Revealing the Cosmic History with Gravitational Waves

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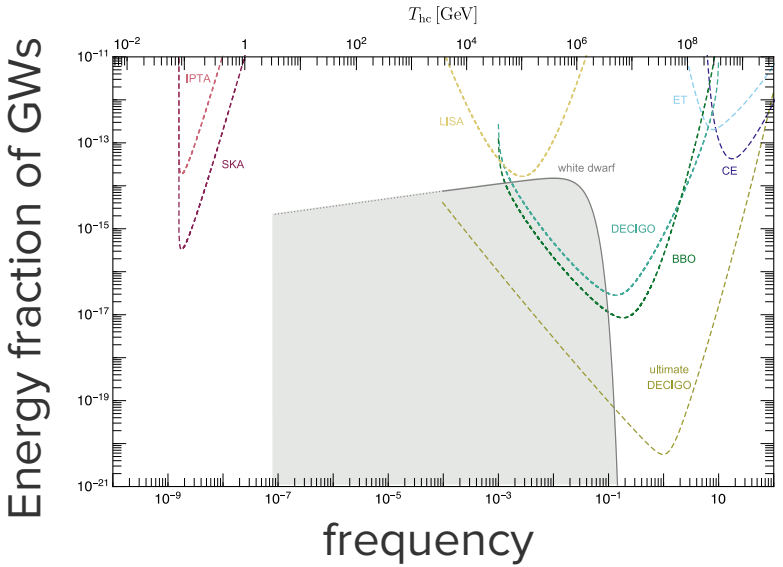
in collaboration with

Andreas Ringwald, DESY

Building on previous work with Ringwald and:

Guillermo Ballesteros, IFT Yvette Welling, DESY	JCAP 09 (2021) 036
Jan-Schütte Engel, Urbana	JCAP 03 (2021) 054
Kenichi Saikawa, Kanazawa U	JCAP 02 (2021) 046

The experimental context



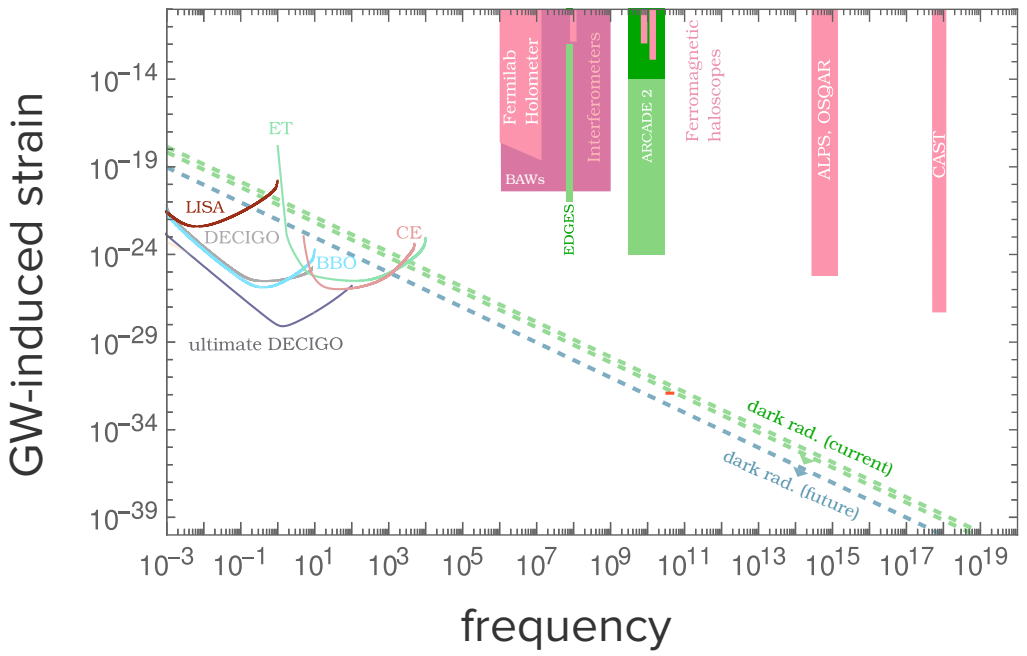
What about high frequencies??

