“Kination”
GW signatures & spinning axions

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with

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based on

2108.10328, 2110.xxxx

(130+ pages)

Mainz, 26.10.2021

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

Take-home messages:

Gravitational waves (GW) as probe of early universe and new physics at high energies.

Non-standard cosmological histories (from BSM physics) induce observable GW signatures.

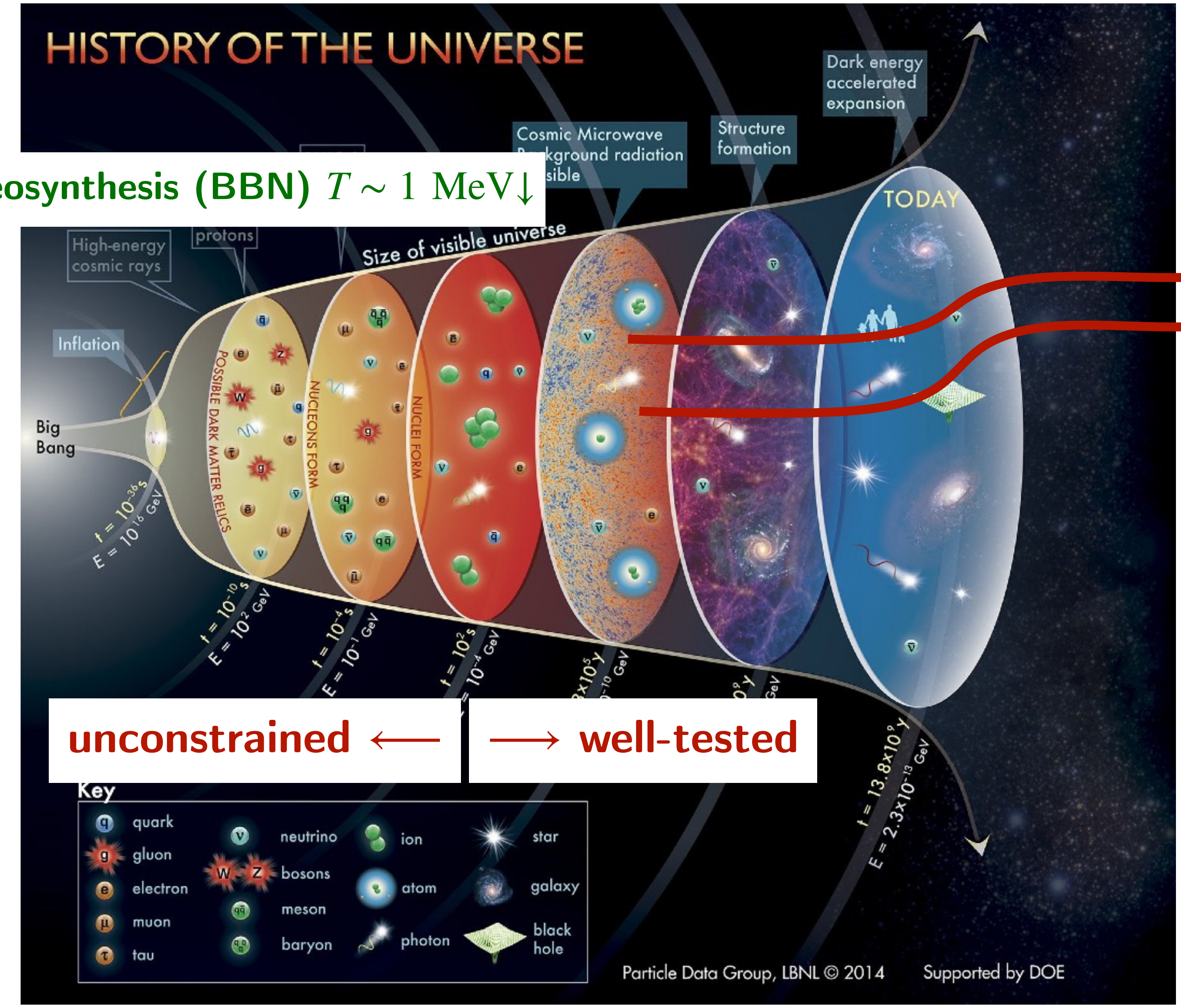
Kination era enhances primordial GW background.

Models of spinning axions generate naturally kination after matter-domination era and leads to observable “GW peak”.

Gravitational waves as probe of early-universe & new physics

high energy ⟵ **low energy**

Big-Bang nucleosynthesis (BBN) $T \sim 1$ MeV↓



CMB

unconstrained ⟵ | ⟶ **well-tested**

Cosmological dark age

reheating,
phase transition,
Baryogenesis,
dark matter,...

The universe is usually assumed to be radiation-dominated era.

Gravitational waves as probe of early-universe & new physics

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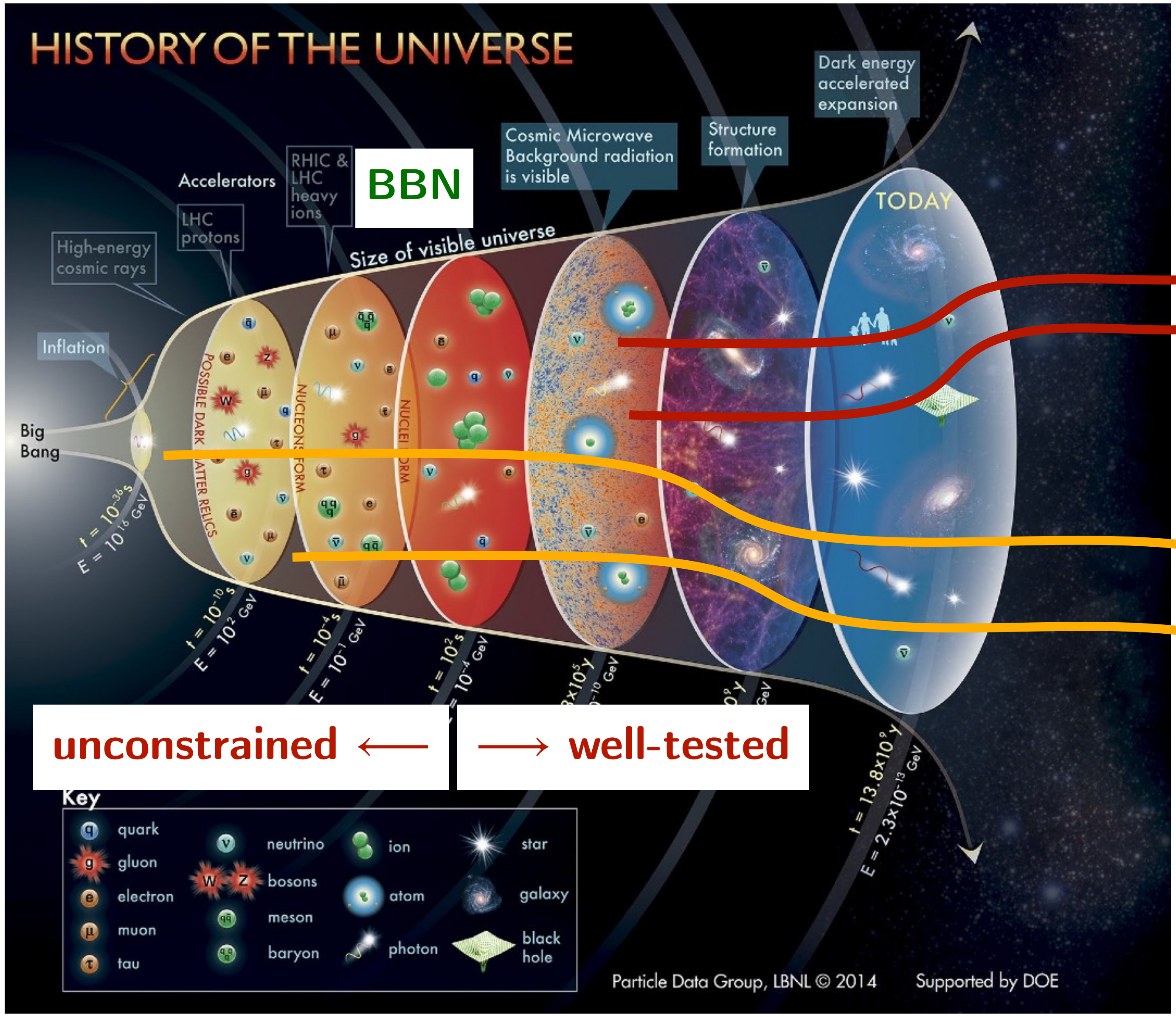

CMB

Cosmological dark age

reheating,
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Primordial GW
(metric tensor perturbation)

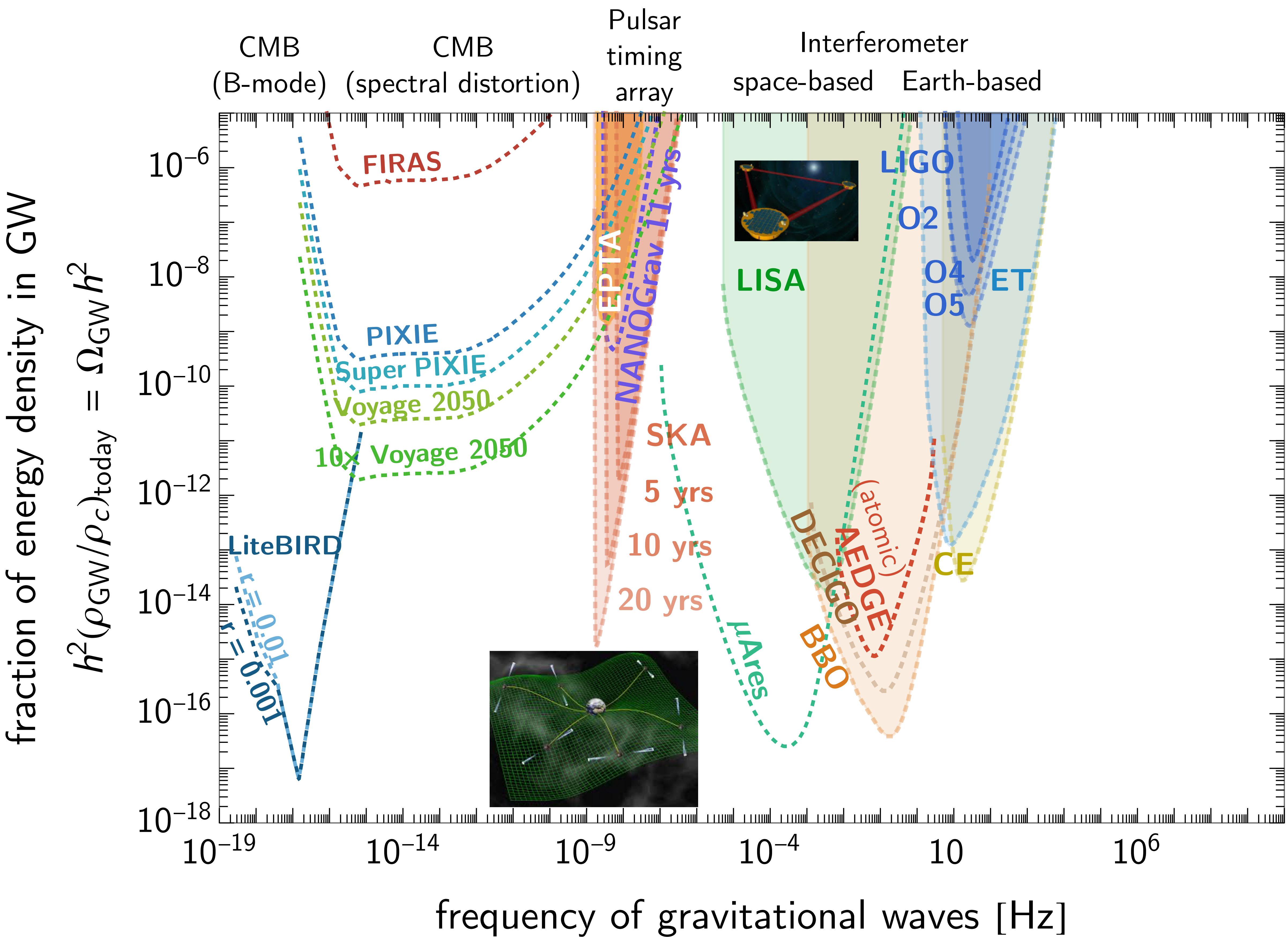
The universe is usually assumed to be radiation-dominated era.

GW is powerful and unique probe
of the pre-Big-Bang-Nucleosynthesis (BBN) era $T > \mathrm{MeV}$

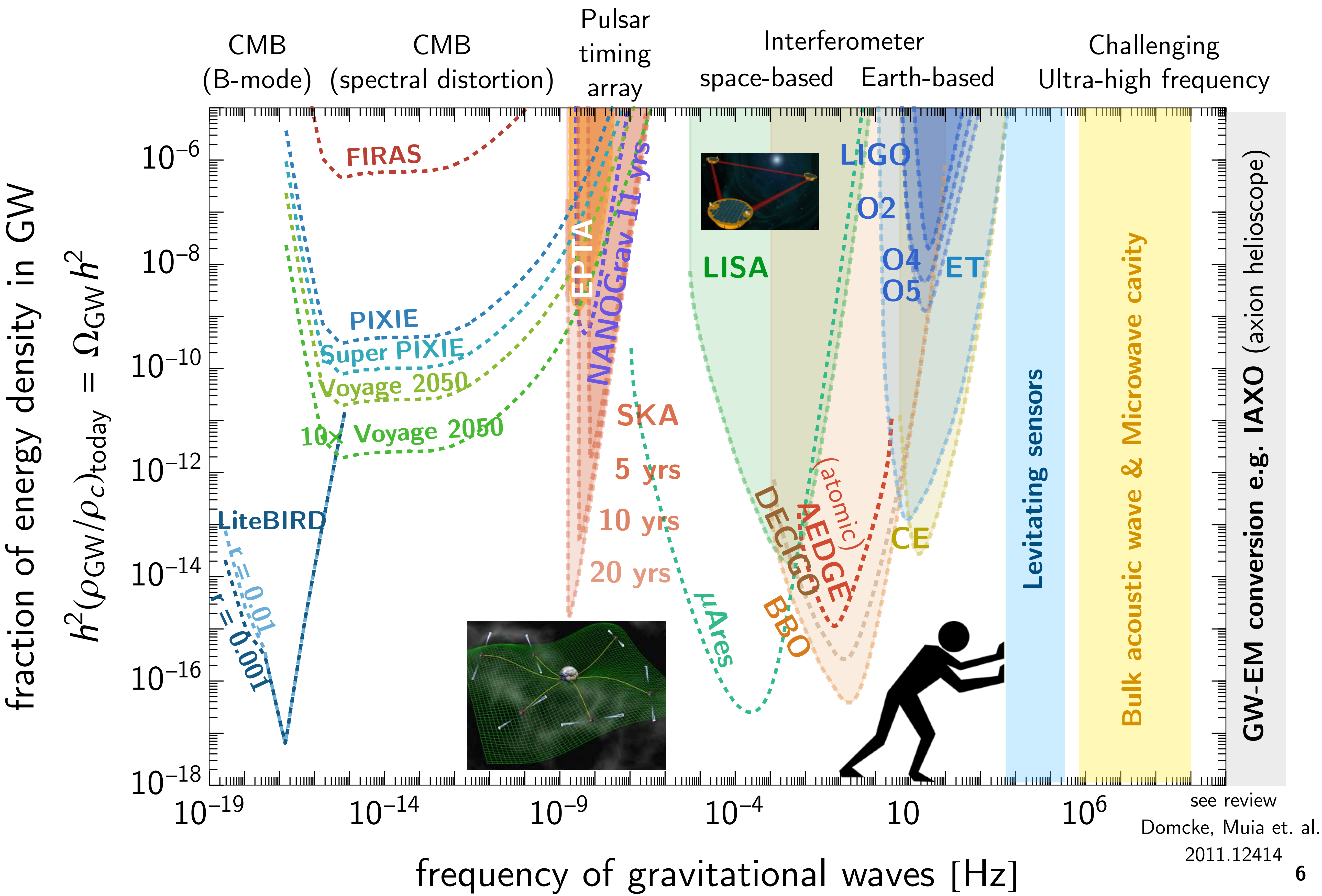
GW interacts feebly and propagates freely in the early universe:

$$\frac{\Gamma_{\rm GW}(T)}{H(T)} \sim \frac{G^2 T^5}{T^2/M_{\rm pl}} = \left(\frac{T}{M_{\rm pl}}\right)^3$$

Future prospect of GW experiments



Future prospect of GW experiments

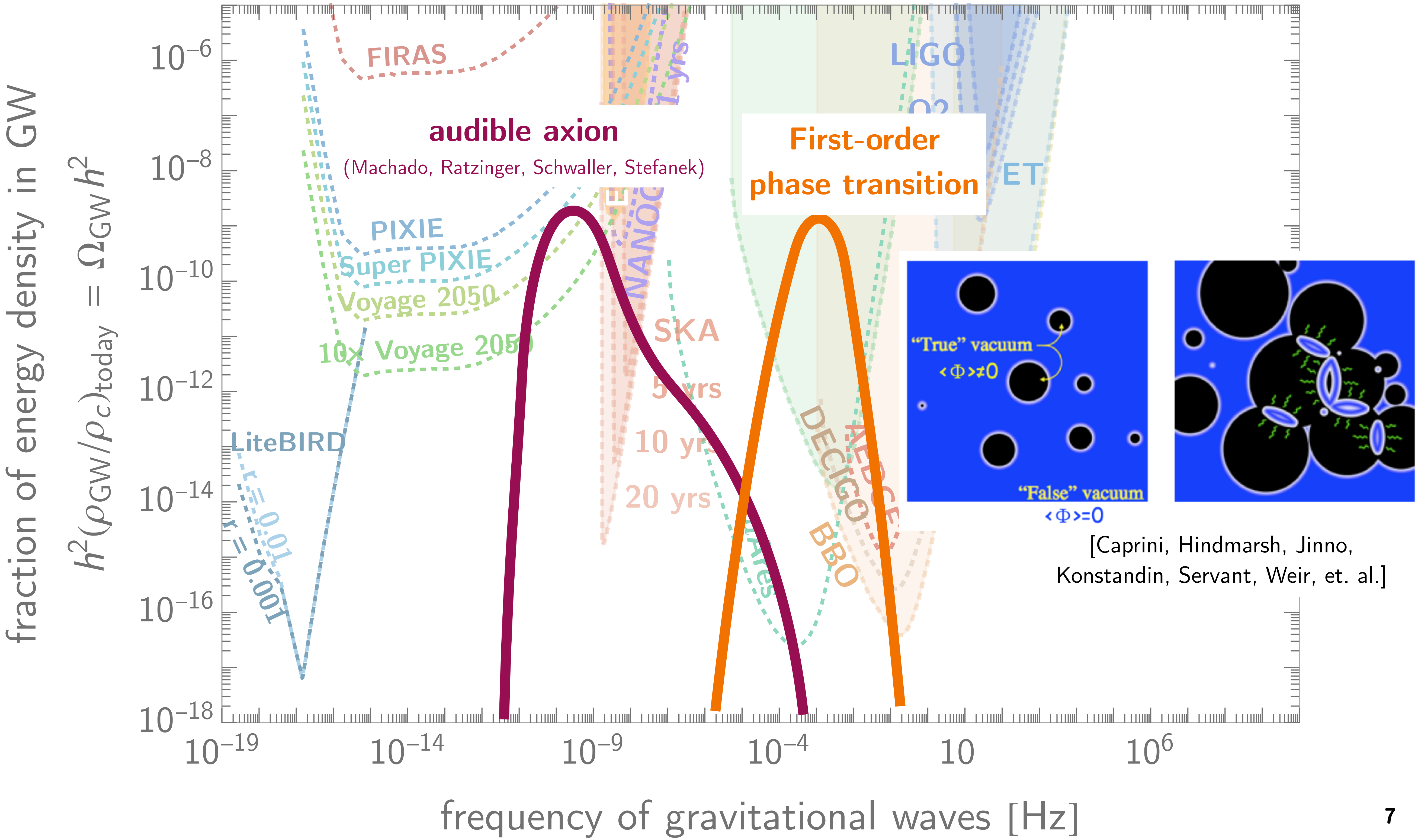


see review
Domcke, Muia et. al.,
2011.12414

Some main sources of primordial gravitational waves

Short-lasting (localized at some frequency)
first-order phase transition
explosion of particles (e.g. preheating or audible axion)

Long-lasting (spanning over many frequencies)
quantum fluctuation from primordial inflation
network of topological defects (e.g. cosmic strings)



[Caprini, Hindmarsh, Jinno, Konstandin, Servant, Weir, et. al.]

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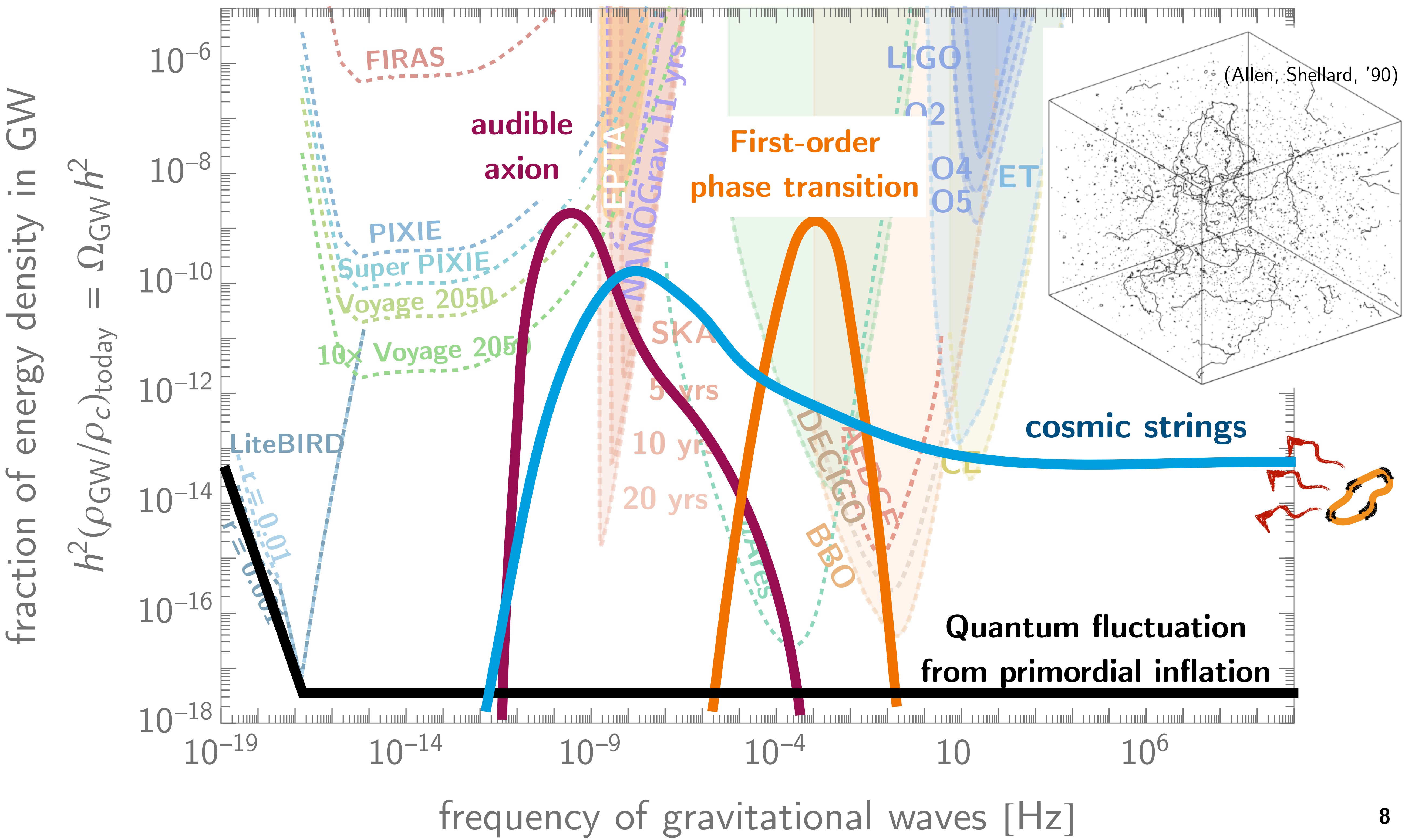

