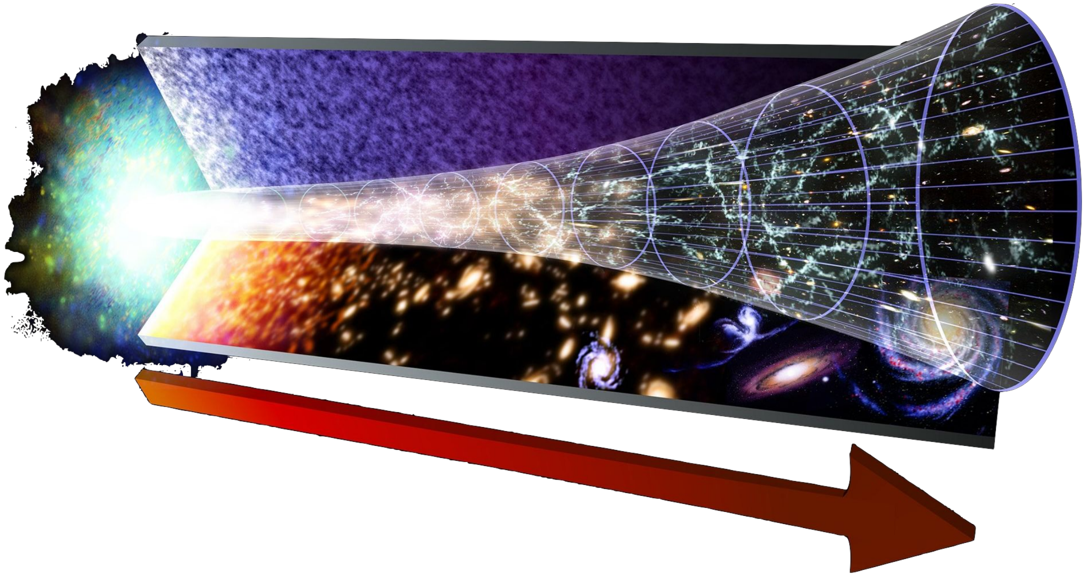


GT05 Cosmological Physics

(Physique de l'inflation et de l'énergie noire)

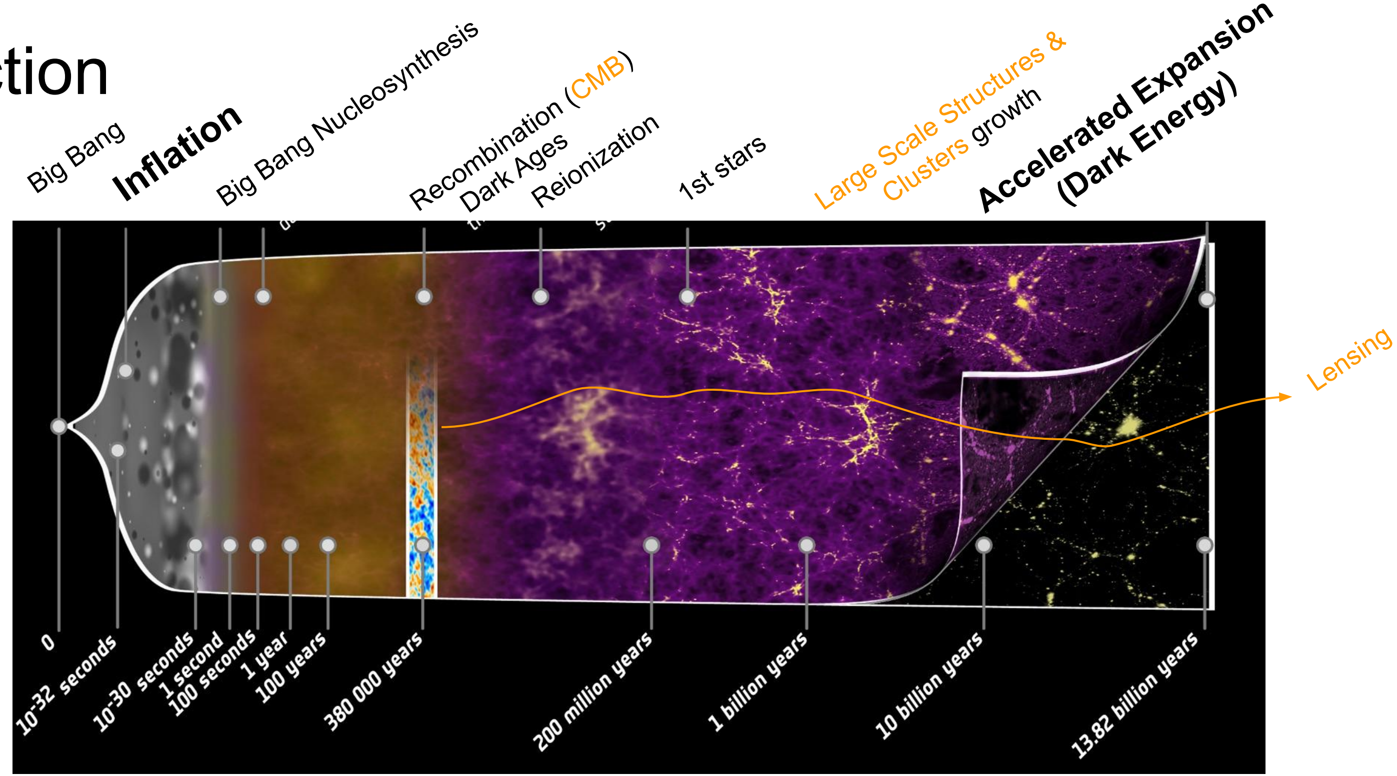
A. Catalano, K. Ganga, E. Gangler, B. Giebels, S. Henrot-Versillé, M. Tristram

21 October 2021

Outline

- Introduction
- White paper collection & Thematic seminar in Grenoble
- Science Drivers
- Scientific programs
- Projects
- Program-wide recommendations
- Project-specific recommendations

Introduction



Inflation: hypothesis

- Flatness problem
- Horizon problem

Accelerated expansion: observation

- Origin unknown
- “Dark energy”

White papers 1

Un groupe de travail (GT) a été mis en place pour la thématique "physique de l'inflation et énergie noire" auquel ont été invités à contribuer tous les chercheurs, ingénieurs et techniciens des laboratoires français. Les questions scientifiques concernent essentiellement

- Les propriétés de l'énergie noire
- L'inflation et la physique associée au CMB

avec une forte priorité sur la déclinaison nationale des priorités stratégiques européennes de la feuille de route 2017-2026 de l'APPEC

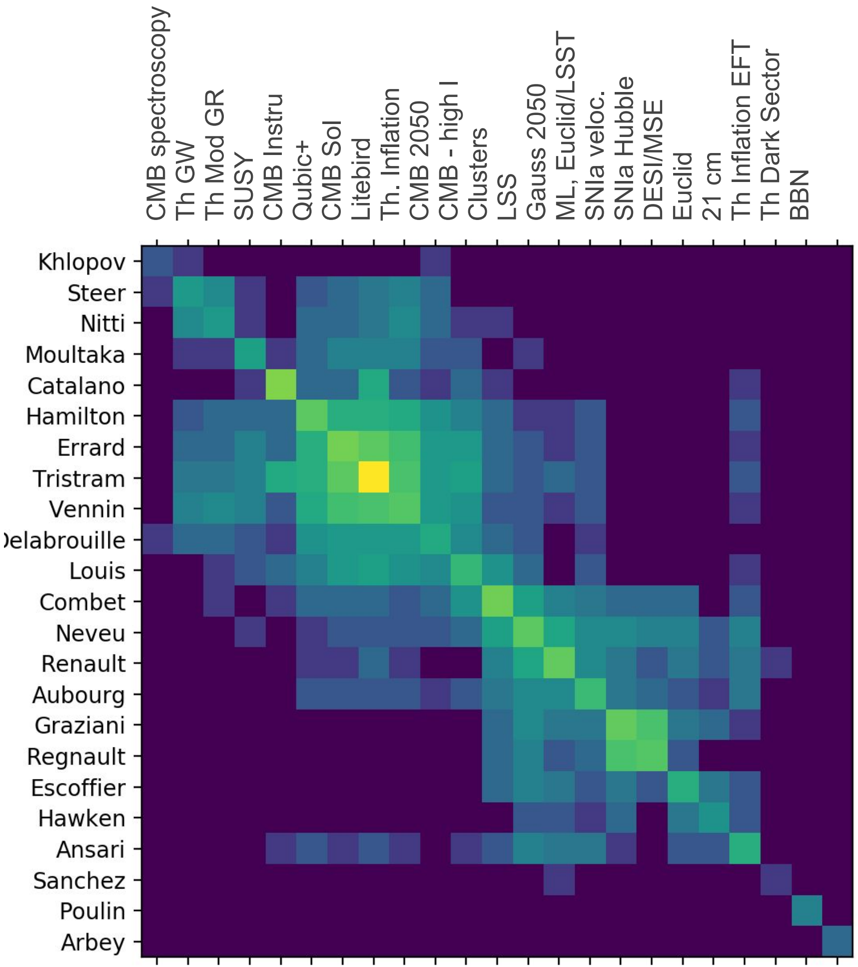
White papers 2

Steering committee has received

- 23 White papers, corresponding to
- 166 unique authors.

