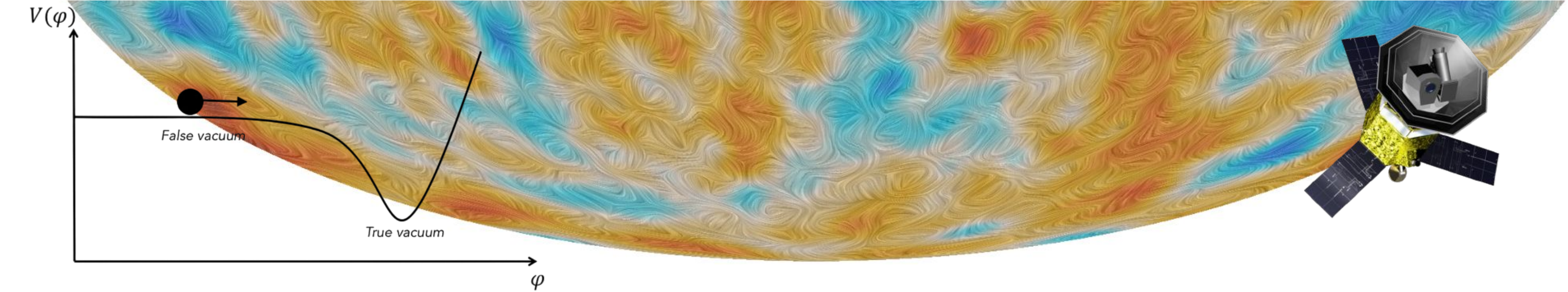


Constraining Cosmological Inflation with LiteBIRD

Gilles Weymann-Despres

on behalf of the

LiteBIRD collaboration

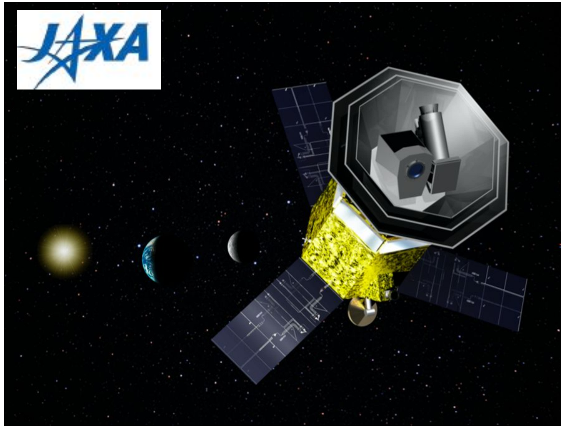
université PARIS-SACLAY

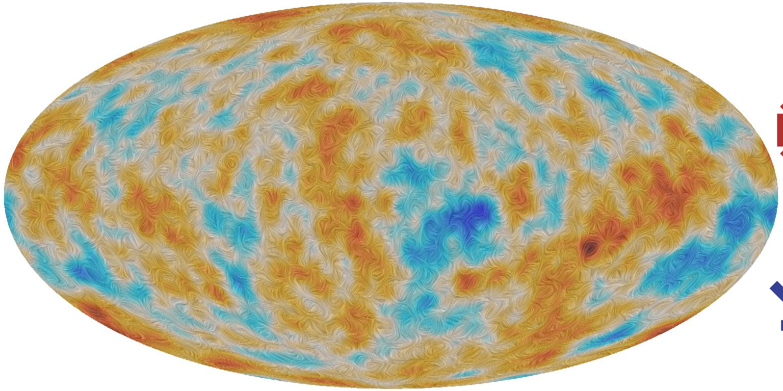
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

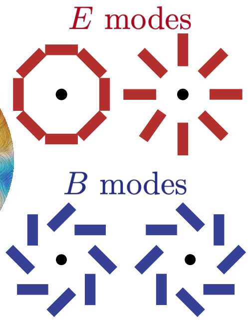
LiteBIRD overview

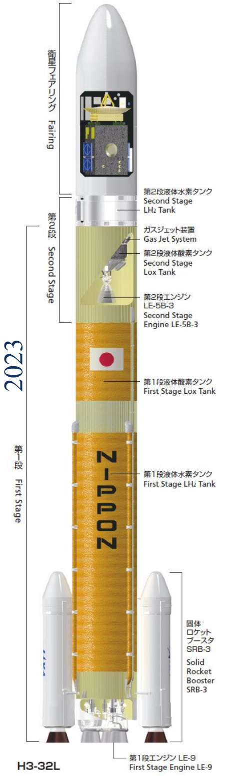
- *Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection*
- **JAXA**'s L-class mission selected in May 2019 to be launched in **~2032** with JAXA's H3 rocket
- LiteBIRD collaboration: Over 400 researchers from **Japan**, **North America** 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

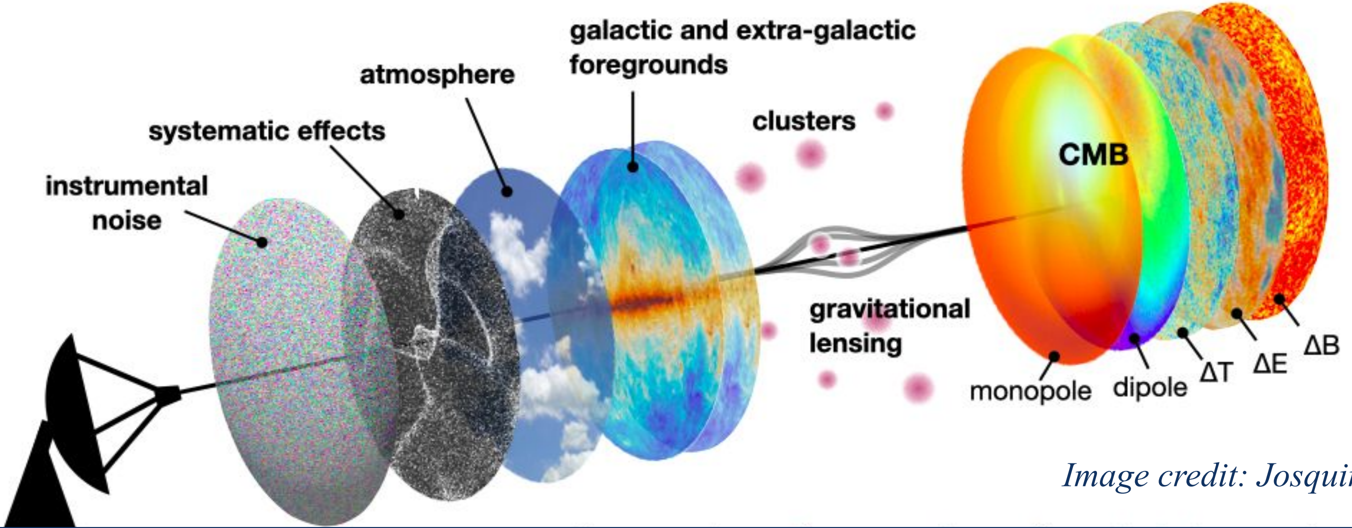
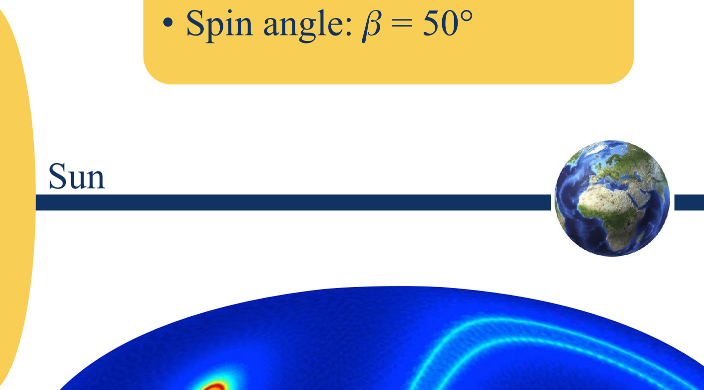
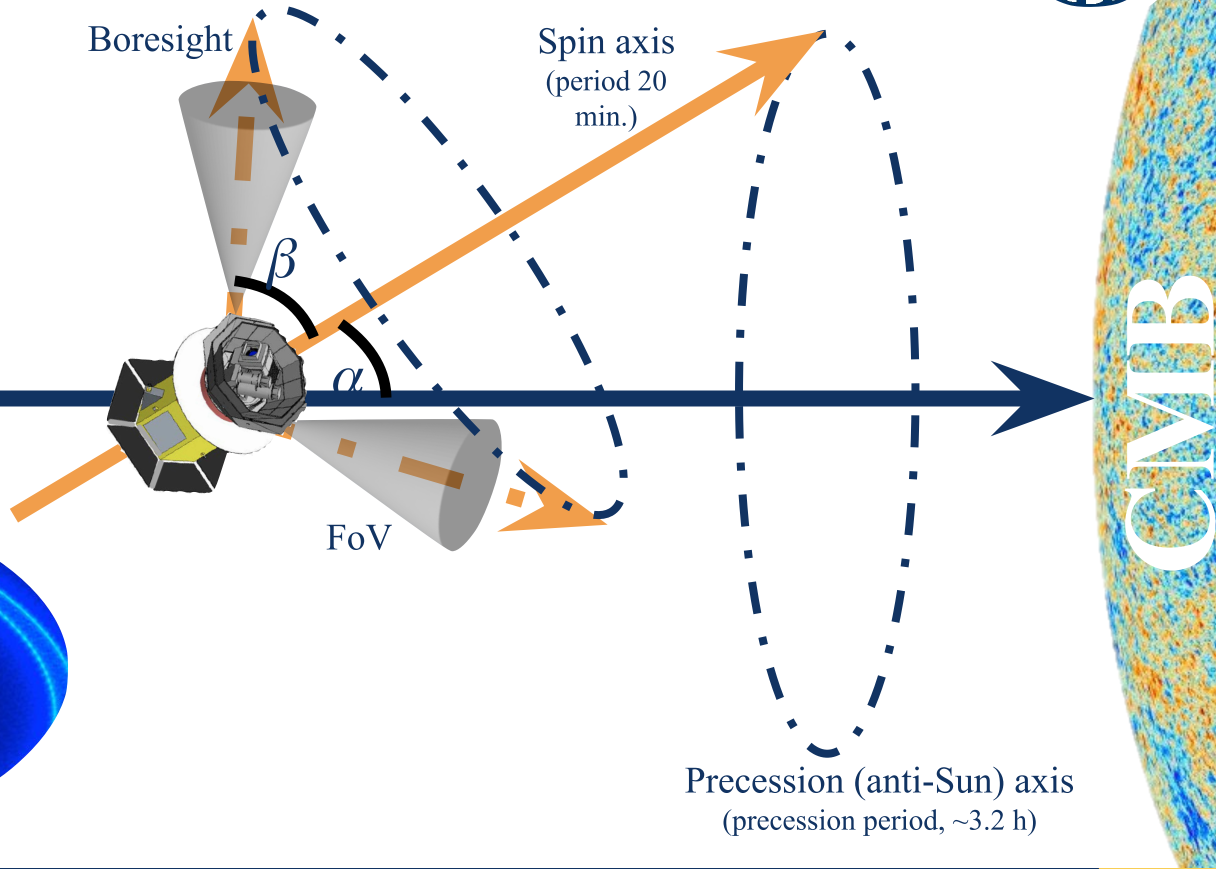


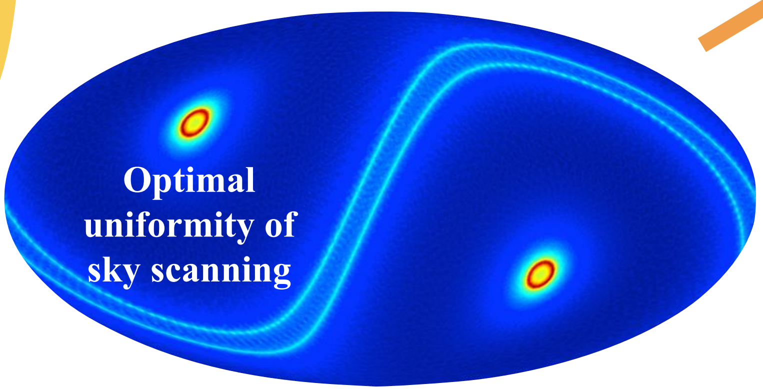
Image credit: Josquin Errard

LiteBIRD scanning strategy

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



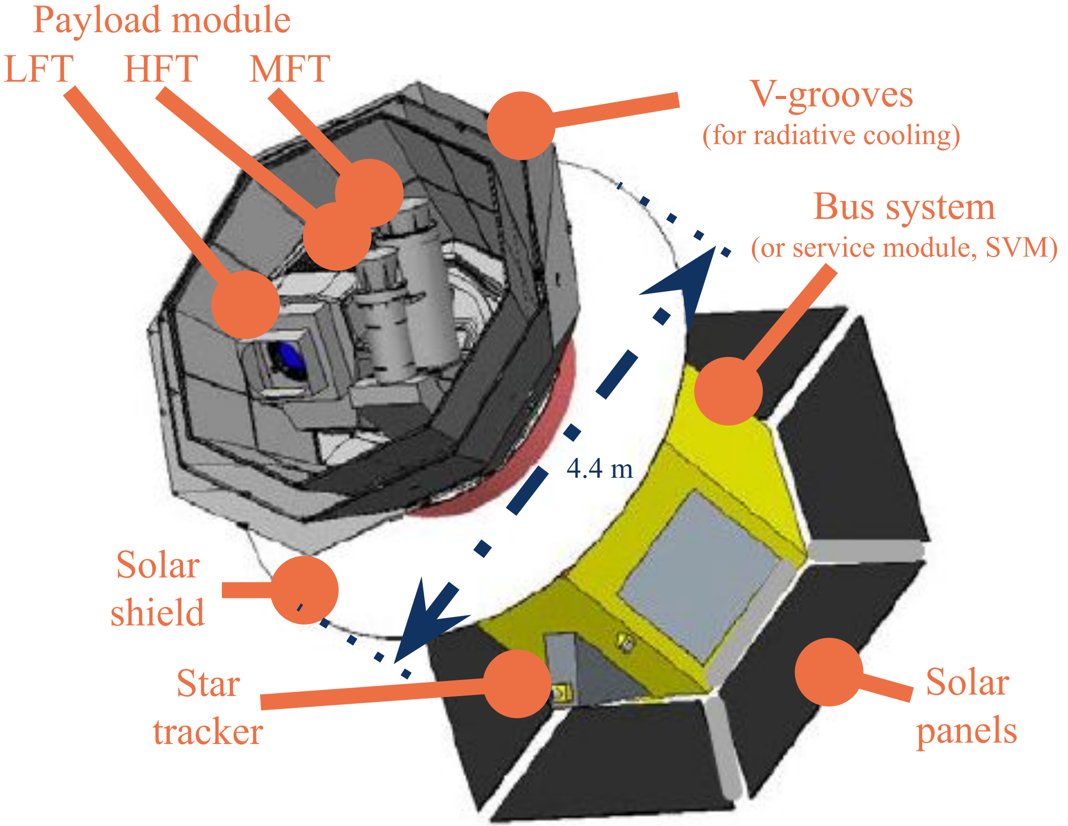




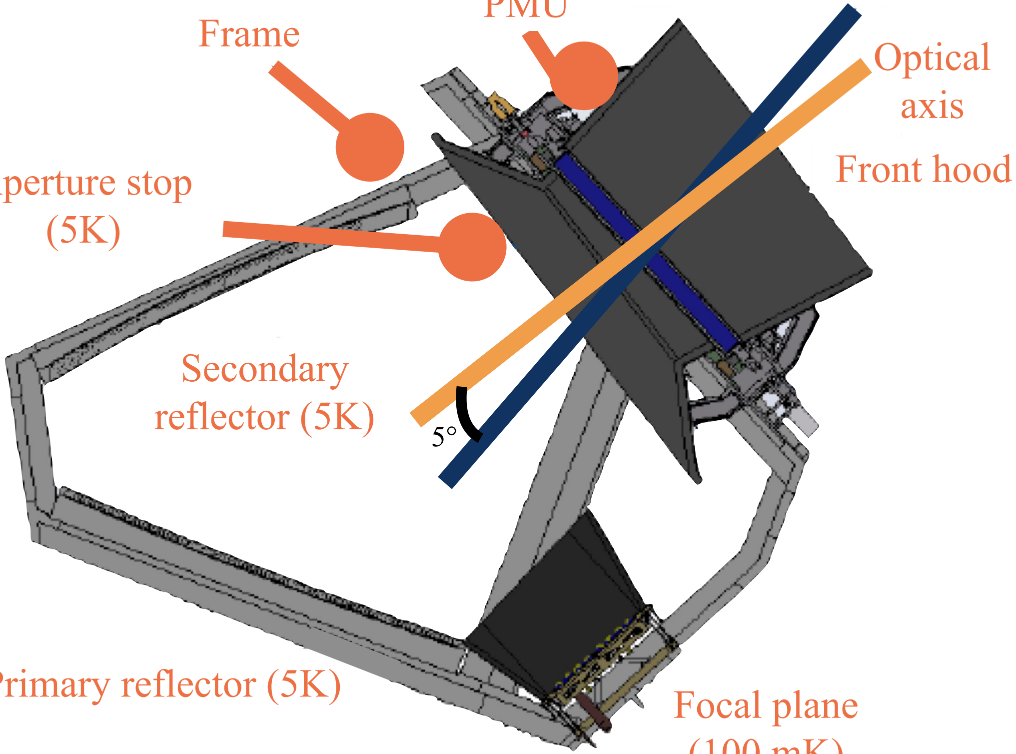
LiteBIRD spacecraft overview

- **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)



