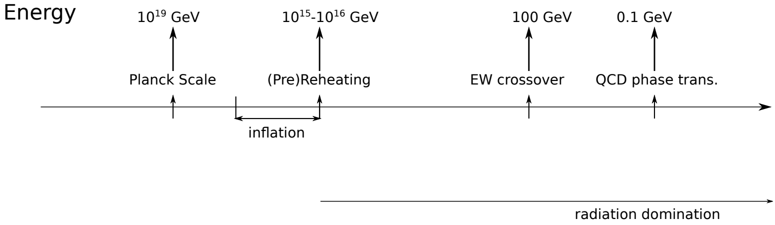
Gravitational Waves as a Big Bang Thermometer

Andreas Ringwald (DESY), Jan Schütte-Engel (UIUC), Carlos Tamarit (TUM)

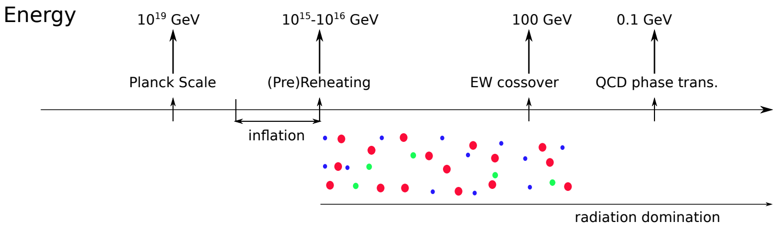
based on JCAP 03 (2021) 054

June 30, 2021

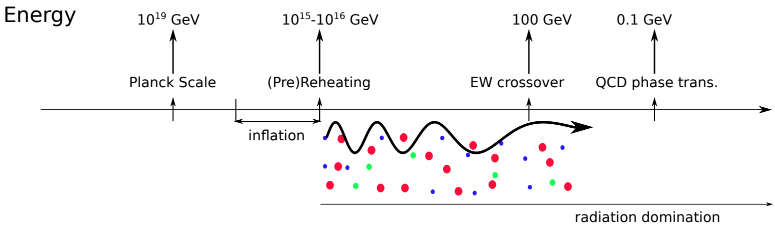
Overview

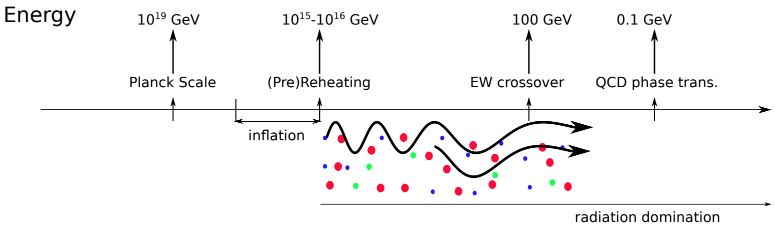


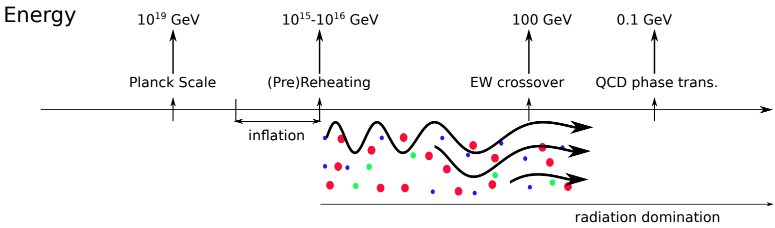
Energy
10^19 GeV
10^15-10^16 GeV
100 GeV
0.1 GeV
Planck Scale
(Pre)Reheating
EW crossover
QCD phase trans.
inflation
radiation domination

