Anisotropies in the Gravitational Wave Background from Cosmological Phase Transitions

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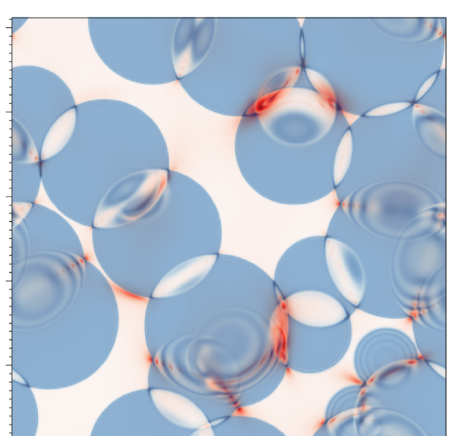
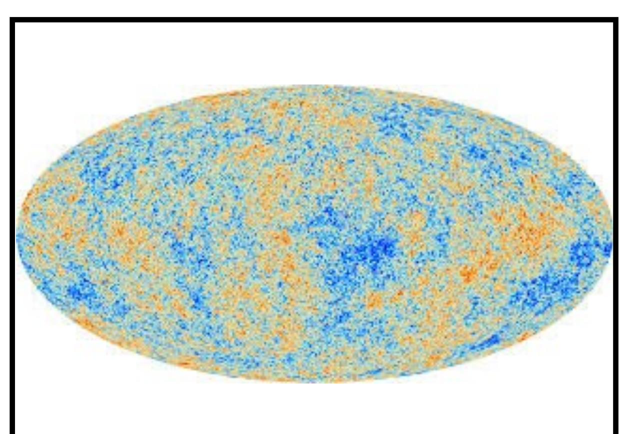
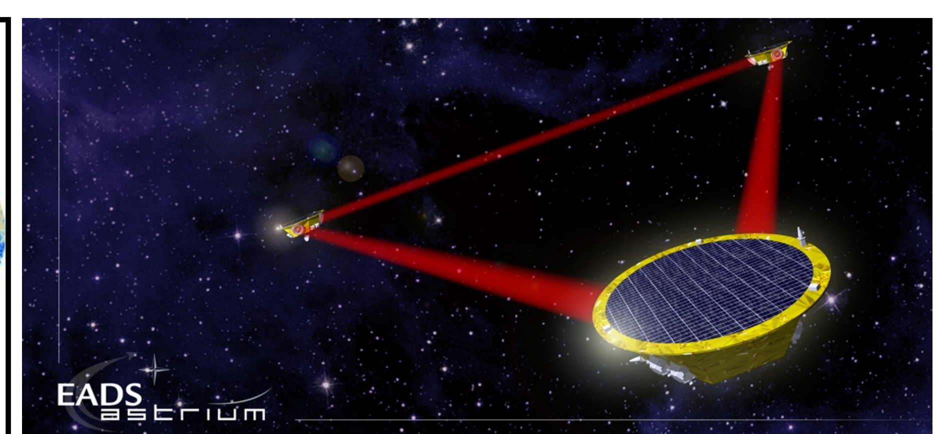
arXiv:1803.10780 M. **G.**, Anson **Ho**ok, Raman **S**undrum, Yuhsin **Tsai**





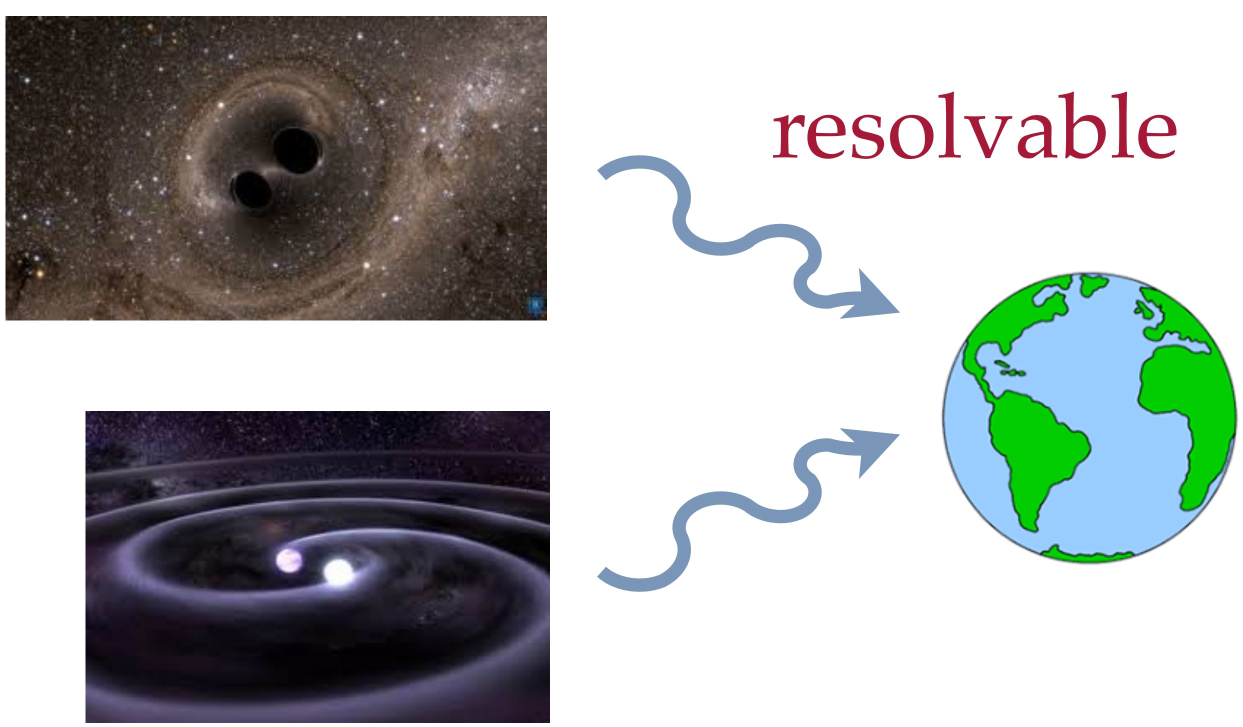


Gravitational Wave (GW) Cosmology

Different sources of GW in the sky

Astrophysical sources

black hole, neutron star, white dwarf mergers



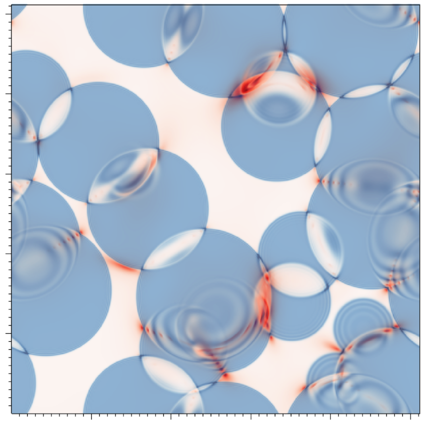
Study physics of gravity, astro dynamics, QCD,