High freqs probe **high-energy processes** in early universe: **inflation, reheating, plasma**

Weak interactions → waves **travel undisturbed: direct probe of primordial physics**

There are **no known astrophysical sources** at **very high-frequencies**

Current constraints at high frequencies



The aim

Motivate search for **high-frequency gravitational waves** (GWs)

Provide a **benchmark** by computing the **complete spectrum** of stochastical **GWs** in a minimal and predictive extension of the SM, **SMASH**

The novelty

We are not aware of other calculations accounting for GWs from inflation, preheating and thermal fluctuations in a single model

(see however [Buchmüller et al])

The plan

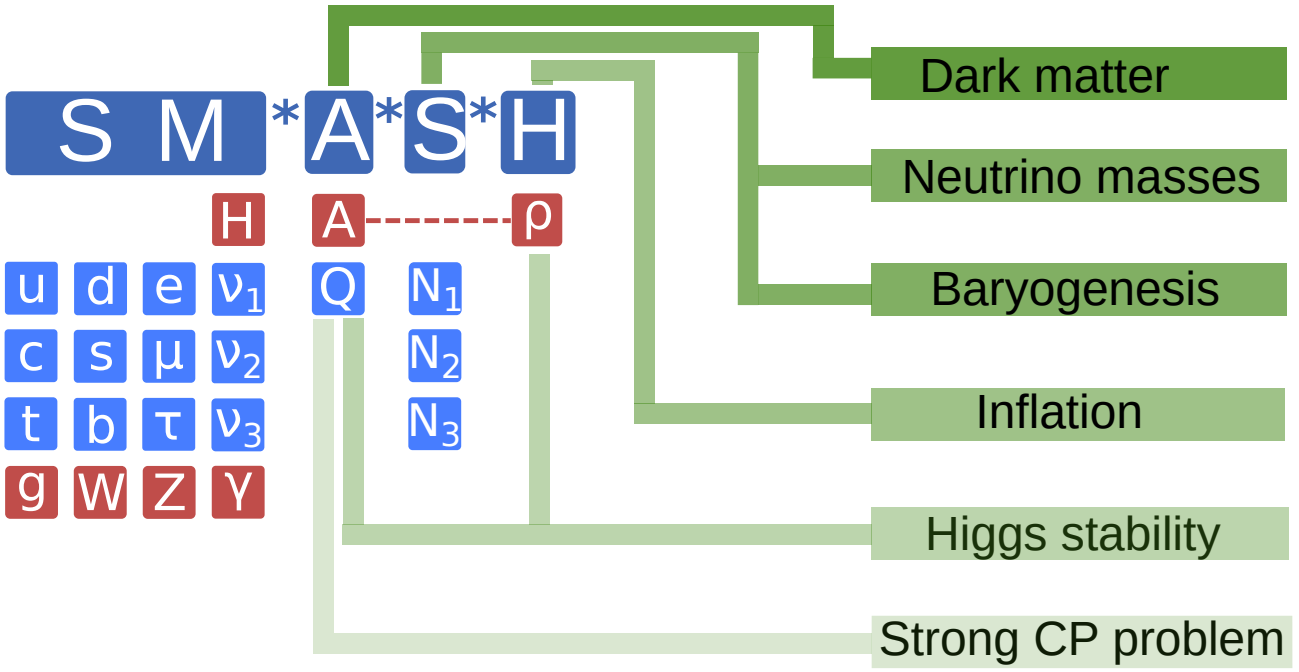
SMASH

GW production in the early universe

- Inflation
- Reheating
- Thermal fluctuations

Overview of SMASH

Ballesteros, Redondo, Ringwald, CT 16



