L.A. Popa, Physics of the Dark Universe (2025) D24, 00862
arXiv: 6128737 [hep-ph]

Gravitational Waves (GWs) dynamics Beyond the Standard Model (BSM) of Particle Physics: Prospects for the future space-borne experiments

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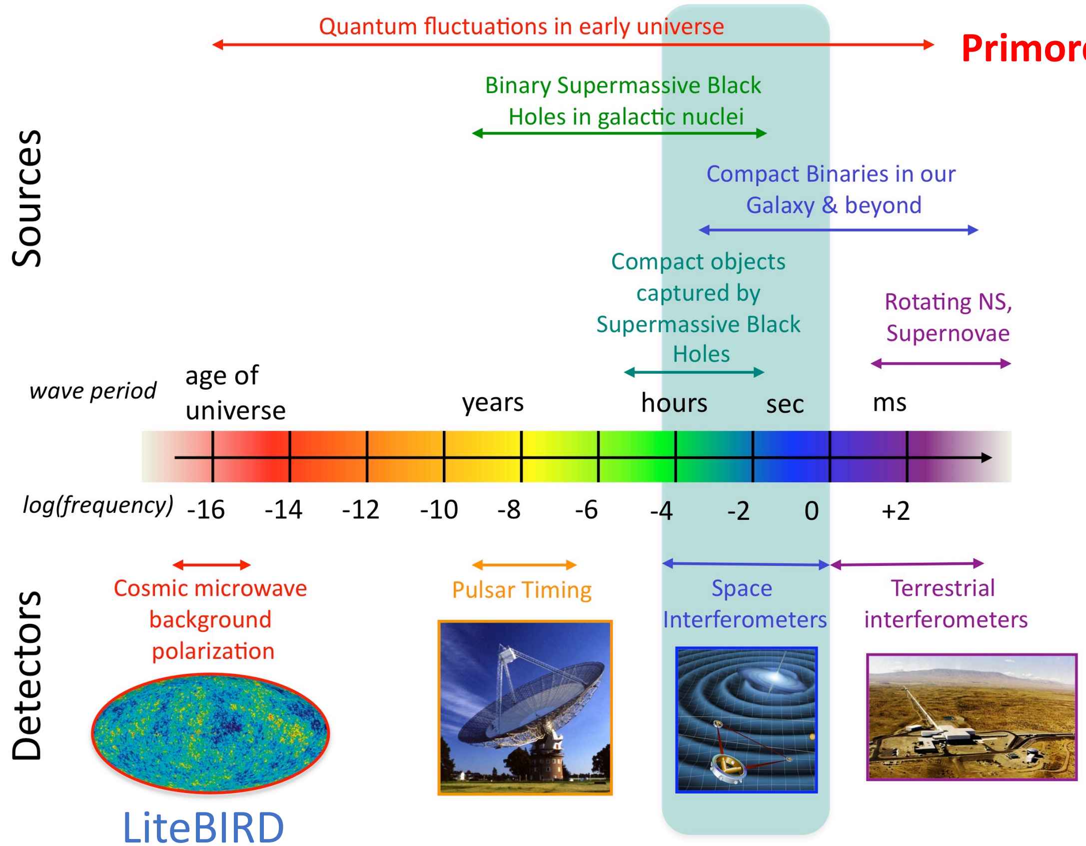
Outline:

1. Motivation
2. BSM to Cosmology
3. GWs background from inflation
4. Constraints and back reactions
5. Prospects for the future space-born GW experiments
6. Conclusions

GWs transport gravitational RADIATION generated by the relative motion of gravitating masses.

The Gravitational Wave Spectrum



Primordial GWs produced during inflation

$$h^2\Omega_{GW}(f) = \frac{3}{128}\Omega_{rad}\mathcal{P}_t^{(s)}(f)\left[\frac{1}{2}\left(\frac{f_{eq}}{f}\right)^2 + \frac{16}{9}\right],$$

N_{eff} =3.046 - SM

Δ N_{eff} - BSM

-neutrino species, hierarchy

-baryon/lepton asymmetry

-recombination, nucleosynthesis

LiteBIRD

Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection

LISA – *Laser Interferometer Space Antenna*

DECIGO - *Deci-Hertz Interferometer GW Observatory*

BBO - *Big-Bang Observer (BBO)*

Popa, L.A., Tonoiu, D., JCAP 9, 066 (2015).
Caramete, A., Popa, L.A., JCAP, 2, 012 (2014).
Popa, L. A., Caramete, A., ApJ 723, 1 803 (2010).

$$f/Hz = 1.5\times10^{-15}k/Mpc^{-1}\ .$$

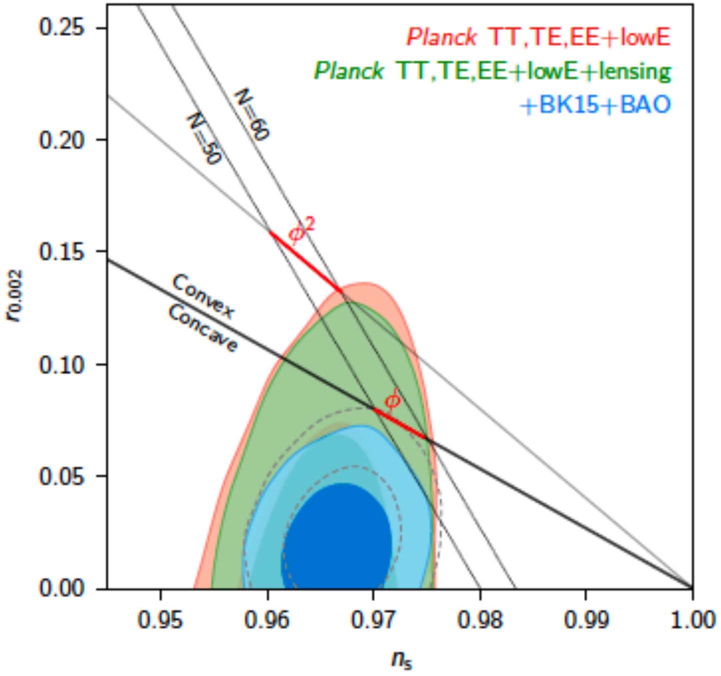
Standard Model of Cosmology
ΛCDM: six free parameters + Inflation + GR

Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	0.0543
$\ln(10^{10}A_s)$	3.0448
n_s	0.96605

All needded to describe the present Universe

$$H_0 = (67.66 \pm 0.42)\ \mathrm{km\ s^{-1}Mpc^{-1}},\quad \Omega_m = 0.3111 \pm 0.0056,$$ 68 %, TT,TE,EE +lowE+lensing +BAO.

$\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).



