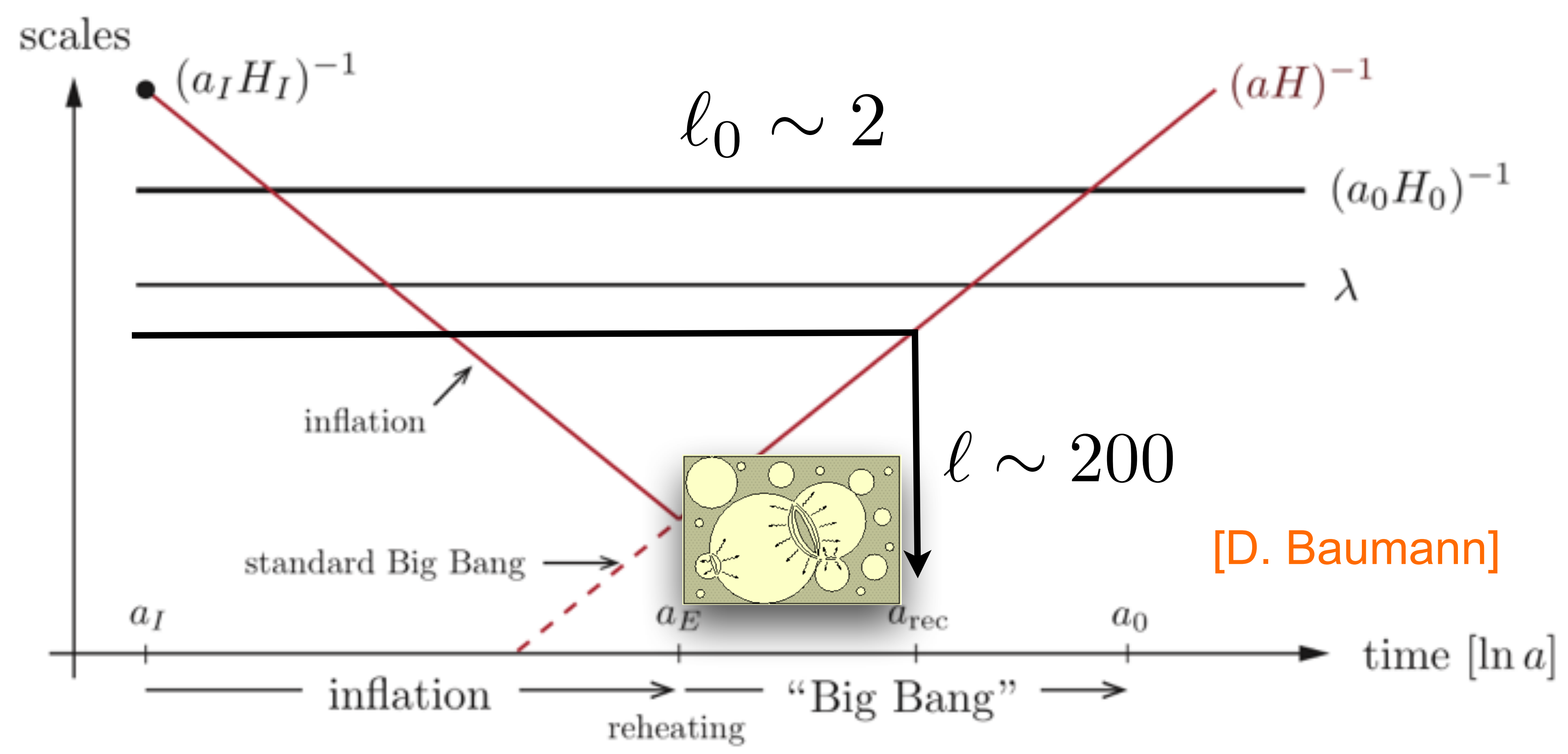
Planck

BICEP II



- Observables: anisotropic fluctuations in temperature and polarization of the CMB
- Well-known target: the GWs generated from vacuum fluctuation during inflation

1st Order CPTs after Reheating

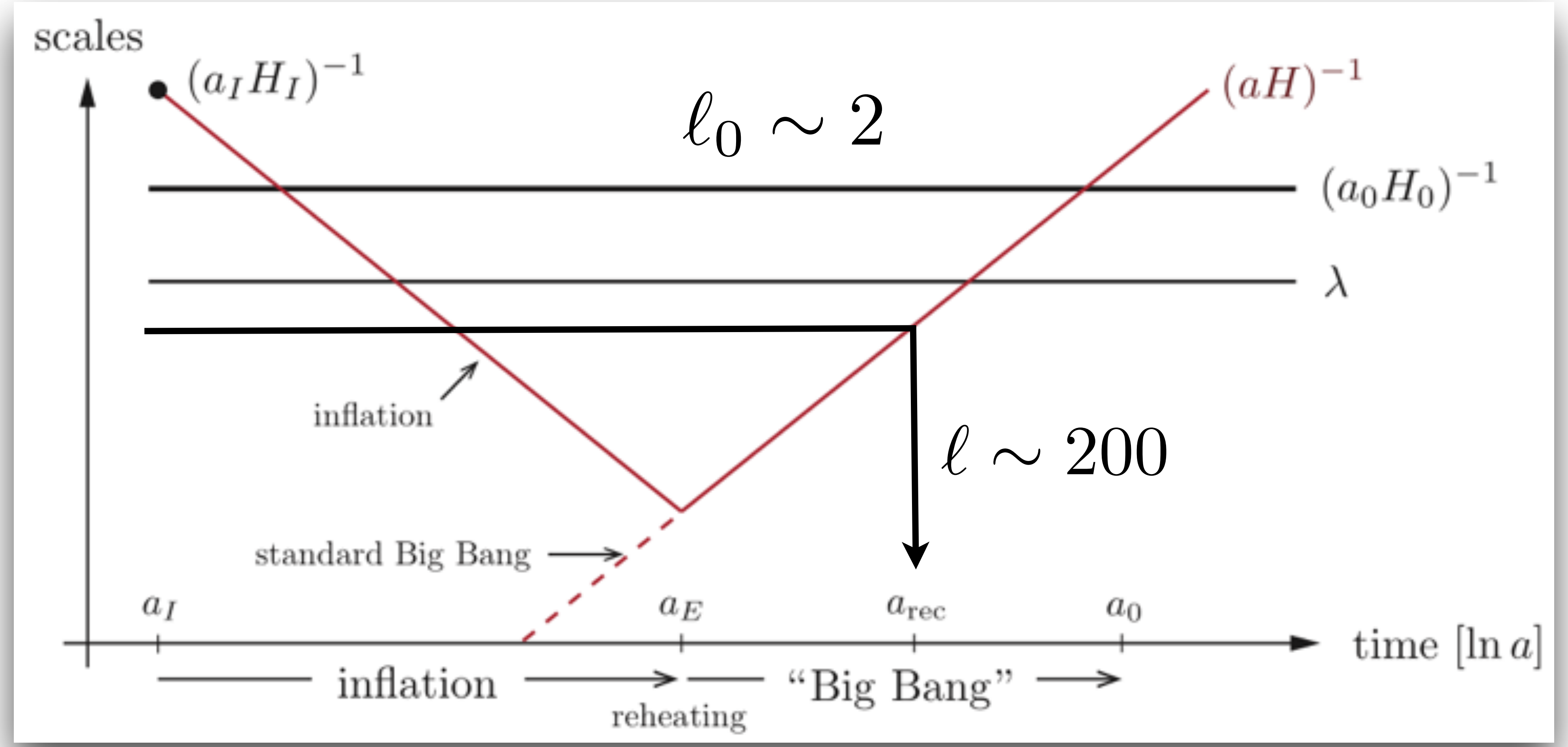


- EWPT: typically O(100-1000) bubbles per horizon volume (e.g., [C. Grojean and G. Servant,'07]

$$\frac{\text{Hubble volume}}{\text{bubble size}} \sim \frac{H^{-3}}{\beta^{-3}} \sim \left(\frac{\beta}{H}\right)^3$$

