Gravitational Waves as a Big Bang Thermometer

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Virtual Physics Colloquium Zeuthen
19 Nov 2020

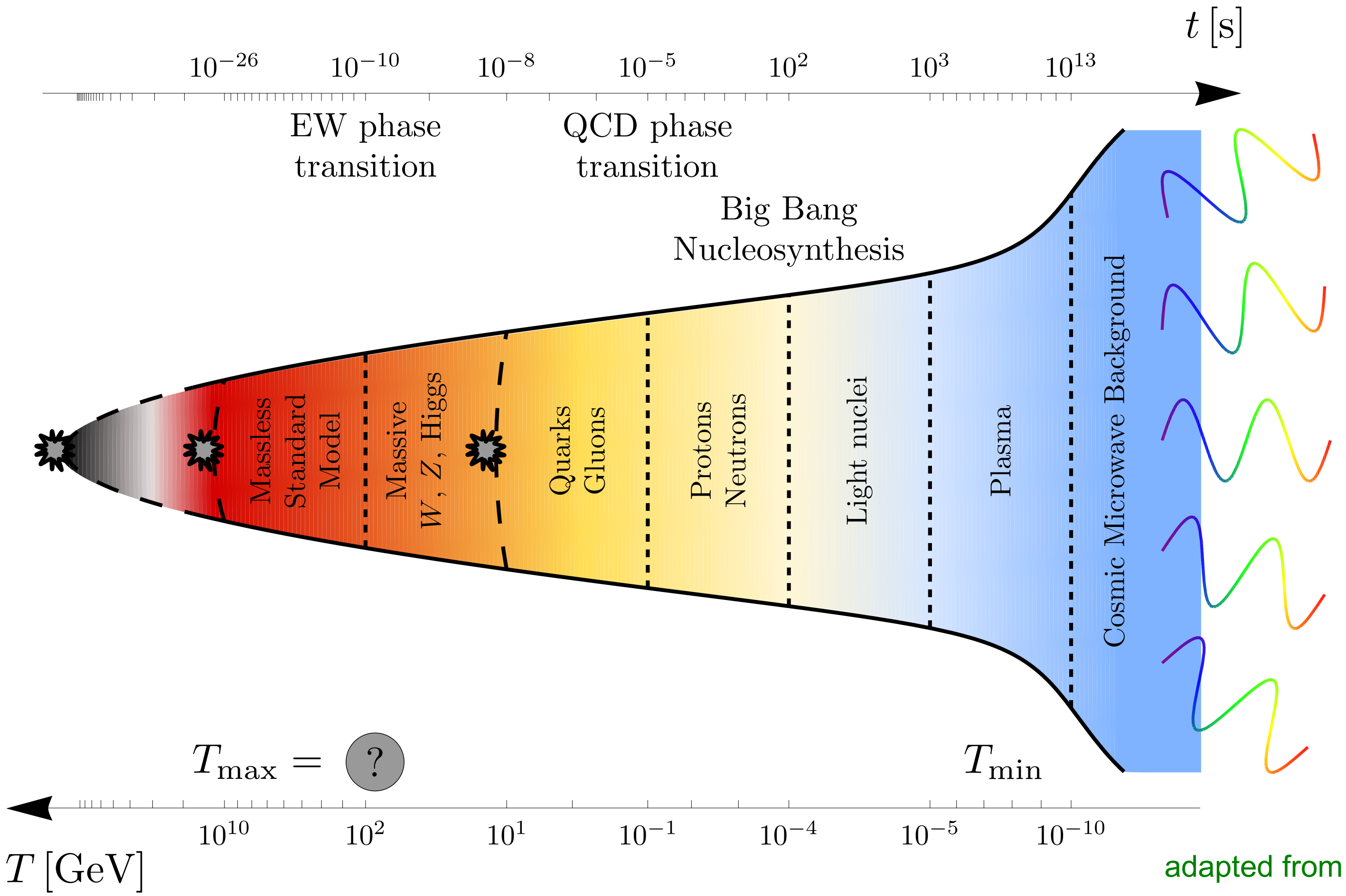
[AR, Jan Schütte-Engel, Carlos Tamarit, arXiv:2011.04731]

Outline

- Big Bang Cosmology
- Gravitational Wave Background Generated from Primordial Thermal Plasma
- Observational Constraints on the Gravitational Wave Background from Primordial Thermal Plasma
- Laboratory Searches for the Gravitational Wave Background from Primordial Thermal Plasma
- Summary

Big Bang Cosmology

Thermal history of the universe



adapted from [Schmitz '12]

- When did the hot big bang era start? What was the maximum temperature at its beginning?

Big Bang Cosmology

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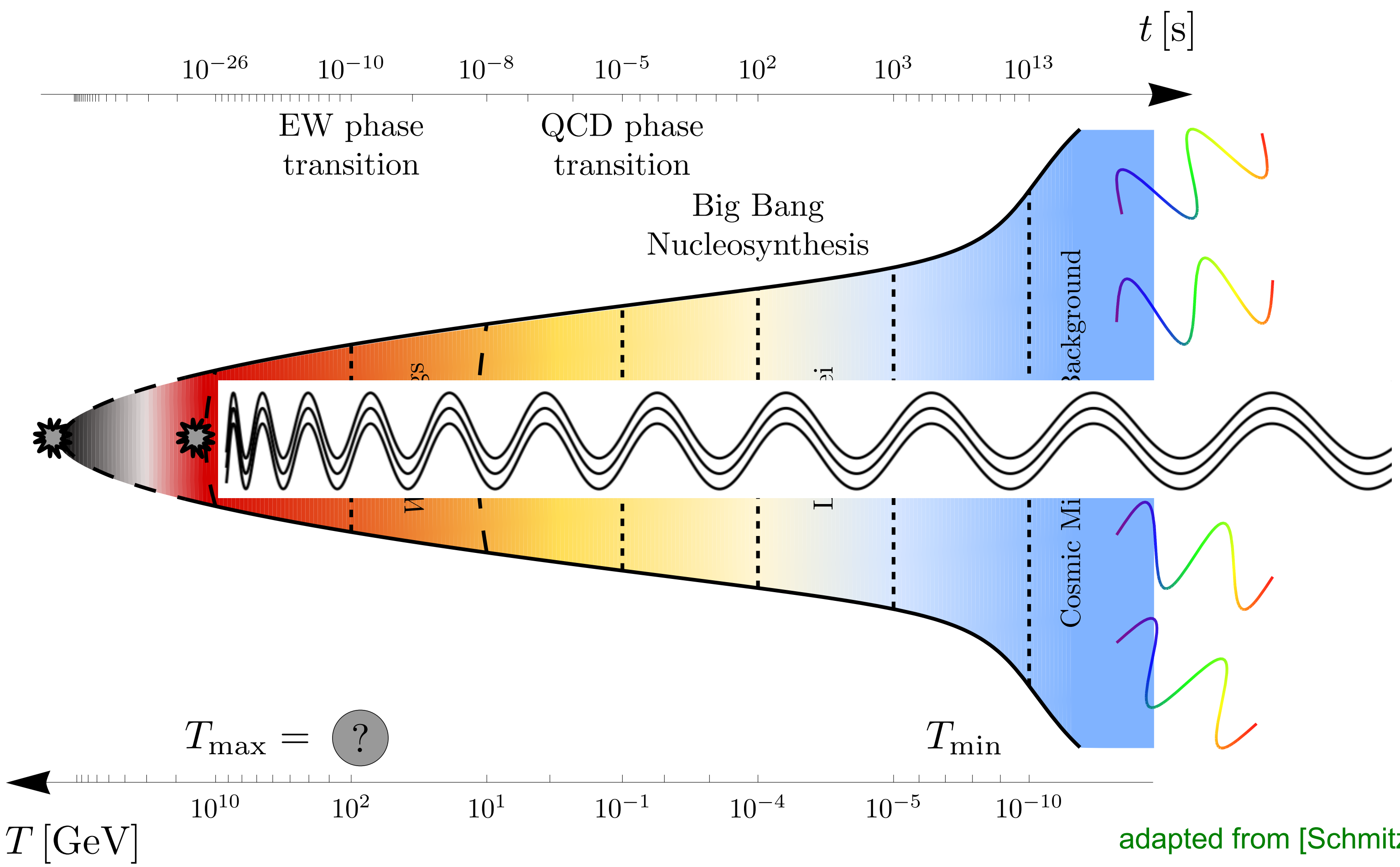


adapted from [Schmitz ‘12]

- Gravitational waves (GWs) generated by the thermal plasma inform us about the maximum temperature!

GW Background from Primordial Thermal Plasma

Case of super-Planckian maximum temperature

[Kolb,Turner '89]

In the case that $T_{\max} > M_P$:

- Gravitons decouple from the thermal bath when their interaction rate $\Gamma = n\sigma|v| \simeq T^5/M_P^4$ falls below the expansion rate $H \simeq T^2/M_P$, that is at $T_{\rm dec} \approx M_P$
- Their cosmic fractional energy densitiy, per unit of logarithmic frequency, has thermal blackbody spectrum:

$$\Omega_{\rm Eq.\,CGMB}(f) \equiv \frac{1}{\rho_c^{(0)}} \frac{{\rm d}\rho^{(0)}_{\rm Eq.\,CGMB}}{{\rm d}\ln f} = \frac{16\pi^2}{3M_P^2 H_0^2} \frac{f^4}{e^{2\pi f/T_{\rm grav}} - 1}$$

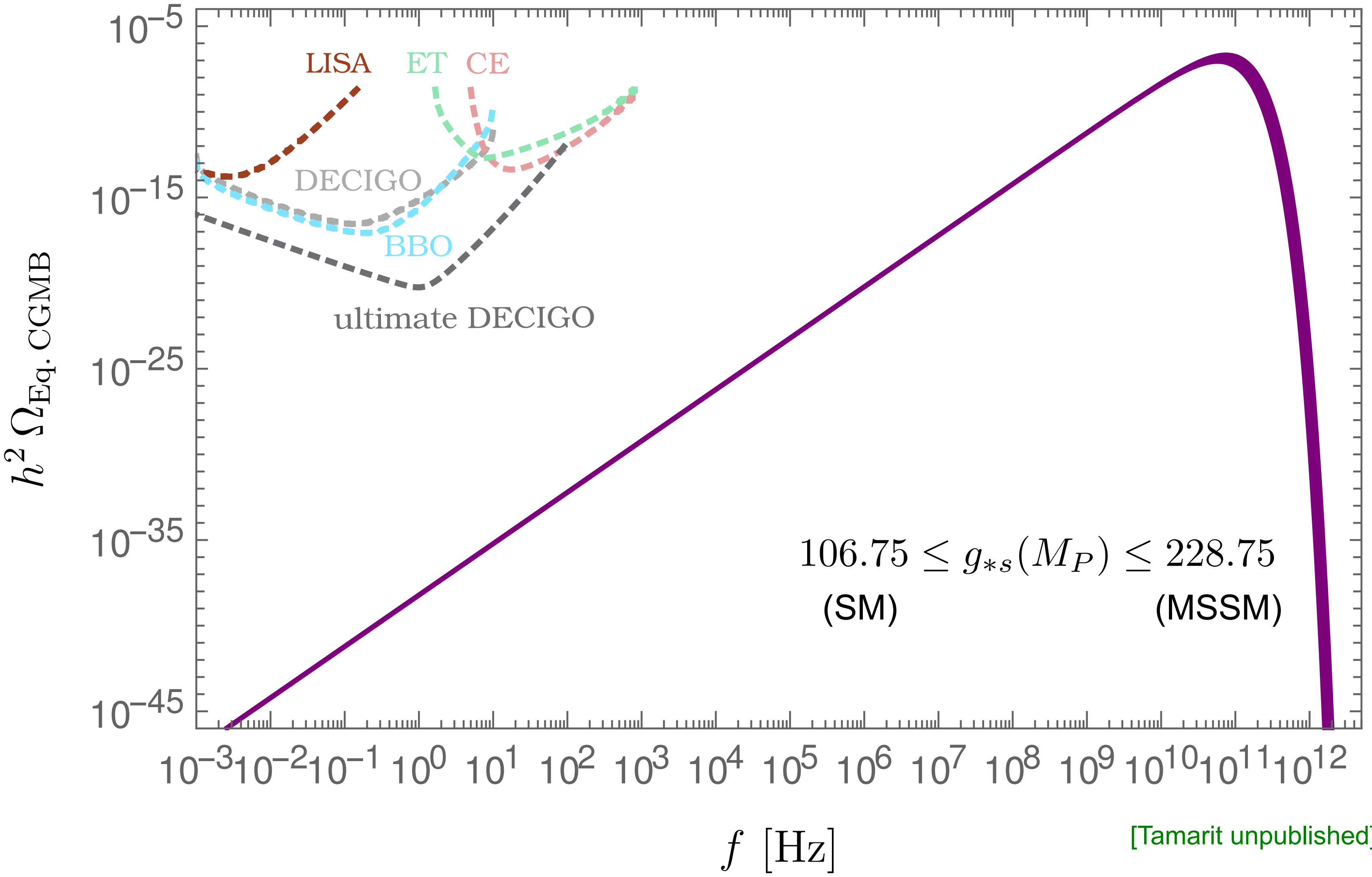
$$T_{\rm grav} = \frac{a(T_{\rm dec})}{a(T_0)} T_{\rm dec} \simeq \left[\frac{g_{*s}({\rm fin})}{g_{*s}(M_P)}\right]^{1/3} T_0 \simeq 0.907\,{\rm K} \left[\frac{g_{*s}(M_P)}{106.75}\right]^{-1/3}$$