Gravitational Wave (GW) Cosmology

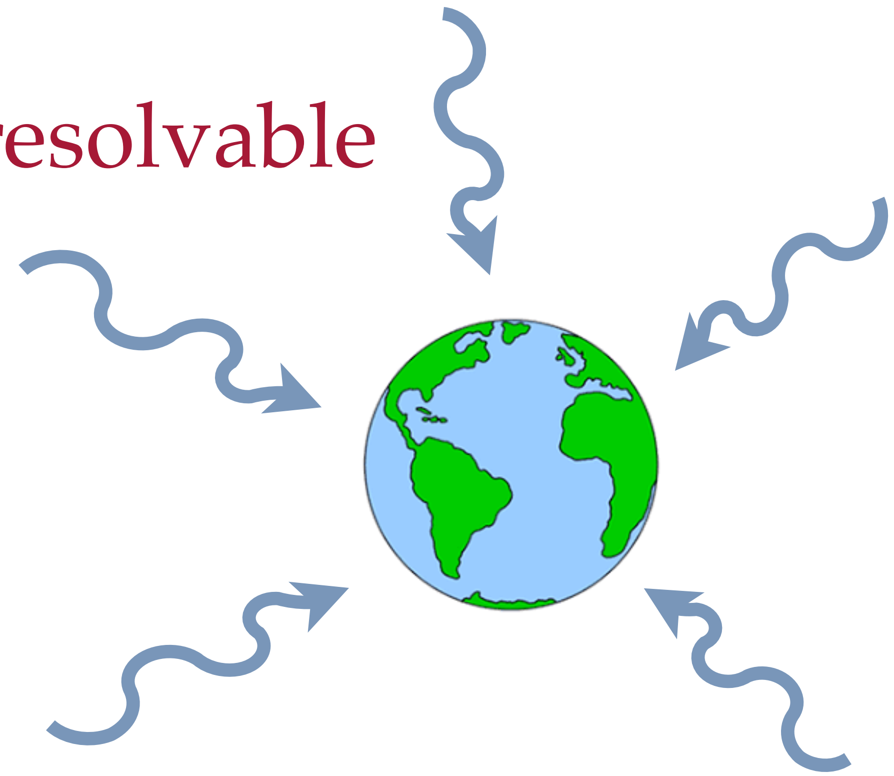
Different sources of GW in the sky

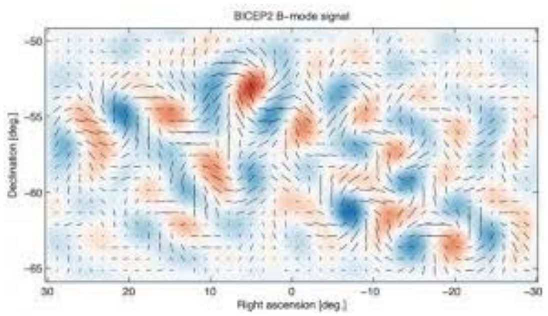
Cosmological sources

Phase transition (PT), inflation, pre-heating, cosmic string,…



unresolvable

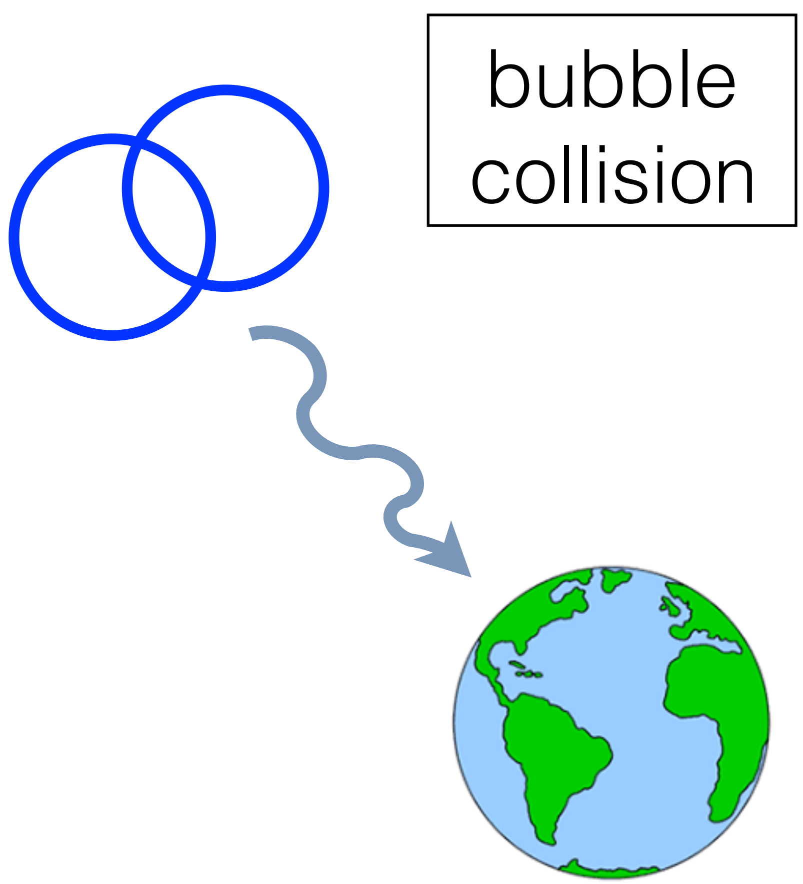


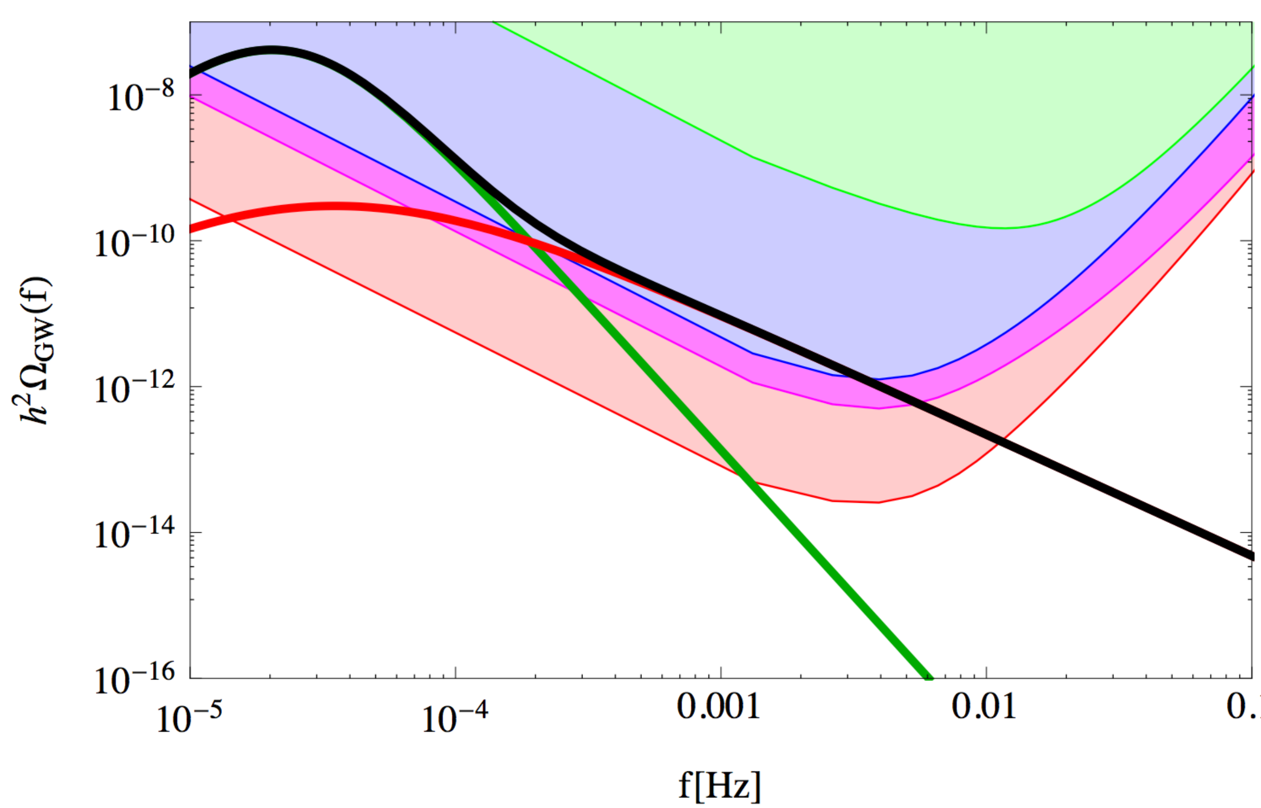


Study physics of inflation/reheating, universe evolution

GW from first order phase transition

Most of the discussions so far have been focusing on GW's energy / frequency spectrum from PT

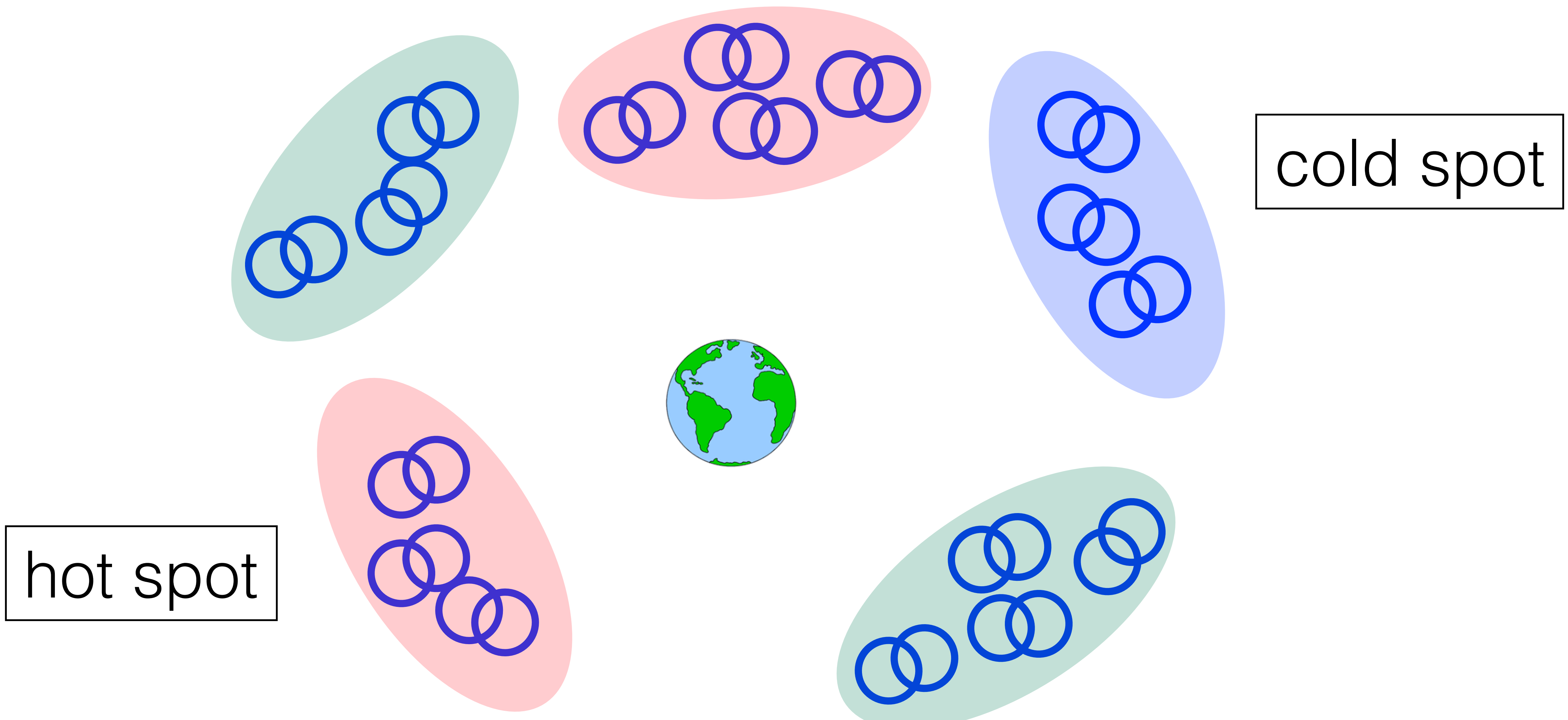




1512.06239

GW from first order phase transition

However, the **anisotropic pattern** of GW provides valuable info of inflation / reheating mechanism



many earlier studies on stochastic GWB,
e.g., see Romano & Cornish (2017) and the reference there

Gravitational Wave Background (GWB)