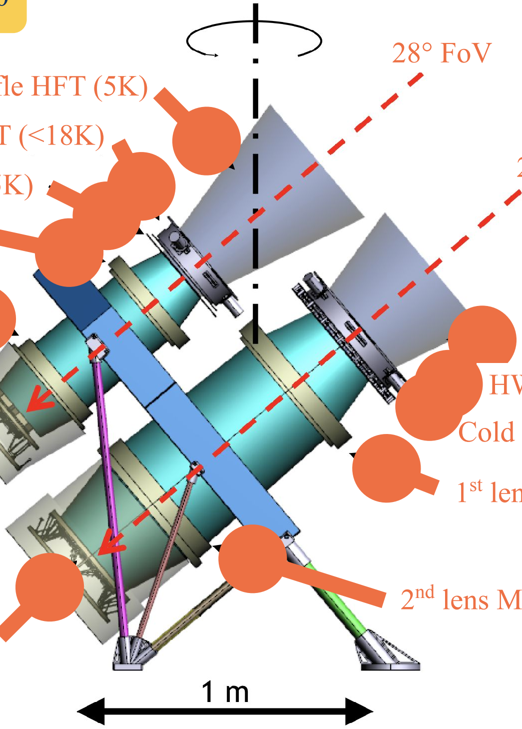
- Polarization Modulation Unit (PMU) as the first sky-side optical element
- **Crossed-Dragone** design
  - Mirrors and aperture stop at **5 K**
  - Made of aluminium
- Field of view: **18° x 9°**
- Aperture diameter: **400 mm**
- Frequency range: **40-140 GHz**
- Angular resolution: **70-24 arcmin**
- 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

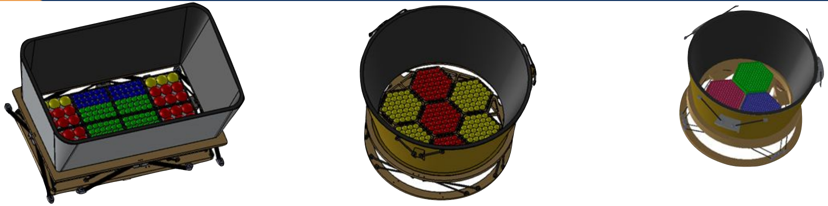
📖 Lamagna+ SPIE 2020

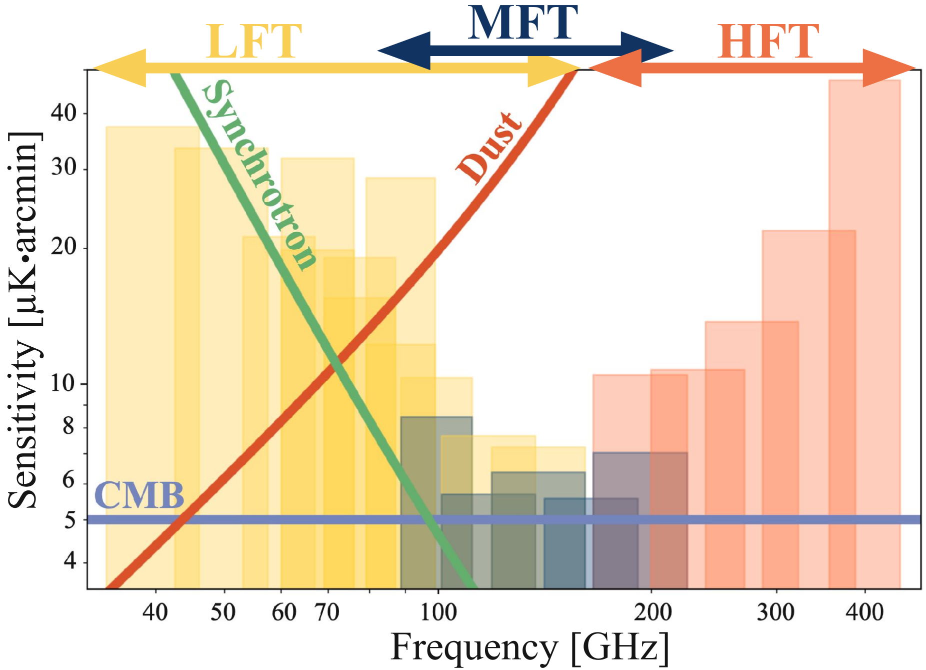


- Refractive optics
- Each telescope has PMU with a half-wave-plate (HWP)
- Optics at **5 K**
- Field of view: **28°**
- Simple and high heritage from ground experiments
- Compact (mass & volume)
- Simplified design for filtering scheme
- PP lenses + ARC
- Weight 180 kg

	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

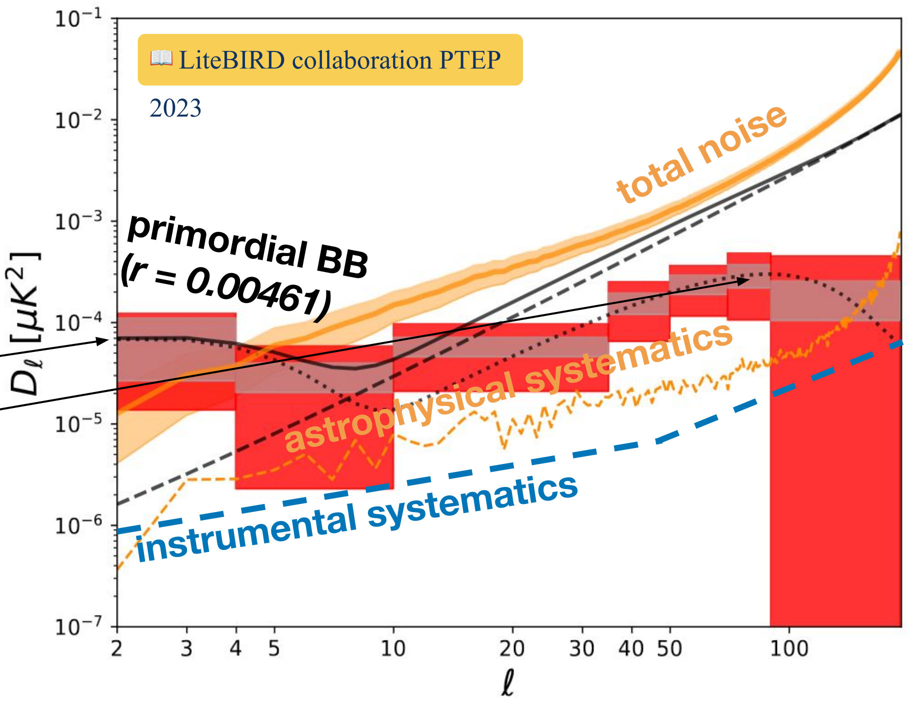
- Combined sensitivity to primordial CMB anisotropies: **2.2 μK·arcmin**

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

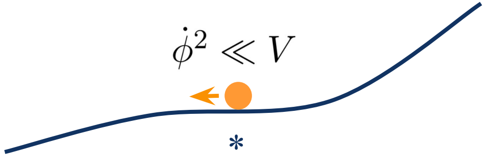
- **Requirements** on the **B modes** and ***r* measurements**:
  - For $r = 0$, **total uncertainty (stat + syst) of $\delta r < 0.001$**
  - For $r = 0.01$, 5-σ independent detection of
    - reionization ($2 < \ell < 10$) peak
    - recombination ($11 < \ell < 200$) peak



LiteBIRD main scientific objectives

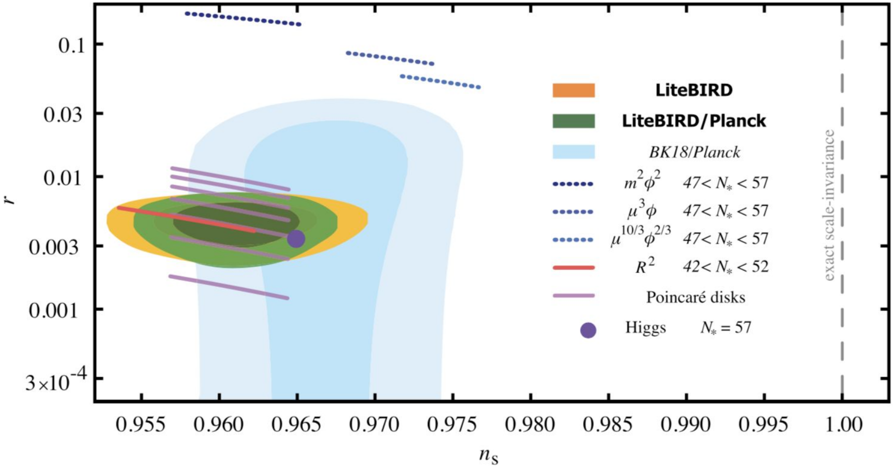
- **Constraints** on **inflation models.**

  eg. single-field slow-roll:



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

- 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)



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A cosmology-particle-physics interface

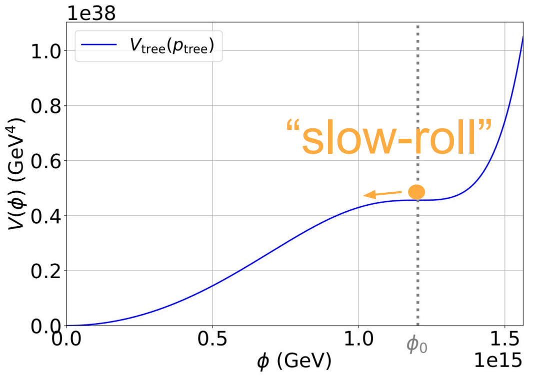
📖 Weymann-Despres+2023

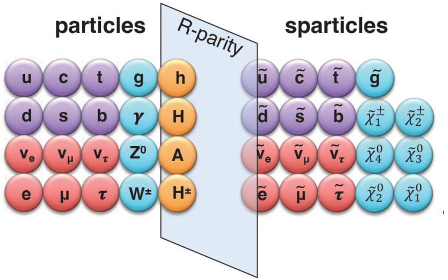
Study-case: Inflation, dark matter and reheating within the MSSM

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

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

$$\begin{cases} m_\phi^2 = \dfrac{m_{\tilde{u}_R^i}^2 + m_{\tilde{d}_R^j}^2 + m_{\tilde{d}_R^k}^2}{3} \\ A_6(M_{\text{SUSY}}) = \dfrac{6-\sqrt{3}}{3-\sqrt{3}} A_t(M_{\text{SUSY}}) \end{cases}$$





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

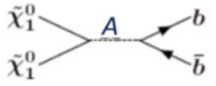
We have identified **some points** for **various dark matter annihilation processes** satisfying:

HEP Constraints (~ 80):
- Higgs mass (and BR)
- LHC SUSY searches
- … not exhaustive

+

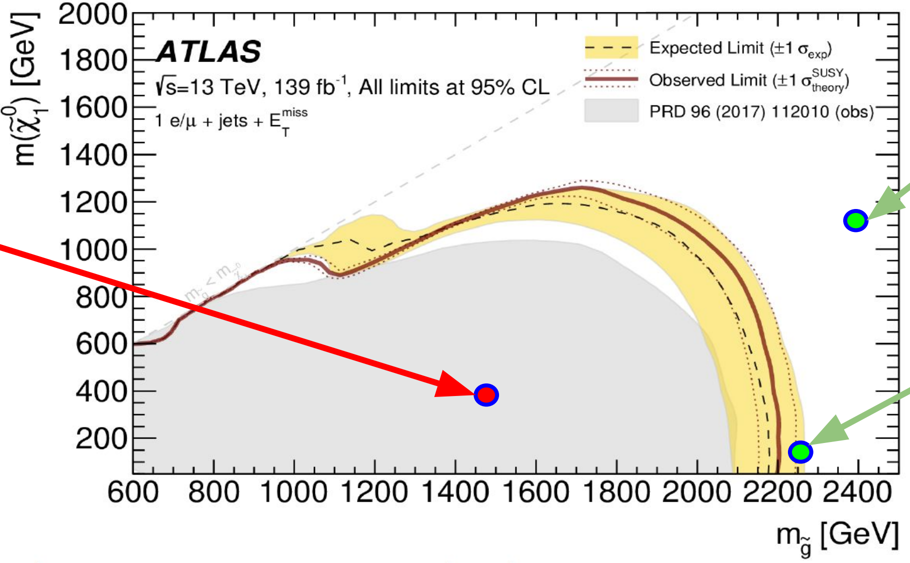
Cosmo constraints:
- $\Omega_{cdm} h^2$
- NEW **As, ns**

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

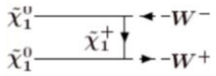


EXCLUDED

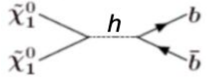
HEP measurements give constraints on inflation



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



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



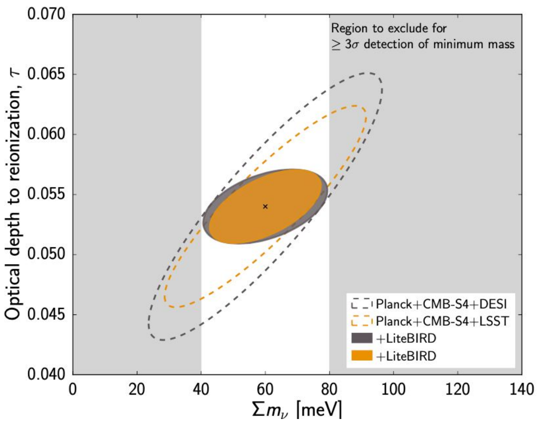
Cosmology restricts the MSSM parameter space

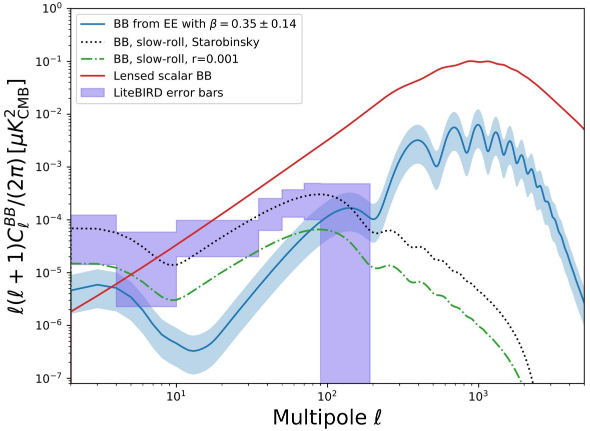
Interplay of the constraints in the same region of the parameter space! ⇒ **HEP-cosmology bridge**

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

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IAS Orsay
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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
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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
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idr
RWTH AACHEN UNIVERSITY
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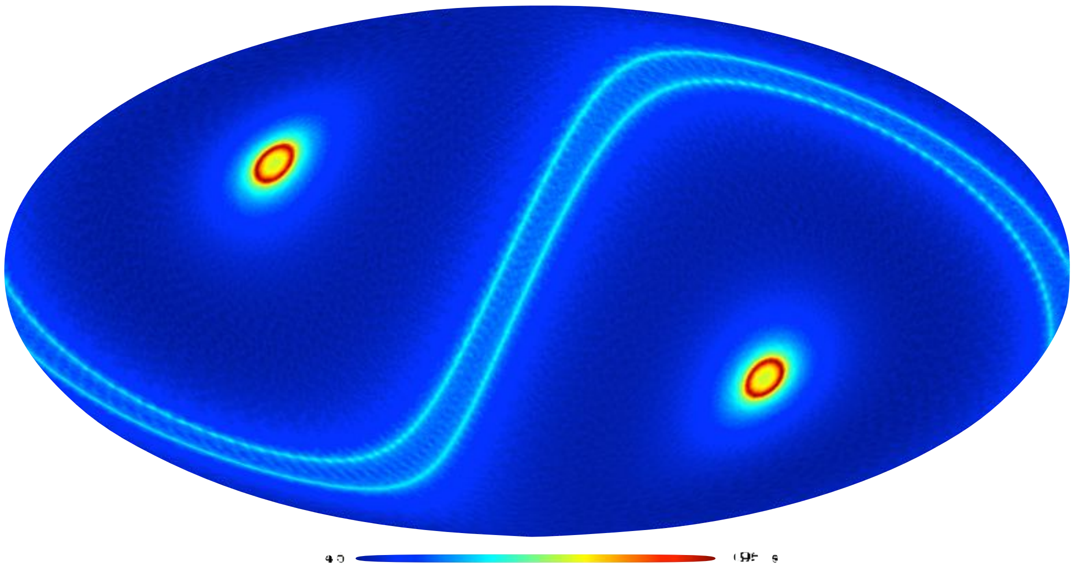
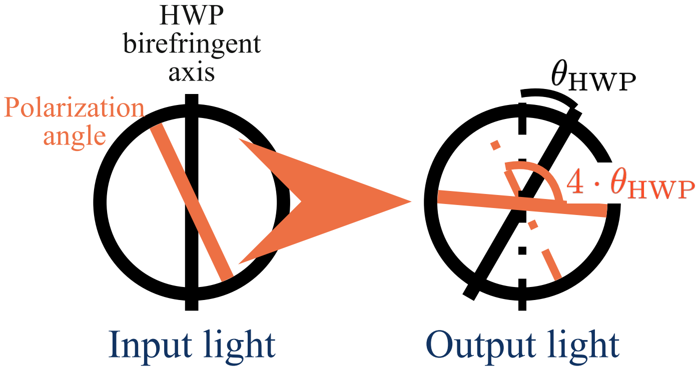
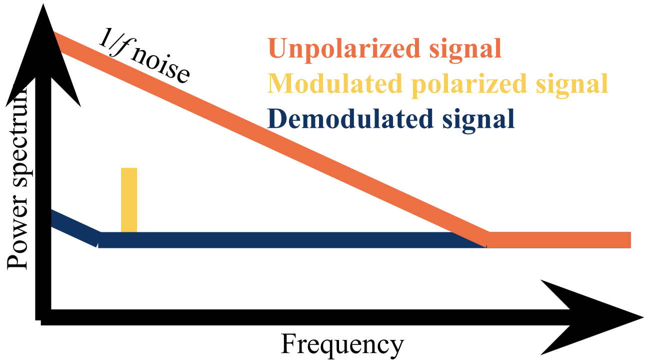