Single new **mass scale**, **predictive** cosmological history

- Addresses **6 problems** in **minimal,** falsifiable **package**

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

INFLATION

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

STABILITY

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

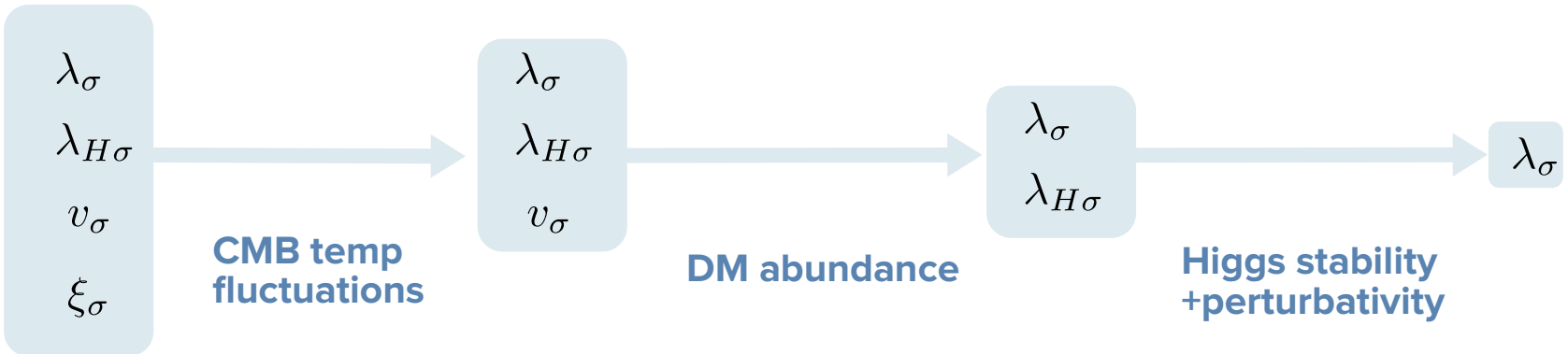
CP, DARK MATTER

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

SEESAW AND LEPTOGENESIS

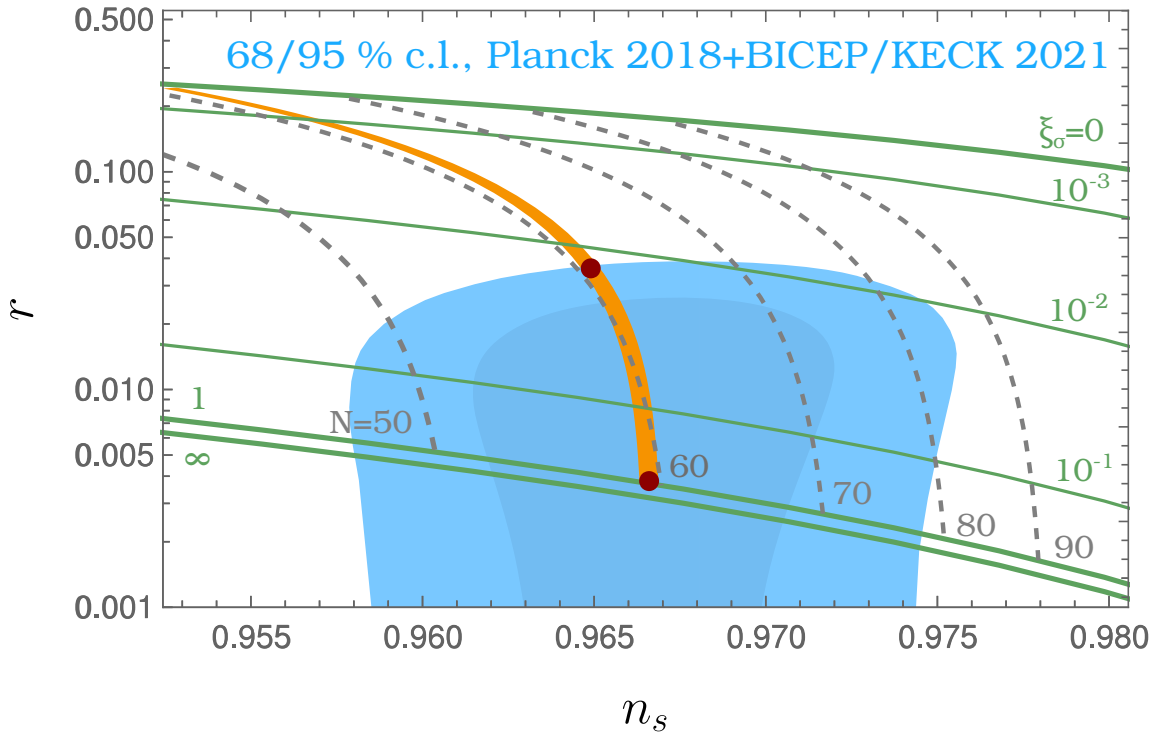
- Most general, renormalizable Lagrangian compatible with **global PQ symmetry**

For $\xi_H \ll \xi_\sigma$, approx. 1 free scalar parameter



- Features of GW **spectra** in SMASH mainly **determined by bosonic BSM couplings**

CMB predictions in SMASH



- Can choose r as free bosonic parameter. Will compute GW spectra for extremal values

Gravity waves in SMASH

What are gravitational waves?