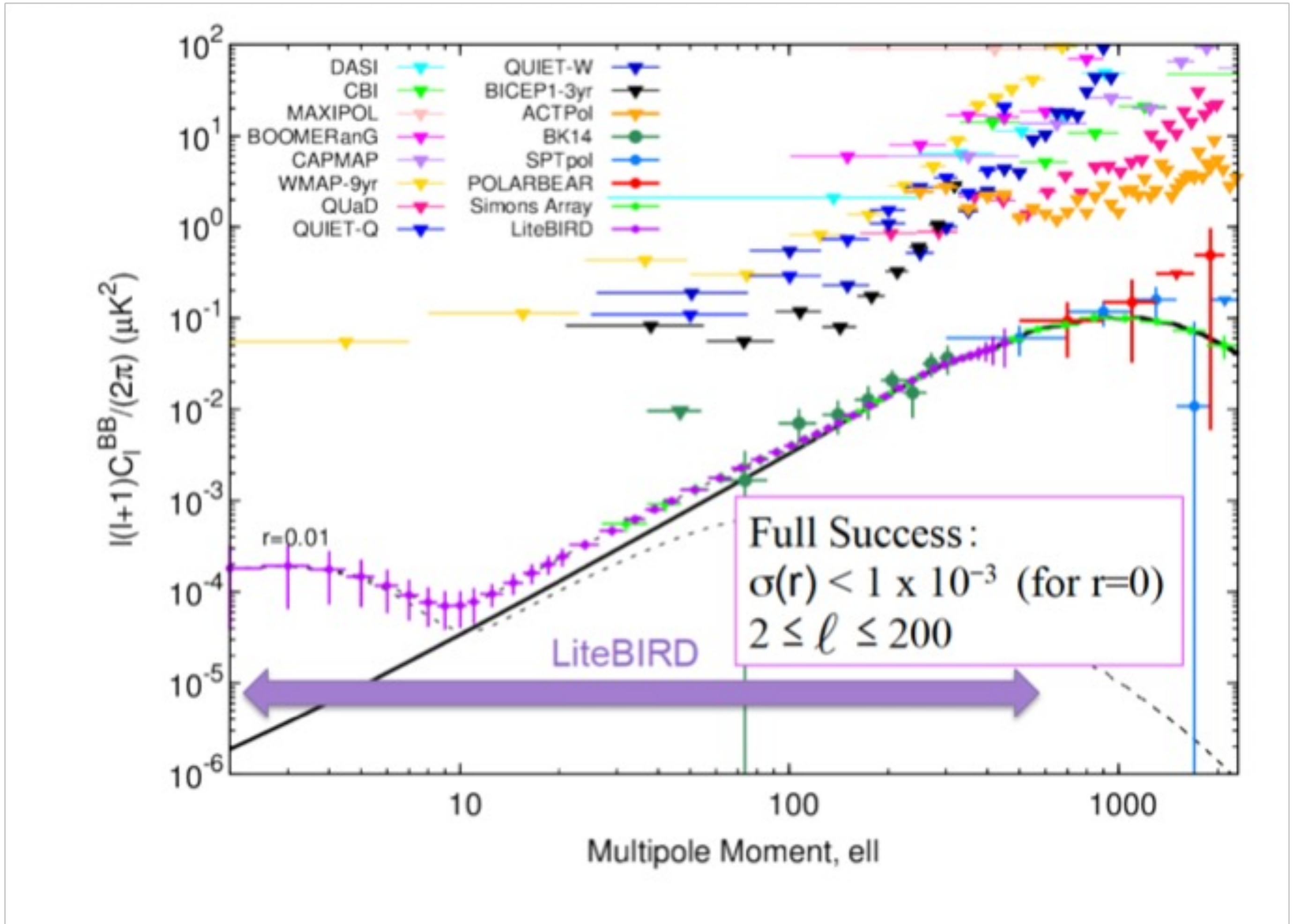
$r_{0.002} < 0.056$ (95 % CL, *Planck* TT,TE,EE +lowE+lensing+BK15).

$$V_*^{1/4} = \left(\frac{3\pi^2 A_s^*}{2} r_*\right)^{1/4} M_{pl} < 1.6 \times 10^{16}\mathrm{GeV}\ \ (95\%\mathrm{CL})\,.$$

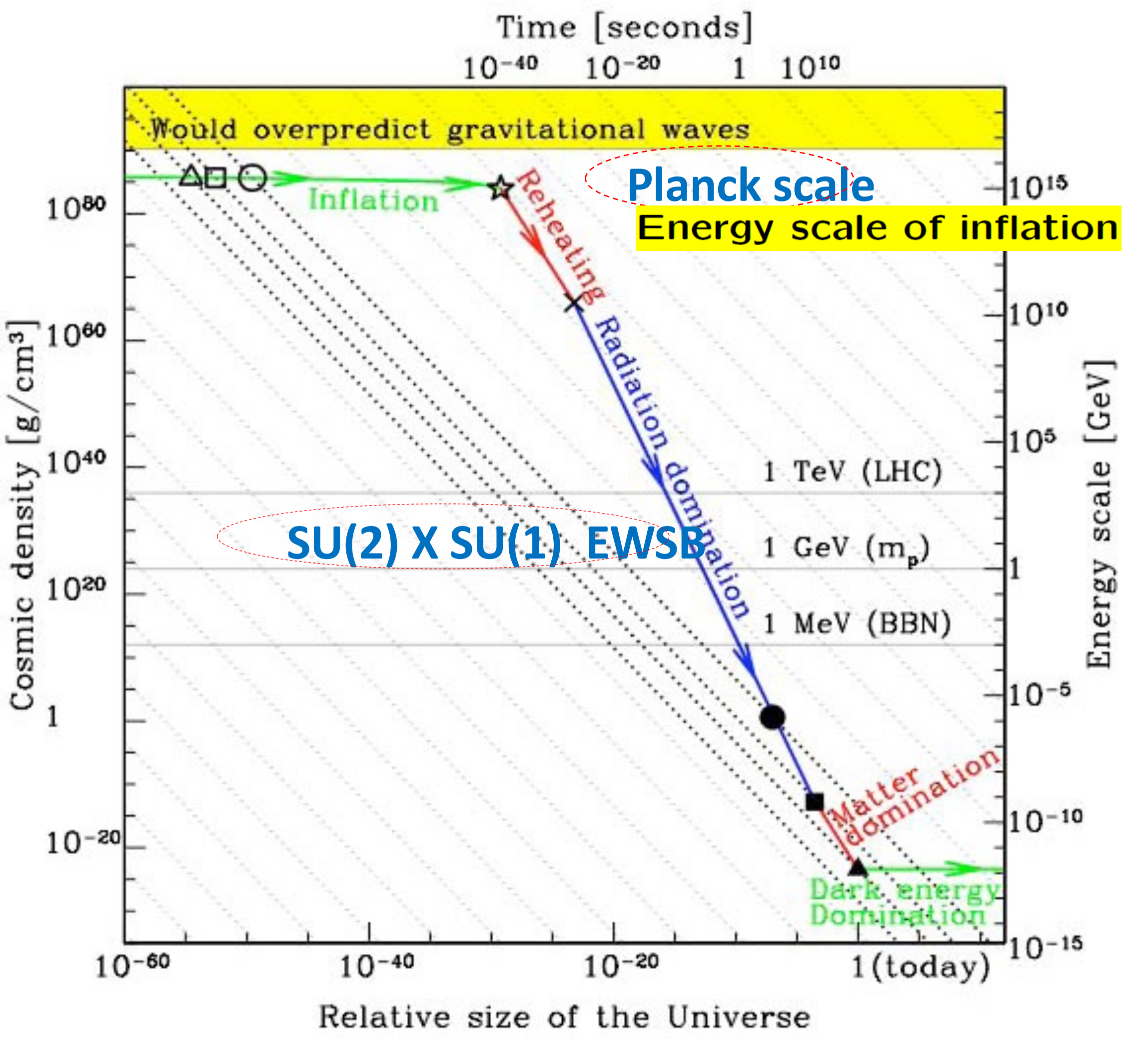
$$H_* < 2.5 \times 10^{-5} M_{pl}\ \ (95\%\mathrm{CL})$$

LiteBIRD expectations:

- Perform a measurement at the limit of $r < 0.001$
- Test the scale dependence, gaussianity, and chirality imprinted on CMB B-mode polarization.
- Provide information on the underlying **REALISTIC** inflationary dynamics.



Issue: Energy scale separation between hidden and visible sectors



$$V_*^{1/4} = \left(\frac{3\pi^2 A_s^*}{2} r_*\right)^{1/4} M_{pl} < 1.6 \times 10^{16}\mathrm{GeV} \;\; (95\%\mathrm{CL}).$$

$$r_* = \frac{\mathcal{P}_h}{\mathcal{P}_\zeta}$$

Origins of the primordial GW background ?

- **Quantum vacuum fluctuations**: nearly scale invariant, nearly non-gaussian, parity conserving (non-chiral)
- **Matter fields:** energetically-excited extra particle content present during inflation (New Physics)

GW background from inflation imprinted in B-mode polarization of the CMB represents one of the main targets of ongoing experimental efforts.

