Gravitational Waves as a Big Bang Thermometer

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Virtual Particle and Astroparticle Physics Colloquium Hamburg
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[AR, Jan Schütte-Engel, Carlos Tamarit, arXiv:2011.04731]

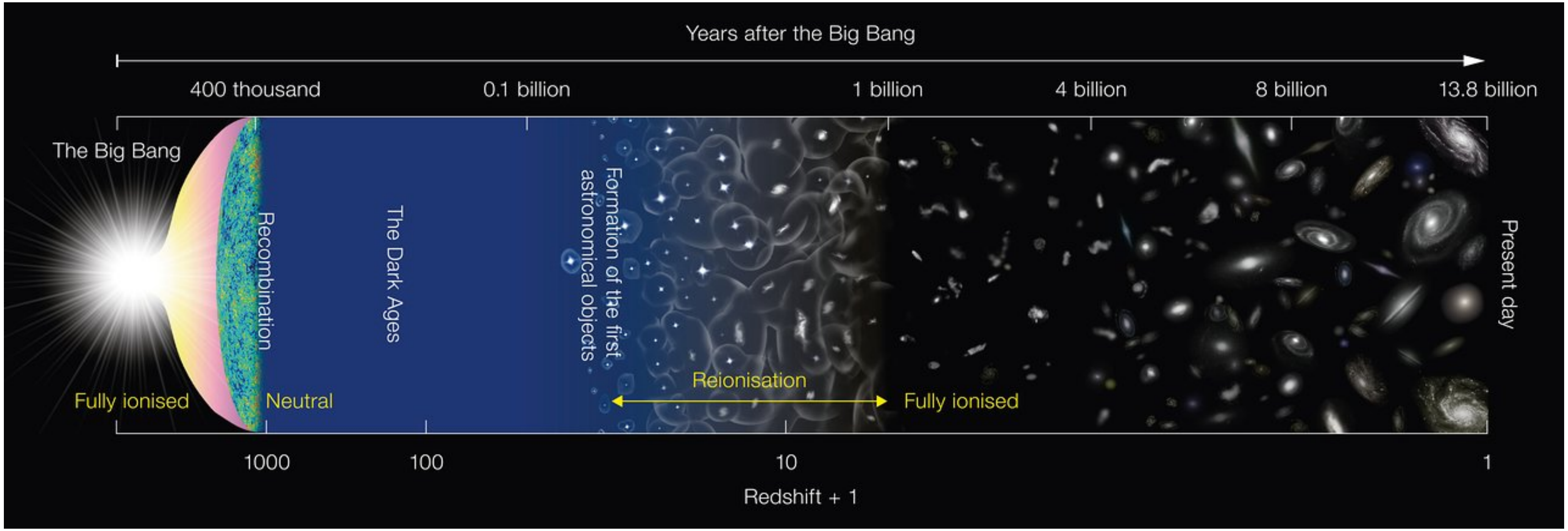
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

DESY.

Big Bang Cosmology

- Describes how the universe expanded from an initial state of extremely high density and high temperature



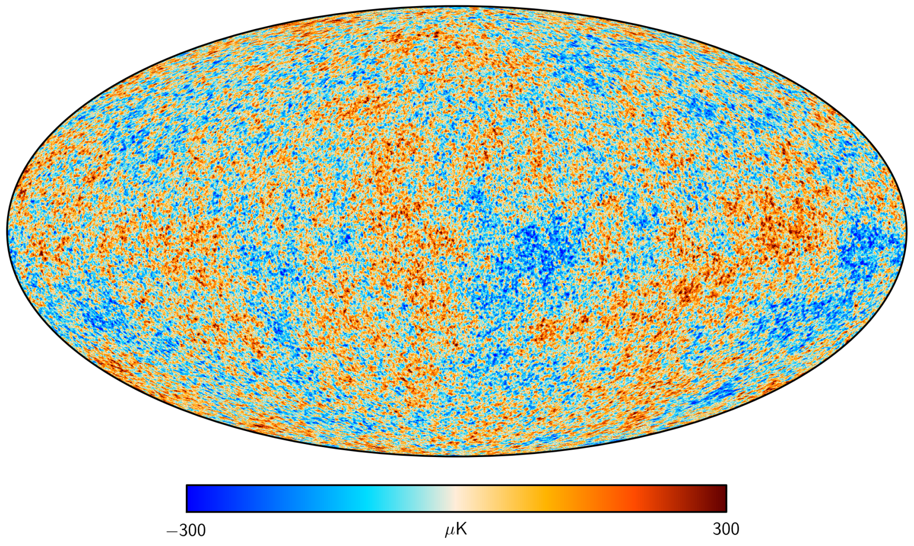
[ESO]

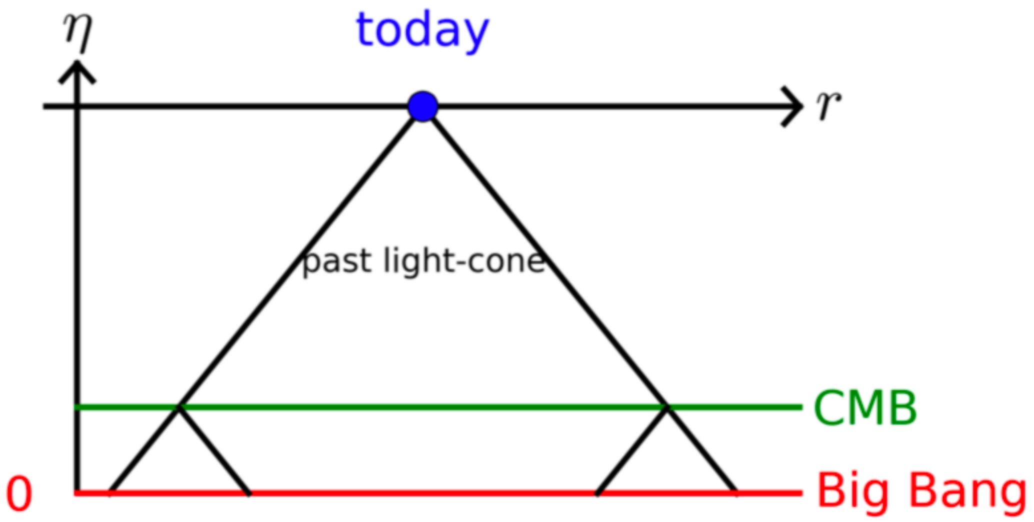
- Offers a comprehensive explanation for a broad range of observed phenomena, including the abundance of light elements, the cosmic microwave background (CMB) radiation, and the Hubble expansion

Big Bang Cosmology

Arguments for a non-thermal era before the hot era

- Standard big bang cosmology suffers from puzzles, notably
  - **Horizon puzzle:** Why is the observed CMB so uniform?





Big Bang Cosmology

Arguments for a non-thermal era before the hot era

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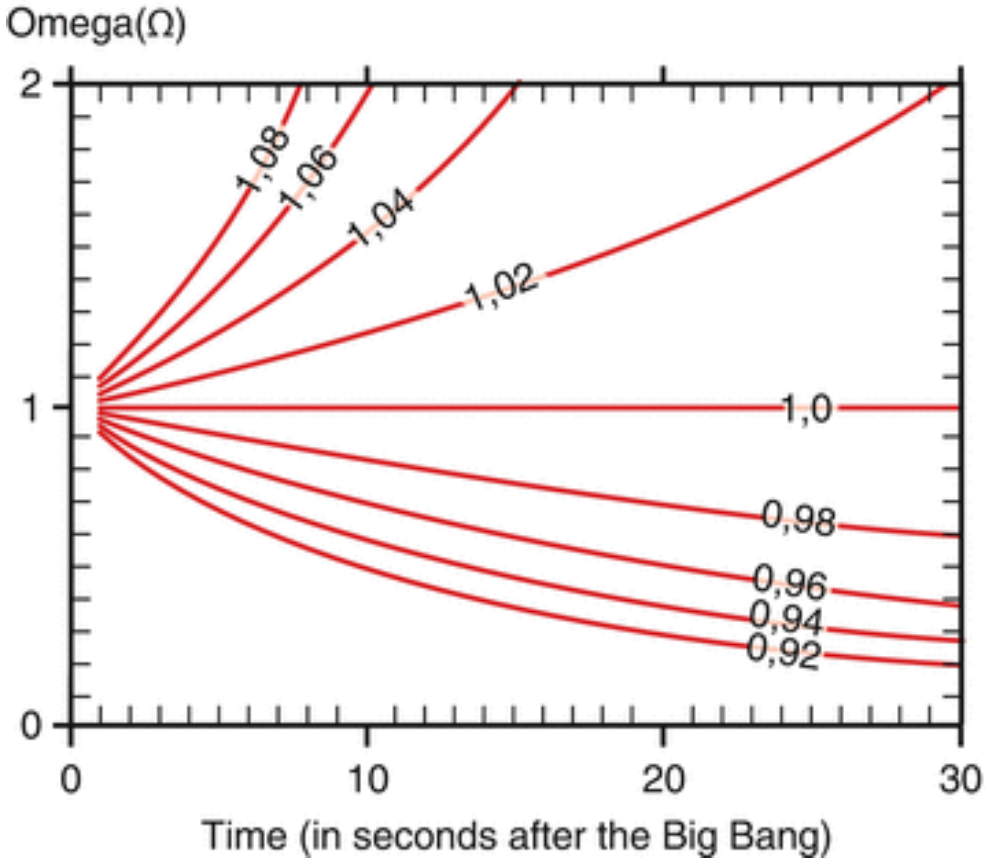
  - Horizon puzzle: Why is the observed CMB so uniform?
  - **Flatness puzzle:** Why is the present cosmic energy density so close to the critical energy density required for a flat universe?



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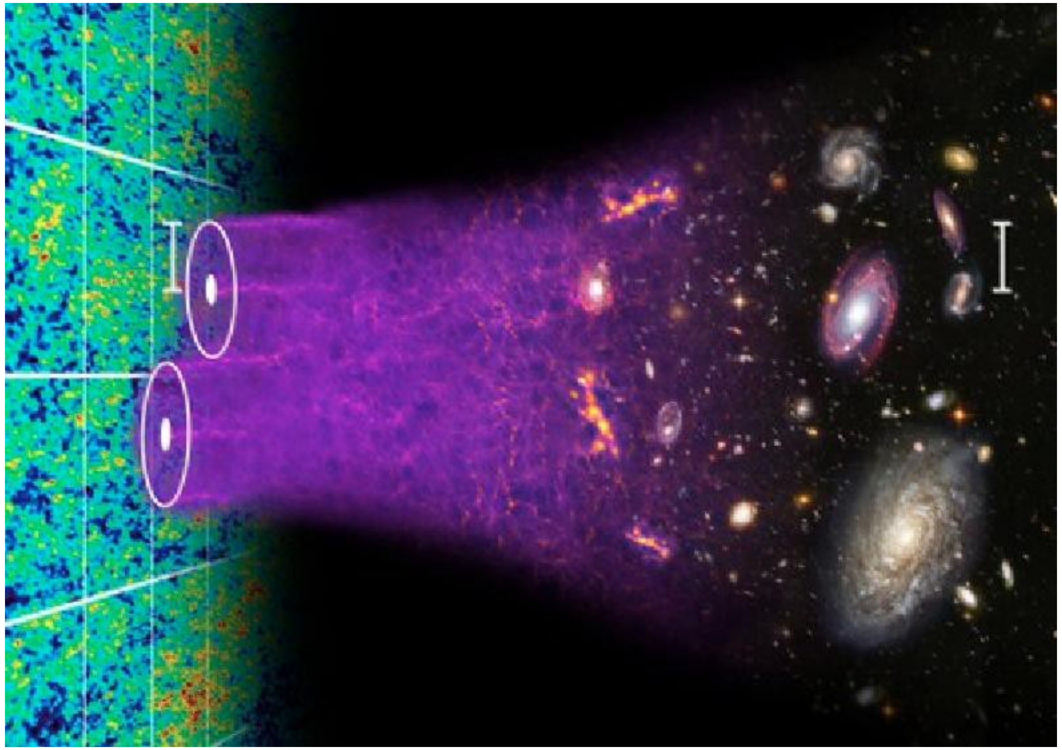
  - How are the **superhorizon-scale density fluctuations**, needed as seeds for **structure formation**, generated?



