Title: TBA - Particle Physics Seminar

Speakers: Arushi Bodas

Collection/Series: Particle Physics

Subject: Particle Physics

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Anisotropic Gravitational Wave Backgrounds from Rotating Axions

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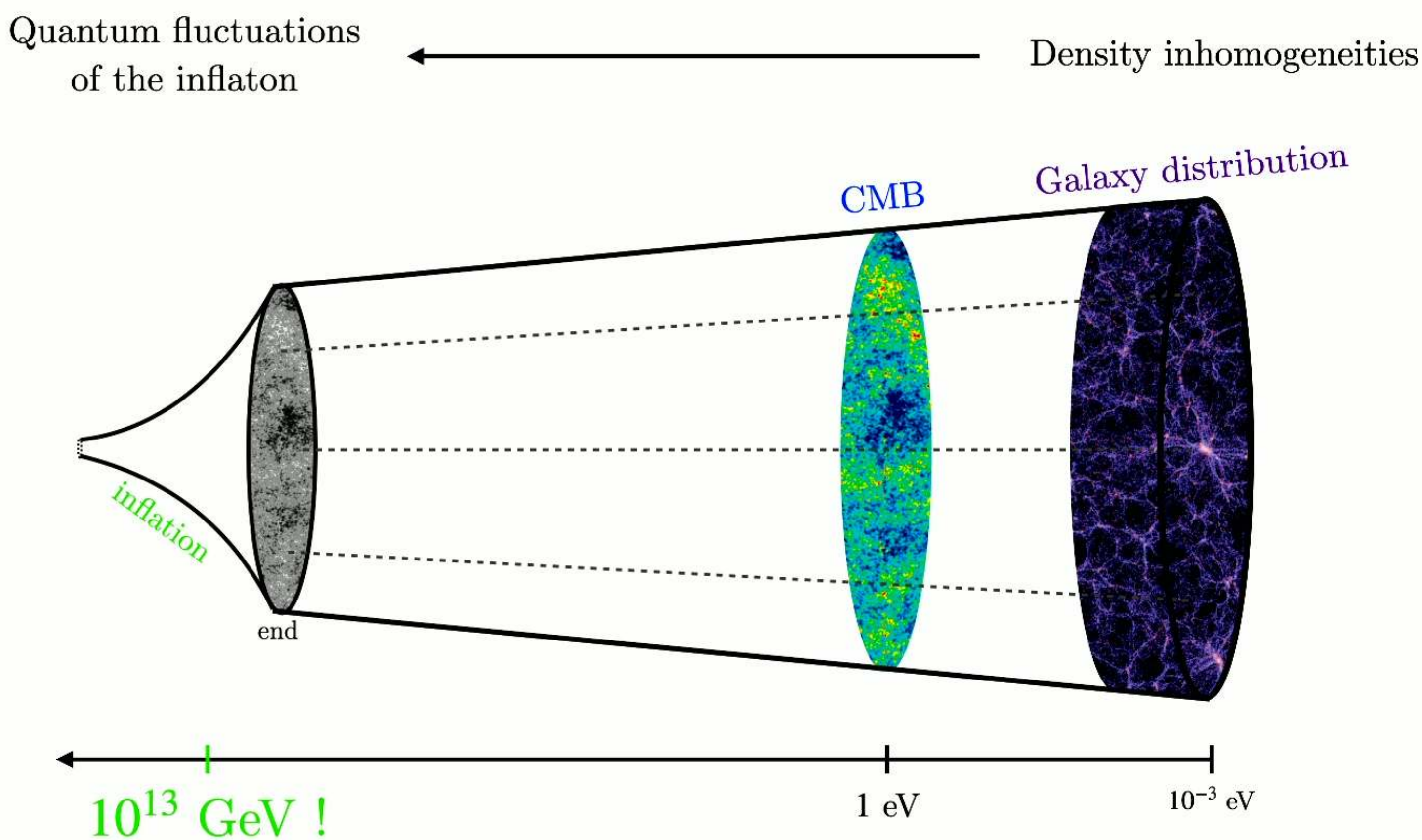
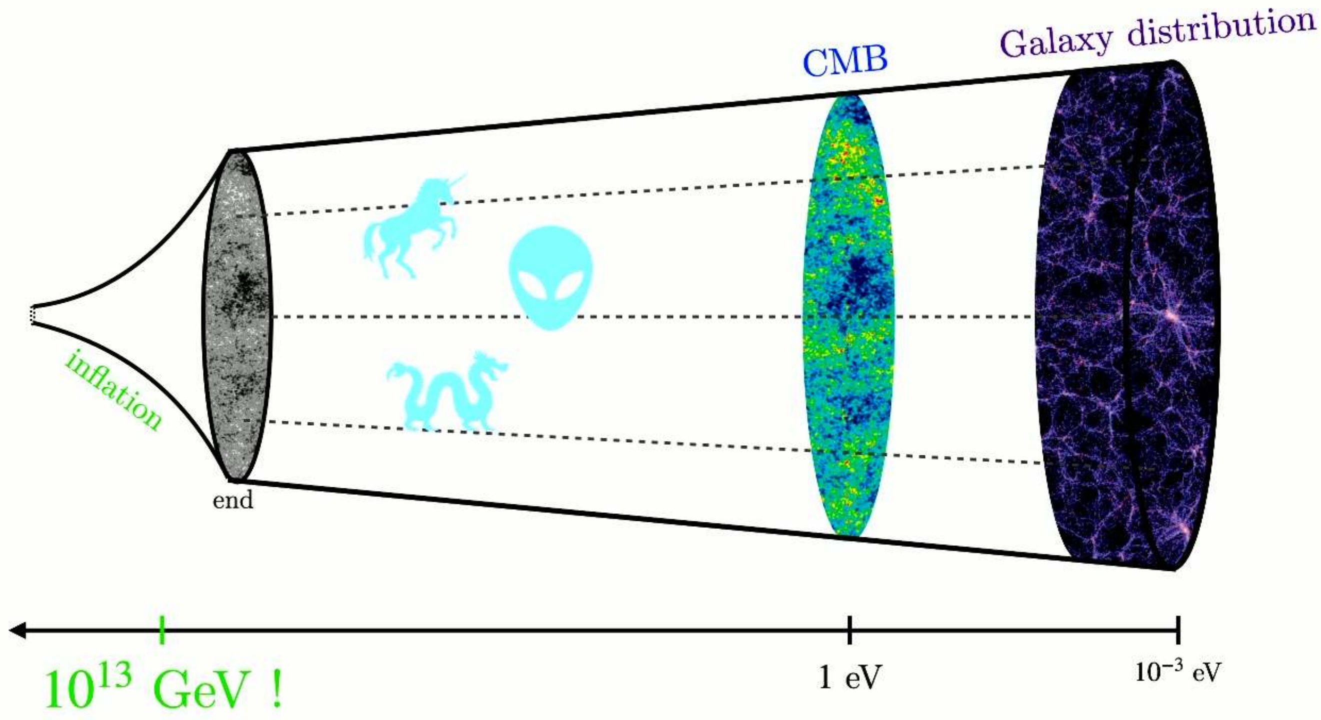
Based on: AB, K. Harigaya, K. Inomata, T. Terada, L-T Wang, 2508.08249


Quantum fluctuations
of the inflaton
Density inhomogeneities
CMB
Galaxy distribution
inflation
end
10^{13} GeV !
1 eV
10^{-3} eV

Superhorizon freezing protects these correlations.



Anisotropy maps give a robust and faithful window into inflation.

Correlations can tell us about the model of inflation, and the field content and interactions during inflation.