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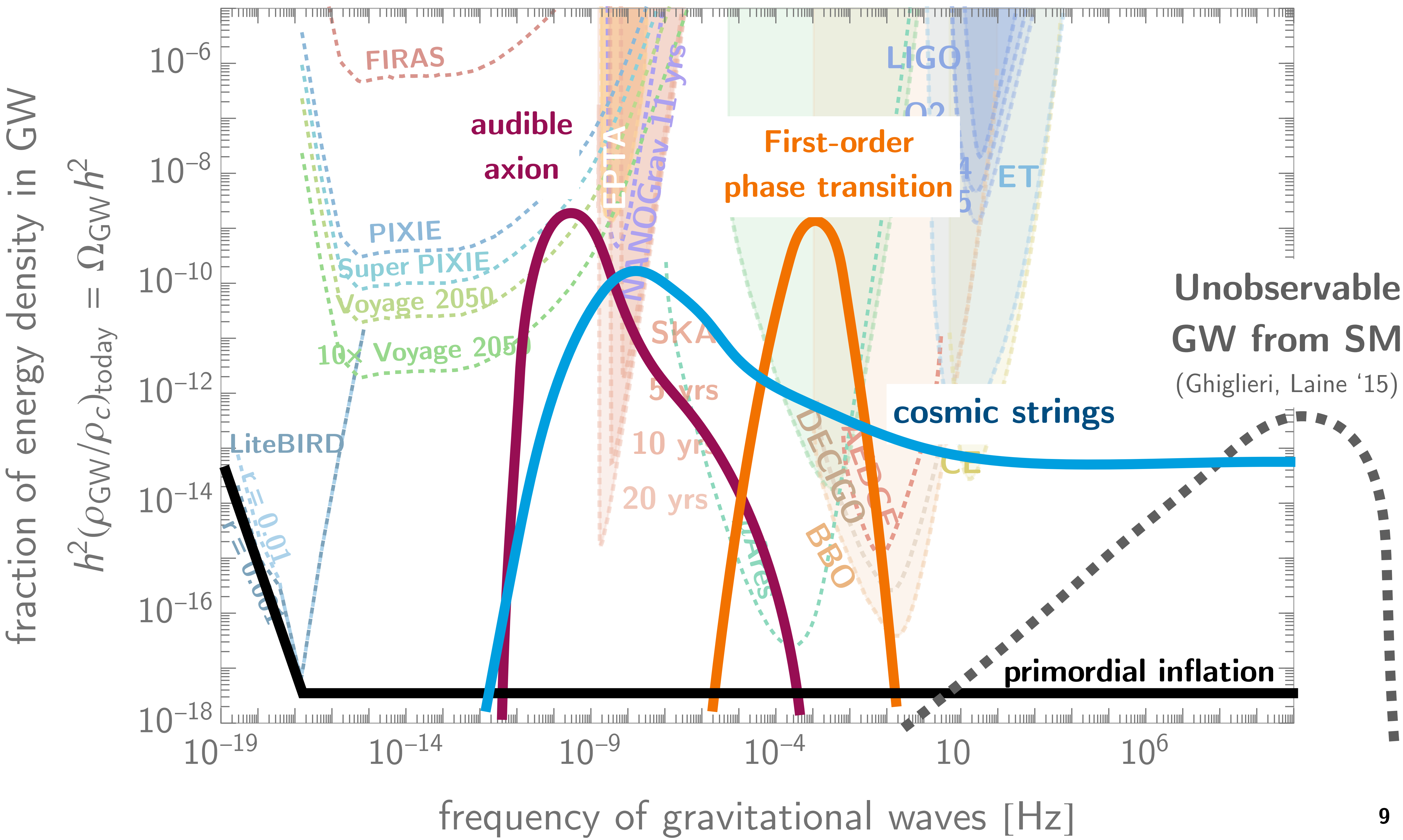
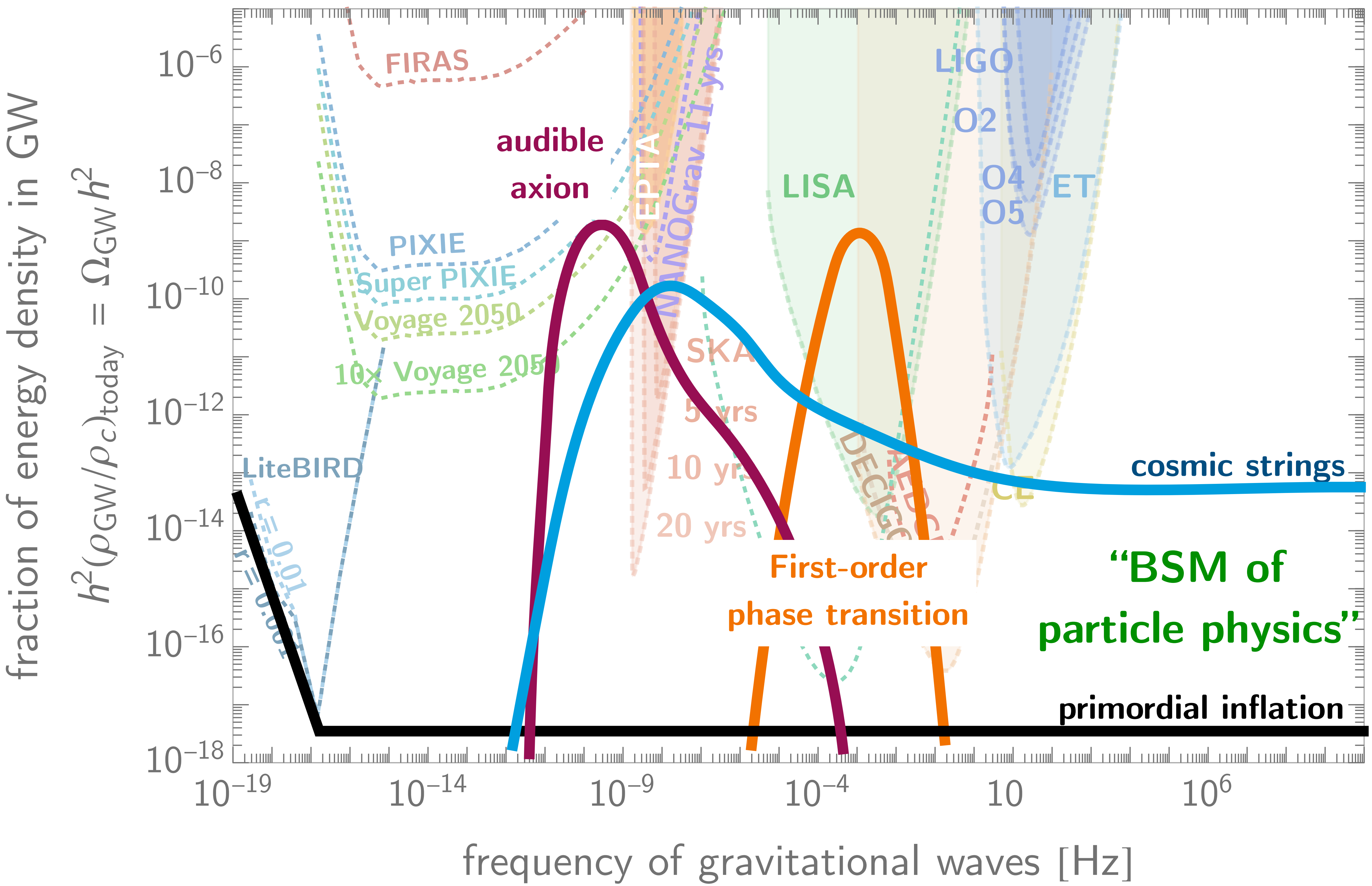


Primordial GW tells us about...



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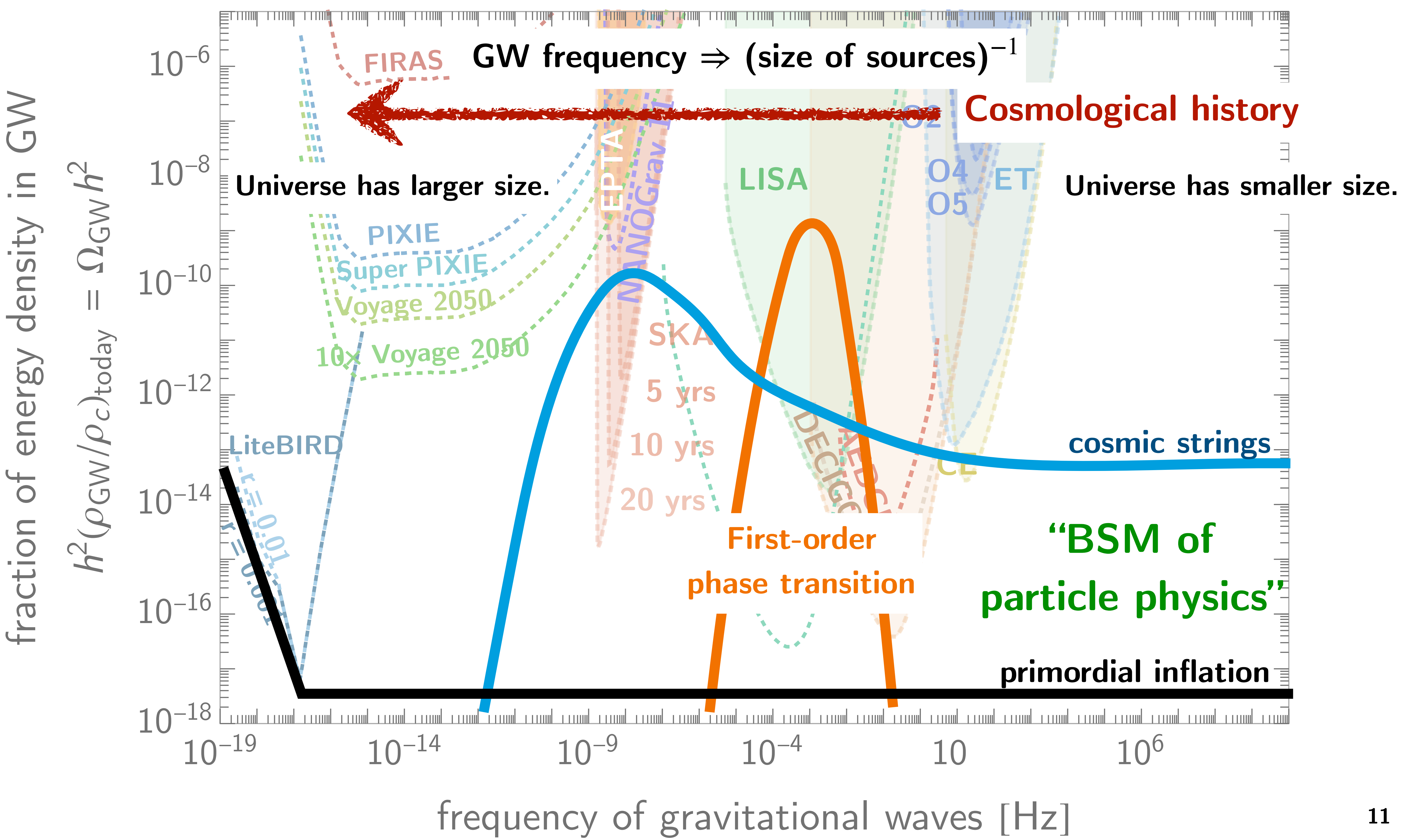

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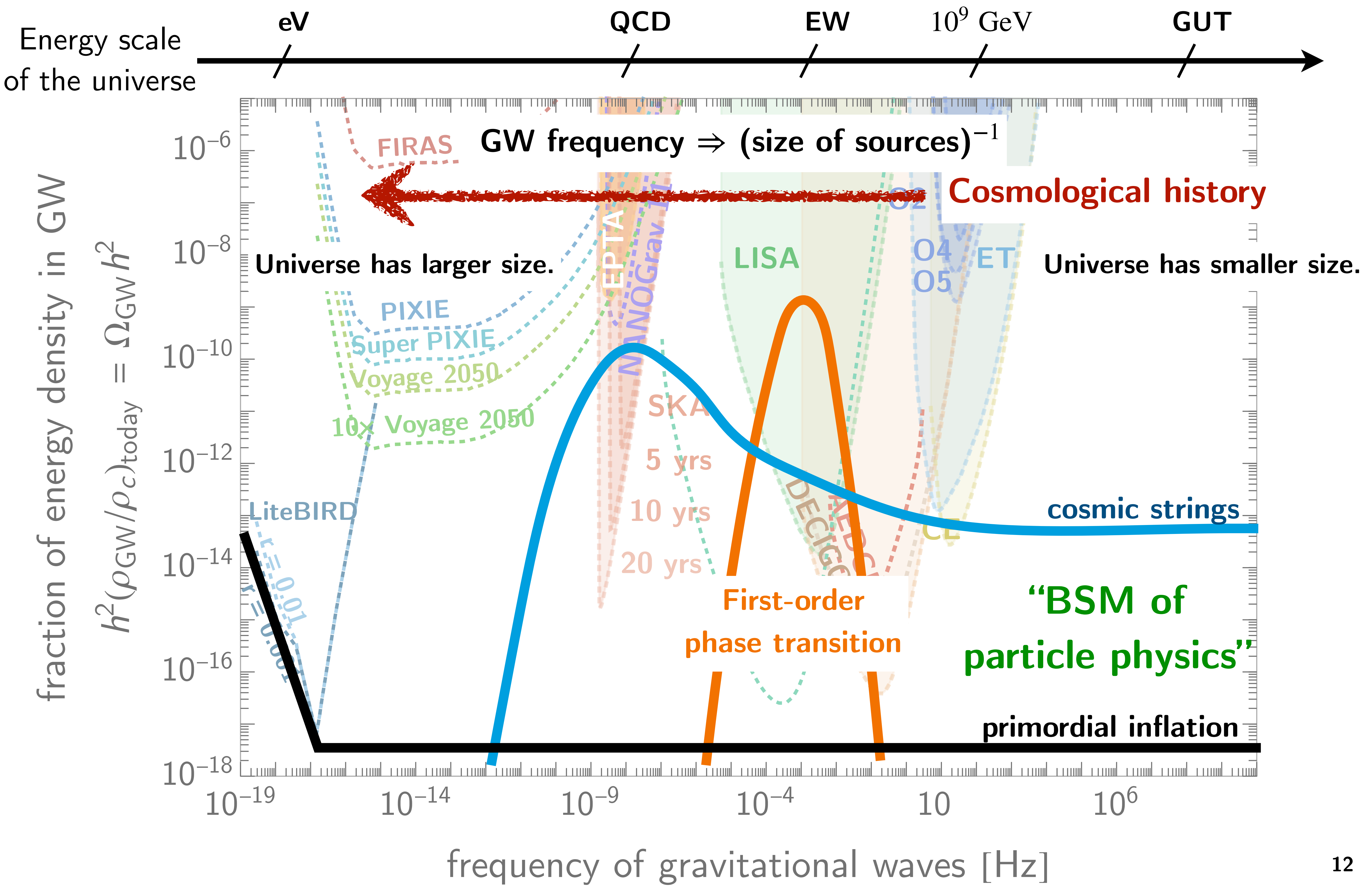


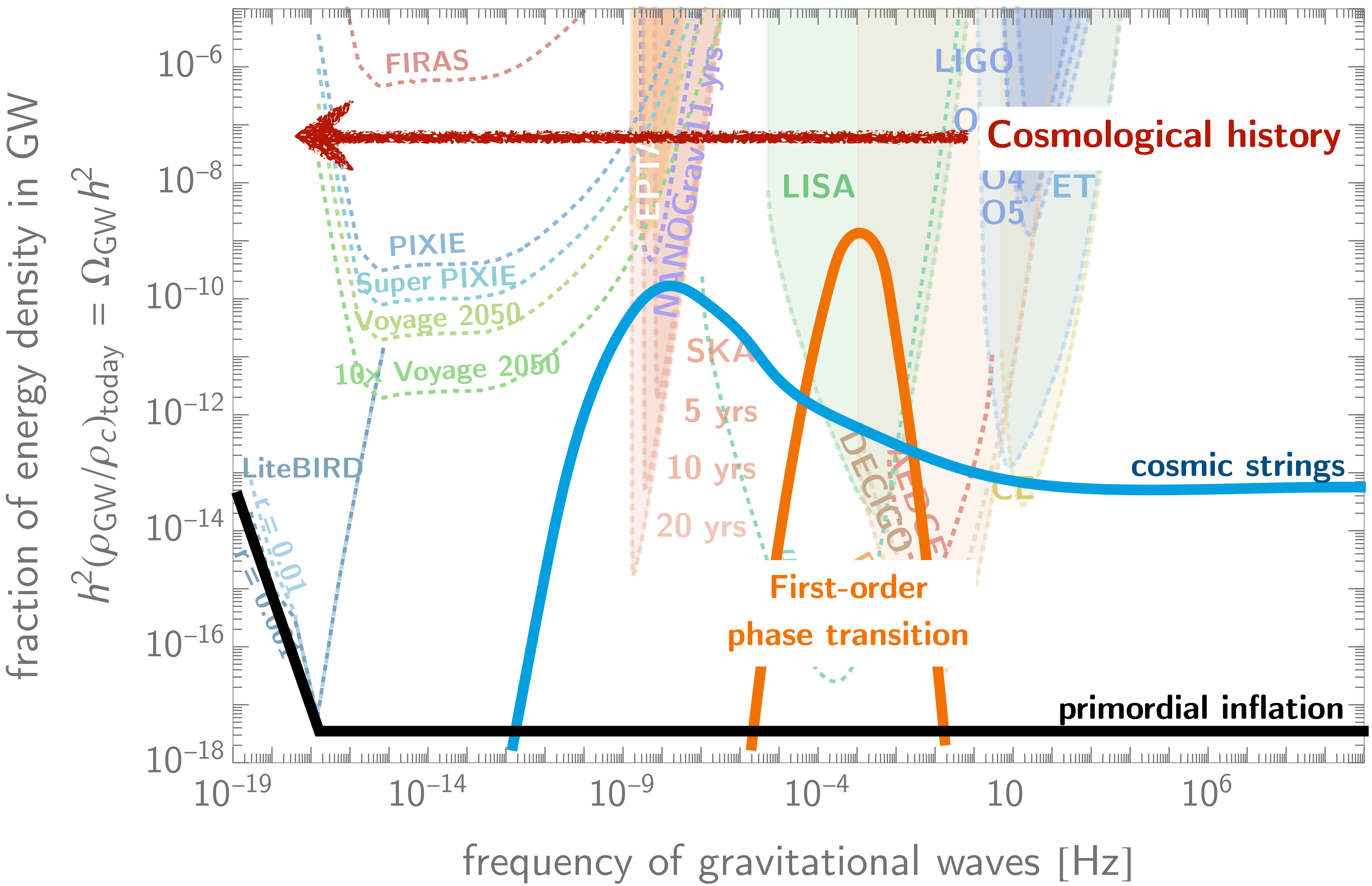
Primordial GW tells us about...

Energy density of GW (red-shift as radiation)

$$\rho^{\rm GW}_{\rm today} = \rho^{\rm GW}_{\rm prod} \left(\frac{a_{\rm prod}}{a_{\rm today}} \right)^4$$

red-shift factor (cosmic evolution) ⇨ **BSM of cosmology**

its production mechanism ⇨ **BSM of particle physics**



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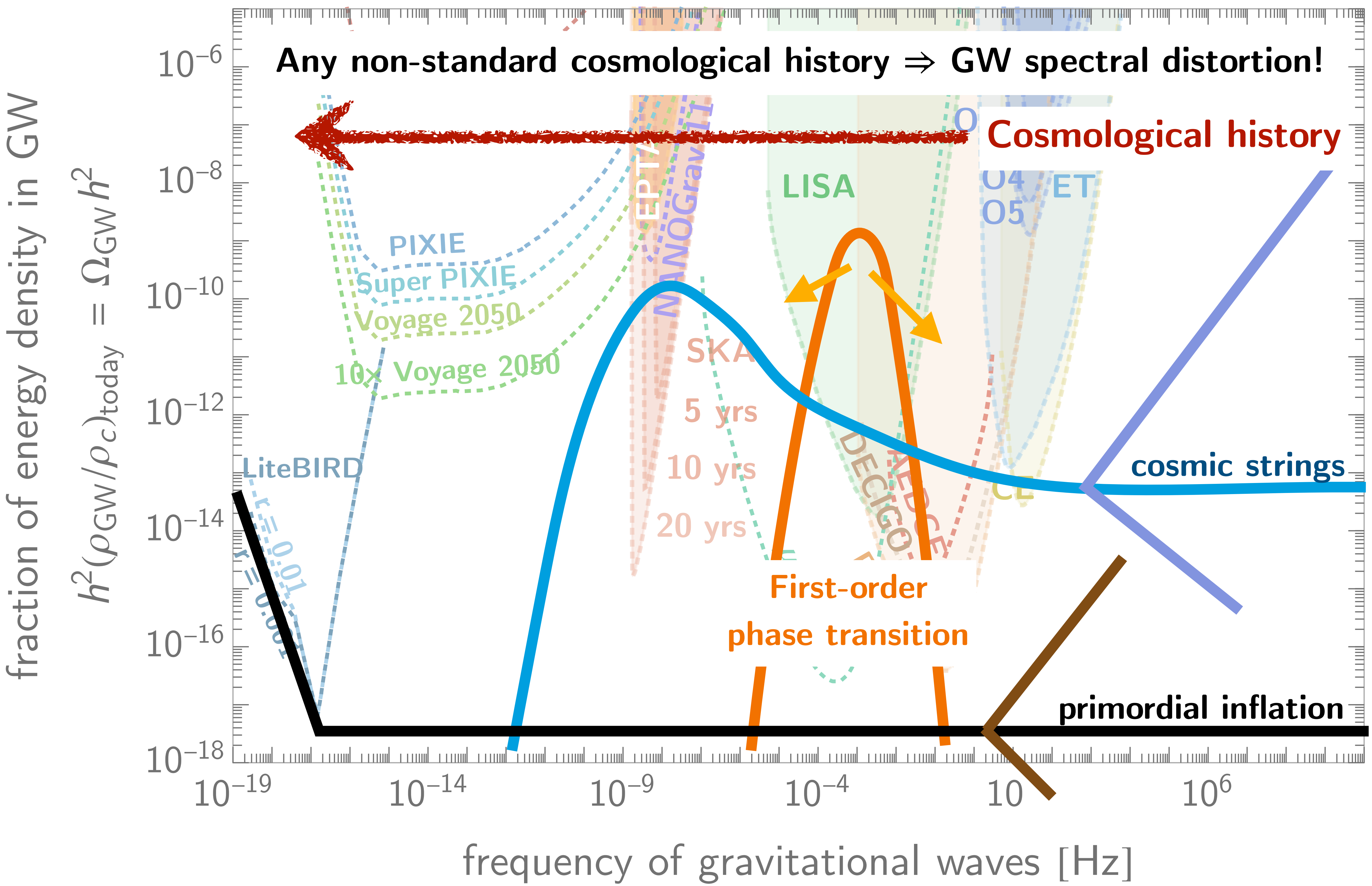
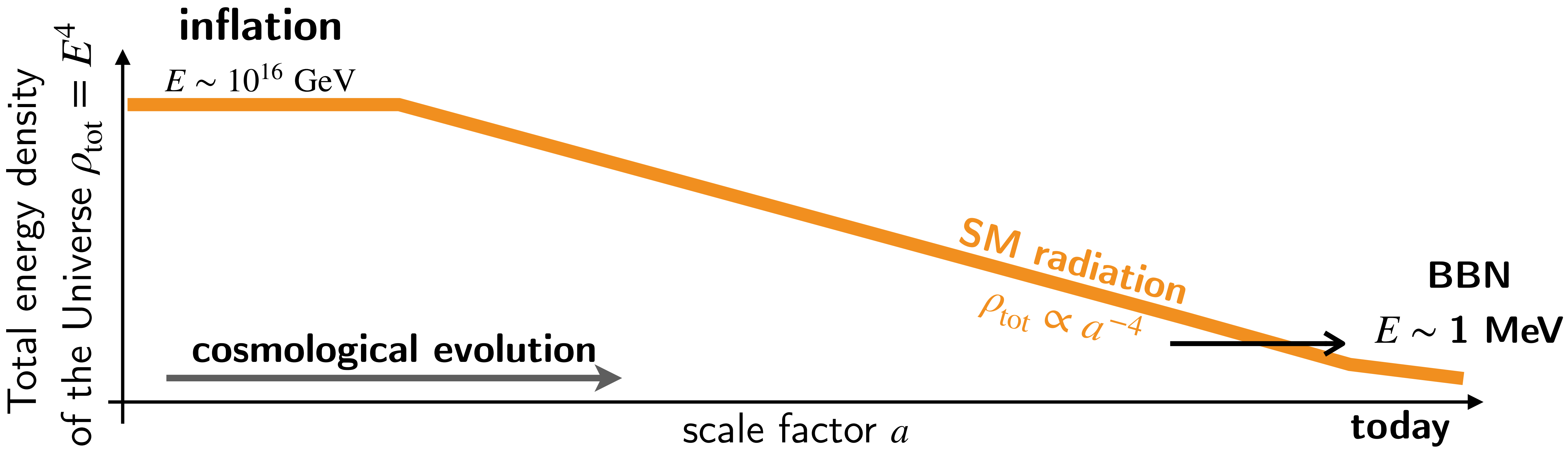
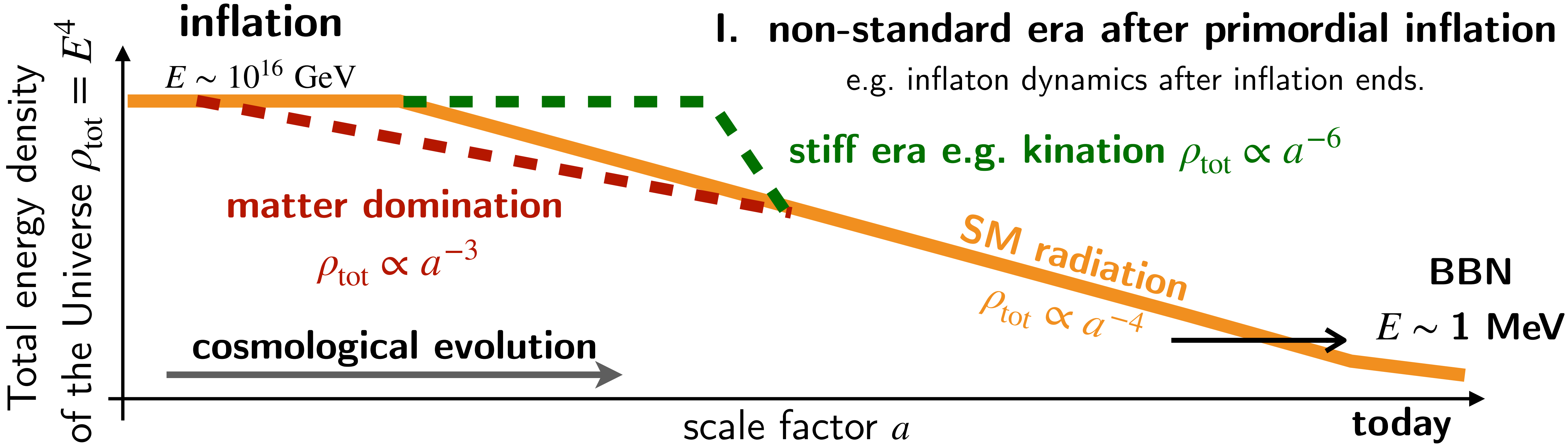


Non-standard cosmological histories induce GW signatures.

