Seeing highly anisotropic gravitational wave backgrounds from phase transitions

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with Raman Sundrum @ University of Maryland

Based on 2211.09301

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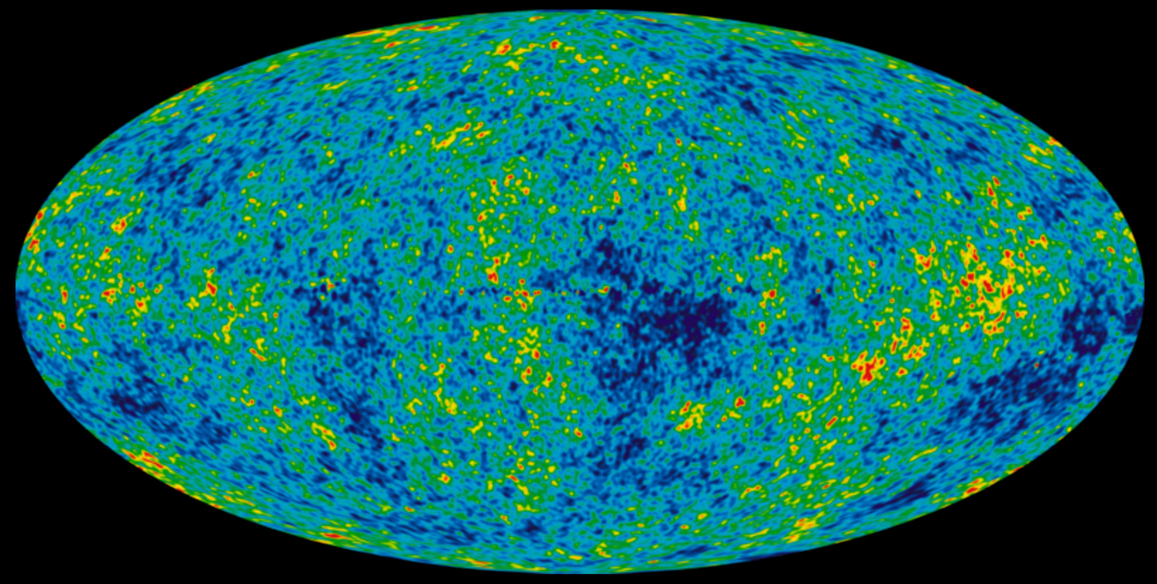

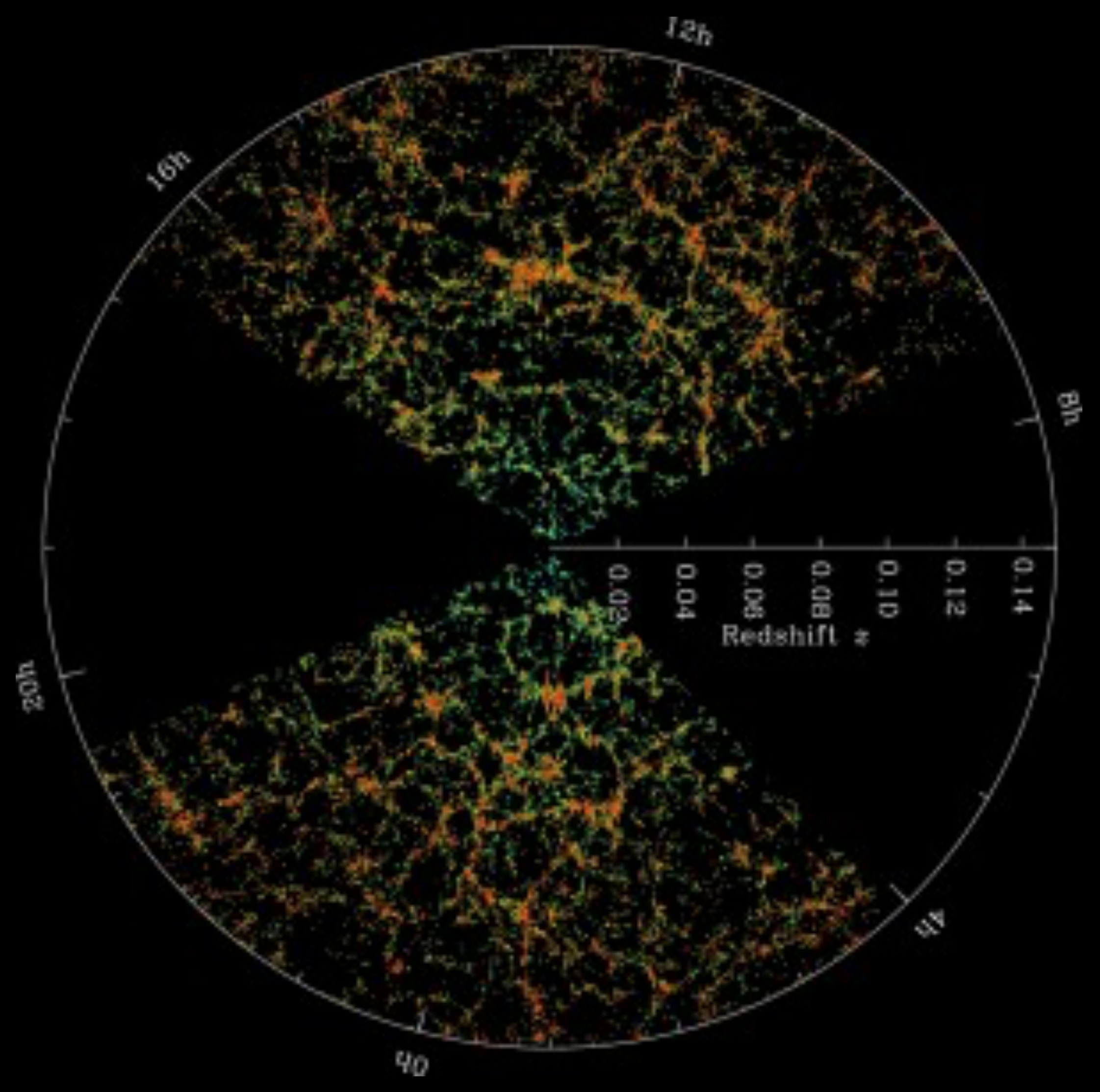

12h
16h
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Redshift z
0.02
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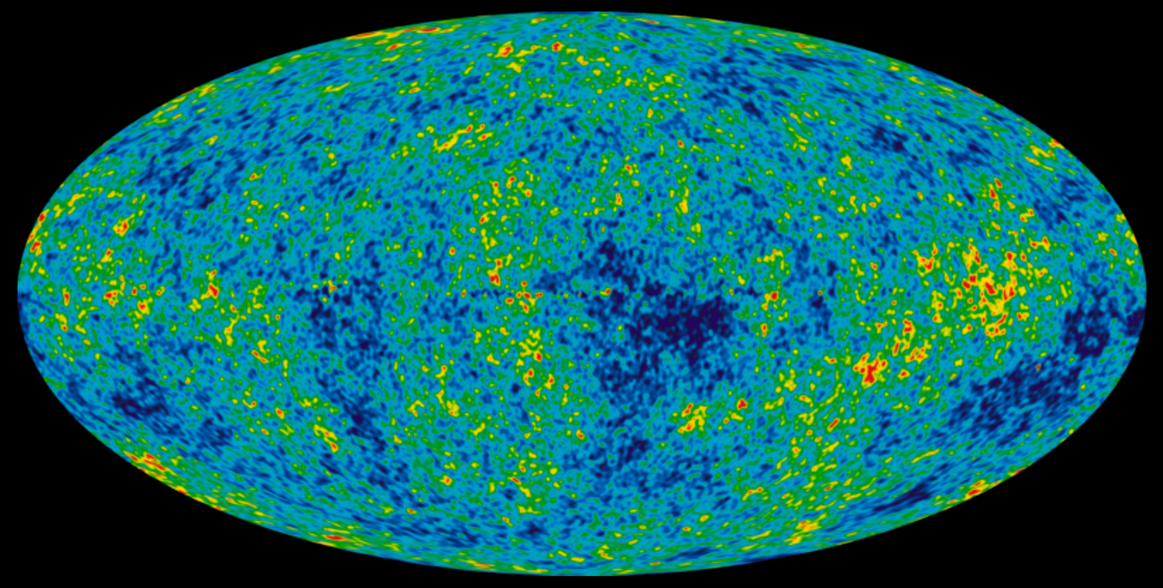
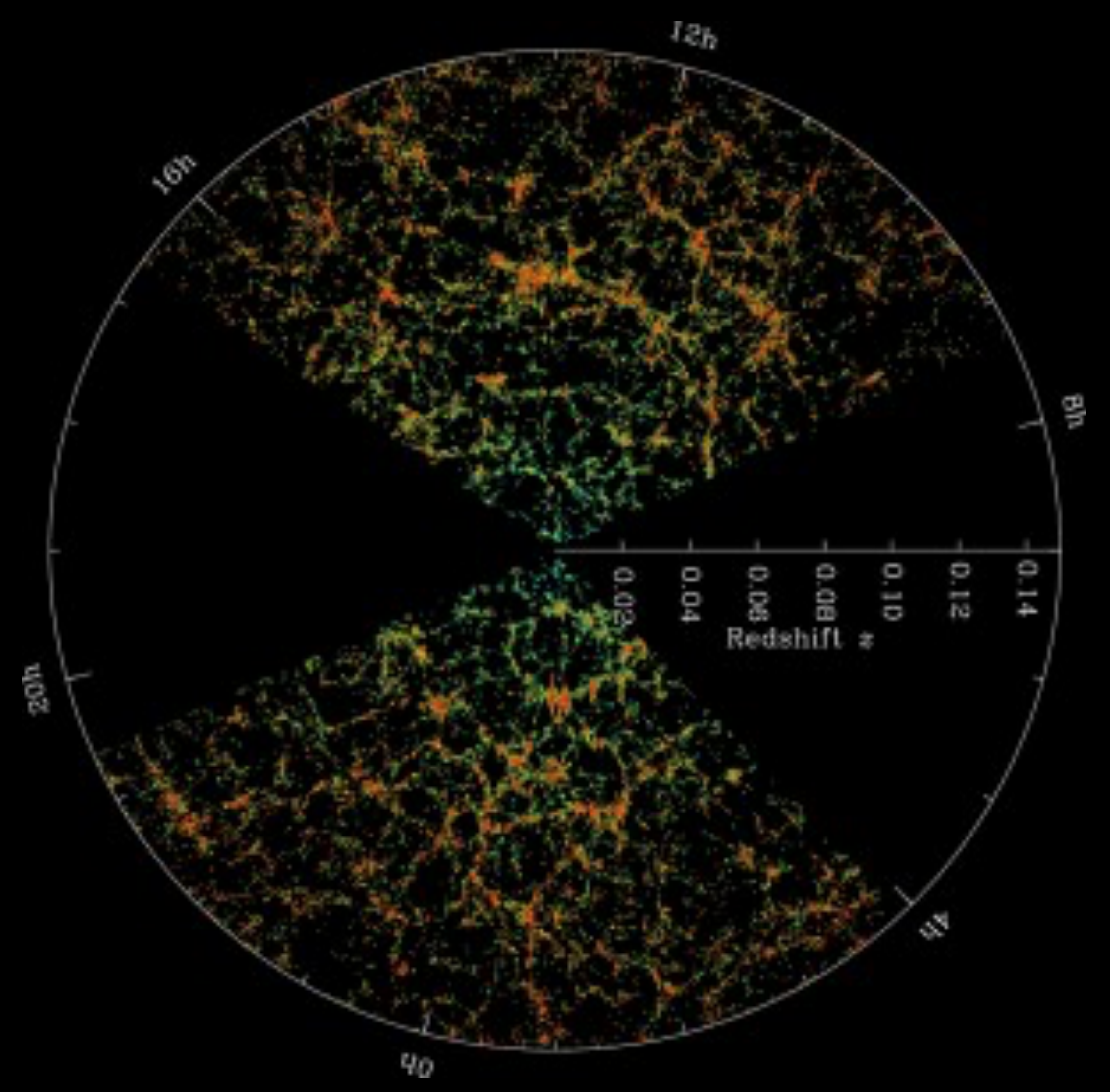




Quantum fluctuations of a single scalar field + inflation

Anisotropy maps are windows into inflation

Can there be new anisotropy maps that may provide information we haven’t already learnt?

Can there be new anisotropy maps that may provide information we haven't already learnt?

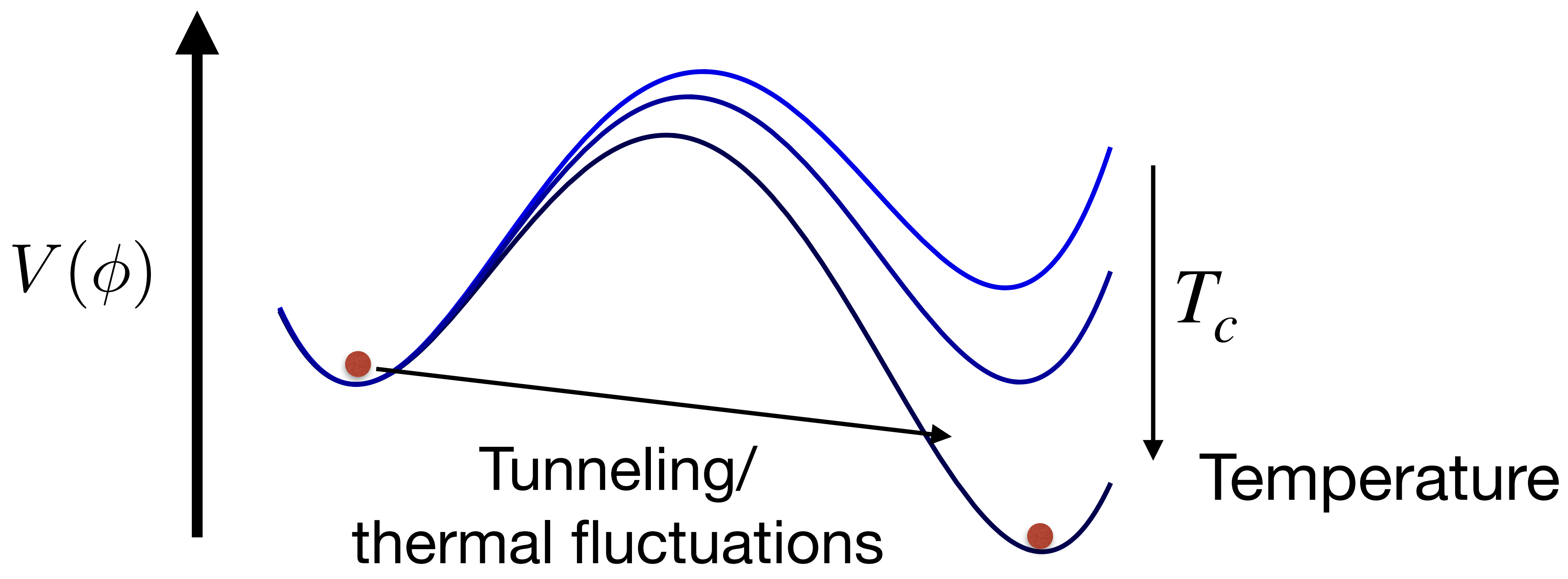
- An example of a new anisotropy map: gravitational wave background (GWB)

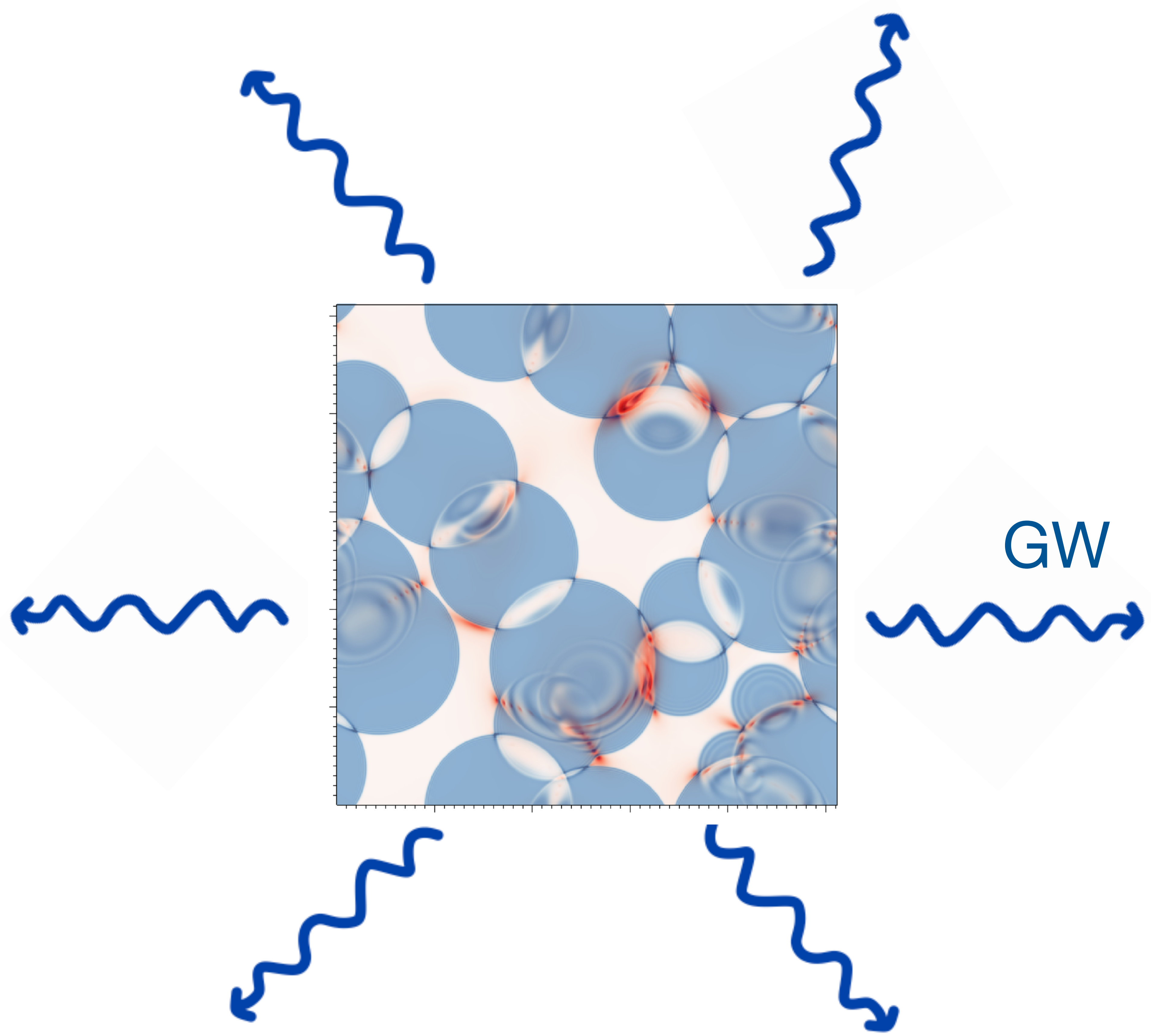
- A simple model to create such a map

- The simple model typically leads to small GW signals (Caveat)