Polarization Modulation Unit (PMU)

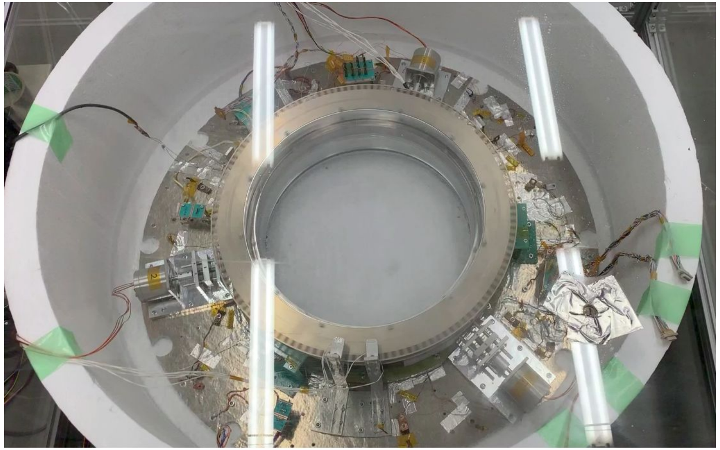
- Rotating a birefringent plate to modulate polarization
- The first sky-side optical element





📖 Sakurai+2020 📖 Komatsu+2020
📖 Toda+2020 📖 Columbro+2020 📖 Sugiyama+2020

- LFT PMU BBM at Kavli IPMU:

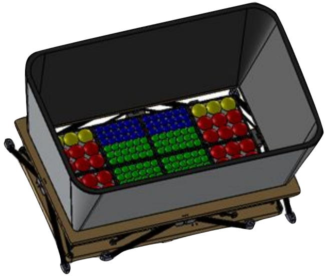


- Rotation test of superconducting magnetic bearing system in the 4K cryostat
- Stable rotation at cryogenic temperature (< 10 K)

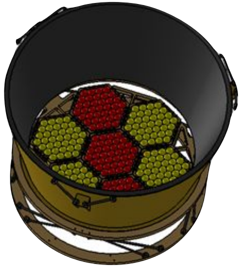
Focal plane configuration

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

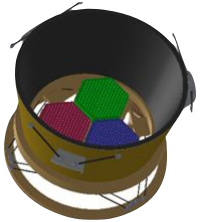
LFT



MFT

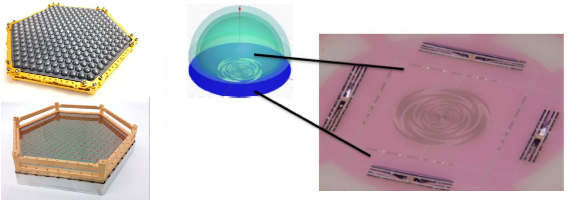


HFT

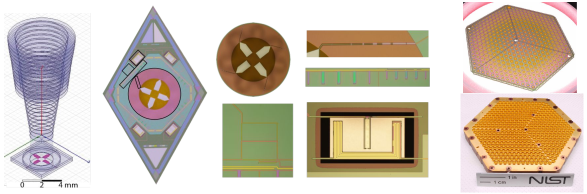


Rule of thumb:
1000 detectors in space = 100 000 detectors on ground

Lensed coupled detectors
Lenslets



Horn coupled detectors
Platelets



MFT (2.5:1) — 89GHz to 225 GHz

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

Bands: 100, 119, 140, 166, 195

LFT (5.7:1) — 34GHz to 161 GHz

Bands: 40, 50, 60, 68, 78, 89, 100, 119, 140
68, 78, 89

1080 detectors
2 x 180 Trichroic TES

HFT (2.7:1) — 166 GHz to 448 GHz

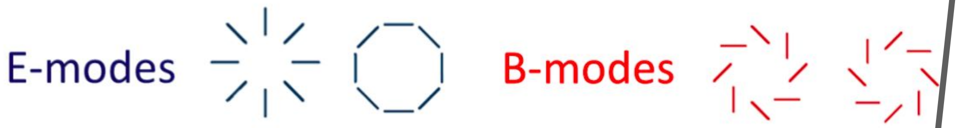
Bands: 195, 235, 280, 337, 402

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

📖 Westbrook+ SPIE 2020

I- Cosmology with the CMB
A) Introduction

In general, the **polarization** pattern has **two geometrical components**.
We can describe it by its **orientation** relative to itself.



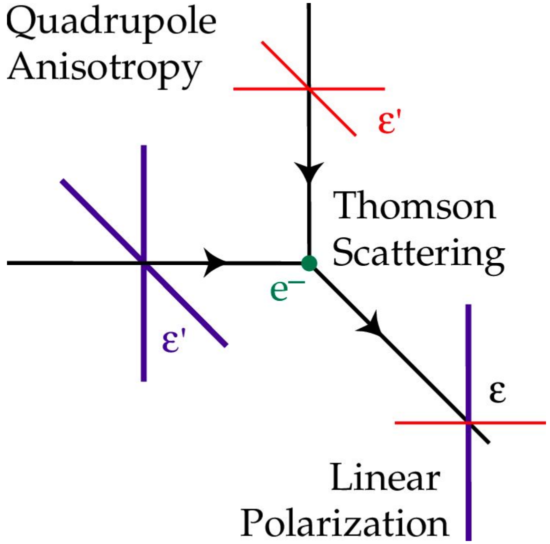
Various **sources** to **polarisation:**

- **Density perturbations (scalar** *ie* **1 dof)** only generate **parallel polarization** *ie* only **E-mode** polarization.

- **Gravitational waves (tensor)** generate both **E** and **B-mode** polarization.

- E-mode lensed into **B-mode** while photons propagate through the late-time universe.

The **quadrupolar variation** in temperature of the **incident radiation** implies a **linear polarisation** of the scattered light by **Thomson** scattering

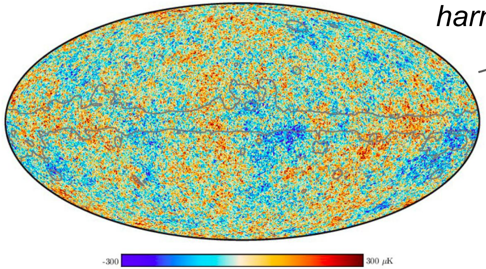


http://background.uchicago.edu/~whu/polar/webversion/node3.html

⇒ **E-modes polarisation anisotropies** **(δ ~ 1e-6).**

I- Cosmology with the CMB
A) Introduction

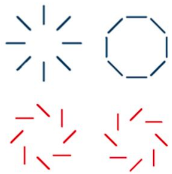
Intensity:
(1 dof T)

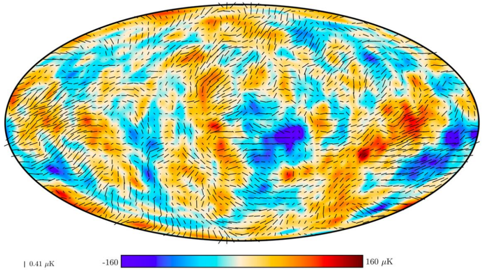


Polarisation:
(2 dof's E & B)

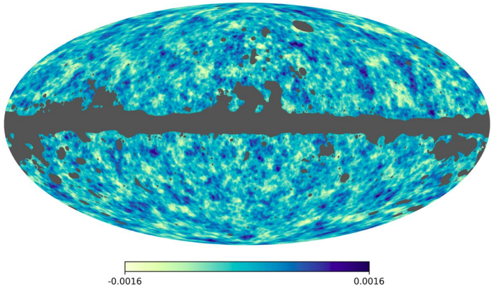
E-modes

B-modes

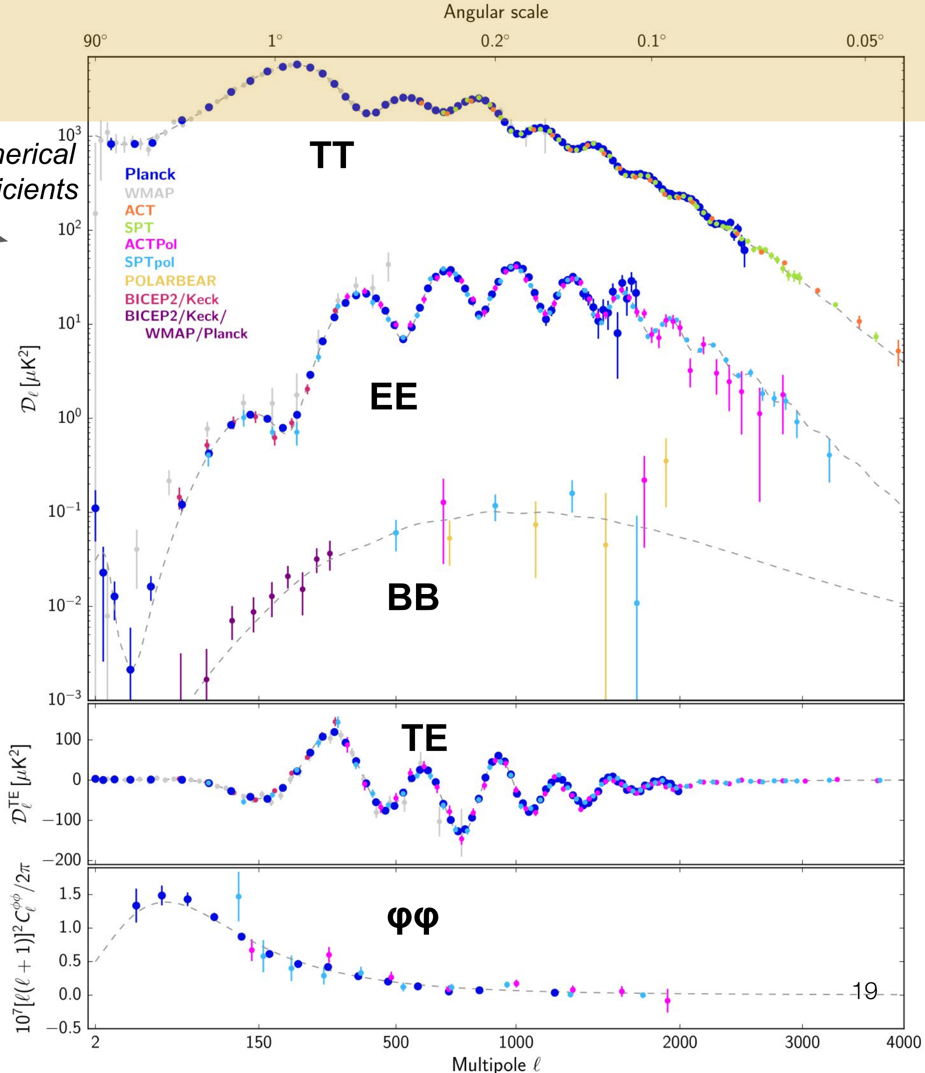




Lensing:
(1 dof φ)

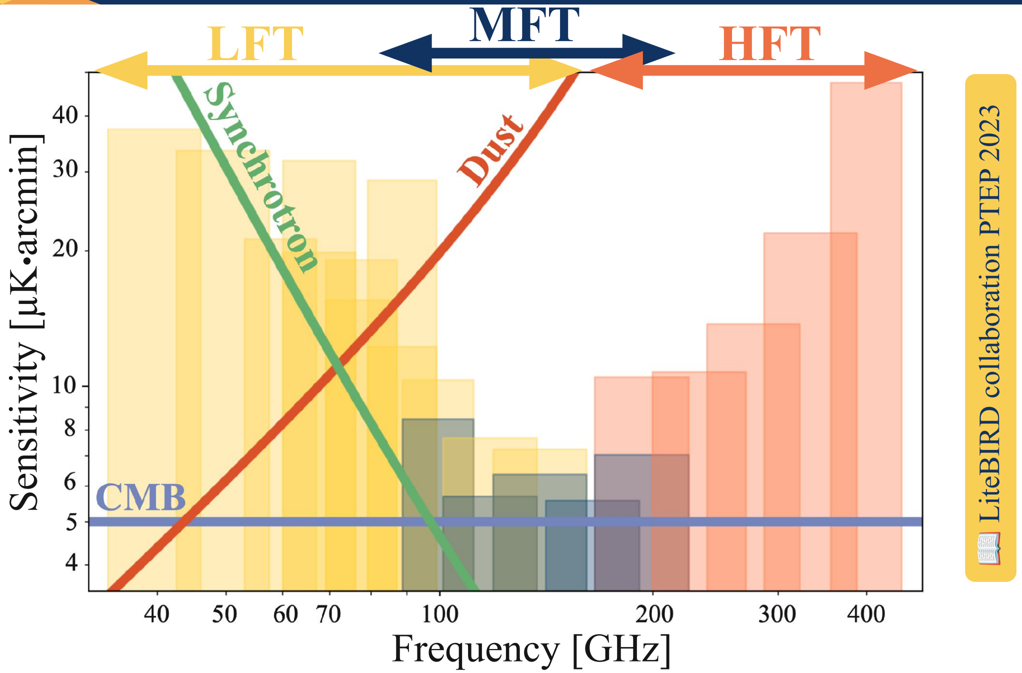


power of the spherical harmonics coefficients



[1807.06205] Planck 2018 results. I

Sensitivity per frequency & foregrounds



- Projected **polarization sensitivities** for a **3-year full-sky survey**
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- **Impact**: Reduction of the foreground signal by several orders of magnitude.
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LiteBIRD main scientific objectives

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

- For $r = 0$, **total uncertainty of $\delta r < 0.001$**
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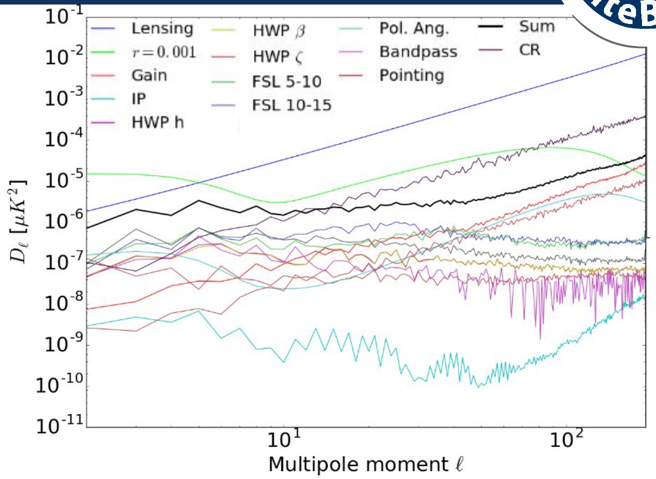
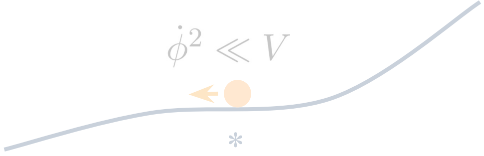
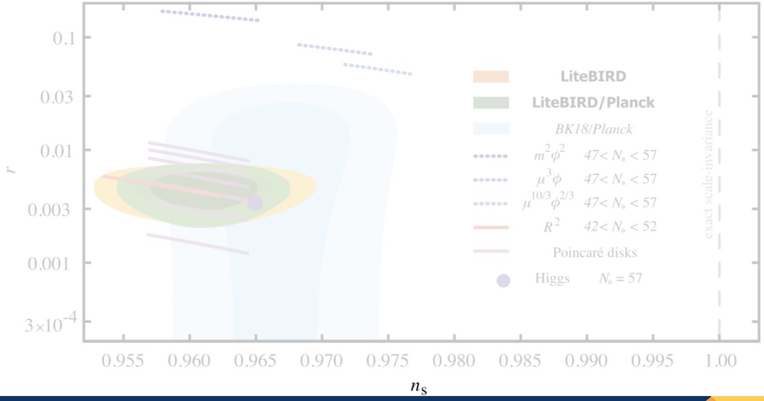


Constraints on **inflation models.** *eg.* single-field slow-roll:
A scalar field dominates the Universe energy budget and slowly rolls on its potential V around an energy scale "$_*$".



