Seeing highly anisotropic gravitational wave backgrounds from the early universe

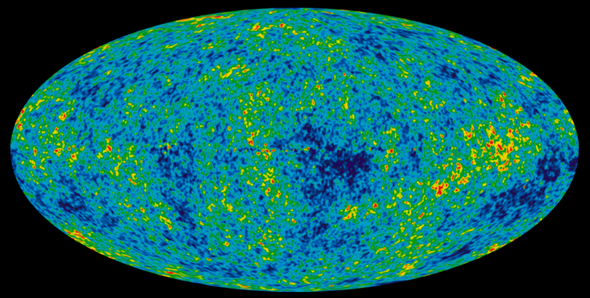
Arushi Bodas

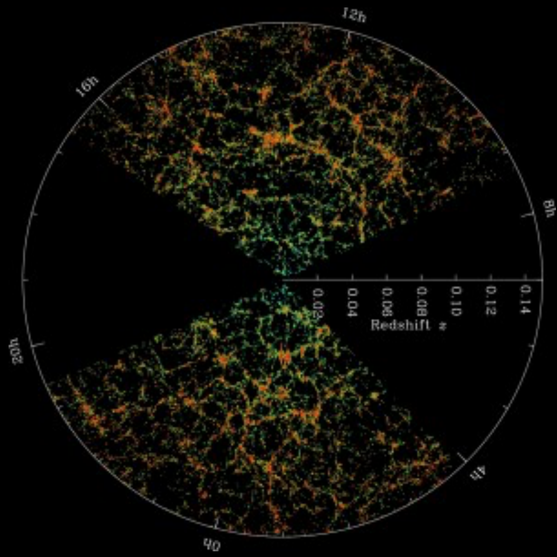
Postdoc @ U.Chicago & Fermilab

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

AB, K. Harigaya, K. Inomata, T. Terada, L-T Wang: Ongoing work

Email: bodas.arushi@gmail.com




12h
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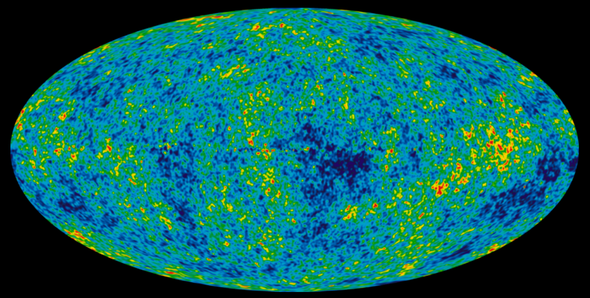
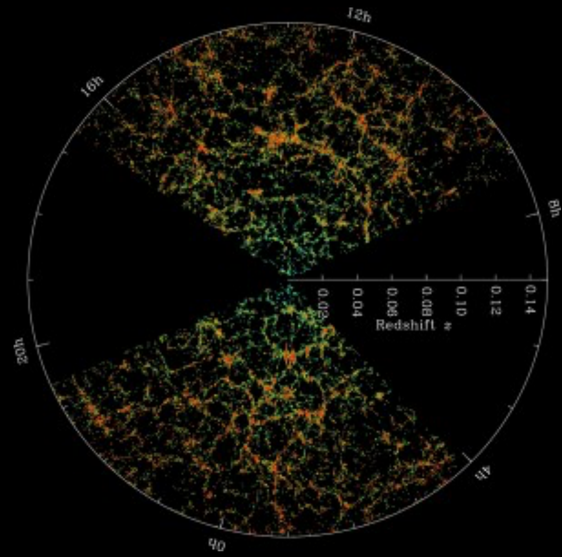
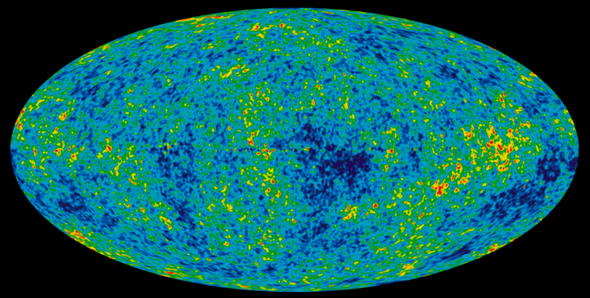
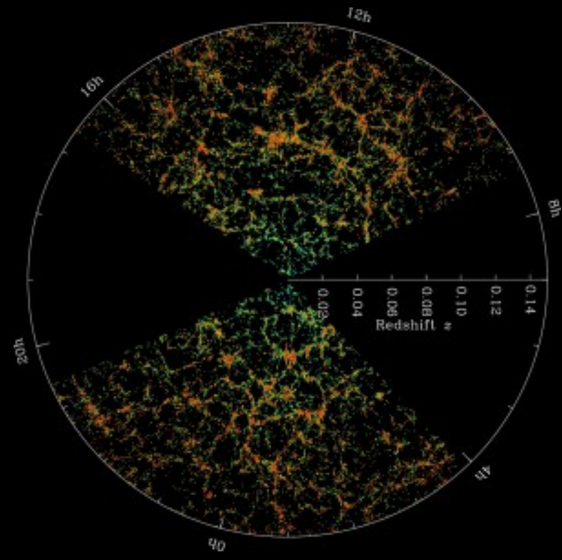
Redshift z





Quantum fluctuations of a scalar field + inflation





Quantum fluctuations of a scalar field + inflation

Anisotropy maps are unique windows into inflationary physics

Common origin 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

- Current observations (CMB) already constrain the prospect of seeing new inflationary physics in future datasets based on SM and DM species (line-intensity, large scale structure).

- Can we think of a fluctuation map that could be very different from the CMB?

What’s the messenger?

- 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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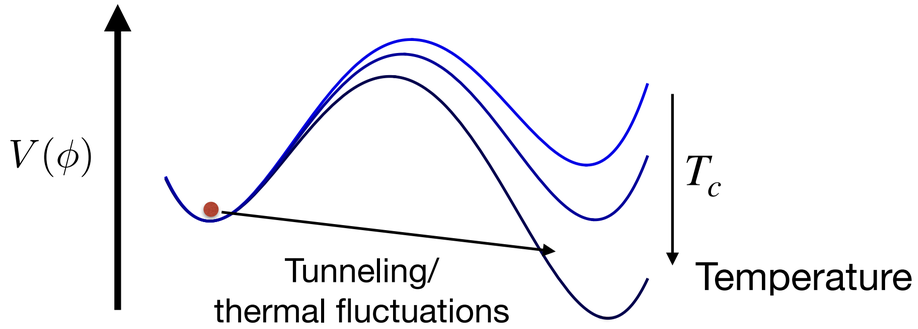
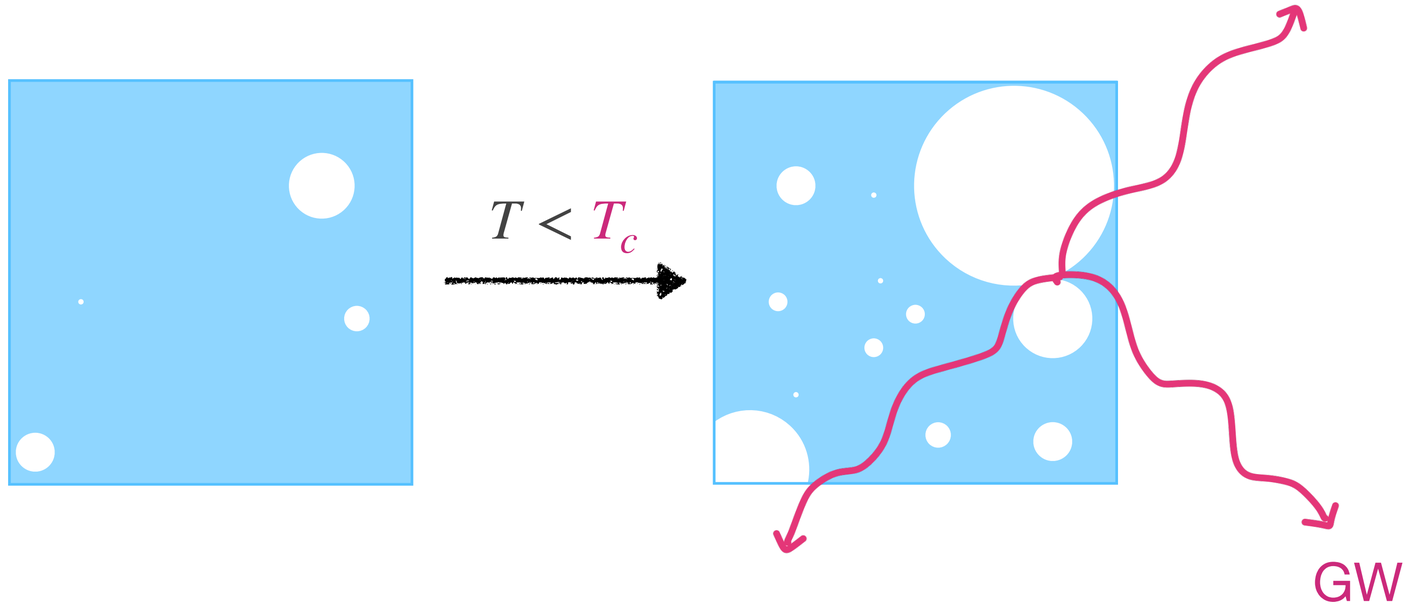
Gravitational waves!

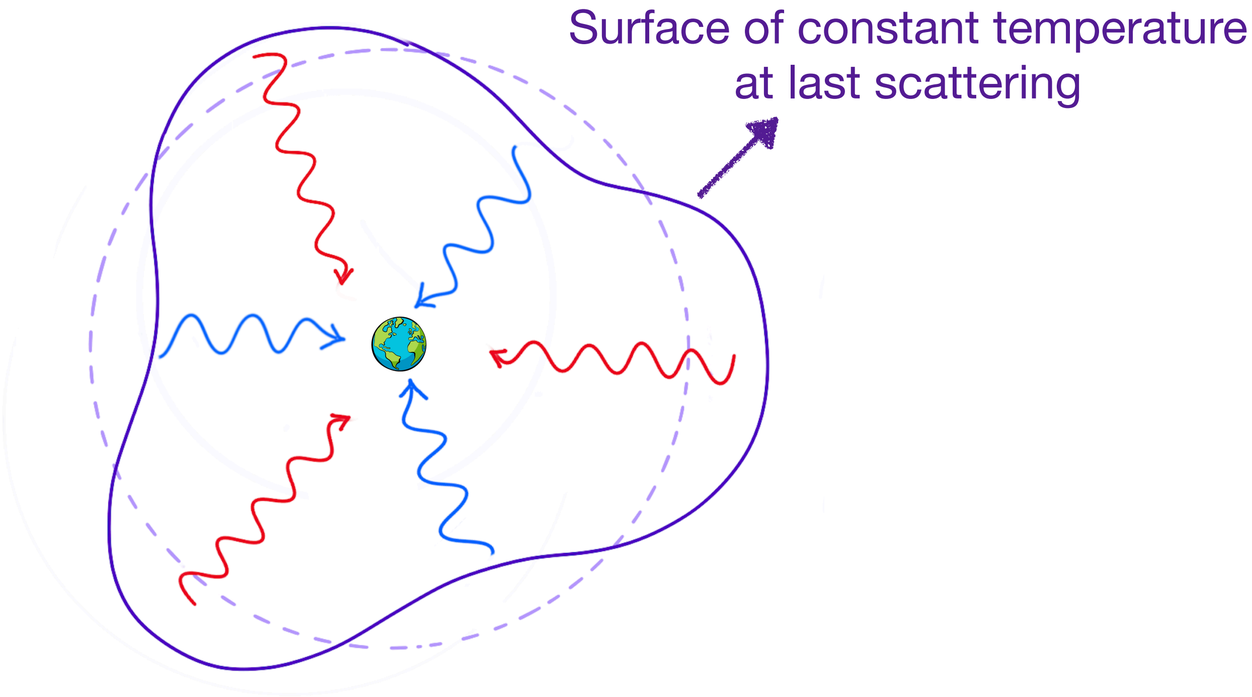
Case 1: Gravitational waves from a phase transition

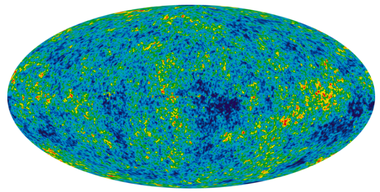




Extensions of SM have PTs at $T_c \sim 1 - 1000$ TeV. Frequency of GW from such PTs would be redshifted to $10^{-4} - 10^{-1}$Hz today, which is the target frequency range of many proposed space-based experiments such as LISA, BBO, etc.

