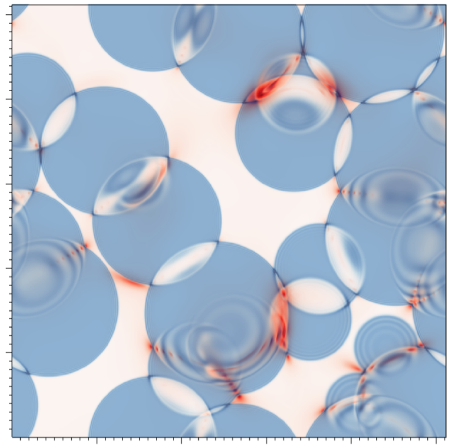
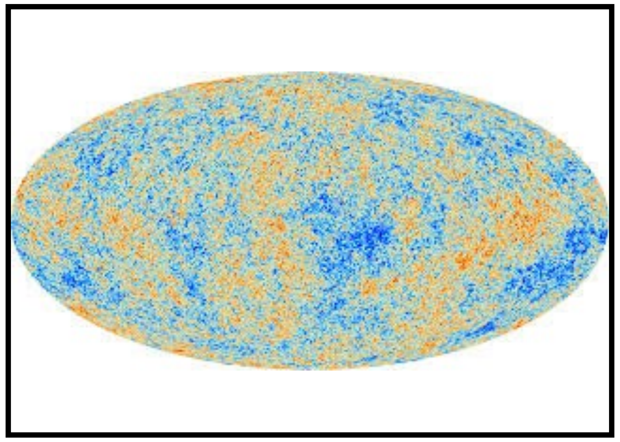
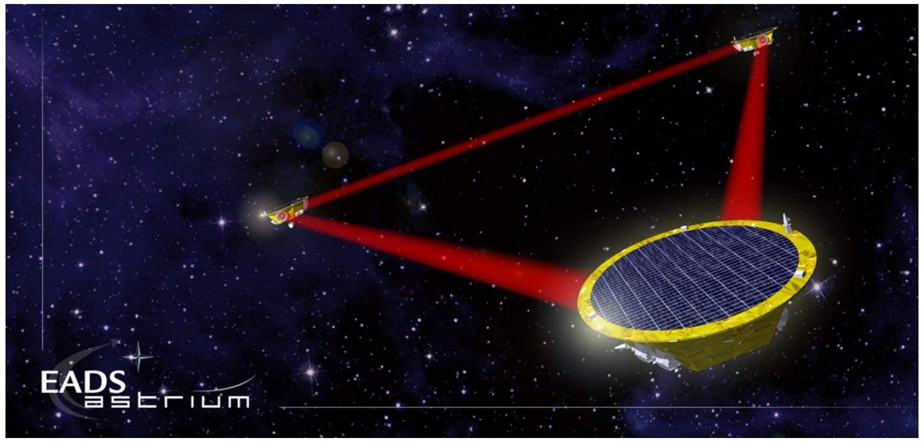
What can we learn from cosmological gravity waves?

Anson Hook
University of Maryland

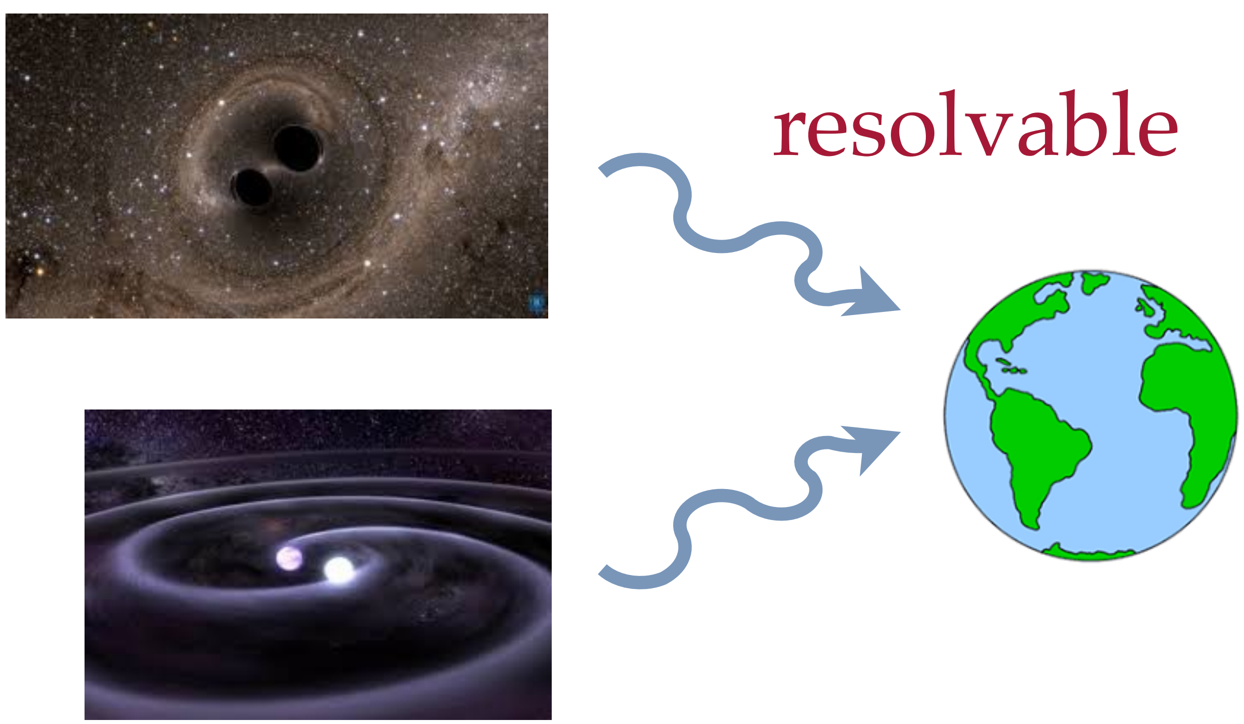




Gravitational Waves (GW)

Different sources of GW in the sky

Astrophysical sources

black hole, neutron star, white dwarf mergers



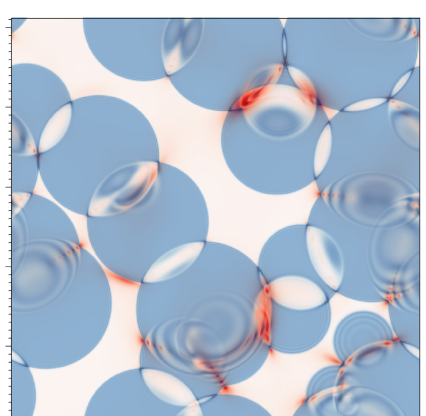
Study physics of gravity, astro dynamics, QCD,

Gravitational Wave (GW)

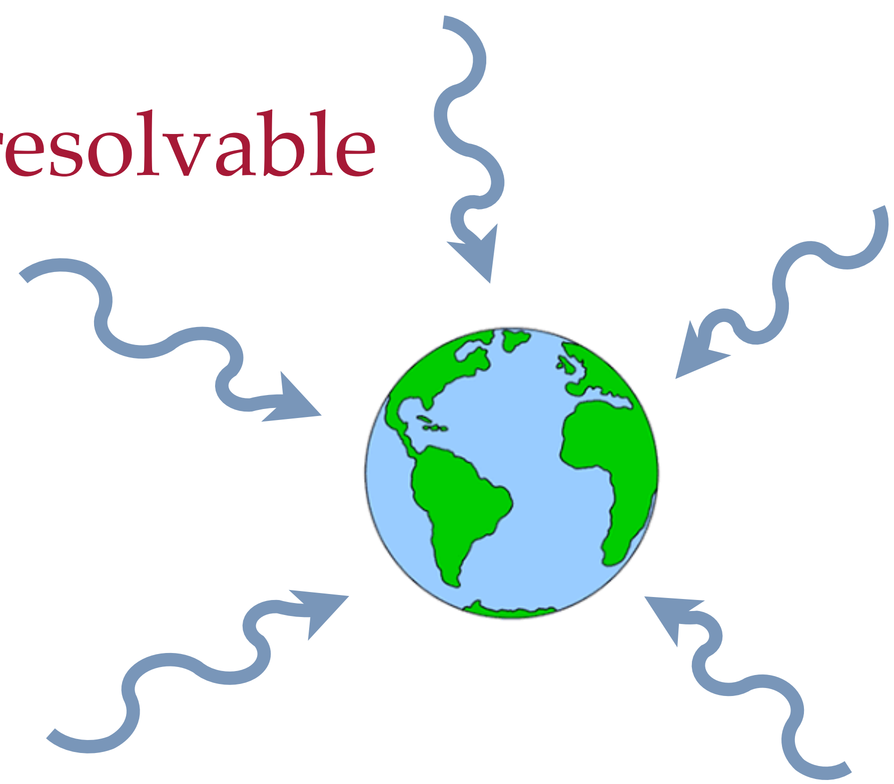
Different sources of GW in the sky

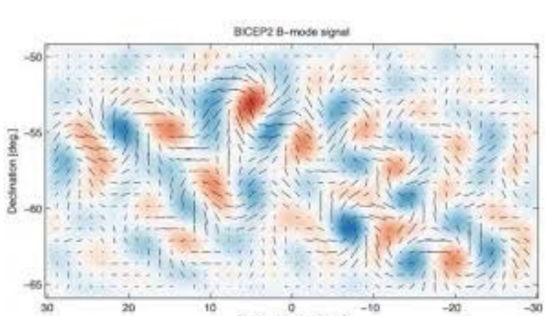
Cosmological sources

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



unresolvable





Study physics of inflation/reheating, universe evolution

Gravitational Wave (GW) Cosmology

GW generated at early times

What can we learn?

Use the CMB as a guide!

Gravitational Wave Background (GWB)

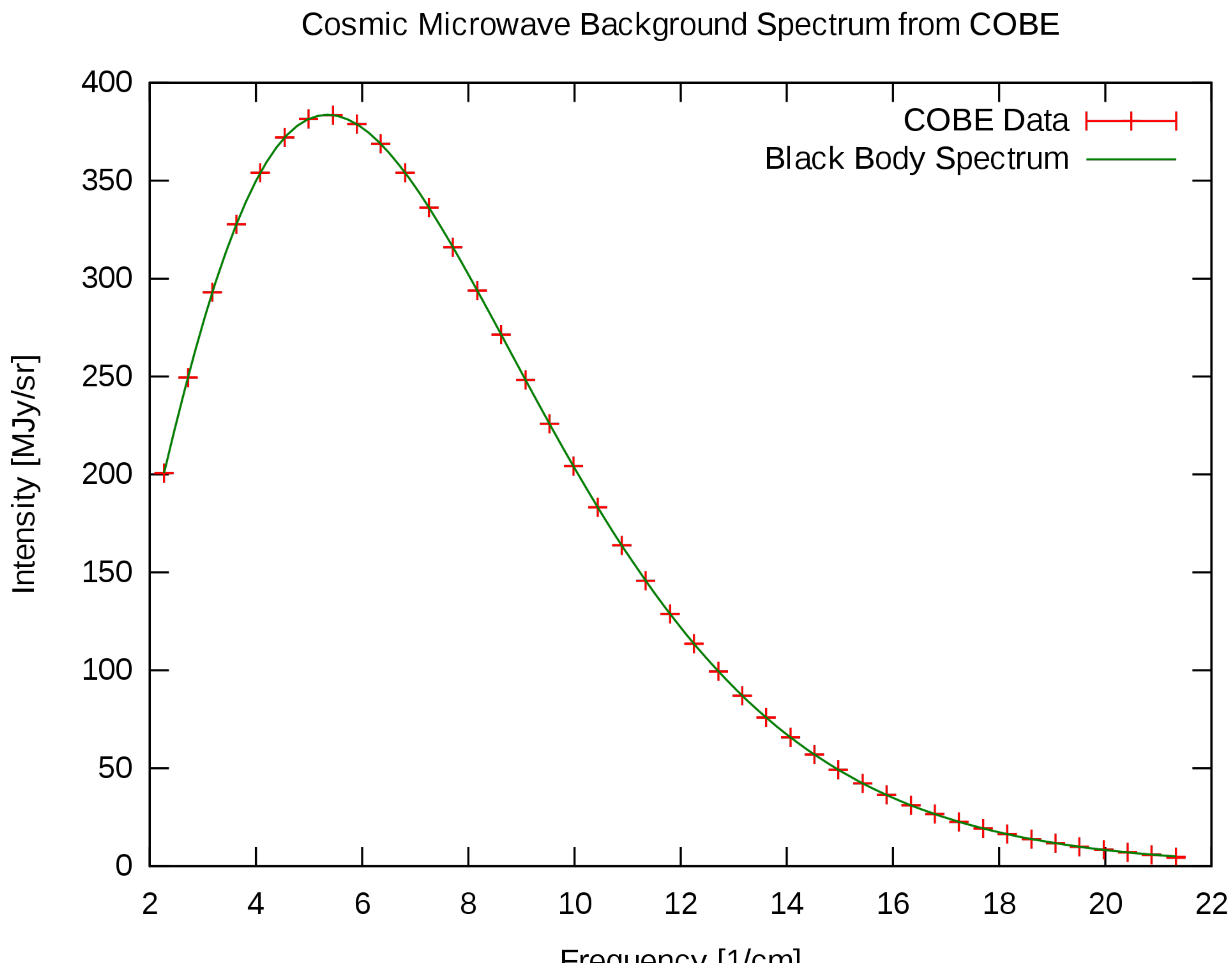
Cosmic Gravity waves are similar to the CMB spectrum

photon from last scattering = GW from cosmic source

Information about a single instant in time

Black body spectrum

Photons in thermal equilibrium



Gravitational Wave Background (GWB)

