# Seeing highly anisotropic gravitational wave backgrounds from phase transitions

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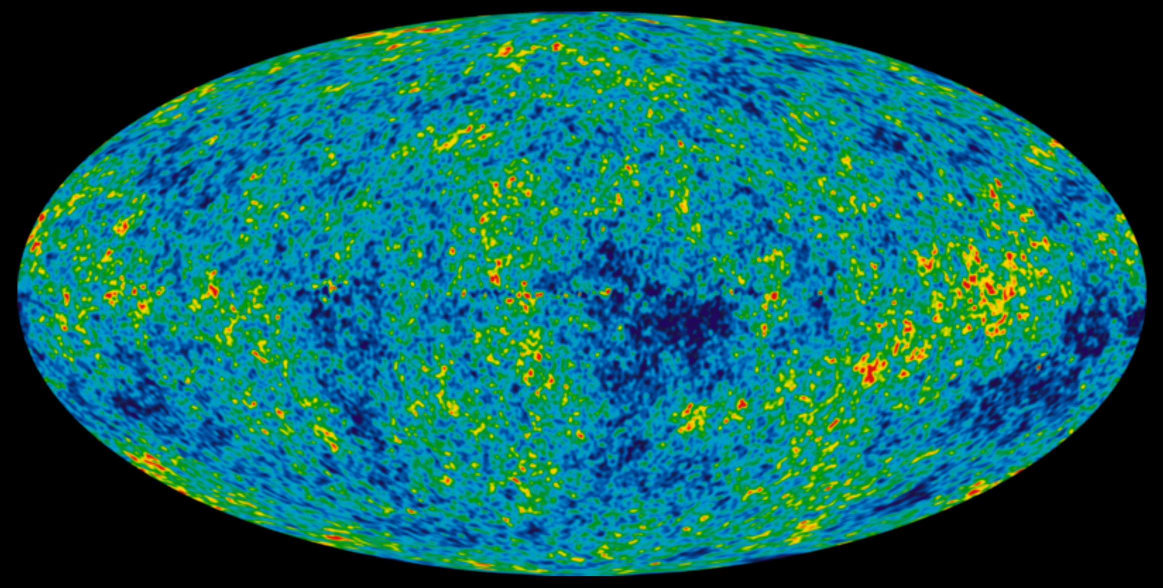
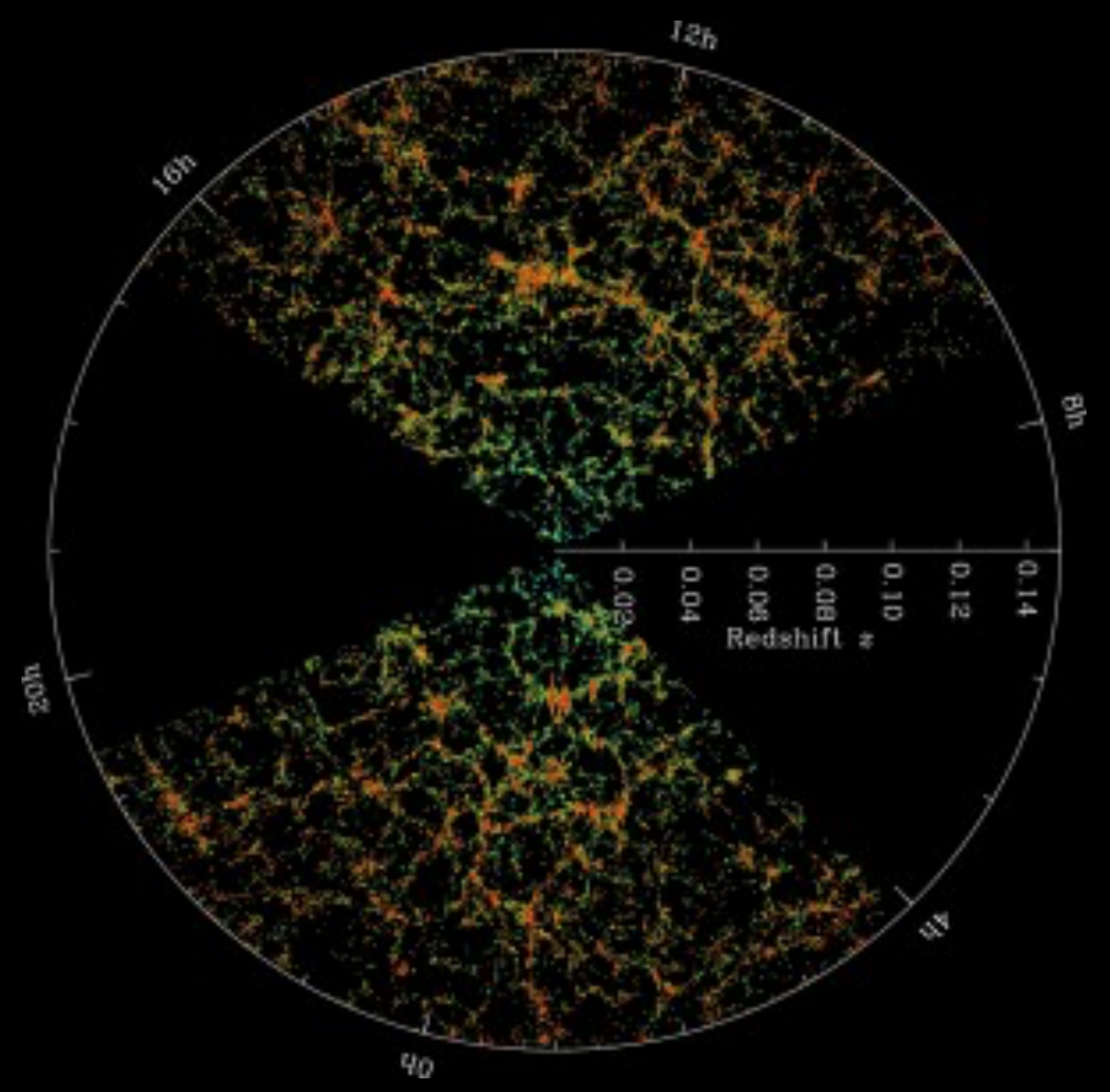
University of Chicago and Fermilab

Based on work with R. Sundrum at University of Maryland, *JHEP* 06 (2023) 029



Email: arushib@uchicago.edu

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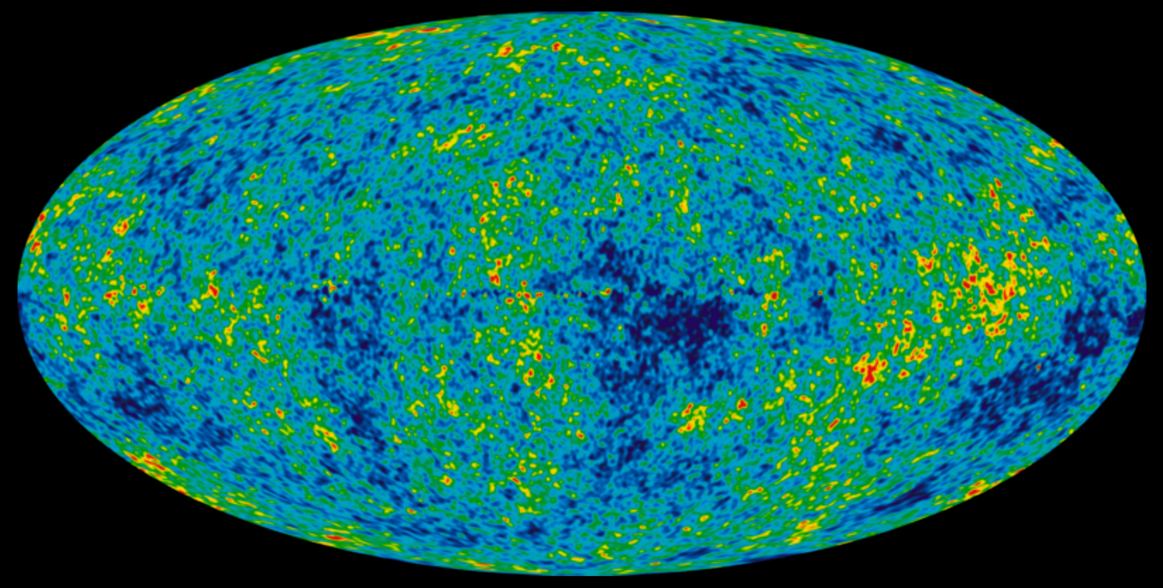
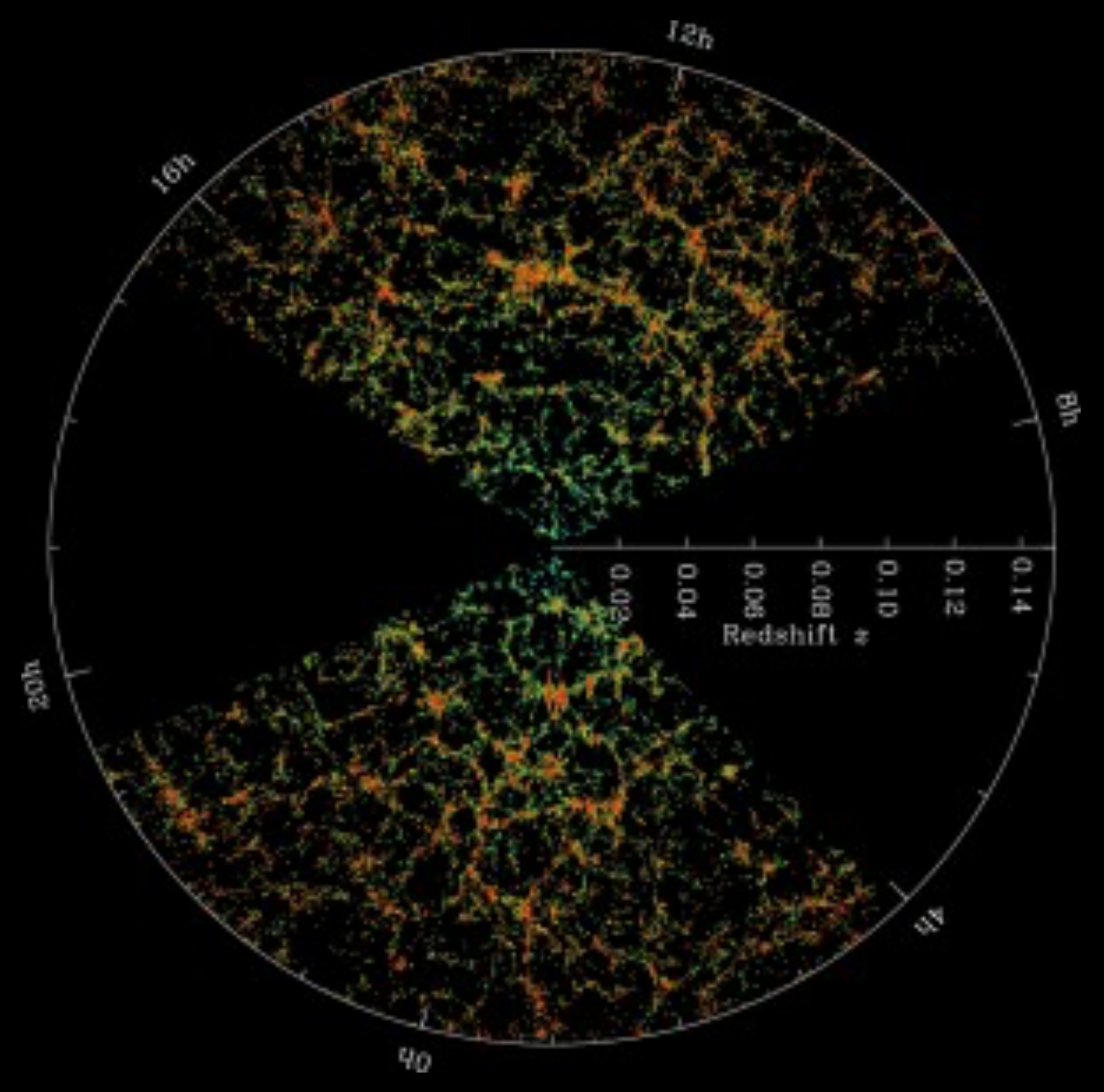
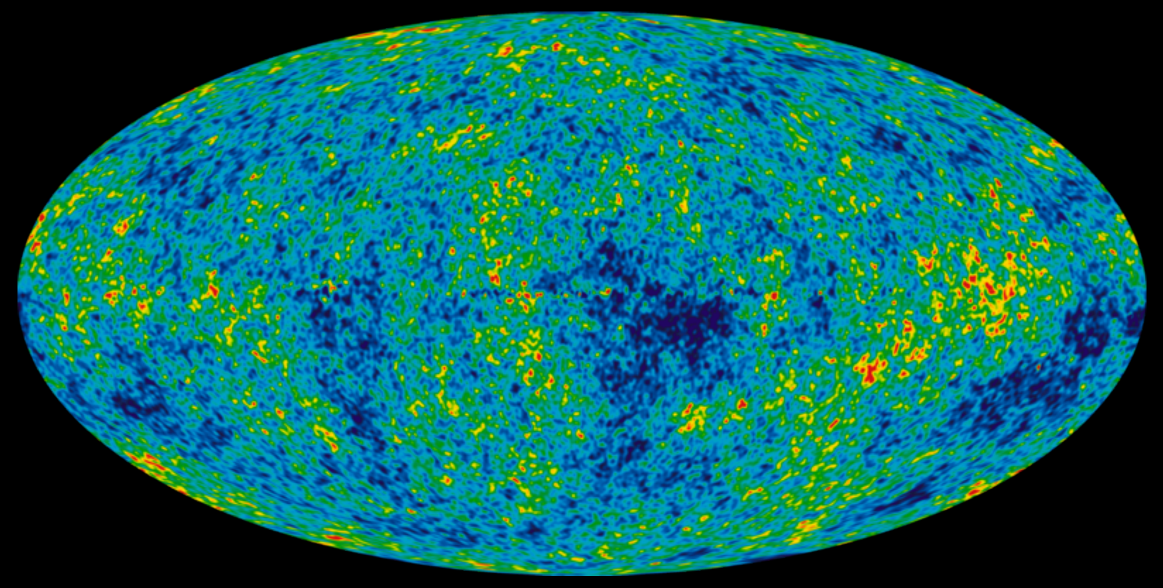
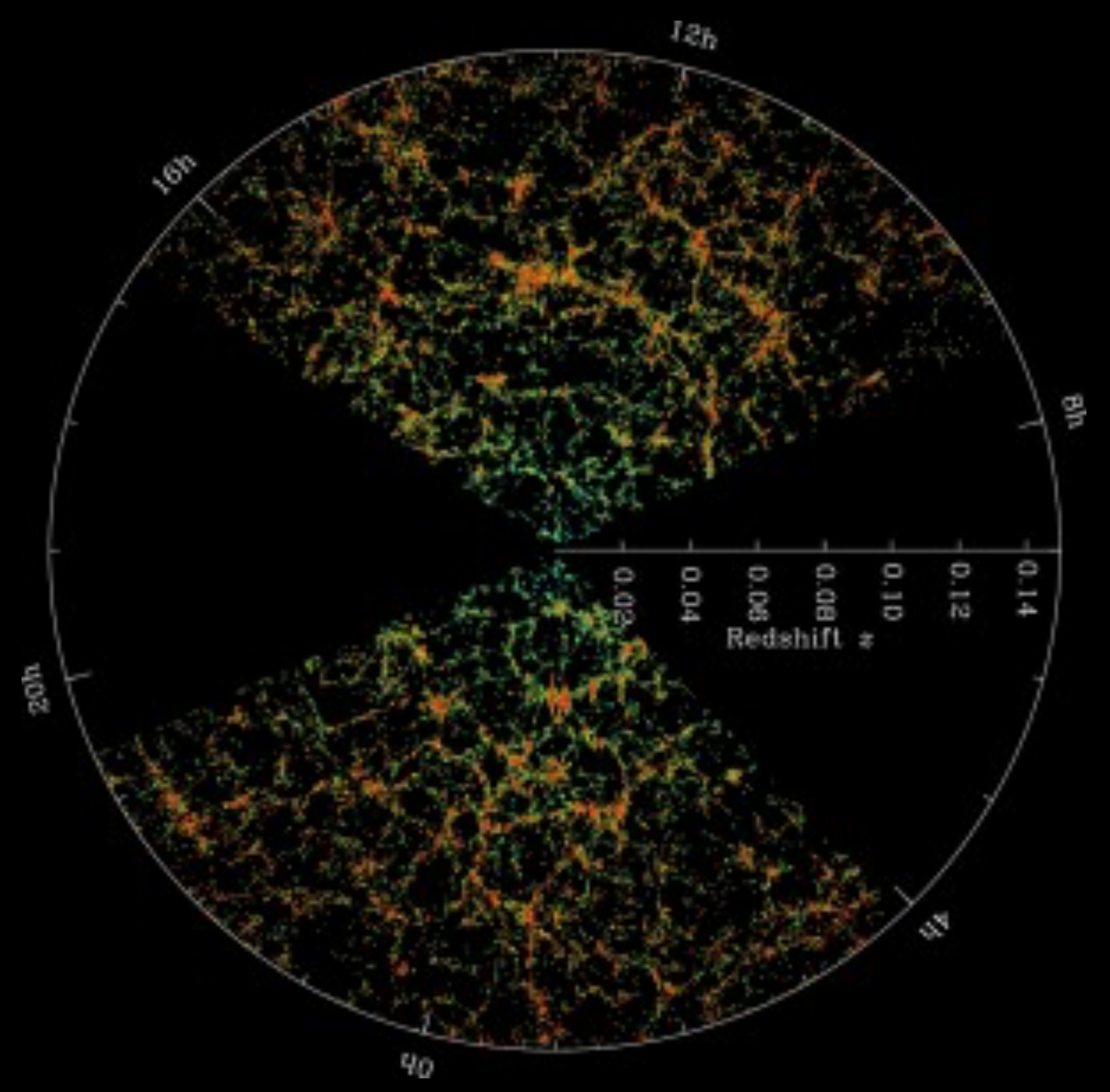





Quantum fluctuations of a scalar field + inflation






Quantum fluctuations of a scalar field + inflation

## Anisotropy maps are windows into inflationary physics

# Adiabatic nature of known datasets

- Current observations tell us that density perturbations in all Standard Model (SM) species and Dark Matter (DM) originate from the same inflationary fluctuation (e.g. the inflaton).

Planck,1807.06211

- Future datasets based SM and DM species (line-intensity maps, C$\nu$B) will also be adiabatic.

- Detection of new inflationary physics in these future maps is already constrained from non-detection in CMB.

- Could there be cosmological anisotropy maps very different from the CMB (dominantly isocurvature)?

# Something that is…

- Copiously produced in the early universe
- Free-streaming (does not thermalize with SM and DM)
- Could be detectable with the technology that we have today

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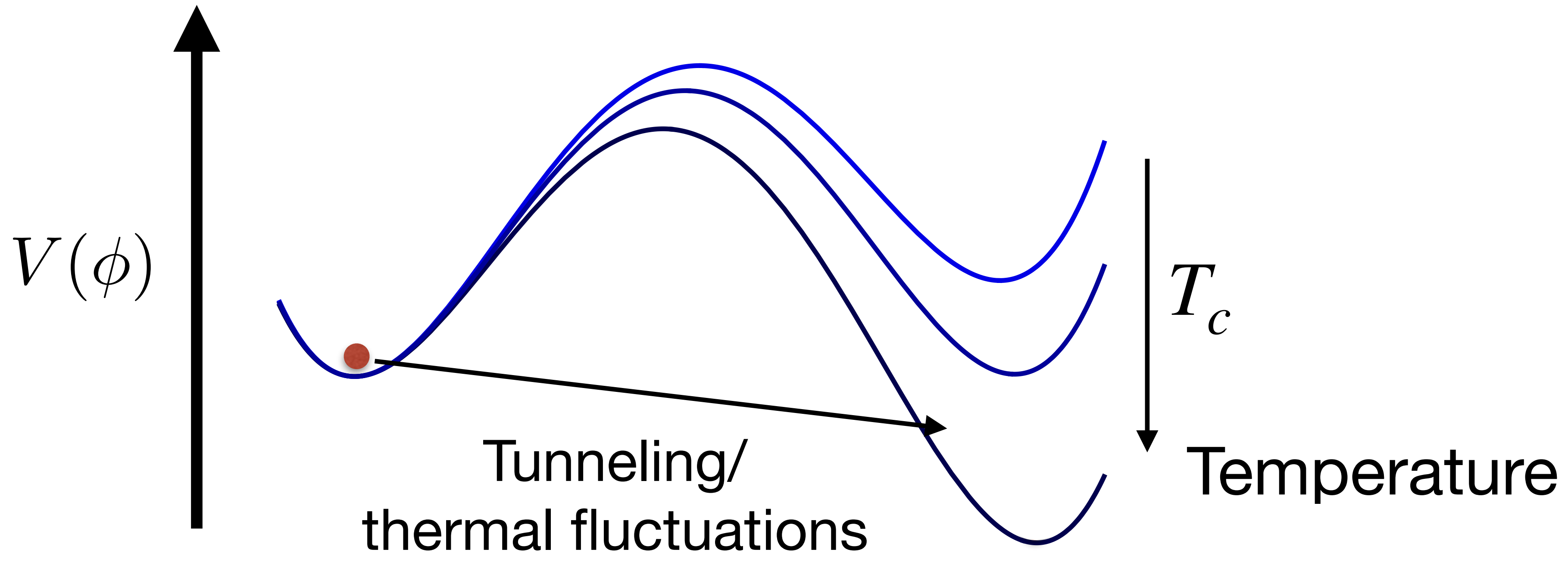
Gravitational waves!