Big Bang Cosmology

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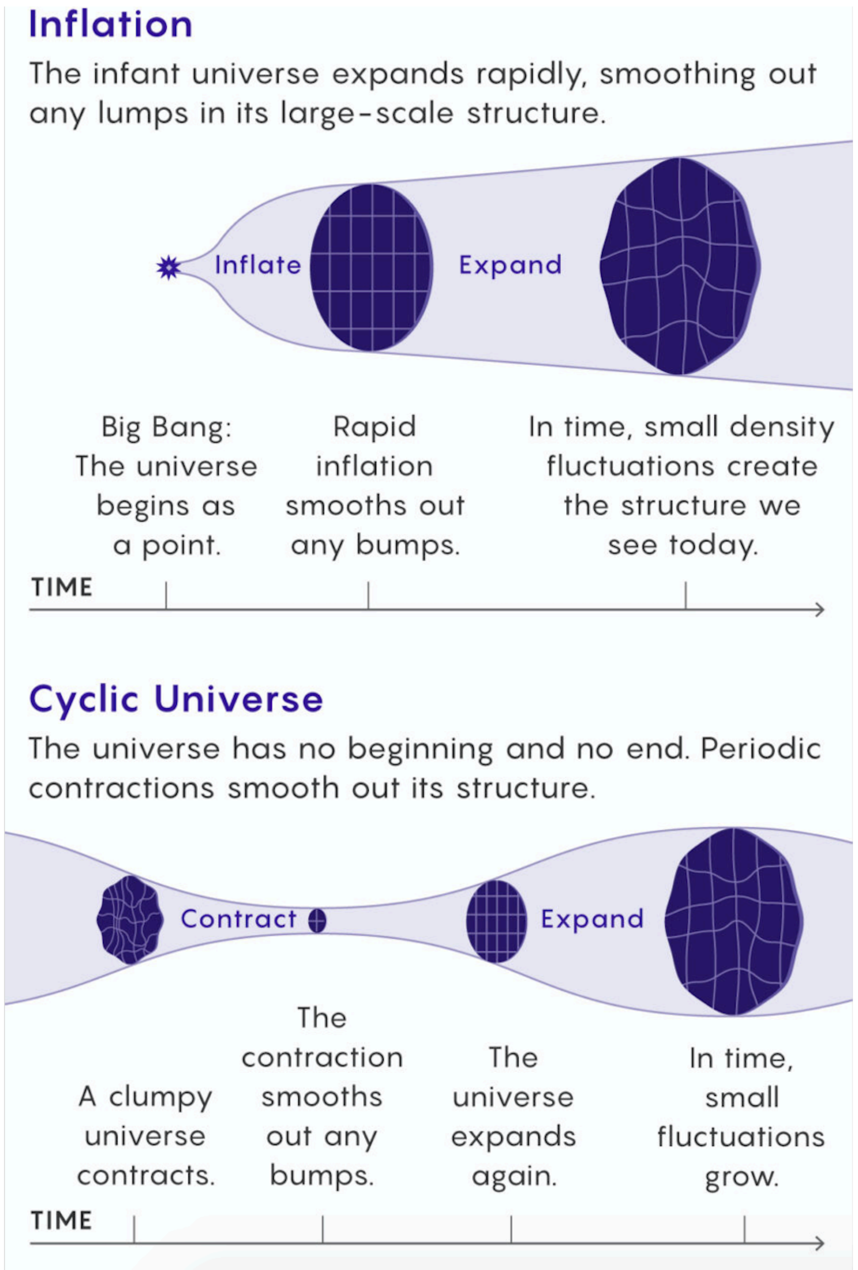
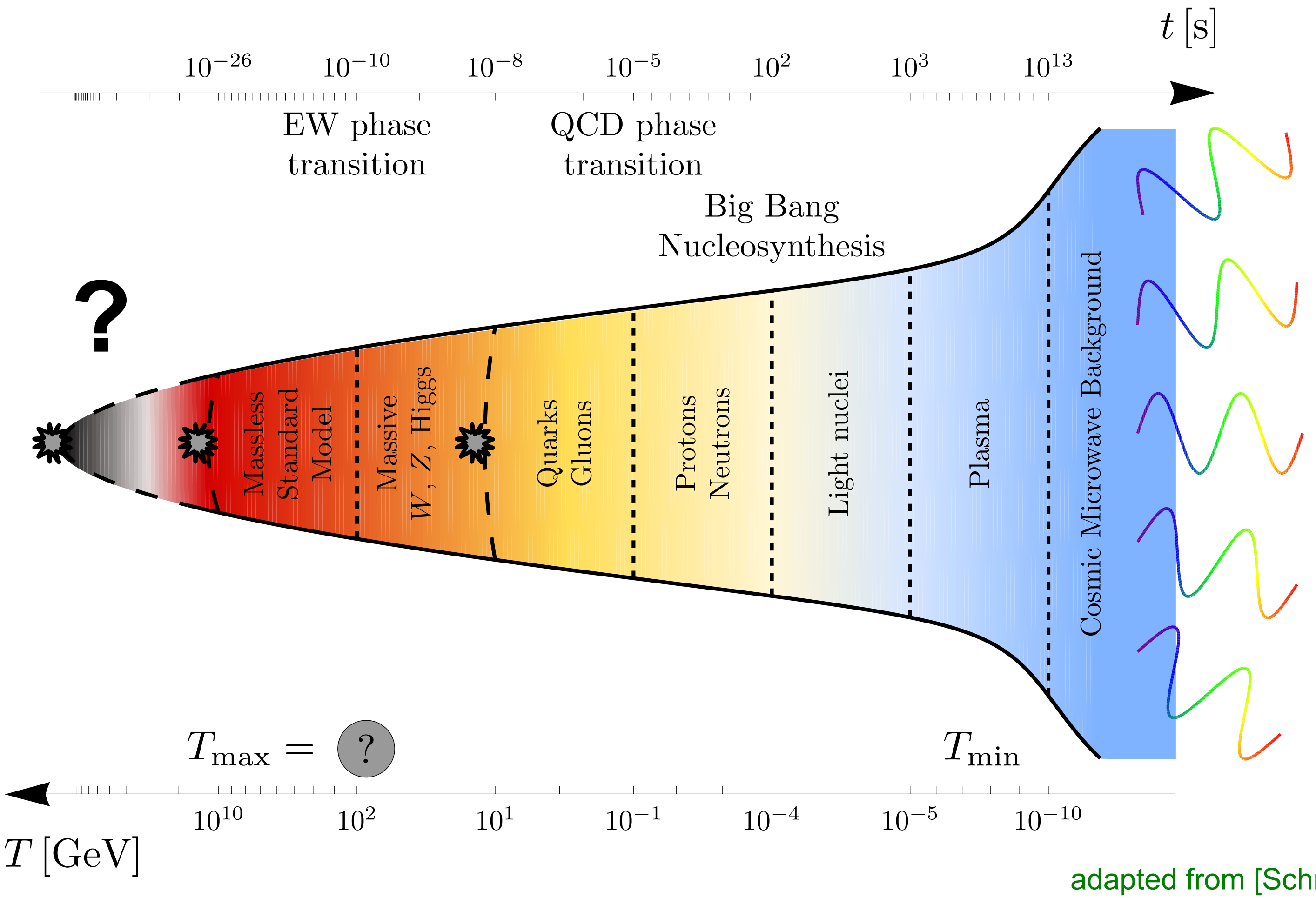
- Standard big bang cosmology suffers from puzzles, notably
  - Horizon puzzle: Why is the observed CMB so uniform?
  - Flatness puzzle: Why is the present cosmic energy density so close to the critical energy density required for a flat universe?
  - How are the superhorizon-scale density fluctuations, needed as seeds for structure formation, generated?
- These puzzles are solved in cosmological scenarios which describe how the hot big bang cosmology emerged dynamically
  - Most popular: **Inflationary cosmologies**
  - Alternative: **Bouncing cosmologies**



Gravitational Waves as a Big Bang/Bounce Thermometer

The temperature the plasma attained at the beginning of the hot era, dubbed T_{max}, may give a way to discriminate between different pre hot big bang scenarios

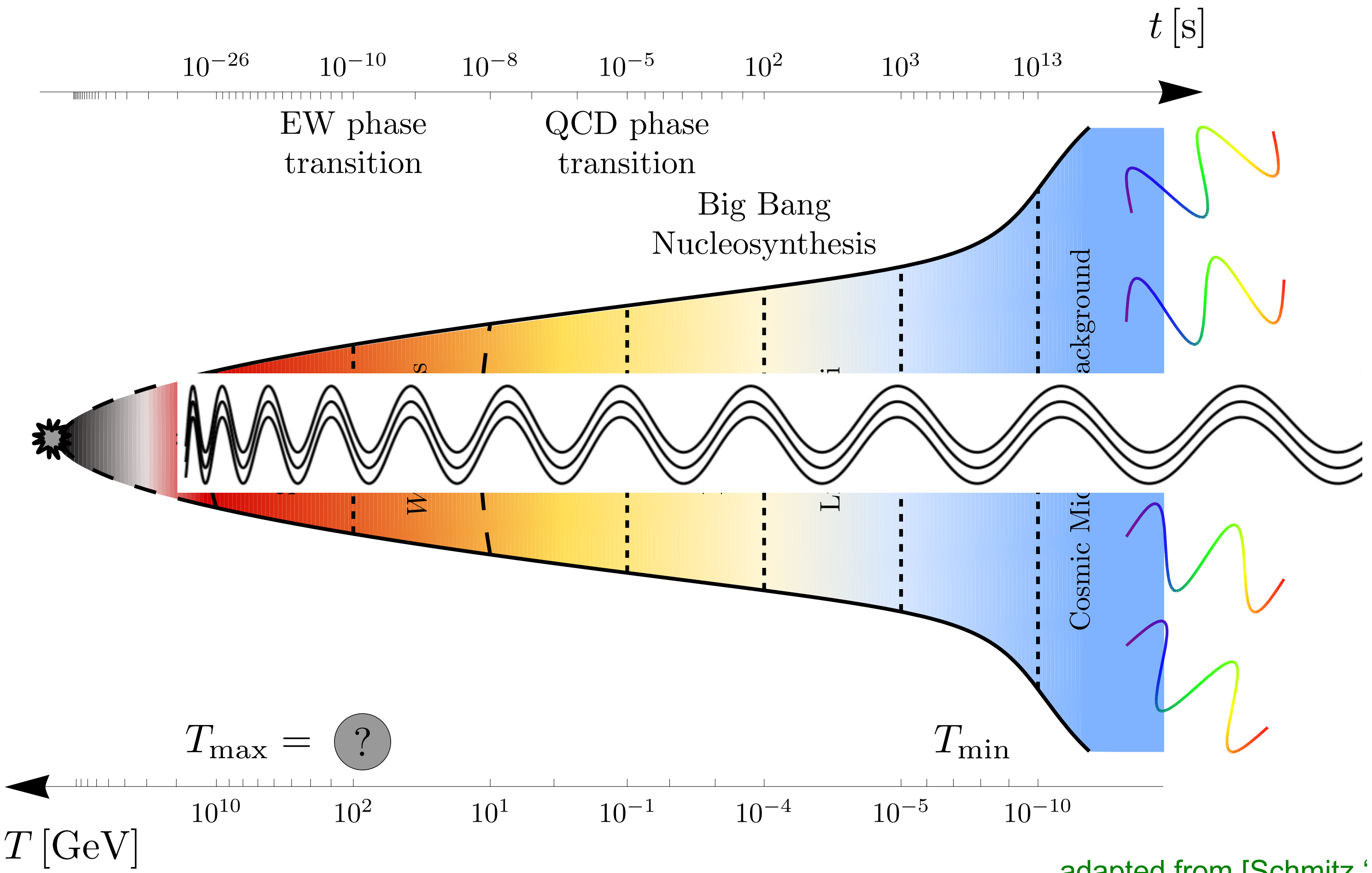


adapted from [Schmitz '12]