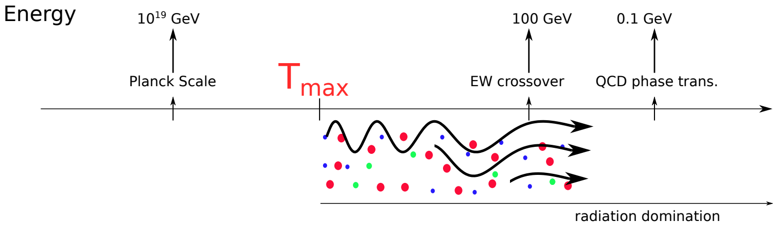


Energy
10^19 GeV
10^15-10^16 GeV
100 GeV
0.1 GeV
Planck Scale
(Pre)Reheating
EW cossover
QCD phase trans.
inflation
radiation domination


Energy
10^19 GeV
10^15-10^16 GeV
100 GeV
0.1 GeV
Planck Scale
(Pre)Reheating
EW crossover
QCD phase trans.
inflation
radiation domination


Energy
10^{19} GeV
10^{15}-10^{16} GeV
100 GeV
0.1 GeV
Planck Scale
(Pre)Reheating
EW crossover
QCD phase trans.
inflation
radiation domination


Energy
10^{19} GeV
10^{15}-10^{16} GeV
100 GeV
0.1 GeV
Planck Scale
(Pre)Reheating
EW crossover
QCD phase trans.
inflation
radiation domination



Cosmic Gravitational Microwave Background (CGMB)

GW production in primordial plasma

GW production in primordial plasma

Energy density of produced GWs from thermal plasma:

$$(\partial_t + 4H)\rho_{\mathrm{CGMB}} = \frac{1}{2M_p^2}\int \frac{d^3k}{(2\pi)^3}\int d^4x e^{ikx}\,\langle T_{ij}^{TT}(x)T_{ij}^{TT}(0)\rangle =: \frac{4T^4}{M_p^2}\int \frac{d^3k}{(2\pi)^3}\hat{\eta}(T,\frac{k}{T})$$

- Computation for SM to leading log accuracy [Ghiglieri, Laine 15] and to full leading order [Ghiglieri, Jackson, Laine, Zhu 20]
- We do the computation for arbitrary theories and specifically for νMSM, SMASH and MSSM

For small k

$$\hat{\eta}\left(T, \frac{k}{T} \equiv \hat{k}\right) = \frac{\eta_{\mathrm{shear}}}{T^3 g_1(T)^4 \ln(5/\hat{m}_1)},$$

with thermal Debye mass

$$\hat{m}_n^2(T) = \frac{m_n^2(T)}{T^2} = g_n^2(T)\left(\frac{1}{3}T_{n,\mathrm{Ad}} + \frac{1}{6}\sum_{\hat{\imath}} T_{n,\hat{\imath}} + \frac{1}{6}\sum_{\hat{\alpha}} T_{n,\hat{\alpha}}\right)$$

GW production in primordial plasma

Energy density of produced GWs from thermal plasma:

$$(\partial_t + 4H)\rho_{\rm CGMB} = \frac{1}{2M_p^2}\int \frac{d^3k}{(2\pi)^3}\int d^4x e^{ikx}\,\langle T_{ij}^{TT}(x)T_{ij}^{TT}(0)\rangle =: \frac{4T^4}{M_p^2}\int \frac{d^3k}{(2\pi)^3}\hat{\eta}(T,\frac{k}{T})$$

- Computation for SM to leading log accuracy [Ghiglieri, Laine 15] and to full leading order [Ghiglieri, Jackson, Laine, Zhu 20]
- We do the computation for arbitrary theories and specifically for νMSM, SMASH and MSSM

For large k

$$\hat{\eta}\left(T,\frac{k}{T}\equiv\hat{k}\right) = \hat{\eta}_{\rm HTL}(T,\hat{k}) + \frac{1}{4}\sum_{i\alpha\beta} |y^i_{\alpha\beta}(T)|^2\, \eta_{sf}(\hat{k}),$$

