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# CMB, cosmology, other astroparticle physics

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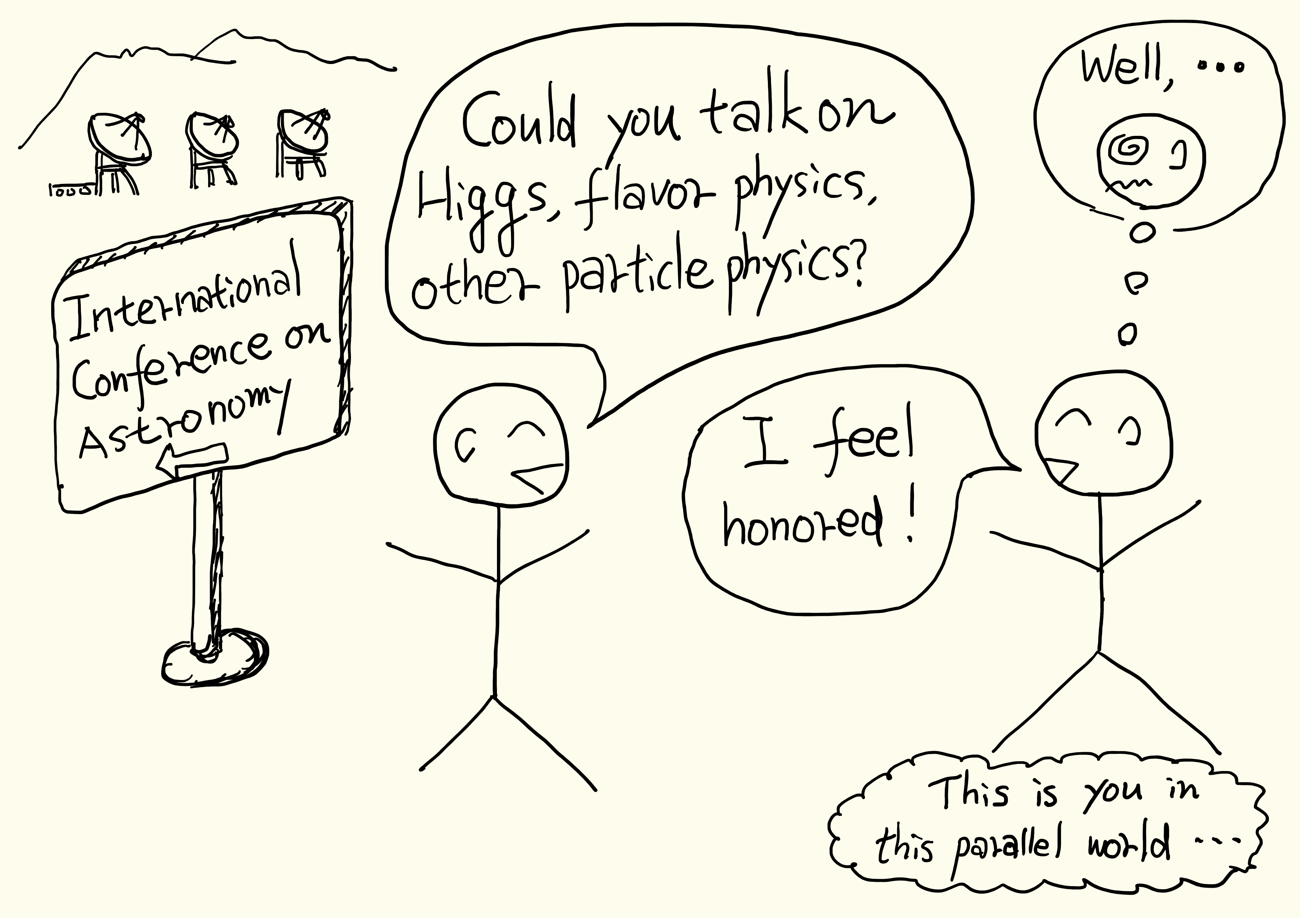
# What if …



International Conference on Astronomy
Could you talk on Higgs, flavor physics, other particle physics?
Well, …
I feel honored!
This is you in this parallel world …

# Outline

1. Introduction to experimental cosmology
2. CMB B-mode for testing inflation & QG*
3. Dark energy
4. Other BSM-related topics

* QG: Quantum theory of gravity, including superstring theory

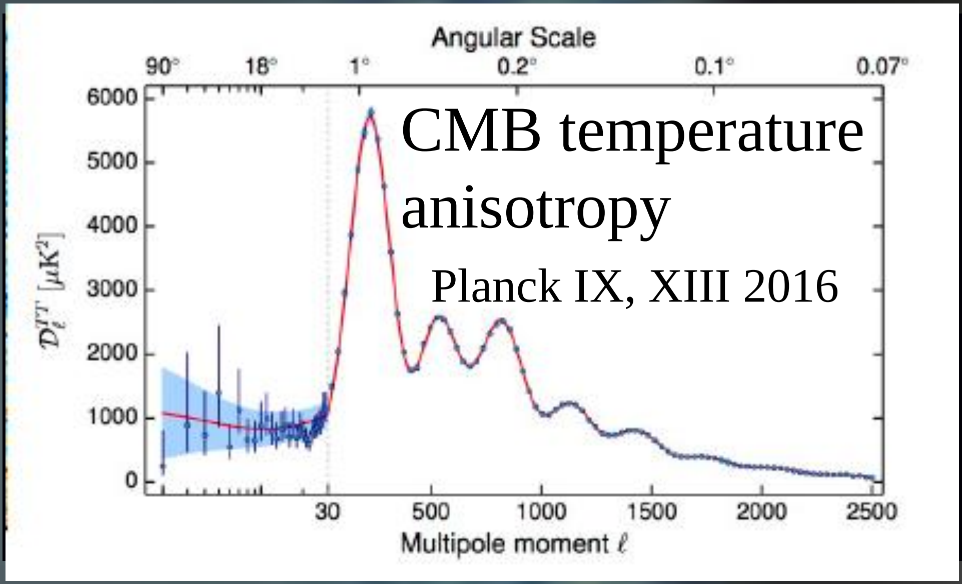
… ***all topics in the quest for the ultimate laws in physics***

# 1. Introduction to experimental cosmology

# Modern cosmology is a precision science like HEP!

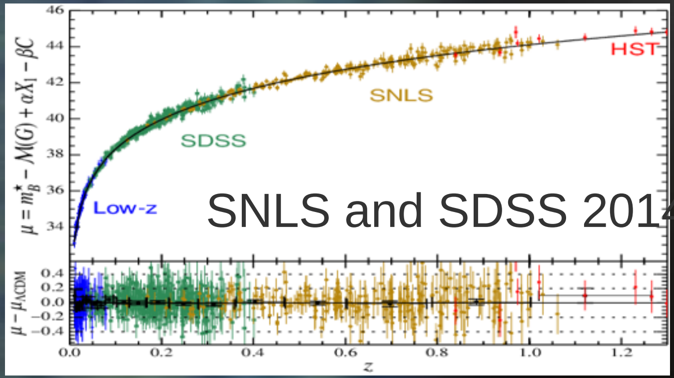
## Why are CMB measurements so precise/accurate?

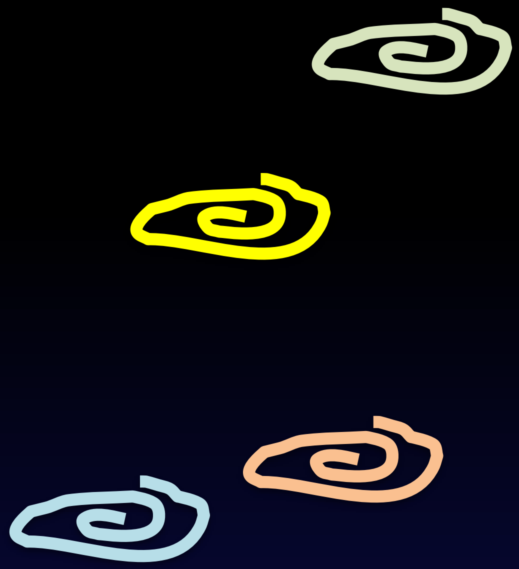
- Linear evolution from initial state to CMB emission
- CMB well preserved until today
- Precision inversely proportional to observing time!
- Remarkable development of observational instruments!

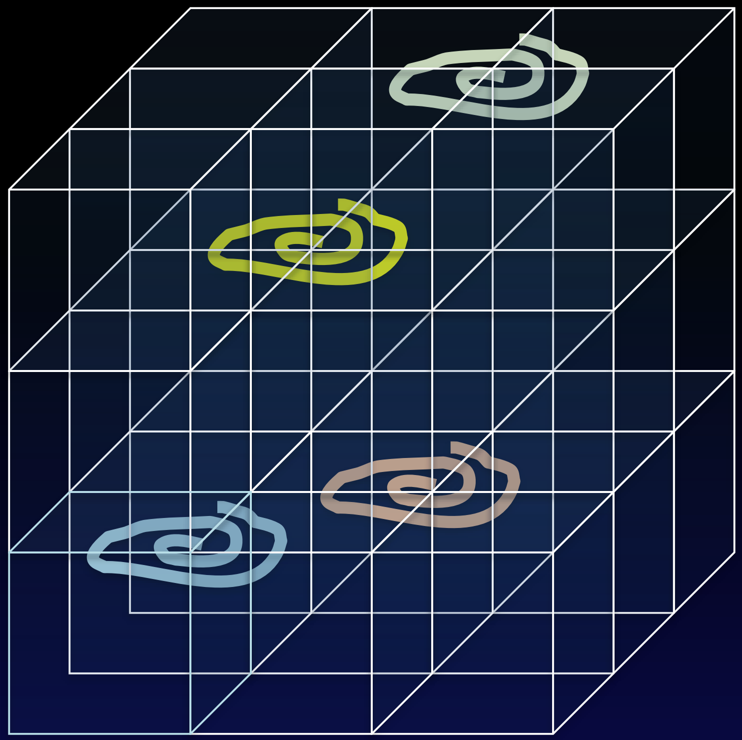


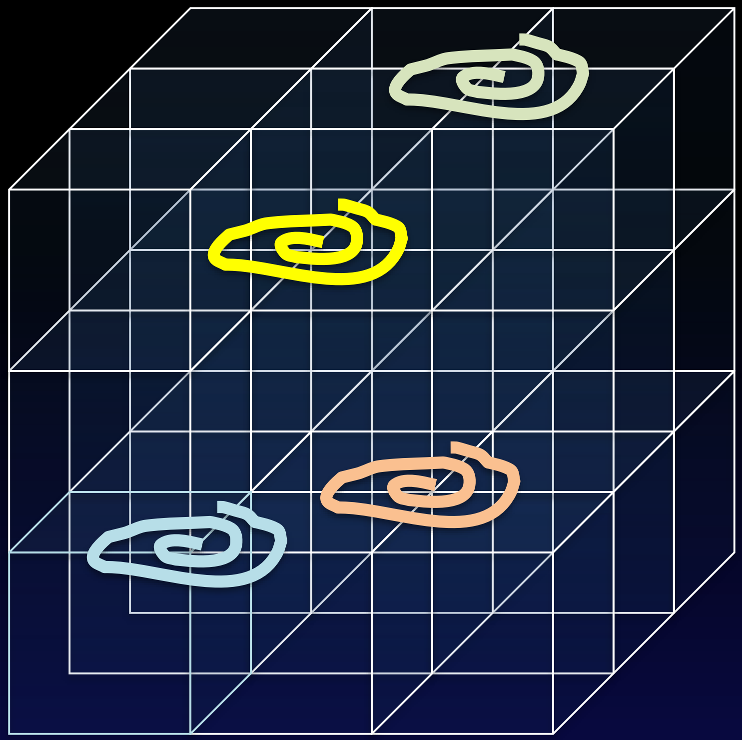

**The Planck legacy release is July 17, 2018!**

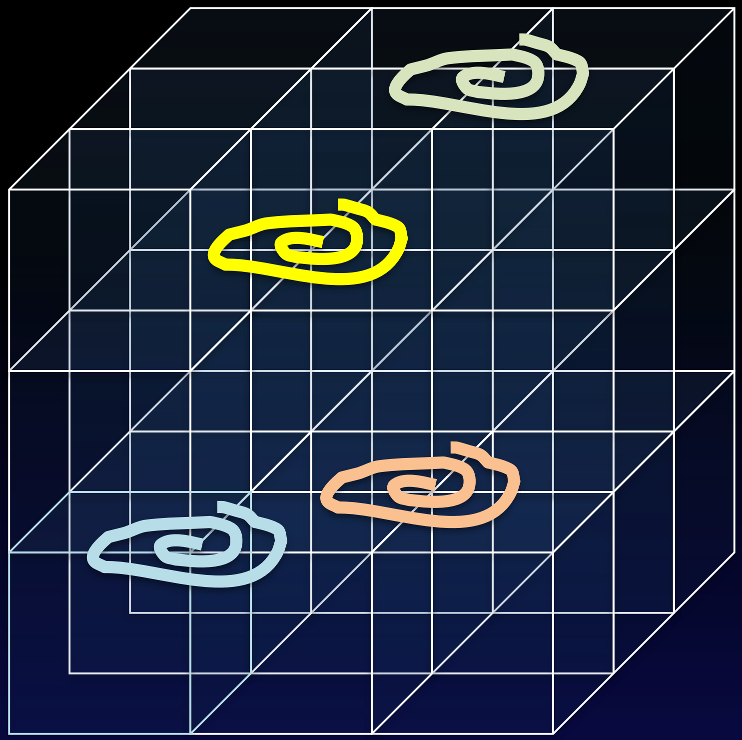
**Other probes (e.g. 3D galaxy maps) are also very useful, complementary and/or unique (with careful treatments of biases and other non-linear effects)**











# Standard Cosmology (ΛCDM)

Precision measurements support a remarkably simple picture!

