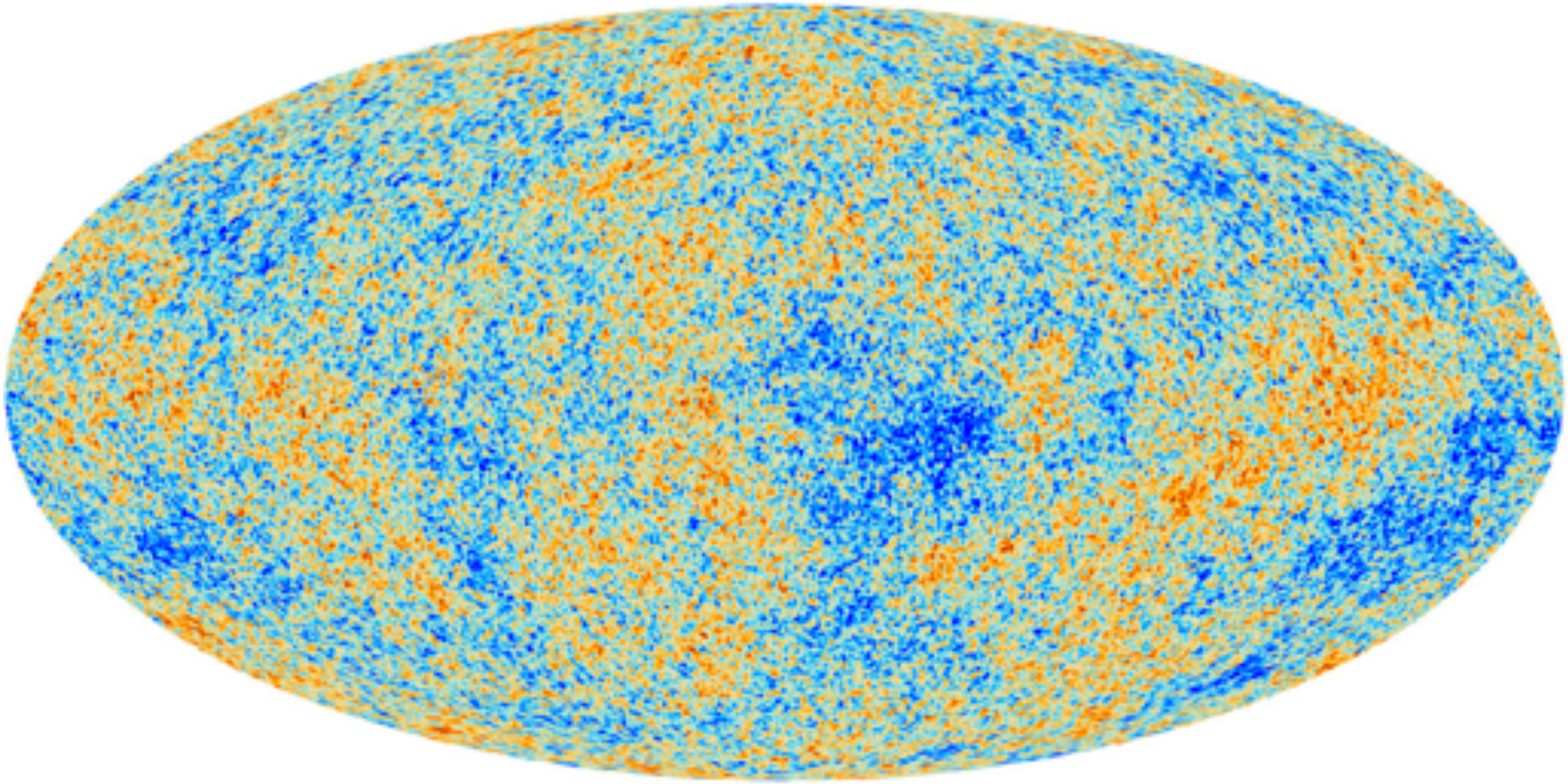
Cosmic anisotropy on large angular scales

Does the cosmic microwave background have hidden symmetries from causally-coherent quantum gravity?

Craig Hogan
University of Chicago
November 2022

https://arxiv.org/abs/2109.11092

Cosmic structure is a relic of quantum fluctuations during inflation



The cosmic background pattern on large scales preserves an intact image of the primordial quantum state

Its angular correlations preserve signatures of the quantum system that underlies space and time

Symmetries hidden in current data could provide unique clues to how quantum gravity works

Standard inflation scenario

CMB photons come from a photosphere at redshift ~1000

Temperature anisotropy comes from distortions in gravitational potential formed during early inflation

Preserves original pattern at large angles

Quantum system and perturbations

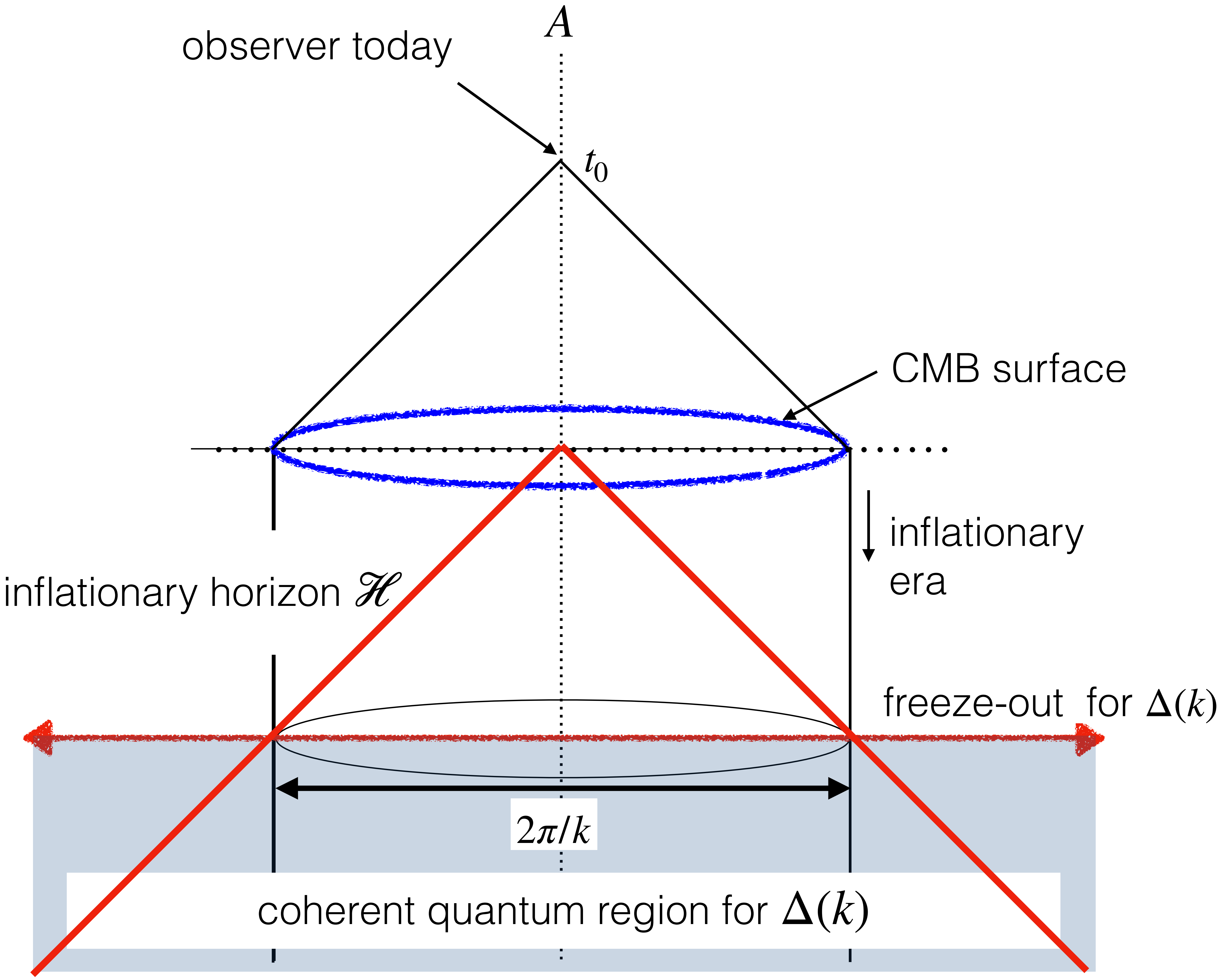
Field modes have vacuum fluctuations

Due to expansion, modes stretch and slow

Gravity of each mode "freezes" into a classical perturbation when its oscillation falls below the expansion rate

3D power spectrum agrees amazingly well with data over a wide range of scales

Comoving conformal causal diagram of standard inflation



Standard inflation scenario

Works great! What's the problem?

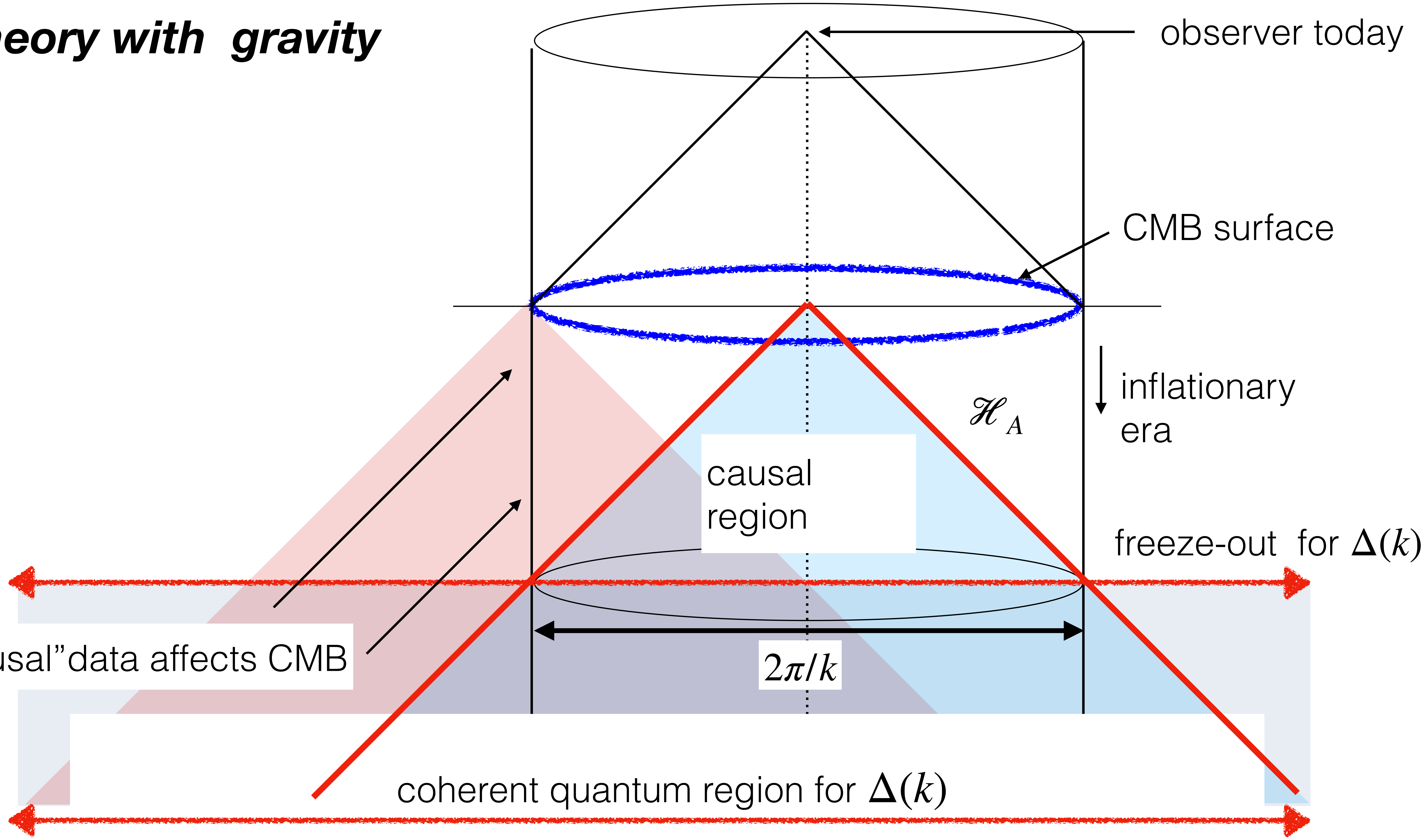
two related theory problems:

acausal initial state
IR inconsistency of quantum field theory with gravity

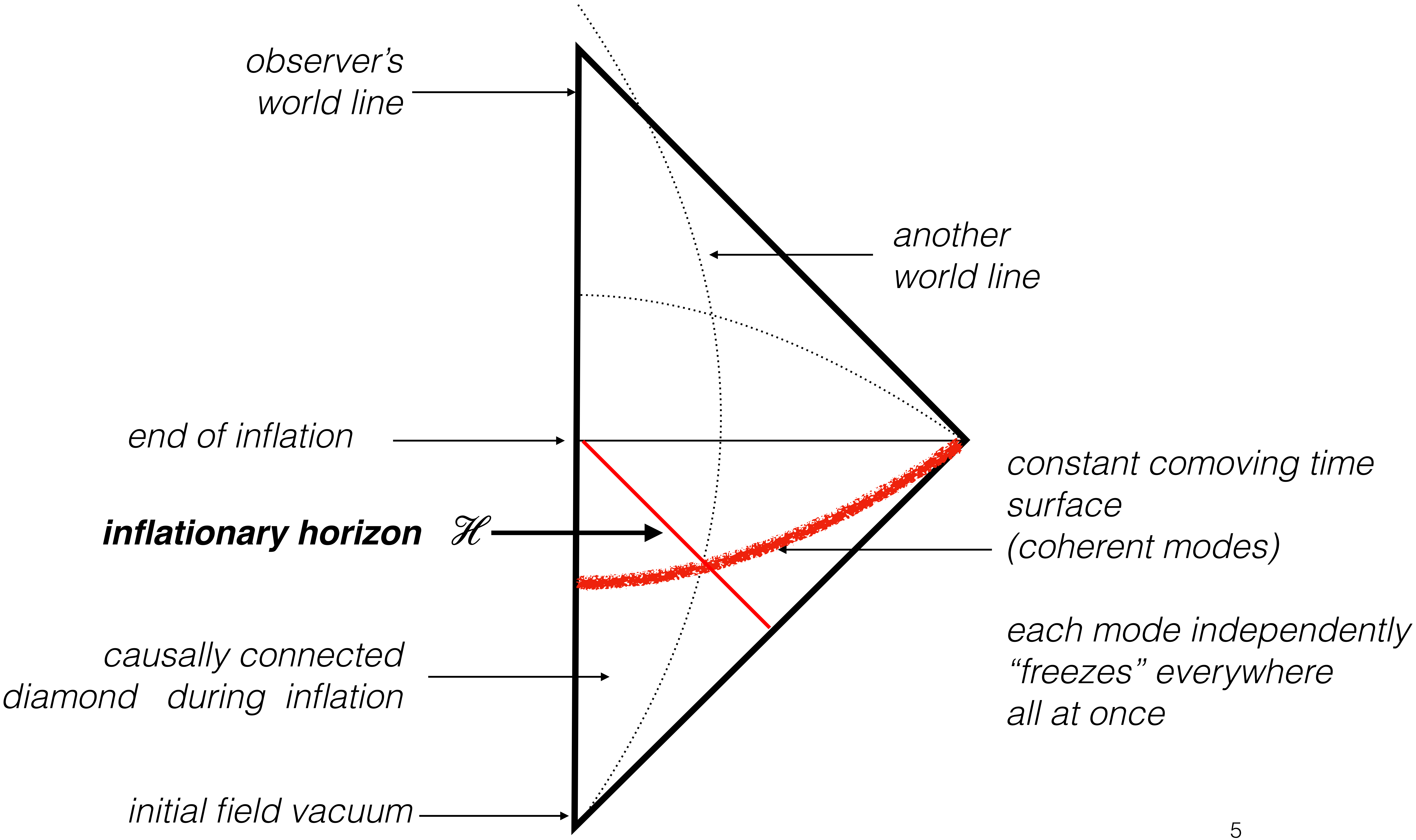
data problem:

anomalies of large angle anisotropy

These problems could be related!



Penrose diagram of standard quantum inflation:
acausal initial coherent mode states extend to spacelike infinity



Standard scenario is also based on a flawed quantum theory

Effective field theory is inconsistent with gravity in the infrared

Degrees of freedom = amplitudes of plane wave field modes
particles = mode excitations
States = superpositions of quantum oscillators
Vacuum = ground state of oscillators

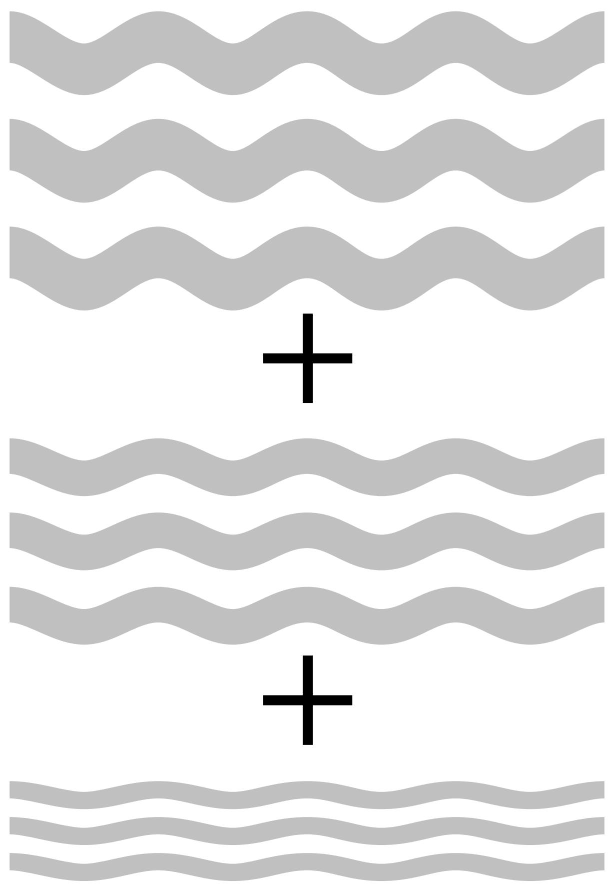
omits gravitational entanglement with causal structure

paradox summarized by Hollands and Wald (2004):

"[because of] the holistic nature of renormalization theory...
an individual mode will have no way of knowing whether its own subtraction is correct unless it `knows' how the subtractions are being done for all other modes."

Important for long waves and large angular scales
This is also where the model does not agree with data
Would a causally coherent model work better?

$$|\Delta_{\vec{k}}\rangle =$$



$$+ \ldots$$

$$|\Delta\rangle = \sum_{\vec{k}} |\Delta_{\vec{k}}\rangle$$

CMB temperature anisotropy

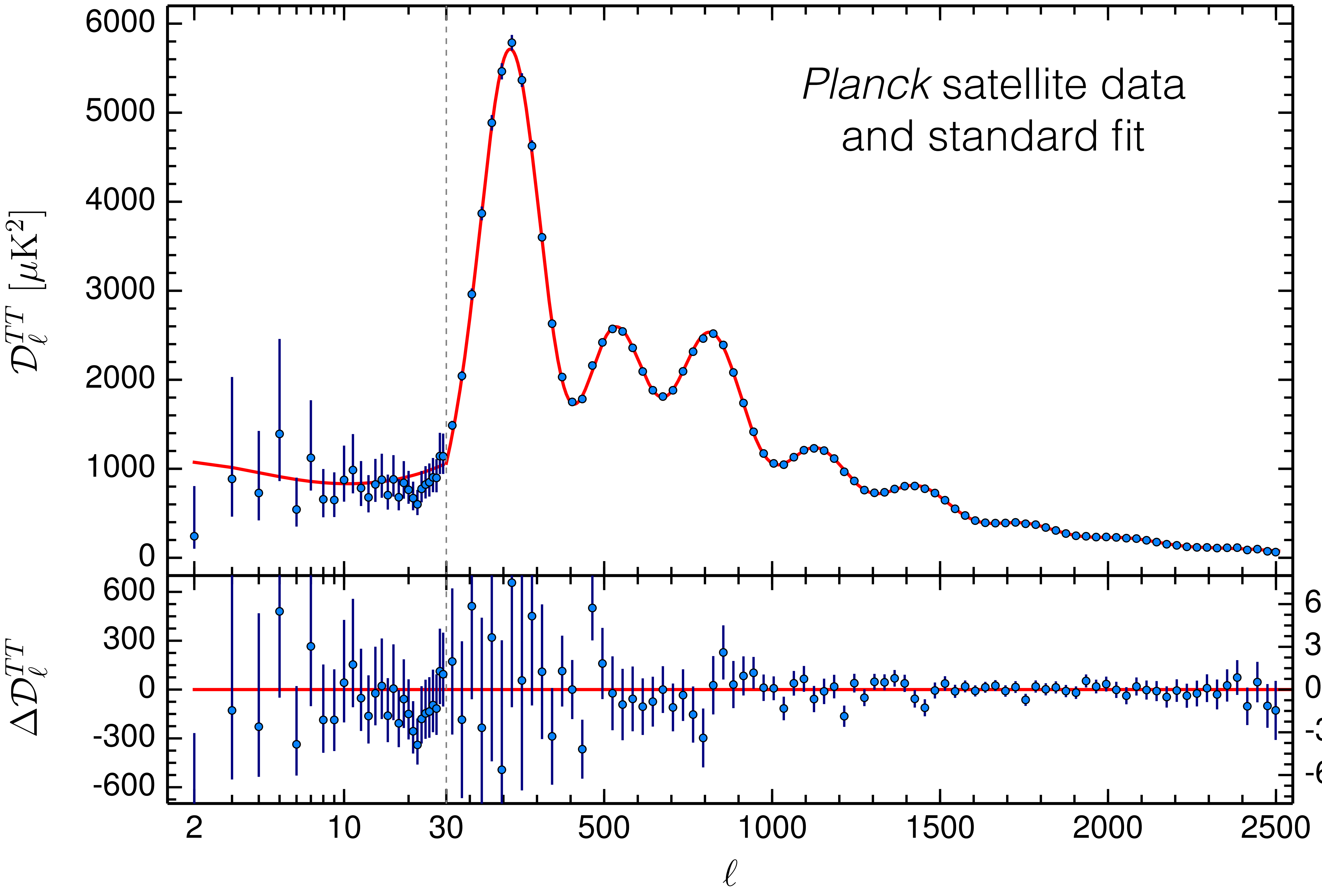
Usually analyzed with the *angular power spectrum* C_ℓ, $\mathscr{D}_\ell$

fits to "concordance cosmology" work amazingly well

Most cosmological fits are based on $\ell \gtrsim 100$

"cosmic variance" dominates formal measurement error up to $\ell \sim 10^3$

data at $\ell \lesssim 30$ (angular scales larger than $\sim 5°$) are often treated differently or omitted

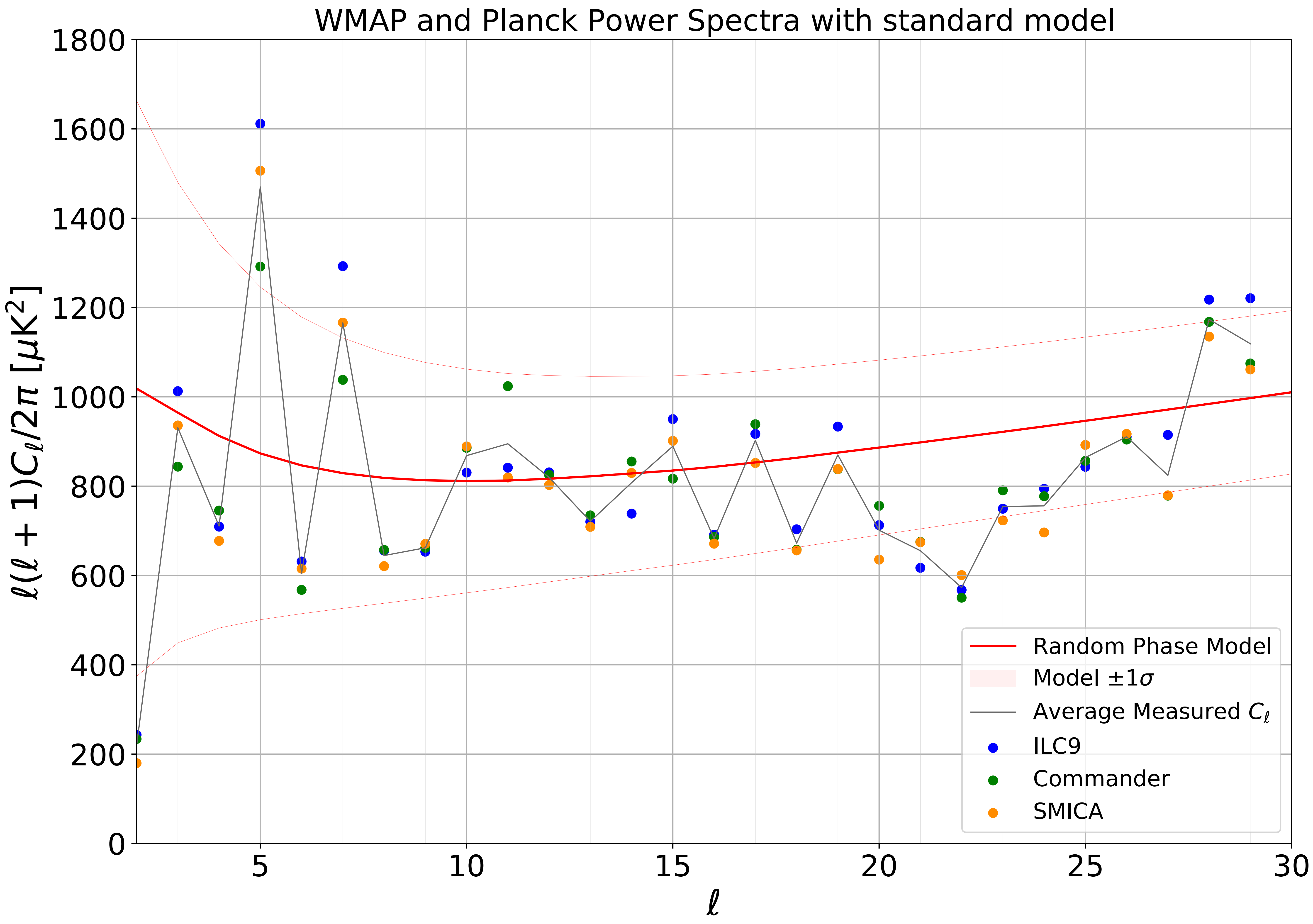


Pattern at $\ell \lesssim 30$ (or $\Theta \gtrsim 5°$) is a nearly intact map of primordial gravitational potential on a sphere