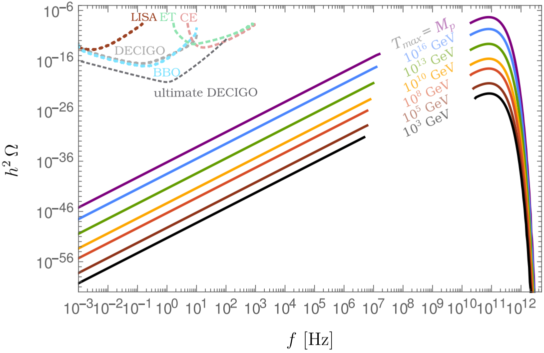
$$+\sum_{n=1}^{\mathcal{N}_g} g_n(T)^2 N_n\left(\frac{1}{2}\, T_{n,\rm Ad}\, \eta_{gg}(\hat{k}) + \sum_{\hat{\imath}} T_{n,\hat{\imath}}\, \eta_{sg}(\hat{k}) + \frac{1}{2}\sum_{\hat{\alpha}} T_{n,\hat{\alpha}}\, \eta_{fg}(\hat{k})\right)$$

Thermal loop functions [Ghiglieri, Jackson, Laine, Zhu 20], Dynkin indices of representations, Gauge and Yukawa couplings

GW production in primordial plasma

$$\frac{1}{\rho_c^{(0)}} \frac{d\rho^0_{\mathrm{CGMB}}}{d\ln f} = \Omega_{\mathrm{CGMB}}(f)$$

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



(for SM)

GW production in primordial plasma

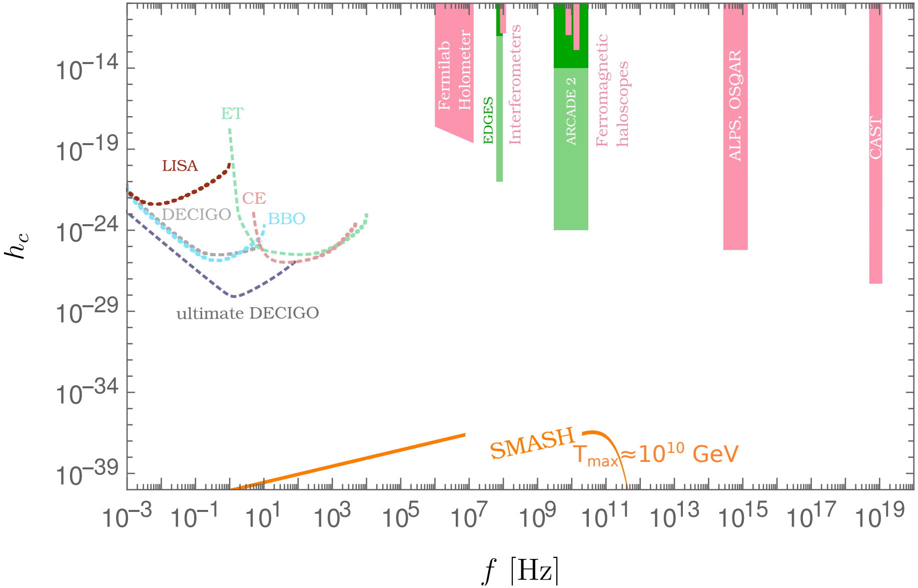
$$\Omega_{CGMB}(f_{\rm peak}) \approx 2.7 \times 10^{-8} \left(\frac{g_{*s}(T_{\rm max})}{106.75}\right)^{-11/6} \frac{T_{\rm max}}{M_p} \times (\text{model dep. factor})$$

$$f_{\rm peak}(T_{\rm max}) \approx 79.8\,\mathrm{GHz} \left[\frac{106.75}{g_{*s}(T_{\rm max})}\right]^{\frac{1}{3}} \times (\text{model dep. factor})$$

