Gravitational wave signatures of axionic domain walls

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Based on:
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with A.Notari, O.Pujolàs, F. Rompineve

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Institute for High Energy Physics

Outline

1. Axionic string-wall networks and GWs
2. The heavy QCD axion case
3. Hints at pulsar timing arrays?
4. Conclusion

Axions and axion-like particles

- Pseudo-goldstone bosons of spontaneously broken global symmetries (e.g U(1))

- Shift-symmetric
(theory invariant under $a \to a + c$)

- Mass generated by non-perturbative effects (e.g. QCD, confining sectors, gravity?)

- General framework.
Expected in different contexts:
QCD axion, string theory, BSM, etc.

- Restrictive.
Shift symmetry only allows specific couplings

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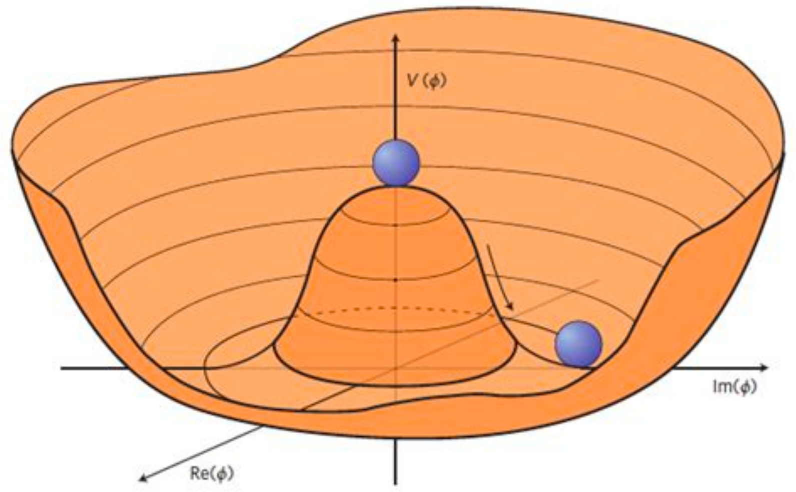
Cosmological evolution

Temperature

f → $\cancel{U(1)}$, axion takes random values $[0,2\pi)$.
Network* of **cosmic strings.**



* Symmetry broken after inflation

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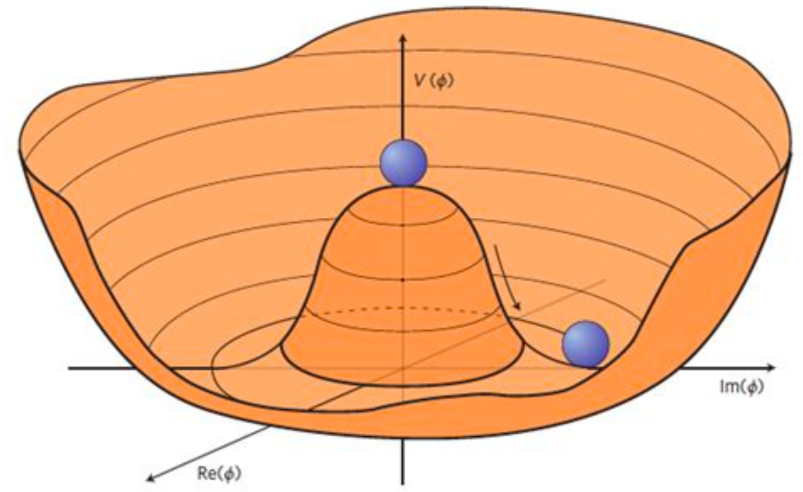
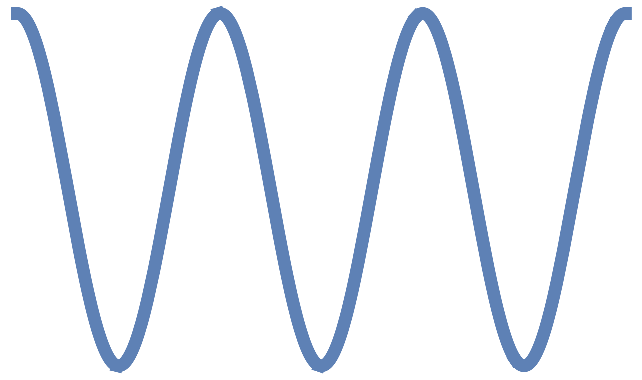


$H(T) \sim m_a$ (DWs form) → Shift-symmetry softly broken $(U(1) \to \mathbb{Z}_{N_{DW}})$:
(explicitly or via non-perturbative effects)



$V_a \sim \Lambda^4 \cos\left(N_{DW}\, a/f\right)$

DW number

Network of **domain walls** with tension

$$\sigma = 8\, m_a f^2, \qquad \begin{cases} N_{DW} = 1 \text{ (unstable)} \\ N_{DW} > 1 \text{ (stable)} \end{cases}$$

[Kibble 76']

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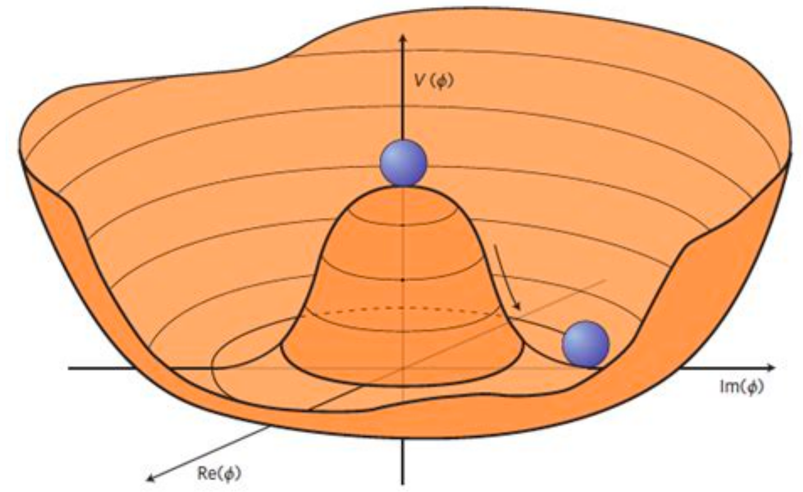