- Power spectrum - Polynomial potentials for the inflaton heavily constrained

  Turns in the field trajectory, axion monodromy models

  $$\frac{\delta P_\zeta}{P_\zeta} \propto \sin\left(\nu \frac{k}{k_*}\right), \sin\left(\nu \log \frac{k}{k_*}\right)$$

- Local non-gaussianity - Multi-field inflation (Curvaton model, modulated reheating, hybrid inflation)
- Equilateral non-gaussianity - Reduced sound speed, DBI inflation
- Non-analytic features - Cosmological collider

  $$B(\vec{k}_1, \vec{k}_2, \vec{k}_3) \propto e^{-\pi \frac{m}{H_{\rm inf}}} \left(\frac{k_S}{k_H}\right)^{3/2} \sin\left(\frac{m}{H_{\rm inf}} \log \frac{k_S}{k_H} + \varphi(m)\right)$$

  AB, E. Broadberry, R. Sundarum, 2409.07524
  AB, E. Broadberry, R. Sundarum, Z. Xu, 2507.22978

  Discriminate between inflation and ekpyrosis

  $$a(t) = e^{H_{\rm inf} t} \to \sin\left(\frac{m}{H_{\rm inf}} \log \frac{k_S}{k_H} + \varphi(m)\right) \qquad \text{vs} \qquad a(t) = t^p \to \sin\left(\frac{p^2}{1-p}\frac{m}{H_{k_S}}\left(\frac{2k_H}{k_S}\right)^{1/p} + \varphi(k_S)\right)$$

Currently these correlations are explored through CMB and LSS, and future maps will continue to expand this frontier.

But they all come from a single source: the inflaton.

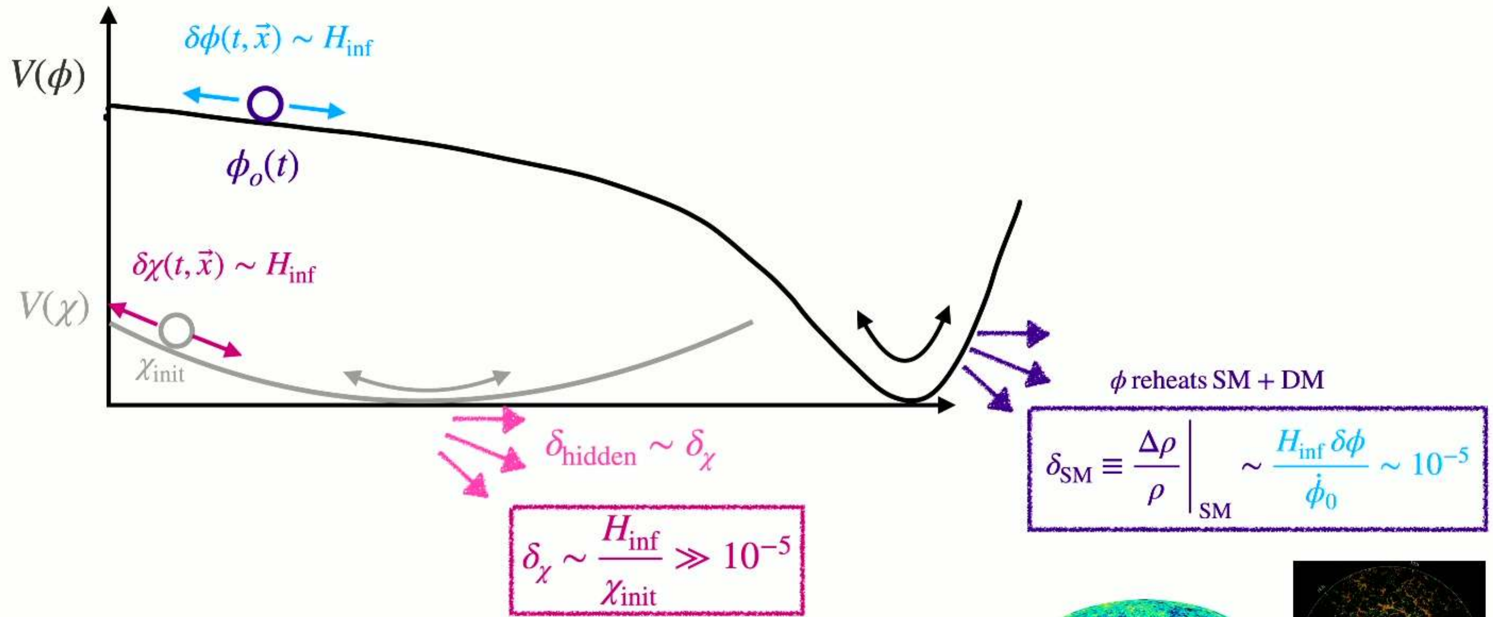
And so far, what we see is consistent with a non-interacting inflaton.

What if the inflaton really *is* non-interacting, and cannot give us information about other fields?

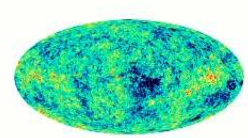
Could there be other kinds of anisotropies?

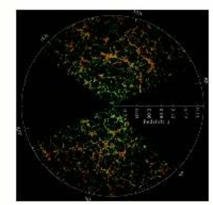
Is it possible to see quantum fluctuations of a different (spectator) field from inflation?

Setup



$\delta\phi(t,\vec{x}) \sim H_{\text{inf}}$
$V(\phi)$
$\phi_o(t)$
$\delta\chi(t,\vec{x}) \sim H_{\text{inf}}$
$V(\chi)$
χ_{init}
ϕ reheats SM + DM
$\delta_{\text{hidden}} \sim \delta_\chi$
$\delta_{\text{SM}} \equiv \frac{\Delta\rho}{\rho}\Big|_{\text{SM}} \sim \frac{H_{\text{inf}}\,\delta\phi}{\dot{\phi}_0} \sim 10^{-5}$
$\delta_\chi \sim \frac{H_{\text{inf}}}{\chi_{\text{init}}} \gg 10^{-5}$





?

What's the messenger?

1. Free-streaming (does not thermalize with SM and DM): $\zeta = f_\phi \zeta_\phi + f_\chi \zeta_\chi$
2. Copiously produced in the early universe
3. Should be detectable with the technology that we have today

Gravitational waves!

Therefore, our target is a strong GWB that inherits fluctuations of the spectator field.

Production: Induced (Secondary) GW

$$h''_{ij} + 2\frac{a'}{a}h'_{ij} - \nabla^2 h_{ij} = 4T_{ij}^{lm} S_{lm}$$

$$S_{lm} = -2\partial_l\Phi\partial_m\Phi - 4\Phi\partial_l\partial_m\Phi + 3H^2 f_c v_{cl} v_{cm}$$

