Selected highlights in axion cosmology .

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CLUSTER OF EXCELLENCE
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This talk

Three distinct topics:

—1— From the "usual" axion to rotating axions :
beyond the standard misalignment mechanism

[Eroncel, Soerensen, Sato, Servant, 2206.14259
[Eroncel, Servant 2207.10111
[Gouttenoire, Servant, Simakachorn, 2111.01150

—2— The "relaxion" : when axion & Higgs cosmologies meet

[Chatrchyan, Servant, 2210.01148 & 2211.15694

— 3— Gravitational-wave signatures of axion cosmology

[Gouttenoire, Servant, Simakachorn, 2108.10328 & 2111.01150
[Gouttenoire, Servant, Simakachorn,
[Servant, Simakachorn, 2307.03121

Axions

Among the most hunted particles.

Axions = Pseudo- Nambu Goldstone bosons (PNGBs) from spontaneous breaking of global symmetry which is not exact but broken weakly.

Axion mass is proportional to this breaking.

Very general context.

Historically: QCD axion. Strong dynamics from QCD provides breaking of symmetry.

Axion-like-particles (ALPs): other axions whose mass is not affected by QCD. They get their mass from other sources.

Ubiquitous in many extensions of the Standard Model (in particular in string theory)

References on axions

Some recent references for reviews

-TASI Lectures on the Strong CP Problem and Axions,
Anson Hook, https://arxiv.org/abs/1812.02669

- ICTP summer school 2015, 3 lectures by Surjeet Rajendran
http://indico.ictp.it/event/a14276/session/27/contribution/110/material/slides/0.pdf
http://indico.ictp.it/event/a14276/session/28/contribution/115/material/slides/0.pdf
http://indico.ictp.it/event/a14276/session/29/contribution/119/material/slides/0.pdf

- 2015 GGI lectures by G. Villadoro:
https://www.ggi.infn.it/ggilectures/ggilectures2015/program.html
https://www.youtube.com/watch?v=Bpund1fndCg&list=PLDxsZU4NC6Z4kL18PhWTeHicRP13OfHYI&index=1

-Review "The landscape of QCD axion models", Di Luzio et al.
https://arxiv.org/pdf/2003.01100.pdf

- **Review by Redondo and Irastorza**
  "New experimental approaches in the search for axion-like particles"
  https://arxiv.org/pdf/1801.08127.pdf

- A. Pich on chiral perturbation theory:
https://arxiv.org/pdf/hep-ph/9502366.pdf
(useful to compute the scalar potential as a function of theta angle)

Axion-Like-Particles (ALPs).

Consider complex scalar field

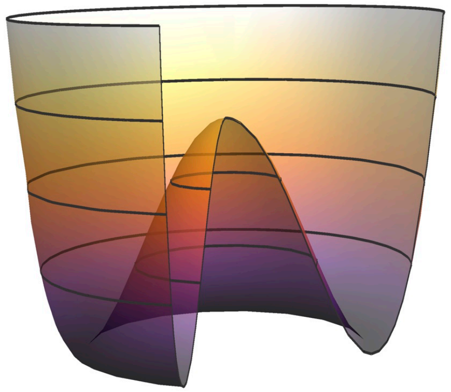
$$\Phi = \phi e^{i\theta}$$

charged under anomalous U(1) global symmmetry (Peccei-Quinn symmetry)

Spontaneously broken at scale f_a

$$V(\varphi) = \lambda \left(|\varphi|^2 - \frac{f_a^2}{2} \right)^2$$

$$\langle \boldsymbol{\varphi} \rangle = f_a / \sqrt{2}$$



Axion as Goldstone boson

$$\theta \to \theta + \text{const.}$$

$$\boxed{\theta = a / f_a}$$

ALPs.

Non-perturbative effects at energy Λ_b << f_a break the shift symmetry and generate a potential/mass for the axion

$$V = m_a^2(T) f_a^2 \left[1 - \cos(\theta)\right]$$

$$m_a = \Lambda_b^2 / f_a$$

QCD axion

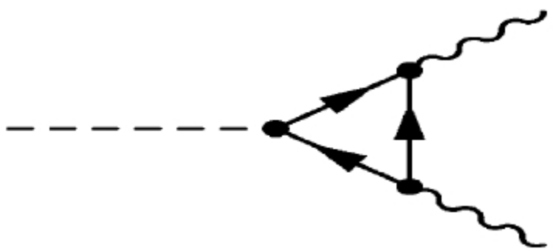
$$m_a^2 f_a^2 \approx (76\ \mathrm{MeV})^4$$

Generic ALP

m_a and f_a : free parameters

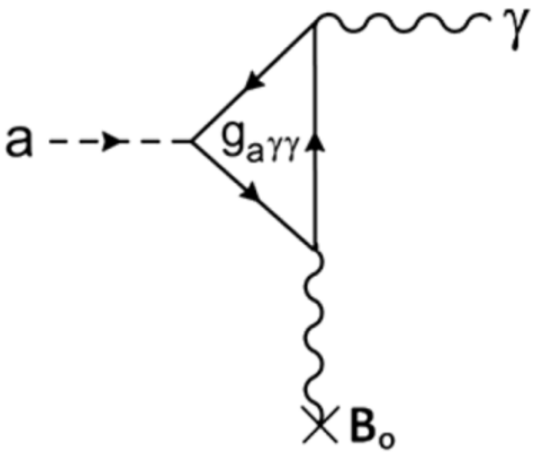
The hunt for axions.

Mainly through Axion-photon coupling



$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

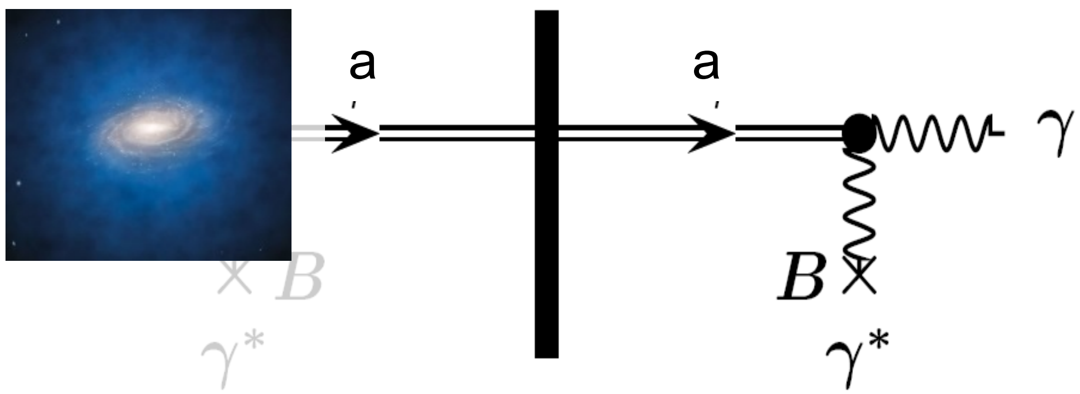
In a background magnetic field:
axion<->photon conversion



If long-lived: Dark Matter candidate

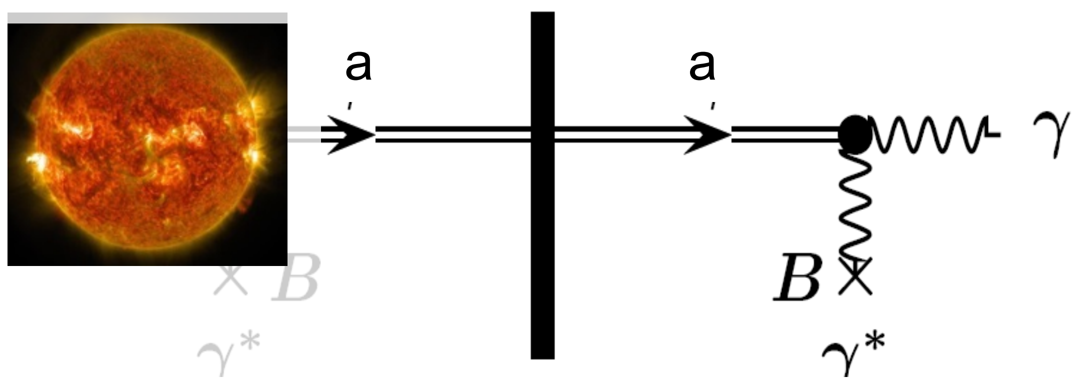
Three main ways to search for ALPs.

All rely on ALP-photon mixing in magnetic field

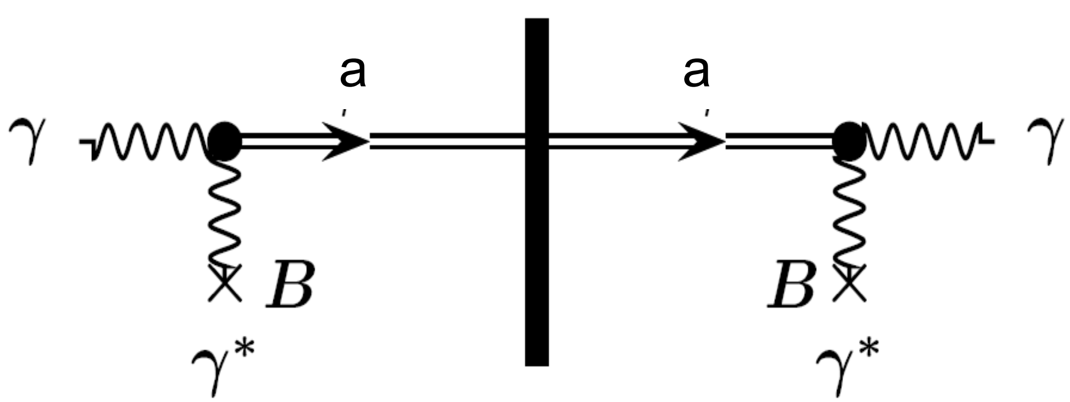


Haloscopes

looking for dark matter constituents, microwaves



Helioscopes
Axions emitted by the sun, X-rays



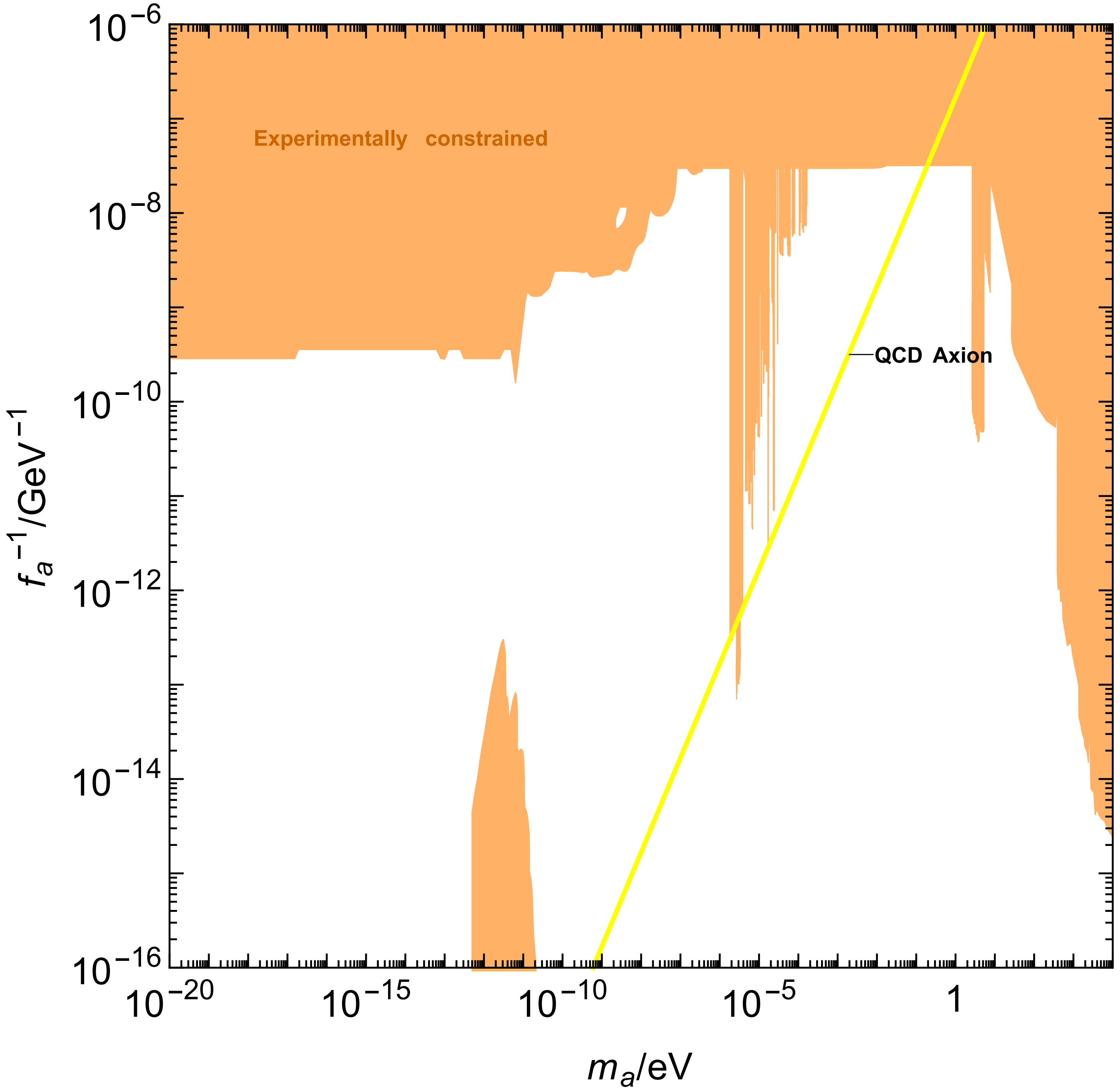
Purely laboratory experiments

“light-shining-through-walls”,

microwaves, optical photons

The Axion-Like-Particle (ALP) parameter space.

If axions are given an interaction to photons then a long list of constraints from ALP searches apply



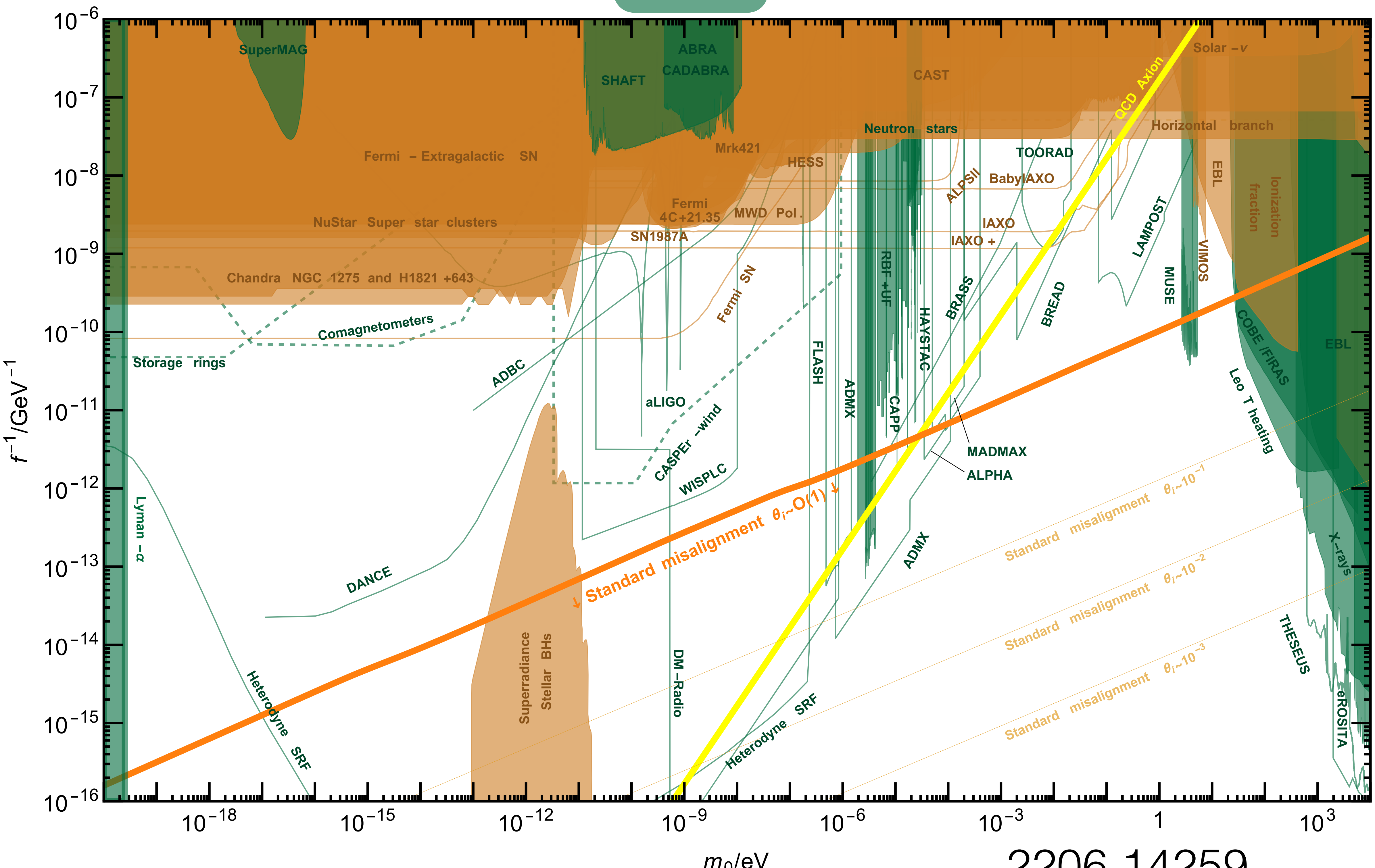
$$\frac{f_\gamma}{f_a} \approx 0.5 \times 10^3$$

assuming KSVZ-like coupling

The hunt for axions.

Any ALP

Only DM



2206.14259

A whole set of experiment constraints.

All data can be found here:

C. O'Hare, *cajohare/axionlimits: Axionlimits*, https://cajohare.github.io/AxionLimits/ (2020) [10.5281/zenodo.3932430].

All experiments also listed in tables 1 and 2 of 2206.14259:

Experiment:	Principle	DM?	Ref.
Haloscope constraints			
ABRACADABRA-10cm	Haloscope	DM	[76]
ADMX	Haloscope	DM	[77–83]
BASE	Haloscope (Cryogenic Penning Trap)	DM	[84]
CAPP	Haloscope	DM	[85–87]
CAST-RADES	Haloscope	DM	[88]
DANCE	Haloscope (Optical cavity polarization)	DM	[89]
Grenoble Haloscope	Haloscope	DM	[90]
HAYSTAC	Haloscope	DM	[91, 92]
ORGAN	Haloscope	DM	[93]
QUAX	Haloscope	DM	[94, 95]
RBF	Haloscope	DM	[96]
SHAFT	Haloscope	DM	[97]
SuperMAG	Haloscope (Using terrestrial magnetic field)	DM	[98]
UF	Haloscope	DM	[99]
Upload	Haloscope	DM	[100]
Haloscope projections			
ABDC	Haloscope	DM	[101]
ADMX	Haloscope	DM	[102]
aLIGO	Haloscope	DM	[103]
ALPHA	Haloscope (Plasma haloscope)	DM	[104]
BRASS	Haloscope	DM	[105]
BREAD	Haloscope (Parabolic reflector)	DM	[106]
DANCE	Haloscope (Optical cavity polarization)	DM	[107]
DMRadio	Haloscope (All stages: 50L, m^3 and GUT)	DM	[108, 109]
FLASH	Haloscope (Formerly KLASH)	DM	[110, 111]
Heterodyne SRF	Haloscope (Superconduct. Resonant Freq.)	DM	[112, 113]
LAMPOST	Haloscope (Dielectric)	DM	[114]
MADMAX	Haloscope (Dielectric)	DM	[115]
ORGAN	Haloscope	DM	[93]
QUAX	Haloscope	DM	[116]
TOORAD	Haloscope (Topological anti-ferromagnets)	DM	[117, 118]
WISPLC	Haloscope (Tunable LC circuit)	DM	[119]
LSW and optics			
ALPS	Light-shining-through wall	Any	[120]
ALPS II	Light-shining-through wall (projection)	Any	[121]
CROWS	Light-shining-through wall (microwave)	Any	[122]
OSQAR	Light-shining-through wall	Any	[123]
PVLAS	Vacuum magnetic birefringence	Any	[124]
Helioscopes			
CAST	Helioscope	Any	[125, 126]
babyIAXO	Helioscope (projection)	Any	[1, 127, 128]
IAXO	Helioscope (projection)	Any	[1, 127, 128]
IAXO+	Helioscope (projection)	Any	[1, 127, 128]

Table 1. List of experimental searches for axions and ALPs. The table is continued in table 2. All experiments here rely on the axion-photon coupling.

Experiment:	Principle	DM?	Reference
Astrophysical constraints			
4C+21.35	Photon-ALP oscillation on the γ-rays from blazars	Any	[129]
Breakthough Listen	ALP $\to$ radio γ in neutron star magn. fields	DM	[130]
Bullet Cluster	Radio signal from ALP DM decay	DM	[131]
Chandra	AGN X-ray prod. in cosmic magn. field	Any	[132–135]
BBN + $N_{\rm eff}$	ALP thermal relic perturbing BBN and $N_{\rm eff}$	Any	[136]
Chandra MWD	X-rays from Magnetic White Dwarf ALP prod.	Any	[137]
COBE/FIRAS	CMB spectral distortions from DM relic decay	DM	[138]
Distance ladder	ALP $\leftrightarrow \gamma$ perturbing luminosity distances	Any	[139]
Fermi-LAT	SN ALP product. $\to$ γ-rays in cosmic magn. field	Any	[140–142]
Fermi-LAT	AGN X-ray production $\to$ ALP in cosmic magn. field	Any	[143]
Haystack Telescope	ALP DM decay $\to$ microwave photons	DM	[144]
HAWC TeV Blazars	$\gamma \to$ ALP $\to \gamma$ conversion reducing γ-ray attenuation	Any	[145]
H.E.S.S.	AGN X-ray production $\to$ ALP in cosmic magn. field	Any	[146]
Horizontal branch stars	stellar metabolism and evolution	Any	[147]
LeoT dwarf galaxy	Heating of gas-rich dwarf galaxies by ALP decay	DM	[148]
Magnetic white dwarf pol.	$\gamma \to$ ALP conversion polarizing light from MWD stars	Any	[149]
MUSE	ALP DM decay $\to$ optical photons	DM	[150]
Mrk 421	Blazar γ-ray $\to$ ALP $\to$ γ-ray in cosmic magn. field	Any	[151]
NuStar	Stellar ALP production $\to \gamma$ in cosmic magn. fields	Any	[152, 153]
NuStar, Super star clusters	Stellar ALP production $\to \gamma$ in cosmic magn. fields	Any	[153]
Solar neutrinos	ALP energy loss $\to$ changes in neutrino production	Any	[154]
SN1987A ALP decay	SN ALP production $\to \gamma$ decay	Any	[155]
SN1987A gamma rays	SN ALP production $\to \gamma$ in cosmic magnetic field	Any	[156, 157]
SN1987A neutrinos	SN ALP luminosity less than neutrino flux	Any	[157, 158]
Thermal relic compilation	Decay and BBN constraints from ALP thermal relic	Any	[159]
VIMOS	Thermal relic ALP decay $\to$ optical photons	Any	[160]
White dwarf mass relation	Stellar ALP production perturbing WD metabolism	Any	[161]
XMM-Newton	Decay of ALP relic	DM	[162]
Astrophysical projections			
eROSITA	X-ray signal from ALP DM decay	DM	[163]
Fermi-LAT	SN ALP production $\to \gamma$ in cosmic magnetic field	Any	[164]
IAXO	Helioscope detection of supernova axions	Any	[165]
THESEUS	ALP DM decay $\to$ x-ray photons	DM	[166]
Neutron coupling:			
CASPEr-wind	NMR from oscillating EDM (projection)	DM	[167, 168]
CASPEr-ZULF-Comag.	NMR from oscillating EDM	DM	[168, 169]
CASPEr-ZULF-Sidechain	NMR (constraint & projection)	DM	[168, 170]
NASDUCK	ALP DM perturbing atomic spins	DM	[171]
nEDM	Spin-precession in ultracold neutrons and Hg	DM	[168, 172]
K-3He	Comagnetometer	DM	[173]
Old comagnetometers	New analysis of old comagnetometers	DM	[174]
Future comagnetometers	Comagnetometers	DM	[174]
SNO	Solar ALP flux from deuterium dissociation	Any	[175]
Proton storage ring	EDM signature from ALP DM	DM	[176]
Neutron Star Cooling	ALP production modifies cooling rate	Any	[177]
SN1987 Cooling	ALP production modifies cooling rate	Any	[178]
Coupling independent:			
Black hole spin	Superradiance for stellar mass black holes	Any	[72–74]
Lyman−α	Modification of small-scale structure	DM	[60]

Table 2. List of experimental searches for axions and ALPs.

— 1 —

Which of these axions can make Dark Matter ?

Axions from the misalignment mechanism.

Start with ALP lagrangian $\mathcal{L} = -\frac{f^2}{2} g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - V(\theta) = -\frac{f^2}{2} g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - m_a^2 f^2(1-\cos\theta).$

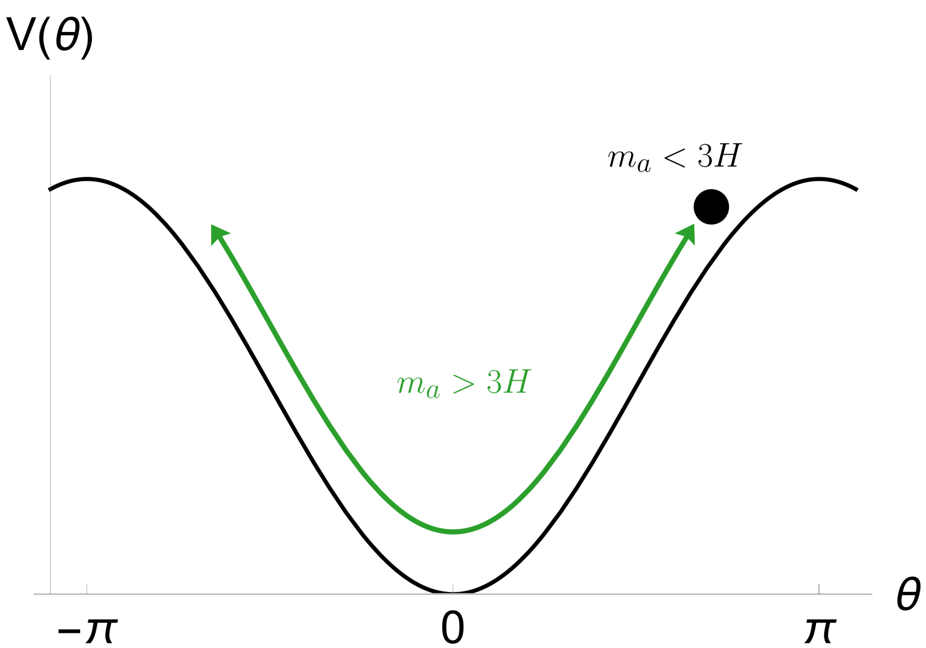
Neglecting fluctuations, the homogeneous zero-mode satisfies

$$\ddot{\Theta} + 3H\dot{\Theta} + m_a^2(T)\sin(\Theta) = 0,$$

H= $\dot{a}$/a= expansion rate of universe

(here a is the scale factor in the Friedmann-Roberston-Walker metric $ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$!)

With initial conditions: $\Theta(t_i) = \Theta_i, \quad \dot{\Theta}(t_i) = 0.$ *standard assumption*



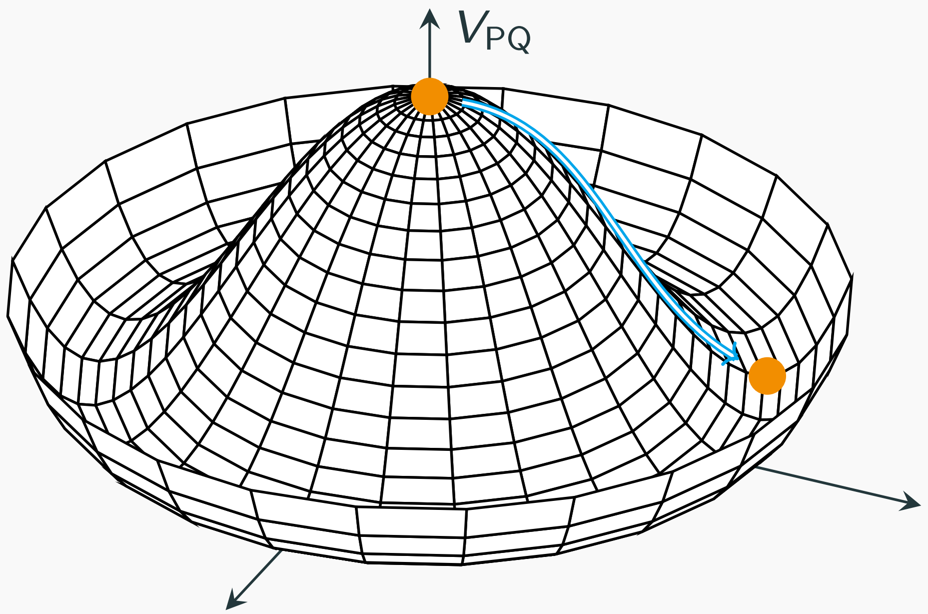
- $m_a \ll 3H \iff \rho_a \propto a^0$ (Frozen)
- $m_a \gg 3H \iff \rho_a \propto a^{-3}$ (Oscillating)

—> standard misalignment mechanism

For $\Theta_i \sim 1 \qquad \rho_{\rm DM} \sim \rho_{osc}\left(\frac{a_{osc}}{a_0}\right)^3 \sim m_a^2 f_a^2 \left(\frac{T_0}{T_{osc}}\right)^3$

$T_{osc} \sim \sqrt{m_a M_{Pl}}$

Pre- and post-inflationary scenarios.



Post-inflationary scenario

- Different initial angle in each Hubble patch.
- Inhomogeneous including topological defects.

Pre-inflationary scenario

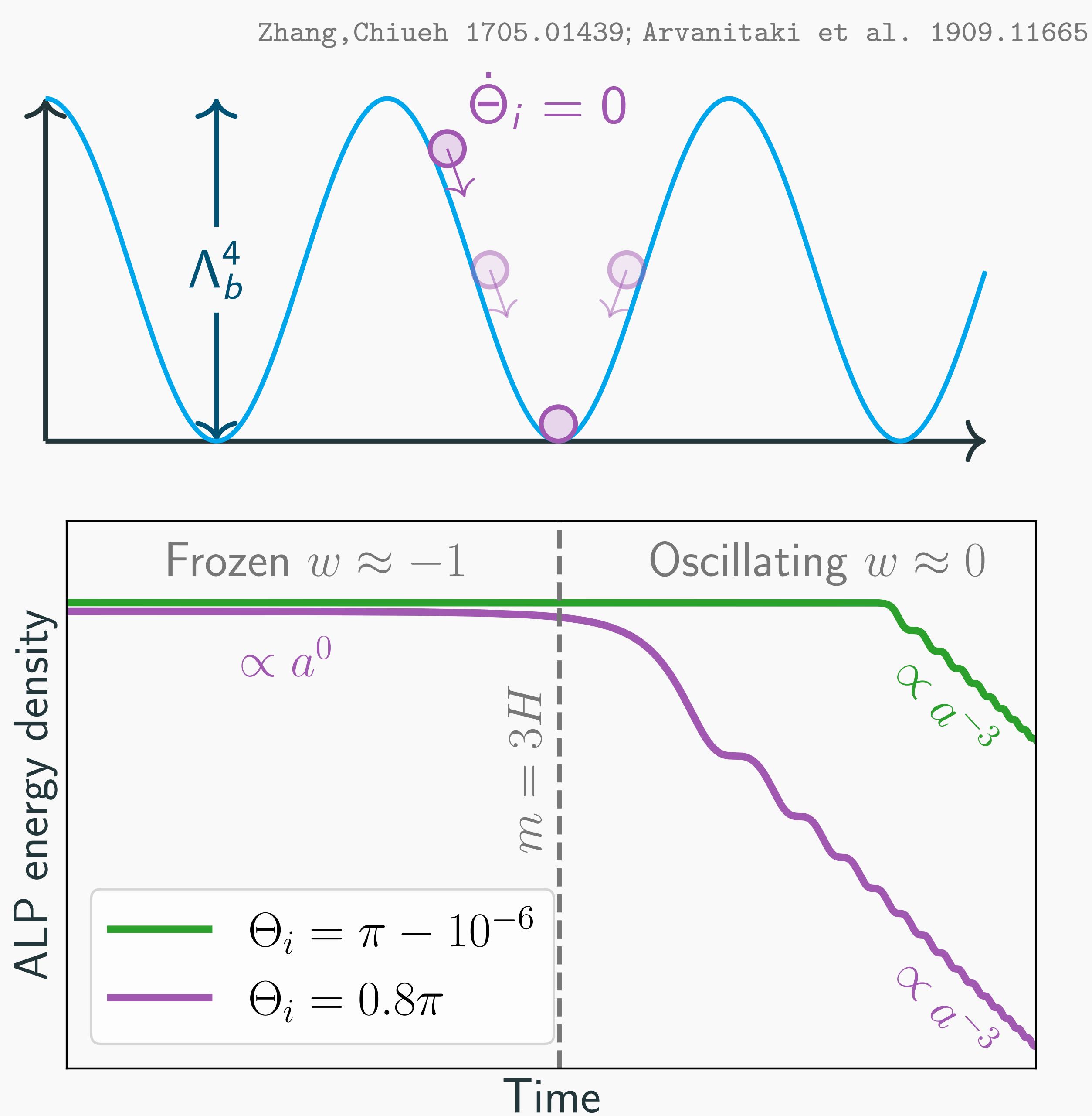
- Random initial angle in the observable universe.
- Initially homogeneous w/o topological defects.

