# Primordial gravitational waves revealed by a spinning axion

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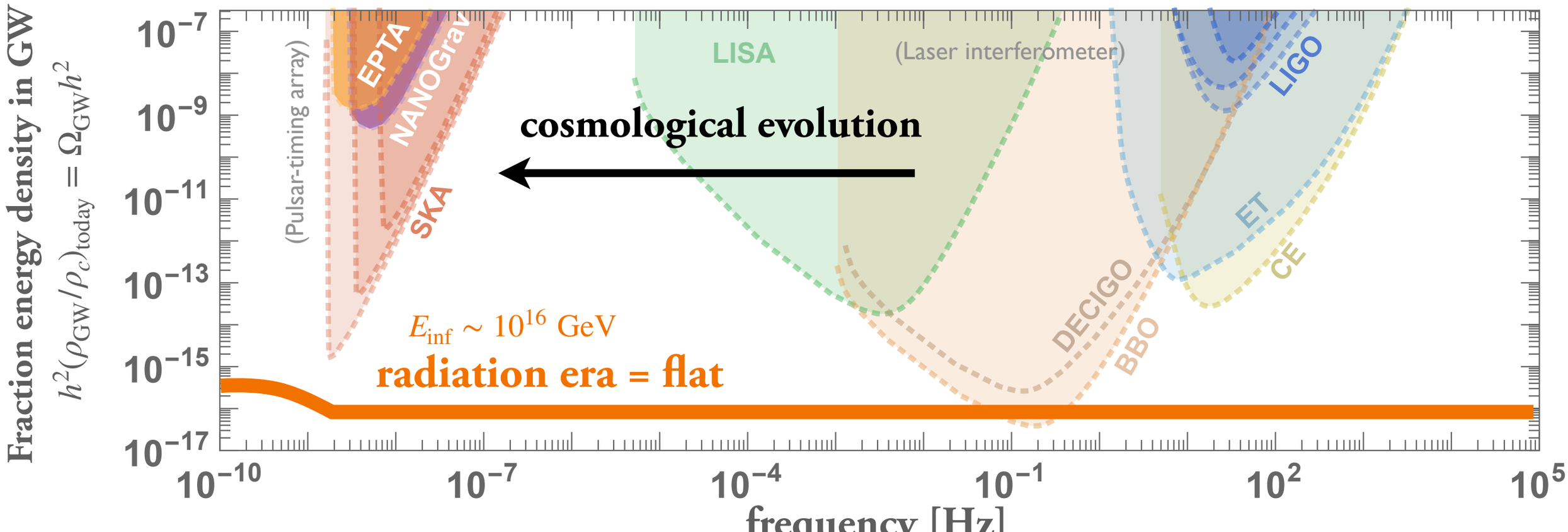
based on: 2108.10328 & 2109.xxxxx

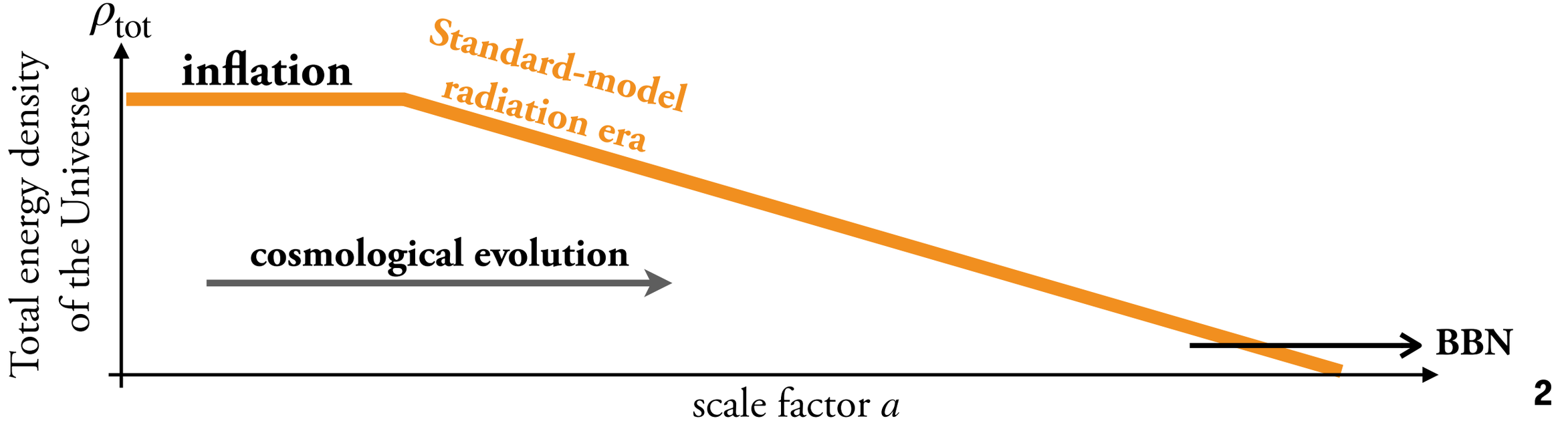
**DESY Theory workshop 2021, 21.09.2021**



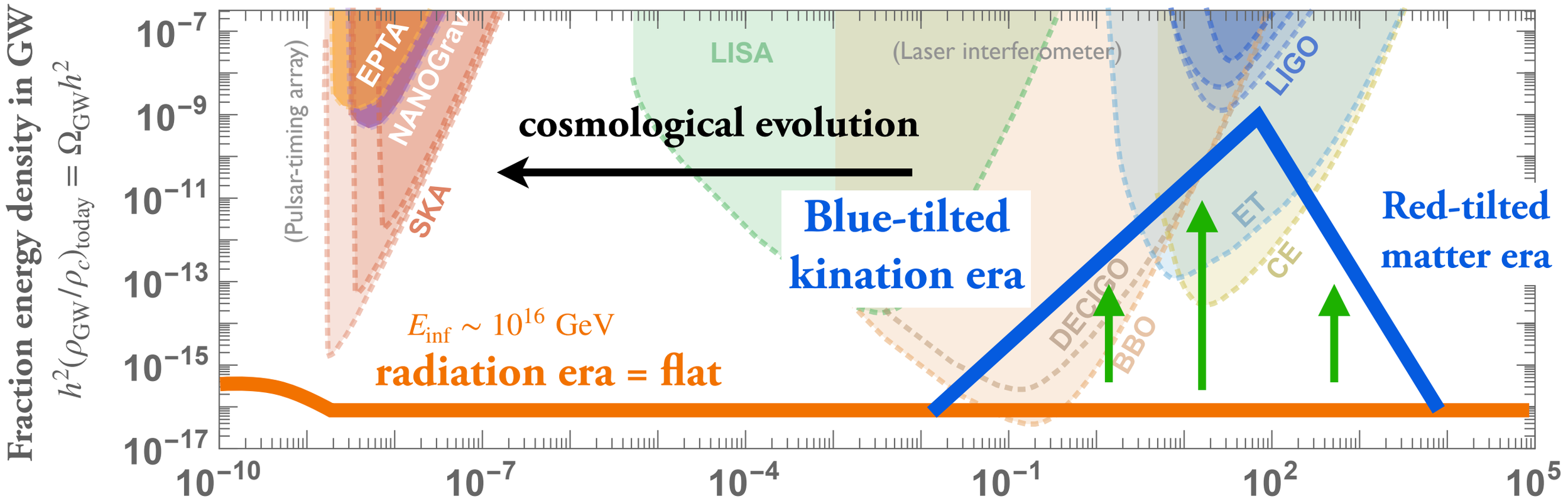
**Irreducible GW background from quantum fluctuation during inflation is typically small.**



