Probing Light Hidden Sectors with Pulsar Timing Arrays

7th Workshop on Theory, Phenomenology and Experiments in Flavour Physics - Capri

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in collaboration with with
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JG|U

PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

In this talk:

Probing hidden sectors:

Gravitational waves from first-order phase transitions

Cosmological constraints

Experimental sensitivity to GW spectra

Example: Higgsed dark-photon model

Talking to the Hidden Sector

The fourth portal

The usual portal suspects:

- Vector: (kinetic mixing, weakly coupled gauge bosons, …)
- Scalar: (Higgs portals, …)
- Fermion: (neutrino portal, …)
- Any combination of the above

Talking to the Hidden Sector

The fourth portal

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Typically we forget about gravity!

The upsides:

- Cannot be switched off
- Gravitational waves may provide brand new insights

Thermalised Hidden Sectors

Phase transition must occur in a thermalised sector to produce observable GW signal

Temperature in hidden sector typically deviates from temperature of the SM thermal bath:

$$\xi_h \equiv \frac{T_h}{T_\gamma} = \left(\frac{g_{*s,\gamma} g_{*s,h}^{\mathrm{dec}}}{g_{*s,\gamma}^{\mathrm{dec}} g_{*s,h}} \right)^{1/3}$$

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Temperature ratio strongly affects GW spectrum

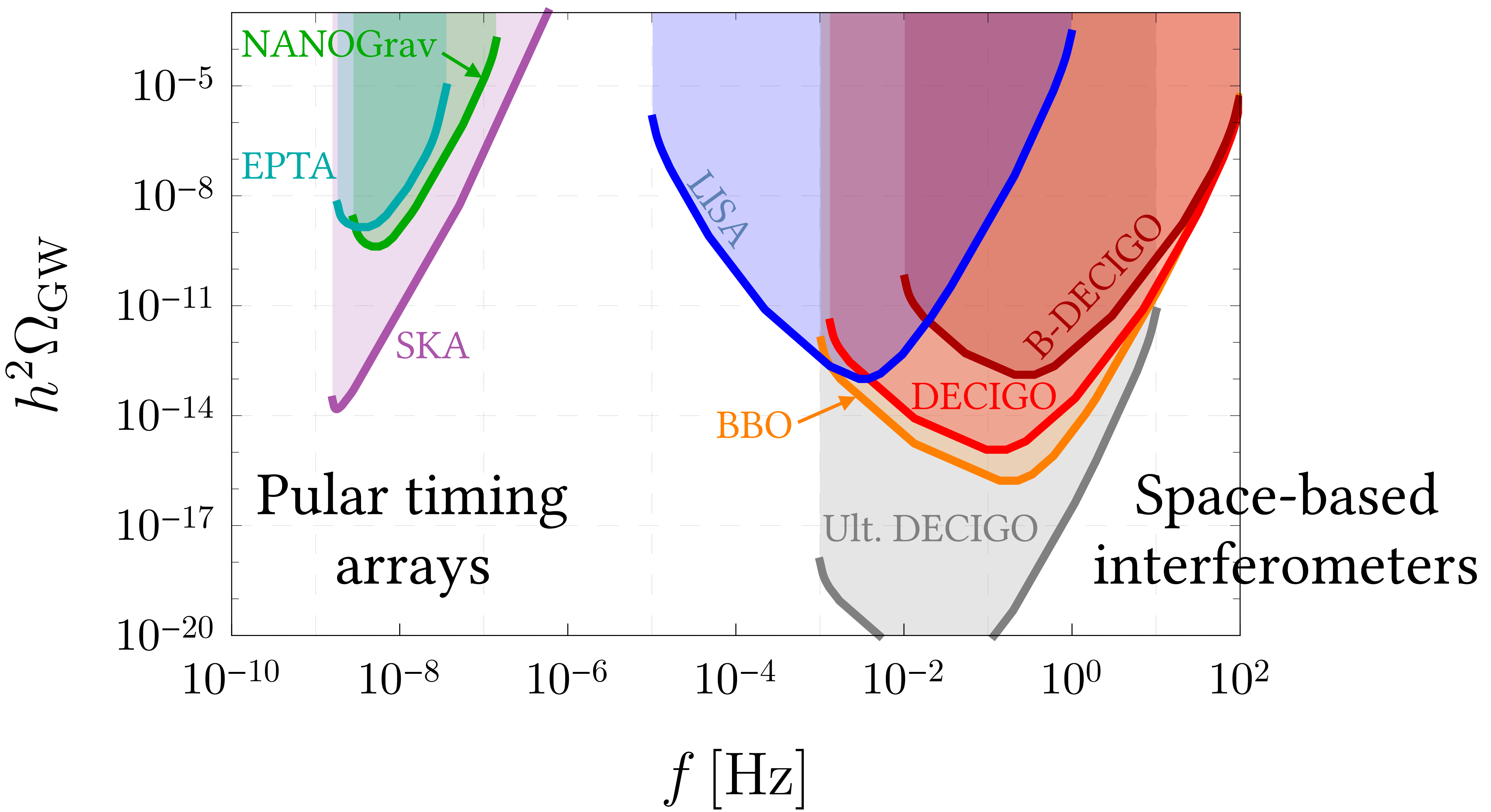
two effects ⟷

Stringent constraints on new thermalised keV/MeV relativistic degrees of freedom

Gravitational waves from first-order phase transitions

Gravitational Waves

Sensitivity curves

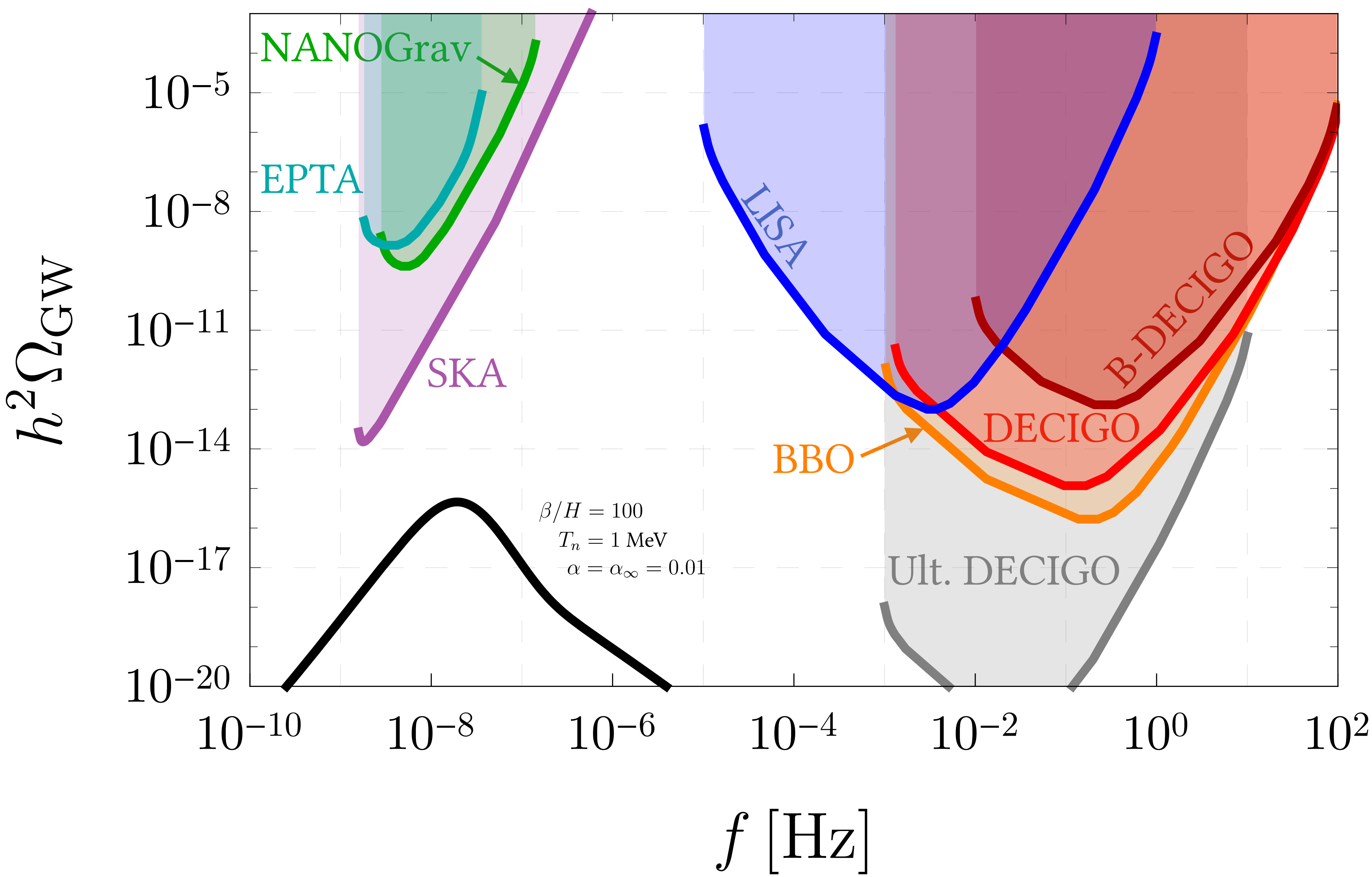


Power-law integrated sensitivity derived from experimental noise curves

[Thrane & Romano - 1310.5300]

Gravitational Waves

Sensitivity curves



Power-law integrated sensitivity derived from experimental noise curves

[Thrane & Romano - 1310.5300]

GW Stochastic Background

First-order phase transitions

Phase transition controlled by effective potential:

$$V_{\text{eff}}\left(\phi, T\right) = V_{\text{tree}}(\phi) + V_{\text{loop}}(\phi) + V_{\text{thermal}}\left(\phi, T\right) + V_{\text{daisy-res.}}\left(\phi, T\right)$$