Gravitational Waves as a Big Bang/Bounce Thermometer

Detection of gravitational waves (GWs) generated by the thermal plasma allows a measurement of T_{max}

[Ghiglieri,Laine '15; Ghiglieri,Jackson,Laine,Zhu '20; AR,Schütte-Engel,Tamarit '20]



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GW Background from Primordial Thermal Plasma

Generation of GWs from fluctuations in a thermal plasma

- In a thermal plasma, GWs are inevitably produced [Weinberg, „Gravitation and Cosmology“, 1972]
- Evolution and production of the energy density in GWs produced by thermal fluctuations described by

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

[Ghiglieri,Laine ’15]

Dilutes like radiation　　　Sourced by thermal fluctuations

Cosmic Gravitational Microwave Background (CGMB)

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[Ghiglieri,Laine ’15]

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

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

[Hawking, ‘76]

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[Hawking, ‘76]

  - Shear viscosity inversely proportional to a scattering cross section and therefore large for a plasma in which there are some weakly interacting particles.
  - In the Standard Model (SM), for temperatures well above the electroweak crossover, $T \gg T_{\rm ewco} \simeq 160\,{\rm GeV}$, and in leading-log (LL) approximation:

$$\eta^{\rm shear}_{\rm LL,SM}(T) = \frac{15.51\,T^3}{g_1(T)^4 \ln(5/\hat{m}_{1,\rm SM}(T))}$$

[Arnold,Moore,Yaffe ’00]

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

Debye thermal mass of hypercharge gauge boson

GW Background from Primordial Thermal Plasma

Generation of GWs from fluctuations in a thermal plasma

- At small wavelengths, corresponding to large wave numbers, $k \gg T$, they are sourced by particle collisions. Corresponding source term suppressed by gauge couplings and Boltzmann factor:

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

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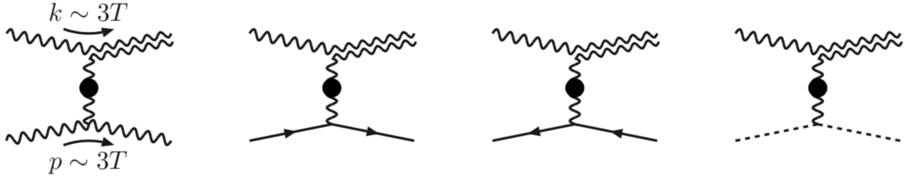
  - In SM and leading-log approximation for $T \gg T_{\rm ewco}$:

$$\hat{\eta}_{\rm LL,SM}(T, k/T) = \frac{1}{8\pi} \sum_{n=1}^{3} N_n \hat{m}^2_{n,{\rm SM}}(T) \log\left(\frac{5}{\hat{m}^2_{n,{\rm SM}}(T)}\right) \frac{k/T}{e^{k/T}-1}, \ \text{for} \ k \gtrsim m_{3,{\rm SM}}(T)$$

[Ghiglieri,Laine ’15]



$$\hat{m}^2_{1,{\rm SM}}(T) = \frac{11}{6} g_1(T)^2, \quad \hat{m}^2_{2,{\rm SM}}(T) = \frac{11}{6} g_2(T)^2,$$
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Debye thermal masses of SM gauge bosons

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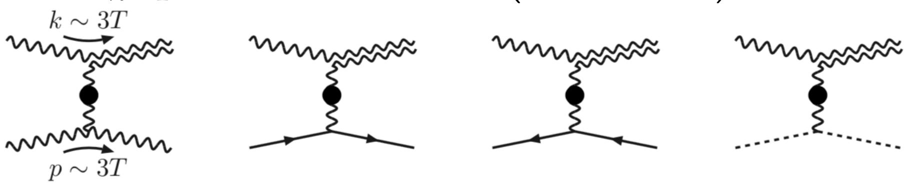

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Debye thermal masses of SM gauge bosons

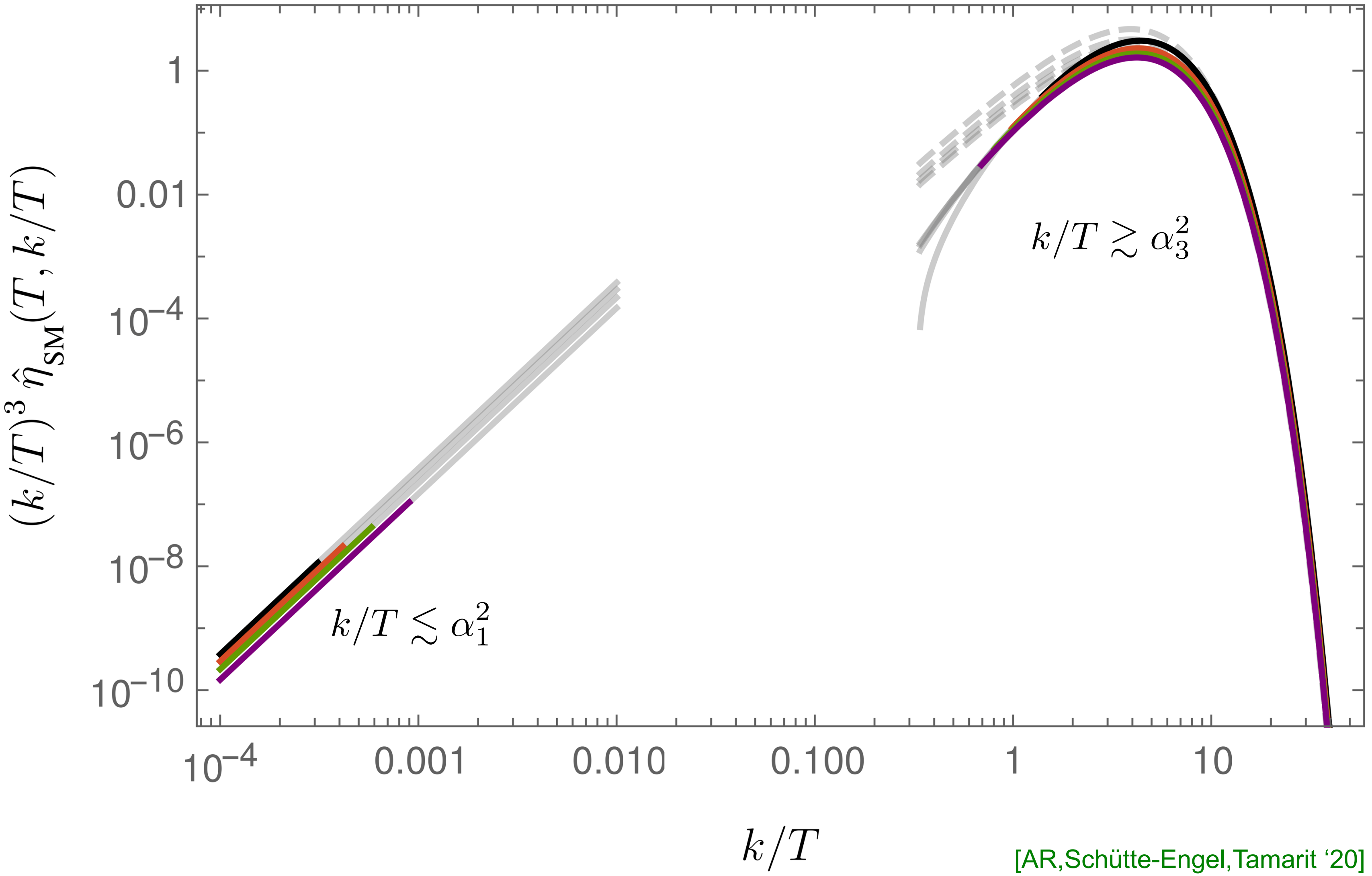
  - Recently the complete leading order approximation has been obtained for the SM [Ghiglieri,Jackson,Laine,Zhu '20] and then extended to generic weakly interacting BSM extension (gauge fields, fermions, scalars) [AR,Schütte-Engel,Tamarit '20]

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

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

GW Background from Primordial Thermal Plasma

Source term in case of SM



[AR,Schütte-Engel,Tamarit '20]

GW Background from Primordial Thermal Plasma

Spectrum of primordial GWs from thermal plasma

- Solving evolution equation ($\Omega_{\rm CGMB}(f) \equiv \frac{1}{\rho_c^{(0)}} \frac{{\rm d}\rho^{(0)}_{\rm CGMB}}{{\rm d}\ln f}$, $M_P \equiv 1/\sqrt{8\pi G_N}$):

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

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

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

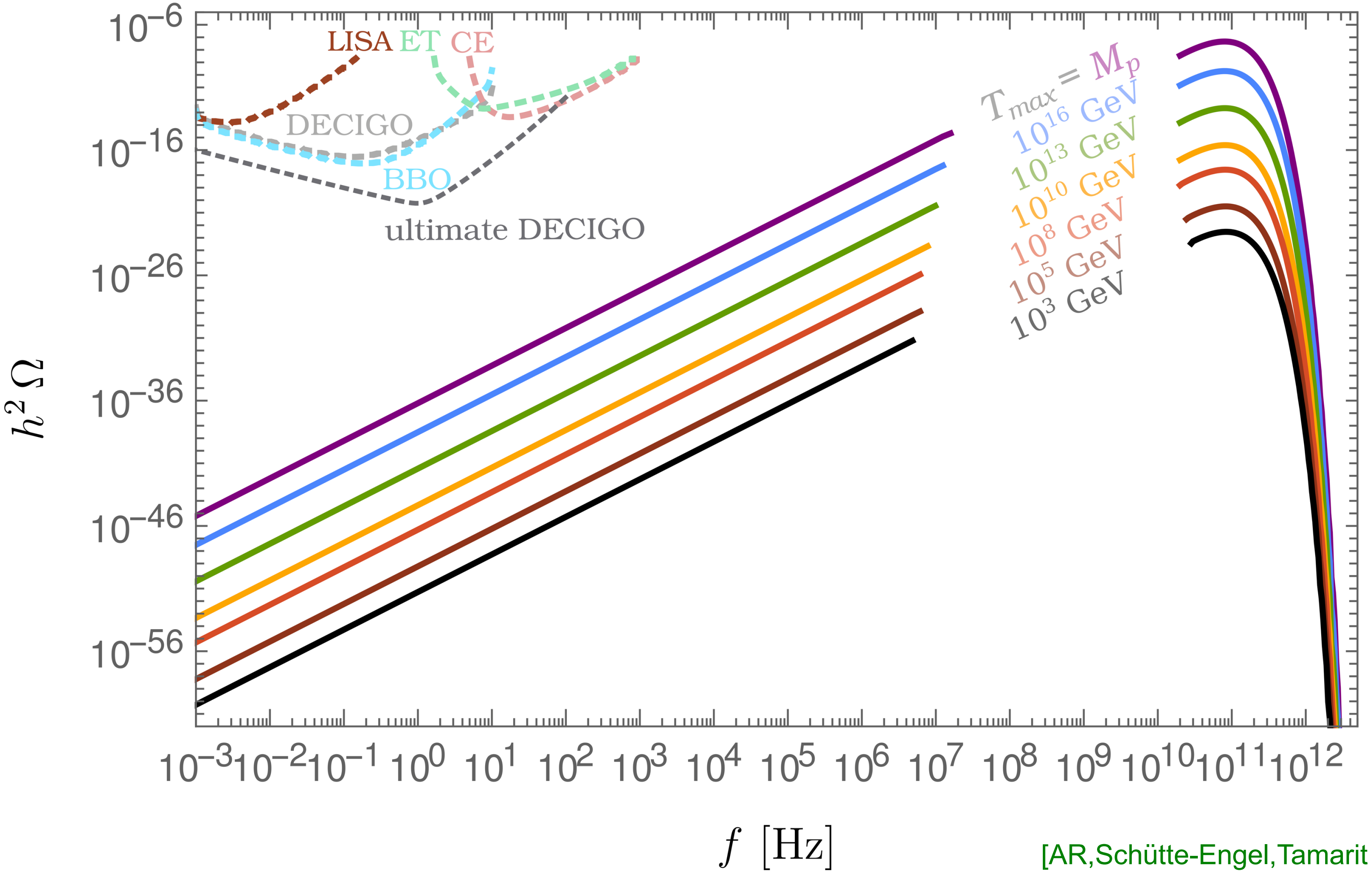
  - Scales approximately linearly with maximum temperature: **Big Bang Thermometer!**
  - Peaks at microwave frequencies: $f_{\rm peak}^{\Omega_{\rm CGMB}} \simeq 80\,{\rm GHz}\,\left[106.75/g_{*s}(T_{\rm max})\right]^{1/3}$

Cosmic Gravitational Microwave Background (CGMB)!

