

Primordial gravitational waves boosted by the axion



based on

[2108.10328](#), [2111.01150](#)

(Kination from a rotating axion)

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with

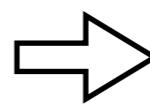
Yann Gouttenoire (Tel Aviv U.),
Géraldine Servant (DESY & U.Hamburg)

GW workshop
MITP, 11.08.2022



Universität Hamburg
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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE



from ~November 2022
with Daniel Figueroa



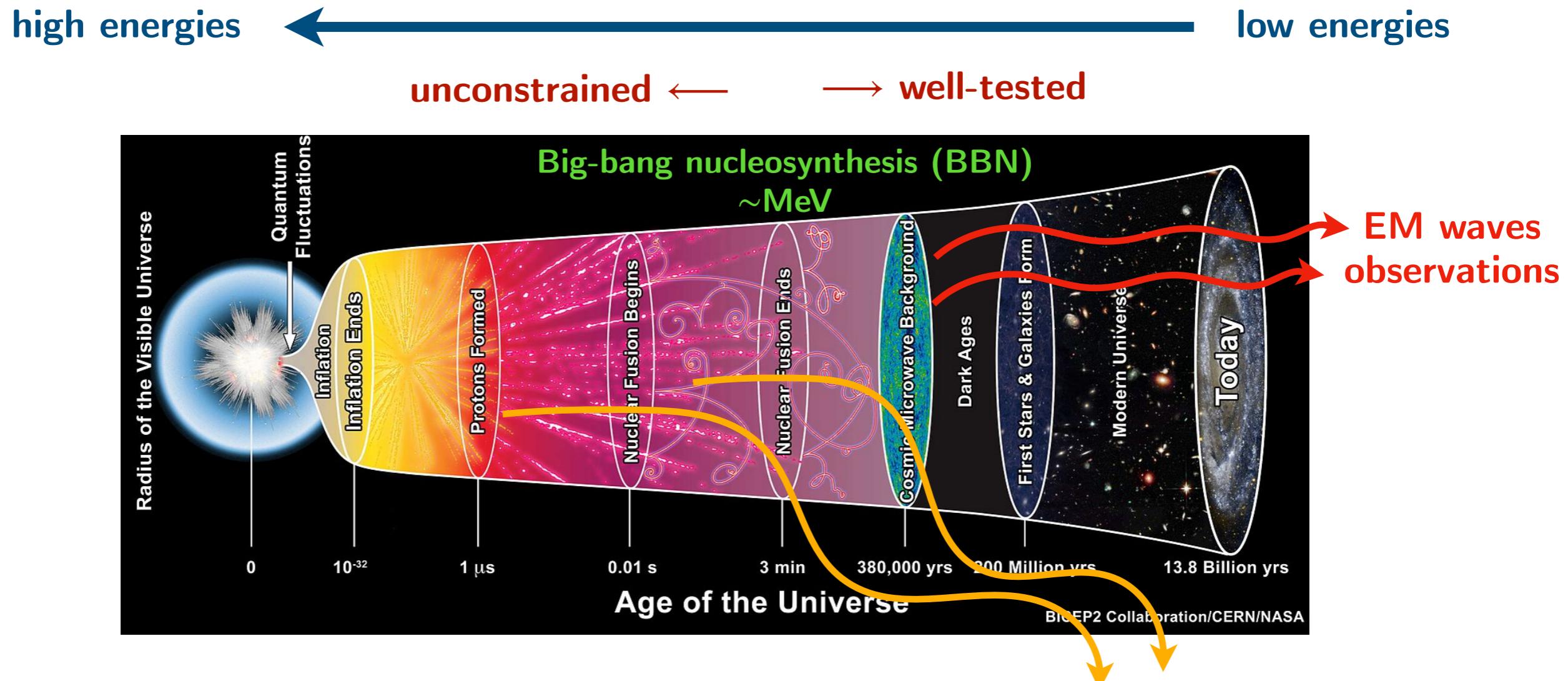
Cosmic Archeology with Gravitational Waves

Study implications of non-standard cosmological histories
of the early Universe — High-Energy Particle Physics!

Aim

The early-Universe **axion** dynamics can
induce a non-trivial cosmological history — ***kination***,
that associates with distinct signatures in GW background.

Gravitational waves as probes of the very early universe



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

Primordial GW

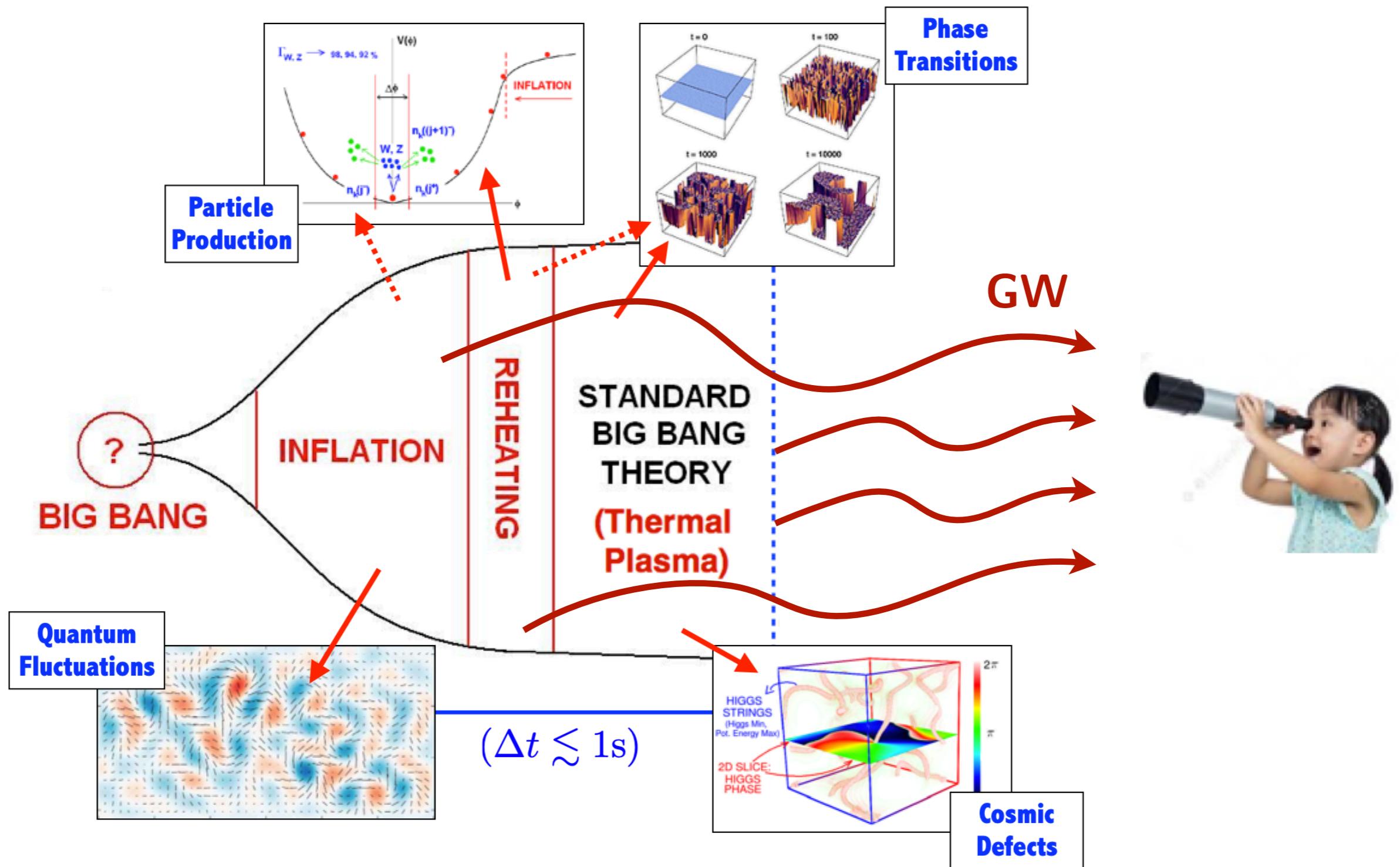
GW produced below $M_{\text{Pl}} \sim 10^{18}\ \text{GeV}$ propagates freely after production.

Energy density of GW background: $\rho_{\text{today}}^{\text{GW}} = \rho_{\text{prod}}^{\text{GW}} \left(\frac{a_{\text{prod}}}{a_{\text{today}}} \right)^4$

The universe is expanding. \Rightarrow BSM of cosmology

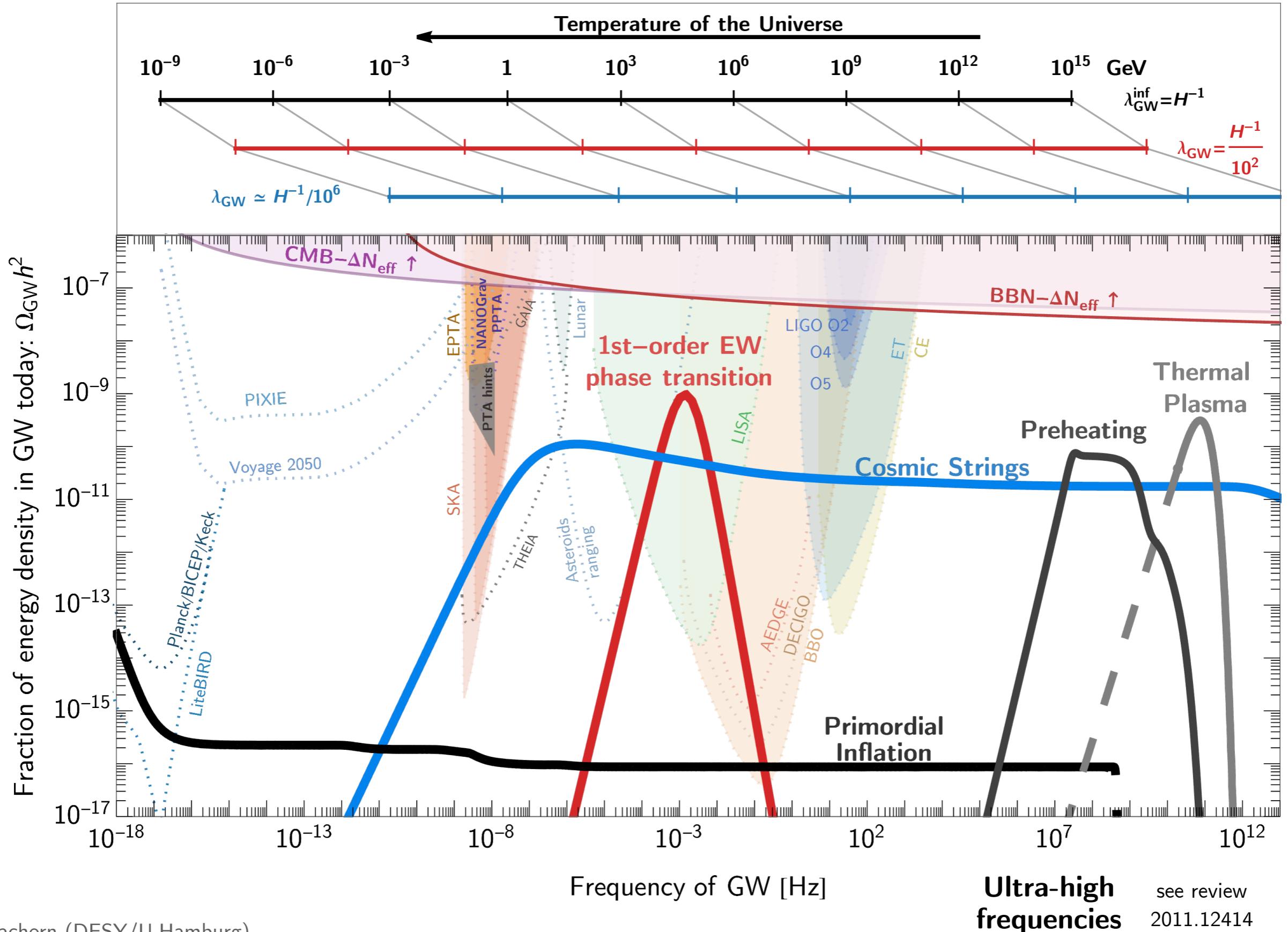
its production mechanism \Rightarrow BSM of particle physics

GW from the early-Universe = Primordial GW



Borrowed from a talk of Daniel G. Figueroa

Landscape of Primordial GW



Cosmic Archeology with Gravitational Waves (from long-lasting sources)

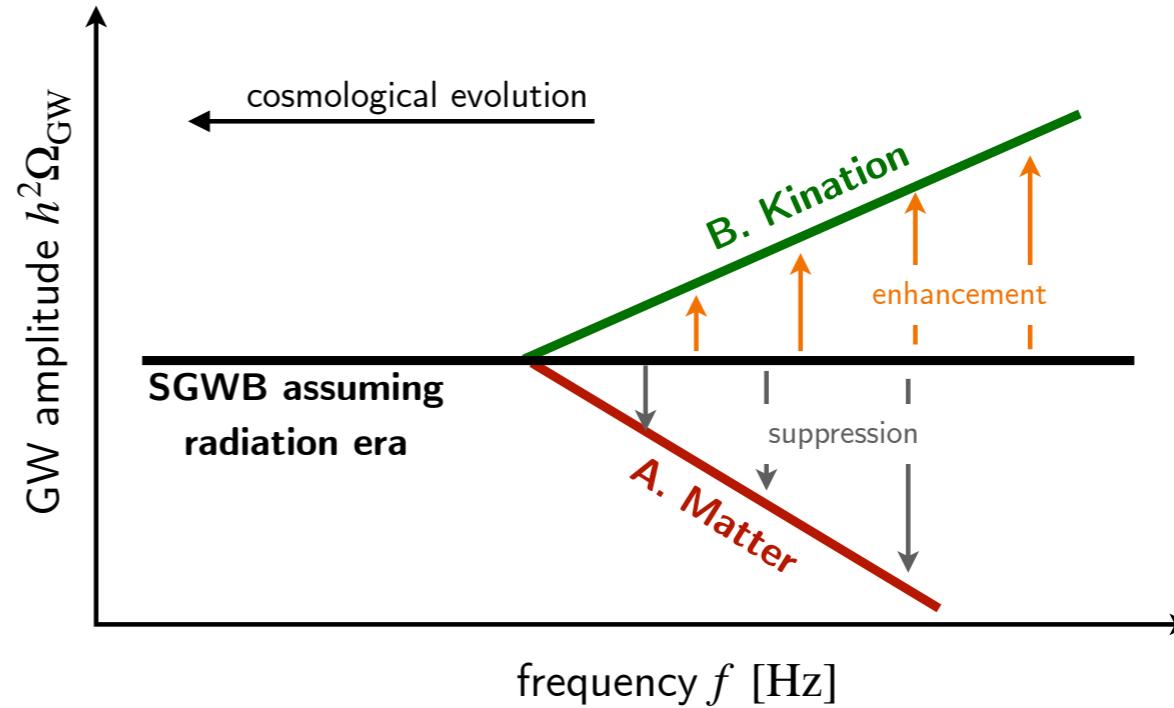
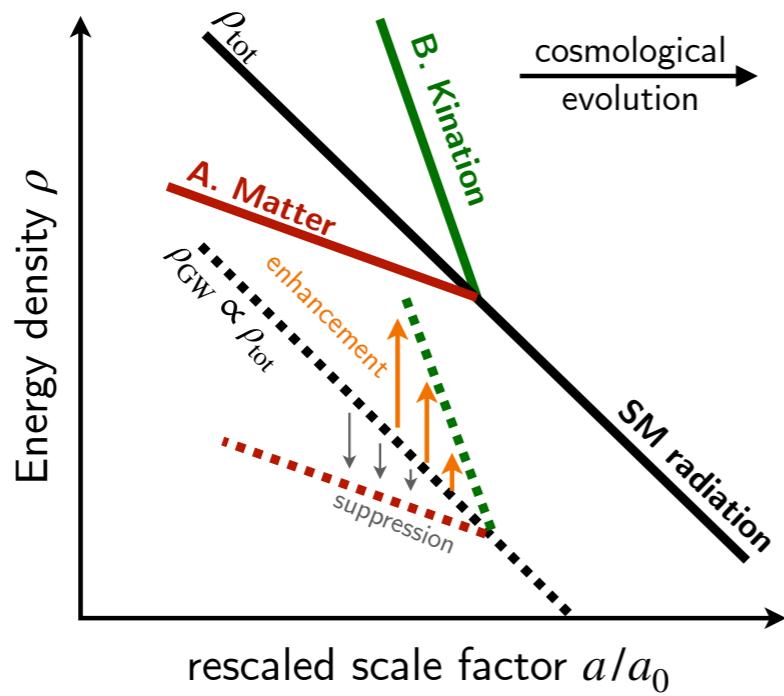
for a review

See 2006.16182 “*The first three seconds : ...*”