- Acronym **CGMB** (Cosmic Gravitational Microwave Background): peaks in microwave range similar to CMB

$$f_{\rm peak}^{\Omega_{\rm Eq.\,CGMB}} \simeq 74\,{\rm GHz} \left[\frac{g_{*s}(M_P)}{106.75}\right]^{-1/3}, \quad h^2\Omega_{\rm Eq.CGMB}(f_{\rm peak}^{\Omega_{\rm Eq.CGMB}}) = 2.23 \times 10^{-7} \left[\frac{g_{*s}(M_P)}{106.75}\right]^{-4/3}$$

GW Background from Primordial Thermal Plasma

Spectrum of the Equilibrium CGMB



[Tamarit unpublished]

GW Background from Primordial Thermal Plasma

Case of sub-Planckian maximum temperature

CGMB for $T_{\rm ewco} < T_{\rm max} < M_P$: [Ghiglieri,Laine ’15; Ghiglieri,Jackson,Laine,Zhu ‘20; AR,Schütte-Engel,Tamarit ‘20]

- Production and evolution of the energy density in GWs produced by thermal fluctuations described by

$$(\partial_t + 4H(t))\, \rho_{\rm CGMB}(t) = \frac{4\,T^4}{M_P^2} \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\, \hat{\eta}\left(T, \frac{k}{T}\right)$$

- Dimensionless production rate $\hat{\eta}$ for generic BSM (gauge bosons, scalars, fermions) with Debye thermal masses of gauge fields: $m_n^2(T) = g_n^2(T) T^2 \left(\frac{1}{3} T_{n,\rm Ad} + \frac{1}{6} \sum_{\hat{\imath}} T_{n,\hat{\imath}} + \frac{1}{6} \sum_{\hat{\alpha}} T_{n,\hat{\alpha}} \right) \equiv T^2 \hat{m}_n^2(T)$

GW Background from Primordial Thermal Plasma

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  - For $k/T \lesssim \alpha_1^2$: Originating from macroscopic hydrodynamic fluctuations described by shear viscosity [Arnold,Moore,Yaffe '00]

$$\hat\eta = \frac{\eta^{\rm shear}}{T^3} \simeq \frac{\bar\eta}{g_1(T)^4\ln(5/\hat m_1)}$$

$$\bar\eta = \zeta(5)^2\left(\frac{5}{2}\right)^3\left(\frac{12}{\pi}\right)^5\left(\frac{N_{\rm leptons}}{9\pi^2 + 224 N_{\rm species}}\right)$$

$$N_{\rm species} = \frac{1}{2}\sum_{\hat\imath} T_{1,\hat\imath} + \frac{1}{2}\sum_{\hat\alpha} T_{1,\hat\alpha}\,, \qquad N_{\rm leptons} = \frac{1}{2}\sum_{\hat\alpha: T_{n,\hat\alpha}=0, n>1} T_{1,\hat\alpha}$$

GW Background from Primordial Thermal Plasma

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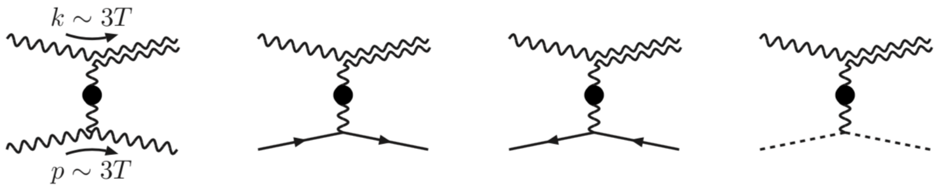
  - For $k/T \gtrsim \max\{\alpha_n^2\}$: Originating from microscopic particle collisions; in leading log:



$$\hat\eta_{\rm LL}(T,\hat k) = \frac{\hat k}{8\pi(e^{\hat k}-1)}\sum_n N_n\hat m_n^2(T)\log\left(\frac{5}{\hat m_n^2(T)}\right)$$

[Ghiglieri,Laine ’15]

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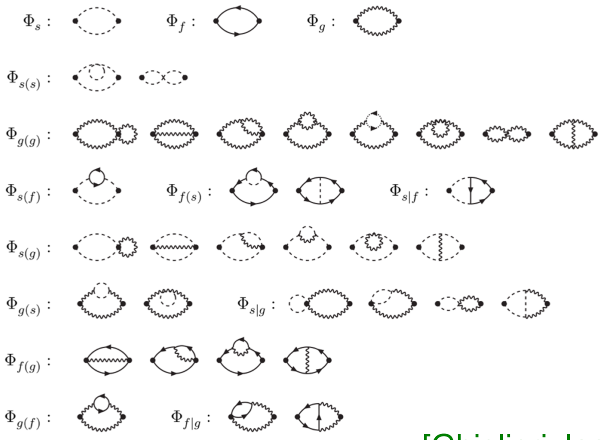

[Ghiglieri,Jackson,Laine,Zhu '20]

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  - For $k/T \gtrsim \max\{\alpha_n^2\}$: Originating from microscopic particle collisions; complete leading order:

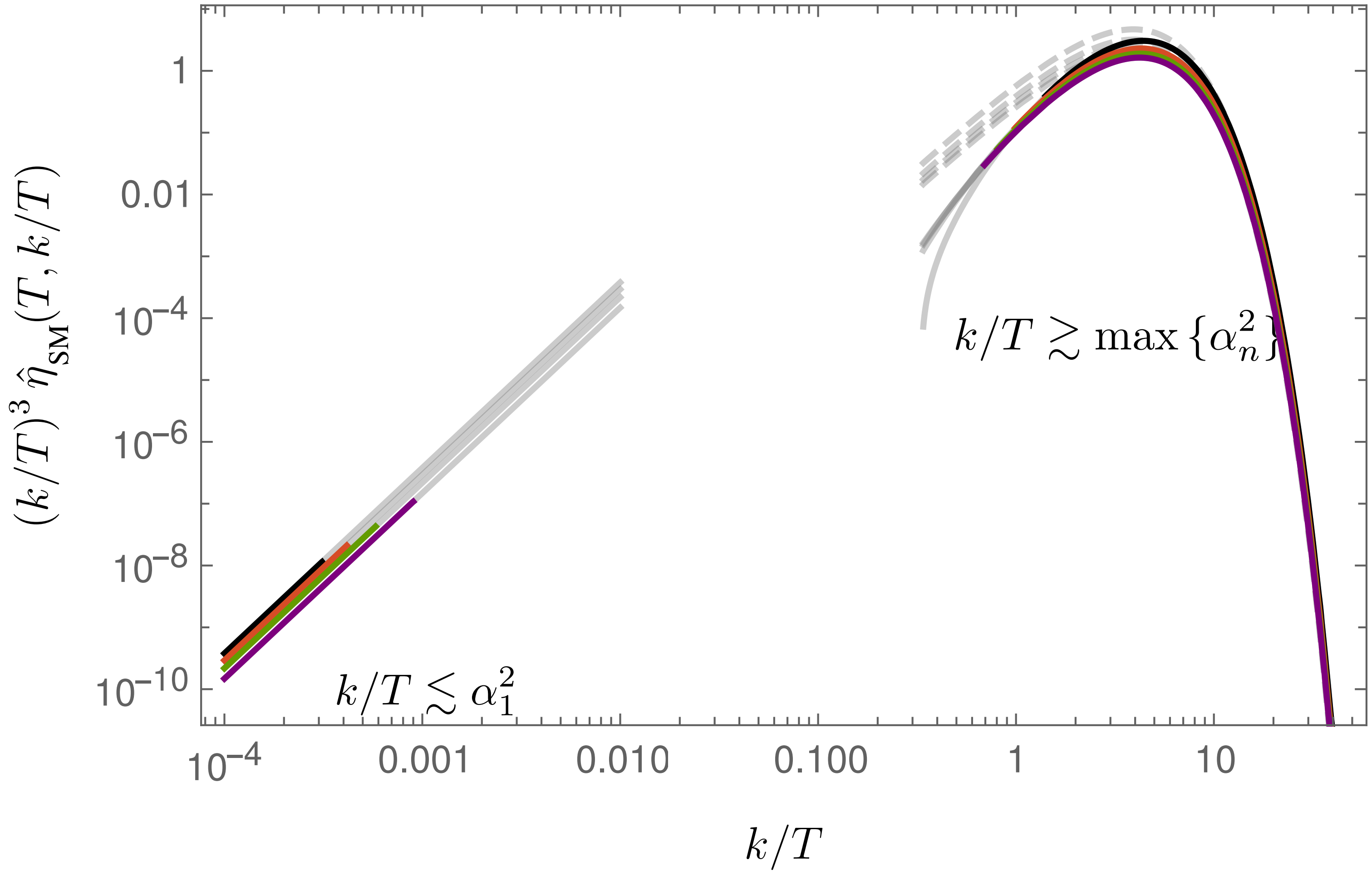
$$\hat\eta\left(T,\frac{k}{T}\equiv\hat k\right) \simeq \hat\eta_{\rm HTL}(T,\hat k) + \sum_{n=1}^{\mathcal{N}_g} g_n(T)^2 N_n\left(\frac{1}{2}T_{n,{\rm Ad}}\,\eta_{gg}(\hat k)\right.$$
$$\left. + \sum_{\hat\imath}T_{n,\hat\imath}\,\eta_{sg}(\hat k) + \frac{1}{2}\sum_{\hat\alpha}T_{n,\hat\alpha}\,\eta_{fg}(\hat k)\right)$$
$$+ \frac{1}{4}\sum_{i\alpha\beta}|y^i_{\alpha\beta}(T)|^2\,\eta_{sf}(\hat k),$$

$$\hat\eta_{\rm HTL}(T,\hat k) = \frac{\hat k}{16\pi(e^{\hat k}-1)}\sum_n N_n\hat m_n^2(T)\log\left(1 + 4\frac{\hat k^2}{\hat m_n^2(T)}\right)$$

[Ghiglieri,Jackson,Laine,Zhu '20; AR,Schütte-Engel,Tamarit '20]

GW Background from Primordial Thermal Plasma

Dimensionless production rate



SM:

$$\hat m^2_{1,\rm SM}(T) = \frac{11}{6} g_1(T)^2, \quad \hat m^2_{2,\rm SM}(T) = \frac{11}{6} g_2(T)^2,$$
$$\hat m^2_{3,\rm SM}(T) = 2 g_3(T)^2$$

$$\hat\eta_{\rm SM} \simeq \begin{cases} \dfrac{15.51}{g_1^4 \ln(5/\hat m_{1,\rm SM})}, & \hat k \lesssim \alpha_1^2, \\ \hat\eta_{\rm HTL,SM}(T,\hat k) + (3g_2^2 + 12 g_3^2)\eta_{gg}(\hat k) & \\ \quad + (g_1^2 + 3g_2^2)\eta_{sg}(\hat k) + (5g_1^2 + 9g_2^2 + 24 g_3^2)\eta_{fg}(\hat k) & \hat k \gtrsim \max\{\hat m_n\}. \\ \quad + (3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2)\,\eta_{sf}(\hat k), & \end{cases}$$

$$\hat\eta_{\rm HTL,SM}(T,\hat k) = \frac{\hat k}{16\pi(e^{\hat k}-1)} \sum_{n,\rm SM} N_{n,\rm SM} \hat m^2_{n,\rm SM}(T) \log\left(1 + 4\frac{\hat k^2}{\hat m^2_{n,\rm SM}(T)}\right)$$

[AR,Schütte-Engel,Tamarit '20]

GW Background from Primordial Thermal Plasma

Spectrum of CGMB

- Solving evolution equation:

$$\Omega_{\rm CGMB}(f) \simeq \frac{1440\sqrt{10}}{2\pi^2 M_P}\,\Omega_\gamma\,\left[g_{*s}(\text{fin})\right]^{1/3}\frac{f^3}{T_0^3}\times$$
$$\times\int_{T_{\rm ewco}}^{T_{\rm max}} dT\,\frac{g_{*c}(T)}{\left[g_{*s}(T)\right]^{4/3}\left[g_{*\rho}(T)\right]^{1/2}}\,\hat{\eta}\left(T, 2\pi\left[\frac{g_{*s}(T)}{g_{*s}(\text{fin})}\right]^{1/3}\frac{f}{T_0}\right)$$

- Production rate depends on temperature only logarithmically, and effective degrees of freedom at tempe-ratures far away from phase transitions almost constant and equal; correspondingly