- Bubble collision at sub-horizon scale => too small to see in CMB

1st Order CPTs after Reheating

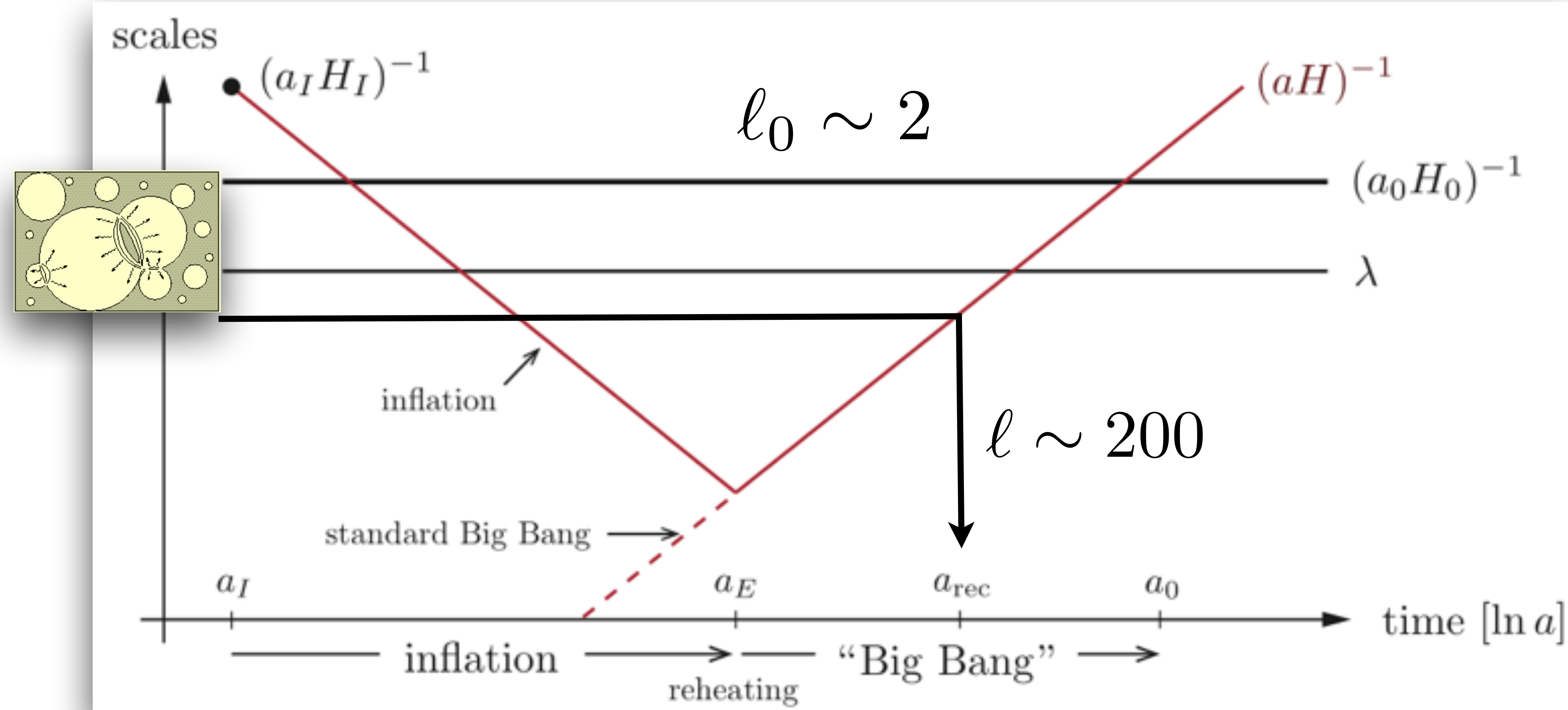


- EWPT: typically O(100-1000) bubbles per horizon volume (e.g., [C. Grojean and G. Servant,'07]

$$\frac{\text{Hubble volume}}{\text{bubble size}} \sim \frac{H^{-3}}{\beta^{-3}} \sim \left(\frac{\beta}{H}\right)^3$$

- Bubble collision at sub-horizon scale => too small characteristic wavelength => suppressed echo in CMB
- Any other possibilities?

1st Order CPTs after Reheating



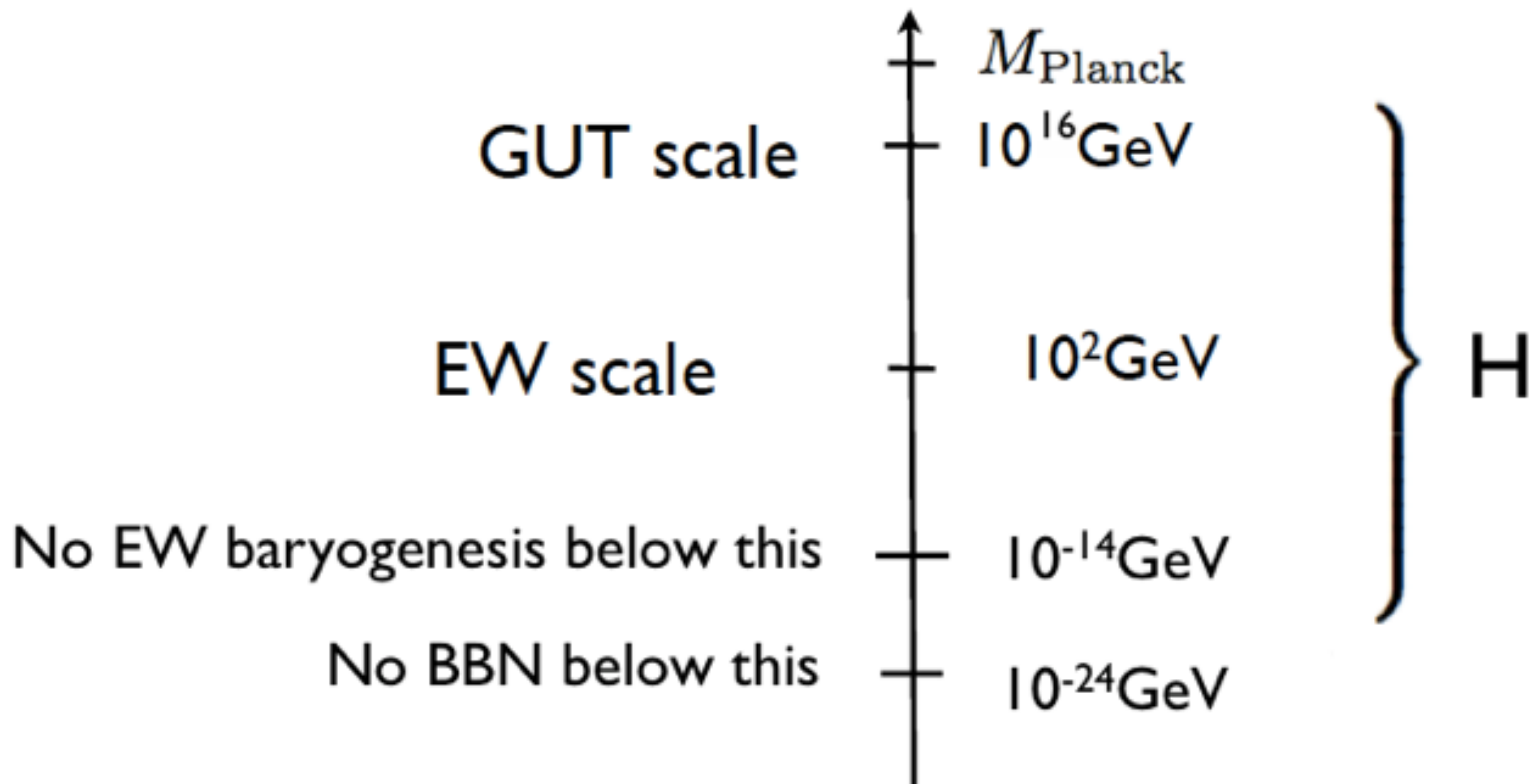
- EWPT: typically O(100-1000) bubbles per horizon volume (e.g., [C. Grojean and G. Servant,'07]

$$\frac{\text{Hubble volume}}{\text{bubble size}} \sim \frac{H^{-3}}{\beta^{-3}} \sim \left(\frac{\beta}{H}\right)^3$$