Analysis of author similarities has shown:

- Presence of sub-communities:
  - CMB
  - Wide field surveys
  - Theory
- links between proposals, thus a unity of the field



Grenoble workshop

- 43 participants (semi-remote)
- 11 speakers : White paper summaries
  - Theory: dark sectors (energy and matter), inflation
  - Wide field surveys: larges structures, clusters, supernovae, spectroscopy
  - CMB : space, ground,instrumental developments
  - 21 cm cosmology

Many thanks to: C. Combet, J. Errard, S. Escoffier, E. Kiristis, T. Louis, O. Perdereau, N. Regnault, C. Roucelle, P. Serpico, D. Steer, S. Torchinsky

Science Drivers

To consolidate our knowledge of fundamental physics from cosmological observations, the five intertwined science drivers for the field of cosmological physics are:

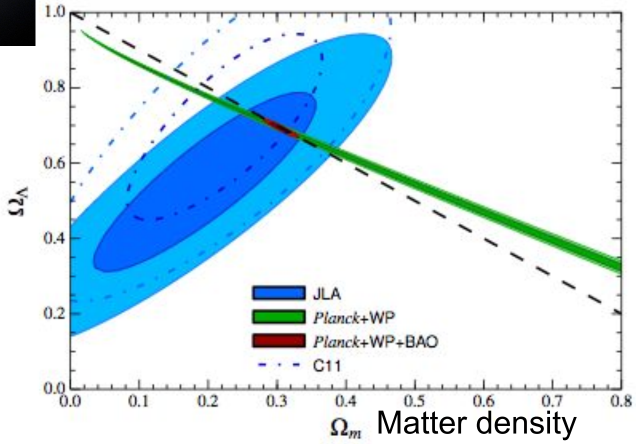
- Understand the **global expansion**
- Probe **gravitational models** (at cosmological scales)
- Explore **cosmic inflation**
- Test the robustness of the **concordance model**
- Understand the **fundamental constituents of the Universe** (through cosmology)

Main Probes of the expansion

Supernovae : sensitive to expansion rate evolution

Bétoule 2014

Dark Energy density



Matter density

→ **dark energy equation of state:** distinctive signature of alternate models

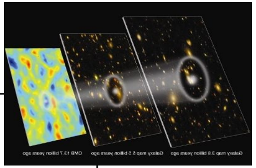
$$P = w\,\rho = [w_0 + w_a(1-a)]\,\rho$$

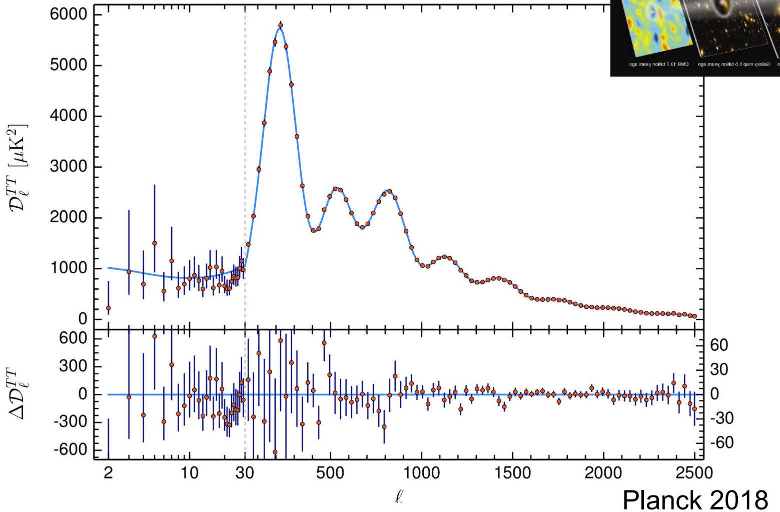
Key is to **constrain w0 and wa** (FoM)

CMB, BAO : scale parameter evolution

→ sensitive to Ωtot

+ power spectrum, polarization ...

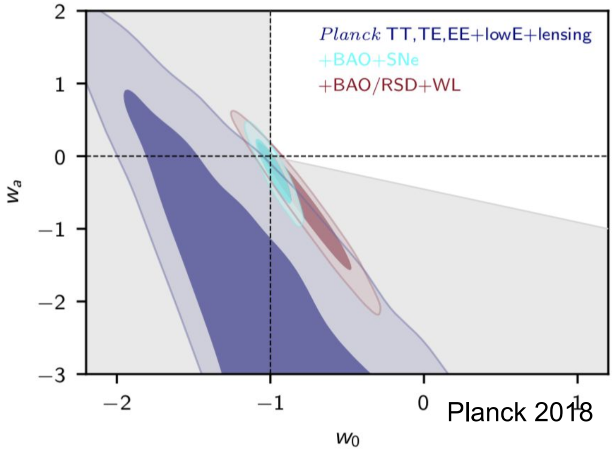




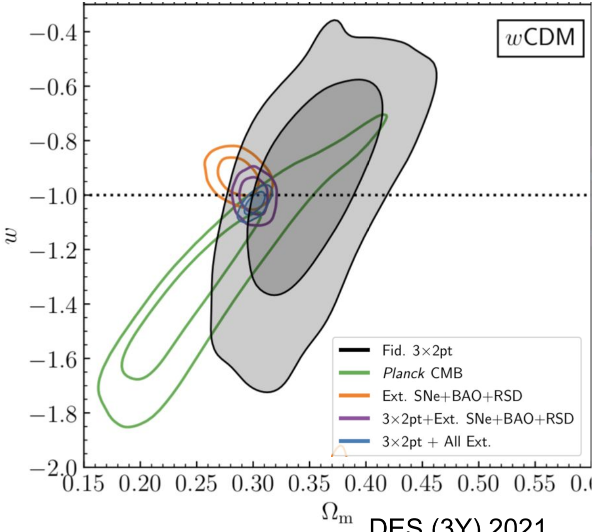
Planck 2018

LSS x WL (3x2pt): Structure growth (LSS x WL)→ sensitive to Ω_M & GR

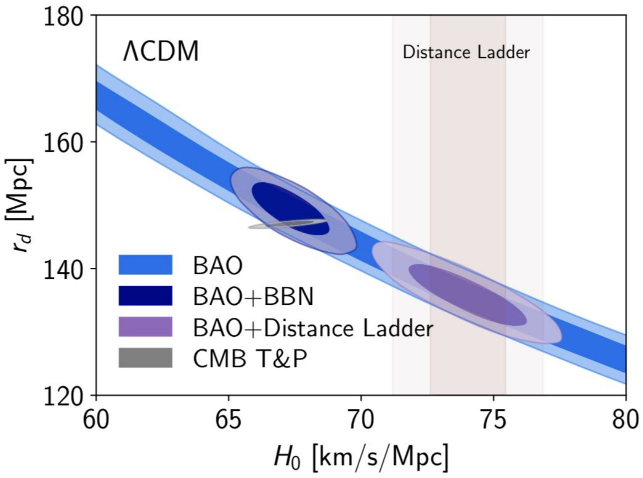
The DE equation of state today



Planck 2018



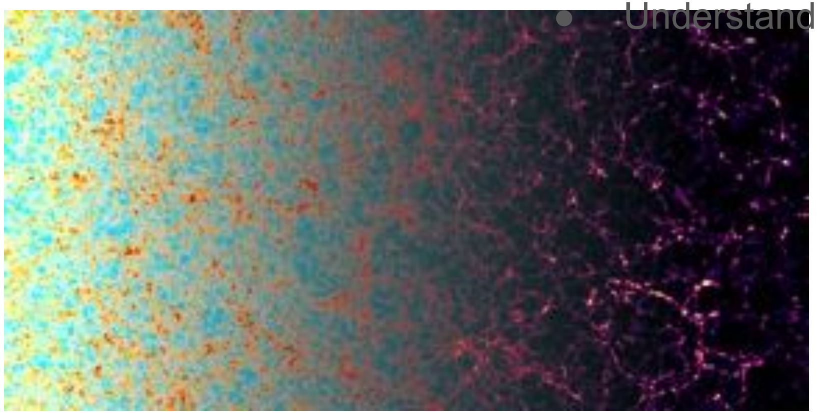
DES (3Y) 2021



→ **Concordance model** flat-ΛCDM quite robust … so far ?