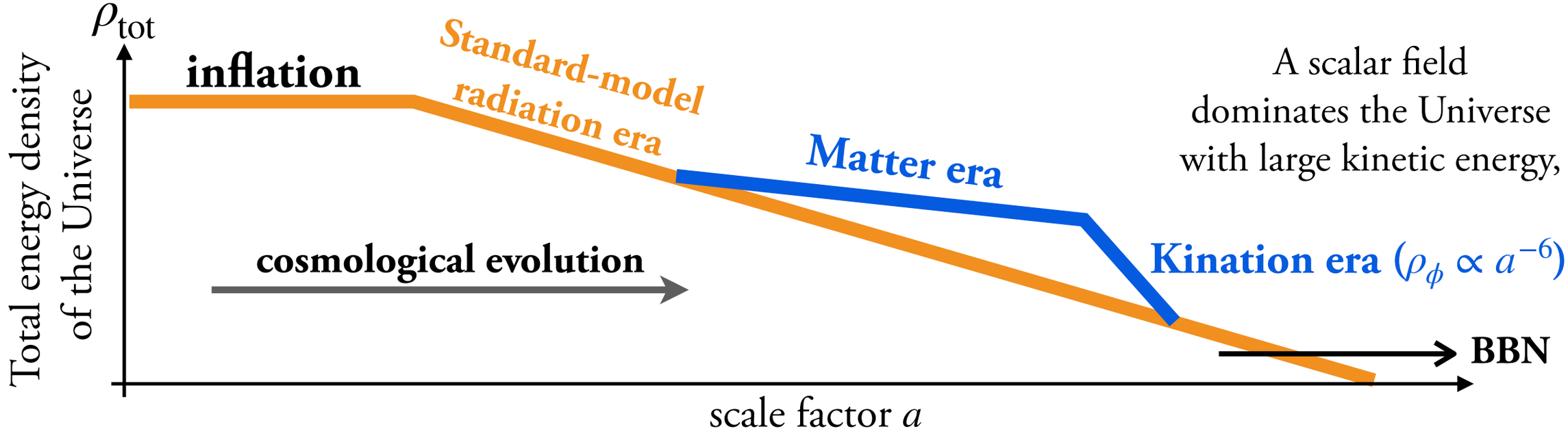

**Spectral distortion of the primordial GW provide a hint of the cosmological history.**



## Irreducible GW background from quantum fluctuation during inflation is typically small.

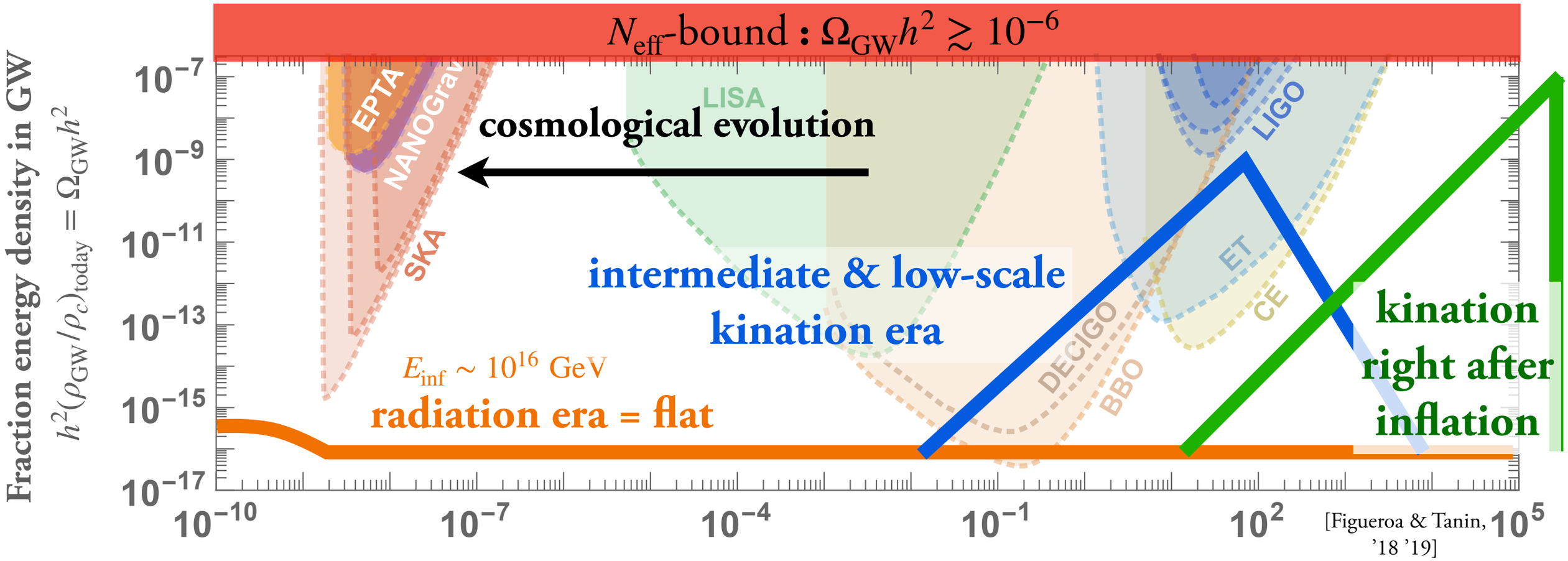



## Spectral distortion of the primordial GW provide a hint of the cosmological history.



# Long kination ⇒ too much GW as extra radiation

@ BBN/CMB, extra relativistic *dof*: $\Delta N_{\rm eff} \lesssim 0.2$



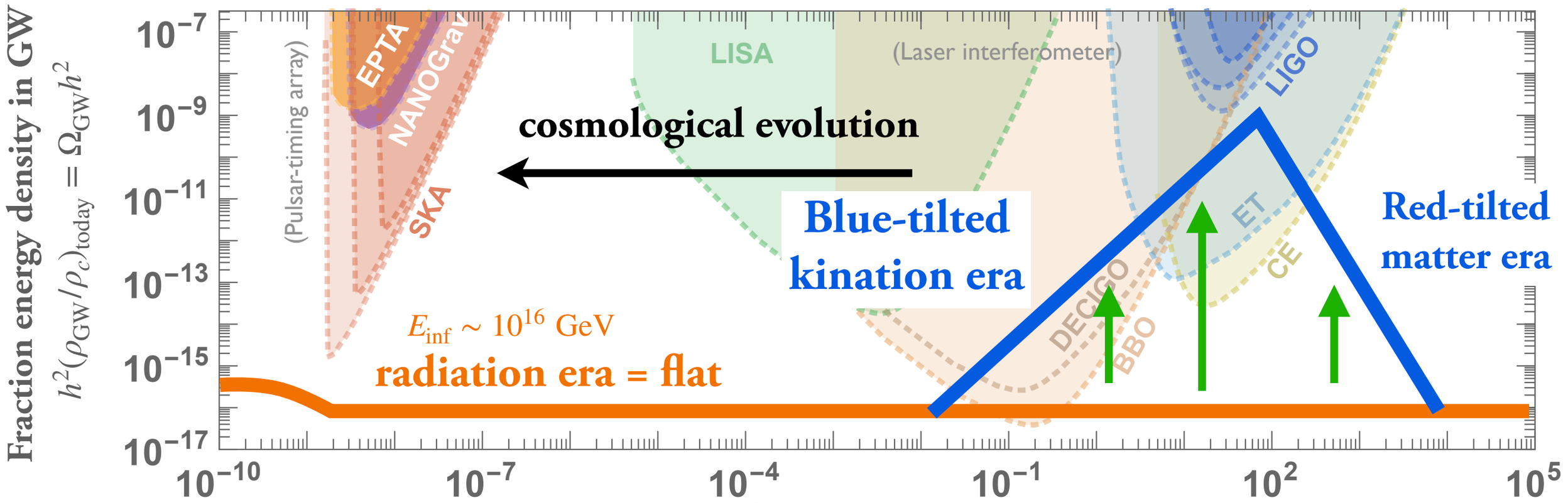

Probing high-scale kination era right after inflation needs ultra high-frequency experiments.

