Probing Axion Physics with LIGO/Virgo

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Iberian Gravitational Wave Meeting 2020
(IGWM2020)

Based on JHEP 04 (2020) 195 arXiv:1912.07587,
with B von Harling, A Pomarol and F Rompineve

Cosmological phase transitions in the early universe

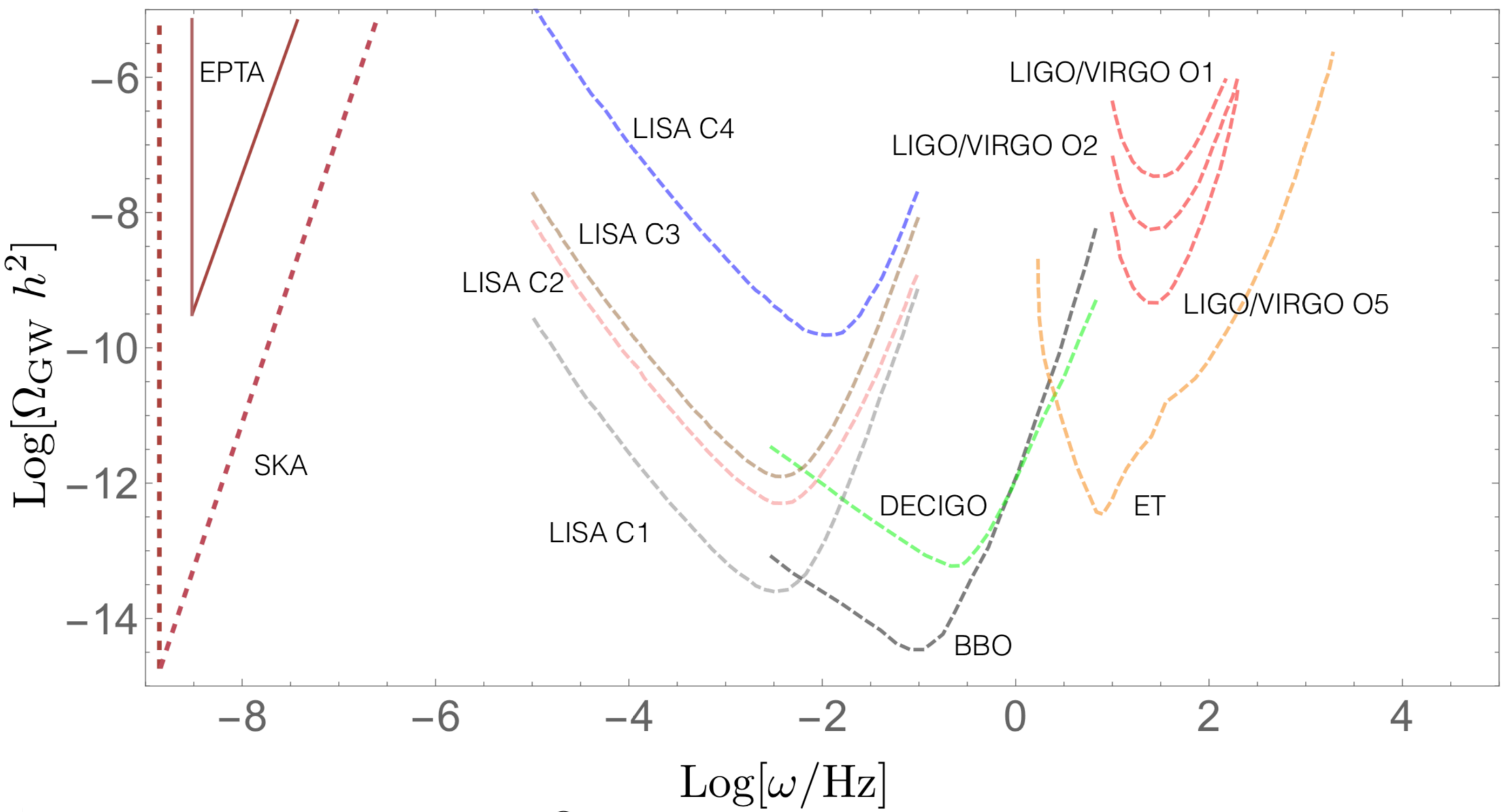
1) they are expected

2) If bubbles => they generate a stochastic GW signal

"first order"

with peak frequency

$$f_{peak} \propto T$$



QCD

Electro-weak

LIGO/Virgo frequency band, $f \sim 30\ Hz$

corresponds to *cosmological phase transition* at

$$T \sim 10^8 GeV$$

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➡ **LIGO/Virgo = High Energy Physics machines**

➡ $T \sim 10^8 GeV$ **is an interesting hotspot:**

~ Peccei Quinn scale (post-inflationary)

AXIONS

Strong CP problem: $\theta \, \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a$ $\theta \lesssim 10^{-10}$

Q) why is θ so small?

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Q) why is θ so small?

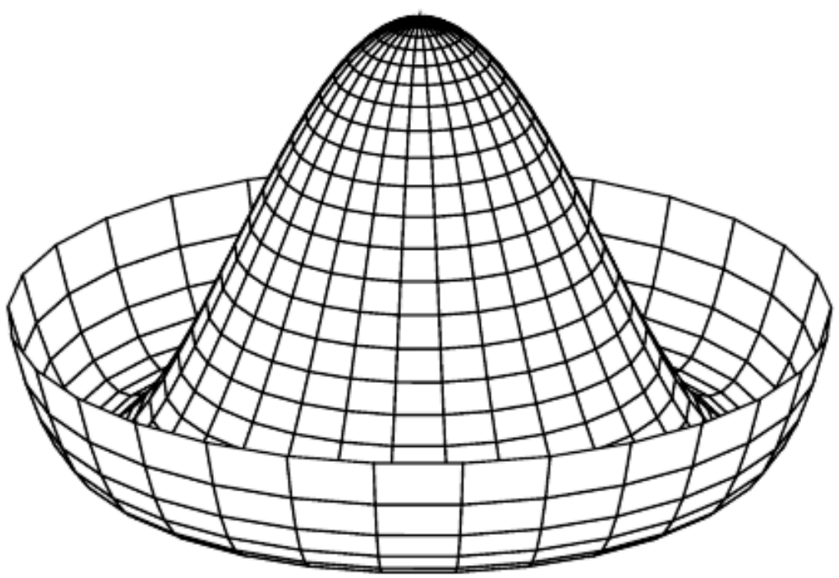
A) *Peccei-Quinn* Mechanism: $\Phi = e^{i\, a(x)/F_a}$ F_a

Spontaneously broken U(1)$_{PQ}$ with U(1)$_{PQ}$-SU(3)$_c$-SU(3)$_c$ anomaly

$$\frac{\alpha_s}{8\pi} \frac{a}{F_a} G^{\mu\nu} \widetilde{G}_{\mu\nu}$$

$$QCD \;\Rightarrow\; V(a) \qquad \langle a \rangle = 0 \qquad m_a^2 \simeq \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 F_\pi^2}{F_a^2}$$

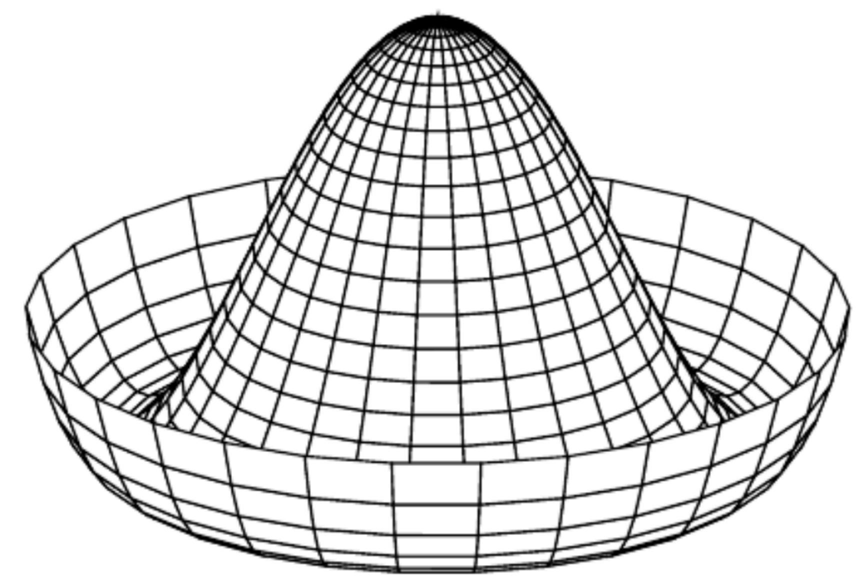
AXIONS



Peccei-Quinn symmetry is Spontaneously broken at F_a

$$\langle|\Phi|\rangle = F_a$$

AXIONS



***Peccei-Quinn** symmetry is Spontaneously broken at* F_a

$$\langle|\Phi|\rangle = F_a$$

The axion field starts to *exist* when PQ-symmetry is broken

$$\Phi = e^{i\,a(x)/F_a}\;F_a$$

(-> F_a is the scale of the axion 'birth')

AXIONS

There are 2 main ways to do this

- ***Spontaneously broken $U(1)_{PQ}$***
- ***$U(1)_{PQ}$-$SU(3)_c$-$SU(3)_c$ anomaly***
- ***(F_a= high energy scale)***

1) KSVZ (Kim, Shifman, Vainshtein, Zakharov)

