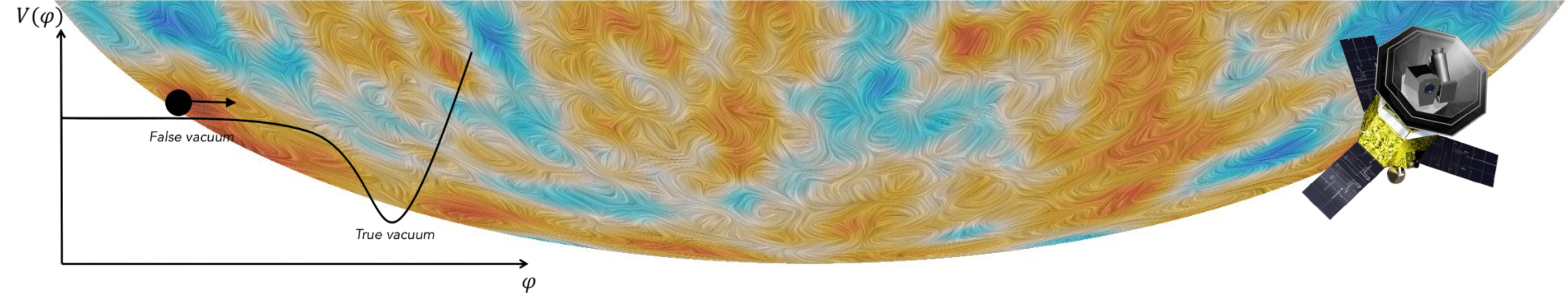


Constraining Cosmological Inflation with LiteBIRD

Gilles Weymann-Despres

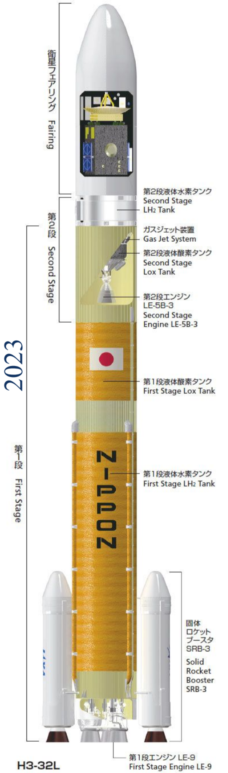
on behalf of the

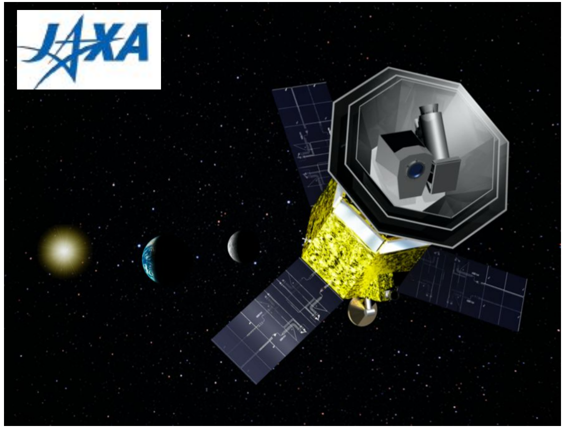
LiteBIRD collaboration

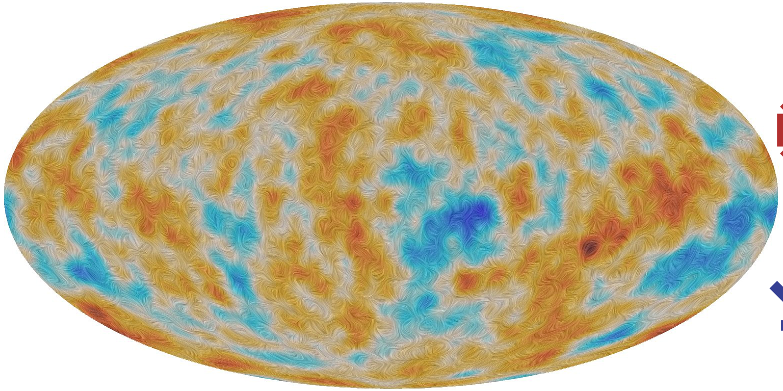
LiteBIRD overview

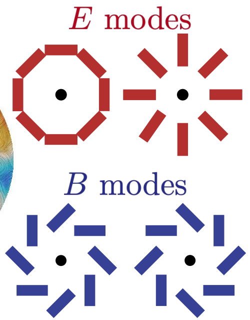
- *Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection*
- **JAXA**'s L-class mission selected in May 2019 to be launched in **~2032** with JAXA's H3 rocket
- LiteBIRD collaboration: Over 400 researchers from **Japan**, **North America** and **Europe**
- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
- Making a discovery or ruling out well-motivated inflationary models, insight into the quantum nature of gravity, the primordial *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***.
- LiteBIRD will improve current sensitivity on *r* by a factor ~50

LiteBIRD collaboration PTEP 2023









The challenge of B-modes detection

- The *B*-mode signal is expected to have an amplitude at least 3 orders of magnitude below the CMB temperature anisotropies
- LiteBIRD is targeting a sensitivity level in polarization ~30 times better than Planck
- This extremely good statistical uncertainty must go in parallel with exquisite control of:
  1. **Instrument systematic** uncertainties
  2. **Galactic foreground** contamination
  3. **"Lensing B-mode signal"** induced by gravitational lensing
  4. Observer biases

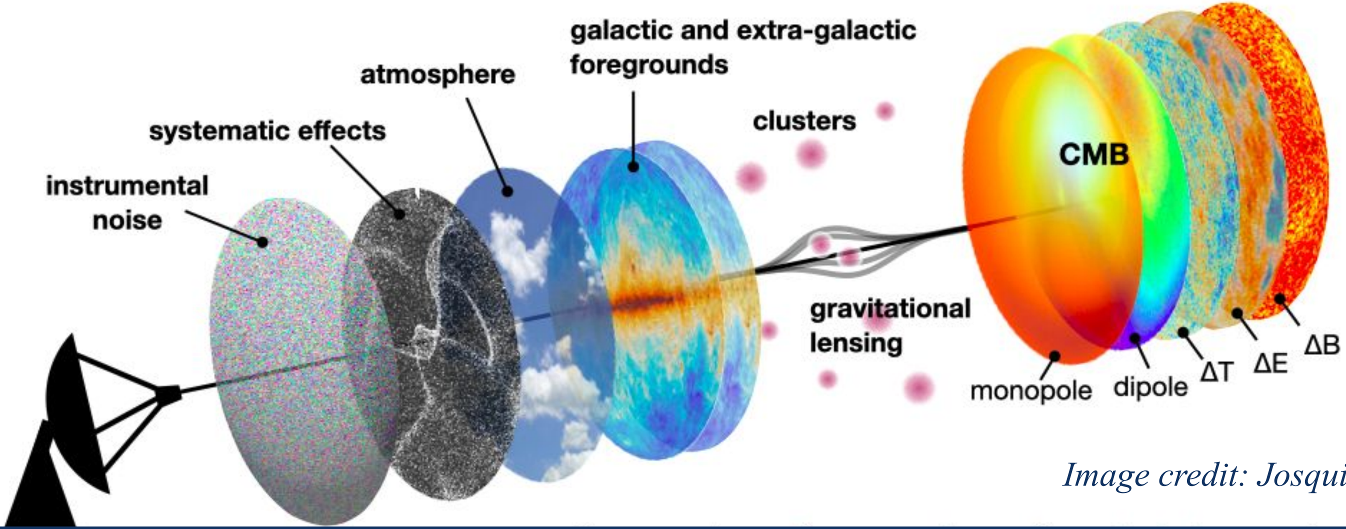
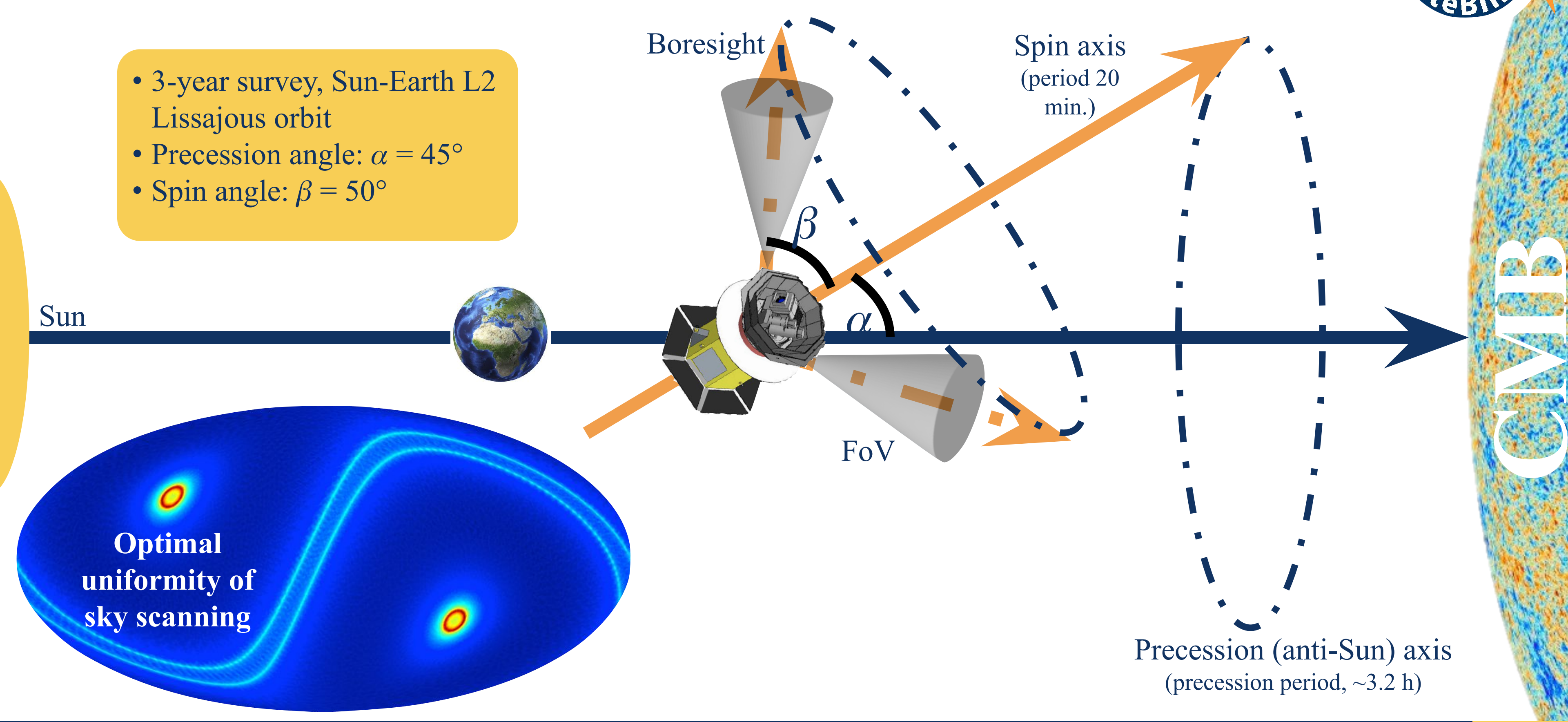


Image credit: Josquin Errard

LiteBIRD scanning strategy

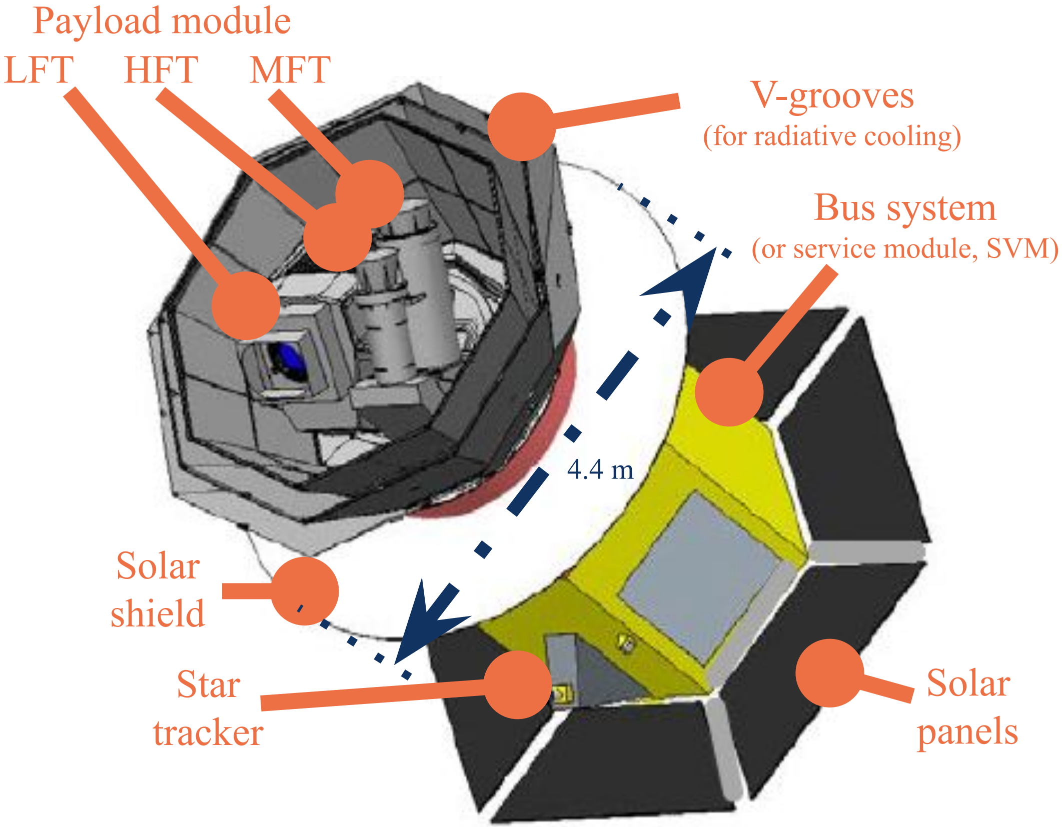
- 3-year survey, Sun-Earth L2 Lissajous orbit
- Precession angle: $\alpha = 45°$
- Spin angle: $\beta = 50°$



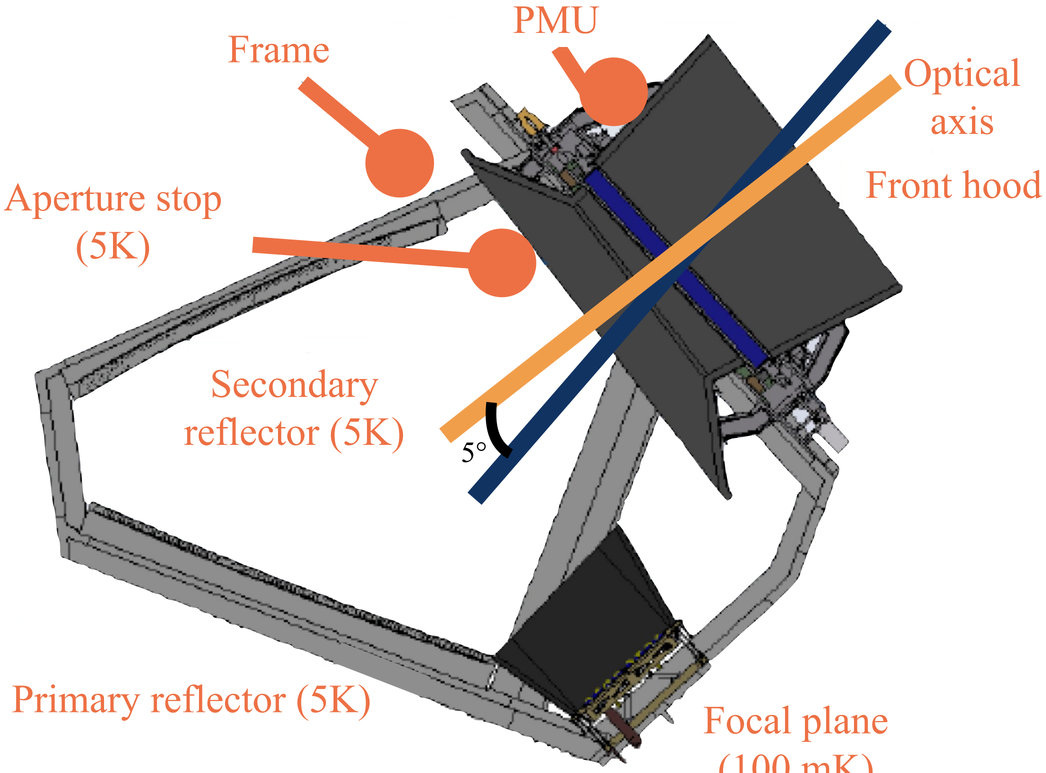
LiteBIRD spacecraft overview

- **3 telescopes** are used to provide the **40-402 GHz** frequency coverage
  1. **LFT** (low frequency telescope)
  2. **MFT** (middle frequency telescope)
  3. **HFT** (high frequency telescope)
- 4508 multi-chroic transition-edge sensor (TES) on **bolometer arrays** cooled to **100 mK**
- **Rotating half-wave plate** (HWP), for 1/*f* noise and systematics reduction
- Optics cooled to **5 K**

- Mass: 2.6 t
- Power: 3.0 kW
- Data: 17.9 Gb/day



Low Frequency Telescope (LFT)



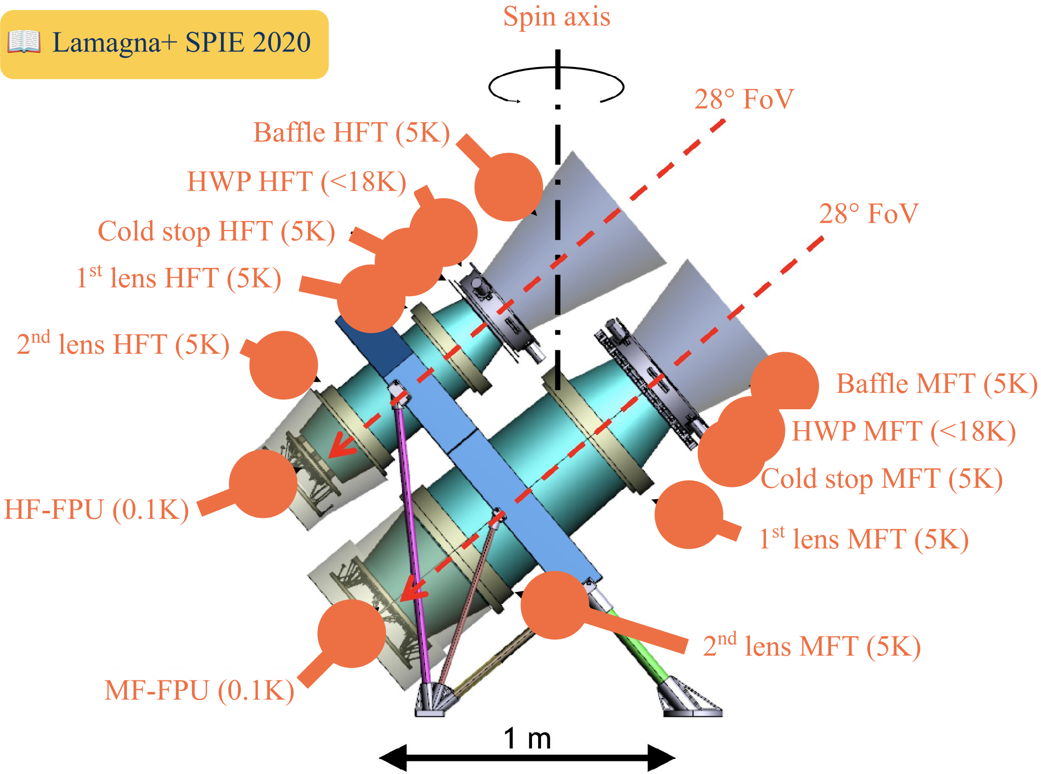
- Polarization Modulation Unit (PMU) as the first sky-side optical element
- **Crossed-Dragone** design
  - Mirrors and aperture stop at **5 K**
  - Made of aluminium
- Field of view: **18° x 9°**
- Aperture diameter: **400 mm**
- Frequency range: **40-140 GHz**
- Angular resolution: **70-24 arcmin**
- Cross-polarization < **-30 dB**
- Rotation of the polarization angle across the FoV < ±1.5°
- Weight < 200 kg