Standard versus kinetic Misalignment.

Two ways to delay the onset of oscillations

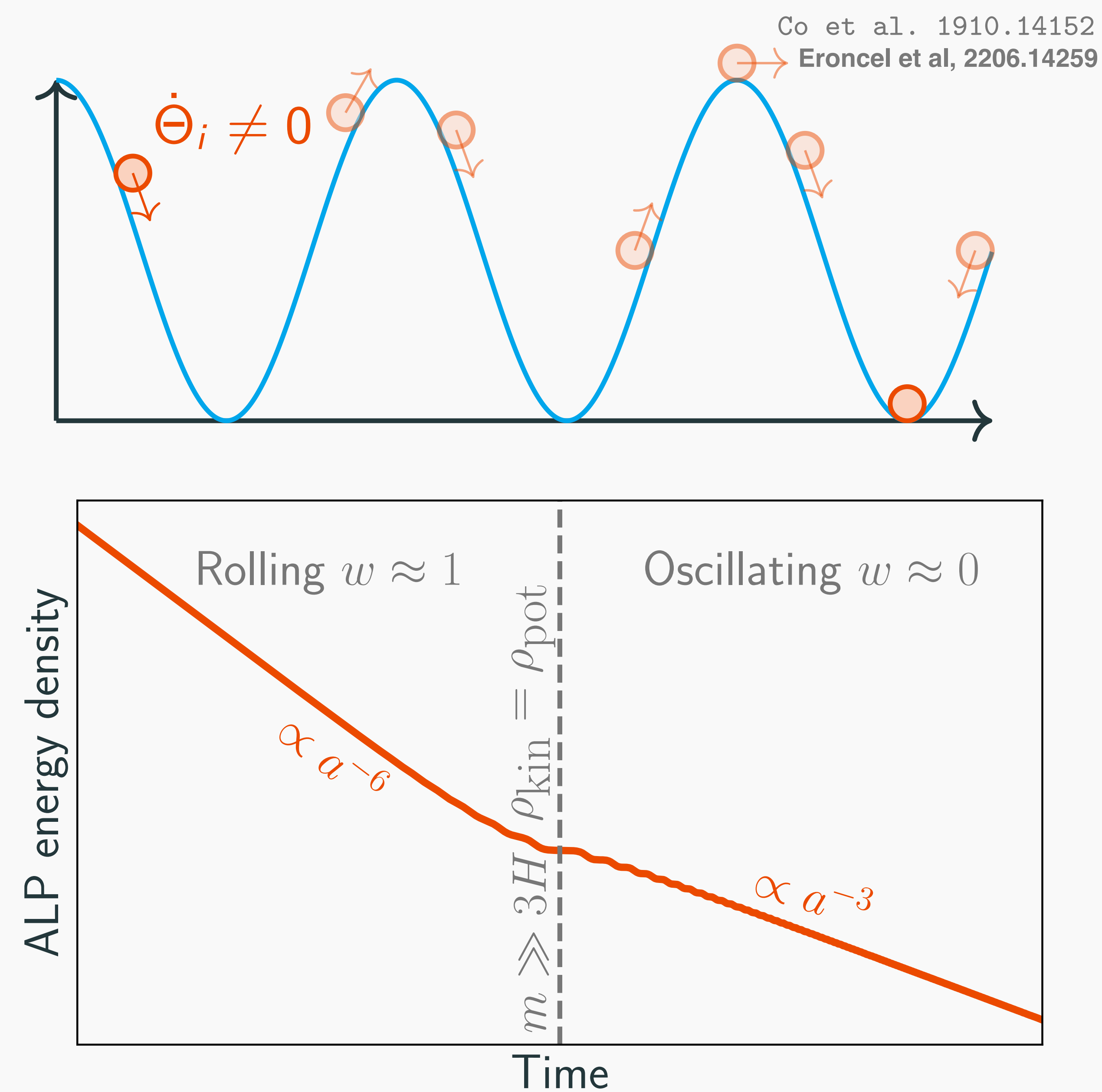
Initial field value tuned to top of potential:

Standard (Large) misalignment

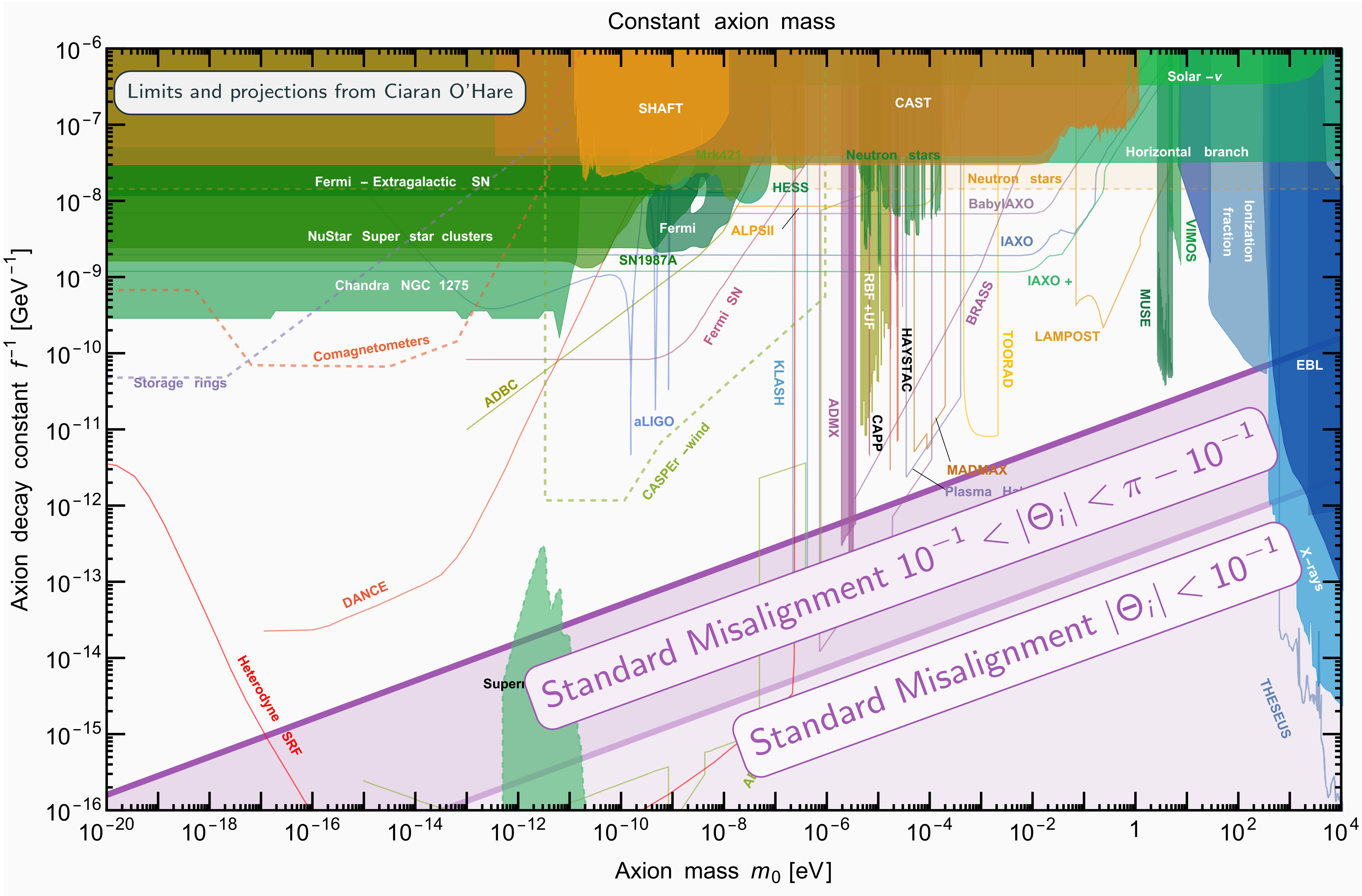


Large initial velocity

Kinetic misalignment



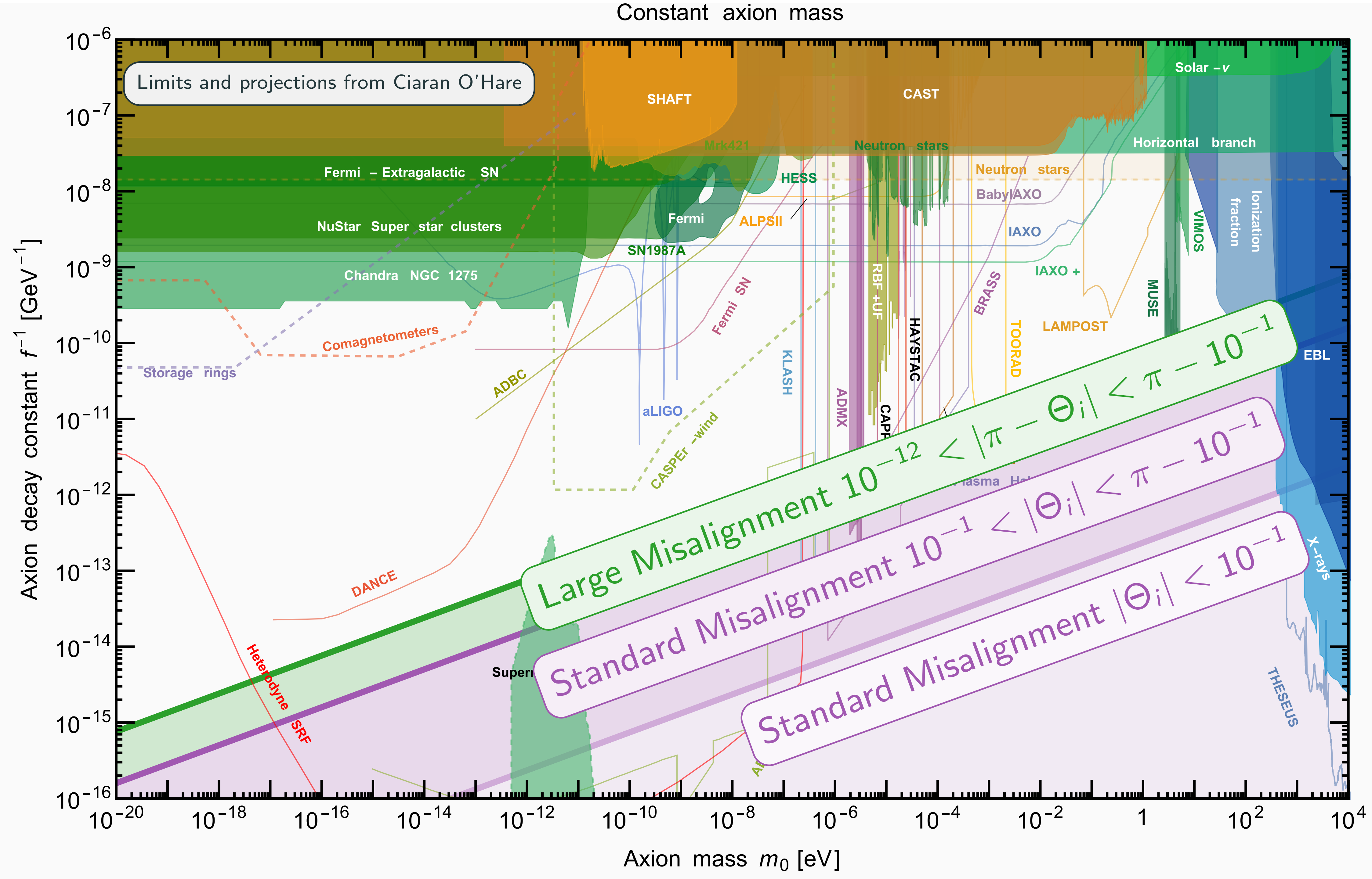
ALP DM parameter space.



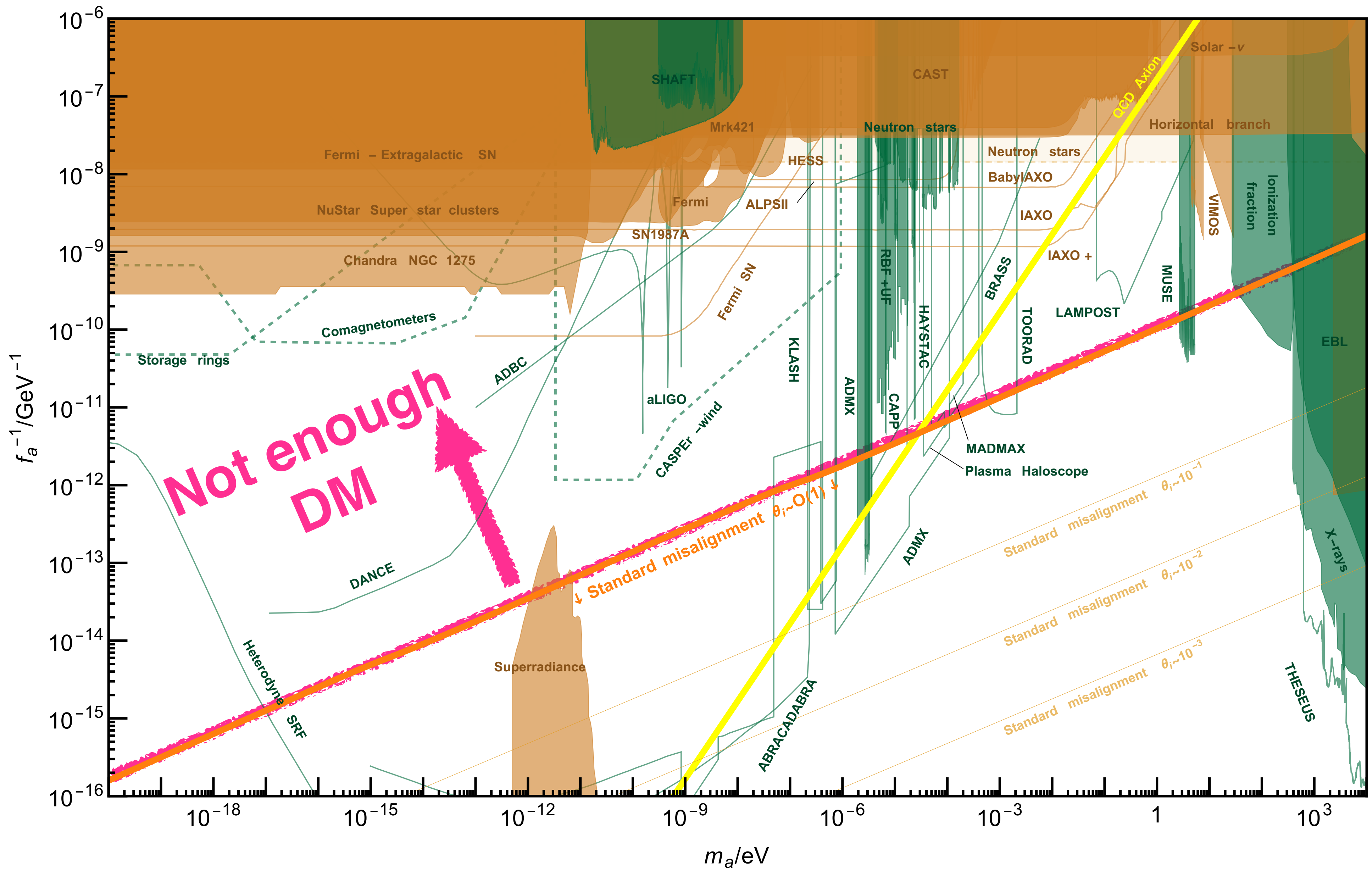
(KSVZ-like coupling)

$$g_{\theta\gamma} = (\alpha_{\mathbf{em}}/2\pi)(1.92/f))$$

ALP DM parameter space.



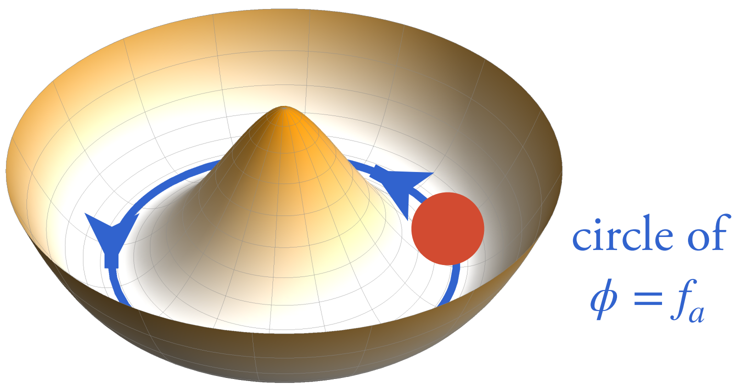
Conventional misalignement makes too little DM for low f_a .

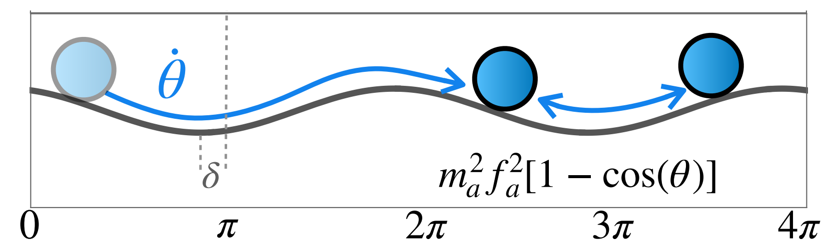


A way out: switch on initial velocity for the axion

Kinetic misalignment.

Add kinetic energy to delay onset of oscillations





> Delay oscillations
$\Rightarrow$ less redshift
$\Rightarrow$ more DM
$\Rightarrow$ lower f_a

-> ALP can be DM for low f_a

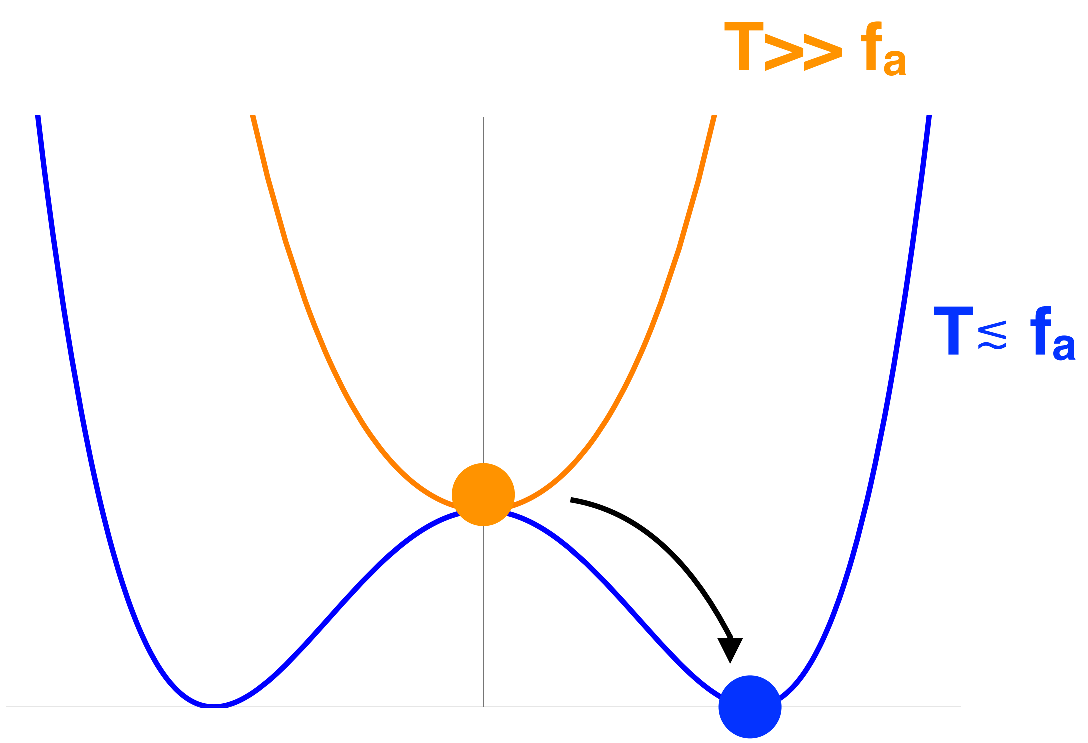
Co, Harigaya et al '19
Chang, Cui'19
Eroncel et al, '22

Axion cosmology.

"Usual" story:

Starts at $<\phi>=0$

Studies axion cosmology ignoring the radial mode

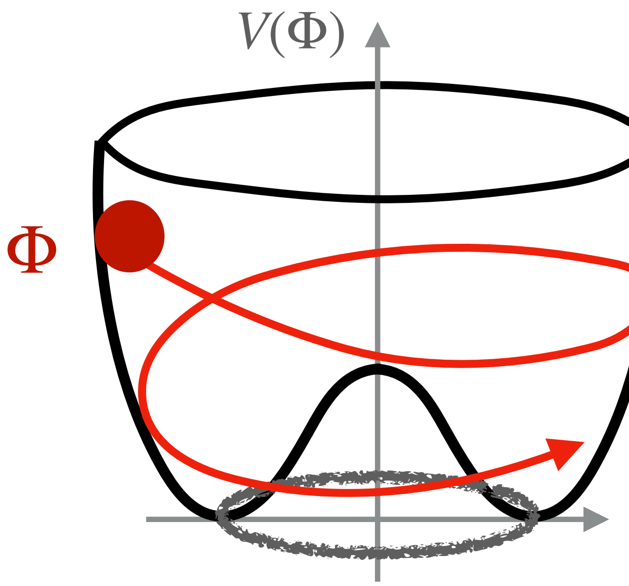


Alternative:

Starts at $<\phi> >> f_a$

(field can be driven naturally to these large field values during inflation due to a negative Hubble-induced mass term)

Radial mode /axion interplay



How did the axion acquire a kick?

If PQ symmetry is broken explicitly at high energies
—> mexican hat potential is tilted

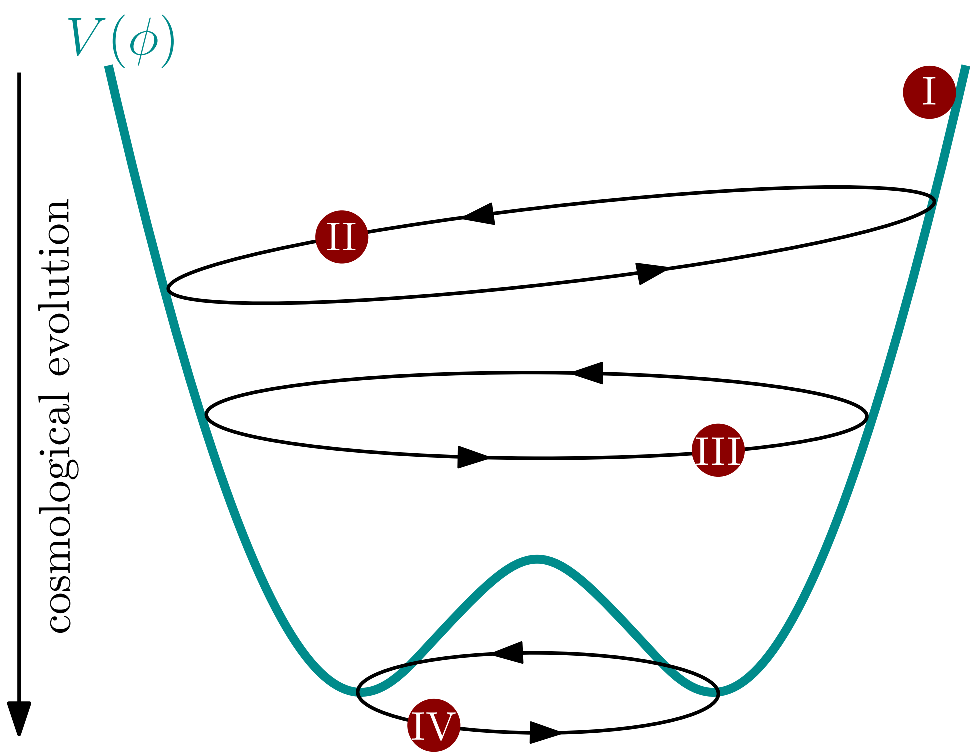


Figure by P. Simakachorn

If radial mode of PQ field starts at large VEV, the angular mode gets a large kick in the early universe

With initial conditions:

$$\frac{1}{2}\dot{\Theta}_i^2 \gg 2m^2(T_i)$$

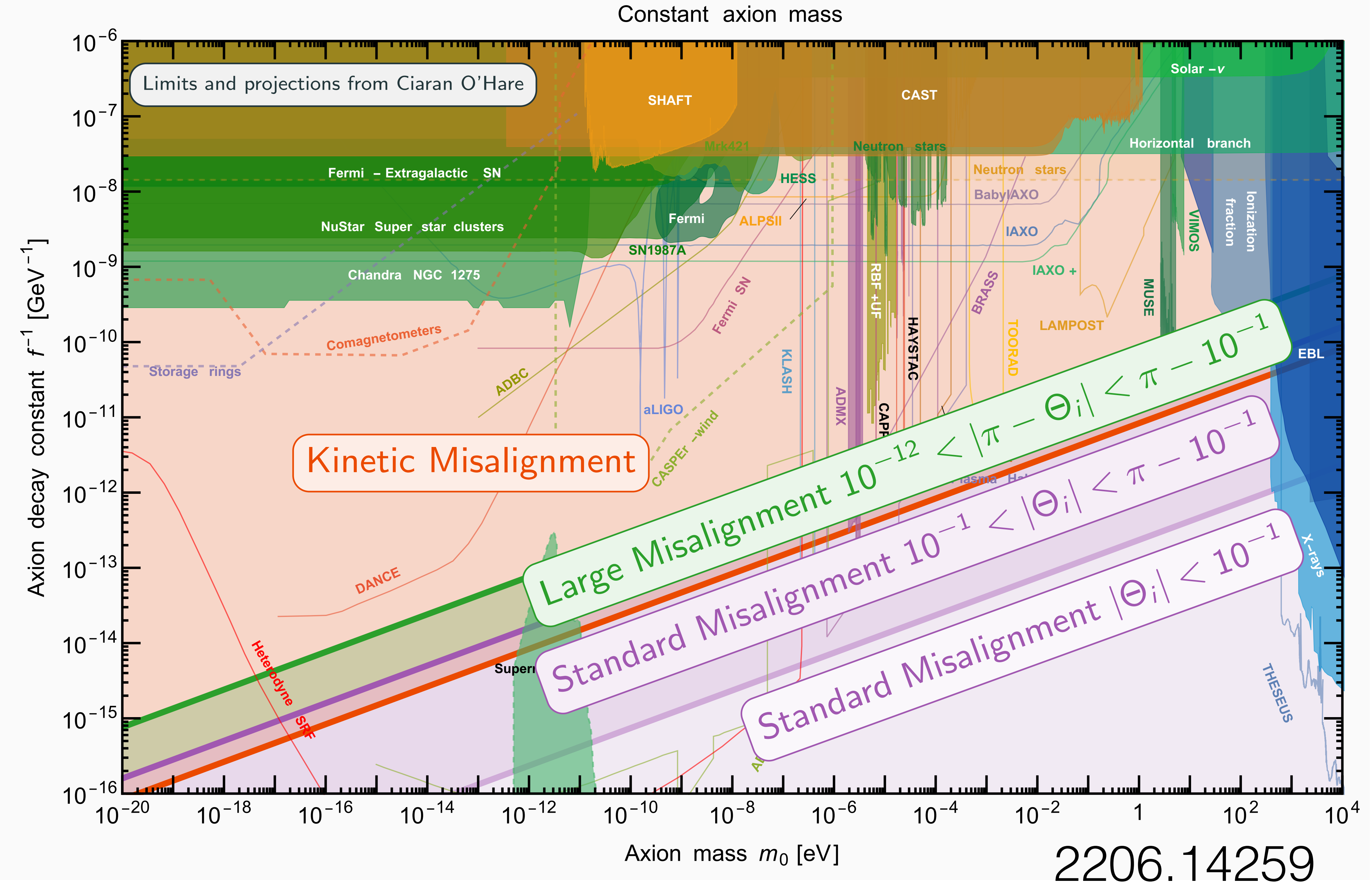
Delayed axion oscillations !

-> kinetic misalignment mechanism

[Co, Harigaya, Hall'19 1910.14152

2004.00629

ALP DM parameter space.



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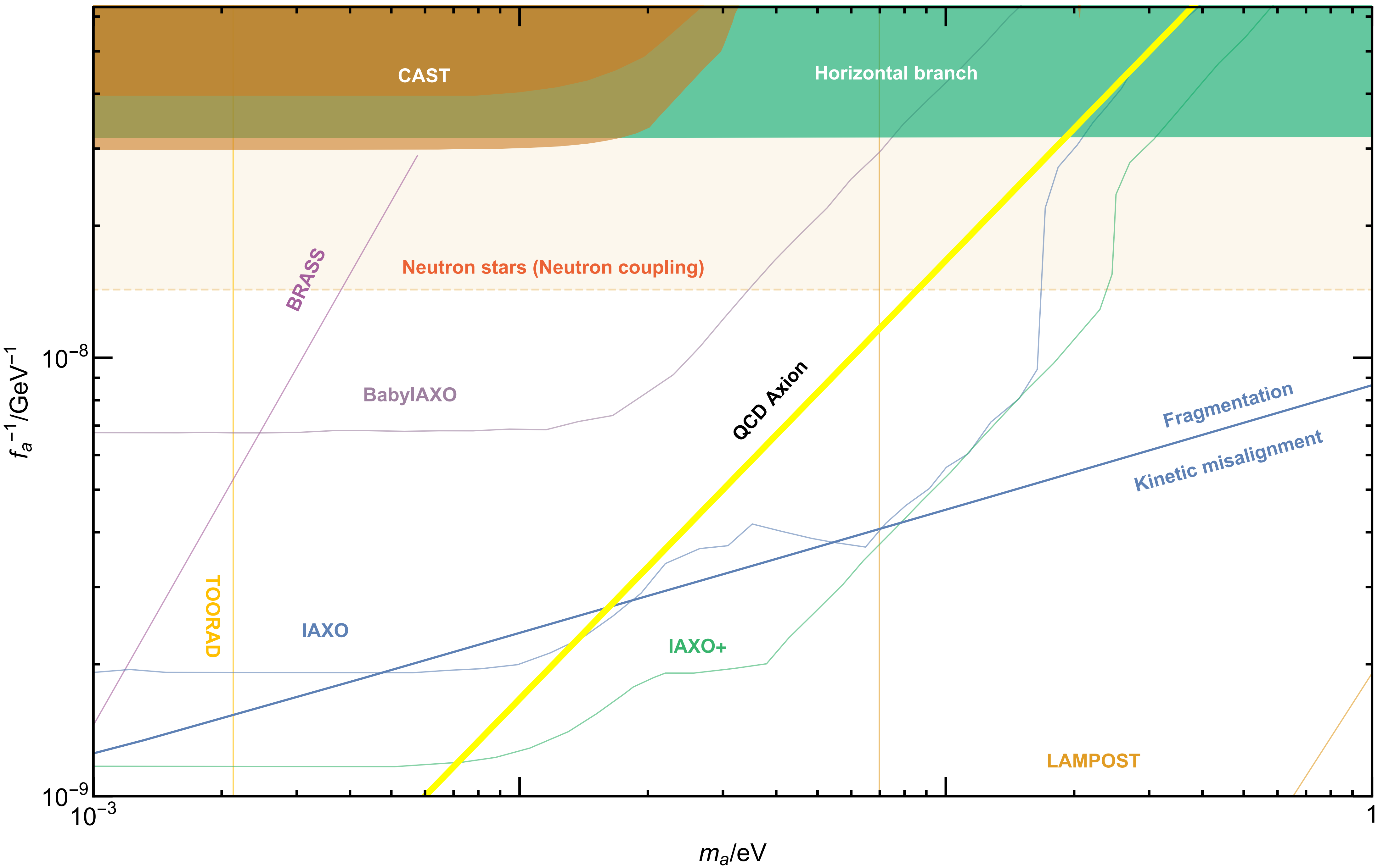
Experimental reach.



