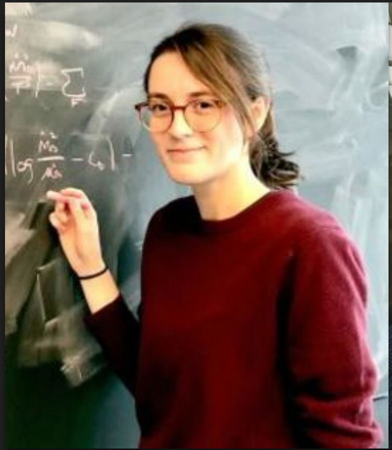
B-Modes Beyond Inflation:

Causal Tensor Sources in the Early Universe

Kylar Greene, Seoul National University

(2410.23348, 2601.20958, 2601.20967, and 2603.00272)

My Collaborators!

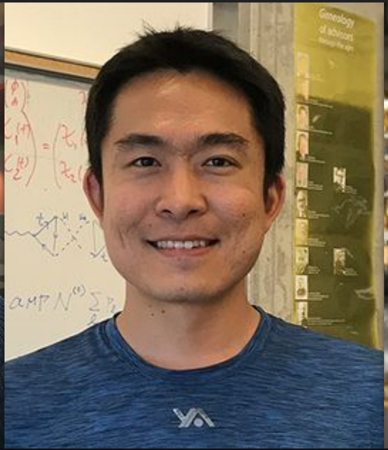


Aurora Ireland

Ph.D. UChicago
Stanford Postdoc

Gordan Krnjaic

Fermilab Scientist
UChicago Assistant Professor
KICP Senior Member



Yuhsin Tsai

University of Notre Dame Assistant Professor

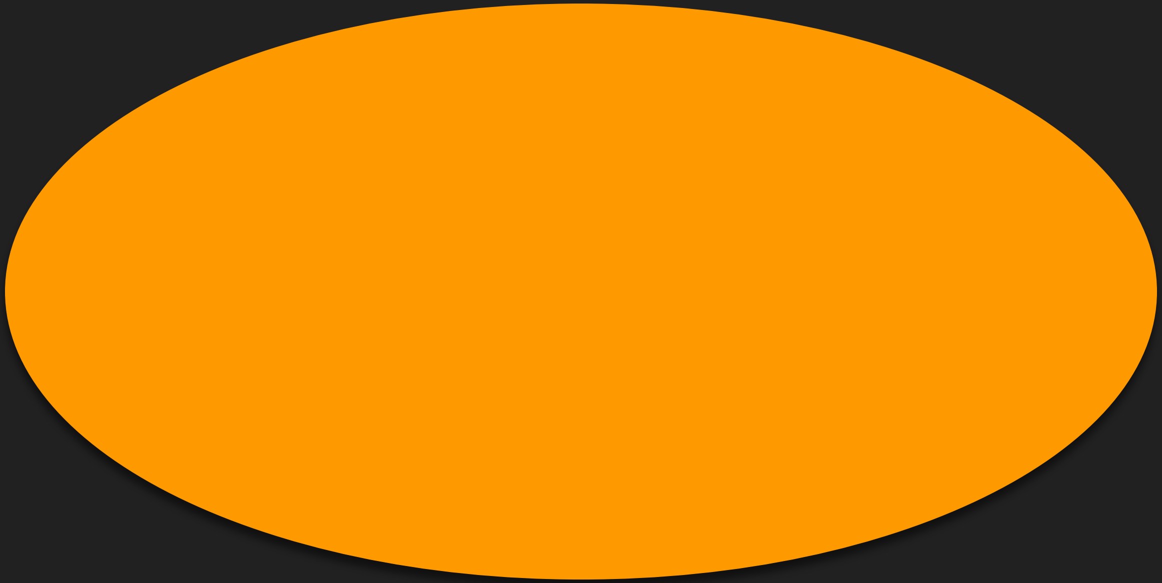
Jessica Zebrowski

UChicago Assistant Professor
SPT-3G Scientist

Christian Reichardt

University of Melbourne Senior Professor
SPT-3G Scientist

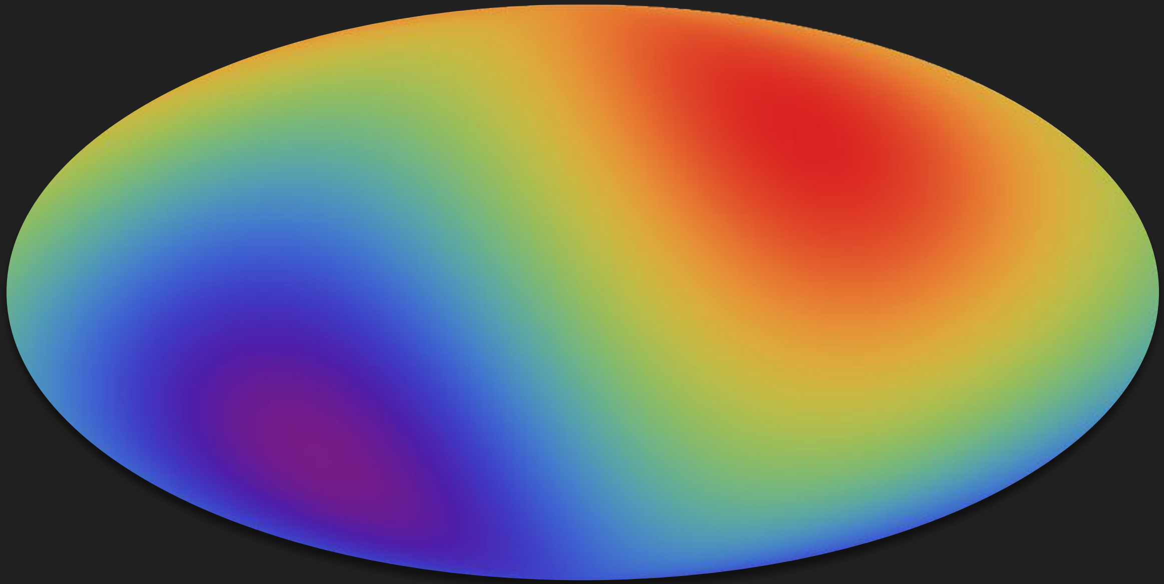
Observing the Cosmic Microwave Background



1965 Discovery: Bell Labs Horn Antenna by Penzias and Wilson

A nearly uniform microwave glow fills the sky: relic light from a hot early Universe.

