

Work with the Simons Observ

Large Aperture Telescope

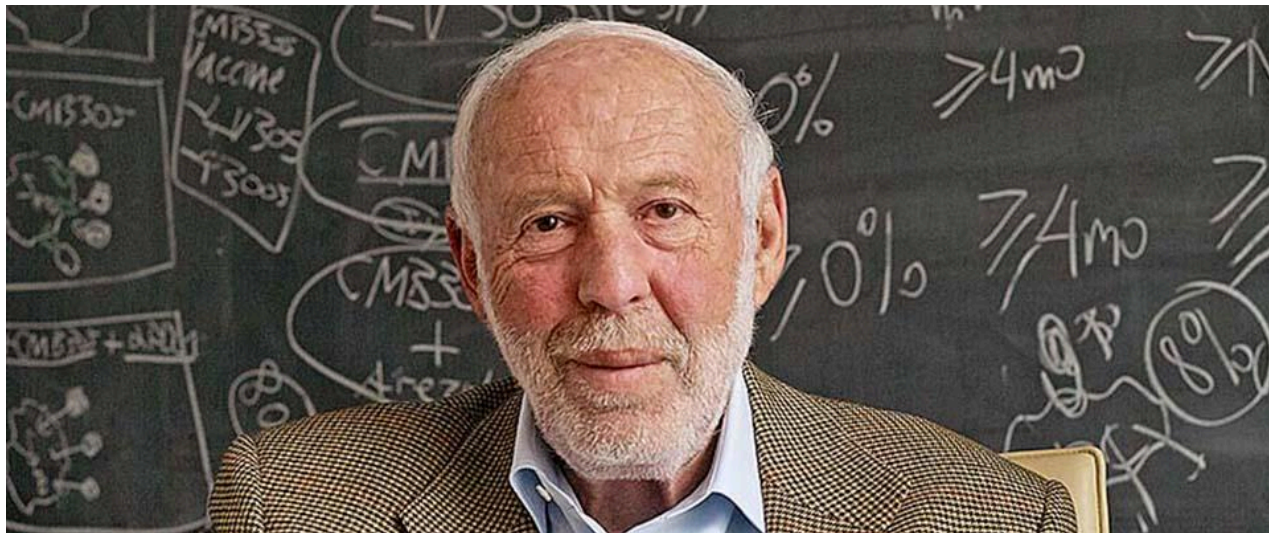
An aerial photograph of the Simons Observatory construction site in a high-altitude desert. In the foreground, a large, white, rectangular telescope enclosure is mounted on a base, with the 'CPI vertex' logo visible. Behind it, several large, circular, metallic structures, likely telescope enclosures or storage tanks, are scattered across the site. The background shows a vast, arid landscape with distant mountains under a clear sky. The text 'Work with the Simons Observ' and 'Large Aperture Telescope' is overlaid on the top half of the image.

arXiv:
1808.07445
2503.00636



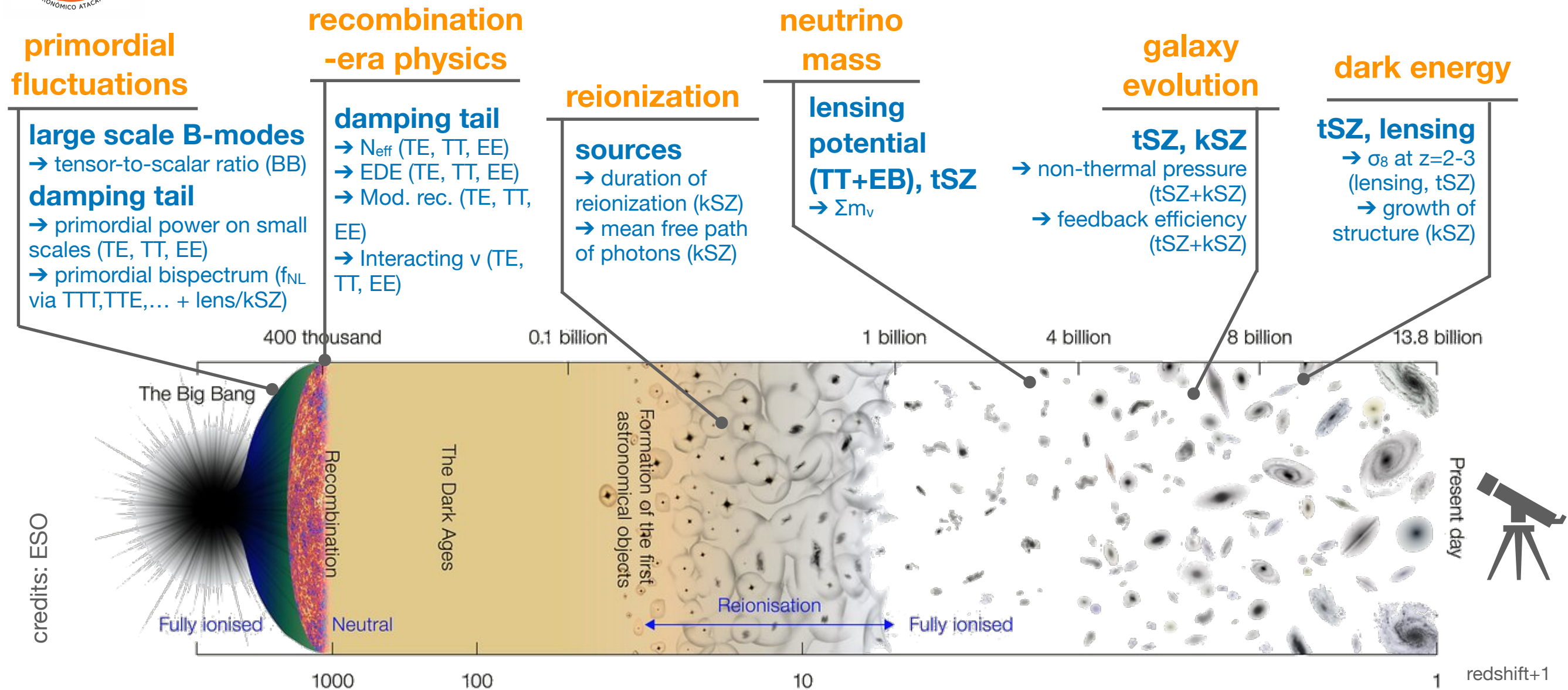


The Simons Observatory is funded by generous grants from the **Simons Foundation** and the **Heising-Simons Foundation**



as well as major contributions from
the Founding Institutions, the US
NSF, UKRI, and Japan





Additional science includes (but is not limited to):

- helium fraction, cosmic birefringence, primordial magnetic fields
- high-redshift clusters
- dark matter annihilation and interactions
- isocurvature
- calibration of multiplicative shear bias (e.g., for LSST)
- new sample of dusty star-forming galaxies
- transient sources
- cosmic infrared background

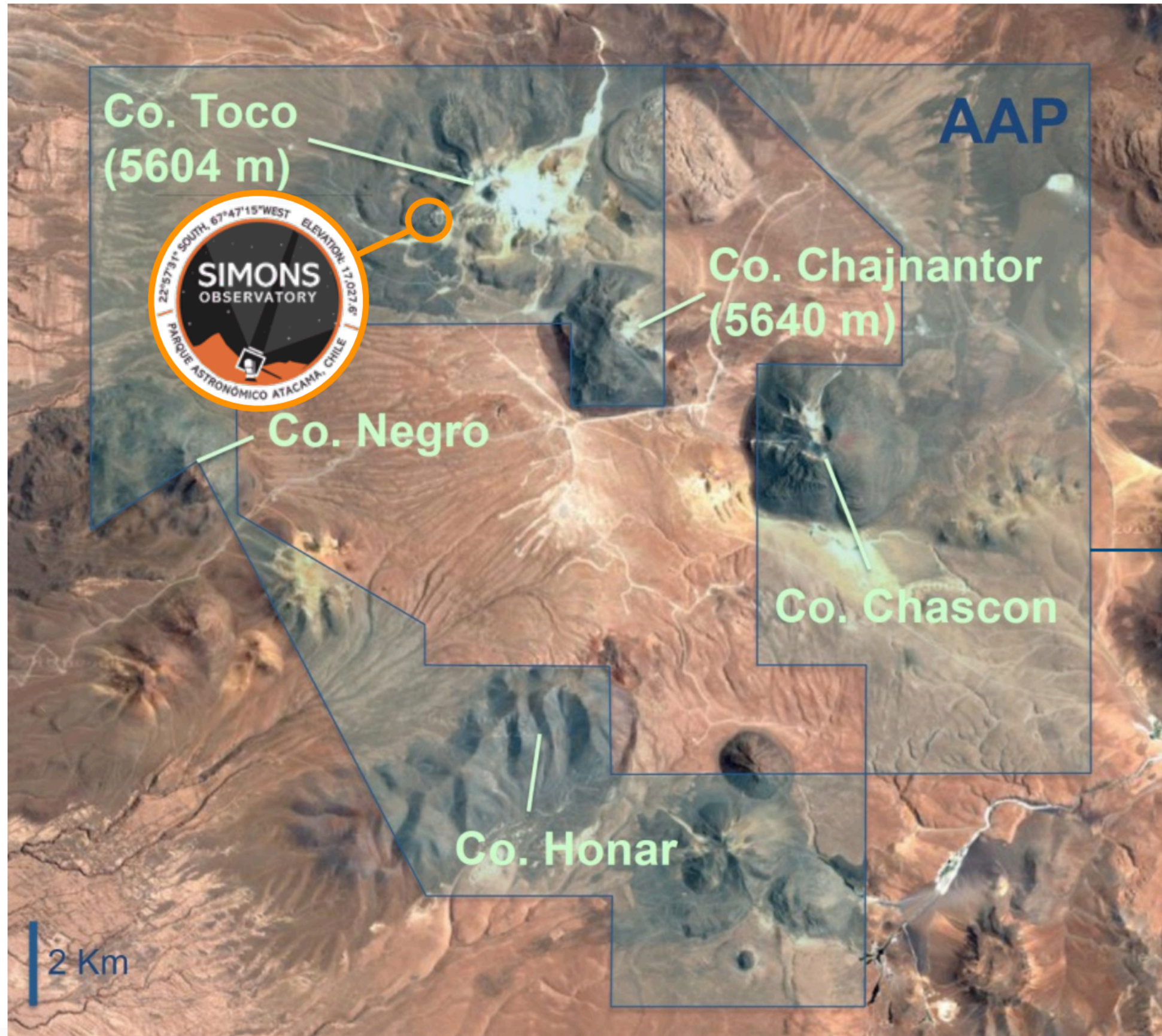
THE SIMONS OBSERVATORY:
SCIENCE GOALS
AND FORECASTS

1808.07445
2503.00636



Simons Observatory Site

Colin Hill
Columbia

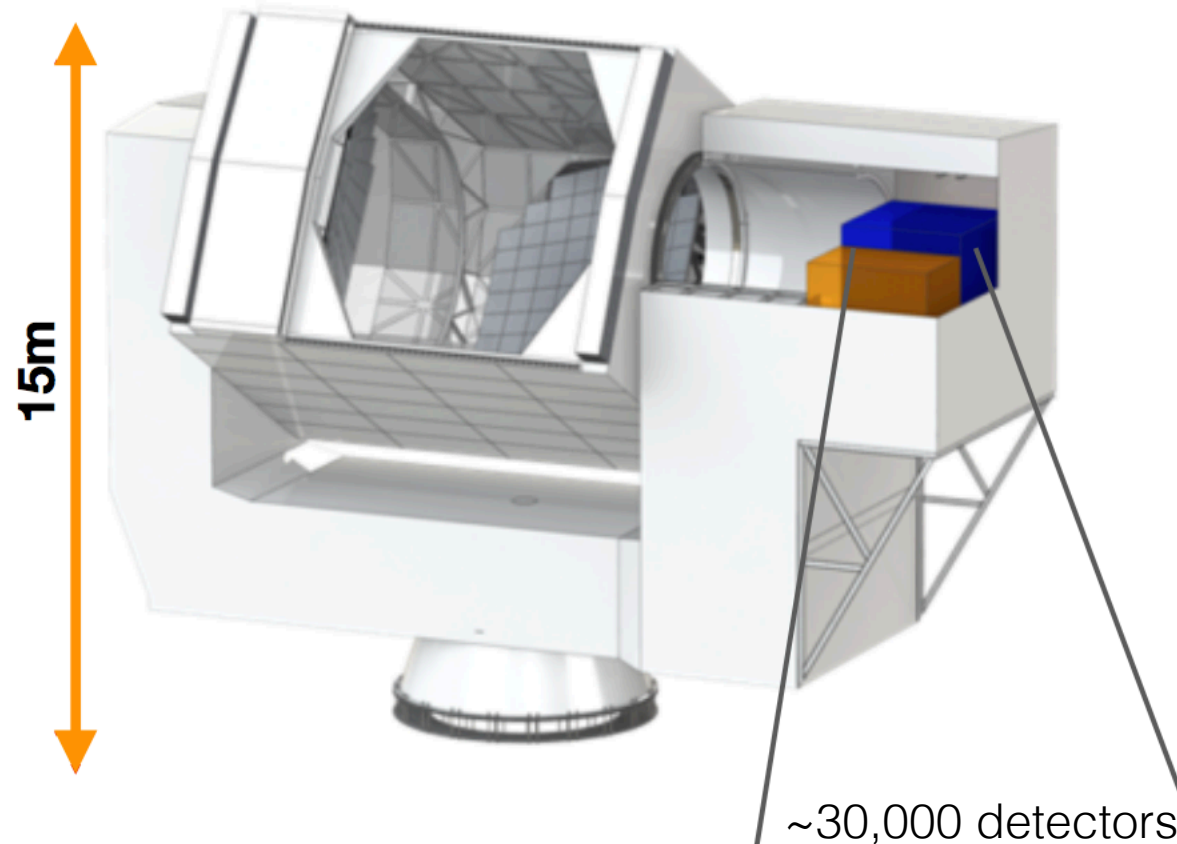


**Parque
Astronómico
Atacama**



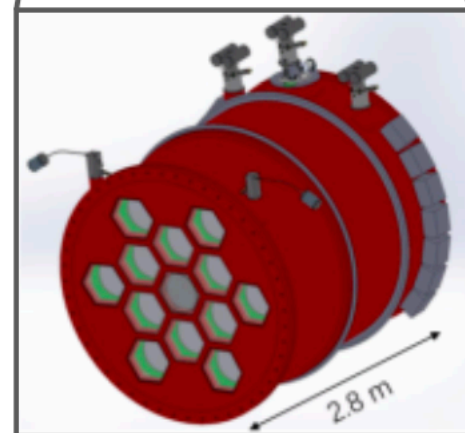
Simons Observatory Instruments & Technology

large aperture telescope

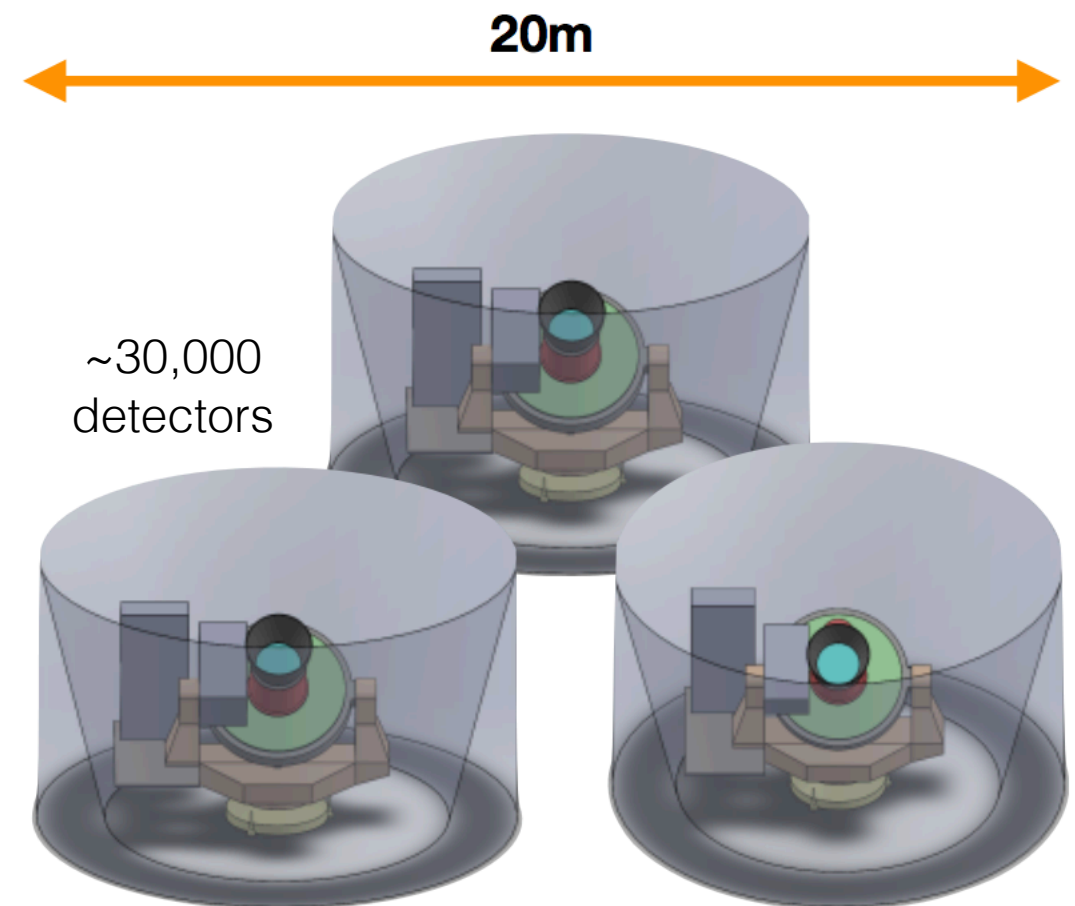


6 m crossed Dragone fed by up to 13, 38 cm optics tubes. baseline=7 tubes for SO, with baseline pixels:

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



small aperture telescopes



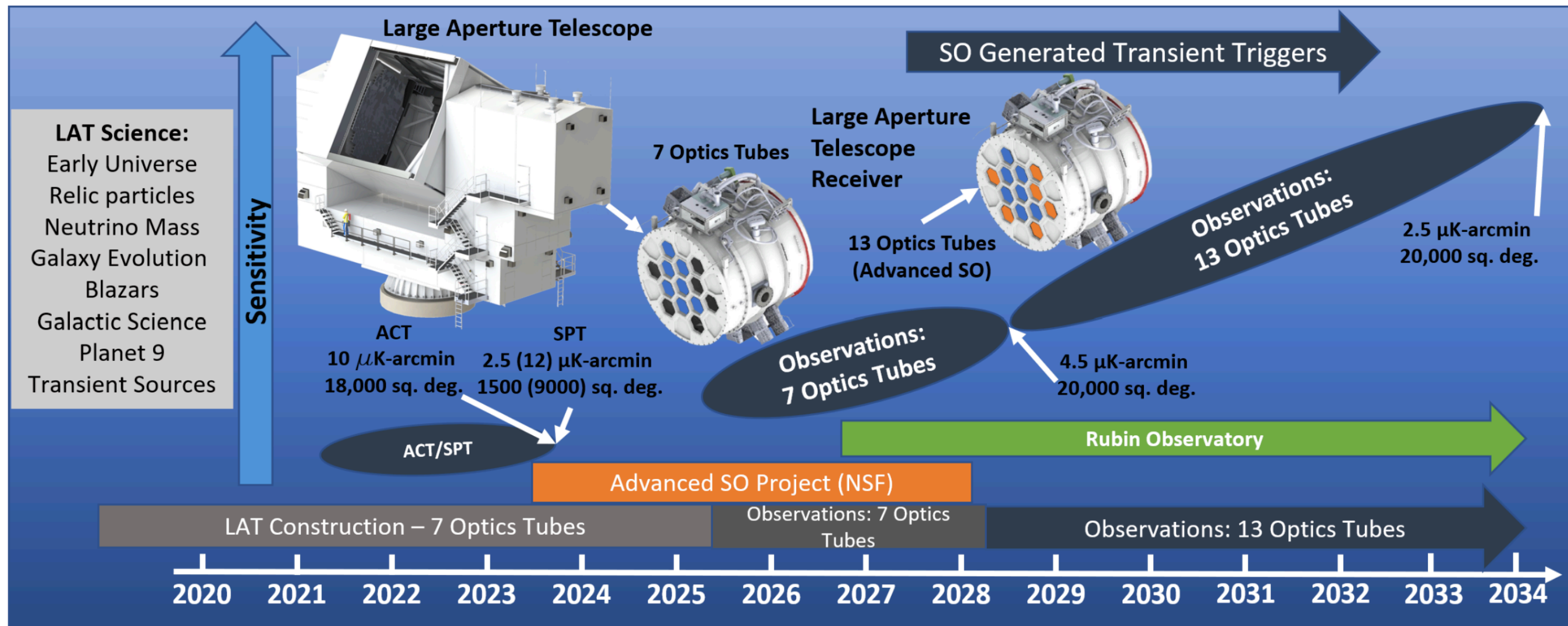
Three 42 cm diameter refractors, baseline dichroic pixels:
30/40 | 90/150 | 90/150 | 220/270 GHz

+ 3 additional SATs coming online by 2027

+ 6 additional OTs installed in 2026

~60,000 detectors in total!