But the particular pattern has no significance in standard theory

Large angles have the fewest modes and the most cosmic variance

Spectrum of standard theory fits data well enough, consistent with cosmic variance



Equivalent information in the angular domain: the angular correlation function $C(\Theta)$

transform of C_ℓ:

$$C(\Theta) = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\cos\Theta)$$

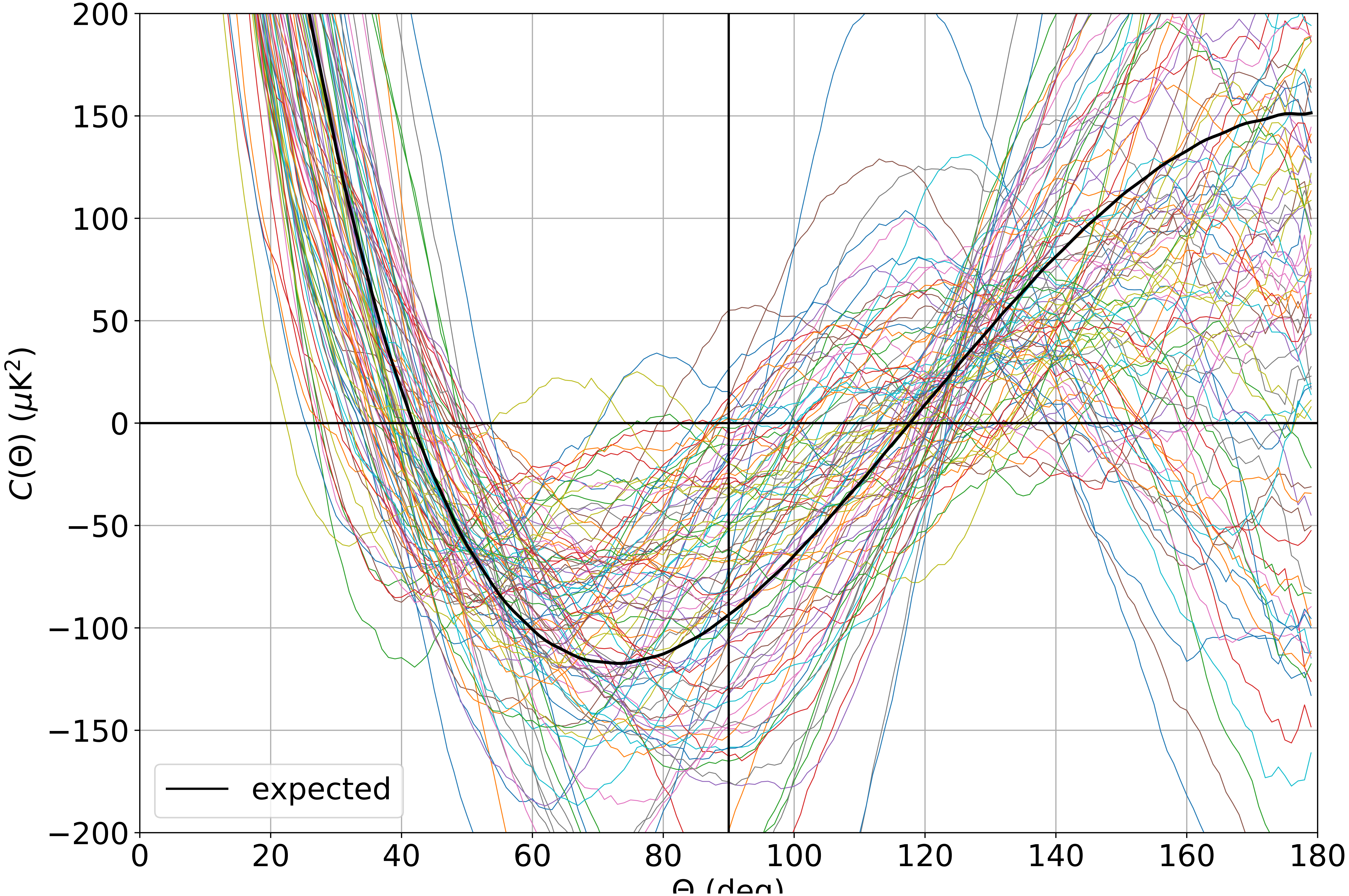
where P_ℓ are Legendre polynomials

Each curve is an equally probable realization in standard quantum inflation

$C(\Theta)$ *at large angles is dominated by small* ℓ *harmonics*

cosmic variation in realizations is dominated by long wavelength perturbations, some larger than the horizon

(spoiler: we will argue that this variation is unphysical)



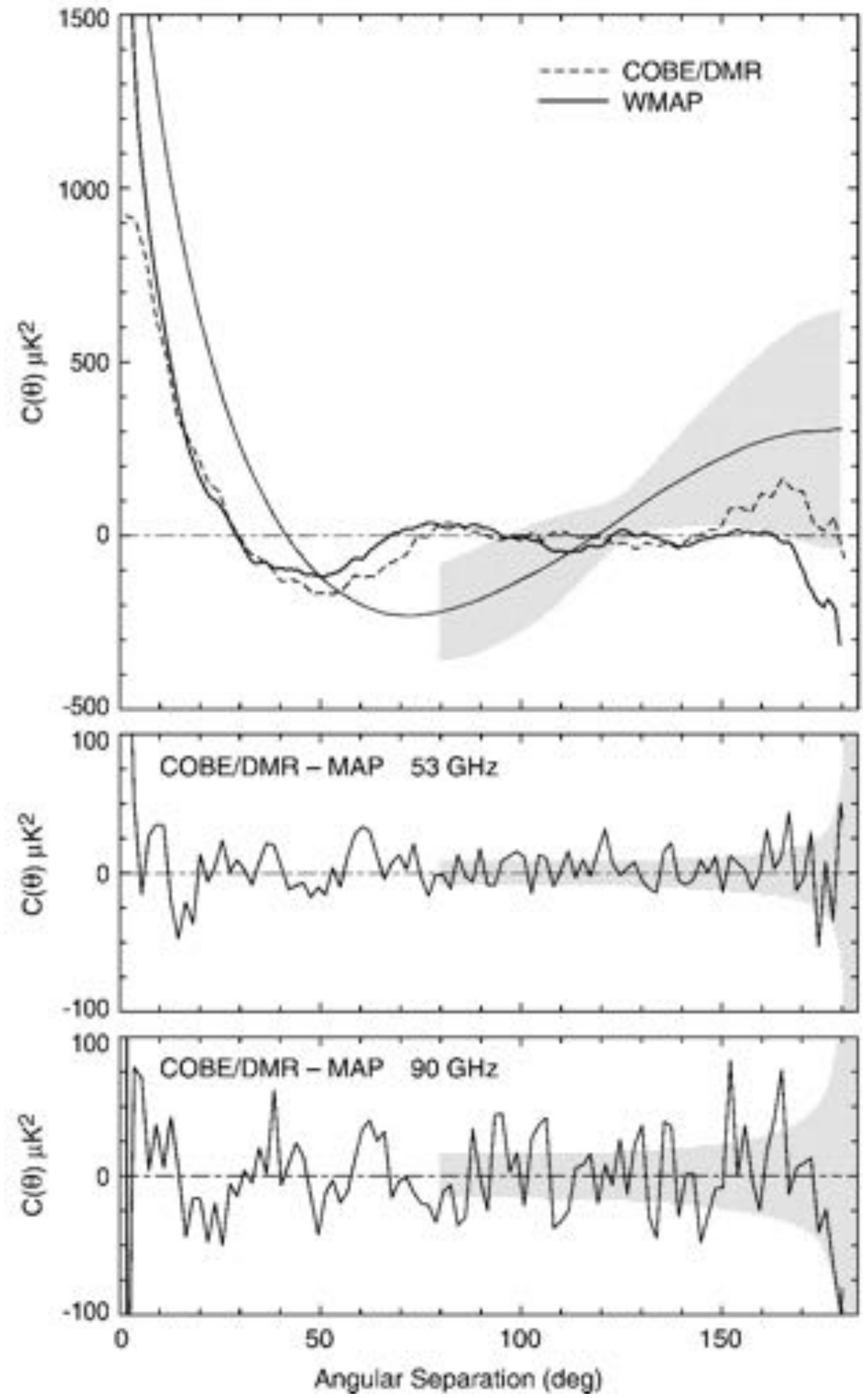
$C(\Theta)$ *of standard expectation and 100 random standard realizations*

$C(\Theta)$ shows a conspicuous "lack of large-angle correlation" compared to standard predictions

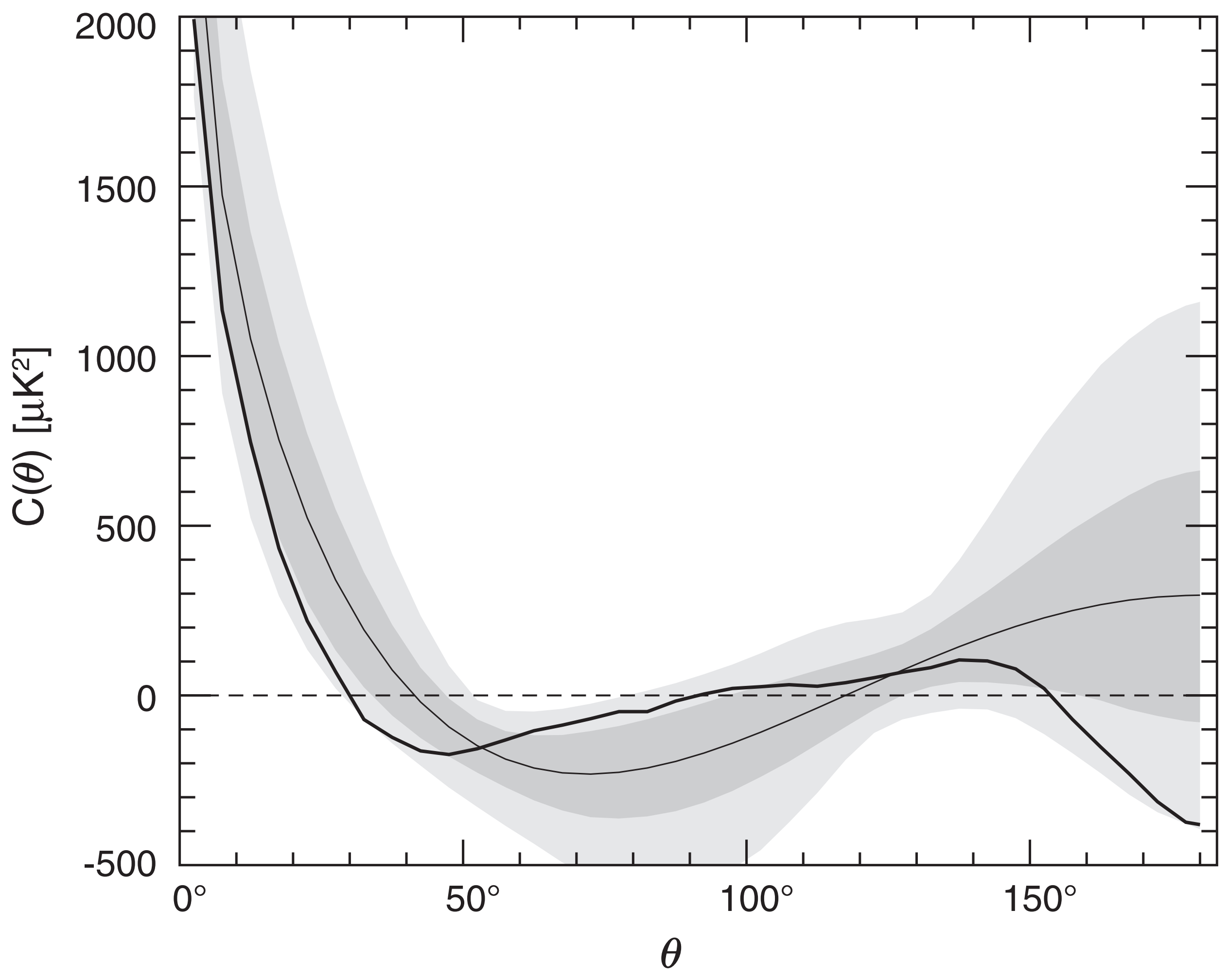
It is one of several long-known "anomalies" not apparent in the power spectrum—-

interpreted in standard theory as a meaningless statistical fluke

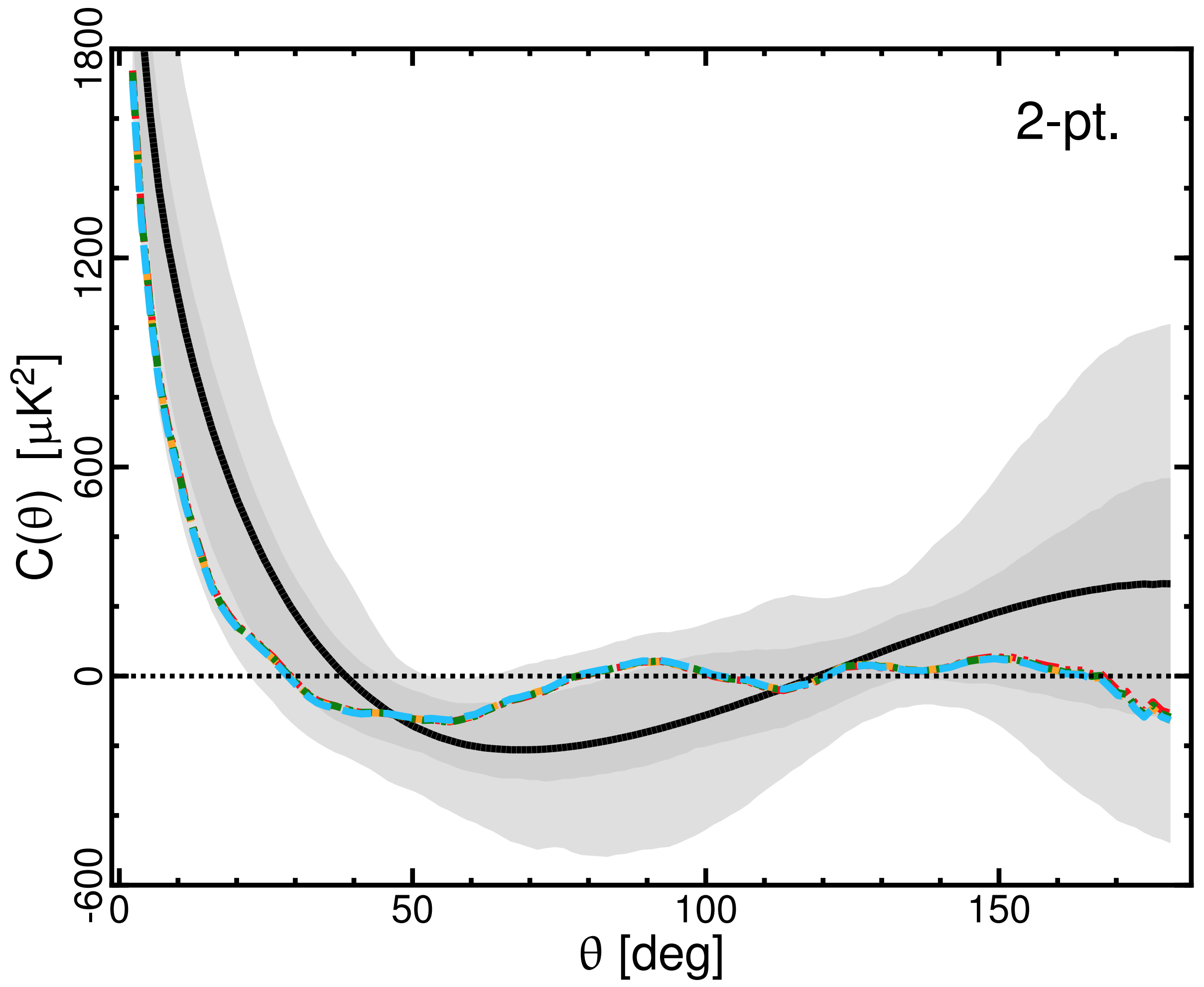
WMAP 2003



WMAP 2011



Planck 2016

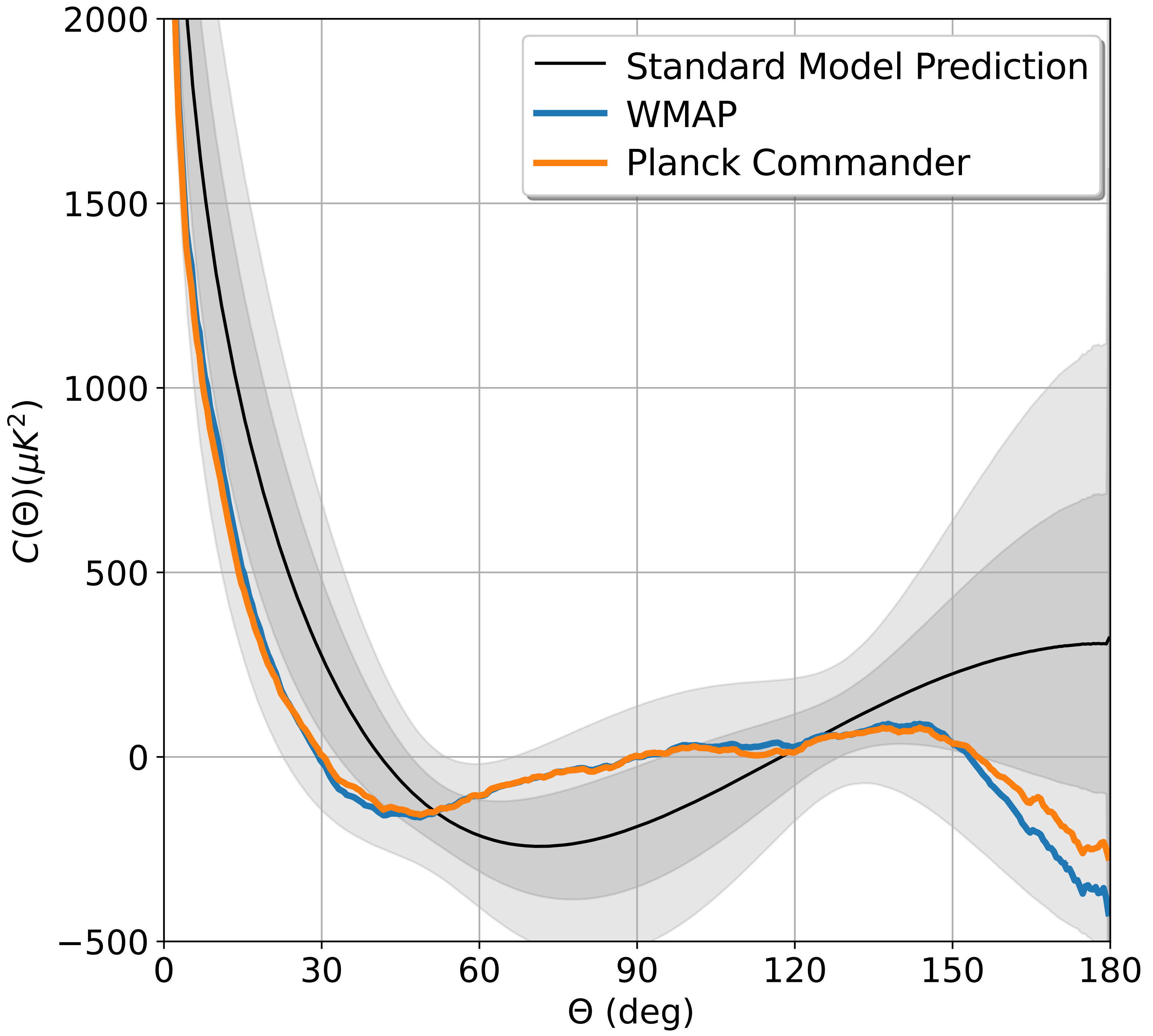


Could small $C(\Theta)$ actually be due to a physical symmetry?

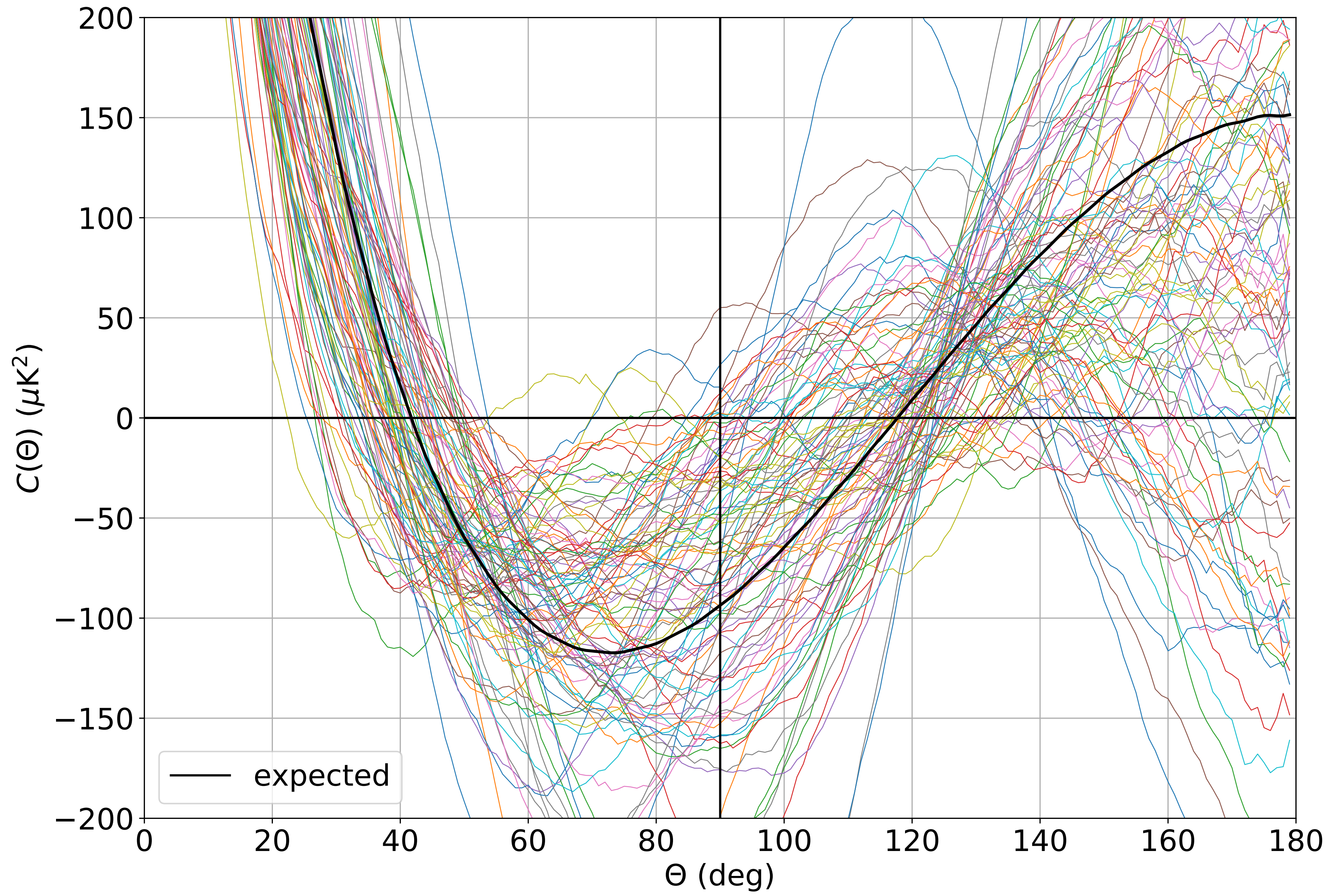
Maybe primordial correlation is not just small, but actually zero