GW Stochastic Background

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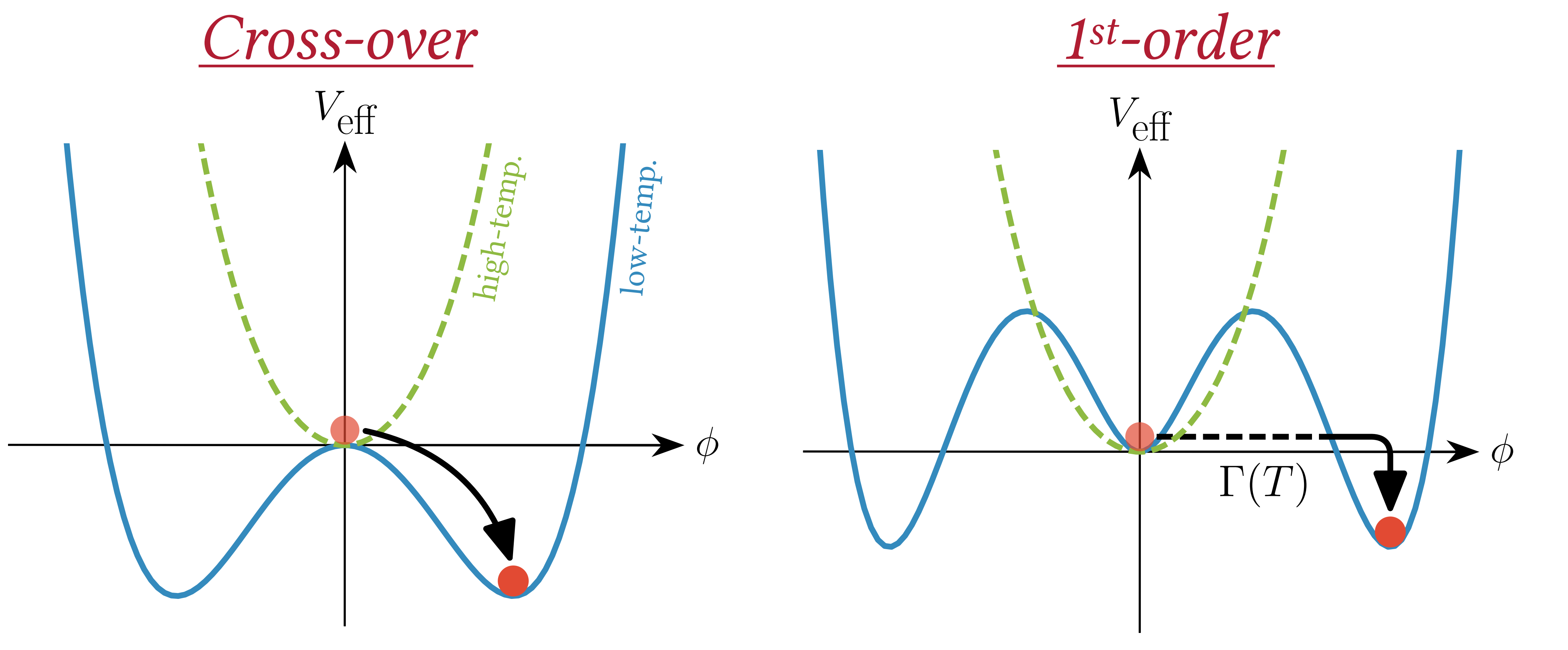
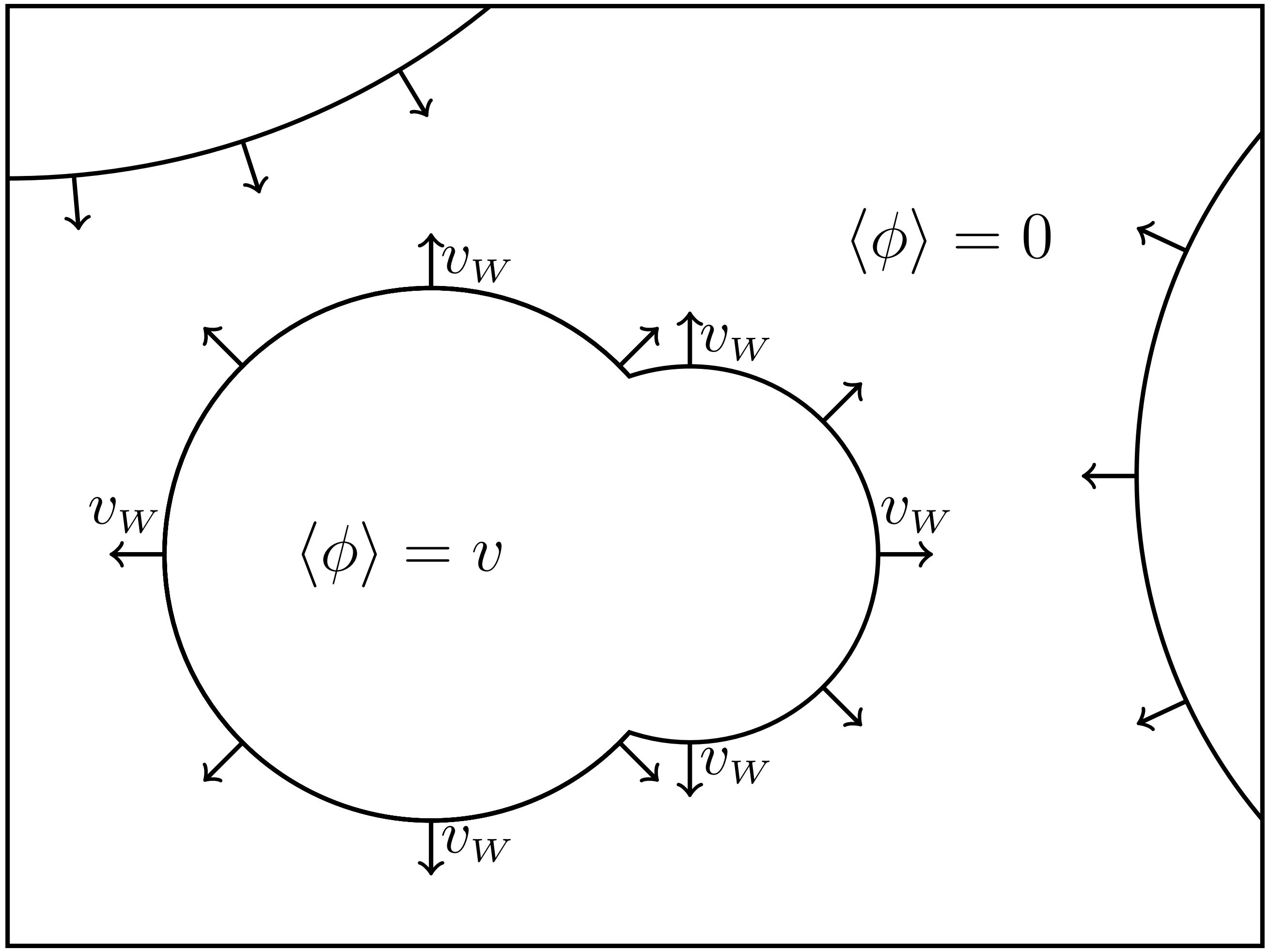


GW Stochastic Background

Sourcing gravitational waves

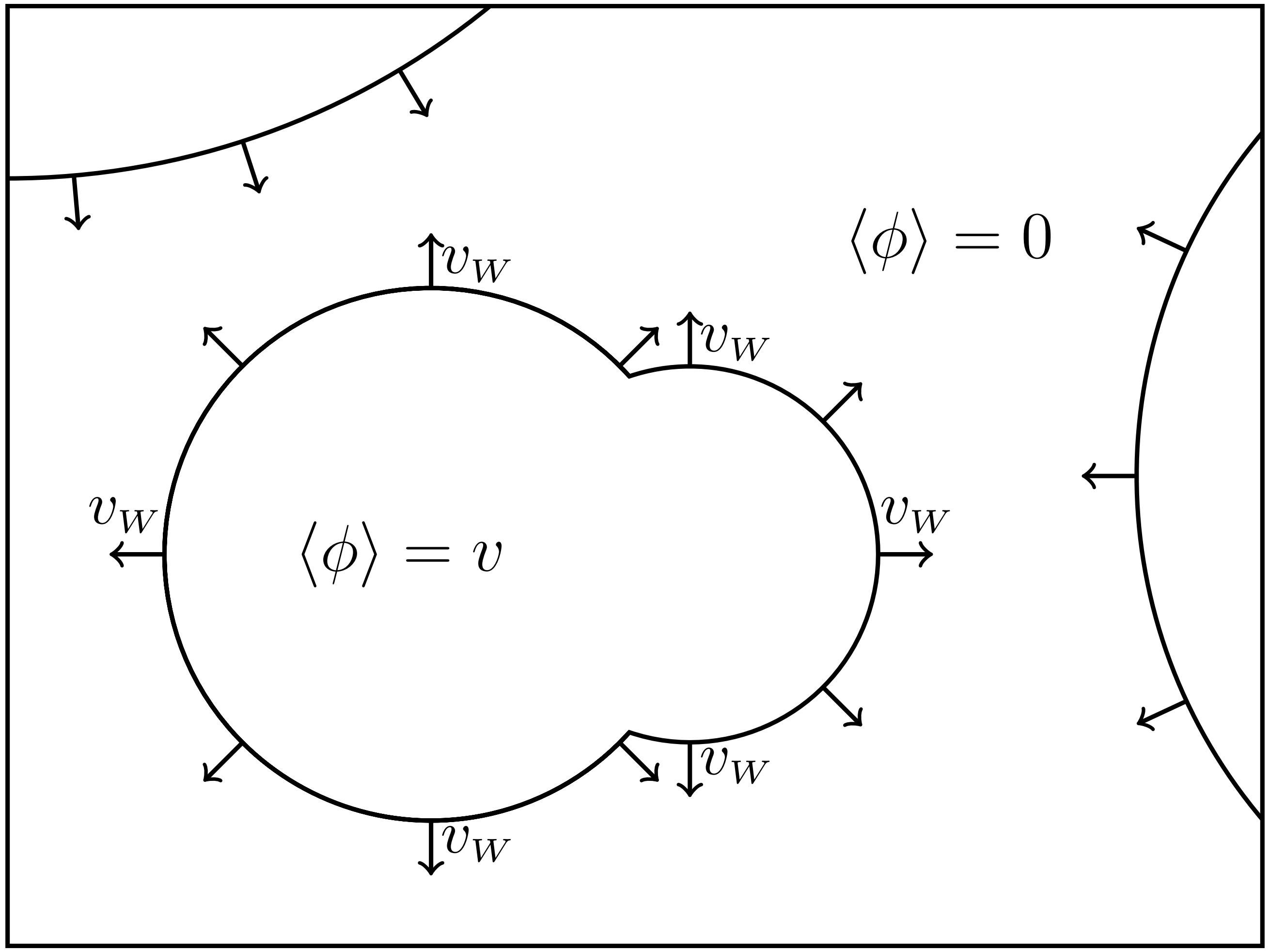


GW Stochastic Background

Sourcing gravitational waves

Nucleation temperature:

$$\Gamma(T_n) \sim H(T_n)$$



GW Stochastic Background

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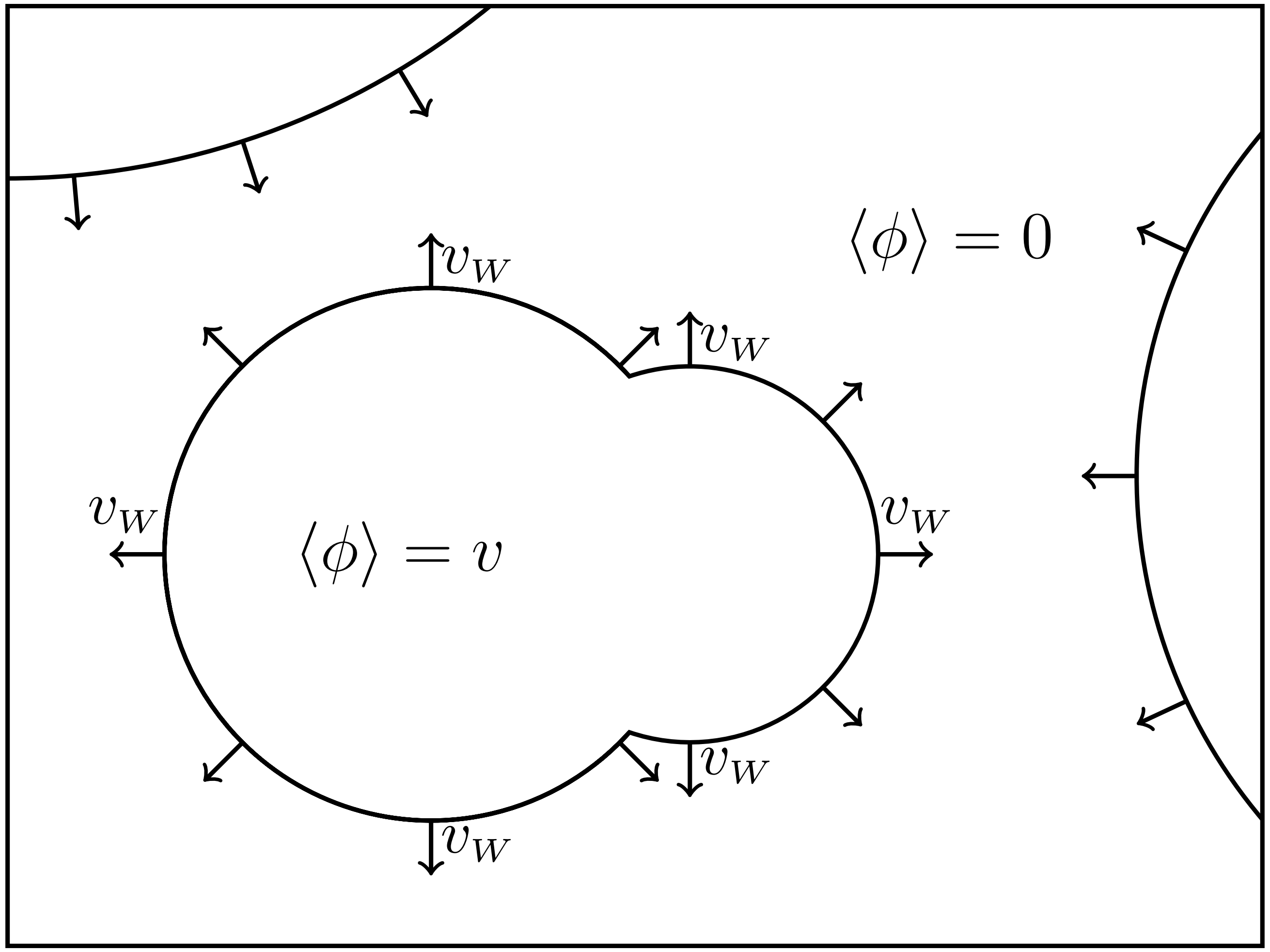

