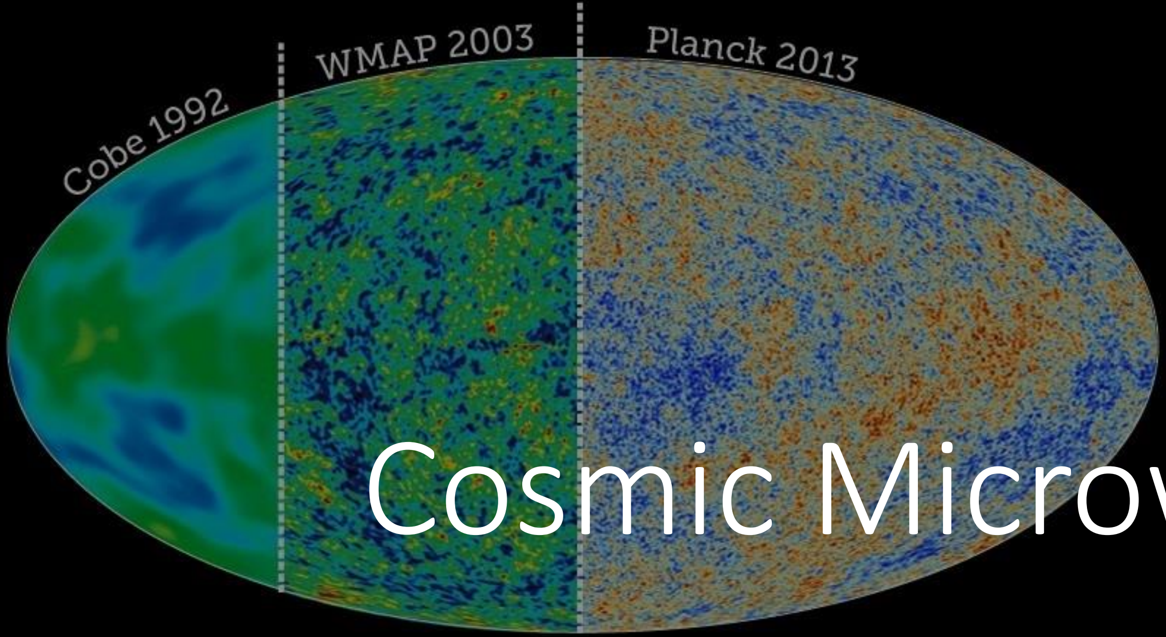


Cosmic Microwave Background

2020年9月30日　将来計画委員会勉強会　第3回

日下 暁人

University of Tokyo / Lawrence Berkeley National Laboratory

Higgs

Light New Particle?

TeV

Yukawa

5th force?

Dark Energy

ν

$\bar{B}/B$

Dark Matter

Inflation

What/Why do we learn from the Universe?

- ***Early Universe***: extreme and clean environment
  - Inflation
  - Relics: Baryogenesis, Dark Matter, Neutrinos, Unknown Unknown
- ***Gravity***: with other forces suppressed
  - Dark Matter and Dark Energy
  - Neutrinos
- ***Vacuum***:
  - Axions
  - Dark Energy
- ***Particle acceleration***

ビッグバンとインフレーション

宇宙進化と素粒子の関係
そして、CMBから何が分かるのか？

CMB: primordial gravitational waves

“Cosmic background is absolutely exciting – I’ve never expected it to be as exciting as it is now. I mean, finding the B modes is just unbelievably important.”

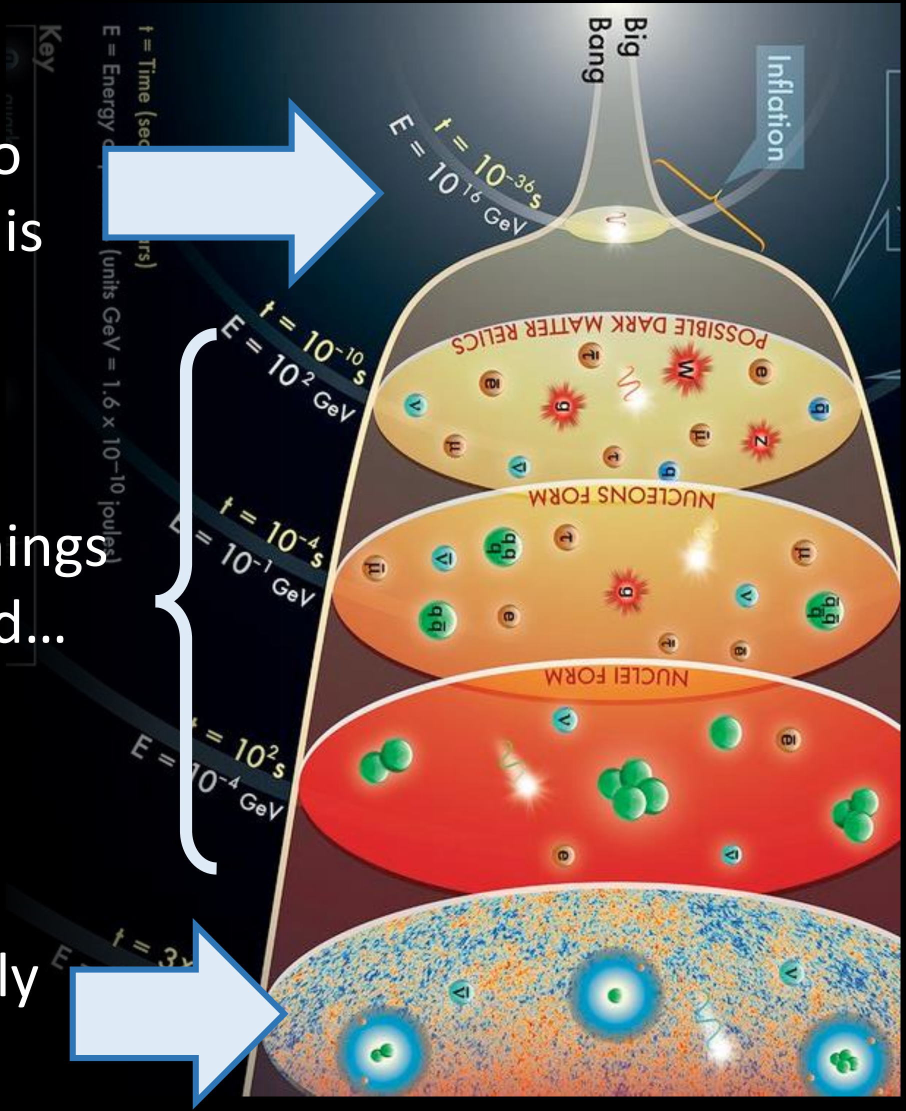
(Rainer Weiss, Segre lecture at UC Berkeley, 2016)

CMB: primordial gravitational waves

- We only observe t=380k yr.
- Really want to know: t≪1 sec.
- Things happened in between:
  - Bad: things get washed out.
  - Good: physics well understood.

Preserved “signal”?

- Gravitational Waves
  - Inflation, gravity quantization
- Sound waves
  - “Seed” of structure
  - Non-Gaussianity



I want to know this

Lots of things happened…

I can only see this

Is there a source? : inflation

- Inflation
  - Rapid expansion of universe
- Quantum fluctuation of metric during inflation
  - Off diagonal component (T) → primordial gravitational waves

Unique probe into

gravity ←→ quantum mechanics connection

Ratio to S (on-diagonal): r=T/S

Theoretically *interesting* parameter space: $0.001 \leq r \leq 0.1$

Primordial B-modes? What does it indicate?

→ Primordial Gravitational Waves

Density perturbationではない、before hot big bang

Inflationary Paradigm

- Primordial Gravitational Waves from quantum metric fluctuation
- r=T/S: expansion ratio of universe during inflation → energy scale.
- $r>0.003$: energy scale ~ GUT scale.
- $r<0.001$: depends on who you ask…

Don't forget: n_S and f_{NL} もある。

CMB: "backlight" shedding on cosmic evolution

A huge HEP laboratory

Axion?

Sterile ν?

$\delta(\sum m_\nu) \sim 30\,\mathrm{meV}$

Implication on hierarchy

Understanding Vacuum

Primordial (quantum) fluctuation

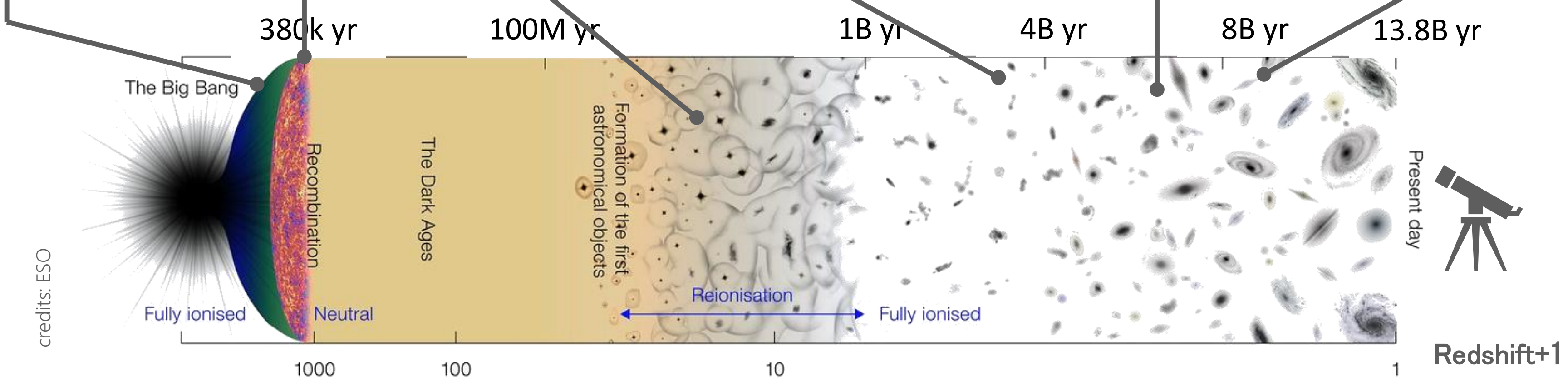
Thermal relics

Reionization

Sum of Neutrino mass

Galaxy Evolution

Dark Energy



credits: ESO

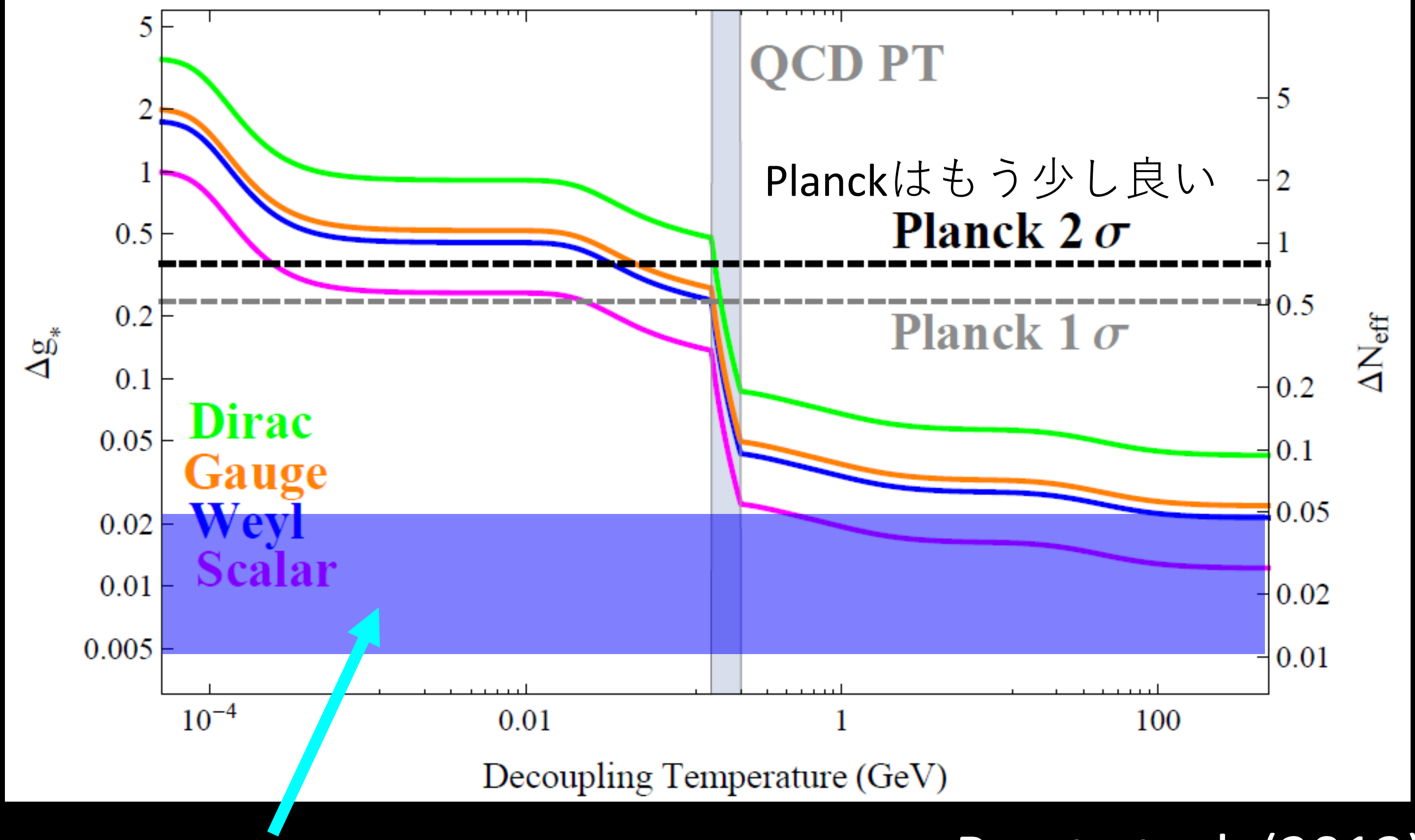
Order ~1 improvement by next-generation instruments → Leap in cosmology and HEP.

N_{eff}: Extra Relativistic Species

Early universe = extremely clean thermal bath.

Additional relativistic species → impact on expansion history ~decoupling.

N_{eff} as a function of decoupling temperature of the extra species.



Planckはもう少し良い

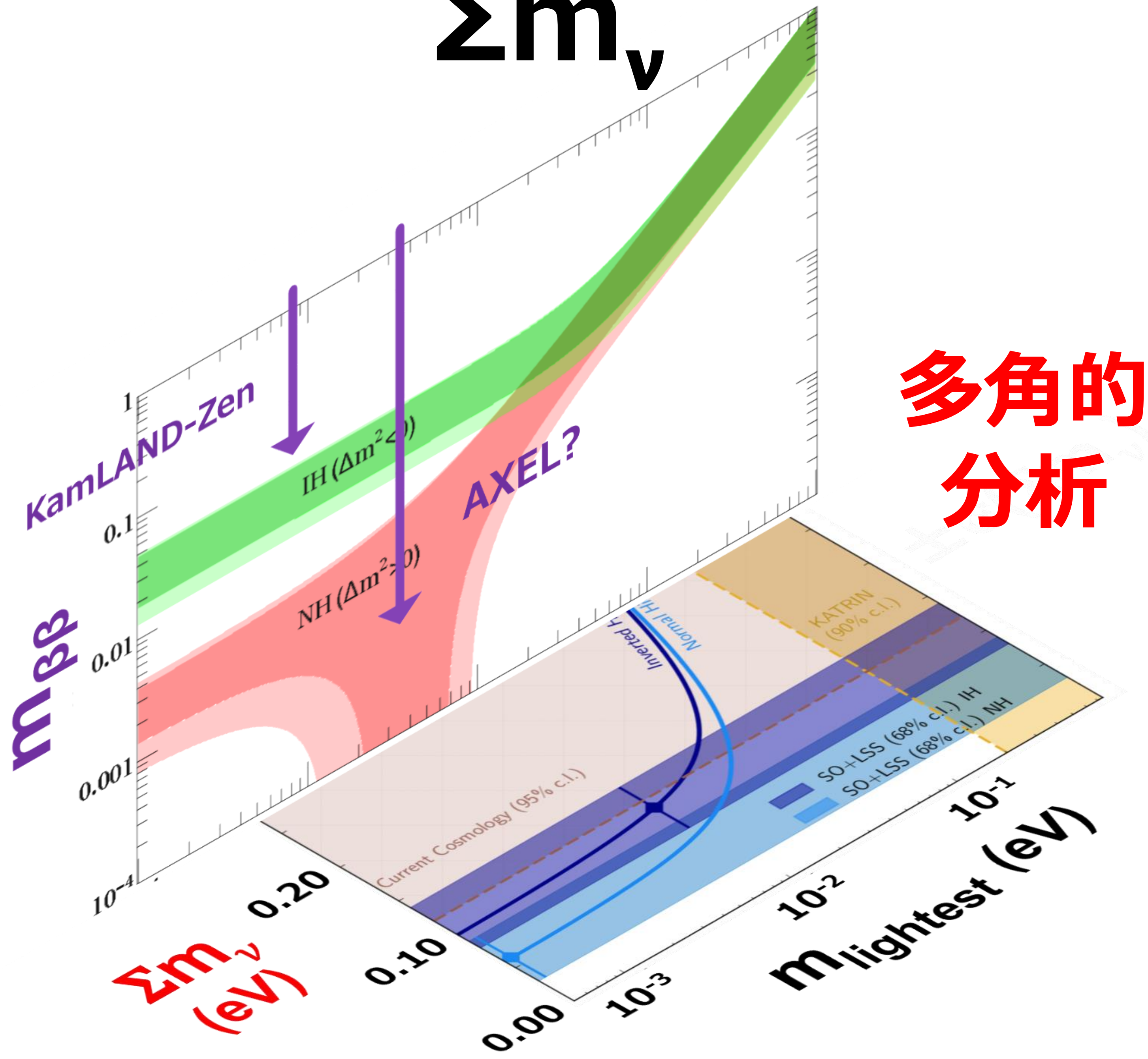
Reach of Stage 4 CMB experiment

Brust et. al. (2013)