↓

$$h \sim \delta^2 \longrightarrow \Omega_{\rm GW} \sim h^2 \sim \delta^4$$

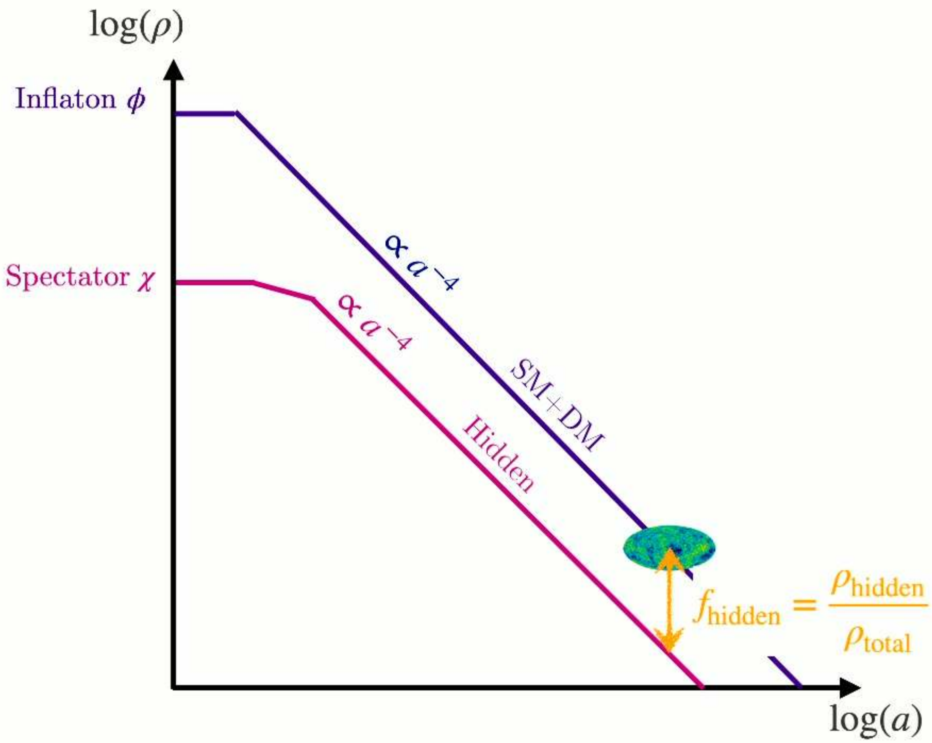
↓

For adiabatic fluctuations, $\Omega_{\rm GW,\,adi} \sim 10^{-20}$, too small

↓

But we have another fluctuation that is large $\delta_\chi \gg 10^{-5}$

CMB constraint



From CMB isocurvature constraint:

$$\delta_{\text{CMB}} \sim \delta_\phi + \underbrace{f_{\text{hidden}}}_{\lesssim 10^{-6}} \delta_\chi$$

$$\delta_\chi \gg 10^{-5} \longrightarrow f_{\text{hidden}} \ll 1$$

Induced GWB:

$$\Omega_{\text{GW}} \sim h^2 \sim \langle(\delta_\phi + \underbrace{f_{\text{hidden}}\,\delta_\chi}_{\lesssim 10^{-6}})^2\rangle^2 \sim \Omega_{\text{GW,adi}}$$

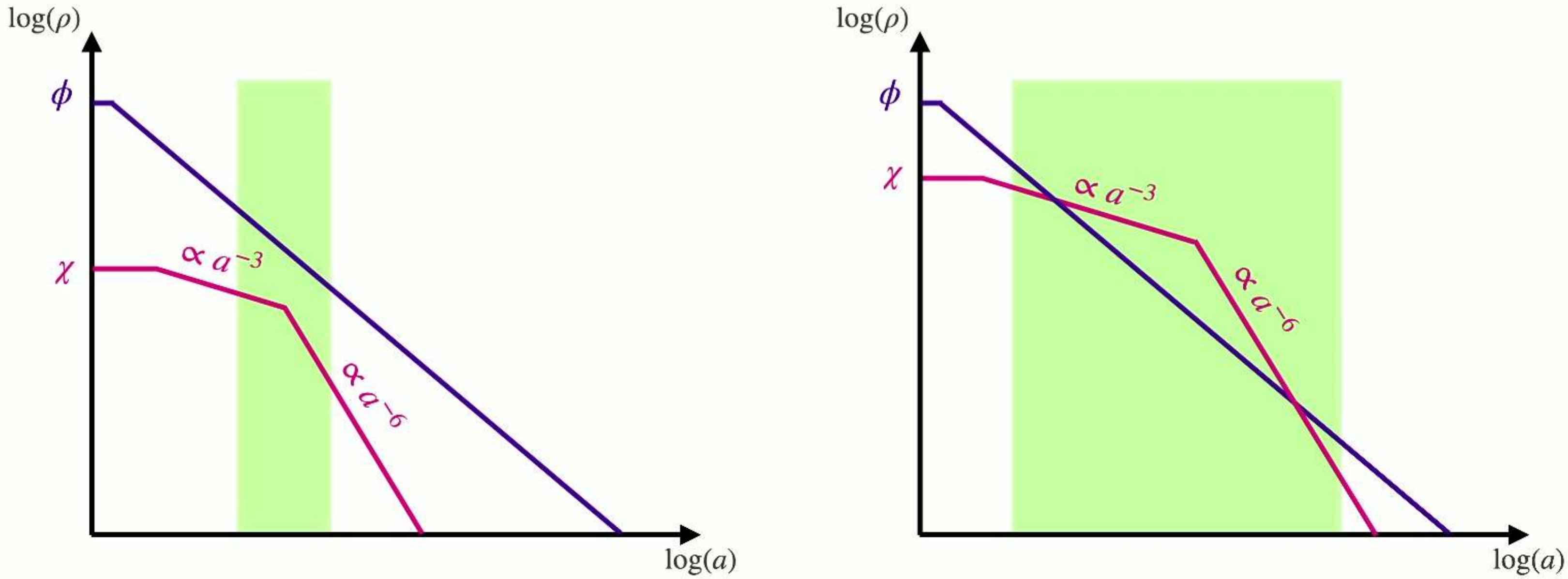
Transient dominance

Enhanced curvature perturbation

AB, K. Harigaya, K. Inomata, T. Terada, L-T Wang: 2508.08249
AB, R. Sundrum: JHEP 06 (2023) 029

$$\zeta_{\rm tot} = f_\chi \zeta_\chi + f_{\rm SM}\zeta_\phi$$

$f_\chi \zeta_\chi > 10^{-5}$



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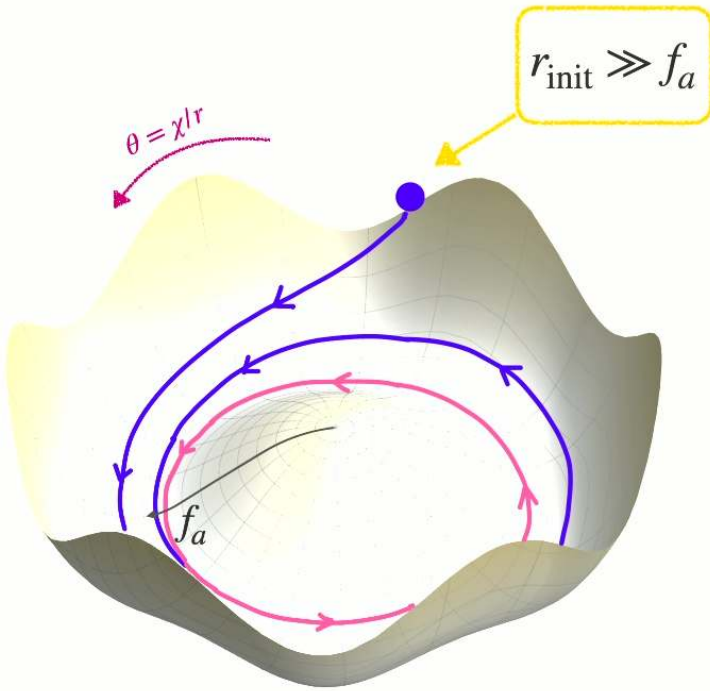
Rotating axion field: Large initial displacement