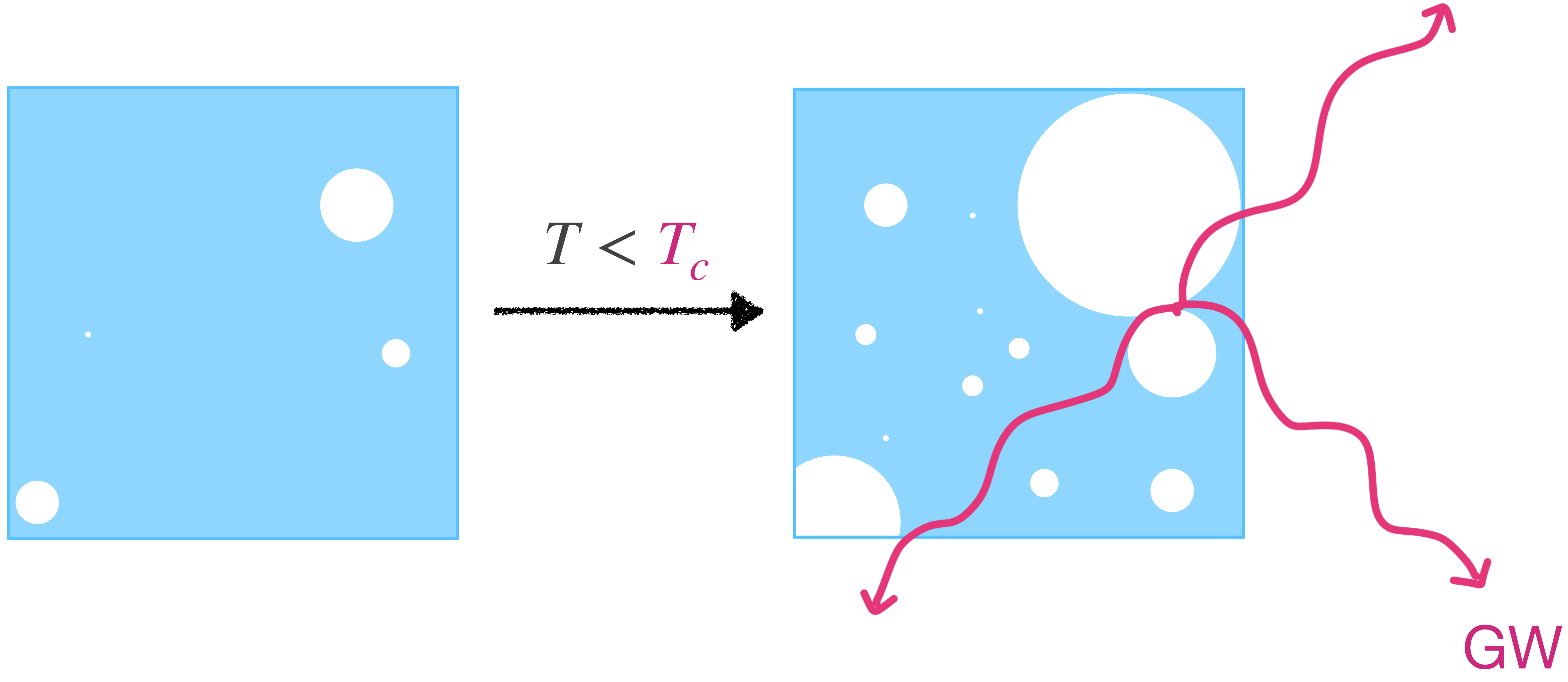
# Outline

- Background: Source and anisotropy of gravitational wave background (GWB)
- A simple model that can produce isocurvature GWB
- Tradeoff: large isocurvature leads to a suppression of the GWB signal
- Our model: weakens this tradeoff, thereby improving detection prospects of highly isocurvature GWB

# Gravitational waves from the early universe

- We focus on first-order phase transitions (PT) as sources of GW.



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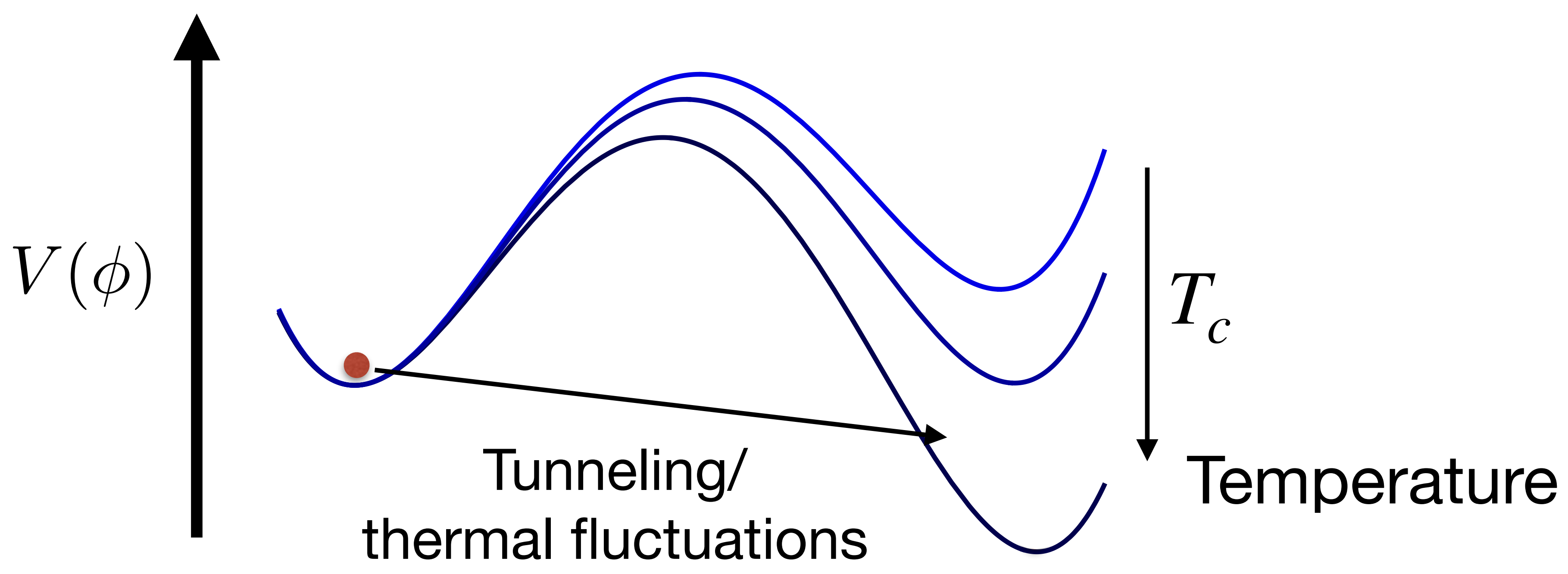
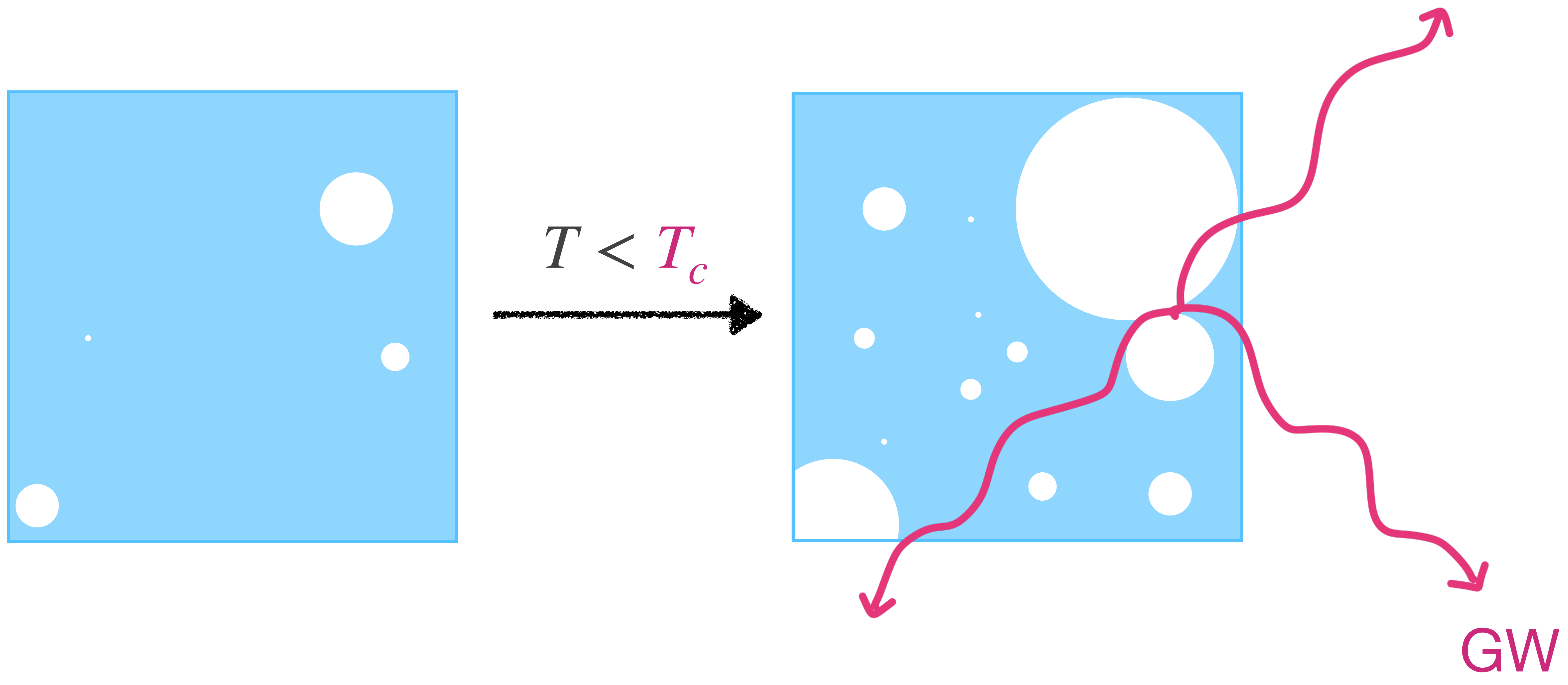
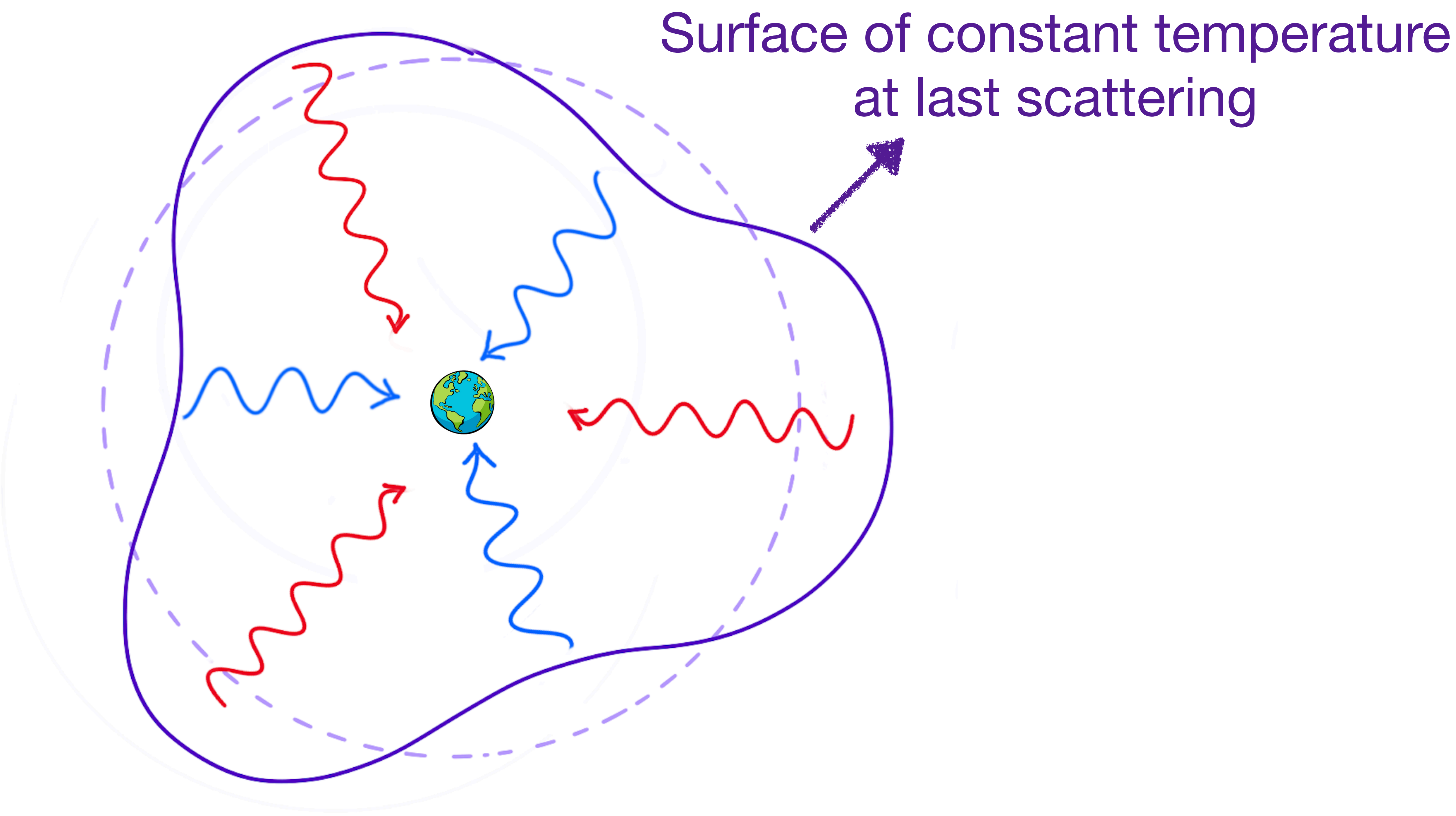


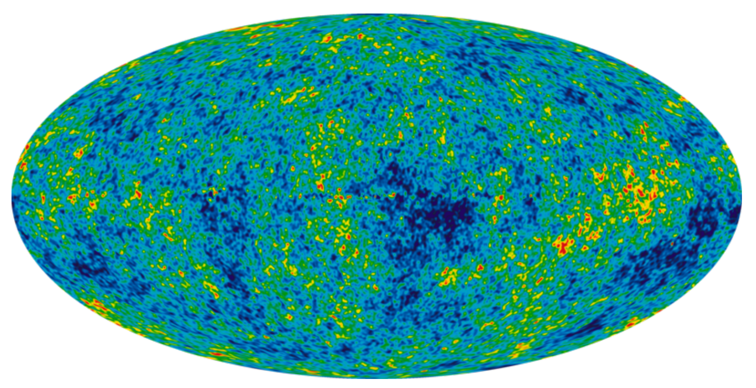




- First order phase transitions are dramatic.

- Phase transitions are “instantaneous”, giving a 2D anisotropy map (analogous to CMB)