see [Domcke, Muia et. al., 2011.12414]

Challenges and Opportunities of High Frequency Gravitational Wave Detection — ICTP

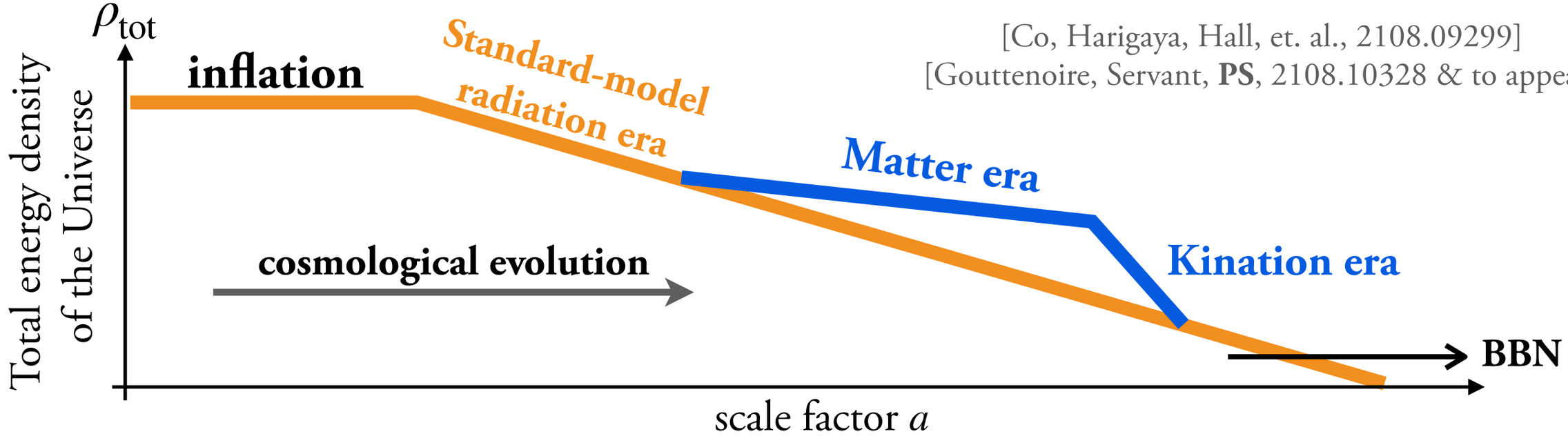
**From the perspective of the future-planned experiments, a intermediate and low-scale kination era is very interesting.**

# Irreducible GW background from quantum fluctuation during inflation is typically small.

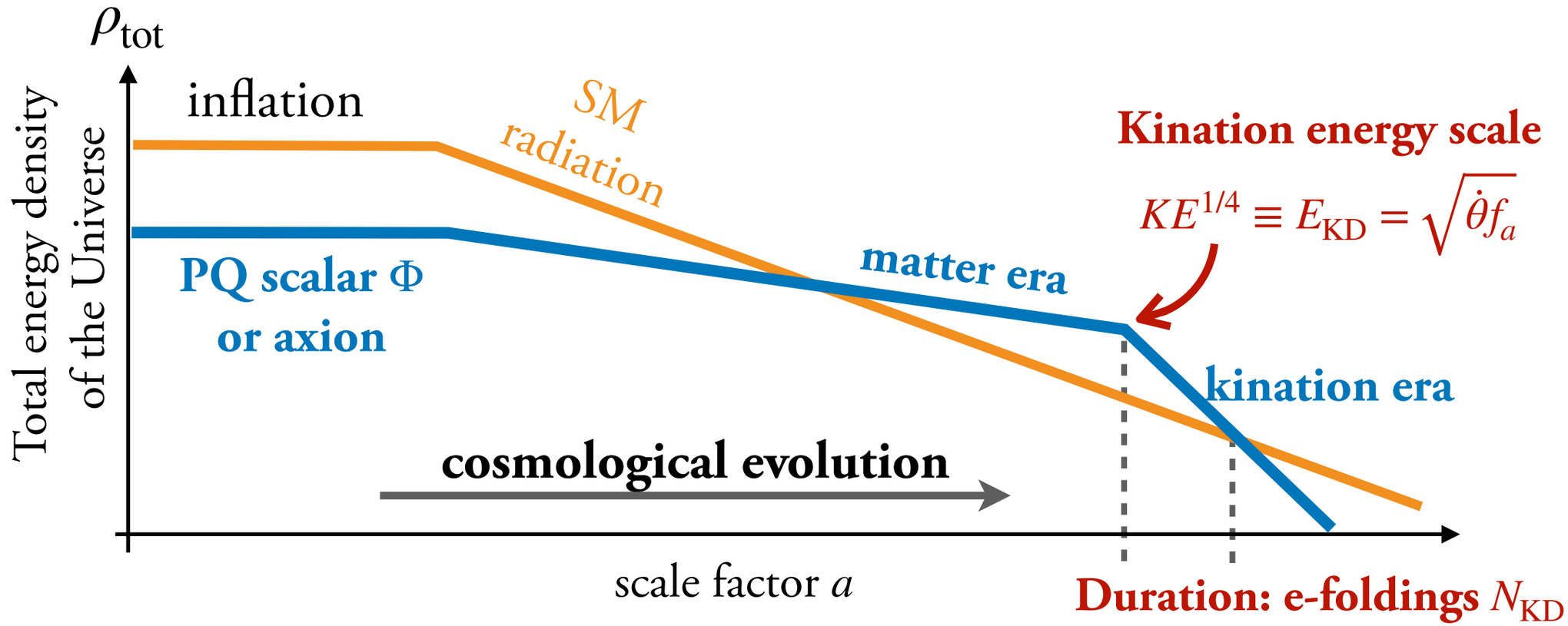



## A intermediate low-scale kination from Spinning axion !

[Co, Harigaya, Hall, et. al., 2108.09299]
[Gouttenoire, Servant, **PS**, 2108.10328 & to appear]



# Model-independent kination from spinning axion



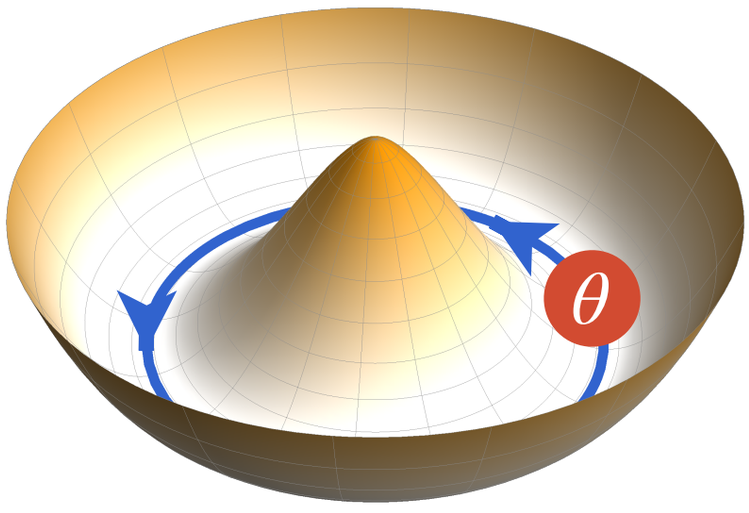

are characterized by
(given the spontaneous symmetry-breaking scale $f_a$)

1. **kination energy scale** $E_{\rm KD} = \sqrt{\dot\theta f_a}$

(the spinning speed of axion $\dot\theta$ when kination starts)

2. **the duration of kination era** $N_{\rm KD} = \log(a_{\rm start}/a_{\rm end})$