Contributions to the spectrum:

[Hindmarsh et al. - 1504.03291]

Ω_ϕ : Collision of bubble walls

GW Stochastic Background

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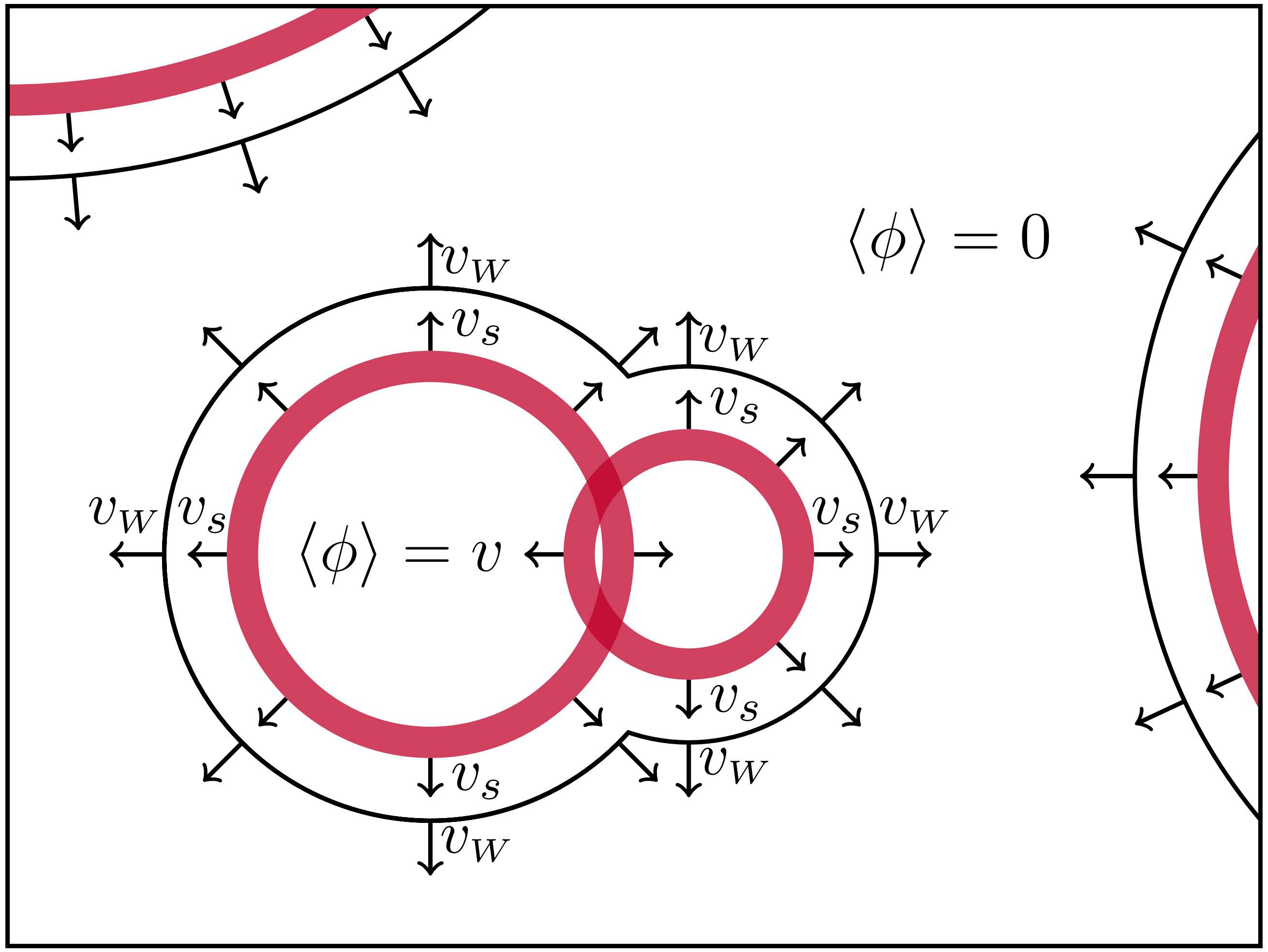


Contributions to the spectrum:

[Hindmarsh et al. - 1504.03291]

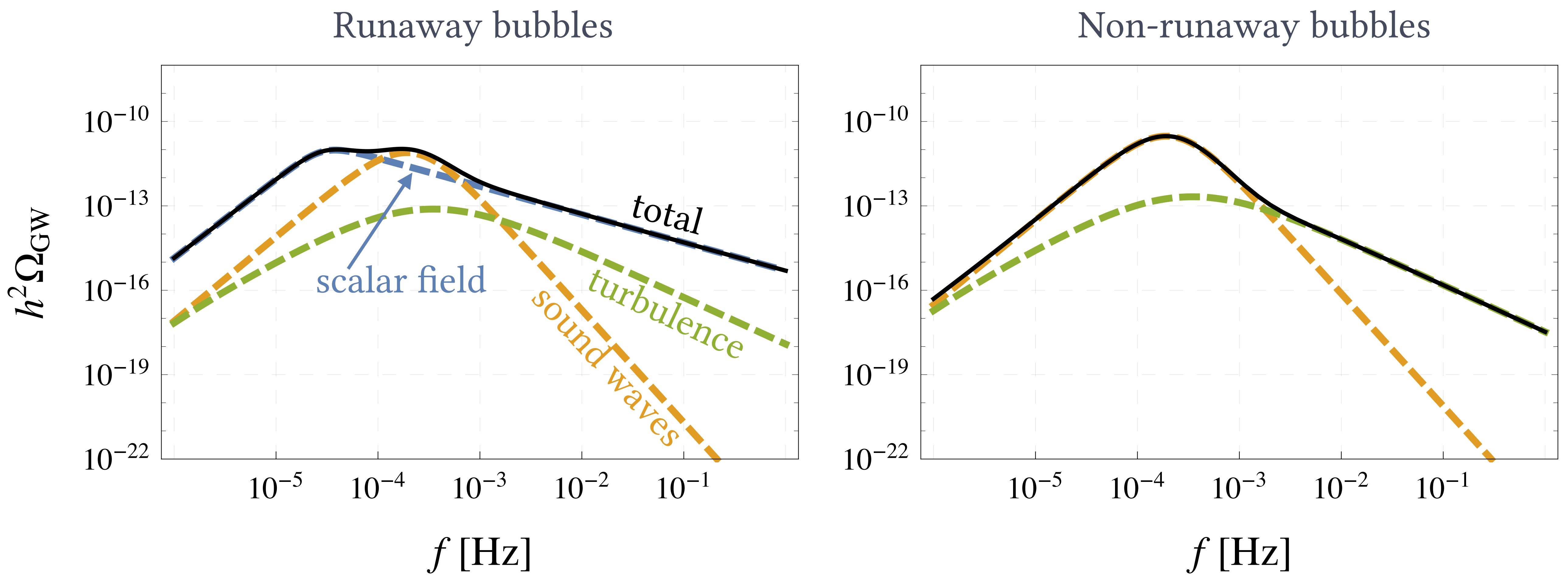
Ω_ϕ : Collision of bubble walls

$\Omega_{\rm sw}$: Collision of sound-waves

$\Omega_{\rm turb}$: Plasma turbulence

GW Stochastic Background

Contributions to the spectrum

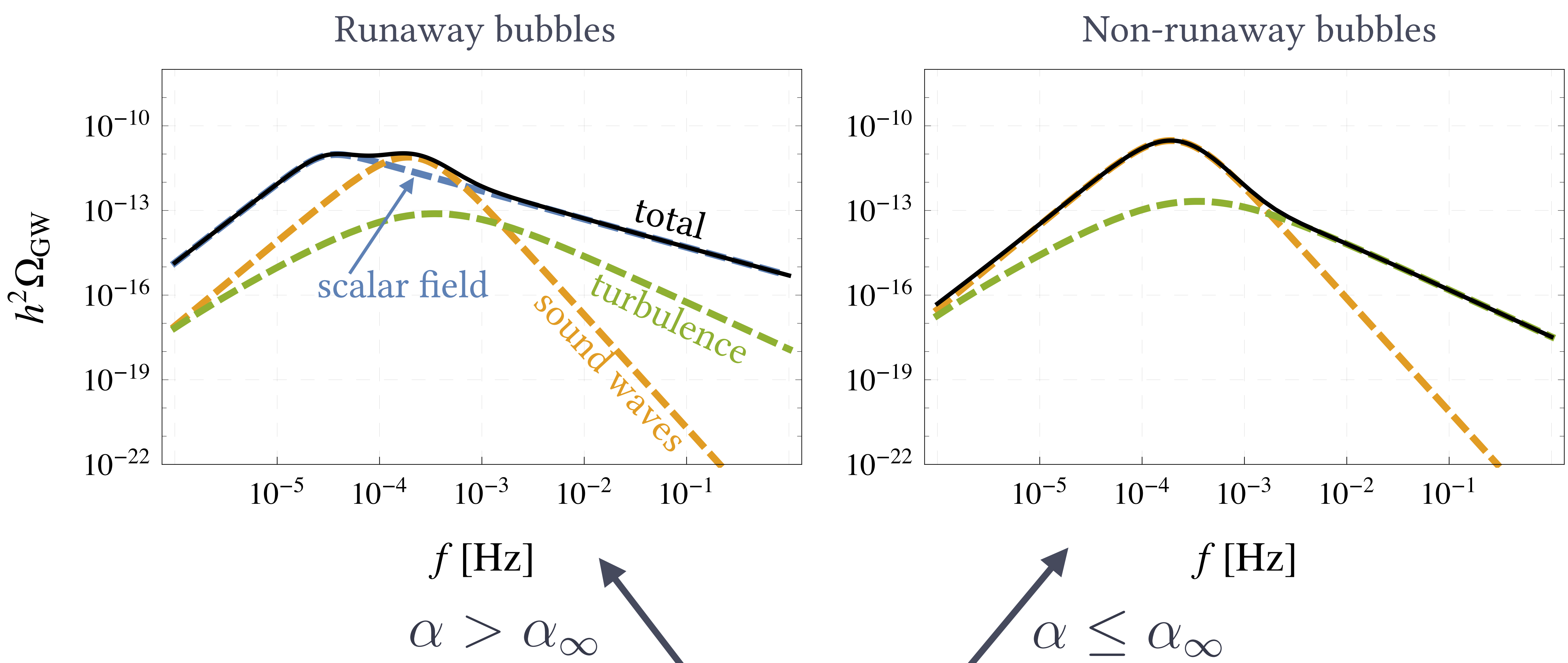


1. Ω_ϕ : Initial collision of bubble walls
2. $\Omega_{\rm sw}$: Collision of sound-waves in the plasma
3. $\Omega_{\rm turb}$: Plasma turbulence after sound wave collision

[Hindmarsh et al. - 1504.03291]

GW Stochastic Background

Contributions to the spectrum



Bubble-wall friction: $\alpha_\infty \sim \sum_a \left[m_a(\phi_{\rm broken}) - m_a(\phi_{\rm unbroken})\right]$

GW Stochastic Background

Parametrising the spectrum

Nucleation temperature: T_n

Strength: $\alpha \equiv \frac{\epsilon}{\rho_{\rm rel}}$

Inverse time-scale: $\frac{\beta}{H} \equiv -T_n \left.\frac{\mathrm{d}S}{\mathrm{d}T}\right|_{T_n}$

Bubble wall velocity: v_w

- Broken-power law spectra $\Omega_{\rm GW}(f)$ from fitting simulations [Huber et al. - 0806.1828, Hindmarsh et al. - 1504.03291, Caprini et al. - 0909.0622]
- Assuming $v_w \simeq 1$: valid for strong transitions