- A measurement of $\Omega_{\rm CGMB}(f_{\rm peak}^{\Omega_{\rm CGMB}})$ and $f_{\rm peak}^{\Omega_{\rm CGMB}}$ would allow to determine $T_{\rm max}$ and $g_{*s}(T_{\rm max})$

GW Background from Primordial Thermal Plasma

CGMB spectrum for SM



[AR,Schütte-Engel,Tamarit '20]

GW Background from Primordial Thermal Plasma

Case of super-Planckian maximum temperature

In the case that $T_{\rm max} > M_P$: [Wheeler `58; Zeldovich `65; Winterberg `68; Matzner `68; Weinberg `69; ...]

- In this case, GWs are expected to thermalize; that is their cosmic fractional energy densitiy, per unit of logarithmic frequency, is expected to attain a thermal blackbody form:

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

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

- Peaks also 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

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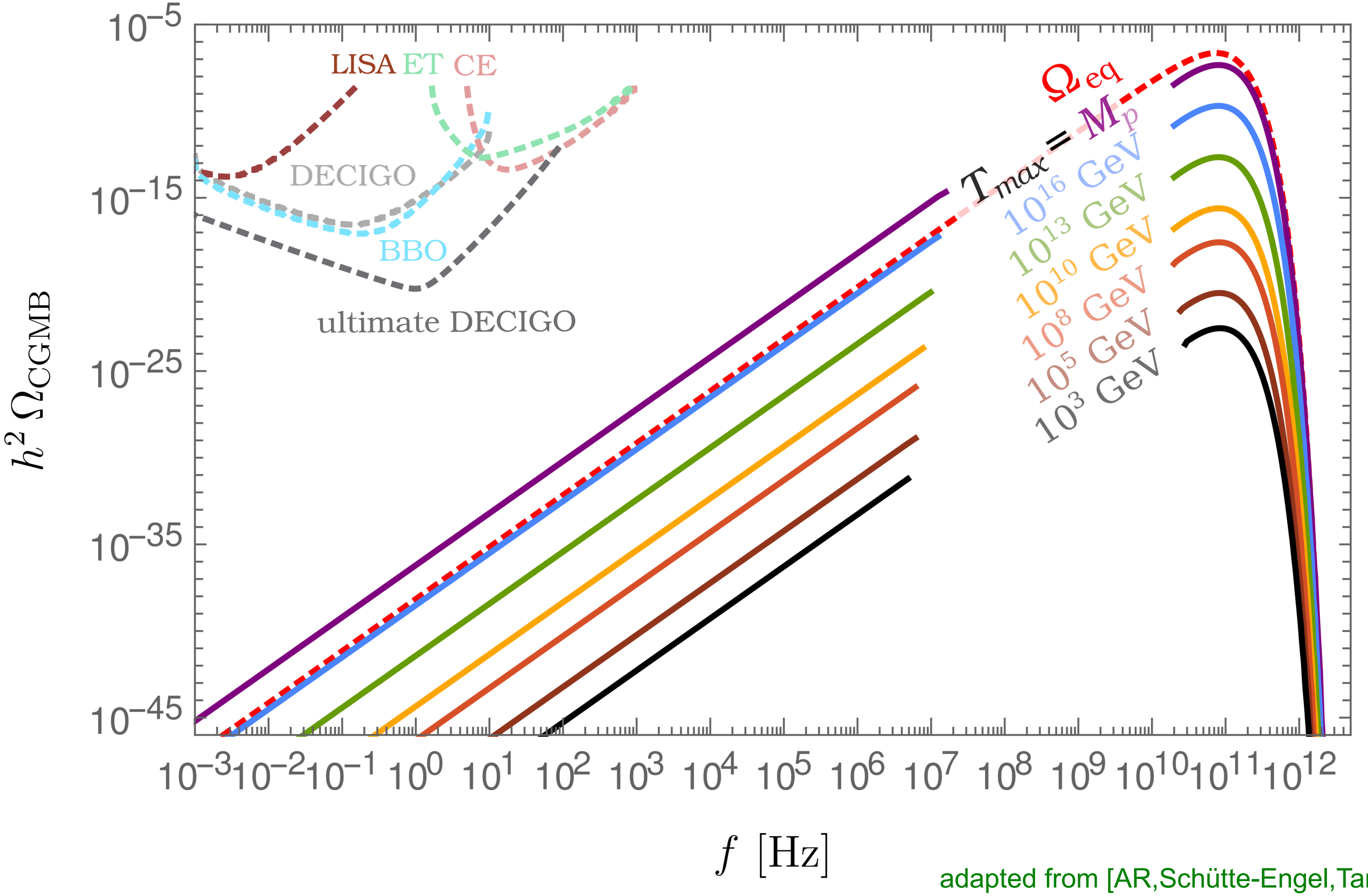
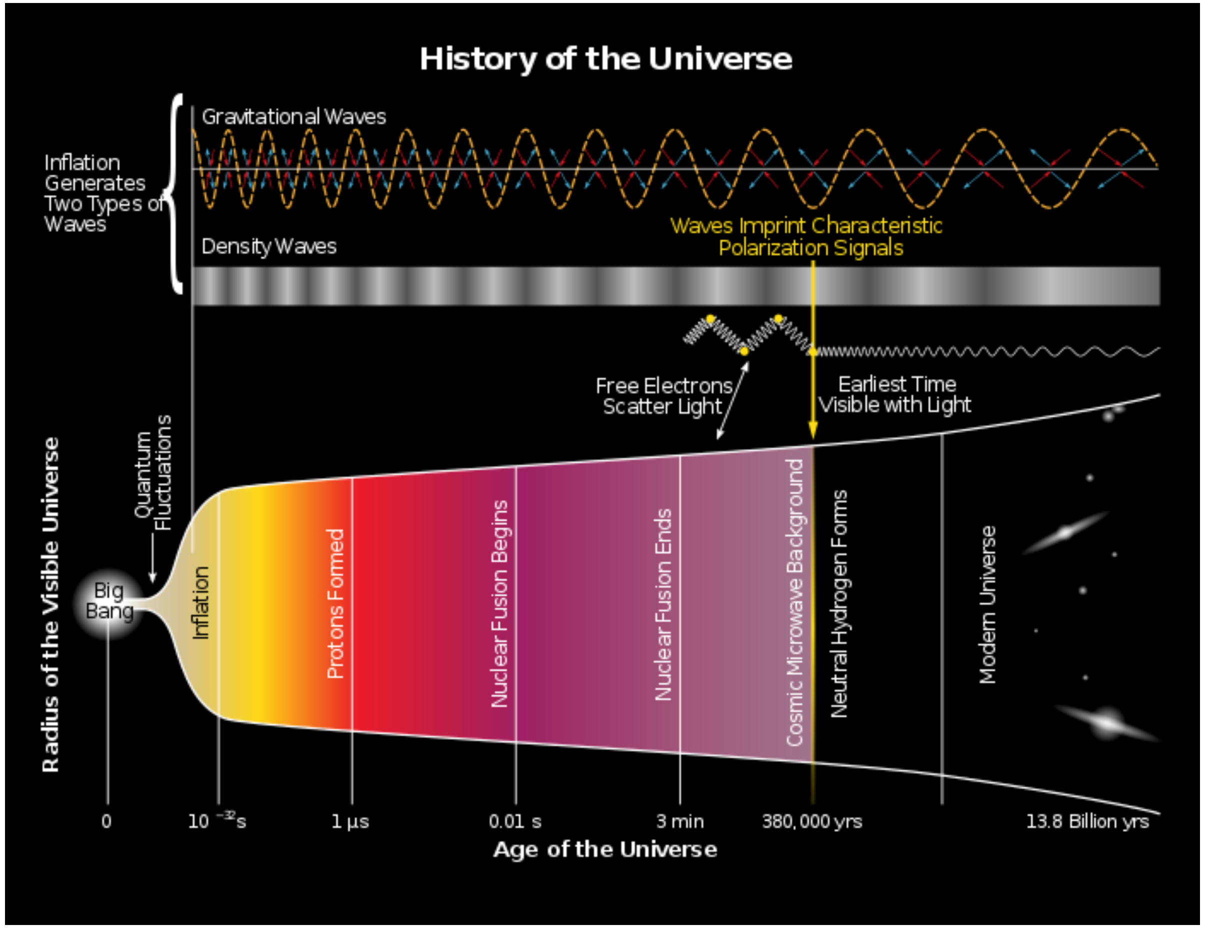


adapted from [AR,Schütte-Engel,Tamarit '20]

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:

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

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- 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:

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

[Akrami et al., 1807.06211]

GW Background from Primordial Thermal Plasma

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- 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

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- Any measurement of $T_{\rm max}$ above this value would be ground-breaking, since it would rule out standard slow-roll inflation as a viable pre hot big bang scenario and perhaps point towards a bouncing scenario!

GW Background from Primordial Thermal Plasma

Minimal BSM extensions featuring Higgs(-portal) inflation

The **nuMSM** extends the SM by

- 3 right-handed SM singlet neutrinos N_i

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

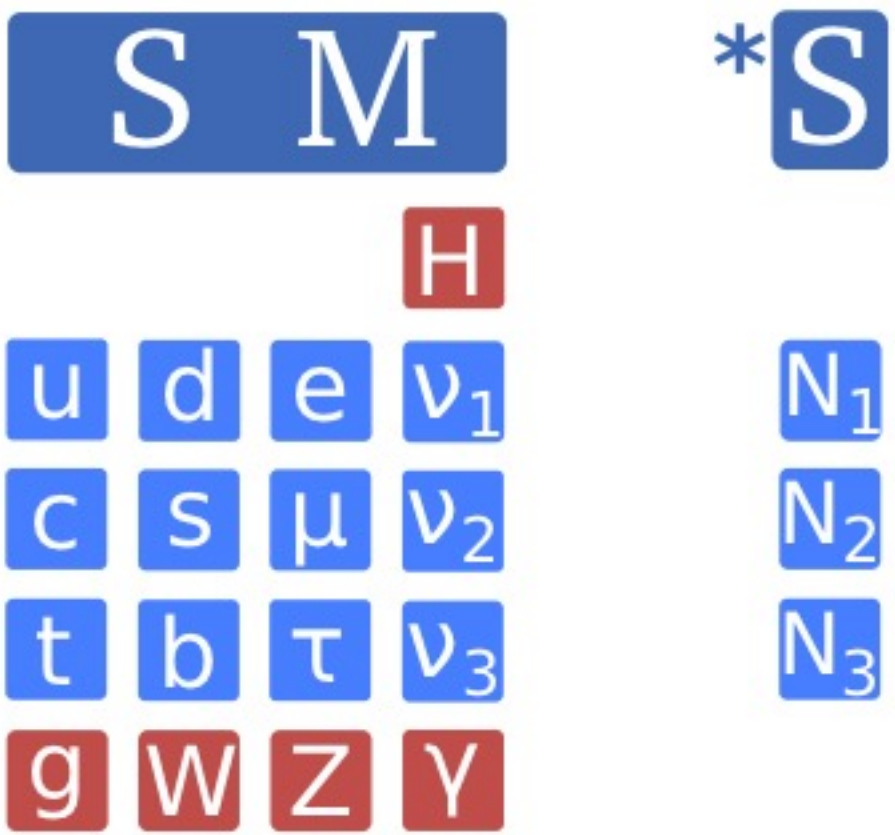
thereby solving four big problems in particle physics and cosmology in one go:

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

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

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

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



GW Background from Primordial Thermal Plasma

Minimal BSM extensions featuring Higgs(-portal) inflation

SMASH extends the SM by

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

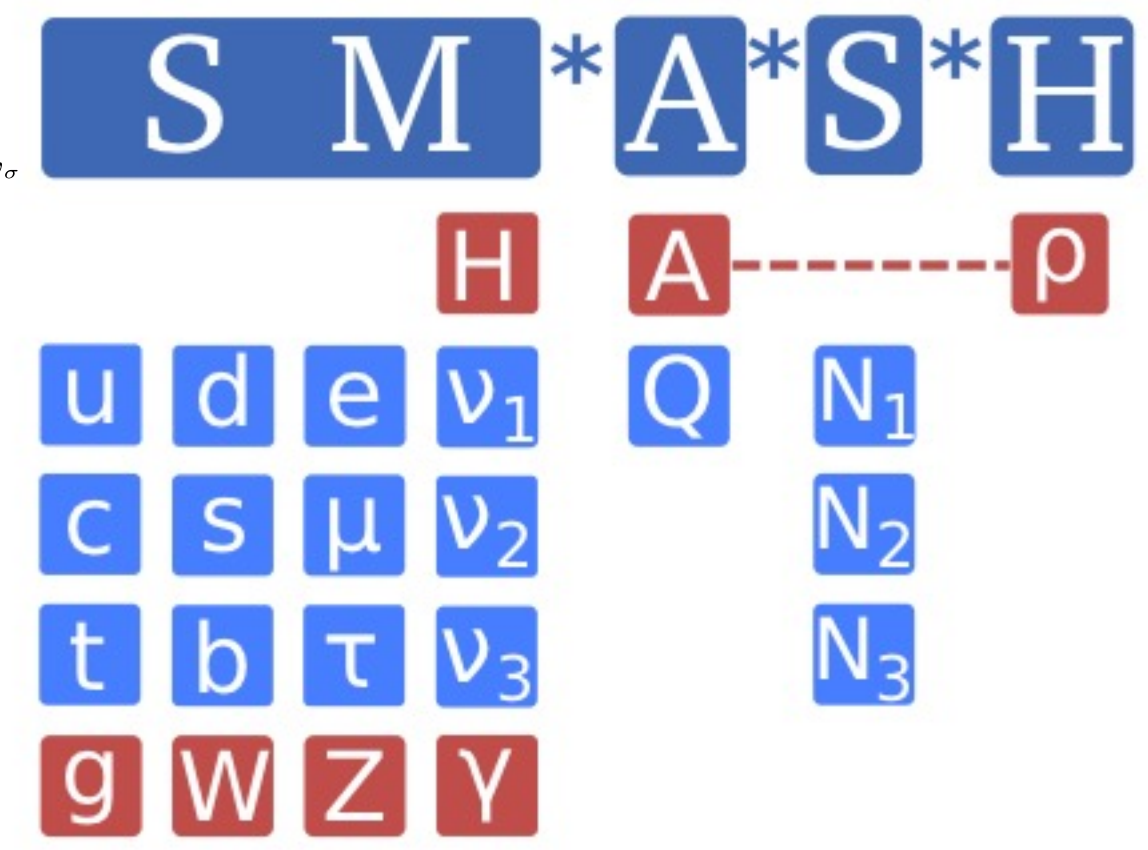
thereby solving five big problems in particle physics and cosmology in one smash:

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

It predicts:

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

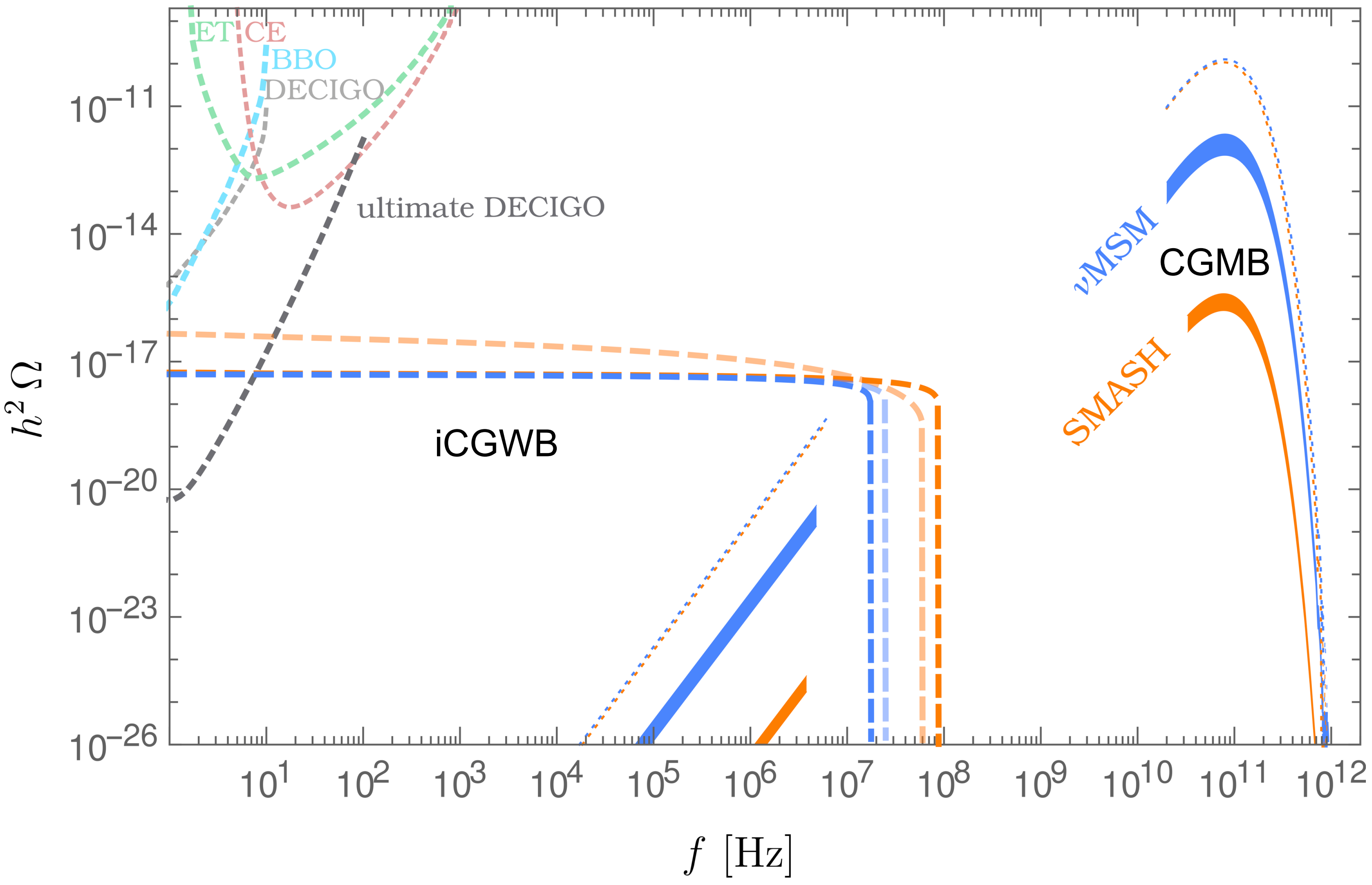
$$g_{*s}(T_{\max}^{\mathrm{SMASH}}) \simeq 124.5$$



[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:

$$h^2 \int_0^\infty \frac{{\rm d}f}{f}\,\Omega_{\rm CGMB}(f) = h^2\,\frac{\rho^{(0)}_{\rm CGMB}}{\rho_c^{(0)}} \lesssim 5.6\times 10^{-6}\,\Delta N_{\rm eff}$$

- Current best bounds:
  - $h^2\,\frac{\rho^{(0)}_{\rm CGMB}}{\rho_c^{(0)}} < 1.2\times 10^{-6}$, for adiabatic initial conditions [Pagano,Salvati,Melchiorri,´16]
  - $h^2\,\frac{\rho^{(0)}_{\rm CGMB}}{\rho_c^{(0)}} < 2.9\times 10^{-7} \quad (95\%\ {\rm CL})$, for homogeneous 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, $M_P \equiv 1/\sqrt{8\pi G} \simeq 2.435 \times 10^{18}\,\mathrm{GeV}$

- On the other hand, the Equilibrium CGMB predictions, applicable for $T_{\max} > M_P$,

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

  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:

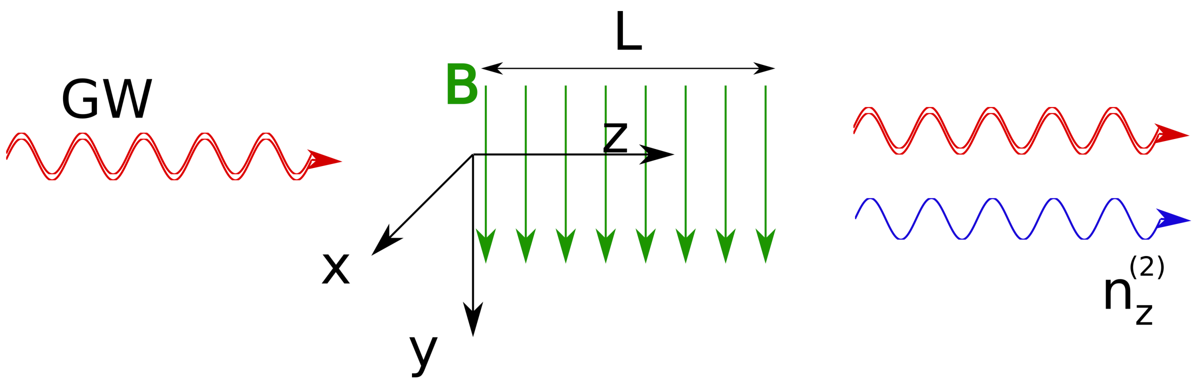
	SM	νMSM	SMASH	MSSM
$T_{\max}^{\Delta N_{\mathrm{eff}}=0.001}$ [GeV] $<$	2.3×10^{17}	2.4×10^{17}	2.7×10^{17}	4.39×10^{17}

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]

