Cosmic Domain Walls & their Gravitational signatures

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Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE INVESTIGACIÓN

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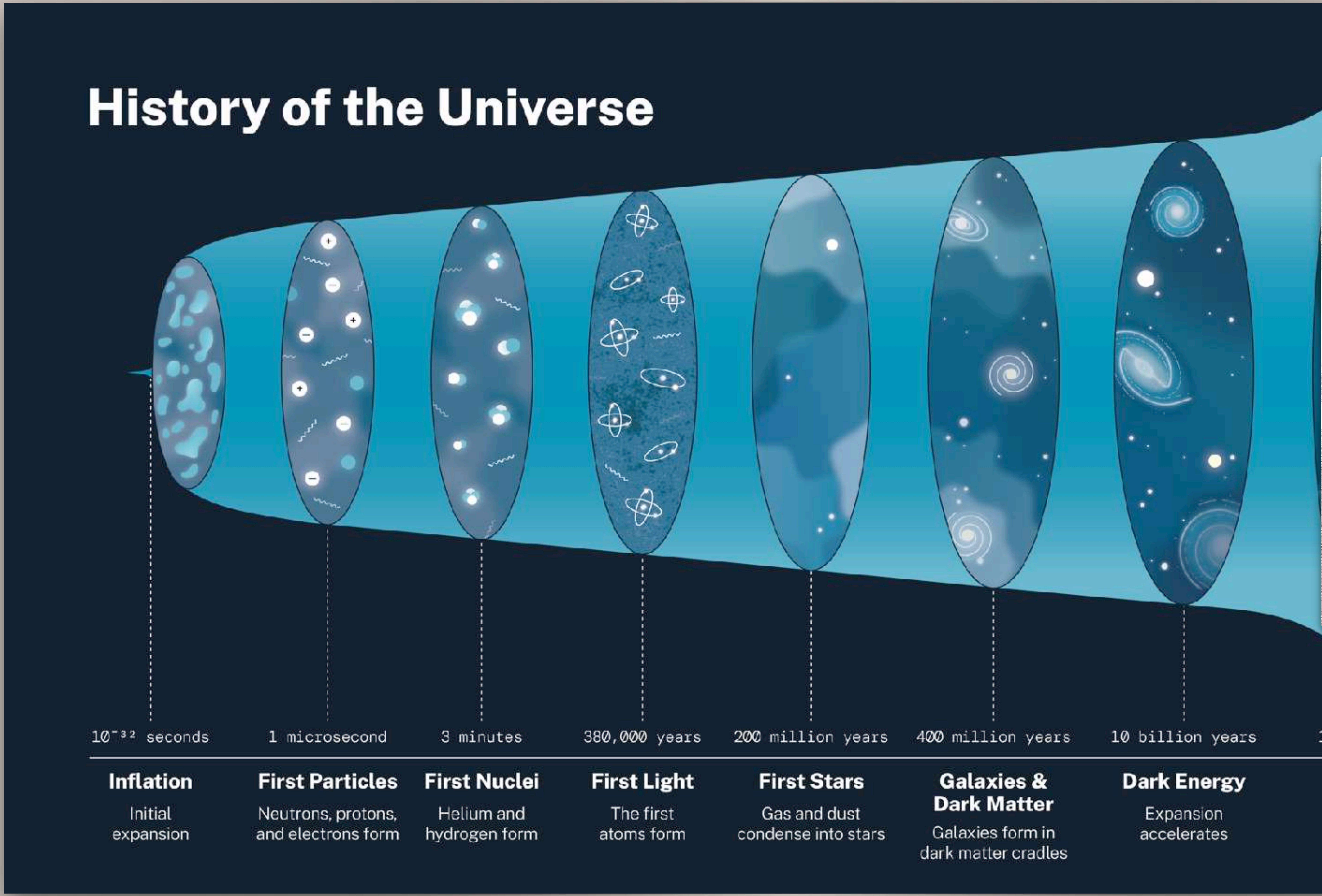
Mostly based on work w/

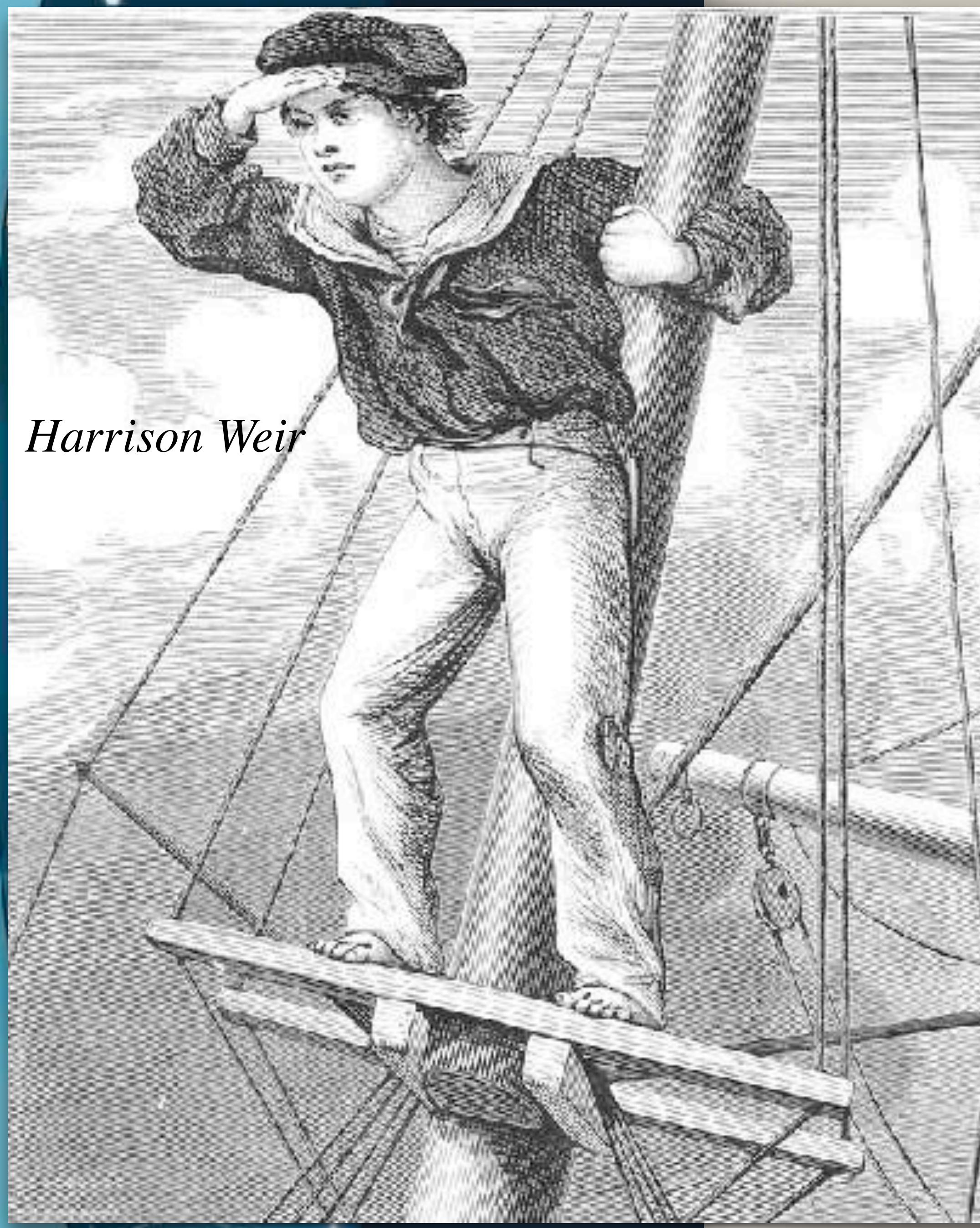
Caprini, Pujolàs, Quelquejay-Leclere, Steer 24,

R.Z. Ferreira, A. Notari, O. Pujolàs, '22, 24',

Ferrer, Masso, Panico, Pujolàs 18

Credit: nasa science





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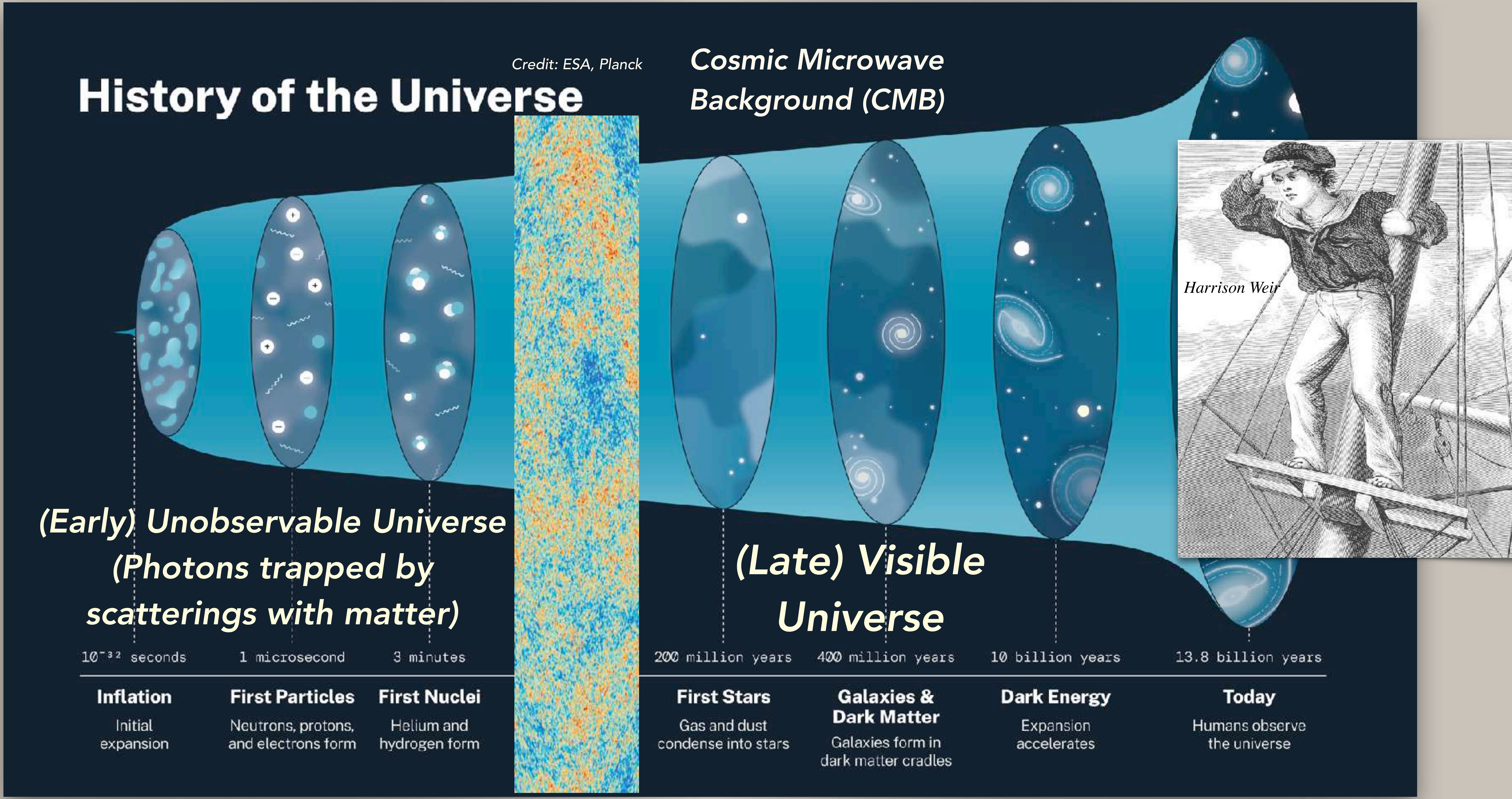


The early Universe

$$ds^2 = dt^2 - a(t)d\mathbf{x}^2$$

Minimal cosmological history:
early Universe dominated by gas of relativistic particles (radiation domination)

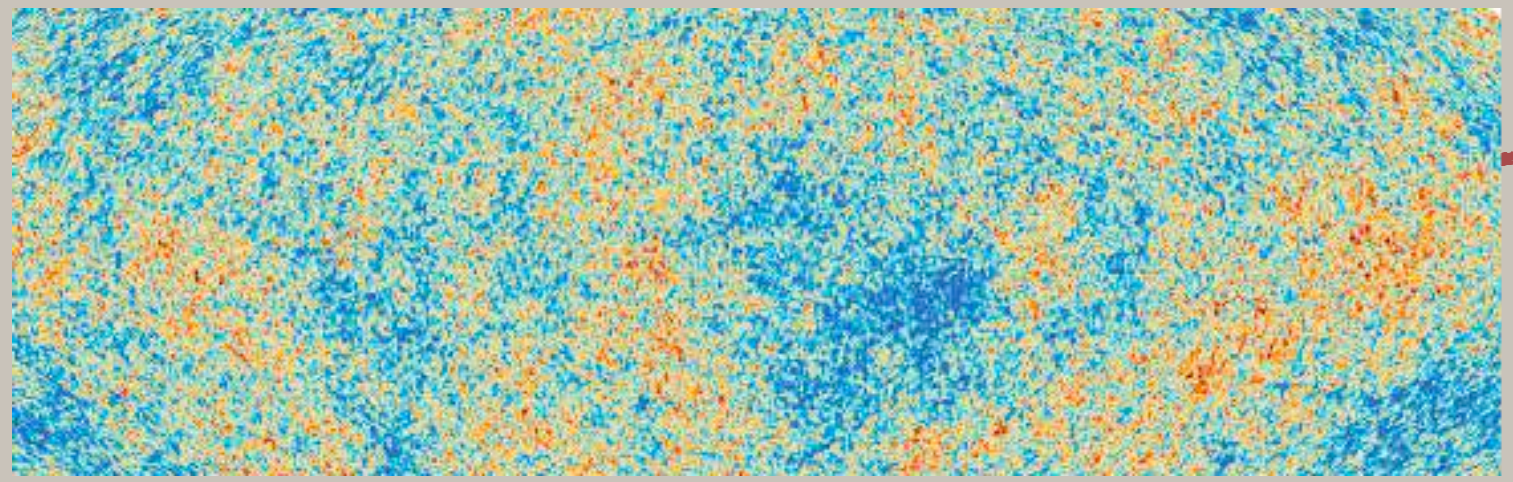
At each epoch, causal contact maintained only in regions of size

$$H^{-1}(T)$$

Hubble expansion rate

$$H \equiv \dot{a}/a \sim T^2/M_p$$

$$T \lesssim \text{eV}$$



$$T$$

Recombination (CMB)

$$M_p = (8\pi G)^{-1/2} \simeq 10^{18}\ \text{GeV}$$

The early Universe

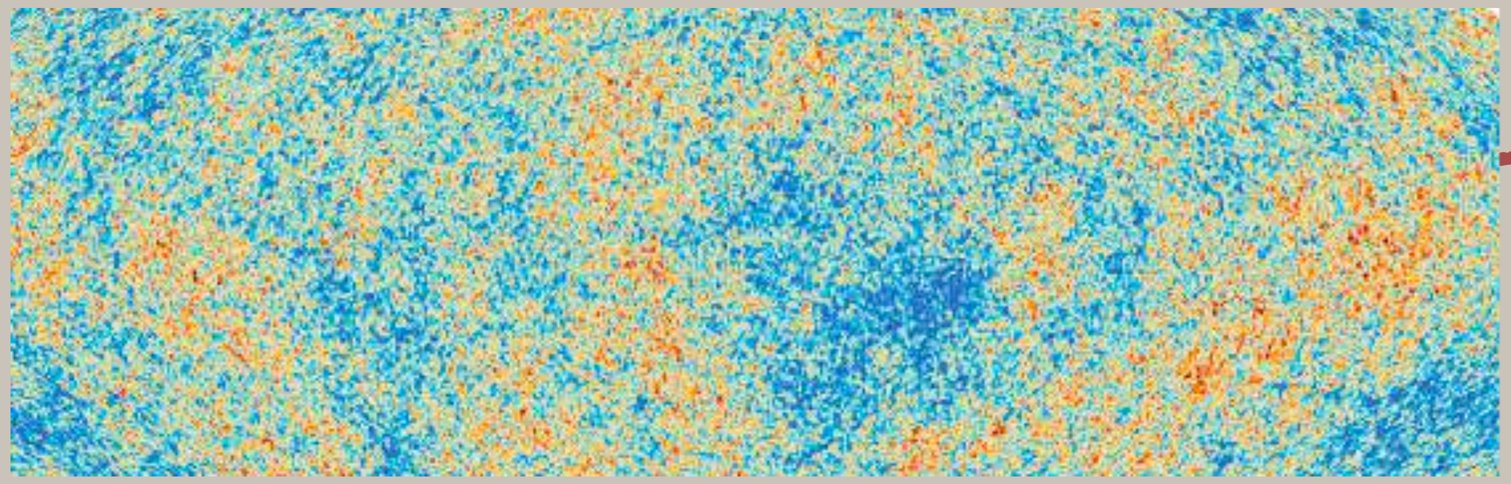
$$H \equiv \dot{a}/a \sim T^2/M_p$$

Minimal cosmological history:

early Universe dominated by gas of relativistic particles (radiation domination)

$T \lesssim \mathrm{eV}$

Big Bang Nucleosynthesis (BBN)



T

Recombination (CMB)

$T \lesssim \mathrm{MeV}$

The early Universe

$$H \equiv \dot{a}/a \sim T^2/M_p$$

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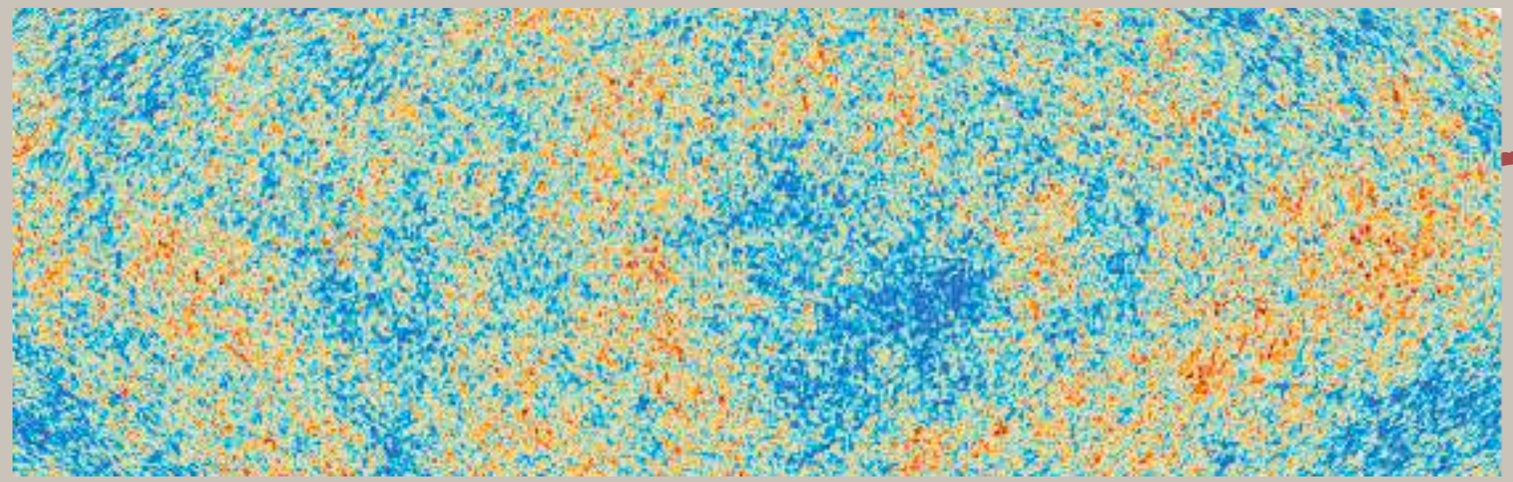


Recombination (CMB)

$T \lesssim \mathrm{MeV}$

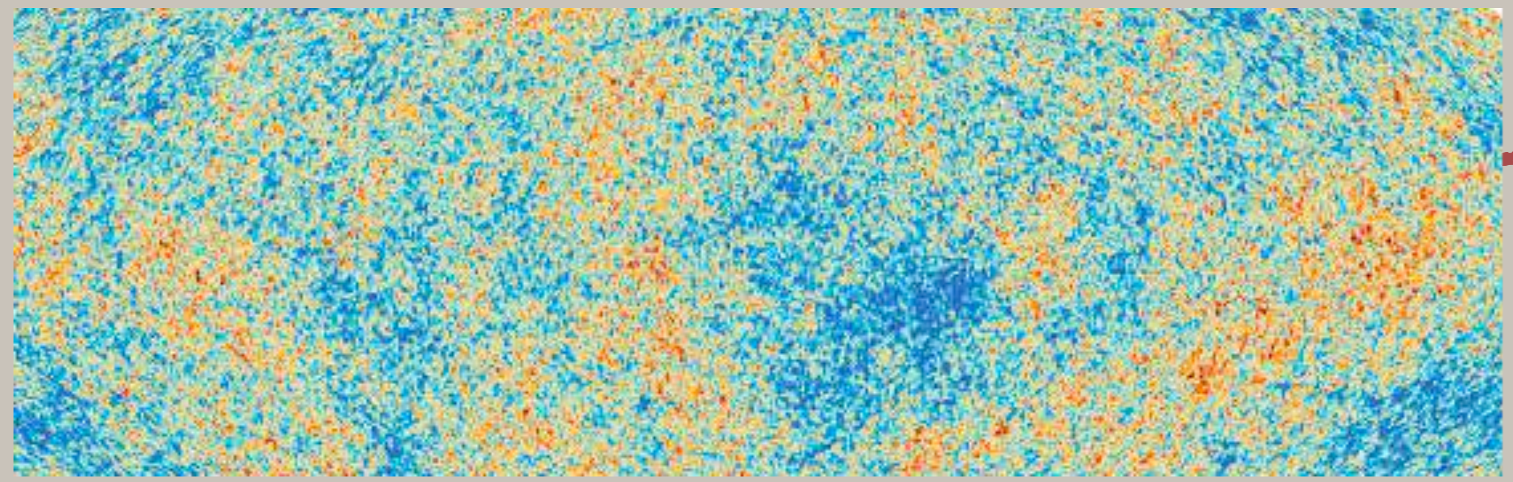
T

Inflation

$T \lesssim 10^{16}\ \mathrm{GeV}$?????

Expectations from Standard Model

$T \lesssim \mathrm{eV}$



Recombination
(CMB)

BBN

$T \lesssim \mathrm{MeV}$

Confinement

ElectroWeak
Symmetry
Breaking

T

Inflation

$T \lesssim \mathrm{GeV}$

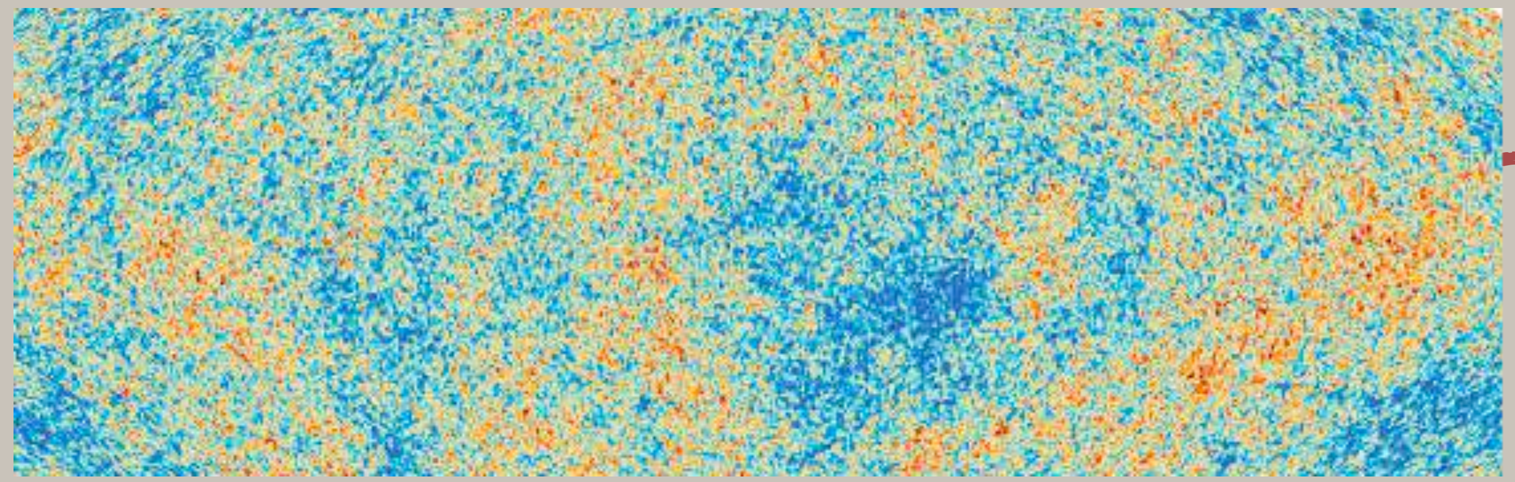
$T \sim 100\ \mathrm{GeV}$

$T \lesssim 10^{16}\ \mathrm{GeV}$

?????

And from BSM?