- GR + cosmological principle
  - Physical existence of space is expressed by the scale "*a*" alone
  - Friedmann equation for time evolution of flat universe $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$
- Initial adiabatic, Gaussian perturbation
  - Consistent with inflation hypothesis
- Only six fit parameters are sufficient to describe the current set of precision data !
  - Flat universe assumption works fine.

# ΛCDM with six fit parameters

Baryon

| Dark Energy (69%) | DM (26%) | 5 % |
|---|---|---|

| - - - *Planck* 2015 6-parameter fit to flat ΛCDM cosmology - - - - - - - - - - | | Planck results in PDG2018 |
|---|---|---|
| baryon density of the Universe | $\Omega_b = \rho_b/\rho_{crit}$ | $^{\ddagger}0.02226(23)\,h^{-2} = {}^{\dagger}0.0484(10)$ |
| cold dark matter density of the Universe | $\Omega_c = \rho_c/\rho_{crit}$ | $^{\ddagger}0.1186(20)\,h^{-2} = {}^{\dagger}0.258(11)$ |
| 100 × approx to $r_*/D_A$ | $100 \times \theta_{MC}$ | $^{\ddagger}1.0410(5)$ |
| reionization optical depth | $\tau$ | $^{\ddagger}0.066(16)$ |
| scalar spectral index | $n_s$ | $^{\ddagger}0.968(6)$ |
| ln power prim. curv. pert. ($k_0$=0.05 Mpc$^{-1}$) | $\ln(10^{10}\Delta^2_{\mathcal{R}})$ | $^{\ddagger}3.062(29)$ |

2 parameters for initial conditions

- Other parameters (e.g. $\Omega_\Lambda$, $t_0$ ) are derived.

# Extensions to ΛCDM

- No evidence for need to introduce an additional parameter
- May change w/ more precise measurements in the future
- Following are in particular interesting
  - Tensor-to-scalar ratio (from inflation): $r$
  - Dark energy equation of state parameters: $w_0$, $w_a$

# Simplicity as working assumption


# Tests in extreme environments

# 2. CMB B-mode for testing inflation & QG

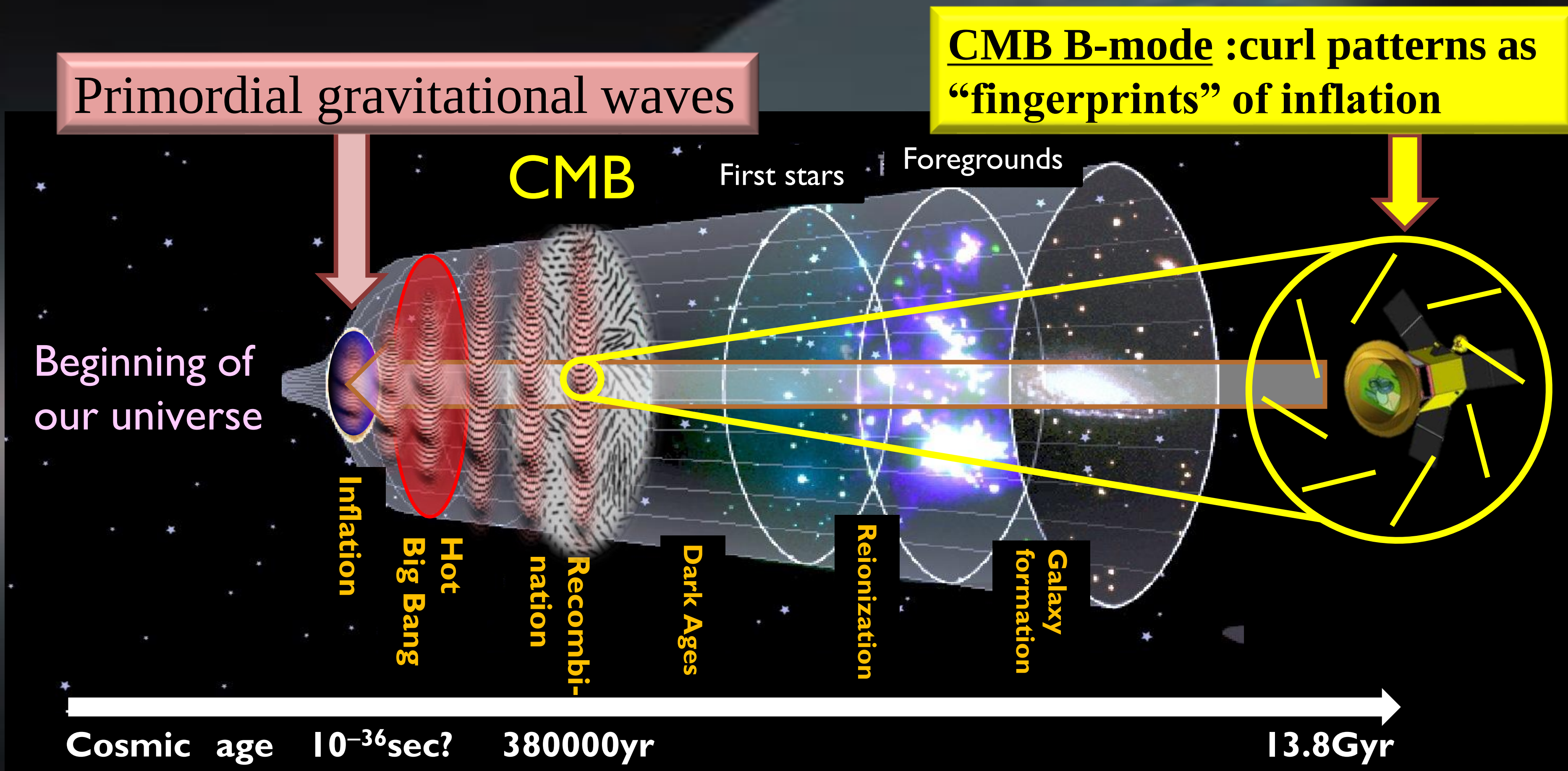
# Physics of Cosmic Inflation

- Inflation: primordial accelerating expansion
  - successfully solve problems of naïve big-bang model
- Underlying physics is unknown
  - Leading hypothesis: new scalar field $\phi$ "Inflaton" with potential V($\phi$) → source of acceleration!
- In case of single-field slow-roll inflation (simplicity as guideline)

$$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$

- r (tensor-to-scalar ratio) is a key parameter

# CMB B-mode as signal of inflation

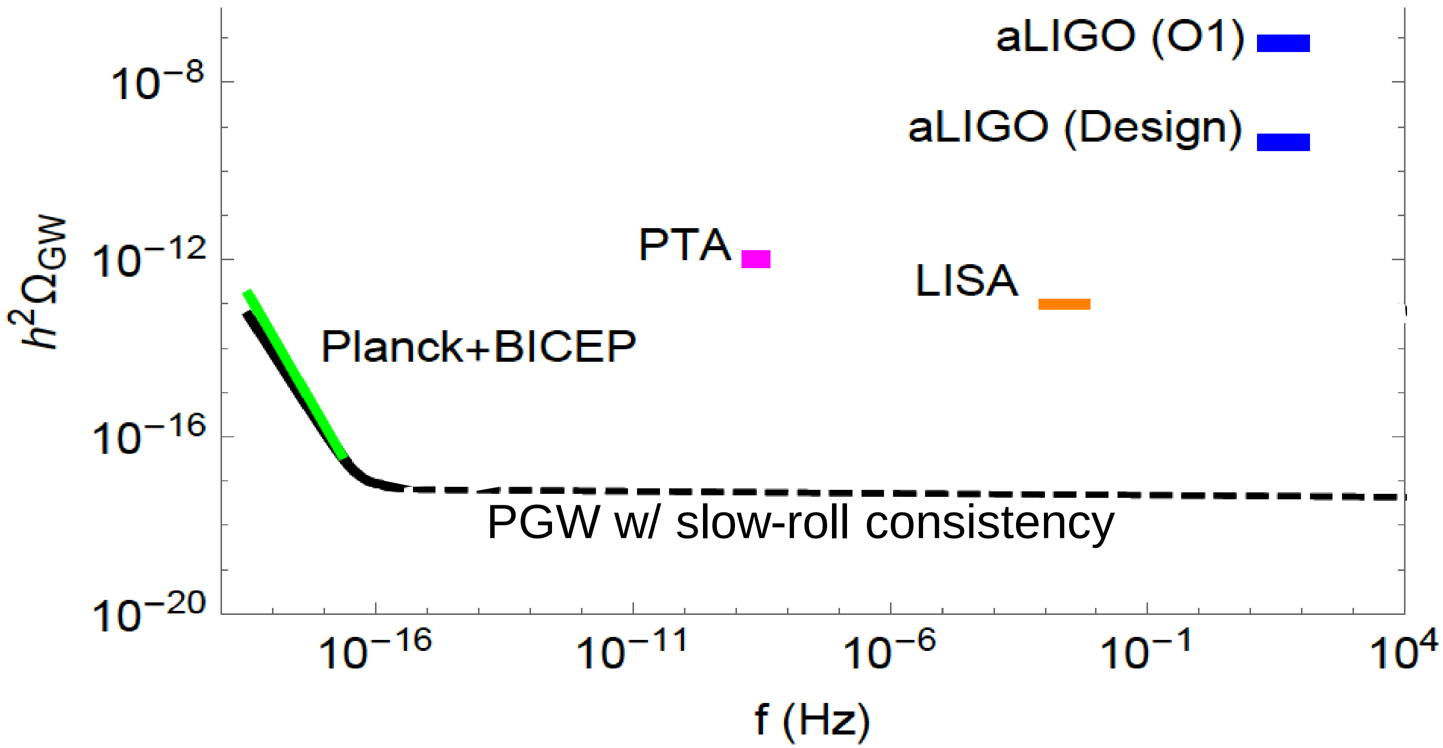



CMB B-mode is the best probe for primordial gravitational waves.
"Direct detection" of primordial GW w/ CMB as an experimental apparatus !