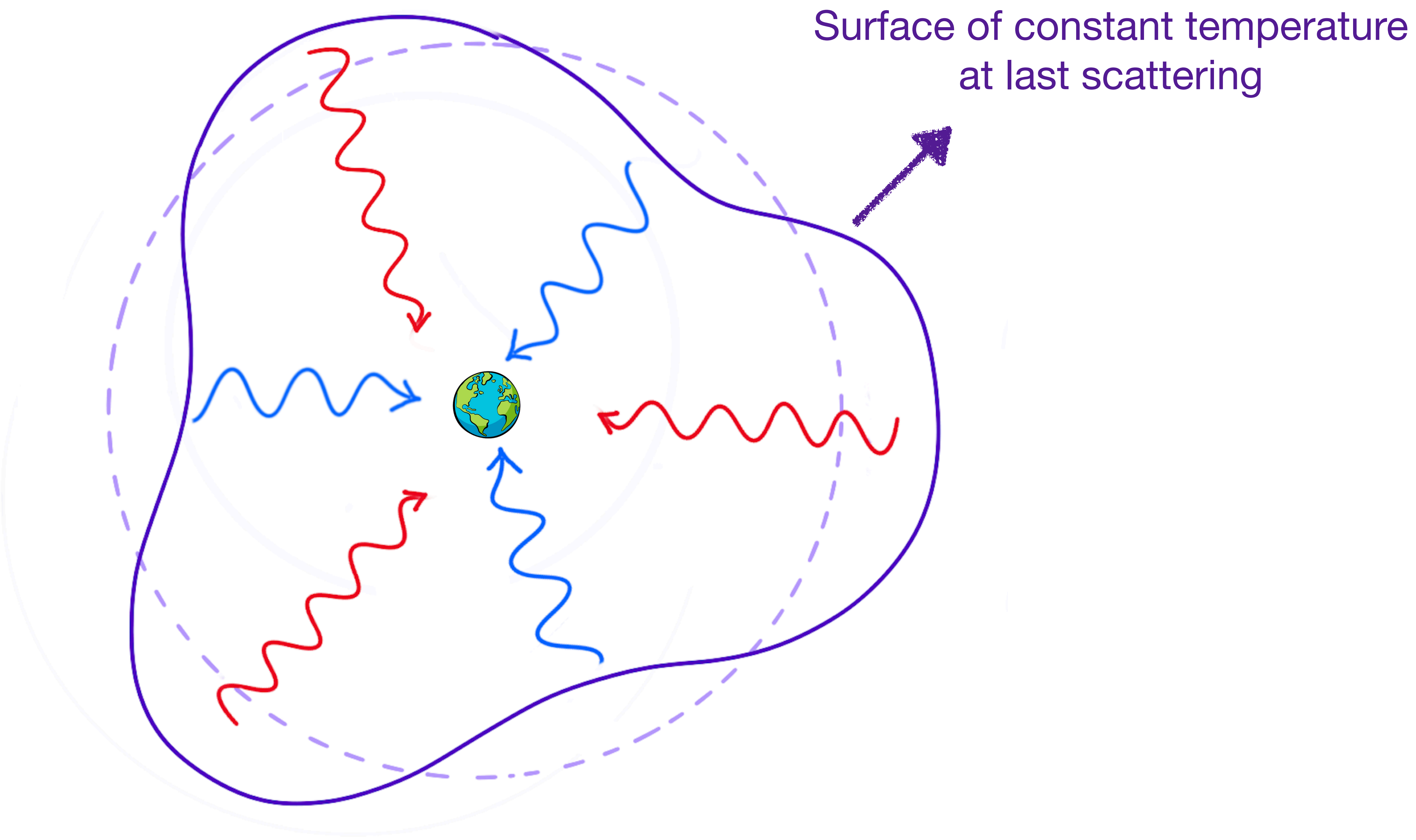
# Recap: CMB anisotropies

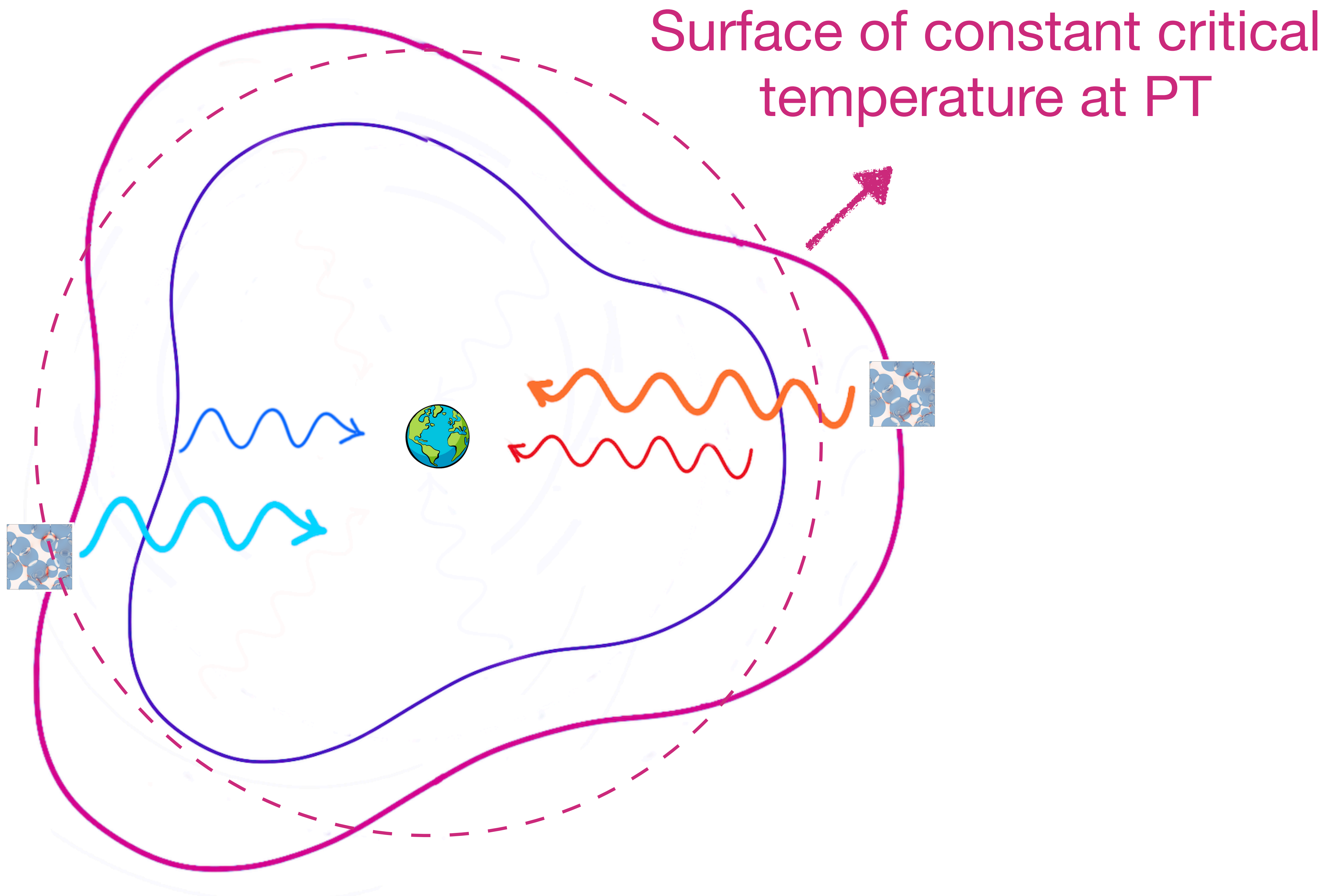


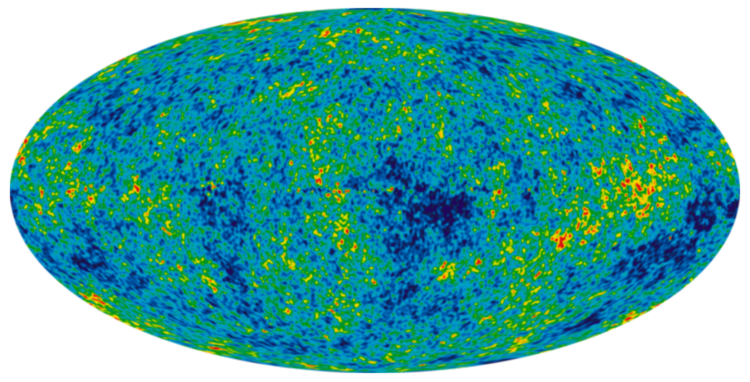



$$\delta_{\rm CMB} \equiv \frac{\Delta T}{\bar{T}} \sim 10^{-5}$$

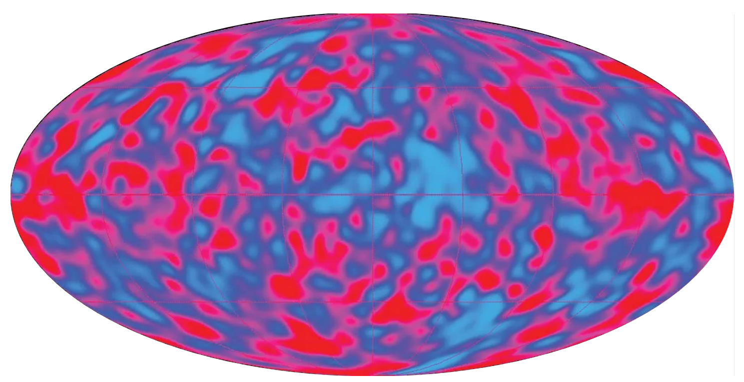
# GWB anisotropies



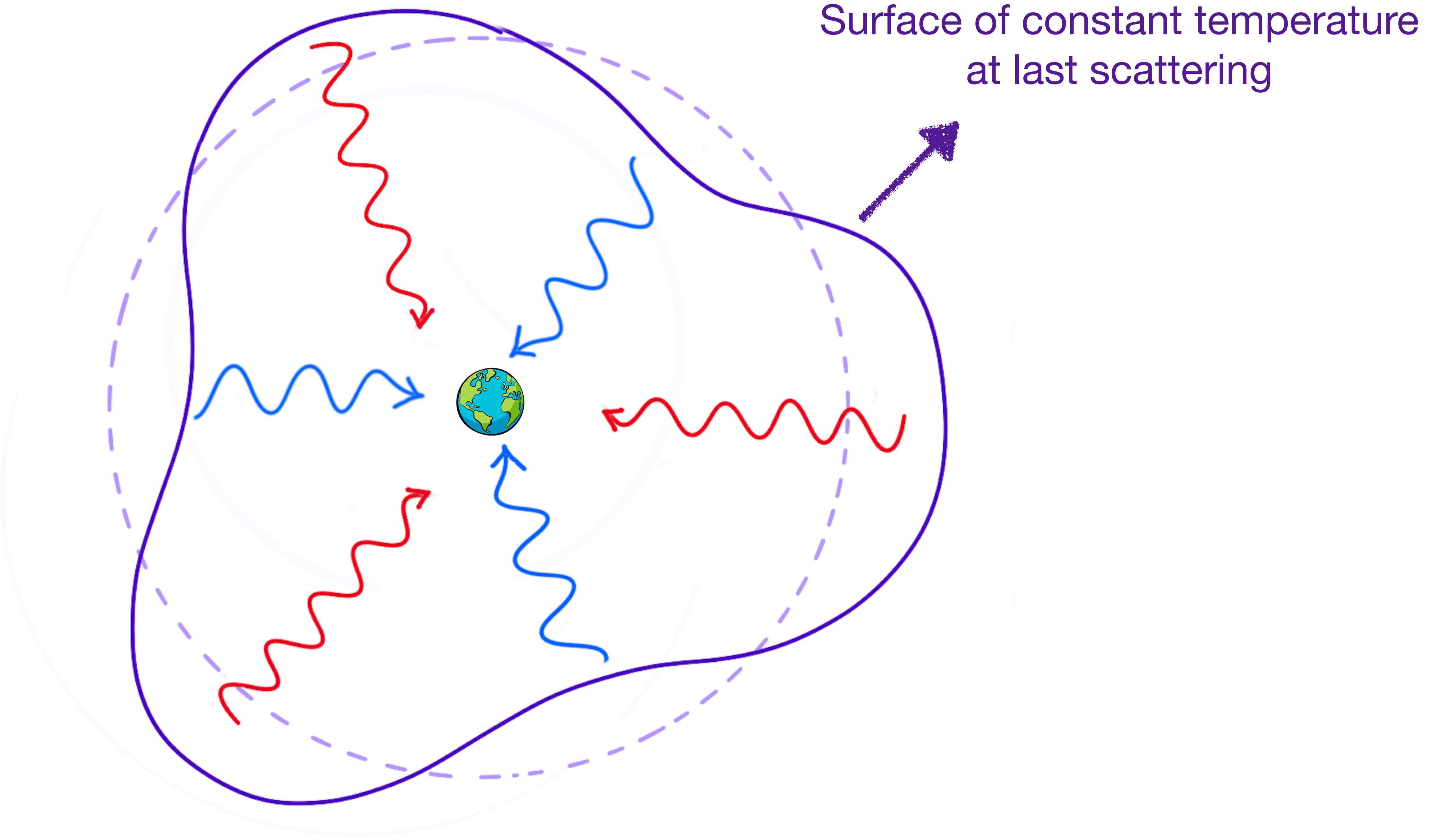



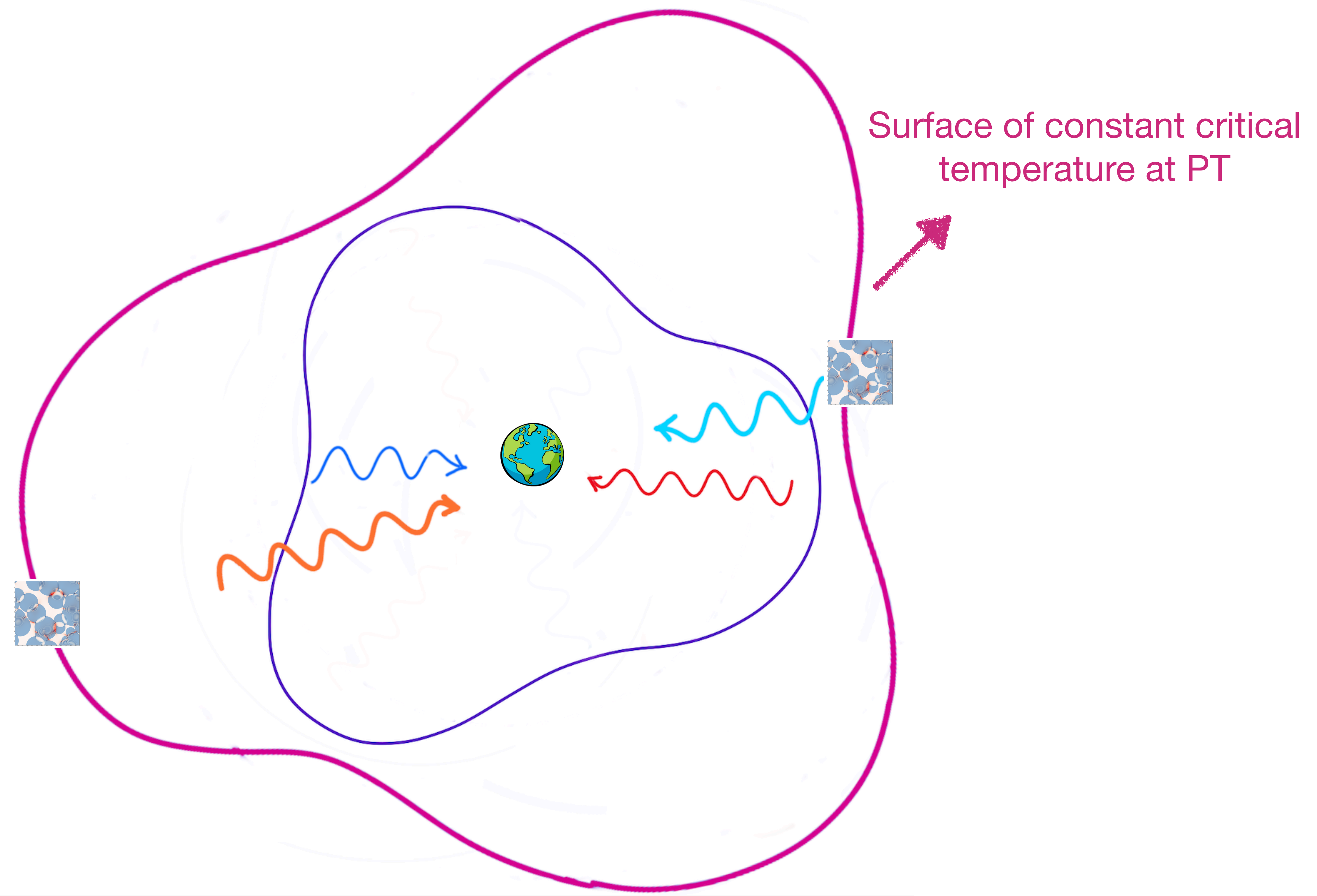
$$\delta_{\mathrm{CMB}} \equiv \frac{\Delta T}{\bar{T}} \sim 10^{-5}$$

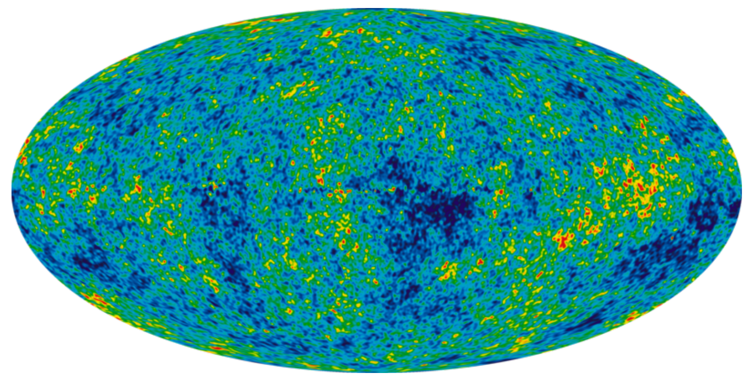


$$\delta_{\mathrm{GW}} \equiv \frac{\Delta \rho_{\mathrm{GW}}}{\bar{\rho}_{\mathrm{GW}}} \sim 10^{-5}$$

# Isocurvature GWB anisotropy



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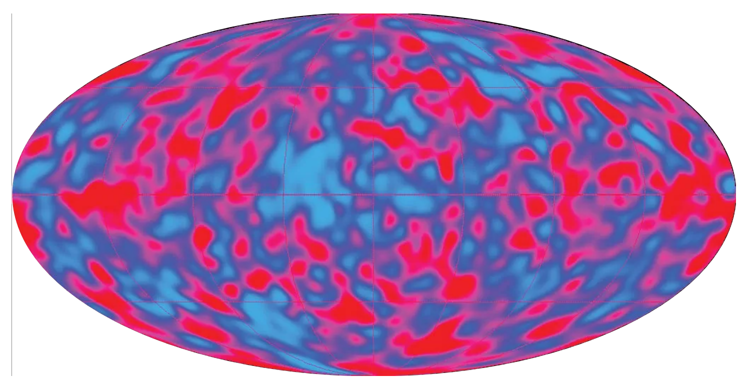
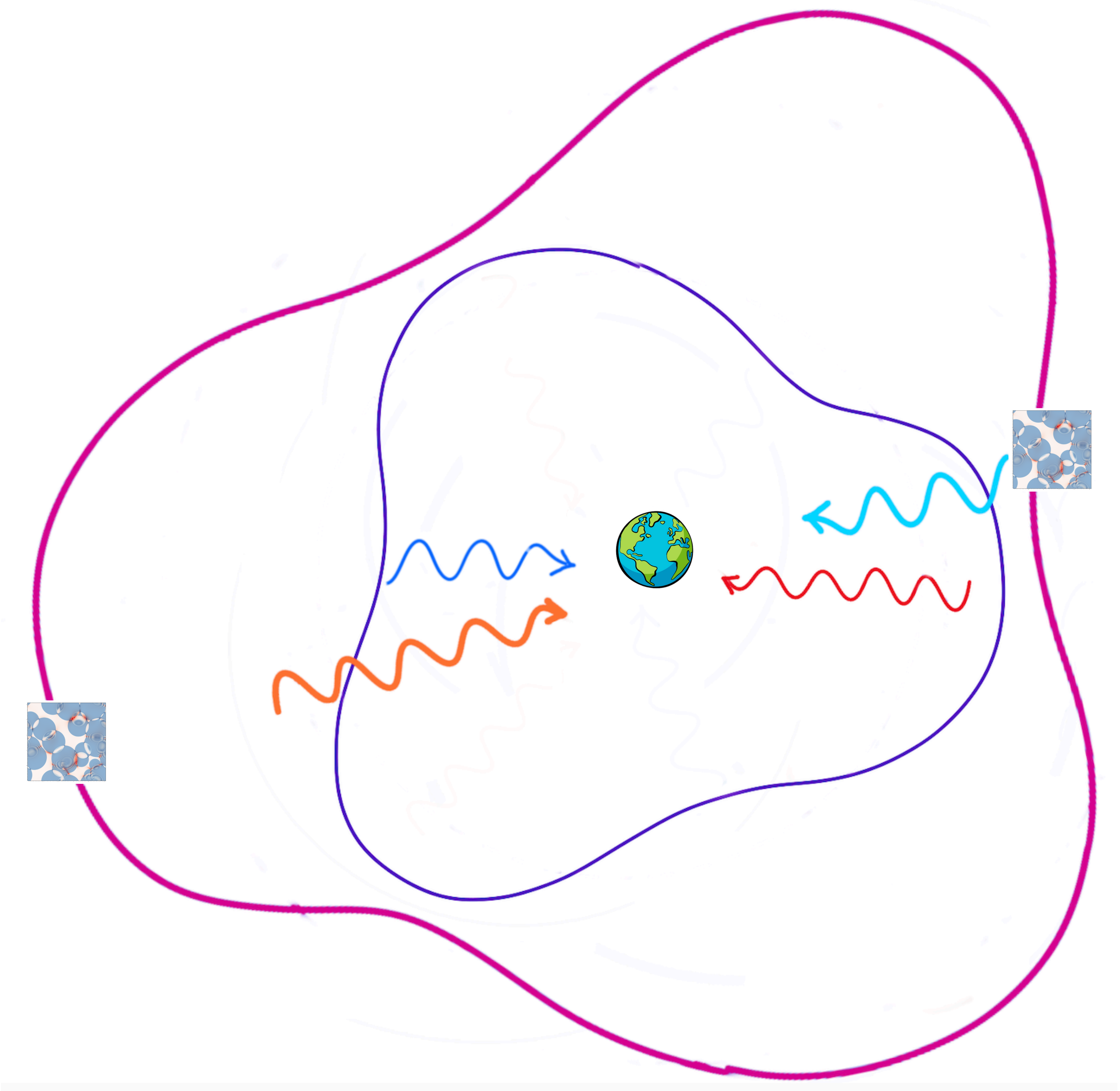


$$\delta_{\rm GW} \equiv \frac{\Delta \rho_{\rm GW}}{\bar{\rho}_{\rm GW}} \neq 10^{-5}$$

# Isocurvature GWB anisotropy



Uncorrelated large-scale fluctuations → another light field from inflation

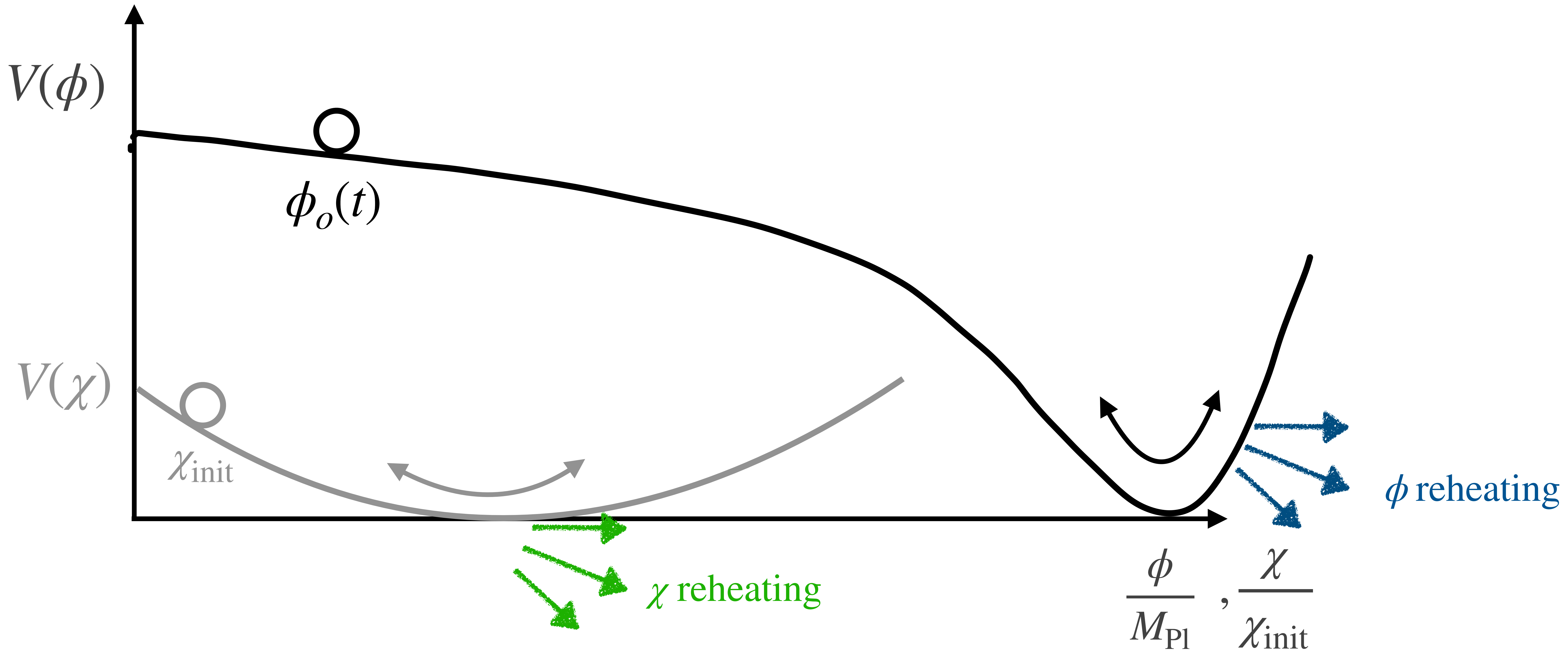
Interesting features such as tilt, scale-invariance breaking feature, non-Gaussianity → new signatures of physics from inflation