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



- Huge **discovery impact**: inflation **energy scale** V (and V', V''), **field excursion** ($r > 0.01$ => excursion exceeding the Planck mass)
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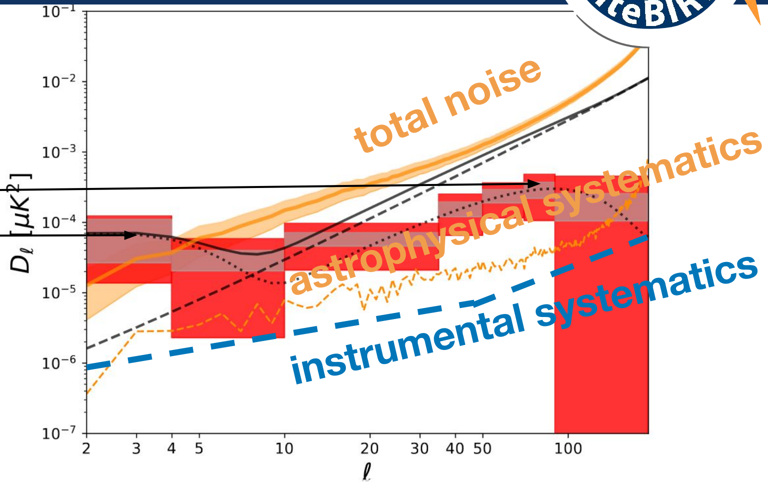
  - reionization ($2 < \ell < 10$) peak



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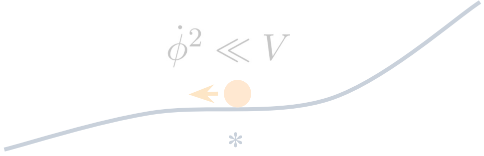

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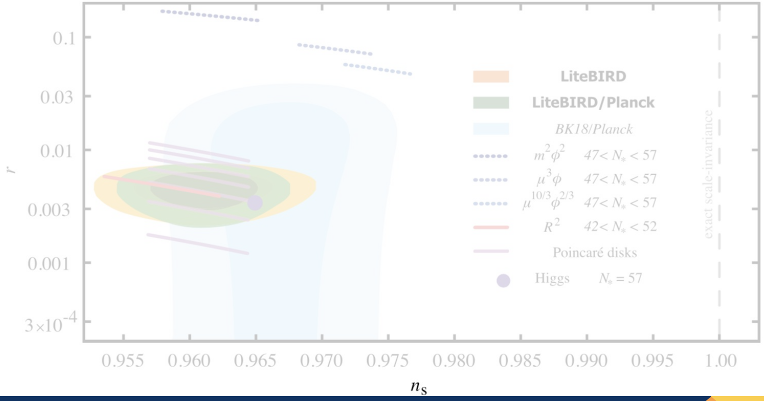

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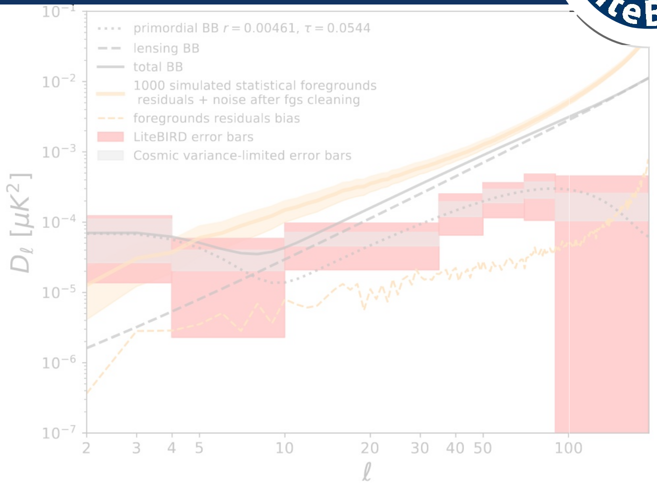

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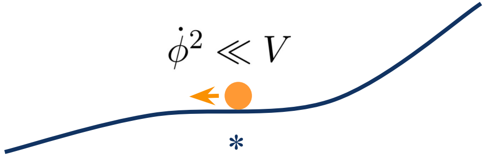
eg. single-field slow-roll:



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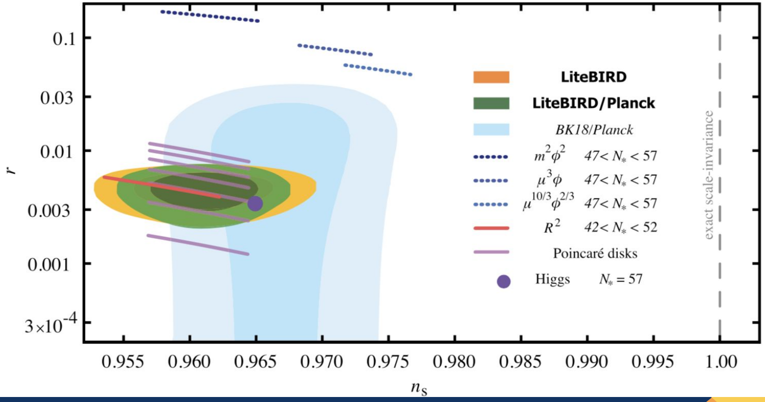

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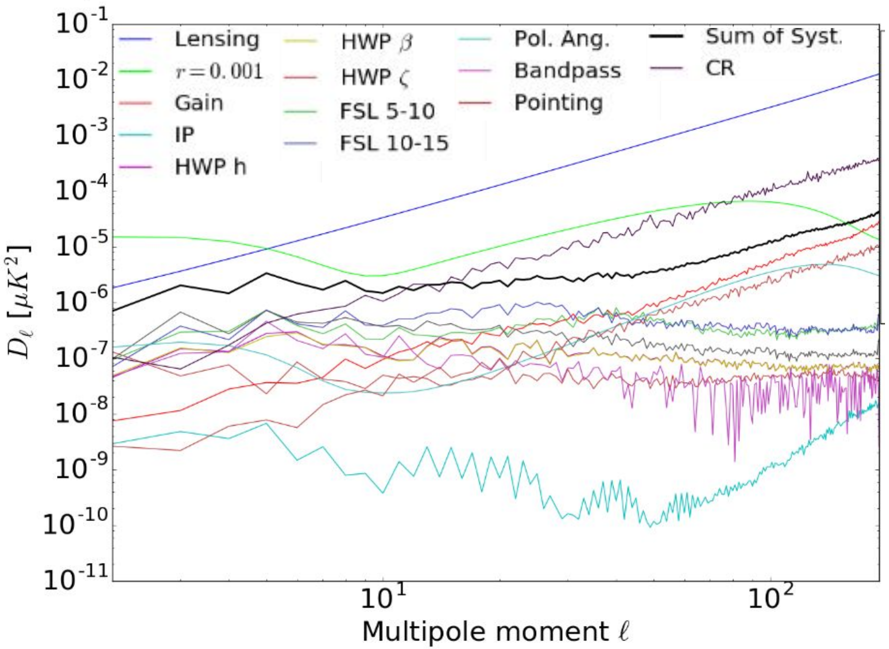

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LiteBIRD constraints on inflation

- **HOW?**

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

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

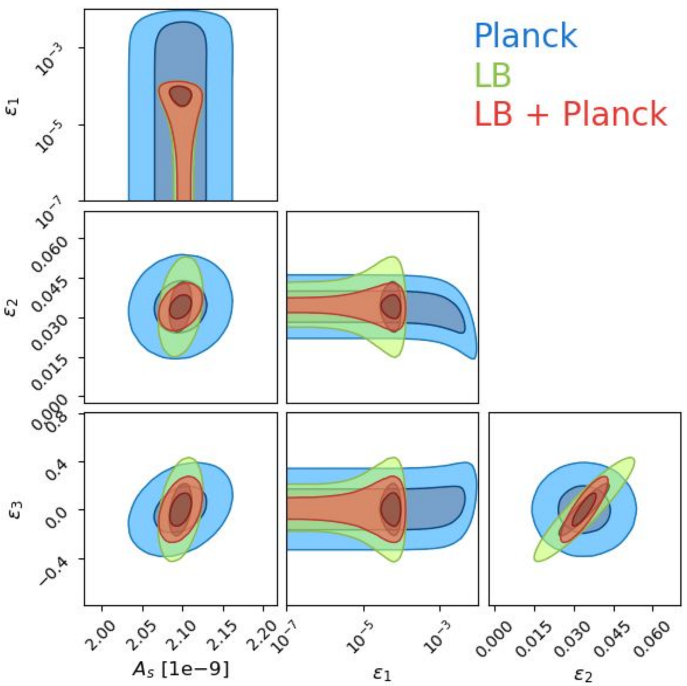
$$n_s \equiv 1 + \left.\frac{\mathrm{d}\ln \mathcal{P}_\zeta}{\mathrm{d}\ln k}\right|_{k_*} \overset{\text{SRLO}}{\simeq} 1 - 2\varepsilon_{1*} - \varepsilon_{2*}$$

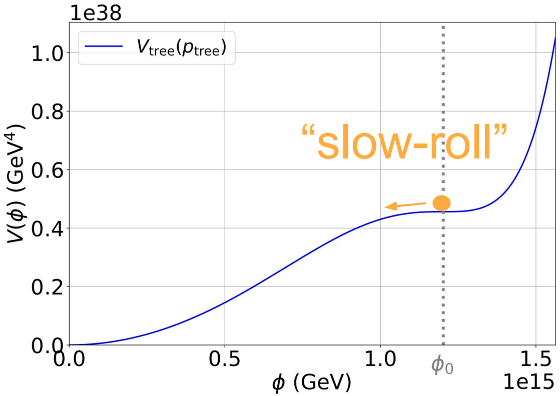
$$n_T \equiv \left.\frac{\mathrm{d}\ln \mathcal{P}_h}{\mathrm{d}\ln k}\right|_{k_*} \overset{\text{SRLO}}{\simeq} -2\varepsilon_{1*}$$

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

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

illustrative forecast figure





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

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

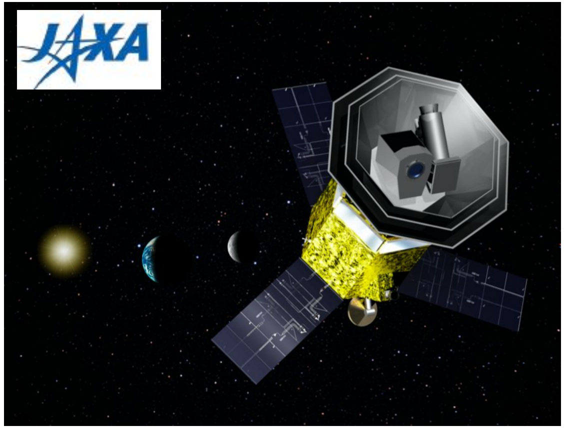
$$\varepsilon_3 \overset{\text{SRLO}}{\simeq} \frac{2}{\varepsilon_2}M_{\text{Pl}}^4\left[\frac{V_{\phi\phi\phi}V_\phi}{V^2} - 3\frac{V_{\phi\phi}}{V}\left(\frac{V_\phi}{V}\right)^2 + 2\left(\frac{V_\phi}{V}\right)^4\right],$$

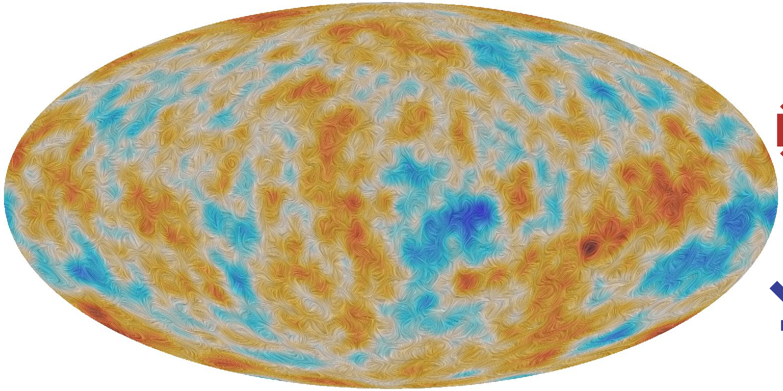
Exciting science goal:
an *r* measurement with **LiteBIRD** => constraints on V, V' and V'' in single-field slow-roll scenario

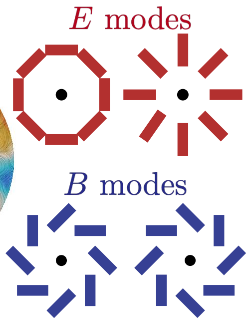
LiteBIRD overview

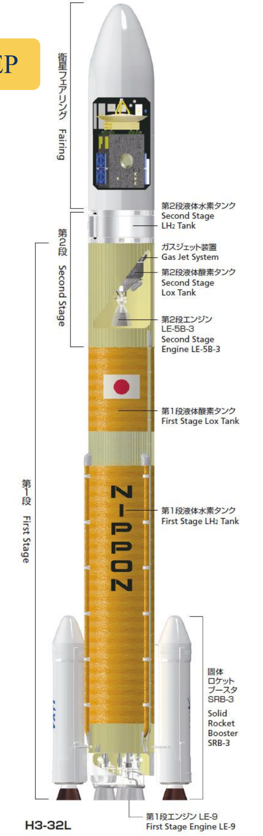
- Lite (Light) satellite for the study of *B*-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's L-class mission selected in May 2019
- Expected launch in **JFY 2032** with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency 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



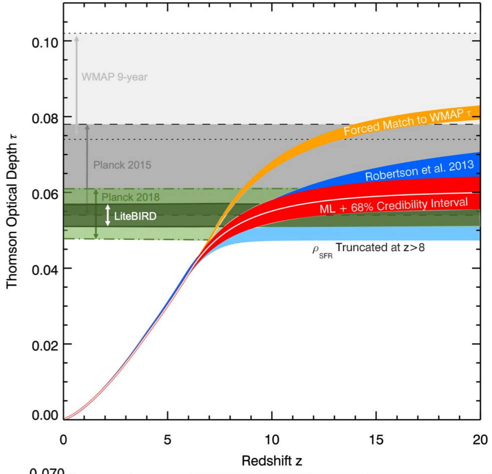




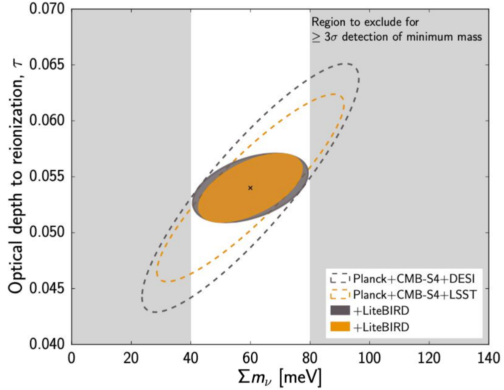


Optical depth, reionization and neutrino masses

- 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 $\Delta(z_{\text{reion}})$
  - **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



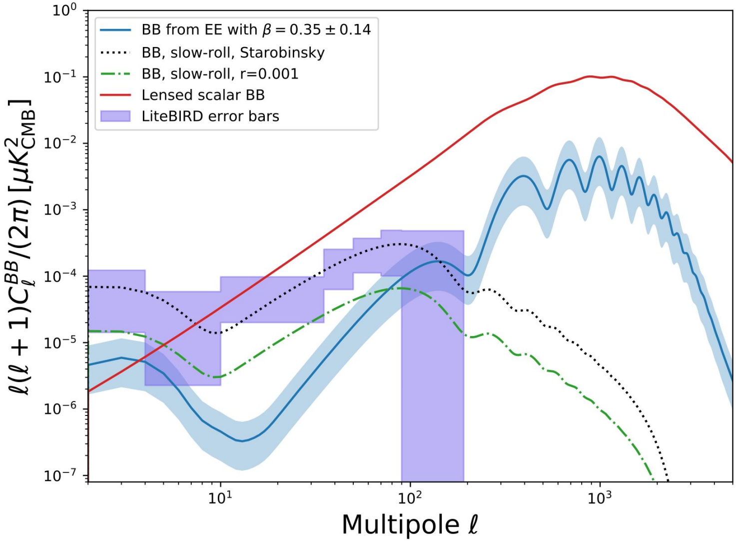
📖 adapted from Robertson+2015



📖 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 **$\beta = (0.34 \pm 0.09)°$** (📖 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**