# CMB B-mode vs. interferometer

Caprini, Figueroa, arXiv1801.04268 (line w/ nt = 0.2 removed as it is irrelevant)

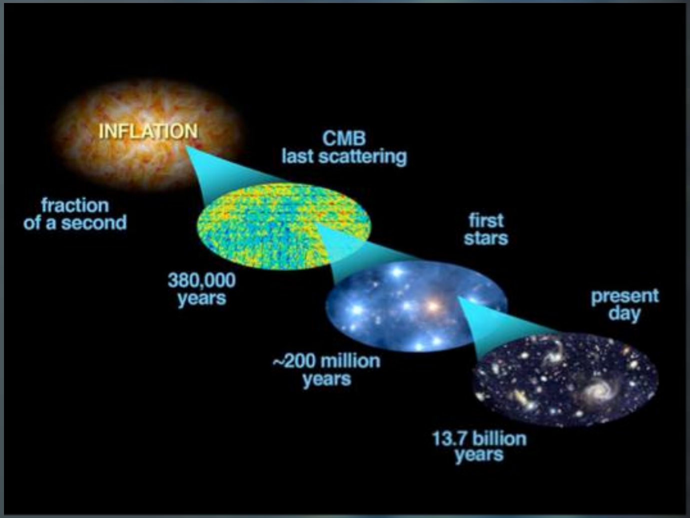
$$\Omega_{gw}(f) = \frac{3}{128}\,\Omega_{\rm rad}\, r\, A_s \left(\frac{f}{f_*}\right)^{n_t} \left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{4}{9}(\sqrt{2}-1)\right]$$




Discovery with CMB B-mode will provide a clear target for a future space interferometer.

*"Detecting primordial gravitational waves would be one of the most significant scientific discoveries of all time."*

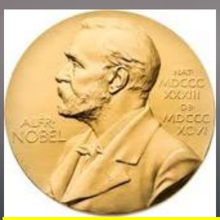
Final report of the task force on cosmic microwave background research
"Weiss committee report"
July 11, 2005, arXiv/0604101



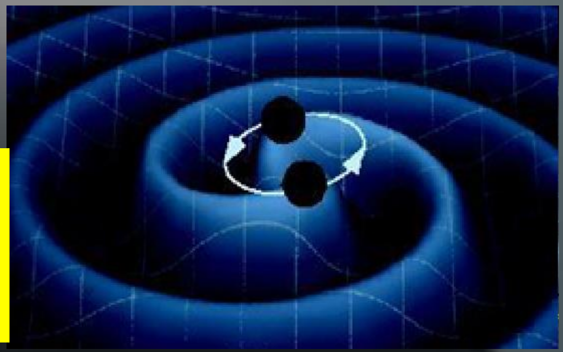
# Big leap from
# LIGO to CMB B-mode

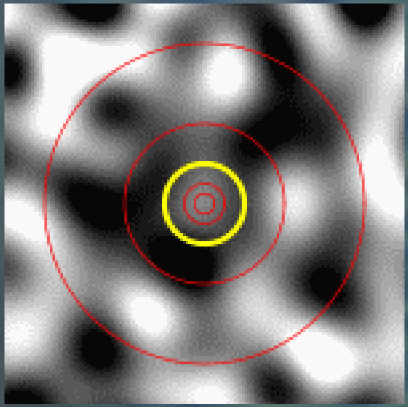
within
Einstein's theory
of general relativity

beyond Einstein



The 2017
Nobel Prize
in Physics





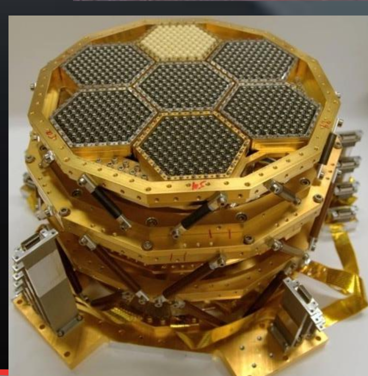
- LIGO: gravitational waves with classical origin
- CMB B-mode: gravitational waves with quantum origin

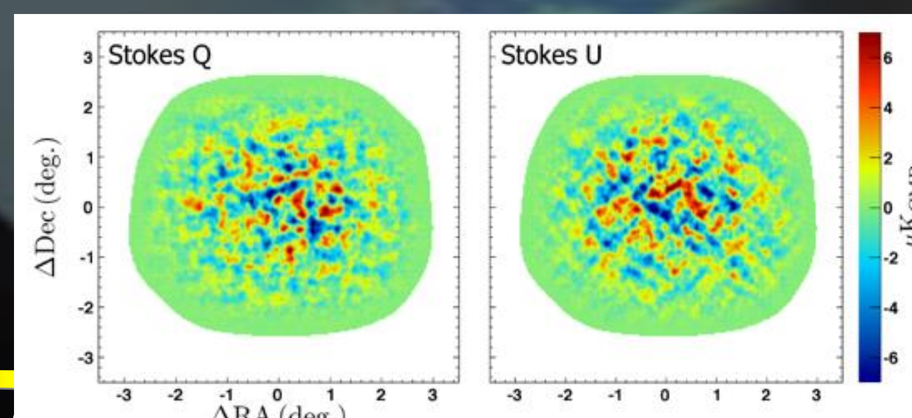
# Modern CMB instrument: POLARBEAR as an example

Site:
Atacama, Chile


TES
bolometer
array

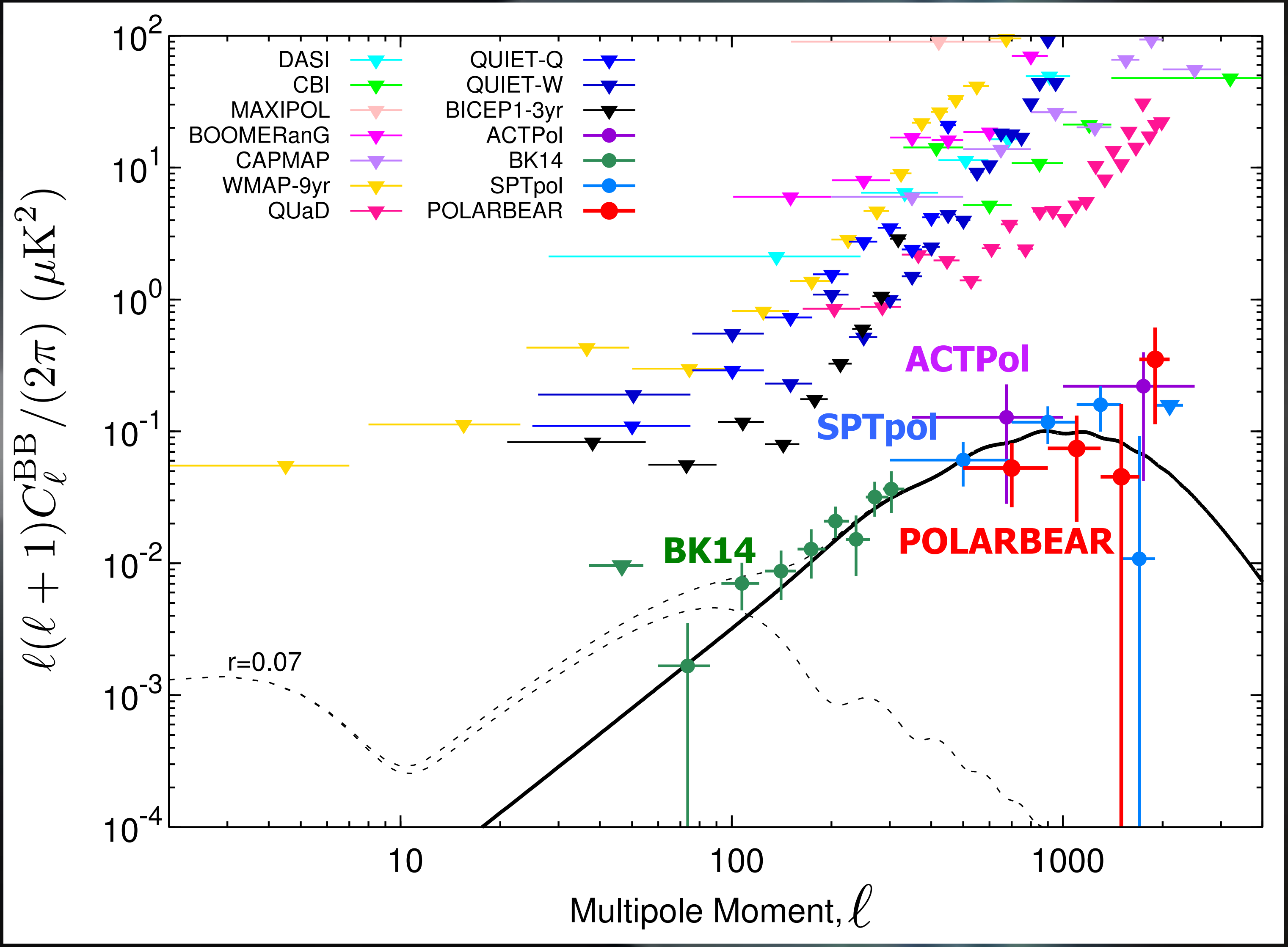
( UC Berkeley )