Excitations of the **metric** field **sourced** by **anisotropies** in the **stress-energy** momentum tensor. In local Minkowski frame

$$ds^2 \supset -dt^2 + (\delta_{ij} + h_{ij}) dx^i dx^j$$

$$\Box \left(h_{ij} - \frac{1}{2}\delta_{ij} h \right) = \frac{2}{M_P^2} T_{ij}^{\mathrm{TT}},$$

$$\partial^i h_{ij} = 0, \quad T^{\mathrm{TT}}{}_{i}^{i} = 0, \quad \partial^i T_{ij}^{\mathrm{TT}} = 0$$

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

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

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

Sources of GWs in the SMASHY universe

Inflation

(Almost) no source term

Reheating

Nonperturbative scalar field fuctuations (inflaton fragmentation) contribute to T_{ij}^{TT}

Need **lattice simulations**

Thermal excitations

Additional contributions to T_{ij}^{TT} from **viscosity** and **quasi-particle excitations**

Interdependence between sources

Inflation

sets the initial conditions for

Reheating

which fixes the value of the reheating temperature and the scale of

Thermal excitations

We expect correlations within SMASH of spectra coming from different sources

GWs from inflation

GWs from inflation: the bigger picture

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

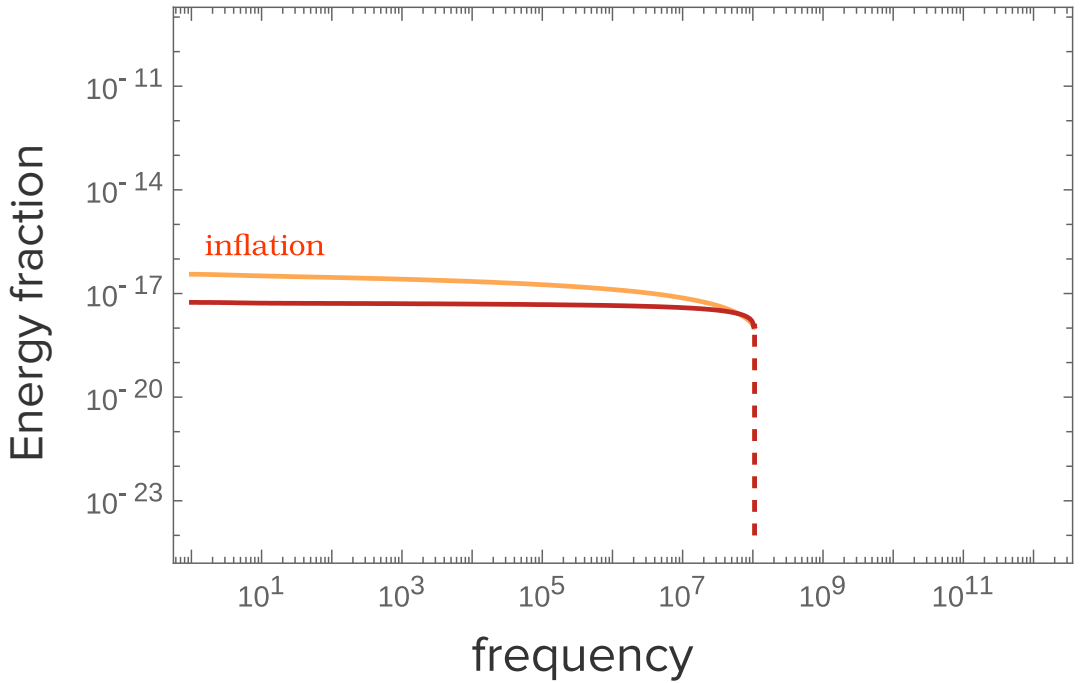
Inflationary power spectrum (nearly flat)