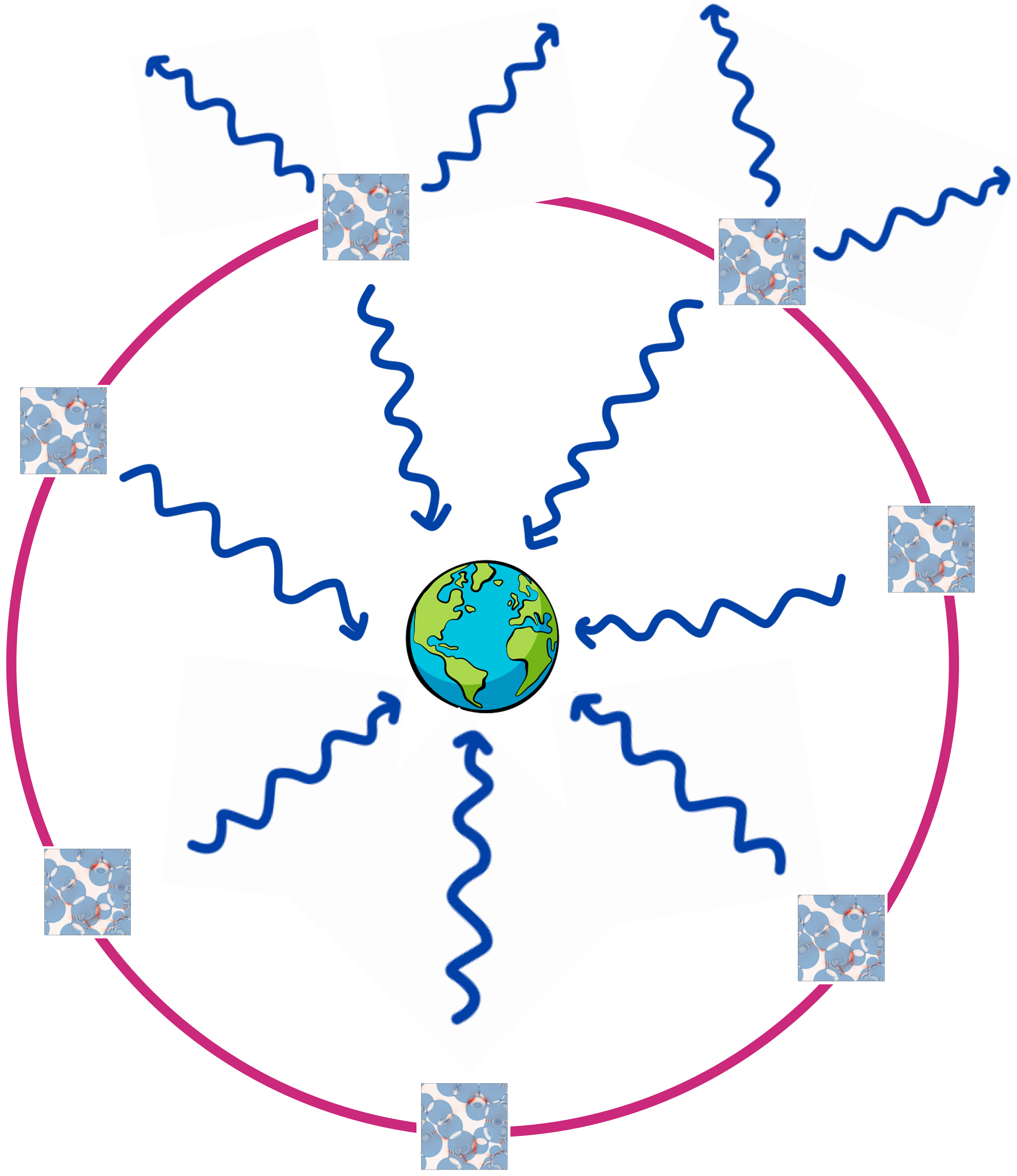
- Our model with early matter dominance can enhance the GW signal from naive expectation, significantly improving its detection prospects at GW detectors