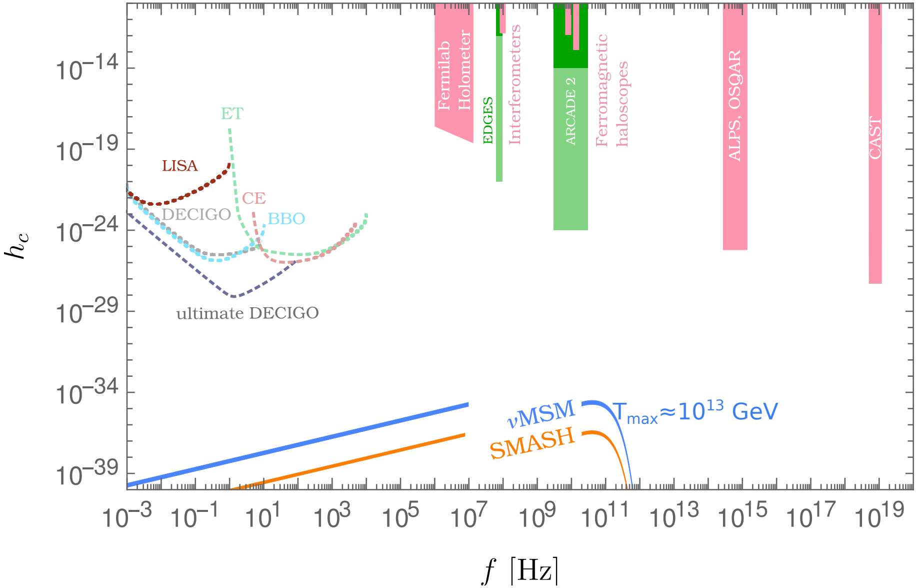
	SM	νMSM	SMASH	MSSM
$g_{*s}(T_{\rm max}) \approx$	106.75	109.75	124	228

characteristic amplitude:

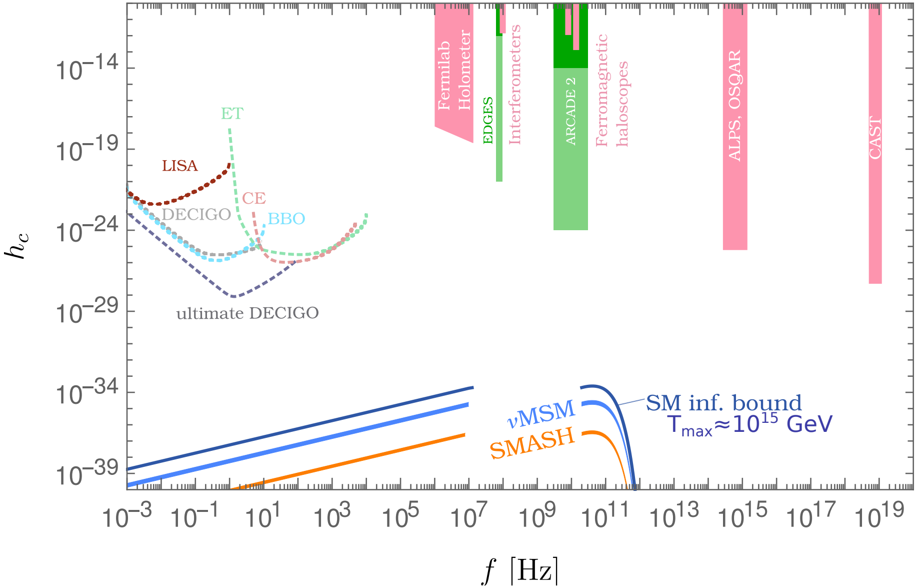
$$h_c(f) = 1.26 \times 10^{-18} \left[\frac{\mathrm{Hz}}{f}\right] \times \sqrt{h^2\,\Omega_{\rm GW}^{(0)}(f)}\,.$$