📖 Sekimoto+ SPIE 2020

Middle-High Frequency Telescopes (MFT/HFT)

📖 Montier+ SPIE 2020

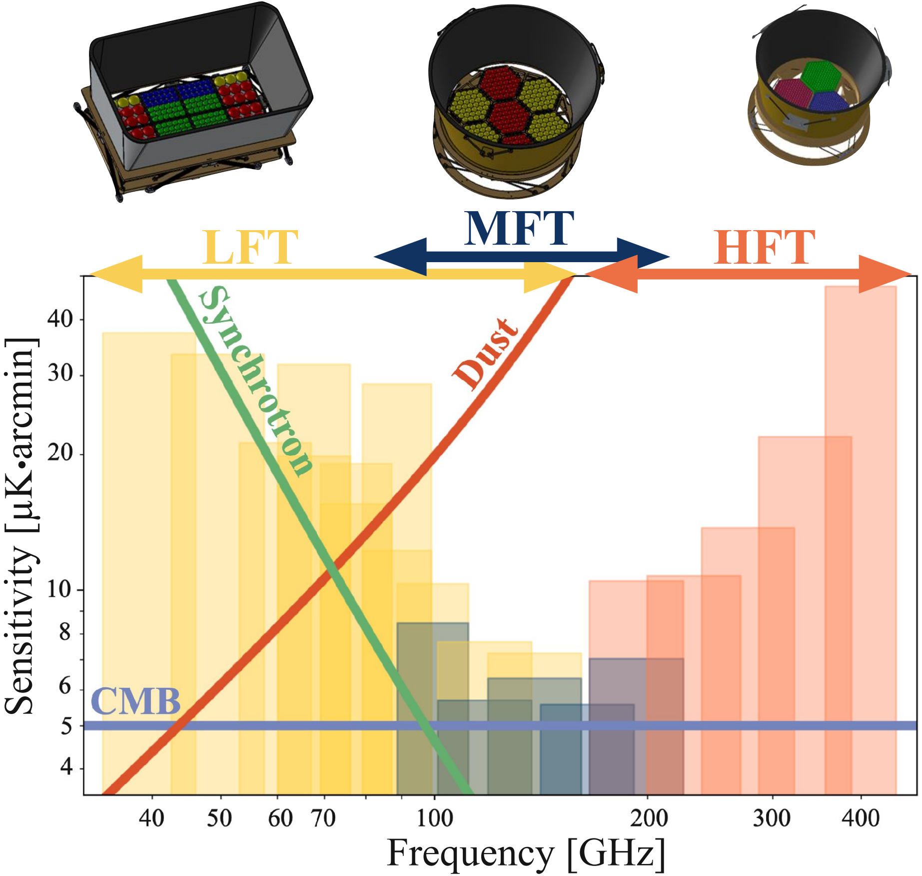
📖 Lamagna+ SPIE 2020



- Refractive optics
- Each telescope has PMU with a half-wave-plate (HWP)
- Optics at **5 K**
- Field of view: **28°**
- Simple and high heritage from ground experiments
- Compact (mass & volume)
- Simplified design for filtering scheme
- PP lenses + ARC
- Weight 180 kg

	MFT	**HFT**
ν (GHz)	**100-195**	**195-402**
Ap. diameter (mm)	**300**	**200**
Ang. res. (arcmin)	**38-28**	**29-18**

Sensitivity per frequency & foregrounds



LiteBIRD collaboration PTEP 2023

Rule of thumb:
1000 detectors in space =
100 000 detectors on
ground

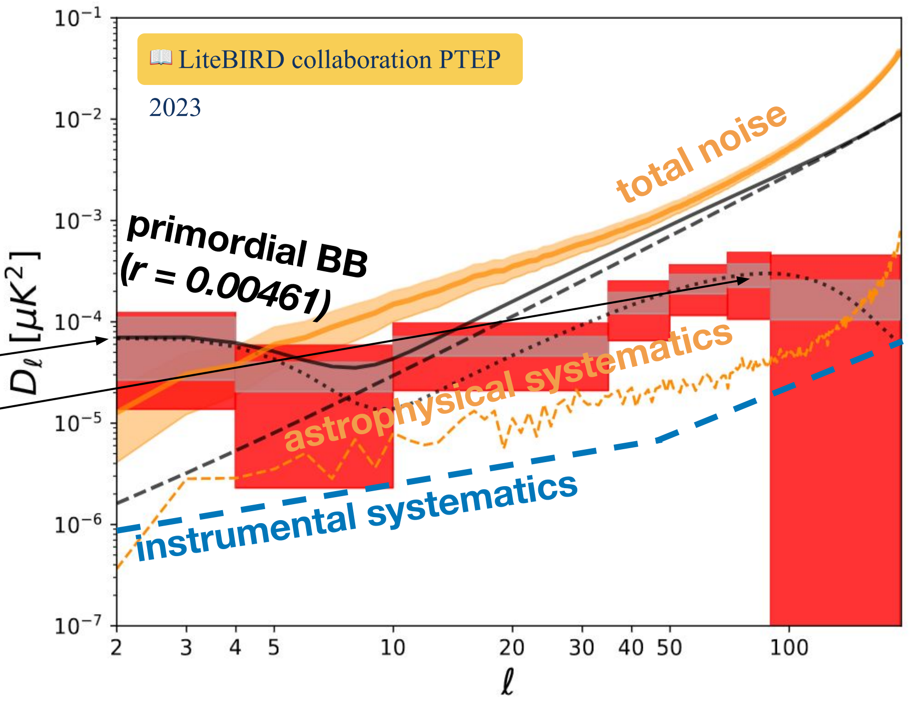
- Combined sensitivity to primordial CMB anisotropies: **2.2 µK·arcmin**

Foreground cleaning:

- Take benefit of the **frequency coverage** to fit the frequency-dependent astrophysical components
- **Impact**: Reduction of the foreground signal by several orders of magnitude.
- **Counterpart**: systematic residual and noise degradation

LiteBIRD main scientific objectives

- **Requirements** on the **B modes** and ***r* measurements**:
  - For $r = 0$, **total uncertainty (stat + syst) of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ independent detection of
    - reionization ($2 < \ell < 10$) peak
    - recombination ($11 < \ell < 200$) peak



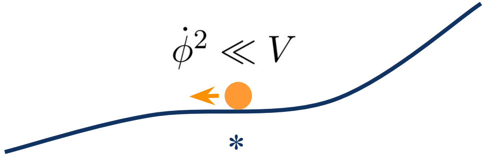
📖 LiteBIRD collaboration PTEP

2023

LiteBIRD main scientific objectives

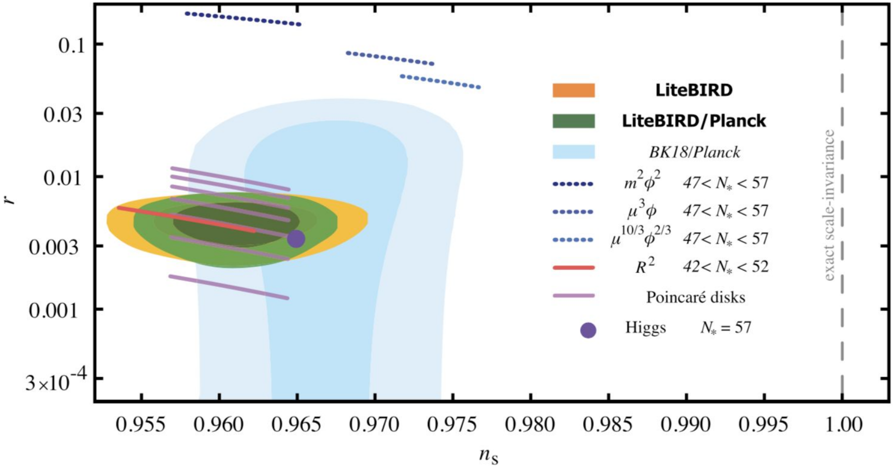
- **Constraints** on **inflation models.**

  eg. single-field slow-roll:



$$\begin{pmatrix}A_S\\ n_S\\ r\end{pmatrix} \underset{\substack{k\simeq k_*\\ \text{slow-roll}}}{=\!=} f\begin{pmatrix}V_*,\ V'_*\\ V_*,\ V'_*,\ V''_*\\ V'_*\end{pmatrix}$$

- Huge **discovery impact**: inflation **energy scale** V (and V', V''), **field excursion** ($r > 0.01$ => excursion exceeding the Planck mass)
- An **upper limit** would disfavour the simplest inflationary scenarios (large-field ones, with $\mathbf{M} > M_p$)



📖 LiteBIRD collaboration PTEP 2023

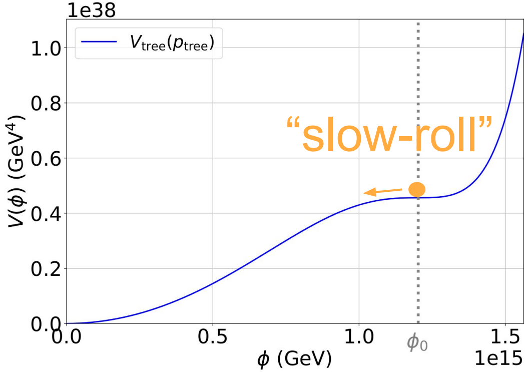
A cosmology-particle-physics interface

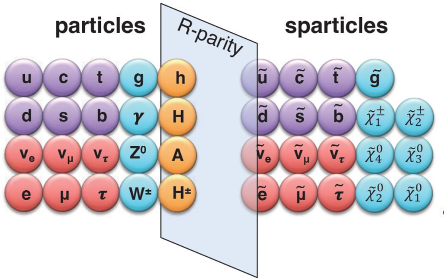
📖 Weymann-Despres+2023

Study-case: Inflation, dark matter and reheating within the MSSM

Inflaton = scalar field, evolves with the Klein-Gordon equation in the **MSSM scalar potential** along its **valleys**.

$$V_{\text{tree}}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 - \sqrt{2} A_6 \frac{\lambda_6 \phi^6}{6 M_{\text{Pl}}^3} + \lambda_6^2 \frac{\phi^{10}}{M_{\text{Pl}}^6} \rightarrow \begin{cases} m_\phi^2 = \dfrac{m^2_{\tilde{u}^i_R} + m^2_{\tilde{d}^j_R} + m^2_{\tilde{d}^k_R}}{3} \\ A_6(M_{\text{SUSY}}) = \dfrac{6-\sqrt{3}}{3-\sqrt{3}} A_t(M_{\text{SUSY}}) \end{cases}$$





NEW Inclusion of **RGE radiative corrections**: we have shown that this is key for a robust inflationnary inference of the MSSM spectrum.

A cosmology-particle-physics interface

📖 Weymann-Despres+2023

We have identified **some points** for **various dark matter annihilation processes** satisfying:

HEP Constraints (~ 80):
- Higgs mass (and BR)
- LHC SUSY searches

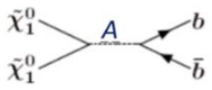
… not exhaustive

+

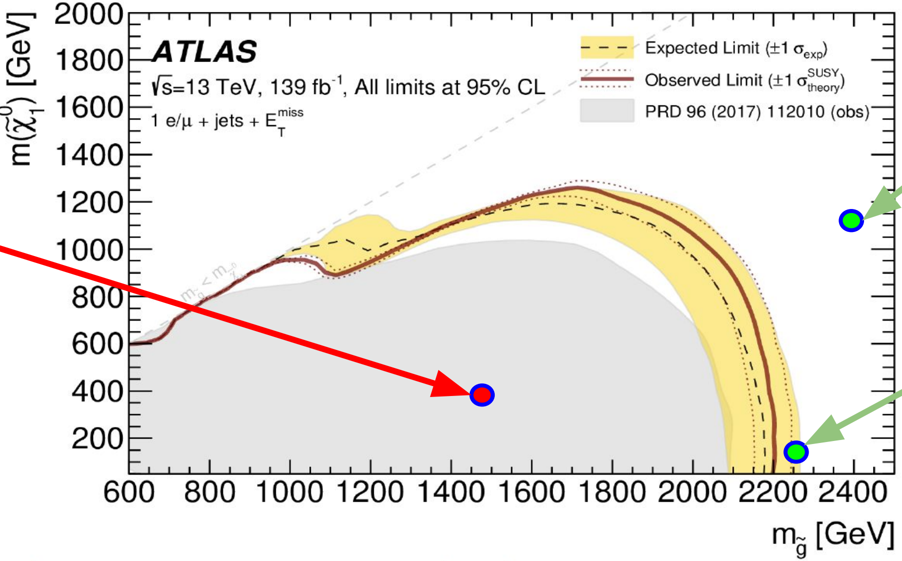
Cosmo constraints:
- $\Omega_{\text{cdm}} h^2$

NEW **As, ns**

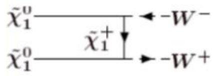
ϕ_0 $9.58\ 10^{14}$ GeV
$m_\phi(\phi_0)$ 6601.5 GeV



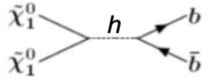
EXCLUDED



ϕ_0 $1.57\ 10^{15}$
$m_\phi(\phi_0)$ 16954



ϕ_0 $1.41\ 10^{15}$
$m_\phi(\phi_0)$ 13933



HEP measurements give constraints on inflation

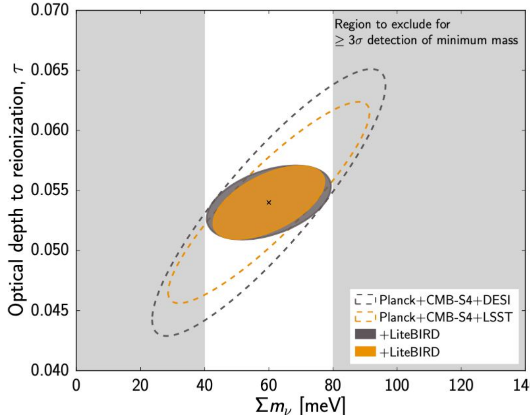
Cosmology restricts the MSSM parameter space

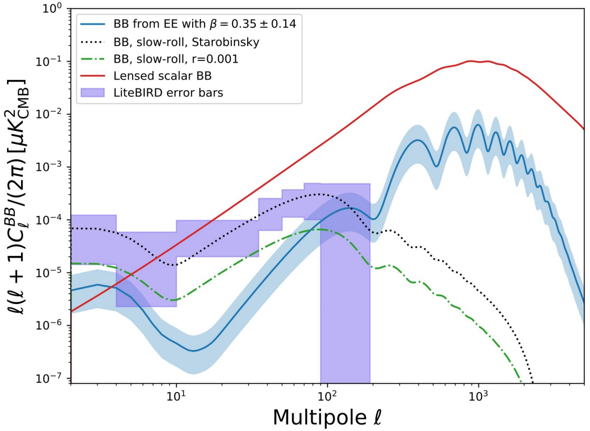
Interplay of the constraints in the same region of the parameter space! ⇒ **HEP-cosmology bridge**

LiteBIRD other science outcomes

- The mission specifications are driven by the required **sensitivity on *r*** that will update our understanding of the **very-early universe**, as well as fundamental and particle physics.

- Meeting those sensitivity requirements will allow us to address other important scientific topics:
  1. Characterize the *B*-mode power spectrum and search for source fields (e.g. **scale-invariance**, **non-Gaussianity**, **parity violation**, …)
  2. Cosmic-variance-limited detection of large-scale ***E*-modes**
     - **Reionization** (improve $\sigma(\tau)$ by a factor of 3)
     - **Neutrino mass** ($\sigma(\sum m_\nu) = 12$ meV)
  3. Constraints on **cosmic birefringence**
  4. Investigating the **SZ effect**
  5. Constraints on **primordial magnetic fields**
  6. Elucidating **anomalies**
  7. Tackling **Galactic science**





📖 LiteBIRD collaboration PTEP 2023

LiteBIRD

APC
ASI
Berkeley UNIVERSITY OF CALIFORNIA
BERKELEY LAB
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
cea
Centre Pierre Binétruy CNRS • Berkeley
cnes
cnrs
CSA ASC Canada

CSIC Consejo Superior de Investigaciones Científicas
CSL CENTRE SPATIAL DE LIÈGE
ENS
PSL
erc European Research Council
EXCELENCIA MARÍA DE MAEZTU
EXCELENCIA SEVERO OCHOA
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
Forskningsrådet The Research Council of Norway

NASA Goddard Space Flight Center
GSSI GRAN SASSO SCIENCE INSTITUTE
INSTITUTO DE ASTROFISICA DE CANARIAS IAC
IAP
IAS Orsay
IFCA Instituto de Física de Cantabria
ifpU
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

INFN
INAF ISTITUTO NAZIONALE DI ASTROFISICA
IPMU
IPNS 素粒子原子核研究所 Institute of Particle and Nuclear Studies
irap astrophysique & planétologie
JAXA
NASA Jet Propulsion Laboratory California Institute of Technology

NATIONAL INSTITUTE OF TECHNOLOGY KAGAWA COLLEGE 香川高専
KEK
KIPAC
KMI Kobayashi-Maskawa Institute Nagoya University
LMU
LPSC GRENOBLE | MODANE

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK
McGill
Maynooth University National University of Ireland Maynooth
名古屋大学 NAGOYA UNIVERSITY
NÉEL institut
NIST

HK Norwegian Directorate for Higher Education and Skills
OAC
岡山大学 OKAYAMA UNIVERSITY
QUP International Center for Quantum-field Measurement Systems for Studies of the Universe and Particles
POLITÉCNICA
idr
RWTH AACHEN UNIVERSITY

SAPIENZA UNIVERSITÀ DI ROMA
SISSA
SORBONNE UNIVERSITÉ
SRON
SSDC SPACE SCIENCE DATA CENTER
LELAND STANFORD JUNIOR UNIVERSITY 1891
Stockholm University
公立諏訪東京理科大学 Suwa University of Science
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ULB UNIVERSITÉ LIBRE DE BRUXELLES
Universidad de La Laguna

MANCHESTER 1824 The University of Manchester
UiO University of Oslo
UNIVERSITY OF OXFORD
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Università degli Studi di Ferrara
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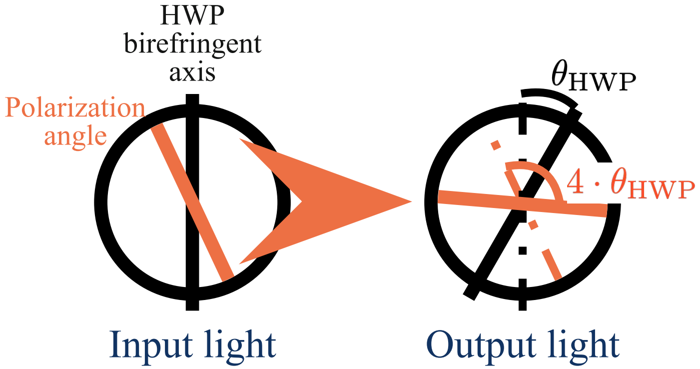
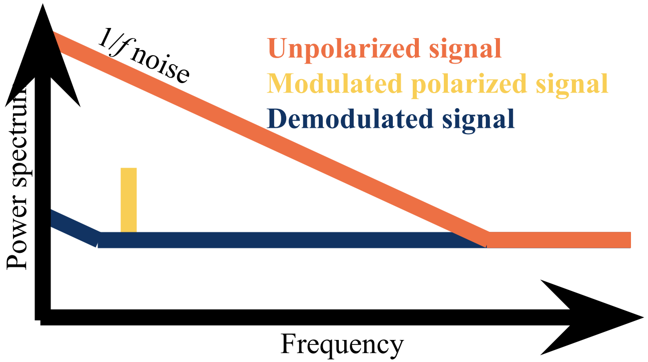
UNIVERSITÀ DEGLI STUDI DI PADOVA
THE UNIVERSITY OF TOKYO
UNIVERSITY OF TORONTO