New map: Gravitational wave backgrounds from First-order phase transitions

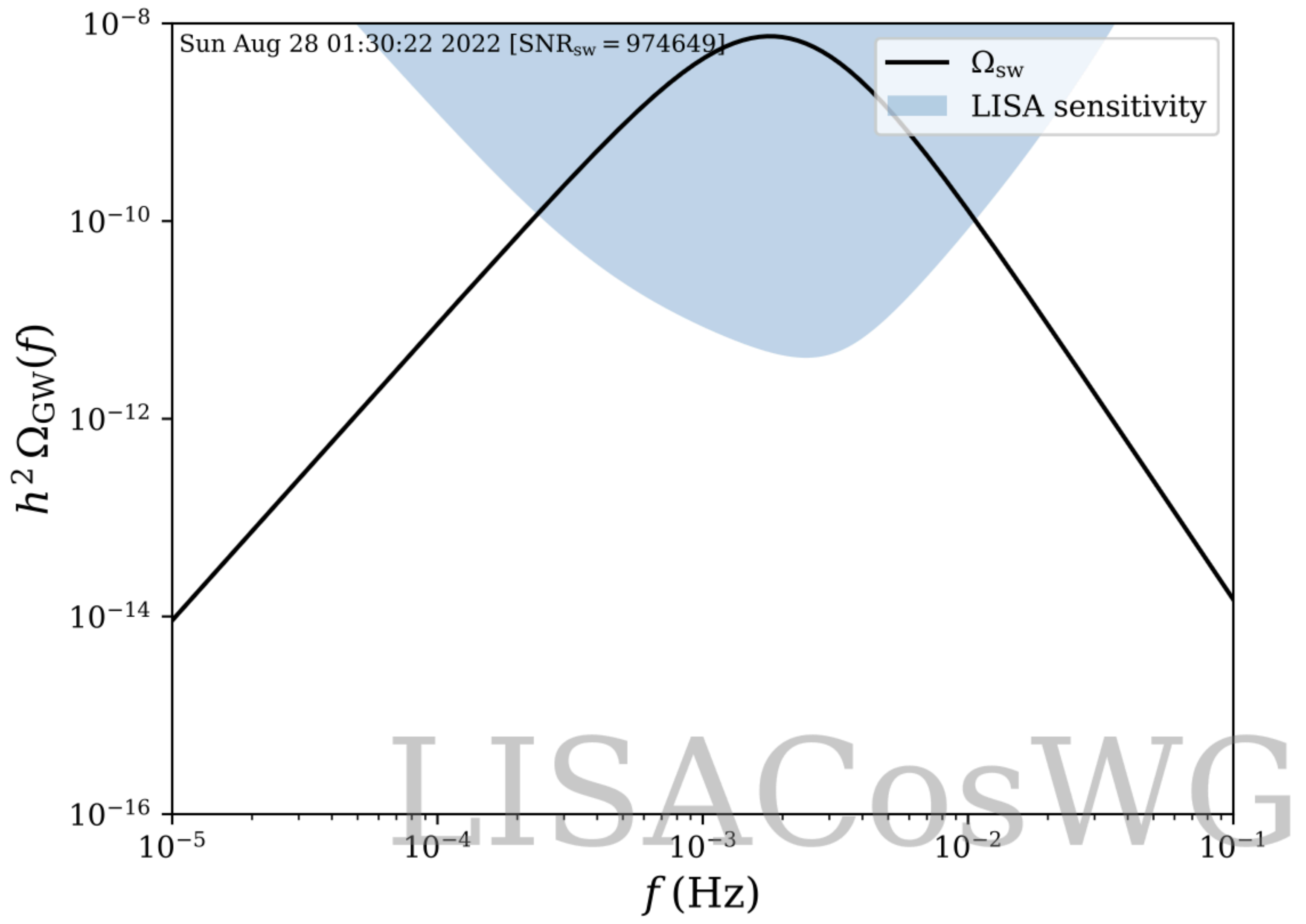




Cutting, Hindmarsh, Weir ’18

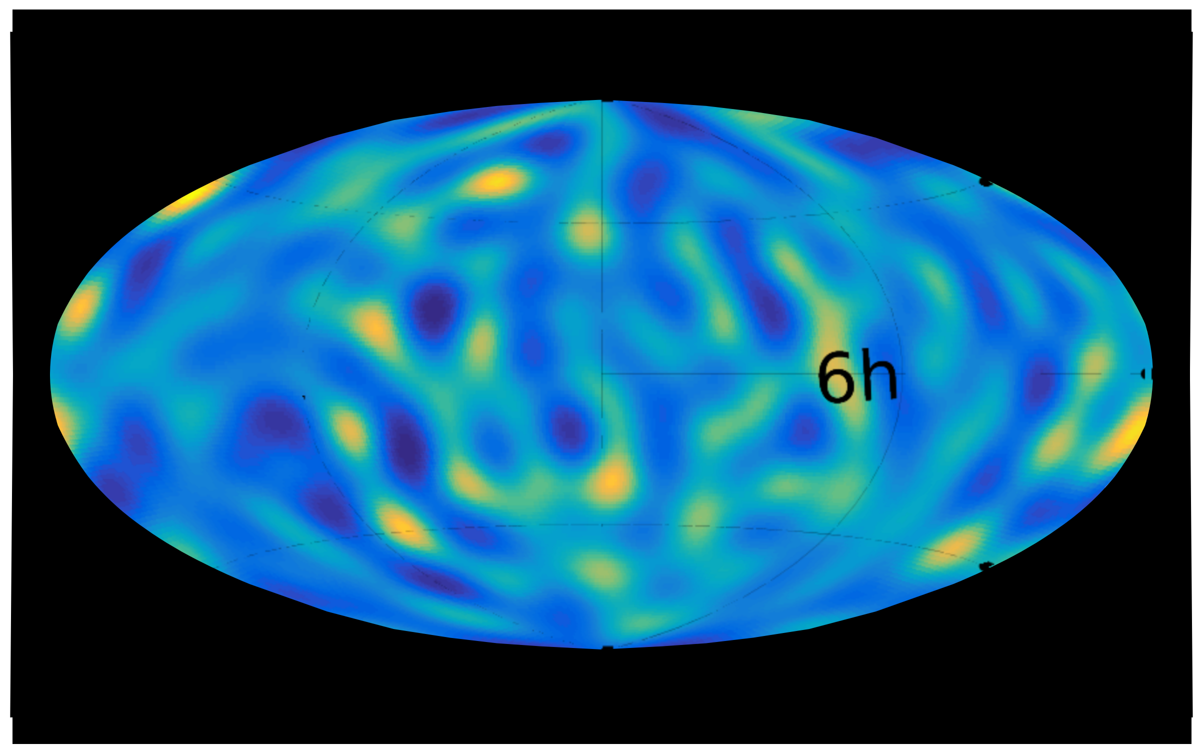


Frequency spectrum



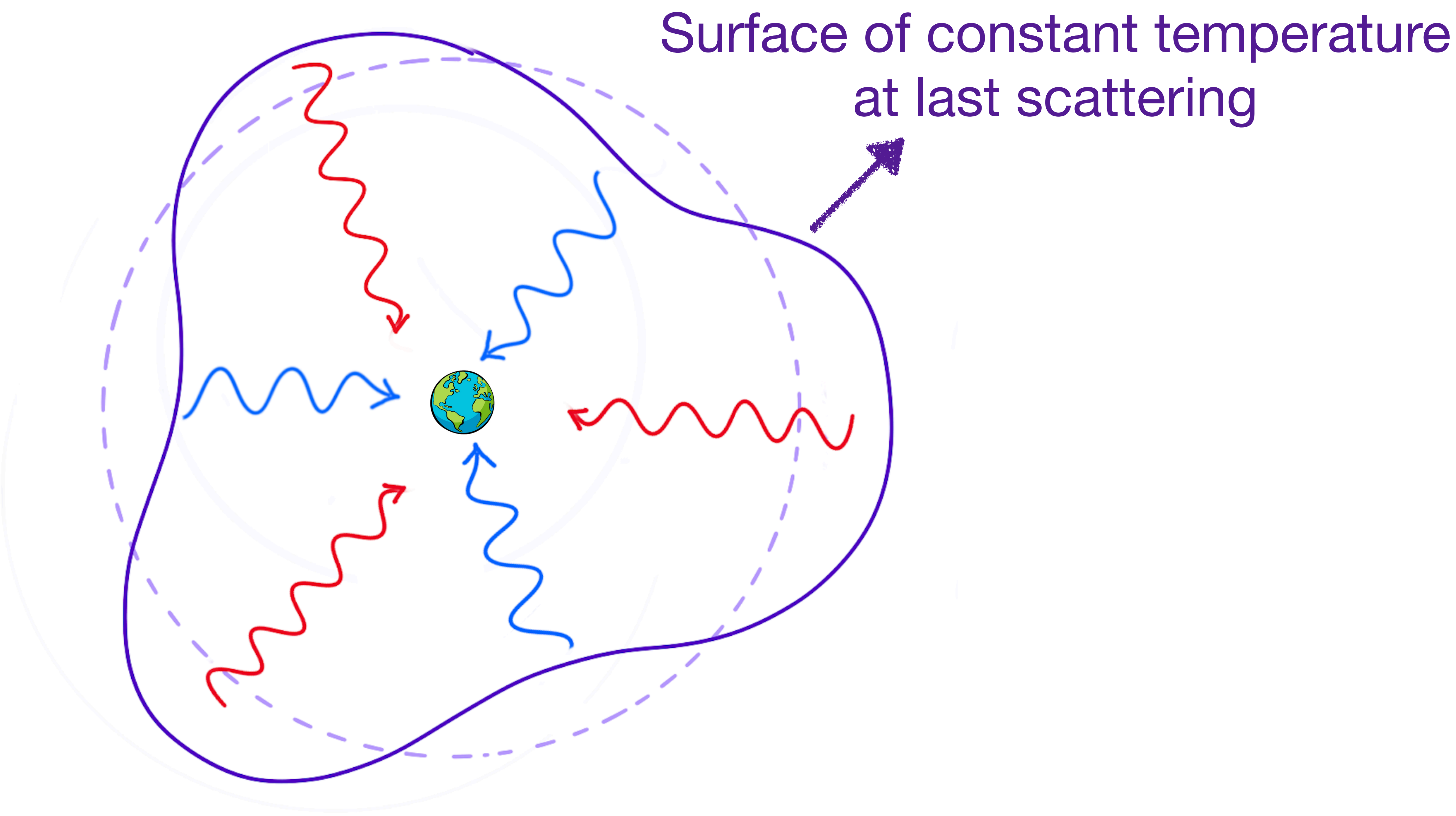
PTPlot.org

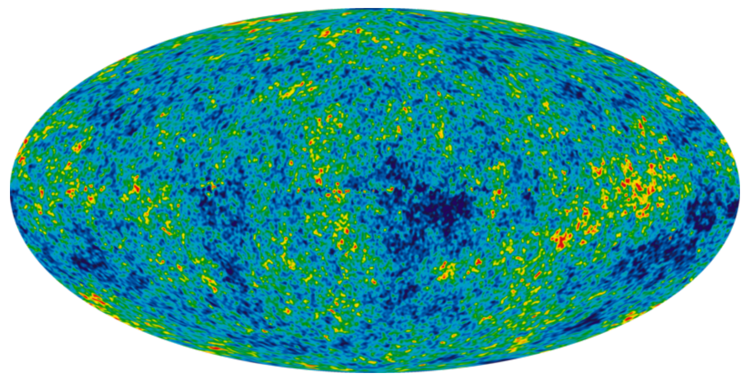
Angular power spectrum



LIGO template

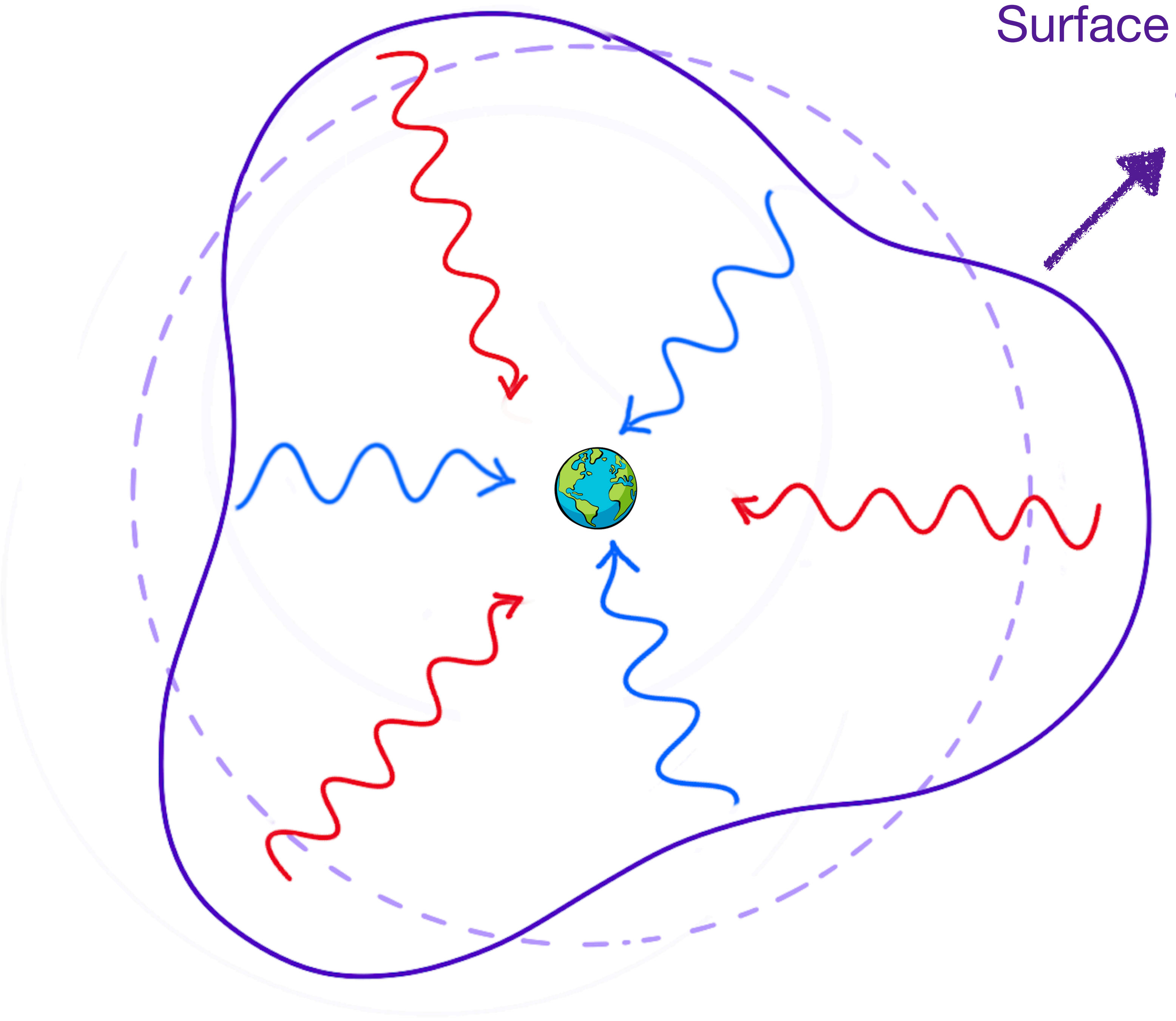
Recap: CMB anisotropies

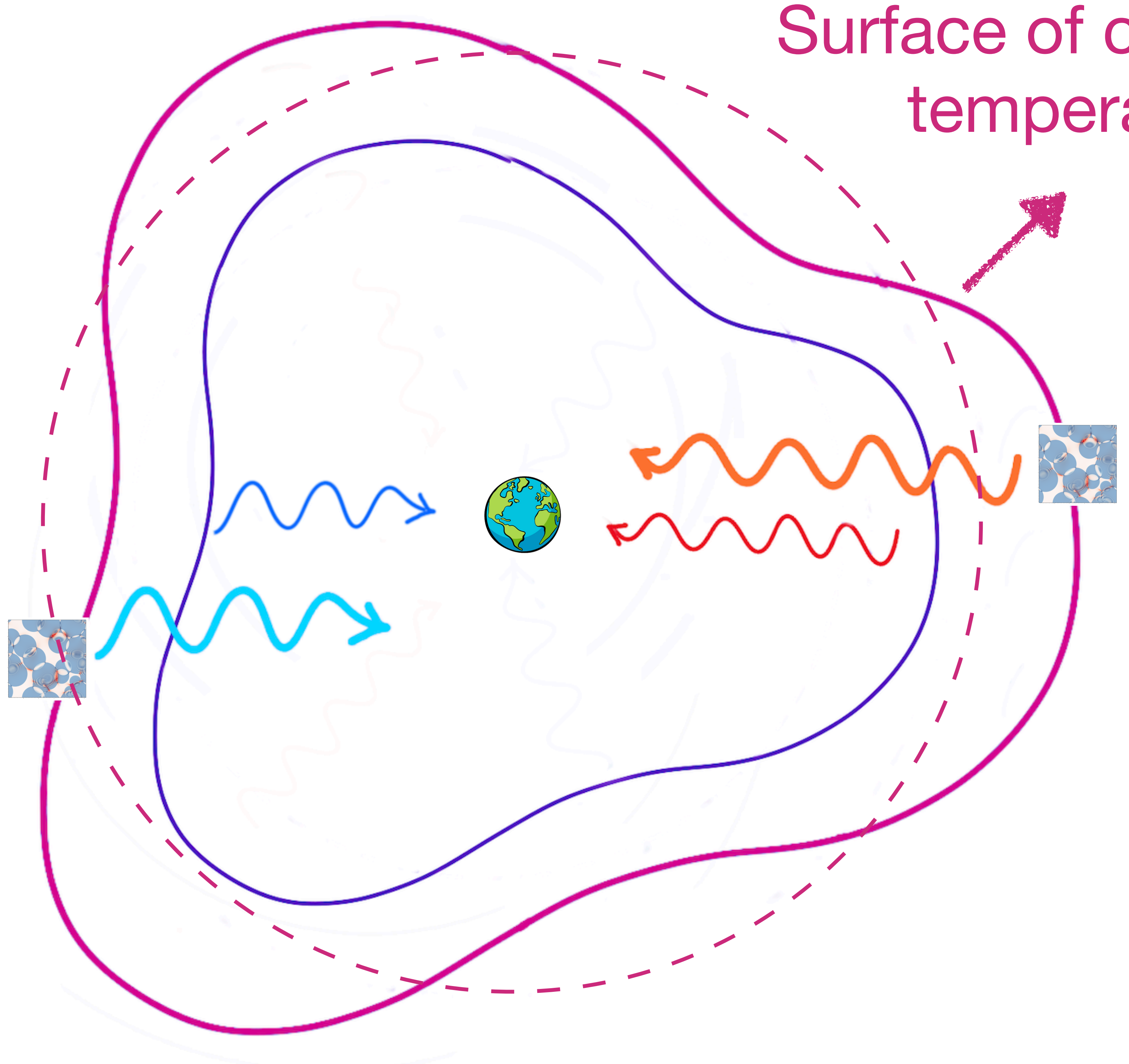


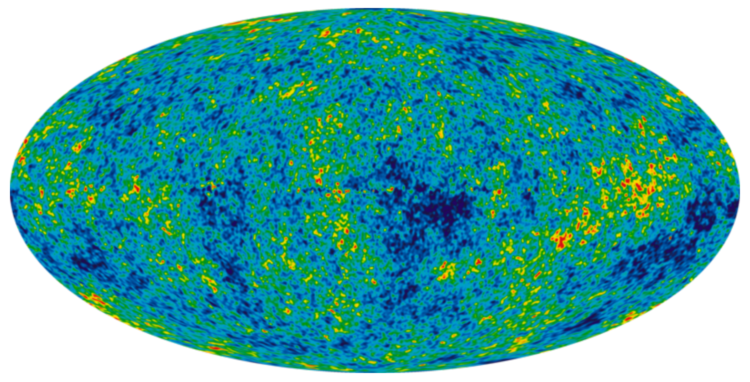


$$\delta_{\rm CMB} \equiv \frac{\Delta T}{\bar{T}} \sim 10^{-5}$$

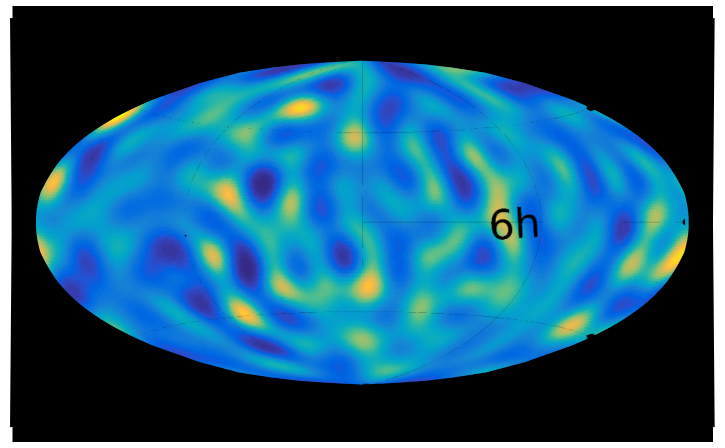
GWB anisotropies







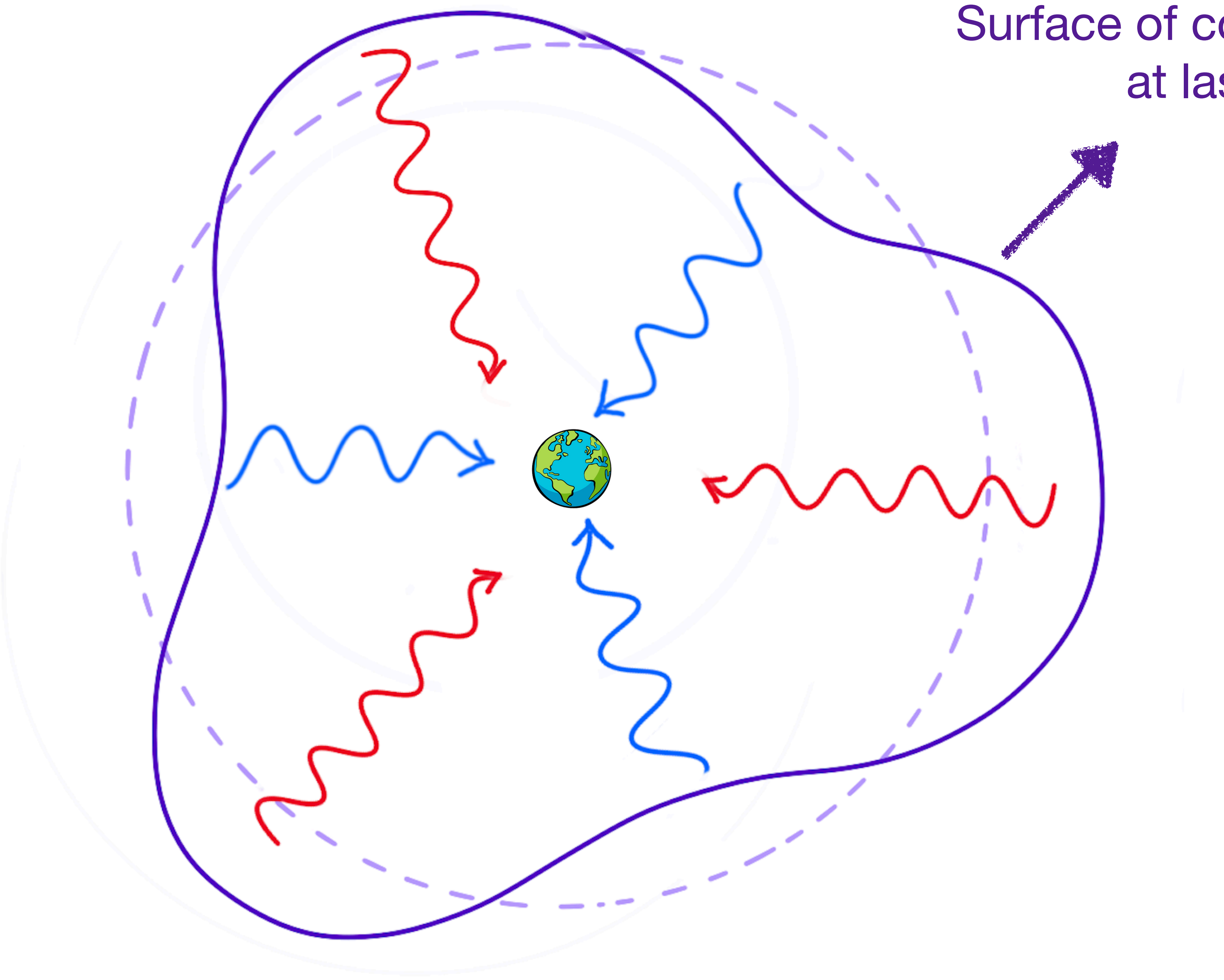
$$\delta_{\rm CMB} \equiv \frac{\Delta T}{\bar{T}} \sim 10^{-5}$$



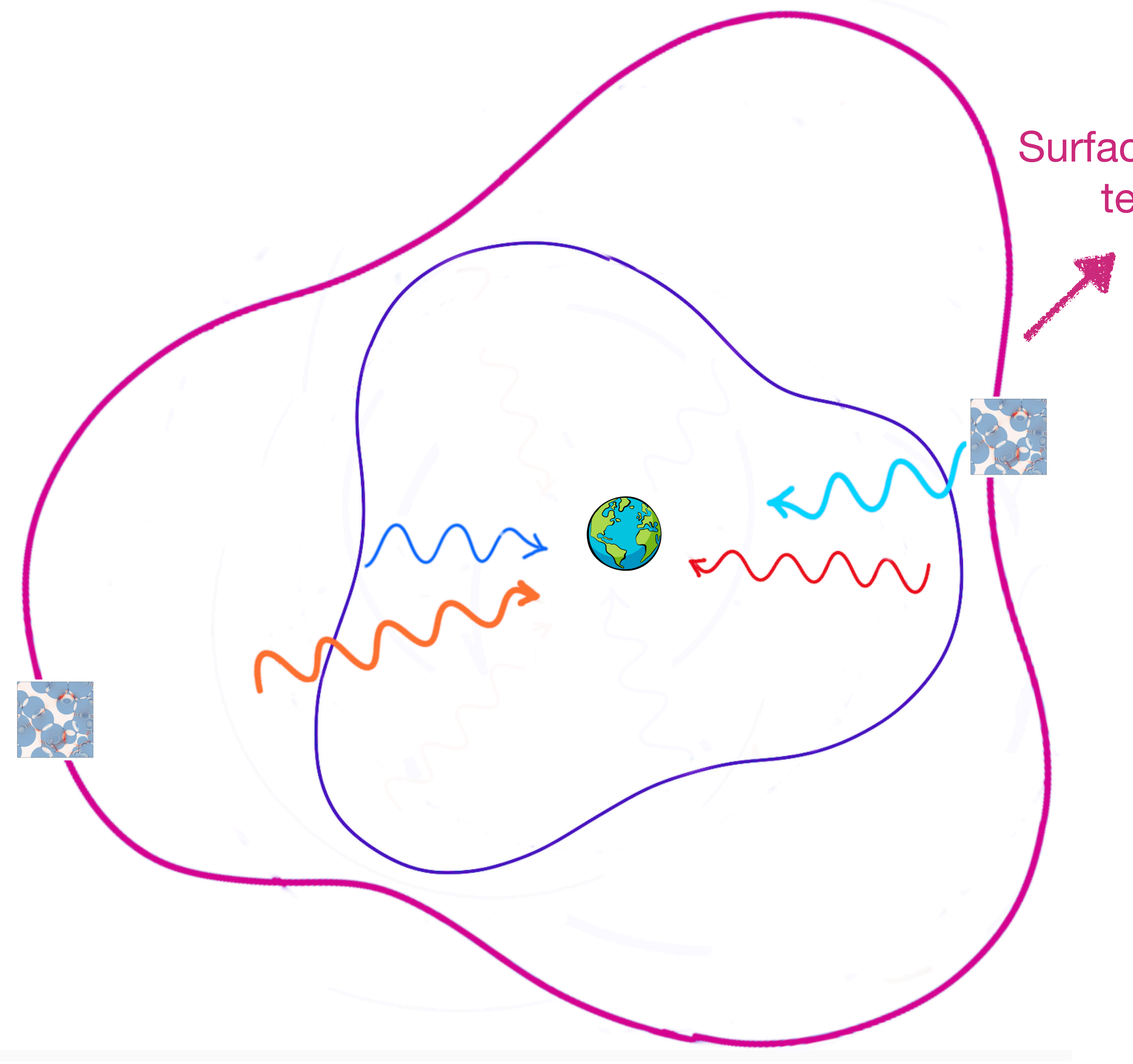
$$\delta_{\rm GW} \equiv \frac{\Delta \rho_{\rm GW}}{\bar{\rho}_{\rm GW}} \sim 10^{-5}$$

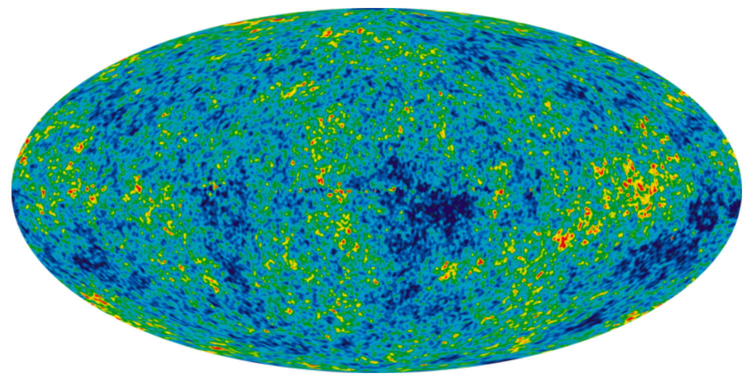
Uncorrelated GWB anisotropy

Surface of constant temperature at last scattering

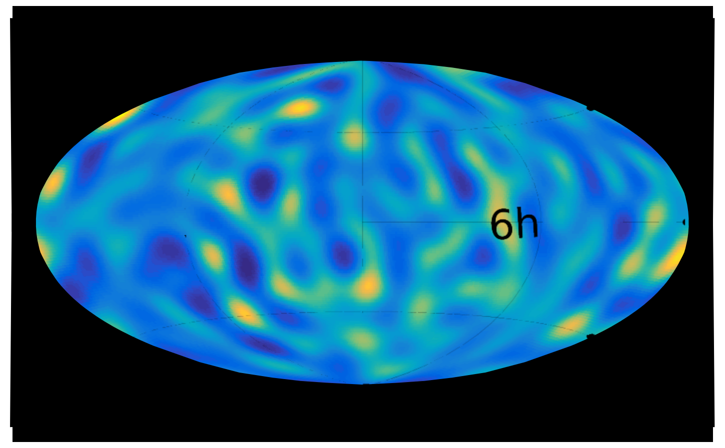


Surface of constant critical temperature at PT



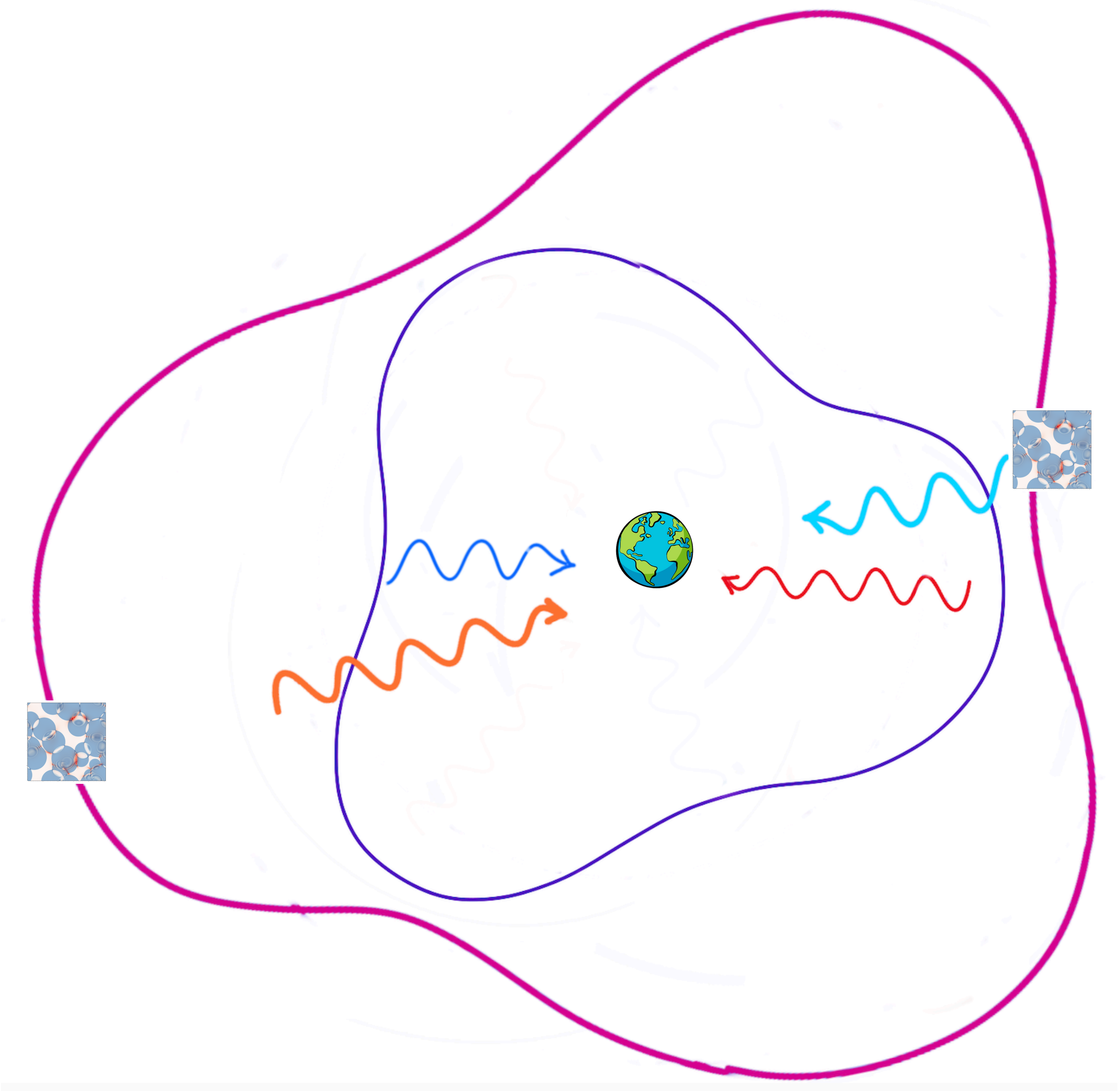


$$\delta_{\mathrm{CMB}} \equiv \frac{\Delta T}{\bar{T}} \sim 10^{-5}$$



$$\delta_{\mathrm{GW}} \equiv \frac{\Delta \rho_{\mathrm{GW}}}{\bar{\rho}_{\mathrm{GW}}} \neq 10^{-5}$$