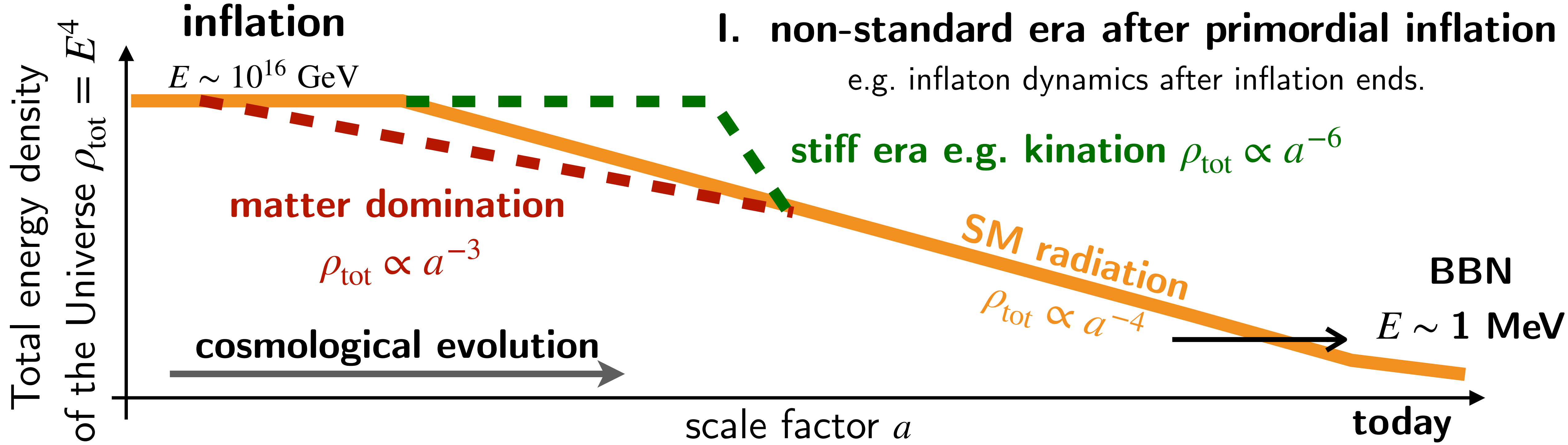
Standard cosmological history



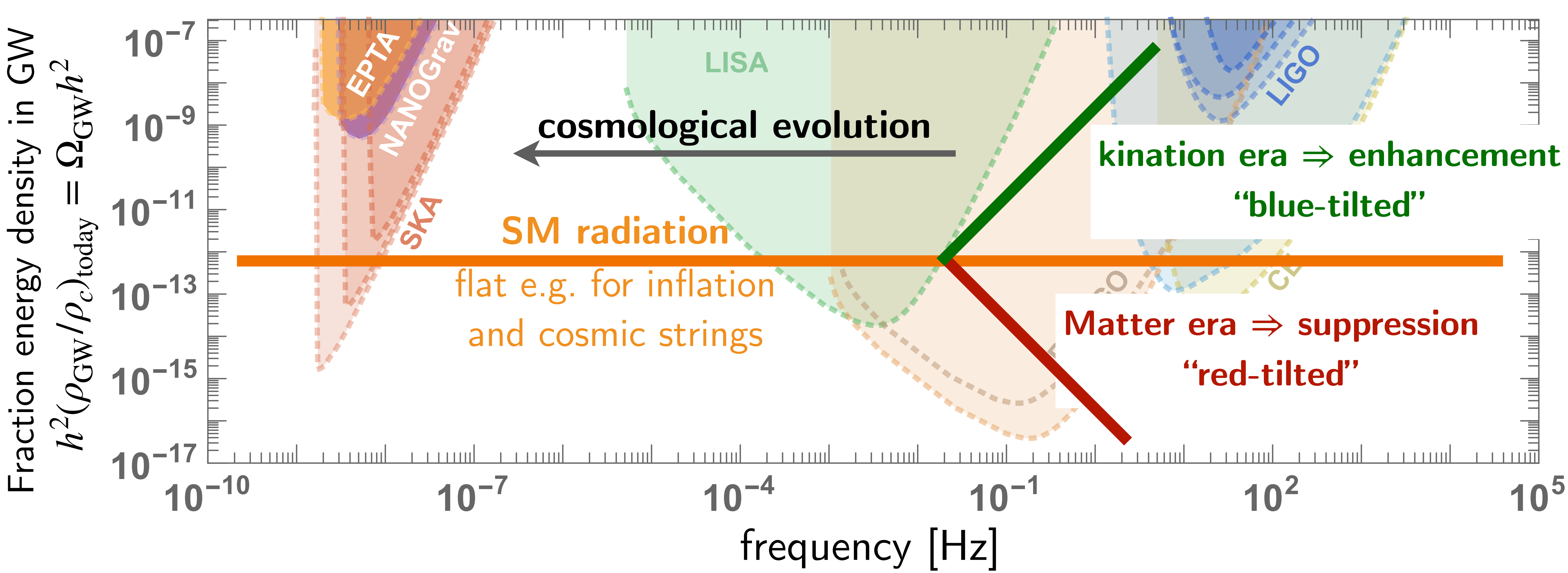
Non-standard cosmological histories



Non-standard cosmological histories



Distortion of GW from long-lasting sources



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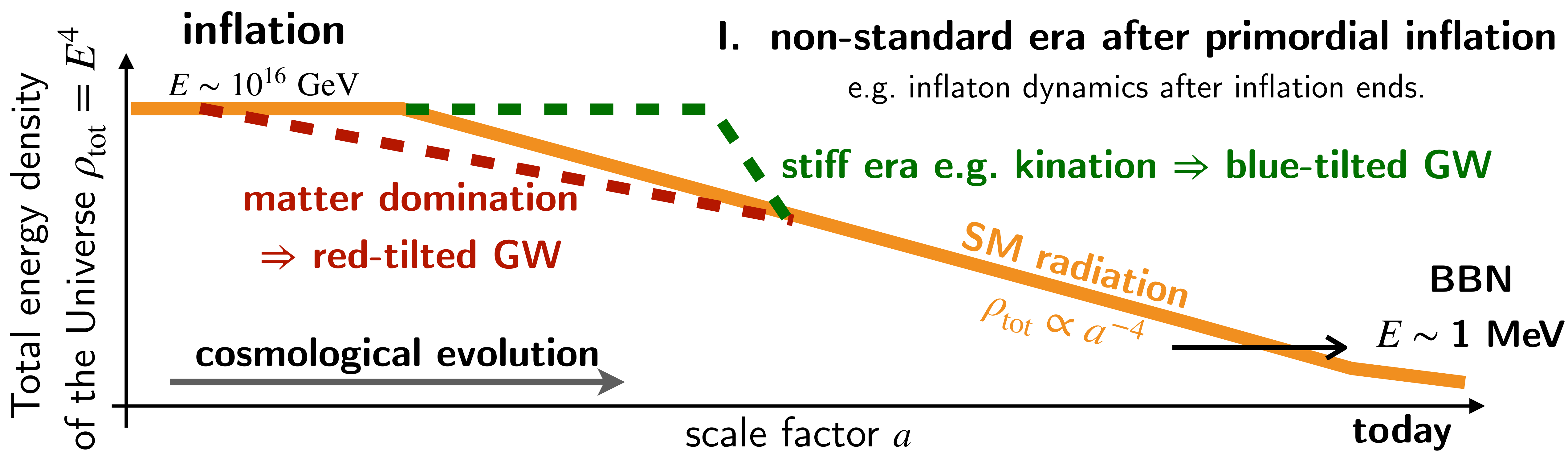
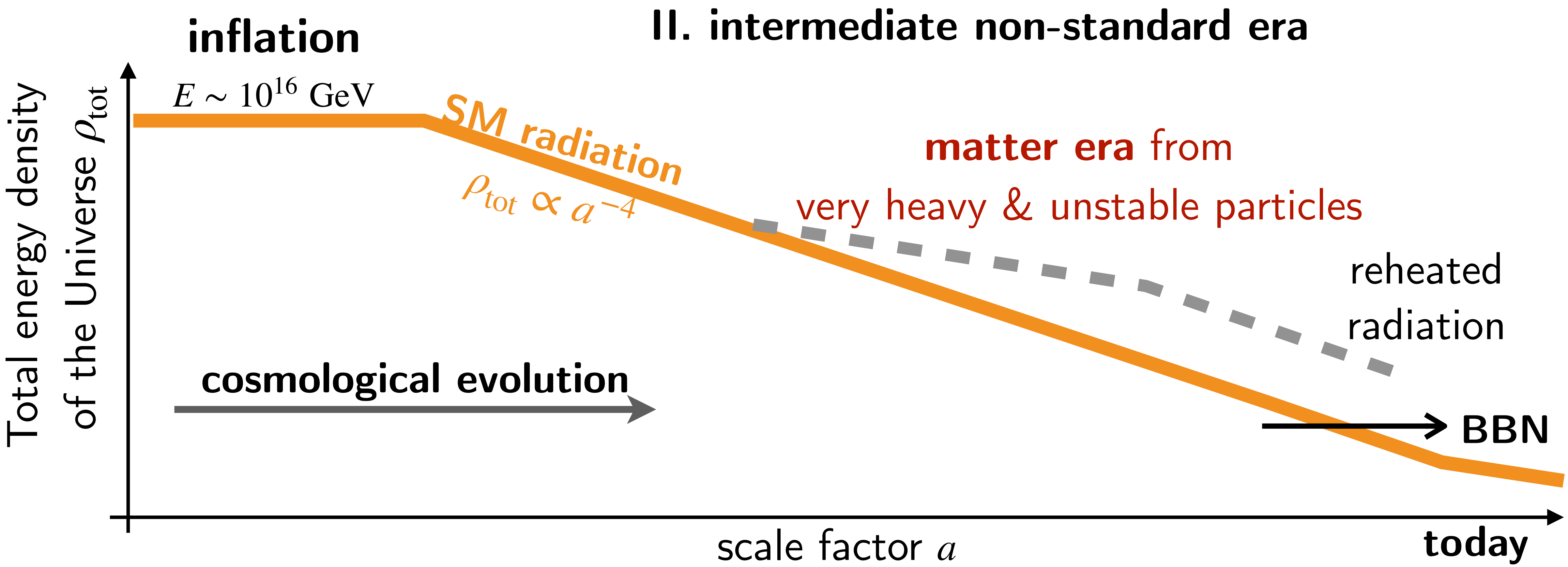
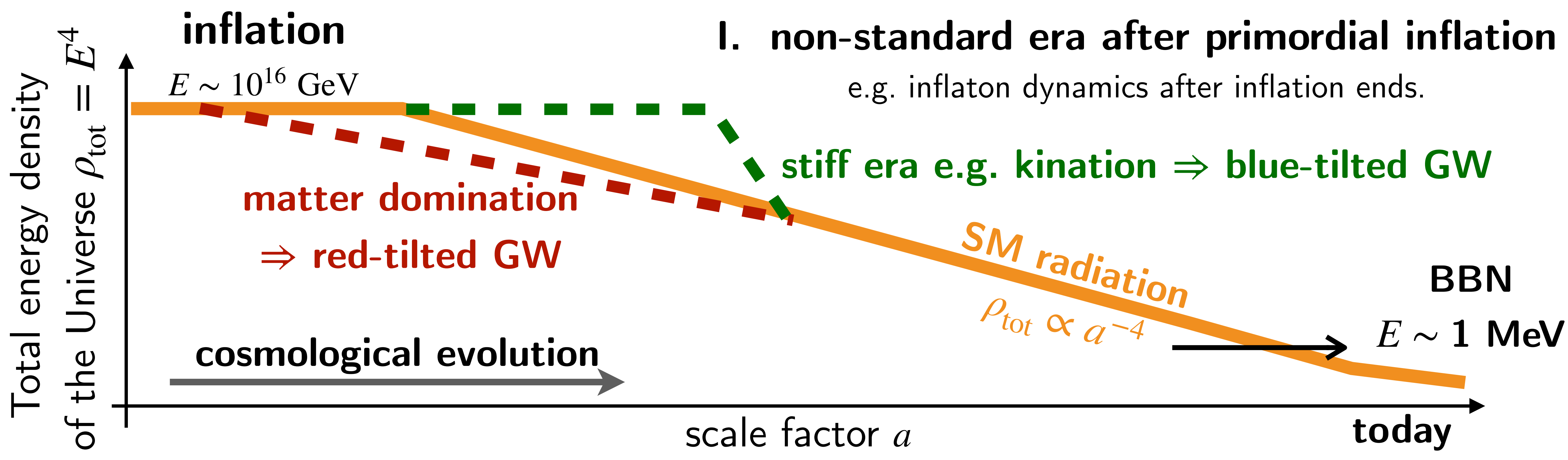
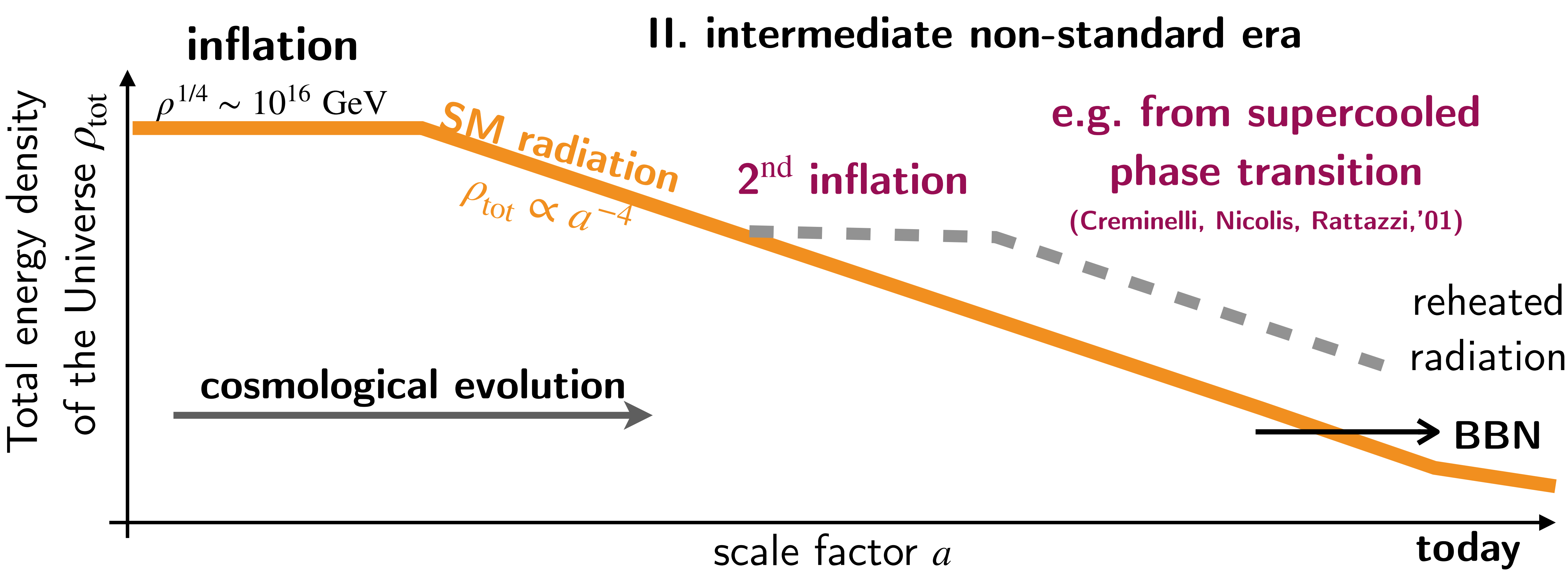




Non-standard cosmological histories





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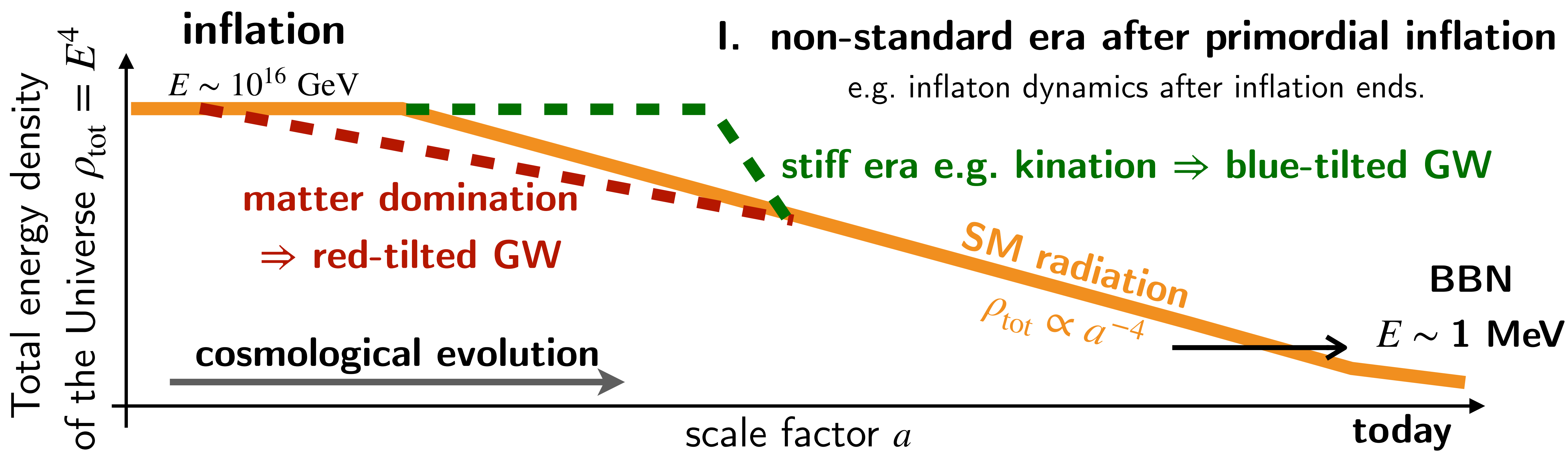
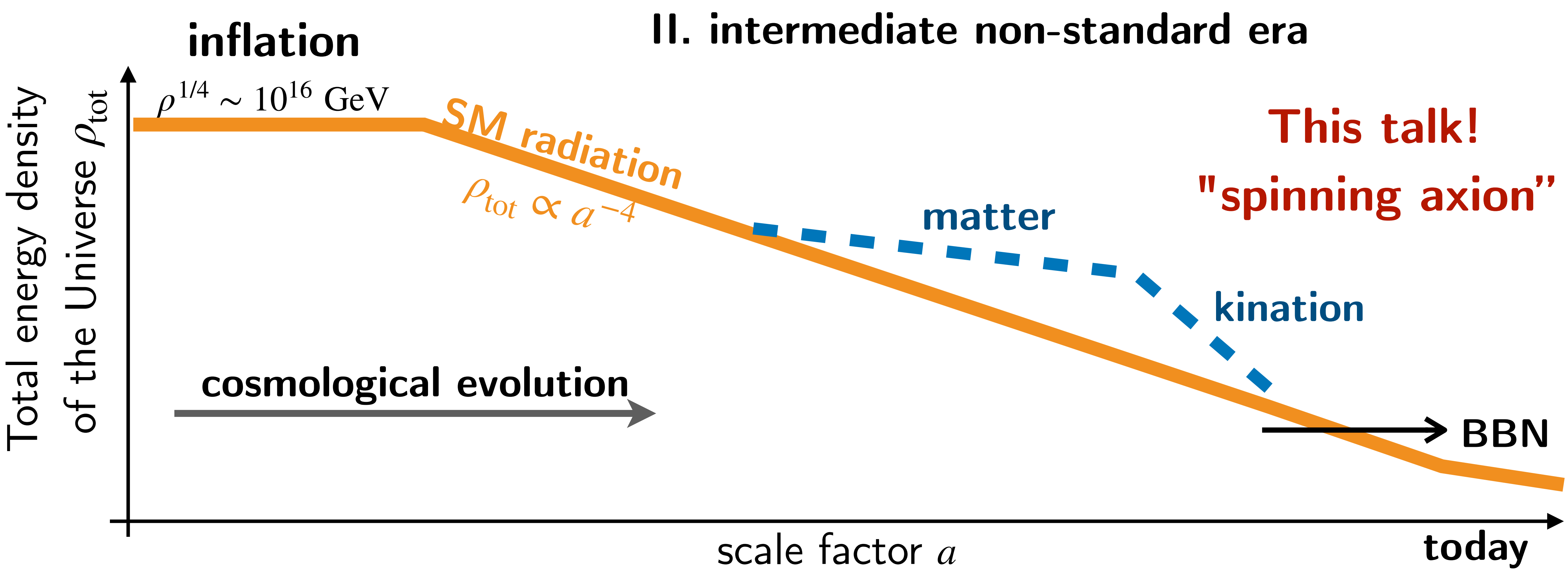
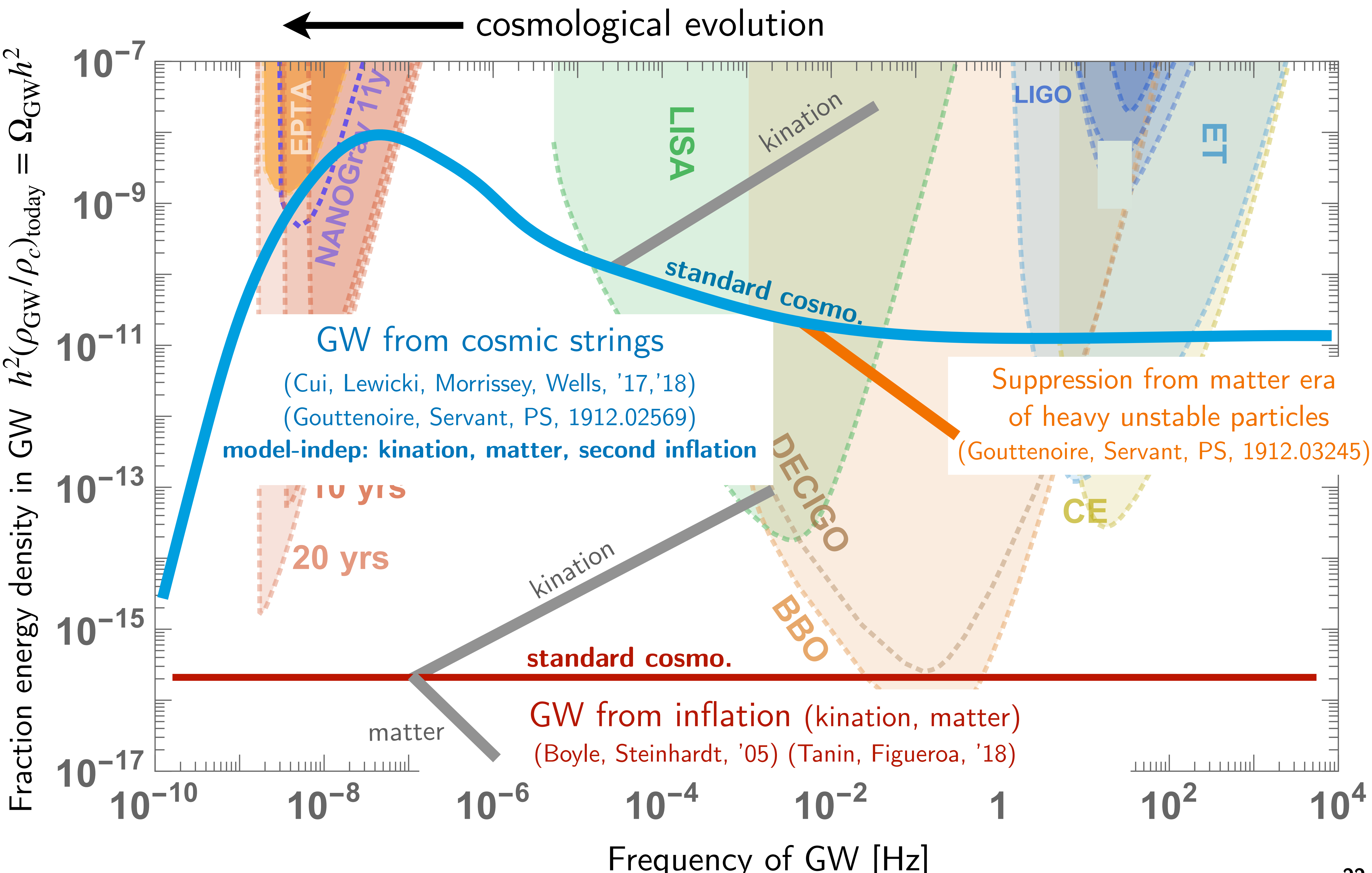




Overview: Cosmic archeology with GW



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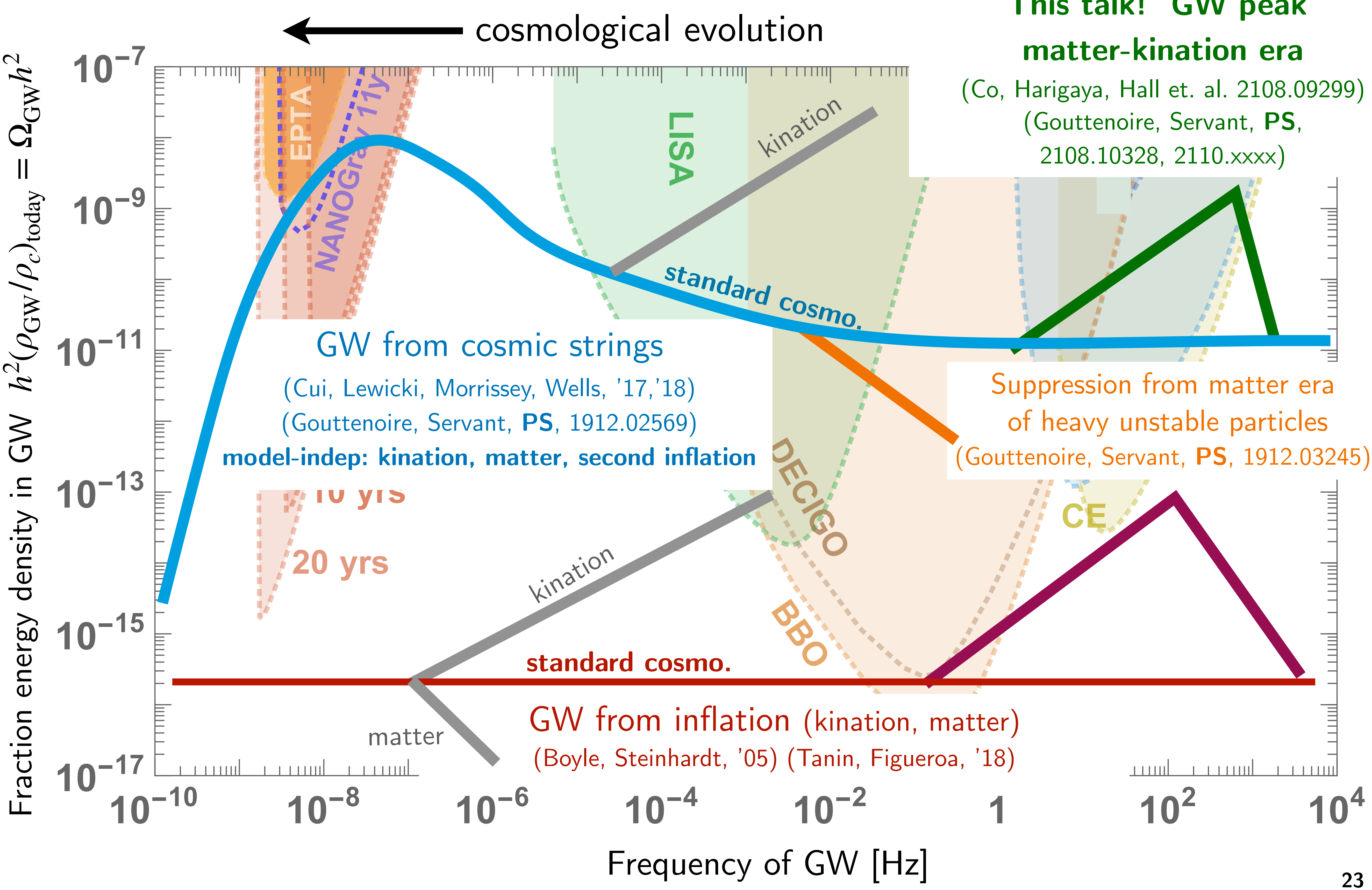
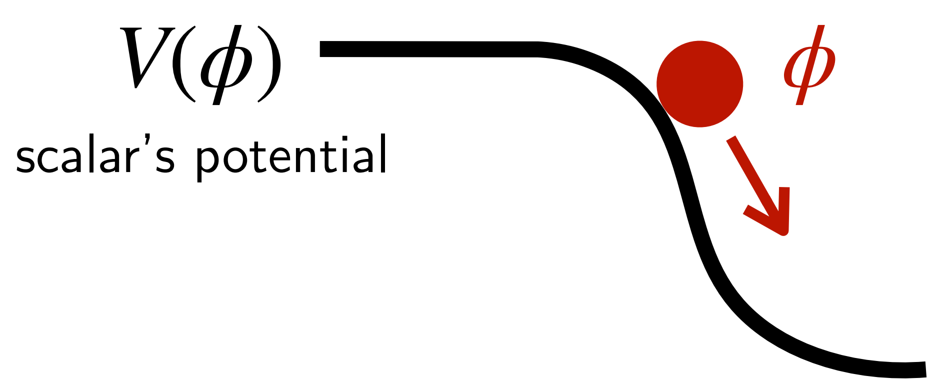


Kination enhances primordial GW.