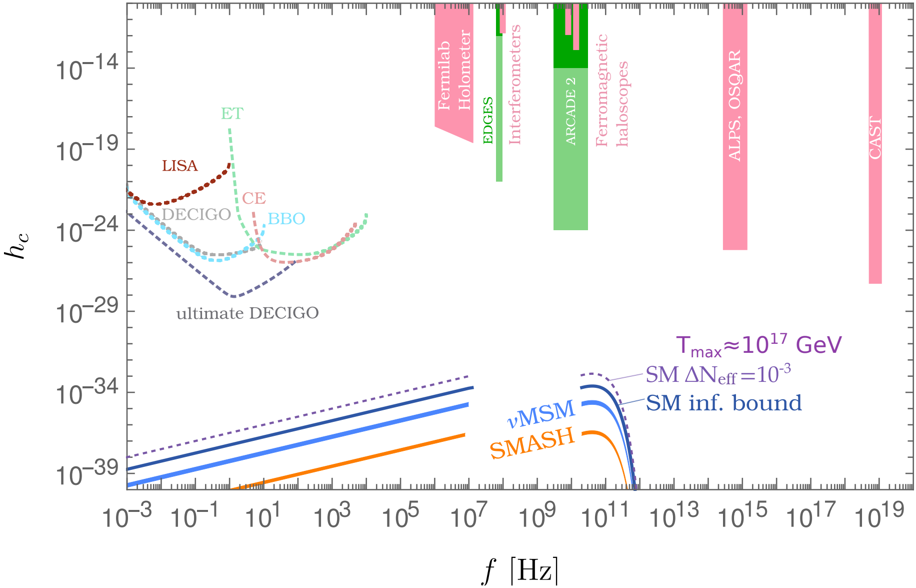
Fermilab Holometer
EDGES
Interferometers
ARCADE 2
Ferromagnetic haloscopes
ALPS, OSQAR
CAST
ET
LISA
CE
DECIGO
BBO
ultimate DECIGO
SMASH
$T_{max} \approx 10^{10}$ GeV
h_c
f [Hz]
10^{-14}
10^{-19}
10^{-24}
10^{-29}
10^{-34}
10^{-39}
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19}



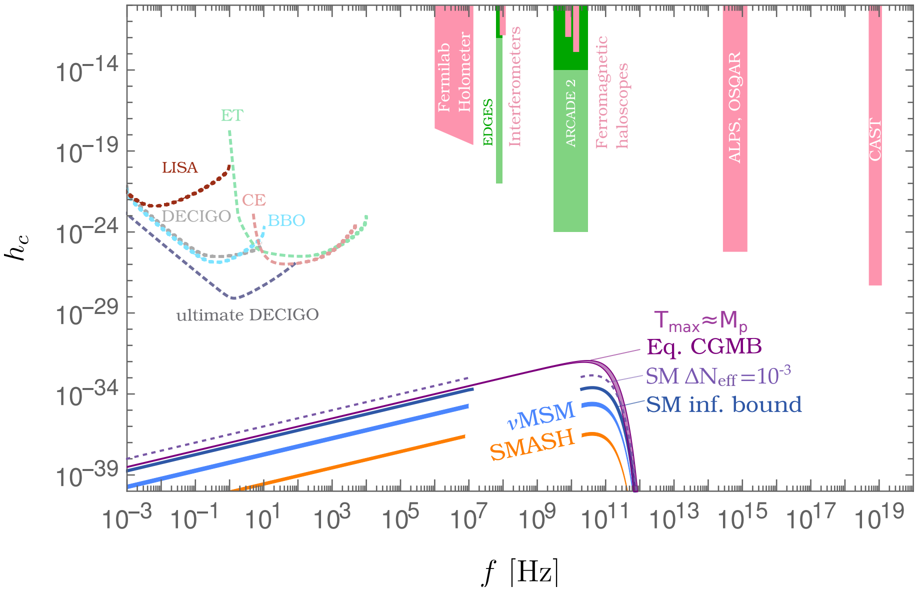
Fermilab Holometer
EDGES
Interferometers
ARCADE 2
Ferromagnetic haloscopes
ALPS, OSQAR
CAST
ET
LISA
CE
DECIGO
BBO
ultimate DECIGO
νMSM
SMASH
$T_{max} \approx 10^{13}$ GeV
10^{-14}
10^{-19}
10^{-24}
10^{-29}
10^{-34}
10^{-39}
h_c
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19}
f [Hz]