(related to the beginning of the matter era)

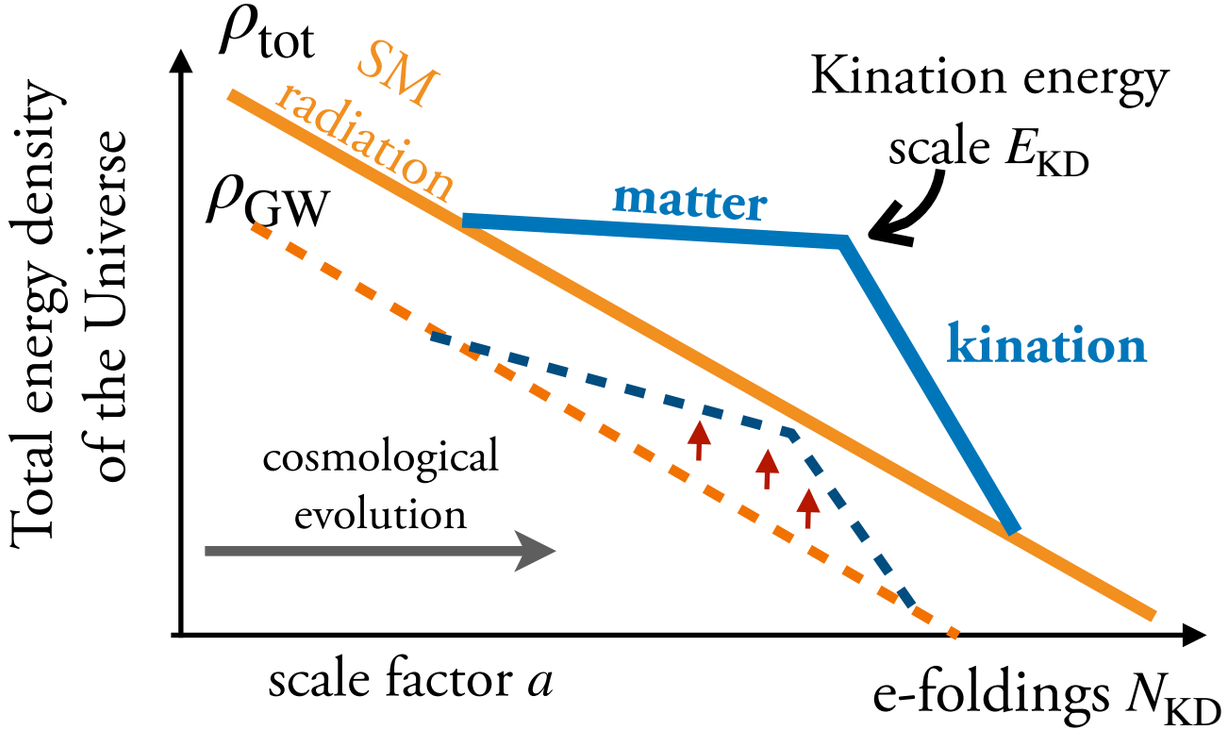


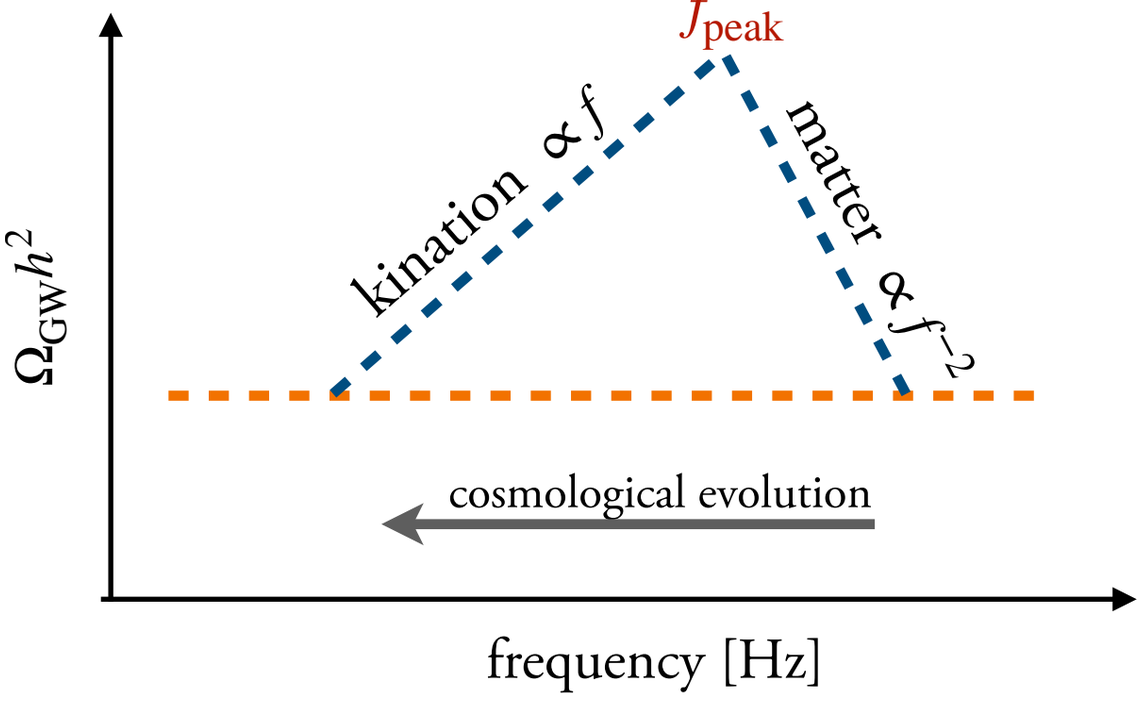

circle of $\phi = f_a$

# Signature in inflationary GW: "Peak"

Frequency of today GW: $f_{\rm today}^{\rm GW} \simeq H_k a_k / a_0 \propto a_k^{-2}$ (kination), $a_k^{-1}$ (radiation), $a_k^{-1/2}$ (matter)

spectral tilt: $\Omega_{\rm GW} \simeq \left(\frac{H_k^2 a_k^4}{H_0^2}\right)\left(\frac{E_{\rm inf}}{M_{\rm Pl}}\right)^4 \propto f_{\rm today}$ (kination), $f_{\rm today}^0$ (radiation), $f_{\rm today}^{-2}$ (matter)