- Bubble collision at sub-horizon scale => too small characteristic wavelength => suppressed echo in CMB
- Assumption so far: 1st-order CPTs after reheating

Hubble Scale during Inflation

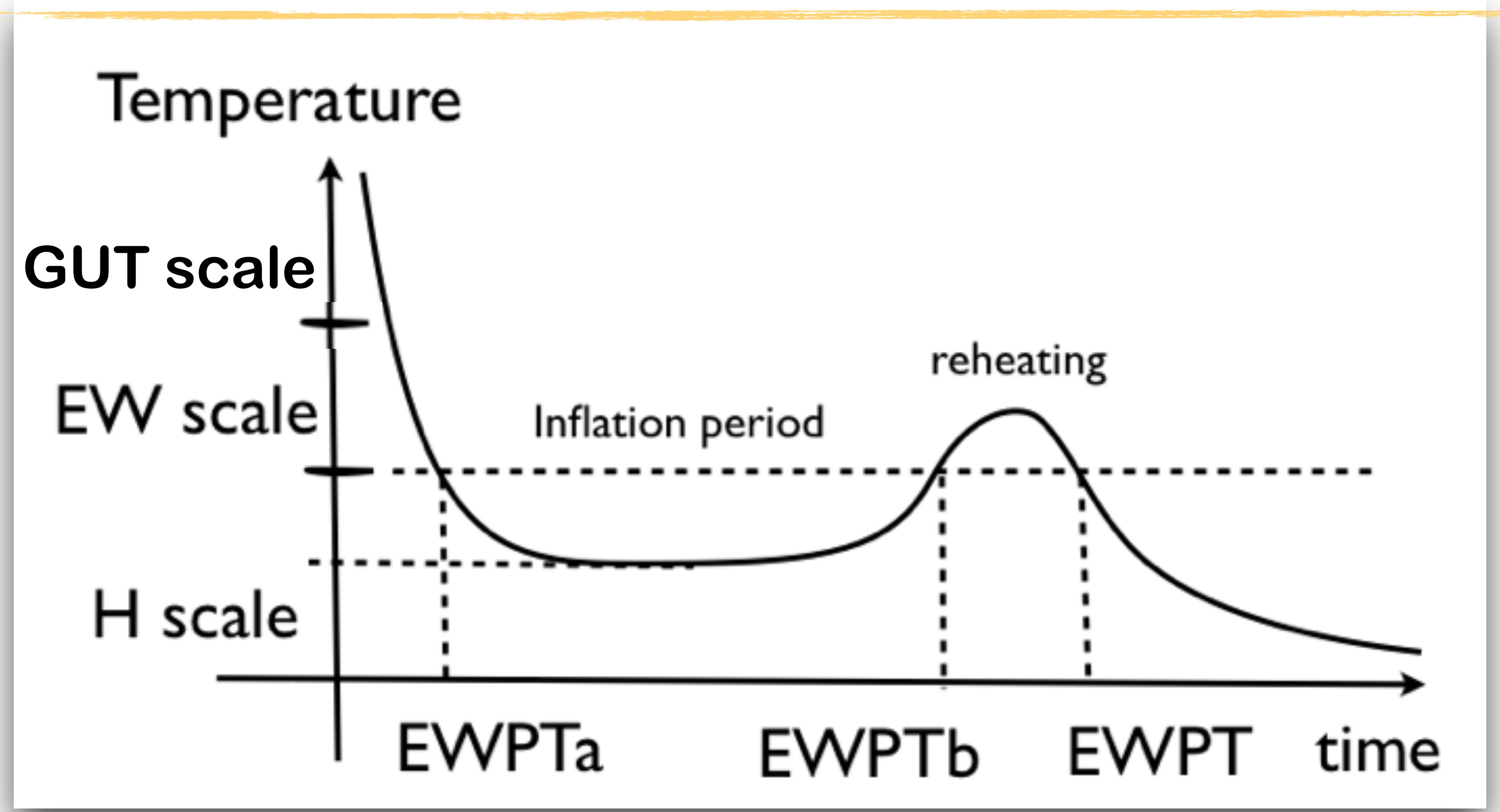
Experimentally valid inflation scale H



$$H^2 \sim \frac{1}{M_{\text{Pl}}^2}(\rho_{\text{inf}} + \rho_{\text{Higgs}} + \rho_{\text{rad}})$$

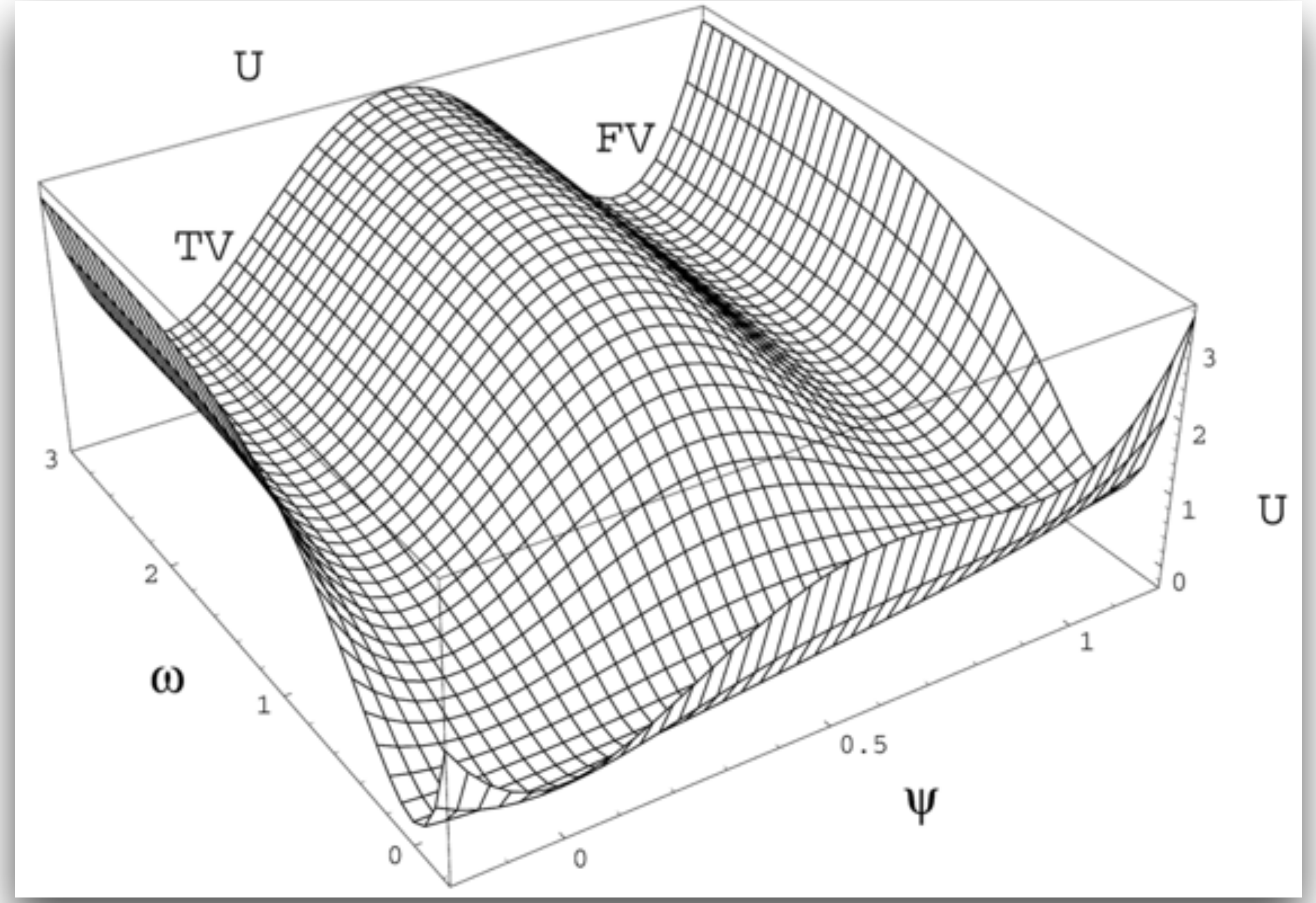
- Hubble scale during inflation - varies from 10^{-24} GeV up to GUT scale.
- H < 10^{-14} GeV => reheating temperature < 100 GeV => no EWPT after reheating
- H < 10^{-24} GeV => reheating temperature < 1 MeV => no big bang nucleosynthesis

Can We Hear the Echoes of 1st Order CPT in CMB?