$T \lesssim \mathrm{eV}$



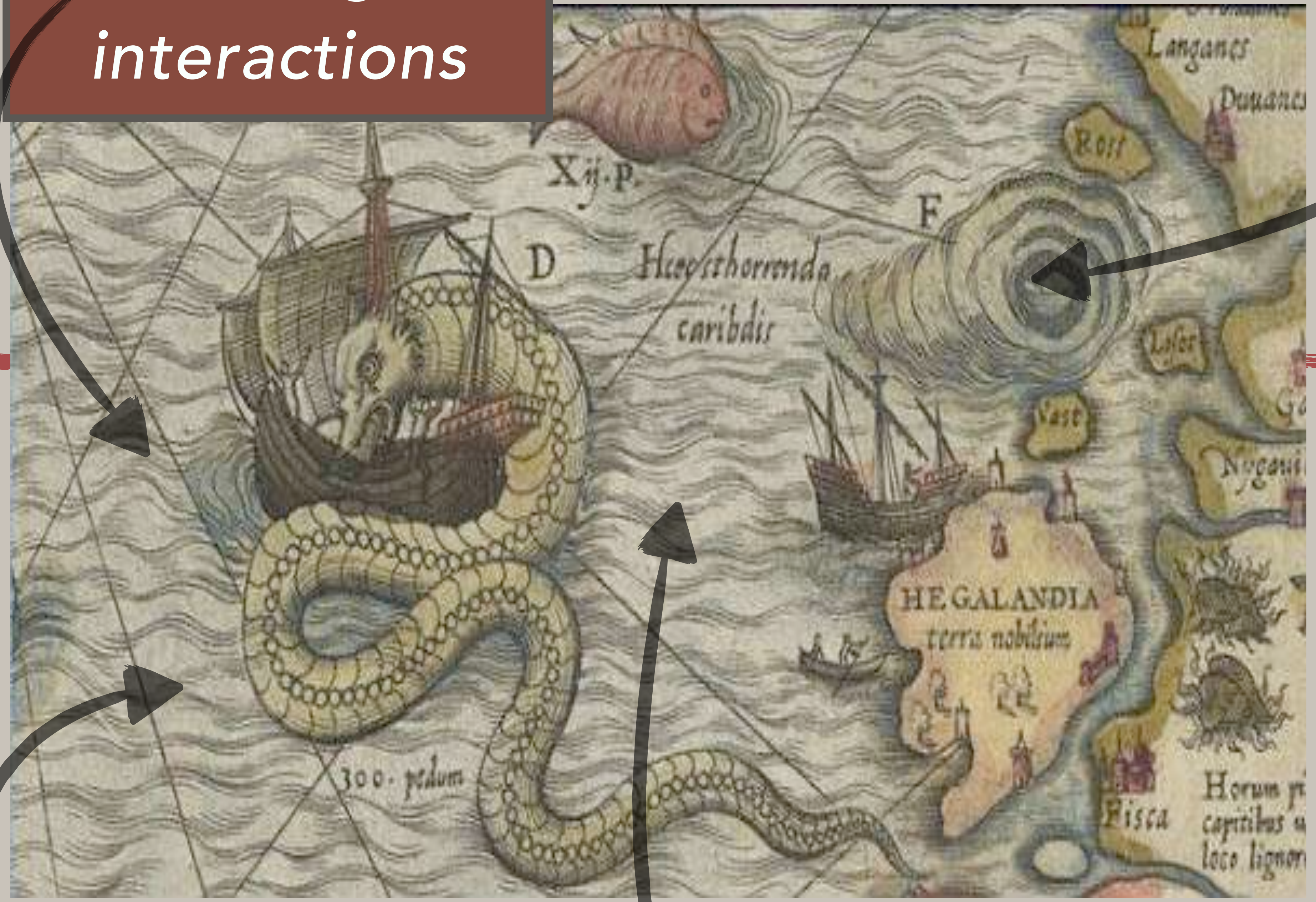
Recombination
(CMB)

BBN

$T \lesssim \mathrm{MeV}$

CP violation in strong interactions

(Un)naturalness of weak scale



T

Inflation

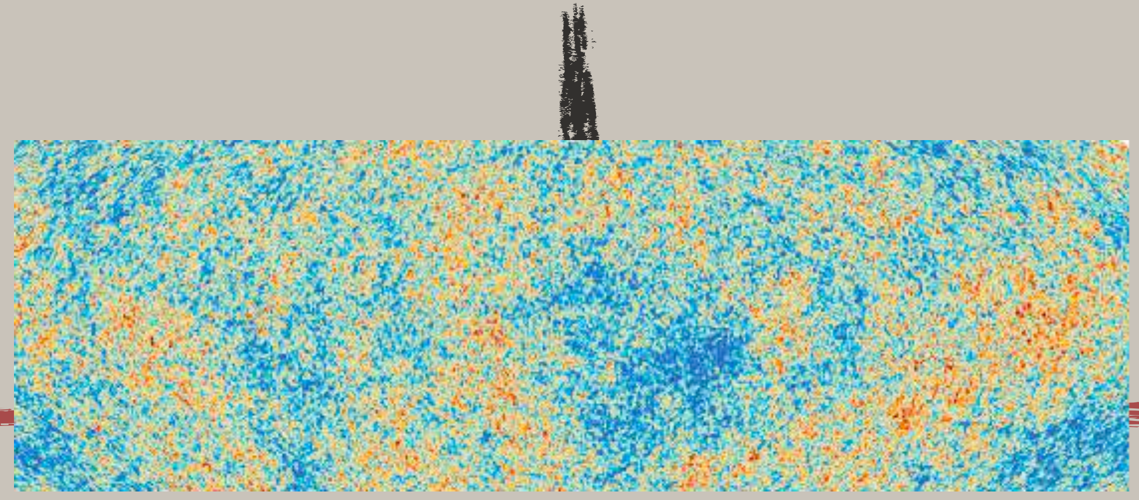
Baryon asymmetry

Dark Matter Production

Seeing via gravitational backgrounds

EARLY UNIVERSE

LATE UNIVERSE



Recombination
(CMB)

T

Species that interact only gravitationally reach the late Universe unaltered ***(Free-streaming)!*** *(except for expansion dilution)*

Gravity is extremely weak!

Provide a background of early Universe relics that can be observed today!

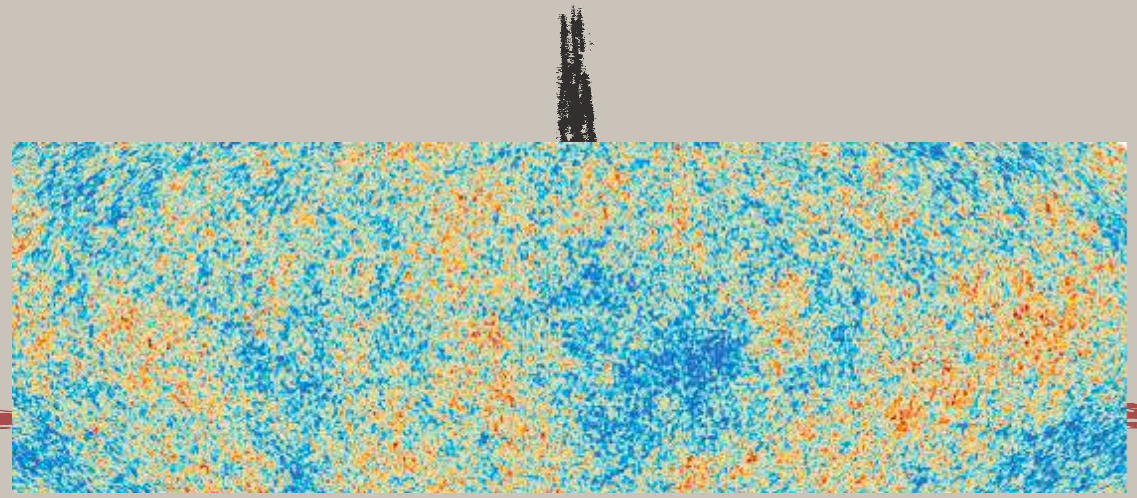
Relics with additional interactions can also survive, abundance set by interactions

See talk by Josef Pradler!

Seeing via gravitational backgrounds

EARLY UNIVERSE

LATE UNIVERSE



Recombination
(CMB)

T

Provide a background of early Universe relics that can be observed today!

~isotropic stochastic background, analogous to the CMB

Relativistic

"Dark radiation"

Non-Relativistic

Dark matter

Relativistic relics: (Cosmological) Gravitational Waves

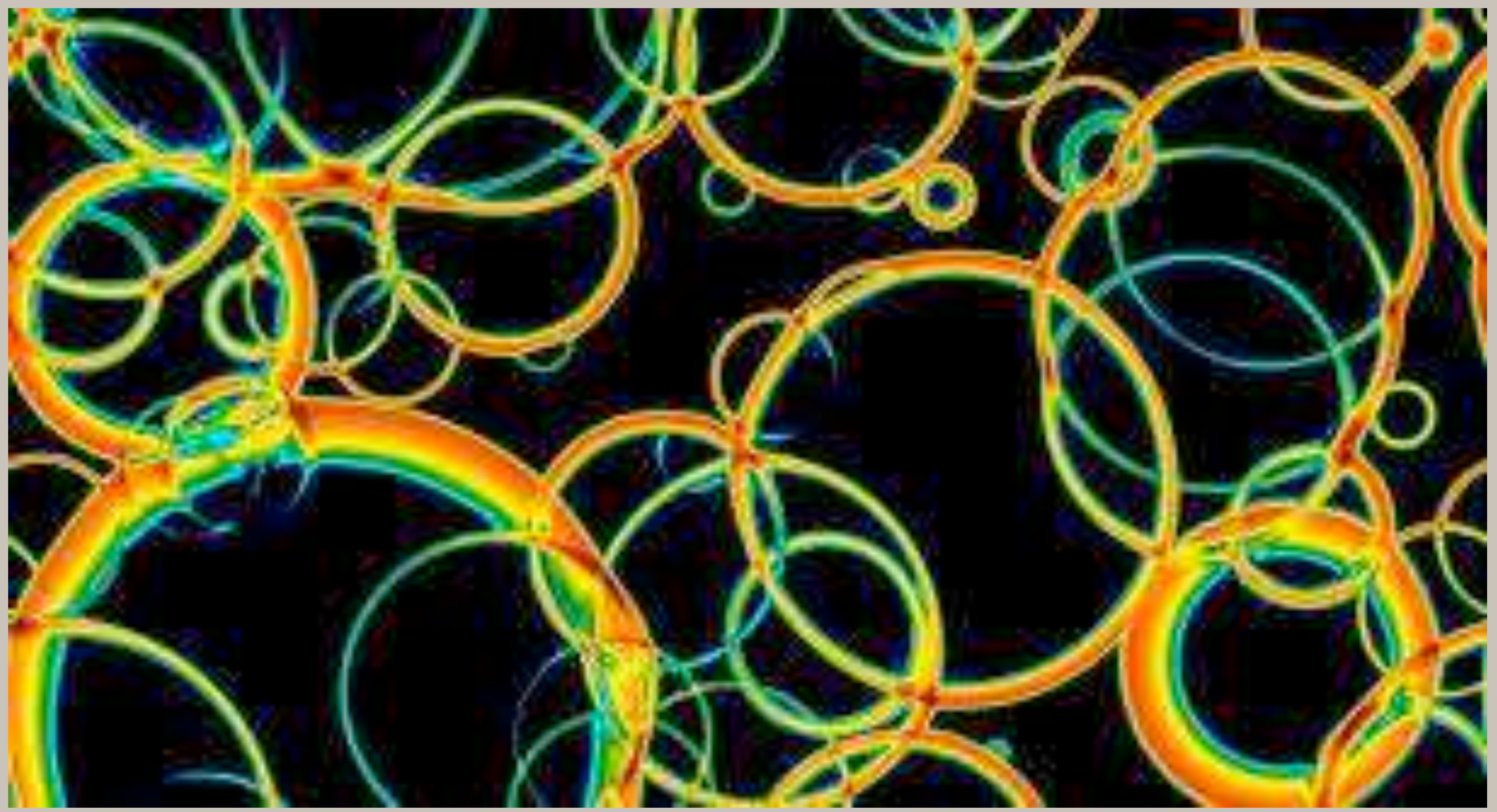
Other relics also possible: e.g. light axions, dark "photons", etc

Radiated by any mass/energy distribution **with sufficiently large time-varying quadrupole moment**

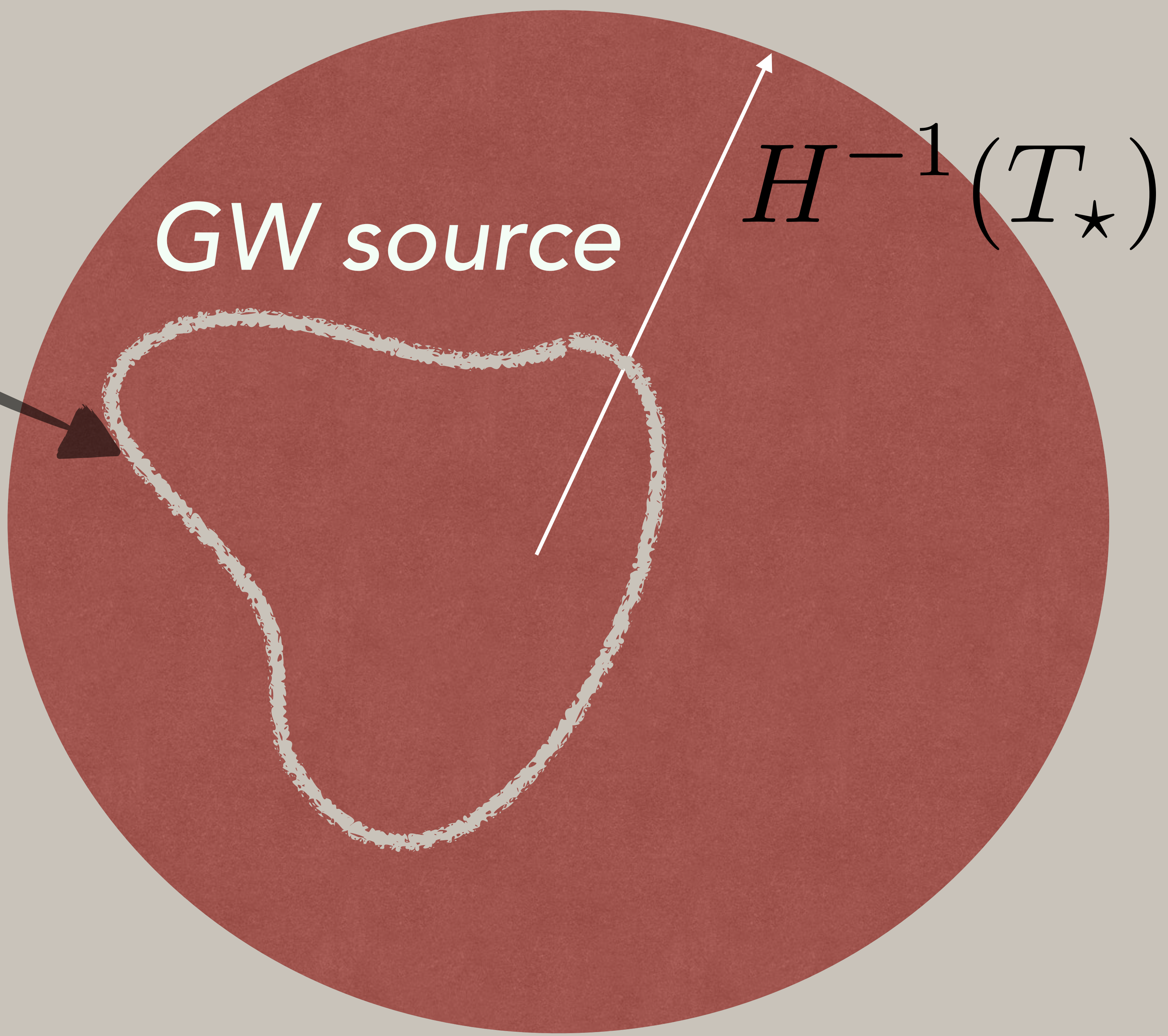
Broad class of sources: **transient in cosmological history,** i.e. active at definite epoch/temperature, then shut off

Non-transient sources also possible

e.g. bubbles of a first order PT



Credit: David Weir



Hubble sphere

Transient sources

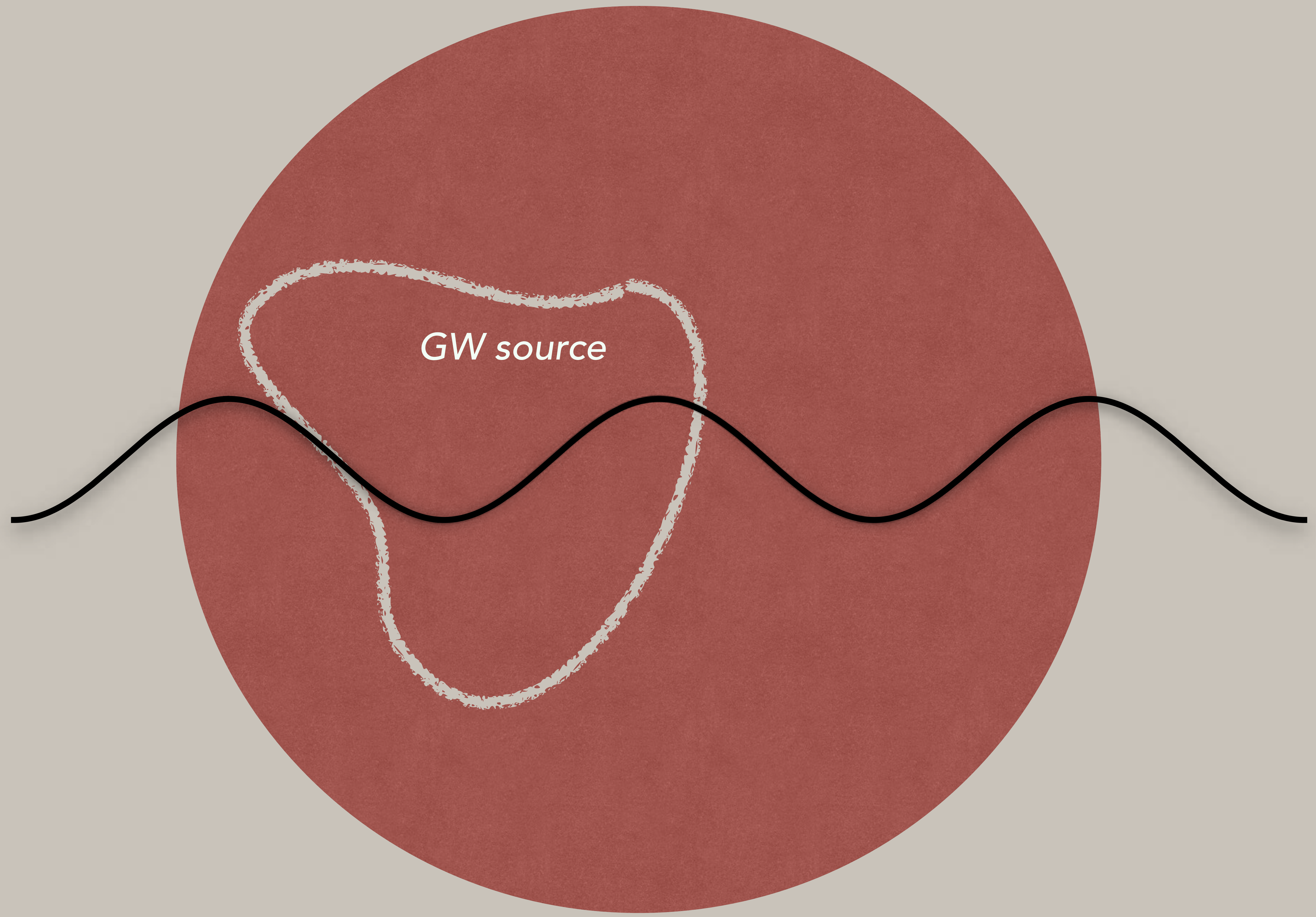
But persistent background in the detector!!

(Mostly) Active at definite epoch/temperature, then shut off

$$t_\star \lesssim H^{-1}(T_\star)$$

Typical GW (peak) frequency

$$f_\star \gtrsim 1/t_\star$$

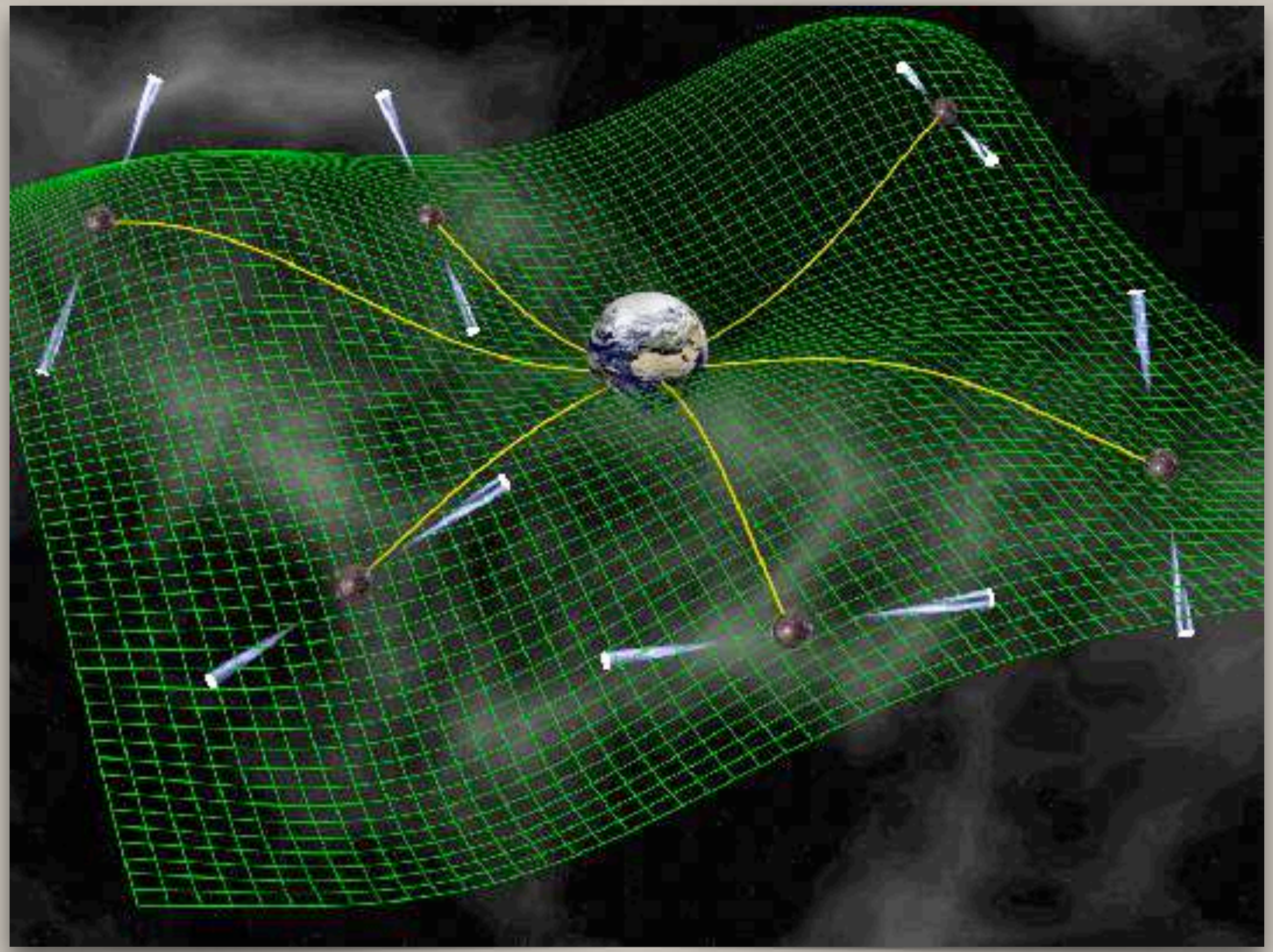


Frequency today

$$f_\star \simeq t_\star^{-1} \lesssim H_\star \Rightarrow$$

Pulsar Timing Arrays!

(European PTA, NANOGrav, PPTA +)



credit: David J. Champion

$$f_\star^0 \simeq 7 \text{ nHz} \left(\frac{t_\star^{-1}}{H_\star}\right)\left(\frac{g_*(T_\star)}{15}\right)^{\frac{1}{6}}\left(\frac{T_\star}{60 \text{ MeV}}\right)$$

Interferometers *(LIGO/Virgo/KAGRA)*

$$f_\star^0 \simeq 10 \text{ Hz} \left(\frac{t_\star^{-1}}{H_\star}\right)\left(\frac{g_*(T_\star)}{15}\right)^{\frac{1}{6}}\left(\frac{T_\star}{10^8 \text{ GeV}}\right)$$

Credit: The Virgo Collaboration/CCO 1.0

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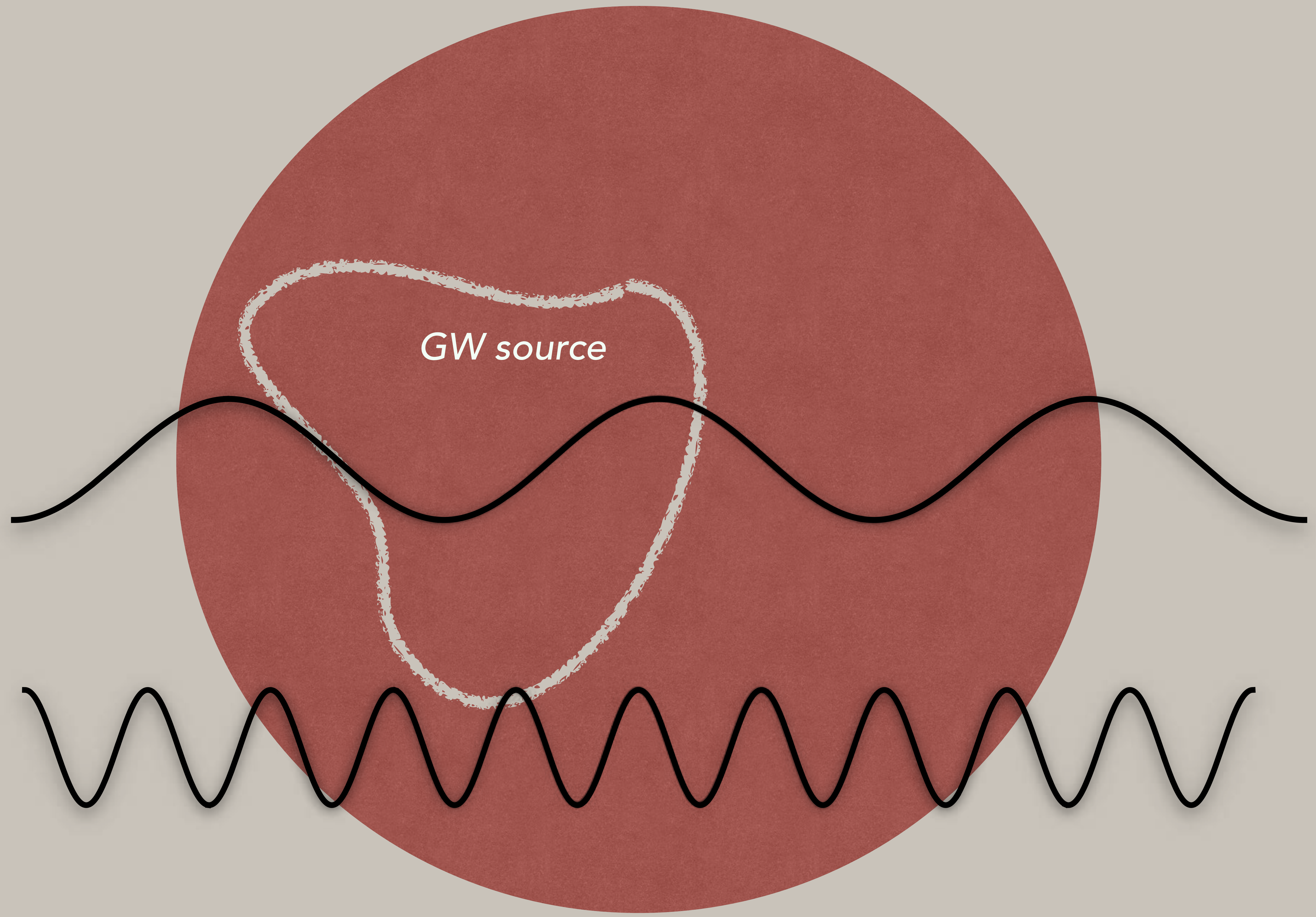


Peak and high frequency tail probe microscopic properties of the source
Model-dependent!