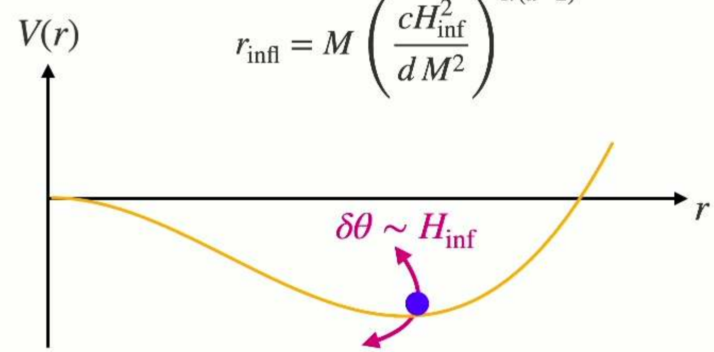


$$P = \frac{1}{\sqrt{2}} r e^{i\theta}$$

Set dynamically during inflation

$$V(r) = \frac{(m_r^2 - cH_{\rm inf}^2)\, r^2}{2} + \frac{r^d}{M^{d-4}}$$

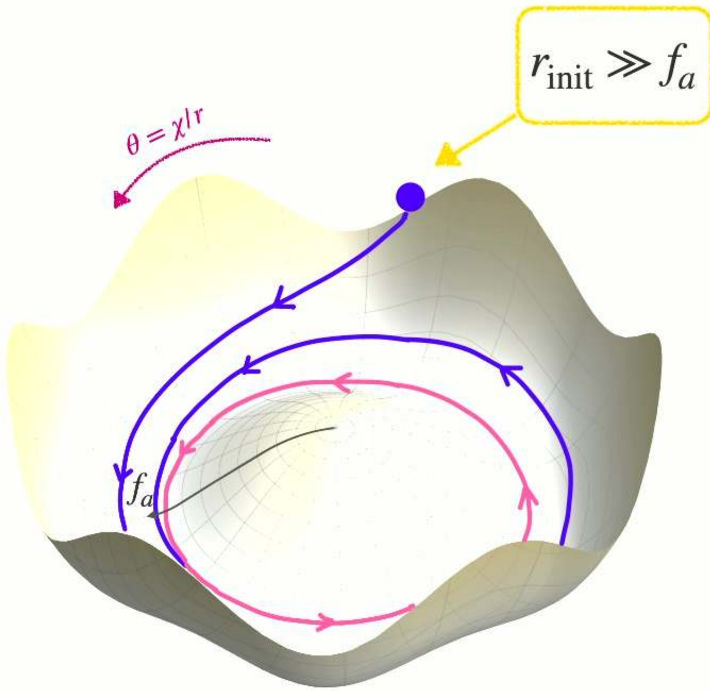
$$r_{\rm infl} = M \left(\frac{cH_{\rm inf}^2}{d\, M^2} \right)^{1/(d-2)}$$



θ direction still light → approximately scale-invariant spectrum

$$\sqrt{\mathscr{P}_\theta} \approx \frac{H_{\rm inf}}{2\pi r_{\rm inf}} \gg 10^{-5}$$

Rotating axion field: Large initial displacement



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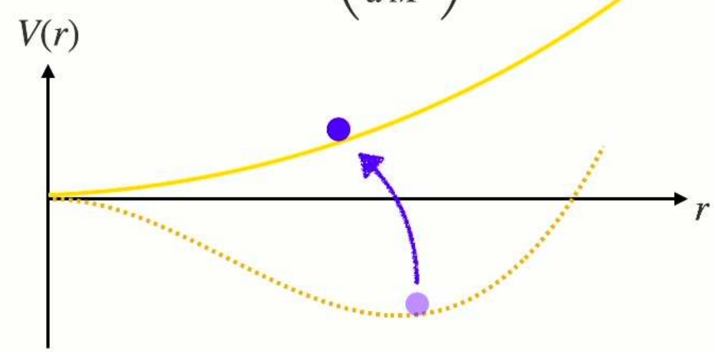
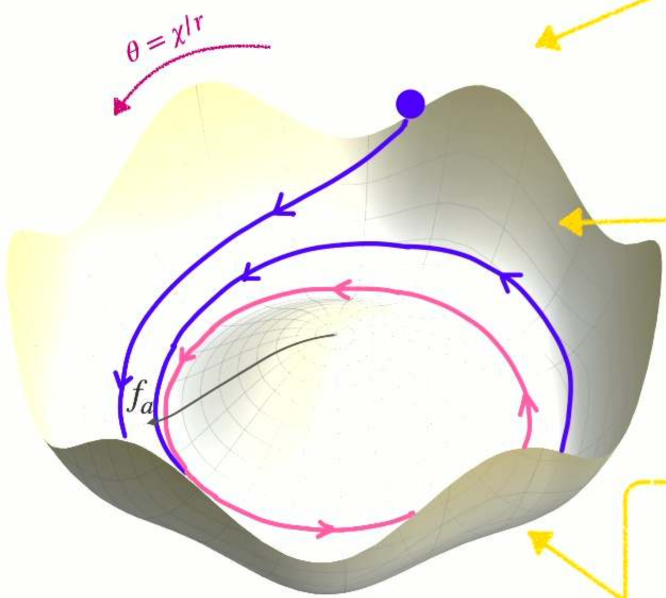


Rotating axion field: Angular kick

$$V(P)_{\not{U}(1)} \sim \frac{P^n}{\Lambda^{n-4}} e^{i\varphi} + hc \sim \frac{r^n}{\Lambda^{n-4}} \cos\left(n\theta + \varphi\right)$$

Kick in θ direction when field starts rolling at $m_r \sim H$



$$P = \frac{1}{\sqrt{2}} r e^{i\theta}$$

$V(P)_{\not{U}(1)}$ becomes small $\rightarrow U(1)$ charge is conserved

$$n_\theta = i(\dot{P}^\dagger P - \dot{P} P^\dagger) = r^2 \dot{\theta} \propto a^{-3}$$

$$\delta_\chi \equiv \frac{\delta n_\theta}{n_\theta} \approx n \frac{\cos[n\theta]}{\sin[n\theta]} \delta\theta \gg 10^{-5}$$

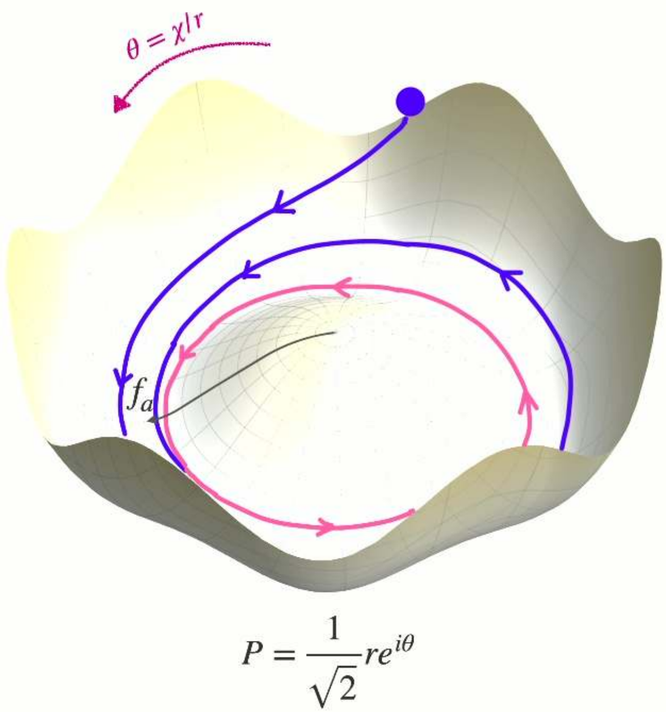
Thermalization with a bath to make orbit circular