=> *extra heavy quarks with PQ-charge*

2) DFSZ (Dine, Fischler, Srednicki, Zhitnitsky)

=> *extra Higgs doublet with PchargeQ-*

➡ **Bonus: axion = good DM candidate**

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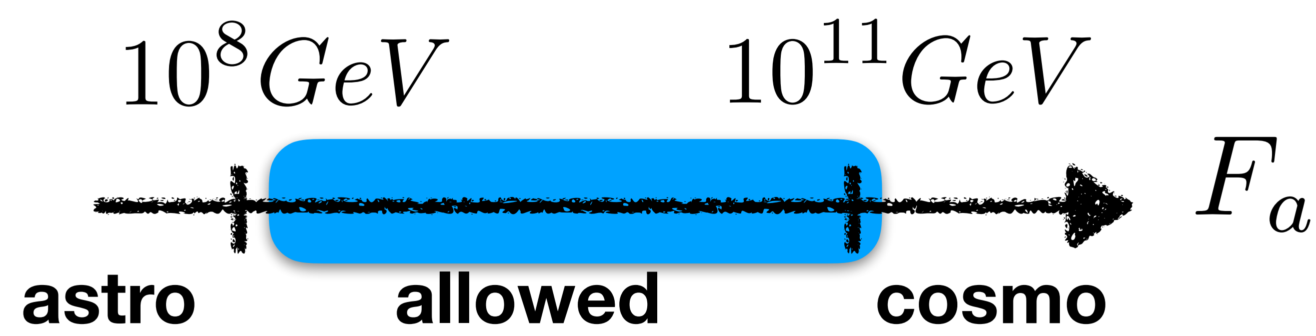
$$F_a < T_{reh}$$

1) **PQ after inflation**

$$F_a > T_{reh}$$

2) **PQ during inflation**

Bonus: axion = good DM candidate



$F_a < T_{reh}$

1) PQ after inflation

The most constrained scenario:

=> global *cosmic strings* produced at the PQ transition $T \sim F_a$

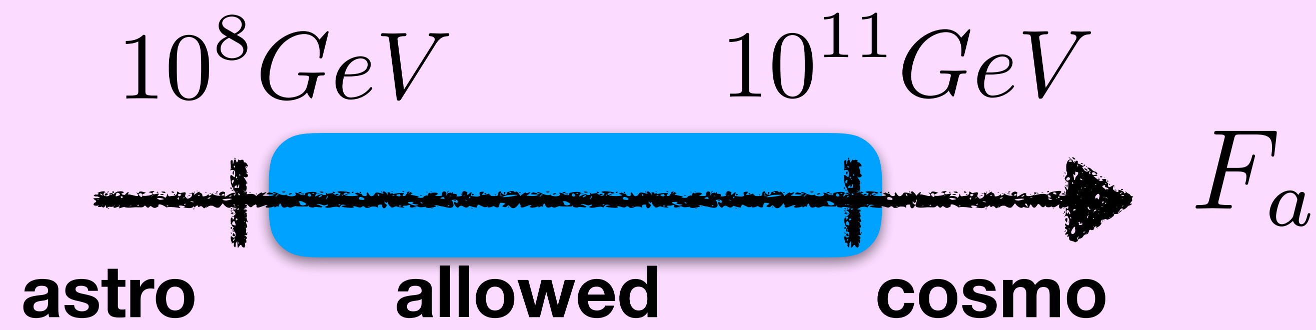
=> domain walls produced at QCD epoch $T \sim \Lambda_{QCD}$

$F_a > T_{reh}$

2) PQ during inflation

exponential dilution => small misalignment angle is ok

➡ Bonus: axion = good DM candidate



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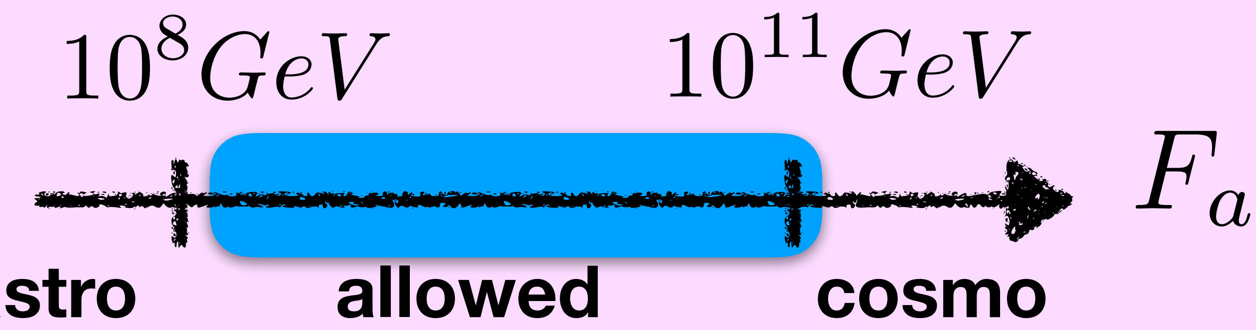

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exponential dilution => small misalignment angle is ok

(in this case, F_a can be much higher, axion lighter
=> LIGO/Virgo probe axions via *superradiance*, e.g. arXiv:1604.03958)

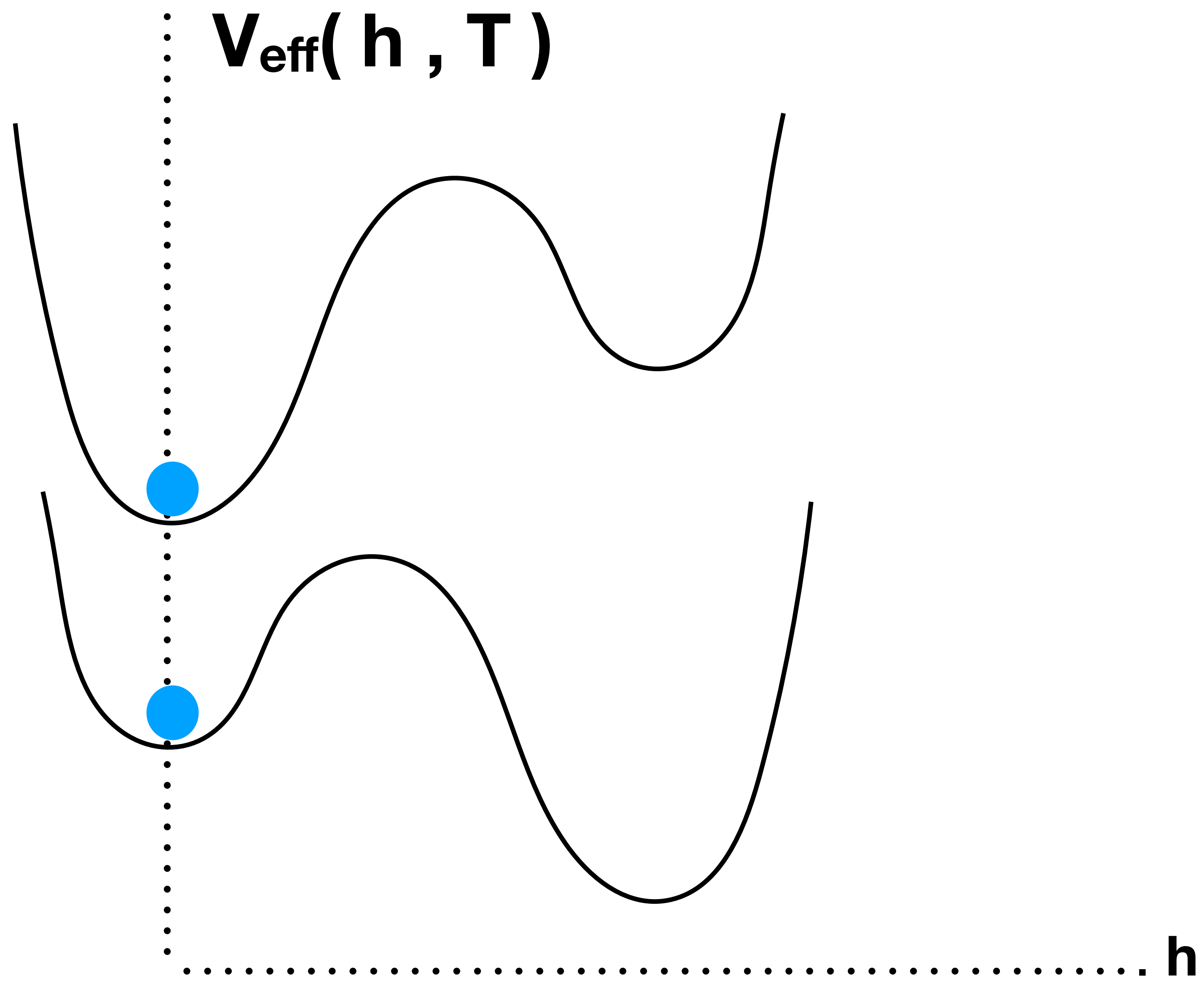
- **Axion models with Peccei-Quinn SSB after inflation must contain a cosmological Phase Transition at**

$$T \sim F_a$$

- **If the phase transition is of first order, it proceeds by nucleation of bubbles**

- **Bubble collisions are violent events in the primordial plasma, able to generate loud enough GW stochastic background <=> if the PT is strong enough**