L. Valbusa Dall'Armi et al 2021

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

**AB**, R. Sundrum 2022

# A new light field from inflation: ALP ($\chi$)



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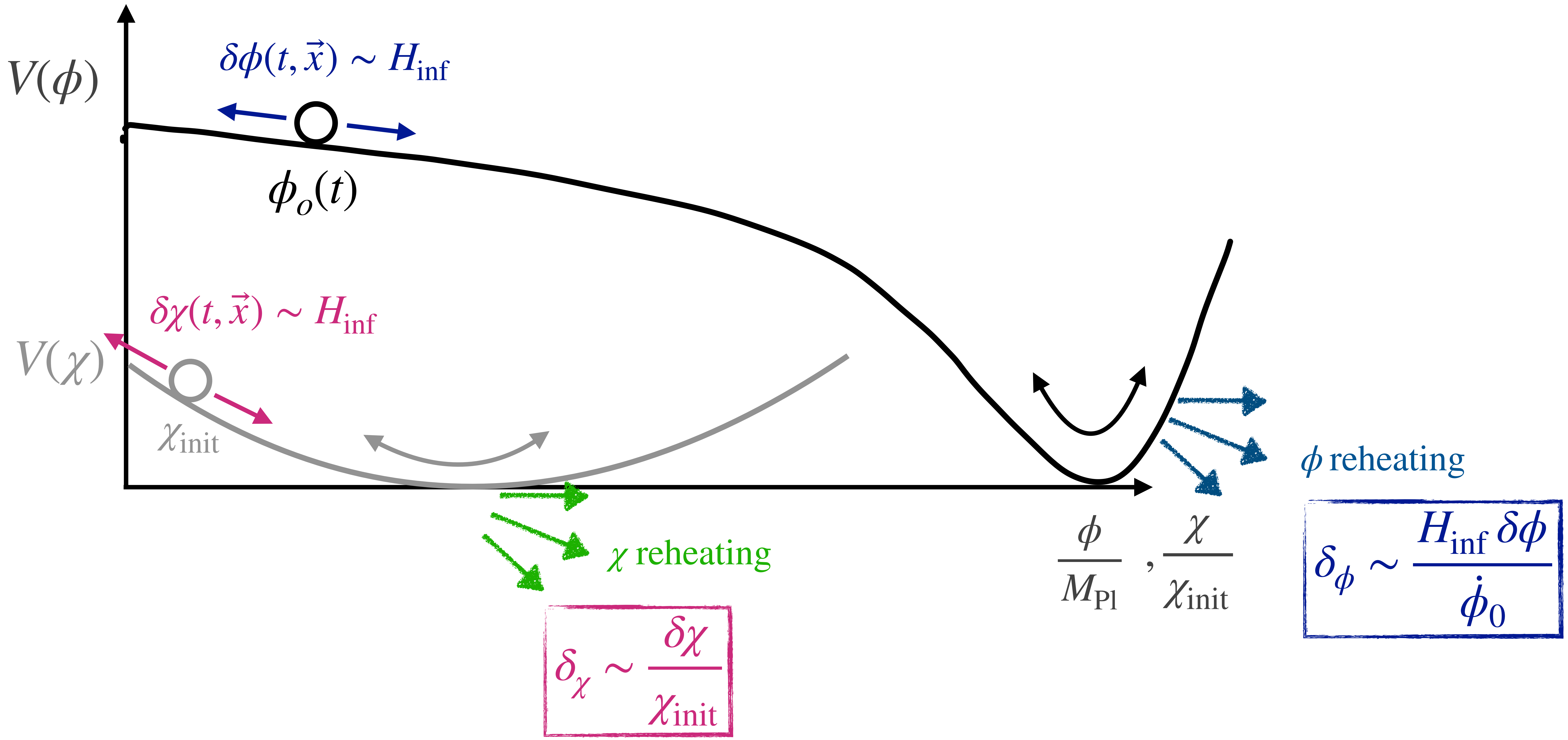
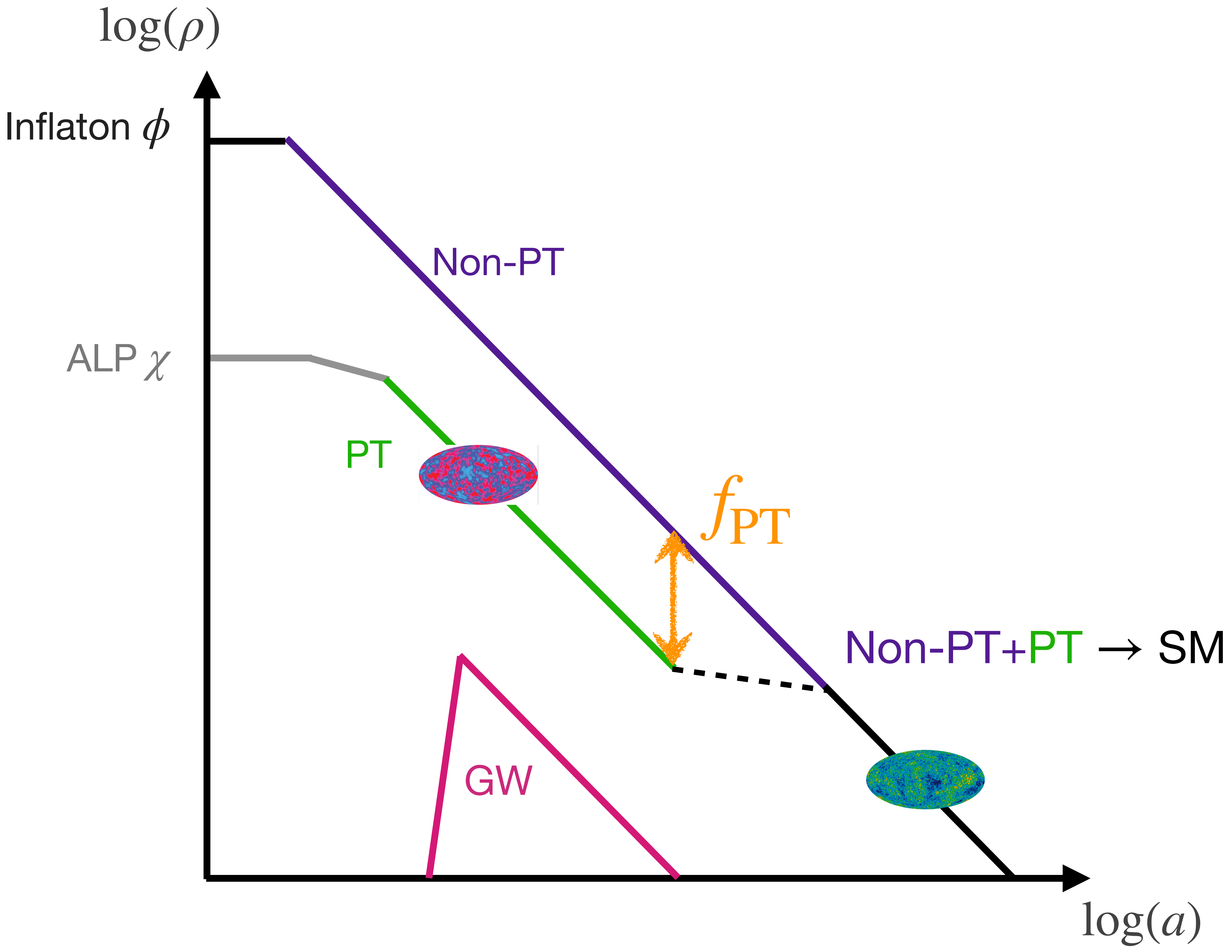


# A model of isocurvature GWB

Geller, Hook, Sundrum, Tsai 1803.10780



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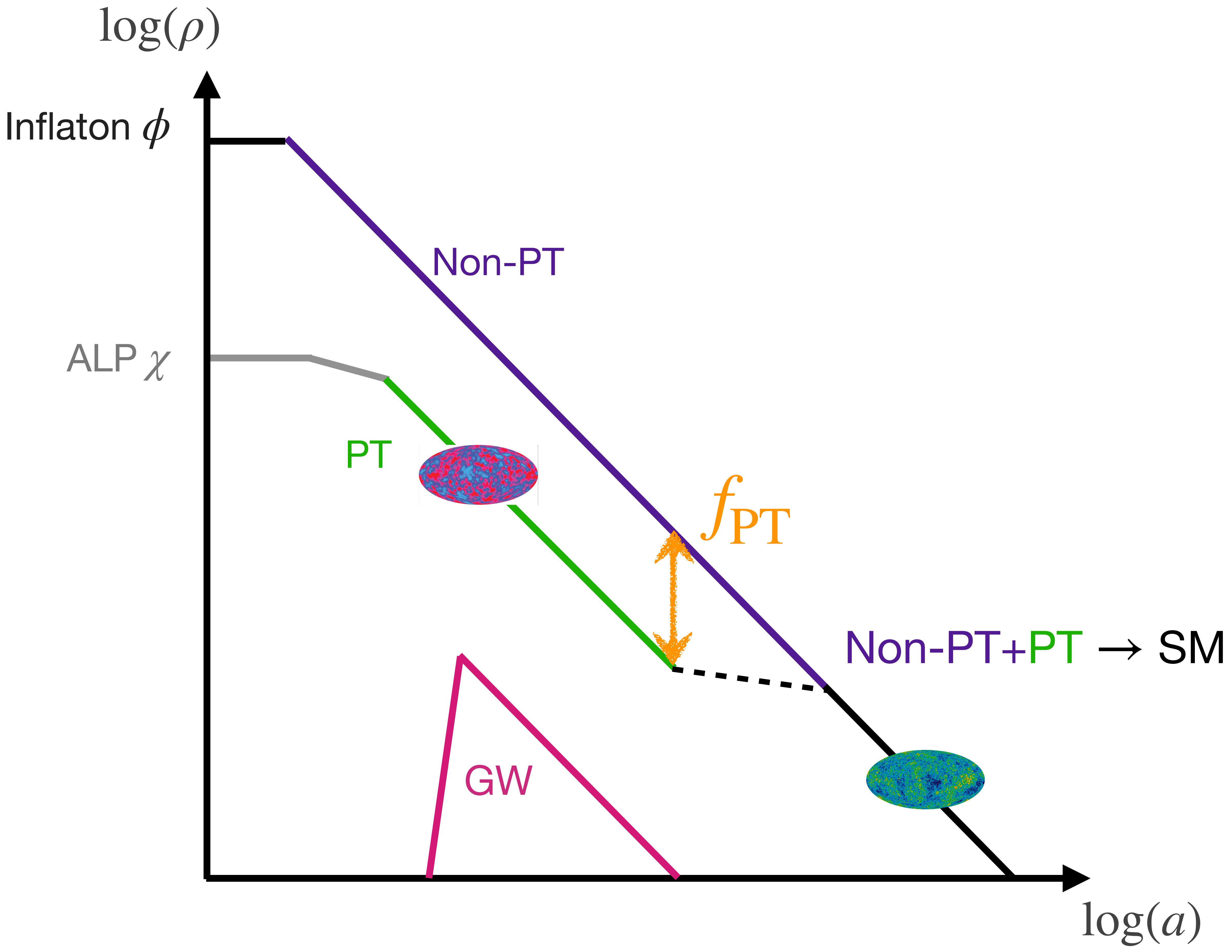


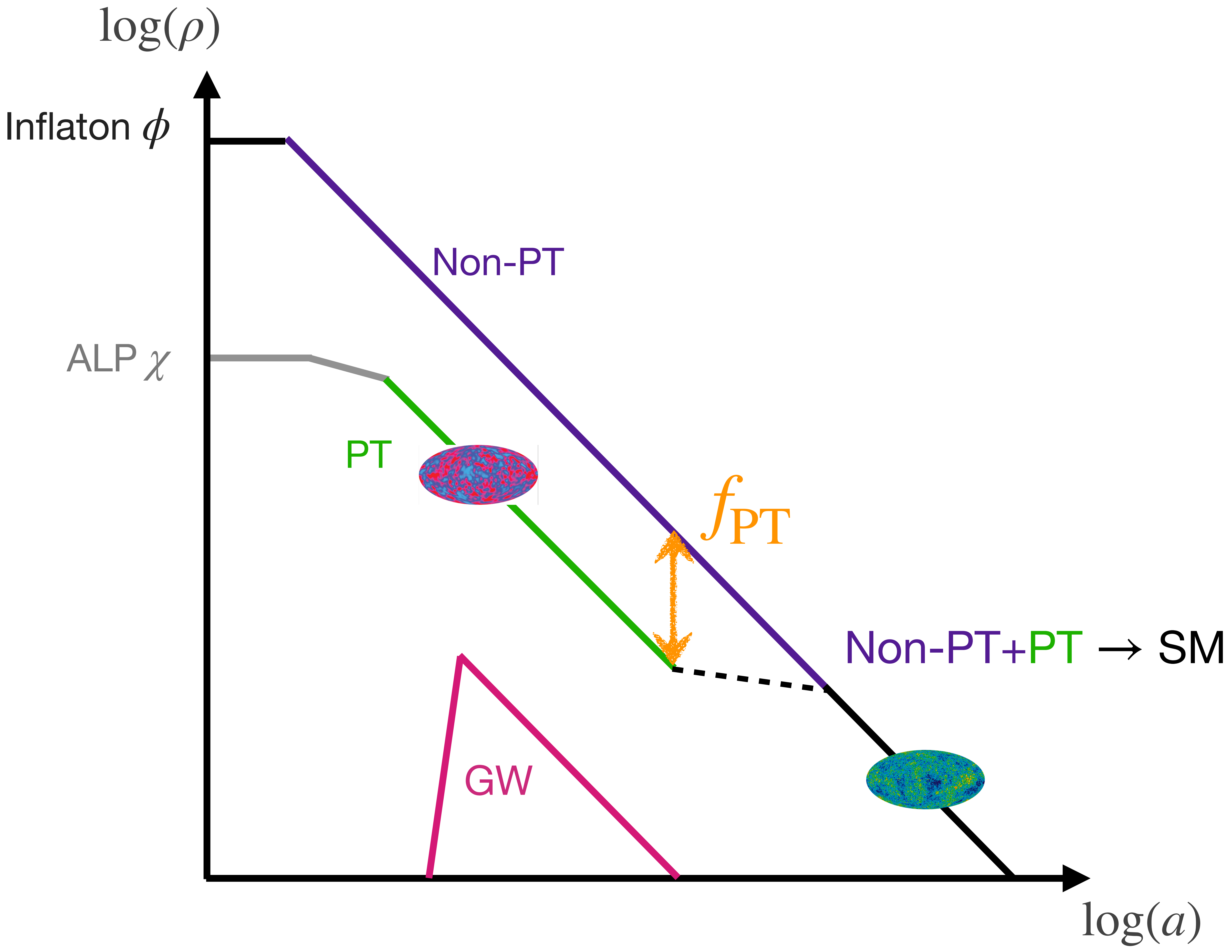

$$\delta_{\rm GW} \sim \delta_\chi + \delta_\phi$$

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

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

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

# Large isocurvature is more interesting

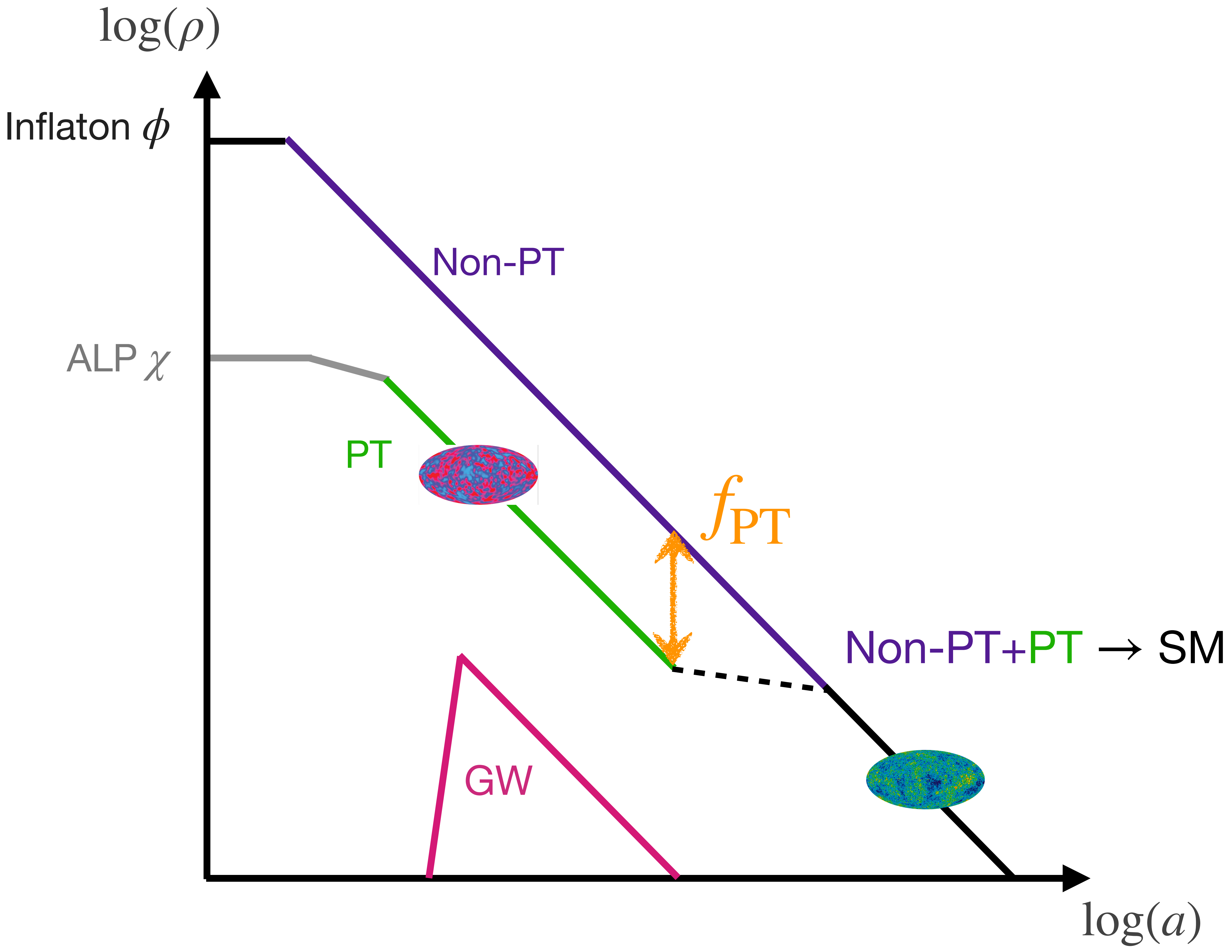



$\delta_{GW} \sim \delta_\chi + \delta_\phi$

$\sim 10^{-5}$

- $\delta_\chi > 10^{-5}$ is more distinct

# Large isocurvature is more interesting




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

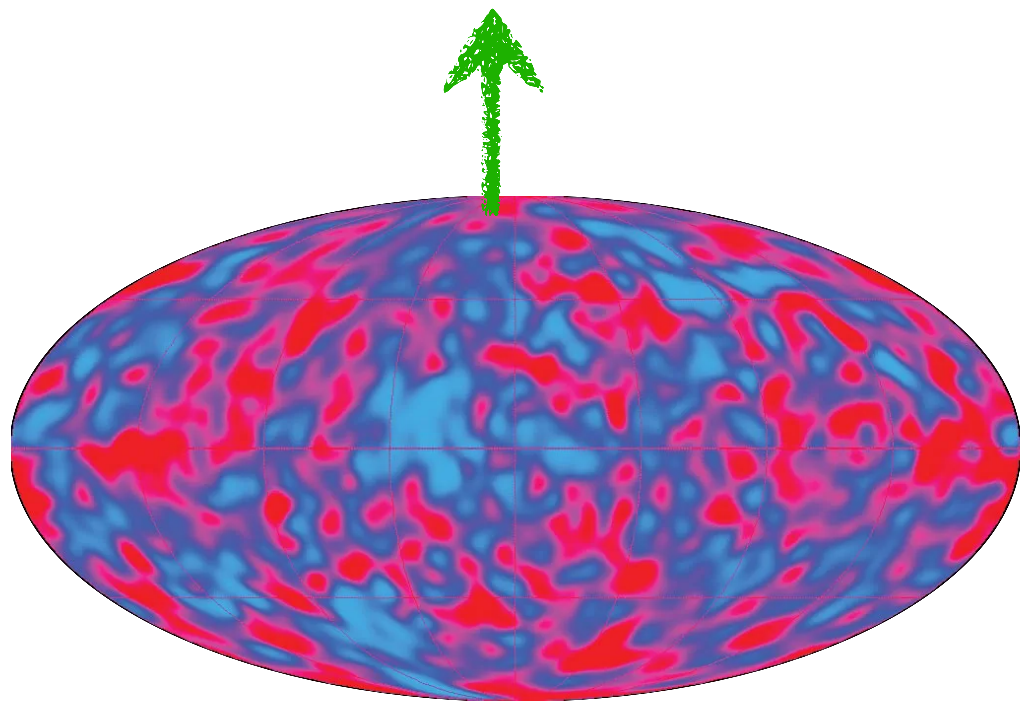
$\sim 10^{-5}$

- $\delta_\chi > 10^{-5}$ is more distinct
- $\delta_\chi \sim \dfrac{H_{\rm inf}}{\chi_{\rm init}}$ → in high-scale inflation

$H_{\rm inf} \sim 10^{-5} M_{\rm Pl}$, any sub-Planckian misalignment $\chi_{\rm init}$ gives $\delta_\chi > 10^{-5}$

# The tradeoff

Geller et al. 1803.10780
M. Breitbach et al. 1811.11175
M. Fairbairn et al. 1901.11038



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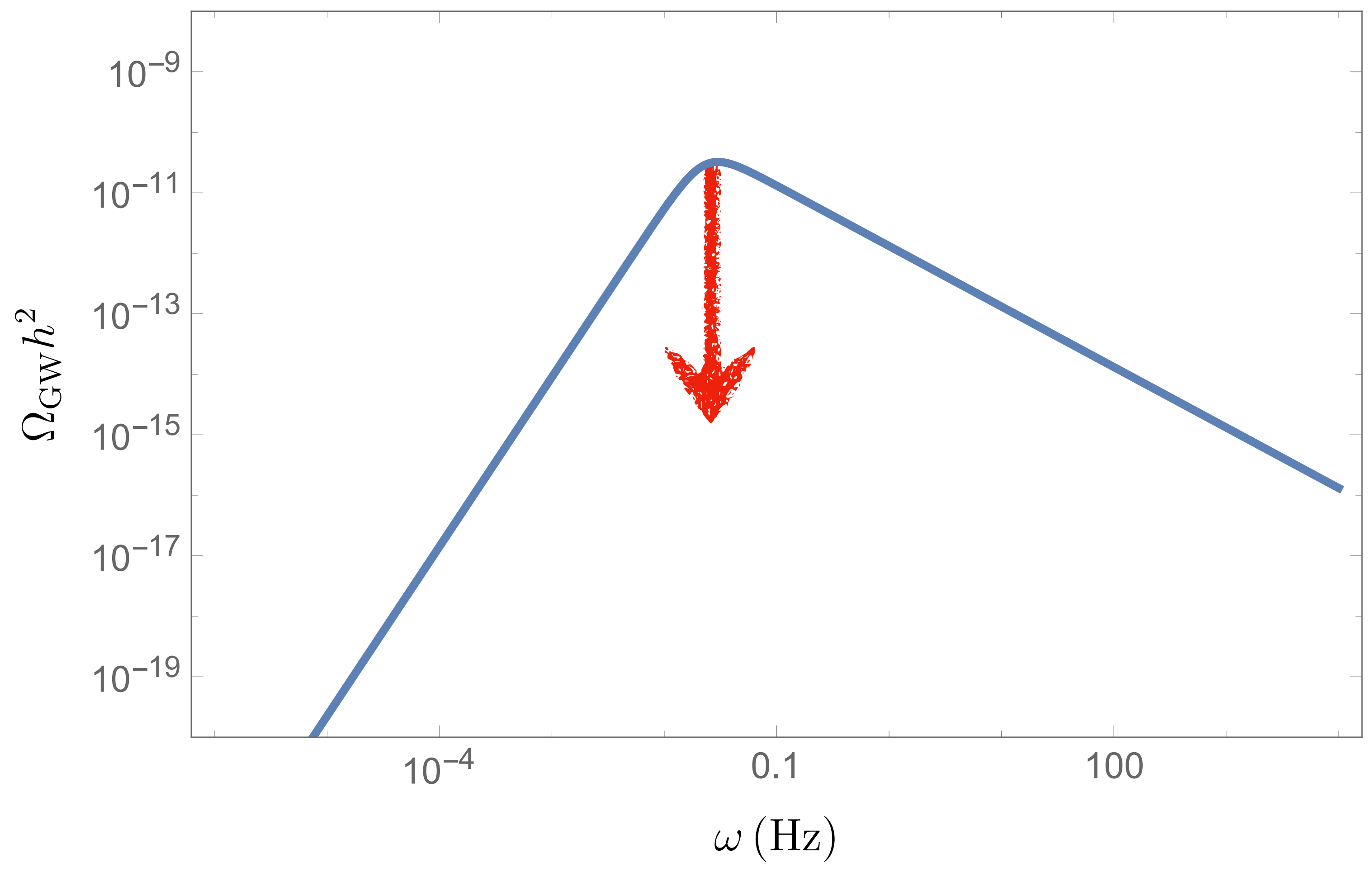