But persistent background in the detector!!

Transient sources

(Mostly) Active at definite epoch/temperature, then shut off

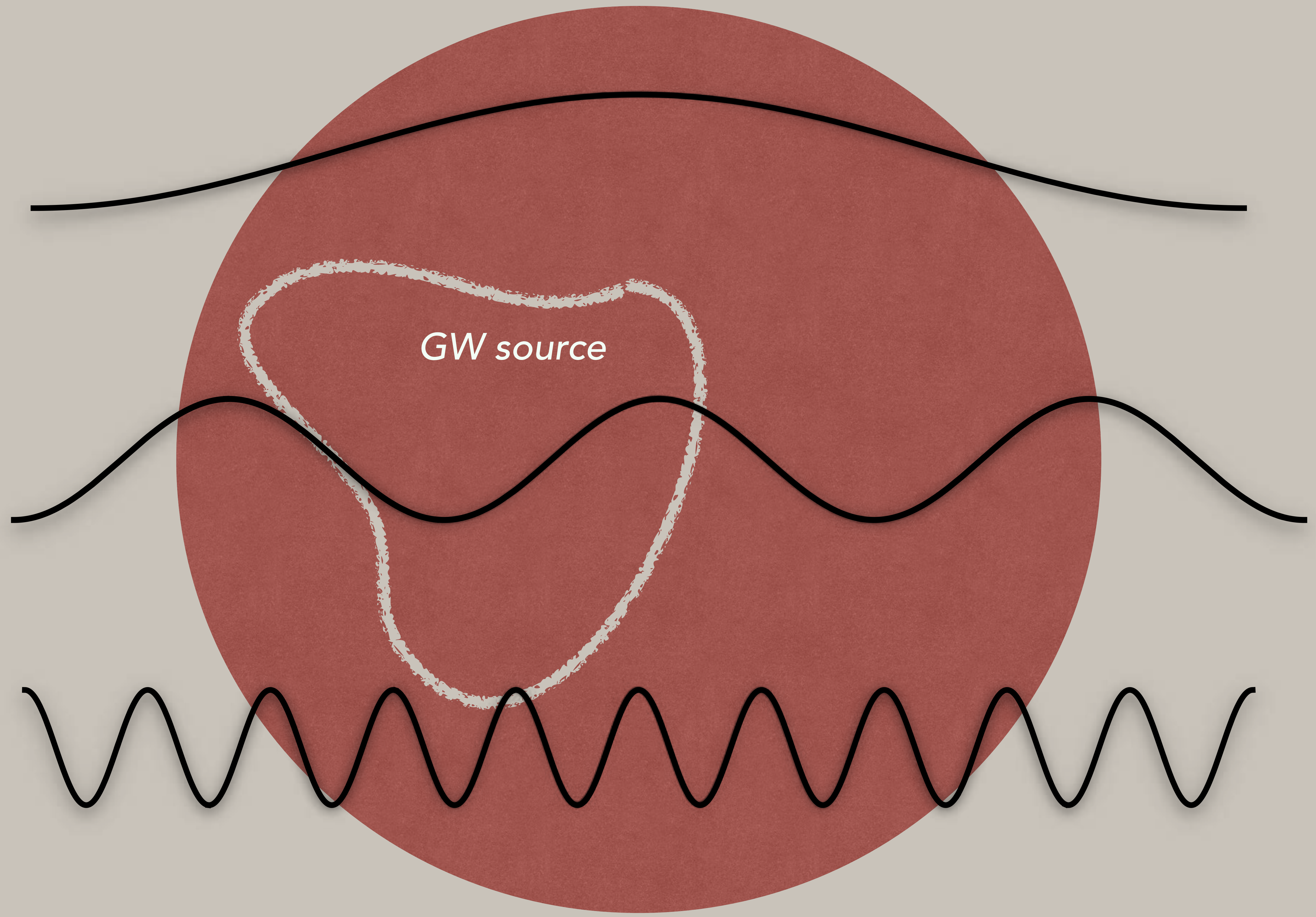
$$t_\star \lesssim H^{-1}(T_\star)$$

$$\lambda_{\rm gw} \gg H^{-1}(T_\star)$$

Super-horizon modes cannot know about details of source (Causality): Model-independent

Typical GW (peak) frequency

$$f_\star \gtrsim 1/t_\star$$



Peak and high frequency tail probe microscopic properties of the source Model-dependent!

Relic Gravitational Waves: amplitude

Back-of-the-envelope (quadrupole formula)

$$P_{\rm gw} \sim G_N \dddot{Q}_{ij}^{\,2}$$

Quadrupole moment

Einstein 1918 (Non-relativistic source)

$$\rho_{\rm gw} \sim E_{\rm gw}/V \sim P_{\rm gw} t_\star t_\star^3 \sim \rho_\star \times \epsilon \left[\left(\frac{t_\star^{-1}}{H_\star} \right)^p , \ldots \right] \left(\frac{\rho_s}{3H_\star^2 M_p^2} \right)^2$$

Total energy density in the Universe

$$\rho_\star = 3H(T_\star)^2 M_p^2$$

Relic Gravitational Waves: amplitude

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Einstein 1917
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Energy fraction of the source:
how much of the total energy density of the Universe is in the source at the time $t_\star$

$$\equiv \alpha_\star$$

Relic Gravitational Waves: amplitude

Back-of-the-envelope (quadrupole formula)

$$P_{\rm gw} \sim G_N \dddot{Q}_{ij}^2$$

Quadrupole moment

Einstein 1917
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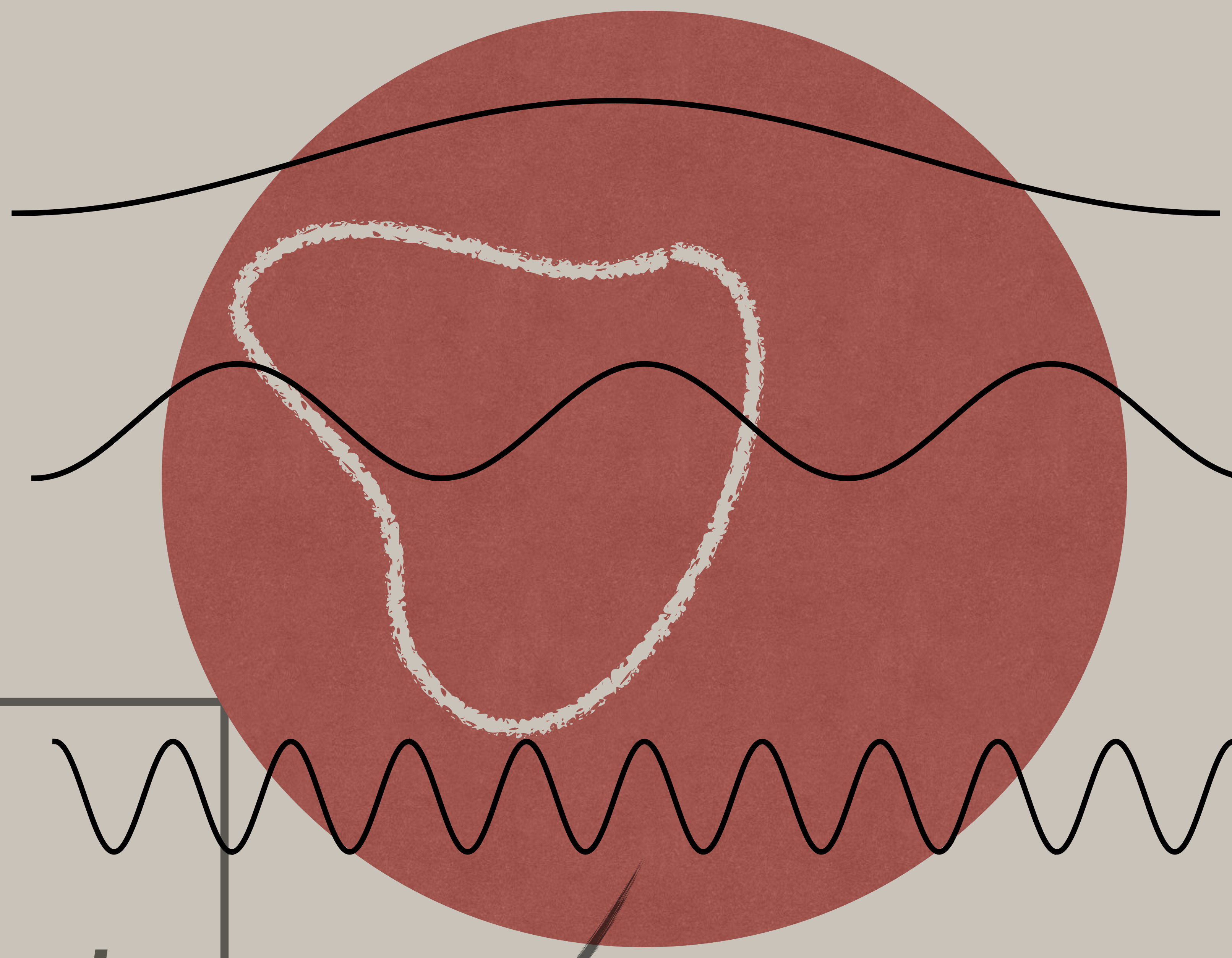
Suppression factor due to:
sub-Hubble size of the source, non-relativistic velocities, …

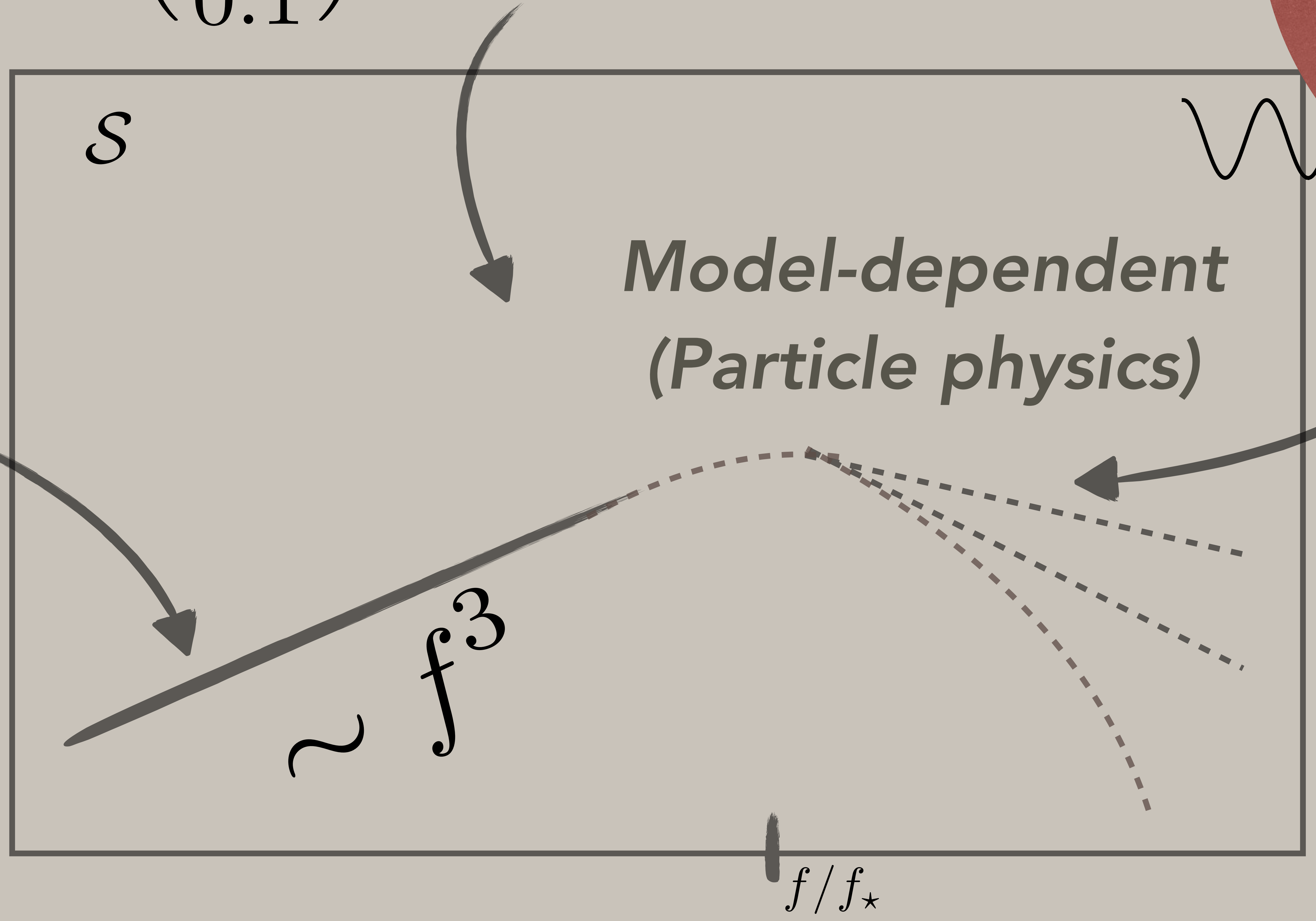
Relic Gravitational Waves Spectrum

$$\Omega_{\rm gw}(f)h^2 \equiv \frac{h^2}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln f}$$

Analogous to relic abundance of any other component

$$\simeq 10^{-8}\epsilon\left(\frac{\alpha_\star}{0.1}\right)^2 \mathcal{S}(f/f_\star) \quad (\alpha_\star \leq 1)$$



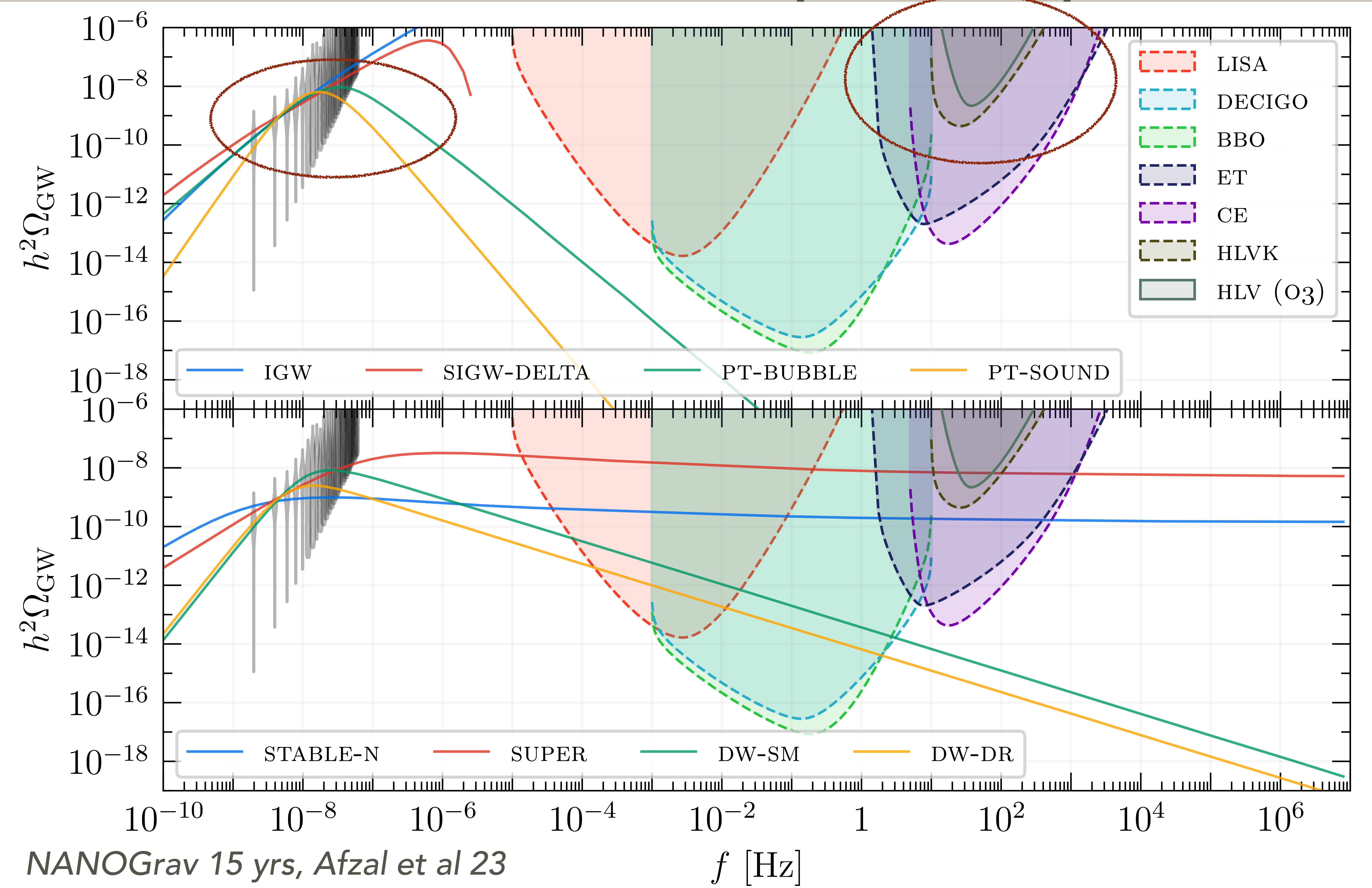


Model-independent (Causality)

Non-transient sources have different spectrum!

Typically requires numerical simulations!

GW detection landscape: the present



NANOGrav 15 yrs, Afzal et al 23

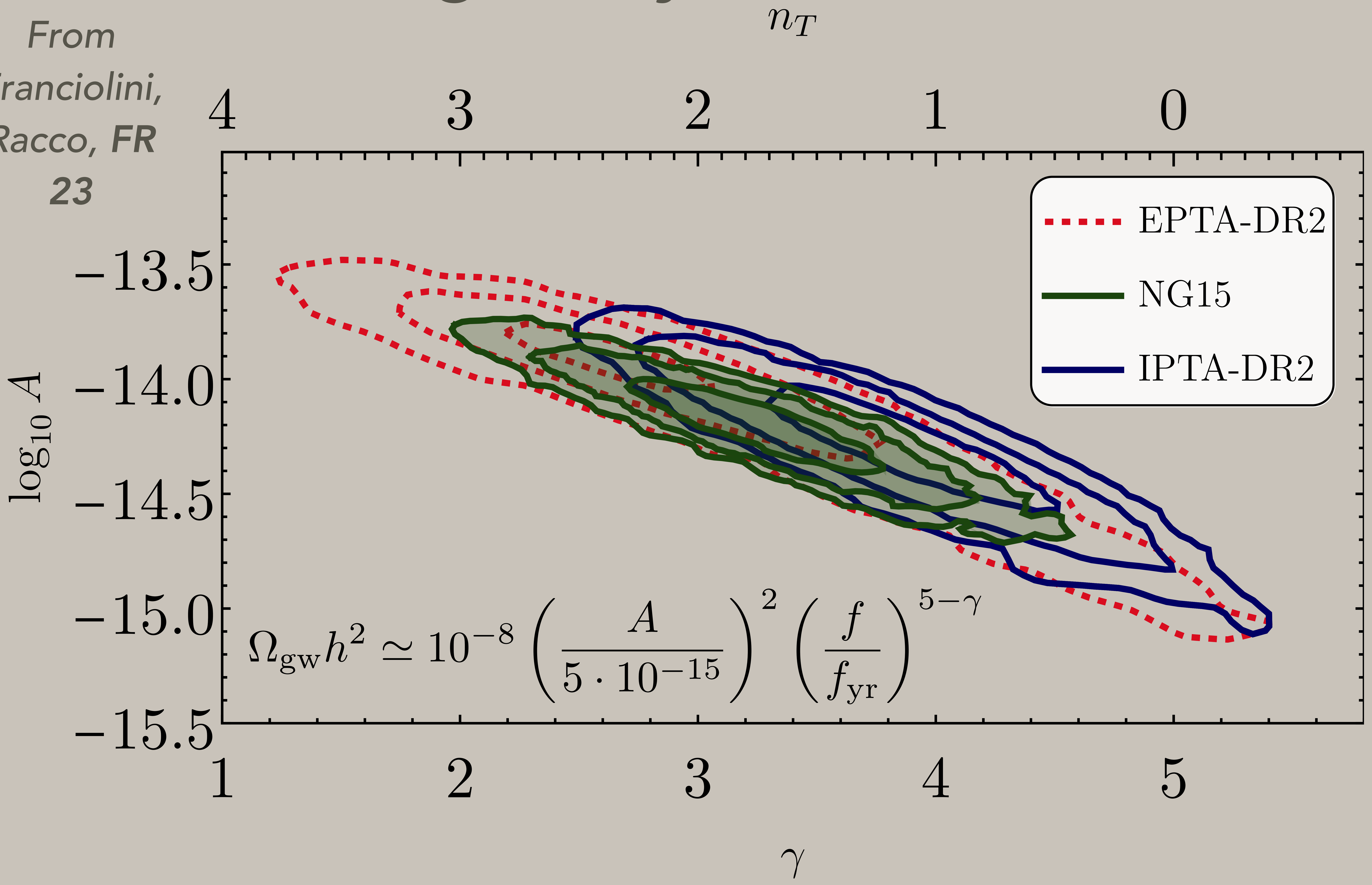
Pulsar Timing Array evidence for GW background

From Franciolini, Racco, FR 23

EPTA-DR2 Antoniadis+ 23

NANOGrav 15 yrs, Agazie+ 23

IPTA-DR2 Antoniadis+ 22



Astrophysical candidate:

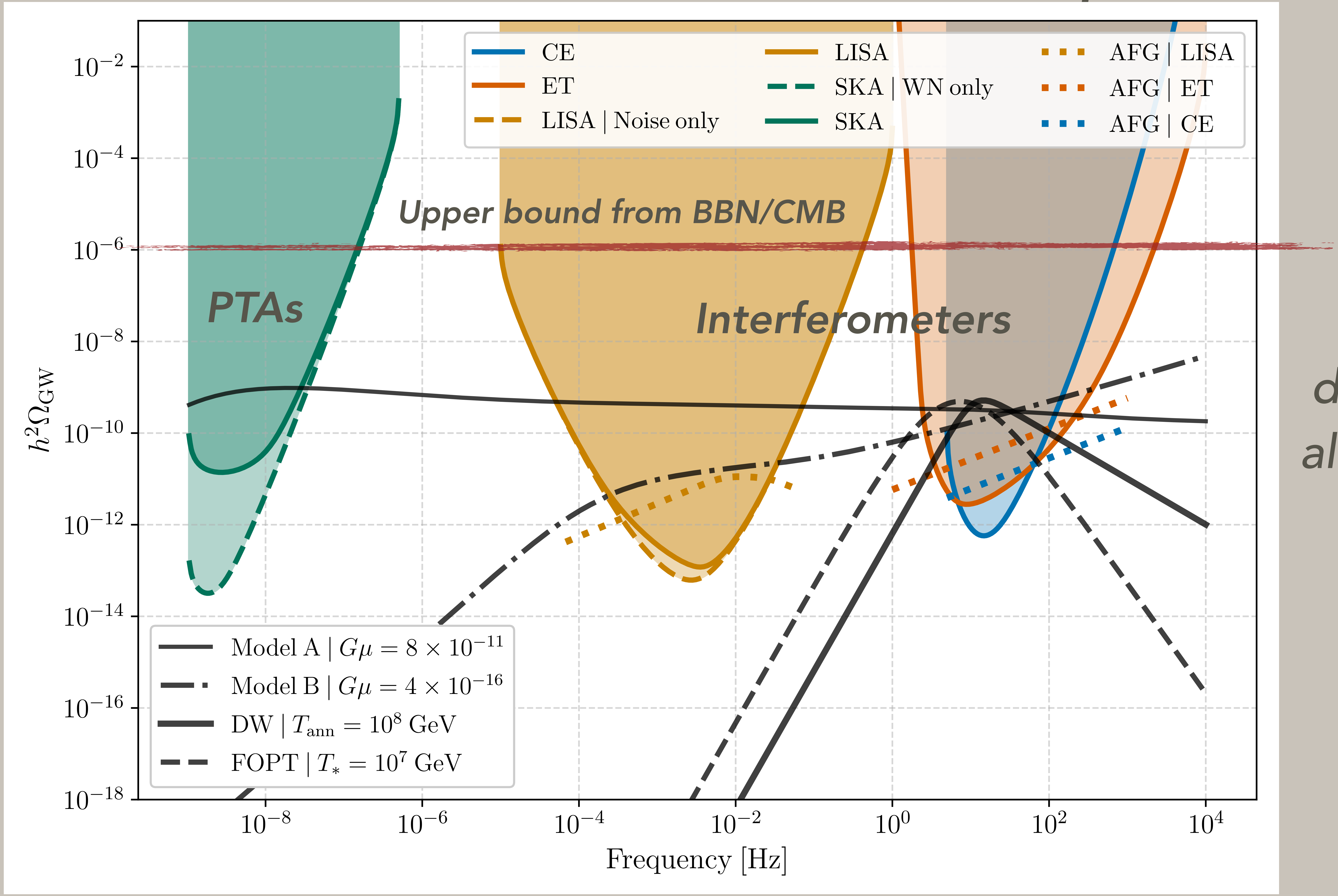
Supermassive Black Hole Binaries

Currently probing

$$\alpha_\star \gtrsim 0.05$$

GW detection landscape: the future

Adapted from Caprini, Pujolàs, Quelquejay-Leclere, Steer, FR 24



Upcoming future detectors (2035+) will allow to probe sources with

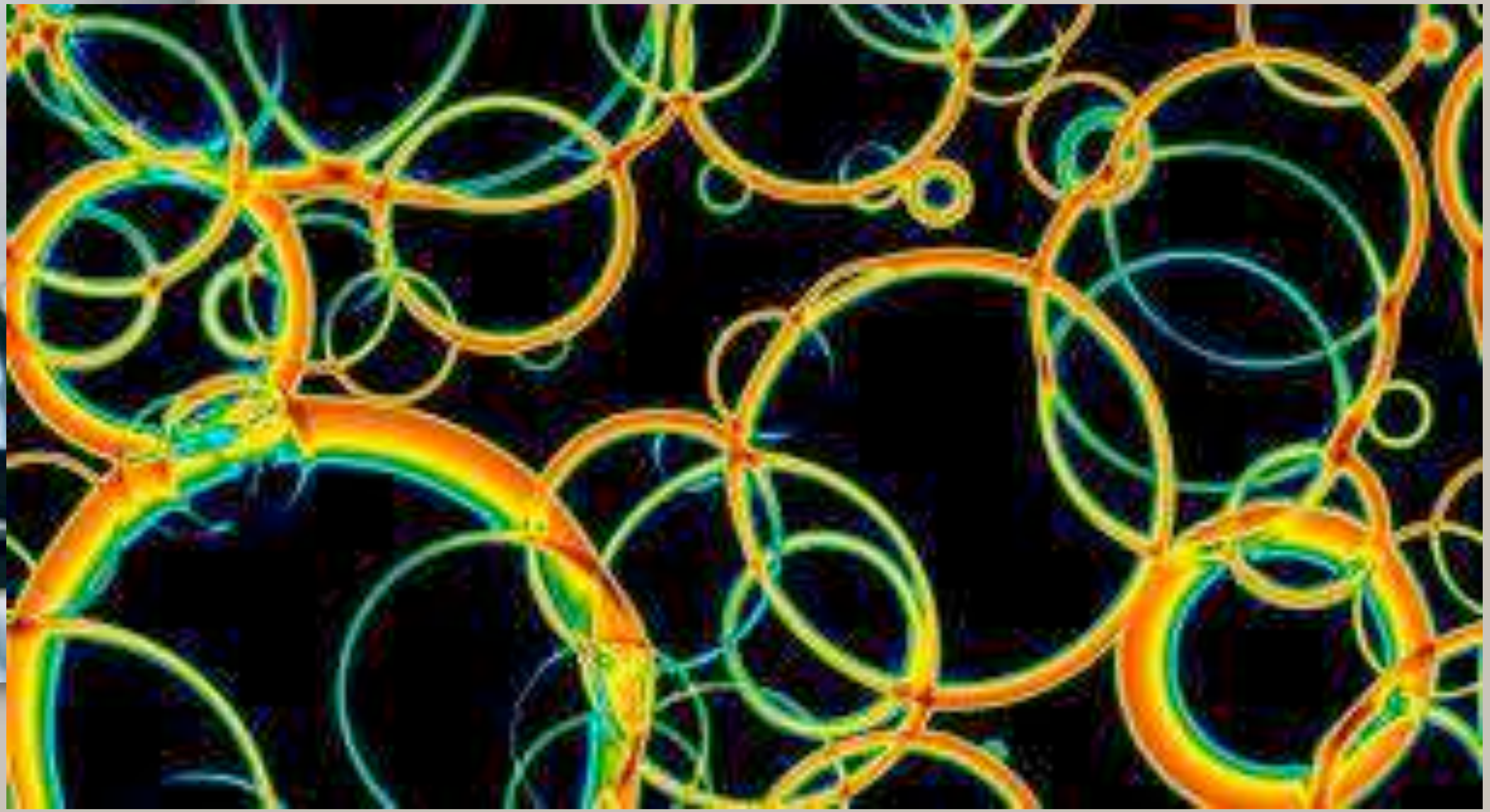
$$\alpha_\star \gtrsim 0.001$$

‼️

Sources

Everyone talks about:
first order phase transitions

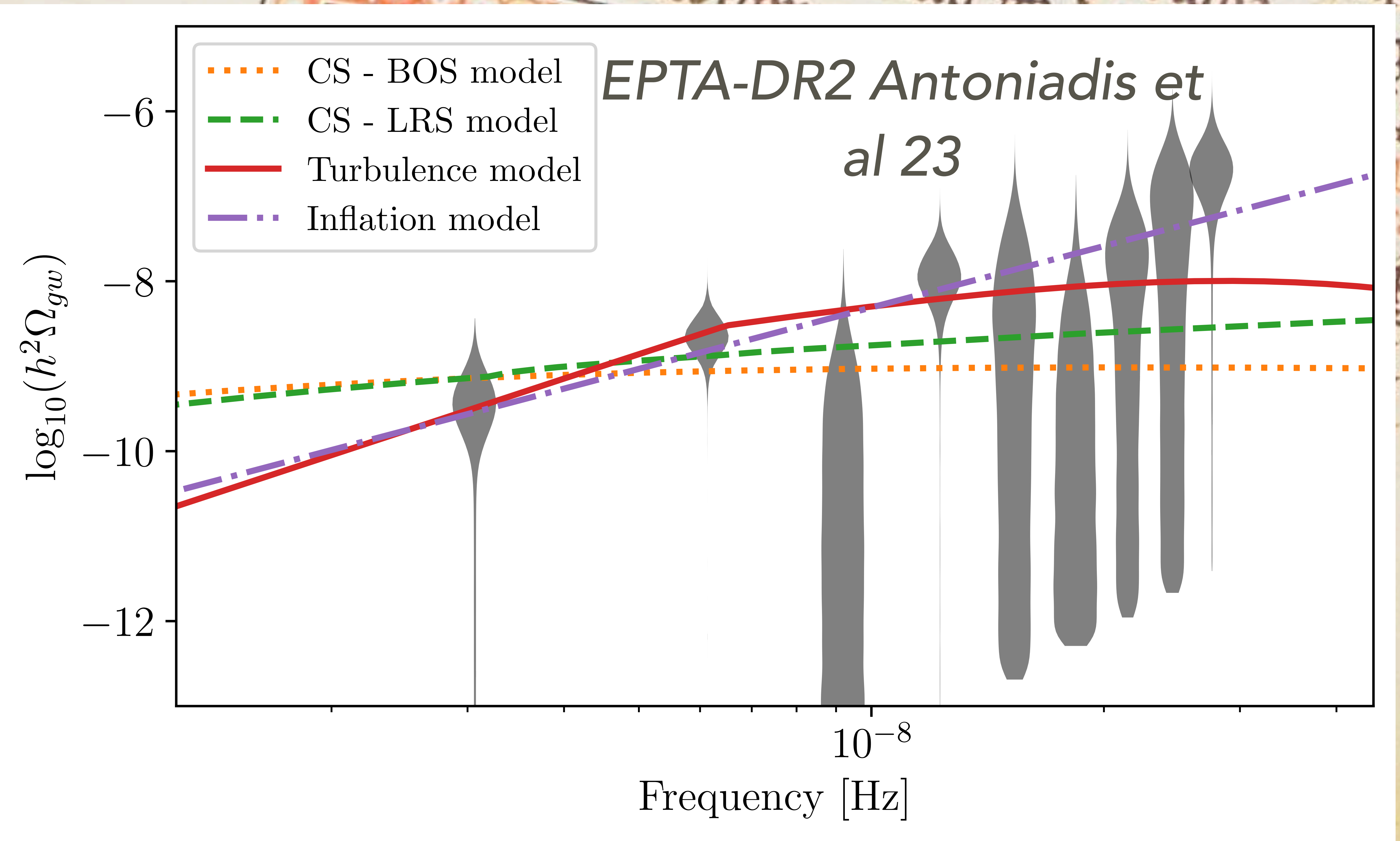
Credit: David Weir

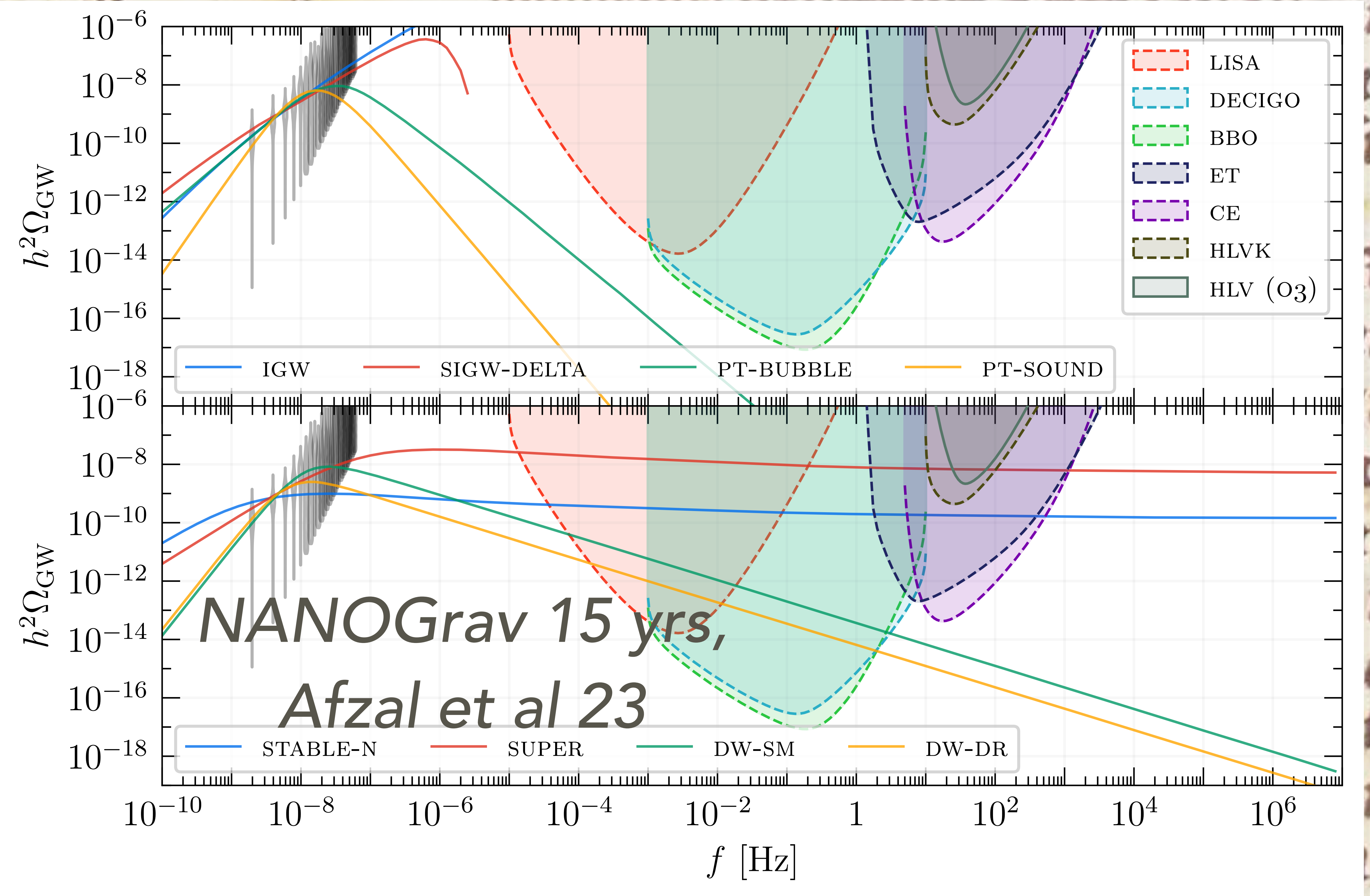


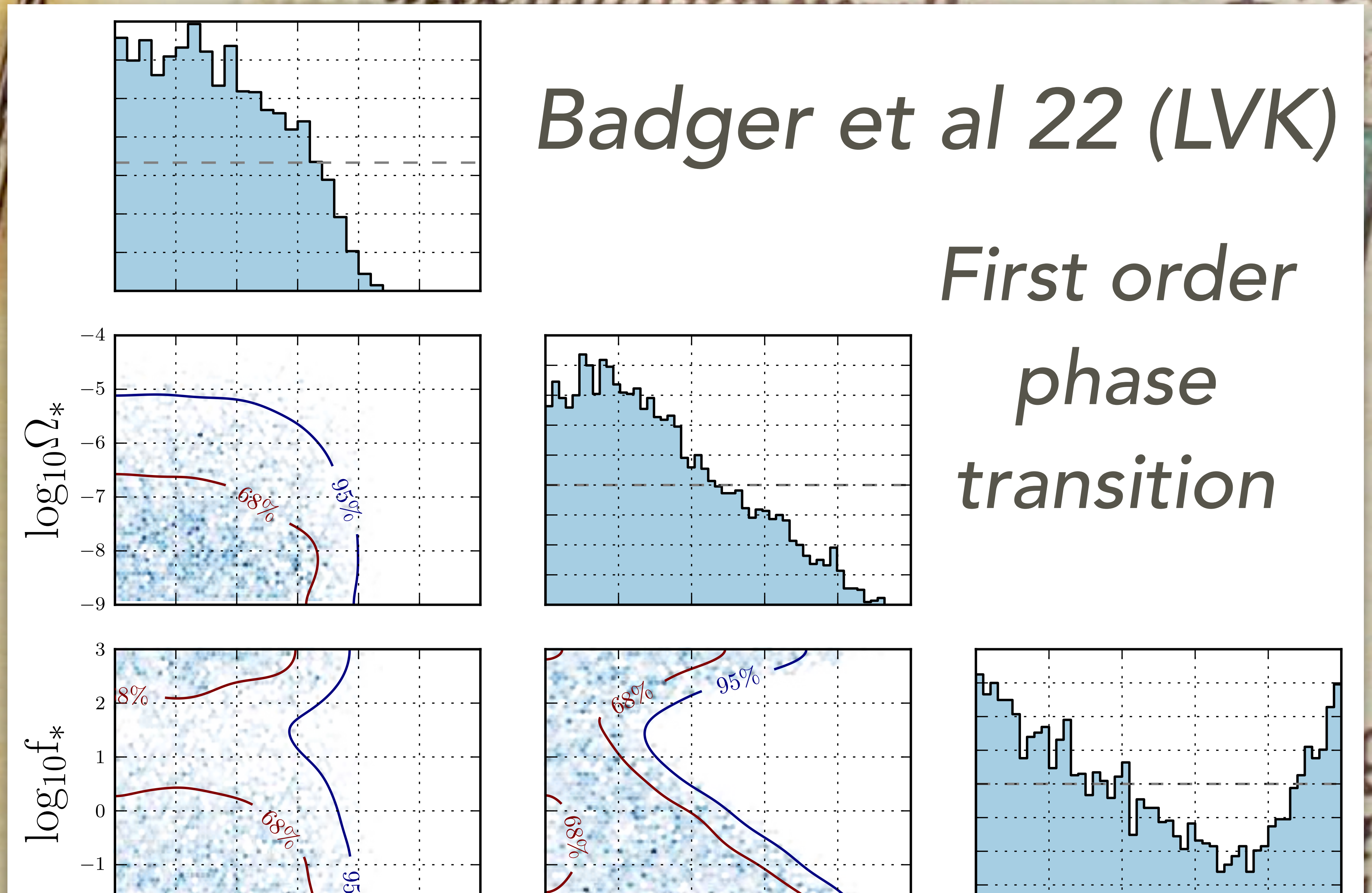
*But: **Not strong enough in the Standard Model***

QCD confinement, EW symmetry breaking expected to be crossovers

BSM sources?







Several currently searched for by collaborations

What could we hear now?

$$\Omega_{\rm gw}(f)h^2 \simeq 10^{-8}\epsilon\left(\frac{\alpha_\star}{0.1}\right)^2 \mathcal{S}(f/f_\star) \quad (\alpha_\star \leq 1)$$

$$\epsilon \propto \left(\frac{H_\star}{t_\star^{-1}}\right)^p \leq 1$$

Time/length scale of the source
Compared to causal size of the Universe at that time

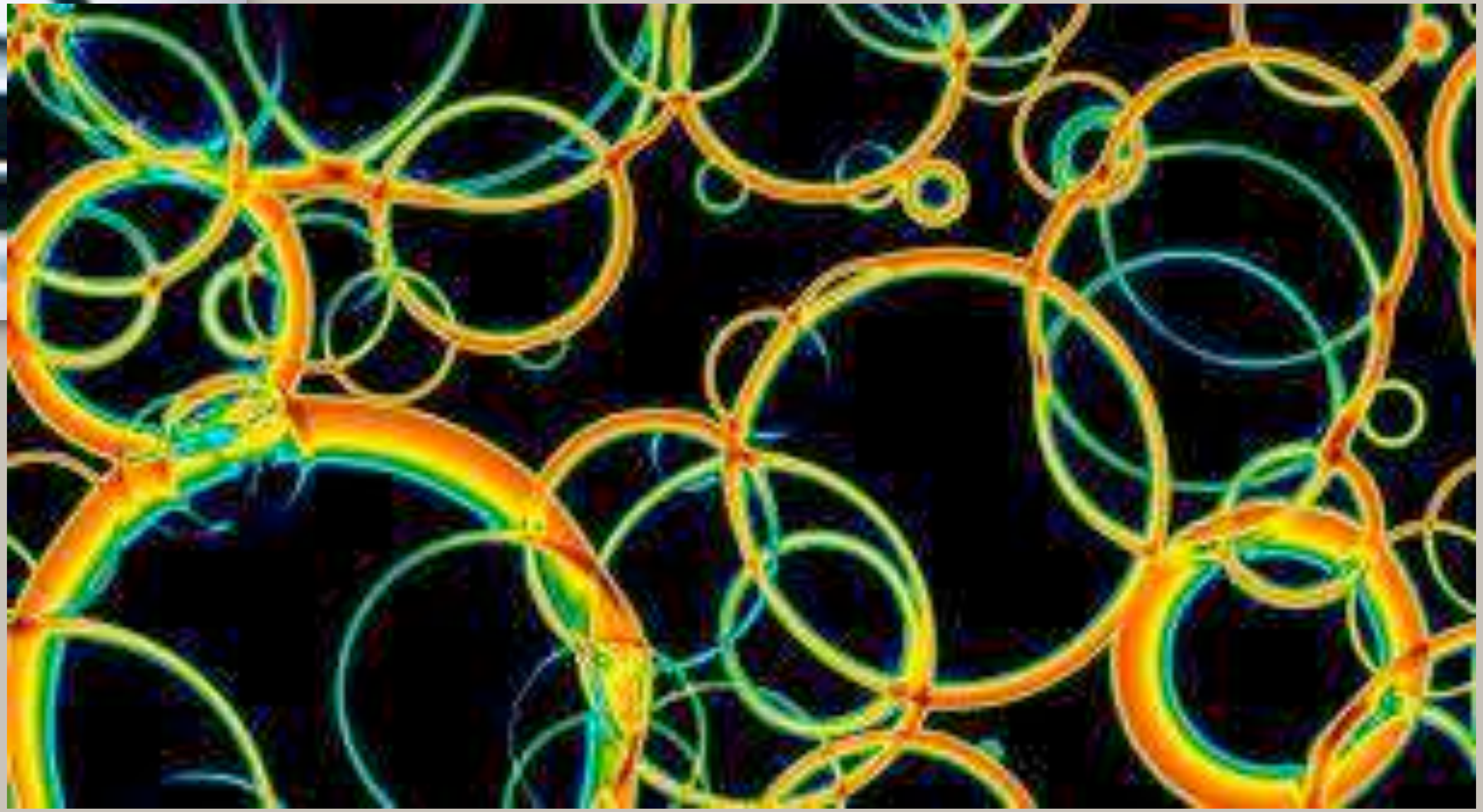
Signal is loud enough to be observable now and in the (near) future if

$$t_\star \lesssim H_\star$$

i.e. if the source is Hubble-sized and relativistic

Challenging for first order PT!

Typically many small bubbles, otherwise transition does not complete!



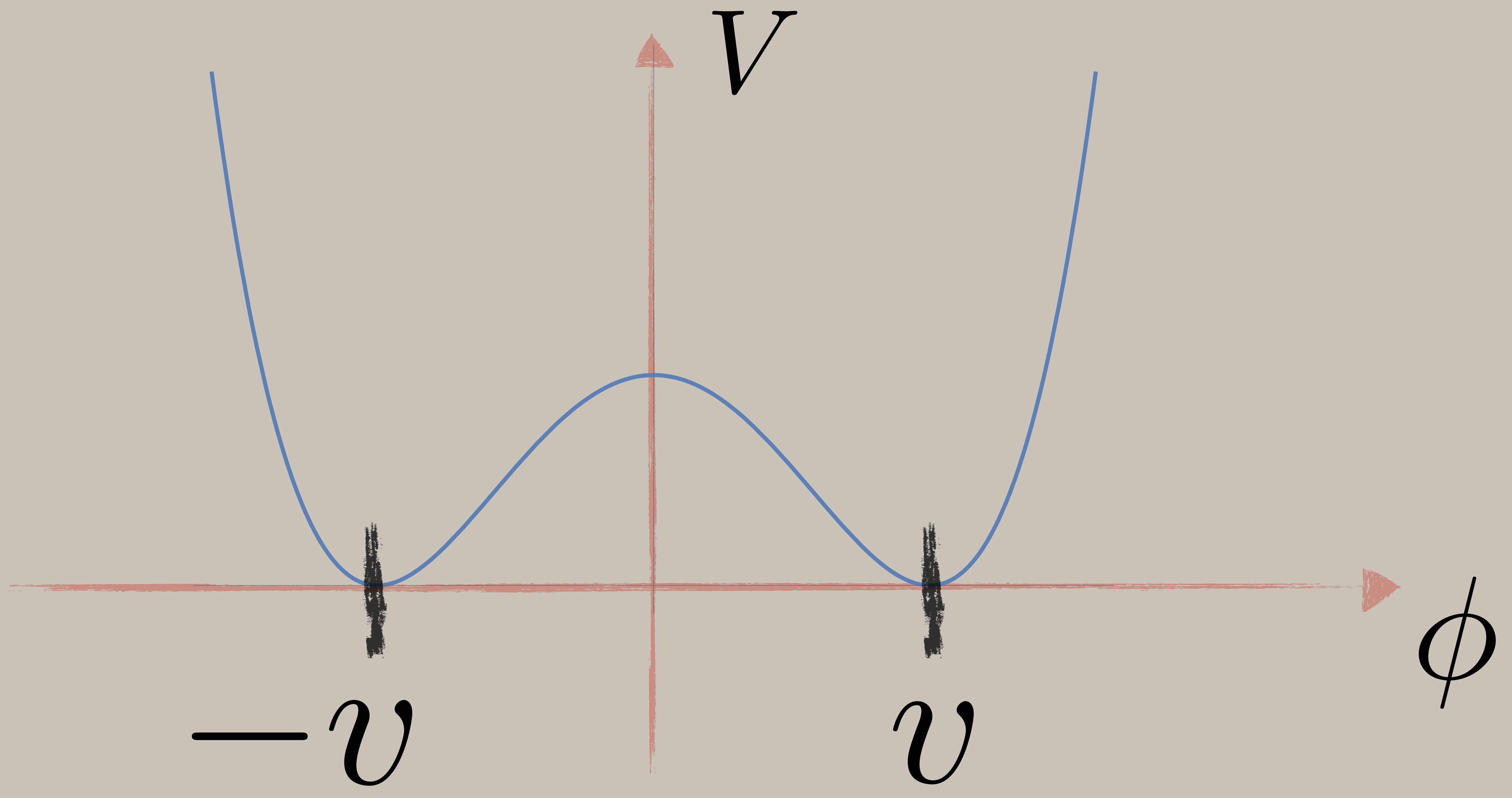
Still possible in extreme (supercooled) cases

*…/Baratella, Pomarol, **FR** 18 /von Harling, Pomarol, Pujolàs, **FR** 19/…*

Credit: David Weir

“Attractive” possibility:
Spontaneous breaking of a discrete symmetry

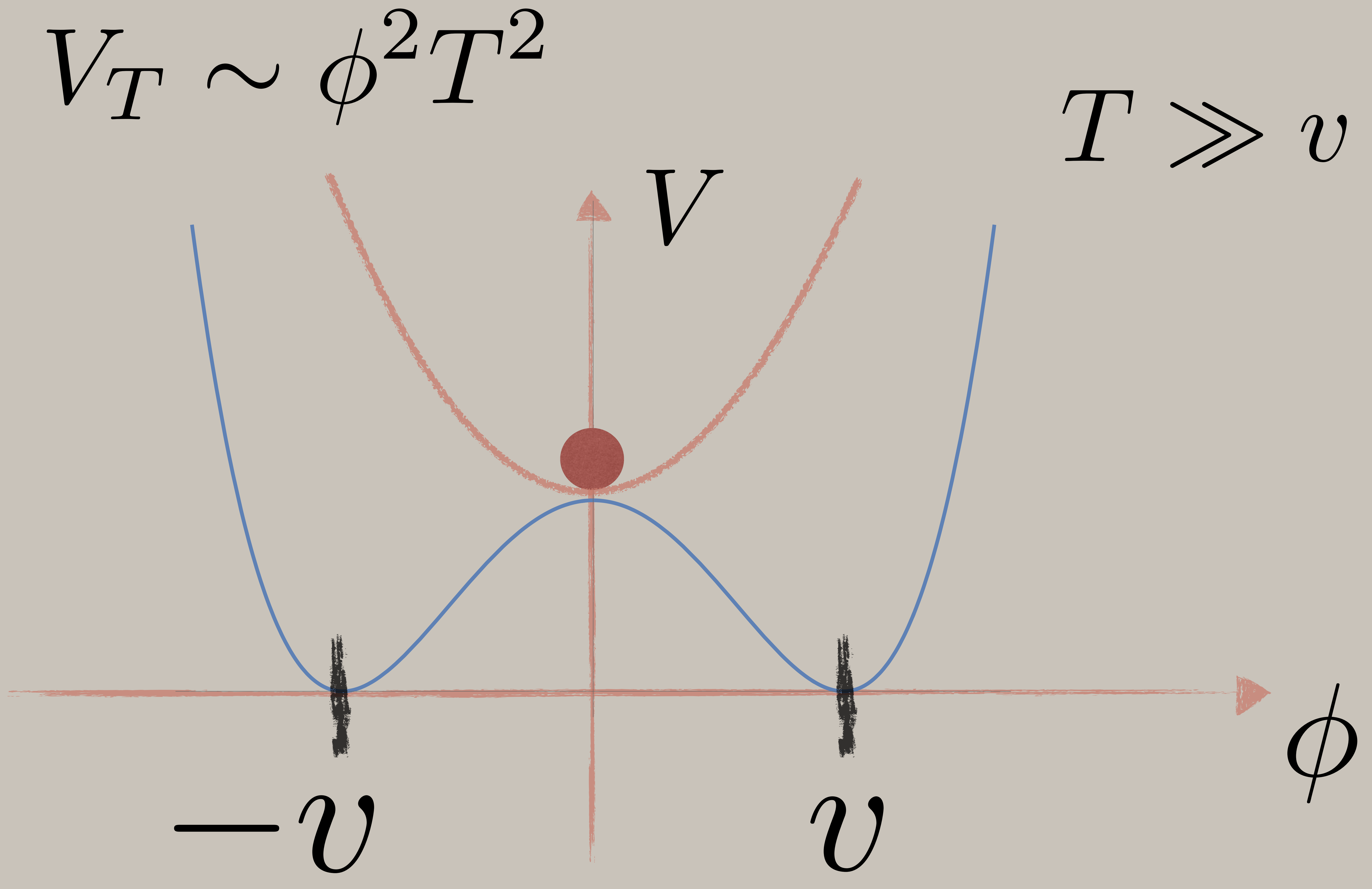
Simple model: real scalar field with $\mathbb{Z}_2$ symmetric potential