(First Order-) Cosmological Phase Transitions



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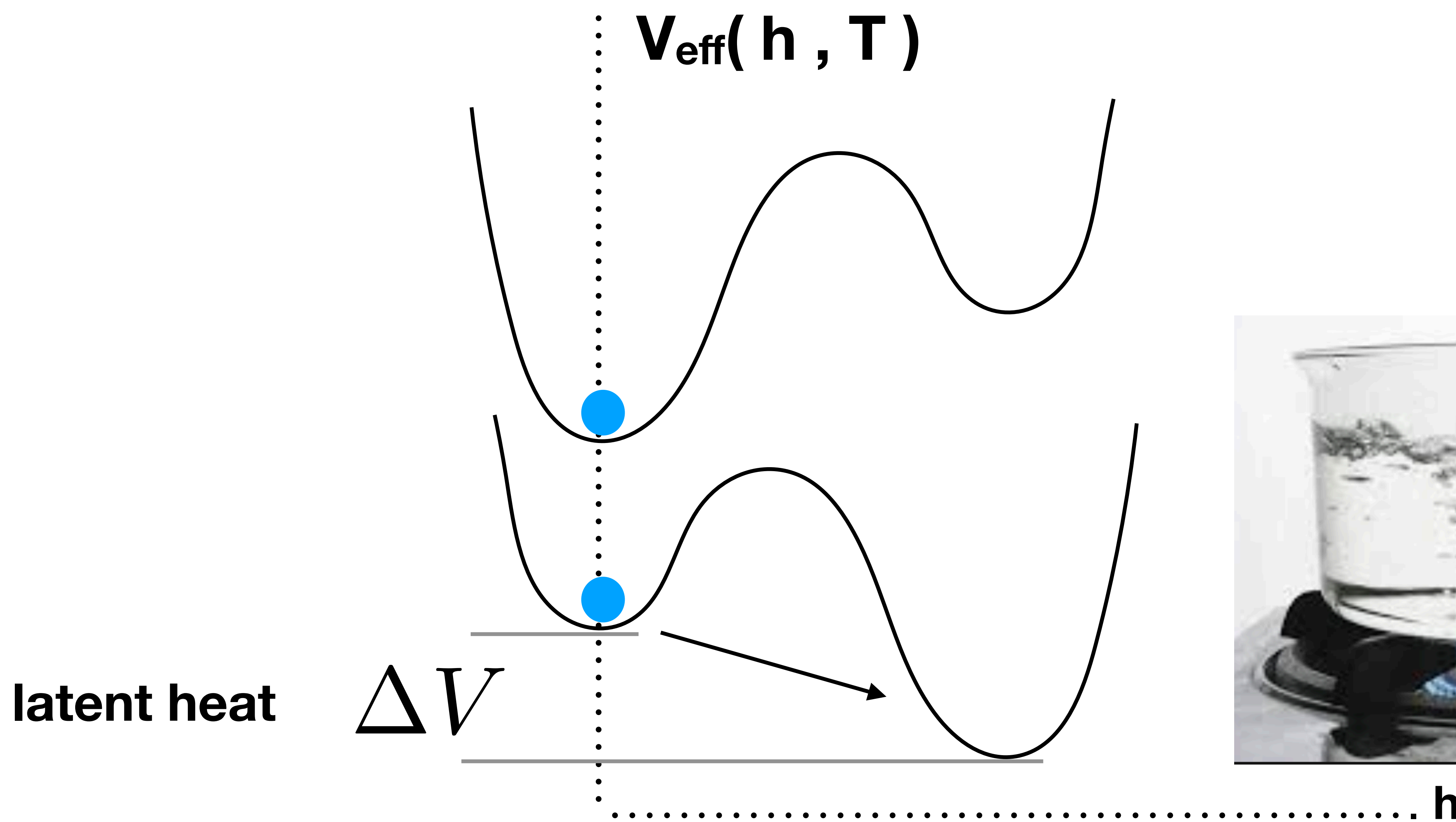
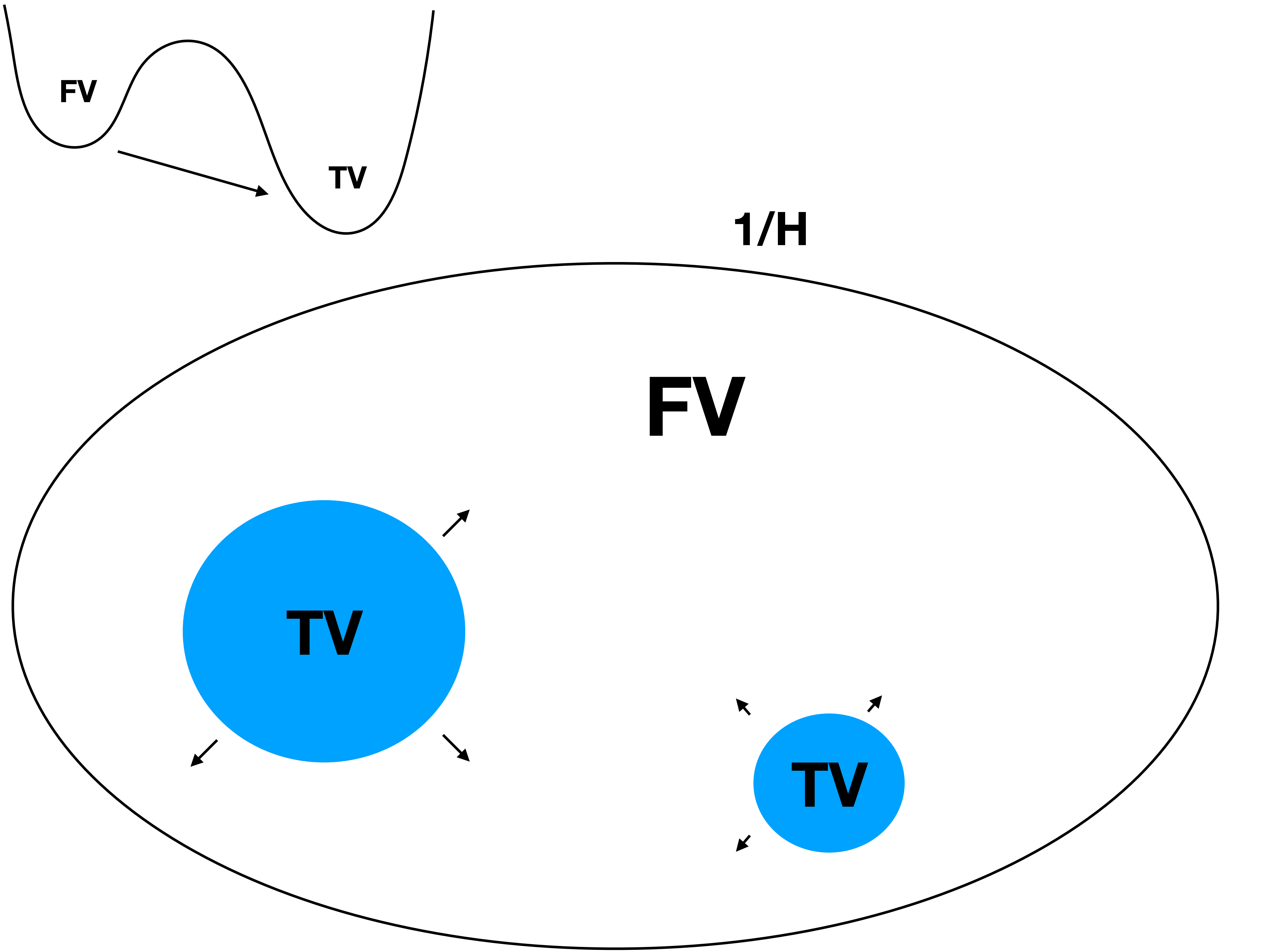
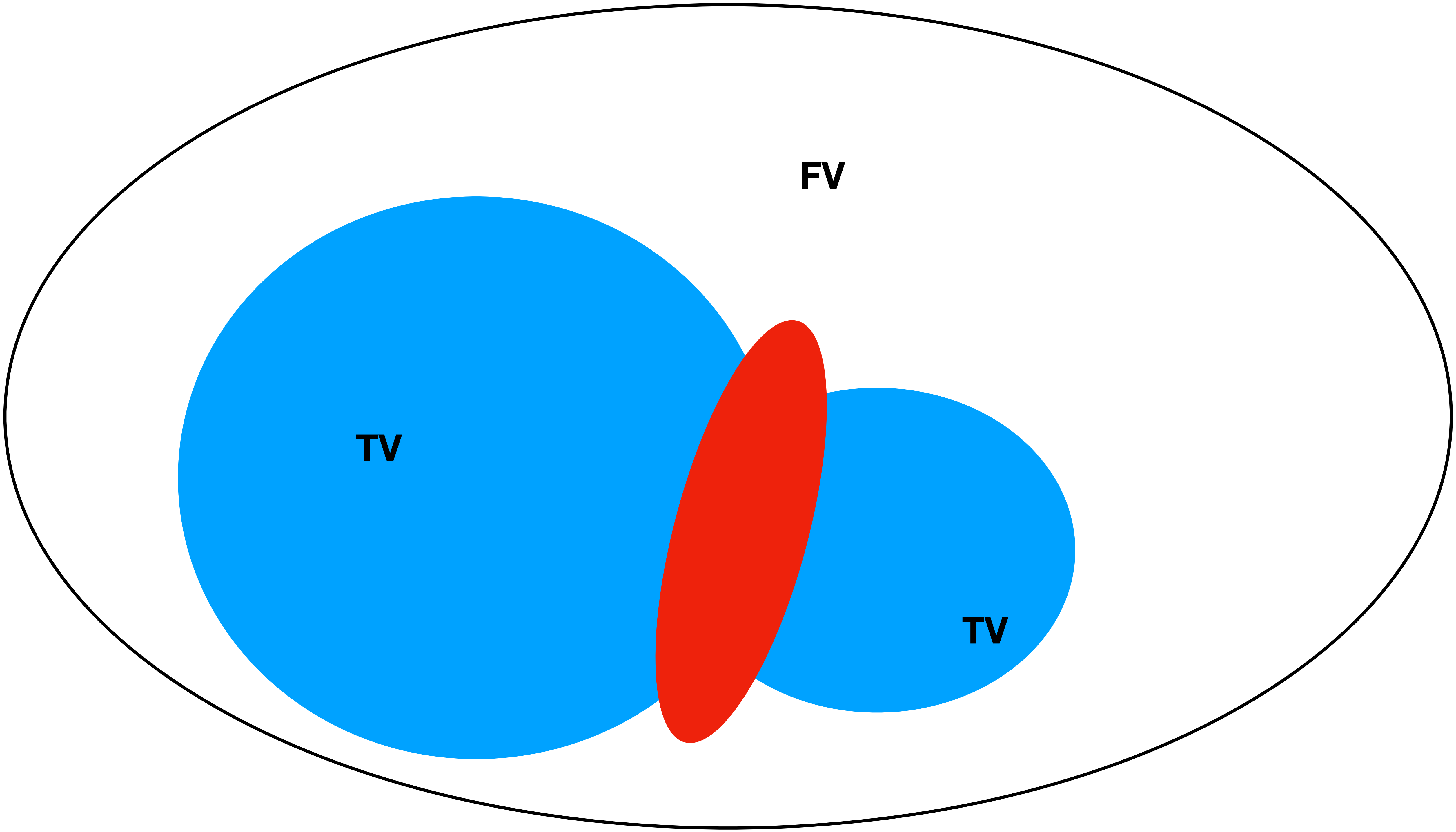