Uncorrelated GWB anisotropy



Uncorrelated large-scale fluctuations → a different quantum field from inflation

$$\delta_{GW} \equiv \frac{\Delta\rho_{GW}}{\bar{\rho}_{GW}} \gg 10^{-5}$$

Interesting features such as tilt, scale-invarince breaking feature, non-gaussianity → new signatures of physics from inflation

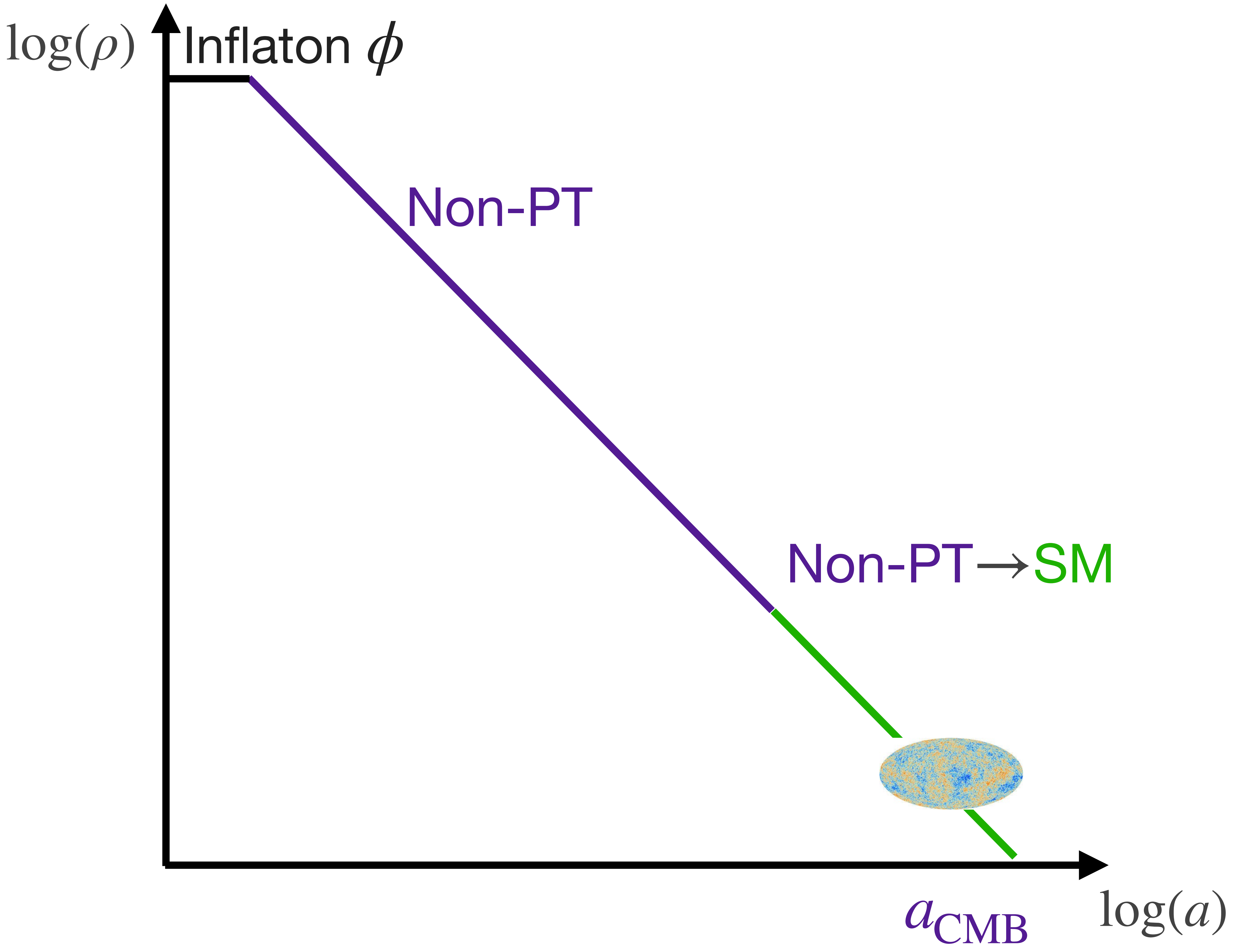
L. Valbusa Dall'Armi et al 2021

S. Kumar, R. Sundrum and Y. Tsai 2021

AB, R. Sundrum 2022

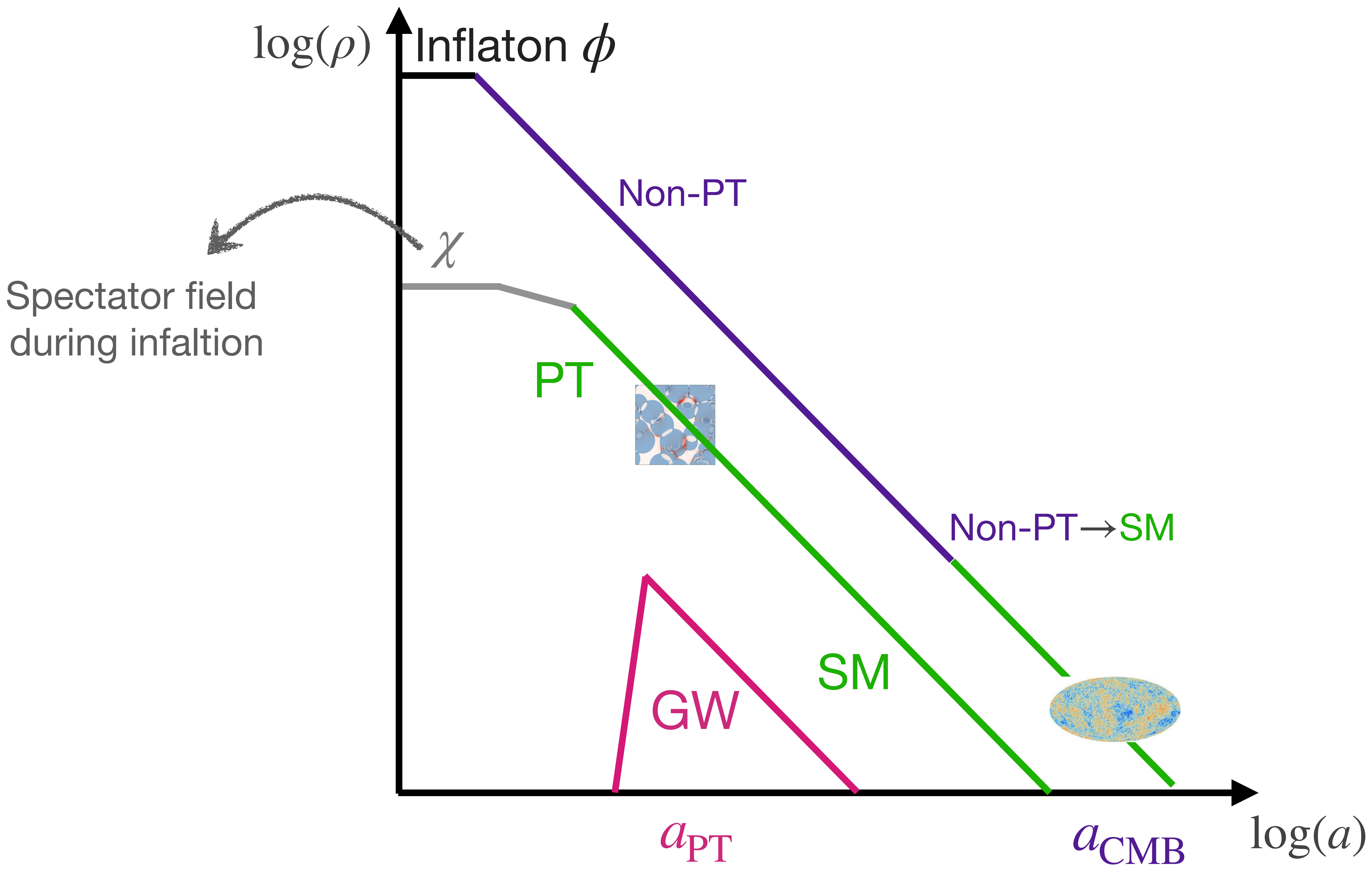
Simple model of uncorrelated GW anisotropy

Geller, Hook, Sundrum, Tsai 1803.10780



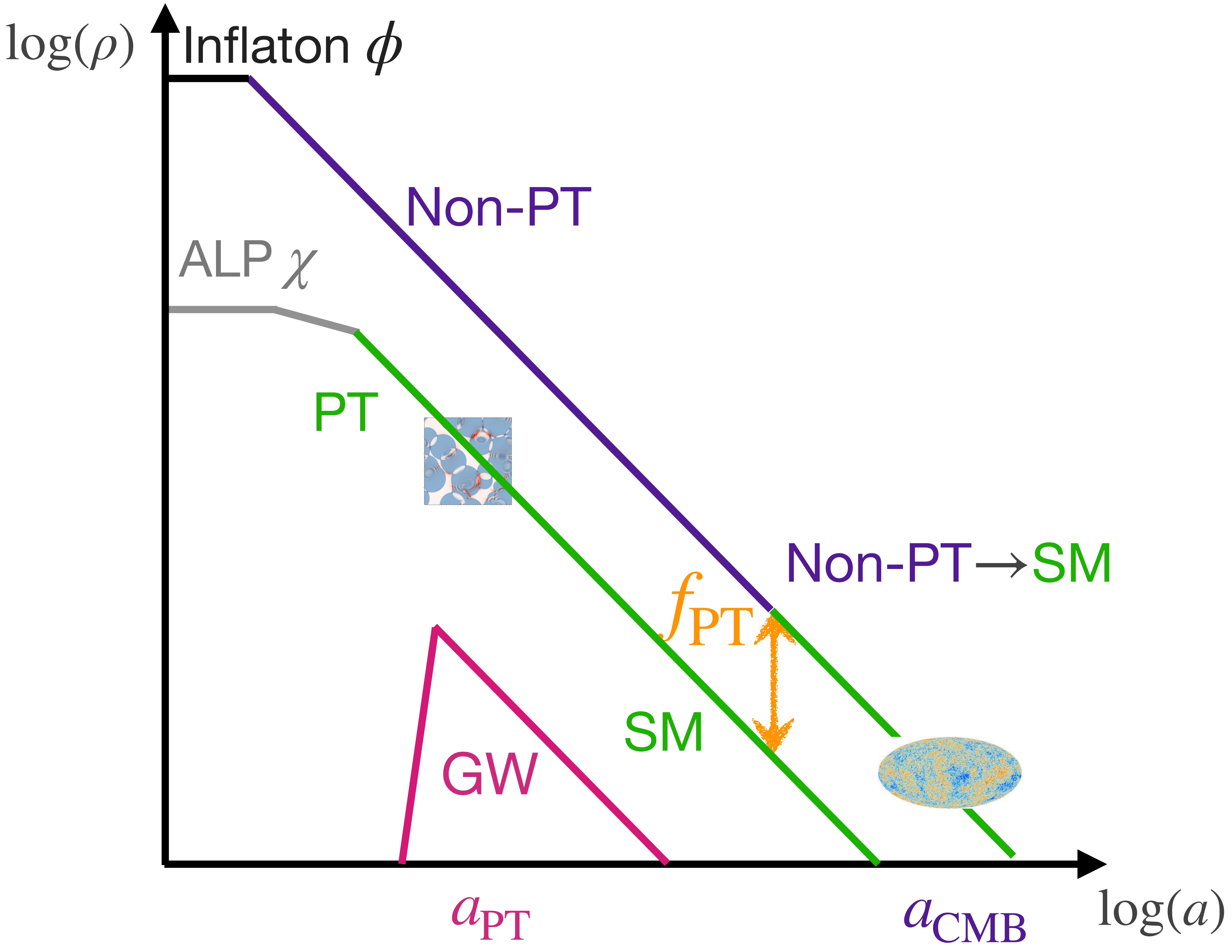
Non-PT sector: a weakly interacting sector that does not participate in the phase transition, and decays to SM (+DM) at some late time

Simple model of uncorrelated GW anisotropy



PT Sector: an extension of SM that undegoes a phase transition in the multi-TeV range.
Weakly interacting with the non-PT sector.

Simple scenario with isocurvature GW anisotropy



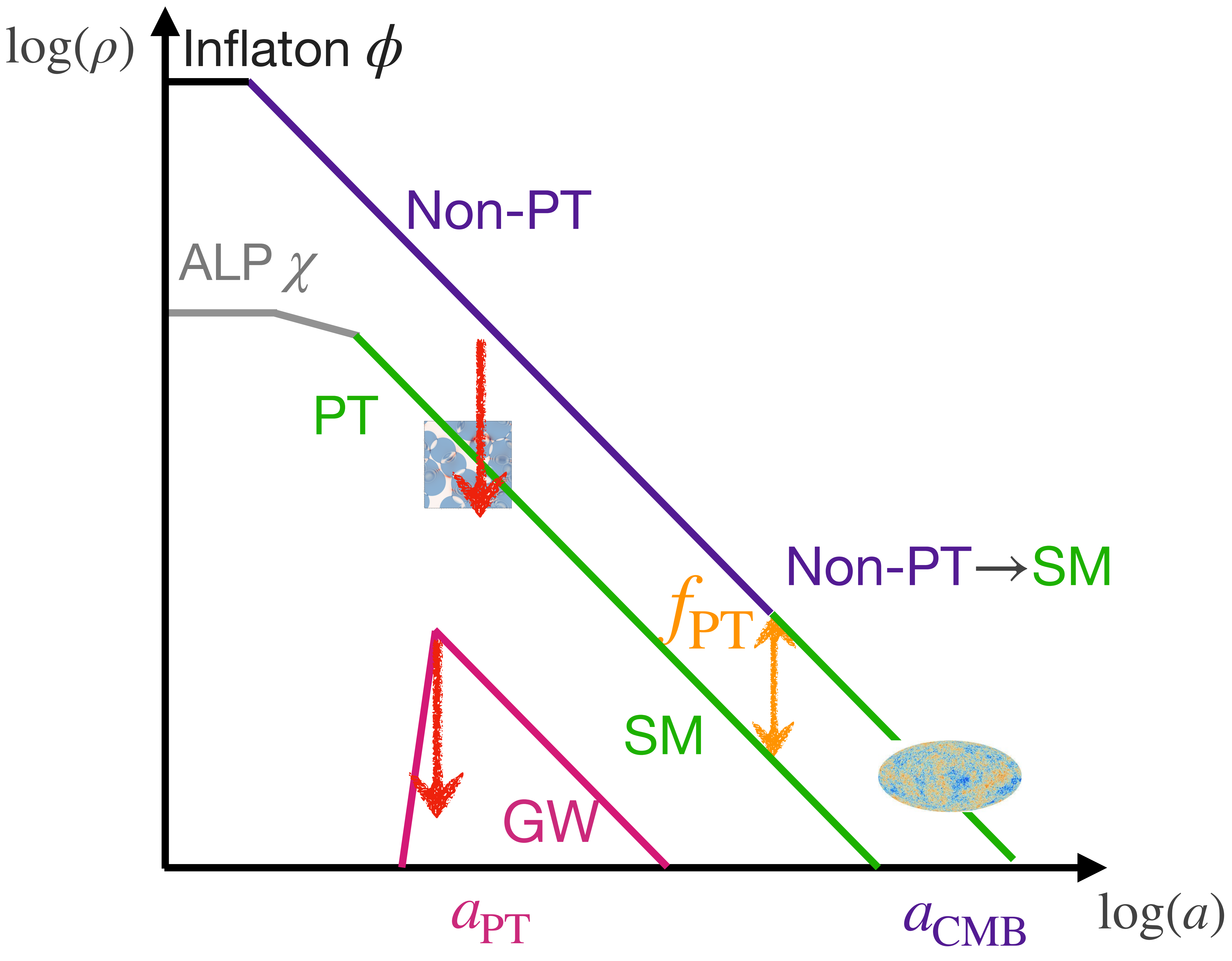
$$\delta_{\rm GW} \sim \delta_\chi + \delta_\phi$$