GW Stochastic Background

Parametrising the spectrum

$\xi_h \neq 1$

Nucleation temperature:	T_n	$T_n = \xi_h^{-1} (T_n)_h$
Strength:	$\alpha \equiv \frac{\epsilon}{\rho_{\rm rel}}$	$\alpha = \xi_h^4 \alpha_h$
Inverse time-scale:	$\frac{\beta}{H} \equiv -T_n \left. \frac{\mathrm{d}S}{\mathrm{d}T} \right\|_{T_n}$	$\frac{\beta}{H} = \xi_h^2 \left(\frac{\beta}{H} \right)_h$
Bubble wall velocity:	v_w	

- Broken-power law spectra $\Omega_{\rm GW}(f)$ from fitting simulations [Huber et al. - 0806.1828, Hindmarsh et al. - 1504.03291, Caprini et al. - 0909.0622]
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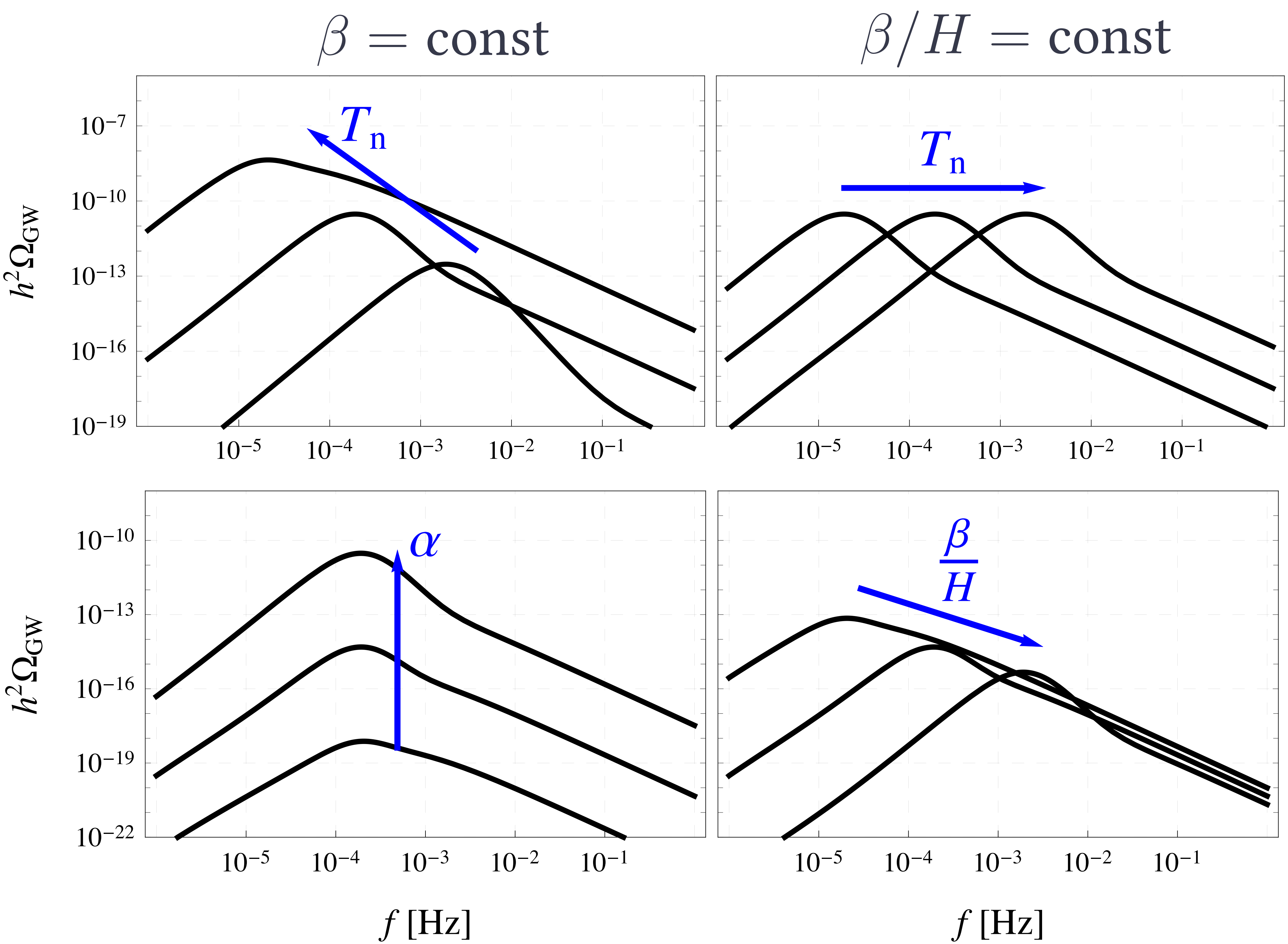
GW Stochastic Background

Scaling behaviour

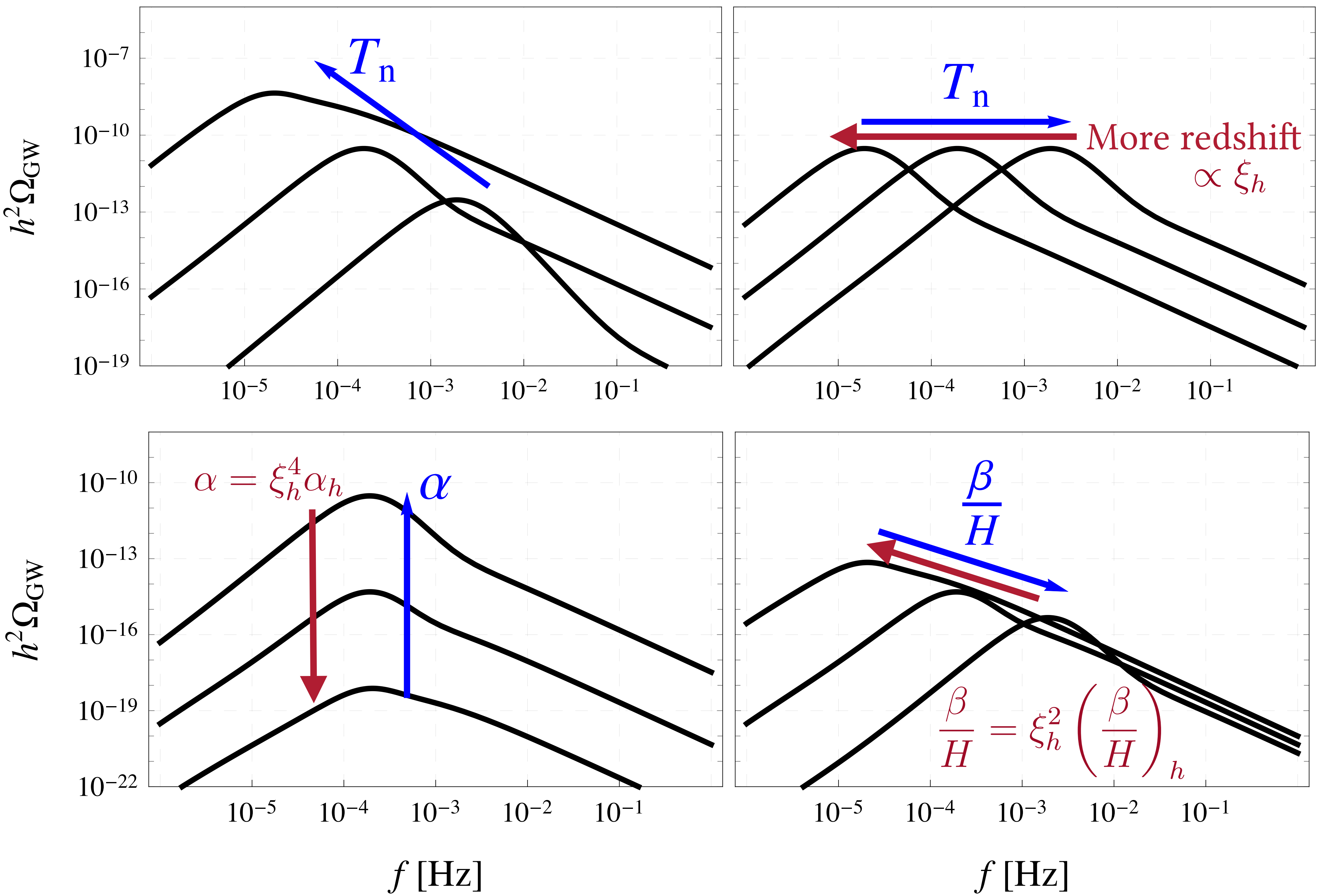


GW Stochastic Background

ξ_h decreasing

Scaling behaviour

$\beta = \text{const}$ | $\beta / H = \text{const}$



Cosmological Constraints

Cosmological Constraints

Thermal history

Non-standard thermal history essential ingredient for MeV/keV scale phase transitions

$$N_{\mathrm{eff}} = \frac{8}{7}\left(\frac{\rho_{\mathrm{R}} - \rho_\gamma}{\rho_\gamma}\right)\left(\frac{T_\gamma^{\mathrm{SM}}}{T_\nu^{\mathrm{SM}}}\right)^4$$

Extra relativistic DOFs until after phase transition

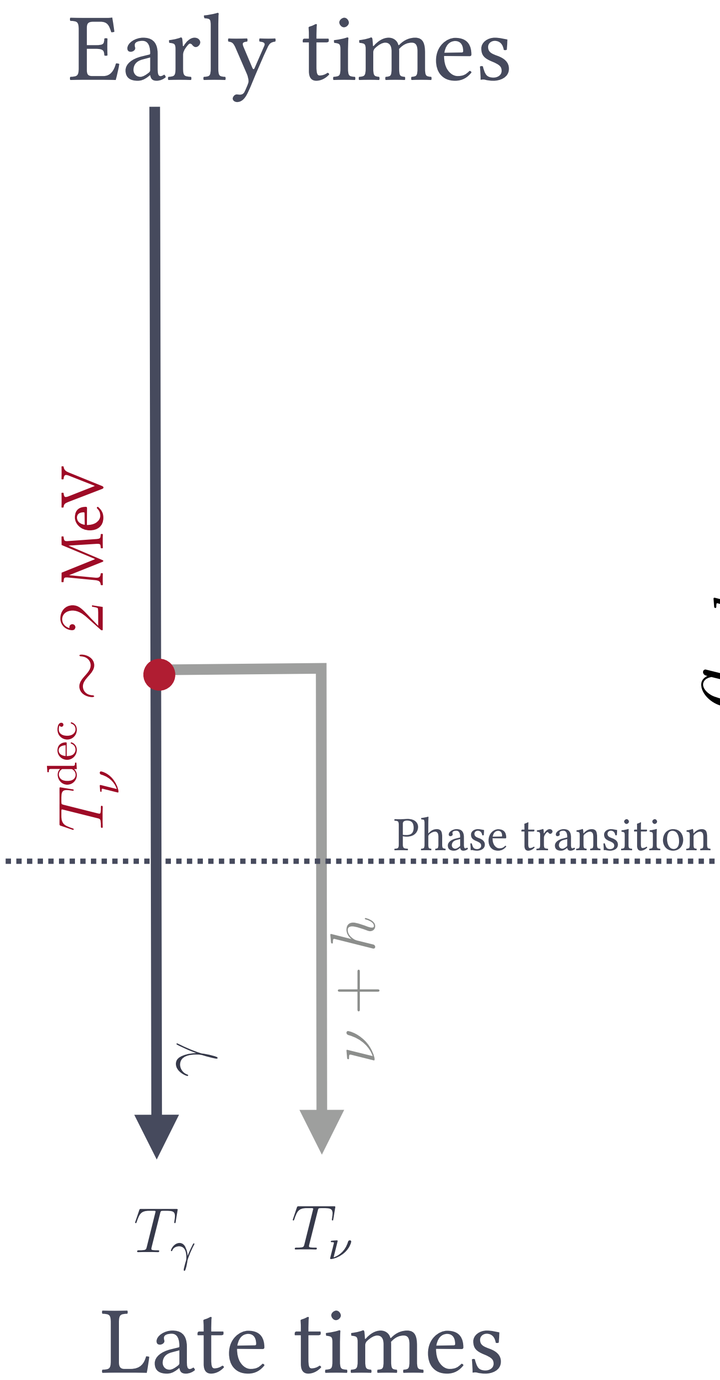
Three possibilities:

- Hidden sector remains coupled to photons or neutrinos
- Hidden sector decouples at early times
- Hidden sector decouples at early times but re-equilibrates with neutrinos below T_ν^{dec}

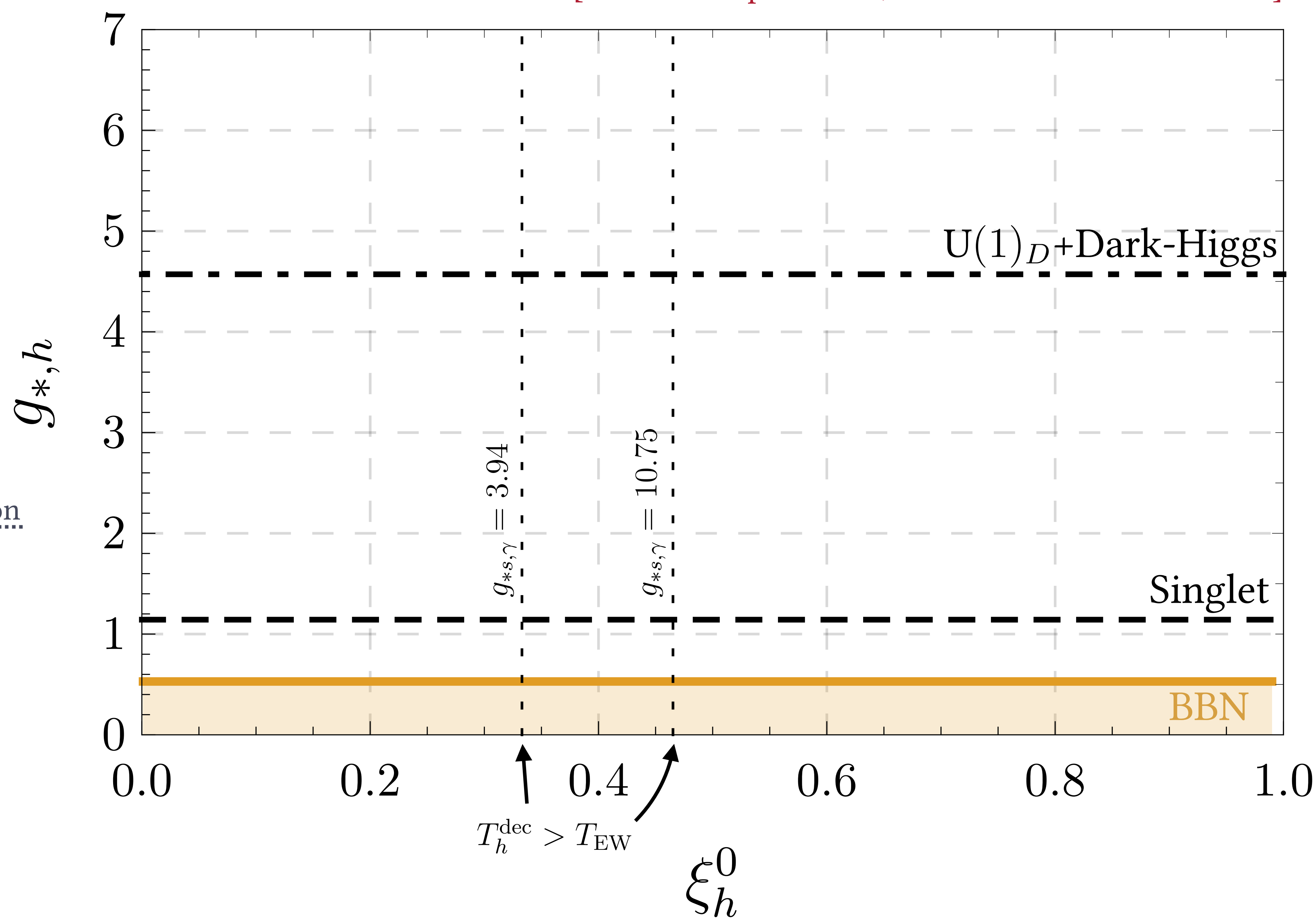
Cosmological Constraints

$N_{\rm eff}$ constraints

Hidden sector thermalised with neutrinos:



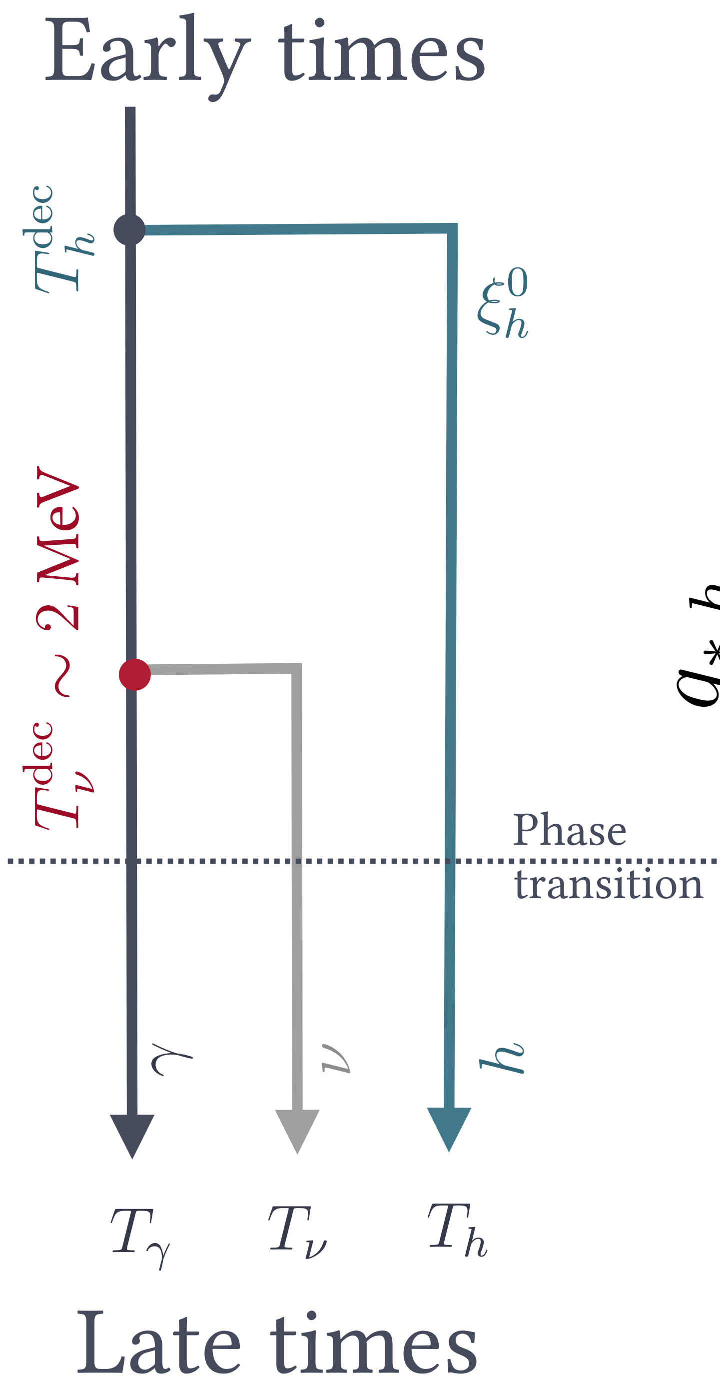
[see for example Bœhm, Dolan & McCabe - 1207.0497]



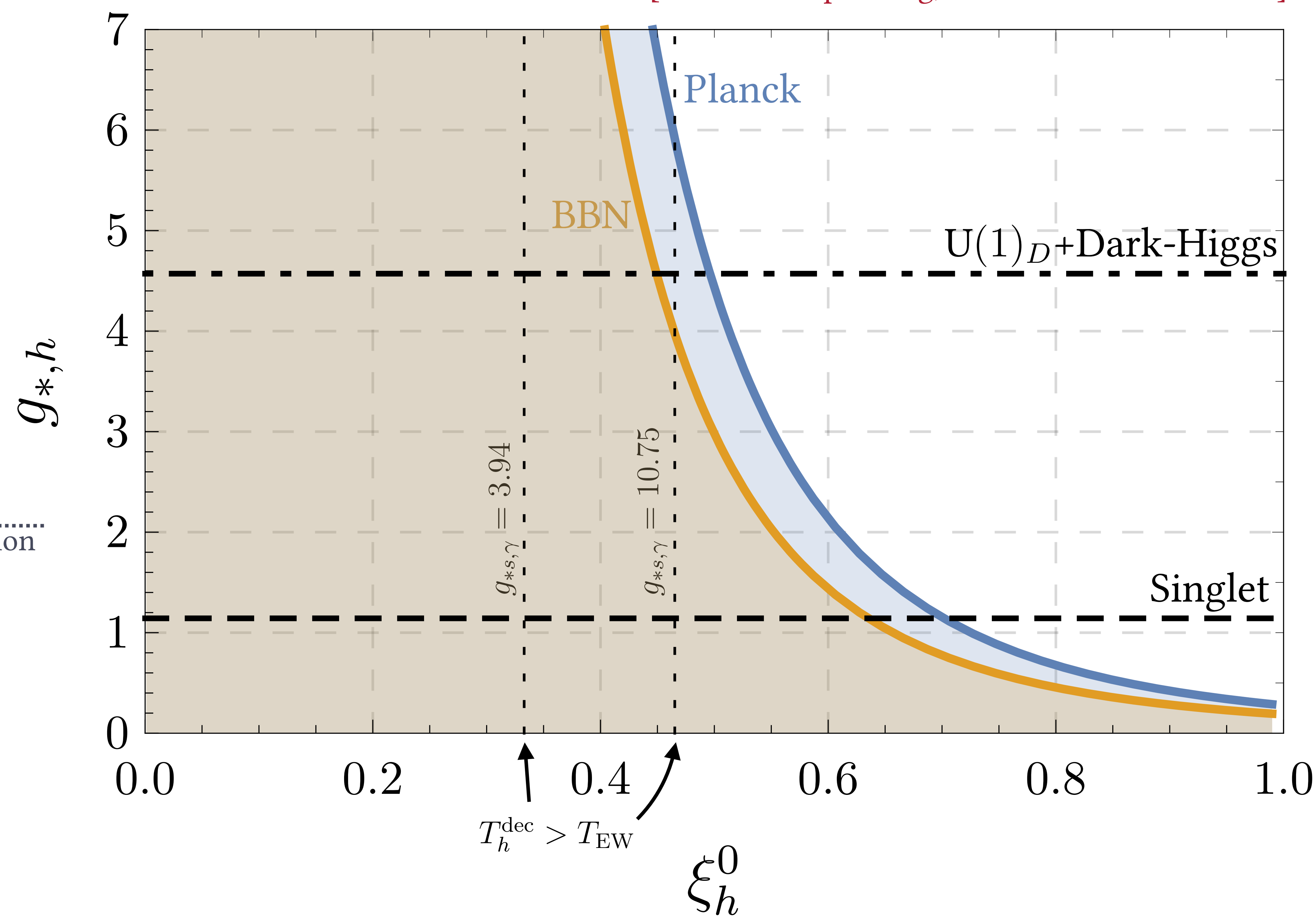
Cosmological Constraints

$N_{\rm eff}$ constraints

Decoupled hidden sector:



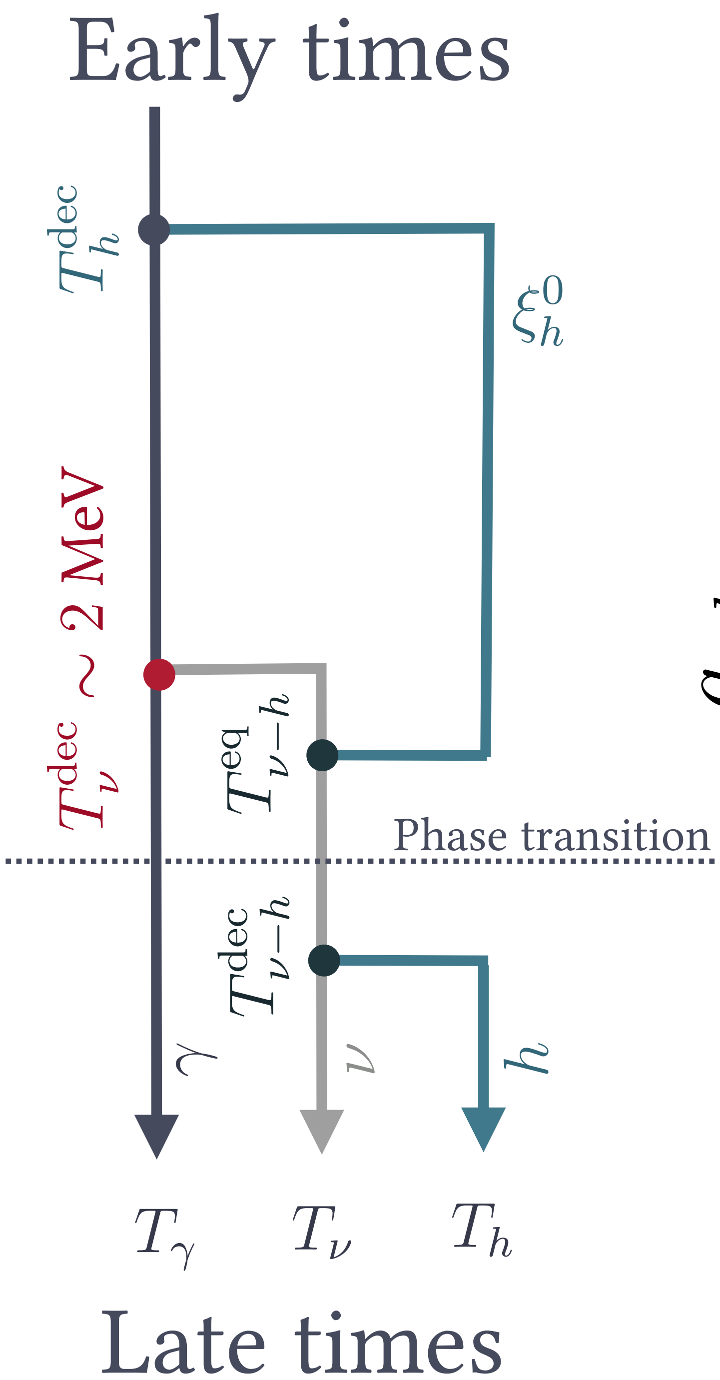
[see for example Feng, H. Tu & H. Yu -0808.2318]



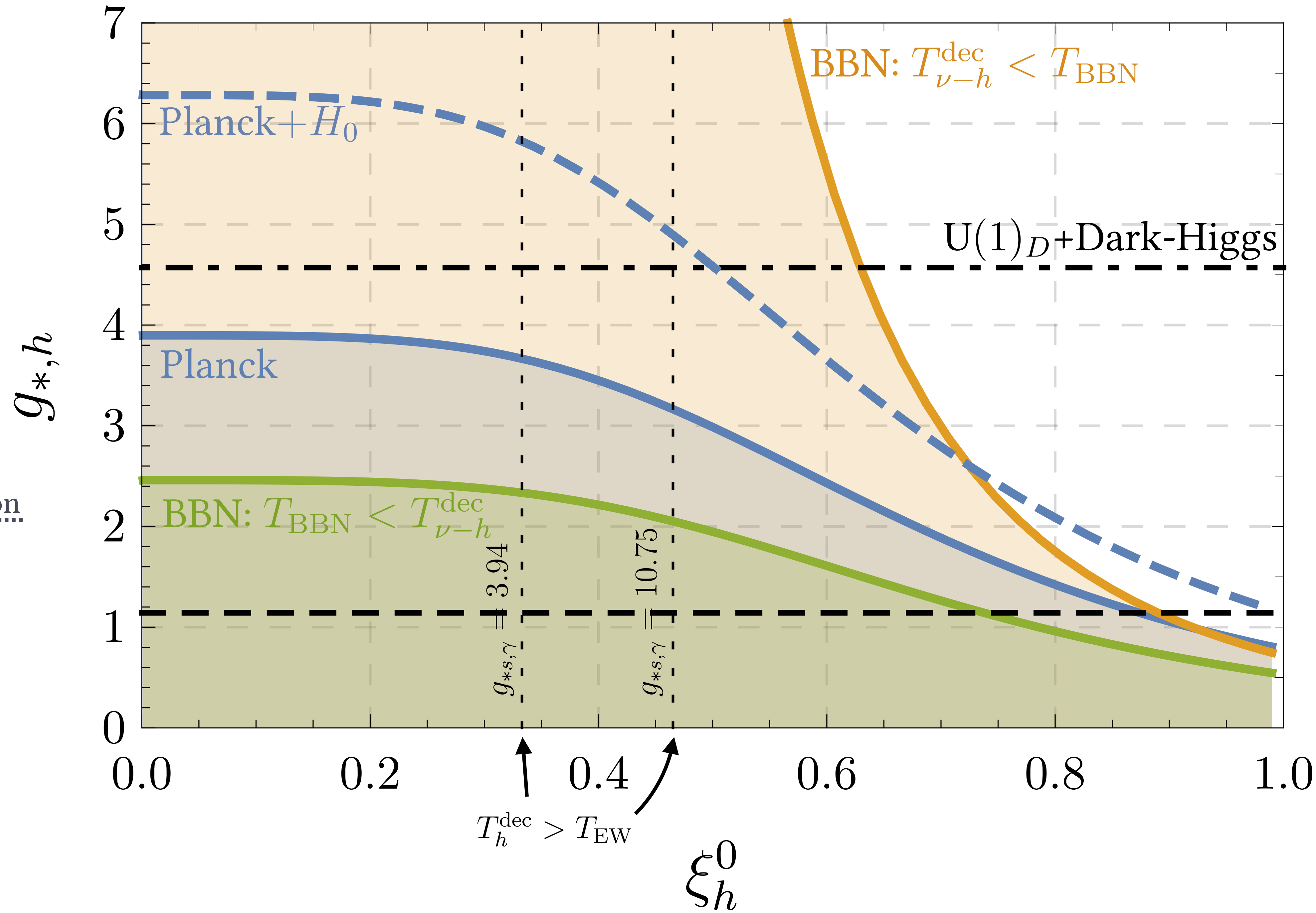
Cosmological Constraints

$N_{\rm eff}$ constraints

Re-equilibration with neutrinos:



[Chacko et al. hep-ph/0312267; Berlin & Blinov 1706.07046]



Cosmological Constraints

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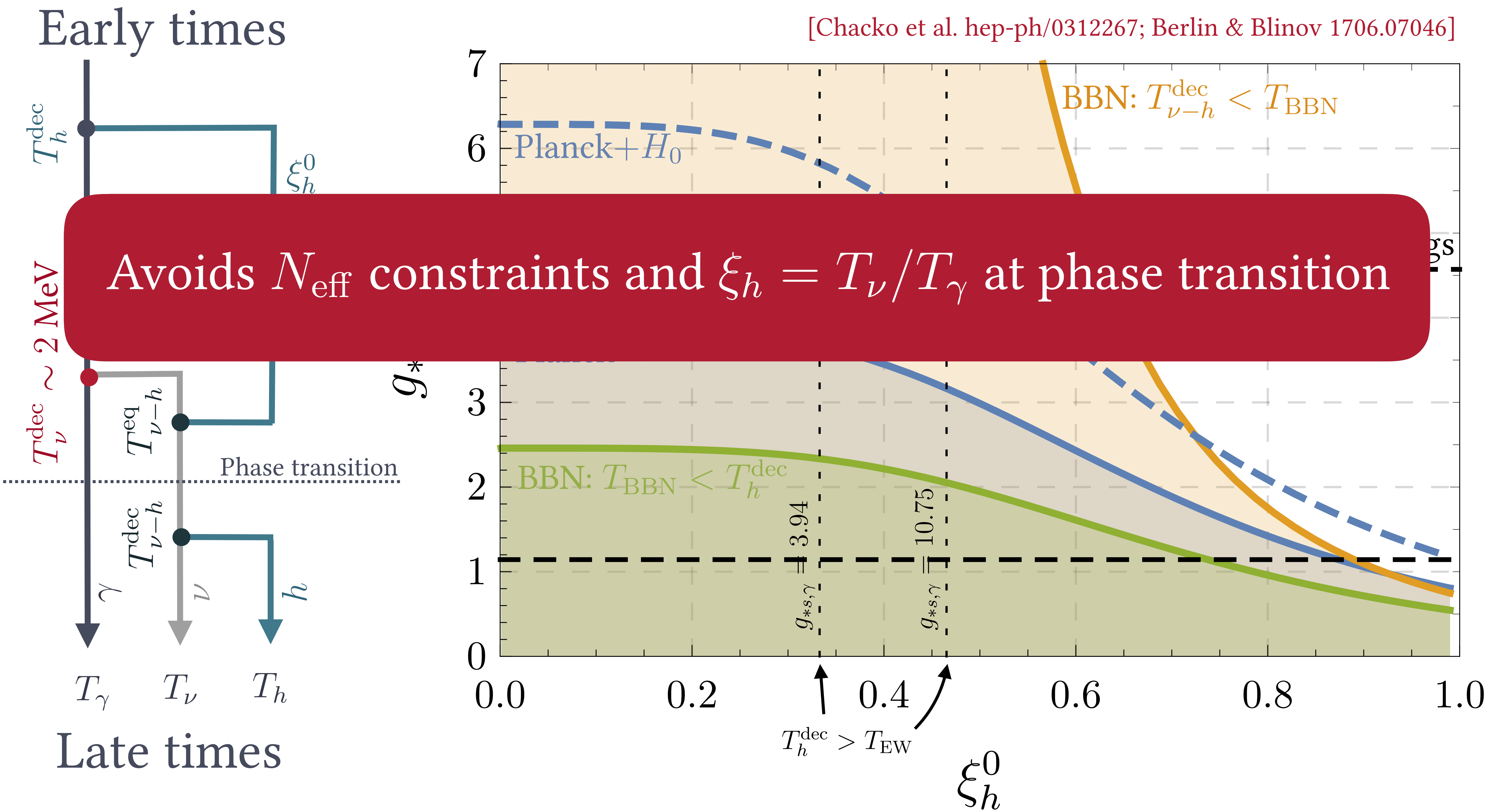
Re-equilibration with neutrinos:

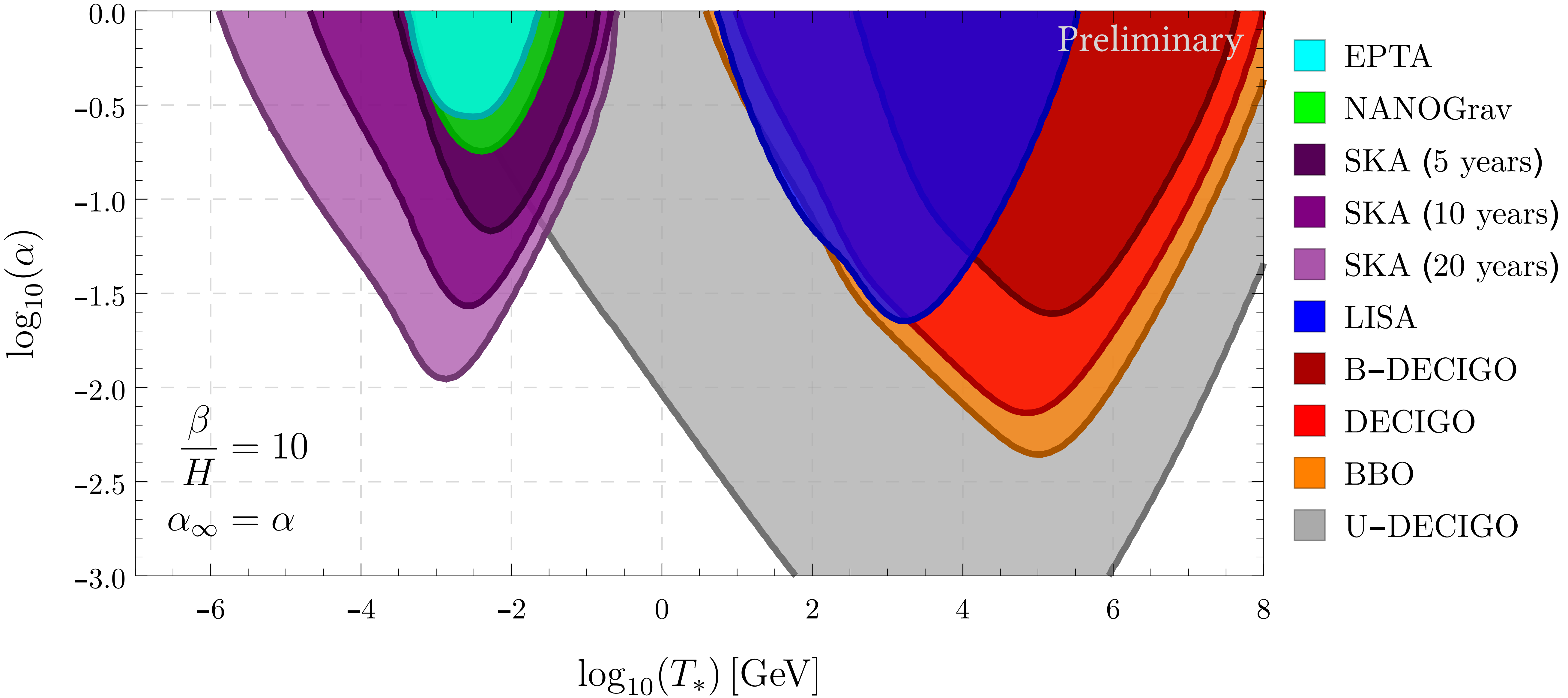


Avoids $N_{\rm eff}$ constraints and $\xi_h = T_\nu/T_\gamma$ at phase transition