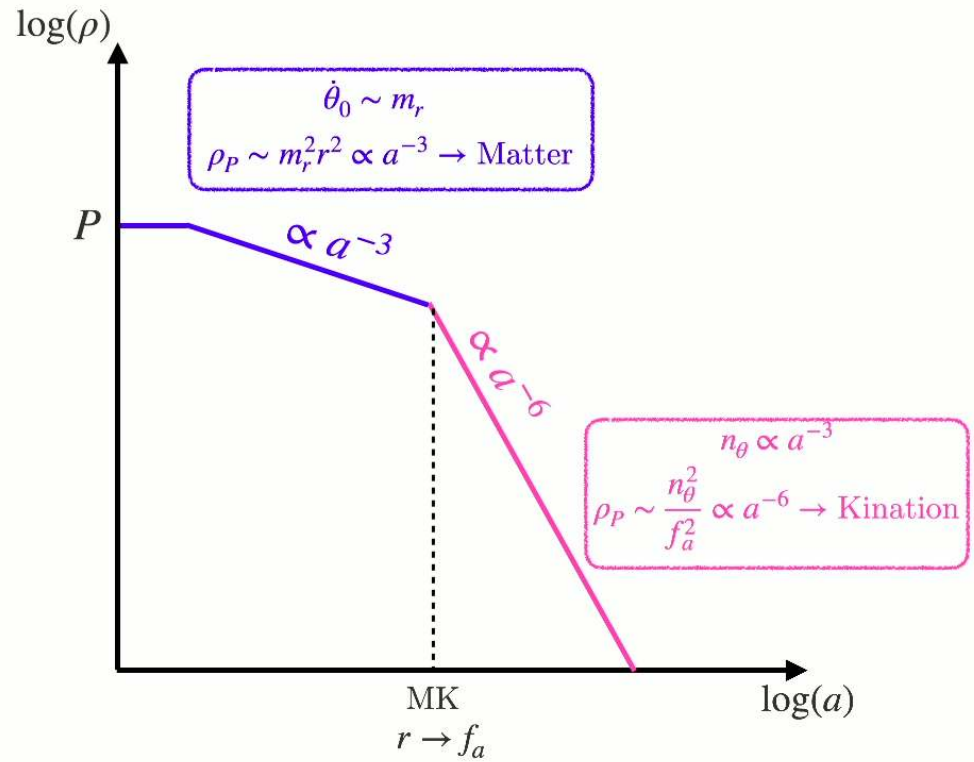
$$\mathscr{L} \supset y r \overline{\psi} \psi$$

$r_{\rm th} \gg T_{\rm th} \rightarrow$ most charge in rotation n_θ

$$\ddot{r}_0 + 3H\dot{r}_0 + (-\dot{\theta}_0^2 + m_r^2) r_0 = 0 \rightarrow \dot{\theta}_0 \sim m_r, r^2 \propto a^{-3}$$

Rotating axion field: equation of state





Story so far

Spectator field (axion) with large fluctuations

↓

It can dominate the total perturbation for a short time
if it undergoes classical rotations after inflation.

↓

Its short-wavelength fluctuations that re-enter the horizon during this period
produce strong GW signal at second order.

↓

Its long-wavelength fluctuations modulate this GWB produced by short-wavelength modes,
giving a highly anisotropic GWB.

Calculation of induced-GWB

$$\Omega_{\mathrm{GW}}(\eta_c, k) = \frac{k}{6\sqrt{2}\mathcal{H}_{\mathrm{KR}}}[x\overline{\mathcal{P}_h(\eta, k)}]_{\mathrm{kin}}$$

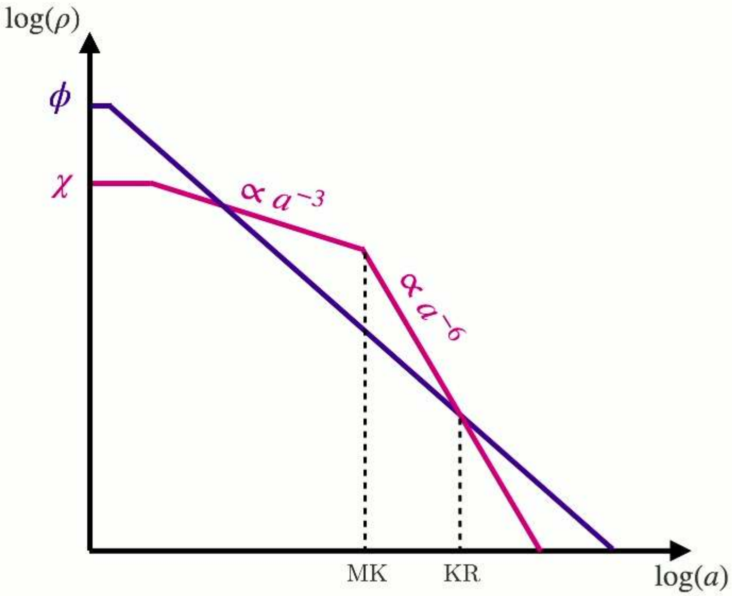
$$\overline{\mathcal{P}_h(\eta, k)} = 4\int_0^\infty \mathrm{d}v \int_{|1-v|}^{1+v} \mathrm{d}u \left(\frac{4v^2 - (1+v^2-u^2)^2}{4uv}\right)^2 \overline{I^2(u, v, x)}\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv)$$

Kination era: $\overline{I^2(u, v, x(\gg 1))} \simeq \frac{9}{16\pi u^4 v^4 x}\left\{\frac{(3(u^2+v^2-1)^2 - 4u^2v^2)^2}{4u^2v^2 - (u^2+v^2-1)^2} + 9(u^2+v^2-1)^2\right\}$

Radiation era: $\overline{I^2(x \to \infty, k, u, v)} \simeq \frac{1}{2}(J^2_{c,\infty}(k, u, v) + J^2_{s,\infty}(k, u, v)).$