The simplest kination era



equation-of-state: $\omega_\phi = P_\phi/\rho_\phi = \dfrac{E_{\text{kinetic}} - E_{\text{potential}}}{E_{\text{kinetic}} + E_{\text{potential}}}$

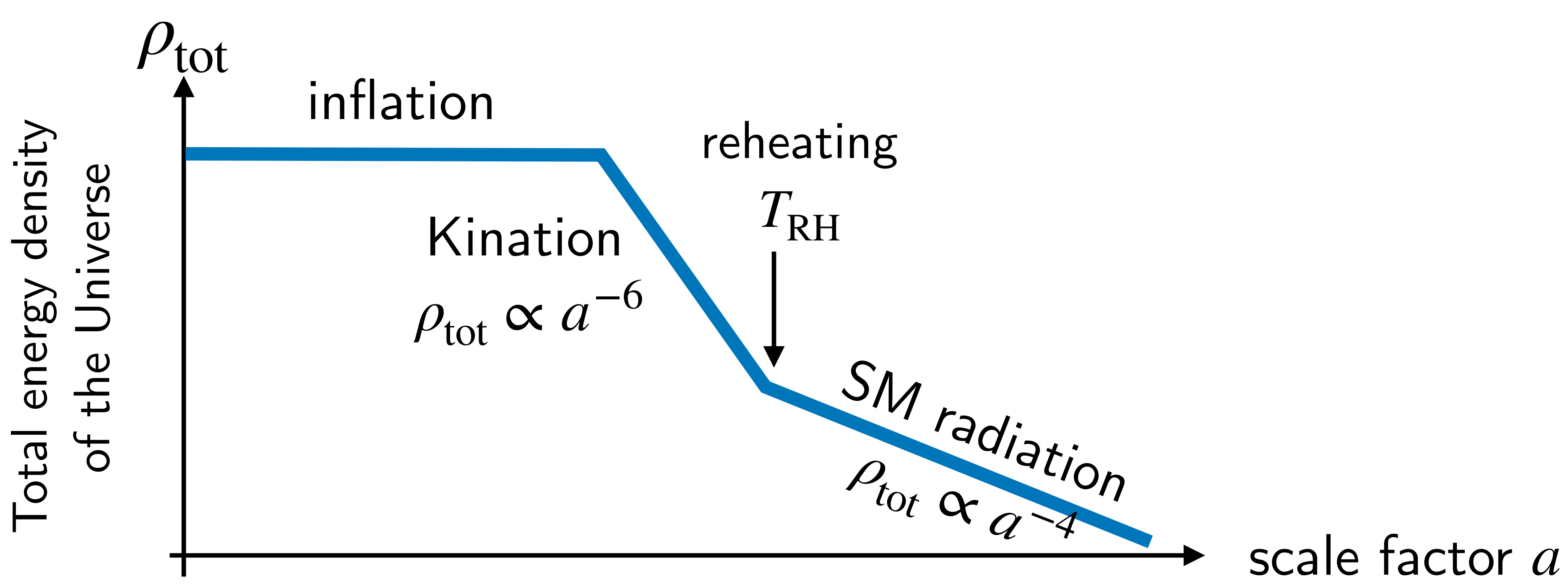
Larger than radiation if $\omega_\phi > 1/3$, $\rho_\phi \propto a^{-3(1+\omega_\phi)}$

Largest $\omega_\phi = 1$, when $E_{\text{kinetic}} \gg E_{\text{potential}}$

A scalar field dominates the universe with large kinetic energy,
so-called "Kination" era. ($\rho_\phi \propto a^{-6}$)

[Spokoiny 1993, Joyce, 1997]

Examples: scalar quickly moves after the slow-roll inflation.
Naturally, kination era is at high-energy scales after inflation



Why enhancement?

Fraction of energy density in GW today

$$\Omega_{GW,0} = \left(\frac{\rho_{GW,prod}}{\rho_{tot,0}}\right)\left(\frac{a_{prod}}{a_0}\right)^4 = \left(\frac{\rho_{GW,prod}}{\rho_{tot,prod}}\right)\left(\frac{\rho_{tot,prod}}{\rho_{tot,0}}\right)\left(\frac{a_{prod}}{a_0}\right)^4$$

constant

Inflationary GW

scale-invariant tensor perturbation

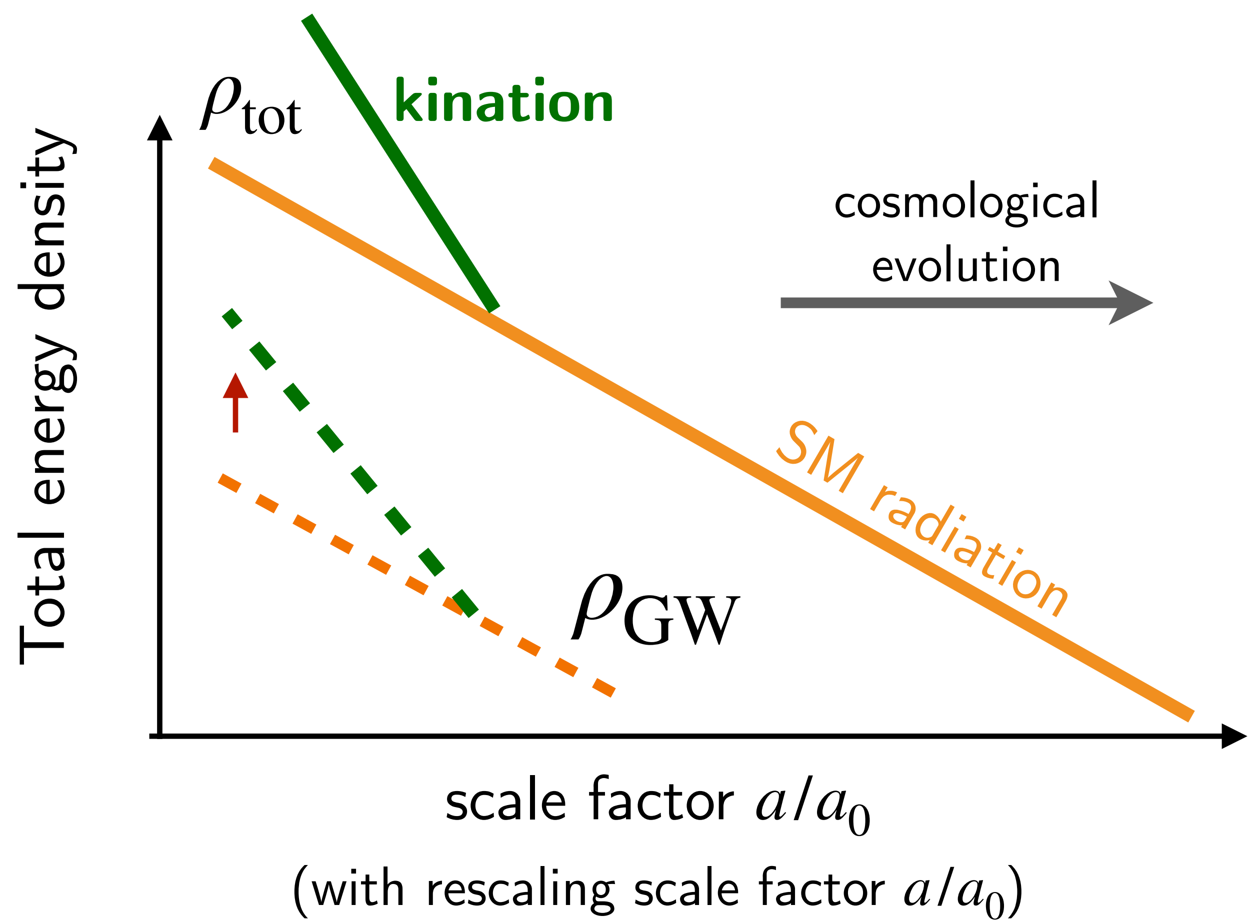
$(\rho_{GW}/\rho_{tot})_{prod} = \text{constant}$

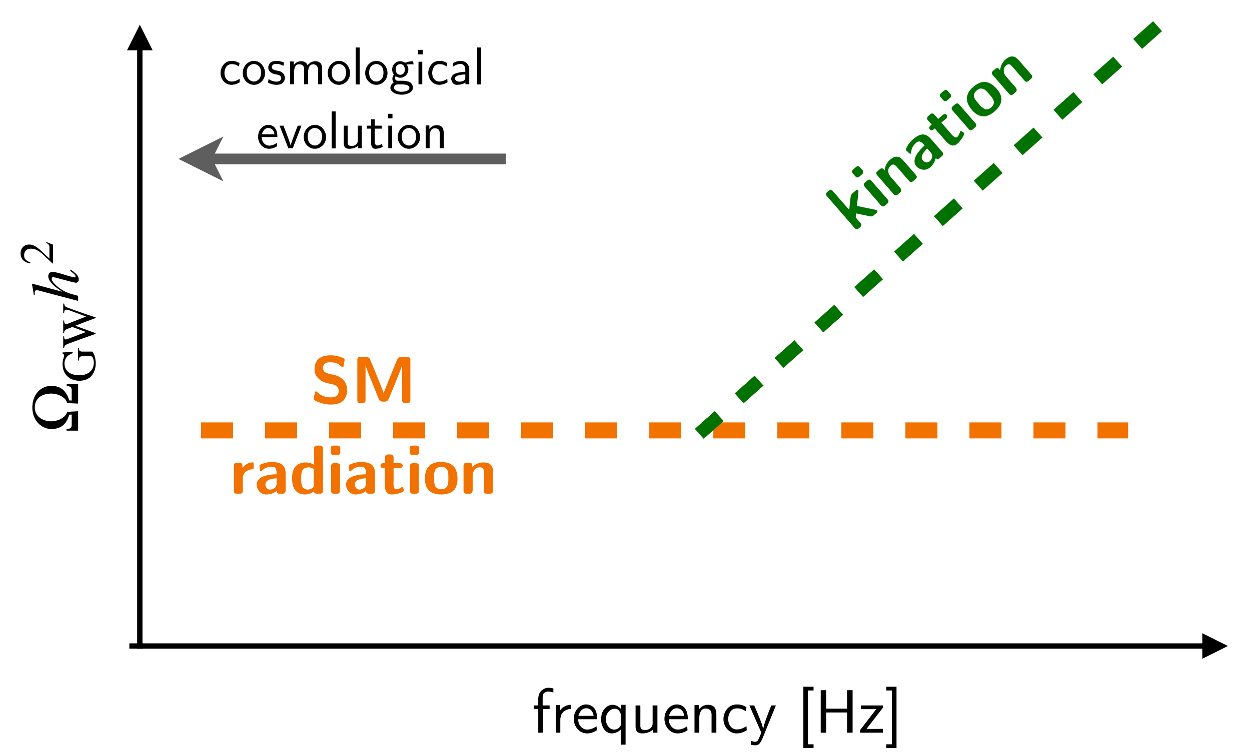
Cosmic-string GW:

$\rho_{GW} \propto \rho_{string-network} \propto \rho_{tot}$

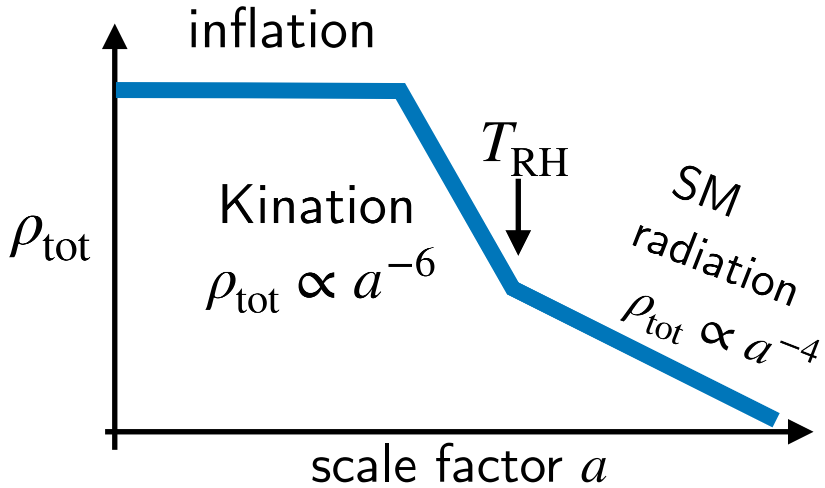
in the so-called "scaling regime"

Larger ρ_{tot} during kination ⇒ Enhancement in GW spectrum Ω_{GW}



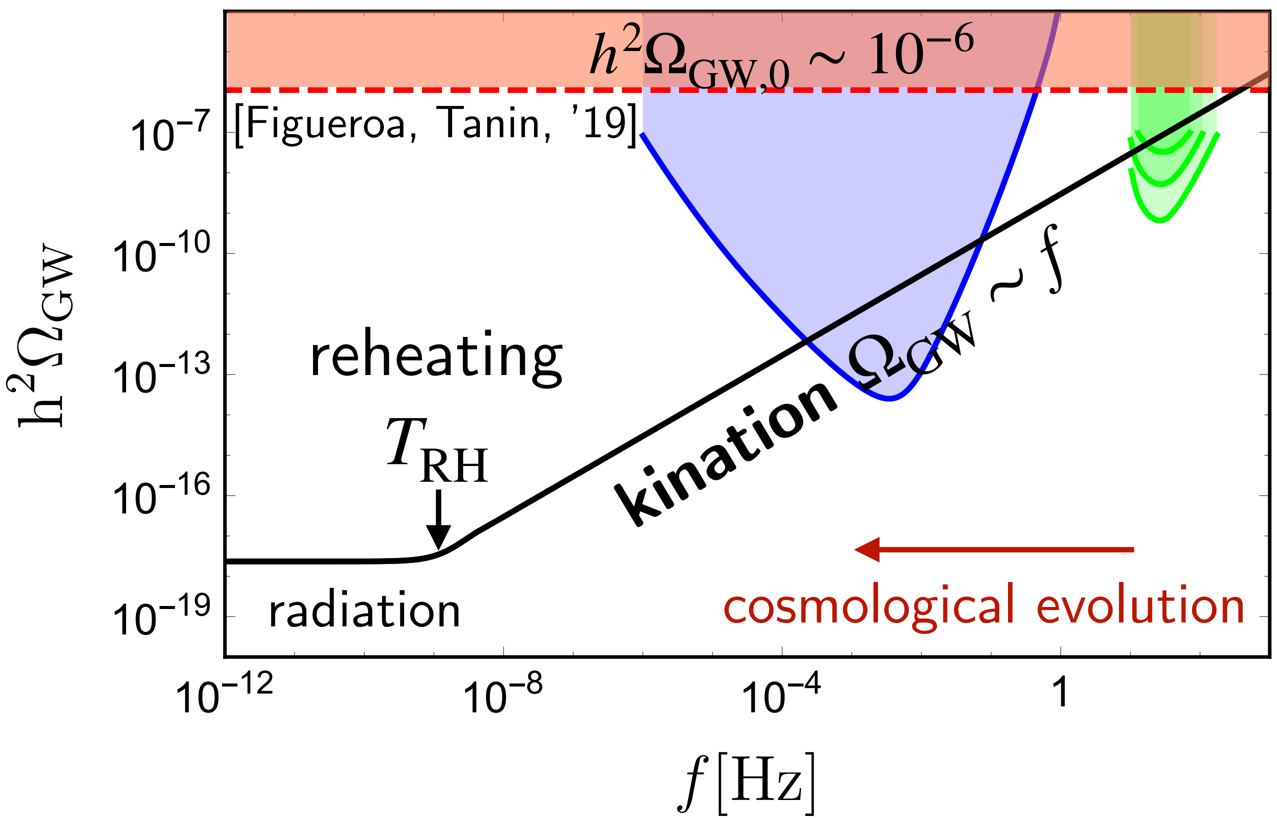


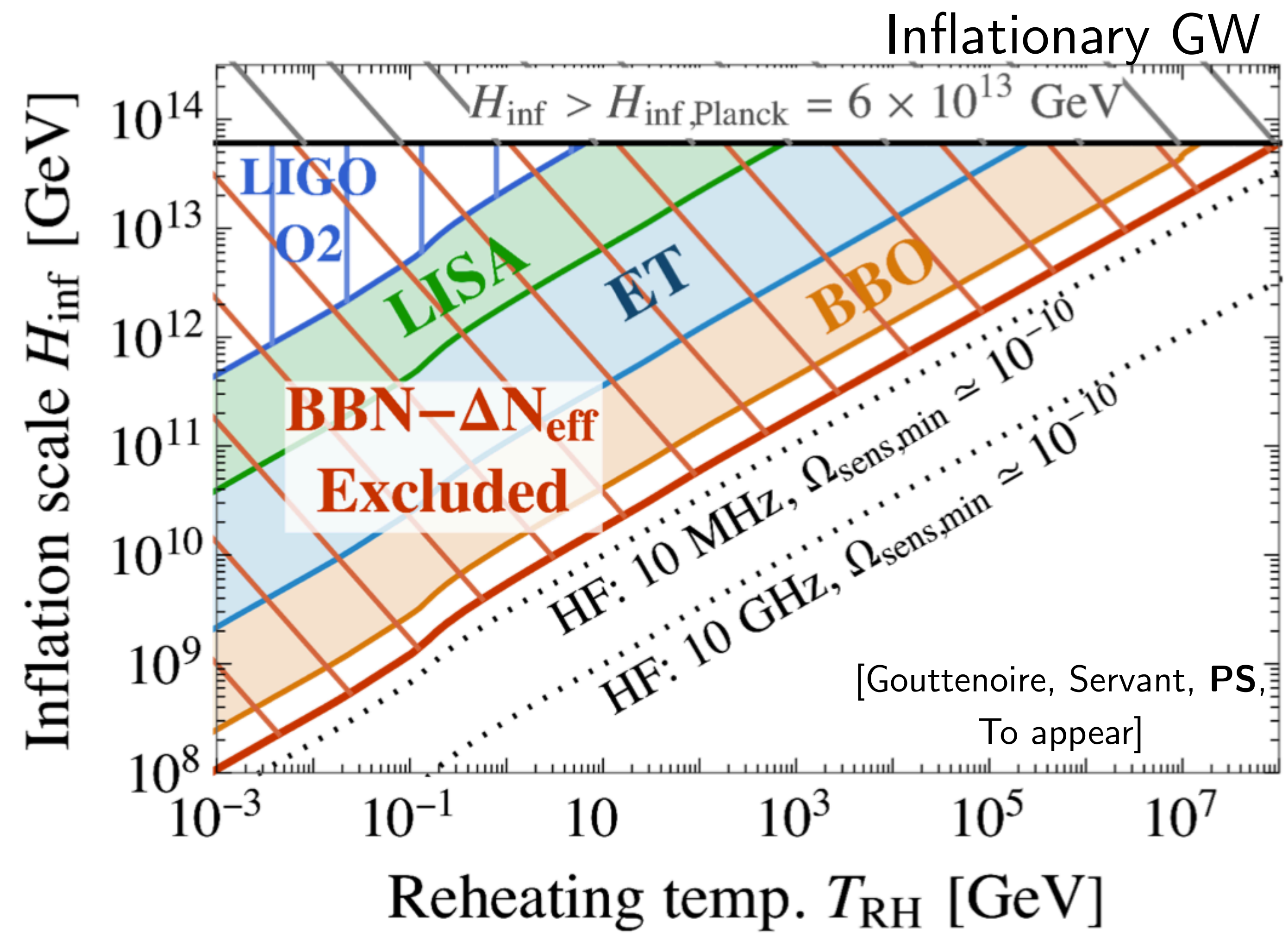
GW is an extra radiation.



Long Kination ⇒ too much GW @ BBN/CMB

Extra relativistic degrees-of-freedom : $\Delta N_{\rm eff} \lesssim 0.2$





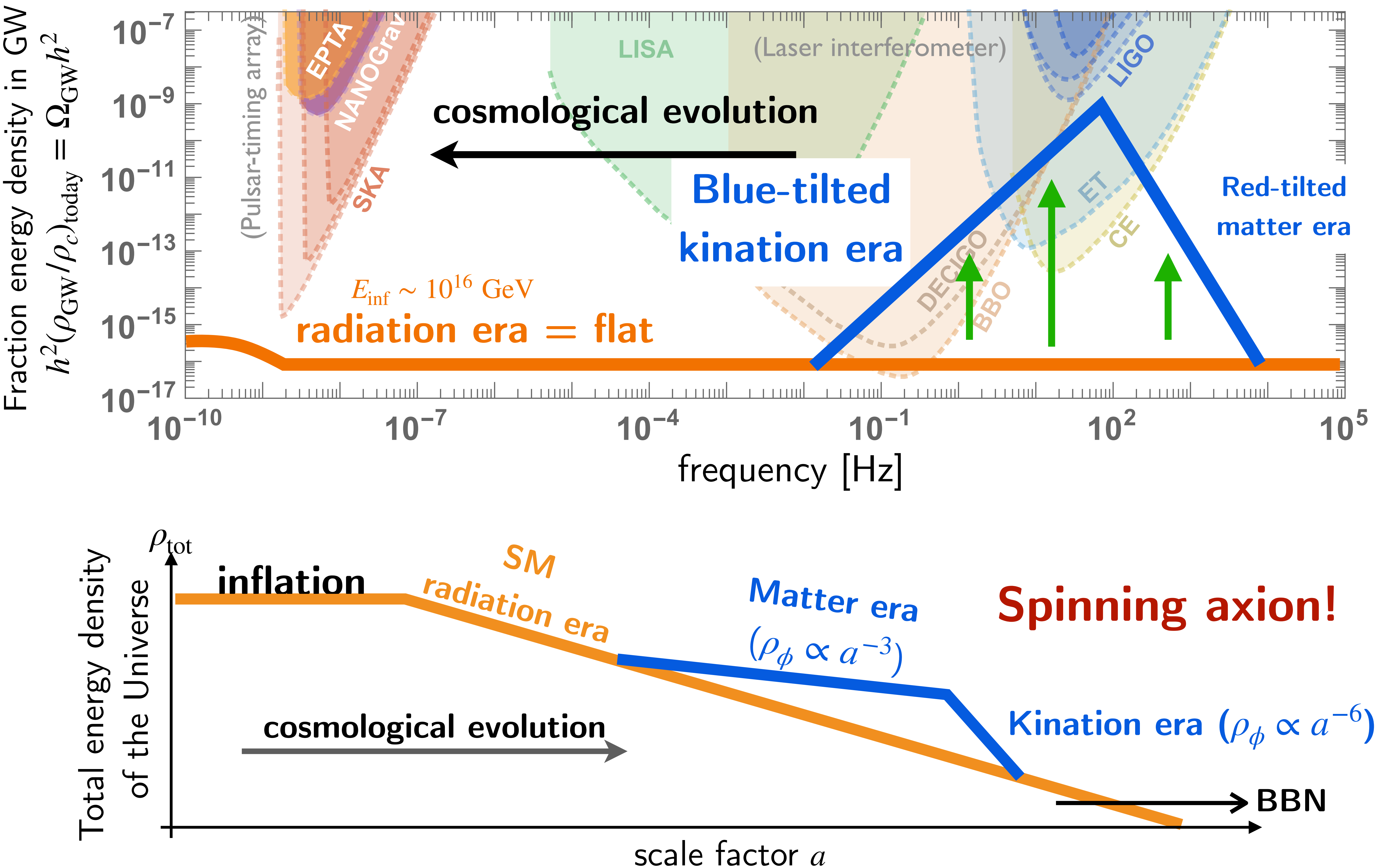
see [Domcke, Muia et. al., 2011.12414]

Challenges and Opportunities of High Frequency Gravitational Wave Detection
ICTP

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

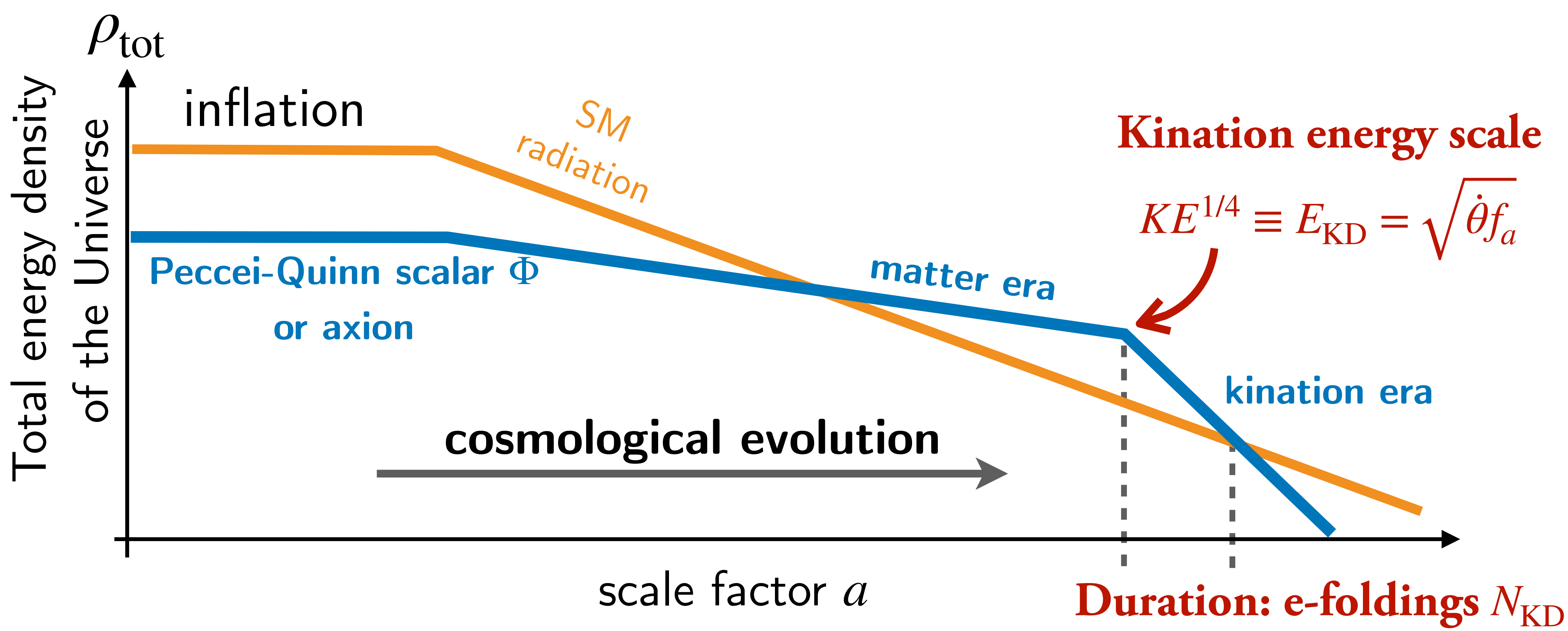
From the perspective of the future-planned experiments, **an intermediate and low-scale kination** era is very interesting.