**A peak corresponds to $E_{\rm KD}$, why?**

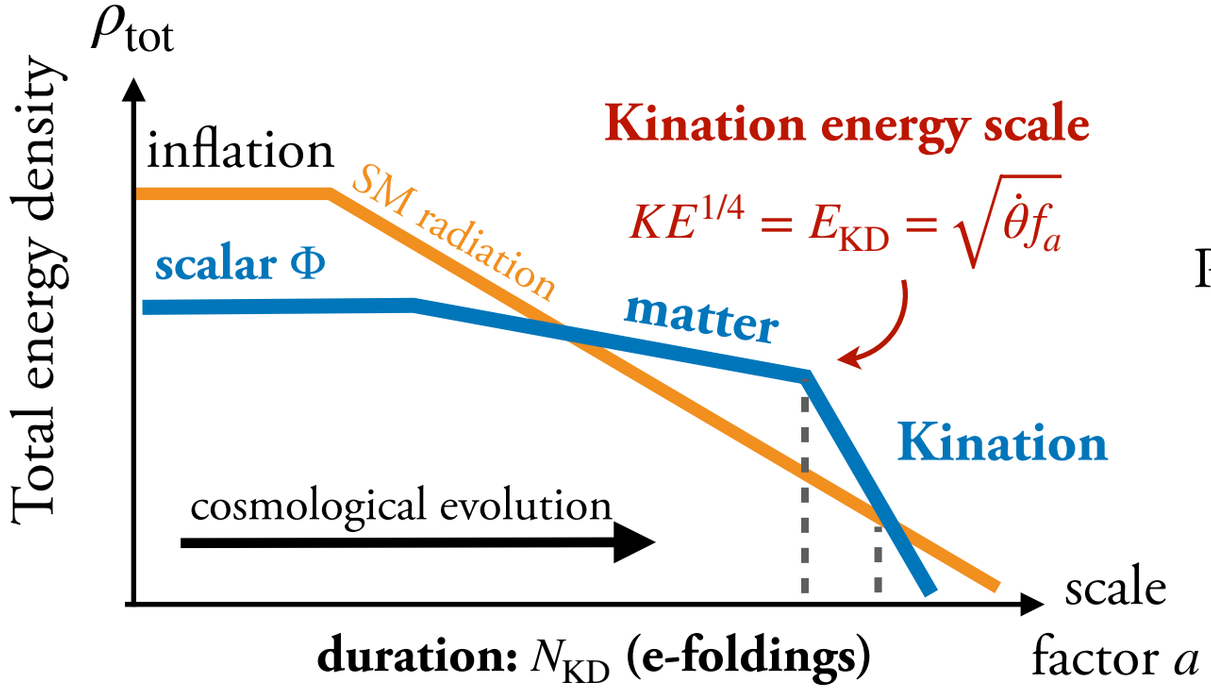
$\rho_{\rm GW} \propto \rho_{\rm total}$

Larger $\rho_{\rm tot}$, larger GW amplitude, compared to the standard cosmology.

**Peak at** $\left.\frac{\rho_{\rm tot,non-st}}{\rho_{\rm tot,st}}\right|_{\rm max}$ **at the beginning of kination $E_{\rm KD}$.**

# Signature in inflationary GW: "Peak"






Peak frequency: $f_{\rm peak} \approx 10\ {\rm Hz} \left(\frac{E_{\rm KD}}{10^8\ {\rm GeV}}\right) \left[\frac{\exp(N_{\rm KD}/2)}{10}\right]$

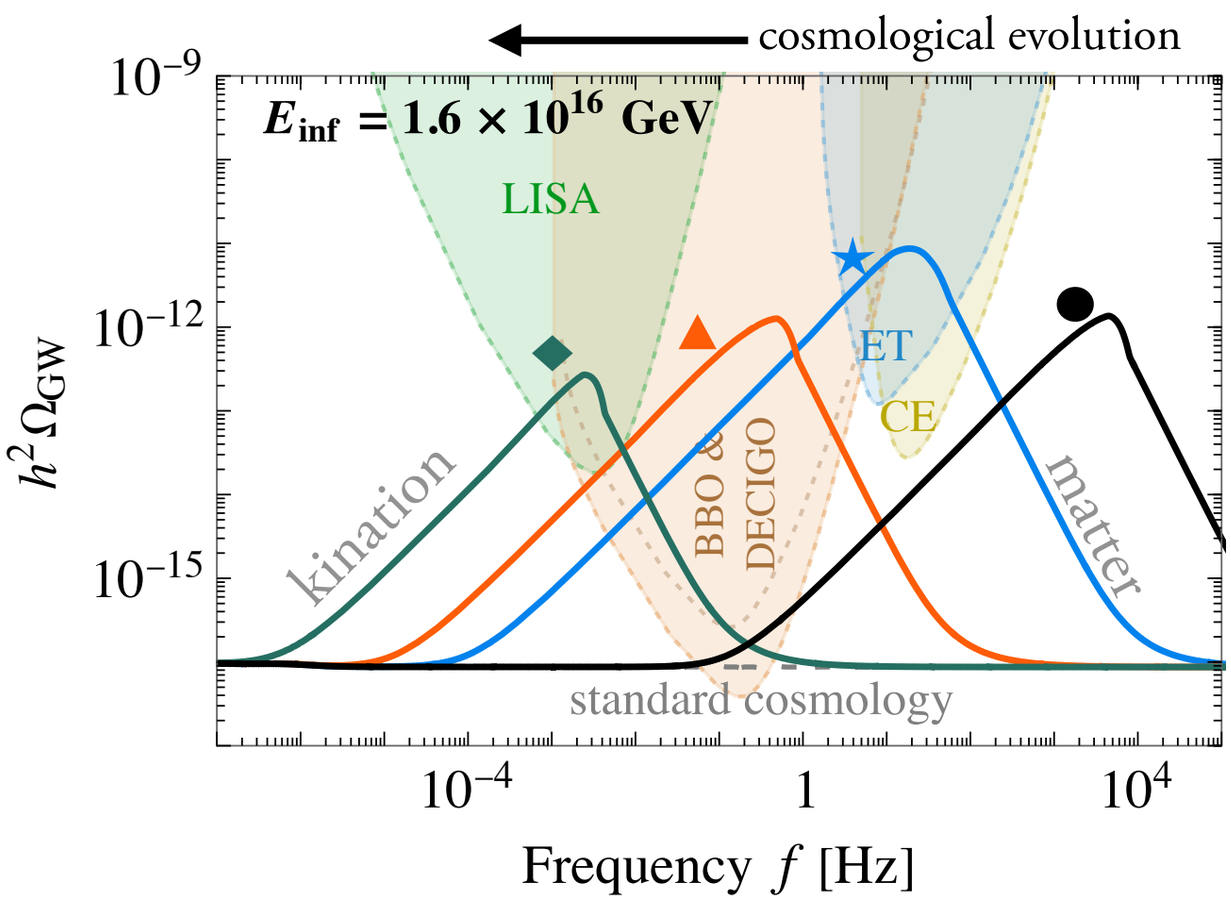
Peak amplitude: $\Omega_{\rm peak} h^2 \approx 10^{-12} \left(\frac{E_{\rm inf}}{1.6\times 10^{16}\ {\rm GeV}}\right)^4 \left[\frac{\exp(2N_{\rm KD})}{10^4}\right]$