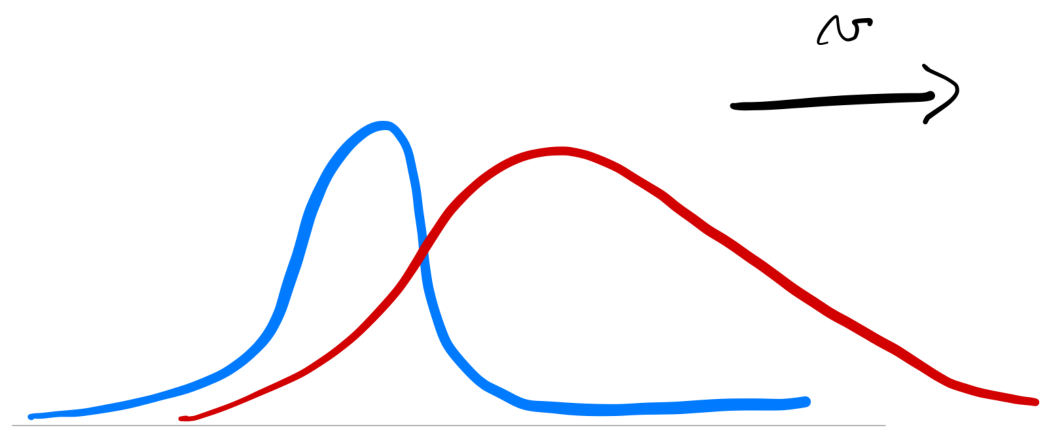

FV
TV
1/H
FV
TV
TV

Bubble collisions are violent events,
enough to produce sizeable GWs



Very rich & interesting problem!

expanding scalar wall coupled to surrounding plasma



scalar wall motion
fluid motion
turbulence
heat transfer
friction
…

all in a relativistic regime
and the most interesting case is the most violent one

“ABC” of (1st order) cosmological phase transitions

$\alpha = \dfrac{\Delta V}{\rho_\gamma(T_n)}$	**latent heat**
$\beta = \dfrac{\dot{\Gamma}}{\Gamma}\Big\rvert_{T_n}$	**inverse duration**
$\Gamma = \mathcal{A}\, e^{-S_B}$	**nucleation rate**
T_n	**nucleation temperature**
T_*	**transition completed**

$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_c}\frac{d\,\rho_{\mathrm{GW}}}{d\,\ln f}$$

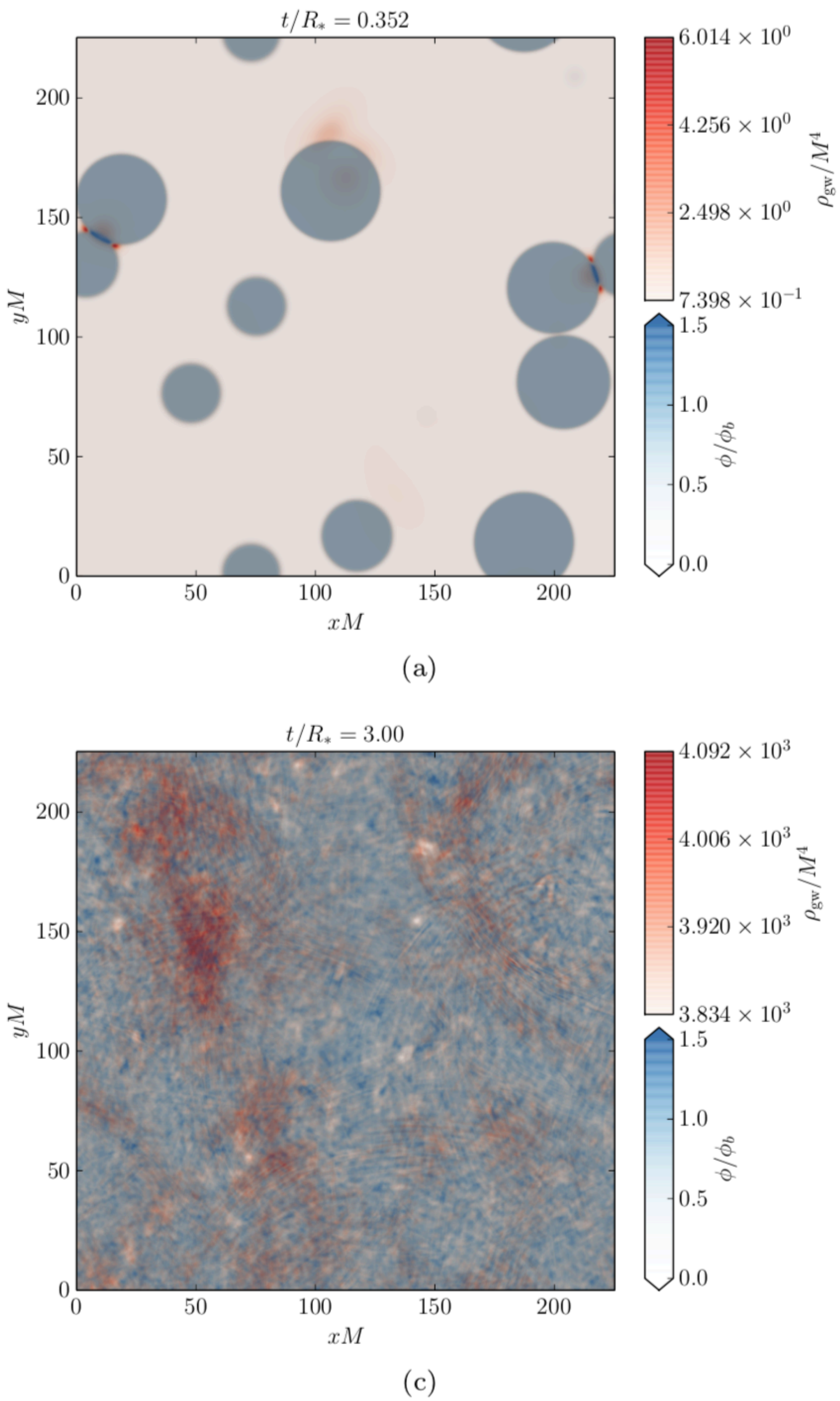
$$\Omega_{\mathrm{GW}} = \Omega_\phi + \Omega_{sw} + \Omega_t$$