Experimental Sensitivity to gravitational wave spectra

Detectability

Non-runaway bubbles



Detectability

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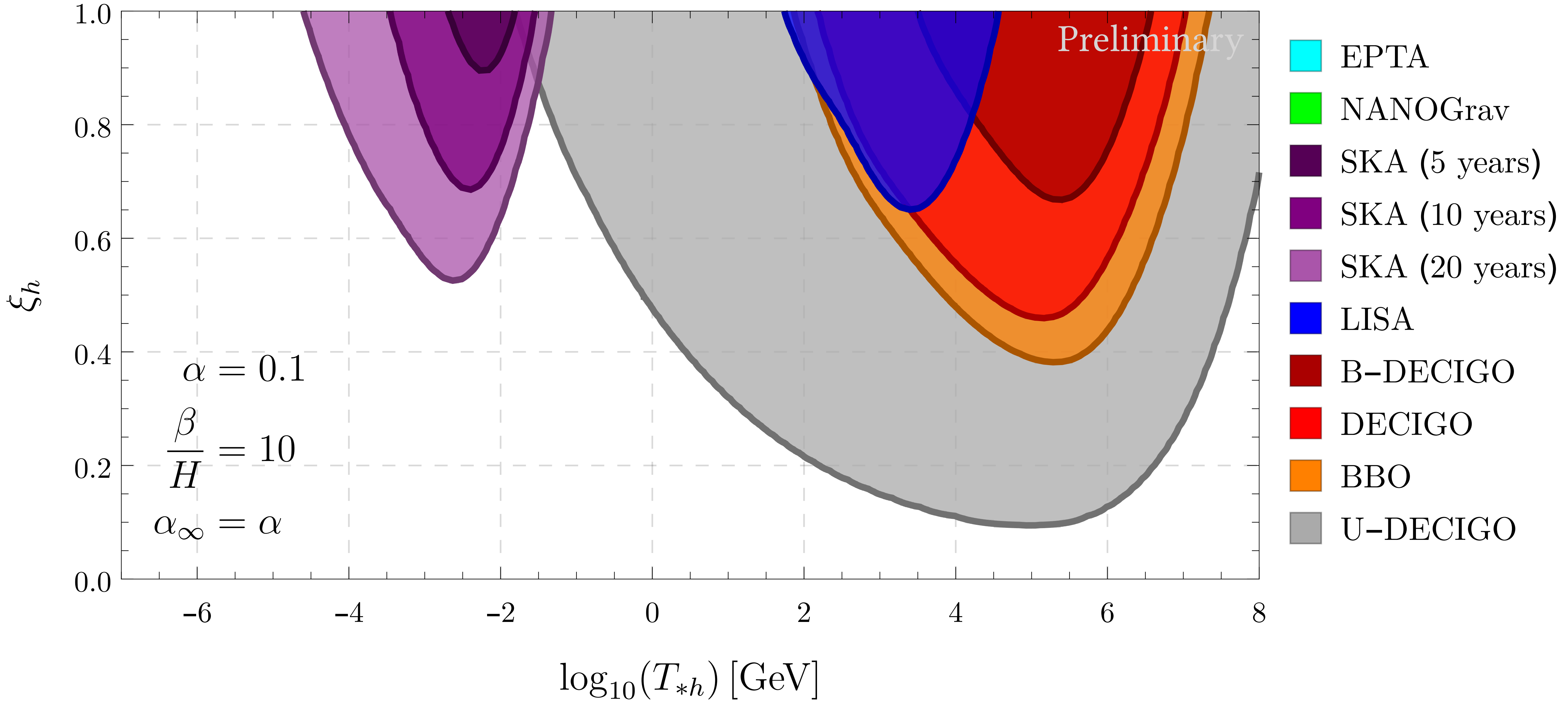

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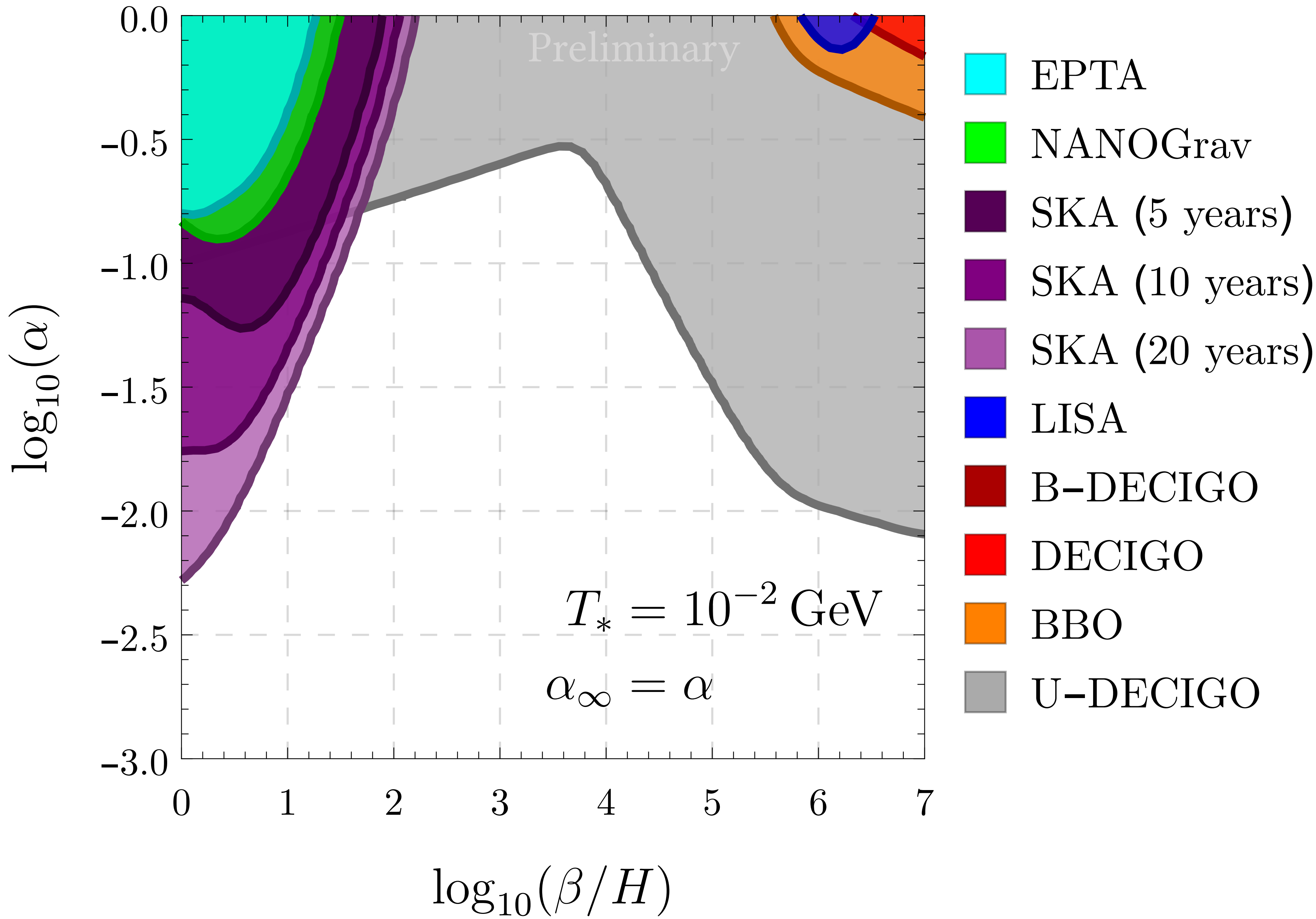