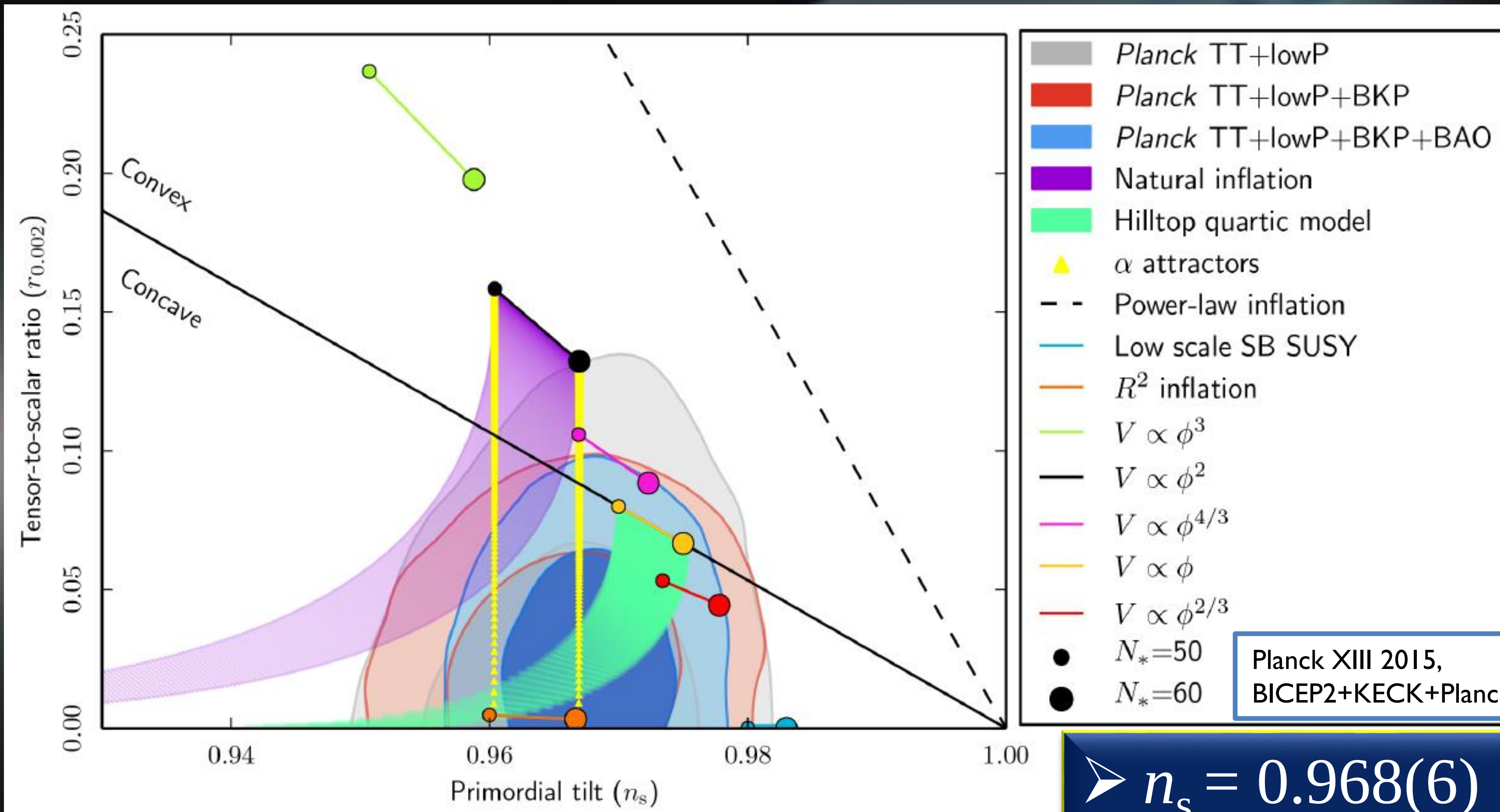
# CMB power spectra

2017




Y. Chinone
(UC Berkeley)

# Test of inflation models w/ $n_s$ and $r$

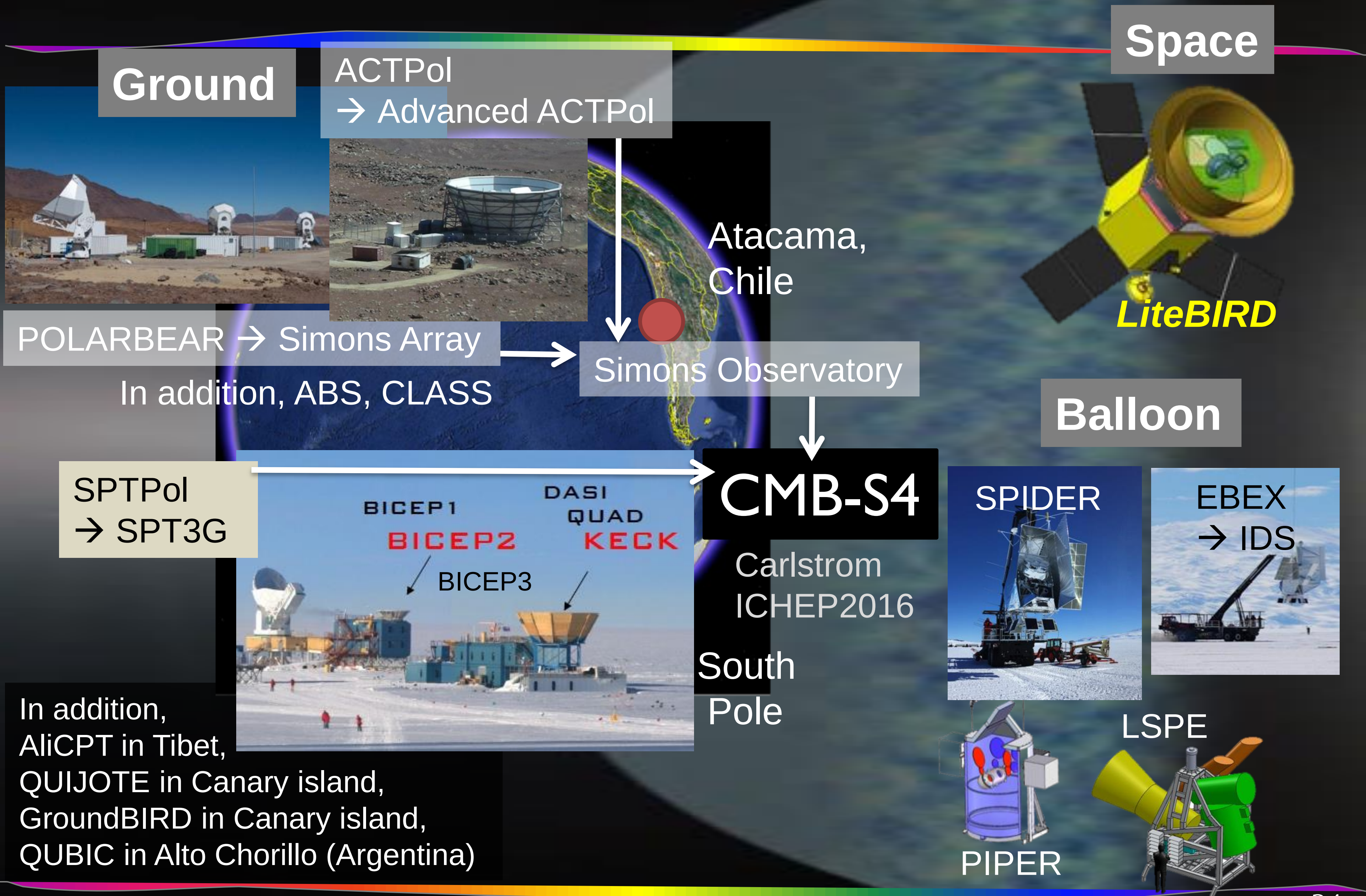



Planck XIII 2015,
BICEP2+KECK+Planck (BKP)

- $n_s = 0.968(6)$
- $r < 0.07$ (95%CL)

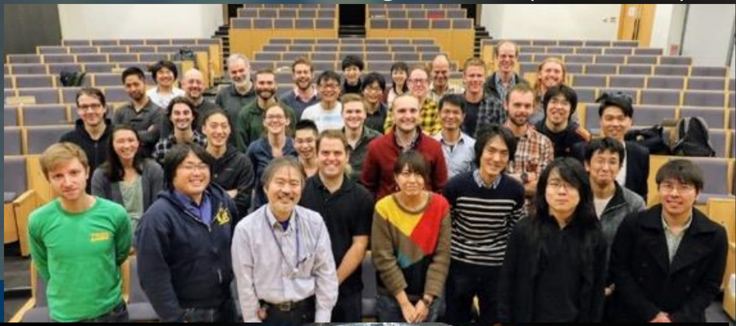
- $n_s < 1$ firmly established!
- The simplest chaotic inflation ($\phi^2$) already ruled out!

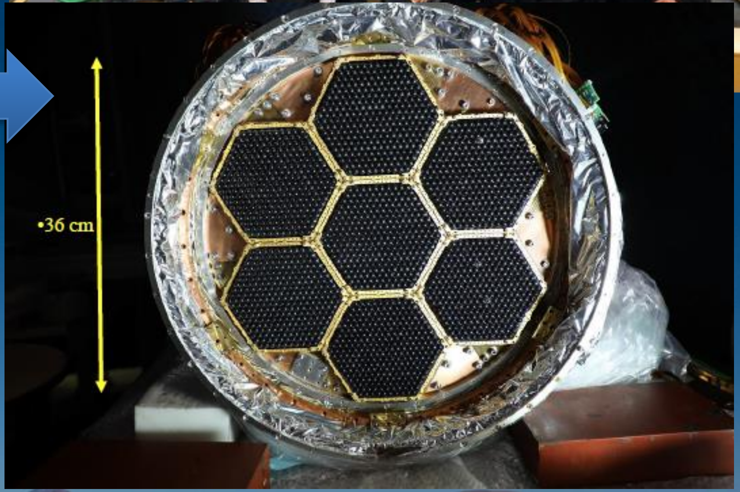
# On-going & future multi-frequency B-mode projects



# Simons Array: [σ(r) ~0.006, 4bands]

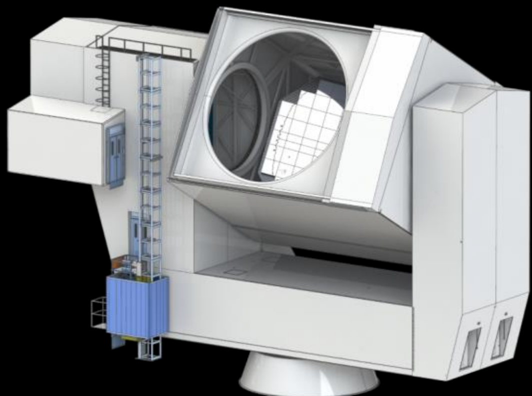

Collaboration meeting at KEK (Mar 2017)



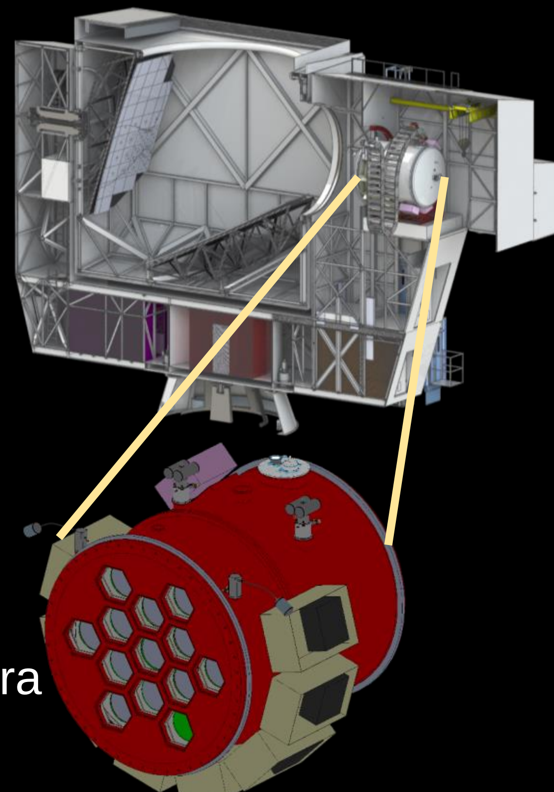



# Simons Observatory

**Full operations in 2021**

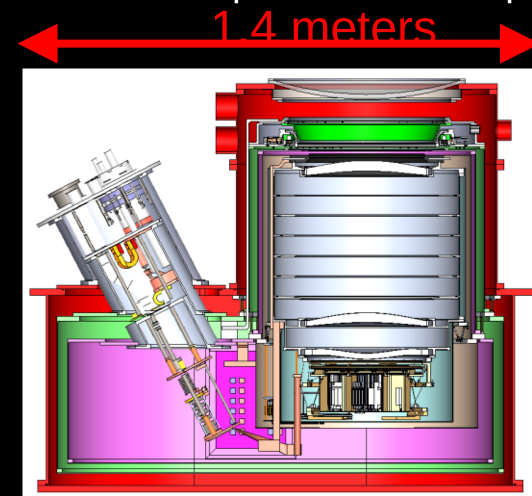


Large Aperture Telescope



Large Aperture Telescope Camera

Small Aperture Telescopes

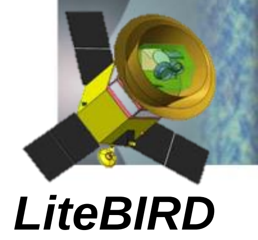



- Three telescopes each with a 50 cm aperture.
- A total of 30,000 detectors

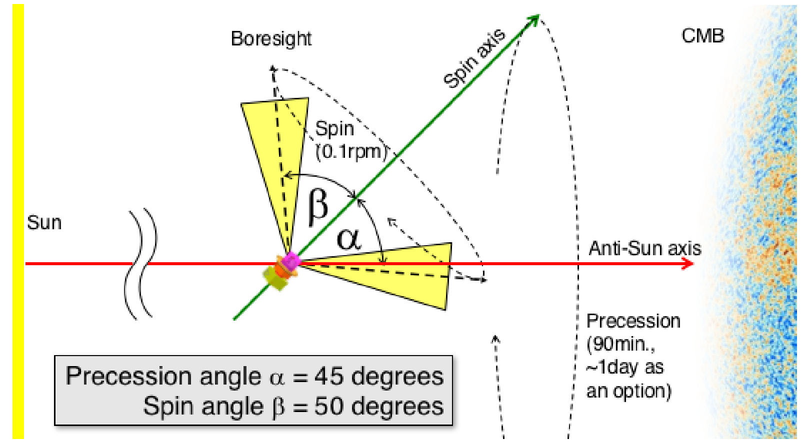
- 6 meter off-axis Cross Dragone design
- 9 degree field of view – 9 times the throughput of ACT
- 1.7 arcmin resolution at 150 GHz
- Up to 70,000 detectors can be accommodated (30,000 planned)