Scalar

plasma sound waves

Turbulence

Bubble collisions — numerics



arXiv:1802.05712

$\Omega_\phi(f)$

$$h^2\Omega_\phi(f) = 1.66 \cdot 10^{-5} \left(\frac{H_*}{\beta}\right)^2 \frac{\kappa_\phi^2\, \alpha^2}{(1+\alpha)^2} \left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} \frac{v_w^3}{1+2.4\, v_w^2} \frac{(f/f_\phi)^{2.8}}{1+2.8\,(f/f_\phi)^{3.8}}$$

$$f_\phi = 56.8\,\mathrm{Hz} \times \left(\frac{\beta/H_*}{10}\right) \left(\frac{T_*}{10^8\,\mathrm{GeV}}\right) \left(\frac{1}{1-0.05 v_w + 0.55\, v_w^2}\right) \left(\frac{g_*(T_*)}{100}\right)^{\frac{1}{6}}$$

arXiv:1801.04268

$$\Omega_{sw}(f)$$

$$h^2\Omega_{sw}(f) = 1.88 \cdot 10^{-5} \left(\frac{H_*}{\beta}\right) \frac{\kappa_{sw}^2\,\alpha^2}{(1+\alpha)^2} \left(\frac{100}{g_*(T_*)}\right)^{\frac{1}{3}} v_w \, \frac{(f/f_{sw})^3}{[1+0.75\,(f/f_{sw})^2]^{7/2}}$$

$$f_{sw} = 19\,\mathrm{Hz} \times \frac{1}{v_w} \left(\frac{\beta/H_*}{10}\right) \left(\frac{T_*}{10^7\,\mathrm{GeV}}\right) \left(\frac{g_*(T_*)}{100}\right)^{\frac{1}{6}}$$

arXiv:1801.04268

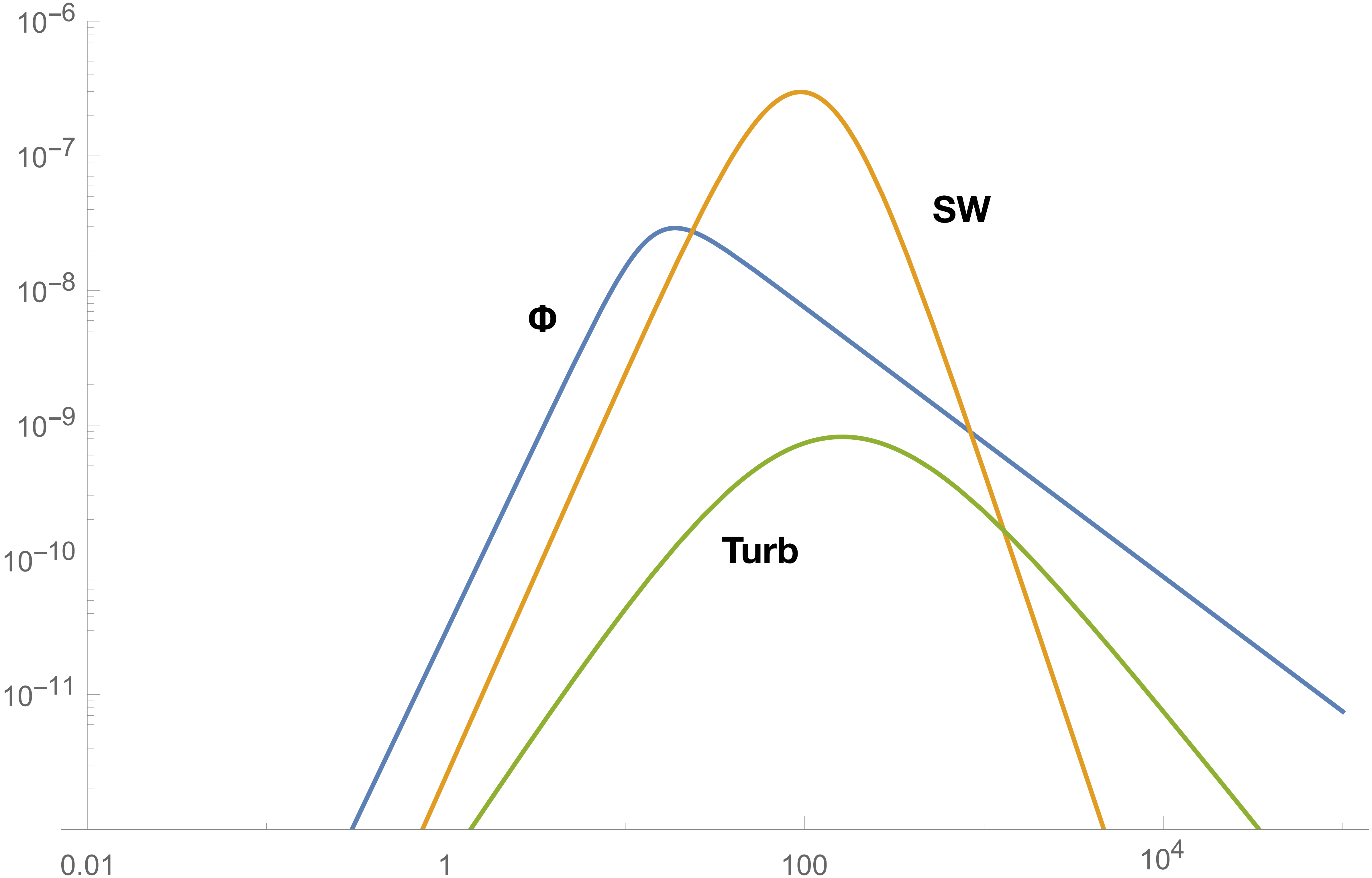
$\Omega_t(f)$

$$h^2\Omega_{\rm turb}(f) = 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\,\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*(T_*)}\right)^{1/3} v_w$$
$$\times\frac{(f/f_{\rm turb})^3}{[1+(f/f_{\rm turb})]^{\frac{11}{3}}\,(1+8\pi f/h_*)}$$

$$f_{\rm turb} = 2.7\times10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*(T_*)}{100}\right)^{\frac{1}{6}}$$

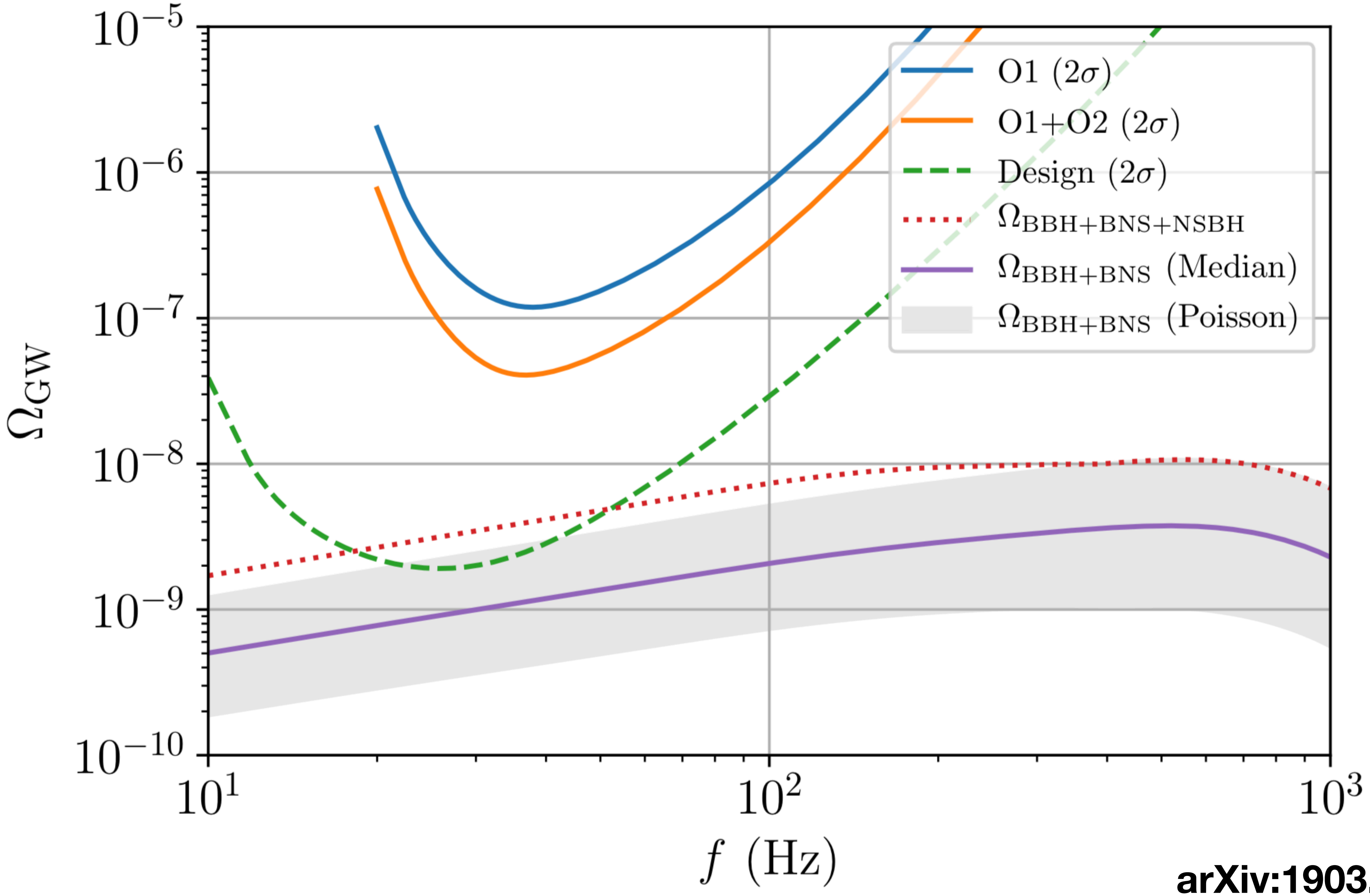
arXiv:1801.04268

shapes:



Searches

Power-law sensitivity curves



arXiv:1903.02886

[see also JHEP 04 (2020) 025]

Peccei-Quinn Phase Transition at LIGO

Benedict von Harling[a], Alex Pomarol[a,b], Oriol Pujolàs[a]