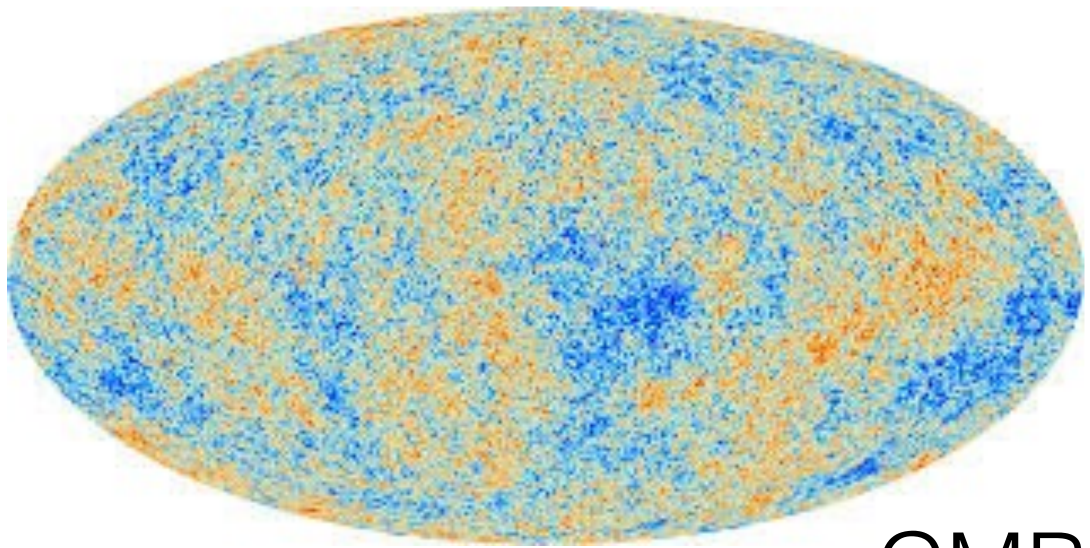
Similar to the CMB spectrum, but with

photon from last scattering -> GW from PT

hot spot

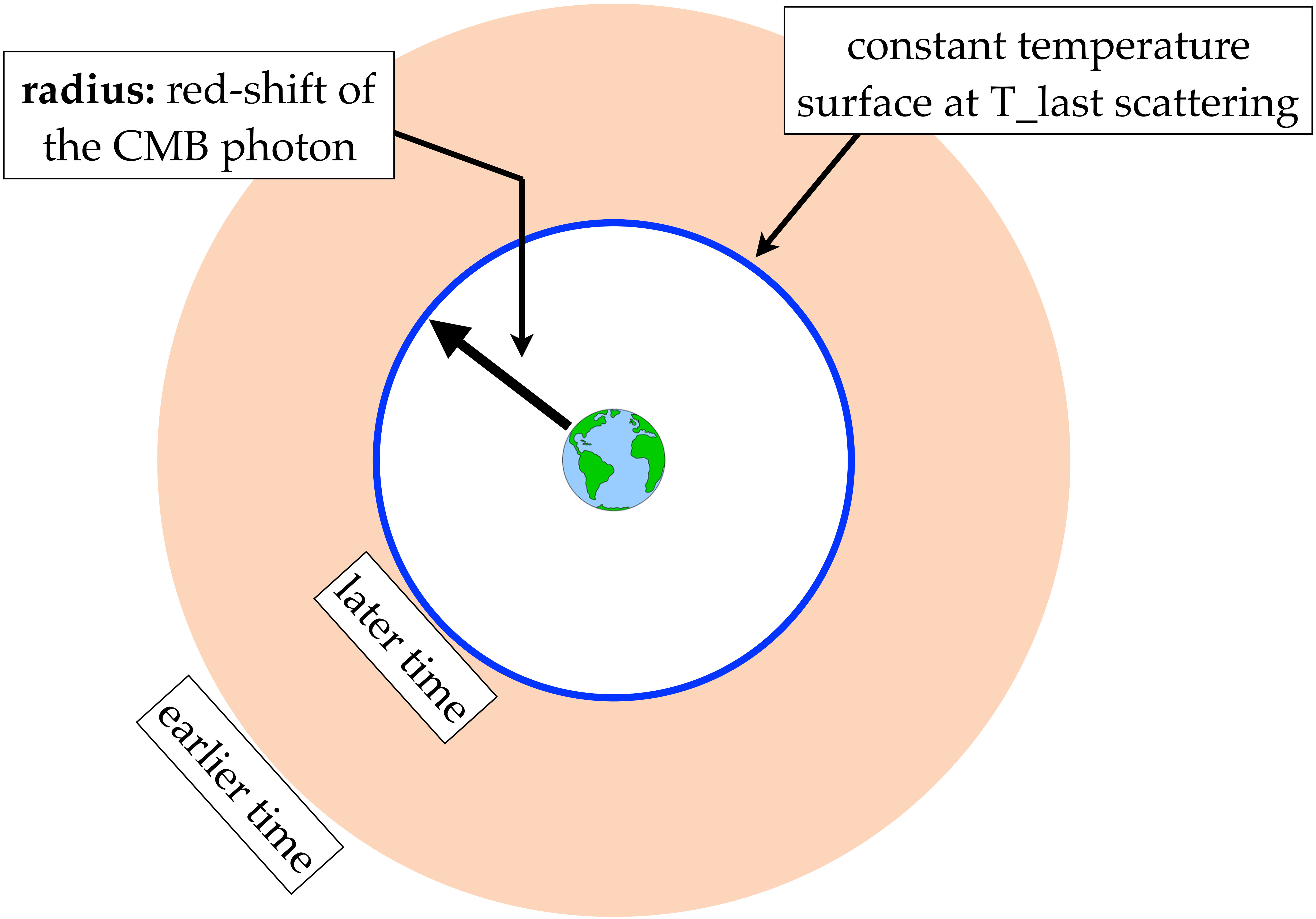
Higher energy photons

Higher energy GW

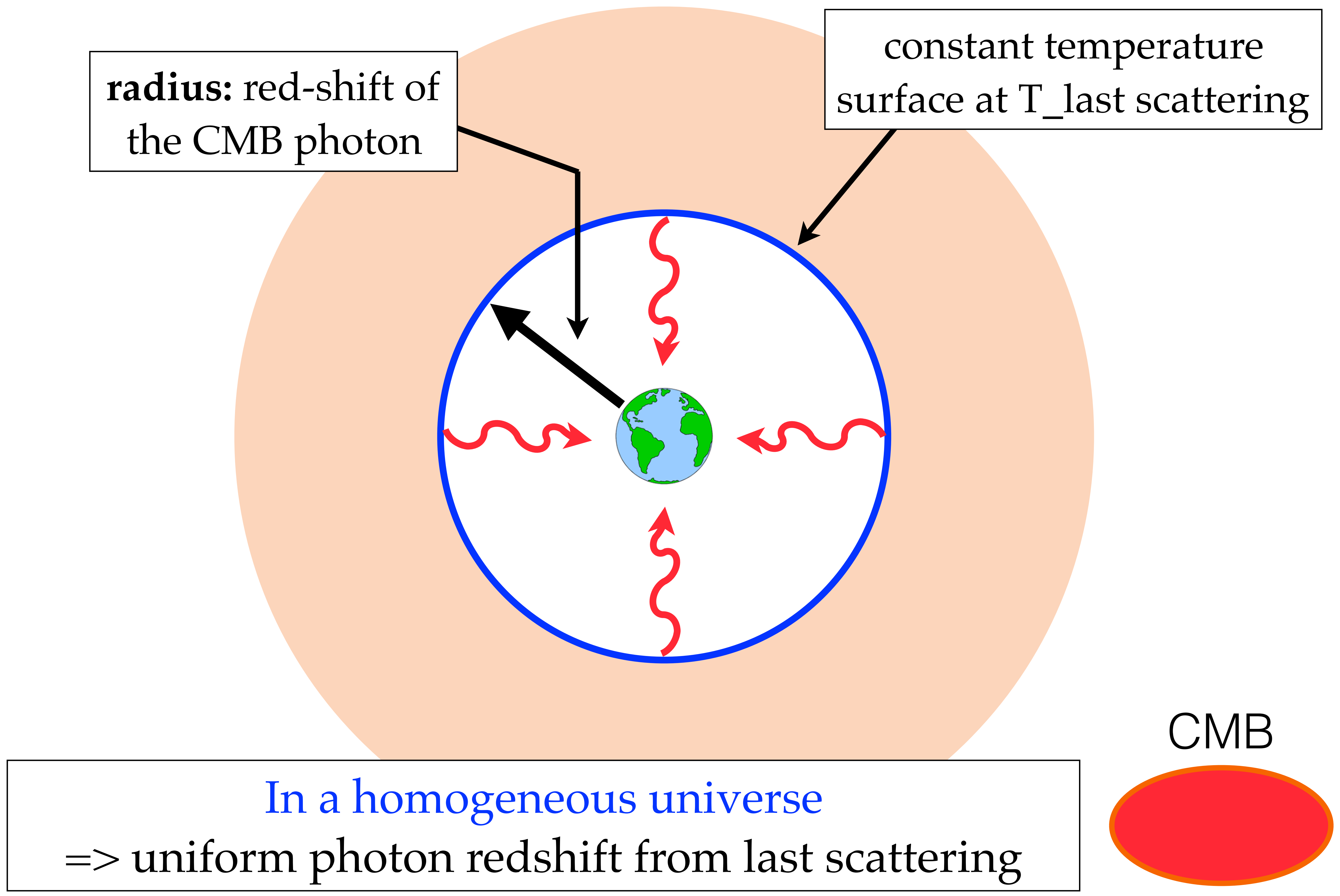


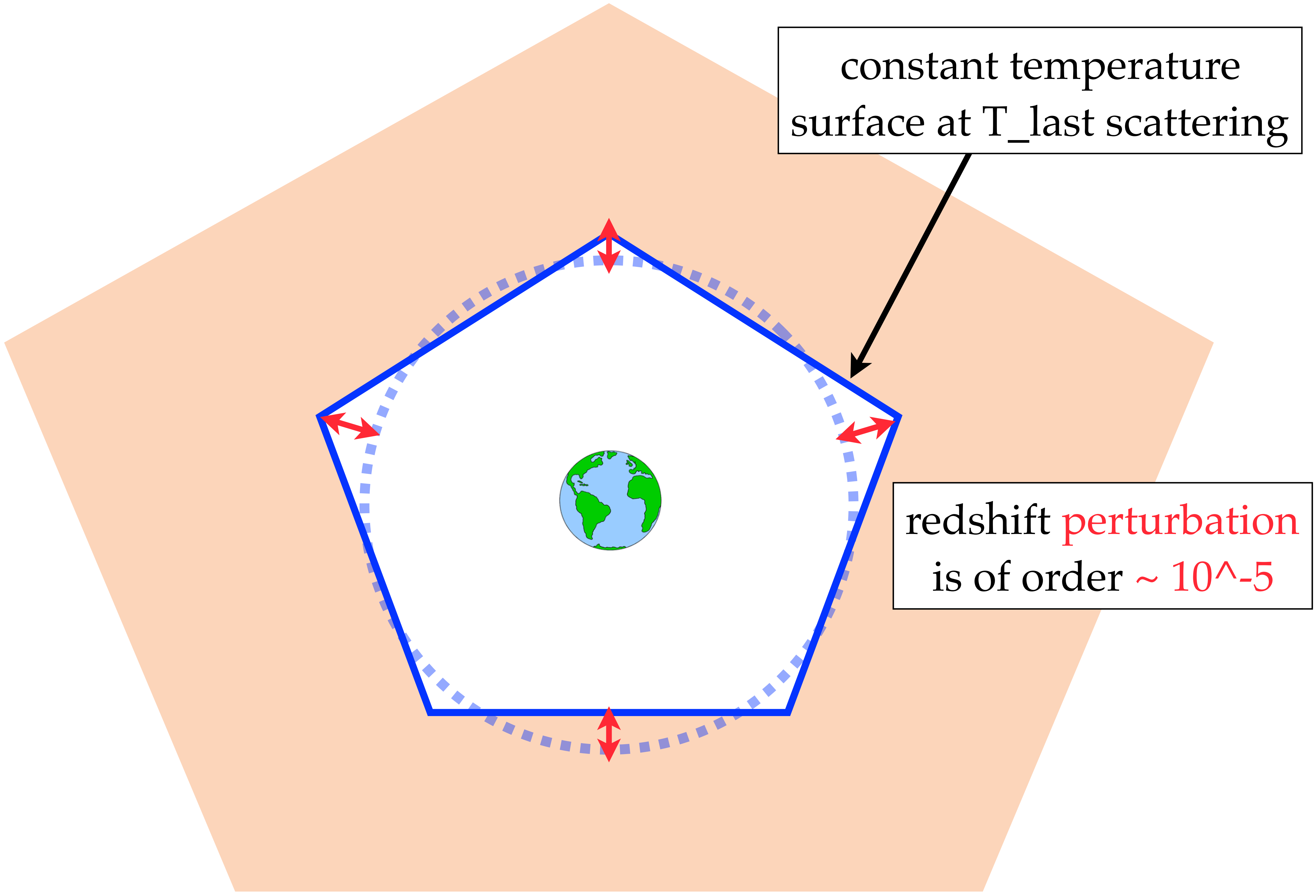
CMB

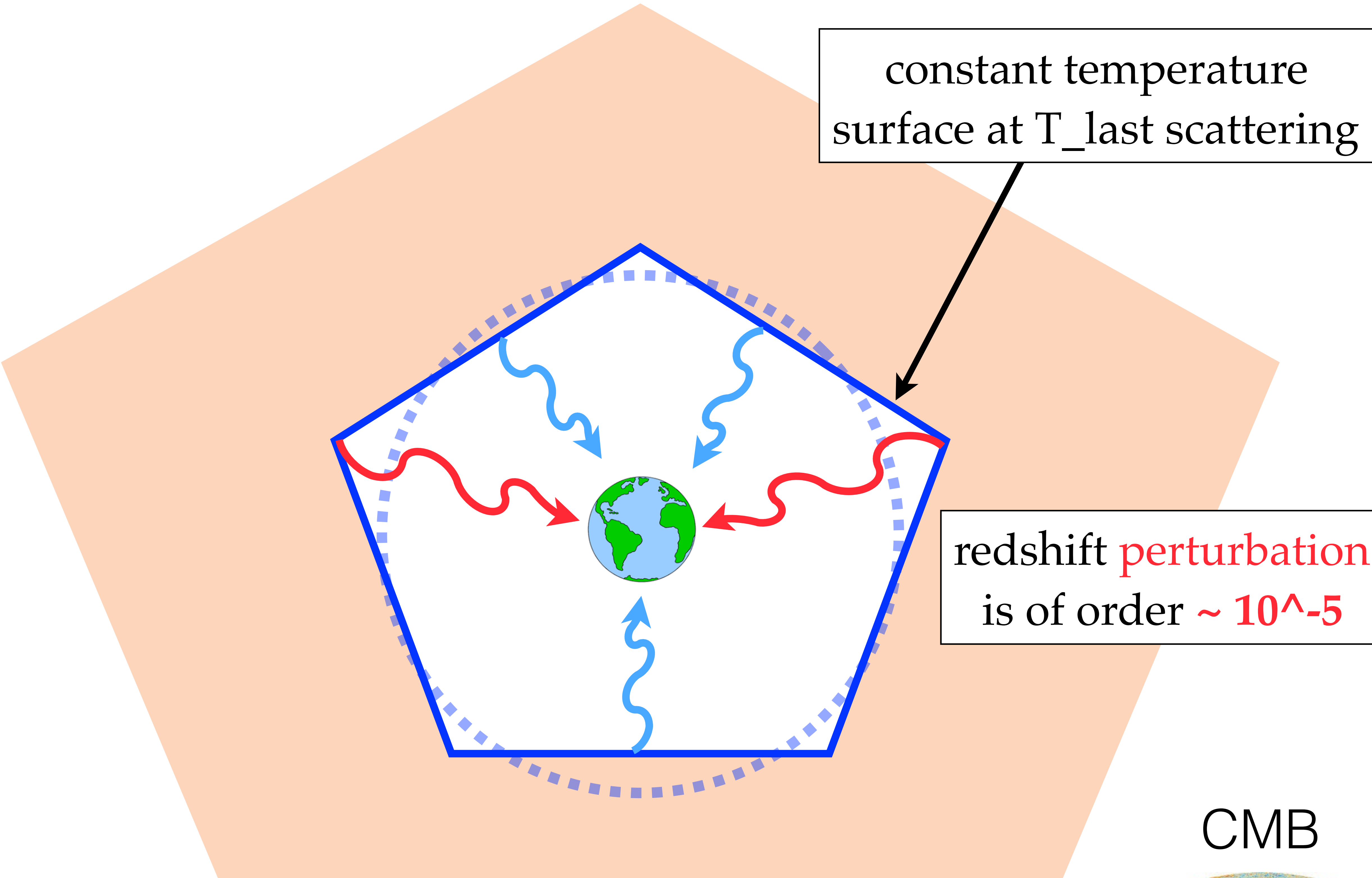
where does the hot / cold spot come from?



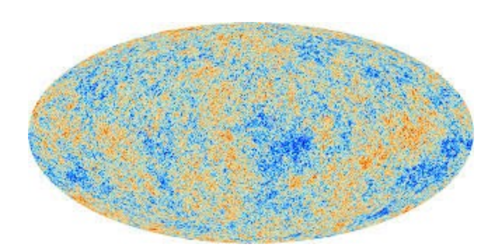
radius: red-shift of the CMB photon
constant temperature surface at T_last scattering
later time
earlier time


radius: red-shift of the CMB photon
constant temperature surface at T_last scattering
CMB
In a homogeneous universe
=> uniform photon redshift from last scattering


constant temperature
surface at T_last scattering
redshift perturbation
is of order ~ 10^-5