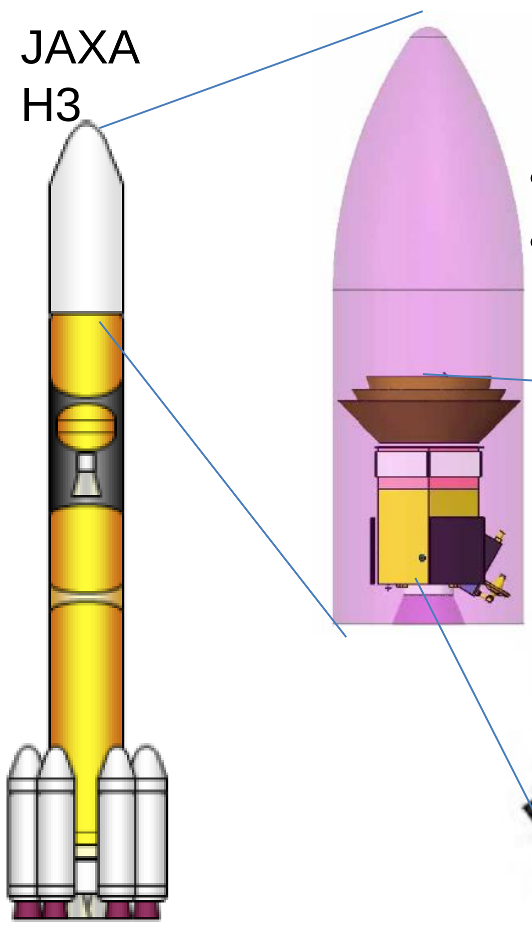
- Extensive site infrastructure in Chile
- Data pipeline and analysis development

# LiteBIRD



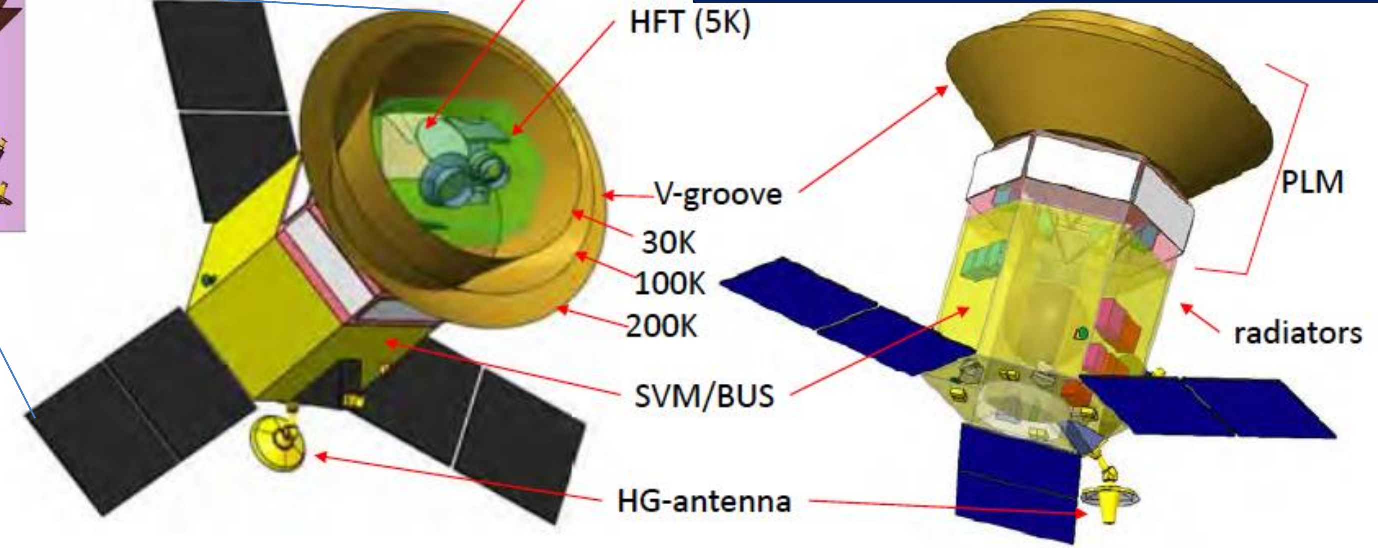

- JAXA-led international mission proposal (12 countries)
- Status: Phase A (concept development)
- 3yr observations at L2



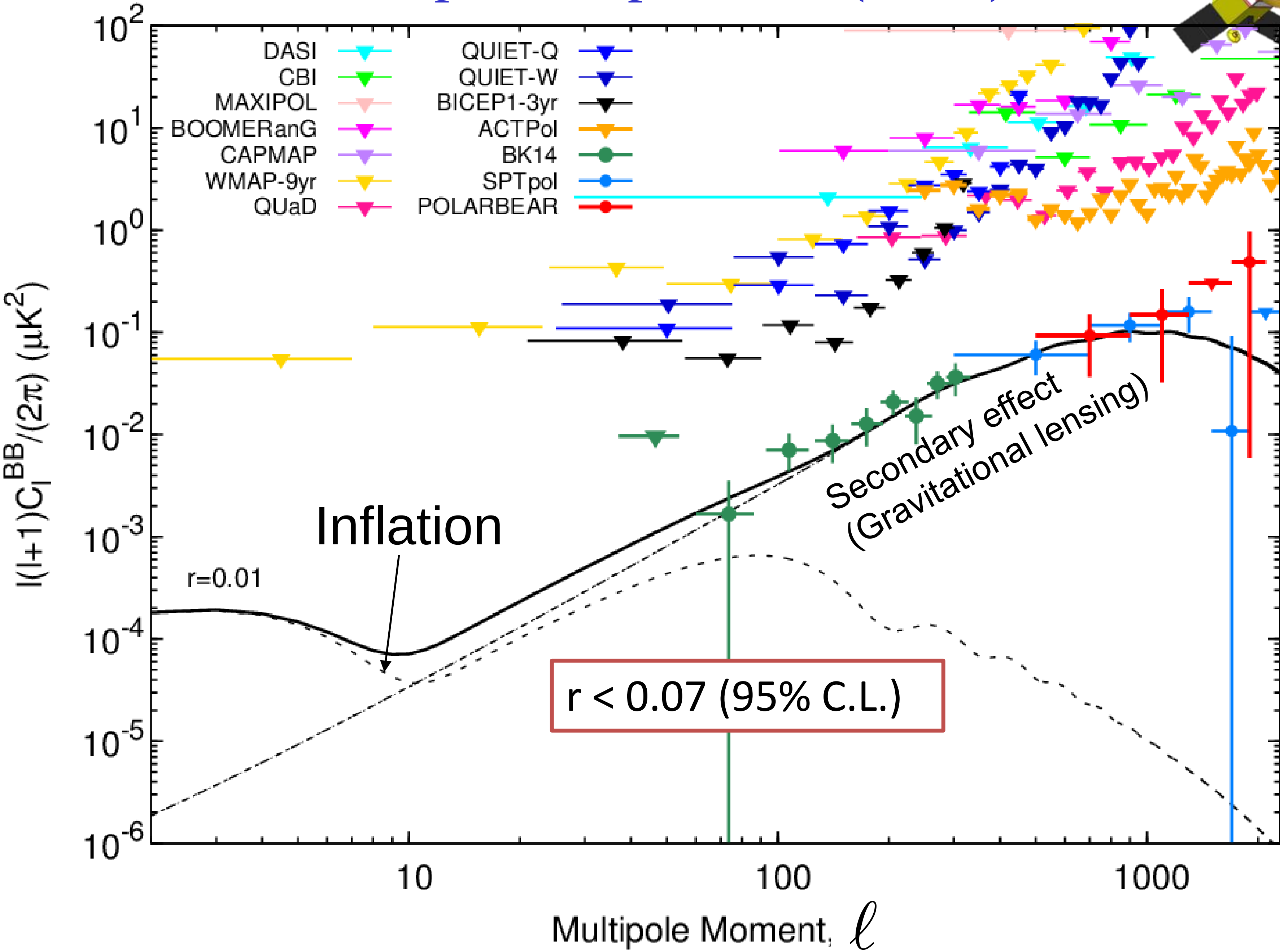




- The only space mission proposal in Phase A in the world
- Final selection in 2019
- Launch in 2027

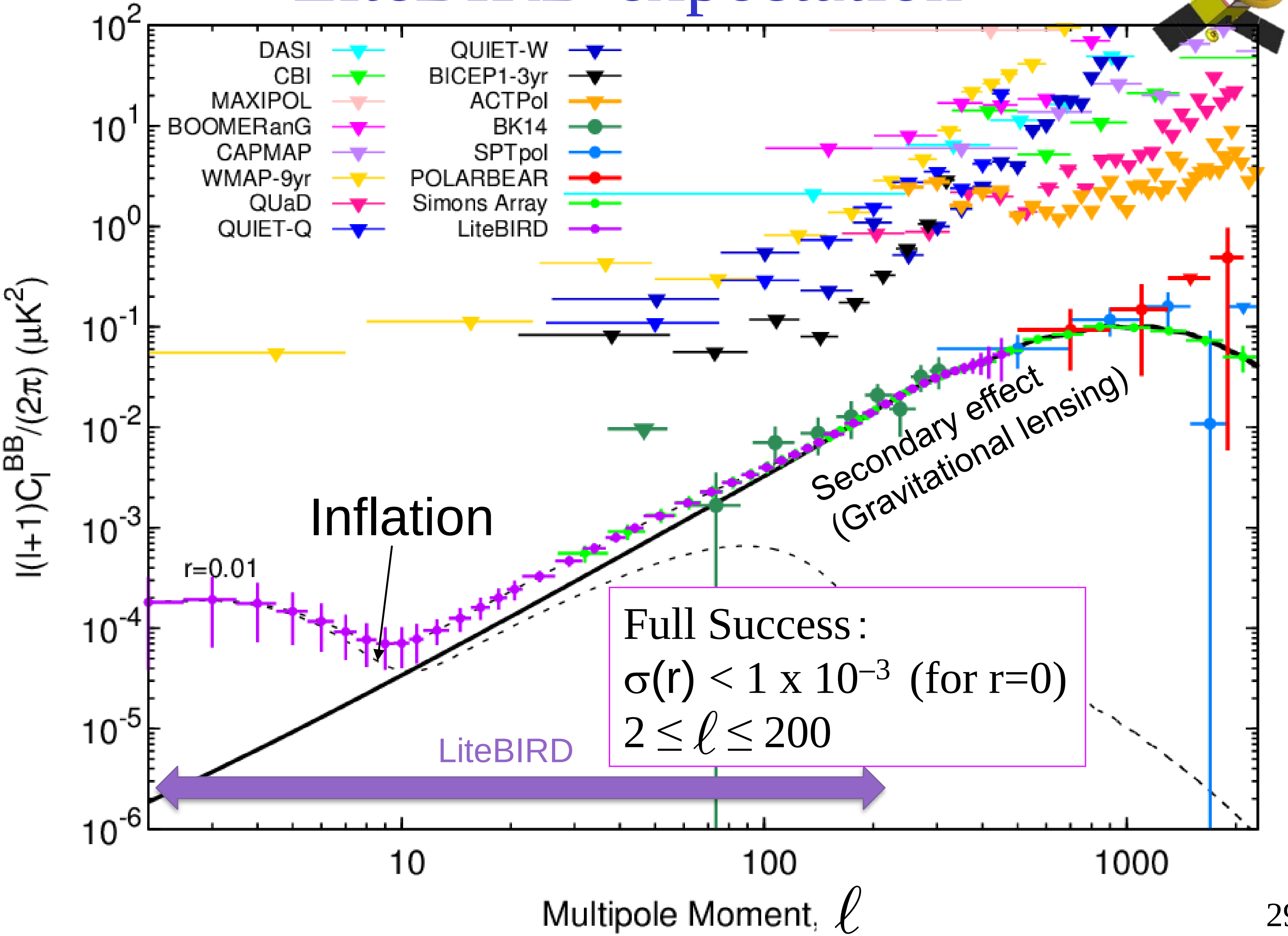
15 bands (34 – 448 GHz)



# B-mode power spectrum (2016)



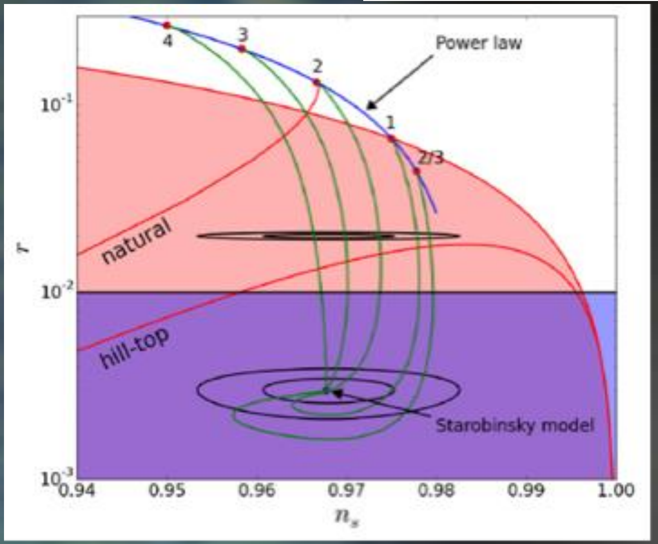
# LiteBIRD expectation



# Impacts of discovery

- Direct evidence for cosmic inflation
  - Many models predict $0.003 < r < 0.05$
  - Narrowing down models in r vs. $n_s$ plane
- Shed light on GUT-scale physics

$$V^{1/4} = 1.04 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} [GeV]$$




- New era of physics w/ experimental tests of QG
  - First observation of quantum fluctuation of space-time
  - Studies on top-down constraints in string theory in progress
    - r > 0.01 not easy (super-Planckian field excursions)
- Sense of wonder beyond science!