Fermilab Holometer
EDGES
Interferometers
ARCADE 2
Ferromagnetic haloscopes
ALPS, OSQAR
CAST
ET
LISA
CE
DECIGO
BBO
ultimate DECIGO
SM inf. bound
$T_{max} \approx 10^{15}$ GeV
νMSM
SMASH
h_c
f [Hz]
10^{-14}
10^{-19}
10^{-24}
10^{-29}
10^{-34}
10^{-39}
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19}

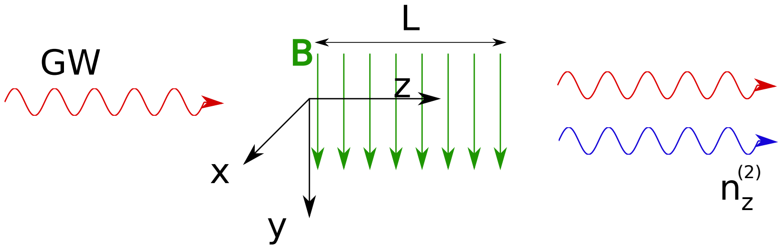


Fermilab Holometer
EDGES
Interferometers
ARCADE 2
Ferromagnetic haloscopes
ALPS, OSQAR
CAST
ET
LISA
CE
DECIGO
BBO
ultimate DECIGO
$T_{max} \approx 10^{17}$ GeV
SM $\Delta N_{eff} = 10^{-3}$
SM inf. bound
νMSM
SMASH
h_c
f [Hz]


Fermilab Holometer
EDGES
Interferometers
ARCADE 2
Ferromagnetic haloscopes
ALPS, OSQAR
CAST
ET
LISA
CE
DECIGO
BBO
ultimate DECIGO
$T_{max} \approx M_p$
Eq. CGMB
SM $\Delta N_{eff} = 10^{-3}$
SM inf. bound
νMSM
SMASH
h_c
f [Hz]
10^{-14}
10^{-19}
10^{-24}
10^{-29}
10^{-34}
10^{-39}
10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5} 10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19}

Direct detection of the CGMB

Magnetic conversion

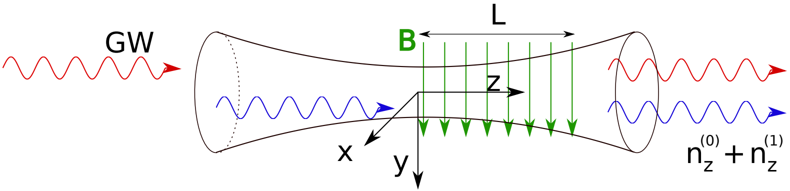


[Gertsenshtein]

Single photon detection:

$$\left[h_c^{\rm CGMB}\right]_{\rm sens}^{\rm SPD} \simeq 7.71 \times 10^{-24} \left[\frac{\rm S/N}{2}\right]^{1/2} \left[\frac{\pi \times 10^7 \,\rm s}{\Delta t}\right]^{1/4} \left(\frac{10^{-4}\,\rm eV}{\Delta\omega}\right)^{1/2} \times$$
$$\times \epsilon^{-1/2} \left[\frac{\Gamma_{\rm D}}{10^{-3}\,\rm Hz}\right]^{1/4} \left[\frac{\rm T}{B}\right] \left[\frac{\rm m}{L}\right] \left[\frac{\rm m^2}{A}\right]^{1/2} .$$