Polarization Modulation Unit (PMU)

- Rotating a birefringent plate to modulate polarization
- The first sky-side optical element

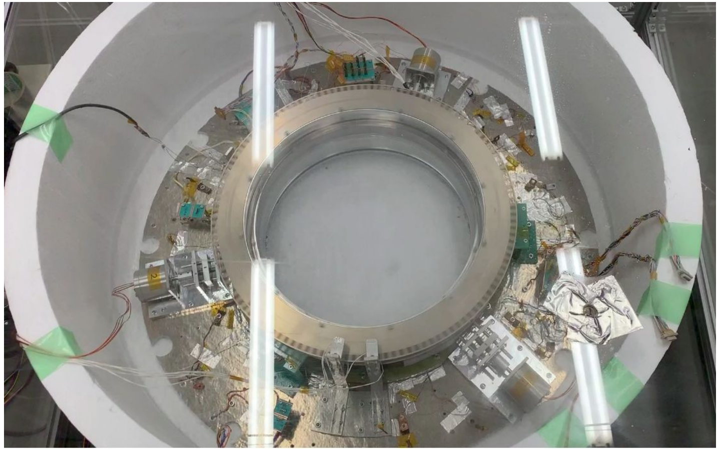




📖 Sakurai+2020 📖 Komatsu+2020

📖 Toda+2020 📖 Columbro+2020 📖 Sugiyama+2020

- LFT PMU BBM at Kavli IPMU:



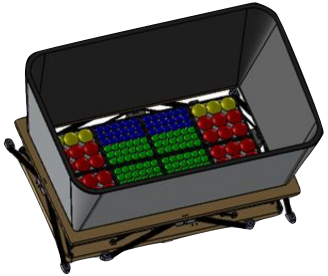
- Rotation test of superconducting magnetic bearing system in the 4K cryostat
- Stable rotation at cryogenic temperature (< 10 K)

Focal plane configuration

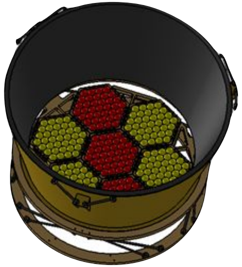
- Transition-Edge Sensor (TES) arrays
- Multichroic detectors
- Number of detectors: 4508
- 15 bands including overlap between instruments

Rule of thumb:
1000 detectors in space =
100 000 detectors on ground

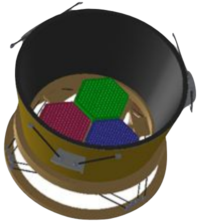
LFT



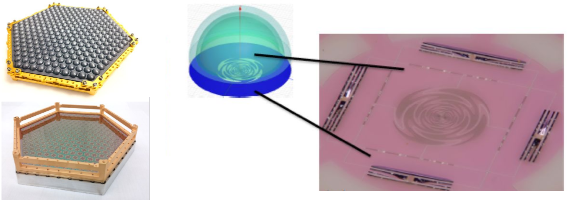
MFT



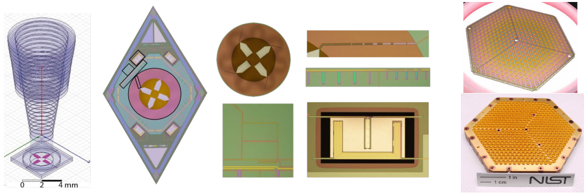
HFT



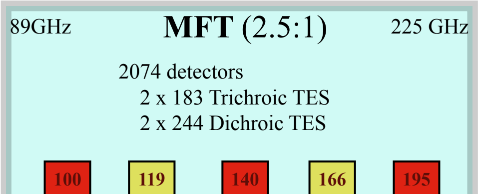
Lensed coupled detectors
Lenslets



Horn coupled detectors
Platelets

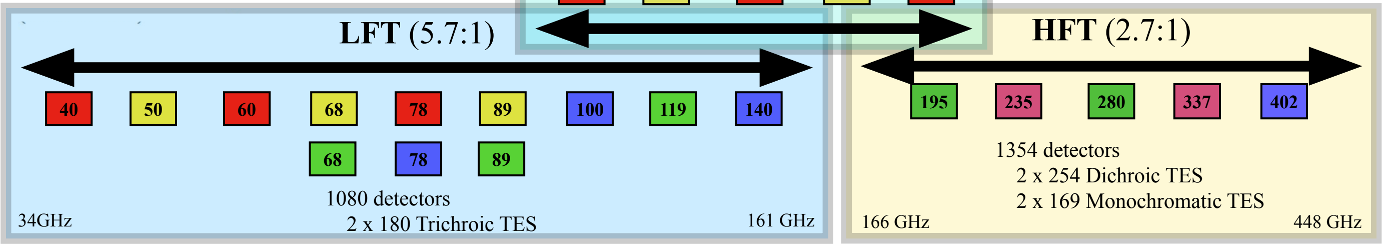


📖 Westbrook+ SPIE 2020



89GHz **MFT** (2.5:1) 225 GHz

2074 detectors
2 x 183 Trichroic TES
2 x 244 Dichroic TES



LFT (5.7:1)

1080 detectors
2 x 180 Trichroic TES

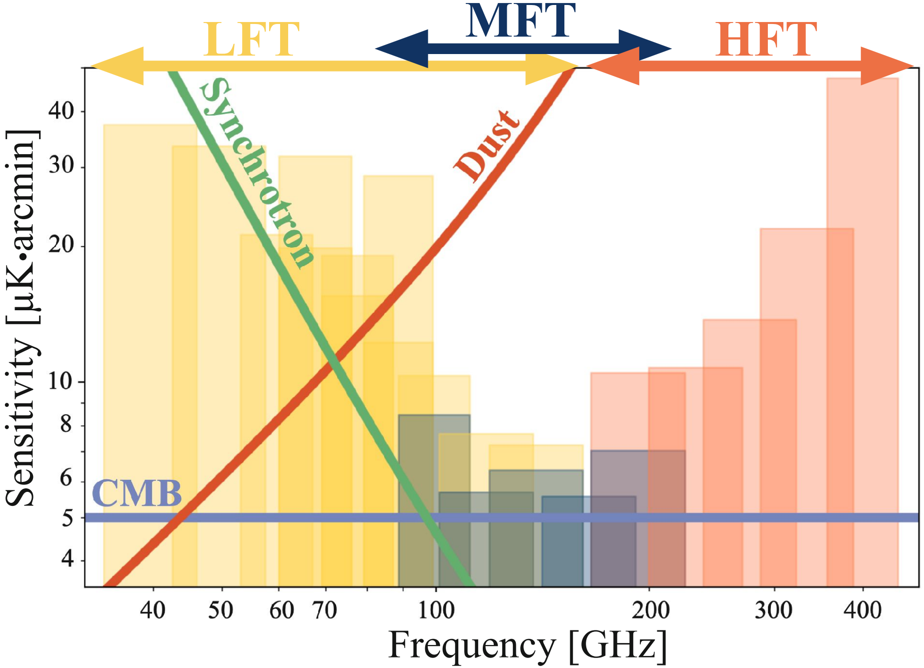
34GHz 161 GHz

HFT (2.7:1)

1354 detectors
2 x 254 Dichroic TES
2 x 169 Monochromatic TES

166 GHz 448 GHz

Sensitivity per frequency & foregrounds



📖 LiteBIRD collaboration PTEP 2023

- Projected **polarization sensitivities** for a **3-year full-sky survey**
- Best of 4.6 μK·arcmin @ 119 GHz
- Combined sensitivity to primordial CMB anisotropies: **2.2 μK·arcmin**

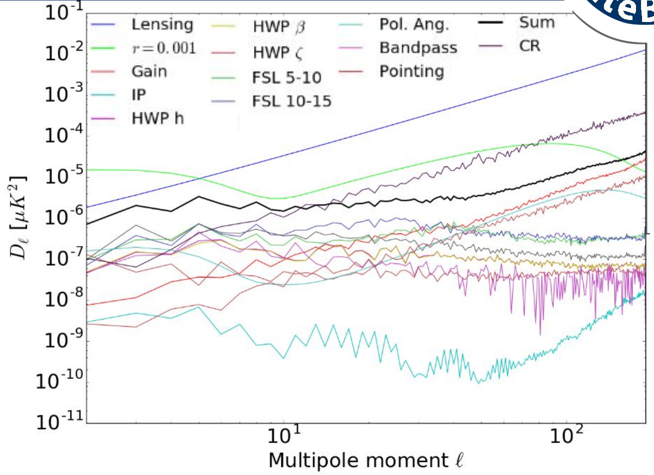
Foreground cleaning:

- Take benefit of the **frequency coverage** to fit the frequency-dependent astrophysical components
- *eg.* **parametrize** the foreground frequency dependency.
  Synchrotron: power law with spatially-varying index
  Dust: modified blackbody
- **Impact**: Reduction of the foreground signal by several orders of magnitude.
- **Counterpart**: systematic residual and noise degradation

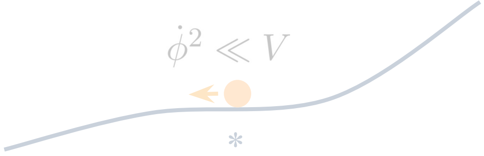
LiteBIRD main scientific objectives

Requirements on the **B modes** and ***r* measurements**:

- For $r = 0$, **total uncertainty of $\delta r < 0.001$**
- For $r = 0.01$, 5-σ independent detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks
- **$\sigma_{stat} < 6\times10^{-4}$** and **$\sigma_{sys} < 6\times10^{-4}$** + additional security margin of **$\sigma_{margin} < 6\times10^{-4}$**

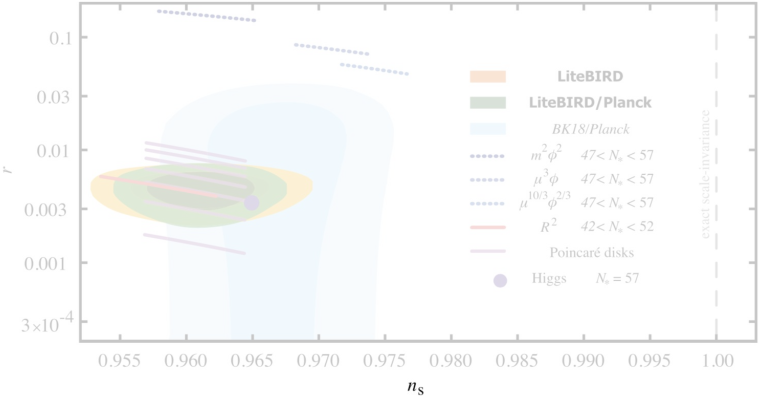


Constraints on **inflation models.** *eg.* single-field slow-roll:
A scalar field dominates the Universe energy budget and slowly rolls on its potential V around an energy scale “$_*$”.



$$\begin{pmatrix} A_S \\ n_S \\ r \end{pmatrix} \underset{\text{slow-roll}}{\overset{}{\underset{k\simeq k_*}{=\!=}}} f\begin{pmatrix} V_*,\ V'_* \\ V_*,\ V'_*,\ V''_* \\ V'_* \end{pmatrix}$$

- Huge **discovery impact**: inflation **energy scale** V (and V’, V”), **field excursion** ($r > 0.01$ => excursion exceeding the Planck mass)
- An **upper limit** would disfavour the simplest inflationary scenarios (large-field ones, with **M** > M_p)



LiteBIRD main scientific objectives

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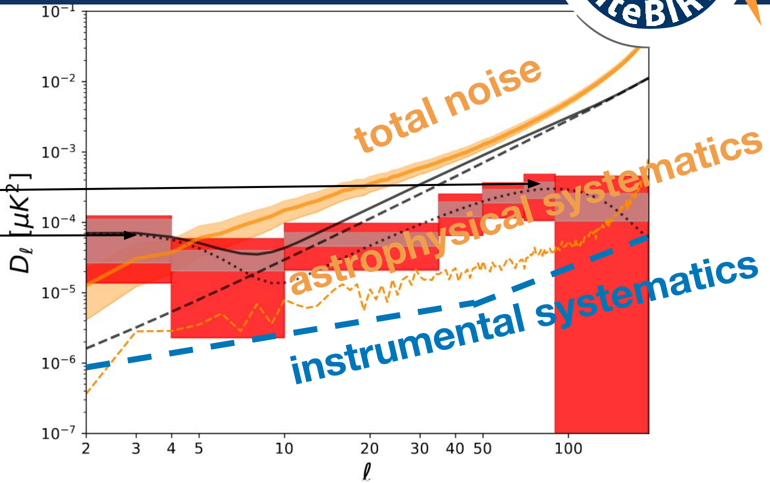
  - ○ recombination ($11 < \ell < 200$) peak
  - ○ reionization ($2 < \ell < 10$) peak



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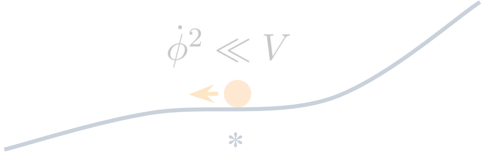
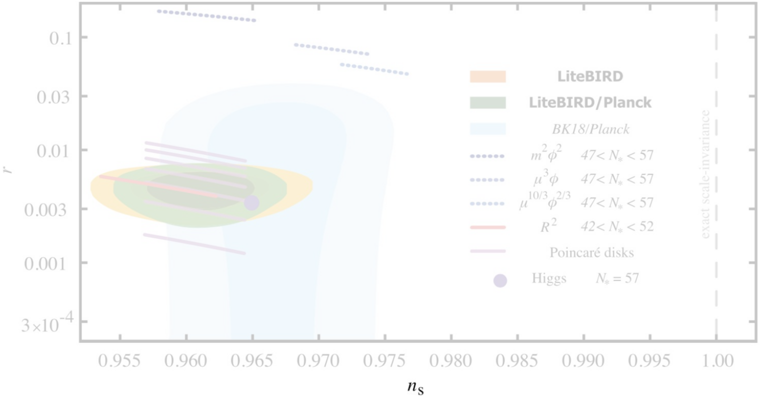


$$\begin{pmatrix} A_S \\ n_S \\ r \end{pmatrix} \underset{\text{slow-roll}}{\overset{}{\underset{k \simeq k_*}{==}}} f \begin{pmatrix} V_*,\ V'_* \\ V_*,\ V'_*,\ V''_* \\ V'_* \end{pmatrix}$$

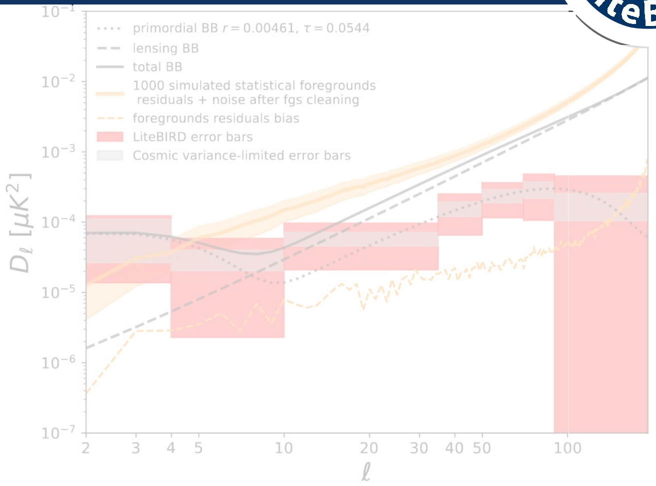
- Huge **discovery impact**: inflation **energy scale** V (and V’, V”), **field excursion** ($r > 0.01$ => excursion exceeding the Planck mass)
- An **upper limit** would disfavour the simplest inflationary scenarios (large-field ones, with **M** > M_p)



LiteBIRD main scientific objectives

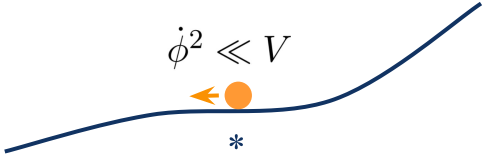
Requirements on the **B modes** and ***r* measurements**:

- For $r = 0$, **total uncertainty of $\delta r < 0.001$**
- For $r = 0.01$, 5-σ independent detection of the reionization ($2 < \ell < 10$) and recombination ($11 < \ell < 200$) peaks
- $\sigma_{\mathrm{stat}} < 6\times10^{-4}$ and $\sigma_{\mathrm{sys}} < 6\times10^{-4}$ + additional security margin of $\sigma_{\mathrm{margin}} < 6\times10^{-4}$

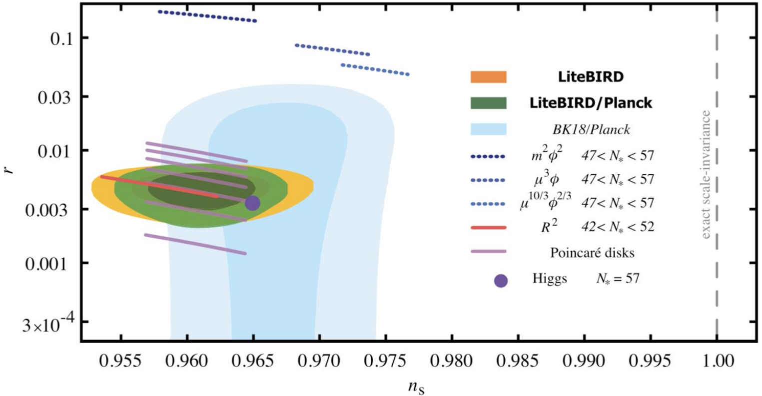


Constraints on **inflation models.**

eg. single-field slow-roll:



$$\begin{pmatrix} A_\mathrm{S} \\ n_\mathrm{S} \\ r \end{pmatrix} \underset{\substack{k\simeq k_* \\ \mathrm{slow-roll}}}{=\!=} f\begin{pmatrix} V_*,\ V'_* \\ V_*,\ V'_*,\ V''_* \\ V'_* \end{pmatrix}$$



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- Definitive search for the **_B_-mode signal** from **cosmic inflation** in the CMB polarization
    - Making a discovery or ruling out well-motivated inflationary models
    - Insight into the quantum nature of gravity
- The inflationary (*i.e.* primordial) *B*-mode power is proportional to the **tensor-to-scalar ratio, *r***
- Current best constraint: $r < 0.032$ (95% C.L.)
(📖 Tristram et al. 2022, combining BK18 and Planck PR4)
- LiteBIRD will improve current sensitivity on r by a factor ~50
- L1-requirements (no external data):
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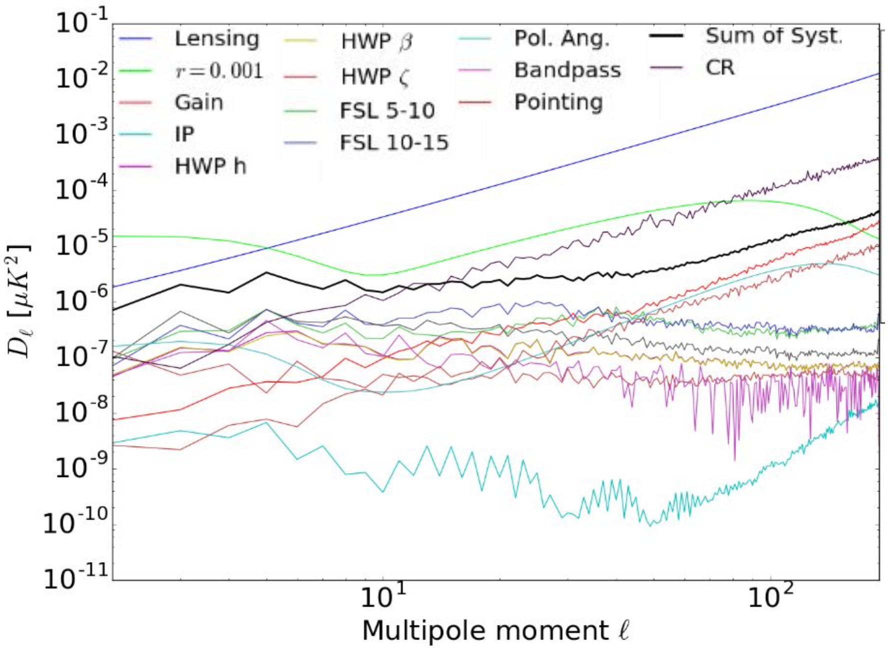