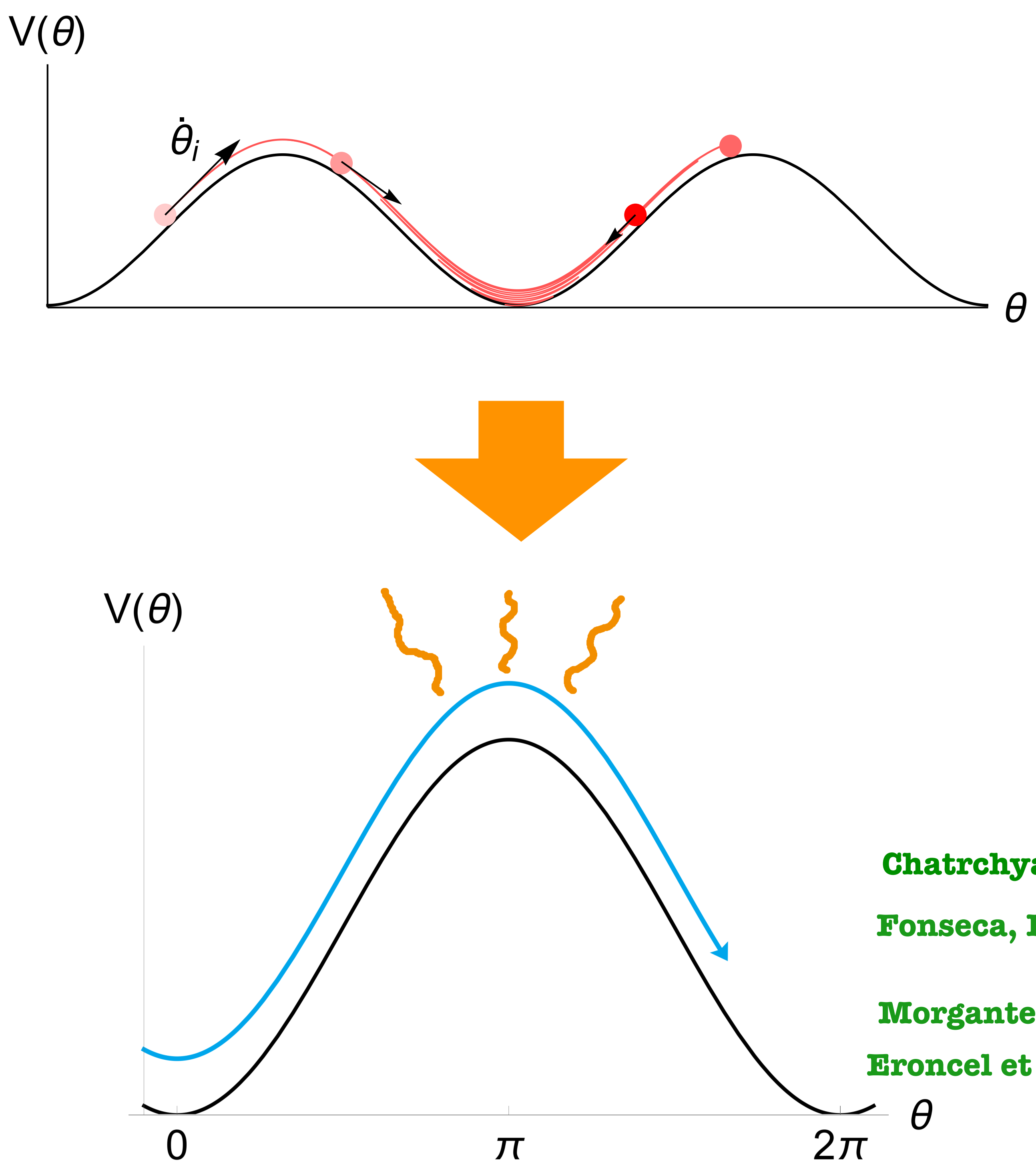
Axion kinetic misalignment:

↓

Axion fragmentation.

↓

Axion fragmentation



Chatrchyan et al, 1903.03116, 2004.07844

Fonseca, Morgante, Sato, Servant, 1911.08472, 1911.08473

Morgante et al, 2109.13823

Eroncel et al'22,

Axion Fragmentation.

Not considered in usual axion phenomenology with oscillations around one minimum: Fragmentation suppressed unless the field starts very close to the top of the potential ("large misalignment mechanism") or for specific potentials with more than one cosine -> parametric resonance.

Greene, Kofman, Starobinsky, hep-ph/9808477
Chatrchyan et al, 1903.03116, 2004.07844
Arvanitaki et al, 1909.11665

However, becomes very relevant when field crosses many wiggles, with interesting implications, e.g. for the relaxion mechanism, but also as a new axion Dark Matter production mechanism.

Chatrchyan et al, 1903.03116, 2004.07844
Fonseca,Morgante,Sato, Servant'19
Morgante et al, 2109.13823

Generalization Eroncel et al,
(fragmentation before and after trapping + detailed application to DM)

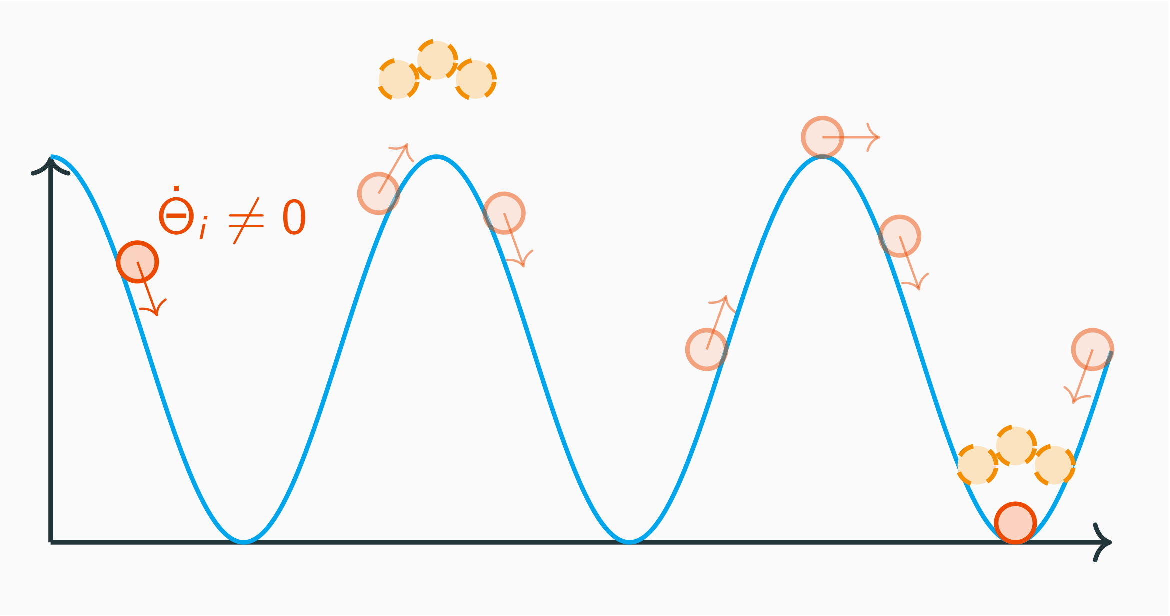
ALP fluctuations.

- ALP field has some fluctuations on top of the homogeneous background, which can be described by the mode functions in the Fourier space.

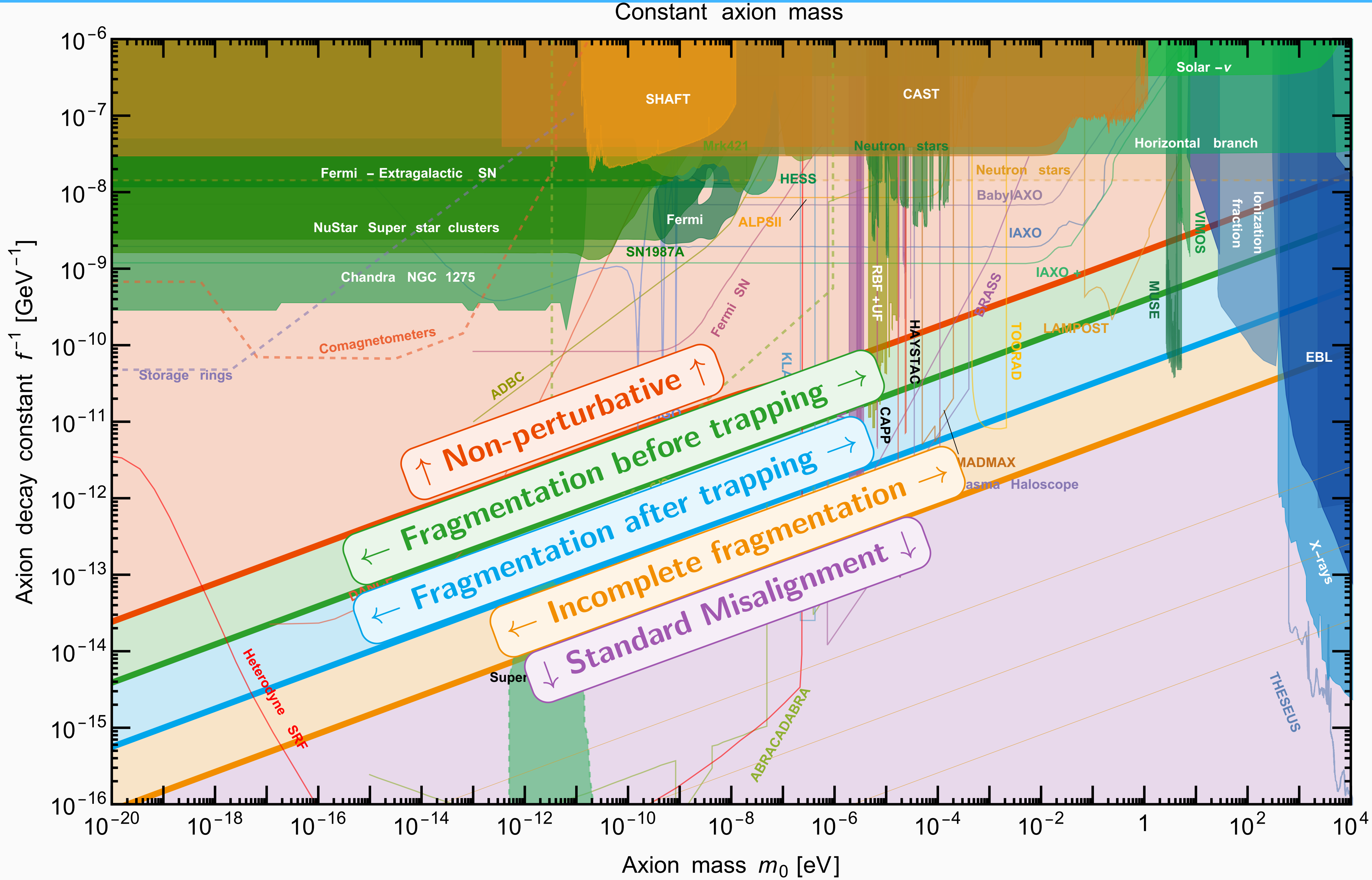
$$\theta(t, \mathrm{x}) = \Theta(t) + \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \theta_k e^{i\vec{\mathrm{k}}\cdot\vec{\mathrm{x}}} + \mathrm{h.c.}$$

ALP fluctuations.

- Even though the fluctuations are small initially, they can be enhanced exponentially later via parametric resonance yielding to fragmentation.
- In the case of efficient fragmentation, all the energy of the homogeneous mode can be transferred to the fluctuations. [Fonseca et al. 1911.08472; Morgante et al. 2109.13823]



Fragmentation regions in ALP parameter space.



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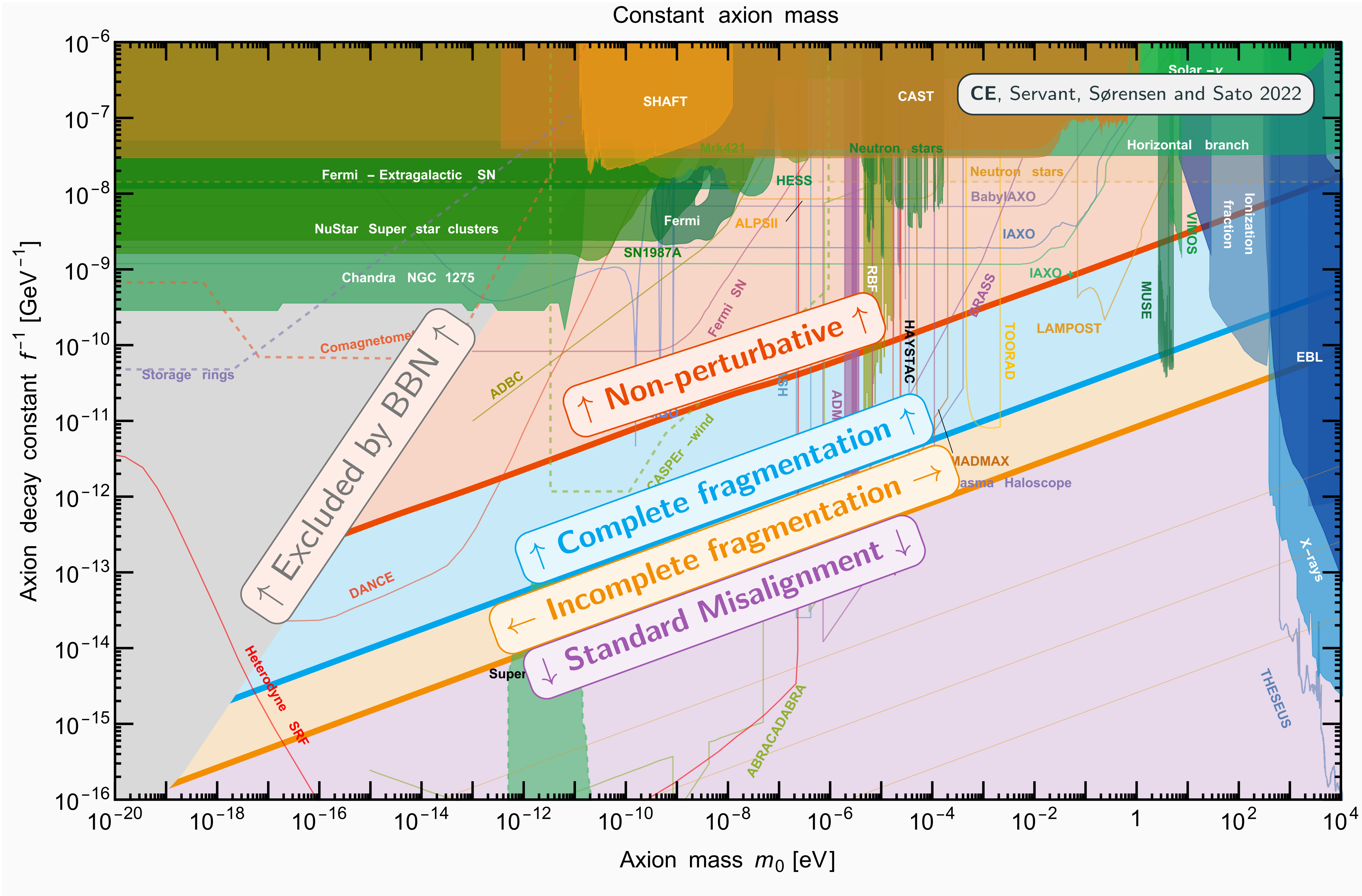
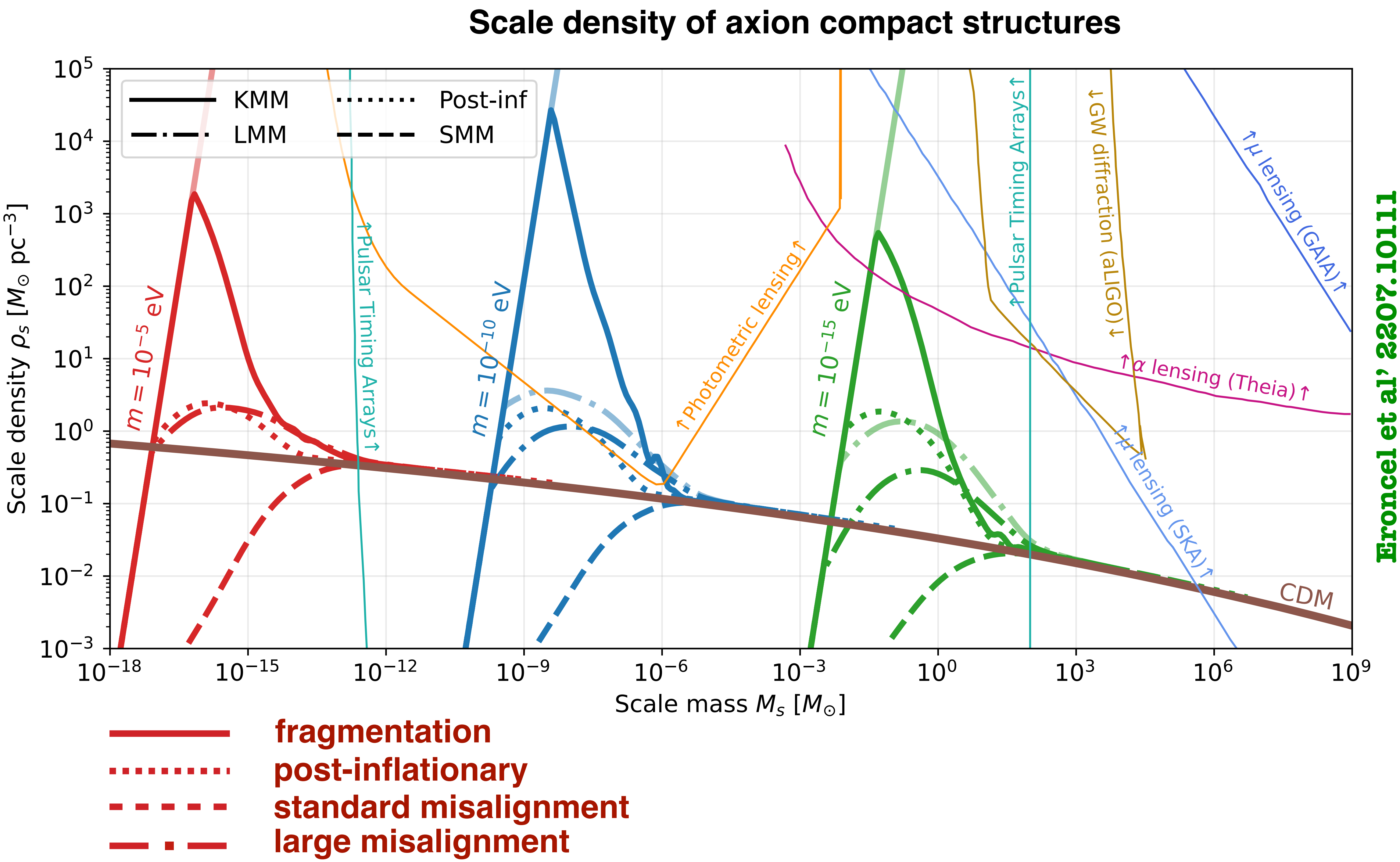
Fragmentation regions in ALP parameter space.



Observational tests: compact axion halos.

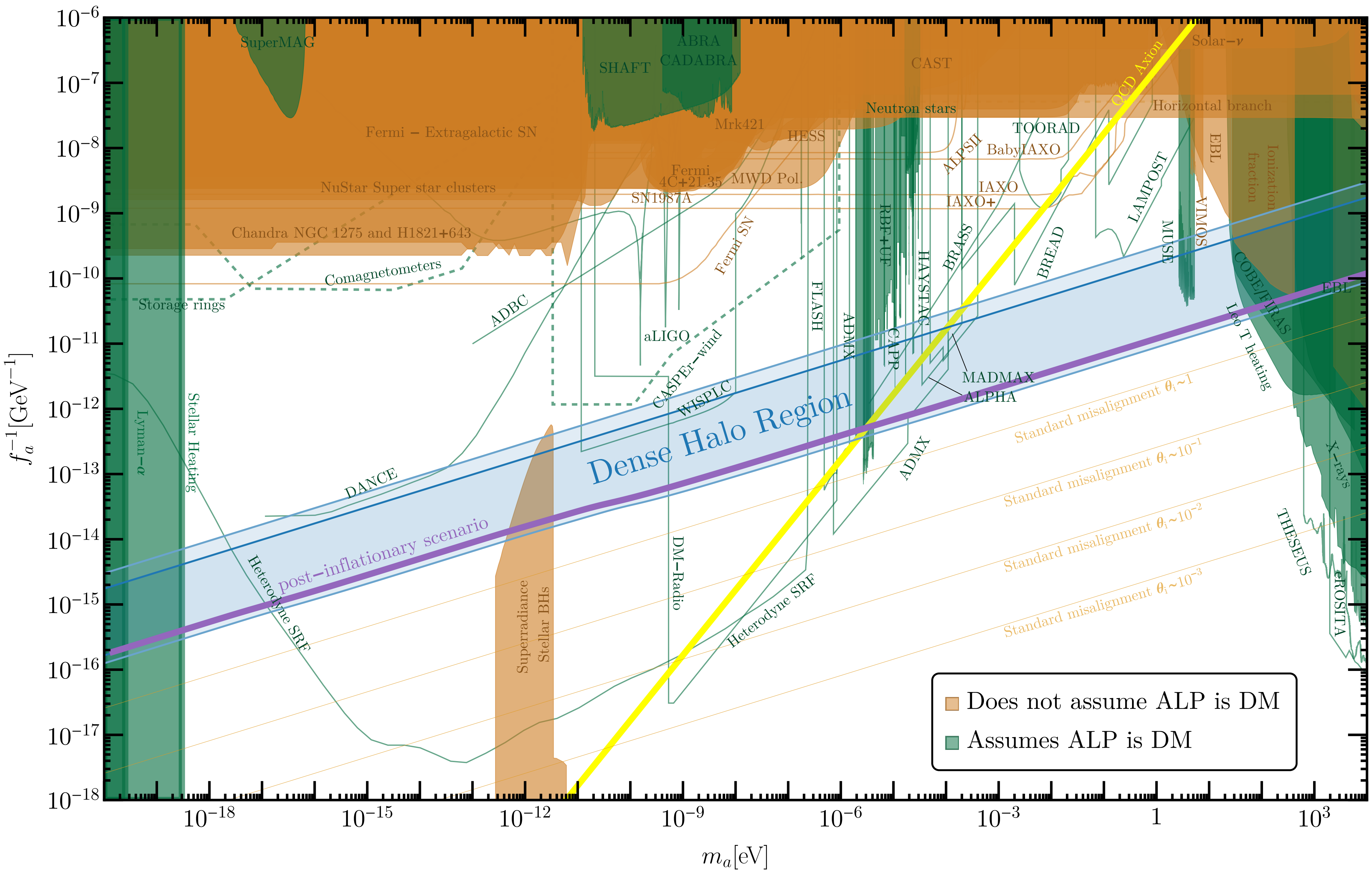
kinetic misalignment—>axion fragmentation-> structure formation enhancement



was studied in the context of large misalignment scenario in [Arvanitaki et al'19]

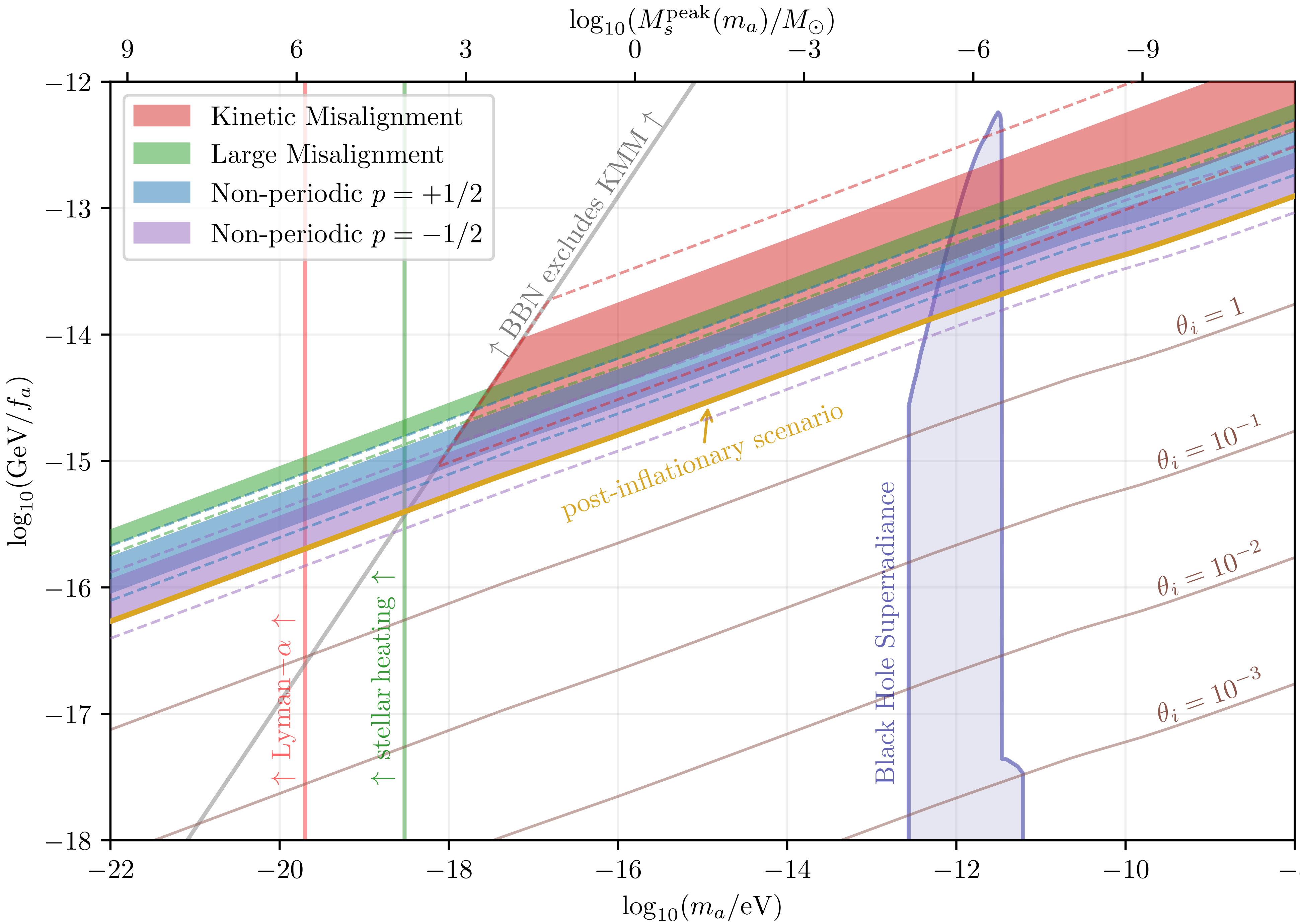
Different in the context of axion kinetic fragmentation: Eroncel et al , 2207.10111

Parameter space where parametric resonance can create compact halos.



Chatrchyan, Eroncel, Koschnitzke, Servant, 2305.03756

Parameter space where parametric resonance can create compact halos.



Chatrchyan, Eroncel, Koschnitzke, Servant, 2305.03756

—2—
Another exciting topic in axion cosmology: Cosmological relaxation of the electroweak scale.

Motivation:
Origin of the Electroweak Scale .

The Hierarchy problem

35

The hierarchy problem.

If Standard Model is an effective field theory below M_{Planck}

$$V = m_H^2\, h^2 + \lambda\, h^4$$

Why $|m_H^2| \ll M_{Planck}^2$ **?**

Why does the Higgs vacuum reside so close to the critical line separating the phase with unbroken (<h>=0) from the phase with broken (<h> ≠0) electroweak symmetry?

Solutions to the Hierarchy Problem .

Adding a symmetry

-> Supersymmetry

-> Global symmetry …

Experimental signals: partners

Lowering the cutoff

-> Randall-Sundrum / Composite Higgs,

-> Large Extra Dimensions …

Experimental signals: resonances

Selecting a vacuum : Relaxation (dynamics),

Experimental signals: typically through cosmology

Relaxation idea.

What if the weak scale is selected by cosmological dynamics, not symmetries?

Special point in parameter space:

$m^2_H = 0$ *not* related to a symmetry
Instead, related to early-universe dynamics!

New Relaxion idea: Higgs mass parameter is field-dependent

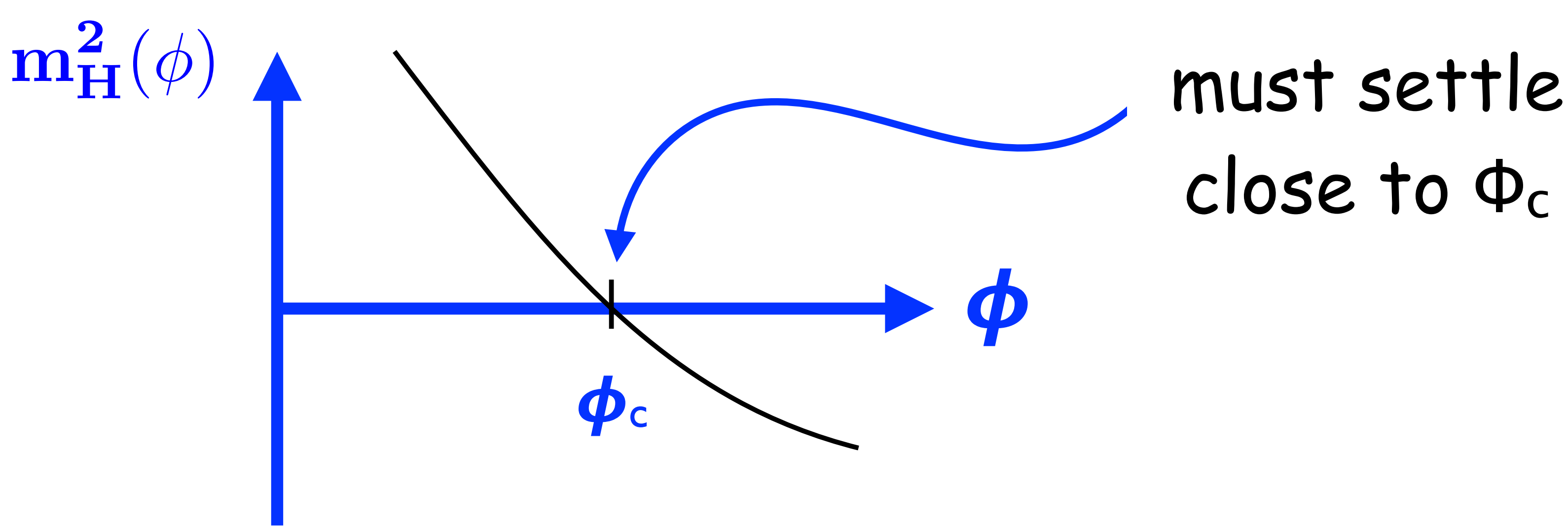
a new scalar field

$$m_H^2 |H|^2 \to m_H^2(\phi)|H|^2$$

Φ can get a value such that $m_H^2(\phi) \ll \Lambda^2$

from a dynamical interplay between H and Φ

UV cutoff



m_H naturally stabilized due to back-reaction of the Higgs field after EW symmetry breaking !

Relaxion mechanism.

[GKR: Graham, Kaplan, Rajendran '15
inspired by Abbott's attempt to solve the Cosmological Constant problem, '85
[for a recent update see

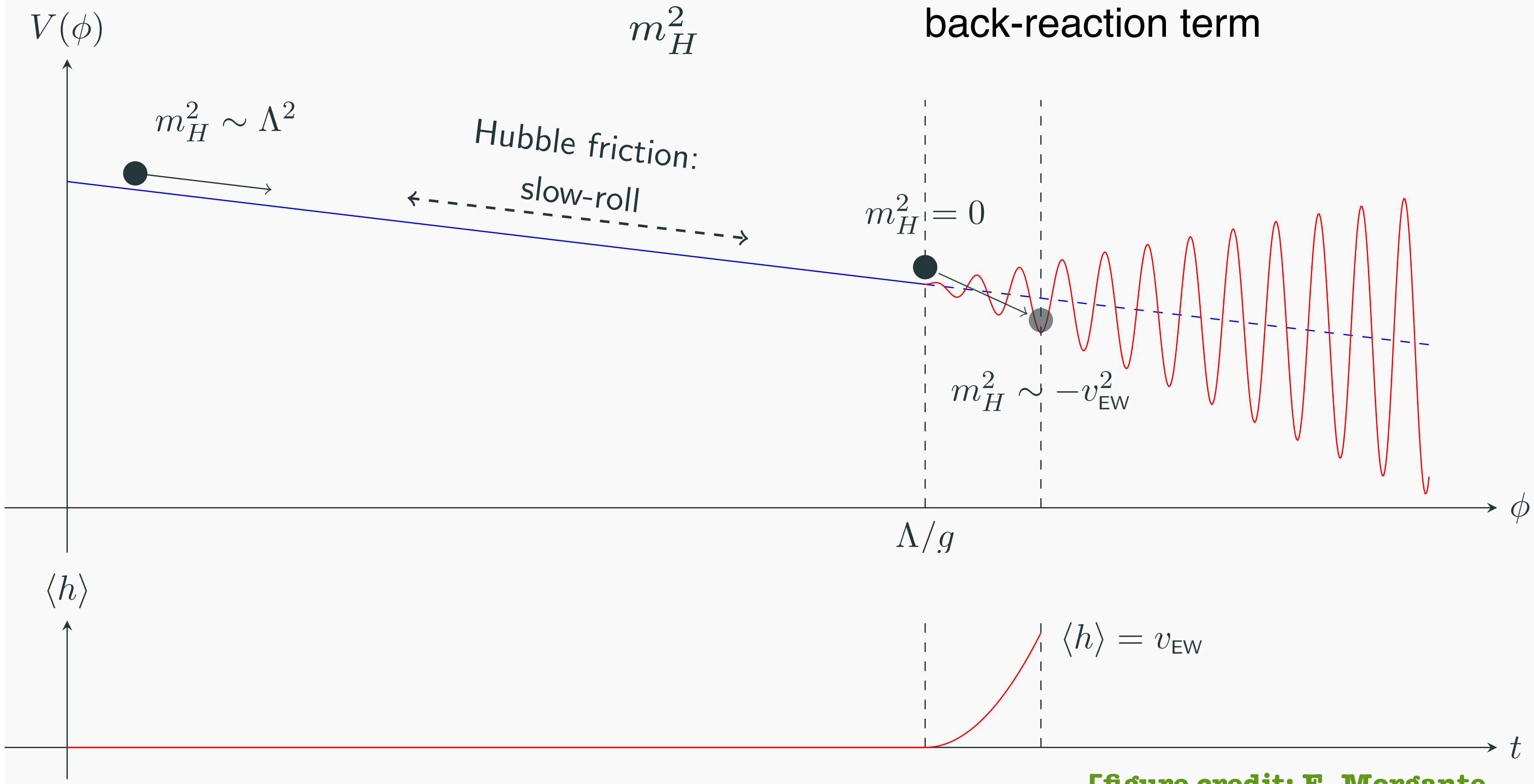
ϕ: relaxion, classically evolving pNGB.

