Exploring the Cosmic History with Gravitational Waves

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SEWM 2022
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Paris, France
23 June 2022

[AR, Kenichi Saikawa, Carlos Tamarit, arXiv:2009.02050]

[AR, Jan Schütte-Engel, Carlos Tamarit, arXiv:2011.04731]

[AR, Carlos Tamarit, arXiv:2203.00621]

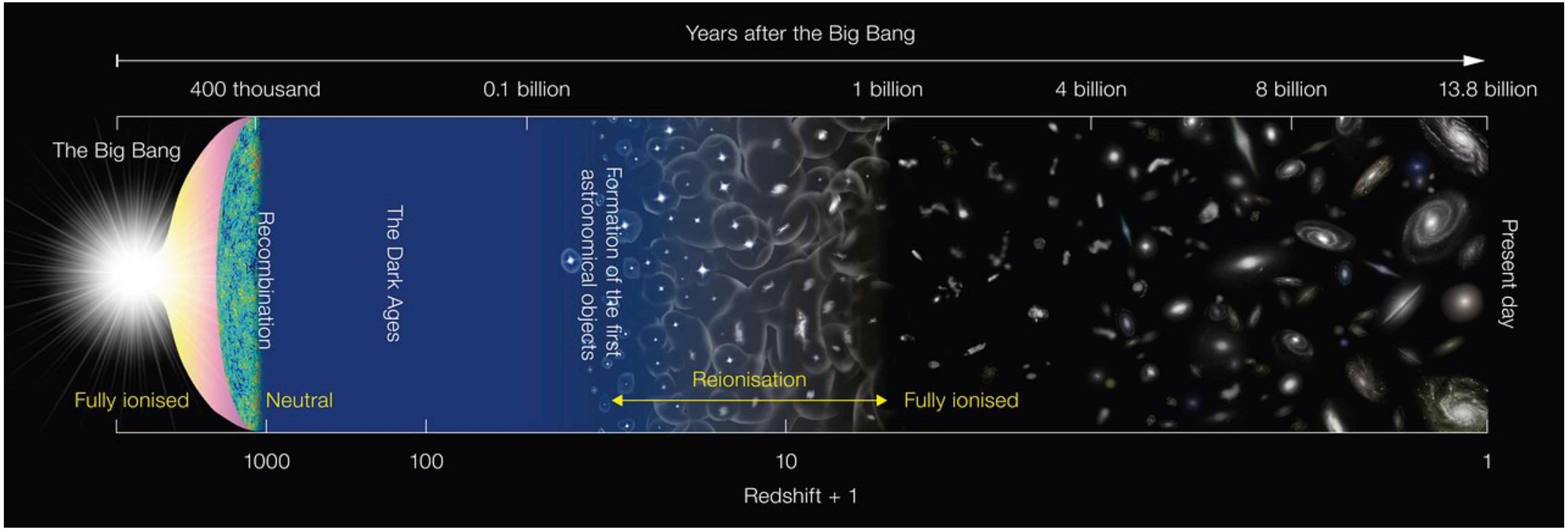
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

Introduction

- Big Bang cosmology describes how the universe expanded from an initial state of extremely high density into the cosmos we currently inhabit



[ESO]

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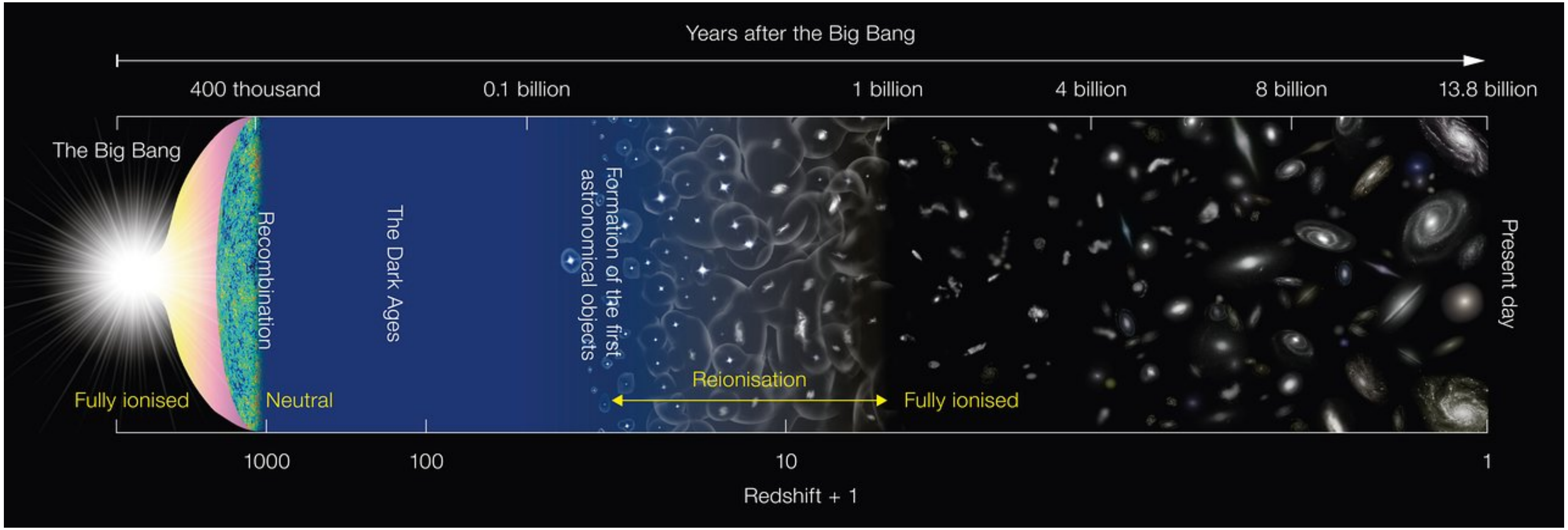
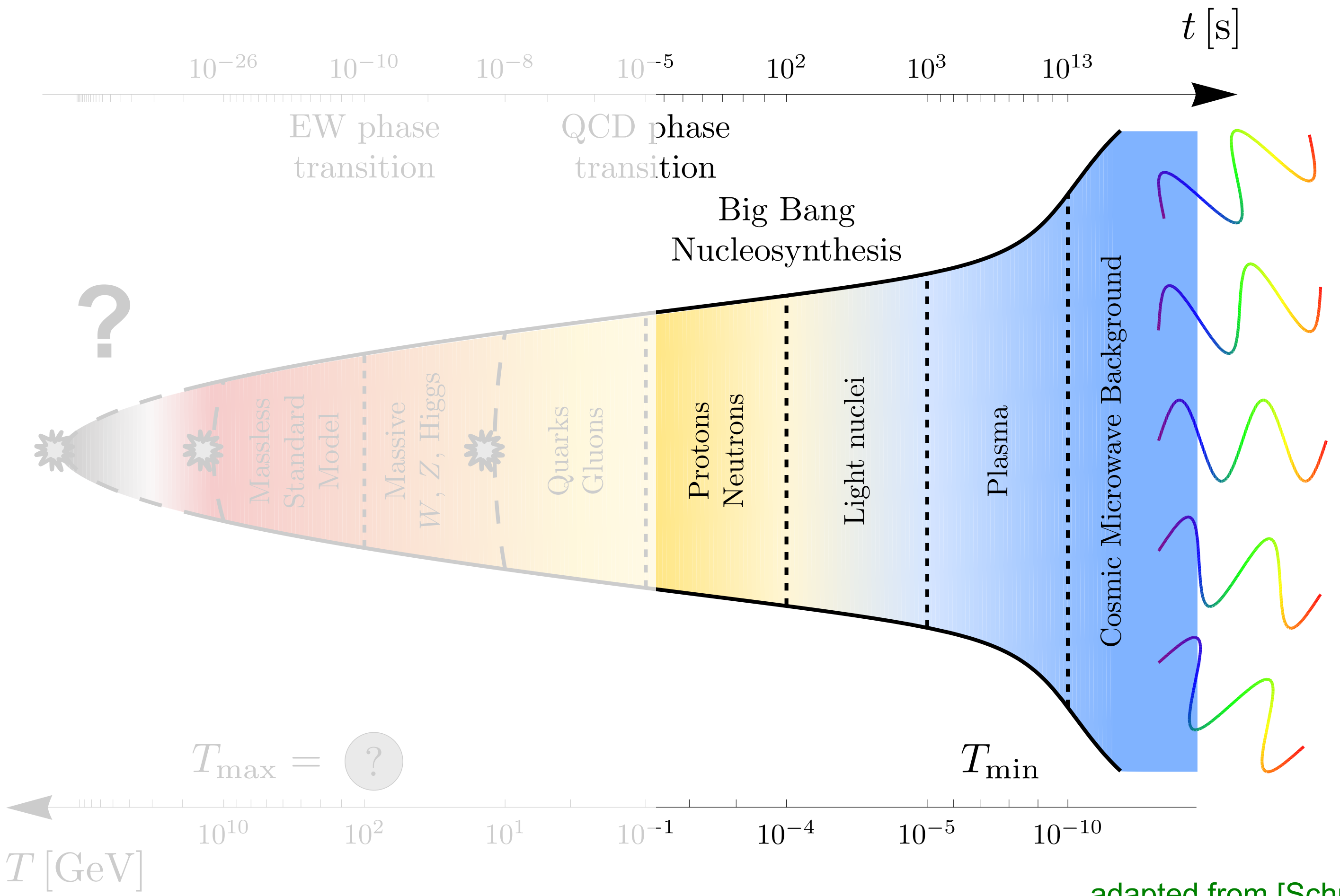


[ESO]

- It comprehensively explains a broad range of observed phenomena, including the abundance of light elements, the Cosmic Microwave Background (CMB) radiation, and the large-scale structure

Introduction

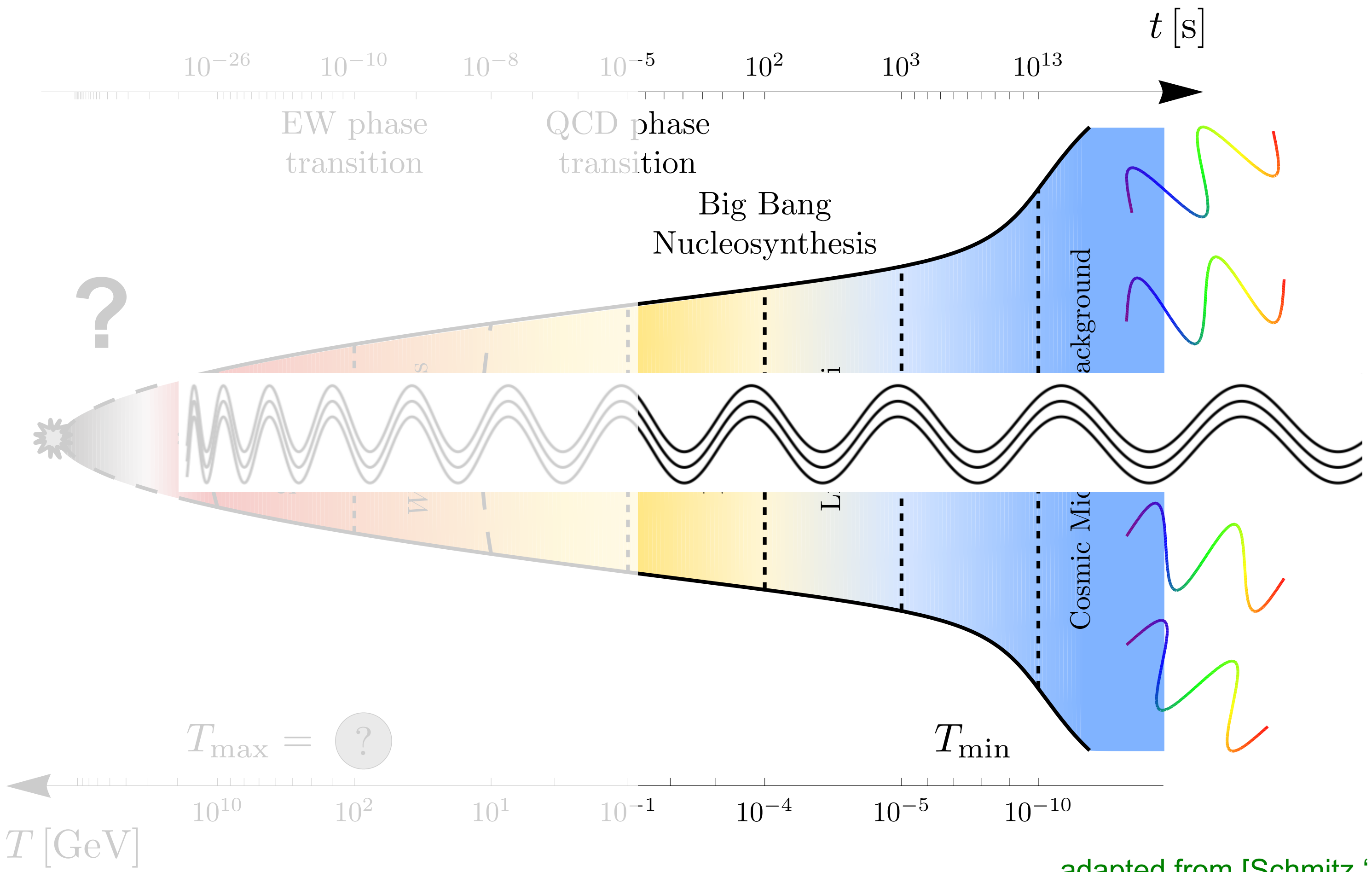
Cosmic history prior to Big Bang Nucleosynthesis (BBN)?



adapted from [Schmitz '12]

Introduction

Cosmic history prior to BBN may be probed directly by Gravitational Waves (GWs)



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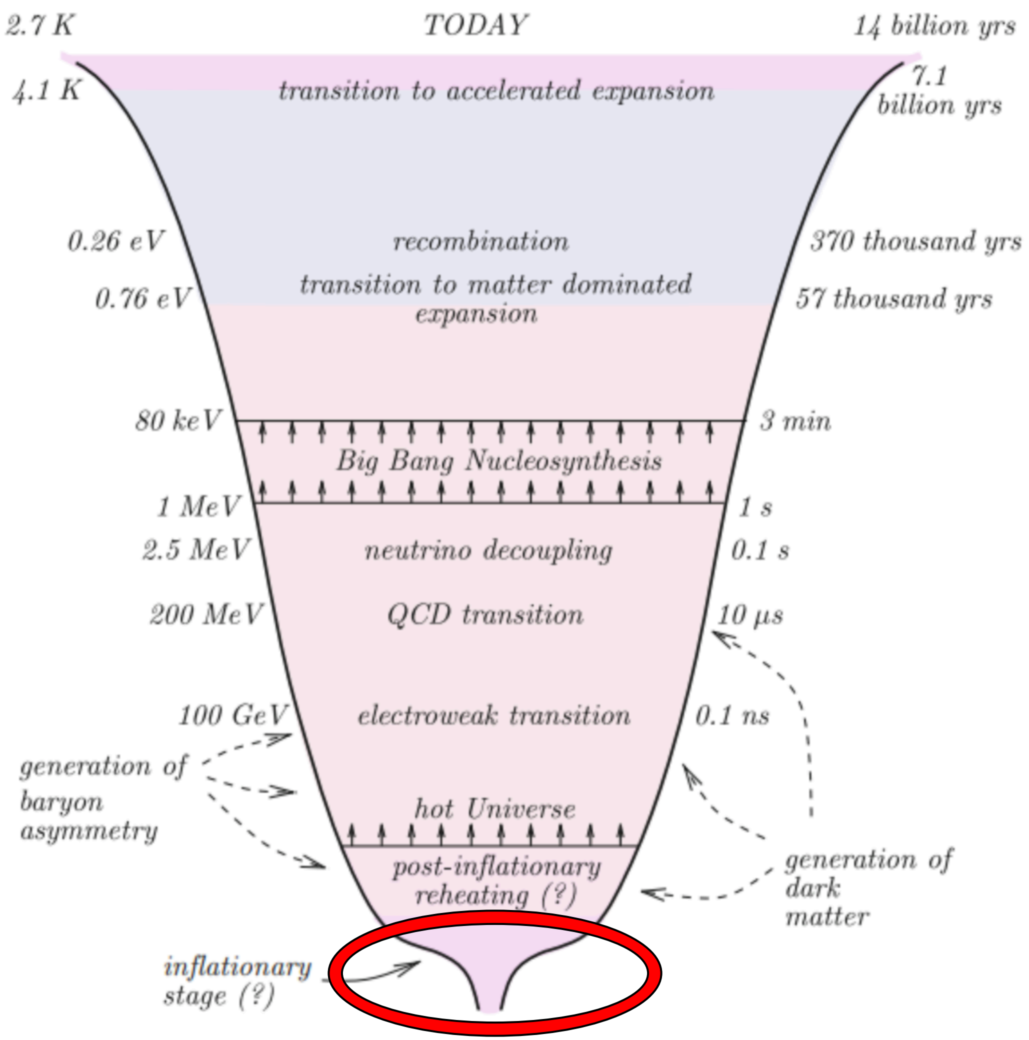

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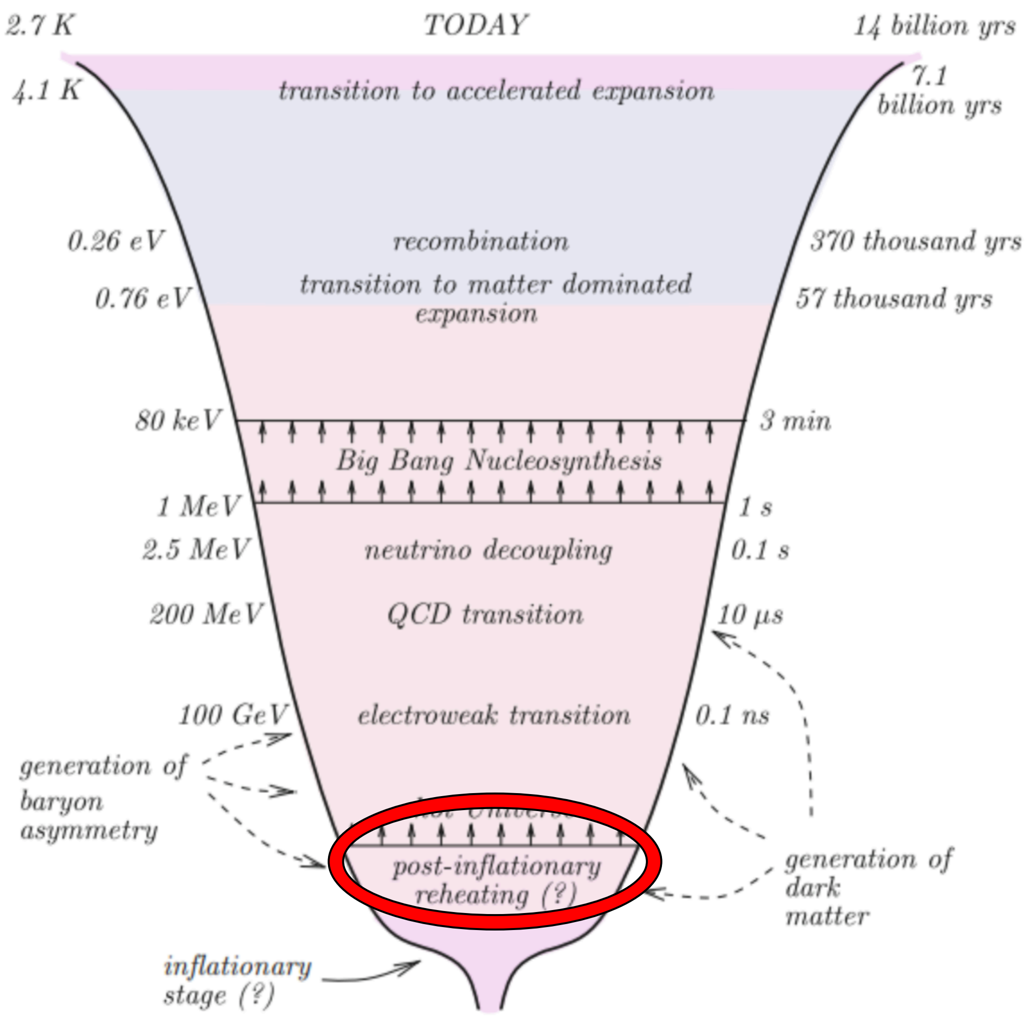

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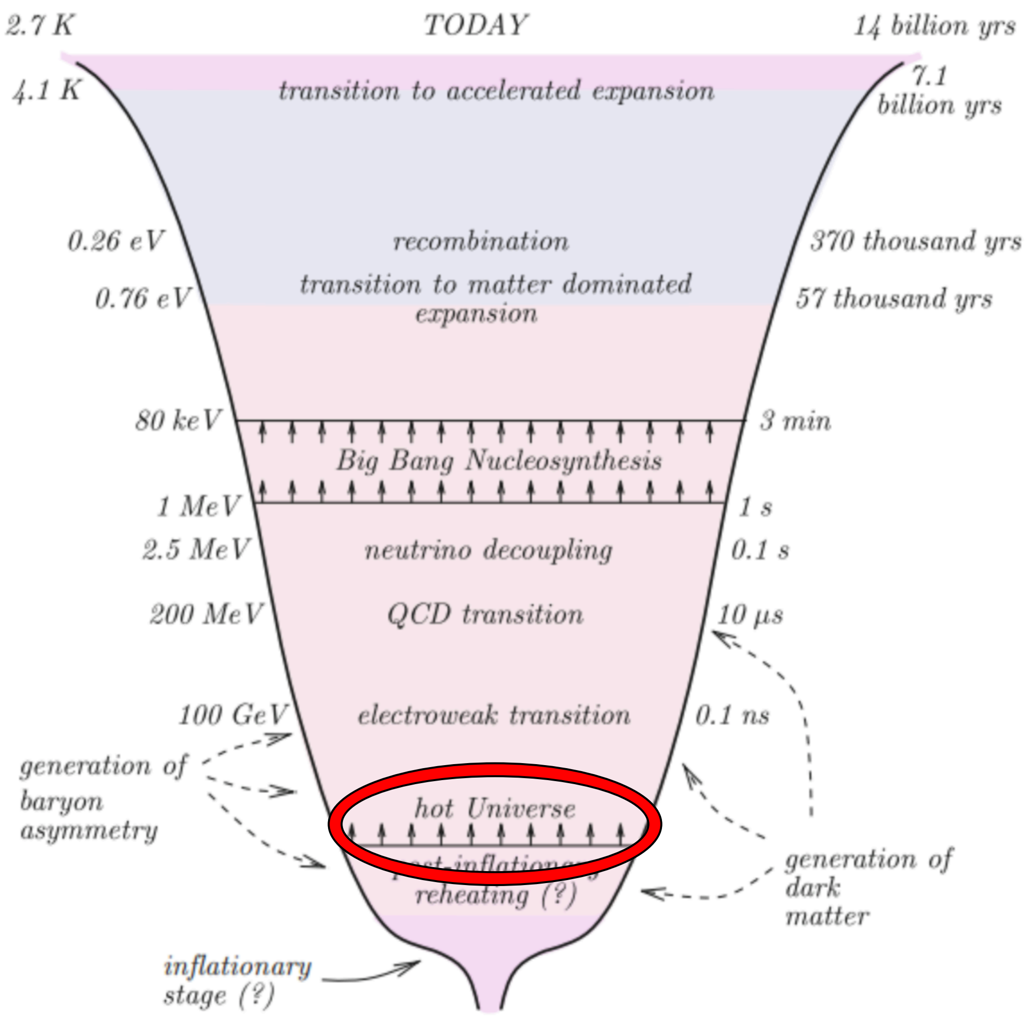

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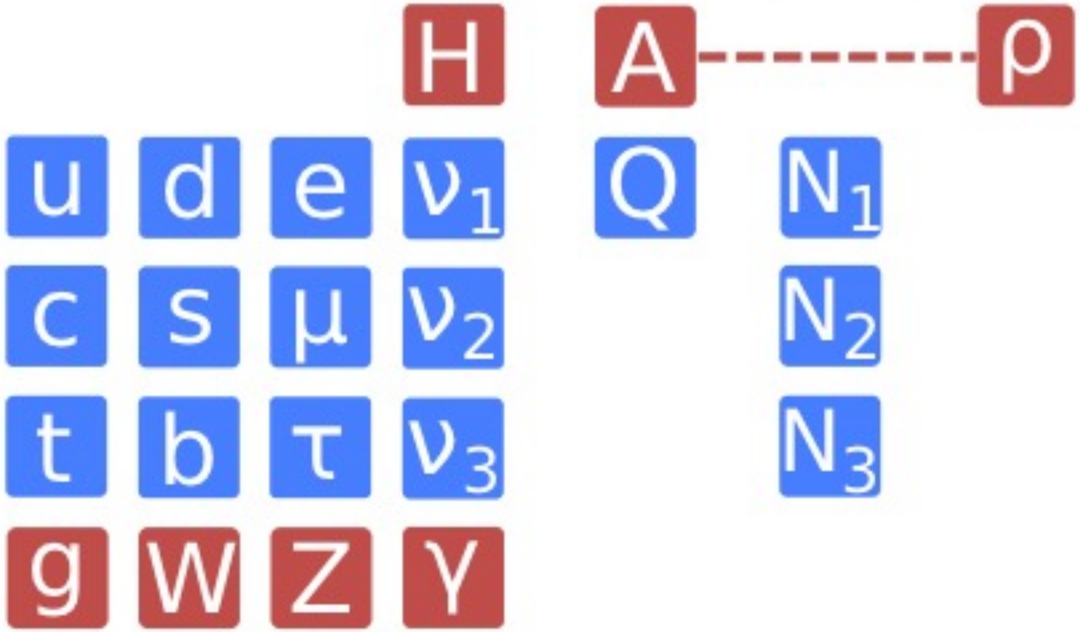