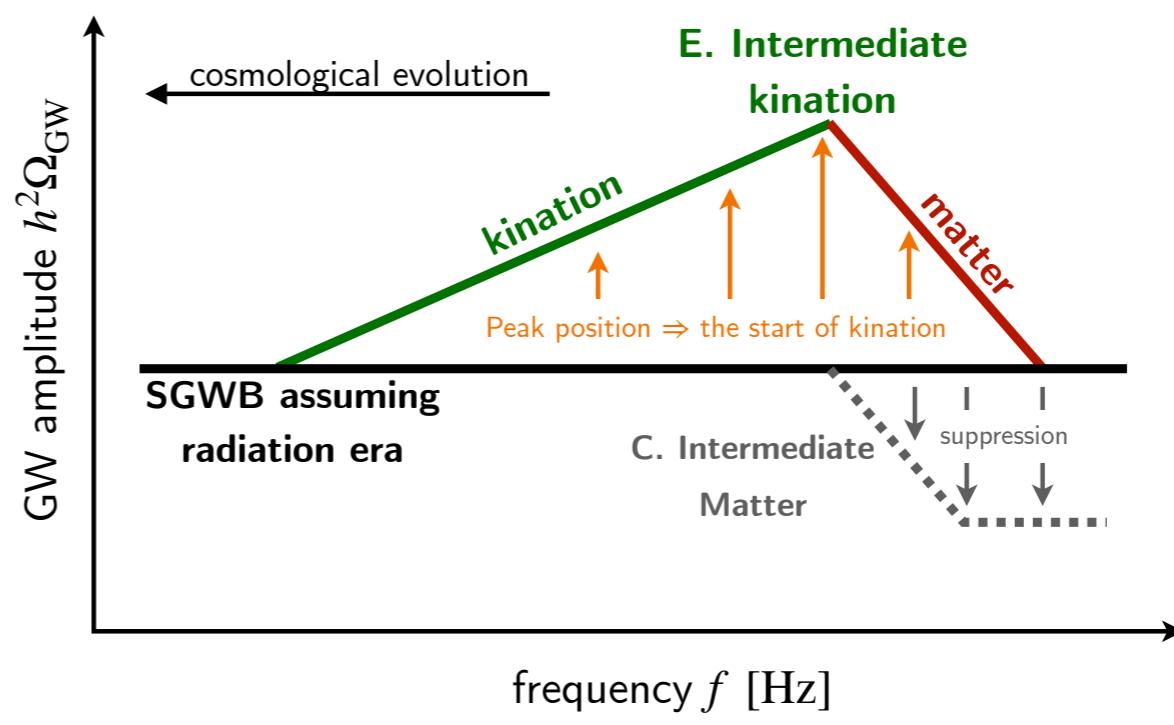
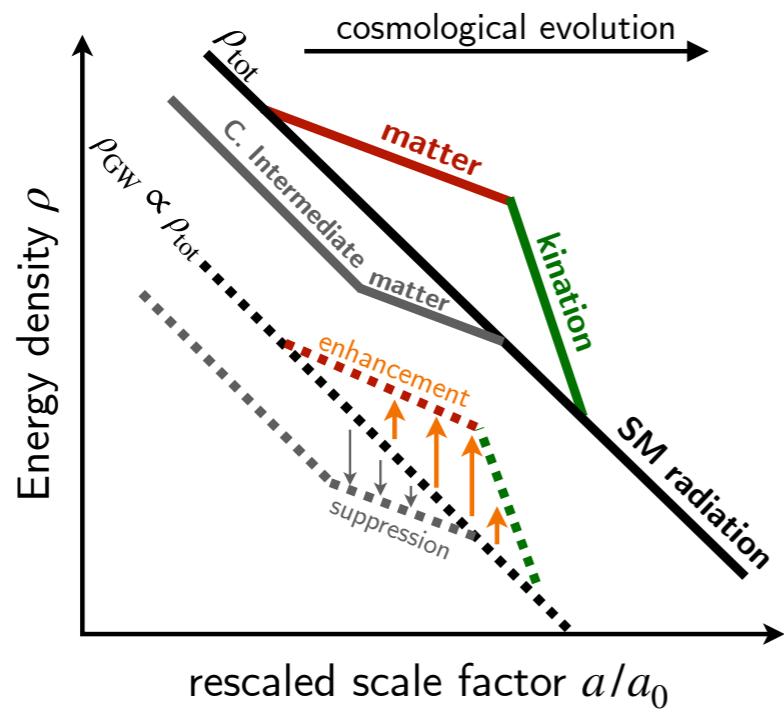
including other probes beyond GW.

Cosmic Archeology with long-lasting primordial GW

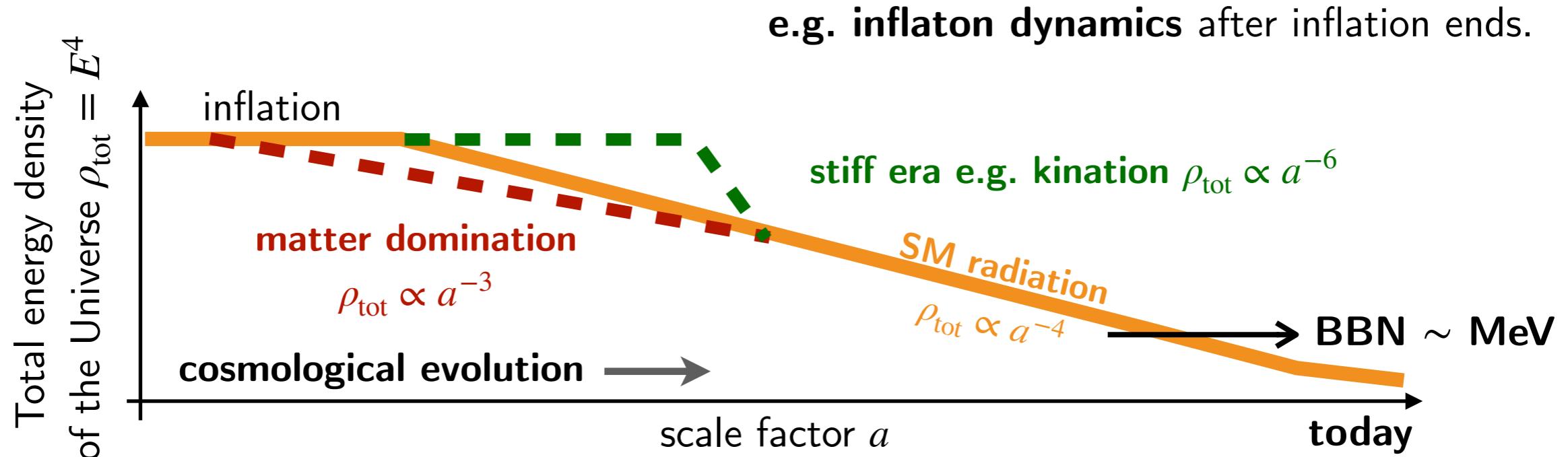
Non-Standard Cosmological Eras right after Inflation



Intermediate Non-Standard Cosmological Eras inside Radiation Era



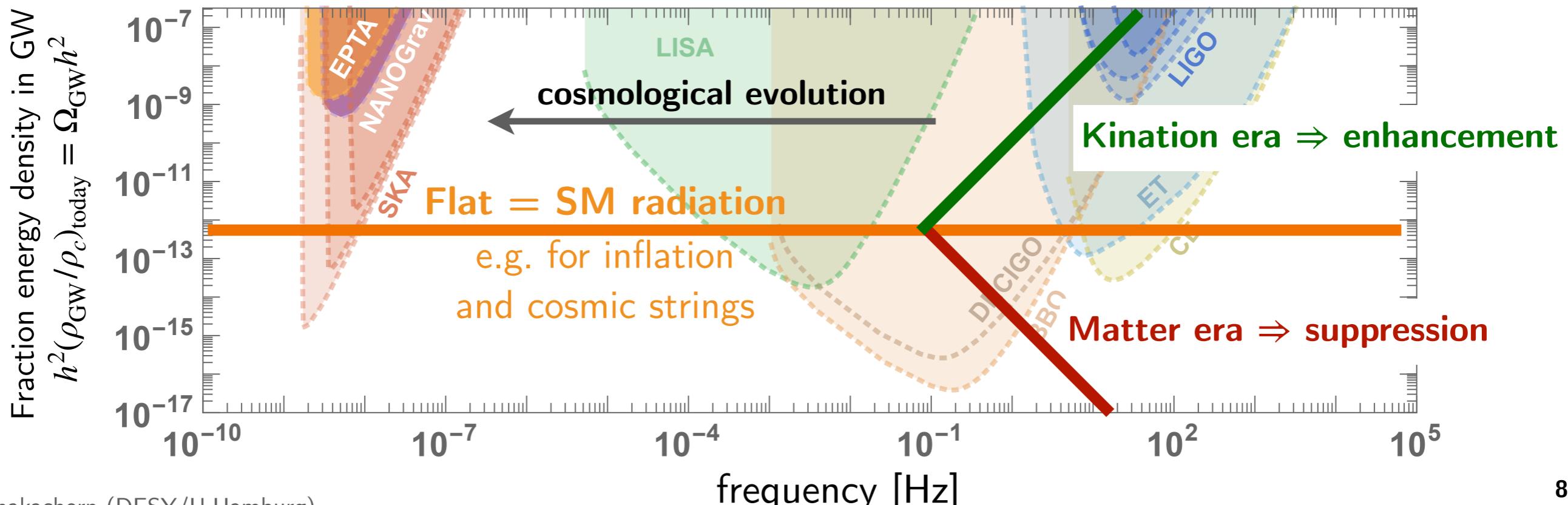
Non-standard cosmological histories



Distortion of GW from long-lasting sources

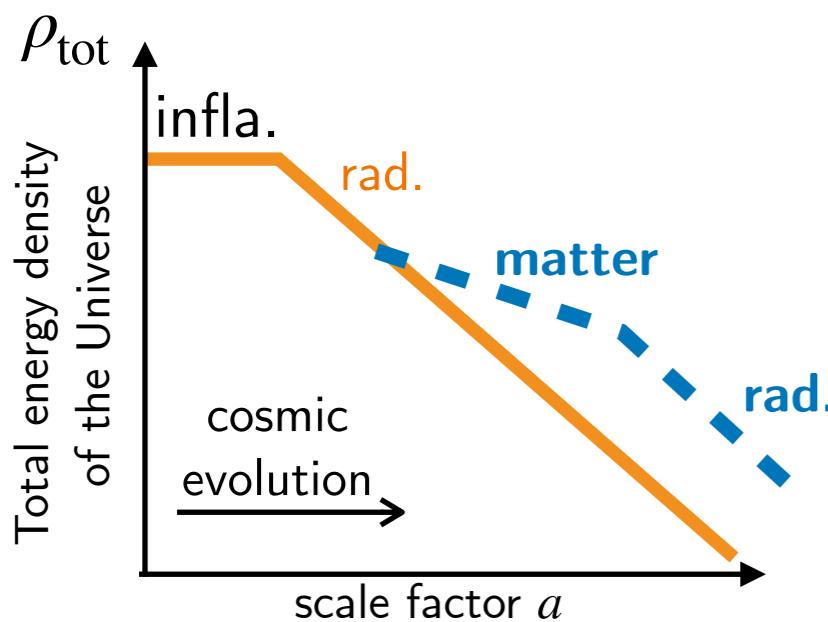
e.g., primordial inflation (Boyle, Steinhardt, '08), cosmic strings (Cui, Lewicki, Wells, '17, '18) (Gouttenoire, Servant, PS, 1912.02569)

causality (IR) tail (Hook, Marques-Tavares, Racco, '20)



II. Non-standard era inside the radiation era from particle physics.

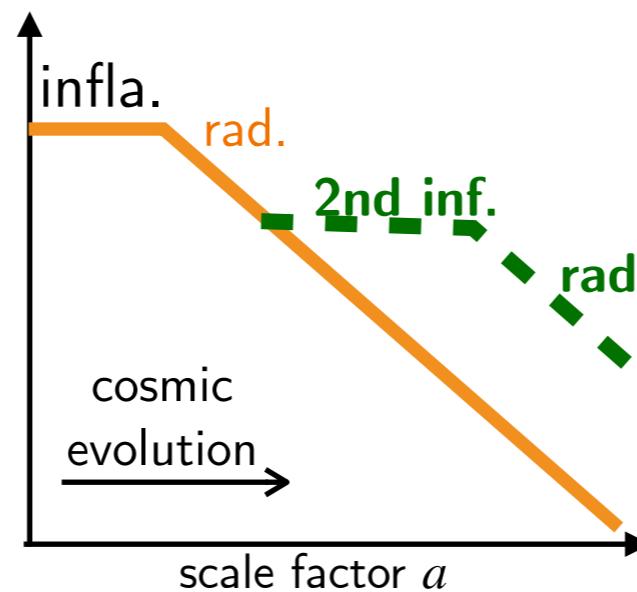
Intermediate matter era



Heavy & unstable particles

[Gouttenoire, Servant, PS,
1912.03245]

Secondary inflation



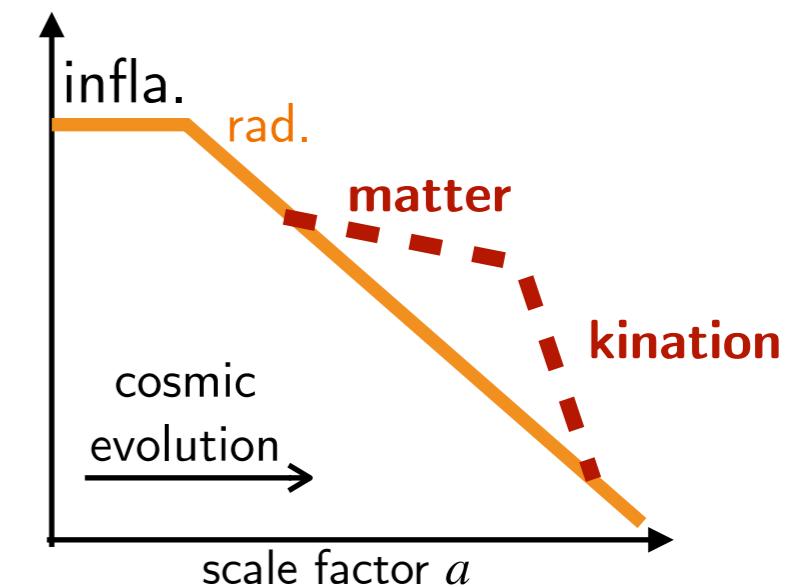
Supercool 1st-order phase transition

[Baldes, Gouttenoire, Servant, Sala, 1912.03245]

Rollercoaster cosmology

[D'Amico, Kaloper 2011.09489]

Intermediate kination

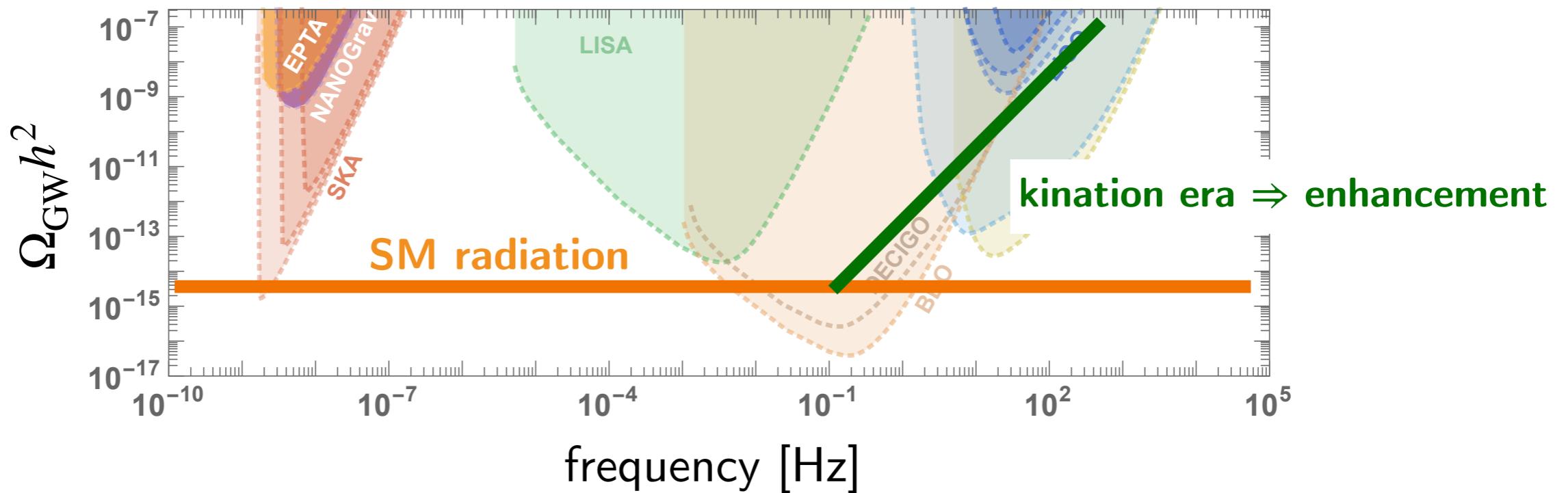


Rotating axion!

[Co, Harigaya, Hall, et. al., 2108.09299]

[Gouttenoire, Servant, PS,
2108.10328 & 2111.01150]

Kination-dominated era.