Simons Observatory LAT Timeline





Anticipated Noise Performance

Colin Hill
Columbia

SO LAT: 2025-2034

assuming 6 additional optics tubes are added in 2028

Frequency [GHz]	FWHM [arcmin]	Baseline Depth [$\mu\text{K} \cdot \text{arcmin}$]	Goal Depth [$\mu\text{K} \cdot \text{arcmin}$]	Frequency Bands	Detector Count	Optics Tubes
27 (22 – 30)	7.4	61	44	LF	354	1
39 (30 – 47)	5.1	30	23		354	
93 (77 – 104)	2.2	5.3	3.8	MF	20,640	8
145 (128 – 169)	1.4	6.6	4.1		20,640	
225 (198 – 256)	1.0	15	10	UHF	10,320	4
280 (256 – 313)	0.9	35	25		10,320	

Combined sensitivity (goal): $2.6 \mu\text{K} \cdot \text{arcmin}$

Significant improvement over previous surveys:

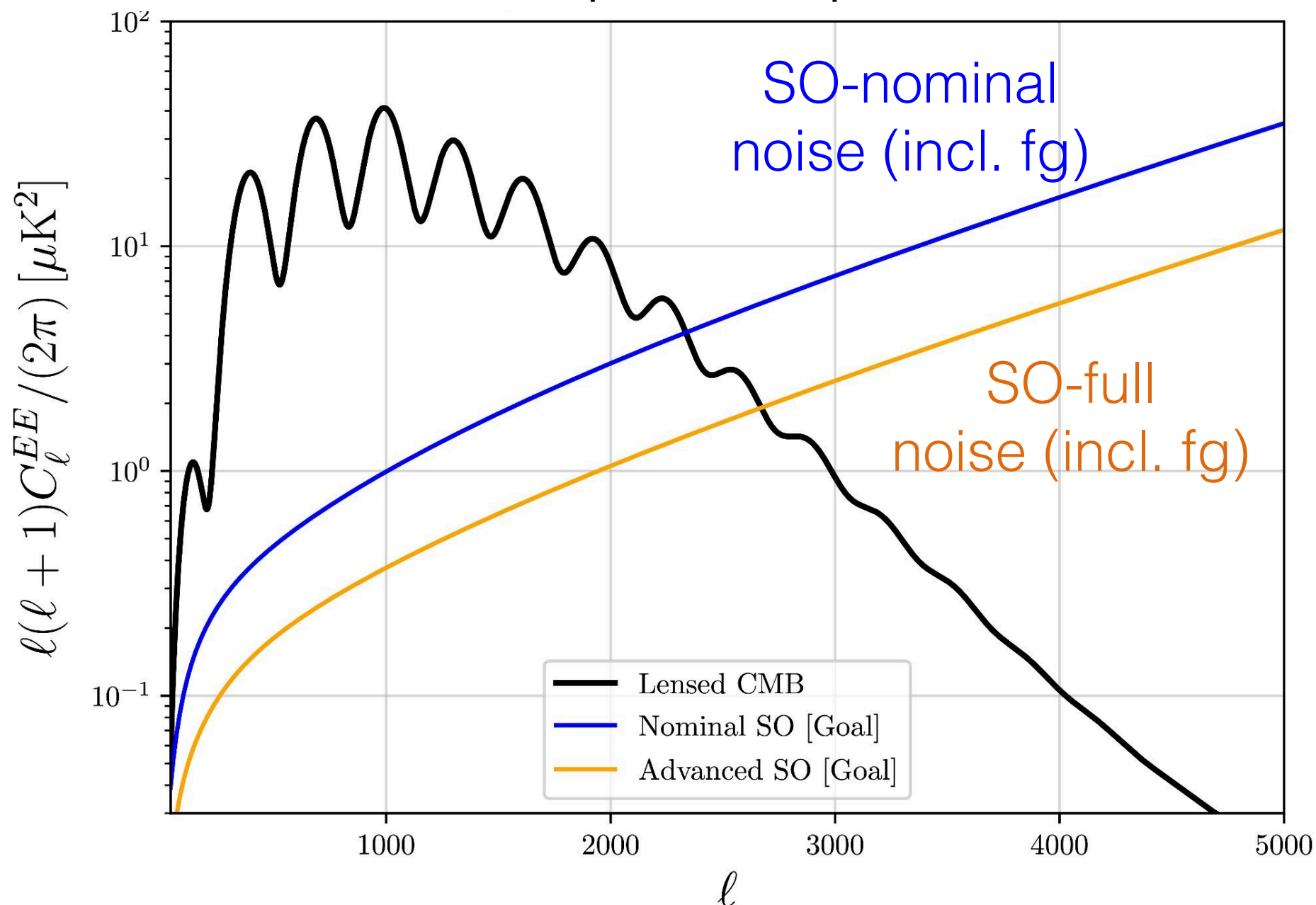
Planck: $\sim 25 \mu\text{K} \cdot \text{arcmin}$ ($\sim 5 \text{ arcmin}$ resolution)

ACT DR6: $\sim 10 \mu\text{K} \cdot \text{arcmin}$

Anticipated Noise Performance

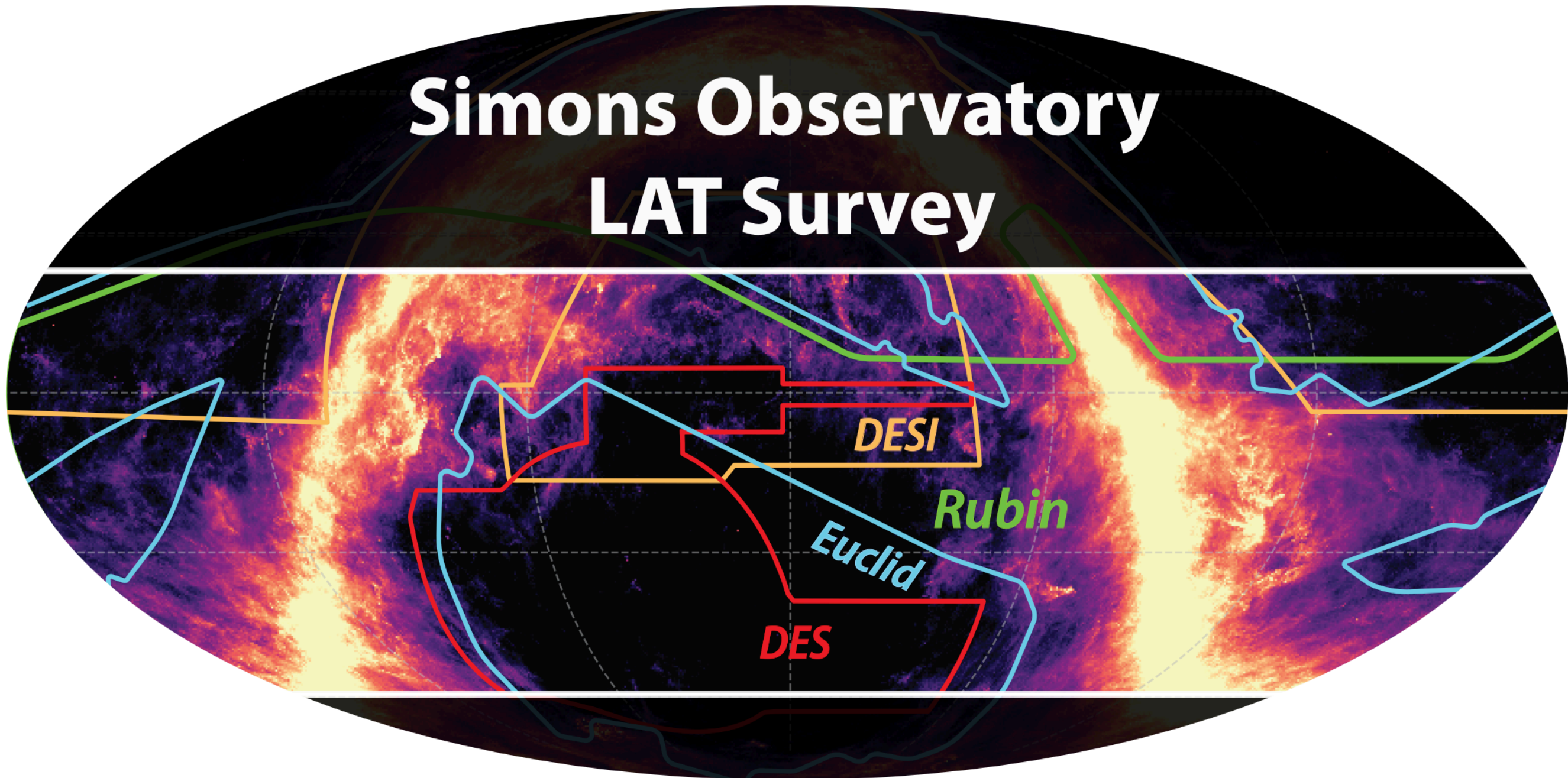
Significant gains from NSF-funded additional optics tubes
(~40% increase in number of signal-dominated E-modes)

E-mode power spectrum:



Anticipated Sky Coverage

Simons Observatory LAT Survey



total $f_{\text{sky}} \sim 60\%$
(cosmological $f_{\text{sky}} \sim 40\%$)

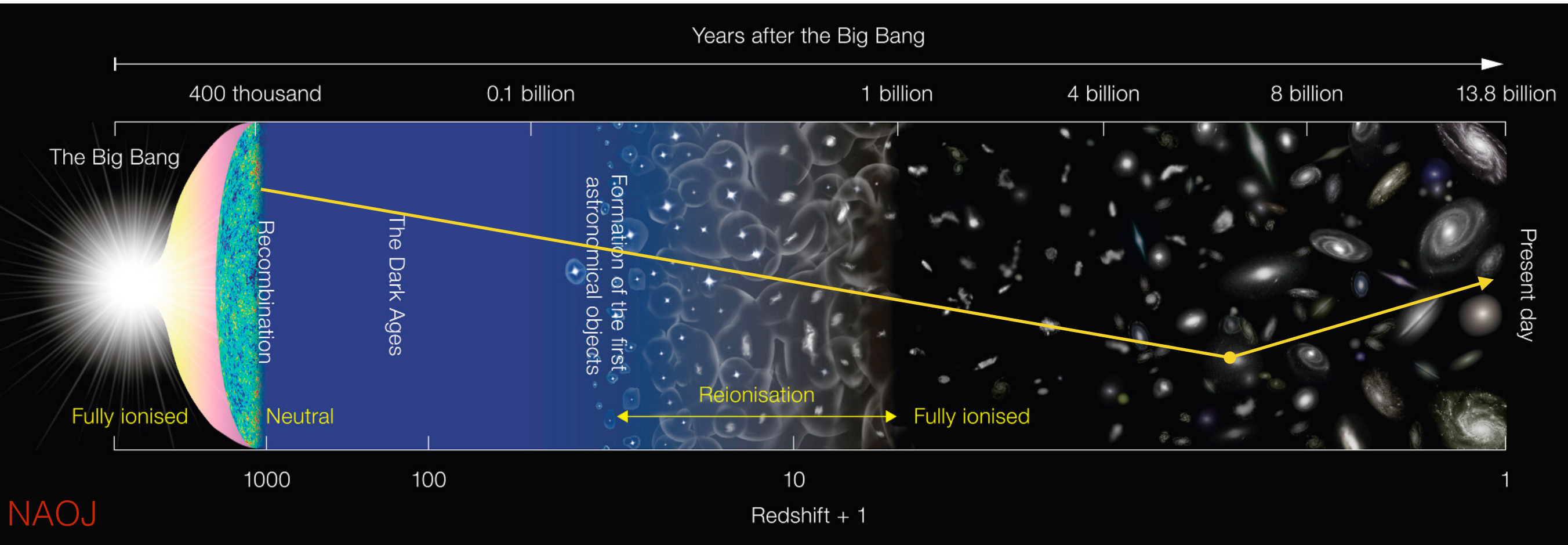
maximal overlap w/
Rubin LSST,
large overlap w/ DESI

- Extragalactic astrophysics: galaxy formation, ICM physics
 - Particle physics: neutrino masses, new light species, BSM
 - Primordial perturbations: non-Gaussianity, $P(k)$
 - Sources: variable blazars, dusty galaxies
 - Transients: uncharted discovery space
 - Milky Way ISM: dust composition, magnetic fields
 - Solar System: Planet 9, asteroids
- + much more

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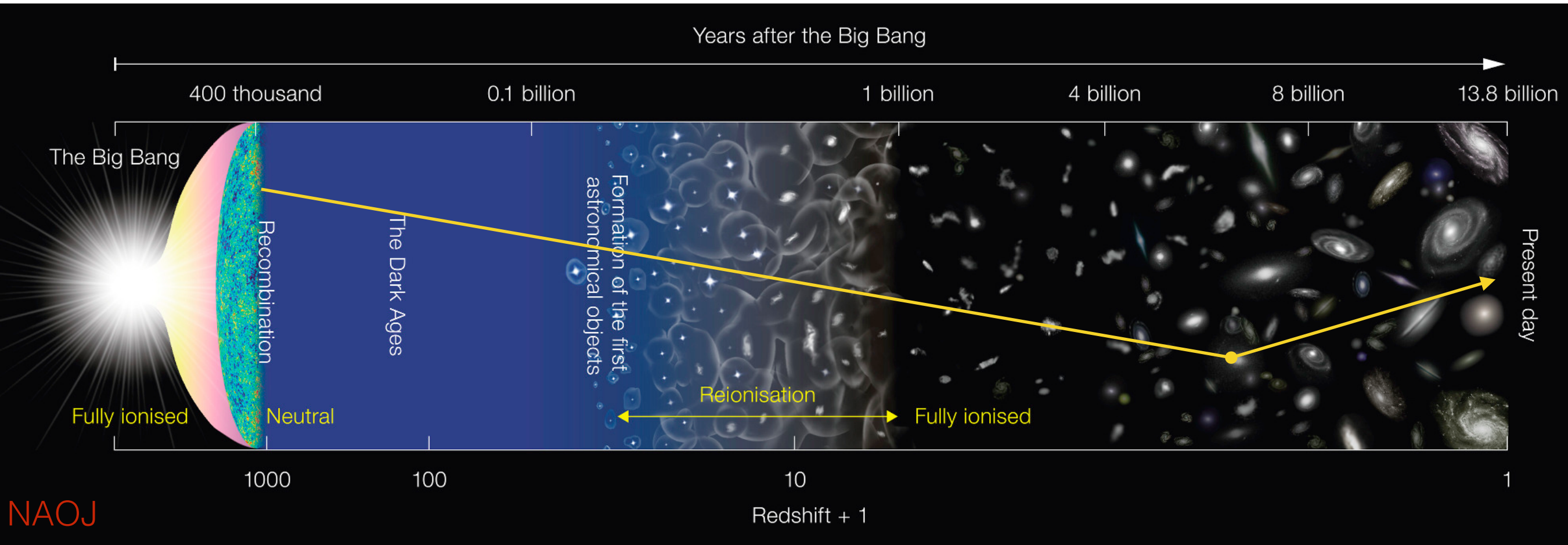
Cosmic Microwave Backlight

Secondary Anisotropies



Cosmic Microwave Backlight

Secondary Anisotropies



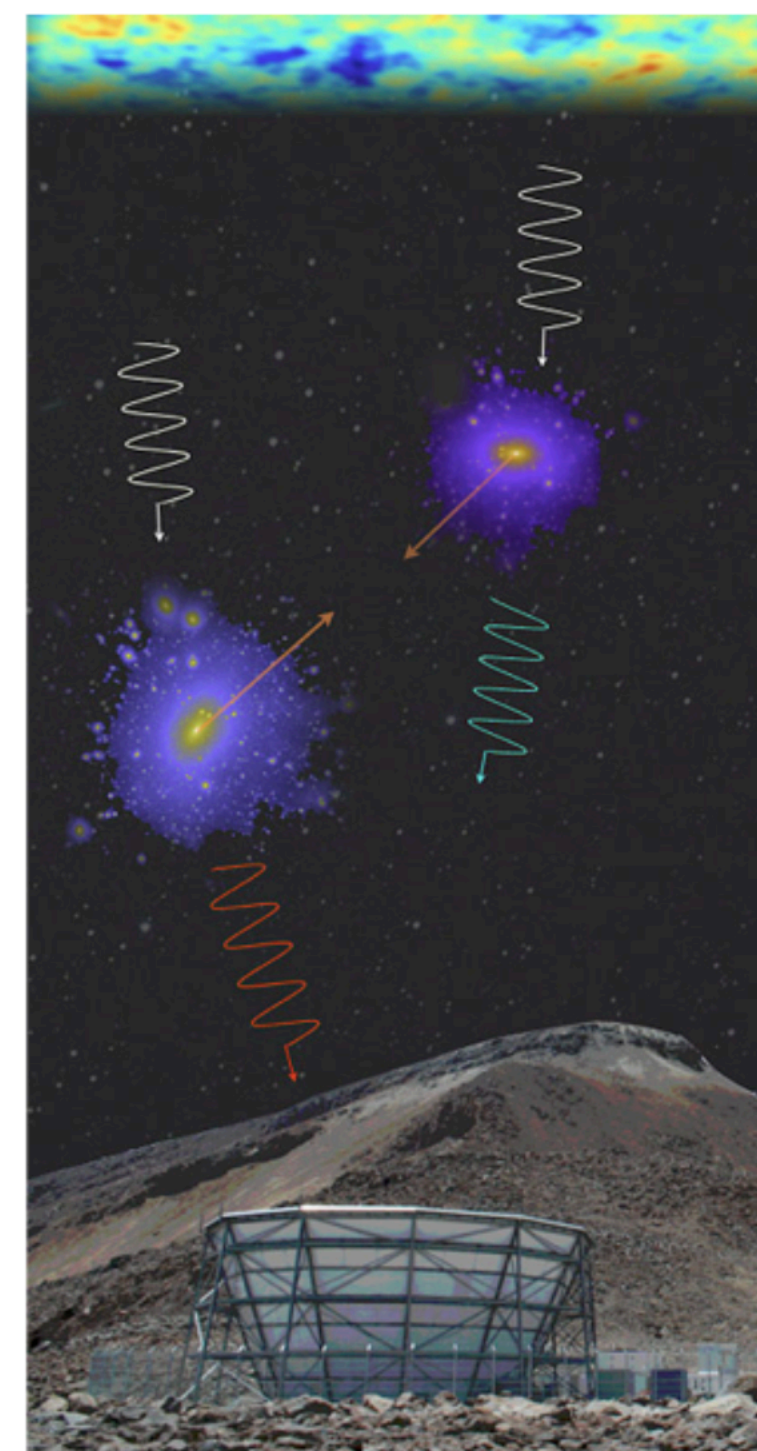
- Deflection: gravitational lensing
- Evolving potentials: integrated Sachs-Wolfe, Rees-Sciama effects
- Scattering: thermal / kinematic Sunyaev-Zel'dovich effects, patchy screening

Extragalactic Astrophysics

Kinematic Sunyaev-Zel'dovich Effect:

Doppler boosting of CMB photons
Compton-scattering off free electrons
with non-zero line-of-sight velocity

Direct probe of gas momentum
→ **gas abundance**



Kinematic Sunyaev-Zel'dovich Effect:

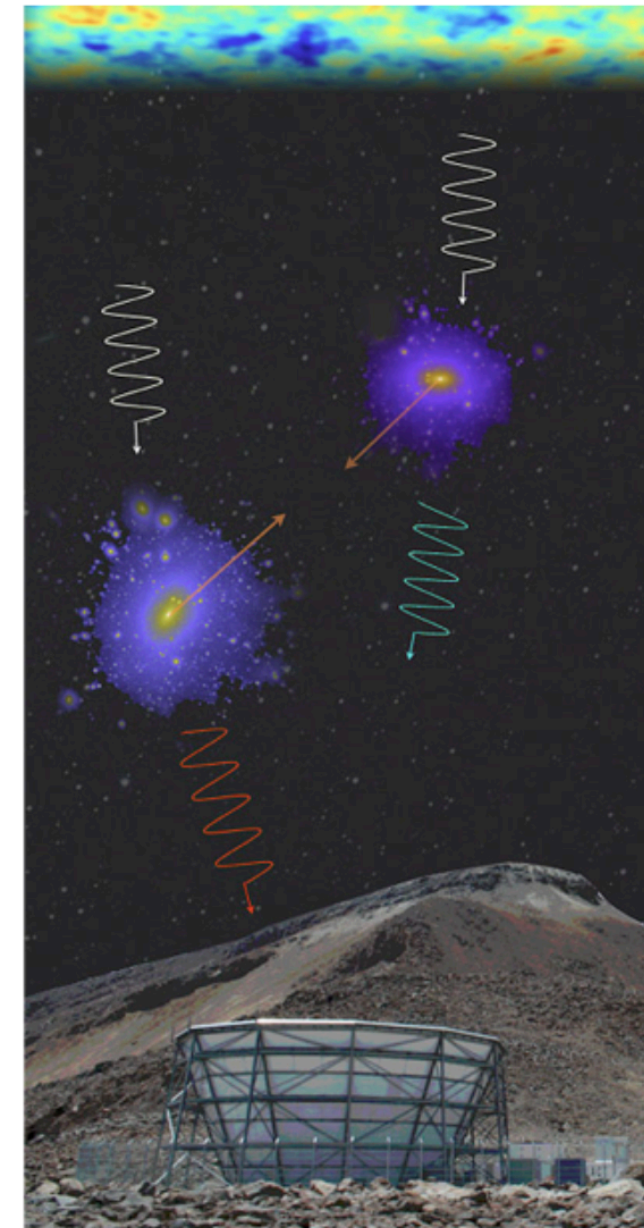
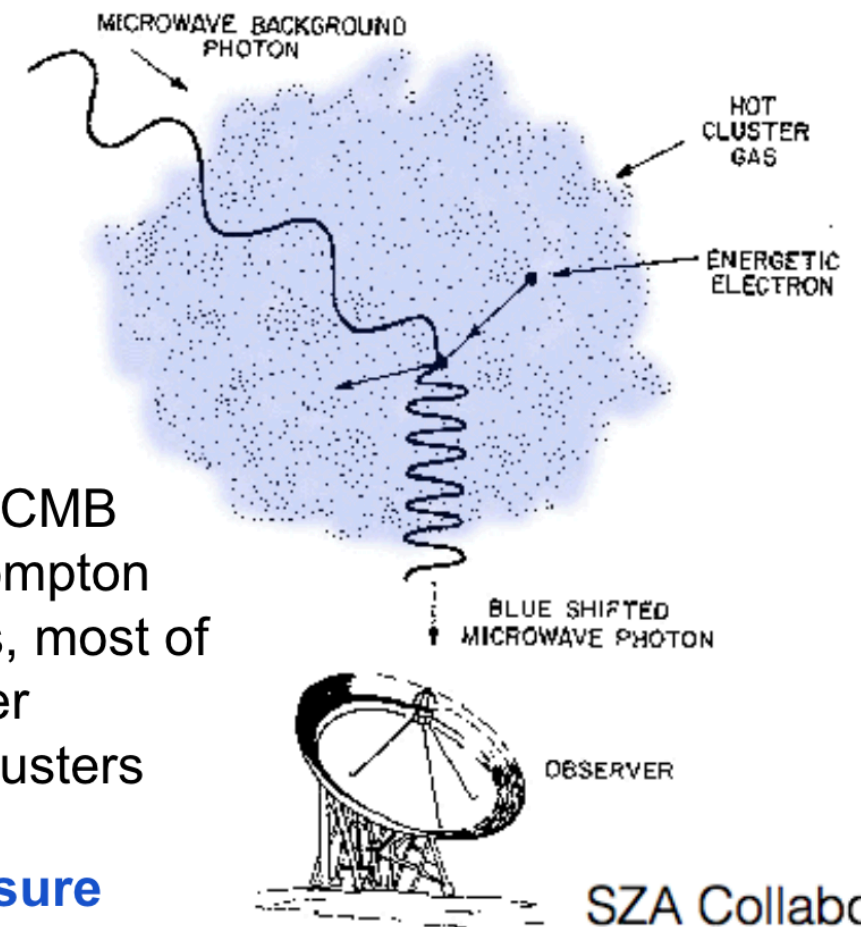
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Direct probe of gas momentum
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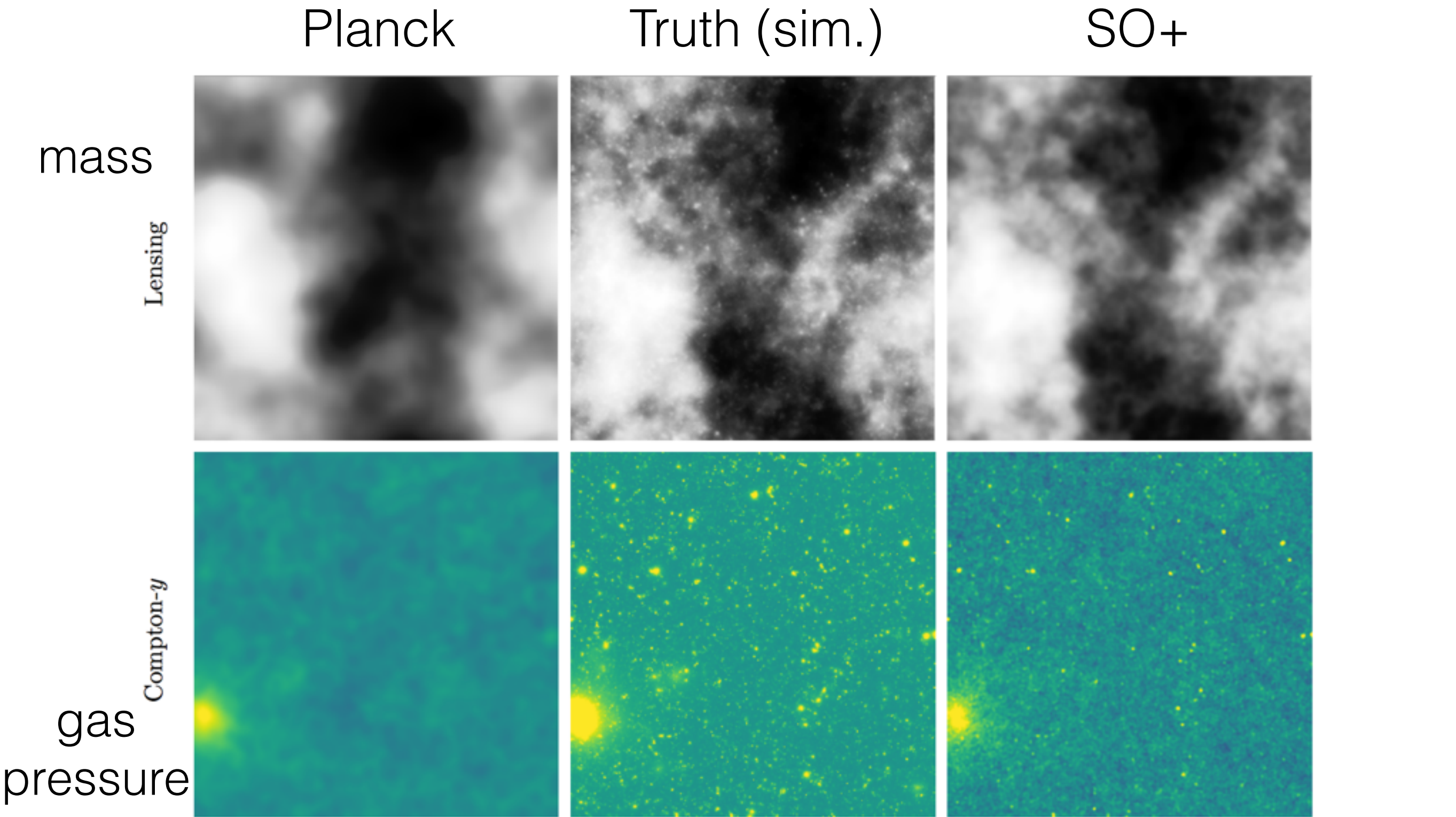
Thermal SZ Effect:

Change in temperature of CMB photons due to inverse Compton scattering off **hot** electrons, most of which are in the intracluster medium (ICM) of galaxy clusters

Direct probe of gas pressure

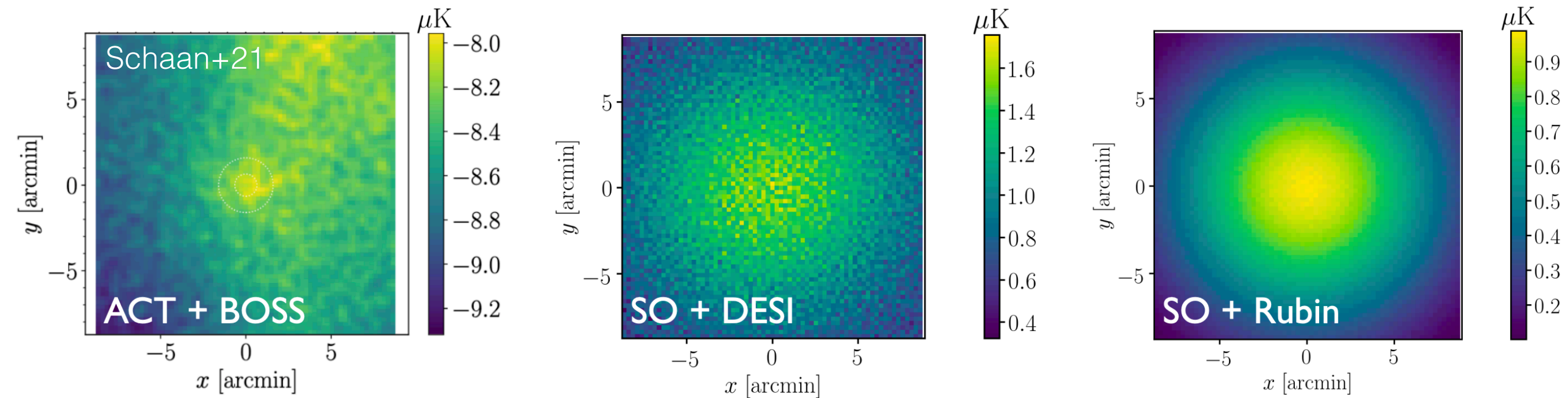


Sudeep Das/ACT



Extragalactic Astrophysics

Velocity-weighted kSZ stacking



- Direct imaging of gas density (kSZ) and pressure (tSZ) in the CGM
- Current stacked kSZ measurements (ACT+BOSS/DESI): $S/N \sim 10$
- SO stacked kSZ measurements (SO+DESI or Rubin): $S/N \sim 100\text{s}$

Direct constraints on galaxy formation physics from stacked kSZ+tSZ

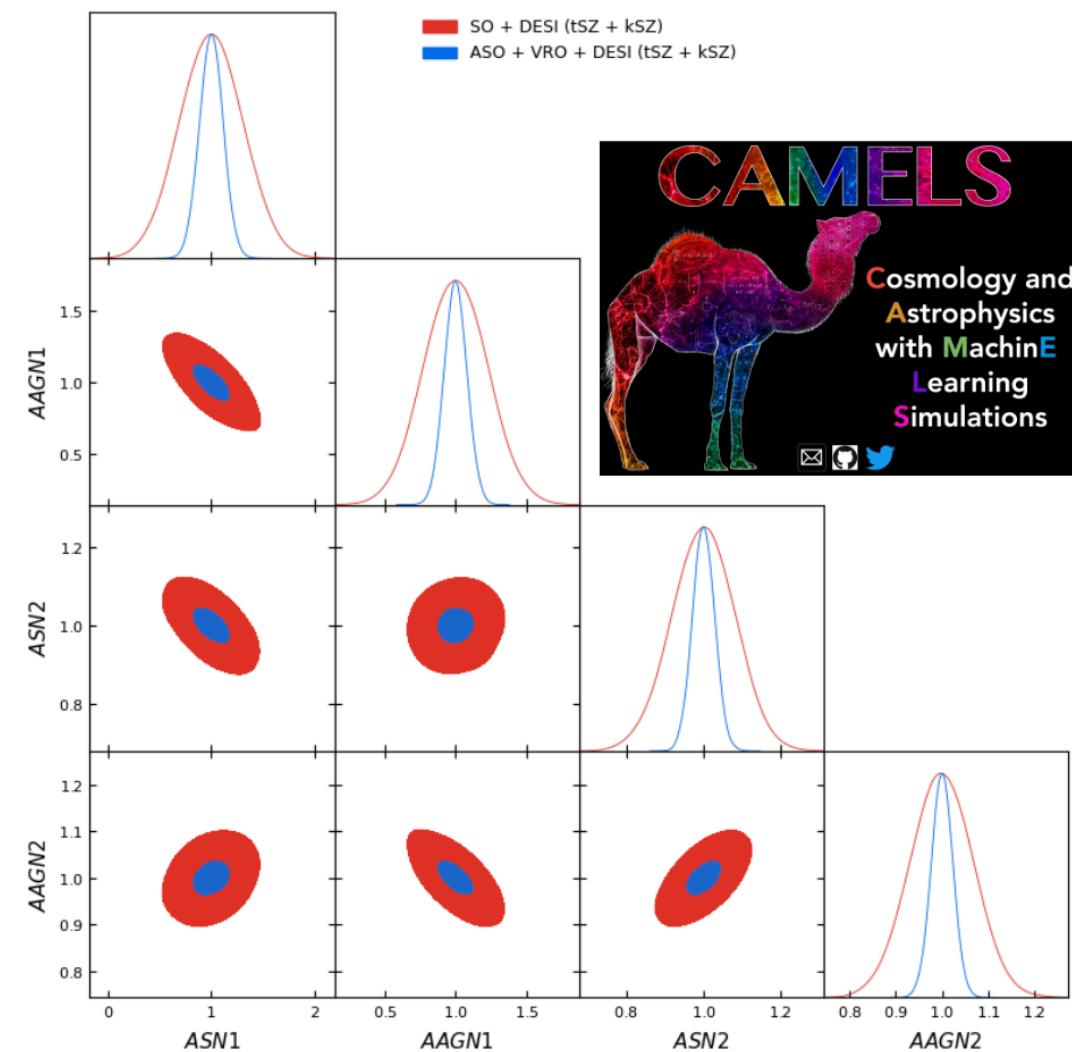
η = efficiency of feedback energy injection ; P_{nt} = non-thermal pressure support in the CGM/ICM

	$\sigma(\eta)$	$\sigma(P_{nt})$
Current (ACT + BOSS)	25%	unconstrained
Nominal SO + DESI	3%	5%
Full SO + Rubin + DESI	0.5%	1%

Direct constraints on sub-grid AGN and supernova feedback parameters in galaxy formation simulations:

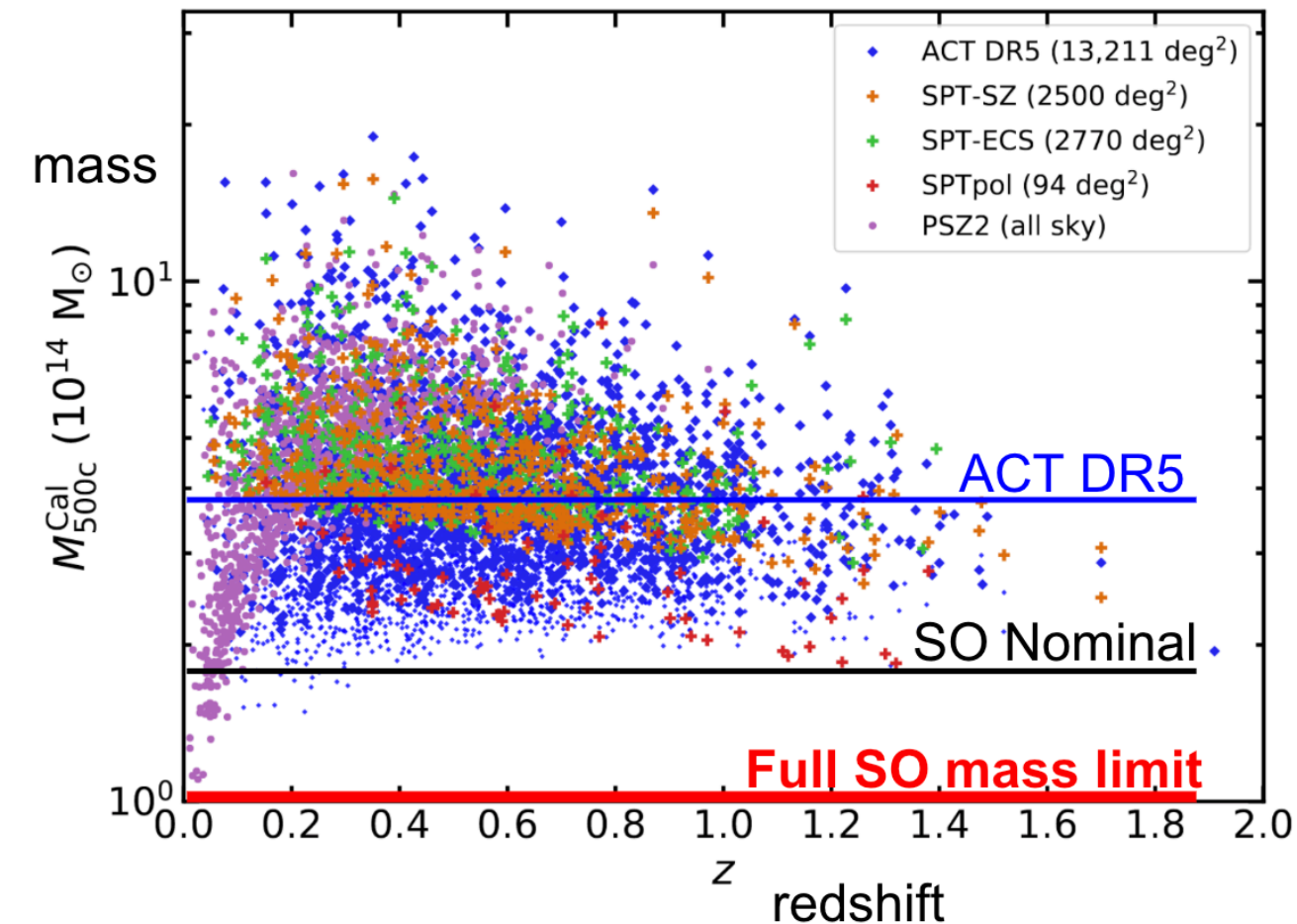
Current (ACT + BOSS): unconstrained
 Nominal SO + DESI: ~7%-30%
Full SO + Rubin + DESI: ~2%-10%

Amodeo+21 [ACT]
 CAMELS (Moser+22)



Extragalactic Astrophysics

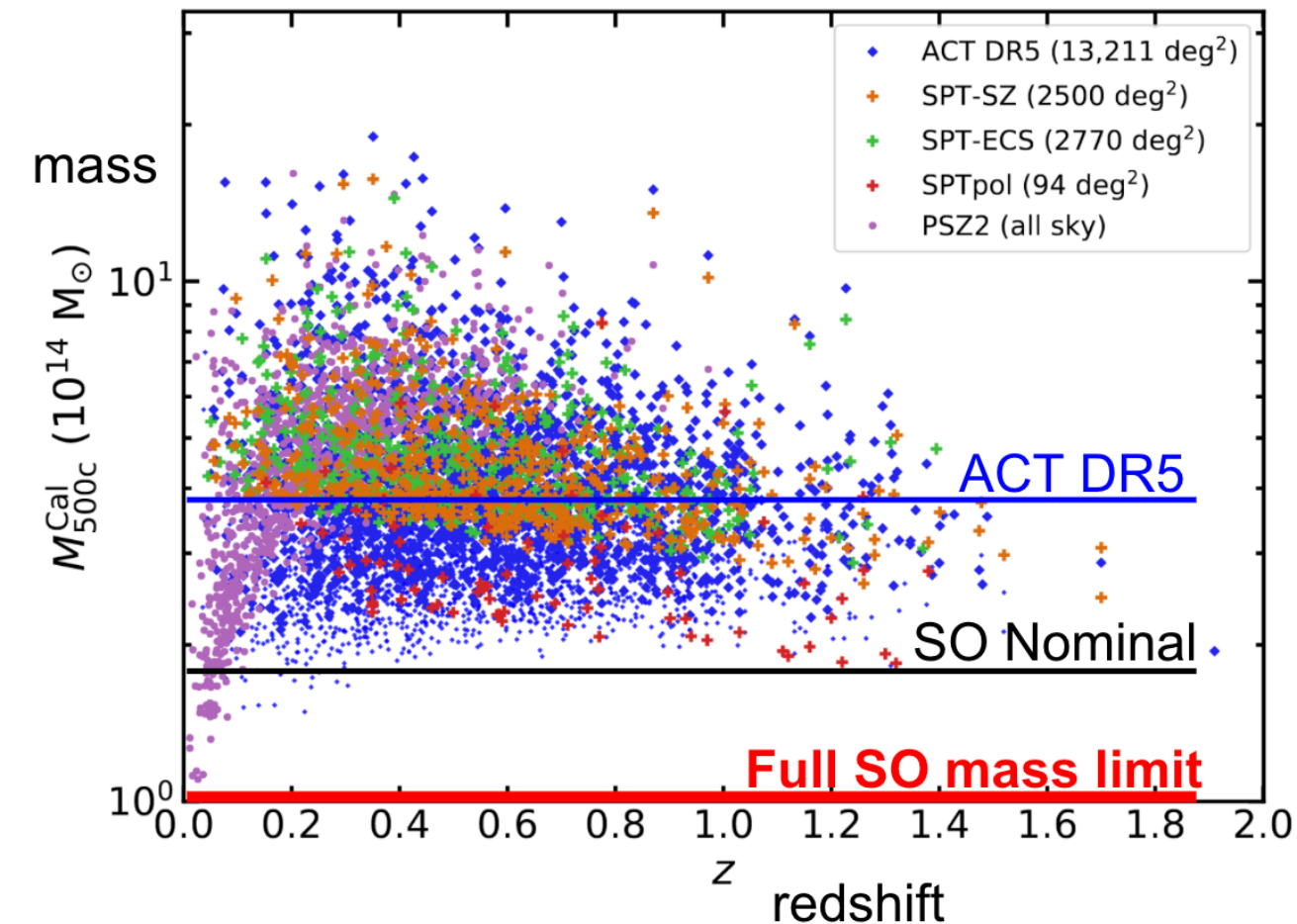
First statistical census of galaxy clusters at $z > 2$



- High-sensitivity, high-resolution tSZ surveys can detect galaxy clusters out to the highest redshifts at which they exist
- Nominal SO: ~40 clusters at $z > 2$ (24,000 total)
- **Full SO: ~200 clusters at $z > 2$ (33,000 total)**

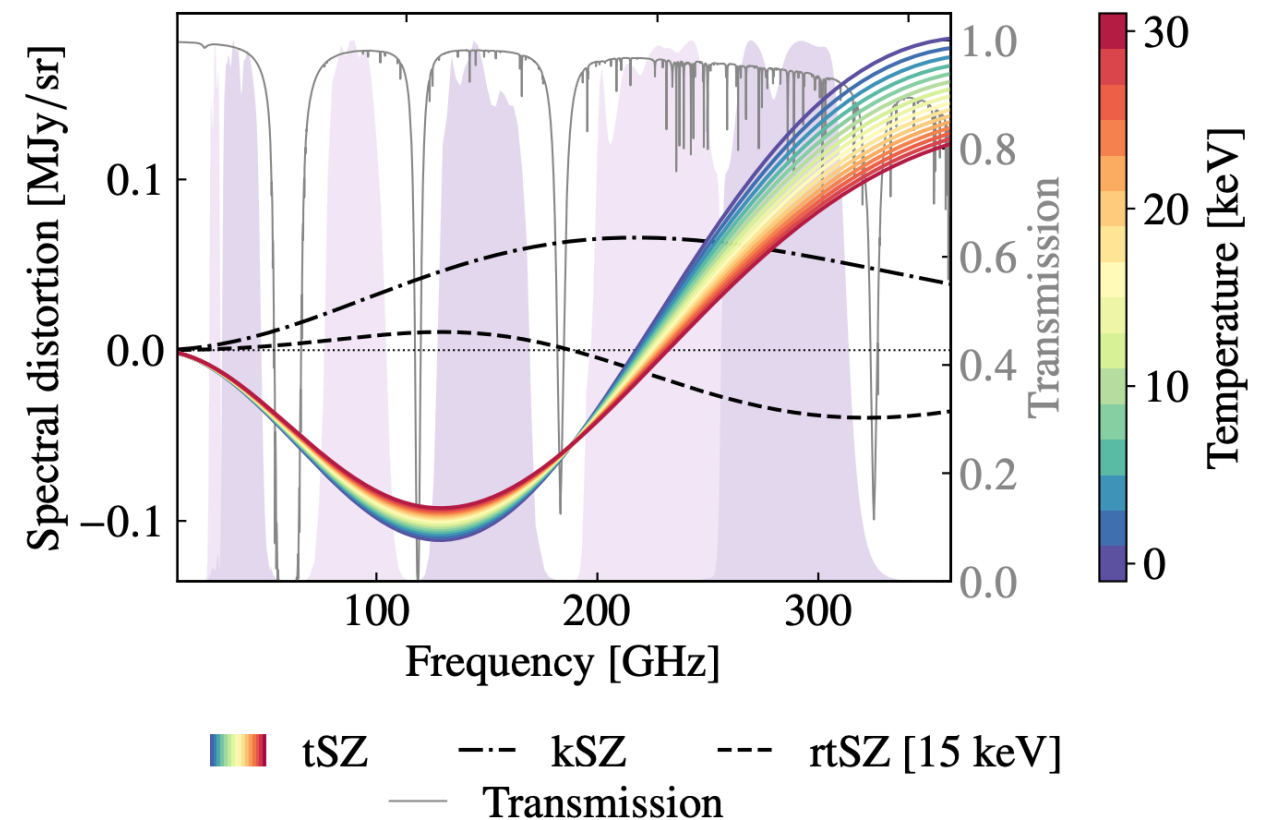
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Spectral coverage for relativistic tSZ

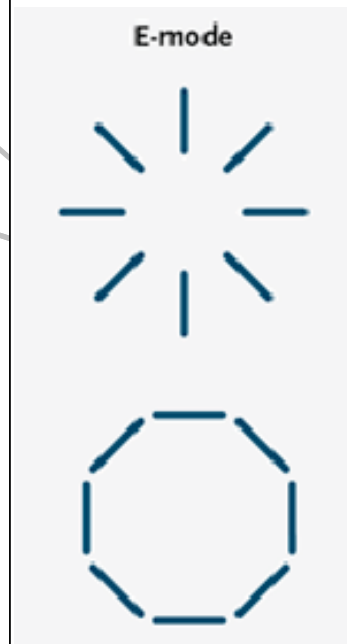
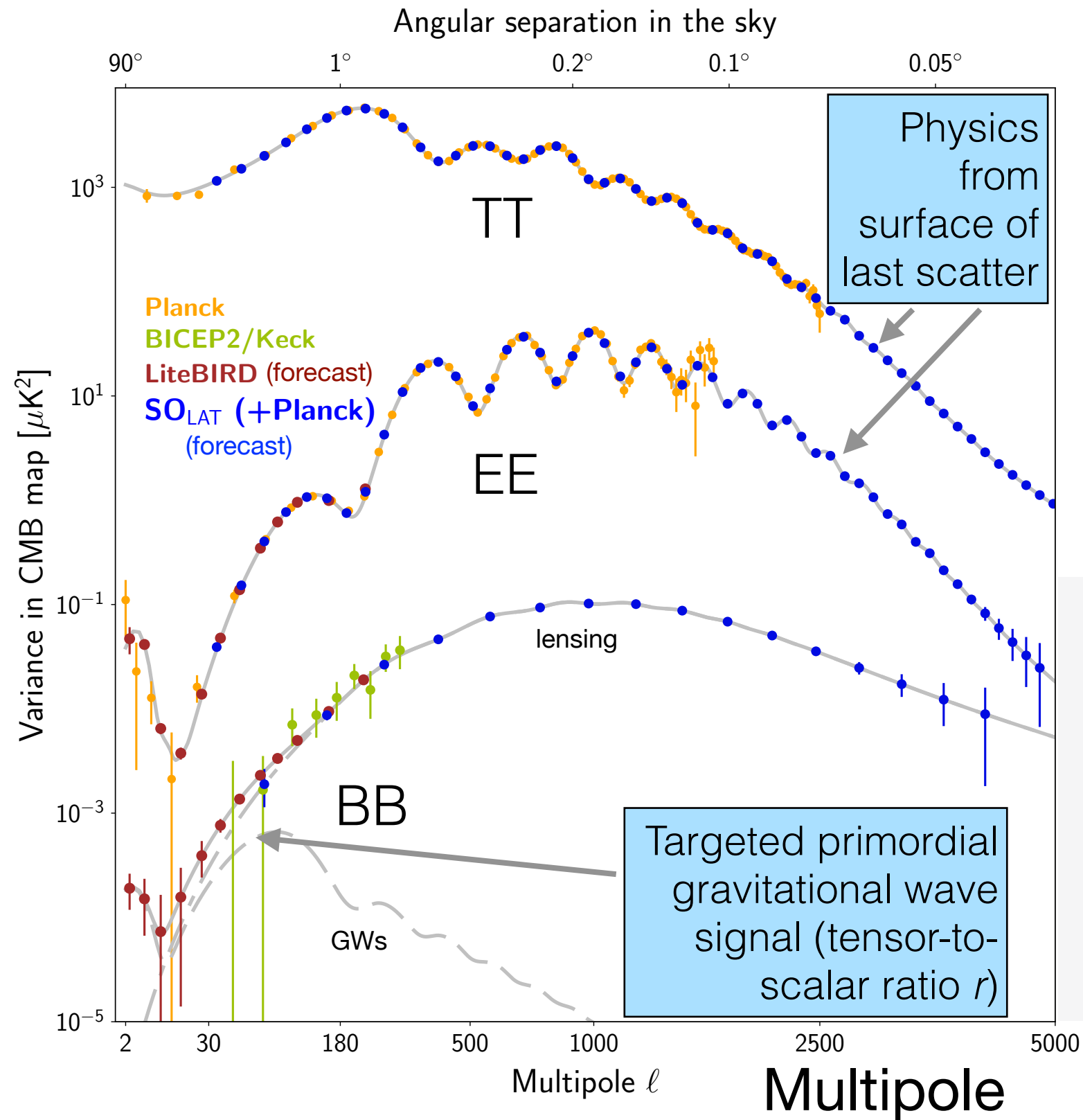