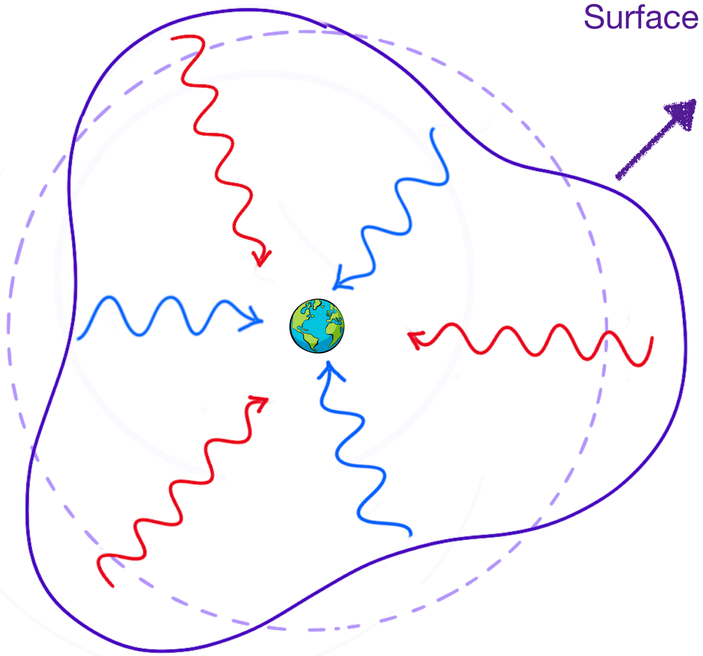
Recap: CMB anisotropies

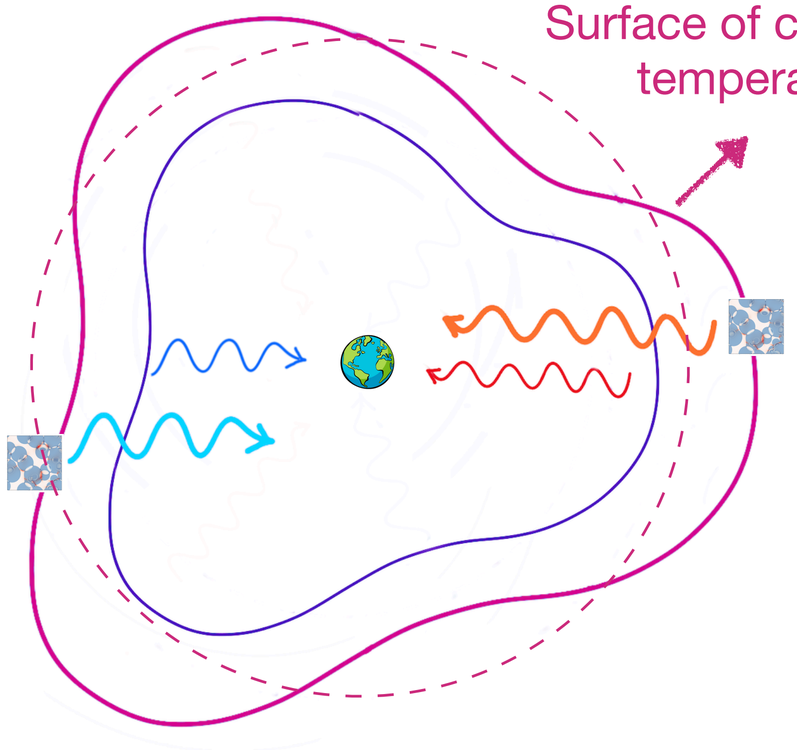


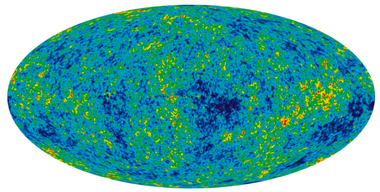


$$\delta_{\rm CMB} \equiv \frac{\Delta T}{\bar{T}} \sim 10^{-5}$$

GWB anisotropies







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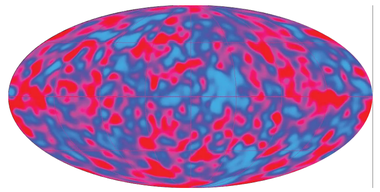
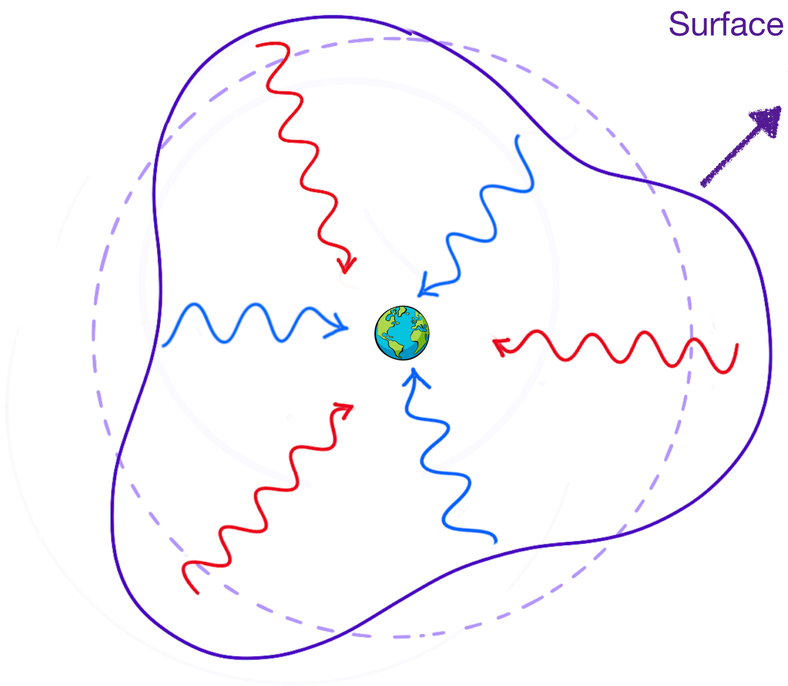
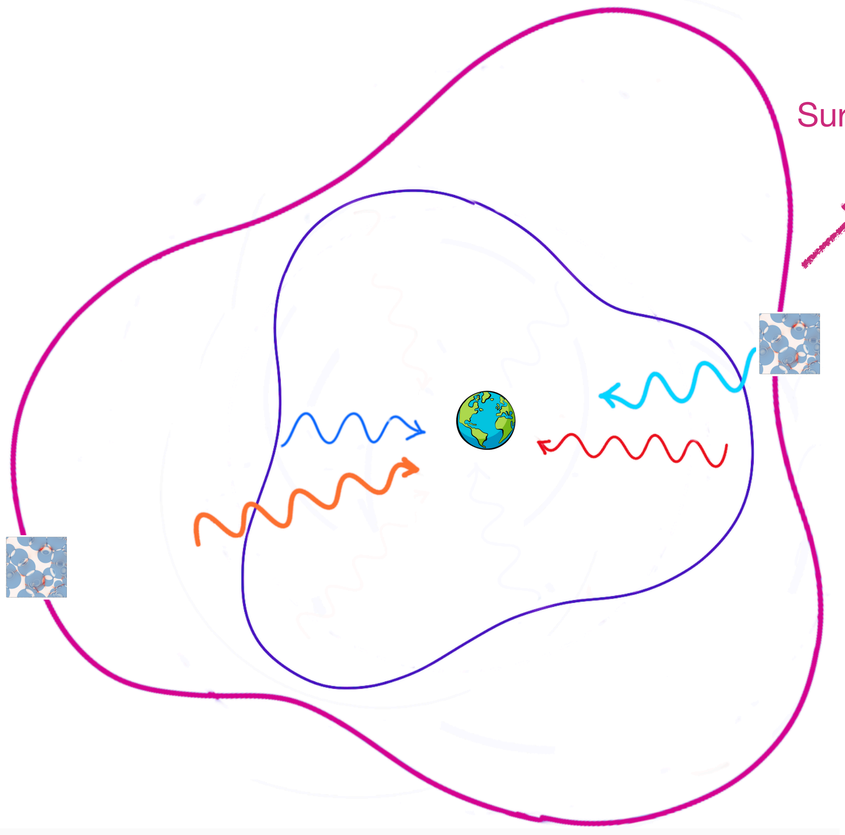
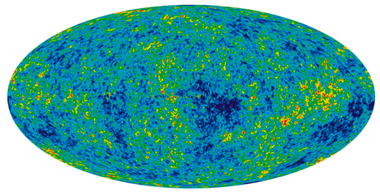


$$\delta_{\rm GW} \equiv \frac{\Delta \rho_{\rm GW}}{\bar{\rho}_{\rm GW}} \sim 10^{-5}$$

Isocurvature GWB anisotropy







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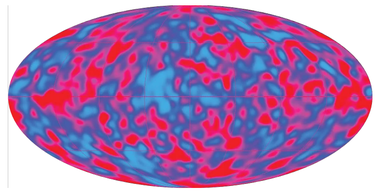
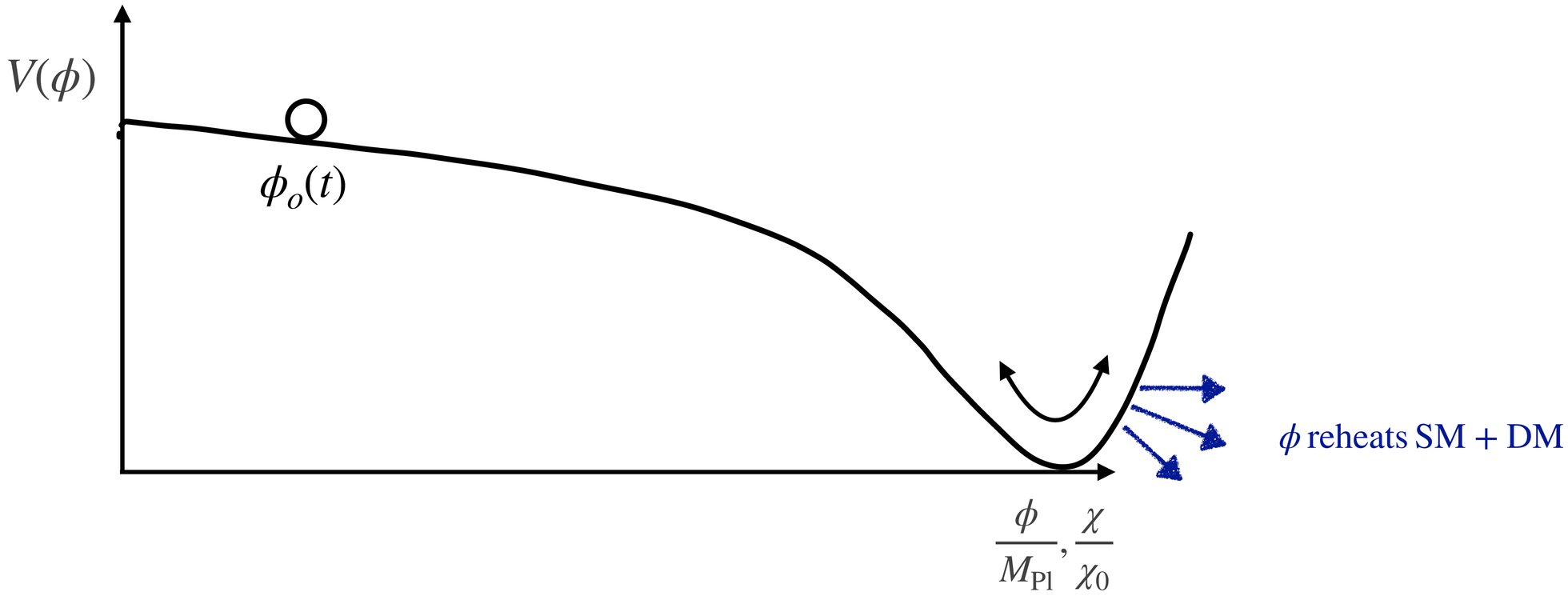


$$\delta_{\rm GW} \equiv \frac{\Delta \rho_{\rm GW}}{\bar{\rho}_{\rm GW}} \neq 10^{-5}$$

Multi-field inflation: Inflaton + ALP (χ)



