Gravitational wave signature from a second-order Peccei-Quinn phase transition

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in collaboration with...

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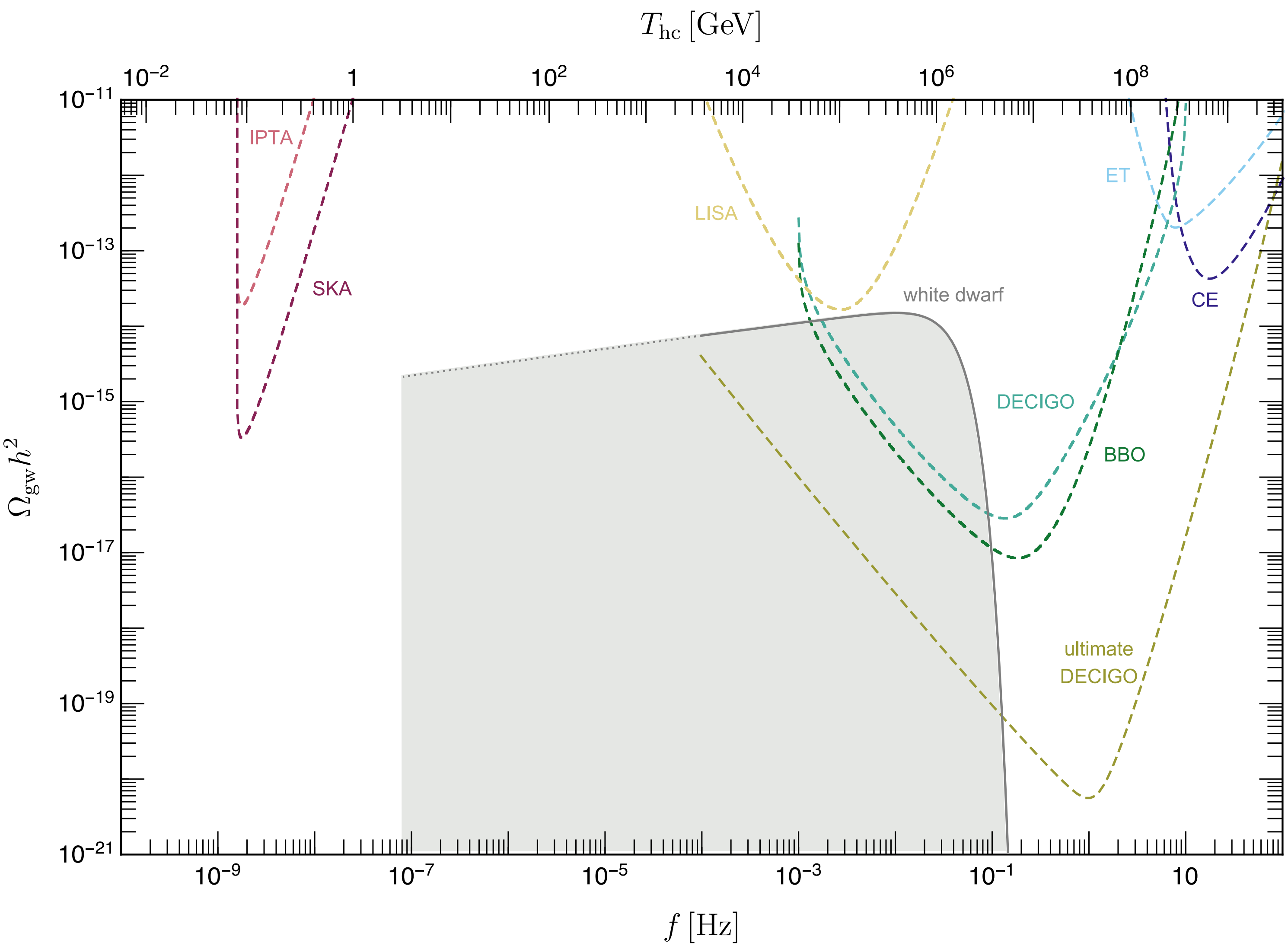
The experimental context



The aim:

Obtain experimental predictions for features in the spectrum of **primordial gravitational** waves in the **SMASH** model associated with the **2nd-order PQ transition**

The novelty:

Focus on 2^{nd}-order BSM transition, rather than 1^{st} order.

Improved formalism for following g_* during the phase transition

Our predictions set a **target** for the **DECIGO** experiment

The plan:

SMASH theory and its motivation

Primordial gravitational waves: from inflation until today

Calculation of g_*

Current spectrum of gravitational waves

SMASH model and its motivation

Current paradigm and open questions

Paradigm from cosmological data: **ΛCDM** model with an early period of **inflation**:

SM + dark matter + cosmological constant + inflationary sector.

Open questions addressed in SMASH [Ballesteros, Redondo, Ringwald, CT]

mechanism of inflation	**Smallness of nu masses**
dark matter	**Strong CP problem**
baryogenesis	
Higgs stability	

All those problems… all those solutions

Inflation	Scalar inflaton
Higgs stability	Scalar interactions
Small neutrino masses	Seesaw models, radiative mass generation
CP problem*	Axion, Nelson-Barr
Dark matter	WIMP, sterile neutrinos, axion
Baryogenesis	Electroweak baryogenesis, leptogenesis, Affleck-Dine…

*See however arXiv:2001.07152 [hep-th]

S.M.A.S.H

Minimal SM extension providing a **consistent, predictive picture** of:

Particle physics from the electroweak to the Planck scale

Cosmology from inflation to today

Highlights:

Single new scale, playing a role in stability, the CP problem, neutrino masses, dark matter, and baryogenesis

Predictive inflation free from unitarity concerns

Detailed understanding of **parameter space** yielding **stability**

Detailed understanding of **reheating** and **post-inflationary history**

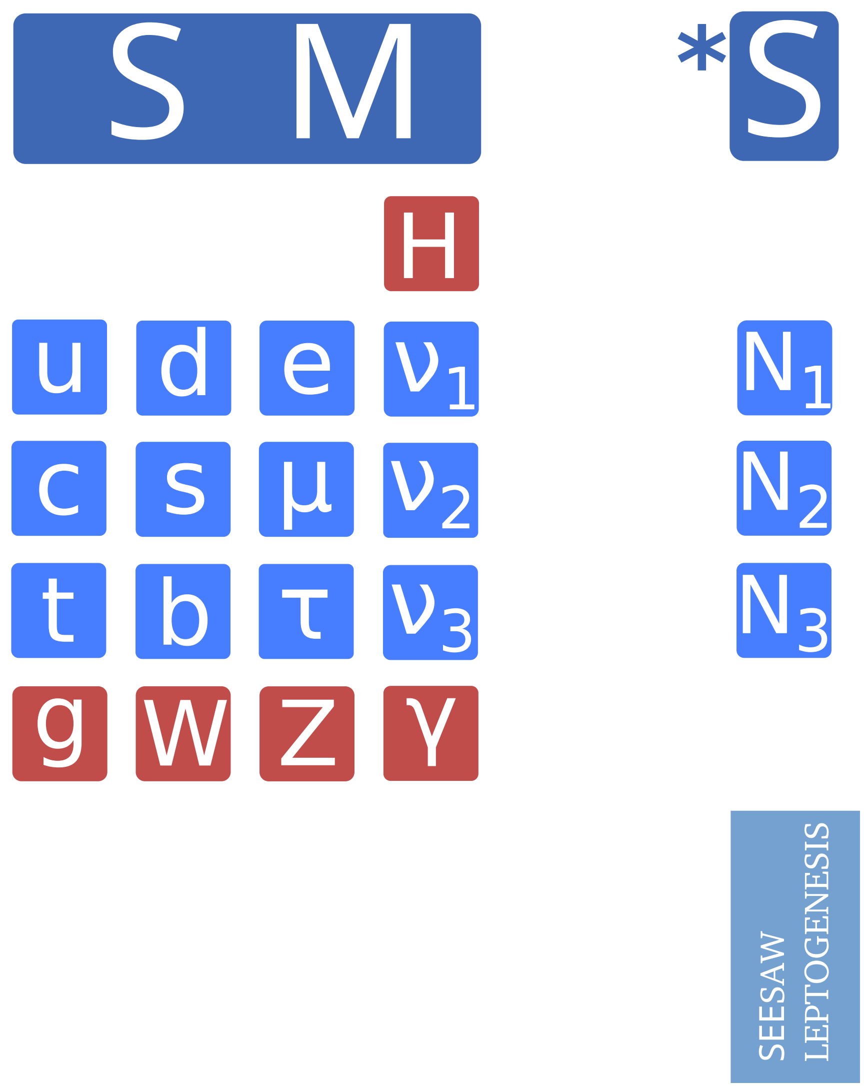
Accurate **predictions** for **cosmological parameters** and the **axion mass** in reach of future experiments

Building up SMASH

6 problems addressed with 3 new types of particles.

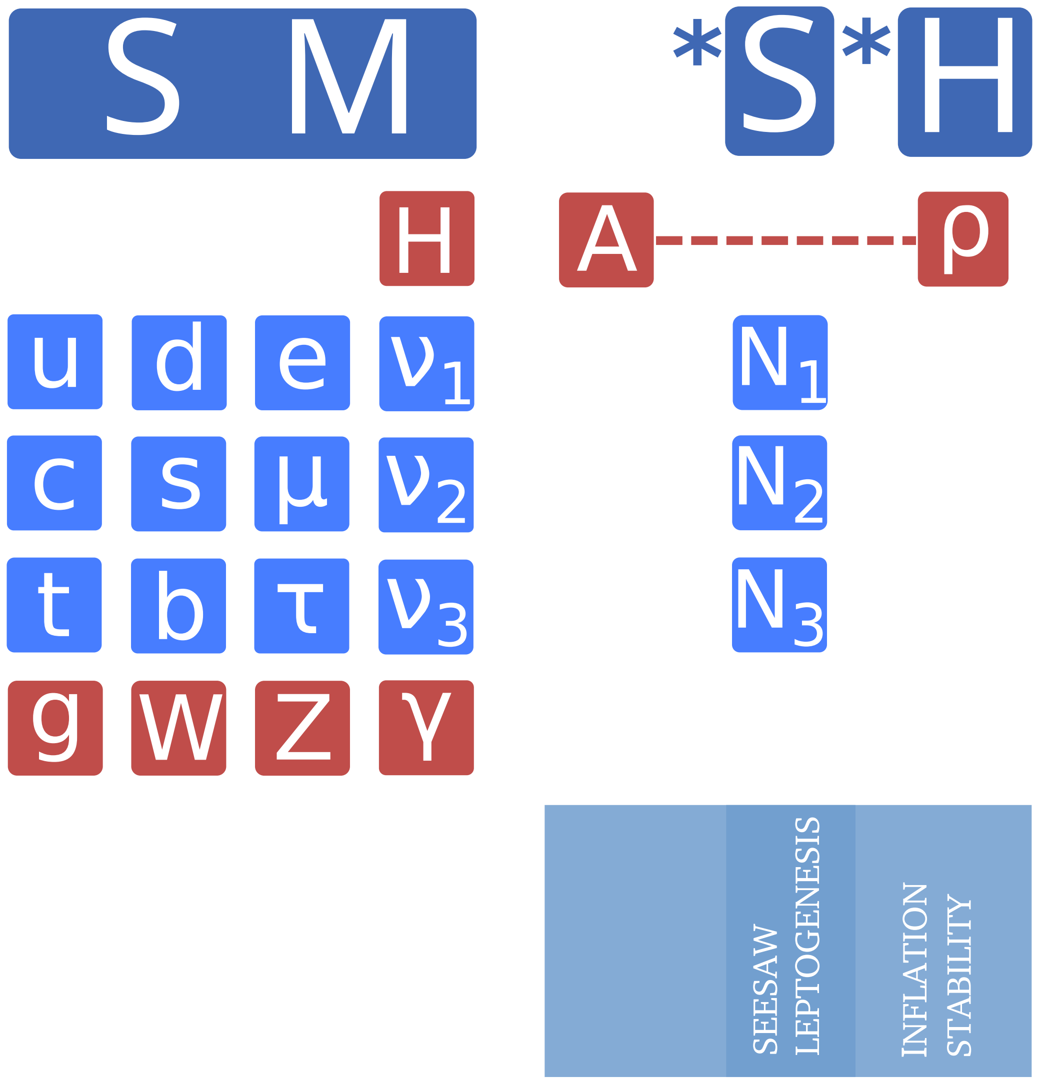
Building up SMASH

Start with right handed neutrinos, addressing ν masses and baryogenesis.