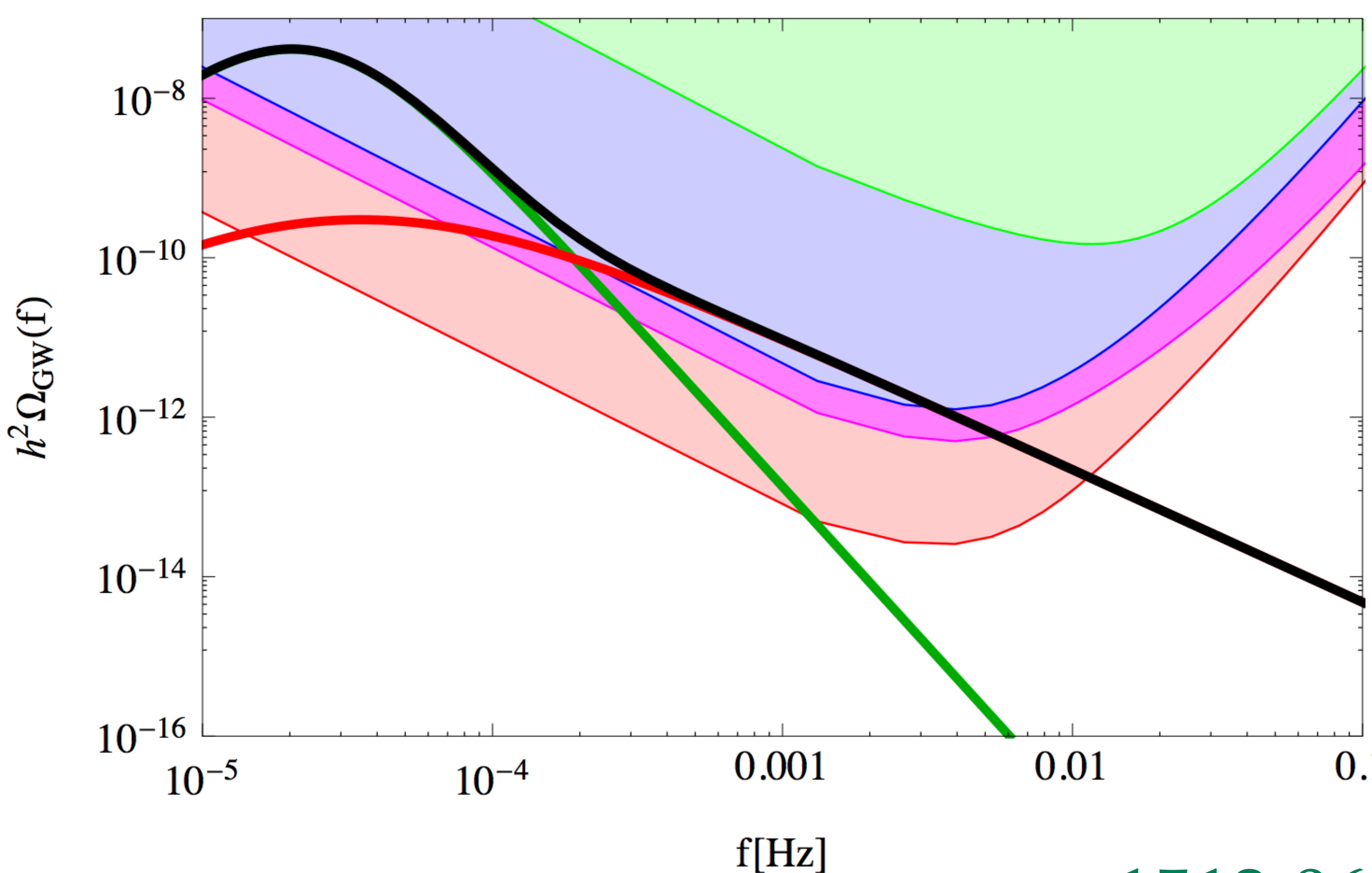
Cosmic Gravity waves are similar to the CMB spectrum

photon from last scattering = GW from cosmic source

Information about a single instant in time

GW spectrum

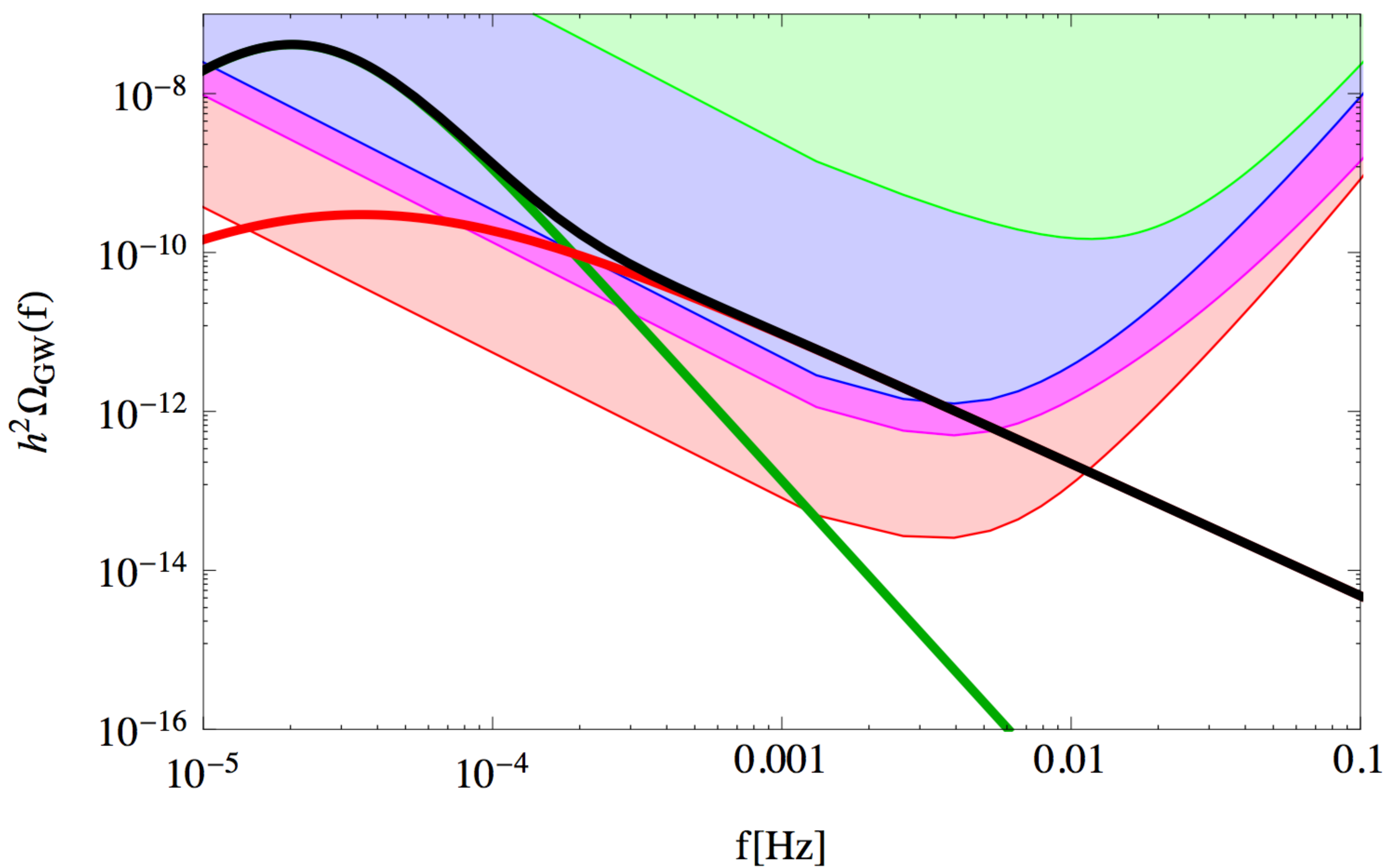
How was it generated



1512.06239

GWs

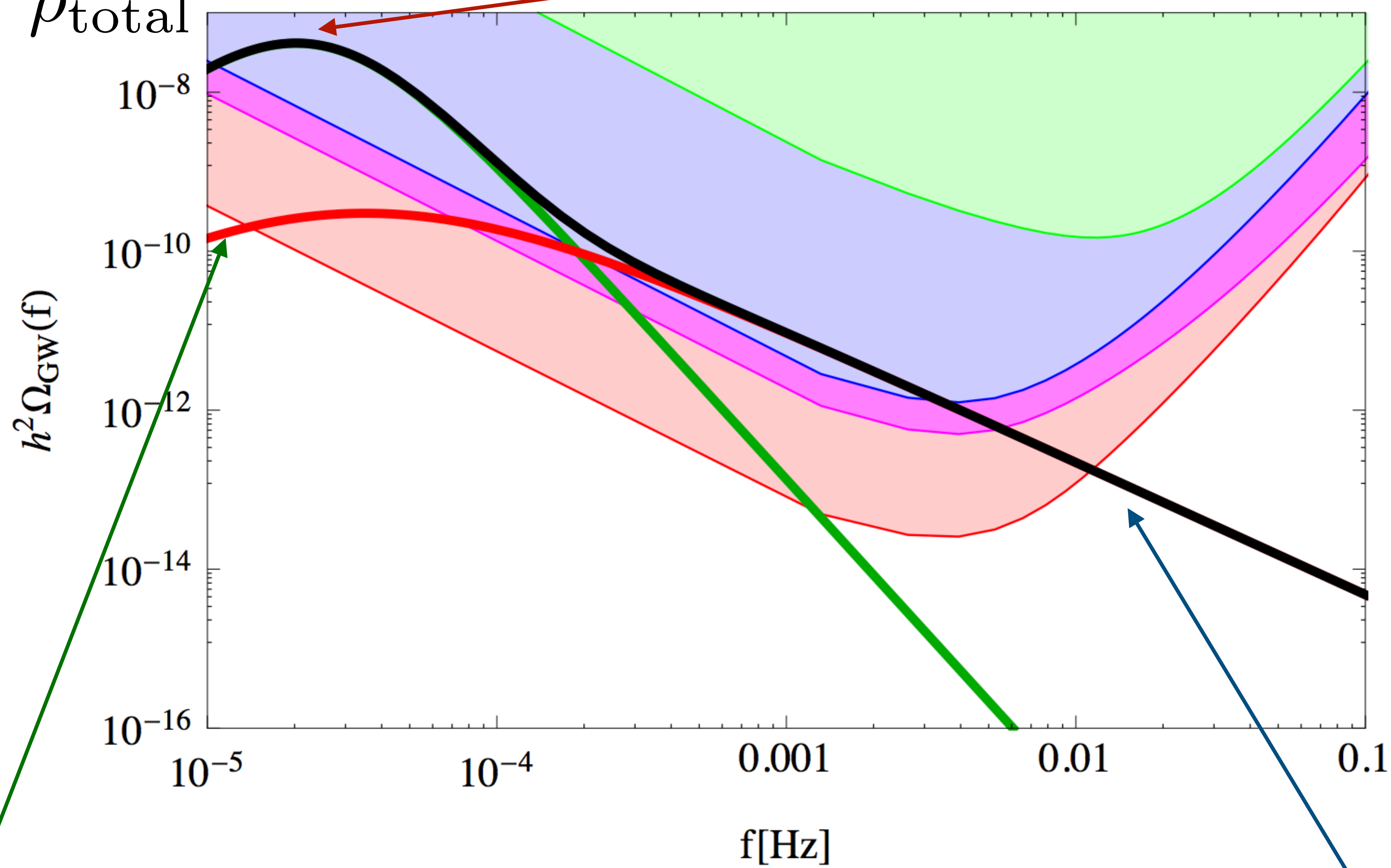
Must of the discussions so far have been focusing on GW's energy / frequency spectrum



GWs

$$\rho_{GW} \sim \frac{\rho_{\text{sector}}^2}{\rho_{\text{total}}}$$

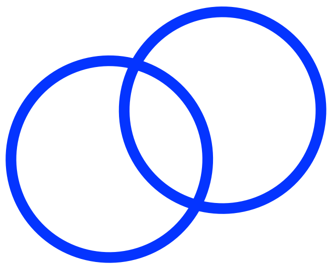
Length scale : Hubble



k fall off : Causality

Model dependent : Very uncertain

Energy density of GW from PT

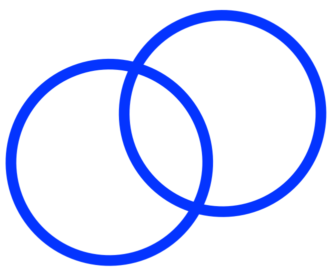


Einstein eq. $\omega_{\rm GW}^2\,\delta g_{\rm GW} \sim G_N\,\rho_{PT}$

$$\Box\phi = J$$

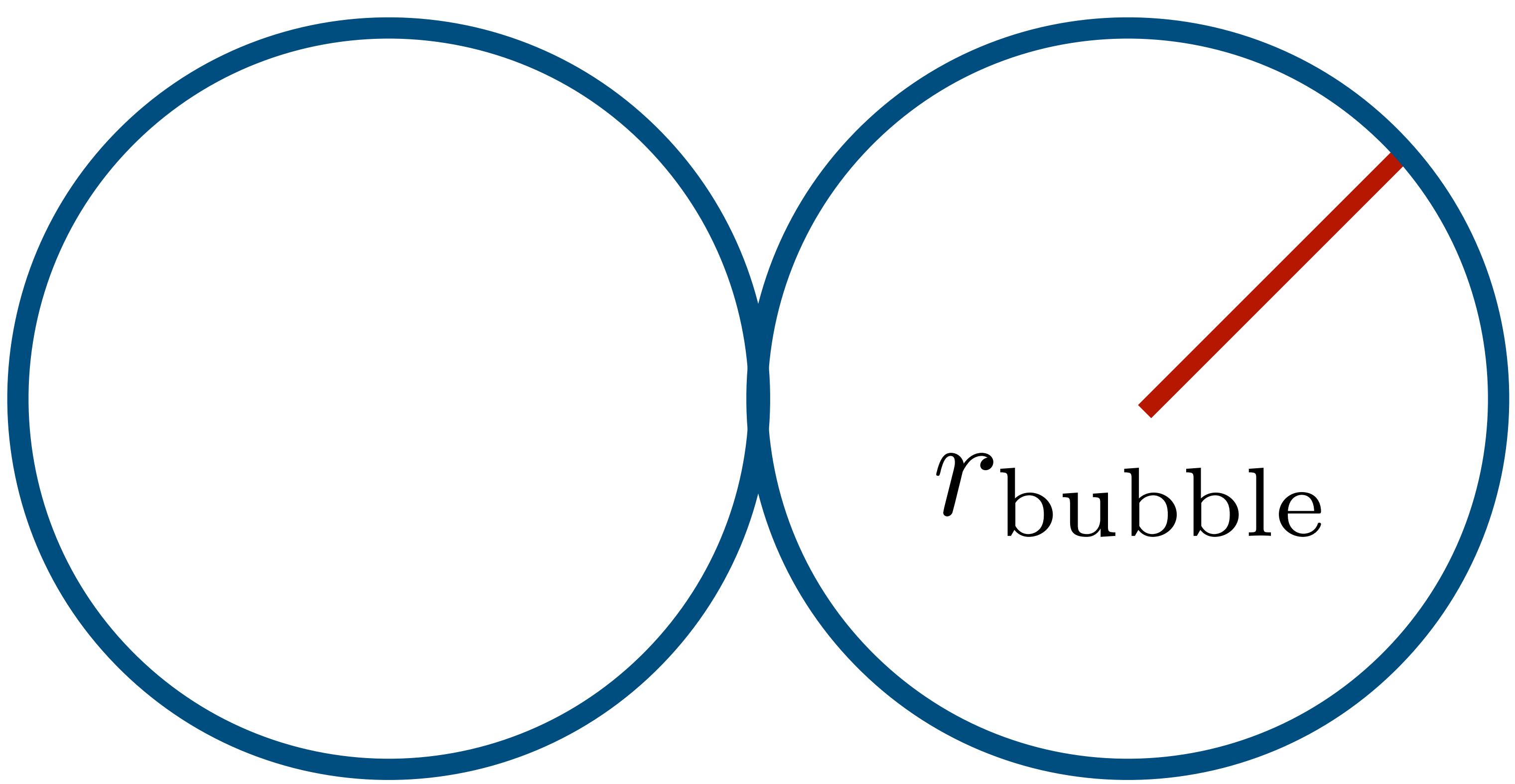
$$\Box h_{\mu\nu} \sim G_N T_{\mu\nu}$$

Energy density of GW from PT

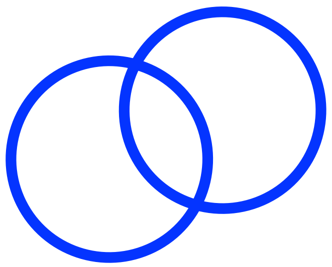


Einstein eq. $$\omega_{\rm GW}^2\,\delta g_{\rm GW} \sim G_N\,\rho_{PT}$$

Typical frequency (micro-phys) $$\omega_{GW} \sim \frac{v}{r_{\rm bubble}}$$

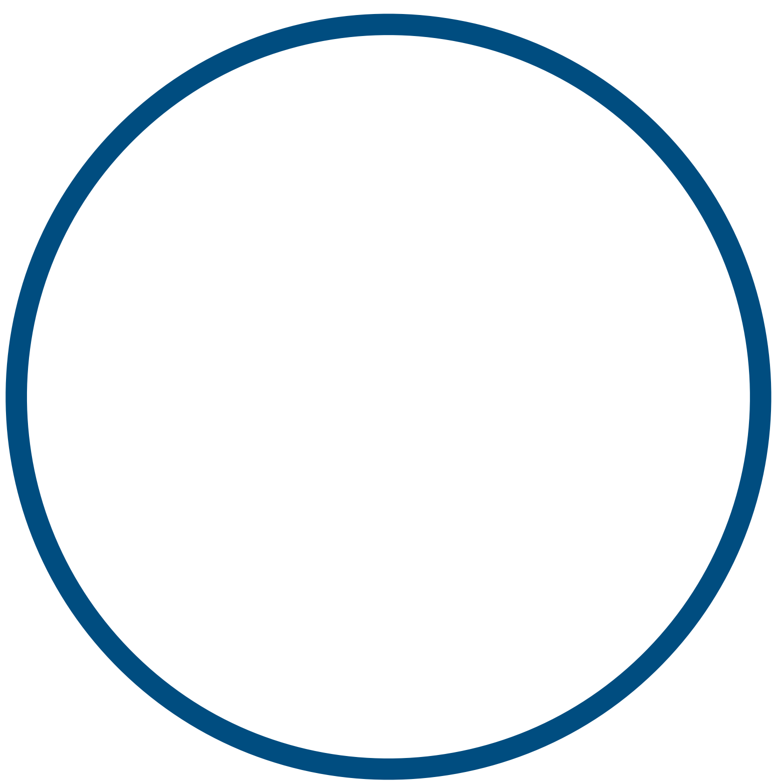


Energy density of GW from PT



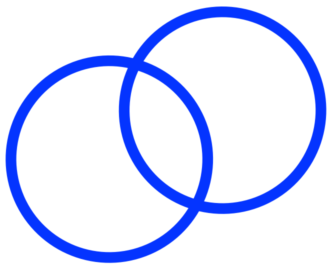
Einstein eq. $\omega^2_{\rm GW}\,\delta g_{\rm GW} \sim G_N\,\rho_{PT}$