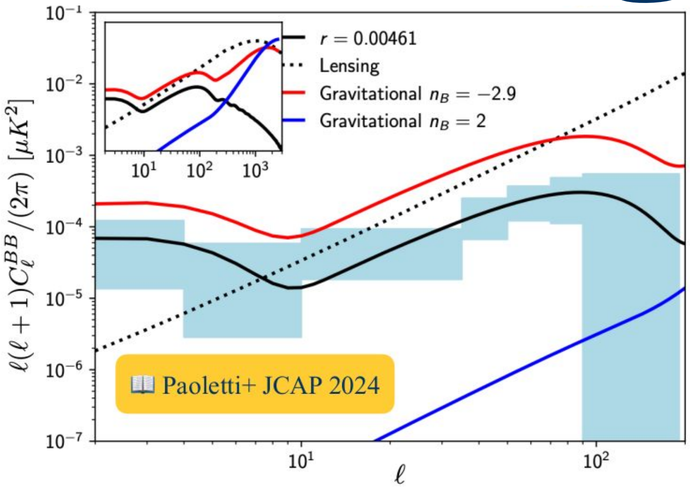


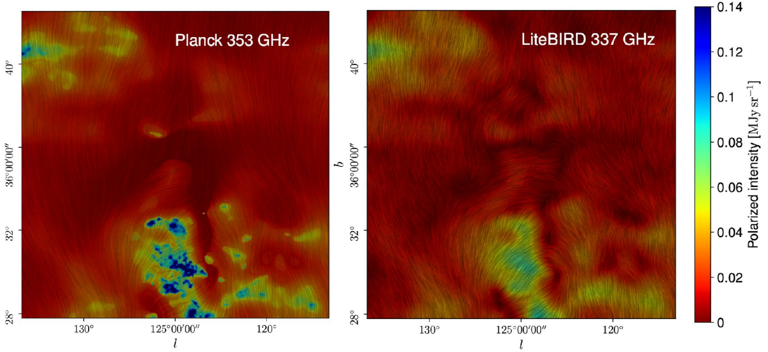
📖 LiteBIRD collaboration PTEP 2023

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

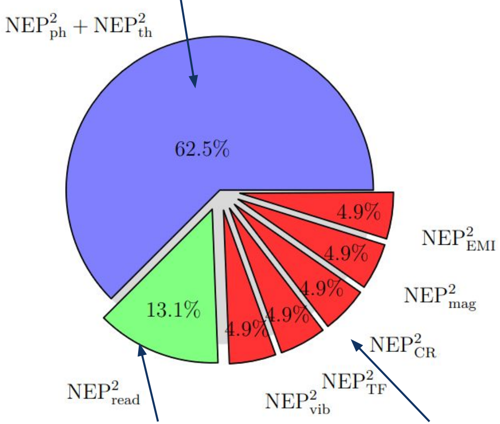




Error budget after foreground cleaning

Statistical uncertainties = Systematic uncertainties

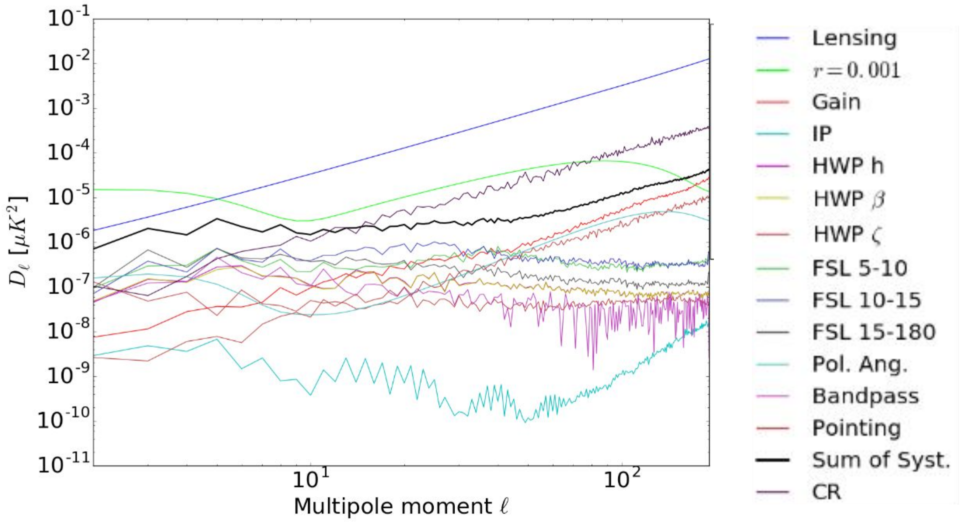
Fudamental noise



+ Readout noise **+ External noise**

(increased by foreground cleaning)

Instrumental systematics:



+ Astrophysical systematics

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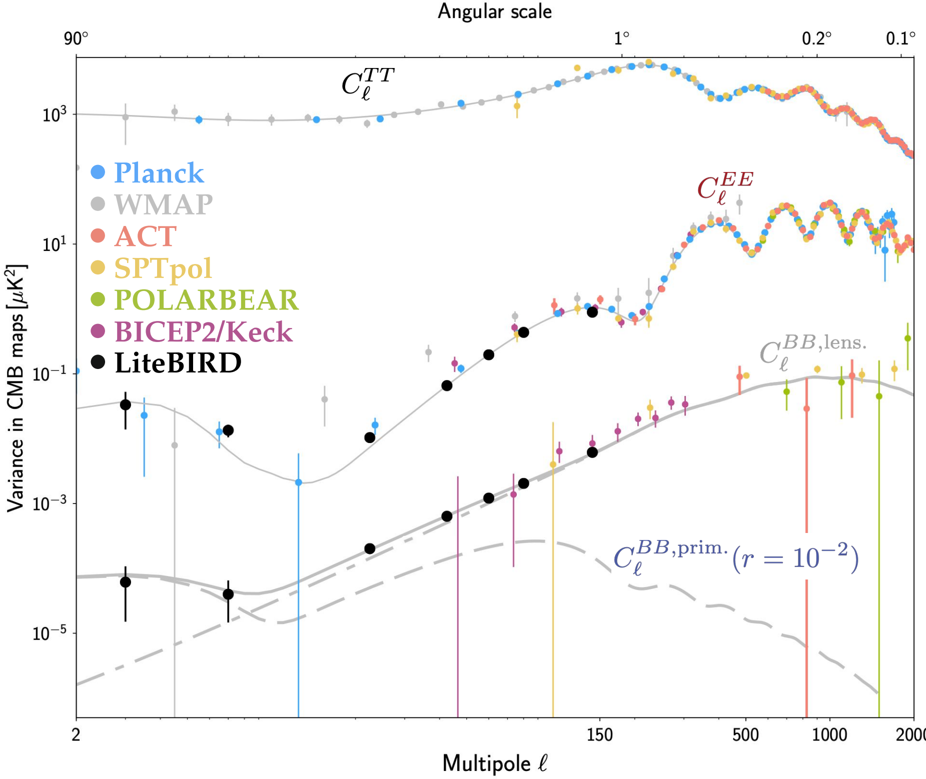
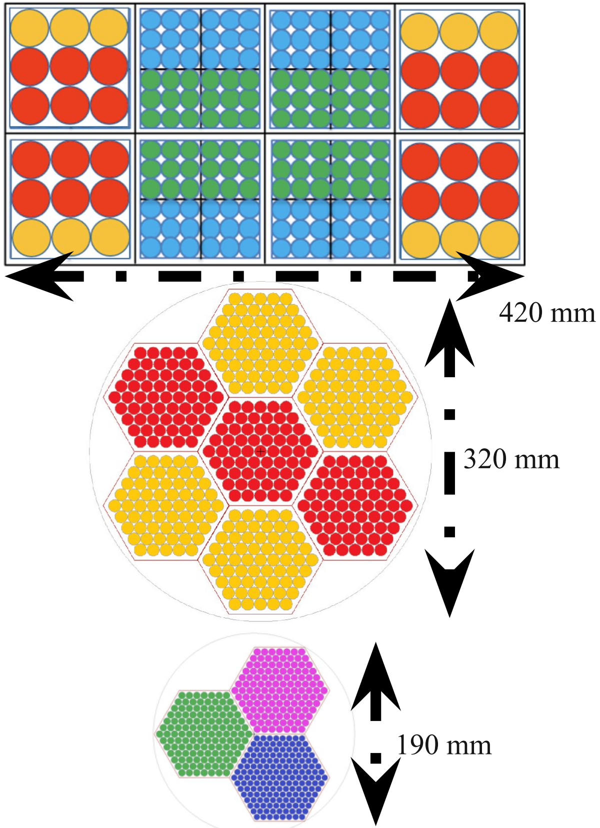


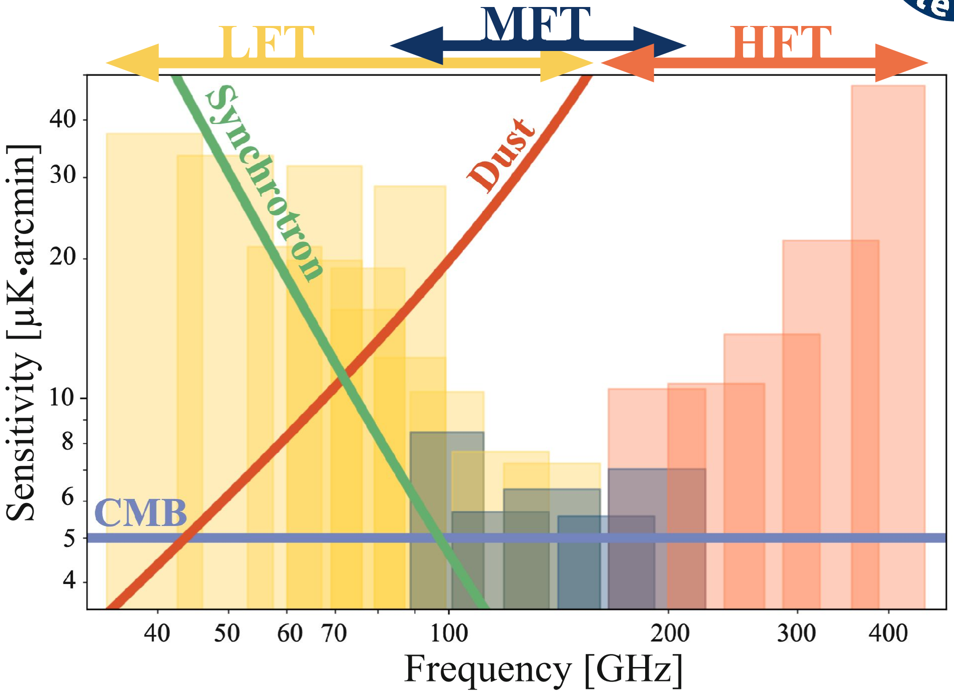
LiteBIRD sensitivities

LFT



MFT

HFT



LiteBIRD collaboration PTEP 2023

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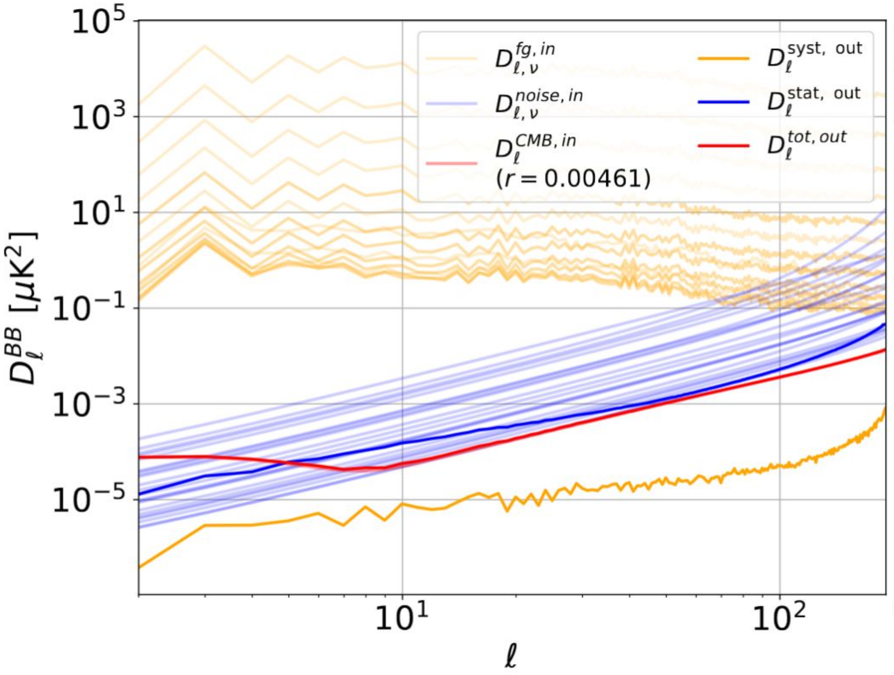
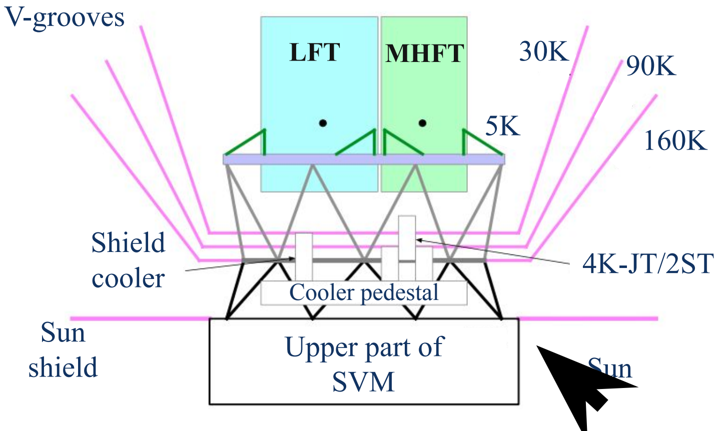
- Take benefit of the **frequency coverage** to fit the frequency-dependent astrophysical components
- **Parametrize** the foreground frequency dependency.
- **Synchrotron**: power law with spatially-varying index
- **Dust**: modified blackbody
- **Multi-Clustering** interface with foregrounds data to 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

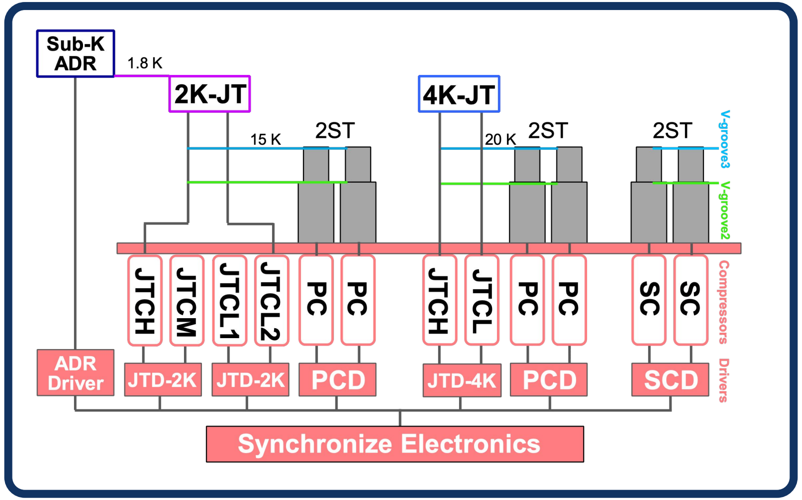
Impact on the recovered spectra:



method: fgbuster, details in

LiteBIRD cryogenic system

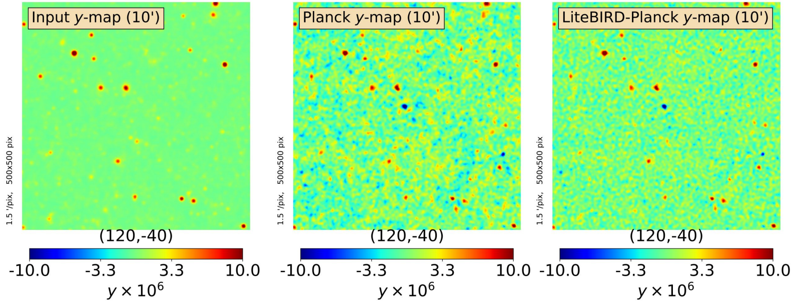


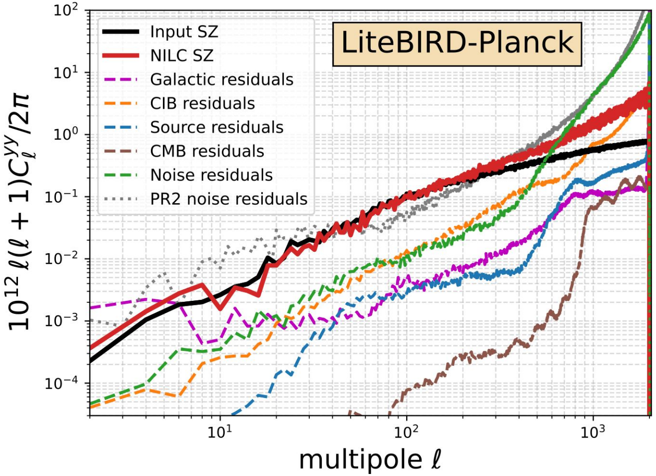


- Optimized to ensure **maximum stability** of the focal planes and of the optical elements of the telescopes
  - Radiative cooling to 30 K with V-grooves
  - Two 2ST are used for cooling V-grooves 2 and 3
  - A 4K-JT and two 2ST are used to cool the LFT and the MHFT
  - A 2K-JT, two 2ST, and a sub-K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