The simplest **kination** era



$$\text{equation-of-state: } \omega_\phi = \frac{E_{\text{kinetic}} - E_{\text{potential}}}{E_{\text{kinetic}} + E_{\text{potential}}}$$

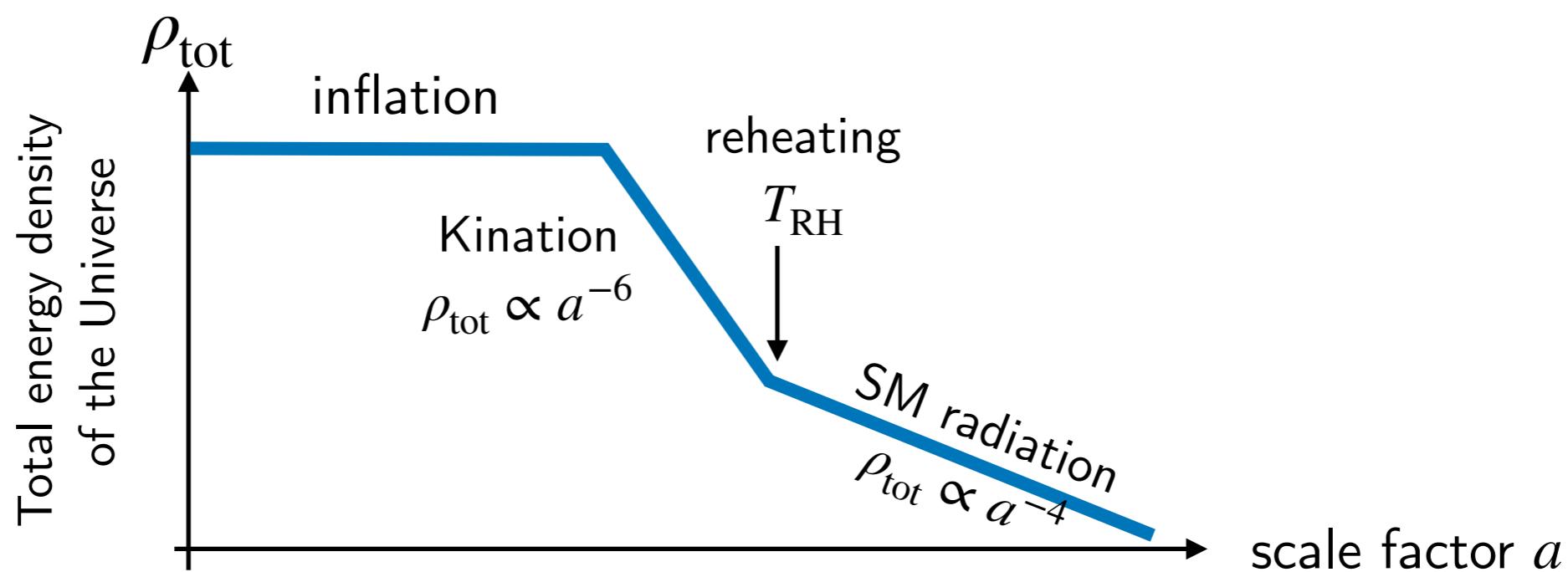
Maximum $\omega_\phi = 1$, when $E_{\text{kinetic}} \gg E_{\text{potential}}$

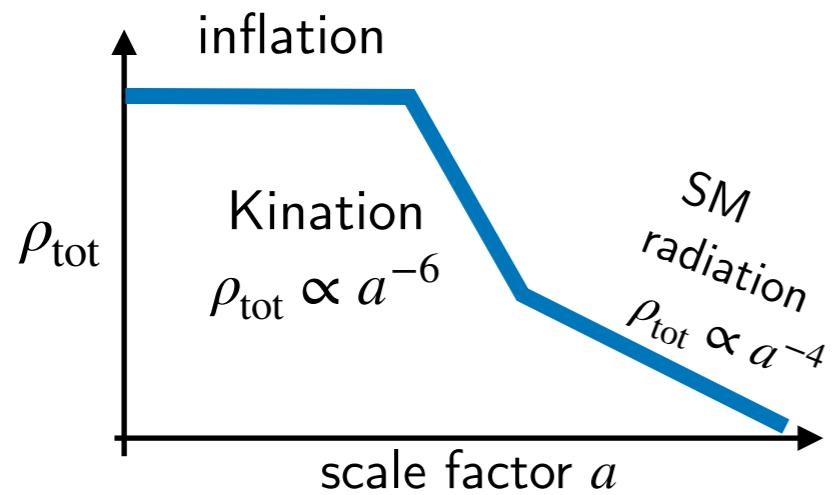
A scalar field dominates the universe with large kinetic energy,

“Kination” era. ($\rho_\phi \propto a^{-6}$)

[Spokoiny 1993, Joyce, 1997]

Examples: kination era is at **high-energy scales** after slow-roll inflation.

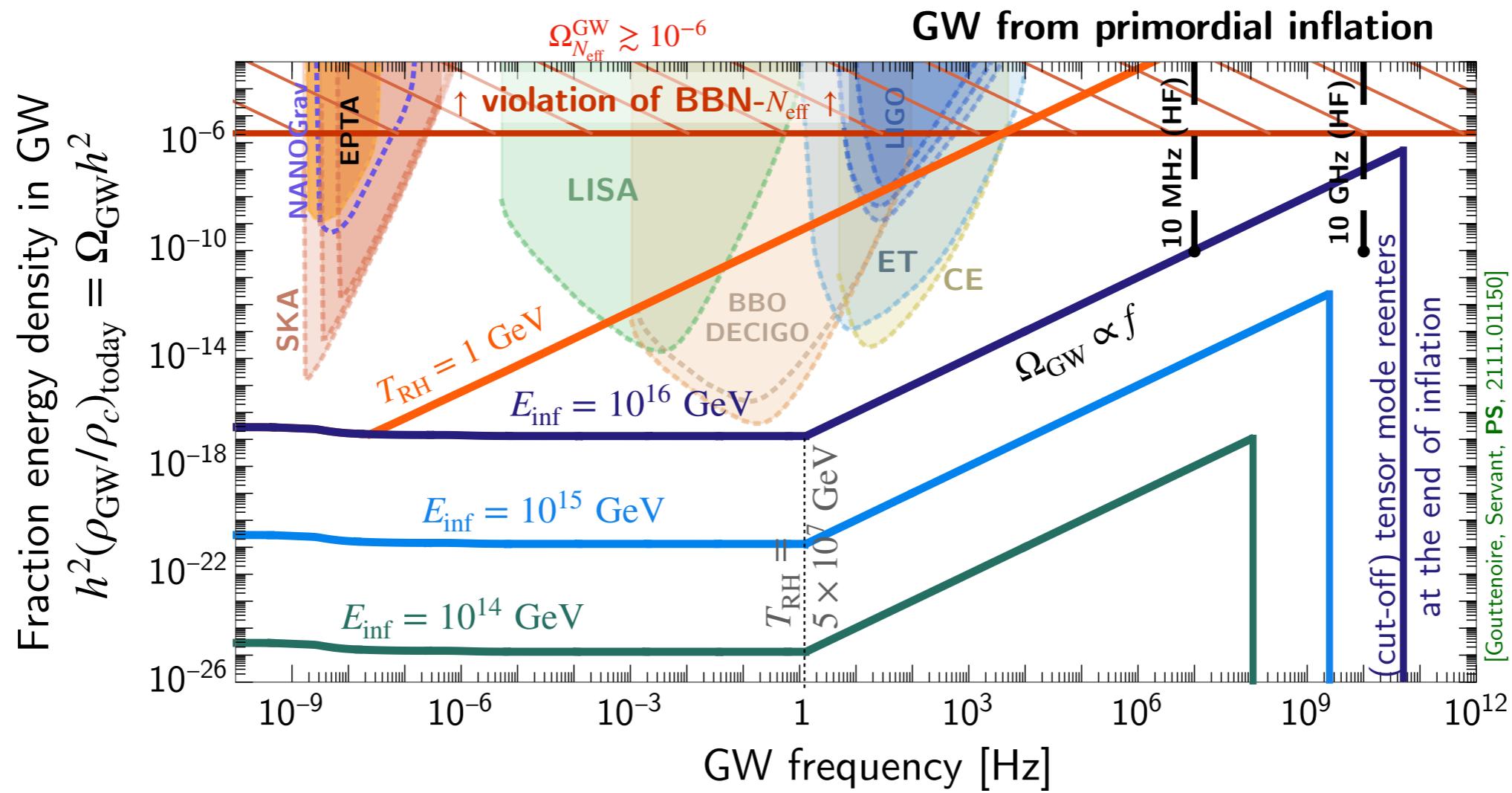


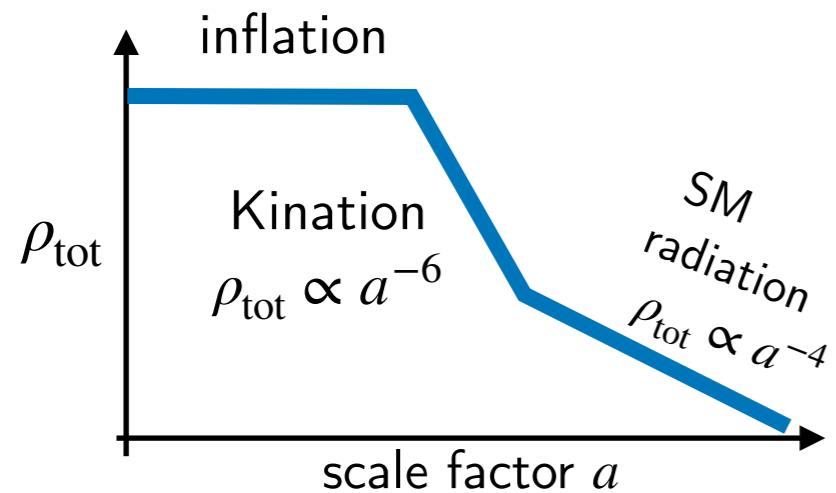


GW is an extra radiation.

Too much GW @ BBN/CMB violates
extra relativistic degrees-of-freedom : $\Delta N_{\text{eff}} \lesssim 0.2$

A long kination after inflation **cannot** have observable signal.

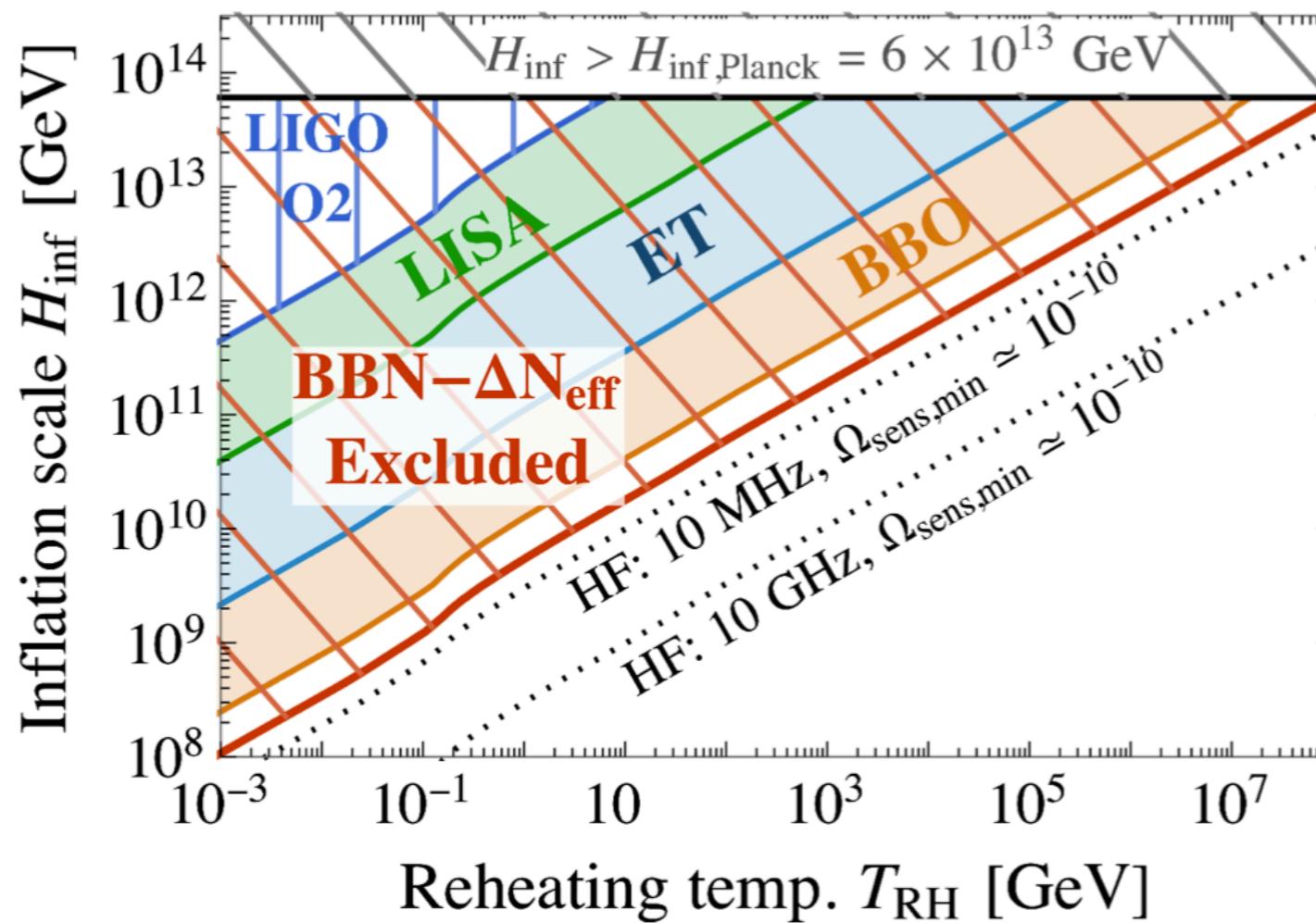




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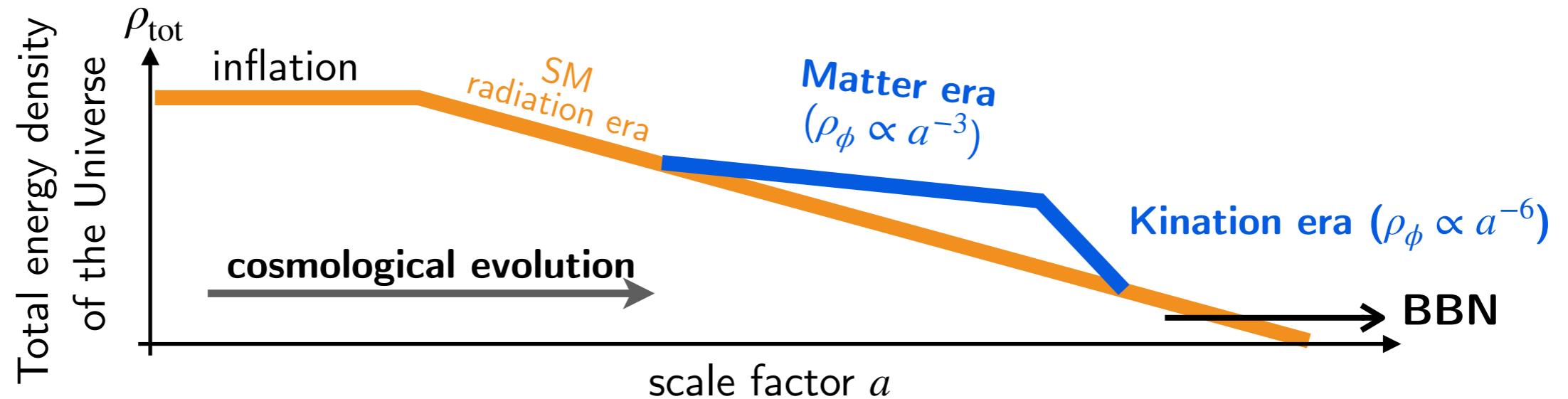
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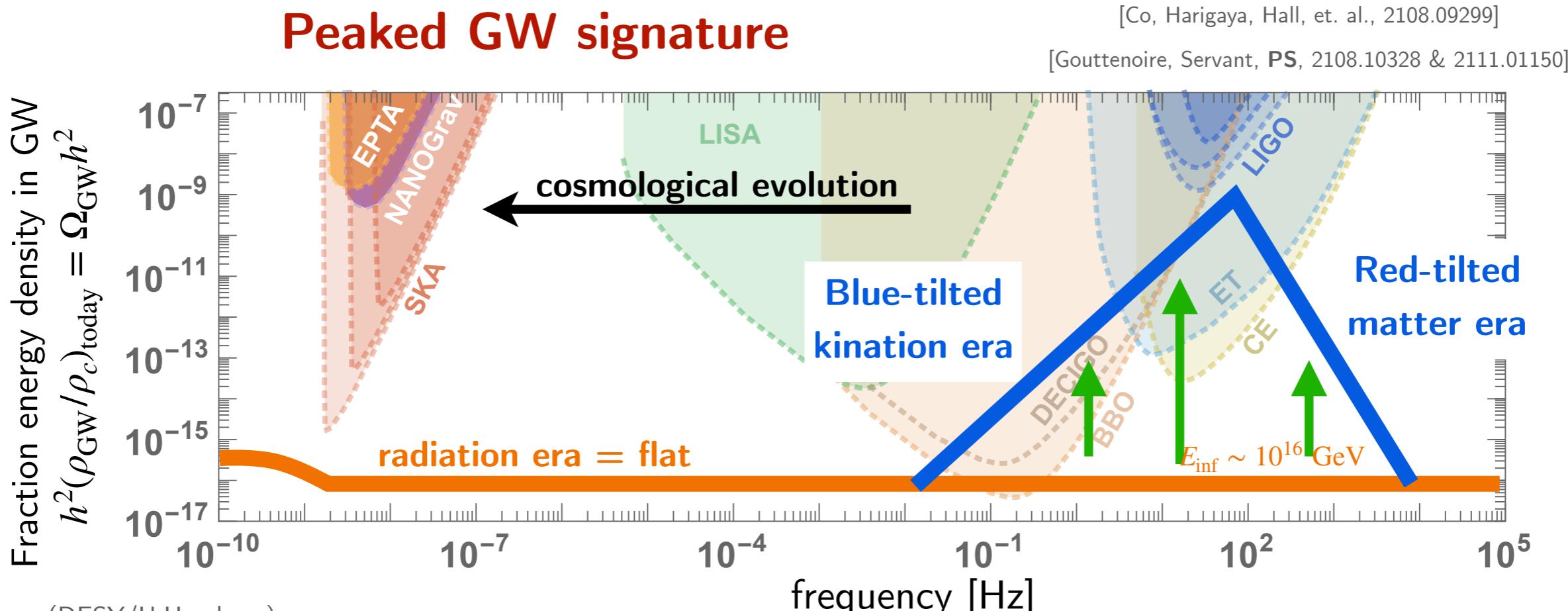


[Gouttenoire, Servant, PS,
2111.01150]

For the current/future-planned experiments,
an intermediate and low-scale kination era is very interesting.



Rotating axion!