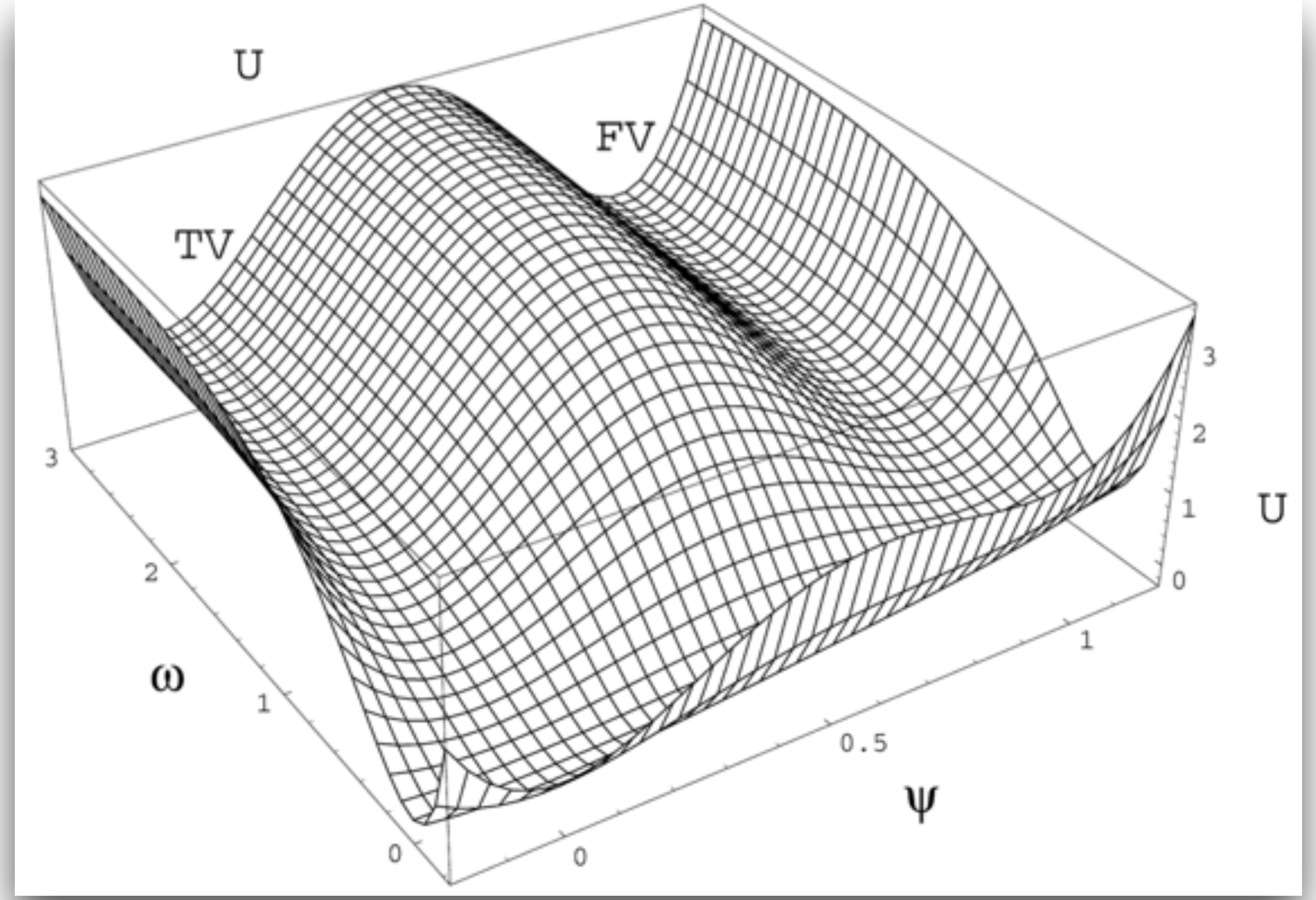
- At pre-inflation stage, radiation temperature decreases due to redshift
- Then the vacuum is stabilized to Hubble scale of inflation => G-H temperature
- 1st-order CPTs could occur at the pre-inflation stage if $\Lambda > H$
- E.g., 10^{-14} GeV < H < 100 GeV => reheating temperature > 100 GeV => three ``EWPT"

Inflationary Potential with a 1st Order CPT



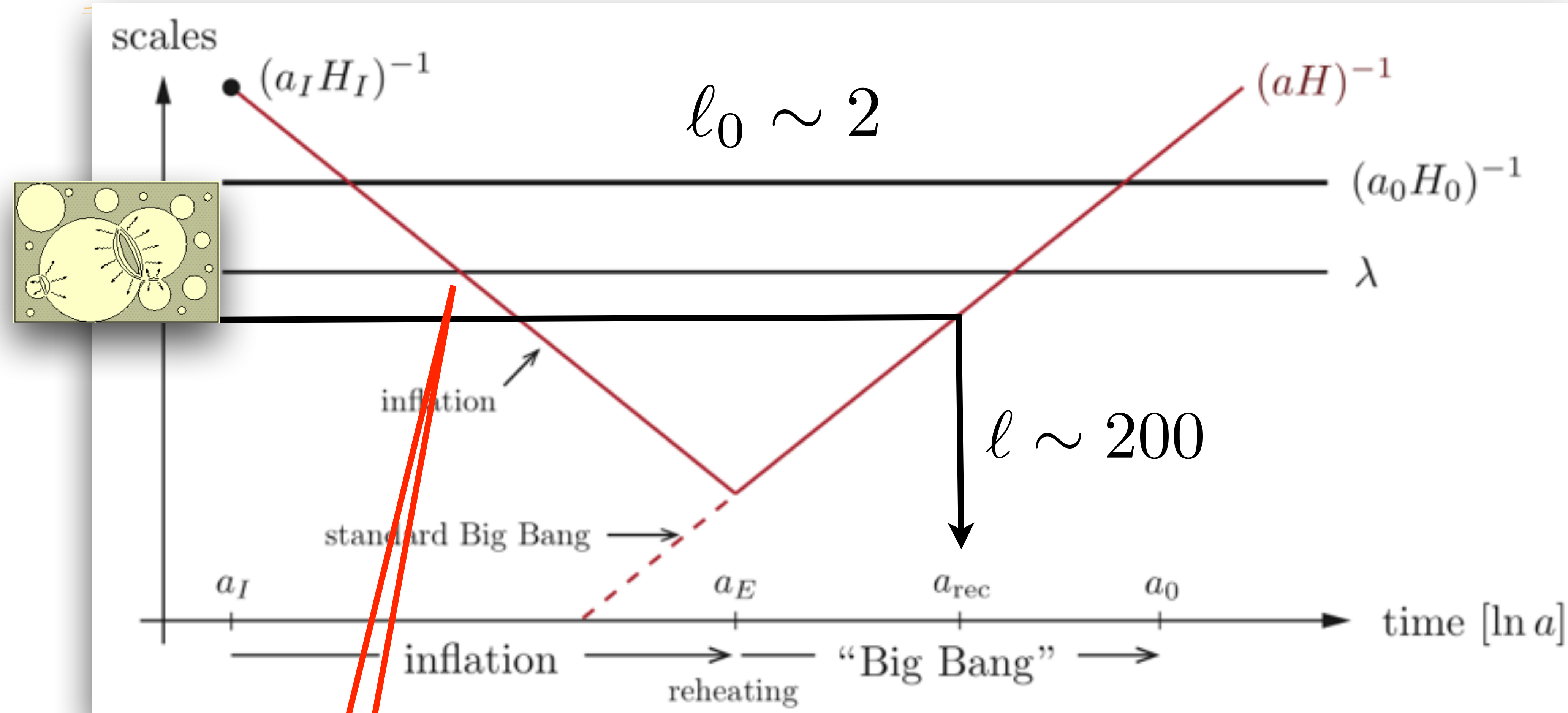
- Old inflation - 1st order CPT occurs along the inflaton direction
    - inflation happens outside the bubbles
    - no bubble collision => reheating or inflation exit problem