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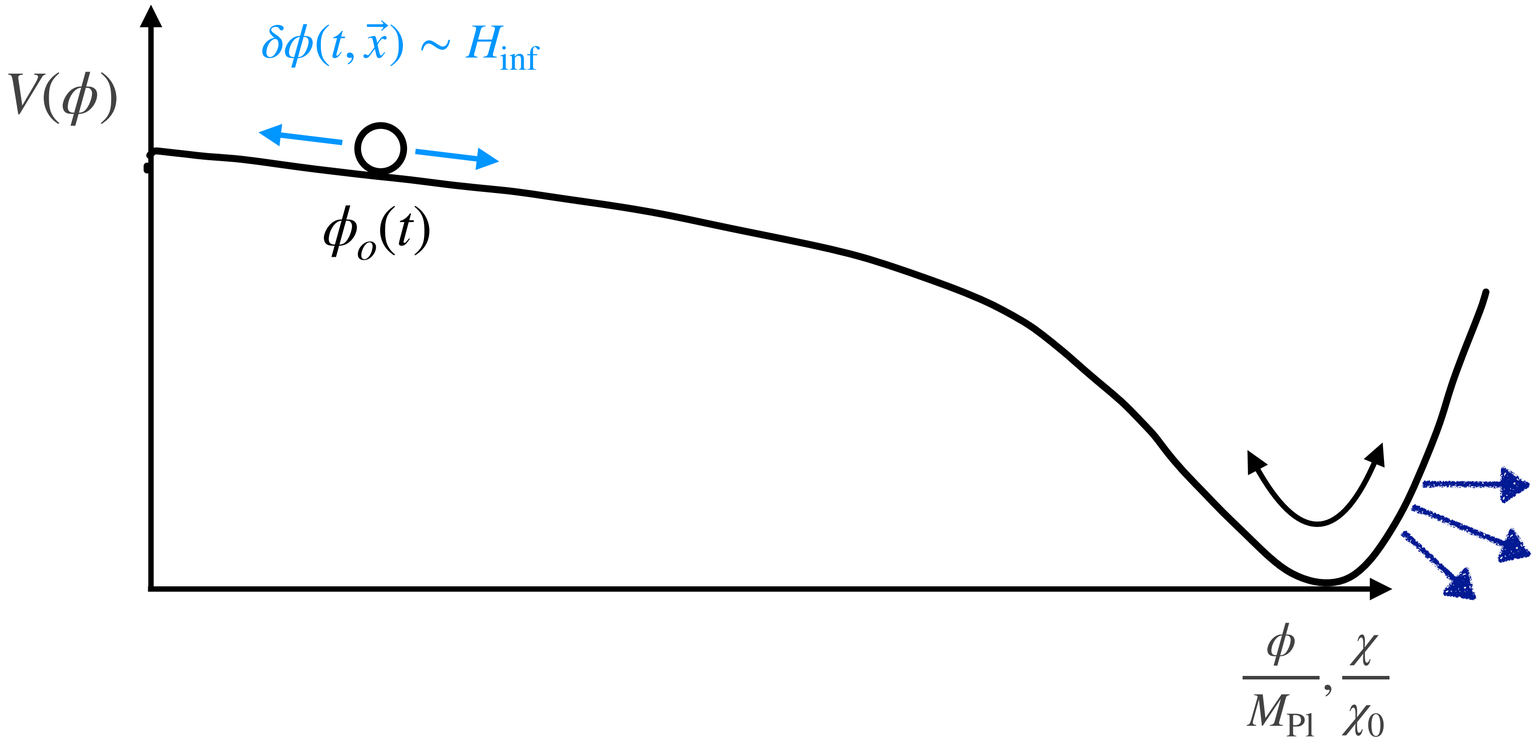

ϕ reheats SM + DM

$$\delta_{\rm SM} \equiv \left.\frac{\Delta V}{V}\right|_{\phi} \sim \frac{H_{\rm inf}\,\delta\phi}{\dot{\phi}_0}$$

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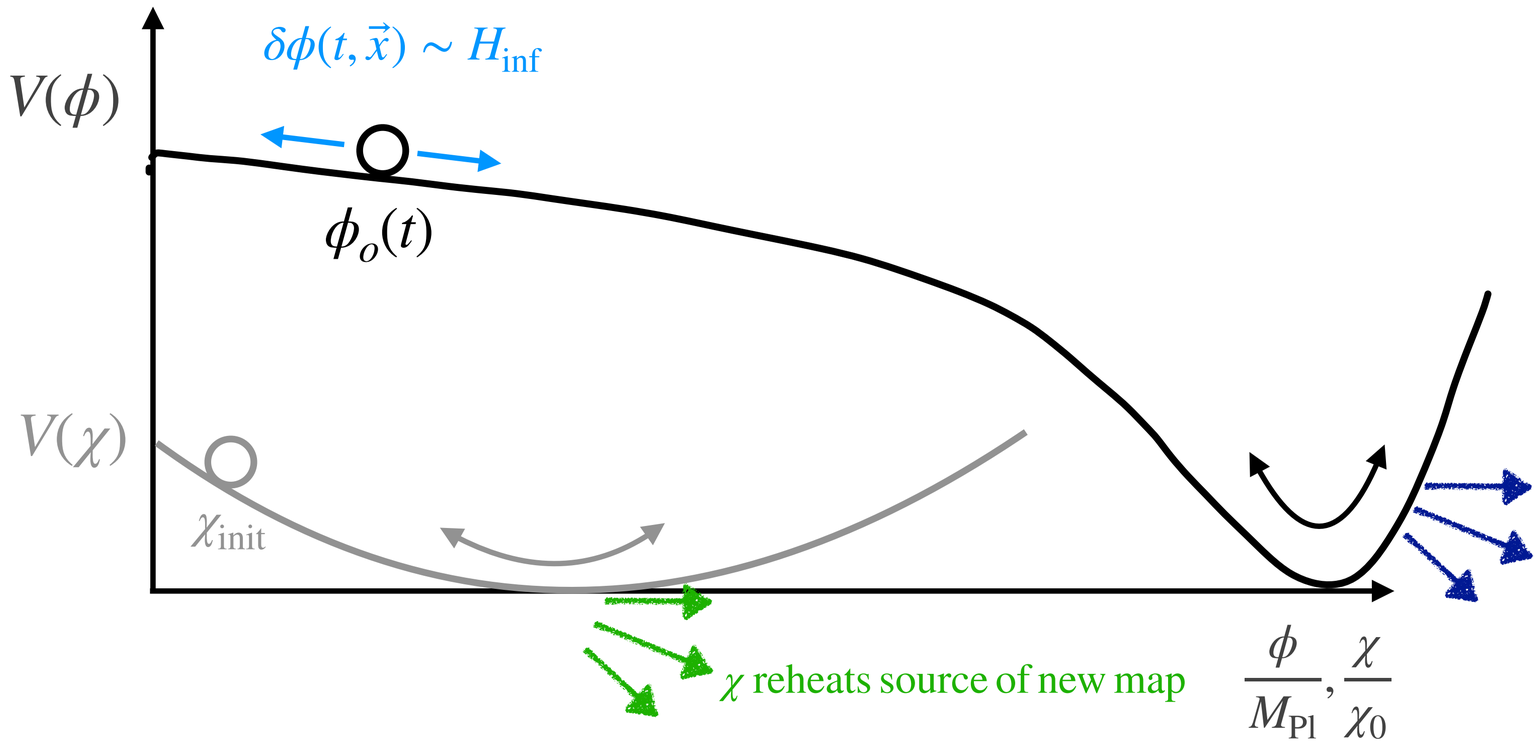

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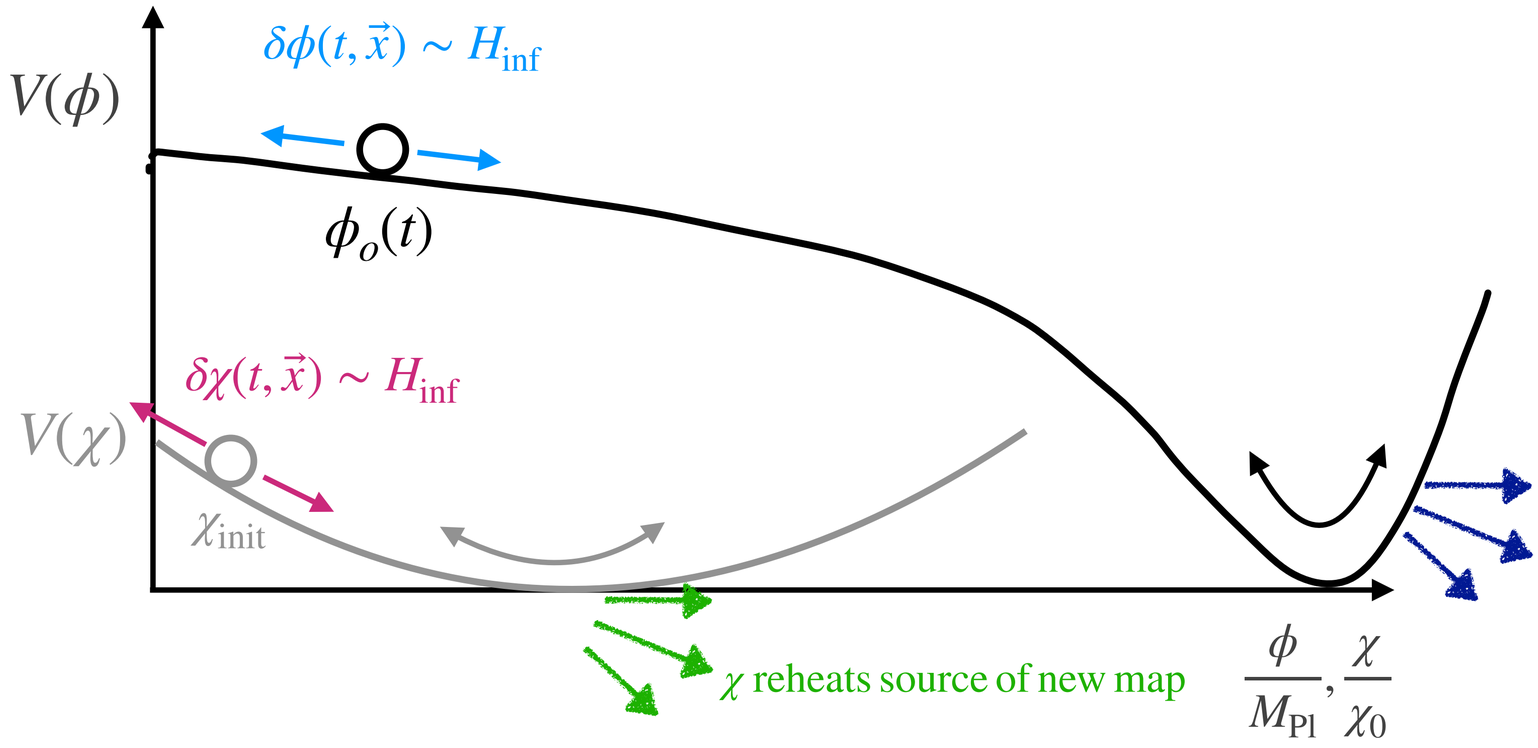


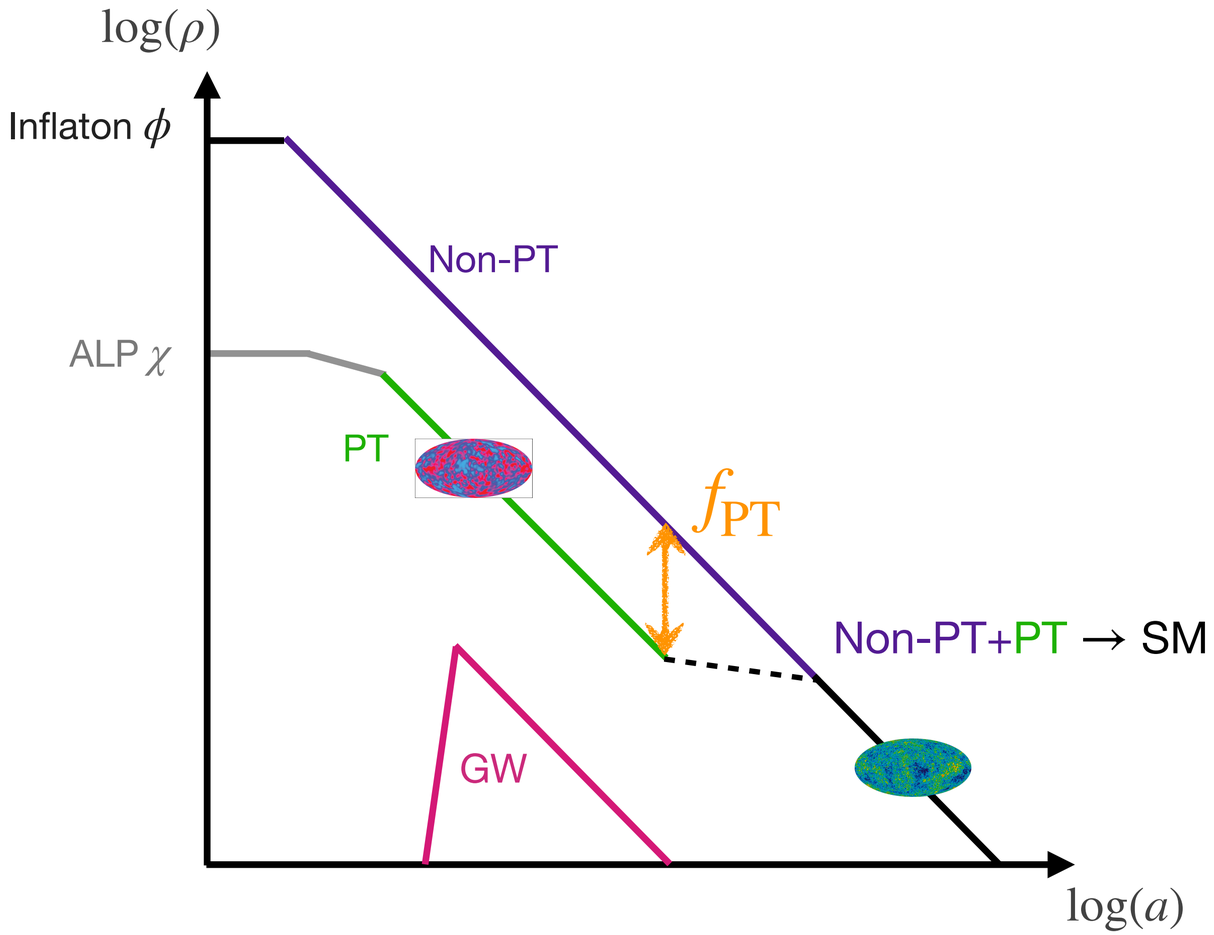
ϕ reheats SM + DM

$$\delta_{\rm SM} \equiv \left.\frac{\Delta V}{V}\right|_{\phi} \sim \frac{H_{\rm inf}\,\delta\phi}{\dot{\phi}_0}$$

$$\delta_{\rm new} \equiv \left.\frac{\Delta V}{V}\right|_{\chi} \sim \frac{\delta\chi}{\chi_{\rm init}}$$