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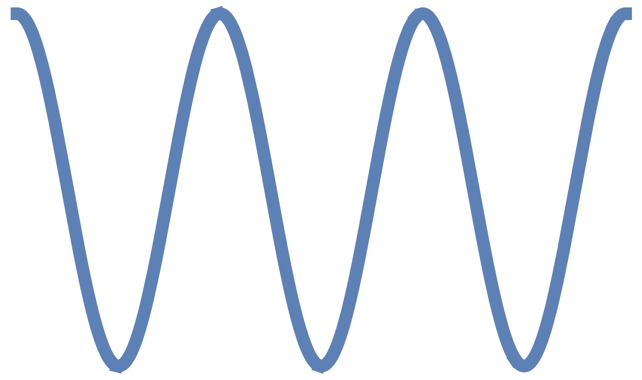

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Domain wall problem:

$\rho_{DW} \sim \sigma H$ redshifts slowly

Ways out:

1- $\mathbb{Z}_{N_{DW}}$ is not exact

2- Tension is small ($\sigma^{1/3} \lesssim$ MeV)

[Kibble 76']

[Zeldovich 75']

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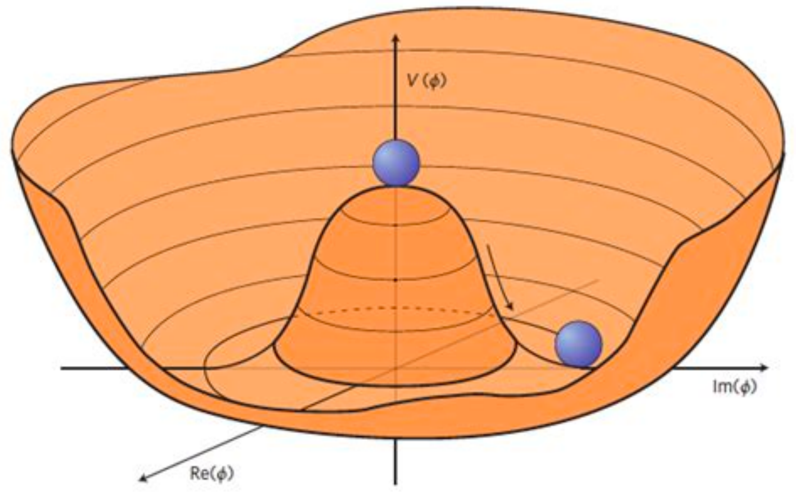

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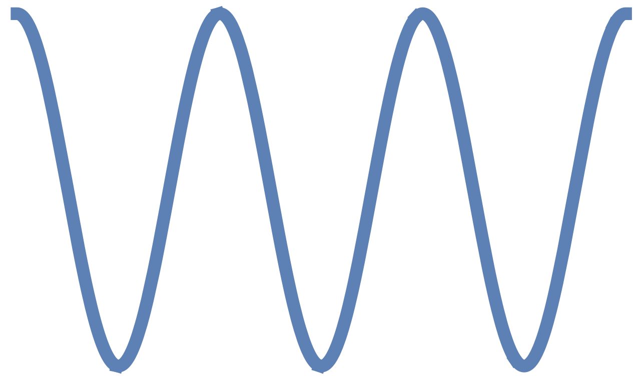

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[Zeldovich 75']

What if $\mathbb{Z}_{N_{DW}}$ is not exact…

$V_{mis} \sim \rho_{dw}$

(DWs annihilate)

- **Misaligned contributions** (e.g from gravity, confining sectors, etc.) to the axion potential break $\mathbb{Z}_{N_{DW}}$

[Sikivie 82', Gelmini+ 89', Vlikenkin 94']

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and cause the **annihilation** of the network when $\rho_{DW}(t_{ann}) \sim V_{mis}$.

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- However … if network is **long lived,** $\alpha \equiv \rho_{dw}/\rho_{tot}$ can be large at t_{ann} and generate a large **stochastic GW signal**

$$\Omega_{\rm gw}\, h^2 \sim 10^{-10}\, \tilde{\epsilon} \left(\frac{10.75}{g_*(T_\star)}\right)^{\frac{1}{3}} \left(\frac{\alpha(t_{ann})}{0.01}\right)^2$$

[Hiramatsu+ 13',
RZF, Notari, Pujolàs, Rompineve 21']

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within reach of **current** GW detectors!

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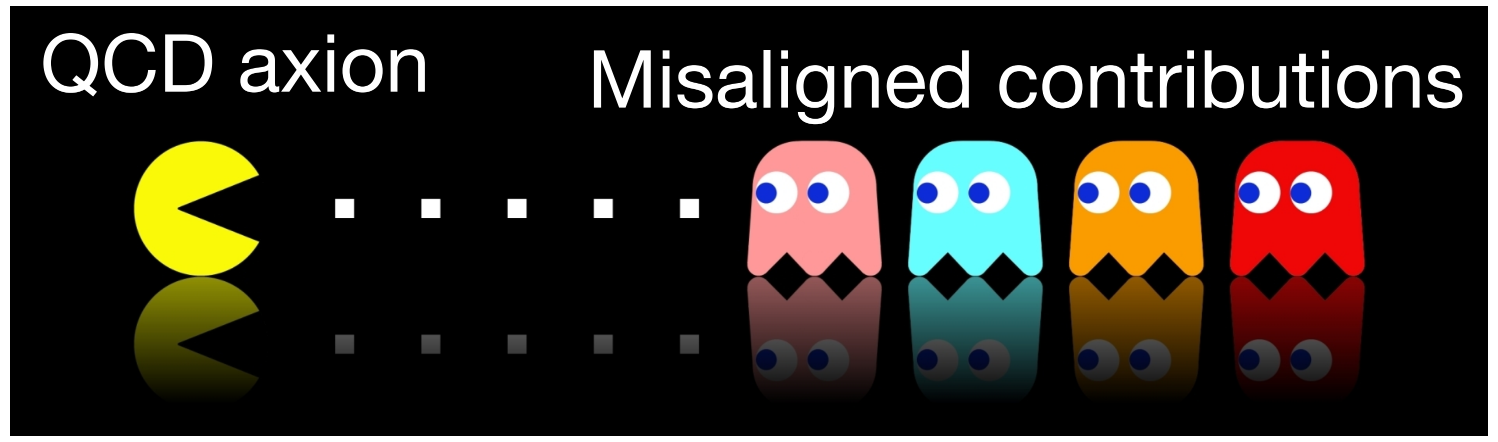
Example: the Heavy QCD axion

- **Motivation:** ‘Quality problem’

  PQ breaking terms are in general **misaligned** $(\delta \sim 1)$ and can spoil the solution to the strong CP problem.