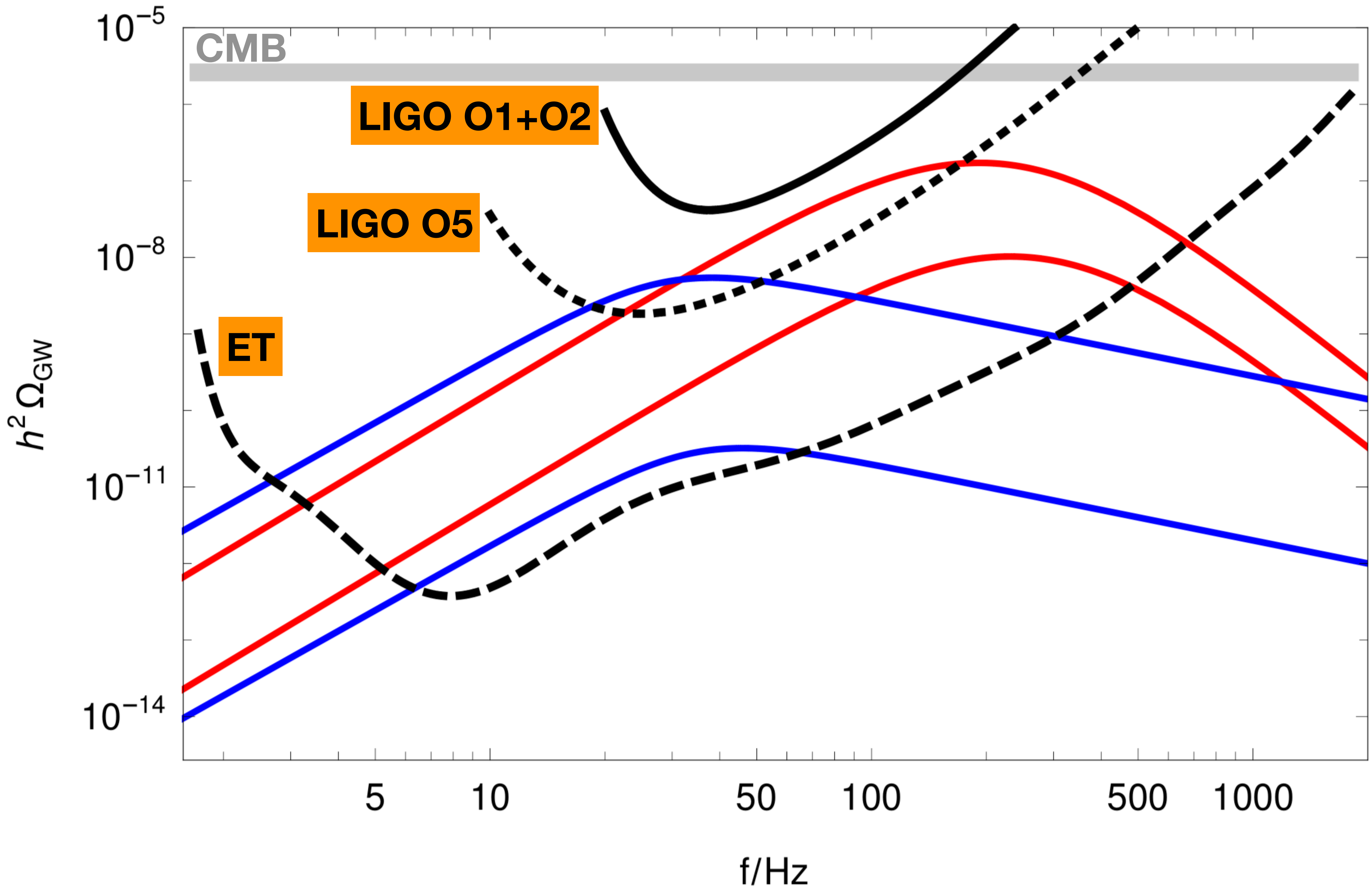
and Fabrizio Rompineve[c]

arXiv:1912.07587
JHEP 04 (2020) 195

1) sensitivity reach to cosm. PT's

2) identifying models with strong PT's

1) sensitivity reach to PTs

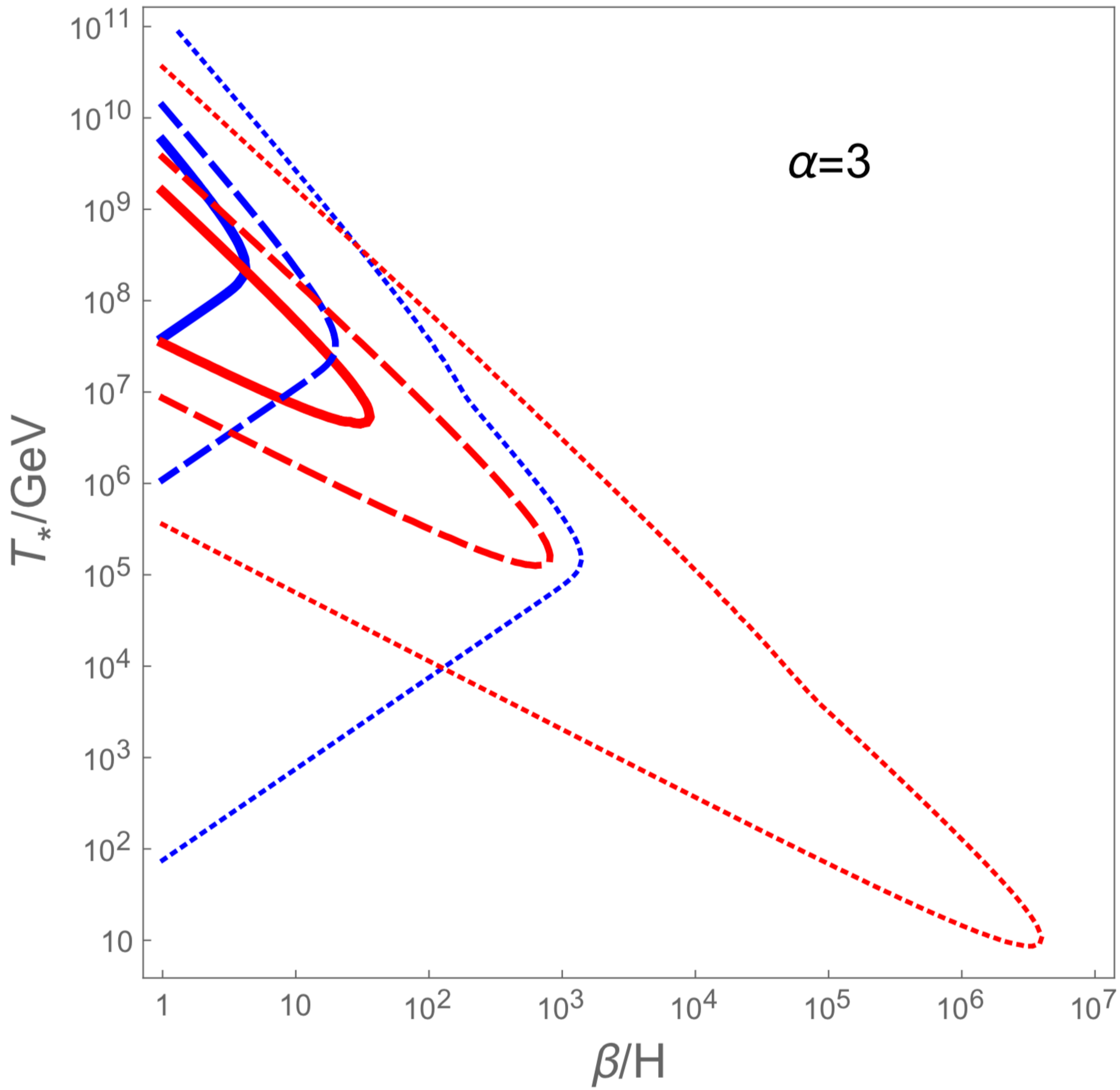


$F_a = 10^8\ GeV\ with\ \alpha \approx 3.5$ $F_a = 10^9\ GeV\ with\ \alpha \sim 10^6$