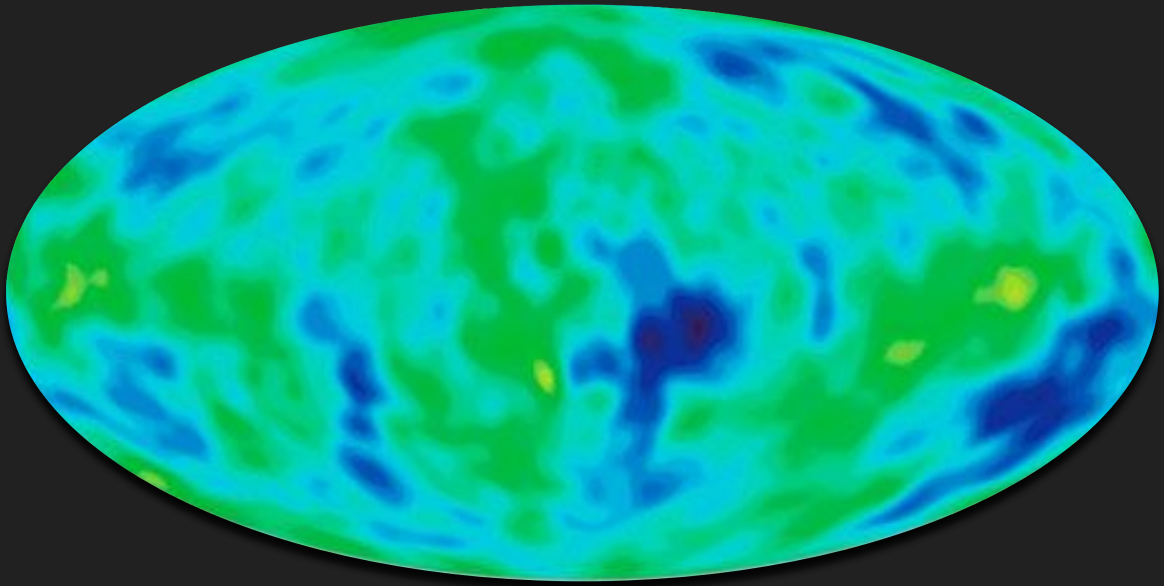
Observing the Cosmic Microwave Background



1977 The Dipole: Berkeley / U-2 Radiometer

The first strong pattern is not primordial structure, but our motion through the CMB rest frame.

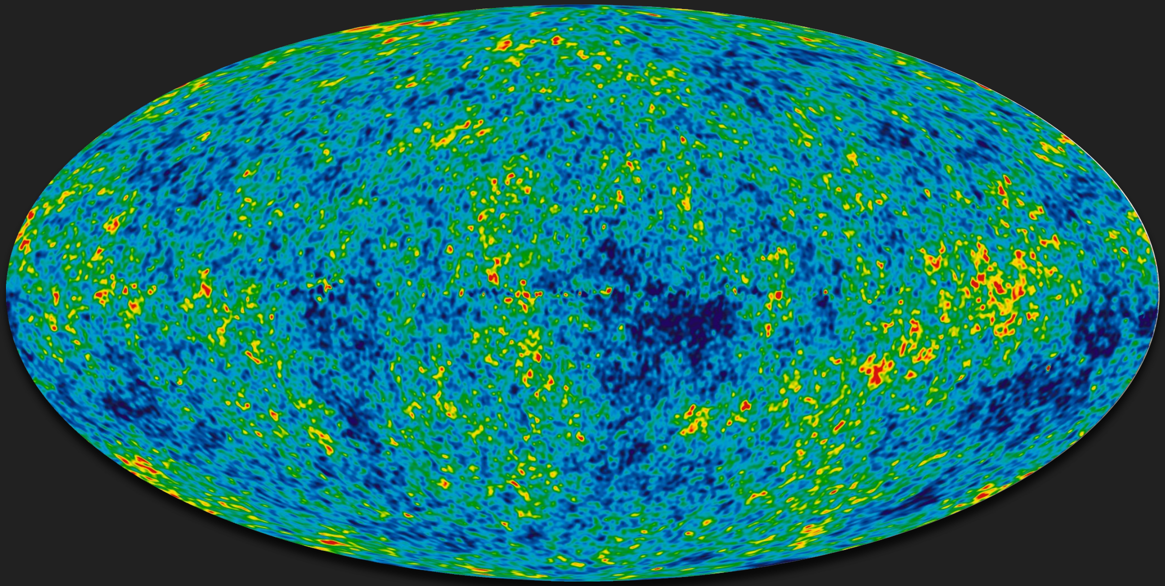
Observing the Cosmic Microwave Background



1992 COBE: First Primordial Fluctuations

After removing the dipole, tiny temperature variations appear: the seeds of cosmic structure.

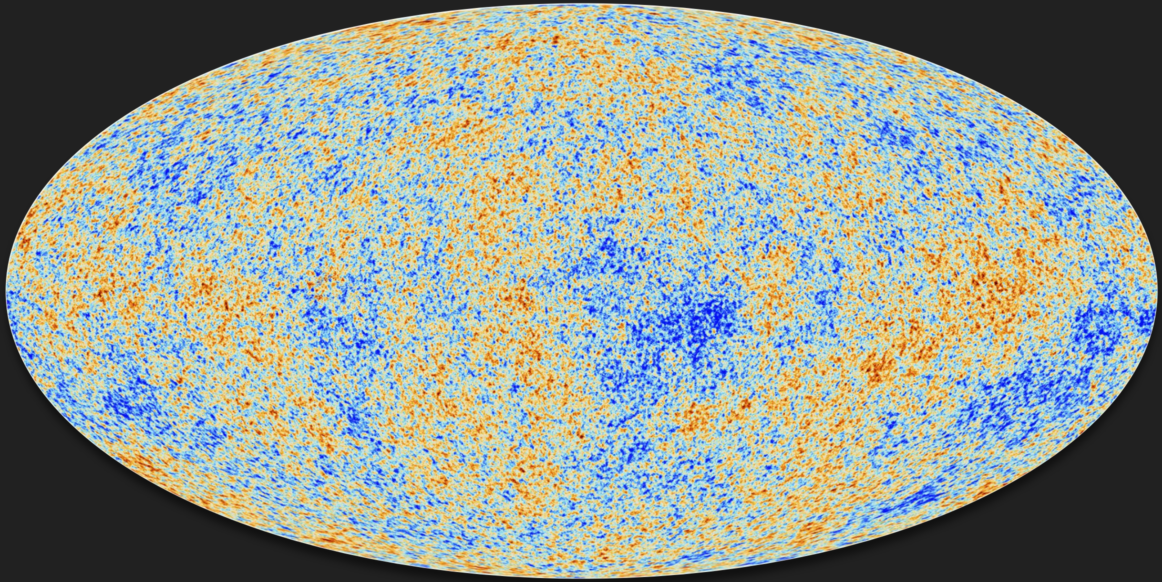
Observing the Cosmic Microwave Background



2003 WMAP: Precision Cosmology Begins

The fluctuations sharpen into acoustic structure, revealing the geometry and contents of the Universe.