- L2-requirements:
    - $\boldsymbol{\sigma_{stat} < 6\times10^{-4}}$ and $\boldsymbol{\sigma_{sys} < 6\times10^{-4}}$ + additional security margin of $\boldsymbol{\sigma_{margin} < 6\times10^{-4}}$

LiteBIRD constraints on inflation

- **HOW?**

$$A_{\rm S} \equiv \mathcal{P}_\zeta\big|_{k_*} \overset{\text{SRLO}}{\simeq} \frac{V_*}{24\pi^2 M_{\rm Pl}^4 \varepsilon_{1*}},$$

$$\boxed{r \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta}\bigg|_{k_*} \overset{\text{SRLO}}{\simeq} 16\varepsilon_{1*}},$$

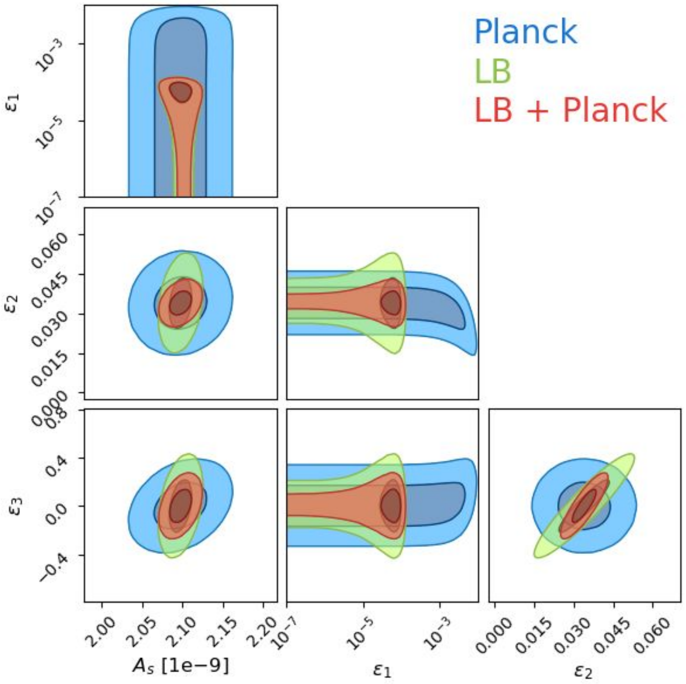
$$n_{\rm S} \equiv 1 + \frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k}\bigg|_{k_*} \overset{\text{SRLO}}{\simeq} 1 - 2\varepsilon_{1*} - \varepsilon_{2*}$$

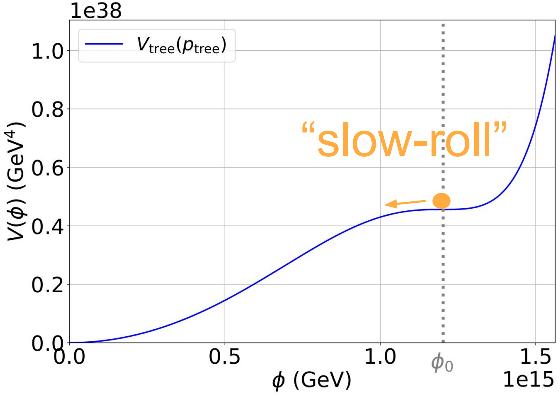
$$n_{\rm T} \equiv \frac{\mathrm{d}\ln\mathcal{P}_h}{\mathrm{d}\ln k}\bigg|_{k_*} \overset{\text{SRLO}}{\simeq} -2\varepsilon_{1*}$$

$$n_{\rm S,run} \equiv \frac{\mathrm{d}^2\ln\mathcal{P}_\zeta}{(\mathrm{d}\ln k)^2}\bigg|_{k_*} \overset{\text{SRLO}}{\simeq} -2\varepsilon_{1*}\varepsilon_{2*} - \varepsilon_{2*}\varepsilon_{3*}$$

$$n_{\rm T,run} \equiv \frac{\mathrm{d}^2\ln\mathcal{P}_h}{(\mathrm{d}\ln k)^2}\bigg|_{k_*} \overset{\text{SRLO}}{\simeq} -2\varepsilon_{1*}\varepsilon_{2*}$$

illustrative forecast figure





$$\varepsilon_1 \overset{\text{SRLO}}{\simeq} \frac{M_{\rm Pl}^2}{2}\left(\frac{V_\phi}{V}\right)^2,$$

$$\varepsilon_2 \overset{\text{SRLO}}{\simeq} 2M_{\rm Pl}^2\left[\left(\frac{V_\phi}{V}\right)^2 - \frac{V_{\phi\phi}}{V}\right],$$

$$\varepsilon_3 \overset{\text{SRLO}}{\simeq} \frac{2}{\varepsilon_2}M_{\rm Pl}^4\left[\frac{V_{\phi\phi\phi}V_\phi}{V^2} - 3\frac{V_{\phi\phi}}{V}\left(\frac{V_\phi}{V}\right)^2 + 2\left(\frac{V_\phi}{V}\right)^4\right],$$

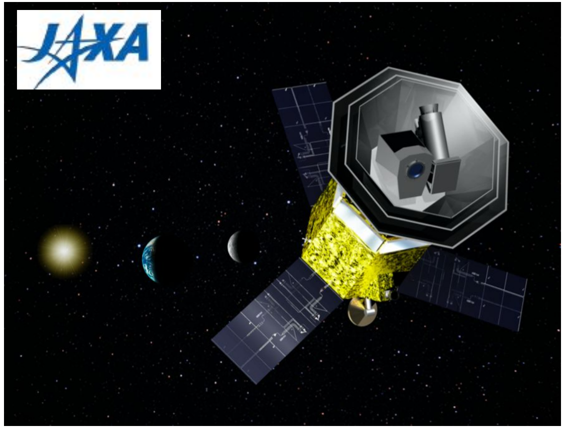
Exciting science goal:

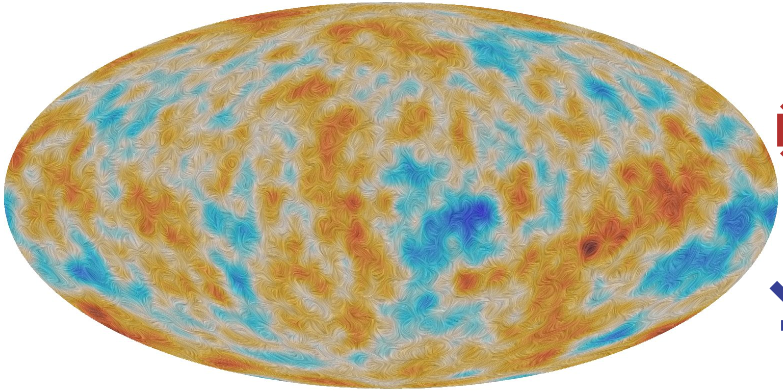
an *r* measurement with **LiteBIRD** => constraints on V, V' and V'' in single-field slow-roll scenario

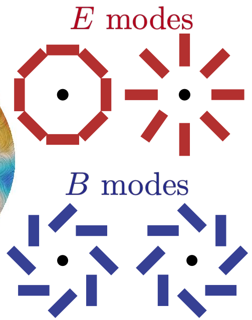
LiteBIRD overview

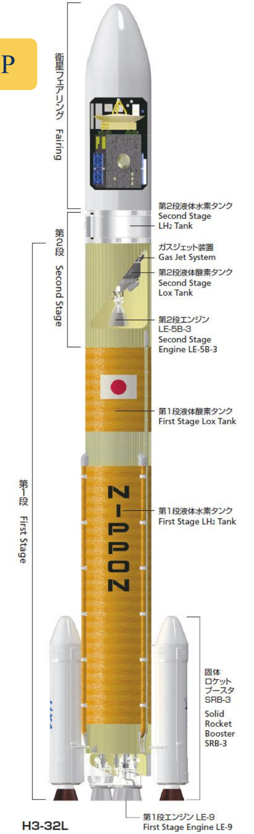
- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in **JFY 2032** with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the **CMB *B*-modes**
- Final combined sensitivity: **2.2 μK·arcmin**

📖 LiteBIRD collaboration PTEP 2023



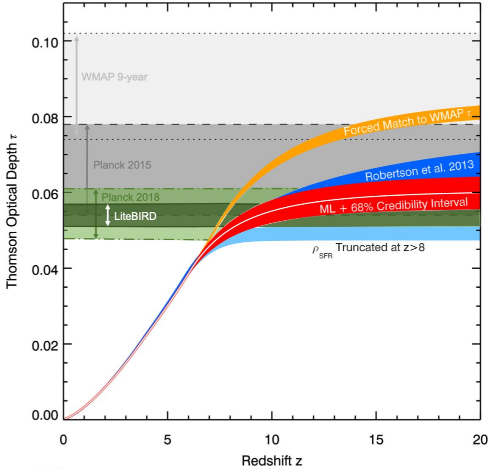




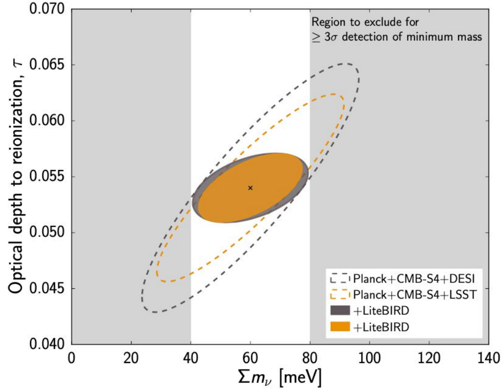


Optical depth, reionization and neutrino masses

- LiteBIRD will provide a cosmic-variance limited measurement of the ***E*-mode** power spectrum at large scales ($2 < \ell < 200$)
- This will lead to improved constraints on:
  - **Reionization**
    - Cosmic-variance measurement of the **optical depth** to reionization $\Rightarrow \sigma(\tau) \approx 0.002 \Rightarrow \times 2$ improvement with respect to Planck (📖 Planck Int.Res. LVII, 2020)
    - Improved constraints on reionization history models: 35% improvement on the uncertainty of $\Delta(z_{\mathrm{reion}})$
  - **Neutrino masses**
    - $\times 2$ improvement on $\sigma(\sum m_\nu)$
    - $\sigma(\sum m_\nu) = 12$ eV $\Rightarrow 5\sigma$ detection for a minimum value of $\sum m_\nu = 60$ meV (allowed by flavour-oscillation experiments) or larger
    - Potentially allow to distinguish between the inverted neutrino mass ordering and the normal ordering



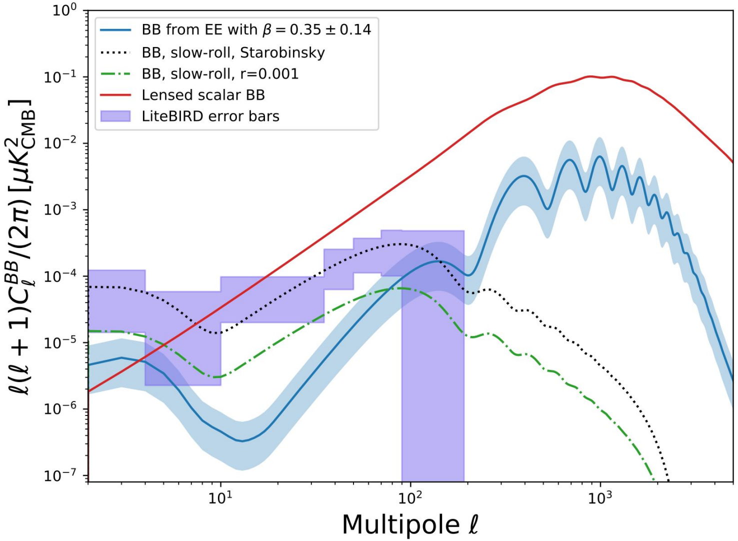
📖 adapted from Robertson+2015



📖 adapted from Calabrese+2017

Constraints on cosmic birefringence

- **Cosmic birefringence** could be seeded by parity-violating processes in Universe
- Could occur if dark matter or dark energy are a pseudo-scalar field coupled to electromagnetism that changes sign under inversion of spatial coordinates
- Induces non-zero *TB* and *EB* and also a *B*-mode signal
- Constraints from the CMB must account jointly for i) a possible detector angle miscalibration (📖 Minami et al., 2019) and ii) a positive EB signal from Galactic foregrounds (📖 Diego-Palazuelos et al., 2022)
- Recent measurements show a tentative detection of a birefringence angle of **β = (0.34±0.09)°** (📖 Eskilt & Komatsu 2022, from a combination of WMAP and Planck PR4)
- LiteBIRD has the potential to:
  - Reduce the error bar on a global β leading to a **~10-sigma detection**
  - Produce a map of β to test for **cosmic-birefringence anisotropy**

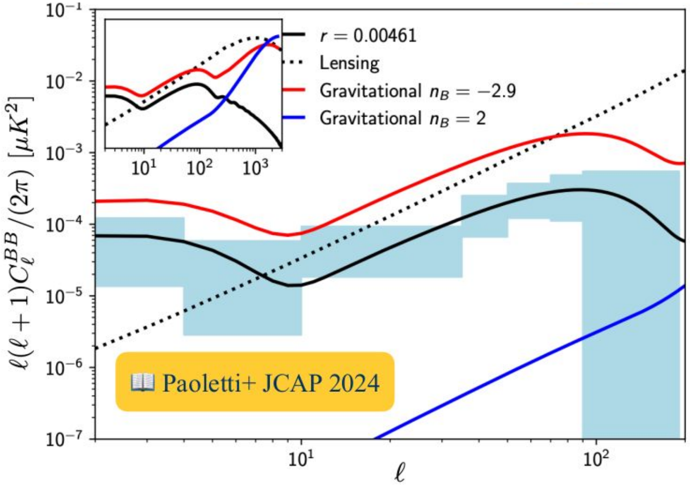


📖 LiteBIRD collaboration PTEP 2023

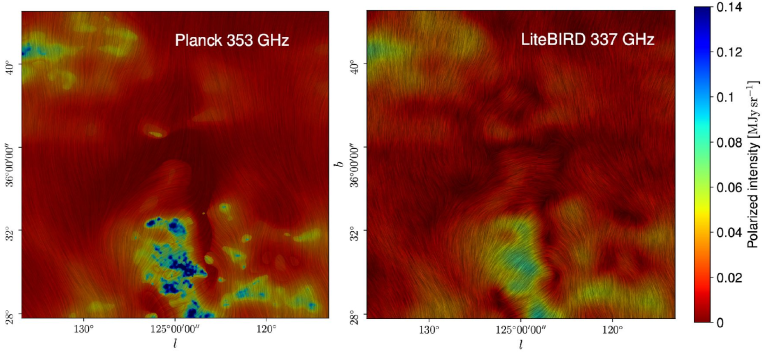
LiteBIRD other science outcomes

- The mission specifications are driven by the required sensitivity on *r*
- Meeting those sensitivity requirements would allow to address other important scientific topics, such as:

1. **SZ effect** (thermal, diffuse, relativistic corrections)
2. Constraints on **primordial magnetic fields**
3. Elucidating **anomalies**
4. **Galactic science**
    - Characterizing the foreground SED
    - Large-scale Galactic magnetic field
    - Models of dust polarization



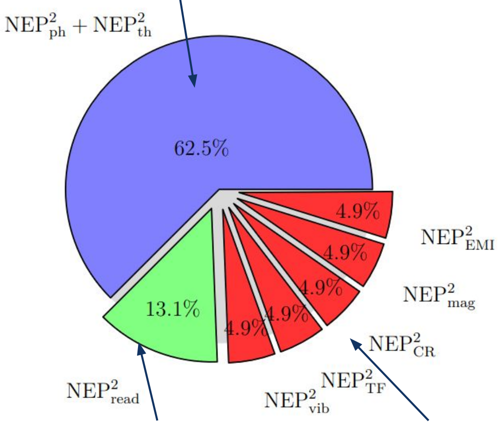
📖 Paoletti+ JCAP 2024



Error budget after foreground cleaning

Statistical uncertainties = **Systematic uncertainties**

Fudamental noise

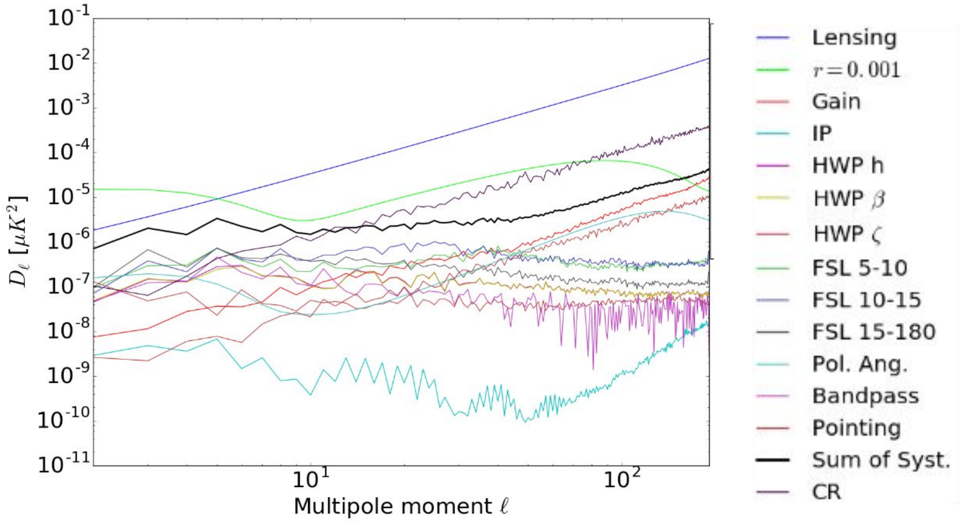


+ Readout noise

+ External noise

(increased by foreground cleaning)

Instrumental systematics:



+ Astrophysical systematics

LiteBIRD main scientific objectives

- Definitive search for the ***B*-mode signal** from **cosmic inflation** in the CMB polarization
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  - Insight into the quantum nature of gravity
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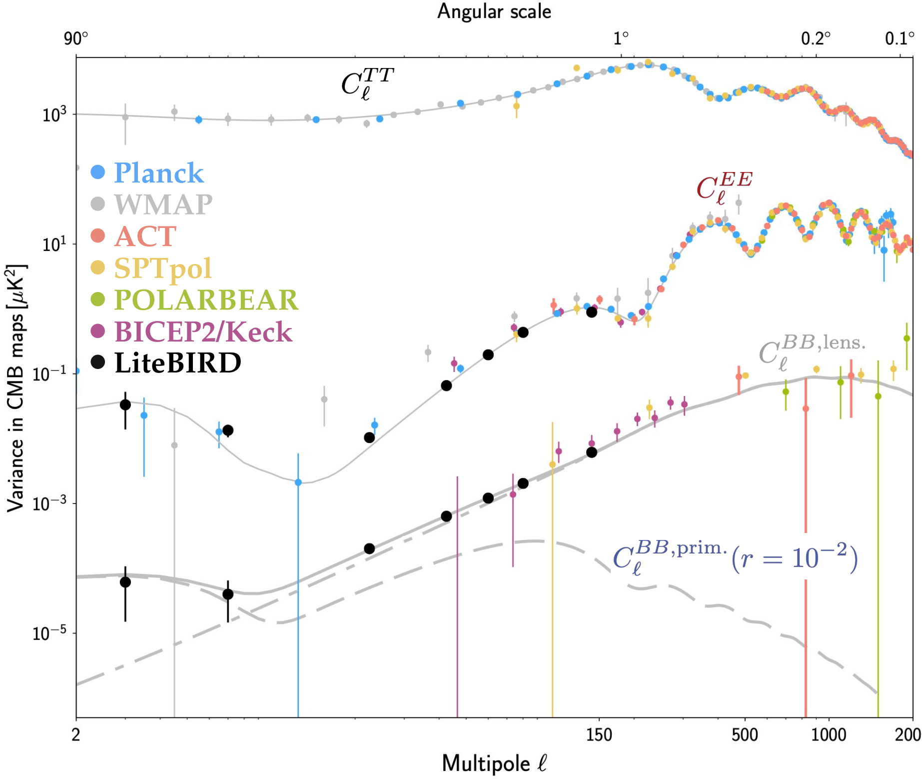