  $\Rightarrow$ PQ symmetry needs to be of **high quality.**



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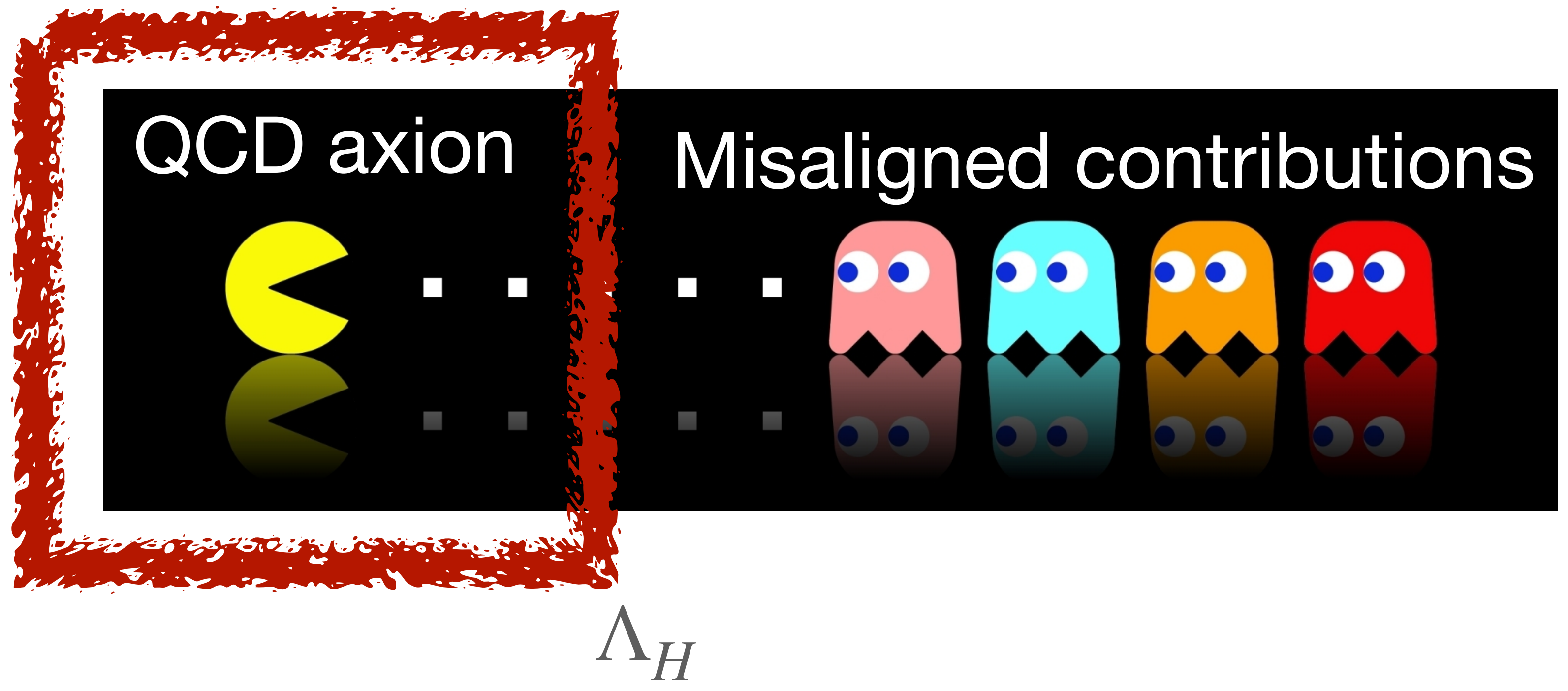


- **Improved quality:**

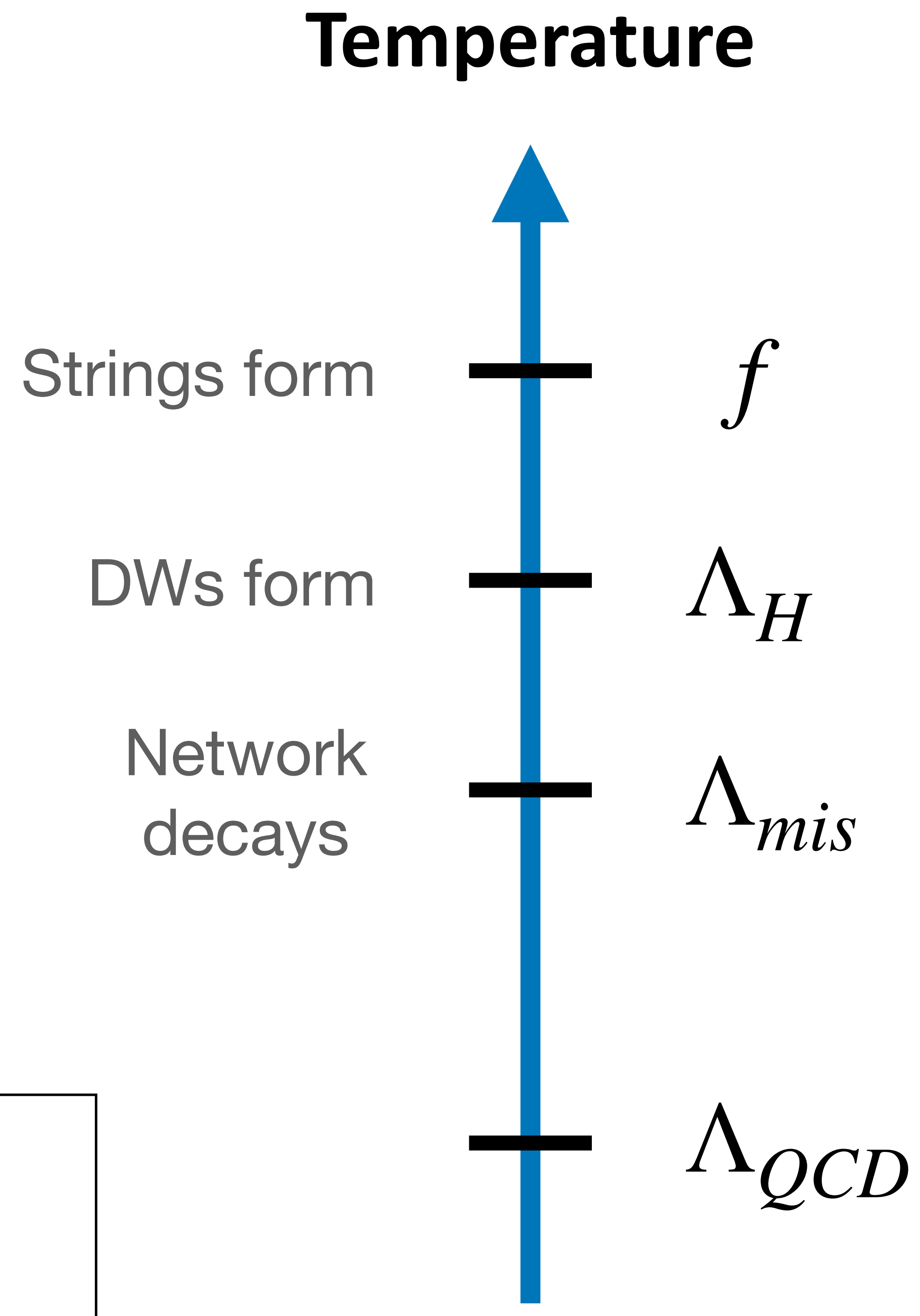
  QCD axion is coupled to a heavier sector $(\Lambda_H \gg \Lambda_{QCD})$, **aligned** with QCD.