Symmetries of $C(\Theta)$ do not occur in the standard picture

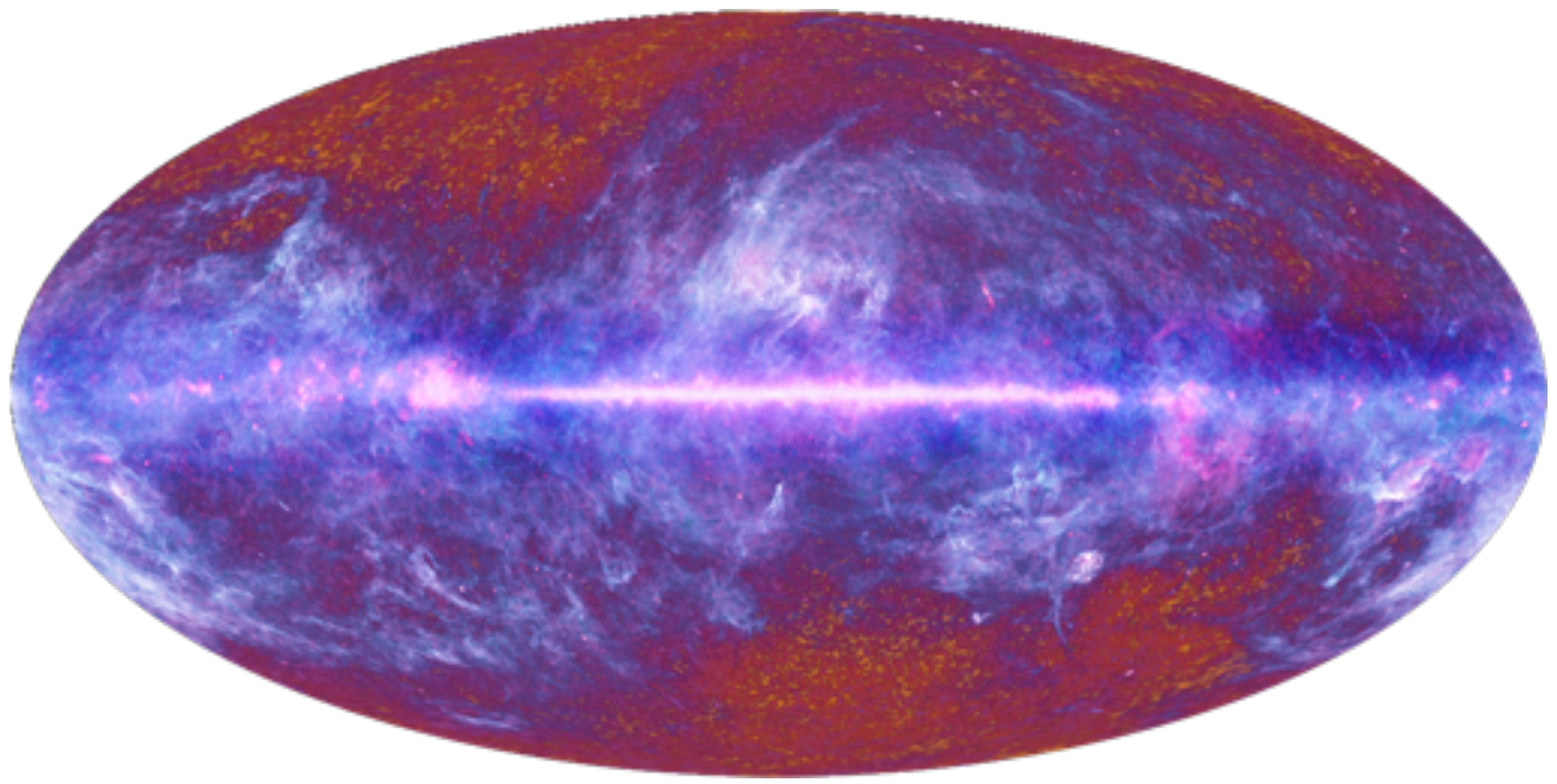
A true angular symmetry would be a clue to new fundamental physics

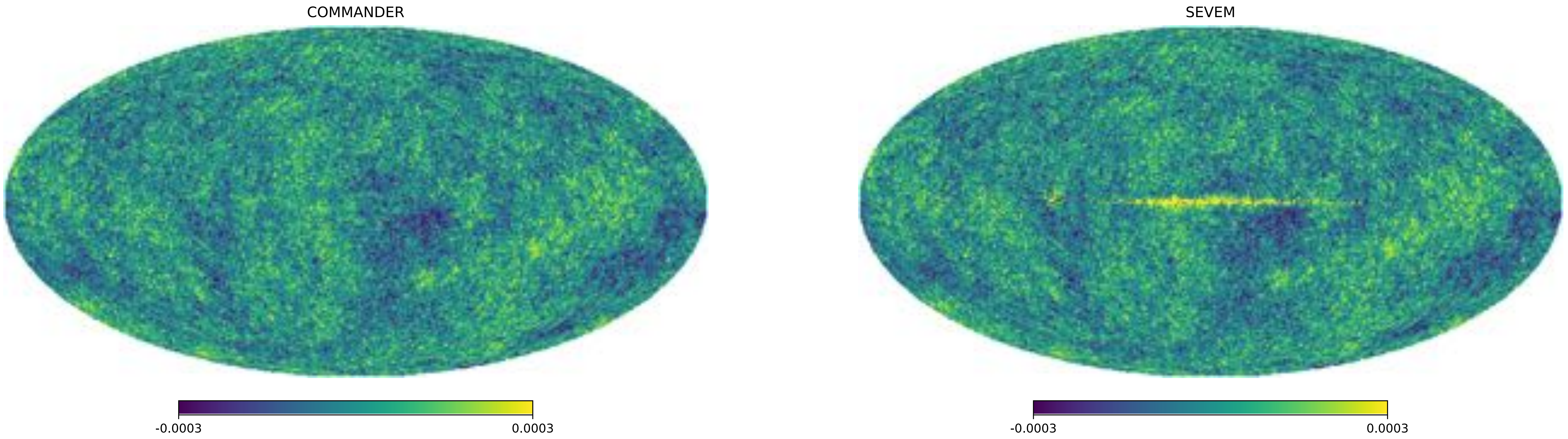


`` As far as I can see, all a priori statements in physics have their origin in symmetry.''
—- Hermann Weyl



Challenge for measurement of precise angular symmetries on the real sky: foreground Galactic emission





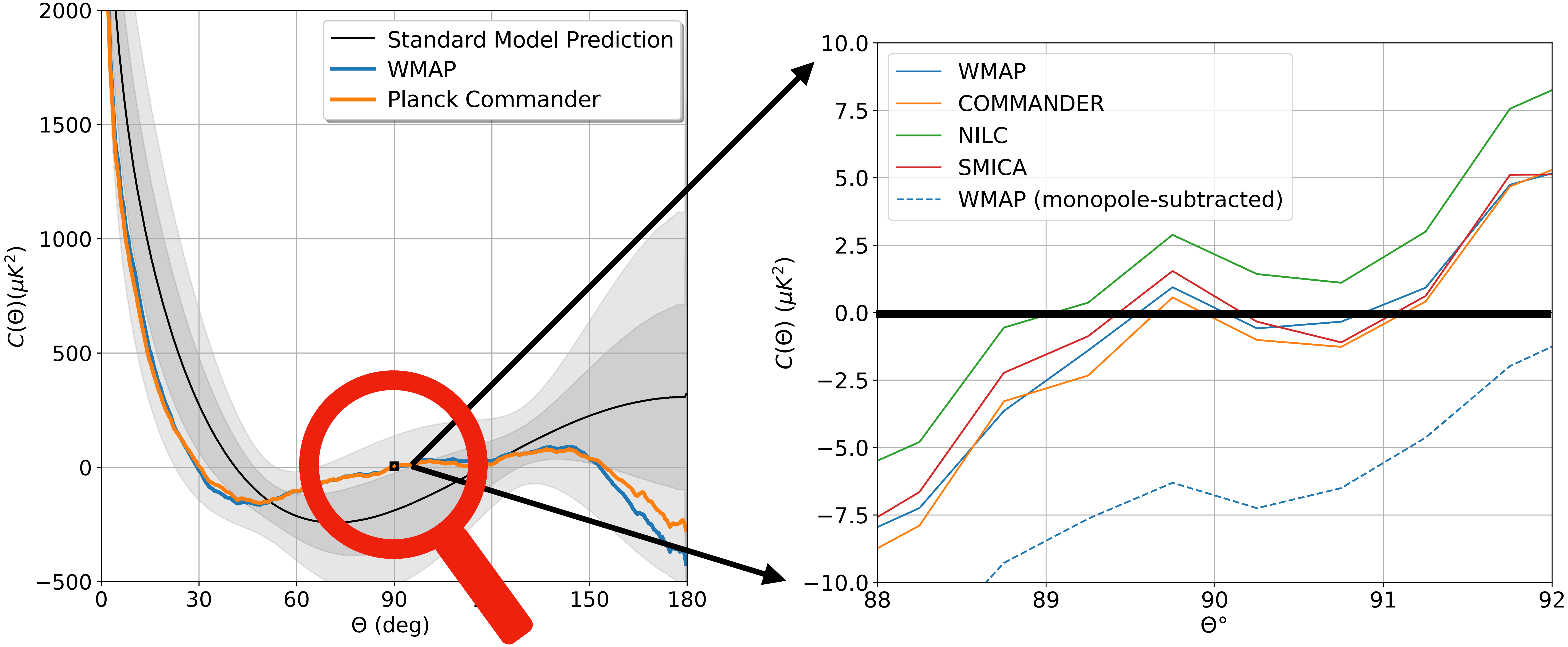
Reconstructed Planck CMB sky with two different foreground models (note problem with SEVEM in the Galactic plane)

Planck and WMAP correlation functions near $\Theta = 90^\circ$, *with no masks,*
show agreement of maps from different satellites and foreground models

Range at 90° is remarkably small, and consistent with exactly zero

zero is a special number, 90° is a special angle

Miracle or symmetry?



Symmetries of CMB Temperature Correlation at Large Angular Separations
Hagimoto, Hogan, Lewin, Meyer, 2020
https://arxiv.org/abs/1910.13989
The Astrophysical Journal Letters, Volume 888, Number 2

Hidden symmetry at other angles: effect of dipole subtraction

Because of a large dipole $\delta T \propto \cos(\theta)$ from our peculiar motion, the primordial dipole is not measured

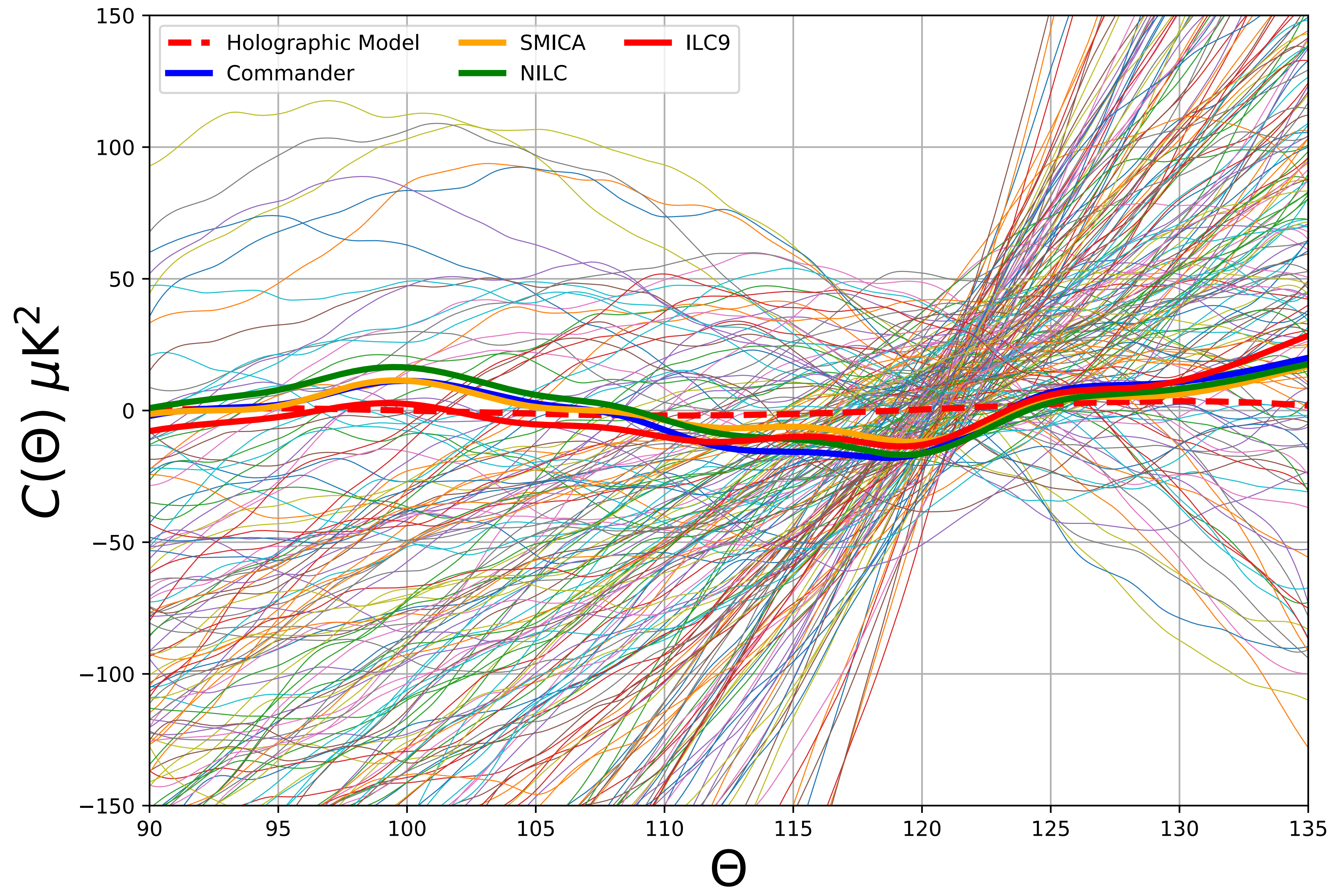
Primordial dipole contributes correlation of the form $\delta C(\Theta) \propto \cos(\Theta)$, which vanishes at $90°$

Dipole subtraction changes measured correlation by $\delta C(\Theta) \sim -\cos(\Theta)$

Allowing for the unobserved dipole and Galactic contamination, data are consistent with zero angular correlation not only at $\Theta = 90°$, but over a wide range of angles

this symmetry of the real sky is extremely improbable in standard inflation

Could it be a new angular symmetry of quantum gravity?

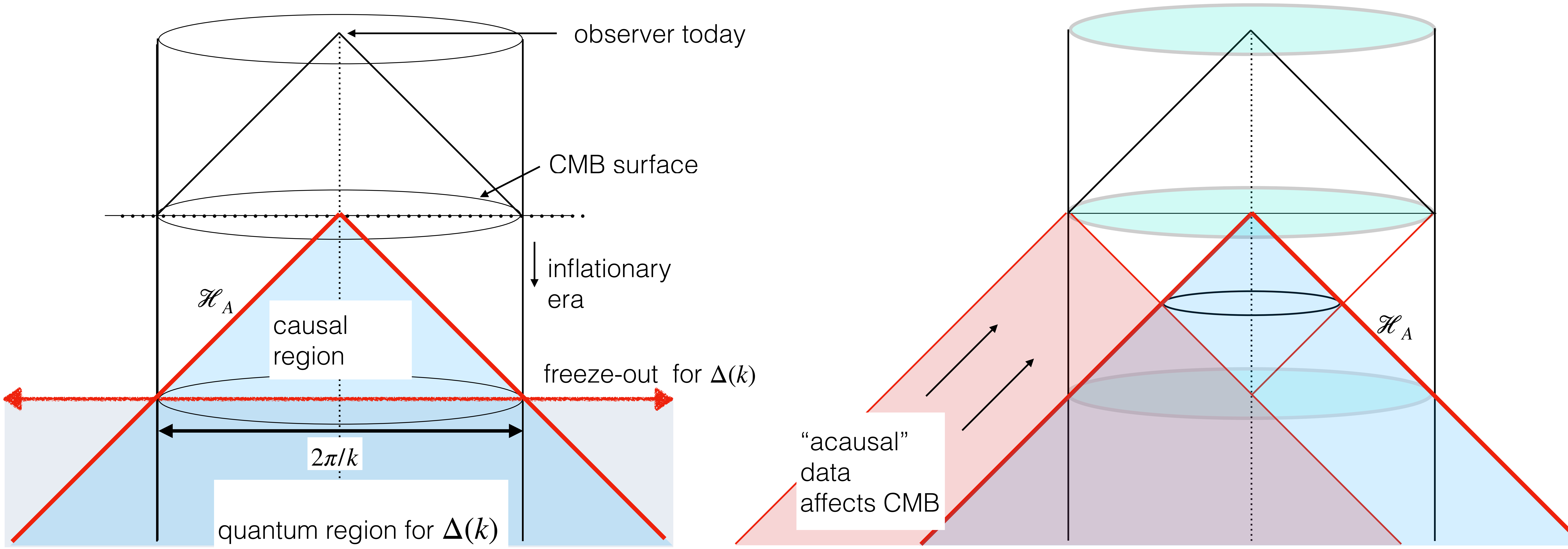


Large angle pattern is sensitive to long wavelength modes

Standard quantum inflation model based on field theory is acausally coherent on constant time surfaces

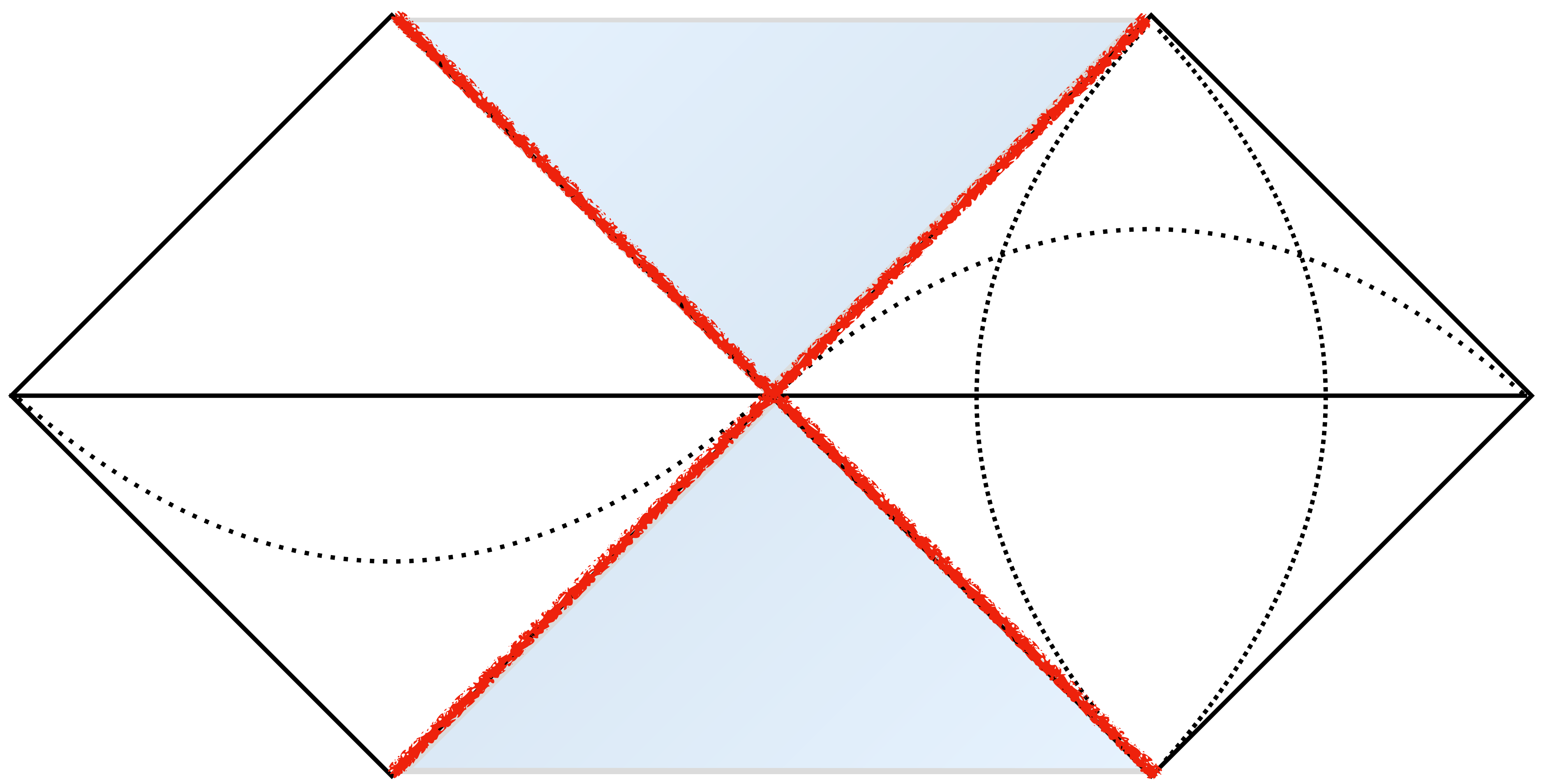
Radical alternative proposed here: coherence on causal diamonds

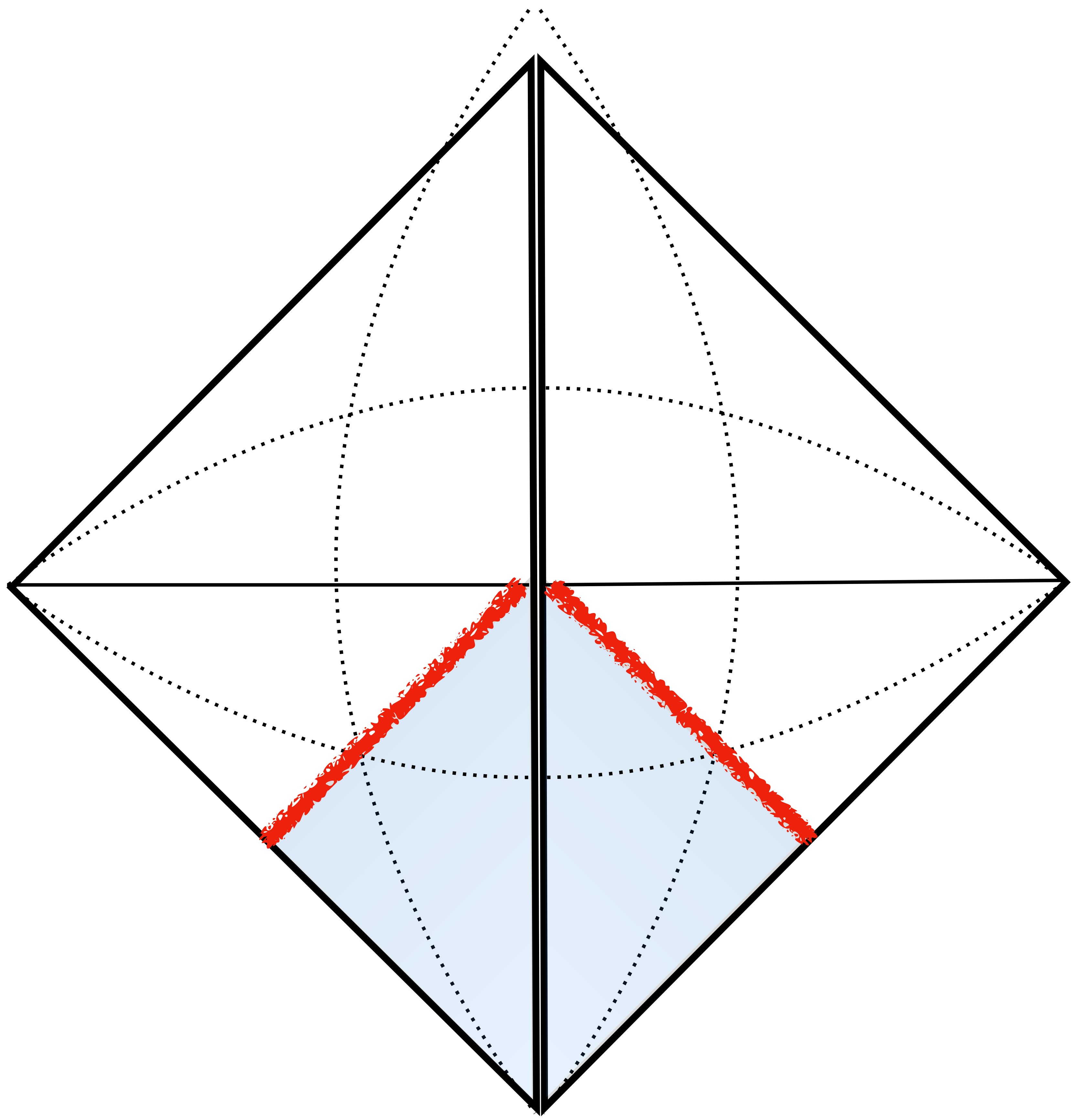
Comoving conformal causal diagram of standard inflation



Suppose quantum geometrical states are coherent on causal diamonds instead of constant-time surfaces

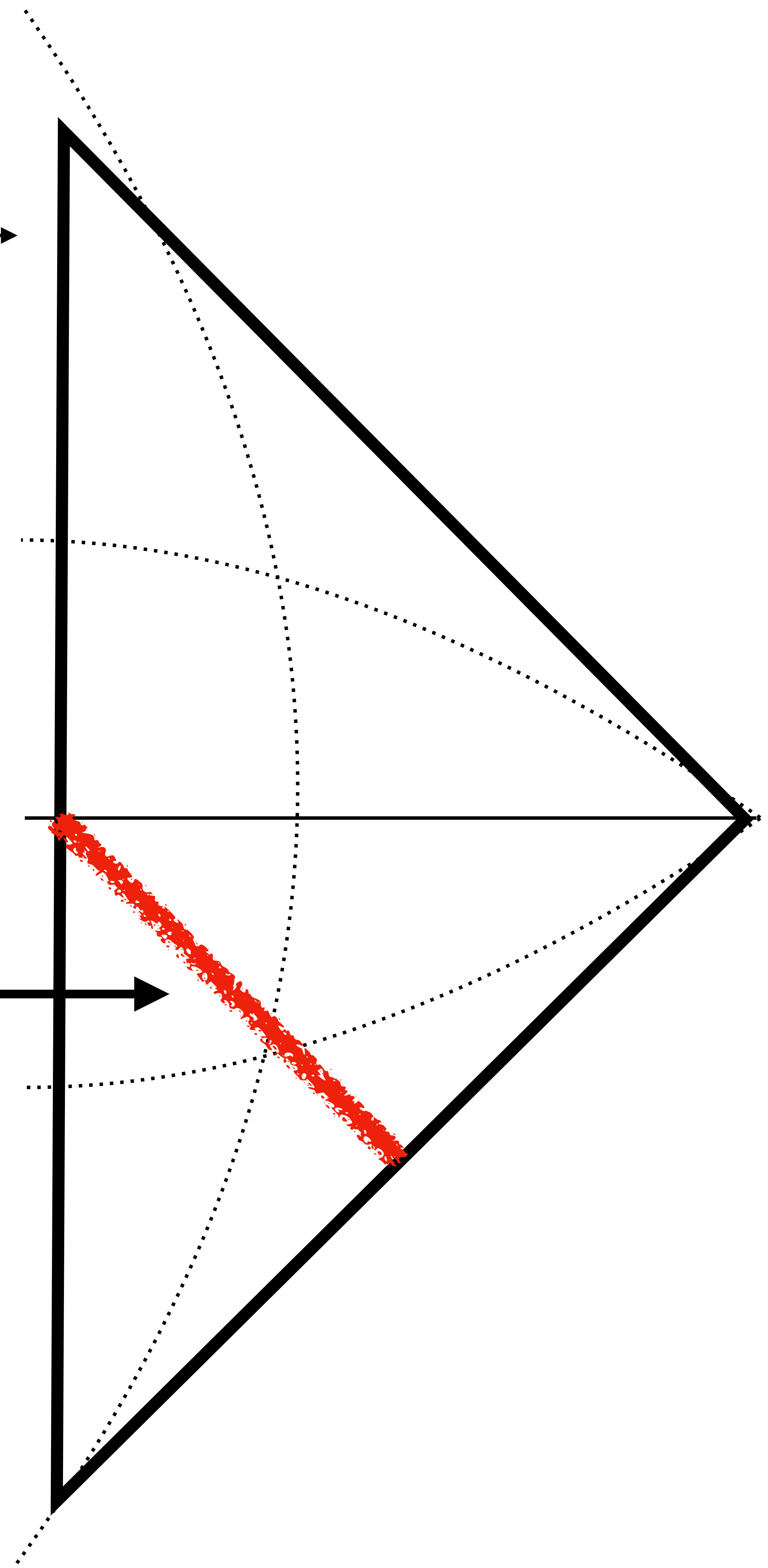
black hole and inflationary horizons are then coherent objects