# 3. Dark Energy

# In a pub in Oxford

# Dark energy overview

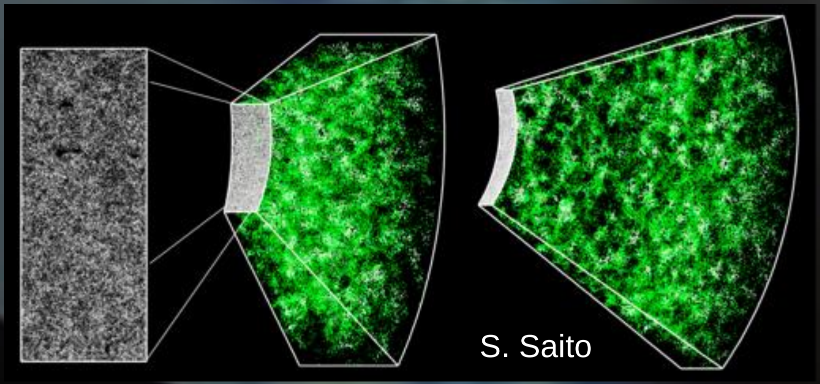
- Multiple consistent observations
- Accelerating expansion, which is not realized by ordinary matter
- Just Λ? still very weird "cosmo-illogical constant"
  - Why so small?
  - Why now $\Omega_\Lambda \sim \Omega_m$?
- Next logical step: check equation of state
- Observational probes
  - SNe
  - Weak Lensing
  - Baryon Acoustic Oscillation (BAO)
  - Sunyaev Zel'dovich Effect (SZE)

$$\Omega_\Lambda = 0.692(12)$$

$$w = -1.01(4)$$

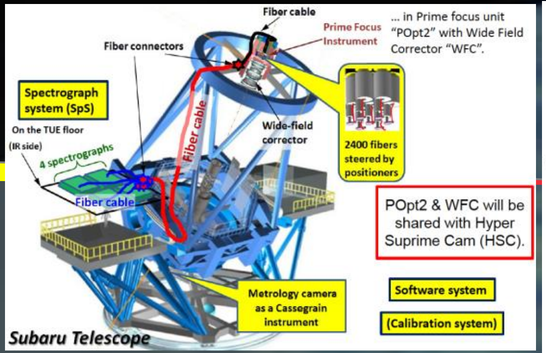
Ed Witten: ".. would be the number one on my list of things to figure out"

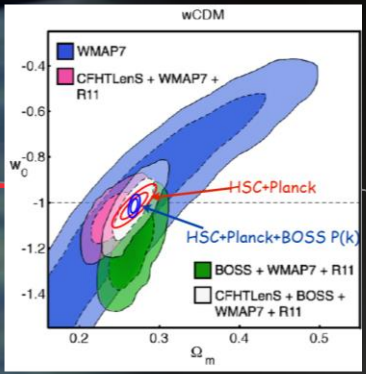
$$w(a) \equiv \frac{p}{\rho} = w_0 + (1-a)w_a$$

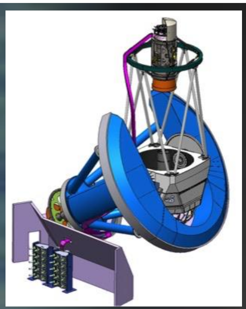


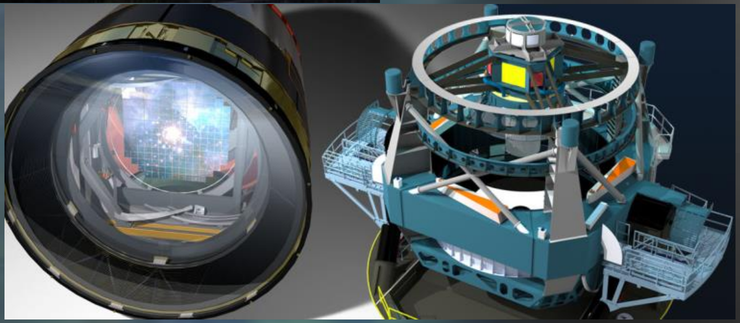
# Future prospects

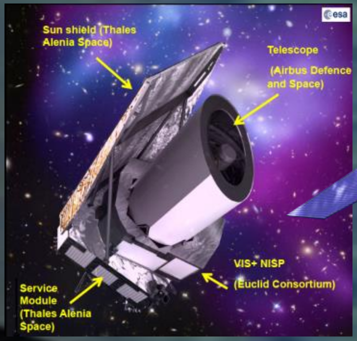
Many ambitious projects !
Significant improvement
on $w_0$ and $w_a$ expected!

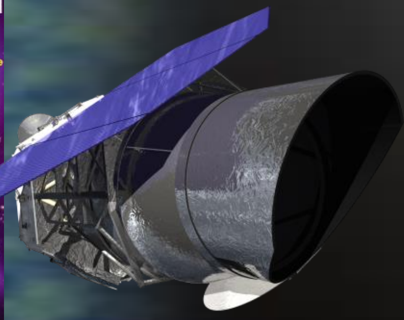






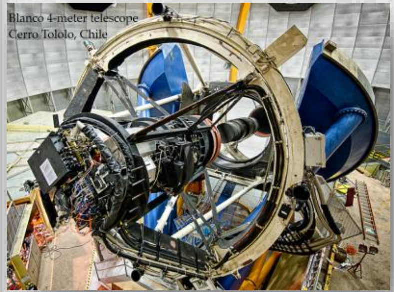
| Project | Dates | Area/deg$^2$ | Data | Spec-$z$ Range | Methods |
|---|---|---|---|---|---|
| BOSS | 2008-2014 | 10,000 | Opt-S | 0.3 – 0.7 (gals)<br>2 – 3.5 (Ly$\alpha$F) | BAO/RSD |
| DES | 2013-2018 | 5000 | Opt-I | —— | WL/CL<br>SN/BAO |
| eBOSS | 2014-2020 | 7500 | Opt-S | 0.6 – 2.0 (gal/QSO)<br>2 – 3.5 (Ly$\alpha$F) | BAO/RSD |
| SuMIRE | 2014-2024 | 1500 | Opt-I<br>Opt/NIR-S | <br>0.8 – 2.4 (gals) | WL/CL<br>BAO/RSD |
| HETDEX | 2014-2019 | 300 | Opt-S | $1.9 < z < 3.5$ (gals) | BAO/RSD |
| DESI | 2019-2024 | 14,000 | Opt-S | 0 – 1.7 (gals)<br>2 – 3.5 (Ly$\alpha$F) | BAO/RSD |
| LSST | 2020-2030 | 20,000 | Opt-I | —— | WL/CL<br>SN/BAO |
| *Euclid* | 2020-2026 | 15,000 | Opt-I<br>NIR-S | <br>0.7 – 2.2 (gals) | WL/CL<br>BAO/RSD |
| *WFIRST* | 2024-2030 | 2200 | NIR-I<br>NIR-S | <br>1.0 – 3.0 (gals) | WL/CL/SN<br>BAO/RSD |

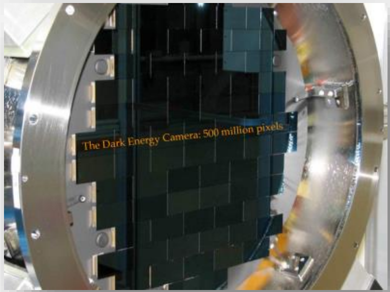
Data: optical (Opt) or near-infrared (NIR) imaging (I) or spectrocopy (S)
Spec-z Range: for galaxies (gals), quasars (QSOs) or Lyman-$\alpha$ forest (Ly$\alpha$F)
Methods: weak lensing (WL), clusters (CL), supernovae (SN), baryon acoustic oscillations (BAO), redshift-space distortions (RSD)

(Ramon Miquel, July 7 parallel session)

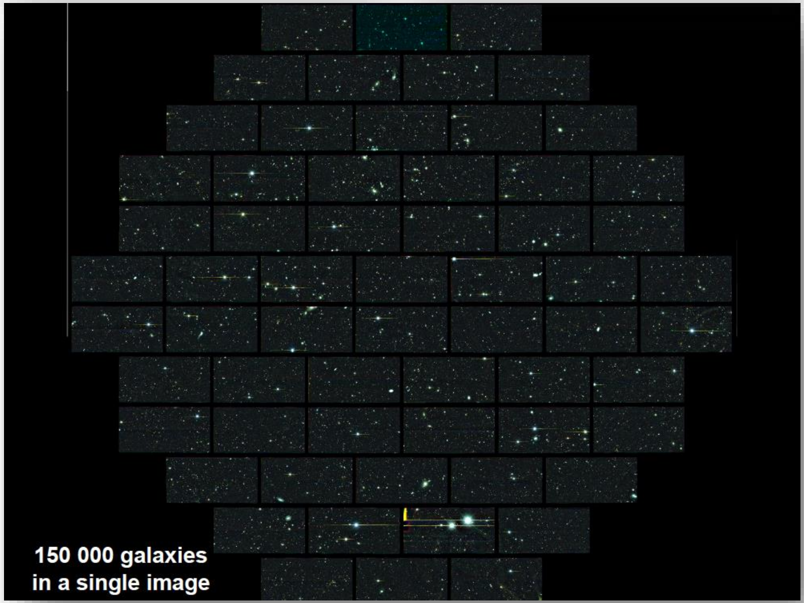
# Dark Energy Survey (DES)

DARK ENERGY SURVEY




- Imaging galaxy survey on the 4-m Blanco telescope (Chile) to study Dark Energy
- 350 scientists in 28 institutions in USA, Spain, UK, Brazil, Switzerland, Germany, Australia
- Is mapping 1/8 of sky (5000 deg$^2$) to z ~ 1.3 in 5 optical bands: 300 million galaxies
- Started in 2013. 577 nights in 6 seasons
- Four dark energy probes:
  - Galaxy cluster counting
  - Galaxy distribution (including BAO)
  - Type-Ia supernovae
  - Weak gravitational lensing