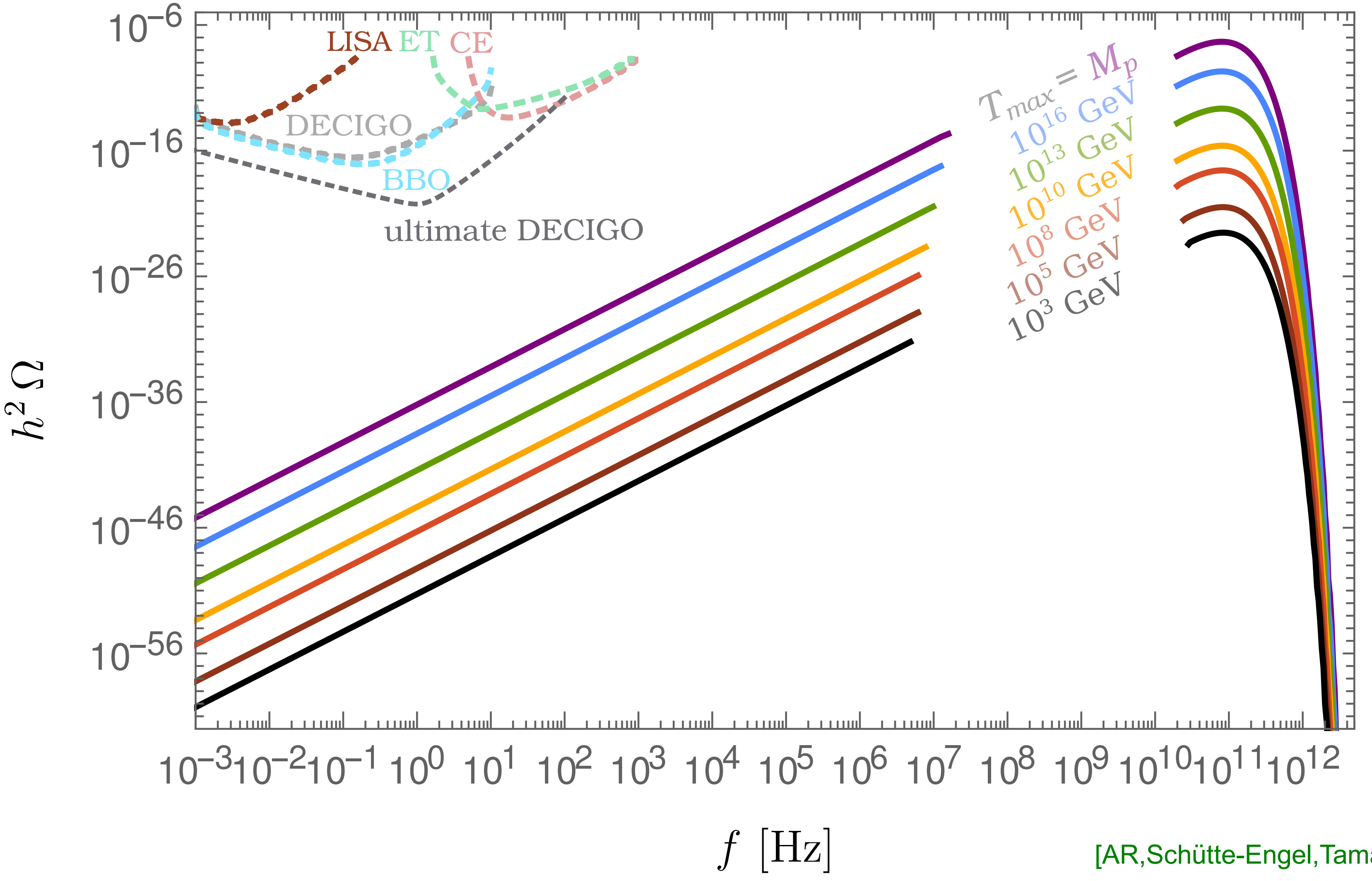
$$h^2\,\Omega_{\rm CGMB}(f) \approx 2.06\times 10^{-6}\left[\frac{T_{\rm max}}{M_P}\right]\left[\frac{g_{*s}(T_{\rm max})}{106.75}\right]^{-5/6}\left[\frac{f}{80\,\text{GHz}}\right]^3\hat{\eta}\left(T_{\rm max}, 4.23\left[\frac{g_{*s}(T_{\rm max})}{106.75}\right]^{1/3}\left[\frac{f}{80\,\text{GHz}}\right]\right)$$

  - Scales approximately linearly with maximum temperature
  - Peaks at $f^{\Omega_{\rm CGMB}}_{\rm peak} \simeq 80\,\text{GHz}\,[106.75/g_{*s}(T_{\rm max})]^{1/3}$

$$\Omega_{\rm CGMB}(f^{\Omega}_{\rm peak}(T_{\rm max})) \approx \left(\frac{g_{*s,\rm SM}(T_{\rm max})}{g_{*s}(T_{\rm max})}\right)^{11/6}\Omega_{\rm CGMB,SM}(f^{\Omega}_{\rm peak,SM}(T_{\rm max}))$$

GW Background from Primordial Thermal Plasma

CGMB spectrum for SM



[AR,Schütte-Engel,Tamarit '20]

GW Background from Primordial Thermal Plasma

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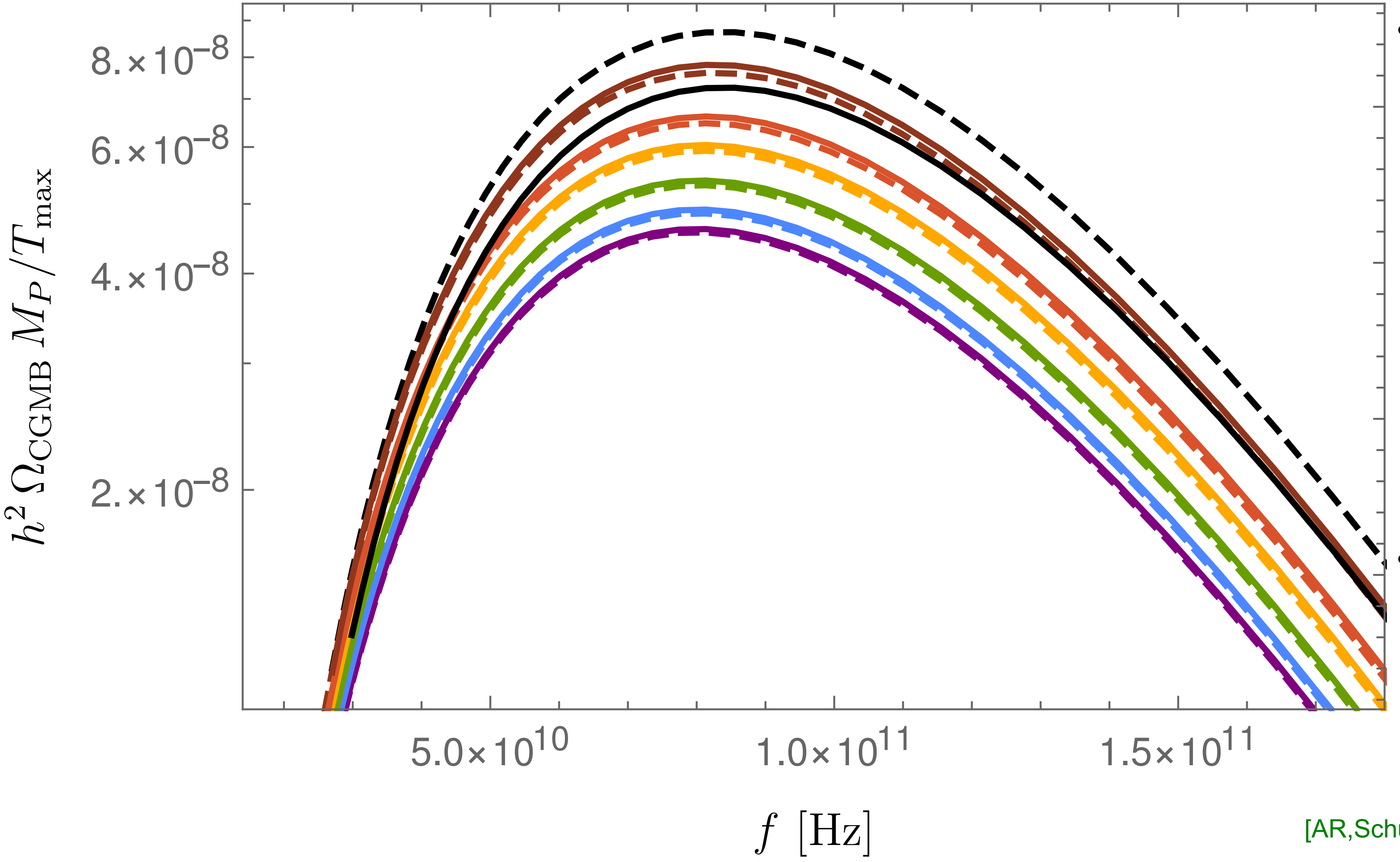
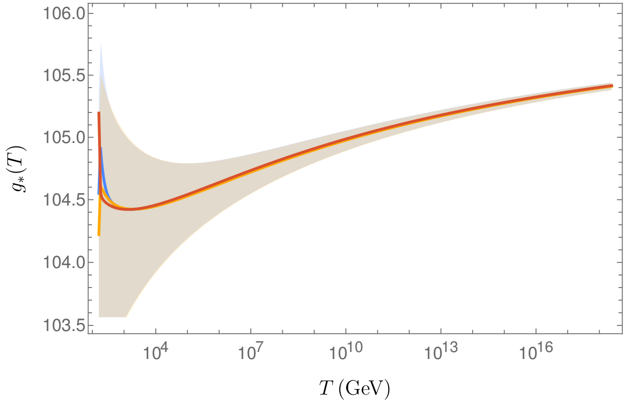


- Solid lines:

$$\Omega_{\rm CGMB}(f) \simeq \frac{1440\sqrt{10}}{2\pi^2 M_P}\,\Omega_\gamma\,[g_{*s}({\rm fin})]^{1/3}\,\frac{f^3}{T_0^3}\times$$
$$\times\int_{T_{\rm ewco}}^{T_{\rm max}} {\rm d}T\,\frac{g_{*c}(T)}{[g_{*s}(T)]^{4/3}\,[g_{*\rho}(T)]^{1/2}}\,\hat\eta\left(T, 2\pi\left[\frac{g_{*s}(T)}{g_{*s}({\rm fin})}\right]^{1/3}\frac{f}{T_0}\right)$$

SM



- Dotted lines:

$$h^2\,\Omega_{\rm CGMB}(f) \approx 2.06\times10^{-6}\left[\frac{T_{\rm max}}{M_P}\right]\left[\frac{g_{*s}(T_{\rm max})}{106.75}\right]^{-5/6}\times$$
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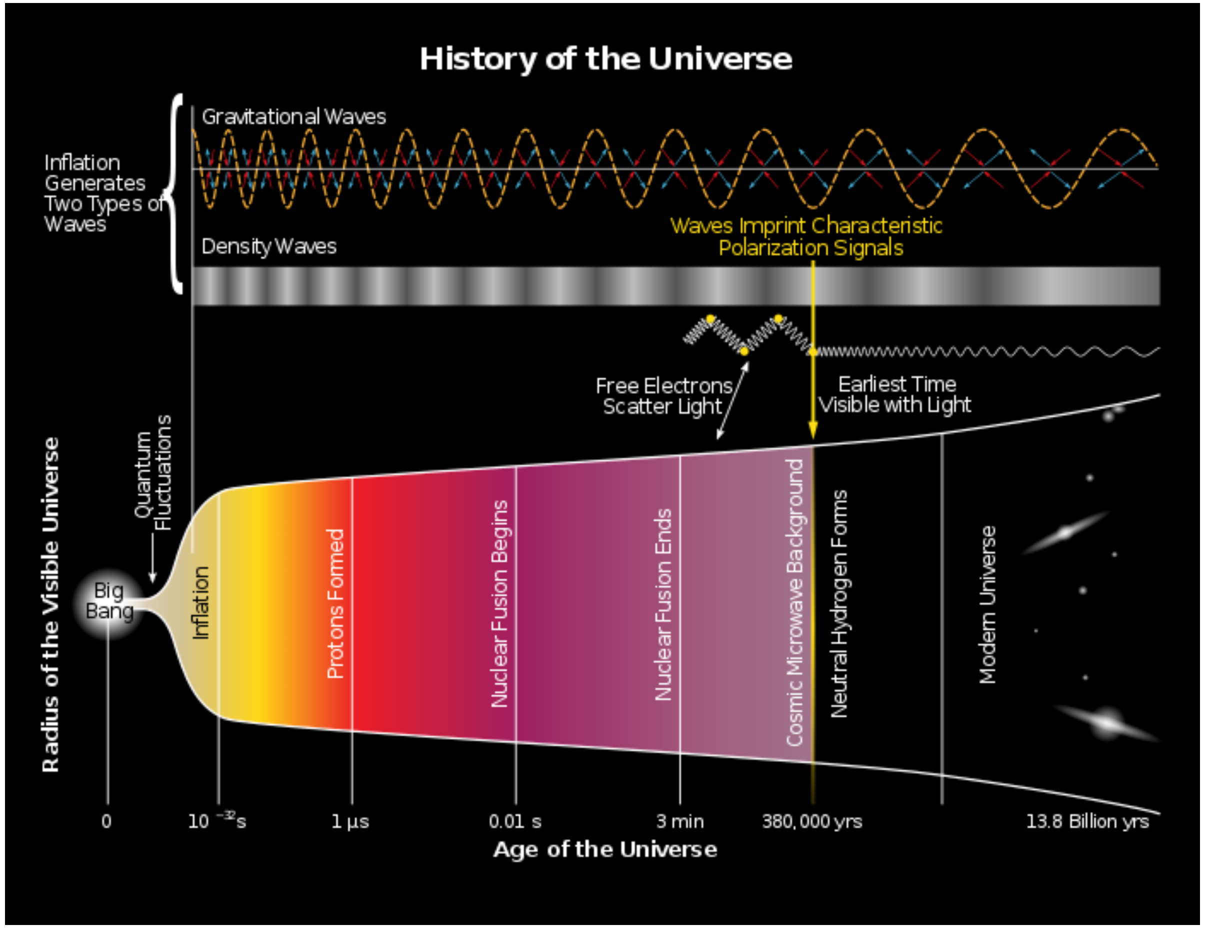
[AR,Schütte-Engel,Tamarit '20]