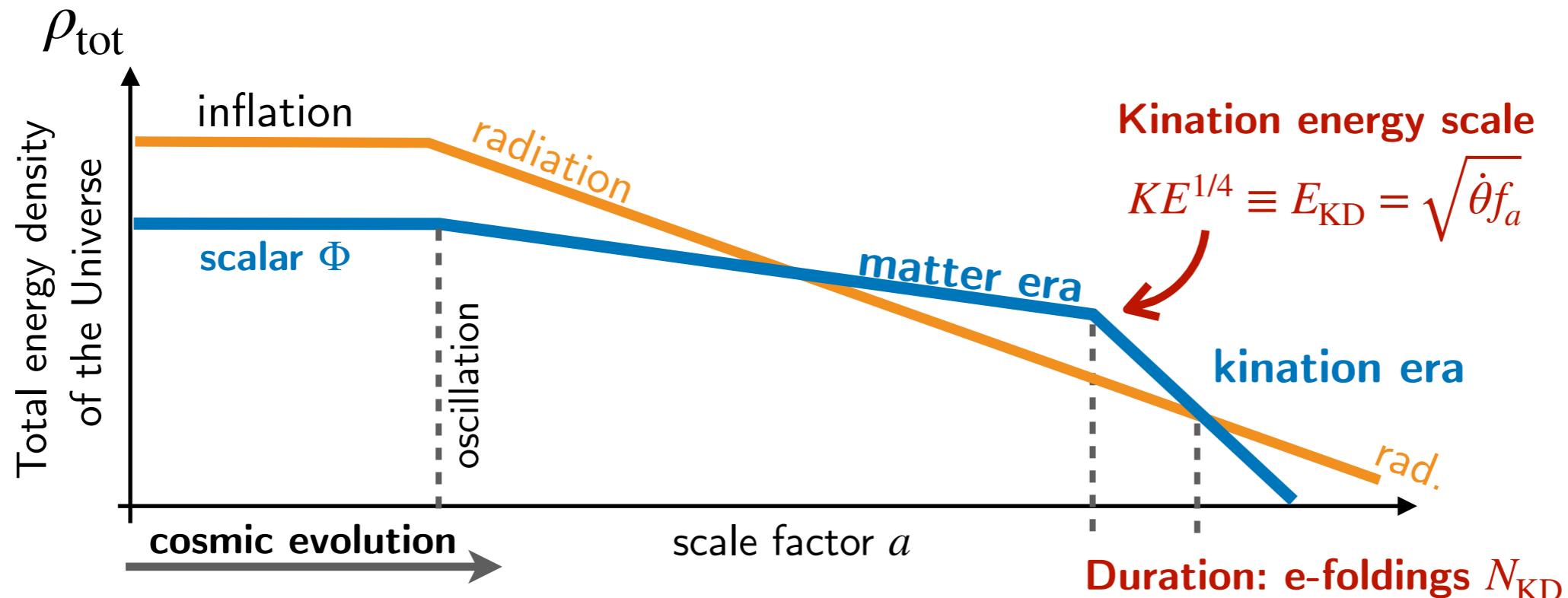


“Axion Kination”

**Intermediate kination
from a rotating axion!**

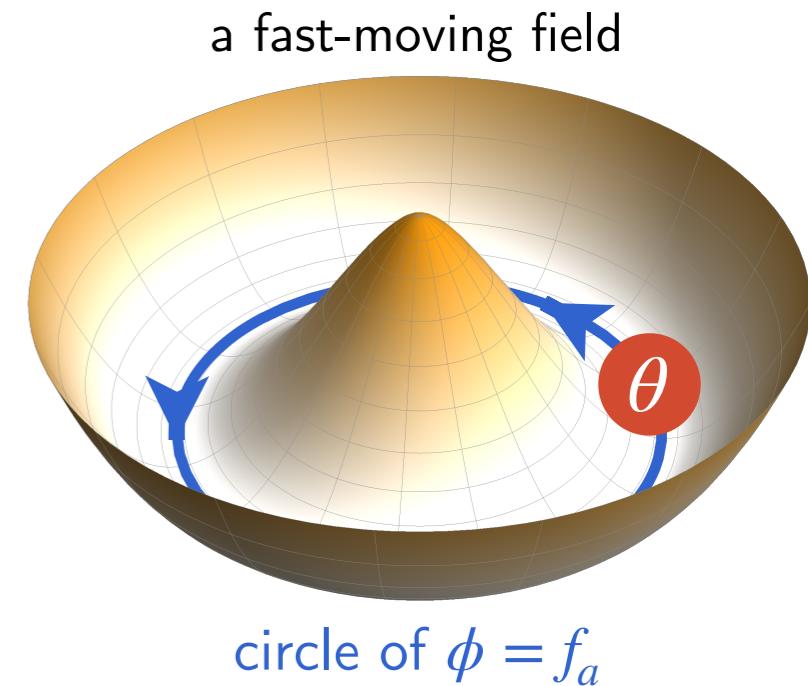
[Co, Harigaya, Hall, et. al., 2108.09299]
[Gouttenoire, Servant, PS, 2108.10328 & 2111.01150]

Model-independent: intermediate kination



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

1. **kination energy scale** $E_{KD} = \sqrt{\dot{\theta}f_a}$
(the spinning speed of axion $\dot{\theta}$ when kination starts)
2. **the duration of kination era** $N_{KD} = \log(a_{start}/a_{end})$
(related to the beginning of the matter era)



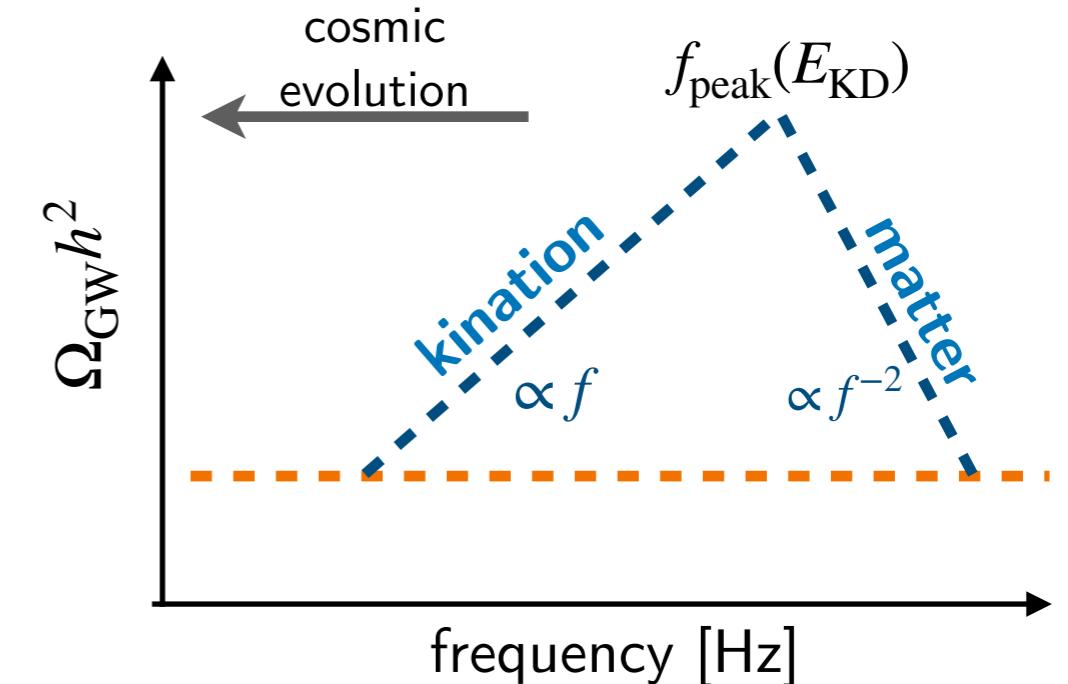
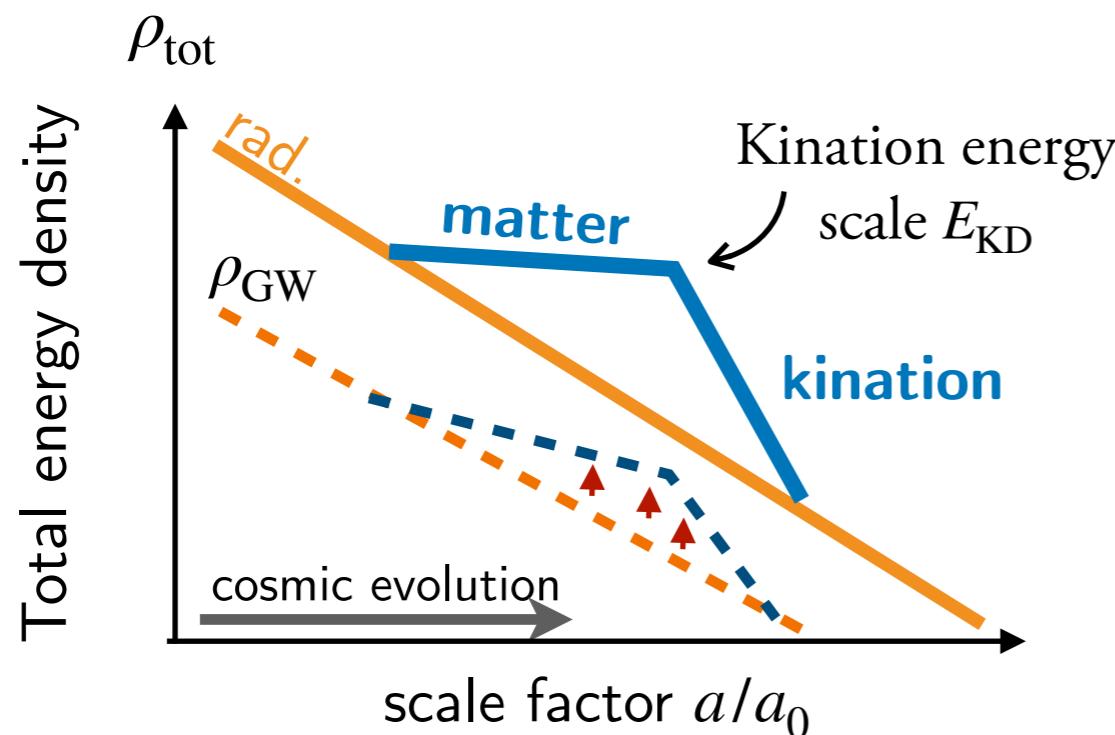
GW signature from matter-kination era (skipped!)

**Fraction of energy density
in GW today**

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

constant

GW from inflation
and cosmic strings

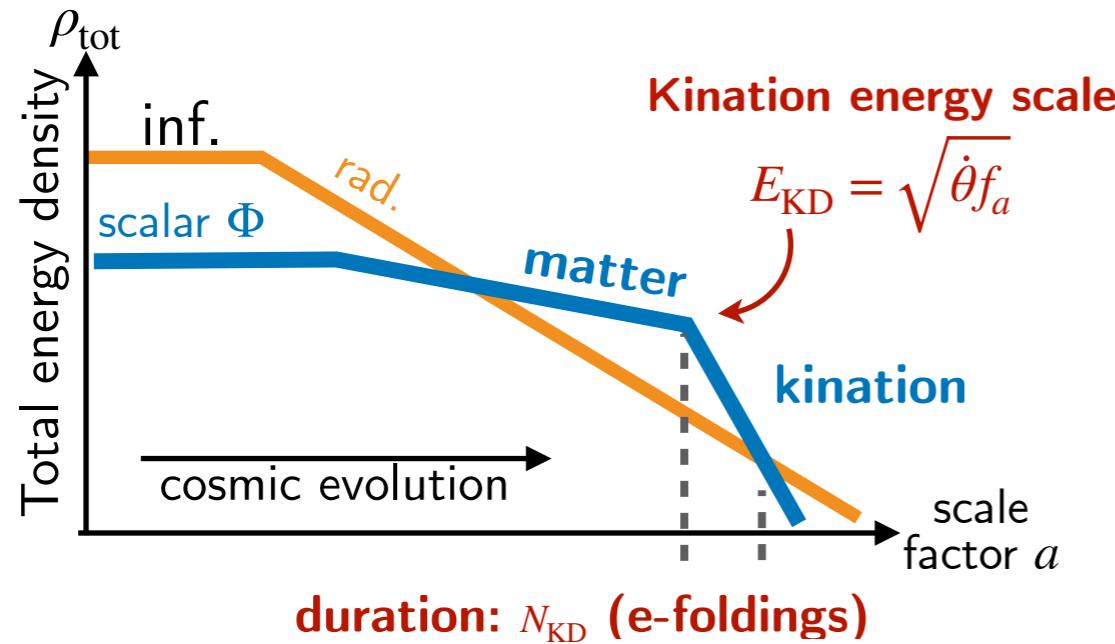


Peak at the start of kination E_{KD}

$$\text{where } \frac{\rho_{\text{tot,non-st}}}{\rho_{\text{tot,st}}} \Big|_{\text{max}}$$

“Broad peak”
distinguishable from other
primordial GW,
e.g. 1st-order phase transitions

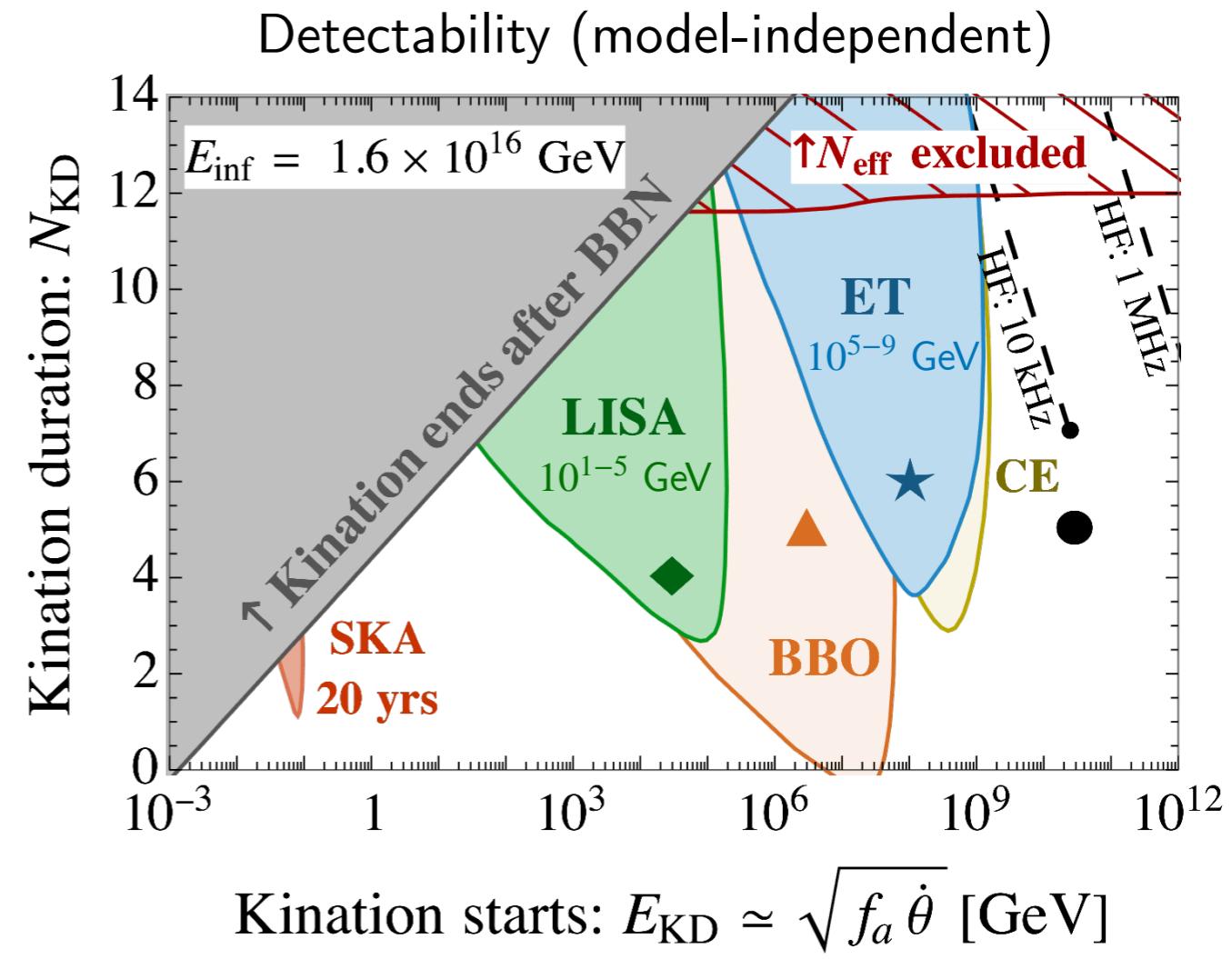
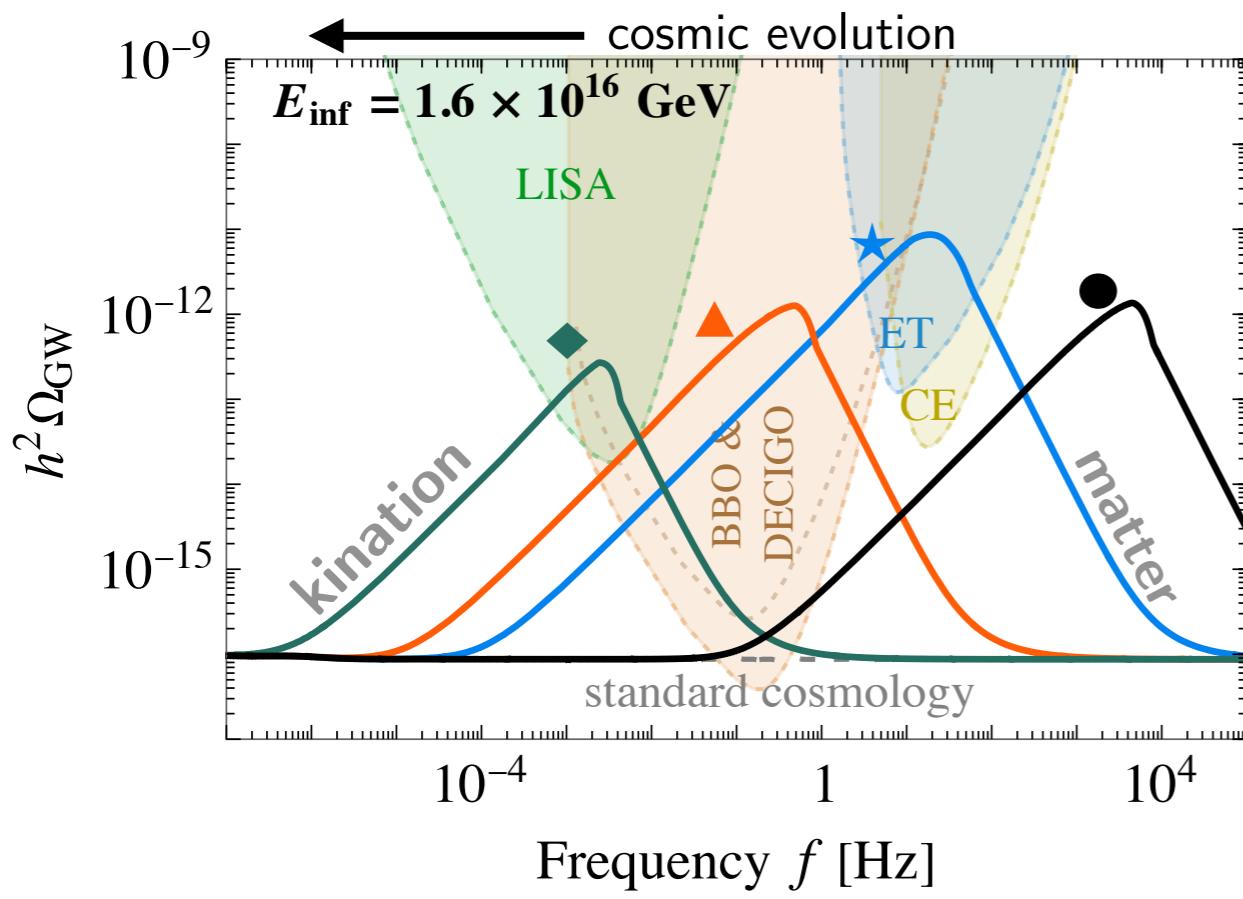
GW signature: a “peak”



Peak position for GW from inflation.