Sachs-Wolfe contribution $\sim 10^{-5}$

$$\delta_{\rm CMB} \sim \delta_\phi + f_{\rm PT}\,\delta_\chi \sim 10^{-5}$$

$$f_{\rm PT} = \frac{\rho_{\rm PT}}{\rho_{\rm total}} \ll 1$$

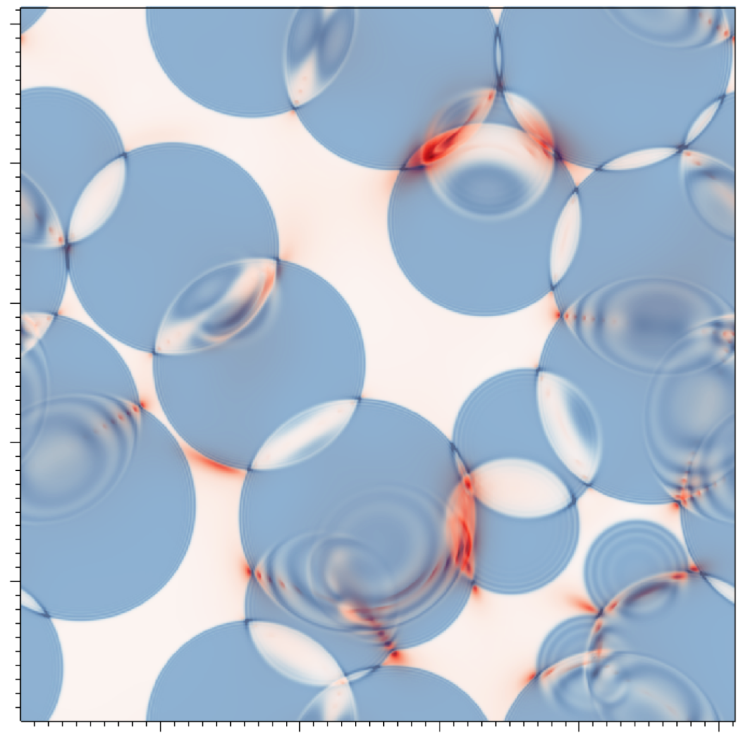
Caveat



$\delta_{\rm GW} \sim \delta_\chi + \delta_\phi$

$\delta_{\rm CMB} \sim \delta_\phi + f_{\rm PT}\,\delta_\chi \sim 10^{-5}$

Energy density in GWB at production



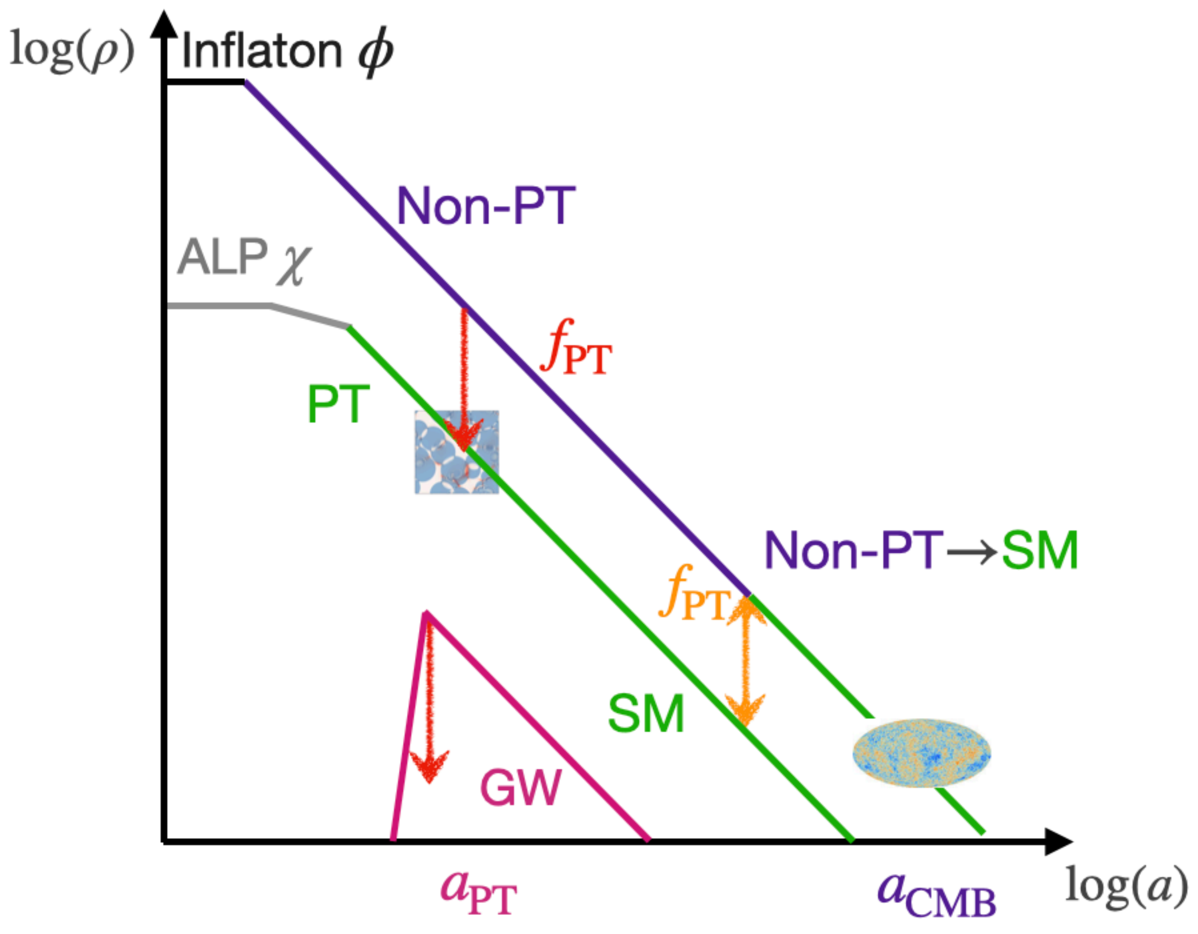
Einstein eq: $h^{\mathrm{TT}} \propto \rho_{\mathrm{PT}}$

$\rho_{\mathrm{GW}} \propto (h^{\mathrm{TT}})^2 \propto \rho_{\mathrm{PT}}^2$

$$\boxed{\Omega_{\mathrm{GW}} := \frac{\rho_{GW}}{\rho_{\mathrm{total}}} \propto \left(\frac{\rho_{\mathrm{PT}}}{\rho_{\mathrm{total}}}\right)^2}$$

Kosowsky, Turner, Watkins ’92
Kamionkowski, Kosowsky, Turner ’94

Caveat: $f_{\rm PT}^2$ suppression in isotropic GWB

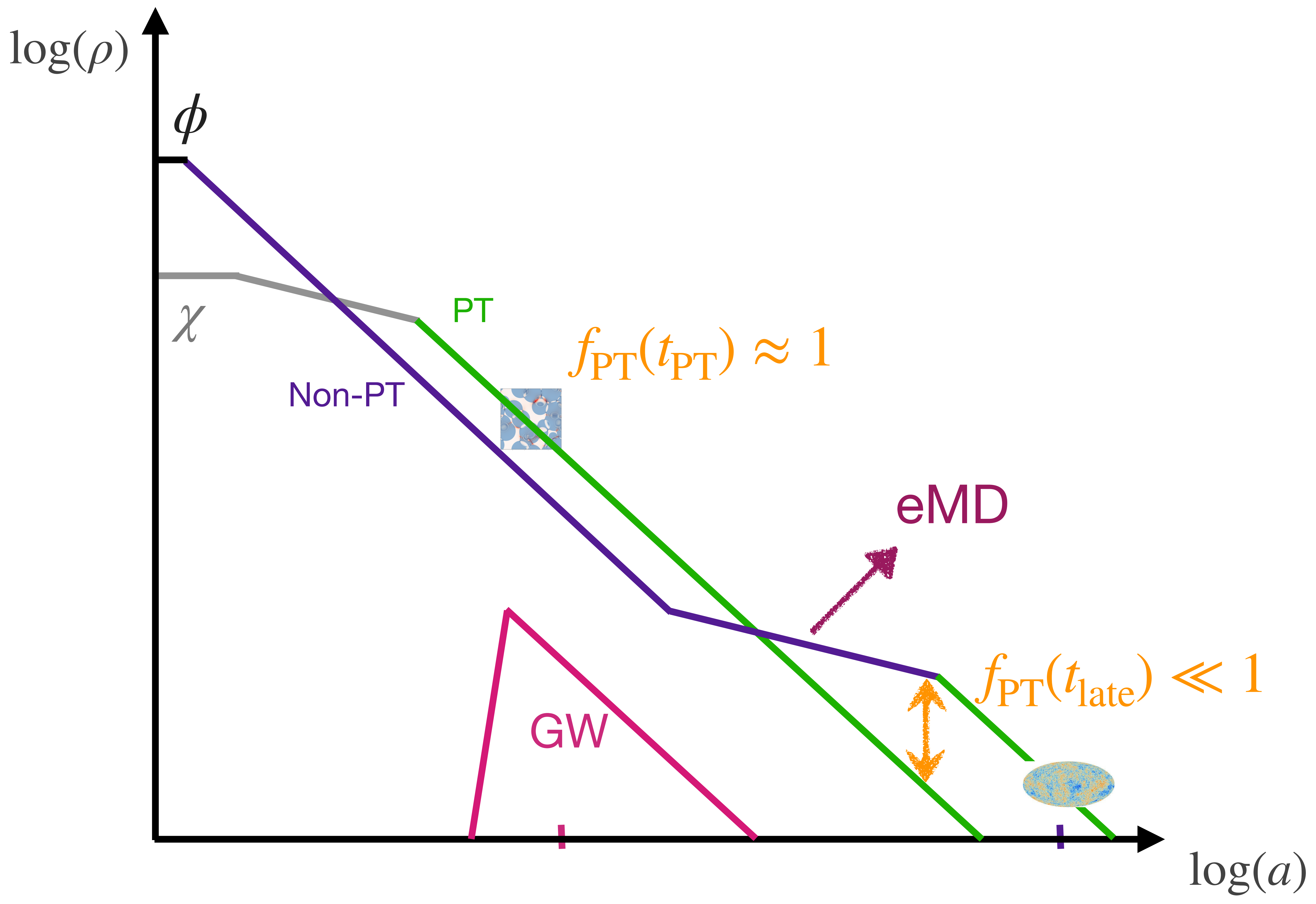


$$\boxed{\Omega_{\rm GW} := \frac{\rho_{GW}}{\rho_{\rm total}} \propto \boxed{\left(\frac{\rho_{\rm PT}}{\rho_{\rm total}}\right)^2}} \rightarrow f_{\rm PT}^2$$

$$\delta_{\rm CMB} \sim \delta_\phi + \underset{\downarrow}{f_{\rm PT}}\, \overset{\uparrow}{\delta_{\rm GW}} \sim 10^{-5}$$

Our model with early Matter Dominance

Matter dilutes slower that radiation



AB, Sundrum 2211.09301

Our model with early Matter Dominance

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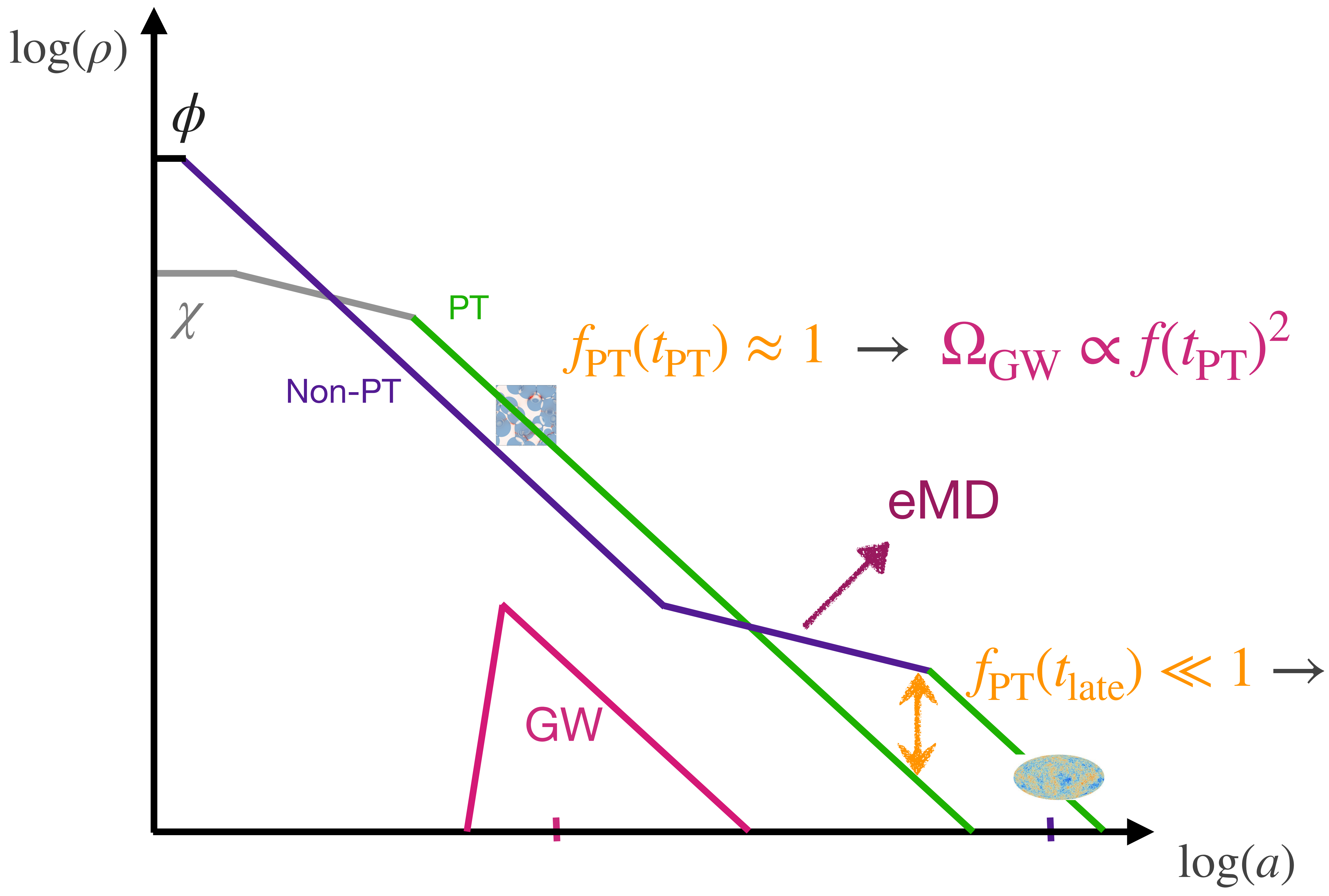
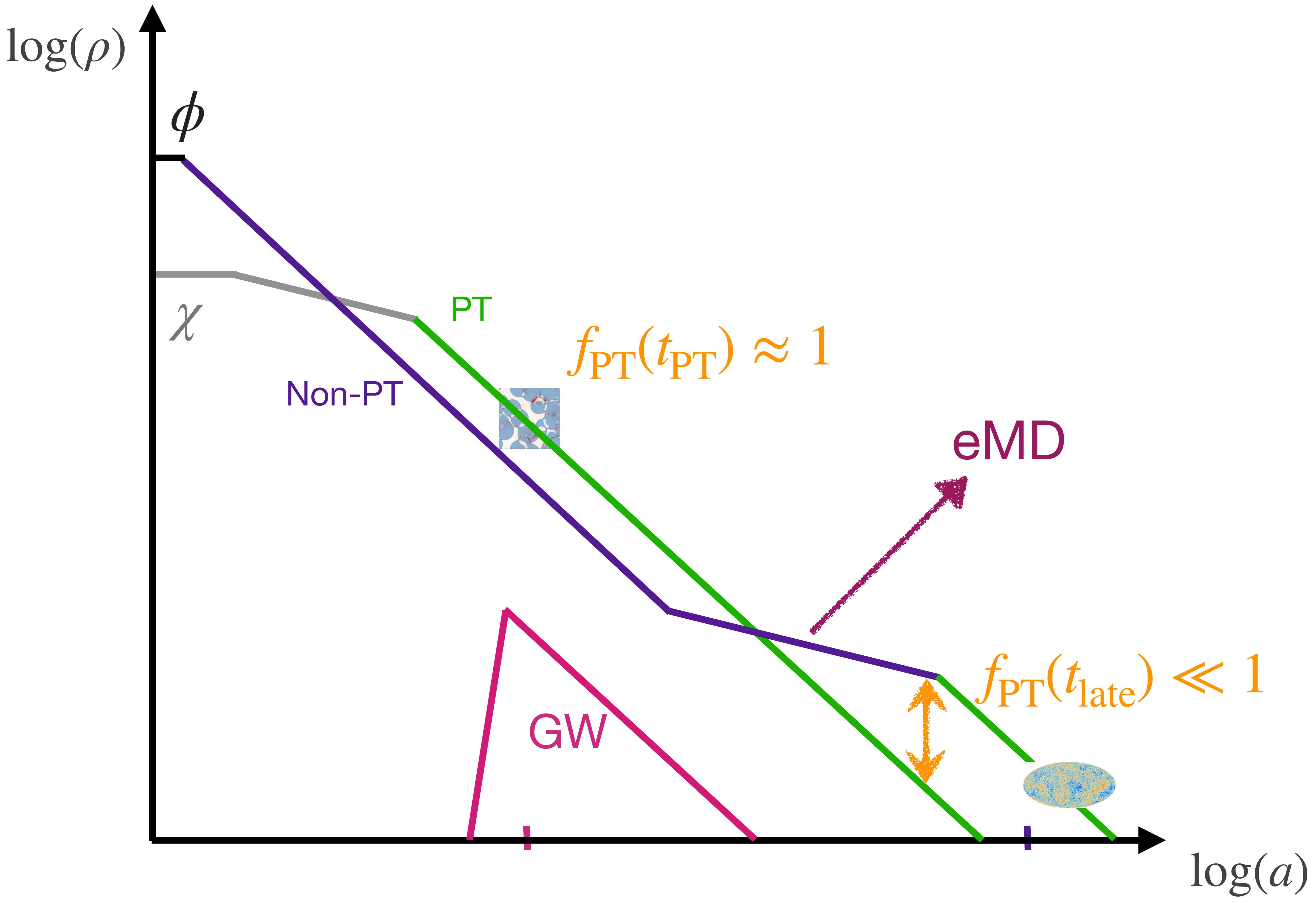


$f_{\rm PT}(t_{\rm PT}) \approx 1 \;\rightarrow\; \Omega_{\rm GW} \propto f(t_{\rm PT})^2$

$f_{\rm PT}(t_{\rm late}) \ll 1 \rightarrow\;\; \delta_{\rm CMB} \sim \delta_\phi + f_{\rm PT}(t_{\rm late})\,\delta_\chi \sim 10^{-5}$

AB, Sundrum 2211.09301

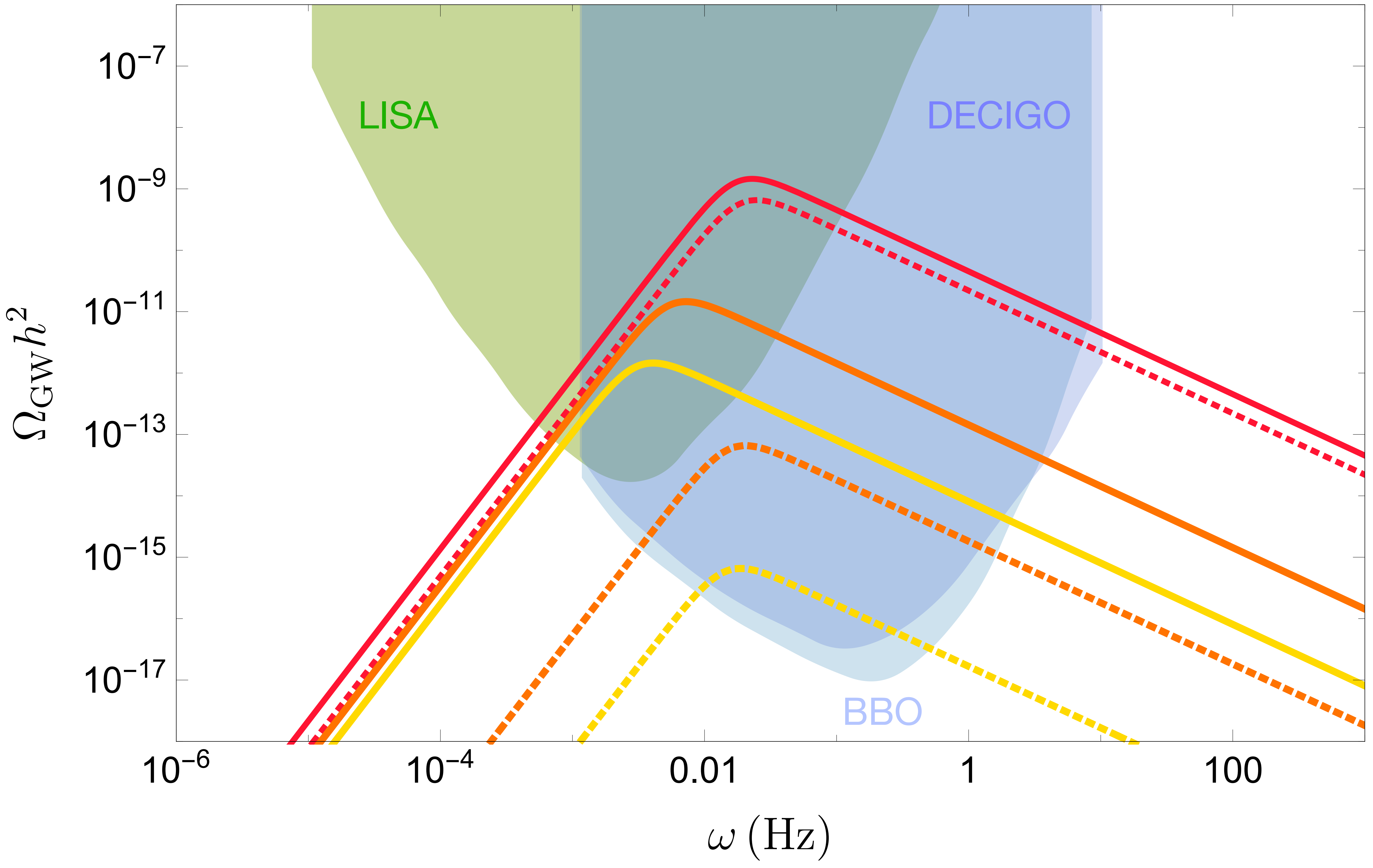
Our model with eMD



No suppression at production!