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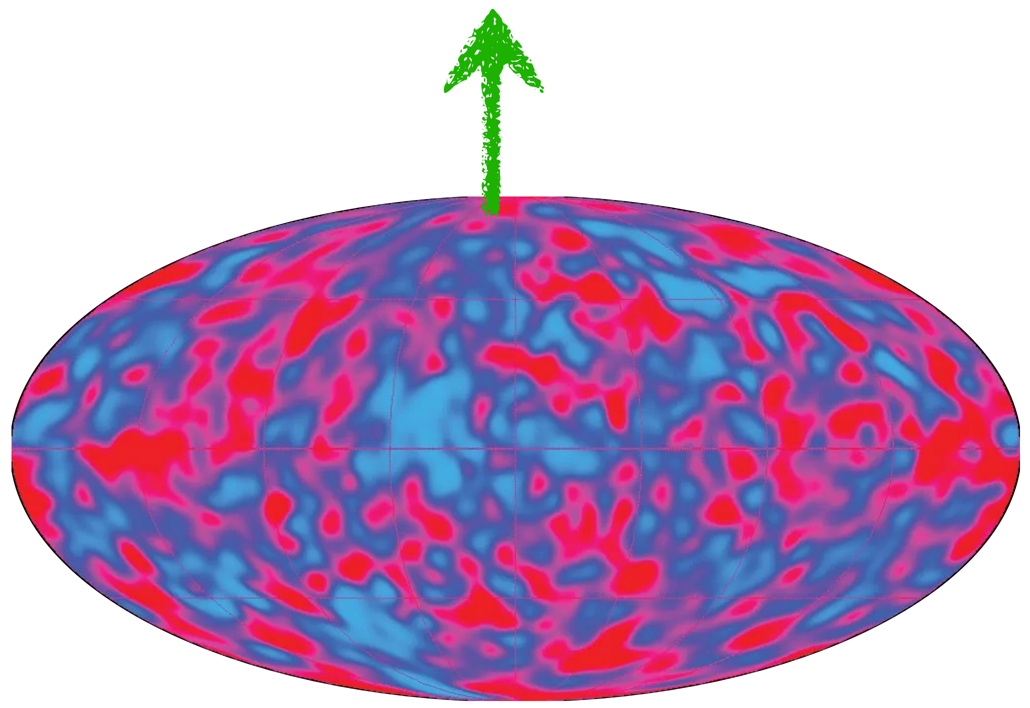

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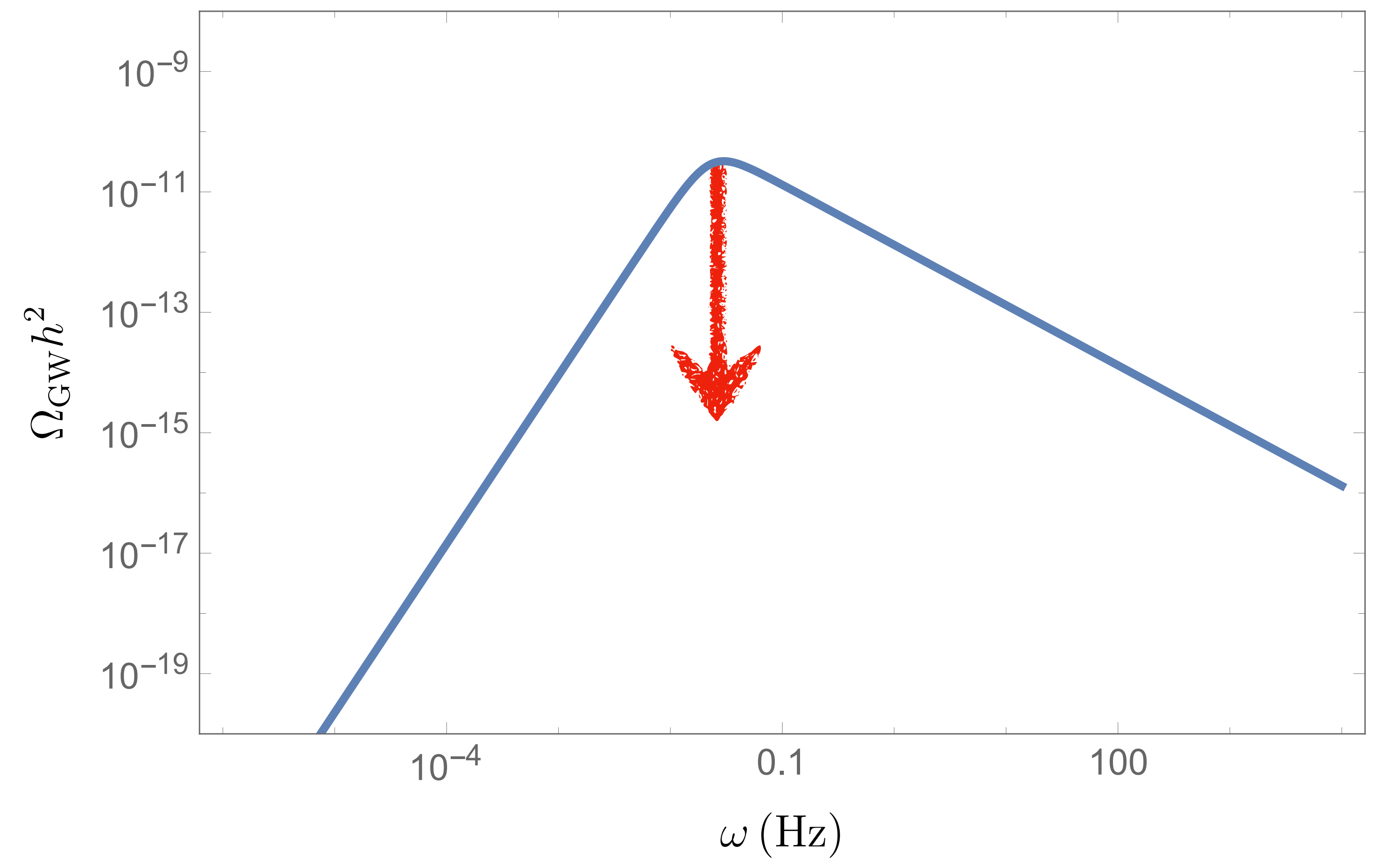


$$\delta_{\rm CMB} \sim \delta_\phi + f_{\rm PT}\,\delta_\chi \sim 10^{-5}$$

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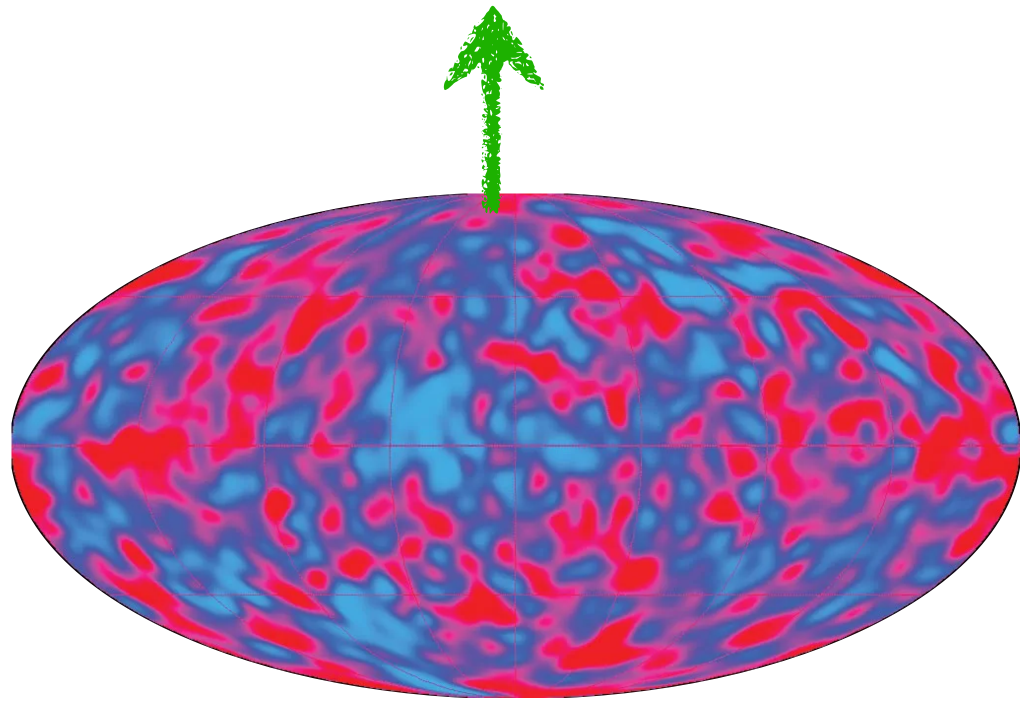

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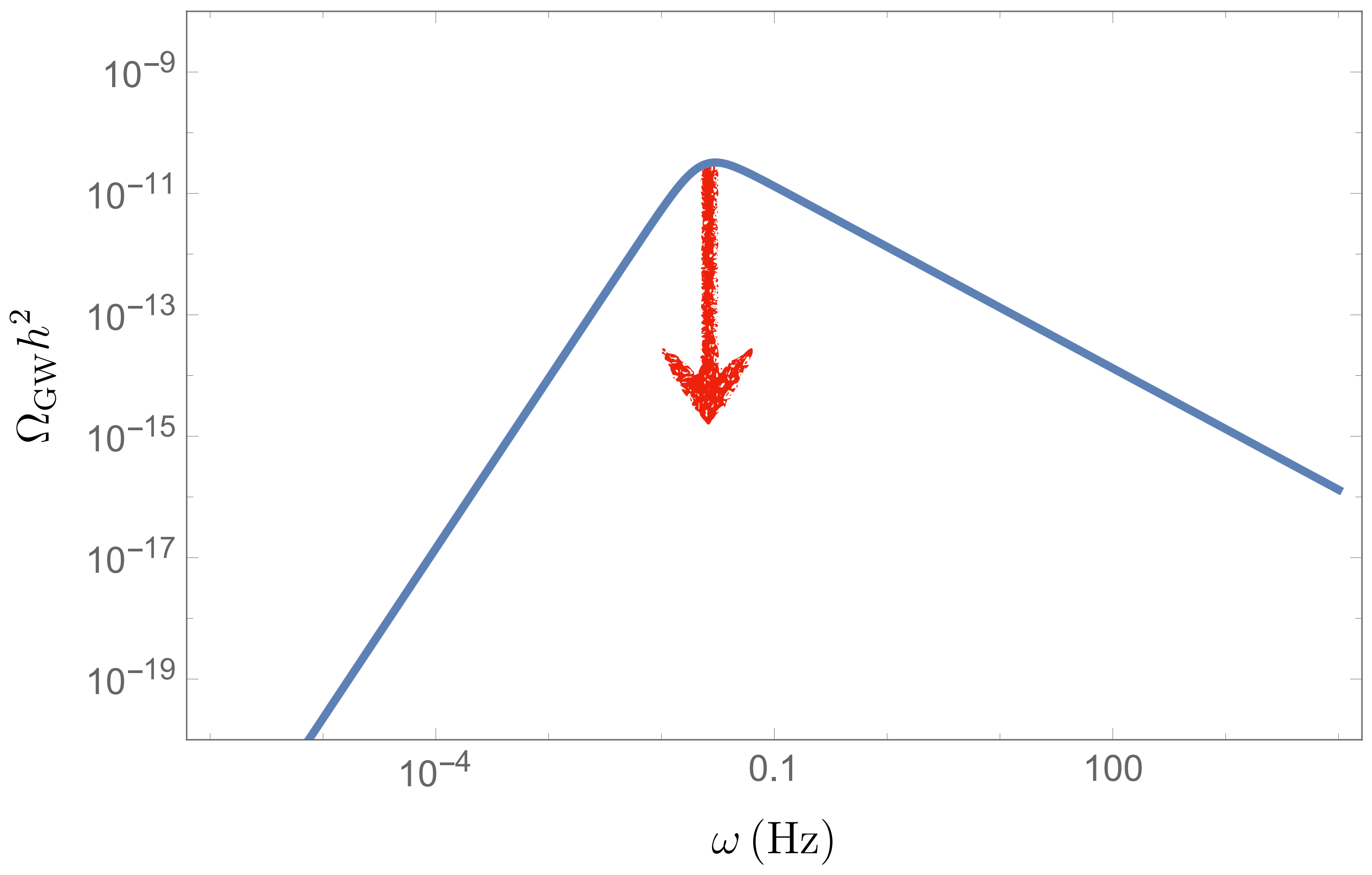


$$\delta_{\rm CMB} \sim \delta_\phi + f_{\rm PT}\,\delta_\chi \sim 10^{-5}$$

$$\Omega_{\rm GW} := \frac{\rho_{GW}}{\rho_{\rm total}} \propto f_{\rm PT}^2$$

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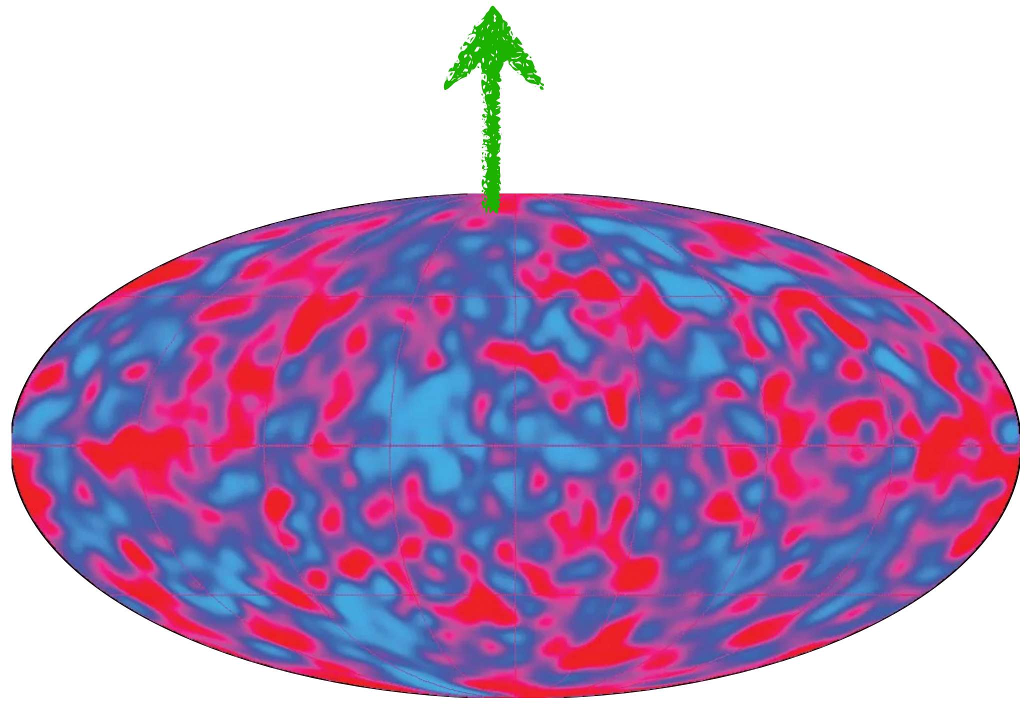

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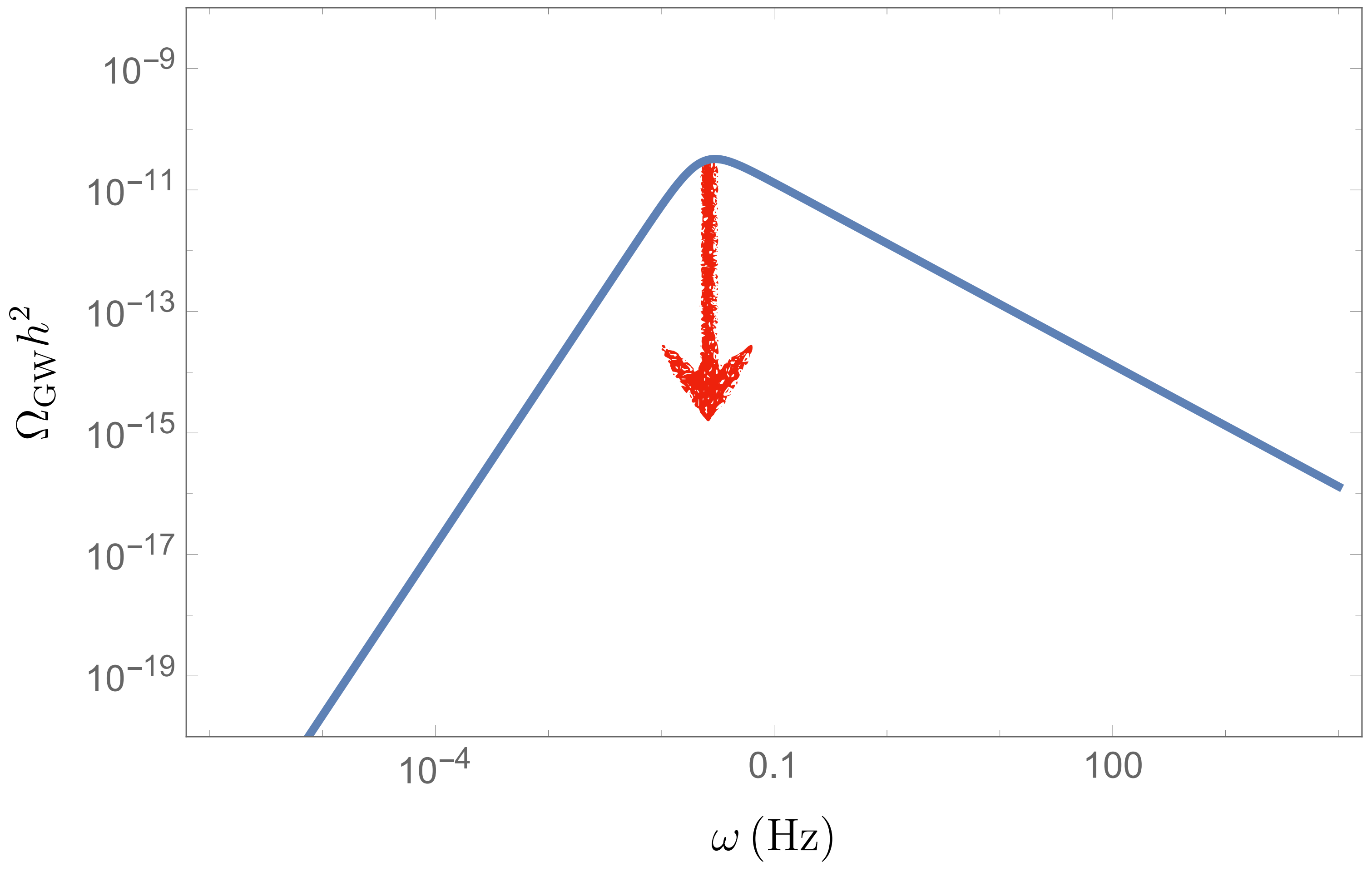