Higgs-portal to inflation

$\mathcal{O}_2 = H^\dagger H$ Higgs field is the single gauge and Lorentz invariant dimension–2 operator in SM

Higgs – portal: couple visible and "hidden" sectors at the renormalizable level

$$\Delta\mathcal{L} = cHH^\dagger S^2$$

$\langle S \rangle \neq 0$ *inflaton*

$\langle S \rangle = 0$ *DM particle*

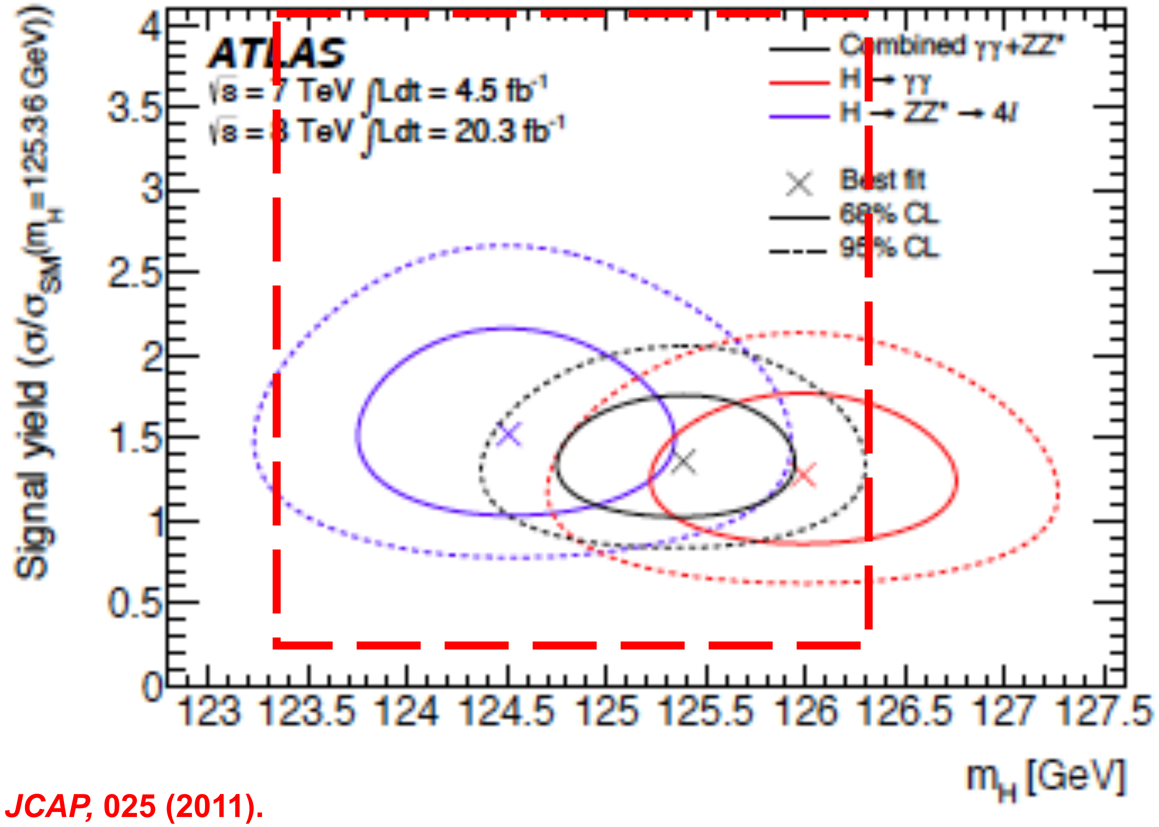
Can be proved at the LHC by measuring production cross sections for the Higgs–like states

Atlas - $M_H = 125.36 \pm 0.41$ GeV

CMS - $M_H = 125.03 \pm 0.29$ GeV

Planck: 124 GeV < M_H < 127 GeV at 95% CL

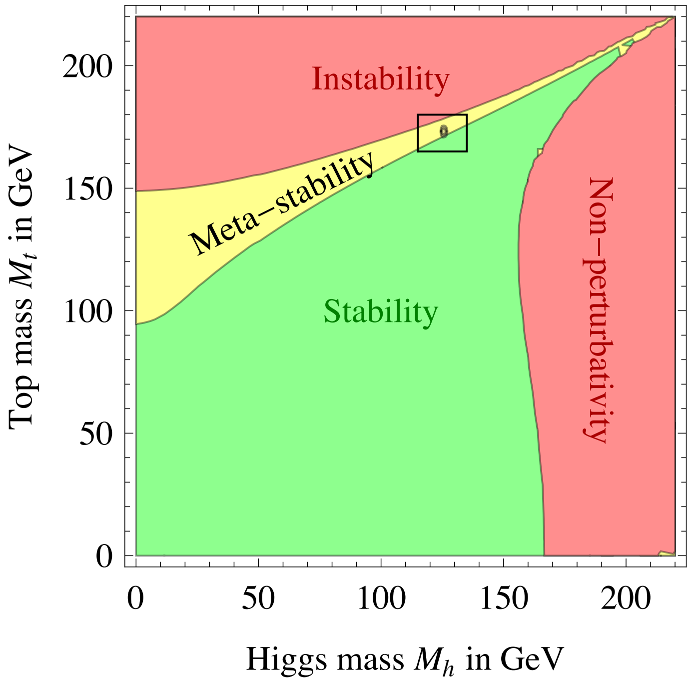
M_{Top}= 172 GeV



Popa, L.A., *JCAP,* 025 (2011).
Popa, L. A., Caramete, A., ApJ 723, (2010).
Popa, L. A., Mandolesi, N., Caramete, A., Burigana, C., APJ 706 (2009).

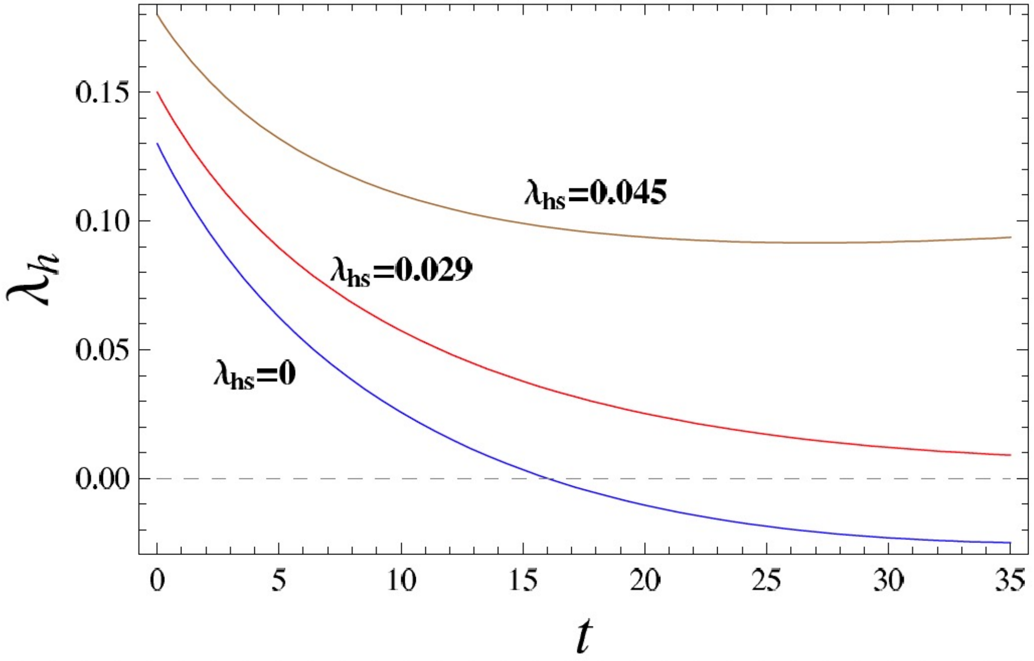
Renormalization Group of the SM couplings:

$$
\begin{aligned}
16\pi^2 \frac{d\lambda_h}{dt} &= 24\lambda_h^2 - 6y_t^4 + \frac{3}{8}\Big(2g^4 + (g^2 + g'^2)^2\Big) \\
&+ (-9g^2 - 3g'^2 + 12y_t^2)\lambda_h + \frac{1}{2}\lambda_{hs}^2 \, , \\
16\pi^2 \frac{d\lambda_{hs}}{dt} &= 4\lambda_{hs}^2 + 12\lambda_h\lambda_{hs} - \frac{3}{2}(3g^2 + g'^2)\lambda_{hs} \\
&+ 6y_t^2\lambda_{hs} + 6\lambda_s\lambda_{hs} \, , \\
16\pi^2 \frac{d\lambda_s}{dt} &= 2\lambda_{hs}^2 + 18\lambda_s^2 \, ,
\end{aligned}
$$