→ **But issue with Hubble Constant**

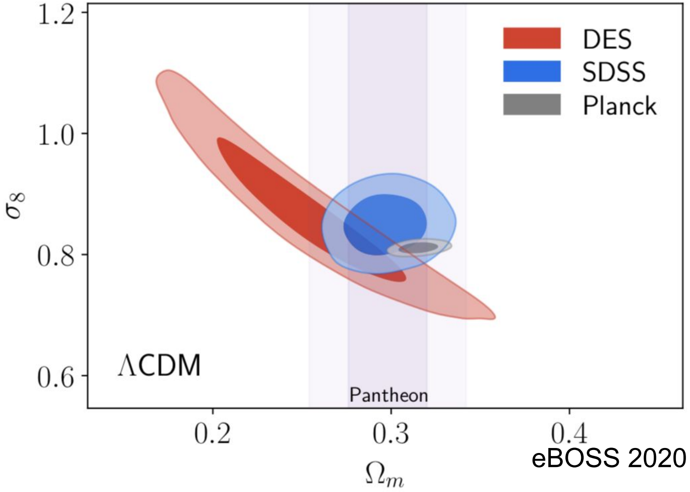
Growth of structures



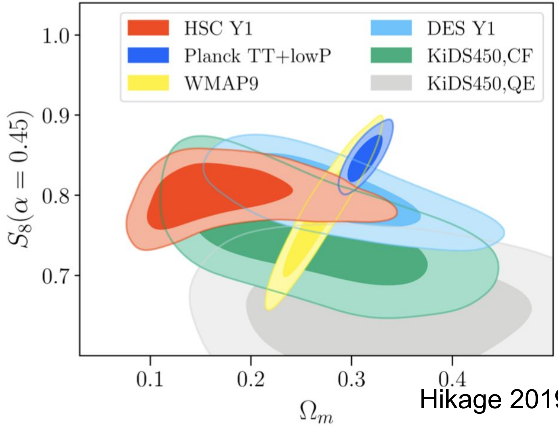
ΛCDM + Initial perturbations + GR
→ structure growth is fully determined
Key parameters: Ω_M, σ_8/S_8, $\gamma=0.55$

Probes of recent universe
- **3x2 pt**
- **clusters**
- **RSD**

→ tension with Planck
HSC, DES



eBOSS 2020



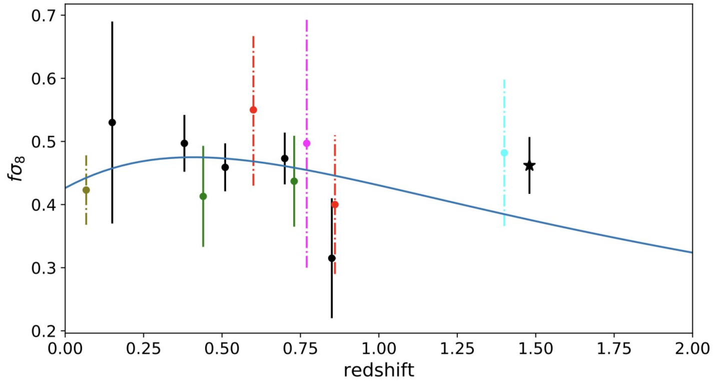
Hikage 2019

- Understand **Dark Energy**
- Probe **gravitational models**

Testing General Relativity

Testing the growth :

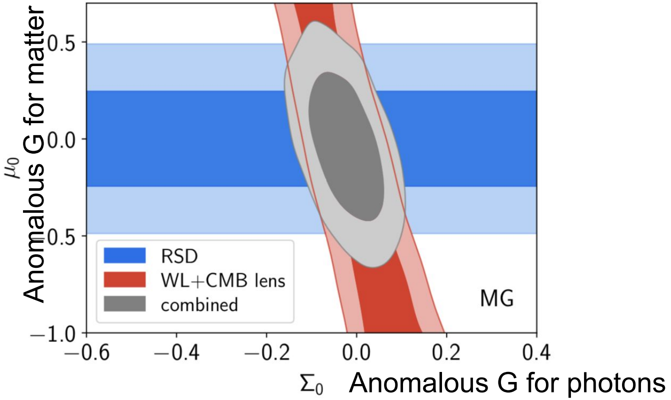
$$f = \Omega_M(z)^\gamma$$



Testing alternatives :

(μ_0,Σ_0) parametrization

eBOSS 2020



The path forward:

- Precision cosmology (target ?)
- Combine probes

- Understand **Dark Energy**
- Probe **gravitational models**

Dark Energy: theoretical perspective

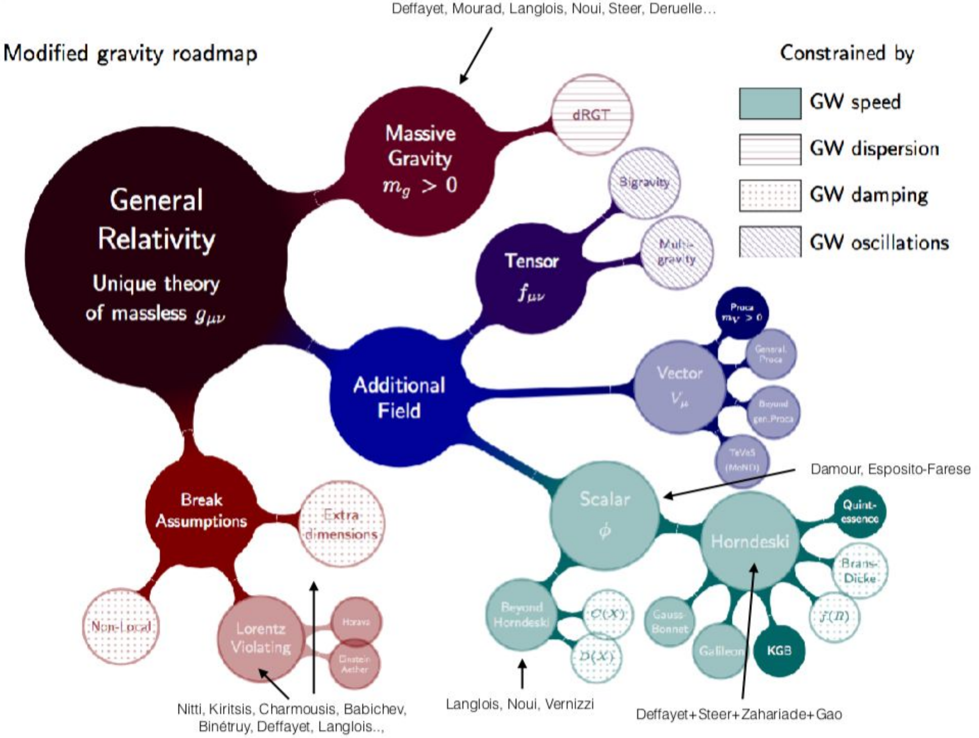
What is the source of accelerated expansion ?

- The Cosmological Constant problem:
  - why so small ?
  - why comparable to matter density today ?
- Is it a constant, or is it dynamic ?
  - A new energy component ?
  - Or a modification of GR ?