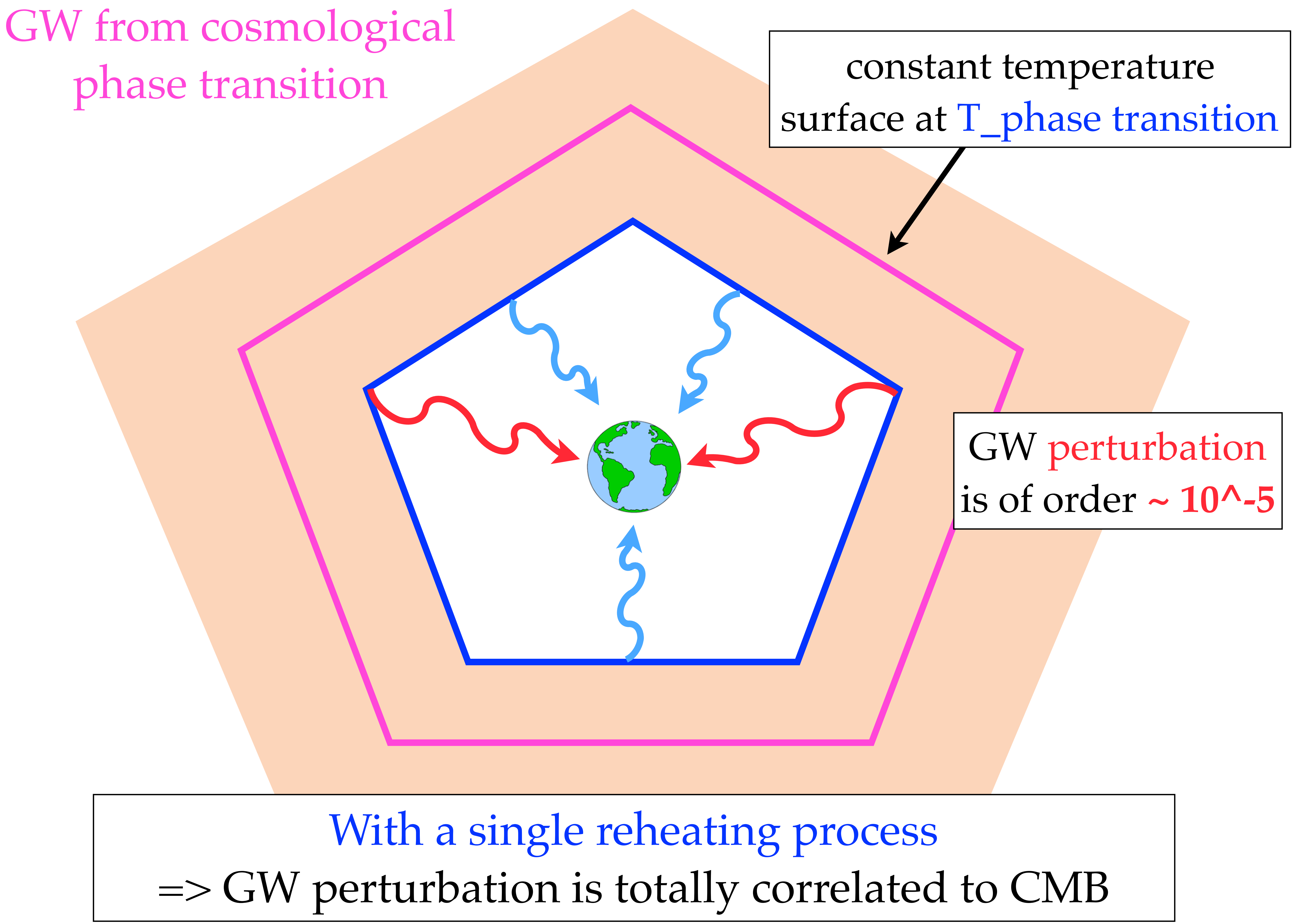


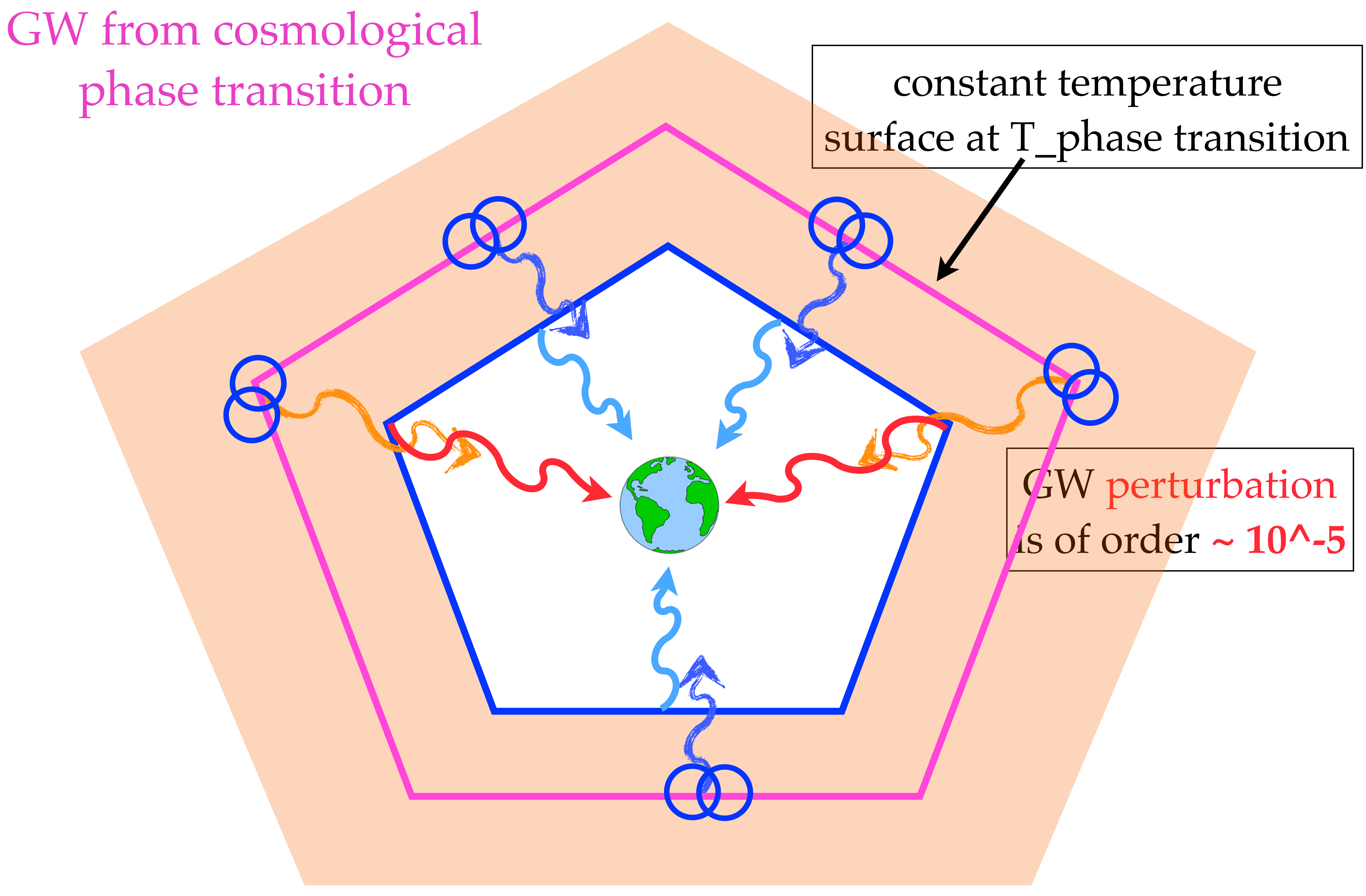
CMB



With primordial temperature perturbation

=> anisotropic redshift for last scattering photon


GW from cosmological
phase transition
constant temperature
surface at T_phase transition
GW perturbation
is of order ~ 10^-5
With a single reheating process
=> GW perturbation is totally correlated to CMB

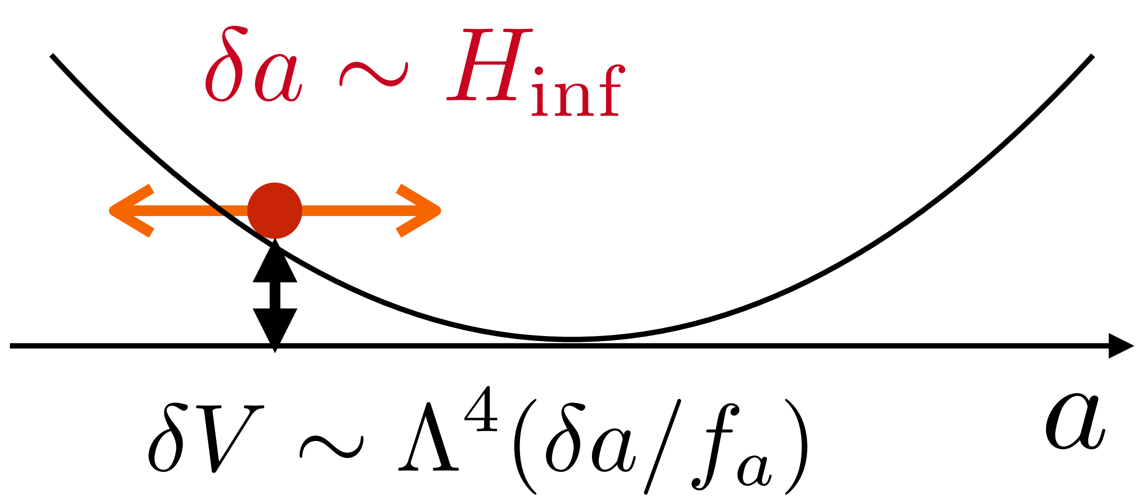

GW from cosmological
phase transition
constant temperature
surface at T_phase transition
GW perturbation
is of order ~ 10^-5

Iso-curvature perturbation

If in addition to the inflaton, there's an **axion-like particle** fluctuating during inflation

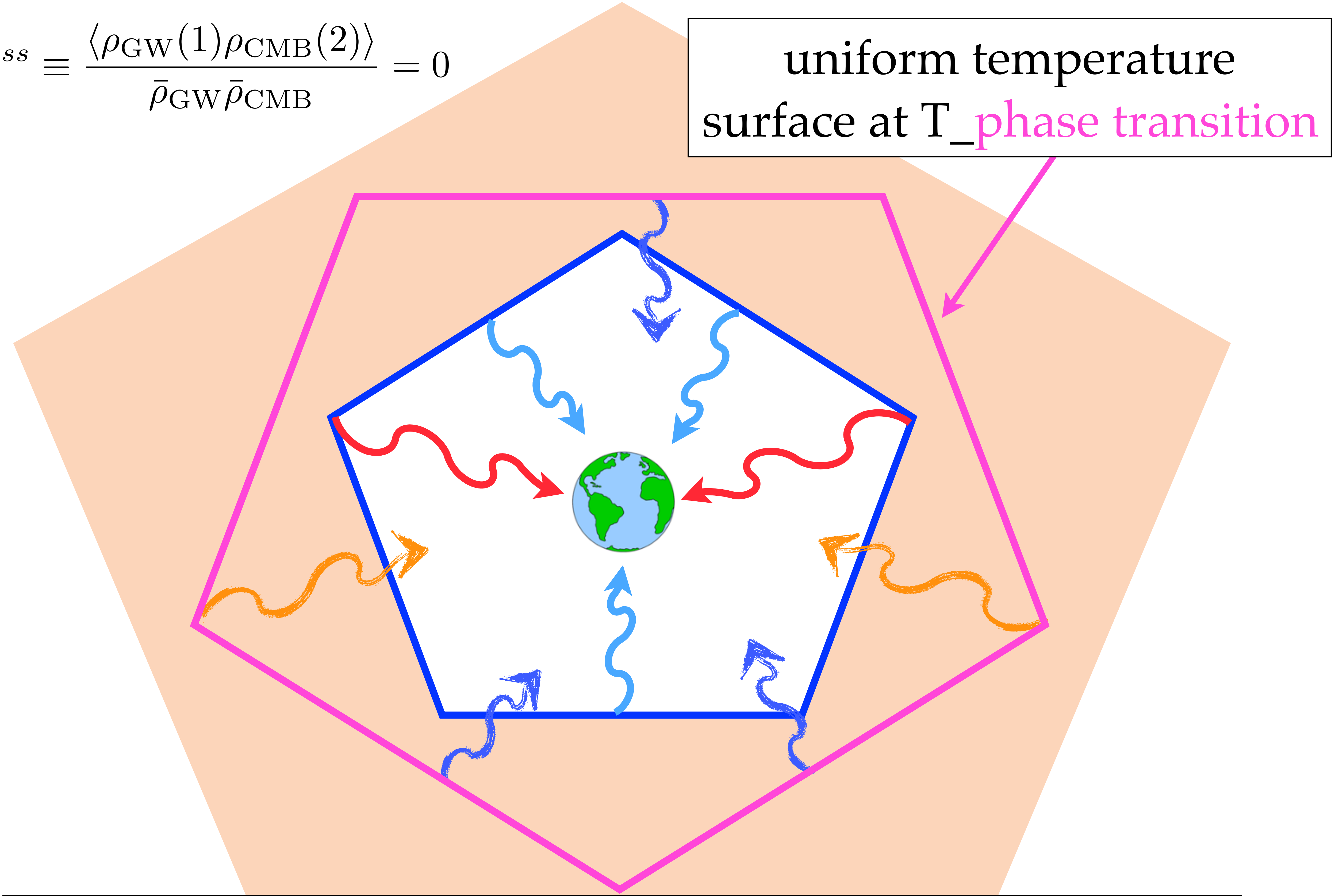
$$V = \Lambda^4 \left(1 - \sin \frac{a}{f_a}\right)$$

$$\frac{\delta \rho_a}{\rho_a} \sim \frac{\delta V}{V} \sim \frac{H_{\text{inf}}}{f_a}$$