Hilton+21 [ACT]

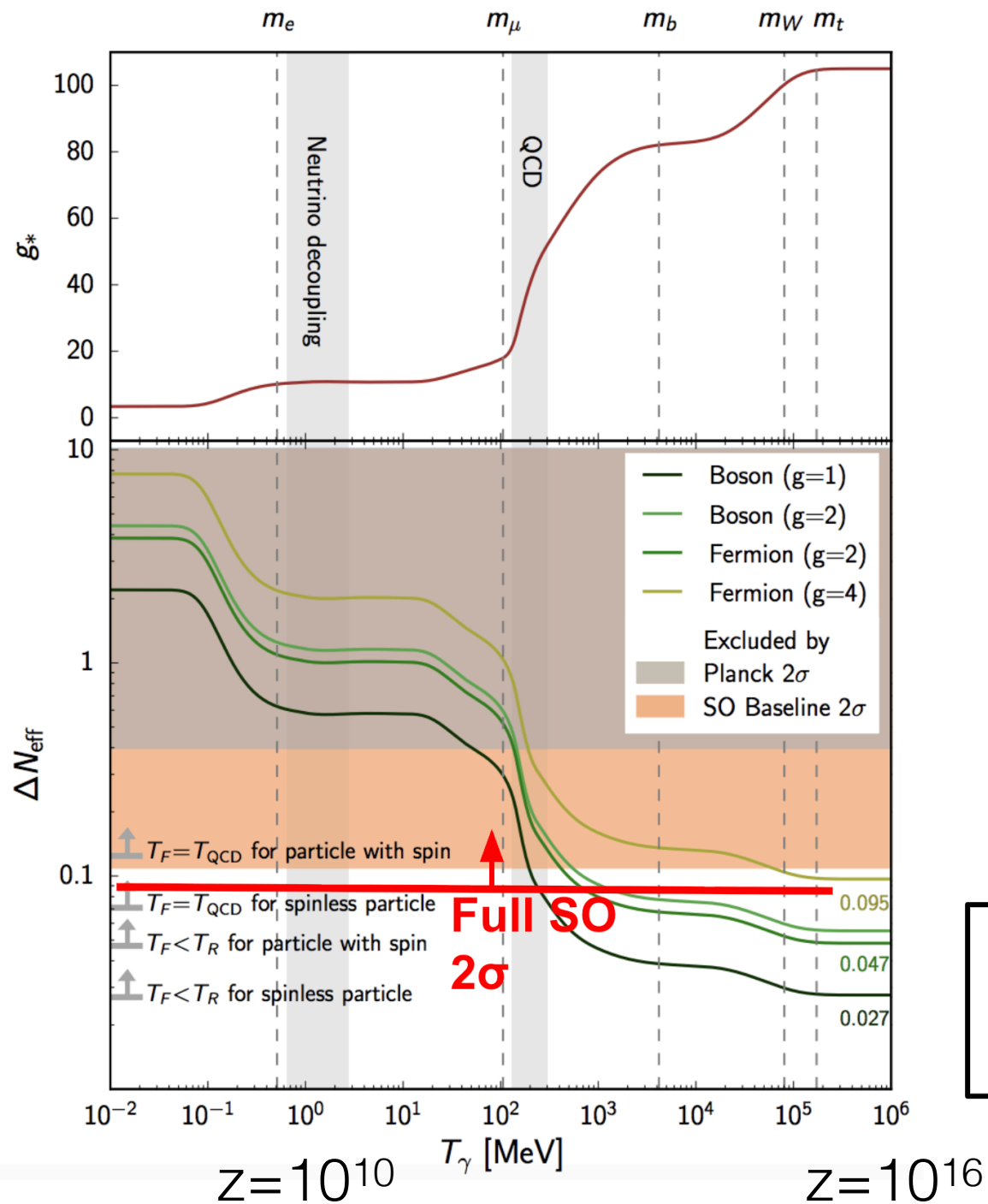
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Primary CMB

Angular
Power
Spectrum



CMB: Relativistic Particle Detector



- The CMB power spectra are sensitive to any light particles (mass $< \text{eV}$) that were ever in thermal contact with the primordial plasma (“dark radiation”, e.g., neutrinos)
- N_{eff} is a simple parametrization that captures a wide range of beyond-standard-model theories, with canonical value $N_{\text{eff}} = 3.044$ for the SM neutrinos:

$$N_{\text{eff}} = \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \frac{\rho_\nu}{\rho_\gamma}$$

	Current Data [ACT+Planck]	SO Nominal	Full SO
$\sigma(N_{\text{eff}})$	0.13	0.06	0.045

SO: sensitive to any light spin-3/2 particle that was in thermal contact at any time back to reheating

CMB: Potential Hints of New Physics in H_0

- Disagreement has reached 5σ between CMB and SH0ES: if not a systematic (robust confirmation still needed), this requires new physics beyond Λ CDM

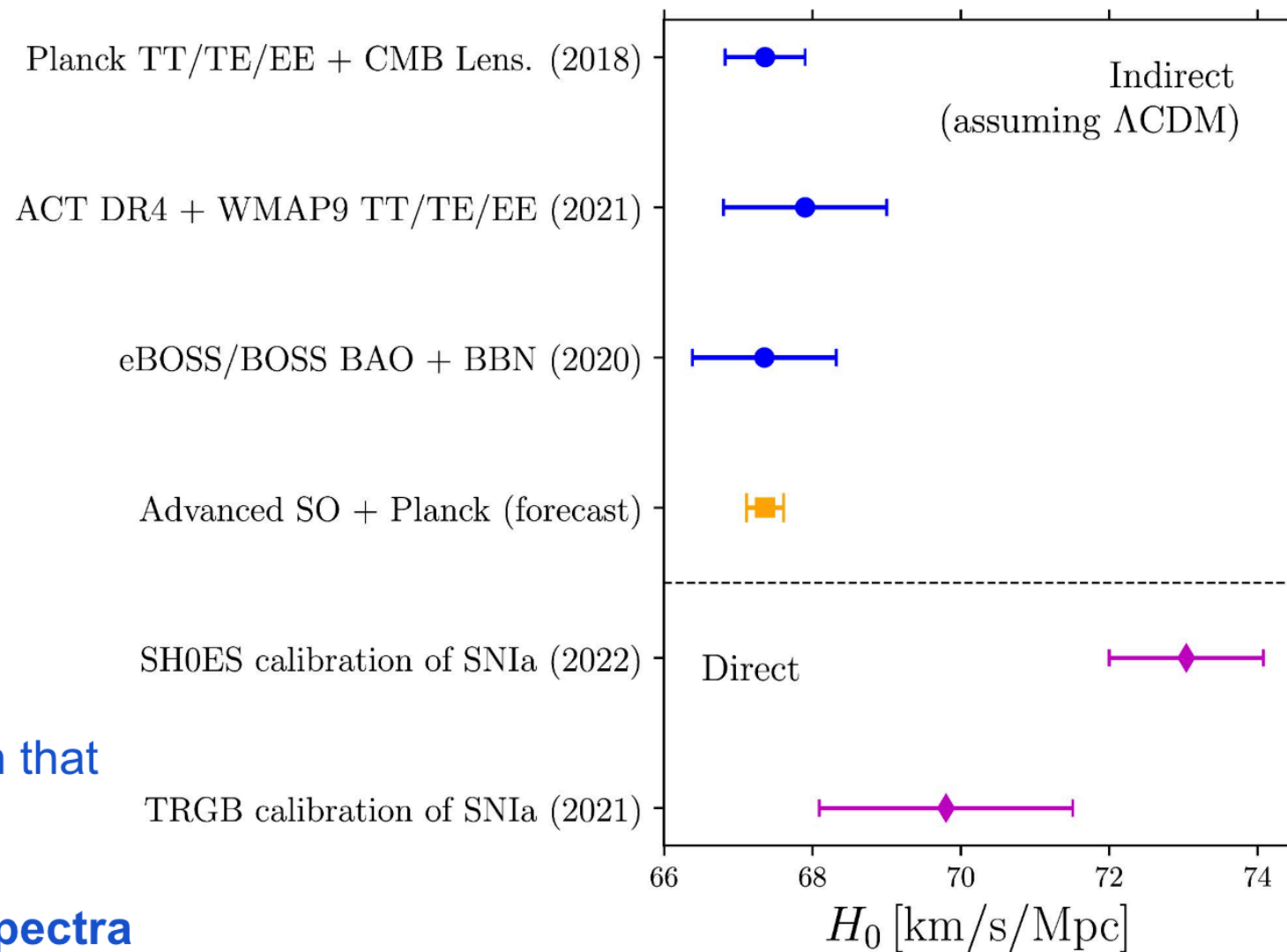
- **Not a CMB systematic:** Planck/ACT/SPT agree within Λ CDM

- **Not specific to CMB:** other cosmological probes (BAO + BBN + others) agree

- How can we increase the value of H_0 inferred from CMB and large-scale structure data?

→ Introduce new physics just prior to recombination that modifies the physical size of the sound horizon

→ **This yields novel signals in the CMB power spectra**



CMB: Potential Hints of New Physics in H_0

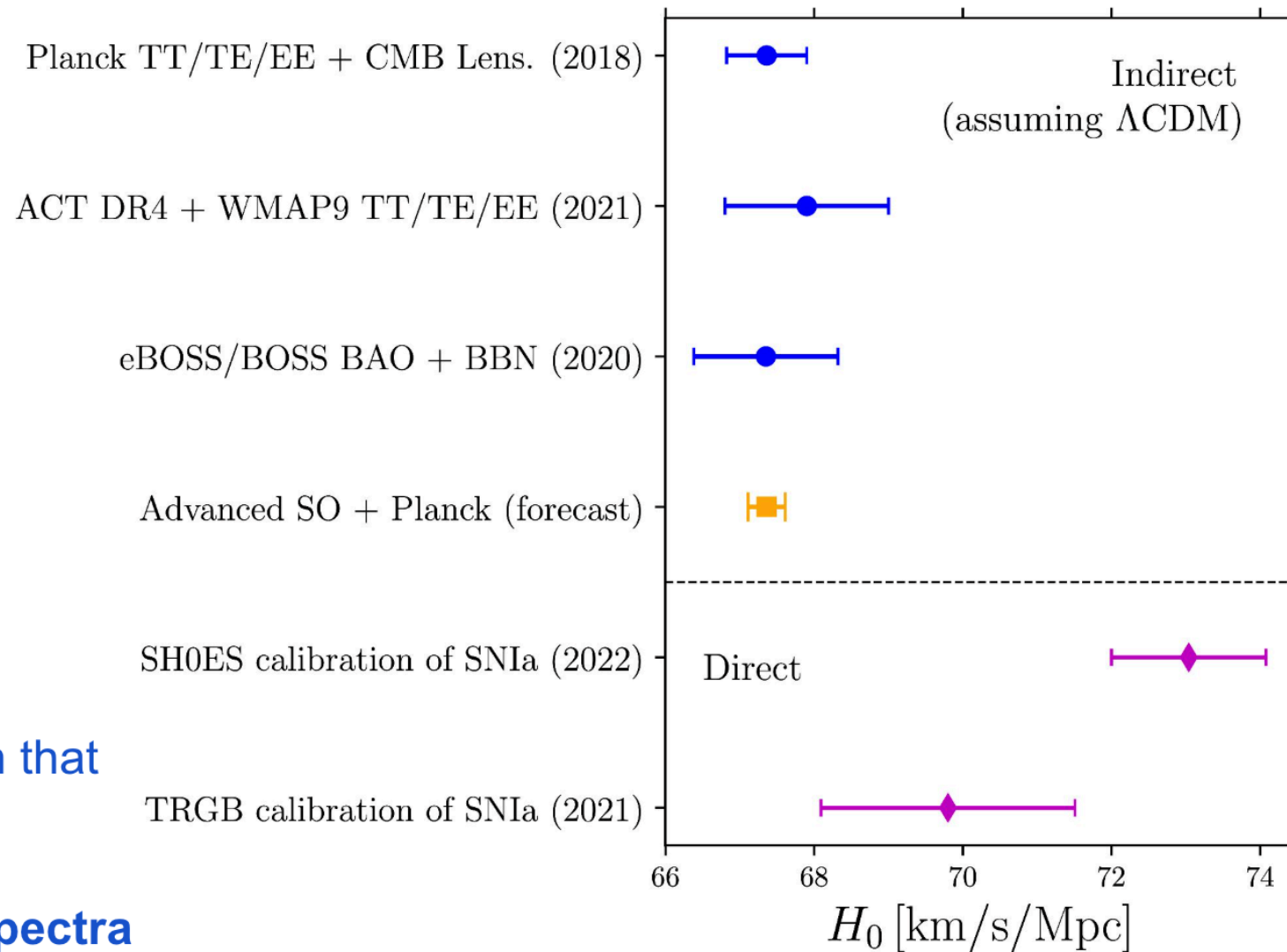
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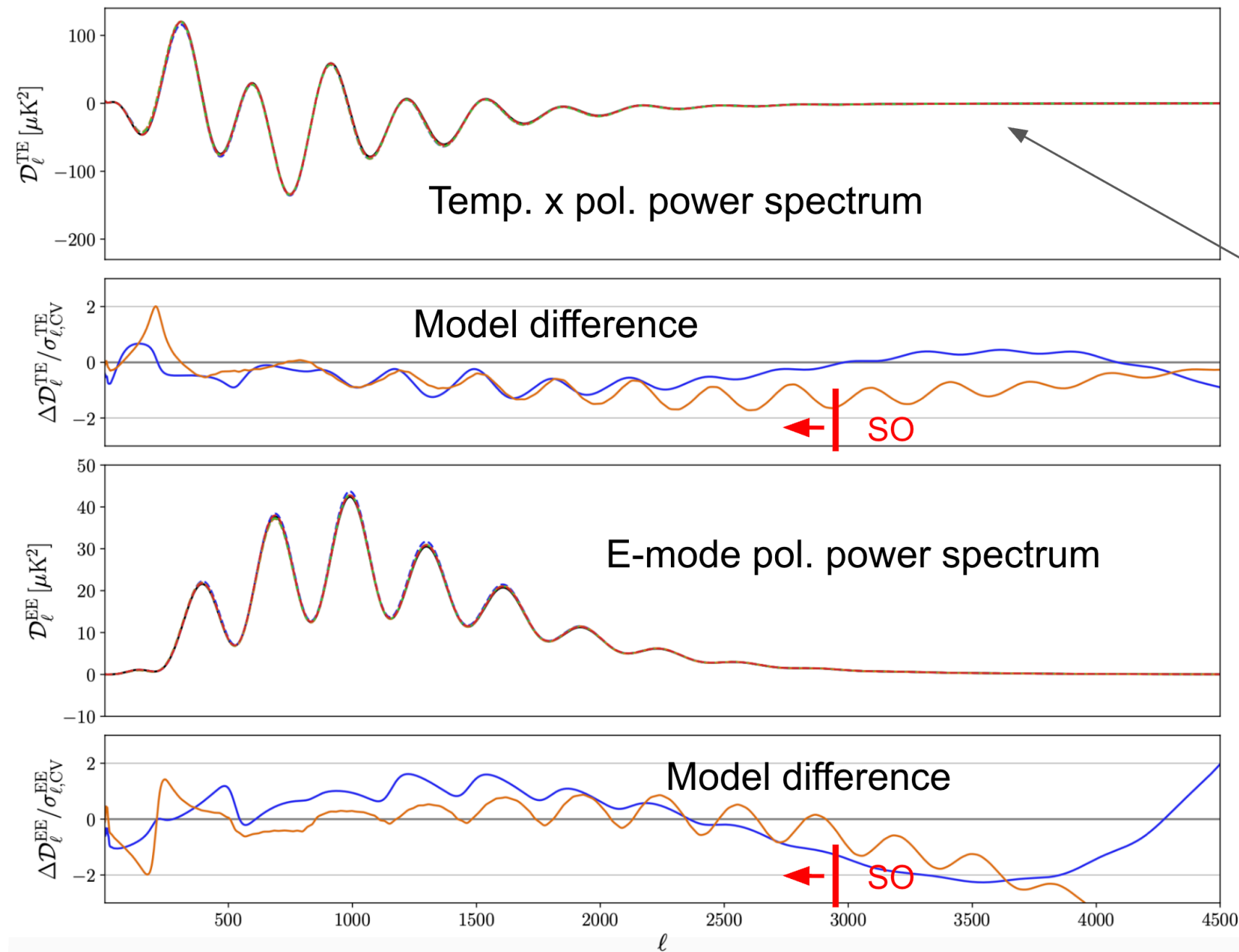
→ **This yields novel signals in the CMB power spectra**



Many well-motivated models now exist with the potential to explain the H_0 problem via new physics that can only be seen unambiguously via high-S/N measurements of the CMB polarization power spectra

- Early dark energy ([Poulin+19](#), [Lin+19](#), [Agrawal+19](#), [Hill+21](#)) / early dark sector ([McDonough, Lin, Hill+21](#))
- Strongly interacting neutrinos ([Kreisch+19](#))
- “Stepped” strongly interacting dark radiation ([Aloni+21](#))
- Mirror world dark sector ([Cyr-Racine+21](#))
- Primordial magnetic fields ([Jedamzik & Pogosian 19](#))
- Varying electron mass + curvature ([Sekiguchi & Takahashi 20](#))

CMB: Potential Hints of New Physics in H_0



Example: early dark energy (EDE) scenario

Idea: brief period of cosmic acceleration just prior to recombination

Example EDE and ΛCDM models

EDE ($f_{\text{EDE}} \sim 0.2$) - Planck best-fit ΛCDM
 EDE ($f_{\text{EDE}} \sim 0.1$) - Planck best-fit ΛCDM

Key differences are seen in pol. power spectra – but signal is tiny

We need as many high-S/N modes as possible to maximize discovery potential – low noise and wide area:

If EDE were present: 50σ in full SO data

Hill et al. [ACT] (2021)



Neutrino Mass... Need τ !

Astro2020: “[constraining neutrino masses] is typically done by comparing the amplitude of clustering at $z = 1100$ from CMB observations to that in the late-time evolved universe.”

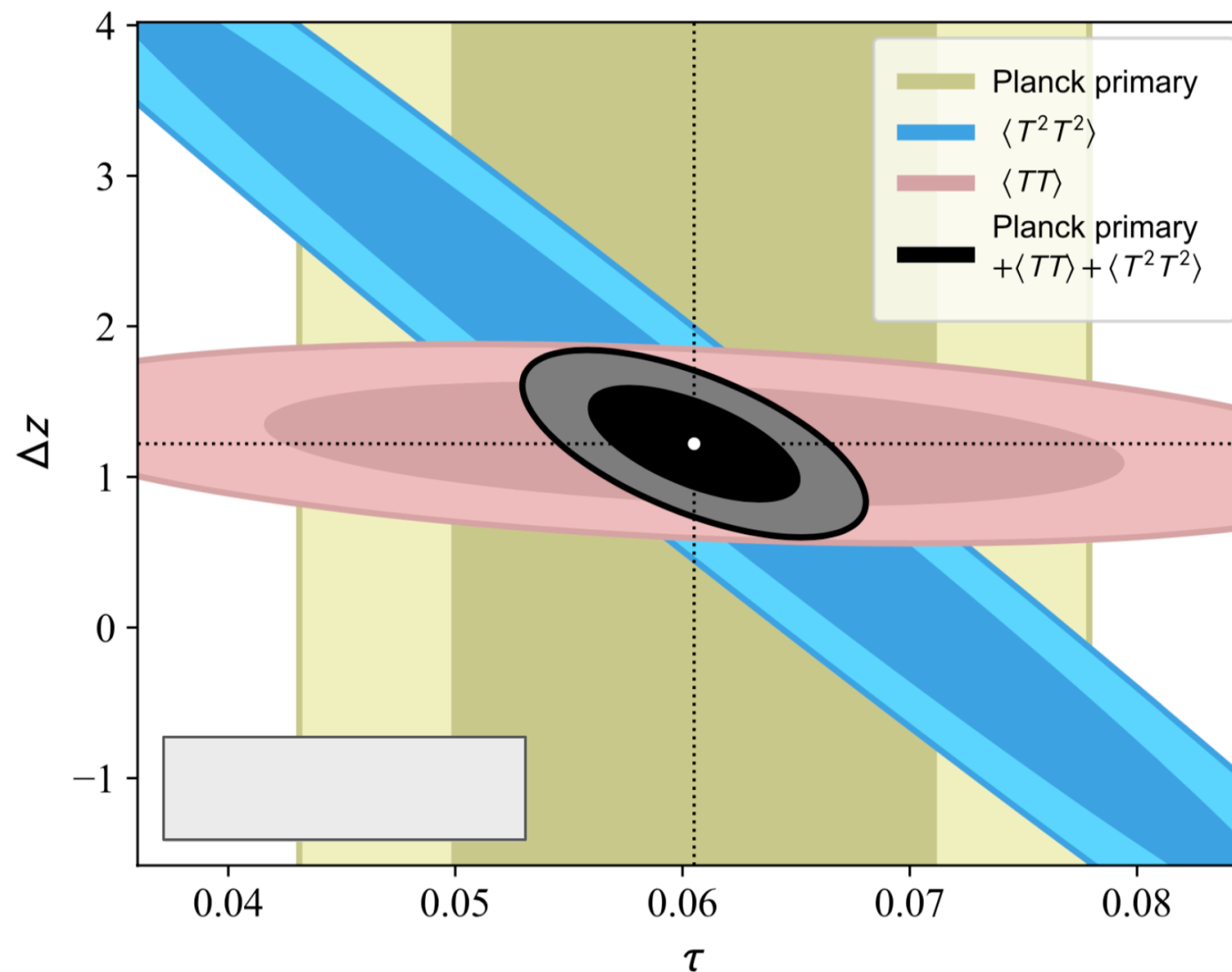
↓
origin of the τ degeneracy

Target signal: 0.06 eV (minimal total mass allowed by neutrino oscillation data)

Neutrino Mass... Need τ !