Stabilization of EW vacuum

$$
\lambda_h\Big|_{Higgs+singlet} = \lambda_h^{SM} + \frac{\lambda_{hs}^2}{4\lambda_s} \, .
$$



$m_h^{SM} = 125.10$ GeV $\lambda_h^{SM} \simeq 0.128.$

$v \equiv (\sqrt{2}G_F)^{1/2} = 246.22$ GeV

Vacuum fluctuations from Higgs-singlet inflation

Jordan frame action:

$$\mathcal{S}_J = \int \mathrm{d}^4x\sqrt{-\hat{g}}\ [\underbrace{\frac{1}{2}(1+\xi_h h^2+\xi_\phi\phi^2)\hat{\mathcal{R}}}_{\mathcal{L}_{grav}} - \underbrace{\frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}(\partial_\mu\phi)^2 + V(h,\phi)}_{\mathcal{L}_{infl}}$$

$$\underbrace{-\frac{1}{2}(\partial\sigma)^2 - U_a(\sigma) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{\lambda\sigma}{4f}F^a_{\mu\nu}\tilde{F}^{a\mu\nu}]}_{\mathcal{L}_{spec}}$$

Z_2 - symmetric BSM inflation potential:

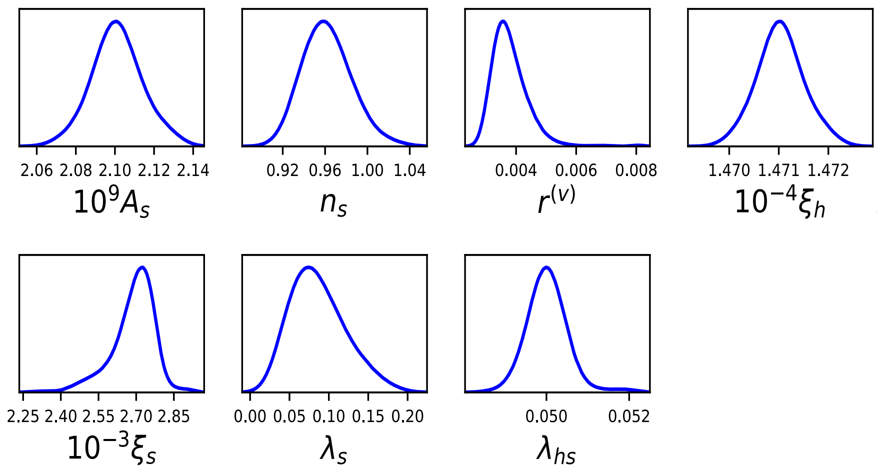
$$V(h,\phi) = \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_{h\phi}h^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4 + \frac{1}{2}m_h^2h^2 + \frac{1}{2}m_\phi^2\phi^2$$

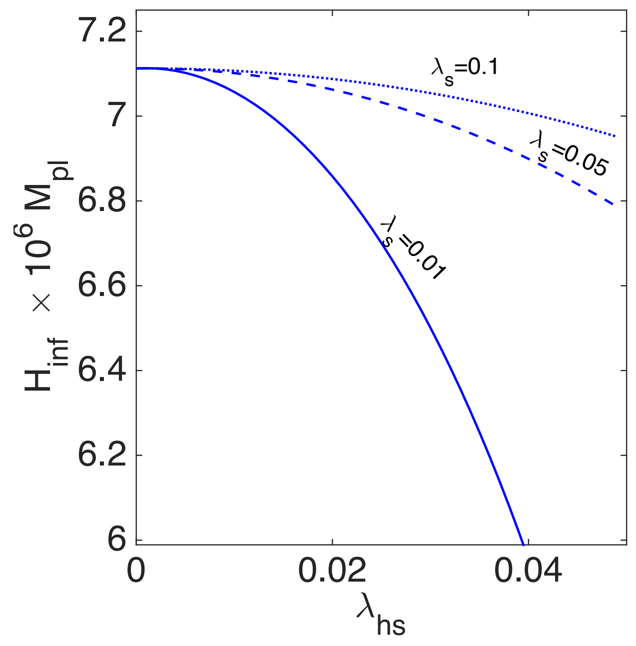
Conformal transformation:

$$g_{\mu\nu} = \Omega^2\hat{g}_{\mu\nu} \qquad \Omega = 1+\xi_h^2+\xi_\phi\phi^2$$

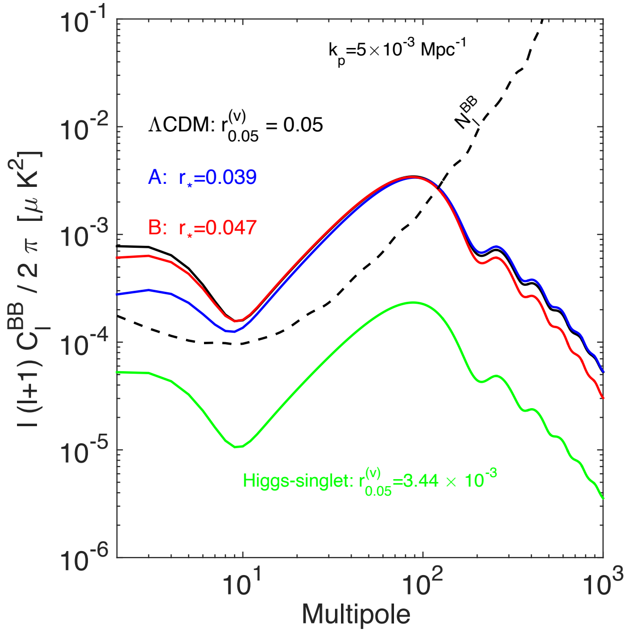
$$\xi_h h^2 + \xi_\phi\phi^2 \gg 1$$

Higgs-singlet inflation: quantum vacuum fluctuations





B-mode APS



VeV:

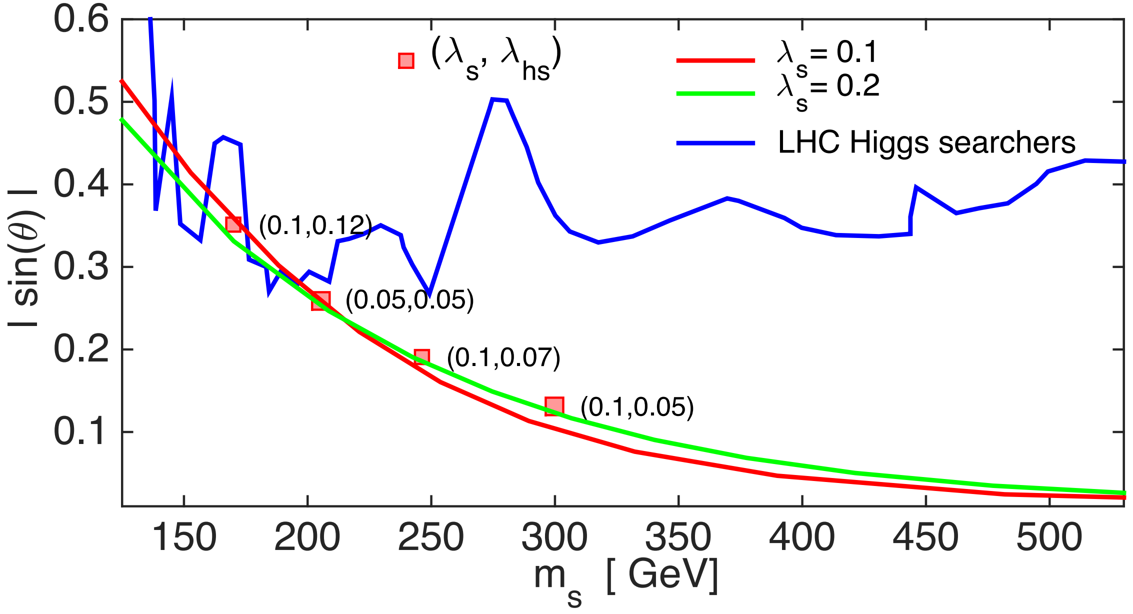
$$v^2 = 2\,\frac{\lambda_{hs} m_s^2 - 2\lambda_s m_h^2}{4\lambda_s\lambda_h - \lambda_{hs}^2}\,,$$
$$u^2 = 2\,\frac{\lambda_{hs} m_h^2 - 2\lambda_h m_s^2}{4\lambda_s\lambda_h - \lambda_{hs}^2}\,.$$