Peaked GW signature from intermediate kination era



Probing intermediate kination with GW.

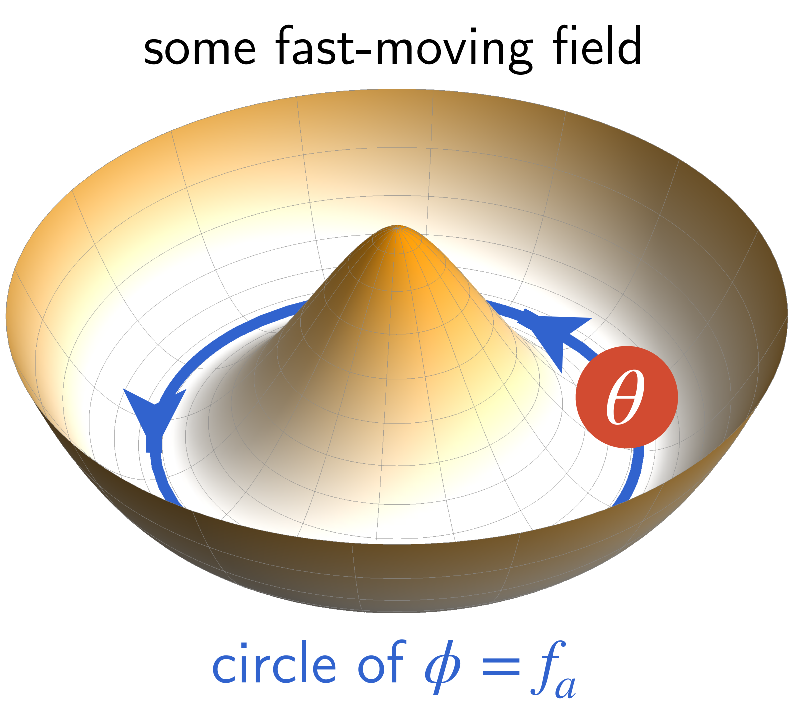
Model-independent: intermediate kination scenario



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)



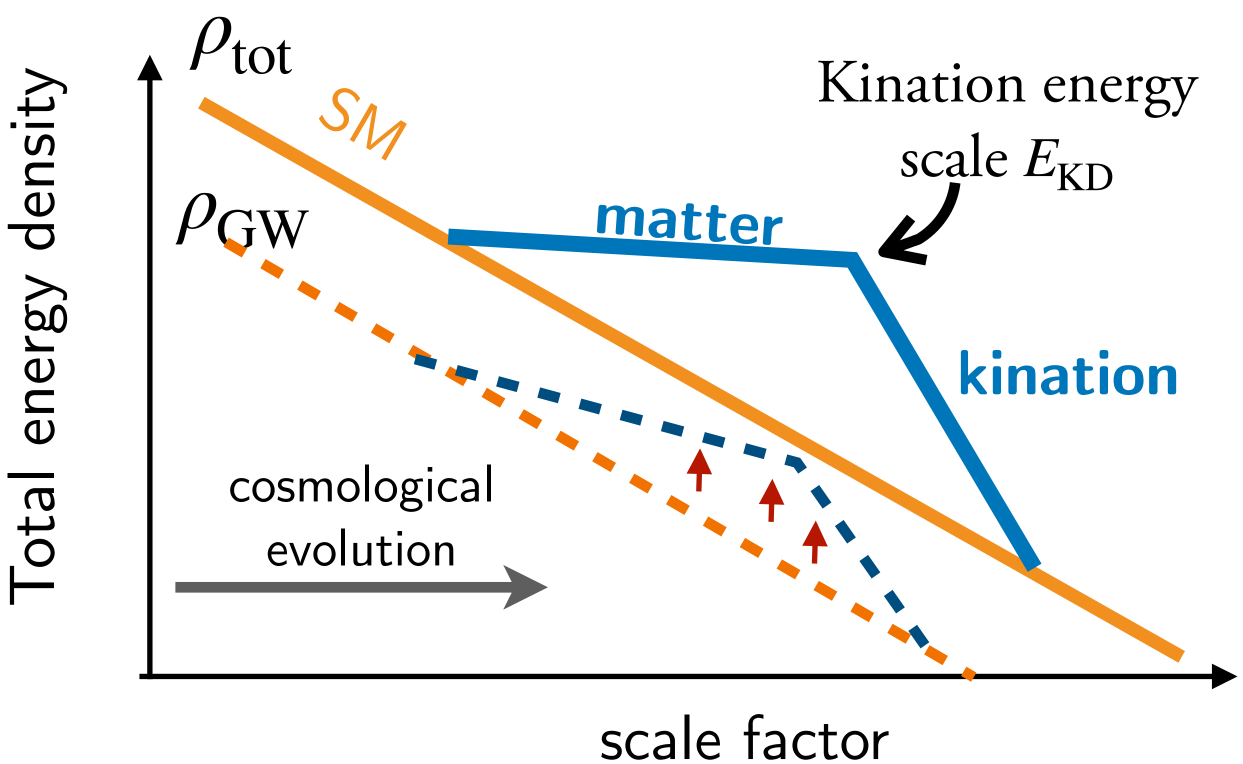
Why GW peaked signature?

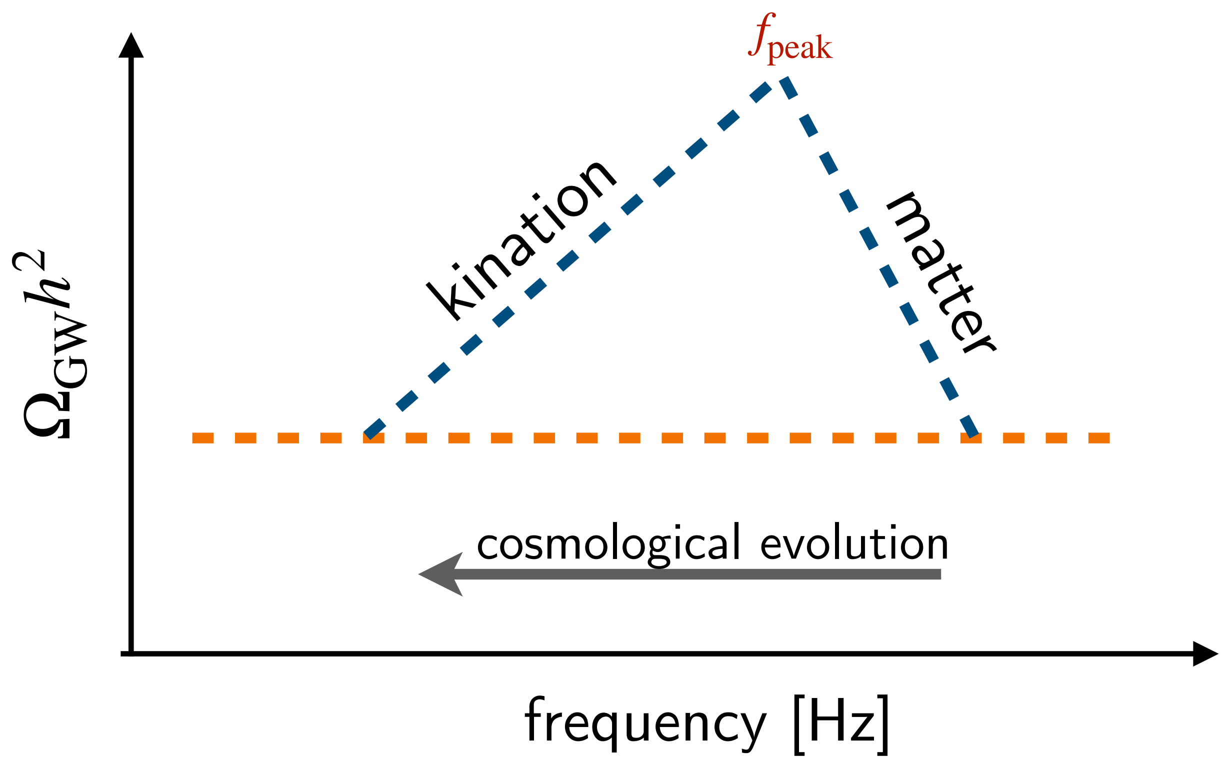
Fraction of energy density in GW today

$$\Omega_{\mathrm{GW},0} = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4 = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot,prod}}}\right)\left(\frac{\rho_{\mathrm{tot,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4$$

constant

Assuming $\rho_{\mathrm{GW}} \propto \rho_{\mathrm{total}}$ at production e.g. cosmic strings and inflation



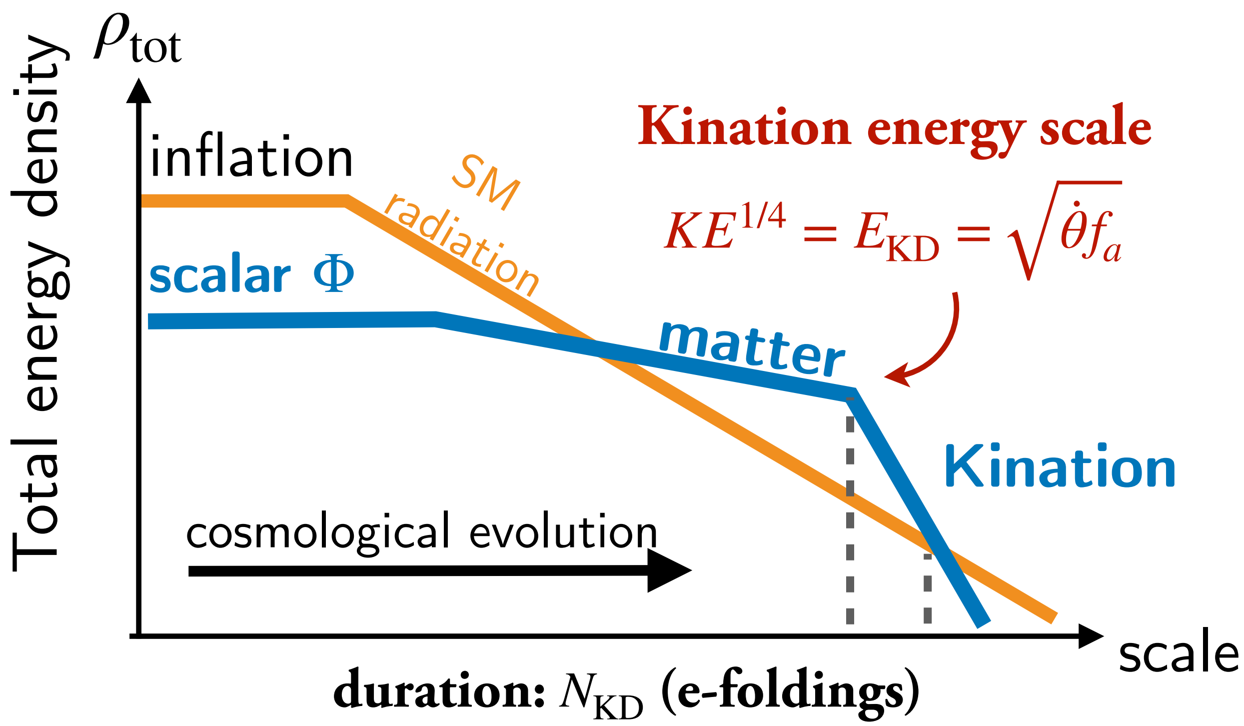


A peak corresponds to E_{KD}, why?

Larger ρ_{tot}, larger GW amplitude, compared to the standard cosmology.

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

Signature in inflationary GW: "Peak"



Peak frequency:

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

Peak amplitude:

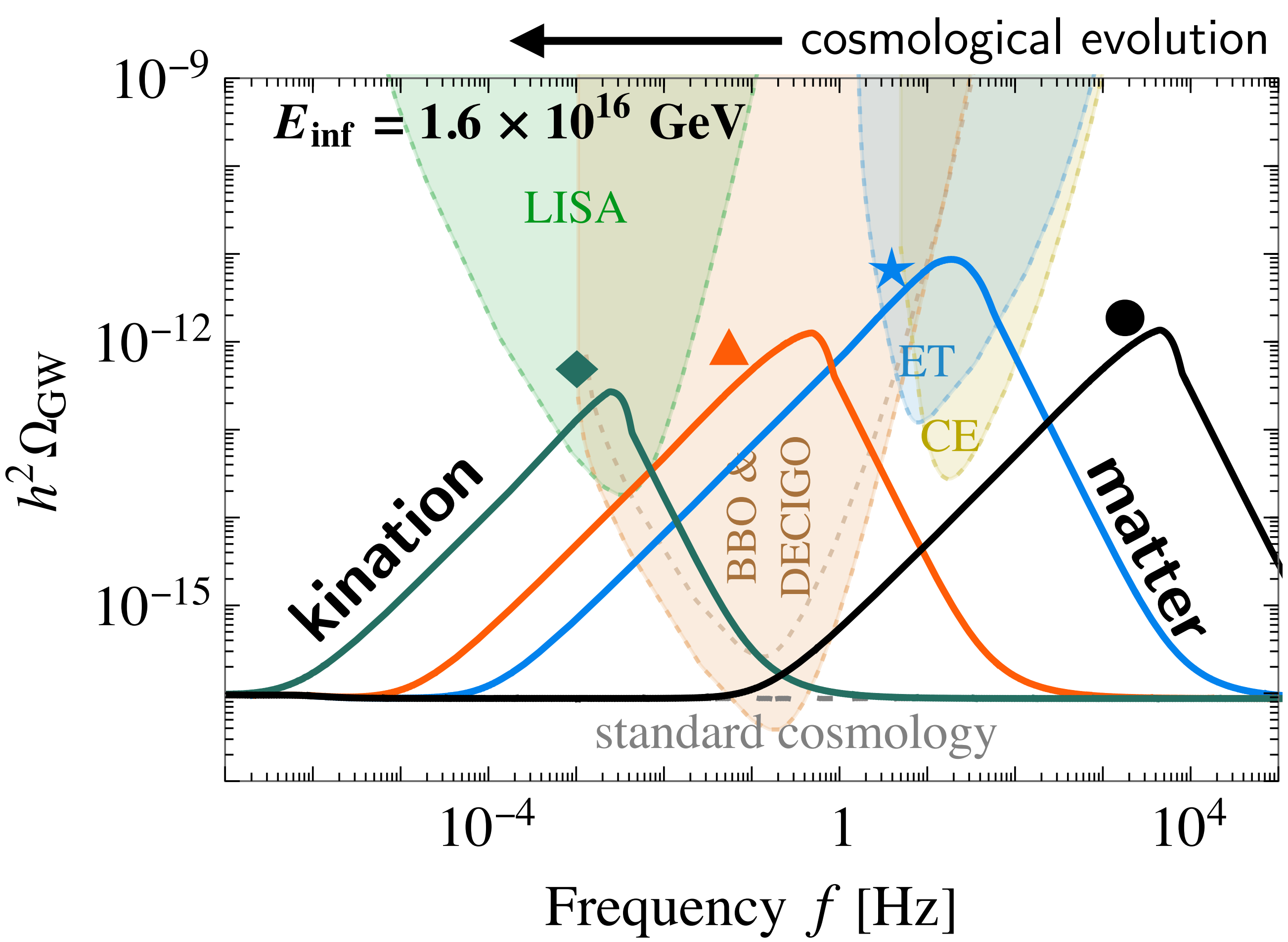
$$\Omega_{peak} h^2 \approx 10^{-12} \left(\frac{E_{inf}}{1.6 \times 10^{16} \text{ GeV}}\right)^4 \left[\frac{\exp(2N_{KD})}{10^4}\right]$$

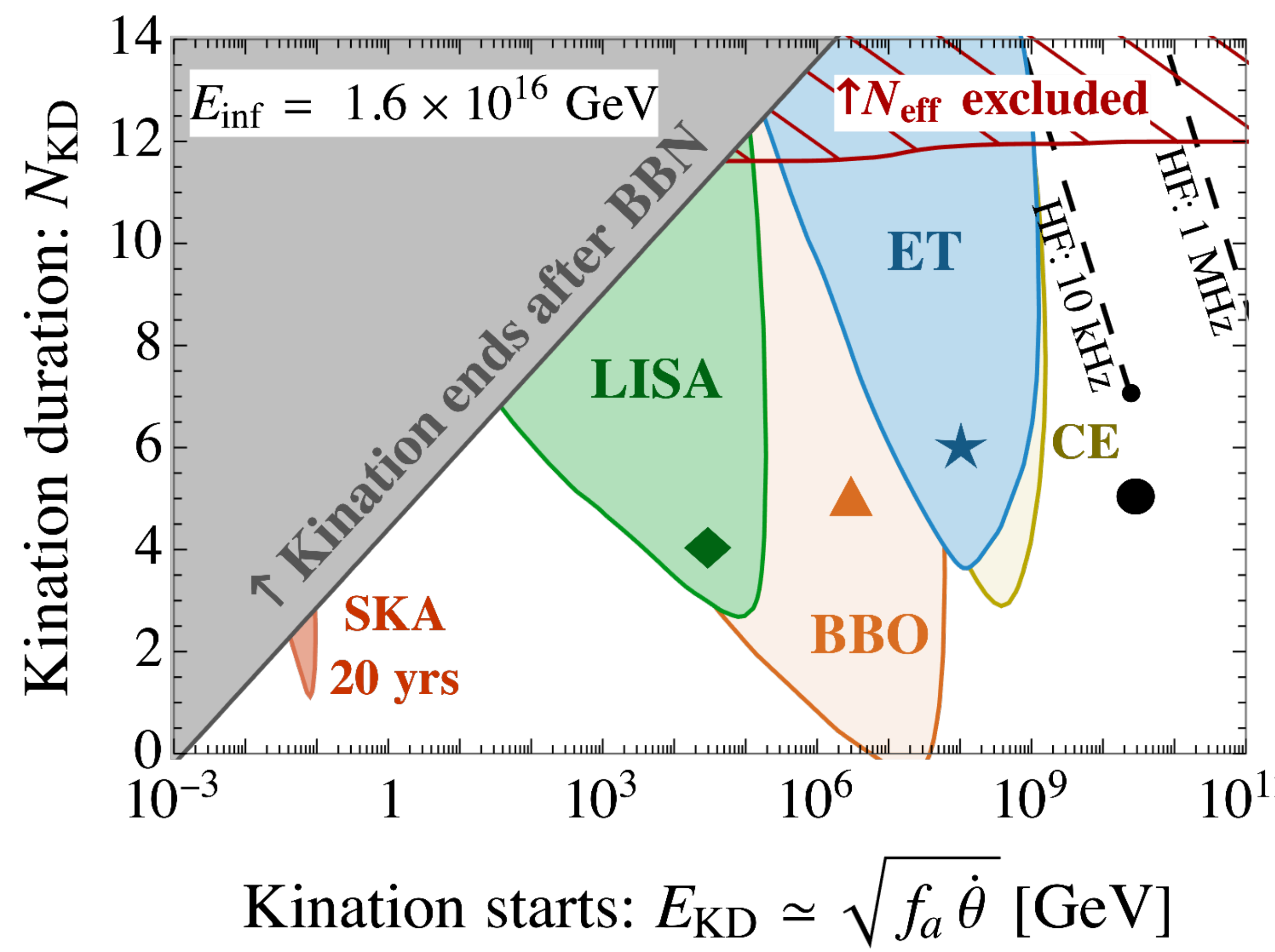
Detectability

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

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

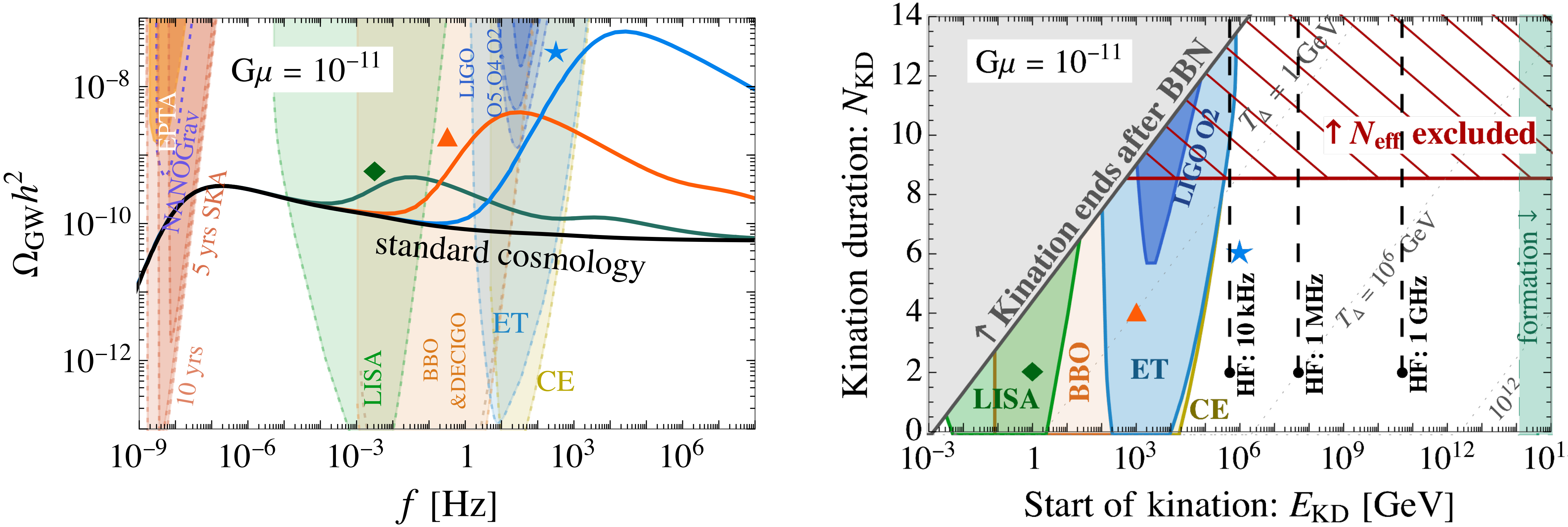
High-frequency (HF) experiments for large E_{KD}



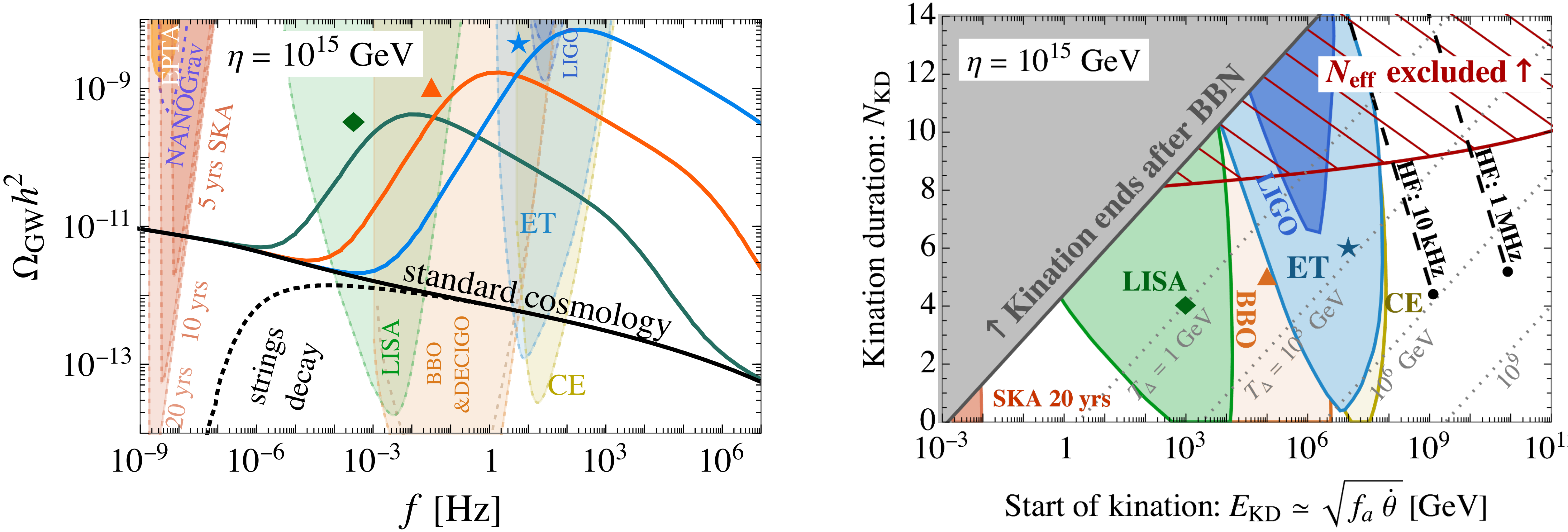


Gouttenoire, Servant, **PS**, 2108.10328 & to appear]