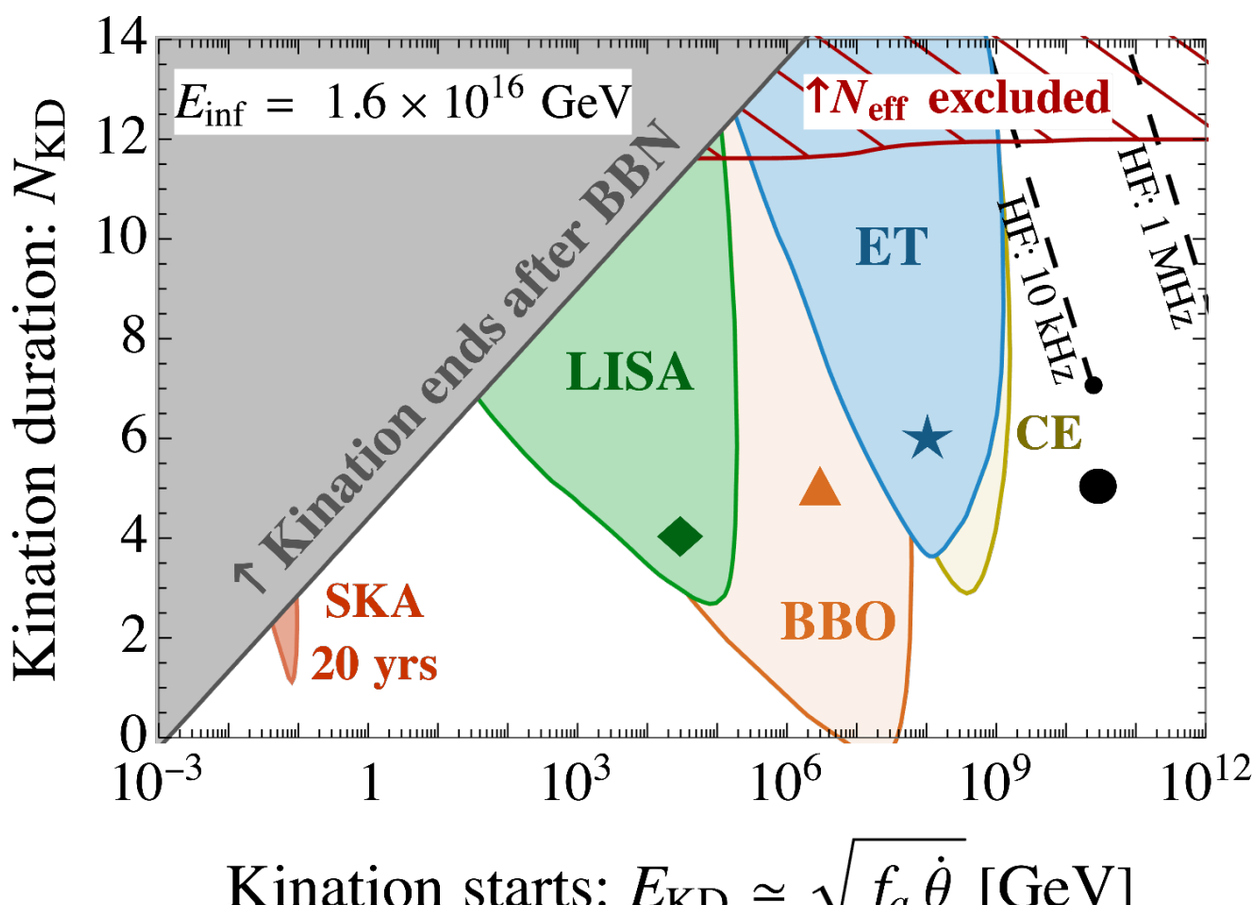
**"Peak's detectability"**

ET & CE probes $\sim 10^{6-9}$ GeV kination

LISA probes $\sim 10^{2-5}$ GeV kination

High-frequency (HF) experiments for large $E_{\rm KD}$



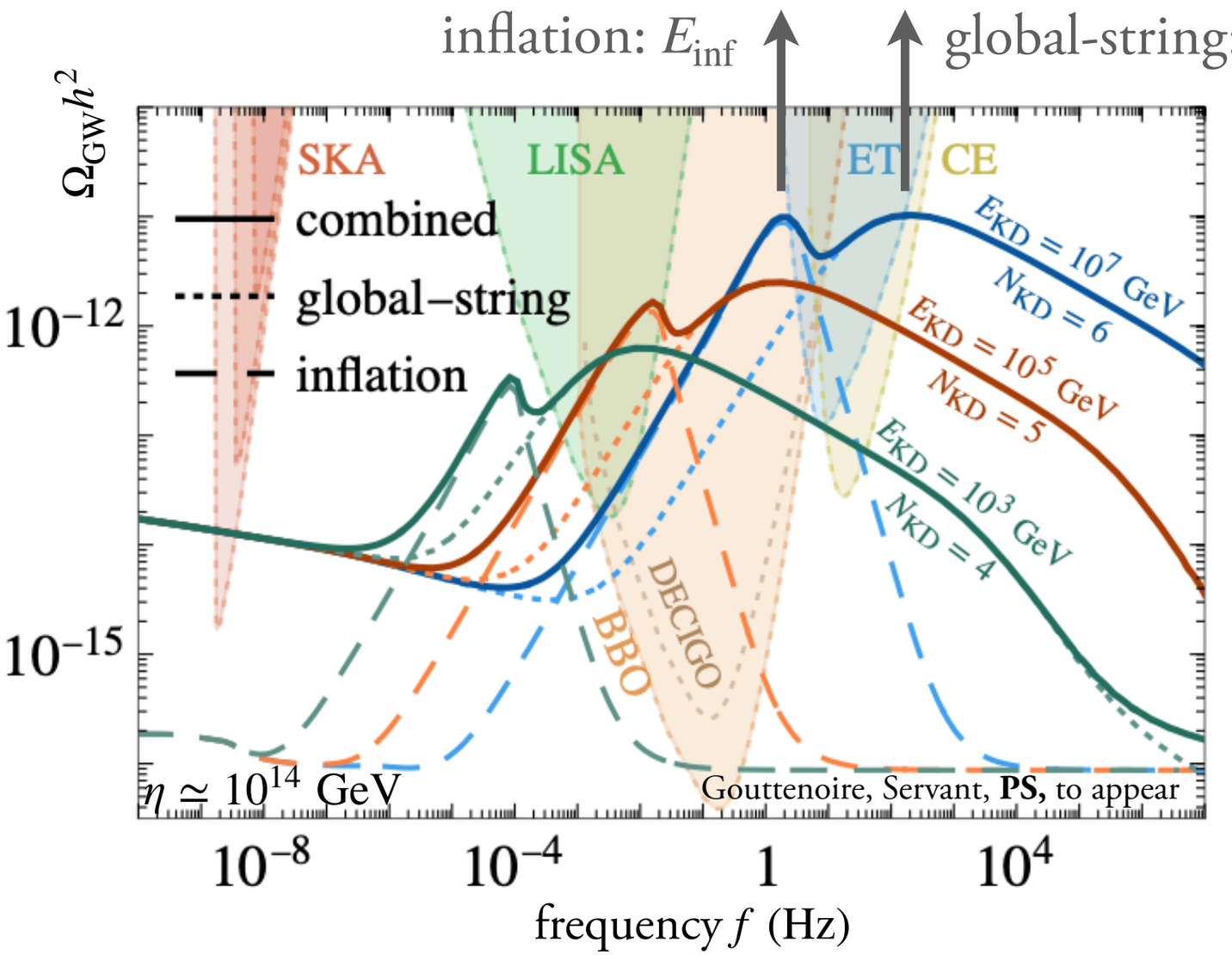

[Gouttenoire, Servant, **PS**, 2108.10328 & to appear]

# Signature in global-string GW: another "Peak"

String network formed at energy scale $\eta$
continuously produces loops which decay into GW (and also particles.)

E.g. Axionic strings from PQ symmetry breaking with $\eta \sim f_a$ .

Kination peak amplitude from global strings: $\Omega_{\rm peak}^{\rm glob} h^2 \approx 10^{-14} \left(\frac{\eta}{10^{15}\ \text{GeV}}\right)^4 \left[\frac{\exp(2N_{\rm KD})}{10^4}\right] \log^3(\cdots)$




Fixed peak separation

$f_{\rm inf}/f_{\rm glob} = \mathcal{O}(10^{-2})$

[for loops' size: $(0.1)H^{-1}$]

With $E_{\rm inf} \sim 10^{16}$ GeV,

**two-peak signature**

for $10^{12} \lesssim \frac{\eta}{\text{GeV}} \lesssim 10^{15}$.

# GW peak from "Spinning axion"

Going beyond the assumption of vanishing velocity of axion.