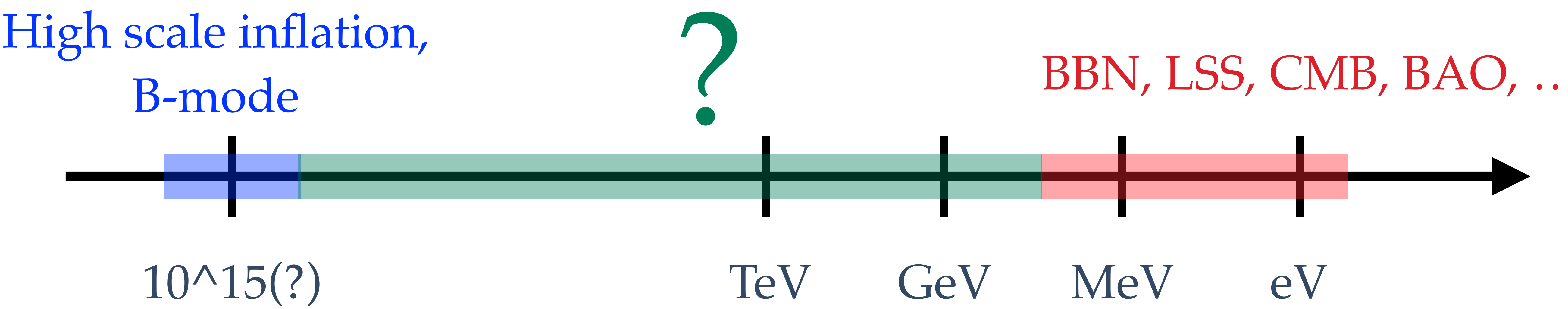
can generate larger & uncorrelated perturbations to the inflaton fluctuation

$$C^{cross} \equiv \frac{\langle \rho_{\rm GW}(1)\rho_{\rm CMB}(2)\rangle}{\bar{\rho}_{\rm GW}\bar{\rho}_{\rm CMB}} = 0$$

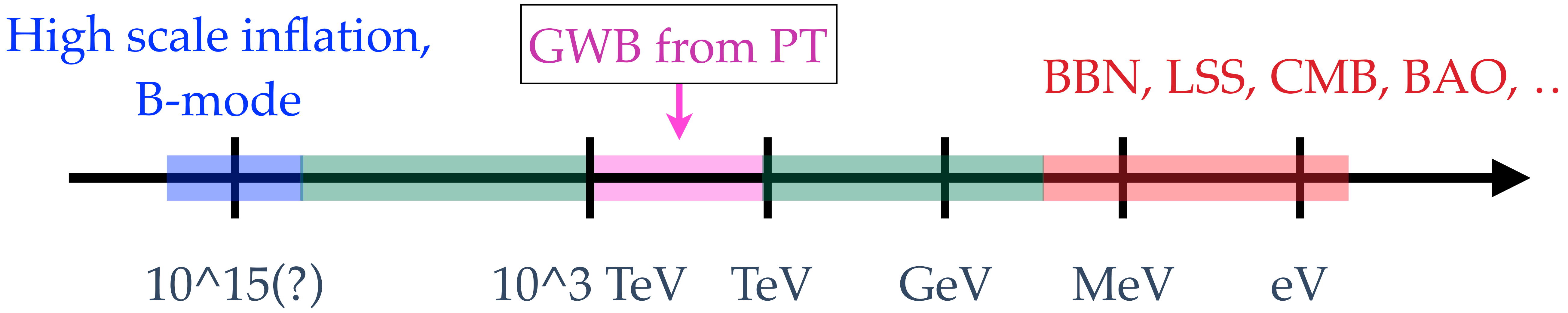


GW perturbation comes from different reheating process
=> GWB can be ``uncorrelated” with CMB

GW provides a probe of the unknown thermal history



GW provides a probe of the unknown thermal history

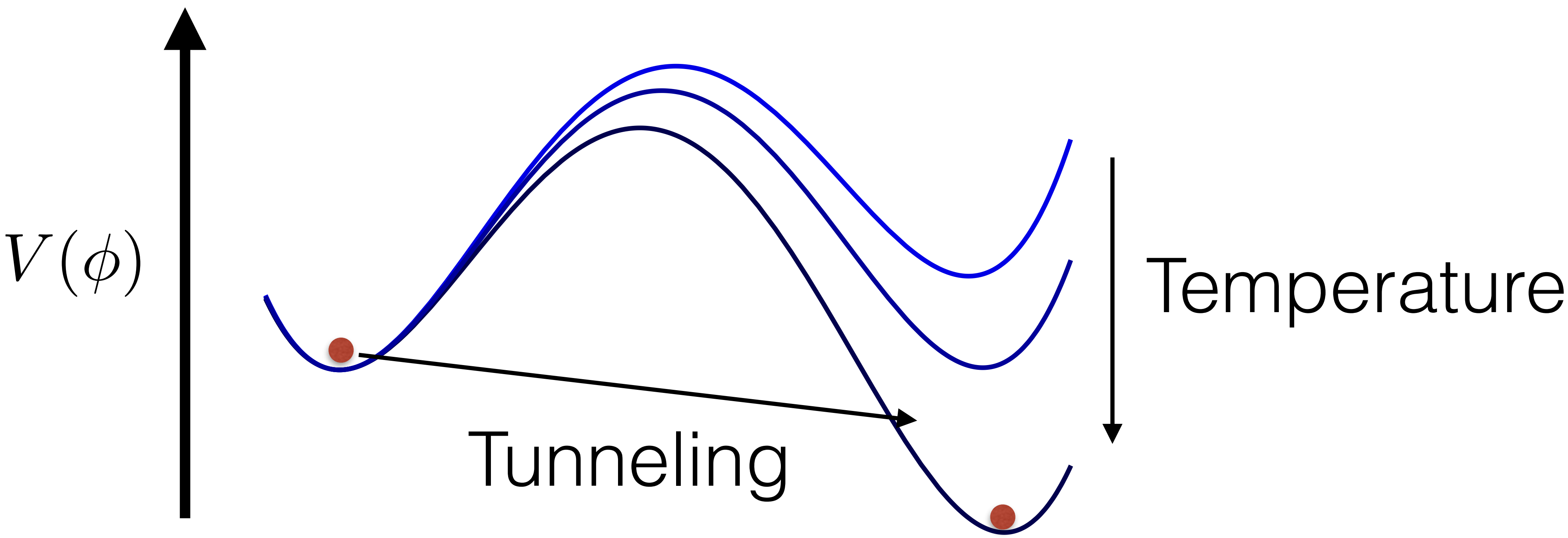


Existence of cosmological PT?

Is there only one source of the density perturbation?

Is there only one reheating process?

First order phase transition

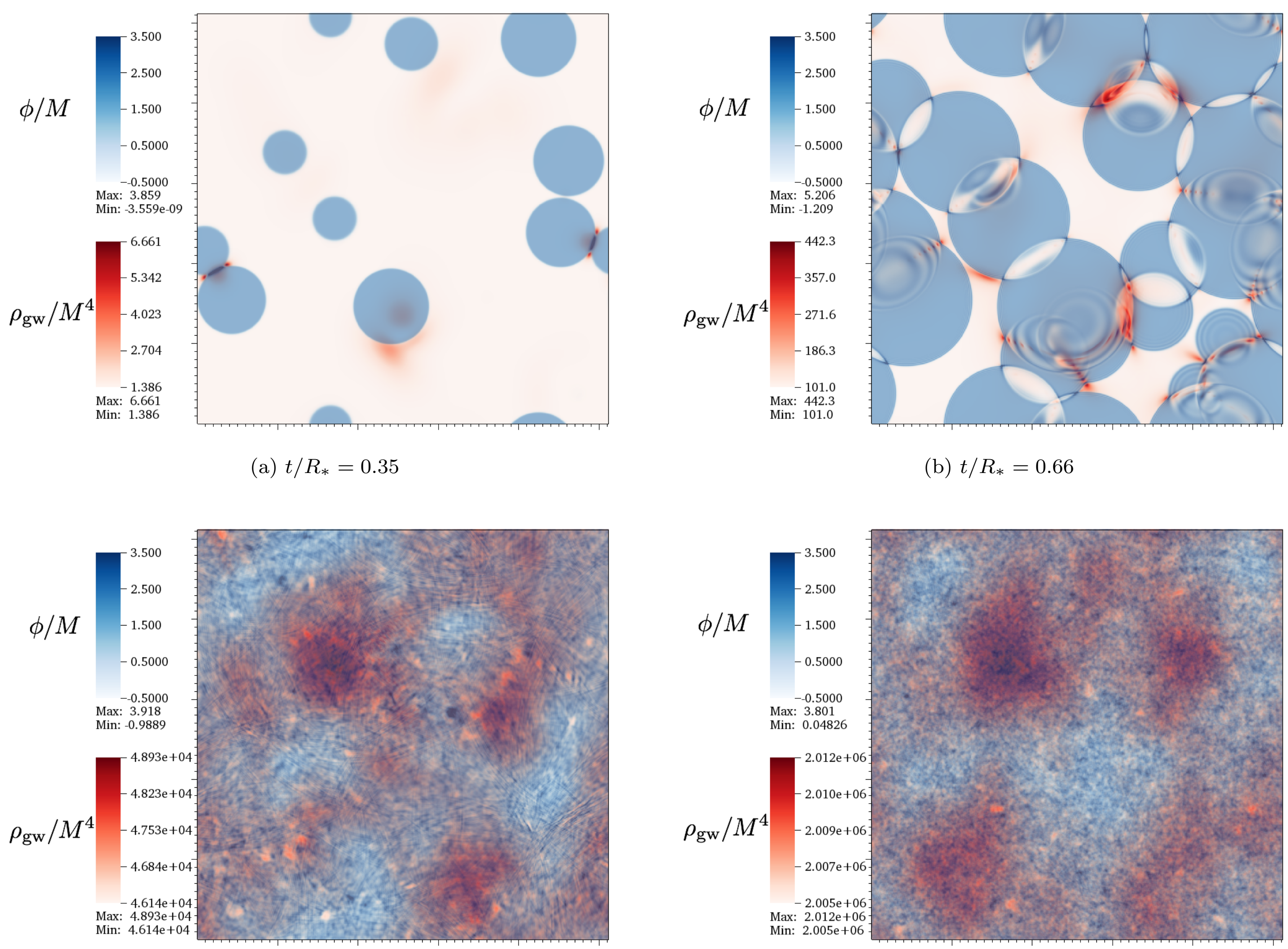


$$\Gamma(T) = A(T)\, e^{-S(T)}$$

PT rate as a function of temperature

GW from first order PT

- The collisions of the bubbles generate gravity waves (need quadruple mass for GW)



(a) $t/R_* = 0.35$ (b) $t/R_* = 0.66$

(c) $t/R_* = 2.50$ (d) $t/R_* = 7.8$

In the sky today:

$> 10^{30}$ bubbles

from TeV scale PT

Energy density of GW from PT

$$\rho_{\rm GW} \sim \frac{\rho_{PT}^2}{\rho_{total}} \left(H_{PT}\Delta t_{PT}\right)^2$$

$$\rho_{\rm GW}^{today} \approx 0.1 \left(H_{PT}\Delta t_{PT}\right)^2 \rho_\gamma \approx 10^{-5} - 10^{-2} \rho_\gamma$$

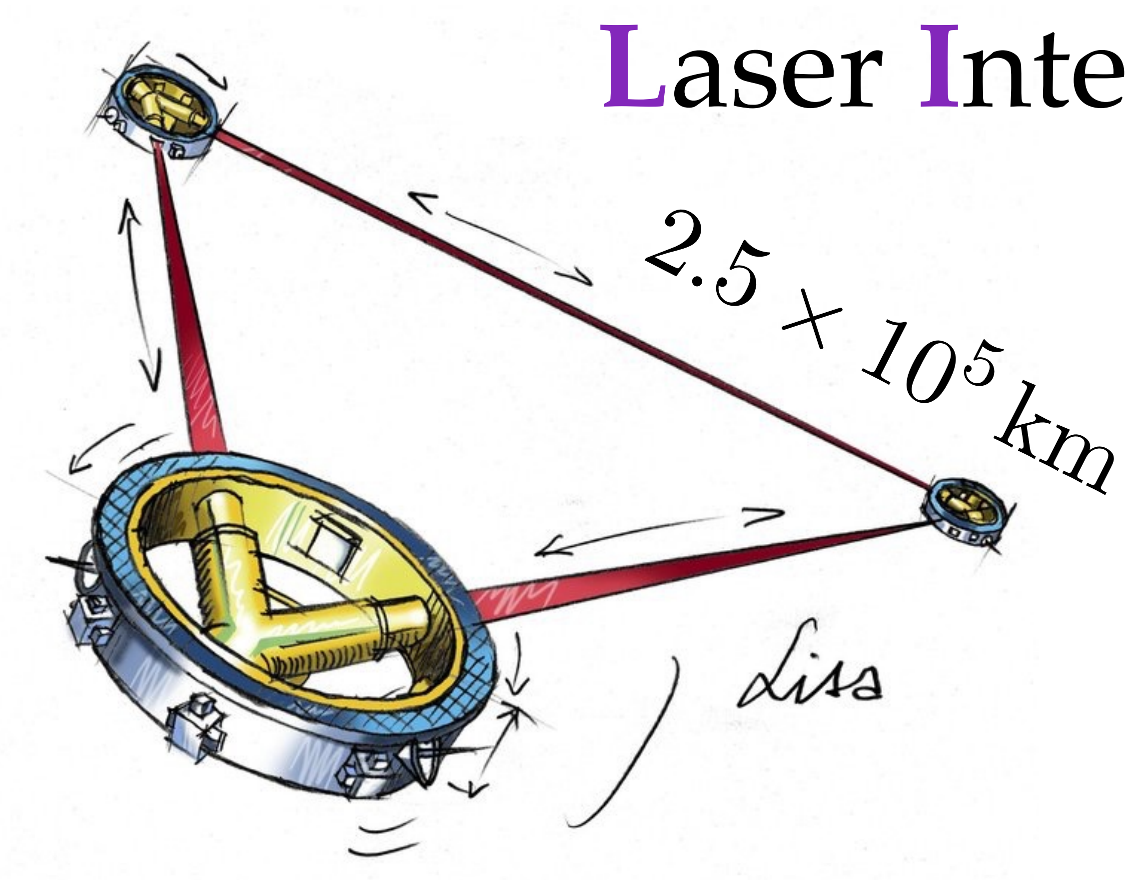
$$\omega_{\rm GW}^{today} \sim H_{PT} \left(\frac{T_{\rm CMB}^{today}}{T_{PT}}\right) \sim {\rm mHz} - {\rm Hz}$$