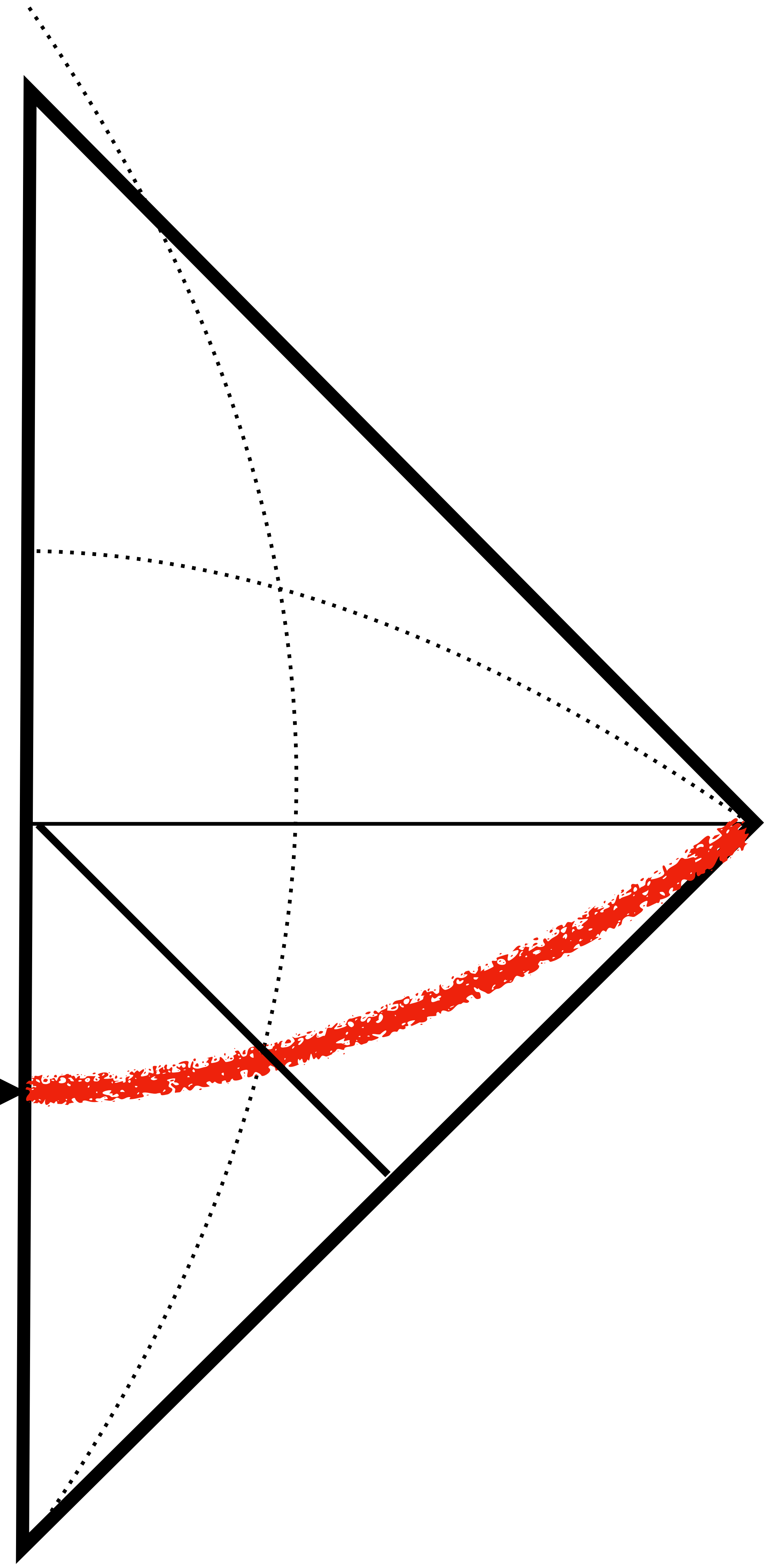
causally coherent inflationary horizon

observer's world line



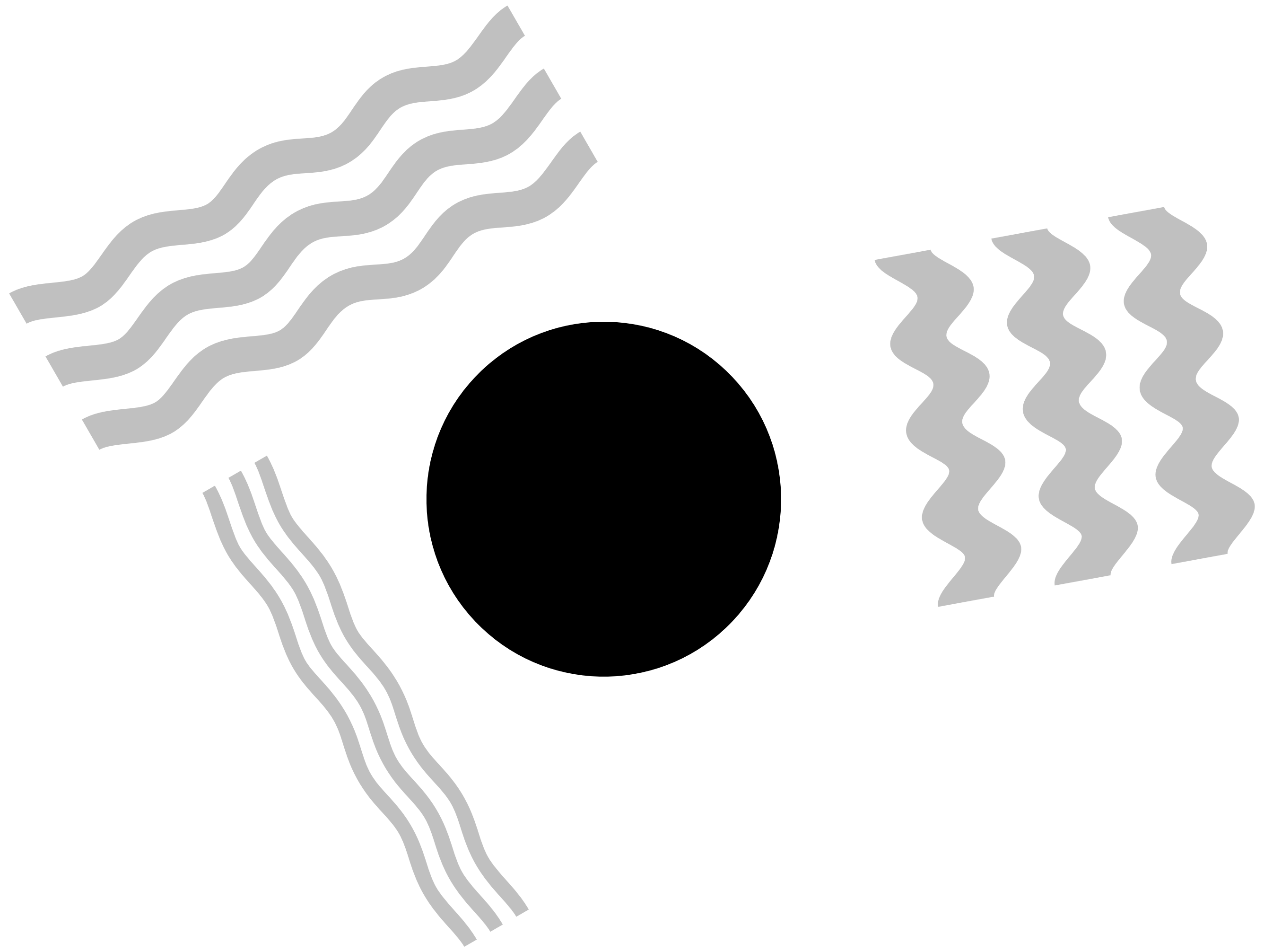
inflationary horizon
incoming light cone that arrives at the end of inflation

standard coherent mode

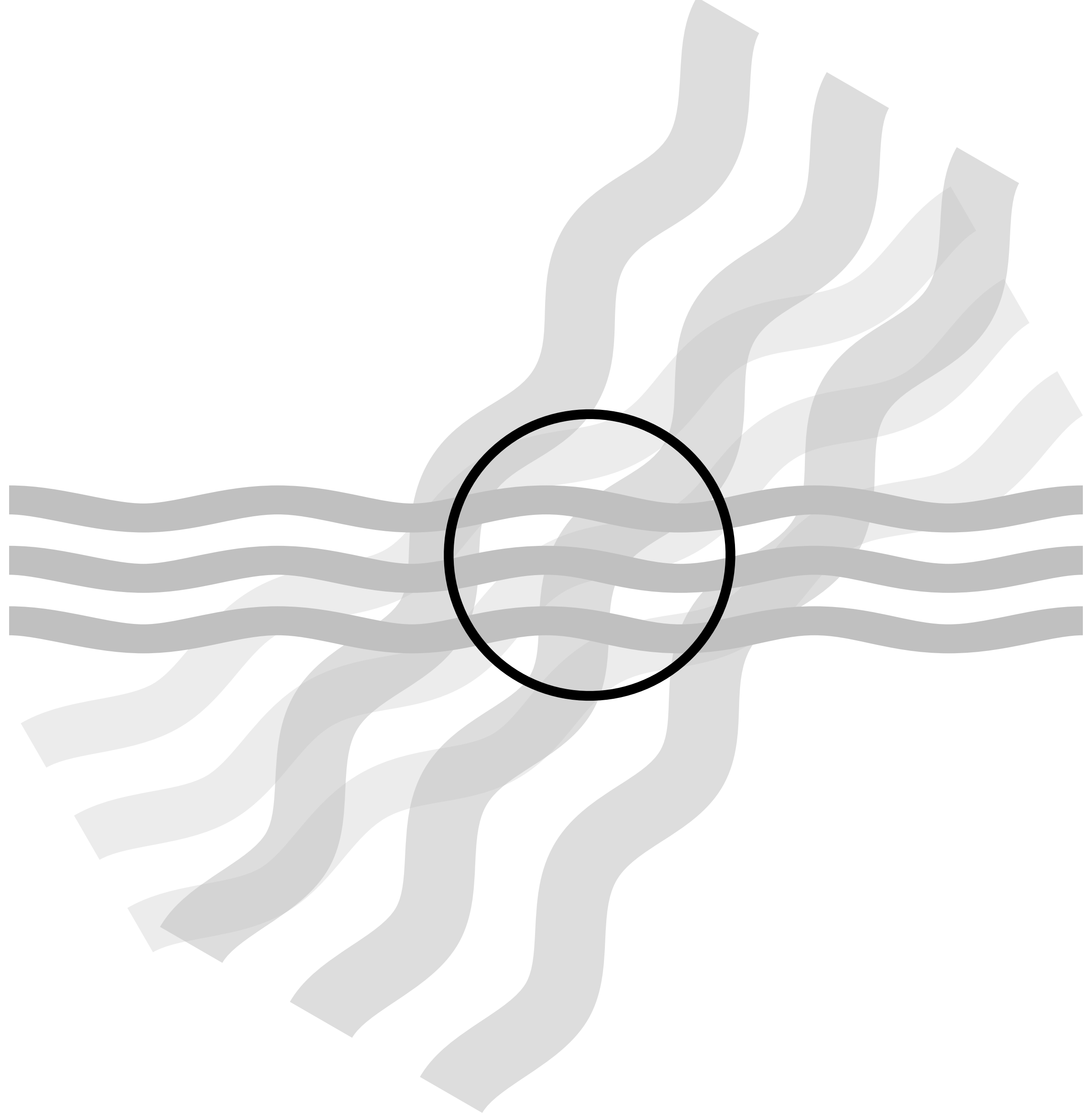


constant time surface

a black hole horizon that radiates and absorbs independent local field modes has too much information to be consistent with black hole entropy

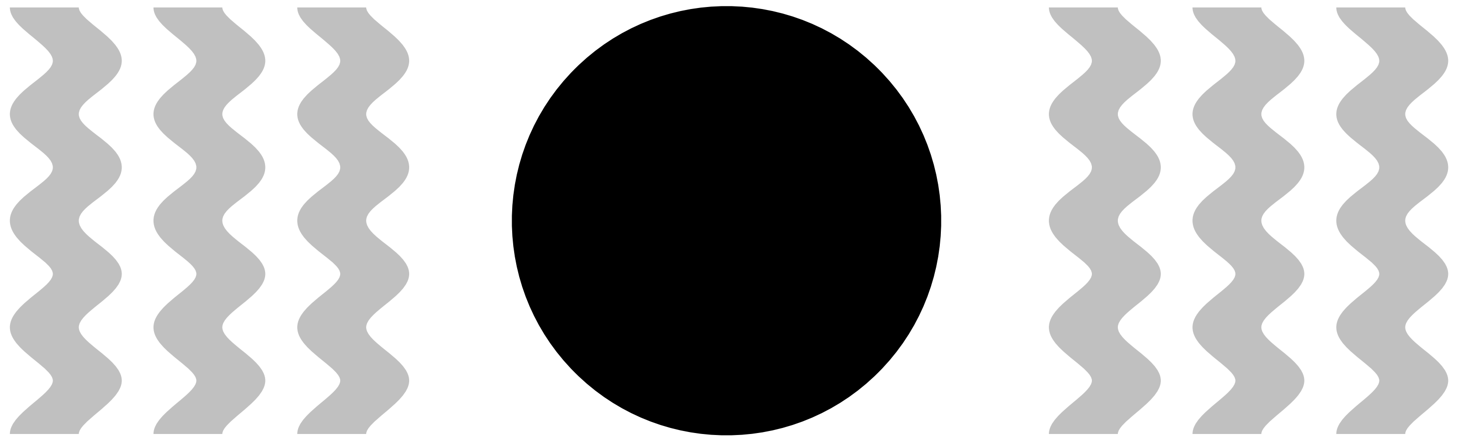


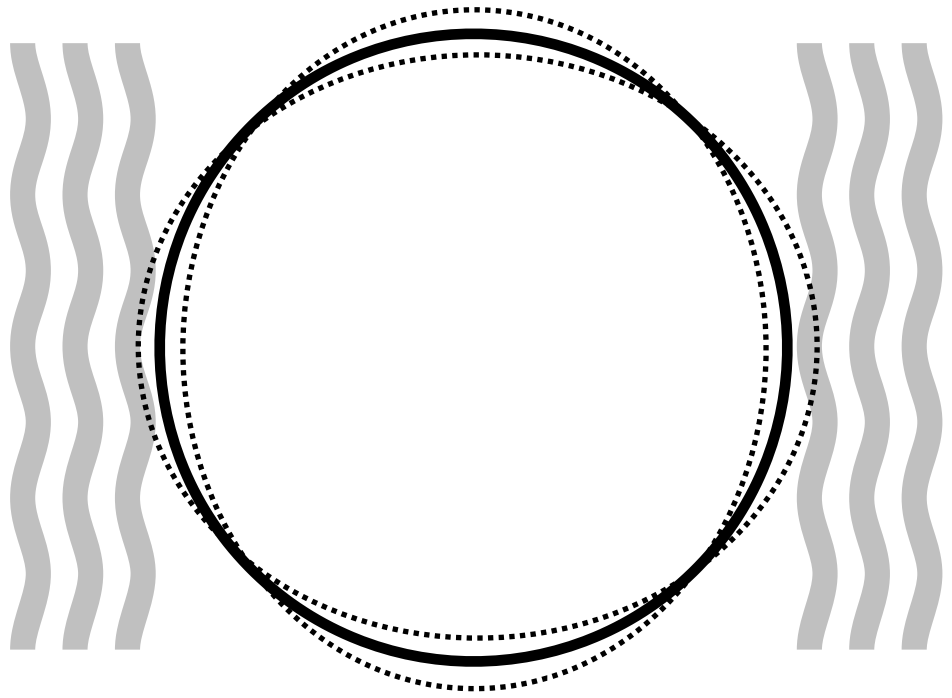
same problem for standard quantum model of the inflationary horizon



solution: coherent gravitational states on causal diamonds

coherent horizons and causal diamonds are like atoms: coherent quantum objects

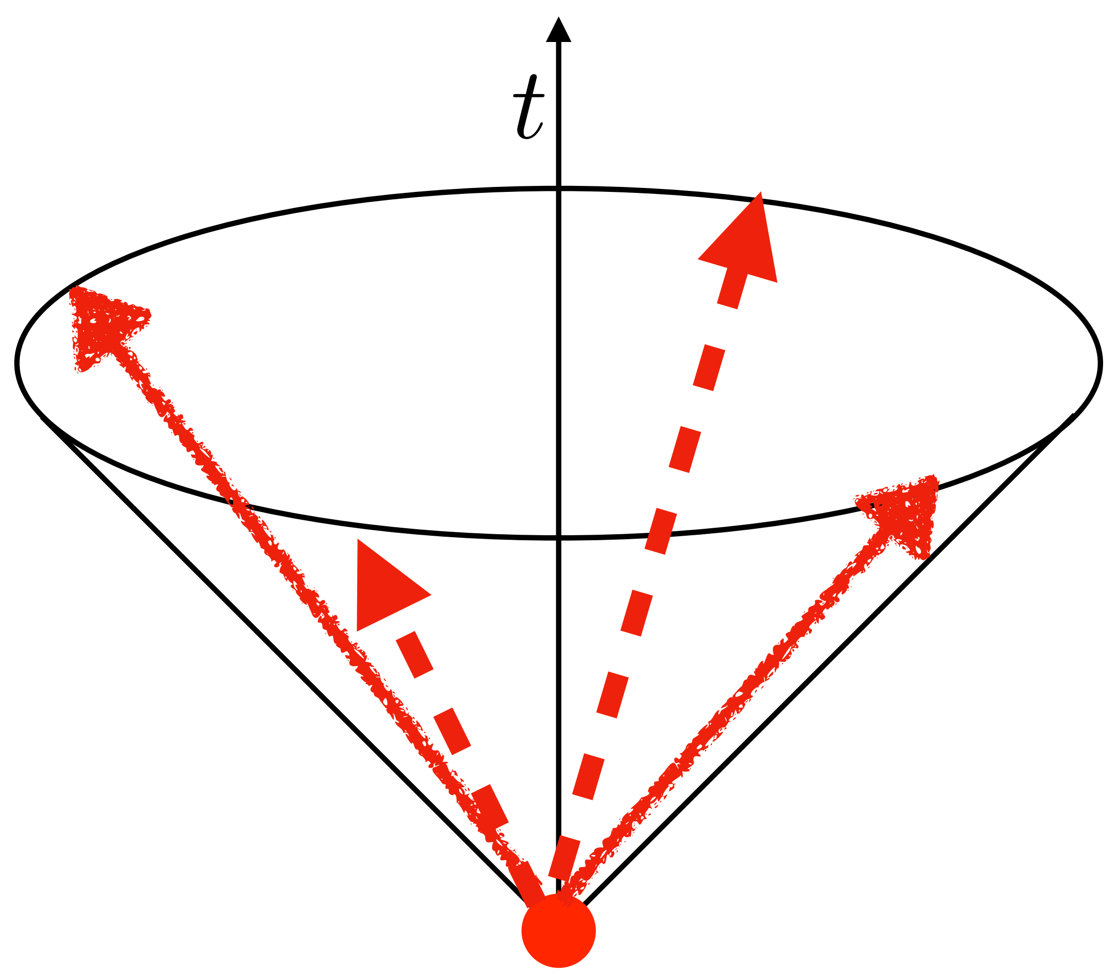




Quantum gravity somehow has to include nonlocal, coherent, causal directional correlations of ***geometry itself***

"…in the gravitational theory we should be able in principle to dispense with the concepts of space and time and take as the basis of our description of nature the elementary concepts of world line and light cone."

— John Wheeler, 1946

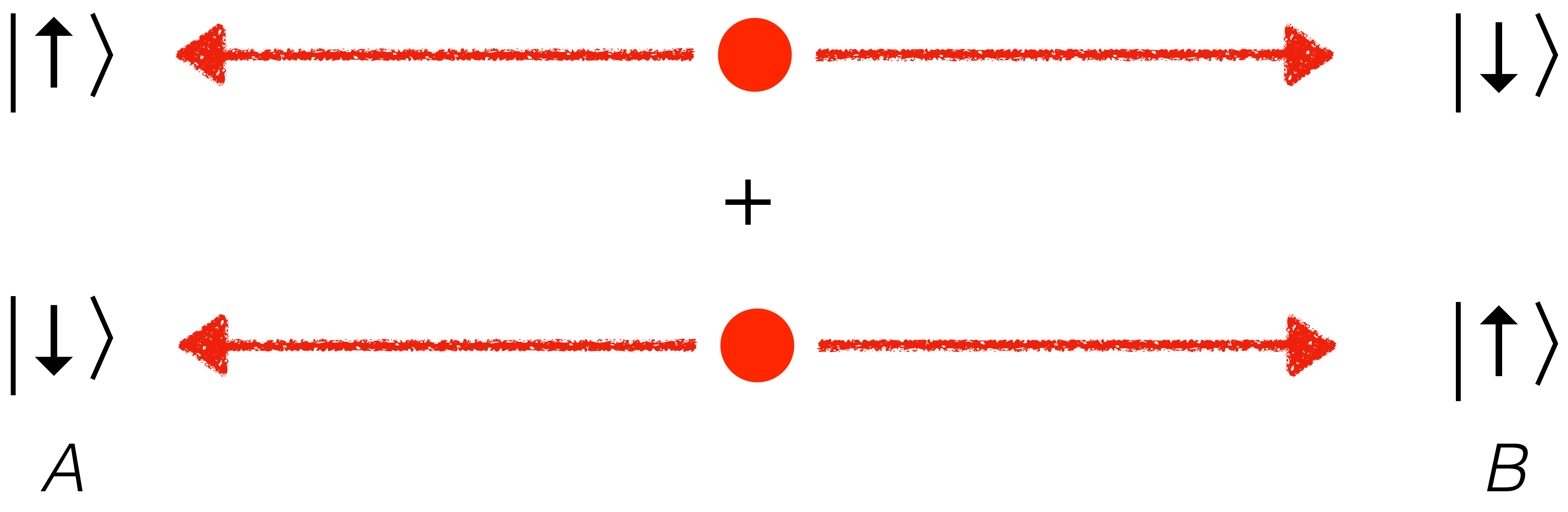


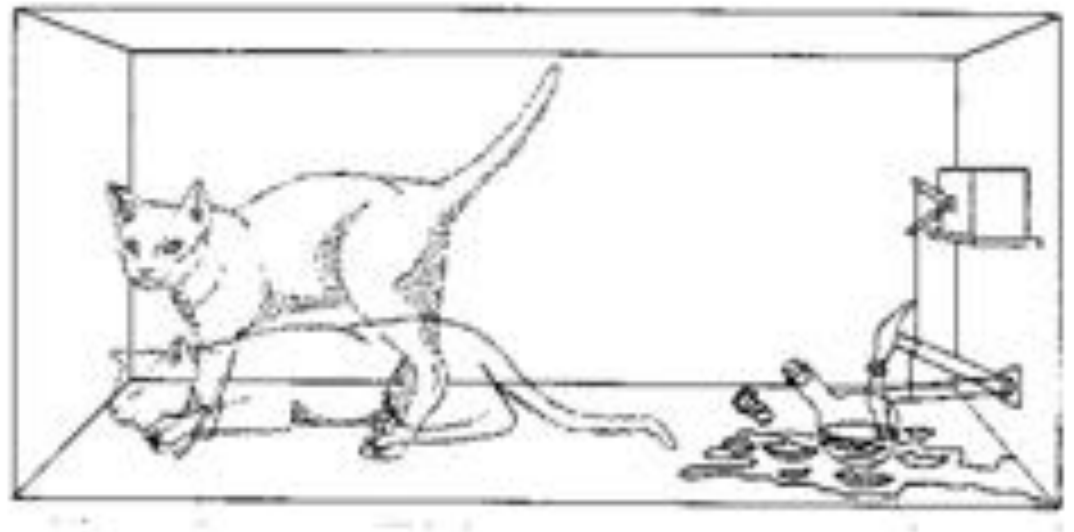
Original example of "spooky" nonlocal entanglement: Einstein-Podolsky-Rosen (EPR) system (1935)

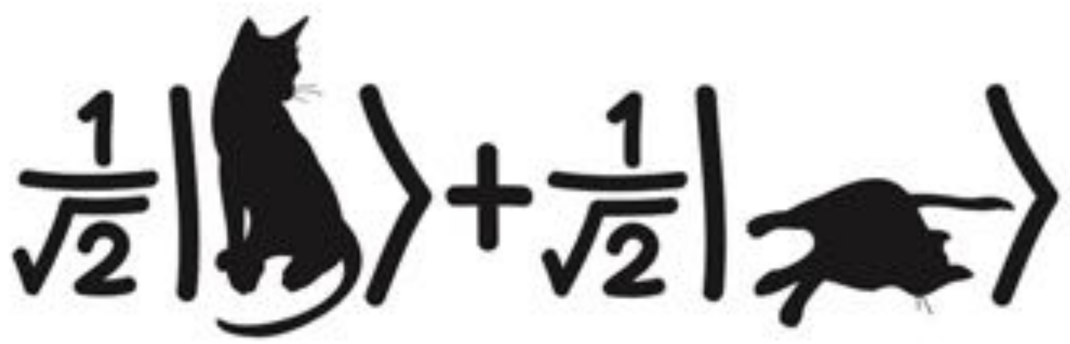
Positronium atom decays by annihilation
Photons travel in opposite directions
Their states are "entangled" (Schrödinger)