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

$$s = \frac{2\pi^2}{45} g_{*,s} T^3$$

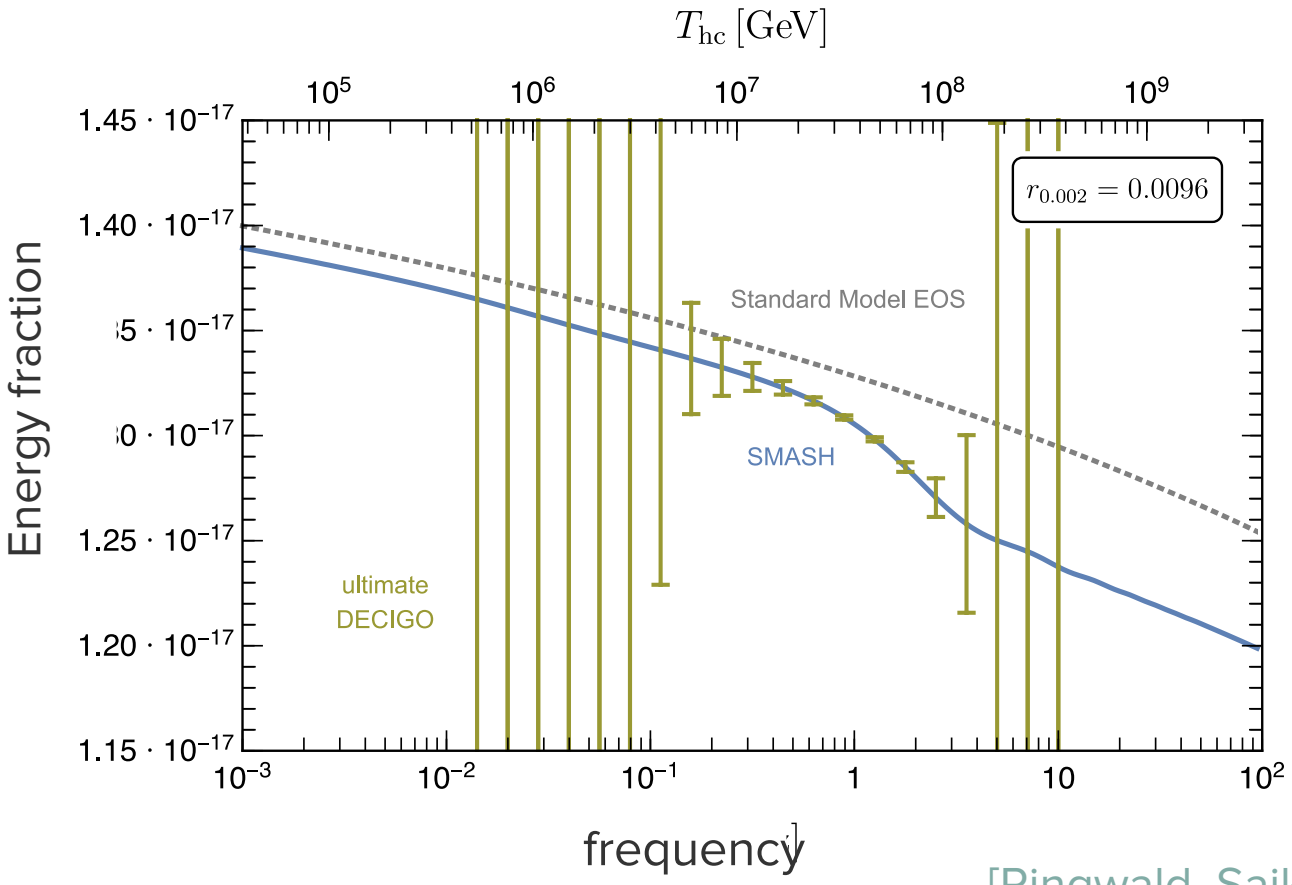
Sudden changes in $g_{*\rho}, g_{*s}$ (as in PQ transition) can lead to **steps in power spectrum**