Modifying GR:

- Theoretical conceptual and technical issues.
- Link to measurable quantities

[Ezquiaga and Zumalacarregui 1807.09241



- Understand the **global expansion**

Dark Energy: the global expansion

Equation of state: $P = w\,\rho = [w_0 + w_a(1-a)]\,\rho$

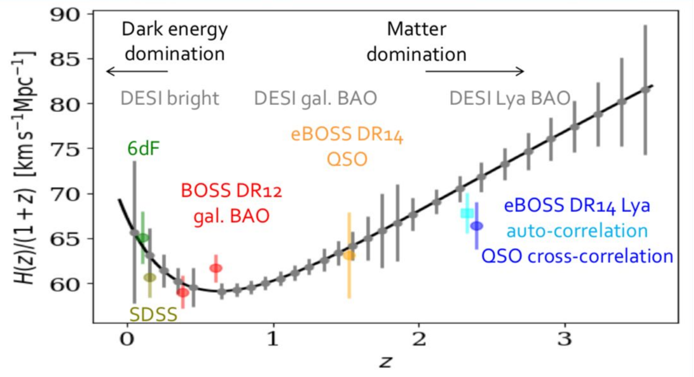
This will be addressed by probe combination:

- Spectroscopic surveys: history of expansion (BAO)
- Photometric surveys: combination of probes (3x2pt, SN)
- Planck/CMB data

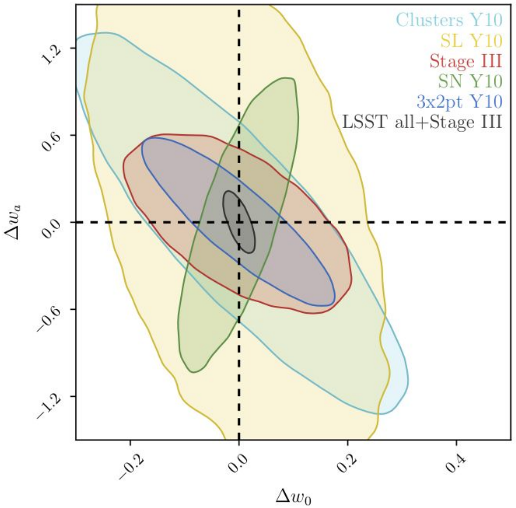
H_0 tension is not understood

- Gravitational waves as a new probe.

DESI forecasts



LSST forecasts

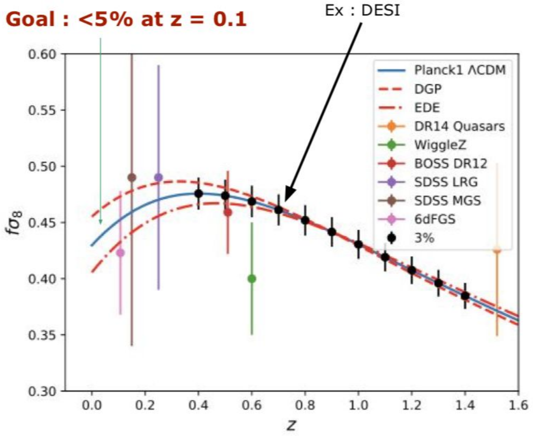


- Understand **Dark Energy**
- Probe **gravitational models**

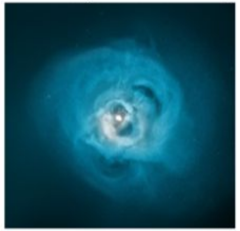
Dark Energy: the growth of structures

Main probes of gravitational structures:

- RSD (Spectroscopic surveys: DESI, Euclid)
- Supernovae peculiar velocities
- Cross-correlations structures + lensing + CMB Lensing = 5x2 pt
- Clusters/voids: X-ray, optical, SZ



Perseus (Chandra/XMM)

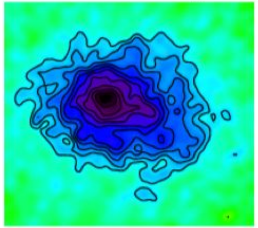


Xray

Abell 370 (HST)

Optical

PSZ2-G0144.83+25.11(NIKA2)



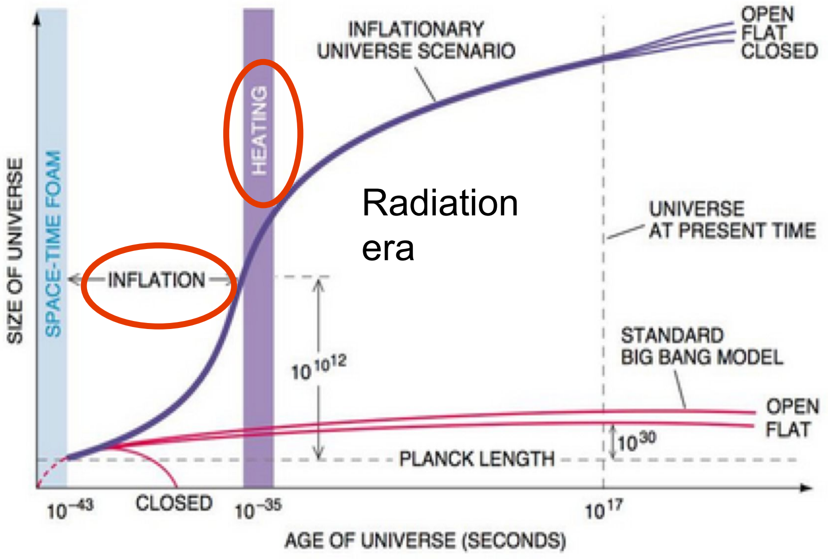
mm

Project	FoM	$\sigma(\gamma)$	$\sigma(\Sigma m_\nu)(meV)$	$\sigma(f_{NL})$
Current	31	0.07	< 90 (95%CL)	5
DESI	704	0.04	20	2.5
Euclid	430	0.02	30	2
LSST	505	0.02	30	< 1

The current picture: the very early Universe

Inflation was introduced to explain:
- The flatness problem
- The horizon problem
- The monopole problem

A lot of questions...
- What is the energy scale of Inflation
- What are the physical processes at the origin of Inflation
- What is the field content of the very early universe
- How did the inflation energy transfer to the standard-model particles
- Is there a quantum origin of cosmological perturbations



Inflation is an extremely rapid acceleration in the universe soon after its creation.

The current picture: inflation physics

Inflation predicts the existence of two types of perturbations:

- fluctuations of the scalar inflaton field: scalar perturbations
- fluctuations of the gravitational field: tensor perturbations
  The so-called primordial gravitational waves !

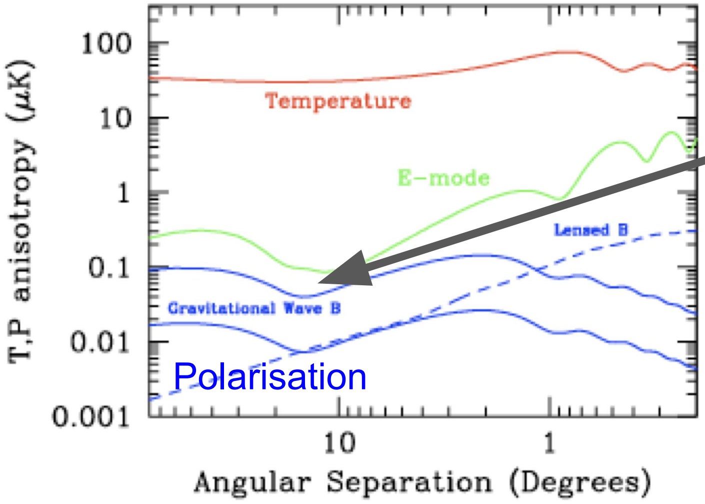
$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \quad \text{scalar}$$

$$\mathcal{P}_{\mathcal{T}}(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} \quad \text{tensor}$$

$$r = A_t / A_s$$

"Tensor to scalar ratio"

Amplitude of the CMB Bmode spectrum at large scales



In slow-roll inflation (favored by current data): given it is generated by one scalar field:

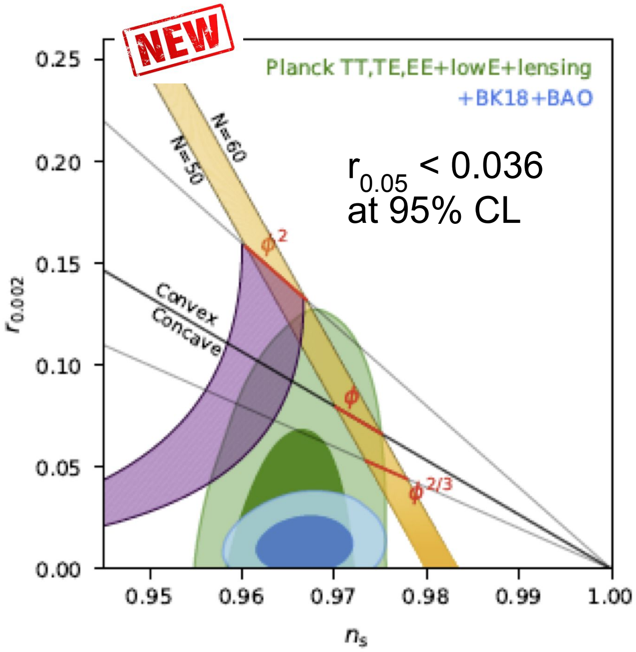
$$r = 8M_{\rm Pl}^2 \left(\frac{V_\phi}{V}\right)^2$$

$$n_s - 1 \equiv \frac{d\ln \mathcal{P}_\zeta}{d\ln k} \simeq -3M_{\rm Pl}^2 \left(\frac{V_\phi}{V}\right)^2 + 2M_{\rm Pl}^2 \frac{V_{\phi\phi}}{V}$$