Typical frequency
(micro-phys)



$$r_{\rm bubble} \sim \Delta t_{PT} \sim \min(\frac{1}{H}, \frac{\Gamma}{\dot{\Gamma}})$$

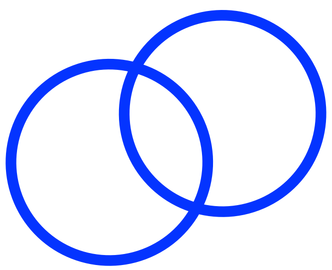
Energy density of GW from PT



Einstein eq. $$\omega_{\mathrm{GW}}^2 \, \delta g_{\mathrm{GW}} \sim G_N \, \rho_{PT}$$

Typical frequency (micro-phys) $$\omega_{\mathrm{GW}} \sim \frac{1}{\Delta t_{PT}} \sim \left(\frac{\dot{\Gamma}}{\Gamma} \right)_{T_{PT}}$$

Energy density of GW from PT



Einstein eq.

$$\omega_{\rm GW}^2\, \delta g_{\rm GW} \sim G_N\, \rho_{PT}$$

Typical frequency (micro-phys)

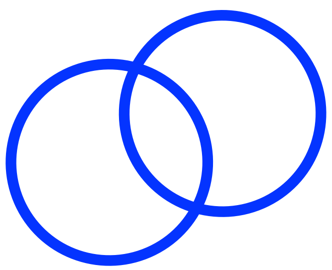
$$\omega_{\rm GW} \sim \frac{1}{\Delta t_{PT}} \sim \left(\frac{\dot{\Gamma}}{\Gamma}\right)_{T_{PT}}$$

Energy density in GW

$$\rho_{\rm GW} \sim \frac{1}{G_N} \omega_{\rm GW}^2 (\delta g_{\rm GW})^2$$

$$\rho_{GW} \sim \frac{1}{2} (\partial h)^2$$

Energy density of GW from PT



Einstein eq. $\omega_{\mathrm{GW}}^2\, \delta g_{\mathrm{GW}} \sim G_N\, \rho_{PT}$

Typical frequency (micro-phys) $\omega_{\mathrm{GW}} \sim \dfrac{1}{\Delta t_{PT}} \sim \left(\dfrac{\dot{\Gamma}}{\Gamma}\right)_{T_{PT}}$

Energy density in GW $\rho_{\mathrm{GW}} \sim \dfrac{1}{G_N} \omega_{\mathrm{GW}}^2 (\delta g_{\mathrm{GW}})^2$

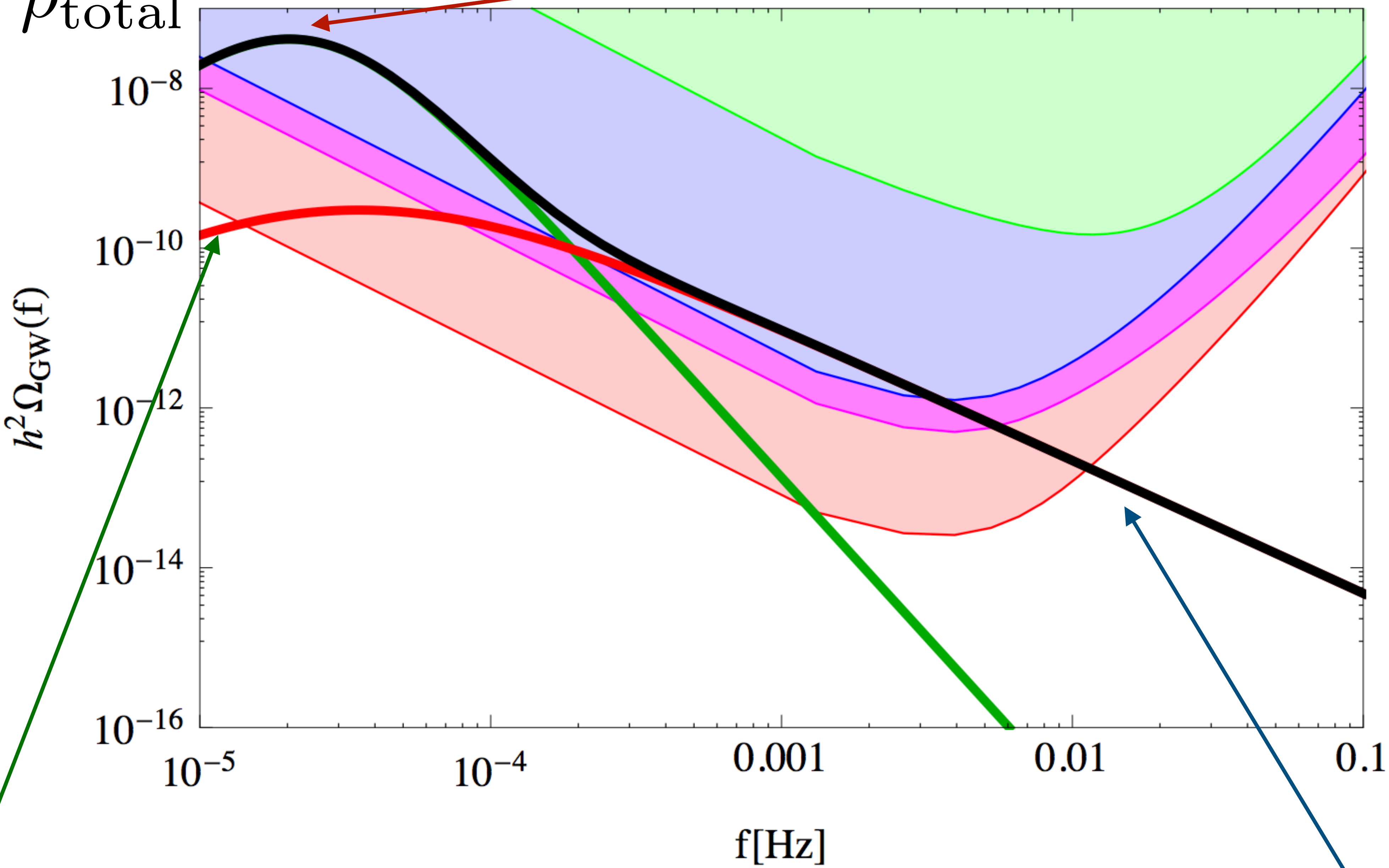
$H_{PT}^2 \sim G_N\, \rho_{total}$

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

GWs

$$\rho_{GW} \sim \frac{\rho^2_{\rm sector}}{\rho_{\rm total}}$$

Length scale : Hubble



k fall off : Causality

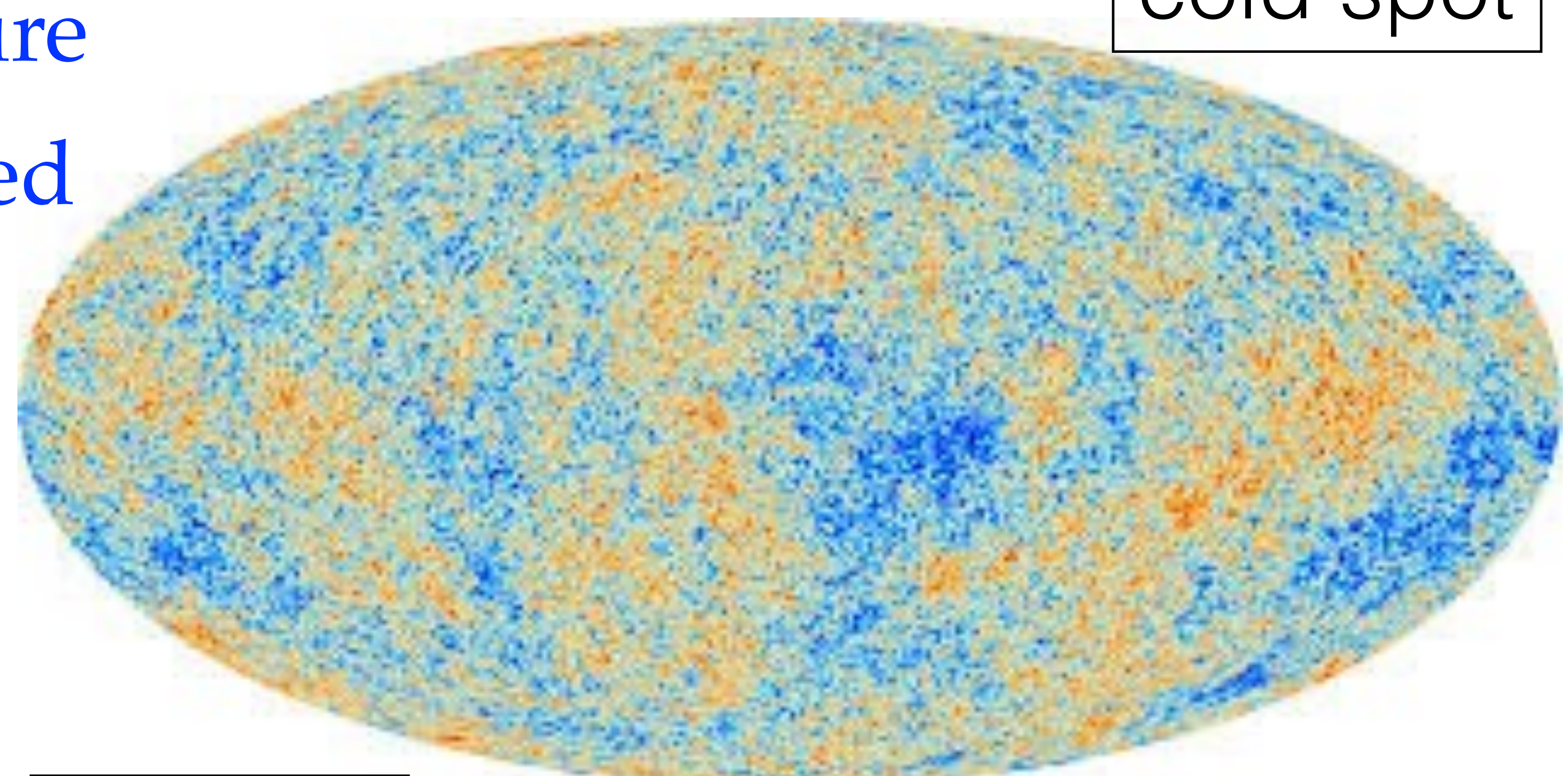
Model dependent : Very uncertain

Gravitational Wave Background (GWB)

CMB most well known for its information on “acausal” dynamics

Almost same temperature for causally disconnected patches

cold spot

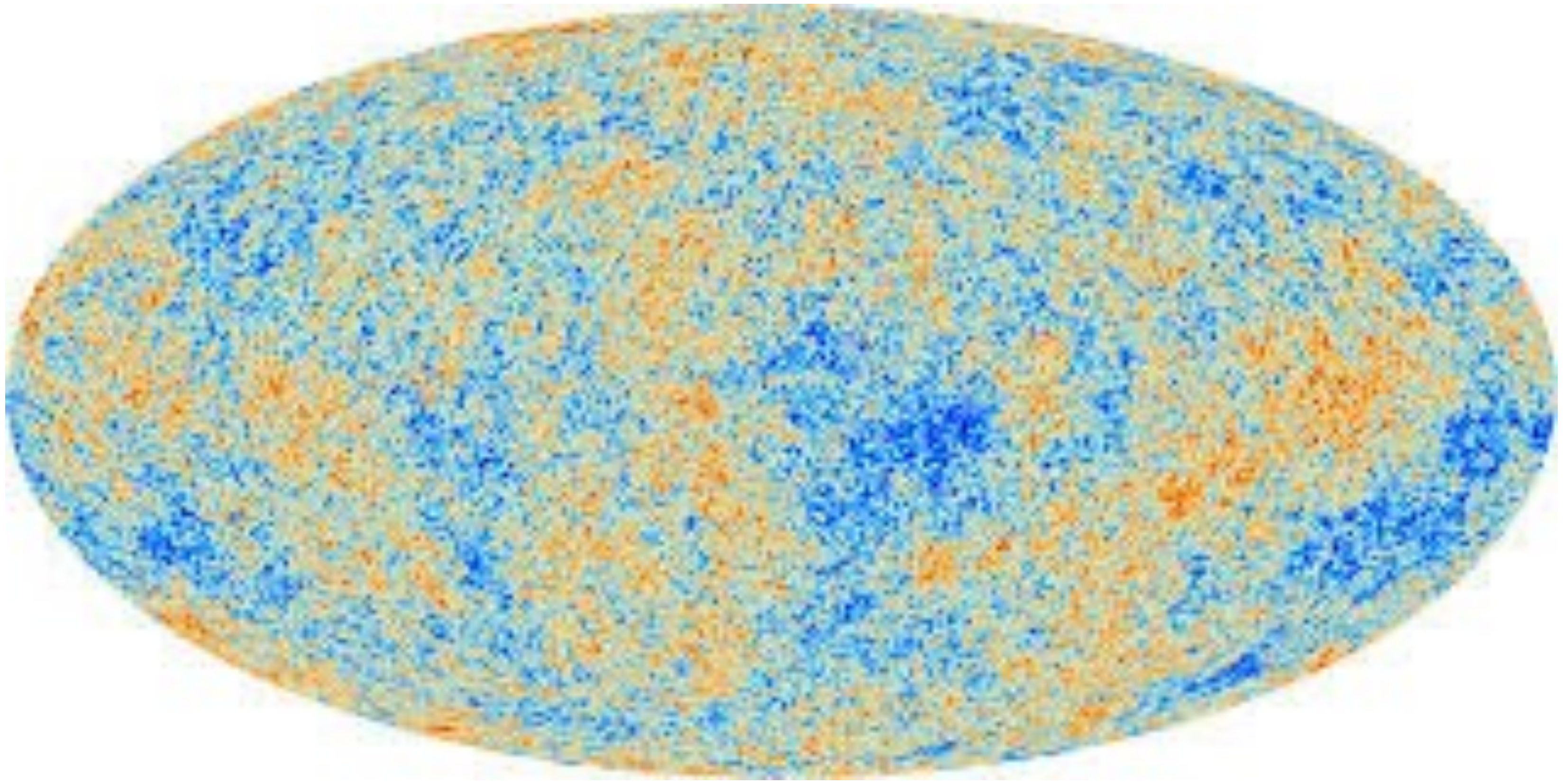


hot spot

CMB

Gravitational Wave Background (GWB)

