Anisotropies in the Gravitational Wave Background from Cosmological Phase Transitions

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(borrowing from Yuhsin Tsai)

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PRL 121, 201303 (2018), arXiv:1803.10780

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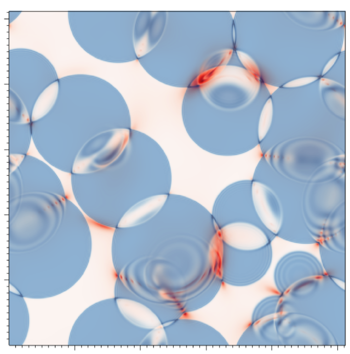
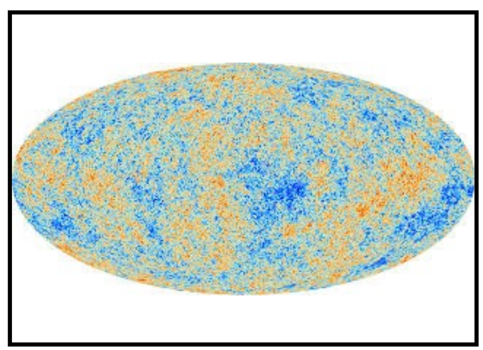
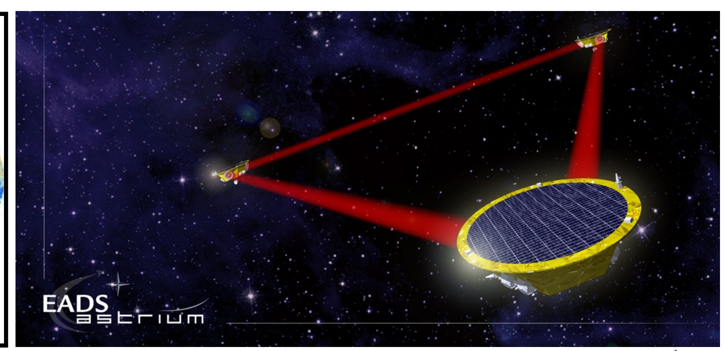




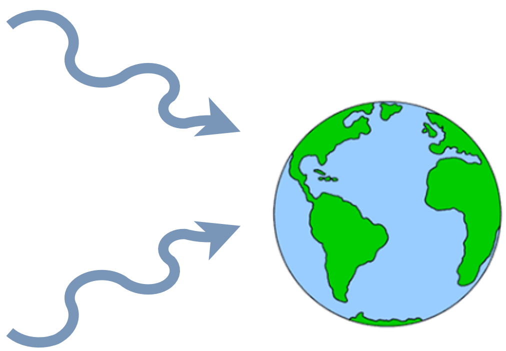


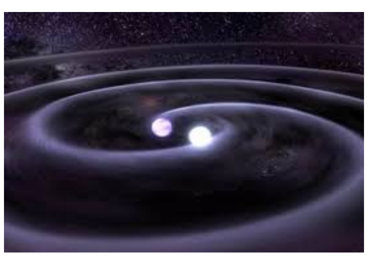
Gravitational Waves (GW)

Astrophysical sources

black hole, neutron start, white dwarf mergers

can be resolvable



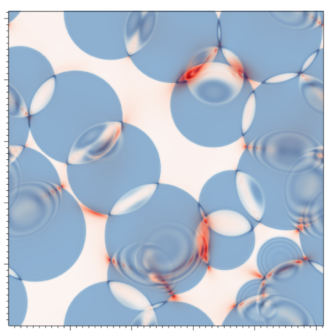


study physics of gravity, QCD, galaxy formation,…

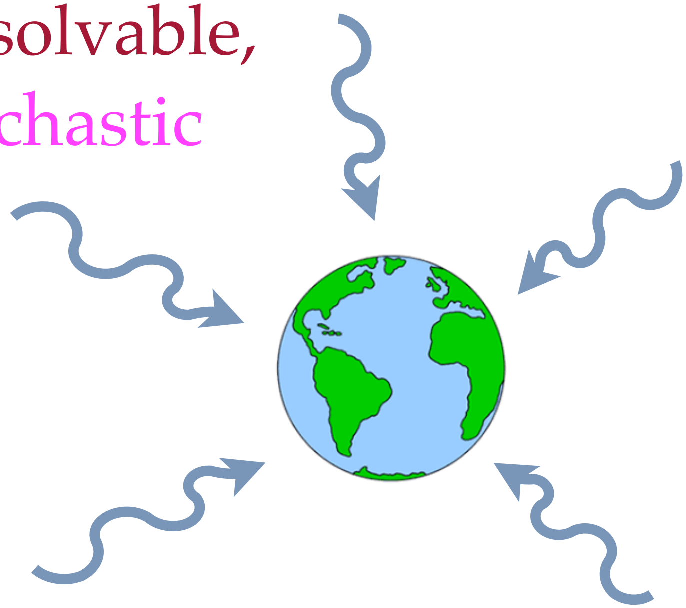
GW Cosmology

Cosmological sources

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



unresolvable,
stochastic

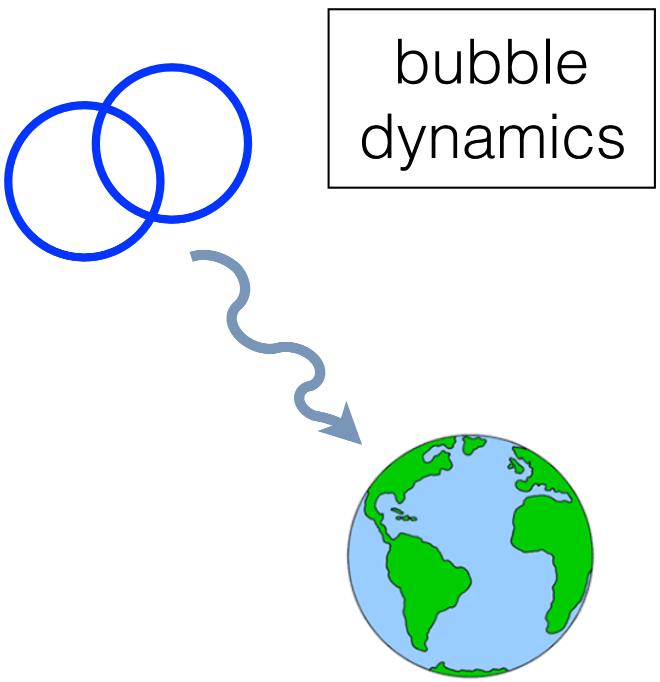


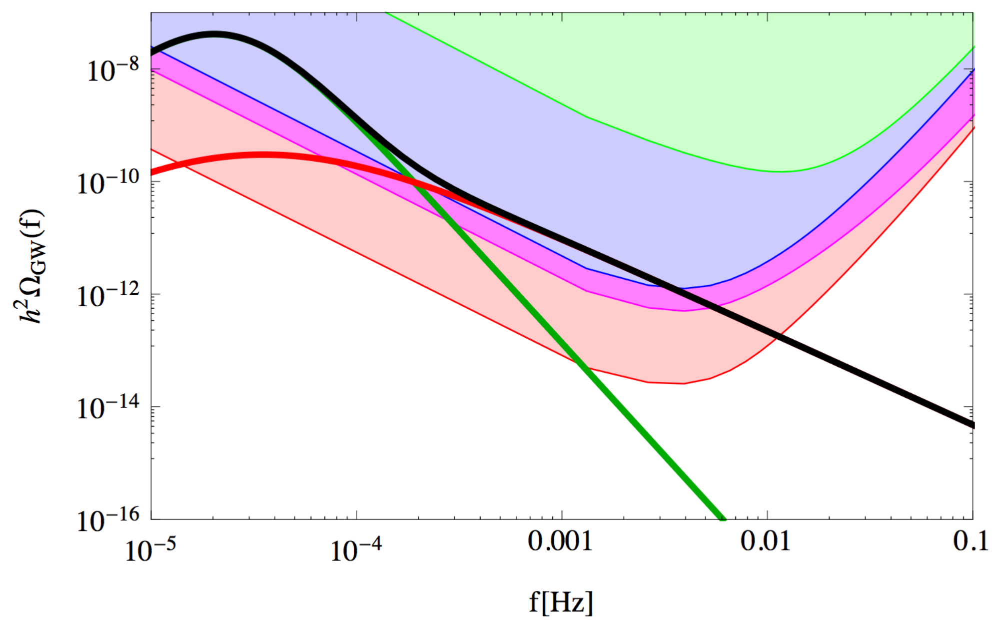
study Higgs sectors,
Baryogenesis,
inflation, reheating…

GW from first order Phase Transitions

Most discussions focus on
GW energy / frequency spectrum from PT.

PT ~ TeV-100TeV => GW frequencies ~ proposed detectors!



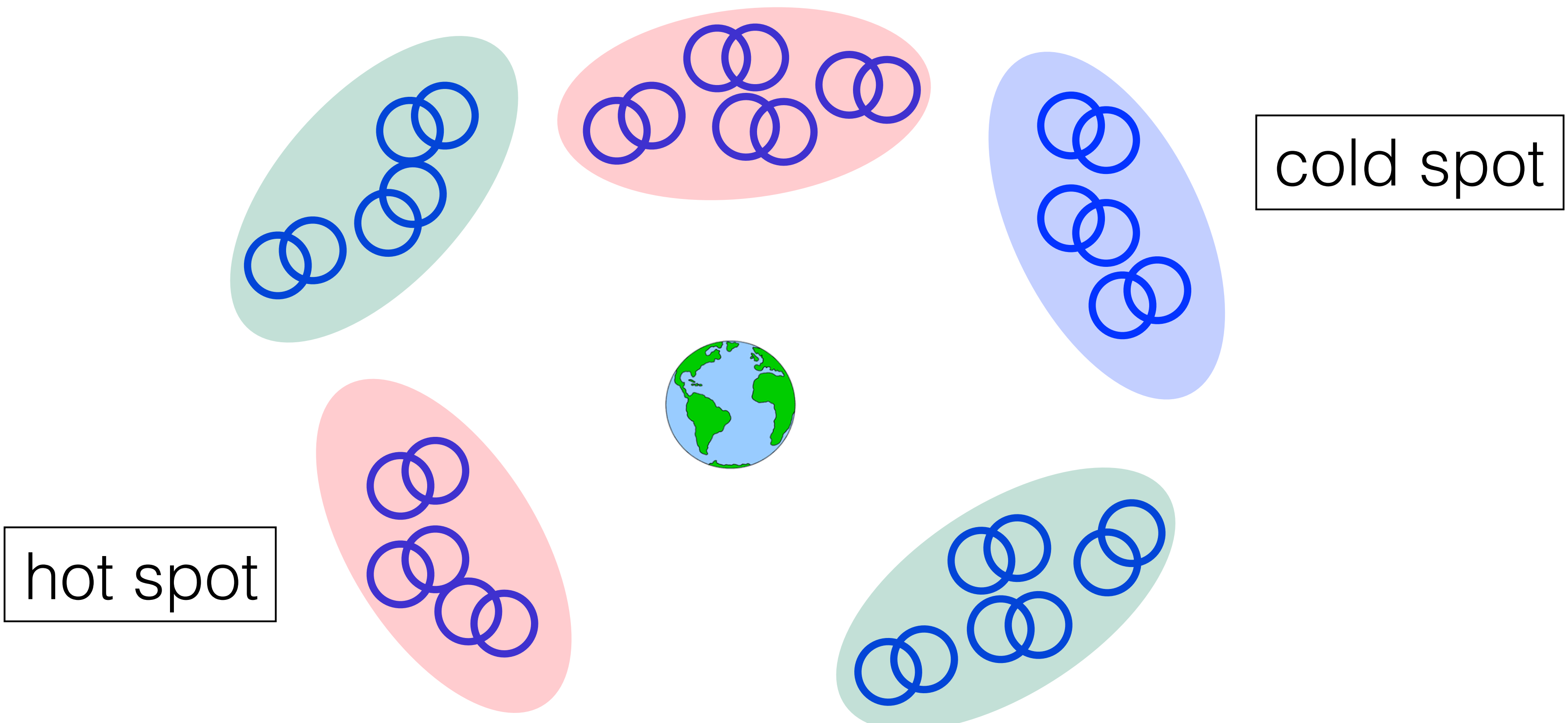


1512.06239

studies on stochastic GW, see e.g. Romano & Cornish (2017)

GW from first order PT

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



GW anisotropies in other contexts

Astro sources: Cutler, Holz ’09; Cusin et al ’17

Inflationary preheating: Bethke et al ’13, ’14;

Analytic frameworks: Cusin et al ’17, Olmec et al ’12,

applied to Cosmic string networks: Jenkins et al ’18

Non-Gaussianities in pulsar timing arrays: Tsuneto et al ‘19

Gravitational Wave Background (GWB)

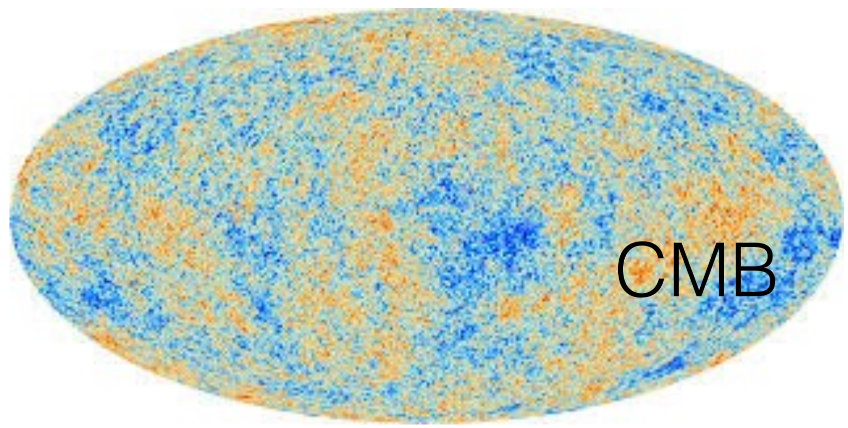
Similar to the CMB spectrum, but with

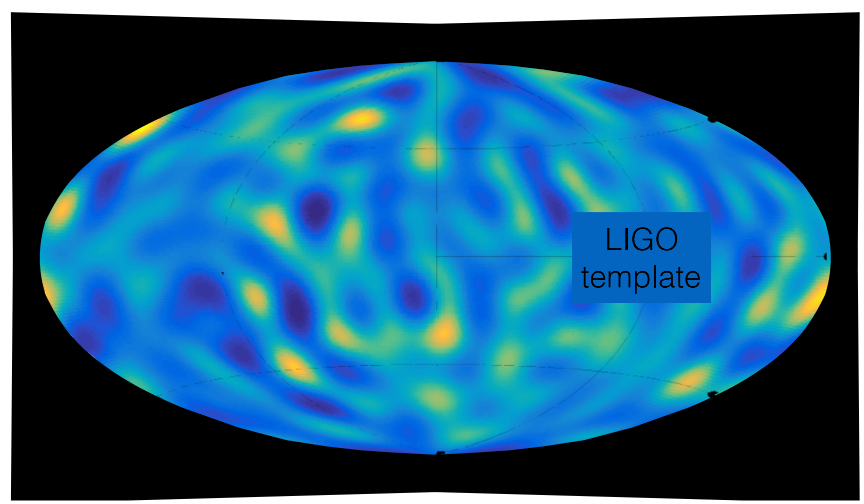
photon -> GW from PT

hot spot =>

Higher energy photons

-> Higher energy GW





Gravitational Wave Background (GWB)