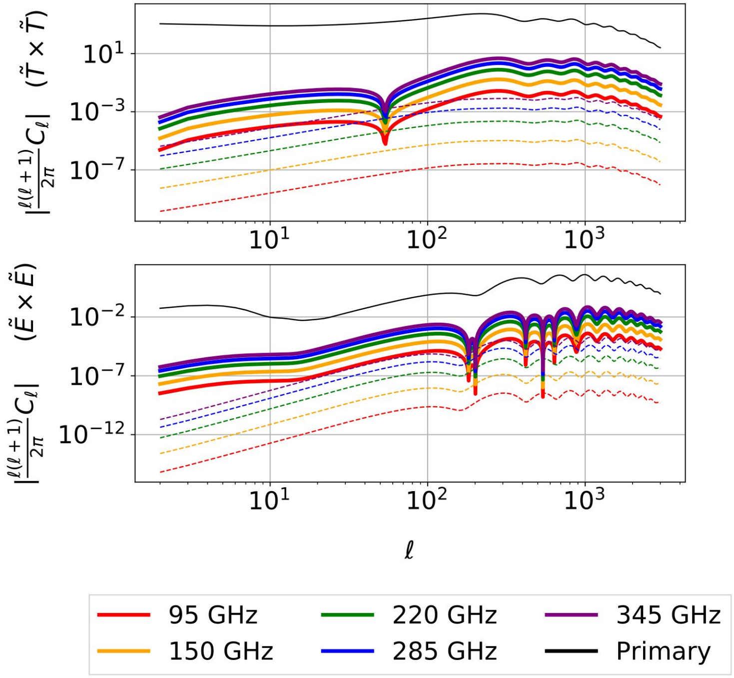




Remazeilles+ JCAP 2024

Anisotropic CMB spectral distortions

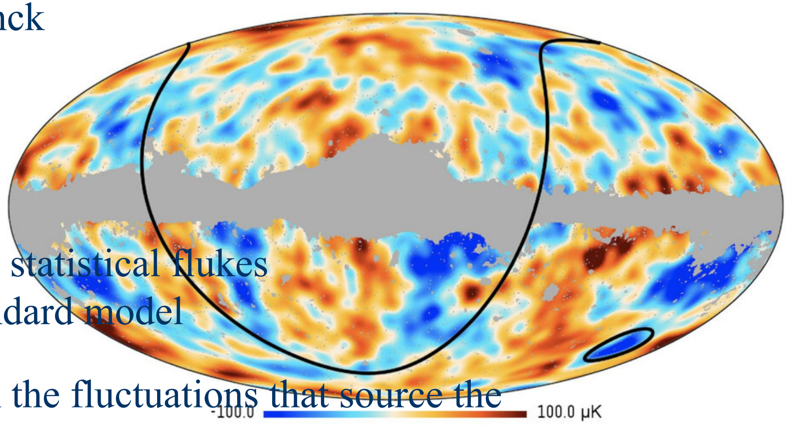
- LiteBIRD will be sensitive to any **spatially-varying CMB spectral distortion**, beyond the SZ effect
  - **Rayleigh scattering**. LiteBIRD will have sensitivity to measure at **25-sigma** (📖 Beringue et al. 2021) the frequency-dependent CMB anisotropies due to Rayleigh scattering by HI at the LSS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

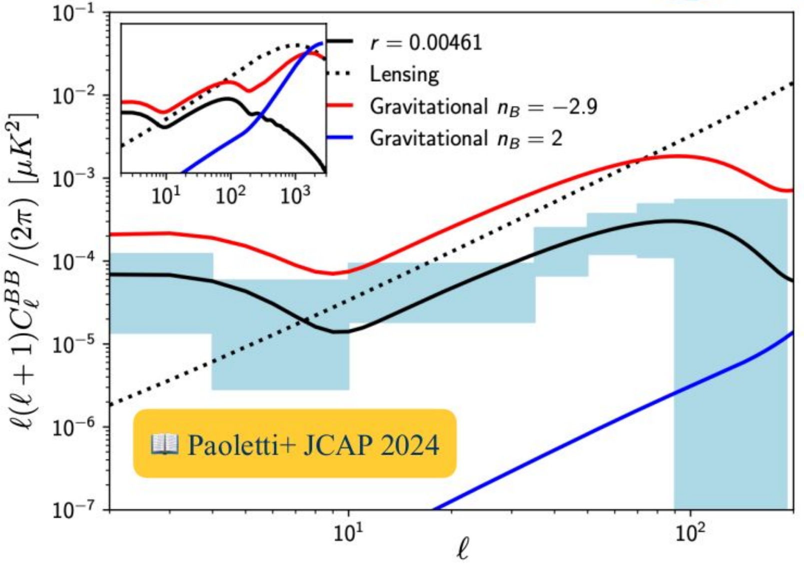
- Various so-called anomalies have been found in WMAP and Planck temperature data that exert a mild tension against the ΛCDM cosmological model:
  - a lack of power on large angular scales
  - the alignment of the quadrupole and octopole moments
  - a hemispherical asymmetry in power on the sky
  - a 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

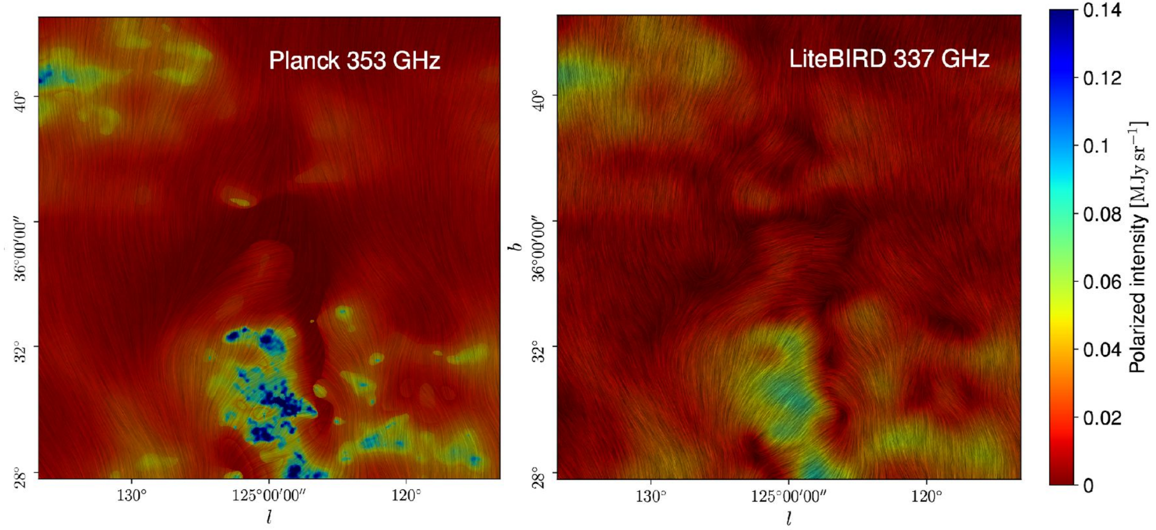


Upper limits on PMF amplitude for n_B = -2.9	
Gravitational effect	$B_{1Mpc} < 0.8$ nG
Ionization history	$\sqrt{<B^2>} < 0.7$ nG
Faraday rotation	$B_{1Mpc} < 3.2$ nG
Non-Gaussianities	$B_{1Mpc} \lesssim 1$ nG

Galactic astrophysics

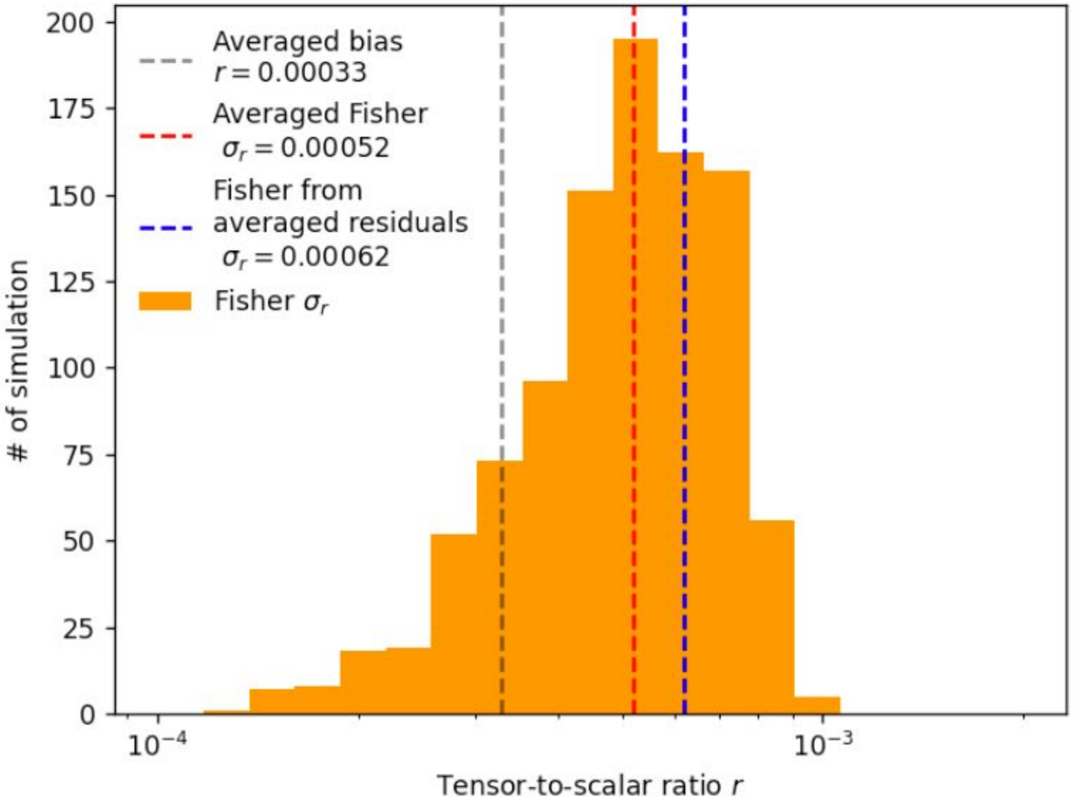
- LiteBIRD will provide 15 high-sensitivity polarization full-sky maps from 40 to 402 GHz
- Sensitivity improved by a factor of 5 at 40 GHz and 10 at 402, with respect to Planck
- Gain in spectral resolution

- **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!

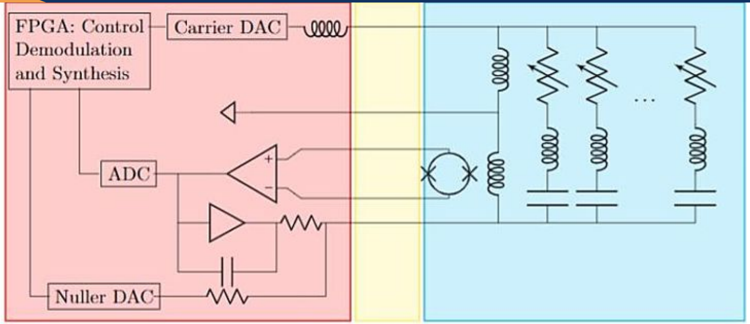


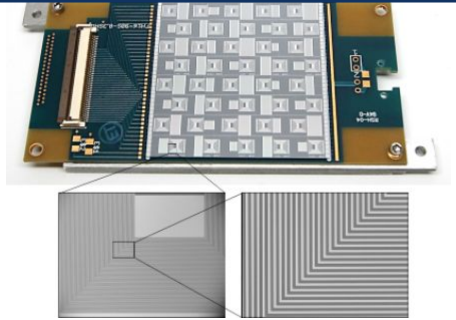
Foreground cleaning

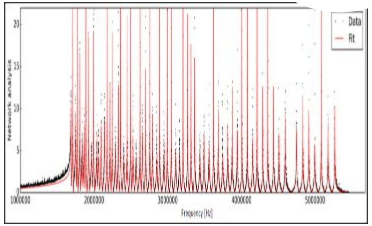
- "Multi-Clustering technique" (extension of xForecast)
- Distribution of the recovered r in 1000 simulations with input $r = 0$, with and without foreground residuals
- Bias from foreground (PySM `d1s1`) residuals is found to be small
- Final value: **$r = (3.3 \pm 6.2)\times10^{-4}$**



LiteBIRD readout system







Cold Readout LC filters for MUX

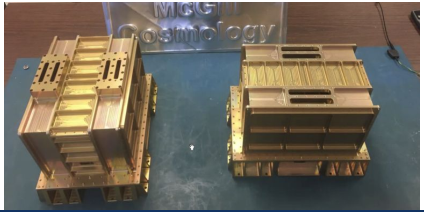
- Digital frequency multiplexing (**DfMux**) readout technology enables the readout of many Transition Edge Sensors (TES) with fewer components and a low wire count, with no increase of system noise (⇒ **photon noise limited** detector performance)
- Superconducting resonators are used to assign unique 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

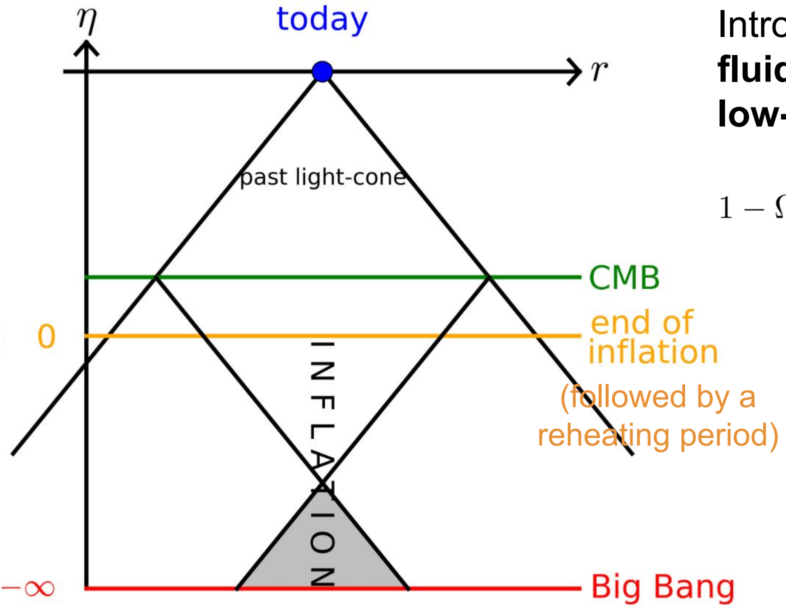
Digitizer assembly / Signal Processing Unit

Digitizer assembly



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**.

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

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

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

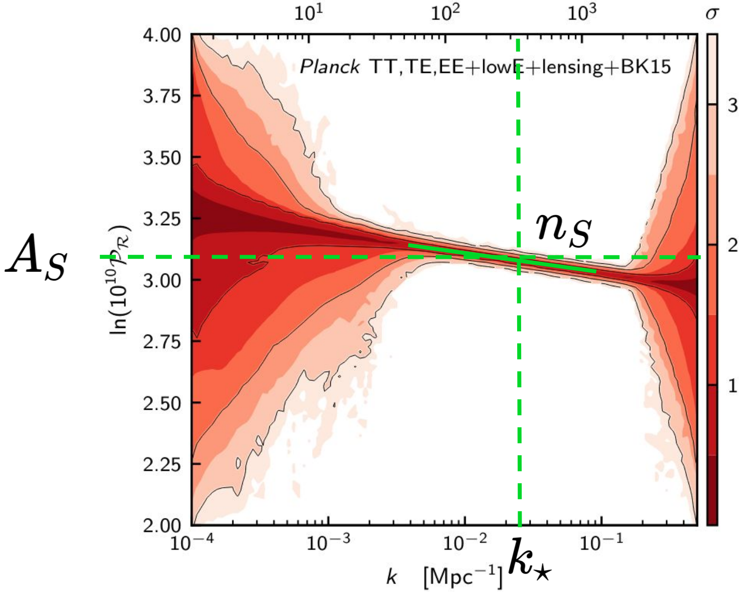
A ($\ddot{a} > 0$: **accelerated**) **universe** before radiation era solves them all if $N_{\rm tot} \equiv \ln\frac{a_{\rm end}}{a_{\rm in}} \geq 50$

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: A_S, n_S

consistent with 0: α_S



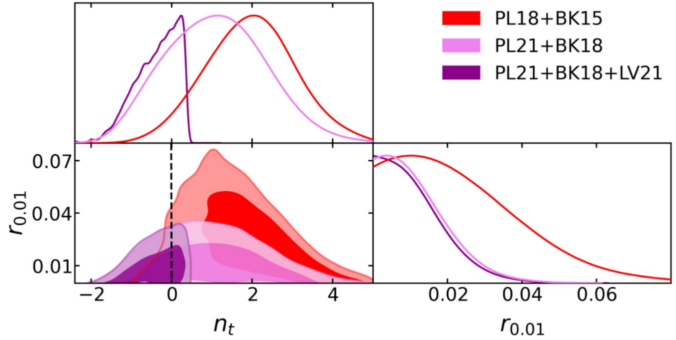
[1807.06211] Planck 2018 results. X. Constraints on inflation

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

consistent with 0: r, n_t

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	$f_{NL} = -0.9 \pm 5.1$
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:

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

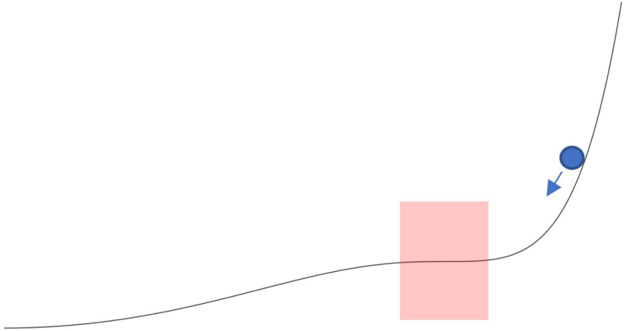
$$' = \frac{\mathrm{d}}{\mathrm{d}\phi}$$

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

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**.