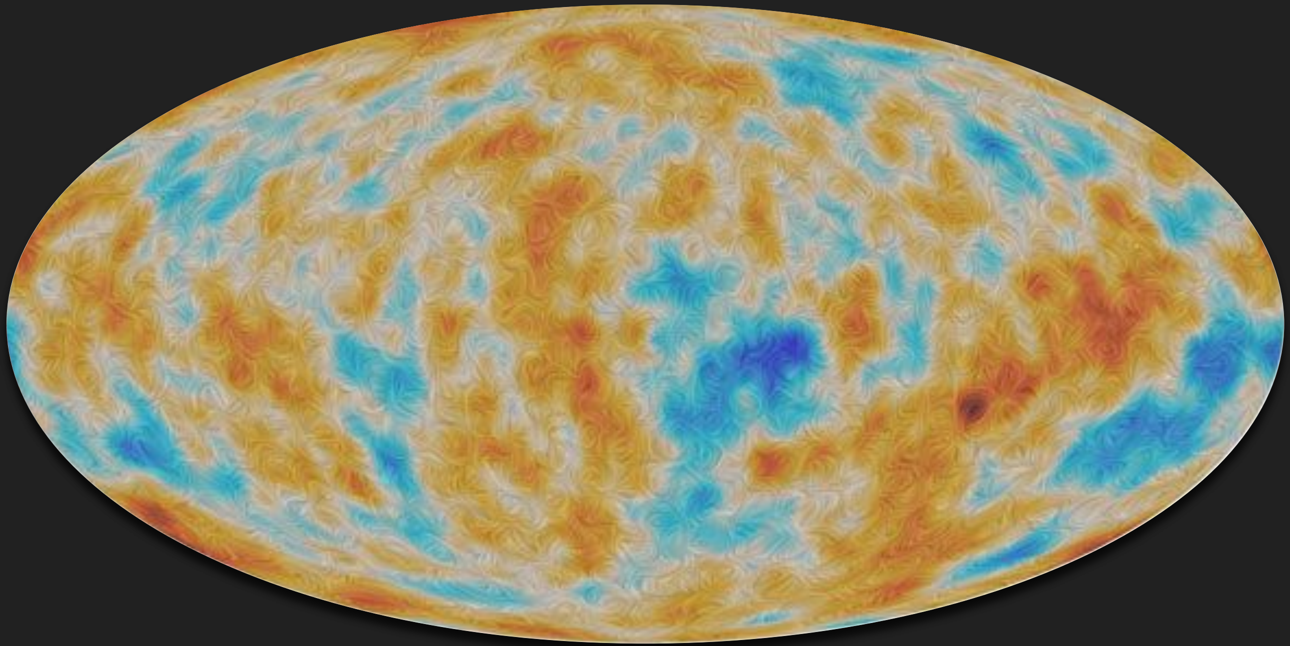
Observing the Cosmic Microwave Background

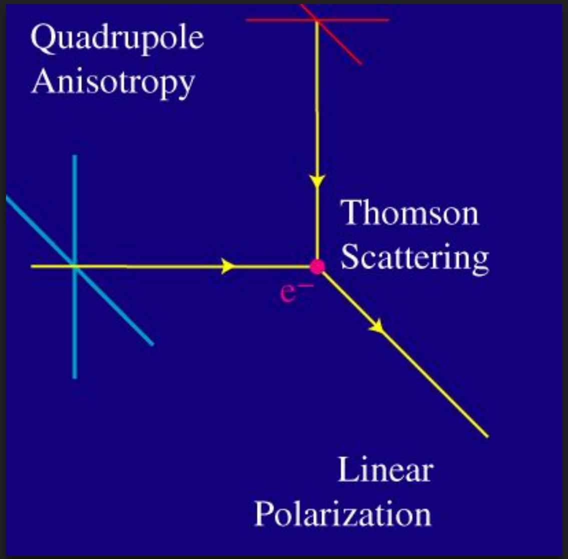


2013 Planck: The High-Precision CMB Sky

The CMB becomes a precision map of the early Universe, setting the benchmark for modern cosmology.

Polarization of the CMB



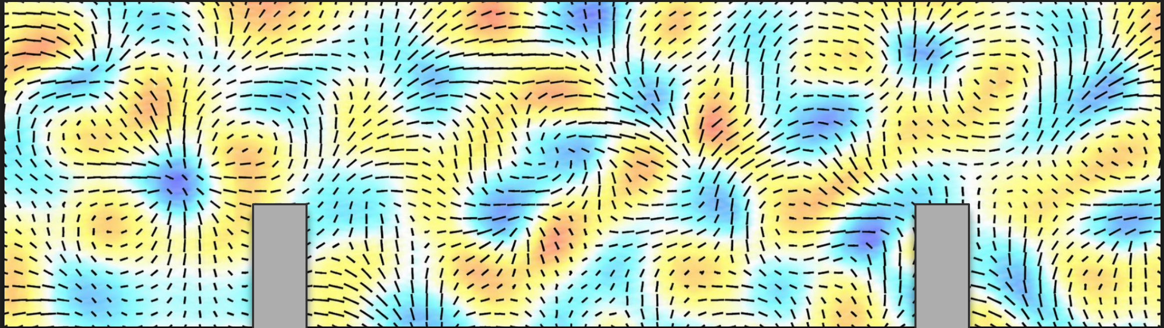


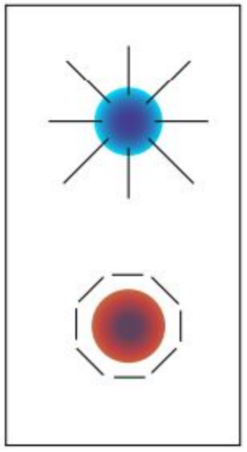
Temperature maps show **where** the early Universe was more or less dense.

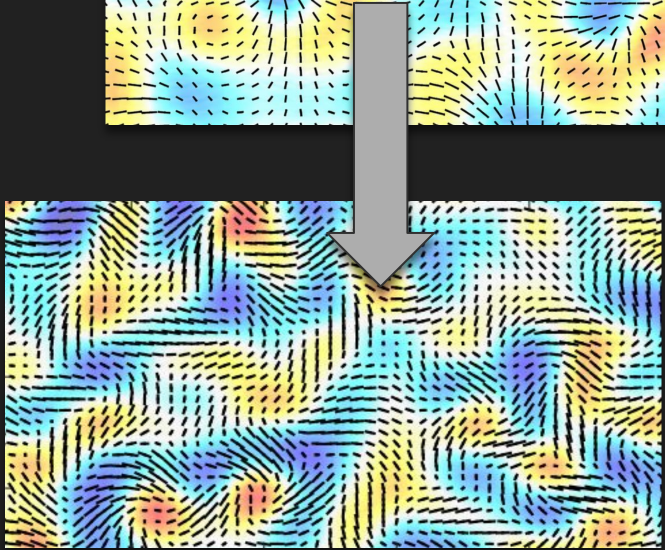
Polarization maps tell us **how** photons were last scattered, encoding velocity flows and geometry.

What patterns can the polarization take?