GWs from inflation: the bigger picture



- Spectrum tied to **Hubble scale during inflation**

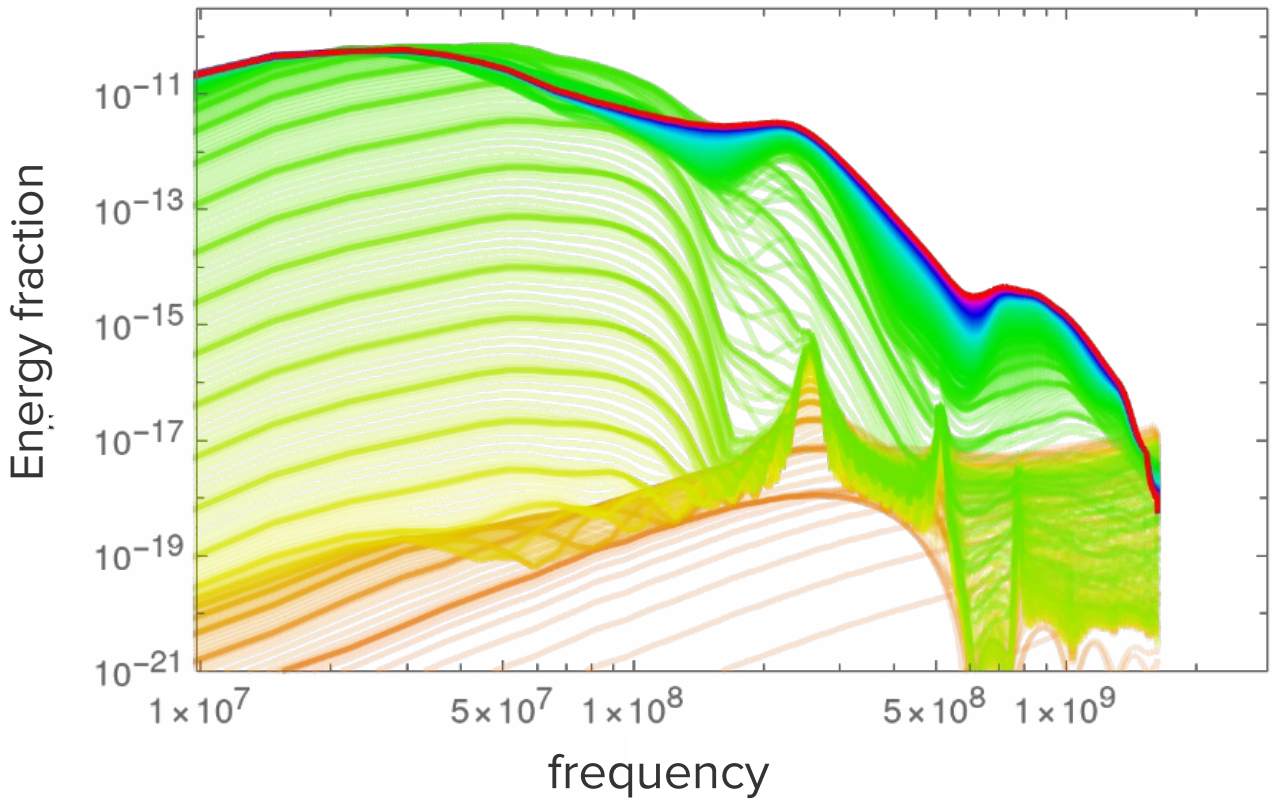
The PQ transition affects inflationary GWs



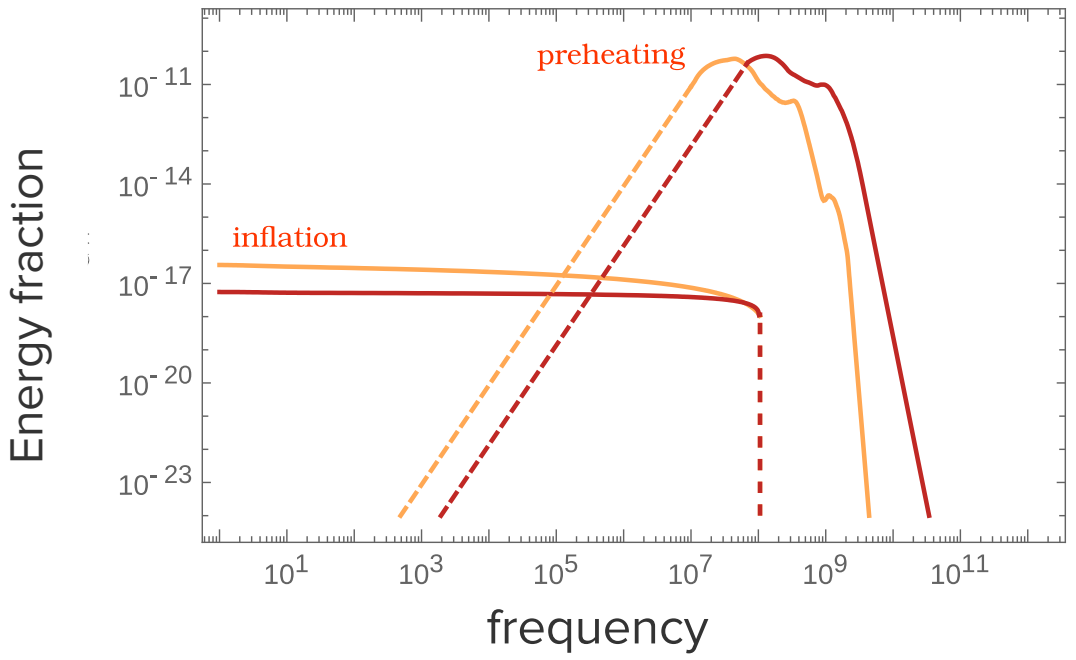
[Ringwald, Saikawa, CT]