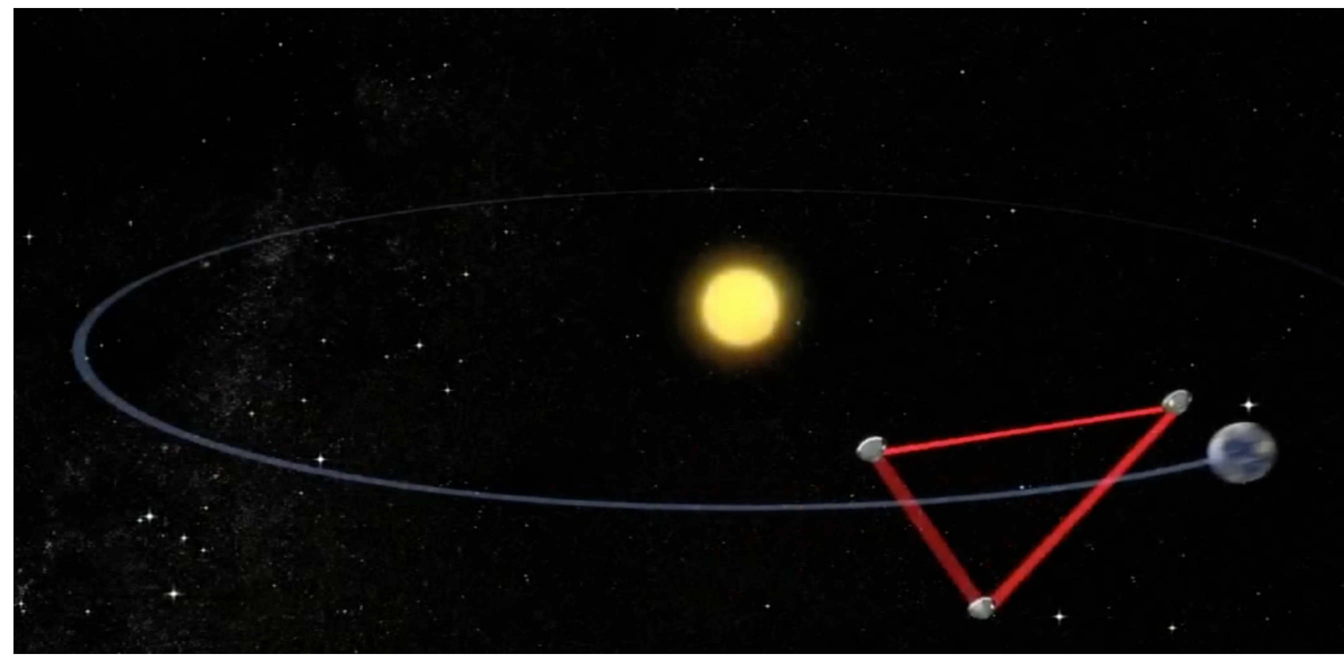
$$T_{PT} \sim {\rm TeV} - 10^3 {\rm TeV}$$

See also 1512.06239

GW detectors

Laser **I**nterferemeter **S**pace **A**ntenna

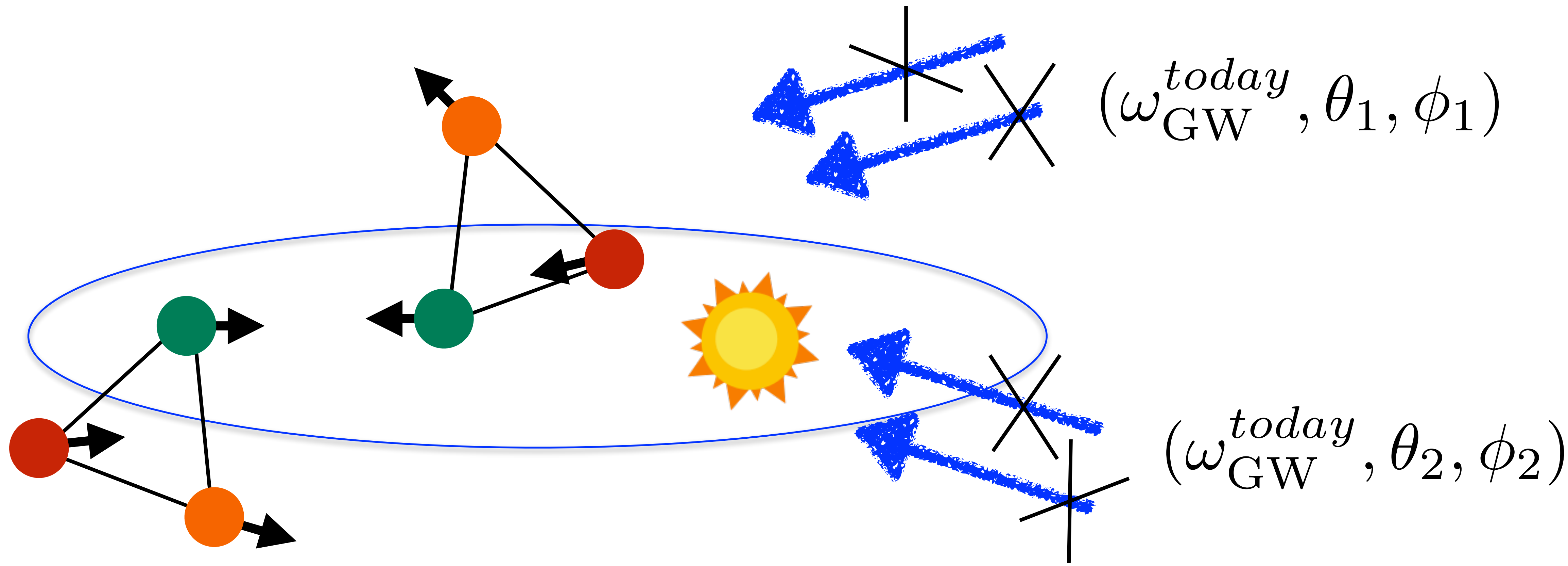




Similar ideas, more futuristic

BBO, DECIGO, ALIA

Angular measurement



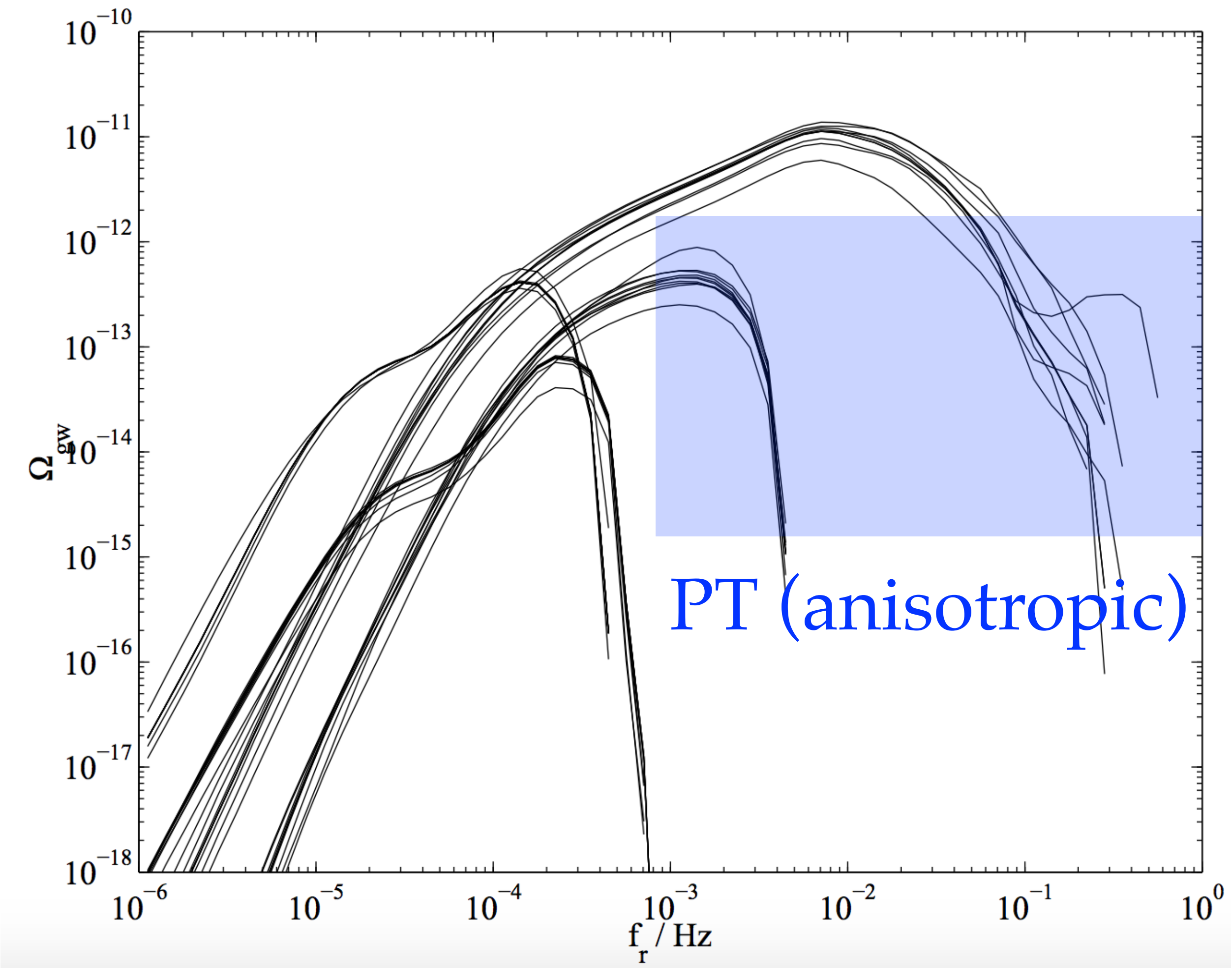
- **Method:** variation of **strains** in time for each polarization mode with different detector location/Doppler shift
- LISA may get to ~ 0.01 steradians ($\ell_{\rm max} = \mathcal{O}(10)$), more detectors (BBO/DECIGO) can do better [Cutler(1997), Giampieri et al (1997)]

Astrophysical foreground

Unresolvable white dwarf merger generates the dominant background to our signal

However, most of these background **follow galaxy distribution** and can be subtracted with enough data