First and second derivative of the potential

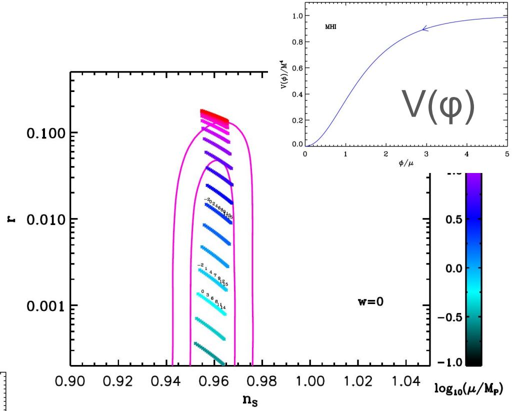
The current picture: inflation physics

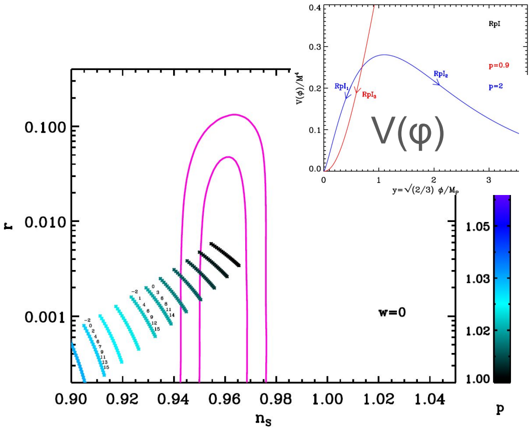
BICEP / *Keck* XIII: Improved Constraints on Primordial Gravitational Waves using *Planck*, WMAP, and BICEP/*Keck* Observations through the 2018 Observing Season

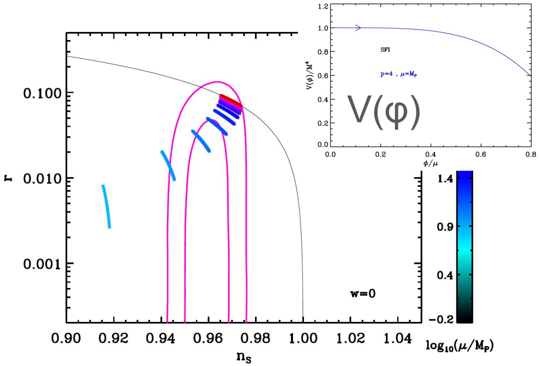


$r_{0.05} < 0.036$ at 95% CL

favor/disfavor one potential or another..
Close interaction with theoreticians







arXiv:2110.00483

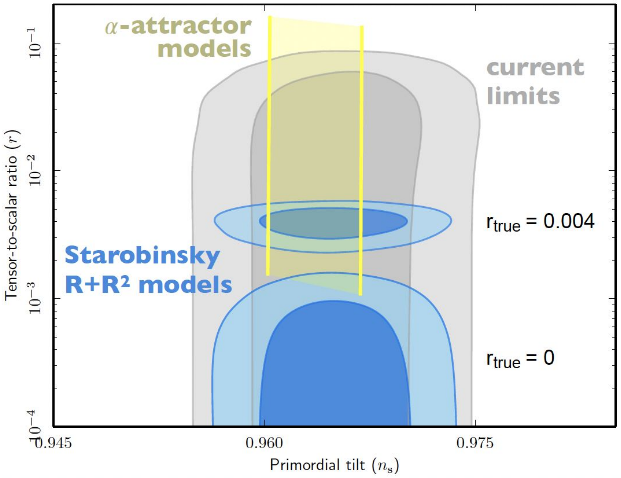
ArXiv 1303.3787

Explore cosmic inflation

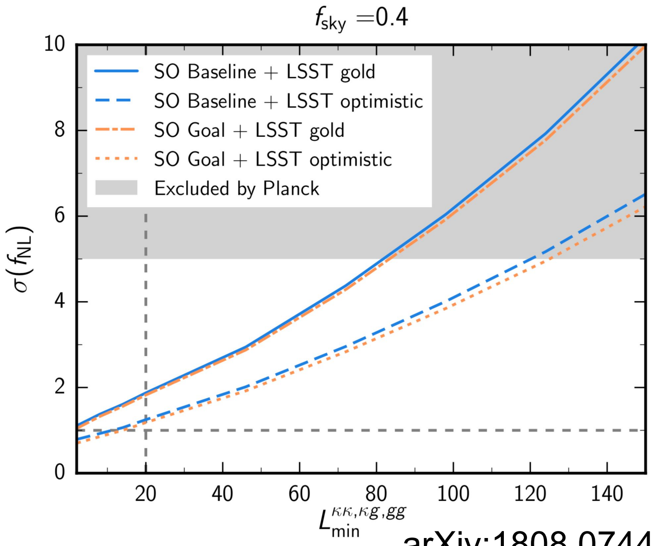
Beyond (r,ns):

- Non-gaussianities (f_{NL}) - LSS and CMB
- gravitational waves energy density spectrum
  - CMB, Pulsar timing, GW

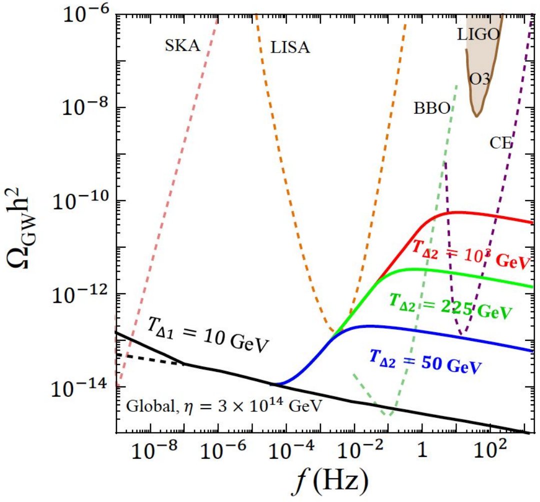
Future Project	$\sigma(r)$
CMB S4	0.0005
LiteBIRD	$< 10^{-3}$
Simons Obs.	0.003



- Large discovery potential for 0.005 < r < 0.05



arXiv:1808.07445



arXiv:2106.09746

Robustness of the concordance model

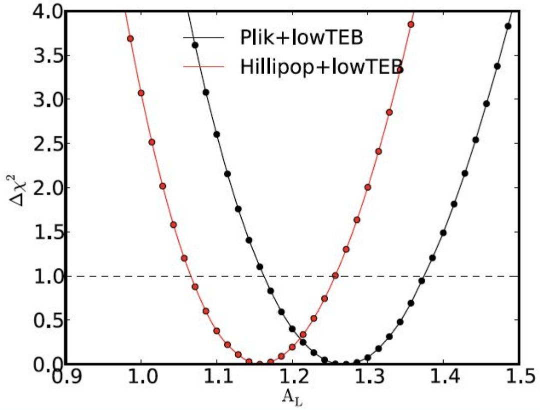
A comprehensive cosmological model should lead to a coherent picture, beyond the sole issues of Inflation and Dark Energy.

Tensions may indicate new physics:

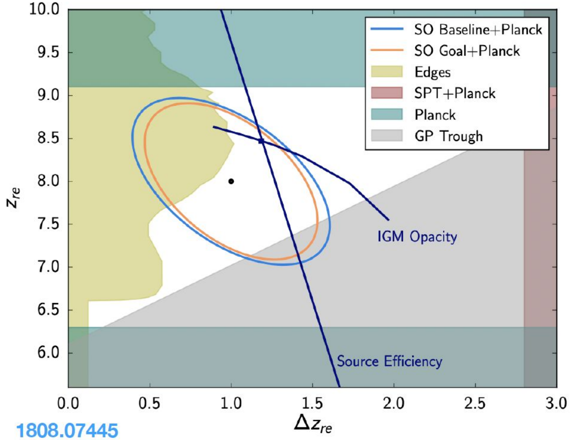
- H_0 tension
- A_L tension
- Low-ell CMB anomalies...