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

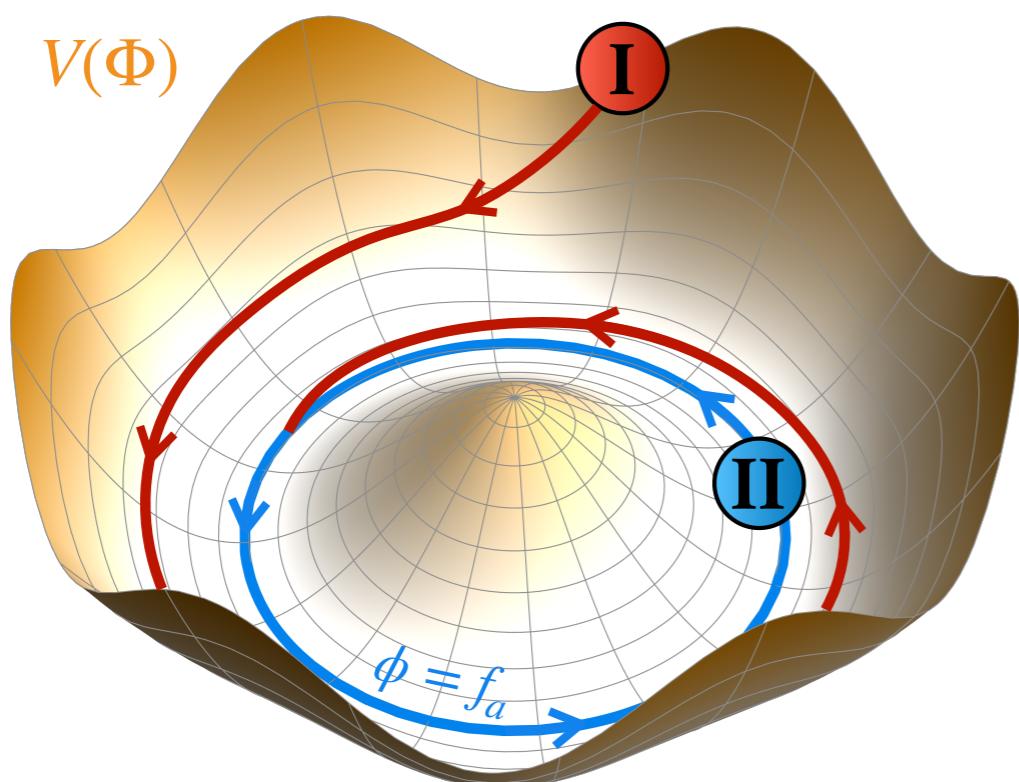
$$\Omega_{\text{peak}} h^2 \approx 10^{-12} \left(\frac{E_{\text{inf}}}{1.6 \times 10^{16} \text{ GeV}} \right)^4 \left[\frac{\exp(2N_{\text{KD}})}{10^4} \right]$$



[Gouttenoire, Servant, **PS**, 2108.10328 & 2111.01150]

Rotating Axion.

Going beyond usual assumption of vanishing axion's velocity.

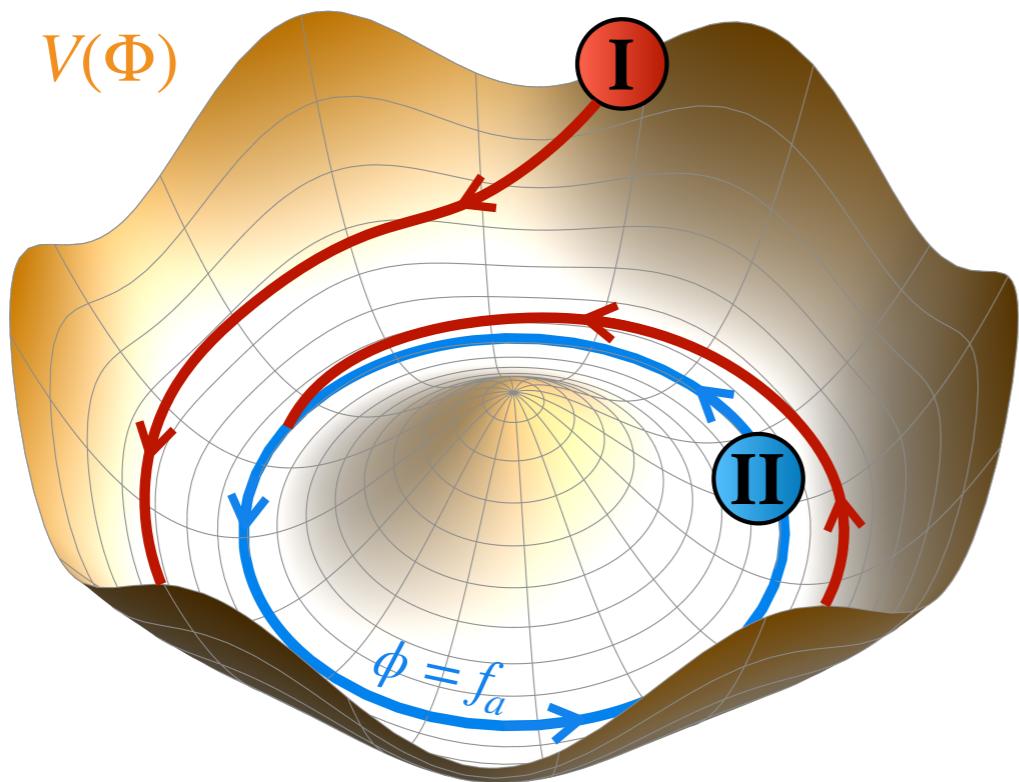


Examples:

- “Affleck-Dine Baryogenesis” (Affleck, Dine, 1984)
- “Spontaneous Baryogenesis” (Cohen, Kaplan, 1987)
- “Spintessence” (Boyle, Caldwell, Kamionkowski, 2001)
- “Affleck-Dine Magnetogenesis” (Kamada, Shin, 2019)
- “Axiogenesis” (Co, Harigaya, 2019)

Example: Rotating complex scalar field

“Affleck-Dine Axionogenesis” (Co, Harigaya, ’19)



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

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

Angular mode θ “axion” rotates, with large kinetic energy.

Requirements for the successful kination era

1. $U(1)$ -symmetric (quadratic) potential with spontaneous symmetry-breaking minimum
2. Explicit $U(1)$ -breaking term (wiggle for angular velocity)
3. Large initial scalar VEV
4. Radial damping mechanism

Ingredients 1 & 2 : scalar potential

$$V(\Phi) = m_r^2 |\Phi|^2 \left[\log \left(\frac{|\Phi|^2}{f_a^2} \right) - 1 \right] + \Lambda_b^4 \left[\left(\frac{\Phi}{M_{\text{Pl}}} \right)^l + \left(\frac{\Phi^\dagger}{M_{\text{Pl}}} \right)^l \right] + \frac{\lambda^2}{M_{\text{Pl}}^{2l-6}} |\Phi|^{2l-2}$$

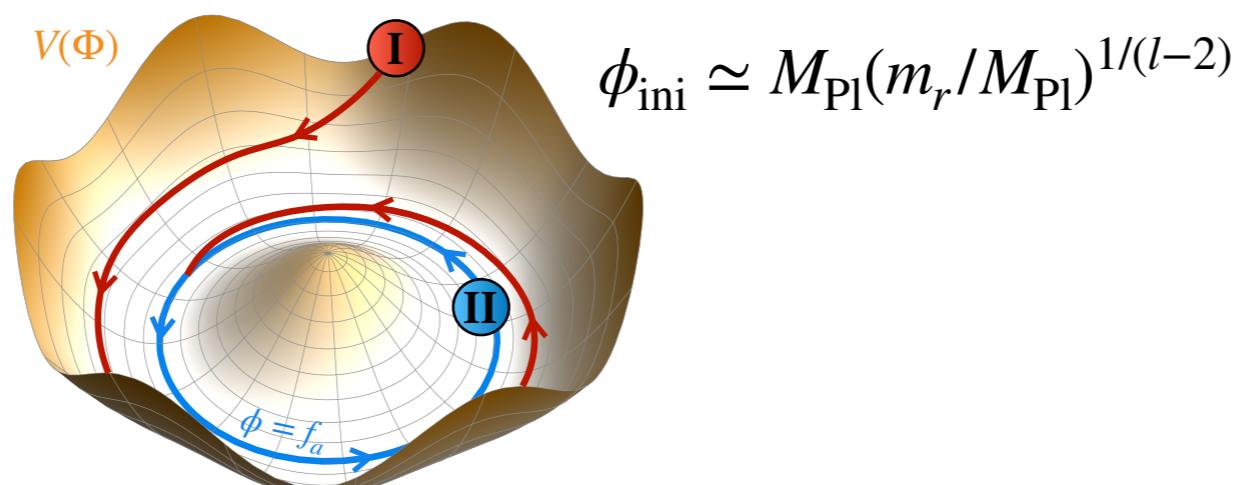
$U(1)$ -conserving potential
(quadratic)
with a minimum f_a
(motivated by supersymmetric setups)

$\propto \cos(l\theta)$
explicit breaking term
(e.g. $U(1)$ is not exact
at high scales.)

stabilization

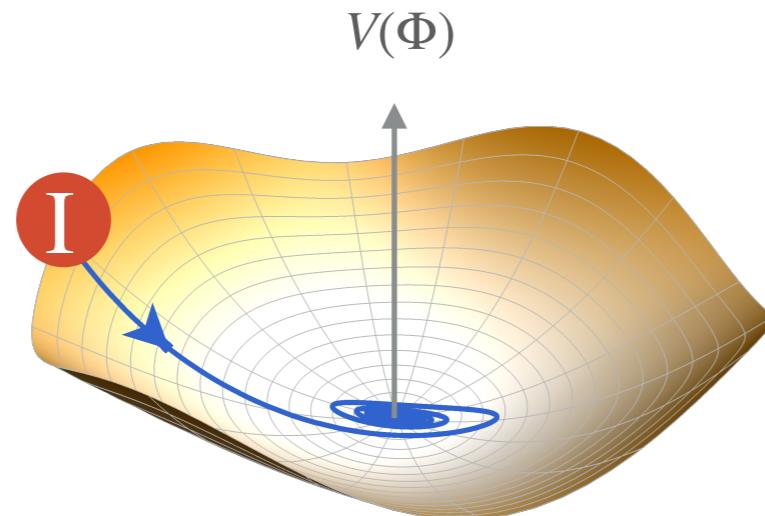
Ingredient 3 : large initial VEV ϕ_{ini}

Driven away from $\phi = 0$ at early times ($H \gg m_r$)
by a negative Hubble mass $V_H(\Phi, H) \supset -cH^2 |\Phi|^2$ (e.g. Dine, Randall, Thomas, 1995)



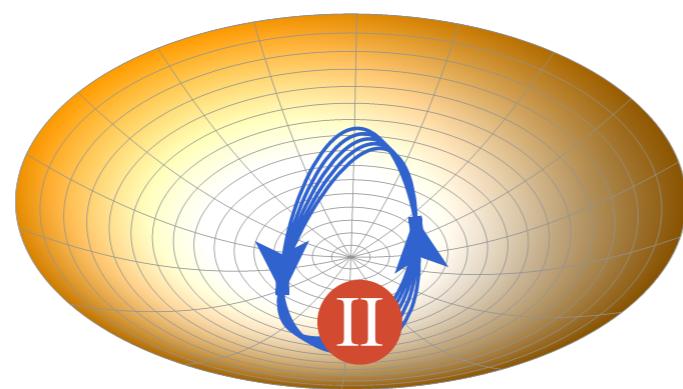
Field Evolution #1

At $3H \sim m_r$:



$U(1)$ -conserved part \Rightarrow **radial** motion
 $U(1)$ -breaking part \Rightarrow **angular** motion

At $3H \lesssim m_r$:

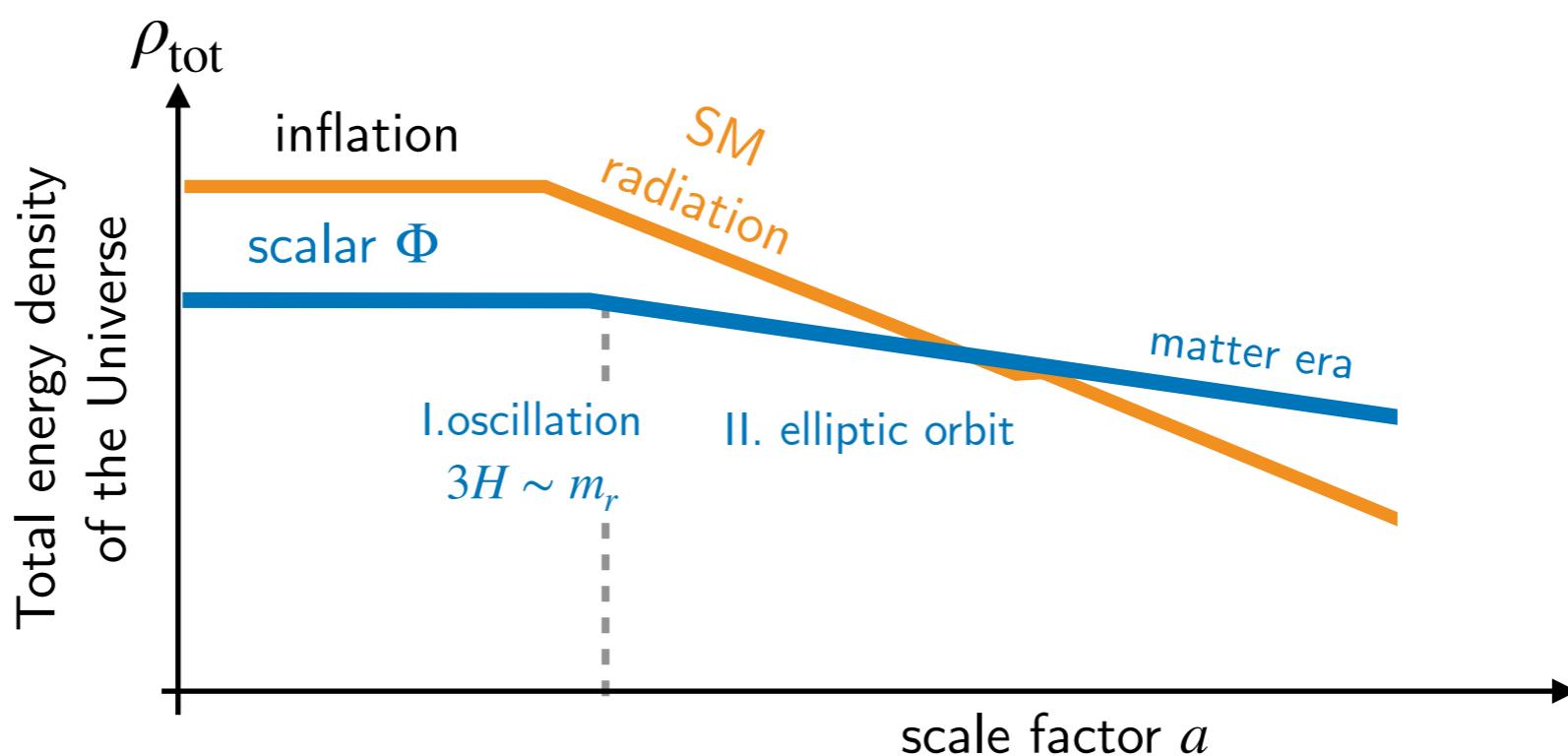


Elliptic orbit with size
 $\phi \sim a^{-3/2}$ (quadratic potential)
 $(\phi \propto a^{-6/(2+n)} \text{ for } V \propto \phi^n \propto a^{-6n/(2+n)})$