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  - $\sigma_{\mathrm{stat}} < 6\times10^{-4}$ and $\sigma_{\mathrm{sys}} < 6\times10^{-4}$
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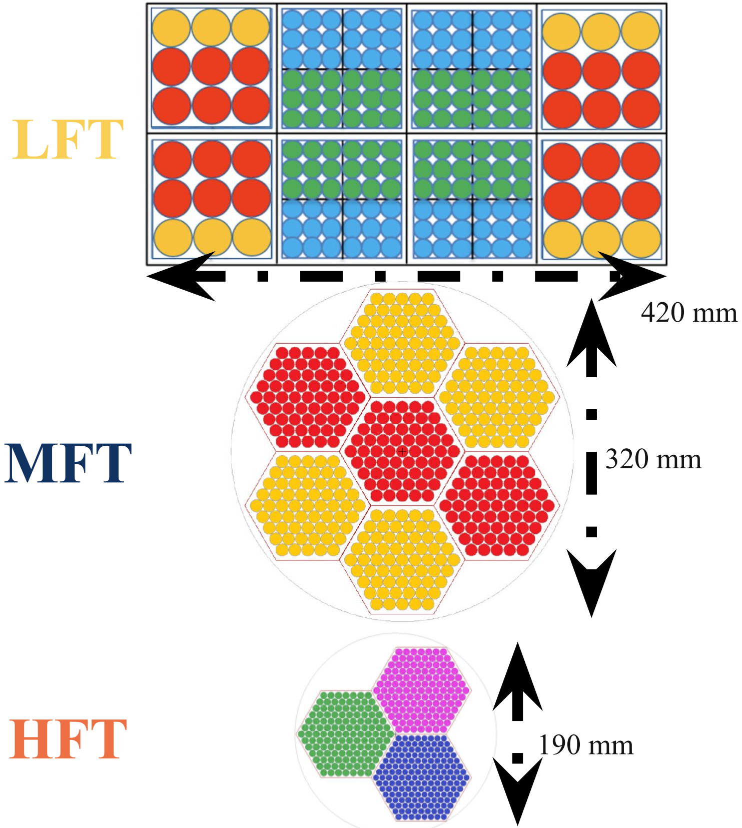
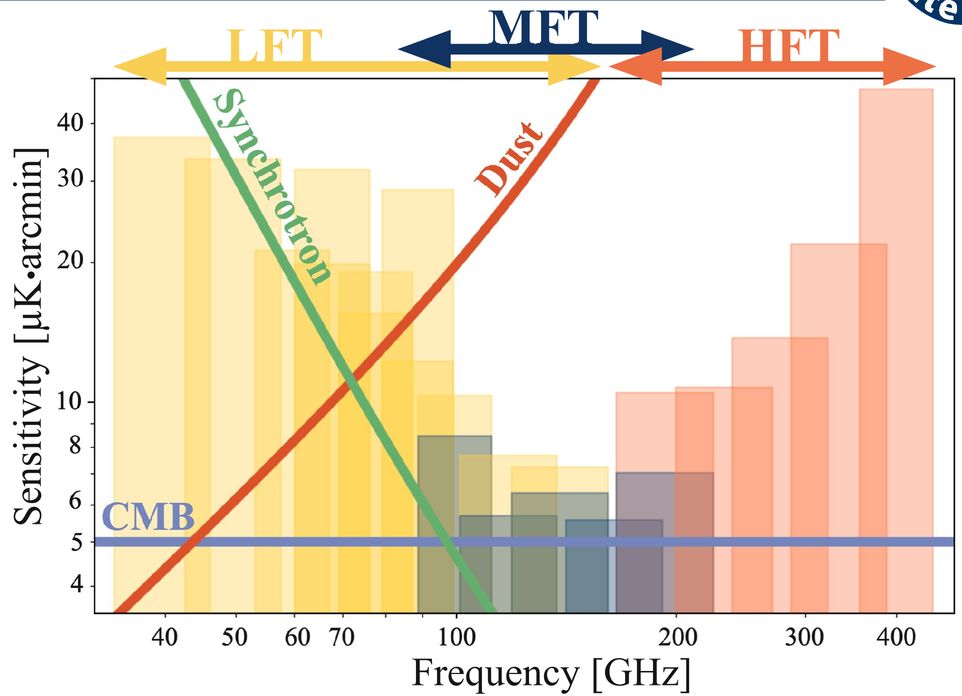
LiteBIRD sensitivities





📖 LiteBIRD collaboration PTEP 2023

- Projected **polarization sensitivities** for a **3-year full-sky survey**
- Best of 4.6 μK·arcmin @ 119 GHz
- Combined sensitivity to primordial CMB anisotropies: **2.2 μK·arcmin**

Foreground cleaning

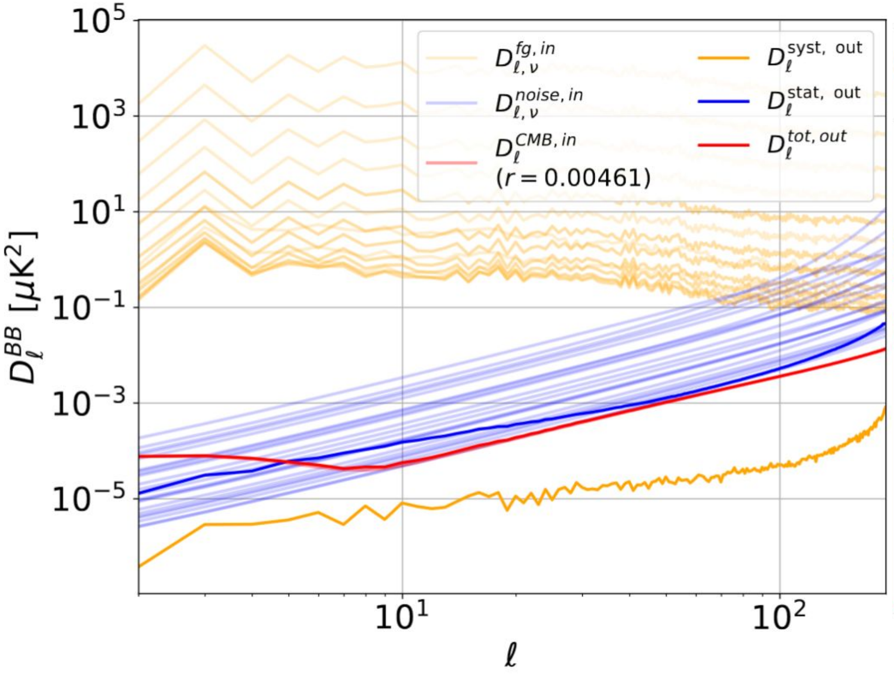
- Take benefit of the **frequency coverage** to fit the frequency-dependent astrophysical components

- **Parametrize** the foreground frequency dependency.

- **Synchrotron**: power law with spatially-varying index
- **Dust**: modified blackbody

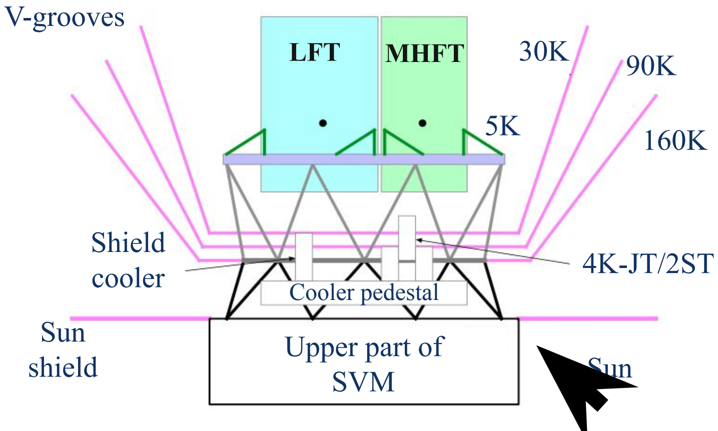
- **Multi-Clustering** interface with foregrounds data to account for spatial variability (📖 Puglisi et al. 2022, Carones et al. 2023)
- **Impact**: Reduction of the foreground signal by several orders of magnitude.
- But: systematic residual and noise degradation

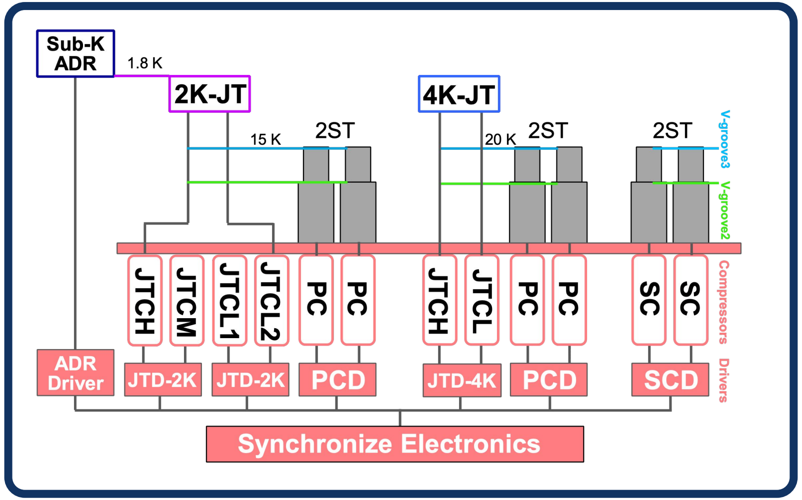
Impact on the recovered spectra:



method: fgbuster, details in

LiteBIRD cryogenic system

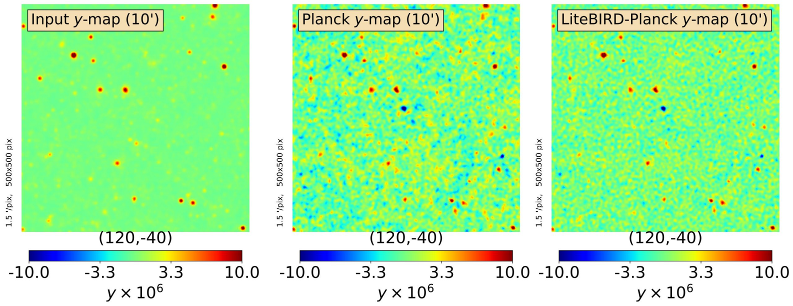


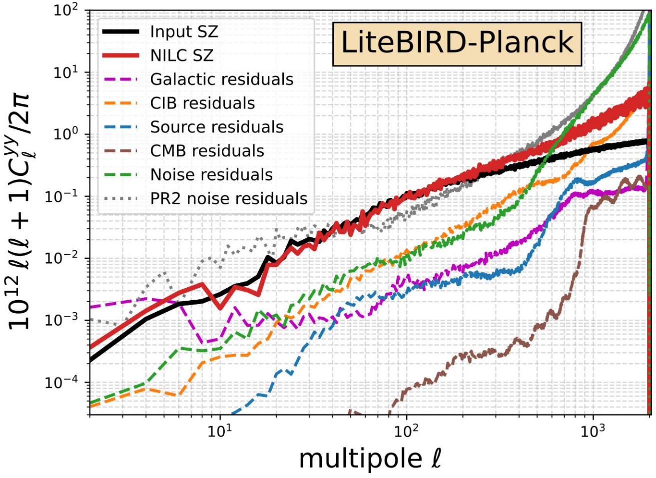


- Optimized to ensure **maximum stability** of the focal planes and of the optical elements of the telescopes
  - Radiative cooling to 30 K with V-grooves
  - Two 2ST are used for cooling V-grooves 2 and 3
  - A 4K-JT and two 2ST are used to cool the LFT and the MHFT
  - A 2K-JT, two 2ST, and a sub-K ADR are used for cooling the focal plane down to **100 mK**

Mapping the hot gas in the Universe

- The **Sunyaev-Zel'dovich** effect provides a mean to map the distribution of hot electrons in the Universe
- Improved sensitivity and frequency coverage of LiteBIRD crucially contributes to improve these studies
- Combination with Planck adds the benefit of angular resolution
- LiteBIRD will **improve ×10 the noise in the SZ map** wrt Planck
- This will allow to:
    - Produce a high-fidelity SZ map over the full-sky essentially **free of contamination at $\ell < 200$**
    - Test theories of structure formation via **hot-gas tomography** from SZ × galaxy surveys correlations
    - Search form **WHIM** in filaments connecting clusters
    - Study an **inhomogeneous reionization** process via cross-correlations of SZ × CMB optical depth
    - Measure the mean gas T_e via the relativistic SZ





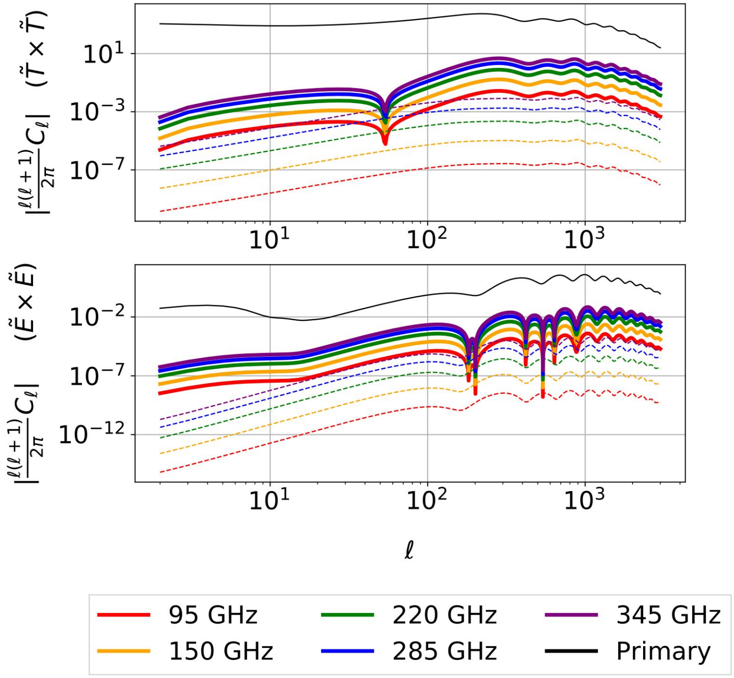
📖 Remazeilles+ JCAP 2024

Anisotropic CMB spectral distortions

- LiteBIRD will be sensitive to any **spatially-varying CMB spectral distortion**, beyond the SZ effect
  - **Rayleigh scattering**. LiteBIRD will have sensitivity to measure at **25-sigma** (📖 Beringue et al. 2021) the frequency-dependent CMB anisotropies due to Rayleigh scattering by HI at the LSS

    ➡ Such a detection would allow to derive improved constraints on N_{eff} and $\sum m_\nu$
  - **μ distortion**. LiteBIRD can detect an anisotropic μ distortion induced by non-Gaussian fluctuations induced during inflation

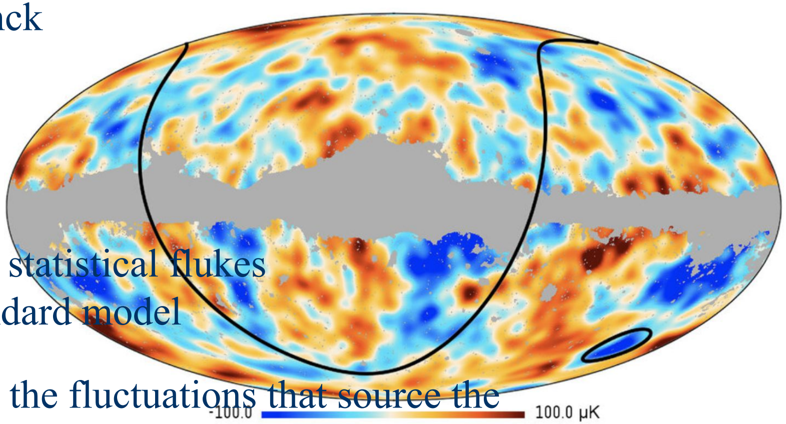
    ➡ This would offer a power test of inflation at its onset
  - **Axion decay**. LiteBIRD can look for polarized spectral distortions produced by resonant conversion of axions into photons by the Galactic magnetic field



📖 Dibert+ PhysRevD 2022

Elucidating spatial anomalies with polarization

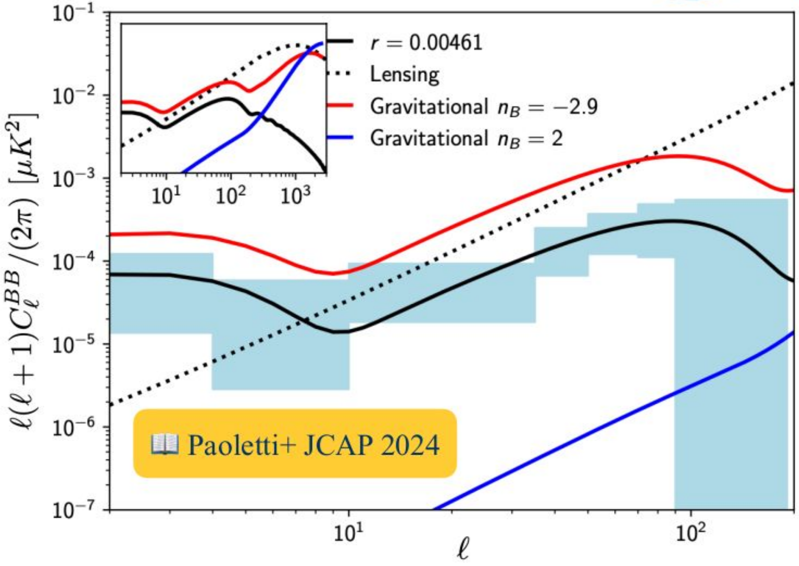
- Various so-called anomalies have been found in WMAP and Planck temperature data that exert a mild tension against the ΛCDM cosmological model:
  - a lack of power on large angular scales
  - the alignment of the quadrupole and octopole moments
  - a hemispherical asymmetry in power on the sky
  - a lack of correlation at large angular scales
  - parity asymmetry in the power associated with even/odd mode
  - an anomalous "Cold Spot" on a scale of ~10°
  - anomalously low temperature variance
- Given their modest statistical significance, these could simply be statistical flukes
- However, they may also be hints of **new physics** beyond the standard model
- Polarized CMB anisotropies provide independent information on the fluctuations that source the temperature anisotropy
- **LiteBIRD E-mode polarisation sky maps will allow further tests** on the nature of these spatial anomalies at close to the cosmic-variance level of sensitivity



Credit ESA/Planck Collaboration

Constraints on primordial magnetic fields

- Primordial magnetic fields (PMFs) affect the CMB via different effects:
  - **Gravitational effects** with magnetically-induced perturbations
  - Impact on the **ionization history** of the Universe due to their post-recombination dissipation
  - Induce a **Faraday rotation** of the CMB polarization
  - **Non-Gaussinity** induced in the CMB polarization anisotropies
- LiteBIRD:
  - Is a **sensitive probe** to PMFs through all these effects, thanks mainly to its remarkable sensitivity in polarization
  - Will **break the nG threshold** improving current upper limits by a factor of ~ 3
  - Will be able to **univocally identify the PFMs contribution to CMB** by joining all these effects together
  - Will allow a detection of **nG fields** with high significance