N_{eff}: Extra Relativistic Species

- 条件：standard modelとのCouplingを持っていること。
  - Couplingのモデル依存性は低い
- ただし
  - Lite relicsがdecoupleした後で、BSMな（別の）粒子がstandard modelにpair annihilateすると、N_{eff}がdiluteされてしまう。
  - 実際はLHCのリミットがあるので、robust

Σm_ν



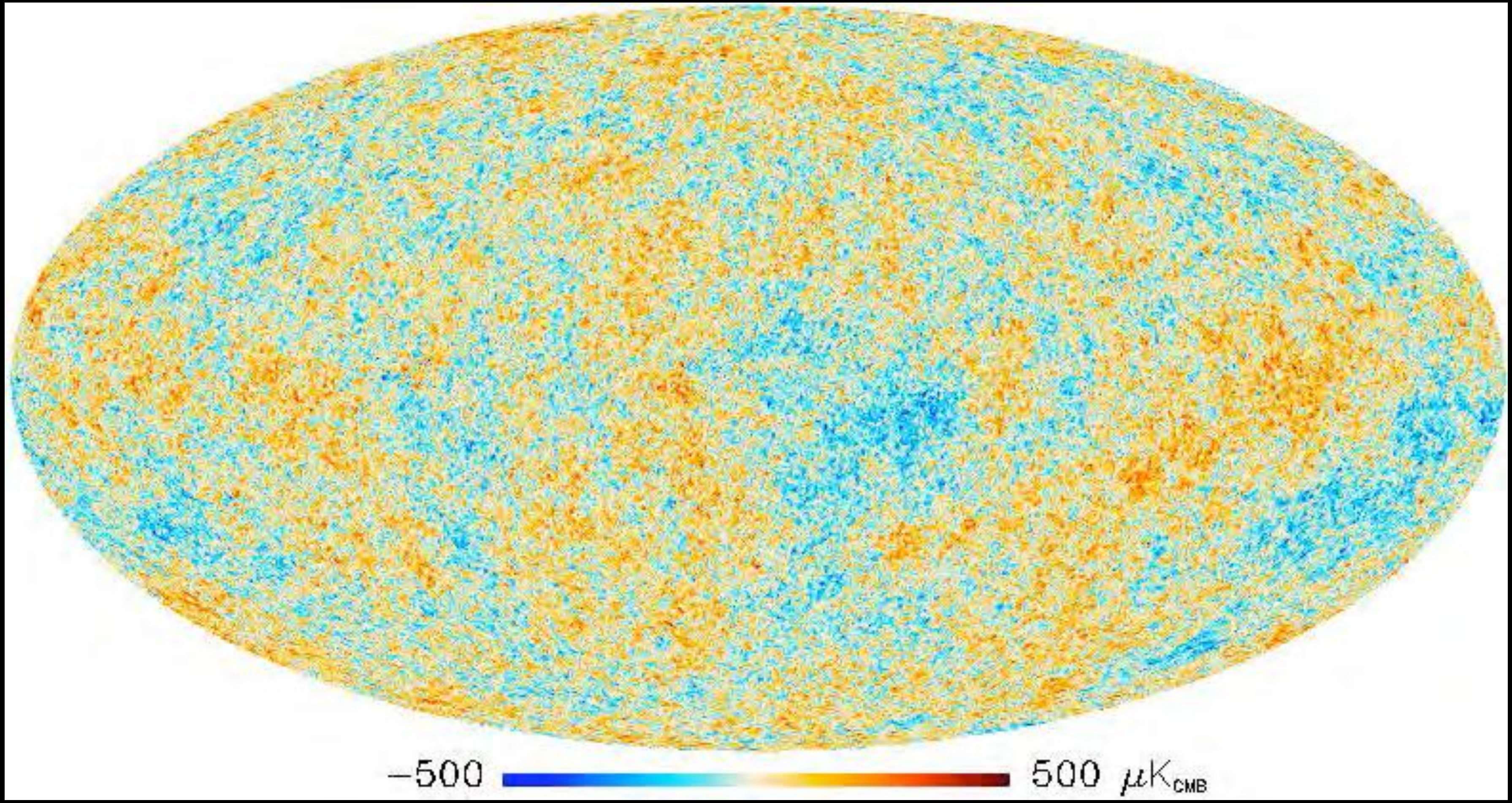
多角的分析

Sum of neutrino masses

- ビッグバンで生成された “宇宙背景ニュートリノ” : 既に明確に観測されている
  - Through N_{eff}
  - Energy budget: ~0.7 × photons
- 宇宙観測からのニュートリノ質量測定
  - 質量和 (Σm_ν) に感度を持つ
    - 地上実験と相補的
  - ニュートリノにより大規模構造の形成が阻害される効果を図る
    - 銀河サーベイのデータを使っての測定も可能 → Astrophysics起因の系統誤差抑制
- 大角度スケール測定があるとさらに感度向上できる。

2013

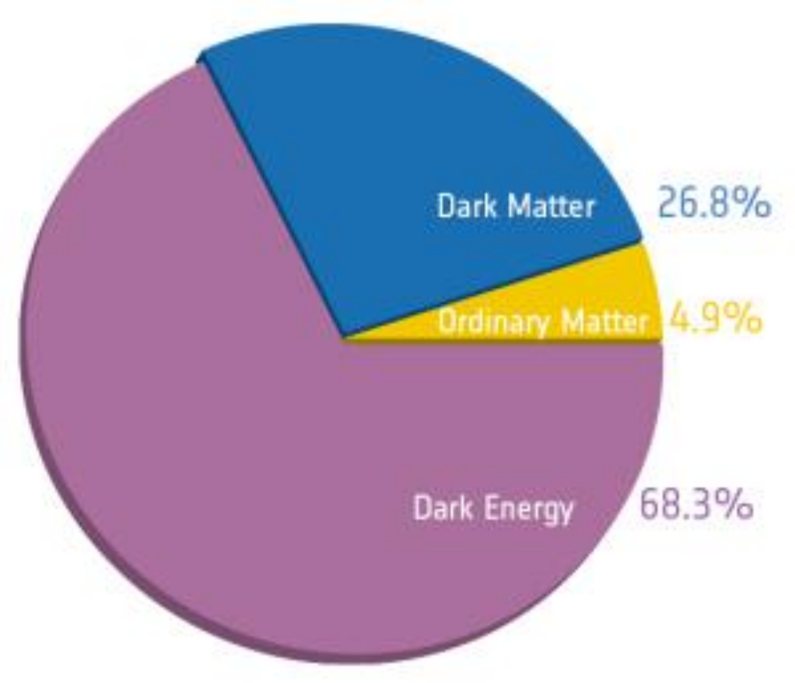
CMB Temperature



Planck Collaboration (2014)

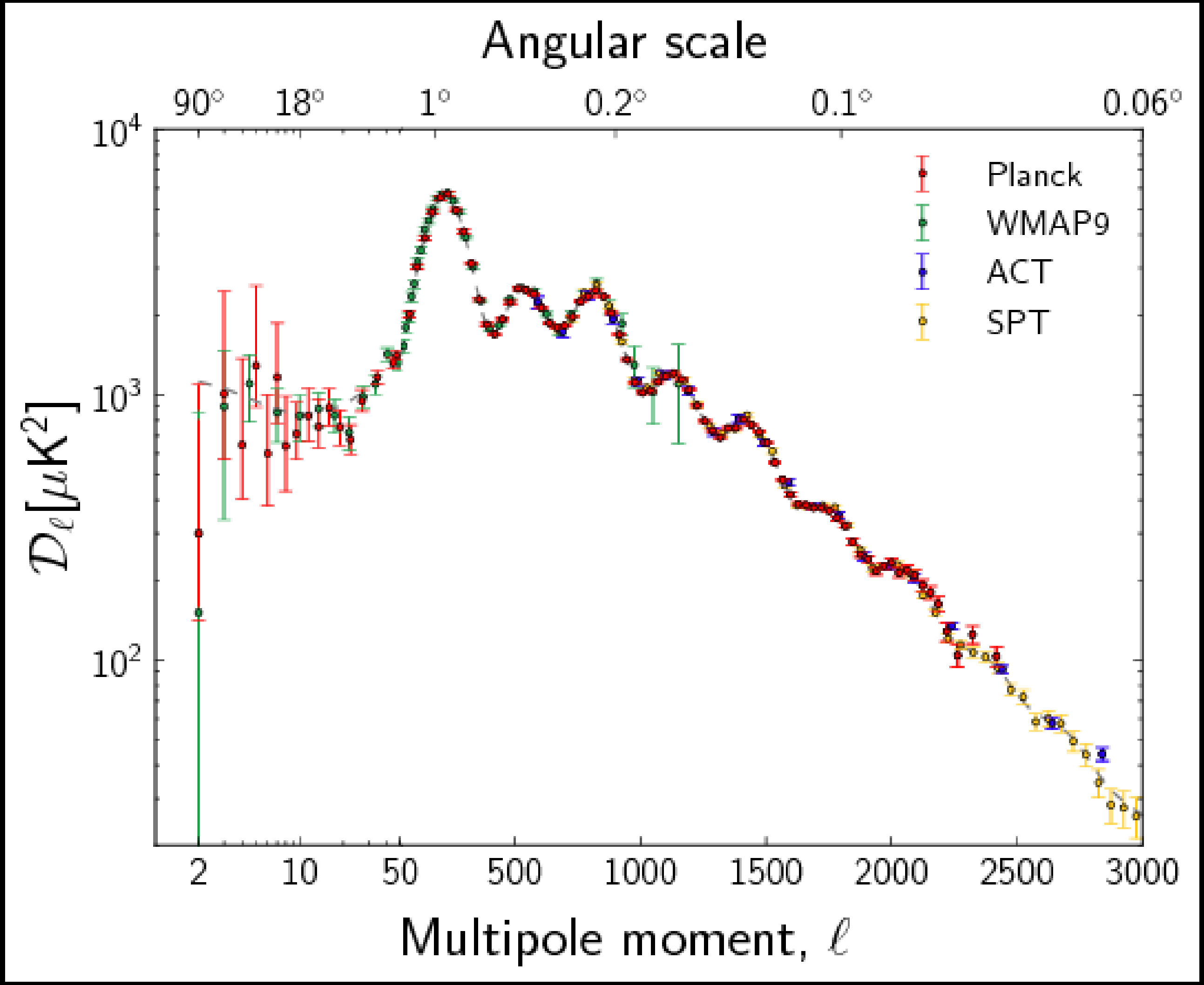
2015

CMB Temperature



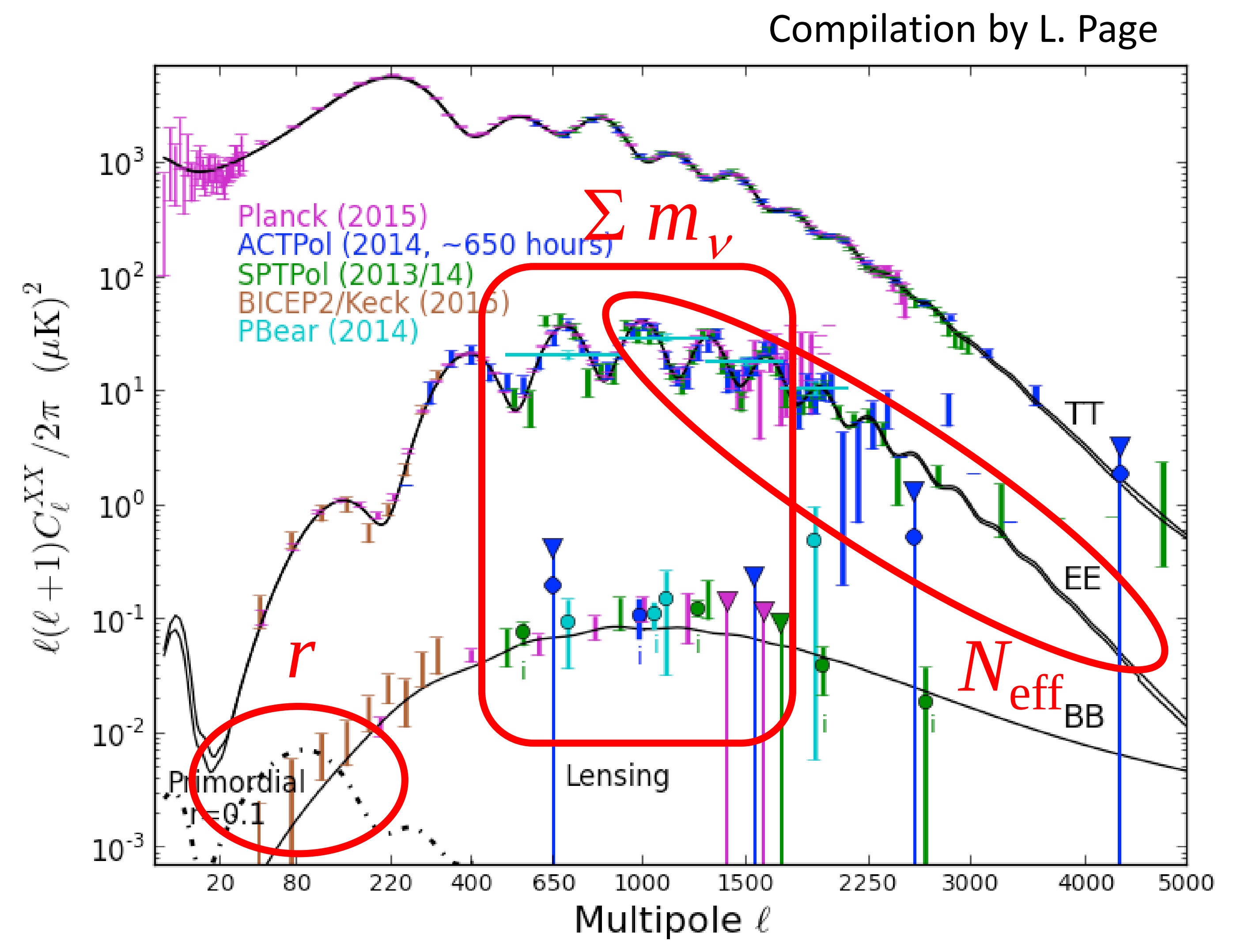
Planck Collaboration
(2015)

$\Omega_k = 0 \pm 0.005$ (w/ BAO)
Gaussian

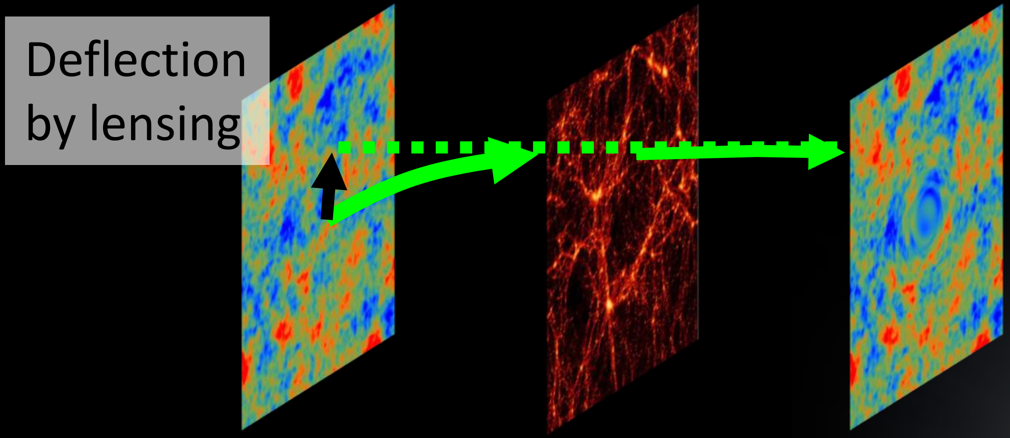


Planck Collaboration (2014)