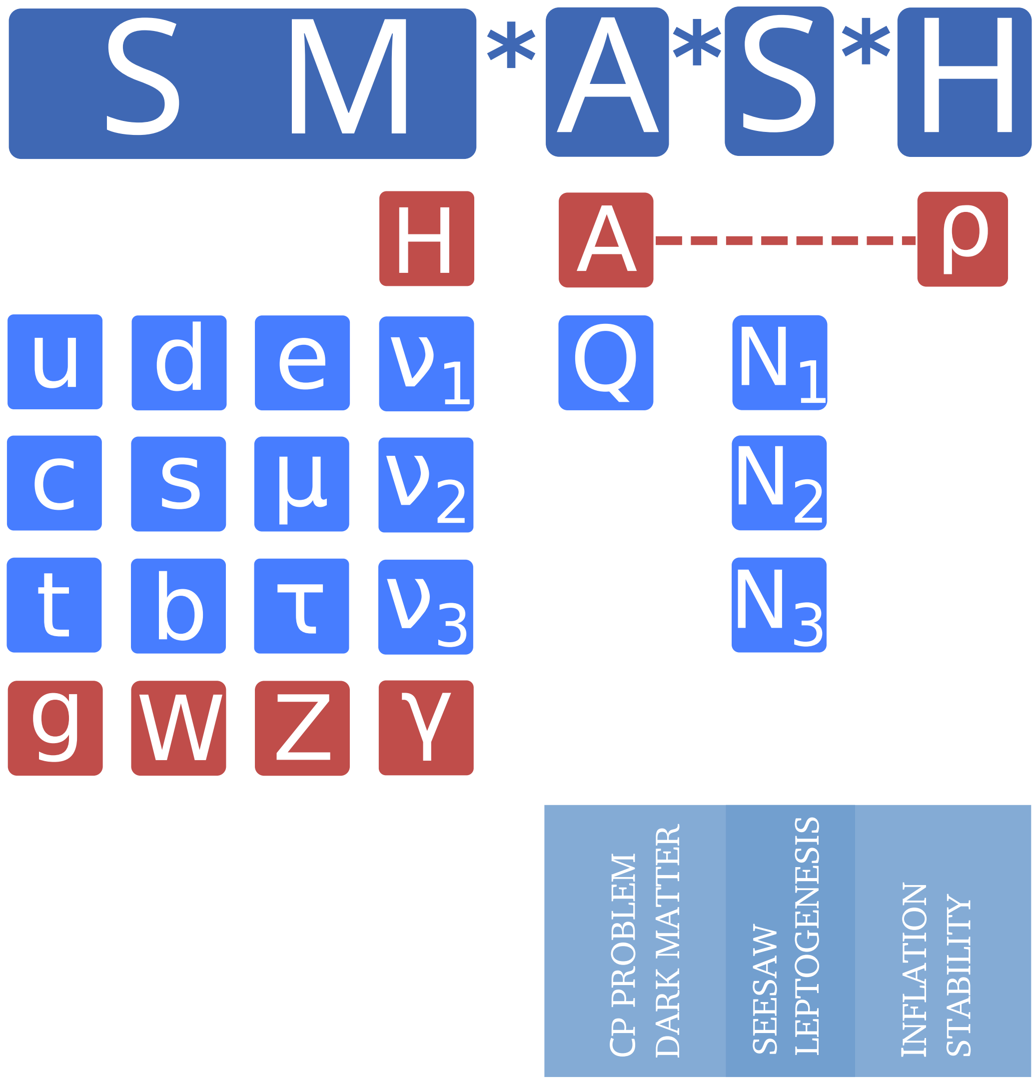
Building up SMASH

Add a new scalar σ to provide inflation. As a bonus, it can stabilize the Higgs, more so if it gets a VEV! (threshold mechanism [Lebedev, Elias-Miró et al])



Building up SMASH

Singlet scalar with VEV can implement the KSVZ axion solution to the CP problem.
Need a Dirac fermion in the fundamental of SU(3). Bonus: axion can be dark matter!



SMASH recap

$$\mathcal{L} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm yuk}^{SM}$$

$$-\left[\frac{M^2}{2} + \xi_H\, H^\dagger H + \xi_\sigma\, |\sigma|^2\right] R$$

$$-\lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2 - 2\lambda_{H\sigma}\left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)$$

STABILITY

$$-\lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 - [y\sigma\tilde{Q}Q + y_{Q_{d_i}}\sigma Q d_i + c.c]$$

CP, DARK MATTER

INFLATION

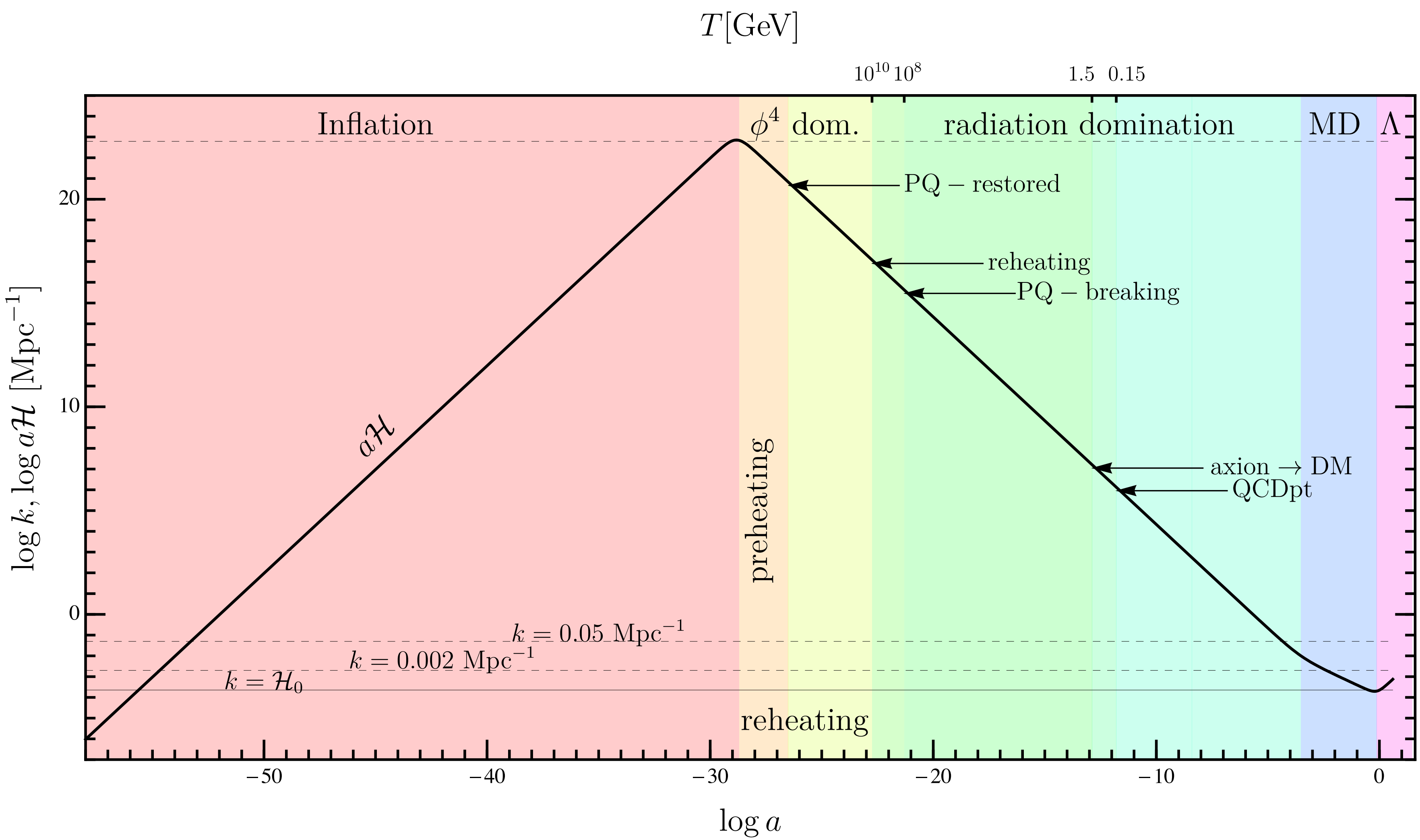
$$-[F_{ij}L_i\epsilon H N_j + \frac{1}{2}Y_{ij}\sigma N_i N_j + c.c.]$$

SEESAW AND LEPTOGENESIS

Most general, renormalizable Lagrangian compatible with the following global PQ symmetry:

q	u	d	L	N	E	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

SMASHy history of the Universe



Preferred parameter choices

From **inflation** and **unitarity:**

$$5 \times 10^{-13} \lesssim \lambda_\sigma \lesssim 5 \times 10^{-10}$$

From **Higgs stability:**

$$\lambda_{H\sigma} \sim 0.3\sqrt{\lambda\sigma}$$

From **stability** of **σ:**

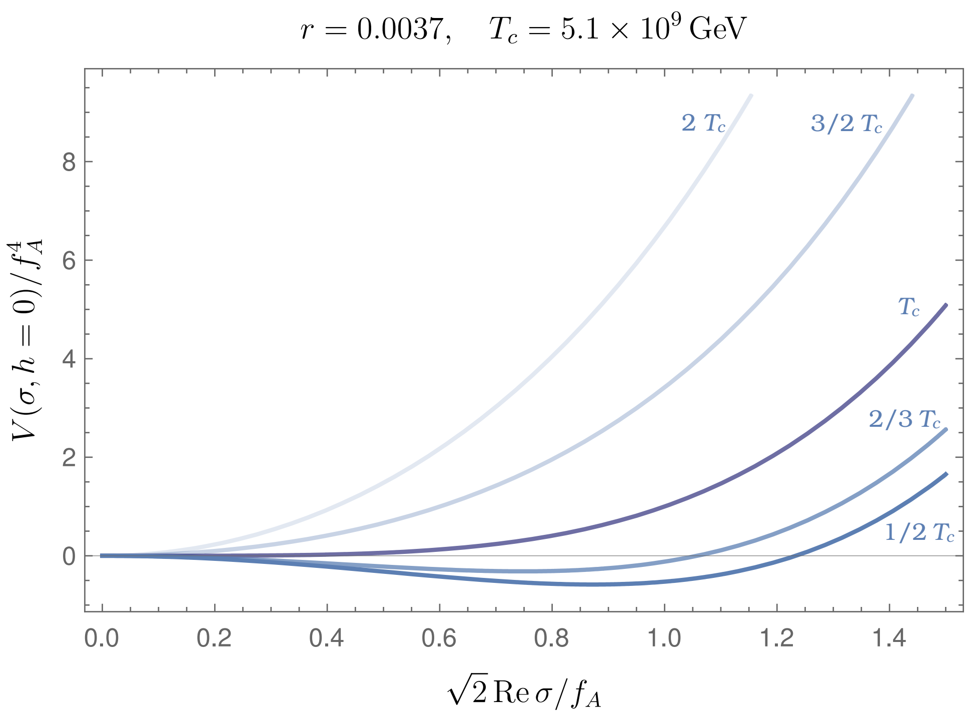
$$Y_{ij}, y \lesssim \sqrt{\lambda_\sigma}$$

PQ phase transition in SMASH

PQ phase transition predicted around a **particular window of temperatures**

$$T_c \simeq \frac{2\sqrt{6\lambda_\sigma} v_\sigma}{\sqrt{8(\lambda_\sigma + \lambda_{H\sigma}) + \sum_i Y_{ii}^2 + 6y^2}} \sim \lambda_\sigma^{1/4} v_\sigma \sim \mathcal{O}(10^6 - 10^9)\,\text{GeV}$$