A model of isocurvature GWB

Geller, Hook, Sundrum, Tsai 1803.10780



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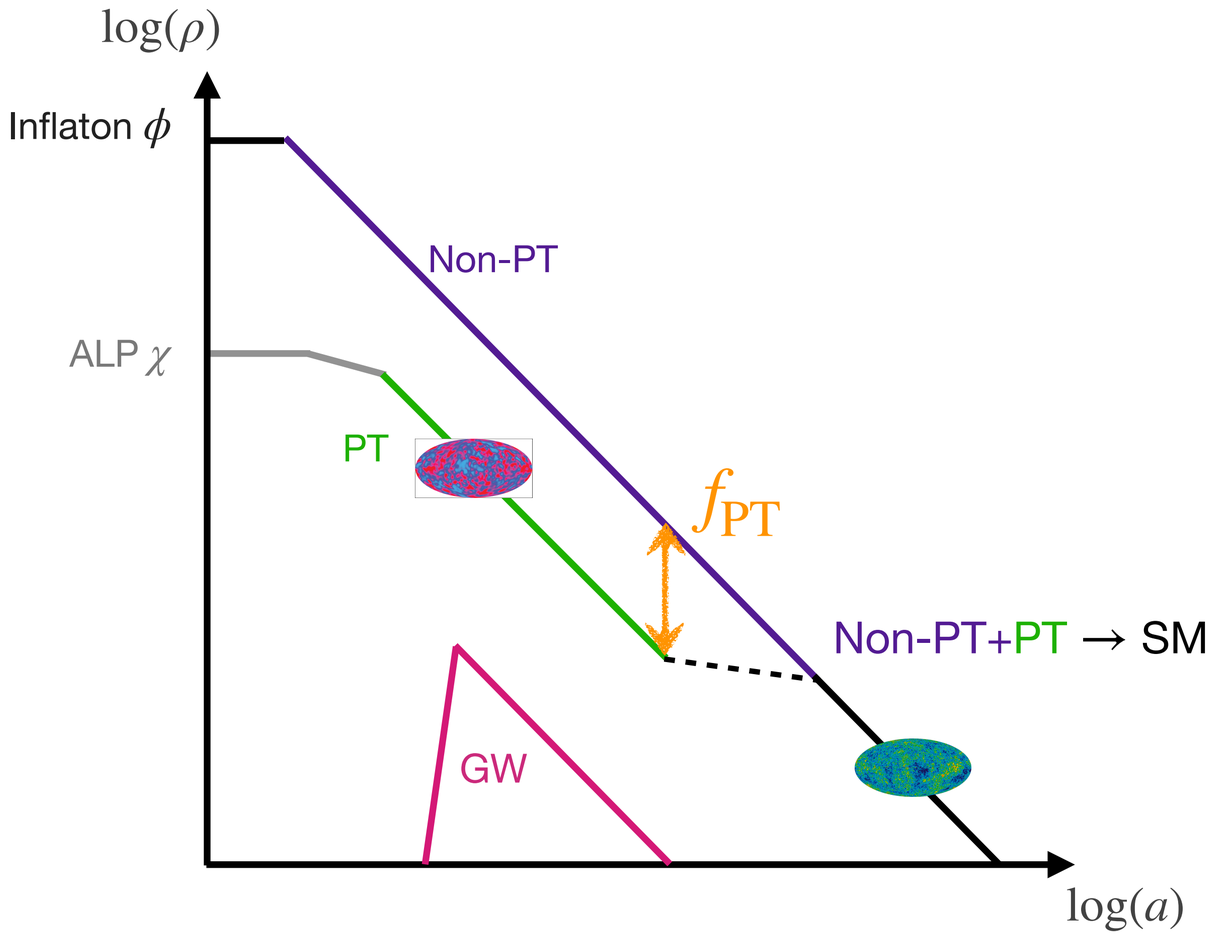

$$\delta_{GW} \sim \delta_\chi + \delta_\phi$$

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

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

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

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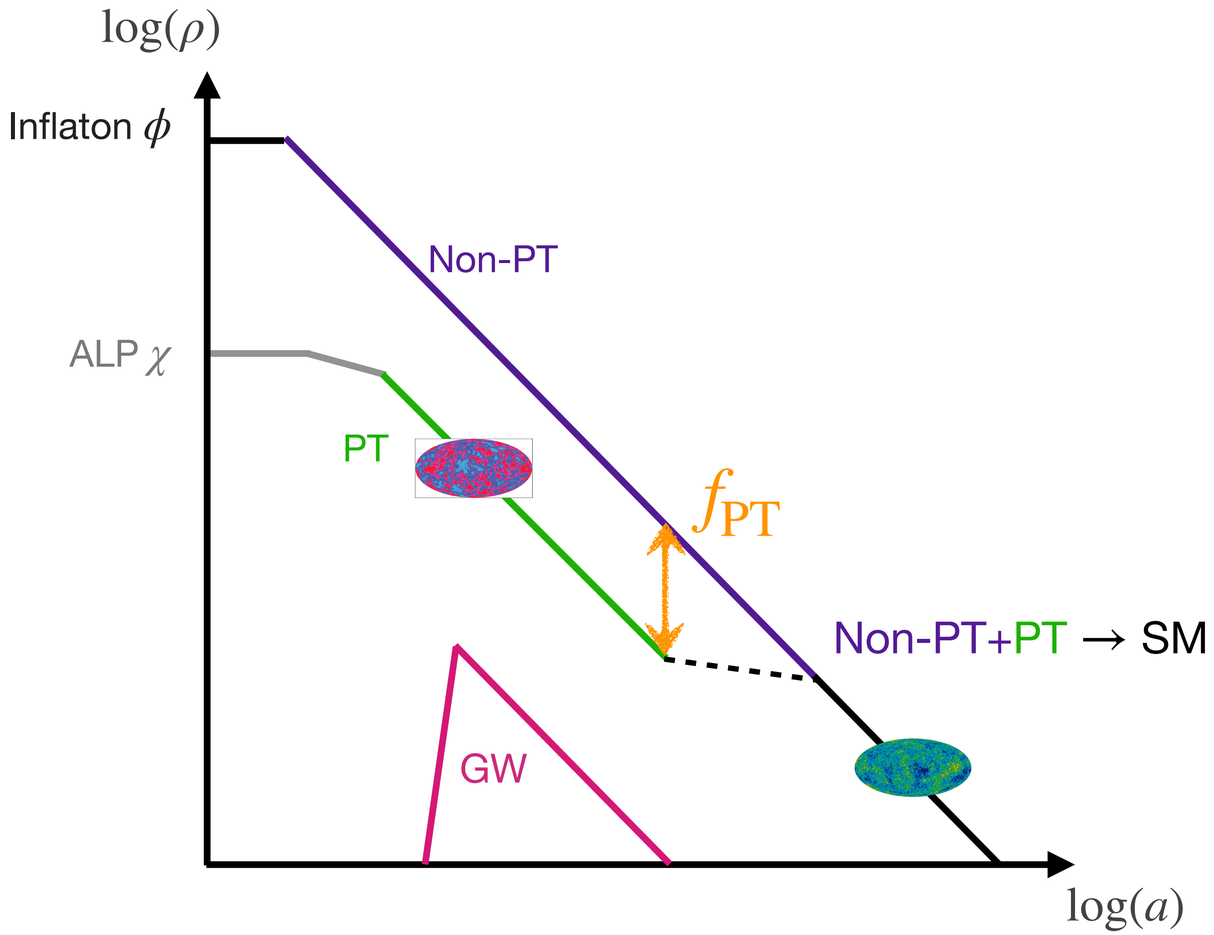

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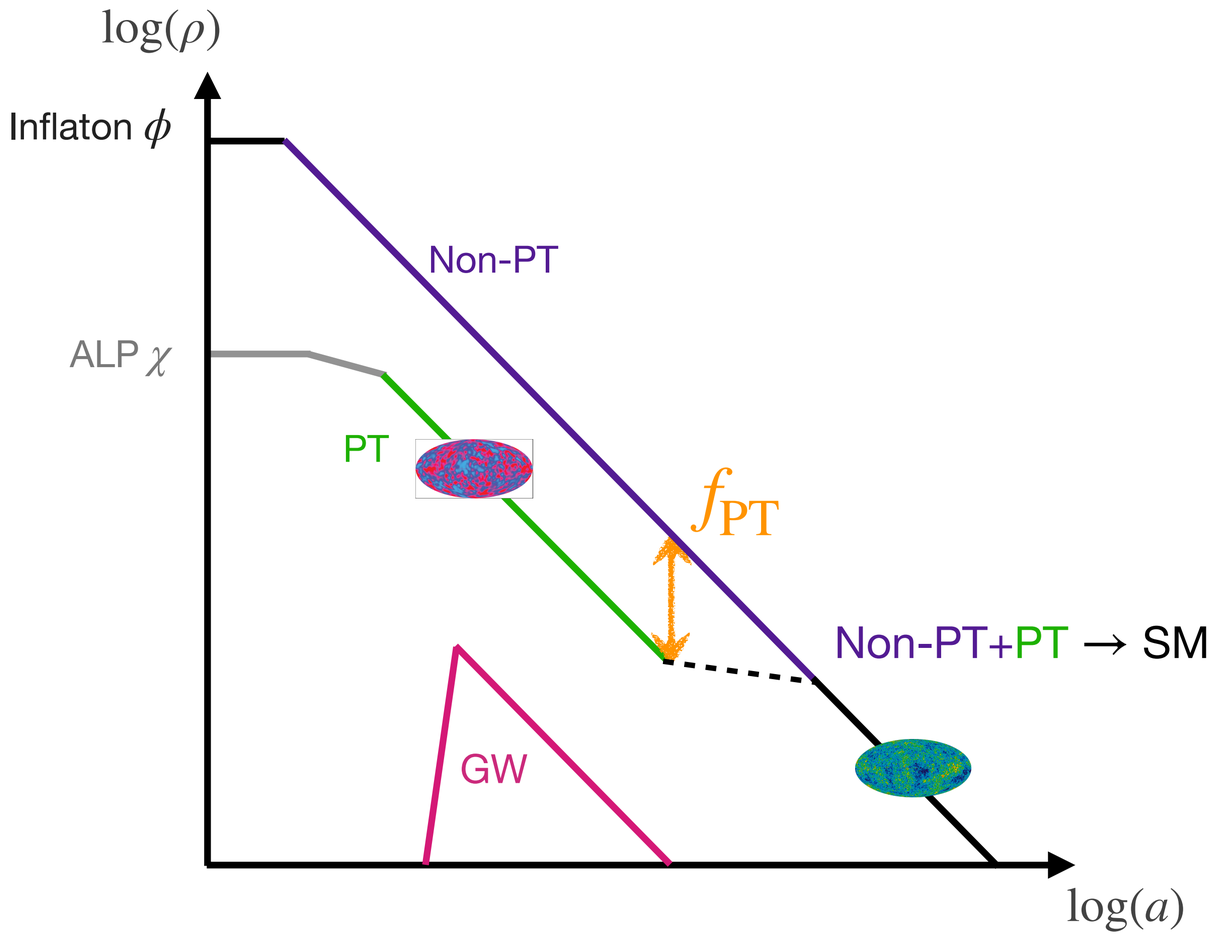
$$\boxed{\delta_\chi \gg \delta_\phi}$$