Some other ways of testing the coherence:

- Measuring the spectral distortions of the CMB spectrum
- Testing cosmic birefringence
- Cross-correlations between probes (lensing, clusters, ...)
- Reionisation



A&A 597, A126 (2017)



1808.07445

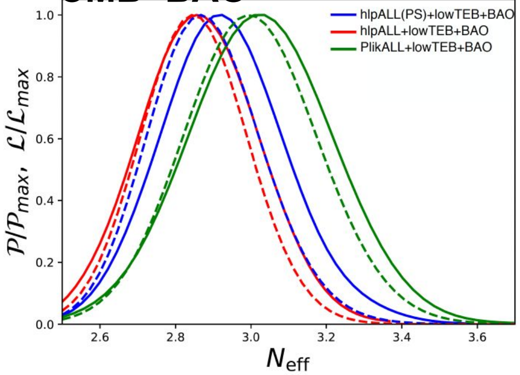
The current picture (neutrinos)

- Understand the **fundamental constituents of the Universe** (through cosmology)

Effective # of relativistic species

BBN	$N_{\rm eff} = 2.92 \pm 0.28$
Planck+BAO	$N_{\rm eff} = 2.99 \pm 0.17$
Planck+BAO+H0	$N_{\rm eff} = 3.27 \pm 0.15$

CMB+BAO



Fields et al. 1912.01132,
Planck 2018, 1807.06209,

Σm_ν (eV)

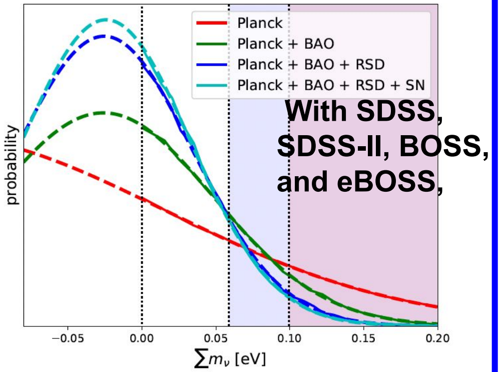
Planck 2018

$\sum m_\nu < 0.54\,\mathrm{eV}$ **(95 % CL, TT+lowE)**

$\sum m_\nu < 0.26\,\mathrm{eV}$ **(95 % CL, TTTEEE+lowE)**

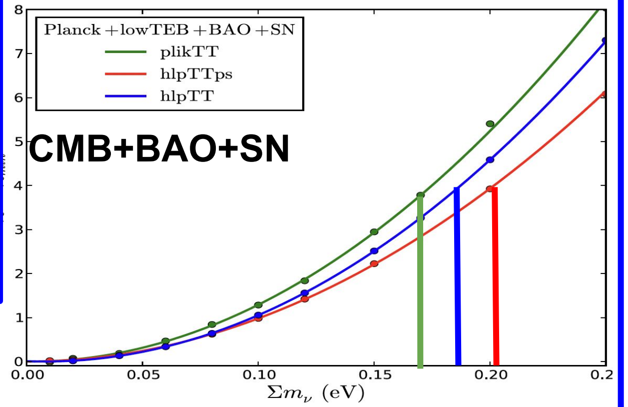
$\sum m_\nu < 0.24\,\mathrm{eV}$ **(95 % CL, TTTEEE+lowE+lensing)**

$\sum m_\nu < 0.12\,\mathrm{eV}$ **(95 % CL, TTTEEE+lowE+lensing+BAO)**



Planck+BAO varying the cosmo model

$\sum m_\nu < 0.12\,\mathrm{eV}$	**Standard Case** Planck 1807.06209
$\sum m_\nu < 0.25\,\mathrm{eV}$	**Dark Energy dynamics** Choudhury & Hannestad 19'
$\sum m_\nu < 0.15\,\mathrm{eV}$	**Varying Curvature** Choudhury & Hannestad 19'
$\sum m_\nu < 0.23\,\mathrm{eV}$	**Varying $N_{\rm eff}$** Planck 1807.06209
$\sum m_\nu < 0.17\,\mathrm{eV}$	**Varying $N_{\rm eff}$+ω+α_s+m_ν** di Valentino et al. 1908.01391



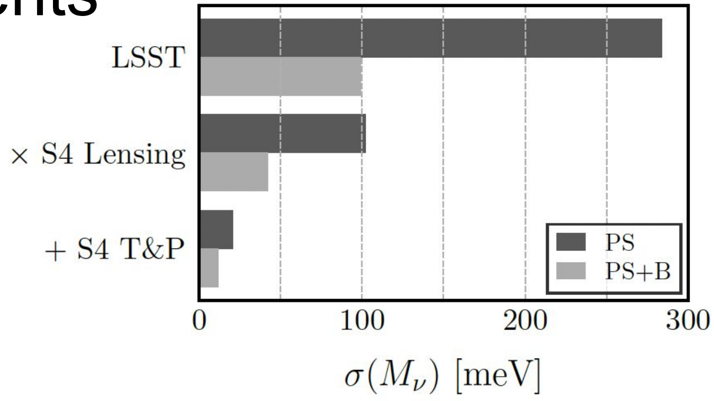
arXiv:2007.08991
arXiv:1703.10829

- Understand the **fundamental constituents of the Universe** (through cosmology)

Understand the fundamental constituents

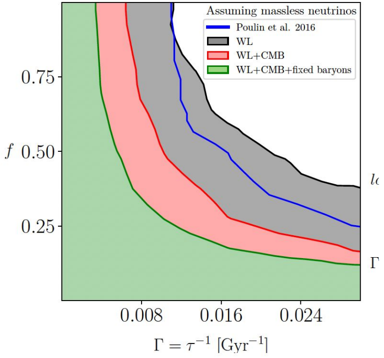
Cosmological observations are sensitive to particles physics (energy injections, annihilation processes...)

- the Neutrino sector:
  sum of masses (hierarchy), Neff,
  tests of sterile neutrinos
- the Dark Matter sector: Ωcdm,
  DM annihilation, decays rates

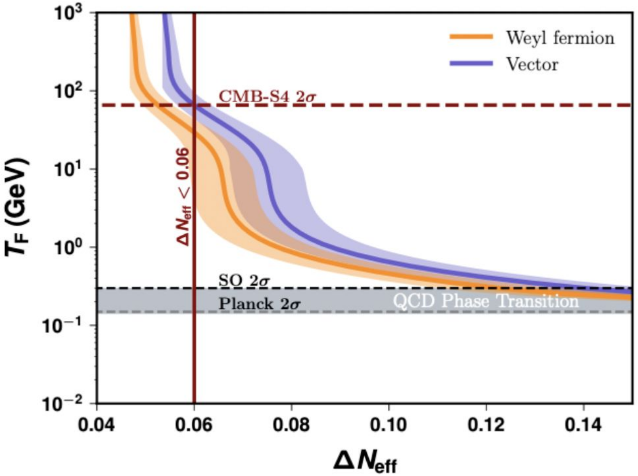


arXiv:2103.01229

arXiv:2104.07675



fraction of decaying to-total dark matter (f)



Projects

All projects discussed within the Cosmological Physics working group make use of electromagnetic radiation:

- Optical or Near-Infrared (Euclid, LSST, DESI, MSE, Gauss)
- Infrared (Roman telescope)
- Submm (SO, S4, LiteBIRD, NIKA, CONCERTO, KISS, QUBIC)
- Radio (HIRAX, Tian Lai, ..)

and heavily rely on instrumental developments occurring in French laboratories, some of which supported by CNES.