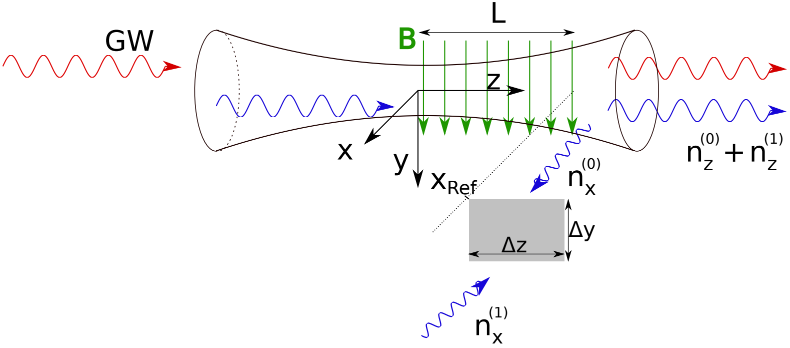
Magnetic conversion with Gaussian beam



[Li et al.]

We get first order flux, but... noise much larger than in inverse Gertsenshtein setup

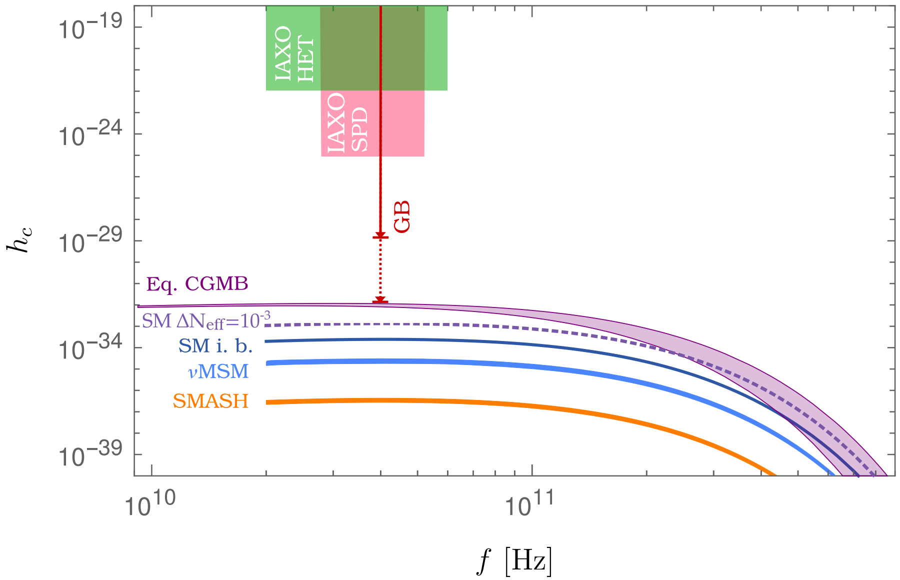
Magnetic conversion with Gaussian beam



[Li et al.]

$$\left[h_c^{\mathrm{CGMB}}\right]^{\mathrm{GB}}_{\mathrm{sens}} \simeq 4.02 \times 10^{-29}\, \eta^{-1} \left[\frac{\mathrm{S/N}}{2}\right] \left[\frac{10^4\, s}{\Delta t}\right]^{1/2} \left[\frac{10^{-6}}{\frac{\Delta f_0}{f_0}}\right] \left[\frac{10^{-5}}{\mathcal{F}_x^{(1)}(x_{\mathrm{Ref}})}\right]$$

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



IAXO HET
IAXO SPD
GB
Eq. CGMB
SM ΔN_eff=10^-3
SM i. b.
νMSM
SMASH
10^-19
10^-24
10^-29
10^-34
10^-39
h_c
10^10
10^11
f [Hz]

Conclusions

- Guaranteed CGMB peaks in the GHz region
- CGMB scales with maximum temperature: $\Omega_{\mathrm{CGMB}} \sim T_{\mathrm{max}}$
- Probe particle physics models at T_{max} because $f_{\mathrm{peak}} \sim (g_{*s})^{-1/3}$
- Prospect to probe inflation
- Detection possible but challenging
- Synergies to axion search experiments

Thanks for your attention