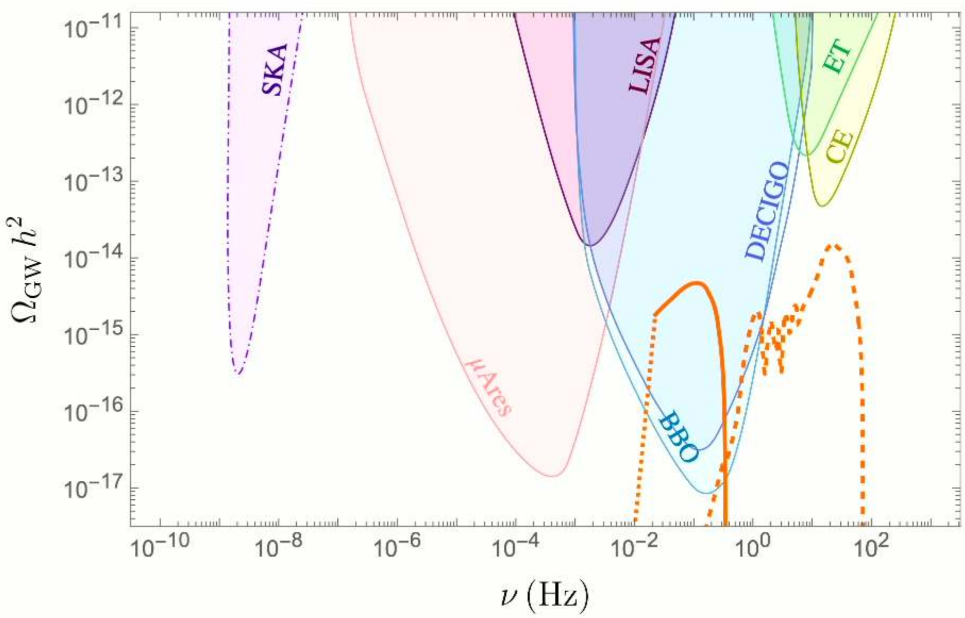
$$\begin{aligned} J_{c,\infty}(k,u,v) = \frac{9}{32u^4v^4\kappa^2}\Bigg\{ & -3u^2v^2 + (-3+u^2)(-3+u^2+2v^2)\ln\left|1-\frac{u^2}{3}\right| \\ & +(-3+v^2)(-3+v^2+2u^2)\ln\left|1-\frac{v^2}{3}\right| \\ & -\frac{1}{2}(-3+v^2+u^2)^2\ln\left[\left|1-\frac{(u+v)^2}{3}\right|\left|1-\frac{(u-v)^2}{3}\right|\right]\Bigg\}, \\ J_{s,\infty}(k,u,v) = \frac{9\pi}{32u^4v^4\kappa^2}\Bigg\{ & 9 - 6v^2 - 6u^2 + 2u^2v^2 + (3-u^2)(-3+u^2+2v^2)\Theta\left(1-\frac{u}{\sqrt{3}}\right) \\ & +(3-v^2)(-3+v^2+2u^2)\Theta\left(1-\frac{v}{\sqrt{3}}\right) \\ & +\frac{1}{2}(-3+v^2+u^2)^2\left[\Theta\left(1-\frac{u+v}{\sqrt{3}}\right)+\Theta\left(1+\frac{u-v}{\sqrt{3}}\right)\right]\Bigg\}, \end{aligned}$$

Shape of GWB

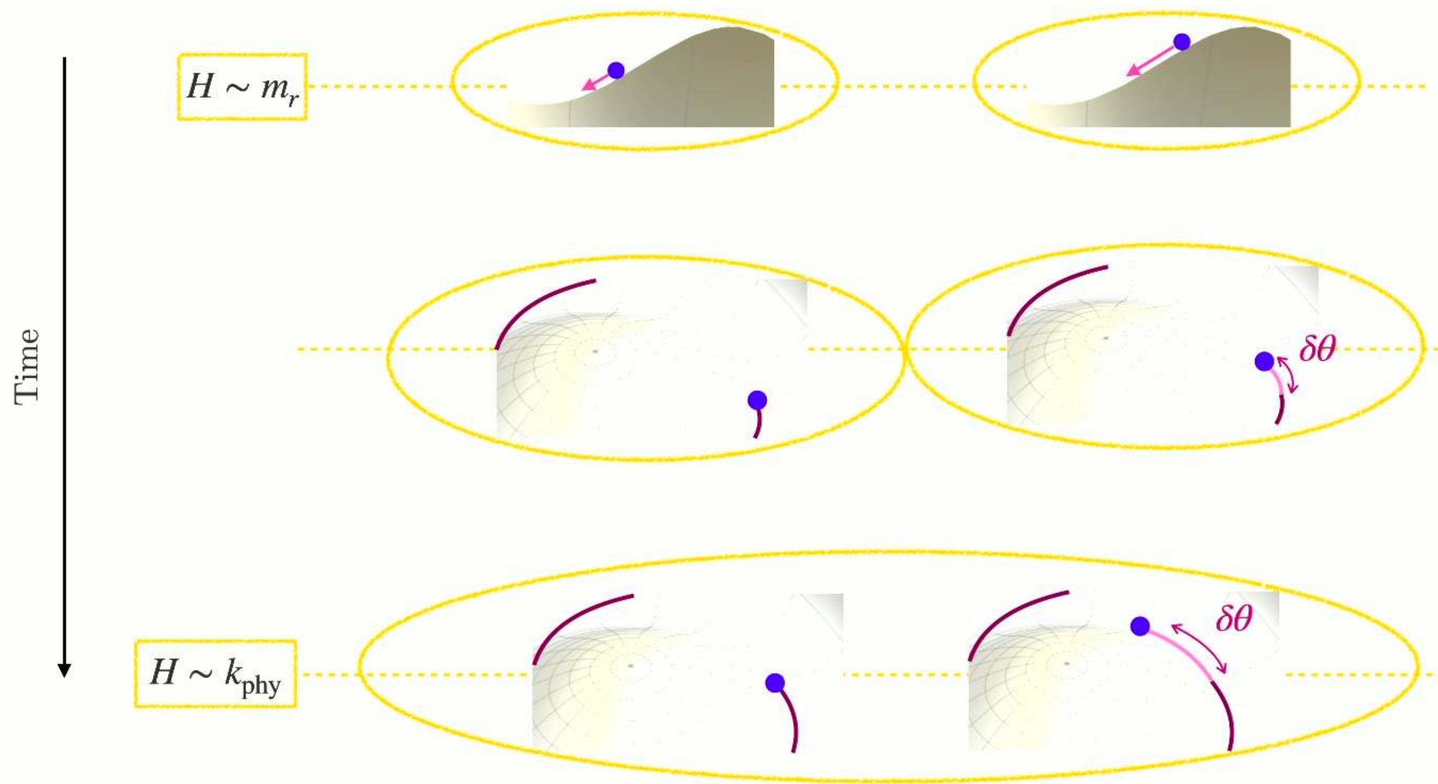


$$\Omega_{GW}^{today}h^2\Big|_{kination} = 2.9\times10^{-5}\,\mathcal{P}_{\zeta_\chi}^2(k_{short})\left(\frac{\nu}{\nu_{MK}}\right)$$

$$\nu_{MK} = 4\,\mathrm{mHz}\left(\frac{a_{MK}}{a_{KR}}\right)\left(\frac{T_{MK}}{100\,\mathrm{TeV}}\right)$$



$T_{MK} = 10^3\,\mathrm{TeV}$, $(a_{KR}/a_{MK}) = 3$, $\zeta_\chi = 0.003$



$$\delta\theta_{\rm initial} \sim \delta_\chi$$

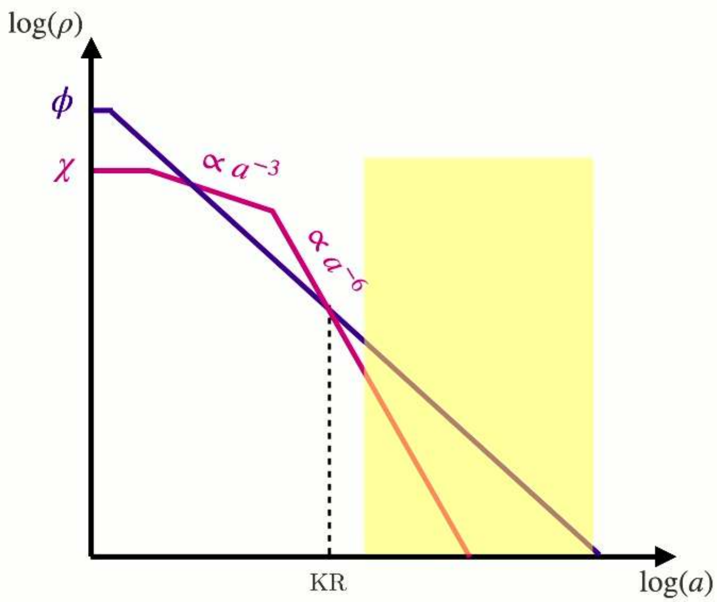
$$\delta\theta = \int \delta\dot{\theta}\, dt = \delta_\chi \int \dot{\theta}_0(t) dt$$

$$\delta\theta_{\rm final} - \delta\theta_{\rm initial} \sim \delta_\chi\, f_{\rm MK}^{1/2} \frac{M_{\rm Pl}}{f_a}$$