But relative dilution from eMD

$\Omega_{\rm GW}^{\rm today} \propto f_{\rm PT}$ instead of $f_{\rm PT}^2$



Dashed lines: Simple model

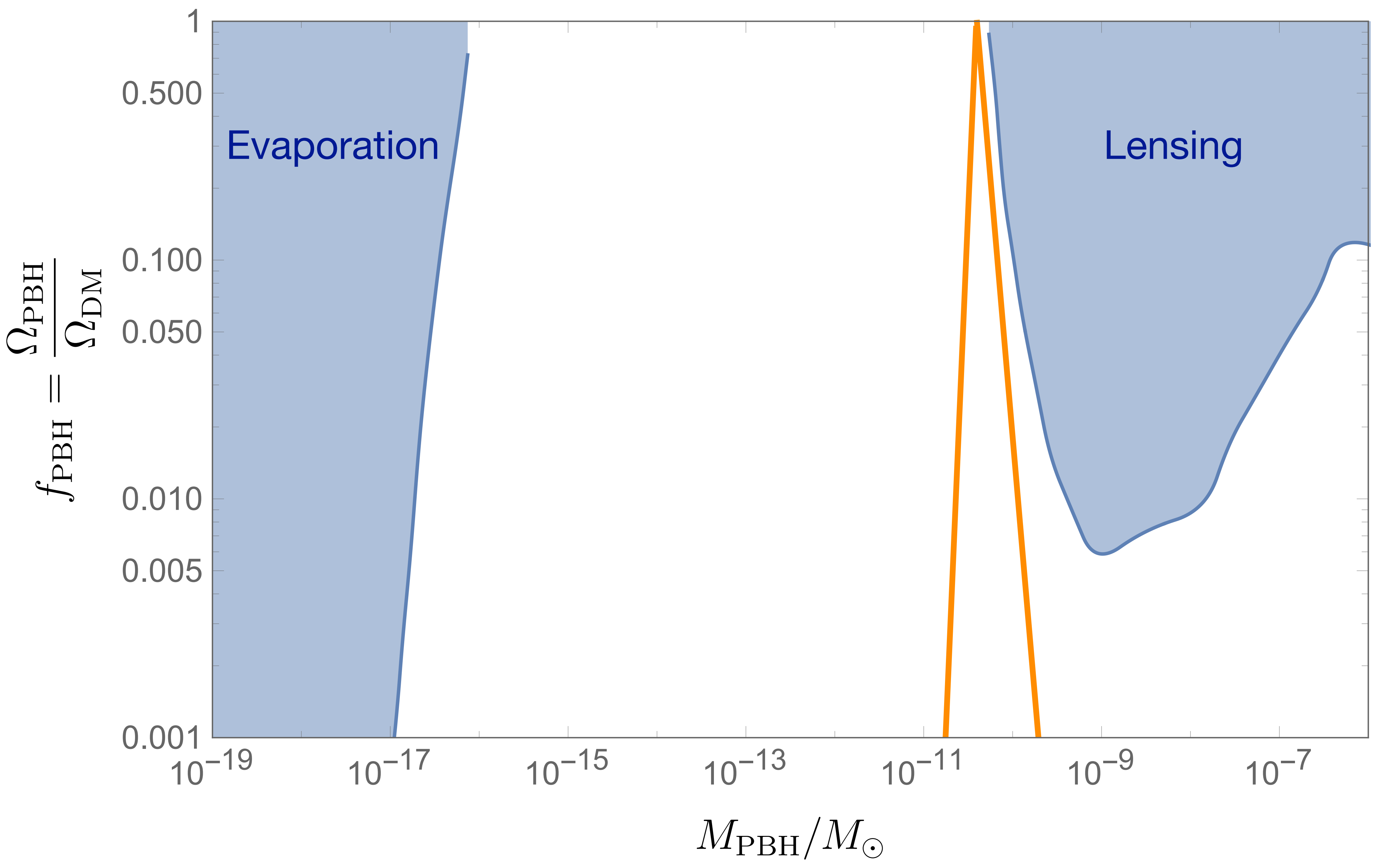
Solid lines: eMD model

$\delta_{\rm GW} \sim 10^{-4}$, $f_{\rm PT} \sim 10^{-1}$

$\delta_{\rm GW} \sim 10^{-2}$, $f_{\rm PT} \sim 10^{-3}$

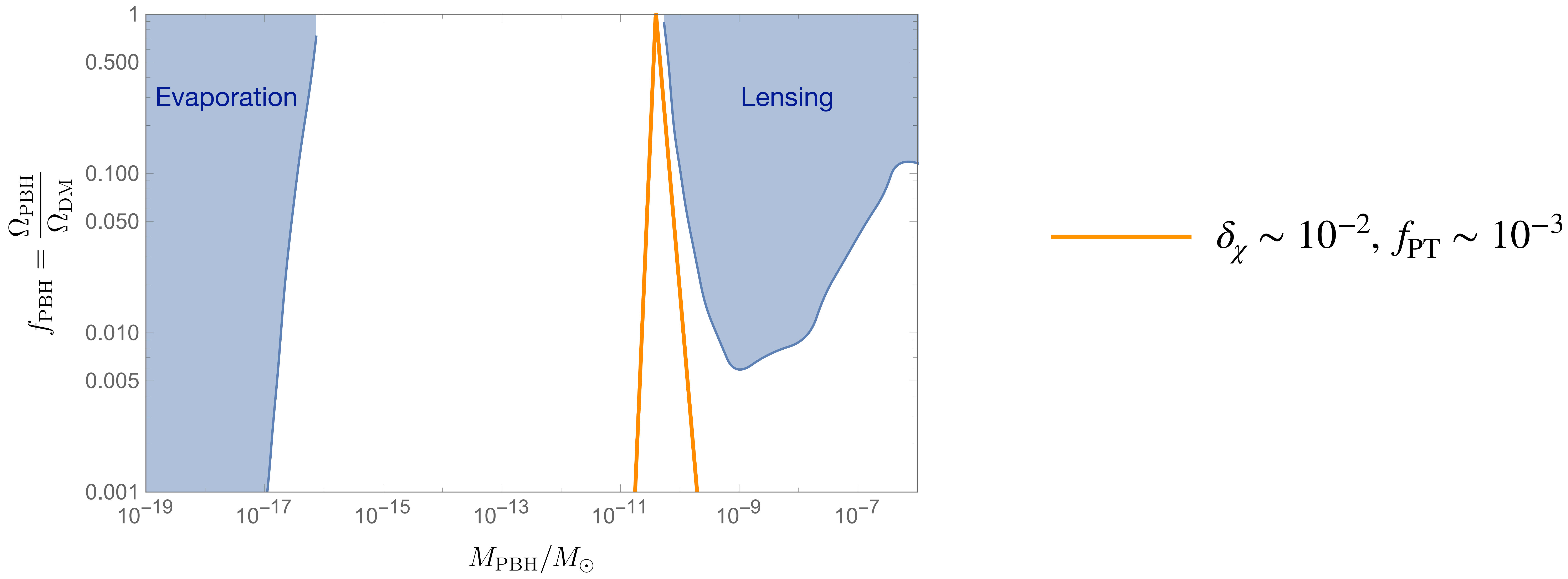
$\delta_{\rm GW} \sim 10^{-1}$, $f_{\rm PT} \sim 10^{-4}$

Other interesting feature: primordial black holes



$\delta_\chi \sim 10^{-2}$, $f_{\rm PT} \sim 10^{-3}$

Other interesting feature: primordial black holes



For $\delta_\chi > 0.01$ on large scales, need a significantly red-tilted spectrum.

Summary

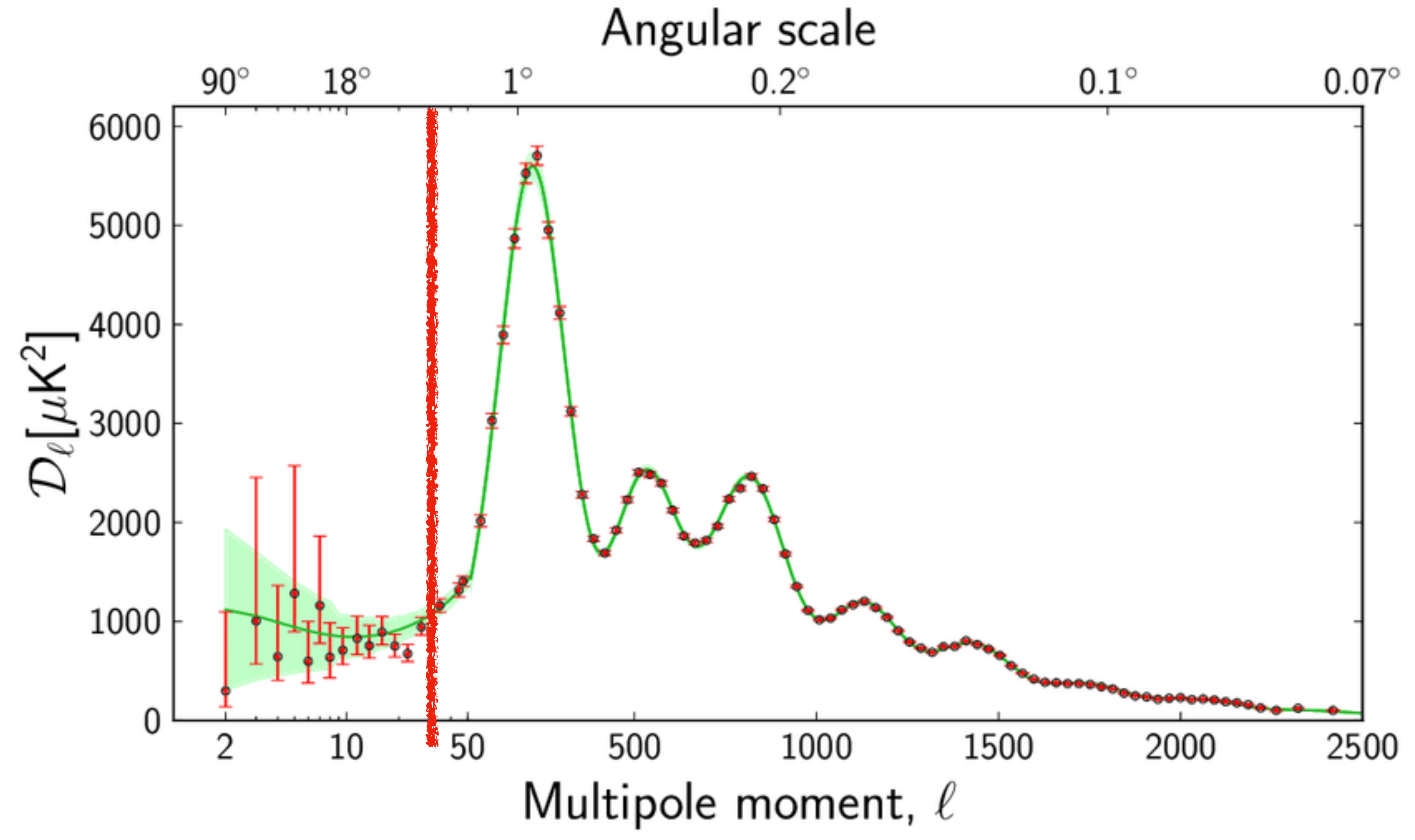
- There can be new cosmological maps signficantly different from CMB.
- Example: highly anisotropic stochastic gravitational wave background from a first-order phase transition.
- In a simple model, the expected signal strength is small due to CMB isocurbature constraints.
- Our model with an earlier period of matter dominance can give larger signal strength, bringing a wider range of GWB anisotropies within the sensittivies of future detectors like LISA.

Back-up slides

GWB is a “pristine” map

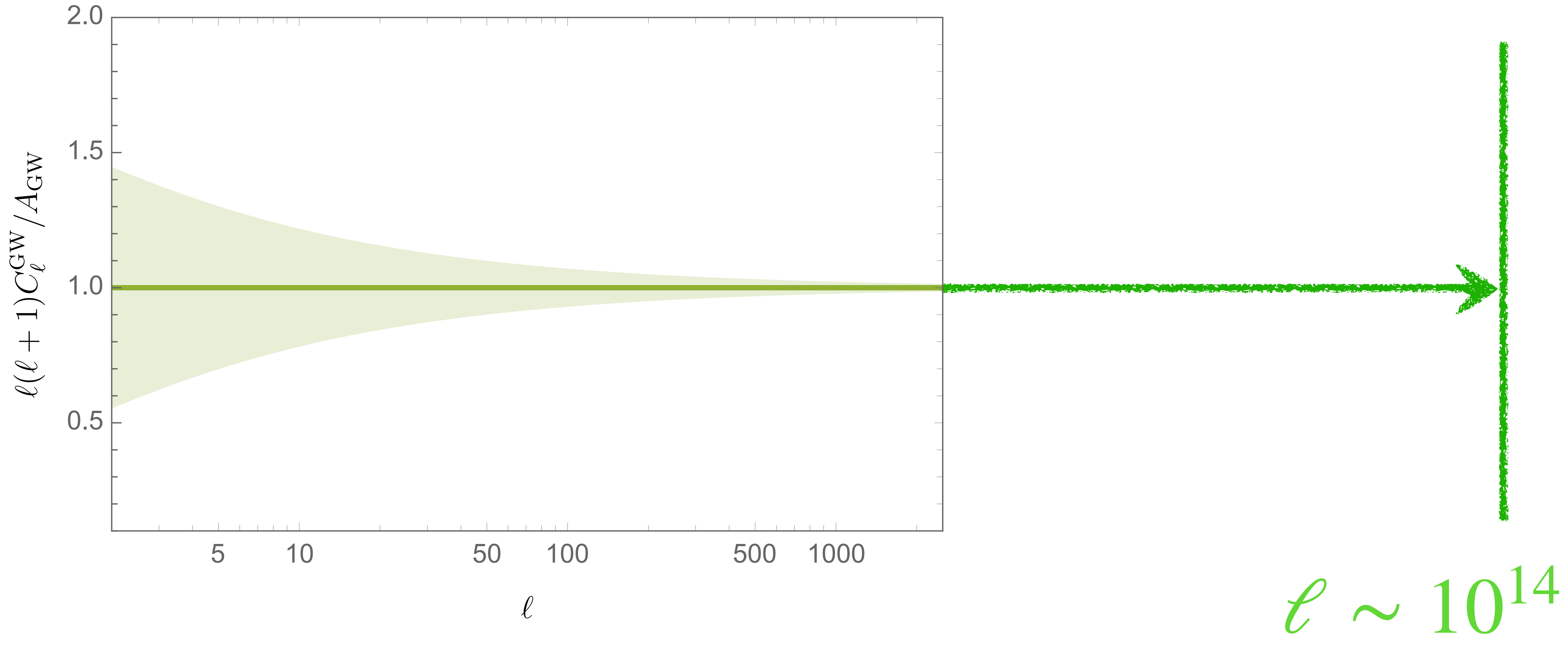
Earlier production + free-streaming of GW → large range of scales is unaltered by subhorizon physics

CMB

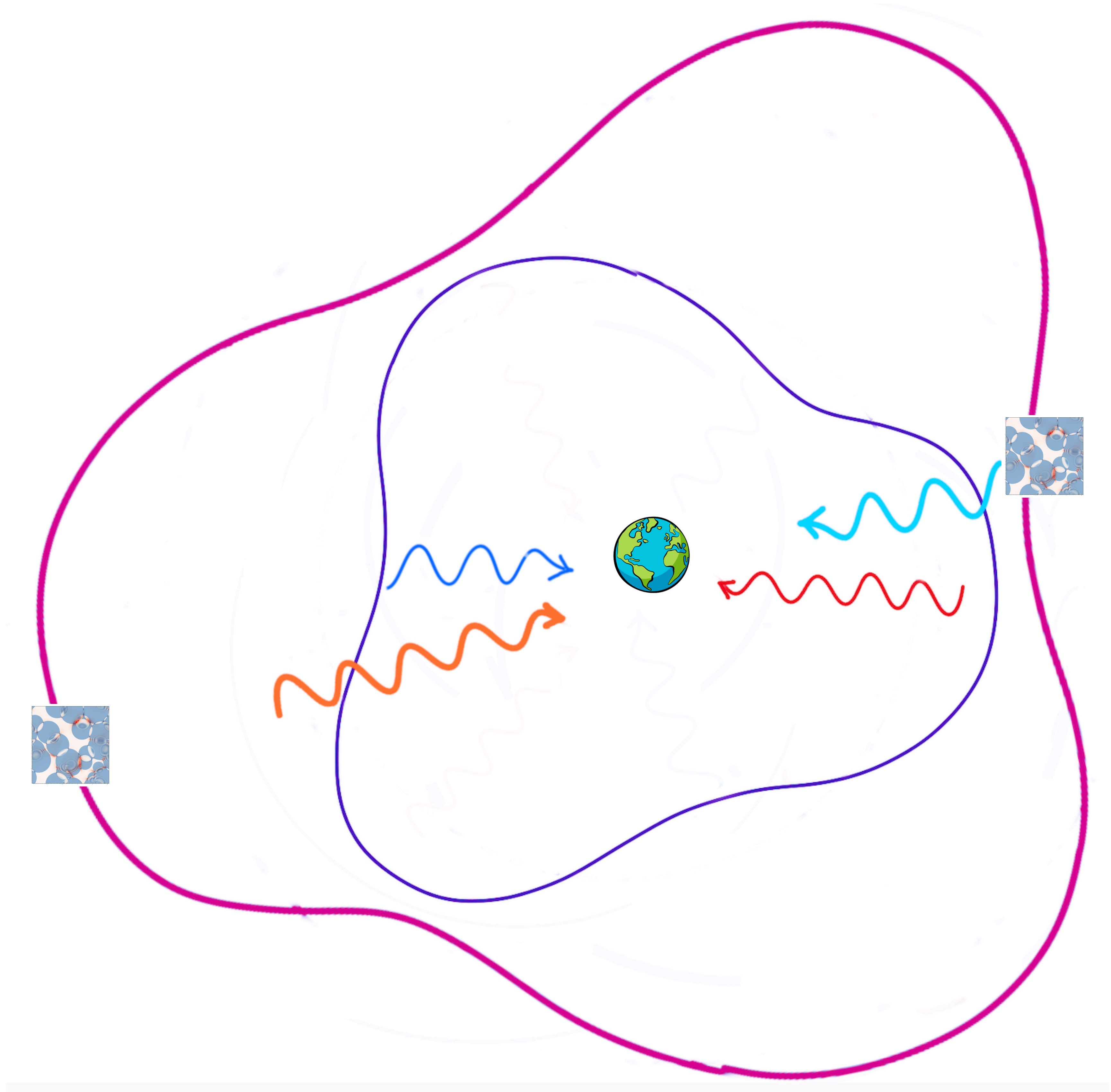


Planck

GWB



Bubbles are unresolvable



Caution: Zoomed in!