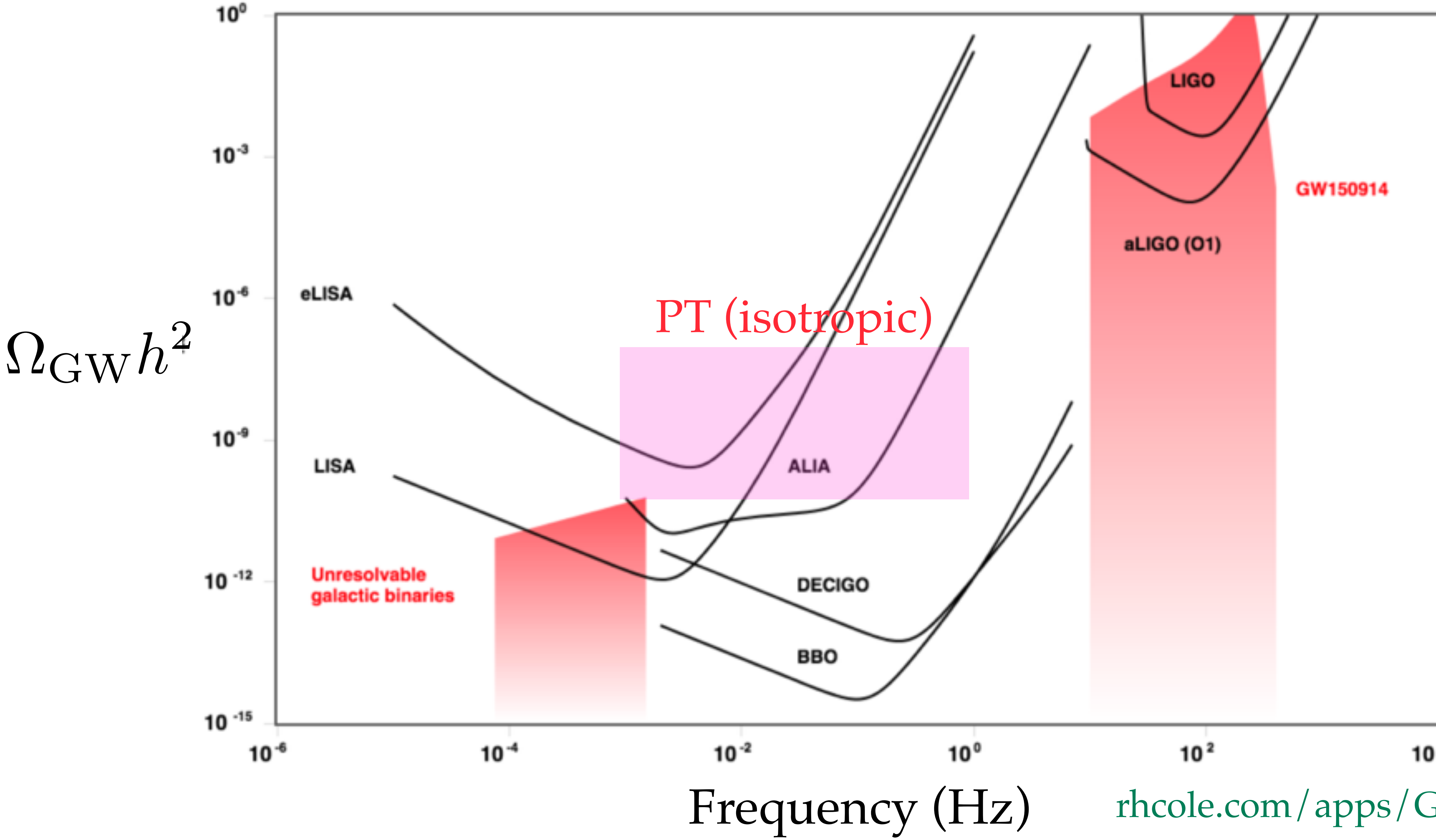
Adams & Cornish (2013)



Farmer & Phinney (2003)

Energy density of GW from PT

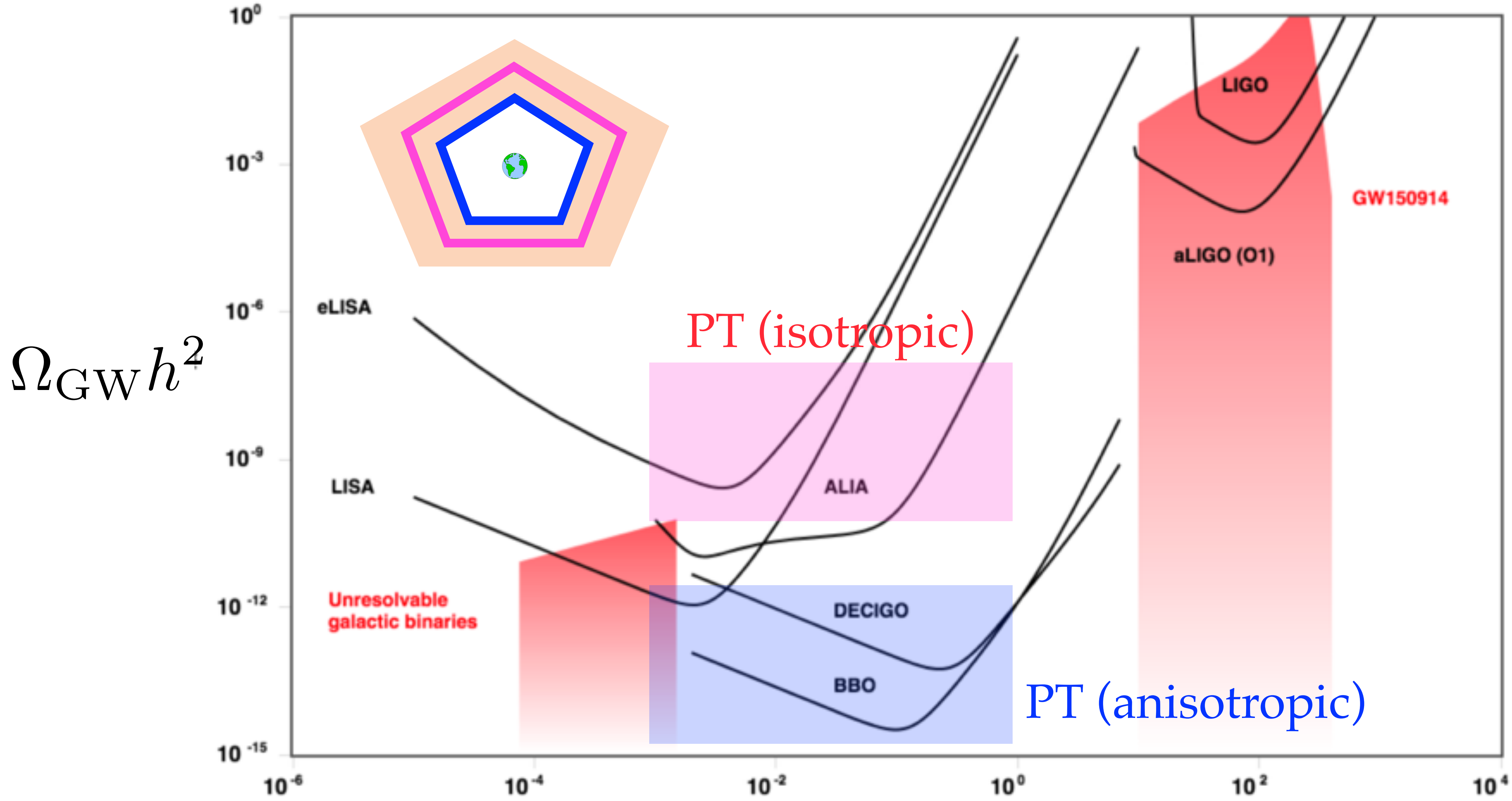
$$\rho_{\rm GW}^{today} \approx 10^{-5} - 10^{-2}\rho_\gamma$$



rhcole.com/apps/GWplotter/

Detection possibility

$$\delta\rho_{\rm GW}^{today} \approx 10^{-10} - 10^{-7}\rho_\gamma$$



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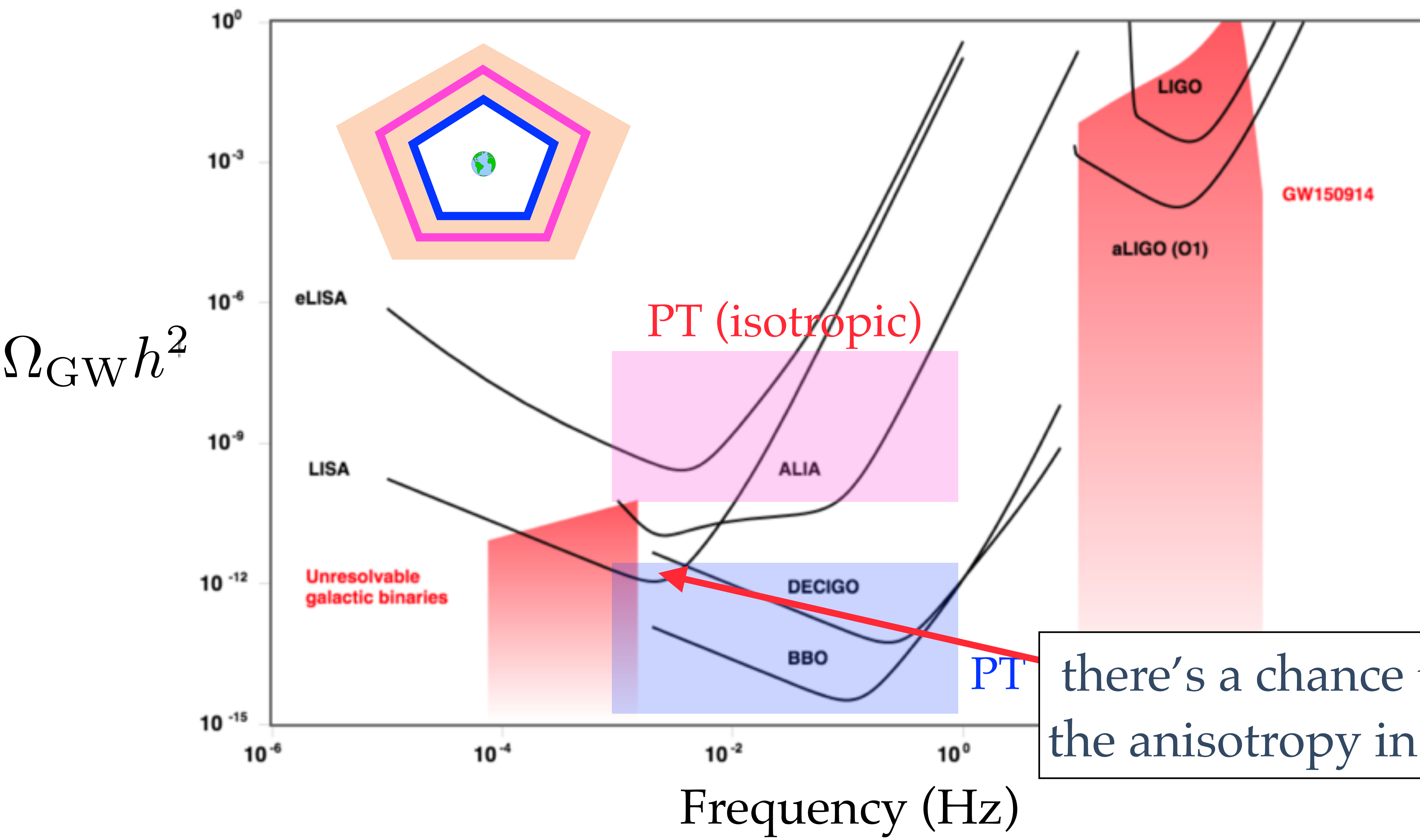
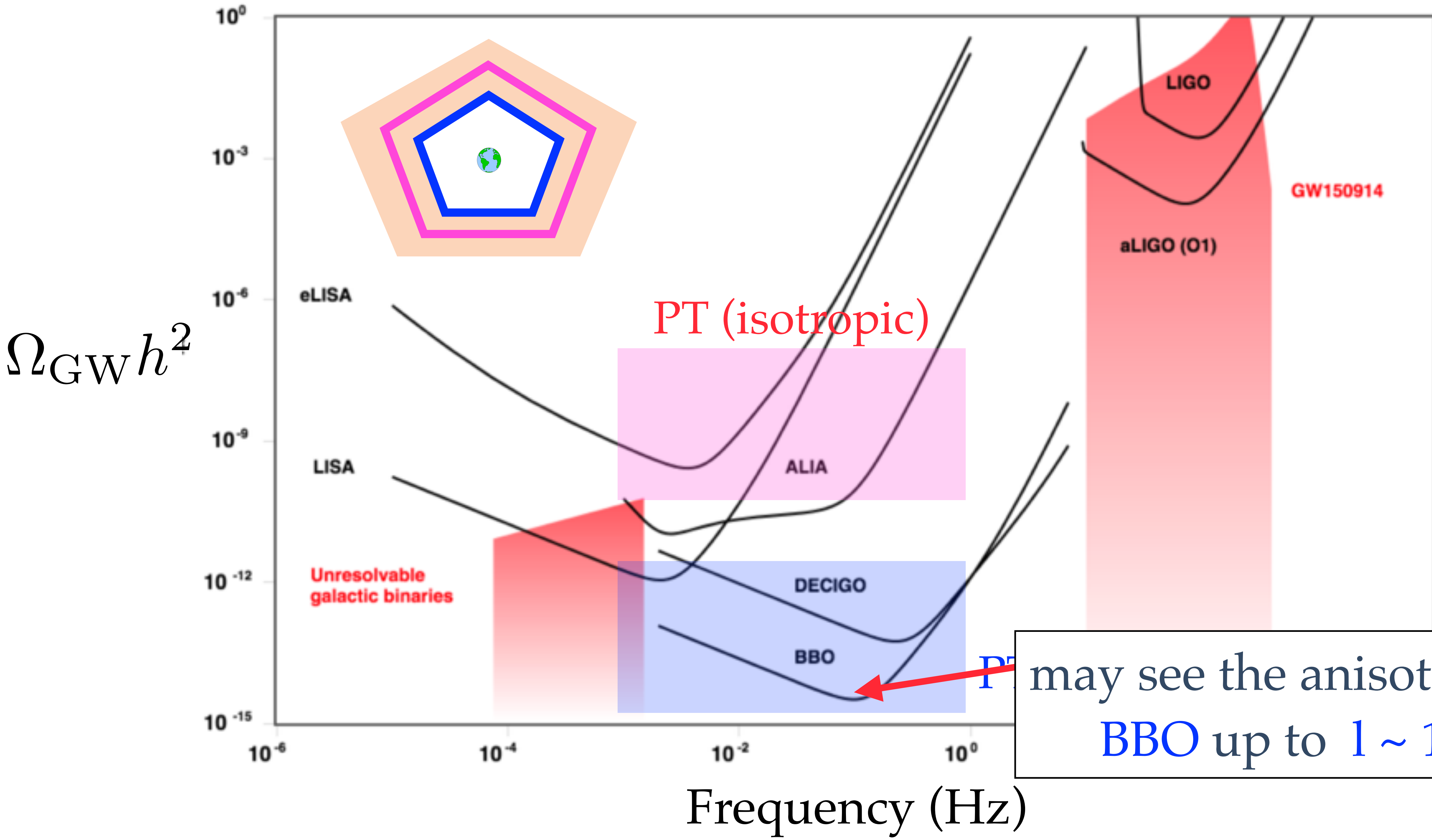


there's a chance to see the anisotropy in LISA!