GW Background from Primordial Thermal Plasma

Inflationary predictions of maximum temperature

- Inflationary era preceding hot big bang era solves shortcomings of hot big bang cosmology (flatness and horizon problem) and explains origin of density fluctuations needed as seeds of structure formation



GW Background from Primordial Thermal Plasma

Inflationary predictions of maximum temperature

- In slow-roll inflationary cosmology, the energy density at the end of inflation can be inferred from the ratio of the amplitudes of tensor and scalar fluctuations, r, and the amplitude of scalar perturbations, A_S, generated during inflation:

$$\rho_{\rm inf} \approx \frac{3}{2}\,\pi^2\, r\, A_S M_P^4$$

- The measurement of A_S and the upper limit on r by the CMB observatories Planck and BICEP2/Keck Array provide an upper bound on the energy scale of inflation: [Akrami et al., 1807.06211]

$$\rho_{\rm inf} \; < \; \left(1.6\times 10^{16}\,{\rm GeV}\right)^4 \qquad (95\%\ {\rm CL})$$

- This may be turned into an upper bound on the maximum temperature of the post-inflationary hot big bang era by assuming instantaneous and thus maximally efficient reheating:

$$T_{\rm max}^{\rm inf} < \left[\frac{\left(1.6\times 10^{16}\,{\rm GeV}\right)^4}{\frac{\pi^2}{30}\, g_{*\rho}(T_{\rm max}^{\rm inf})}\right]^{1/4} = 6.6\times 10^{15}\,{\rm GeV}\left[\frac{g_{*\rho}(T_{\rm max}^{\rm inf})}{106.75}\right]^{-1/4}$$

GW Background from Primordial Thermal Plasma

Minimal BSM extensions predicting maximum temperature

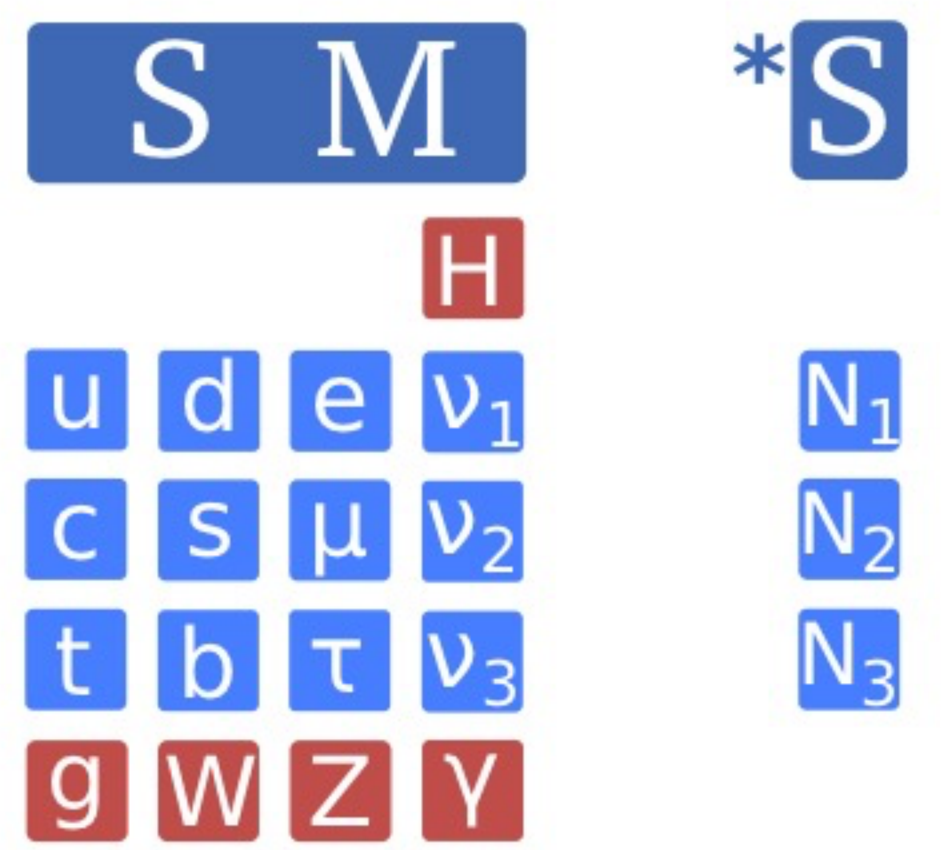
The **nuMSM** extends the SM by

- 3 right-handed SM singlet neutrinos N_i

[Asaka,Blanchet,Shaposhnikov ´05, Asaka,Shaposhnikov ´05]

thereby solving four big problems in particle physics and cosmology in one go:

1. Neutrino masses and mixing
2. Dark matter
3. Baryon asymmetry
4. Inflation



It predicts: [Bezrukov,Gorbunov.Shaposhnikov ´09]

$$3.4 \times 10^{13}\,\mathrm{GeV} \lesssim T_{\max}^{\nu\mathrm{MSM}} \lesssim 9.3 \times 10^{13}\,\mathrm{GeV} \left(\frac{\lambda_H}{0.13}\right)^{1/4}$$

$$g_{*s}(T_{\max}^{\nu\mathrm{MSM}}) \simeq 109.75$$

GW Background from Primordial Thermal Plasma

Minimal BSM extensions predicting maximum temperature

SMASH extends the SM by

- 3 right-handed SM singlet neutrinos N_i
- 1 SM singlet complex scalar $\sigma(x) = \frac{1}{\sqrt{2}}(v_\sigma + \rho(x))\, e^{iA(x)/v_\sigma}$
- 1 vector-like extra quark Q

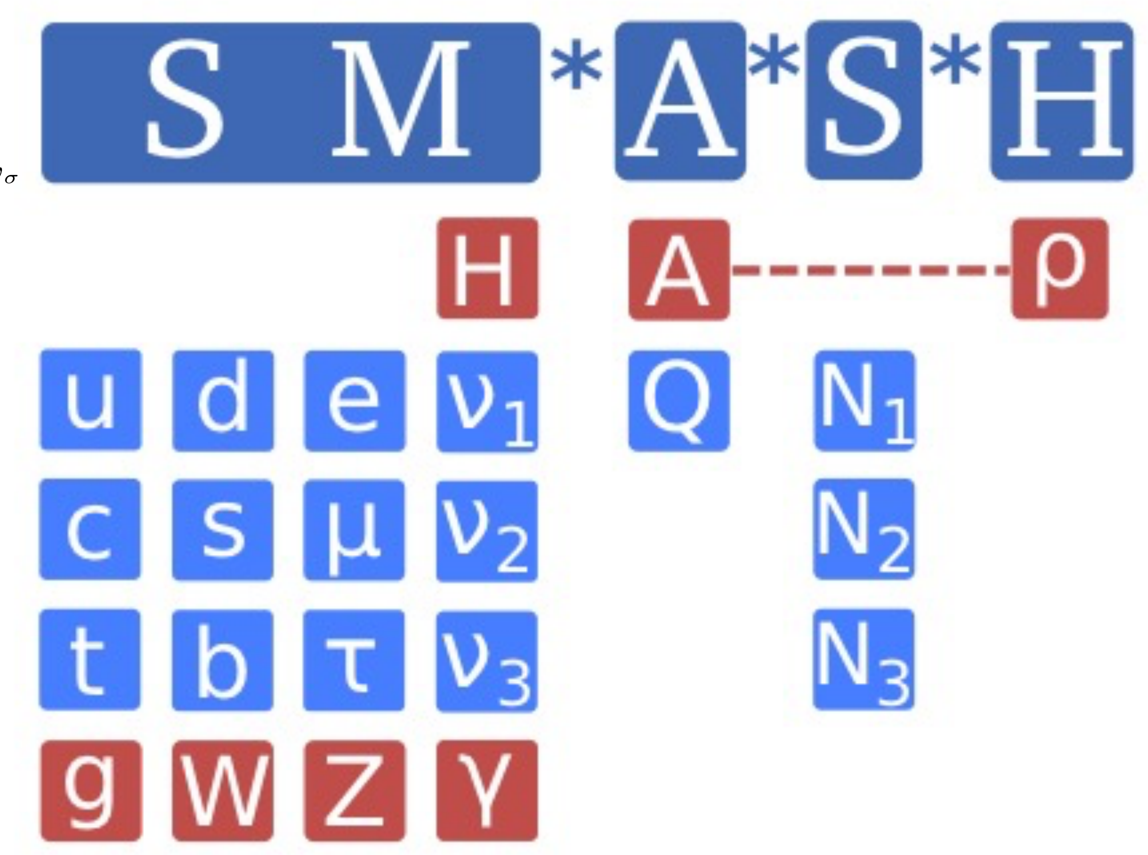
thereby solving five big problems in particle physics and cosmology in one smash:

1. Neutrino masses and mixing
2. Dark matter
3. Baryon asymmetry
4. Inflation
5. Strong CP problem

It predicts:

$$8 \times 10^9\,\mathrm{GeV} \lesssim T_{\max}^{\mathrm{SMASH}} \lesssim 2 \times 10^{10}\,\mathrm{GeV}$$

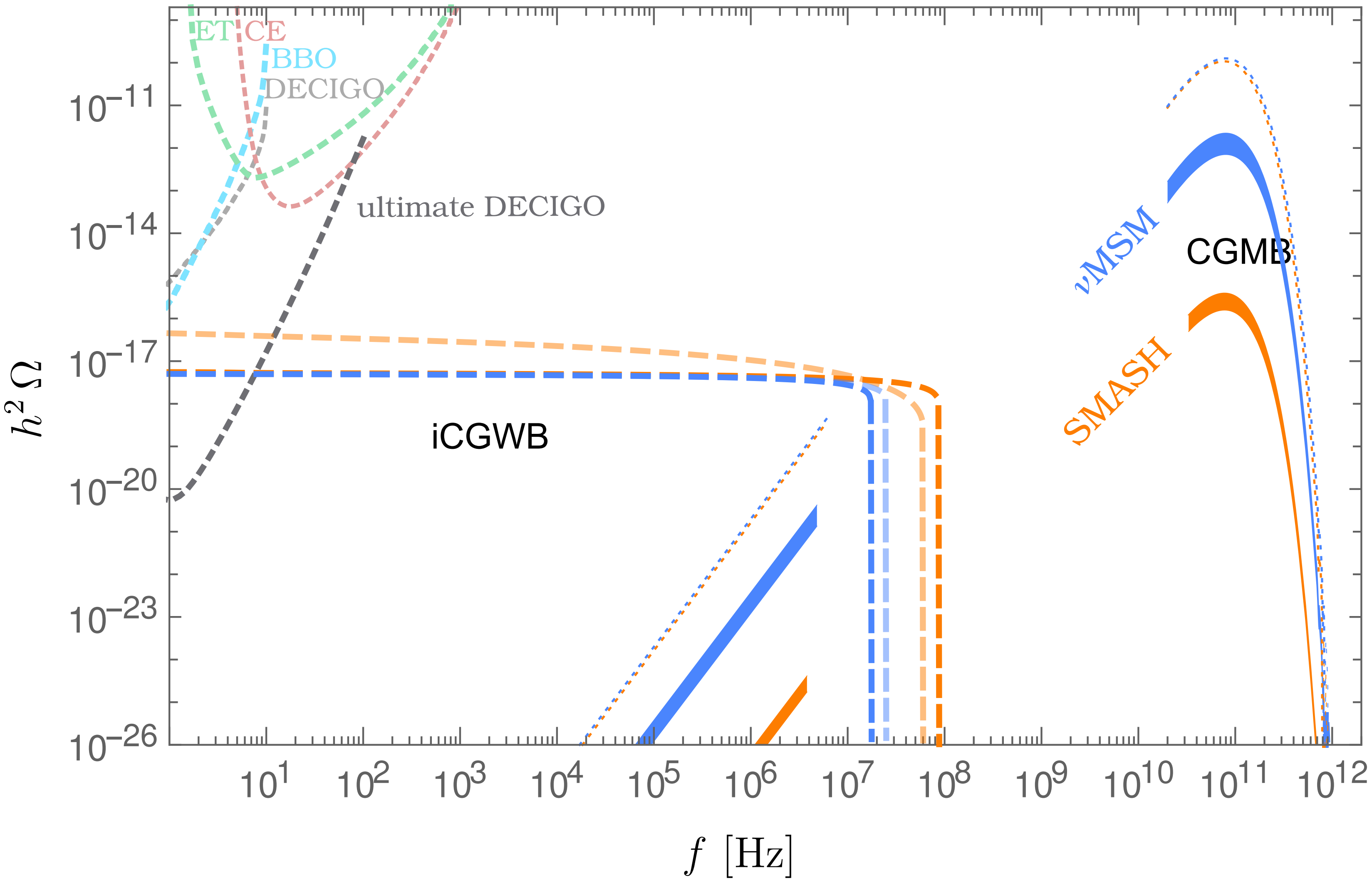
$$g_{*s}(T_{\max}^{\mathrm{SMASH}}) \simeq 124.5$$