Similar to the CMB spectrum, but with

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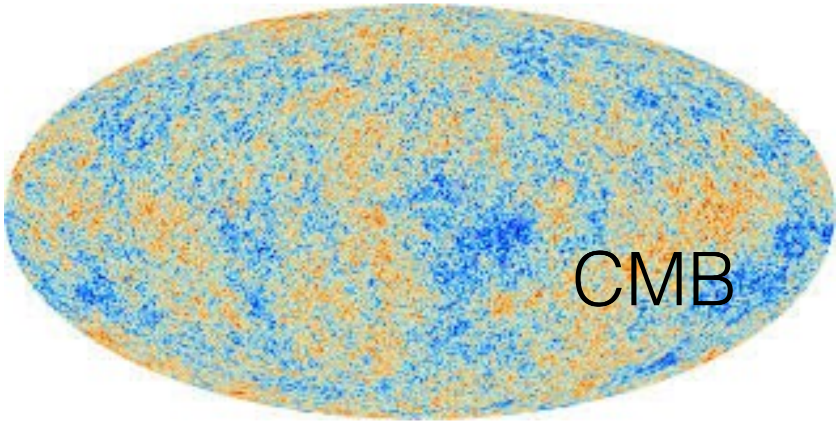
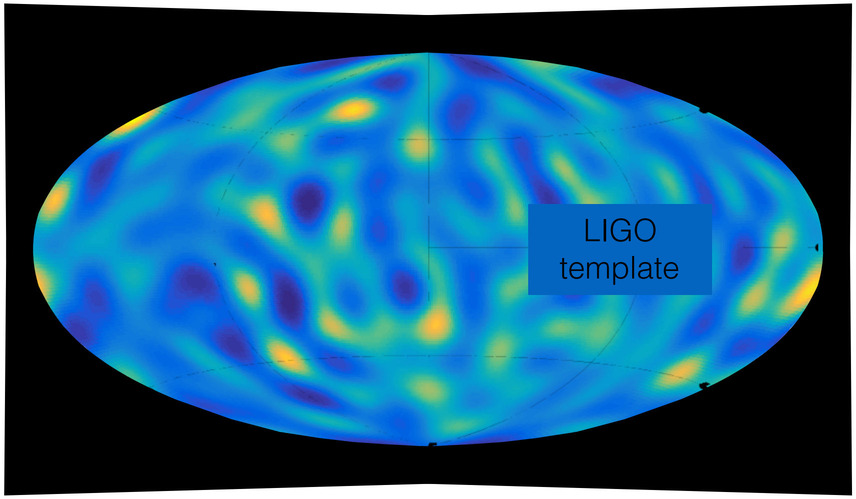
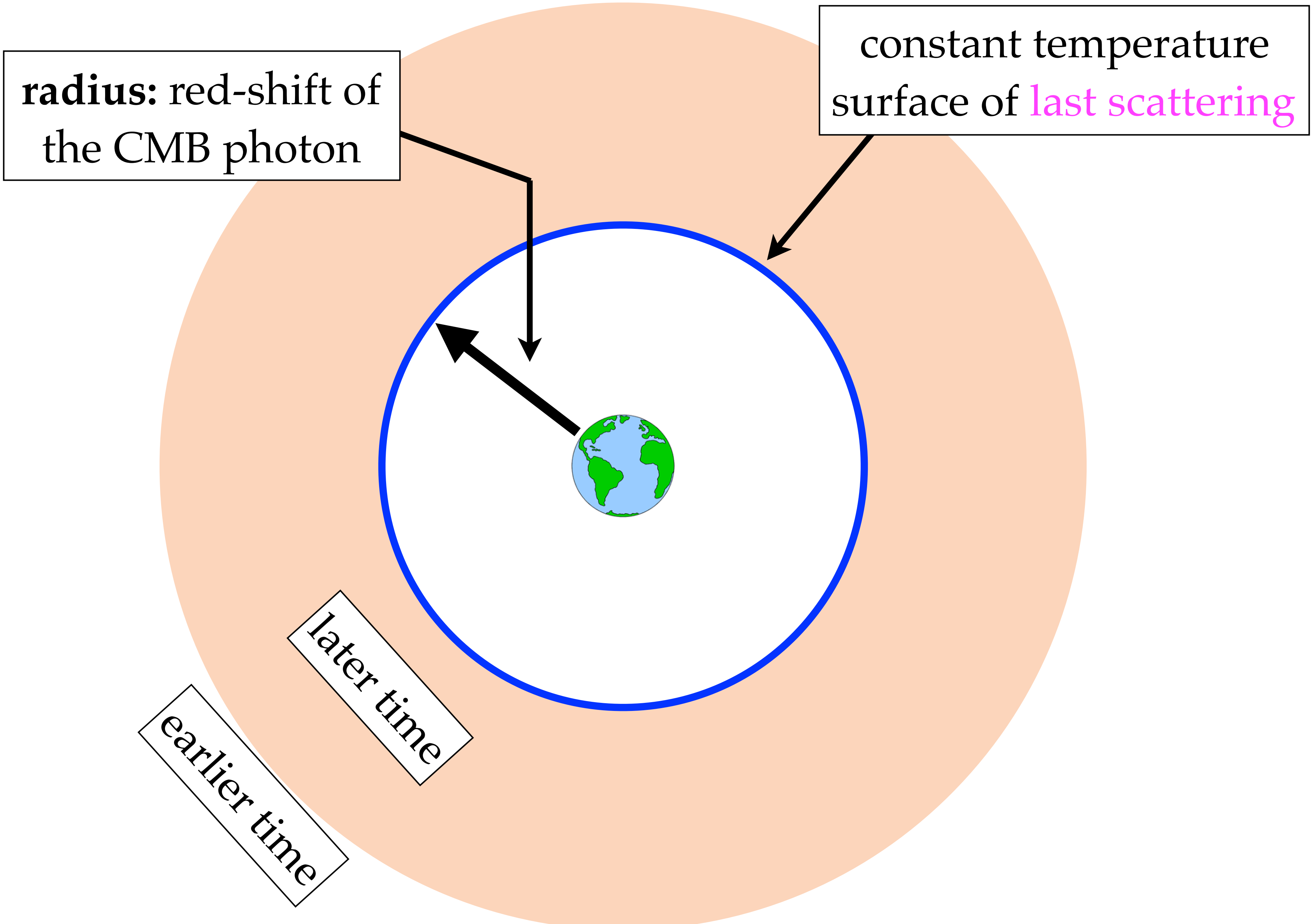
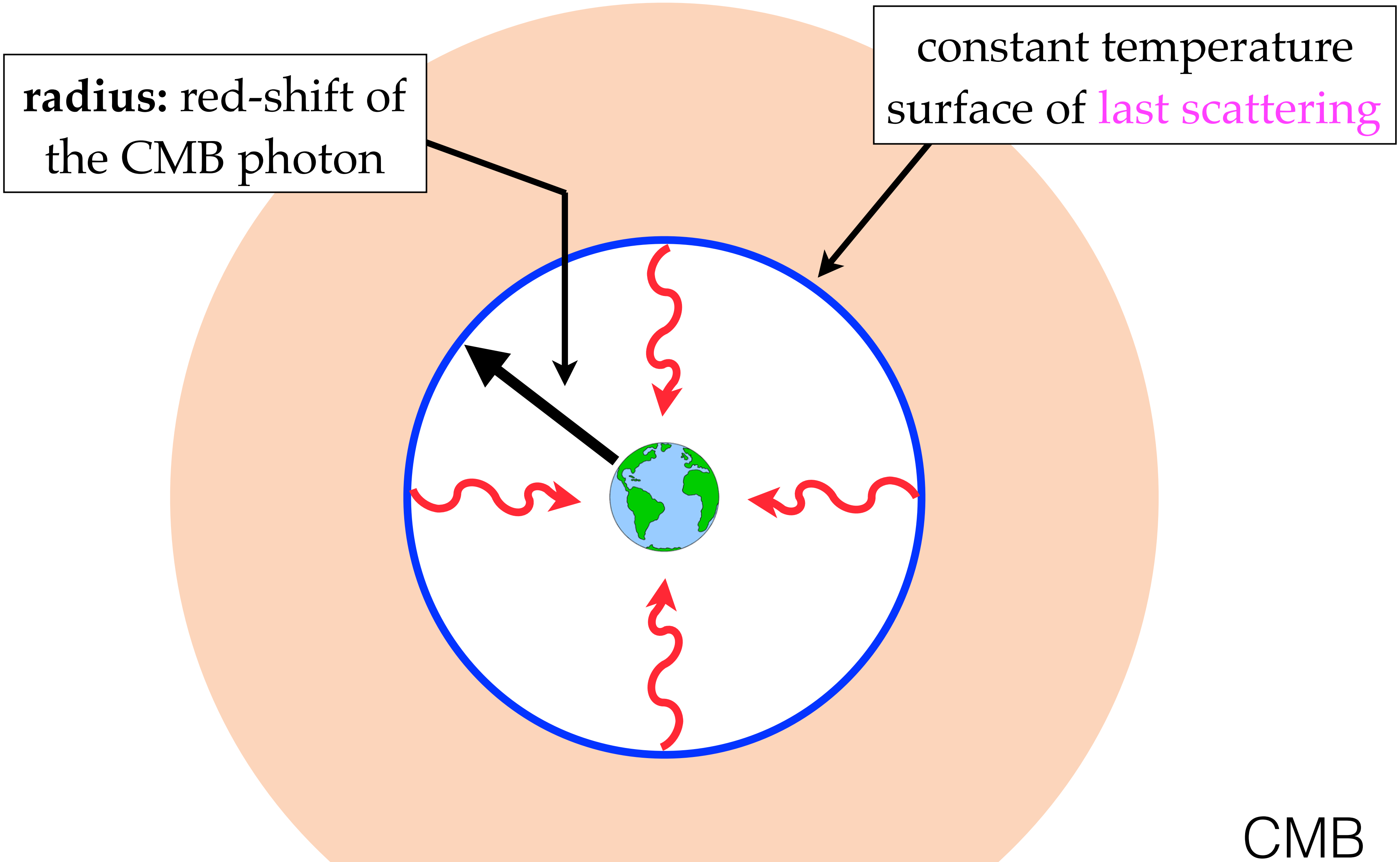




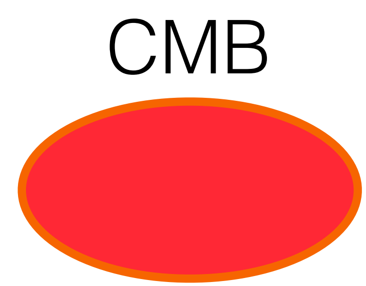
where do hot / cold spots come from?

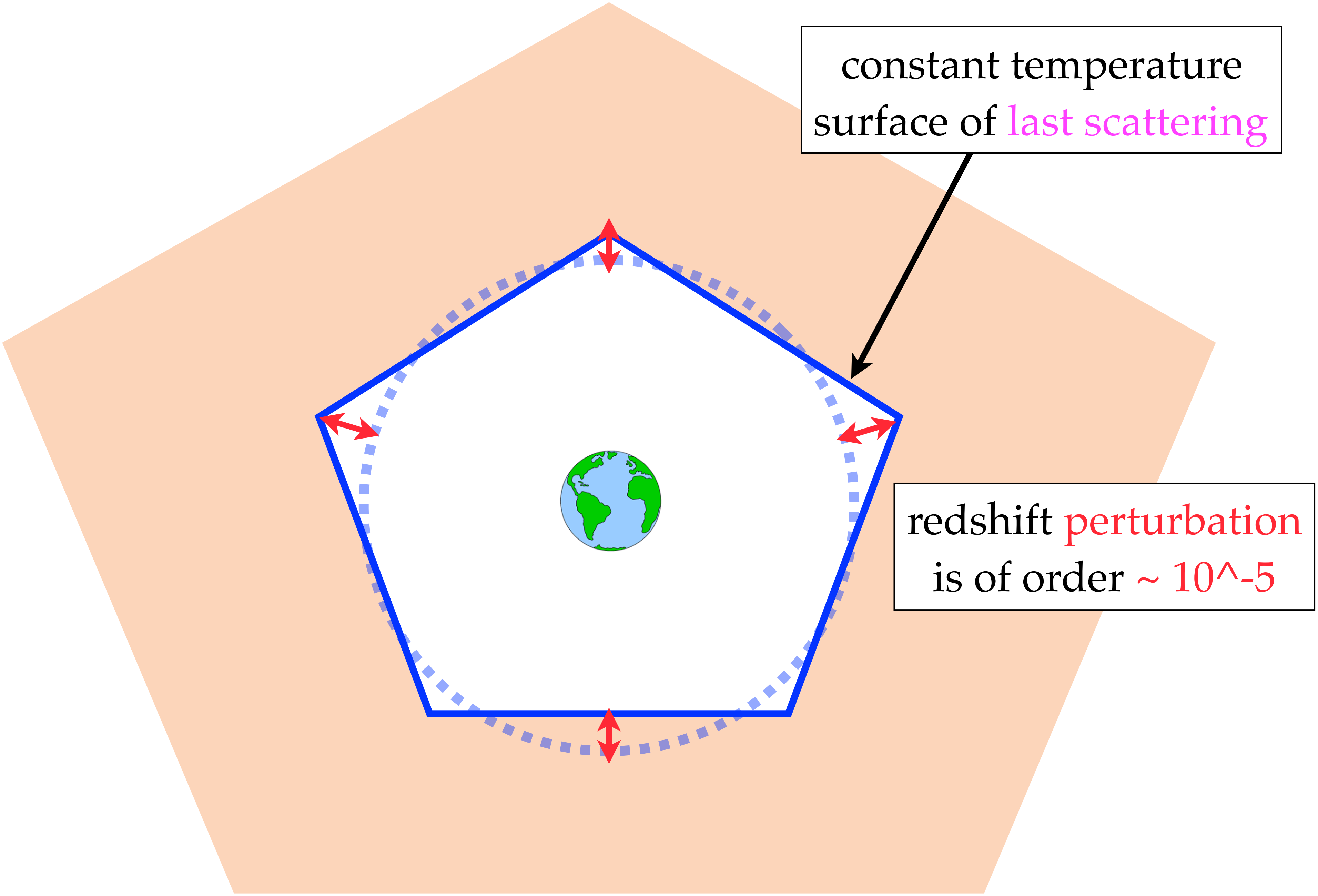

radius: red-shift of the CMB photon
constant temperature surface of last scattering
later time
earlier time