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

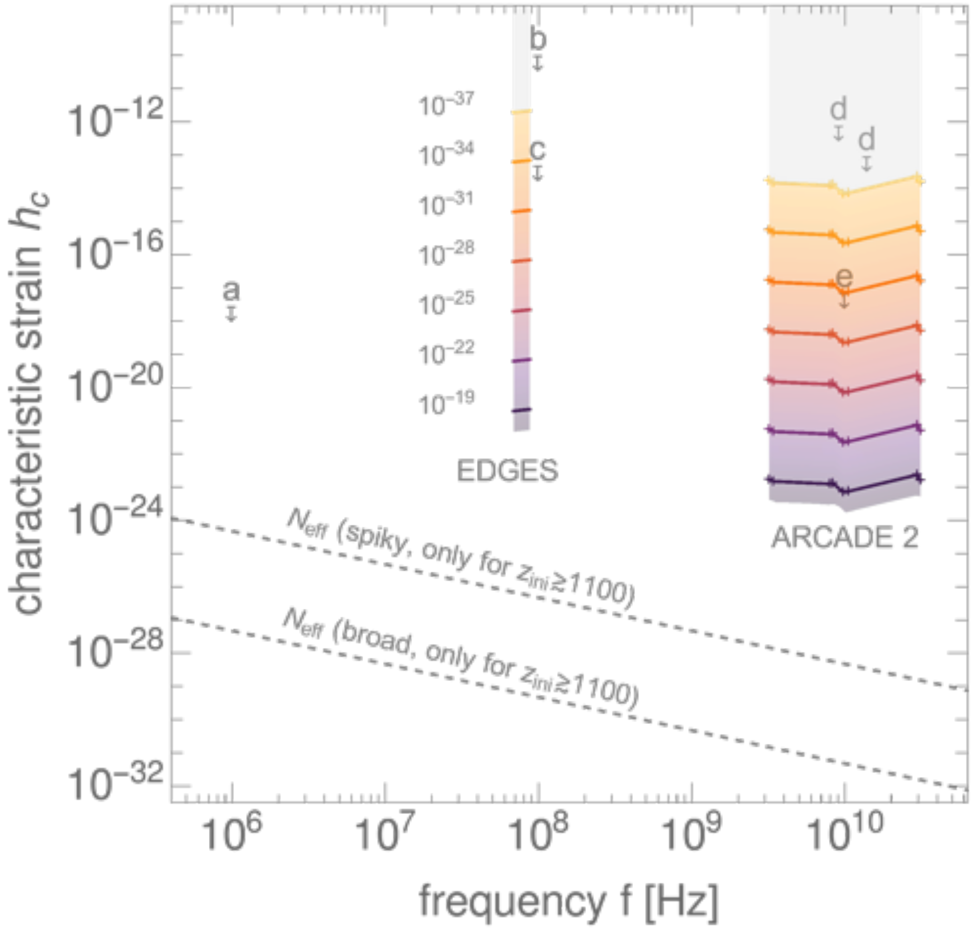
  [Gertsenshtein `62,Boccaletti,.. `70,Zeldovich,.. `73,DeLogi,.. `77,Raffelt,.. `87]

- 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 dimensionless amplitude of stochastic GWs,

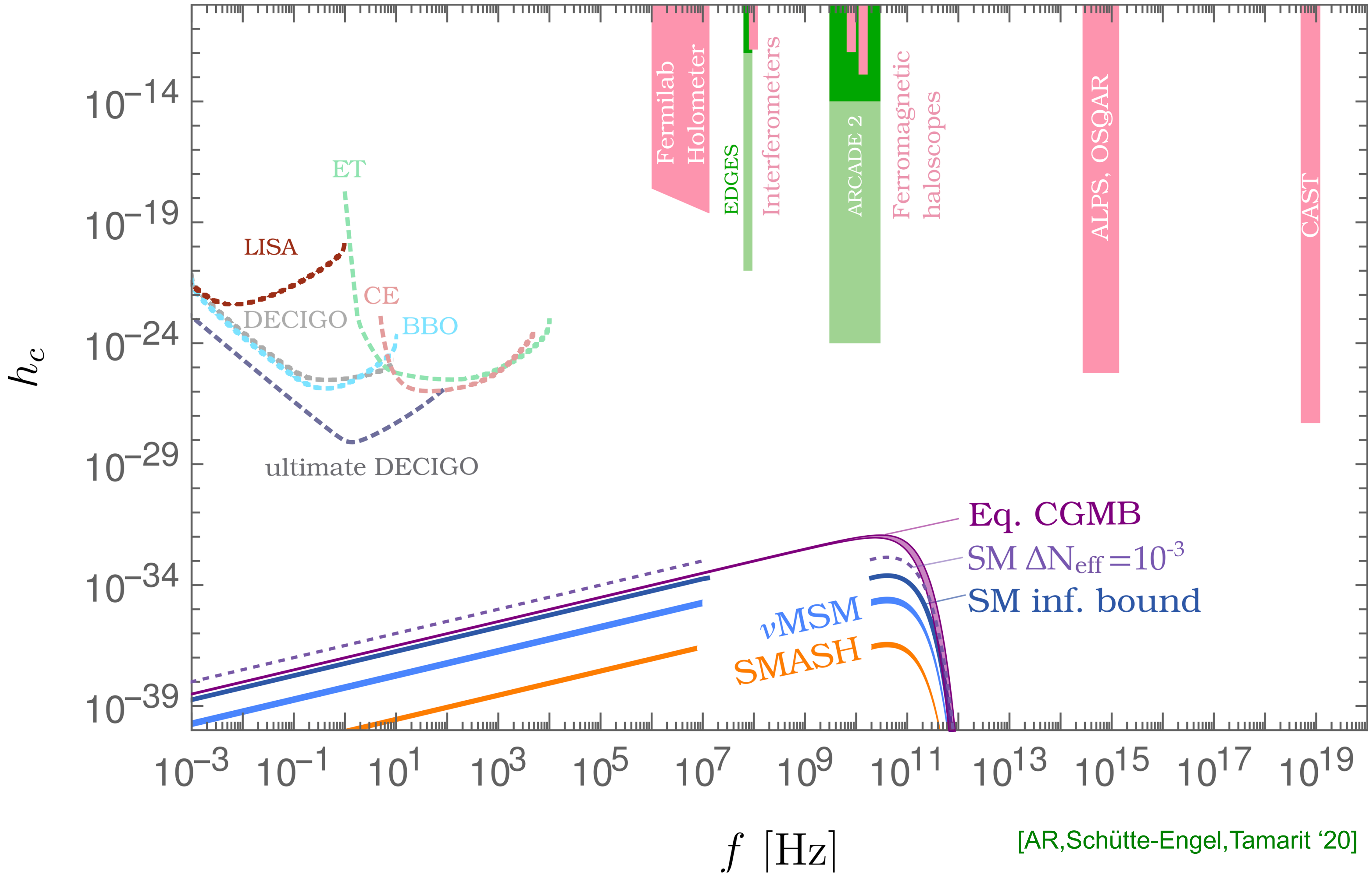
$$h_c(f) \equiv 1.26 \times 10^{-27} \left[\frac{\mathrm{GHz}}{f}\right] \sqrt{h^2\, \Omega_{\mathrm{GW}}(f)}$$

- 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

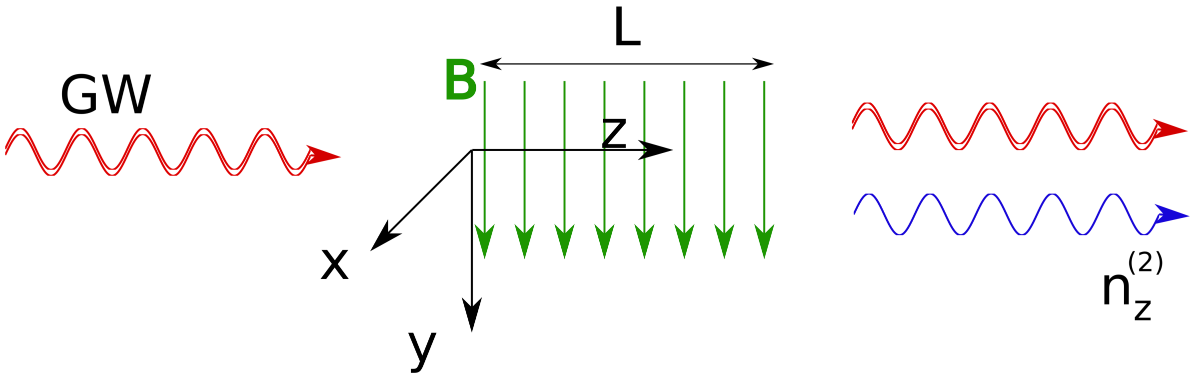


[AR,Schütte-Engel,Tamarit ‘20]

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,

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

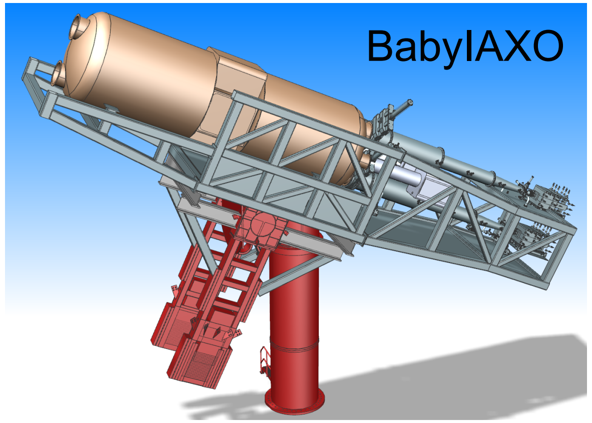
- Figure of merit is $BLA^{1/2}$: similar to axion experiments (Light-Shining-through-Wall (LSW); Helioscope; Haloscope)

Laboratory Searches for the CGMB

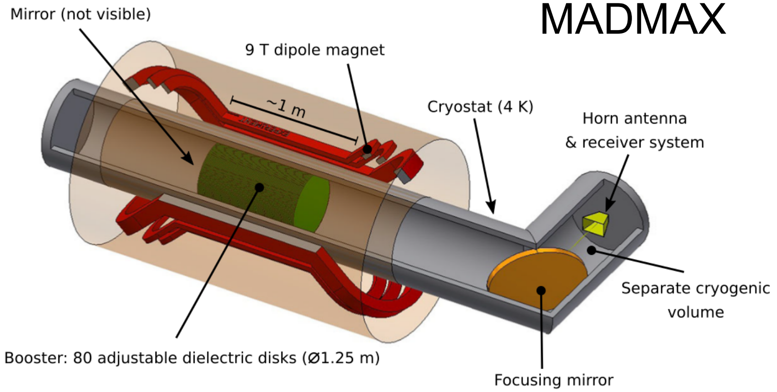
Magnetic GW-EMW conversion in vacuum

- Exploiting magnet field regions from available or planned axion experiments:

ALPS IIc



MADMAX



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

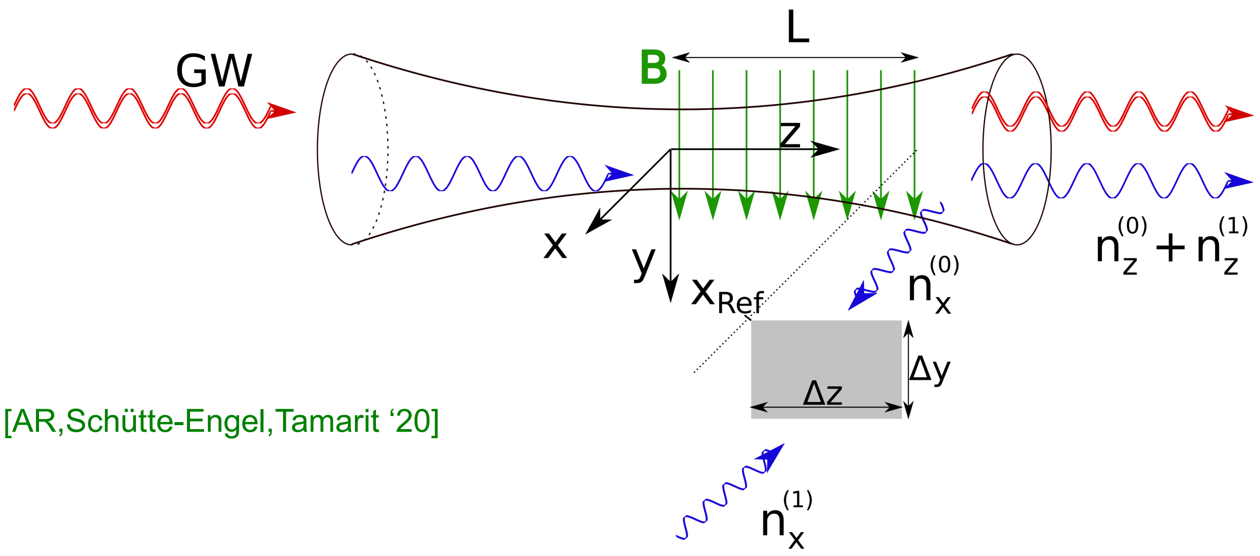
- To probe $h_c(40\,\mathrm{GHz}) \sim 10^{-32}$, corresponding to $T_{\max} \sim M_P$, would need to increase $BLA^{1/2}$ by more than six orders of magnitude!