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

GW Background from Primordial Thermal Plasma

Primordial GW spectra for nuMSM and SMASH



[AR,Schütte-Engel,Tamarit ‘20]

Observational Constraints on the CGMB

Dark radiation constraint

- CGMB acts as an additional dark radiation field in the universe
- BBN and the process of photon decoupling of the CMB yield a very precise measurement of the energy density, when the universe had a temperature of $T_{\rm BBN} \sim 0.1\,{\rm MeV}$ and $T_{\rm CMB} \sim 0.3\,{\rm eV}$, respectively
- Constraint on presence of `extra' radiation is usually expressed in terms of an extra effective number of neutrinos species, $\Delta\rho_{\rm rad}(T) = \frac{\pi^2}{30}\,\frac{7}{4}\,\Delta N_\nu(T)\,T^4$:

$$h^2 \int_0^\infty \frac{{\rm d}f}{f}\,\Omega_{\rm CGMB}(f) = h^2\,\frac{\rho^{(0)}_{\rm CGMB}}{\rho^{(0)}_c} \leq 5.658\times 10^{-6}\left[\frac{g_{*s}(T)}{10.75}\right]^{-4/3}\Delta N_\nu(T)$$

- Current best bounds:
  - $h^2\,\frac{\rho^{(0)}_{\rm CGMB}}{\rho^{(0)}_c} < 1.2\times 10^{-6}$, for adiabatic initial conditions [Pagano,Salvati,Melchiorri,´16]
  - $h^2\,\frac{\rho^{(0)}_{\rm CGMB}}{\rho^{(0)}_c} < 2.9\times 10^{-7}$, for homogenous initial conditions [Clarke,Copeland,Moss ´20]

Observational Constraints on the CGMB

Dark radiation constraint

- Confronting the CGMB predictions with the dark radiation constraints gives the following bounds on the maximum temperature:

	SM	νMSM	SMASH	MSSM
$T_{\max}$ [GeV] $<$	$(1.2\text{-}5.1) \times 10^{19}$	$(1.3\text{-}5.4) \times 10^{19}$	$(1.4\text{-}6.0(1)) \times 10^{19}$	$(2.3\text{-}9.4) \times 10^{19}$

  - Limits larger than the reduced Planck scale, $M_P \equiv 1/\sqrt{8\pi G} \simeq 2.435 \times 10^{18}\,\text{GeV}$
- On the other hand, the Equilibrium CGMB predictions, applicable for $T_{\max} > M_P$,

$$h^2 \frac{\rho^{(0)}_{\text{Eq.CGMB}}}{\rho^{(0)}_c} = \frac{h^2\pi^2 T_0^4}{45 H_0^2 M_P^2}\left[\frac{g_{*s}(\text{fin})}{g_{*s}(M_P)}\right]^{4/3} = 3.0 \times 10^{-7}\left[\frac{g_{*s}(M_P)}{106.75}\right]^{-4/3}$$

  just saturates the dark radiation bound obtained assuming homogeneous initial conditions, if $g_{*s}(M_P) \approx 106.75$

- Future prospects of dark radiation constraints:

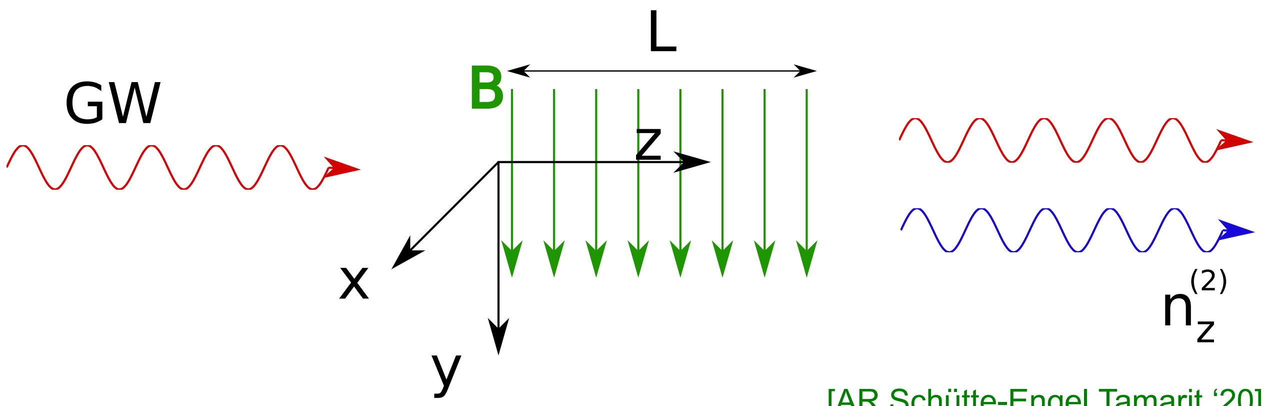
	SM	νMSM	SMASH	MSSM
$T_{\max}^{\Delta N_\nu = 0.001}$ [GeV] $<$	2.3×10^{17}	2.4×10^{17}	2.7×10^{17}	4.39×10^{17}

Observational Constraints on the CGMB

CMB Rayleigh-Jeans tail constraint

- In the presence of magnetic fields, GWs are converted into electromagnetic waves (EMWs) and vice versa. This is called the (inverse) Gertsenshtein effect

  [Gertsenshtein `62,Boccaletti,.. `70,Zeldovich,.. `73,DeLogi,.. `77,Raffelt,.. `87]



[AR,Schütte-Engel,Tamarit ‘20]

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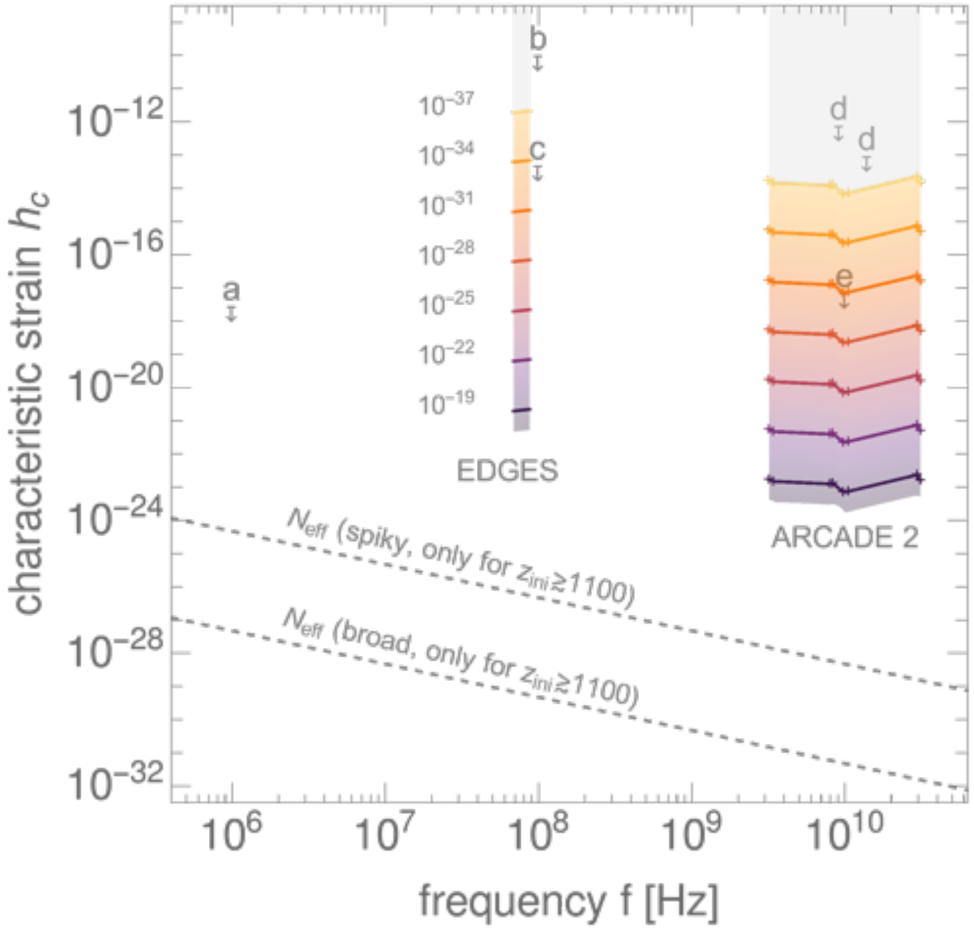
  [Gertsenshtein `62,Boccaletti,.. `70,Zeldovich,.. `73,DeLogi,.. `77,Raffelt,.. `87]
- This conversion distorts the CMB, which can act therefore as a detector for MHz to GHz GWs [Domcke,Garcia-Cely `20]
- Measurements of the radio telescope EDGES and ARCADE 2 have been turned into bounds on the characteristic dimension-less amplitude of stochastic GWs,

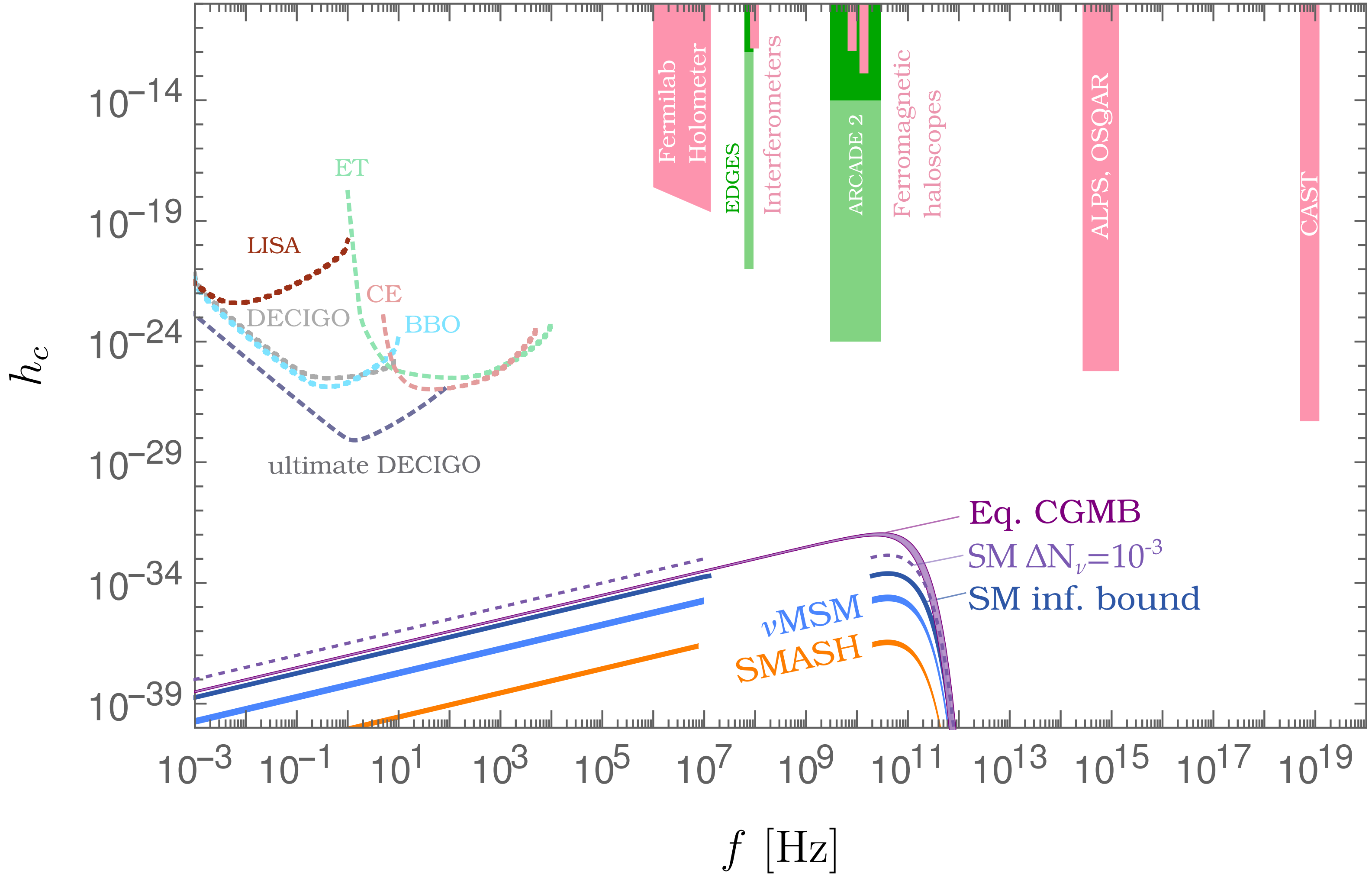
$$h_c(f) \equiv 1.26 \times 10^{-27} \left[\frac{\mathrm{GHz}}{f}\right] \sqrt{h^2\,\Omega_{\mathrm{GW}}(f)}$$