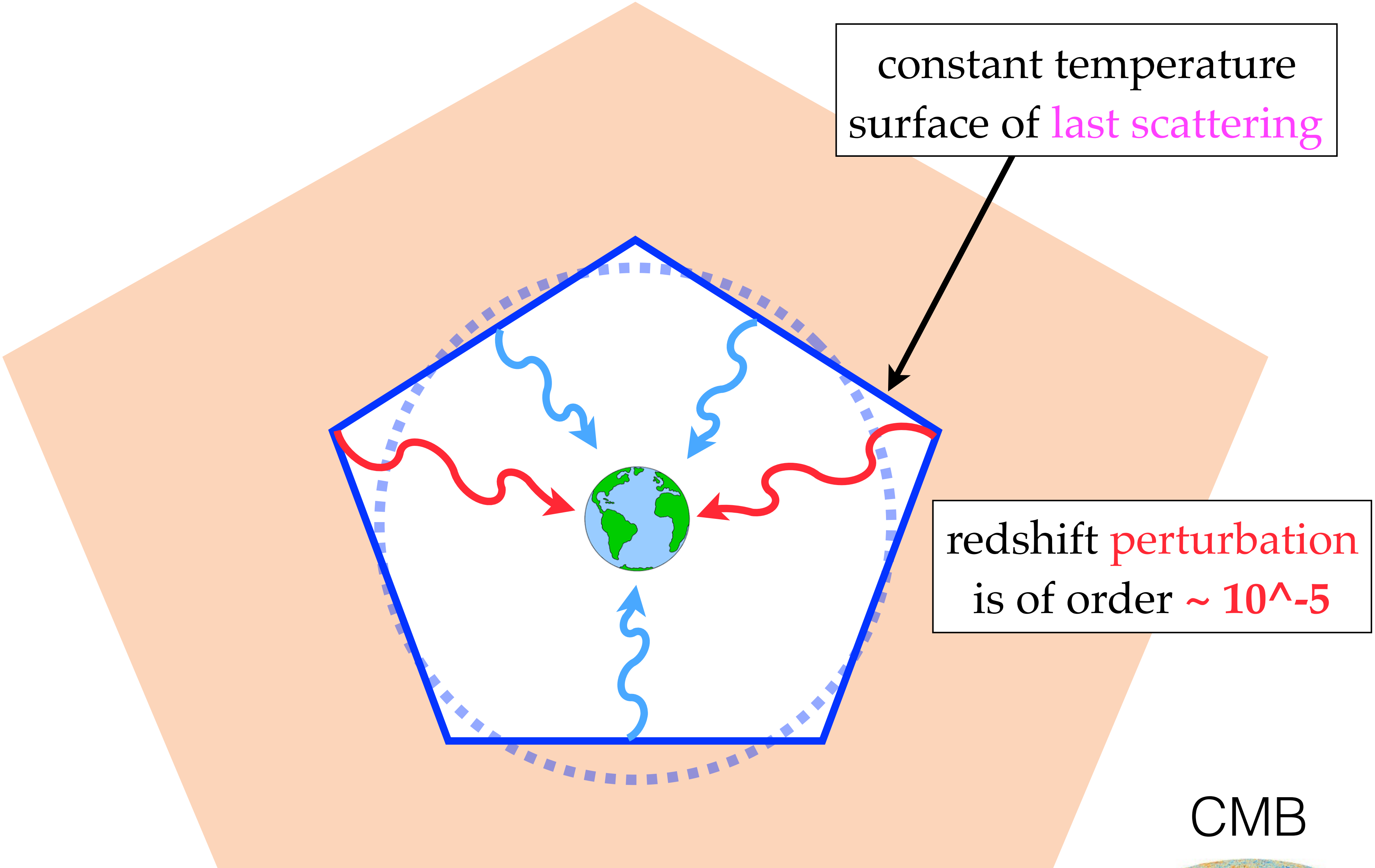


In a homogeneous universe

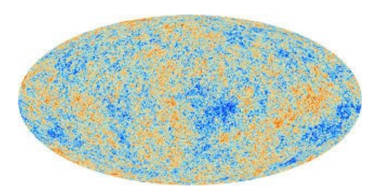
=> uniform photon redshift from last scattering




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

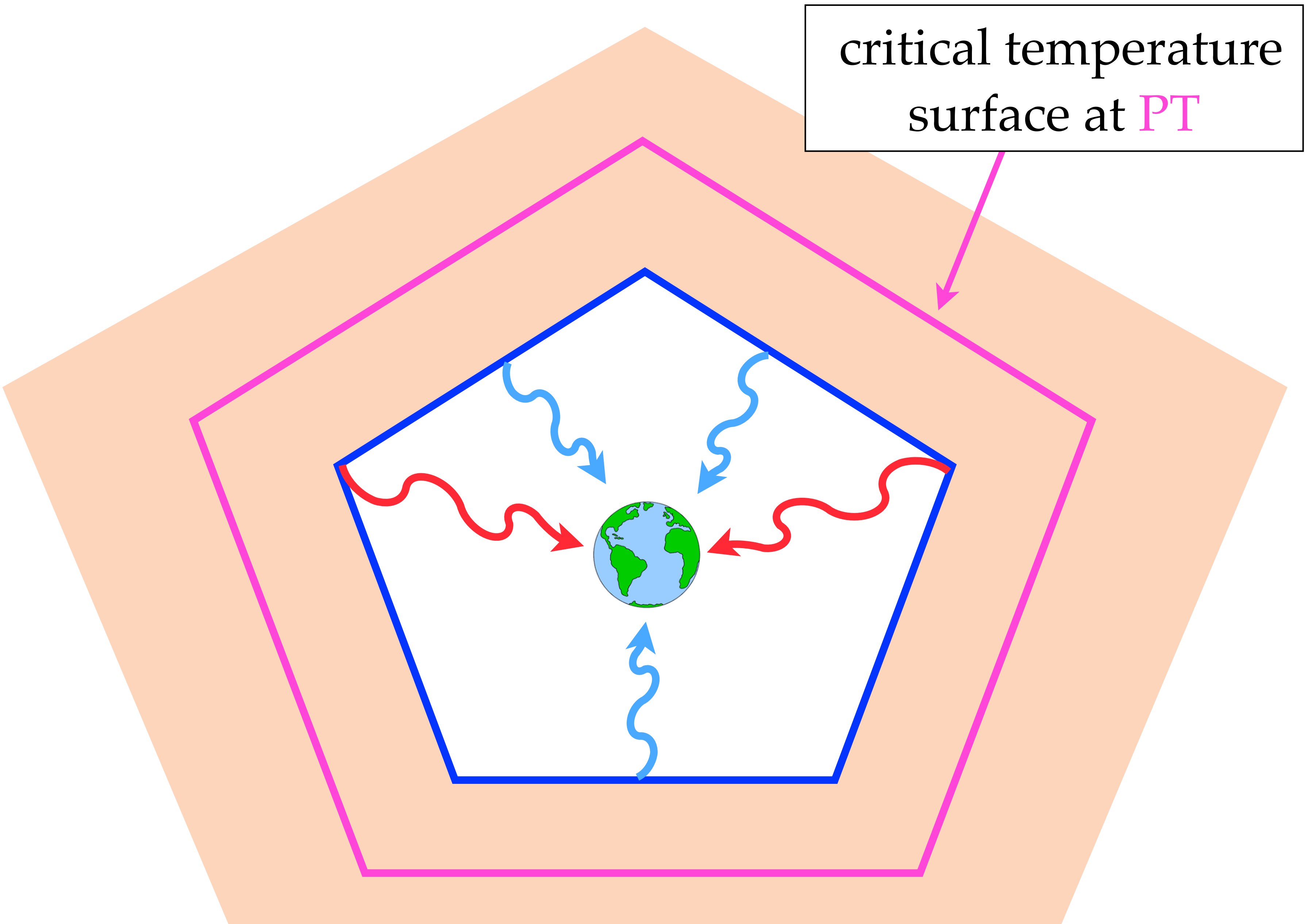


CMB



With primordial temperature fluctuations

=> anisotropic redshift for last scattering photons

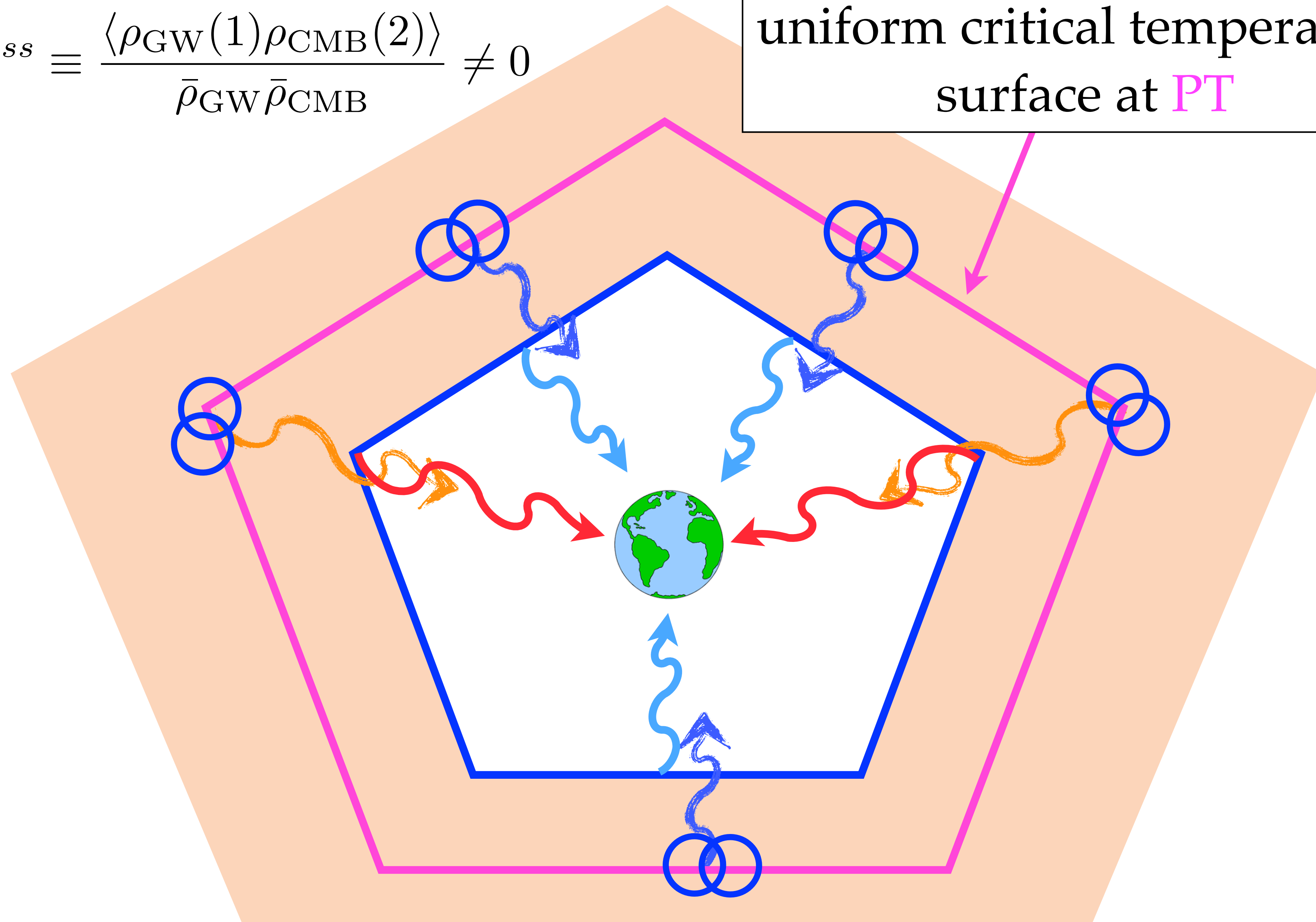


With a single reheating process after inflation

=> GW fluctuations correlated with CMB

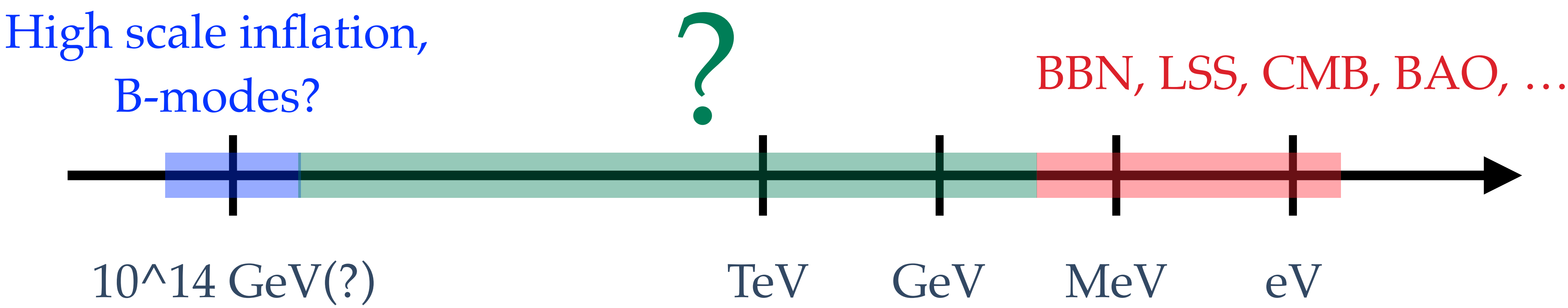
$$C^{cross} \equiv \frac{\langle \rho_{\rm GW}(1)\rho_{\rm CMB}(2)\rangle}{\bar{\rho}_{\rm GW}\bar{\rho}_{\rm CMB}} \neq 0$$

uniform critical temperature surface at PT

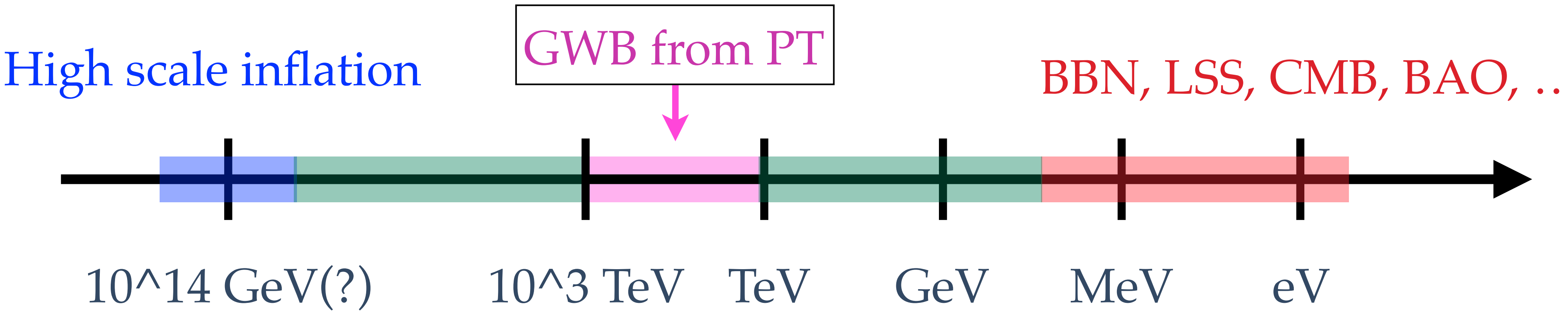


With only gravitational interactions
=> GW fluctuations nearly "pristine"