$$V \sim (\Lambda_{QCD}^4 + \Lambda_H^4) \cos\left(N_{DW}\frac{a}{f}\right)$$

- Examples:
  - *small instantons,* strong coupling effects at high energies;
  - Z_2 symmetry;
  - additional gauge group with unification heavier

[Holdom et al. 82', …, Berezhiani et al. 01'…, Tye et al. 81', …]

Quite predictive…



Size of misaligned contributions

Large

→ DW network is **short lived**

→ **Sizeable correction** to θ_{SM}

$$\Delta\theta \sim r^4, \qquad r \equiv V_{mis}/\Lambda_H$$

(probed at **neutron/proton EDM** experiments)

Small

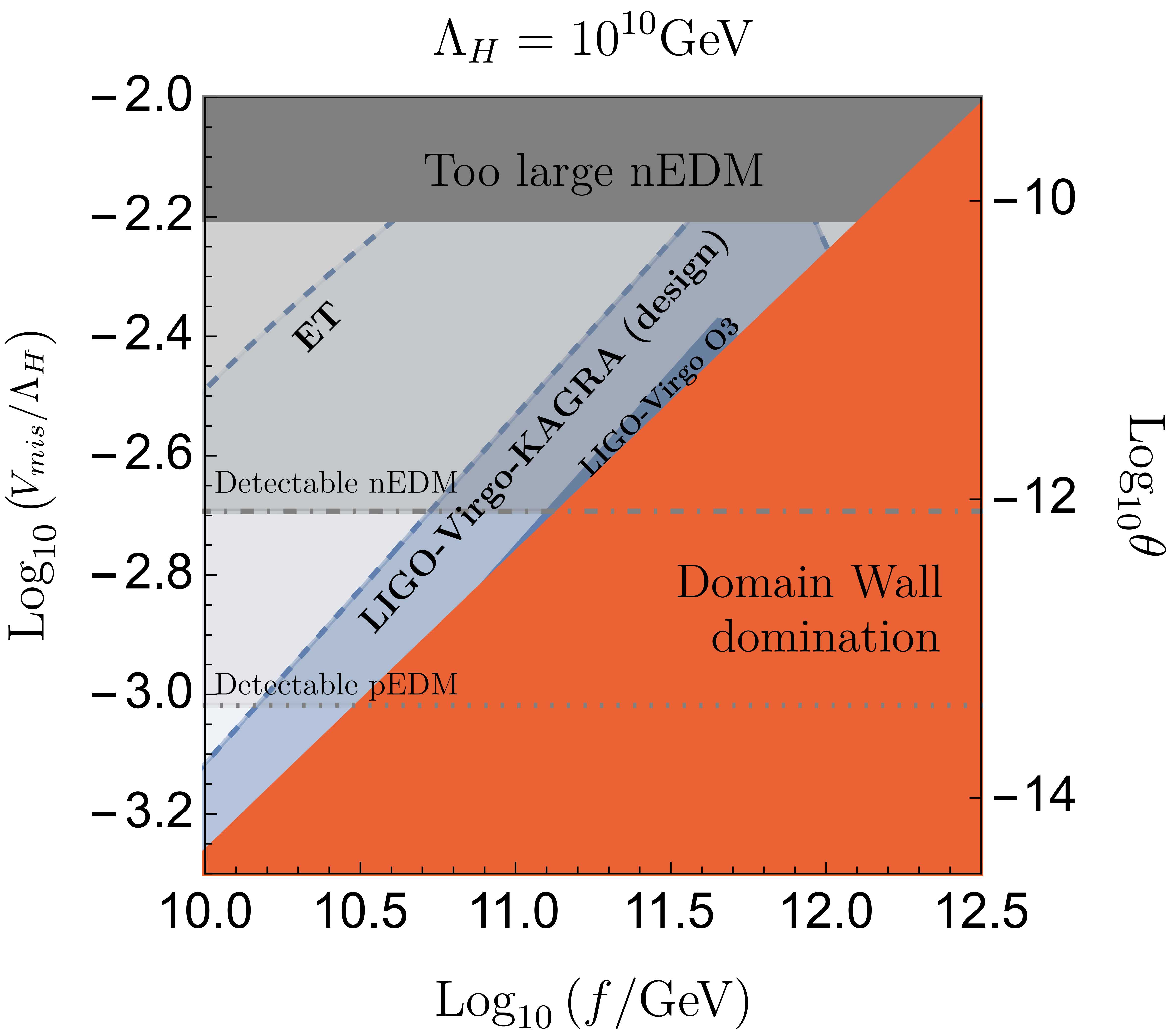
→ DW network is **long lived**

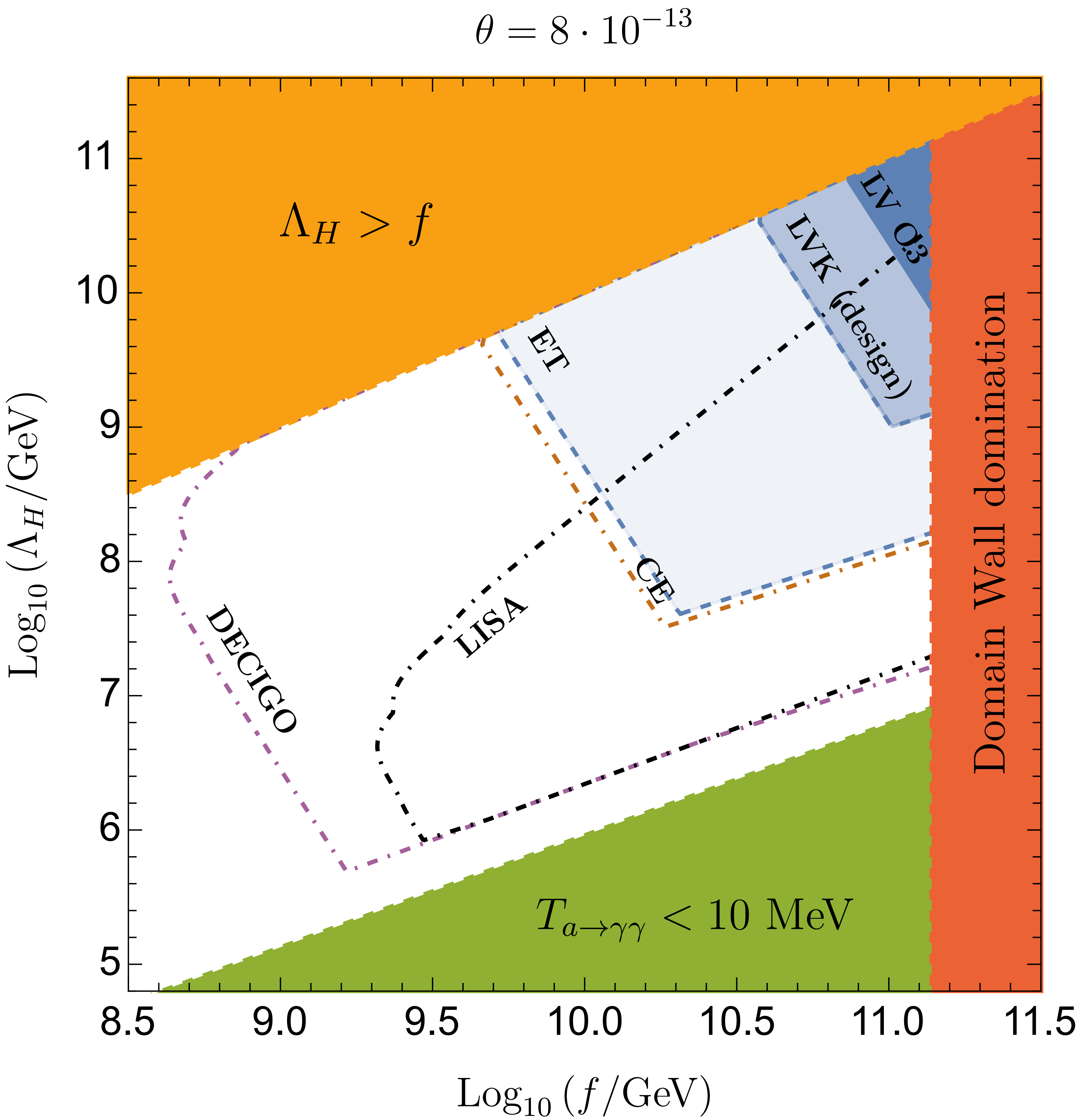