CMB Polarization power spectrum

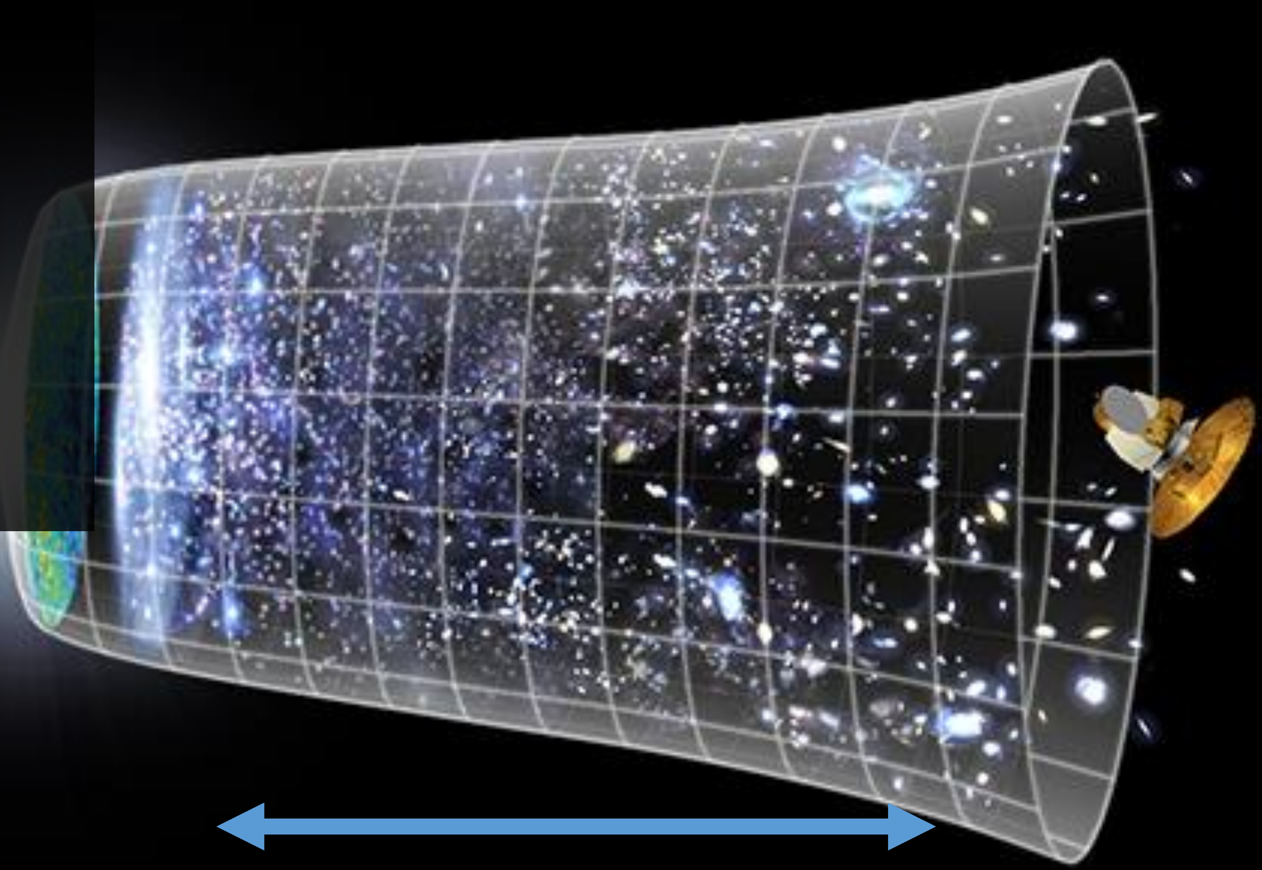


Lensing: B-modes created from E-modes



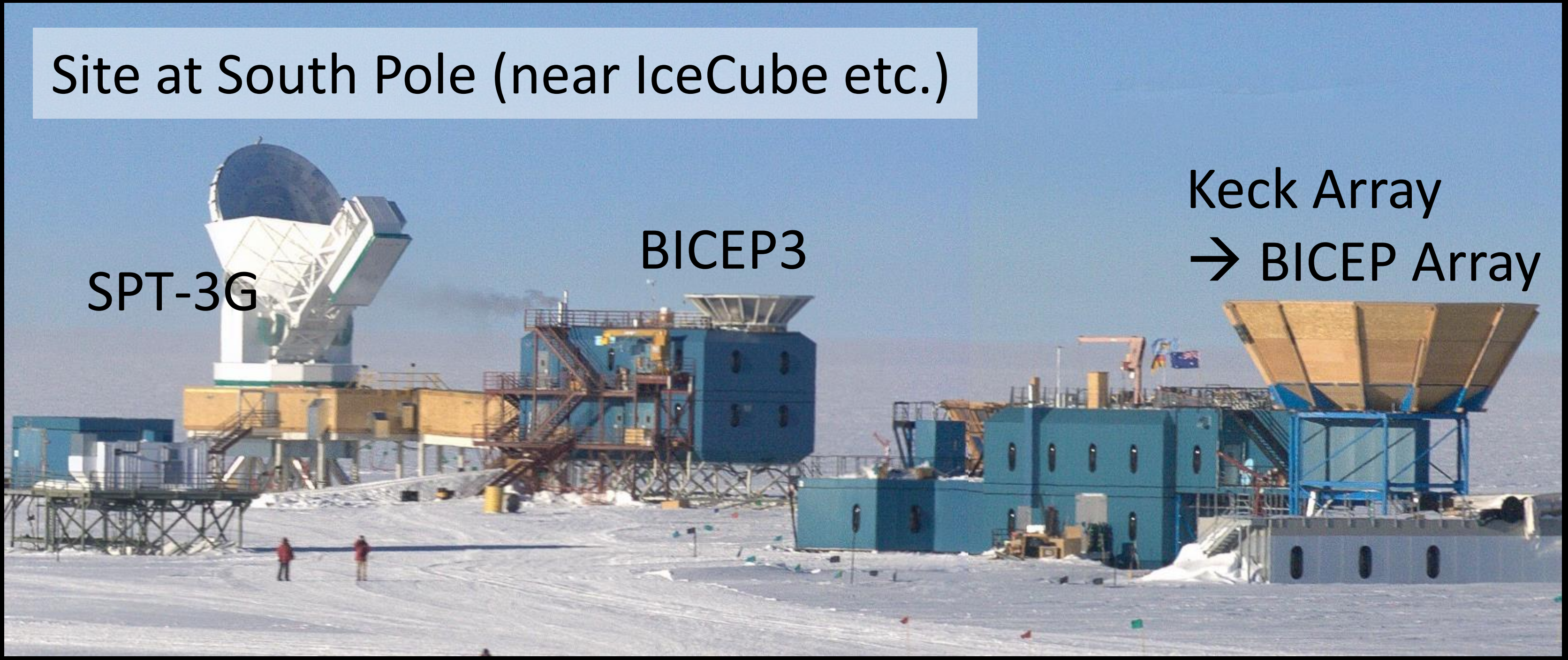
(Nearly) Gaussian
(Nearly) pure E modes

Non-Gaussian
Non-zero B modes

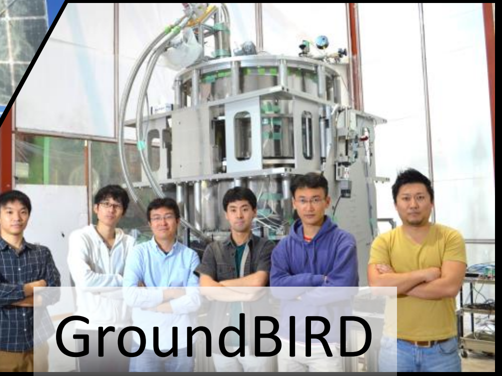


重力レンズ効果を通して、
宇宙構造形成を測る

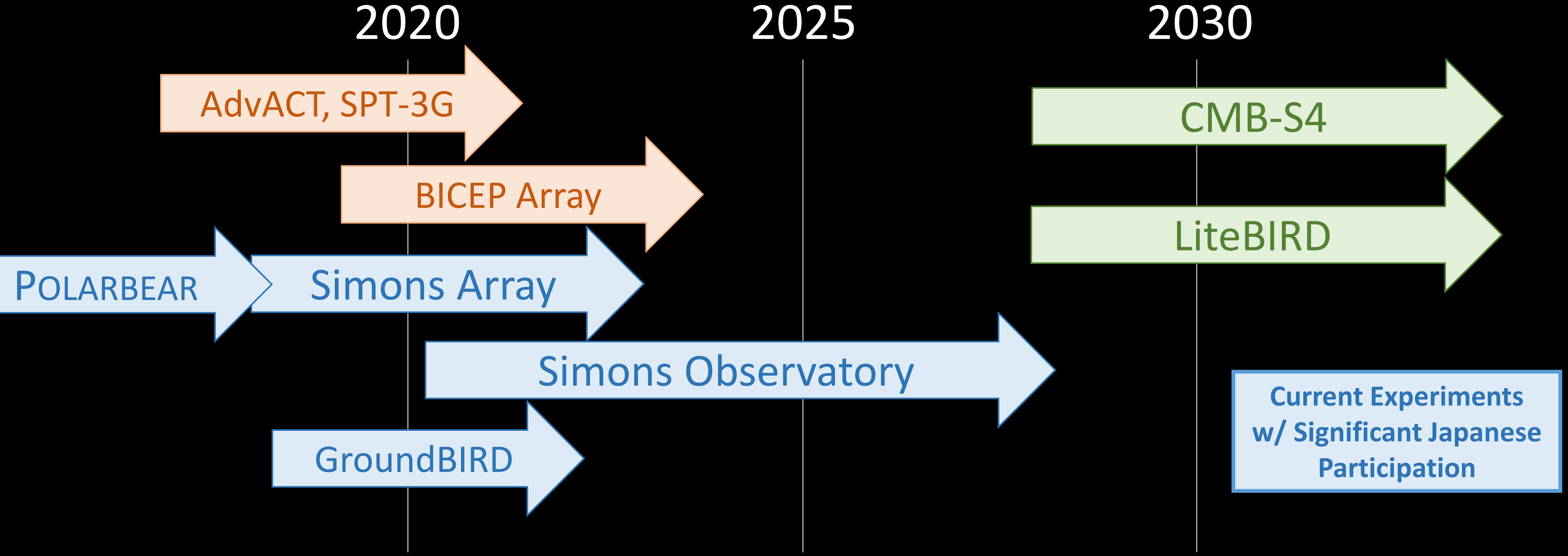
Site in Northern Chile (near ALMA)



Site at South Pole (near IceCube etc.)

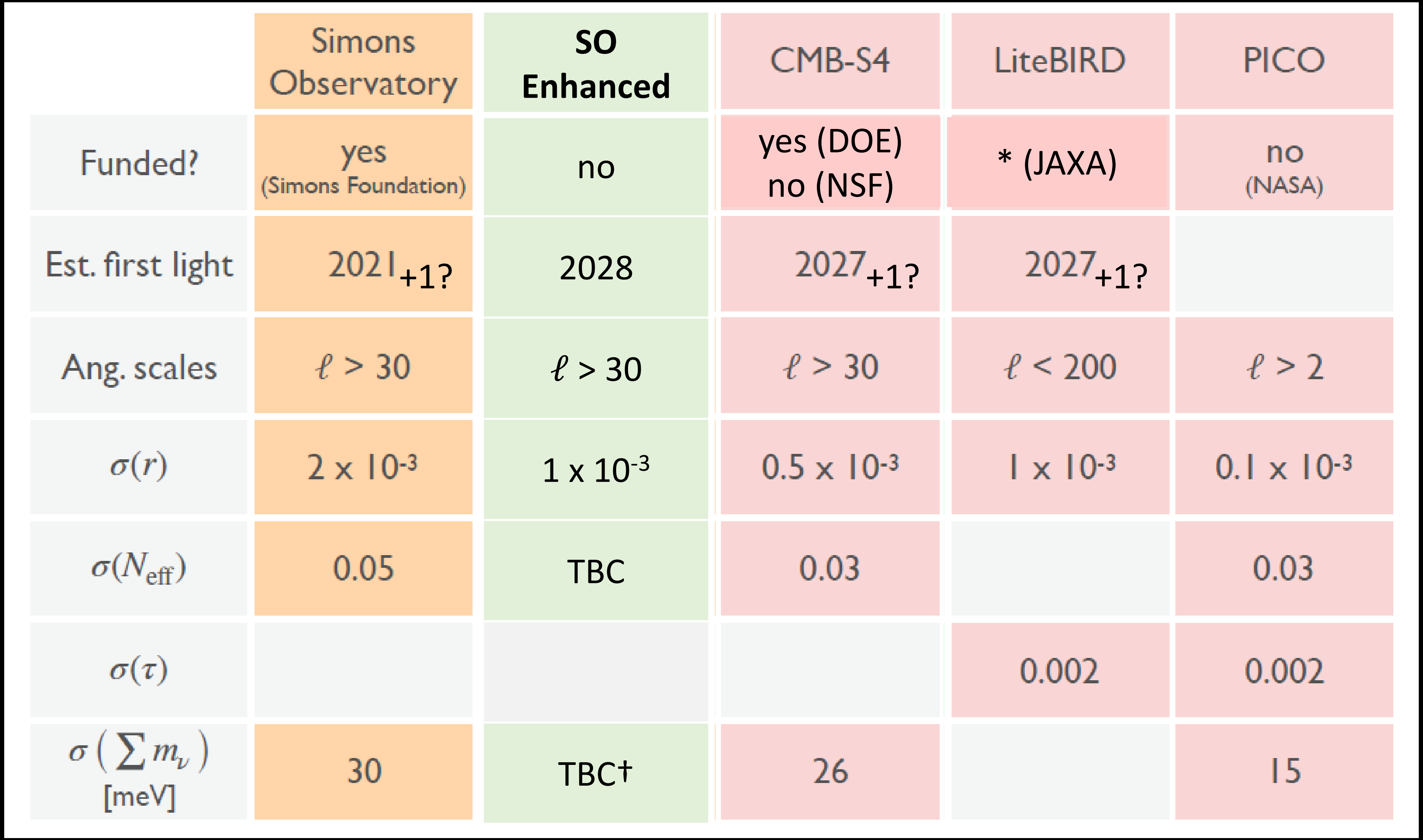


Timeline



$\sigma(r)$ ~ 0.006 $0.003 \sim 0.002$ ~ 0.001

Science Forecast
(Stolen and modified from A. Fraisse slides @ AAS 2019)



	Simons Observatory	**SO Enhanced**	CMB-S4	LiteBIRD	PICO
Funded?	yes (Simons Foundation)	no	yes (DOE) no (NSF)	* (JAXA)	no (NASA)
Est. first light	$2021_{+1?}$	2028	$2027_{+1?}$	$2027_{+1?}$	
Ang. scales	$\ell > 30$	$\ell > 30$	$\ell > 30$	$\ell < 200$	$\ell > 2$
$\sigma(r)$	2 x 10^{-3}	1 x 10^{-3}	0.5 x 10^{-3}	1 x 10^{-3}	0.1 x 10^{-3}
$\sigma(N_{\mathrm{eff}})$	0.05	TBC	0.03		0.03
$\sigma(\tau)$				0.002	0.002
$\sigma\left(\sum m_\nu\right)$ [meV]	30	TBC†	26		15