Dark Ages of Cosmology



GW can probe uncharted thermal history

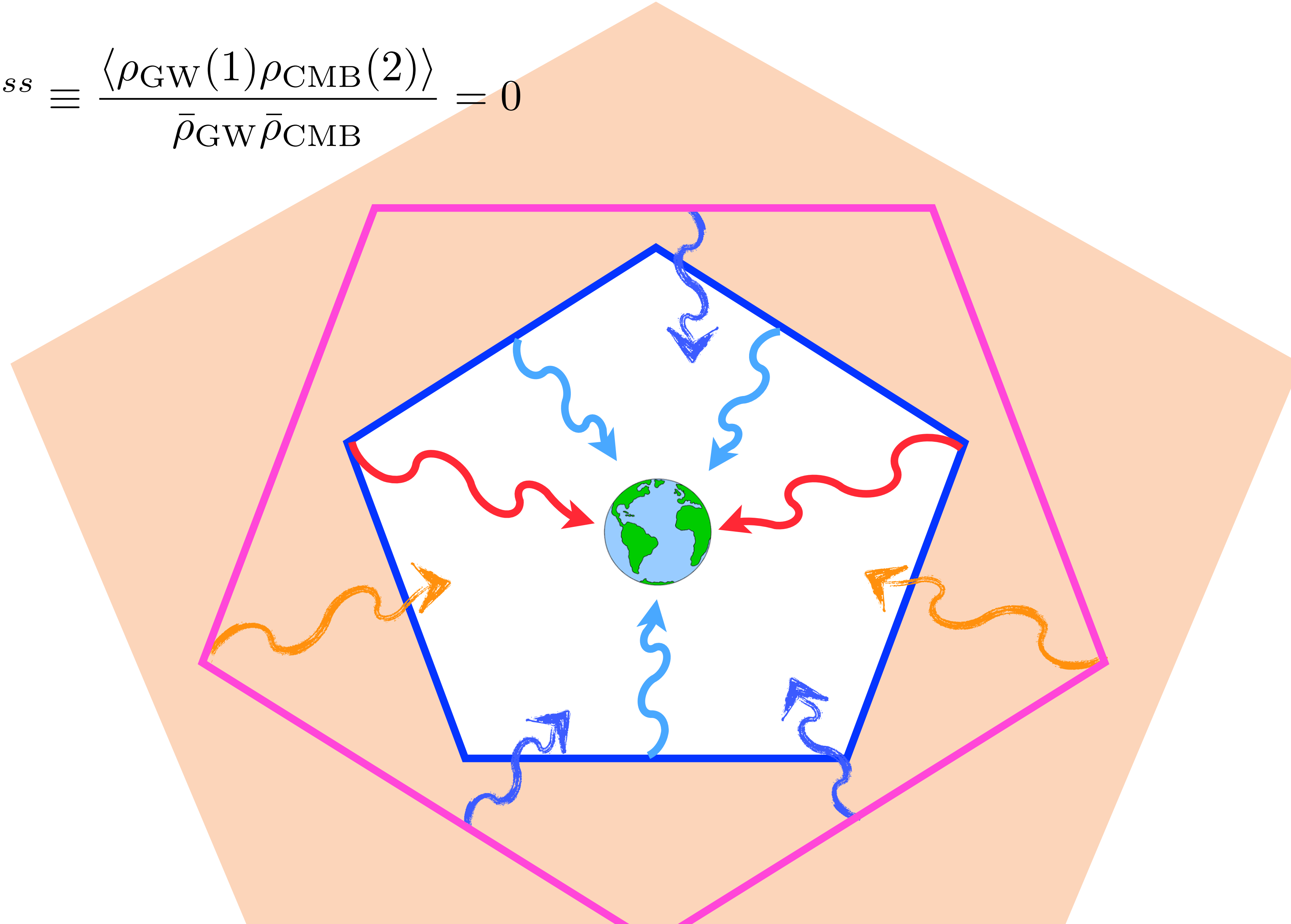


Energy scale and physics of cosmological PT? - Frequency spectrum

Multiple sources of primordial density perturbations and reheating processes during/after inflation? - Anisotropies

Eg.

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



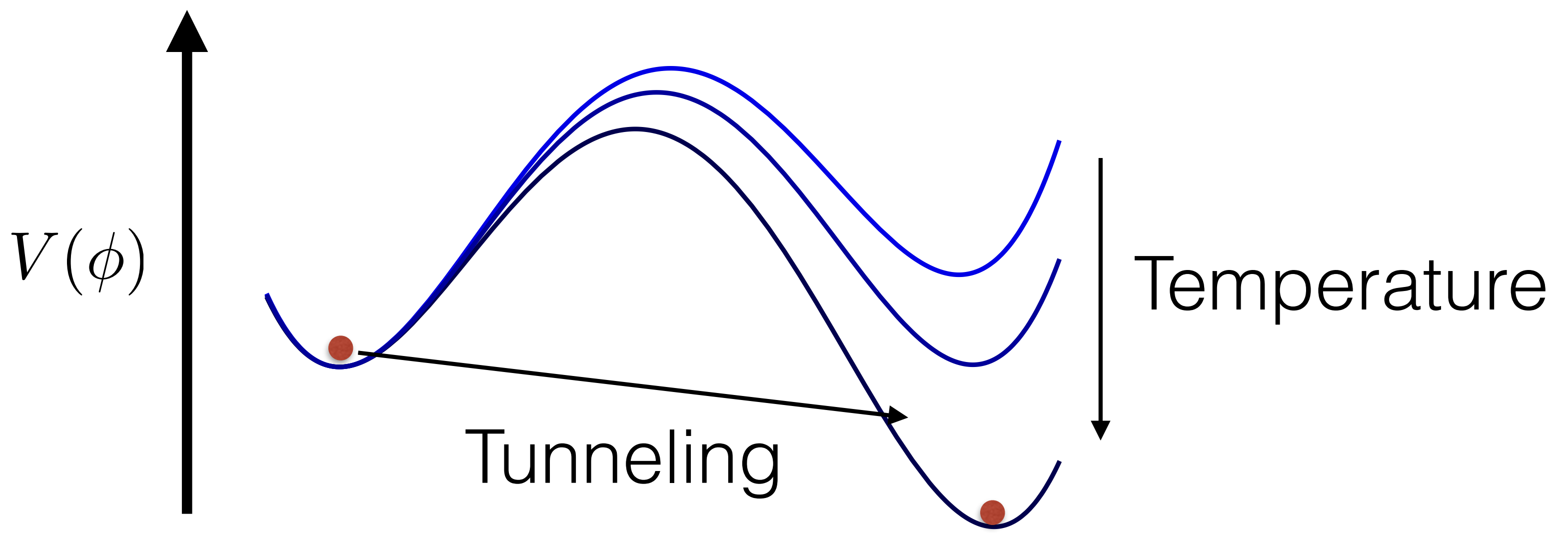
If PT physics and CMB have different sources of primordial fluctuations and reheating history

=> GWB can be ``uncorrelated" with CMB

Can we see the GW anisotropy?

GW from first order PT

First order phase transition

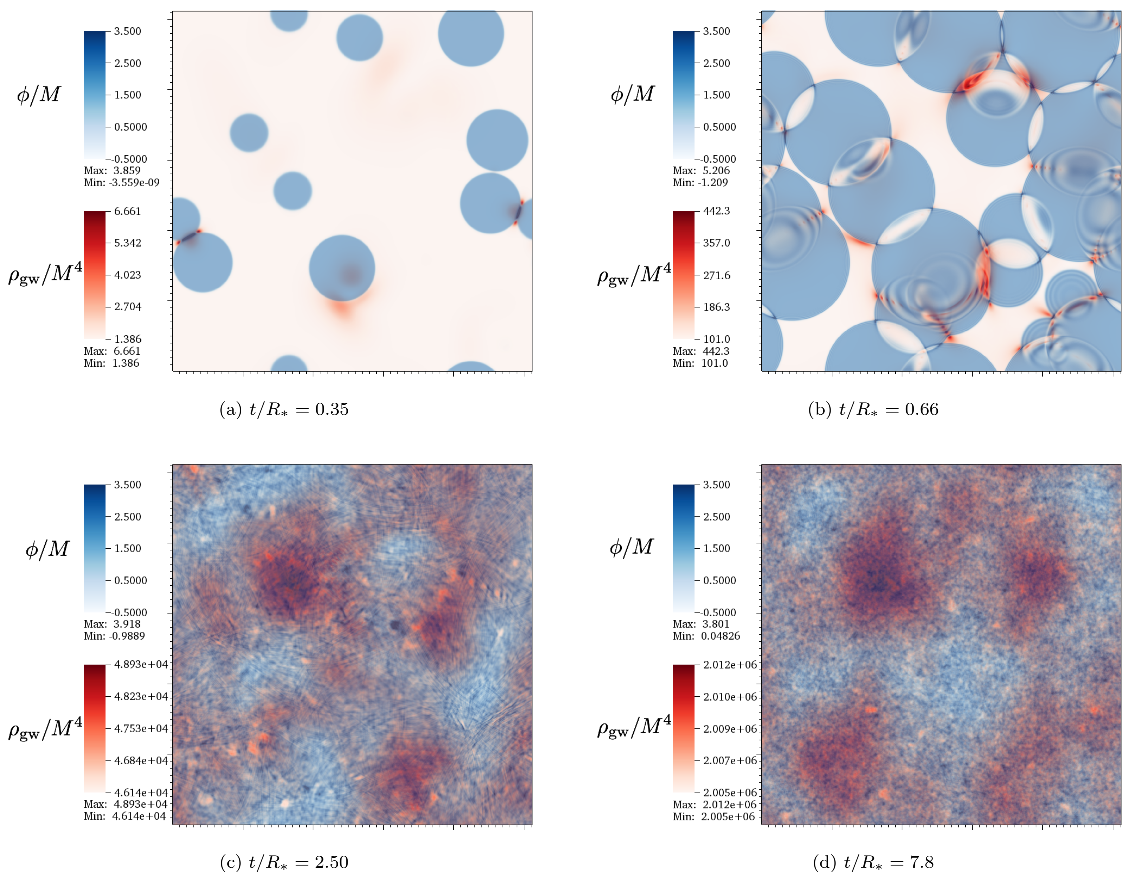


$$\Gamma(T) = A(T)\, e^{-S(T)}$$

PT rate as a function of temperature

GW from first order PT

- The dynamics and collisions of the bubbles generate gravity waves



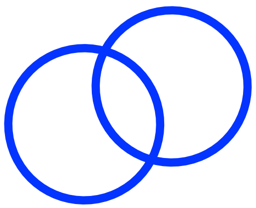
In the sky today:

$> 10^{30}$ bubbles

from TeV scale PT

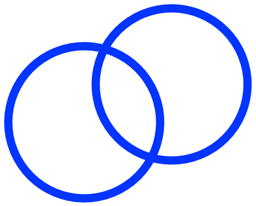
Cutting, Hindmarsh, Weir (2018)

Energy density of GW from PT



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

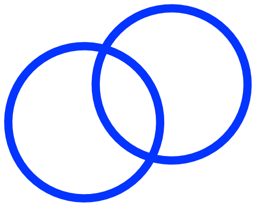
Energy density of GW from PT



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 of GW from PT



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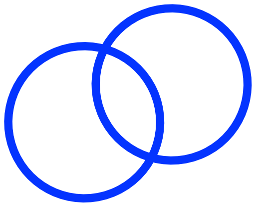
Energy density in GW $$\rho_{\rm GW} \sim \frac{1}{G_N} \omega_{\rm GW}^2 (\delta g_{\rm GW})^2$$

Energy density of GW from PT



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

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

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

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

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

Energy density of GW from PT

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

Typical Estimate: $H_{PT}\Delta t_{PT} \sim 10^{-2}$

RS1/Composite Higgs
Hawking-Page/conformal -> confinement PT: $H_{PT}\Delta t_{PT} \to 1$

Randall, Servant '07; Konstandin, Servant '11

(or ordinary PT by tuning)

See 1512.06239 for a review of PT models

$$h^2\Omega_{\rm env}(f) \;=\; 1.67\times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\,v_w^3}{0.42+v_w^2}\right)S_{\rm env}(f)$$