CMB most well known for its information on "acausal" dynamics

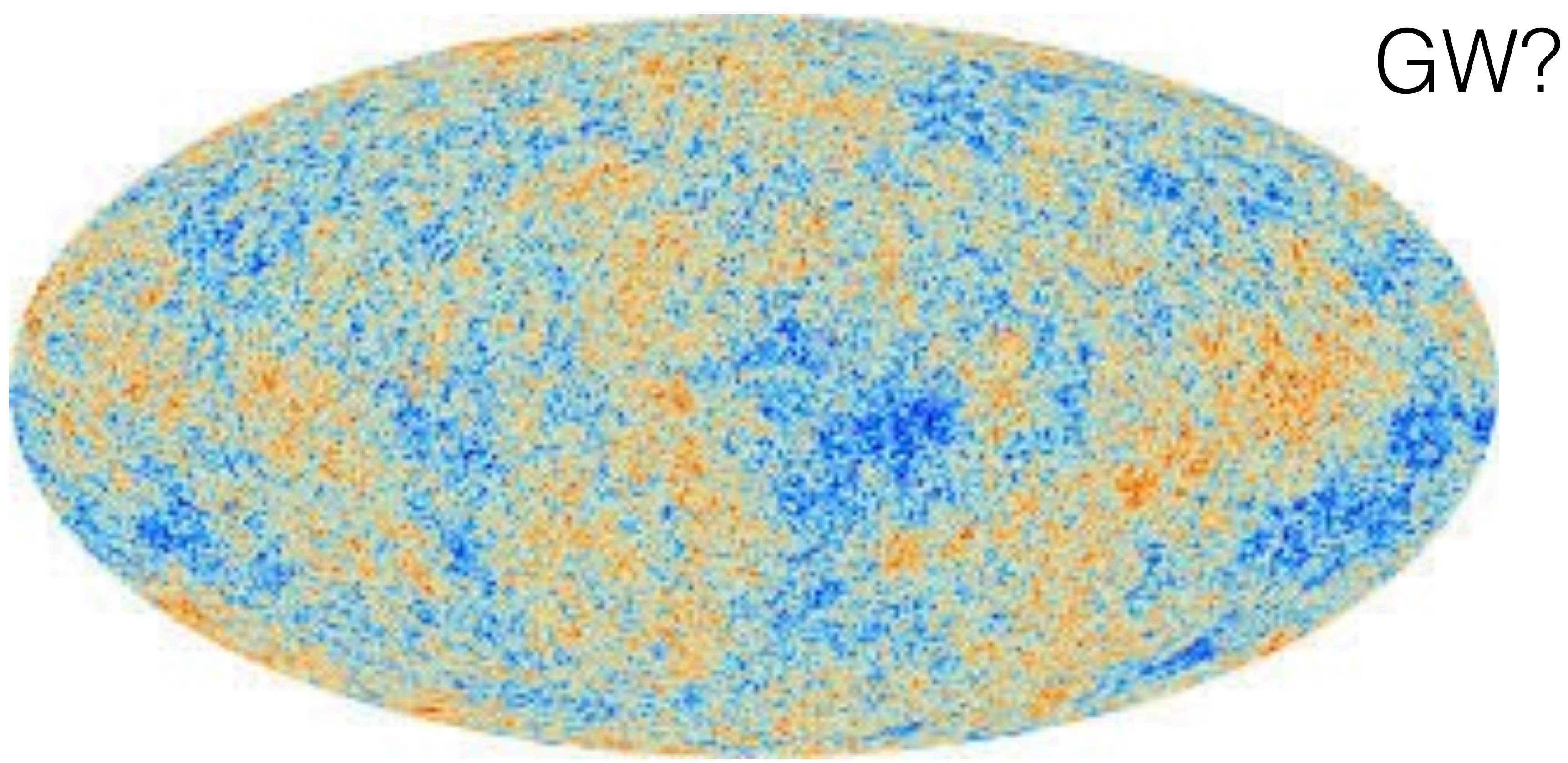


All information on inflation comes from CMB

CMB

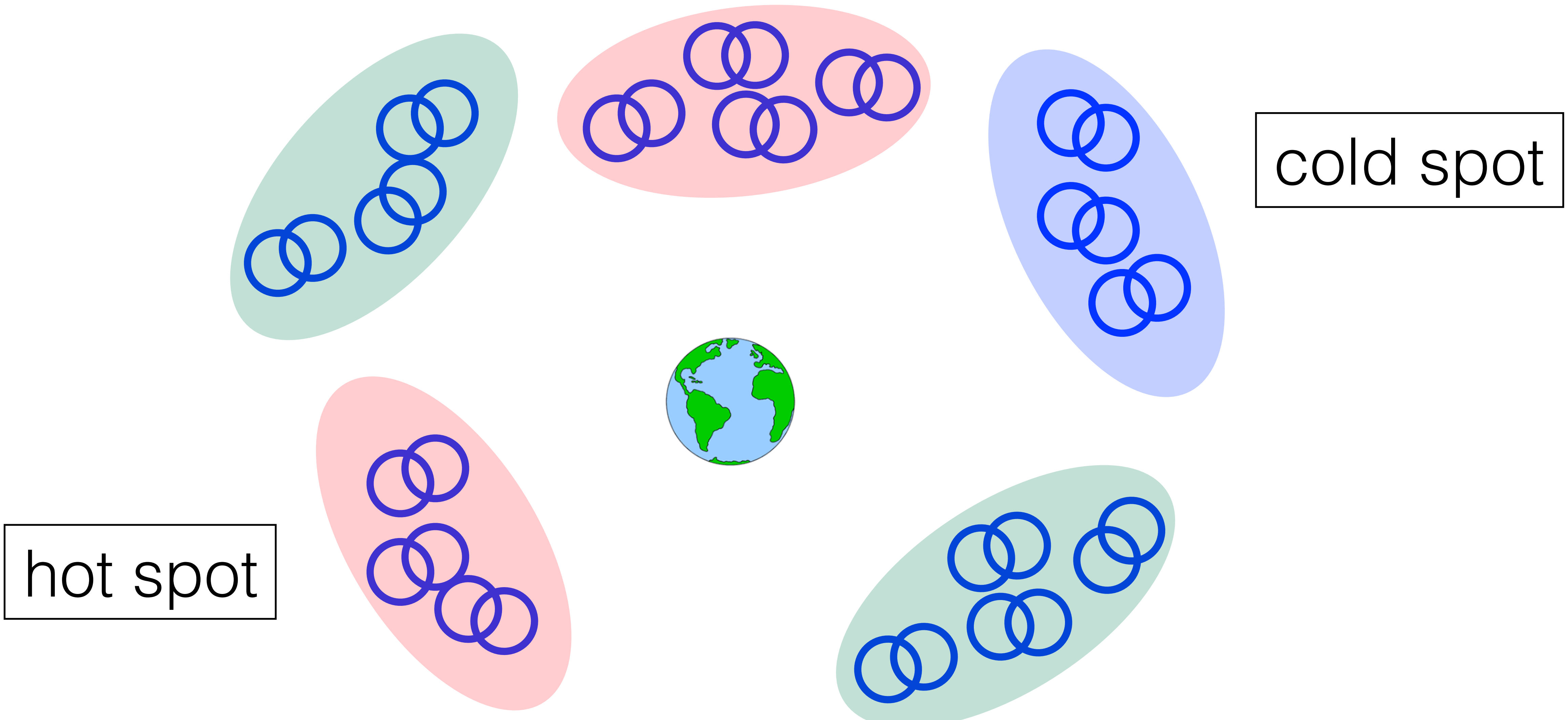
Gravitational Wave Background (GWB)

CMB most well known for its
information on "acausal" dynamics

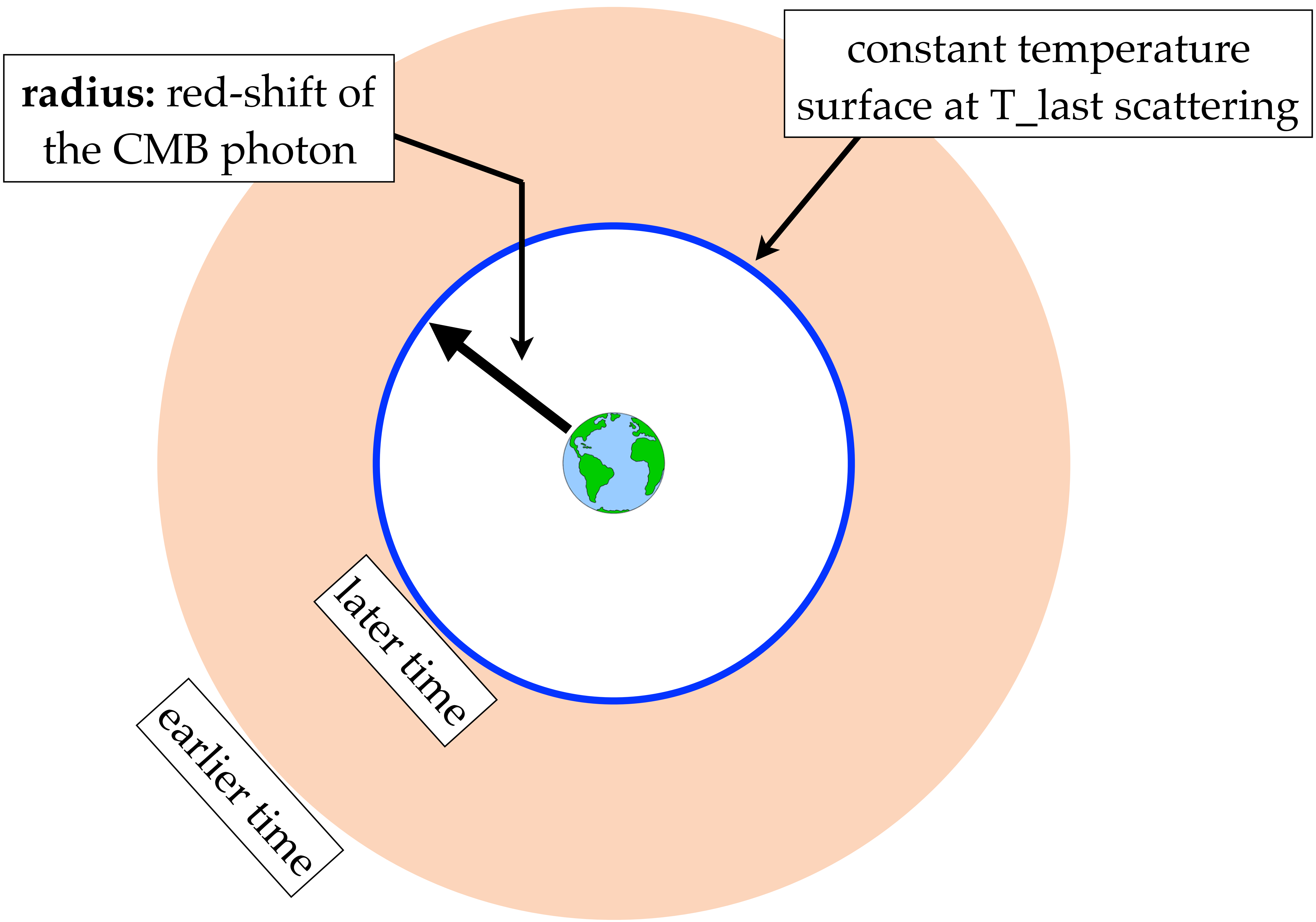


Any new information on inflation?

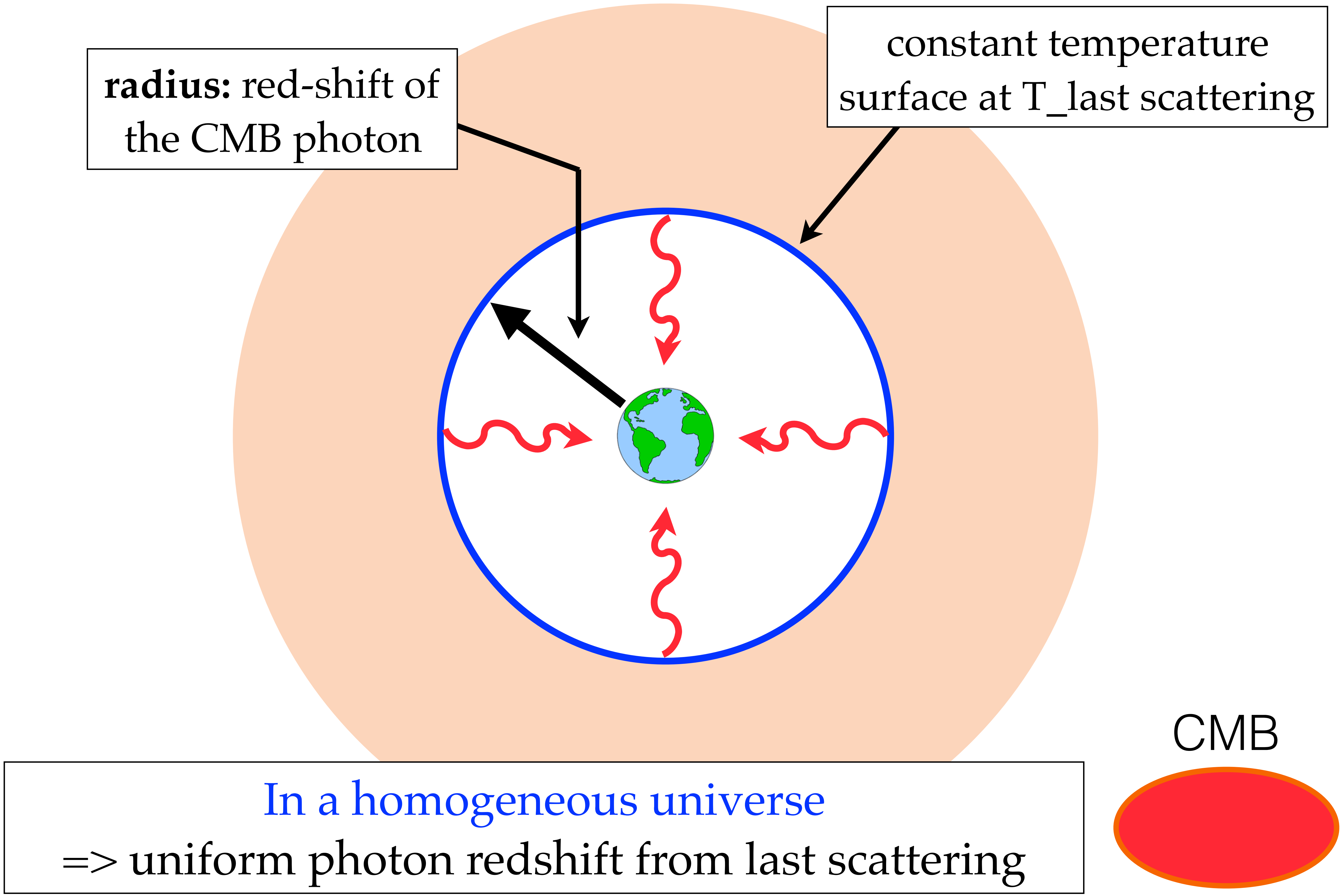
The **anisotropic pattern** of GW provides valuable info of inflation / reheating mechanism