→ DW **energy density** becomes **large**

(**large GW production**)

[**RZF**, Notari, Pujòlas, Rompineve 21']

Results





Quality

[**RZF**, Notari, Pujòlas, Rompineve 21']

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Hints of DWs at PTAs?

- **Pulsar Timing Array (PTA) observatories** time the radio signals from many (an array) of milisecond pulsars.

- 3 different collaborations (EPTA, NANOGrav, PPTA) found **evidence** for a signal in time residuals.

- Data well fitted by a **stochastic GW background**.

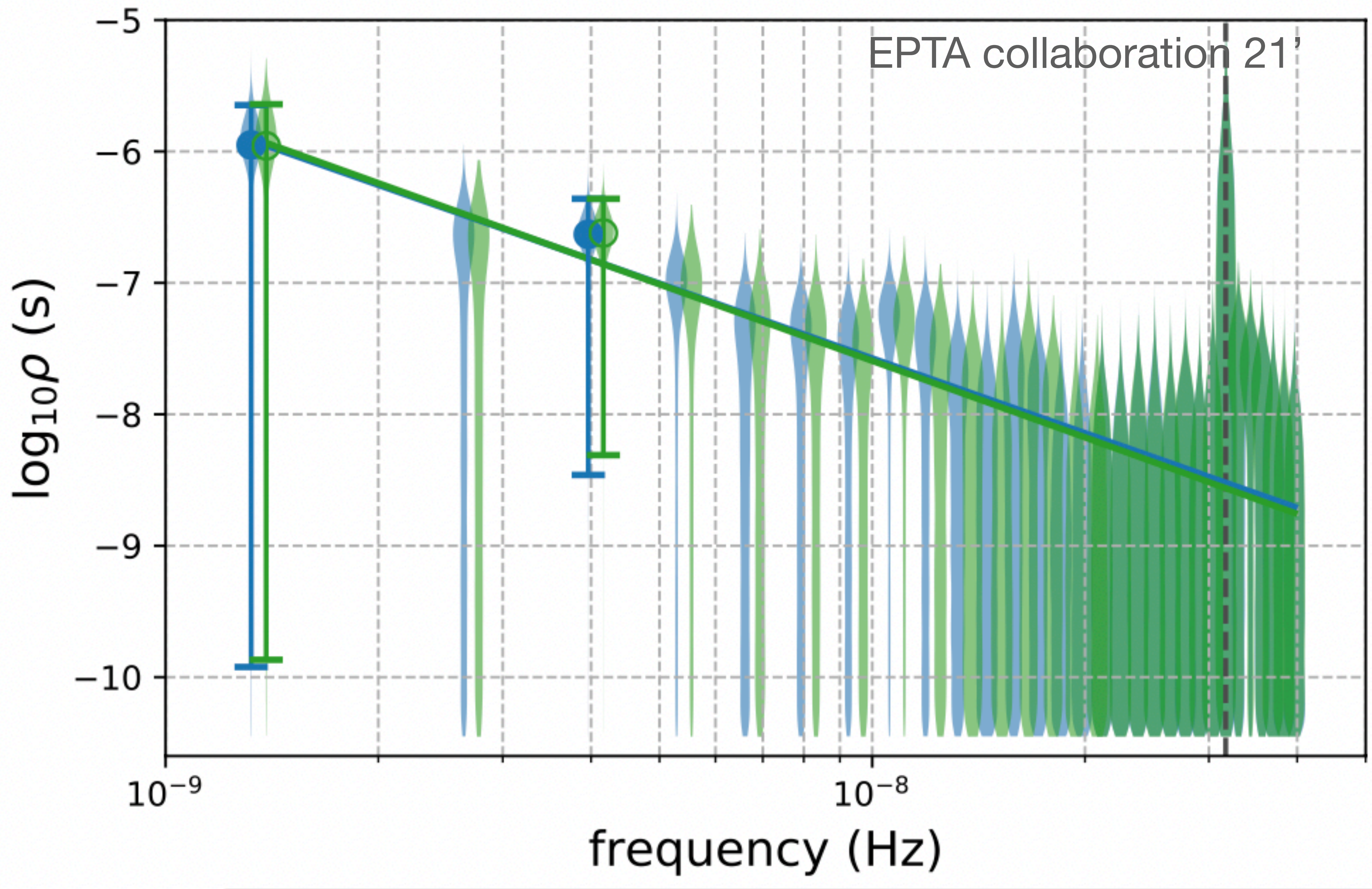
- Compatible with signal from **supermassive BH binaries.**