- Bounds strongly depend on the uncertain strength of cosmic magnetic fields



Laboratory Searches for the CGMB

Current and projected bounds on the amplitude of GWs

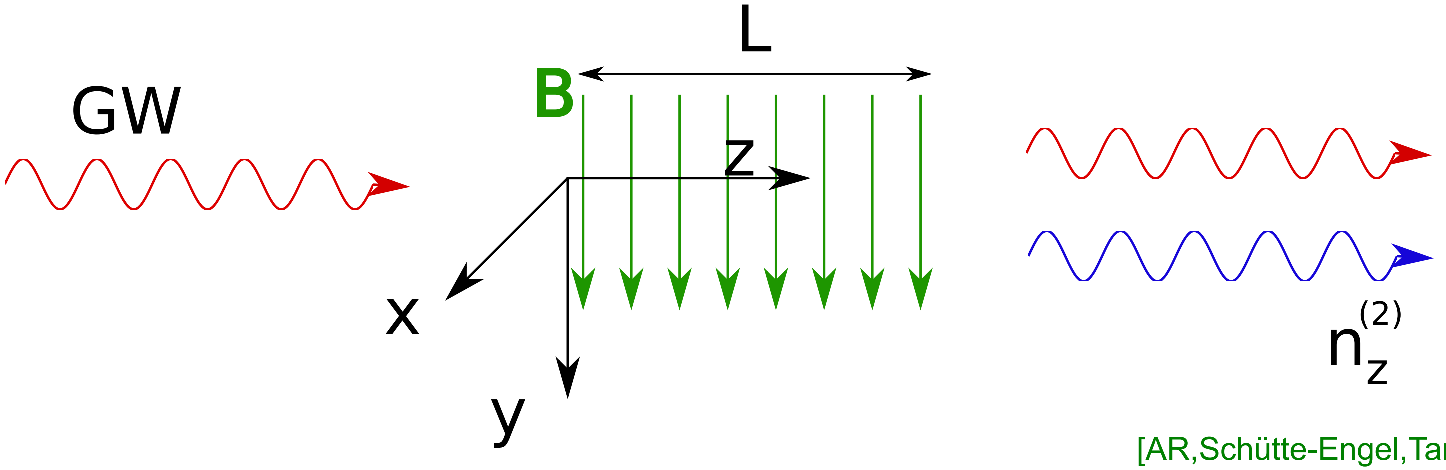


[AR,Schütte-Engel,Tamarit '20]

Laboratory Searches for the CGMB

Magnetic GW-EMW conversion in vacuum

- Inverse Gertsenshtein effect: [Gertsenshtein `62,Boccaletti,.. `70,Zeldovich,.. `73,DeLogi,.. `77,Raffelt,.. `87]



[AR,Schütte-Engel,Tamarit '20]

  - Average power of the generated EMW, per logarithmic frequency interval, at the terminal position of the magnetic field:

$$f\frac{\mathrm{d}P^{(2)}_{\mathrm{EMW}}}{\mathrm{d}f} \simeq \pi^2 f^2 h_c^2(f)\, B^2 L^2 A = 4.20\times 10^{-23}\,\mathrm{W}\left[\frac{f}{40\,\mathrm{GHz}}\right]^2\left[\frac{h_c(f)}{10^{-21}}\right]^2\left[\frac{B}{\mathrm{T}}\right]^2\left[\frac{L}{\mathrm{m}}\right]^2\left[\frac{A}{\mathrm{m}^2}\right]$$

  - Average number of generated photons, per unit logarithmic frequency interval,

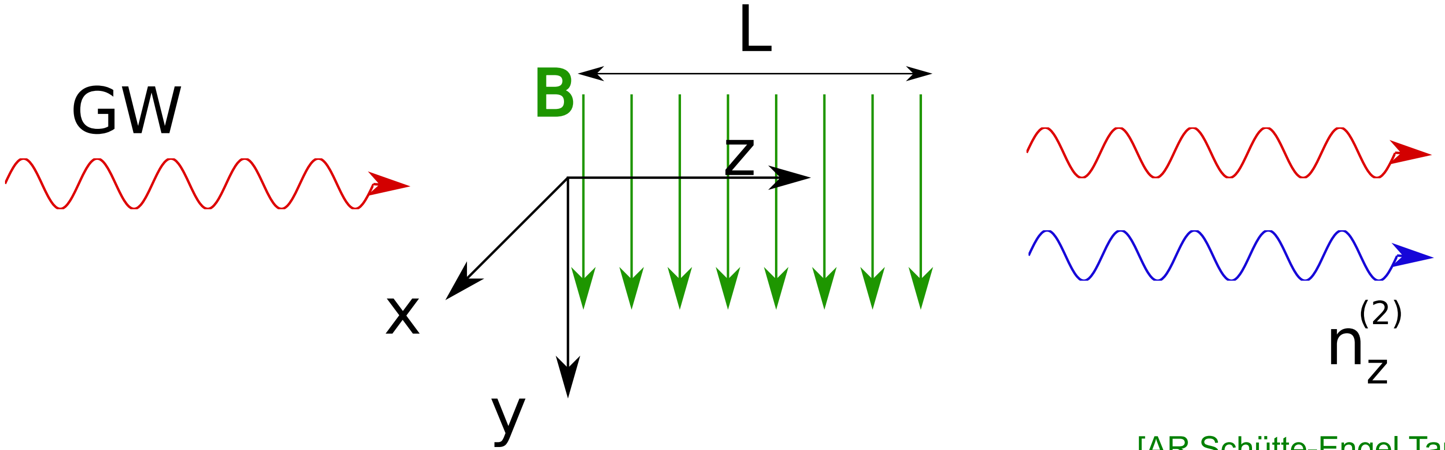
$$f\frac{\mathrm{d}N^{(2)}_z}{\mathrm{d}f} \simeq \frac{\pi}{2} f\, h_c^2(f)\, B^2 L^2 A\,\Delta t = 1.59\left[\frac{f}{40\,\mathrm{GHz}}\right]\left[\frac{h_c(f)}{10^{-21}}\right]^2\left[\frac{B}{\mathrm{T}}\right]^2\left[\frac{L}{\mathrm{m}}\right]^2\left[\frac{A}{\mathrm{m}^2}\right]\left[\frac{\Delta t}{\mathrm{s}}\right]$$

  - Similar to axion experiments (Light-Shining-through-Wall (LSW); Helioscope): Figure of merit is $BLA^{1/2}$

Laboratory Searches for the CGMB

Magnetic GW-EMW conversion in vacuum

- Inverse Gertsenshtein effect: [Gertsenshtein `62,Boccaletti,.. `70,Zeldovich,.. `73,DeLogi,.. `77,Raffelt,.. `87]



[AR,Schütte-Engel,Tamarit '20]

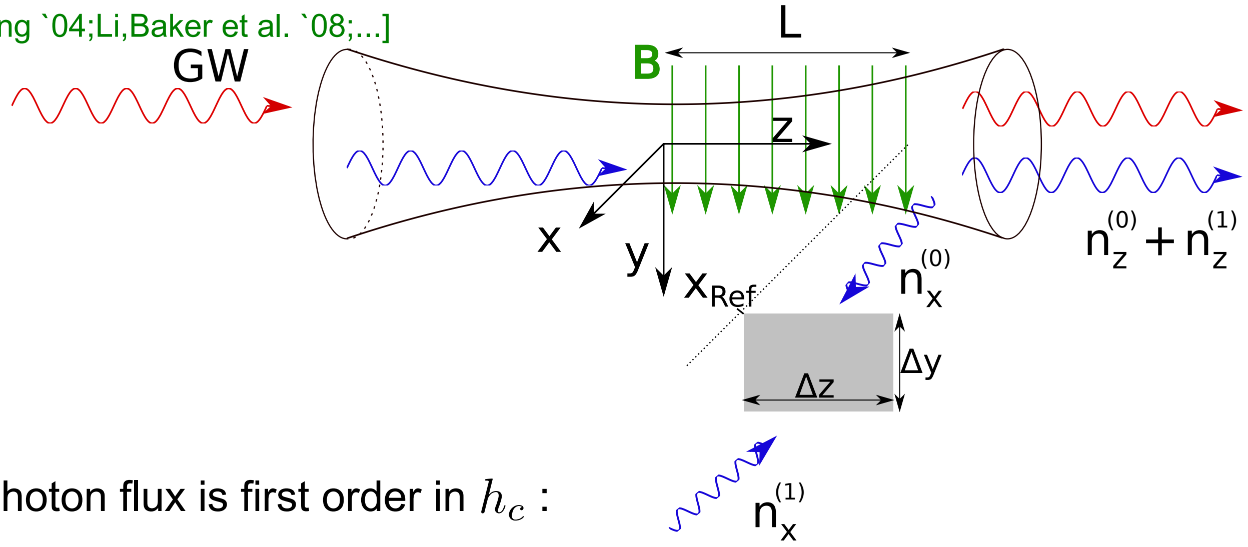
	B [T]	L [m]	d [m]	$n_{\rm tubes}$	$BLA^{1/2}$	f_c [Hz]	$[h_c^{\rm CGMB}]^{\rm HET}_{\rm sens}$	$[h_c^{\rm CGMB}]^{\rm SPD}_{\rm sens}$
ALPS IIc	5.3	211	0.05	1	$49.6\,{\rm Tm}^2$	4.6×10^{12}	–	–
BabyIAXO	2.5	10	0.7	2	$21.9\,{\rm Tm}^2$	1.1×10^{9}	4.41×10^{-22}	3.52×10^{-25}
MADMAX	4.83	6	1.25	1	$32.1\,{\rm Tm}^2$	1.9×10^{8}	3.01×10^{-22}	2.40×10^{-25}
IAXO	2.5	20	0.7	8	$87.7\,{\rm Tm}^2$	2.2×10^{9}	1.10×10^{-22}	8.79×10^{-26}

- To probe $h_c(40\,{\rm GHz}) \sim 10^{-32}$, corresponding to $T_{\rm max} \sim M_P$, would need to increase $BLA^{1/2}$ by more than six orders of magnitude!

Laboratory Searches for the CGMB

Magnetic GW-EMW conversion in a VHF EM Gaussian beam

- Li effect: [Li,Tang,Shi ’03;Li,Yang `04;Li,Baker et al. `08;...]