Phase transition is **second order**



Gravitational waves from inflation

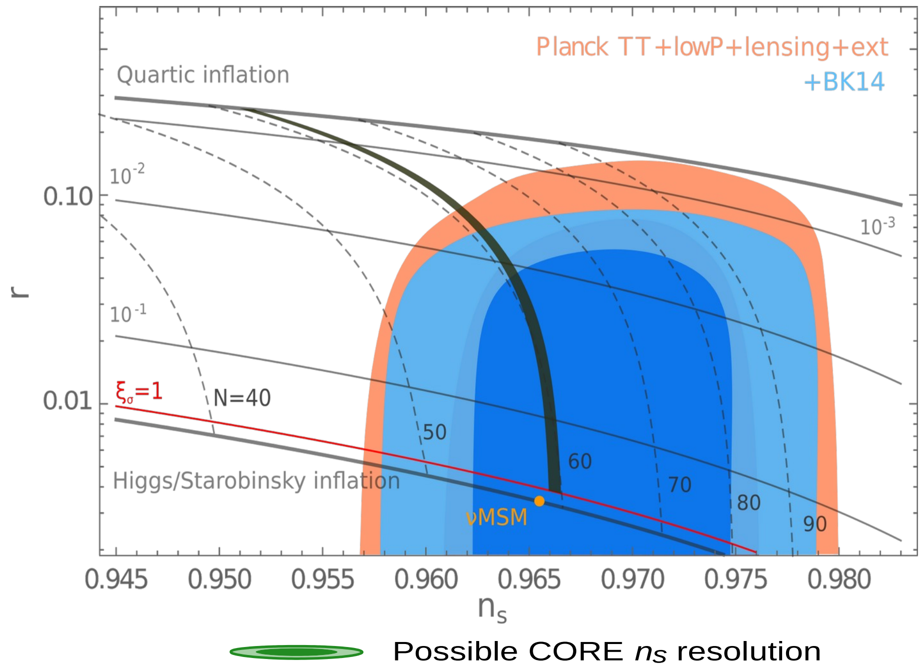
$$ds^2 \supset -dt^2 + a^2(t)(\delta_{ij} - 2\mathcal{R} + h_{ij})dx^i dx^j,$$

$$\langle \mathcal{R}(t,\vec{x})\mathcal{R}(t,\vec{x}')\rangle = \int \frac{dk}{k}\,\Delta^2_{\mathcal{R},k} \qquad \Delta^2_{\mathcal{R},k,\mathrm{prim}} \approx A_s(k_*)\left(\frac{k}{k_*}\right)^{n_s(k_*)-1}$$

spectral index

$$\sum_{ij}\langle h_{ij}(t,\vec{x})\,h_{ij}(t,\vec{x}))\rangle = \int \frac{dk}{k}\,\Delta^2_{T,k}(t) \qquad \Delta^2_{T,k,\mathrm{prim}} \approx r A_s(k_\star)\left(\frac{k}{k_*}\right)^{-r/8}$$

tensor-to-scalar ratio
current bound $r < 0.058$



Gravitational waves from the PQ transition?

Second-order phase **transition** proceeds adiabatically, **without** further **breaking** of spatial **homogeneity**

Sourcing gravitational waves requires spatial anisotropies (quadrupole contributions to energy-momentum tensor)

Thus the **PQ phase transition** does not source new gravitational waves, but it **affects the propagation of primordial waves** generated during inflation

This is in contrast to first-order phase transitions proceeding through bubble nucleation and sourcing gravitational waves

Primordial gravitational waves:
from inflation until today

Thermodynamics during radiation domination

Energy density and **entropy** during **radiation domination:**

$$\rho = \left.\frac{\partial U}{\partial V}\right|_T \equiv \frac{\pi^2}{30} g_{*\rho} T^4 \qquad s = \left.\frac{\partial S}{\partial V}\right|_T \equiv \frac{2\pi^2}{45} g_{*s} T^3$$

Both **related to pressure** from thermodynamical identities

$$s = \frac{\partial p}{\partial T} \qquad dU = TdS - pdV \Rightarrow \rho = Ts - p = T\frac{\partial p}{\partial T} - p$$

Free-energy density ⟷ **finite T effective potential** ⟷ **pressure**

$$A = U - TS \Rightarrow \left.\frac{\partial A}{\partial V}\right|_T = V_{\text{eff,min}}(T, \bar{\phi}_i) - V_{\text{eff}}(0, \bar{\phi}_i) \equiv \Delta V(T) = -p$$

$$g_{*\rho} = \frac{30}{\pi^2 T^4}\left(\Delta V(T) - T\frac{\partial \Delta V(T)}{\partial T}\right),$$

$$g_{*s} = -\frac{45}{2\pi^2 T^3}\frac{\partial \Delta V(T)}{\partial T}.$$

Can be computed directly from finite T effective potential!

Metric perturbations and power spectrum

$$ds^2 \supset -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j,$$
$$h^i_i = 0$$
$$\partial^i h_{ij} = 0$$

$$h_{ij}(t, \mathbf{x}) = \sum_{\lambda=+,\times} \int \frac{d^3k}{(2\pi)^3} (h^\lambda_{\mathbf{k}}(t) \epsilon^\lambda_{ij}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}} \mathbf{a}^\lambda_{\mathbf{k}} + h^{\lambda *}_{\mathbf{k}}(t) \epsilon^{\lambda *}_{ij}(\mathbf{k}) e^{-i\mathbf{k}\cdot\mathbf{x}} \mathbf{a}^{\lambda\dagger}_{\mathbf{k}}),$$

$$\sum_{ij} \epsilon^\lambda_{ij} \epsilon^{*\,\lambda'}_{ij} = 2\delta^{\lambda\lambda'}$$

$$[\mathbf{a}^\lambda_{\mathbf{k}}, \mathbf{a}^{\lambda'}_{\mathbf{k}}] = (2\pi)^3 \delta^{\lambda\lambda'} \delta^3(\mathbf{k} - \mathbf{k}')$$

$$\sum_{ij} \langle h_{ij}(t, \vec{x})\, h_{ij}(t, \vec{x}))\rangle = \sum_\lambda \int \frac{dk}{\pi^2} k^2 |h^\lambda_{\mathbf{k}}(t)|^2 \equiv \int \frac{dk}{k} \Delta^2_{T,k}(t)$$

Qualitative behaviour of modes

$$\ddot{h}_{\mathbf{k}}^{\lambda} + 3H\dot{h}_{\mathbf{k}}^{\lambda} + \frac{k^2}{a^2}h_{\mathbf{k}}^{\lambda} = 16\pi G\Pi_{\mathbf{k}}^{\lambda}$$

Source is zero for perfect fluid

Superhorizon:

$$\ddot{h}_{\mathbf{k}}^{\lambda} + 3H\dot{h}_{\mathbf{k}}^{\lambda} = 0 \Rightarrow h_{\mathbf{k}}^{\lambda} = \text{constant} \equiv h_{\mathbf{k},\text{prim}}^{\lambda}$$

Modes frozen between horizon crossing in inflation and horizon reentry RD

Subhorizon during radiation domination:

$$\ddot{h}_{\mathbf{k}}^{\lambda} + \frac{k^2}{a^2}h_{\mathbf{k}}^{\lambda} = 0 \Rightarrow h_{\mathbf{k}}^{\lambda} \propto \frac{e^{ik\sqrt{t}}}{a}$$

$$h_{\mathbf{k}}(t) \equiv h_{\mathbf{k},\text{prim}}\chi_k \approx h_{\mathbf{k},\text{prim}}e^{ik(\tau-\tau_{\text{hc}})}\frac{a(t_{\text{hc}})}{a(t)}$$

To leading order, power spectrum at late times simply obtained by redshifting inflationary power spectrum

From power spectrum to energy density

$$\rho_{\rm gw} = \frac{M_P^2}{4}\langle \dot h_{ij}(t,\mathbf{x})\,\dot h_{ij}(t,\mathbf{x})\rangle$$

$$\rho_{\rm crit} = 3H^2M_P^2$$

$$\Omega_{\rm gw} = \frac{\rho_{\rm gw}}{\rho_{\rm crit}} \equiv \int \frac{dk}{k}\Omega_{\rm gw}(k)$$

$$\Omega_{\rm gw}(k) = \frac{1}{12H^2}\frac{k^3}{\pi^2}\sum_\lambda |\dot h_{\mathbf{k}}(t)|^2 = \frac{1}{12H^2a^2}\,\Delta^2_{T,k,\rm prim}|\chi'_{\mathbf{k}}(t)|^2 \approx \frac{1}{24}\,\Delta^2_{T,k,\rm prim}\,\frac{a^4(\tau_{\rm hc})H^2(\tau_{\rm hc})}{a^4(\tau)H^2(\tau)}$$

$$' \equiv \frac{d}{d\tau} = a\frac{d}{dt}$$

$$h_{\mathbf{k}} = h_{\mathbf{k},\rm prim}\chi_{\mathbf{k}}$$

$$\chi_{\mathbf{k}} \approx e^{ik(\tau-\tau_{\rm hc})}\frac{a(\tau_{\rm hc})}{a(\tau)}$$

$$k \equiv a(\tau_{\rm hc})H(\tau_{\rm hc}) \gg aH$$

$$H^2 = \frac{\rho}{3M_P^2}$$

$$S \propto sa(\tau)^3 \propto g_{*s}T^3a^3 = \text{const}$$

$$\rho = \frac{\pi^2}{30}\,g_{*\rho}T^4$$

$$\Omega_{\rm gw}(k) \approx \frac{1}{24}\,\Delta^2_{T,k,\rm prim}\Omega_\gamma\left(\frac{g_{*\rho,\rm hc}}{2}\right)\left(\frac{g_{*s,\rm hc}}{g_{*s,0}}\right)^{-4/3}$$

From power spectrum to energy density

$$\Omega_{\rm gw}(k) \approx \frac{1}{24} \Delta^2_{T,k,\rm prim} \Omega_\gamma \left(\frac{g_{*\rho,\rm hc}}{2}\right) \left(\frac{g_{*s}(T_{\rm hc}(k))}{g_{*s,0}(k)}\right)^{-4/3}$$

$$\Delta^2_{T,k,\rm prim} = \frac{2H^2_{\rm inf}}{\pi^2 M_P^2}\bigg|_{k=a_{\rm inf}H_{\rm inf}} \approx r A_s(k_\star) \left(\frac{k}{k_*}\right)^{-r/8} \qquad r < 0.058$$

Almost scale-invariant spectrum

Sudden changes in $g_{*\rho}, g_{*s}$ can lead to steps in power spectrum

This happens in phase transitions!

[Schwarz, Watanabe & Komatsu, Boyle & Steinhard, Saikawa & Shirai]

Remarks on second-order versus first-order

First order phase transition

Sources new gravitational waves
from expanding and colliding bubbles

Second order phase transition

Leads to steps in power spectrum of primordial
gravitational waves

Does the PQ transition in SMASH lead to observable signatures?

The spectrum time machine

$$f = \frac{k}{2\pi a_0} = \frac{g_{*\rho}^{1/2}(T_{\rm hc})}{2\sqrt{90}} \left(\frac{g_{*s}(T_0)}{g_{*s}(T)}\right)^{1/3} \frac{T_0 T_{\rm hc}}{M_P}$$

Higher frequencies crossed the **horizon earlier**

By looking at higher f we probe how the universe was at earlier and earlier times!