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 :

$$f\frac{\mathrm{d}n_x^{(1)}}{\mathrm{d}f}\,|_{f_0}\simeq \frac{1}{4}\,h_c(f_0)B_y^{(0)}E_0L\,\psi_x^{(1)}\left(\frac{w_0}{z_R},\frac{x}{w_0},\frac{y}{w_0},\frac{z}{z_R},\delta\right)$$

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

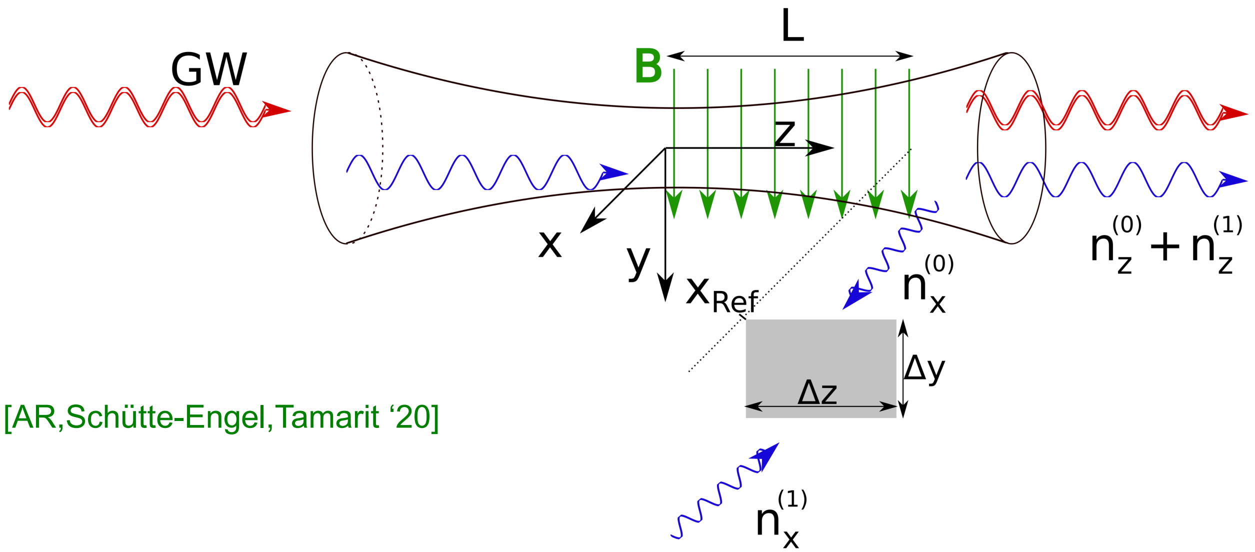
- Depending on overall sign, that is on relative phase difference, flux points either in positive or negative x direction
- Place place at $x=\pm x_{\mathrm{Ref}}$ reflectors, which could reflect and focus a portion of this flux to receivers and detectors pla-ced at positions $x=\pm x_{\mathrm{Det}}$ 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;...]



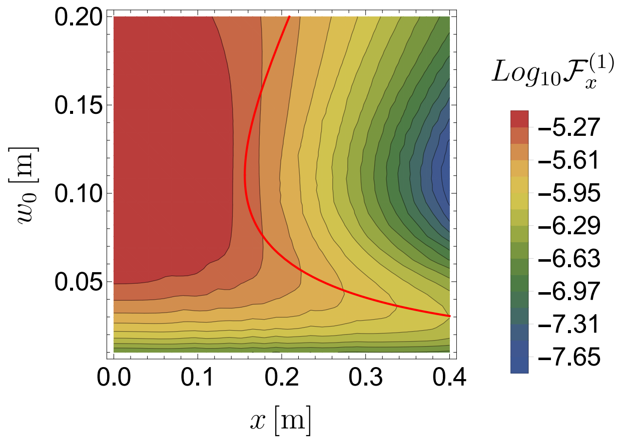
[AR,Schütte-Engel,Tamarit ‘20]

- Sensitivity estimate:

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

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

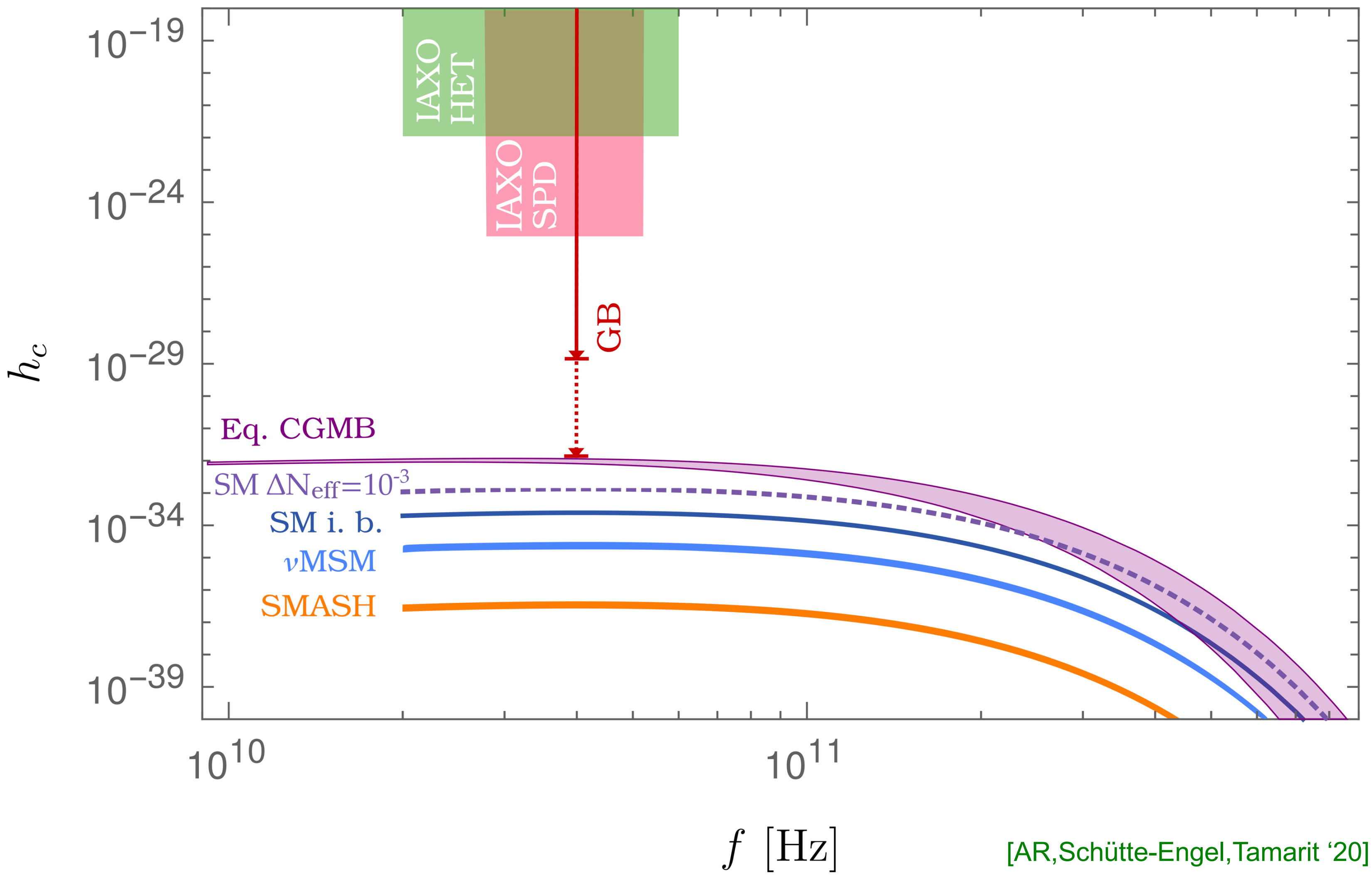
where $$\mathcal{F}_x^{(1)}(x) = \frac{1}{4\pi}\frac{w_0 z_R}{\Delta y\Delta z}\int_0^{2\pi}{\rm d}\delta\left|\int_0^{\frac{\Delta y}{w_0}}{\rm d}y'\int_{\frac{L}{z_R}}^{\frac{L+\Delta z}{z_R}}{\rm d}z'\,\psi_x^{(1)}\left(\frac{w_0}{z_R},x',y',z',\delta\right)\right|$$



- 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

- A measurement of the maximum temperature of the hot big bang era may give a way to discriminate bet-ween different pre hot big bang scenarios
  - Any measurement of $T_{\rm max}$ above $6.6\times 10^{15}\,{\rm GeV}\,[g_{*\rho}(T_{\rm max})/106.75]^{-1/4}$ would rule out slow-roll inflation and perhaps point towards a bouncing scenario
- A measurement of $\Omega_{\rm CGMB}(f_{\rm peak}^{\Omega_{\rm CGMB}})$ or $h_c^{\rm CGMB}(f_{\rm peak}^{h_c^{\rm CGMB}})$ allows to determine $T_{\rm max}$ and $g_{*s}(T_{\rm max})$
- Current dark radiation constraints implies $T_{\rm max}\lesssim 10^{19}\,{\rm GeV}$. Improvement prospects: two orders of magnitude.
- 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.

Outlook

- Currently, a community is forming which seriously considers the search for high-frequency gravitational waves:

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

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

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

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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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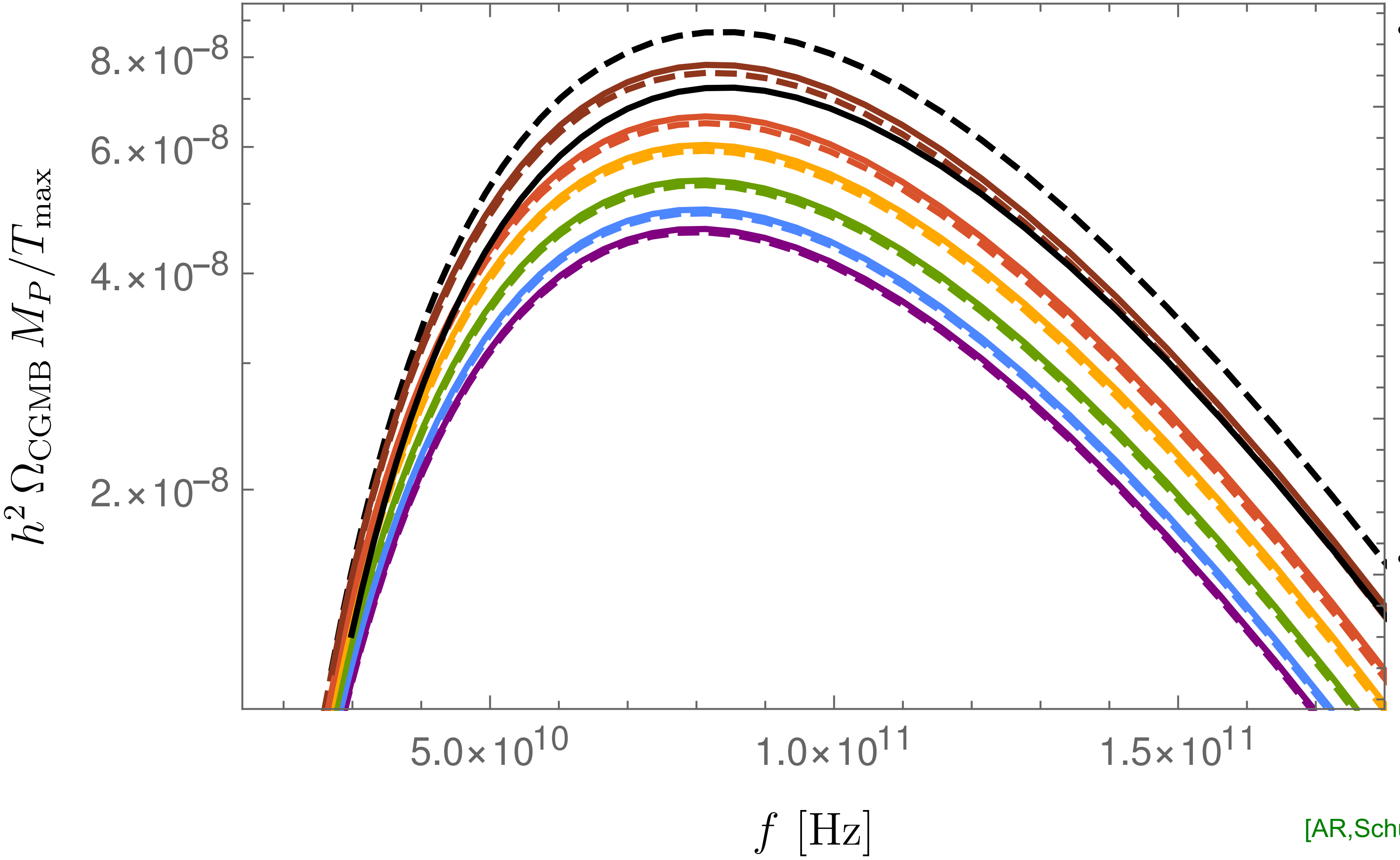
- Detecting the CGMB sets an ambitious, but rewarding goal for this enterprise.