Inflationary Potential with a 1st Order CPT



- 1st-order CPT under study - along Higgs direction
  - inflation happens both outside and inside bubble
  - factor this effect out => bubble collision due to expansion

Scale-dependent Power Spectrum



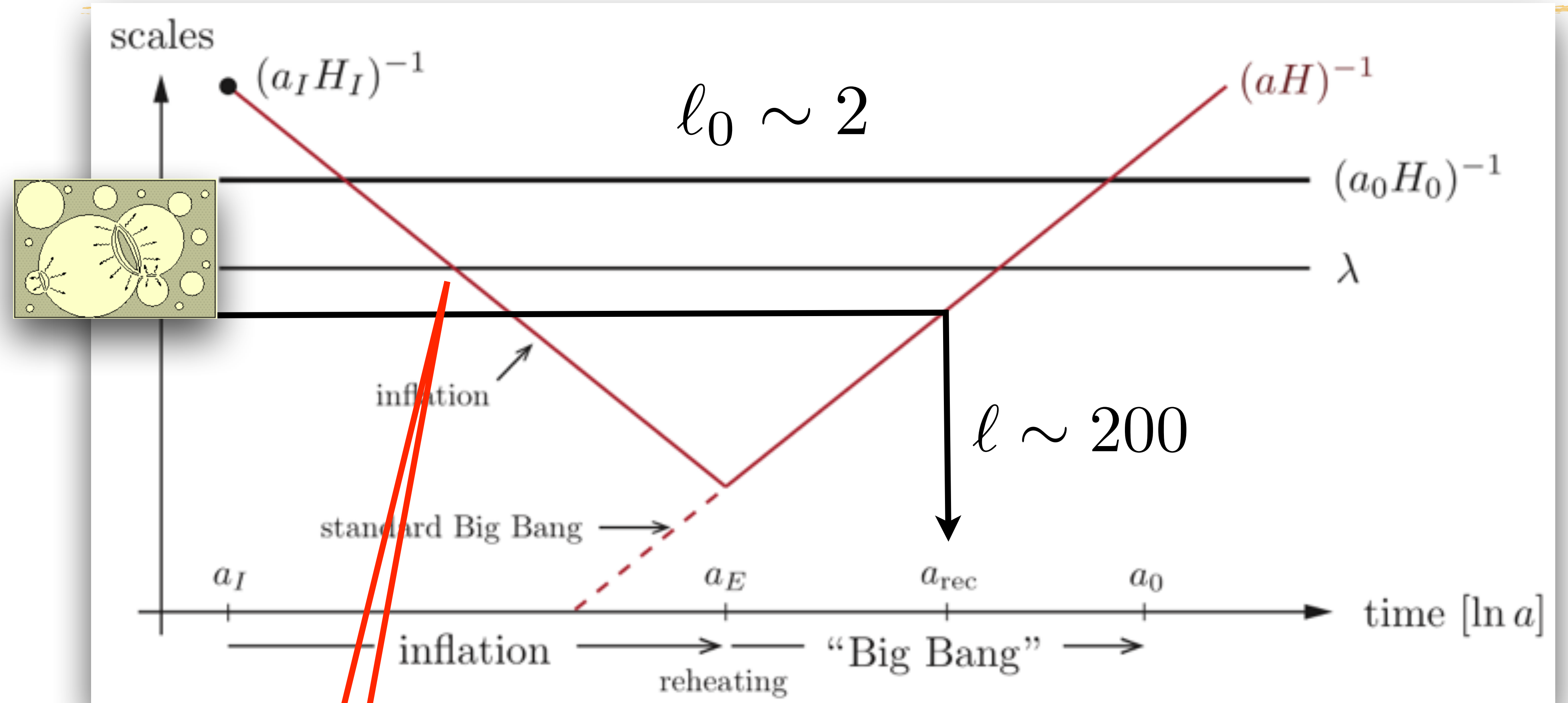
- Bubble collisions at sub-horizon scale => the GW power spectrum when the modes exit the horizon

$$P_\gamma(k, \tau_{obs} \to 0) = P_\gamma^{crit} \left(\frac{k_{crit}}{k}\right)^4 \frac{(a+b)k_{crit}^b k^a}{b k_{crit}^{a+b} + a k^{a+b}} \quad P_\gamma^{crit} \sim \left(\frac{H}{\beta}\right)^6 \left(\frac{\rho_{higgs}}{\rho_{tot}}\right)^2$$

- Need to introduce a cutoff for k - a*H => three free parameters

$$P_\gamma^{crit}, \; k_{crit} \; \text{and} \; k_{cutoff}$$

Scale-dependent Power Spectrum

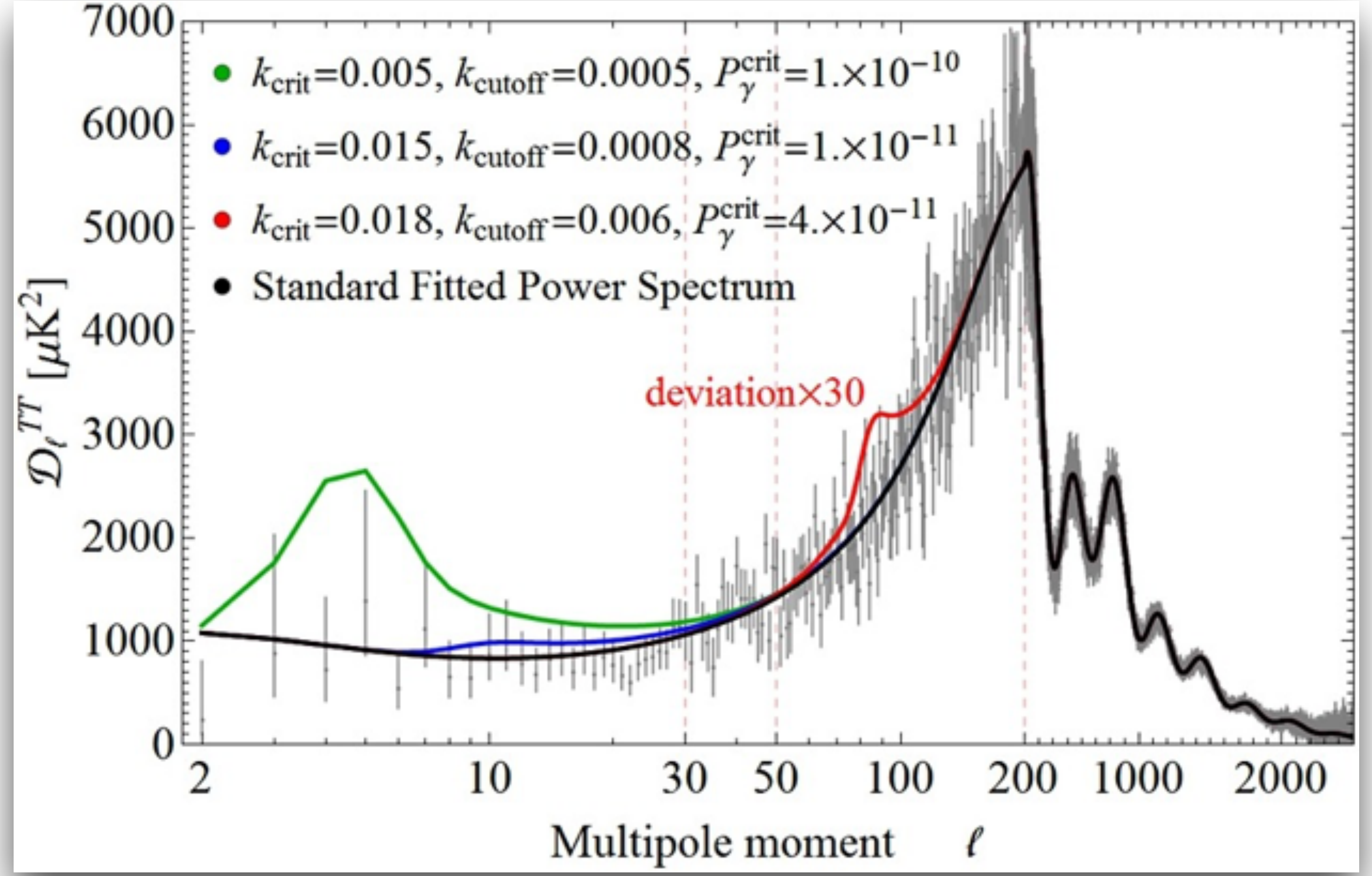


- Bubble collisions at sub-horizon scale => the GW power spectrum when the modes exit the horizon