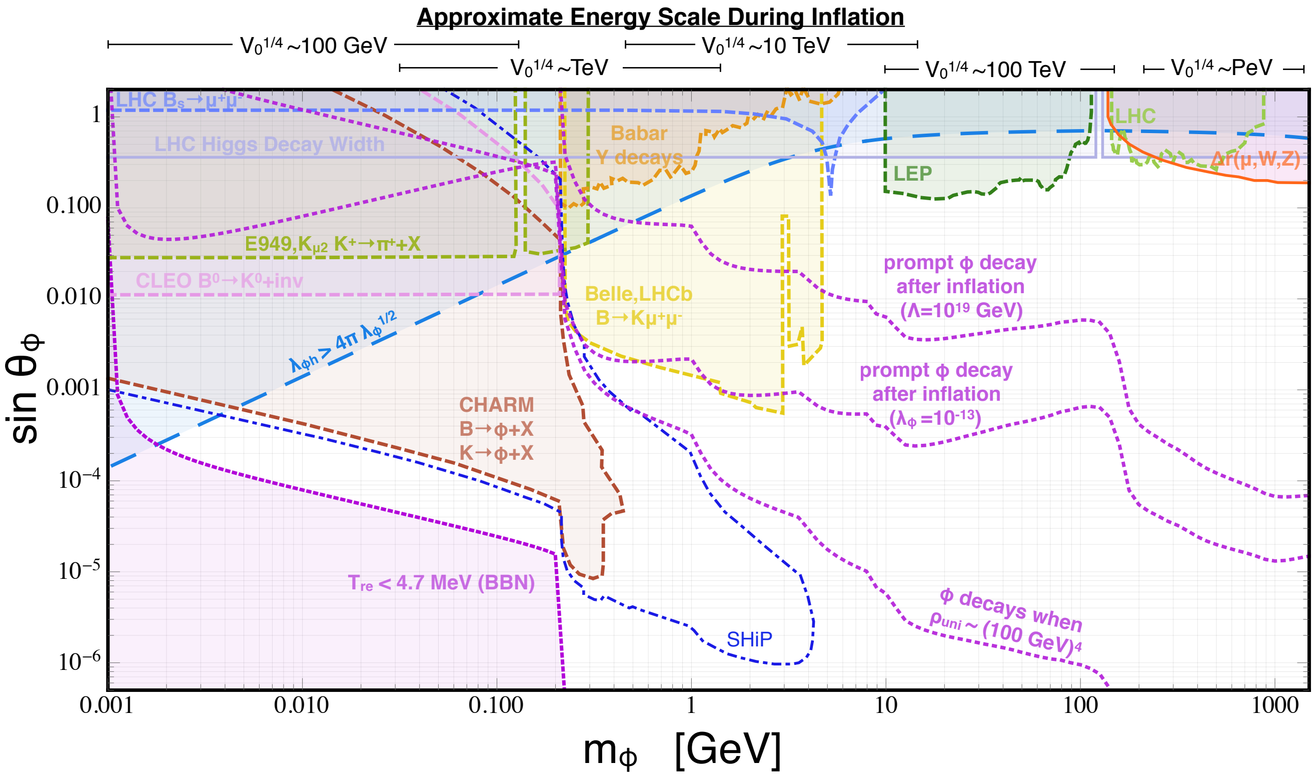
Mass eigenstates:

$$m_{1,2}^2 = \lambda_h v^2 + \lambda_s u^2 \mp \sqrt{(\lambda_s u^2 - \lambda_h v^2)^2 + \lambda_{hs}^2 u^2 v^2}$$

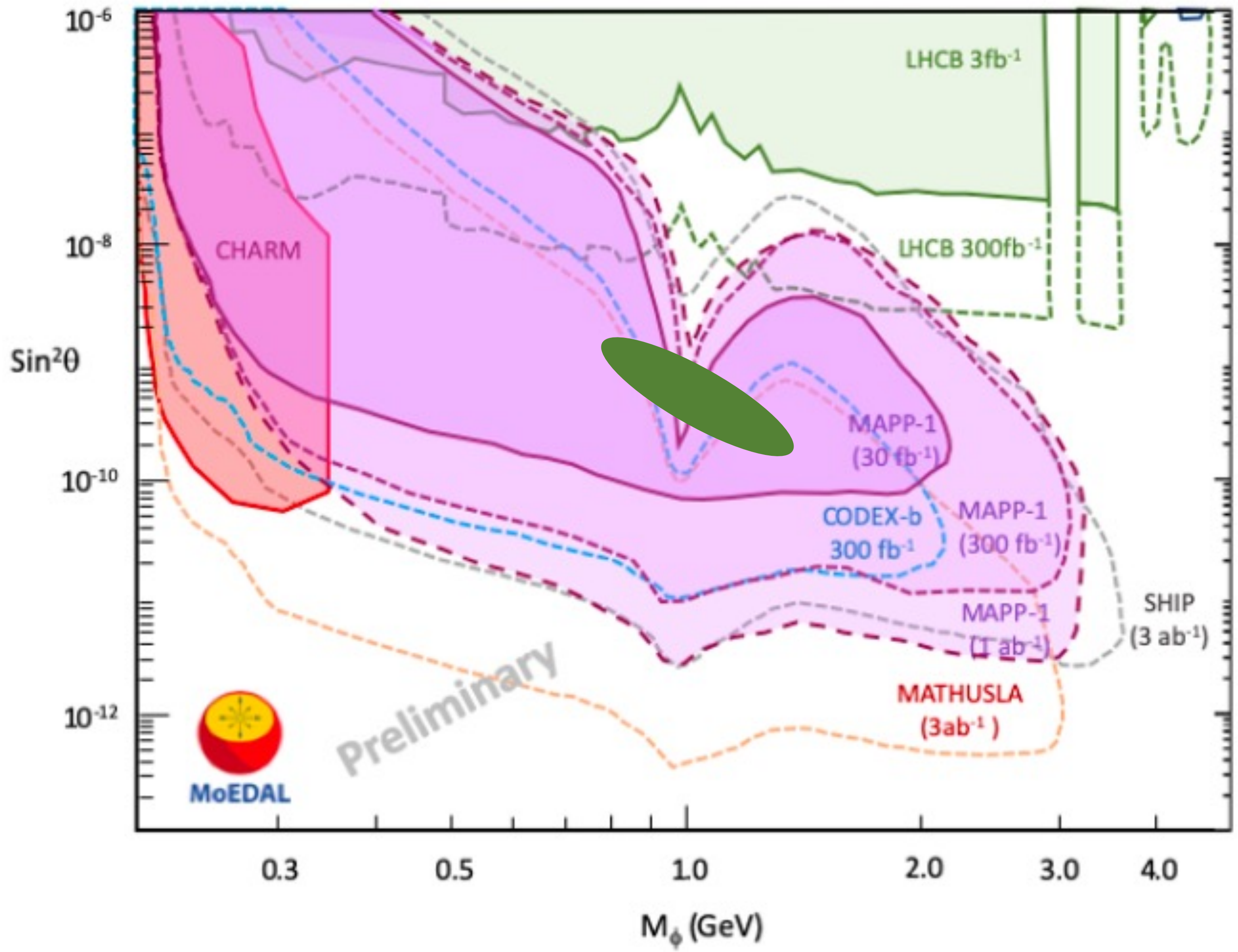
Higgs-singlet mixing angle:

$$\tan 2\theta = \frac{\lambda_{hs} u v}{\lambda_h v^2 - \lambda_s u^2}\,.$$





MoEDAL/MAPP-1 & FASER-2 reach for Higgs-singlet inflaton



L.A. Popa, Universe (2022) 9, 235

L.A. Popa, Universe (**2021**) 7, 309

Transiently rolling spectator :

$$\frac{\mathcal{L}_{spec}}{\sqrt{-g}} = \frac{1}{2}(\partial\hat{\sigma})^2 + \hat{U}_a(\hat{\sigma}) + \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \mathcal{L}_{int}$$

$g_{\mu\nu} = \Omega^2 \hat{g}_{\mu\nu} \qquad \Omega = 1 + \xi_h^2 + \xi_\phi \phi^2$

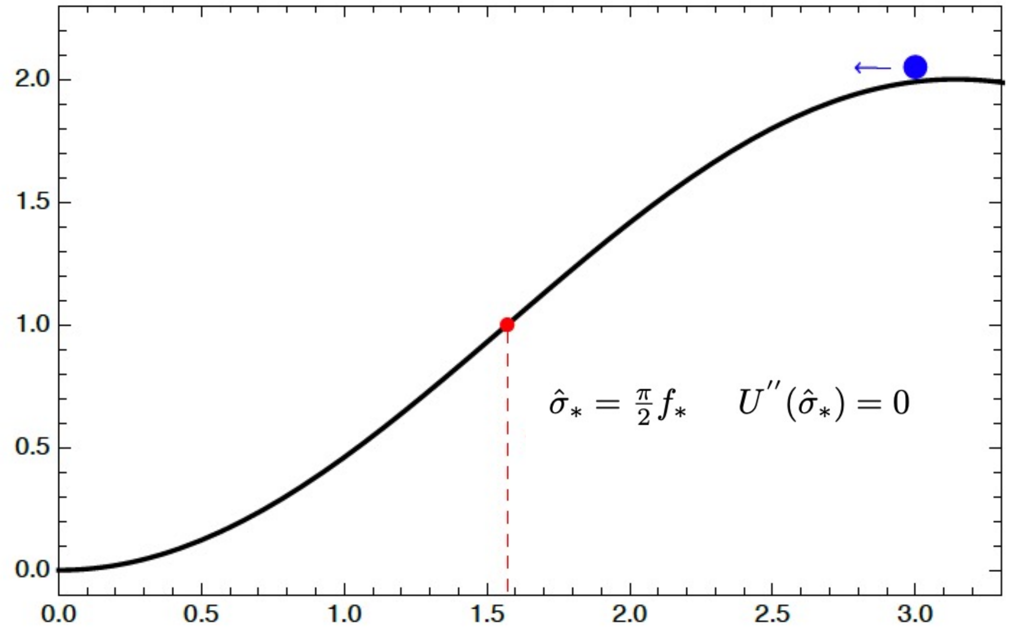
$\xi_h h^2 + \xi_\phi \phi^2 \gg 1$

U(1) axion field : $\hat{\sigma}$ $\qquad \hat{U}_a(\hat{\sigma}) = \frac{\Lambda^4}{\Omega^2}\left[1 - \cos\left(\frac{\hat{\sigma}}{\hat{f}}\right)\right]$ where $\left(\frac{\partial\hat{\sigma}}{\partial\sigma}\right)^2 \simeq \frac{1}{\Omega}$

SU(2) gauge field : A_μ $\qquad F^a_{\mu\nu} = \partial A_\nu - \partial_\nu A_\mu$

Chern-Simons term: $\qquad \mathcal{L}_{int} = \lambda \frac{\hat{\sigma}}{\hat{f}} F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$

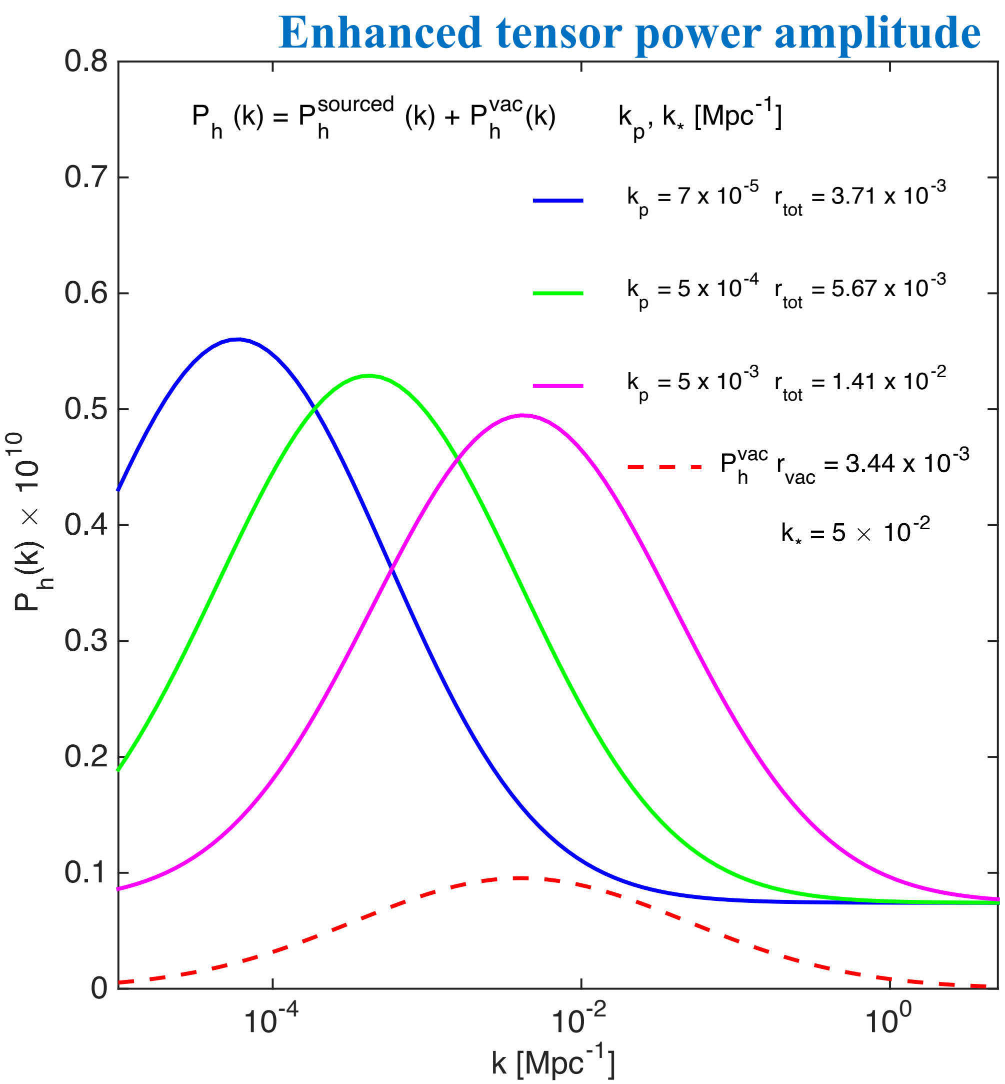
$$\boxed{\xi \equiv \frac{\lambda}{2\hat{f}H_{infl}}\dot{\hat{\sigma}} \qquad m_* = \left(g^2\Lambda^4/3\lambda H^4_{infl}\right)^{1/4}}$$