$> 10^{18}$ bubble collisions/arcsec^2

$\implies$ Bubbles are unresolvable sources : getting a course grained picture of GWB

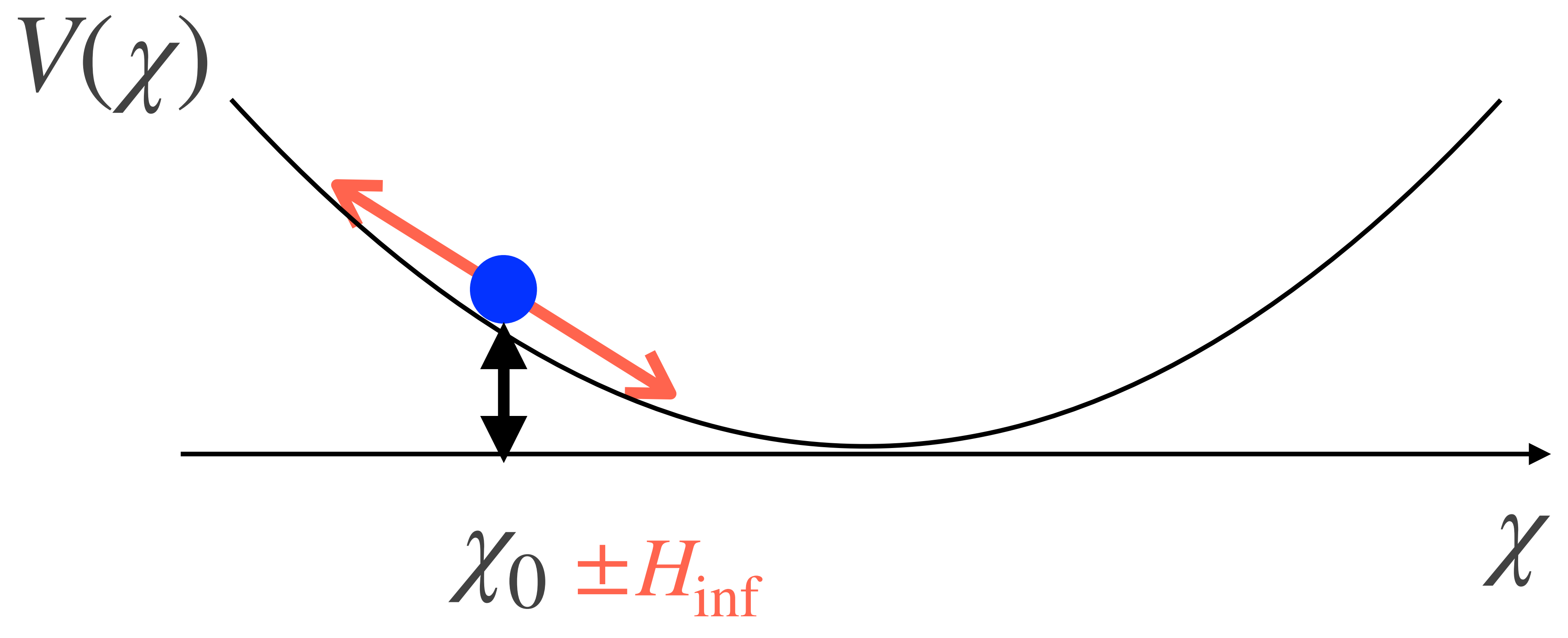
Alternate source of GW anisotropies

Axion-Like Particle $(\mathrm{ALP}\chi)$ will develope (nearly scale-invariant) quantum fluctuations during inflation

$$\Delta V \sim V_0\,(\Delta\chi/\chi_0)$$

$$\Delta\chi \sim H_{\rm inf}$$

$$\delta_\chi := \frac{\Delta\rho_\chi}{\rho_\chi} \sim \frac{H_{\rm inf}}{\chi_0}$$



- δ_χ could be very different from $\delta_\phi \sim \dfrac{H_{\rm inf}\Delta\phi}{\dot\phi_0}$ (source of adiabatic pertubations in CMB)
- When $m_\chi \sim H(t)$, it starts oscillating and decays to radiation. δ_χ is then transferred to decay products.

Large $\delta_\chi > 10^{-5}$ is great!

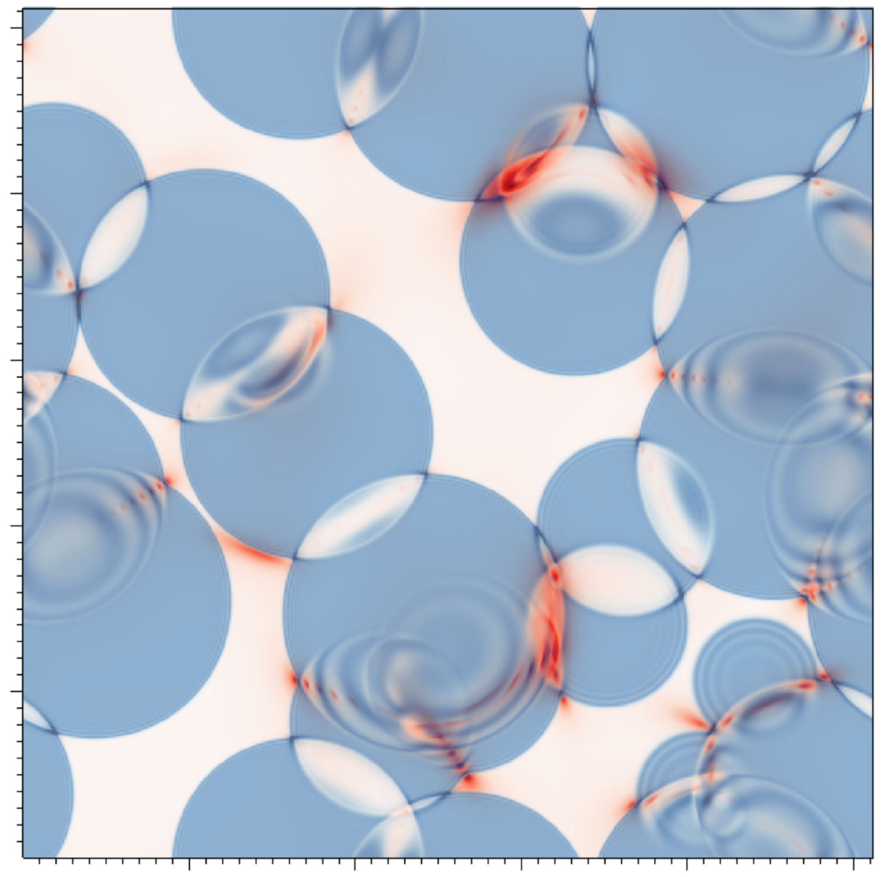
$\delta_{\rm GW} \sim \delta_\chi + \delta_\phi$ $\rightarrow \sim 10^{-5}$

$\delta_{\rm GW} > 10^{-5} \Longrightarrow$ Isocurvature $\rightarrow$ infer existence of an independent light field during inflation

$\delta_\chi \sim \dfrac{H_{\rm inf}}{\chi_0}$ $\rightarrow$ Measure the initial misalignement χ_0 (if $H_{\rm inf}$ is independently known)

In high-scale inflation $H_{\rm inf} \sim 10^{-5} M_{\rm Pl}$, sub-Planckian $\chi_0 \rightarrow \delta_\chi > 10^{-5}$

Energy density in GWB from PT (2)



Power released in bubble collision

$$\frac{dE_{\rm GW}}{dt} \sim G_N \left(\frac{d^3Q}{dt^3}\right)^2$$

Quadrapole moment

$$Q \sim \rho_{\rm lat} r^5 \to \frac{d^3Q}{dt^3} \sim \rho_{\rm lat}\frac{r^5}{(\Delta t_{\rm PT})^3}$$

Typical time scale /length scale (Duration of the PT)

$$r \sim \Delta t_{\rm PT} \equiv \beta^{-1}$$

GW energy density released in bubble collision

$$\rho_{\rm GW} \sim \frac{dE_{\rm GW}}{dt}\frac{\Delta t_{\rm PT}}{r^3} \sim \frac{G_N \rho_{\rm lat}^2}{\beta^2} \xrightarrow{G_{\rm N}\,\rho_{\rm total} \sim H^2} \boxed{\rho_{GW} \sim \left(\frac{H}{\beta}\right)^2 \left(\frac{\rho_{\rm lat}}{\rho_{\rm total}}\right)^2 \rho_{\rm total}}$$

Detectability of anisotropy with future GW detectors

Strong PT : $\beta = 10\,H_{\rm PT}$, $\alpha \approx 1$, $v_{\rm wall} \to 1$

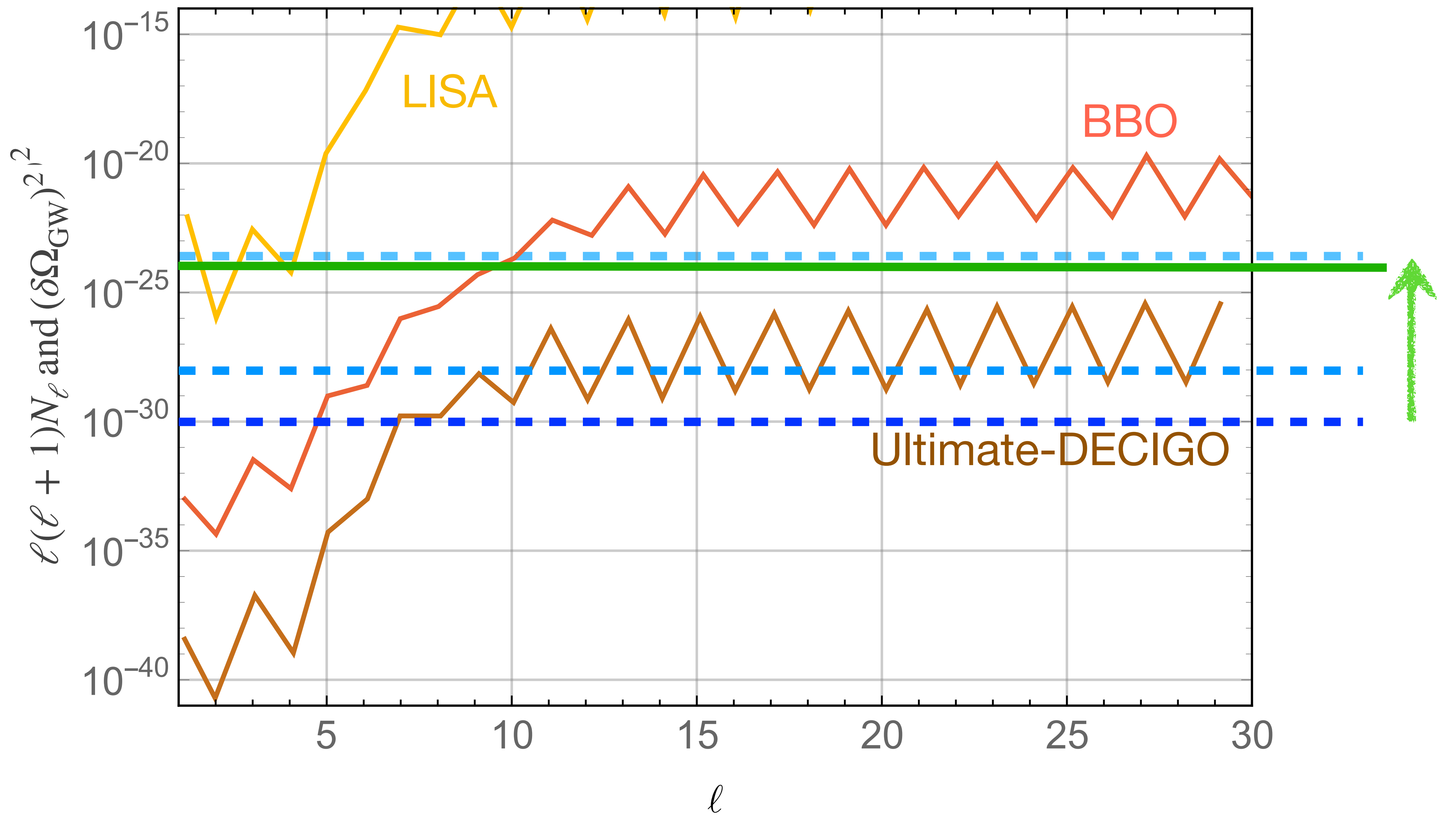
Best case: $f_{\rm PT}\delta_\chi \sim 4 \times 10^{-5}$

no additional cost in $\delta\Omega_{\rm GW}$

1) $\delta_\chi \sim 10^{-4}$, $f_{\rm PT} \sim 4 \times 10^{-1} \to (\delta\Omega_{\rm GW})^2 \sim 10^{-24}$

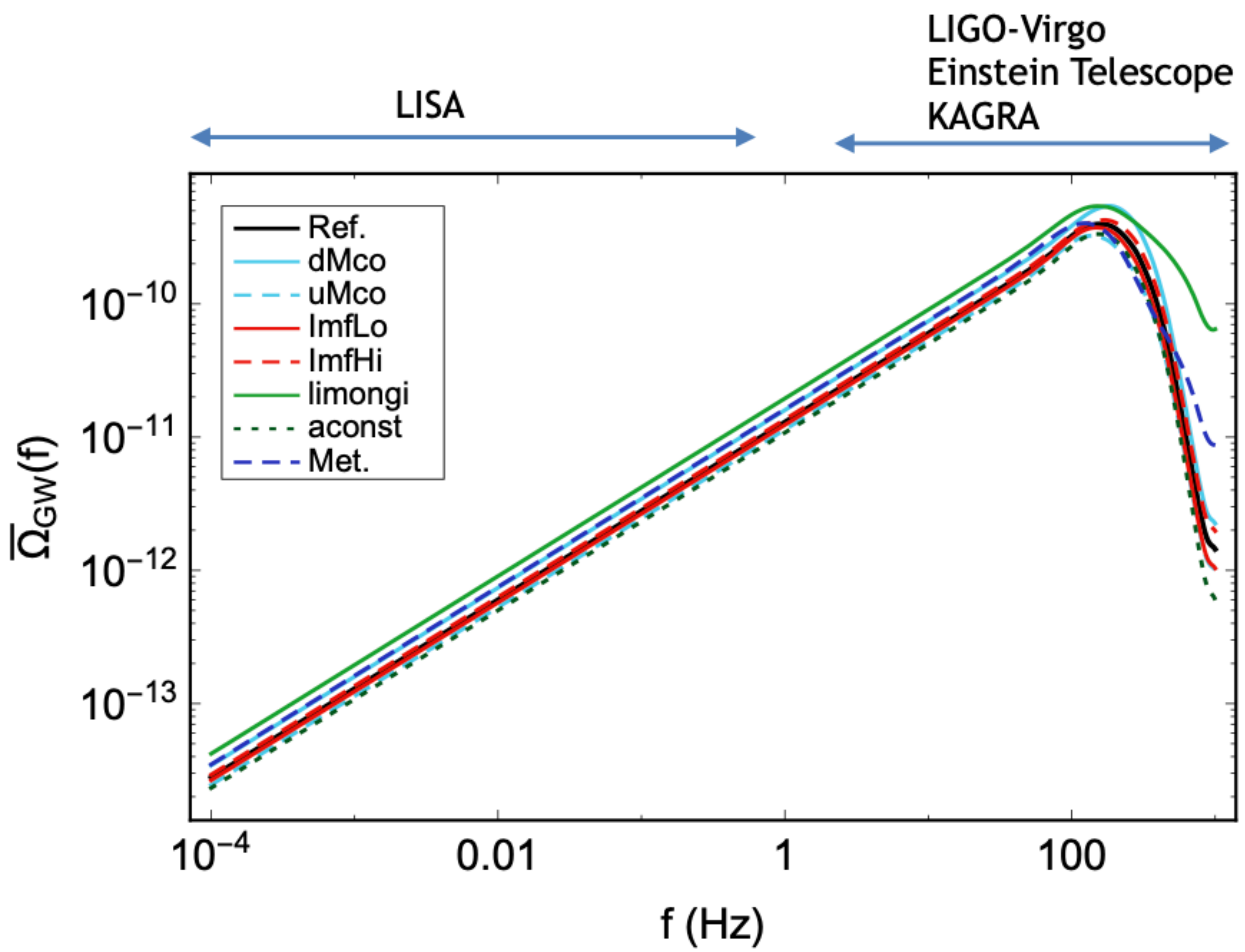
2) $\delta_\chi \sim 10^{-2}$, $f_{\rm PT} \sim 4 \times 10^{-3} \to (\delta\Omega_{\rm GW})^2 \sim 10^{-24}$