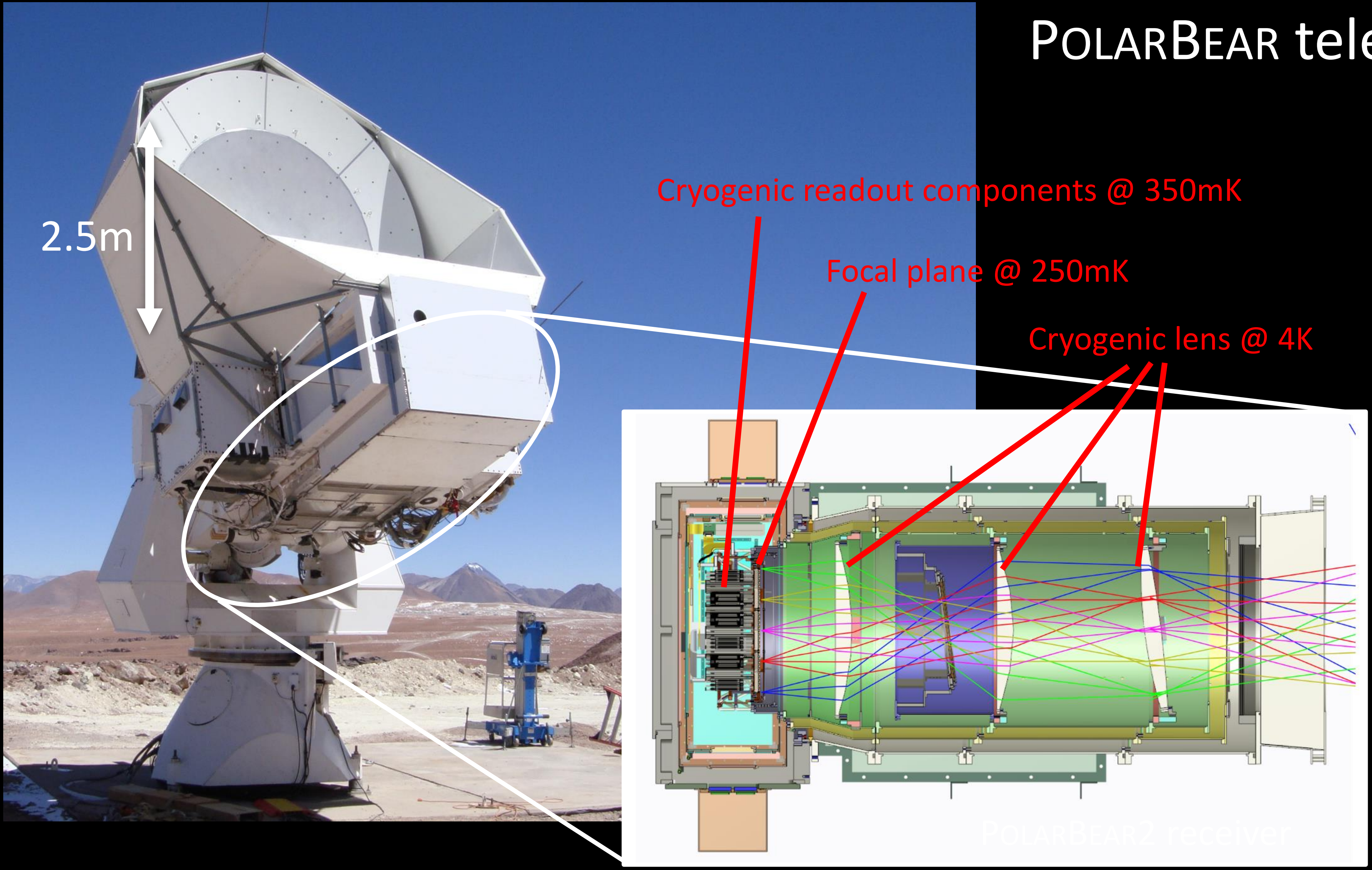
*JAXA戦略的中型
2号機に選定

実験的アプローチ

どうやって「良い」実験を作るのか

A CMB Instrument

Example:
POLARBEAR telescope



Cryogenic readout components @ 350mK

Focal plane @ 250mK

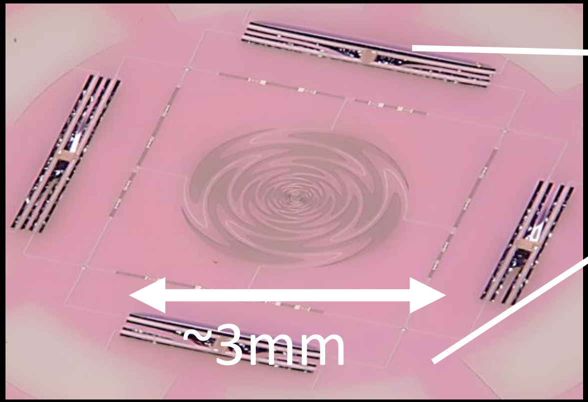
Cryogenic lens @ 4K

POLARBEAR2 receiver

A CMB Camera to achieve *sensitivity*

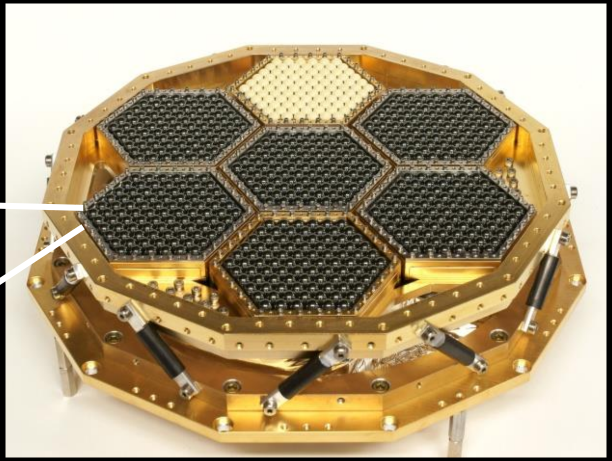
A CMB sensor is similar to this…

CMB検出器ピクセル



ΔT ~ 300μK
each second

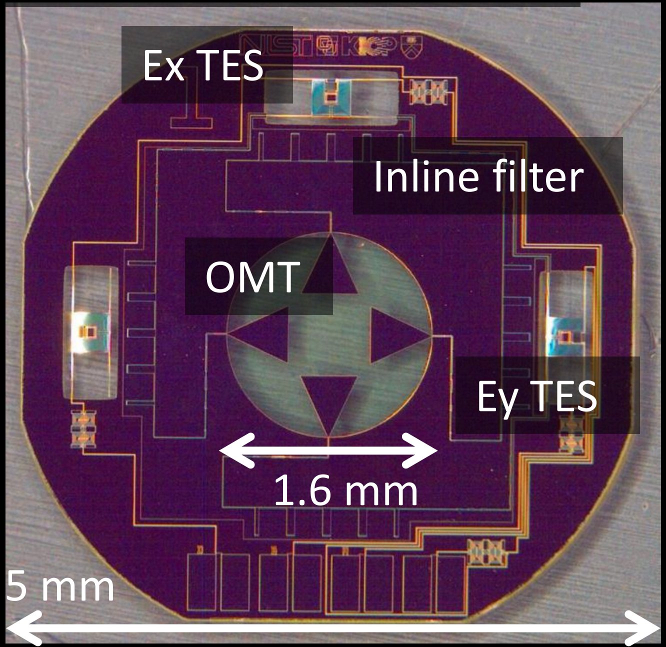
Focal Plane



Observing / Under construction:
~50cm, ~10000 detectors
Next gen:
~2m(?), ~100000 detectors

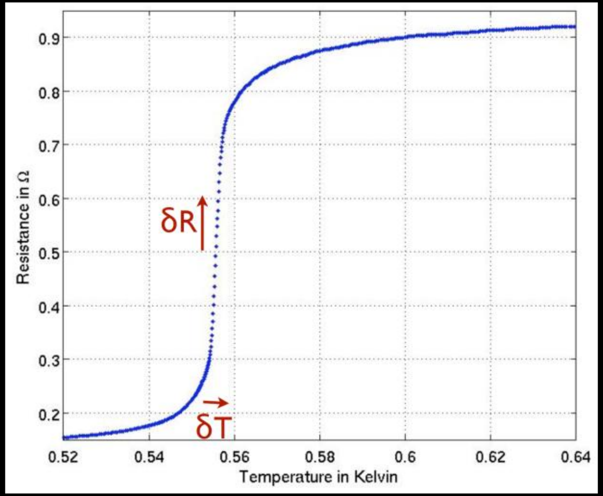
(Some of) Key Technologies

Polarization sensitive TES (from ABS experiment)



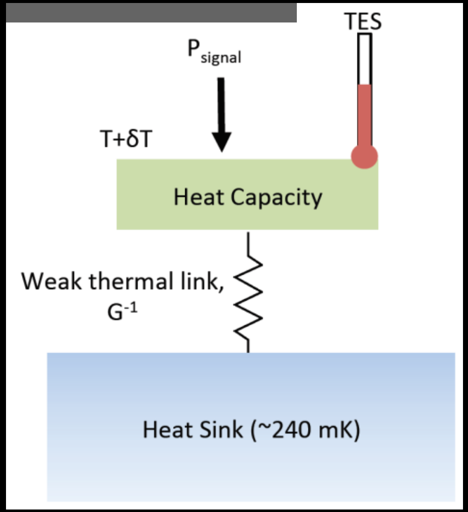
Fabricated at NIST

TES resistance curve



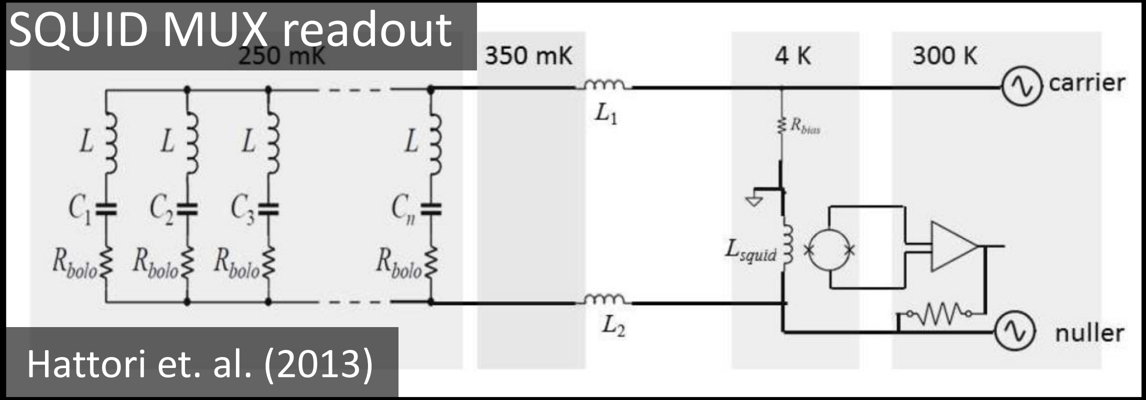
Irwin (1995)

Schematic of a bolometer



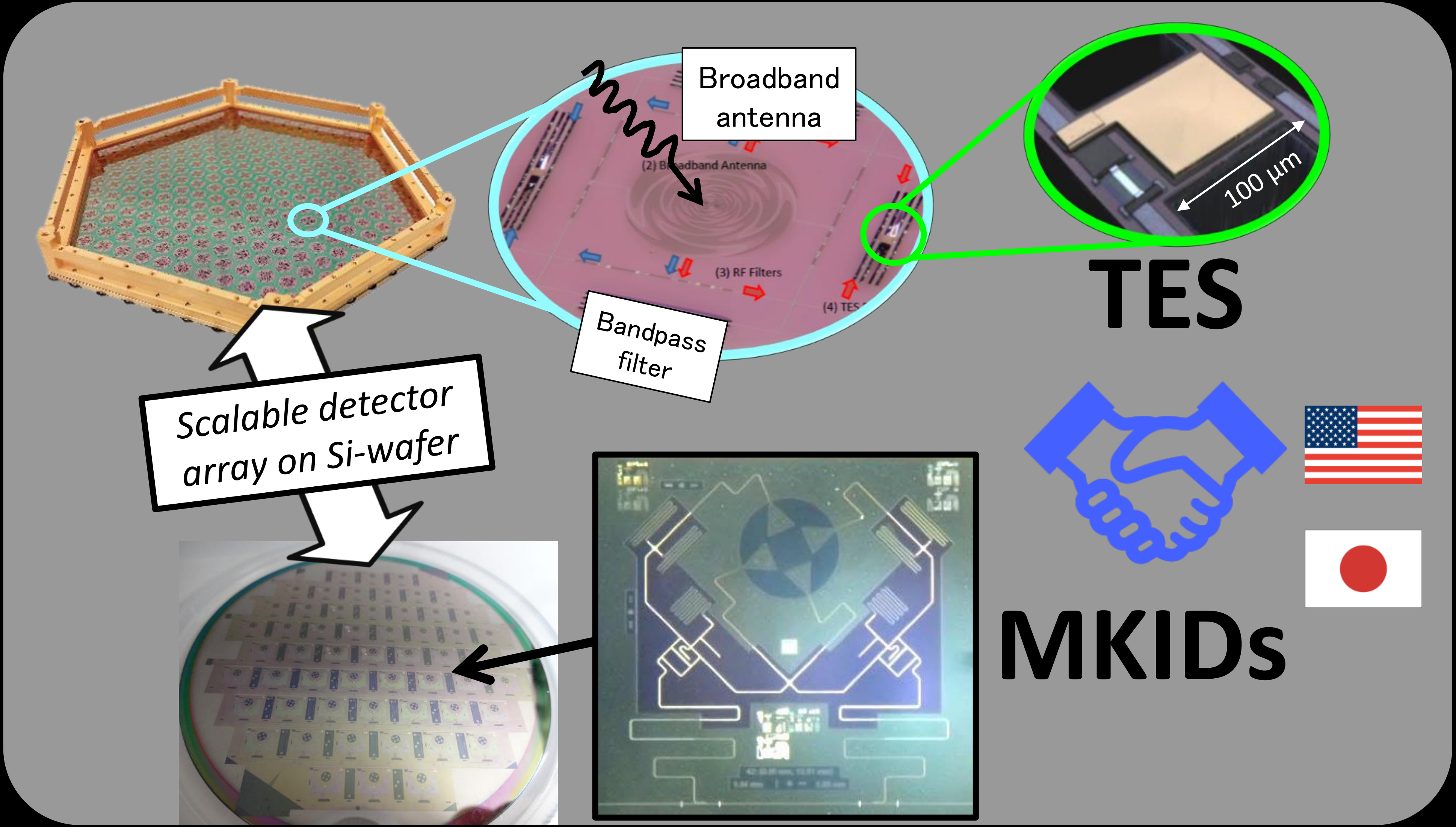
Abazajian et. al. (2014)

SQUID MUX readout



Hattori et. al. (2013)

CMB装置開発 = 超伝導検出器開発の最先端



例：日米
超伝導検出器と
その読出しの開発

Applications:

CMB

Dark Matter
0ν2β
Quantum Sensing

このページで
本当に言いたいこと

News in 2014

Scientific American (Mar. 17, 2014)

Gravity Waves from Big Bang

A curved signature i

Proof of gravitational waves created b
of the cosmic microwave background
at the South Pole. The proof comes in
polarization, a curling of the orientati
black lines on the image. The color in
cosmic microwave background that c

Washington Post (May 16, 2014)

Big Bang backlash: BICEP2 discovery of gravity wave

It was the sc
March 17 an
from the da

Cosmology
mind-boggli
describes th
rapid, inflat

APS News (Jan, 2016)

15

We are moving forward.

visions in the U.S. and across the world in 2015. These may not be the most scientifically notable events, but they are the ones that captured the public imagination.

Deflategate

The ideal gas law rarely makes headlines, but last January it was on the lips of journalists everywhere. After the New England Patriots football team was accused of intentionally deflating footballs in a playoff game — which they won, to go on to a Super Bowl victory — physicists weighed in. Could the temperature difference

BICEP2's claimed detection of primordial gravitational waves was definitively refuted in 2015. In January, a joint analysis from BICEP2 and the European Space Agency's Planck collaboration concluded that the observations of swirling patterns in the polarization of the Cosmic Microwave Background could be chalked up to dust in our galaxy, instead of inflation in the early universe. For now, the search continues.

Prizewinning Particles

Neutrinos raked in the awards this past year. In October, the

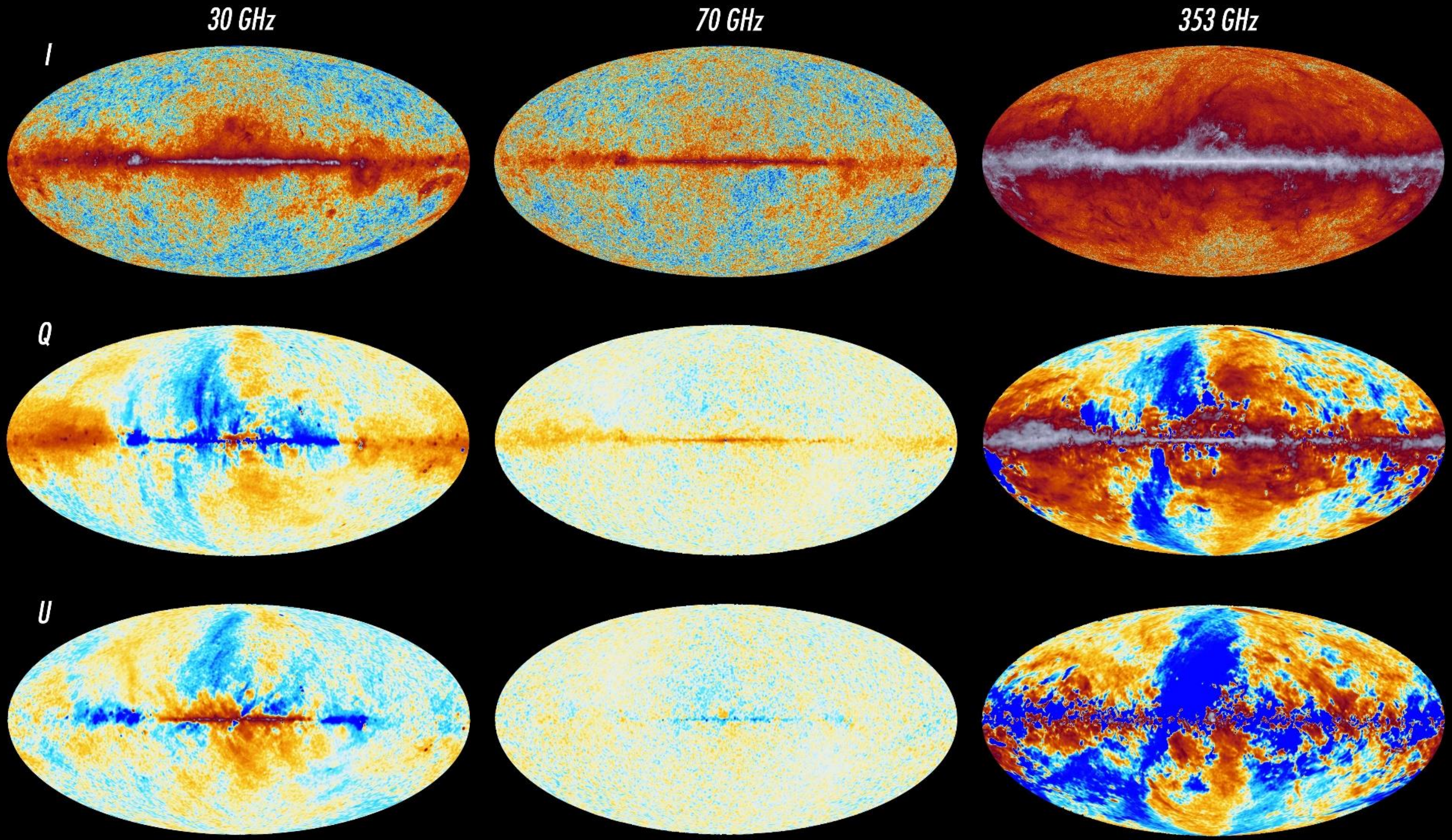
NASA/JHUAP/SwRI

Stunning views of Pluto

from being a boring, dead world, scientists found plenty of surprises: unblemished plains of nitrogen and methane ice, free from impact craters; towering mountains of water ice; and an extended, hazy atmosphere.