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

$$\Rightarrow \quad p = -\rho$$

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**

$$\varepsilon_0 = \frac{H_{\rm in}}{H}$$
$$\varepsilon_{n+1} = \frac{\mathrm{d}\ \ln|\varepsilon_n|}{\mathrm{d}N} \ll 1$$

in terms of V (SRLO):

$$\varepsilon_1 \simeq \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$
$$\varepsilon_2 \simeq 2M_{\rm Pl}^2\left[\left(\frac{V'}{V}\right)^2 - \frac{V''}{V}\right] \ll 1$$
$$\ldots$$

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** $\mathscr{P}_\zeta$ and **tensor** $\mathscr{P}_h$.

<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>

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

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

<u>Tilt</u>

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

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

<u>Running</u>

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

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

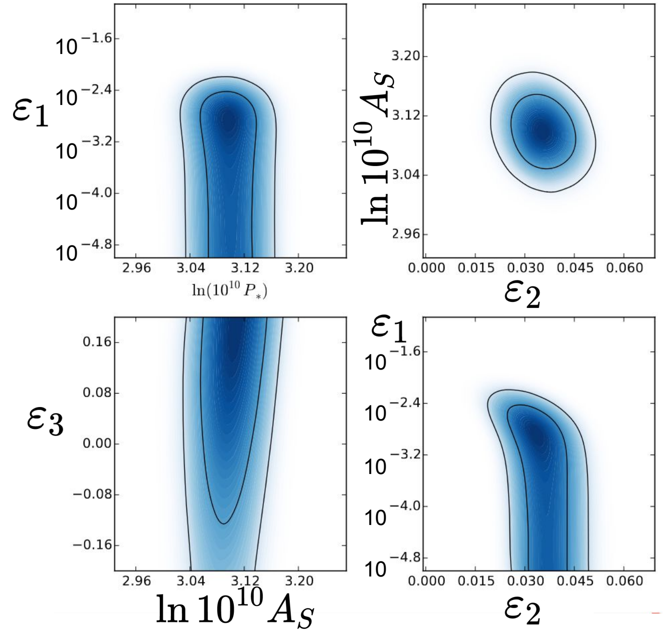
$\rho_\star = V_\star = 3M_\mathrm{Pl}^2 H_\star^2 = \dfrac{3\pi^2 M_\mathrm{Pl}^4 A_S r}{2}$: measure of ***r*** = measure of **inflationary energy scale**

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

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

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

Planck data



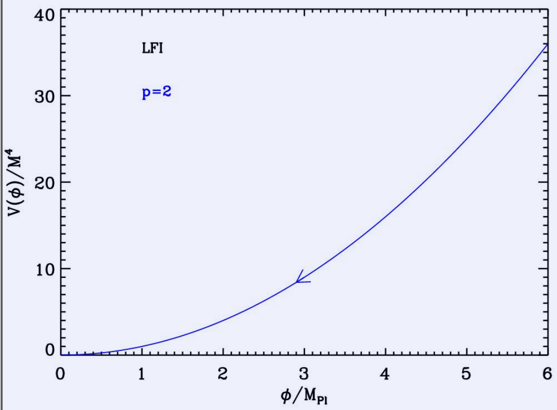
J. Martin, C. Ringeval and V. Vennin
Information Gain on Reheating: the One Bit Milestone (2016)

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

$$\phi \rightarrow V(\phi, p), \; \ln R_{\rm rad} \implies \phi_* \implies \{\varepsilon_{i*}\} \implies \{A_S,\, n_S,\, n_{S,\rm run},\, r,\, n_T,\, n_{T,\rm run},\, N_{\rm e-folds}\, ...\}$$

(Motivated) choice. Eg:

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



(Motivated) choice for the reheating duration

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

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

See appendix

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

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

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

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

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

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

$$\ldots$$

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Amplitude

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

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Tilt

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

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

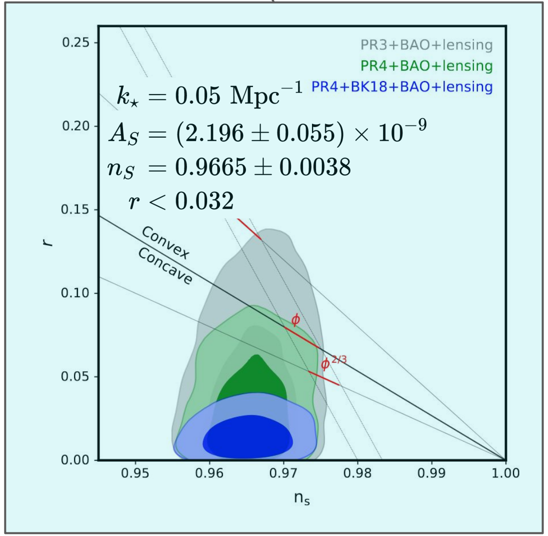
Running

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

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

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

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

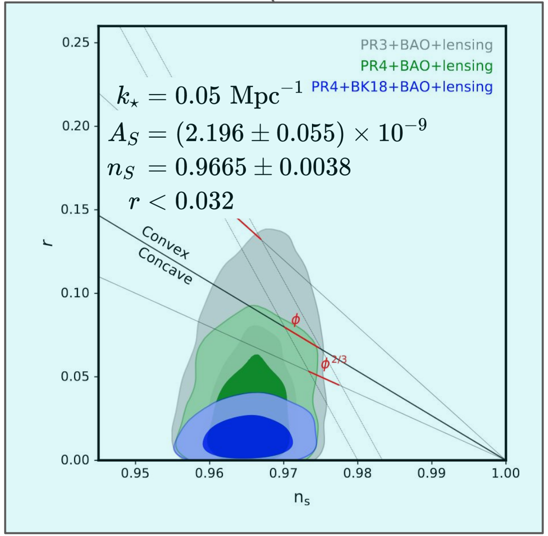


M. Tristram et al. (2022), ***2112.07961***

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

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

for a given potential shape

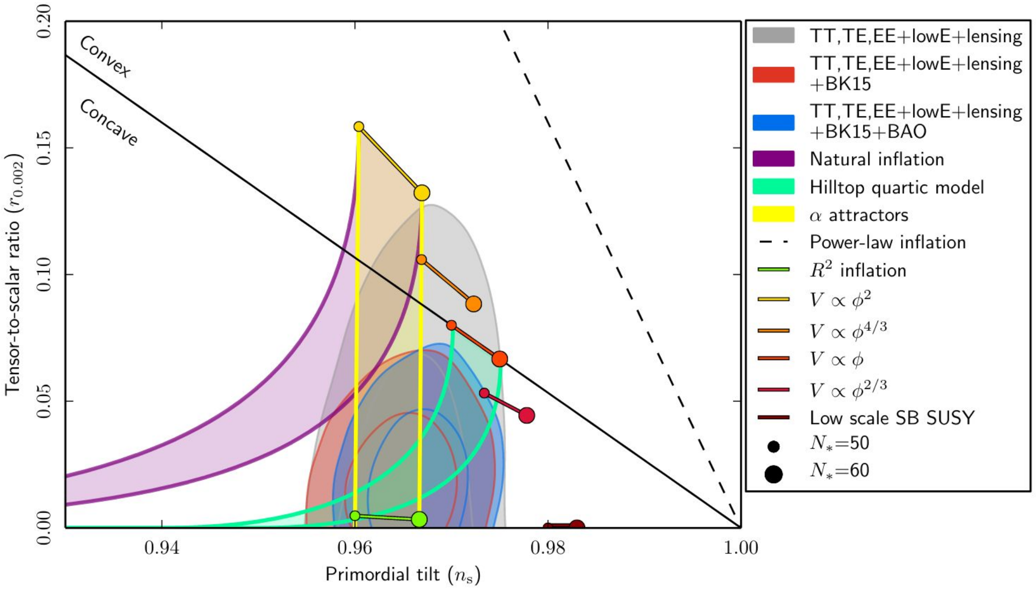


M. Tristram et al. (2022), ***2112.07961***

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:

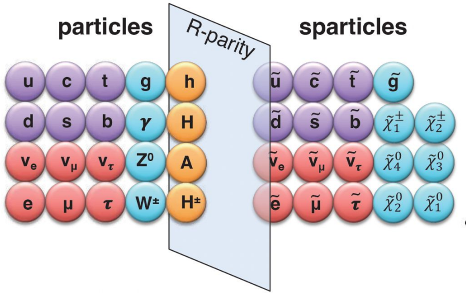
$$k_\star = 0.05 \text{ Mpc}^{-1}$$

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

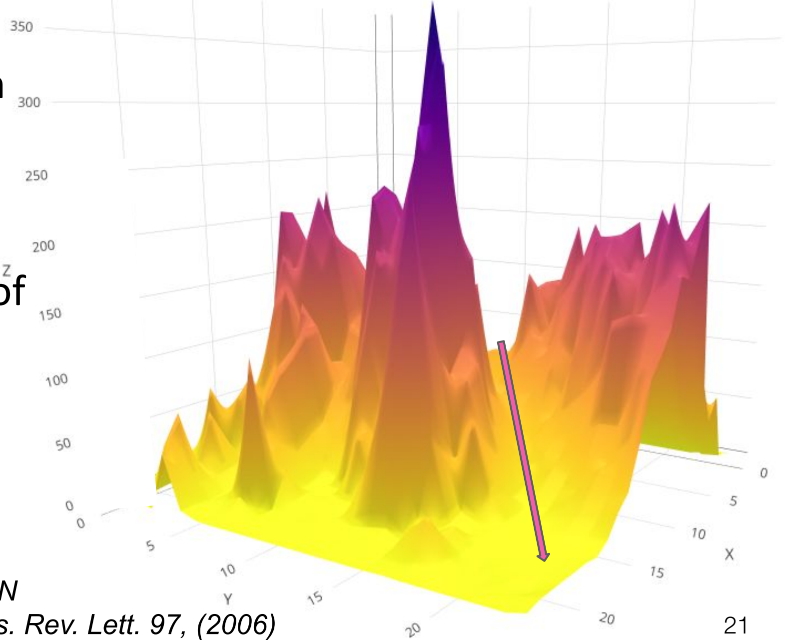
Planck Collaboration VI, Astron. Astrophys. 641, A6 (2020).

- 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



- **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)
....

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

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**:

$$m_\phi^2 = \frac{m^2_{\tilde{u}^i_R} + m^2_{\tilde{d}^j_R} + m^2_{\tilde{d}^k_R}}{3}$$

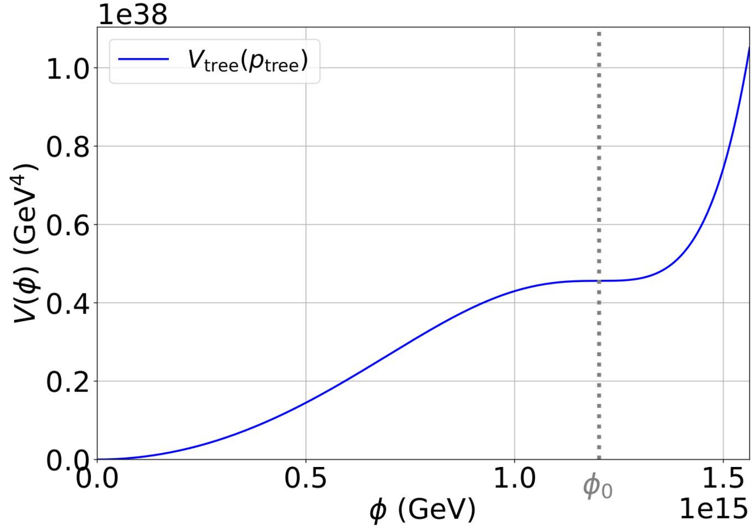
$$A_6(M_{\mathrm{SUSY}}) = \frac{6-\sqrt{3}}{3-\sqrt{3}}A_t(M_{\mathrm{SUSY}})$$

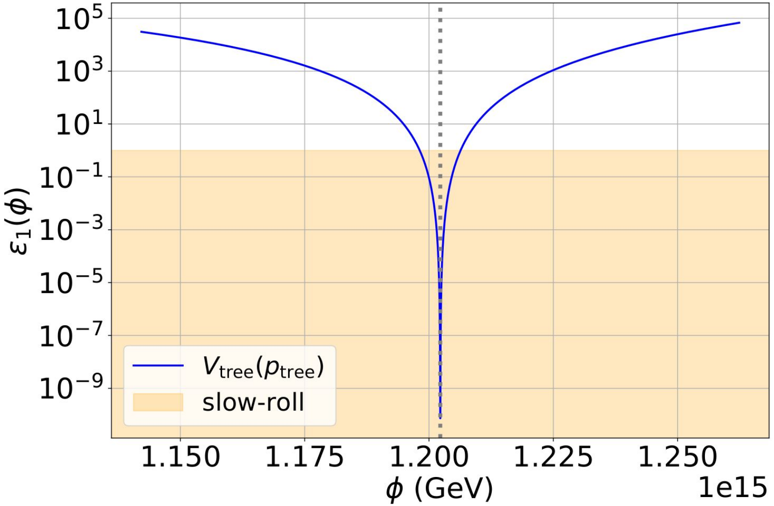
A) Example of a well-embedded model in particle-physics: MSSM-inflation

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

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.

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

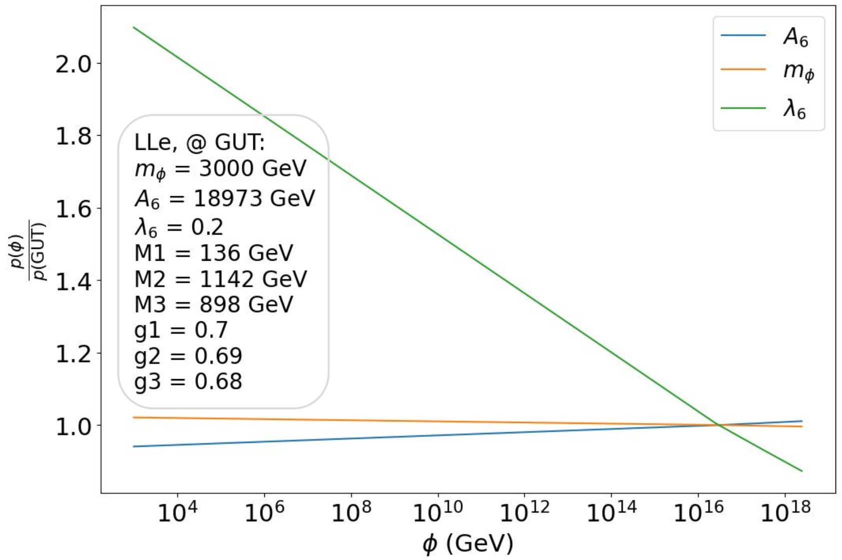
- **Radiative corrections**
  - fully computable with the **Renormalization Group Equations**
  - functions of the **gaugino masses** and the **gauge couplings** at **GUT scale**.
  - vary whether the inflaton is along ***udd*** or ***LLe***

Ex : *LLe*

$$Q\frac{dm_\phi^2}{dQ} = -\frac{1}{6\pi^2}\left(\frac{9}{10}M_1^2 g_1^2 + \frac{3}{2}M_2^2 g_2^2 + Y_{m_\phi}^{L^i L^j e^k}\right),$$

$$Q\frac{d\widetilde{A}_6}{dQ} = \frac{1}{2\pi^2}\left(\frac{9}{10}M_1 g_1^2 + \frac{3}{2}M_2 g_2^2 + Y_{A_6}^{L^i L^j e^k}\right),$$

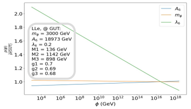
$$Q\frac{d\lambda_6}{dQ} = -\frac{\lambda_6}{4\pi^2}\left(\frac{9}{10}g_1^2 + \frac{3}{2}g_2^2 + Y_{\lambda_6}^{L^i L^j e^k}\right),$$