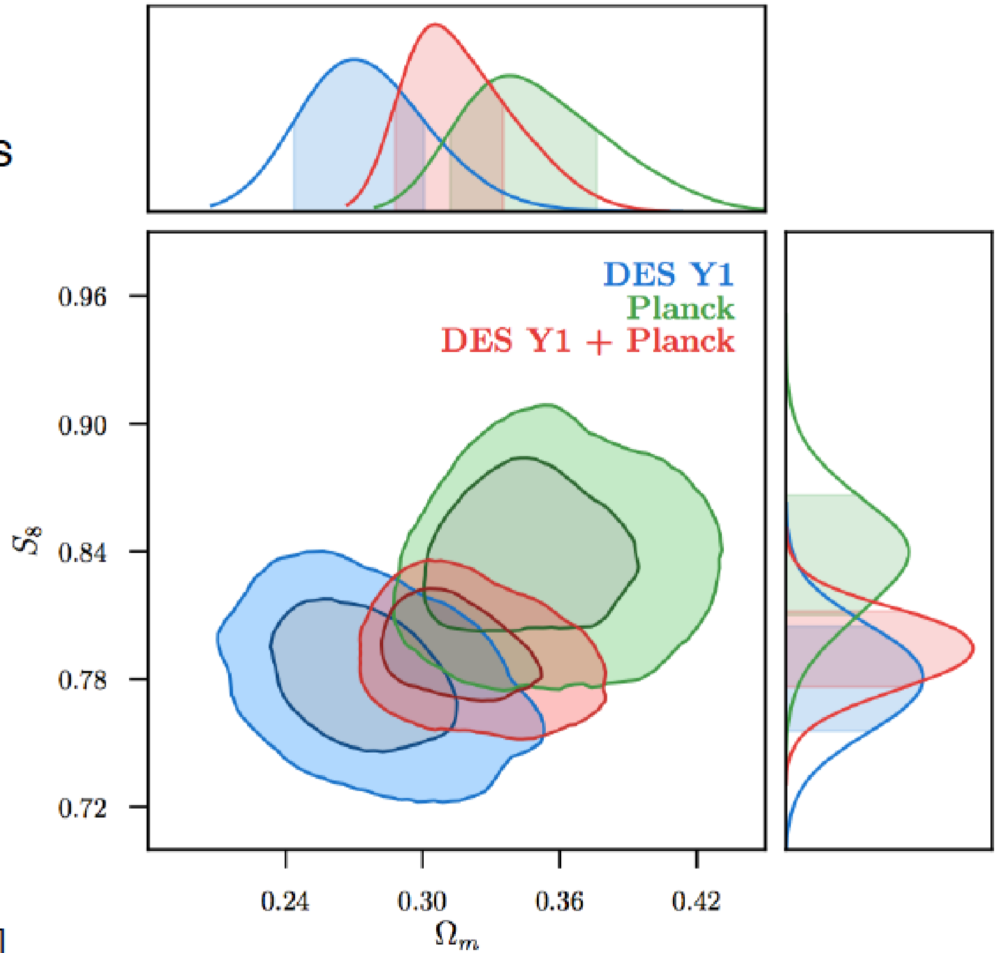


(Ramon Miquel, July 7 parallel session)

# DES-Y1 cosmological results (I)

DARK ENERGY SURVEY

- $S_8 = \sigma_8 (\Omega_m / 0.3)^{0.5}$ describes the **inhomogeneity of the matter distribution now**: $\sigma_8$ is the standard deviation of the matter-density distribution in spheres of radius 8 Mpc/h.
- **$\Omega_m$ : fraction of matter in the total matter-energy of the universe now**.
- First measurement in late universe with **precision comparable to CMB**.




DES Collaboration, arXiv:1708.01530 [astro-ph.CO]

# 4. Other BSM-related topics

# 4-1. Yet another inflationary probe: non-Gaussianity

- **Non-Gaussianity ($f_{NL}$)** – Sensitive to **Inflaton field**, single- or multi-field

$$\phi = \phi_{linear} + f_{NL}\,\phi^2_{linear}$$

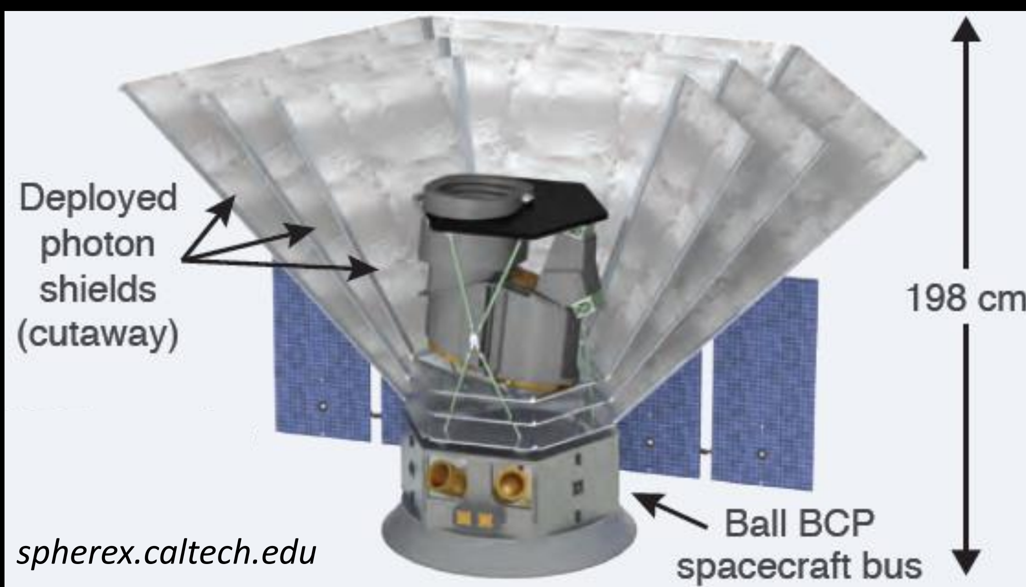
$$\text{CMB: } f_{NL} < 10.8\ (2\sigma)$$

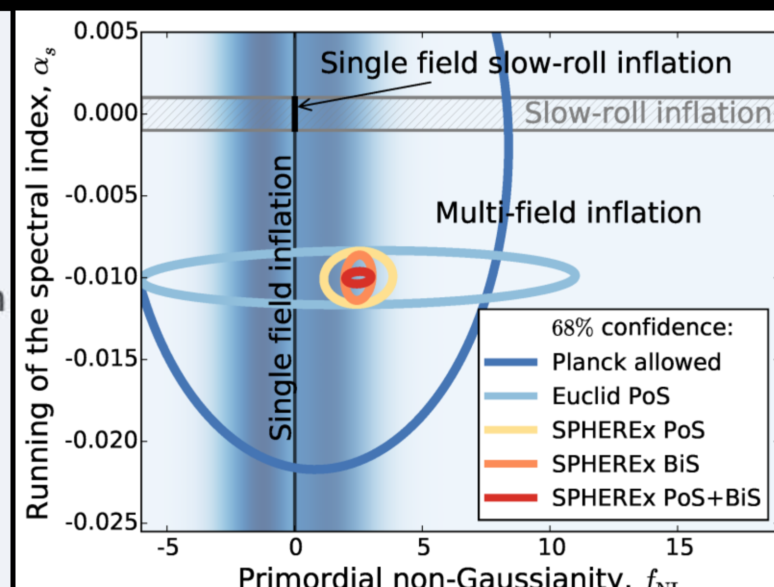
CMB near cosmic limits – use large-scale structure!

Local $f_{NL}$; Planck 2015 results

## SPHEREx: Near-Infrared All-Sky Spectral Survey

- NASA MIDEX in competitive Phase A (selection early 2019, launch 2023)
- Large-volume galaxy redshift survey designed for large spatial scales
- Broad science includes studies of extragalactic background and interstellar ices



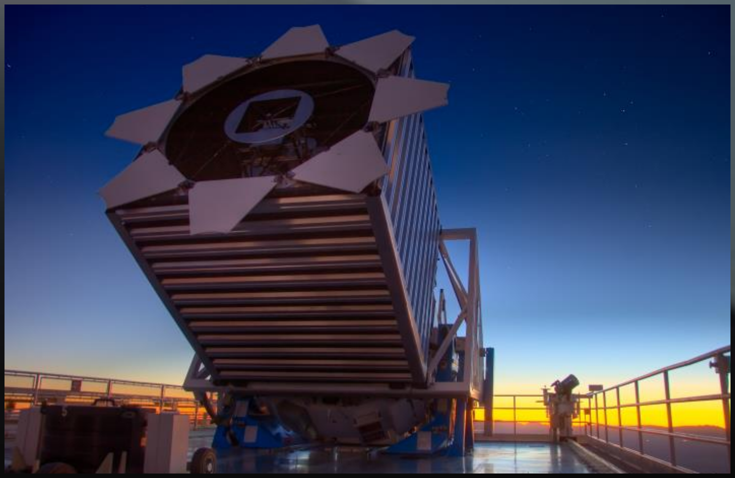
# 4-2. Neutrinos in cosmology

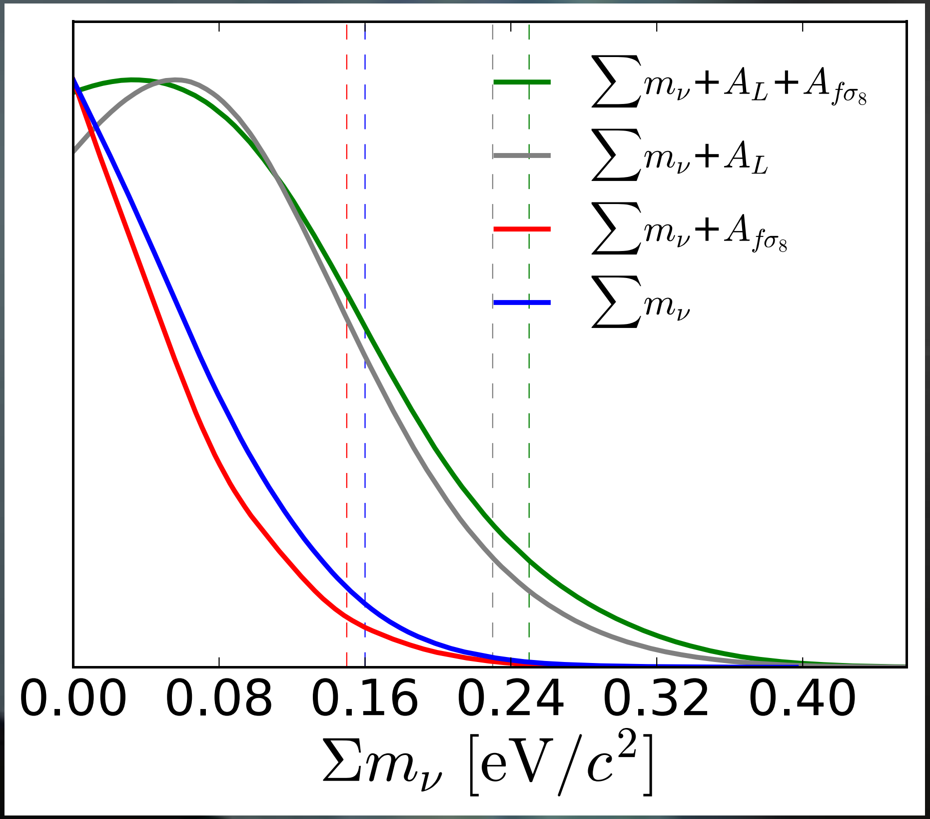
## Baryon Oscillation Spectroscopic Survey (BOSS)

$$\sum m_\nu < 0.16\text{eV (95\%C.L.)}$$

BOSS 2017

- Part of SDSS-III
- Spectroscopy (redshift) of ~1 M galaxies up to z=0.75 → 3D galaxy map