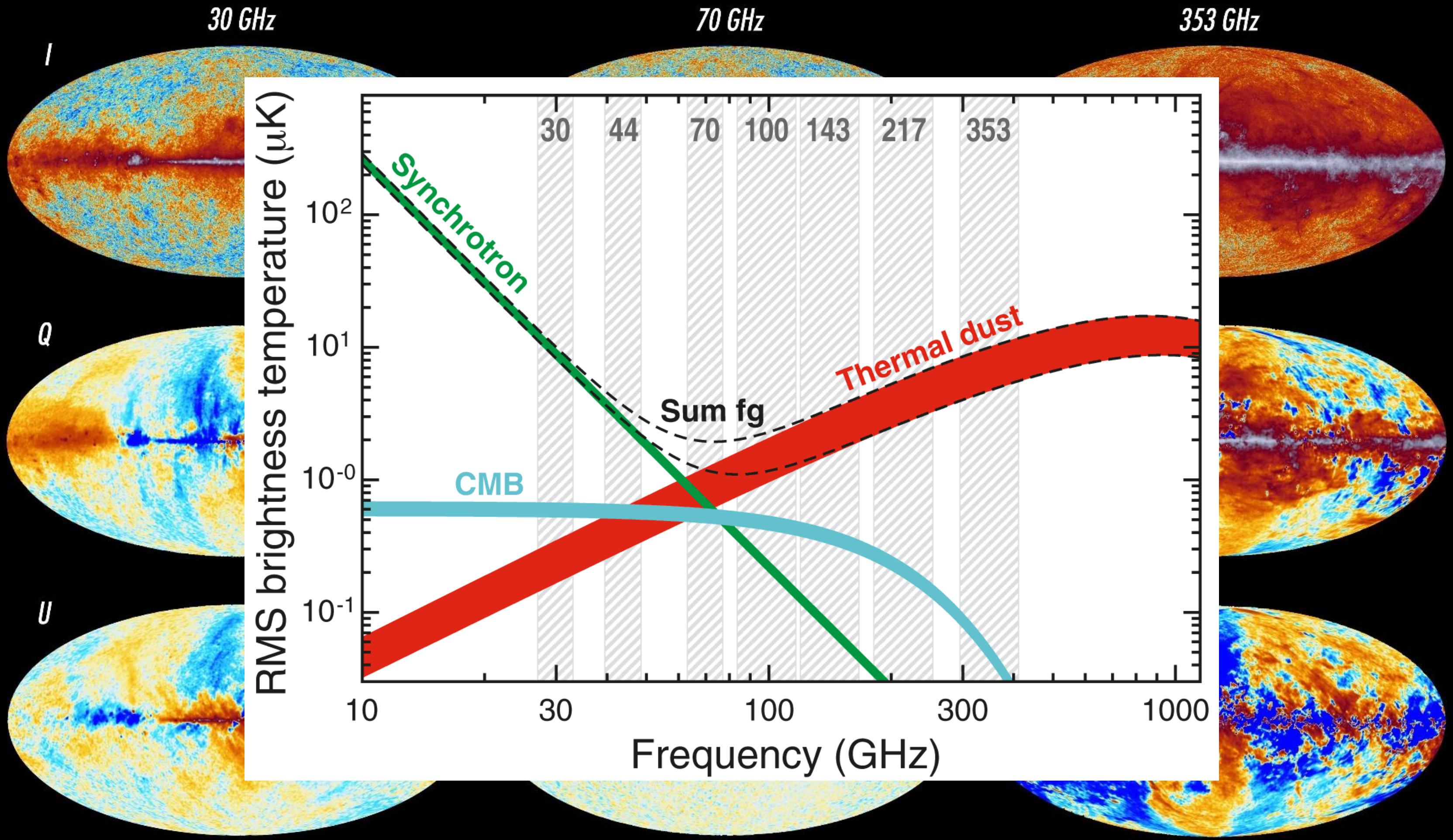
A Special Year in Physics

Foregrounds

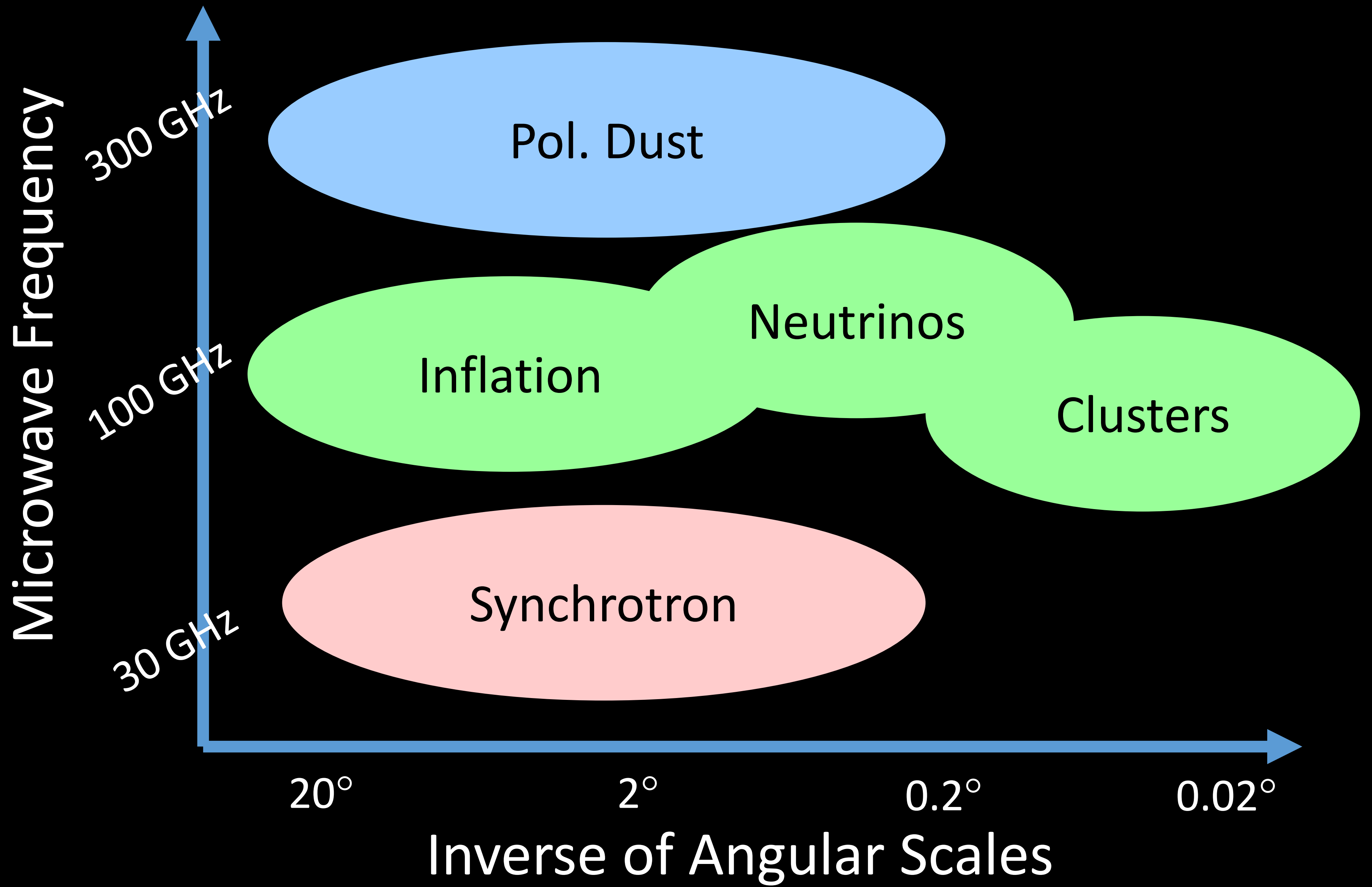


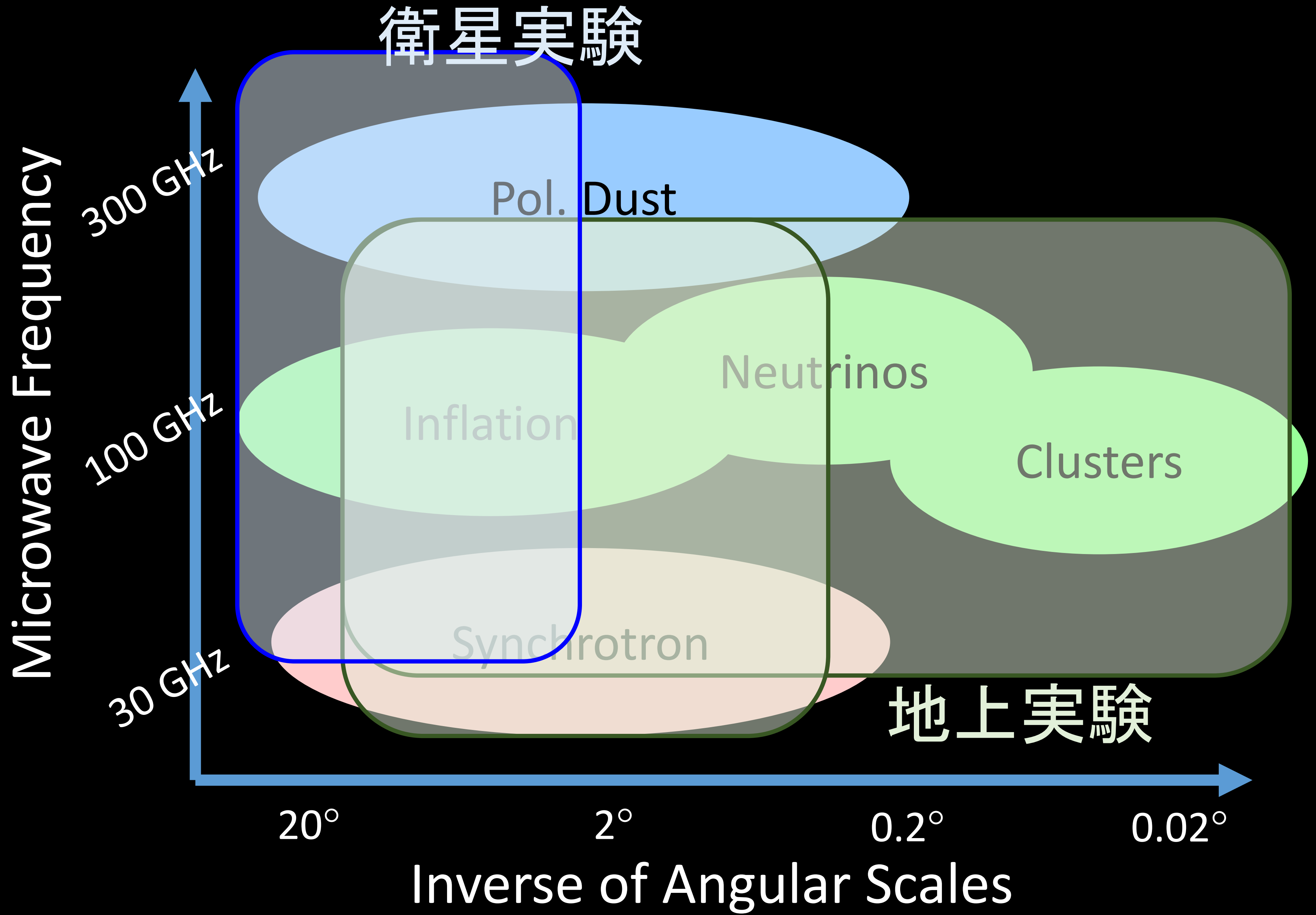
Planck Collaboration (2015)

Foregrounds



Planck Collaboration (2015)


Microwave Frequency
300 GHz
100 GHz
30 GHz
Pol. Dust
Neutrinos
Inflation
Clusters
Synchrotron
20°
2°
0.2°
0.02°
Inverse of Angular Scales

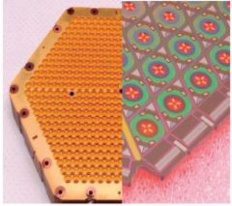

衛星実験
Pol. Dust
Neutrinos
Inflation
Clusters
Synchrotron
地上実験
Microwave Frequency
300 GHz
100 GHz
30 GHz
20°
2°
0.2°
0.02°
Inverse of Angular Scales

感度

偏光測定

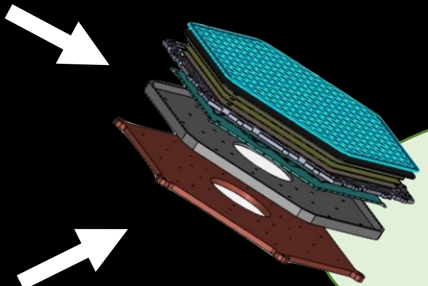
高分解能

系統誤差制御



NIST

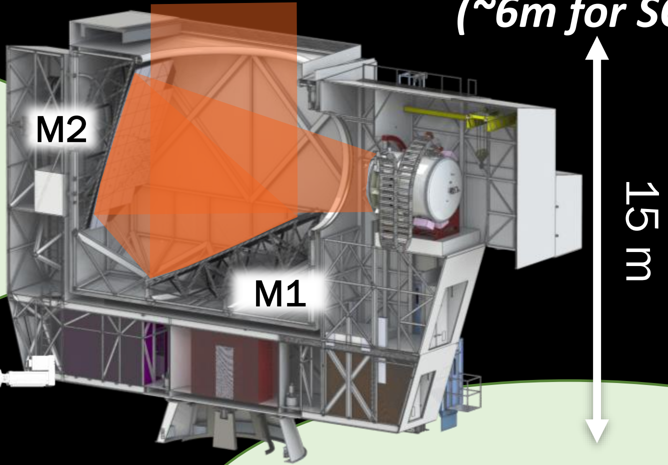
UCB

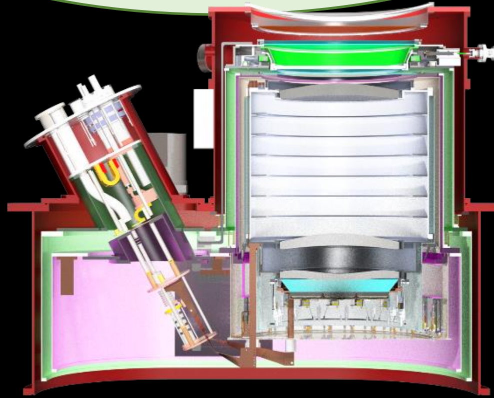


Modular detector unit for Mass production and Quality Control

感度

High-throughput large aperture telescope (~6m for SO and S4)





偏光測定

高分解能

High-throughput optics with exquisite baffling

系統誤差制御

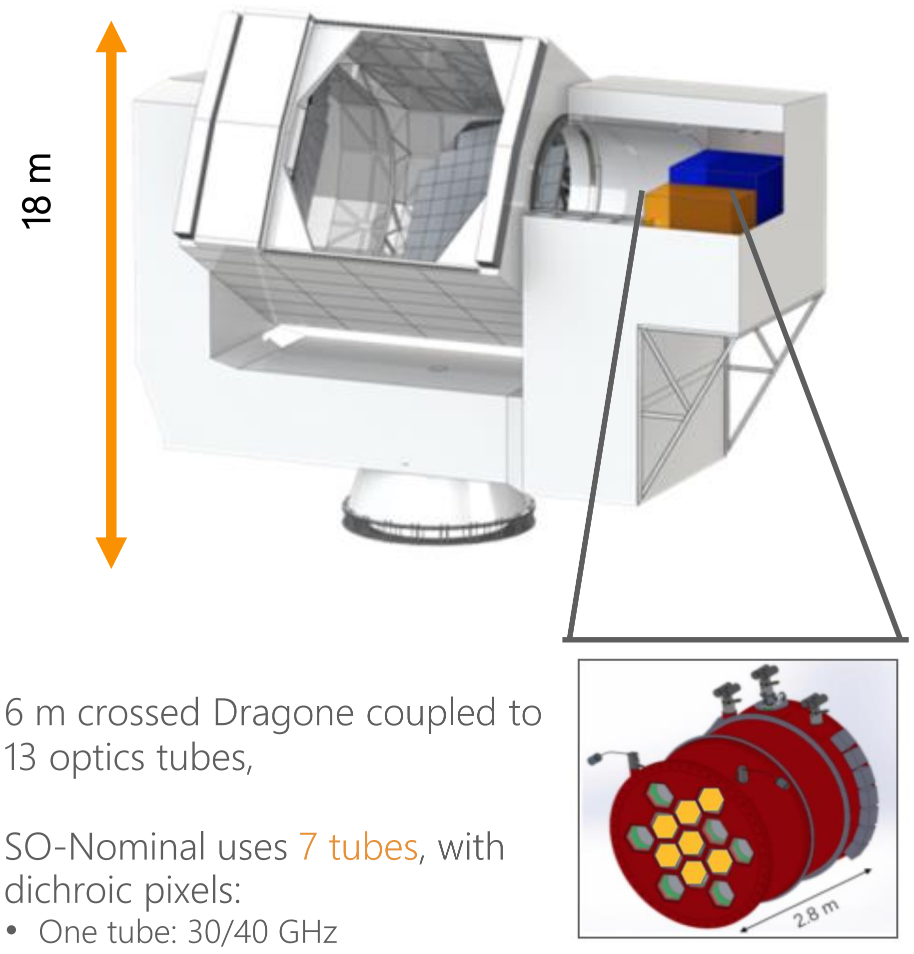
Cryogenic Half-Wave Plate for pol. Modulation