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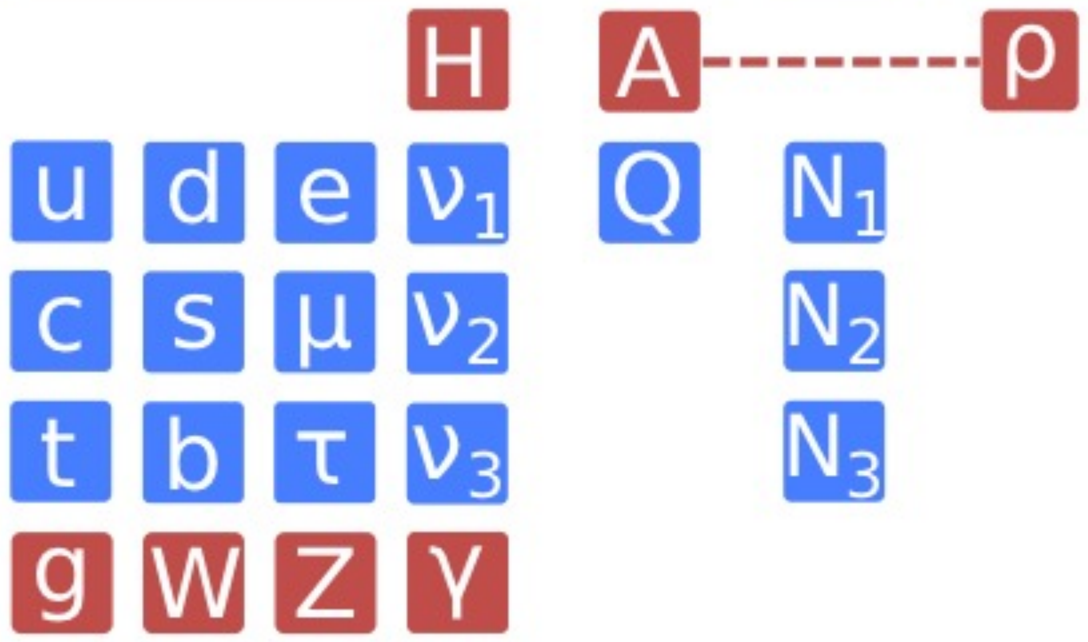

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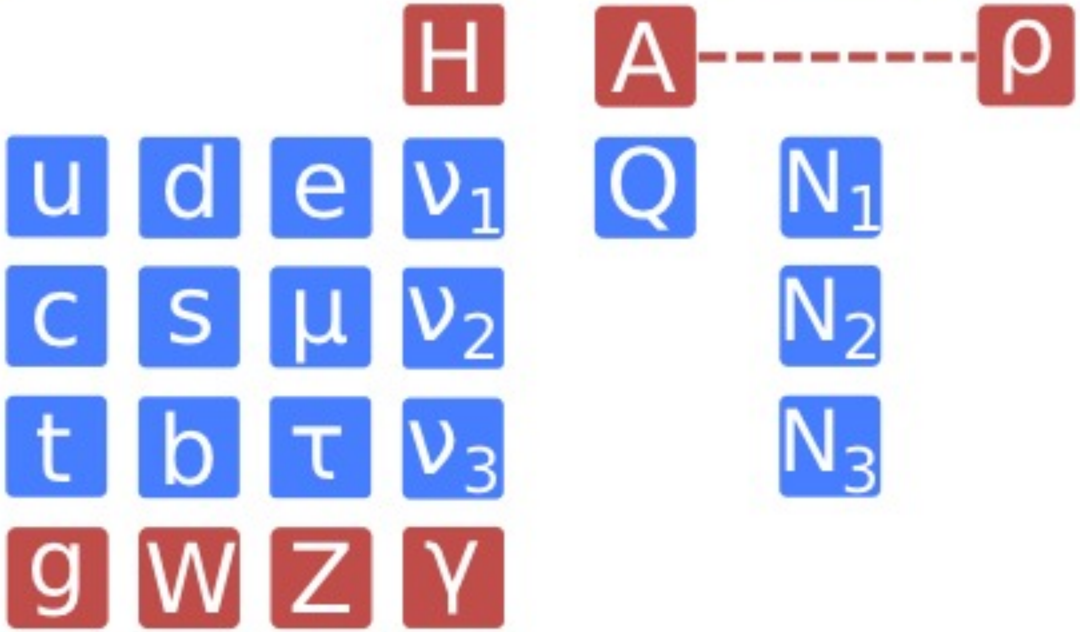

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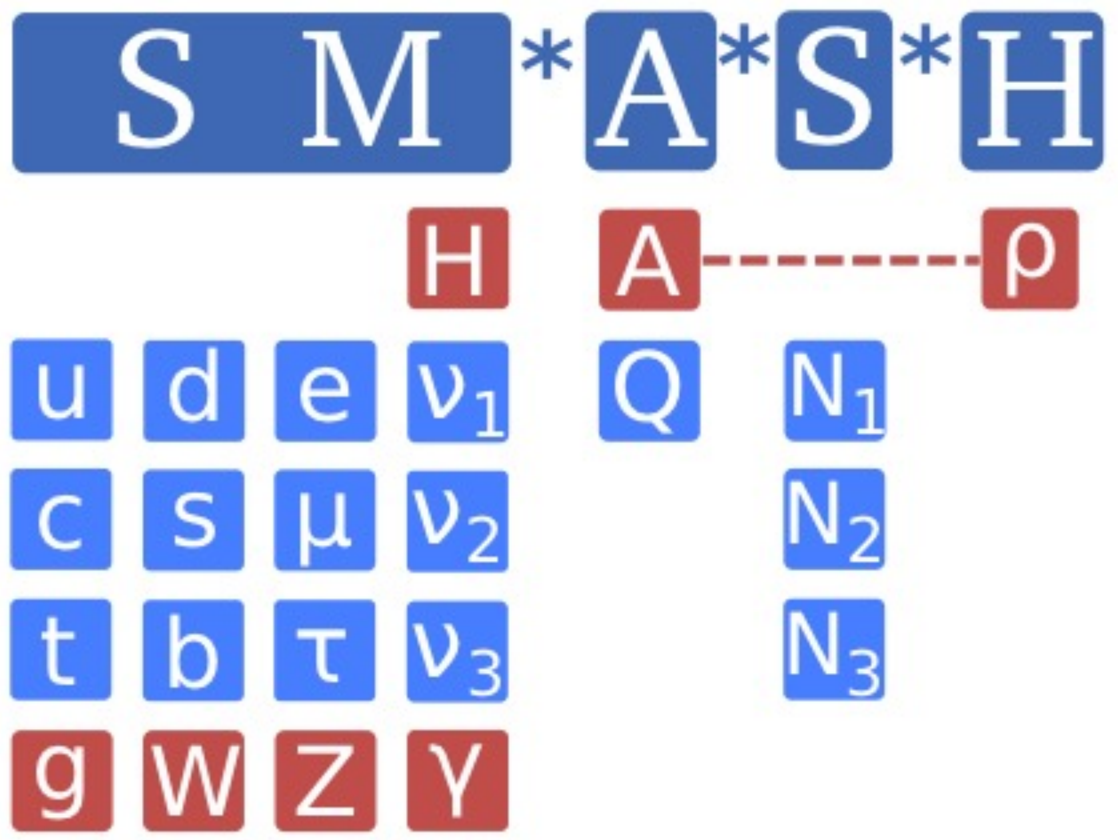
- Has been dubbed SM*A*S*H model

  [Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]



Standard Model*Axion*Seesaw*Higgs-Portal Inflation

Minimal model of particle physics and cosmology [Ballesteros, Redondo, AR, Tamarit, arXiv:1608.05414; 1610.01639]

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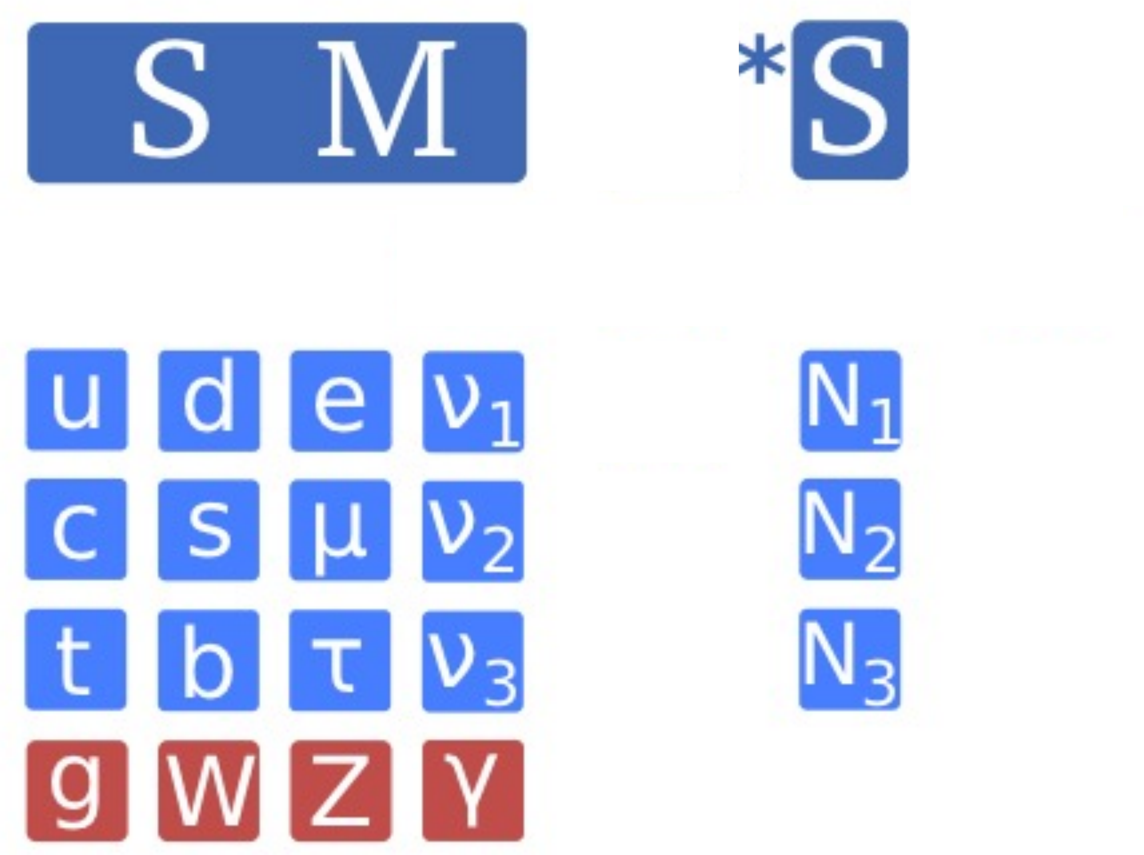

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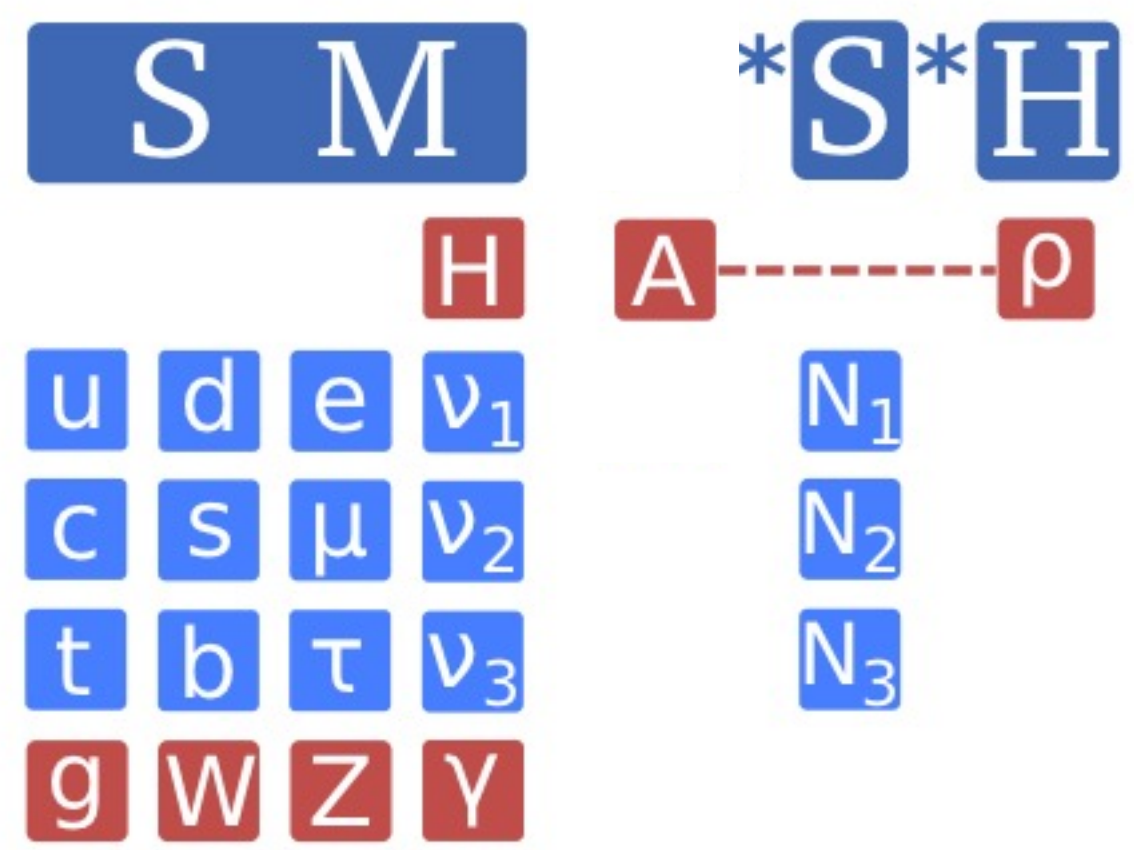

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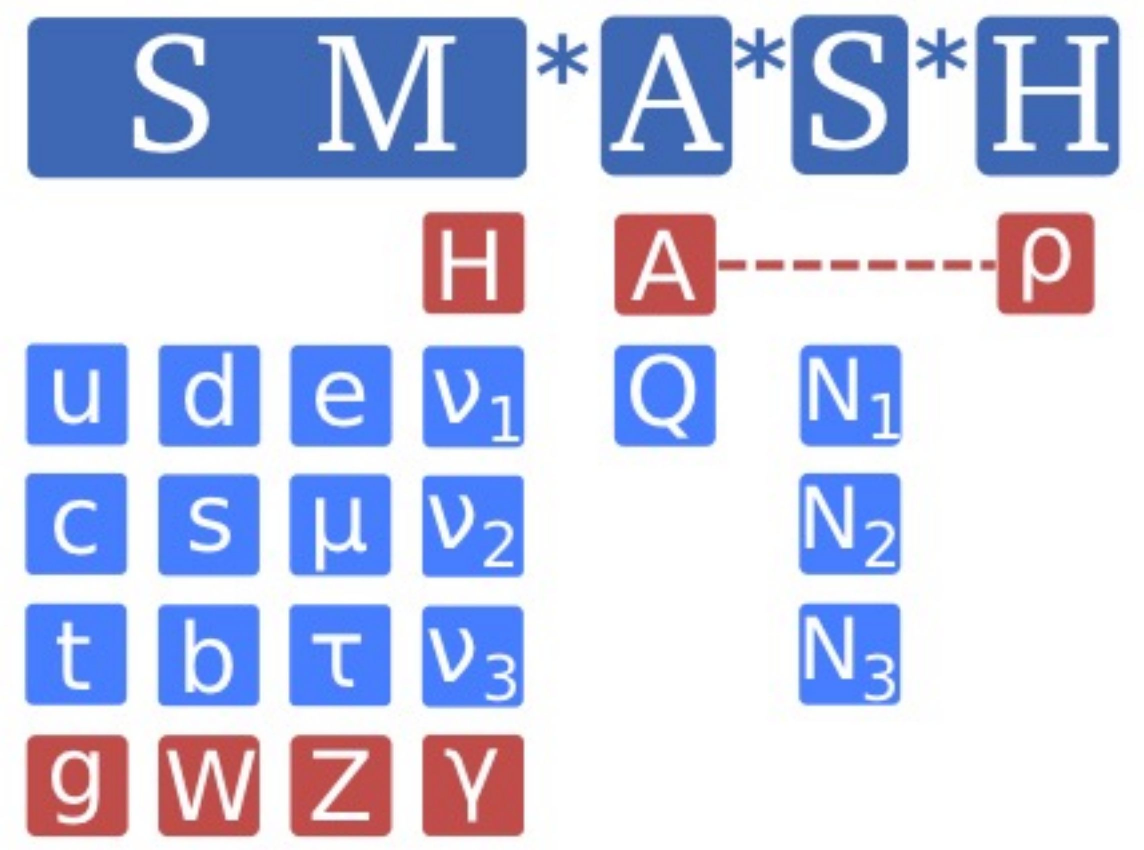

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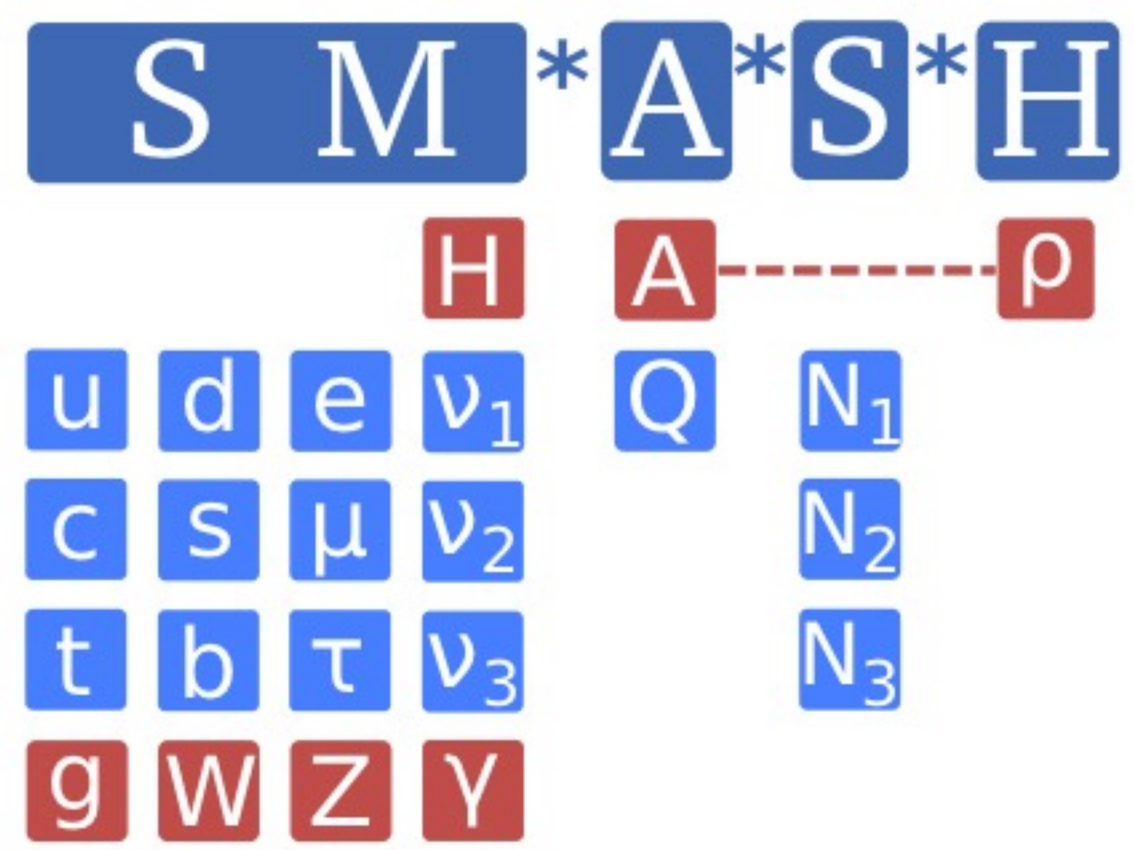

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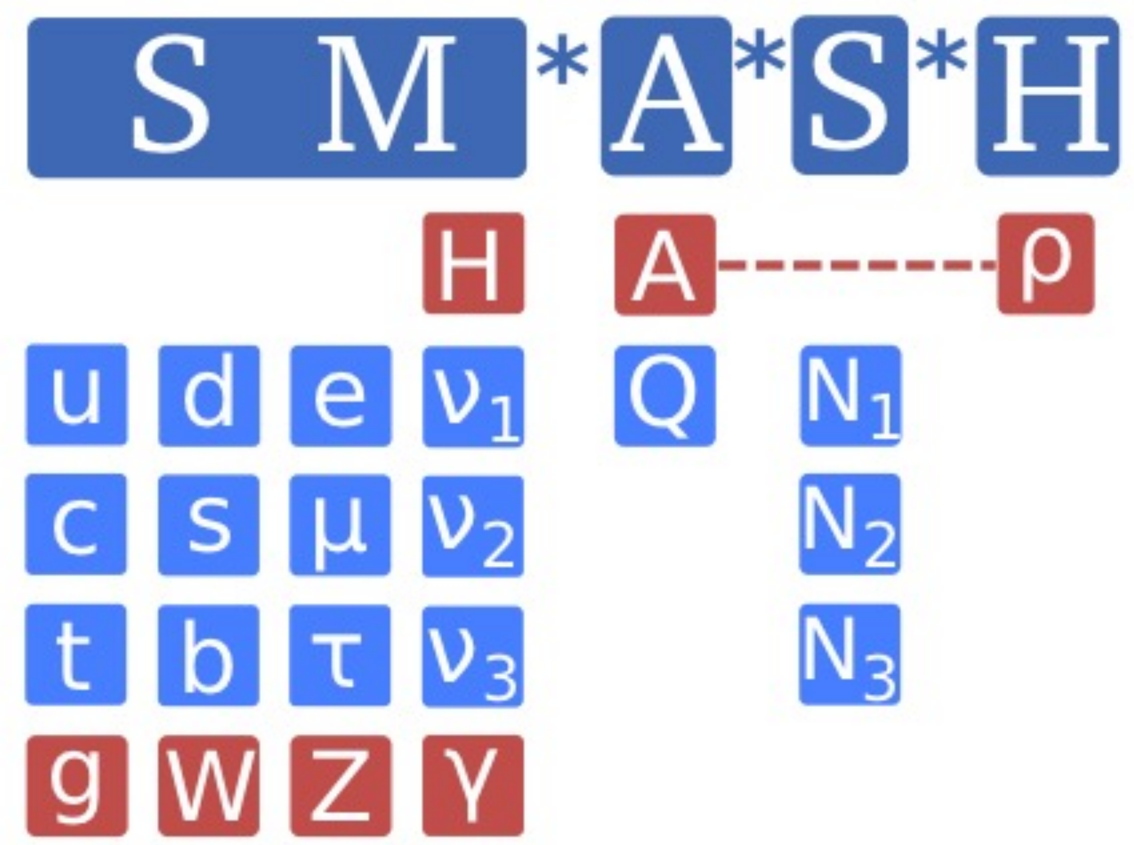

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2. **Dark matter** (Axion)

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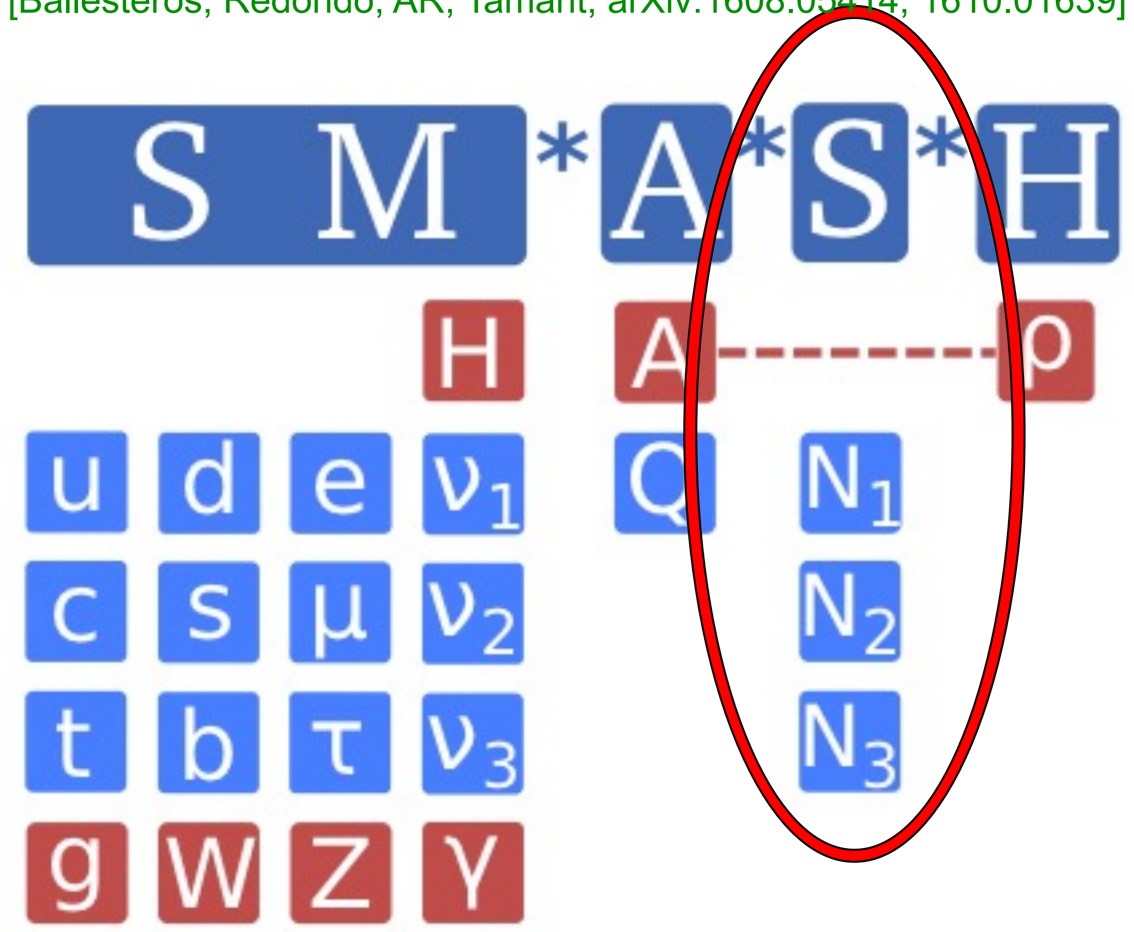