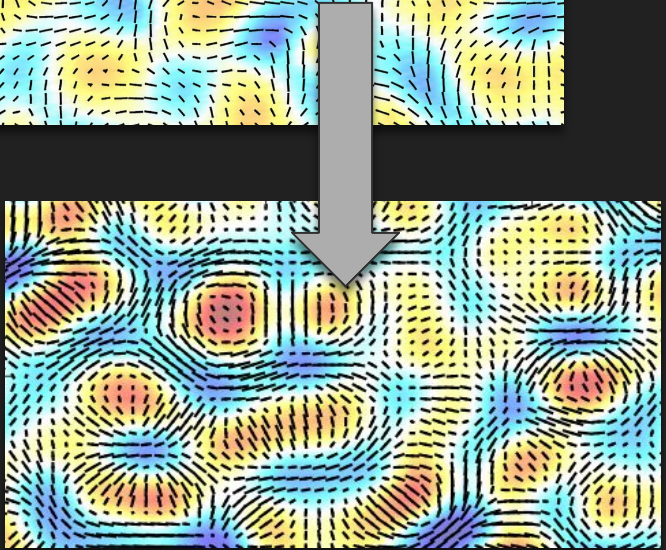
Raw Polarization Pattern



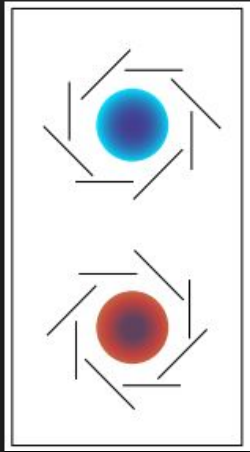




Gradient-like pattern

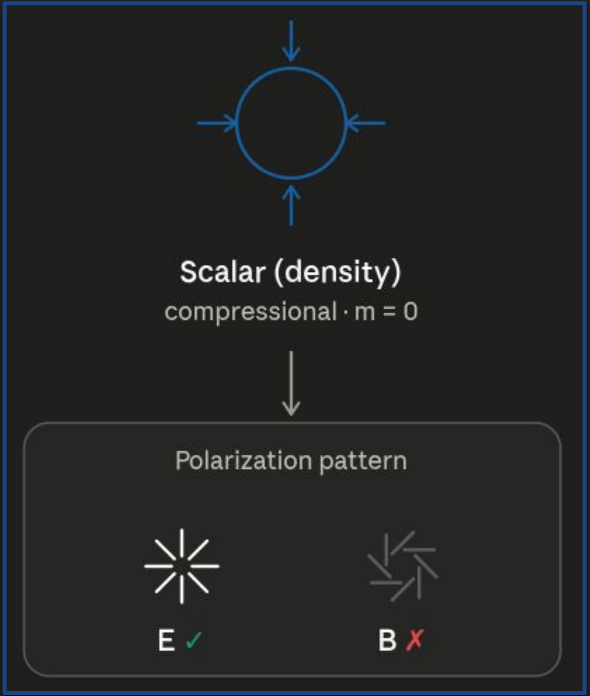


Curl-like pattern



Polarization: Scalars and Tensors

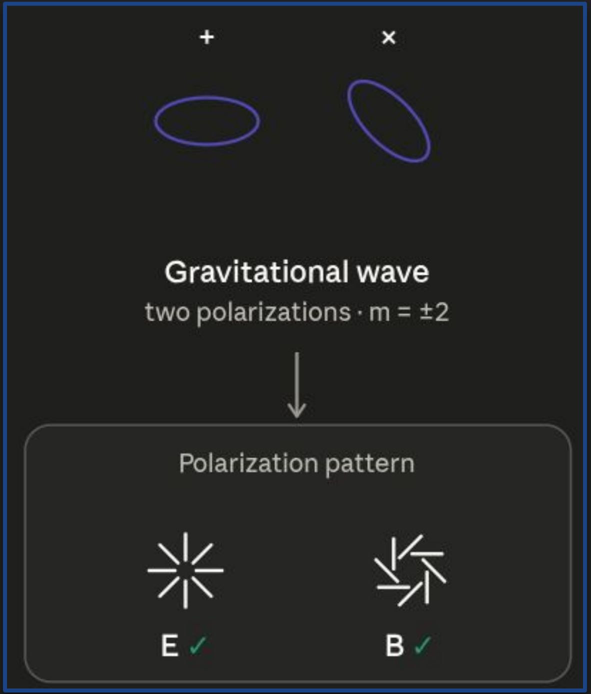
Scalar Perturbations



Only **k** defines a direction.

No handedness: E-modes only.