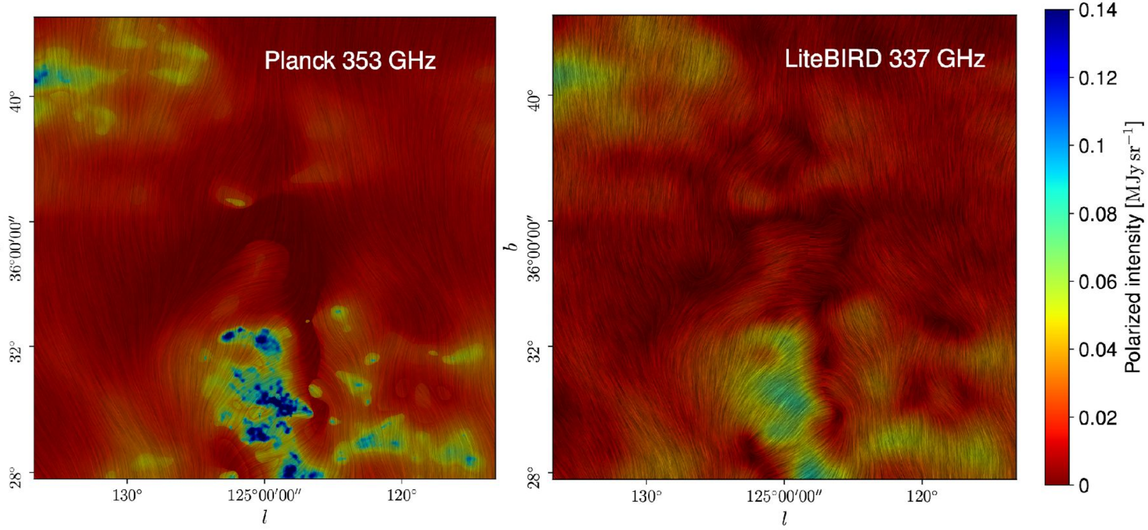
📖 Paoletti+ JCAP 2024

Upper limits on PMF amplitude for n_B = -2.9	
Gravitational effect	$B_{1\mathrm{Mpc}} < 0.8$ nG
Ionization history	$\sqrt{<B^2>} < 0.7$ nG
Faraday rotation	$B_{1\mathrm{Mpc}} < 3.2$ nG
Non-Gaussianities	$B_{1\mathrm{Mpc}} \lesssim 1$ nG

Galactic astrophysics

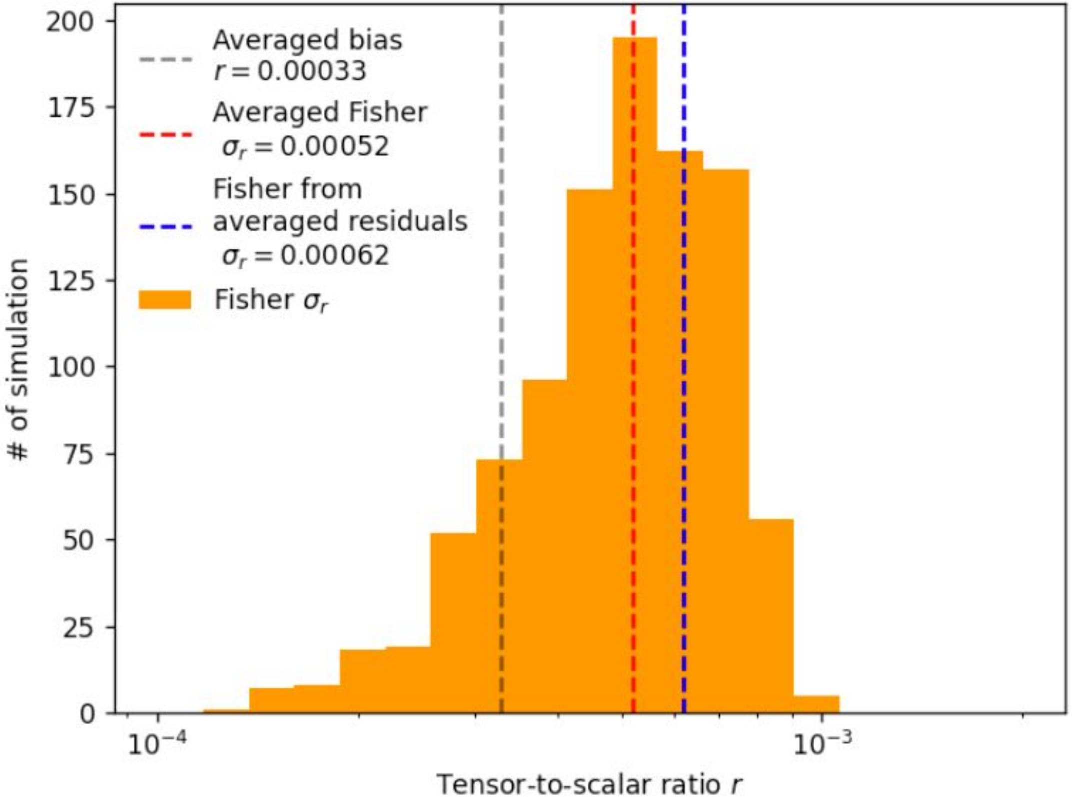
- LiteBIRD will provide 15 high-sensitivity polarization full-sky maps from 40 to 402 GHz
- Sensitivity improved by a factor of 5 at 40 GHz and 10 at 402, with respect to Planck
- Gain in spectral resolution

- **Wealth of Galactic science possible**:
  - Geometry of the Galactic magnetic field
  - Interstellar turbulence
  - Dust composition
  - Grain alignment
  - Cold clumps
  - Geometry of synchrotron-bright loops
  - SED of the synchrotron emission
  - Nature of AME and spectral variations...
  - … and many others!

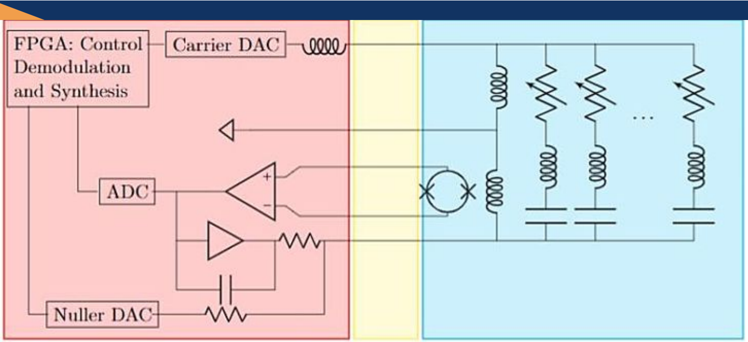


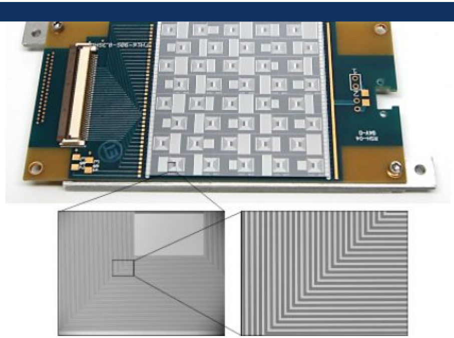
Foreground cleaning

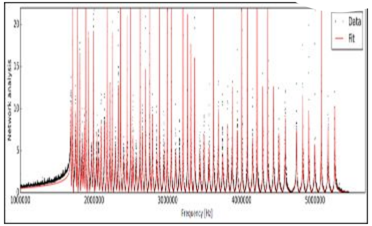
- "Multi-Clustering technique" (extension of xForecast)
- Distribution of the recovered *r* in 1000 simulations with input $r = 0$, with and without foreground residuals
- Bias from foreground (PySM `d1s1`) residuals is found to be small
- Final value: **$r = (3.3 \pm 6.2)\times 10^{-4}$**



LiteBIRD readout system







Cold Readout LC filters for MUX

- Digital frequency multiplexing (**DfMux**) readout technology enables the readout of many Transition Edge Sensors (TES) with fewer components and a low wire count, with no increase of system noise (⇒ **photon noise limited** detector performance)
- Superconducting resonators are used to assign unique frequency channels to the **TES sensors**.
- The signal is read out using a low-noise **SQUID amplifier** and an **FPGA controller**.
- This approach saves on mass, volume, power consumption, and cost.
- The technique draws its heritage from ground-based CMB experiments.

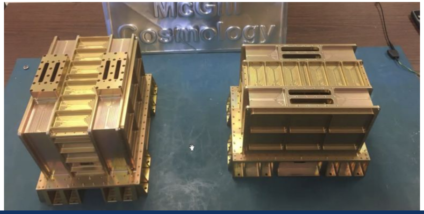
SQUID controller board

SQUID controller assembly

Digitizer assembly

Signal Processing Unit

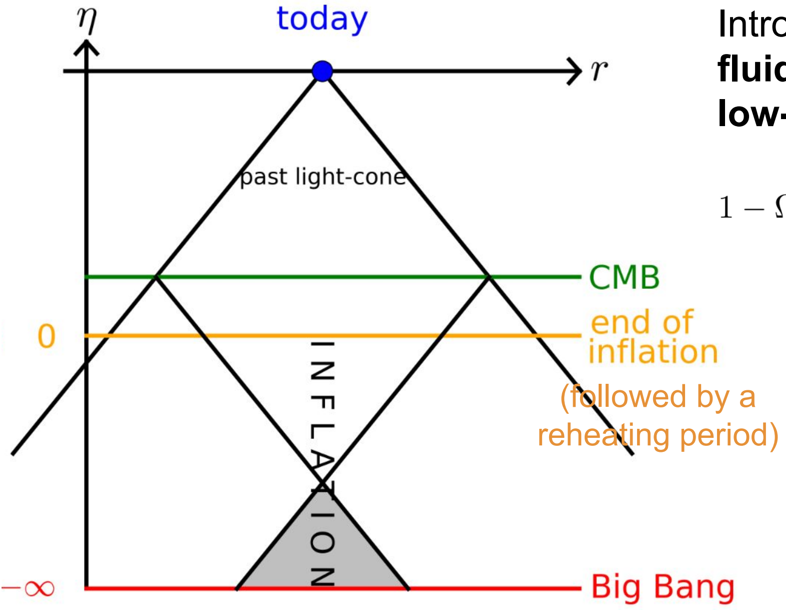
Digitizer assembly



I- Cosmology with the CMB
C) ΛCDM conceptual problems

A ($\ddot{a} < 0$: **decelerated**) **radiation-era** universe all the way to **Big-Bang** raises **conceptual issues**:

Horizon problem:



[hal:tel-01127242]

Flatness problem:

Introducing a well-chosen **primordial fluid *X*** can naturally bring to **low-curvature initial conditions**

$$1 - \Omega_{\rm tot}^{\rm end} = \frac{1}{1 + \frac{\Omega_X^{\rm in}}{1 - \Omega_{\rm tot}^{\rm in}} \left(\frac{a_{\rm end}}{a_{\rm in}}\right)^{-1-3w_X}}$$

Monopole problem:

GUT ⇒ magnetic monopoles.

$$\Omega_{\rm mon} = \frac{M_{\rm GUT}}{3H_0^2 M_{\rm Pl}^2 \cancel{\int_{t_{\rm BB}}^{t_{\rm GUT}} \frac{{\rm d}t}{a/a_0}}} \simeq 10^{15}$$

$$z_{\rm eq}^{1/4} \sqrt{\frac{H_0}{H_{\rm GUT}}} H_0^{-1} {\rm e}^{(1-3w_X)\frac{N}{4}}$$

A.H.Guth (1981) 10.1103/PhysRevD.23.347

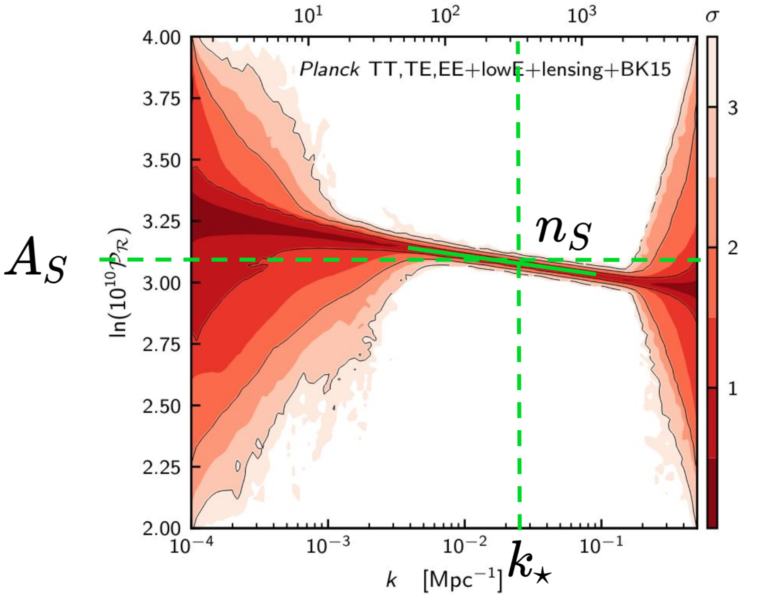
A ($\ddot{a} > 0$: **accelerated**) **universe** before radiation era solves them all if $N_{\rm tot} \equiv \ln \frac{a_{\rm end}}{a_{\rm in}} \geq 50$

I- Cosmology with the CMB
C) Current constraints on inflation

$$P_\zeta(k) = A_S \left(\frac{k}{k_\star}\right)^{n_S - 1 + \frac{1}{2}\alpha_S \ln(k/k_*) + \dots}$$

🟩 detected

🟥 consistent with 0

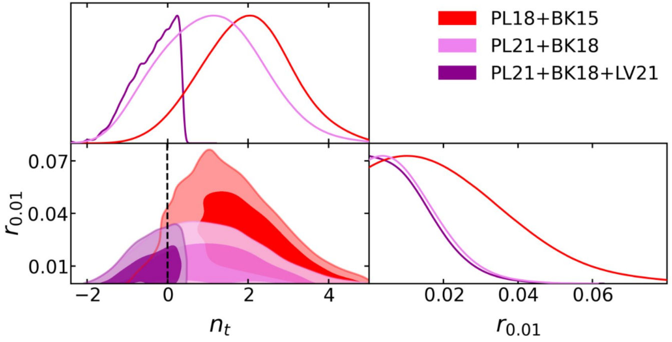


[1807.06211] Planck 2018 results. X. Constraints on inflation

$$P_h(k) = r A_S \left(\frac{k}{k_\star}\right)^{n_t + \dots}$$

Actually expected for **simplest** inflation realisations. More generally:

Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.065$
which are Gaussian	$f_{\rm NL} = -0.9 \pm 5.1$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$



[2208.00188] G. Galloni et al.

Single field slow-roll inflation

II- Single-field slow-roll inflation
A) Scalar field slow-rolling on its potential

Λ: example of realisation of a (quasi)-**de-Sitter** universe (**$\ddot{a} > 0$**)

- **Galaxies diluted exponentially**
- Ω_Λ remains **constant** with the expansion
- Friedmann equations ⇒ behaves like a **fluid** with $p = -\rho$

Action of a **single scalar field** minimally coupled to gravity:

$$S_\phi = -\int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + V\left(\phi\right)\right]$$

$$T_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}}\frac{\partial S_{\mathrm{matter}}}{\partial g_{\mu\nu}}$$

Energy-momentum tensor:

$$T_{\mu\nu}^{(\phi)} = \partial_\mu\phi\partial_\nu\phi + g_{\mu\nu}\left[-\frac{1}{2}g^{\rho\sigma}\partial_\rho\phi\partial_\sigma\phi + V\left(\phi\right)\right]$$

T00 is the density
Tii the pressure

Density and pressure:

$$\rho = \frac{\dot{\phi}^2}{2} + V$$

$$p = \frac{\dot{\phi}^2}{2} - V$$

In the Friedmann equations:

Klein-Gordon equation:

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

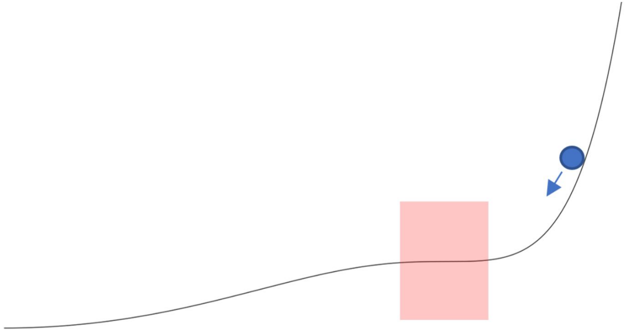
$$' = \frac{\mathrm{d}}{\mathrm{d}\phi}$$

$$\dot{} = \frac{\mathrm{d}}{\mathrm{d}t}$$

Same equation: **ball rolling down** a **slope**!

II- Single-field slow-roll inflation
A) Scalar field slow-rolling on its potential

If the potential has a **flat region**, the scalar field **velocity** will become small and its kinetic energy **negligible** with respect to its **potential energy**.



$$\rho = \cancel{\frac{\dot\phi^2}{2}} + V\,, \qquad p = \cancel{\frac{\dot\phi^2}{2}} - V\,. \qquad \Longrightarrow \qquad p = -\rho$$

The **slow-roll approximation** consists of that alongside with $\cancel{\ddot\phi} + 3H\dot\phi + V' = 0$

Equivalent to conditions on the **Hubble SR parameters**, that quantify

- the **deviation from de-Sitter**
- the **flatness of the potential**

$$\varepsilon_0 = \frac{H_{\mathrm{in}}}{H}$$

$$\varepsilon_{n+1} = \frac{\mathrm{d}\ \ln|\varepsilon_n|}{\mathrm{d}N} \ll 1$$

in terms of V (SRLO):

$$\varepsilon_1 \simeq \frac{M_{\mathrm{Pl}}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\varepsilon_2 \simeq 2M_{\mathrm{Pl}}^2\left[\left(\frac{V'}{V}\right)^2 - \frac{V''}{V}\right] \ll 1$$

$$\ldots$$

III- Single-field slow-roll inflation
A) Link to CMB

Now we have a **quasi de-Sitter** universe that can **solve** the ΛCDM **opened questions**, and in particular which **predicts** the origin of the **perturbations**, and their primordial power spectra, **scalar** $\mathcal{P}_\zeta$ and **tensor** $\mathcal{P}_h$.