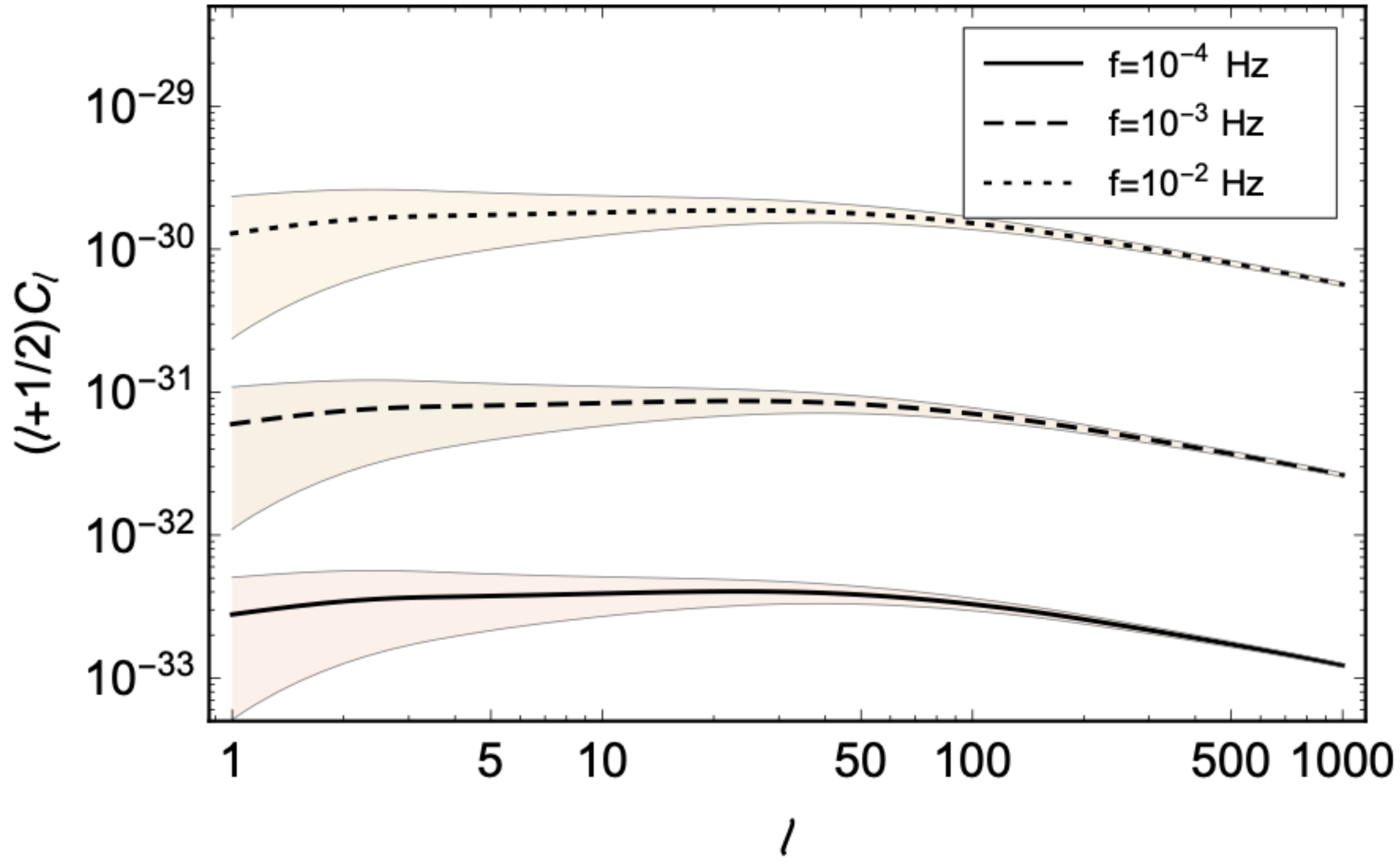
3) $\delta_\chi \sim 0.1$, $f_{\rm PT} \sim 4 \times 10^{-4} \to (\delta\Omega_{\rm GW})^2 \sim 10^{-24}$



Astrophysical foregrounds in mHz range

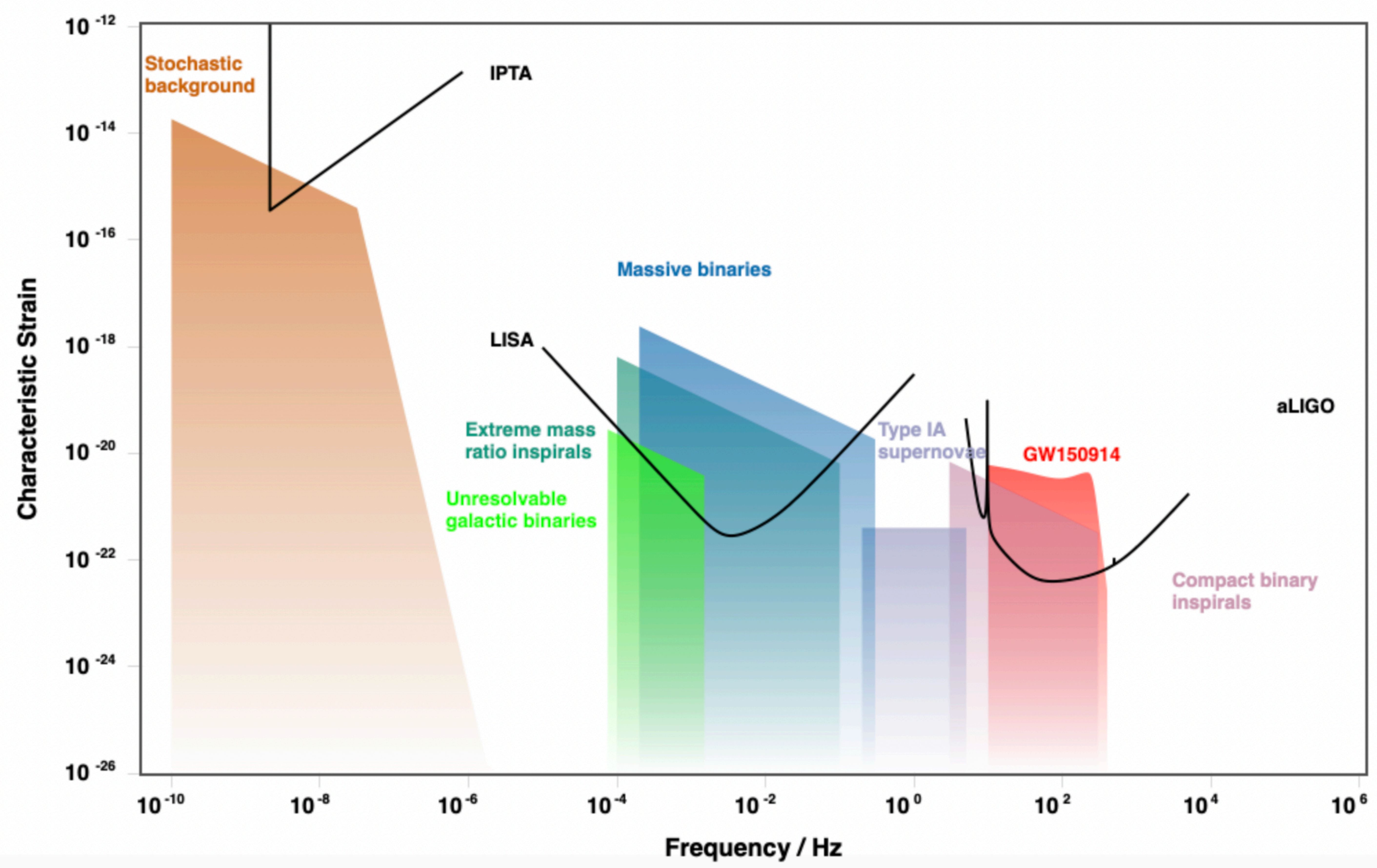
Inspiraling stellar-mass BH





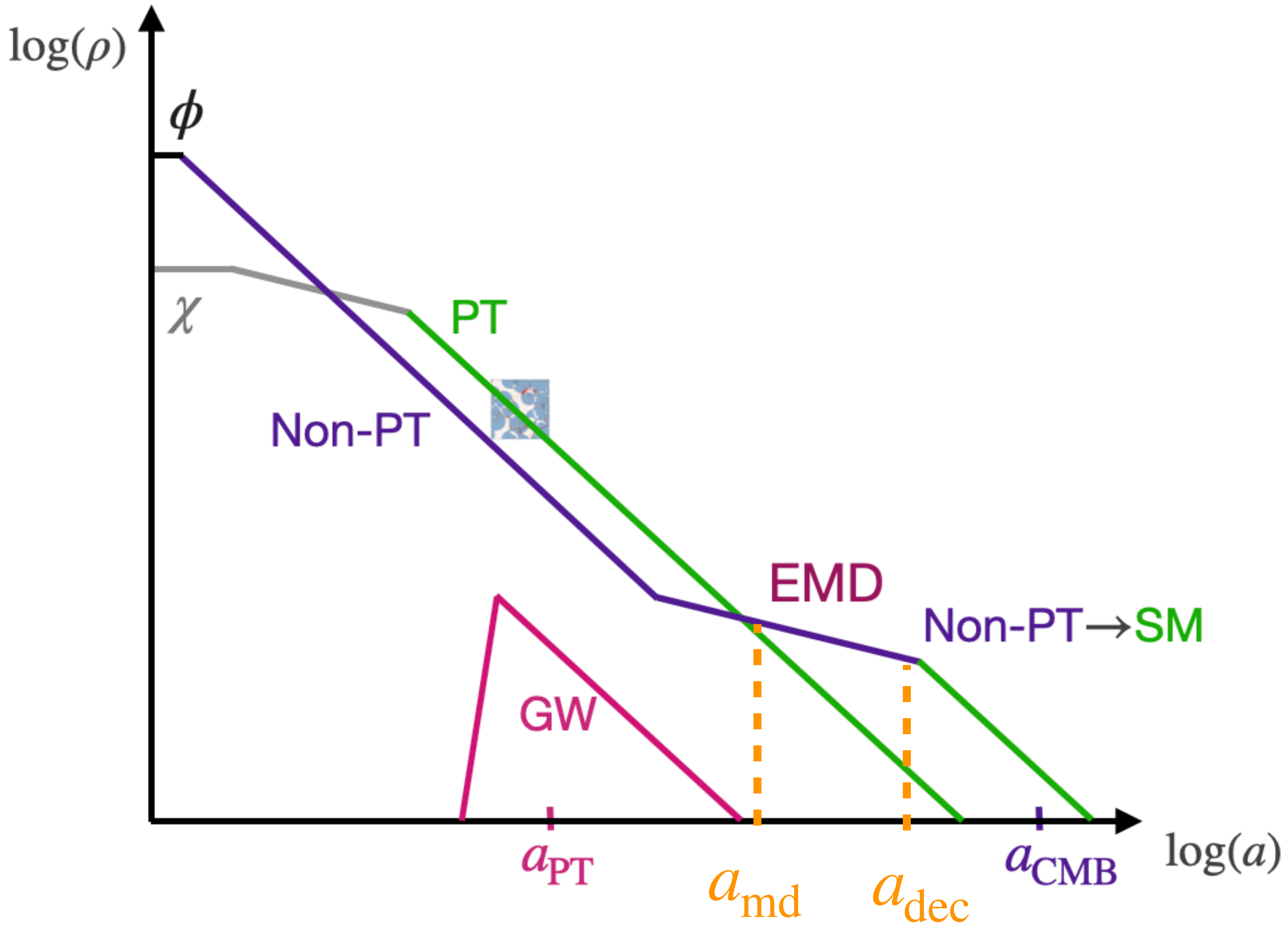
Giulia Cusin, Irina Dvorkin, Cyril Pitrou, Jean-Philippe Uzan: 1904.07757v2

Also see: 2201.08782v from LISA working group



rhcole.com/apps/GWplotter/

Constraints on eMD model: small scale structure



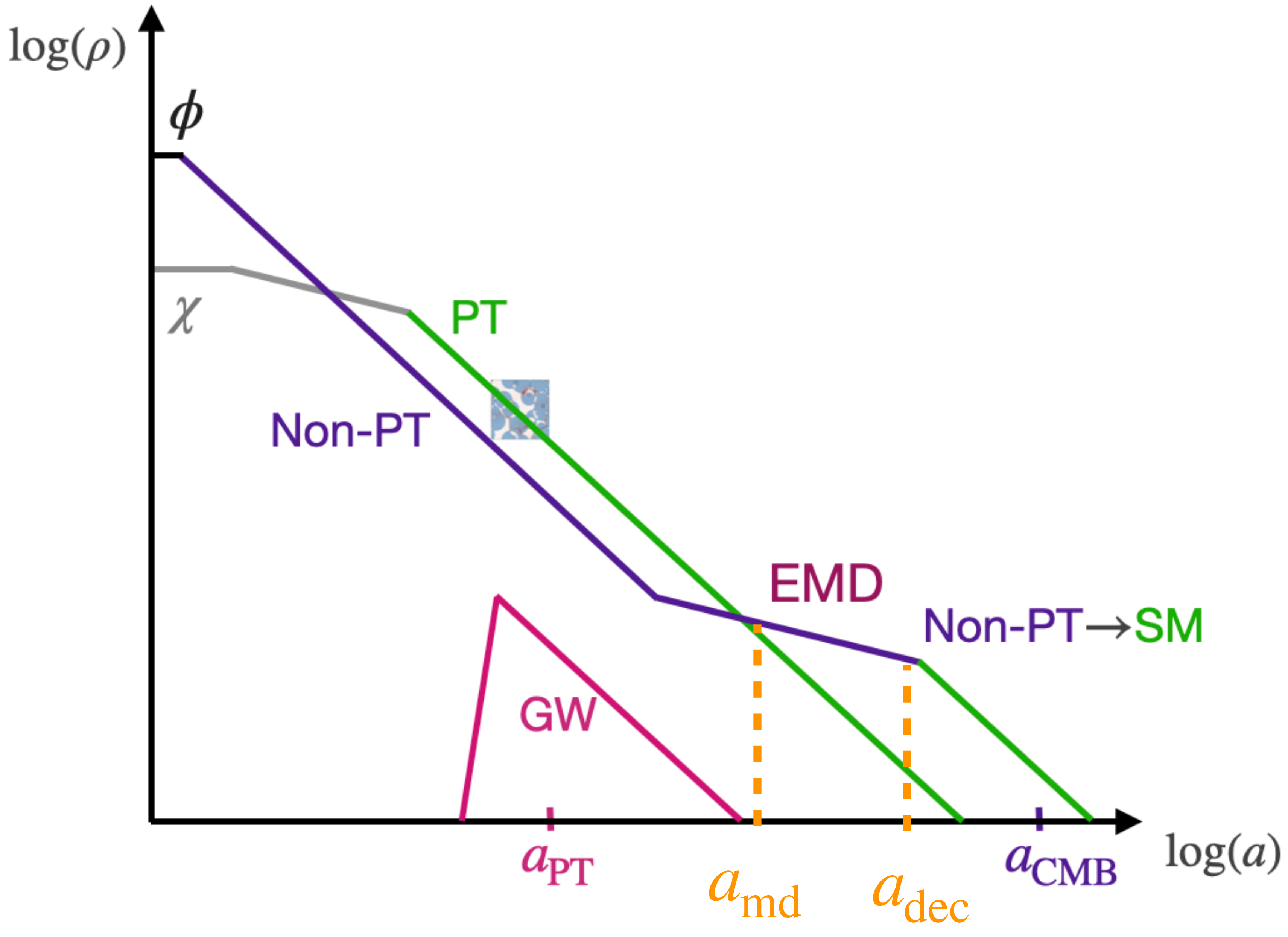
During eMD, $\delta_{\rm mat} \propto a$, could form structures on small scales with potential observational constraints

However, several mechanism erase these large fluctuations after the decay of non-PT sector into SM:

- Damping of radiation perturbation during the decay
  Fan, Özsoy, and Watson ’14
- Frictional damping during kinetic decoupling of DM
  Loeb, Zaldarriaga ’05, Bertschinger ’06
- Free-streaming of DM after kinetic decoupling
  Loeb, Zaldarriaga ’05, Bertschinger ’06
- Silk damping in photons and baryons
  Silk ’68, Hu, Sugiyama ’96

Decay before DM decoupling $\rightarrow T_{\rm dec} \gtrsim 100$ GeV

Secondary (induced) GW



$$\frac{a_{\rm dec}}{a_{\rm md}} = f_{\rm PT}^{-1}$$

GW sourced by scalar perturbations at second order, larger contribution from early matter domination

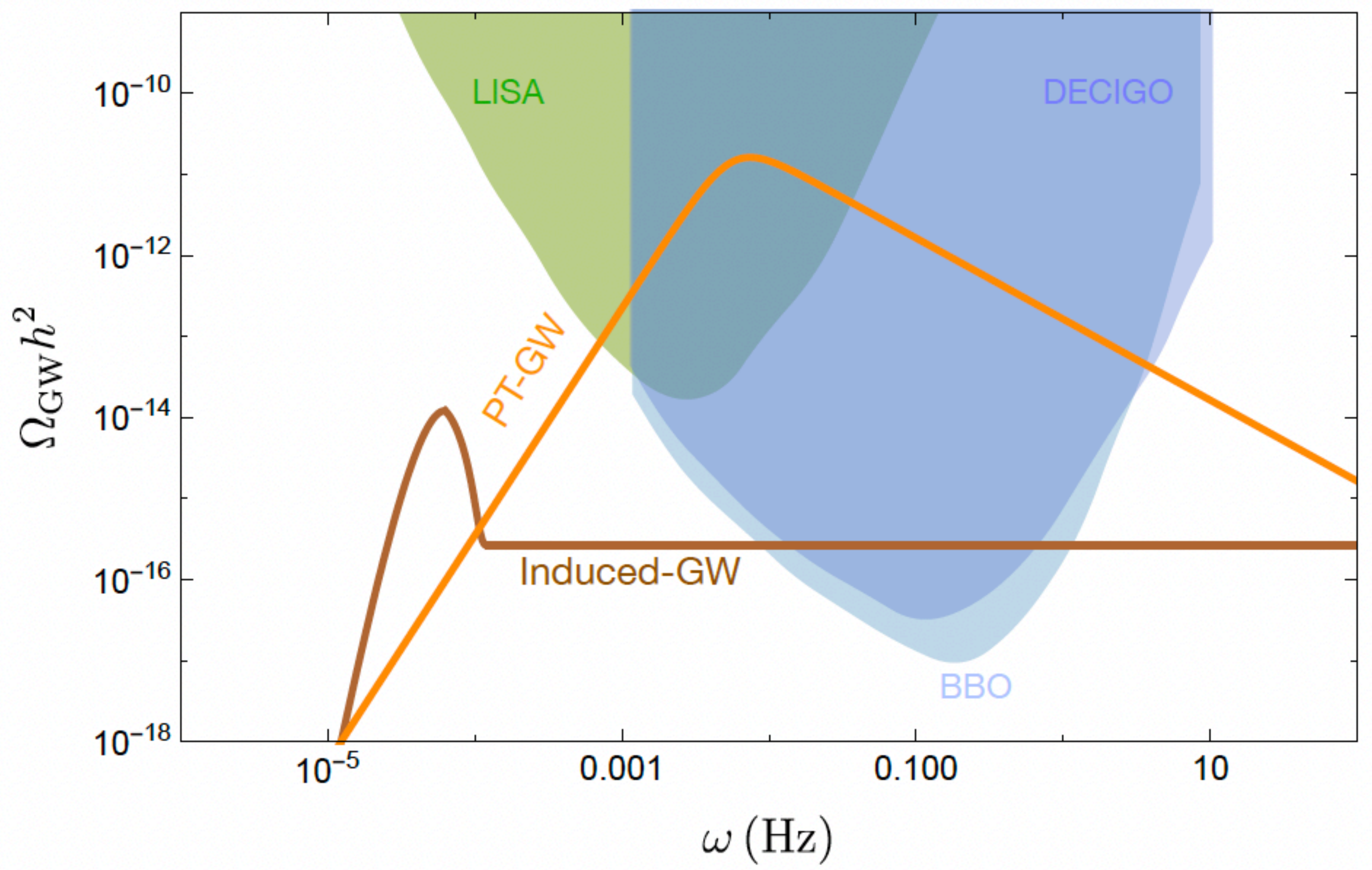
$$(\Omega_{\rm GW}^{\rm sec})_{\rm peak} \sim 10^{-5}\,\frac{a_{\rm dec}}{a_{\rm md}}\,\delta_\chi^4$$

Baumann et al 0703290,
Assadullahi, Wands 0901.0989
Kohri, Terada 1804.08577

eMD imprints unique features in the frequency spectrum of secondary GW.

Gouttenoire, Servant, Simakachorn 2111.01150

Secondary (induced) GW



$\delta_\chi \sim 10^{-2}$, $f_{\rm PT} \sim 10^{-3}$