Spectrum with $f > 0.1$ Hz above white-dwarf noise actually probes $T > 10^6$ GeV

Going beyond simplest picture

Previous calculations ignored source effects

Free-streaming particles source anisotropies in the stress-energy tensor, which contribute to **source in wave equation** [Weinberg]

$$h_{\mathbf{k}}(t) \equiv h_{\mathbf{k},\mathrm{prim}} \chi_k \qquad u = k\tau$$

$$\frac{d^2\chi(u)}{du^2} + \frac{2}{a(u)}\frac{da(u)}{du}\frac{d\chi(u)}{du} + \chi(u) = -24 \sum_{i=\gamma,\nu,a} F_i(u) \left[\frac{1}{a(u)}\frac{da(u)}{du}\right]^2 \int_{u_i}^{u} dU \left[\frac{j_2(u-U)}{(u-U)^2}\right] \frac{d\chi(U)}{dU},$$

$$F_i(u) \equiv \frac{\rho_i(u)}{\rho_{\mathrm{crit}}(u)}$$

Time at which species i starts to free-stream

Still need $g_{*\rho}, g_{*s}$ to relate u with temperature and compute $F_i(u)$

The plan

Precise calculation of $g_{*\rho}, g_{*s}$ throughout the PQ phase transition in SMASH

Solve the differential equations for χ including the effect of **free-streaming** photons, neutrinos and relativistic axions

Calculation of g_* and g_{*s}

Main features of our calculation

Full one-loop finite T potential with **improved Daisy resummation** of thermal self-energies of H, σ, B_μ

3 loop QCD corrections to pressure

Corrections from **axion decoupling**

Finite temperature effective potential

$$g_{*\rho} = \frac{30}{\pi^2 T^4}\left(\Delta V(T) - T\frac{\partial \Delta V(T)}{\partial T}\right),$$
$$g_{*s} = -\frac{45}{2\pi^2 T^3}\frac{\partial \Delta V(T)}{\partial T}.$$

Finite T captured at **leading order** by $\Delta m_\sigma^2(T) \sim \text{coupling}^\kappa T^2$

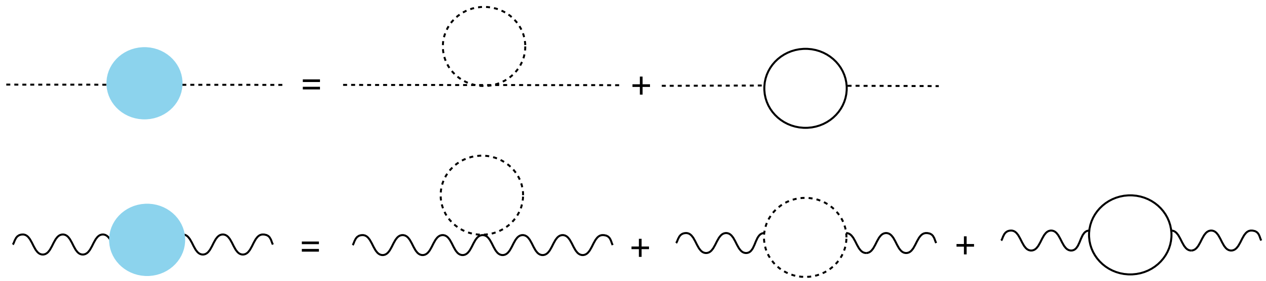
Thermal ***N*-loop corrections** from **bosonic self-energies** go as

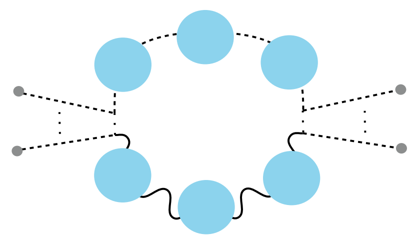
$$(0\ \text{T result}) \times \left(\frac{\text{coupling}^\kappa\, T^2}{m_\sigma^2}\right)^N$$

Phase transition happens when $\Delta m_\sigma^2(T) \sim m_\sigma^2$: **all loop corrections similar!**

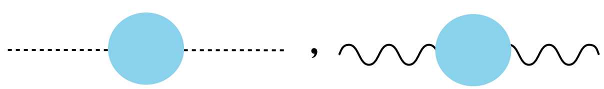
Need to resum N-loop effects: **Daisy resummation** of bosonic self-energies

The trouble with the usual Daisys





Usually, the **leading order** contribution a **high-T expansion** is taken:

 $\sim \text{coupling}^{\kappa} T^2$

Phase transition makes some particles **massive**

Massive particles decouple from thermal plasma

Usual **Daisy resummation incompatible with decoupling**: overestimates $g_{*\rho}, g_{*s}$

Improved resummation

Instead of a high-T expansion, we capture the **full T dependence at zero momentum**

We apply improved resummation to contributions to bosonic self-energies from **particles that get heavy during PQ phase transition**

Particles getting heavy:

$$\sigma, Q, \tilde{Q}, N_i$$

Contribute to self-energies of

H, σ, B_μ	Improved resummation
$G^a_\mu, \quad a = 1, \ldots 8$	Alternate treatment

Improved resummation

Improved resummation can be captured by mass corrections that do not go as T^2

Corrected mass of a scalar coupling to heavy scalars and fermions:

$$\Delta m^2_{\phi_j}(\bar{\phi}_i, T) \supset \sum_B \frac{T^2}{\pi^2} J'_B\left(\frac{m_B^2(\bar{\phi}_i)}{T^2}\right) \frac{\partial m_B^2(\phi_i)}{\partial \phi_j^2}\bigg|_{\phi_i \to \bar{\phi}_i} - 2\sum_F \frac{T^2}{\pi^2} J'_F\left(\frac{m_F^2(\bar{\phi}_i)}{T^2}\right) \frac{\partial m_F^2(\phi_i)}{\partial \phi_j^2}\bigg|_{\phi_i \to \bar{\phi}_i}$$

Corrected mass of gauge field coupling to heavy fermions;

$$\Delta m^2_G(\bar{\phi}_i, T) \supset \sum_F \frac{\tilde{g}^2 q_F^2 T^2}{\pi^2} K_F\left(\frac{m_F^2(\bar{\phi}_i)}{T^2}\right)$$

$$J_B(x) = \int_0^\infty dy\, y^2 \log\left[1 - \exp(-\sqrt{x+y^2})\right], \quad J_F(x) = \int_0^\infty dy\, y^2 \log\left[1 + \exp(-\sqrt{x+y^2})\right].$$

$$K_F(x) = \int_0^\infty dy\, \frac{y^2 e^{\sqrt{x+y^2}}}{(e^{\sqrt{x+y^2}}+1)^2}.$$

3 loop QCD corrections to ΔV

QCD corrections to ΔV are known to **3 loop** order in a theory with **arbitrary massless fermionic flavours** **[Kajantie et al]**

Using the former with the improved Daisy resummation would incur into **double-counting**

We implement the **decoupling** of $Q, \tilde{Q}$ by **interpolating** in temperature between SM 6 flavour result and SMASH 7 flavour result, weighing with thermal loop functions

$$\Delta V^{QCD}(T) = \left(1 - \frac{J_F\left(m_Q^2/T\right)}{J_F(0)}\right) \Delta V^{QCD}_{6\text{ flavours}}(T) + \frac{J_F\left(m_Q^2/T\right)}{J_F(0)} \Delta V^{QCD}_{7\text{ flavours}}(T)$$

Assembling pieces

$$V_{\rm eff}(\sigma,T) = V(H=0,\sigma) + V^{\rm CW}(\sigma,T) + \Delta V^{T}(\sigma,T) + V^{\rm QCD}(T).$$

$$V^{\rm CW}(\sigma,T) = \frac{1}{64\pi^2}\left[\sum_V m_V^4(\sigma,T)\left(\log\frac{m_V^2(\sigma,T)}{\mu^2}-\frac{5}{6}\right)+\sum_S m_S^4(\sigma,T)\left(\log\frac{m_S^2(\sigma,T)}{\mu^2}-\frac{3}{2}\right)\right.$$
$$\left.-\sum_F m_F^4(\sigma,T)\left(\log\frac{m_F^2(\sigma,T)}{\mu^2}-\frac{3}{2}\right)\right],$$

$$V^{T} = \frac{T^4}{2\pi^2}\left[\sum_B J_B\left(\frac{m_B^2(\sigma,T)}{T^2}\right)-\sum_F J_F\left(\frac{m_F^2(\sigma,T)}{T^2}\right)-\sum_G J_B(0)\right],$$

B: Vectors (V, 3 pol. in Landau gauge) + real scalars (S)
F: Weyl fermions
G: Ghosts

2 and 3 loop QCD corrections

Axion decoupling effects

Axion remains approximately massless but **loses kinetic equilibrium** with the rest of the plasma as interaction rates go as T^3/f_A^2

We **approximate decoupling temperature** by T for which **trace of energy momentum tensor is maximal** (signalling completion of phase transition and emergence of PQ scale).

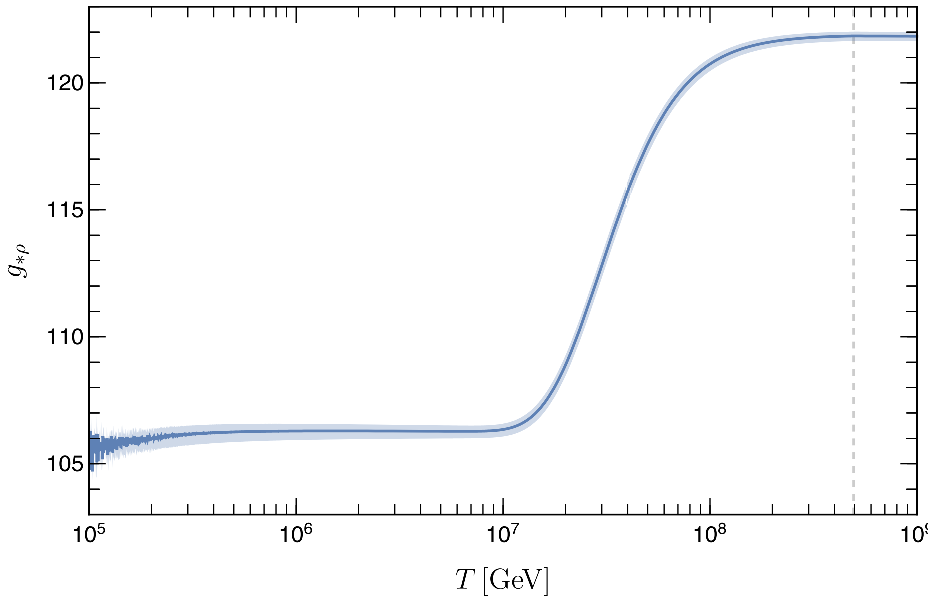
$$\Delta(T) = \frac{T^{\mu}_{\mu}}{T^4} = \frac{\rho - 3p}{T^4} = \frac{1}{T^4}\left(4V_{\mathrm{eff,min}}(T) - T\frac{\partial V_{\mathrm{eff,min}}(T)}{\partial T}\right).$$

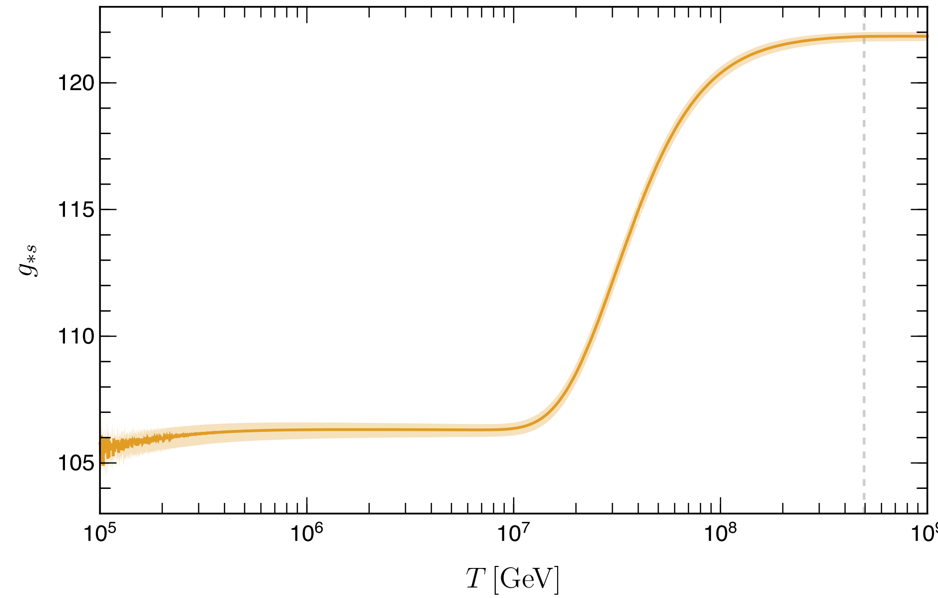
After decoupling, **entropies** of axion and plasma **separately conserved**: **axion bath has its own temperature**.