Epoch of Reionization

**Reionization optical depth τ is by far the least well-constrained parameter of Λ CDM:
SO can improve upon current constraints by factor of 2.5 using kinematic SZ data**



kSZ power spectrum
is a sensitive probe of
duration of
reionization

Four-point function
breaks degeneracy
with low- z component
to constrain τ

Planck E-mode pol.:
 $\sigma(\tau) \sim 0.1$

Nominal SO kSZ:
 $\sigma(\tau) = 0.007$

Full SO kSZ:
 $\sigma(\tau) = 0.0035$

Alvarez, Ferraro, Hill, Hlozek, Ikape 20; Smith & Ferraro 17,18; Calabrese+14;



Neutrino Mass

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↓
origin of the τ degeneracy

Target signal: 0.06 eV (minimal total mass allowed by neutrino oscillation data)

SO will use multiple probes to constrain M_ν via the late-time amplitude of structure (similar to dark energy)

Focus here on the CMB lensing power spectrum + primary CMB + τ from reionization kSZ 2pt/4pt

	Current Data	SO Nominal [w/ kSZ τ]	Full SO [w/ kSZ τ]
$\sigma(M_\nu)$ [eV]	0.05	0.03	0.02 [> 3 σ detection]

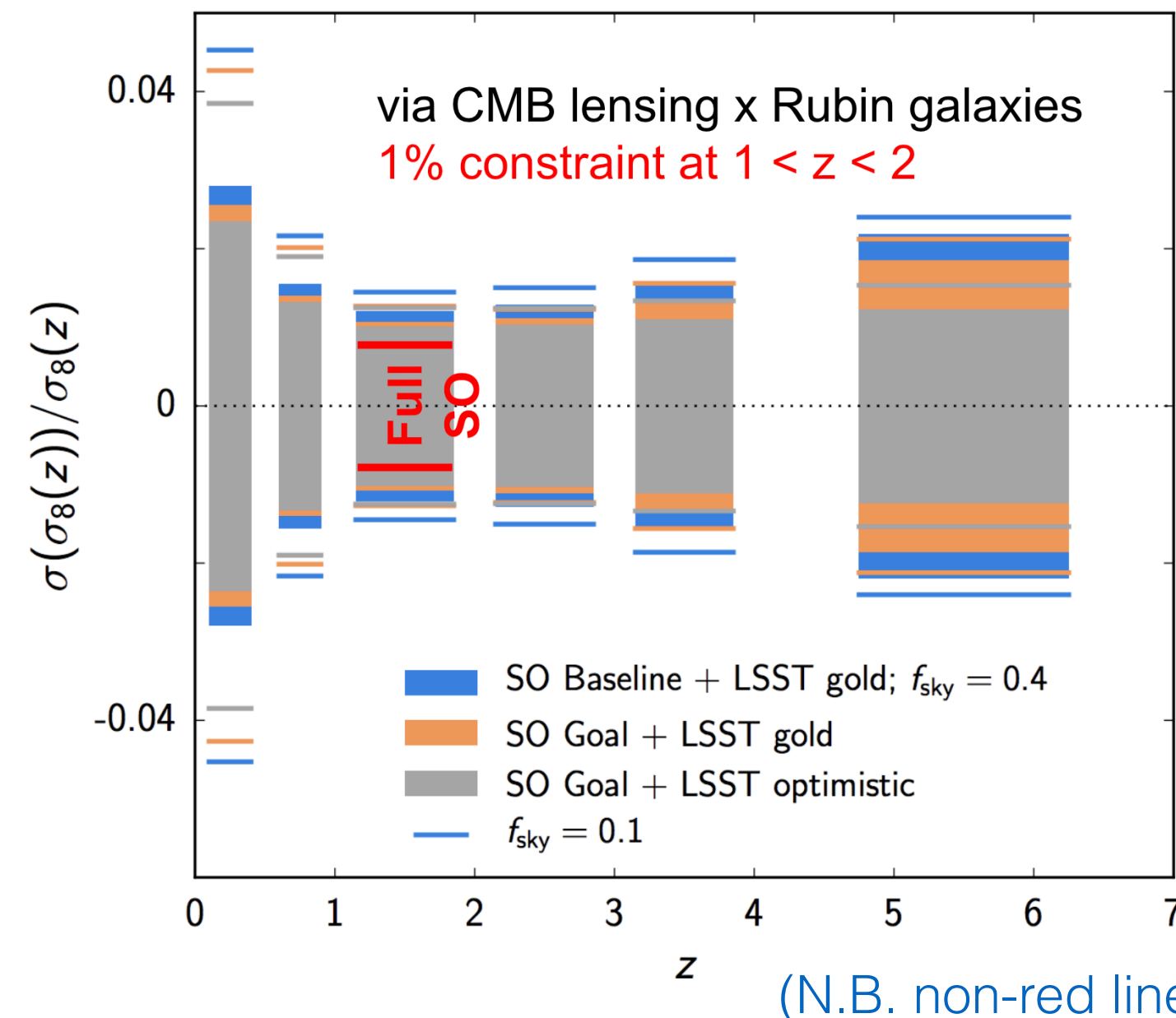
No external data assumed here (LiteBIRD/CLASS)

(0.03 eV, with Planck EE τ)
(0.015 eV, with CV-limited EE τ from external data)

Constraints derived from tSZ cluster counts (+LSST WL and/or SO CMB lensing), and CMB lensing cross-correlations w/ LSST galaxies

Amplitude of fluctuations as a function of redshift

DE equation of state (via tSZ cluster counts)



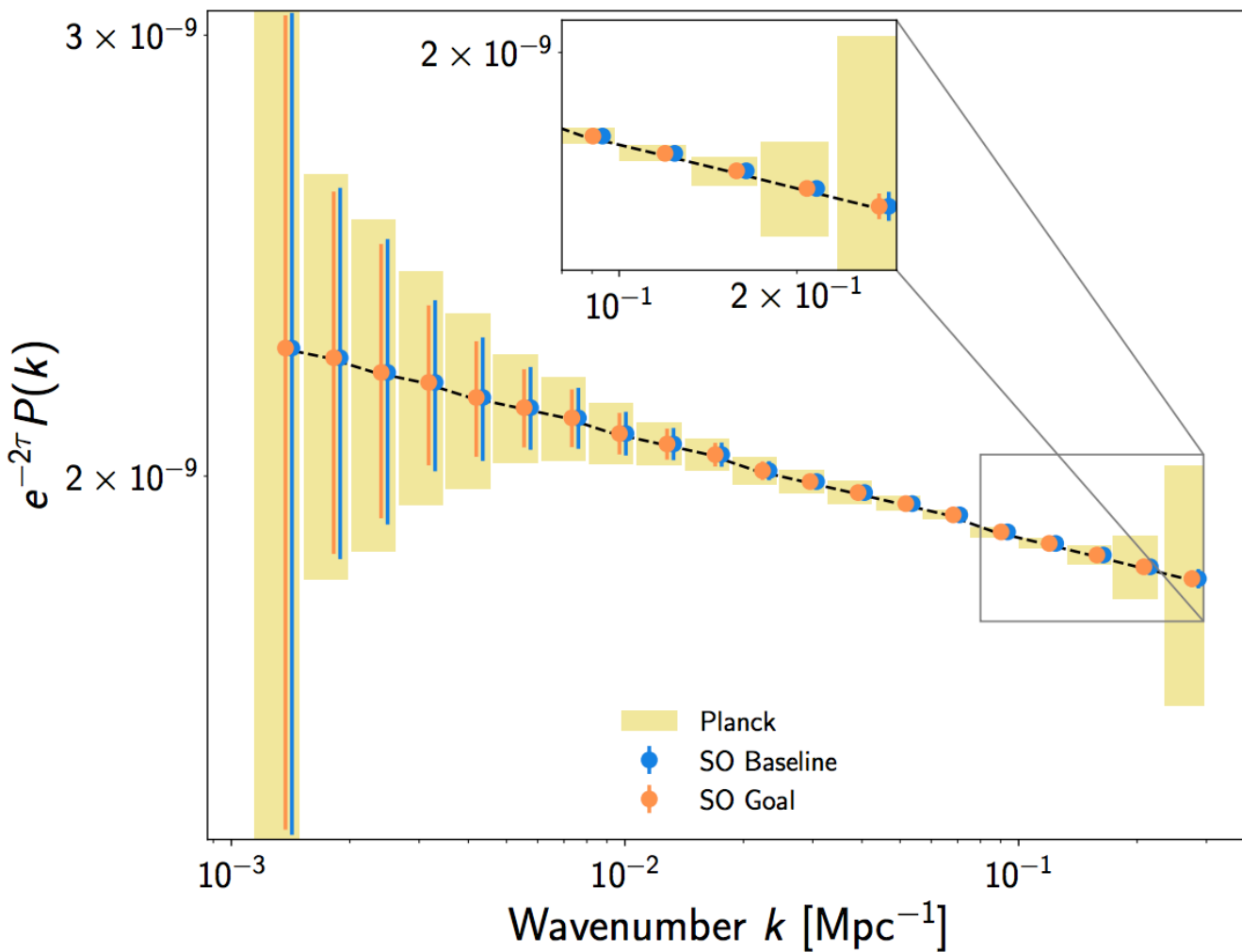
$$\begin{aligned} \sigma(w_0) &= 0.06, & \Lambda\text{CDM} + w_0 + w_a \\ \sigma(w_a) &= 0.20, \\ \sigma(w_0) &= 0.08, & \Lambda\text{CDM} + w_0 + w_a + \Sigma m_\nu \\ \sigma(w_a) &= 0.32, \end{aligned}$$

Unique ability to search for deviations from Λ at $z > 1$ (complementary to lower-redshift WL and galaxy surveys)

- Extragalactic astrophysics: galaxy formation, ICM physics
 - Particle physics: neutrino masses, new light species, BSM
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Primordial Scalar Perturbations

Primordial scalar power spectrum

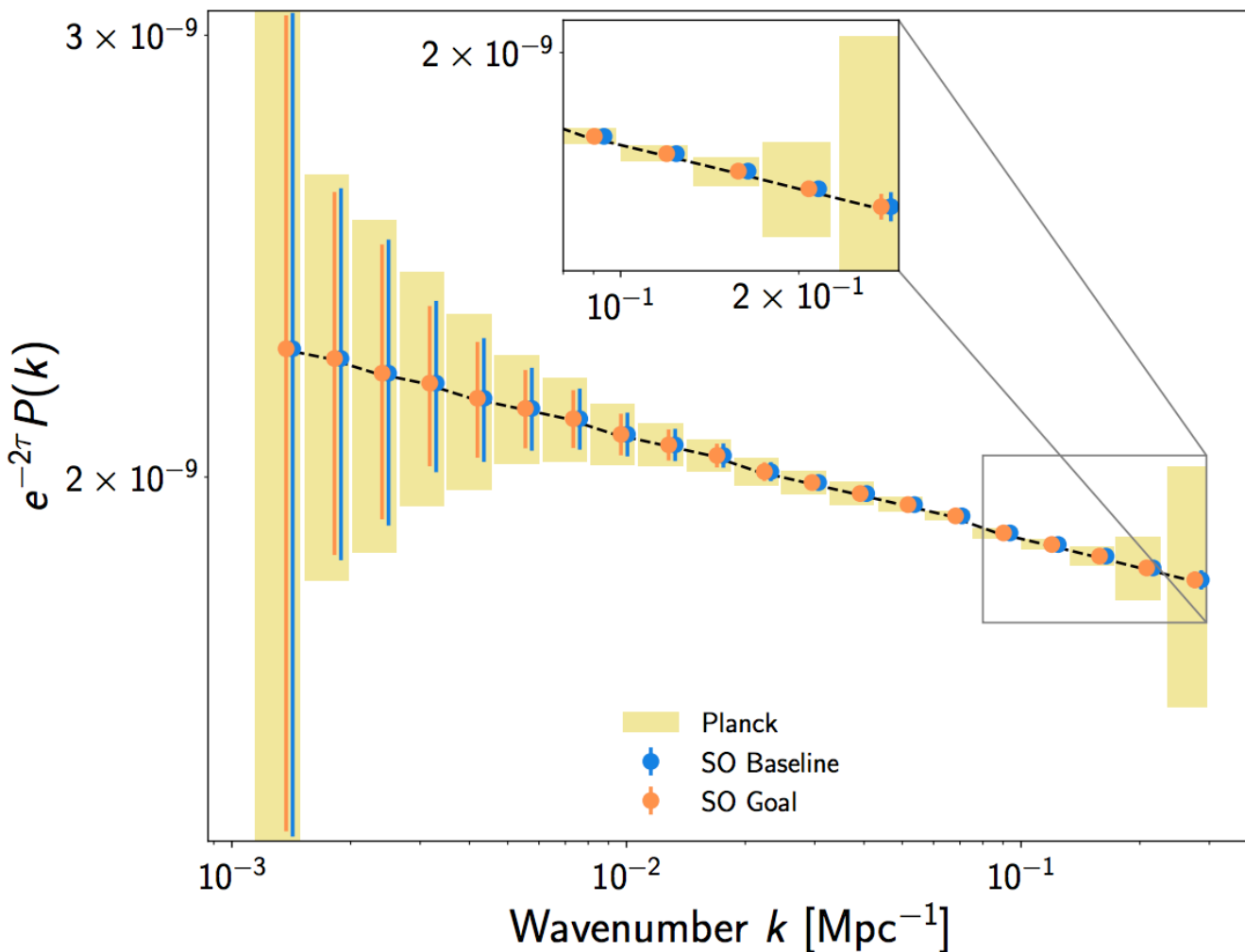


(N.B. these are nominal-SO errors)

$$\sigma(n_s) = 0.002$$

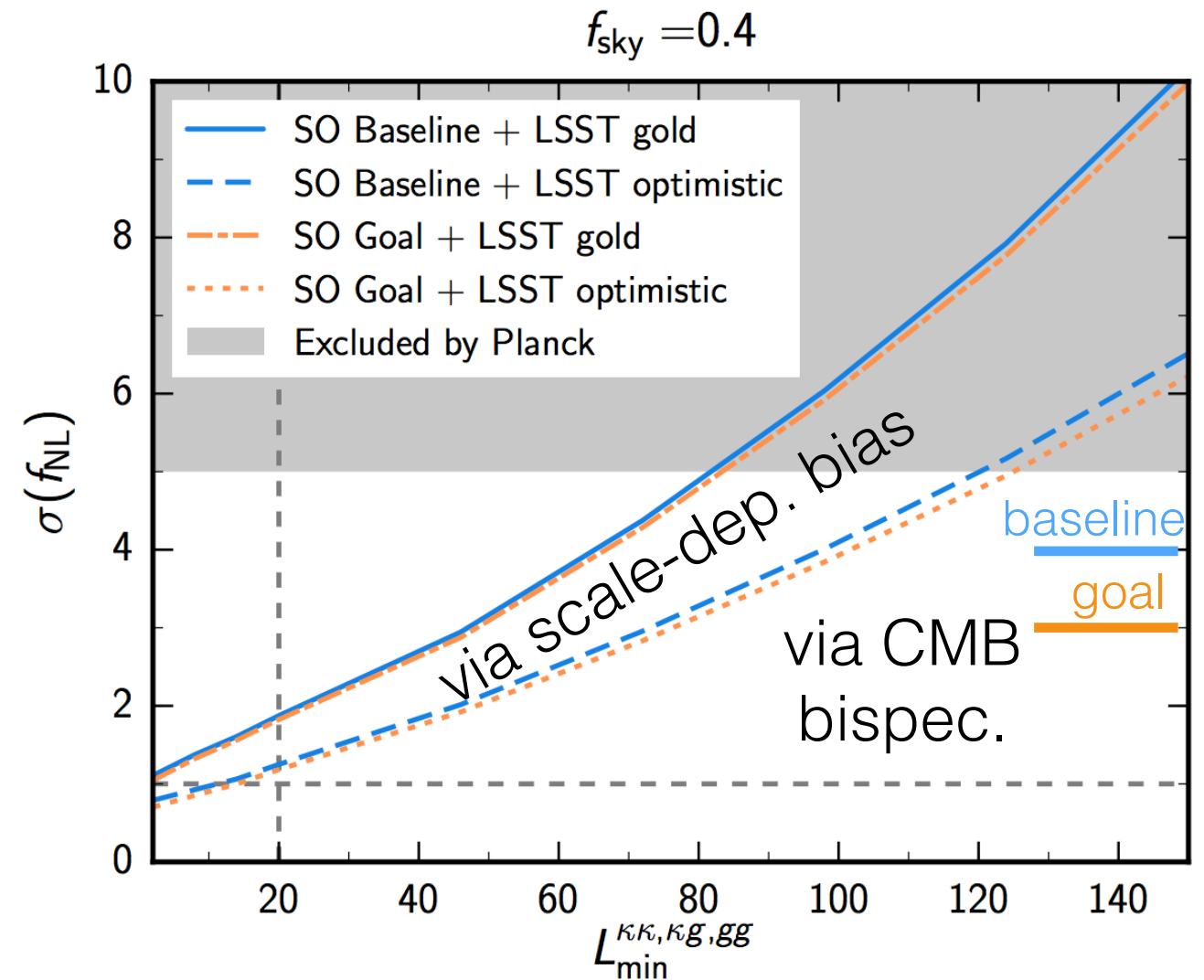
Primordial Scalar Perturbations

Primordial scalar power spectrum



(N.B. these are nominal-SO errors)

Local-type primordial non-Gaussianity

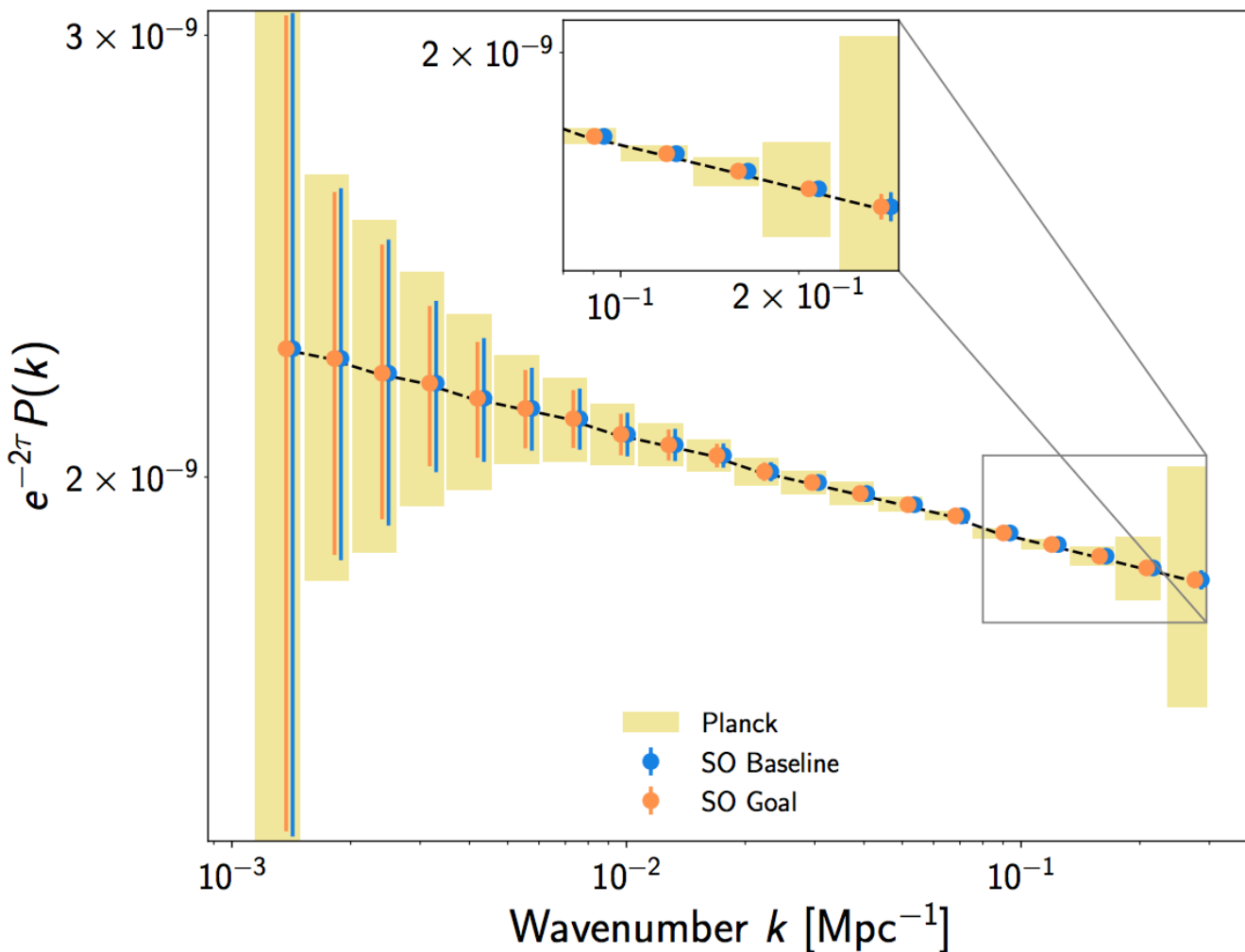


Shape ($\langle \zeta \zeta \zeta \rangle$) $\langle TTT \rangle, \langle TTE \rangle,$ $\langle TEE \rangle, \langle EEE \rangle$	Current (<i>Planck</i>)	SO Baseline	SO Goal
local	5	4	3
equilateral	43	27	24
orthogonal	21	14	13