<u>How</u>? Add a perturbation to the scalar action, derive the new equations of motion for the perturbation, quantize them…

<u>Result</u>:

<u>Amplitude</u>

$$A_\mathrm{S} \equiv \mathcal{P}_\zeta\Big|_{k_*} \overset{\text{SRLO}}{\simeq} \frac{V_*}{24\pi^2 M_\mathrm{Pl}^4 \varepsilon_{1*}},$$

$$r \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta}\Big|_{k_*} \overset{\text{SRLO}}{\simeq} 16\varepsilon_{1*},$$

<u>Tilt</u>

$$n_\mathrm{S} \equiv 1 + \frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k}\Big|_{k_*} \overset{\text{SRLO}}{\simeq} 1 - 2\varepsilon_{1*} - \varepsilon_{2*}$$

$$n_\mathrm{T} \equiv \frac{\mathrm{d}\ln\mathcal{P}_h}{\mathrm{d}\ln k}\Big|_{k_*} \overset{\text{SRLO}}{\simeq} -2\varepsilon_{1*}$$

<u>Running</u>

$$n_\mathrm{S,run} \equiv \frac{\mathrm{d}^2\ln\mathcal{P}_\zeta}{(\mathrm{d}\ln k)^2}\Big|_{k_*} \overset{\text{SRLO}}{\simeq} -2\varepsilon_{1*}\varepsilon_{2*} - \varepsilon_{2*}\varepsilon_{3*}$$

$$n_\mathrm{T,run} \equiv \frac{\mathrm{d}^2\ln\mathcal{P}_h}{(\mathrm{d}\ln k)^2}\Big|_{k_*} \overset{\text{SRLO}}{\simeq} -2\varepsilon_{1*}\varepsilon_{2*}$$

$\rho_\star = V_\star = 3M_\mathrm{Pl}^2 H_\star^2 = \dfrac{3\pi^2 M_\mathrm{Pl}^4 A_S r}{2}$: measure of ***r*** = measure of **inflationary energy scale**

$(\&\ V_\star,\ V'_\star,\ V''_\star)$

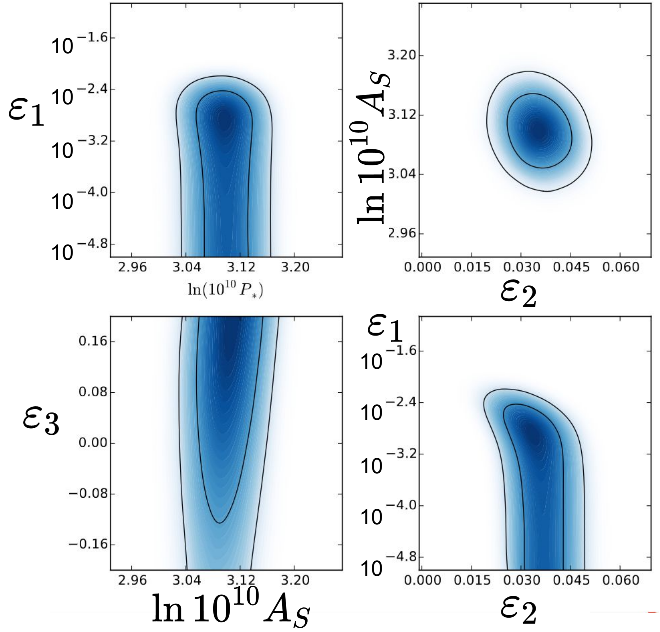
$n_T = -r/8$: slow-roll **consistency relation**

II- Single-field slow-roll inflation

B) Recipe: constraining its phenomenology

First thing we can do is to derive **constraints** on this **slow-roll** parameterisation:

Planck data



J. Martin, C. Ringeval and V. Vennin
Information Gain on Reheating: the One Bit Milestone (2016)

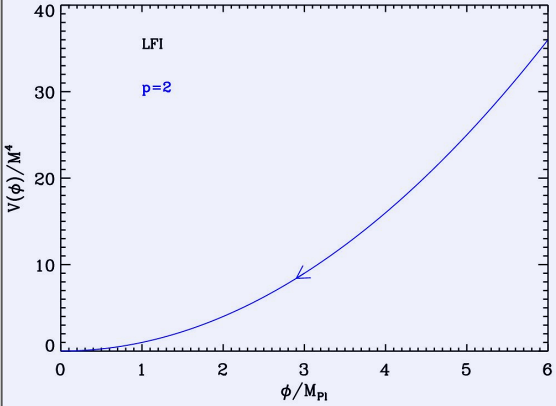
II- Single-field slow-roll inflation
B) Recipe: constraining its phenomenology

We want more: derive **constraints** on the potential parameters

$$\boxed{\phi \to V(\phi,p)},\ \boxed{\ln R_{\mathrm{rad}}} \Longrightarrow \phi_* \Longrightarrow \{\varepsilon_{i}*\} \Longrightarrow \{A_{\mathrm{S}},\ n_{\mathrm{S}},\ n_{\mathrm{S,run}},\ r,\ n_{\mathrm{T}},\ n_{\mathrm{T,run}},\ N_{\mathrm{e-folds}}\ \dots\}$$

(Motivated) choice. Eg:

$$V(\phi) = M^4\left[1-\left(\frac{\phi}{\mu}\right)^p\right]$$



(Motivated) choice
for the reheating duration

II- Single-field slow-roll inflation
B) Recipe: constraining its phenomenology

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$$\phi \rightarrow V(\phi,p),\ \ln R_{\mathrm{rad}} \Longrightarrow \phi_* \Longrightarrow \{\varepsilon_i *\} \Longrightarrow \{A_{\mathrm{S}},\ n_{\mathrm{S}},\ n_{\mathrm{S,run}},\ r,\ n_{\mathrm{T}},\ n_{\mathrm{T,run}},\ N_{\mathrm{e-folds}}\ \ldots\}$$

See appendix

$$\Delta N_* \overset{\text{SRLO}}{\simeq} \ln R_{\mathrm{rad}} - \ln\left(\frac{k_*}{a_0 \tilde{\rho}_\gamma^{1/4}}\right) - \frac{1}{4}\ln\left[\frac{9V_{\mathrm{end}}}{\varepsilon_{1*}(3-\varepsilon_{1\mathrm{end}})V_*}\right] + \frac{1}{4}\ln(8\pi^2 A_{\mathrm{S}})$$

$$\Delta N_* \overset{\text{SRLO}}{\simeq} \int_{\phi_{\mathrm{end}}}^{\phi_*} \frac{V(\phi)}{V_\phi(\phi)}\mathrm{d}\phi$$

II- Single-field slow-roll inflation
B) Recipe: constraining its phenomenology

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$$\varepsilon_1 \simeq \frac{M_{\mathrm{Pl}}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

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$$\cdots$$

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B) Recipe: constraining its phenomenology

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$$\phi \rightarrow V(\phi,p),\ \ln R_{\rm rad} \Longrightarrow \phi_* \Longrightarrow \boxed{\{\varepsilon_i *\} \Longrightarrow \{A_{\rm S},\ n_{\rm S},\ n_{\rm S,run},\ r,\ n_{\rm T},\ n_{\rm T,run},\ N_{\rm e-folds}\ ...\}}$$

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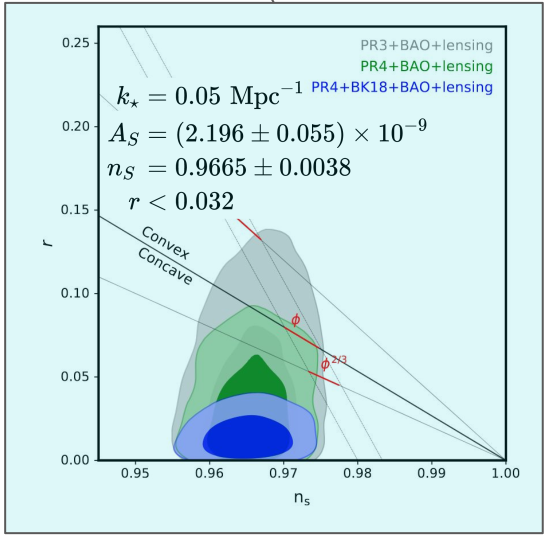
II- Single-field slow-roll inflation
B) Recipe: constraining its phenomenology

We want more: derive **constraints** on the potential parameters

$$\phi \to V(\phi, p),\ \ln R_{\mathrm{rad}} \implies \phi_* \implies \{\varepsilon_{i*}\} \implies \boxed{\{A_{\mathrm{S}},\ n_{\mathrm{S}},\ n_{\mathrm{S,run}},\ r,\ n_{\mathrm{T}},\ n_{\mathrm{T,run}},\ N_{\mathrm{e-folds}}\ \ldots\}}$$


$k_\star = 0.05\ \mathrm{Mpc}^{-1}$
$A_S = (2.196 \pm 0.055) \times 10^{-9}$
$n_S = 0.9665 \pm 0.0038$
$r < 0.032$

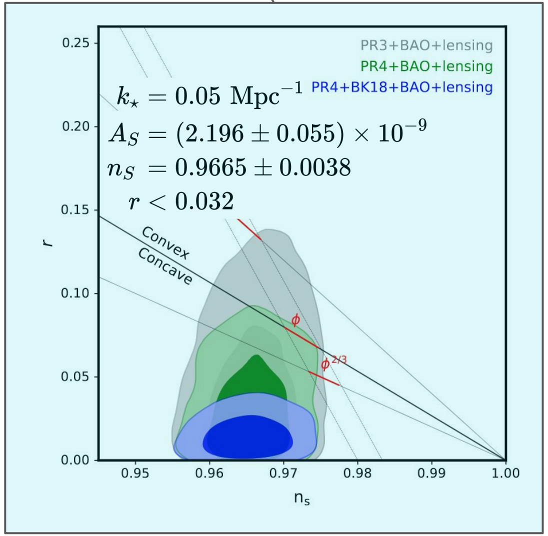
M. Tristram et al. (2022), ***2112.07961***

II- Single-field slow-roll inflation
B) Recipe: constraining its phenomenology

We want more: derive **constraints** on the potential parameters

$$\phi \to V(\phi, \boxed{p}), \boxed{\ln R_{\rm rad}} \Longrightarrow \phi_* \Longrightarrow \{\varepsilon_i *\} \Longrightarrow \boxed{\{A_{\rm S},\, n_{\rm S},\, n_{\rm S,run},\, r,\, n_{\rm T},\, n_{\rm T,run},\, N_{\rm e-folds} \dots\}}$$

for a given potential shape

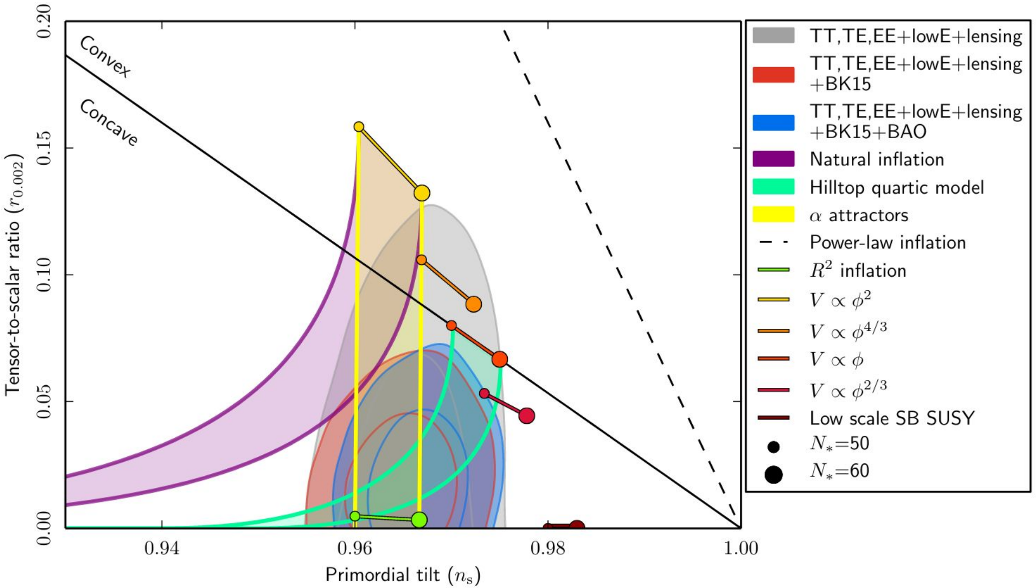


M. Tristram et al. (2022), **2112.07961**

To gain **intuition**: **grid** on the **potential** parameters for some models and **compare** to **experimental** constraints

Has been done for 100’s of potentials in [http://cp3.irmp.ucl.ac.be/~ringeval/aspic.html]

II- Single-field slow-roll inflation
C) Constraining its phenomenology



Planck collaboration X, Astron. Astrophys. 641, A10 (2020).

- In this work:

$$k_\star = 0.05\ \mathrm{Mpc}^{-1}$$

Measurement	Value and error
A_S	3.047 ± 0.014
n_S	0.9665 ± 0.0038

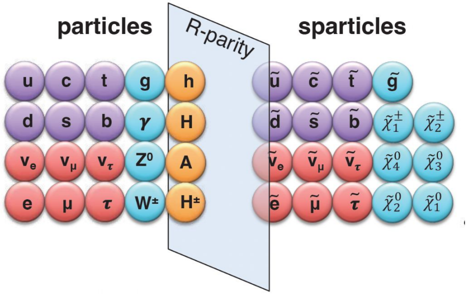
Planck Collaboration VI, Astron. Astrophys. 641, A6 (2020).

- The shape of these **potentials** are theoretically well-**motivated** but still quite **effective**
- **Few** of them come with a **complete study of their embedding** within a **model** of particle physics
- In the following, a case study: MSSM-inflation *[Phys. Rev. D **108**, 023511, GWD et al.]*

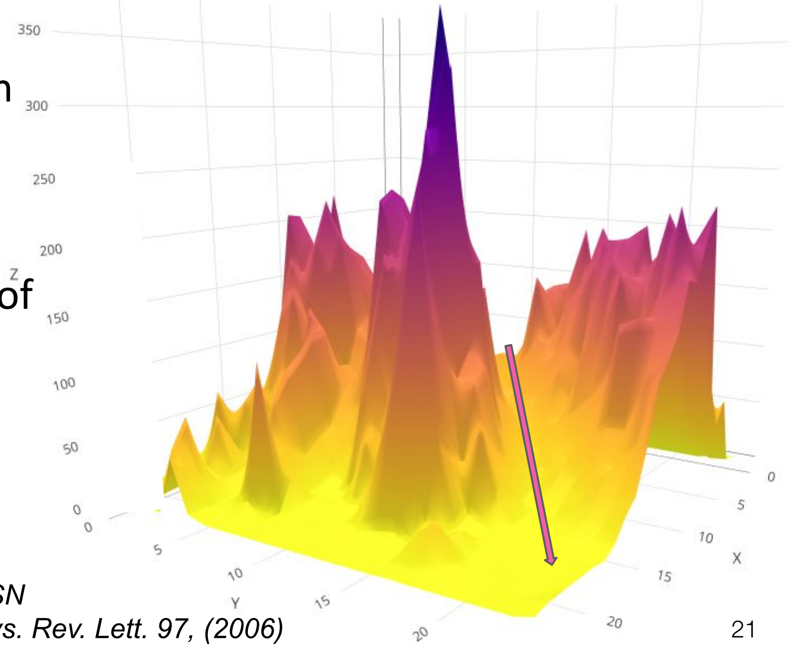
Establishing the link between inflation and particles

Study-case: MSSM-inflation

III- Embedding slow-roll in HEP
A) Example of a well-embedded model in particle-physics: MSSM-inflation



- **MSSM** = **SUperSYmmetric** extension of the HEP SM.
  - Naturally provides a **WIMP** that can explain the measured $\Omega_{\rm cdm}h^2$.
  - Only a **small fraction** of its parameter space is **excluded** by LHC data.



- **Inflaton** = **scalar field**, evolves with the Klein-Gordon equation in the **MSSM scalar potential** along its **valleys ("flat directions")**.

- We focus on two of its **flat-directions** combinations of **scalar fields:**
  - ***"LLe"***
  - ***"udd"***

Studied previously in (not exhaustive):
K. Enqvist and A. Mazumdar, Physics Reports 380, 99 (2003), ISSN
R. Allahverdi, K. Enqvist, J. Garcia-Bellido, and A. Mazumdar, Phys. Rev. Lett. 97, (2006)
C. Boehm, J. Da Silva, A. Mazumdar, and E. Pukartas, Phys. Rev. D 87, 023529 (2013)
....

III- Embedding slow-roll in HEP

A) Example of a well-embedded model in particle-physics: MSSM-inflation

The **potential** for ***LLe*** and ***udd:*** $V_{\rm tree}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 - \sqrt{2} A_6 \frac{\lambda_6 \phi^6}{6 M_{\rm Pl}^3} + \lambda_6^2 \frac{\phi^{10}}{M_{\rm Pl}^6}$

where ϕ is the real **field value** associated to the inflaton, m_ϕ its **mass**. m_ϕ and A_6 are **linked** to the underlying **supersymmetric parameters**:

$$m_\phi^2 = \frac{m^2_{\tilde{u}_R^i} + m^2_{\tilde{d}_R^j} + m^2_{\tilde{d}_R^k}}{3}$$

$$A_6(M_{\rm SUSY}) = \frac{6-\sqrt{3}}{3-\sqrt{3}} A_t(M_{\rm SUSY})$$

III- Embedding slow-roll in HEP

A) Example of a well-embedded model in particle-physics: MSSM-inflation

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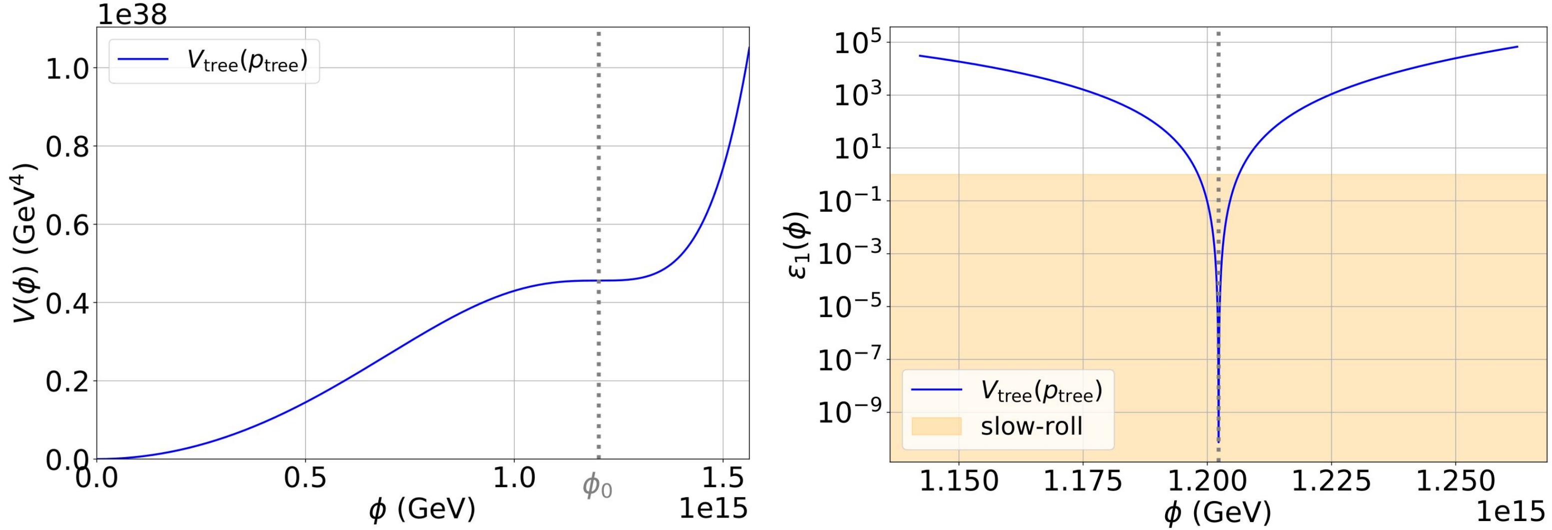
$$V_{\rm tree}(\phi) = \frac{1}{2}m_\phi^2\phi^2 - \sqrt{2}A_6\frac{\lambda_6\phi^6}{6M_{\rm Pl}^3} + \lambda_6^2\frac{\phi^{10}}{M_{\rm Pl}^6}$$

where ϕ is the real **field value** associated to the inflaton, m_ϕ its **mass**. m_ϕ and A_6 are **linked** to the underlying **supersymmetric parameters**.

Recipe ⇒



- **Narrow slow-roll** region ($|\phi-\phi_0| \sim \frac{\phi_0^3}{60M_{\rm P}^2}$) & **very-close-from-flat inflection point** ϕ_0.

III- Embedding slow-roll in HEP
B) MSSM-inflation: Radiative corrections impact on the potential

NEW • $V_{\rm RGE}$ whose parameters depend on ϕ.