GW from PT

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

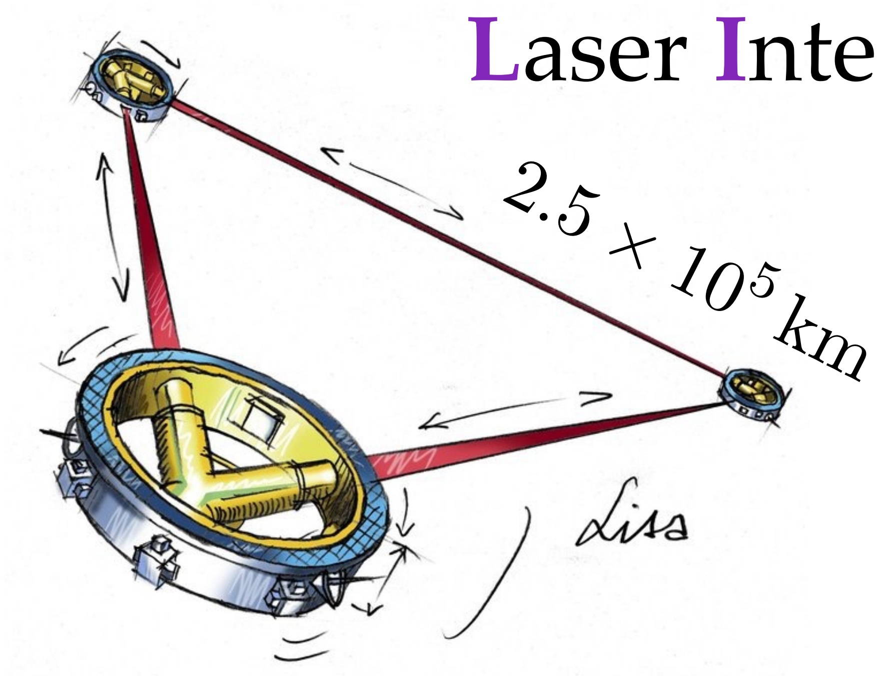
$$\rho_{\mathrm{GW}}^{today} \approx 0.1 \left(H_{PT} \Delta t_{PT}\right)^2 \rho_\gamma \approx 10^{-5} - 10^{-2} \rho_\gamma$$

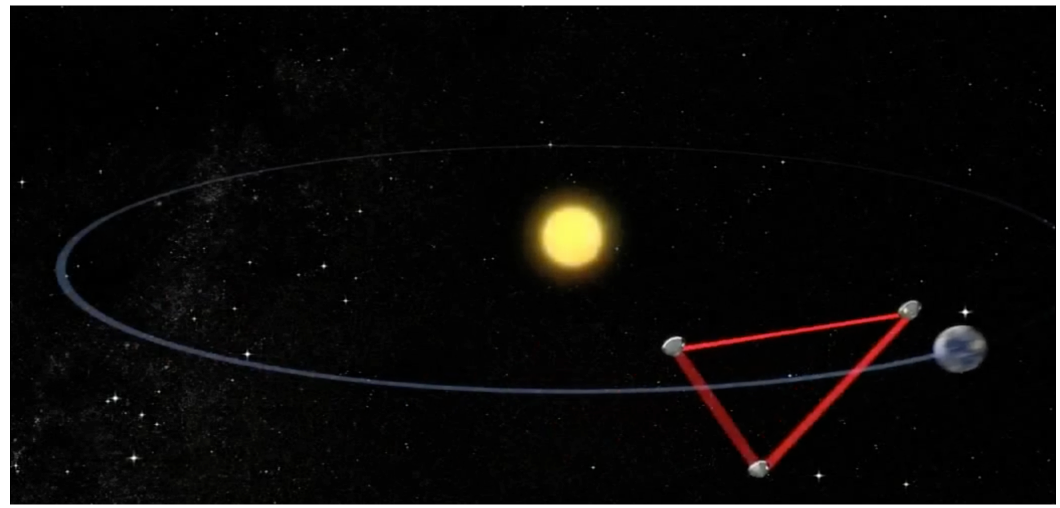
< CMB N_eff bounds

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

GW detectors

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



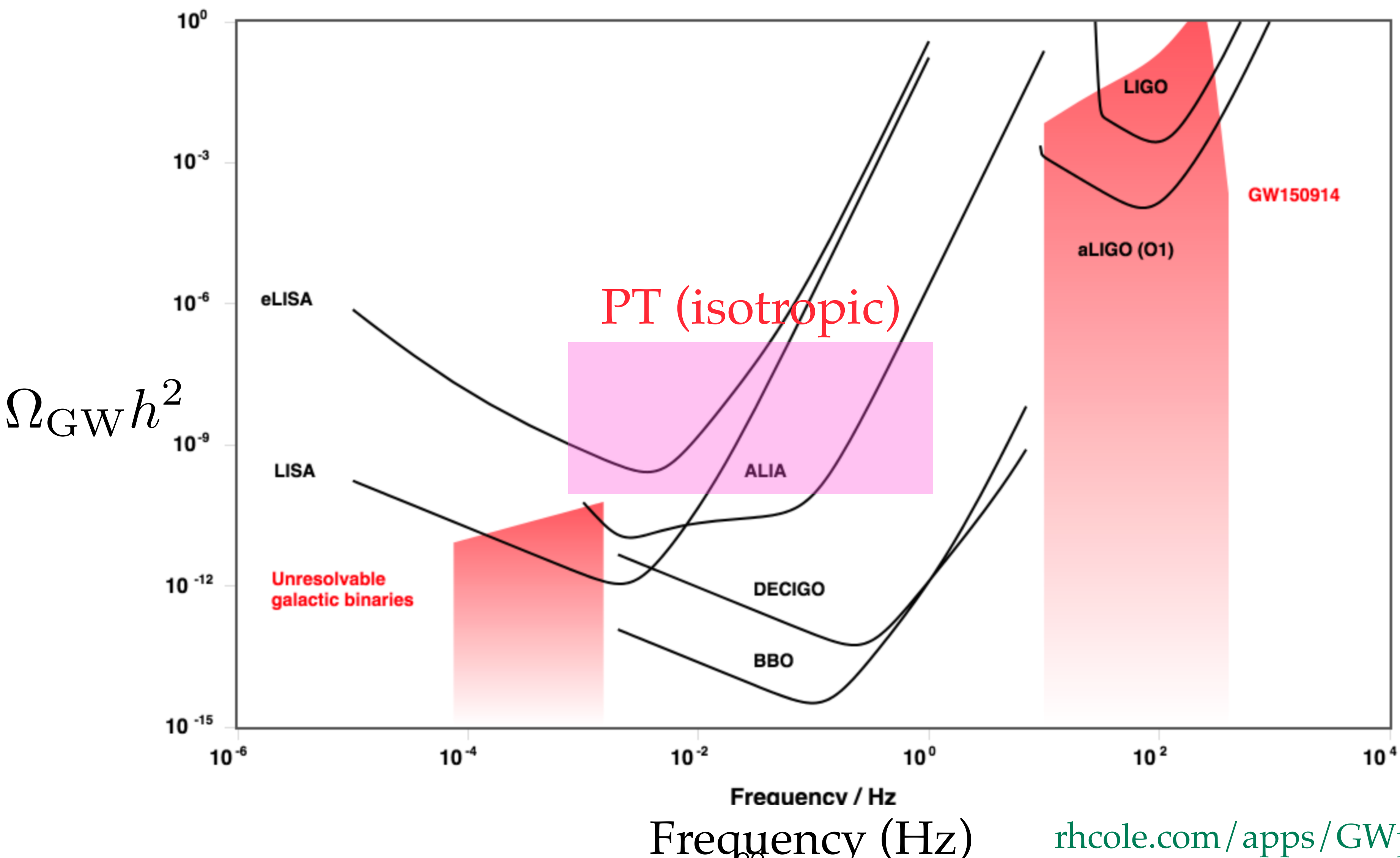


Similar idea, more satellites, more futuristic

BBO, DECIGO, ALIA

plus atomic interferometry: MAGIS

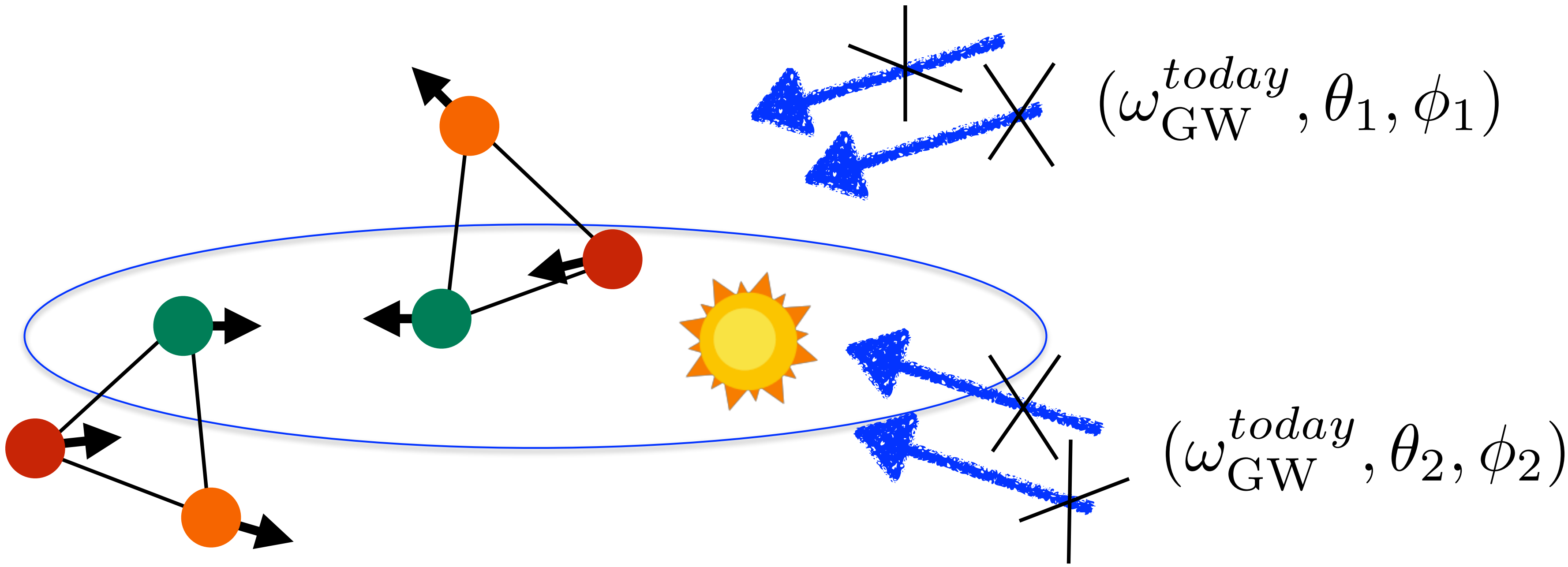
Energy density of GW from PT



rhcole.com/apps/GWplotter/

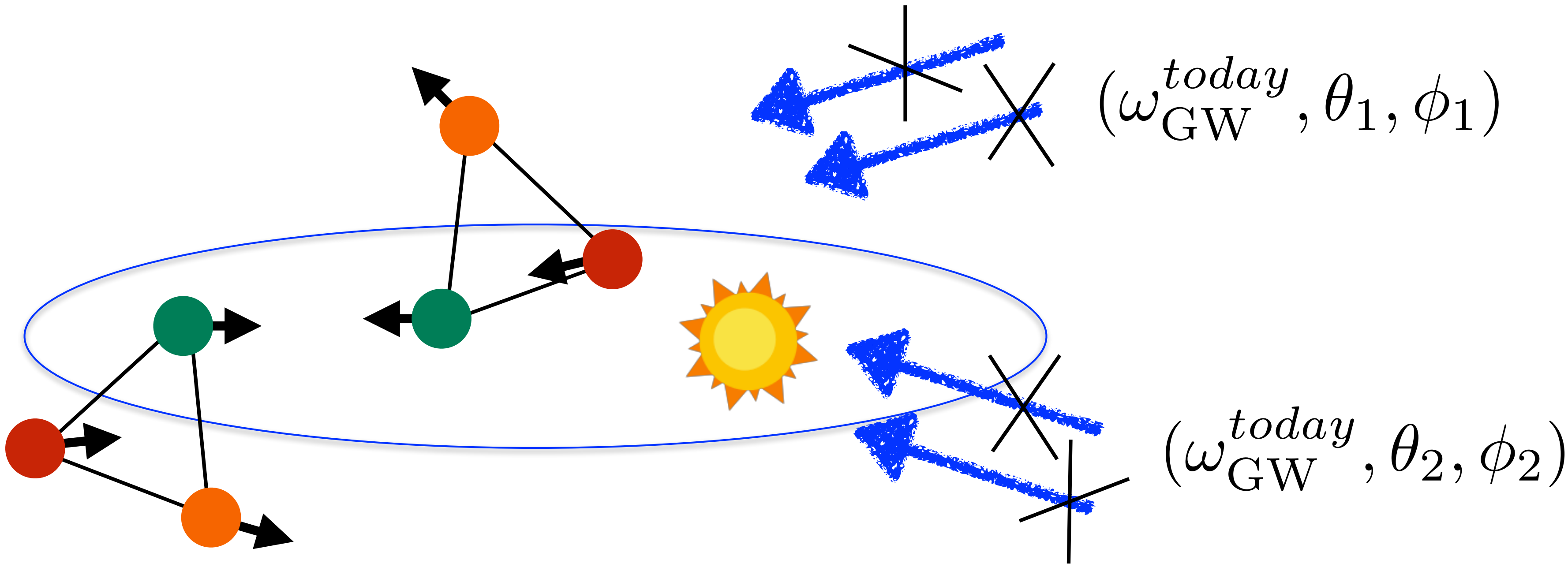
Seeing the anisotropic pattern

Angular measurement



Method: variation of strains in time for each polarization mode with different detector location / doppler shift