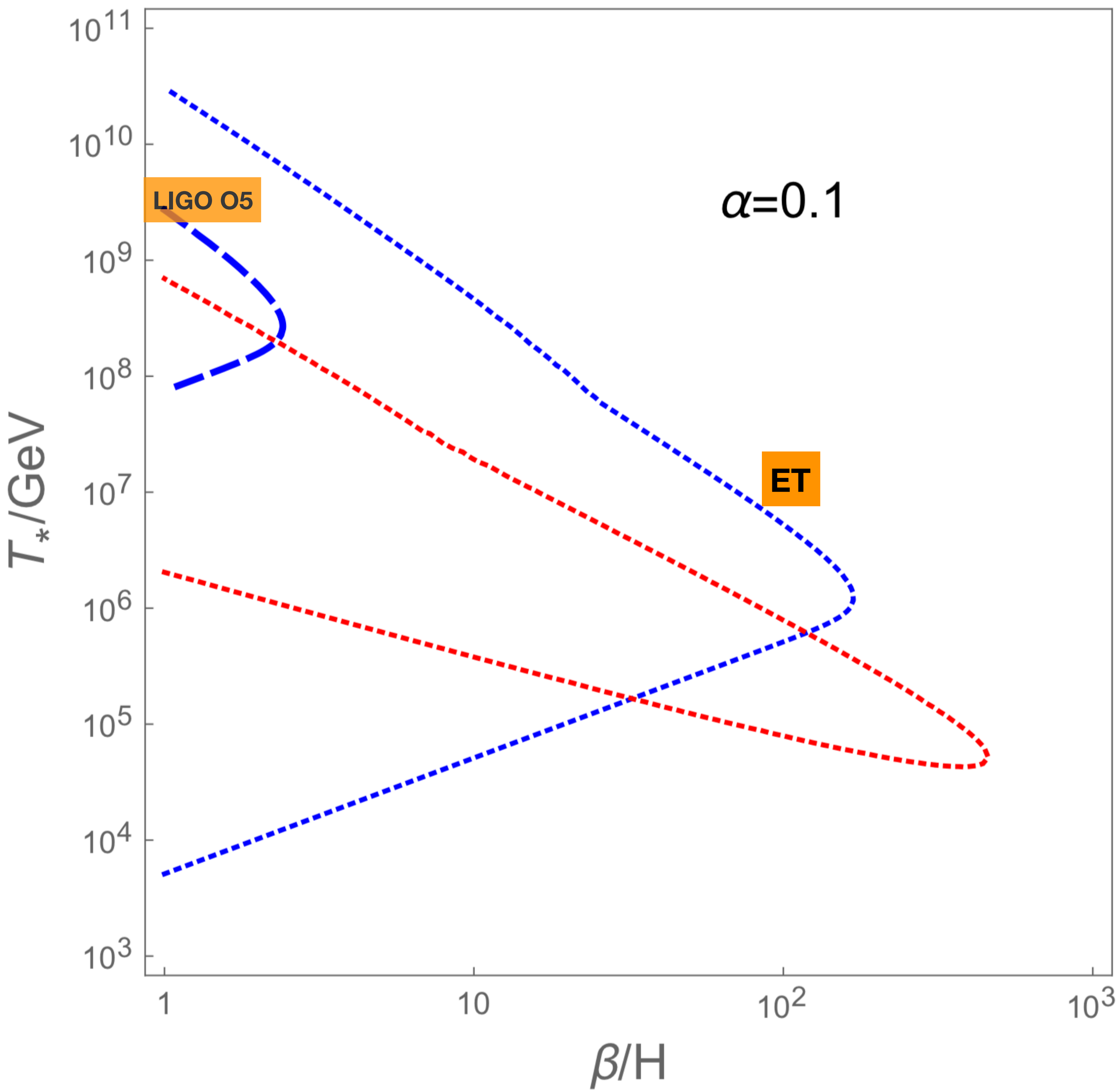
1) sensitivity reach to PTs

already ruling-out some parameter space!

(solid lines)



1) sensitivity reach to PTs



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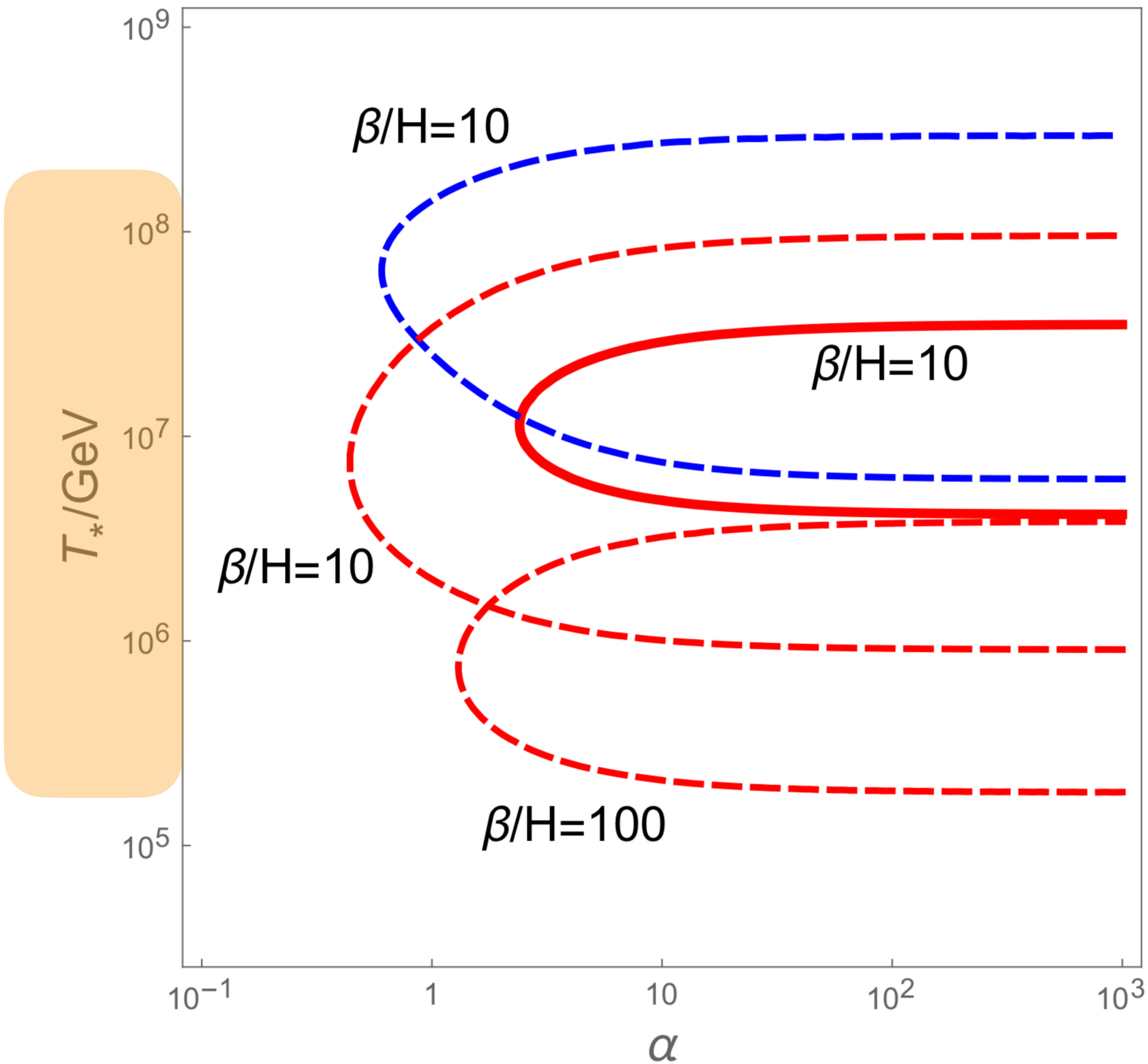