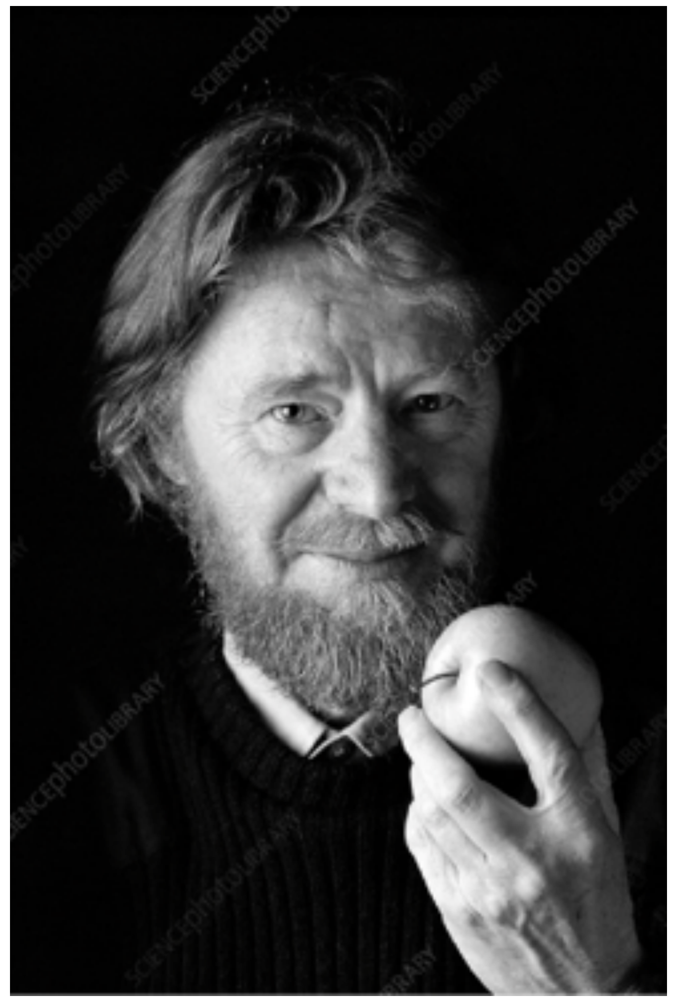
spooky correlations between entangled "EPR pairs" have been measured with Earth-scale separations

$$\frac{1}{\sqrt{2}}|\uparrow\rangle_A\,|\downarrow\rangle_B + \frac{1}{\sqrt{2}}|\downarrow\rangle_A\,|\uparrow\rangle_B$$







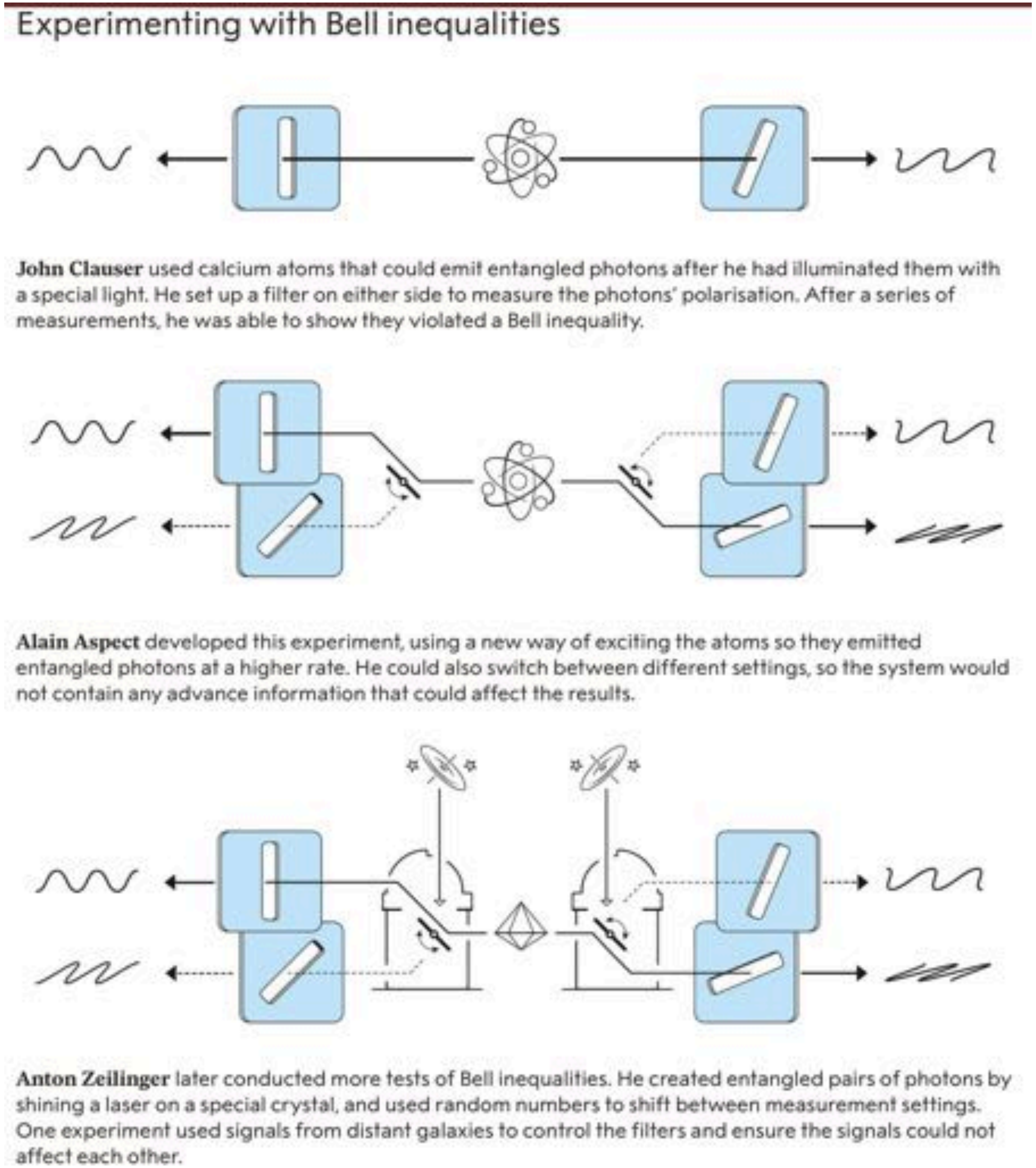


John Bell

Nobel Prize in Physics, 2022

Clauser, Aspect, Zeilinger: experiment proof of nonlocal, spooky entanglement

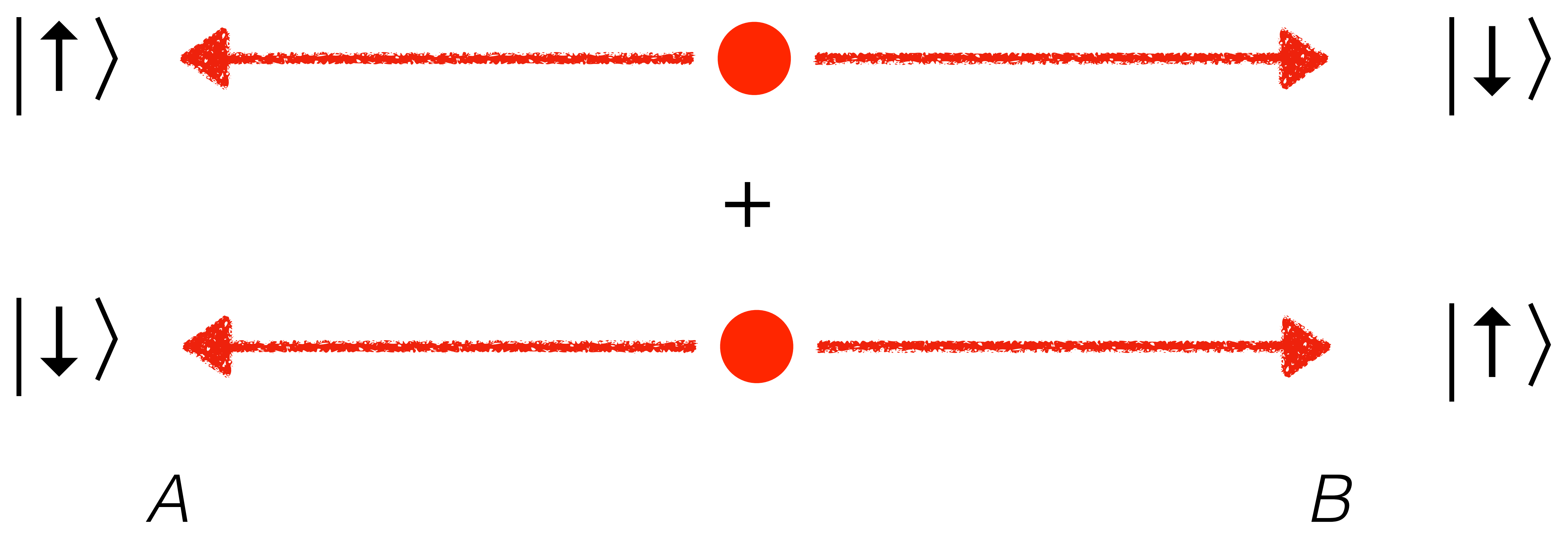
Spatially separate events are not independent: nothing happens at a definite place and time



Quantum nonlocality, “spooky” entanglement, and coherence in the EPR system

Measurement of “one” nonlocally affects the state of the “other”
Two particles are not really separate: they are a single “coherent” system
Preparation and measurement are causal
Projection of state is set by measurement *(e.g.,* ↘↖, ↻↺, ↑↓, …)

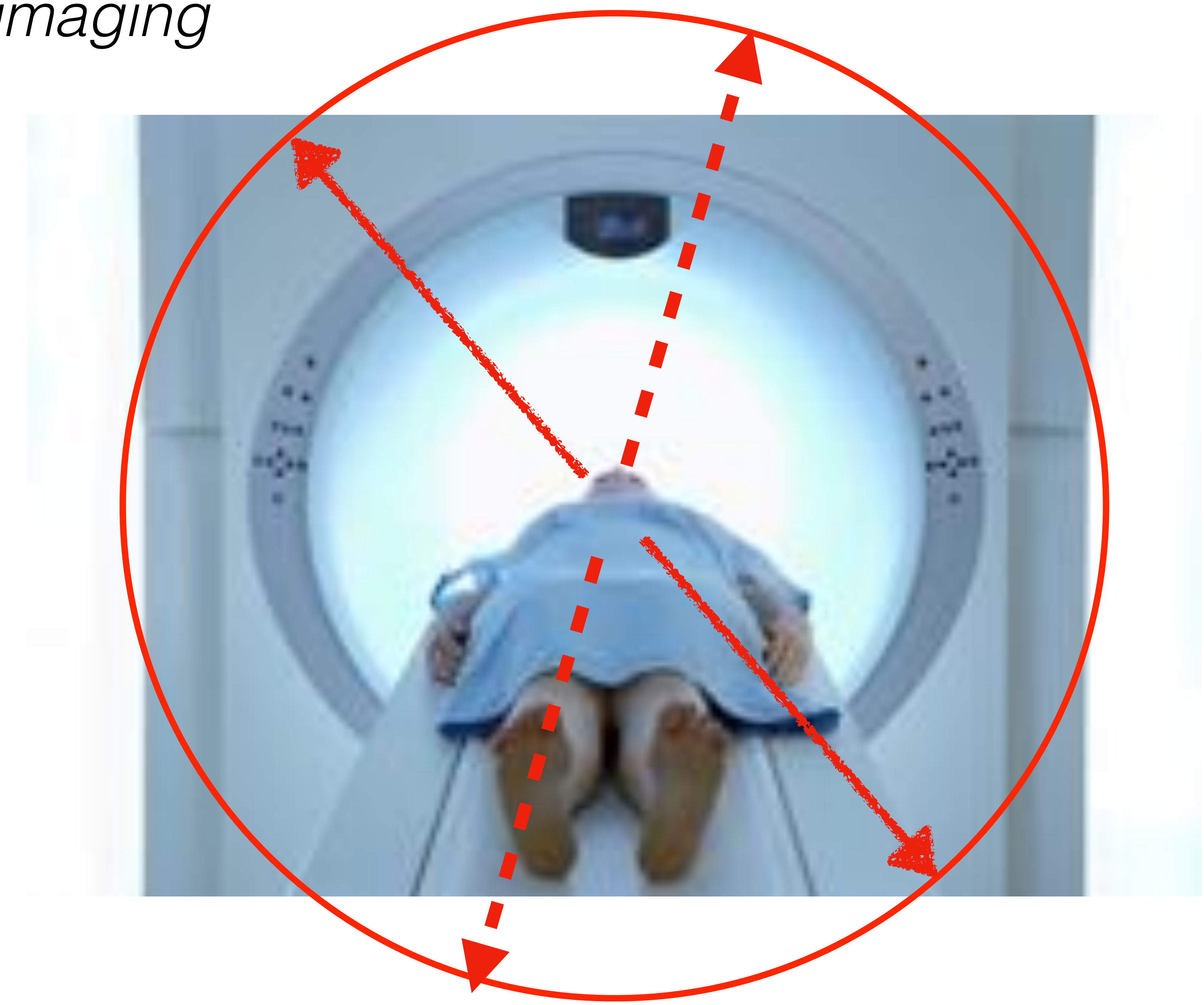
$$\frac{1}{\sqrt{2}}|\uparrow\rangle_A\,|\downarrow\rangle_B + \frac{1}{\sqrt{2}}|\downarrow\rangle_A\,|\uparrow\rangle_B$$



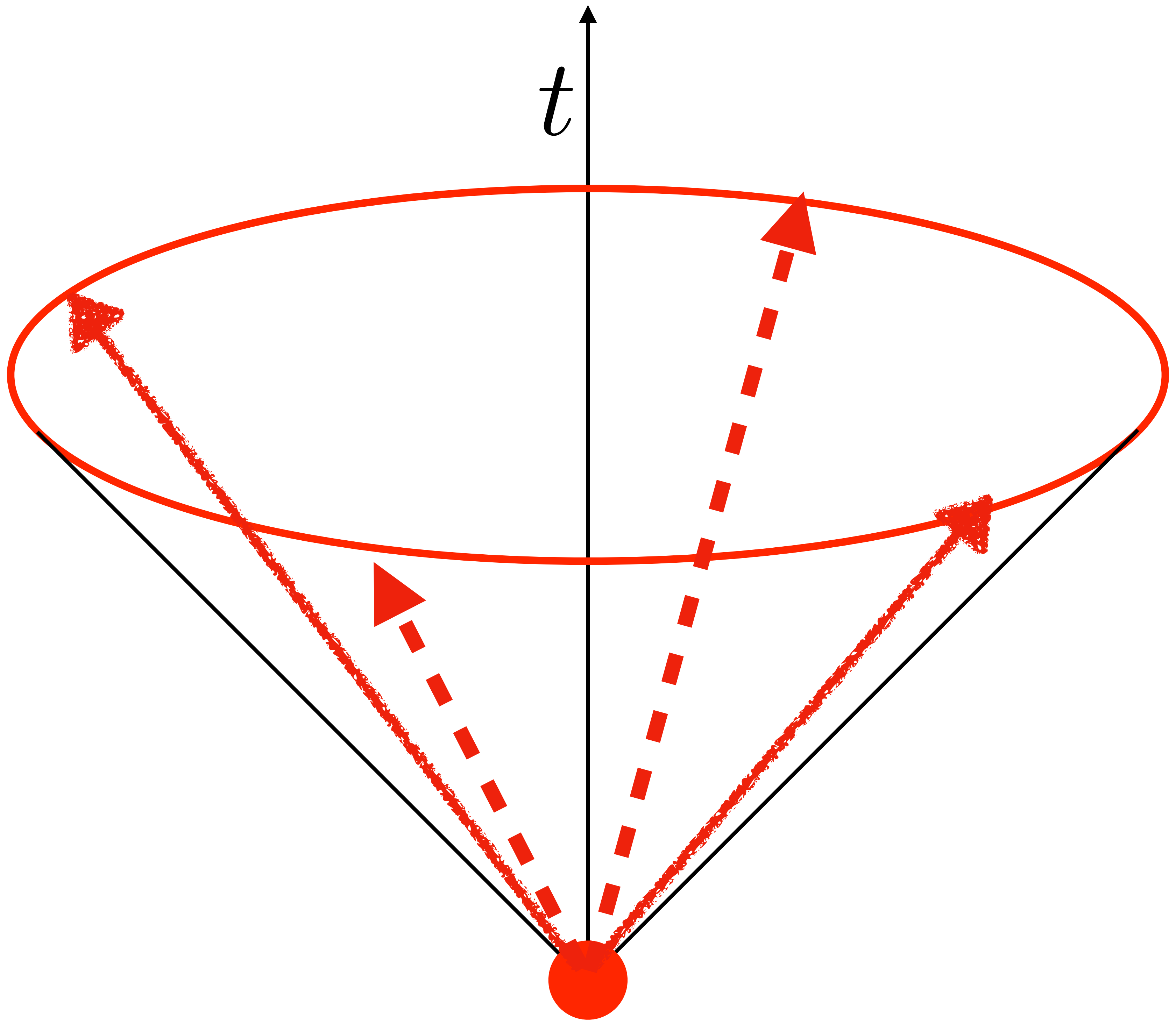
EPR system: spooky nonlocal entanglement of past and future

Quantum state of “two” photons lives on a light cone
Causal coherence extends indefinitely on the light cone in all directions
Nonlocal spacelike correlation of directions has real-world applications

PET imaging



World line of sample

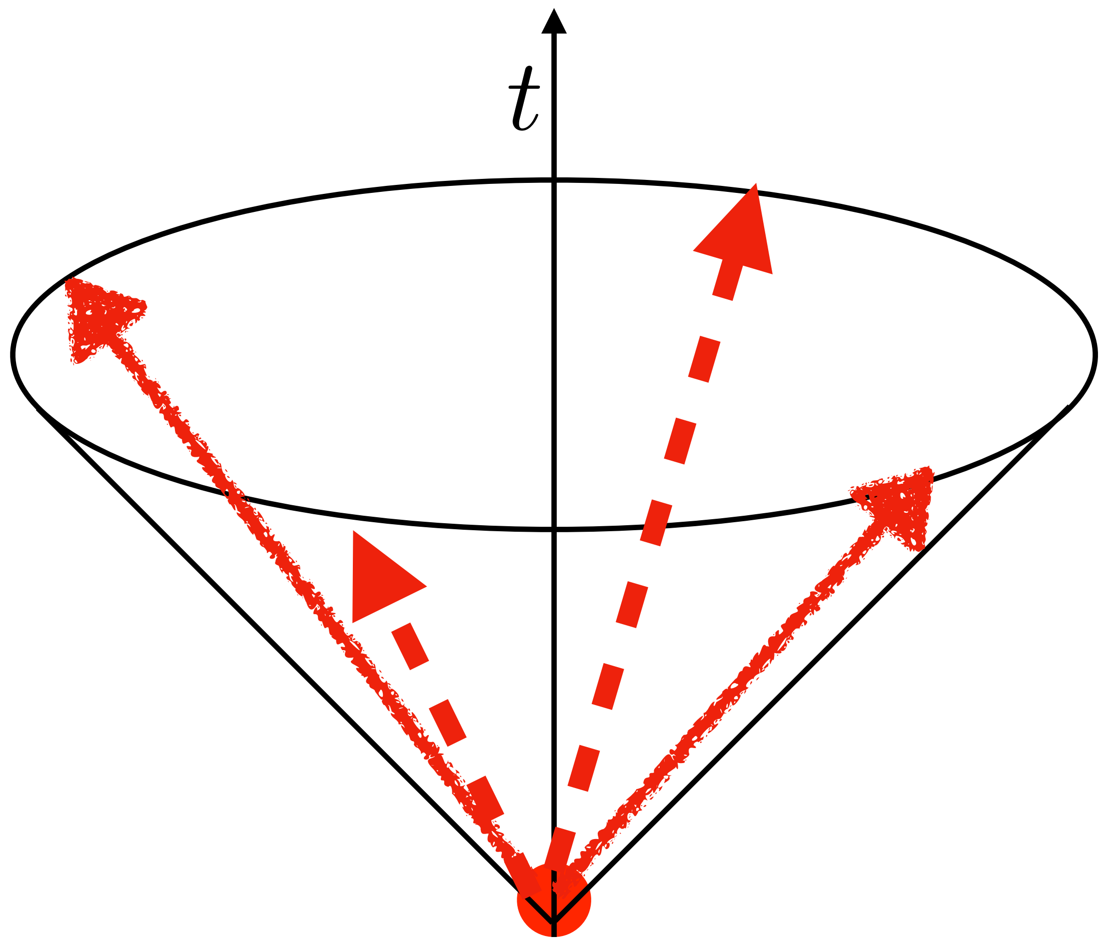


Quantum mechanics nonlocally entangles the past and the future on causal diamonds

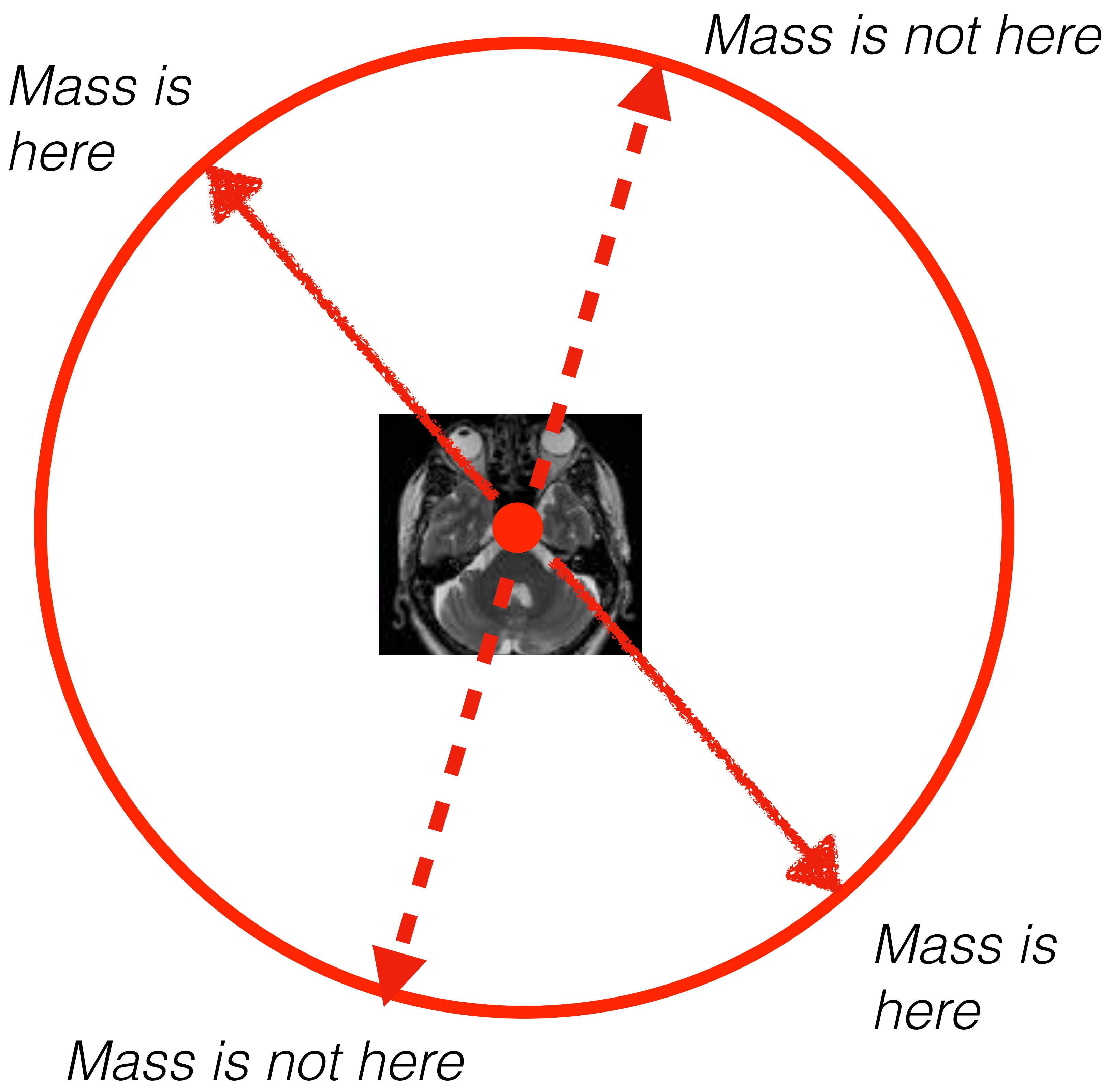
State is reduced nonlocally by measurement on spacelike surface
Quantum gravity must be consistent with the mass distribution for any measurement choice