[AR,Schütte-Engel,Tamarit ‘20]

- Generated transverse photon flux is first order in h_c :

$$f \frac{\mathrm{d}n_x^{(1)}}{\mathrm{d}f}\Big|_{f_0} \simeq \frac{1}{4}\, h_c(f_0) B_y^{(0)} E_0 L\, \psi_x^{(1)}\left(\frac{w_0}{z_R}, \frac{x}{w_0}, \frac{y}{w_0}, \frac{z}{z_R}, \delta\right)$$

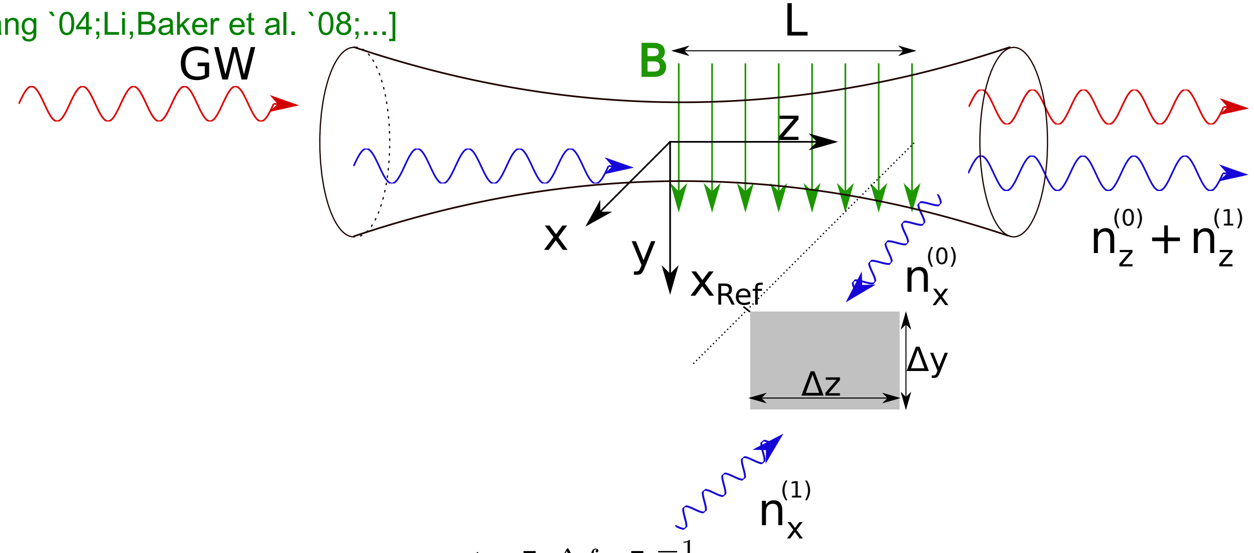
where $$\psi_x^{(1)}\left(\frac{w_0}{z_R}, x', y', z', \delta\right) \simeq \frac{w_0}{z_R}\, \frac{\frac{y'}{z'}\exp\left(-\frac{x'^2+y'^2}{[1+z'^2]}\right)}{[1+z'^2]^{1/2}} \times$$
$$\left\{\frac{1}{[1+z'^{-2}]}\cos\left(\frac{z'^{-1}(x'^2+y'^2)}{[1+z'^{-2}]} - \tan^{-1} z' + \delta\right) - \frac{z'}{[1+z'^2]}\sin\left(\frac{z'^{-1}(x'^2+y'^2)}{[1+z'^{-2}]} - \tan^{-1} z' + \delta\right)\right\}$$

- Depending on overall sign, that is on relative phase difference, flux points either in positive or negative x direction
- Place place at $x = \pm x_{\rm Ref}$ reflectors, which could reflect and focus a portion of this flux to receivers and detectors placed at positions $x = \pm x_{\rm Det}$ which are further away from the GB and therefore expected to suffer less from noise

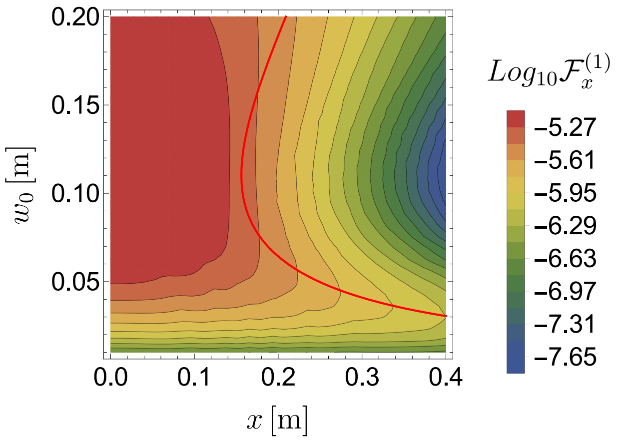
Laboratory Searches for the CGMB

Magnetic GW-EMW conversion in a VHF EM Gaussian beam

- Li effect: [Li,Tang,Shi '03;Li,Yang `04;Li,Baker et al. `08;...]



[AR,Schütte-Engel,Tamarit '20]



  - Sensitivity estimate:

$$\left[h_c^{\rm CGMB}\right]^{\rm GB}_{\rm sens} \simeq 4.02\times 10^{-29}\,\eta^{-1}\left[\frac{\rm S/N}{2}\right]\left[\frac{\Delta t}{10^4\,s}\right]^{-1/2}\left[\frac{\frac{\Delta f_0}{f_0}}{10^{-6}}\right]^{-1}\times$$

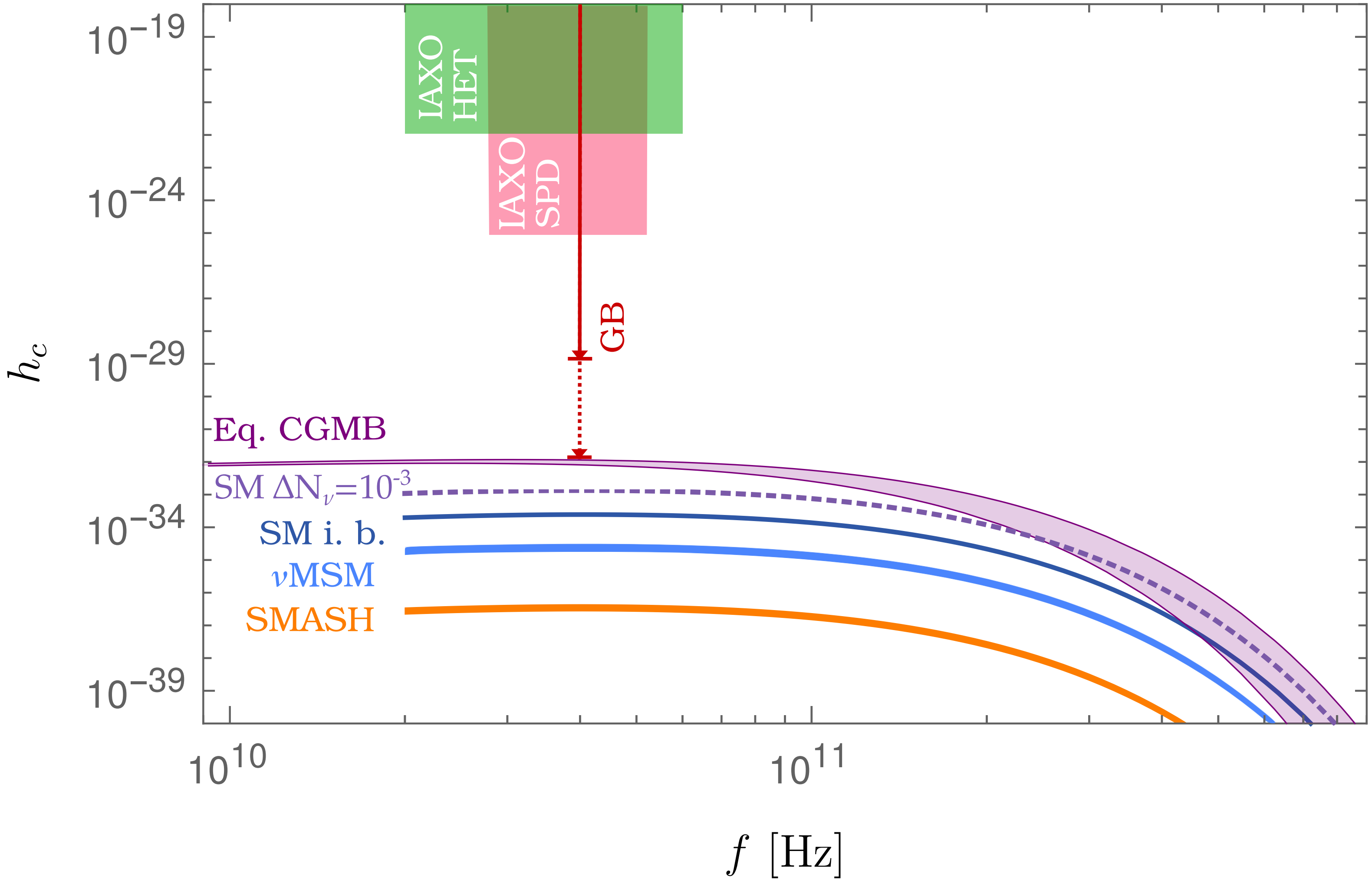
$$\times\ \epsilon^{-1}\left[\frac{\Gamma_{\rm D}}{10^{-3}\,{\rm Hz}}\right]^{1/2}\left[\frac{E_0}{5\times 10^5\,{\rm V/m}}\right]^{-1}\left[\frac{B_y^{(0)}}{10\,{\rm T}}\right]^{-1}\left[\frac{L}{5\,{\rm m}}\right]^{-1}\left[\frac{\Delta y\Delta z}{0.01\,{\rm m}^2}\right]^{-1}\left[\frac{\mathcal{F}_x^{(1)}(x_{\rm Ref})}{10^{-5}}\right]^{-1}$$

where $$\mathcal{F}_x^{(1)}(x) = \frac{1}{4\pi}\frac{w_0 z_R}{\Delta y\Delta z}\int_0^{2\pi}{\rm d}\delta\left|\int_0^{\frac{\Delta y}{w_0}}{\rm d}y'\int_{\frac{L}{z_R}}^{\frac{L+\Delta z}{z_R}}{\rm d}z'\,\psi_x^{(1)}\left(\frac{w_0}{z_R},x',y',z',\delta\right)\right|$$

- To probe $h_c(40\,{\rm GHz})\sim 10^{-32}$, corresponding to $T_{\rm max}\sim M_P$, seems possible in long term!

Laboratory Searches for the CGMB

Projected sensitivities



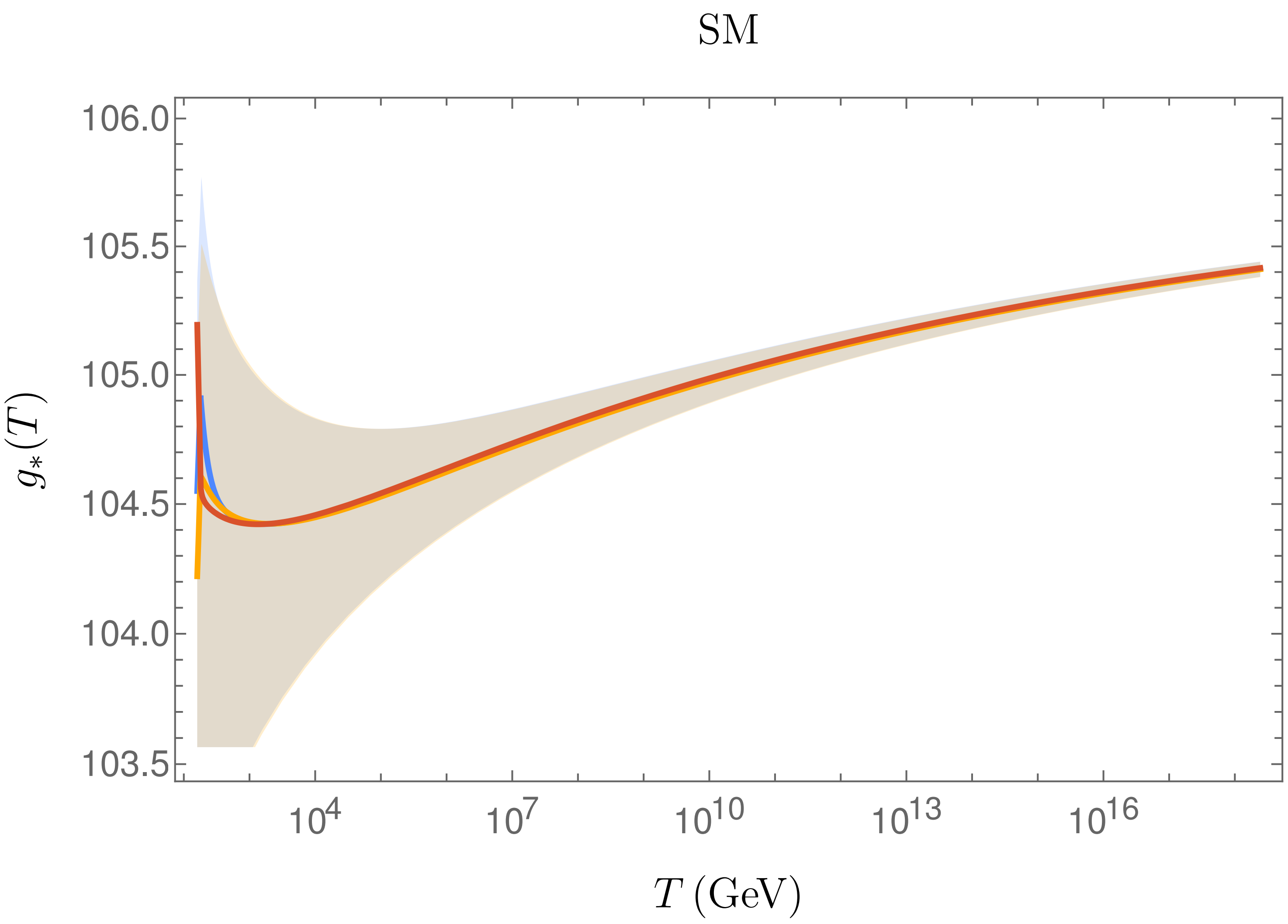
[AR,Schütte-Engel,Tamarit ‘20]