**e.g. Kinetic-misalignment & axion fragmentation**

[Co, Harigaya, Hall, '19 & Chang, Cui, '19] [Fonseca, Morgante, Sato, Servant, '19 & Philip Sørensen's talk on Wednesday]

## example I: complex scalar field

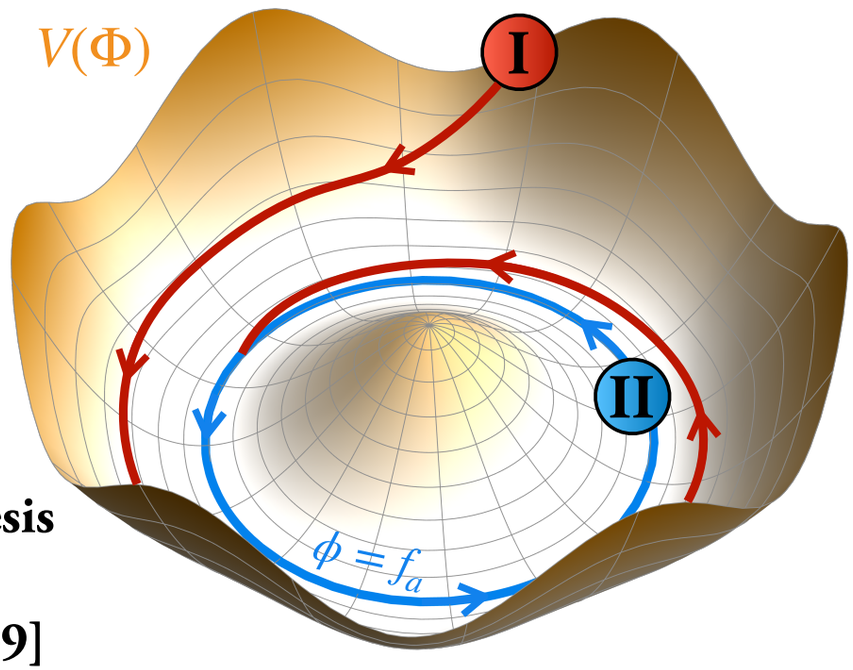
[Co, Hall, Harigaya, et. al., '19 '20]

$\Phi \sim \phi e^{i\theta}$ with $U(1)$-symmetry

Radial mode $\phi$ oscillates in potential with mass $\sqrt{V''(\Phi)}$.

Angular mode $\theta$ "axion" spins, with large kinetic energy.

Dynamics starts with $\phi \gg f_a$



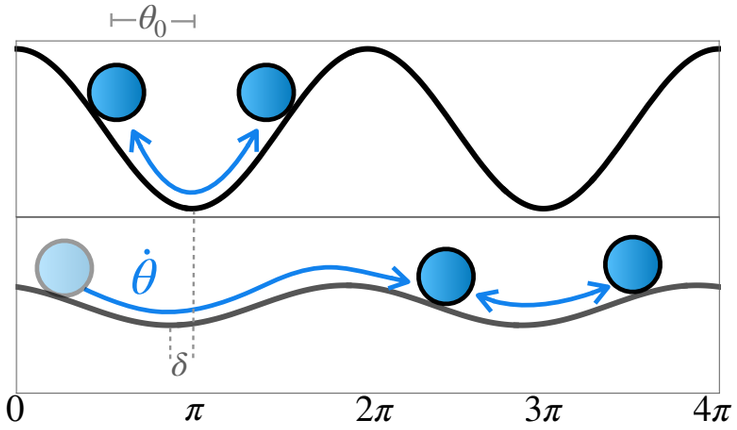

## example II: Trapped misalignment

[Di Luzio, Gavela, Quilez, Ringwald, '21]

High-temperature axion potential is unconstrained.

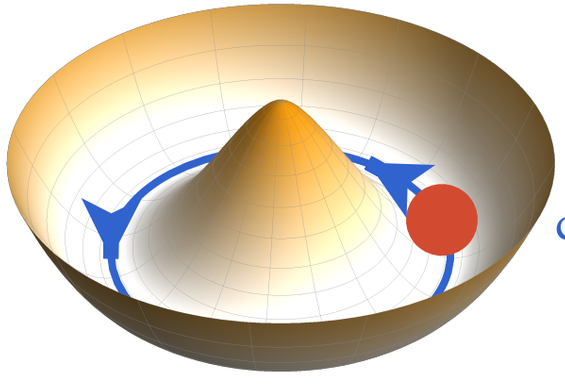
For instance, the $\mathbb{Z}_N$ axion model [Hook,'18] leads to axion potential at $T \gg \Lambda_{\rm QCD}$.

Dynamics starts with $\phi = f_a$

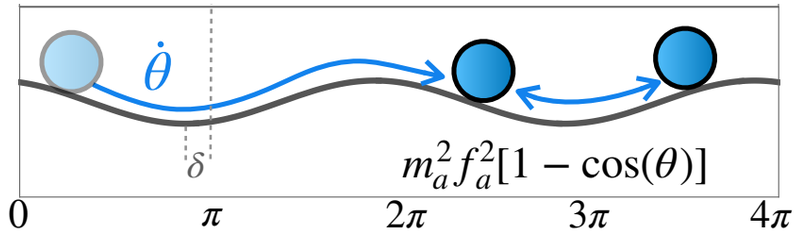



**See also GW peak & DM & Baryogenesis from the complex-scalar model Co, Harigaya, Hall, et. al. [2108.09299]**

# Axion Dark Matter and Peaked signature



circle of
$\phi = f_a$




PQ charge in the spinning axion transfers to the axion number density via kinetic misalignment & axion fragmentation

$$\left.\frac{n_a}{s}\right|_0 \simeq \left.\frac{n_\theta}{s}\right|_{\rm KD} \equiv \frac{f_a^2\dot{\theta}}{s_{\rm KD}}$$

[Co, Harigaya, Hall, '19 & Chang, Cui, '19]

[Fonseca, Morgante, Sato, Servant, '19 & Philip Sørensen's talk on Wednesday]

## Peak position for axion dark matter

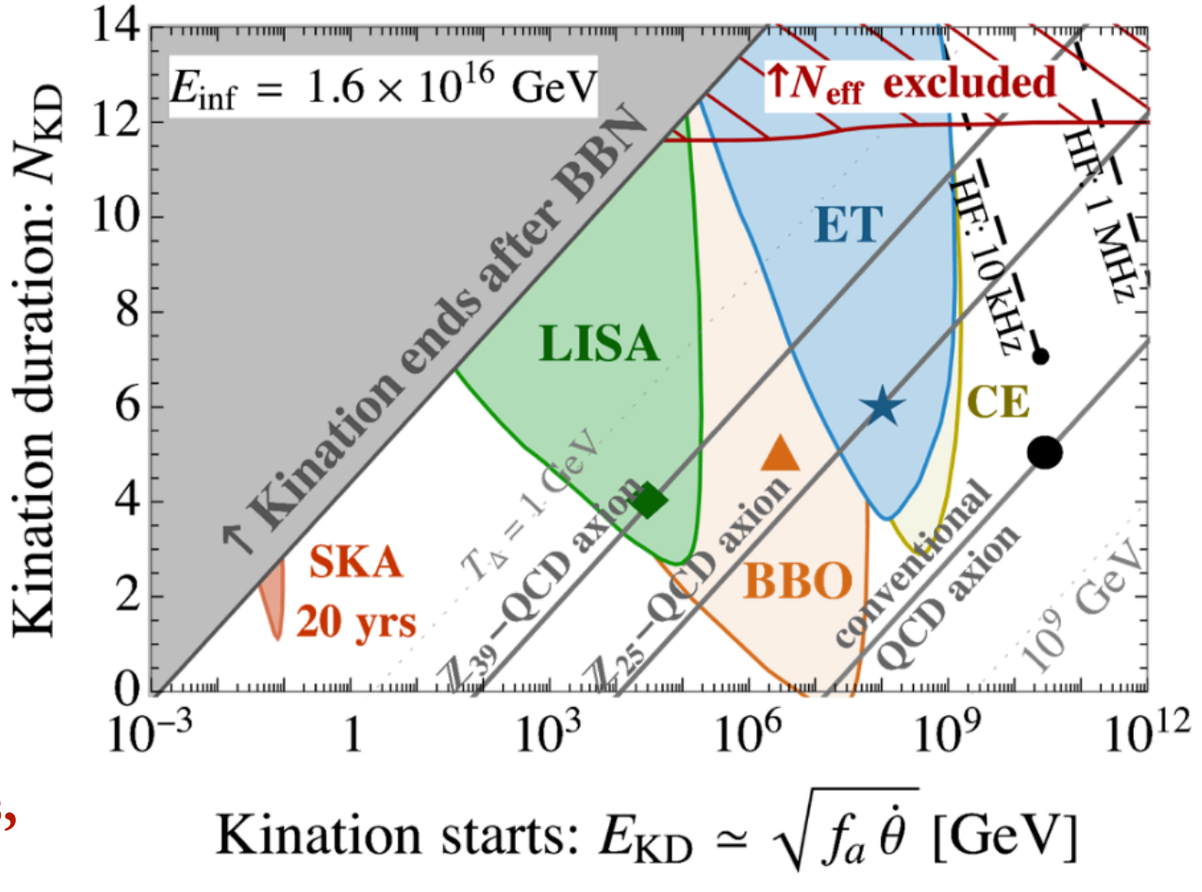
$$f_{\rm peak} \approx 10\ {\rm kHz} \left(\frac{\sqrt{m_a f_a}}{100\ {\rm MeV}}\right)^2 \left(\frac{E_{\rm KD}}{10^9\ {\rm GeV}}\right)^{4/3} \left(\frac{\Omega_{a,0}}{\Omega_{\rm DM,0}}\right)^{1/3}$$