Scalar Φ behaves as matter ($\rho \propto \phi^2 \propto a^{-3}$). Allowing Φ -domination

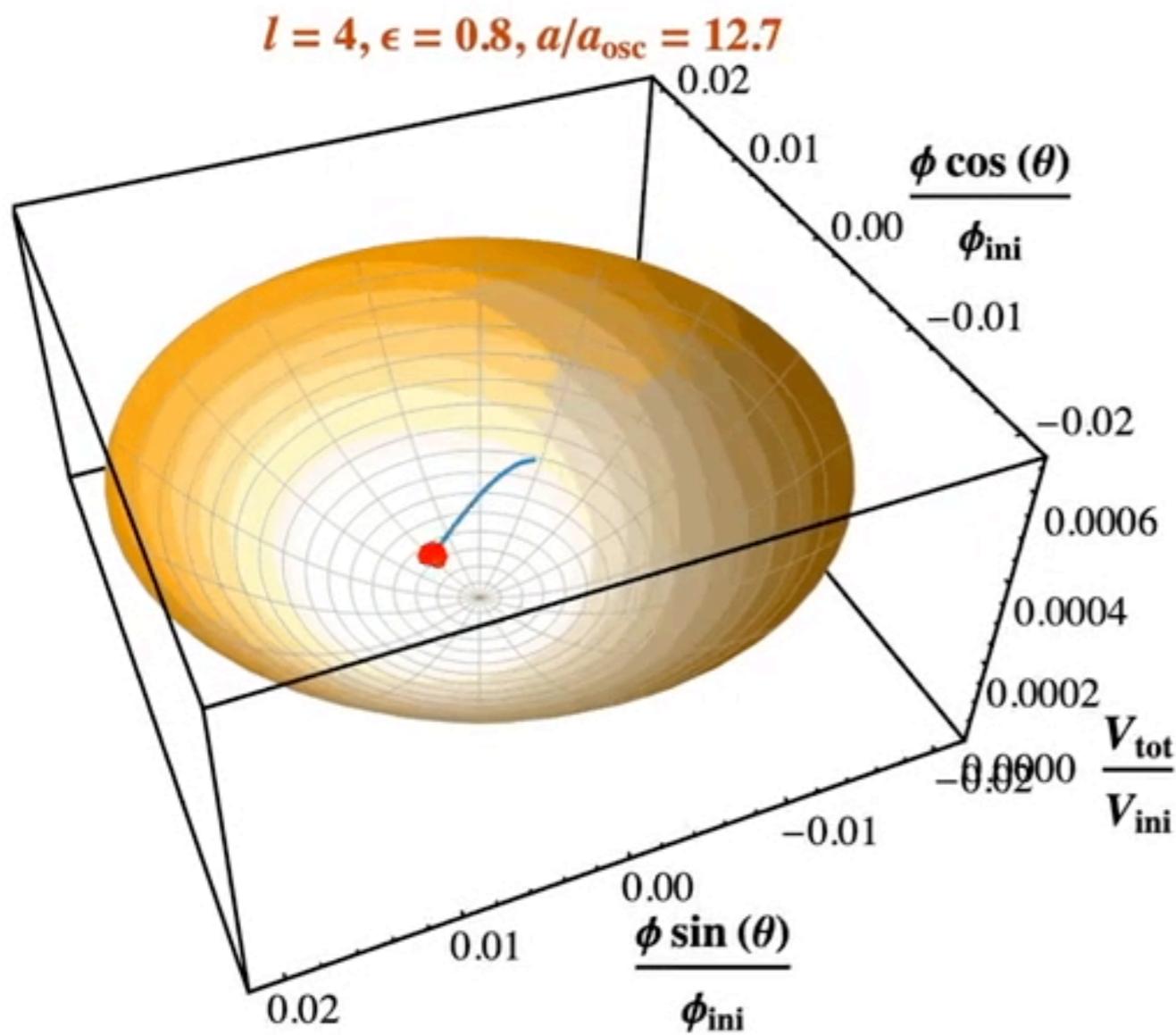
Later,
 $U(1)$ symmetry restores.
 Conserved charge:

$$\frac{d}{dt}(a^3 \phi^2 \dot{\theta}) = 0 \text{ & } \langle \dot{\theta} \rangle \simeq \sqrt{V'/\phi} \simeq m_r$$

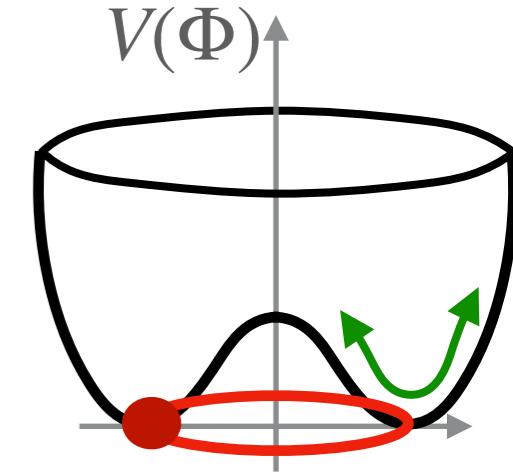


Ingredients 4: radial damping

Elliptic orbit
(matter-domination)



Radial oscillation **over-closes** the universe.



Radial motion must be **damped**, while the **rotation remains**.

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

Friction of oscillation \sim interaction rate of ϕ

[Abbott, Farhi, Wise 1982]

Scalar Φ orbit becomes circle ($H \sim \Gamma$), behaves as matter for $\phi > f_a$.

i.e. $\rho_{\text{kinetic}} = \rho_{\text{potential}}$

balance between the centrifugal force and potential gradient.

Damping scenarios

Scenario I (non-thermal): e.g. parametric resonance extracts energy from zero-mode
 Damping happens fast after oscillation. (Completely damped? Further study)



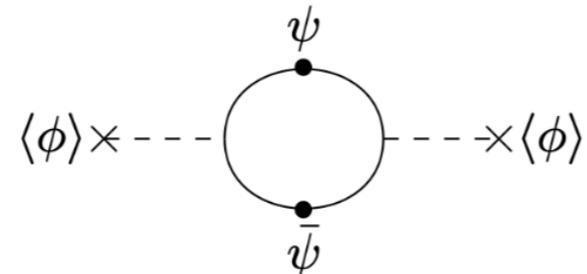
Thermal damping: $\mathcal{L} \supset y_\psi \phi \psi^\dagger_L \psi_R + h.c. + g \bar{\psi} \gamma^\mu \psi A_\mu$

e.g. [Abbott, Farhi, Wise 1982]
 [Mukaida, Nakayama, 2012]

Relativistic fermion @ oscillation ($y_\psi \phi \lesssim T$)

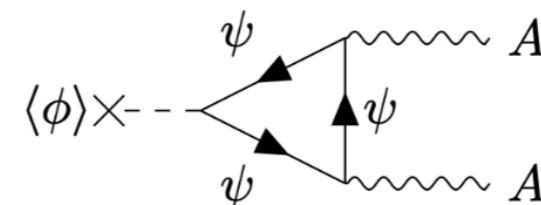
$$\Gamma \sim y_\psi^2 \alpha T$$

$$V_{\text{th}}(\phi) \sim y_\psi^2 \phi^2 T^2$$



(if $m_r > m_\psi$, damping by the direct decay $\Gamma \sim y_\psi^2 m_r$ instead.)

Non-relativistic fermion @ oscillation ($y_\psi \phi \gtrsim T$)



$$\Gamma \sim \alpha^2 T^3 / \phi^2$$

$$V_{\text{th}}(\phi) \sim \alpha^2 T^4 \ln\left(\frac{y_\psi^2 \phi^2}{T^2}\right)$$

Scenario II: relativistic fermion @ oscillation \Rightarrow *too large thermal mass*

Axion rotation is suppressed and kination era is absent.



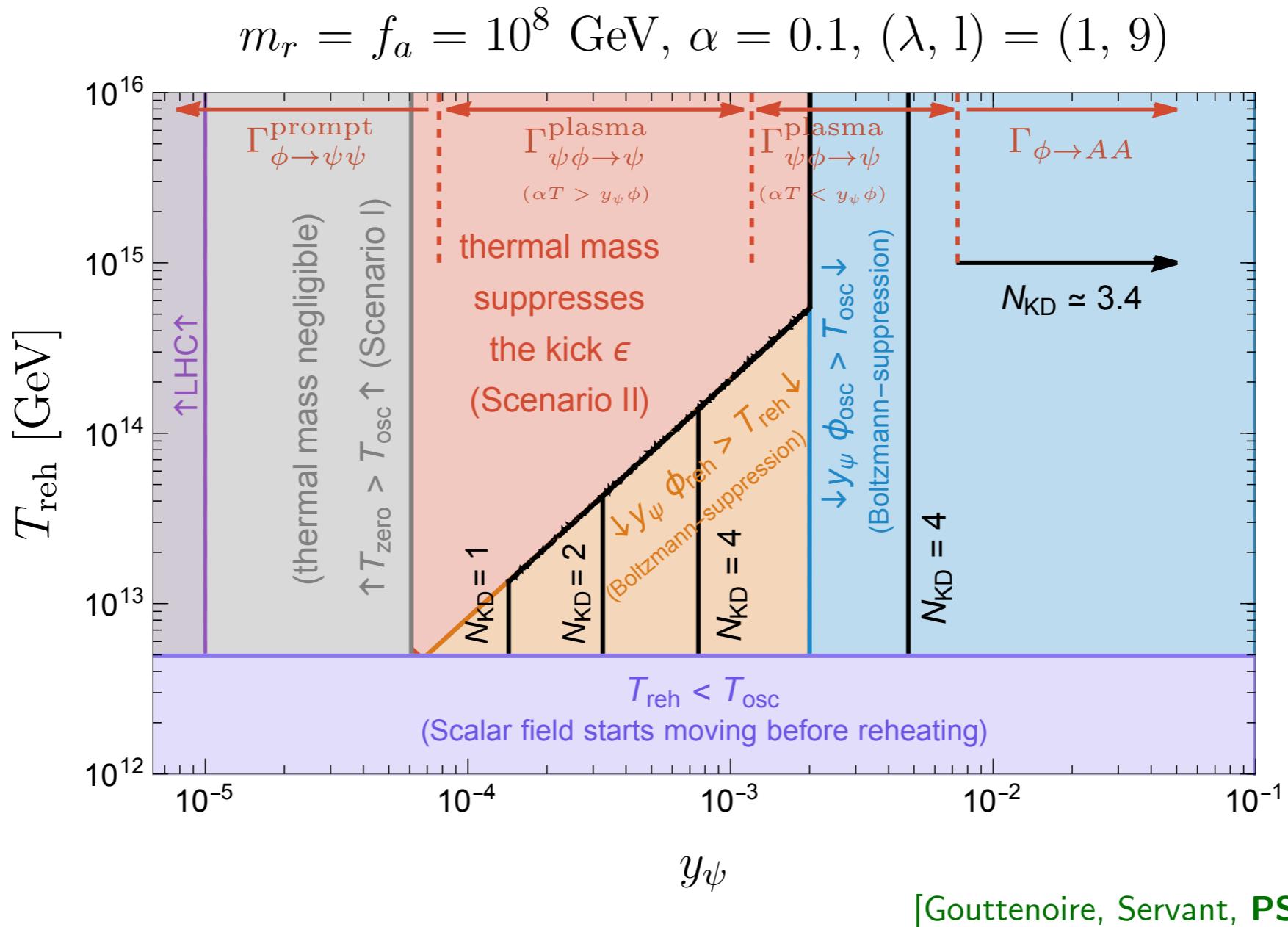
Scenario III: non-relativistic fermions @ oscillation

Thermal correction can be *smaller* than the zero-T potential.

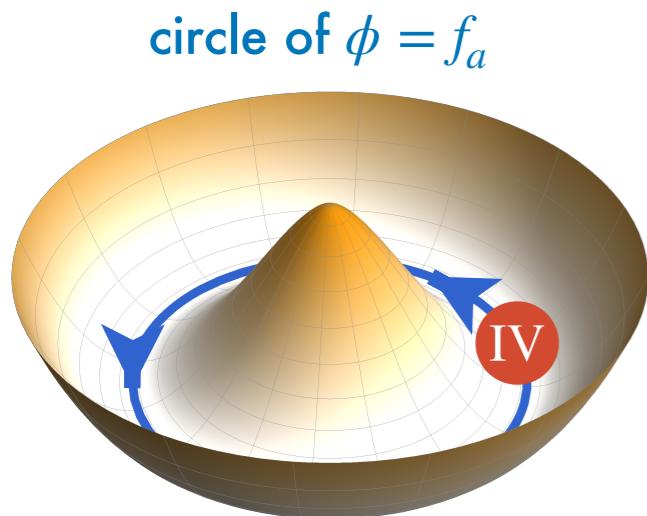
Realized by having large y_ψ or lowering T_{reh}



Thermal damping: $\mathcal{L} \supset y_\psi \phi \psi_L^\dagger \psi_R + h.c. + g \bar{\psi} \gamma^\mu \psi A_\mu$



Field Evolution #2: approaching minimum



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

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

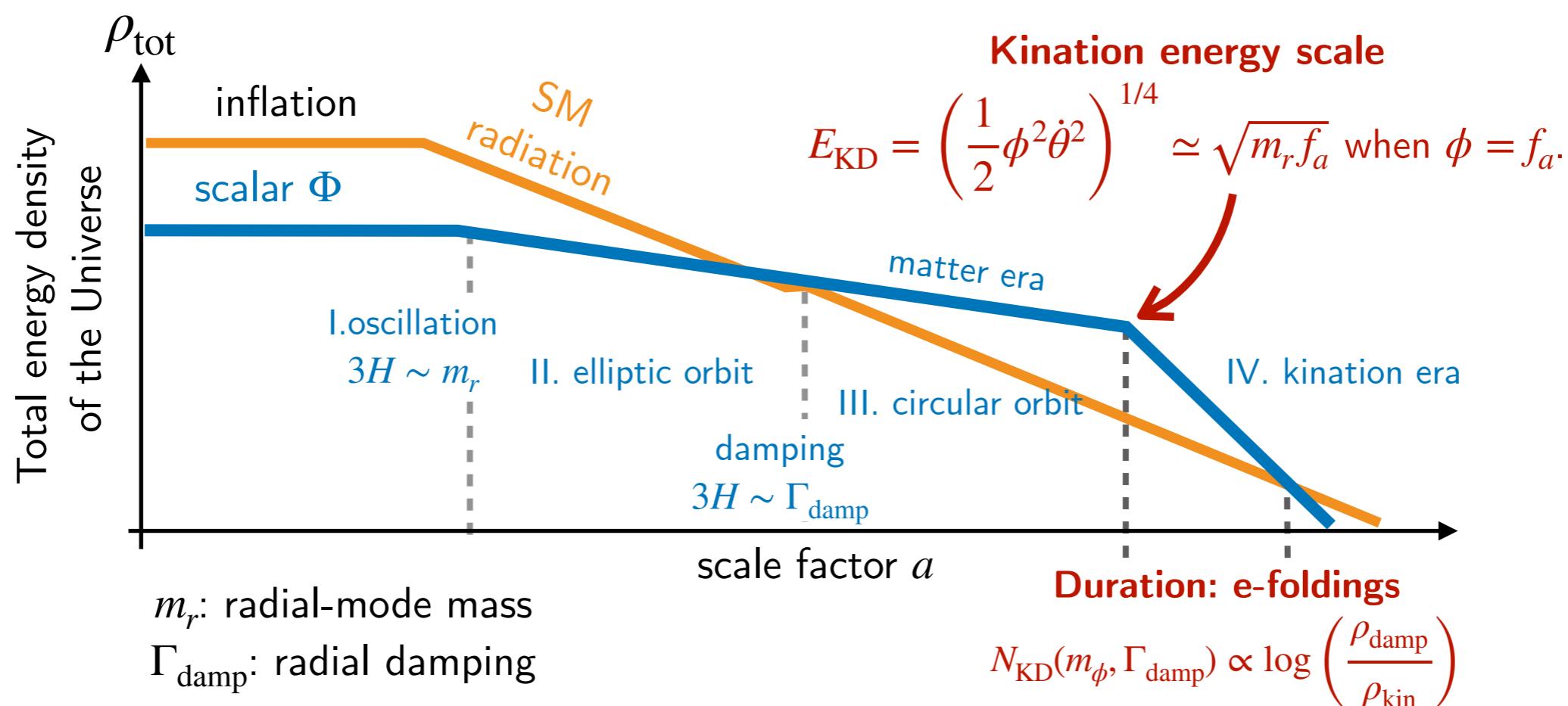
The conserved $U(1)$ -charge is

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

Kinetic energy dominates

$$\rho_\Phi = E_{\text{KD}}^4 \propto \dot{\theta}^2 \propto a^{-6}$$

and behaves as **kination**.