Many concrete implementations in BSM: composite Higgs, SUSY, metastability, axions, …

Spontaneous breaking of a discrete symmetry

Simple model: real scalar field with $\mathbb{Z}_2$ symmetric potential



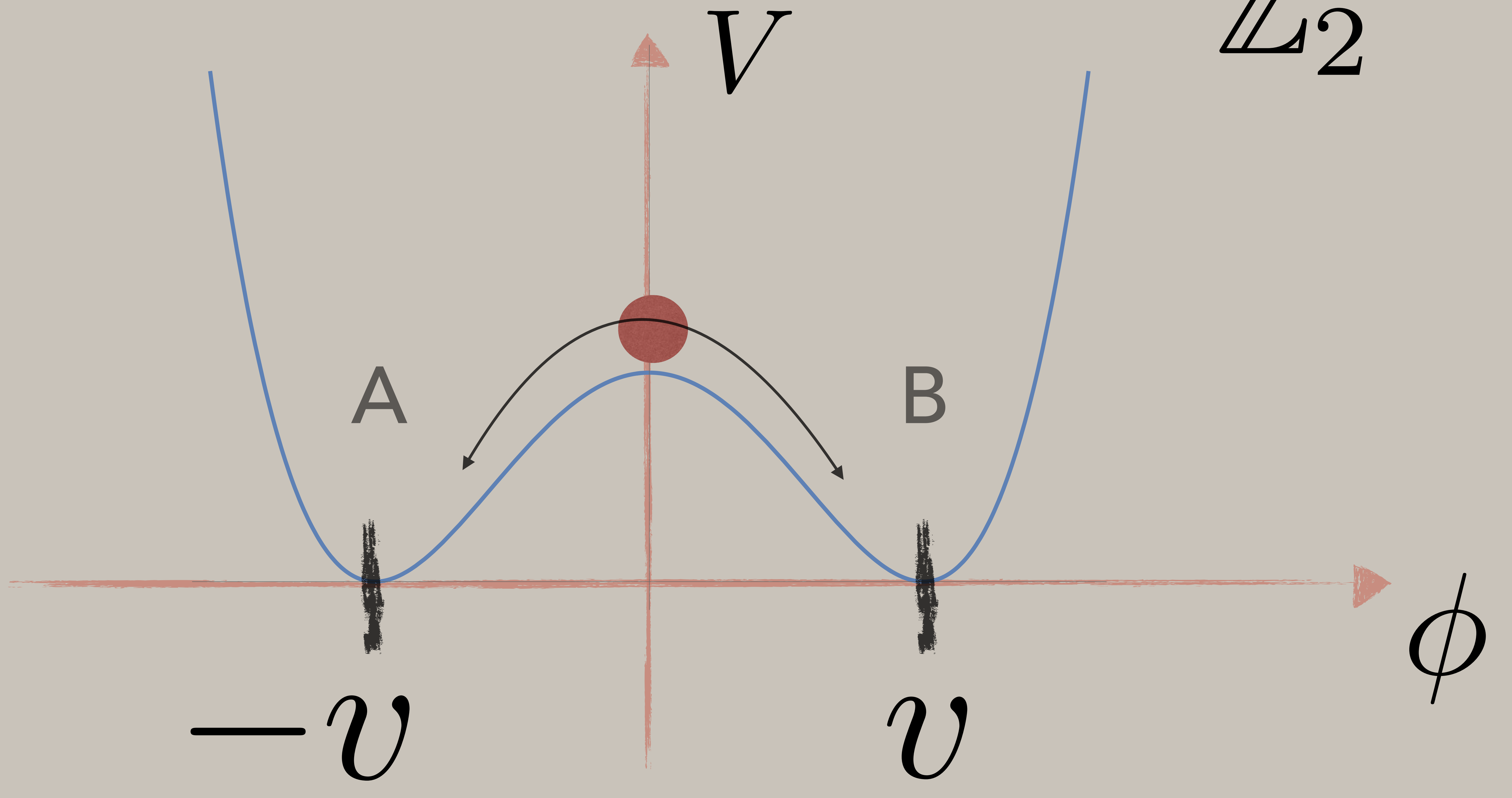
Many concrete implementations in BSM (composite Higgs, SUSY, metastability, axions, …)

Spontaneous breaking of a discrete symmetry

$T \lesssim v$

$\mathbb{Z}_2$

Different vacua are populated randomly in different regions of the Universe due to (thermal) fluctuations



Many concrete implementations in BSM (composite Higgs, SUSY, metastability, axions, …)

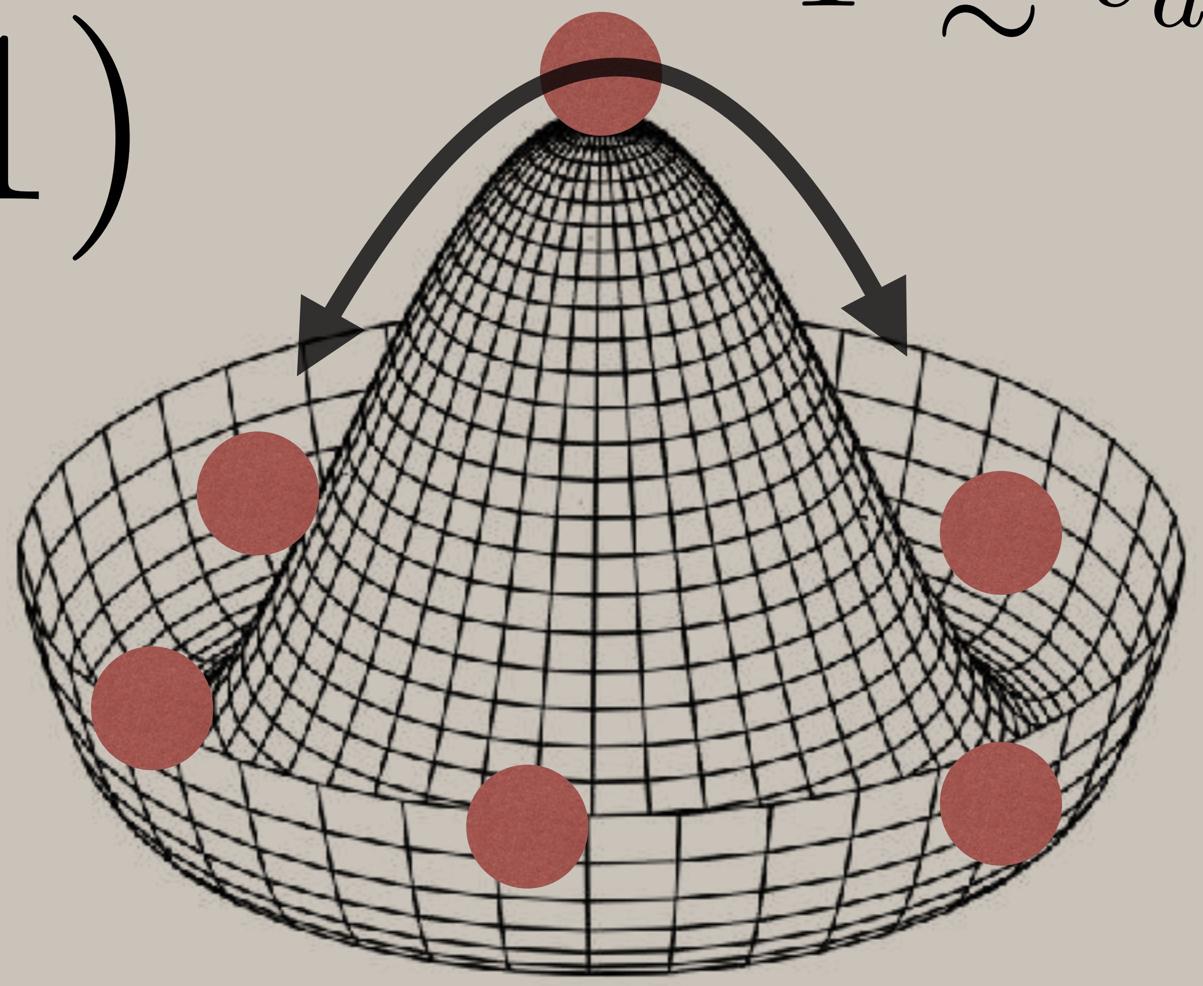
Kibble mechanism

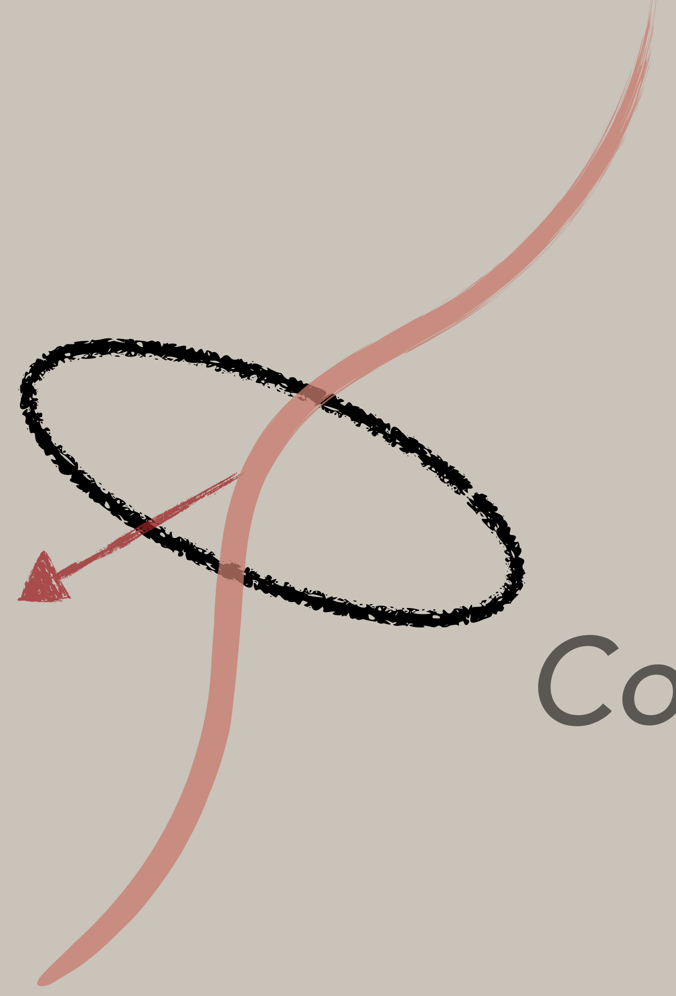
The axion case

Complex scalar

$$U(1)$$

$$T \lesssim v_a \Rightarrow \Phi \sim \varphi e^{i\frac{a}{v_a}}$$





Loop in physical space

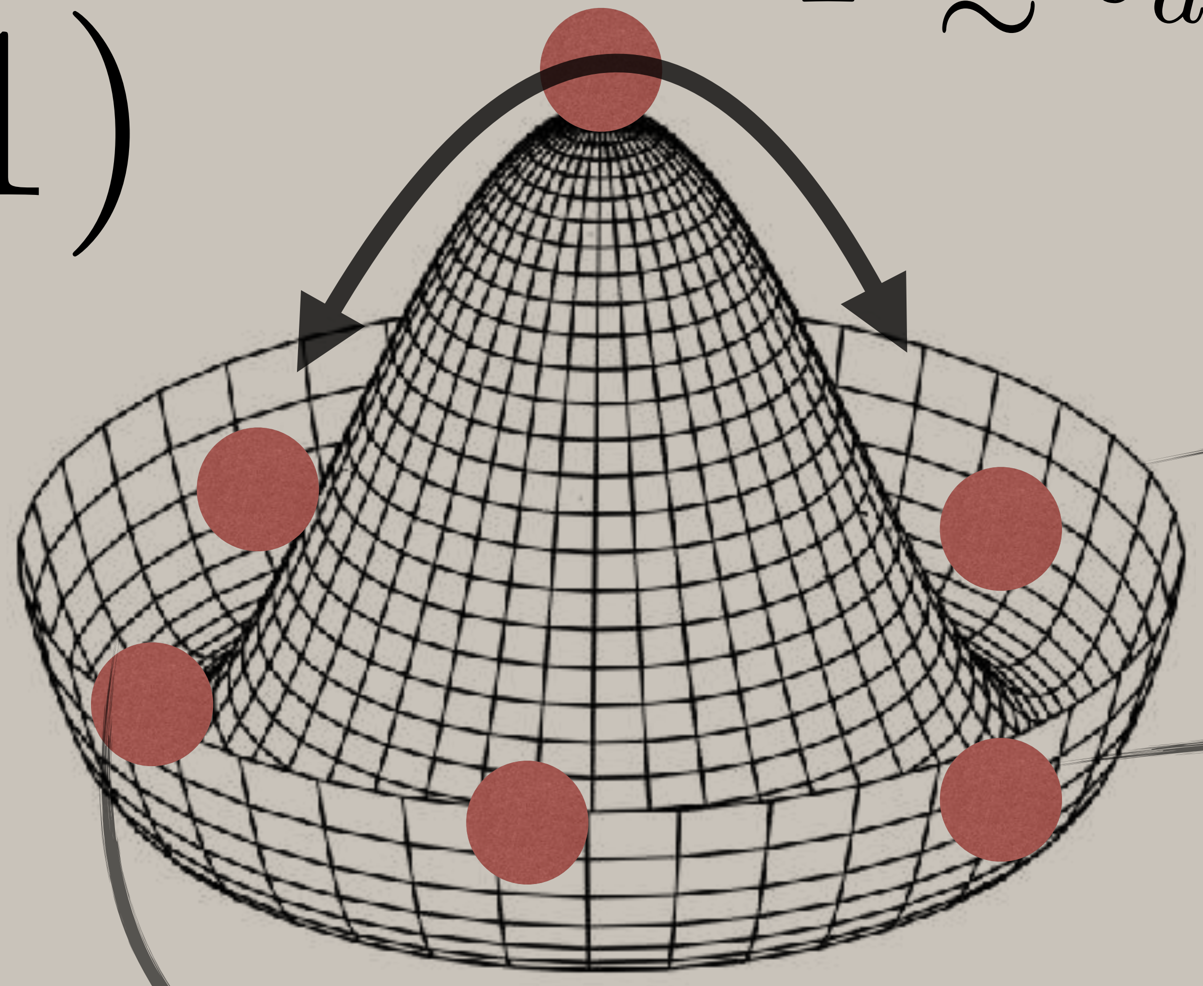
Cosmic string defect

The axion case

Complex scalar

$$T \lesssim v_a \Rightarrow \Phi \sim \varphi e^{i\frac{a}{v_a}}$$

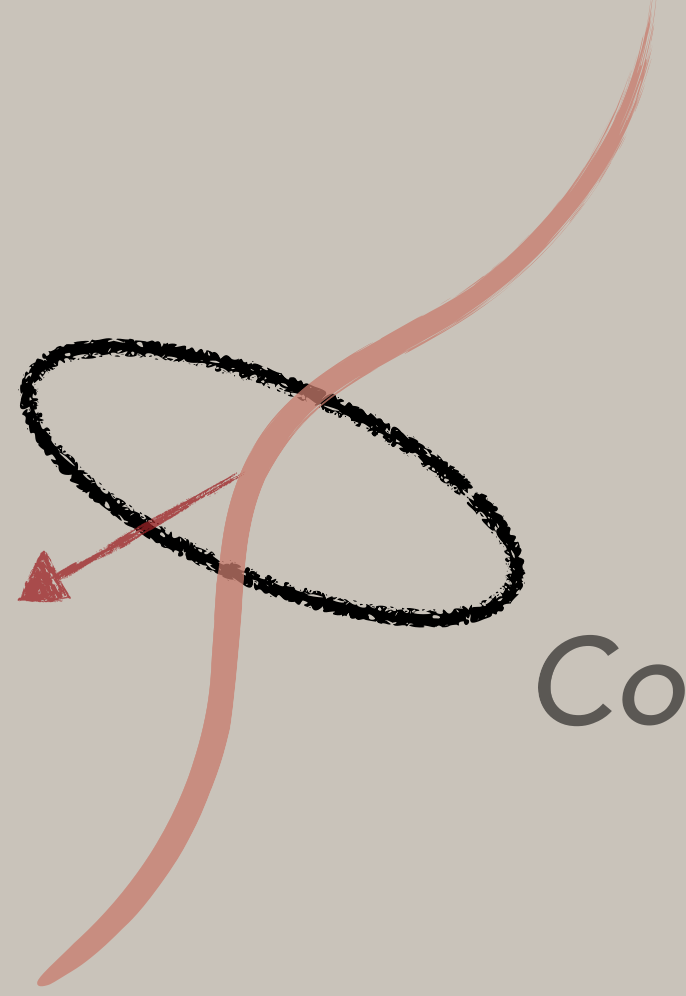
$U(1)$



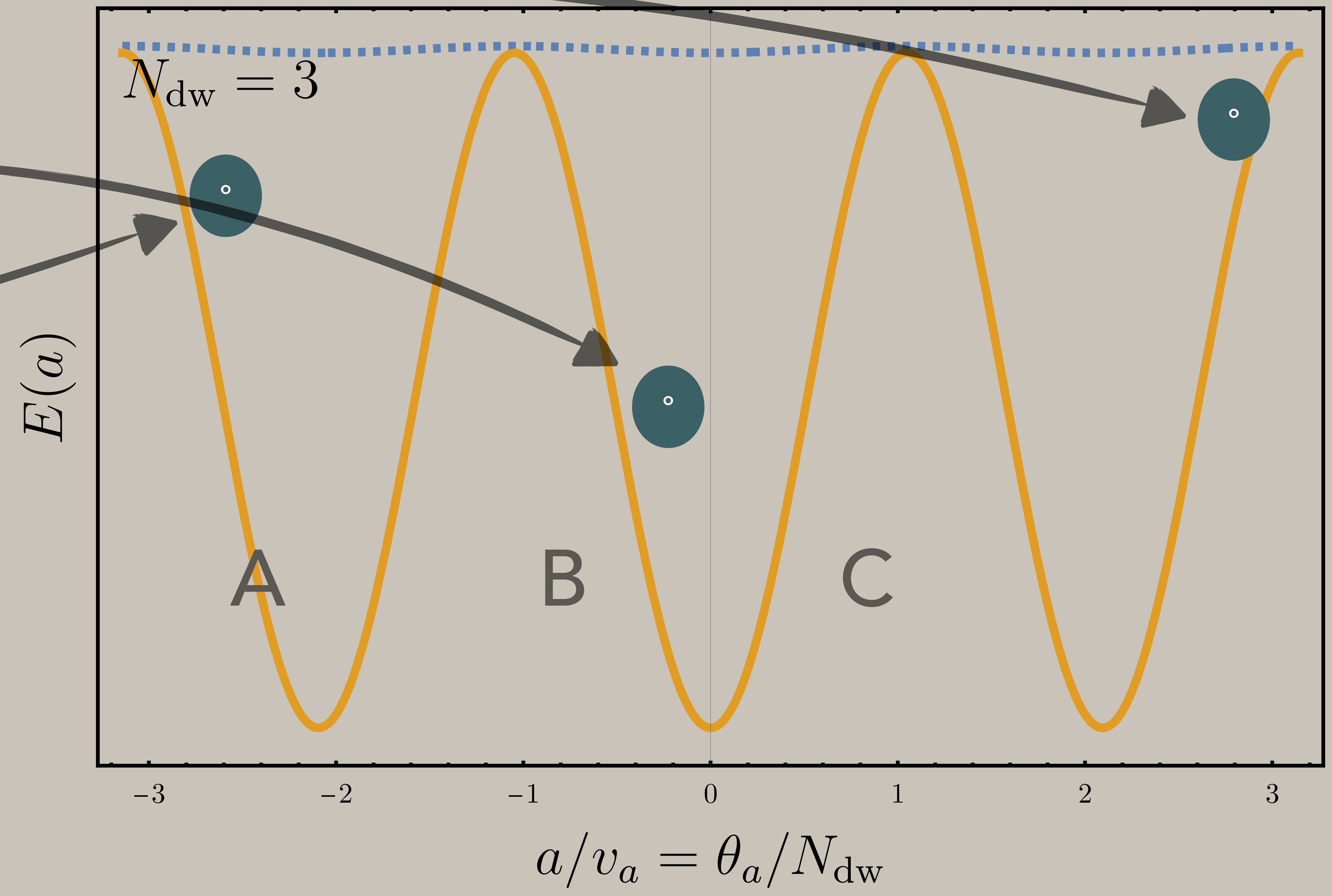
$\mathbb{Z}_N$

QCD (or dark sector) non-perturbative effects preserve discrete subgroup of global Peccei-Quinn symmetry