+ tensor NGs

Primordial Scalar Perturbations

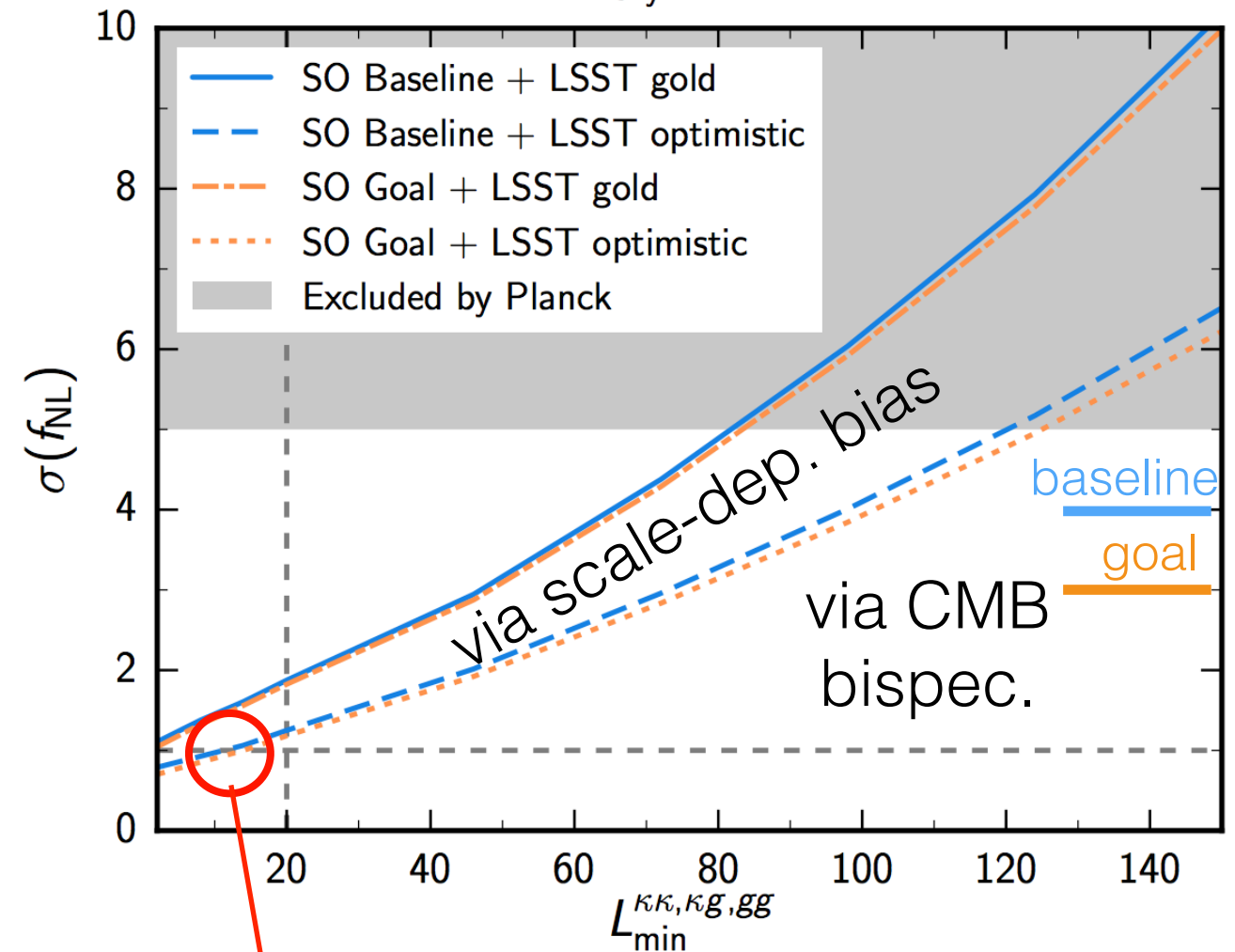
Primordial scalar power spectrum



(N.B. these are nominal-SO errors)

Local-type primordial non-Gaussianity

$$f_{\text{sky}} = 0.4$$

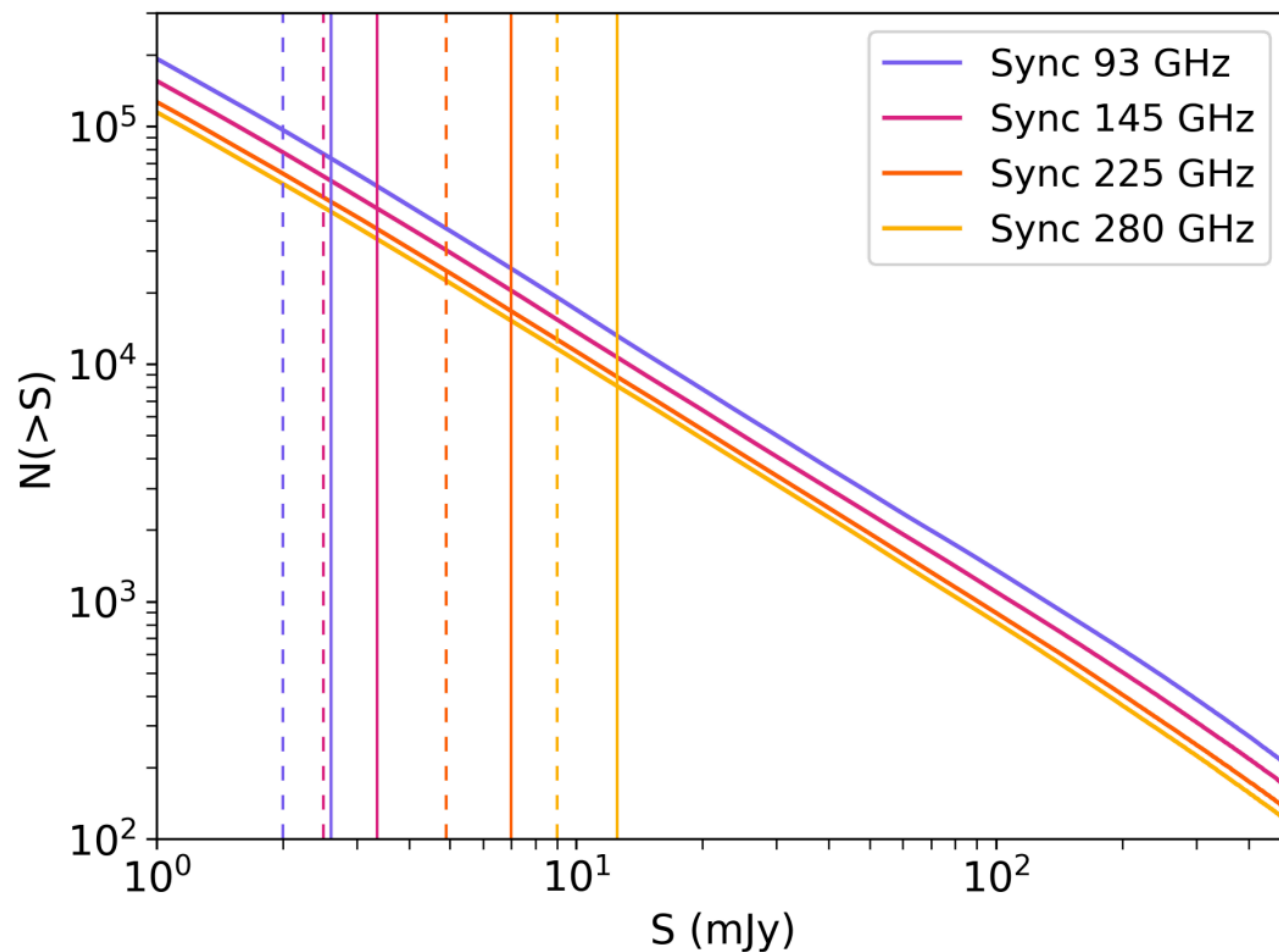


can reach $\sigma(f_{\text{NL}}) < 1$ with sufficient control of large-scale systematics in SO CMB lensing x LSST galaxies

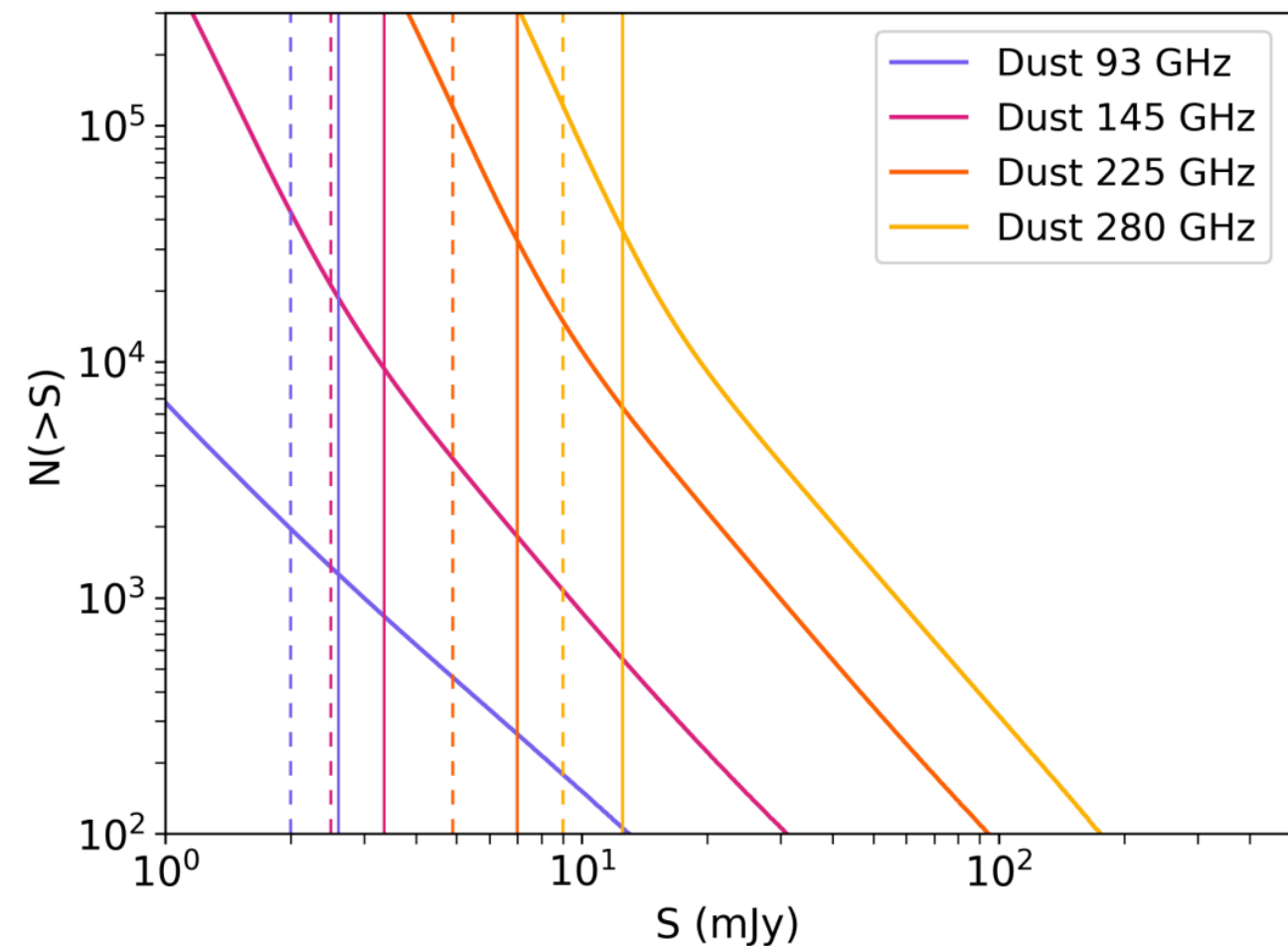
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Source Sensitivity

AGN (radio)

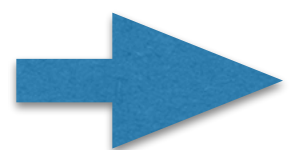


DSFGs (dust)



SO will detect $\sim 96,000$ AGN and $\sim 30\text{-}40,000$ dusty galaxies

$\sim$ daily cadence monitoring
for 7,500 of these AGN

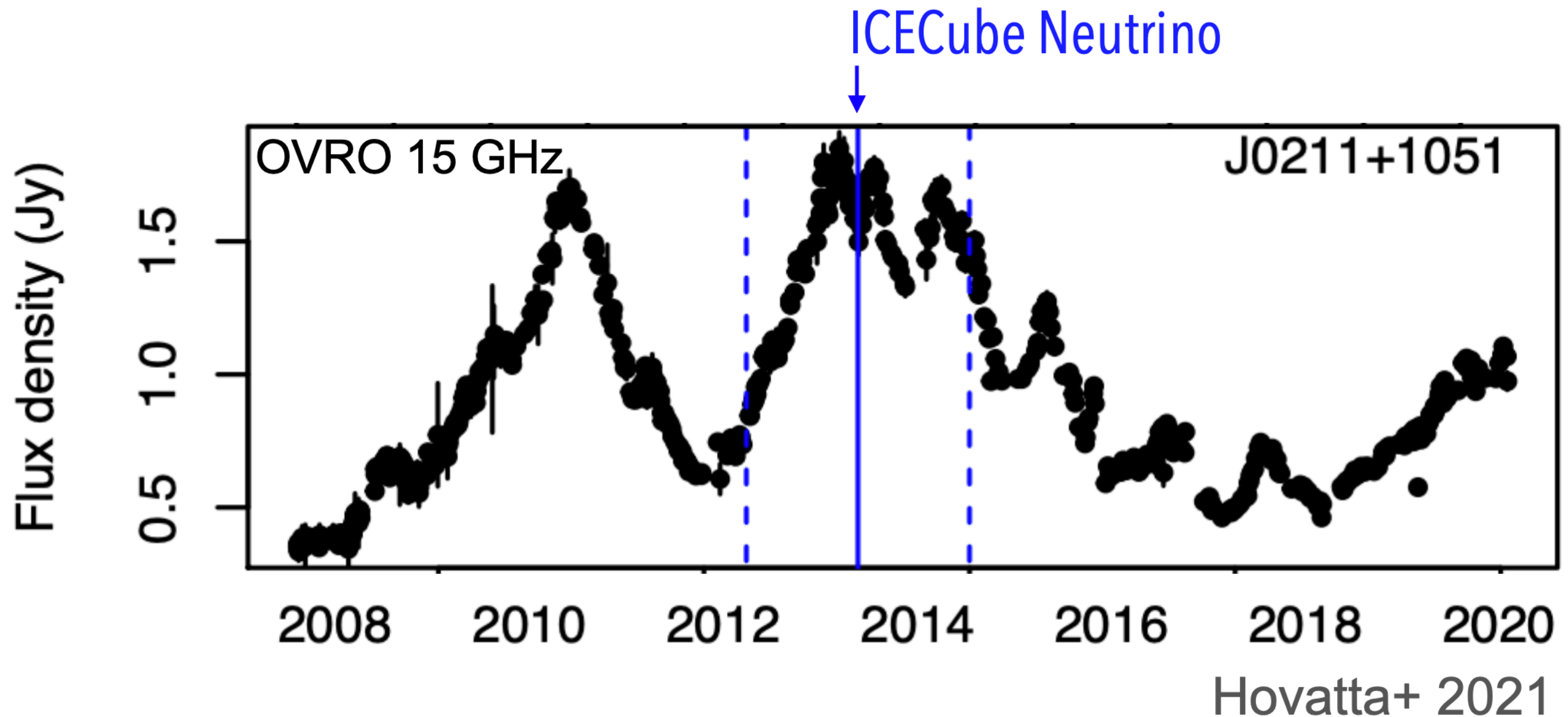


may detect ~ 100 SMBH binaries via sinusoidal light curves

Variable AGN

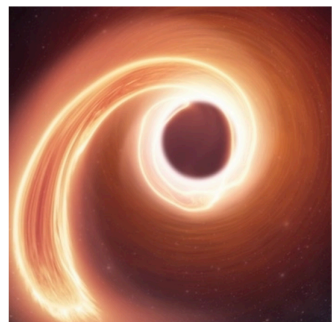
SO will continuously monitor and publicly release light curve data for $\sim 40,000$ AGN (after completion of NSF-funded pipeline in ~ 2028)

Enables multi-wavelength and multi-messenger (e.g., neutrino) probes of AGN physics



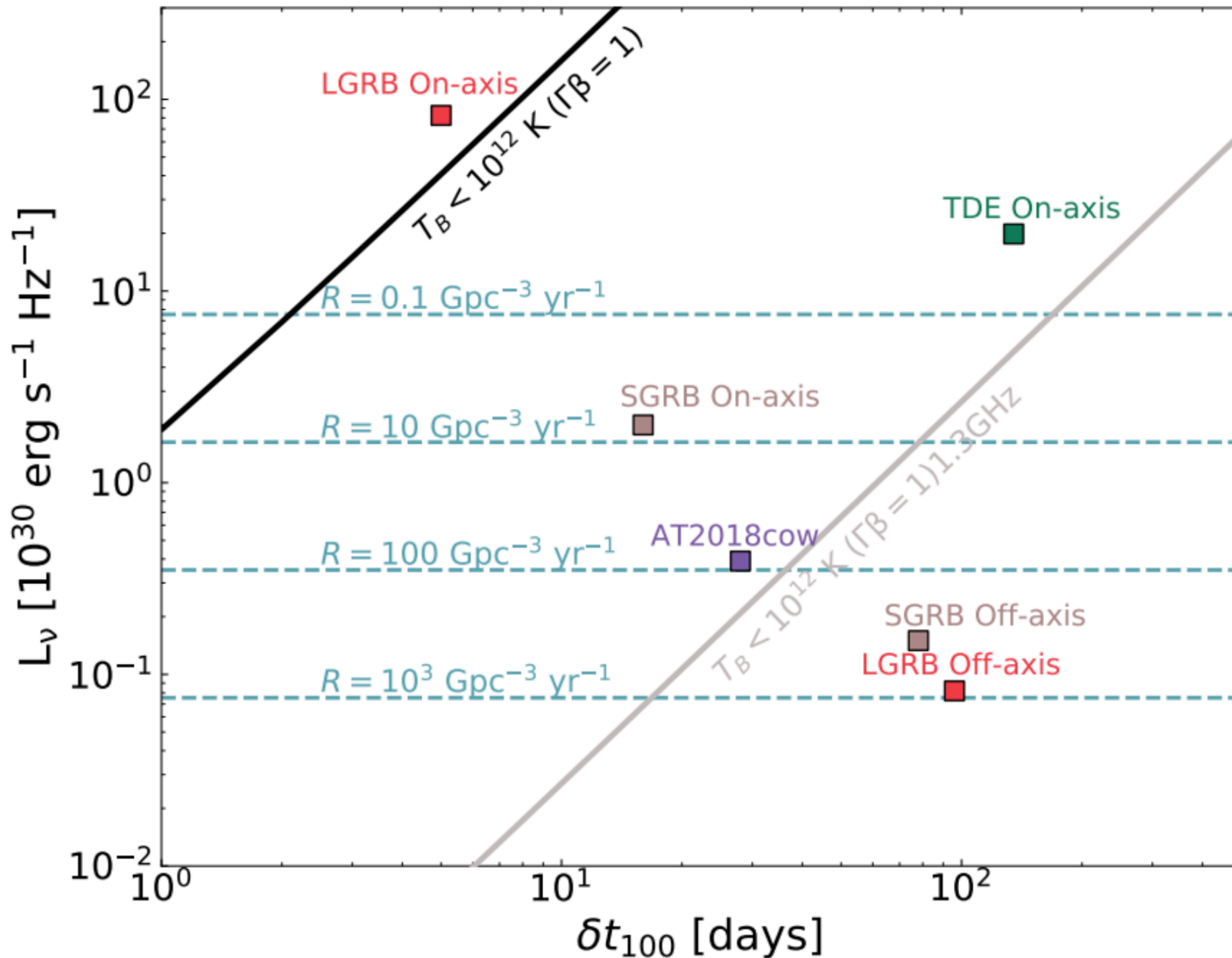
SO LAT Science

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Known classes of extragalactic synchrotron transients (100 GHz)

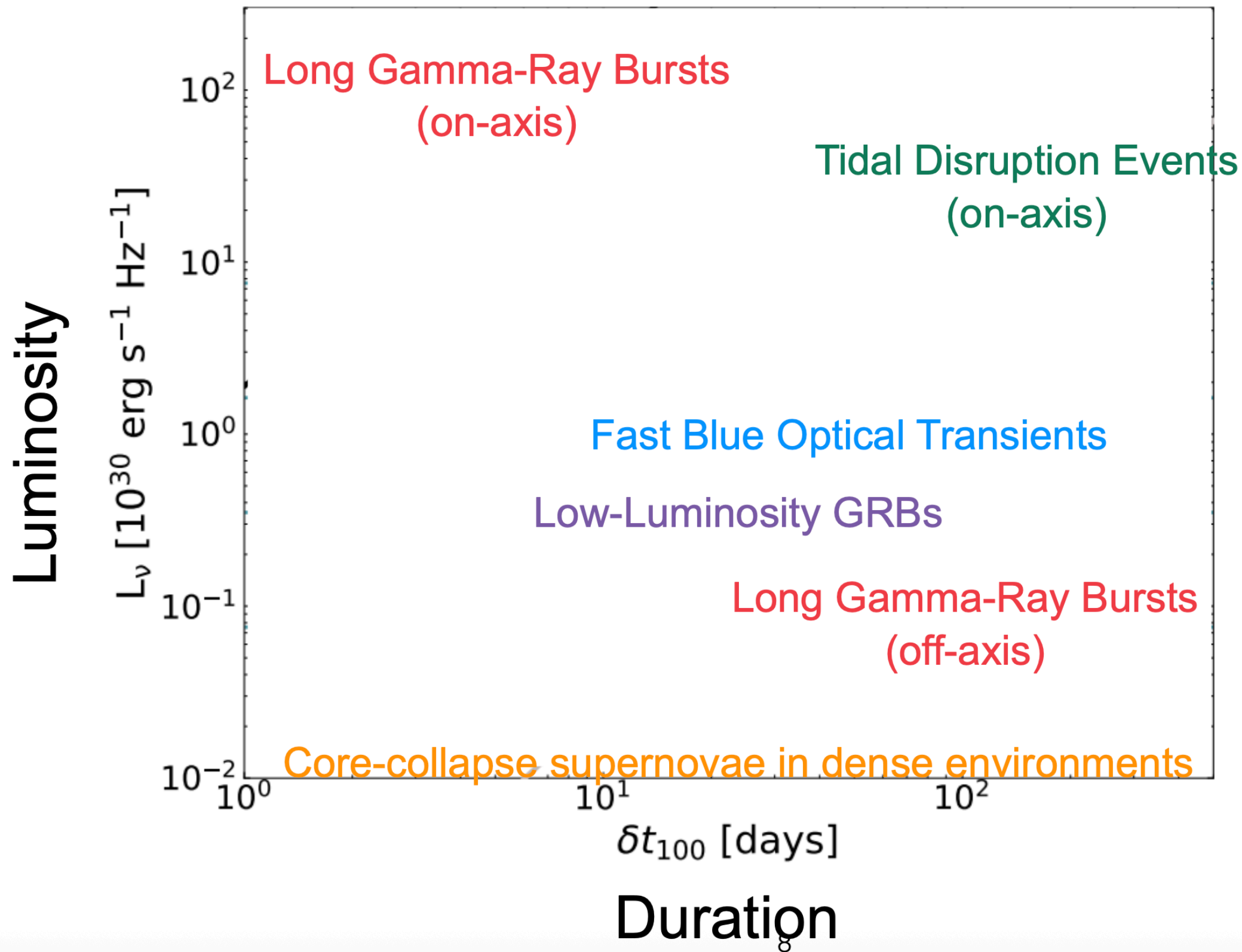
Luminosity



Duration

minimum
volumetric event
rate leading to one
transient detection

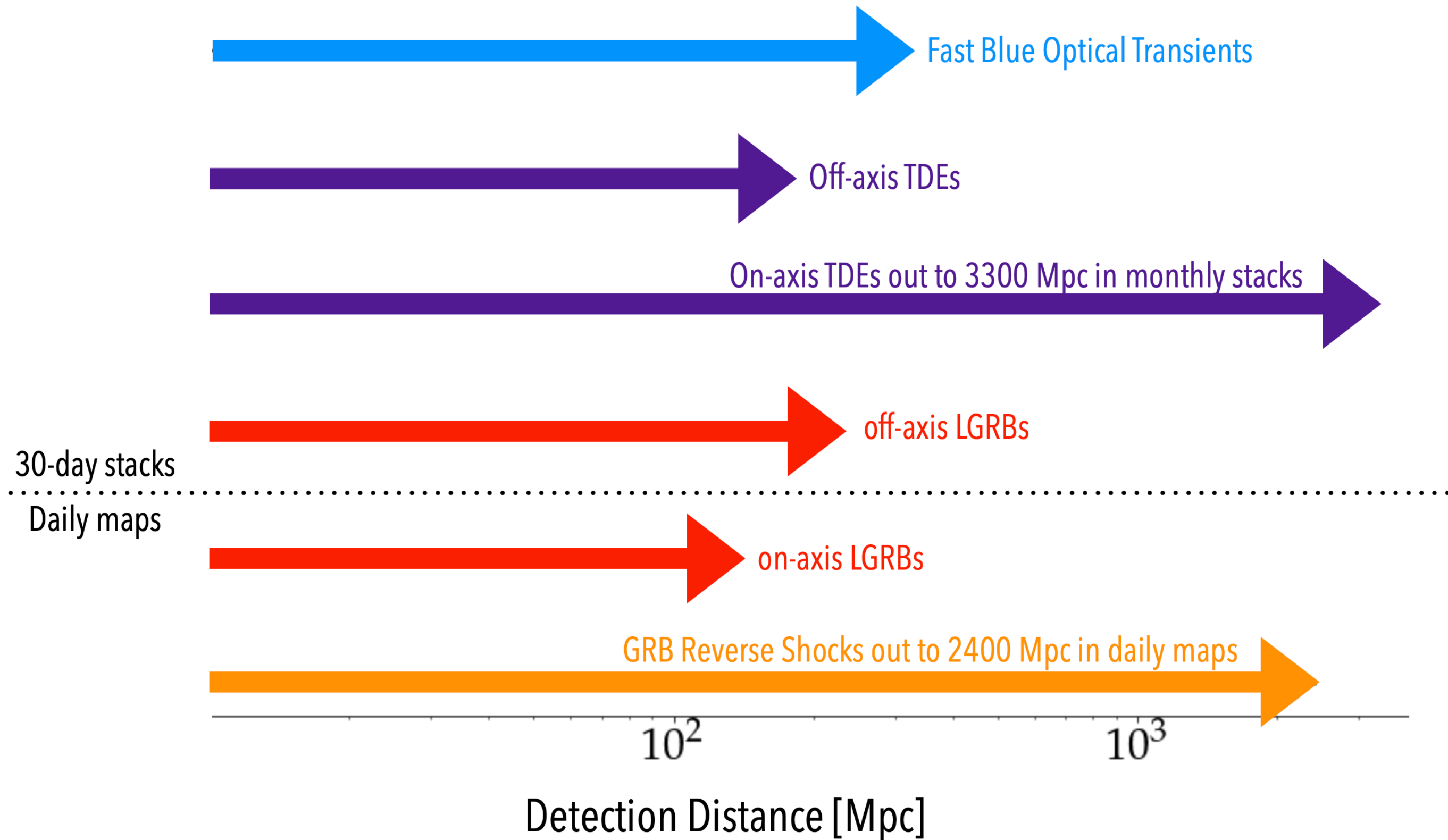
Known classes of extragalactic synchrotron transients