Summary

- Presented formulae for production of GWs from a primordial plasma at temperatures $T_{\rm ewco} < T < M_P$ in general gauge theory with scalars and fermions
- Derived general expressions for the current energy fraction of these primordial GWs per logarithmic frequency interval, $\Omega_{\rm CGMB}(f)$, and the corresponding characteristic amplitude h_c
- Showed that a measurement of $\Omega_{\rm CGMB}(f_{\rm peak}^{\Omega_{\rm CGMB}})$ or $h_c^{\rm CGMB}(f_{\rm peak}^{h_c^{\rm CGMB}})$ would allow to determine $T_{\rm max}$ and $g_{*s}(T_{\rm max})$
- Found that naive application of current dark radiation constraints implies $T_{\rm max} \lesssim 10^{19}\,{\rm GeV}$
- Investigated magnetic GW-EMW conversion in a 40 GHz Gaussian beam, delivered by a MW-scale gyrotron, as a search technique for stochastic GWs at frequencies around $f_{\rm peak}^{h_c^{\rm CGMB}} \simeq 40\,{\rm GHz}\,[g_{*\rho}(T_{\rm max})/106.75/]^{-1/3}$. The direct detection of the CGMB at a level corresponding to $T_{\rm max} \sim M_P$ seems possible, although challenging.
- In this connection, it should be emphasized that the search for the CGMB is truly a critical endeavour. Any measurement of $T_{\rm max}$ above $6.6\times 10^{15}\,{\rm GeV}\,[g_{*\rho}(T_{\rm max})/106.75]^{-1/4}$ would be ground-breaking, since it would rule out inflation as a viable pre hot big bang scenario

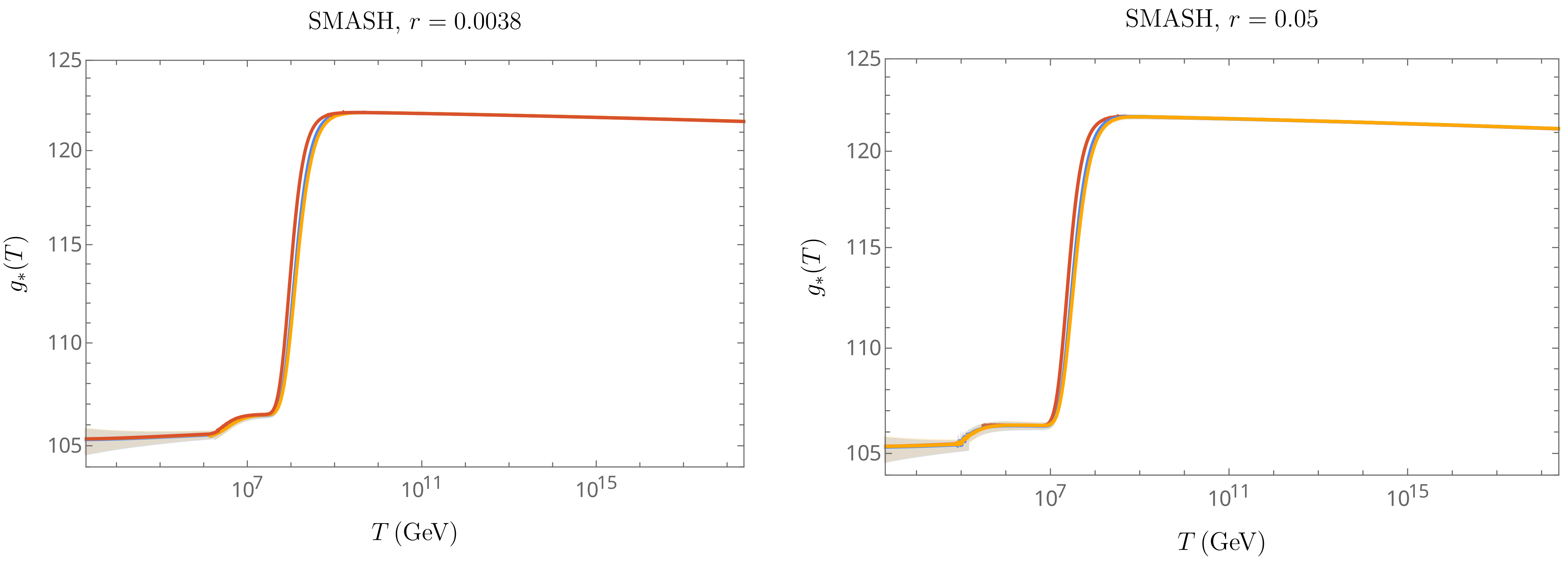
GW Background from Primordial Thermal Plasma

Effective number of degrees of freedom in SM



GW Background from Primordial Thermal Plasma

Effective number of degrees of freedom in SMASH



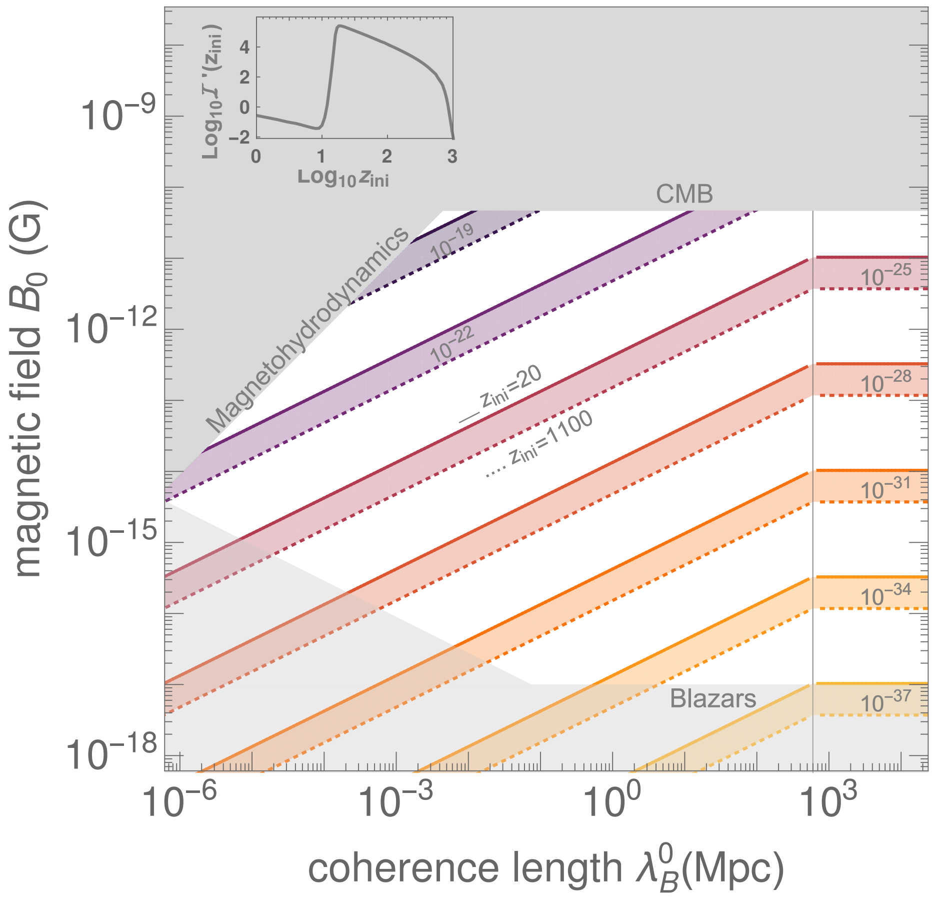
Observational Constraints on the CGMB

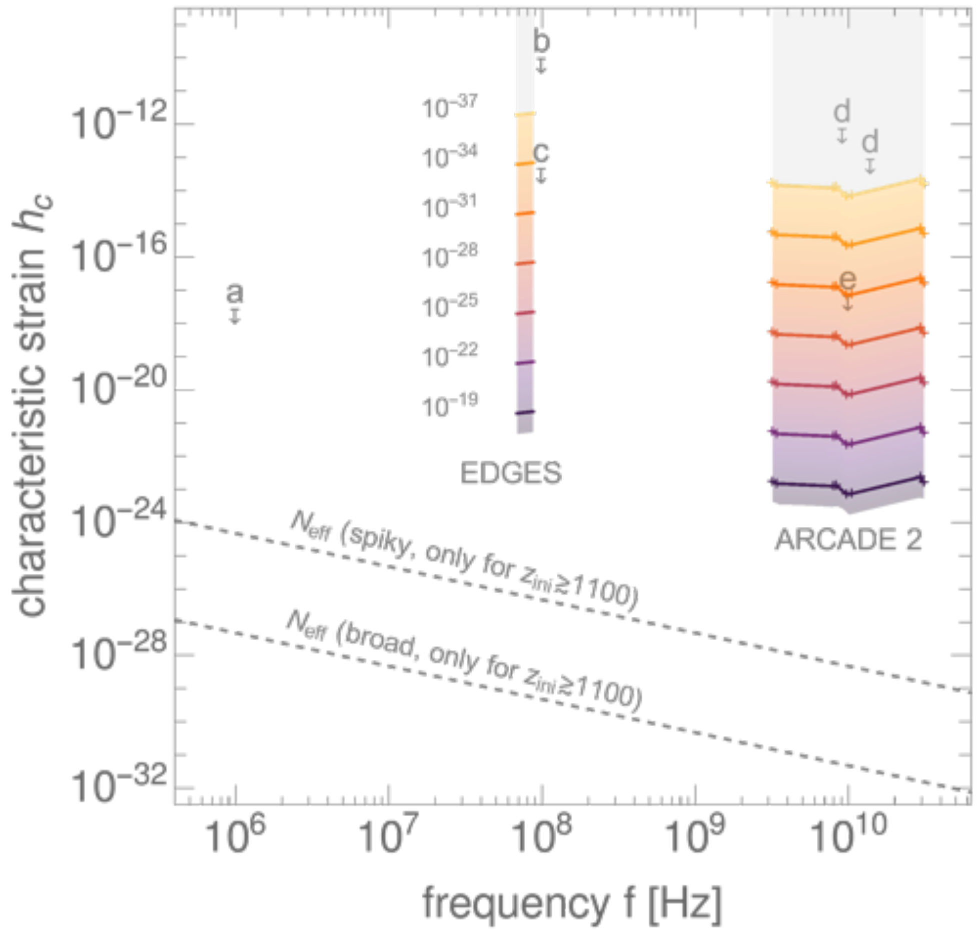
Peak values

	$T_{\rm max}$ [GeV]	$f_{\rm peak}^{\Omega_{\rm CGMB}}$ [GHz]	$f_{\rm peak}^{h_c^{\rm CGMB}}$ [GHz]	$h^2\Omega_{\rm CGMB}(f_{\rm peak}^{\Omega_{\rm CGMB}})$	$h_c^{\rm CGMB}(f_{\rm peak}^{h_c^{\rm CGMB}})$
SM	$> M_P$ 2.3×10^{17} 6.6×10^{15}	74.45 80.09 80.23	30.26 40.48 40.69	2.27×10^{-7} 4.47×10^{-9} 1.34×10^{-10}	1.17×10^{-32} 1.42×10^{-33} 2.45×10^{-34}
νMSM	$> M_P$ 2.4×10^{17} 6.6×10^{15} $(3.4\text{-}11)\times10^{13}$	73.75 79.34 79.48 79.73-79.67	29.98 40.10 40.32 40.69-40.60	2.19×10^{-7} 4.43×10^{-9} 1.27×10^{-10} $(7.02\text{-}22.34)\times10^{-13}$	1.16×10^{-32} 1.43×10^{-33} 2.41×10^{-34} $(1.78\text{-}3.19)\times10^{-35}$
SMASH (r=0.0037)	$> M_P$ 2.7×10^{17} 6.4×10^{15} $(8\text{-}20)\times10^{9}$	70.99 76.72 76.83 77.56-77.44	28.85 38.98 39.18 40.35-40.22	1.88×10^{-7} 4.40×10^{-9} 1.09×10^{-10} $(1.64\text{-}4.02)\times10^{-16}$	1.11×10^{-32} 1.47×10^{-33} 2.30×10^{-34} $(2.79\text{-}4.37)\times10^{-37}$
SMASH (r=0.05)	$> M_P$ 2.7×10^{17} 6.4×10^{15} $(8\text{-}20)\times10^{9}$	71.06 76.81 76.91 77.57-77.49	28.88 39.04 39.24 40.39-40.28	1.89×10^{-7} 4.45×10^{-9} 1.10×10^{-10} $(1.65\text{-}4.06)\times10^{-16}$	1.11×10^{-32} 1.48×10^{-33} 2.31×10^{-34} $(2.79\text{-}4.39)\times10^{-37}$
MSSM	$> M_P$ 4.4×10^{17} 5.5×10^{15}	57.50 64.75 64.87	23.37 36.29 36.48	8.09×10^{-8} 4.60×10^{-9} 5.76×10^{-10}	9.02×10^{-33} 1.72×10^{-33} 1.92×10^{-34}

Observational Constraints on the CGMB

CMB Rayleigh-Jeans tail constraint





[Domcke,Garcia-Cely `20]