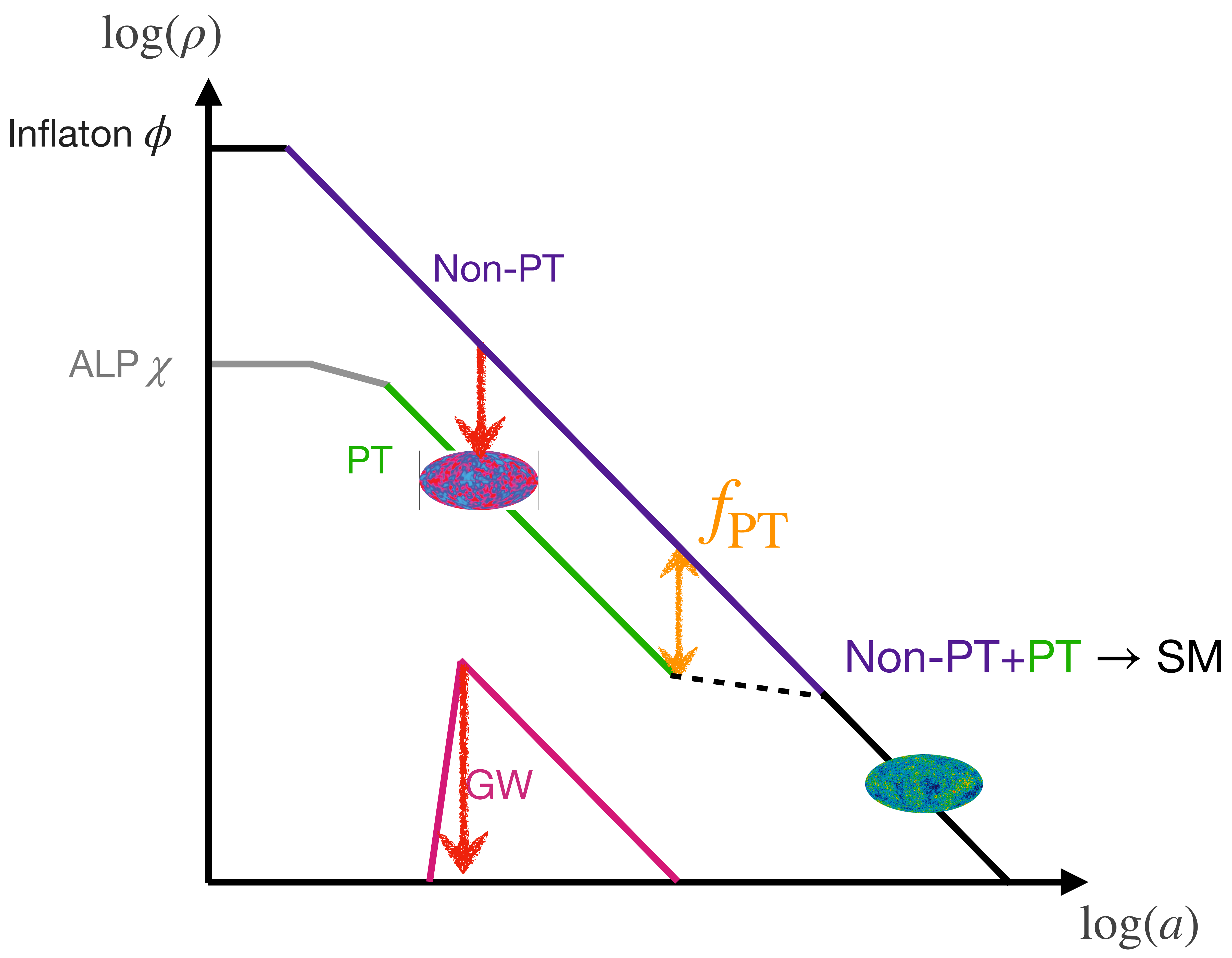

$$\delta_{\rm CMB} \sim \delta_\phi + f_{\rm PT}\,\delta_\chi \sim 10^{-5}$$

$$\Omega_{\rm GW} := \frac{\rho_{GW}}{\rho_{\rm total}} \propto f_{\rm PT}^2$$

$$h^{\rm TT} \propto \rho_{\rm PT}$$

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

# The solution



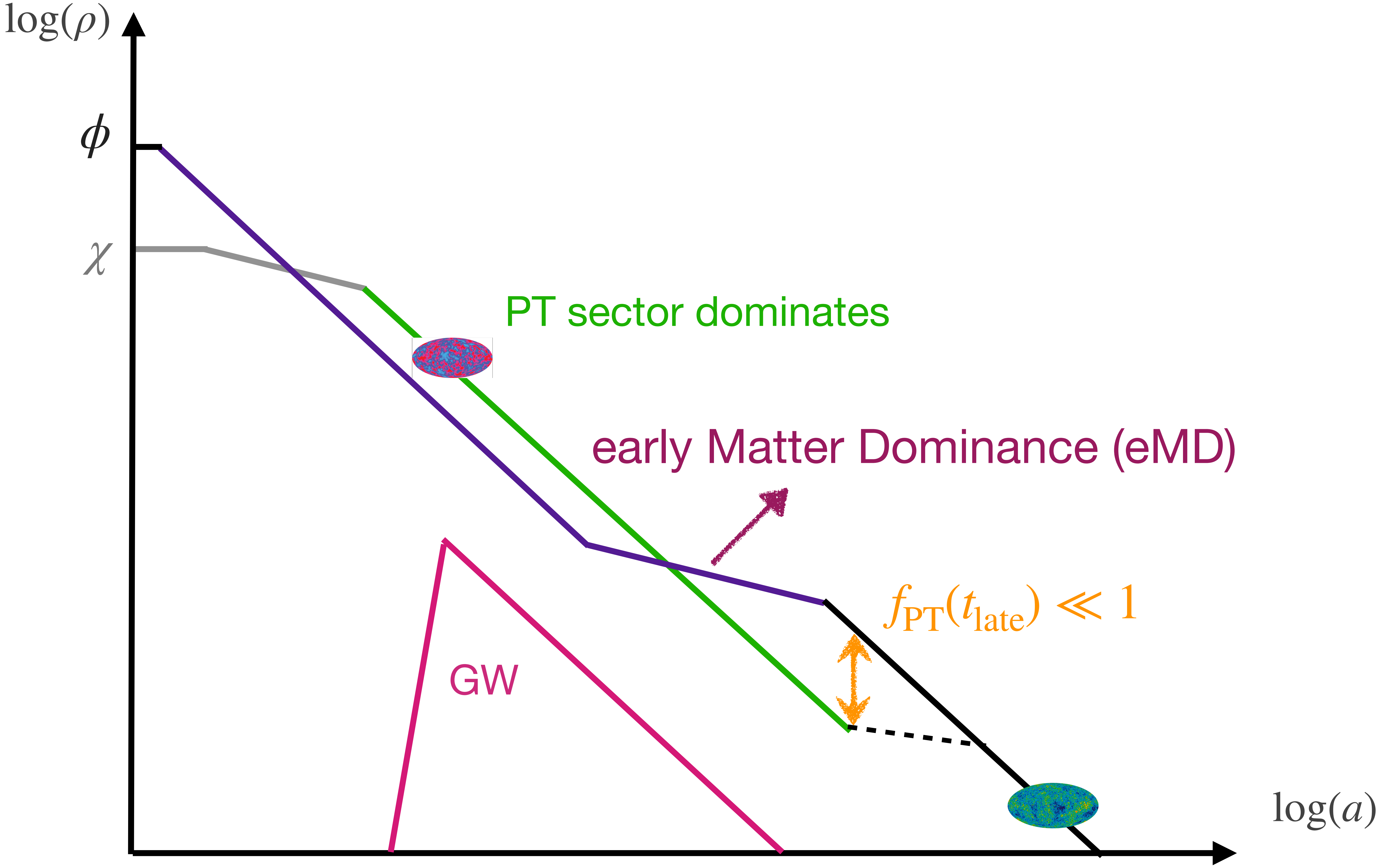

Make $f_{PT}$ time-dependent such that:

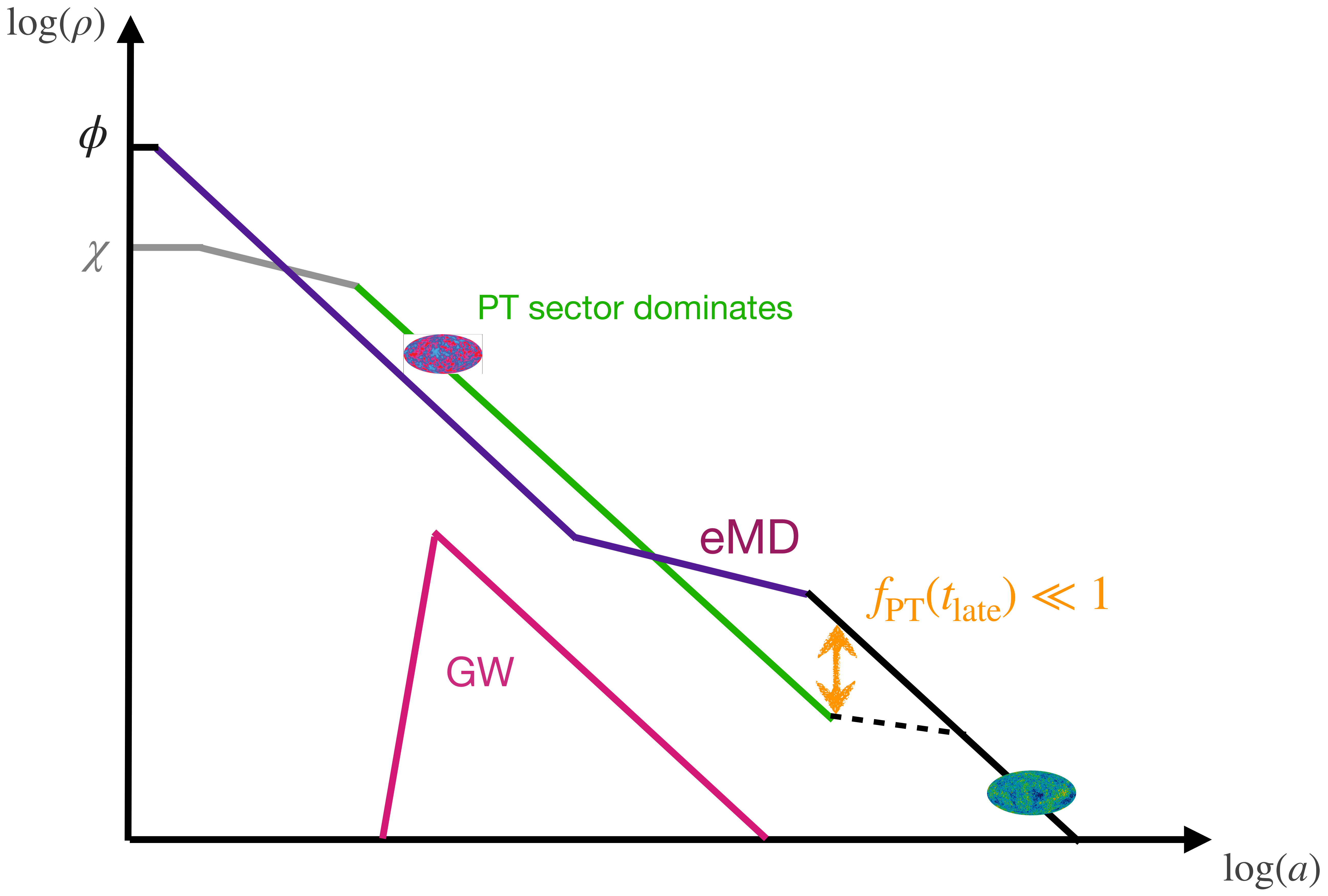
$f_{PT} \sim 1$ at PT

$f_{PT} \ll 1$ at CMB

# Utilize slower dilution of matter compared to radiation

AB, R. Sundrum: JHEP 06 (2023) 029



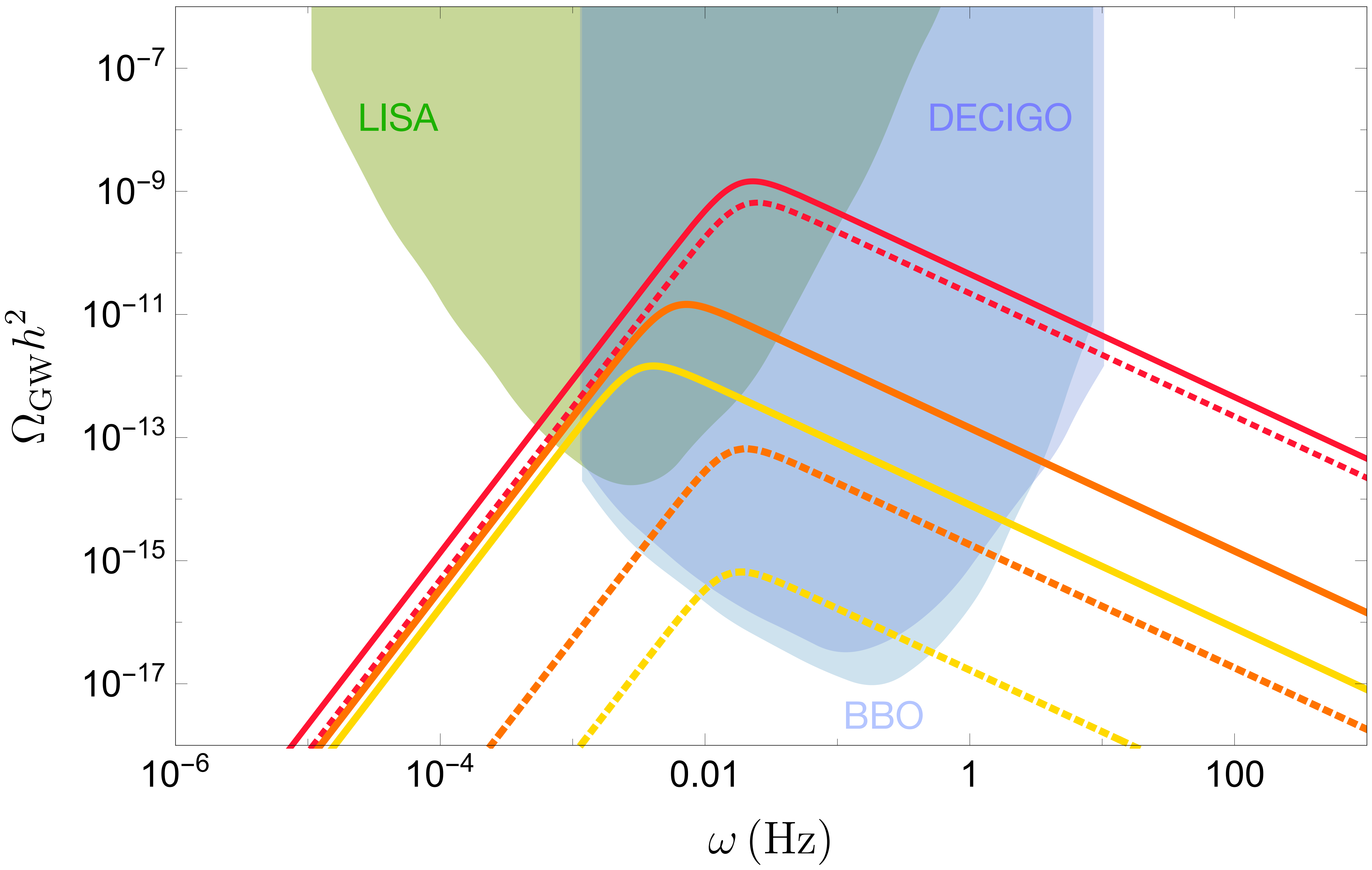



No suppression at production

Relative dilution from eMD

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

# Improvement in the GWB signal




Dashed lines: First model

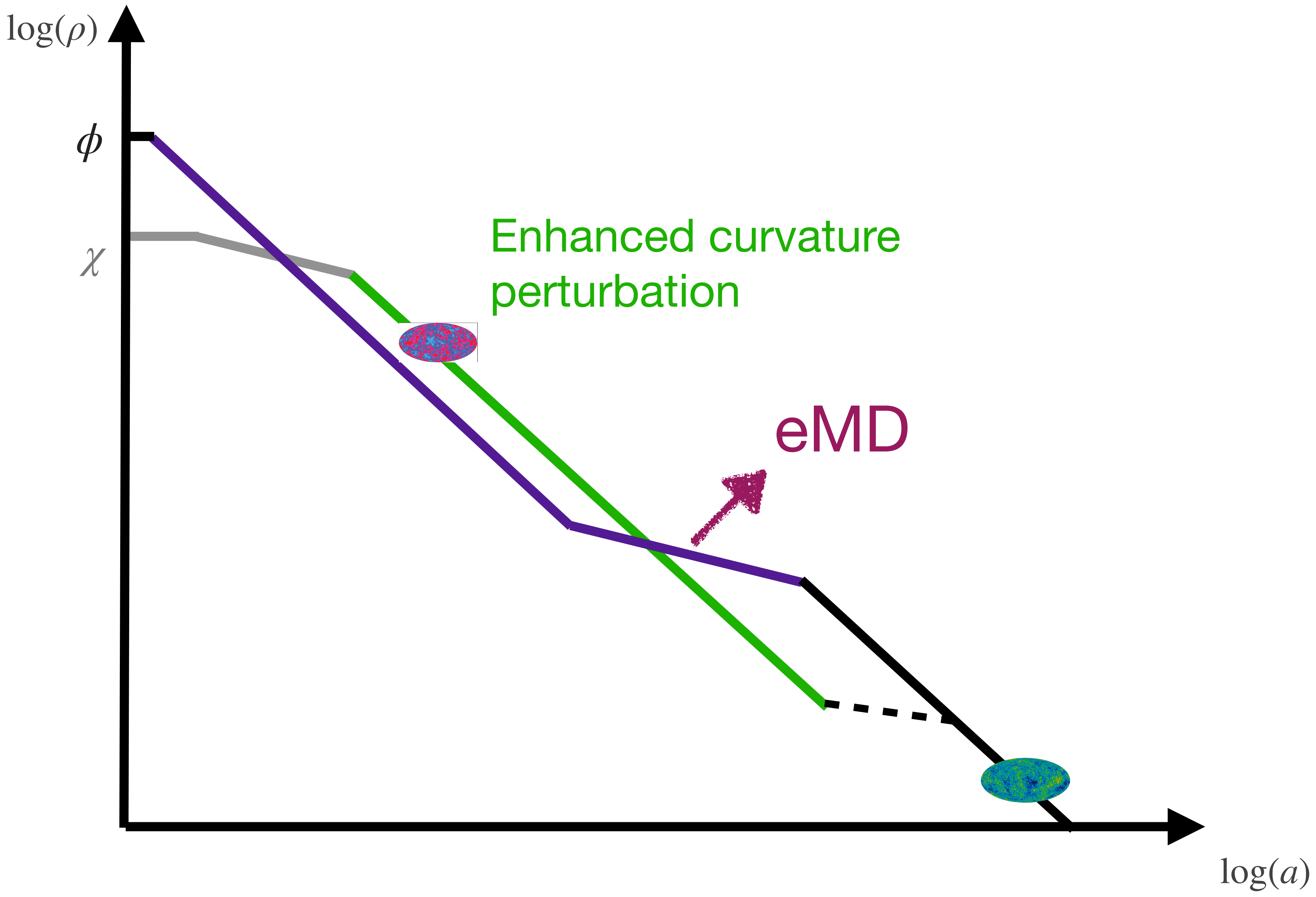
Solid lines: eMD model

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

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

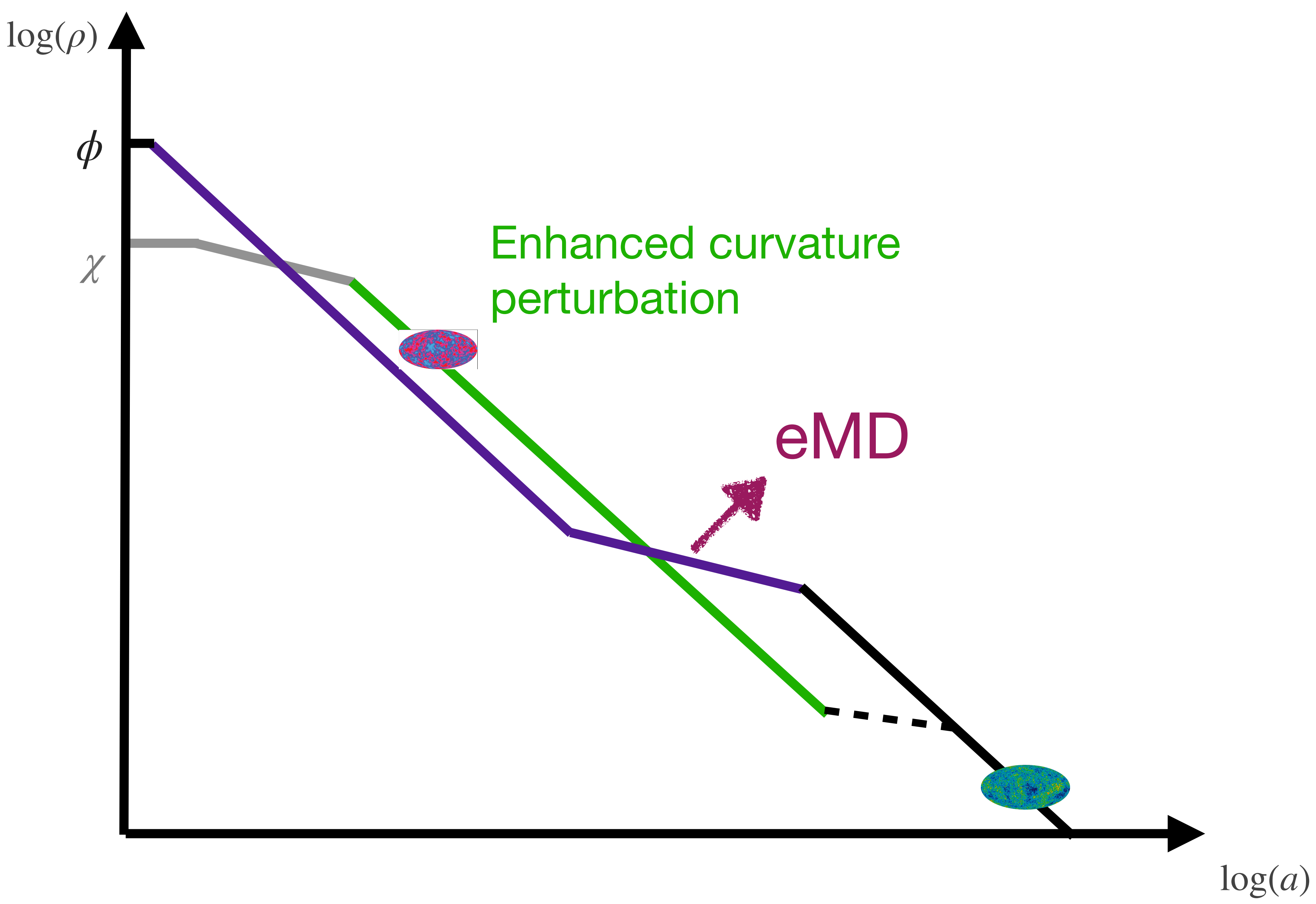
$\delta_{\rm GW} \sim 10^{-1}$, $f_{\rm PT} \sim 10^{-4}$

# Primordial black holes




Require $\delta_\chi < 0.01$ on small scales

# Primordial black holes

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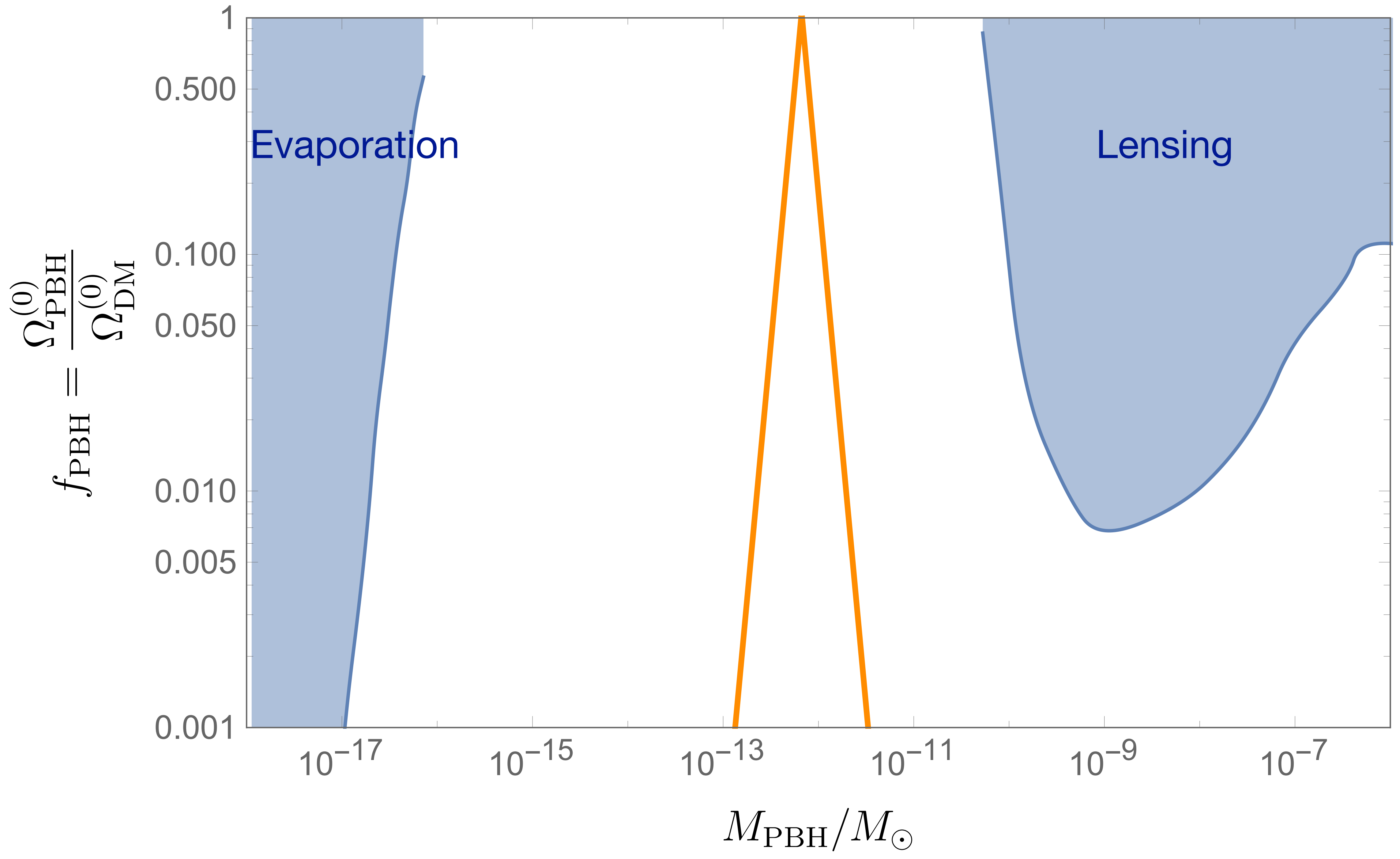


$\delta_\chi \sim 10^{-2}$, $f_{\rm PT} \sim 10^{-3}$

# Summary and future directions

- GWB from phase transitions could be highly anisotropic.
- Country to the previous belief, such highly anisotropic GWB could be within the reach of detectors like LISA.
- In the future, it would be interesting to extend the study of isocurvature GWB from other sources.
- I invite you to think about other kinds of isocurvature maps, which may reveal new physics from the inflationary era.