Loop in physical space



Cosmic string defect



The axion case

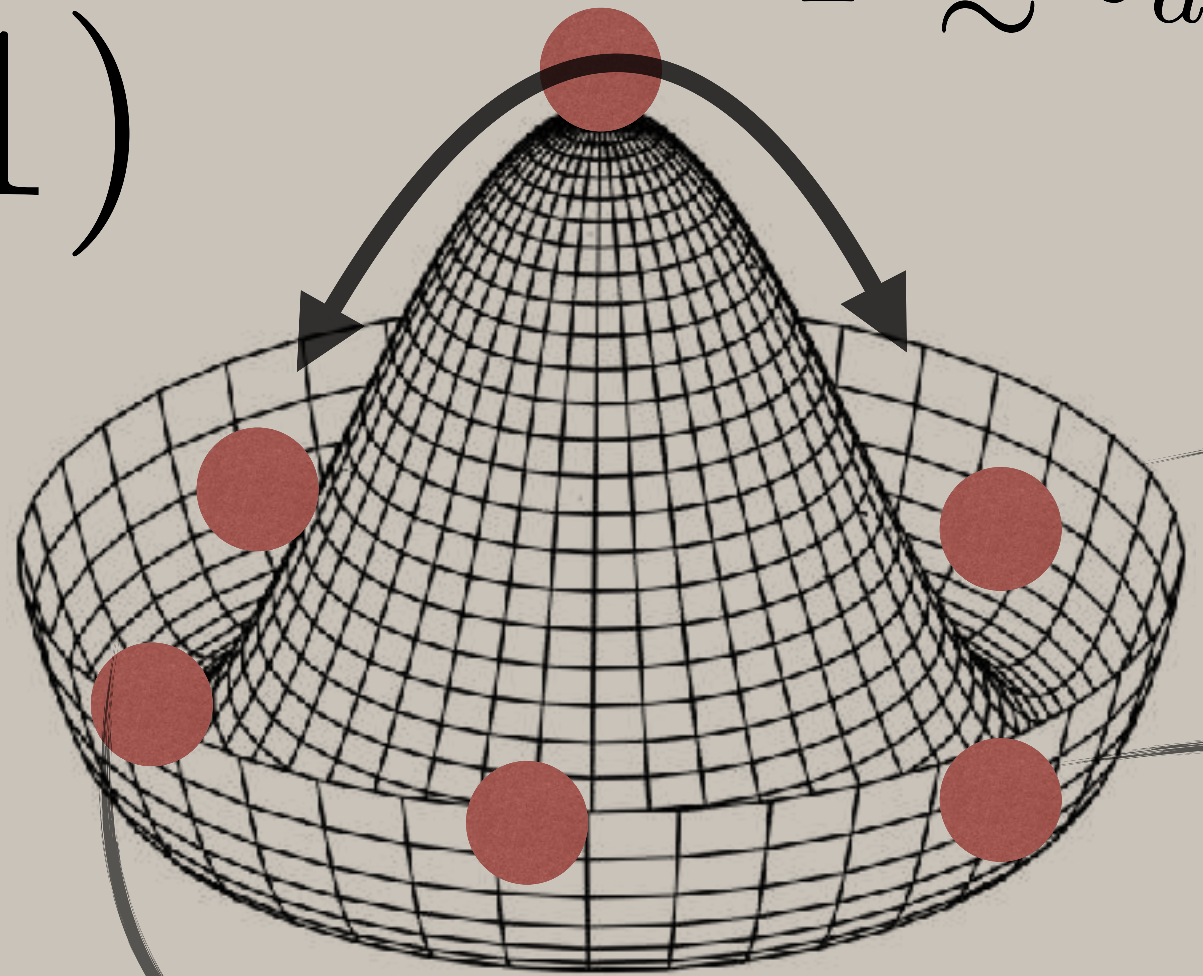
Complex scalar

$$T \lesssim v_a \implies \Phi \sim \varphi e^{i\frac{a}{v_a}}$$

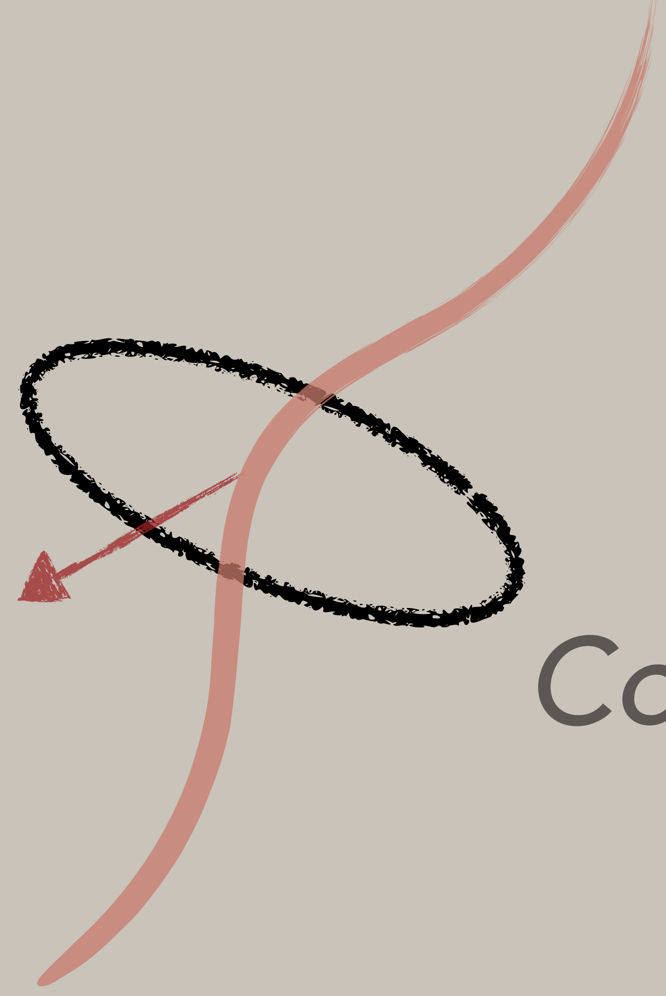
$U(1)$

$\downarrow$

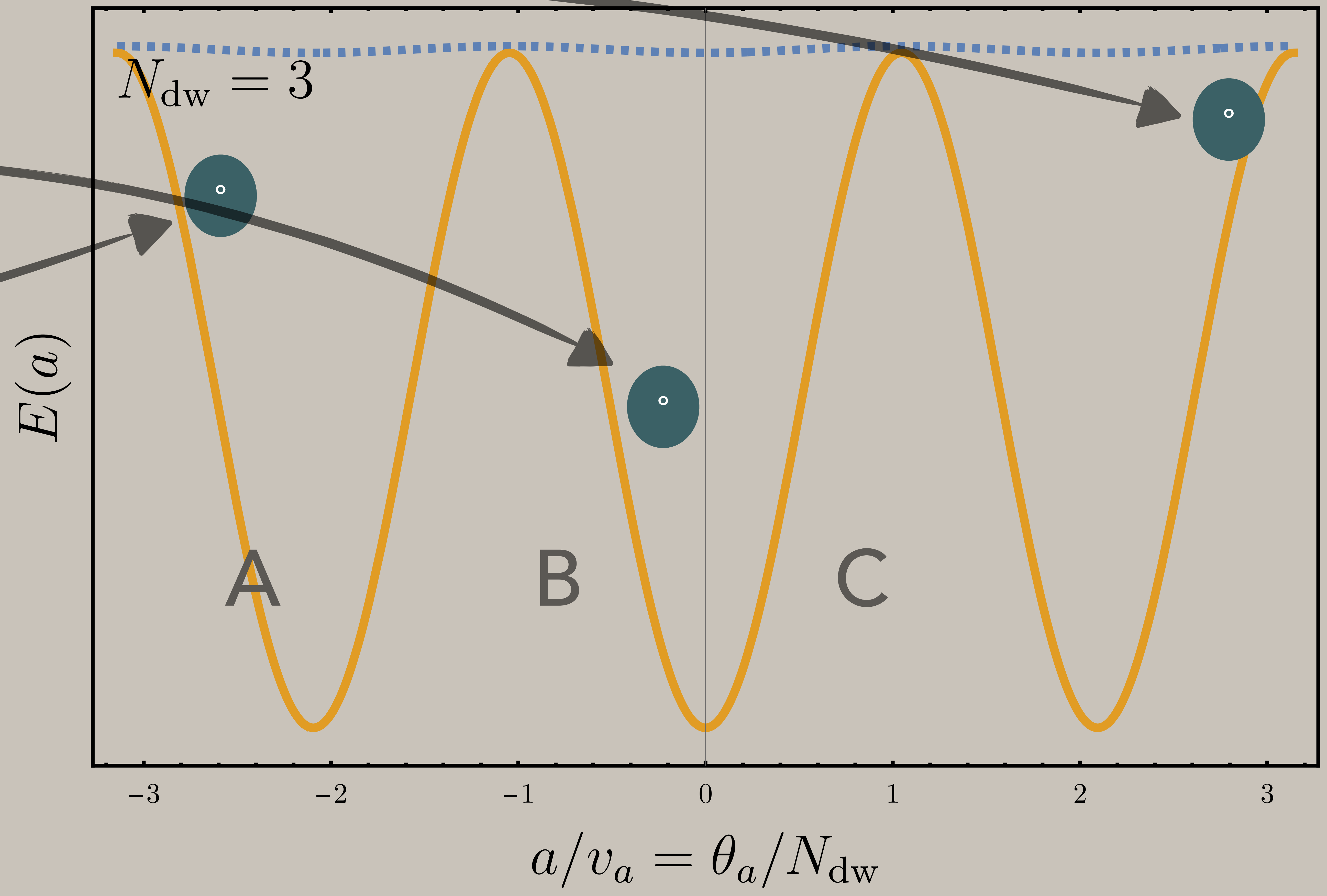
$\mathbb{Z}_N$



Loop in physical space



Cosmic string defect



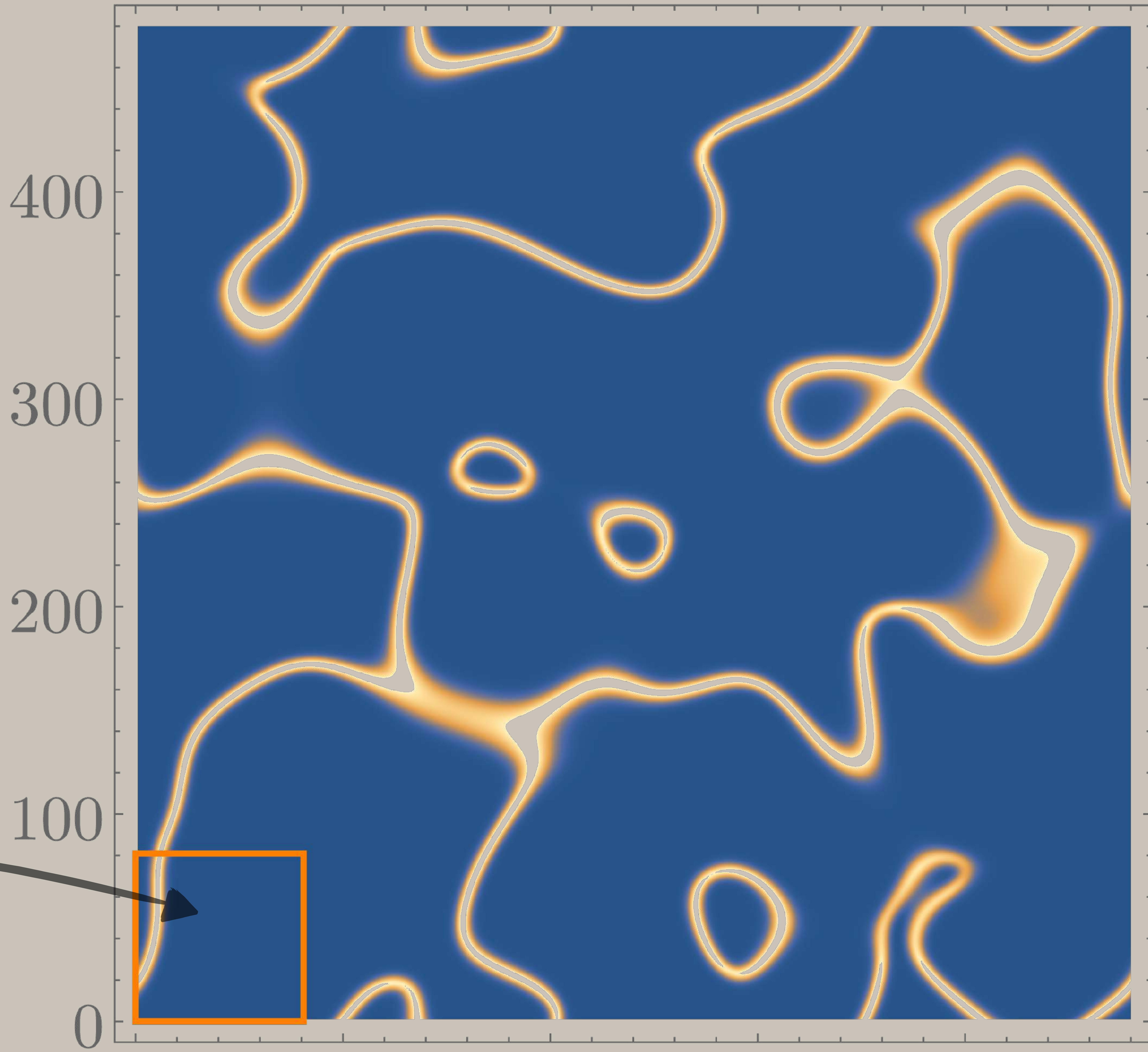
Domain walls form once

$$m_a \gtrsim H$$

Domain wall networks

Results from lattice field theory simulations in expanding Universe

2D slice of gradient energy density



Regions in different vacua are separated by two-dimensional "walls" of energy density

Wall "mass" = ***tension*** *(energy/surface)* σ

$= [E]^3$

Size of an Hubble patch

Produced using ***Cosmolattice*** *(Figueroa et al 21)*

Crucial property: scaling

Expanding Hubble patch

***At every Hubble time**, the network is made of*
a fixed O(1-few) number of Hubble-sized walls

Scaling regime:
Achieved via collisions and reconnections

In scaling regime

$$\rho_{\rm dw} \sim \sigma H \sim a^{-2}$$

Walls are diluted more slowly than radiation and matter, so they tend to dominate ***(ruled out by observations)***

Zeldovich et al 74

In scaling regime

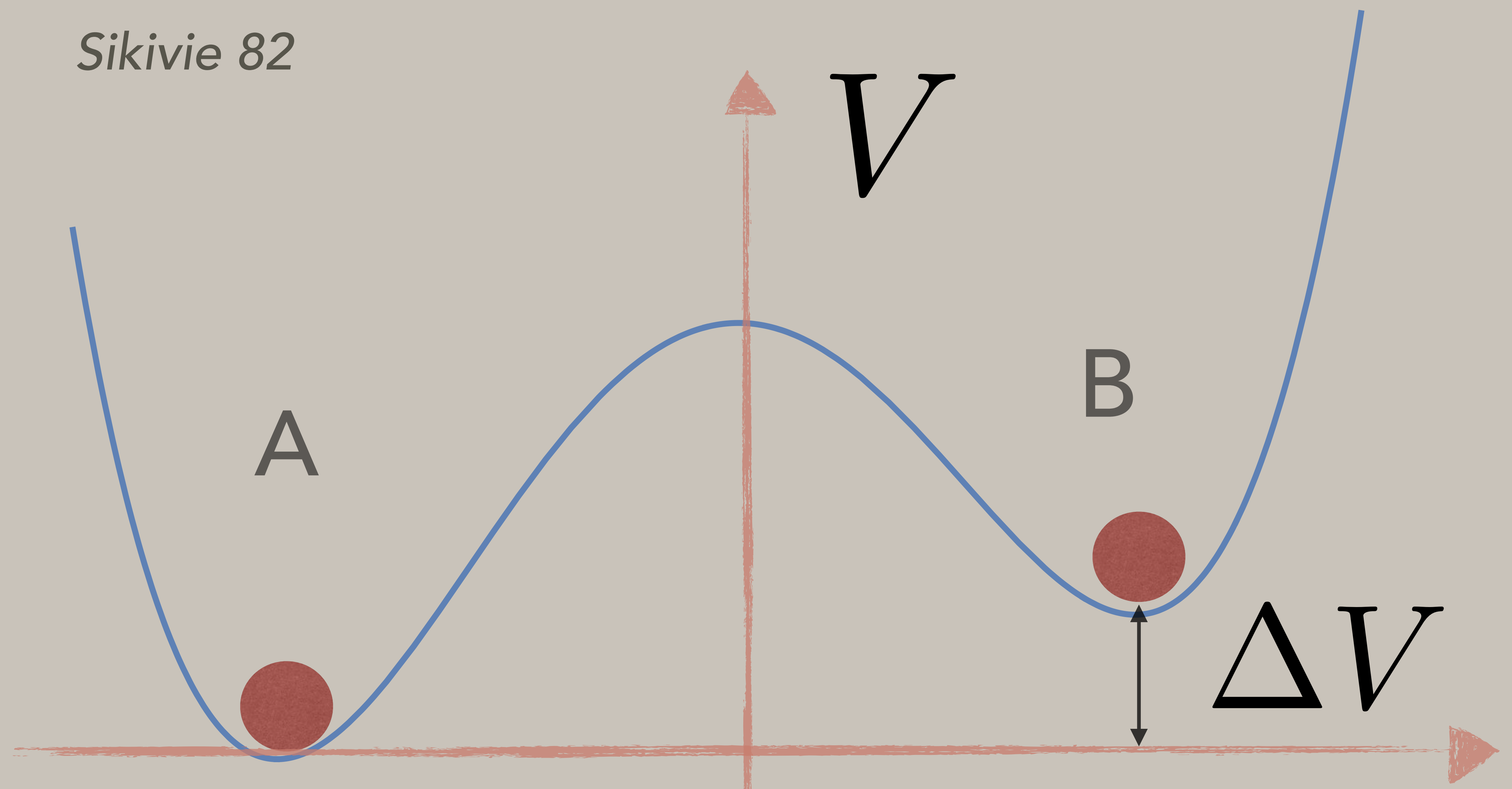
$$\rho_{\rm dw} \sim \sigma H \sim a^{-2}$$

*Walls are diluted more slowly than radiation and matter, so they tend to dominate (**ruled out by observations**)*

Zeldovich et al 74

However, modern viewpoint on global symmetries: not exact!

Sikivie 82



Vacuum Pressure causes acceleration

$$\ddot{x} \simeq \Delta V/\sigma$$

And walls annihilate once:

$$\Delta V/\sigma \gtrsim H$$

Domain Wall annihilation

Implications for gravitational waves from domain walls

$$\Omega_{\rm gw} h^2 \simeq 10^{-8} \epsilon \left(\frac{\alpha_\star}{0.1}\right)^2 \mathcal{S}(f/f_\star)$$

Scaling until annihilation implies

1. Easy to get large fraction of energy density in the network

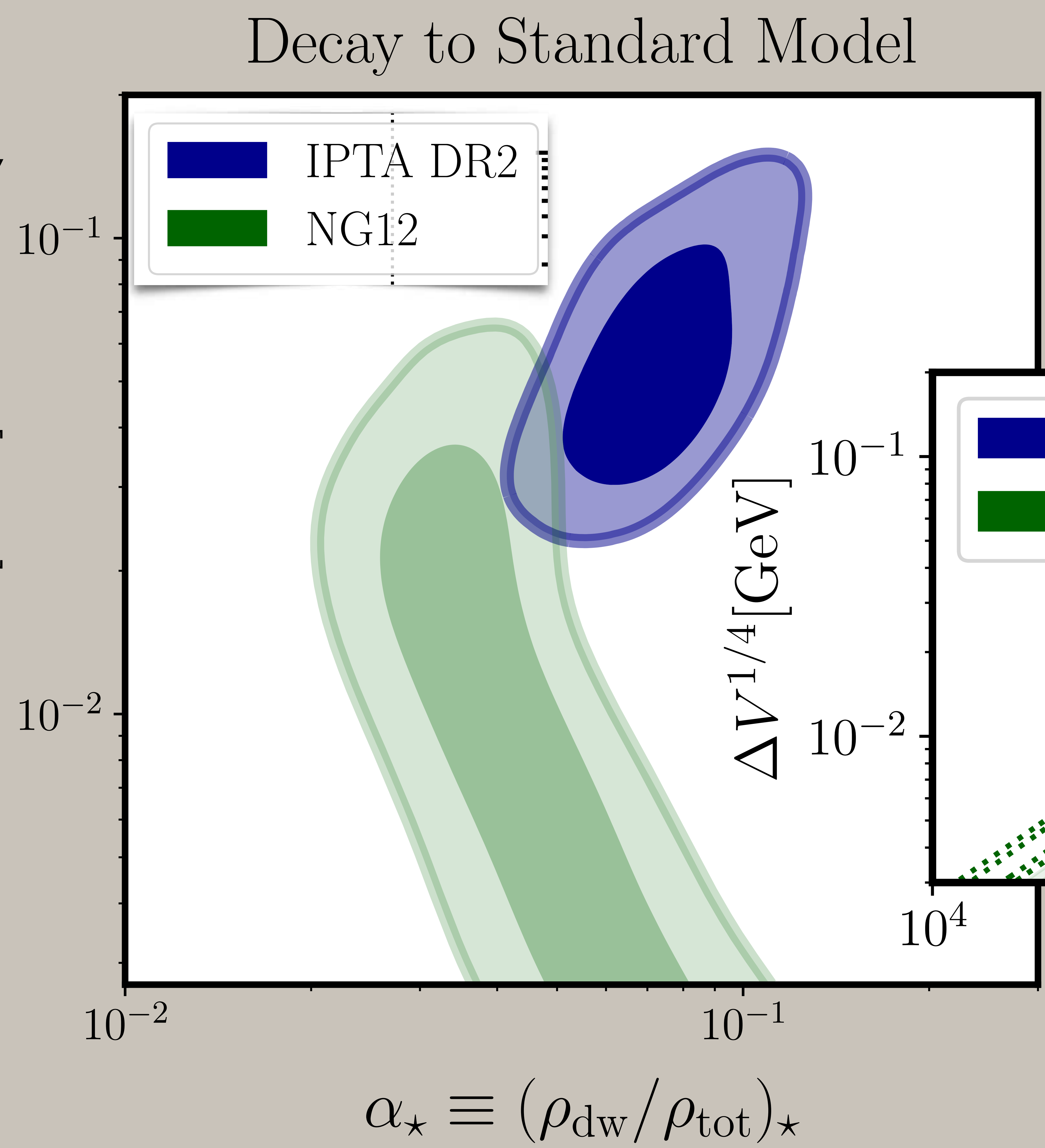
2. Hubble-sized and relativistic

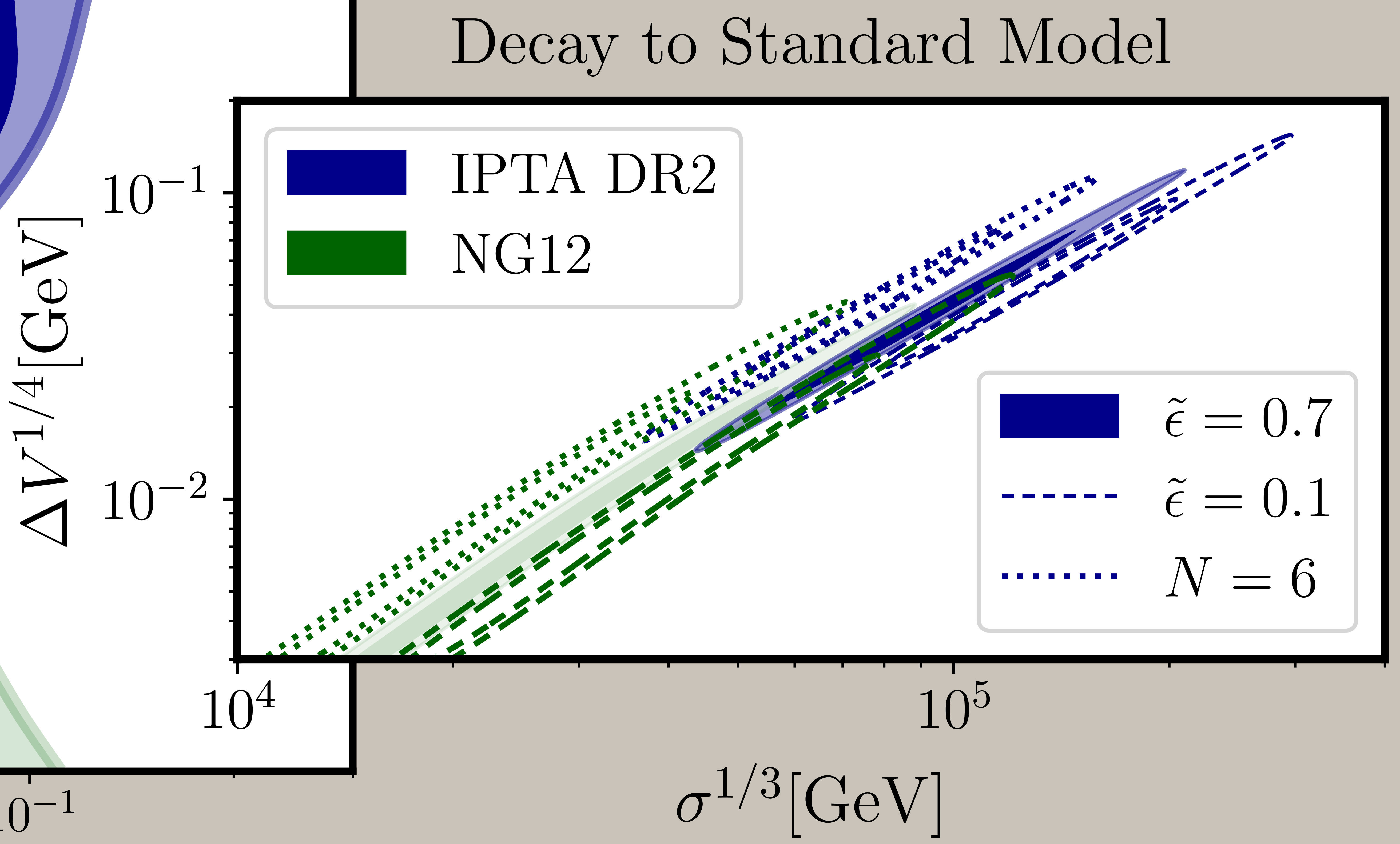
$$\epsilon \simeq 1$$

Observable (now) gravitational wave signal possible!