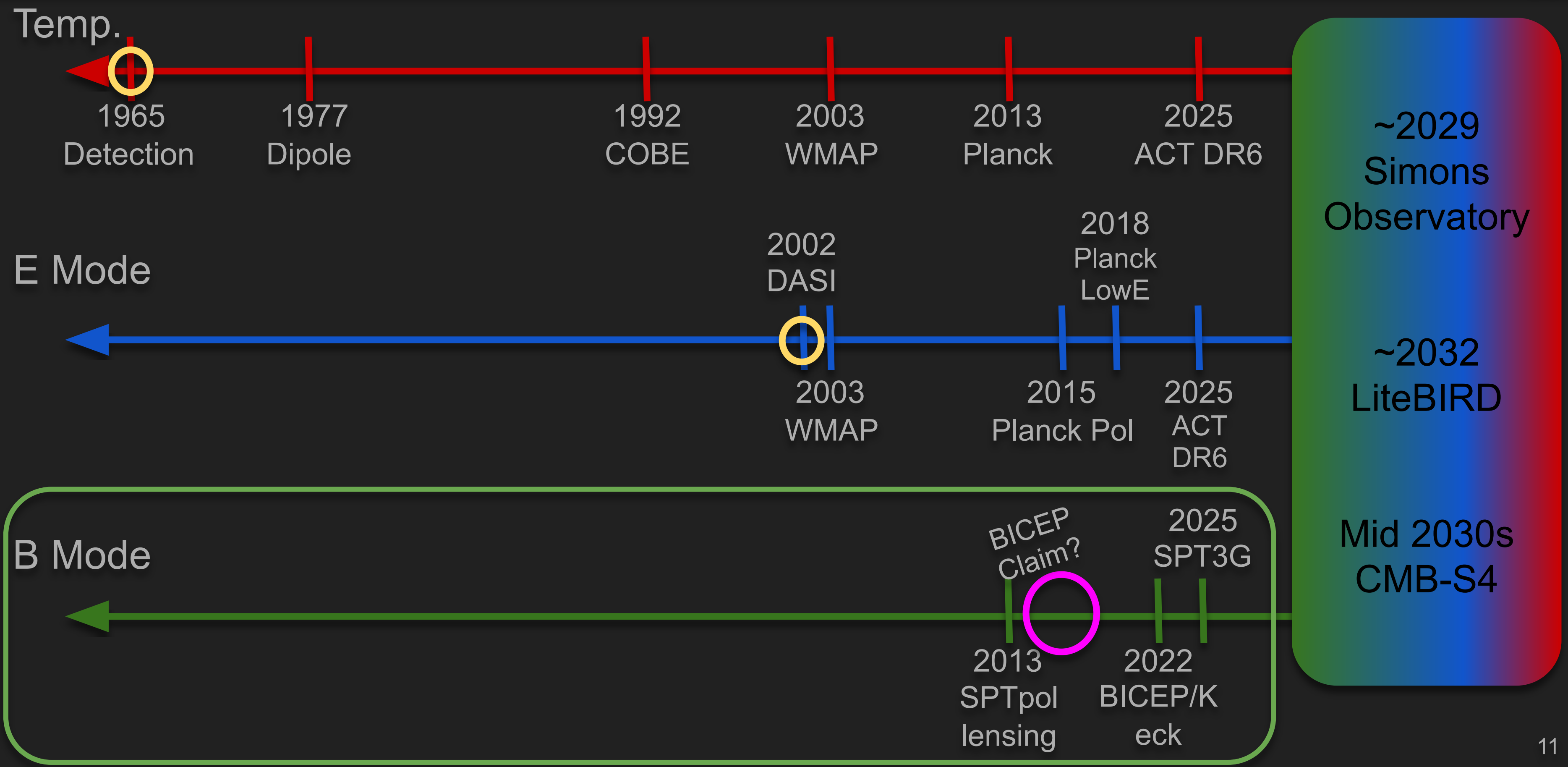
Tensor Perturbations



Transverse shear defines orientation.

Handedness allowed: E- **and** B-modes.

Timeline of CMB Observations (2026)



A Future B-Mode Detection: Inflation?

Tensor fluctuations are a prime target for future observations of the cosmic microwave background, because if detected they can provide a conclusive verification of the theory of inflation and a unique tool for exploring the details of this theory.

- Flauger & Weinberg (2007) [0703179]

A positive detection of a CMB B-mode consistent with a primordial stochastic gravitational wave background (SGWB) is widely viewed as a smoking gun for an inflationary phase.

- Bahr-Kalus, Parkinson, & Easther (2022) [2212.04115]

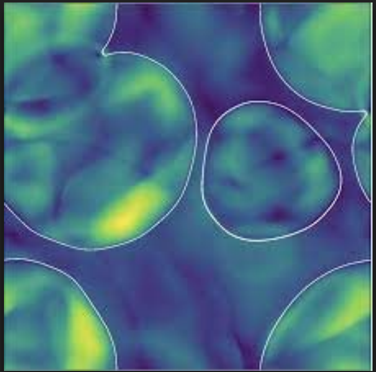
Next-generation CMB experiments, both space-borne (e.g., LiteBIRD [680]) and ground-based (e.g., Simons Observatory [681] and CMB-S4 [682]), aim to achieve precise measurements of CMB polarization. A clear science goal is to detect the imprint on CMB pattern of primordial GWs, which are the smoking gun of an inflationary phase in the early Universe [680, 683, 684].

- CosmoVerse White Paper (2025) [2504.01669]

A Future B-Mode Detection: What Generated the Tensors?

Inflation is not the only process in the early Universe that can generate tensor perturbations.

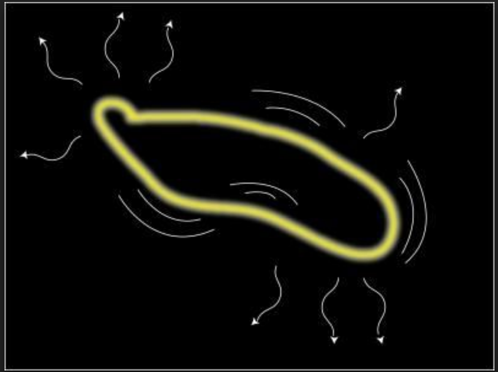
Phase Transitions



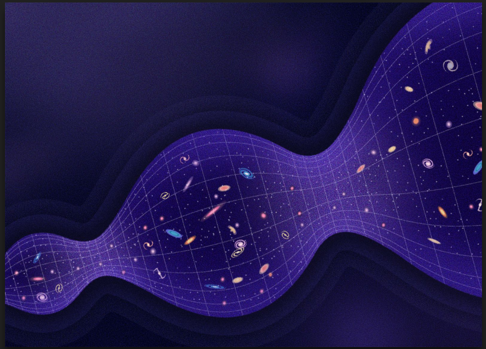
First-order phase transitions (FOPTs) generate tensor perturbations via bubble collision.

Topological Defects

Cosmic strings and domain walls generate tensor perturbations via motion and collisions.



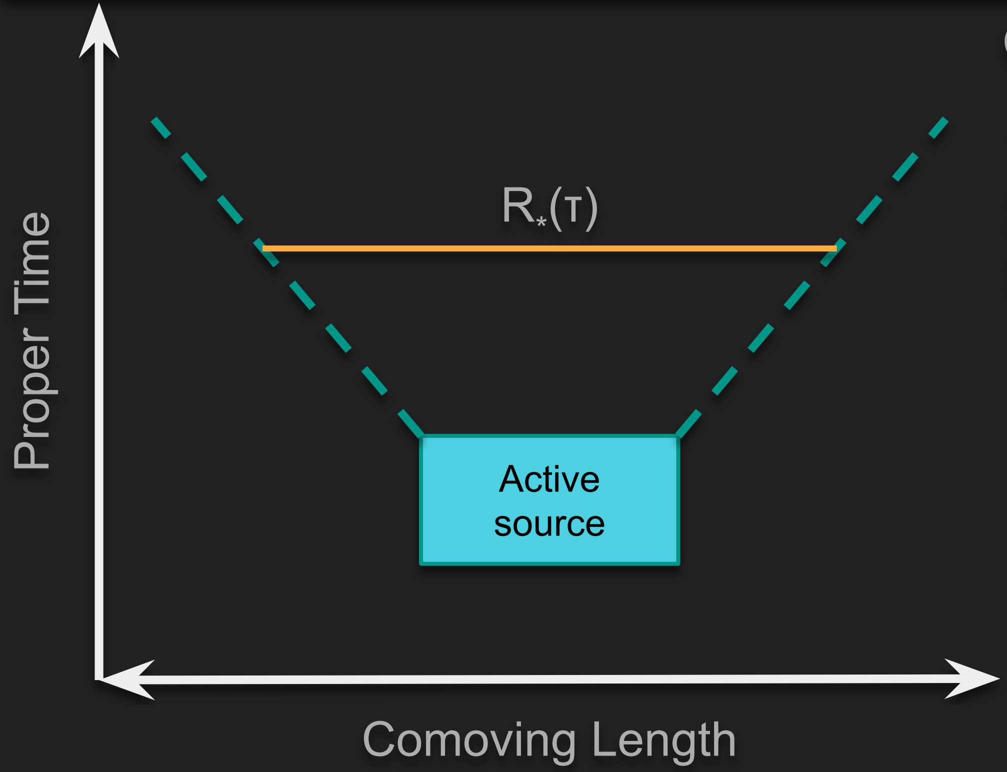
Other Cosmologies



Bouncing and ekpyrotic Universes can generate tensor perturbations during the collapse and bounce phases.