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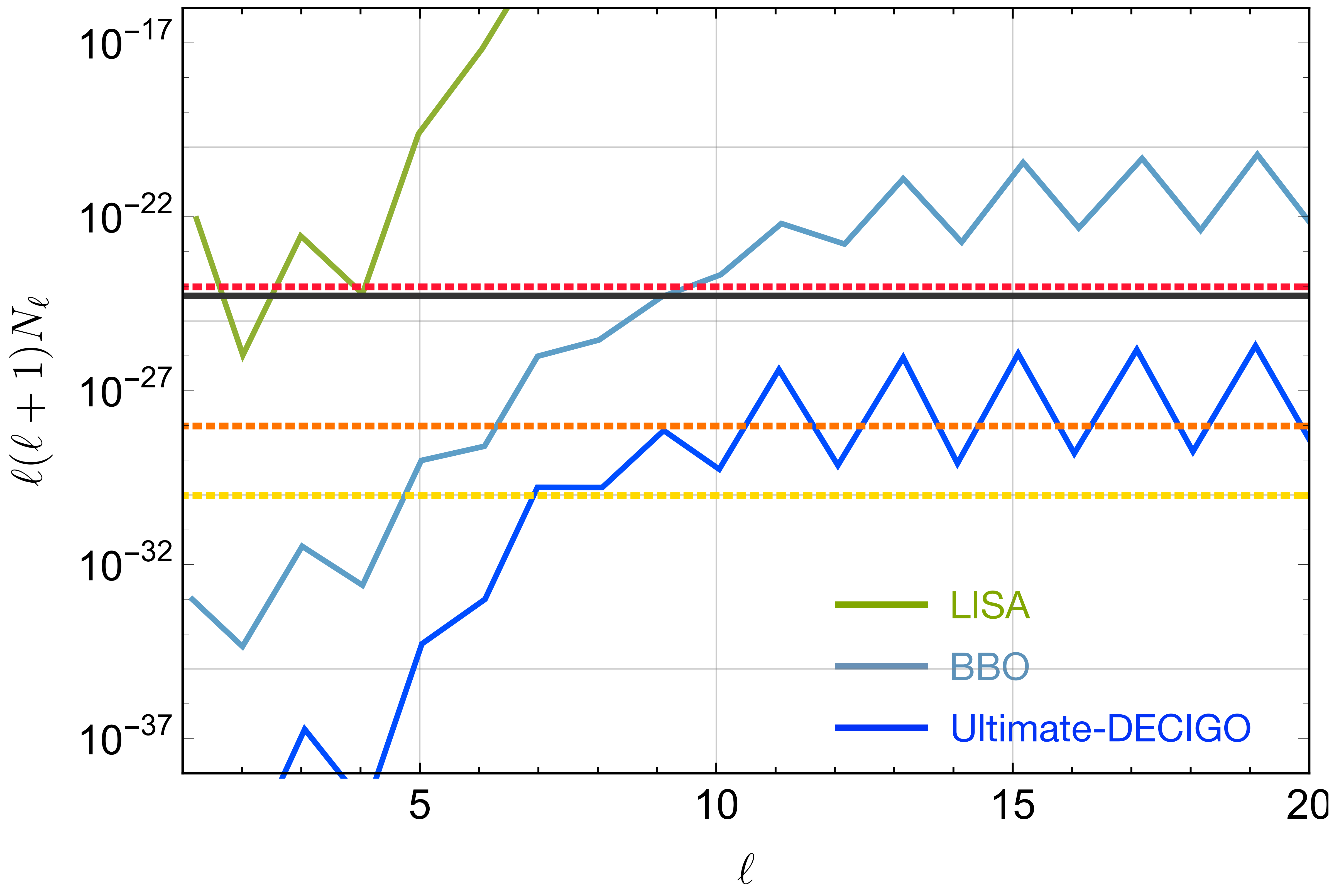
Thank you!

# Back-up slides

# Detectability of large anisotropy




Dashed lines: Simple model

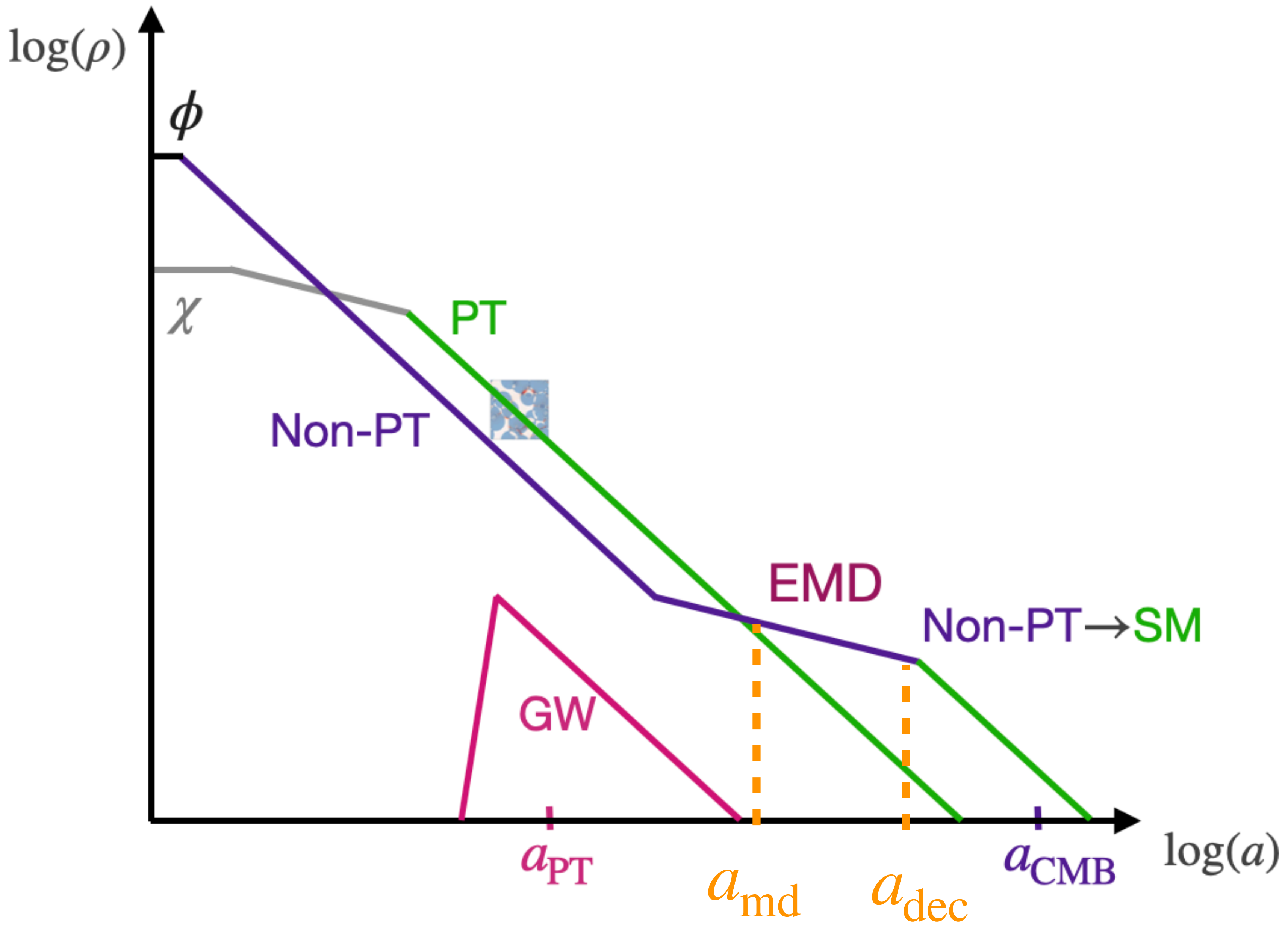
Solid lines: eMD model

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

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

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

# Constraints on eMD model: small scale structure



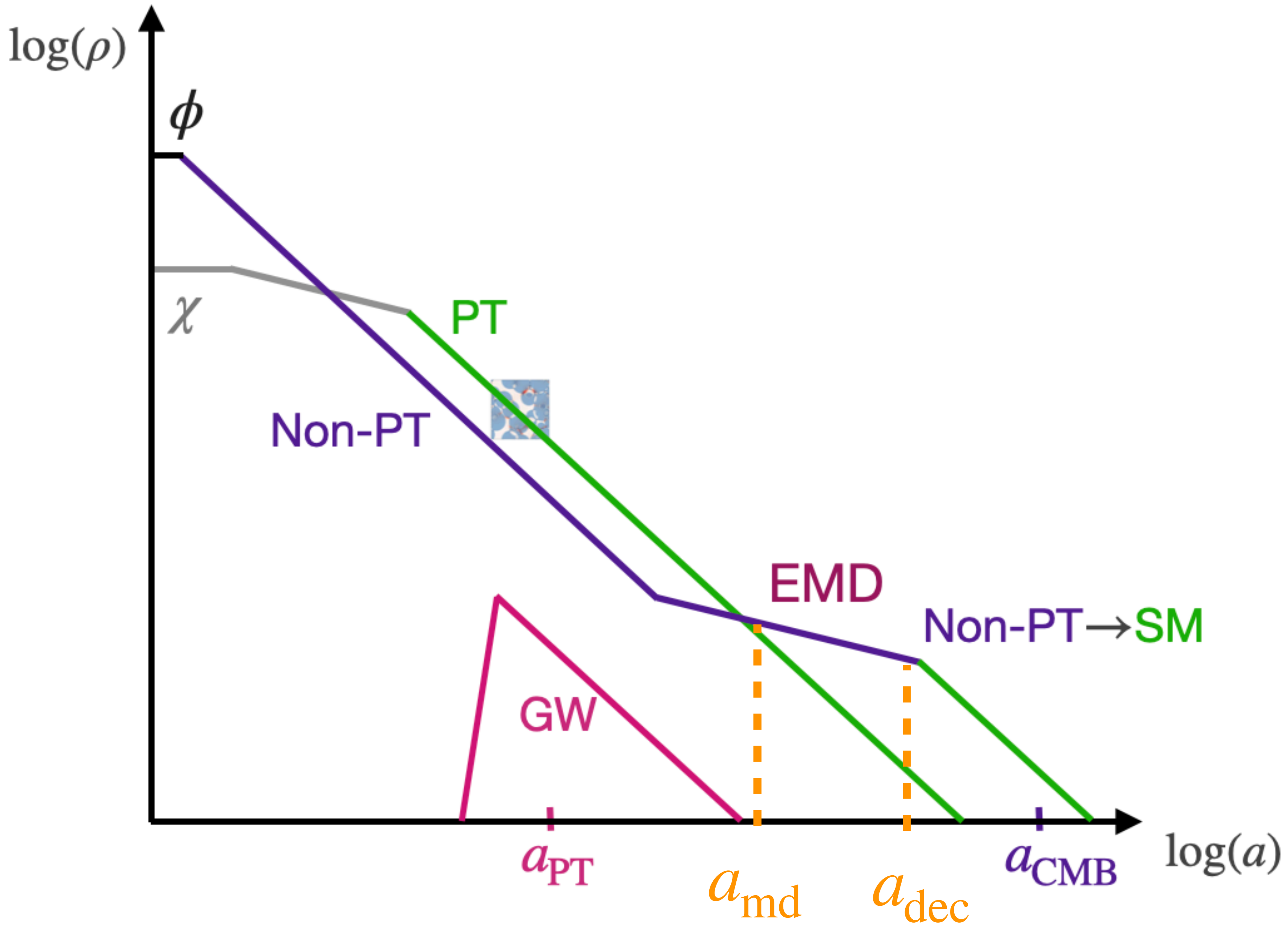

During eMD, $\delta_{\rm mat} \propto a$, could form structures on small scales with potential observational constraints

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




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

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

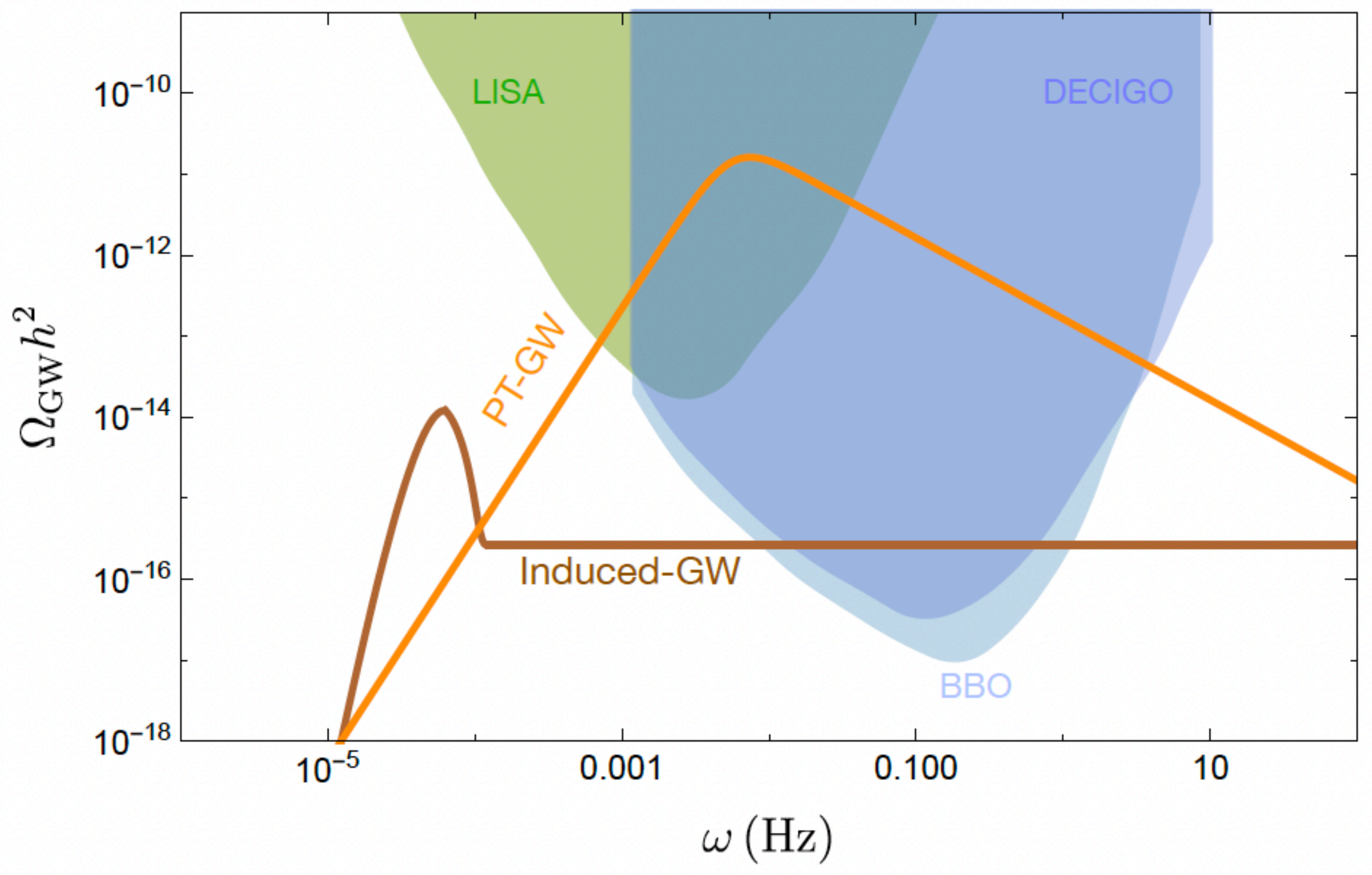
$$(\Omega_{GW}^{sec})_{peak} \sim 10^{-5} \frac{a_{dec}}{a_{md}} \delta_\chi^4$$

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

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

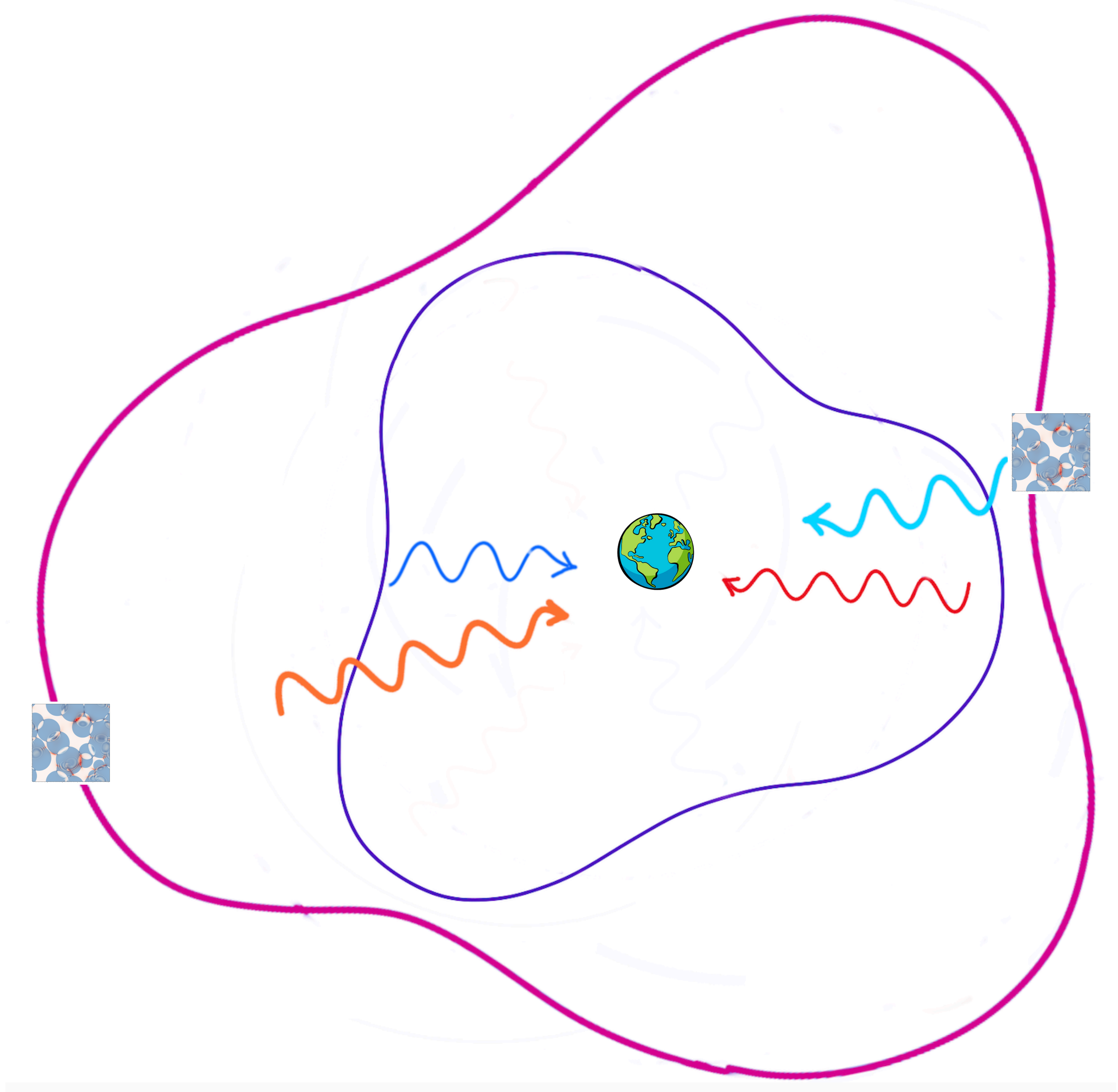
Gouttenoire, Servant, Simakachorn 2111.01150