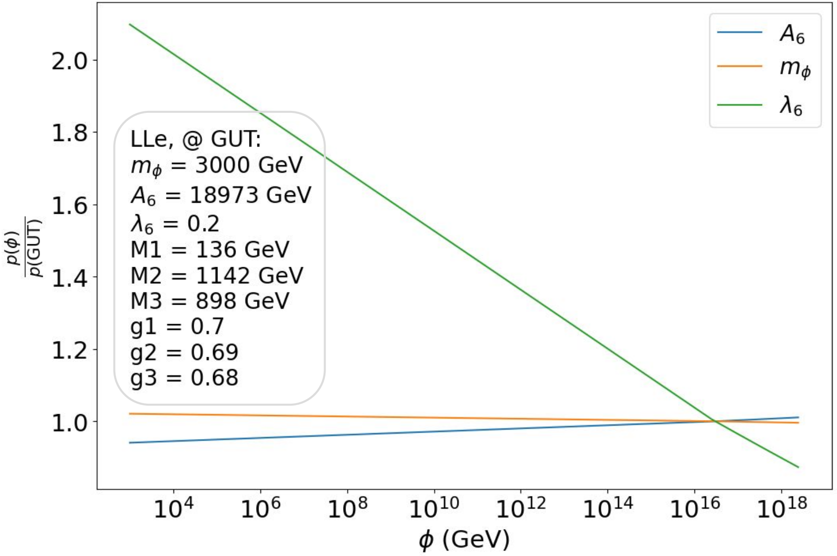
- **Radiative corrections**
  - fully computable with the **Renormalization Group Equations**
  - functions of the **gaugino masses** and the **gauge couplings** at **GUT scale**.
  - vary whether the inflaton is along ***udd*** or ***LLe***

Ex : *LLe*

$$Q\frac{\mathrm{d}m_\phi^2}{\mathrm{d}Q} = -\frac{1}{6\pi^2}\left(\frac{9}{10}M_1^2 g_1^2 + \frac{3}{2}M_2^2 g_2^2 + \mathrm{Y}_{m_\phi}^{L^iL^je^k}\right),$$

$$Q\frac{\mathrm{d}\widetilde{A}_6}{\mathrm{d}Q} = \frac{1}{2\pi^2}\left(\frac{9}{10}M_1 g_1^2 + \frac{3}{2}M_2 g_2^2 + \mathrm{Y}_{A_6}^{L^iL^je^k}\right),$$

$$Q\frac{\mathrm{d}\lambda_6}{\mathrm{d}Q} = -\frac{\lambda_6}{4\pi^2}\left(\frac{9}{10}g_1^2 + \frac{3}{2}g_2^2 + \mathrm{Y}_{\lambda_6}^{L^iL^je^k}\right),$$



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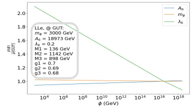
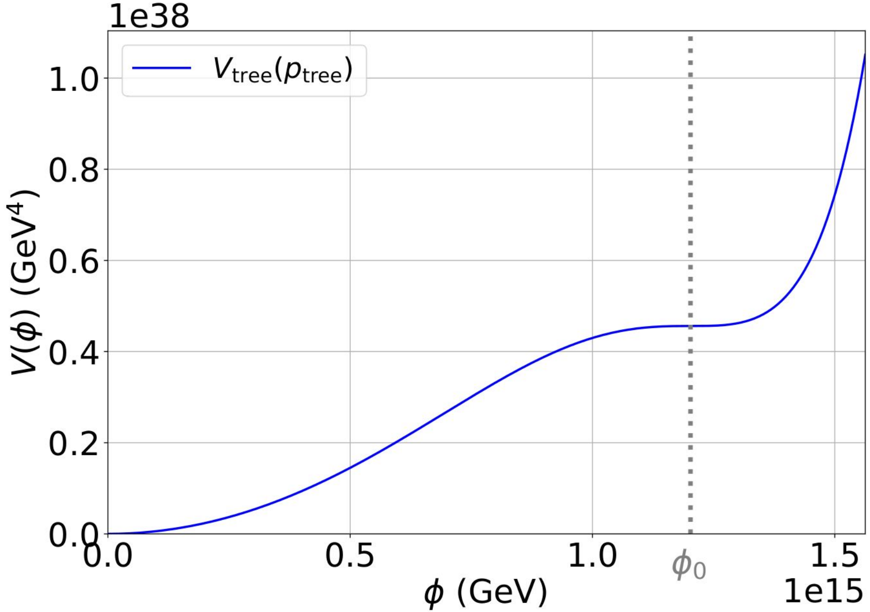
$$m_\phi^2 = m_\phi^2(\phi)$$

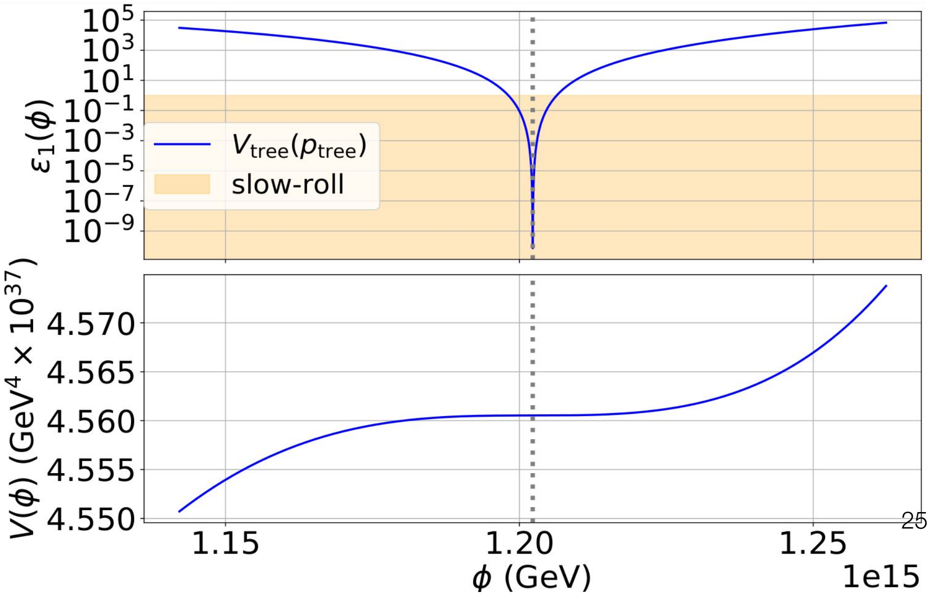
$$A_6 = A_6(\phi)$$

$$\lambda_6 = \lambda_6(\phi)$$



LLe, @ GUT:
m_ϕ = 3000 GeV
A_6 = 18973 GeV
λ_6 = 0.2
M1 = 136 GeV
M2 = 1142 GeV
M3 = 898 GeV
g1 = 0.7
g2 = 0.69
g3 = 0.68





III- Embedding slow-roll in HEP
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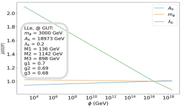

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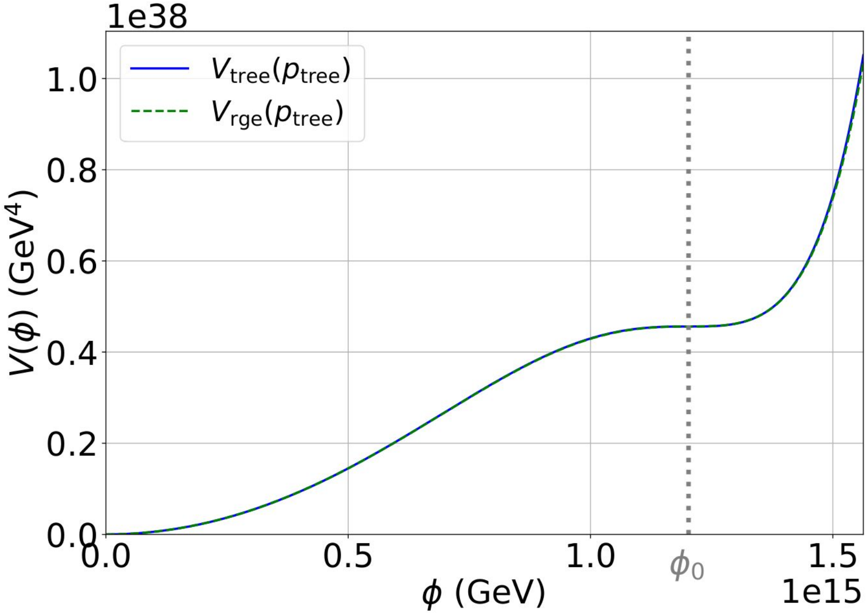

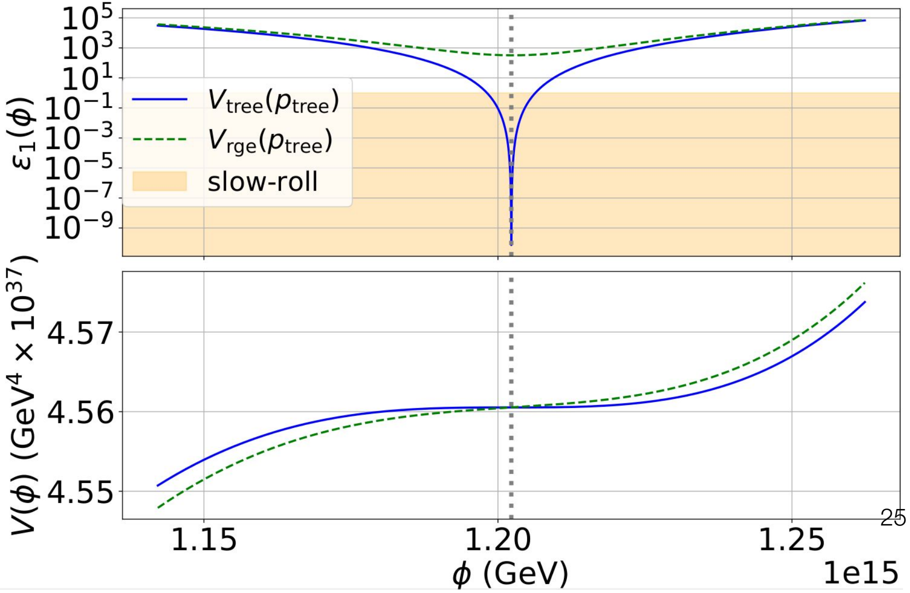

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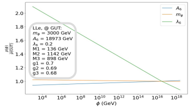
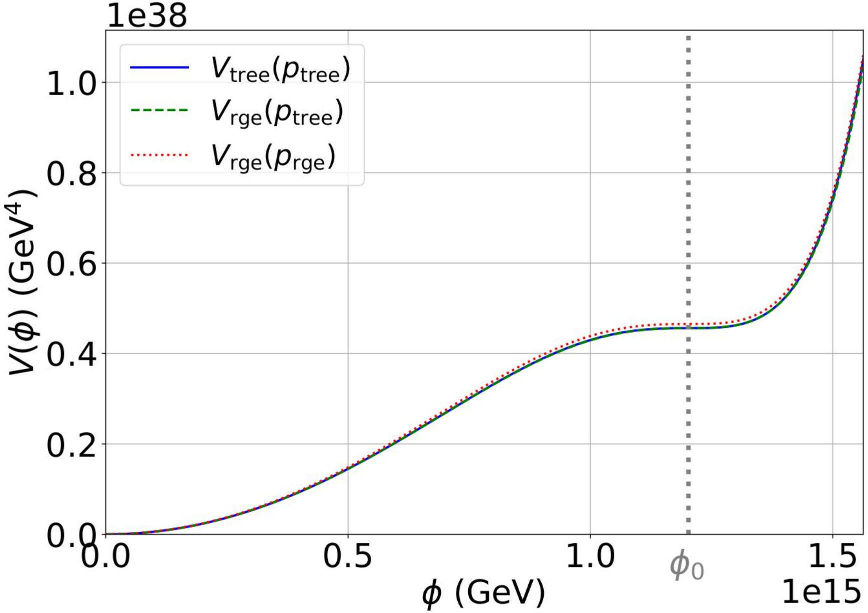
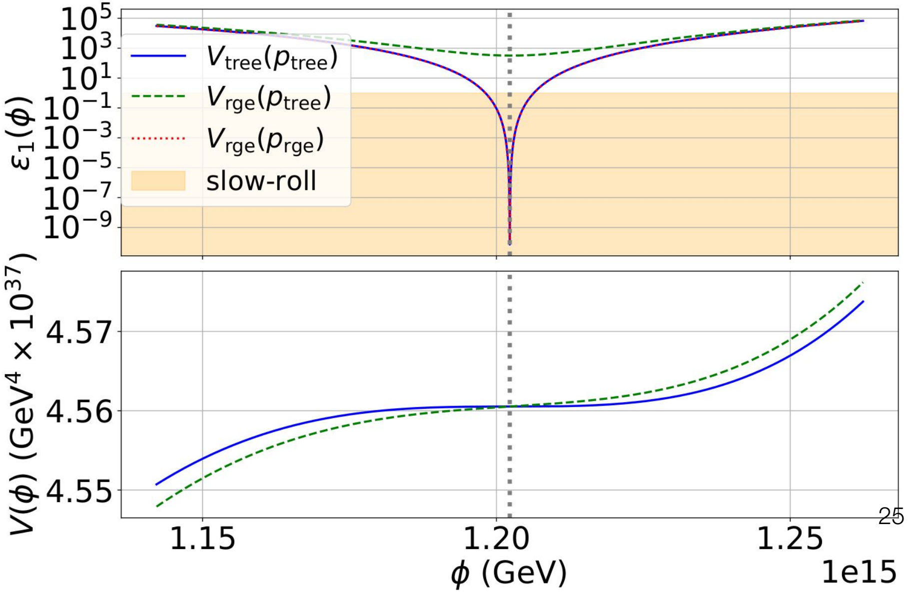
$$\lambda_6 = \lambda_6(\phi)$$

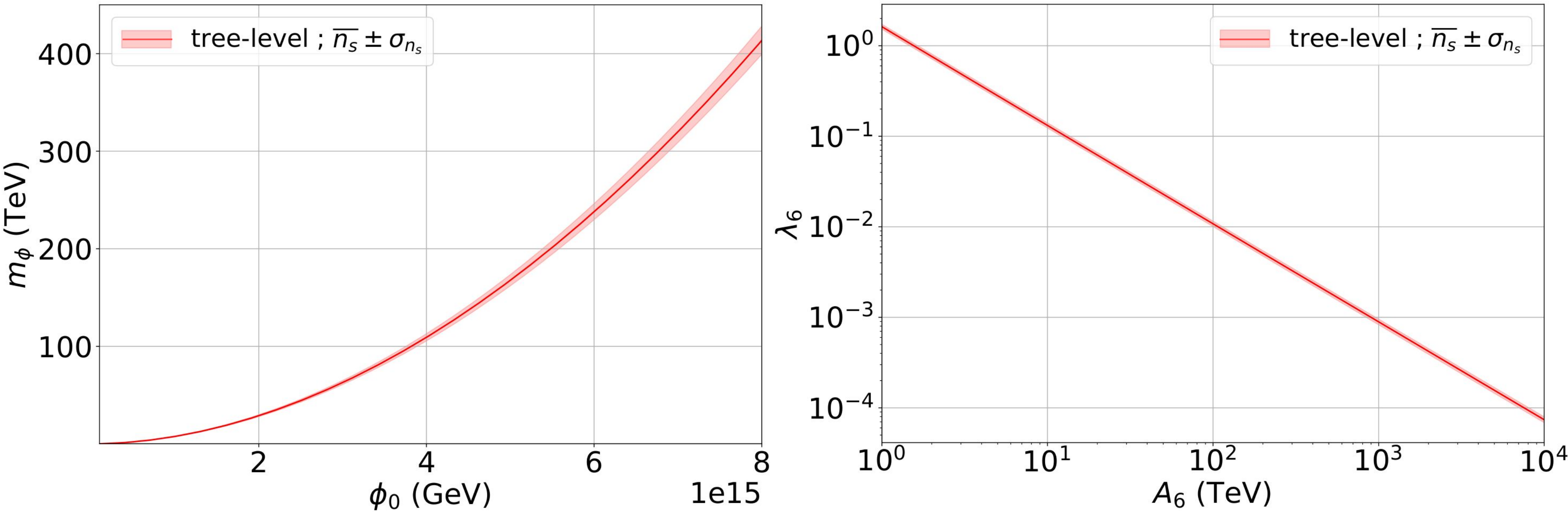






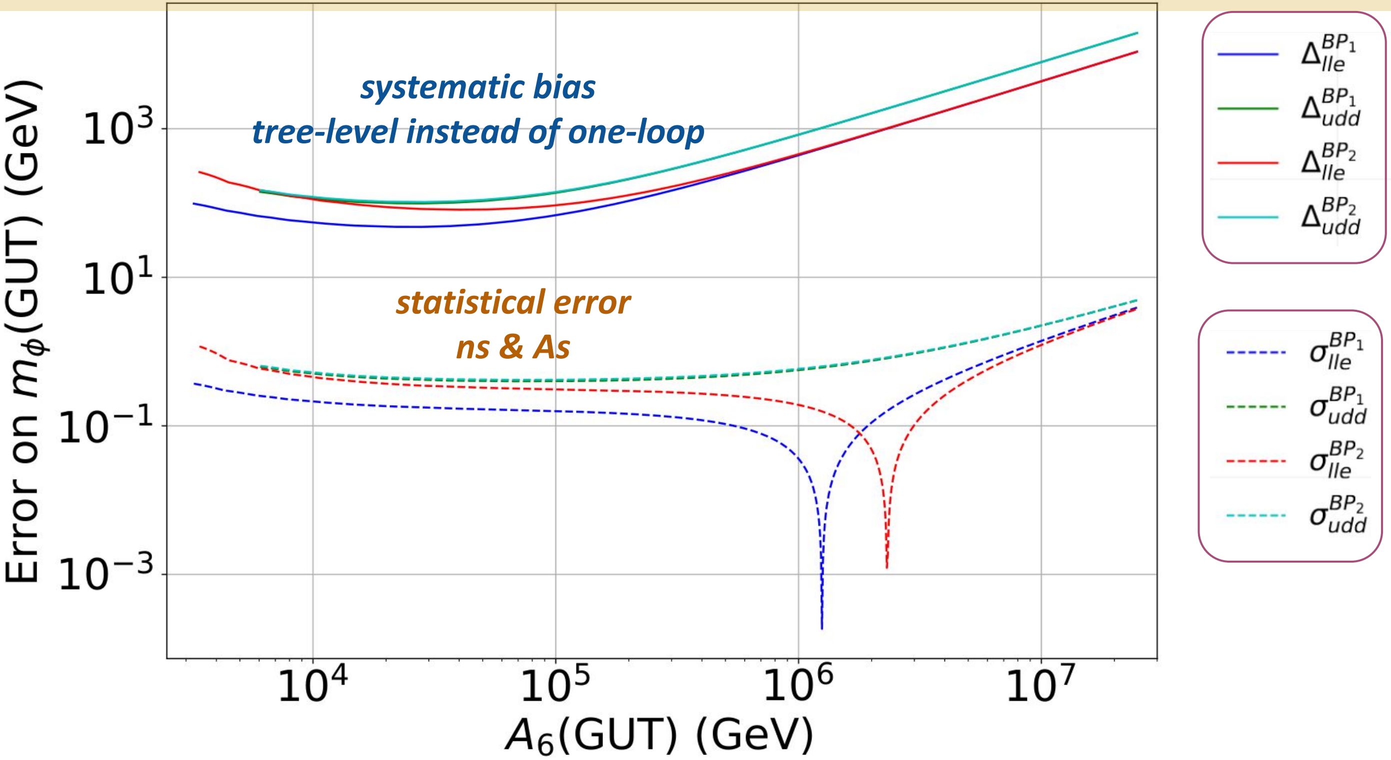
III- Embedding slow-roll in HEP
B) MSSM-inflation: Radiative corrections impact on the potential

- **Regions allowed by cosmology** in (illustrative) plans of the **tree-level** parameter space:



- How do these contours **change** beyond tree-level?

III- Embedding slow-roll in HEP
B) MSSM-inflation: Radiative corrections impact on the potential



systematic bias
tree-level instead of one-loop

statistical error
ns & As

- **Not** taking properly **into account** the **RGE corrections** induces a ***systematic bias***:
    - of order **100-1000 GeV** depending on the inflation scale!
    - **well above the *ns & As statistical error***!

Crucial RGE impact!