$$P_\gamma(k, \tau_{obs} \to 0) = P_\gamma^{crit} \left(\frac{k_{crit}}{k}\right)^4 \frac{(a+b)k_{crit}^b k^a}{b k_{crit}^{a+b} + a k^{a+b}} \quad P_\gamma^{crit} \sim \left(\frac{H}{\beta}\right)^6 \left(\frac{\rho_{higgs}}{\rho_{tot}}\right)^2$$

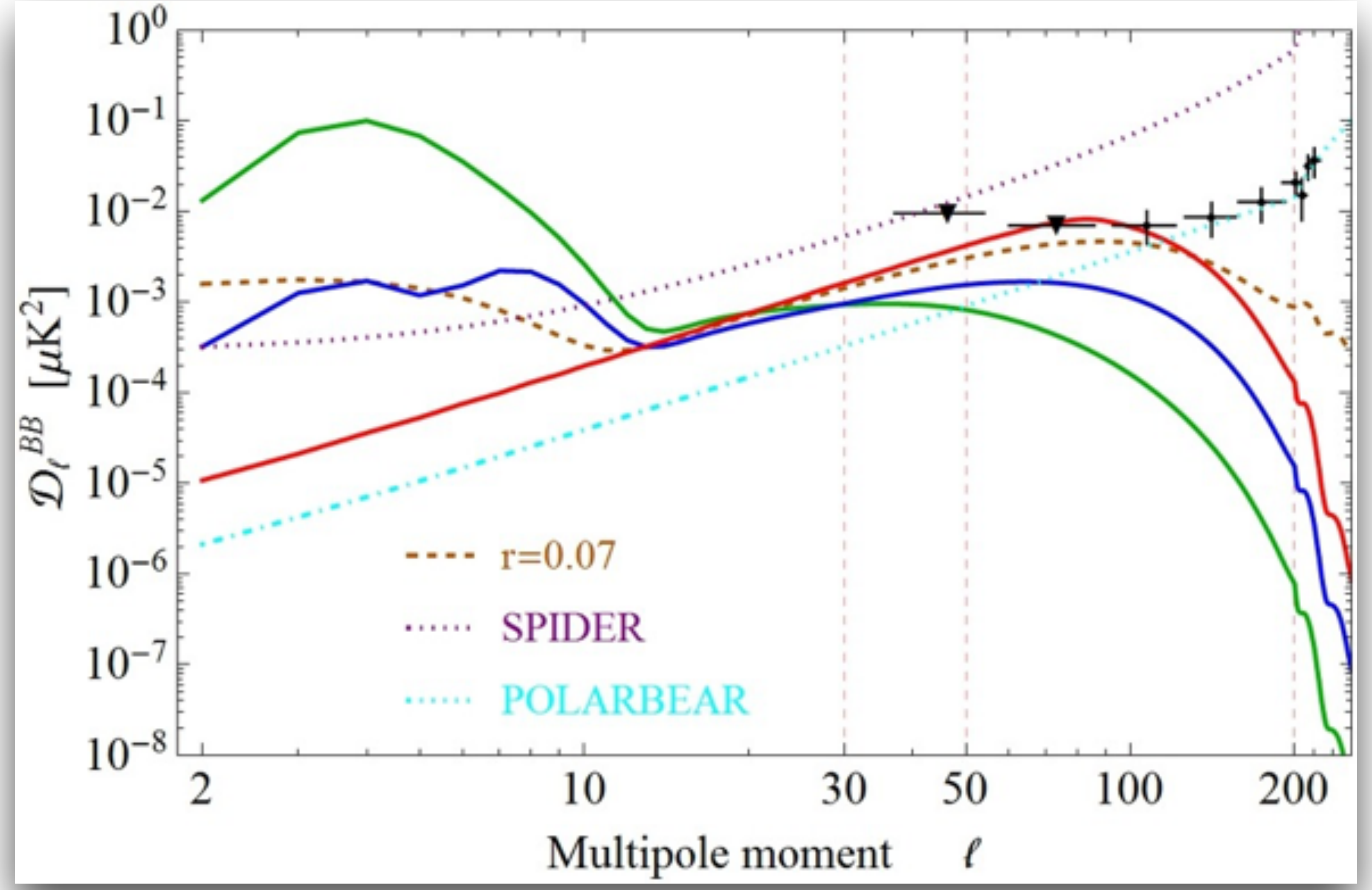
- Scale-dependent - different from power spectrum of primordial GWs!