The tradeoff



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

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

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

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

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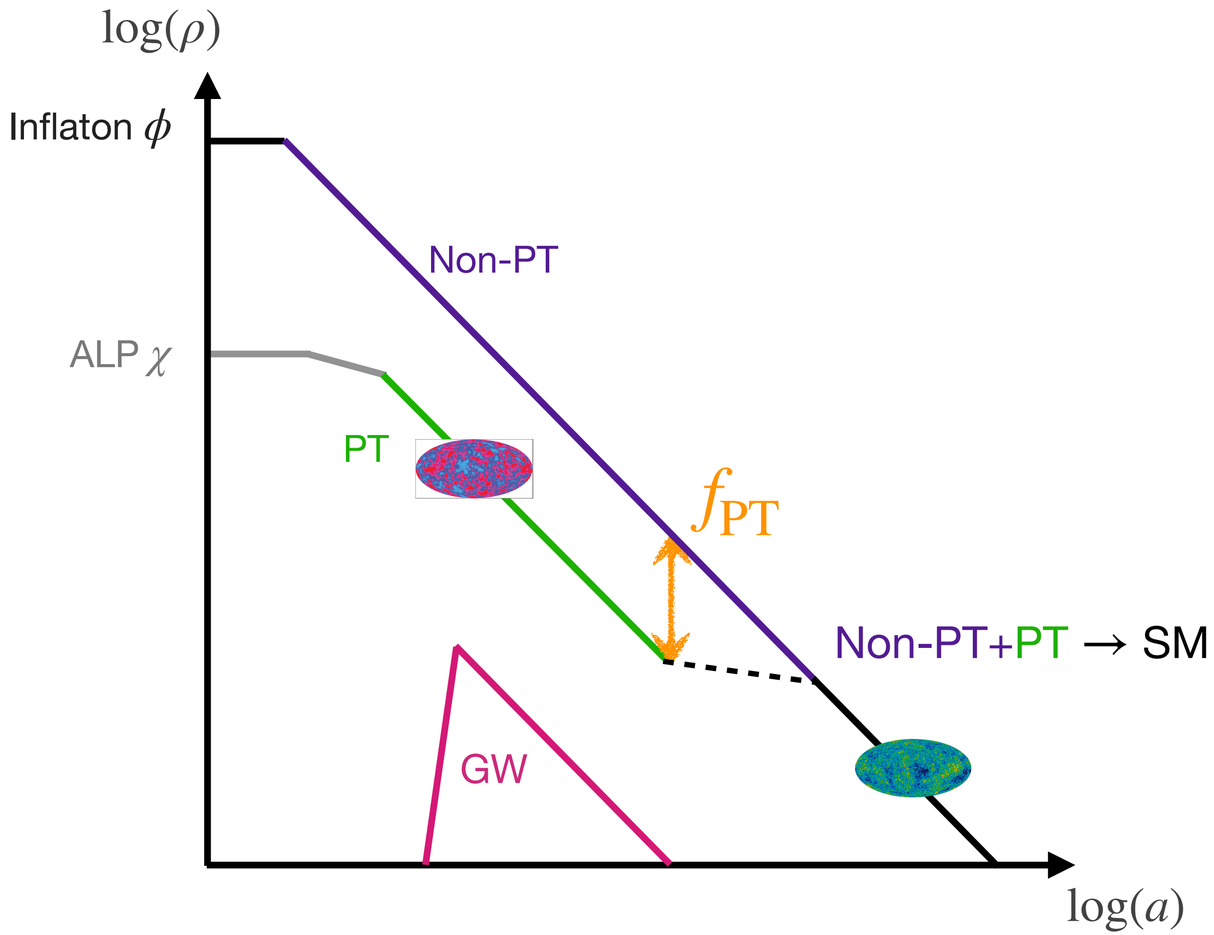

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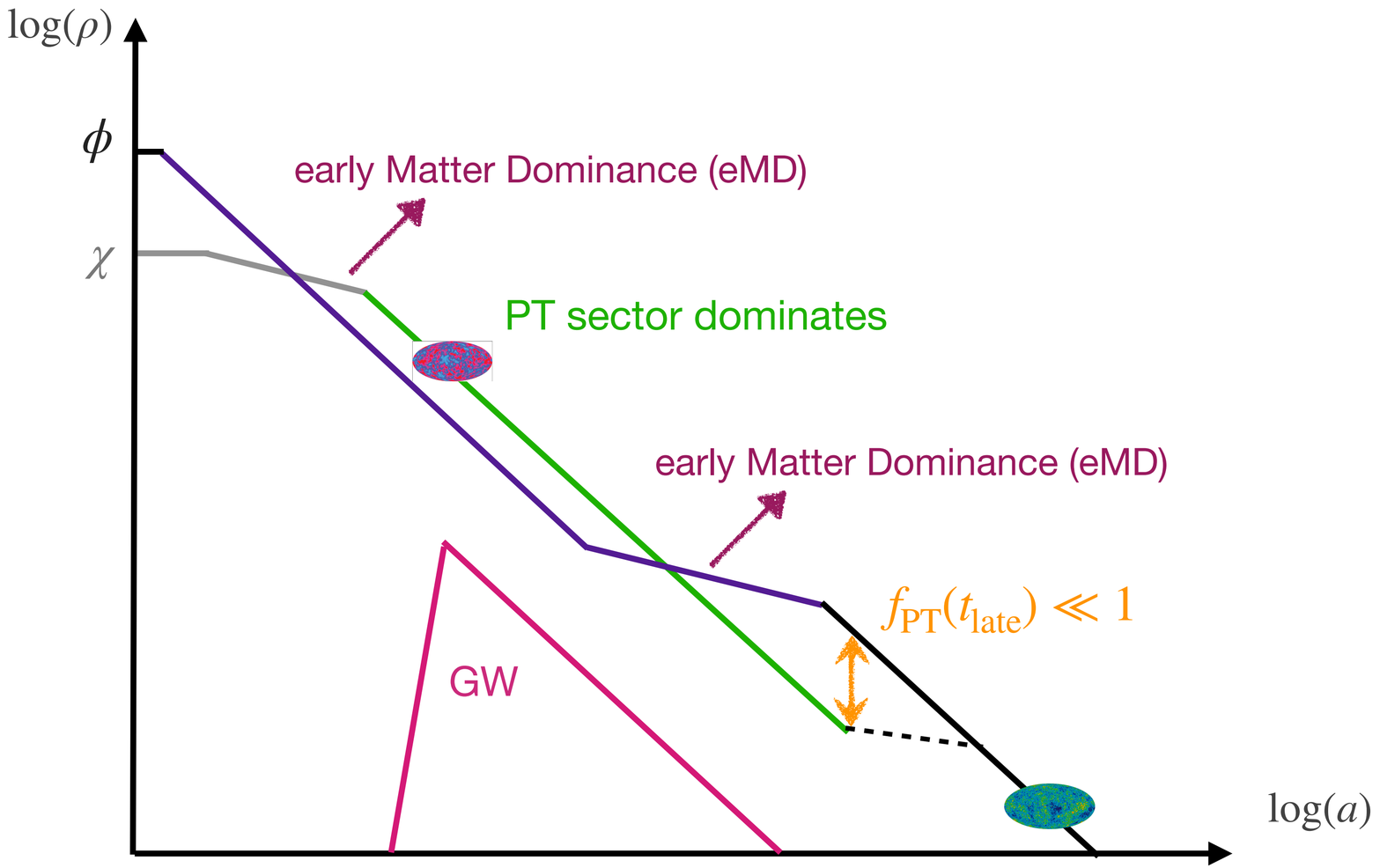
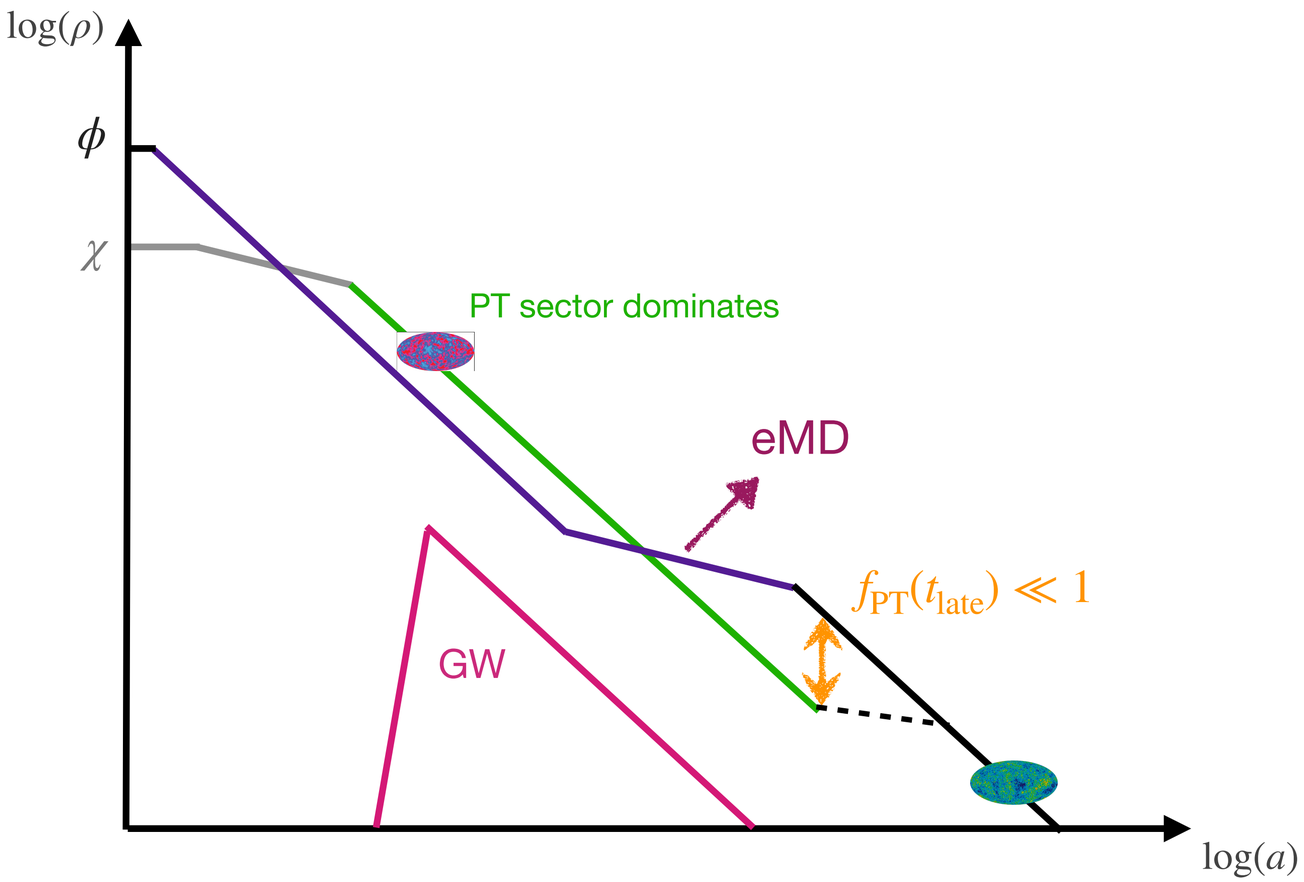
Can the PT sector be dominant during phase transition?