Multi frequency measurement for Foreground mitigation

将来の展望

SO-Nominal Instrumentation Suite

Large Aperture Telescope

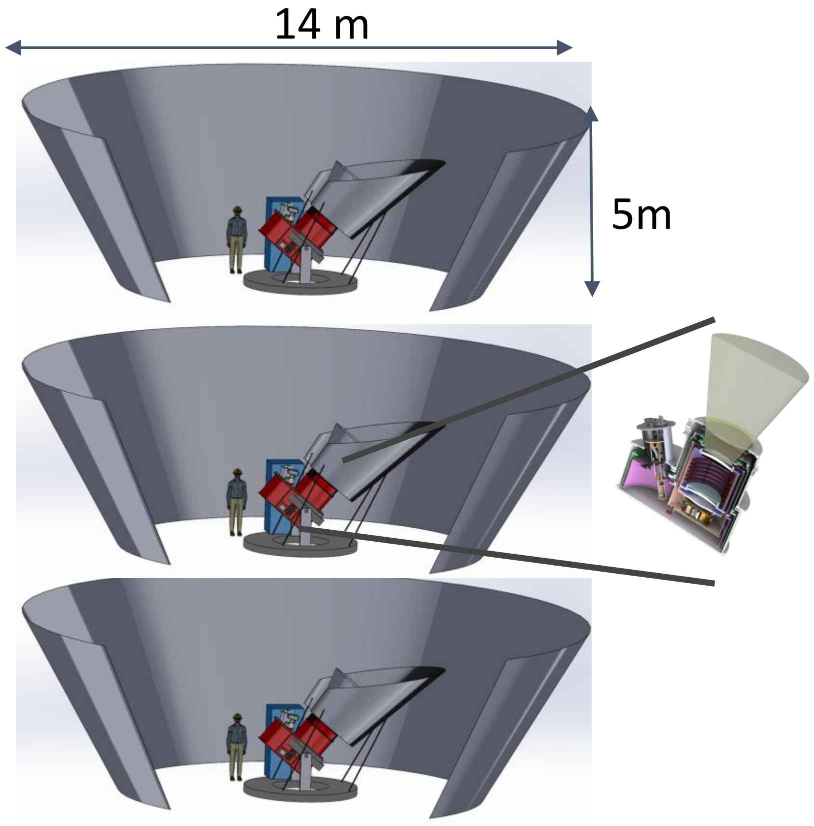


6 m crossed Dragone coupled to 13 optics tubes,

SO-Nominal uses 7 tubes, with dichroic pixels:

- One tube: 30/40 GHz
- Four tubes: 90/150 GHz
- Two tubes: 220/270 GHz

Small Aperture Telescopes



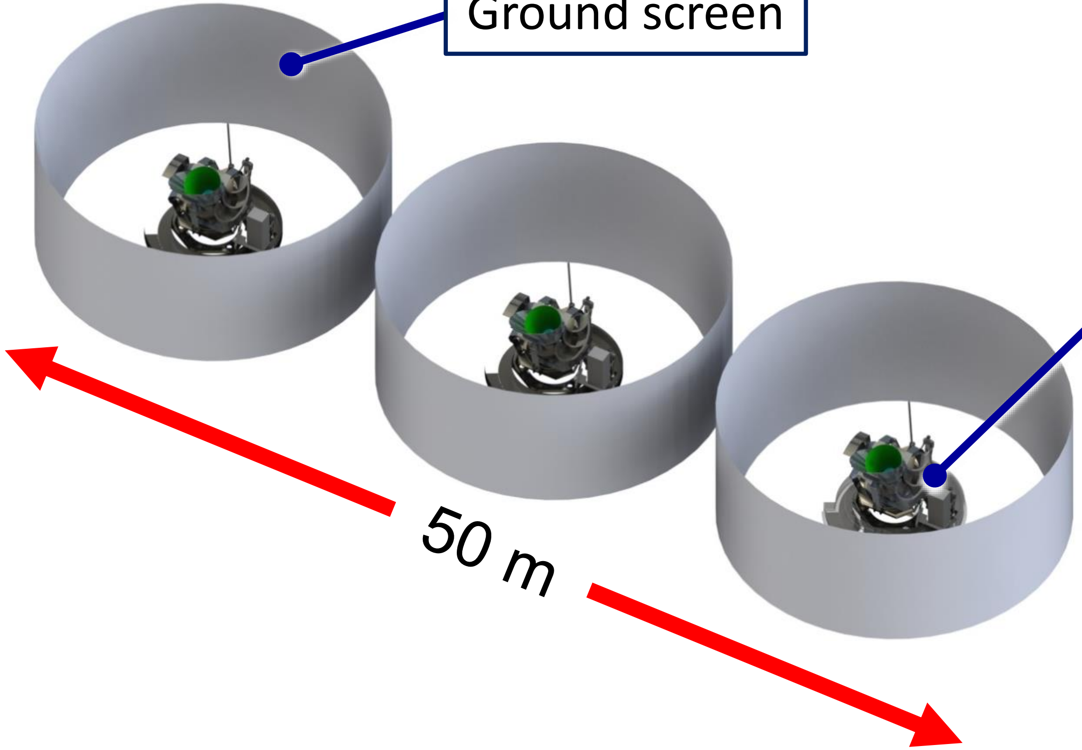
SO-Nominal deploys three refractors 42 cm in diameter, rotating half-wave plate.
Dichroic pixels:
30/40 | 90/150 | 220/270 GHz

SO uses two types of optical systems to provide a large dynamic range of angular scales.

From slides @ Astro2020
(by A. Lee and S. Staggs)

Simons Observatory

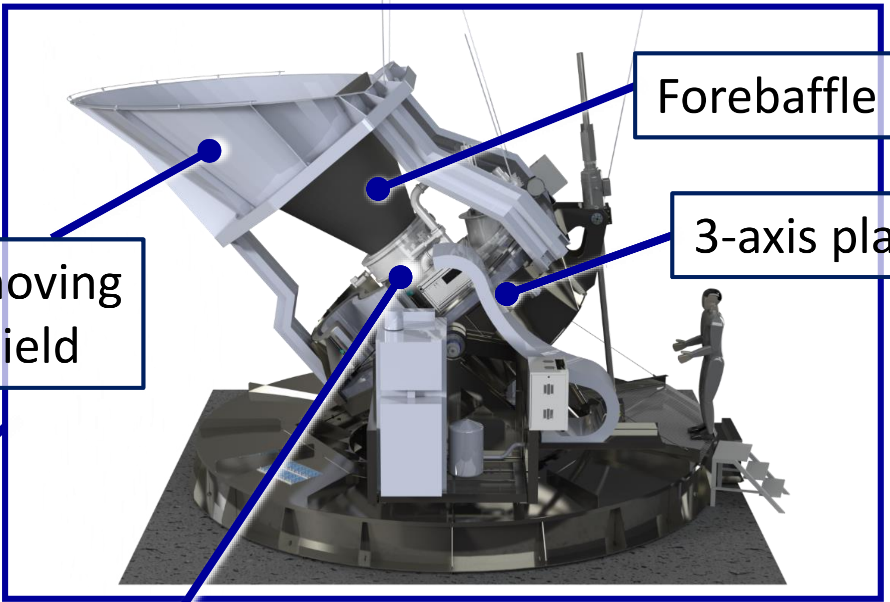
Small Aperture Telescopes



Ground screen

50 m

Three 42 cm aperture refractors
Dichroic pixels sensitive at:
30/40 | 90/150 | 90/150 | 220/270 GHz



Forebaffle

3-axis platform

Comoving Shield

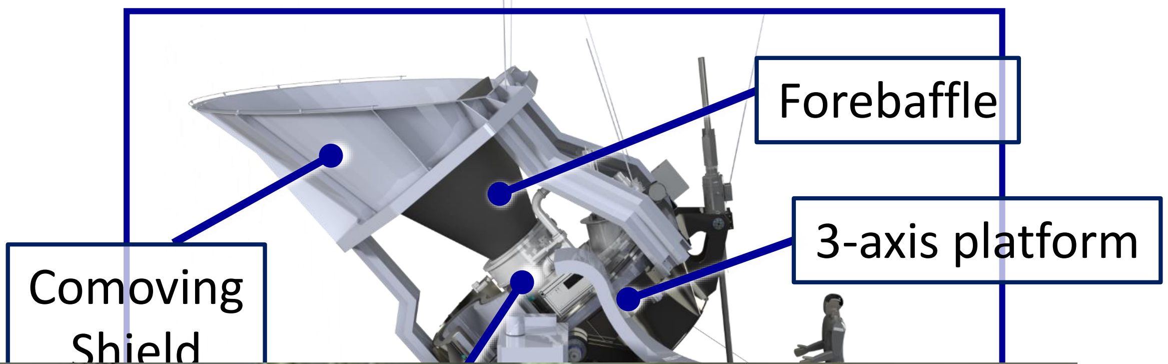
SAT cryostat

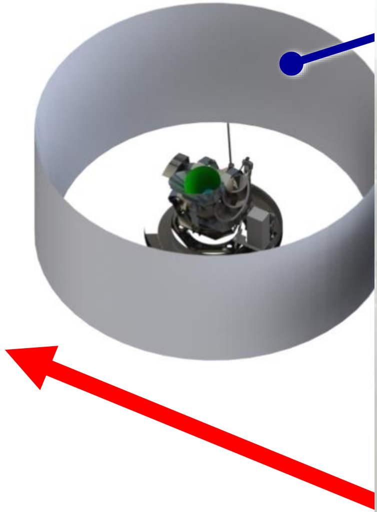
- ~30,000 detectors for three SATs
- Dilution-refrigerator-cooled 100-mK focal plane
- Cryogenic half-wave plate
- 1-K cryogenic 3-lens Si optics and 1-K stop

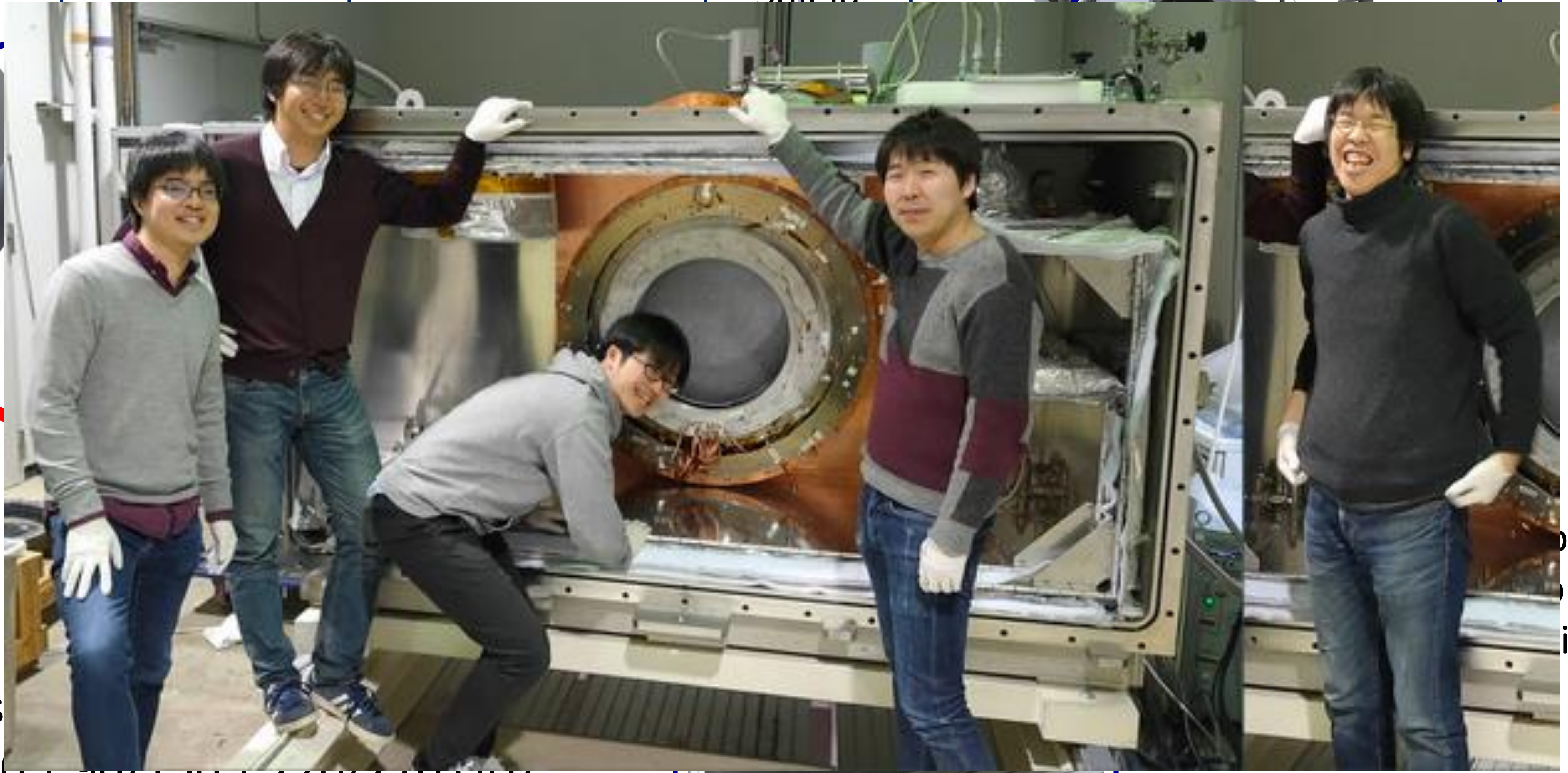
Simons Observatory

Small Aperture Telescopes

日本の若者も活躍中





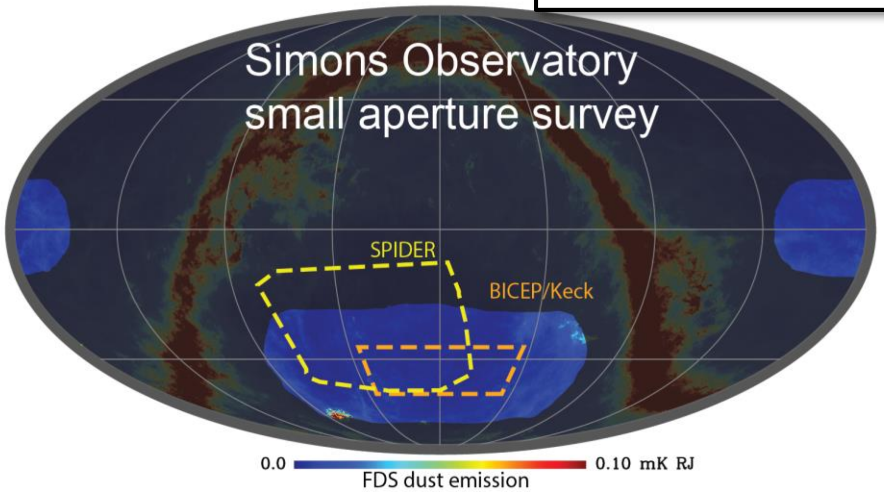


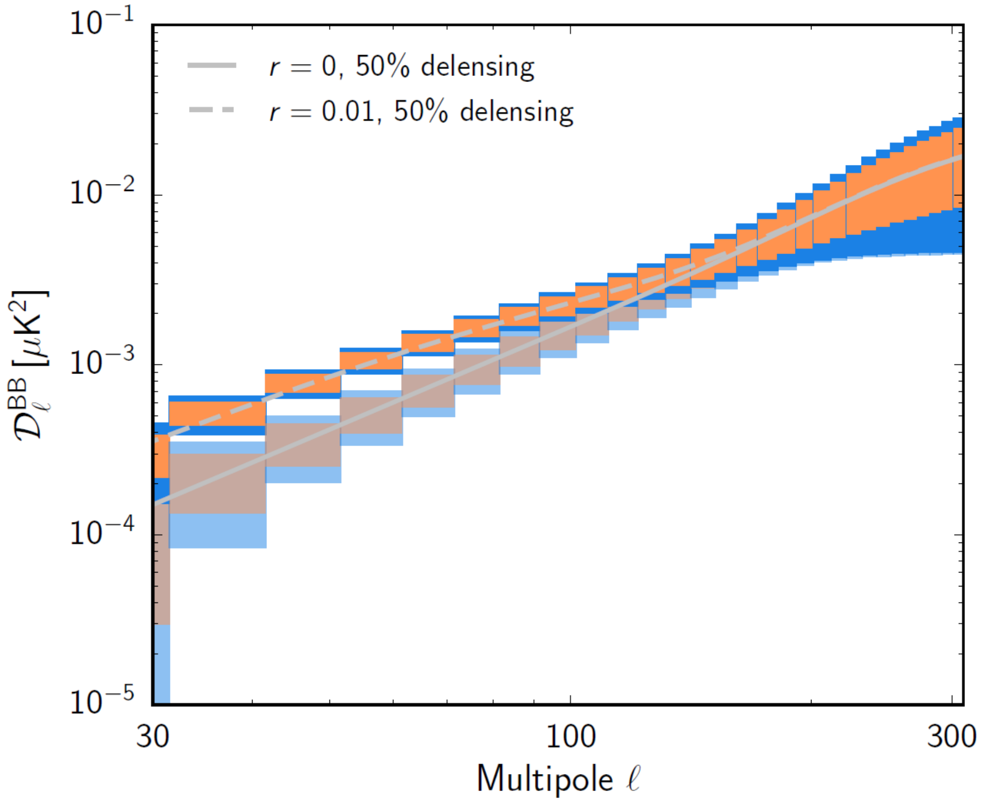
Three 42 cm a
Dichroic pixels
30/40 | 90/150 | 90/150 | 220/270 GHz