A deconvolution problem

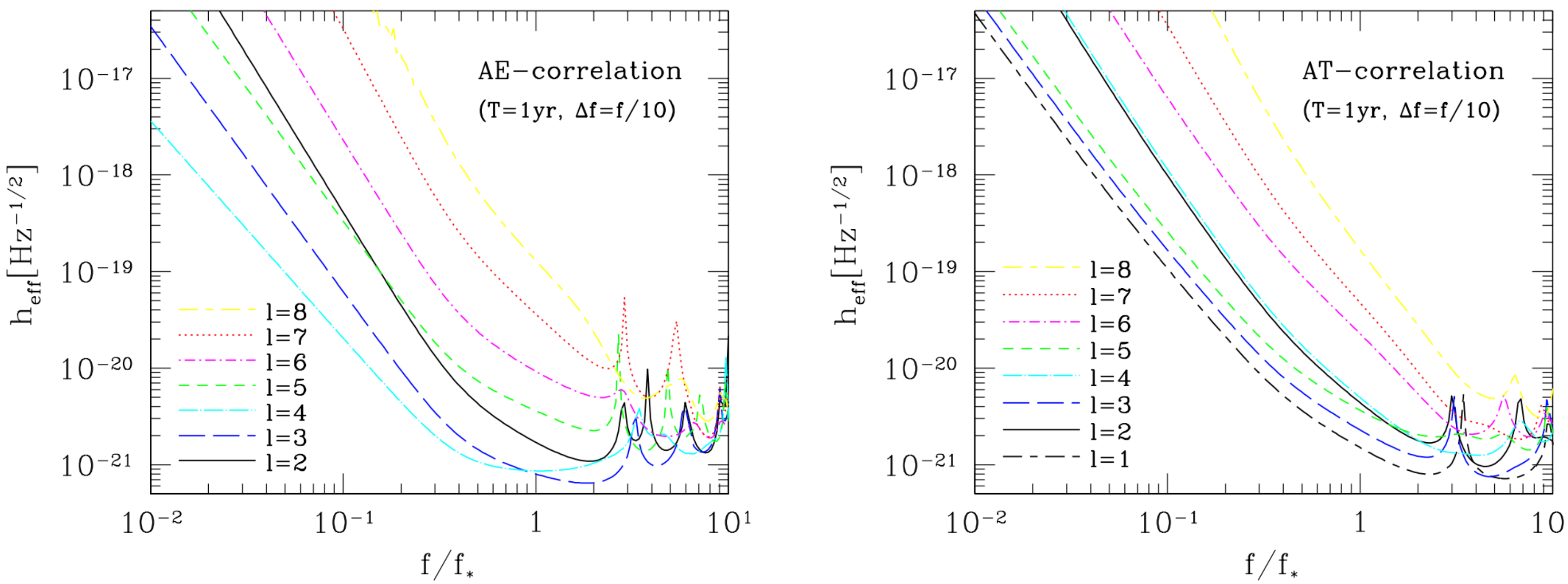


$$\widetilde{C}(t, f) = \frac{1}{4\pi} \sum_{\ell m} \left[p^E_{\ell m}(f)\right]^* a^E_{\ell m}(f, t)$$

output data | GW background | antenna pattern

Angular measurement

Projected sensitivity for LISA, Kudoh & Taruya (2005)



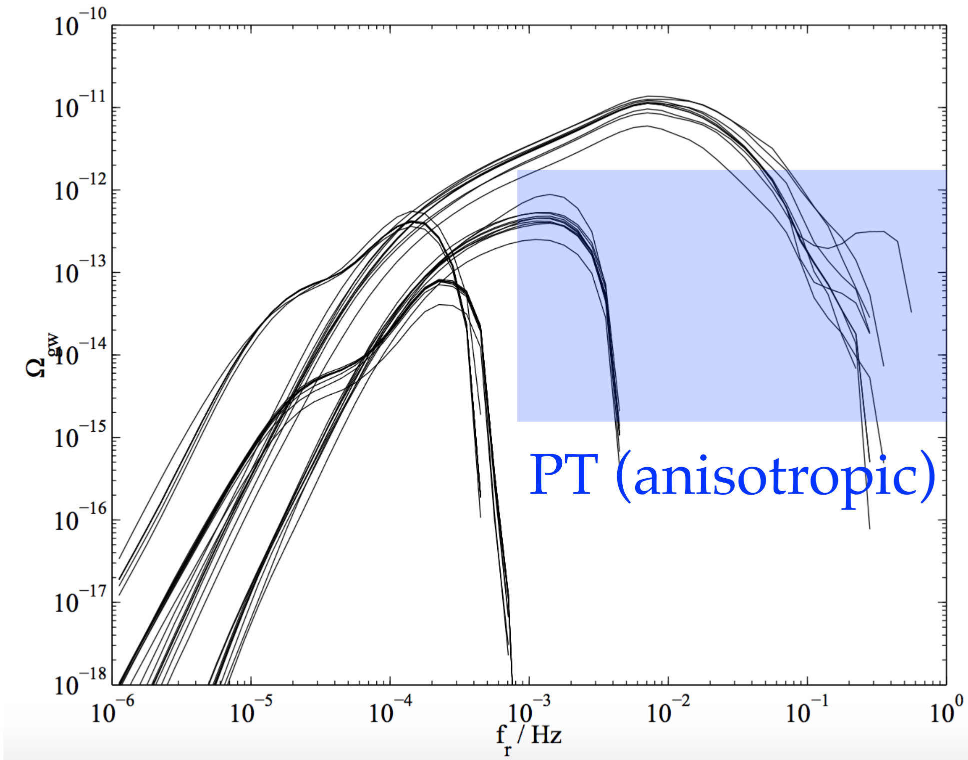
Using cross correlation between different phase readout, **LISA** may get to $\ell_{\rm max} \sim 10$, more detectors (**BBO** / **DECIGO**) can do much better [e.g., Cutler & Holz (2009)]

Astrophysical foreground

Unresolvable white dwarf merger generates the dominant background to our signal

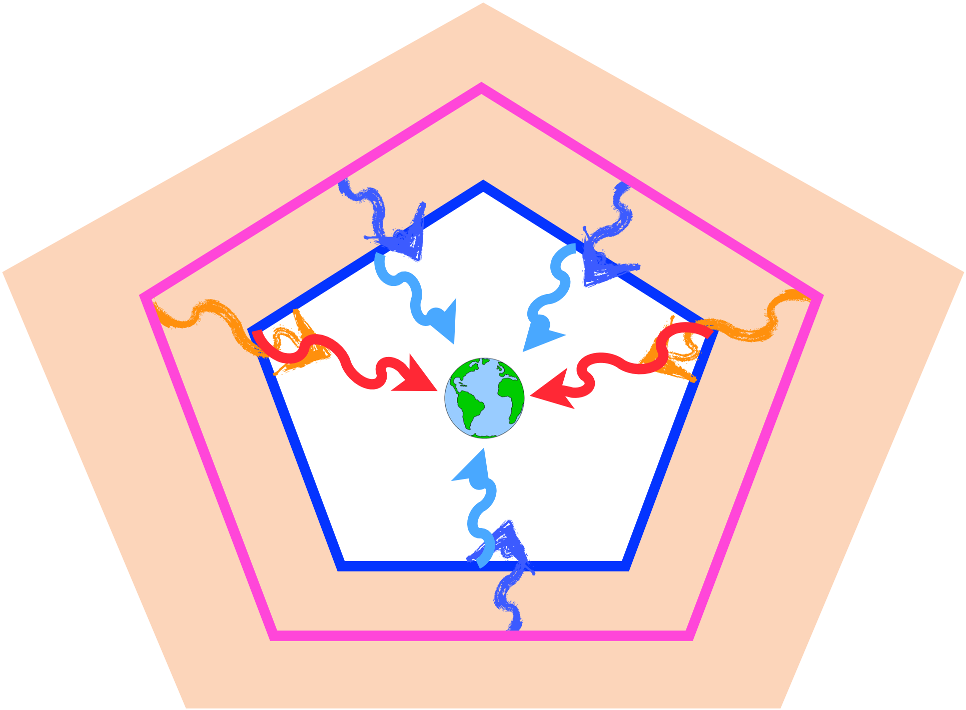
However, most of these backgrounds **follow galaxy distribution** and can be subtracted with enough data

Adams & Cornish (2013)



Farmer & Phinney (2003)

Anisotropic GW: minimal story



Anisotropic Signal

- Natural to have anisotropic GW signal (like CMB)

$$\rho_{\rm GW}(\theta,\phi) = \bar{\rho}_{\rm GW} + \delta\rho_{\rm GW}(\theta,\phi)$$

- Two-point correlators of signal fluctuations

GW-GW $$C^{\rm GW}(\theta) \equiv \frac{\langle \rho_{\rm GW}(1)\rho_{\rm GW}(2)\rangle_\theta}{\bar{\rho}_{\rm GW}^2}$$

GW-CMB $$C^{\rm cross}(\theta) \equiv \frac{\langle \rho_{\rm GW}(1)\rho_{\rm CMB}(2)\rangle_\theta}{\bar{\rho}_{\rm GW}\,\bar{\rho}_{\rm CMB}}$$

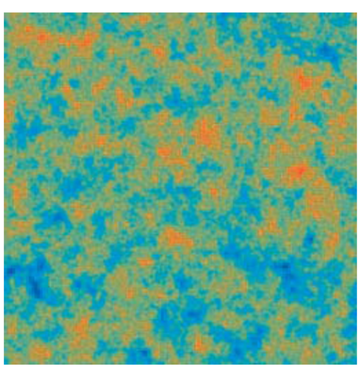
In order to see the anisotropy

$$C^{\mathrm{GW}}(\hat{n}) = \sum_{\ell m} C_{\ell m}\, Y_{\ell m}(\hat{n})$$

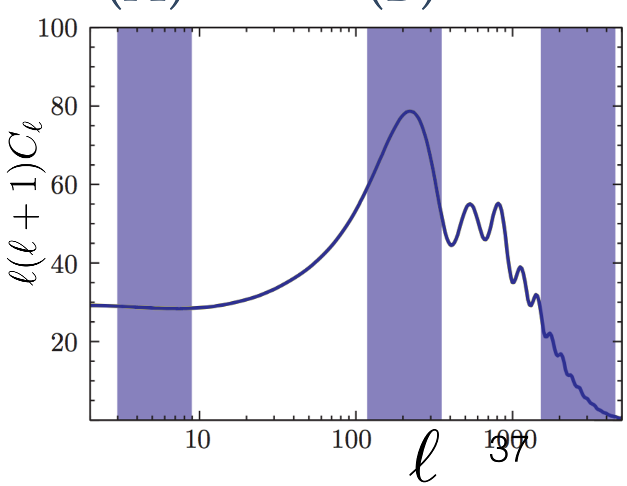
$\sqrt{C_\ell} >$ detector sensitivity

Angular resolution $< \pi\, \ell_{\max}^{-1}$

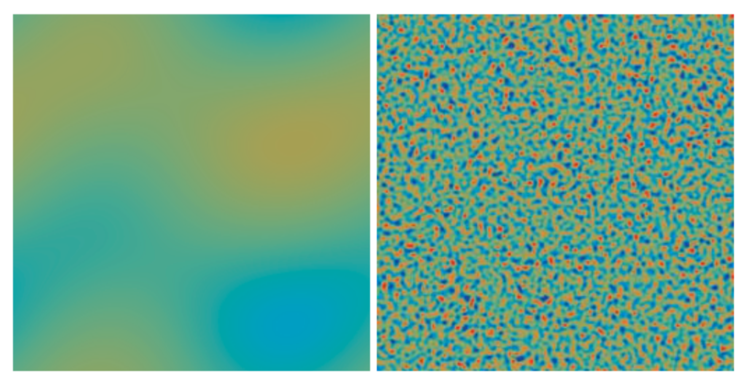
CMB



(A) (B)



(A) (B)