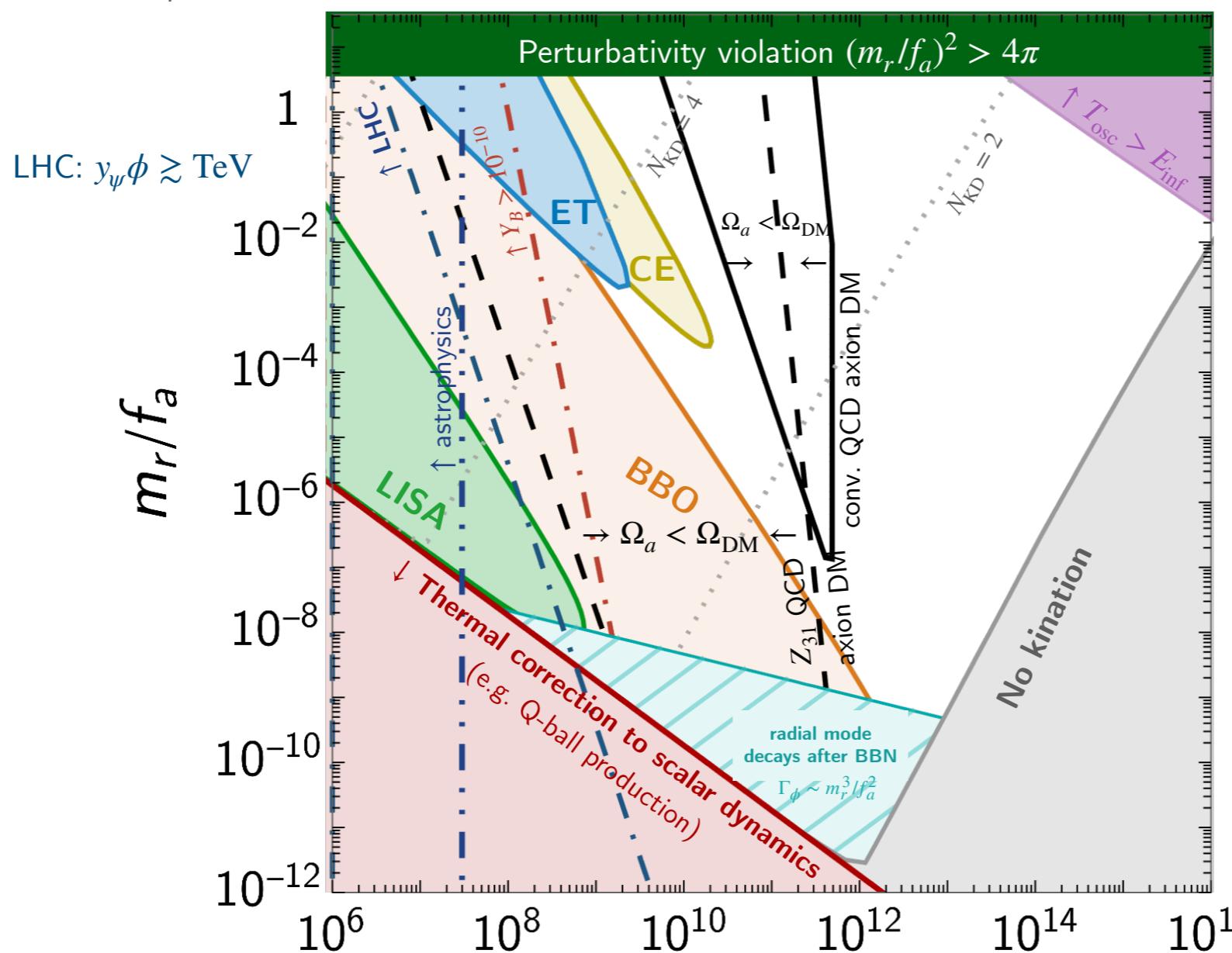
Detectability of GW peak from kination

Radial mode mass m_r
controls axion speed $\dot{\theta}$.

$$\dot{\theta} = \sqrt{V'/\phi} \simeq m_r$$

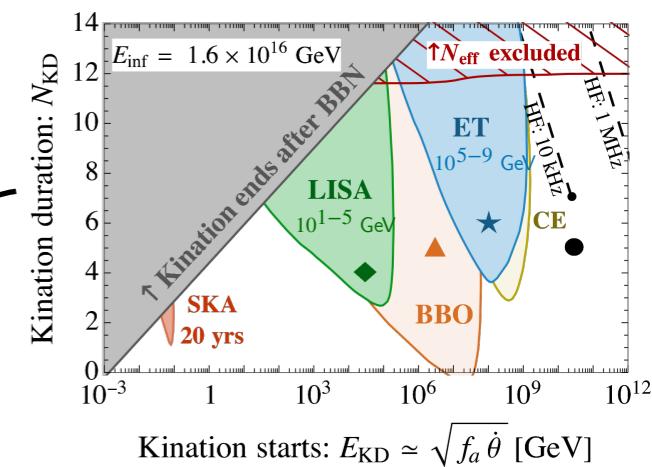
In terms of model parameters

$$E_{\text{KD}} = \sqrt{\dot{\theta} f_a} = \sqrt{m_r f_a}, \exp(N_{\text{KD}}) = \frac{\phi_{\text{ini}}^{4/3}(m_r, f_a)}{M_{\text{Pl}} f_a^{1/3}}$$



$$l = 12, \lambda = 1 \quad f_a \text{ [GeV]}$$

Gouttenoire, Servant, **PS**, 2108.10328, 2111.01150



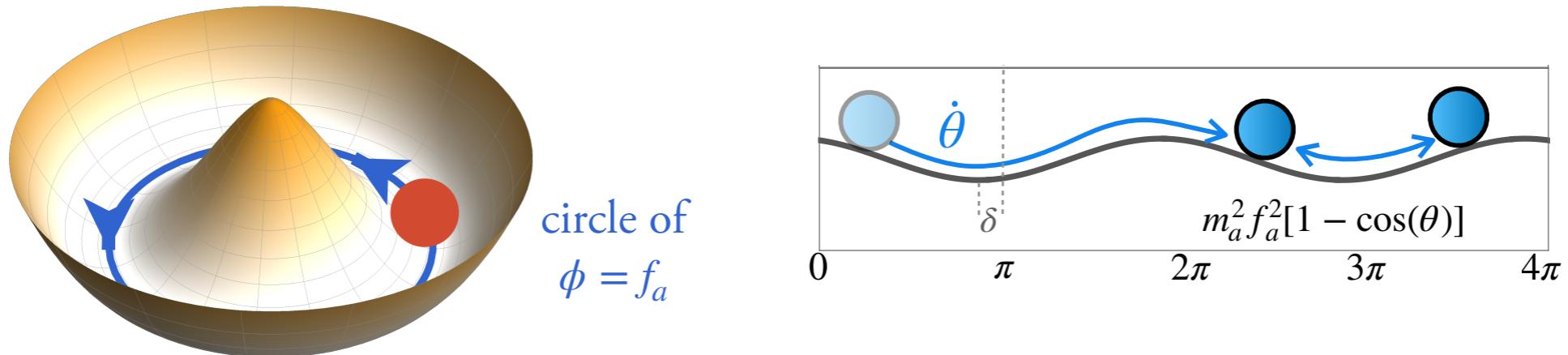
complex scalar field
oscillates before reheating.

Thermal damping scenario

$y_\psi = y_{\psi,\text{best}}$
i.e. N_{KD} is maximized,
no entropy injection from damping.

**GW signature
associated to axion dark matter
from the axion kination.**

Axion Dark Matter



After QCD scale, the fast-spinning axion still skips the potential barrier and the axion oscillation is delayed ($H_a^{\text{osc}} \ll m_a$).

Kinetic energy red-shifts $\dot{\theta}^2 f_a^2 \propto a^{-6}$ until $\dot{\theta} \simeq m_a$.

Peccei-Quinn 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]
[Erönçel, Sato, Servant, Sørensen, 2206.14259]

$$\left. \frac{n_a}{s} \right|_0 \simeq \left. \frac{n_\theta}{s} \right|_{\text{KD}} \equiv \frac{f_a^2 \dot{\theta}_{\text{KD}}}{s_{\text{KD}}} \simeq \frac{f_a}{E_{\text{KD}}} e^{3N_{\text{KD}}/2}$$

Gravitational waves and axion dark matter.

via kinetic misalignment & axion fragmentation

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

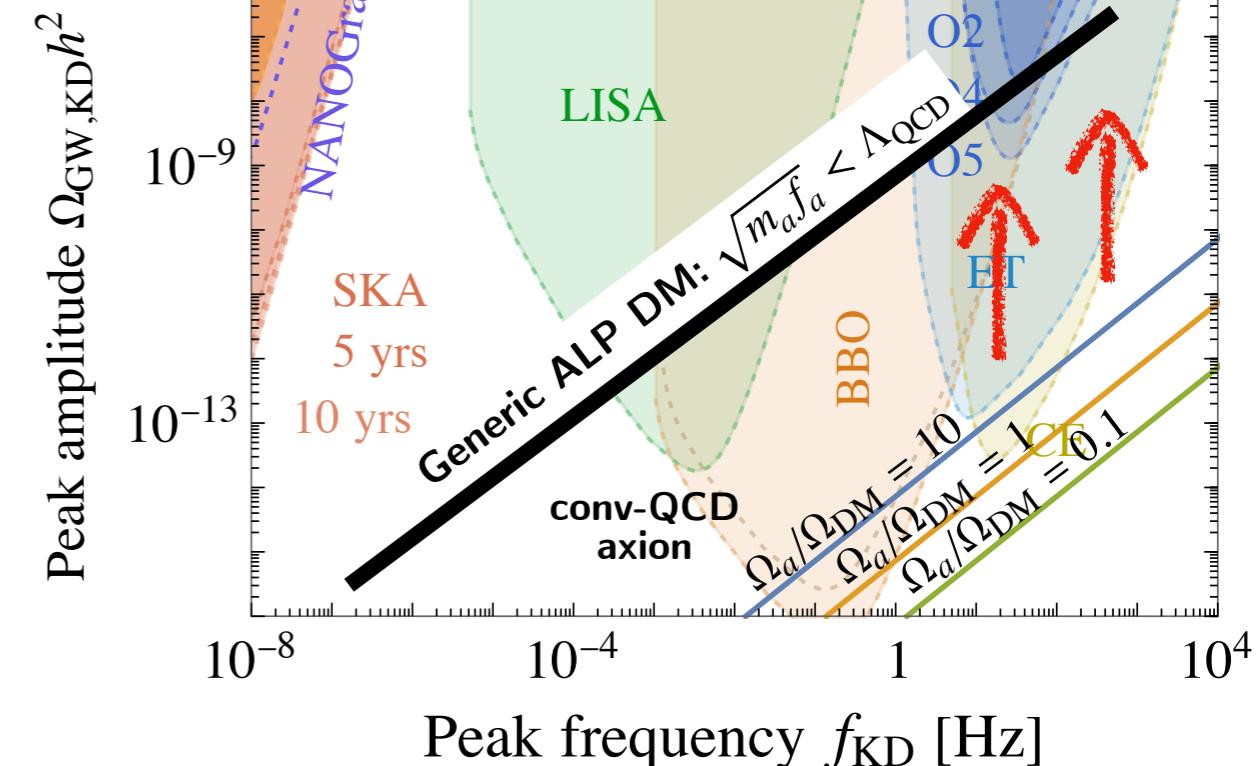
[Fonseca, Morgante, Sato, Servant, '19]
[Eröncel, Sato, Servant, Sørensen, soon!]

$$Y_a = \frac{n_a}{s} \Big|_0 \approx \frac{f_a^2 \dot{\theta}}{s_{\text{KD}}} \approx \frac{f_a}{E_{\text{KD}}} e^{3N_{\text{KD}}/2}$$

GW peak & axion DM abundance

$$f_{\text{peak}} \approx 21 \text{ Hz} \left(\frac{\text{GeV}}{\sqrt{m_a f_a}} \right)^{2/3} \left(\frac{E_{\text{KD}}}{10^9 \text{ GeV}} \right)^{4/3} \left(\frac{\Omega_{a,0}}{\Omega_{\text{DM},0}} \right)^{1/3}$$

$$\Omega_{\text{peak}} h^2 \approx 10^{-18} \left(\frac{f_{\text{peak}}}{\text{Hz}} \right) \left(\frac{E_{\text{inf}}}{10^{16} \text{ GeV}} \right)^4 \left(\frac{\text{GeV}}{\sqrt{m_a f_a}} \right) \left(\frac{\Omega_{a,0}}{\Omega_{\text{DM},0}} \right)$$



The conventional QCD axion DM cannot be observed at planned experiments, except BBO and require ultra-high frequency GW experiments.

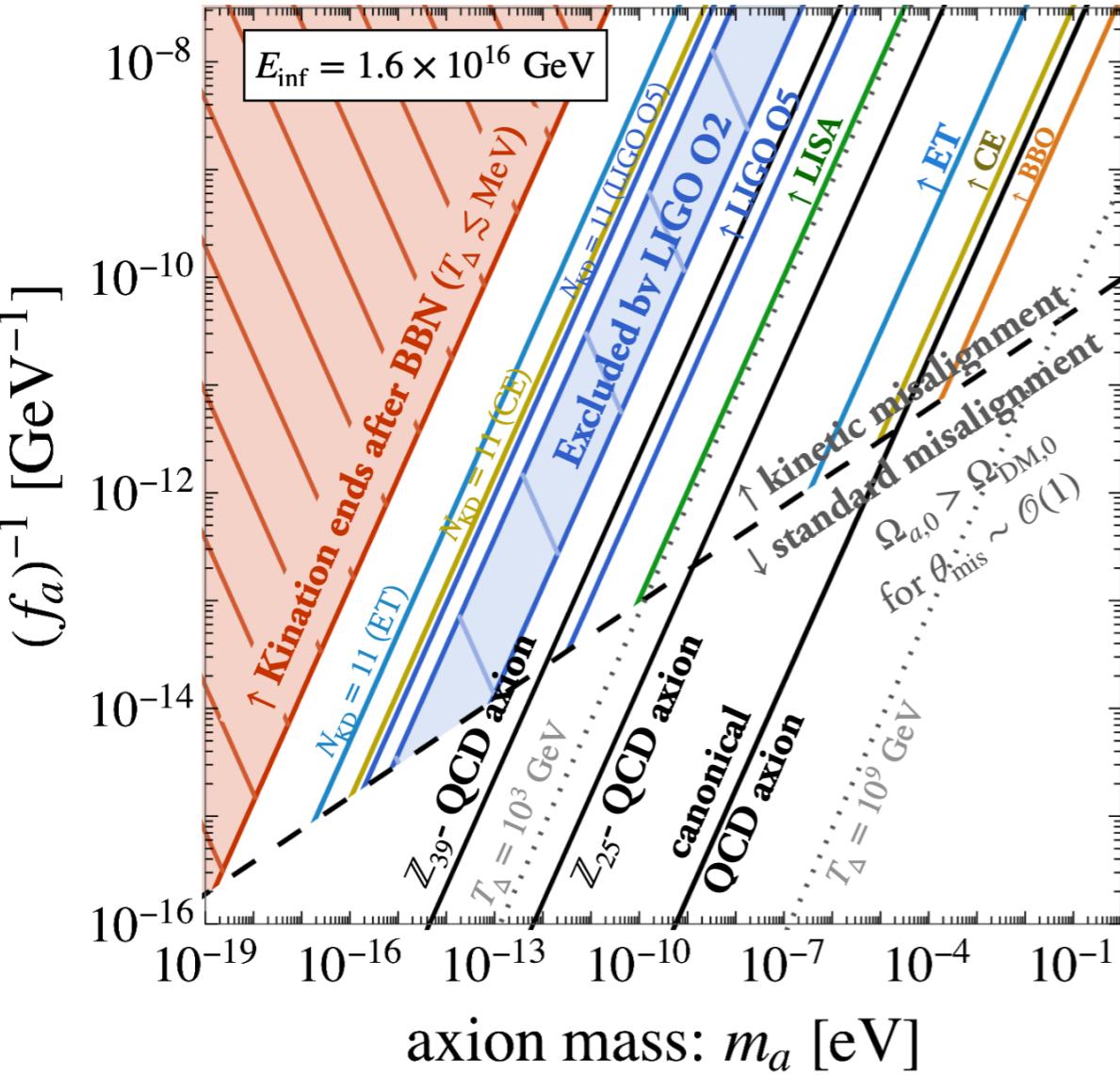
Observable signals for generic ALP DM and QCD axion DM with lighter mass, e.g., the \mathbb{Z}_N -axion.

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

Gravitational waves and axion dark matter.