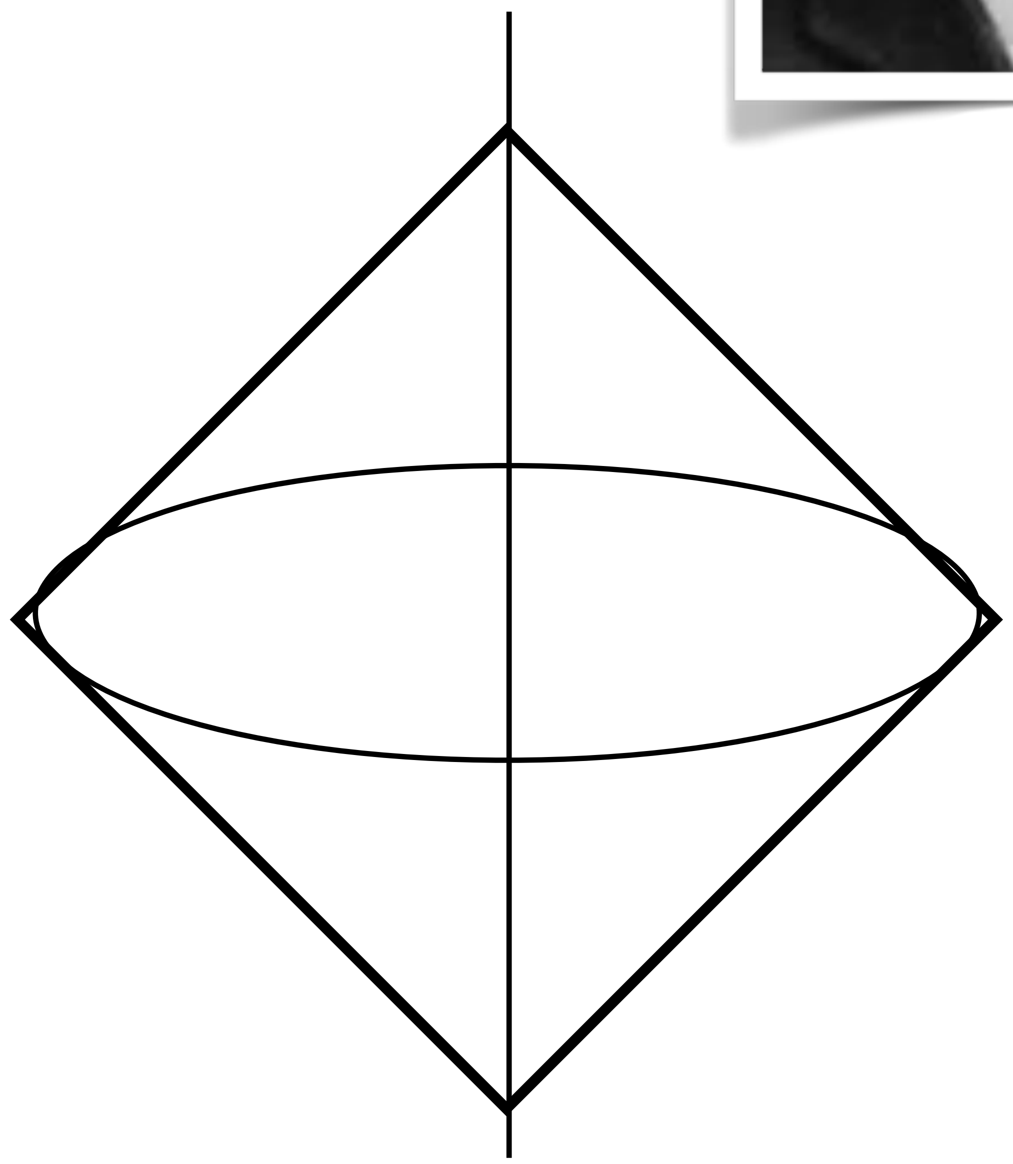
Coherence of causal structures must match coherence of matter states

Wave function of space-time is causally coherent



https://arxiv.org/abs/1412.1807



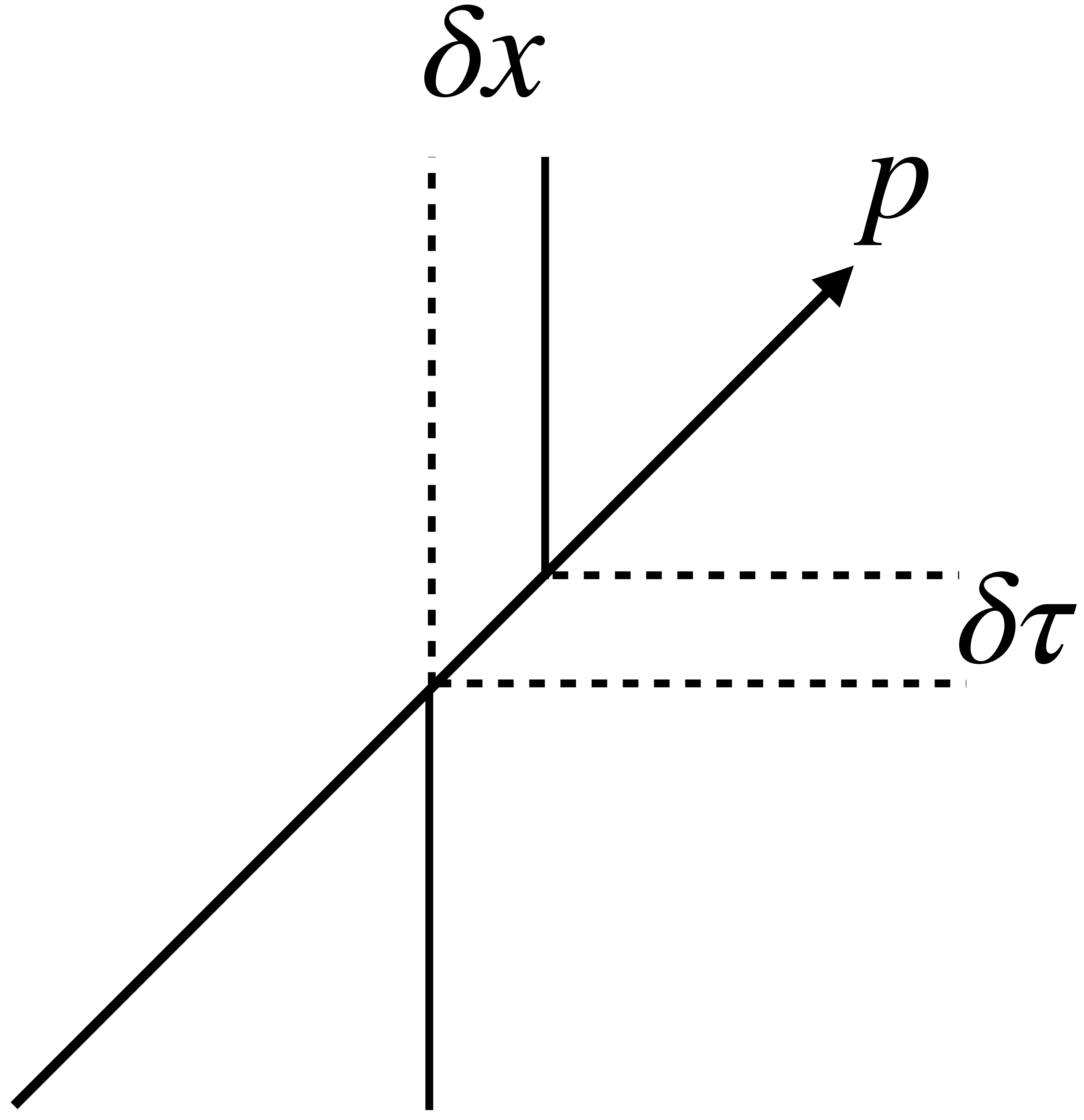


Causally coherent classical gravity

null gravitational shock of photon

photon with momentum p creates discontinuous shift of position and causal structure

$$\delta\tau = \delta x / c = Gp/c^4$$



Gravity of the EPR system (two-photon decay)

axially symmetric displacements on spherical gravitational null shock

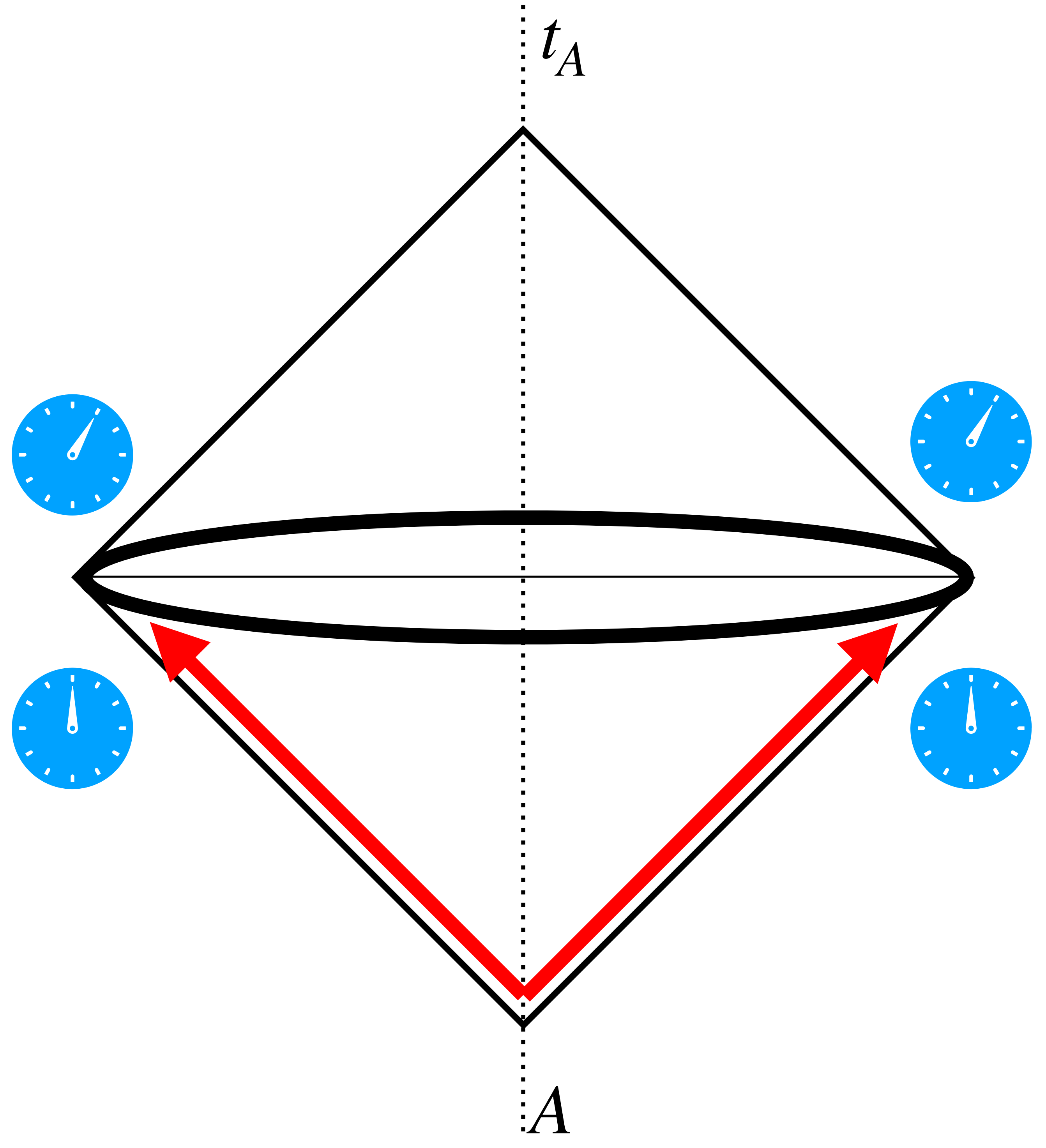
nonlocal anisotropic "gravitational memory" extends indefinitely on a light cone

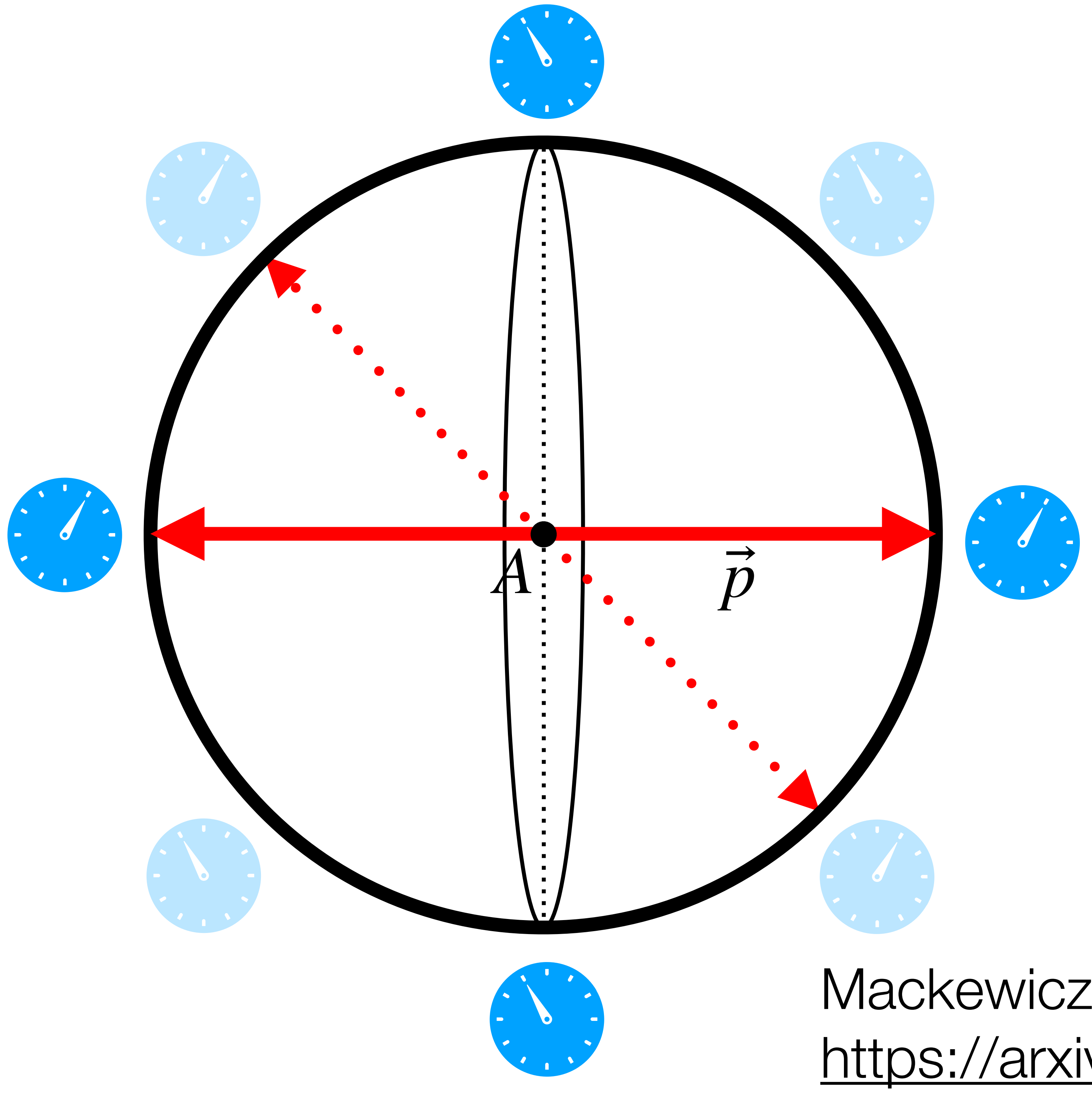
angular spectrum of measured clock displacement is dominated by large angles:

$$\delta\tau_2 = d_{\ell=2}(\theta) = \frac{5}{24}\frac{GM}{c^3}(\cos^2\theta - 1)$$

independent of distance

Implies spooky macroscopic coherence of causal diamond for quantum EPR geometry





Mackewicz and Hogan 2022
https://arxiv.org/abs/2108.03264

Quantum geometry is controlled by the Planck scale

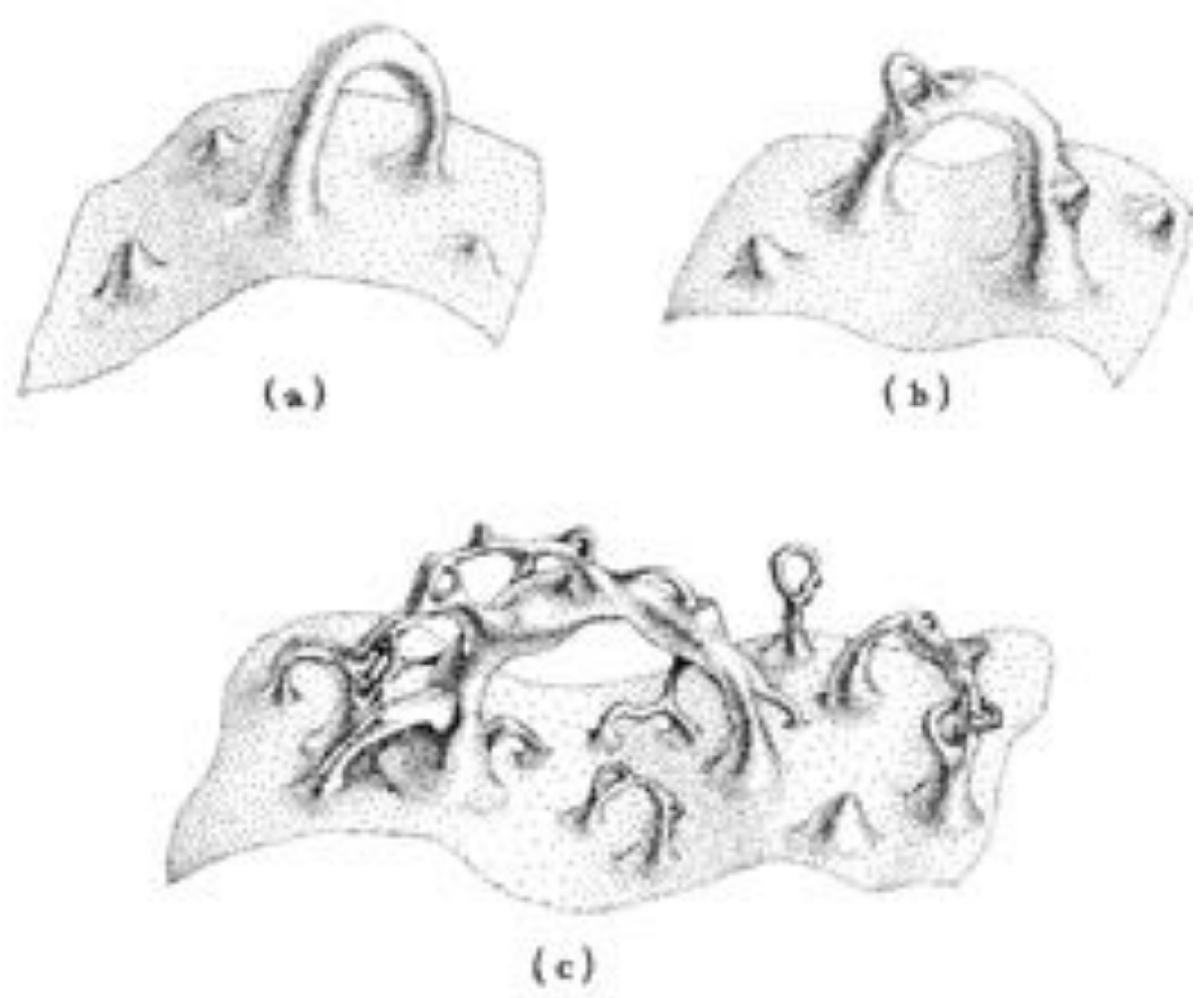
$$t_P \equiv \sqrt{\hbar G/c^5} = 5.4 \times 10^{-44} \text{ sec}$$

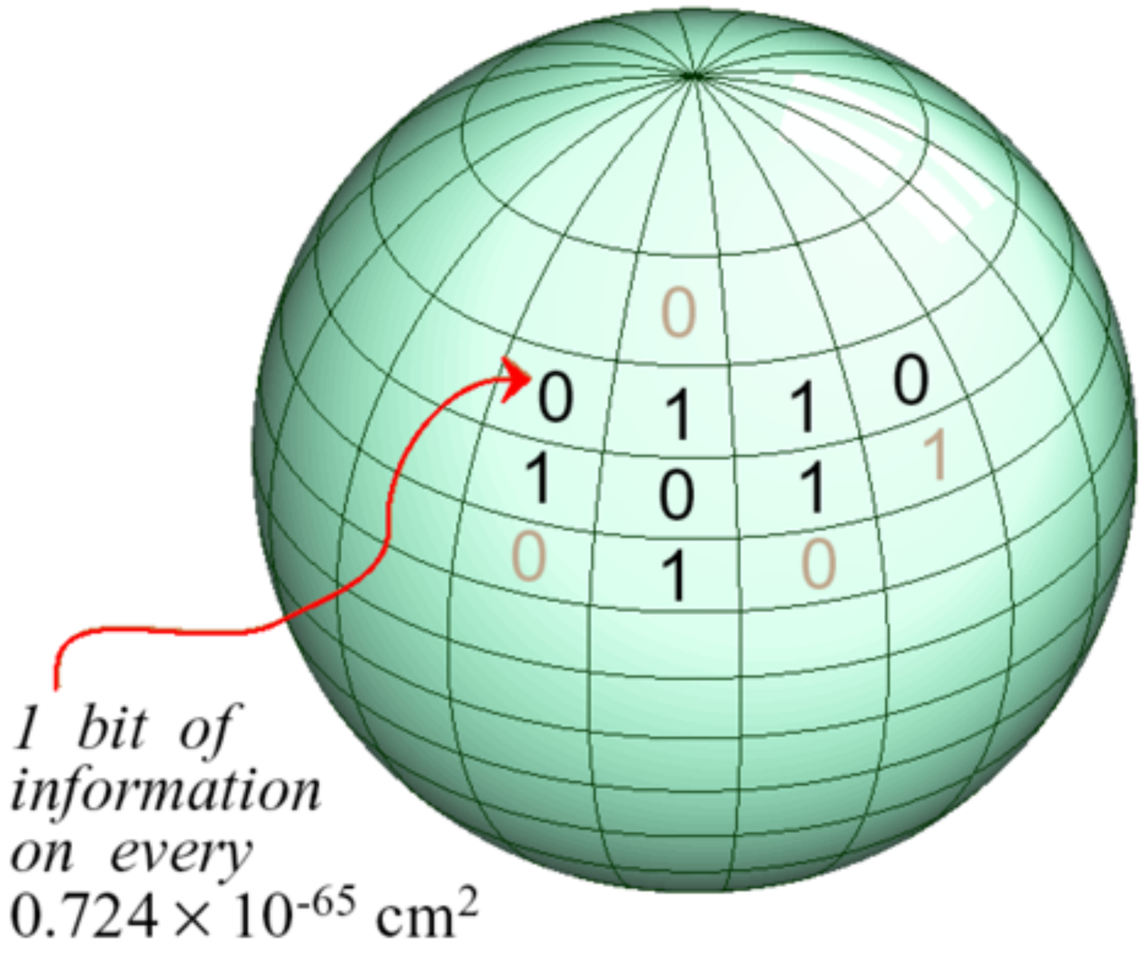
But its quantum coherence is not confined to the Planck scale

Quantum gravity is coherent on macroscopic scales

"If it is true that vacuum fluctuations include virtual black holes, then the structure of space-time is radically different from what is usually thought."