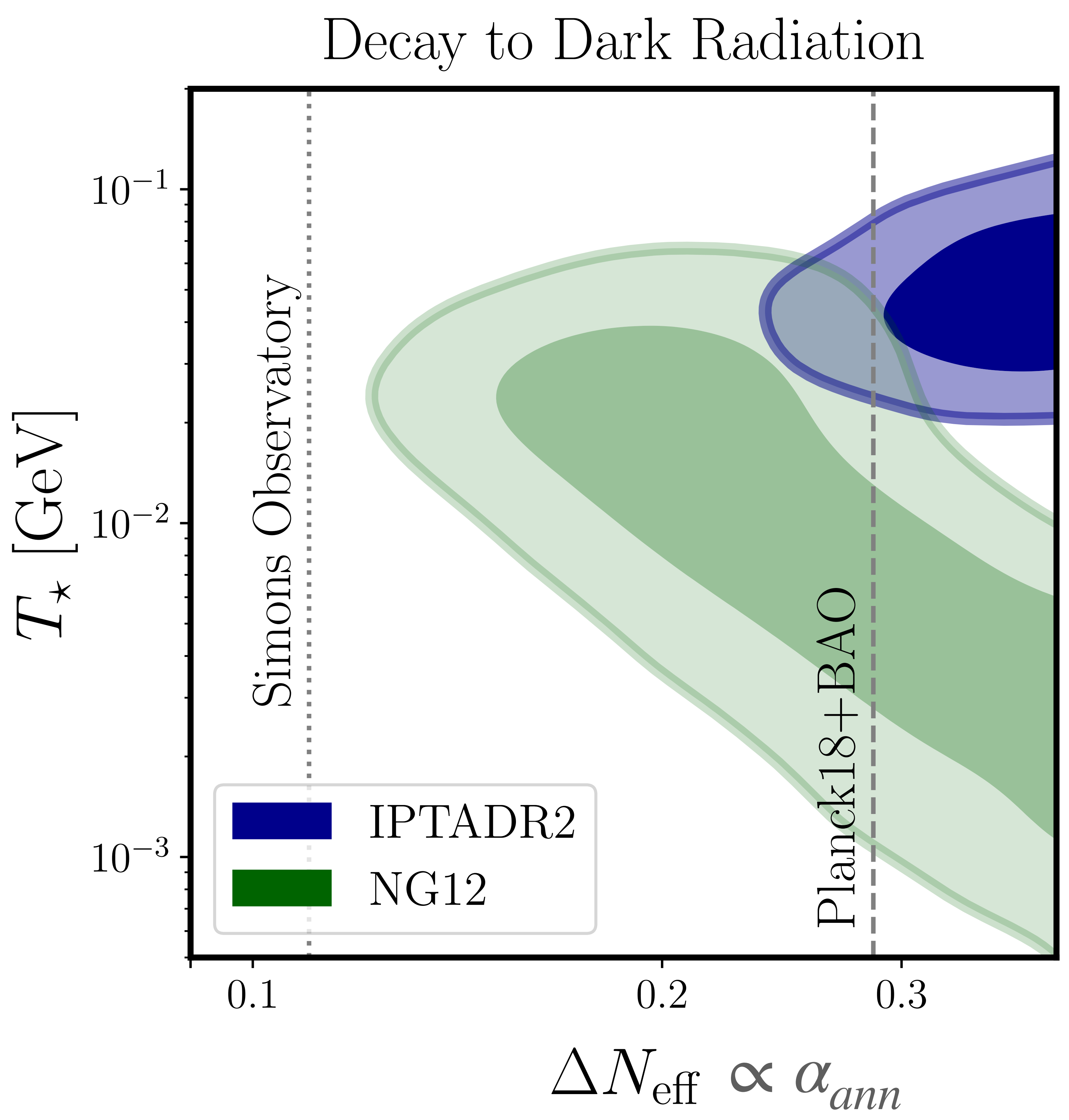
- But early universe origin also possible.
(e.g. 1st order PT, cosmic strings.)