Largest increase in $\delta\theta$ around the end of kination period

Larger gradient energy in $\delta\theta$ for all modes re-entering after kination-radiation transition

Shape of GWB



$$h''_{ij} + 2\frac{a'}{a}h'_{ij} - \nabla^2 h_{ij} = 4T^{lm}_{ij}S_{lm}$$

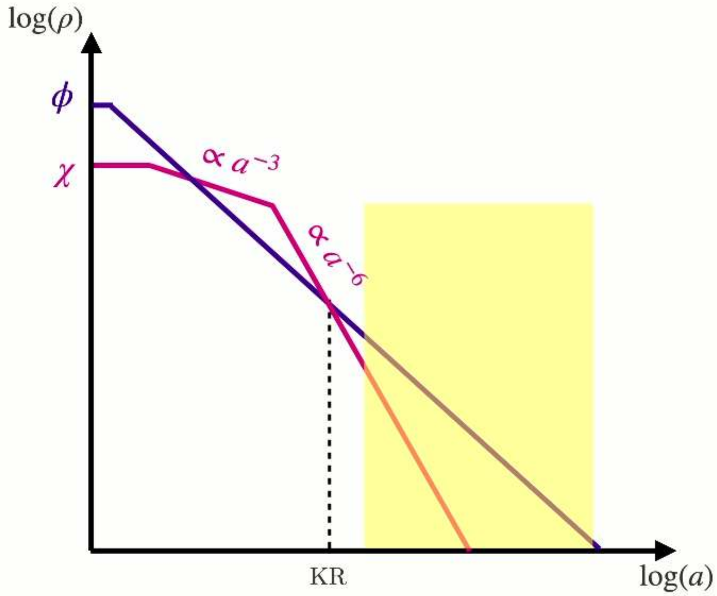
$$S_{lm} = -2\partial_l\Phi\partial_m\Phi - 4\Phi\partial_l\partial_m\Phi + 3H^2 f_c v_{cl} v_{cm}$$

$$\frac{f_a^2}{M_{\rm Pl}^2}\partial_l\delta\theta\,\partial_m\delta\theta$$

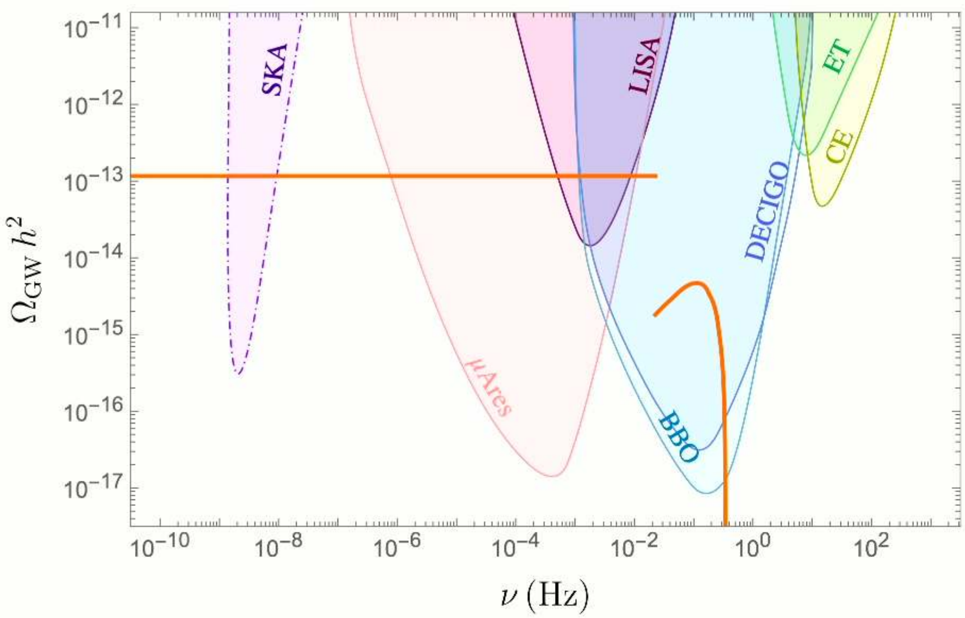
$$\delta\theta \sim \delta_\chi\, f_{\rm MK}^{1/2}\frac{M_{\rm Pl}}{f_a}$$

$$h \propto f_{\rm MK}\delta_\chi^2 \;\rightarrow\; \Omega_{\rm GW} \sim f_{\rm MK}^2\,\delta_\chi^4$$

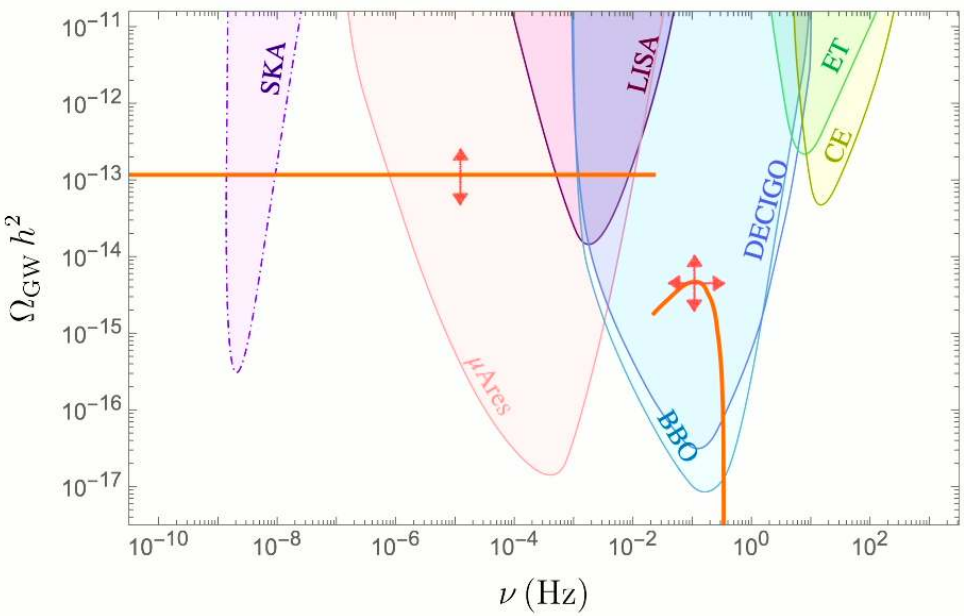
Shape of GWB



$$\Omega_{\rm GW}^{\rm today} h^2 \Big|_{\rm flat} = 2.8 \times 10^{-6}\, \mathscr{P}_{\delta\chi}^2(k_{\rm short})\, \Theta(\nu_{\rm KR} - \nu)$$