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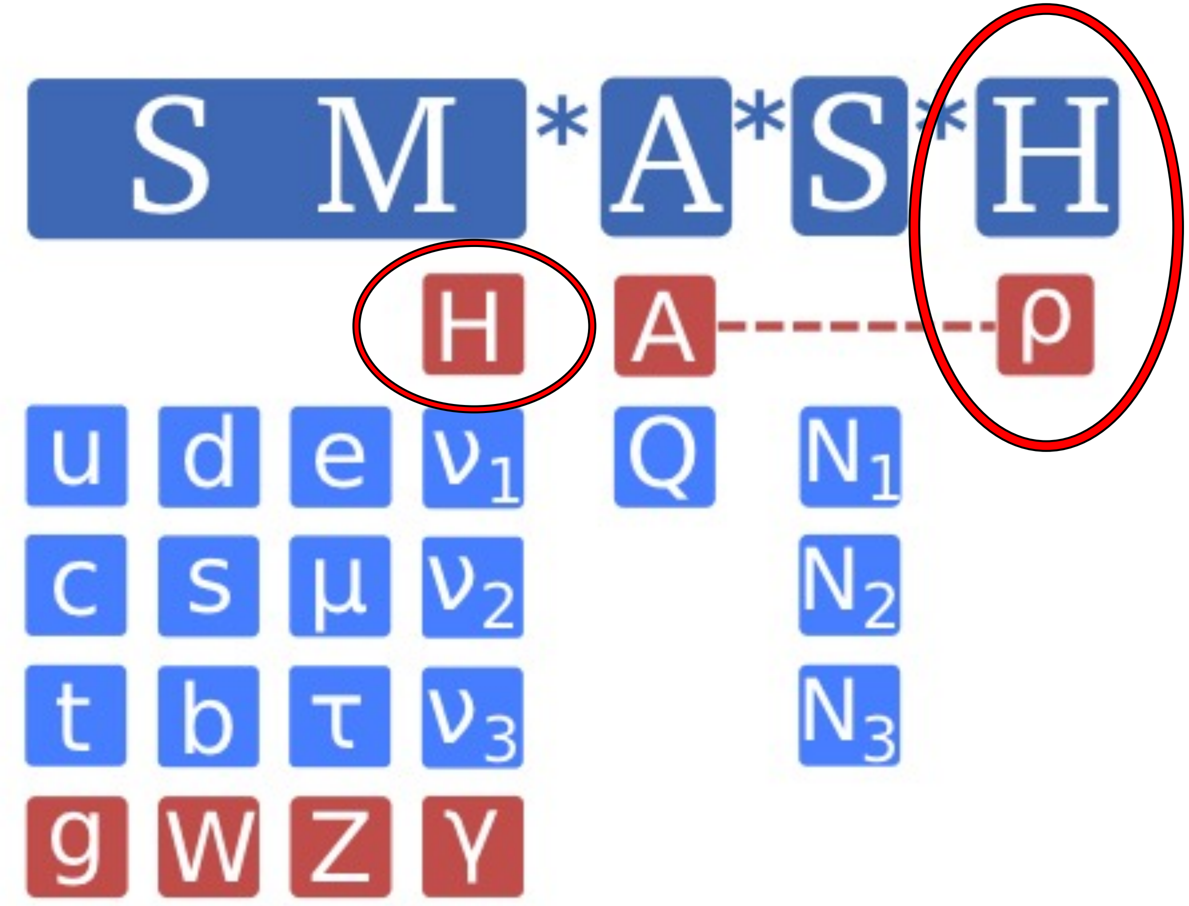
5. **Inflation** (Higgs-portal inflation)



Inflation in SMASH

Higgs-Peccei-Quinn inflation

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Mixture of the modulus $\rho = \sqrt{2} \mid \sigma \mid$ of the Peccei-Quinn (PQ) field with the modulus of the Higgs field is a perfect inflaton candidate

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- Exploit unavoidable non-minimal coupling of Higgs and PQ field to gravity,

$$S \supset - \int d^4x \sqrt{-g} \left[\frac{M^2}{2} + \xi_H \, H^\dagger H + \xi_\sigma \, \sigma^* \sigma \right] R; \qquad M_P^2 = M^2 + \xi_H v^2 + \xi_\sigma v_\sigma^2$$

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$$\tilde{V}(h,\rho) = \frac{1}{\Omega^4(h,\rho)} \left[\frac{\lambda_H}{4} \left(h^2 - v^2\right)^2 + \frac{\lambda_\sigma}{4} \left(\rho^2 - v_\sigma^2\right)^2 + \frac{\lambda_{H\sigma}}{2} \left(h^2 - v^2\right) \left(\rho^2 - v_\sigma^2\right) \right]$$

$$\Omega^2(h,\rho) = 1 + \frac{\xi_H (h^2 - v^2) + \xi_\sigma (\rho^2 - v_\sigma^2)}{M_P^2}$$

[Spokoiny 84; Futamase,Maeda 89; Salopek et al. 89; Fakir,Unruh 90; Bezrukov,Shaposhnikov 08; Fairbairn et al.. 14]

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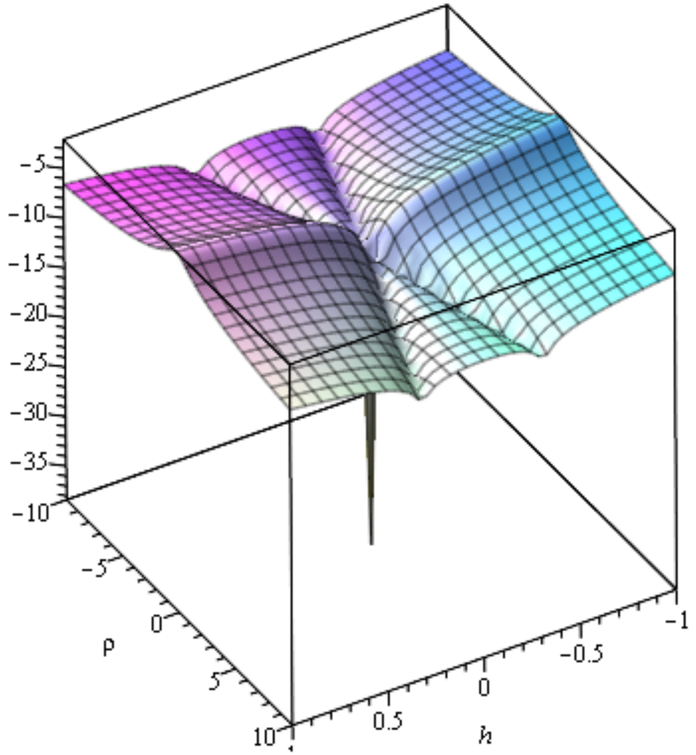

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$$\phi = \sqrt{2}\,\mathrm{Re}\sigma$$

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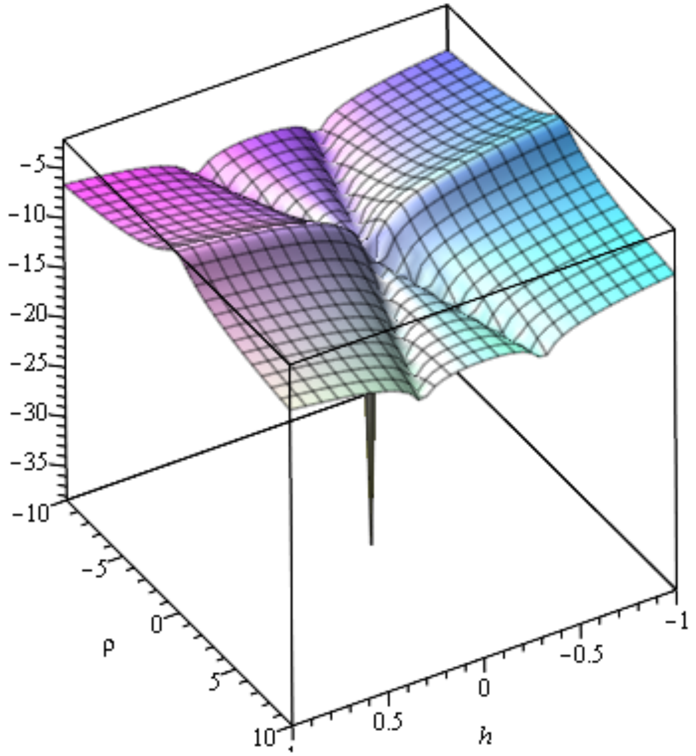

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- Effectively single field inflation with potential (in Einstein frame)

$$\phi = \sqrt{2}\,\mathrm{Re}\sigma$$

$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4\left(1 + \xi_\sigma\frac{\phi(\chi)^2}{M_P^2}\right)^{-2}, \quad \tilde{\lambda}_\sigma \equiv \lambda_\sigma\left(1 - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma\lambda_H}\right)$$

$$\Omega^2\, d\chi/d\phi \simeq \left(b\,\Omega^2 + 6\,\xi_\sigma^2\,\phi^2/M_P^2\right)^{1/2}$$

$$b = 1 + |\lambda_{H\sigma}/\lambda_H|$$

Inflation in SMASH

Density waves and GWs

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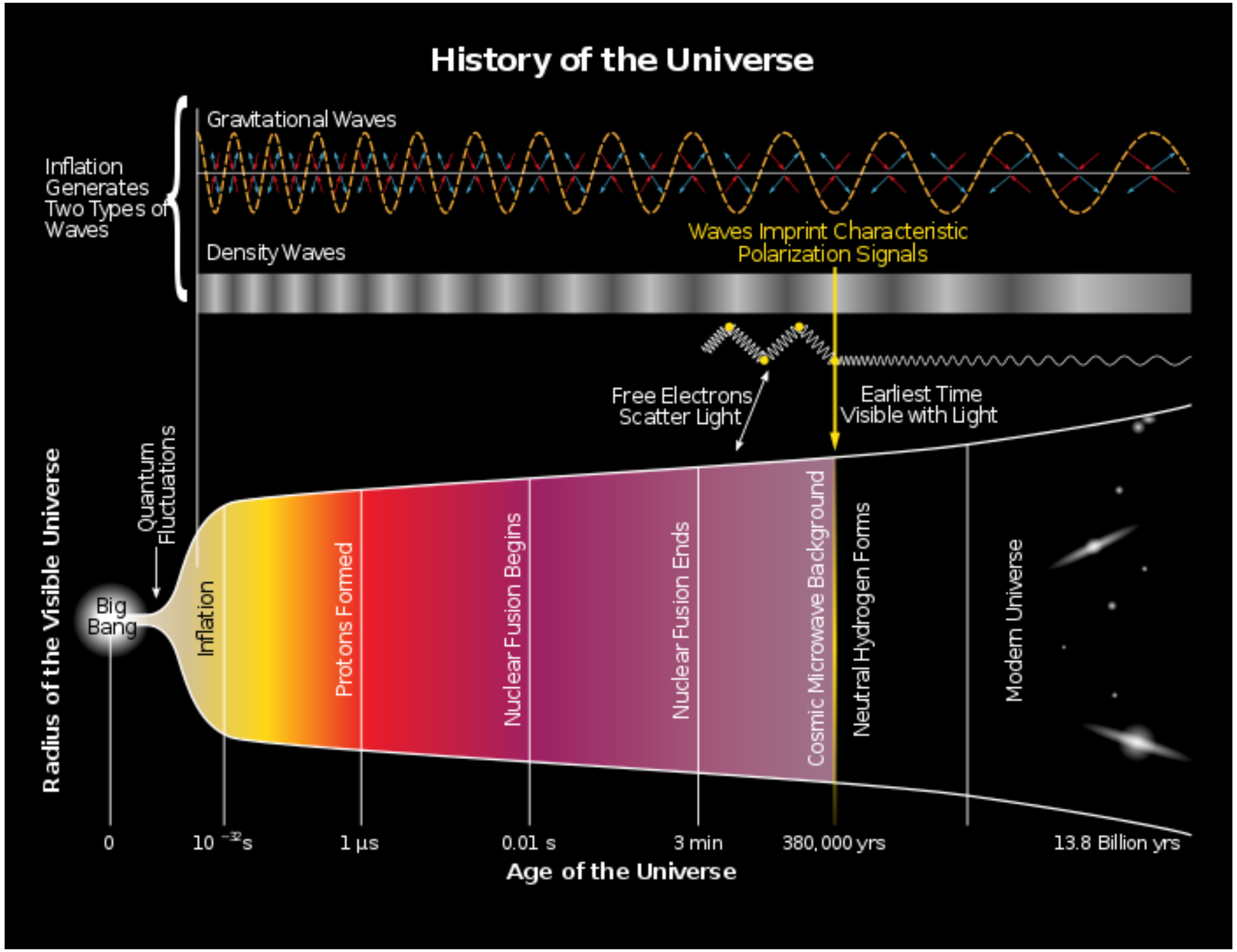
Quantum fluctuations during slow-roll inflation along this potential produce

- power spectra of **density waves** (scalar metric perturbations) and **GWs** (tensor metric perturbations)

$$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$



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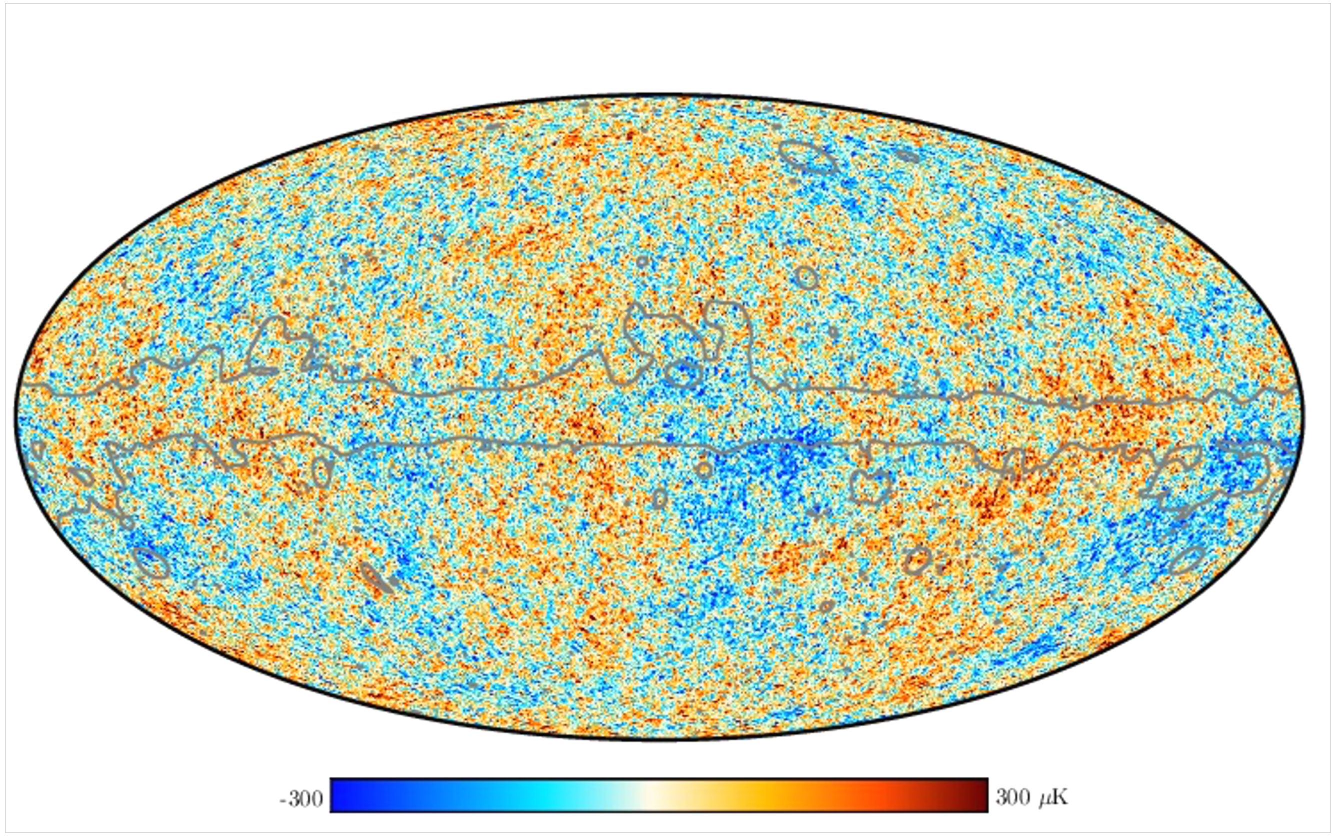
- consistent with CMB **temperature**



[PLANCK Collaboration, arXiv:1807.06205]

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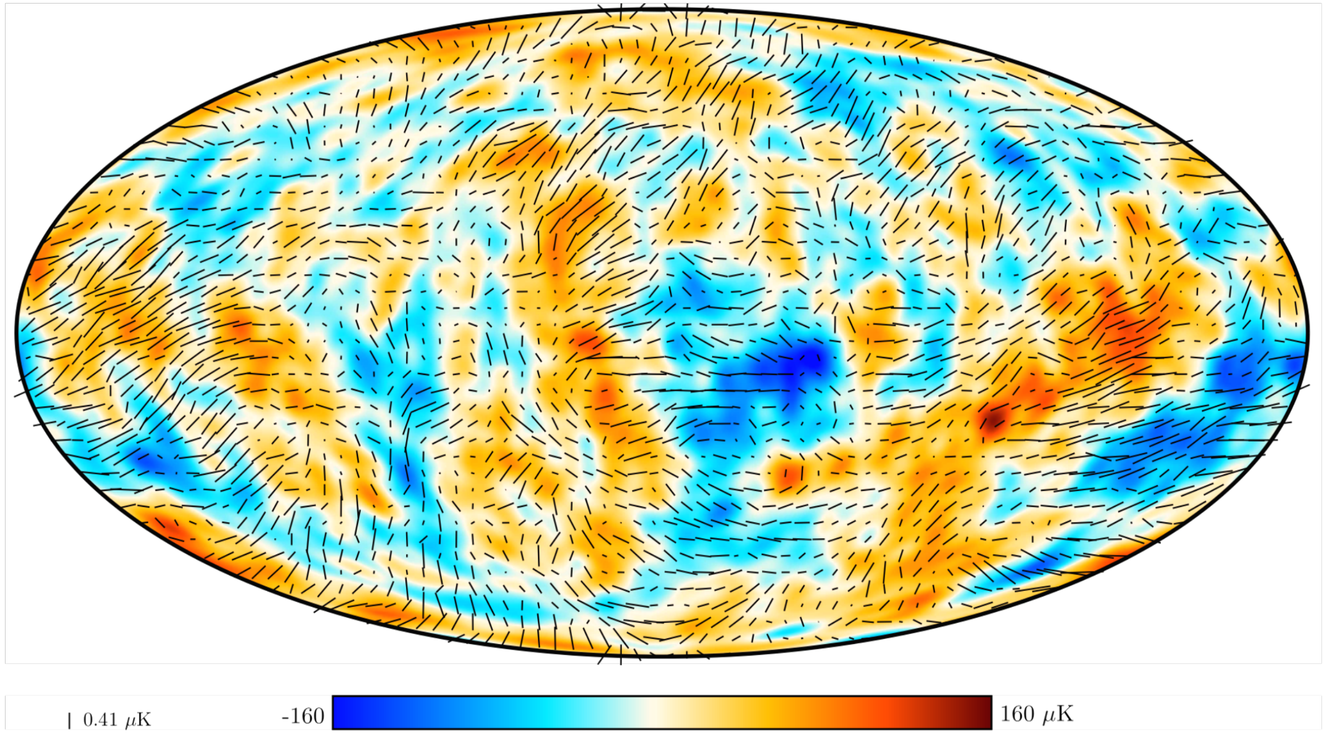
- consistent with CMB **temperature** and **polarization** data



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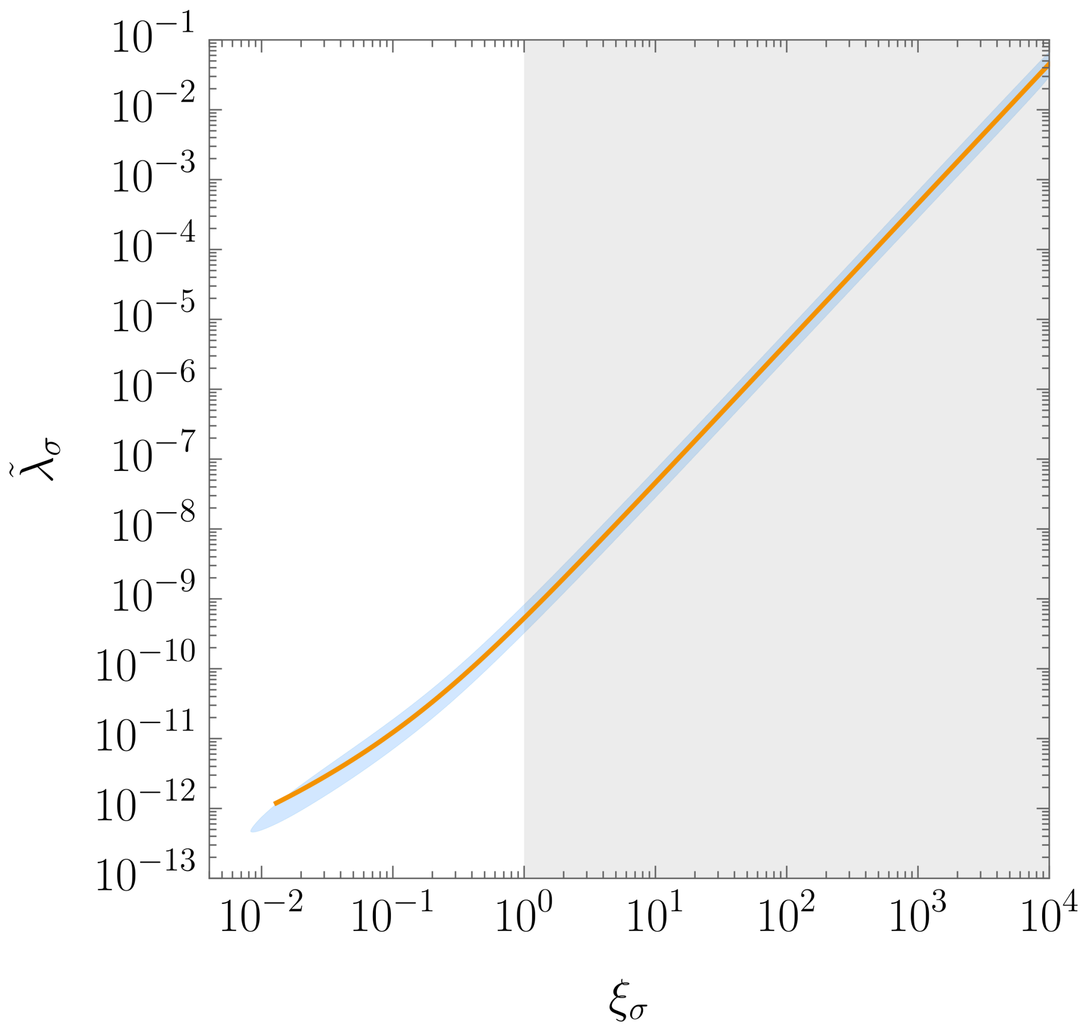
$$7 \times 10^{-3} \lesssim \xi_\sigma \simeq 4 \times 10^4 \sqrt{\tilde{\lambda}_\sigma} \lesssim 1$$