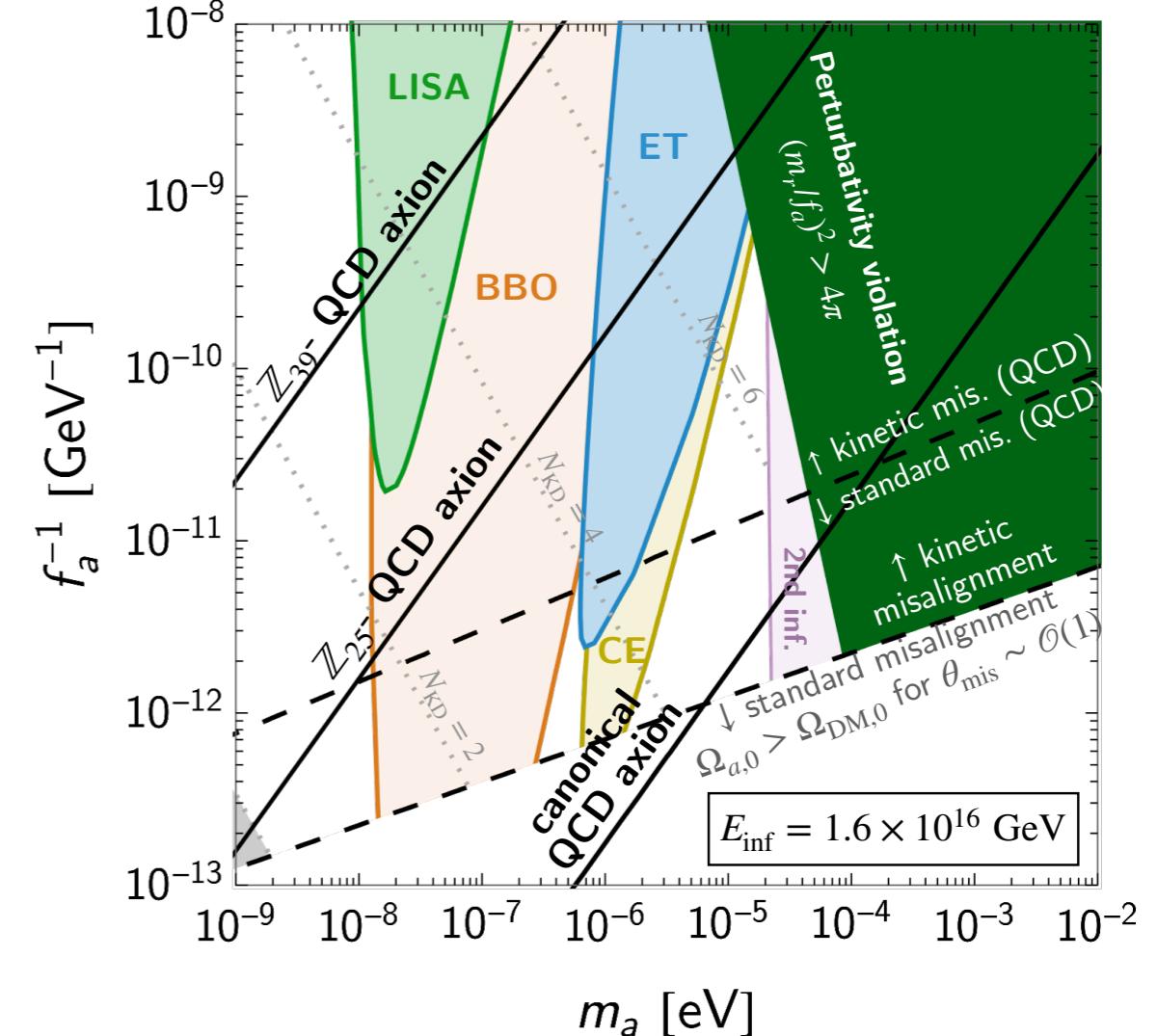
Model Independent

$$\Omega_{a,0} \simeq \Omega_{\text{DM},0}$$



Model dependent

$$l = 12, \lambda = 10^{-8}, \Omega_{a,0} = \Omega_{\text{DM},0}$$



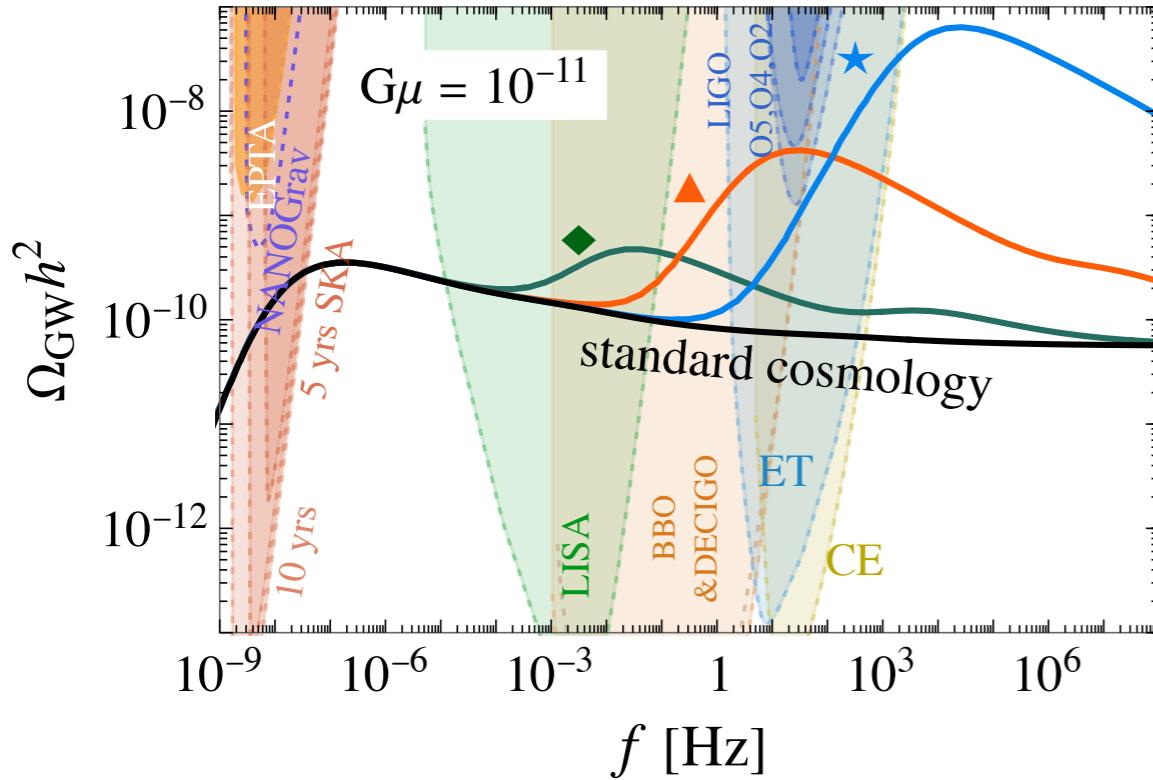
Gouttenoire, Servant, PS
[2111.01150]

Preliminary

Impact of axion kination on GW from cosmic-strings.

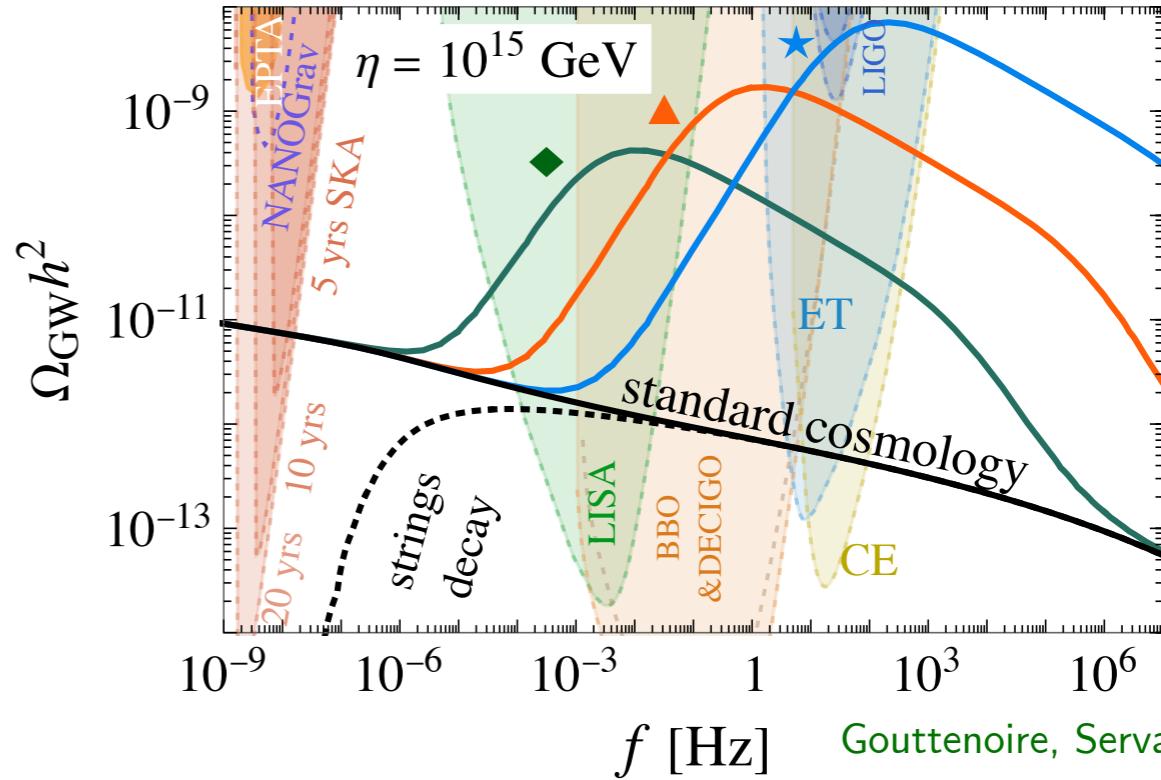
Local cosmic strings

symmetry breaking scale $\simeq M_{\text{pl}} \sqrt{G\mu}$



Global cosmic strings

symmetry breaking scale $\simeq \eta$



Gouttenoire, Servant, PS,
2111.01150

Frequency of GW peak

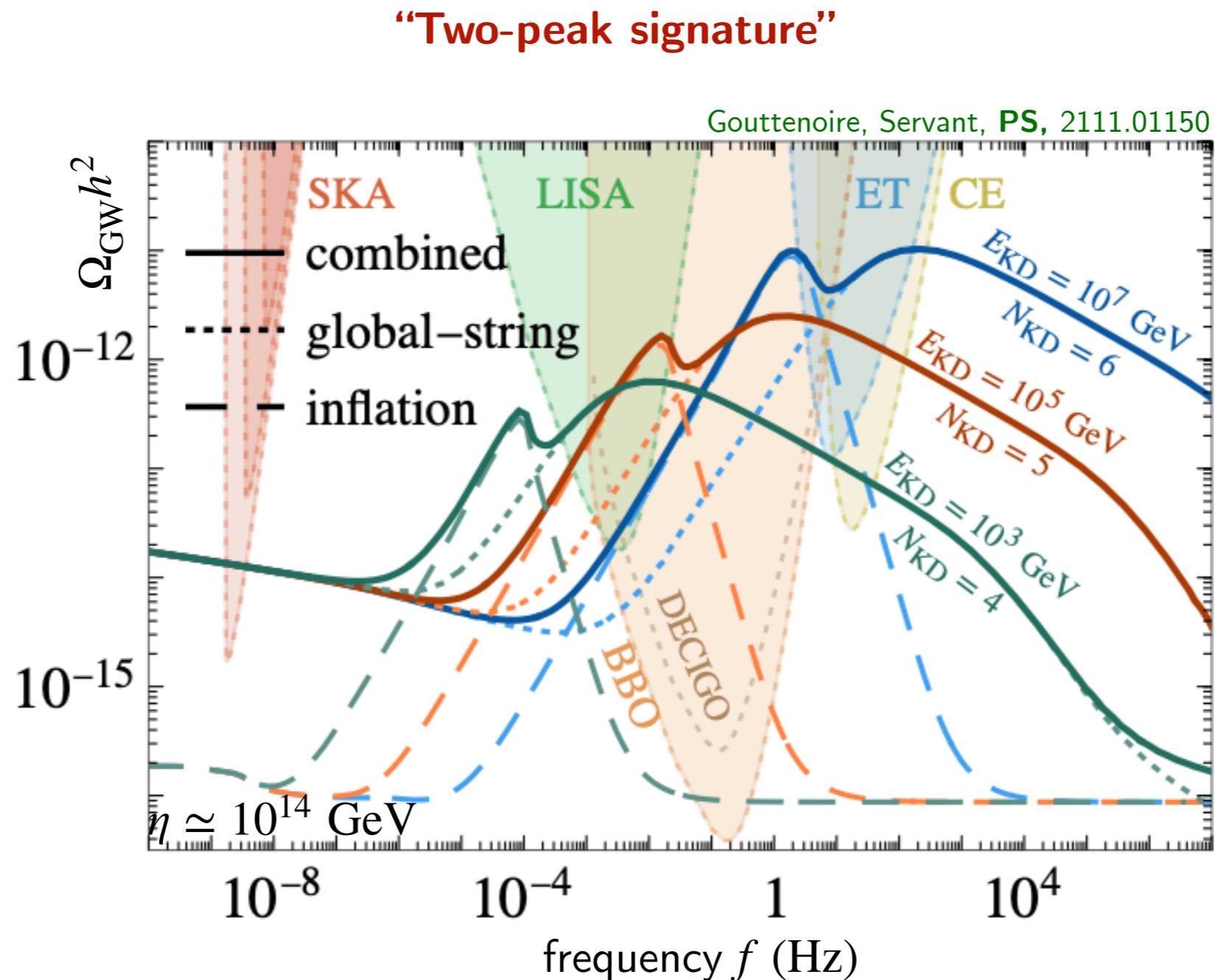
$$f_{\text{KD}} \simeq \begin{cases} (1.8 \times 10^3 \text{ Hz}) \left(\frac{0.1 \times 50 \times 10^{-11}}{\alpha \Gamma G\mu} \right)^{1/2} \left(\frac{E_{\text{KD}}}{10^5 \text{ GeV}} \right) \\ (6.1 \times 10^2 \text{ Hz}) \left(\frac{0.1}{\alpha} \right)^{2/3} \left(\frac{50 \times 10^{-11}}{\Gamma G\mu} \right)^{1/3} \left(\frac{E_{\text{KD}}}{10^5 \text{ GeV}} \right) \left[\frac{\exp(N_{\text{KD}}/2)}{10} \right] \end{cases}$$

for $N_{\text{KD}} < \frac{1}{3} \log \left(\frac{\alpha}{2\Gamma G\mu} \right)$,

for $N_{\text{KD}} > \frac{1}{3} \log \left(\frac{\alpha}{2\Gamma G\mu} \right)$.

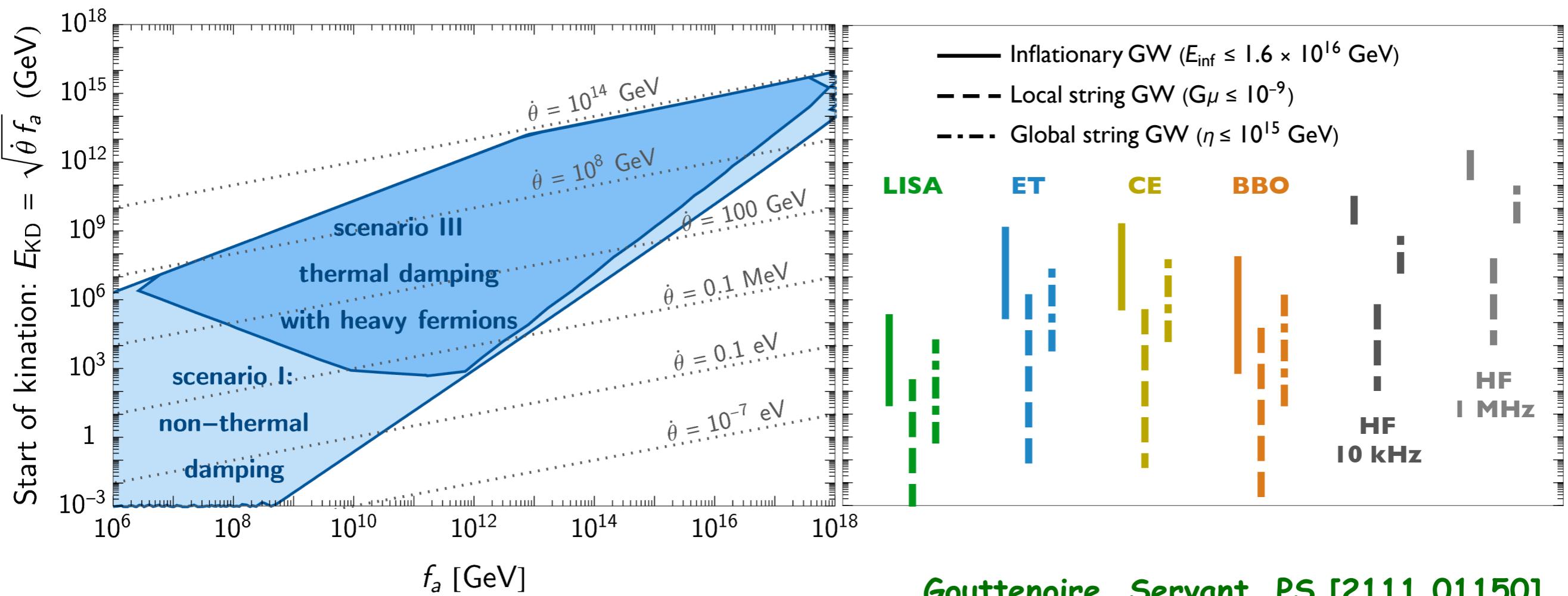
$$f_{\text{KD}} \simeq (0.9 \text{ Hz}) \left(\frac{0.1}{\alpha} \right) \left(\frac{E_{\text{KD}}}{10^5 \text{ GeV}} \right) \left[\frac{\exp(N_{\text{KD}}/2)}{10} \right]$$

GW from inflation + global cosmic strings



Fixed peak separation: $f_{\text{inf}}/f_{\text{glob}} = \mathcal{O}(10^{-2})$
[for loops' size: $(0.1)H^{-1}$]

GW probes of the axion kination



Conclusion

Primordial GW is **enhanced** by
“Kination” — the kinetic energy of scalar field dominates the Universe.

A small period of **matter-kination** inside radiation era leads to
an observable “**GW peak**”, \propto energy scale and duration of kination.

$$\text{LISA for } E_{\text{KD}} \sim \begin{cases} 10^{1-5} \text{ GeV, (inflation)} \\ 10^{(-3)-3} \text{ GeV, (local strings)} \\ 10^{0-4} \text{ GeV, (global strings)} \end{cases} \mid \text{ET \& CE for } E_{\text{KD}} \sim \begin{cases} 10^{6-9} \text{ GeV, (inflation)} \\ 10^{(-1)-6} \text{ GeV, (local strings).} \\ 10^{4-7} \text{ GeV, (global strings)} \end{cases}$$

A rotating axion (or angular mode of some complex-scalar field)
can generate a matter-kination era.

e.g. “Affleck-Dine Axiogenesis” [Co, Harigaya ’19]

Primordial GWs as probes of axion physics

No observable for standard QCD axion DM, except BBO and HF experiments.
GW peak is observable for generic ALP DM.

Axion Fragmentation

also leads to another interesting signature
e.g. miniclusters (Eröncel, Servant, et. al. 2206.14259 & 2207.10111)

Thank you!