GWs from preheating

Results of lattice simulations

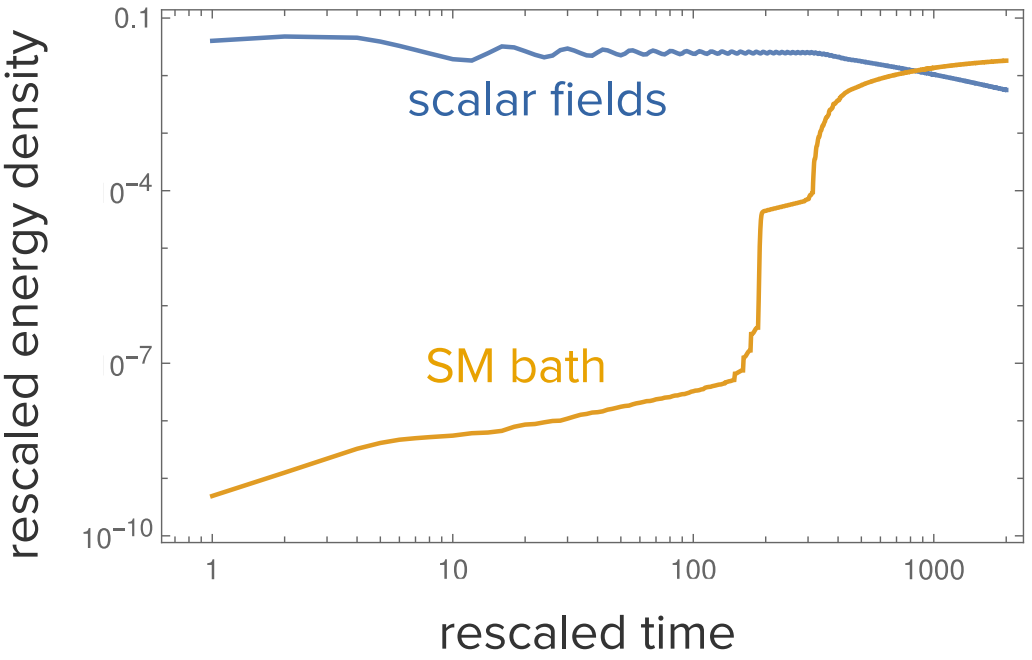


GWs from preheating: the bigger picture



- **Hubble scale during inflation**
- **Hubble scale at inflation's end, length scale of inflaton fragmentation**

Reheating temperature from simulations



$$\rho = \frac{\pi^2}{30} g_{*,\rho} T^4 \Rightarrow T_{\text{reheating}} = 2 \times 10^{12}\ \text{GeV}$$

GWs from thermal fluctuations

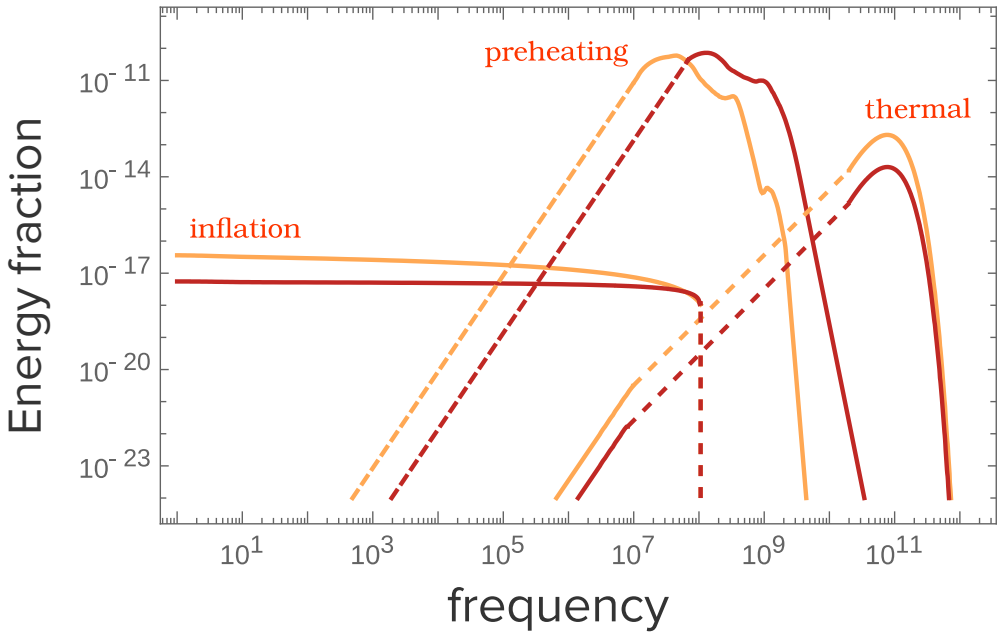
[Ghiglieri et al]
[Ringwald, Schütte-Engel, CT]

$$\Omega_{\rm CGMB}(f) \approx 4.03\times 10^{-12}\left[\frac{T_{\rm max}}{M_P}\right]\left[\frac{g_{*s}(T_{\rm max})}{106.75}\right]^{-5/6}\left[\frac{f}{\rm GHz}\right]^{3}\hat{\eta}\left(T_{\rm max}, 2\pi\left[\frac{g_{*s}(T_{\rm max})}{g_{*s}(\rm fin)}\right]^{1/3}\frac{f}{T_0}\right)$$

- Linear effect: A **Big Bang thermometer**!