Temperature Power Spectrum



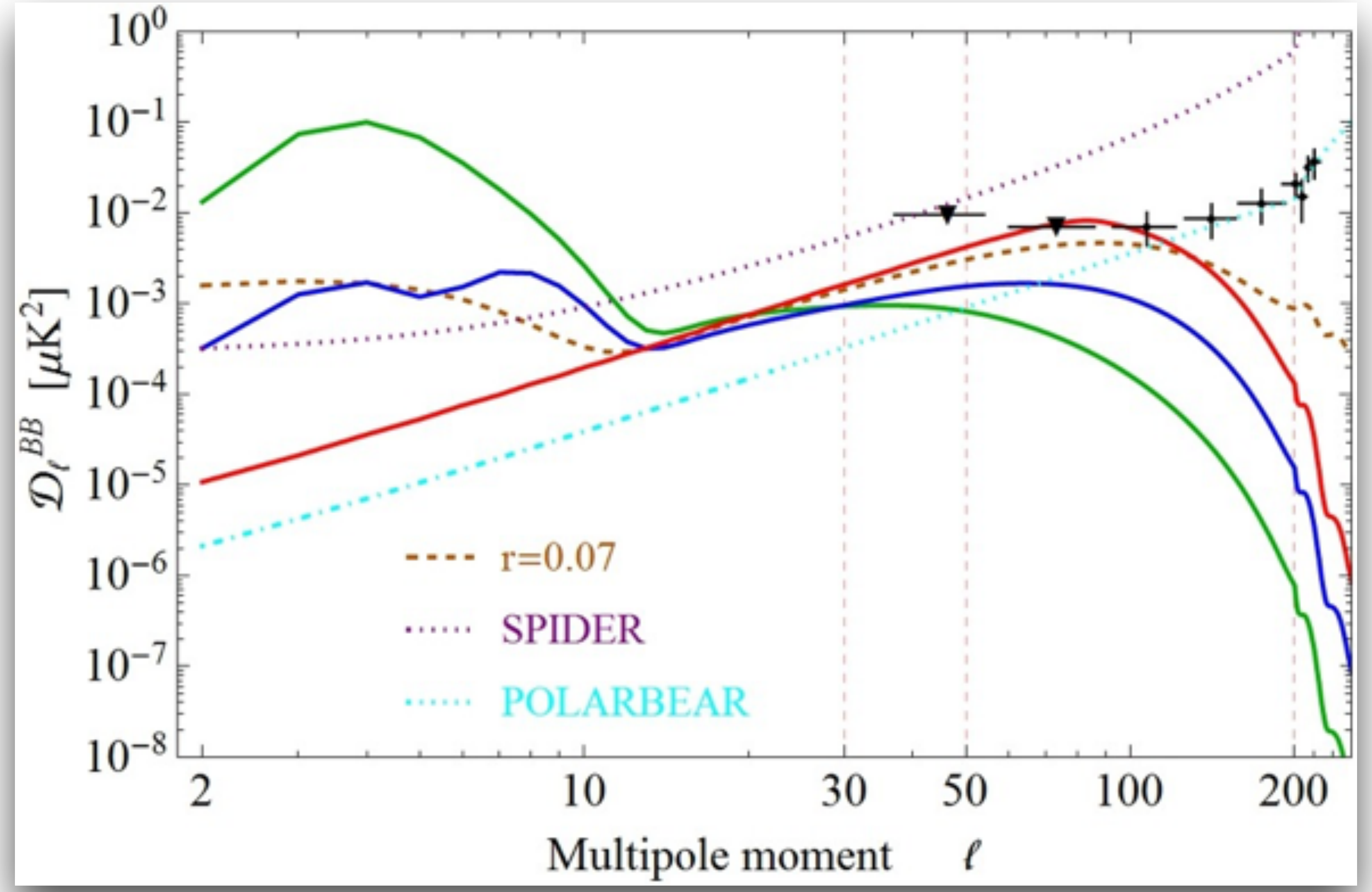
- Resonant-like structure may appear

B-mode Power Spectrum



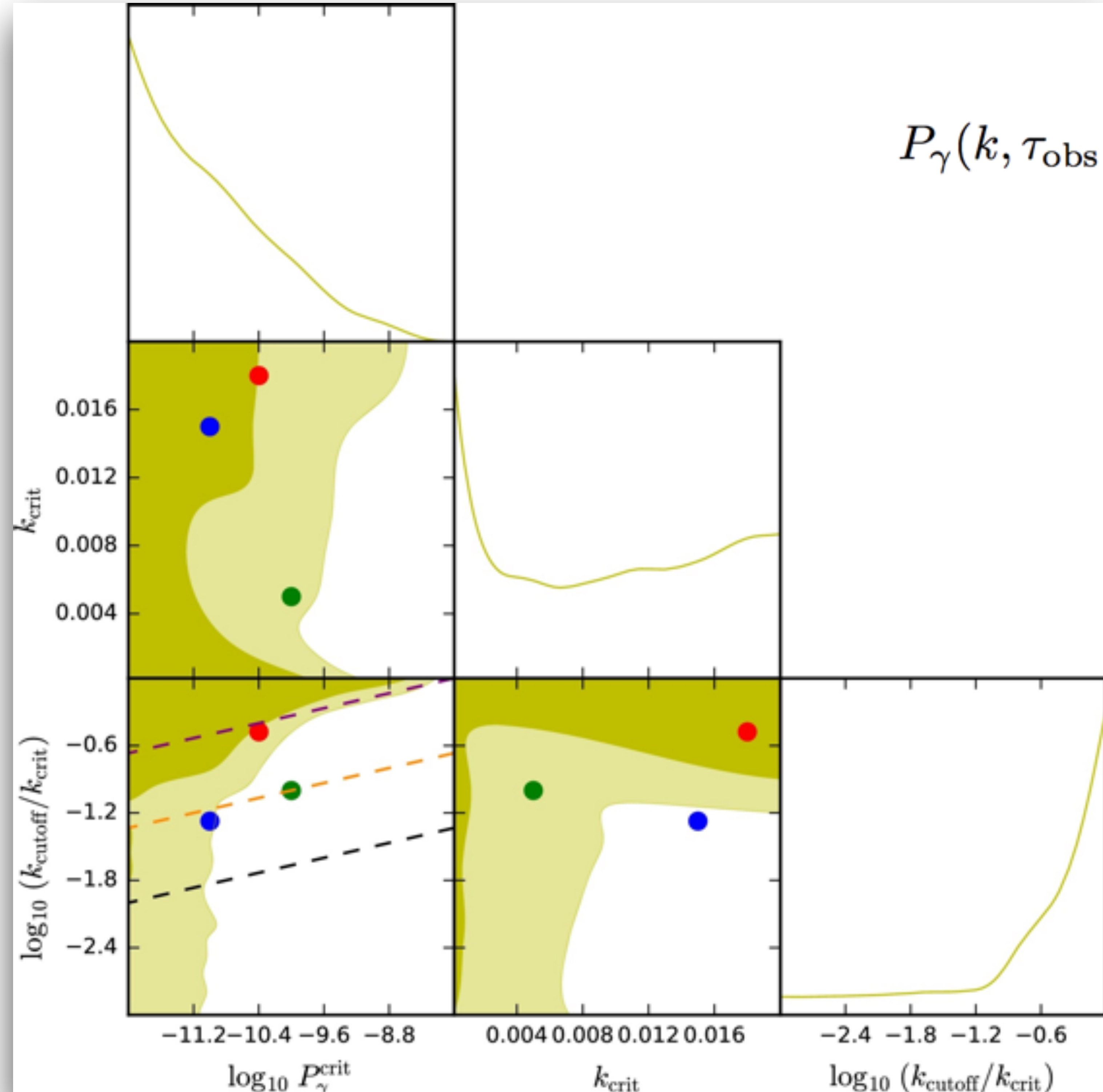
- Primordial GWs: a recombination peak + reionization bump at l < 10
- GWs from 1st-order CPTs: the relative strength of the B-mode spectrum depends on multipole moments more strongly!

B-mode Power Spectrum



- Effective noise level of SPIDER and POLARBEAR: instrumental noise + foregrounds
- POLARBEAR is limited in probing large angular scales due to its relatively small survey areas in sky as a ground-based experiment

Constraints of PLANCK2015 and BICEP/KECK



$$P_\gamma(k, \tau_{\rm obs} \to 0) = P_\gamma^{\rm crit} \left(\frac{k_{\rm crit}}{k}\right)^4 \frac{(a+b)k_{\rm crit}^b k^a}{b k_{\rm crit}^{a+b} + a k^{a+b}}$$

$$P_\gamma^{\rm crit} \sim \left(\frac{H}{\beta}\right)^6 \left(\frac{\rho_{\rm higgs}}{\rho_{\rm tot}}\right)^2$$

- Marginalization (CosmoMC)
- Dashed lines: rho_higgs/ rho_tot = 1, 10^-2, 10^-4
- Sensitive to k_{cutoff} / k_{crit}: characterize the magnitude of P_gamma
- Blue and green benchmarks have been excluded at 2sigma C.L.

GUT and EW Phase Transitions

$$P_\gamma(k, k_{\rm crit}, \tau_{\rm obs} \to 0) = 24\left(\frac{a(\tau_*)H}{k}\right)^4 \Omega_{GW}(k, k_{\rm crit}, \tau_*) \sim \left(\frac{H}{\beta}\right)^6 \left(\frac{\rho_{\rm Higgs}}{\rho_{\rm total}}\right)^2$$

- GUT PT: expected to happen at pre-inflation

$$P_\gamma^{\rm crit} \sim 10^{-10} \;=>\; \left(\frac{H}{\beta}\right)^6 \sim 10^{-6},\; \rho_{\rm GUT} \sim (10^{16}{\rm GeV})^4 \Rightarrow H \sim 10^{13}{\rm GeV}$$

- EWPT: expected to happen at pre-inflation or after reheating

$$P_\gamma^{\rm crit} \sim 10^{-10} \;=>\; \left(\frac{H}{\beta}\right)^6 \sim 10^{-6}, \rho_{\rm EW} \sim (10^2{\rm GeV})^4 \Rightarrow H \sim 10^{-13}{\rm GeV}$$