Local cosmic strings   symmetry breaking scale $\simeq M_{\rm pl}\sqrt{G\mu}$



Global cosmic strings   symmetry breaking scale $\simeq \eta$



Inflation + global cosmic strings

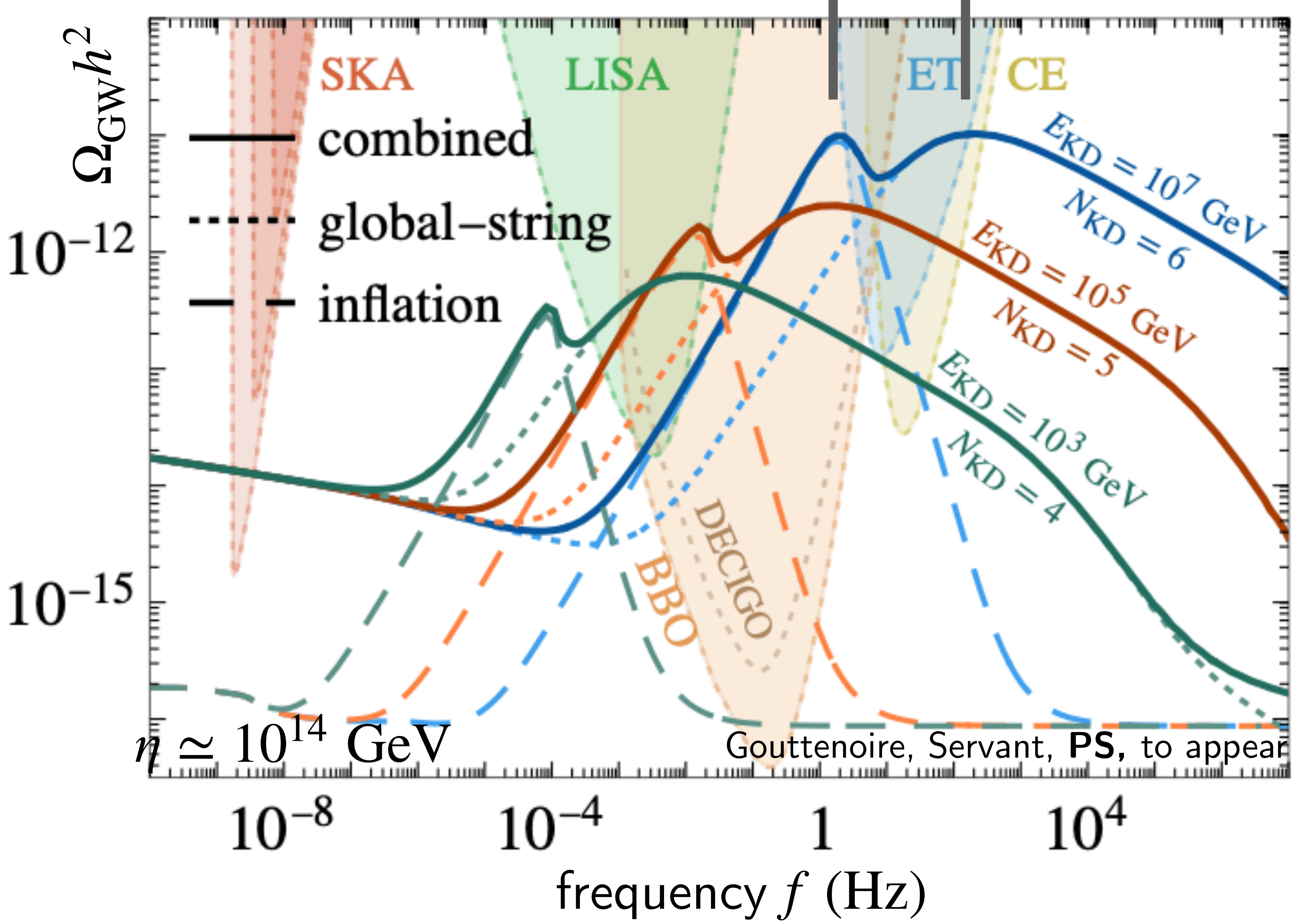
String network formed at energy scale η
continuously produces loops which decay into GW (and also particles.)

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

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

amplitude controlled by

inflation: $E_{\rm inf}$ global-string: η



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

Kination and GW peak from a spinning axion.

"Spinning axion"

Going beyond the assumption of vanishing velocity of axion.

e.g. **Kinetic-misalignment & axion fragmentation** $\Rightarrow$ axion relic abundance.

[Co, Harigaya, Hall, '19 & Chang, Cui, '19] [Fonseca, Morgante, Sato, Servant, '19]

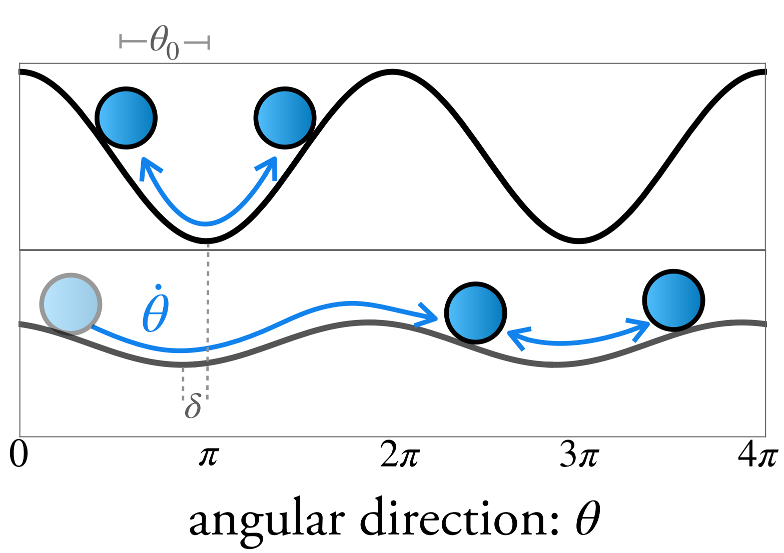
Model A: Trapped misalignment

[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 $\phi = f_a$ and only involves the angular mode "axion"



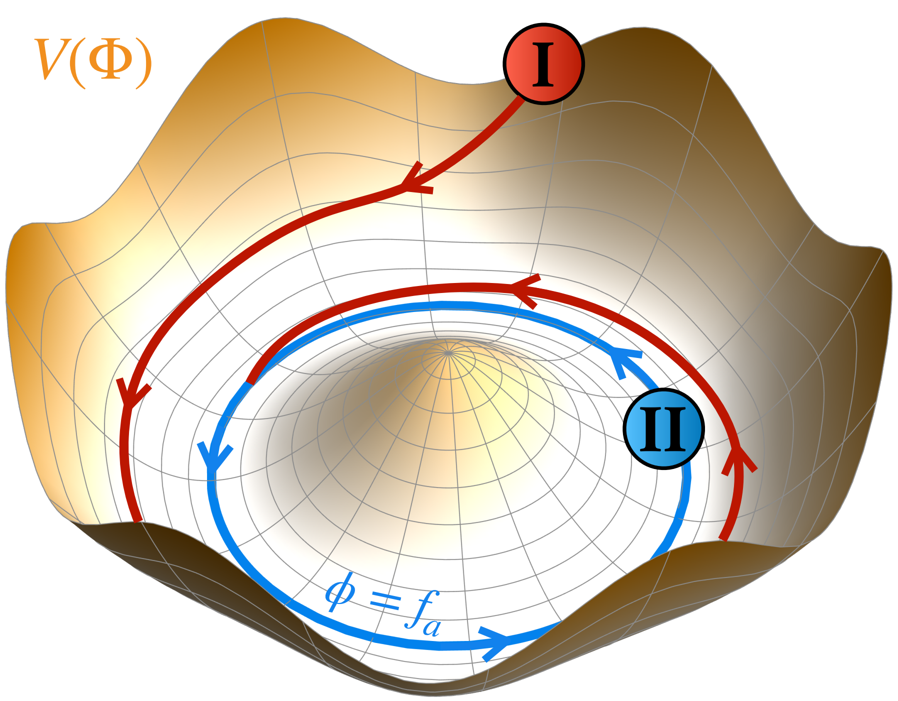
Model B: Complex scalar field

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

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

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

Angular mode θ "axion" spins, with large kinetic energy.

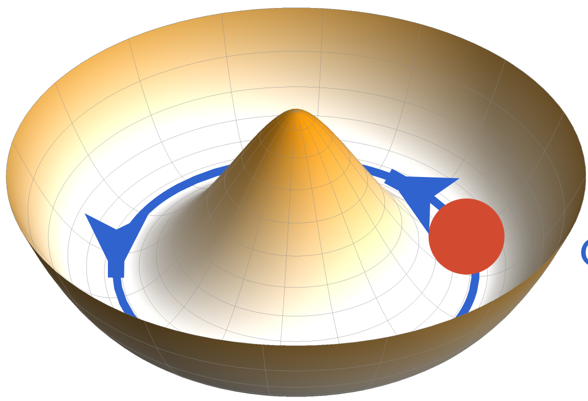


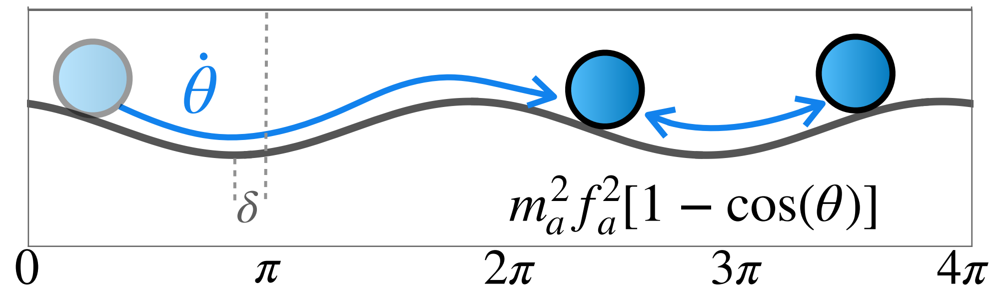
Dynamics starts with $\phi \gg f_a$ and involves radial and angular mode.

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

Dark matter from a spinning axion.

Axion Dark Matter and Peaked GW





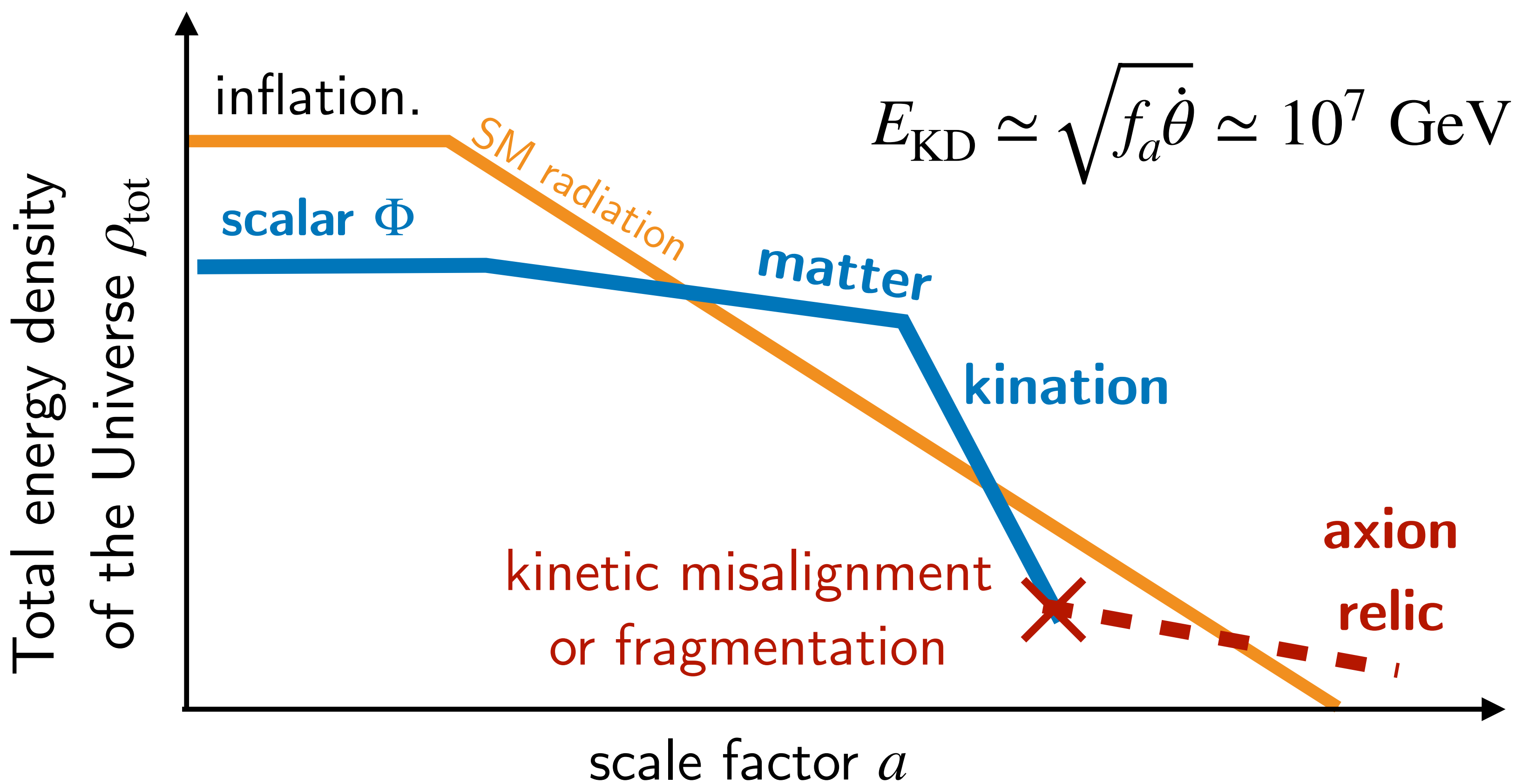
By Hubble friction, $\dot{\theta} \propto a^{-3}$

Later, it gets trapped in potential from instanton effect.

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

[Co, Harigaya, Hall, '19 & Chang, Cui, '19] [Fonseca, Morgante, Sato, Servant, '19]

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



Kination era from spinning axion

$$E_{\rm KD} \simeq \sqrt{f_a \dot{\theta}} \simeq 10^7 \text{ GeV} \left(\frac{f_a}{10^9 \text{ GeV}}\right)\left(\frac{40}{Y_a}\right) \exp(3N_{\rm KD}/2)$$

Axion relic abundance:

$$\frac{\Omega_{a,0}}{\Omega_{\rm DM,0}} \simeq 400 \left(\frac{m_a}{1 \text{ eV}}\right)\left(\frac{Y_a}{40}\right)$$

Axion Dark Matter and Peaked GW

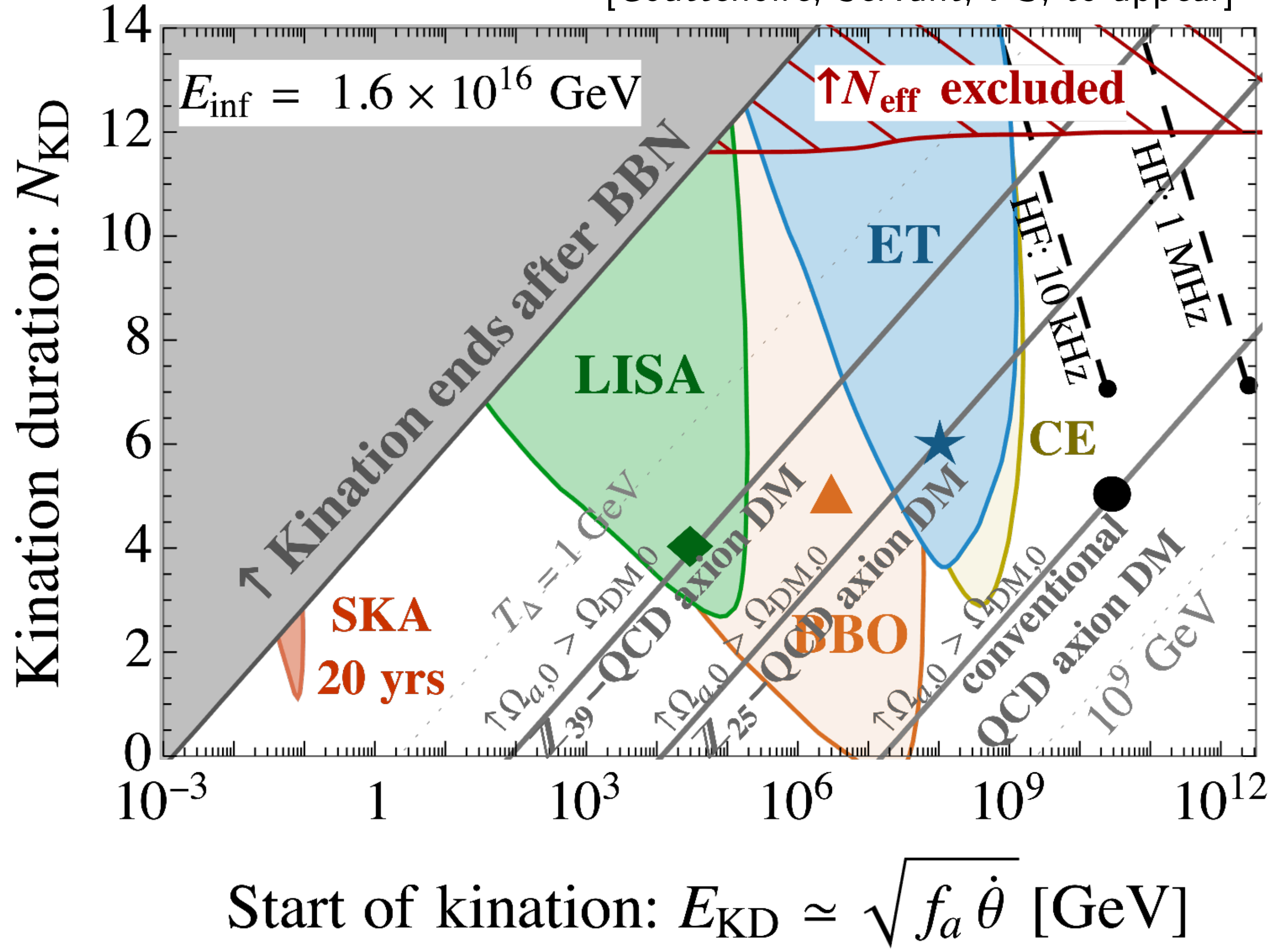
Kination from spinning axion DM: $E_{\rm KD} \simeq 10^9\ \text{GeV} \left(\frac{f_a}{10^9\ \text{GeV}}\right)\left(\frac{m_a}{1\ \text{eV}}\right)\left(\frac{\Omega_{\rm DM,0}}{\Omega_{a,0}}\right)\exp(3N_{\rm KD}/2)$

Peak position for axion dark matter

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

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

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



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 $\mathbb{Z}_{\mathcal{N}}$-axion model

$$m_{a,\mathcal{N}} \sim 2^{-\mathcal{N}/2} m_{a,\rm conv}.$$

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

"Spinning axion"

Going beyond the assumption of vanishing velocity of axion.

e.g. **Kinetic-misalignment** & **axion fragmentation** set axion relic abundance

[Co, Harigaya, Hall, '19 & Chang, Cui, '19] [Fonseca, Morgante, Sato, Servant, '19]

Model A: 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 $\phi = f_a$ and only involves the angular mode "axion"

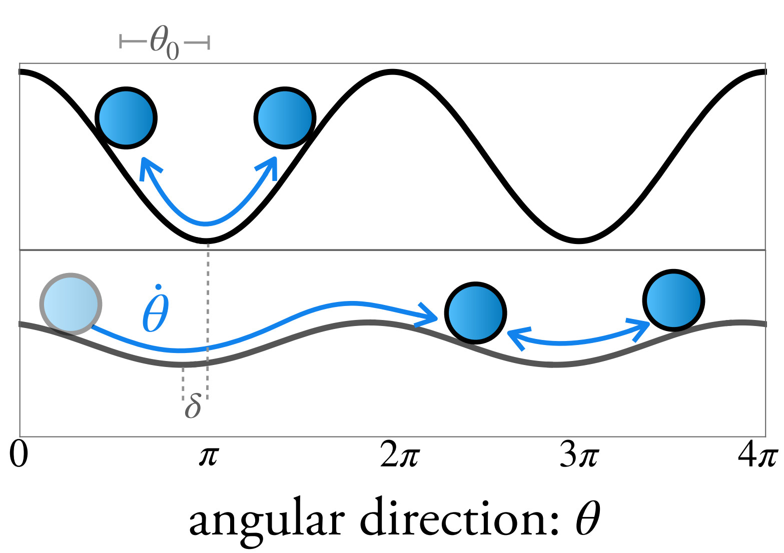
Model B: Complex scalar field

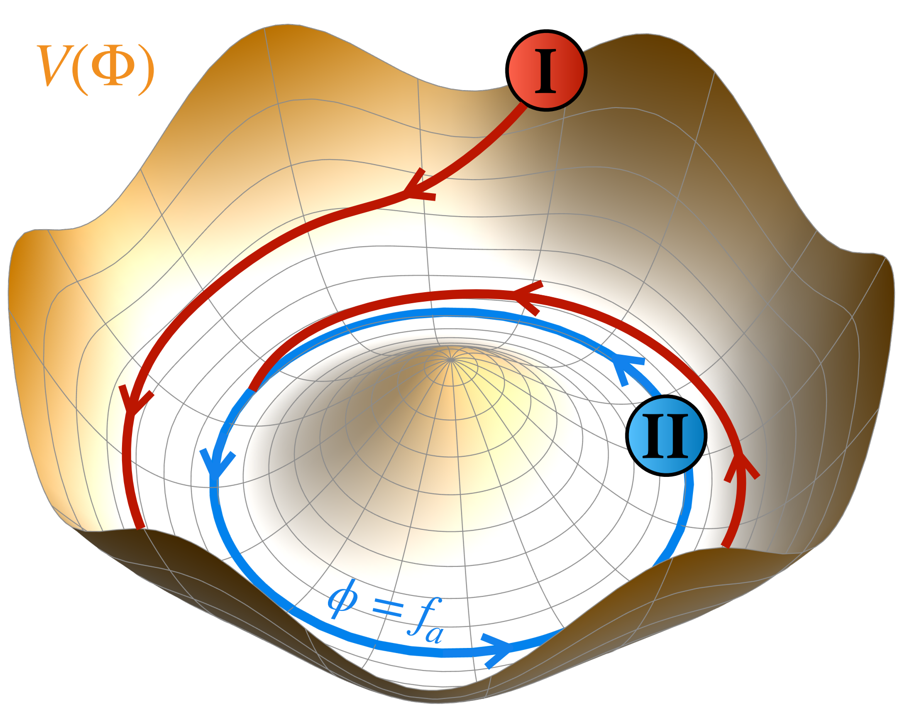
[Co, Hall, Harigaya, et. al., '19 '20]

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

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

Angular mode θ "axion" spins, with large kinetic energy.





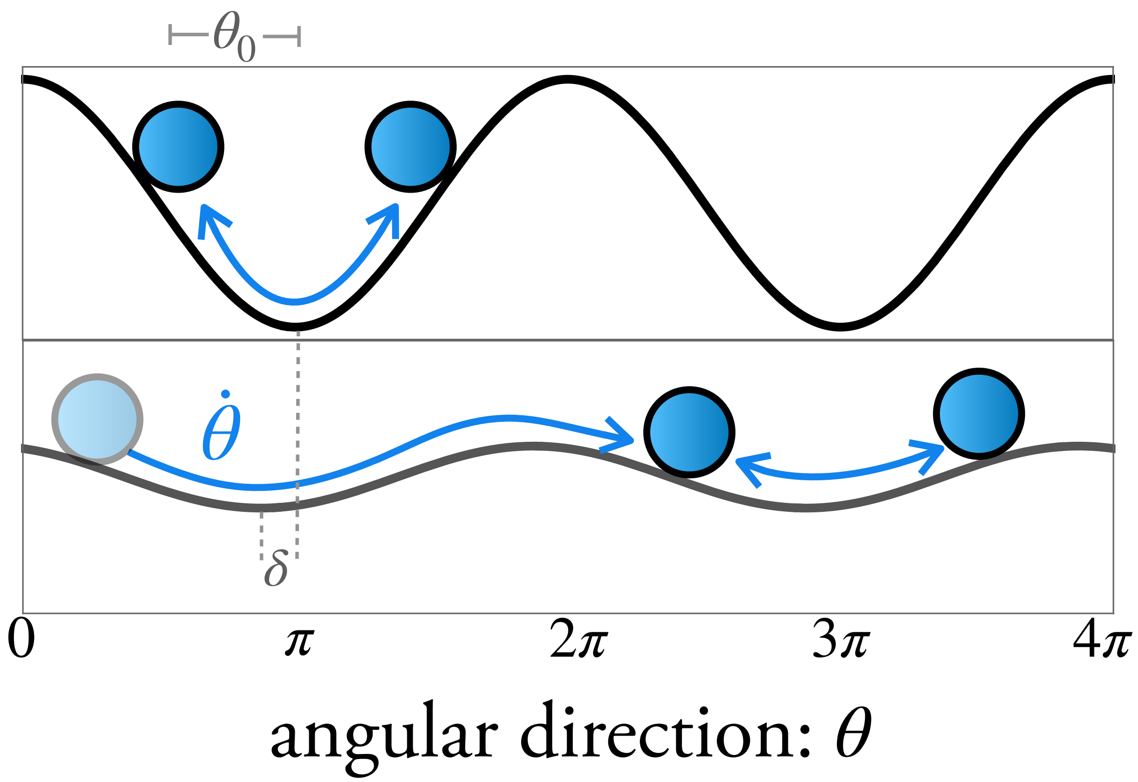
Dynamics starts with $\phi \gg f_a$ and involves radial and angular mode.