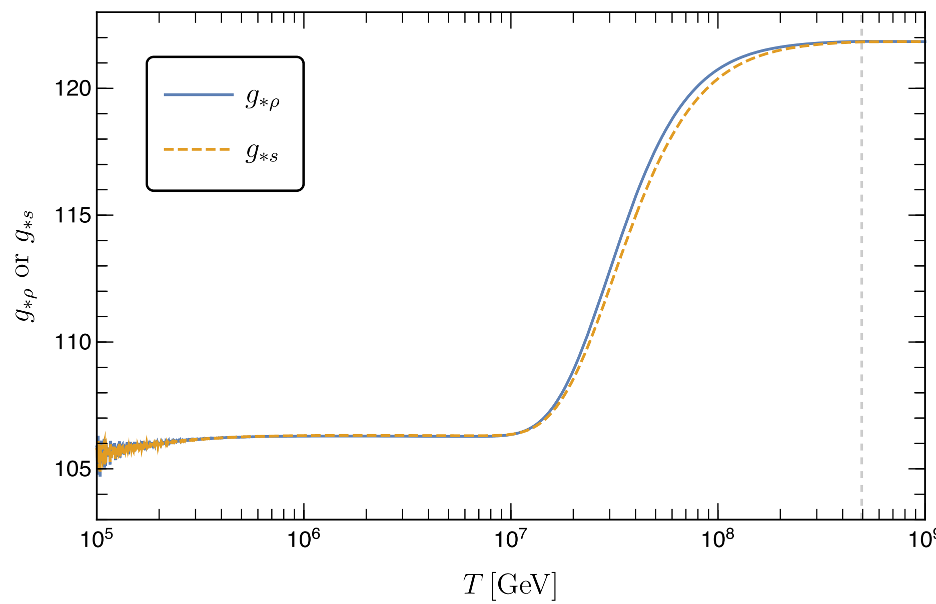
$$T_{\mathrm{axion}} = \begin{cases} T, & T \geq T_{\mathrm{dec}}, \\ \left(\frac{g_{*s}^{\mathrm{bath}}(T)}{g_{*s}^{\mathrm{bath}}(T_{\mathrm{dec}})}\right)^{\frac{1}{3}} T, & T < T_{\mathrm{dec}}. \end{cases}$$

$$g_{*\rho} = g_{*\rho}^{\mathrm{eq}} - 1 + \left(\frac{T_{\mathrm{axion}}}{T}\right)^4, \qquad g_{*s} = g_{*s}^{\mathrm{eq}} - 1 + \left(\frac{T_{\mathrm{axion}}}{T}\right)^3$$

Results during PQ phase transition



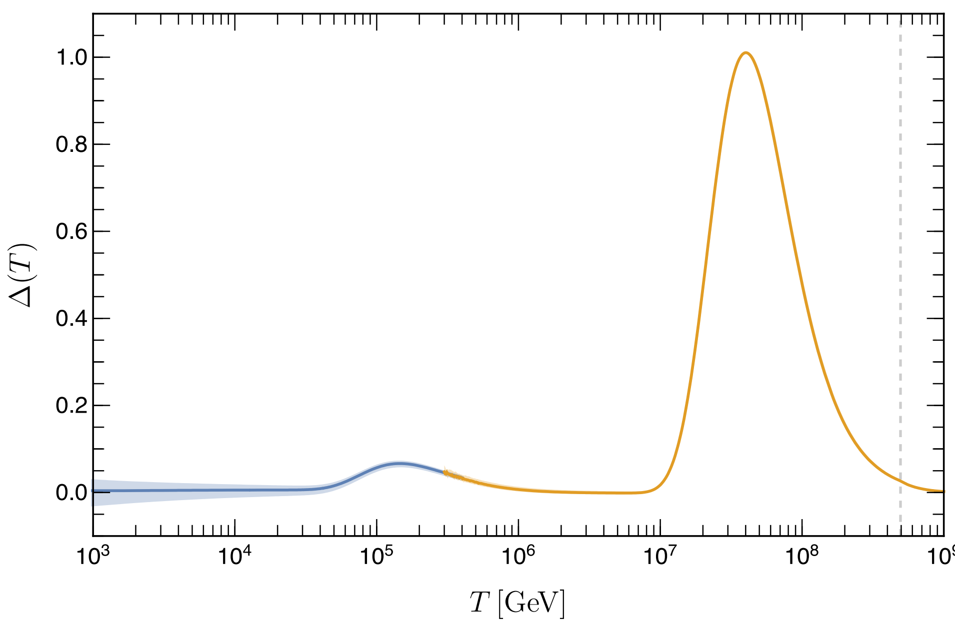


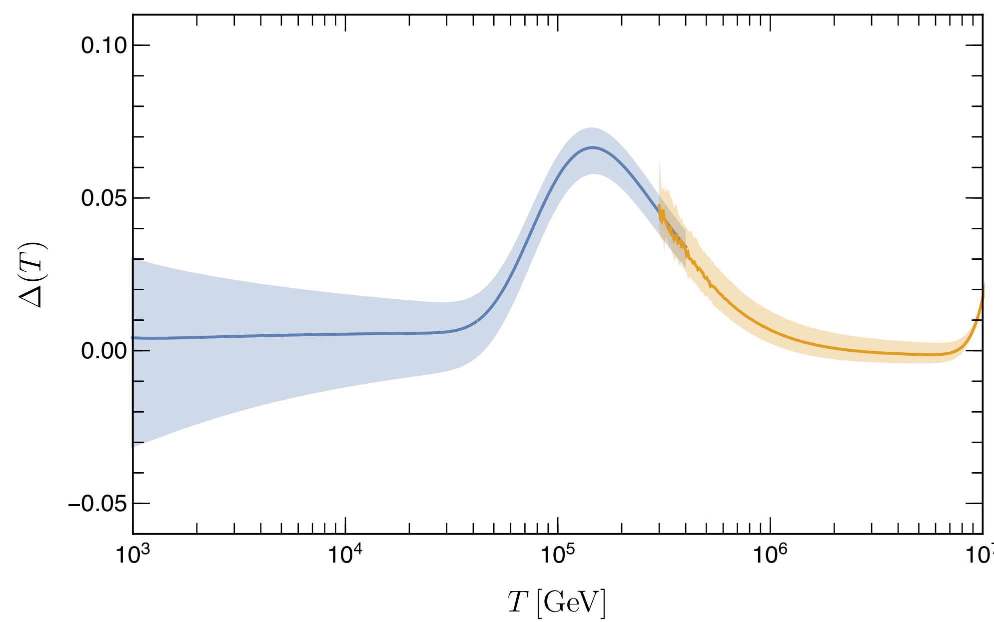


Beyond the PQ phase transition

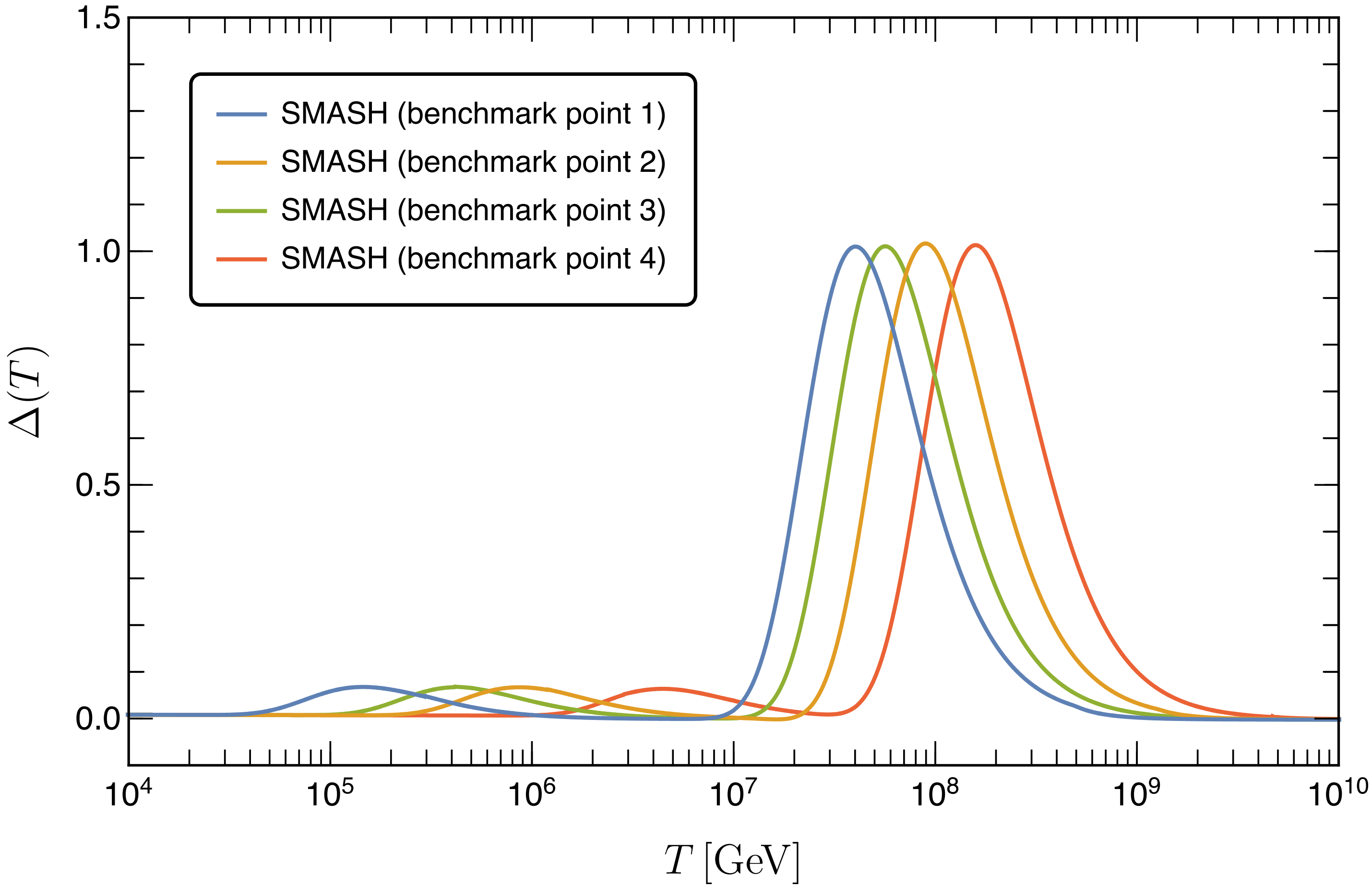
At lower scales we **match** our results to the **SM plus decoupled axion plus massive excitation of real part of σ**.