Higgs-relaxion potential

Λ: cutoff of the Higgs effective theory

$$V(\phi, h) = -g\Lambda^3\phi + \frac{1}{2}\underbrace{(\Lambda^2 - g'\Lambda\phi)}_{m_H^2}h^2 + \Lambda_b^4(h)[1 - \cos(\phi/f)] + \dots$$

back-reaction term



[figure credit: E. Morgante

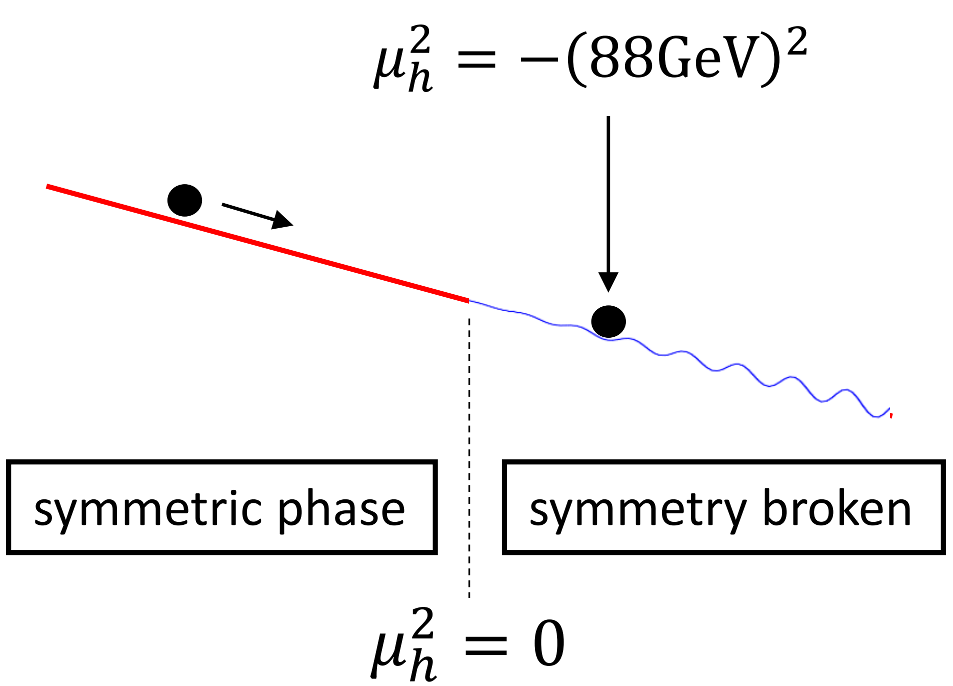
Relaxion mechanism.

potential: $V(\phi) = -g\Lambda^3\phi + \Lambda_b^4(v_h)[1 - \cos(\phi/f)]$

Higgs-vev-dependent barriers

Slow-roll dynamics during inflation

$$\dot{\phi}_{SR} = \frac{V'}{3H_I}$$



Hubble friction needed otherwise field overshoots the barrier

Relaxion stops near the first minimum

$$0 = V'(\phi_0) = -g\Lambda^3 + \frac{\Lambda_b^4(\phi_0)}{f}\sin\left(\frac{\phi_0}{f}\right). \longrightarrow \Lambda_b^4 \sim g\Lambda^3 f$$

The QCD and non-QCD models.

The **QCD** relaxion model

- Higgs-dependent barriers from the **QCD anomaly,**

$$\Lambda_b^4(v_h) \approx \Lambda_{QCD}^3 m_u$$

- Problem: the relaxion no longer solves the **strong CP problem!**

$$\theta_{QCD} \sim \mathcal{O}(1)$$

$$\theta_{\rm QCD} = \frac{\phi_0}{f} = \arcsin\left(\frac{g\Lambda^3 f}{\Lambda_b^4}\right),$$

The **nonQCD** relaxion model

- Higgs-dependent barriers from a **hidden gauge group**

$$\Lambda_b(v_h) < v_h$$

(stability of the potential)

The classical non-QCD relaxion window.

1) Vacuum energy

The **change of relaxion energy** much less compared to the **energy scale of inflation**

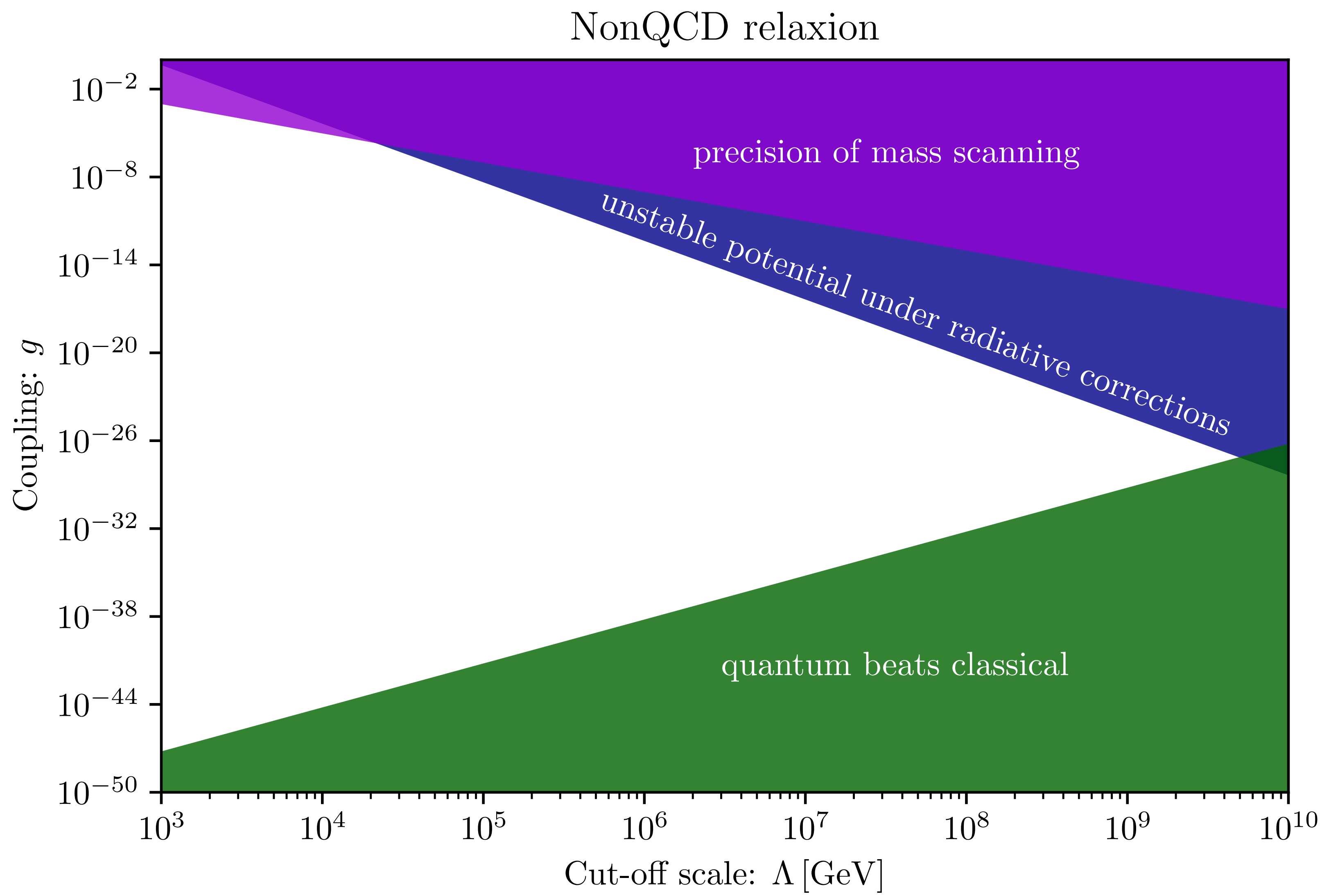
$$\Delta V \sim \Lambda^4 < H_I^2 M_{Pl}^2$$

2) Classical beats quantum

The **slow-roll** ($\dot{\phi} = g\Lambda^3/3H_I$) per unit Hubble time dominates over the random walk ($\Delta\phi \sim H_I$)

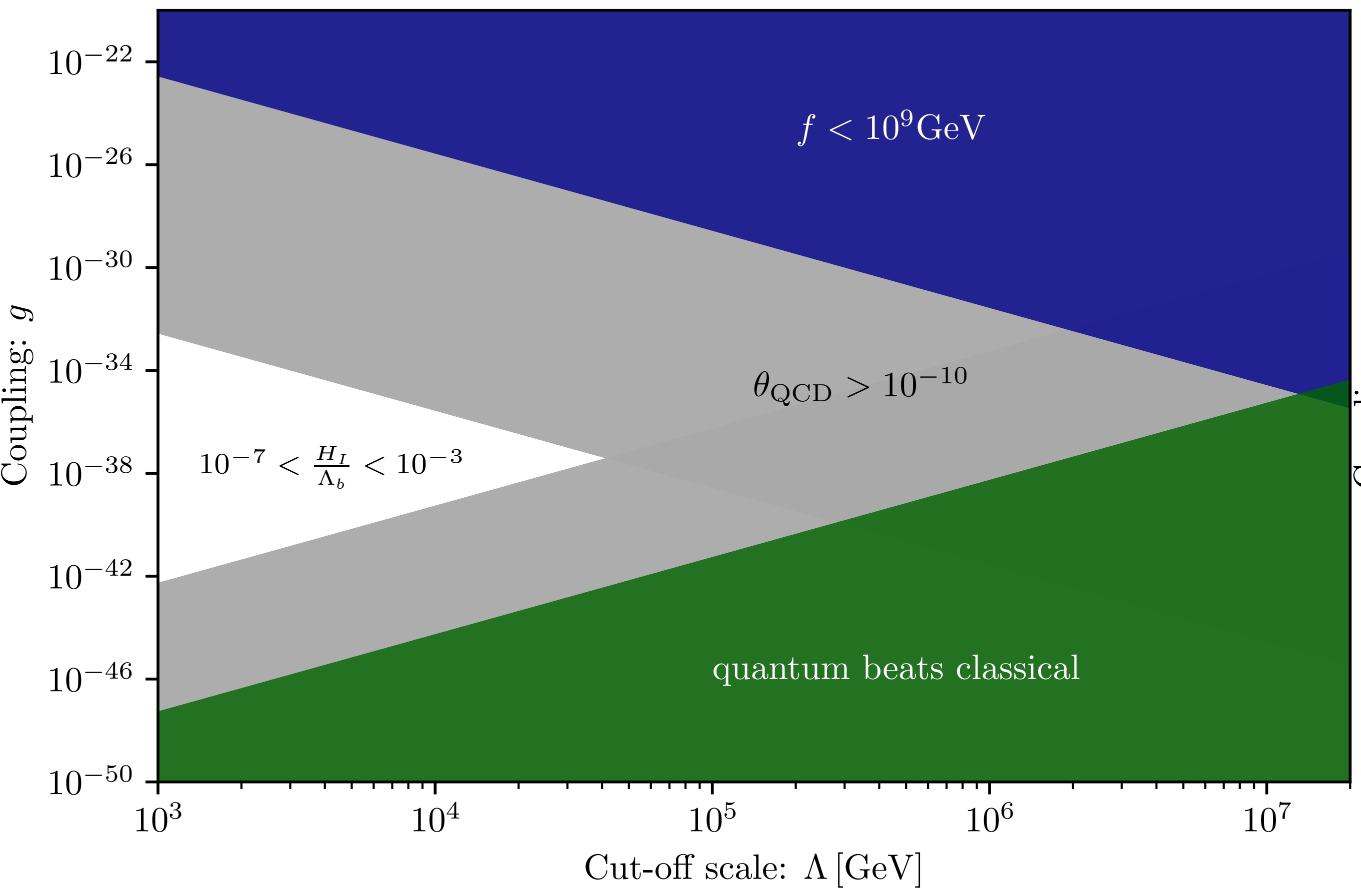
$$H_I < (g\Lambda^3)^{1/3}$$

1) + 2) ➡ $$\frac{\Lambda^2}{M_{Pl}} < H_I < g^{1/3}\Lambda$$

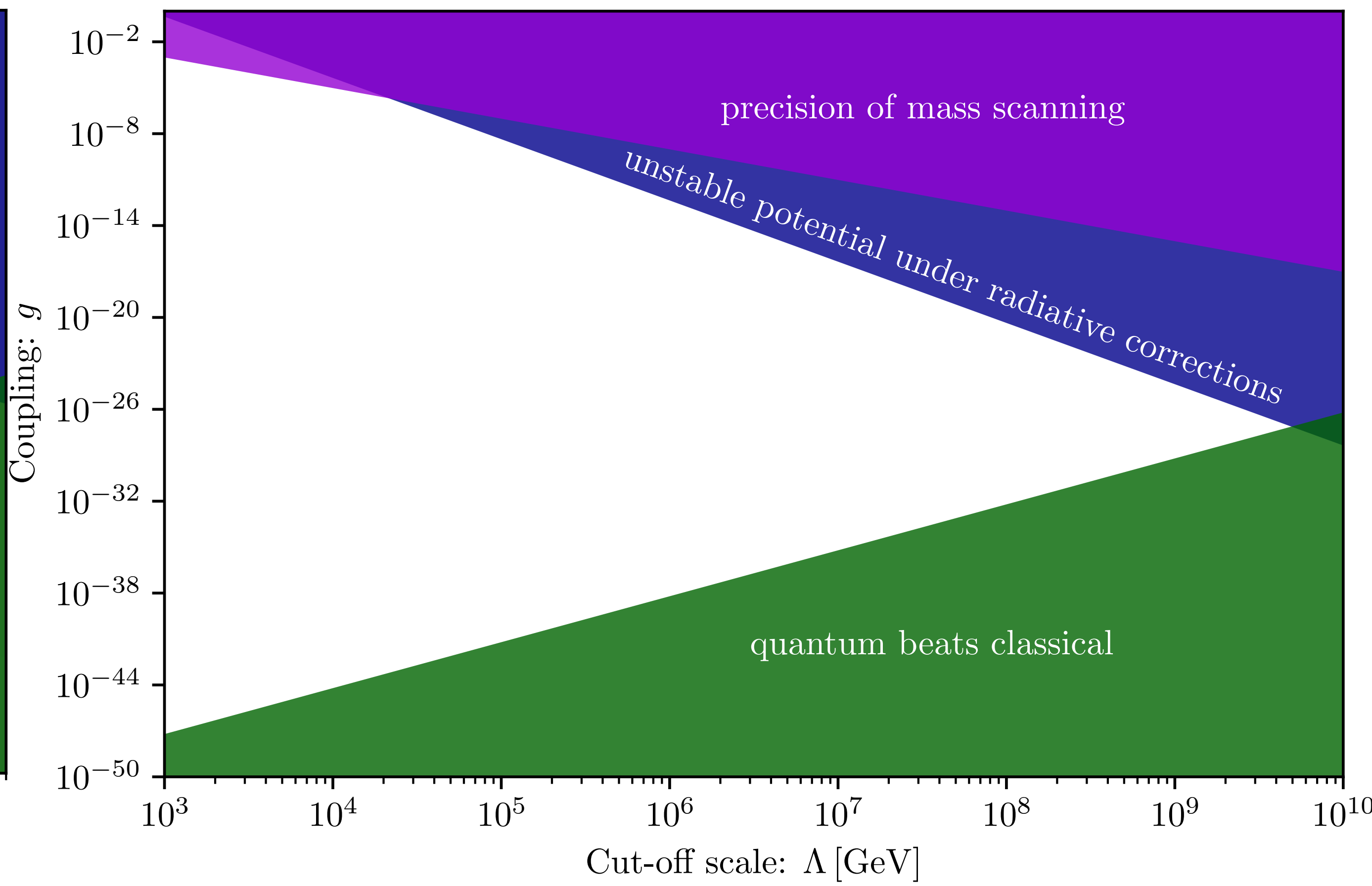


The classical relaxion windows .

QCD relaxion with a change of slope after inflation



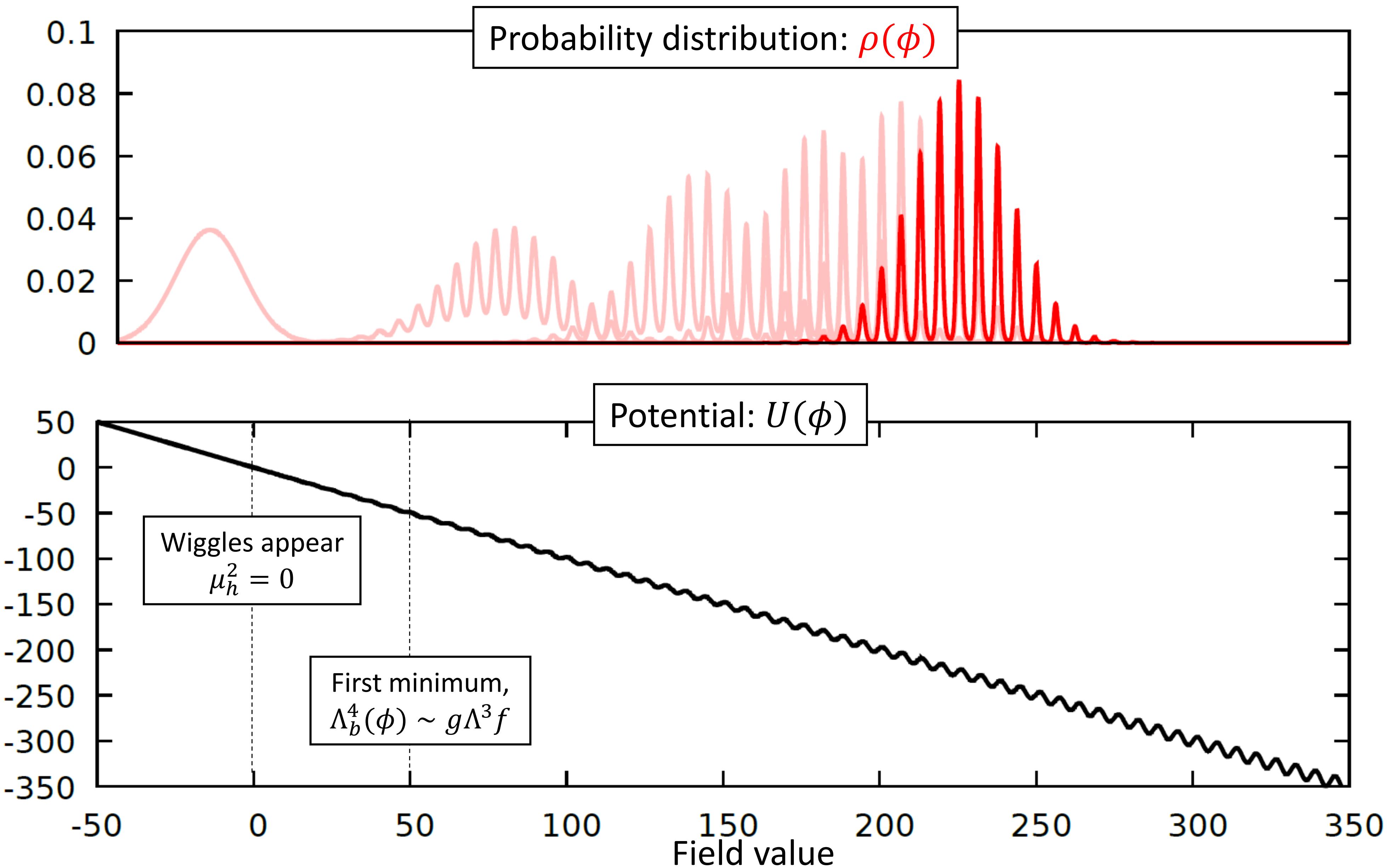
NonQCD relaxion



Beyond the classical relaxion ...
The stochastic relaxion

[Chatrchyan, Servant,

Real-time numerical simulation of the Fokker-Planck equation



The relaxion slows down after

$$\frac{8\pi^2 \Delta V_b}{3H_I^4} < 1$$

The new stopping condition,

$$\Lambda_b^4 \sim \max\left(g\Lambda^3 f, \frac{3H_I^4}{8\pi^2}\right).$$

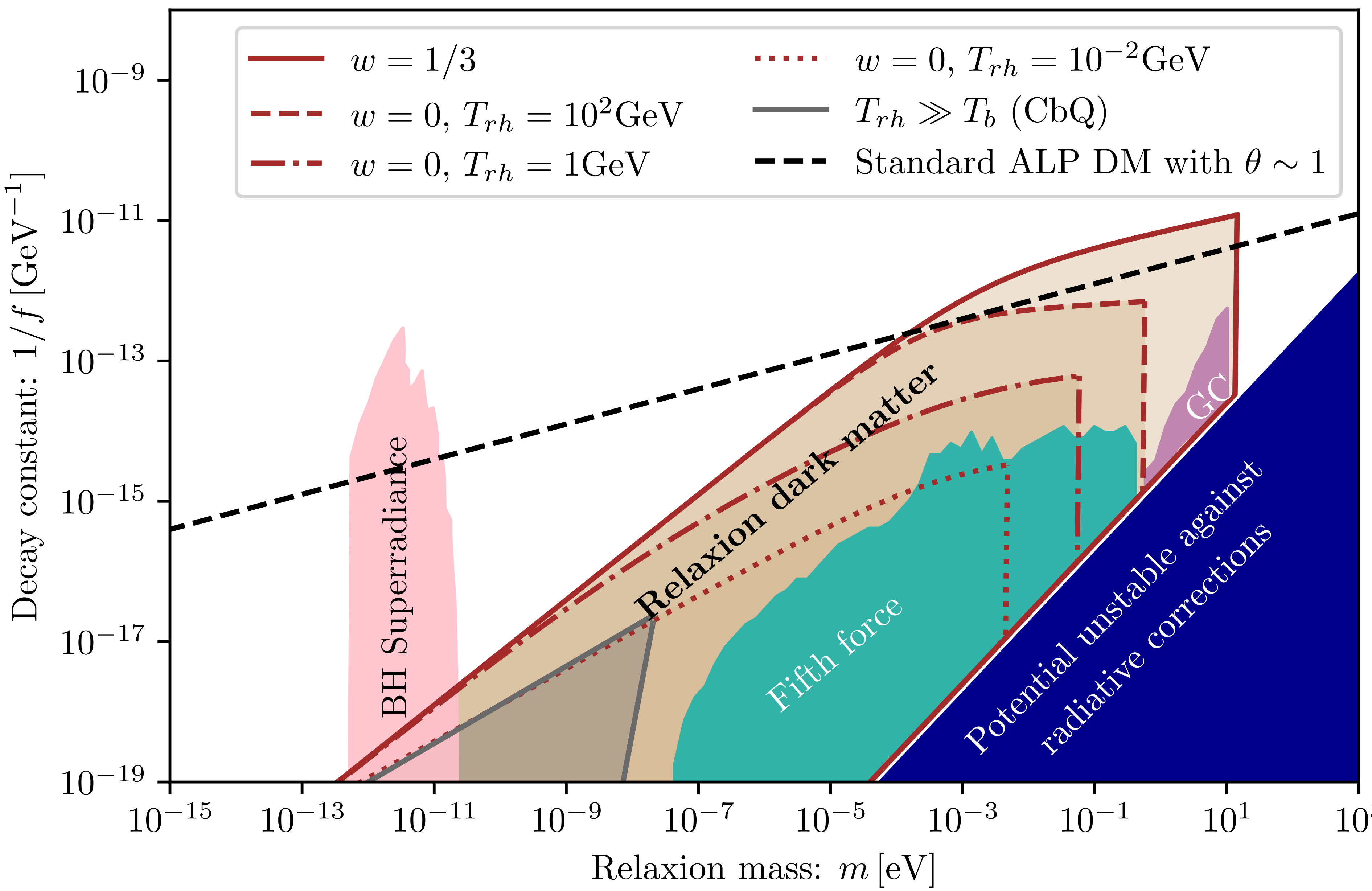
The relaxion can be dark matter

[Chatrchyan, Servant, 2211.15694]

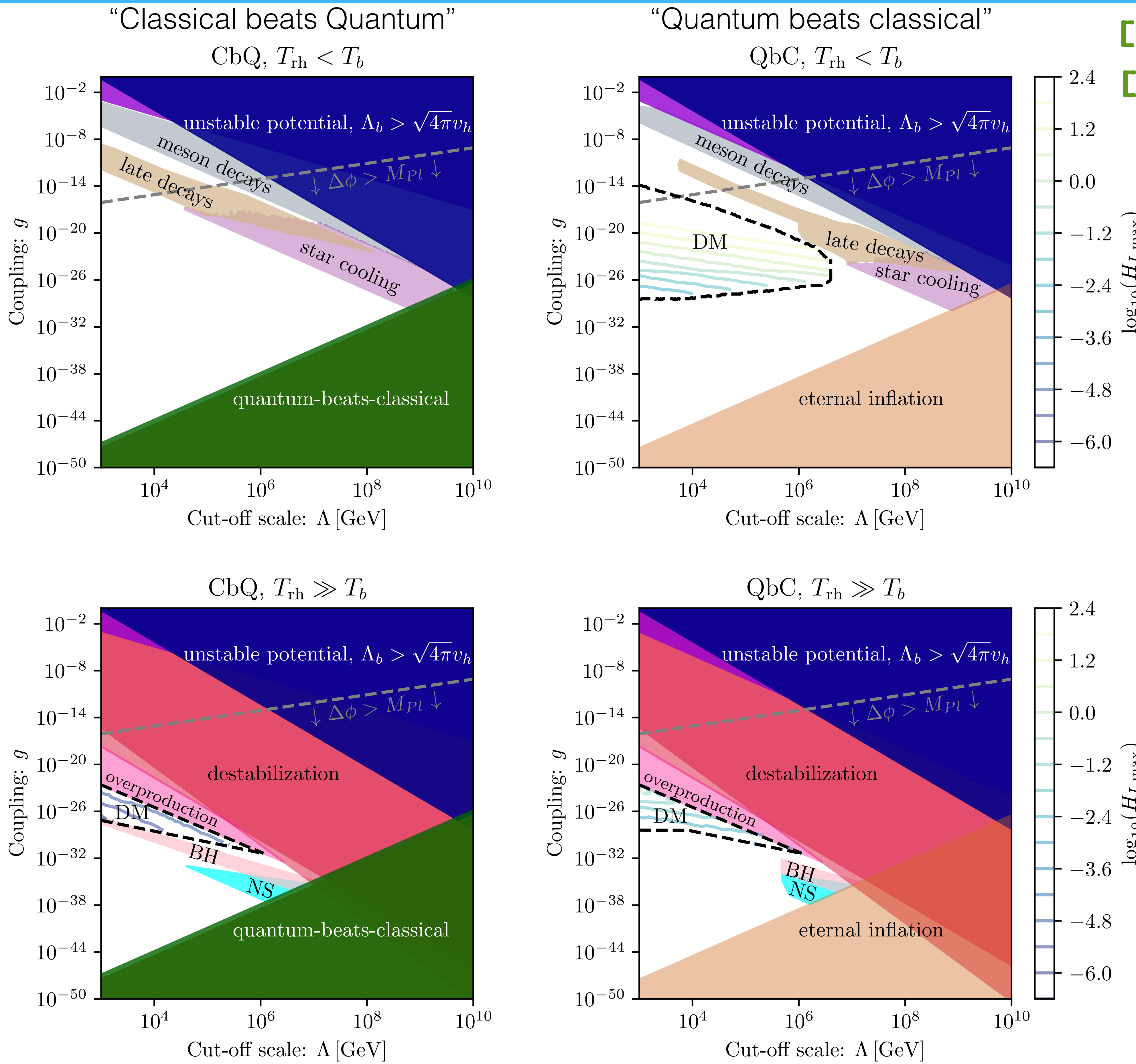
Non-QCD Relaxion Dark Matter window

QbC

CbQ



A rich spectrum of possibilities.



[2211.15694
[

Summary on relaxion.

- A new approach to the hierarchy problem based on intertwined cosmological history of Higgs and axion-like states.
  Connects Higgs physics with inflation & (DM) axions.

- An existence proof that technical naturalness does not require new physics at the weak scale

$$\Lambda < \left(v^4 M_P^3\right)^{1/7} = 3 \times 10^9 \,\mathrm{GeV}$$

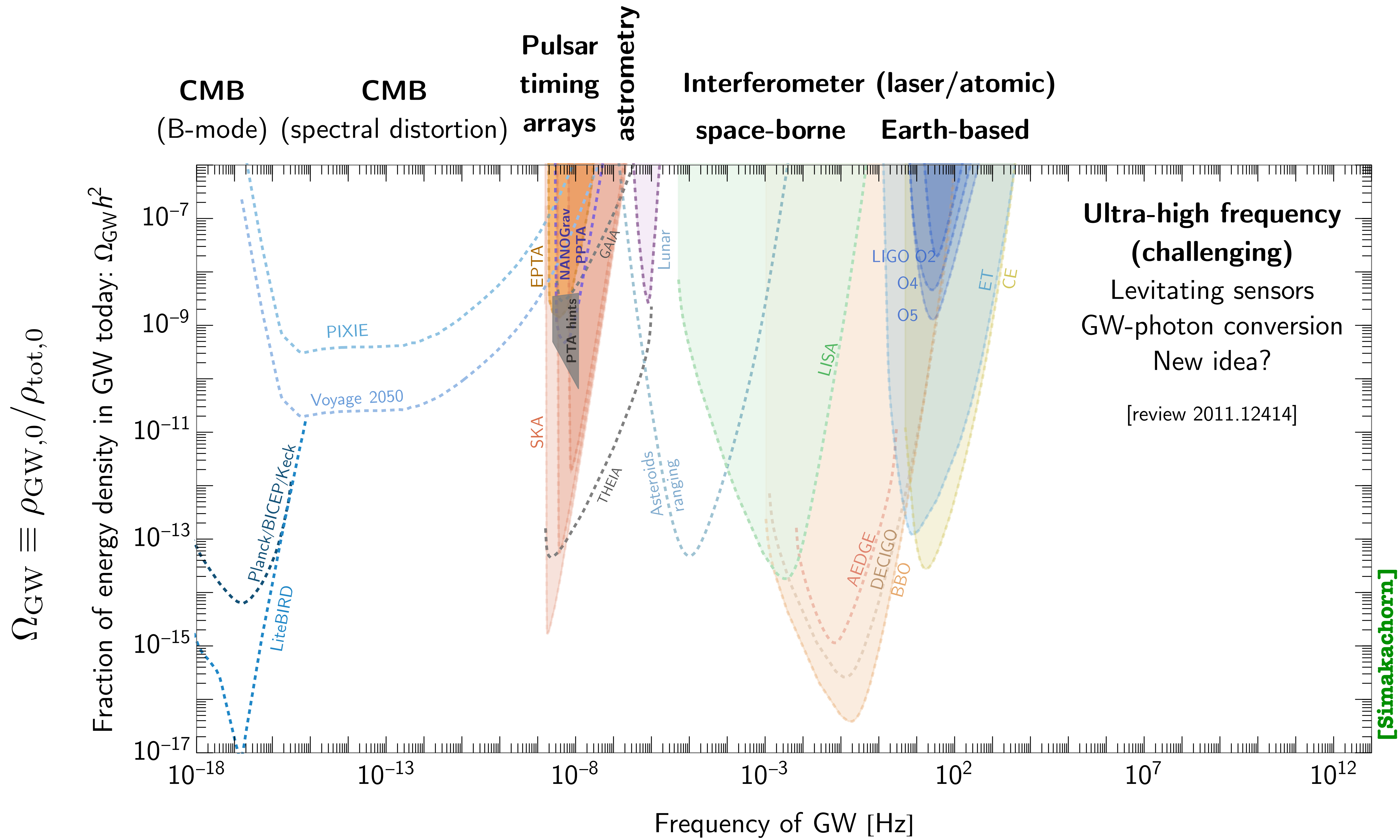
- Change of paradigm:

  no signature at the LHC , new physics are weakly coupled light states which couple to the Standard Model through their tiny mixing with the Higgs.

- Experimental tests from cosmological overabundances, late decays, Big Bang Nucleosynthesis, Gamma-rays, Cosmic Microwave Background...

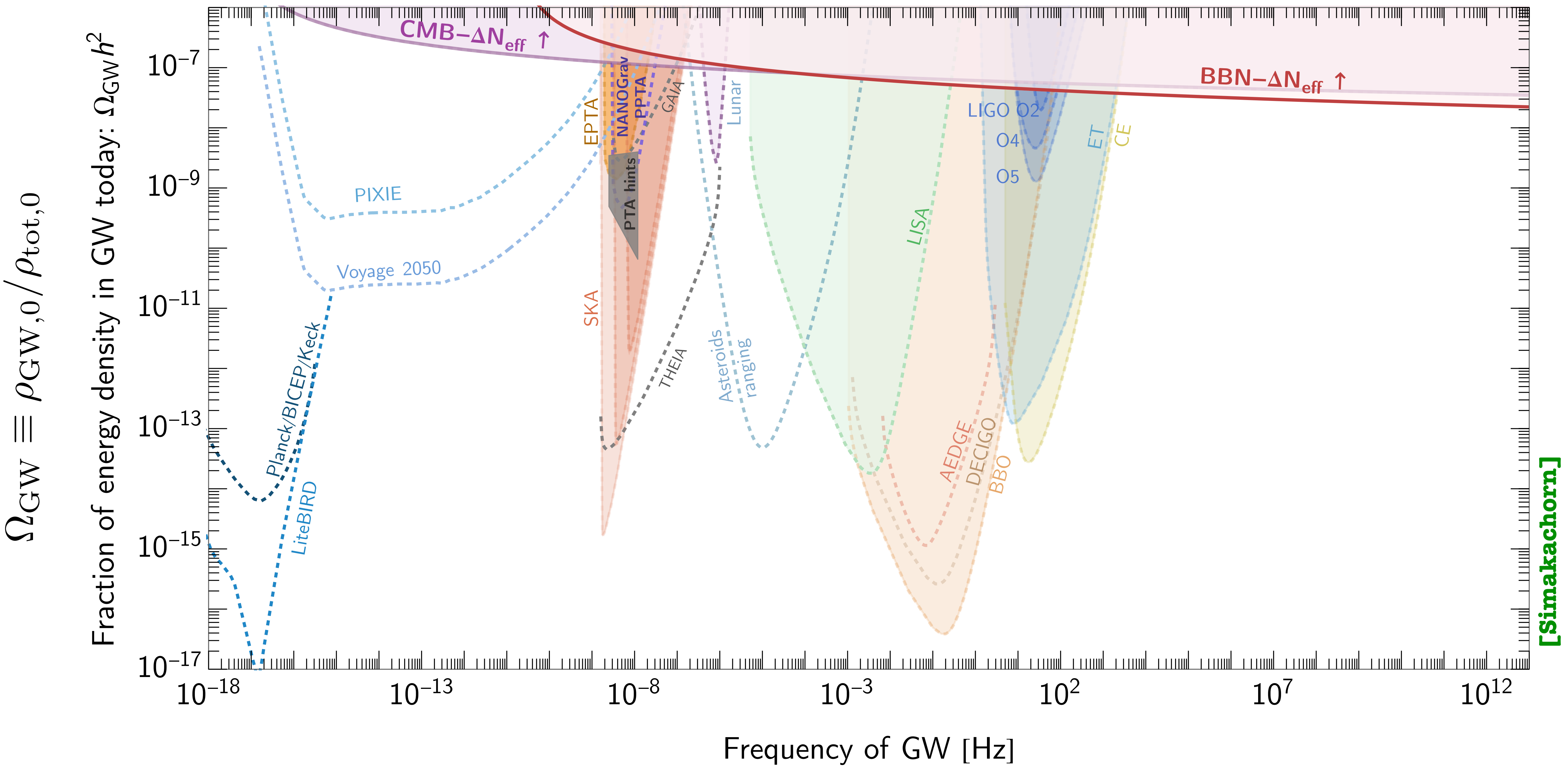
— 3 —
Gravitational-wave signatures of axion cosmology .