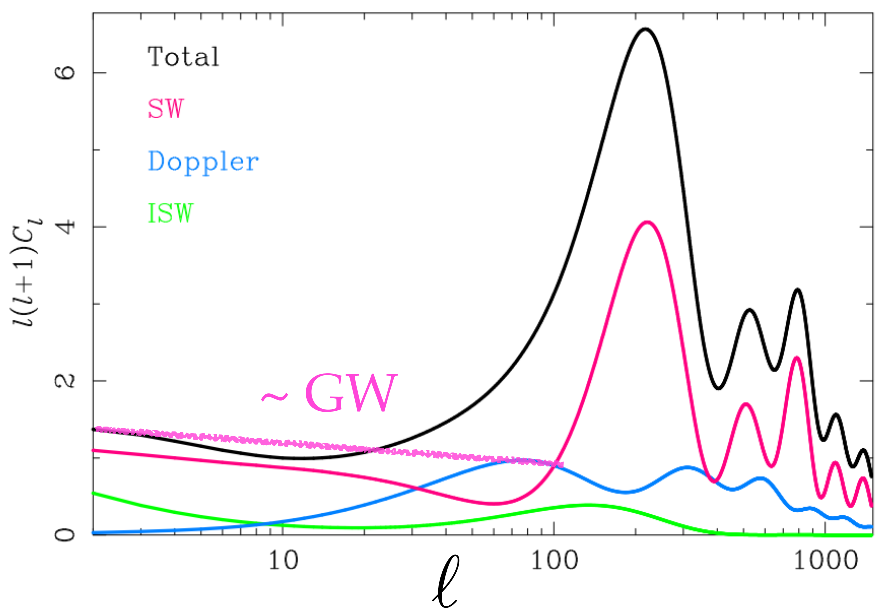


Baumann, TASI lecture

Minimal Story

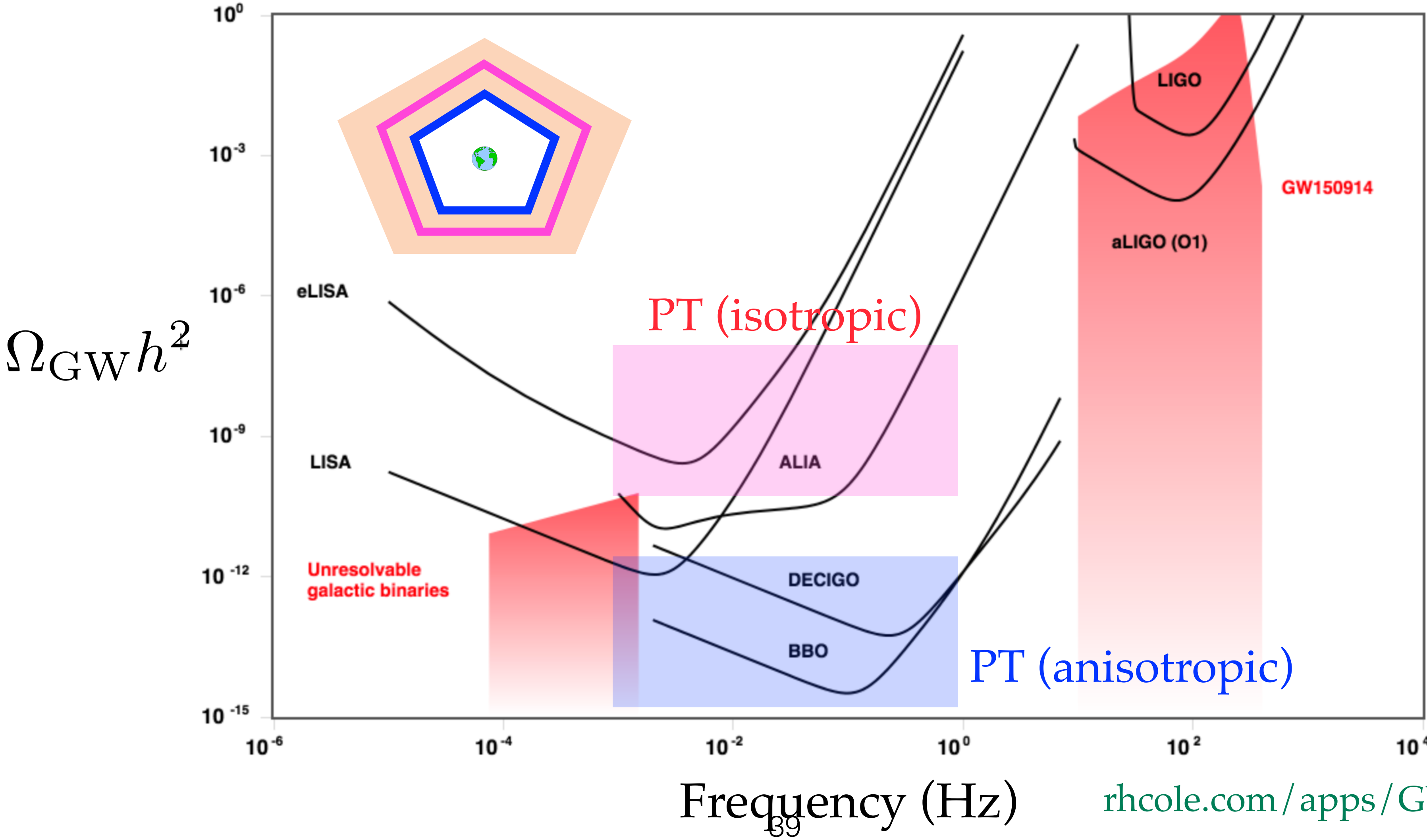
- Single source of primordial perturbations (= quantum fluctuations in inflaton field)
- GW anisotropy is totally correlated with primordial photon perturbation
- Roughly scale-invariant primordial perturbation:

$$\left(\frac{\delta\rho_{\rm GW}}{\rho_{\rm GW}}\right)_\ell \sim \sqrt{C_\ell^{\rm GW}} \sim \frac{10^{-5}}{\ell}$$



Detection possibility

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



rhcole.com/apps/GWplotter/

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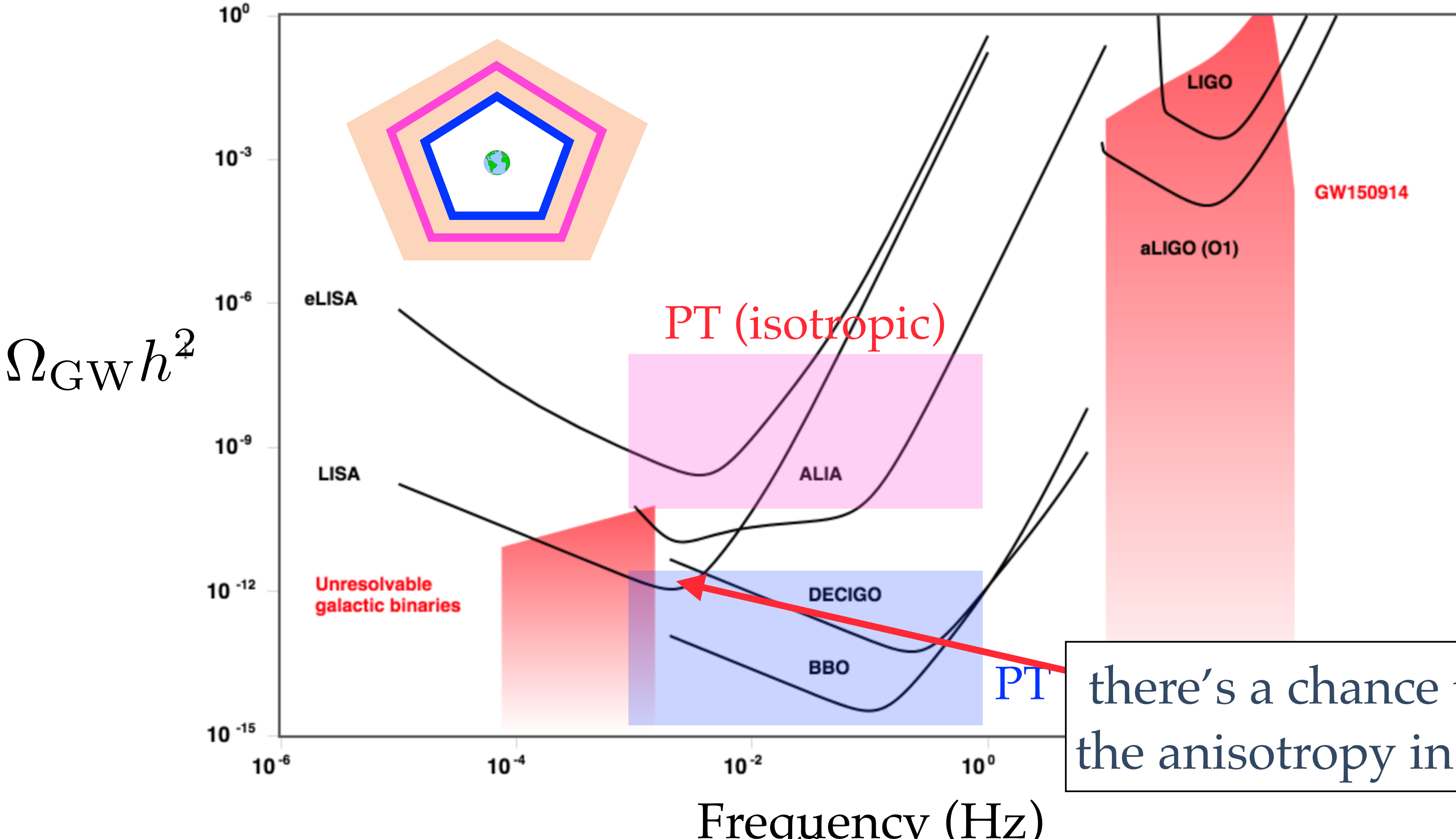
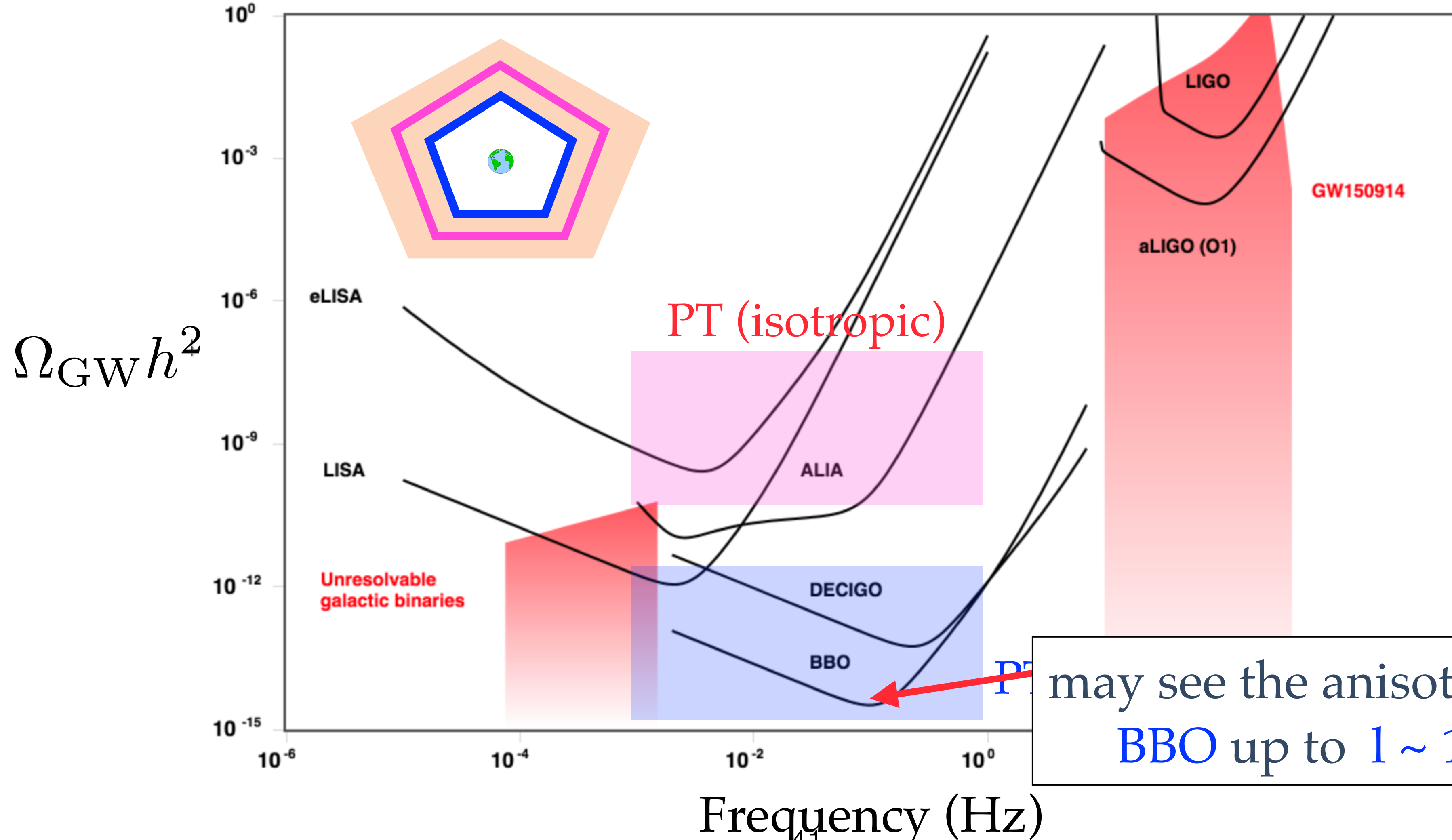


there's a chance to see the anisotropy in LISA!

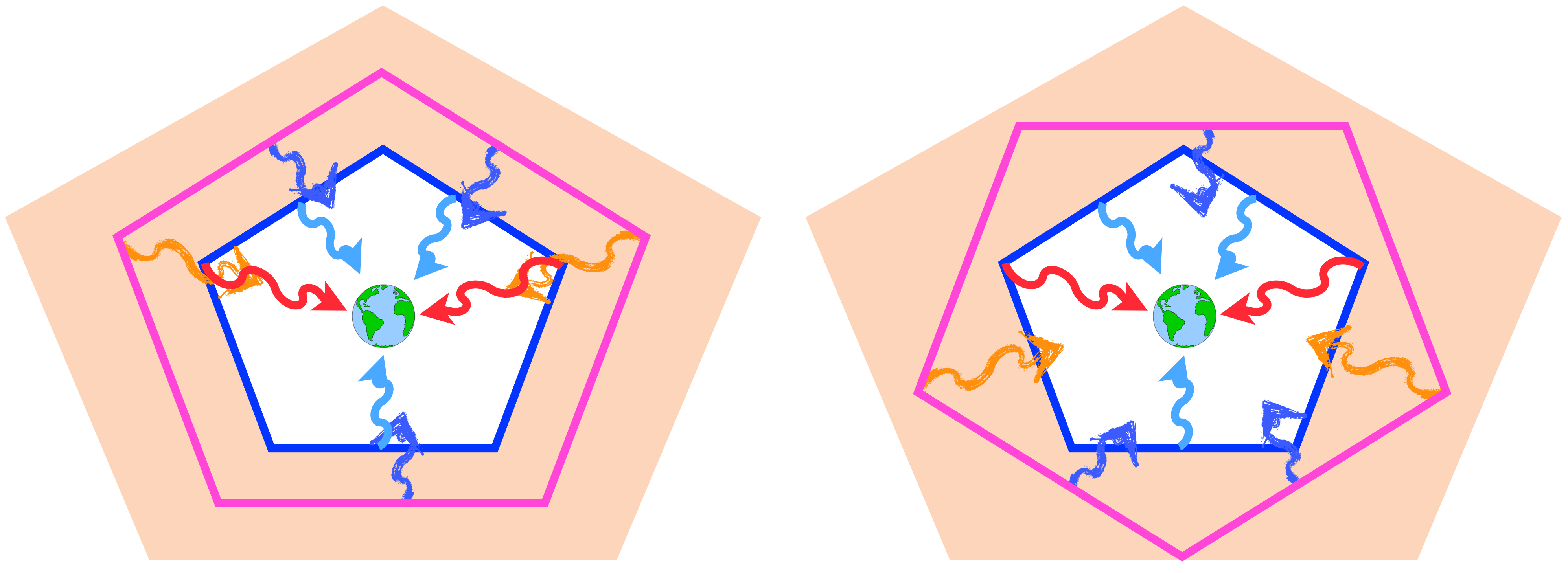
Detection possibility

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



PT may see the anisotropy in BBO up to $1 \sim 100$!