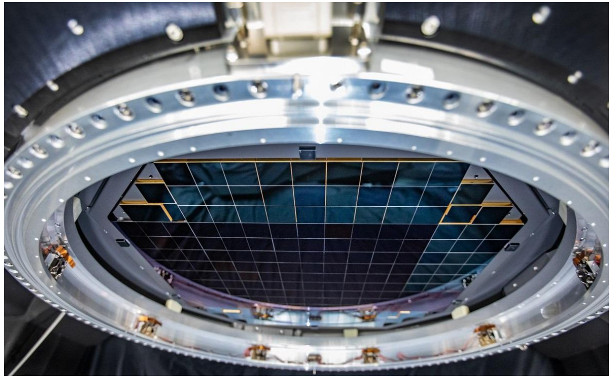
Projects

	Observational Probes	Cosmic Inflation	Global Expansion	Gravitational Models	Universe Constituents
Large Projects					
Simons Obs.	CMB Clusters (SZ)	✓	✓	✓	✓
CMB Stage-4	CMB Clusters (SZ)	✓	✓	✓	✓
LiteBIRD	CMB	✓	✓	✓	✓
SKA	Int. Mapping (21 cm)	—	✓	✓	✓
EUCLID	Galaxies, Clusters Grav. Lens.	—	✓	✓	✓
Rubin Obs. (LSST)	Galaxies, Clusters Grav. Lens., SN	—	✓	✓	✓

	Observational Probes	Cosmic Inflation	Global Expansion	Gravitational Models	Universe Constituents
Medium Projects					
DESI	Galaxies Int. Mapping (ELG)	—	✓	✓	✓
NIKA 2	Clusters	—	✓	—	✓
CONCERTO	Int. Mapping (CII) Clusters	—	✓	—	✓
Small Projects					
QUBIC-TD	CMB	✓	—	—	—
HIRAX	Int. Mapping (21 cm)	—	✓	✓	✓
TianLAi	Int. Mapping (21 cm)	—	✓	✓	✓

Rubin / LSST

- Ground optical telescope
- Chile (Cerro Pachon)
- 8.4m (6.7) telescope
- 3.2 GPix Camera 9.6 sq. deg.
- 6 bands (coadd r~27.5)
- 10 years survey: 2024-2034
    - Wide 18000 sq. deg.
    - Time domain (~800 visits/band)



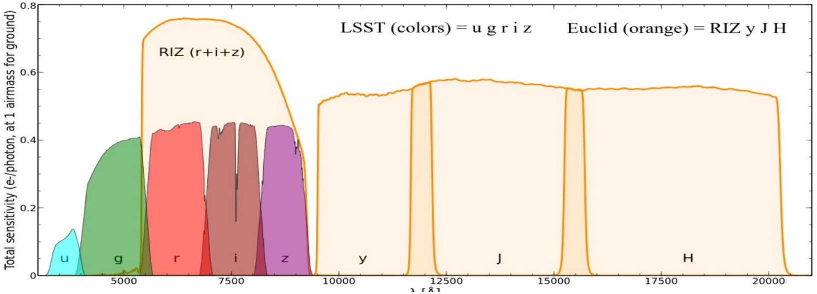
- 20 TB of data / night
- After 10 years:
    - 40 galaxies/arc min
    - 4 Billion galaxies with photo-z
    - 300 000 clusters 0.1<z<1.2
    - 100 000 Supernovae Type I

Euclid

- Space optical +IR telescope
- 1.2m telescope
- 0.6 GPix Camera 0.6 sq. deg.
- 2 instruments:
  - VIS : 0.6 GPix Camera 0.6 sq. deg.
  - NIR (imager+spectrometer)
- 6 years survey: 2023-2029
  - 15000 sq. deg.
- 2 Billion galaxies
- 200000 clusters 0.2<z<2

Euclid-LSST synergies:

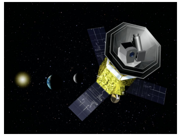
- 7000 sq. deg. in common
- Complementary bands
  - Photo-z
  - Deblending



The far future

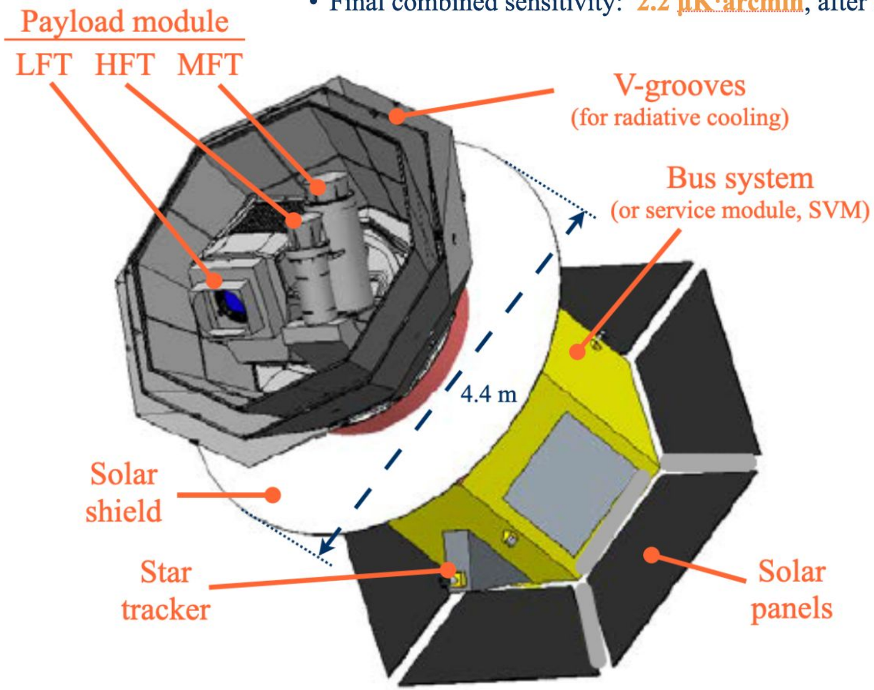
- No current IN2P3 interest for Roman telescope (2027) nor MSE (2029+)
- Answered ESA voyage 2050: GAUSS

LiteBIRD



- 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 late **2029** 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**, after component separation

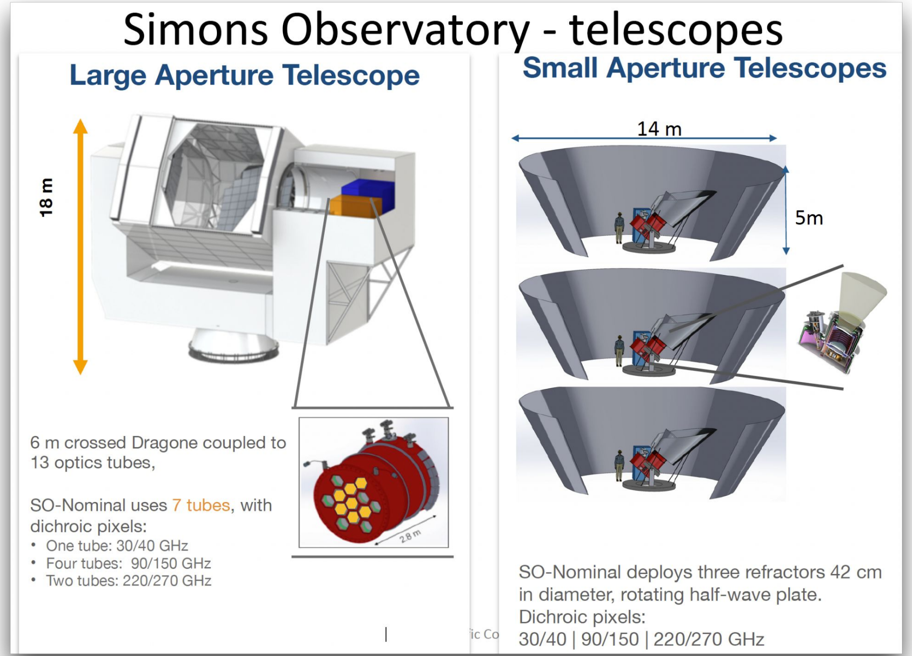
- **3 telescopes** are used to provide the **40-402 GHz** frequency coverage
  1. **LFT** (low frequency telescope)
  2. **MFT** (middle frequency telescope)
  3. **HFT** (high frequency telescope)
- Multi-chroic transition-edge sensor (TES) **bolometer arrays** cooled to **100 mK**
- Polarization modulation unit (PMU) in each telescope with **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

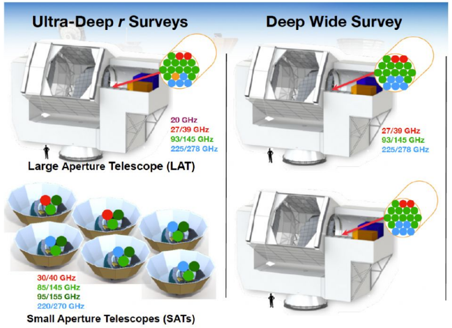
Today: MHFT is under CNES responsibility for a Phase A (design and feasibility study)