Summary

The nature of CPT can serve as a probe for fundamental physics in nature

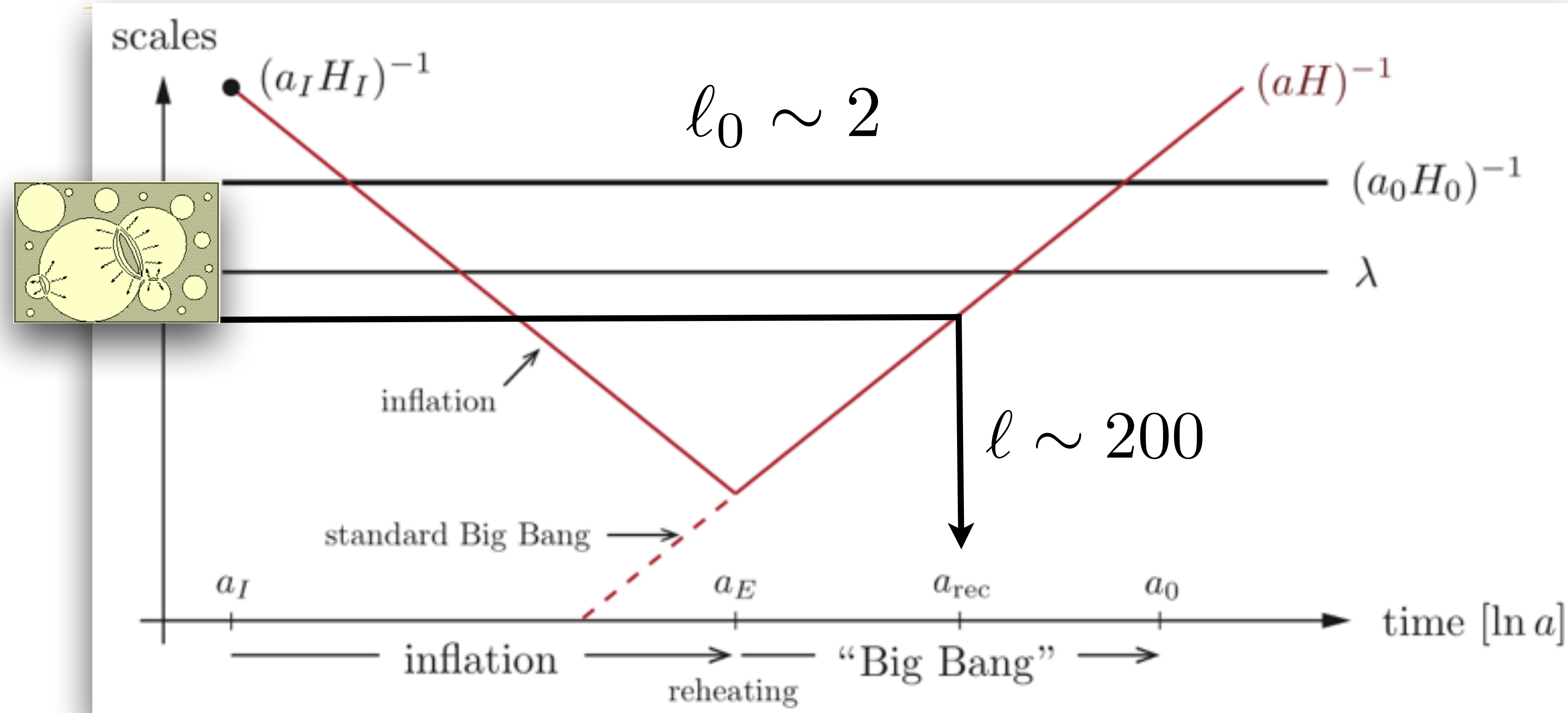
The power spectrum of the GWs produced during 1st-order CPTs is scale-dependent, different from that of primordial GWs.

If being generated before or at the beginning stage of inflation, it may leave an distinguishable imprint in the CMB, and hence can be detected using CMB data.

This provides us a chance to probe the nature of CPTs with CMB.


Thank you!

Scale-dependent Power Spectrum

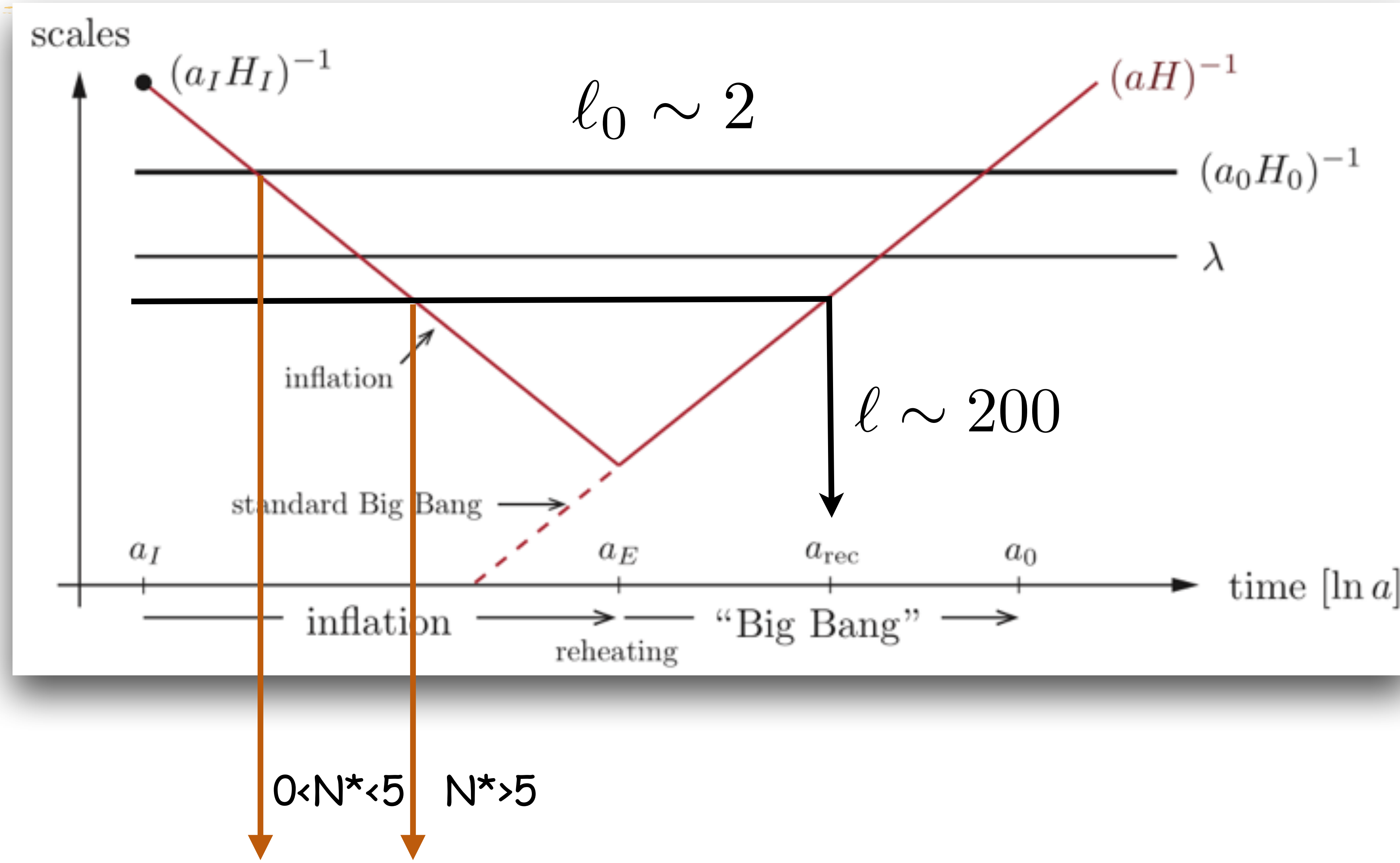


- k_{crit} and k_{cutoff} can be converted to angular multiple moments

$$\ell_{\mathrm{crit}} \sim \ell_0 \frac{e^{N_*}\beta}{(v_b H)} \qquad \ell_{\mathrm{cutoff}} \sim \ell_0 e^{N_*}, \qquad \text{with } \ell_0 \sim 2$$

- N*, the e-folding number counting from the moment that the mode $1/a_0H_0$ exited the horizon to the CPT moment

Scale-dependent Power Spectrum



- N* < 5 => l < 200: scale-dependent power spectrum
- N* > 5 => l > 200: the GW modes re-enter the horizon before recombination, subjecting to rapid decay due to redshift