We estimate characteristic luminosities and intrinsic rates

Transients

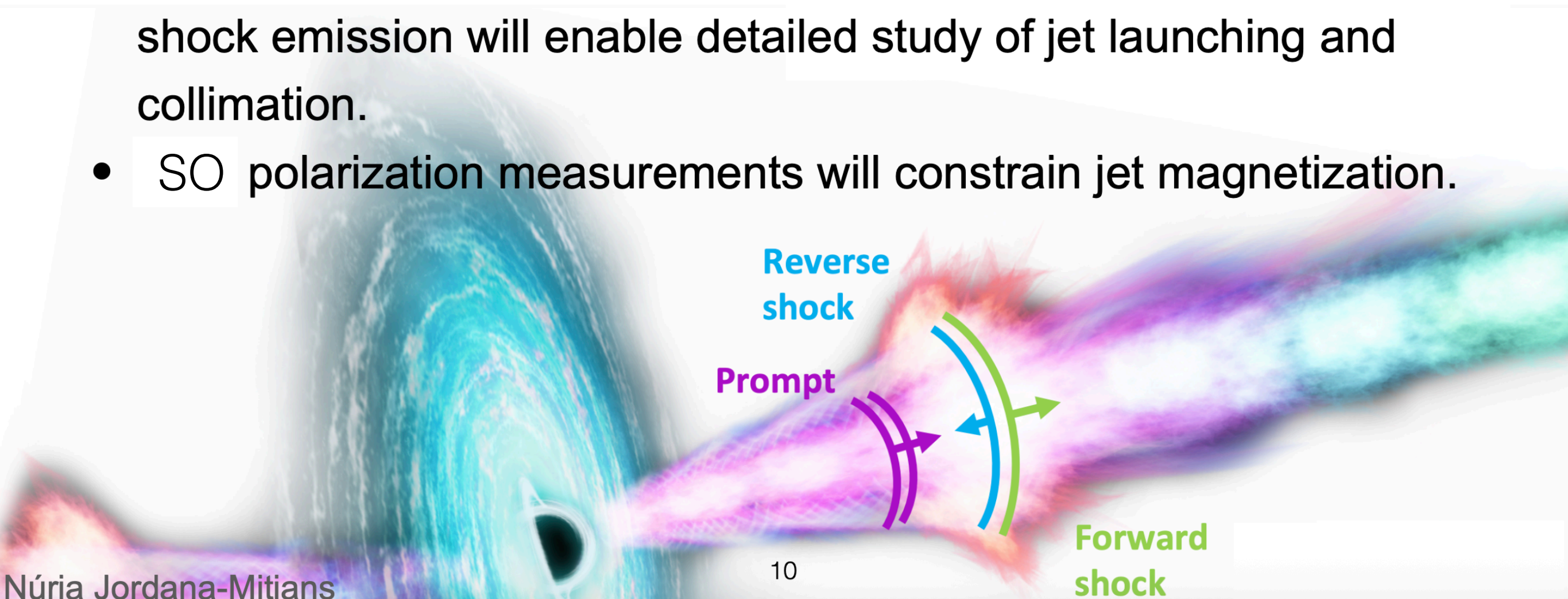
SO will be sensitive to known classes of millimeter-wave transients and to new discoveries



Transients

SO will probe the physics of jet launching and collimation by detecting **GRB reverse shocks**.

- SO will provide **the first unbiased survey** of millimeter-wave GRB reverse shock emission. SO's large sample of reverse shock emission will enable detailed study of jet launching and collimation.
- SO polarization measurements will constrain jet magnetization.



Transients

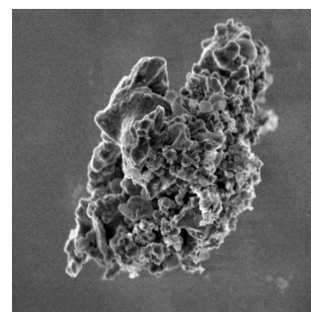
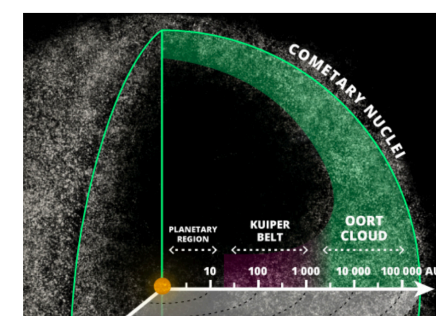
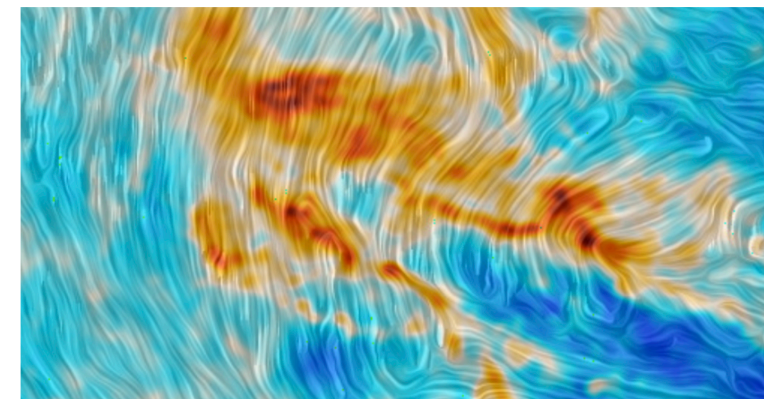
Estimated detection rates (some are highly uncertain)

Class	Volumetric Rate ($\text{yr}^{-1}\text{Mpc}^{-3}$)	L_ν ($\text{erg s}^{-1}\text{Hz}^{-1}$)	Distance (Mpc)	Detection Rate (yr^{-1})
Extragalactic fast (1–10 d duration)	—	—	—	< 10
Long-duration GRB, on-axis	4×10^{-10}	10^{32}	1300	2
Long-duration GRB, off-axis	6×10^{-9}	3×10^{30}	360	0.6
TDE, on-axis	3×10^{-11}	10^{31}	670	0.02
Low-luminosity GRB	2×10^{-7}	$10^{29}\text{--}10^{30}$	70–210	0.1–4
AT2018cow-like FBOT	10^{-7}	10^{30}	210	2
Interacting SN	10^{-8}	$10^{27}\text{--}10^{30}$	< 210	$\lesssim 0.2$
Stellar flares	—	—	—	180

Table 4. Estimated detection rates by SO for different classes of extragalactic transients at 145 GHz, and for stellar flares at 90 GHz. We define off-axis long-duration GRBs to have $\theta_{\text{obs}} = 0.4$.

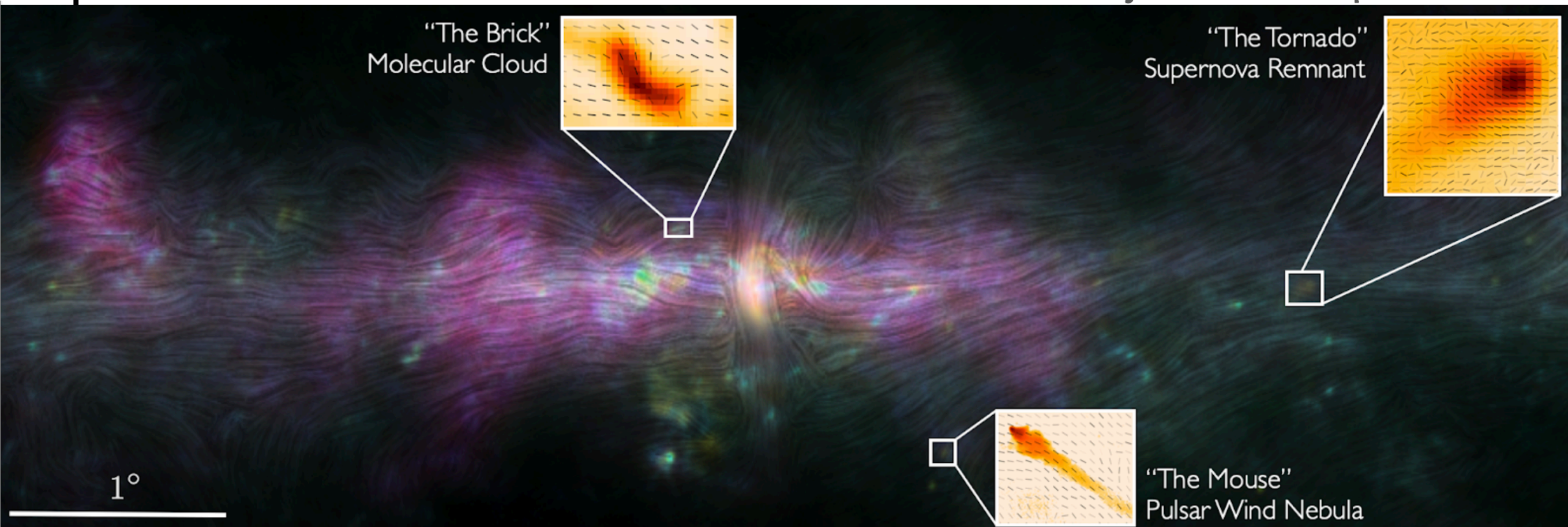
(GRB reverse shocks not listed here, but will be numerous)

- Extragalactic astrophysics: galaxy formation, ICM physics
 - Particle physics: neutrino masses, new light species, BSM
 - Primordial perturbations: non-Gaussianity, $P(k)$
 - Sources: variable blazars, dusty galaxies
 - Transients: uncharted discovery space
 - Milky Way ISM: dust composition, magnetic fields
 - Solar System: Planet 9, asteroids
- + much more



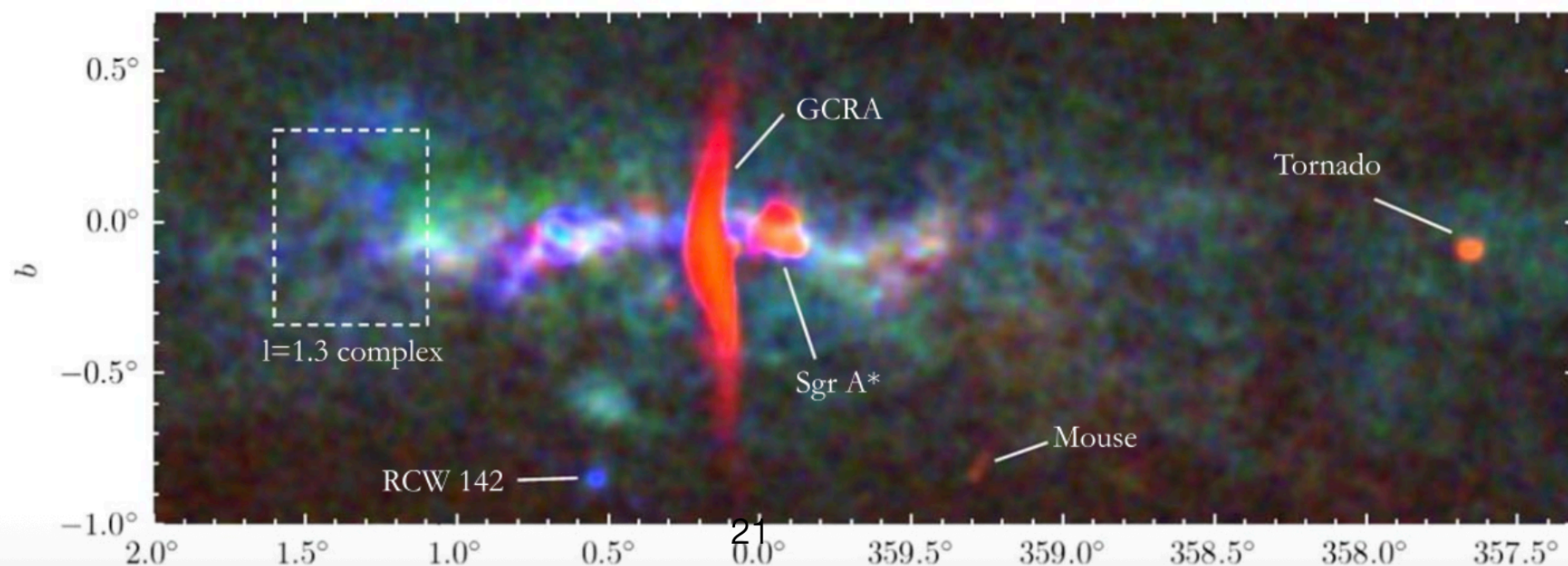
Polarized Galactic Emission

SO will make deep maps of polarized Galactic emission ACT total intensity + 90 GHz polarization



Guan+ 2021

ACT
polarized
intensity



90 GHz

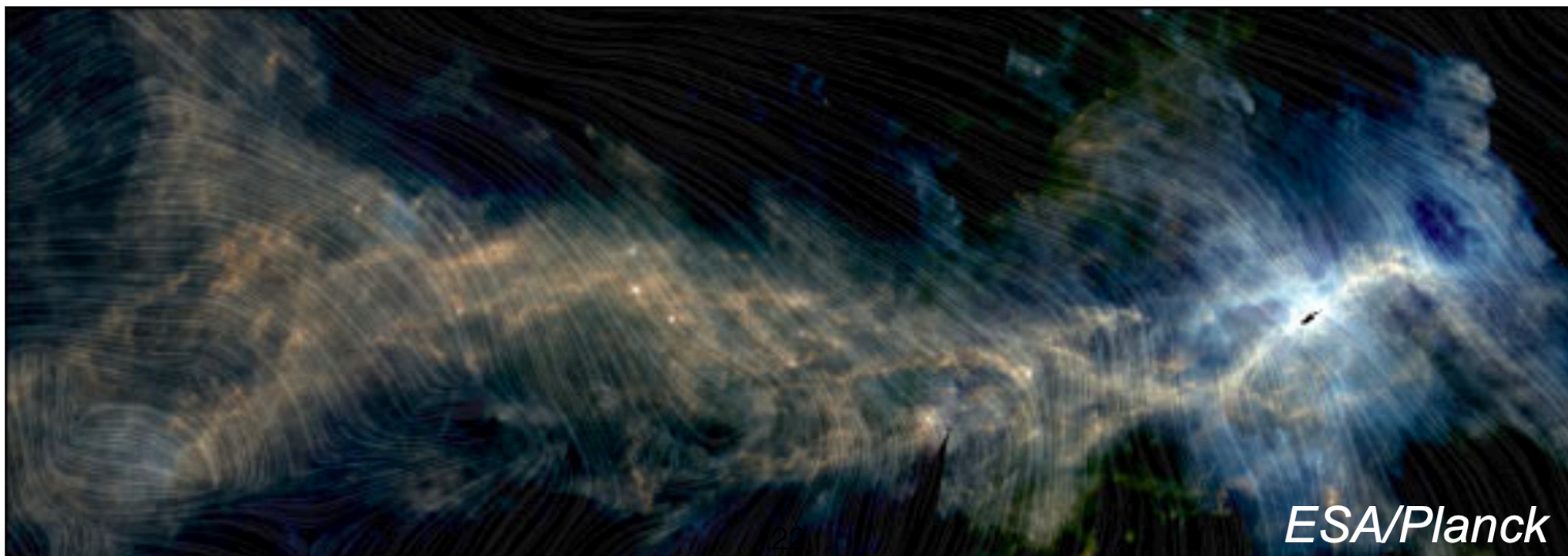
150 GHz

220 GHz

Polarized Galactic Emission

Magnetic fields in molecular clouds

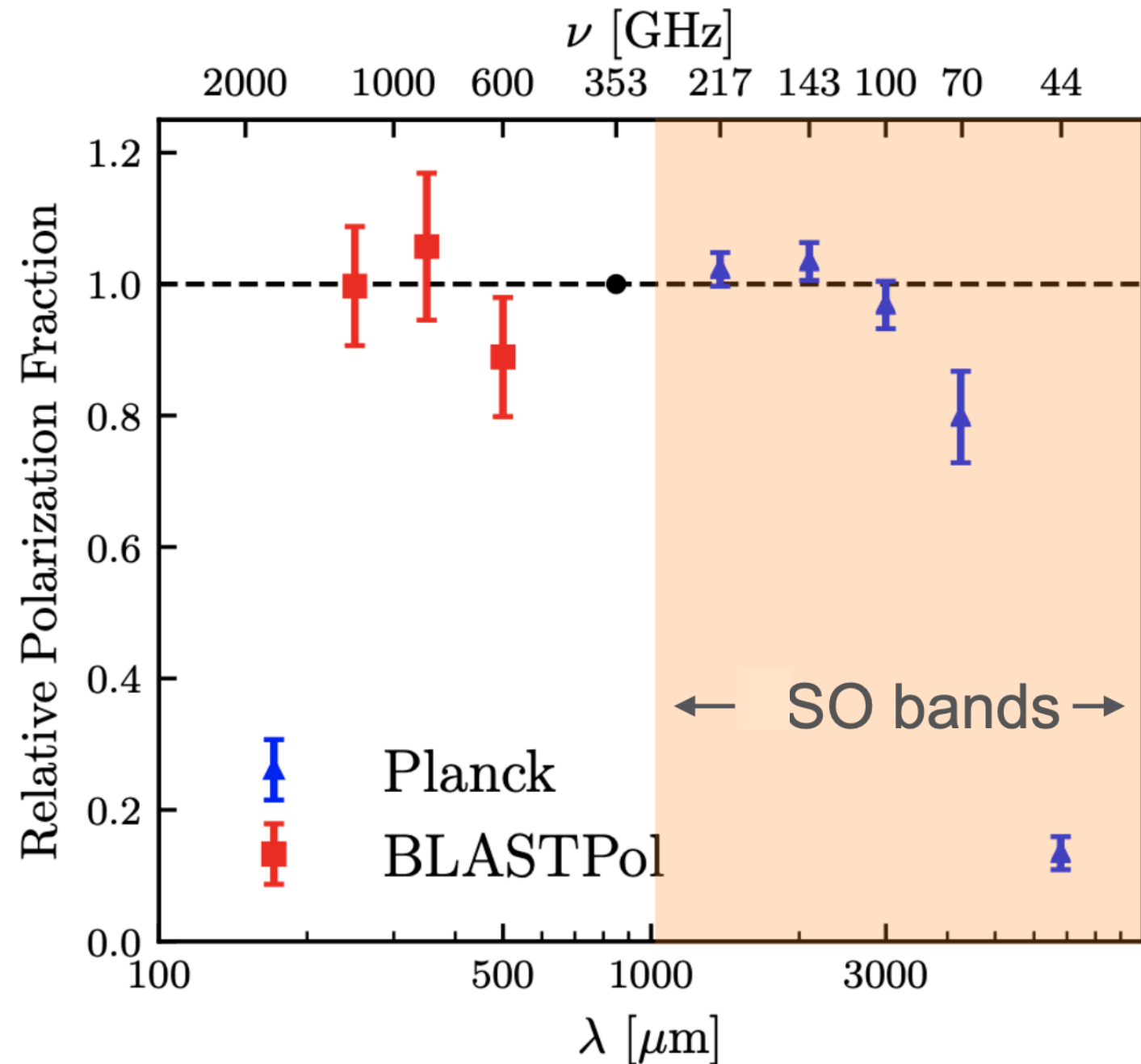
- The role of magnetic fields in the formation and evolution of molecular clouds is poorly understood.
- SO will measure magnetic fields at scales intermediate between *Planck* and ALMA
- 0.9' angular resolution at 280 GHz corresponds to 0.03 pc at a distance of 100 pc
- SO will measure the magnetic field structure of >860 molecular clouds with 1 pc resolution and at least 50 independent, high-SNR polarization measurements per cloud



Polarized Galactic Emission

The composition of interstellar dust

- Does interstellar dust consist of distinct silicate and carbonaceous grains?
- We will test and constrain the classical dust models that predict a divergence of the total intensity and polarization spectra in the frequency range probed by SO.
- We will further constrain dust grain shape and porosity via comparison to starlight polarization measurements