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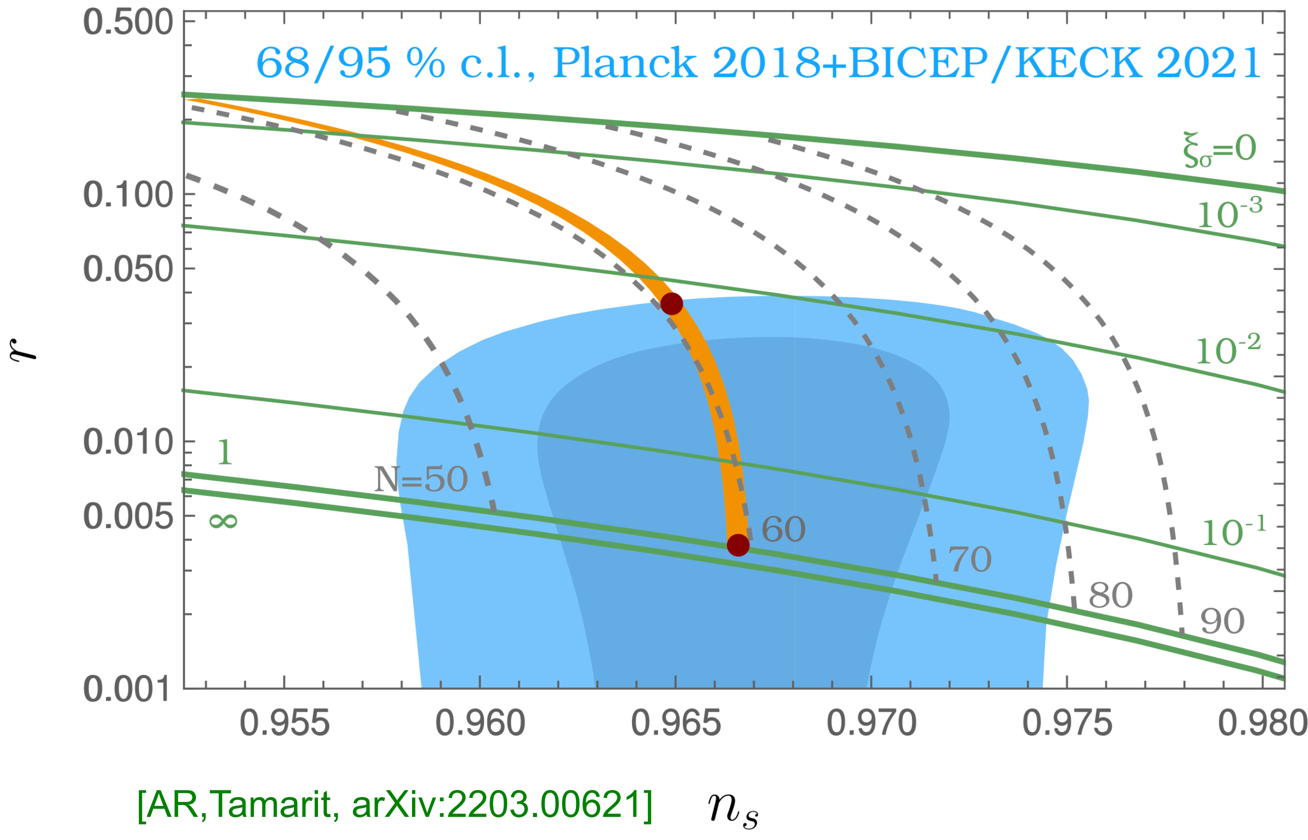
  $$7\times 10^{-3} \lesssim \xi_\sigma \simeq 4\times 10^4 \sqrt{\tilde{\lambda}_\sigma} \lesssim 1$$

- **tensor to scalar ratio,** $r(k) \equiv \Delta_t^2(k)/\Delta_s^2(k)$ which is bounded from below at a level which is observable at next generation CMB polarization experiments [BICEP Array, CMB-S4, LiteBIRD, Simons Obervatory]



[AR,Tamarit, arXiv:2203.00621]

Inflation in SMASH

Density waves and GWs

$$\tilde{V}(\chi) = \frac{1}{4}\tilde{\lambda}_\sigma \phi(\chi)^4 \left(1 + \xi_\sigma \frac{\phi(\chi)^2}{M_P^2}\right)^{-2}$$

Quantum fluctuations during slow-roll inflation along this potential produce

- power spectra of **density waves** (scalar metric perturbations) and **GWs** (tensor metric perturbations)

  $$\Delta^2_{s/t}(k) = A_{s/t}(k_*)\,(k/k_*)^{n_{s/t}(k_*)-1+\cdots}$$

- consistent with CMB **temperature** and **polarization** data for

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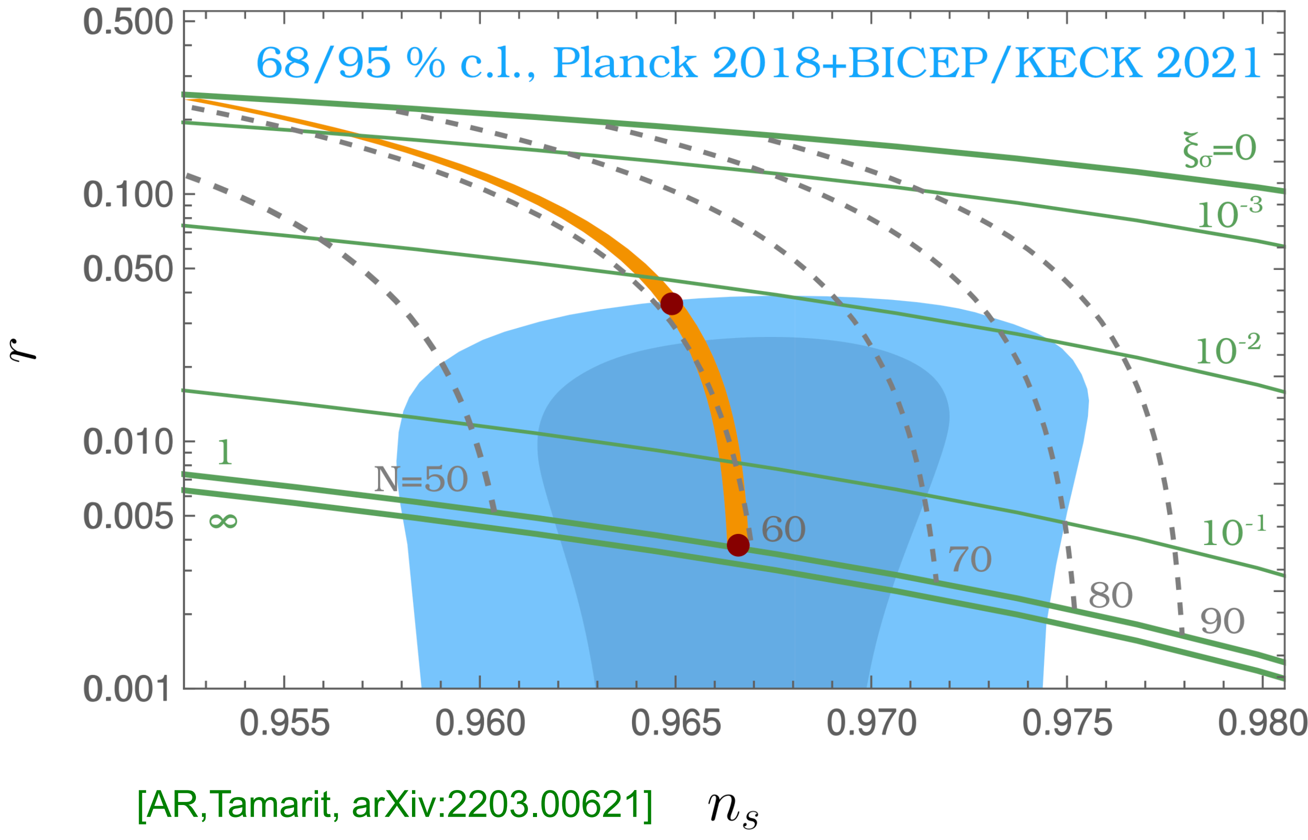

[AR,Tamarit, arXiv:2203.00621]

[CMB data on r probe GW background from quantum fluctuations during inflation (iGWB) at a pivot scale around 0.002 Mpc^{-1}, corres-ponding to a frequency around 10^{-17} Hz]

GWs from Quantum Fluctuations During Inflation

Predicted spectrum

$$\Omega_{\rm iGWB}(f) \equiv \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm iGWB}(f)}{d\ln f} = \mathcal{T}_0(f)\, \Delta_t^2(f)$$

[AR, Saikawa, Tamarit, arXiv:2009.02050]

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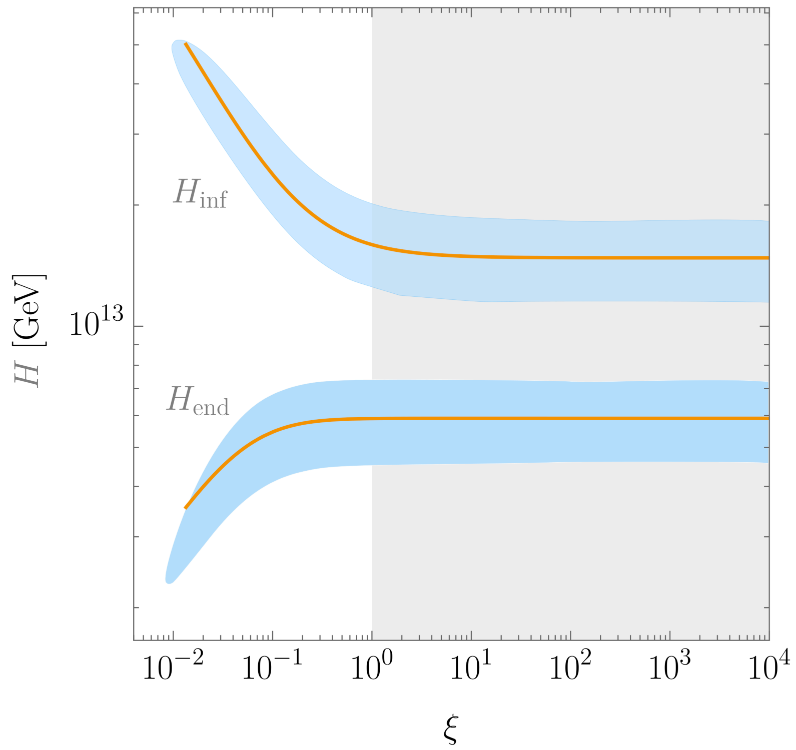
- **Power spectrum of GWs** generated during inflation expressed in terms of the present frequency:

$$\Delta_t^2(f) = \frac{2}{\pi^2} \frac{\mathcal{H}^2}{M_P^2}\bigg|_{2\pi f = (a_{\rm inf}/a_0)\mathcal{H}_{\rm inf}} \approx 3.4 \times 10^{-12} \left(\frac{\mathcal{H}_{\rm inf}}{10^{13}\,{\rm GeV}} \right)^2$$



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- Transfer function accounts for evolution of GWs after their modes re-enter the horizon after inflation
- **Spectrum of primordial GWs** from inflation almost flat up to dips and steps at frequencies corre-sponding to temperatures at which EOS changes considerably,

$$h^2\,\Omega_{\rm iGWB} \approx 1.1 \times 10^{-17} \left[\frac{g_{*\rho}(T_{\rm hc}(f))}{g_{*s}(T_{\rm hc}(f))}\right]^{\frac{4}{3}} [g_{*\rho}(T_{\rm hc}(f))]^{-\frac{1}{3}} \left(\frac{\mathcal{H}_{\rm inf}}{10^{13}\,{\rm GeV}}\right)^2$$

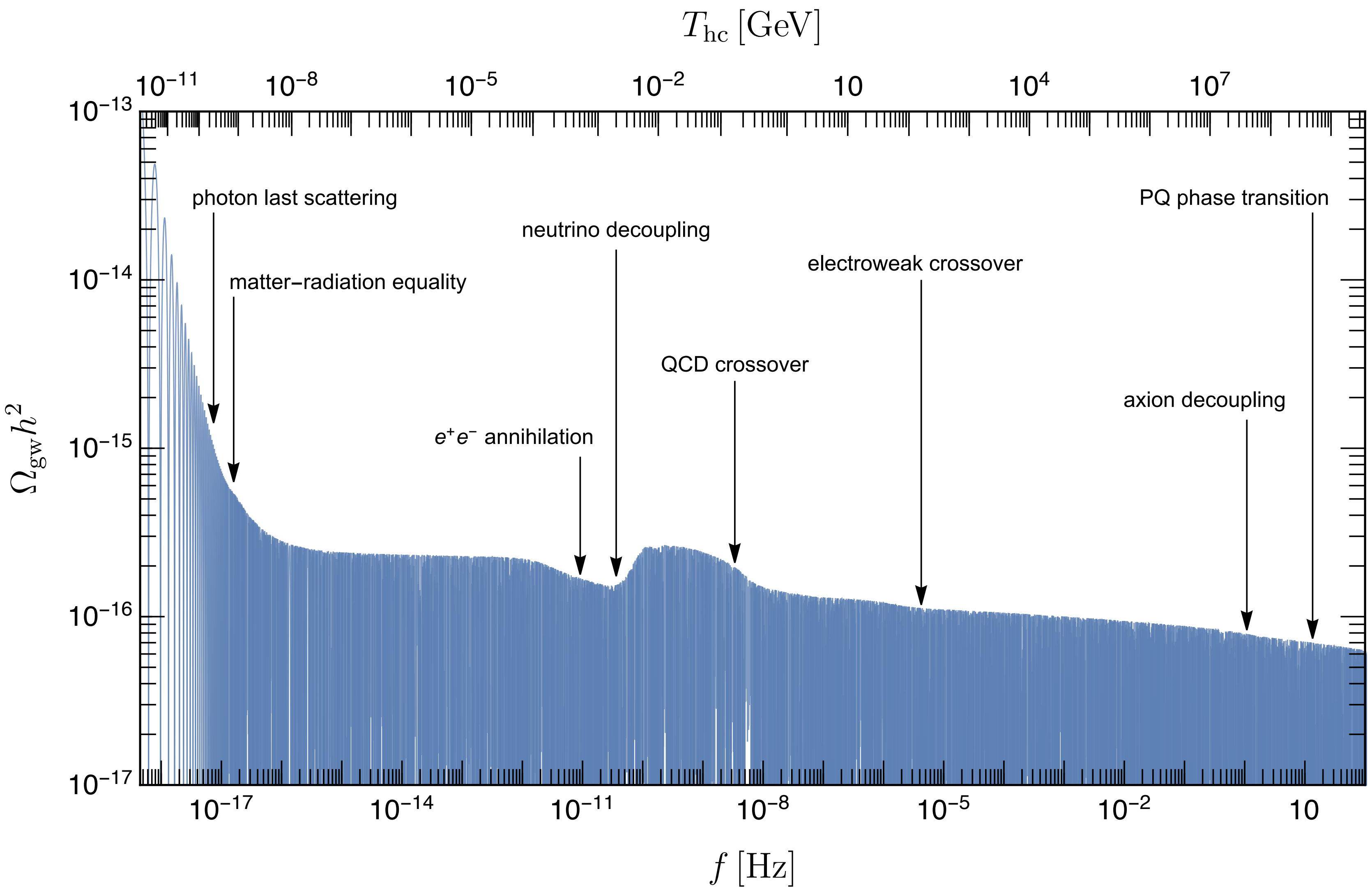
  - $T_{\rm hc}(f)$: Temperature at which mode corresponding to frequency re-entered horizon after reheating:

$$T_{\rm hc}(f) = 10^8\,{\rm GeV}\, \frac{f}{1.2\,{\rm Hz}} \left[\frac{g_{*s}(T_{\rm hc}(f)}{g_{*\rho}(T_{\rm hc}(f))}\right]^{1/2} [g_{*s}(T_{\rm hc}(f)]^{-1/6}$$

GWs from Quantum Fluctuations During Inflation

Cosmic history imprinted in primordial GW spectrum

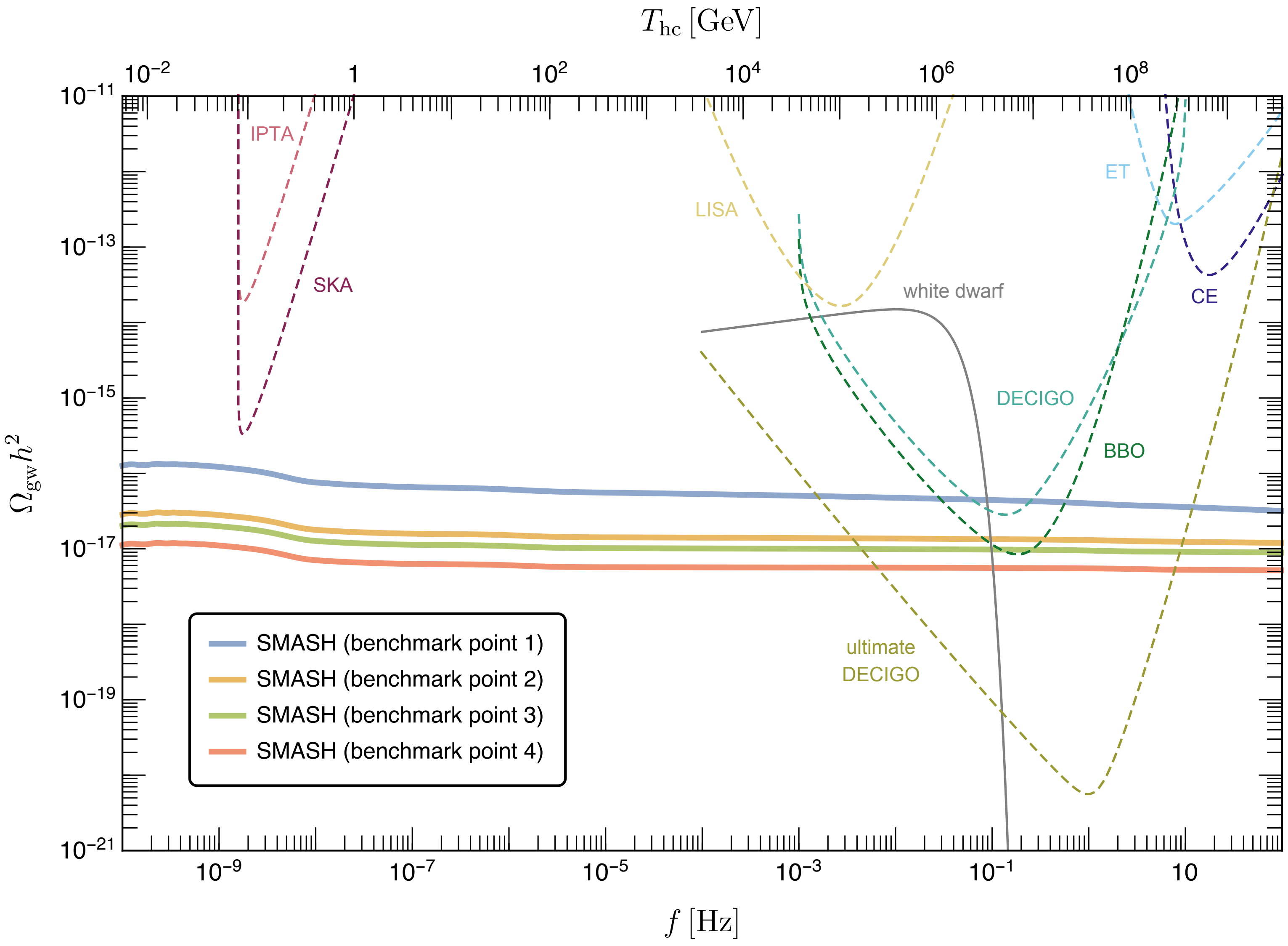
[AR, Saikawa, Tamarit, arXiv:2009.02050]



GWs from Quantum Fluctuations During Inflation

Can be probed directly by future space-born interferometer

[AR, Saikawa, Tamarit, arXiv:2009.02050]

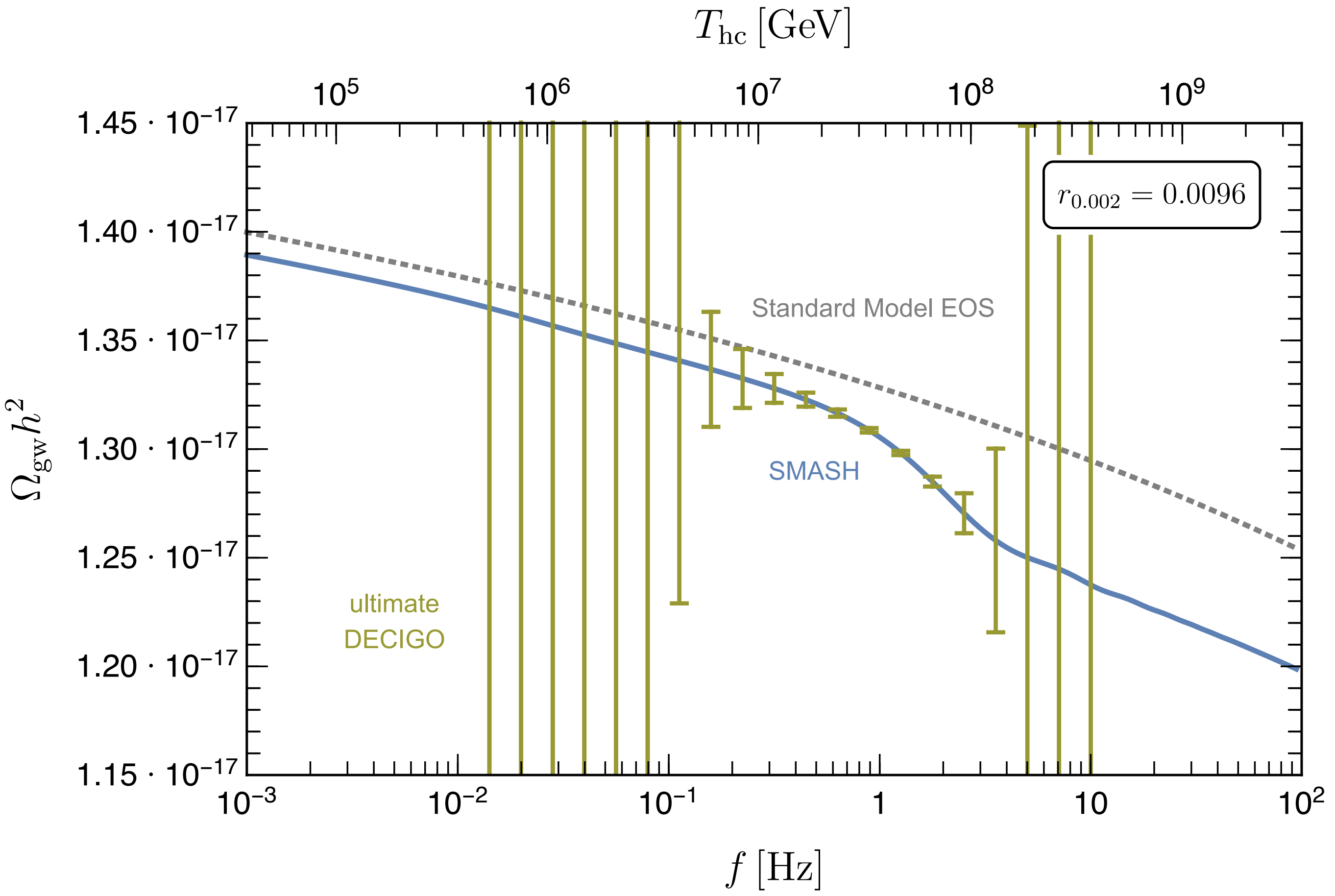


Benchmark point	1	2	3	4
$r(0.002\ \mathrm{Mpc}^{-1})$	0.048	0.0096	0.0068	0.0037
$n_s(0.002\ \mathrm{Mpc}^{-1})$	0.9642	0.9663	0.9665	0.9666
ϕ_*/M_P	22	18	16	8.4
$\xi_\sigma(\phi_*)$	0.0096	0.079	0.14	1.0
$\tilde\lambda_\sigma(\phi_*)$	9.1×10^{-13}	9.0×10^{-12}	2.0×10^{-11}	5.3×10^{-10}
$\lambda_\sigma(M_P)$	4.4×10^{-12}	1.4×10^{-10}	5.0×10^{-11}	4.4×10^{-9}
$\lambda_{H\sigma}(M_P)$	-1.5×10^{-6}	-6.0×10^{-6}	-6.5×10^{-6}	-2.9×10^{-5}
$\lambda_H(M_P)$	0.63	0.26	1.2	0.21
$y(M_P)$	0.00056	0.0014	0.00086	0.0027
$Y_{ii}(M_P)$	0.0011	0.0025	0.0016	0.0045