For the **SM** we use results of [Shaikawa Shirai 18] including **nonperturbative lattice estimates** across the electroweak and QCD crossovers

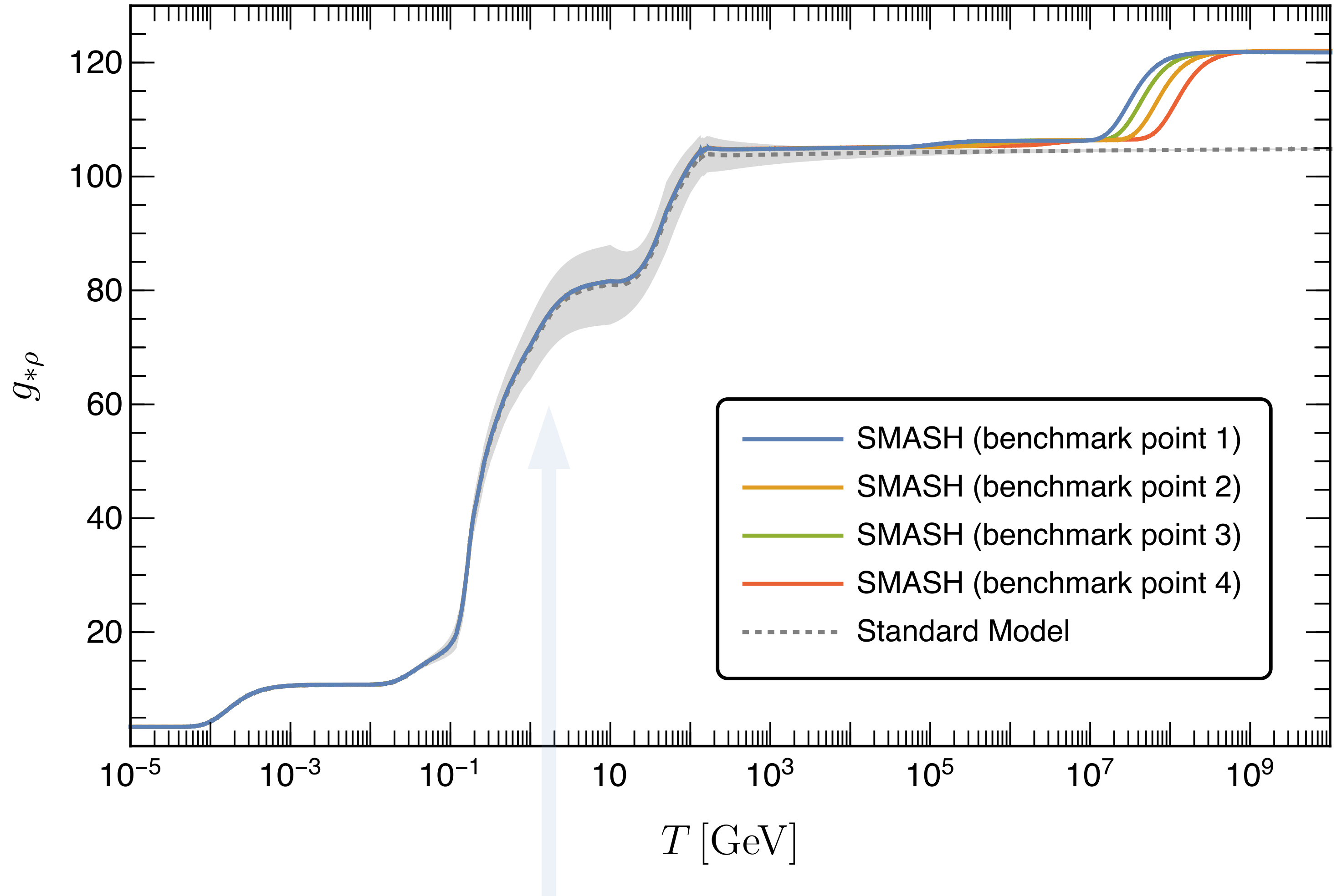




Beyond the PQ phase transition

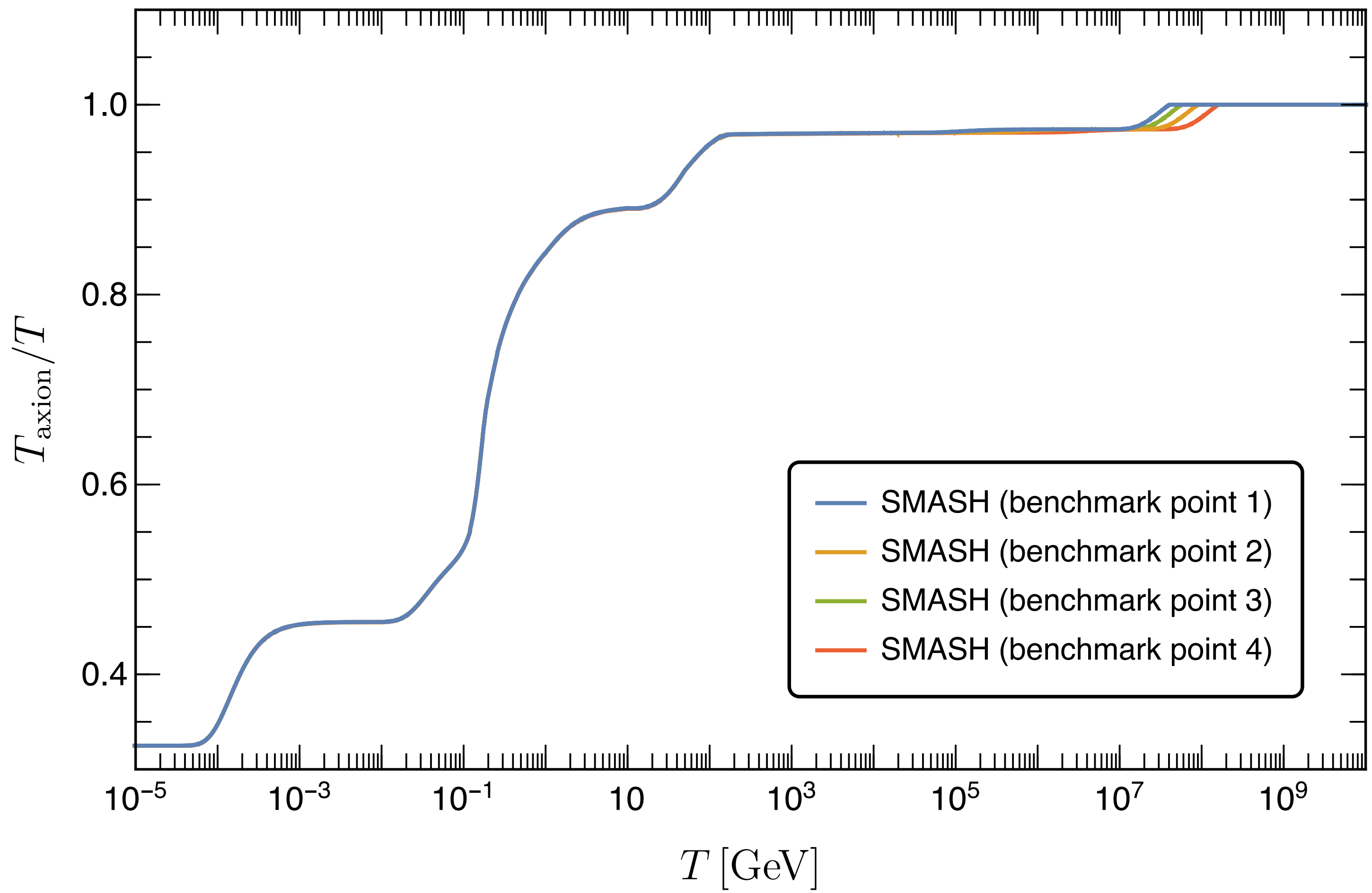


Beyond the PQ phase transition



Bigger SM steps won't be observable because of white-dwarf noise!

Beyond the PQ phase transition



Current spectrum of gravitational waves

Piecing things together

$$\Omega_{\rm gw}(k) = \frac{1}{12H^2a^2}\,\Delta^2_{T,k,\rm prim}\,|\chi'_{\mathbf{k}}(t)|^2 \equiv \mathcal{T}(f)\,\Delta^2_{T,k,\rm prim}$$

$$\Delta^2_{T,k,\rm prim} = \left.\frac{2H^2_{\rm inf}}{\pi^2 M_P^2}\right|_{k=a_{\rm inf}H_{\rm inf}}$$

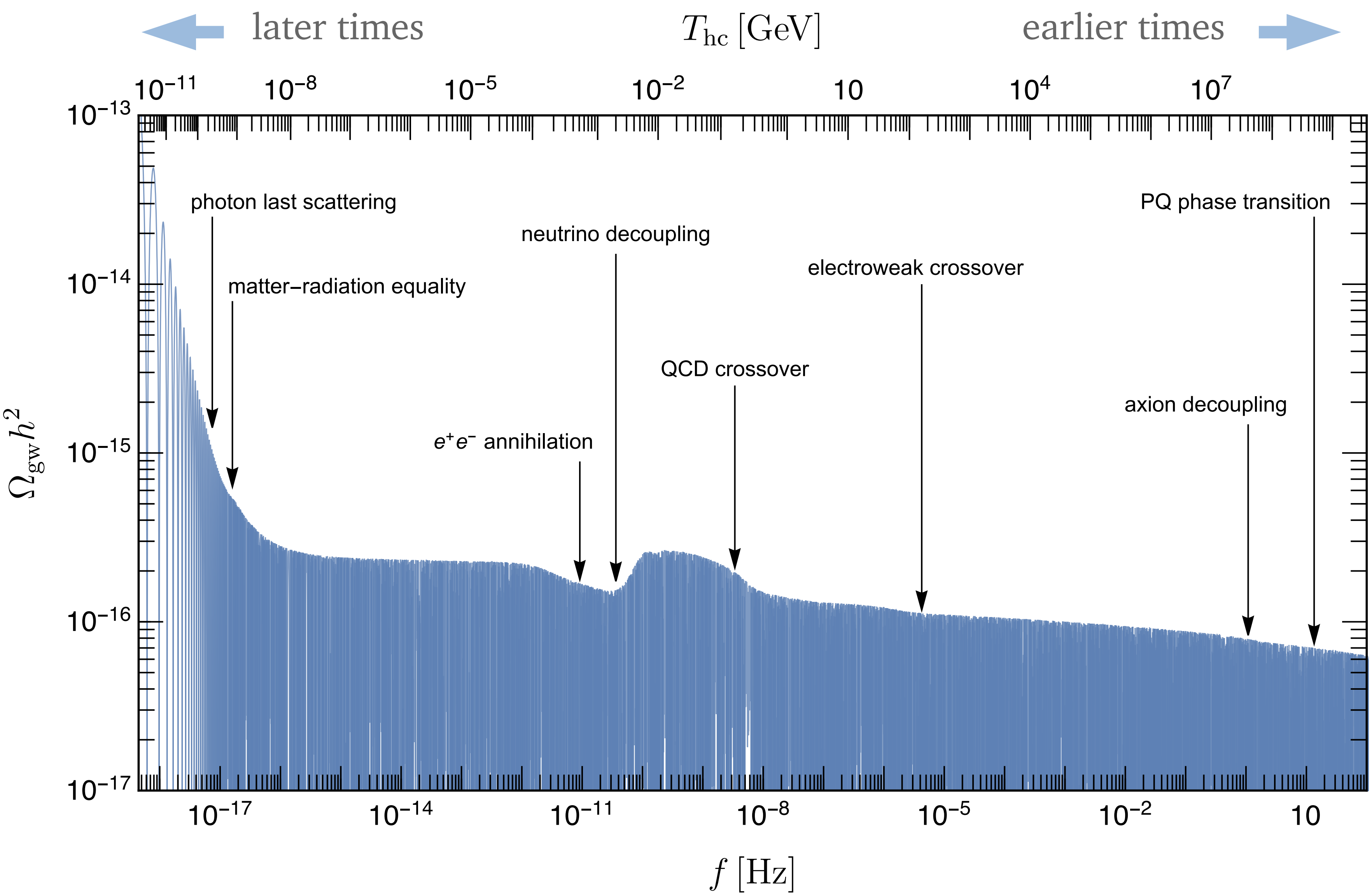
computed beyond slow roll

$$\frac{d^2\chi(u)}{du^2} + \frac{2}{a(u)}\frac{da(u)}{du}\frac{d\chi(u)}{du} + \chi(u) = -24\sum_{i=\gamma,\nu,a} F_i(u)\left[\frac{1}{a(u)}\frac{da(u)}{du}\right]^2 \int_{u_i}^{u} dU\left[\frac{j_2(u-U)}{(u-U)^2}\right]\frac{d\chi(U)}{dU},$$