The landscape of current & future GW experiments.



Upper theoretical bound.

GW as extra radiation: $\int_{f_{\min}}^{f_{\max}} \frac{df}{f}\,\Omega_{\rm GW}(f) \lesssim 0.23\,\Omega_{\rm rad,0}\Delta N_{\rm eff}$ where $\Delta N_{\rm eff}^{\rm BBN,CMB} \lesssim 0.2$



Primordial GW .

Tensor perturbations of Friedmann-Robertson-Walker metric:

$$ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j]$$

Wave equation:

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

Source:

Tensor anisotropic stress

=Transverse Traceless component of the energy-momentum tensor of the source $= (P_{il}P_{jm} - \frac{1}{2}P_{ij}P_{lm})T_{lm}$

$P_{ij} = \delta_{ij} - \hat{k}_i\hat{k}_j$

Well-known cosmological sources .

-> Cosmological Phase Transitions

-> Cosmic Strings

-> Inflation

-> Reheating of the universe

see
-review 1801.04268
-1912.02569 (cosmic strings)
-PhD thesis P. Simakachorn

Characteristic Frequencies for causal (and short-lasting) sources

T_* **temperature of the universe at time of emission**

f_* **frequency at time of emission**

observed frequency: $f \sim f_* \frac{T_0}{T_*} \sim \mathcal{O}(H_*) \frac{T_0}{T_*} \sim \frac{T_*}{M_{Pl}} T_0 \sim T_* \times 10^{-18} 10^{-12}$ **GeV**

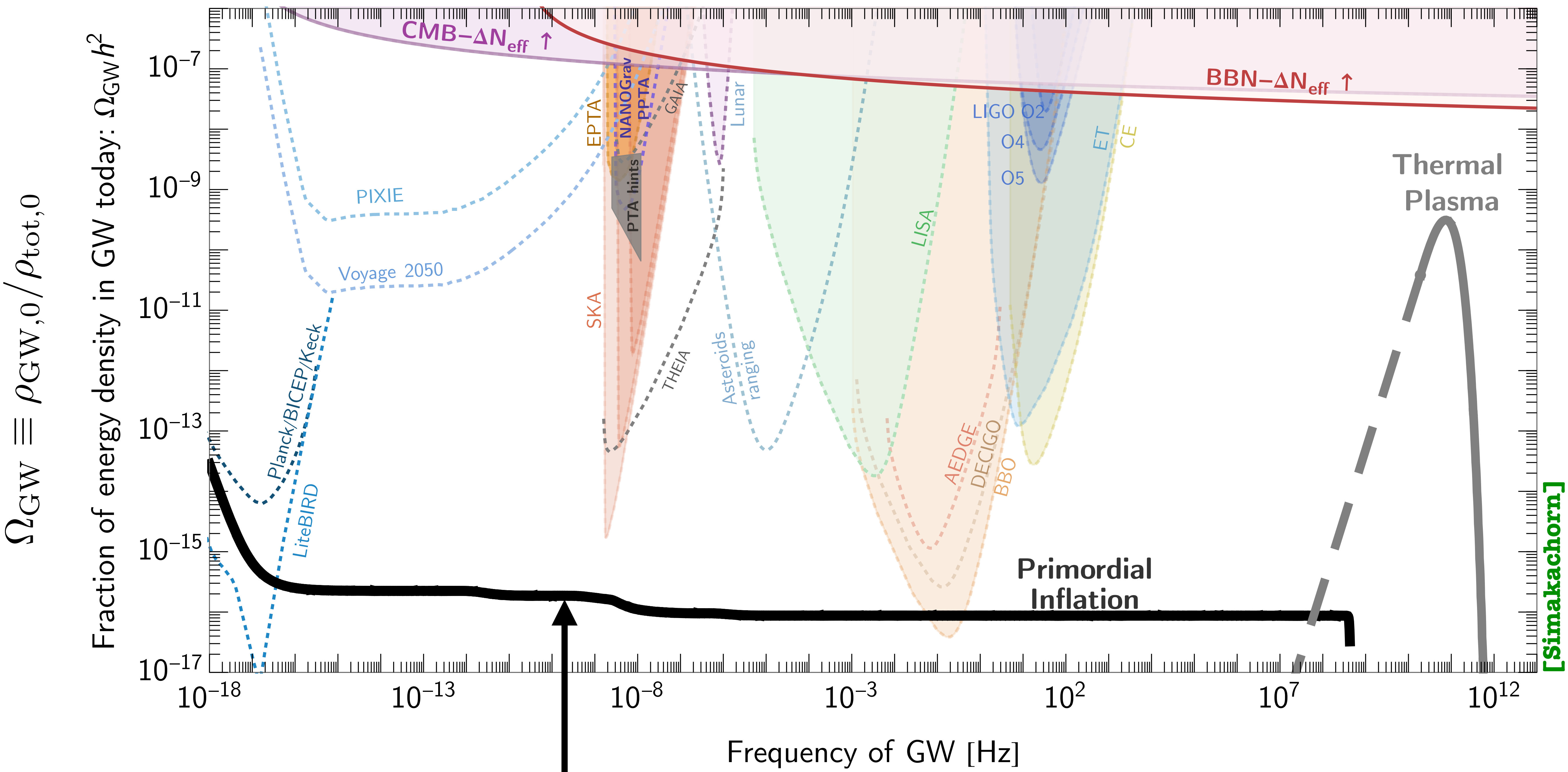
If T_* **~ 100 GeV:**

$$f \sim 10^{-28} \text{ GeV} \sim 10^{-28} \times 10^{25} \text{ Hz} \sim \text{mHz}$$

LISA !

Standard Model sources of primordial GW.

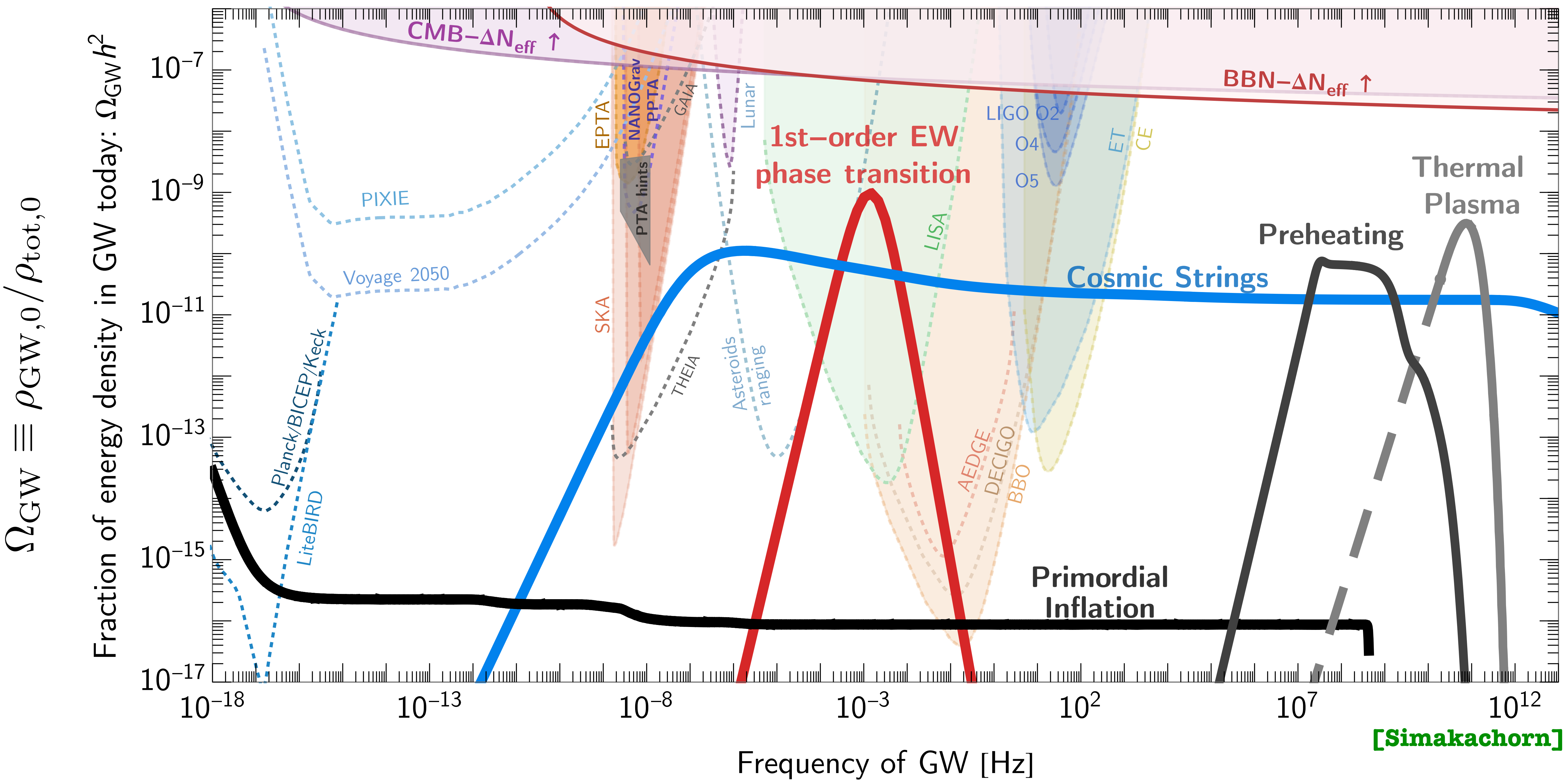
Primordial inflation & Standard Model thermal plasma



Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

Beyond-the-Standard Model sources.

Preheating, first-order phase transitions, cosmic strings



Reading the history of the universe.

GW frequency $f_{\mathrm{GW},0} \simeq \lambda_{\mathrm{GW}}^{-1}\left(\frac{a_{\mathrm{prod}}}{a_0}\right)$

Low-freq. limit

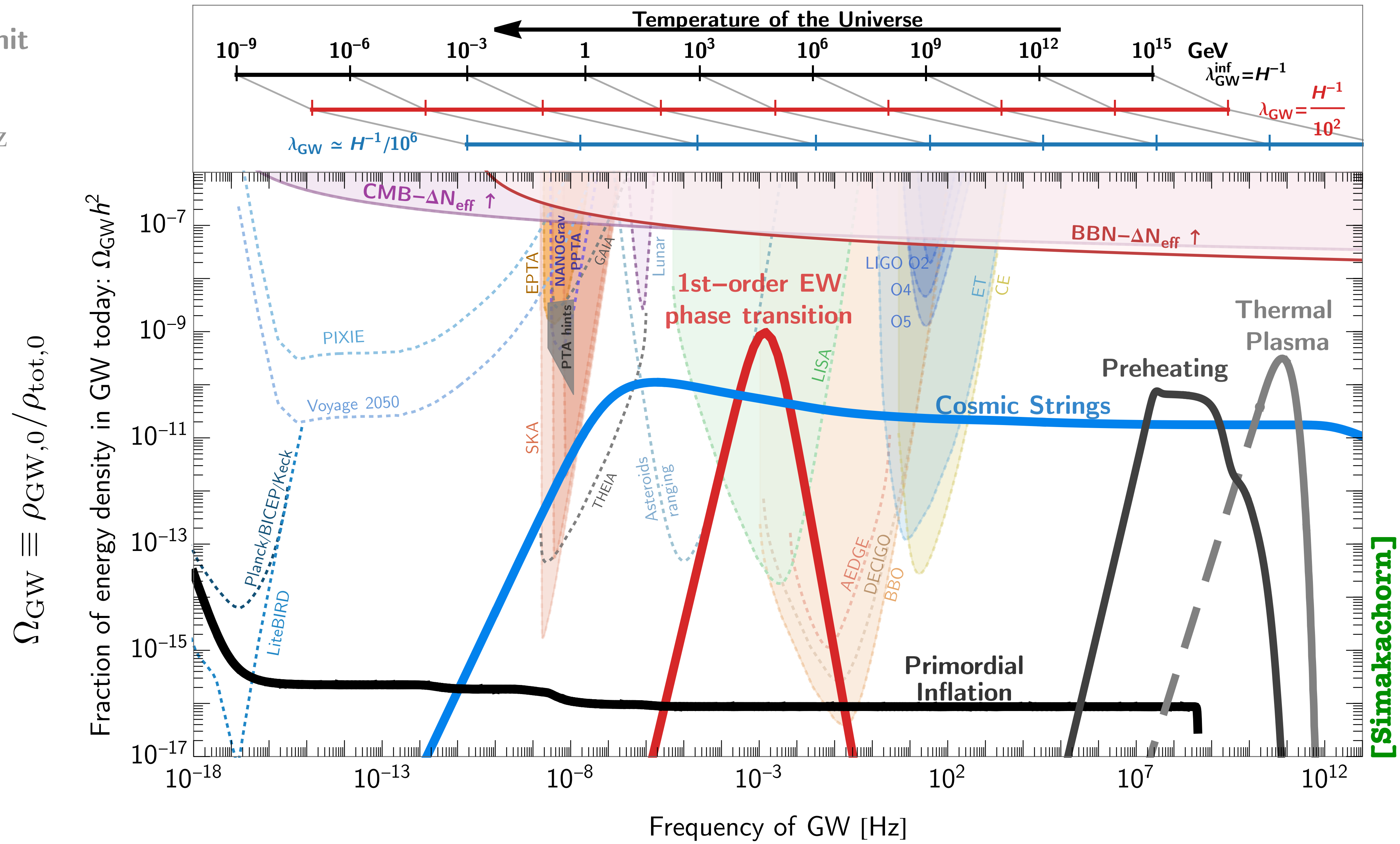
$f_{\mathrm{GW}}^{\min} \simeq H_0^{-1}$

$\simeq 10^{-18}$ Hz

High-freq. limit

$f_{\mathrm{GW}}^{\max} \simeq 10^{13}$ Hz

$(\lambda_{\mathrm{GW}} \sim H^{-1} \sim M_{\mathrm{pl}}^{-1})$



Reading the history of the universe.

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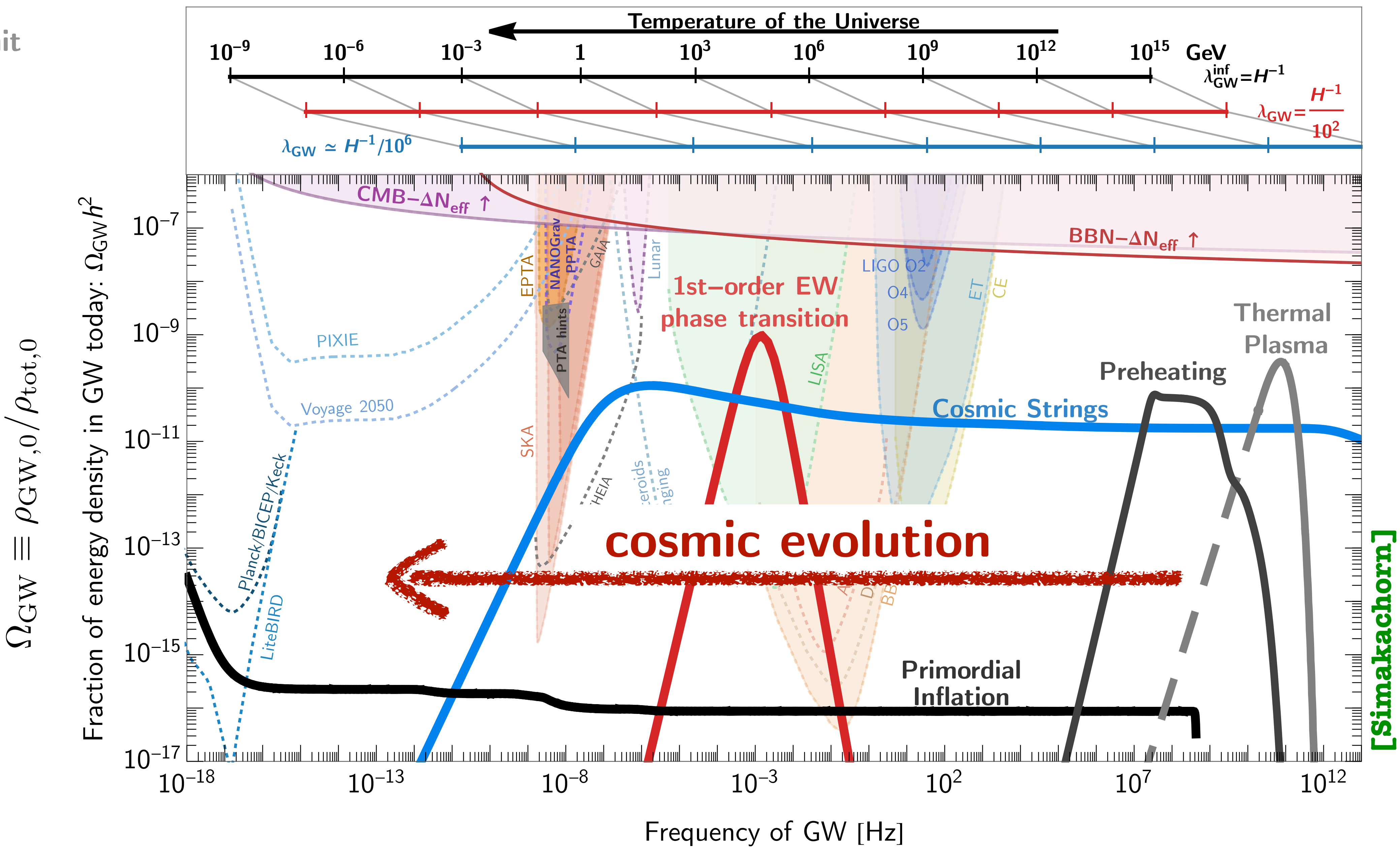
$$f_{\mathrm{GW}}^{\min} \simeq H_0^{-1} \simeq 10^{-18}\ \mathrm{Hz}$$

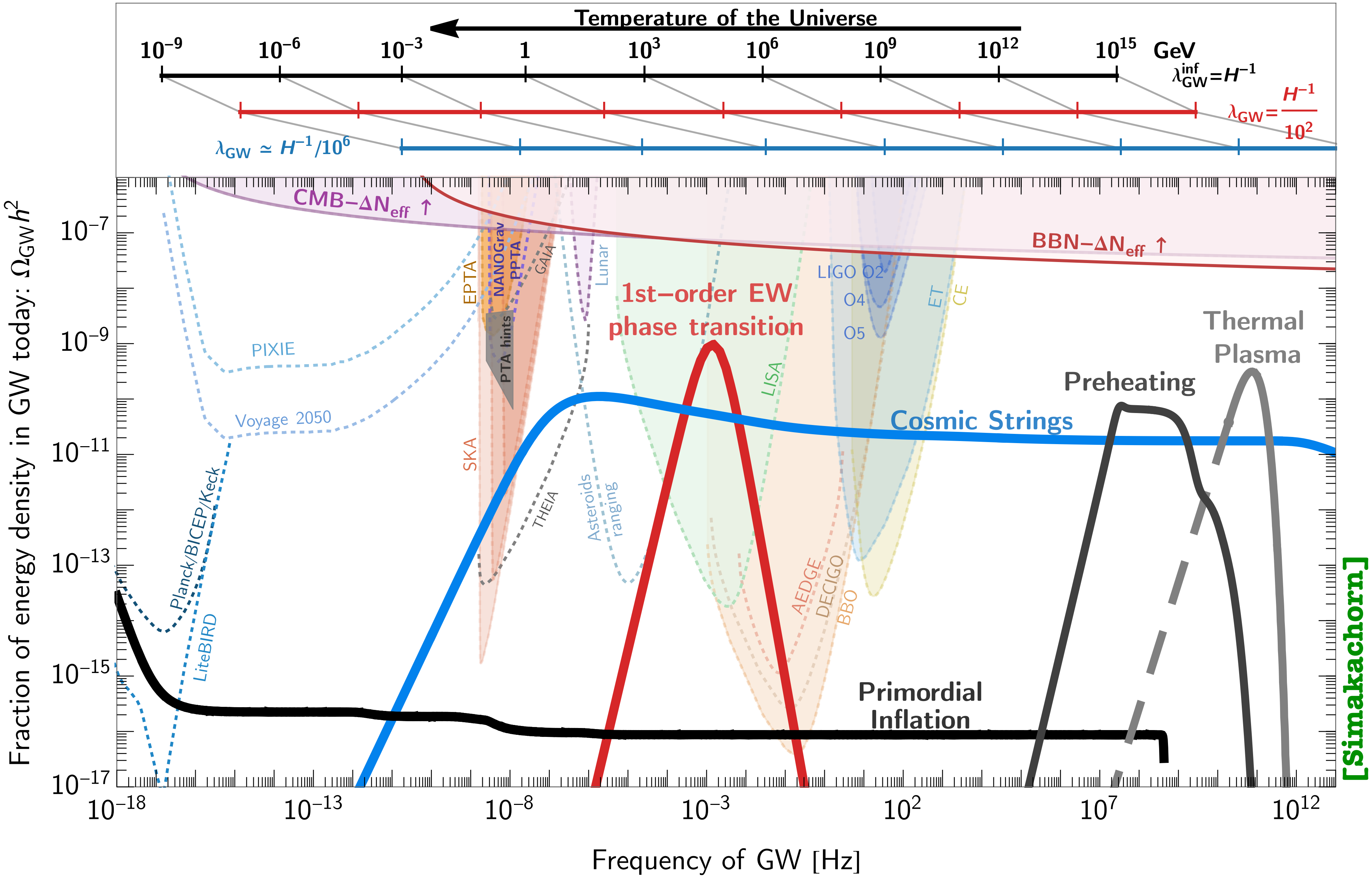


High-freq. limit

$$f_{\mathrm{GW}}^{\max} \simeq 10^{13}\ \mathrm{Hz}$$
$$(\lambda_{\mathrm{GW}} \sim H^{-1} \sim M_{\mathrm{pl}}^{-1})$$

GW spectra are sensitive to the cosmological history.

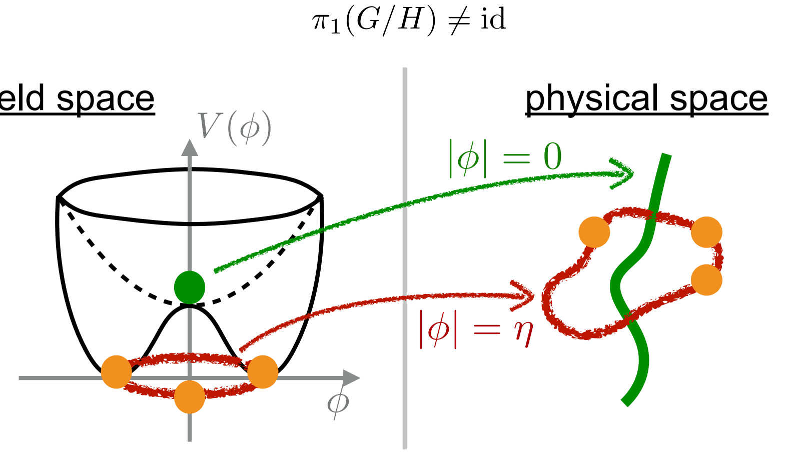
frequency $f_{\mathrm{GW},0} \simeq \lambda_{\mathrm{GW}}^{-1}\left(\frac{a_{\mathrm{prod}}}{a_0}\right)$ **energy density** $\rho_{\mathrm{GW},0} \simeq \rho_{\mathrm{GW}}^{\mathrm{prod}}\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4$

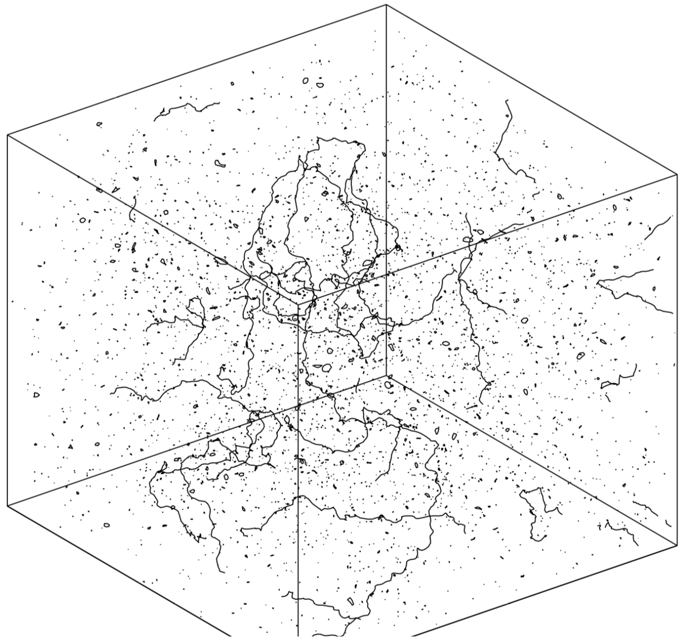


Standard Model radiation era at high energies

What if the universe is not radiation-dominated at high energies?

Gravitational Waves from cosmic strings.



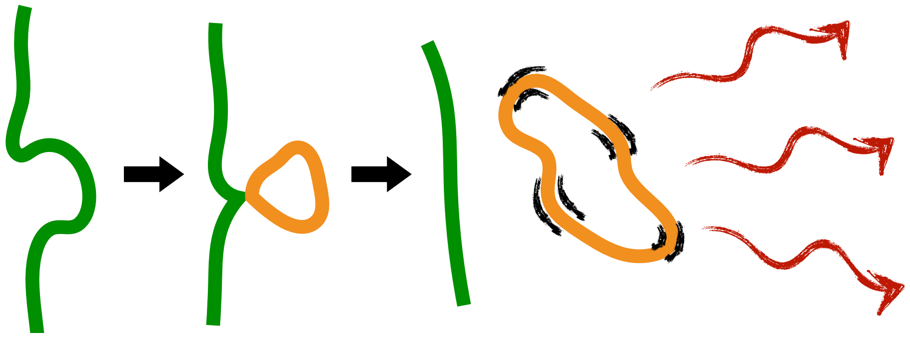


Network of cosmic strings

[Allen & Shellard, 1990]

Cosmic strings:

Long-lasting source of GW



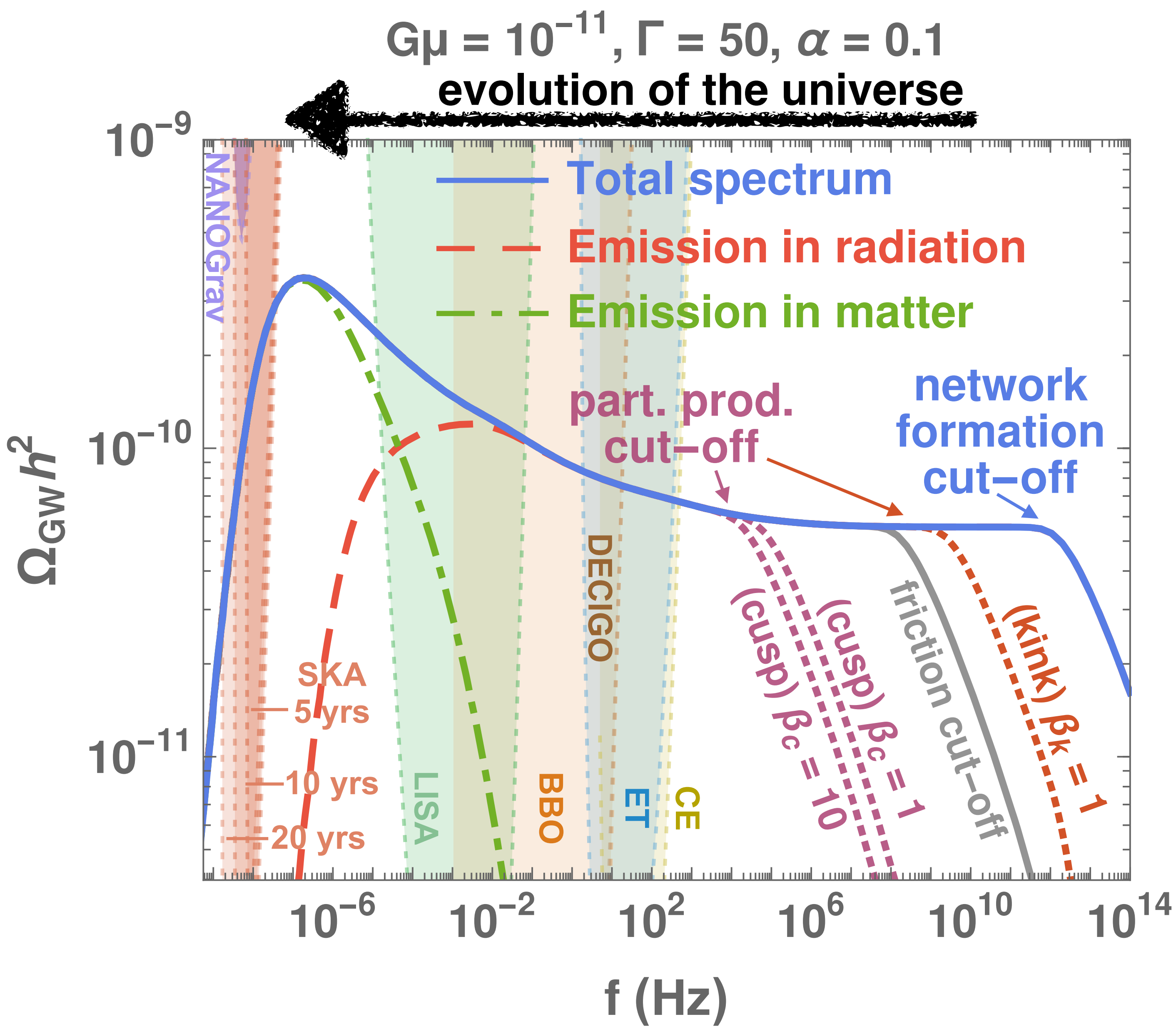
string tension: $\mu \sim \eta^2$

recent review:

JCAP 07 (2020) 032, [1912.02569].

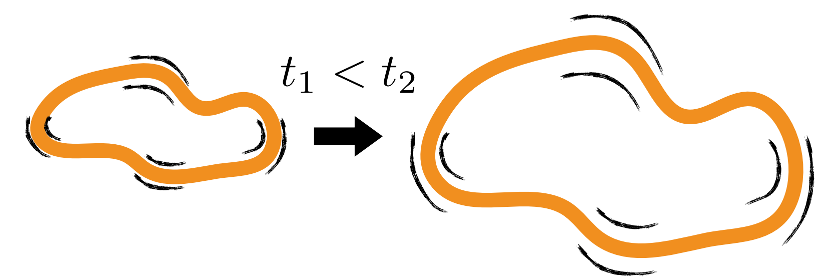
Gravitational Waves from Cosmic strings.

(long-lasting sources).