GWs from Quantum Fluctuations During Inflation

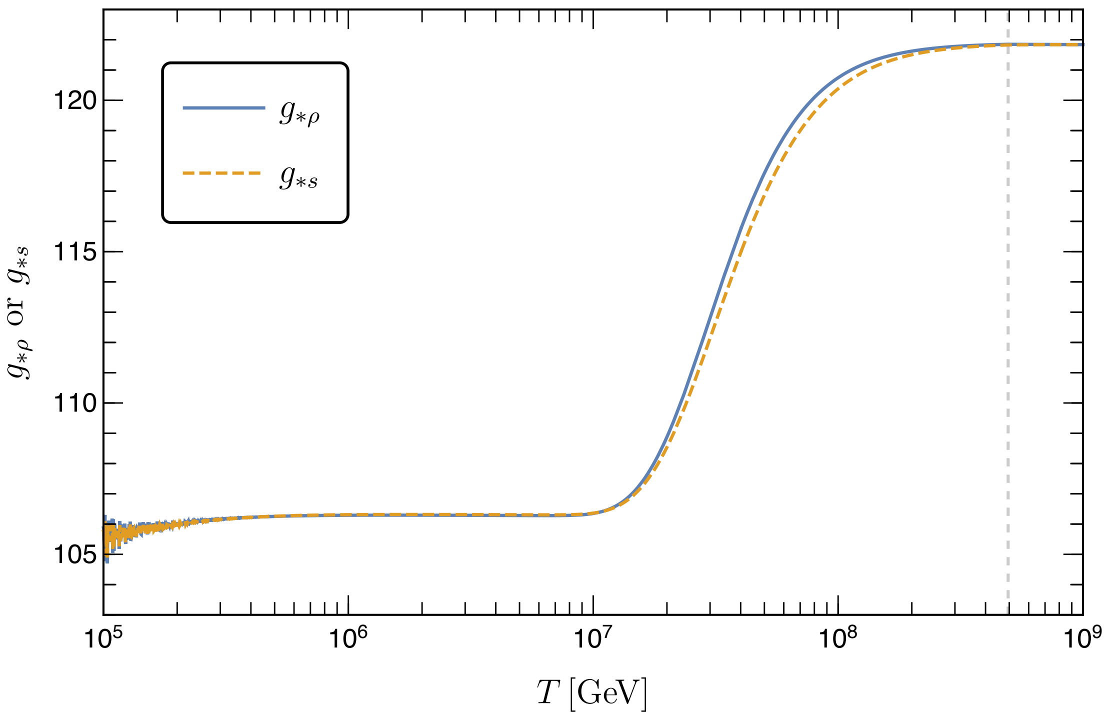
Ultimate DECIGO sensitive to step in primordial spectrum due to PQ phase transition

$$T_c \simeq \frac{2\sqrt{6\lambda_\sigma} v_\sigma}{\sqrt{8(\lambda_\sigma + \lambda_{H\sigma}) + \sum_i Y_{ii}^2 + 6y^2}} \sim \lambda_\sigma^{1/4} v_\sigma$$



Axion 100% DM: 10^{10} GeV $\lesssim v_\sigma \lesssim 2.2 \times 10^{11}$ GeV

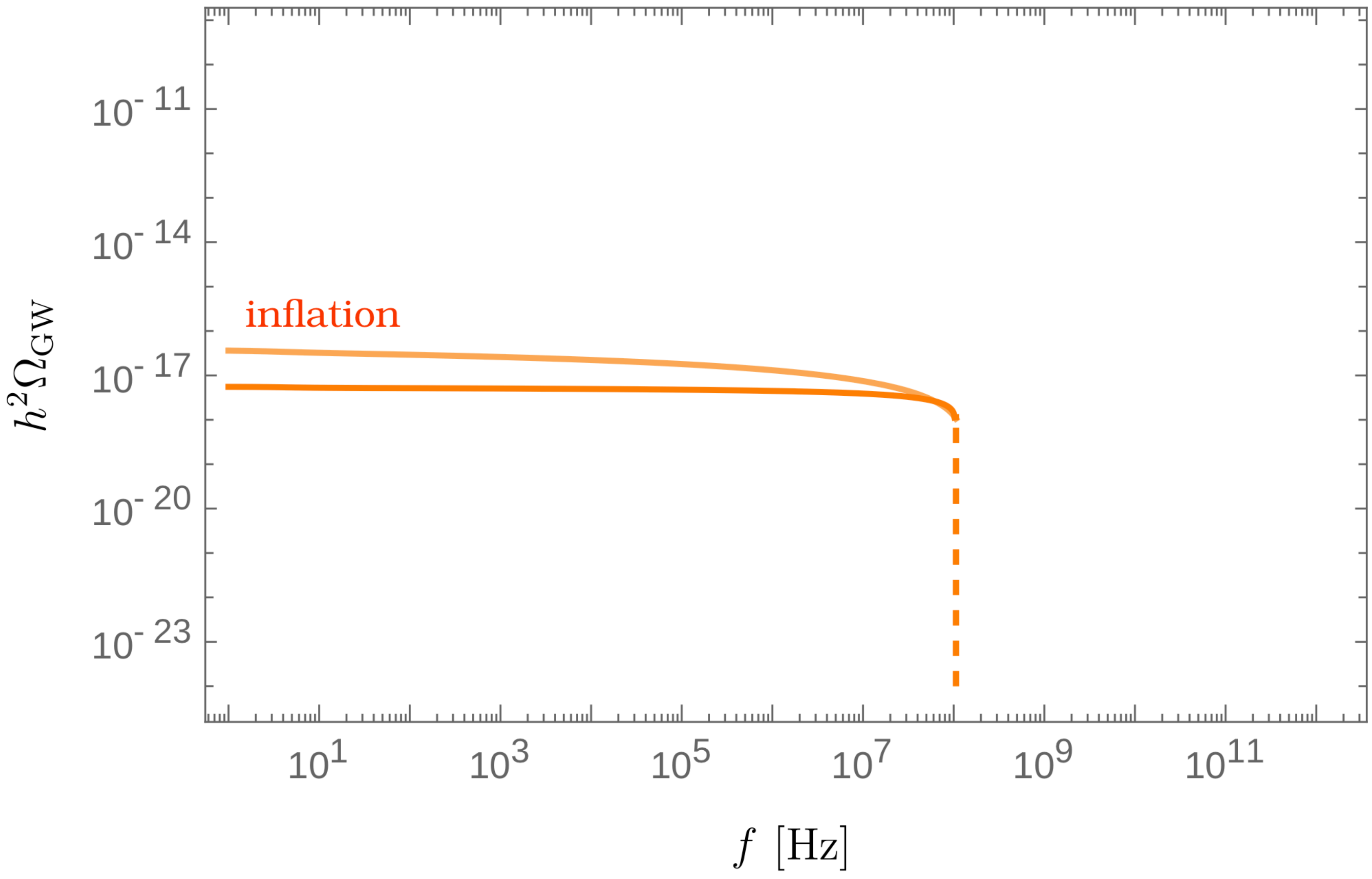
[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; AR,Saikawa `16; Klaer,Moore `17; Gorghetto,Hardy,Villadoro `18; Buschmann et al. 19; Hindmarsh 19; Gorghetto,Hardy,Villadoro '20; Buschmann et al. 21]



[AR, Saikawa, Tamarit, arXiv:2009.02050]

GWs from Quantum Fluctuations During Inflation

The bigger picture



Benchmark for $r(k_*) = 0.036$:

$$\phi_* = 21.4 M_P$$
$$\xi_\sigma(\phi_*) = 0.014$$
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$$\mathcal{H}_{\rm end} = 1.8 \times 10^{-6} M_P$$
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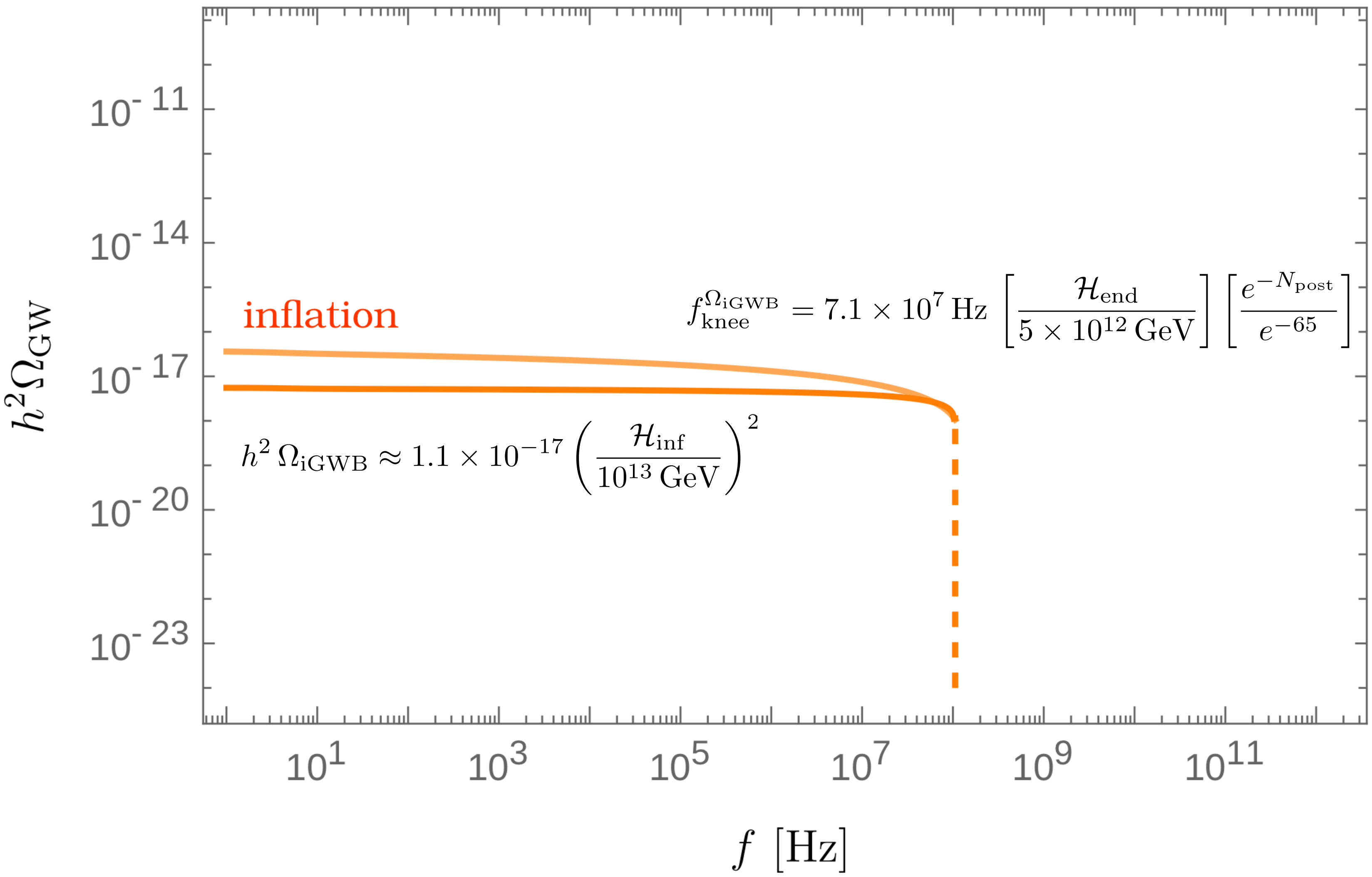

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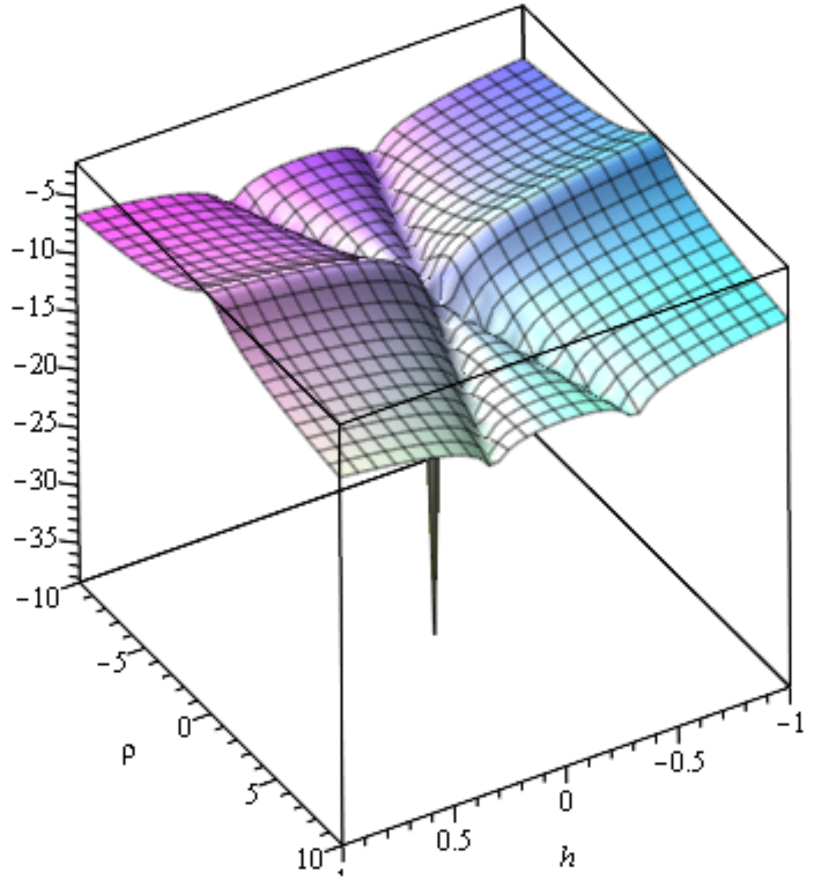
GWs from Stochastic Scalar Fluctuations during Reheating

Reheating after inflation

- Inflation ends when $\phi \sim \mathcal{O}(M_P)$



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

GWs from Stochastic Scalar Fluctuations during Reheating

Reheating after inflation

- Inflation ends when $\phi \sim \mathcal{O}(M_P)$
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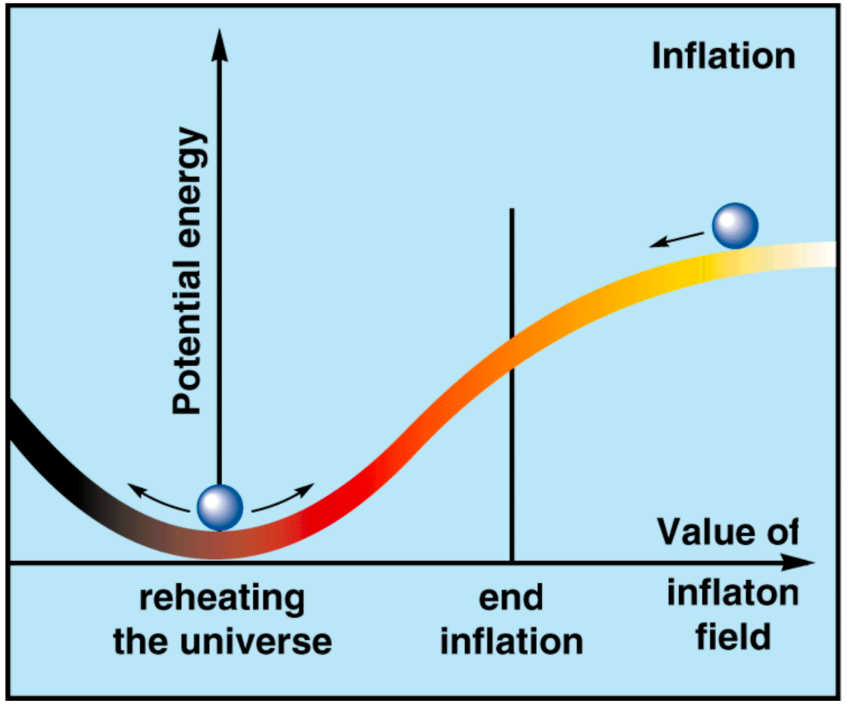
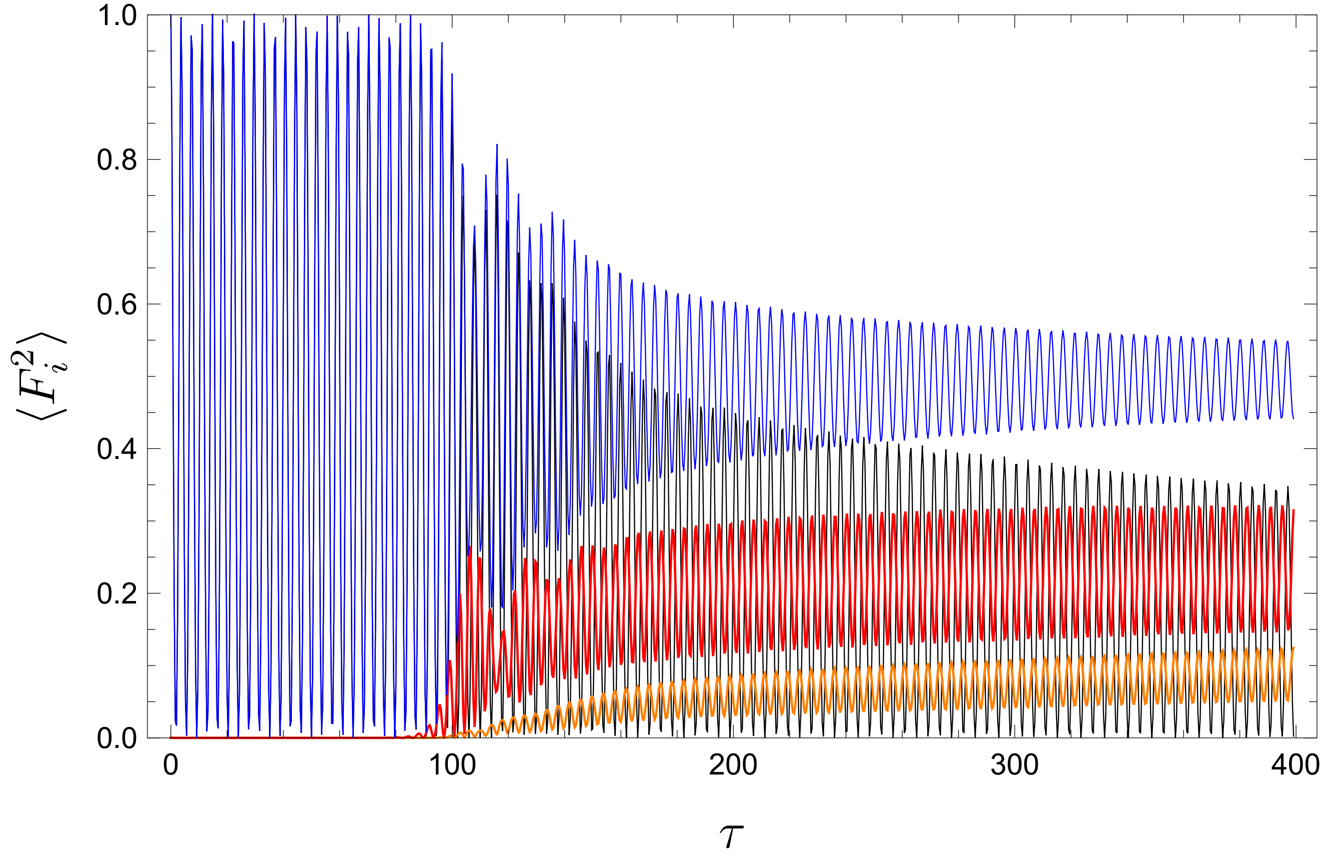


[Garcia-Bellido 99]

GWs from Stochastic Scalar Fluctuations during Reheating

Reheating after inflation

- Inflation ends when $\phi \sim \mathcal{O}(M_P)$
- Preheating
  - Violent decay of inflaton and copious production of fluctuations of bosonic fields coupled to it
  - Exponentially rapid growth of small inhomogeneities emerging from vacuum fluctuations
  - Growth stopped by violent backreaction and rescattering of waves



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GWs from Stochastic Scalar Fluctuations during Reheating

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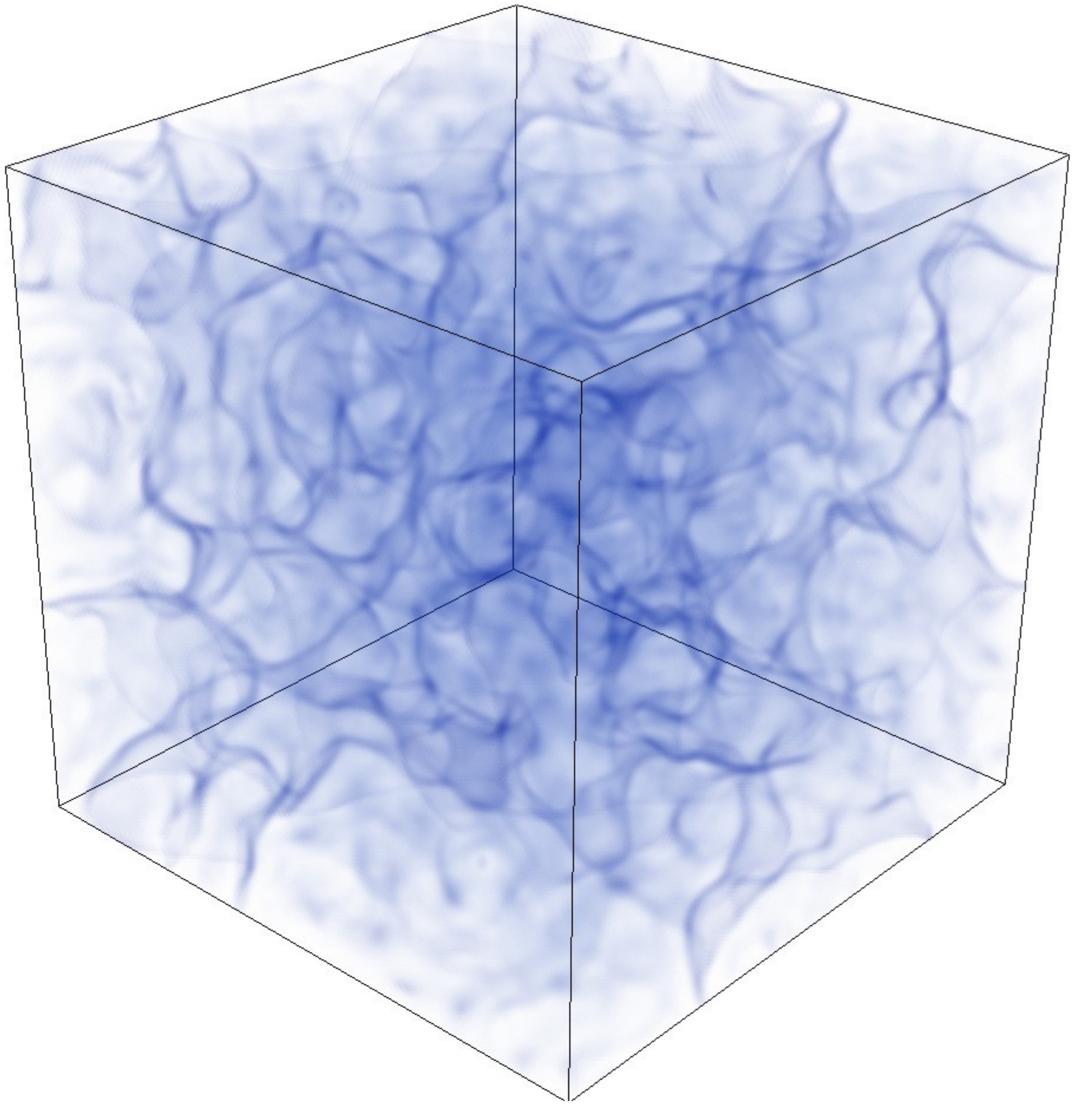
  - Exponentially rapid growth of small inhomogeneities emerging from vacuum fluctuations
  - Growth stopped by violent backreaction and rescattering of waves
  - **Inflaton fragmentation**: nonlinear formation and collision of bubble-like large value field regions
  - **Collisions of bubbles generate gravitational waves**

[Khlebnikov,Tkachev 97; Easther, Lim 06; Easther, Giblin, Lim 06, Felder,Kofman 07; Dufaux et al. 07; Garcia-Bellido, Figueroa 07; Garcia-Bellido, Figueroa, Sastre 08; Easther, Giblin, Lim 08; Dufaux et al. 09]



[Frolov, https://arxiv.org/abs/0809.4904]

GWs from Stochastic Scalar Fluctuations during Reheating

GW spectrum

- Determine GW spectrum at end of preheating by solving linearized GW equation in momentum space in a FRW background using Green's function methods: [Dufaux et al. 07]

$$S_k(\tau_{\rm fin}) = \frac{k^3}{2VM_P^2}\int d\Omega \sum_{m,n}\left\{\left|\int_{\tau_{\rm in}}^{\tau_{\rm fin}} d\tau' \cos(k\tau') a(\tau') T^{\rm TT}_{mn}(\tau',\mathbf{k})\right|^2 + \left|\int_{\tau_{\rm in}}^{\tau_{\rm fin}} d\tau' \sin(k\tau') a(\tau') T^{\rm TT}_{mn}(\tau',\mathbf{k})\right|^2\right\}$$

  - τ denotes conformal time (with current value τ_0 and satisfying $d\tau/dt = 1/a$), V is the 3D spatial volume, $T^{\rm TT}_{mn}(\tau',\mathbf{k})$ are the Fourier transforms of the spatial components of the transverse-traceless projection of the stress-energy tensor,

$$T^{\rm TT}_{mn}(\tau,\mathbf{k}) = \left(P_{mp}(\hat{\mathbf{k}})P_{nq}(\hat{\mathbf{k}}) - \frac{1}{2}P_{mn}(\hat{\mathbf{k}})P_{pq}(\hat{\mathbf{k}})\right)\sum_j \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}}\, p_p p_q \varphi_j(\tau,\mathbf{p})\varphi_j(\tau,\mathbf{k}-\mathbf{p})$$

    - $\hat{\mathbf{k}}$ denotes the unit vector in the direction of the 3-momentum $\mathbf{k}$, while $P_{mn}(\mathbf{k}) = \delta_{mn} - \hat{k}_m\hat{k}_n$ are transverse projectors, and the sum over j runs over all real scalar fields

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- Current spectrum of stochastic GW background from preheating is then

$$h^2\Omega_{\rm pGWB}(f) = h^2\Omega_{\rm rad}\left[\frac{g_{*\rho}(\tau_{\rm rh})}{g_{*\rho}(\tau_0)}\right]^{-1/3}\left[\frac{a(\tau_w)}{a(\tau_{\rm rh})}\right]^{1-3w}\frac{S_k(\tau_f)}{a(\tau_w)^4\rho(\tau_w)}\bigg|_{k=2\pi f a_0}$$

  - $h^2\Omega_{\rm rad} = 4.2\times 10^{-5}$ is the current energy fraction of radiation, while $\rho(\tau)$ is the total energy density, τ_w is the moment at which the time-averaged stress-energy tensor reaches a well defined equation of state $p = w\rho$; $\tau_{\rm rh}$ denotes the time at which the light particles produced by the inflaton's fragmentation dominate the energy density.