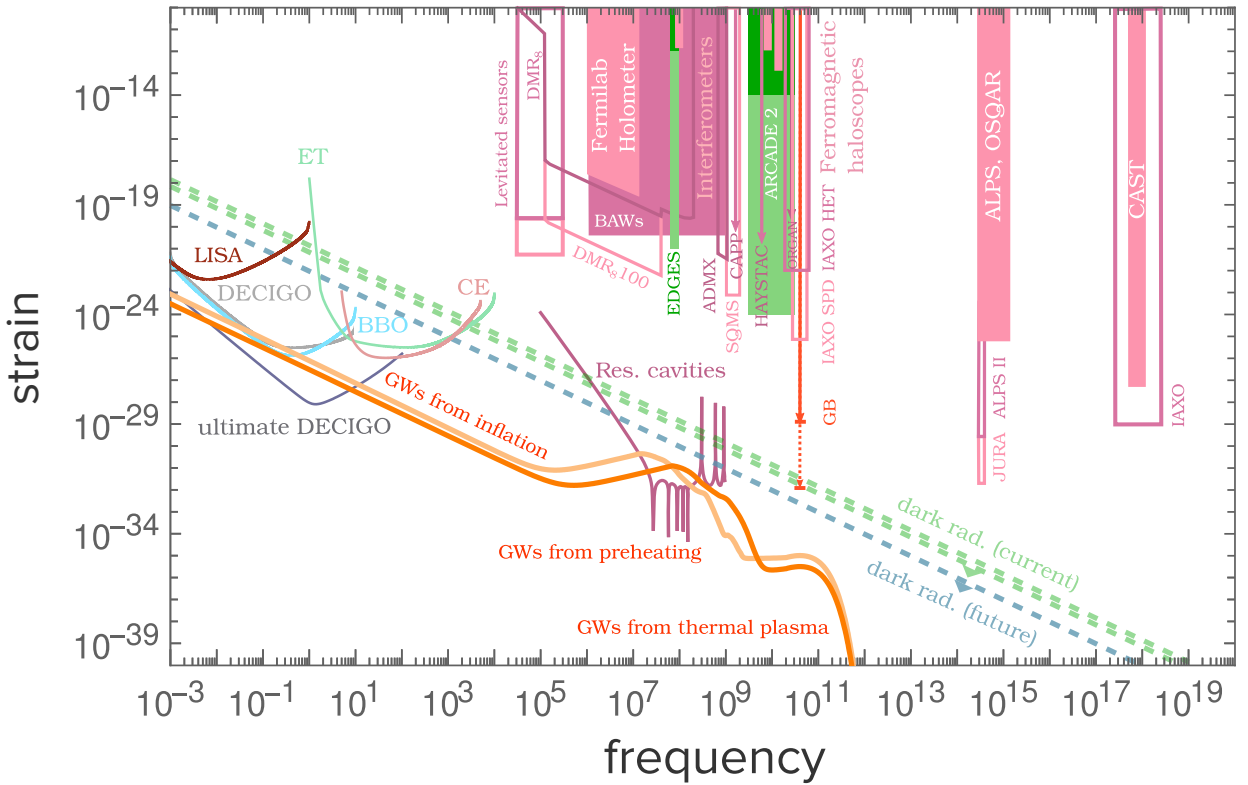
Peak frequency depending on the **number of relativistic degrees of freedom at the Big Bang**!

GWs from thermal plasma: the bigger picture



- Hubble scale during inflation
- Hubble scale at inflation's end, length scale of inflaton fragmentation
- Tmax and number of d.o.f. in hot Big Bang

Confronting with current and future experiments



Conclusions

High-frequency GWs can tell us about:

Hubble scale during and at the end of inflation

Scale of inflaton fragmentation

Reheating temperature and **number of d.o.f.s** in the primordial plasma

Second-order phase transitions in the early universe

SMASH provides a **conservative benchmark** that can hopefully motivate further efforts in the exploration of high-frequency GWs

CERN-TH-2020-185
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DESY 20-195

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

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13 Dec 2021

Thank you!