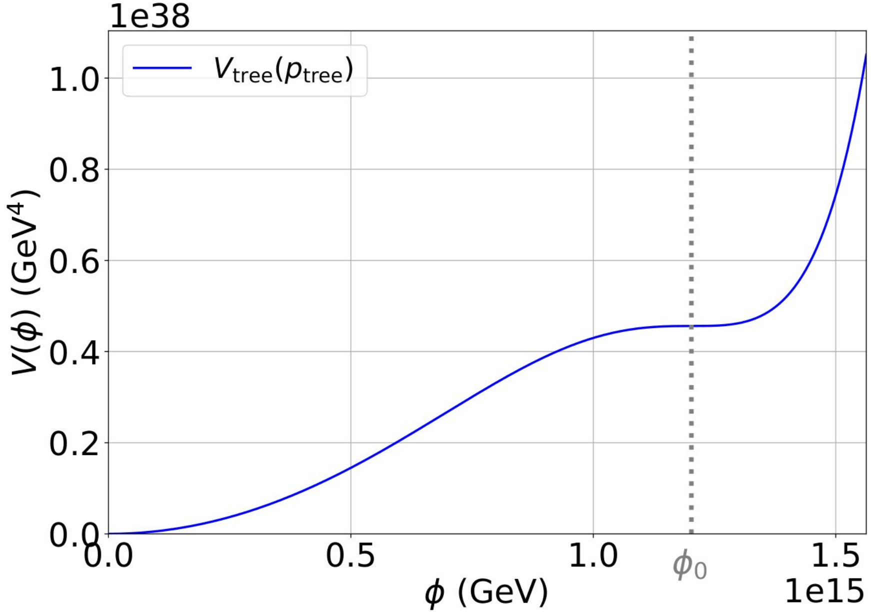


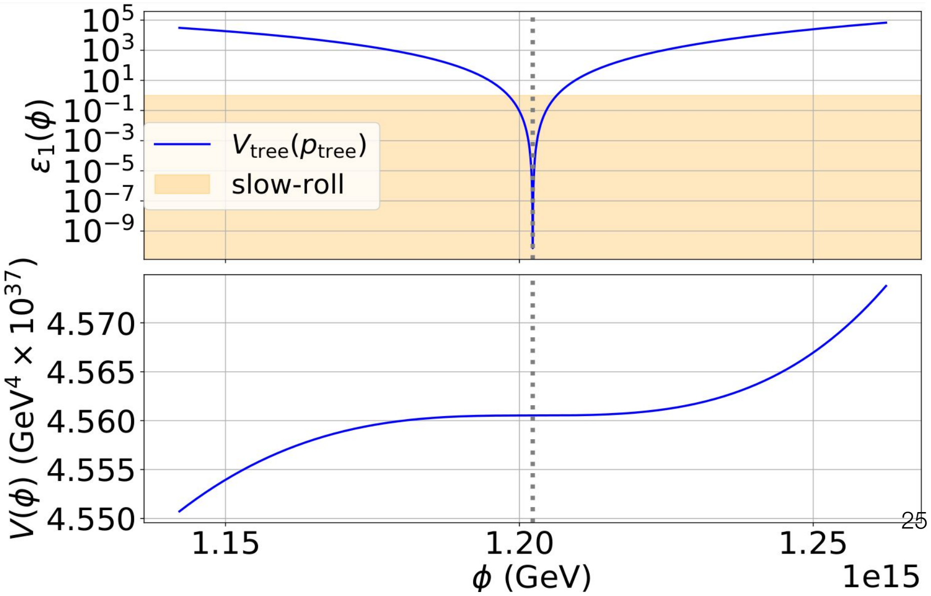
NEW • V_{RGE} whose parameters depend on ϕ.

$$m_\phi^2 = m_\phi^2(\phi)$$
$$A_6 = A_6(\phi)$$
$$\lambda_6 = \lambda_6(\phi)$$

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





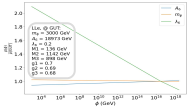


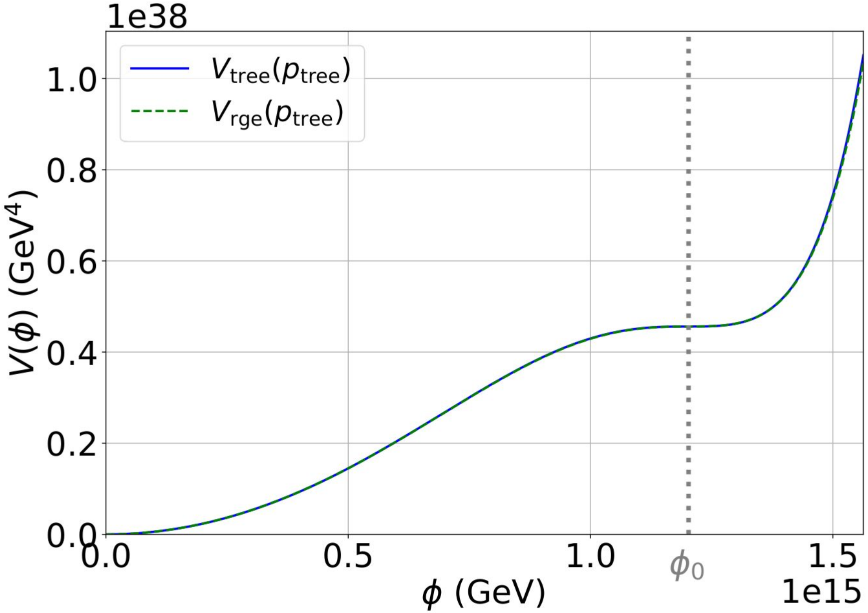
B) MSSM-inflation: Radiative corrections impact on the potential

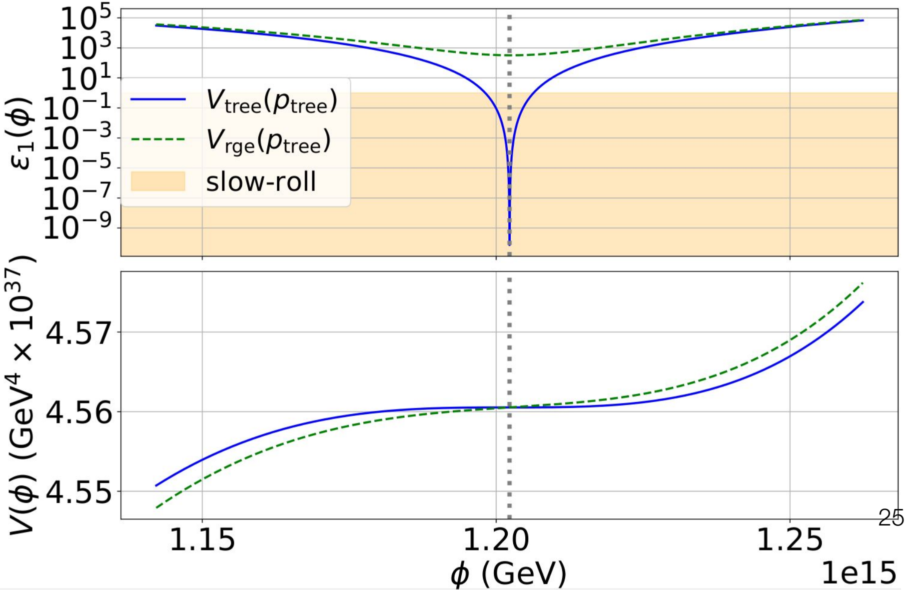
NEW • V_{RGE} whose parameters depend on ϕ.

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

$$m_\phi^2 = m_\phi^2(\phi)$$
$$A_6 = A_6(\phi)$$
$$\lambda_6 = \lambda_6(\phi)$$



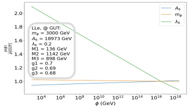




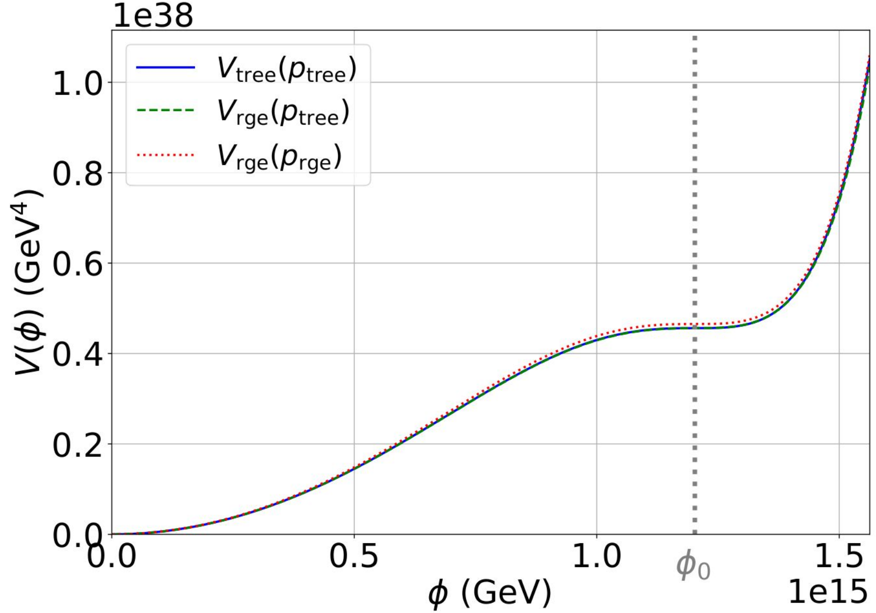
III- Embedding slow-roll in HEP
B) MSSM-inflation: Radiative corrections impact on the potential

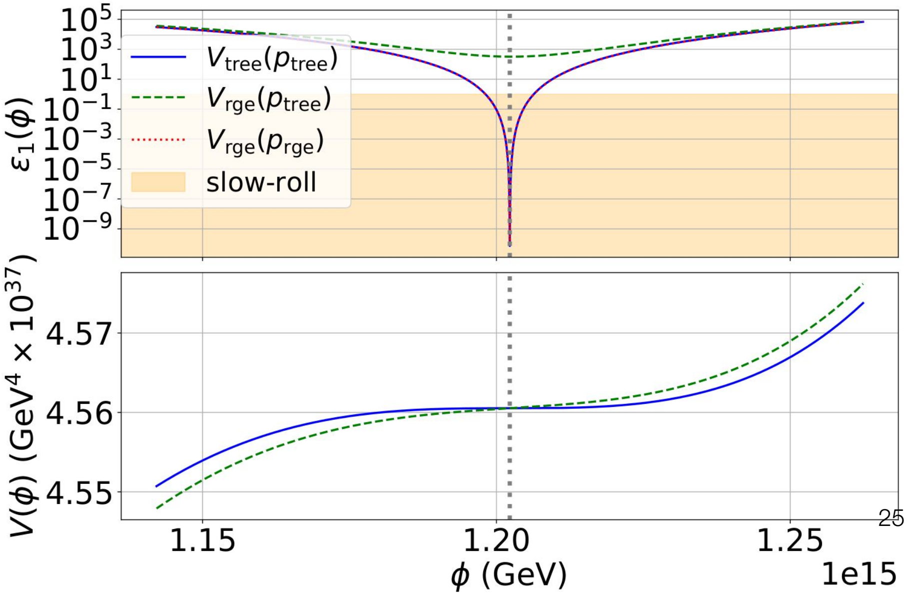
NEW • V_{RGE} whose parameters depend on ϕ.

$$m_\phi^2 = m_\phi^2(\phi)$$
$$A_6 = A_6(\phi)$$
$$\lambda_6 = \lambda_6(\phi)$$



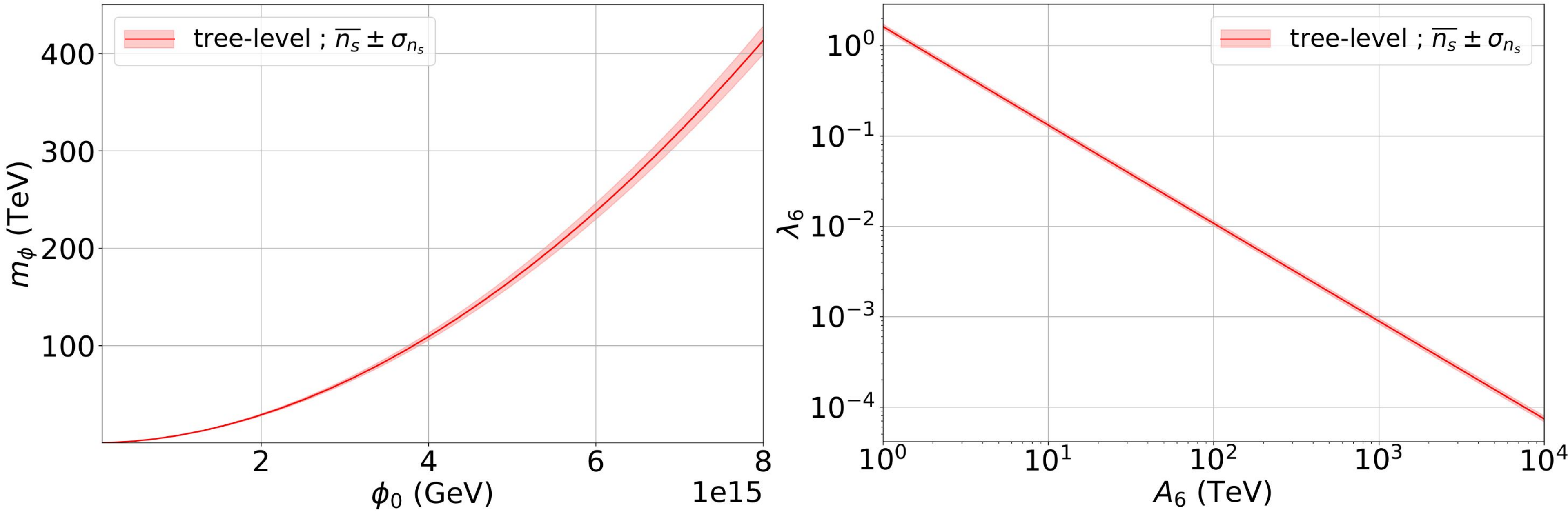
- **Radiative corrections**
  - fully computable with the **Renormalization Group Equations**
  - functions of the **gaugino masses** and the **gauge couplings** at **GUT**.
  - vary whether the inflaton is along ***udd*** *or* ***LLe***



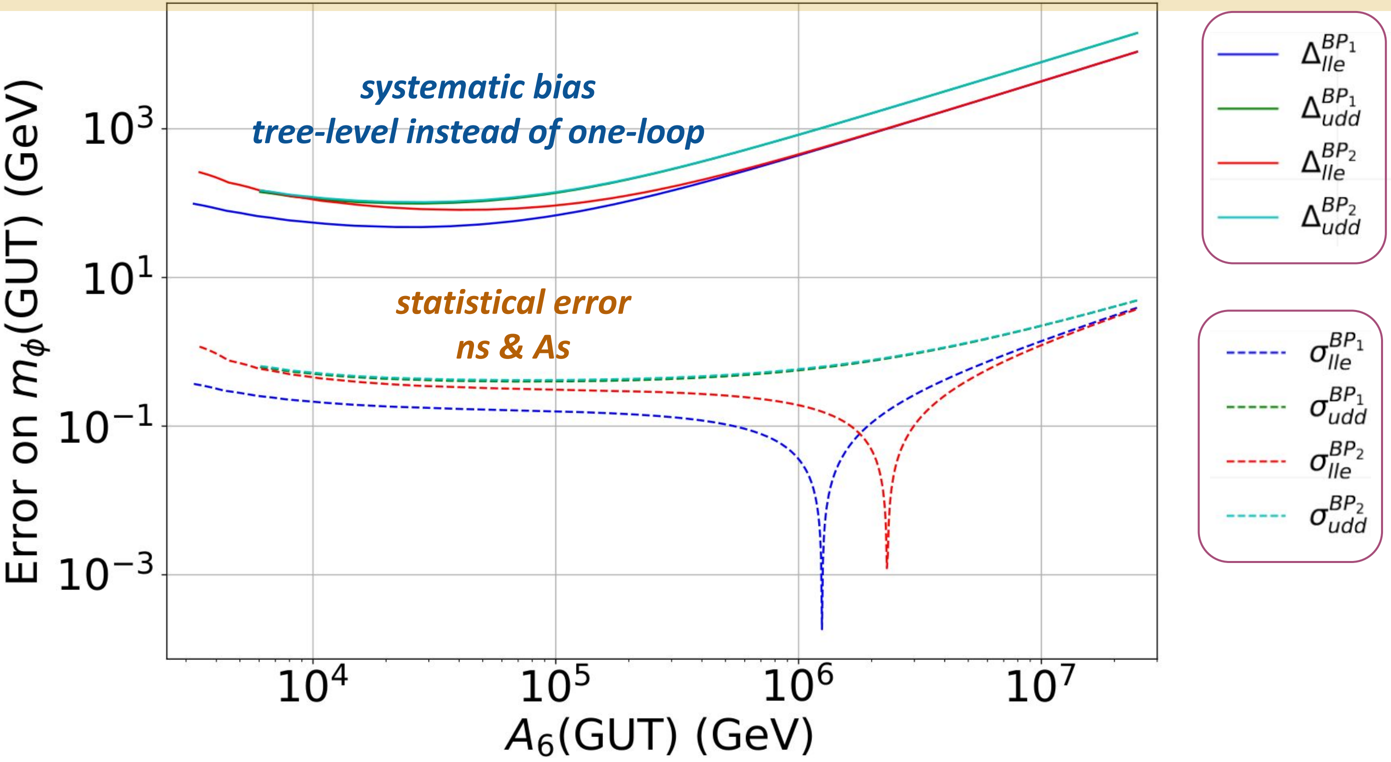


III- Embedding slow-roll in HEP
B) MSSM-inflation: Radiative corrections impact on the potential

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



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



- **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!