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

Model A: trapped misalignment

Model A: Trapped misalignment

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



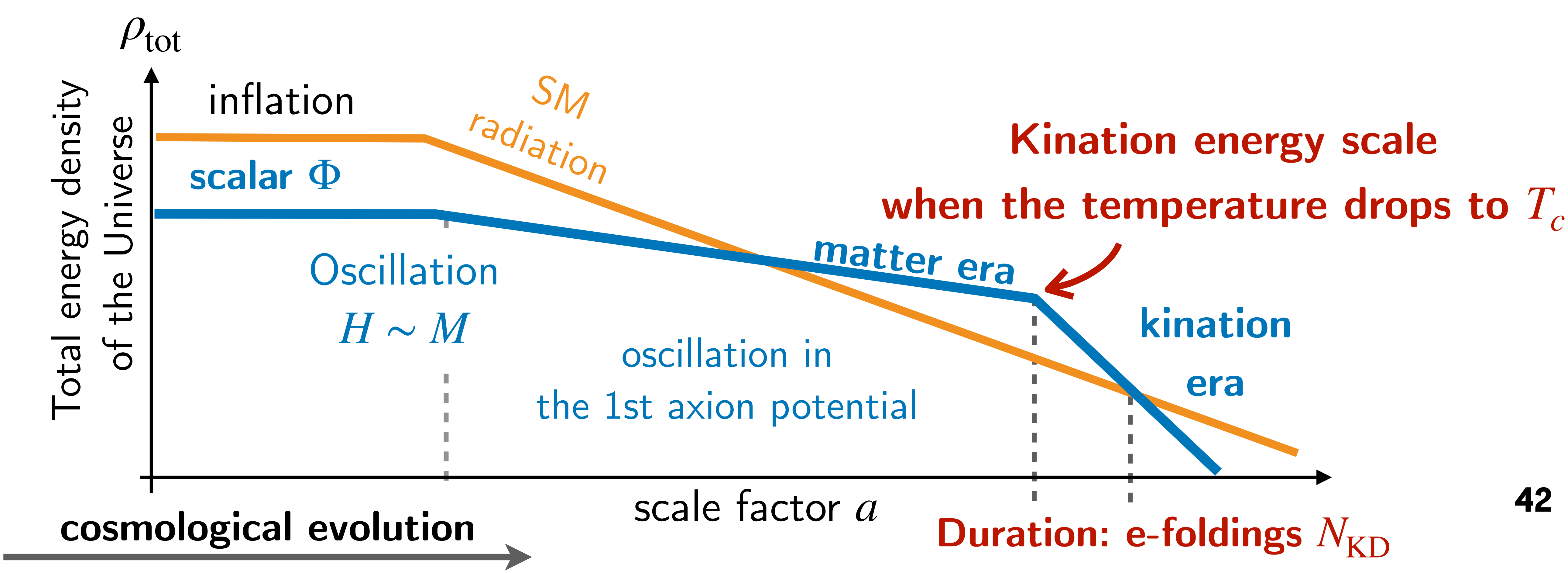
For $T \gtrsim T_c$, $V_{\rm high} \sim M^2 f_a^2 \cos(\theta)$
axion oscillates and behaves as matter.

For $T \lesssim T_c$, $V_{\rm low} \sim m_a^2 f_a^2 \cos(\theta)$ with $M \gg m_a$

Axion rolls freely with large initial speed at T_c

$$\dot\theta_c \sim \frac{T_c^{3/2} M^{1/4}}{M_{\rm Pl}^{3/4}}$$

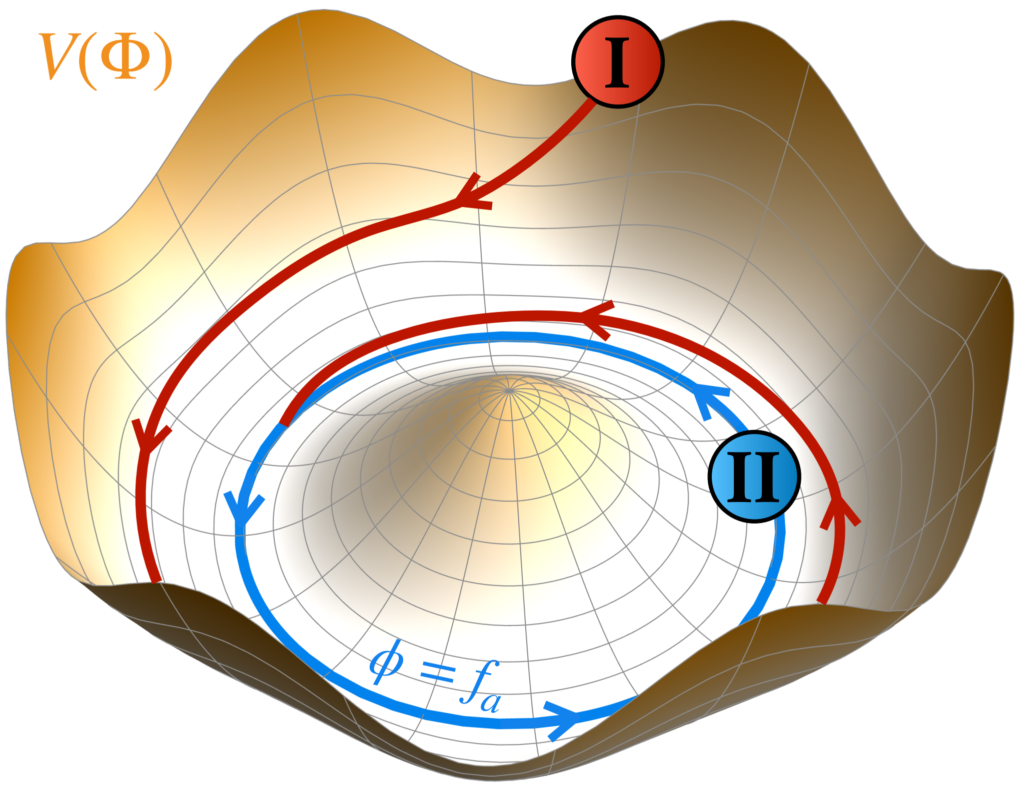
and generates kination era.



Model B: Complex scalar field

Model B: Complex scalar field

"Affleck-Dine Baryogenesis" (Affleck, Dine, 1985)
"Axiogenesis" (Co, Hall, Harigaya, et. al., '19)



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

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

Angular mode θ "axion" spins, with large kinetic energy.

Requirements for the successful kination era

1. $U(1)$-symmetric (quadratic) potential with spontaneous symmetry-breaking minimum

2. Large initial scalar VEV

3. Explicit $U(1)$-breaking term (wiggle for angular velocity)

4. Damping of radial motion

Ingredients I & II & III: scalar potential and large initial VEV

I. Scalar potential: $V(\Phi) = m_r^2|\Phi|^2\left[\log\left(\frac{|\Phi|^2}{f_a^2}\right)-1\right] + \Lambda_b^4\left[\left(\frac{\Phi}{M_{\rm Pl}}\right)^l + \left(\frac{\Phi^\dagger}{M_{\rm Pl}}\right)^l\right] + V_{\rm stab}$

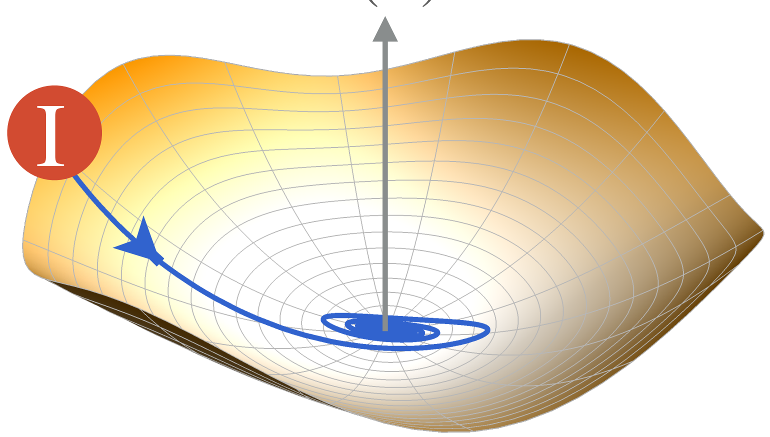
$U(1)$-conserving potential with a Mexican hat near f_a (generic in supergravity)

$\propto \cos(l\theta)$ explicit breaking term

stabilizing term

II. For large-$\phi_{\rm ini}$: Driven away from $\phi = 0$ at early times ($H > m_r$) by a negative Hubble mass $-H^2|\Phi|^2$ (Dine, Randall, Thomas, 1995)

At $3H \sim m_r$:



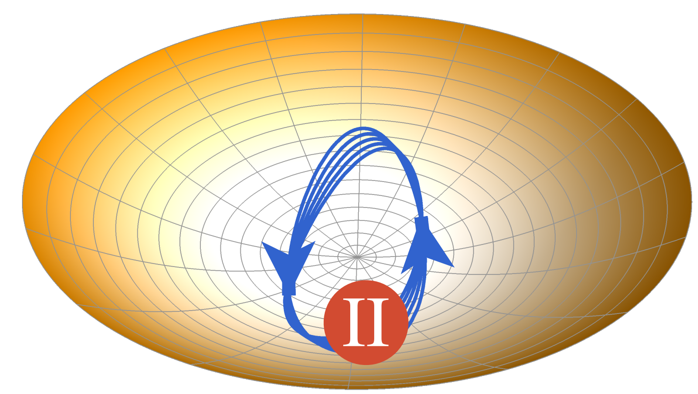
conserved part ⇒ radial motion

breaking part ⇒ angular motion

At $3H \lesssim m_r$:

Elliptic orbit with red-shifting size $\phi \sim a^{-3/2}$ (quadratic potential)

Scalar Φ behaves as matter. (allowing Φ-domination)



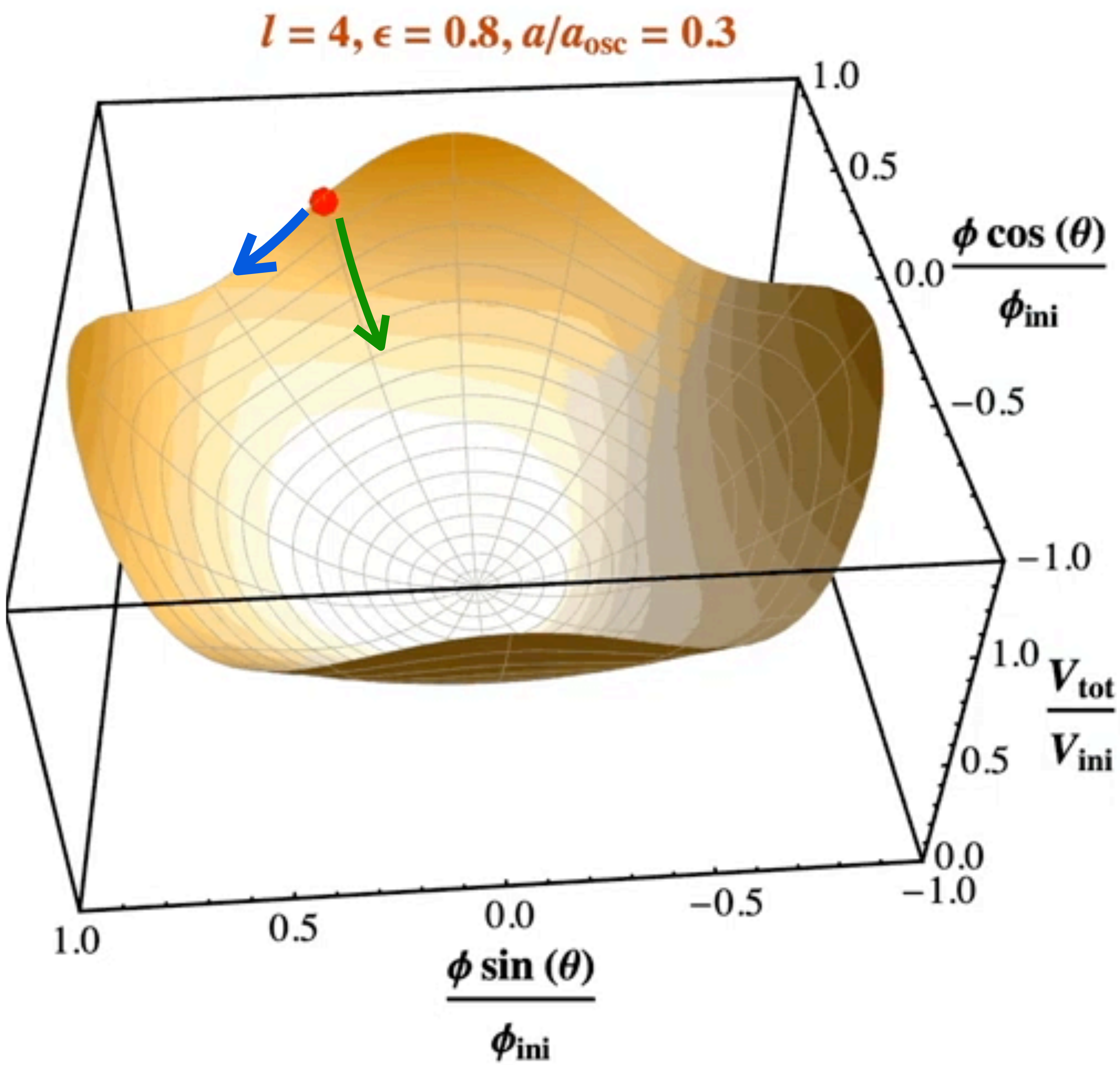
Later, $U(1)$ symmetry restores.

Conserved charge:

$$\frac{d}{dt}(a^3\phi^2\dot{\theta}) = 0 \Rightarrow \dot{\theta} \sim m_r$$

$\phi \propto a^{-6/(2+n)}$ for $V \propto \phi^n \propto a^{-6n/(2+n)}$

Ingredients I & II & III: scalar potential and large initial VEV



[Gouttnoire & Servant & **PS**, to appear]

conserved part ⇒ radial motion

breaking part ⇒ angular motion

For $3H \lesssim m_r$:

Elliptic orbit

with red-shifting size

$\phi \sim a^{-3/2}$

(quadratic potential)

Scalar Φ behaves as matter.

(allowing Φ-domination)

Later,

$U(1)$ symmetry restores.

Conserved charge:

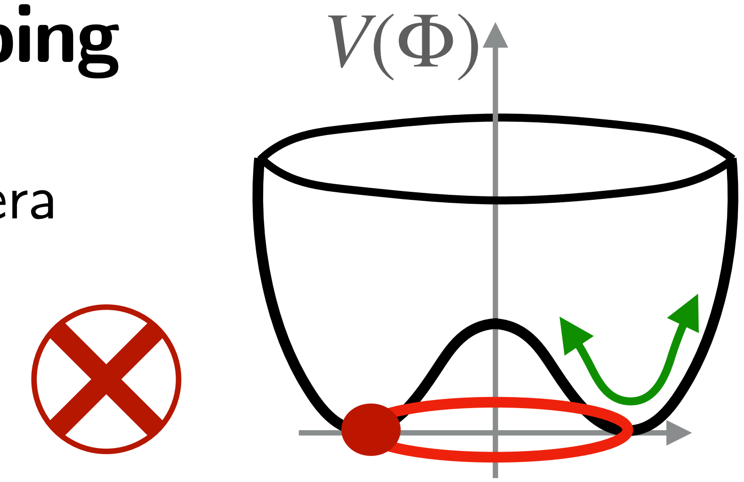
$$\frac{d}{dt}(a^3\phi^2\dot{\theta}) = 0$$

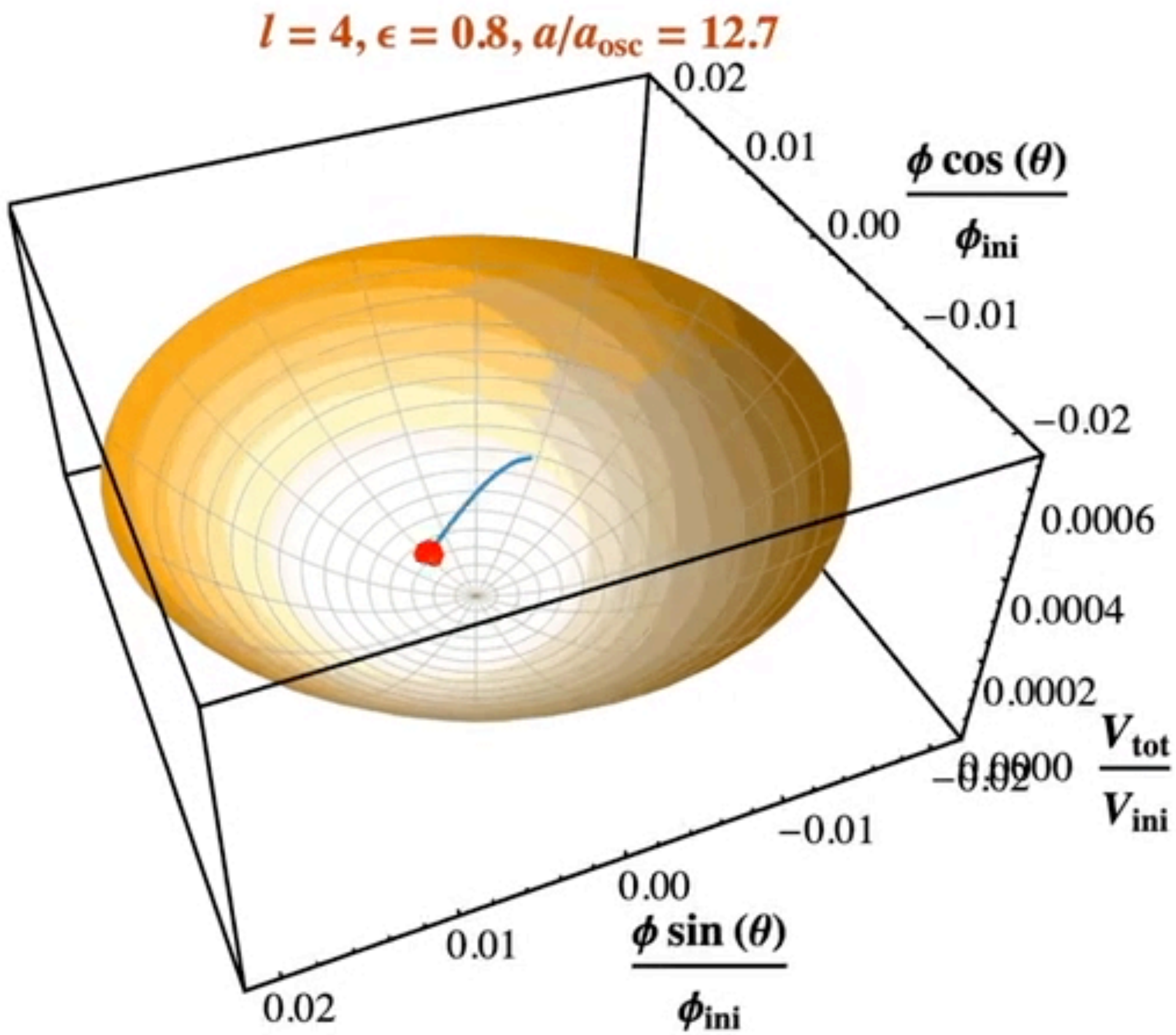
Ingredients IV: radial-motion damping

Elliptic orbit

scalar Φ behaves as matter.
(allowing matter-domination)

Radial oscillation causes matter era
occurs at late times
and over-closes the universe.





Radial motion must be damped, while the rotation of axion remains for kination.

introduce friction term to radial-mode equation of motion

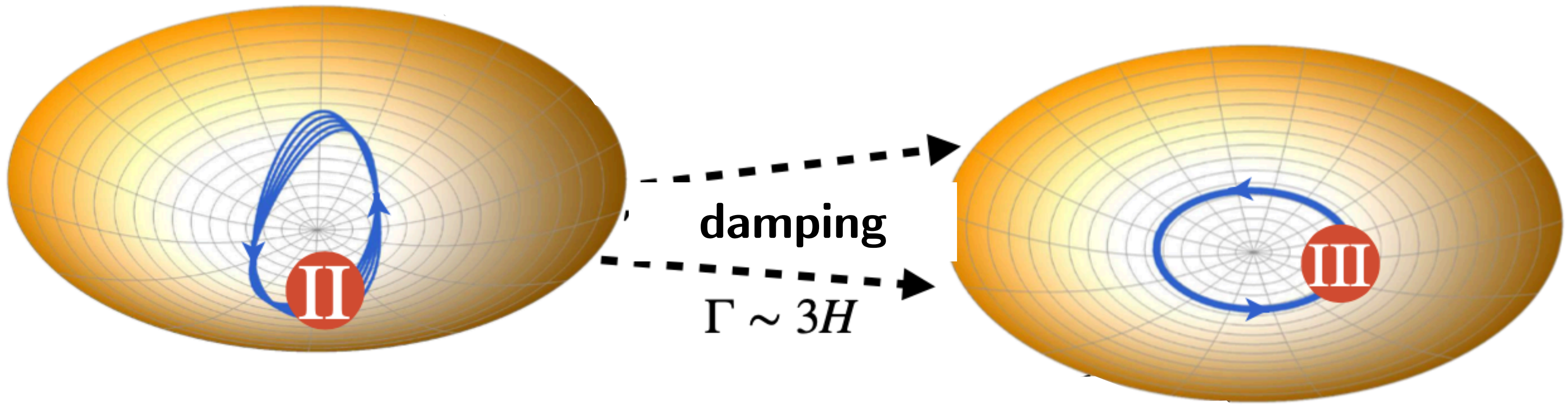
$$\ddot{\phi} + (3H + \Gamma)\dot{\phi} + (m_r^2 - \dot{\theta}^2)\phi = 0$$

Scalar Φ orbit becomes circle, still behaves as matter for $\phi > f_a$.

i.e. $E_{\rm kinetic} = E_{\rm potential}$
balance between the centrifugal force and potential gradient.

[Gouttnoire & Servant & **PS**, to appear]

Damping scenarios



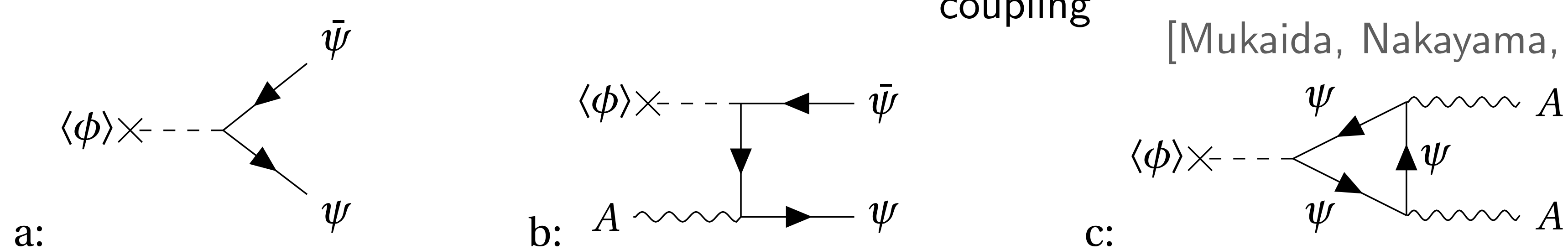
Scenario I: parametric resonance extracts energy from zero-mode
Damping happens fast after oscillation.