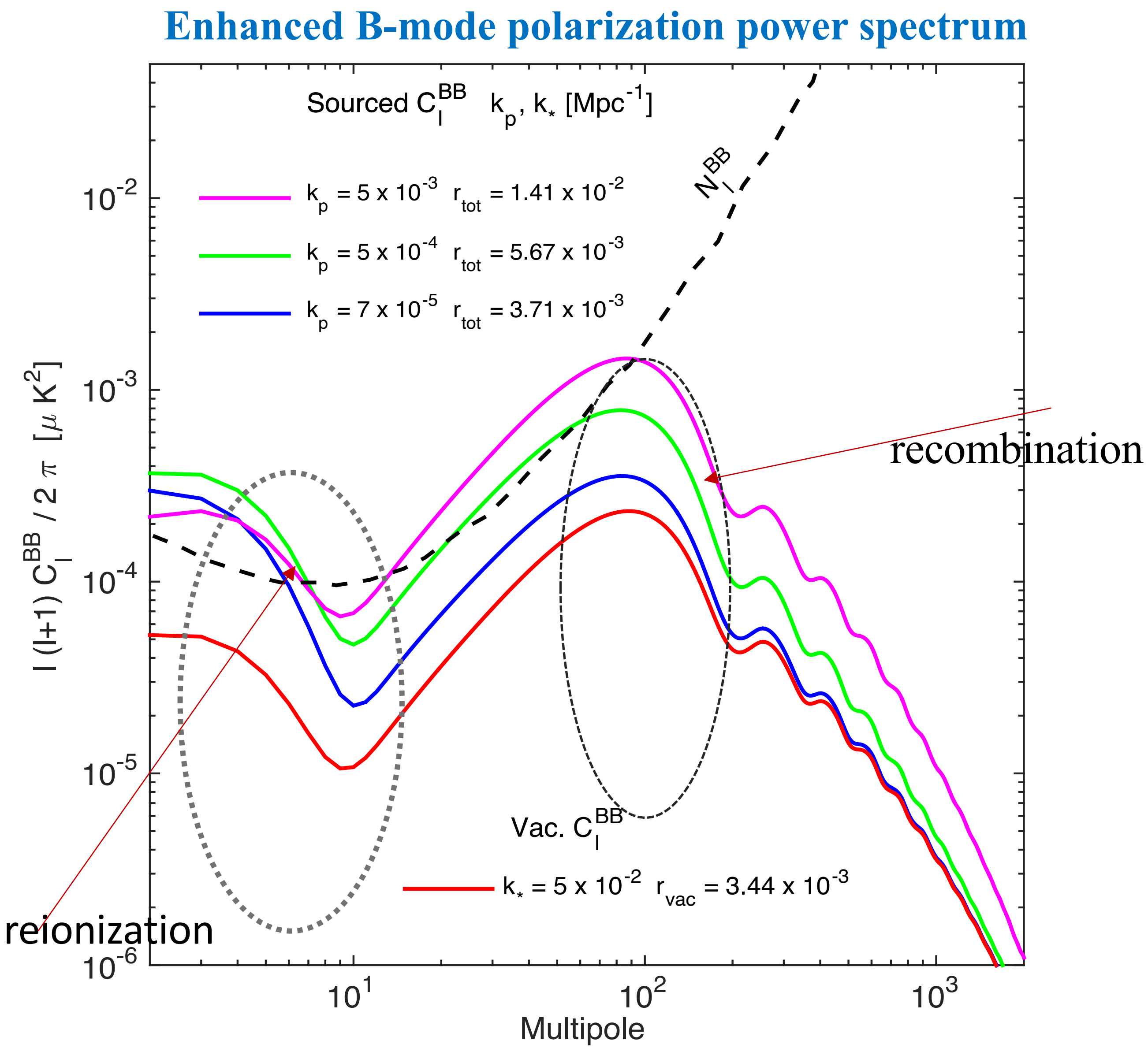


$\xi_*(\hat{\sigma}_*) \simeq m_* + m_*^{-1} \longrightarrow k_*$

scale that exits horizon when axion velocity and SU(2) gauge field mass are maximal

Scale dependence





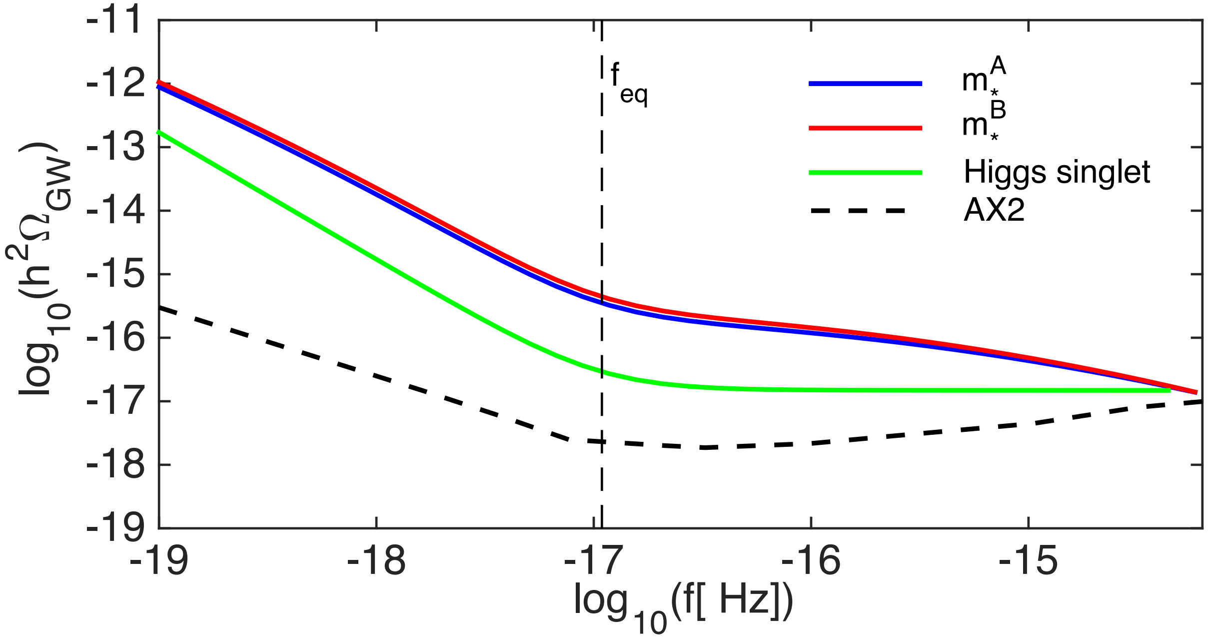
Issue: Gauge field evolution with backreactions