[1912.02569]

Higher f ⇔ Earlier emission



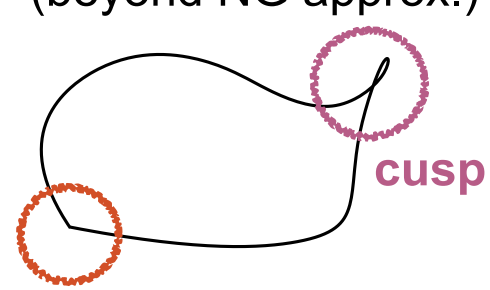
smaller loop ⇔ higher oscillation f

@ earlier t_i

more GW from more loops
but more red-shift

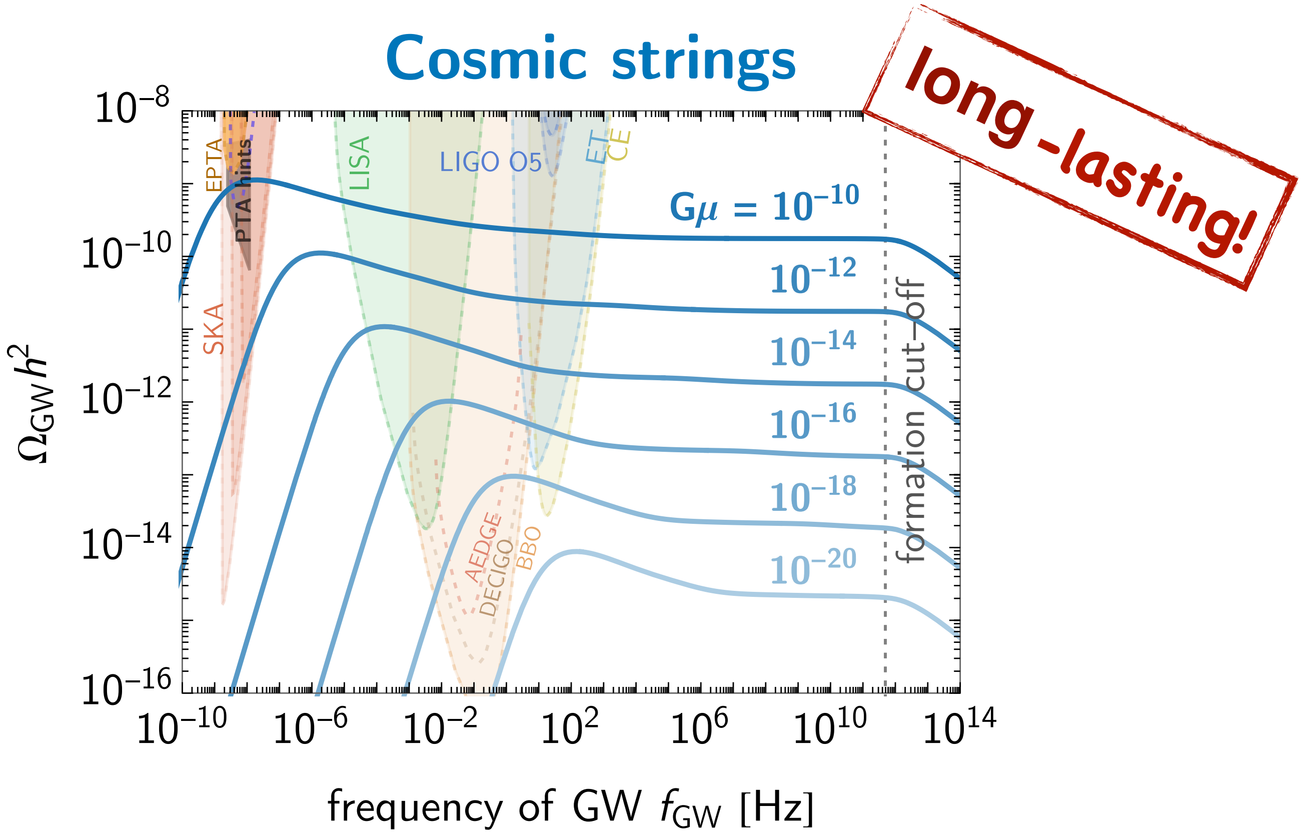
⇨ Flat during radiation

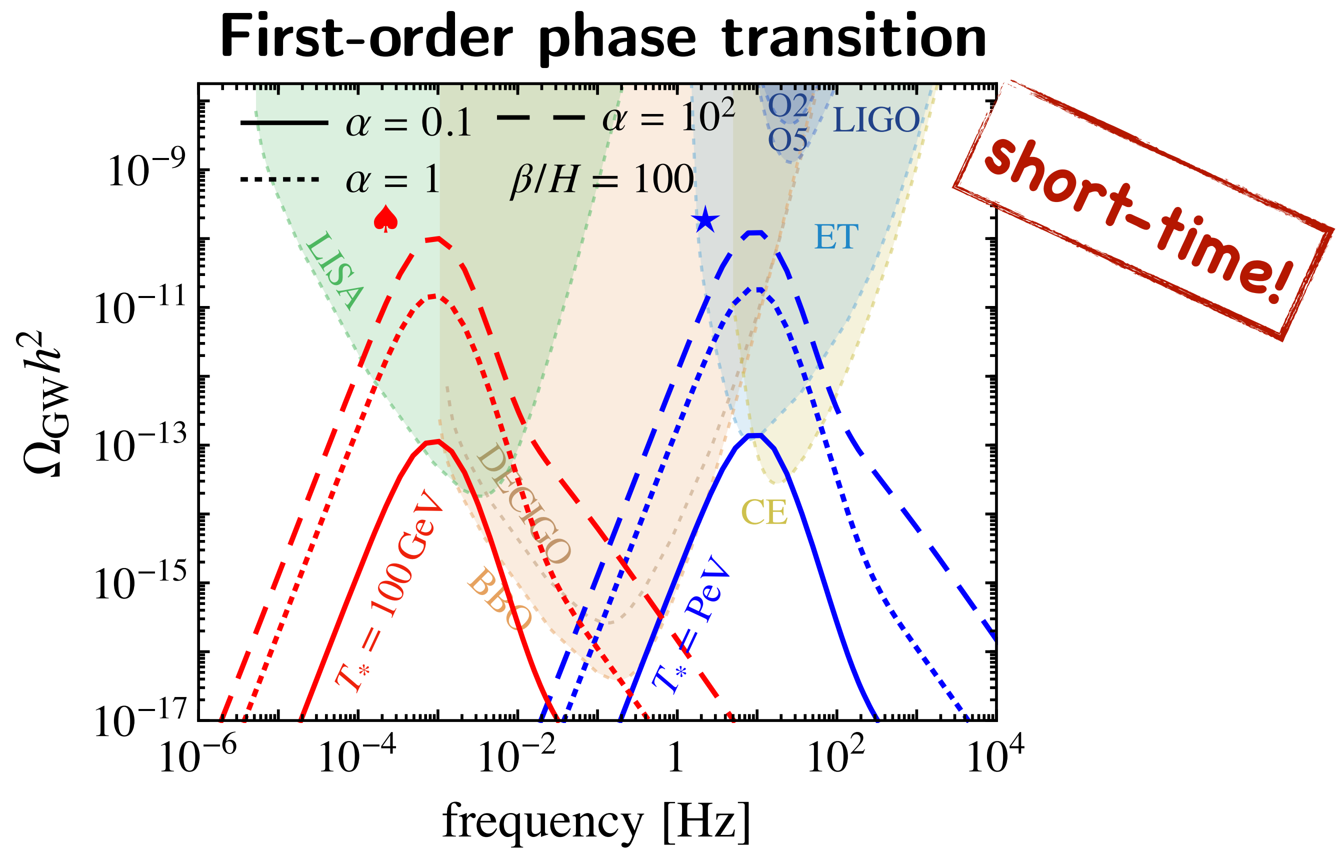
singular structures on loop
(beyond NG approx.)



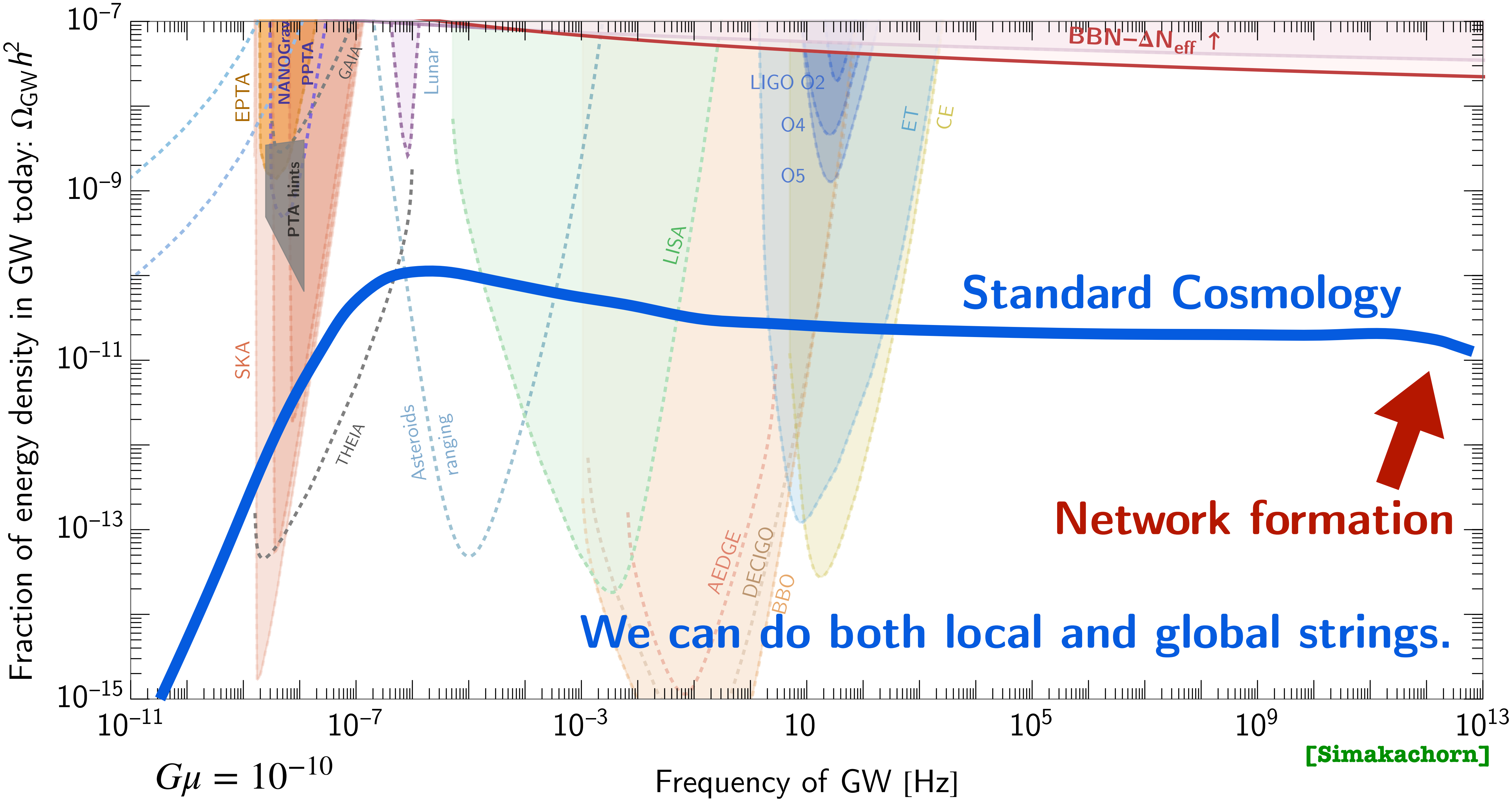
lead to particle emission

Short-lasting vs long-lasting primordial sources.



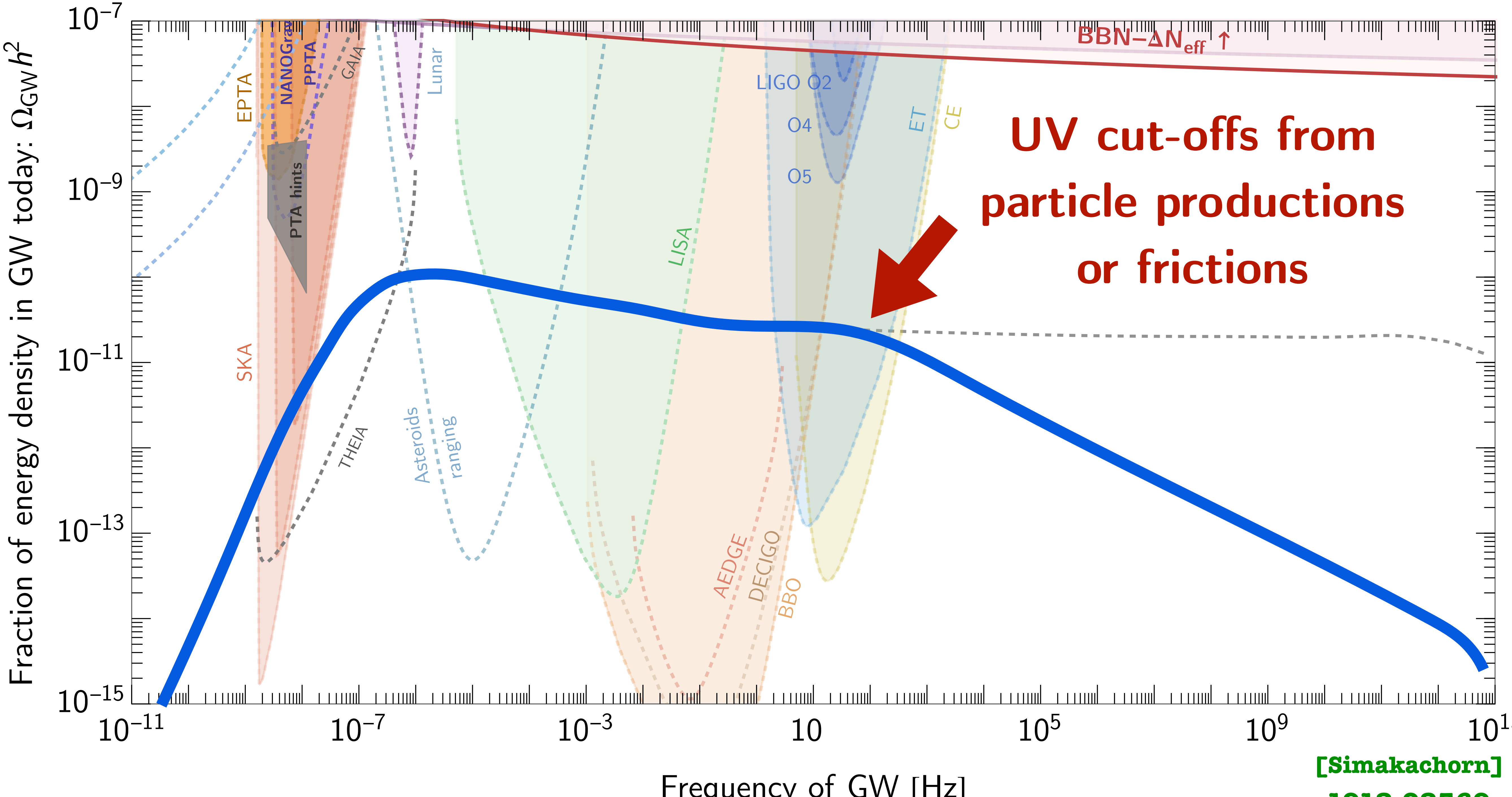


Gravitational Waves from cosmic strings.



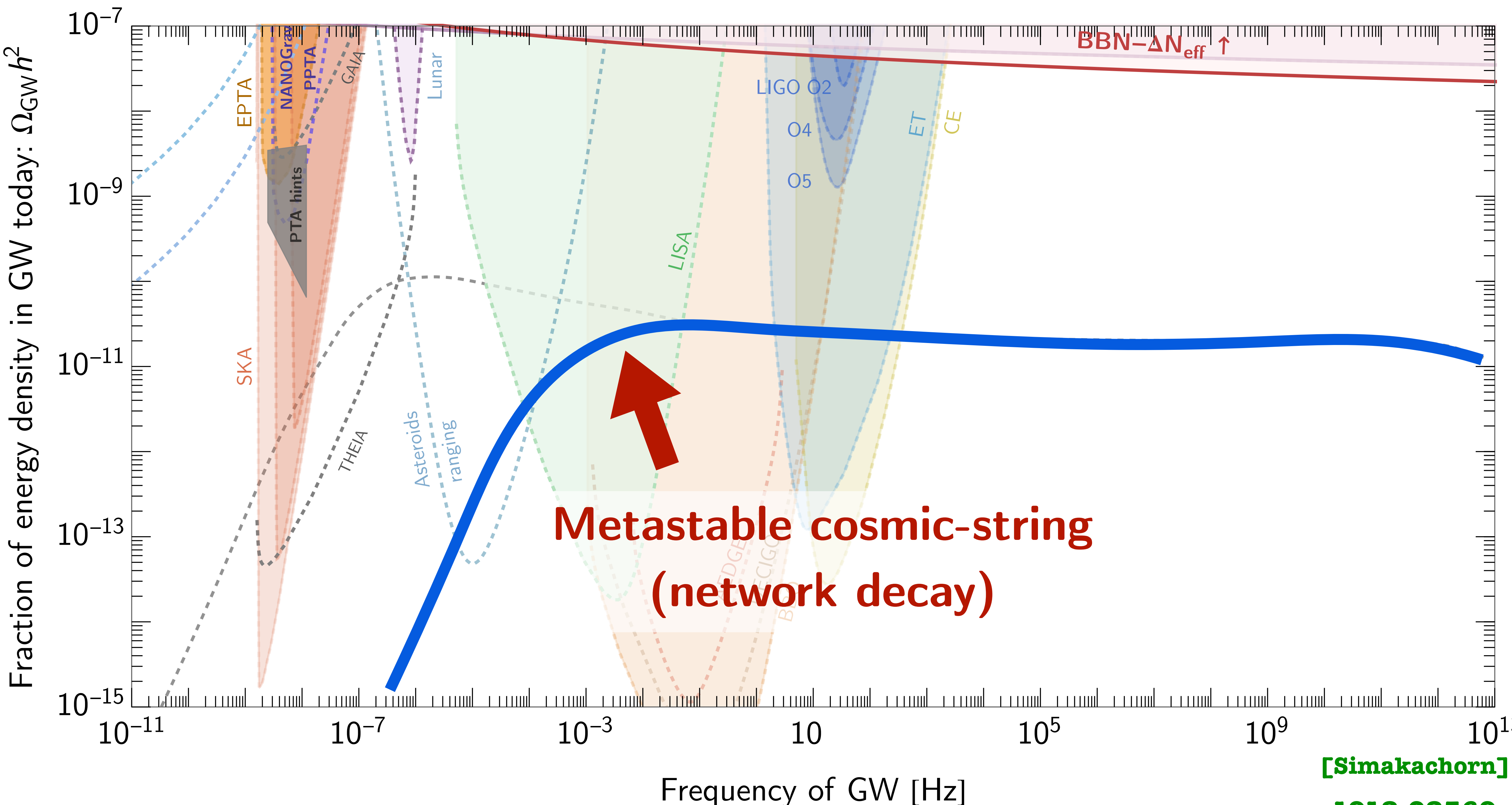
$G\mu = 10^{-10}$

Gravitational Waves from cosmic strings.



[Simakachorn] 1912.02569

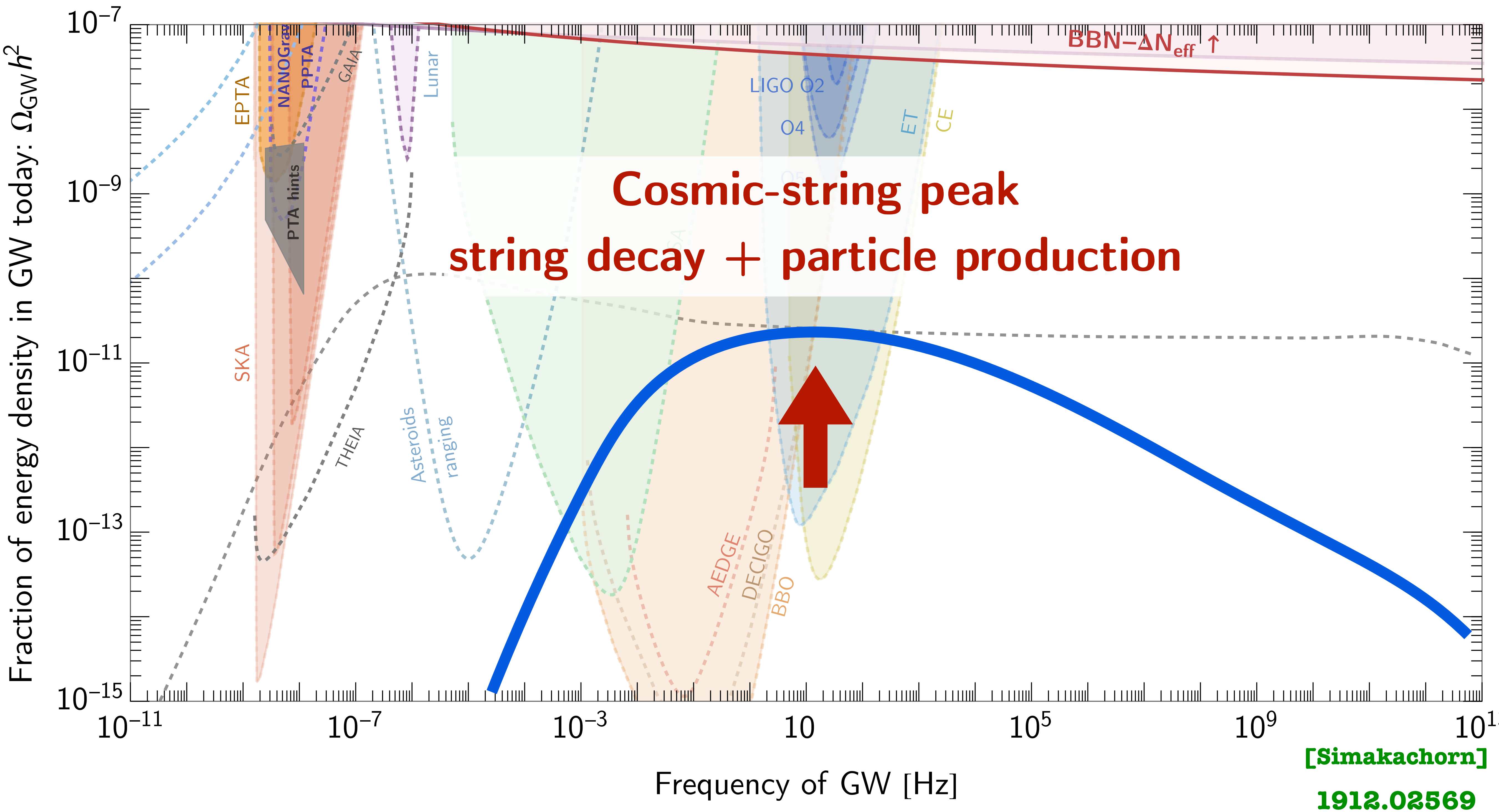
Gravitational Waves from cosmic strings.



[Simakachorn]

1912.02569

Gravitational Waves from cosmic strings.

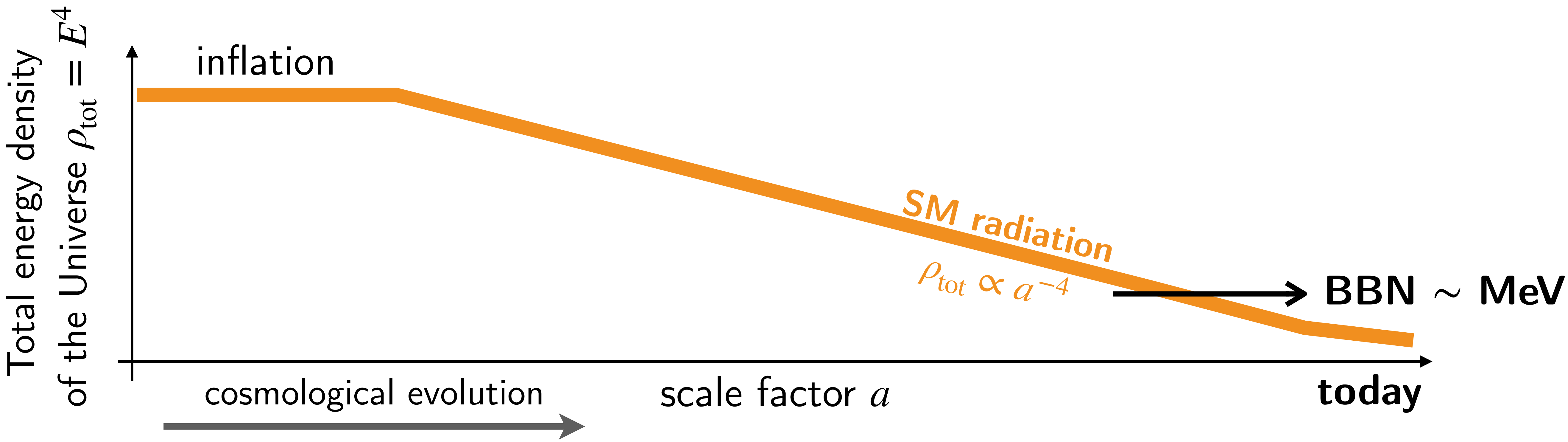


[Simakachorn]

1912.02569

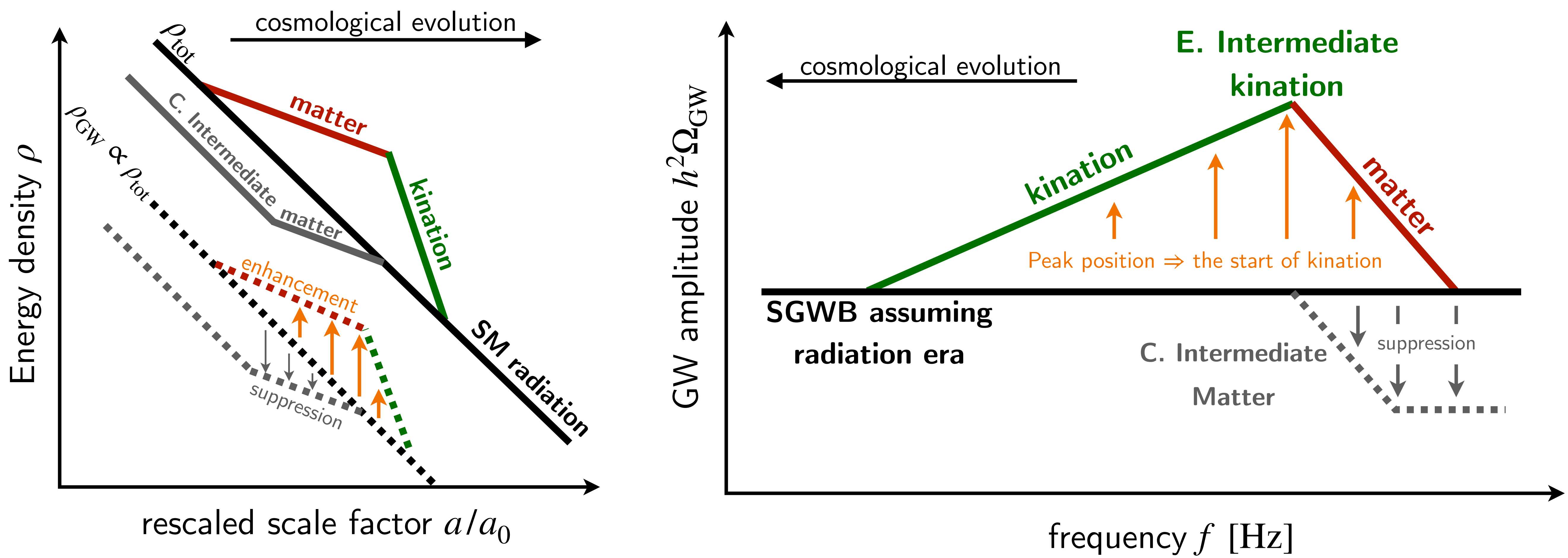
Effect of non-standard cosmology on the GW spectrum.

Standard cosmological history



Impact of the cosmological history on Gravitational Waves:

[1912.02569] [2111.01150]

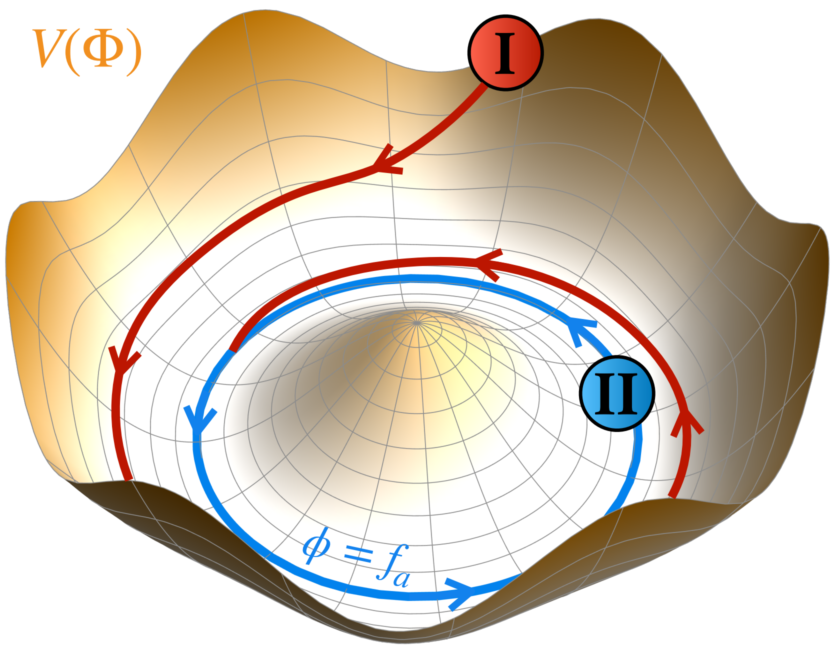


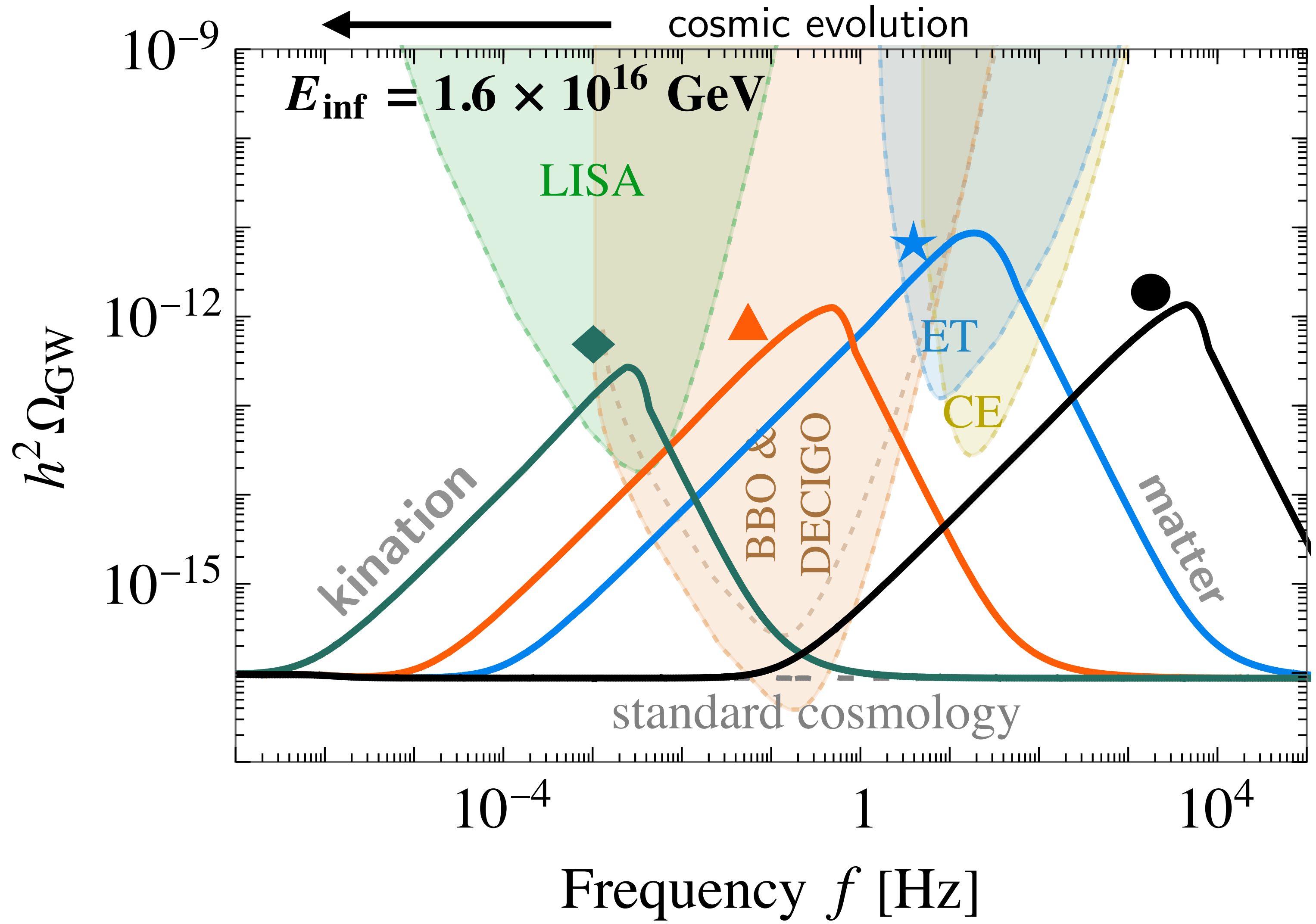
Fraction of energy density in GW today

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

Non-standard cosmology from rotating axions.