# Secondary (induced) GW




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

# Bubbles are unresolvable



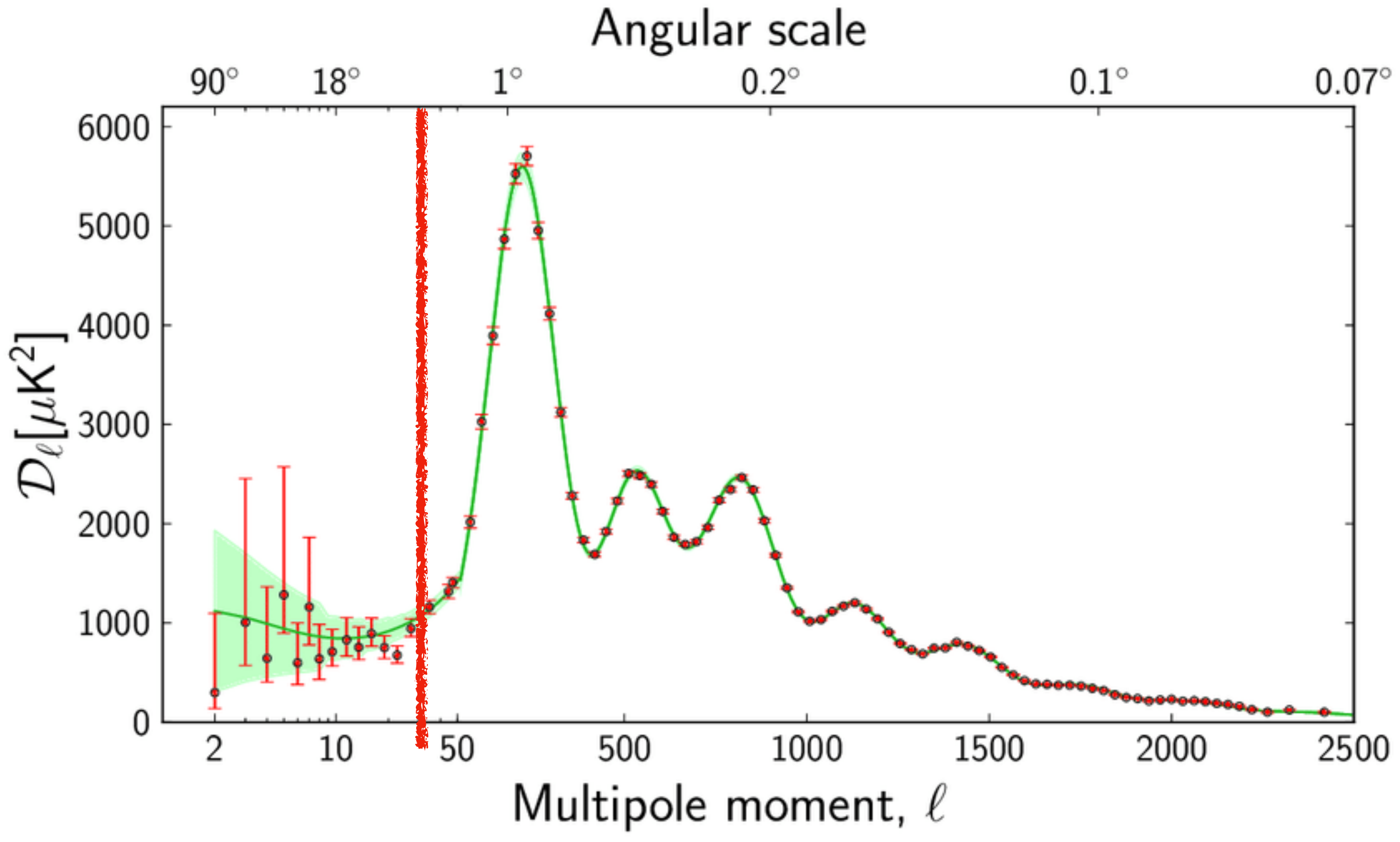
Caution: Zoomed in!

$> 10^{18}$ bubble collisions/arcsec$^2$
$\implies$ Bubbles are unresolvable sources : getting a course grained picture of GWB

# GWB is a "pristine" map

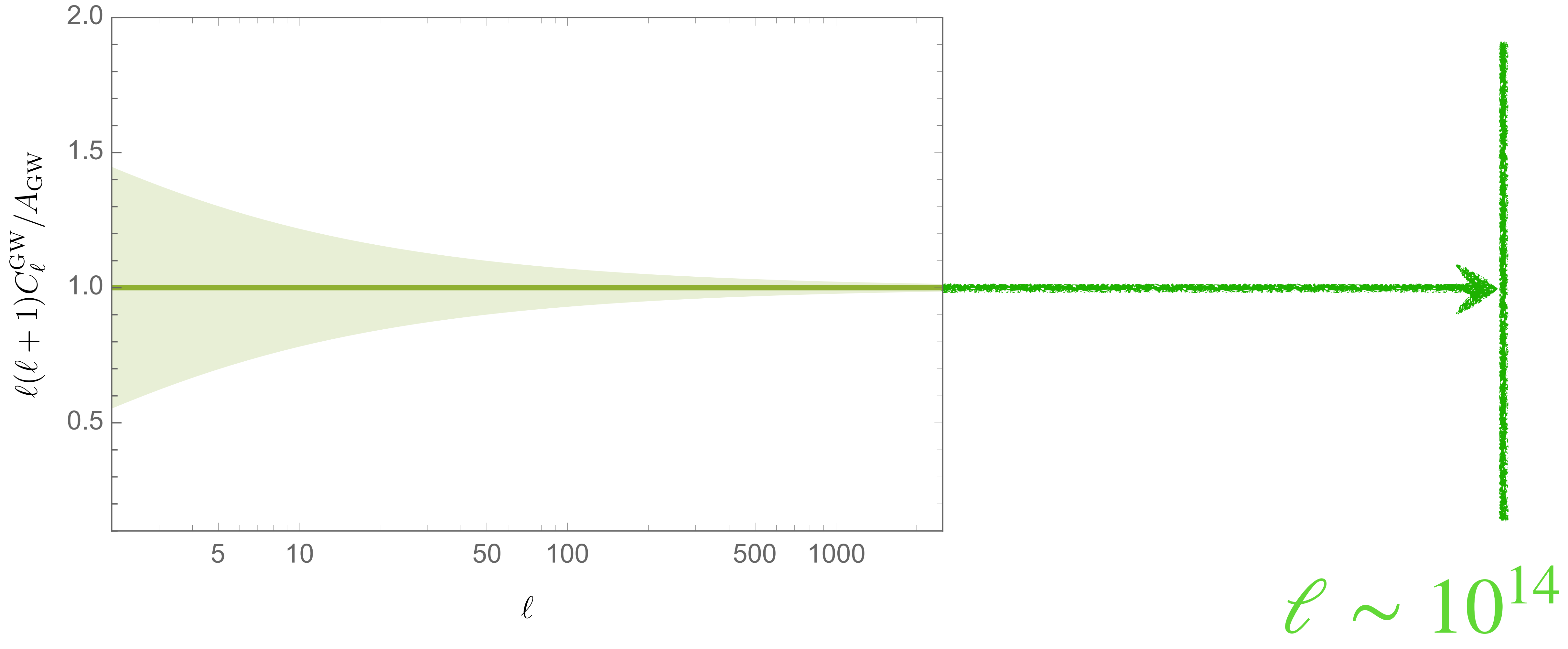
Earlier production + free-streaming of GW → large range of scales is unaltered by sub-horizon physics

CMB

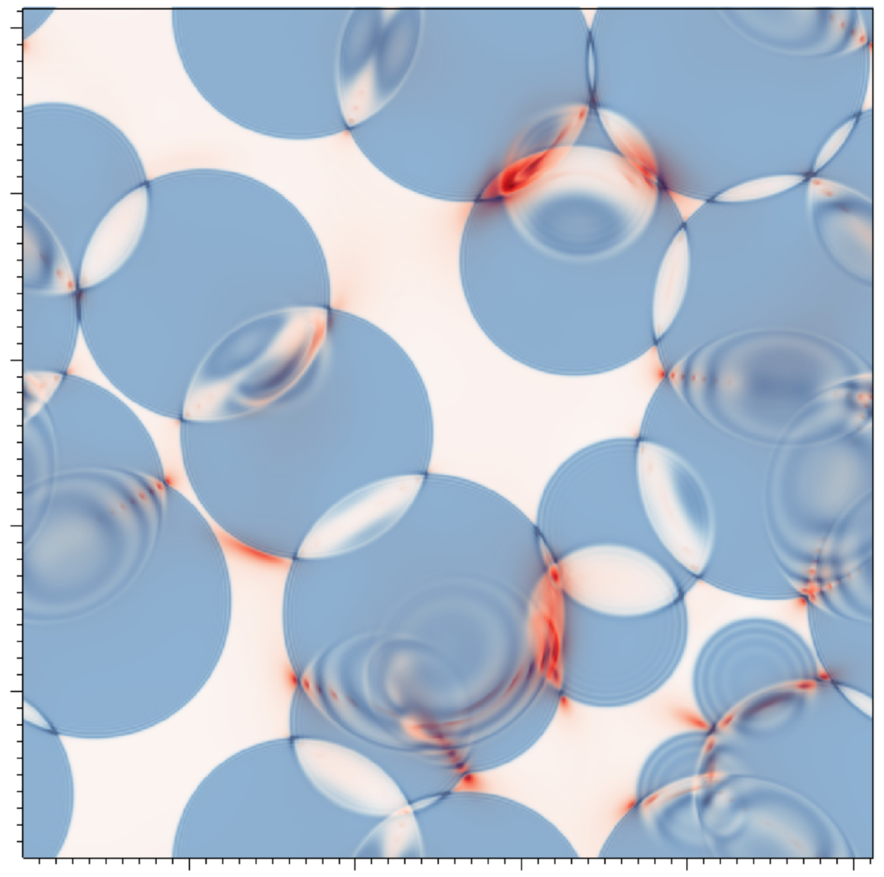



Planck

GWB



# Energy density in GWB from PT (2)



Power released in bubble collision

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

Quadrapole moment

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

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

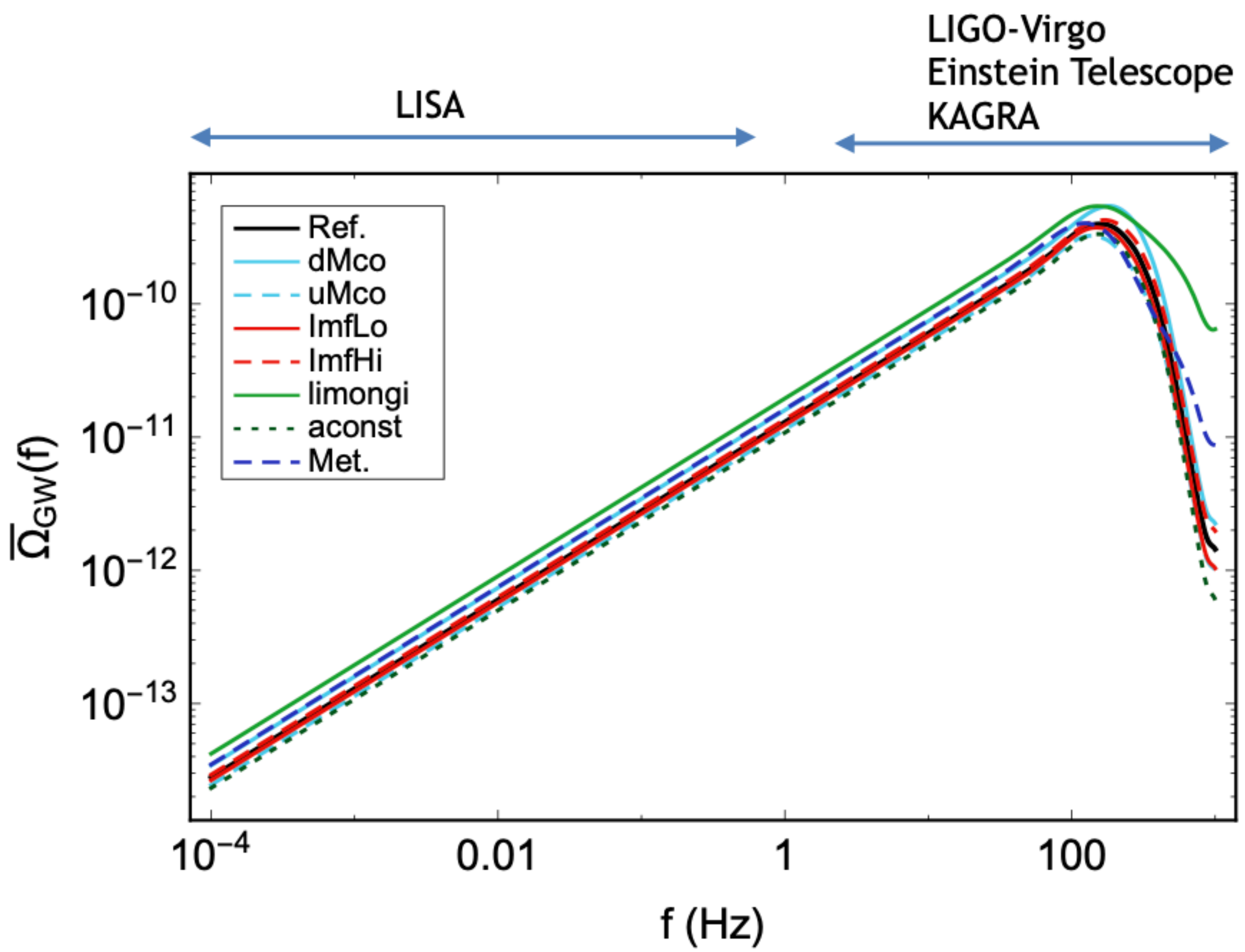
$$r \sim \Delta t_{\rm PT} \equiv \beta^{-1}$$

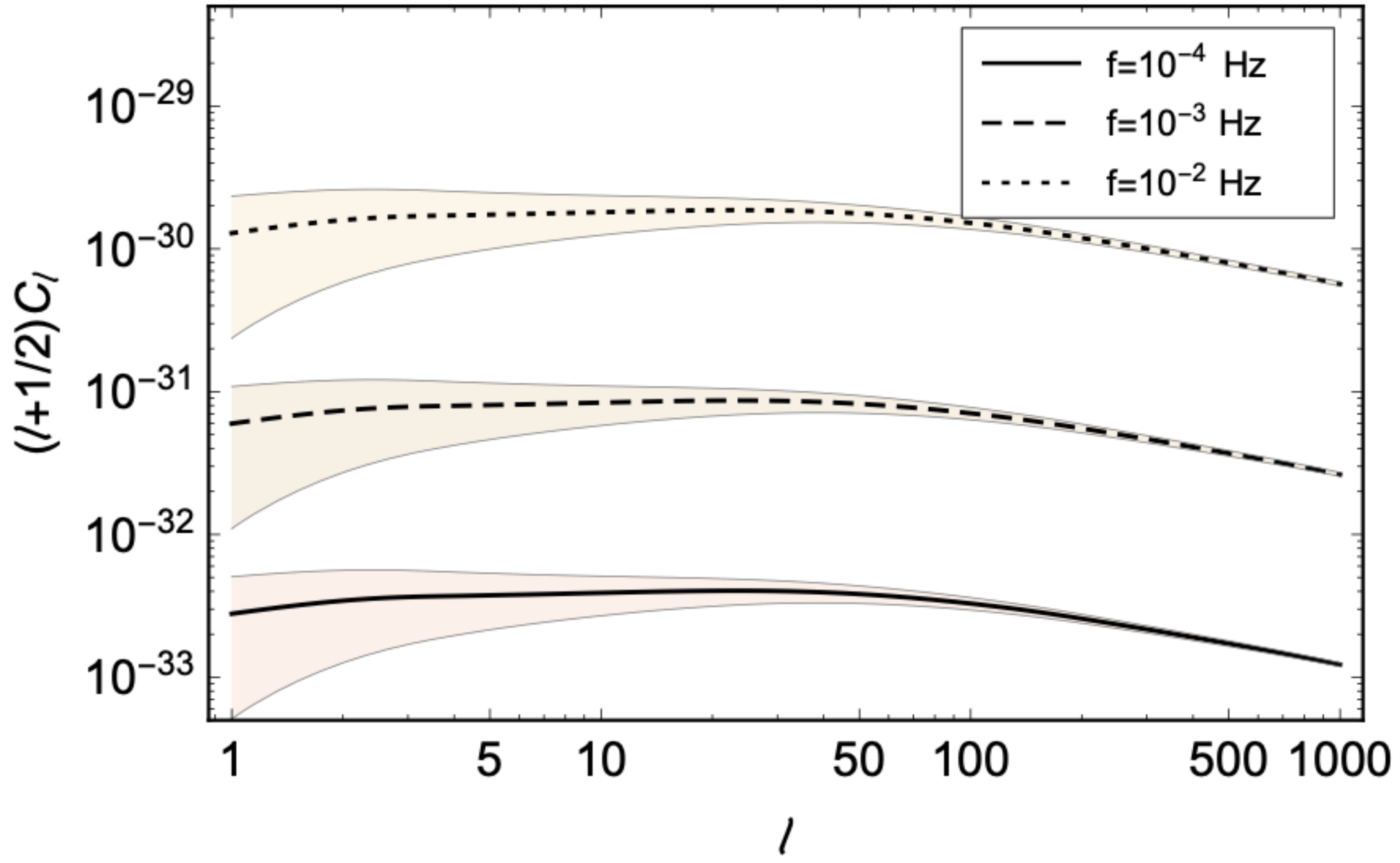
GW energy density released in bubble collision

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

# Astrophysical foregrounds in mHz range

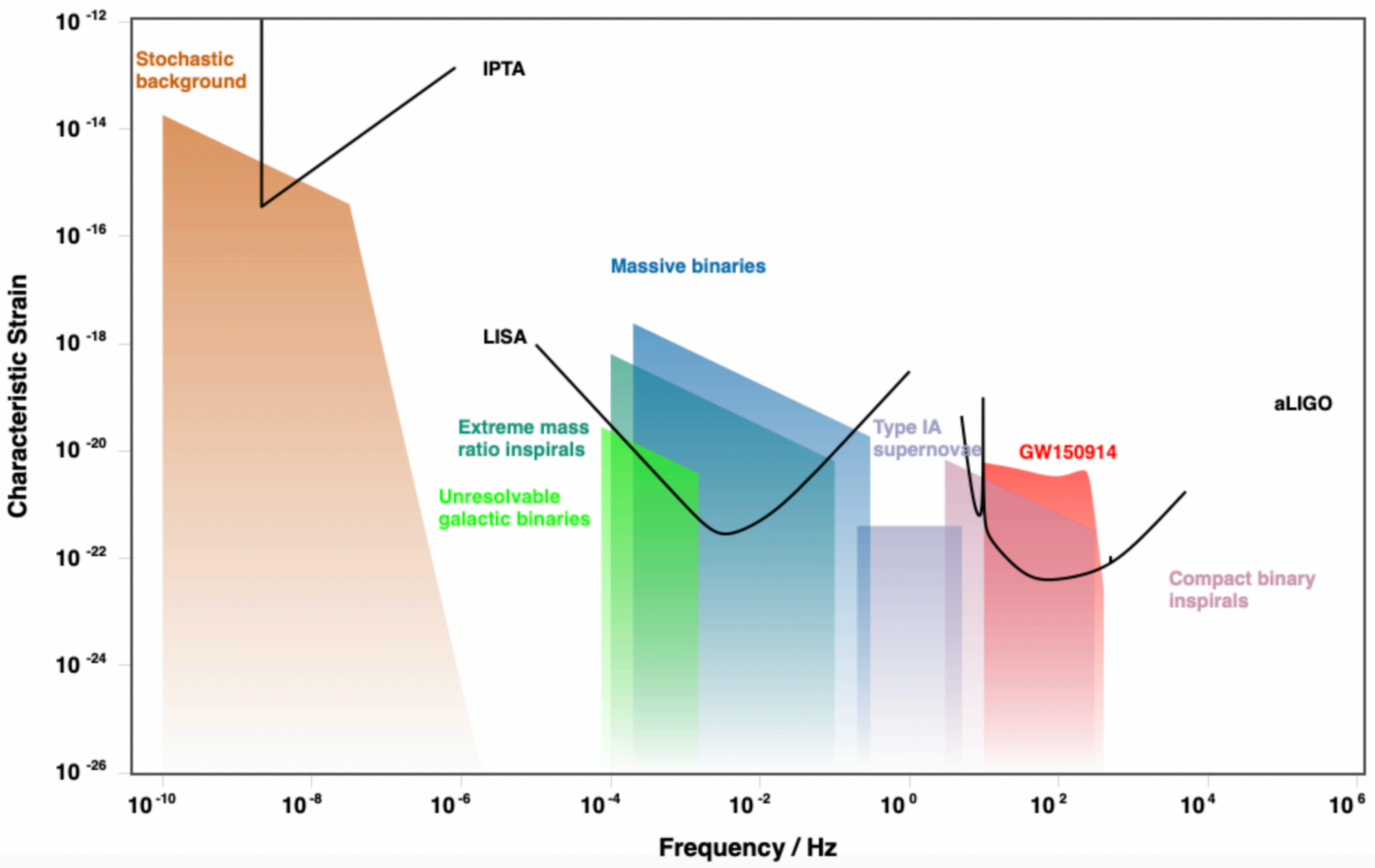
Inspiraling stellar-mass BH




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

Also see: 2201.08782v from LISA working group




rhcole.com/apps/GWplotter/