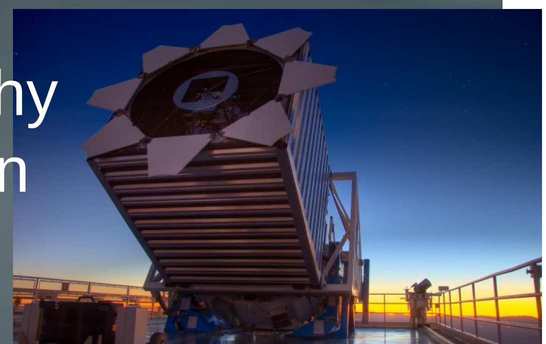




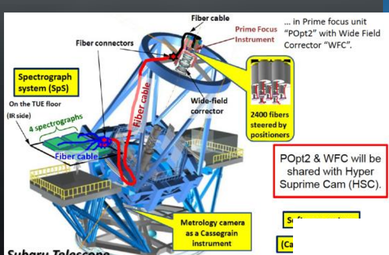
# Future prospects on neutrinos

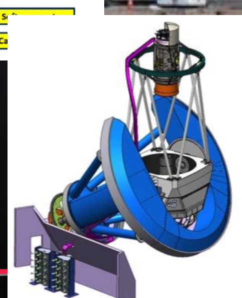
- CMB lensing B-mode
- BAO

Chance to resolve hierarchy independently of oscillation experiments



| $N_{eff}$ | $Sum(m_\nu)$ |
|---|---|
| 3.046 | > 59meV |
| $\sigma(N_{eff})$ | $\sigma(\Sigma m_\nu)$ |
| | ↓ Boss BAO prior |
| 0.14 | 0.15eV |
| | ↓ Boss BAO prior |
| 0.06 | 0.06eV |
| | ↓ DESI BAO + $T_e$ prior |
| **0.027** | **0.015eV** |



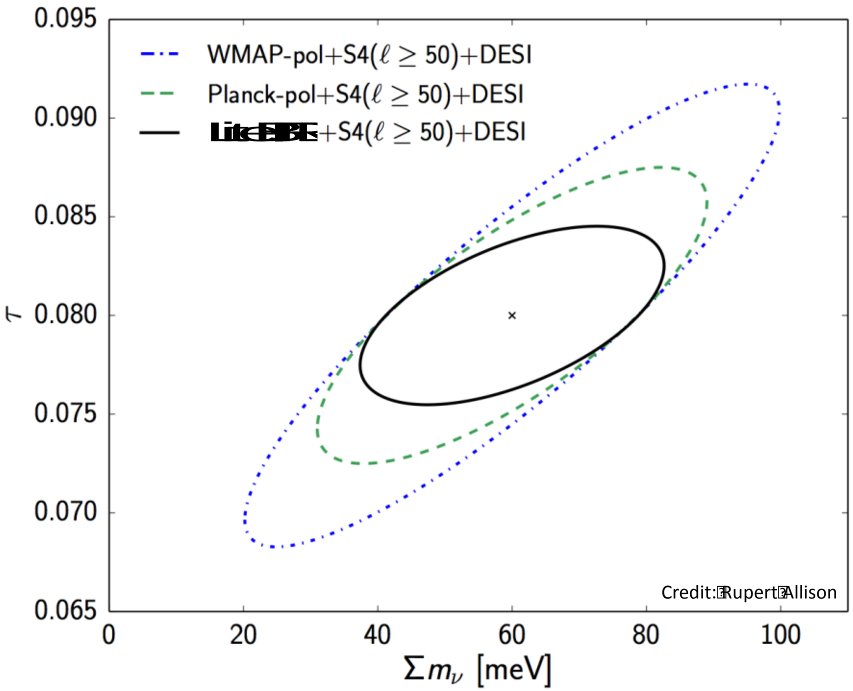



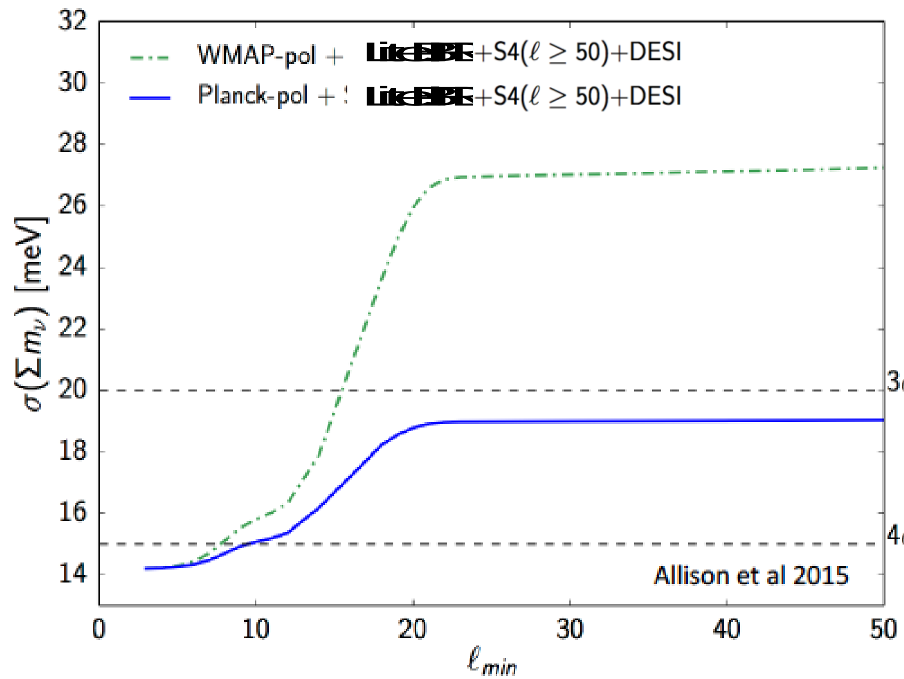
CMB-S4
Next Generation CMB Experiment

in 2020s

# τ(optical depth) and neutrino mass

- Better E-mode measurement for $\ell < 20$ improves τ
- Better τ improves $\Sigma m_\nu$ by resolving degeneracies



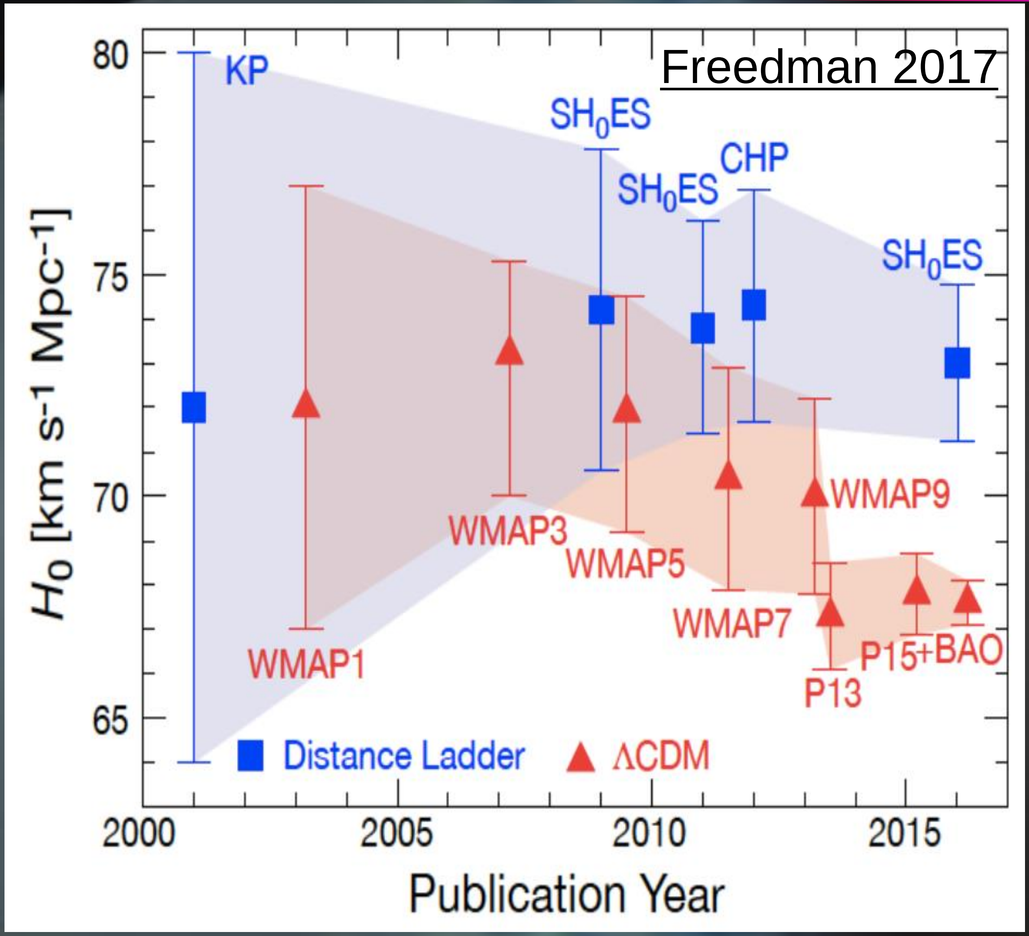




**Low $\ell$ measurements (e.g. LiteBIRD) contribute to $\Sigma m_\nu$ !**

# 4-3. Tension with Hubble constant $H_0$

Local vs. CMB-based
> 3σ

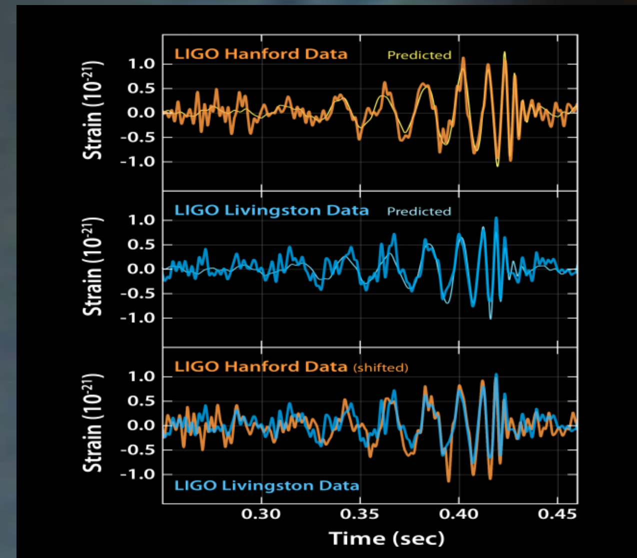
- Systematics?
- Observer bias?
- Are we living in a local void?
- New physics?



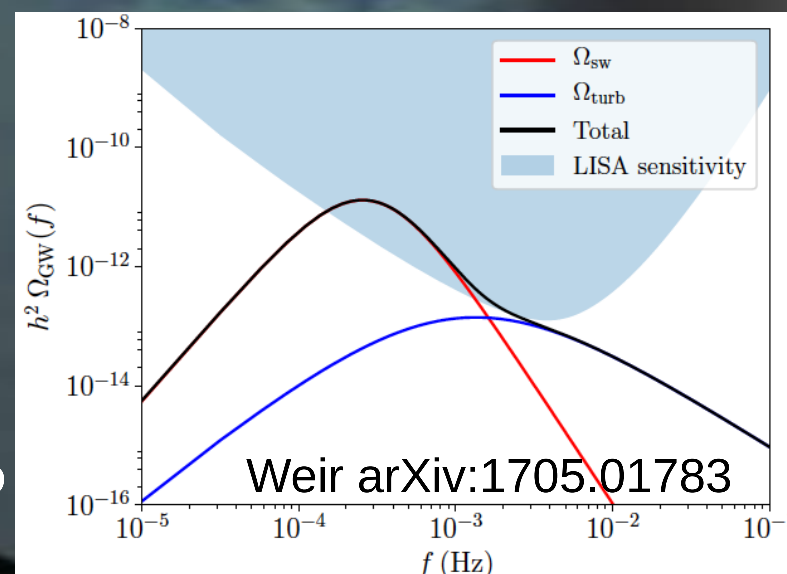

- We always need to be tension/anomaly-conscious
- The best part is that we expect further improvements in the future

# 4-4. Cosmology w/ GW detectors

- Discovery of BH mergers also stimulates cosmology!
  - $H_0$ measurement → talk by Peter Shawhan
  - BHs w/ primordial origin? theoretical attempts to create them from inflation




- Possibility of detecting 1st-order phase transition w/ future space GW detector?



# Summary

- Picture
  - ΛCDM well established (w/ watching $H_0$ tension)
  - Fundamental understanding of acceleraton is the key in the next step
- Signatures
  - Rich set of signatures: CMB polarization, Galaxy surveys w/ various observables, GW, etc.
- Future: simplicity as guideline
  - Primordial CMB B-mode and other inflation probes
  - Dark energy equation of state
  - Neutrinos in cosmology
  - And new probes and totally unexpected!

Exciting projects in experimental cosmology await us!

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- Osamu Tajima
- Masahiro Takada
- Jan Tauber

and many others!