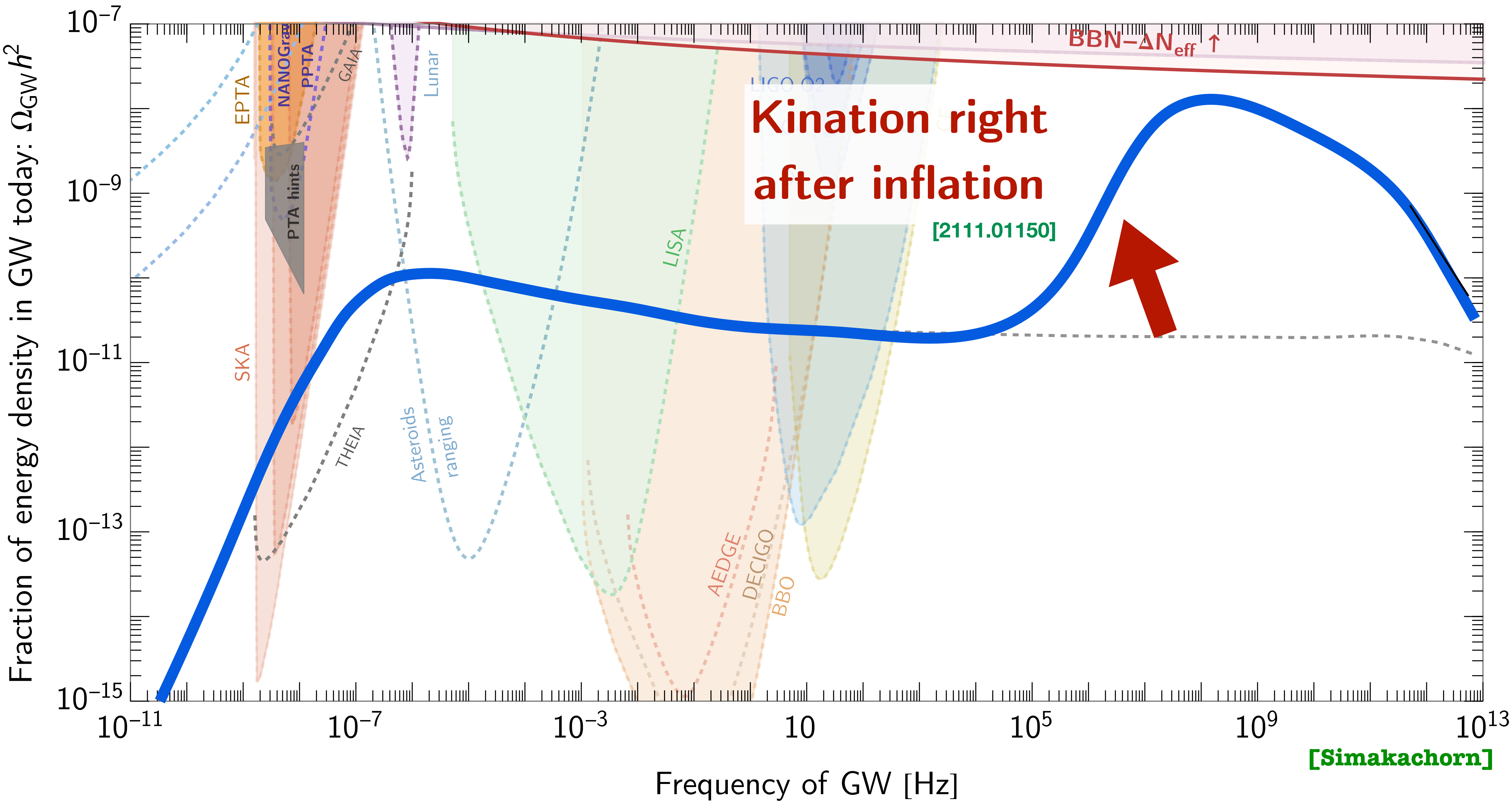
Amplification of inflationary GW from axion-induced kination era





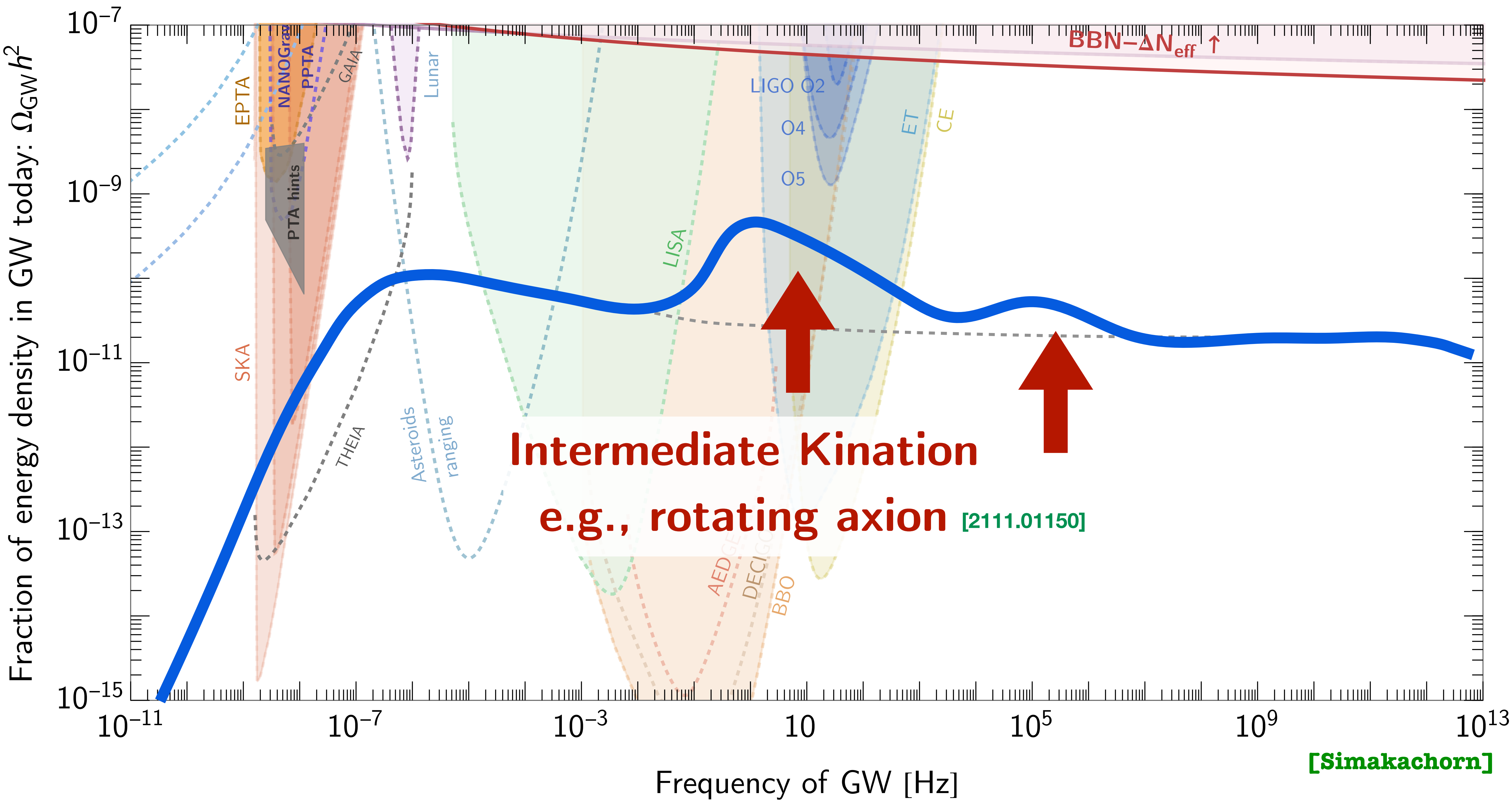
[Gouttenoire, Servant, Simakachorn, 2108.10328 & 2111.01150]

Gravitational Waves from cosmic strings in non-standard cosmology.



[Simakachorn]

Gravitational Waves from cosmic strings in non-standard cosmology.



A new window of observation in the NanoHertz with Pulsar Timing Arrays.

Pulsar Timing Arrays (PTAs) .

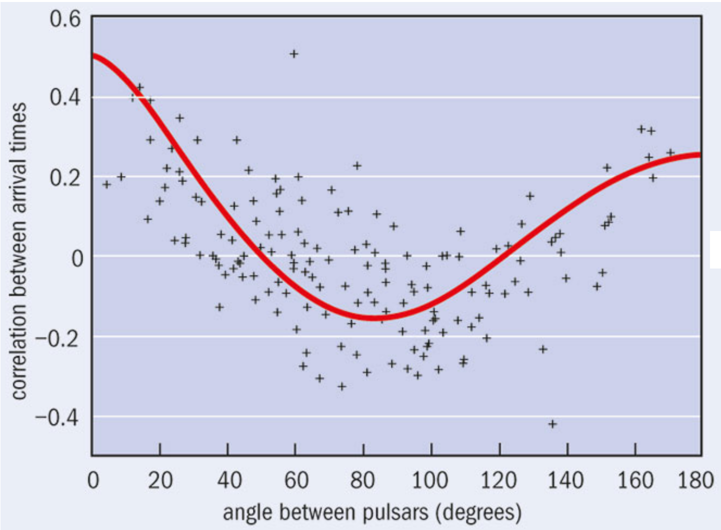
Array of pulsars across the Milky Way → GW detector of galactic dimensions!

Look for tiny distortions in pulse travel times caused by nanohertz GWs.

Measure times of arrival and compare to predictions from a timing model.

sensitive to GW with $f \gtrsim 1/T$

T: observation time



Timing residuals for each individual pulsar

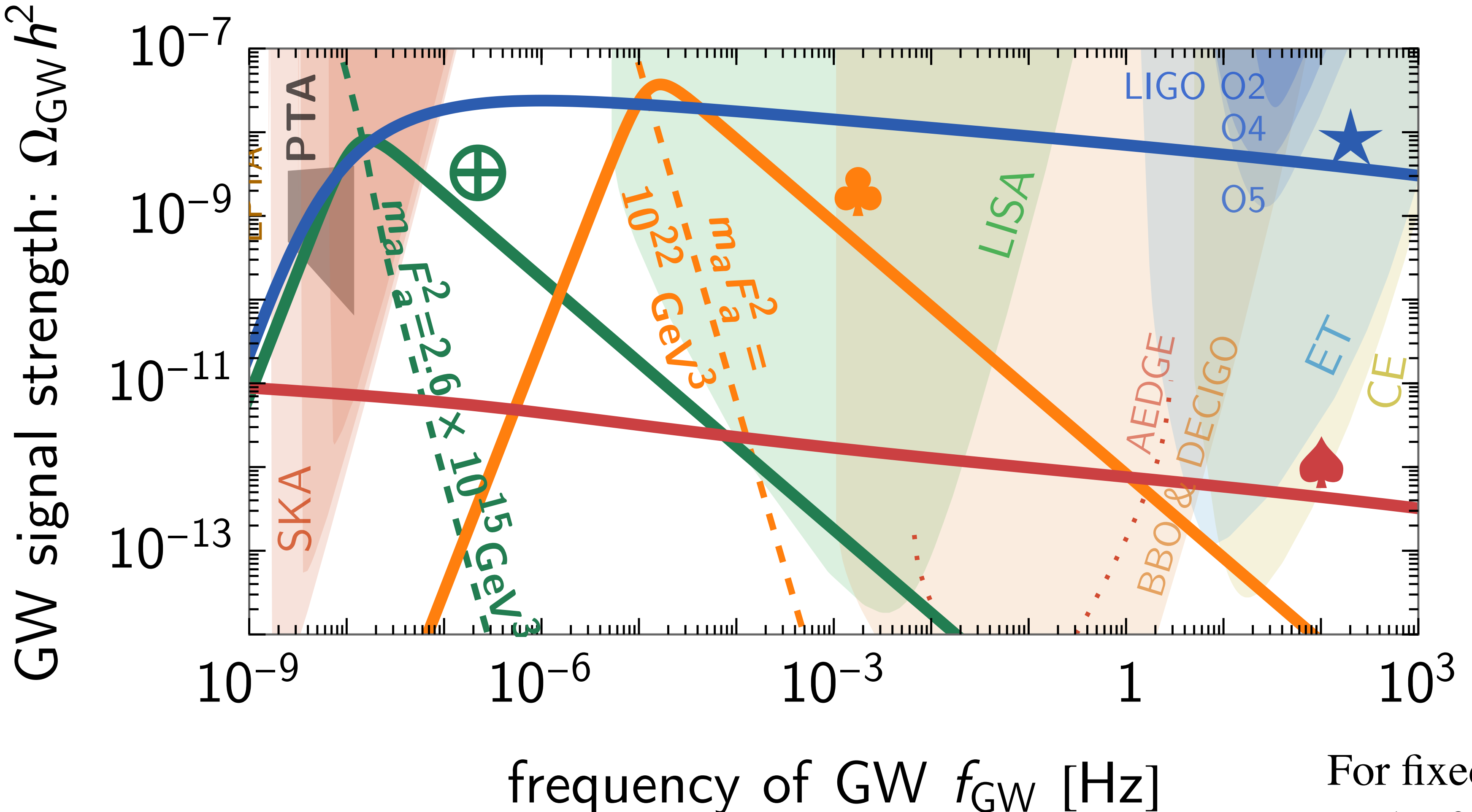
→ GW signature in cross-correlations between arrival times

Hellings–Downs curve

Constraining post-inflationary axions with Pulsar Timing Arrays.

[Servant, Simakachorn, 2307.03121

Stochastic GW background from axionic strings {★, ♠} & domain walls {⊕, ♣}



For fixed {ma,fa} values, the peak of the DW-GW spectrum moves along the dashed line.

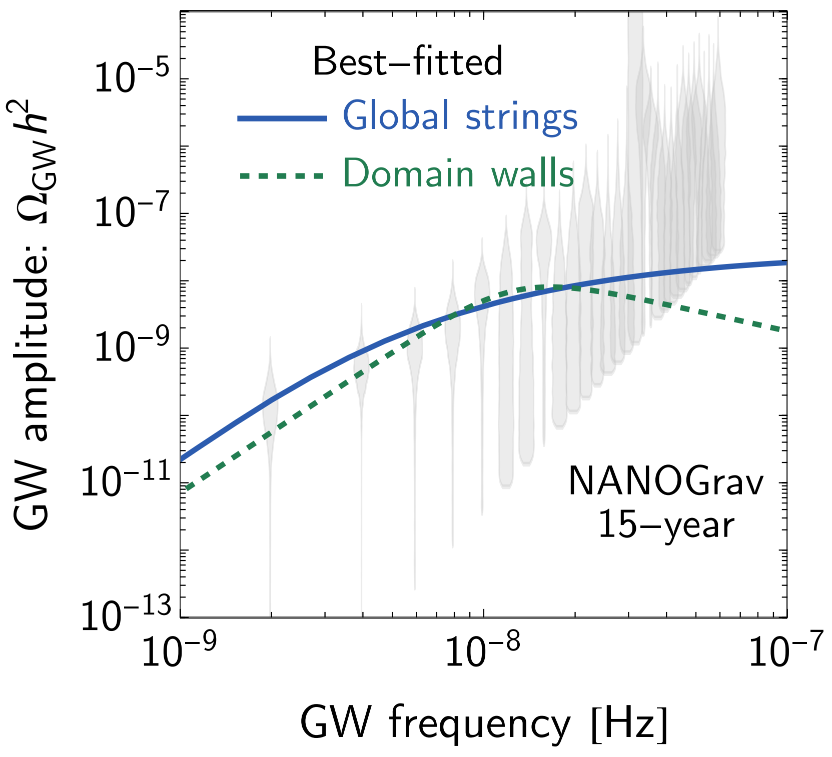
Domain walls decay at T⋆ = {128 MeV, 10^2 GeV} for {⊕, ♣}).

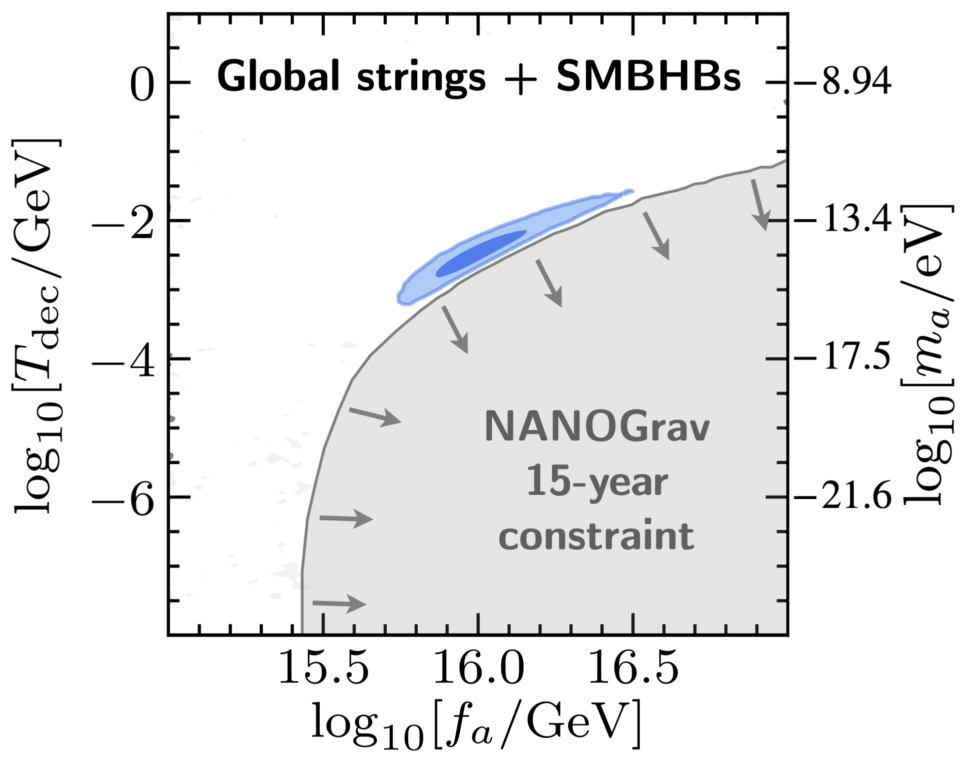
Best-fitted spectra to PTA data: ★ for global strings

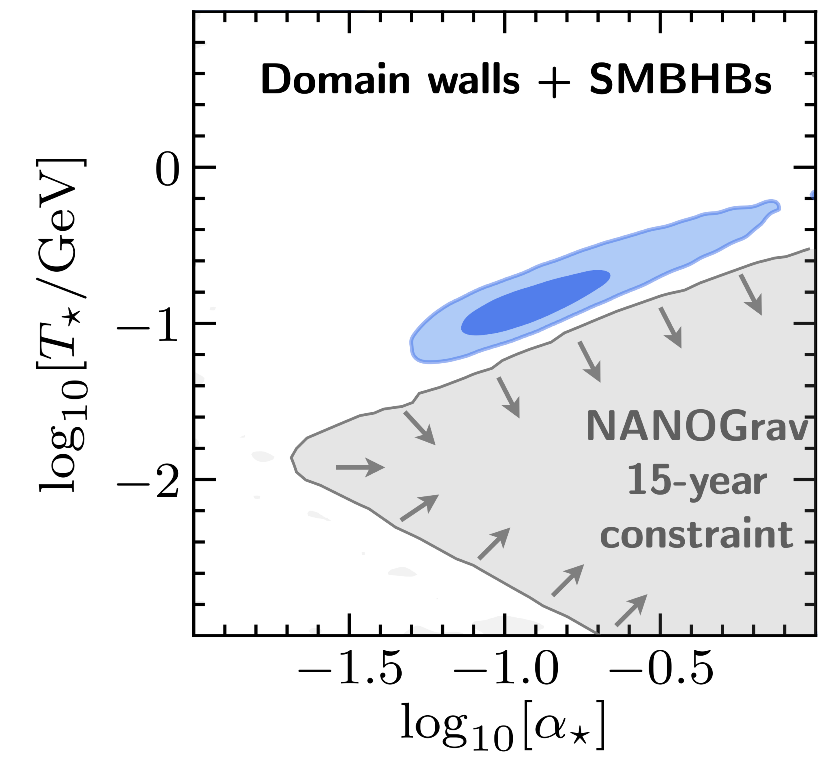
(corresponding to {fa, ma} ≃ {$9.9 \cdot 10^{15}$ GeV, $4.8 \cdot 10^{-15}$ eV})

Constraints from NANOGrav-15 years.

[Servant, Simakachorn, 2307.03121







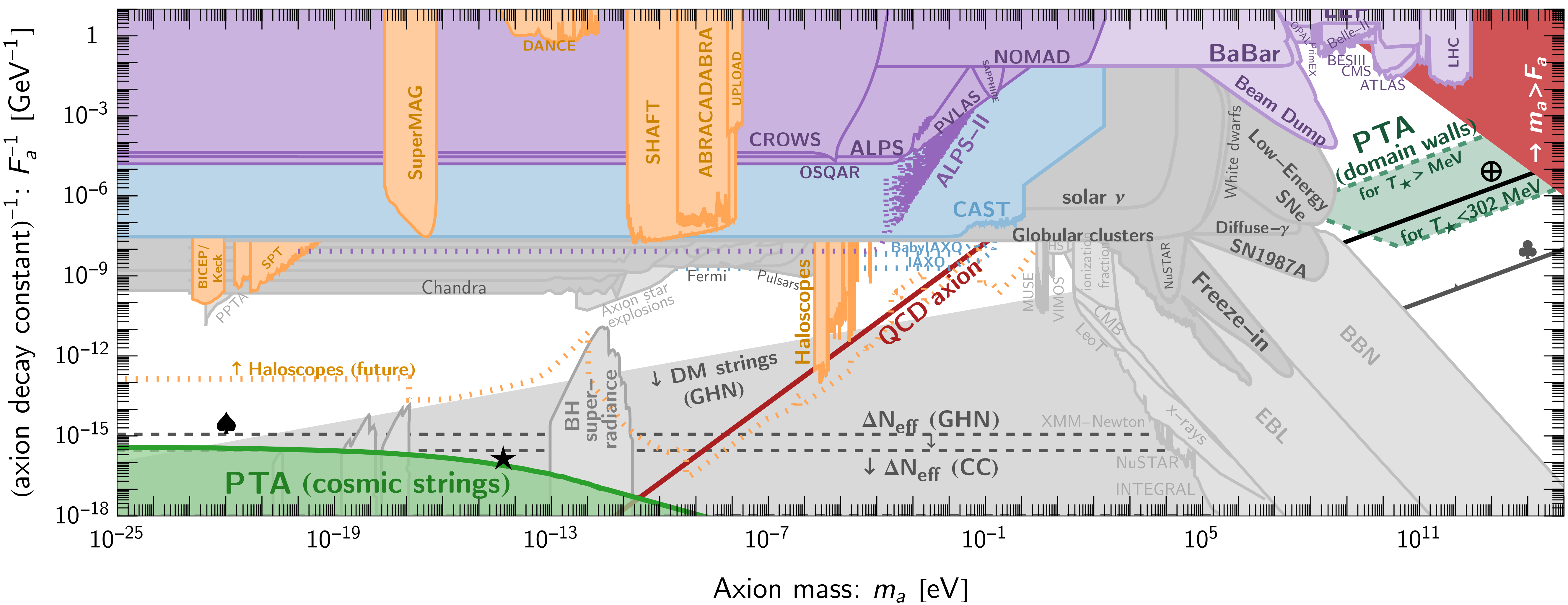
Best-fitted spectra to PTA data:

Domain walls decay $T_\star$ = 128 MeV, $m_a F_a^2 = 2.6 \cdot 10^{15}$ GeV^3

Global strings $\{f_a, m_a\} \simeq \{9.9 \cdot 10^{15}$ GeV, $4.8 \cdot 10^{-15}$ eV$\}$)

Constraining post-inflationary axions with Pulsar Timing Arrays

[Servant, Simakachorn, 2307.03121



Conclusion.

- Axion cosmology: rich phenomenology still to be explored.
  Huge parameter space (axion mass, axion decay constant)
  Many experimental probes:
  laboratory (haloscopes, helioscopes, light-shining-through-the-wall experiments),
  astronomical observations (gravitational lensing),

- Gravitational waves: complementary probes of

  Axion physics (its early universe dynamics, before/during/after inflation)

- Cosmological solutions to the Higgs hierarchy problem:
  e.g. relaxion: Higgs-axion cosmological interplay.
  New paradigm, new opportunities.

Extra material.

axion: particularly motivated by Strong CP problem

Strong CP pb:

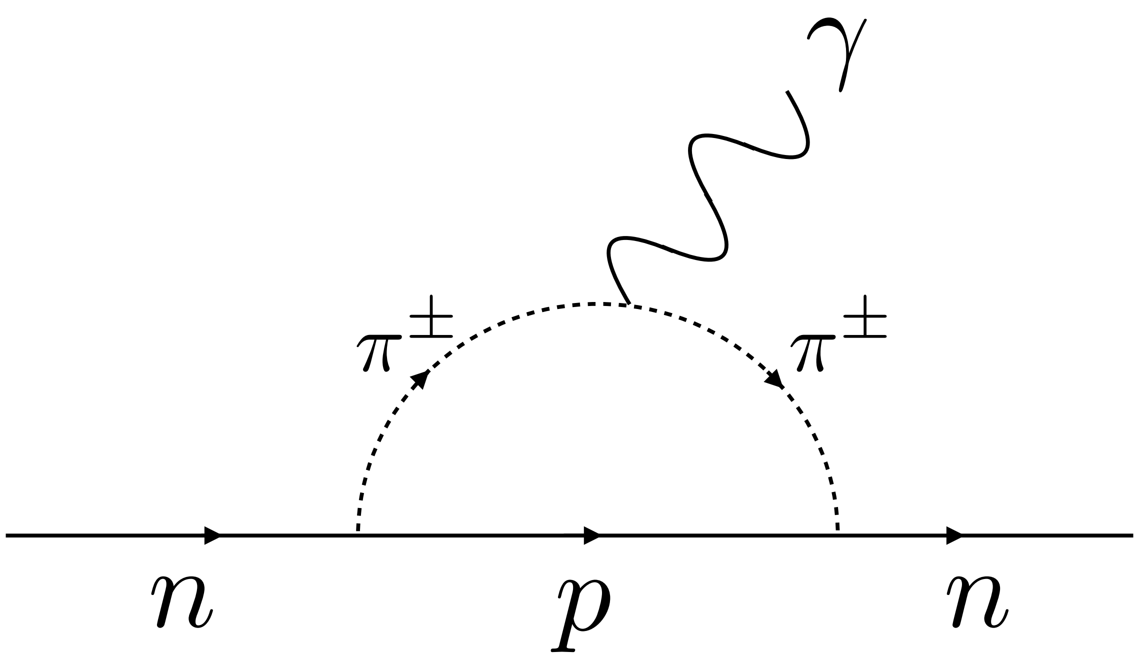
Why is the neutron electric dipole moment (EDM) so small?

$$\mathcal{L} \supset d_n F_{\mu\nu} \overline{n} \gamma^{\mu\nu} i\gamma_5 n.$$

$$iM = 2 d_n \epsilon^*_\mu(q) \overline{u}(p') \gamma^{\mu\nu} q_\nu i\gamma_5 u(p).$$

$$d_n \sim 3 \times 10^{-16}\, \overline{\theta}\, \mathrm{e\ cm}.$$

where $\mathcal{L}_{QCD} \supset -\frac{\overline{\theta}}{32\pi^2} G\tilde{G}$



comparing to the experimental bound leads to

$$\overline{\theta} \lesssim 10^{-10}$$

can be beautifully solved by introducing an axion.

Equation of motion of complex scalar field in expanding universe

$$\ddot{\Phi} - a^{-2}\nabla^2\Phi + 3H\dot{\Phi} + \frac{\partial V}{\partial \Phi^\dagger} = 0$$

with $\Phi = \phi e^{i\theta}$

$$\ddot{\phi} - a^{-2}\nabla^2\phi + 3H\dot{\phi} + V'(\phi) = \phi\dot{\theta}^2 - a^{-2}\phi(\nabla\theta)^2,$$
$$\phi\ddot{\theta} - a^{-2}\phi\nabla^2\theta + 3H\phi\dot{\theta} = -2\dot{\phi}\dot{\theta} + 2a^{-2}\nabla\phi\nabla\theta.$$

For homogeneous field, these are Kepler problem:

centrifugal force

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = \phi\dot{\theta}^2$$

coriolis force

$$\ddot{\theta} + 3H\dot{\theta} = -2\frac{\dot{\phi}}{\phi}\dot{\theta}$$

conservation of charge (angular momentum):

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

Ingredients 1 & 2 : scalar potential

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

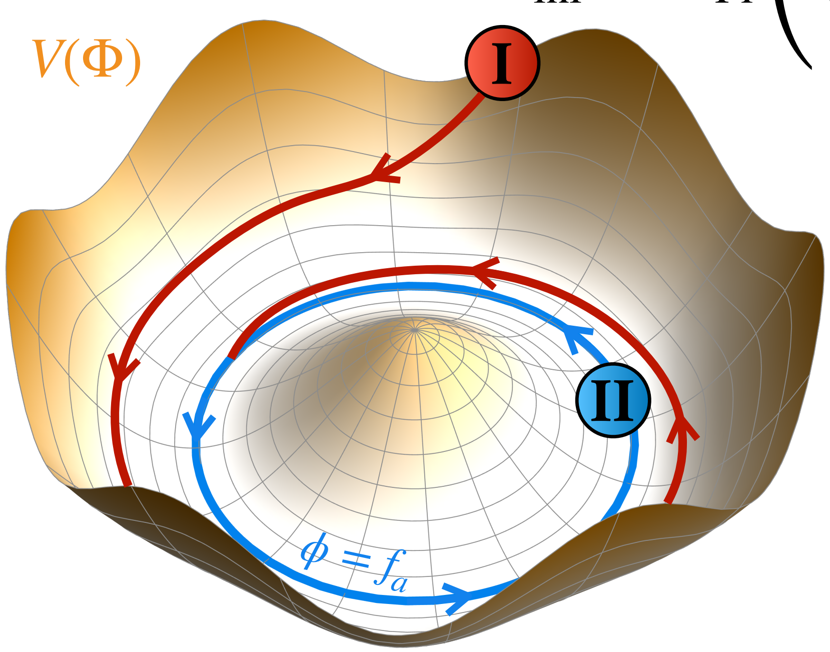
I. $U(1)$-conserving potential
(quadratic)
with a minimum f_a

(motivated by supersymmetric setups)

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

stabilization
i.e., at large $|\Phi|$

$$\phi_{\rm ini} \simeq M_{\rm Pl} \left(\sqrt{\frac{c}{\lambda^2}} \cdot \frac{m_r}{M_{\rm Pl}}\right)^{1/(l-2)}$$



Ingredient 3 : large initial VEV $\phi_{\rm ini}$

By adding a negative Hubble mass

$$V_H(\Phi, H) \supset -cH^2 |\Phi|^2$$

ϕ is driven away from $\phi = 0$ at early times $(H \gg m_r)$

(e.g. Dine, Randall, Thomas, 1995, Fujita & Harigaya 1607.07058)

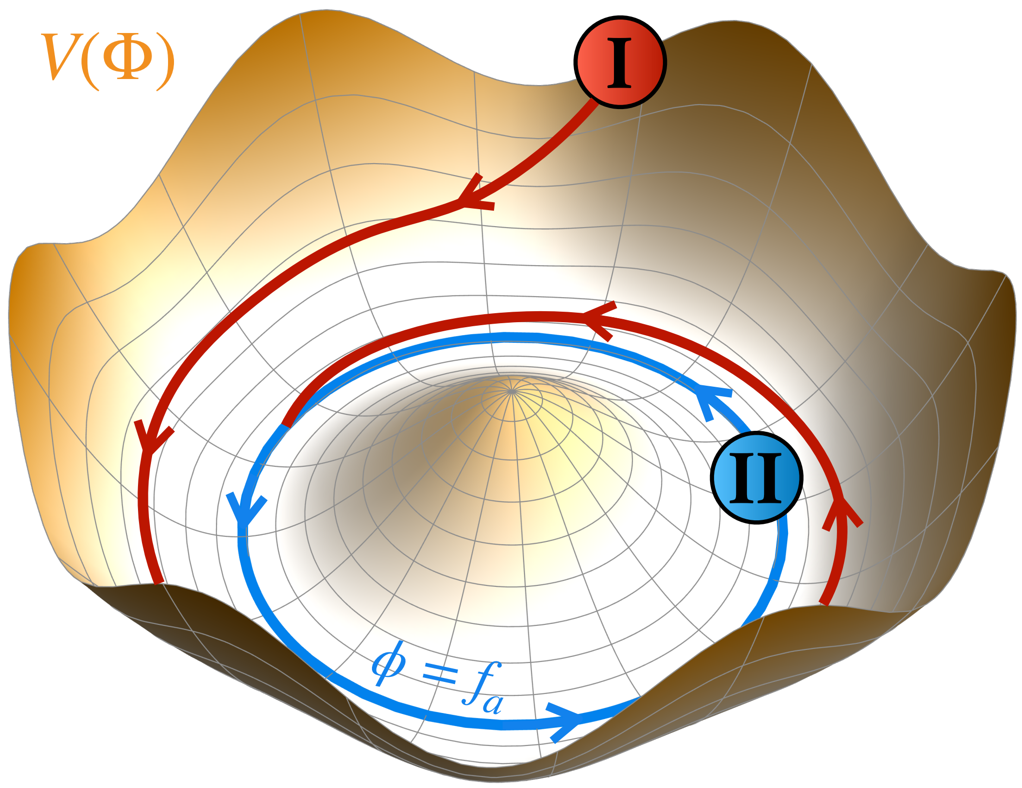
Rotating axion .