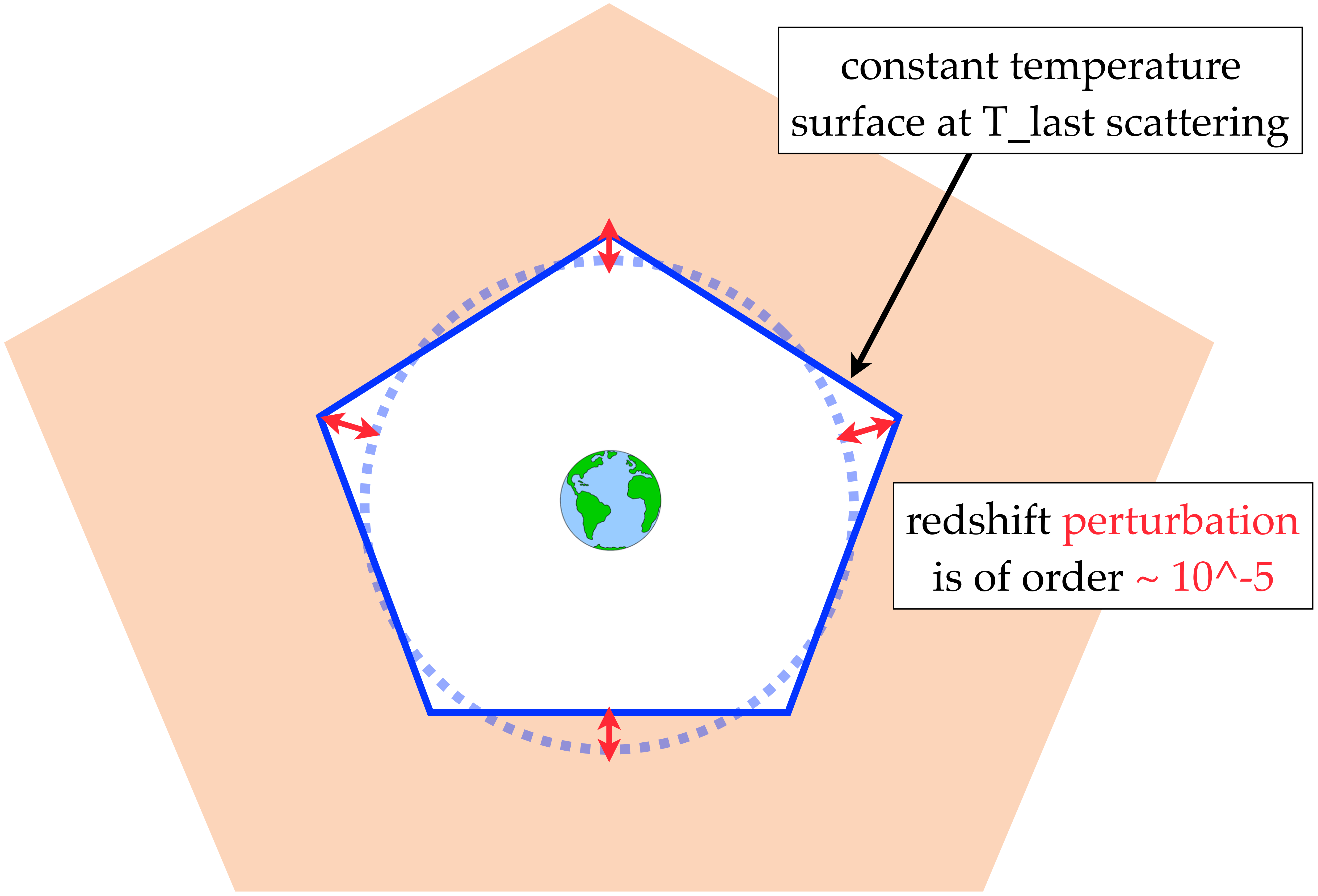


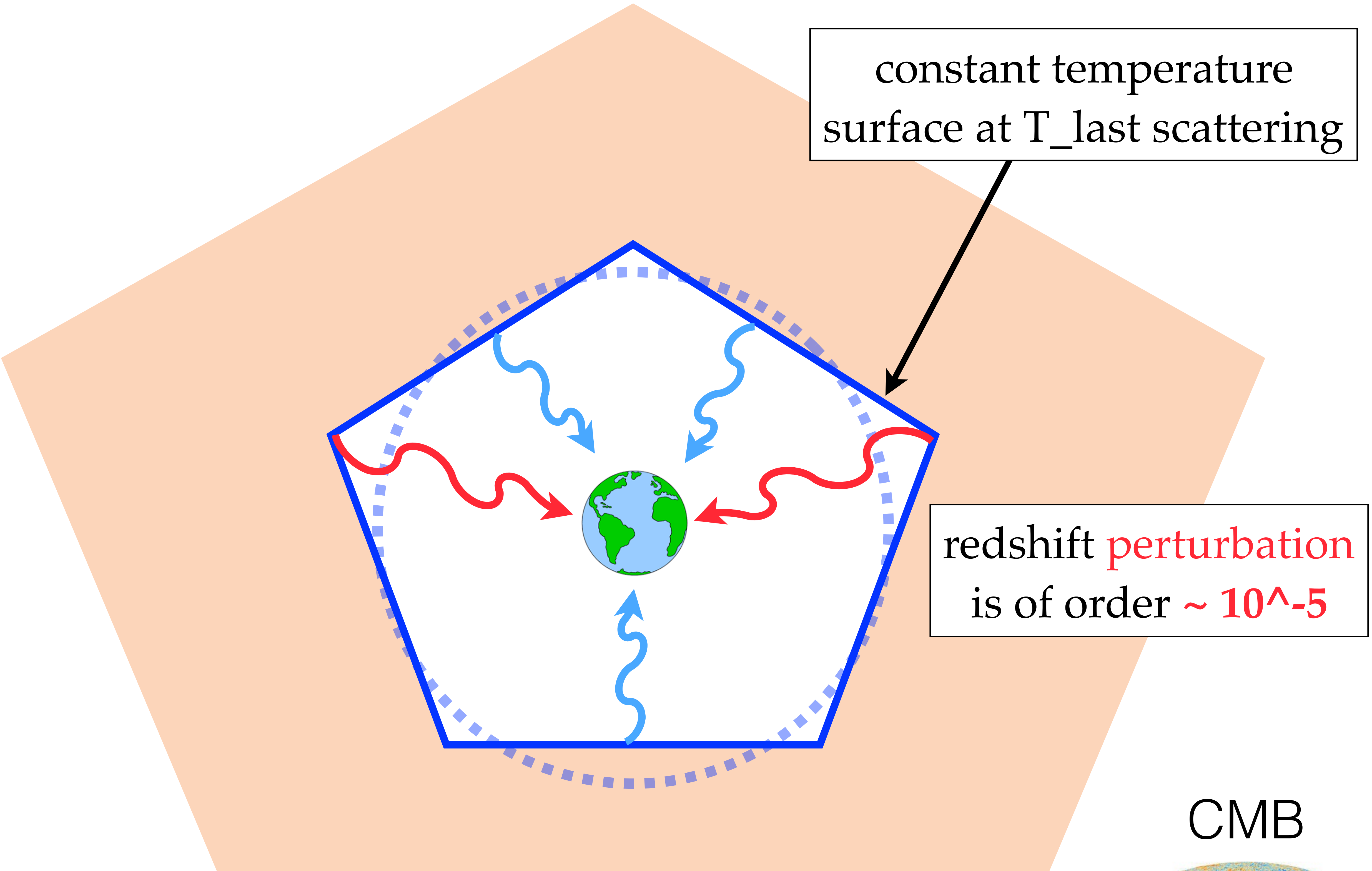
many earlier studies on stochastic GWB,
e.g., see Romano & Cornish (2017) and the reference there



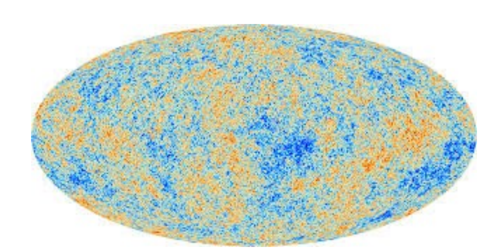
radius: red-shift of the CMB photon
constant temperature surface at T_last scattering
later time
earlier time


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

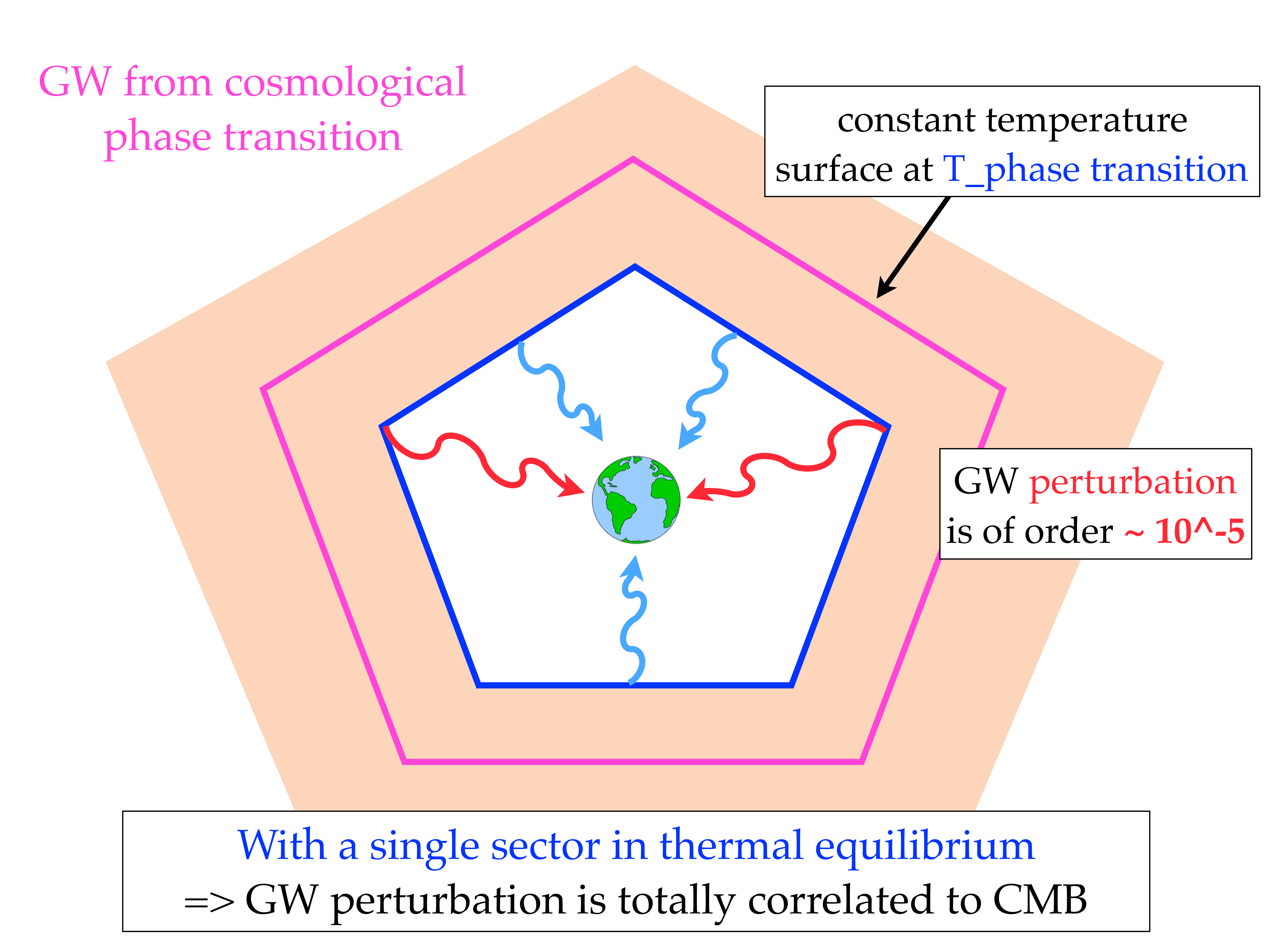


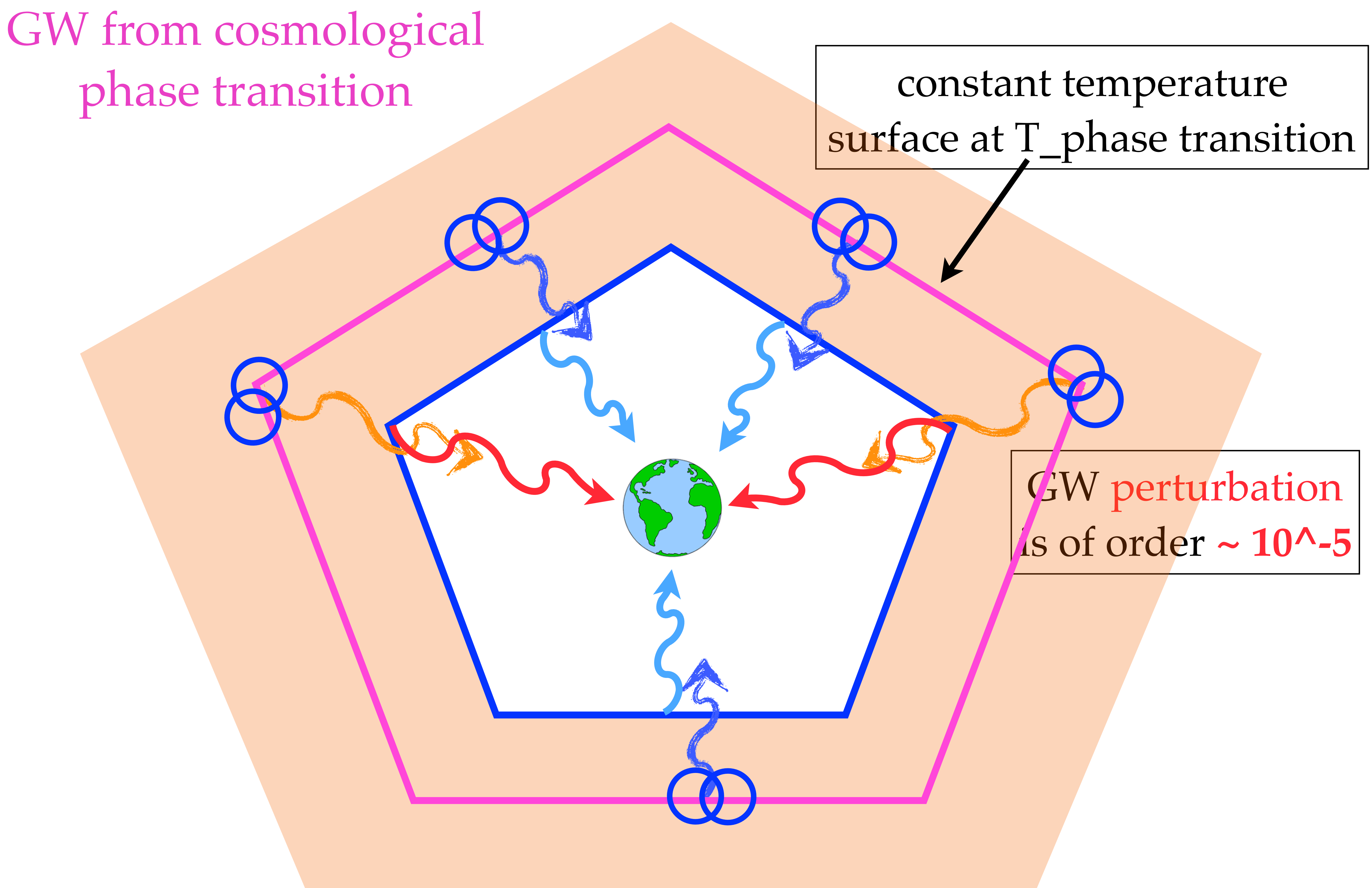
CMB



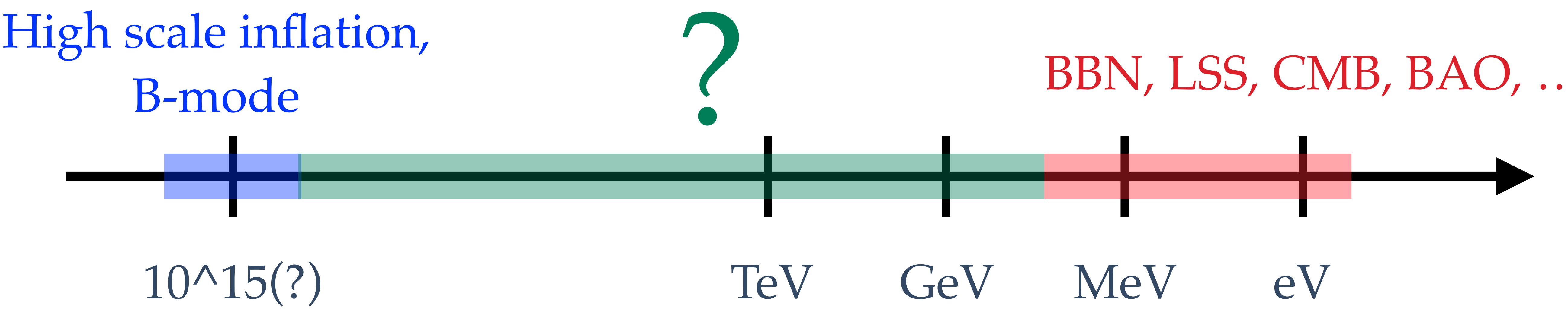
With primordial temperature perturbation