Simons Observatory

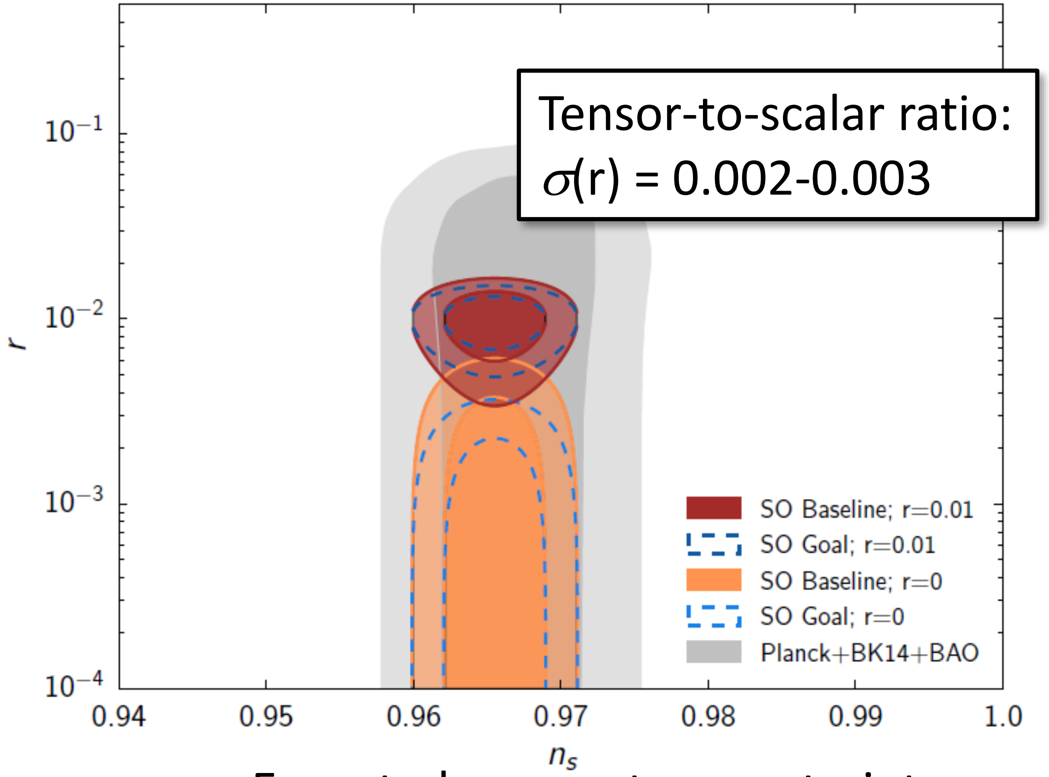
Small Aperture Telescopes

~2μK-arcmin noise





B-mode polarization forecast



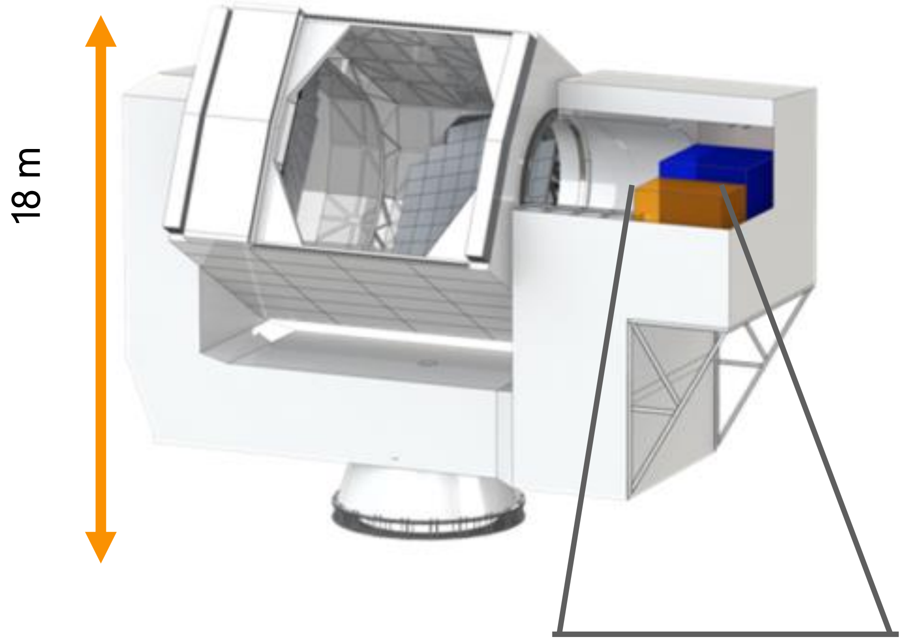
Tensor-to-scalar ratio:
$\sigma(r)$ = 0.002-0.003

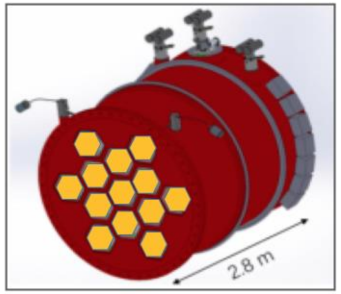
Expected parameter constraint

Simons Observatory Collaboration, *JCAP* 1902 (2019) 056

SO-Enhanced Doubles the Mapping Speed

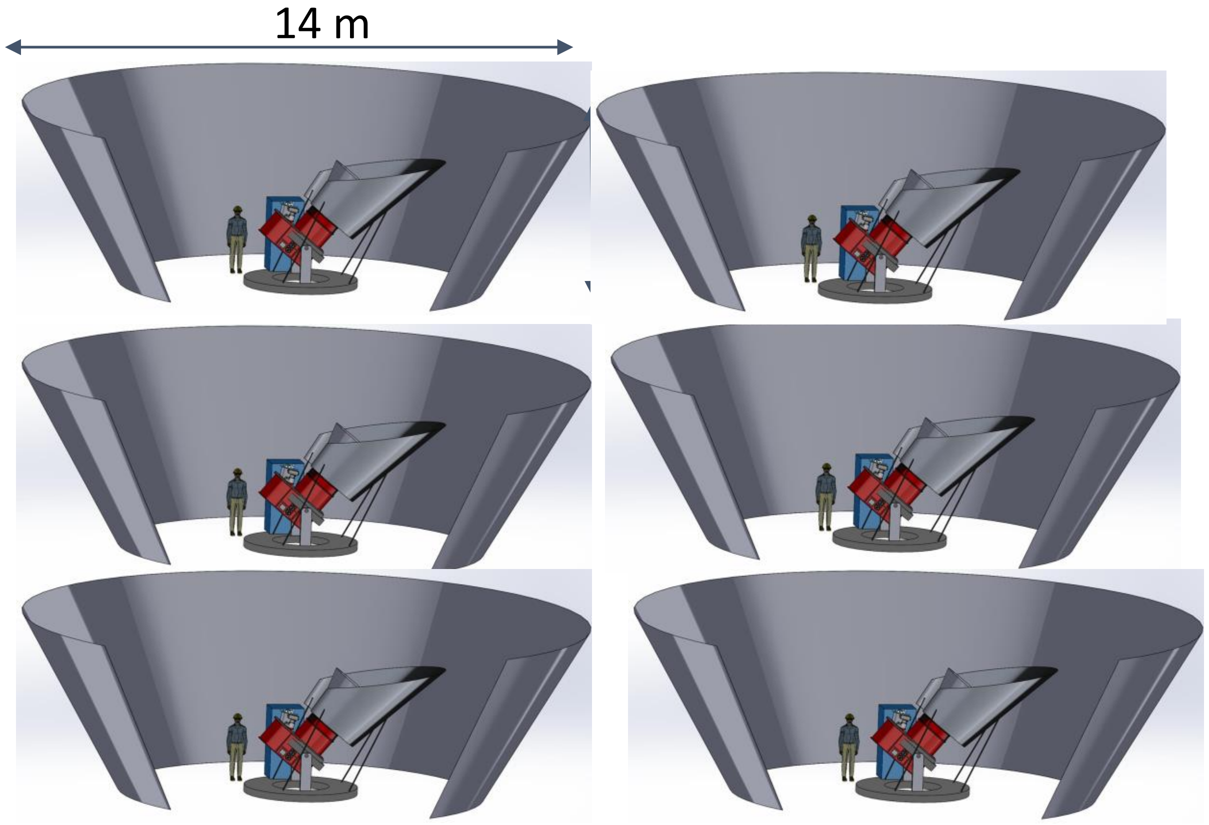
Large Aperture Telescope





SO-Enhanced fills all 13 tubes on the LAT.

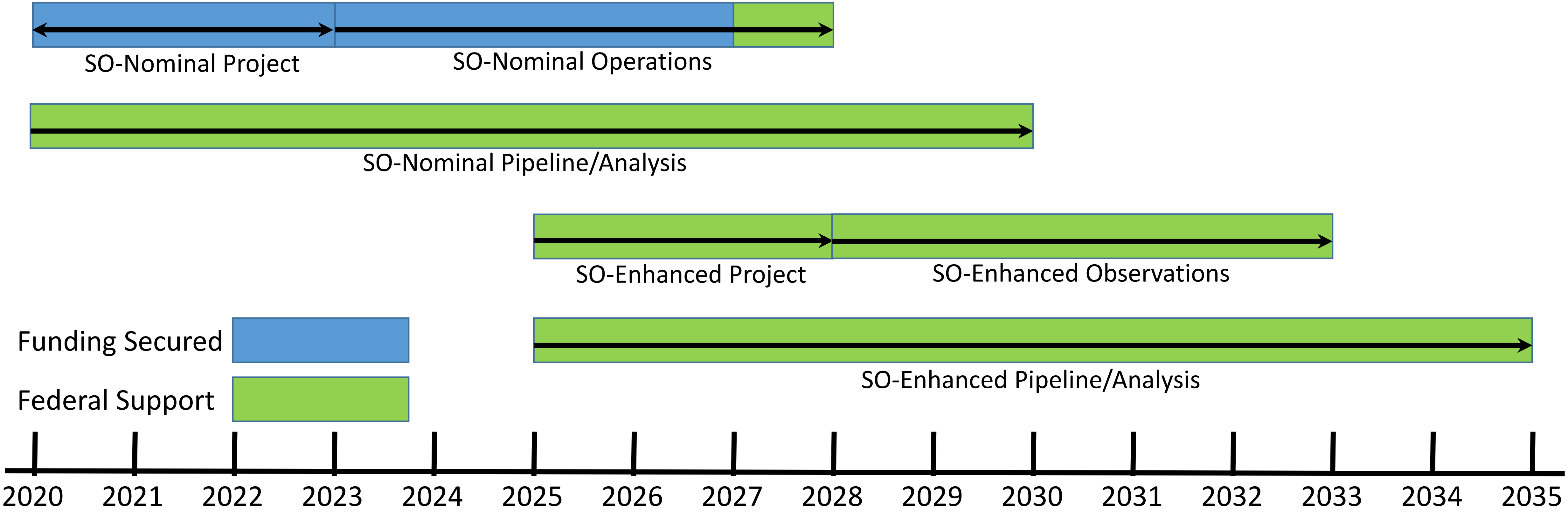
Small Aperture Telescopes



SO-Enhanced adds 3 SATs to SO-Nominal

From slides @ Astro2020
(by A. Lee and S. Staggs)

SO-Nominal and SO-Enhanced Schedule



SO-Nominal Project

SO-Nominal Operations

SO-Nominal Pipeline/Analysis

SO-Enhanced Project

SO-Enhanced Observations

SO-Enhanced Pipeline/Analysis

Funding Secured 🟦

Federal Support 🟩

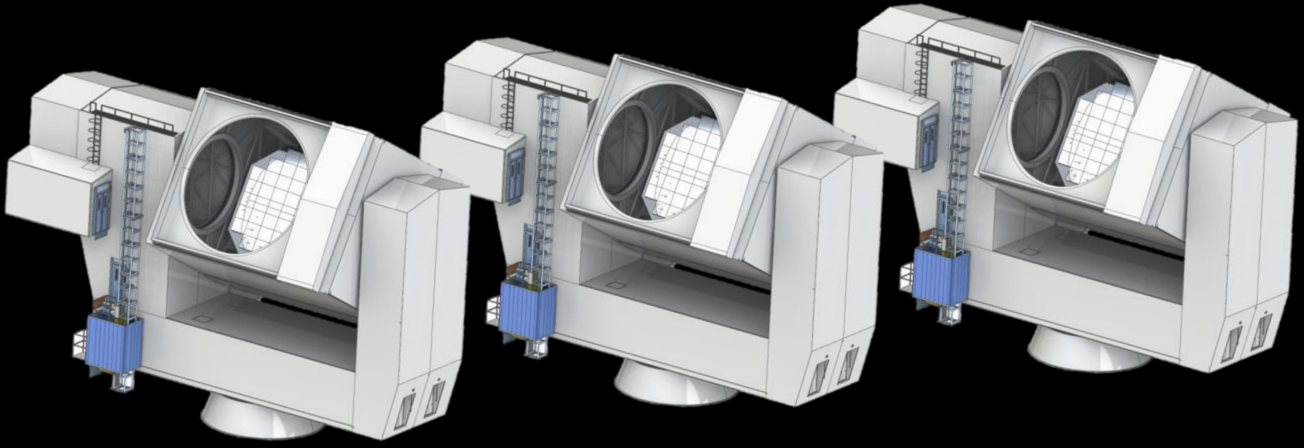
From slides @ Astro2020
(by A. Lee and S. Staggs)

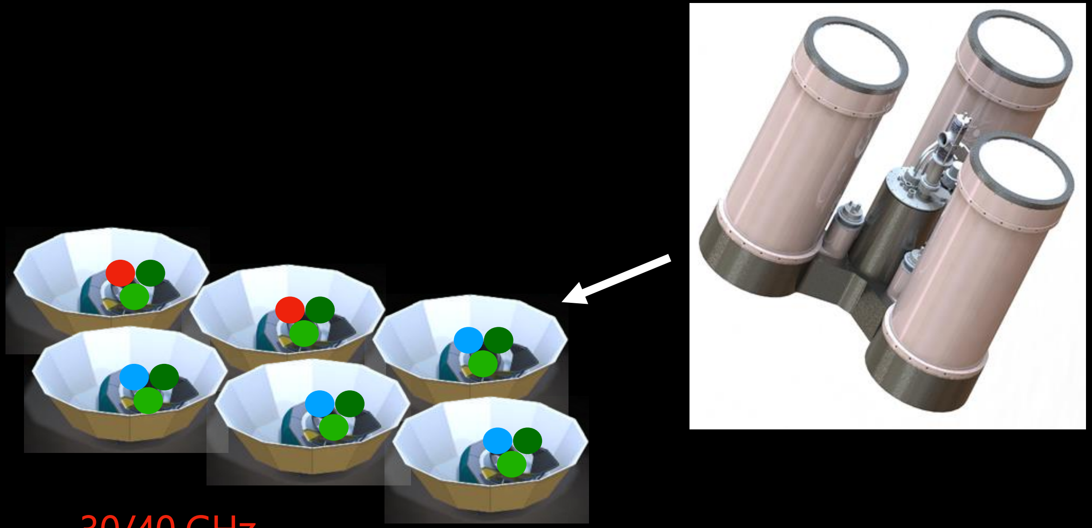
CMB S4
Stage-4 CMB Experiment

CMB S4 Collaboration Workshop at LBNL

~180 participants

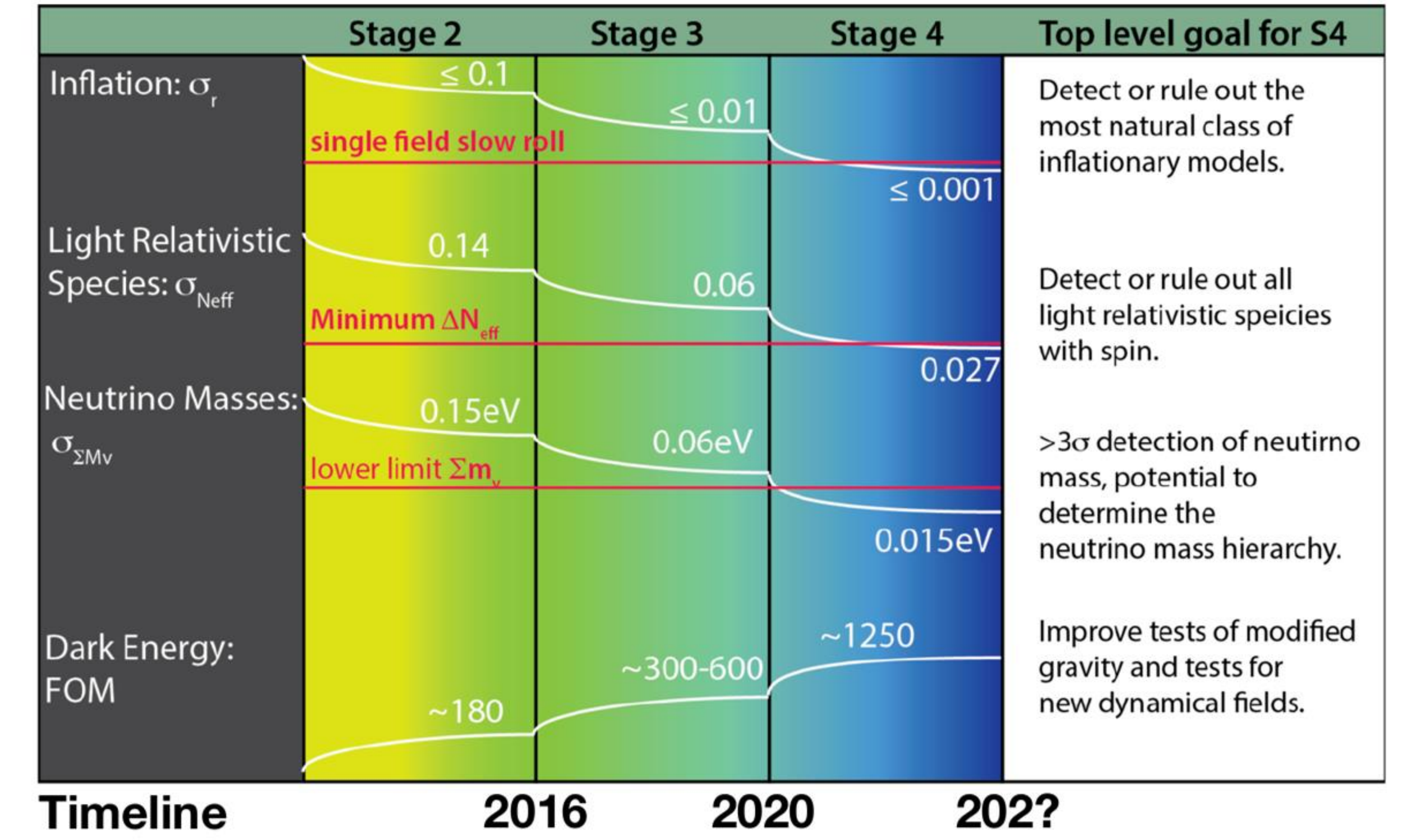
- O(500,000) detectors, multiple telescopes
  - ~x10 of Simons Observatory
- Science: Inflation, Neutrinos, Dark Radiation, Dark Energy, …
  - Large and Small angular scales.
  - 30 – 300 GHz
- Putting together the community