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



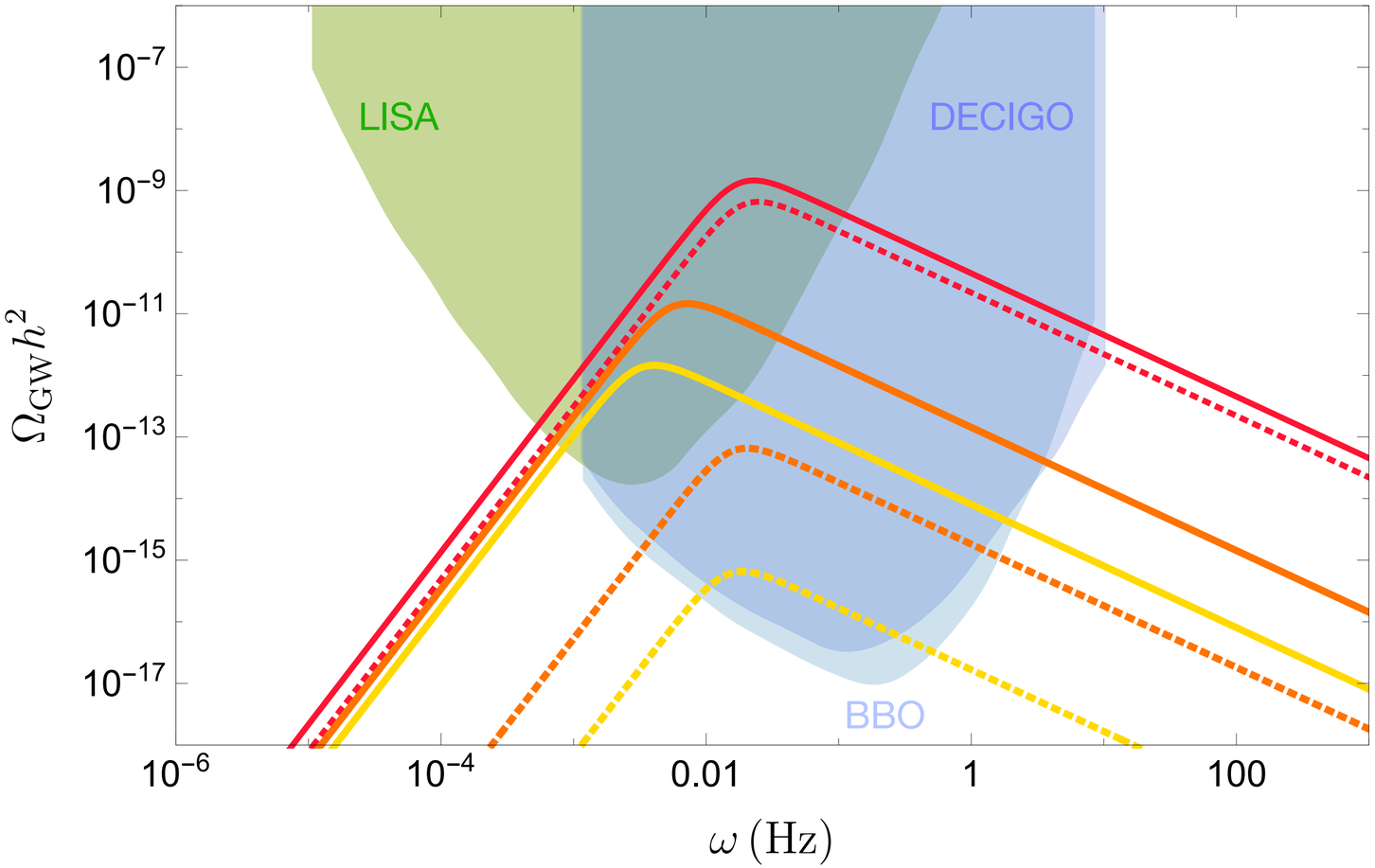


No suppression at production

Relative dilution from eMD

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

Improvement in the GWB signal



Dashed lines: Simple model

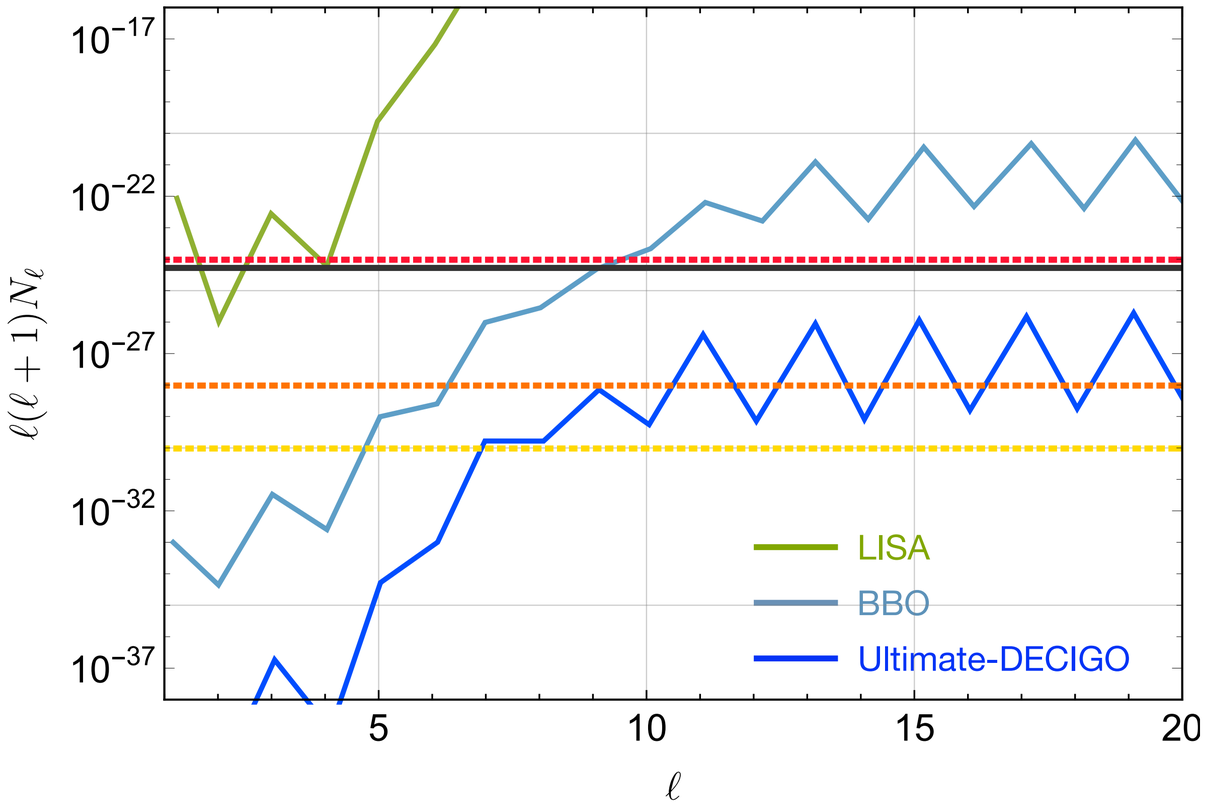
Solid lines: eMD model

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

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

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

Detectability of large anisotropy



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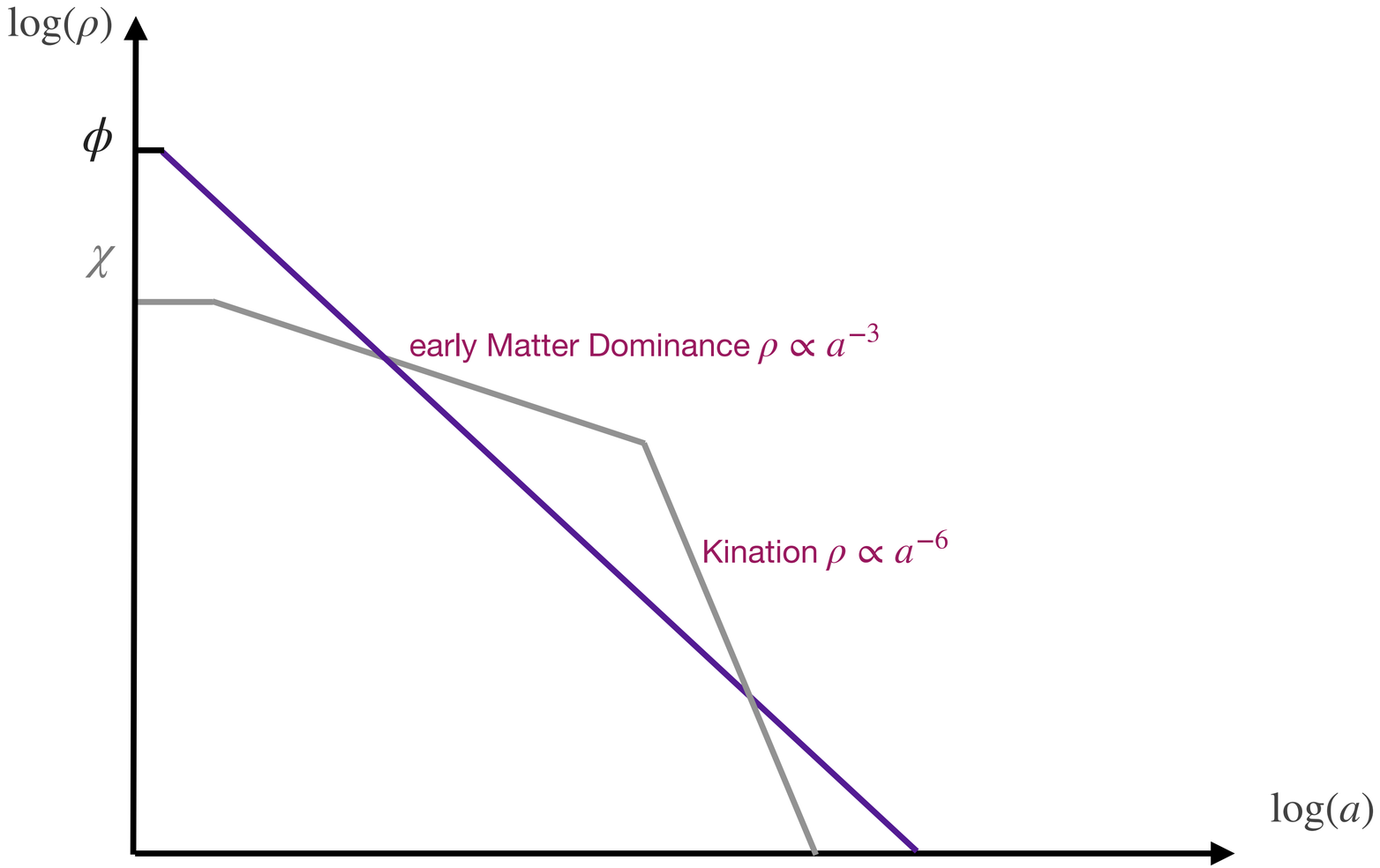
$\delta_{\rm GW} \sim 10^{-1}, f_{\rm PT} \sim 10^{-4}$

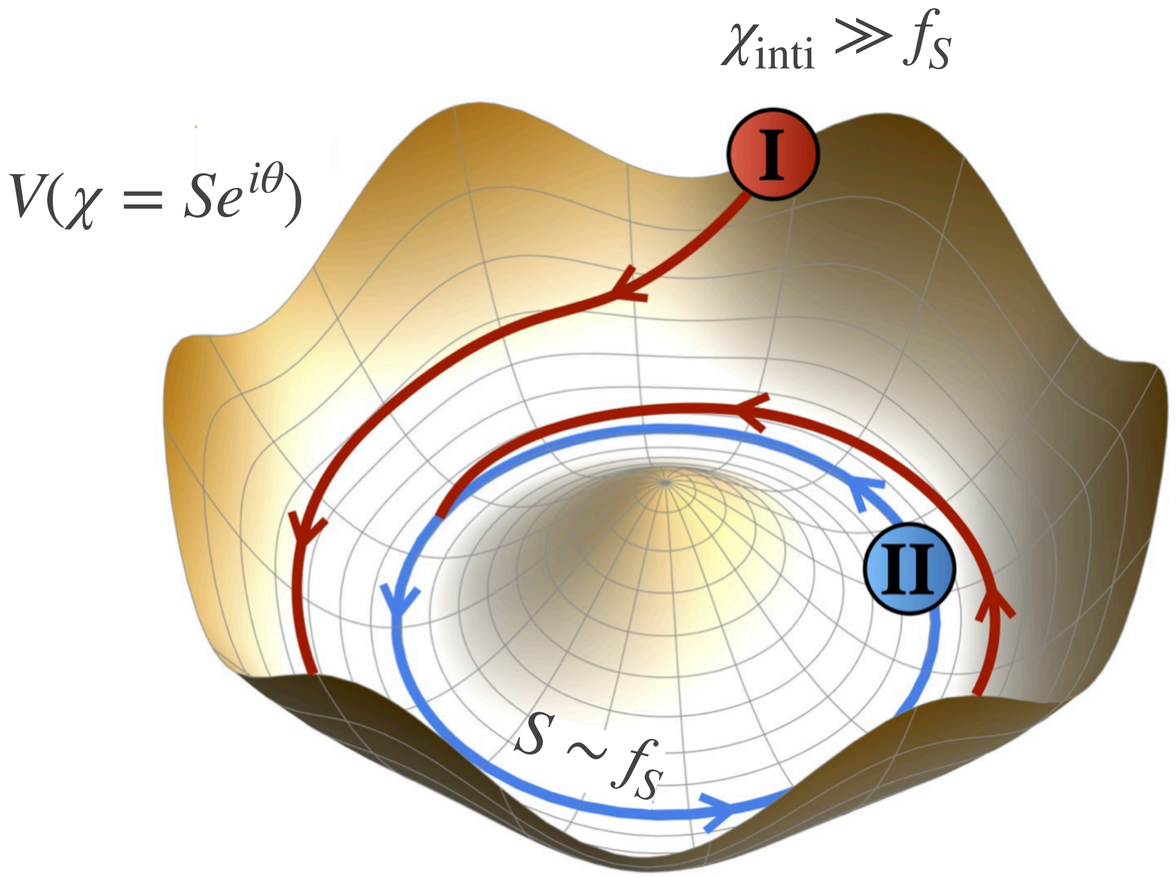
Another possibility

Matter domination followed by a period of kination: rotating ALP field
Induced gravitational waves from large scalar perturbations at small scales