Scenario II: Thermal damping with $U(1)$-conserving interaction with **no thermal mass of ϕ**

scalar condensate Φ $\xleftrightarrow{\lambda_\psi}$ fermion ψ $\xleftrightarrow{\text{gauge coupling}}$ SM plasma

[Mukaida, Nakayama, '12 '13]

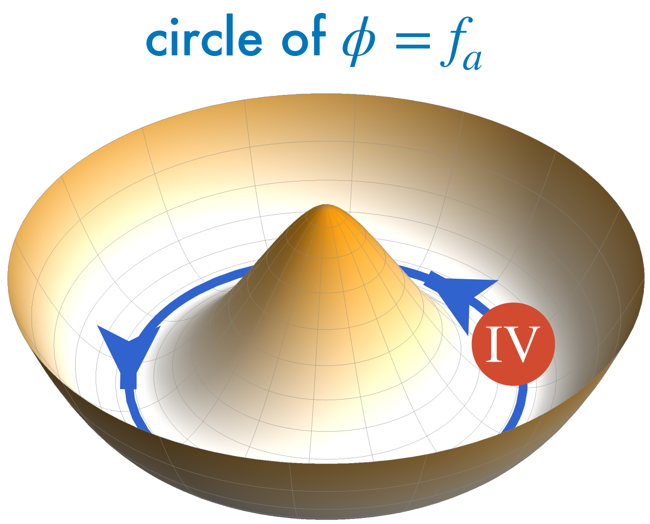
E.g. $\lambda_\psi \phi \bar{\psi} \psi$



No thermal mass requires λ_ψ-suppression $\sim \sqrt{m_r/M_{\rm Pl}}$ $\Rightarrow$ insufficient damping for kination

Scenario III: Allow large λ_ψ $\Rightarrow$ strong radial damping and few efolds of kination
Suppressed the thermal mass by **lowering the reheating temperature.**

Approaching minimum ⇒ kination era



Axion speed $\dot{\theta} \sim m_r$ (from $V''(\phi) \sim \dot{\theta}^2\phi$)

Circle red-shifts to minimum: $\phi = f_a$

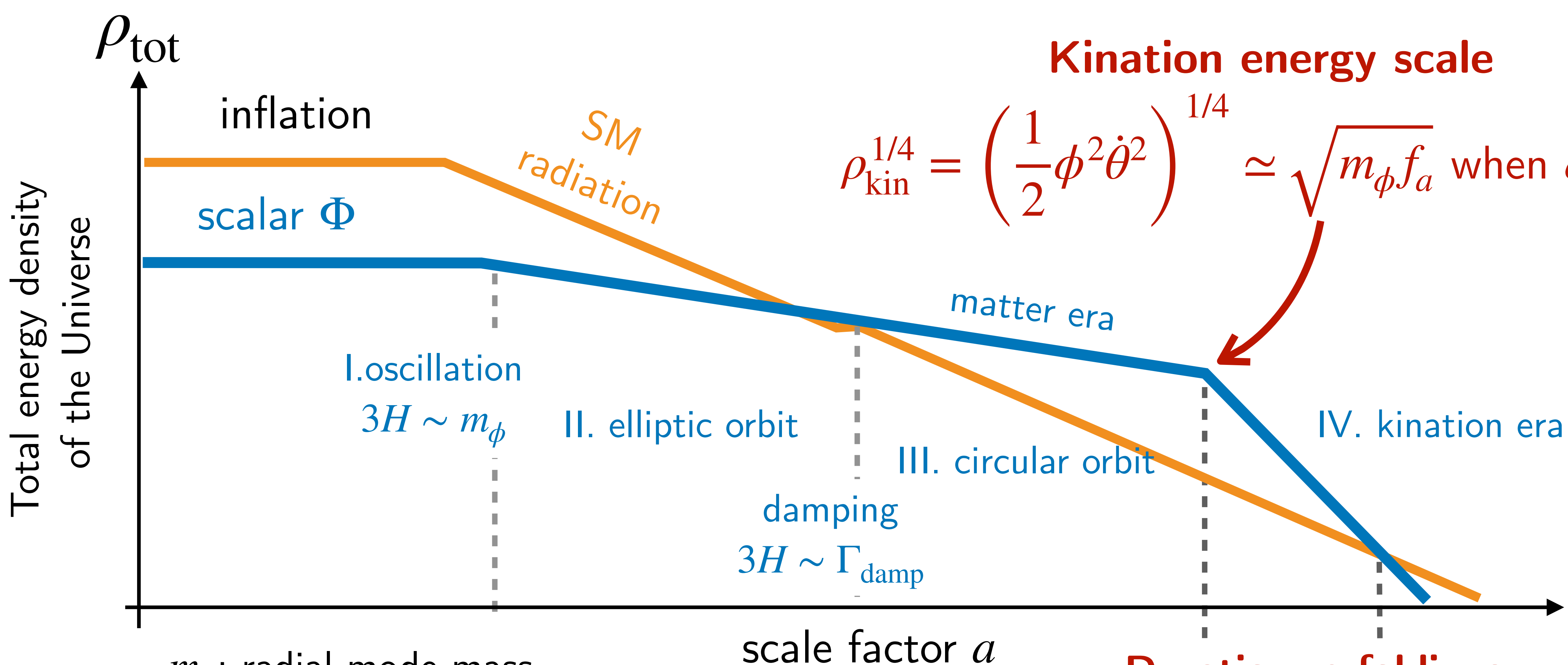
The conserved $U(1)$-charge is

$$\frac{d}{dt}(a^3\phi^2\dot{\theta}) = 0 \;\Rightarrow \dot{\theta} \propto a^{-3}$$

Kinetic energy dominates

$$\rho_\Phi = KE \propto \dot{\theta}^2 \propto a^{-6}$$

and behaves as kination.



Kination energy scale

$$\rho_{\rm kin}^{1/4} = \left(\frac{1}{2}\phi^2\dot{\theta}^2\right)^{1/4} \simeq \sqrt{m_\phi f_a} \text{ when } \phi = f_a.$$

m_ϕ: radial-mode mass

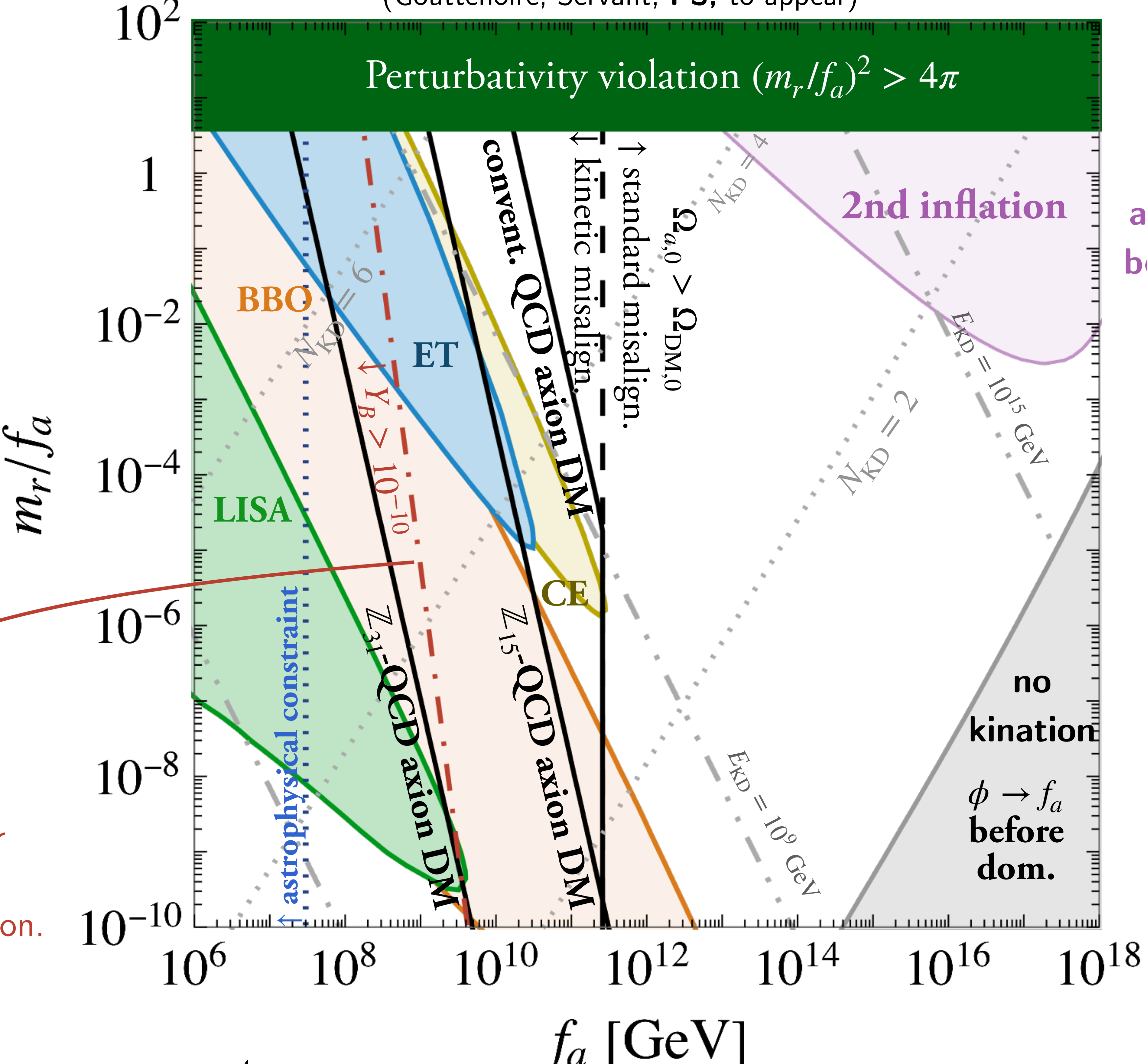
$\Gamma_{\rm damp}$: radial damping rate

Duration: e-foldings

$$N_{\rm KD}(m_\phi, \Gamma_{\rm damp}) \propto \log\left(\frac{\rho_{\rm damp}}{\rho_{\rm kin}}\right)$$

Detectability of model B

(Gouttenoire, Servant, **PS,** to appear)

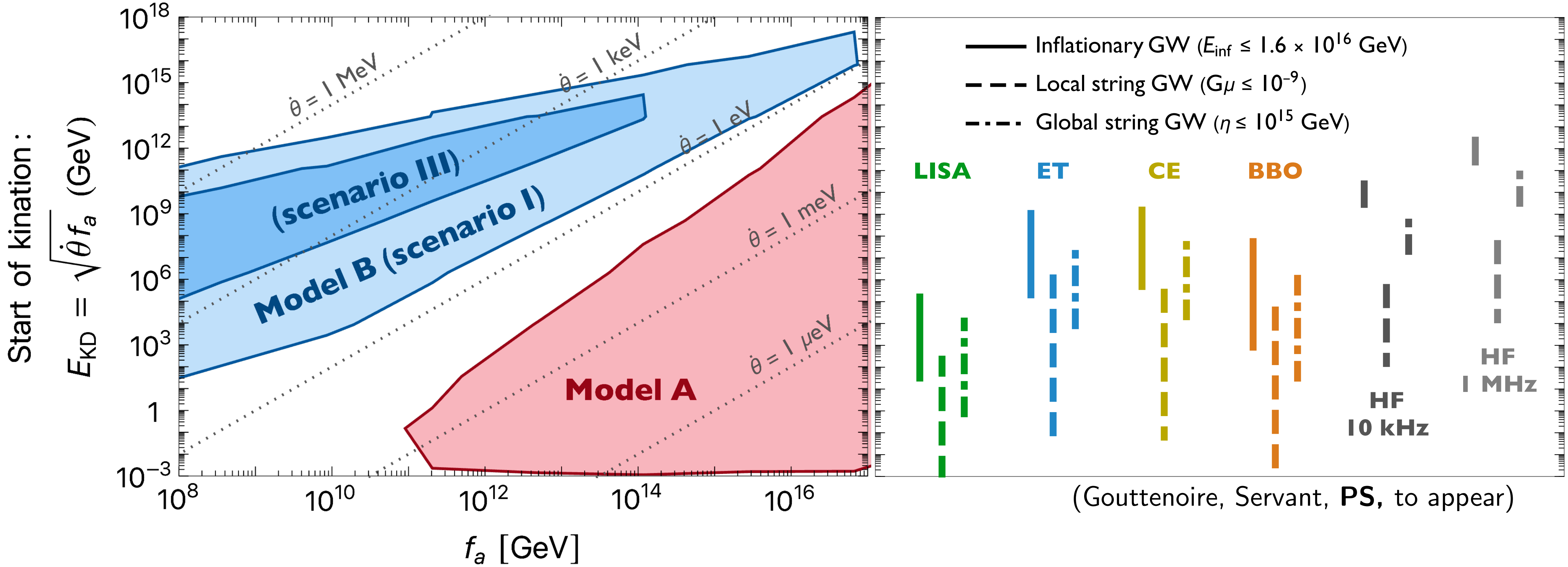


axion dominates before oscillation

Axiongenesis
$U(1)_{PQ}$-charge transfers to baryon number via sphaleron transition.

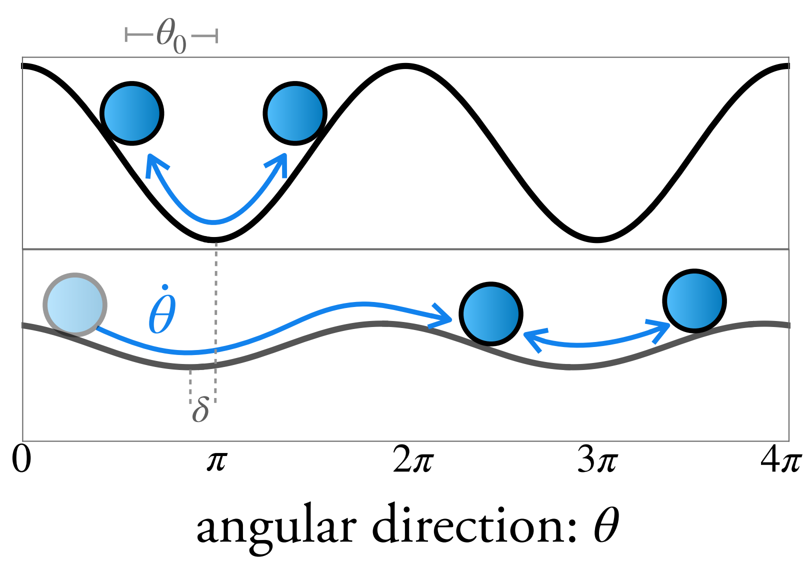
$l = 12,\ \lambda = 10^{-4}$

Probing kination GW peak from spinning axion models



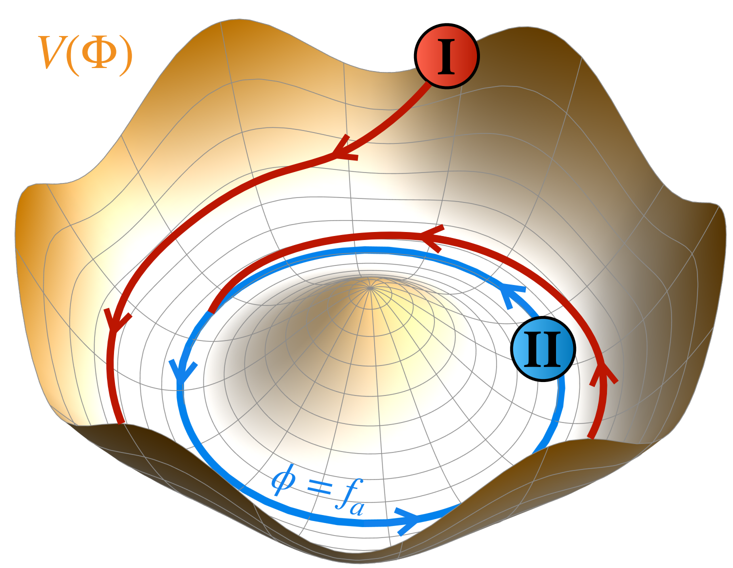
(Gouttenoire, Servant, **PS,** to appear)

Model A: Trapped misalignment



$$\dot{\theta}_c \sim \frac{T_c^{3/2} M^{1/4}}{M_{\rm Pl}^{3/4}} \qquad \text{with } M,\ T_c < f_a$$

Model B: Complex scalar field



$\dot{\theta} \sim m_r$ (radial-mode mass)

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

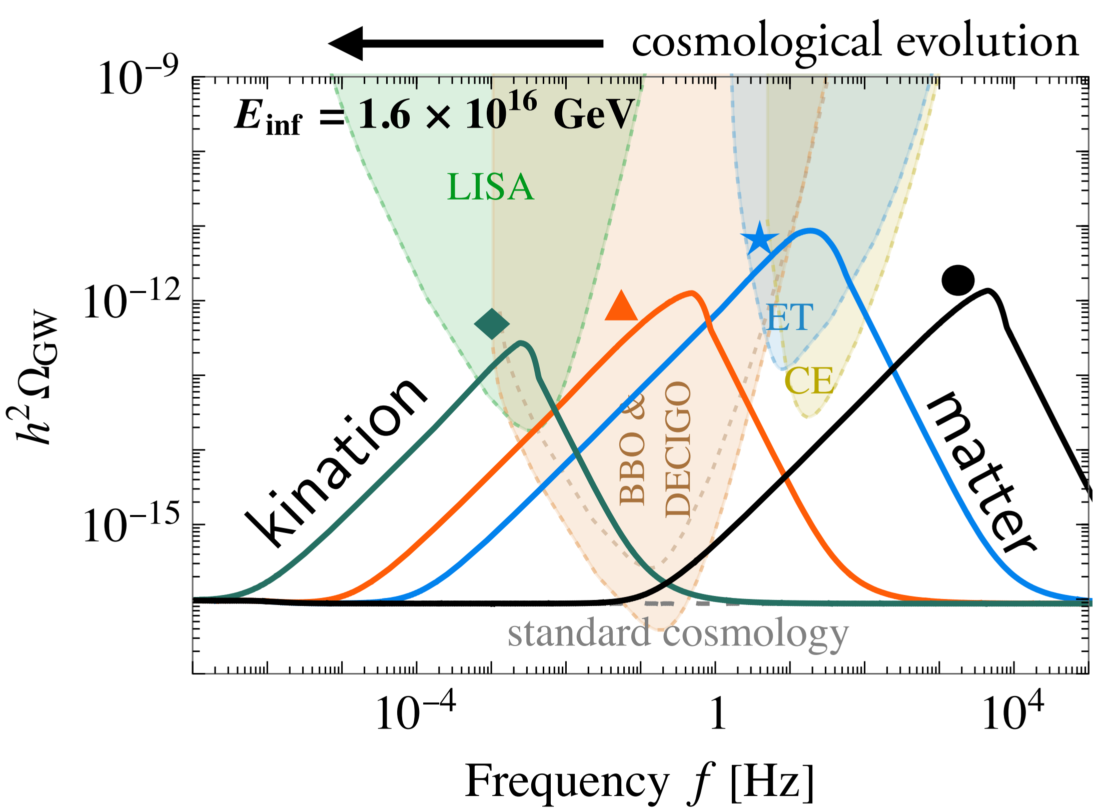
e.g. from complex scalar field (generic in SM extensions) or from trapped misalignment

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

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

$\Omega^{\rm GW}_{\rm peak} \propto$ kination duration

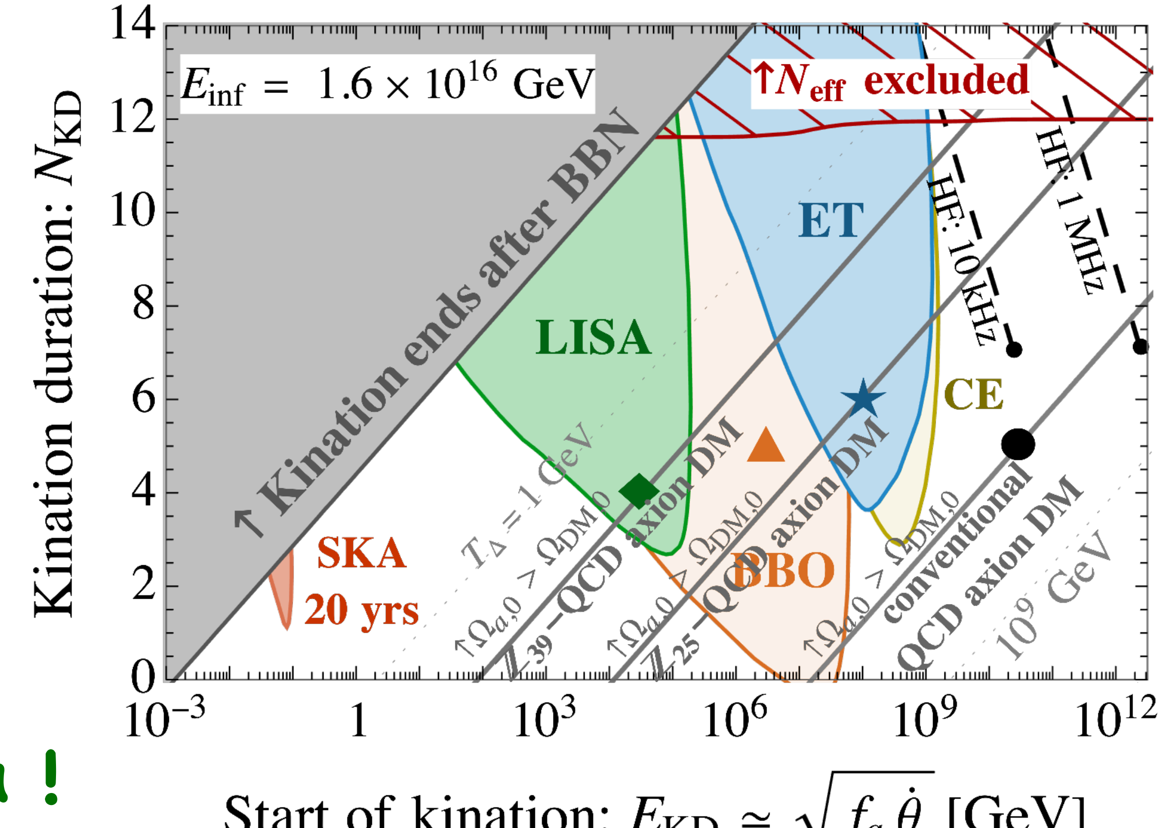
$f_{\rm peak} \propto$ energy scale & duration



Kination peak from QCD axion DM:

the conventional QCD axion ⇒ not observable

the lighter QCD axion ⇒ observable !



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

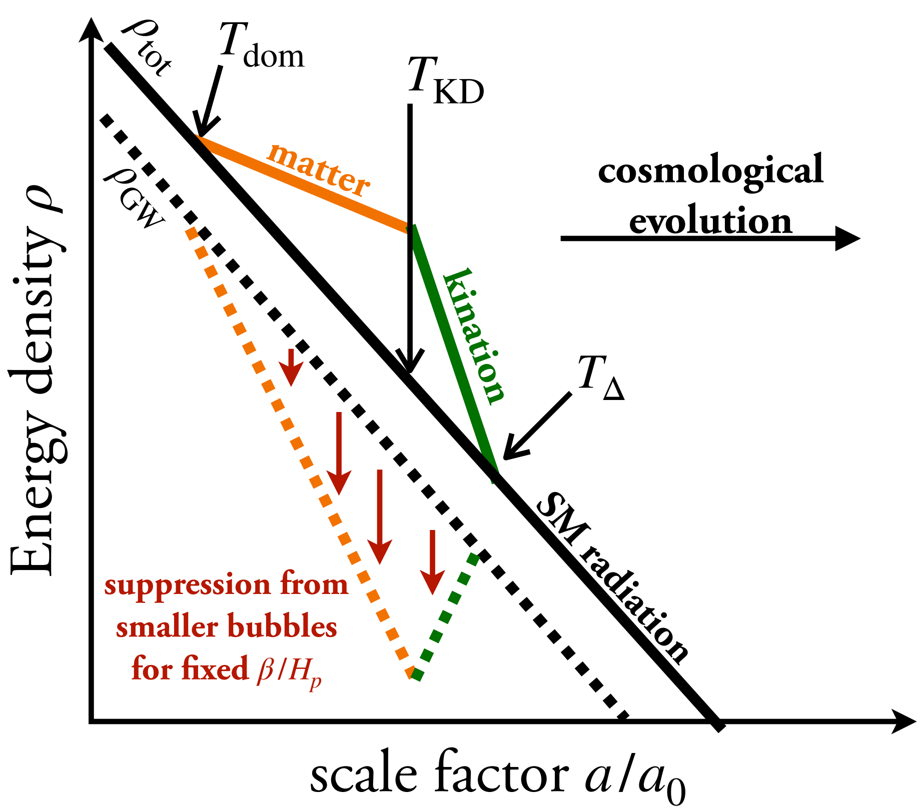
Thank you !

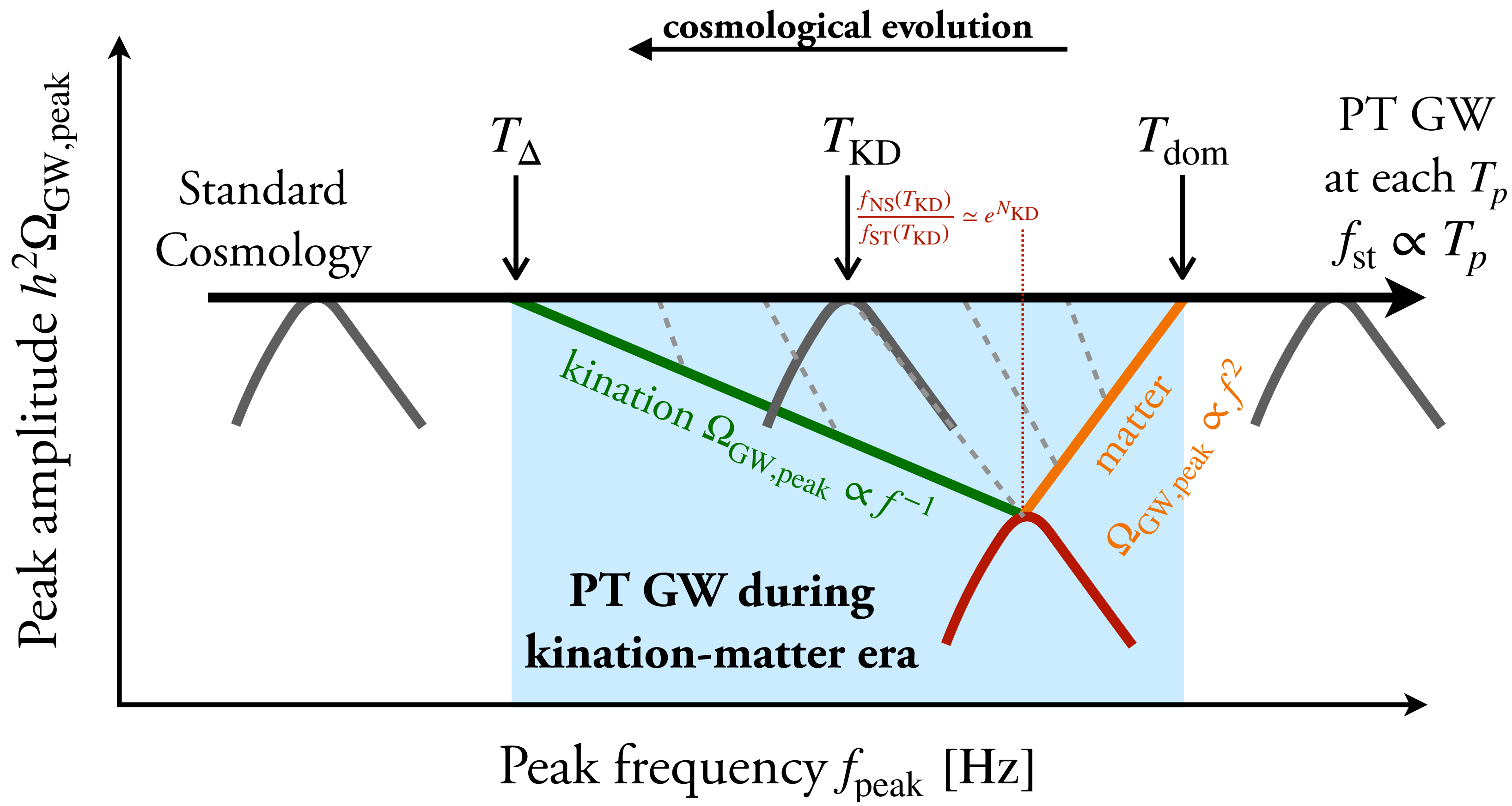
Effect on short-lasting GW

e.g. first-order phase transition

Thermal phase transition where the source of GW is the thermal plasma cannot have the enhancement.

(Gouttenoire, Servant, **PS,** to appear)





Super simplified argument: For fixed β/H_p,
the bubble size is fixed to be some fraction of Hubble horizon.
During the matter-kination era, Universe has smaller size, smaller bubbles, and thus weaker GW.

Other spectral distortions, e.g. causality tail [Hook, Marques-Tavares, Racco, '20]