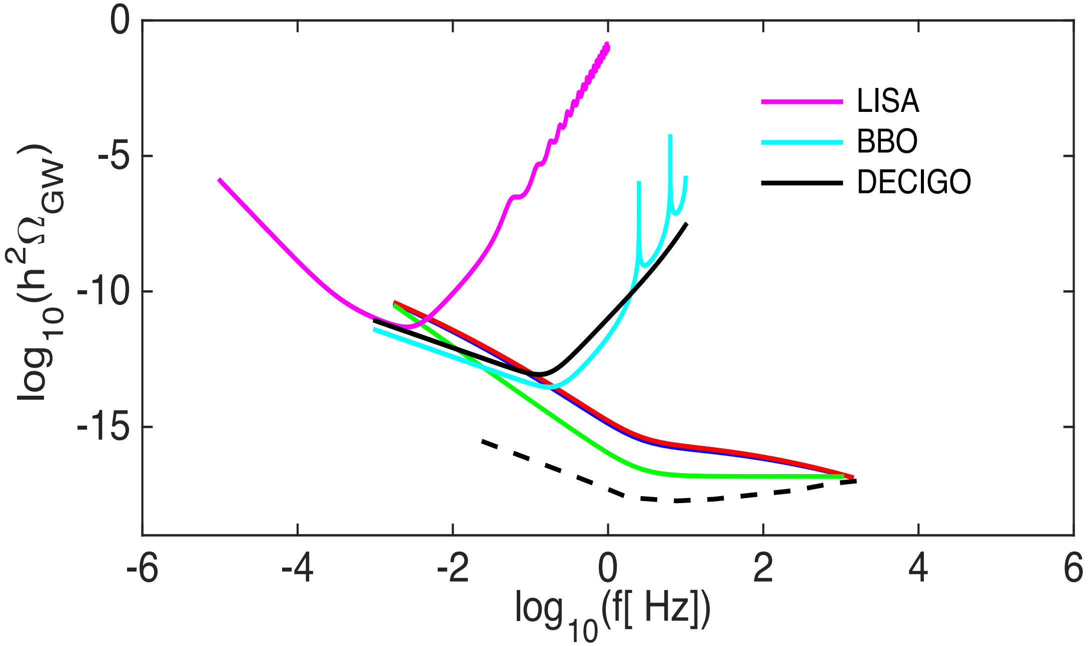
$$3H^2 = \frac{1}{2}\dot{\chi}^2 + V(\chi) + \frac{1}{2}\dot{\phi}^2 + U(\phi) + \frac{3}{2}\left[(\dot{Q} + HQ)^2 + g^2 Q^4\right]$$

$$\begin{aligned}
\ddot{\phi} + 3H\dot{\phi} + U_\phi(\phi) &= 0\,, \\
\ddot{\chi} + 3H\dot{\chi} + V_\chi(\chi) &= -\frac{3g\lambda}{f} Q^2(\dot{Q} + HQ)\,, \\
\ddot{Q} + 3H\dot{Q} + (\dot{H} + 2H^2)Q + 2g^2 Q^3 &= g\frac{\lambda}{f}\dot{\chi} Q^2\,.
\end{aligned}$$

$$\boxed{\mathcal{P}_t^{(s)}(k) = \frac{\epsilon_{Q_B} H^2}{\pi^2} \mathcal{F}^2(m_Q)\,, \qquad m_Q(t) \equiv \frac{gQ(t)}{H}}$$

Primordial GWs energy spectrum for LiteBIRD observing strategy





K. Schmitz, New Sensitivity Curves for Gravitational-Wave Experiments (2020)
https://zendo.org/records/368958

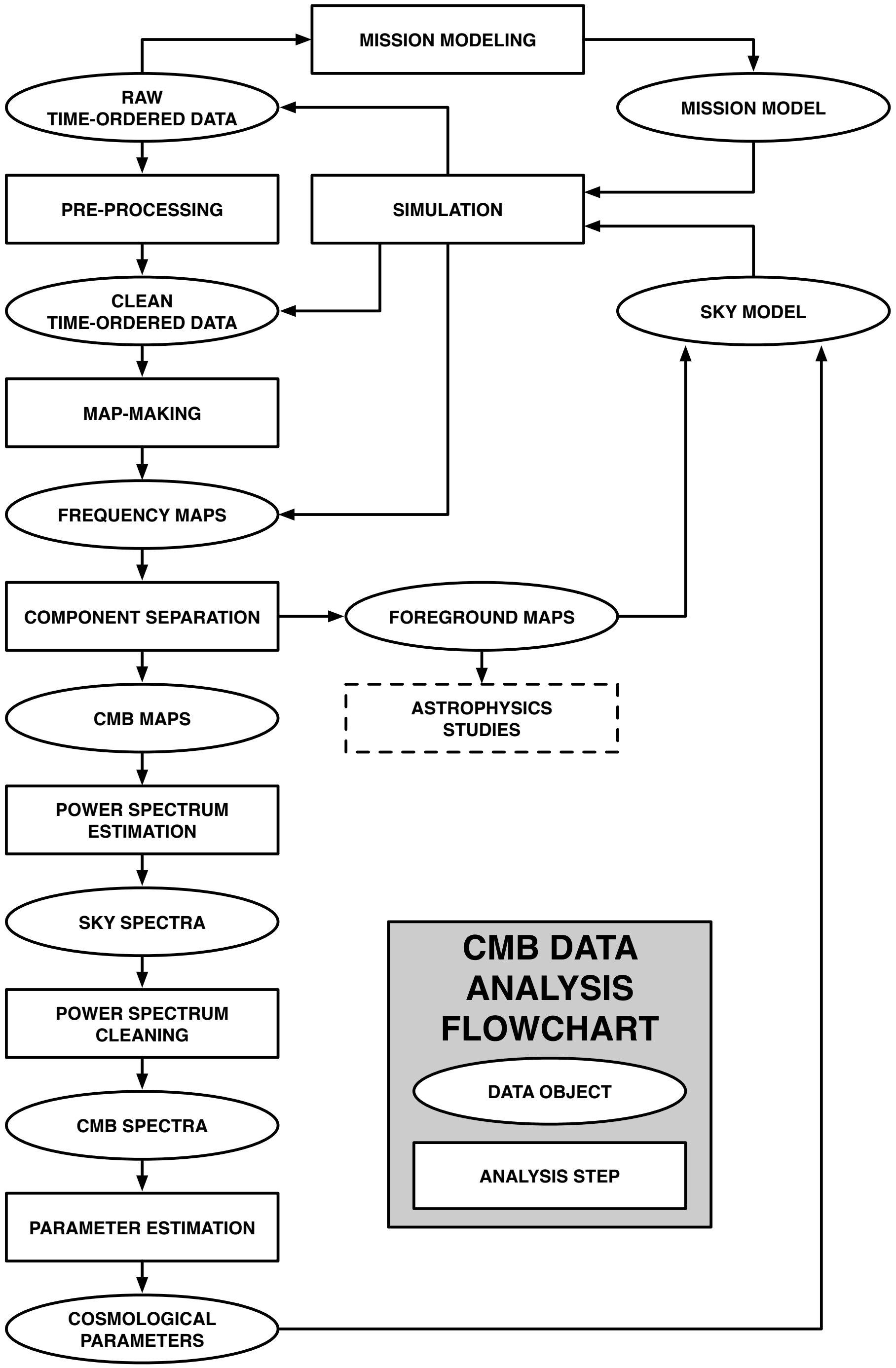
Conclusions

Goal: perform a measurement at the limit of r < 0.001 and testing the scale dependence, gaussianity, and chirality imprinted on CMB B-mode polarization

Higgs portal assisted inflation

- Perturbativity constraints: $\Lambda_U \simeq \frac{M_{pl}}{\sqrt{\xi}}$
- Vacuum stability constraints: $\Delta V = \frac{1}{4}\lambda_{h\phi}h^2\phi^2$
- Background and perturbation evolution for other BSM fields: H_{infl}

B-mode satellite mission with access to large and intermediate CMB scales (e.g. LiteBIRD) and LHC experiments (e.g. ATLAS and CMS) would help in distinguishing source of GW primordial GW.



Science requirements making mechanism

LiteBIRD experimental configuration

Channel (GHz)	$\theta_{\rm FWHM}$ (amin)	$\sigma_{\rm P}(\nu)$ [μK amin]
40.0	69.0	36.8
50.0	56.0	23.6
60.0	48.0	19.5
68.0	43.0	15.9
78.0	39.0	13.3
89.0	35.0	11.5
100.0	29.0	9.0
119.0	25.0	7.5
140.0	23.0	5.8
166.0	21.0	6.3
195.0	20.0	5.7
235.0	19.0	7.5
280.0	24.0	13.0
337.0	20.0	19.1
402.0	17.0	36.9

LiteBIRD experimental sensitivity

$$N_\ell^{BB} = \left[\sum_i \frac{1}{n_\ell(\nu_i) + [C_\ell^{\rm S}(\nu_i) + C_\ell^{\rm D}(\nu_i)]\sigma_{\rm RF} + n_\ell^{\rm RF}(\nu_i)}\right]^{-1},$$

LiteBIRD Col. White Paper, Prog. Theor. Exp. Phys. (2023).