30/40 GHz
85/145 GHz
95/155 GHz
220/270 GHz

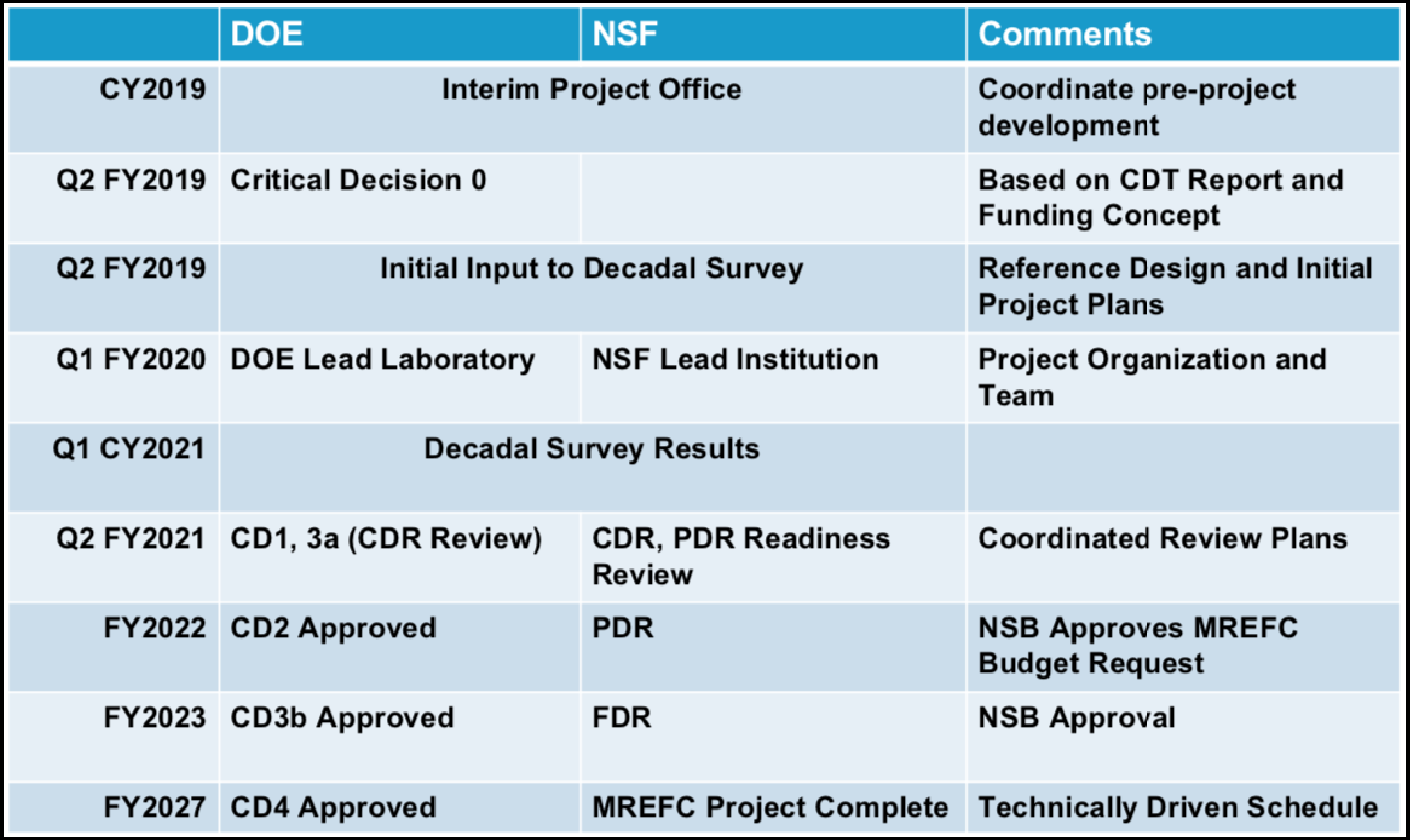
CMB-S4 Science Goals



	Stage 2	Stage 3	Stage 4	Top level goal for S4
Inflation: σ_r	≤ 0.1 single field slow roll	≤ 0.01	≤ 0.001	Detect or rule out the most natural class of inflationary models.
Light Relativistic Species: $\sigma_{N_{eff}}$	0.14 Minimum ΔN_{eff}	0.06	0.027	Detect or rule out all light relativistic speicies with spin.
Neutrino Masses: $\sigma_{\Sigma M\nu}$	0.15eV lower limit Σm_ν	0.06eV	0.015eV	>3σ detection of neutirno mass, potential to determine the neutrino mass hierarchy.
Dark Energy: FOM	~180	~300-600	~1250	Improve tests of modified gravity and tests for new dynamical fields.
Timeline	**2016**	**2020**	**202?**	

CMB-S4 Science Book: https://arxiv.org/abs/1610.02743

Notional DOE/NSF Project Development Timeline



	DOE	NSF	Comments
CY2019	Interim Project Office		Coordinate pre-project development
Q2 FY2019	Critical Decision 0		Based on CDT Report and Funding Concept
Q2 FY2019	Initial Input to Decadal Survey		Reference Design and Initial Project Plans
Q1 FY2020	DOE Lead Laboratory	NSF Lead Institution	Project Organization and Team
Q1 CY2021	Decadal Survey Results		
Q2 FY2021	CD1, 3a (CDR Review)	CDR, PDR Readiness Review	Coordinated Review Plans
FY2022	CD2 Approved	PDR	NSB Approves MREFC Budget Request
FY2023	CD3b Approved	FDR	NSB Approval
FY2027	CD4 Approved	MREFC Project Complete	Technically Driven Schedule

From Nils Halverson’s APS meeting talk (2019)

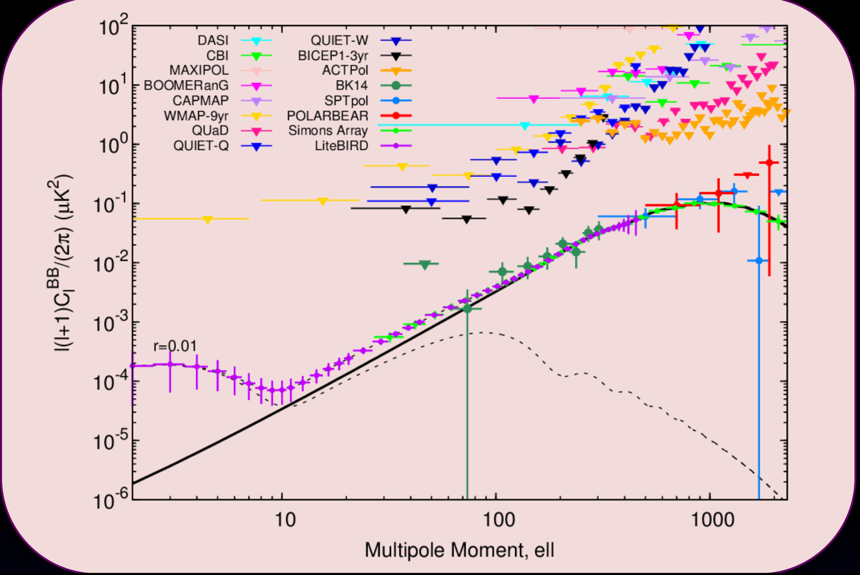
LiteBIRD - JAXA-led CMB polarization satellite

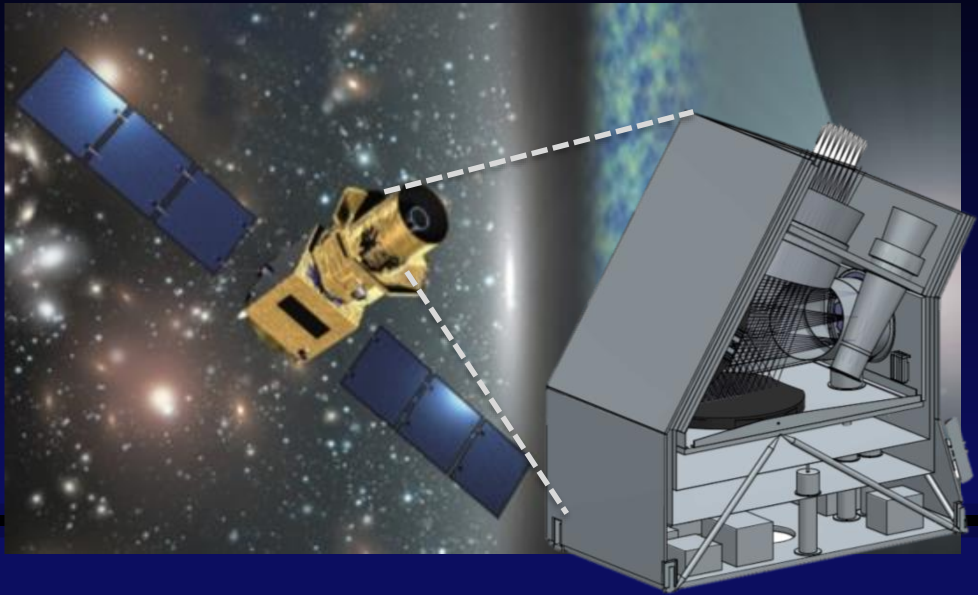
Lite (Light) Satellite for the Studies of B-mode Polarization and Inflation from Cosmic Background Radiation Detection

Primacies

1. 2019年5月にJAXA戦略的中型2号機に選定
2. Full success
   - Total uncertainty on r, $\sigma(r=0) < 0.001$
   - Multipole coverage: $2 \leq \ell \leq 200$

   i.e. both bumps (reionization, recombination) detected with large (>5sigma) significance if r > 0.01





Main specifications (Phase-A baseline design)

Item	Specification
Orbit	L2 halo orbit
Launch year (vehicle)	Late 2020s
Observation (time)	All-sky CMB survey (3 years)
Mass	2.6 t
Power	3.0 kW
Mission instruments	• Superconducting detector arrays • Continuously-rotating half-wave plate (HWP) • Crossed-Dragone mirrors • 0.1K cooling system (ST/JT/ADR)
Frequencies (# of bands)	34 – 448 GHz (15 bands)
Data size	10 GB/day
Sensitivity	3 μKarcmin (3 years) with margin
Angular resolution	0.5deg @ 100 GHz

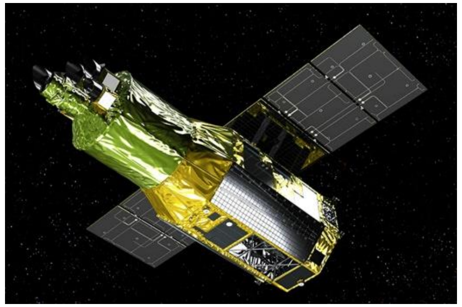
JAXA戦略的中型宇宙科学ミッション

To be planned

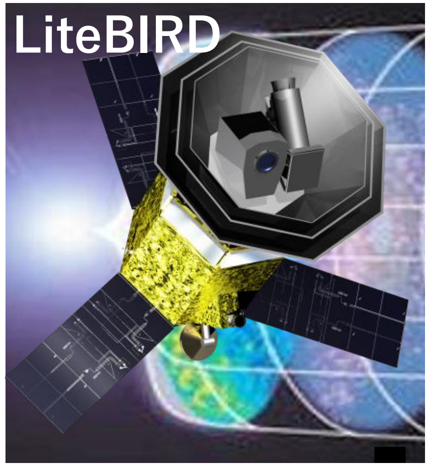
目標とする打上時期

年度	20	21	22	23	24	25	26	27	28	29	30	31	32

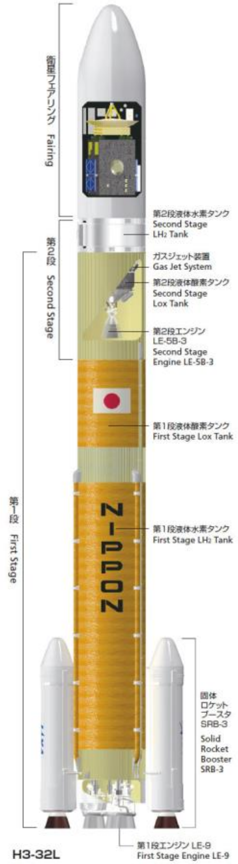
XRISM



戦略的中型
１号機
Martian
Moons
eXploration
(MMX)



戦略的中型
２号機
LiteBIRD 選定
（2019年５月）



Slide from M. Hazumi @ JPS meeting, Sep. 2020

LiteBIRDは明確なゴールとその達成の確かな見通しを持つ

フルサクセス:

- $\delta r < 1$ x 10^{-3} (for r=0)
- r≥0.01の場合は再電離、再結合の信号のそれぞれを5シグマ以上の有意度で検出

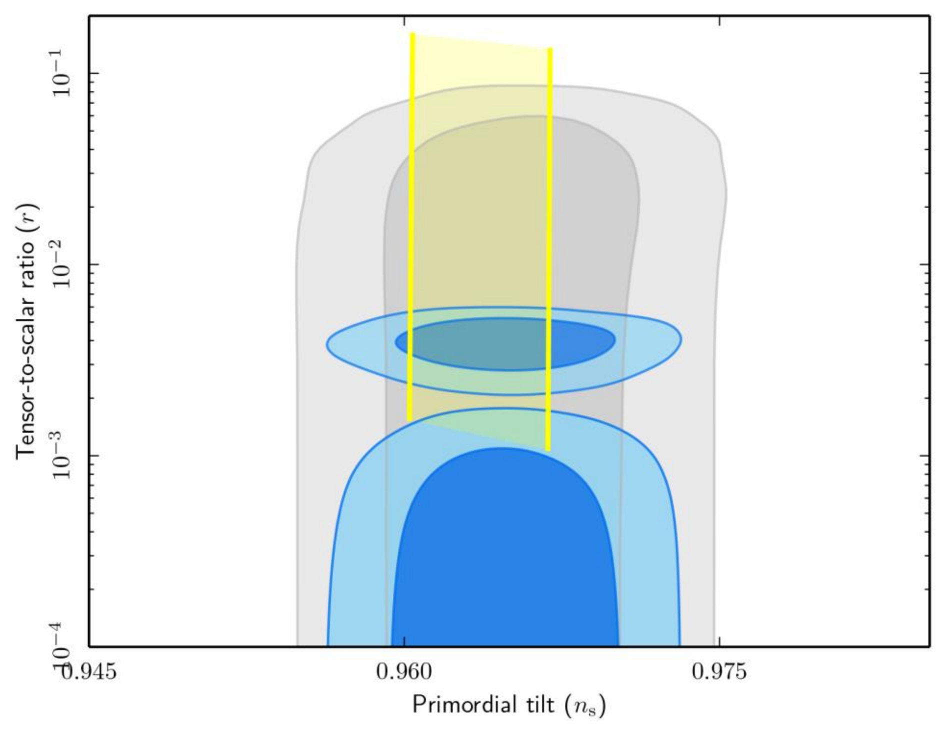
精度設定の理論的根拠

- 0.005 < r < 0.05に大きな発見のチャンス
- 最もシンプルで観測と合う$R+R^2$ モデル（ストラビンスキーモデル）をテストできる
- 一群の有力モデル（単一インフラトン場ポテンシャルがプランクスケールを超える特徴的変動値を持つモデル群）を全て検証できる

(A. Linde, JCAP 1702 (2017) no.02, 006

◆ 詳細な前景放射除去検討により、$\sigma(r=0) = 0.6$ x 10^{-3}の統計誤差を得た

◆ 詳細な系統誤差の検討により、全誤差が$\delta r < 1.0$ x 10^{-3} となることを示した



Slide from M. Hazumi @ JPS meeting, Sep. 2020

LiteBIRD サイエンスアウトカム

1. フルサクセス：→システム要求は、これより導かれる
2. エクストラサクセス：外部データと合わせ、テンソル・スカラー比の決定精度をさらに改善

3. Bモードの特性評価（新しい素粒子の寄与、非ガウス性、スケール依存性、パリティの破れなどの、新しい基礎物理）
4. 大角度Eモードの限界精度測定：
   - ニュートリノ質量和の精密決定、宇宙再電離史
5. 宇宙論的複屈折の探索
6. スニャエフ・ゼルドビッチ効果の精査による天文学
7. 周波数スペクトル歪みの異方性
8. Planck等で見えているアノーマリーの精査
9. 銀河磁場、星間ダストのサイエンス

3. – 9. は、
システム要求を
満たせば自ずと
得られる成果

Slide from M. Hazumi @ JPS meeting, Sep. 2020

まとめ

- CMB測定は、素粒子物理と密接に関連する（または素粒子物理そのもの）物理成果をもたらす
- 原始重力波
  - Hot big bang前からの信号
  - Inflation paradigm: metric quantization, GUTスケール
  - 次の10~15年で、$\sigma(r) \sim 0.001$に到達
- Light relics (N_{eff})
  - モデル依存性の少ない軽いBSM粒子の探索
  - 次の10~15年で$\sigma(N_{eff}) \sim 0.03$
- Neutrino mass
  - 地上実験と相補的な、絶対値測定
  - 次の10～15年で、$\sigma(M_\nu) \sim 20$ meV
- 現行実験も頑張ってます！
  - 将来計画がfirst lightを迎える前にも、物理成果が出てくる。