=> anisotropic redshift for last scattering photon

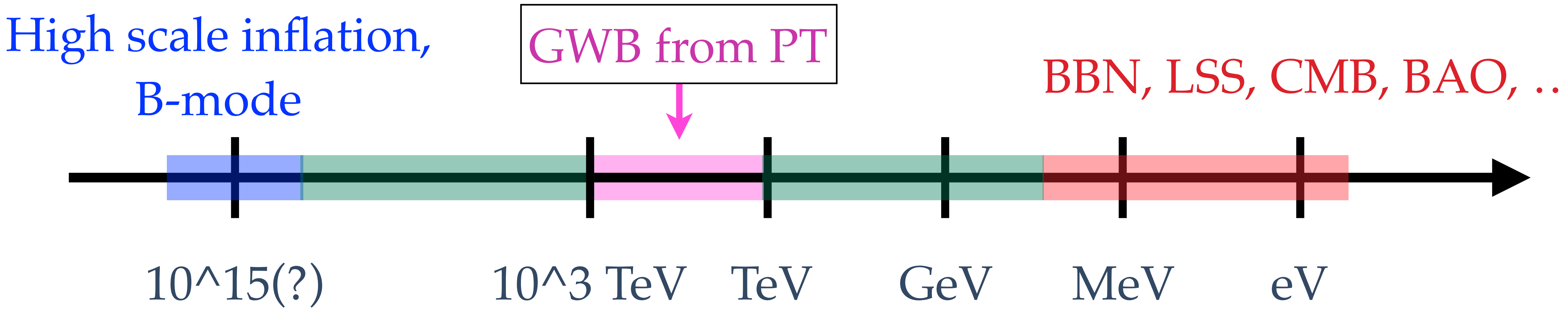

GW from cosmological
phase transition
constant temperature
surface at T_phase transition
GW perturbation
is of order ~ 10^-5
With a single sector in thermal equilibrium
=> GW perturbation is totally correlated to CMB


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

GW provides a probe of the unknown thermal history



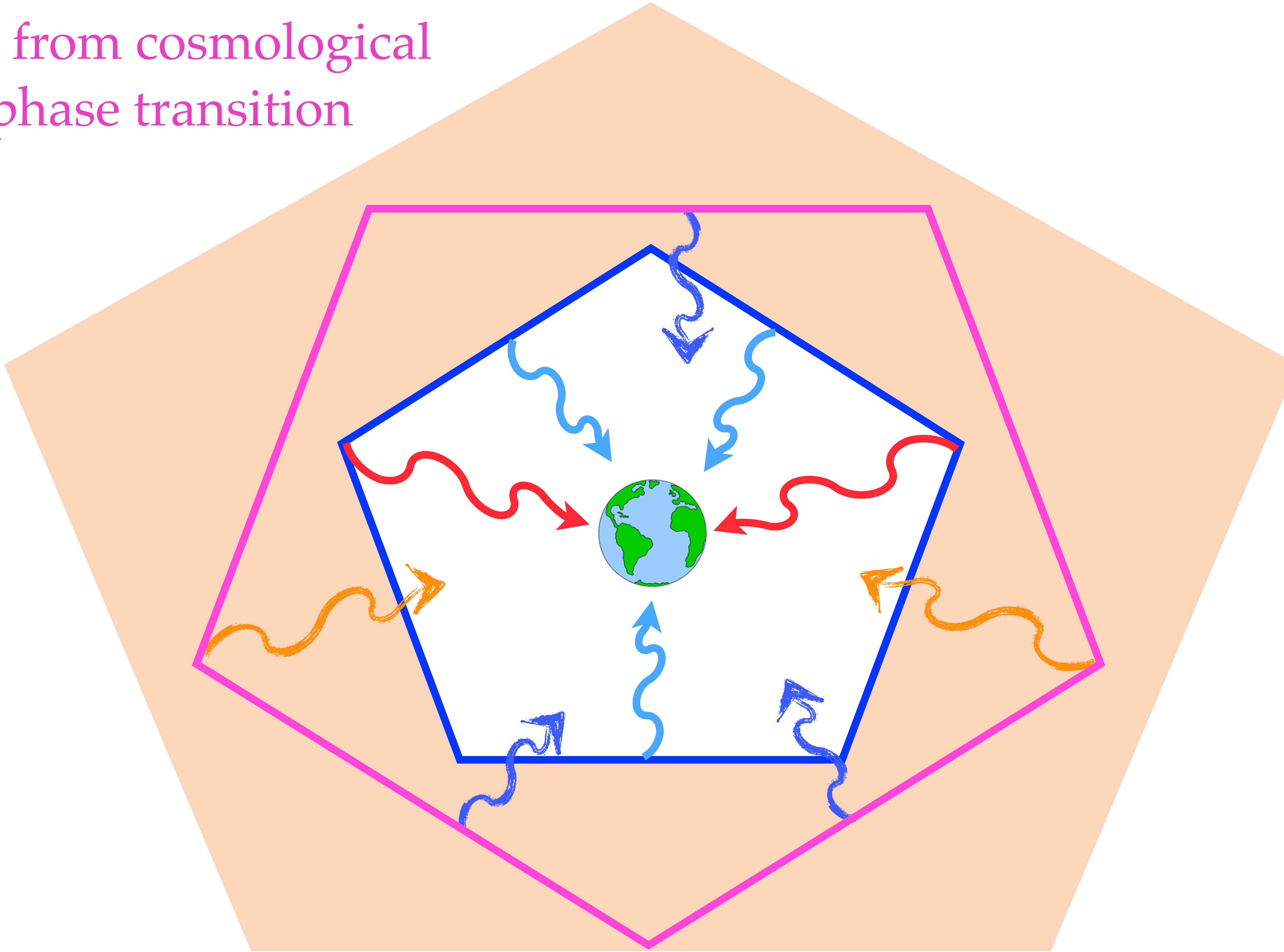
GW provides a probe of the unknown thermal history



Is there only one source of density perturbation?

Is the GW sector in thermal eq. with SM?

GW from cosmological phase transition



If perturbation comes from different reheating process

=> GWB can be ``uncorrelated” with CMB

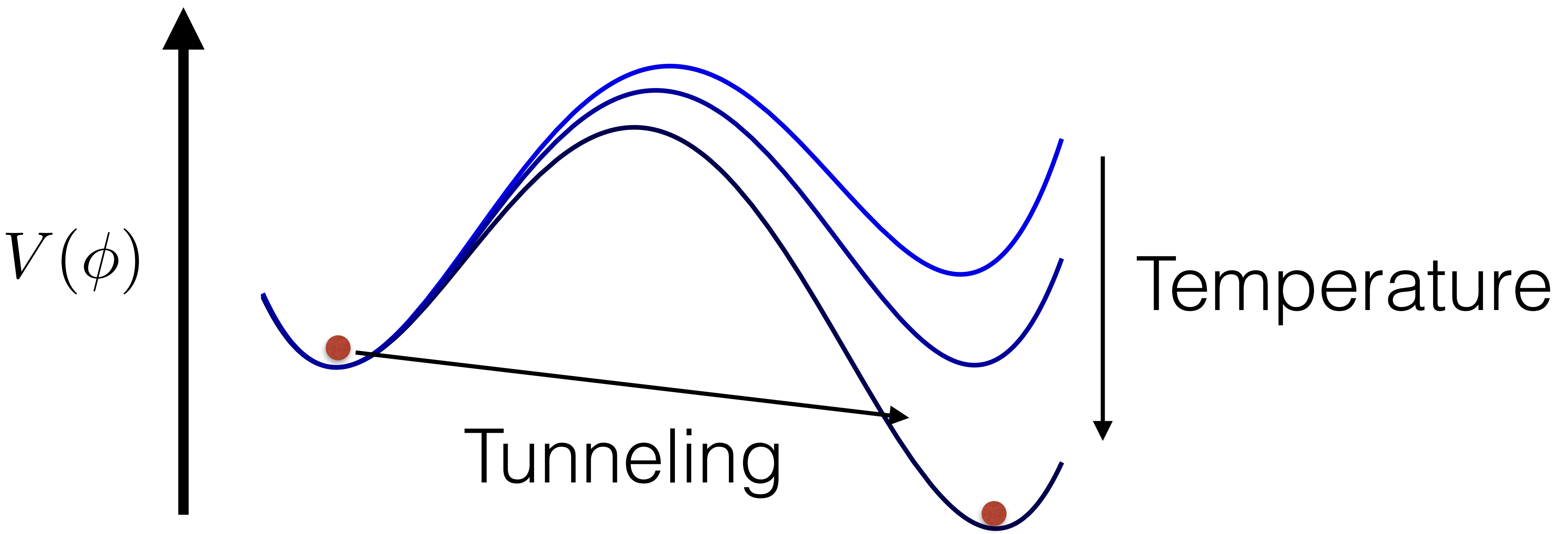
Is any of this visible?

GW from first order PT

Microscopic piece

Black body piece

First order phase transition

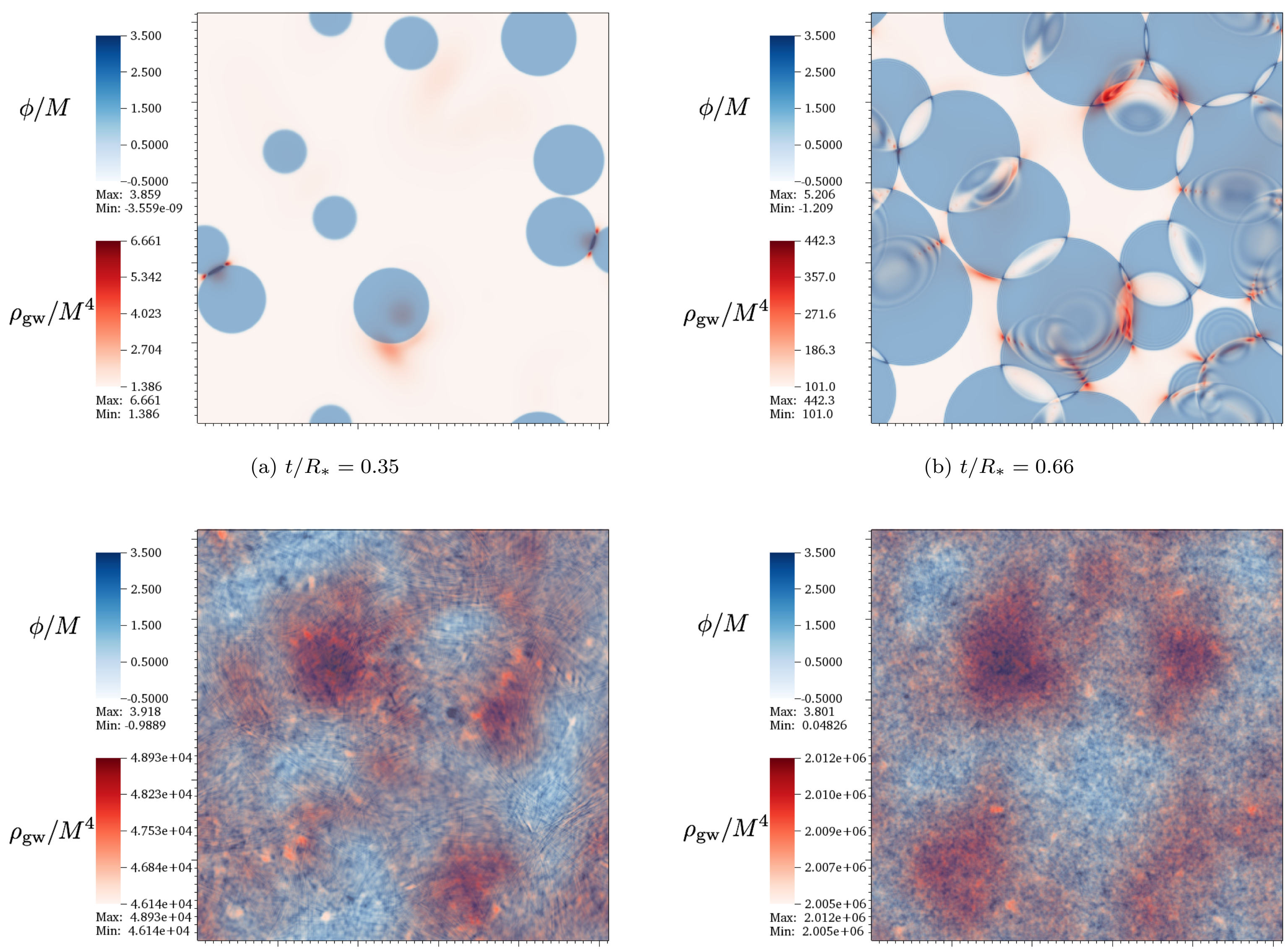


$$\Gamma(T) = A(T)\, e^{-S(T)}$$

PT rate as a function of temperature

GW from first order PT

- The collisions of the bubbles generate gravity waves



(a) $t/R_* = 0.35$

(b) $t/R_* = 0.66$

(c) $t/R_* = 2.50$

(d) $t/R_* = 7.8$

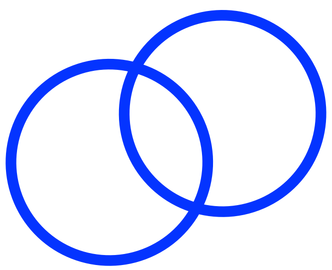
In the sky today:

$> 10^{30}$ bubbles

from TeV scale PT

Cutting, Hindmarsh, Weir (2018)