2) Axion models with strong PT

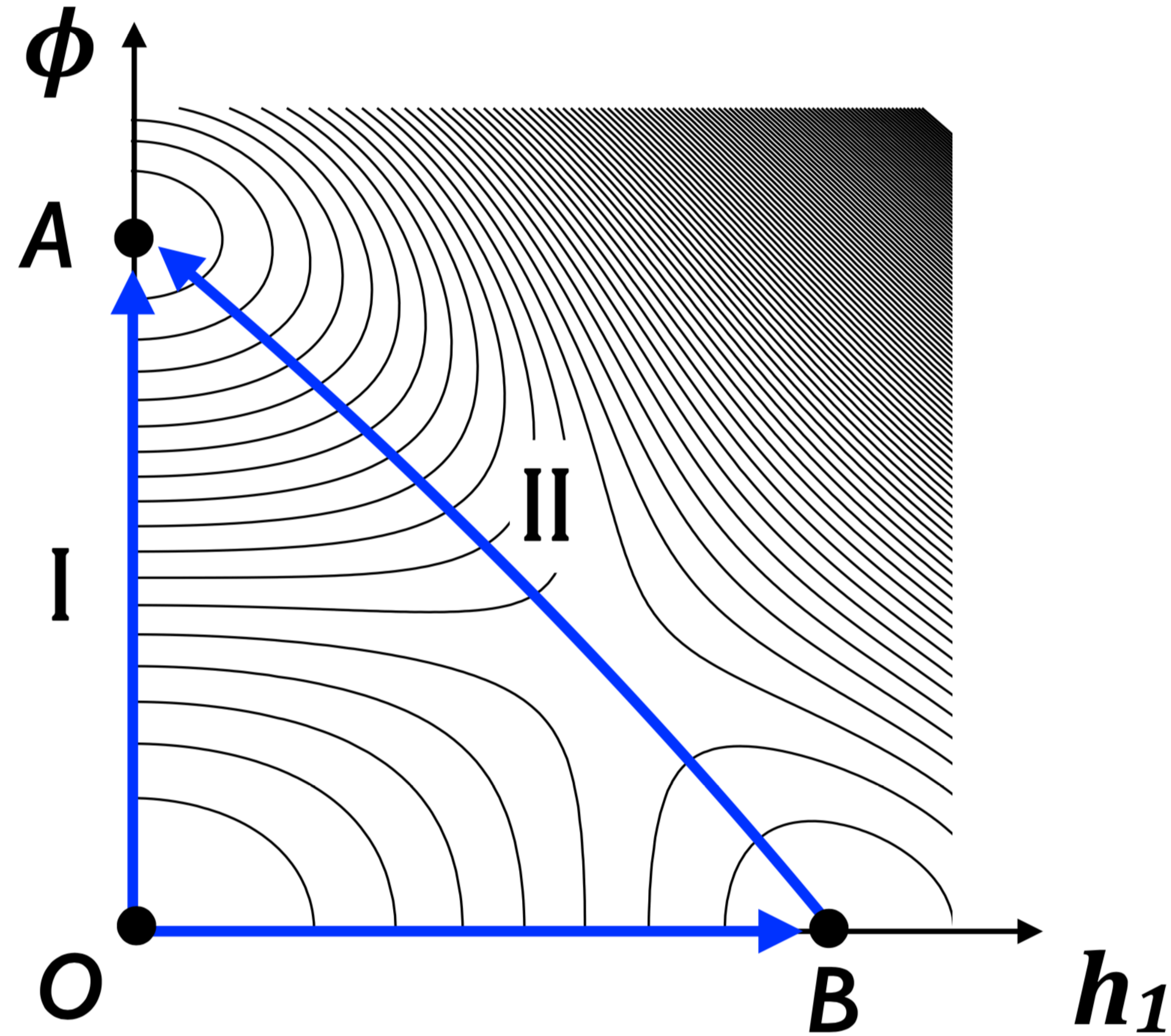
Compute $V_{eff}(\Phi,T)$ => α, β, …

2) Axion models with strong PT

KSVZ can't do it, but …

2) Axion models with strong PT

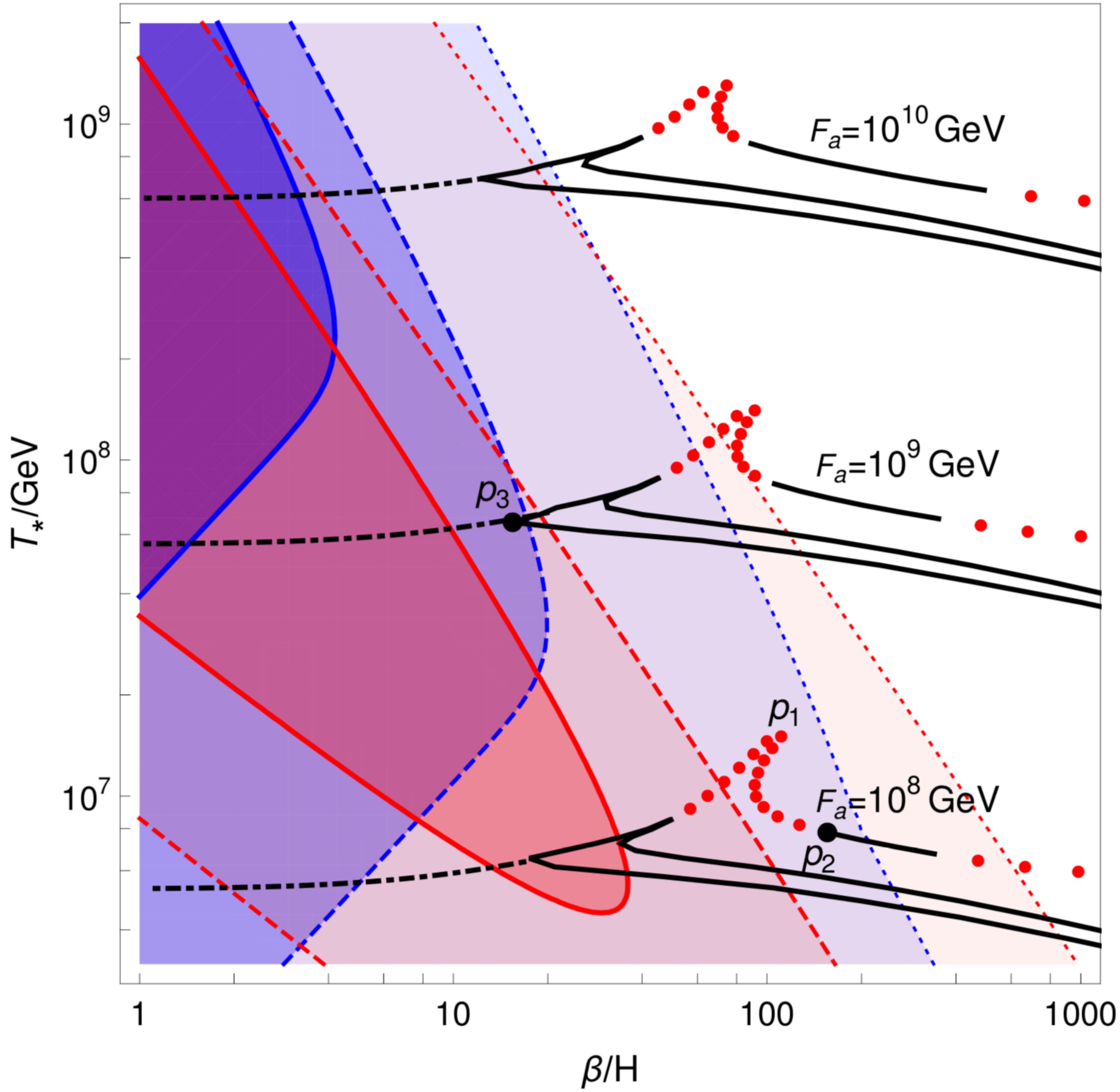
DFSZ can do it !



2) Axion models with strong PT

DFSZ can do it !

T_* **is ~ 1 order of magnitude below** F_a

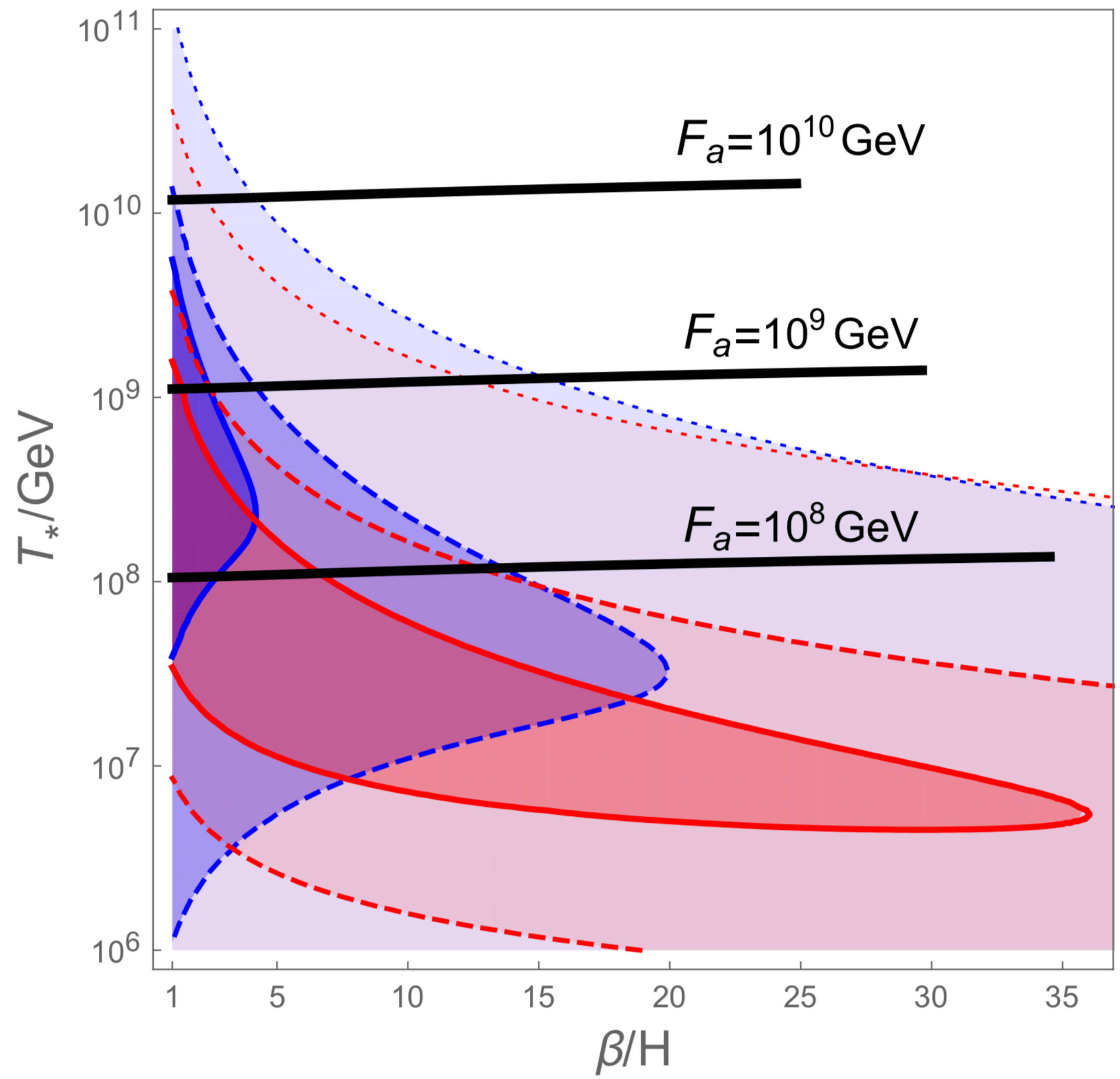


2) Axion models with strong PT

KSVZ/DFSZ can be embedded in larger new physics sectors

- **SUSY version of KSVZ also works**

- **Strong dynamics also**



Conclusions

- LIGO/Virgo are sensitive to phase transitions in the early universe at around $10^8 GeV$ — H.E.P. !
- Detectable signals arise if *supercooling*, $\alpha \gtrsim 1$
- Prospects for the ET are very good
- Very relevant for axion physics: PQ phase transition $T \sim 10^8 - 10^{12}\ \mathrm{GeV}$
- Detectable PQ models: DFSZ, strong dynamics, SUSY…
- Very interesting probe of new physics beyond the SM!
- Complementary to axion tests from superradiance (smaller m_a)

Thank you!