GWs from Stochastic Scalar Fluctuations during Reheating

Lattice simulations

- Simulated 3 real scalars, $\phi_1 = \sqrt{2}\mathrm{Re}\sigma(\mathrm{t},\mathbf{x}), \phi_2 = \sqrt{2}\mathrm{Im}\sigma(\mathrm{t},\mathbf{x}), \mathrm{h}(\mathrm{t},\mathbf{x})$, with h decaying into a relativistic bath of SM particles with energy density $\rho_{\mathrm{SM}}(t)$, in an expanding FRW universe:

$$\ddot{\phi}_n + 3\frac{\dot{a}}{a}\dot{\phi}_n - \frac{1}{a^2}\vec{\nabla}^2\phi_n + \frac{\partial V}{\partial \phi_n}, \; n = 1, 2,$$

$$\ddot{h} + 3\frac{\dot{a}}{a}\dot{h} - \frac{1}{a^2}\vec{\nabla}^2 h + \frac{\partial V}{\partial h} + \Gamma_h \dot{h} = 0,$$

$$\dot{\rho}_{\mathrm{SM}} + 4\frac{\dot{a}}{a}\rho_{\mathrm{SM}} - \Gamma_h \dot{h}^2 = 0,$$

$$3M_P^2\left(\frac{\dot{a}}{a}\right)^2 = \rho_{\mathrm{SM}} + V + \frac{1}{2}\left(\dot{\phi}_1^2 + \dot{\phi}_2^2 + h^2\right) + \frac{1}{2a^2}\left((\nabla\phi_1)^2 + (\nabla\phi_2)^2 + (\nabla h)^2\right) .$$

GWs from Stochastic Scalar Fluctuations during Reheating

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- Used modified version of “CLUSTEREASY” [Felder, Tkachev 08] . Changes account for Higgs decay, SM radiation and impact on scale factor evolution, modified initial conditions for super-horizon modes

[Ballesteros,AR,Tamarit,Welling, arXiv:2104.13847; AR,Tamarit, arXiv: 2203.00621]

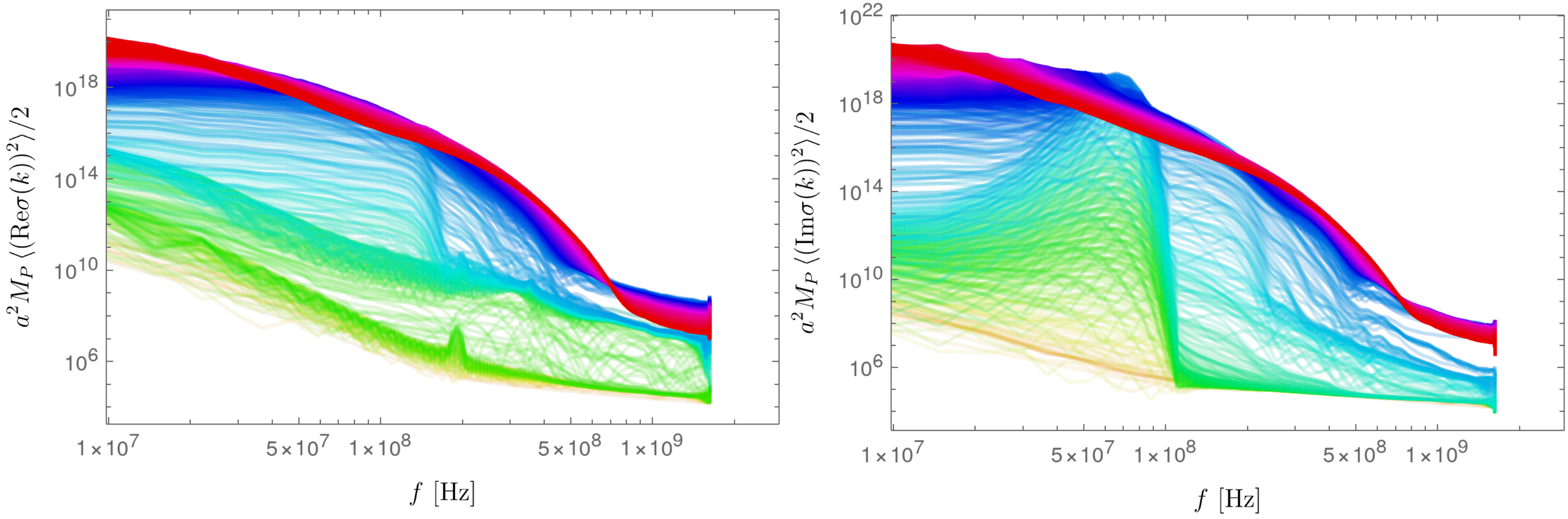
- Used lattices with 256^3 points
- Used 8 powerful CPU cores running for ~7 days,
- Computed up to tau = 2000 (rescaled conformal time in program units)

GWs from Stochastic Scalar Fluctuations during Reheating

Power spectra obtained by lattice simulations

[AR, Carlos Tamarit, arXiv: 2203.00621]

Power spectra of $\mathrm{Re}\,\sigma$ (left) and $\mathrm{Im}\,\sigma$ (right) for BP1, as a function of today's frequency for subsequent values of the conformal time. The red line corresponds to the final time of the simulation.

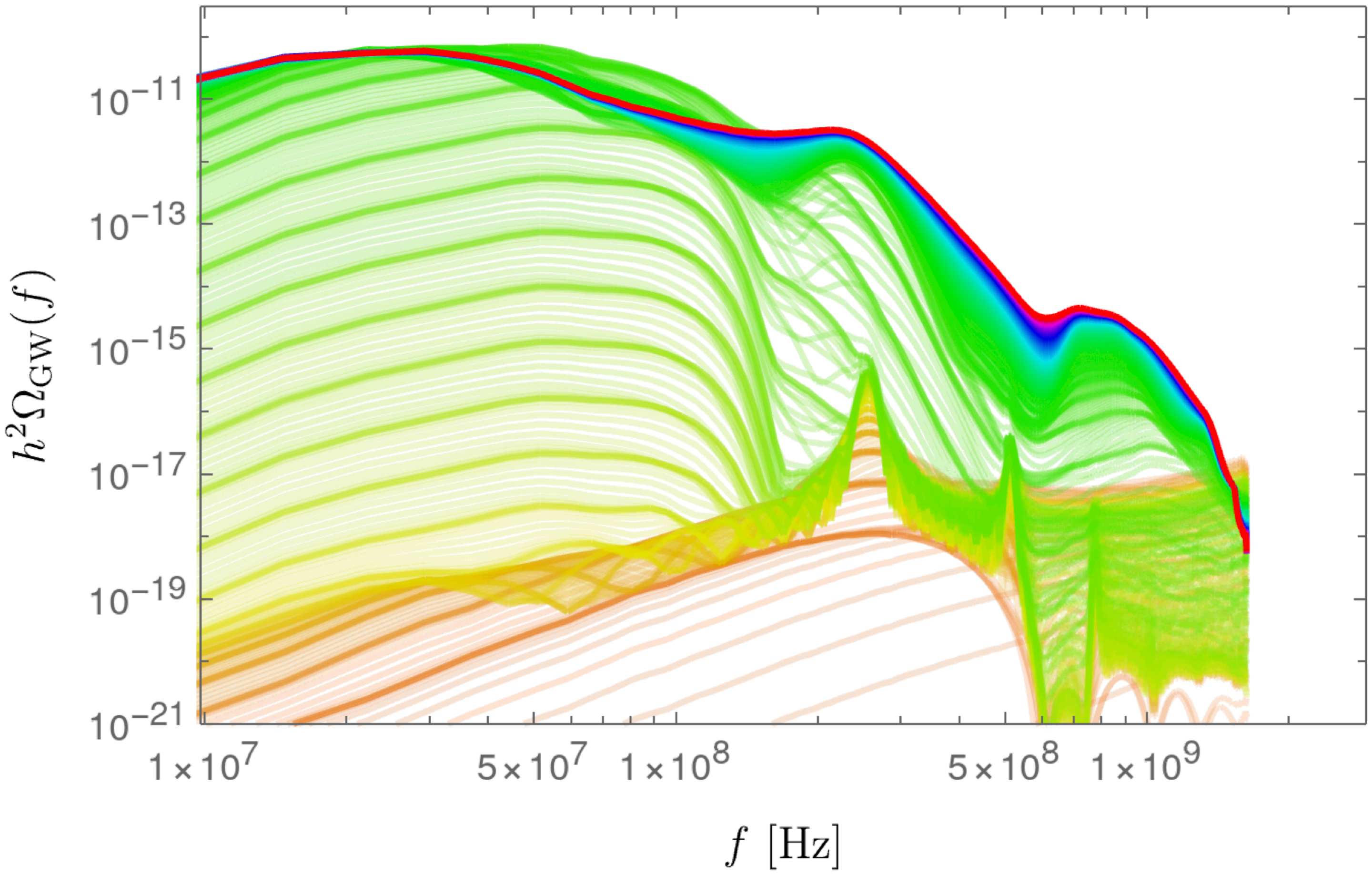


GWs from Stochastic Scalar Fluctuations during Reheating

Power spectra obtained by lattice simulations

[AR, Carlos Tamarit, arXiv: 2203.00621]

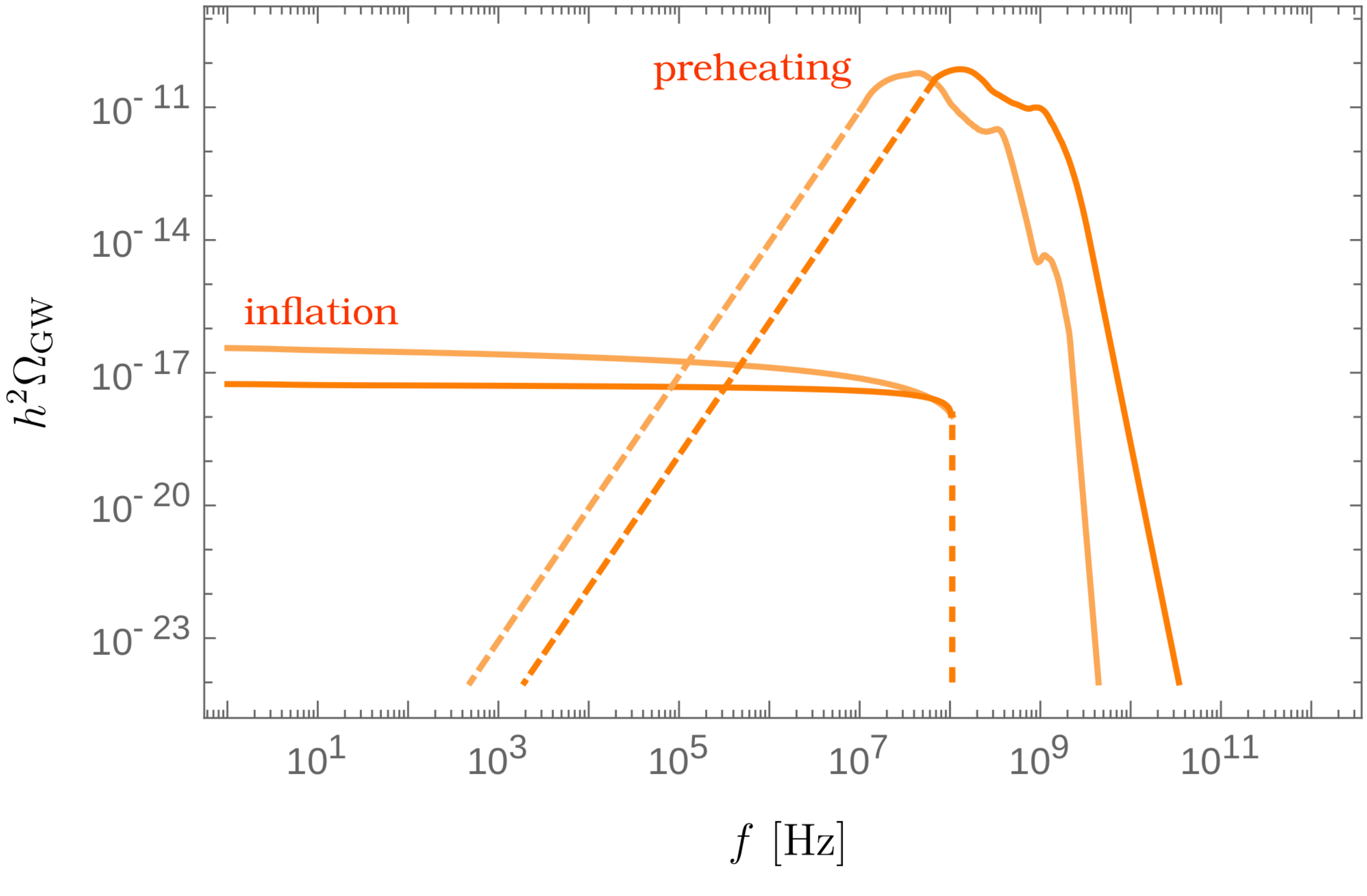
Present energy density of GWs for BP1, with the source integrated up to different times. The red line corresponds to the final time of the simulation.



GWs from Stochastic Scalar Fluctuations during Reheating

The bigger picture

[AR, Carlos Tamarit, arXiv: 2203.00621]



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GWs from Stochastic Scalar Fluctuations during Reheating

The bigger picture

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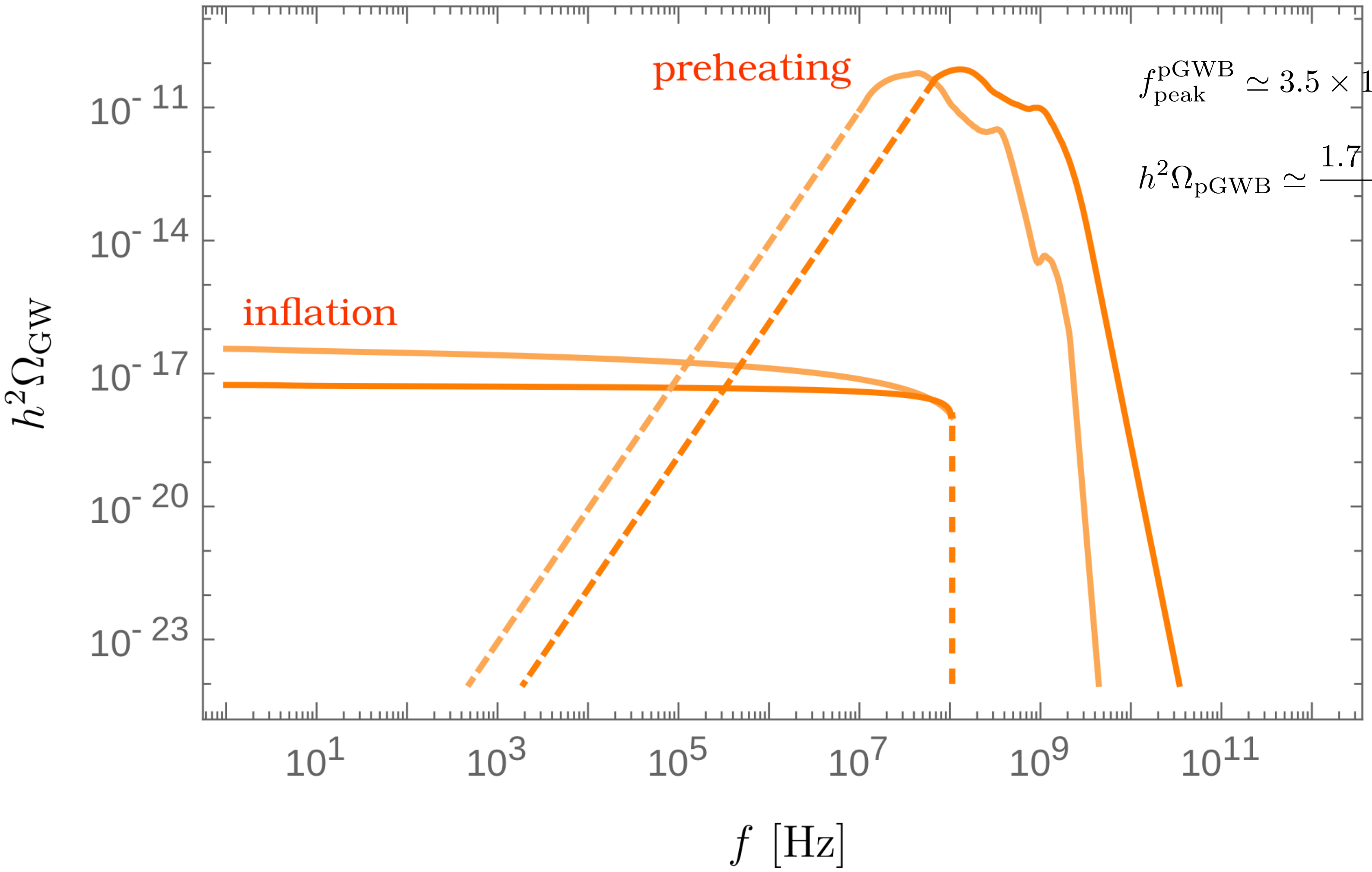


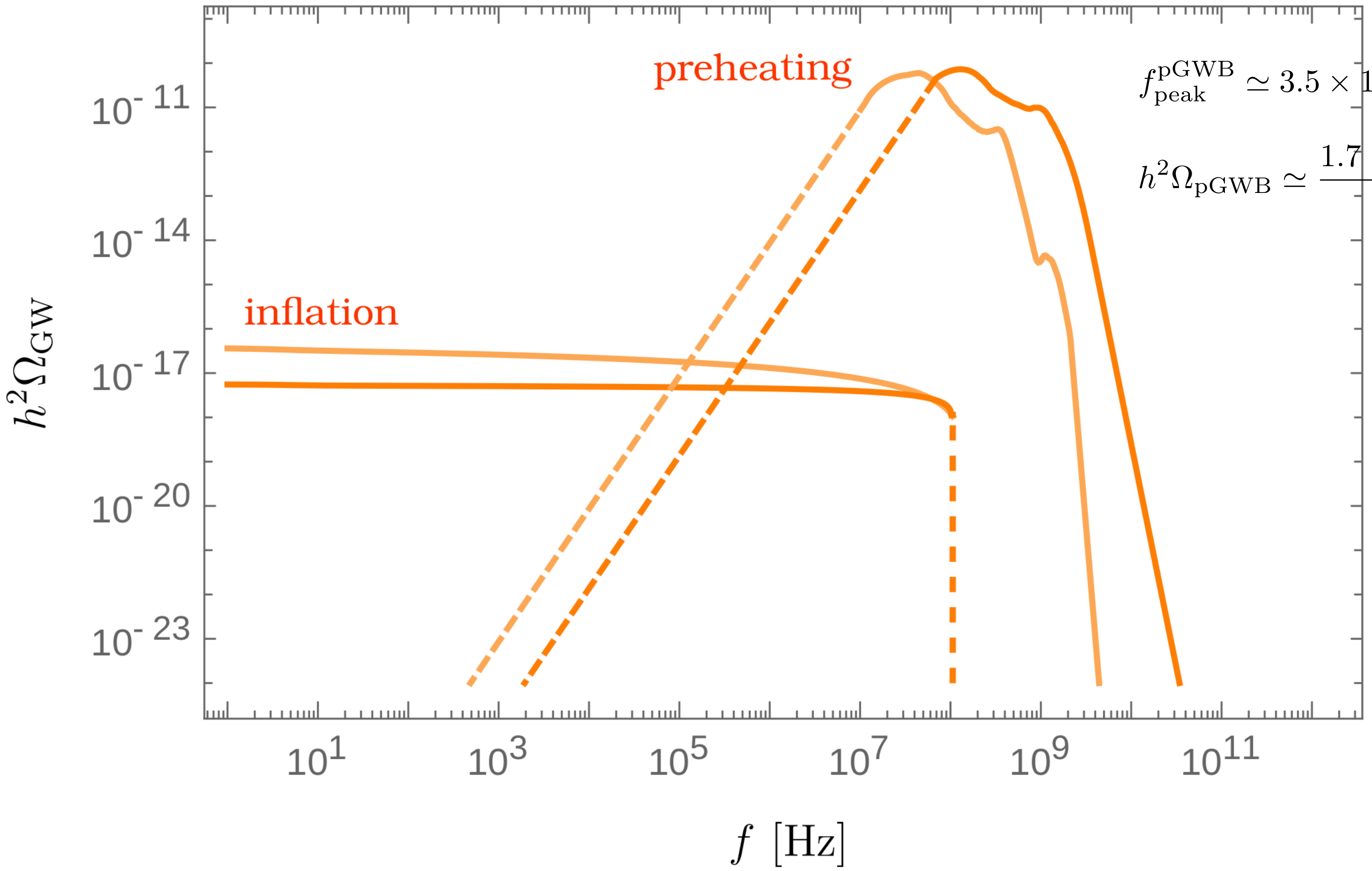
$$f_{\rm peak}^{\rm pGWB} \simeq 3.5\times 10^{13}\,{\rm Hz}\;\hat\kappa\sqrt{\tilde\lambda_\sigma}\left[\frac{\phi_{\rm end}}{M_P}\right]\left[\frac{e^{-N_{\rm post}}}{e^{-65}}\right],$$

$$h^2\Omega_{\rm pGWB} \simeq \frac{1.7\times 10^{-7}\alpha}{\hat\kappa^2}\left[\frac{\mathcal{H}_{\rm end}}{5\times 10^{12}\,{\rm GeV}}\right]^2\left[\frac{e^{-4N_{\rm post}}}{e^{-4\cdot 65}}\right]$$

GWs from Stochastic Scalar Fluctuations during Reheating

The bigger picture

[AR, Carlos Tamarit, arXiv: 2203.00621]



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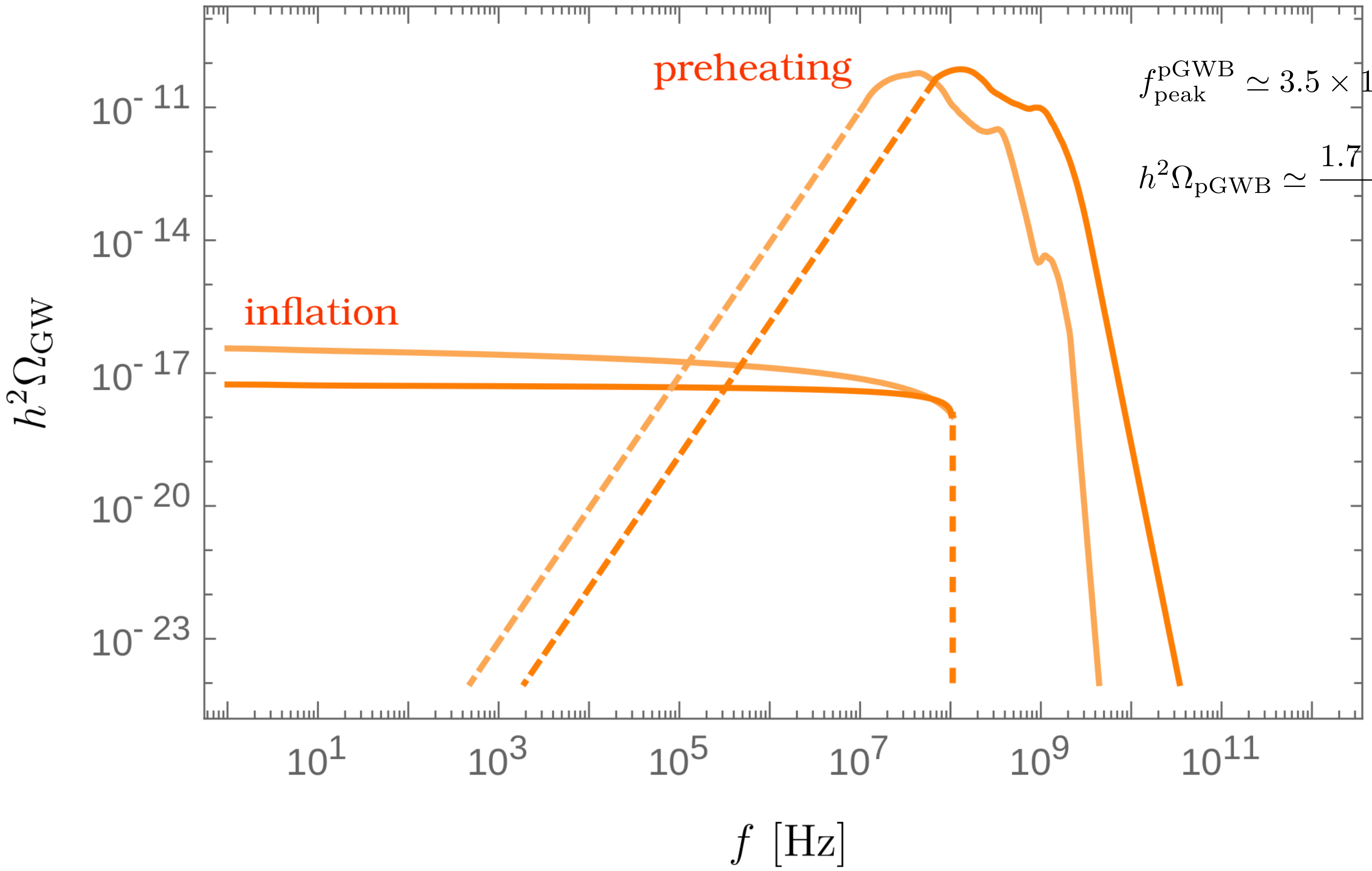
GWs from Stochastic Scalar Fluctuations during Reheating