Anisotropy in GWB



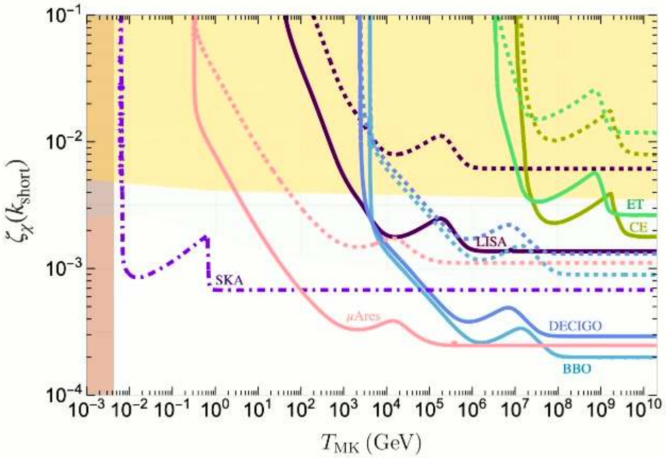
Peak/transition:

$$\frac{\delta\Omega_{\rm GW}}{\Omega_{\rm GW}} = \frac{4}{3}\,(f_{\rm MK} - 2)\,\zeta_\chi(k_{\rm long})$$

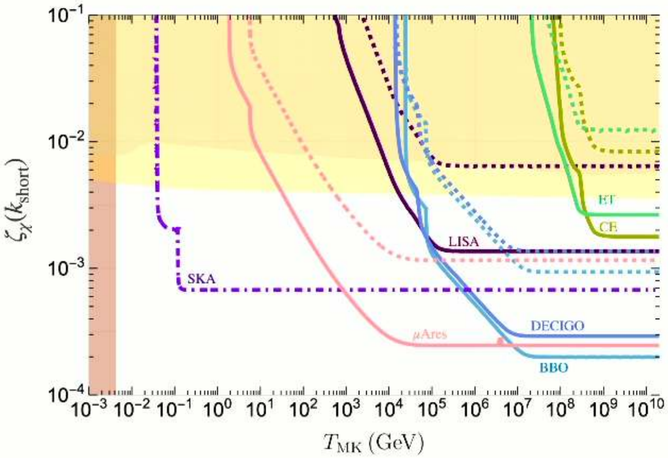
$$\frac{\delta\nu_{\rm MK}(k_{\rm long})}{\nu_{\rm MK}} = \frac{1}{3}\,(2f_{\rm MK} - 1)\,\zeta_\chi(k_{\rm long})$$

Flat part:

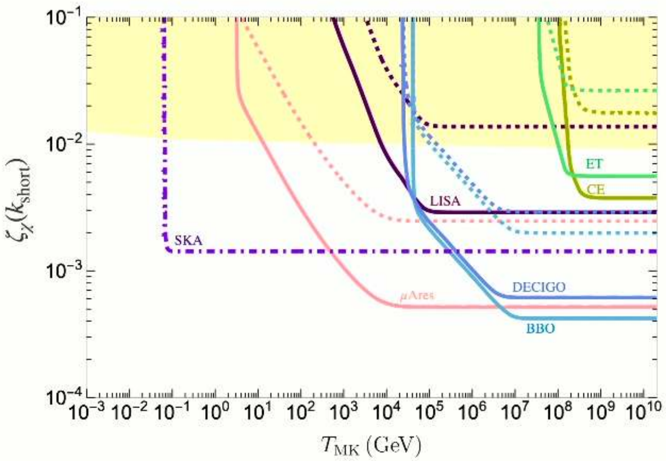
$$\frac{\delta\Omega_{\rm GW}}{\Omega_{\rm GW}} = -\,4(1 + 2f_{\rm MK})\,\zeta_\chi(k_{\rm long})$$



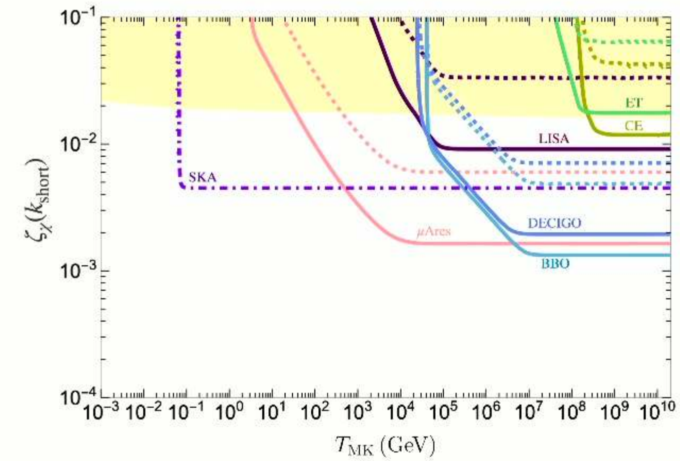
Long eMD: $f_{\rm MK} = 0.99$



Short eMD: $f_{\rm MK} = 0.75$

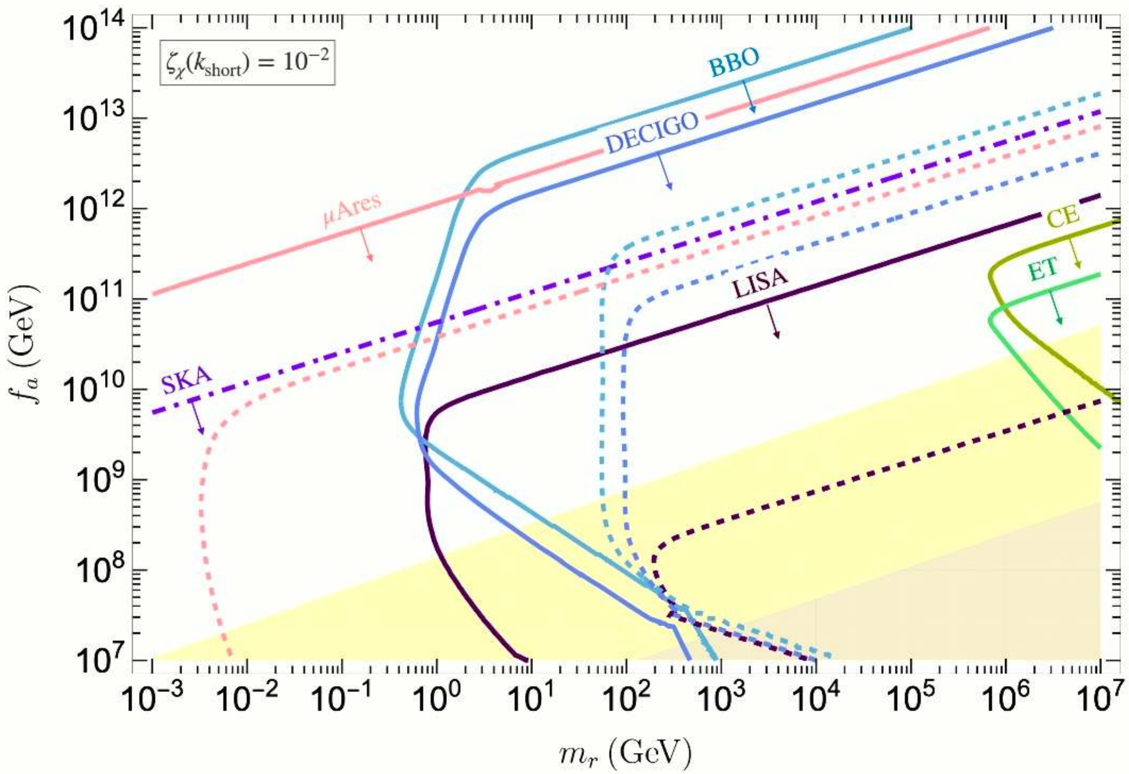


$f_{\rm MK} = 0.1$



$f_{\rm MK} = 0.01$

Detectability of the model



Summary

- There can be new cosmological anisotropy maps significantly different from the CMB.
- Such maps can be realized within GWBs (secondary-GW).
- Such GWB anisotropies give an important new window into the inflationary era.
- Modified post-inflationary cosmologies play an important role in the observability of these highly anisotropic GWB.