$$\Omega_{\rm peak}h^2 \approx 10^{-15} \left(\frac{f_{\rm KD}}{\rm Hz}\right) \left(\frac{E_{\rm inf}}{10^{16}\ {\rm GeV}}\right)^4 \left(\frac{100\ {\rm MeV}}{\sqrt{m_a f_a}}\right)^2 \left(\frac{\Omega_{a,0}}{\Omega_{\rm DM,0}}\right)$$

**The canonical QCD axion has no observable peak, except BBO or HF experiments.**

**Observable signals from QCD axion with lighter mass, e.g., from the $\mathbb{Z}_N$-axion model.**

[Hook, '18 & [Di Luzio, Gavela, Quilez, Ringwald, '21] ]




[Gouttenoire, Servant, **PS**, to appear]

# In summary…

Kination era amplifies any primordial GW induced by a scalar field with large kinetic energy.

e.g. inflationary GW spectrum gets blue-tilted.
(We also look at a peak in cosmic-string GW spectrum.)

**A spinning axion**

**e.g. from complex scalar field (generic in SM extensions) or from trapped misalignment**

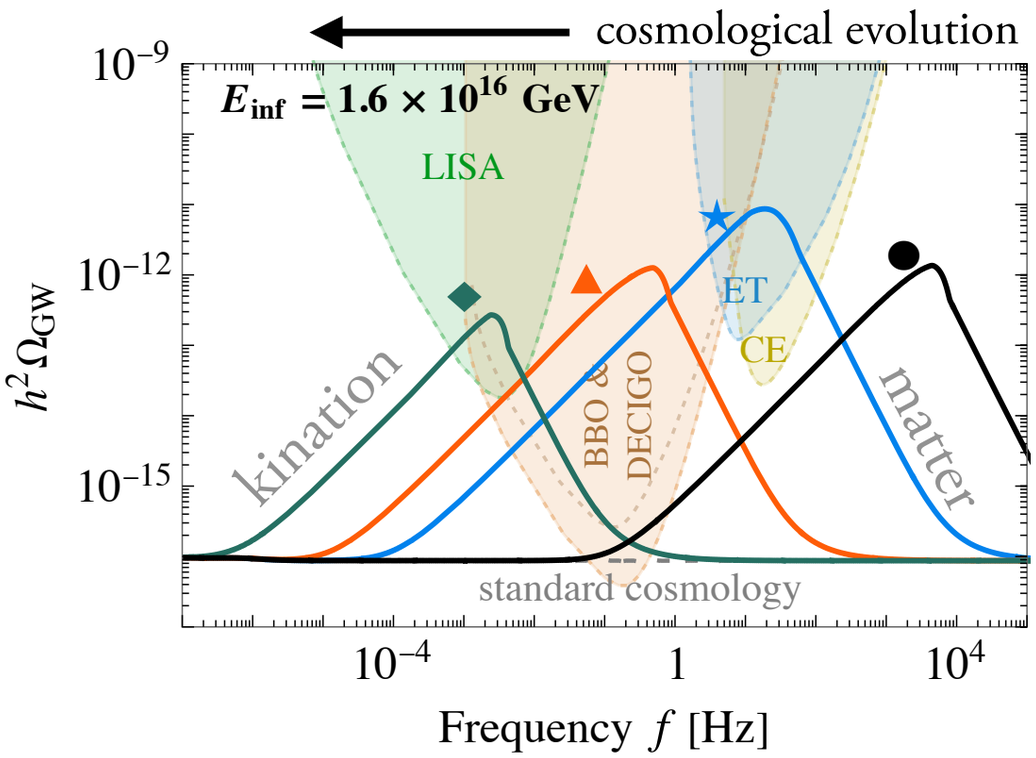
**can generate a intermediate matter-kination during the pre-BBN epoch.**

**"Peaked GW signature"**

$\Omega_{\rm peak}^{\rm GW} \propto$ kination duration

$f_{\rm peak} \propto$ energy scale & duration

LISA for $E_{\rm KD} \sim 10^{2-5}$ GeV | ET & CE for $E_{\rm KD} \sim 10^{6-9}$ GeV.

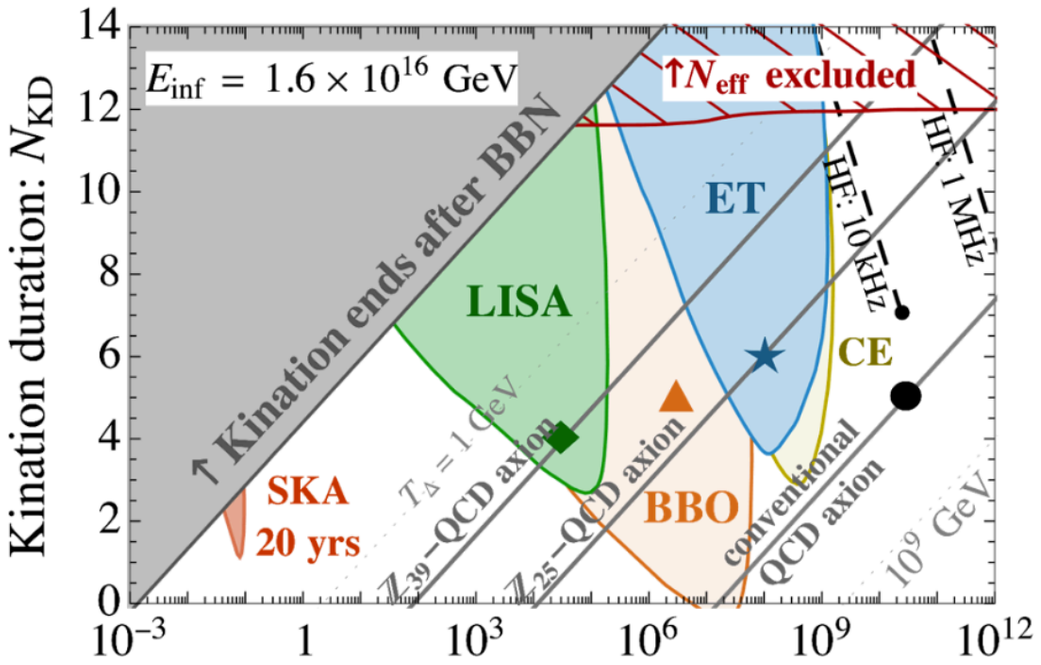



[Gouttenoire, Servant, **PS**, 2108.10328 & to appear]

**Kination peak from QCD axion DM:**

the conventional QCD axion ⇒ not observable

the lighter QCD axion ⇒ observable !




**Thank you !**