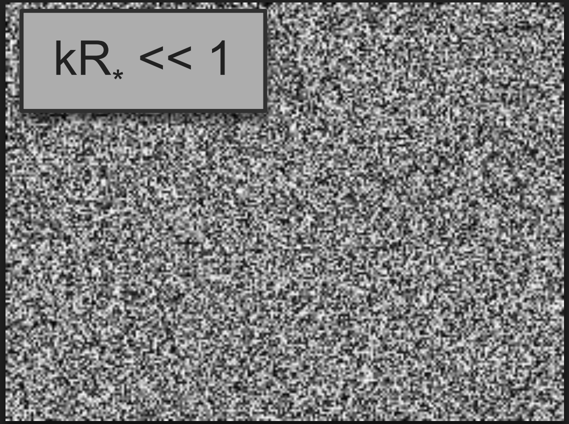
Early Causal Tensor Sources: Superhorizon Tail

Definition: ECTs are post-inflationary causal sources of primordial tensor perturbations with finite coherence in space and time.



Criteria for an ECT:

1) Causal, subhorizon sourcing
2) Finite duration / coherence time
3) Finite correlation length R_*

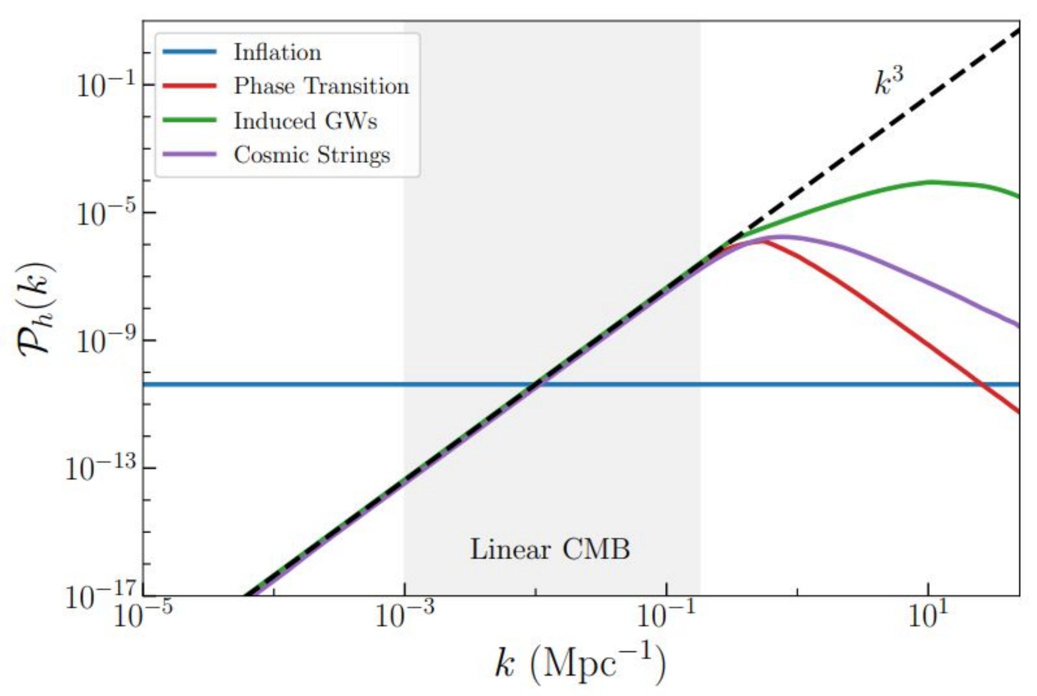


Causality implies k^3

Any process which satisfies the ECT criteria features identical scaling in the IR.

Criteria for an ECT:

1) Causal, subhorizon sourcing
2) Finite duration / coherence time
3) Finite correlation length R_*

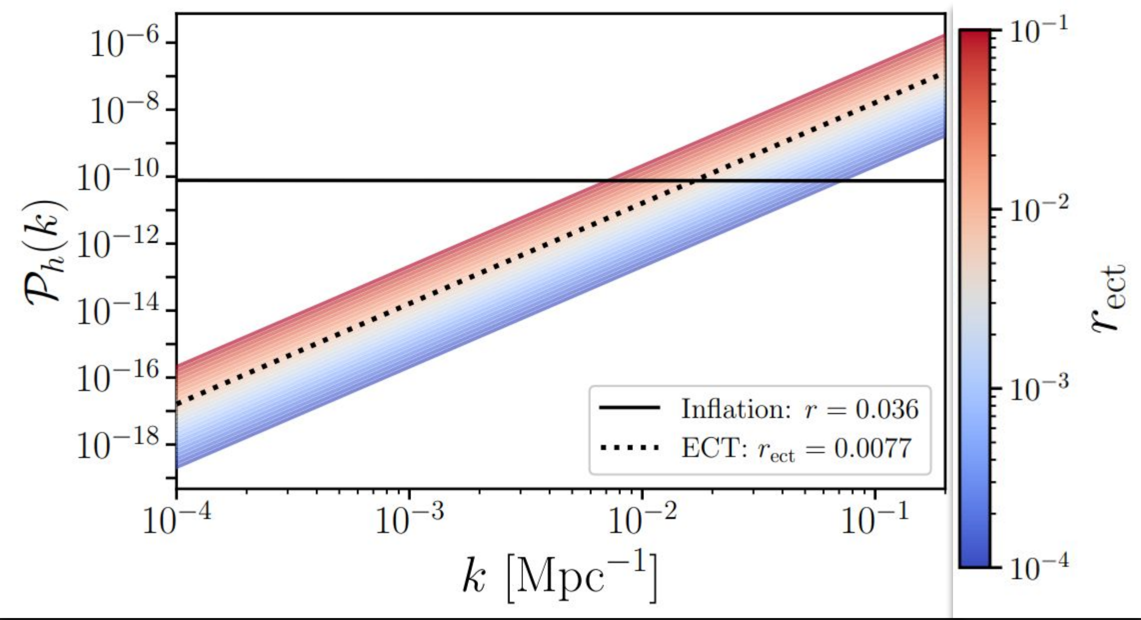


Zebrowski et al. (2601.20958)