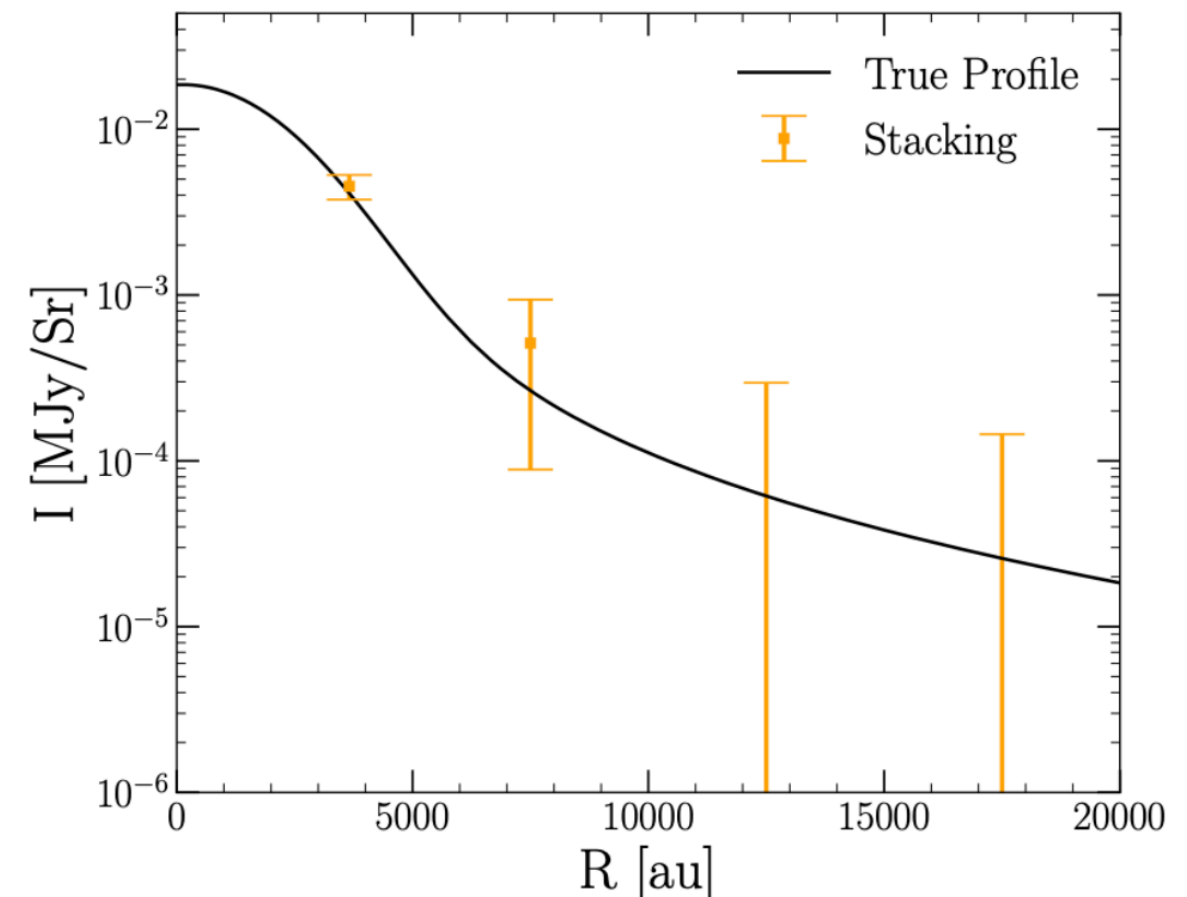
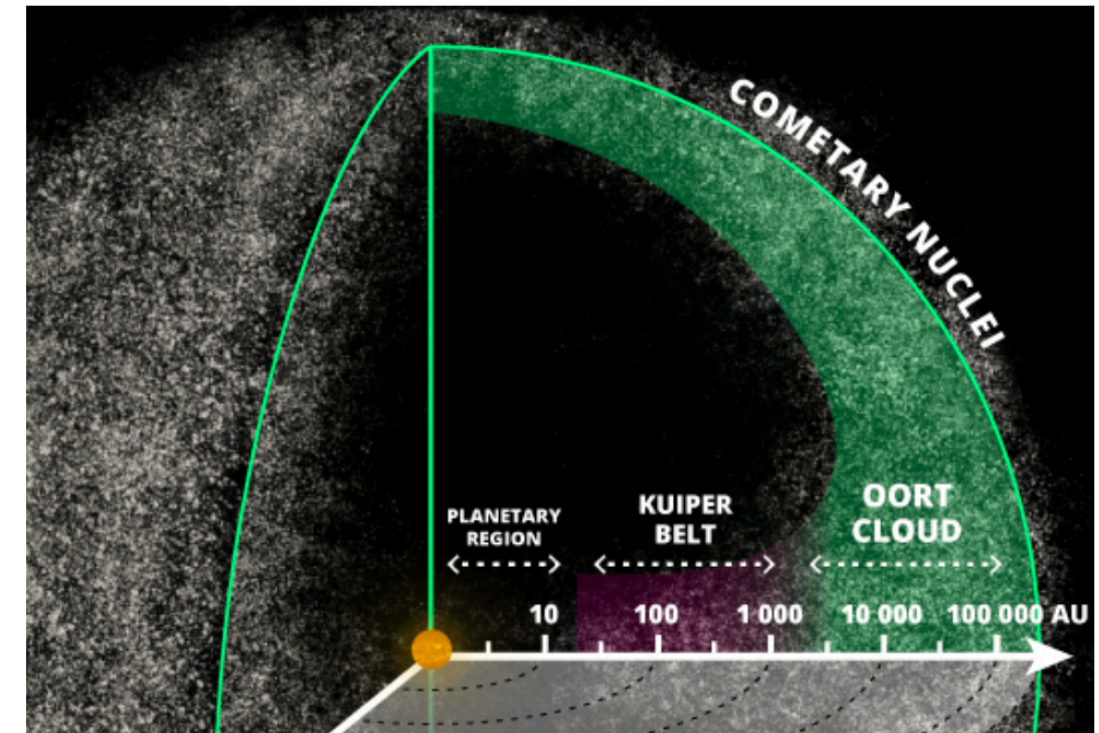
Hensley & Draine 2021

Constraint on dust spectral index:

$$\sigma(\beta_{\text{dust}}) = 0.005$$

Probing solar system formation via exo-Oort clouds

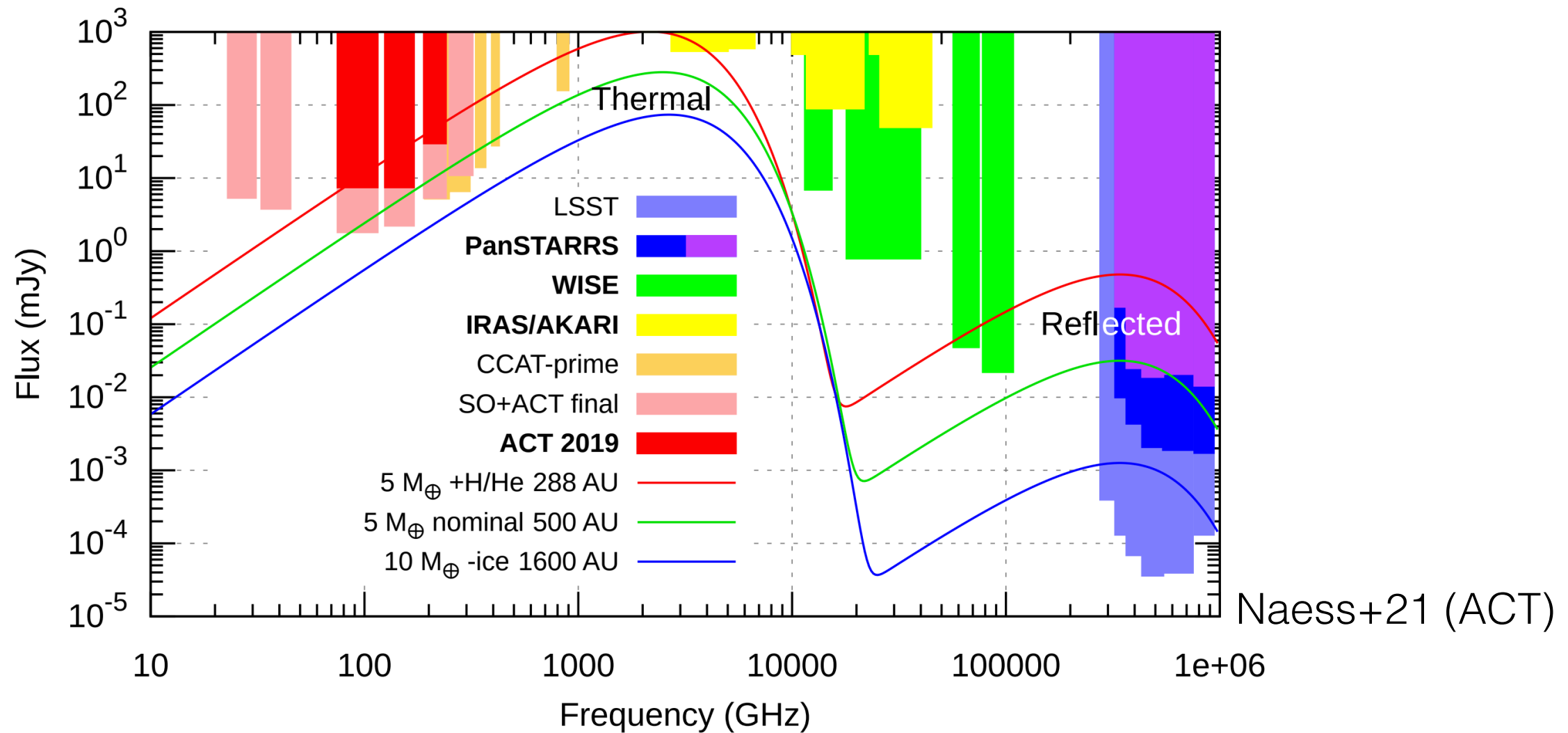
- The Oort Cloud is a roughly isotropic shell of ice and dust that is thought to surround our Sun at $R \sim 10^3 - 10^5$ AU
- We infer the presence of the Oort Cloud dynamically, but it has never been directly observed.
- SO will search for thermal emission from exo-Oort clouds around nearby *Gaia* stars



- Extragalactic astrophysics: galaxy formation, ICM physics
 - Particle physics: neutrino masses, new light species, BSM
 - Primordial perturbations: non-Gaussianity, $P(k)$
 - Sources: variable blazars, dusty galaxies
 - Transients: uncharted discovery space
 - Milky Way ISM: dust composition, magnetic fields
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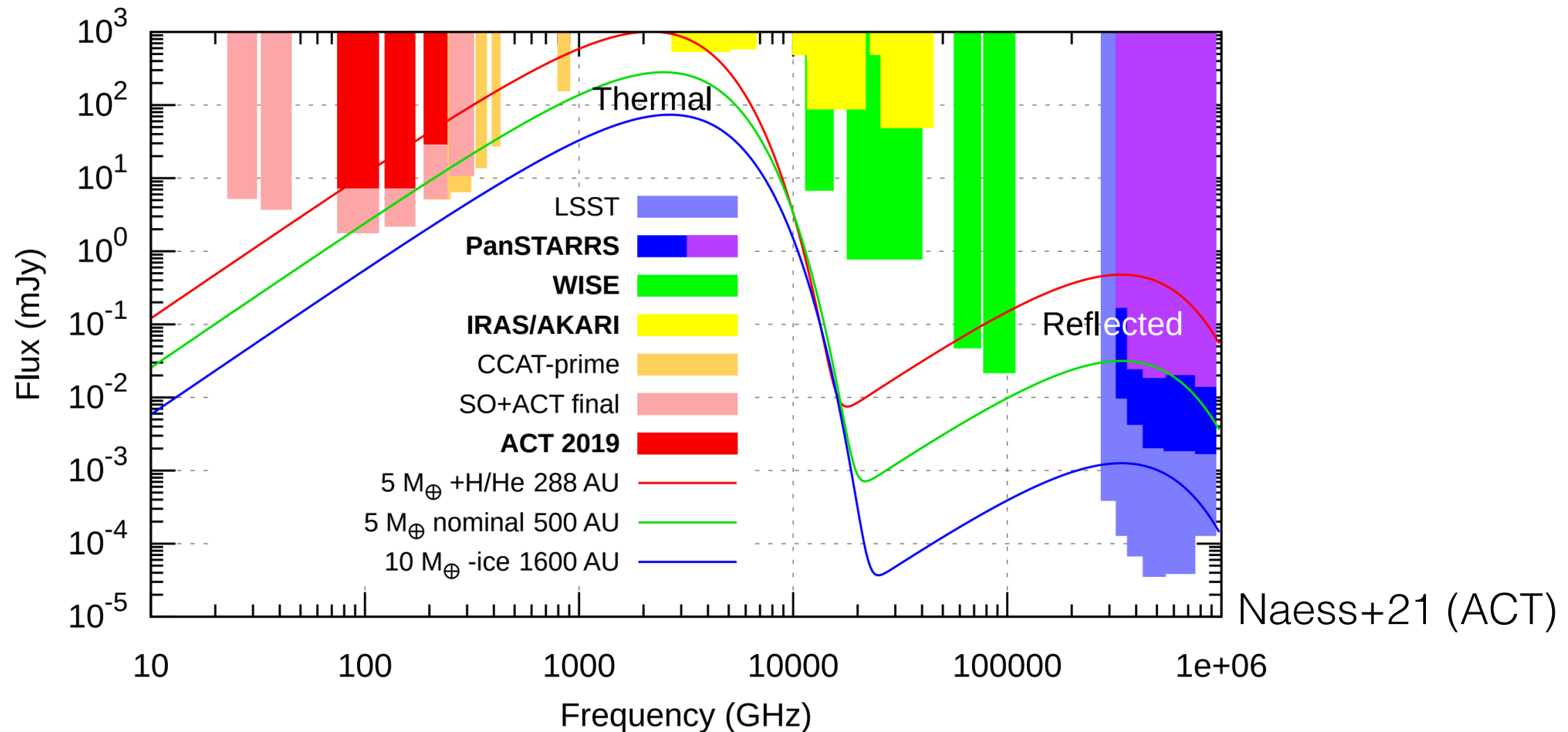
Solar System

SO can search for thermal emission from distant Solar System objects (e.g., “Planet 9”)



Solar System

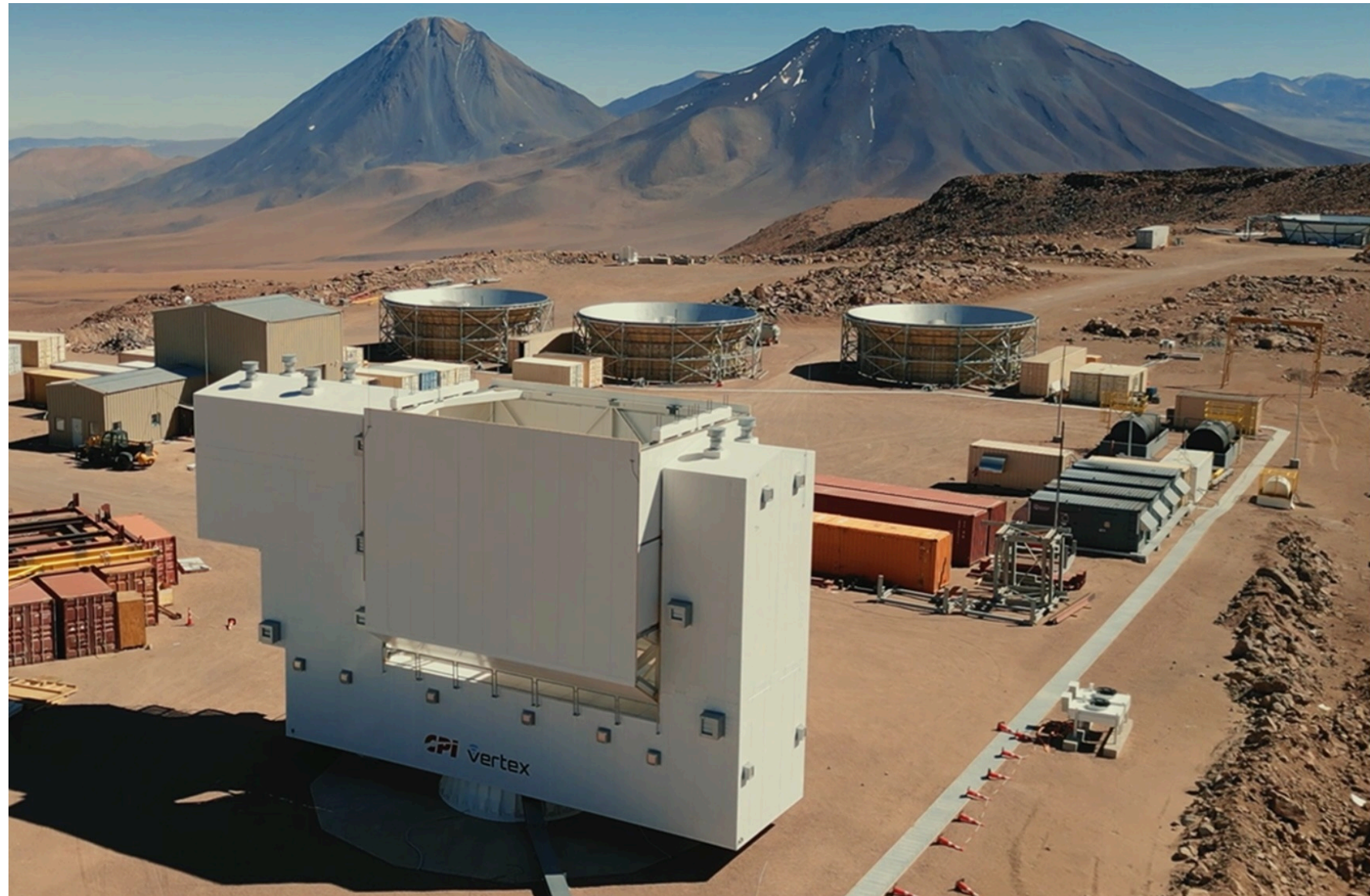
SO can search for thermal emission from distant Solar System objects (e.g., “Planet 9”)



SO can detect a 5 Earth-mass planet out to ~900 AU in the deepest regions of the survey (~500 AU in shallowest)
+ 10⁴ asteroids and many of the largest TNOs (e.g., Pluto)

SO LAT: Status

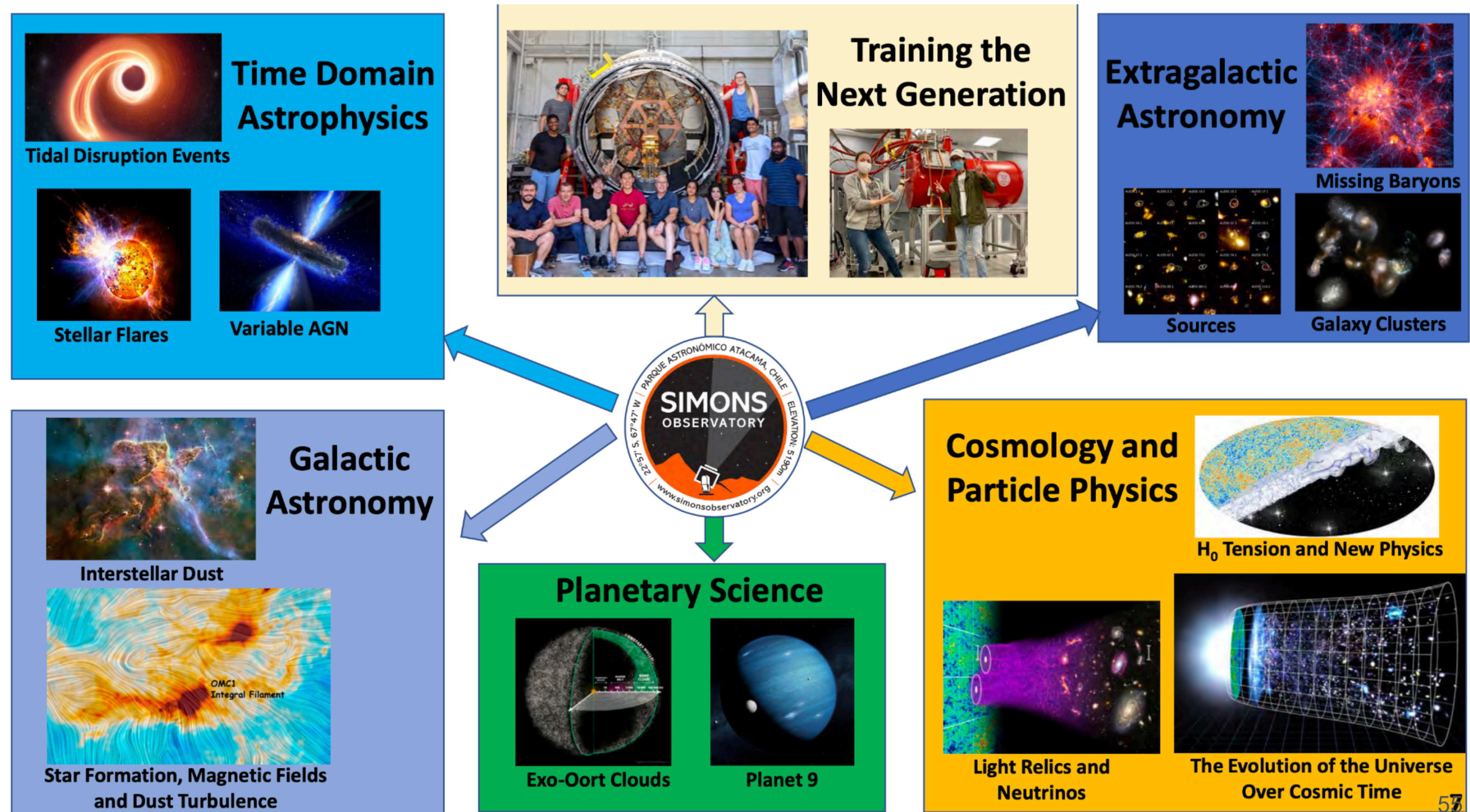
Feb. 2025



Preliminary results shown in the talk are removed.

SO LAT Science: Summary

Colin Hill
Columbia





Thanks!

<https://simonsobservatory.org/>



SO LAT Science: Summary

SO Covers All of A2020/P5 Science

Search for B-modes from the infant universe & inflation signatures
Study the dark universe
Matter mapping

Numbers show 1- σ unless catalog no. or distances	Current	SO 2025-2034	Using Rubin, DESI, or <i>Euclid</i>
Primordial perturbations			
r ($A_L = 0.3$)	0.01	0.0012	✓
n_s	0.003	0.002	-
$e^{-2\tau} \mathcal{P}(k = 0.2/\text{Mpc})$	1%	0.4%	-
$f_{\text{NL}}^{\text{local}}$	5	1	✓
Relativistic species			
$N_{\text{eff.}}$	0.13	0.045	-
Neutrino mass			
m_ν (eV, $\sigma(\tau) = 0.01$)	0.06	0.03	✓
m_ν (eV, $\sigma(\tau) = 0.002$)		0.015	✓
Accelerated expansion			
$\sigma_8(z = 1 - 2)$	7%	1%	✓
Galaxy evolution			
η_{feedback}	50-100%	2%	✓
p_{nt}	50-100%	4%	✓
Reionization			
Δz	~ 1.4	0.3	-
τ	0.007	0.0035	-
Cluster catalog	10000	33,000	✓
AGN catalog	20000	96,000	-
Galactic science			
Molecular cloud B-fields	10s	> 860	-
$\sigma(\beta_{\text{dust}})$	0.02	0.005	-
Solar System Science			
Distance limit for 5 $M_\oplus$ Planet 9	500 AU	900 AU	✓
Asteroid detections		$\sim 10,000$	
Transient detection distance			
Long GRBs, on-axis		1300 Mpc	-
Low-luminosity GRBs		70–210 Mpc	-
TDEs, on-axis		670 Mpc	-

Time-variable mm sky

<https://arxiv.org/abs/1808.07445>

<https://arxiv.org/abs/2503.00636>

& SAT white paper, in prep