Domain Walls as possible interpretation of PTA data

R.Z. Ferreira, A. Notari, O. Pujolàs, **FR** 22'

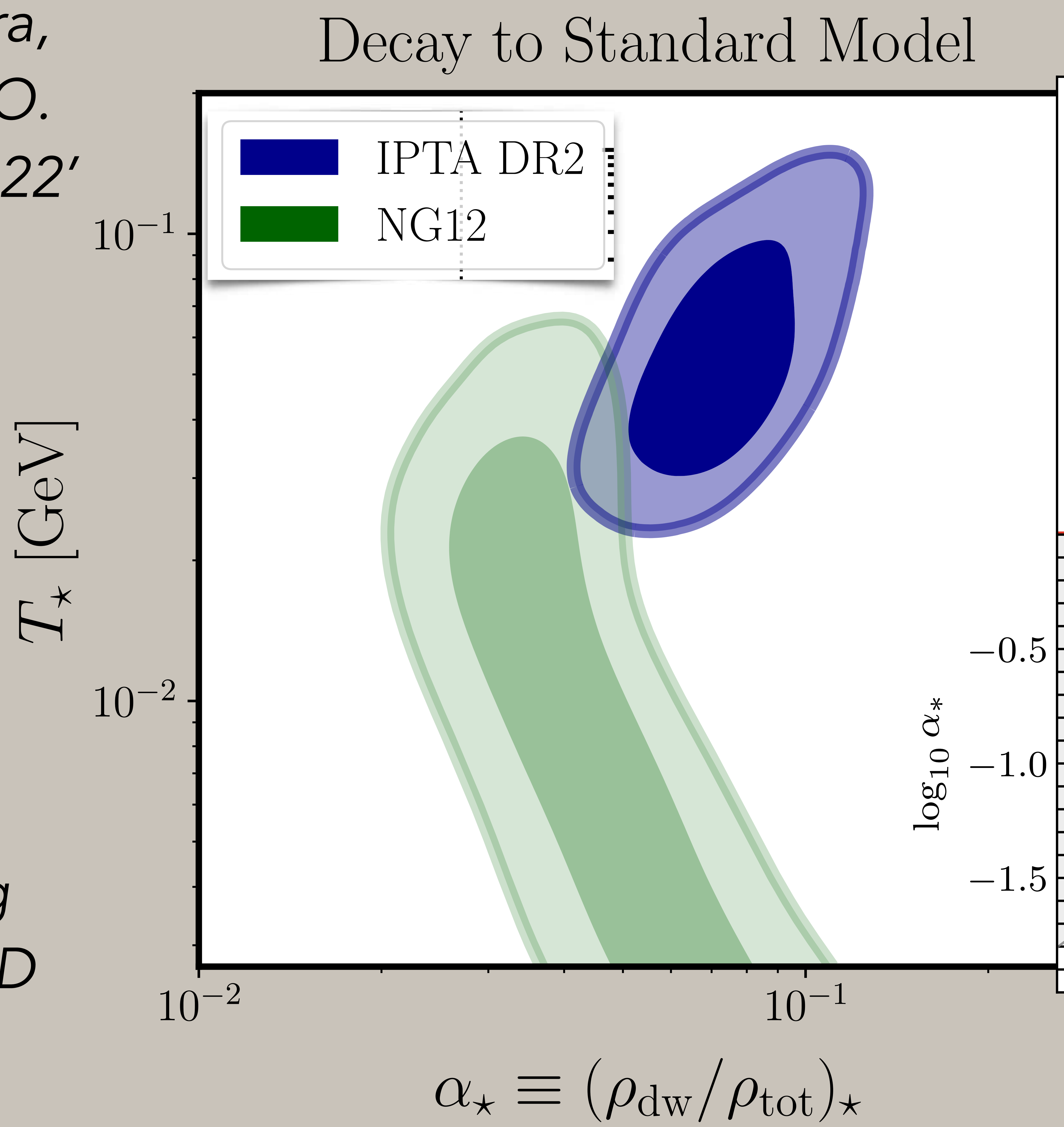


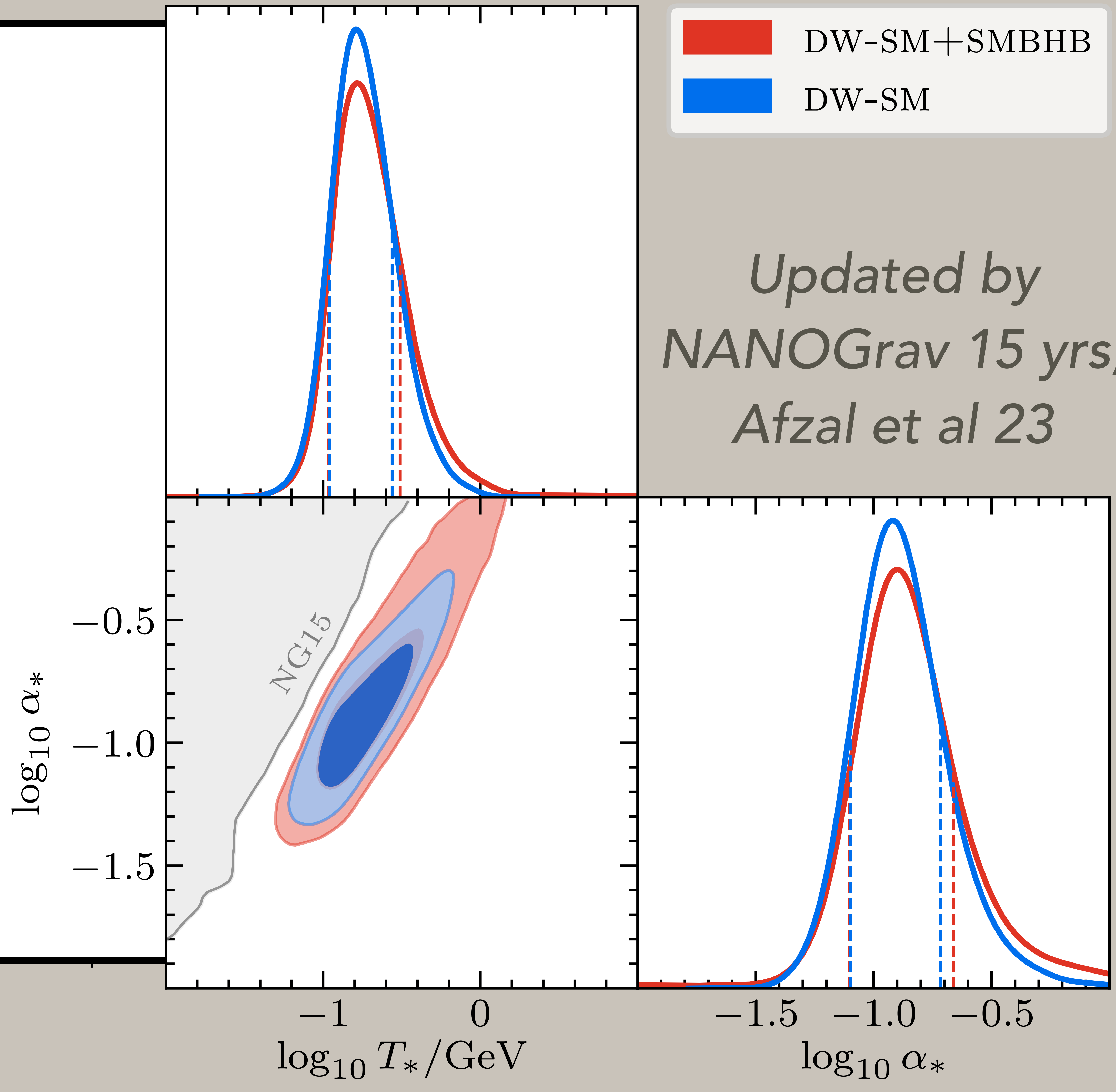


BSM walls annihilating close to QCD epoch!

Domain Walls as possible interpretation of PTA data

*R.Z. Ferreira, A. Notari, O. Pujolàs, **FR** 22'*





Updated by NANOGrav 15 yrs, Afzal et al 23

BSM walls annihilating close to QCD epoch!

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Translation to particle physics models

Example: heavy axion

$$\mathcal{L}_a \supset \frac{\alpha_H}{8\pi}\frac{a}{F_a} G_H \tilde{G}_H$$

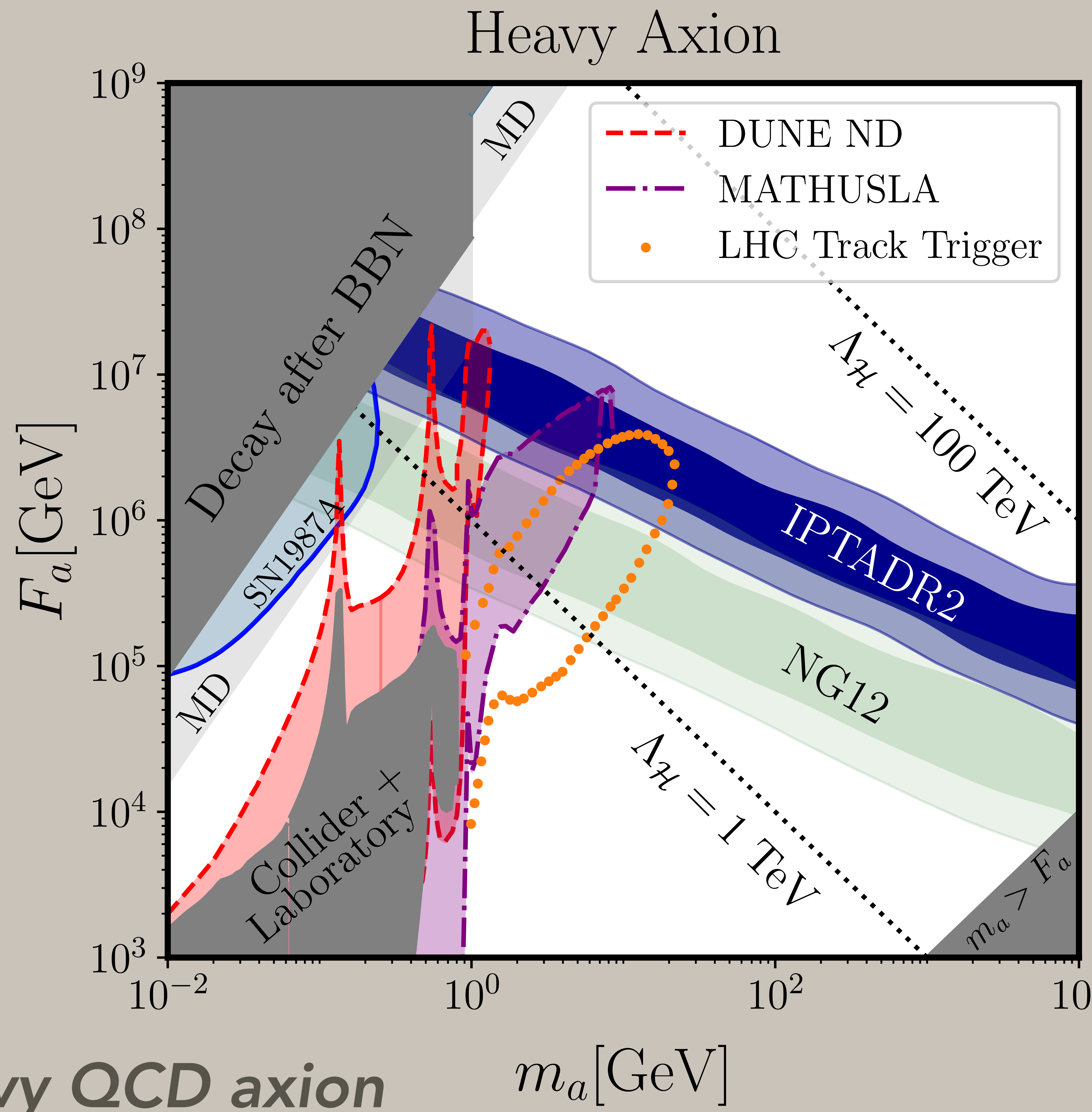
But

$$\Lambda_H \gg \Lambda_{\rm QCD}$$

$$m_a \simeq \Lambda_H^2 / F_a$$

Several models in the literature

Holdom 85/.../
Rubakov 97.../
Hook et al 19/...



Collider constraint apply if heavy QCD axion

Even heavier axion visible at interferometers

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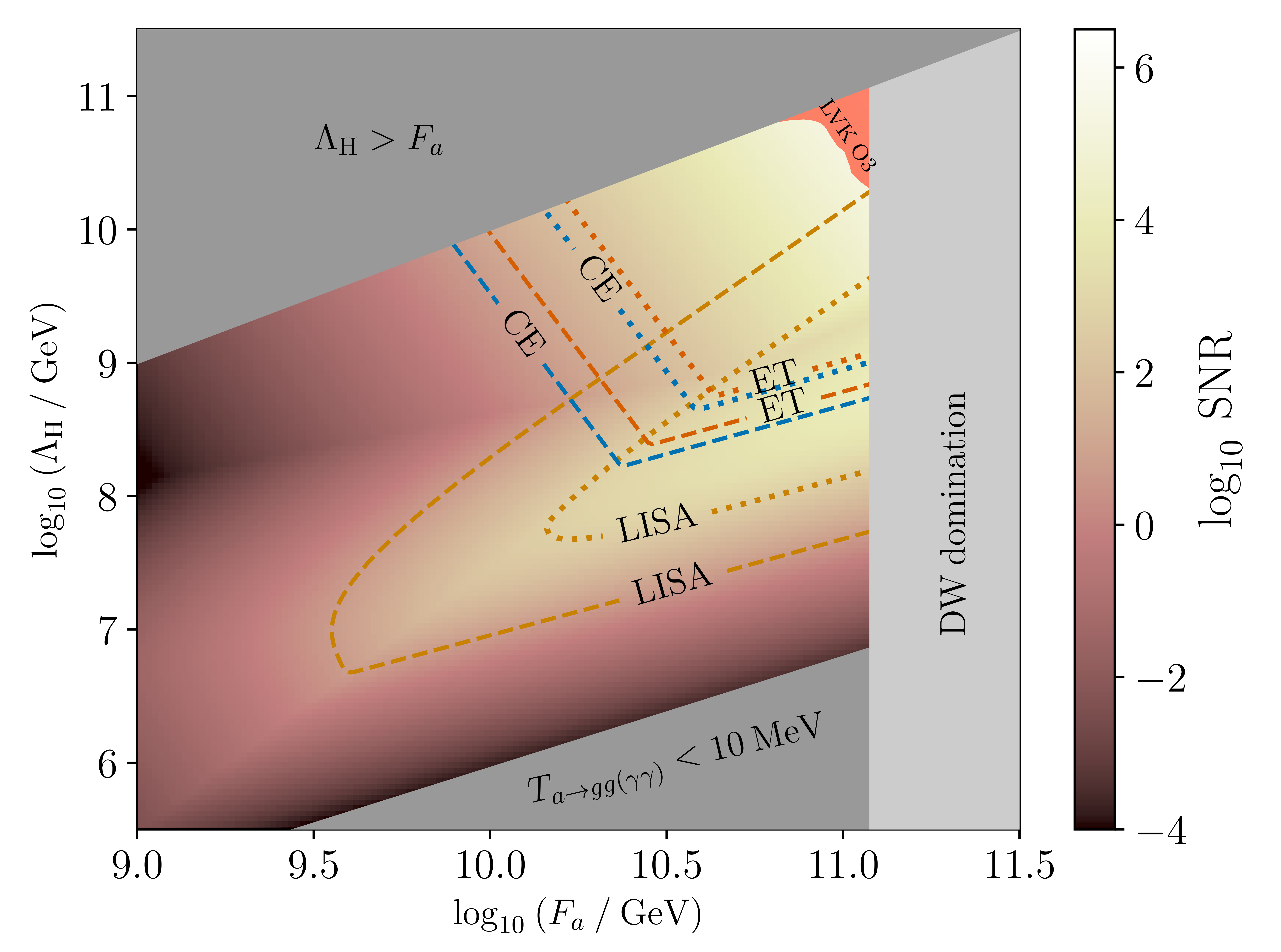
*Caprini, Pujolàs, Quelquejay-Leclere, Steer, **FR 24***

$$\mathcal{L}_a \supset \frac{\alpha_H}{8\pi} \frac{a}{F_a} G_H \tilde{G}_H$$

Example reach for specific bias size

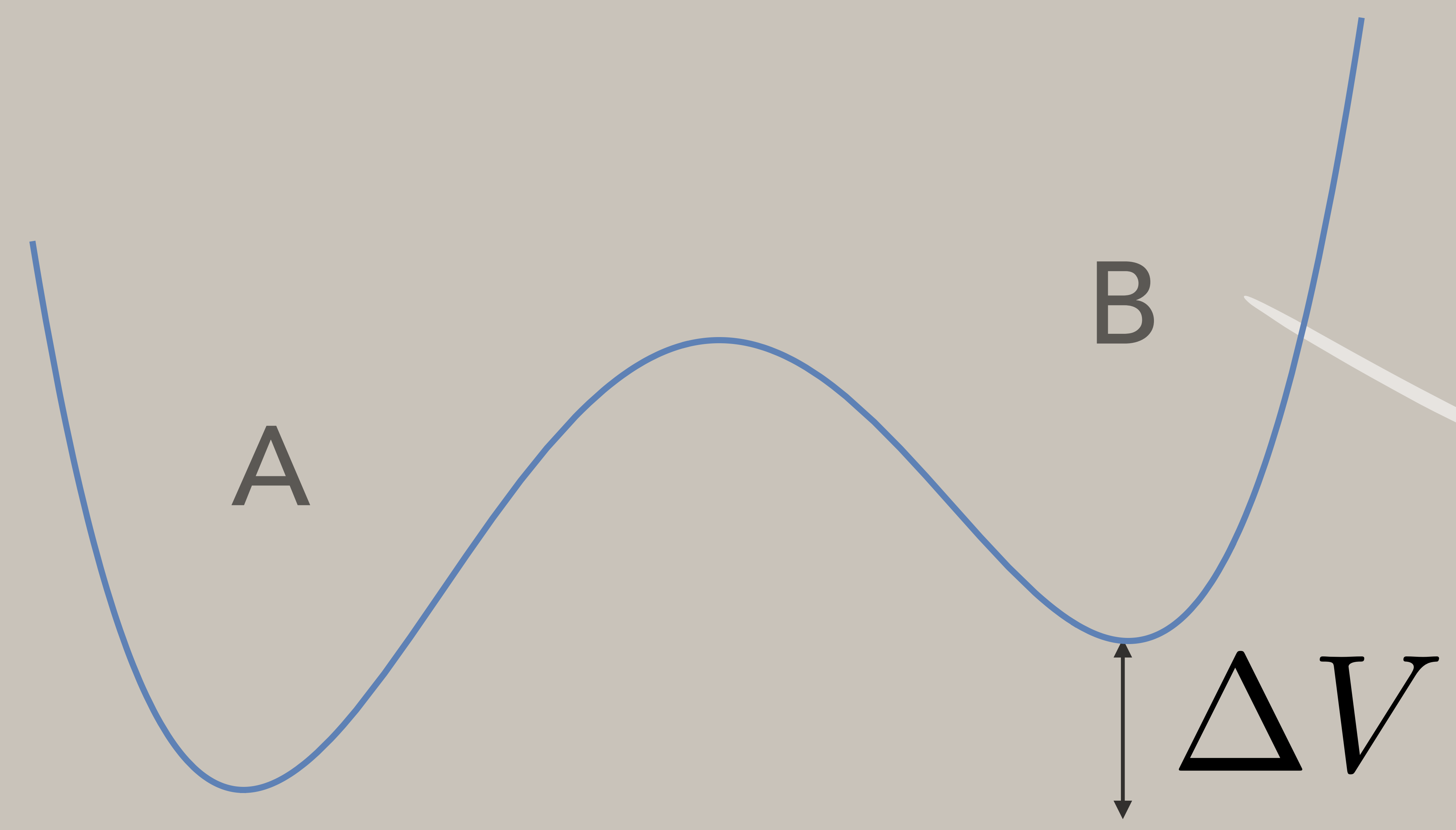


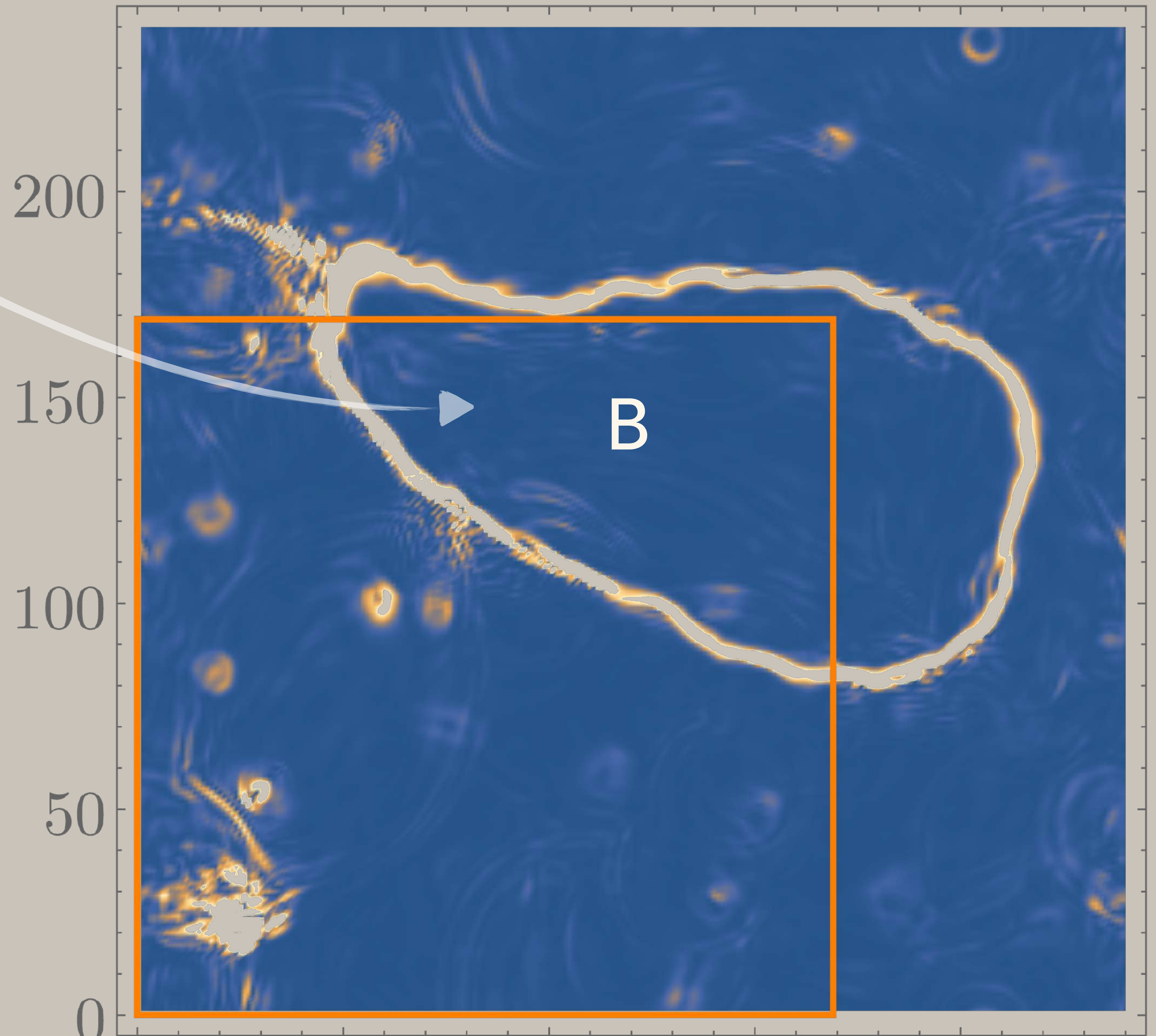
Non-relativistic relics from Domain Walls: ***Primordial Black Holes (PBHs)***

*F. Ferrer, E. Masso, G. Panico, O. Pujolàs, **FR** 18'*

*R.Z. Ferreira, A. Notari, O. Pujolàs, **FR** 24'*

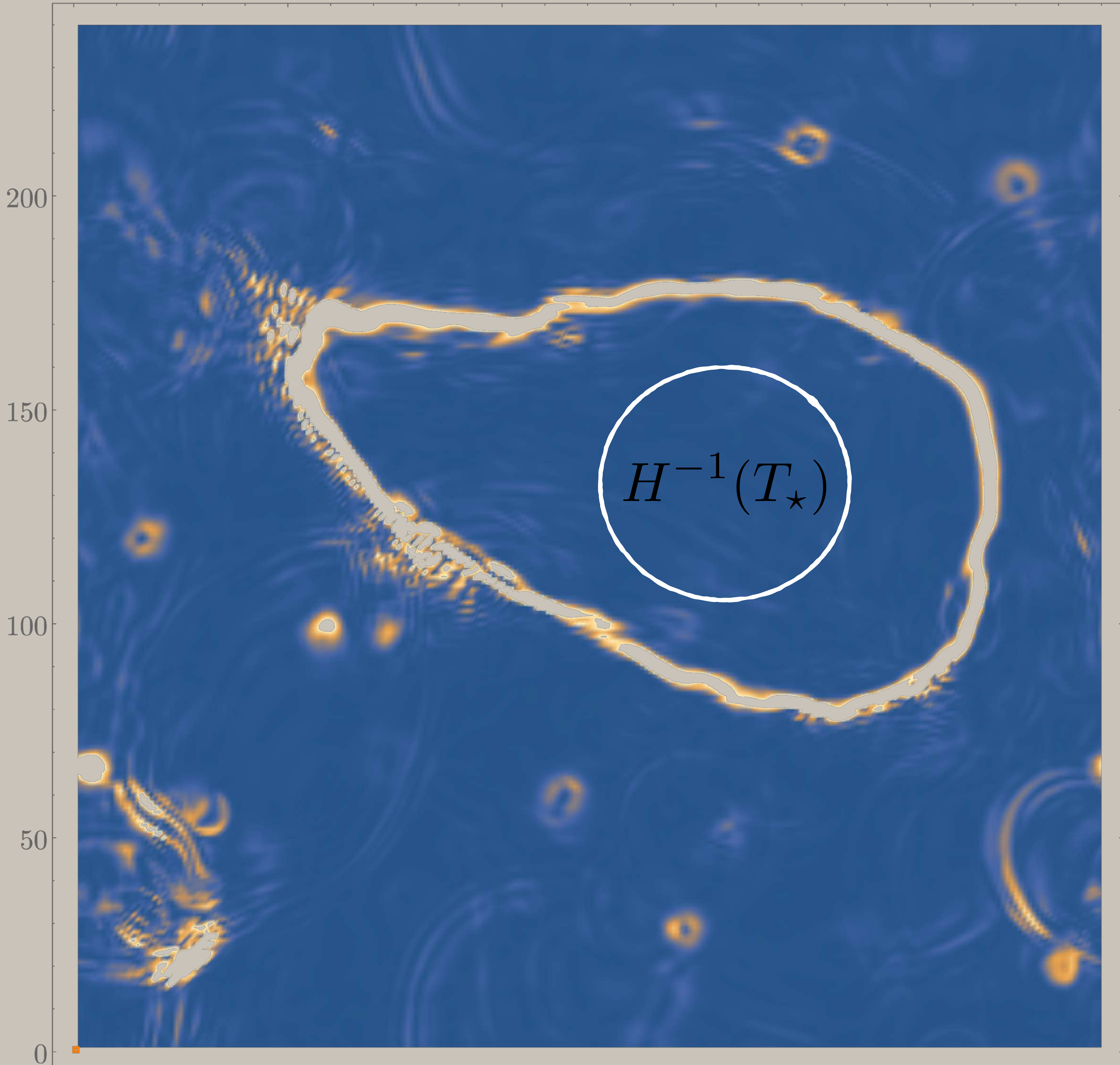
Collapsing false vacuum pockets



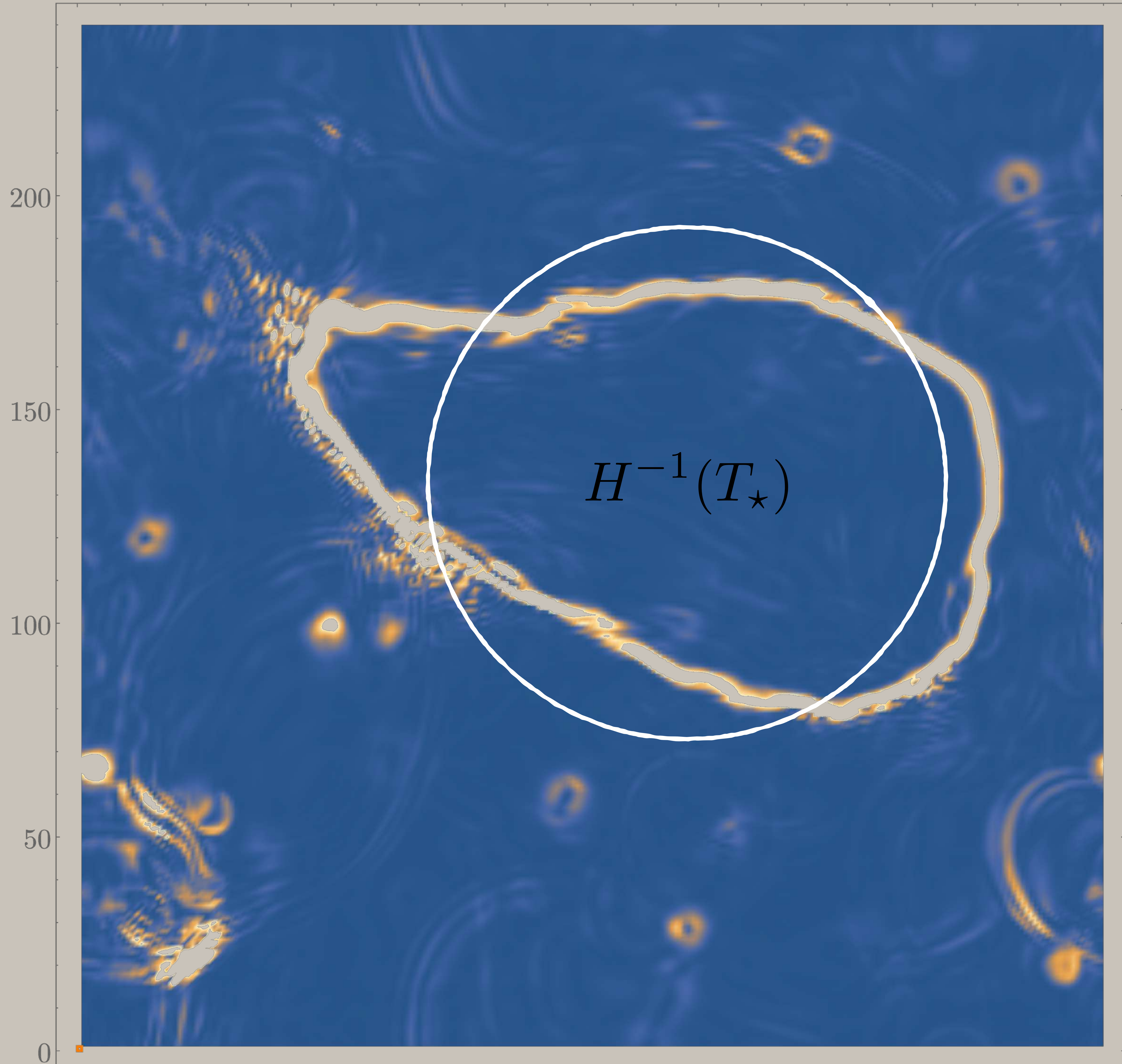


False vacuum pockets shrink because of true vacuum pressure ***(Different from gravitational collapse!)***