Modeling ECTs as Initial Conditions

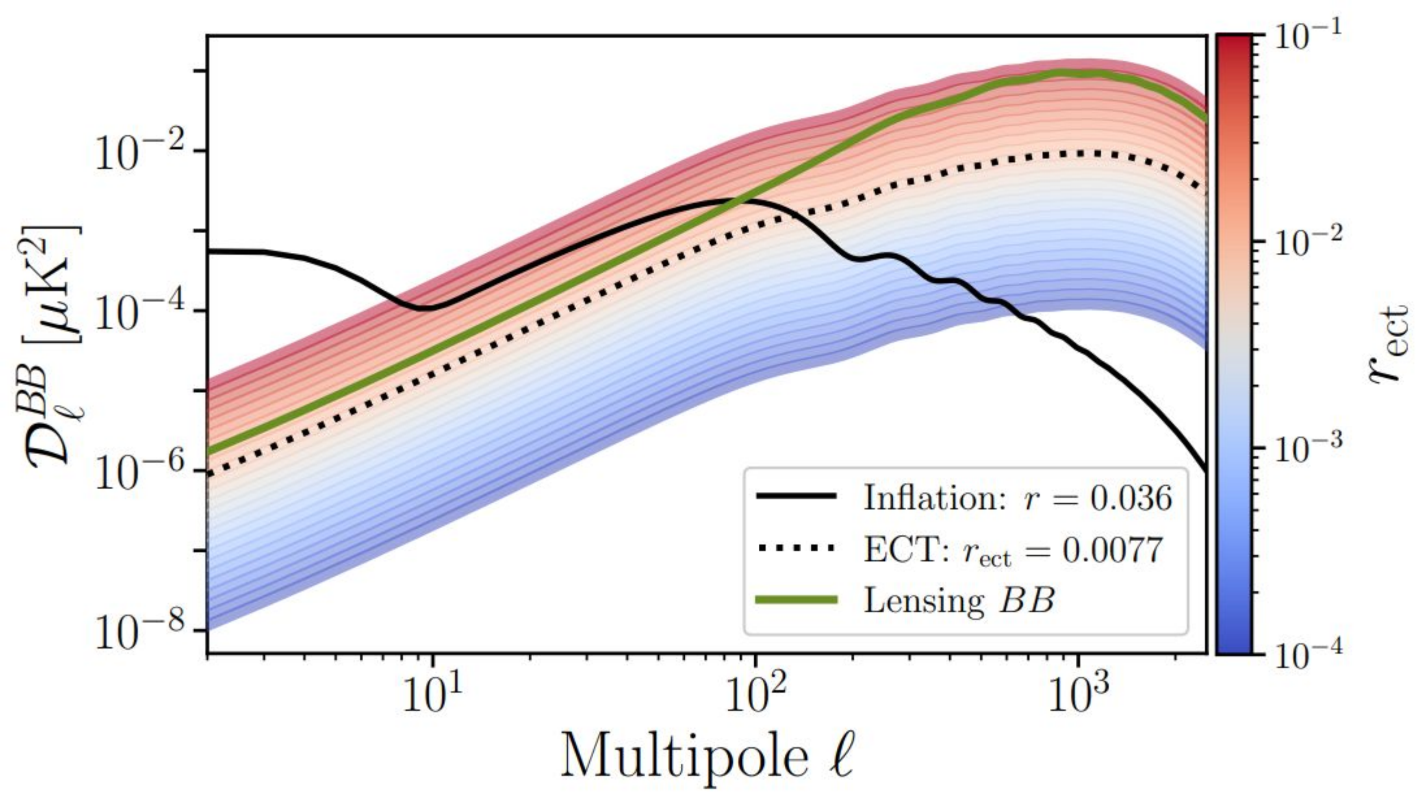
$$r_{\text{inflation}} = \frac{A_t}{A_s}$$

$$\mathcal{P}_h(k) \equiv r_{\text{ect}} A_s \left(\frac{k}{k_{\text{ref}}}\right)^3$$



Greene et al. (2601.20958)

Universal B-mode template for ECTs



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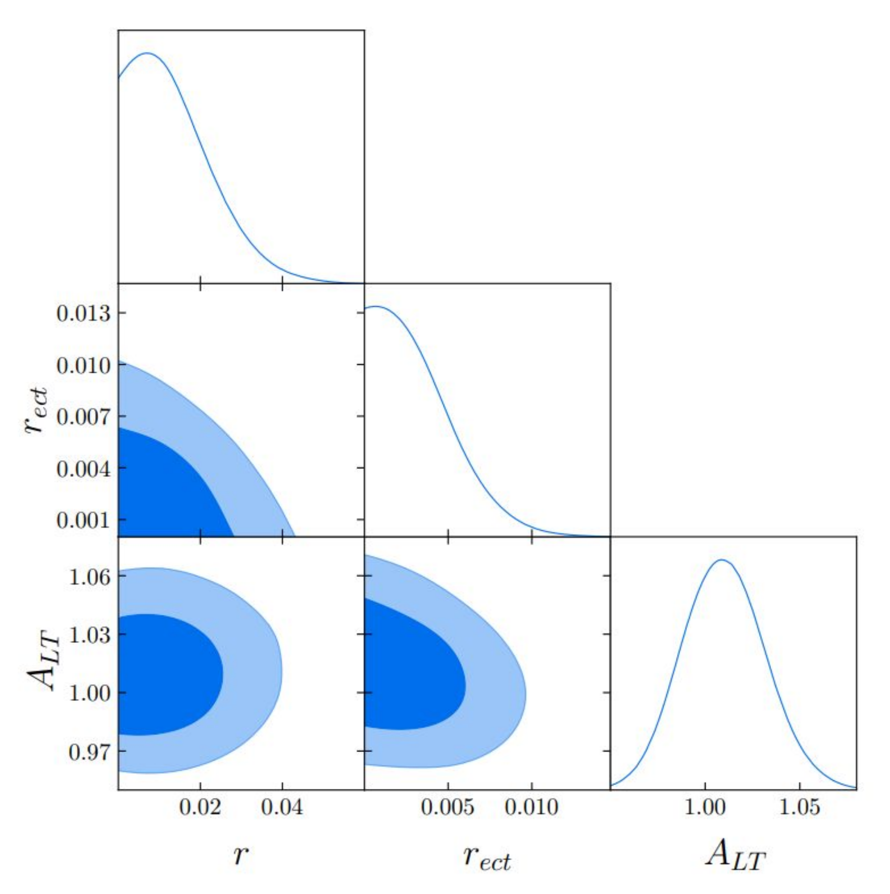
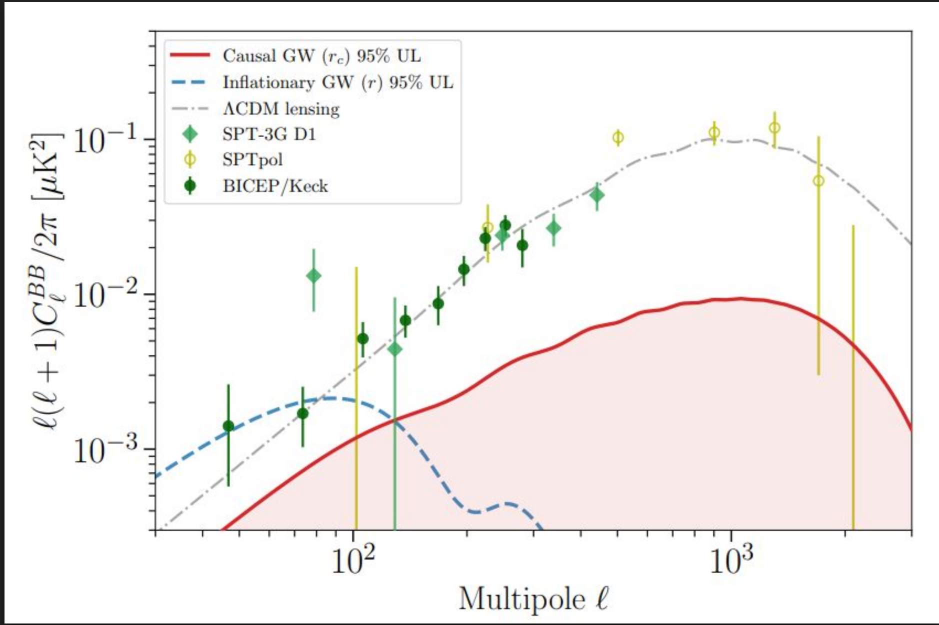
Constraints from SPT-3G