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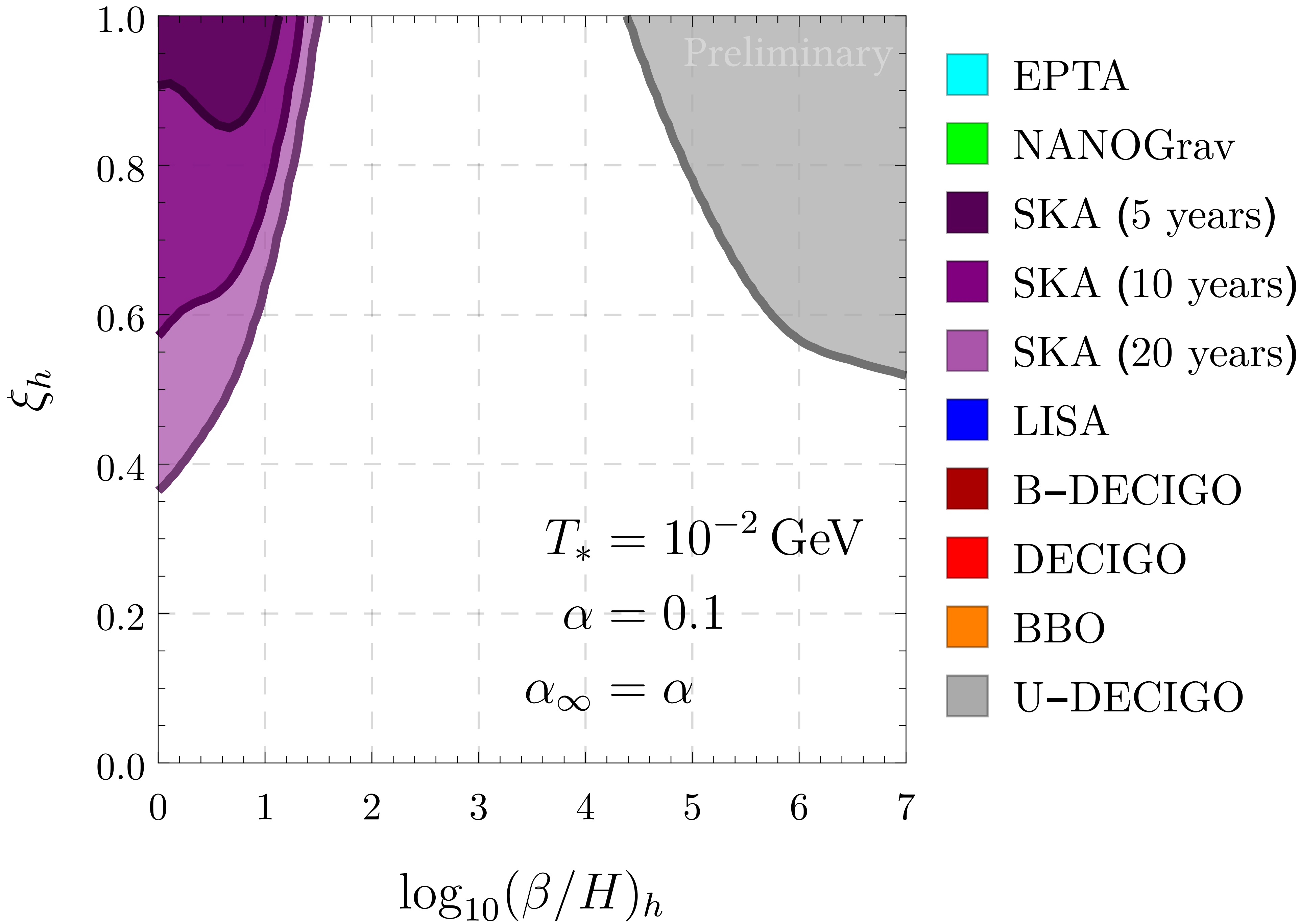
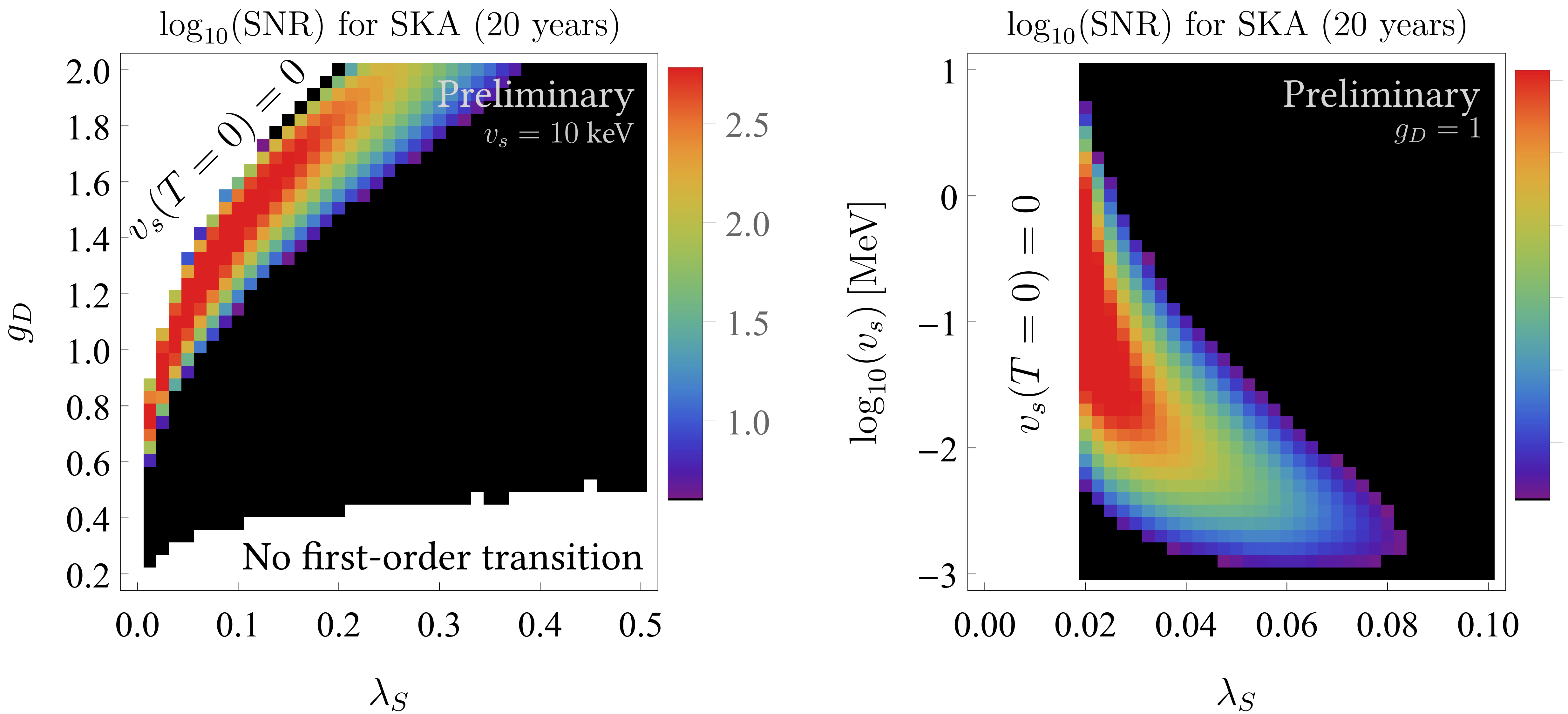


Higgsed Dark-Photon Model

Dark-Photon

First-order phase transition induced by $U(1)_D$ gauge boson

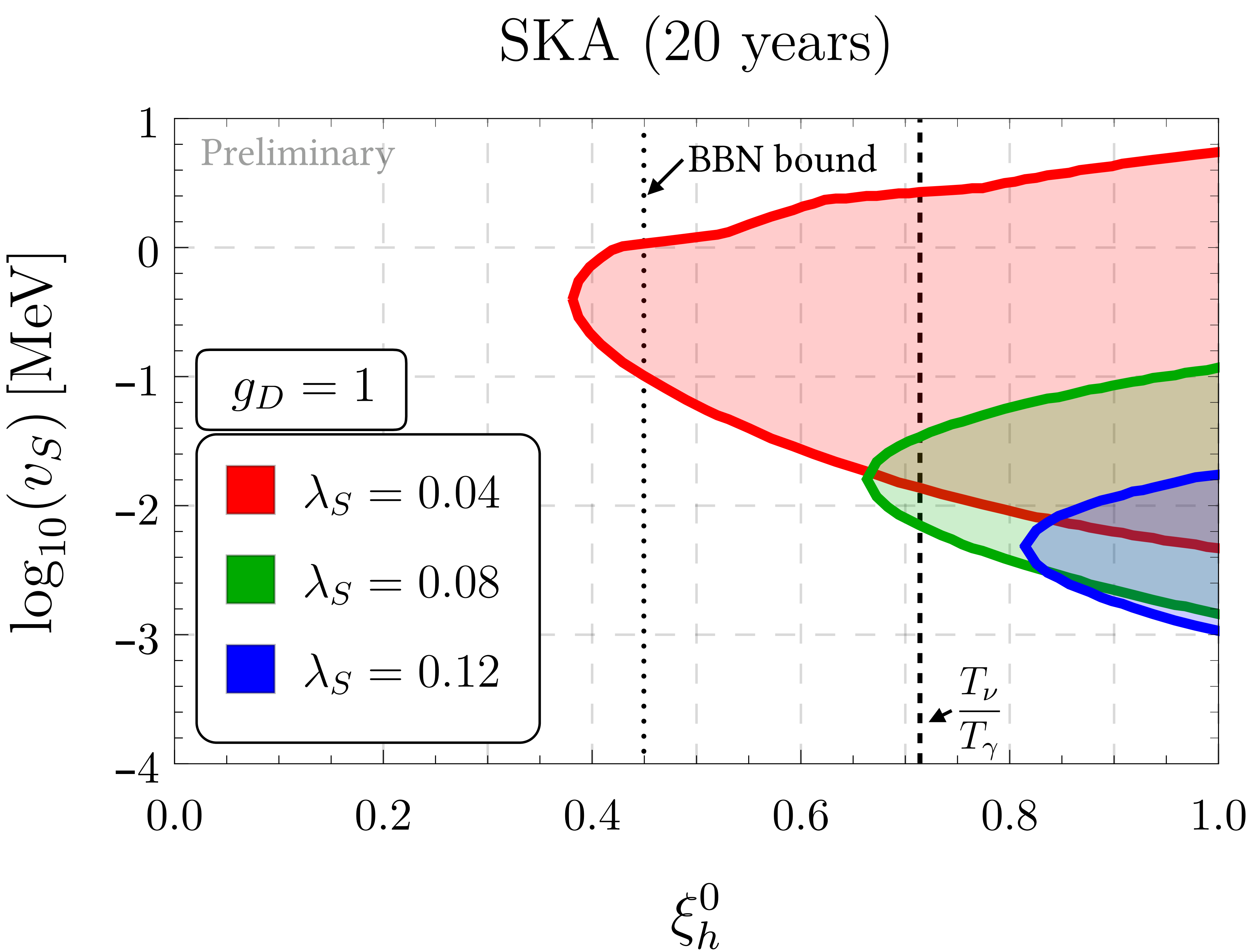
[for space-based experimental sensitivity see Addazi & Marcianò - 1703.03248, Hashino et. al - 1802.02947]



Sensitivity to scenarios where: $m_{A'} > m_{h_D}$

Dark-Photon

Sensitivity



Outlook

This talk

Temperature ratio and thermal history play important roles determining both cosmology constraints and GW signal

Sensitivity to models that are strongly constrained from cosmology

Work in progress

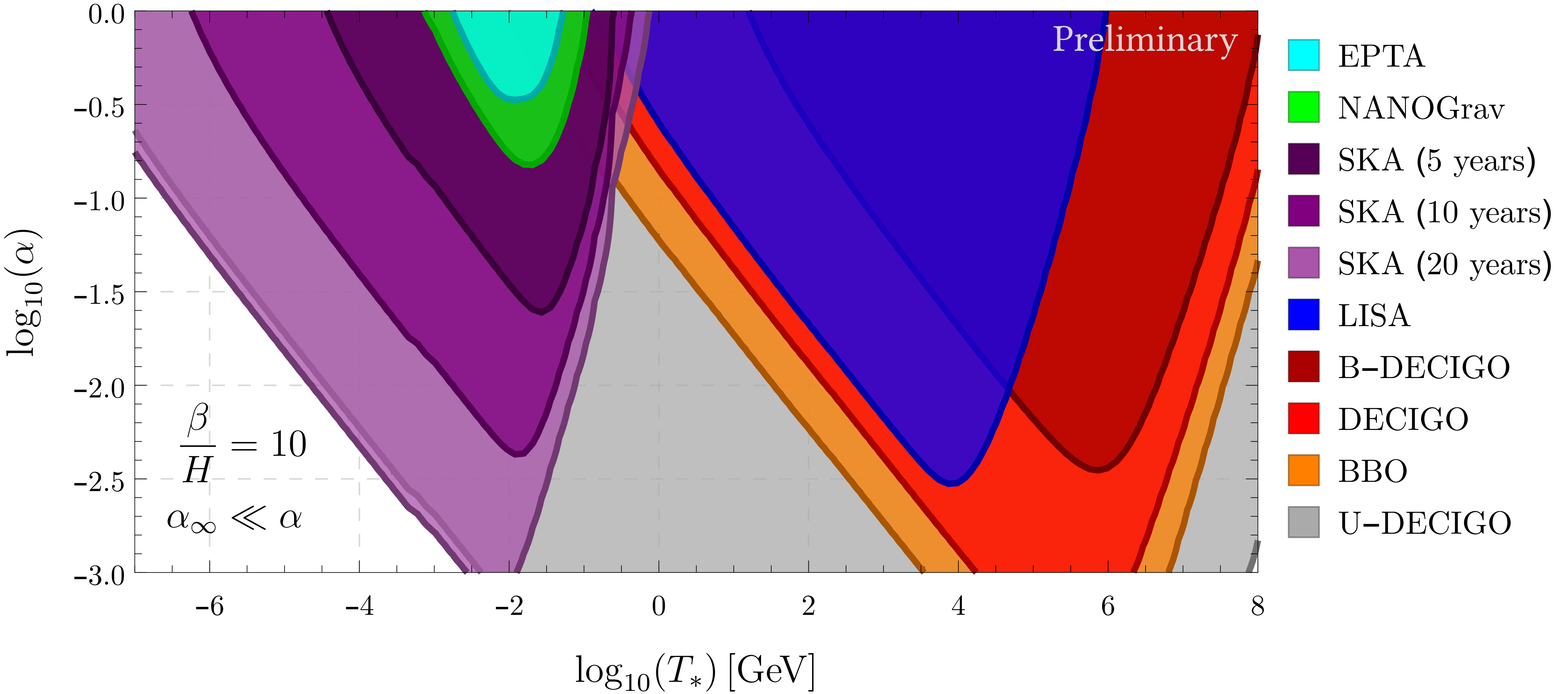
Additional models with fewer DOFs

Automation of GW spectrum calculation through extensions of existing tools

Additional Material

Detectability

Runaway bubbles



Detectability

Runaway bubbles