Rotating ALP field

K. Harigaya, R. Co 1910.02080



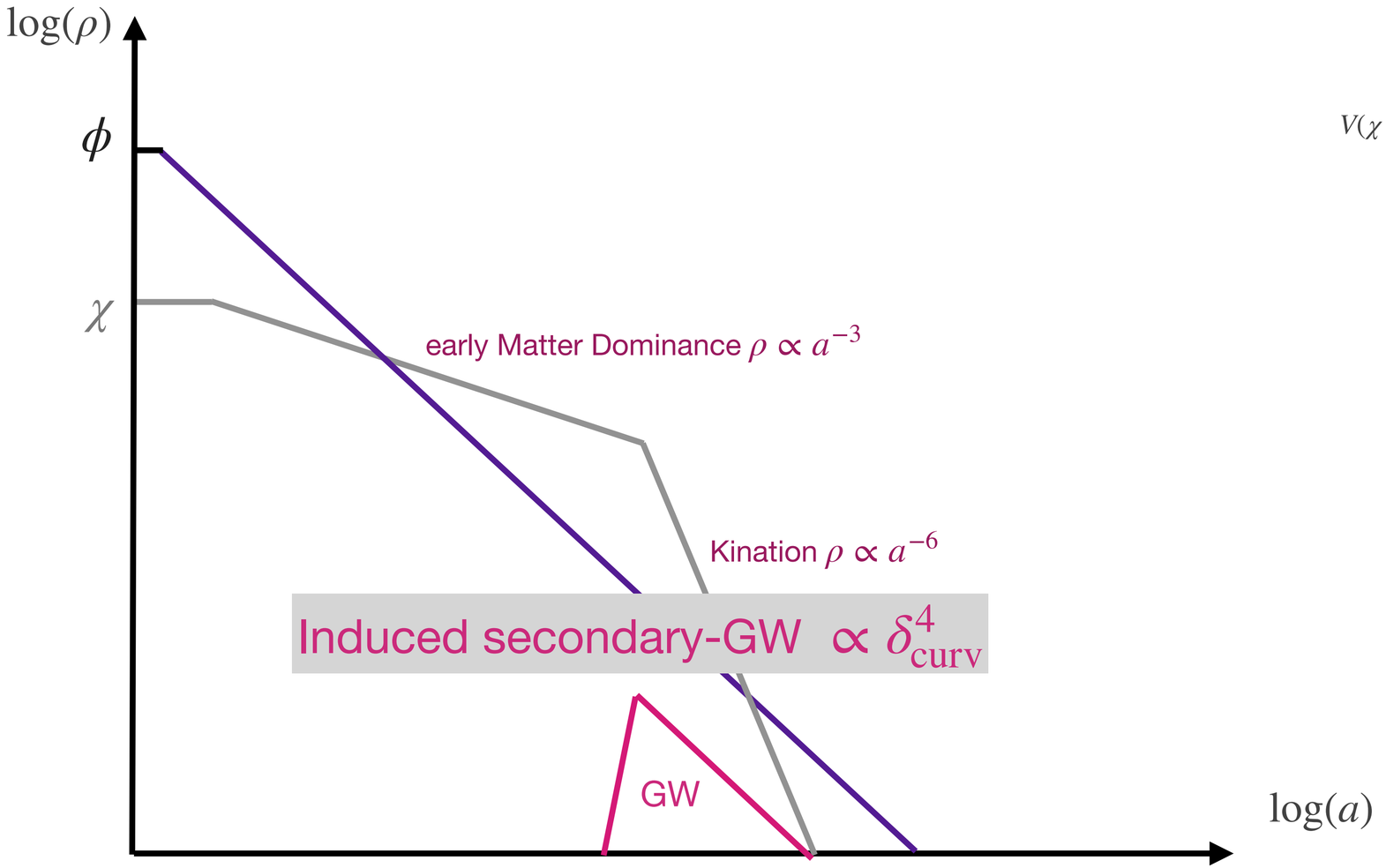
I : matter phase

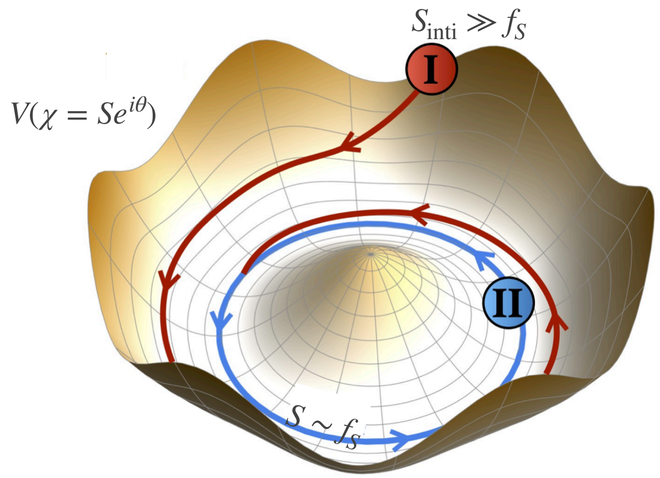
II : kination phase

Fig. from Y. Gouttenoire et al. 2111.01150

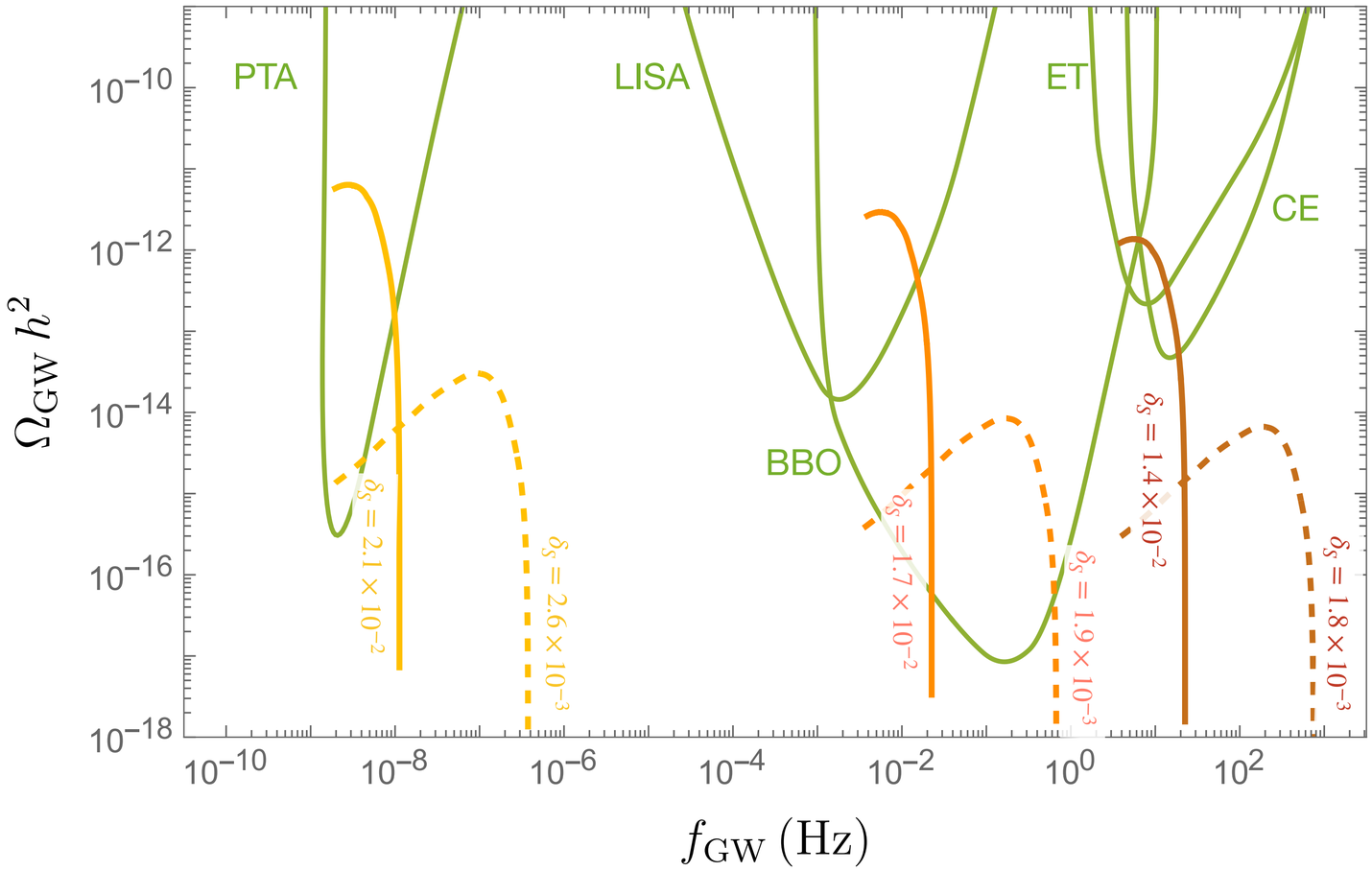
Case 2: Induced secondary-GW

Matter domination followed by a period of kination: rotating ALP field





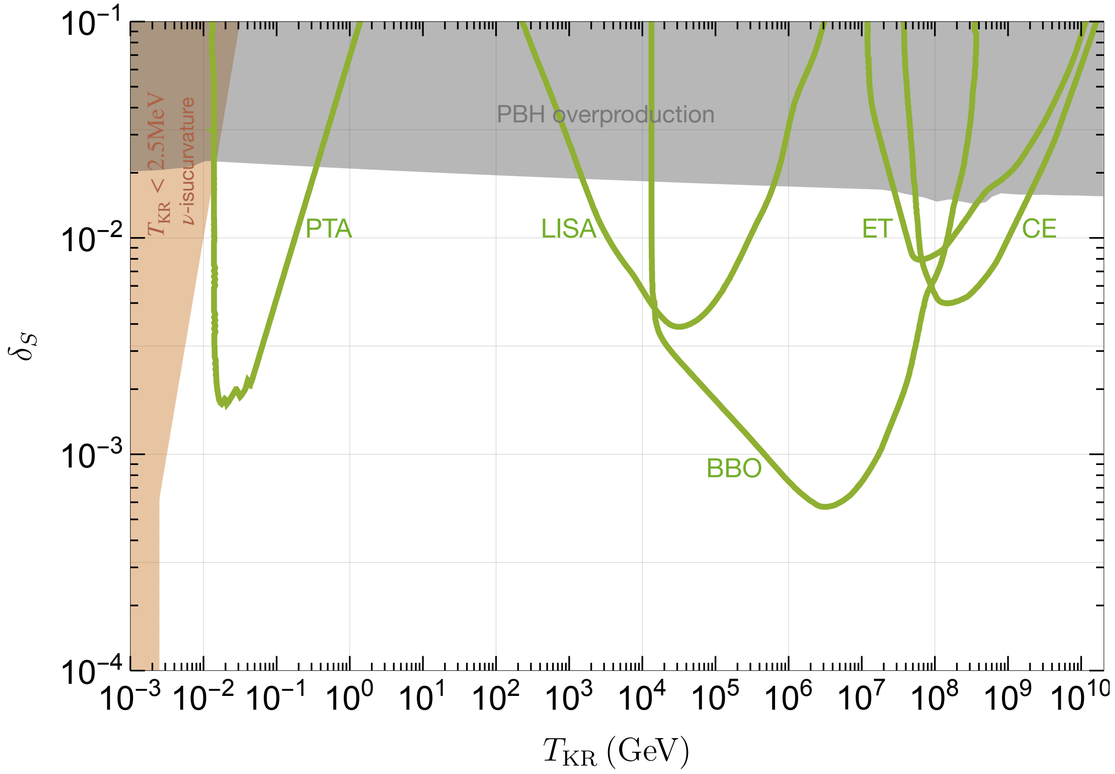
In progress…



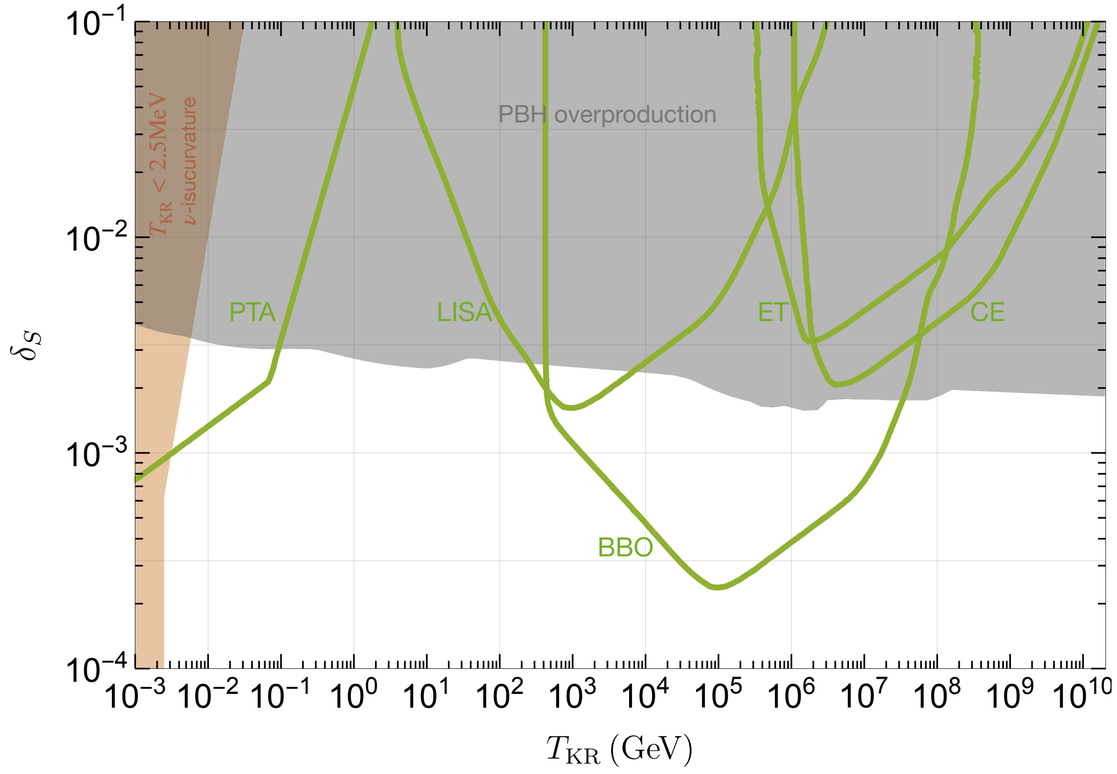
Short eMD (~ 3)

Long eMD (~ 100)

In progress…



Short eMD ~ 3



Long eMD ~ 100

Summary

- There can be new cosmological fluctuation maps significantly different from CMB.
- Such maps can be realized in GWB (first-order phase transition, induced secondary-GW).
- GWB with large (large scale) fluctuations are interesting both experimentally and theoretically.
- Modified post-inflationary cosmologies play an important role in the observability of these highly anisotropic GWB.