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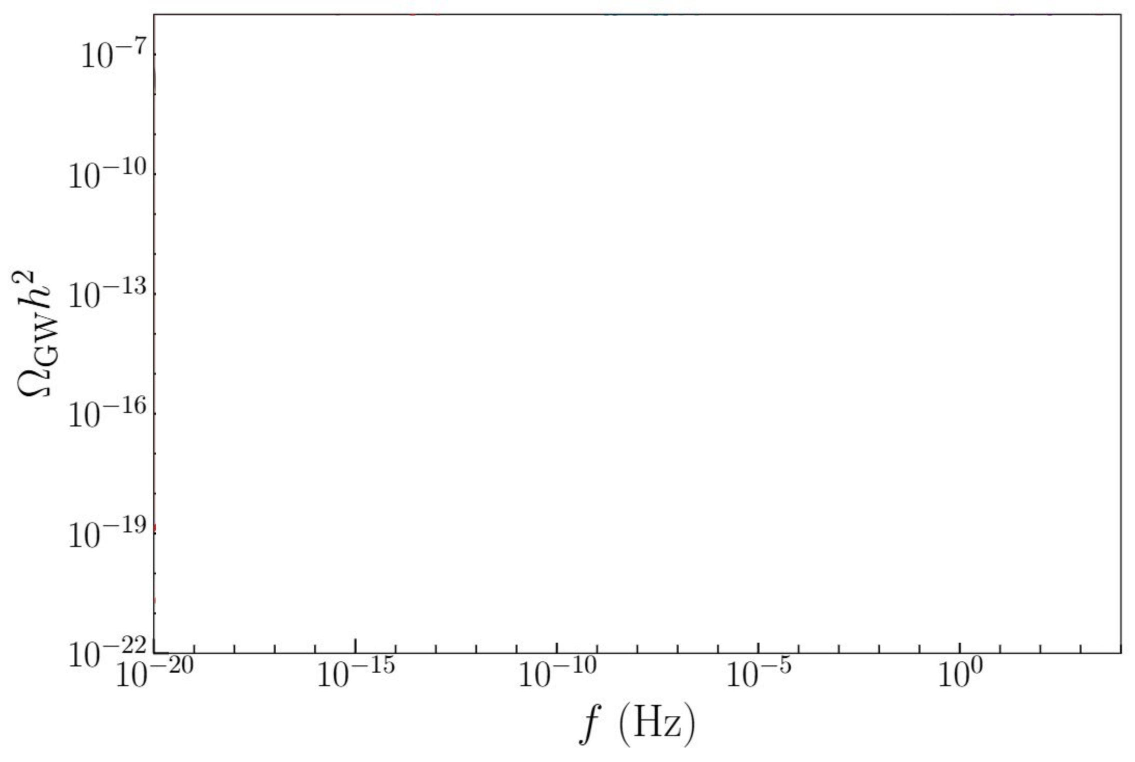
Constraints compared to other probes

Higher frequency probes provide model independent constraints on GW's.

B-mode derived constraints depend on the input model!



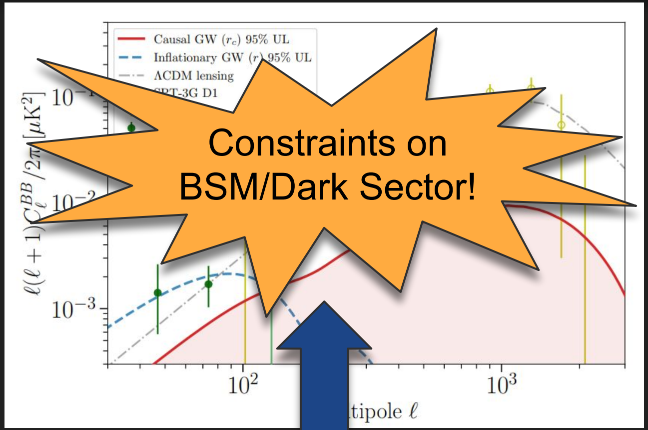
Zebrowski et al. (2601.20958)

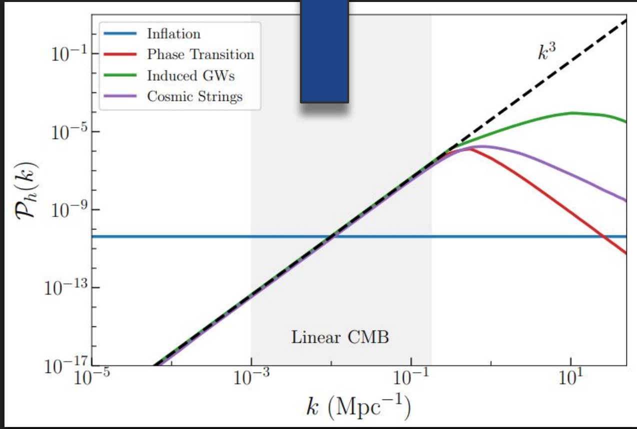
Constraints on BSM physics

Any BSM/dark sector physics with early, causal, finite-coherence dynamics leaves an ECT imprint independent of microphysics.

- Dark QCD
- Dark Electro-weak
- Domain Walls
- Cosmic Strings
- Z^2 symmetry
- Scalar Induced GWs
- Turbulence
- Dark photon instabilities
- PBHs

$$\langle h_\star^\lambda(\vec{k}) h_\star^{\lambda'}(\vec{k}')^*\rangle = \frac{\delta_{\lambda\lambda'}}{2} P_h(k)(2\pi)^3\delta^{(3)}(\vec{k}-\vec{k}')$$





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Conclusion

CMB B-mode polarization can test causal sources of early-Universe gravitational waves, turning future tensor searches into probes of dark-sector and BSM physics beyond just inflation.

Happy to take questions now or at:

kylar.cosmo@pm.me