As the network collapses, there are **(very rare!)** false vacuum pockets that are larger than the Hubble sphere at a given time



As the Universe expands,
pockets re-enter
and ***can collapse to black holes***
(if overdense enough)



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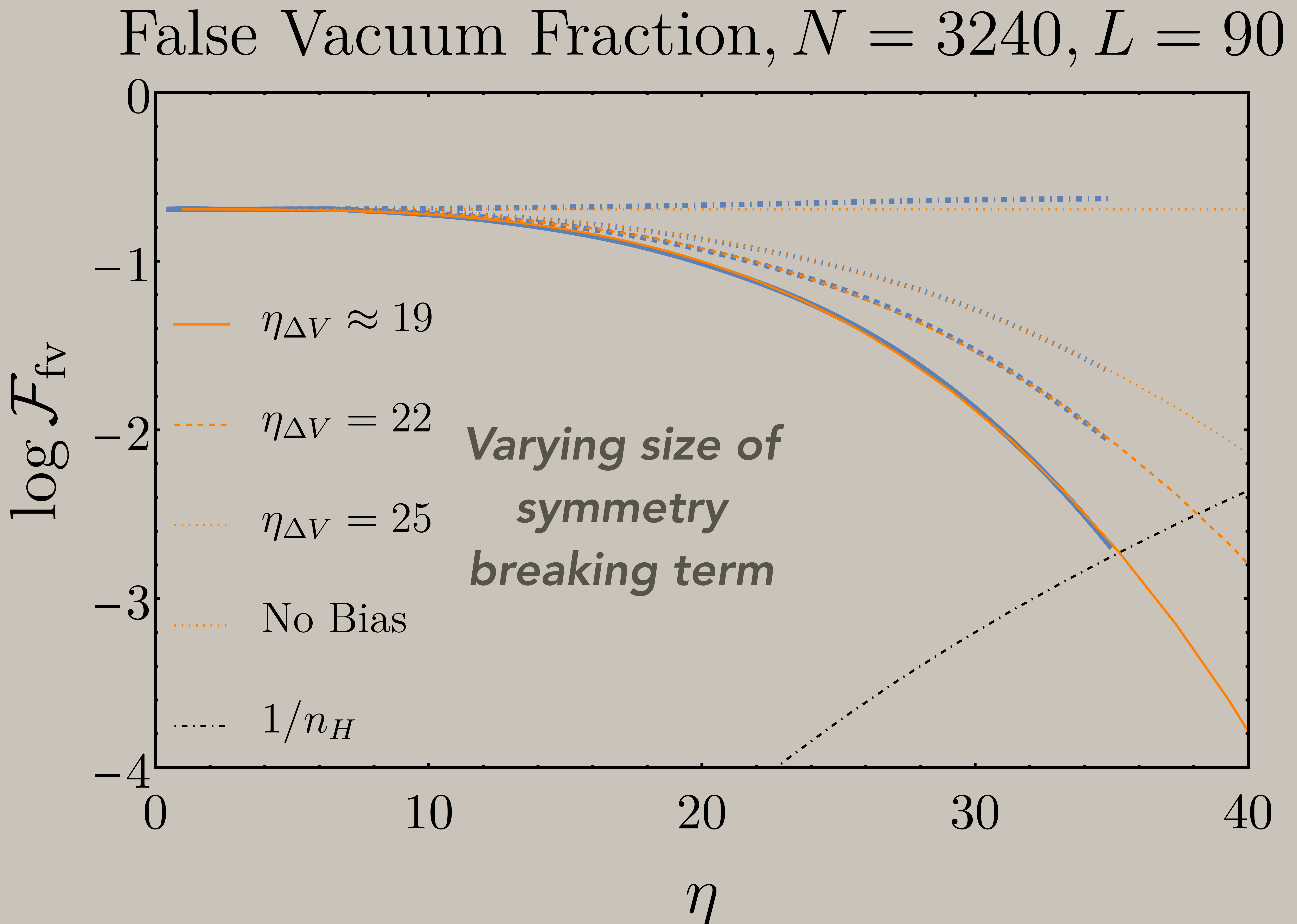
***NEWS** on PBHs from Domain Walls!*

First step:

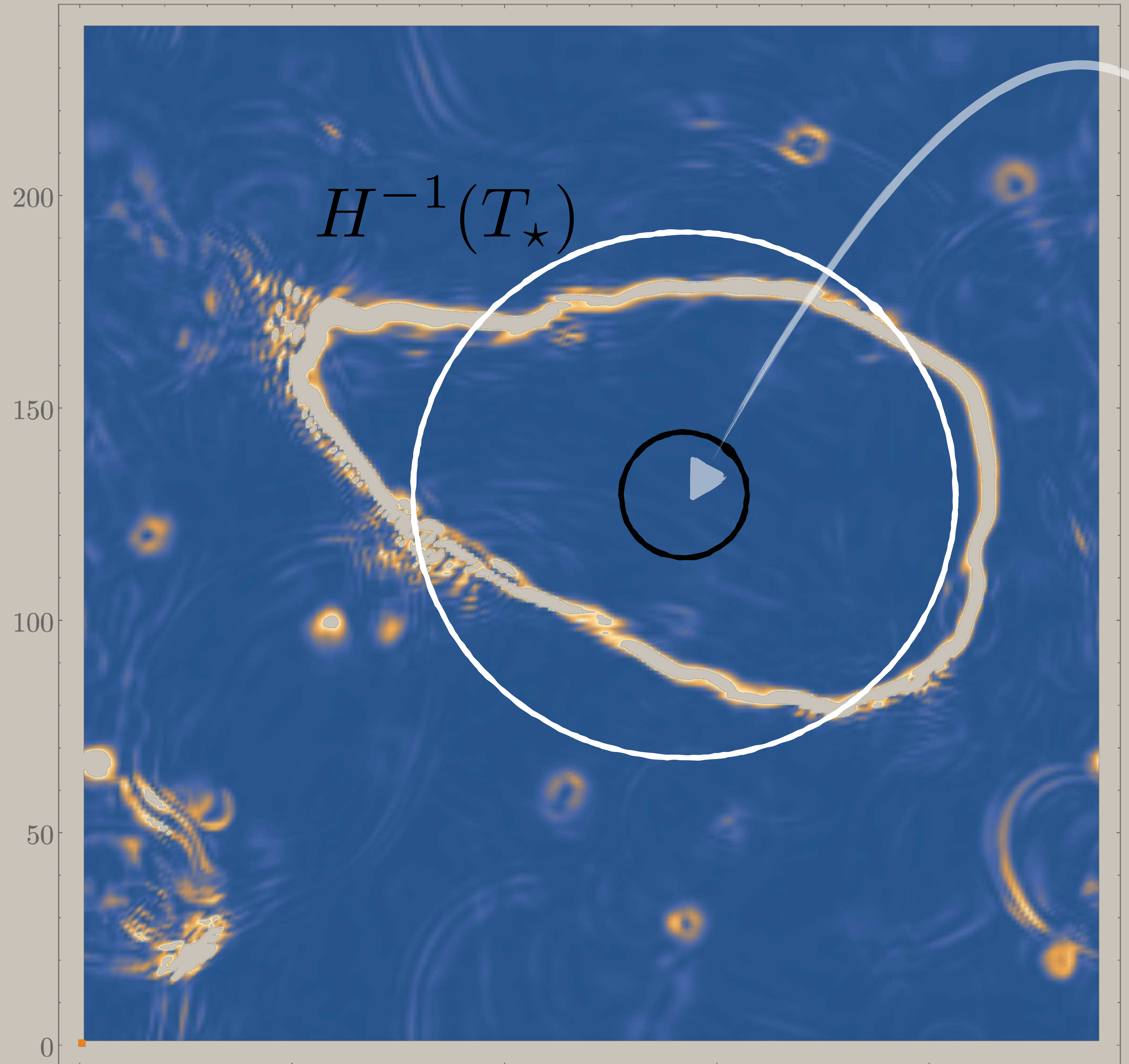
*we know now **how many super-Hubble false vacuum pockets survive** as the network collapses!*

$$\mathcal{F}_{\rm fv} \propto \exp\left[-\left(\frac{\eta}{\eta_{\rm ann}}\right)^3\right]$$



What we still do not know

Second step: *PBH forms only if collapsing walls "fits" into its Schwarzchild radius*



$$R_s \simeq 2G_N M$$

Collapse to PBH is prevented by asphericities and angular momentum!

PBH forms if local over density is above a certain threshold

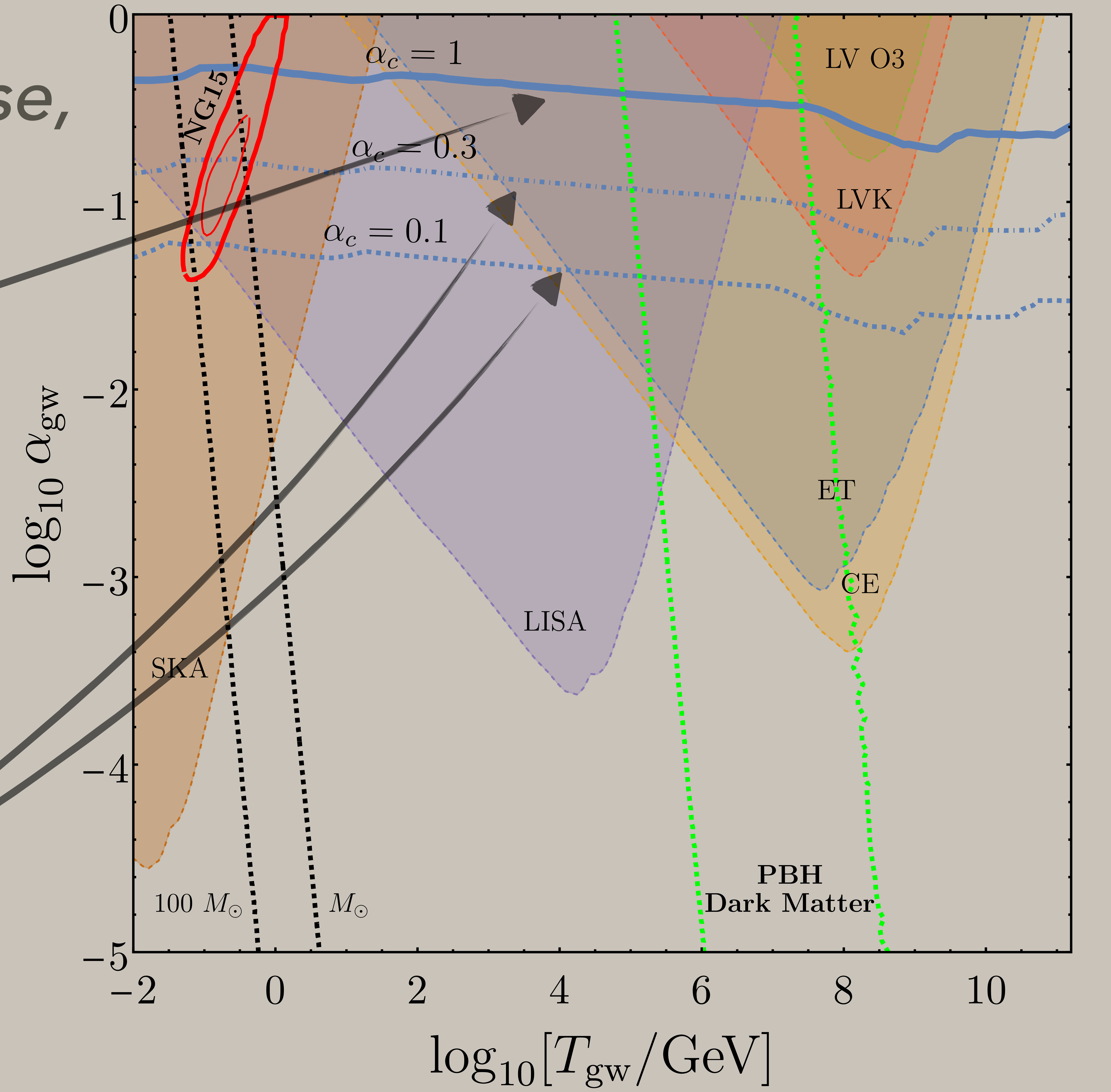
$$\alpha \gtrsim \alpha_c$$

But what is the value of the threshold?

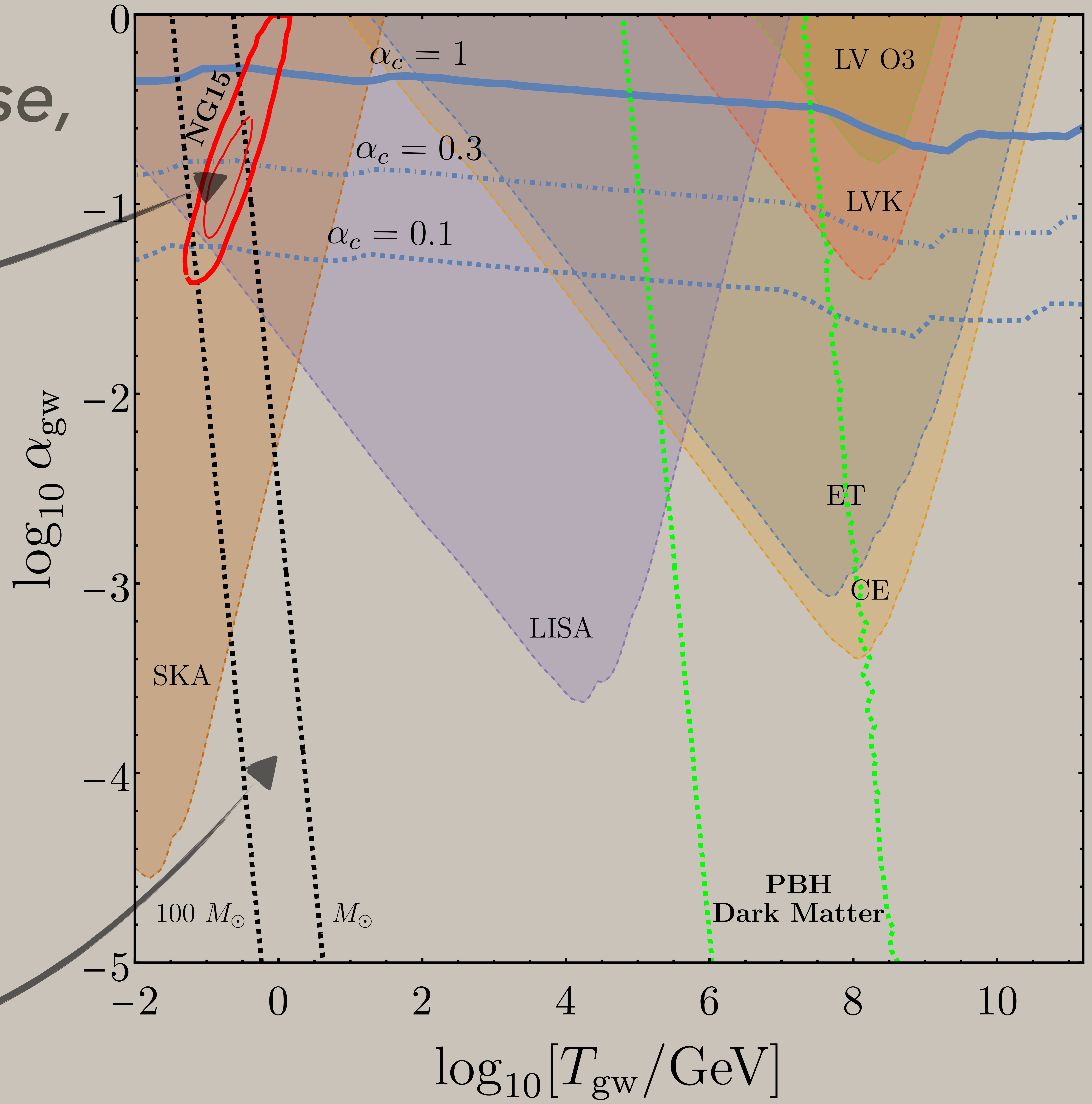
Viable regions (otherwise, too many PBHs)

Conservative threshold (Schwarzschild radius as big as the Hubble sphere)

Less conservative possibilities



Viable regions (otherwise, too many PBHs)



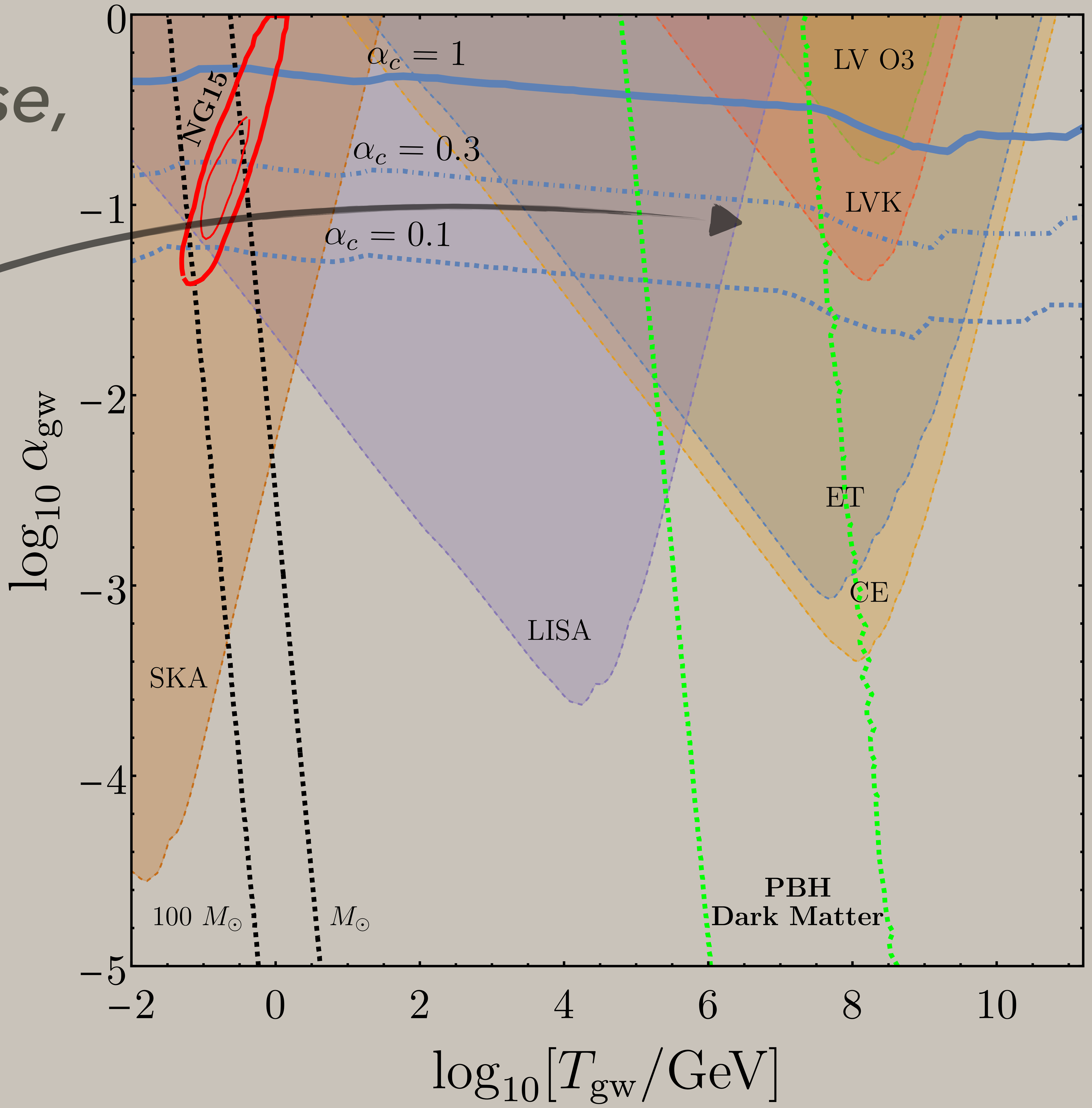
Here GWs from Domain Walls provide interpretation of PTAs!

Coincides with region where PBHs from collapse can be seen at LIGO/Virgo/KAGRA!

Viable regions (otherwise, too many PBHs)

Here PBHs can make all of the dark matter

And GWs from Domain Walls can be seen at interferometers!



Conclusions

Thank you!

Gravitational waves provide channel to access otherwise opaque early Universe

And BSM physics at possibly very high energies

Viable domain wall networks from discrete symmetries are good candidate sources for detection at current and upcoming GW observatories

Domain wall collapse can also lead to significant production of Primordial Black Holes

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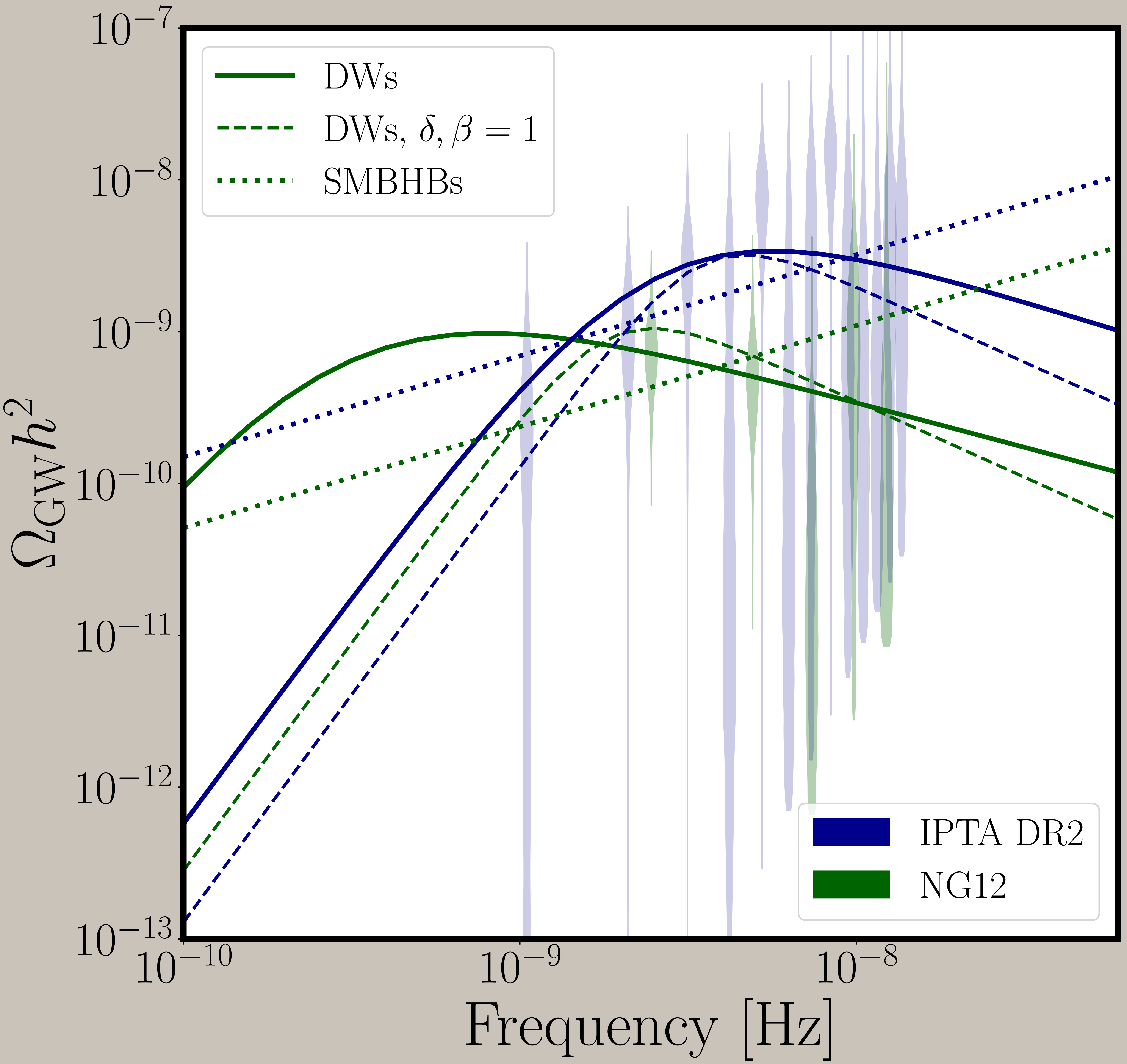

Bestfit spectra

BSM walls annihilating close to QCD epoch!