Complex scalar field

"Affleck-Dine Baryogenesis" (Affleck, Dine, 1985)

"Axiogenesis" (Co, Hall, Harigaya, et. al., '19)

"Kination cosmology" (Gouttenoire et al, '21)



$\Phi \sim \phi e^{i\theta}$ 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

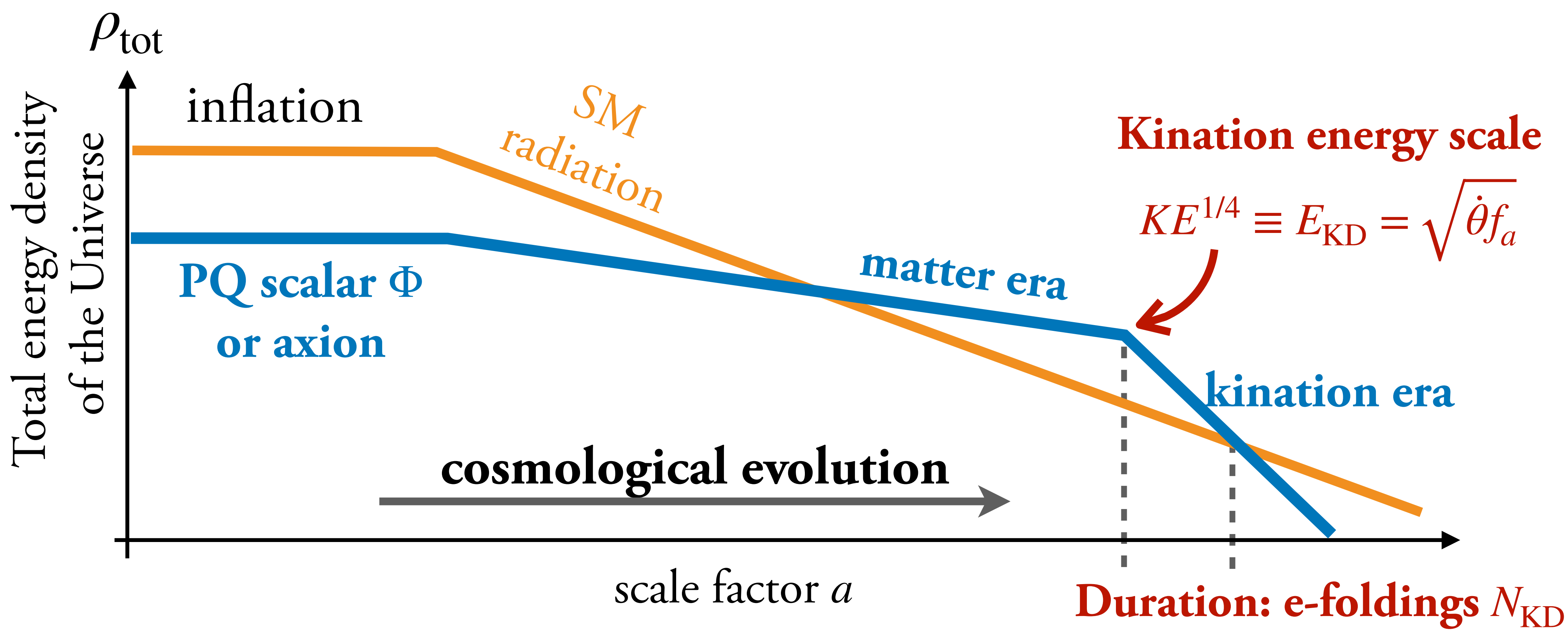
1. $U(1)$-symmetric (quadratic) potential with spontaneous symmetry-breaking minimum

2. Large initial scalar VEV

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

4. Damping of radial motion

Kination from a rotating axion



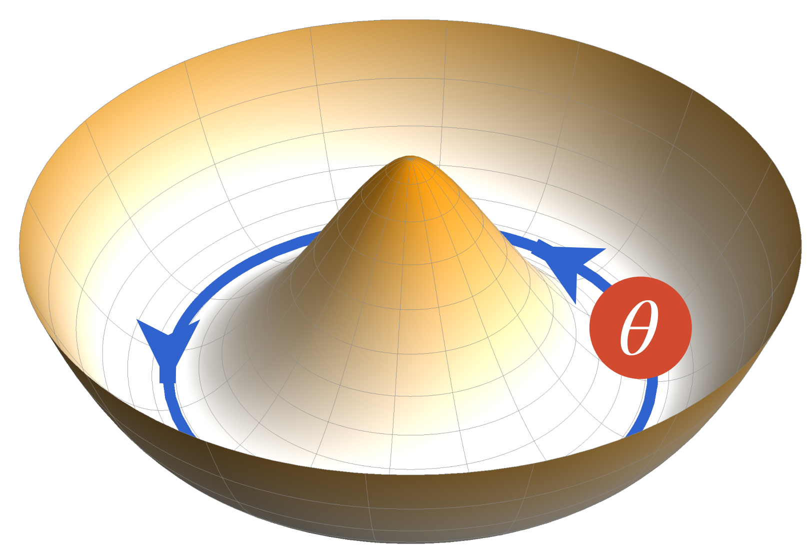
are characterized by
(given the spontaneous symmetry-breaking scale f_a)

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)



circle of $\phi = f_a$

Summary of this part.

Axion cosmology: Rich spectrum of possibilities, role of radial mode of the complex scalar field!

Kinetic Misalignment Mechanism

moves the ALP Dark Matter window into testable territory.

QCD axion DM inside Iaxo sensitivity

Complementary observational tests

Much denser compact axion dark matter halos

Gravitational waves from a rotating axion (alluded to in the last part of this talk)

Higgs and axion-like interplay.

3 terms:

$$V(\phi, h) = -g\Lambda^3\phi - \frac{1}{2}\left(-\Lambda^2 + g'\Lambda\phi\right)h^2 + \frac{\lambda}{4}h^4 + \Lambda_b^4 \cos\left(\frac{\phi}{f}\right)$$

relaxion rolling potential

(breaks the shift symmetry)

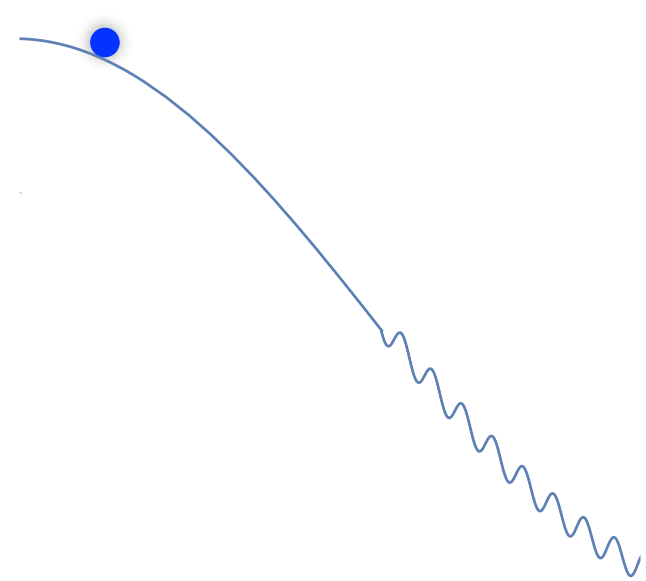
slope for Φ to move forward

relaxion-dependent Higgs mass

Φ scans the Higgs mass

Backreaction sector

barrier stopping Φ when <h> turns on



Higgs (h) and axion-like (ϕ) interplay.

g<<1, breaks the shift symmetry

$$\phi \to \phi + c$$

Λ_b

respects

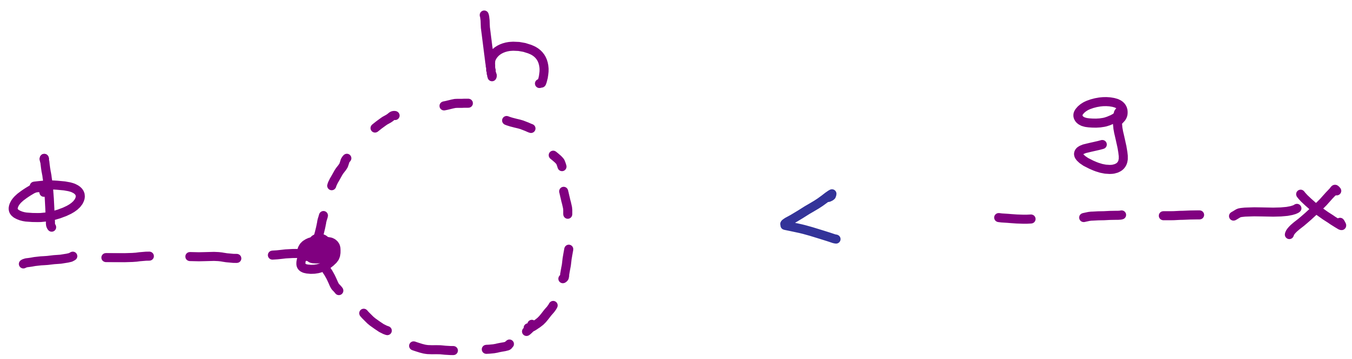
$$\phi \to \phi + 2\pi f$$

$$\phi \to -\phi$$

Potential stable under radiative corrections!

Technical naturalness

V(H,Φ) is radiatively stable



$$g\Lambda \times \frac{\Lambda^2}{16\pi^2} < g\Lambda^3 \quad \checkmark$$

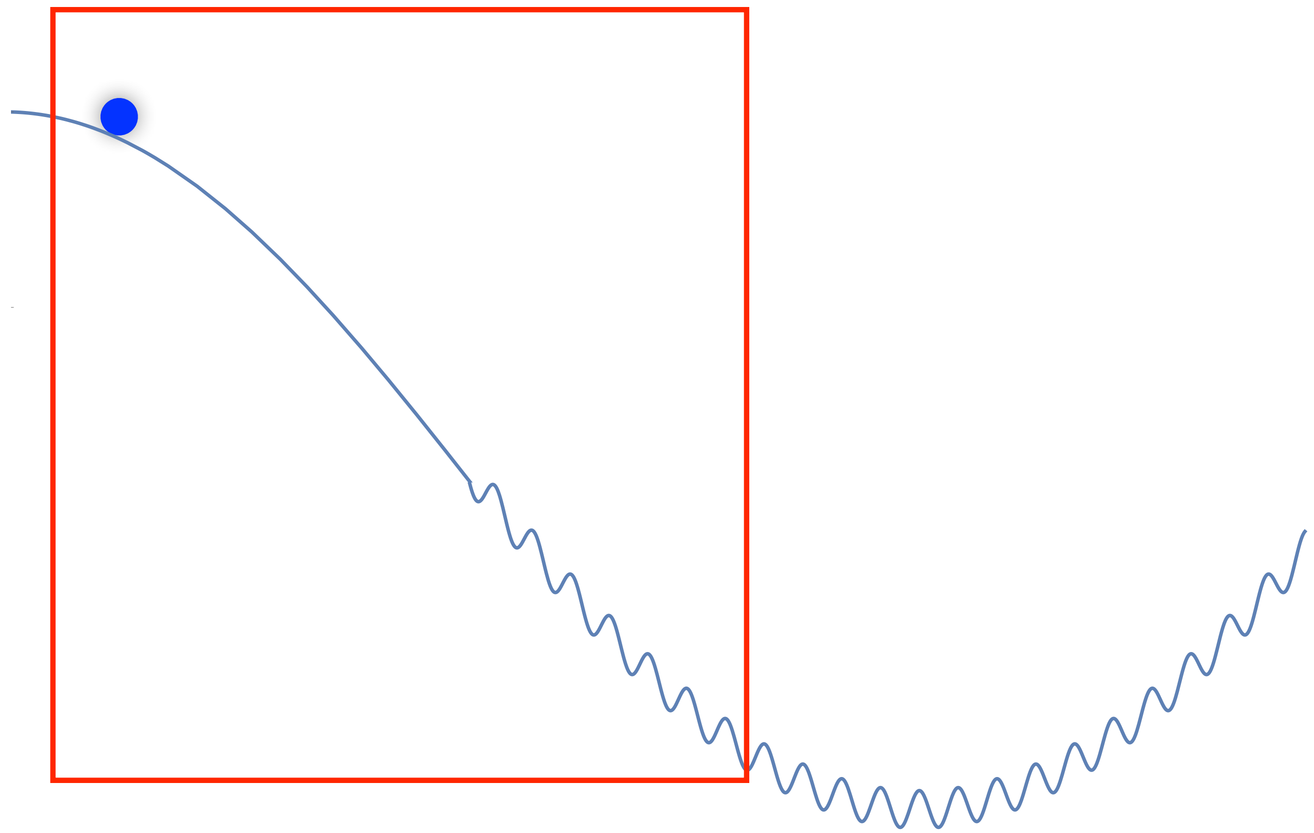
Concerns about V(h,Φ) ?

Relaxion potential may be obtained without breaking of shift symmetry but with hierarchy of decay constants, e.g. "clockwork axion"

Choi, Im'15
Kaplan, Rattazzi'15

Is this natural ?—> multiple axion models

$$V \sim A\cos(\frac{\phi}{f_{eff}}) + B\cos(\frac{\phi}{f_{eff}})h^2 + C(h)\cos(\frac{\phi}{f}), \qquad f_{eff} \sim e^{\zeta N} f \gg f$$

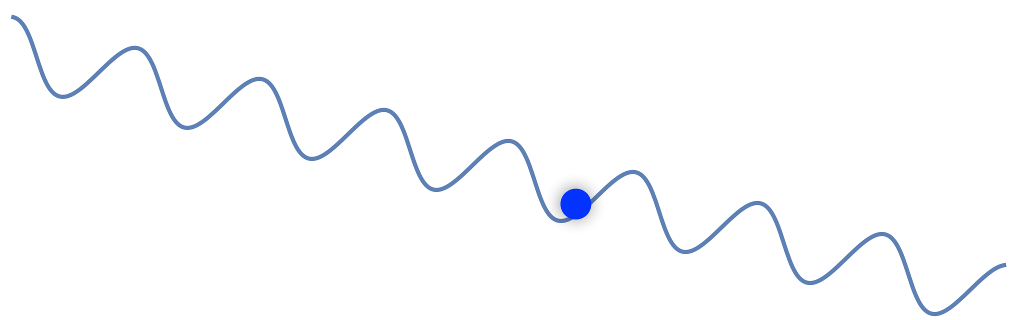


Origin of back-reaction term. Could the relaxion be the QCD axion?

From QCD condensate $\Lambda_b = \Lambda_{QCD}$

$$\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu} \xrightarrow{\text{can be rotated away and replaced by}} m_u(h)\langle q\bar{q}\rangle \cos(\phi/f)$$

but leads to $\theta_{QCD} \sim 1$ **due to the tilt of the potential!**



Problem solved if the tilt disappears at the end of inflation but one can then only explain a little hierarchy:

$\Lambda \lesssim 30$ TeV

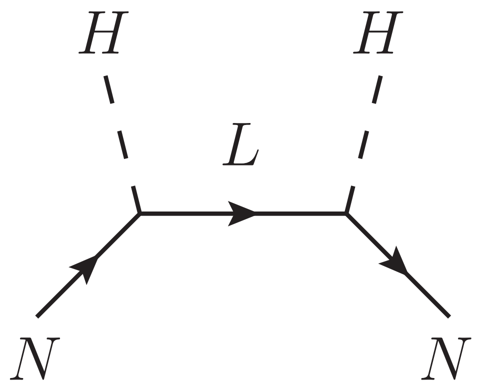
Origin of back-reaction term from a non-QCD axion (generic ALP).

Introduce a new confining hidden gauge group, and new lepton L charged under SU(2) + new singlet N

Similarly to QCD, the anomalous interaction term $\frac{\phi}{f} G'_{\mu\nu} \tilde{G}'^{\mu\nu}$

can be rotated away by a chiral rotation for N , and replaced by the term

$m_N e^{i\phi/f} \bar{N} N + h.c \to \Lambda^3 m_N \cos(\phi/f)$ **where** $\langle \bar{N} N \rangle \sim \Lambda^3$



$$m_N \sim y^2 |H|^2 / m_L$$

Origin of back-reaction term.

[Graham, Kaplan, Rajendran '15

Wiggles from new strong dynamics

$$\mathcal{L} = -m_N N N^c - m_L L L^c + y H L N^c + \tilde{y} H^\dagger L^c N + \frac{\phi}{f} G \widetilde{G} + \text{h.c.}$$

$$m_L \gg 4\pi f_\pi \gg m_N$$

$$\langle N N^c \rangle = 4\pi f_\pi^3$$

should dominate

$$\Rightarrow \quad V = \left(m_N^0 + \frac{y\tilde{y}}{16\pi^2} m_L \log\frac{\Lambda}{m_L} + y\tilde{y}\frac{\langle h\rangle^2}{m_L} + \frac{y\tilde{y}}{16\pi^2}\frac{(4\pi f_\pi)^2}{m_L} \right)(4\pi f_\pi^3)\cos\frac{\phi}{f}$$

Predictions: weak-scale fermions L accessible at colliders.

Way out: By making the envelop of the oscillatory potential field-dependent, one can show that there is no need for new physics at the weak scale

J.R. Espinosa et al [1506.09217]

Parameter space.

$$g\,,\Lambda,\ g',\ \Lambda_b,\ H_I,\ f$$

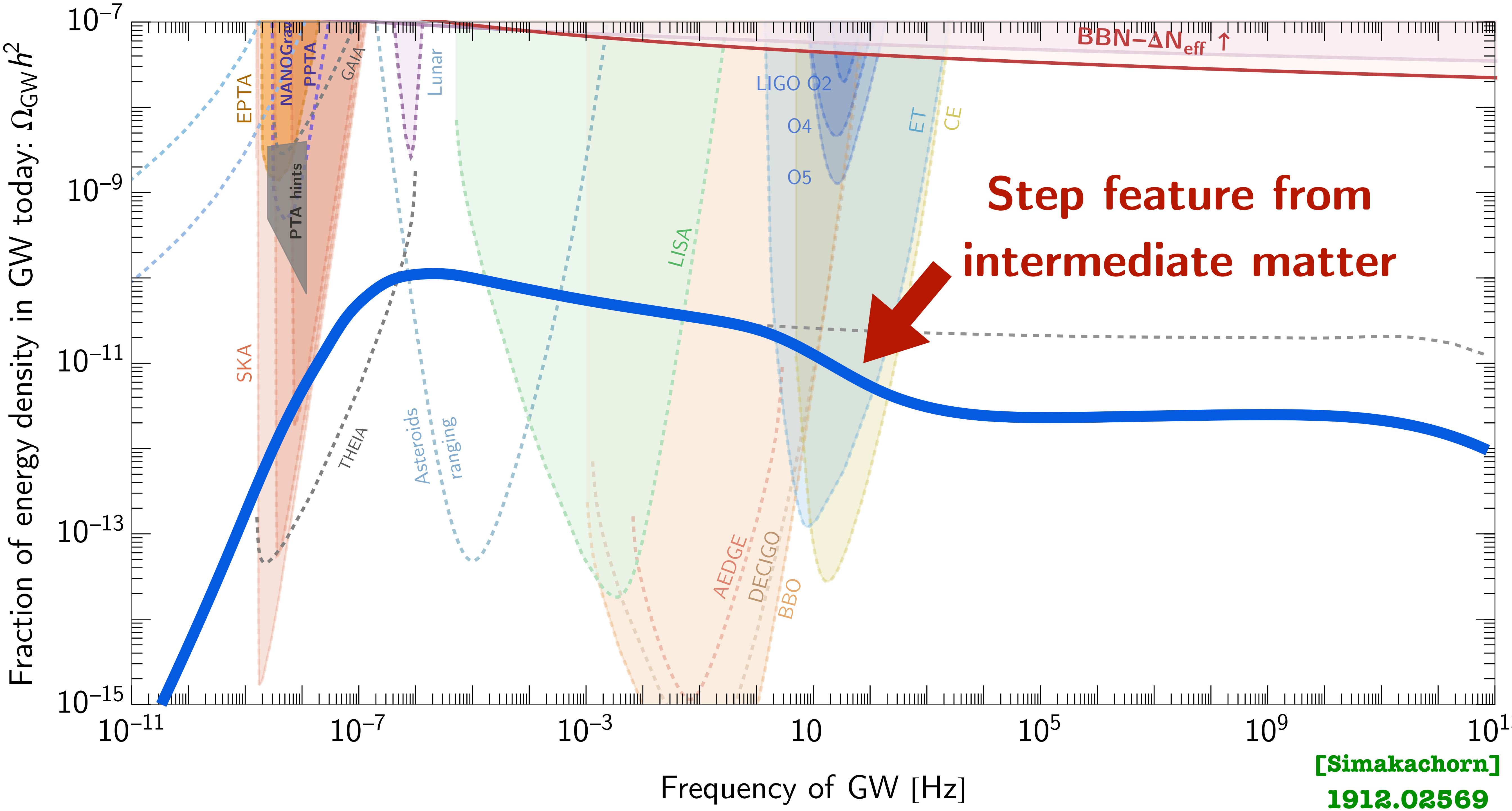
(one often sets g~g')

can be reduced to 4 independent parameters.

List of conditions.

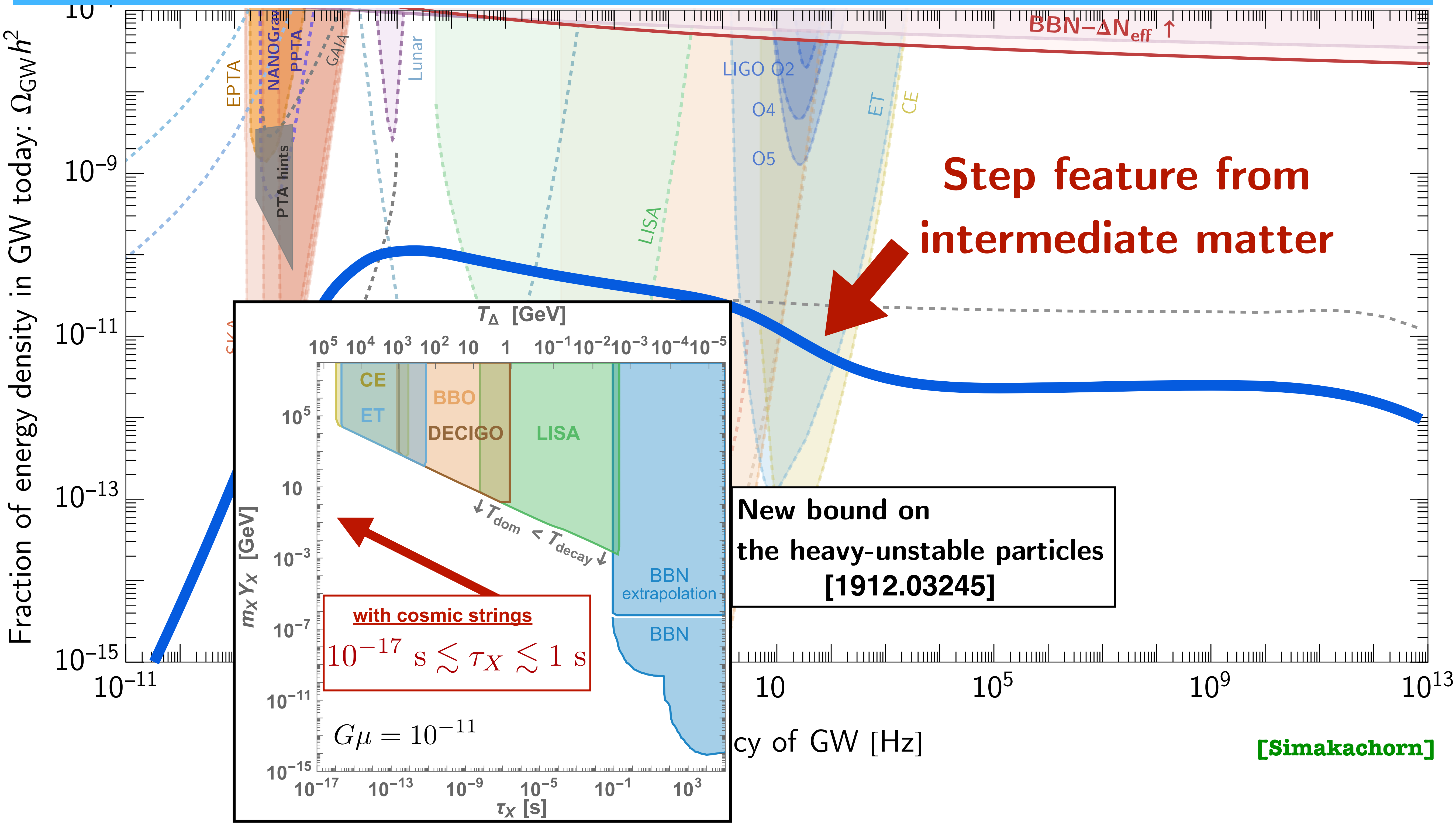
Total field excursion (assume Φ=0 initially)	$\Delta\phi = \frac{\Lambda}{g'}$
Higgs mass scanning precision	$g'\Lambda(2\pi f) < \frac{m_h^2}{2}$
Large barriers	$\frac{\Lambda_b^4}{f} \geq g\Lambda^3$
microscopic origin of barriers	$\Lambda_b < \sqrt{4\pi} v_{\mathrm{EW}}$
symmetry breaking pattern	$f > \Lambda$ $H < f,$

Gravitational Waves from cosmic strings in non-standard cosmology.



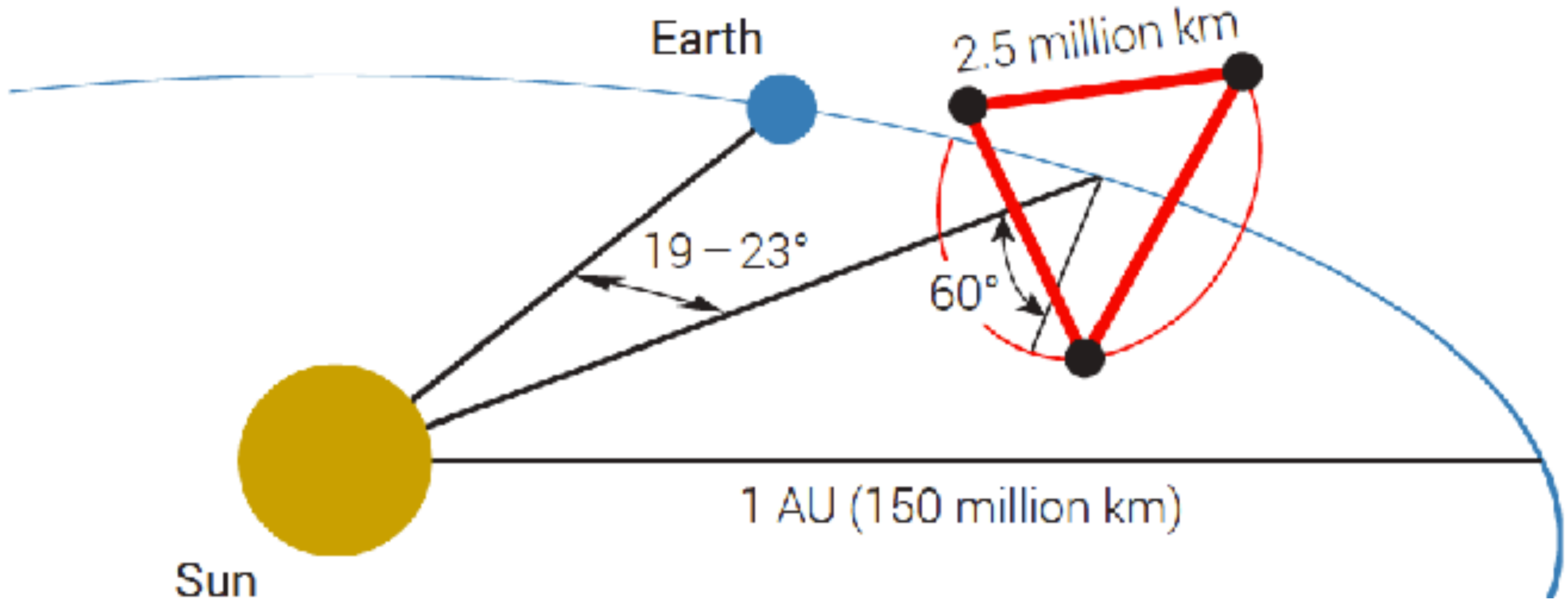
[Simakachorn] 1912.02569

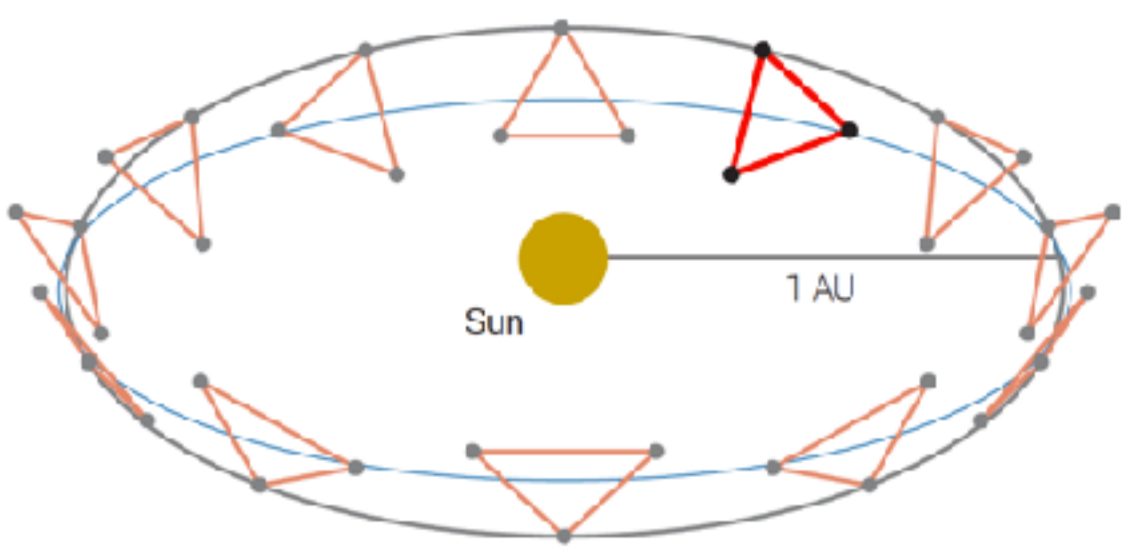
Gravitational Waves from cosmic strings in non-standard cosmology.



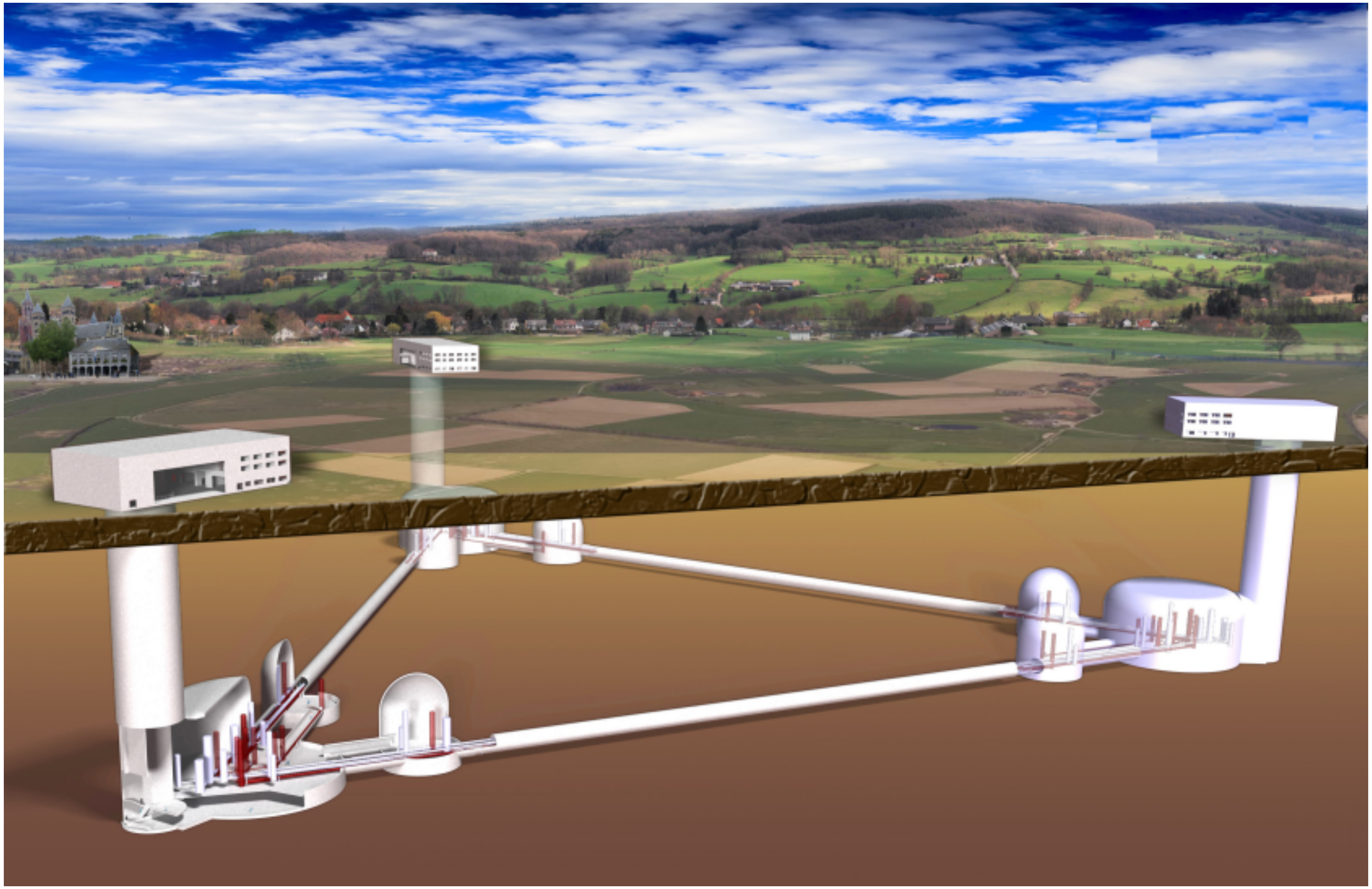
Gravitational-wave observatories.

LISA (Laser Inteferometer Space Antenna)





Eintein Telescope

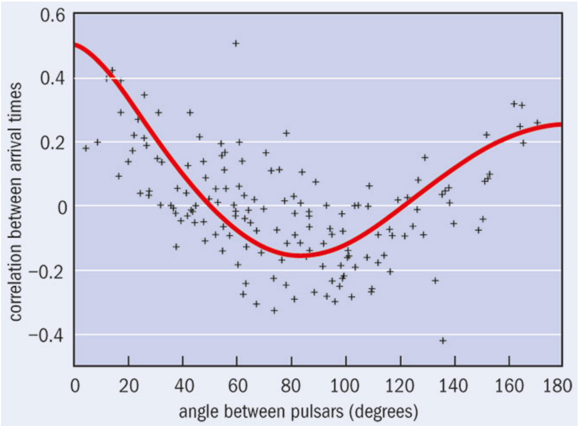


Pulsar Timing Arrays (PTAs) .

Array of pulsars across the Milky Way → GW detector of galactic dimensions!

Look for tiny distortions in pulse travel times caused by nanohertz GWs.

Measure times of arrival and compare to predictions from a timing model.



Hellings–Downs curve

Timing residuals for each individual pulsar

→ GW signature in cross-correlations. between arrival ti