The bigger picture

[AR, Carlos Tamarit, arXiv: 2203.00621]



$$f_{\rm peak}^{\rm pGWB} \simeq 3.5\times 10^{13}\,{\rm Hz}\;\hat\kappa\sqrt{\tilde\lambda_\sigma}\left[\frac{\phi_{\rm end}}{M_P}\right]\left[\frac{e^{-N_{\rm post}}}{e^{-65}}\right],$$

$$h^2\Omega_{\rm pGWB} \simeq \frac{1.7\times 10^{-7}\alpha}{\hat\kappa^2}\left[\frac{\mathcal{H}_{\rm end}}{5\times 10^{12}\,{\rm GeV}}\right]^2\left[\frac{e^{-4N_{\rm post}}}{e^{-4\cdot 65}}\right]$$

Benchmark for $r(k_*) = 0.0037$:

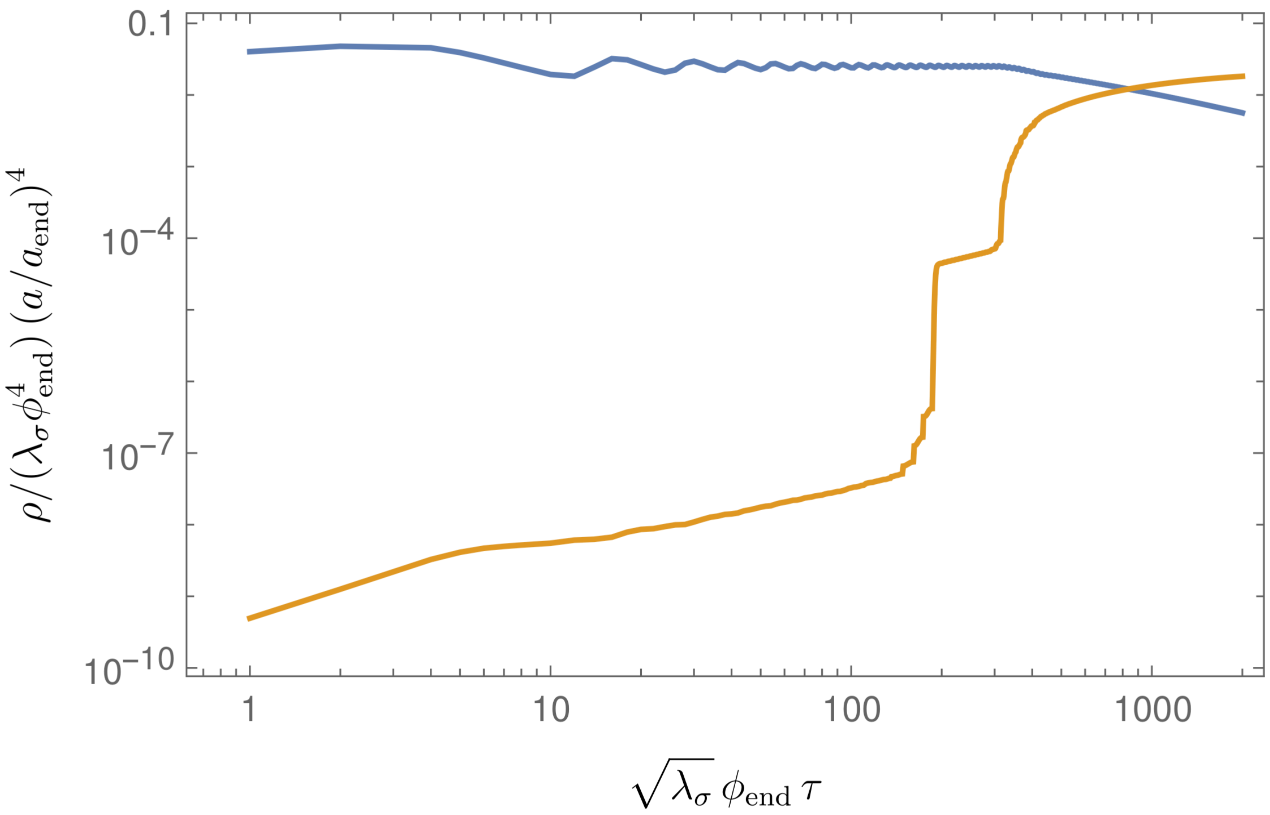
$$\phi_* = 8.4 M_P$$
$$\xi_\sigma(\phi_*) = 1.0$$
$$\tilde\lambda_\sigma(\phi_*) = 5.3\times 10^{-10}$$
$$\hat\kappa = 0.08$$
$$\phi_{\rm end} = 0.76\, M_P$$
$$N_{\rm post} = 64.0$$
$$\alpha = 3\times 10^{-4}$$
$$\mathcal{H}_{\rm end} = 2.4\times 10^{-6} M_P$$

GWs from Thermal Fluctuations after Reheating

Reheating temperature in SM*A*S*H predicted

[AR, Carlos Tamarit, arXiv: 2203.00621]

Evolution of the mean energy densities of the scalars (blue) and radiation bath (orange) for BP1, giving $\tau_{\rm rh} = 835/(\sqrt{\lambda_\sigma}\phi_{\rm end} a_{\rm end})$ captured within the simulation.



$$T_{\rm rh} = (30\,\rho_{\rm rad}(\tau_{\rm rh})/(\pi^2 g_{\star\rho}(T_{\rm rh}))^{1/4}$$

$$= 9.7 \times 10^{12}\,{\rm GeV}$$

GWs from Thermal Fluctuations after Reheating

Cosmic Gravitational Microwave Background (CGMB)

$$h^2\,\Omega_{\rm CGMB}(f) \approx 4.0\times 10^{-12}\left[\frac{T_{\rm rh}}{M_P}\right]\left[\frac{g_{*s}(T_{\rm rh})}{106.75}\right]^{-5/6}\left[\frac{f}{\rm GHz}\right]^3\hat{\eta}\left(T_{\rm rh}, 2\pi\,\left[\frac{g_{*s}(T_{\rm rh})}{3.9}\right]^{1/3}\frac{f}{T_0}\right)$$

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- **At large wavelengths**, corresponding to small wave numbers, $k \ll T$, CGMB sourced by macroscopic hydrodynamic fluctuations, described by the shear viscosity of the plasma:

$$\hat\eta\left(T,\frac{k}{T}\right) \simeq \frac{\eta^{\rm shear}(T)}{T^3}\,,\ \ {\rm for}\ \ k \ll T$$

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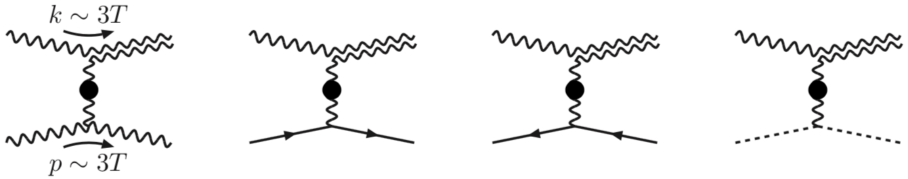

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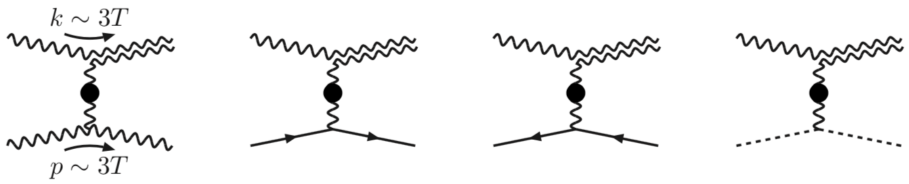

  - Corresponding source term suppressed by gauge couplings and Boltzmann factor:

$$\hat{\eta}\left(T, \frac{k}{T}\right) \sim g(T)^2\ \exp\left(-k/T\right)\,, \quad {\rm for}\ \ k \gg T\ .$$

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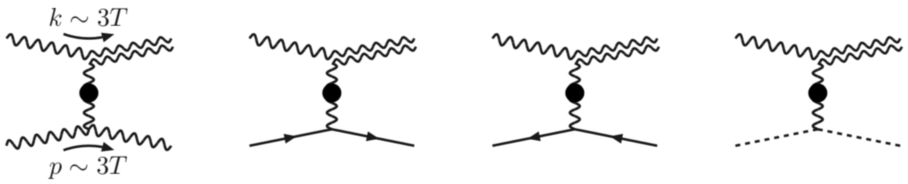

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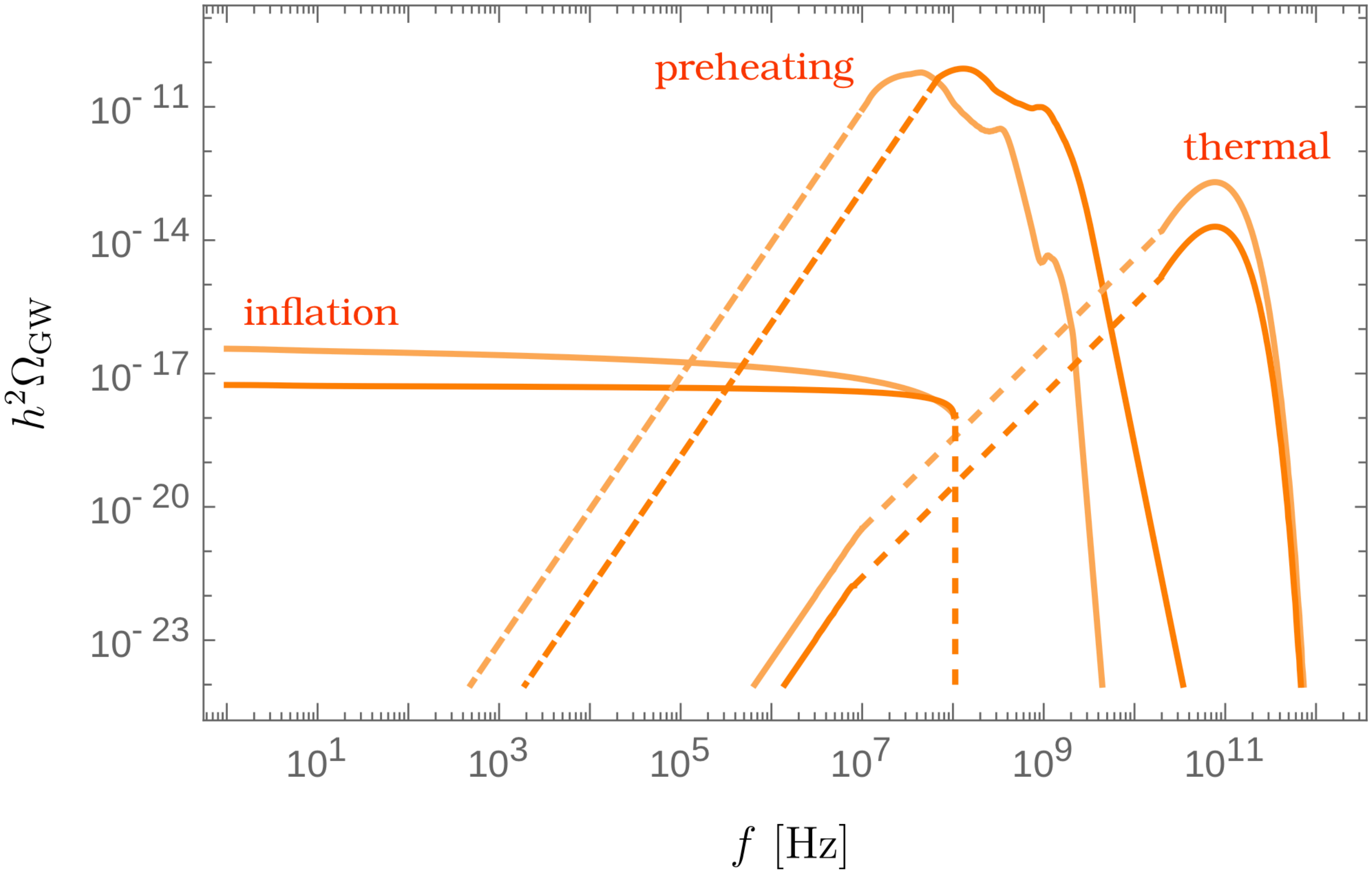
  - Known to complete leading order for generic weakly interacting BSM extension (gauge fields, fermions, scalars) [Ghiglieri,Laine ’15; Ghiglieri,Jackson,Laine,Zhu ’20; AR,Schütte-Engel,Tamarit ‘20]
  - For N=4 SUSY YM known also for strong coupling [Castells-Tiestos, Casalderrey-Solana ´22]

GWs from Thermal Fluctuations after Reheating

CGMB for SM*A*S*H

[AR, Carlos Tamarit, arXiv:2203.00621]



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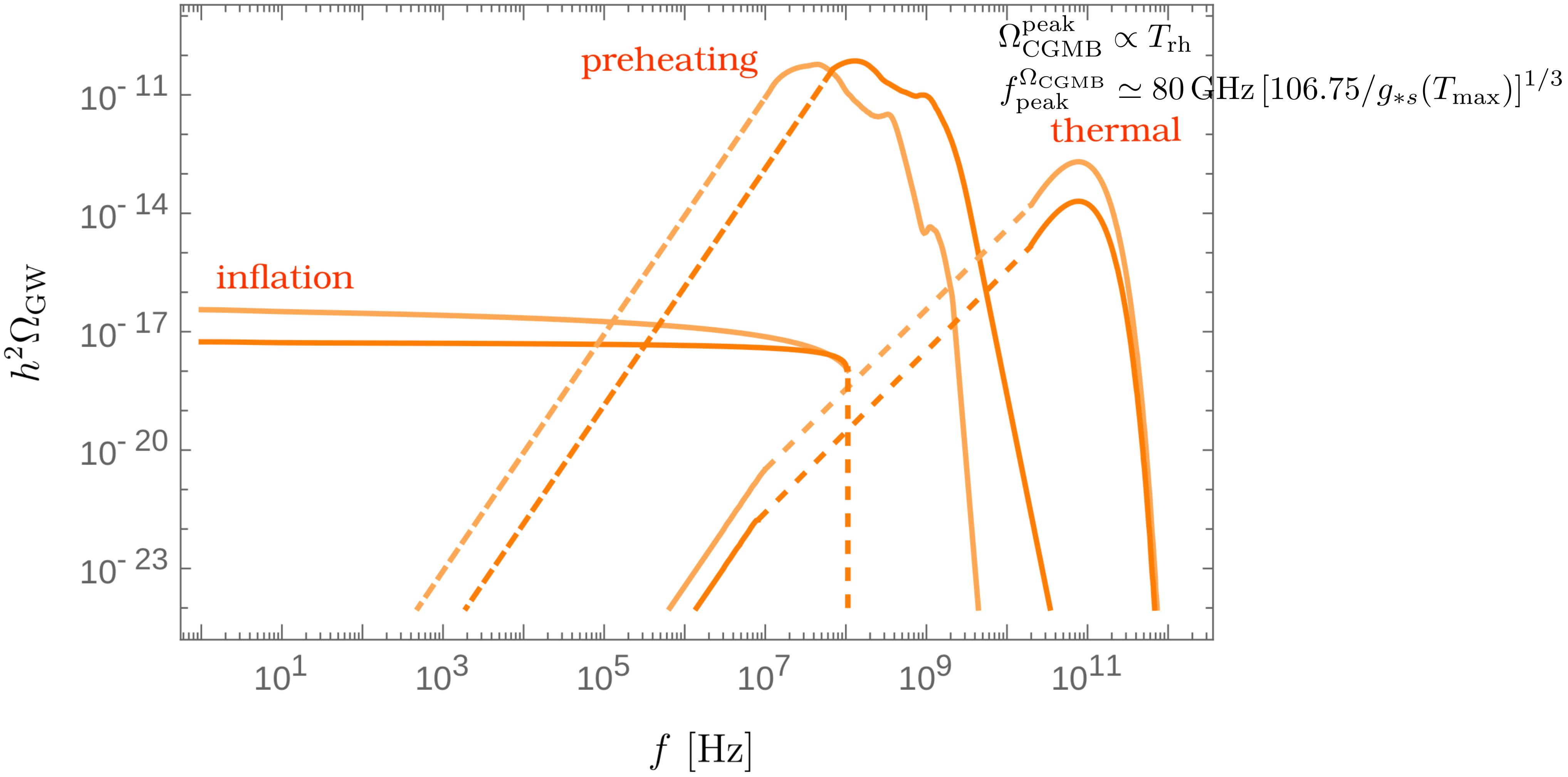
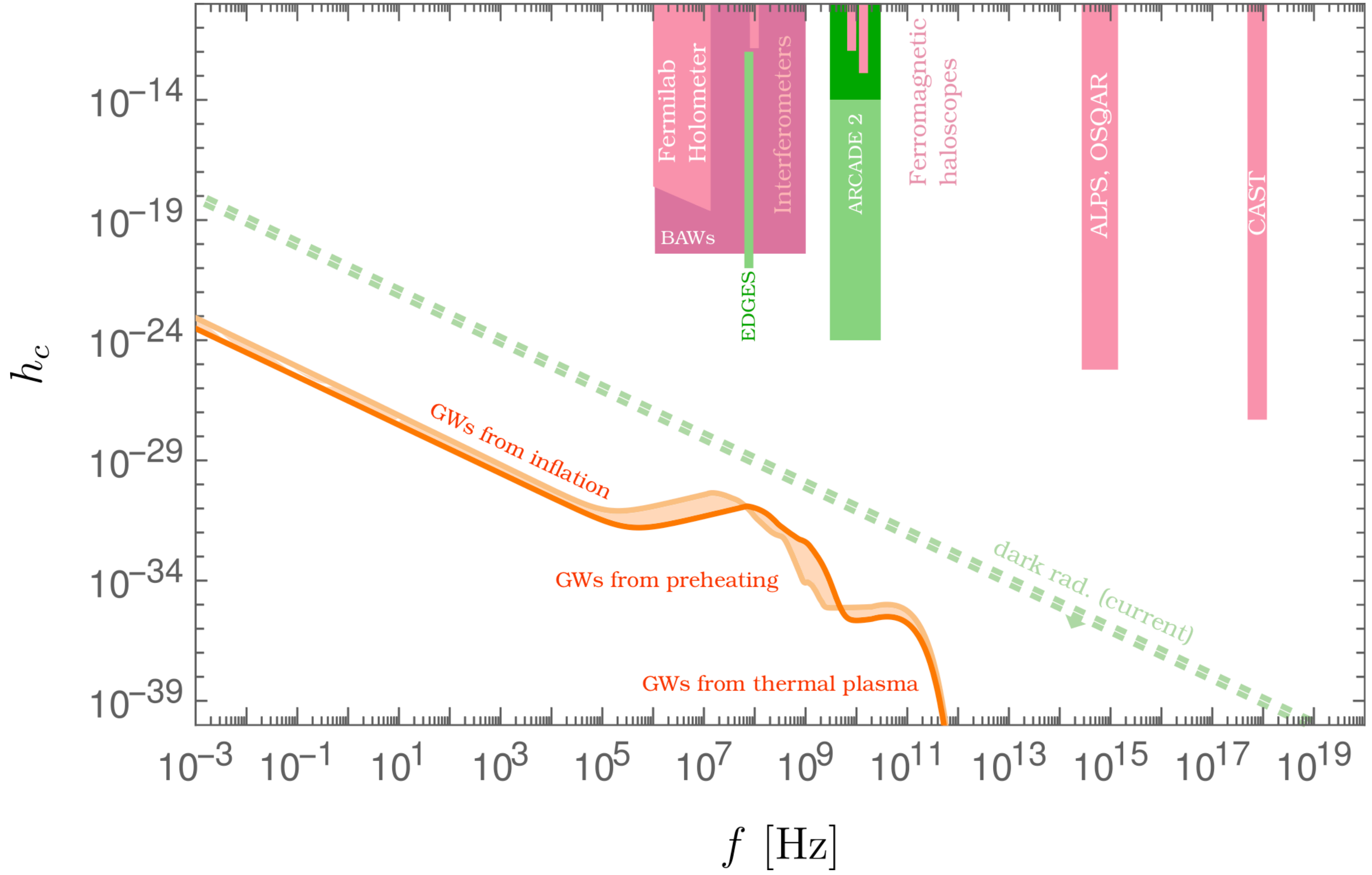


Observational Prospects to Measure Complete Spectrum

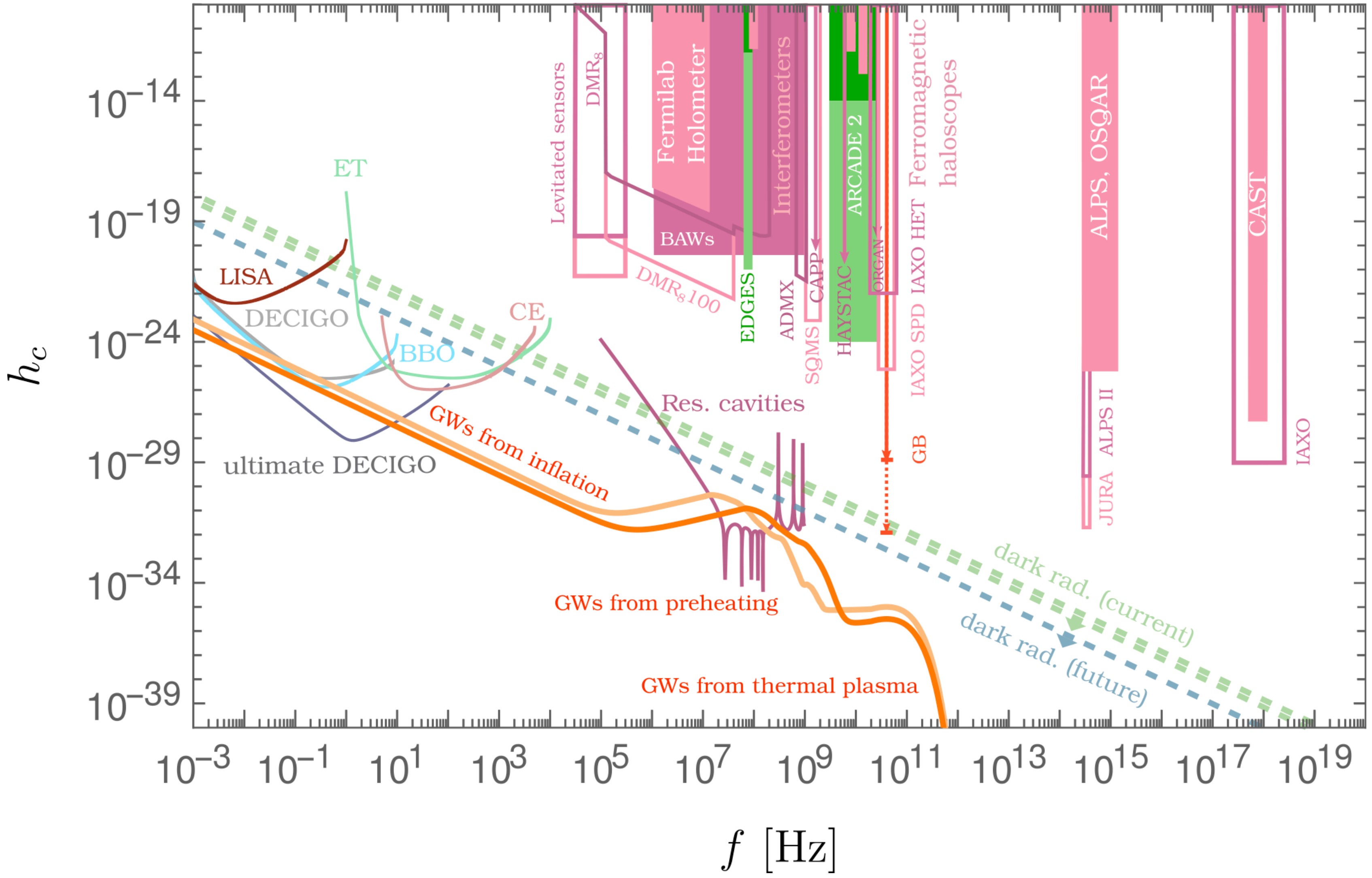
Current bounds on characteristic amplitude of stochastic GWs

[AR, Carlos Tamarit, arXiv:2203.00621]



Observational Prospects to Measure Complete Spectrum

Prospected sensitivity on characteristic amplitude of stochastic GWs [AR, Carlos Tamarit, arXiv:2203.00621]