Energy density of GW from PT



Einstein eq. $$\omega_{\rm GW}^2\,\delta g_{\rm GW} \sim G_N\,\rho_{PT}$$

Typical frequency (micro-phys) $$\omega_{\rm GW} \sim \frac{1}{\Delta t_{PT}} \sim \left(\frac{\dot\Gamma}{\Gamma}\right)_{T_{PT}}$$

Energy density in GW $$\rho_{\rm GW} \sim \frac{1}{G_N}\omega_{\rm GW}^2(\delta g_{\rm GW})^2$$

$$H_{PT}^2 \sim G_N\,\rho_{total}$$

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

To get a strong phase transition

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

$$\left(T\frac{dS}{dT}\right)_{PT} = (\Delta t_{PT}\, H_{PT})^{-1}$$

Need $\Delta t_{PT} H_{PT} > 10^{-2}$

Bubble nucleate too fast
=> not a strong PT

To get a strong phase transition

$$\Gamma(T) = A(T)\, e^{-S(T)} \qquad \left(T\frac{dS}{dT}\right)_{PT} = (\Delta t_{PT}\, H_{PT})^{-1}$$

Need $\Delta t_{PT} H_{PT} > 10^{-2}$

Bubble nucleate too fast
=> not a strong PT

Need $\Delta t_{PT}\, H_{PT} < 1$

Bubble size cannot be larger than Hubble

From naive dimensional analysis $H_{PT} \Delta t_{PT} \sim 10^{-2}$

To get a strong phase transition

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

$$\left(T\frac{dS}{dT}\right)_{PT} = (\Delta t_{PT}\, H_{PT})^{-1}$$

Need $\Delta t_{PT} H_{PT} > 10^{-2}$

Bubble nucleate too fast
=> not a strong PT

Need $\Delta t_{PT}\, H_{PT} < 1$

Bubble size cannot be larger than Hubble

For a stronger PT $H_{PT}\Delta t_{PT} \rightarrow 1$

Energy density of GW from PT

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

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

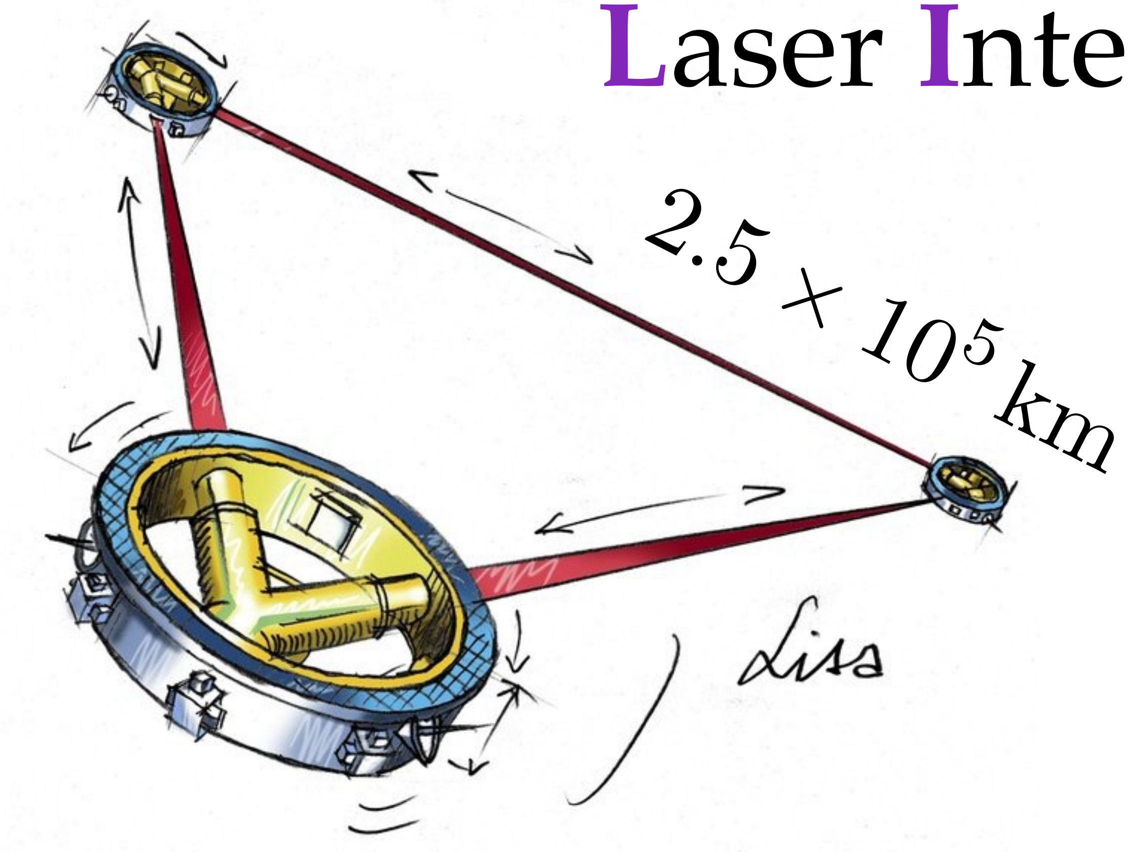
$$\omega_{\mathrm{GW}}^{today} \sim \omega_{\mathrm{GW}} \left(\frac{T_{\mathrm{CMB}}^{today}}{T_{PT}} \right) \gtrsim \text{mHz - Hz}$$

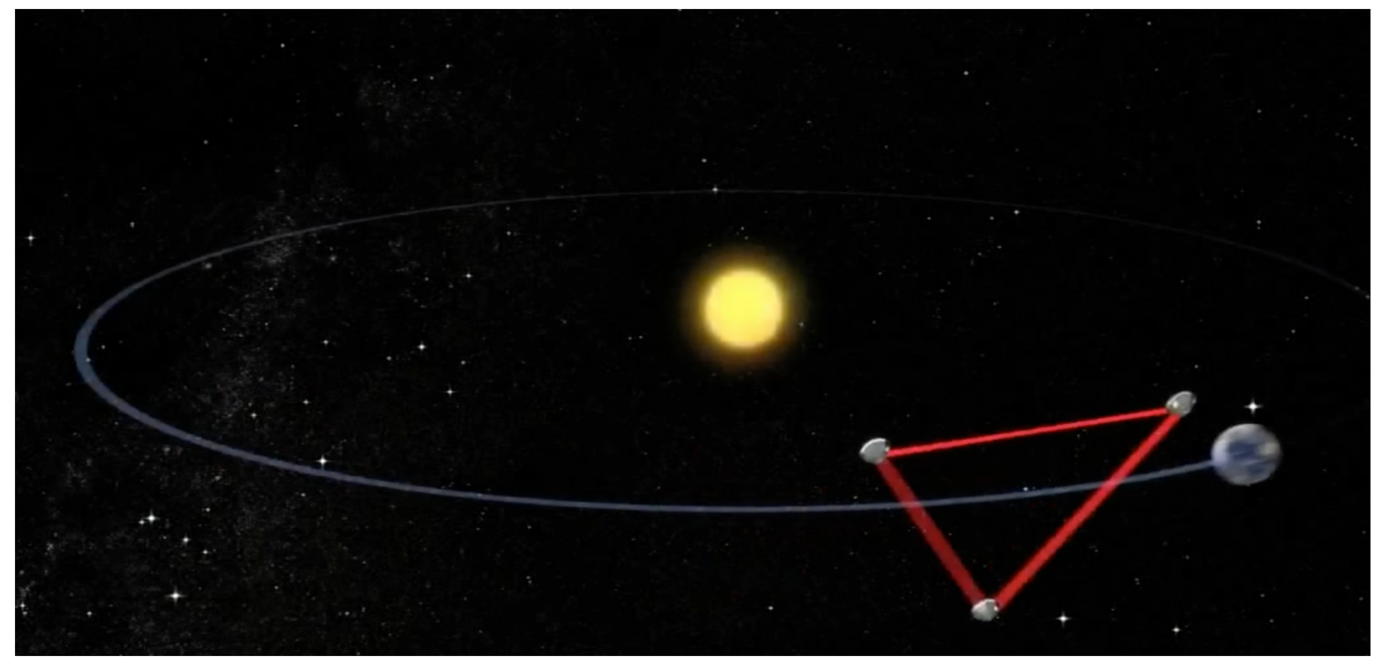
For

$$T_{PT} \sim \text{TeV - PeV}$$

GW detectors

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

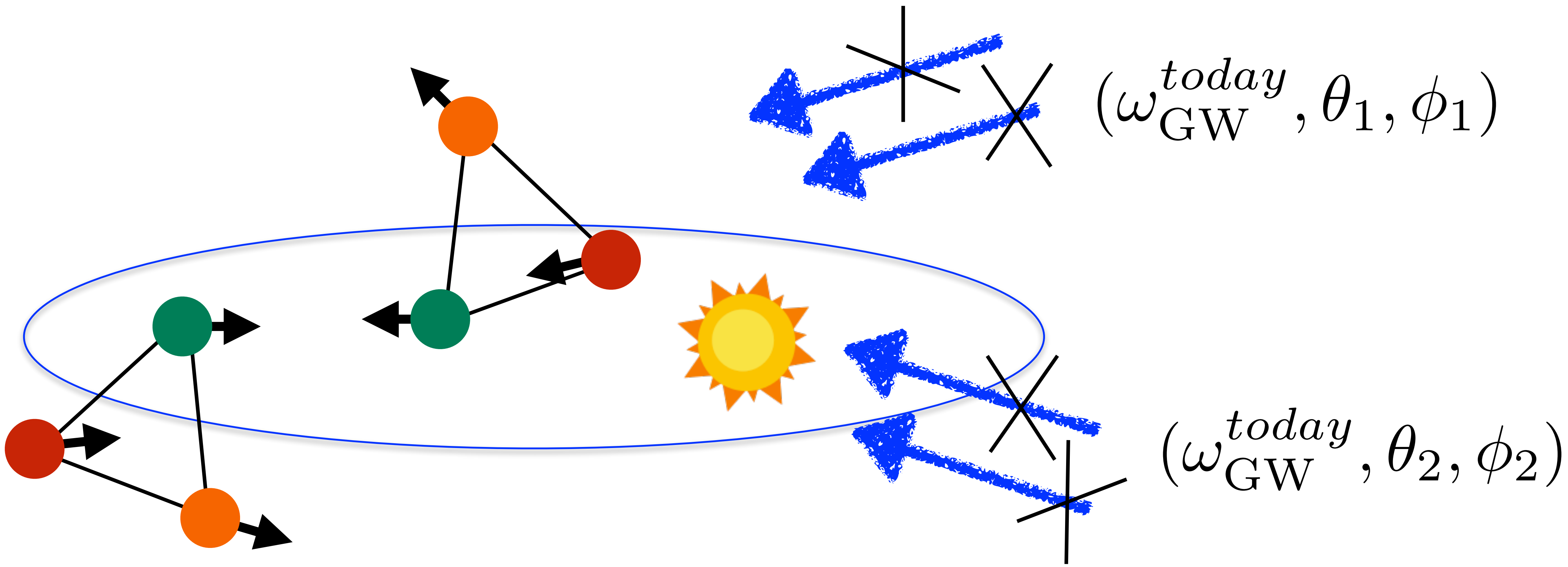




Similar ideas, more futuristic

BBO, DECIGO, ALIA

Angular measurement



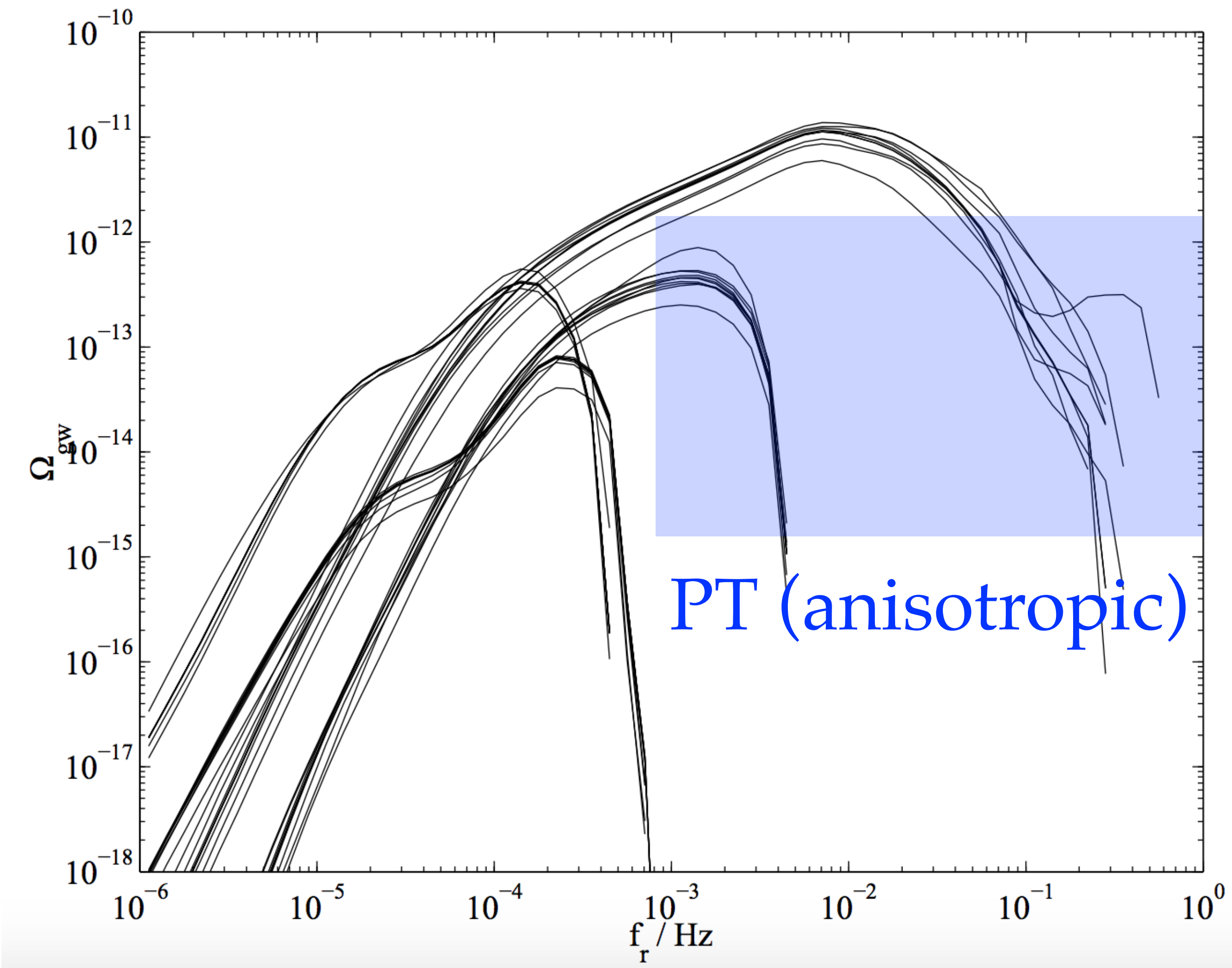
- **Method:** variation of **strains** in time for each polarization mode with different detector location/Doppler shift
- LISA may get to ~ 0.01 steradians ($\ell_{\rm max} = \mathcal{O}(10)$), more detectors (BBO/DECIGO) can do better [Cutler(1997), Giampieri et al (1997)]