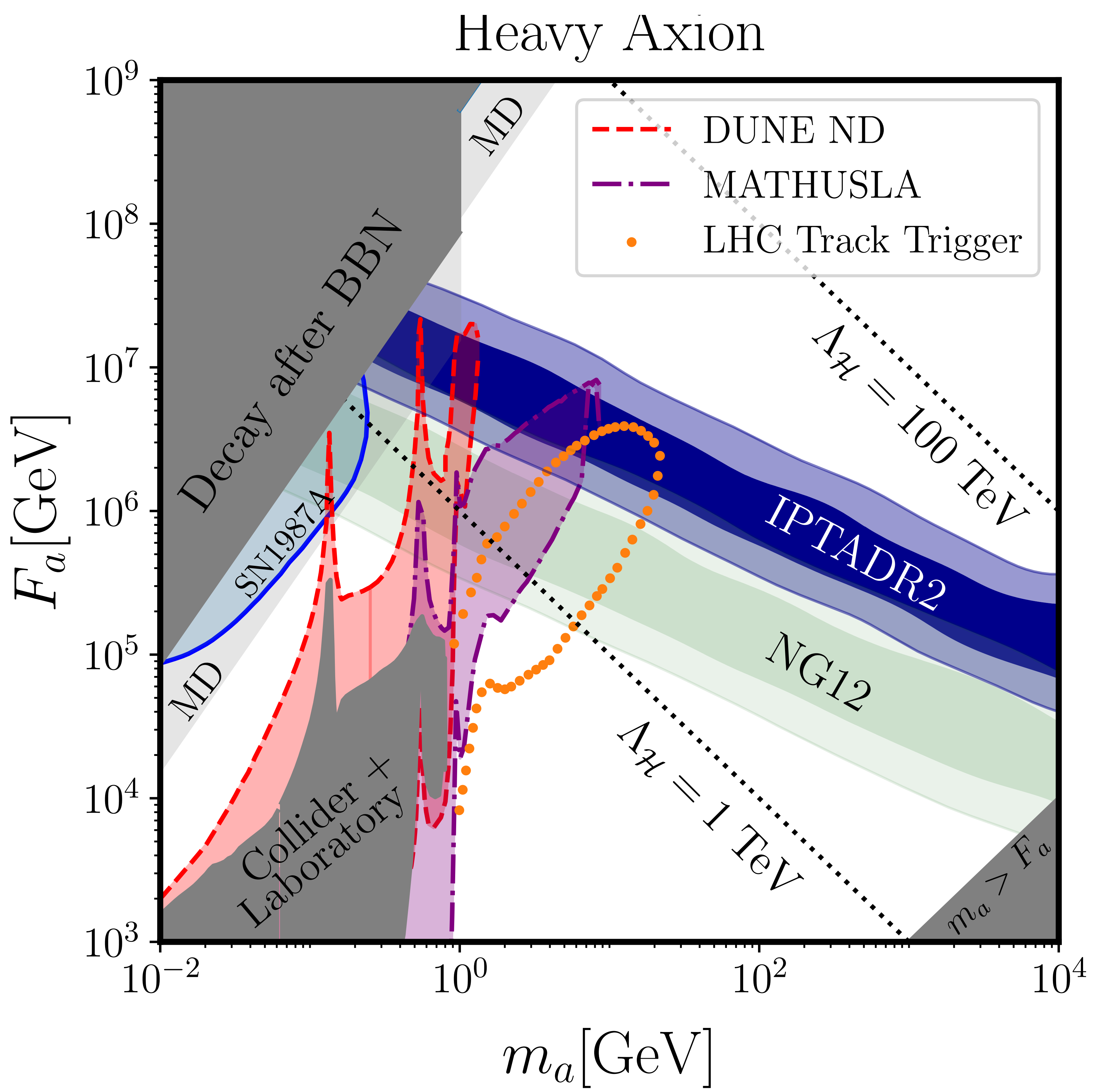
[Bian+ 20', Craig+ 20', Chiang+ 20', Sakharov 21', Wang 22']

- We performed a **dedicated search** for **domains walls** in **NanoGRAV12** and **IPTA DR2 datasets.**

[**RZF,** F. Rompineve, A. Notari, O. Pujolàs, 22']







- Network of DWs with σ**~(40-100 TeV)**^{3}, T_{ann}**~20-50 MeV** provide a **good fit** to both datasets (as good as SMBH binaries).

[**RZF,** F. Rompineve, A. Notari, O. Pujolàs, 22']

- But **network remnants are dangerous**:

  - **Decay to dark radiation** will be fully probes with **future CMB surveys**!
  - **Decay to SM (e.g. Heavy QCD axion)** brings additional collider signatures.

Conclusions

- **Domain walls** are the outcome of many extensions of the SM (e.g. axionic models). Their **tendency for domination** leads to **strong cosmological signals.**

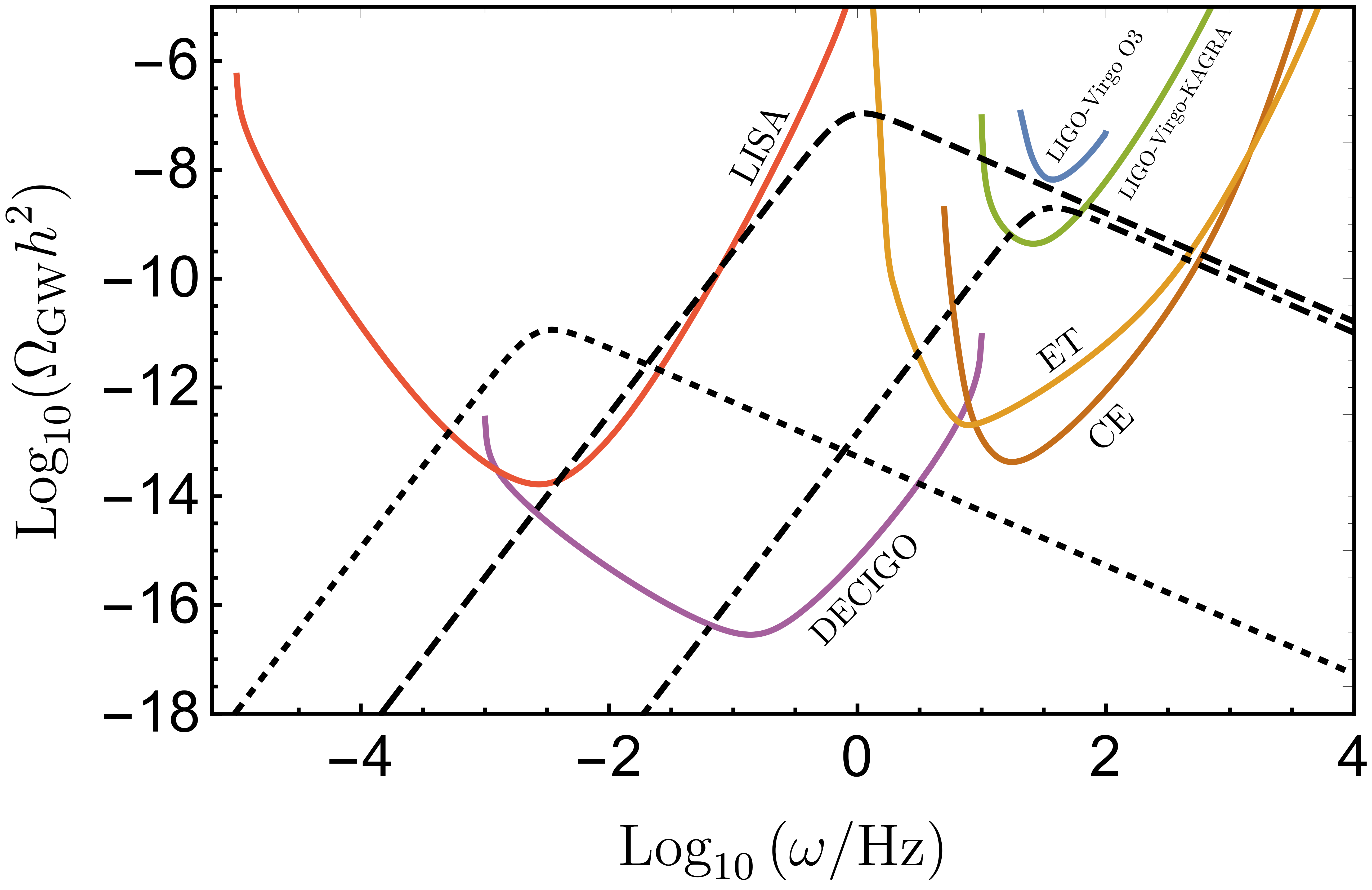
- The **Heavy QCD axion** leads to a **very predictive GW+EDM signal** that is already being probed at LIGO.