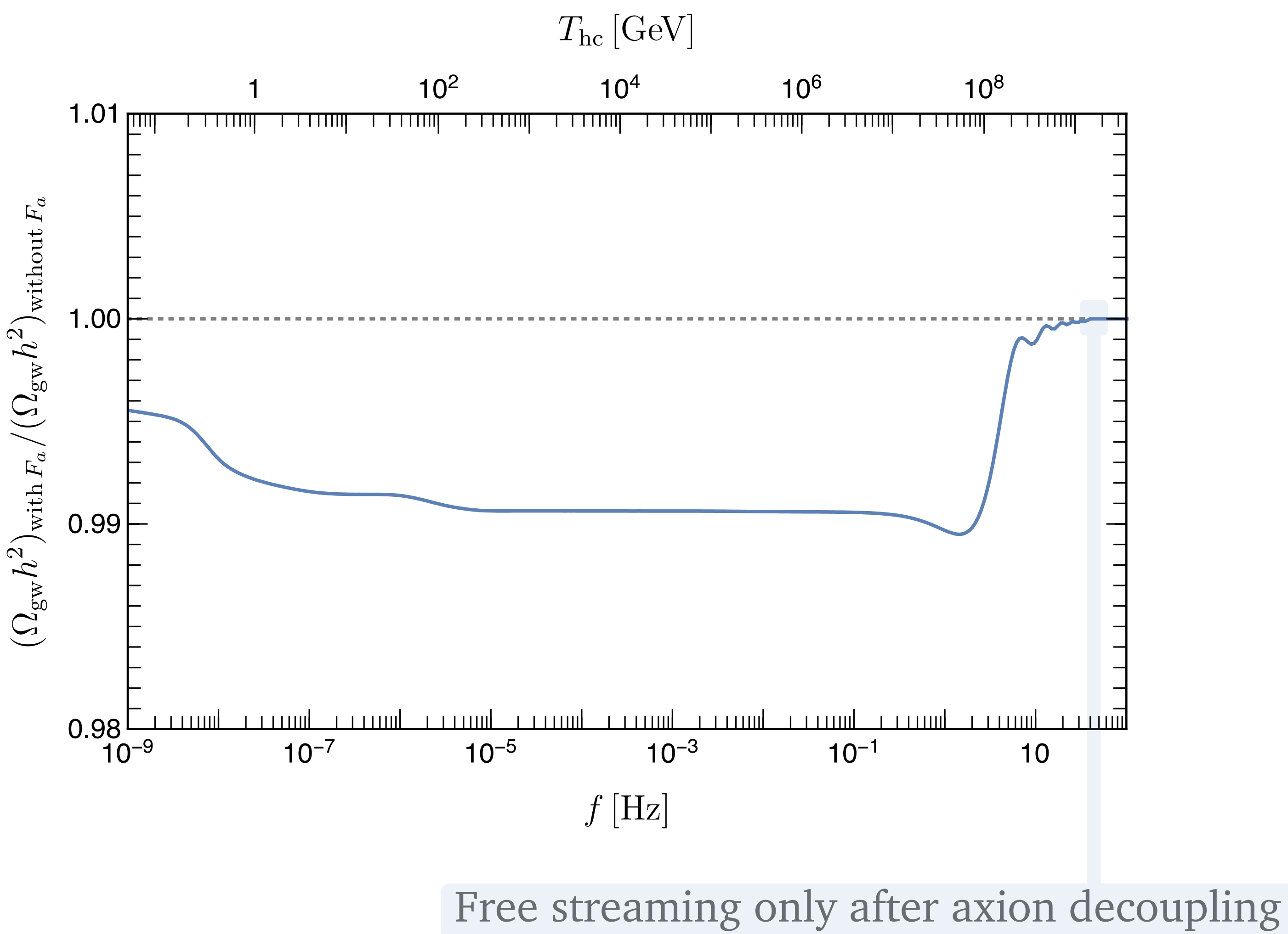
$$\chi(0) = 1, \quad \chi'(0) = 1$$

u_i: u at Decoupling times: $$T = \begin{cases} 3000\,\mathrm{K} & (\gamma) \\ 2\,\mathrm{MeV} & (\nu) \\ T_{\rm dec} & (a) \end{cases}$$

Birds-eye view of the frequency landscape

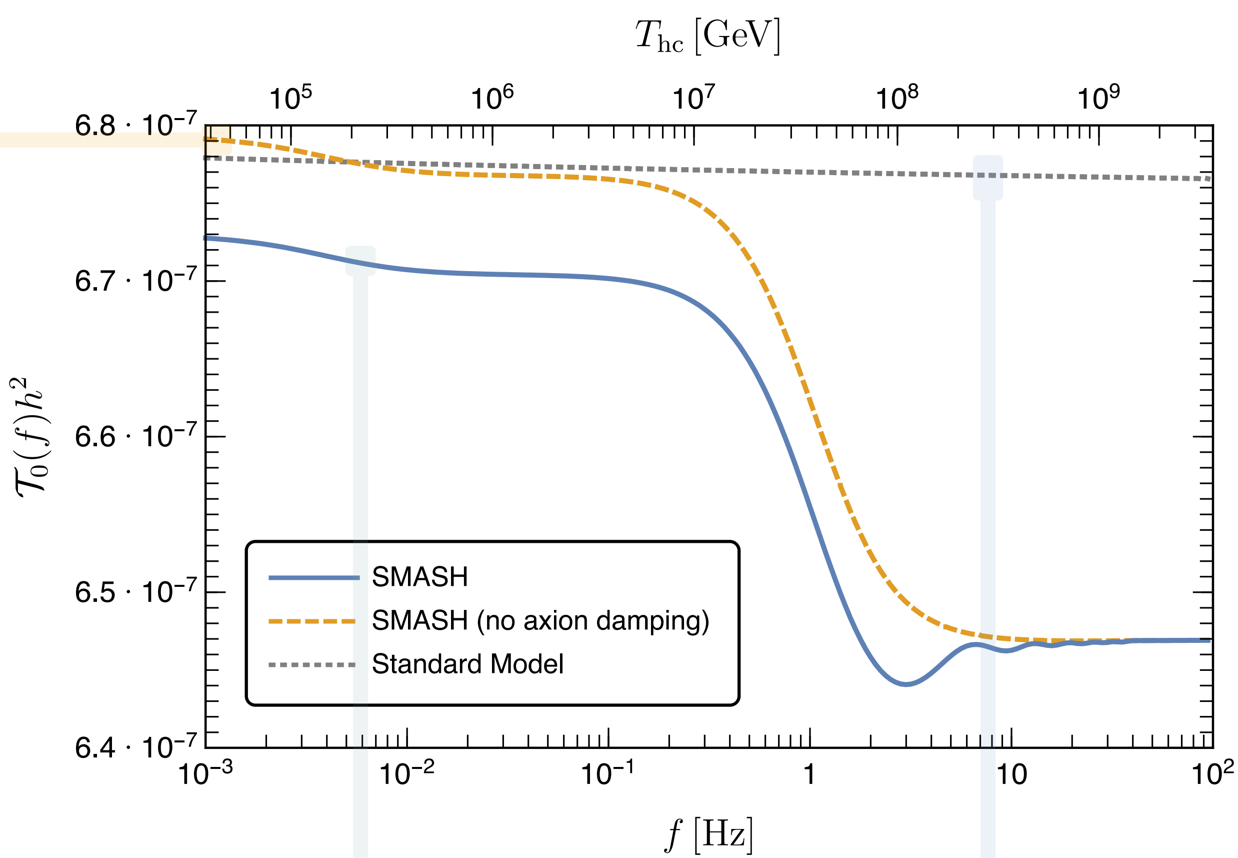


Damping effect from free-streaming axions



Suppression effect of 1% below that of neutrinos (35% below 10^{-10} Hz) and photons (14% below 10^{-17} Hz)

Where is the step?