Summary

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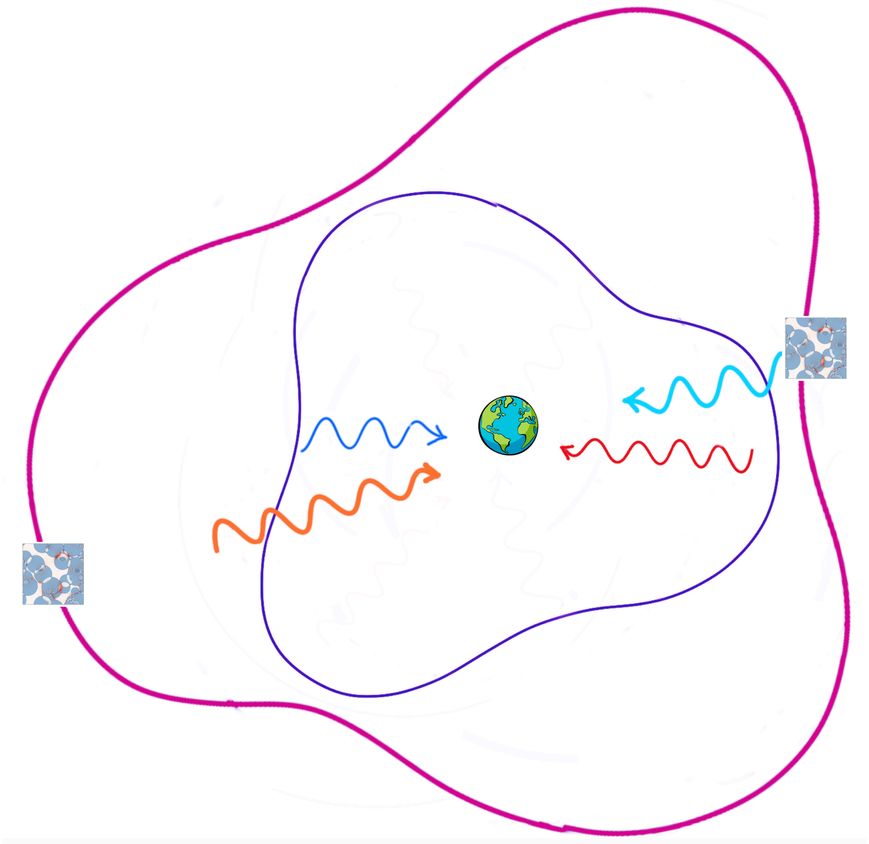
- GWB with large (large scale) fluctuations are interesting both experimentally and theoretically.
- Modified post-inflationary cosmologies play an important role in the observability of these highly anisotropic GWB.

Thank you!

Back-up slides

Bubbles are unresolvable



Caution: Zoomed in!

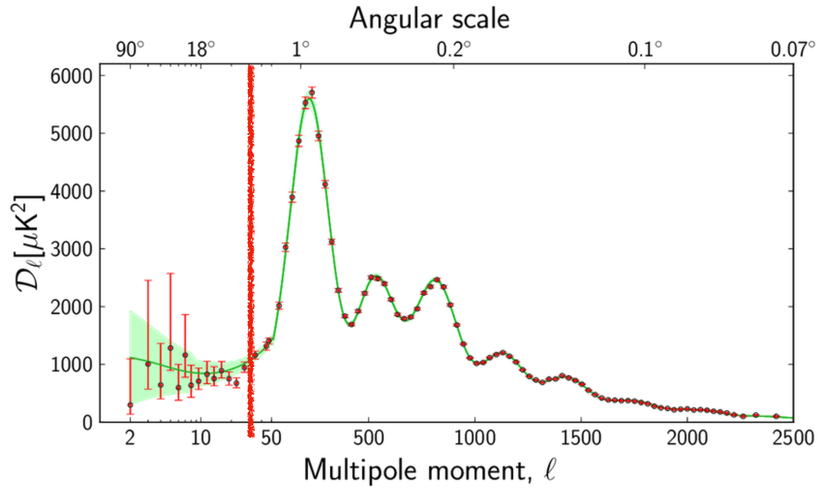
$> 10^{18}$ bubble collisions/arcsec^2

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

GWB is a “pristine” map

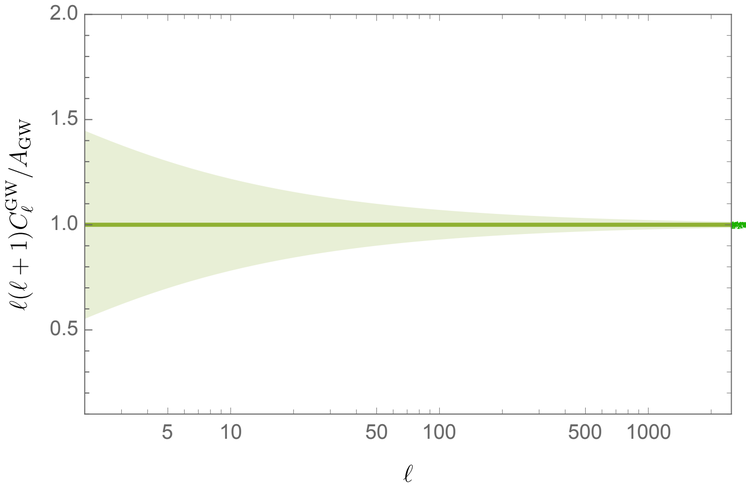
Earlier production + free-streaming of GW → large range of scales is unaltered by sub-horizon physics

CMB



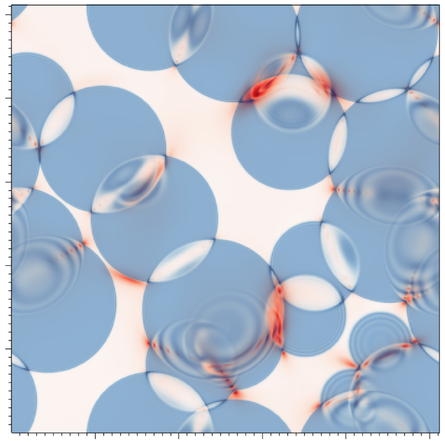
Planck

GWB



$\ell \sim 10^{14}$

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

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

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

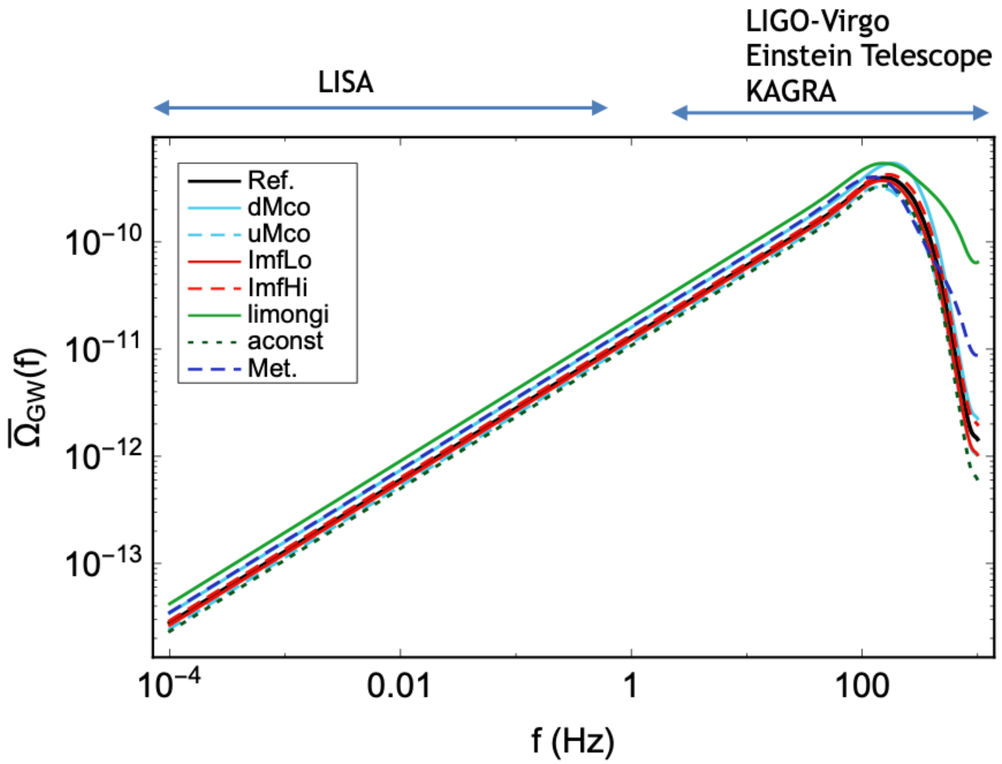
$$r \sim \Delta t_{\rm PT} \equiv \beta^{-1}$$

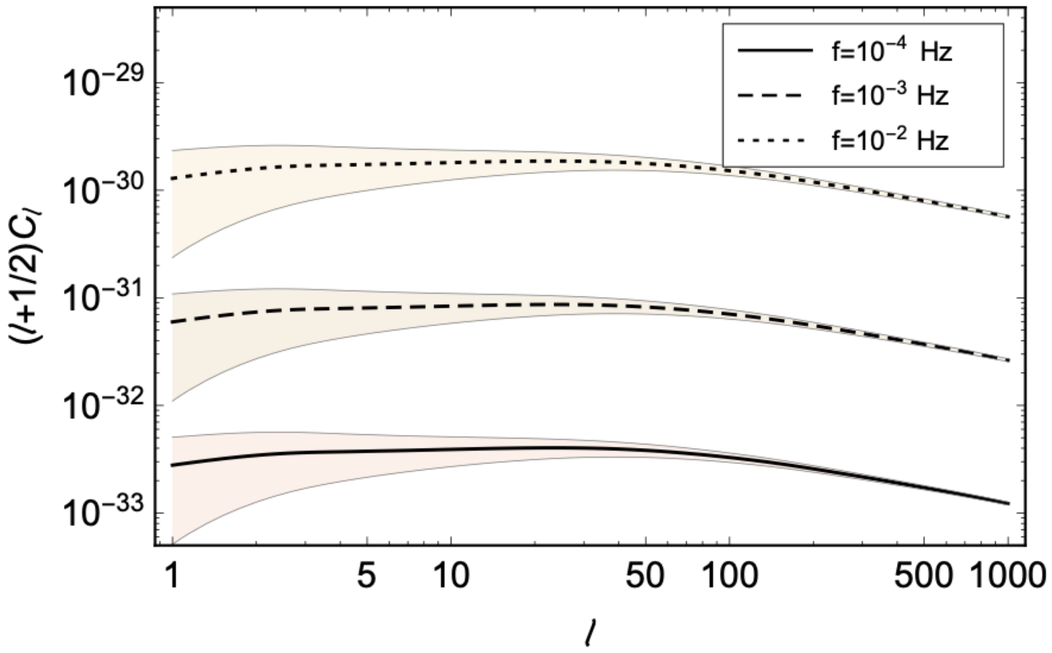
GW energy density released in bubble collision

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

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