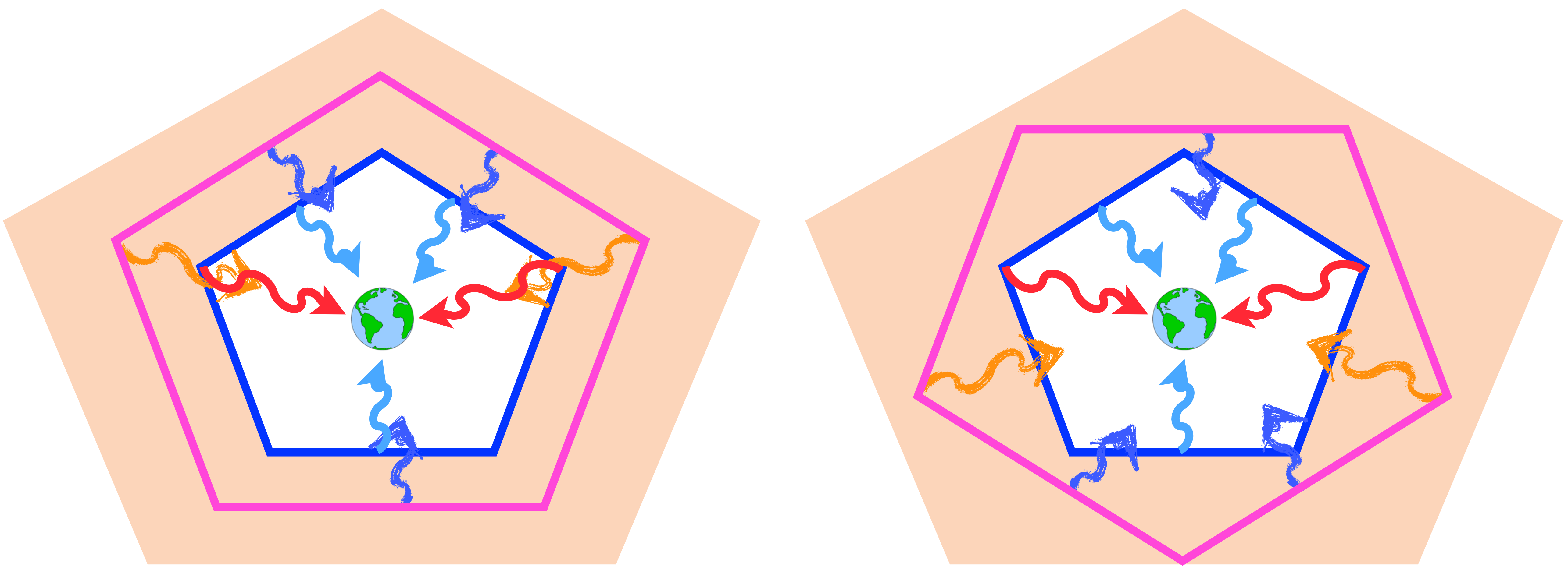
Detection possibility

$$\delta\rho_{\rm GW}^{today} \approx 10^{-10} - 10^{-7}\rho_\gamma$$



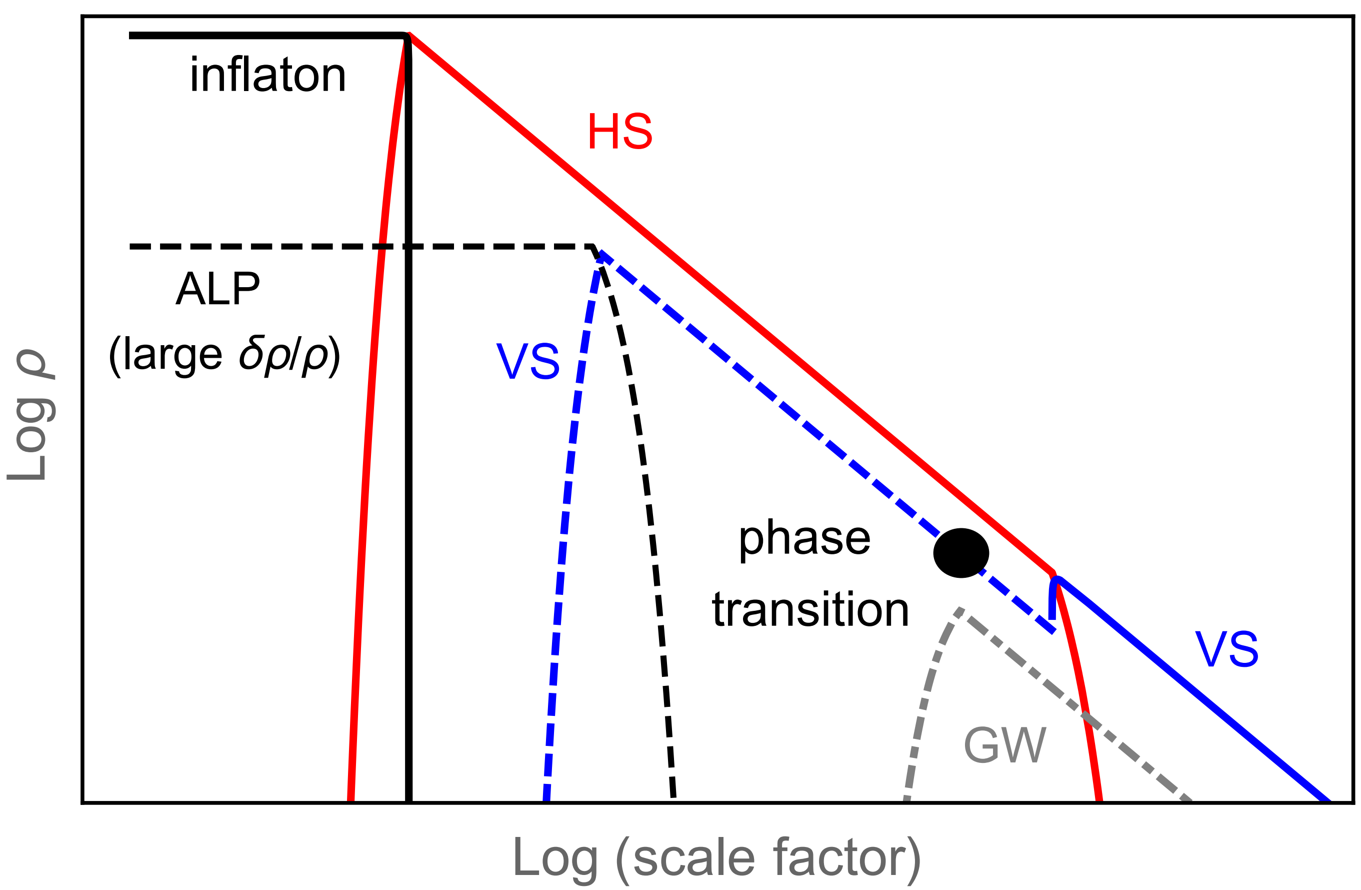
PT may see the anisotropy in BBO up to 1 ~ 100 !

Non-minimal Story



e.g., a curvaton model

$$\delta\rho_{\rm GW} \sim 0.1 \left(\frac{\rho_{\rm VS}}{\rho_{\rm HS}}\right)^2 (H_{PT}\Delta t_{PT})^2 \left(\frac{\delta\rho}{\rho}\right)_{\rm GW} \rho_\gamma$$



$$H_{PT}\Delta t_{PT} = 0.1$$

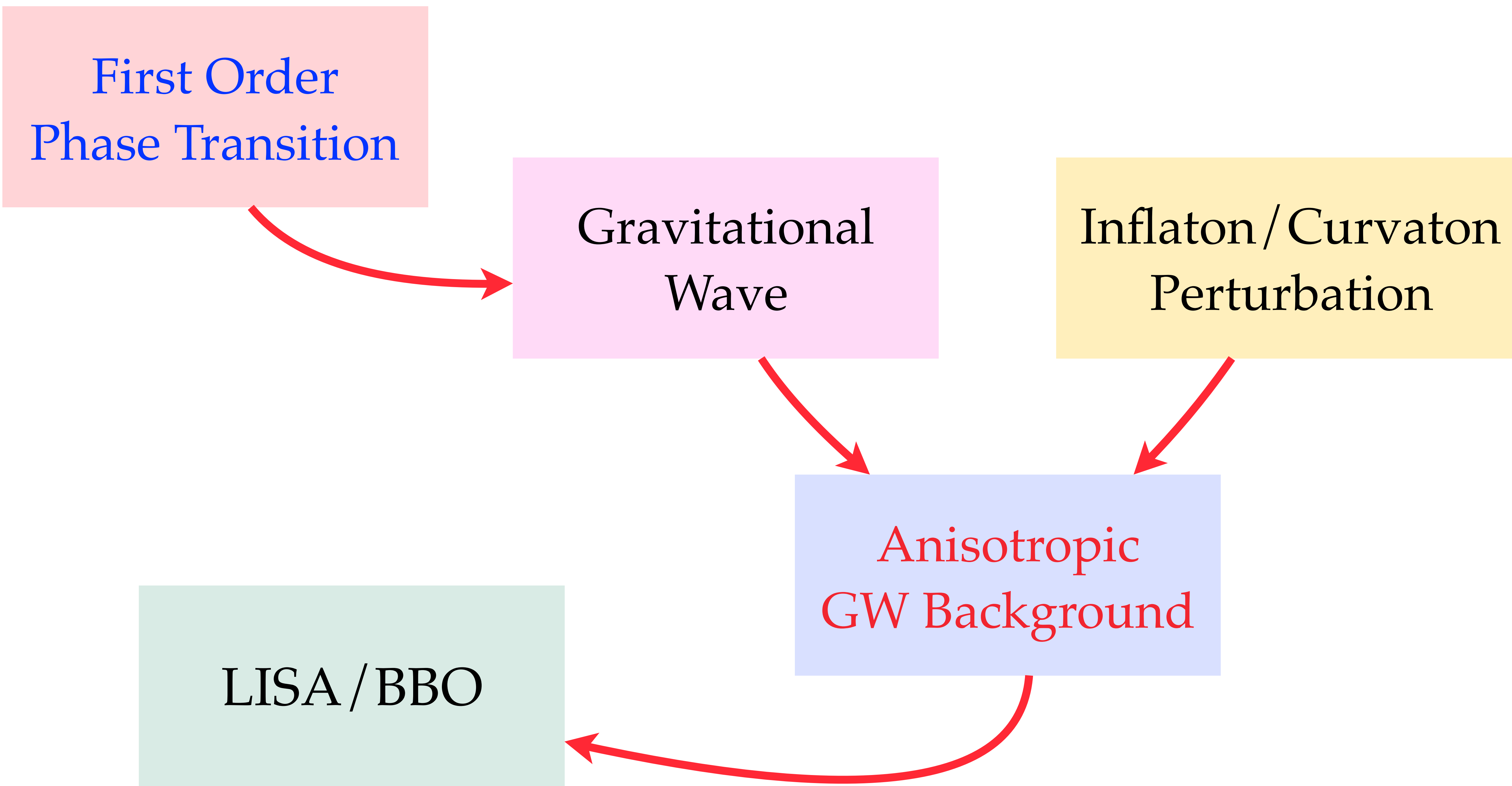
$$\left(\frac{\delta\rho}{\rho}\right)_{\rm GW} = 10^{-4} \qquad \frac{\rho_{\rm VS}}{\rho_{\rm HS}} = 0.1$$

Larger energy contrast

~ CMB isocurvature constraint

Visible at BBO up to $\ell_{\rm max} \approx 100$

Conclusion and outlook



Conclusion and outlook