A Non-minimal Story



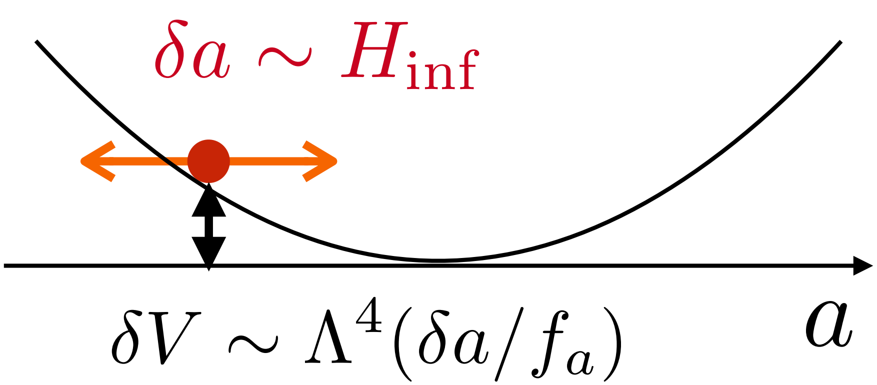
Non-minimal story

- There could be multiple sources of primordial fluctuations
- The GW and CMB maps are not necessarily correlated

e.g. a curvaton model

In addition to the inflaton there is an Axion-Like Particle with quantum fluctuations during inflation

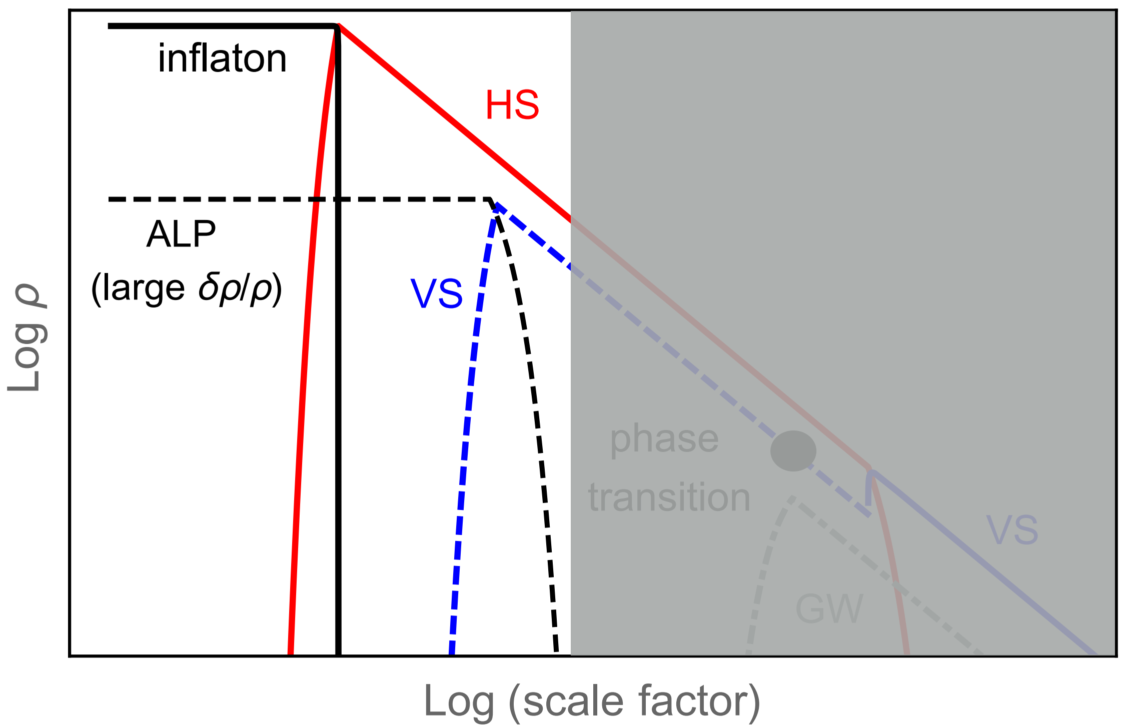
$$V = \Lambda^4 \left(1 - \sin \frac{a}{f_a}\right) \qquad \frac{\delta\rho_a}{\rho_a} \sim \frac{\delta V}{V} \sim \frac{H_{\rm inf}}{f_a}$$



can generate (possibly larger!) uncorrelated perturbations to the inflaton fluctuations

e.g. a curvaton model

ALP with smaller energy density but larger perturbation
decays into visible sector (**VS**) particles,
while inflaton decays into a hidden sector (**HS**)



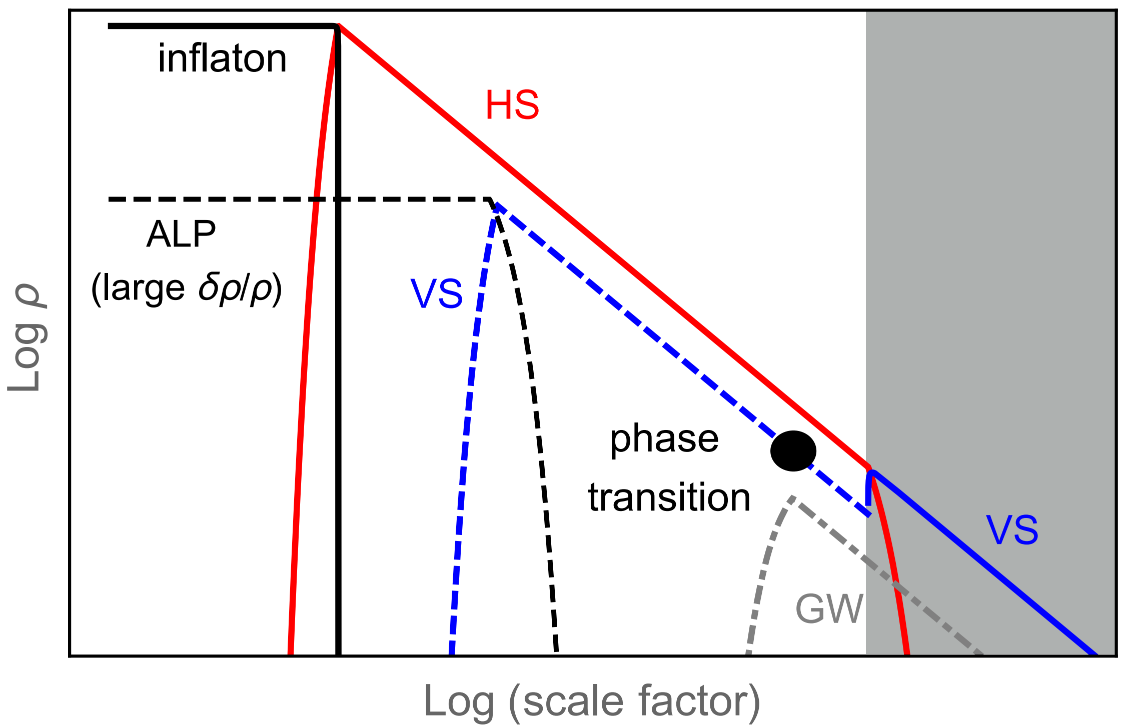
$$\left(\frac{\delta\rho}{\rho}\right)_{\rm HS} \leq 10^{-5}$$

$$\left(\frac{\delta\rho}{\rho}\right)_{\rm VS} \geq 10^{-5}$$

remain uncorrelated if
HS-VS are mostly decoupled

e.g. a curvaton model

VS undergoes a strong first order PT,
producing GW with VS perturbation

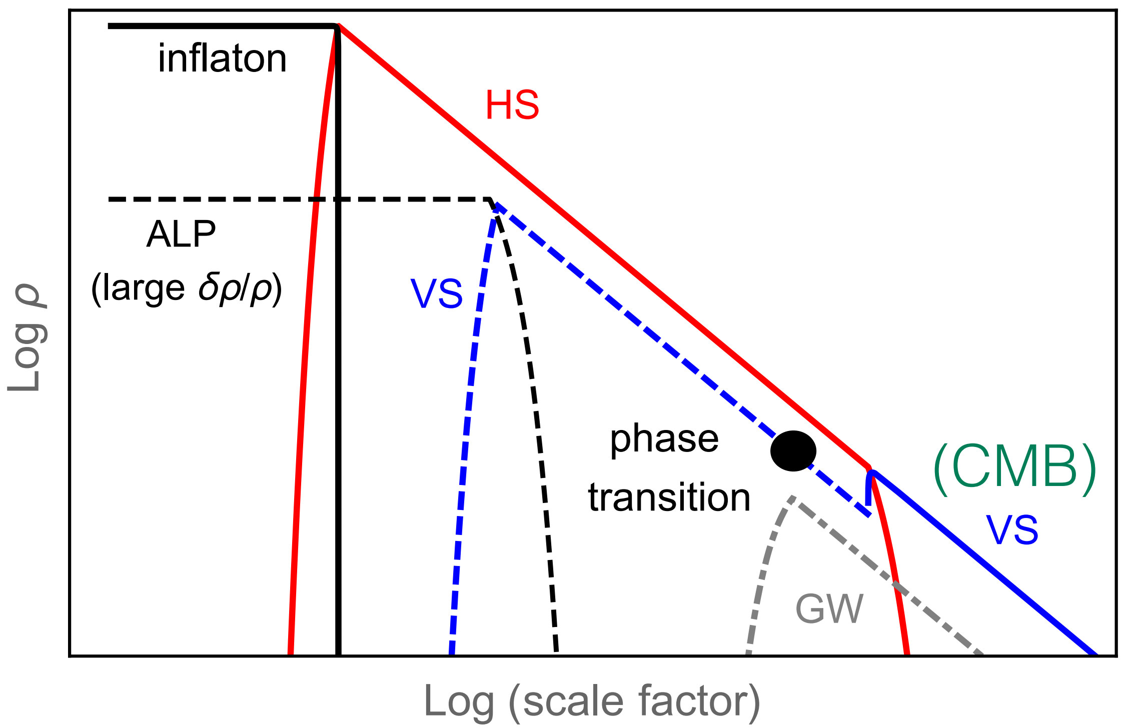


$$\left(\frac{\delta\rho}{\rho}\right)_{\mathrm{HS}} \leq 10^{-5}$$

$$\left(\frac{\delta\rho}{\rho}\right)_{\mathrm{GW}} \sim \left(\frac{\delta\rho}{\rho}\right)_{\mathrm{VS}} \geq 10^{-5}$$

e.g. a curvaton model

HS decays into **VS**, dominates energy density and suppresses photon perturbation to the observed value



before HS decay

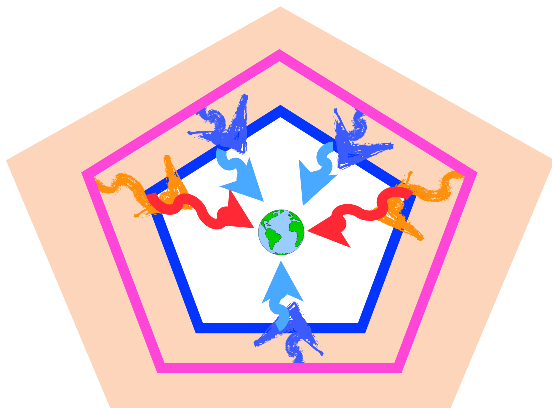
$$\left(\frac{\delta\rho}{\rho}\right)_{\rm CMB} \sim \left(\frac{\rho_{\rm VS}}{\rho_{\rm HS}}\right)\left(\frac{\delta\rho}{\rho}\right)_{\rm GW} + \left(\frac{\delta\rho}{\rho}\right)_{\rm HS}$$

$$\sim 10^{-5}$$

Correlated GWB & CMB

If density perturbation is dominated by the **1st** term

$$\left(\frac{\delta\rho}{\rho}\right)_{\rm CMB} \sim \boxed{\left(\frac{\rho_{\rm VS}}{\rho_{\rm HS}}\right)\left(\frac{\delta\rho}{\rho}\right)_{\rm GW}} + \left(\frac{\delta\rho}{\rho}\right)_{\rm HS} \sim 10^{-5}$$



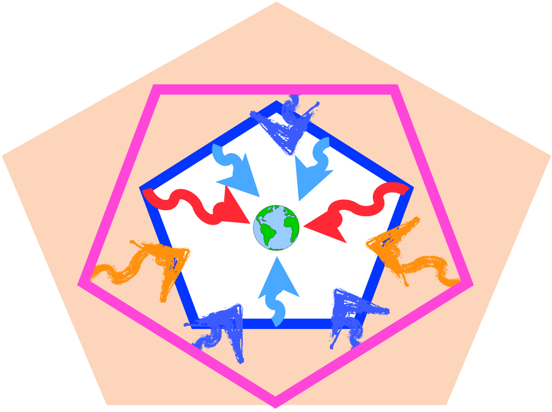
the CMB and GW background are completely **correlated**

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

Un-correlated GWB & CMB

If density perturbation is dominated by the **2nd** term

$$\left(\frac{\delta\rho}{\rho}\right)_{\rm CMB} \sim \left(\frac{\rho_{\rm VS}}{\rho_{\rm HS}}\right)\left(\frac{\delta\rho}{\rho}\right)_{\rm GW} + \boxed{\left(\frac{\delta\rho}{\rho}\right)_{\rm HS}} \sim 10^{-5}$$

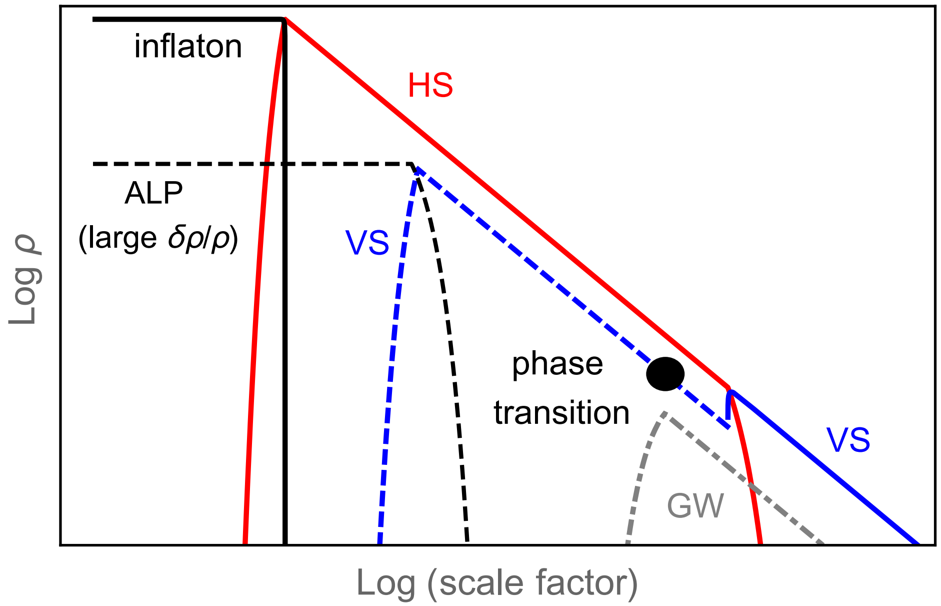


the CMB and GW background are completely **uncorrelated**

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

e.g. a curvaton model

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



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

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

larger energy contrast

anisotropy is visible at BBO up to $\ell_{\rm max} \approx 100$

Conclusion and Outlook