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

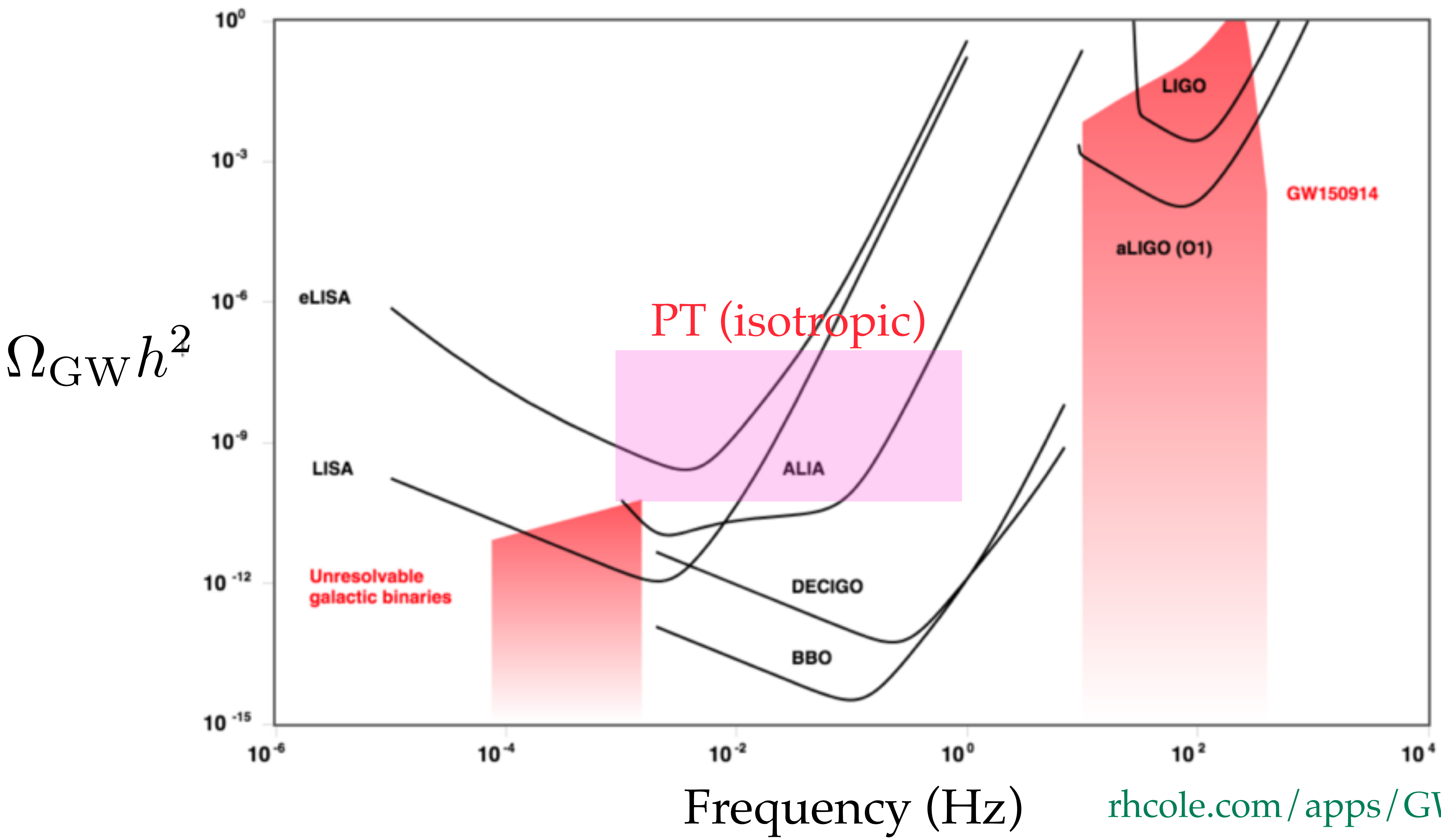
Adams & Cornish (2013)



Farmer & Phinney (2003)

Energy density of GW from PT

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



rhcole.com/apps/GWplotter/

Anisotropy maximal size

CMB constraints

Absolute magnitude of gravity wave perturbations less than CMB perturbations

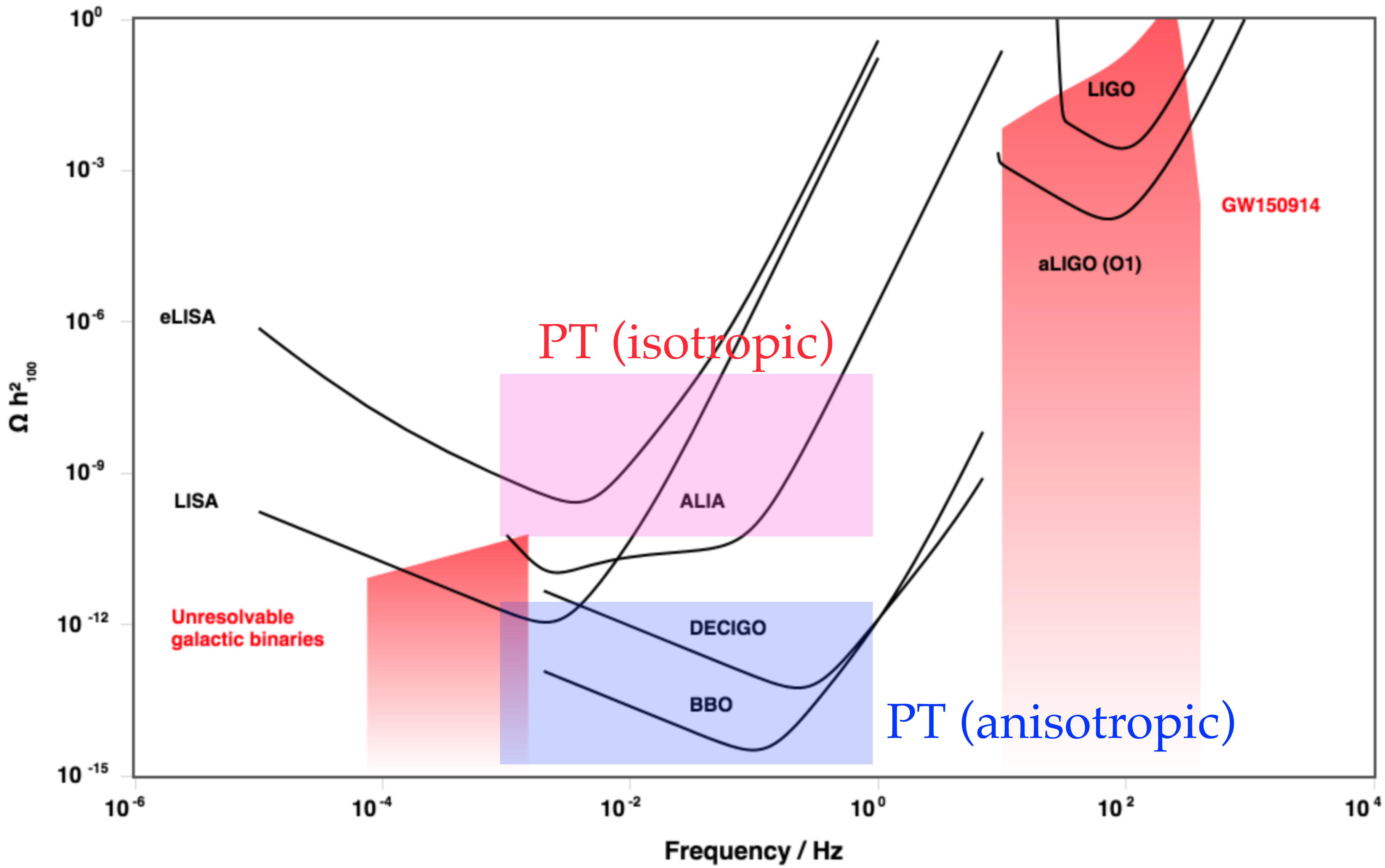
$$\delta\rho_{GW} < \delta\rho_\gamma \sim 10^{-5}\rho_\gamma$$

Gravitational back-reaction measurable

Difficult to saturate

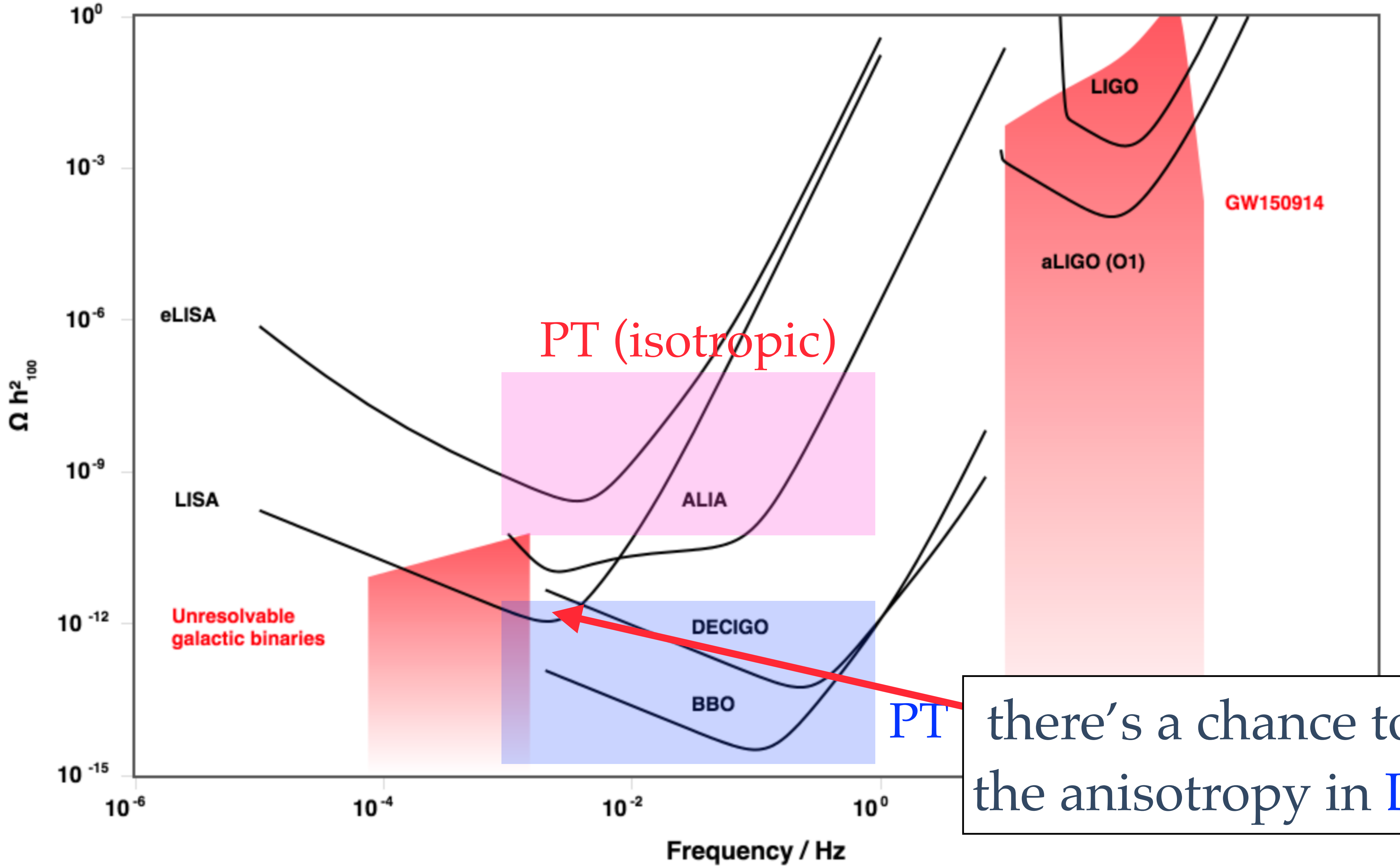
Detection possibility

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



Detection possibility

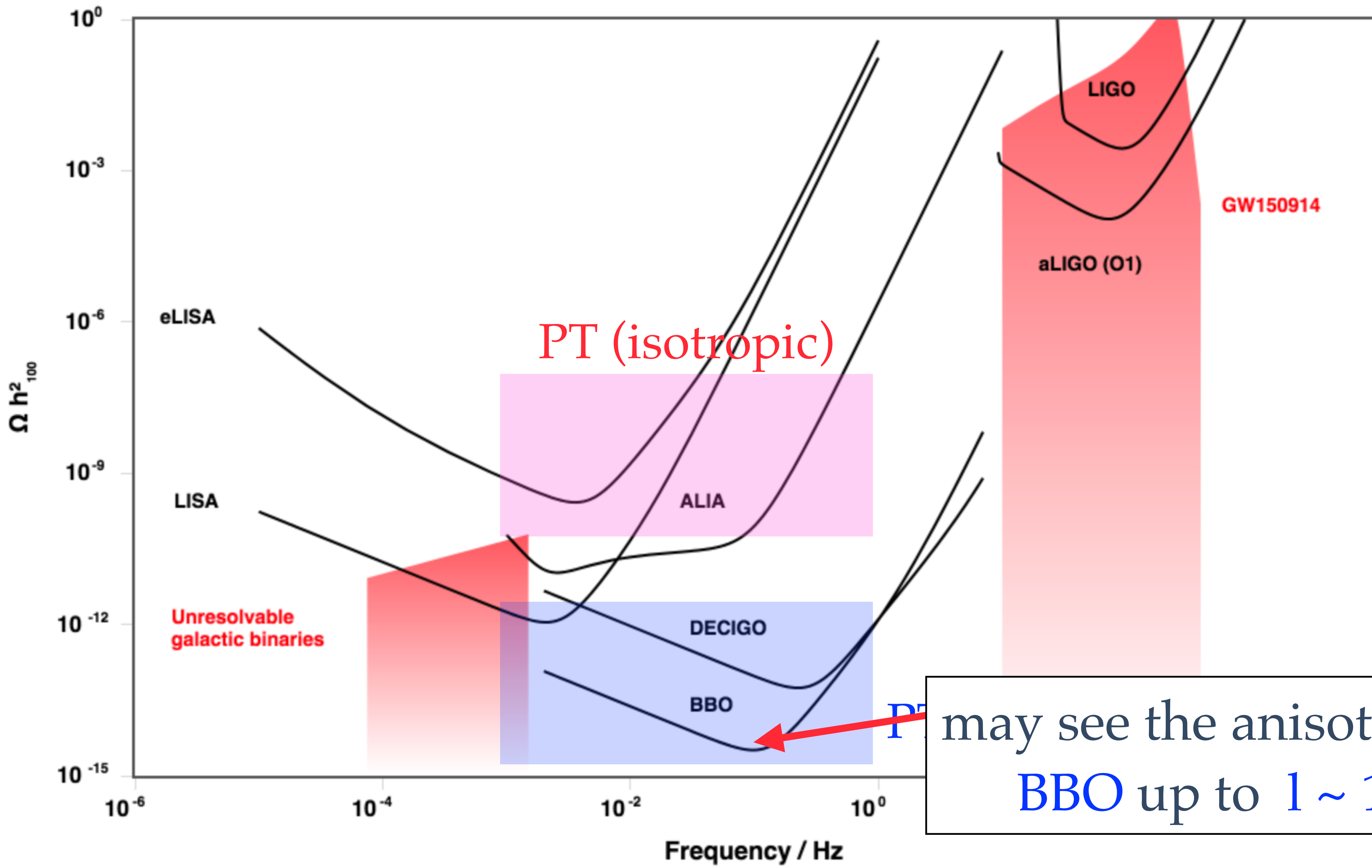
$$\delta\rho_{\rm GW}^{today} \approx 10^{-10} - 10^{-7}\rho_\gamma$$



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 $\ell \sim 100$!

Conclusion

Isotropic Piece

Energy density generating GW

Hubble at which GW are generated

Anisotropic Piece

Is sector in thermal eq. with SM

Are there multiple light scalar fields during inflation