Summary

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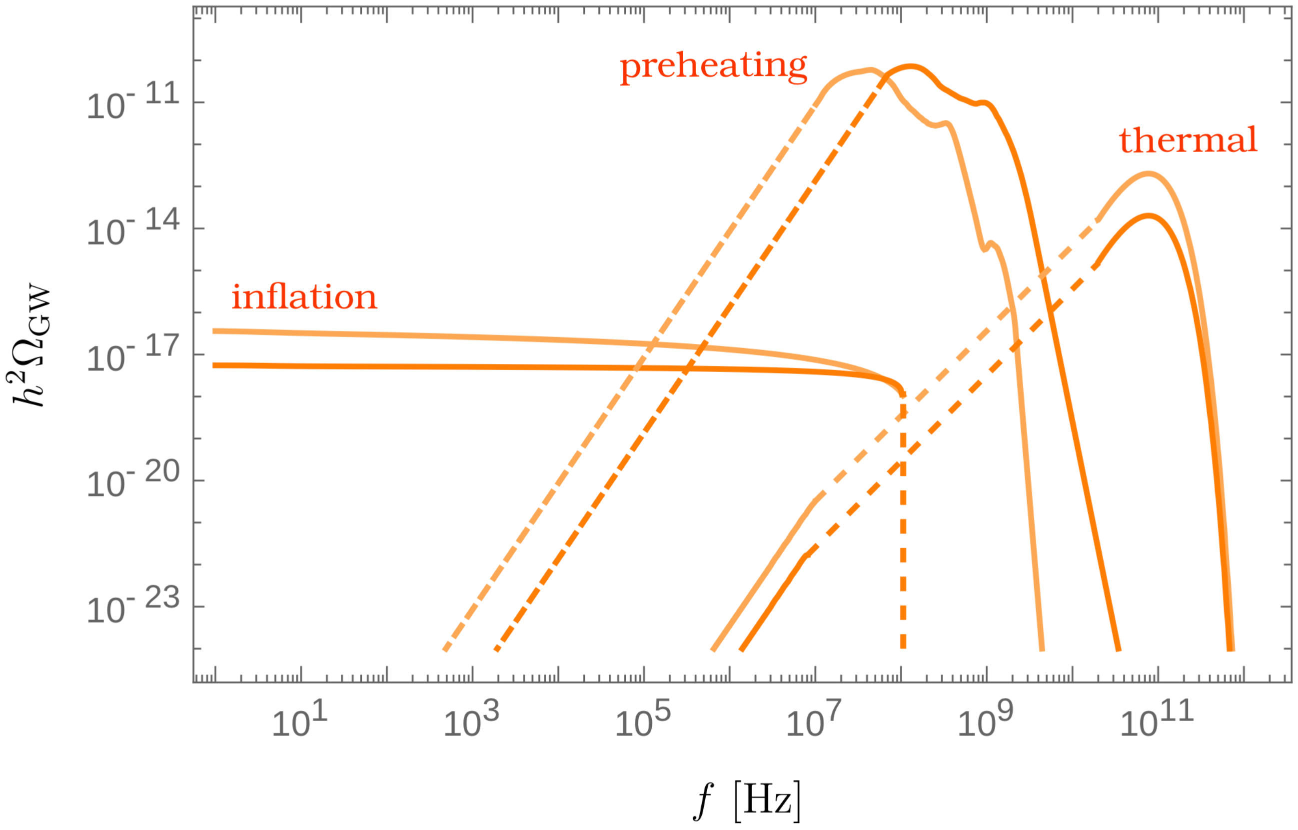
- Can be seen as a conservative benchmark for the expected GWs from the early universe



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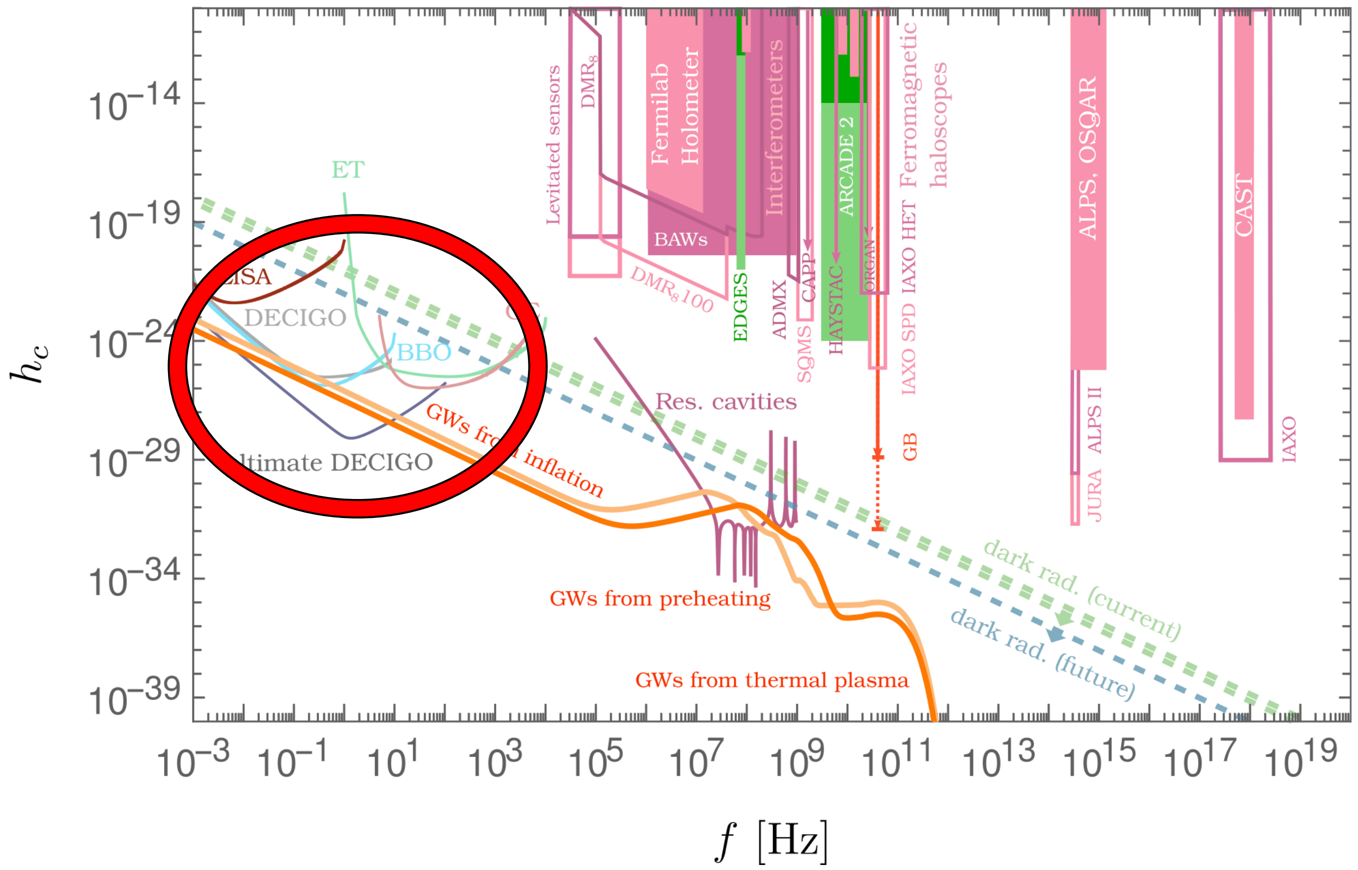

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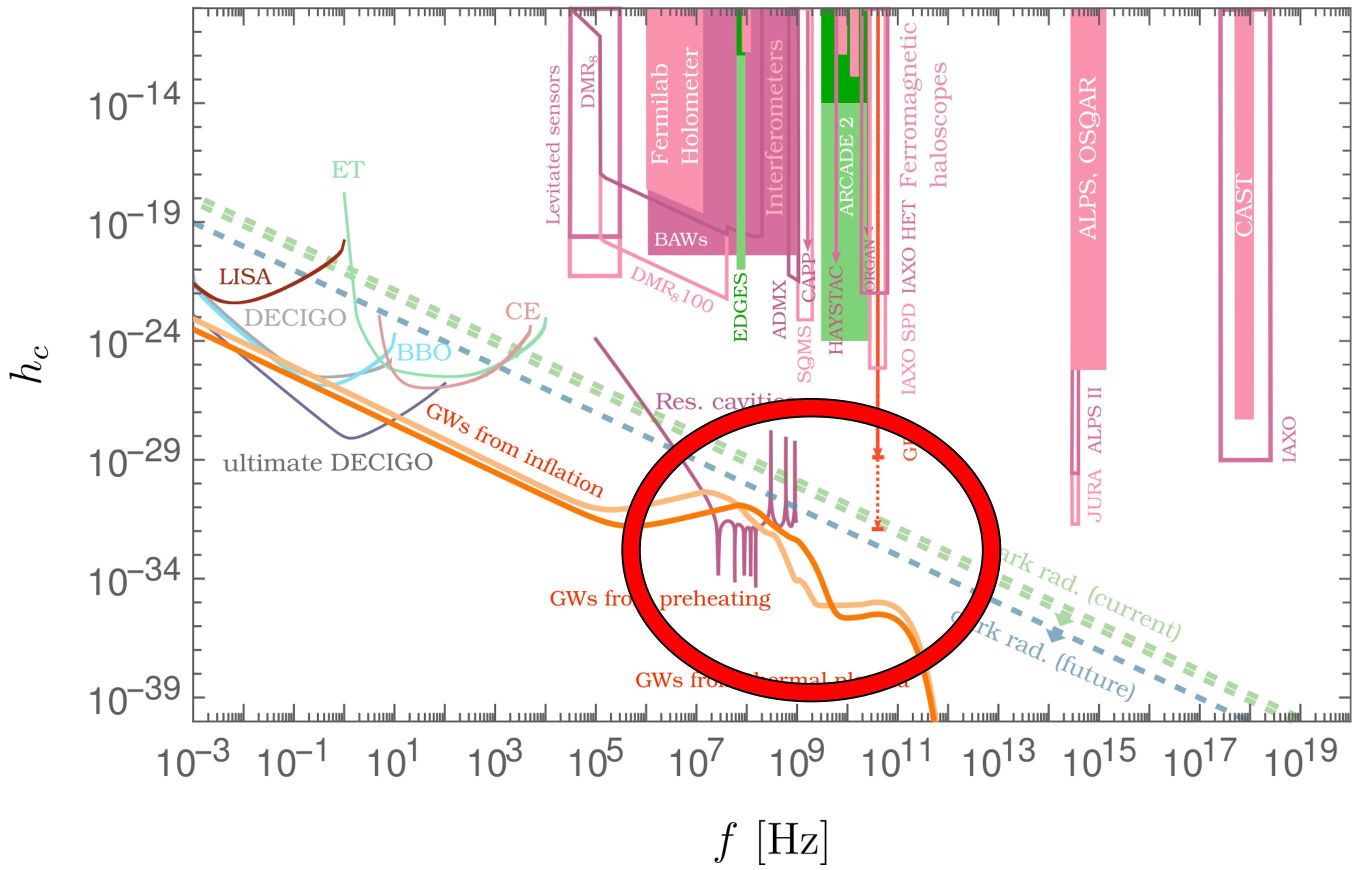

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CERN-TH-2020-185
HIP-2020-28/TH
DESY 20-195

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

N. Aggarwal[a,*], O.D. Aguiar[b], A. Bauswein[c], G. Cella[d], S. Clesse[e], A.M. Cruise[f], V. Domcke[g,h,i,*], D.G. Figueroa[j], A. Geraci[k], M. Goryachev[l], H. Grote[m], M. Hindmarsh[n,o], F. Muia[p,i,*], N. Mukund[q], D. Ottaway[r,s], M. Peloso[t,u], F. Quevedo[p,*], A. Ricciardone[t,u], J. Steinlechner[v,w,x,*], S. Steinlechner[v,w,*], S. Sun[y,z], M.E. Tobar[l], F. Torrenti[α], C. Unal[β], G. White[γ]

arXiv:2011.12414v1 [gr-qc] 24 Nov 2020

Abstract

The first direct measurement of gravitational waves by the LIGO and Virgo collaborations has opened up new avenues to explore our Universe. This white paper outlines the challenges and gains expected in gravitational wave searches at frequencies above the LIGO/Virgo band, with a particular focus on the MHz and GHz range. The absence of known astrophysical sources in this frequency range provides a unique opportunity to discover physics beyond the Standard Model operating both in the early and late Universe, and we highlight some of the most promising gravitational sources. We review several detector concepts which have been proposed to take up this challenge, and compare their expected sensitivity with the signal strength predicted in various models. This report is the summary of the workshop *Challenges and opportunities of high-frequency gravitational wave detection* held at ICTP Trieste, Italy in October 2019.

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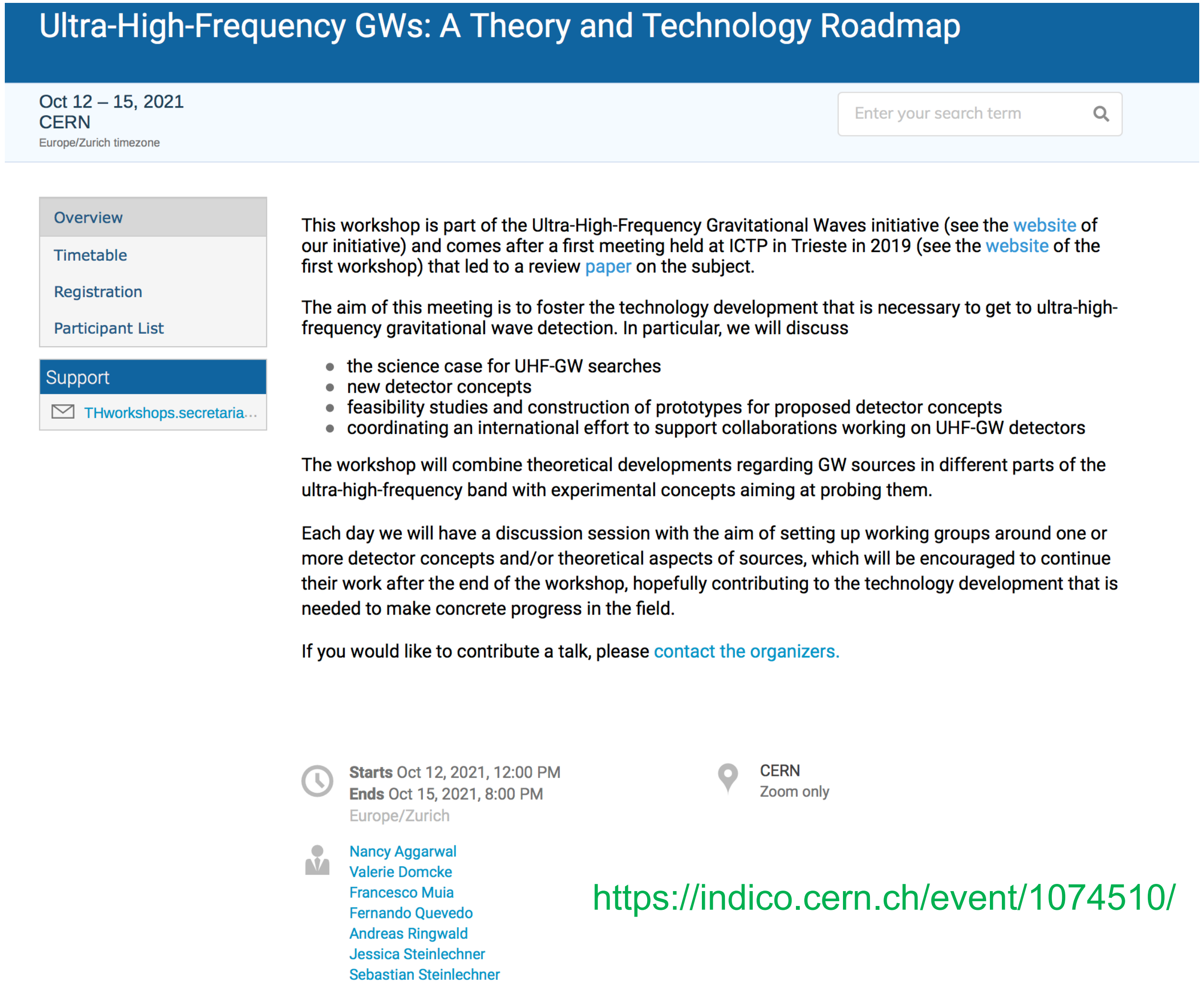
Ultra-High-Frequency GWs: A Theory and Technology Roadmap

Oct 12 – 15, 2021
CERN
Europe/Zurich timezone

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Overview
Timetable
Registration
Participant List

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This workshop is part of the Ultra-High-Frequency Gravitational Waves initiative (see the website of our initiative) and comes after a first meeting held at ICTP in Trieste in 2019 (see the website of the first workshop) that led to a review paper on the subject.

The aim of this meeting is to foster the technology development that is necessary to get to ultra-high-frequency gravitational wave detection. In particular, we will discuss

- the science case for UHF-GW searches
- new detector concepts
- feasibility studies and construction of prototypes for proposed detector concepts
- coordinating an international effort to support collaborations working on UHF-GW detectors

The workshop will combine theoretical developments regarding GW sources in different parts of the ultra-high-frequency band with experimental concepts aiming at probing them.

Each day we will have a discussion session with the aim of setting up working groups around one or more detector concepts and/or theoretical aspects of sources, which will be encouraged to continue their work after the end of the workshop, hopefully contributing to the technology development that is needed to make concrete progress in the field.

If you would like to contribute a talk, please contact the organizers.

Starts Oct 12, 2021, 12:00 PM
Ends Oct 15, 2021, 8:00 PM
Europe/Zurich

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Francesco Muia
Fernando Quevedo
Andreas Ringwald
Jessica Steinlechner
Sebastian Steinlechner

https://indico.cern.ch/event/1074510/

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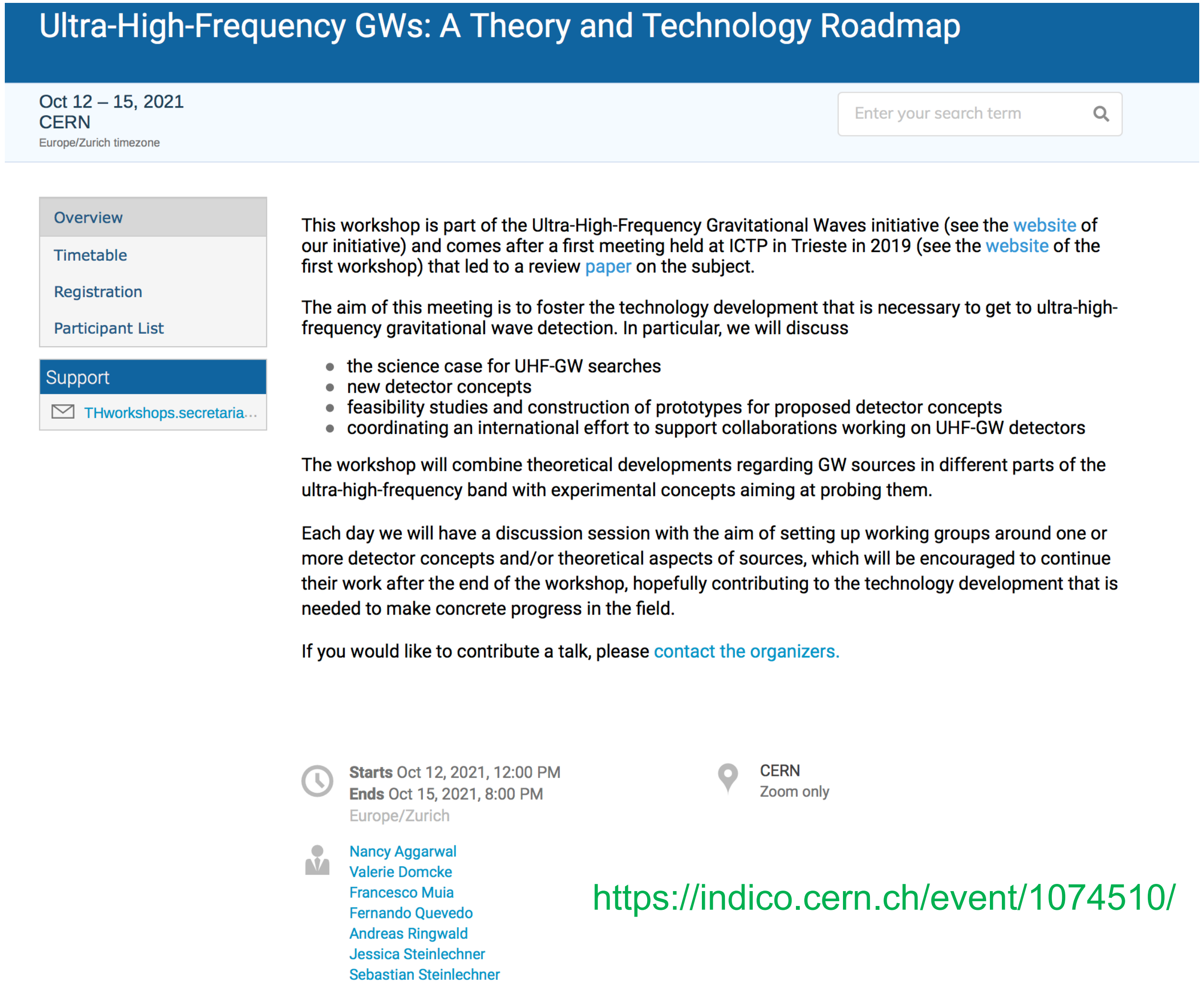
- **Revealing the cosmic history sets an ambitious, but rewarding goal for this enterprise**



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https://indico.cern.ch/event/1074510/

Backup: Resonant Cavity Detector

- Based on conversion of GWs to EMWs in magnetic field background through inverse Gertsensthein effect

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1. WO2019129745 - DEVICES FOR THE DIRECTIONAL EMISSION AND RECEPTION OF GRAVITATIONAL WAVES

PCT Biblio. Data | Description | Claims | Drawings | ISR/WOSA/A17(2)(a) | National Phase | Patent Family | Notices | Documents

PermaLink Machine translation

Publication Number
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Publication Date
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International Application No.
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International Filing Date
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CPC
G01V 7/00 | G01V 7/02

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Priority Data
17210675.9 27.12.2017 EP

Publication Language
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Filing Language
English (EN)

Designated States
View all

Title
(EN) DEVICES FOR THE DIRECTIONAL EMISSION AND RECEPTION OF GRAVITATIONAL WAVES
(FR) DISPOSITIFS D'ÉMISSION DIRECTIONNELLE ET DE RÉCEPTION D'ONDES GRAVITATIONNELLES

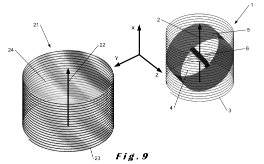

Fig. 9

Abstract
(EN) The present invention relates to electromagnetic devices 1, 21 and associated methods for the directional emission and the detection of gravitational waves. The gravitational wave generating device 1 consists of a cavity 4 carrying electromagnetic waves, which is immersed into an external static magnetic field appropriately oriented for boosting the emission of gravitational waves. It is possible to detect the generated gravitational waves, first through the related energy loss in the generating device 1, and second through the electromagnetic fields that are remotely induced in a gravitational wave detecting device 21. This last device 21 comprises an electromagnet 23 producing a magnetic field which interacts with the incoming gravitational waves in such a way that a magnetic energy is accumulating in a detection region 24 defined by the electromagnet 23.
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Related patent documents
WO/2019/129746

Latest bibliographic data on file with the International Bureau

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1. WO2019129746 - DEVICES FOR THE DIRECTIONAL EMISSION AND RECEPTION OF GRAVITATIONAL WAVES

PCT Biblio. Data | Description | Claims | Drawings | ISR/WOSA/A17(2)(a) | National Phase | Patent Family | Notices | Documents

PermaLink Machine translation

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WO/2019/129746

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CPC
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Designated States
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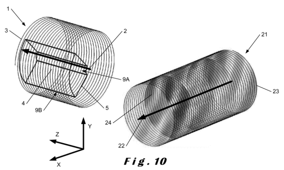

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Related patent documents
WO/2019/129745

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[Füzfa, https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019129746]

PHYSICAL REVIEW D **104,** 023524 (2021)

Detecting planetary-mass primordial black holes with resonant electromagnetic gravitational-wave detectors

Nicolas Herman,[1,*] André Fűzfa,[1,2,†] Léonard Lehoucq,[1,3,‡] and Sébastien Clesse[4,2,§]
[1]*Department of Mathematics and Namur Institute for Complex Systems (naXys), University of Namur, Rue Grafé 2, B-5000, Namur, Belgium*
[2]*Cosmology, Universe and Relativity at Louvain, Institute of Mathematics and Physics, Louvain University, 2 Chemin du Cyclotron, B-1348 Louvain-la-Neuve, Belgium*
[3]*Department of theoretical physics at the ENS Paris-Saclay, University of Paris-Saclay, avenue des Sciences, 91190, Gif-sur-Yvette, France*
[4]*Service de Physique Théorique, Université Libre de Bruxelles (ULB), Boulevard du Triomphe, CP225, B-1050 Brussels, Belgium*

Electromagnetic Antennas for the Resonant Detection of the Stochastic Gravitational Wave Background

Nicolas Herman,[1,*] Léonard Lehoucq,[1,2,†] and André Fűzfa[1,‡]
[1]*Department of Mathematics and Namur Institute for Complex Systems (naXys), University of Namur, Rue Grafé 2, B-5000, Namur, Belgium*
[2]*Department of theoretical physics at the ENS Paris-Saclay, University of Paris-Saclay, avenue des Sciences, 91190, Gif-sur-Yvette, France*
(Dated: March 30, 2022)

Stochastic gravitational wave background from the early Universe has a cut-off frequency close to 100 MHz, due to the horizon of the inflationary phase. To detect gravitational waves at such frequencies, resonant electromagnetic cavities are very suitable. In this work, we study the frequency sensitivity of such detectors, and show how we could use them to probe this cut-off frequency and also the energy density per frequency of this stochastic background. This paper paves the way for further experimental studies to probe the most ancient relic of the Universe.

[https://arxiv.org/abs/2203.15668]