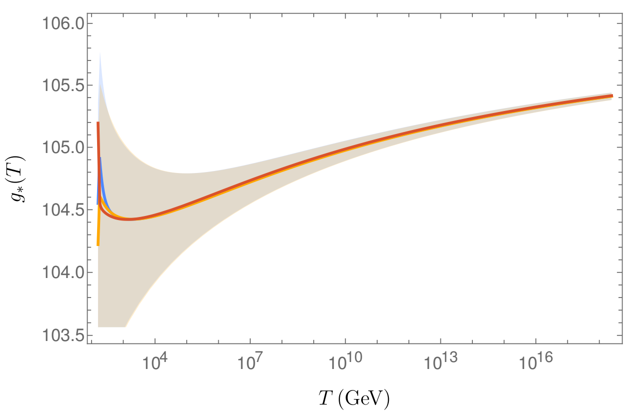
GW Background from Primordial Thermal Plasma

CGMB spectrum for SM



- Solid lines:

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



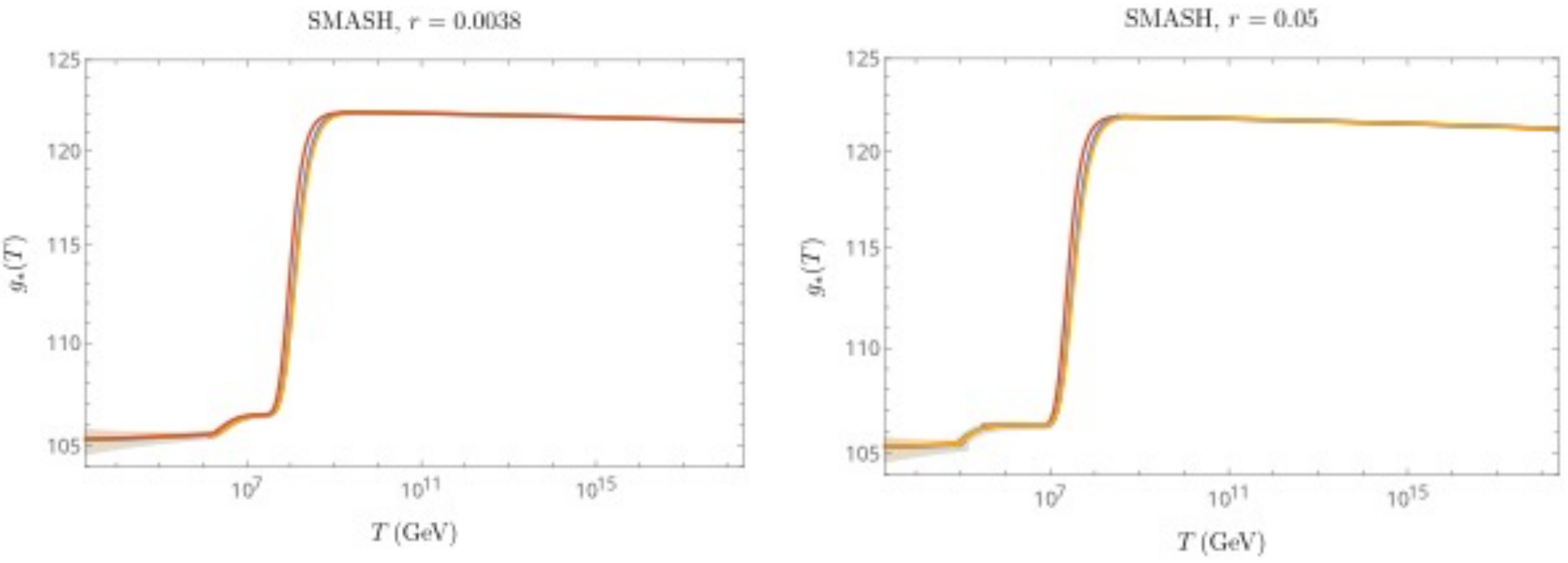
- Dotted lines:

$$h^2\,\Omega_{\rm CGMB}(f) \approx 2.06\times10^{-6}\left[\frac{T_{\rm max}}{M_P}\right]\left[\frac{g_{*s}(T_{\rm max})}{106.75}\right]^{-5/6}\times$$
$$\times\left[\frac{f}{80\,{\rm GHz}}\right]^3\hat{\eta}\left(T_{\rm max}, 4.23\left[\frac{g_{*s}(T_{\rm max})}{106.75}\right]^{1/3}\left[\frac{f}{80\,{\rm GHz}}\right]\right)$$

[AR,Schütte-Engel,Tamarit '20]

GW Background from Primordial Thermal Plasma

Effective number of degrees of freedom in SMASH



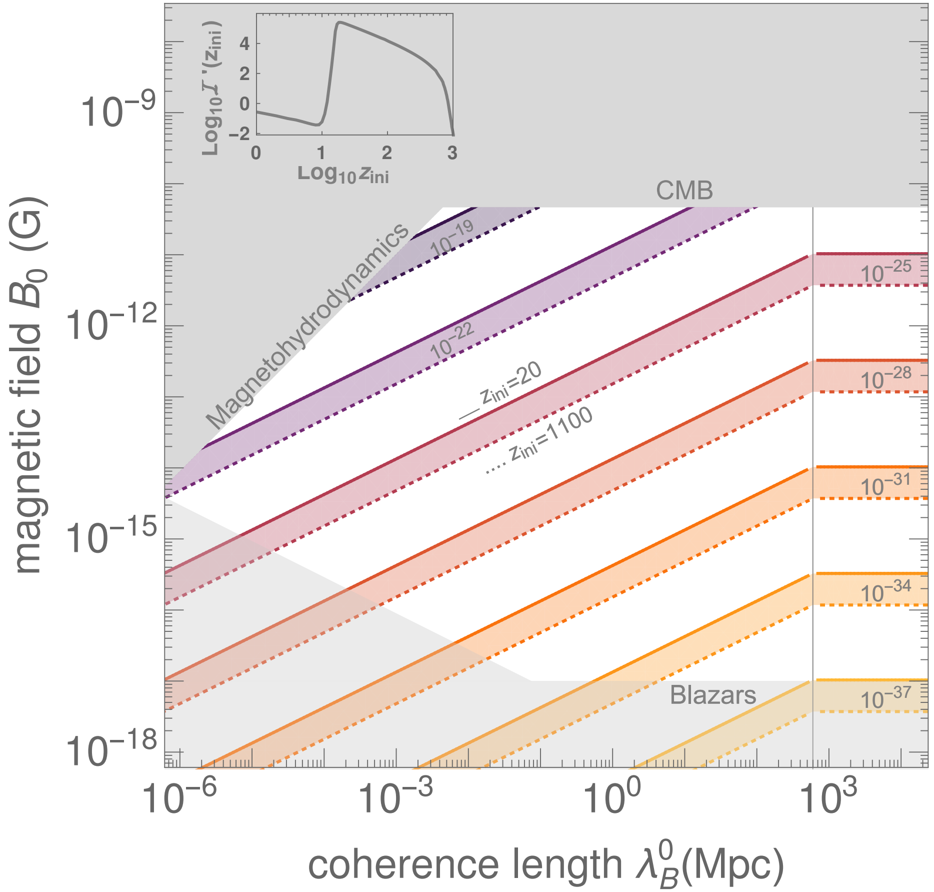
Observational Constraints on the CGMB

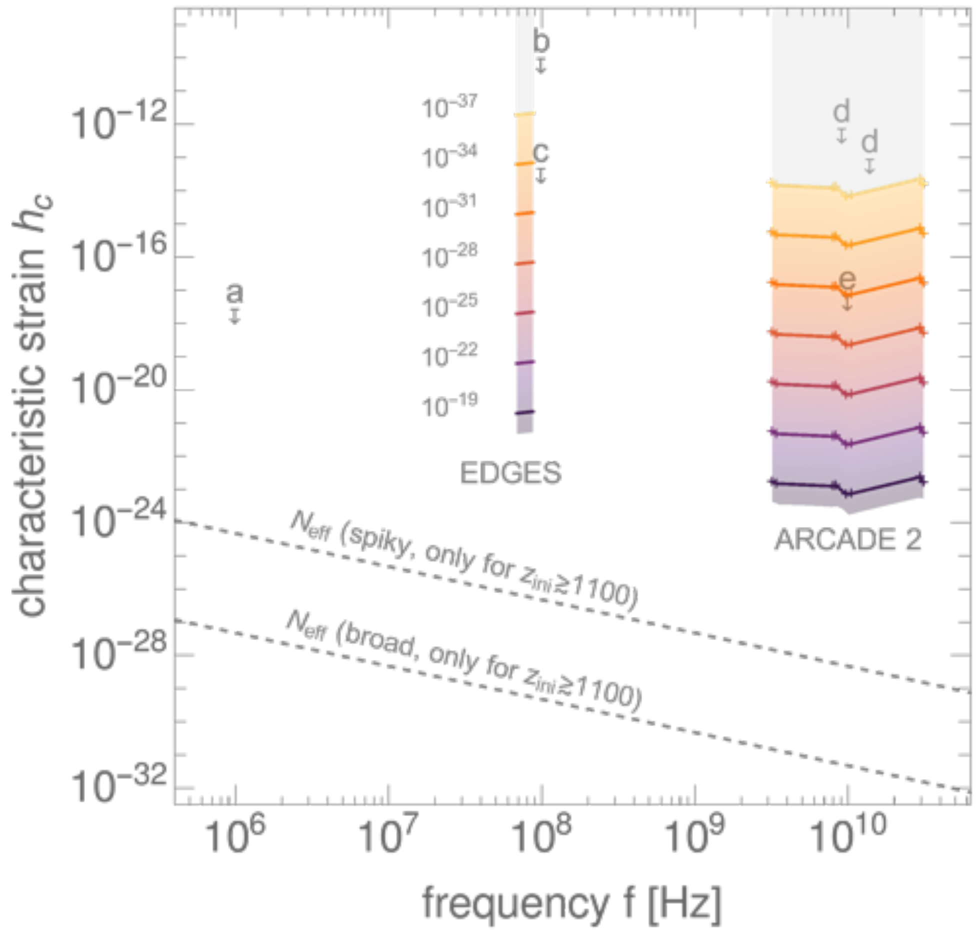
Peak values

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

Observational Constraints on the CGMB

CMB Rayleigh-Jeans tail constraint





[Domcke,Garcia-Cely `20]