Simons observatory and CMB-S4



CMB-S4 – instruments

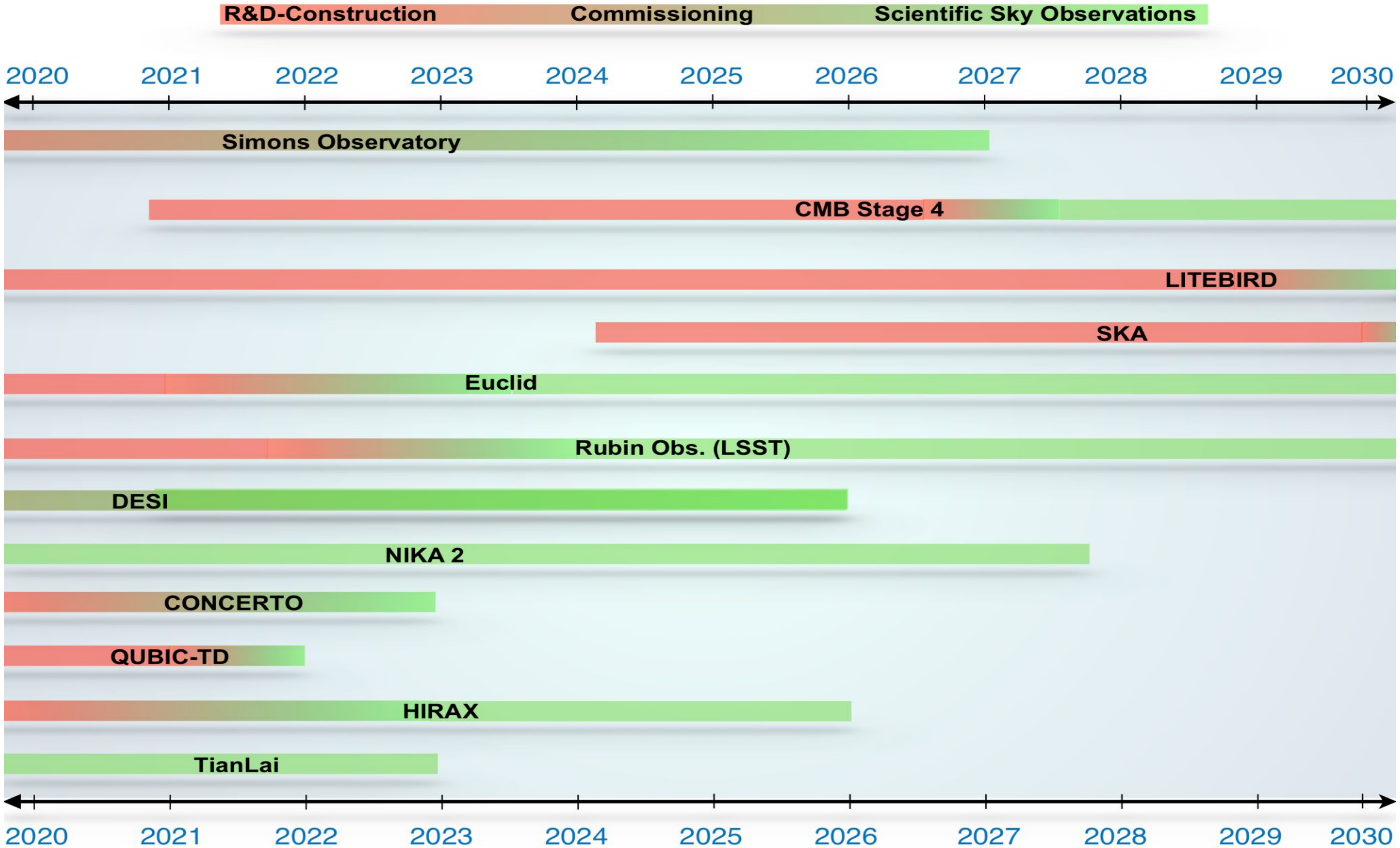
- South Pole:
  18 x 0.55m small refractor telescopes ~150,000 detectors with 8 bands, a dedicated de-lensing 6m telescope with 120,000 detectors, 7 bands



- Chile
  2x 6m telescope with 120,000 detectors each and 7 bands.

- The instrument will feature kilo-pixel arrays, dichroic, horn-coupled, superconducting TES detectors and time-domain multiplexing.

Timeline


R&D-Construction
Commissioning
Scientific Sky Observations
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Simons Observatory
CMB Stage 4
LITEBIRD
SKA
Euclid
Rubin Obs. (LSST)
DESI
NIKA 2
CONCERTO
QUBIC-TD
HIRAX
TianLai

Program-wide recommendations

The ordering of the program-wide recommendations reflects the most promising approaches to assess, based on the science drivers, where French research should go and how to get there.

- **Recommendation 1: Pursue a program to address the five science Drivers.**

  France should support and develop theoretical and experimental research programs adressing the five science drivers in the coming decade. Since the drivers are intertwined they are not prioritized.

- **Recommendation 2: improve cosmological physics exchanges**

  Cosmological physics draws upon the fields of particle and astroparticle physics, astrophysics and cosmology. It transcends scientifically and technologically the GTs of these national 2020 perspectives, as well as the institutional organization of CNRS and CEA, such that theoretical and experimental exchanges in France can be improved through e.g. well organized recurrent meetings. These would allow to develop the full potential of the synergies, which were particularly apparent during the seminal discussions, as well as provide a scientific watch on upcoming opportunities and future projects in the coming decade.

- **Recommendation 3: Develop a scientific program enabled by cross-correlation of probes.**

  There are specific physical signals accessible only by combination of data from different projects and wavelengths. A typical example is the cross-correlation of the CMB lensing data with large-scale structure tracers (e.g., galaxies, quasars), which allows to reconstruct the three-dimensional matter field, and measure the growth of structure with redshift. Such studies, which transcend the experimental projects and research operator perimeters, would benefit from a project organization.

- **Recommendation 4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.**

  Most of the science drivers are primarily addressed by large and mid-scale experiments. It is however possible that small-scale projects can also address questions related to the drivers - and sometimes complement large projects. This includes additional observational projects needed for the scientific analysis of the main programs. Opportunities are likely to arise in the coming decade which can provide leadership roles for scientists and allow for partnerships among laboratories.

- **Recommendation 5: Support computing development for upcoming, data-intensive experiments**

  Computing infrastructure and algorithm development in an astrophysical context, for example in the Rubin Observatory LSST, Euclid and LiteBIRD, is different in some ways from the usual high energy physics computing use cases. As the cosmological physics computing needs evolve, so should its computing resources.

- **Recommendation 6: Develop and maintain R&D programs**

  Advances in experimental cosmological physics which address the science drivers come also from R&D for detectors and experimental techniques. Development of synergies between different institutions to rise the technology readiness for ground and space environment and for different observational approaches (imager, spectrometer, etc...) should be encouraged.

Project-specific recommendations

The ordering of the project-specific recommendations reflects the project's relevance on the science drivers, its timeliness, its feasibility, the existing commitments, and the size of the French collective of scientists involved.

- **Recommendation 7: Complete LSST and EUCLID as planned and ensure the scientific return**

  These large projects represent a major French investment, and will drive the scientific achievements of the next decade. The scientific return should be kept at the height of the investments made.

- **Recommendation 8: Consolidate the French contributions to LiteBIRD.**

  The LiteBIRD project is in a phase A. If further selected, it will drive the science on cosmic inflation for the next decades. French participation to both hardware and science responsibilities should be supported during this phase, and beyond if the mission is approved.

- **Recommendation 9: Define a ground-based CMB path forward**

  A strategy for a French participation in a third generation ground-based CMB project should be developed, to define the objectives and the necessary actions.

Summary and discussion

Science Drivers:

- Understand the **global expansion**
- Probe **gravitational models**
- Explore **cosmic inflation**
- Test the robustness of the **concordance model**
- Understand the **fundamental constituents of the Universe**

Recommandations:

1. Pursue a program to address the five science Drivers.
2. Improve cosmological physics exchanges
3. Develop a scientific program enabled by cross-correlation of probes.
4. Maintain a program of projects of all scales
5. Support computing development
6. Develop and maintain R&D programs
7. Complete LSST and EUCLID as planned and ensure the scientific return
8. Consolidate the French contributions to LiteBIRD
9. Define a ground-based CMB path forward