- **PTA observatories** have found **evidence** for a time delays.
  DW interpretation brings other cosmological or laboratory signatures that allow to distinguish from other onterpretations.

- Better **numerical simulations** of DW networks needed to improve the modelling of the GW signal.

Extra slides

Spectrum

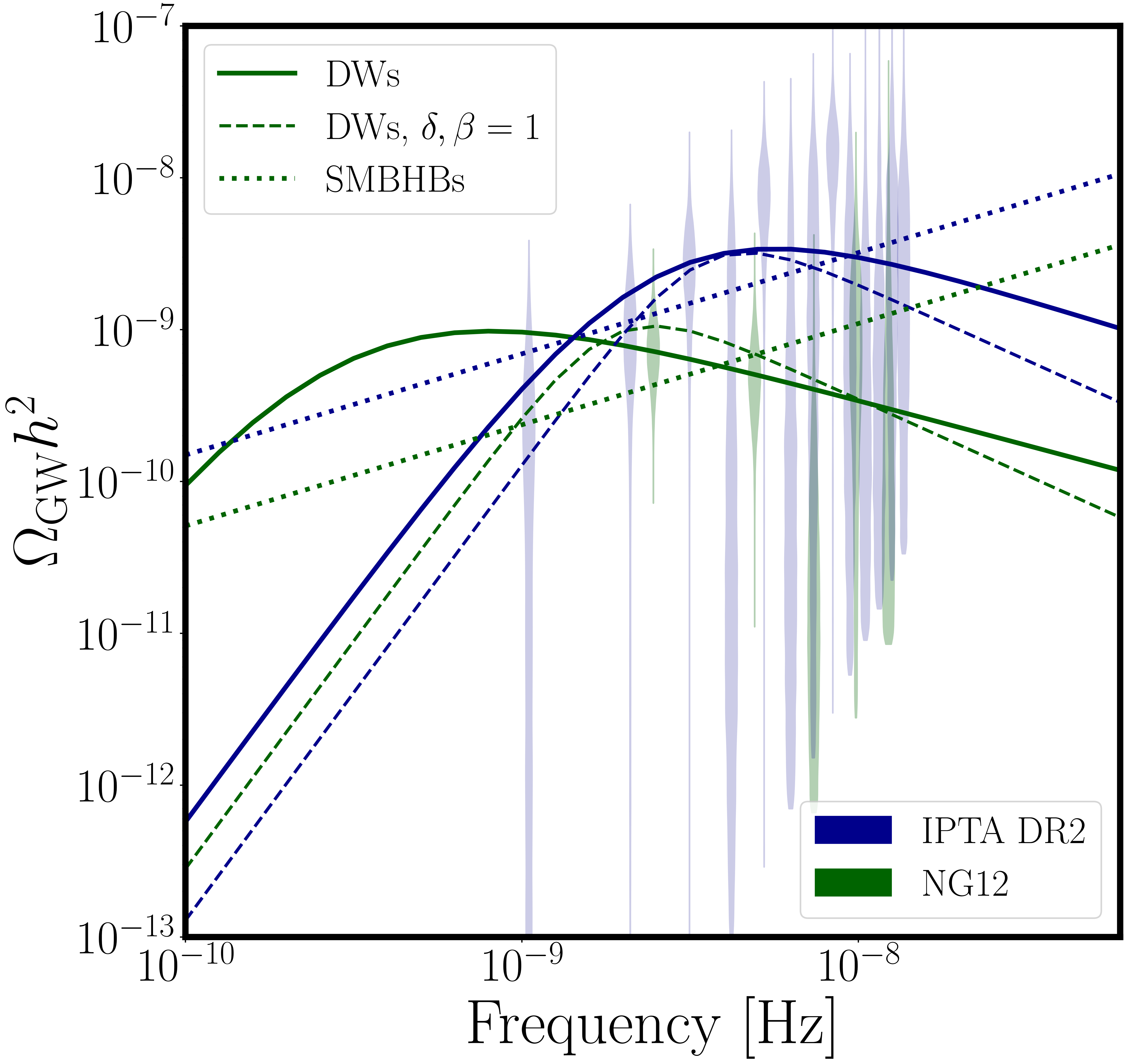


[**RZF**, Notari, Pujòlas, Rompineve 21']
[Hiramatsu et al. 13']

$\Lambda_{\mathrm{H}} = 10^{10}$ GeV, $f \simeq 10^{11}$ GeV, $\Delta\theta \simeq 8 \cdot 10^{-13}$

$\Lambda_{\mathrm{H}} = 10^{7}$GeV, $f \simeq 2.5 \cdot 10^{10}$ GeV, $\Delta\theta \simeq 8 \cdot 10^{-13}$

$\Lambda_{\mathrm{H}} = 10^{11}$ GeV, $f \simeq 1.6 \cdot 10^{11}$ GeV, $\Delta\theta \simeq 1.5 \cdot 10^{-11}$



DWs
DWs, $\delta, \beta = 1$
SMBHBs
IPTA DR2
NG12
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-10}
10^{-9}
10^{-8}
$\Omega_{\rm GW} h^2$
Frequency [Hz]