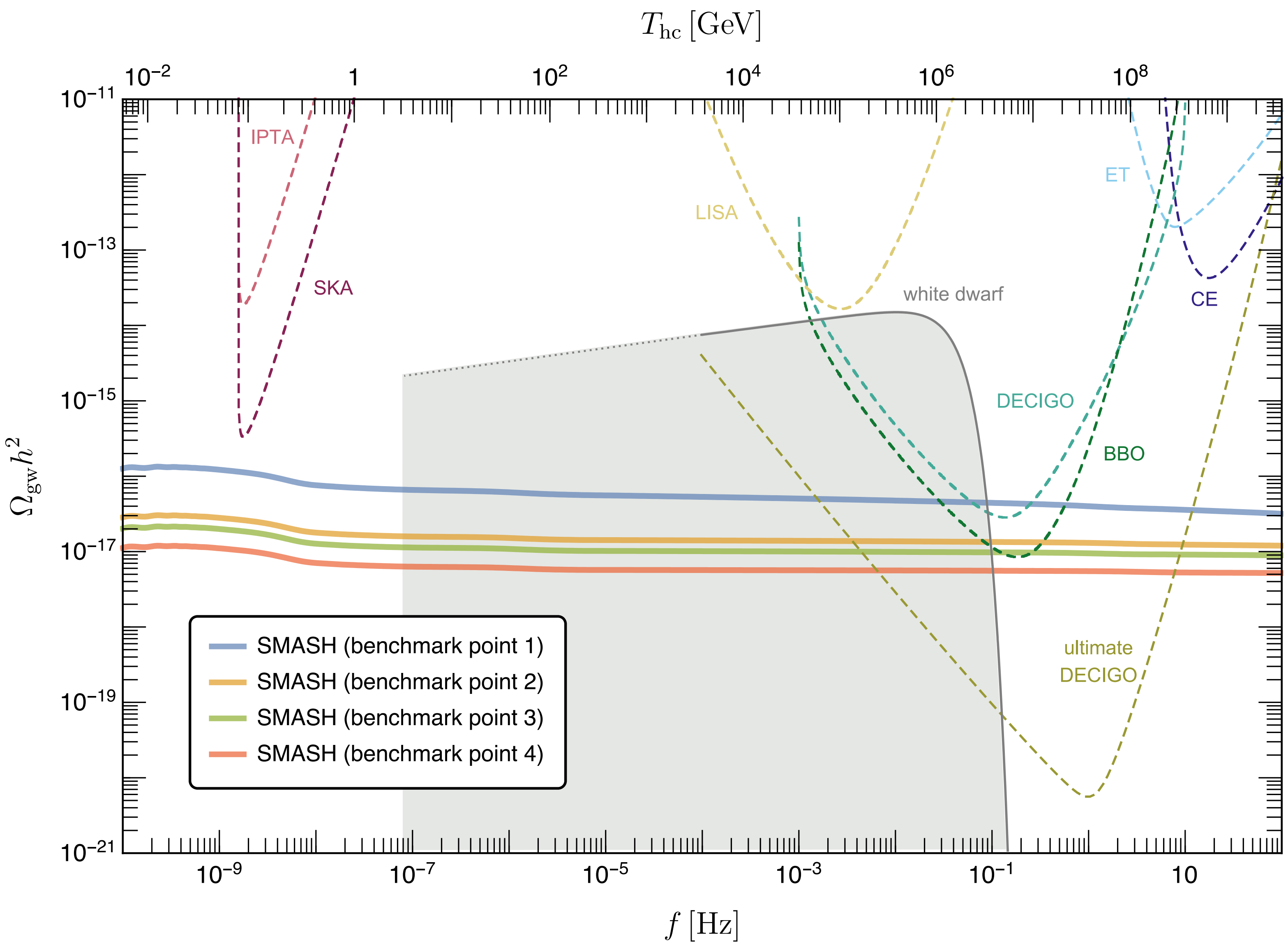


SM transfer function non-flat due to RG running

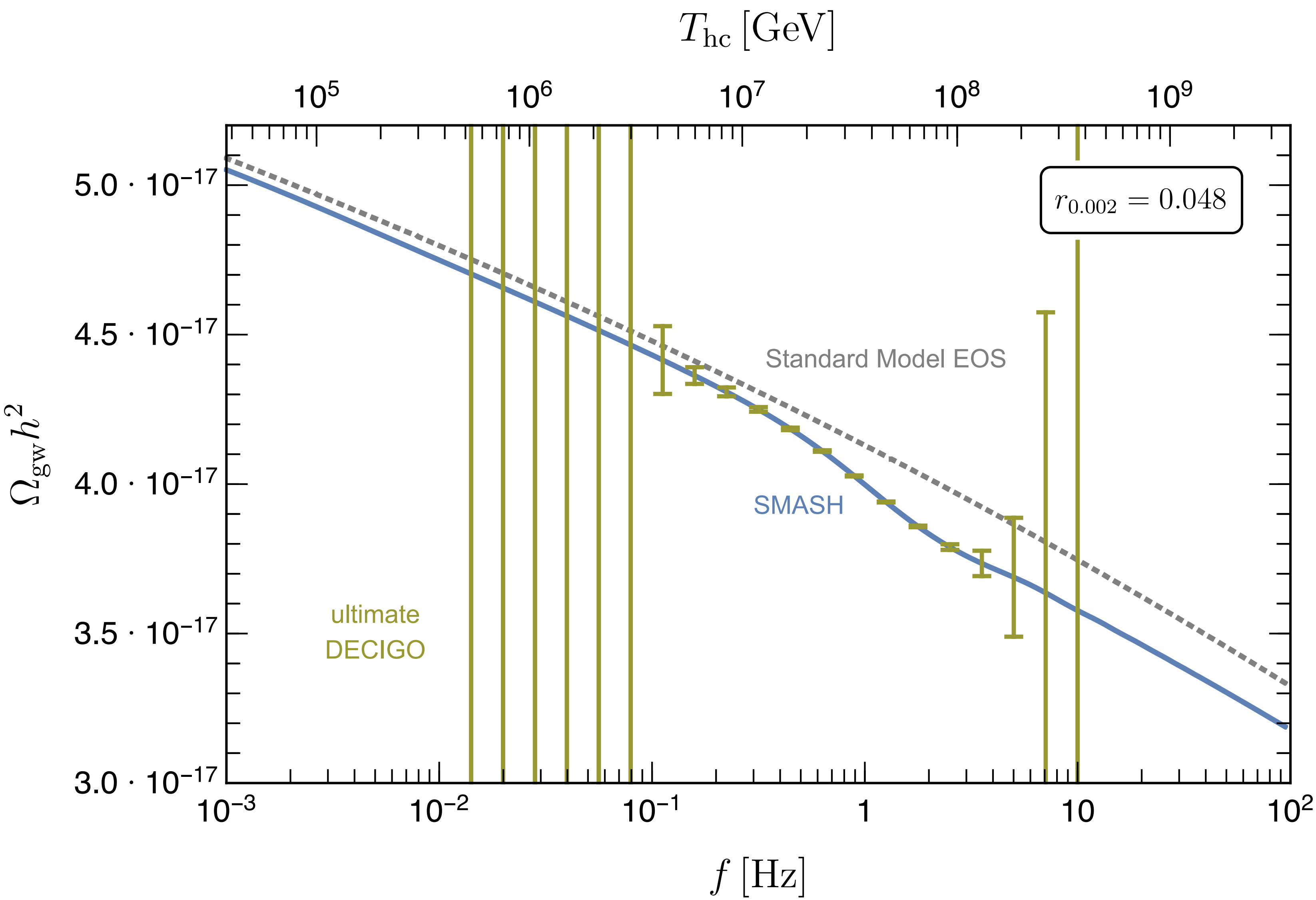
Smaller step due to decoupling of Re(σ)

SMASH curve without damping above SM due to larger value of $g_{*s}(T_0)$

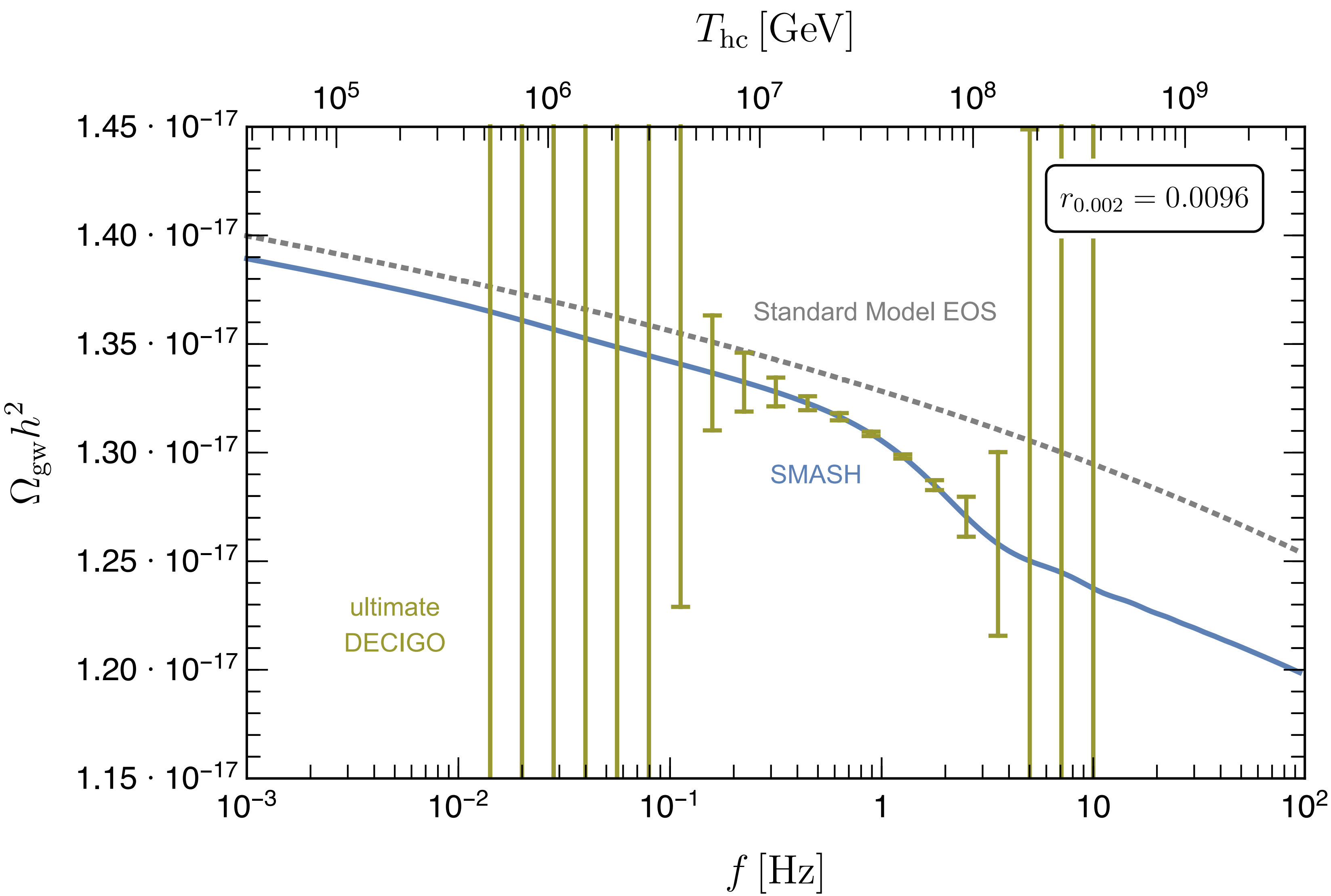
Future experimental sensitivities



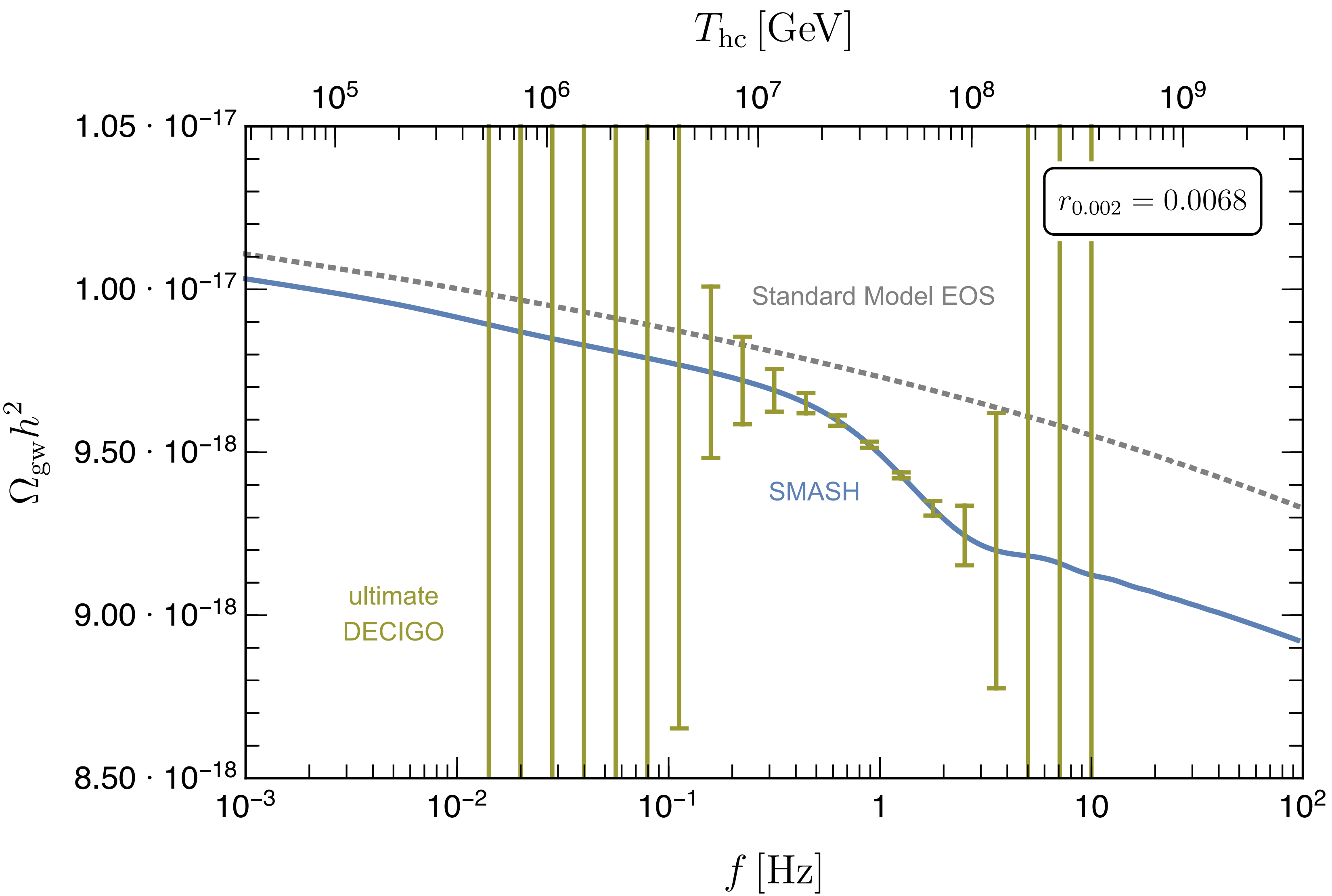
Zooming into the signal region



Zooming into the signal region



Zooming into the signal region



Conclusions

The **2^{nd} order PQ** phase **transition** in **SMASH** predicts a **feature** in the **spectrum** of **primordial gravitational waves** near **1Hz**, corresponding to modes reentering the horizon when the temperature of the universe was $T_{hc} \sim 10^8$ GeV

This feature is just **above the white dwarf noise** and could be **observable** with the **ULTIMATE DECIGO** experiment as the feature is expected **near the peak sensitivity**

For our calculations of g_{*_ρ}, g_{*_s} across the phase transition we developed an **improved Daisy resummation** of thermal corrections which accounts for **decoupling** effects

Thank you!