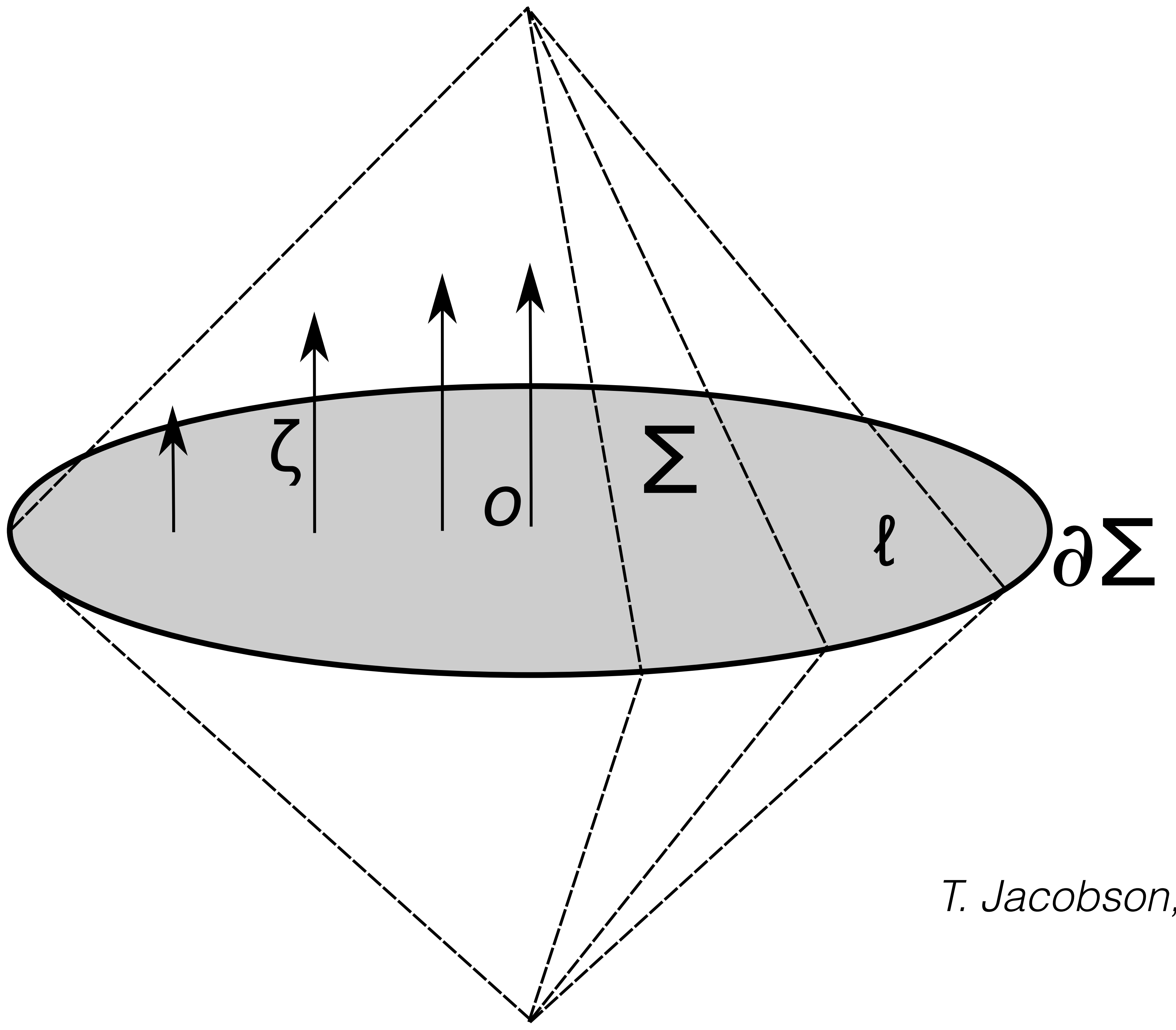
—- G. 't Hooft, Found Phys (2018) 48:1134





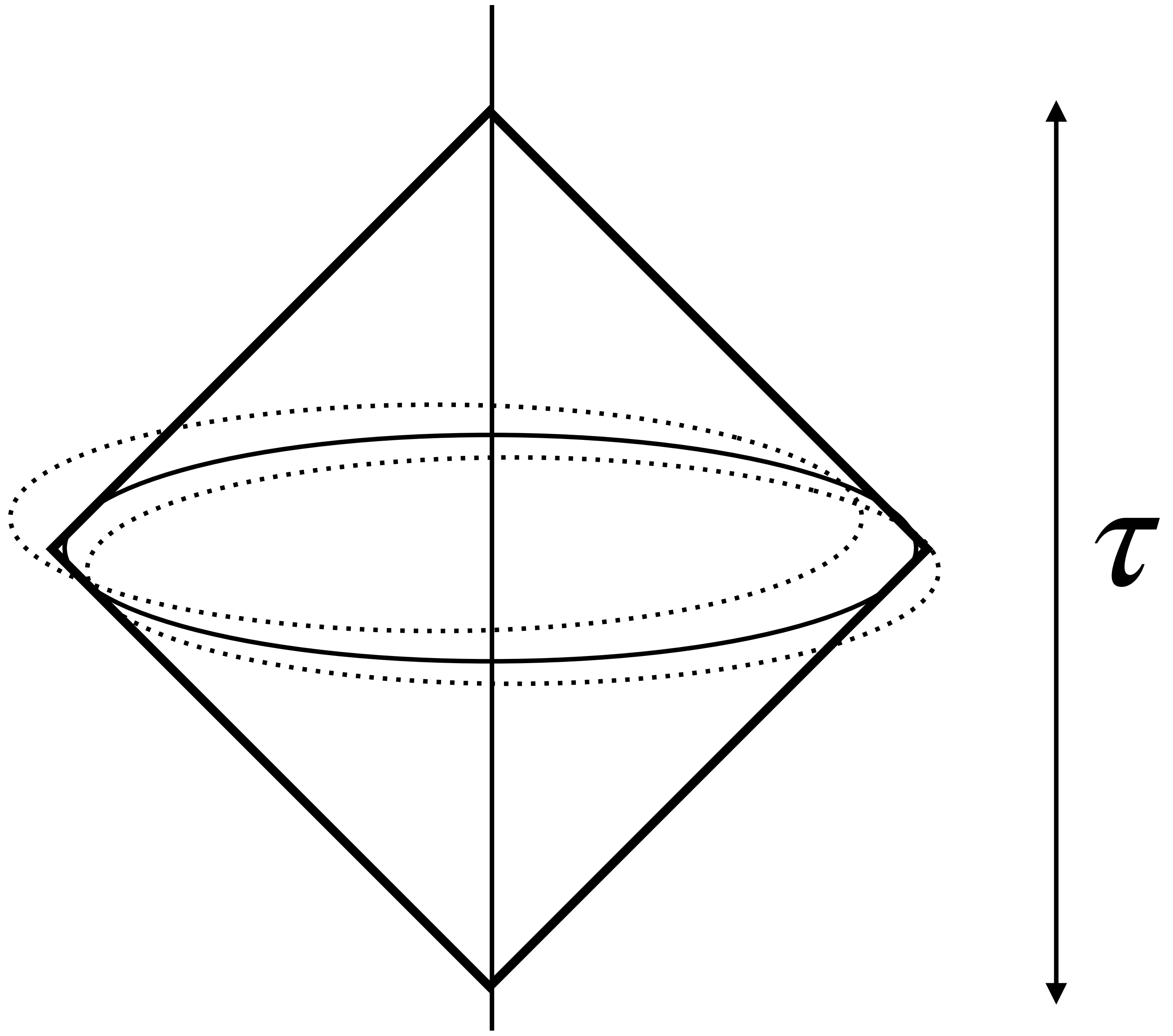
In emergent, entropic, thermodynamic, or holographic gravity, states of causal diamonds are macroscopically and causally coherent

Quantum vacuum fluctuations have large-angle coherence on surfaces of causal diamonds



T. Jacobson, Phys.Rev. Lett. 116 (20) (2016) *coherence produces much larger fluctuations in causal structure than standard zero point fluctuations of fields*

angular structure has fewer independent degrees of freedom, associated with universal angular symmetries



coherent virtual shocks with zero mean and Planck variance lead to

$$\langle \Delta^2 \rangle \sim \langle \delta\tau^2 \rangle / \tau^2 \sim t_P / \tau$$

~ square root of field fluctuation variance

they are comparable to the “standard quantum uncertainty” for measurements of duration τ

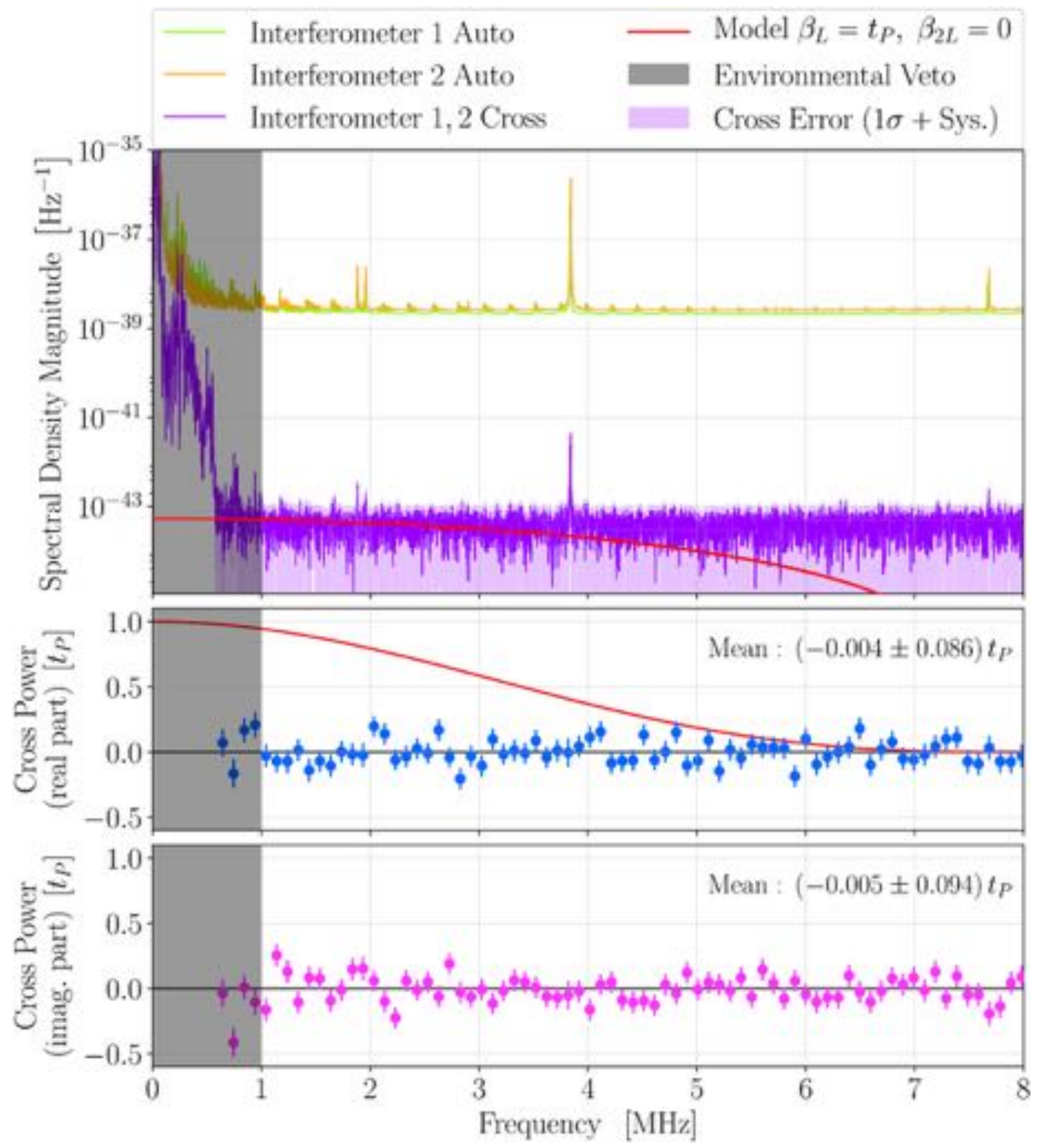
$$\langle \Delta x^2 \rangle > \hbar\tau/m >> (\hbar/mc)^2$$

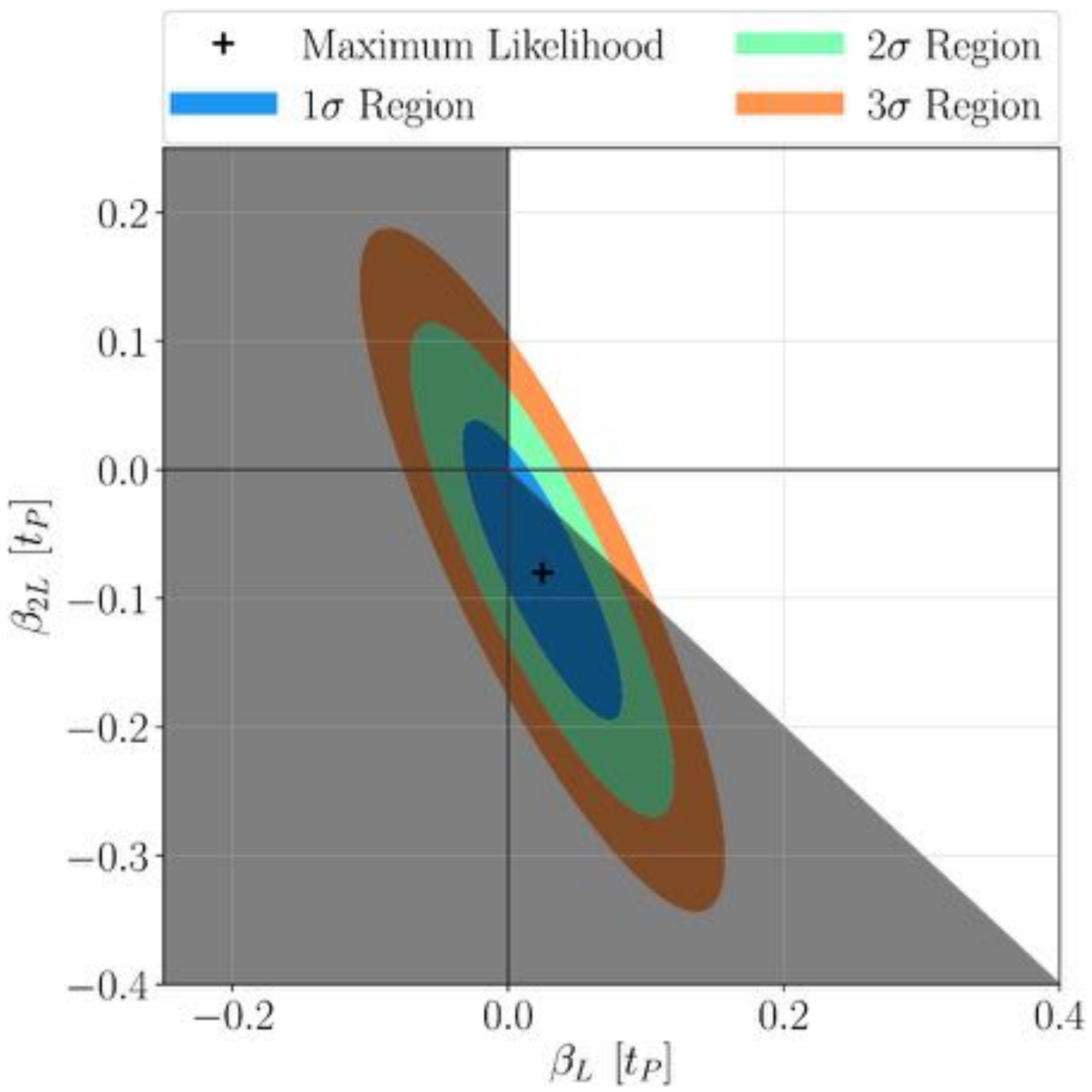
We looked for coherent geometrical fluctuations in the lab with the Fermilab Holometer

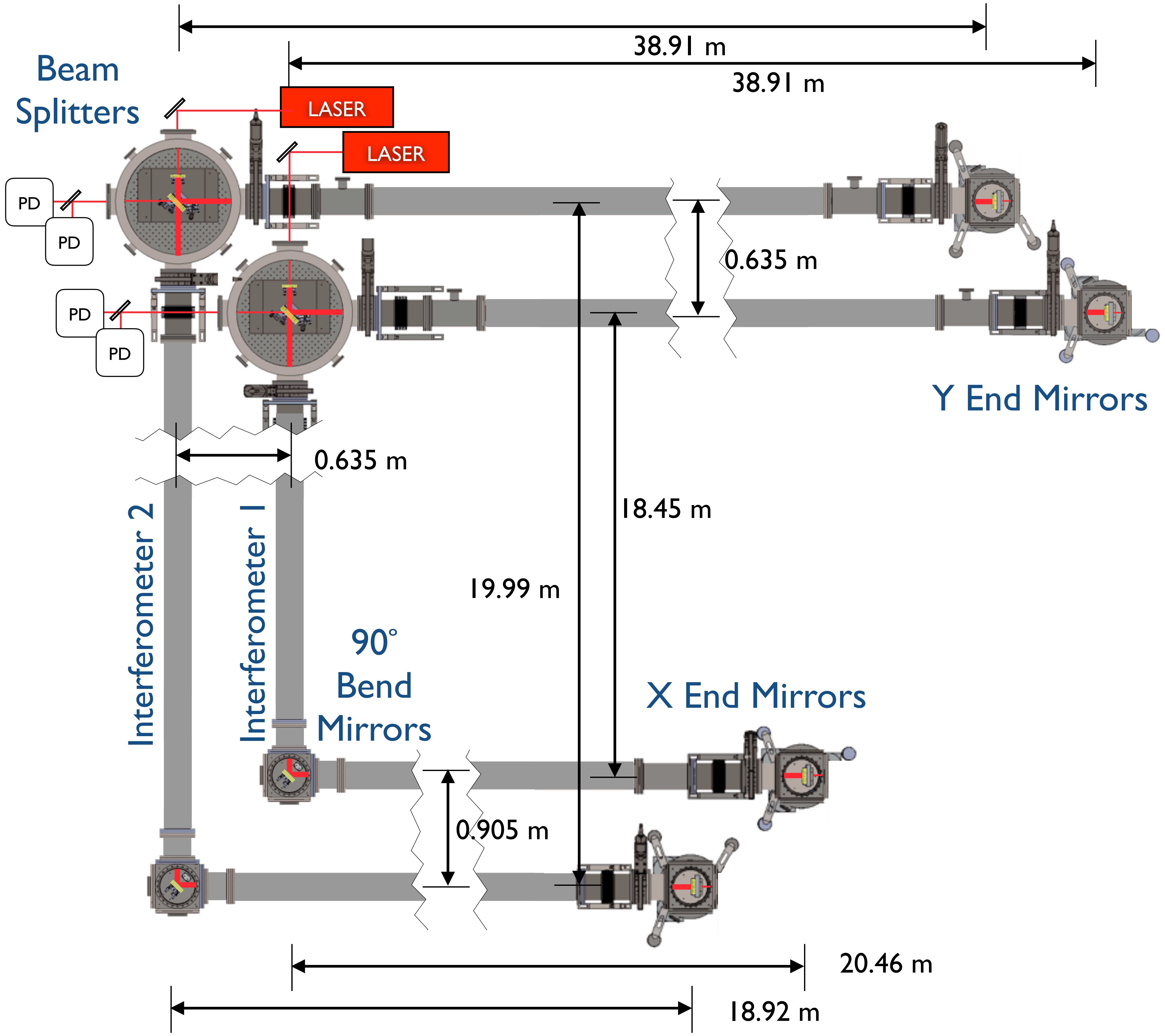
We did not see Planck scale holographic noise

We may have had the wrong layout to detect it

New experiments are under development







A holographic horizon is like an atom

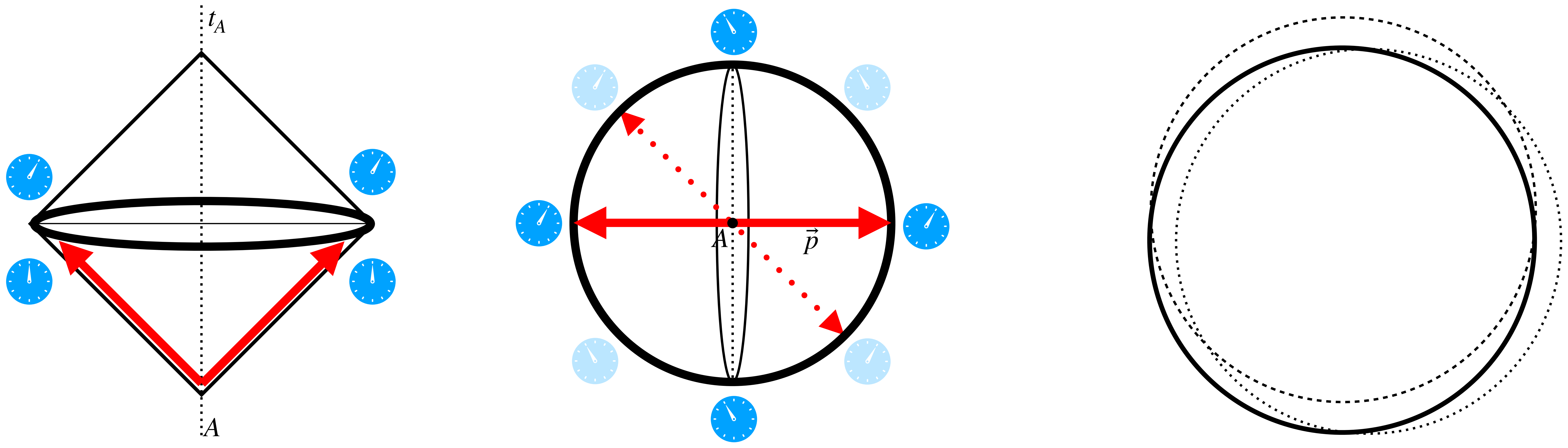
it has a discrete spectrum of directionally coherent states

whole horizon fluctuates and interacts coherently
ground state transitions have low angular harmonics

has a finite (discrete, holographic) number of discrete transitions

creates nonlocal correlations of quantum fluctuations in the emerged metric

https://arxiv.org/abs/1908.07033



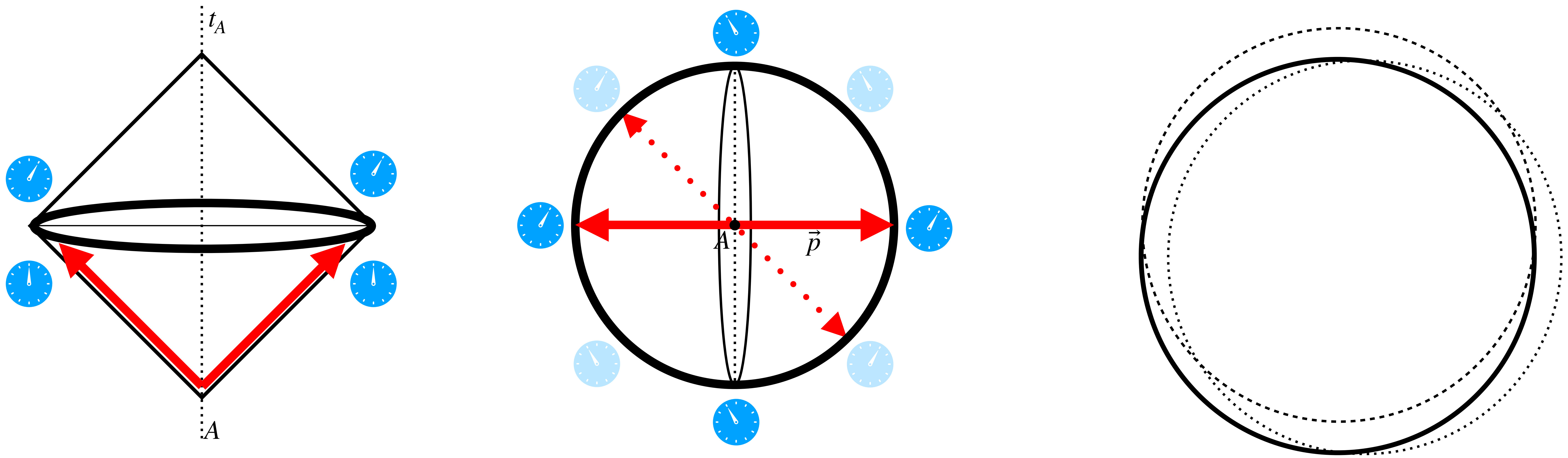
classical inflationary horizon = a sharp edge in space-time defined by a spherical null surface

Vacuum fluctuations create causally coherent perturbations on the incoming light cone

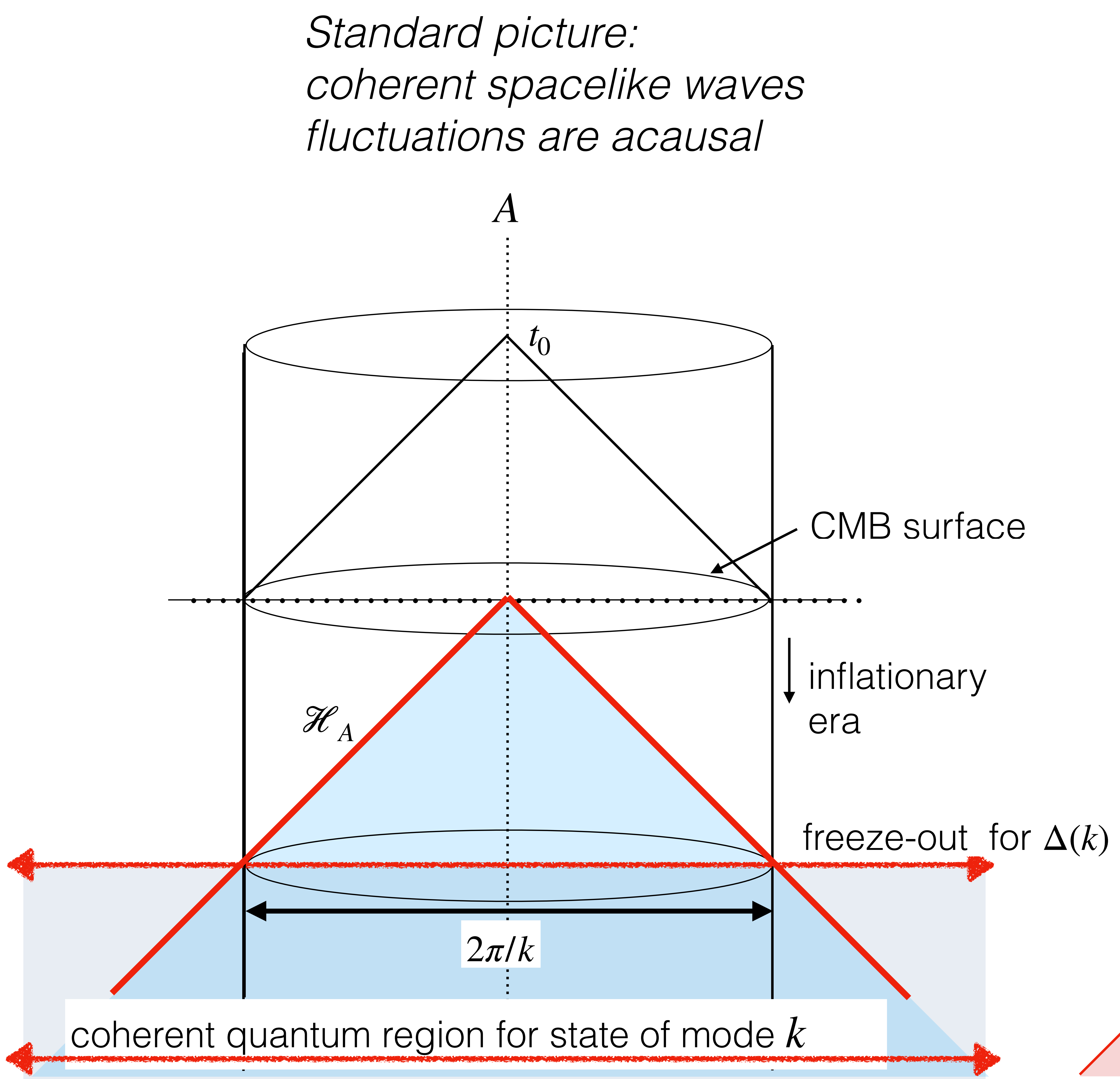
New principles:

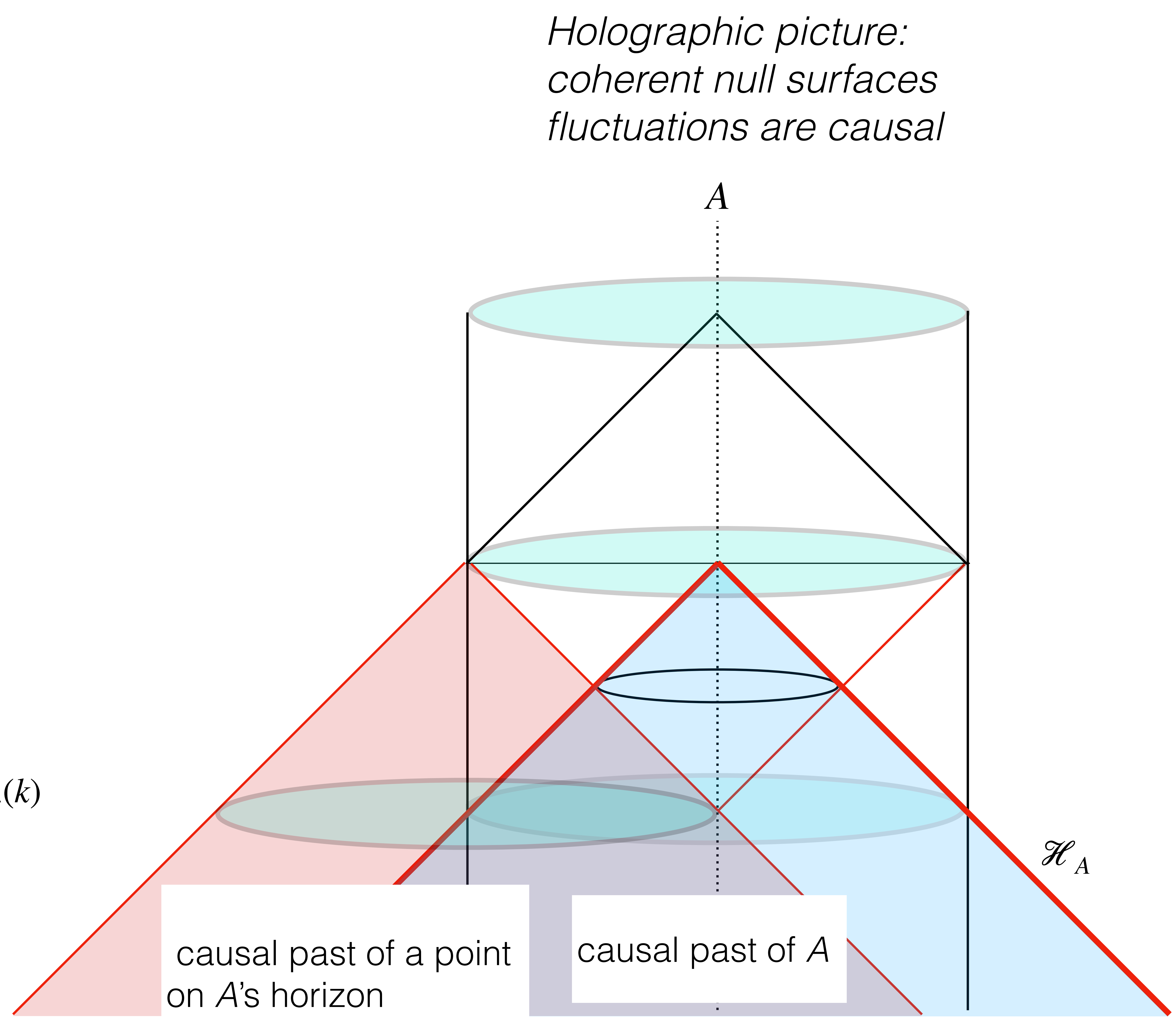
pattern is coherent on ***spherical boundaries of causal diamonds***

pattern is determined by ***projections of displacements on horizons***



To build a model, replace coherent plane wave perturbations with coherent shocks on horizons

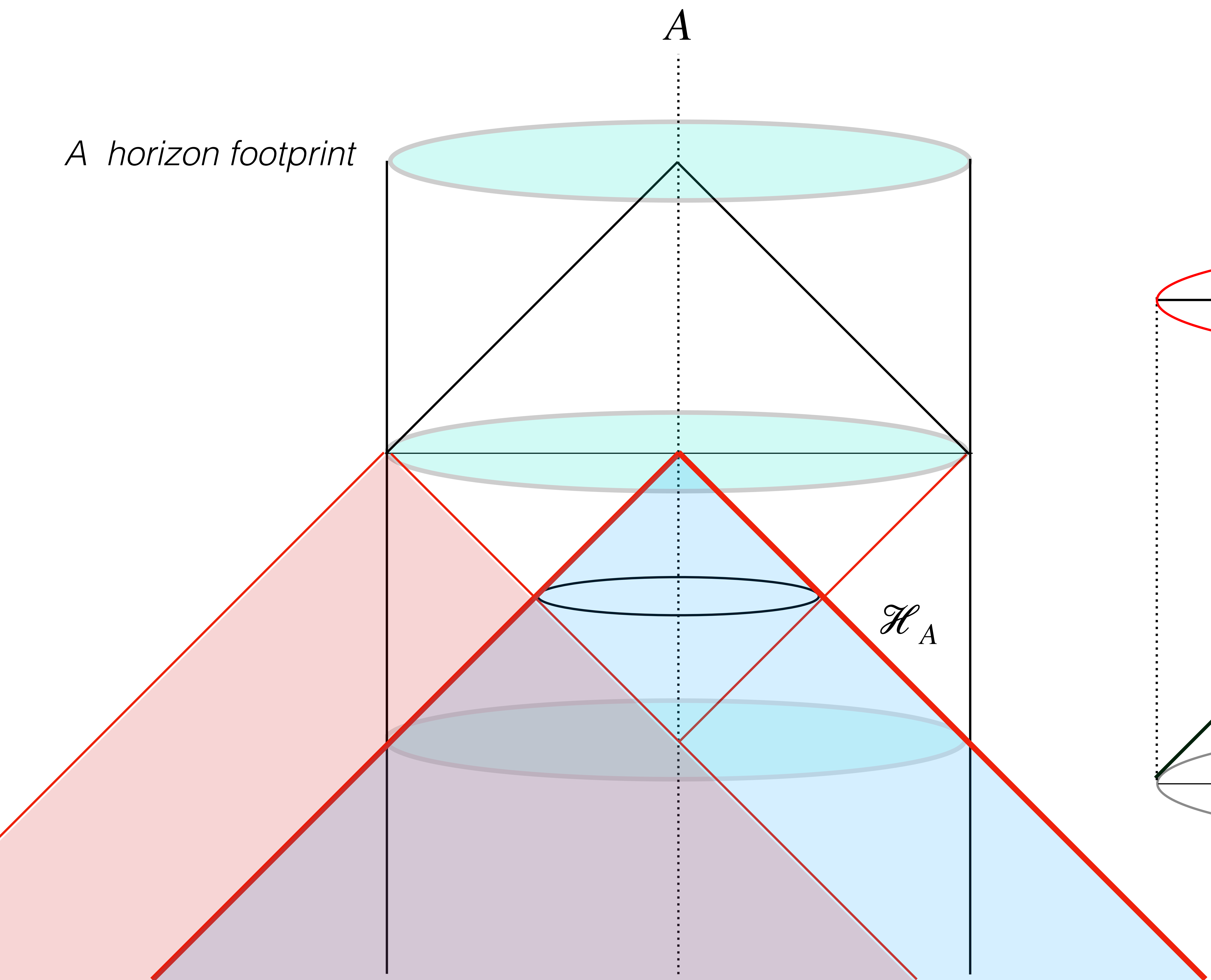


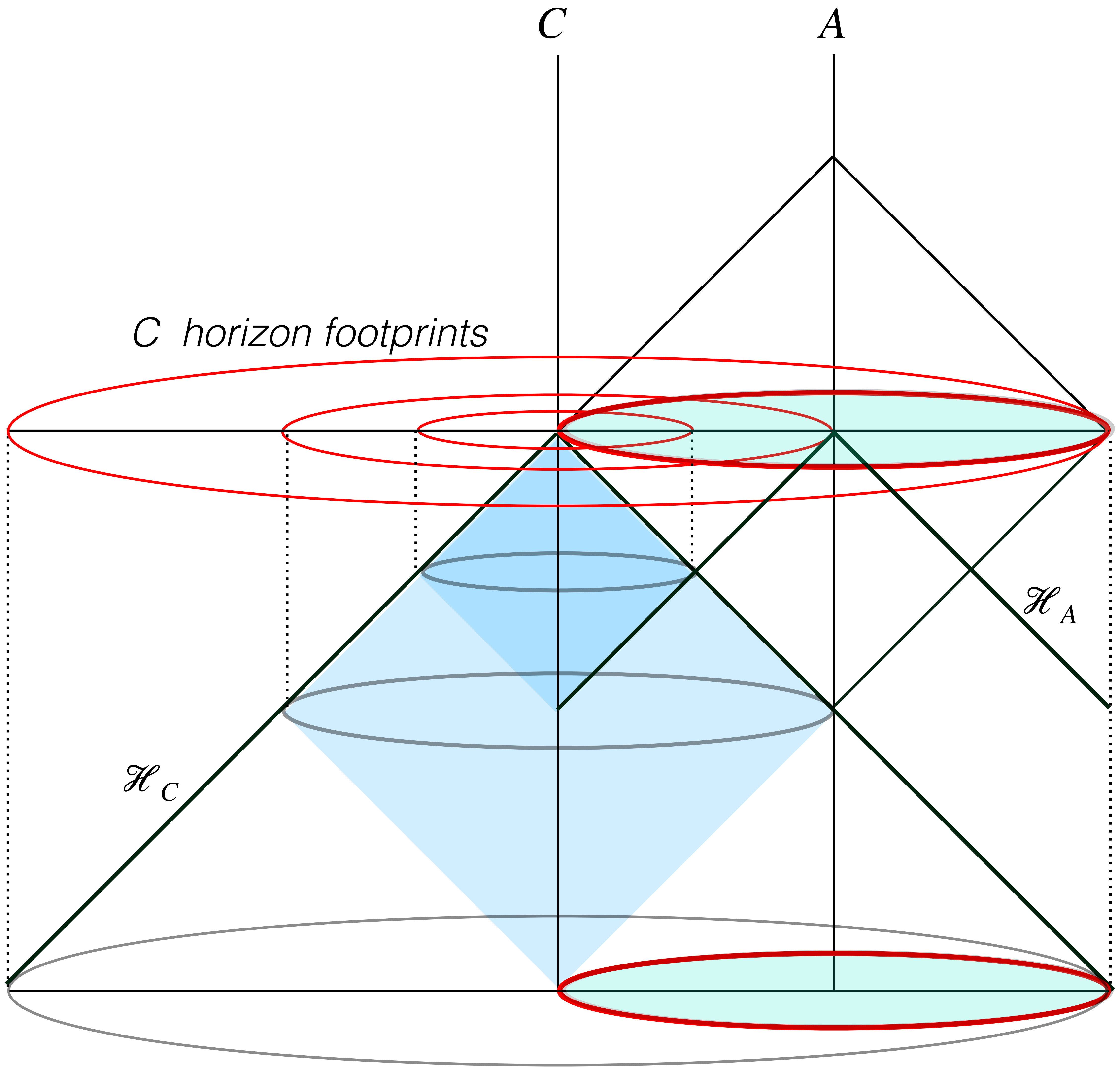


Standard cosmological conformal causal structure

causal diamonds define comoving intersections of horizon footprints

these determine observed displacements





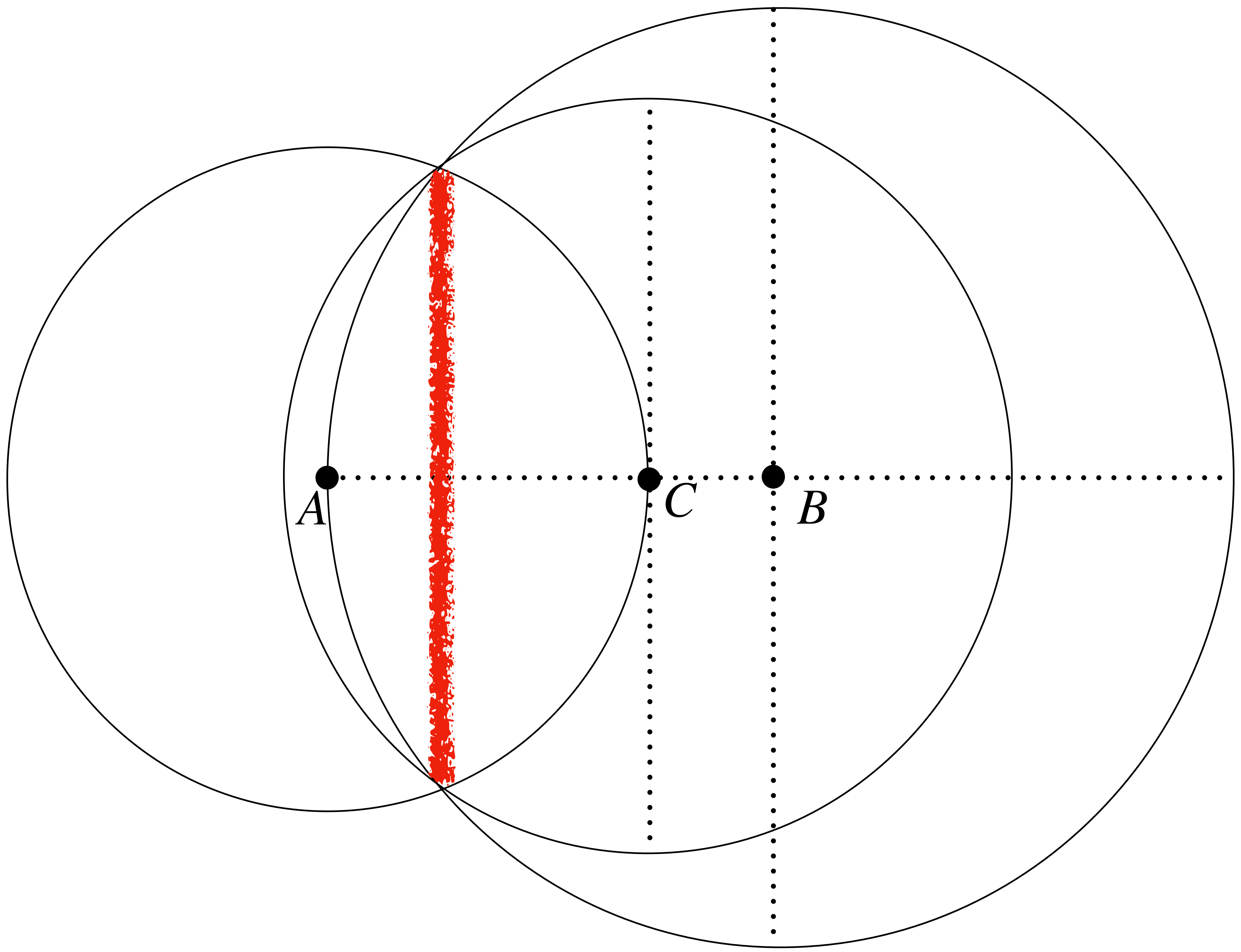
CMB anisotropy ~ causal distortion on horizon footprint of *A*

Total distortion= sum of virtual shocks in many directions

Consider single coherent shock along a particular axis

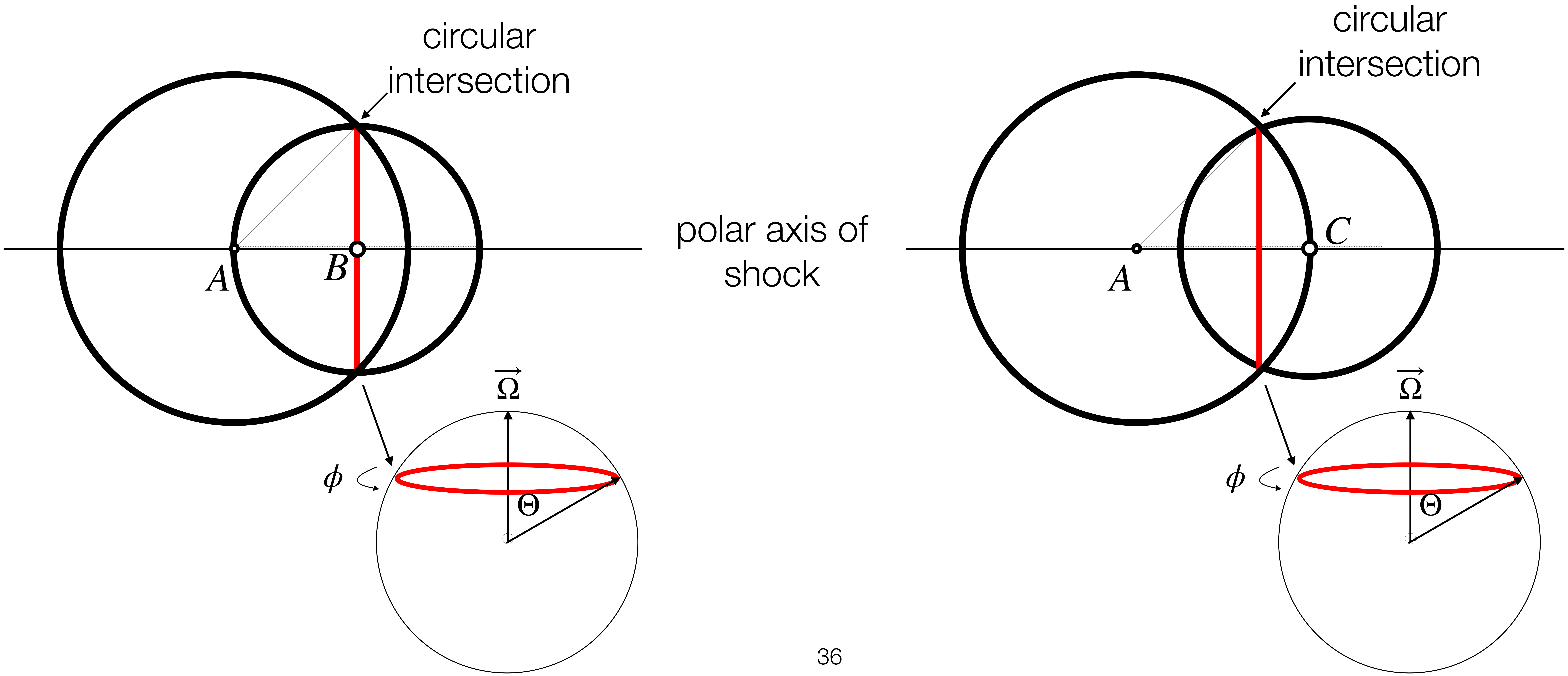
Consider circular intersections of spherical causal diamond boundaries

(= horizon footprints)

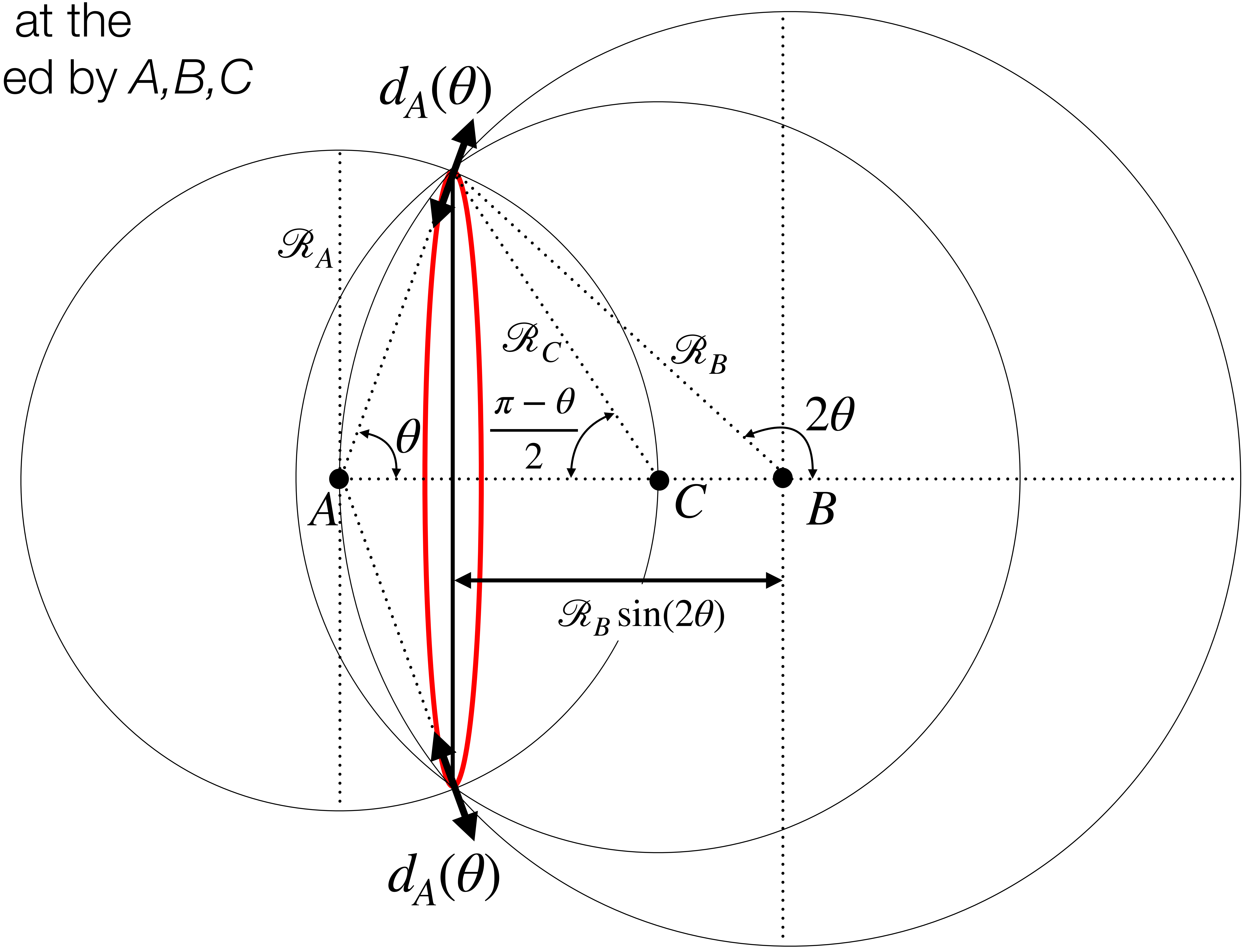


Axially symmetric distortions on circular intersections of causal diamond boundaries

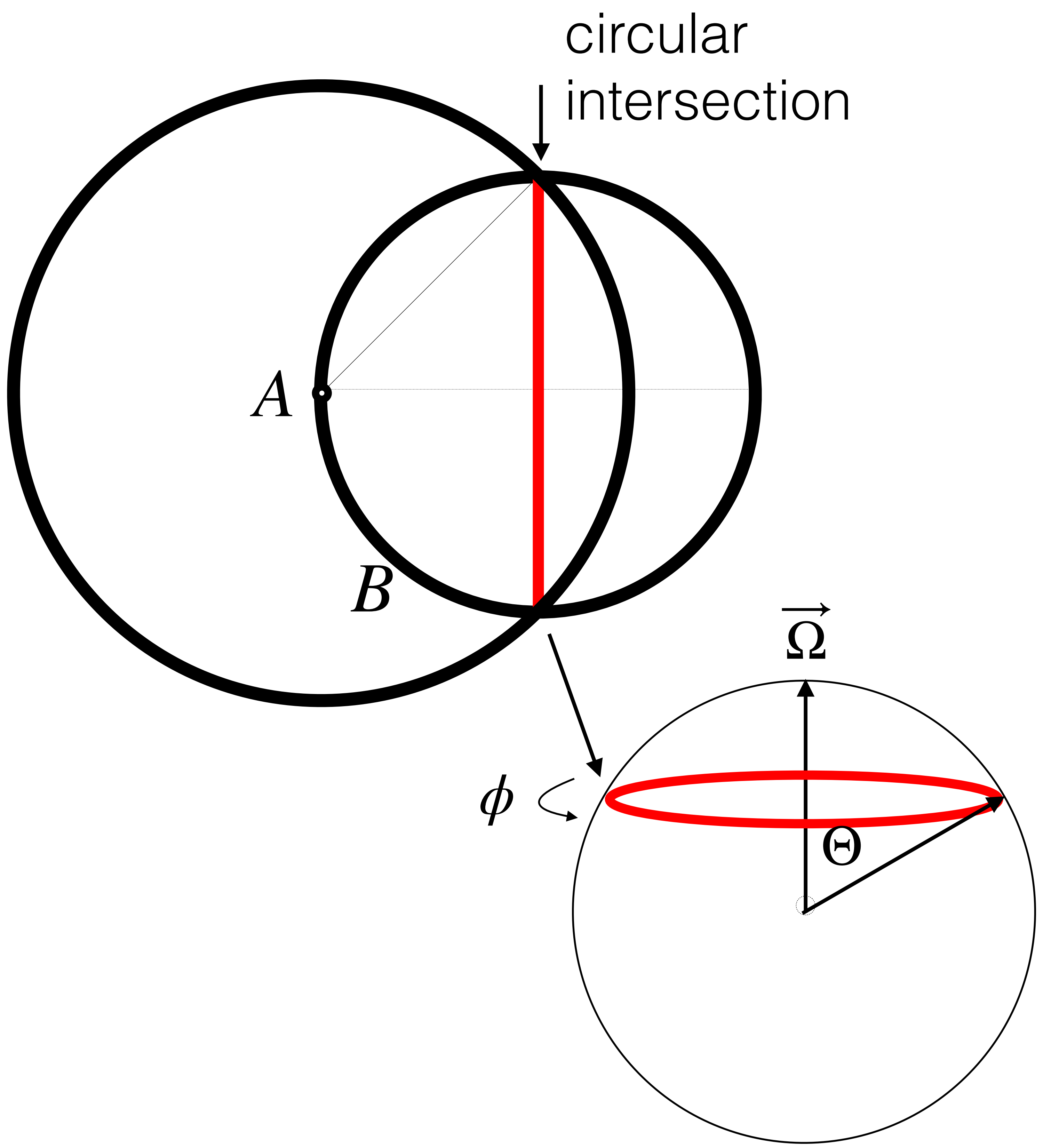
B and *C* horizons control incoming and outgoing causal relationships with *A*
A is on *B*'s footprint
C is on *A*'s footprint



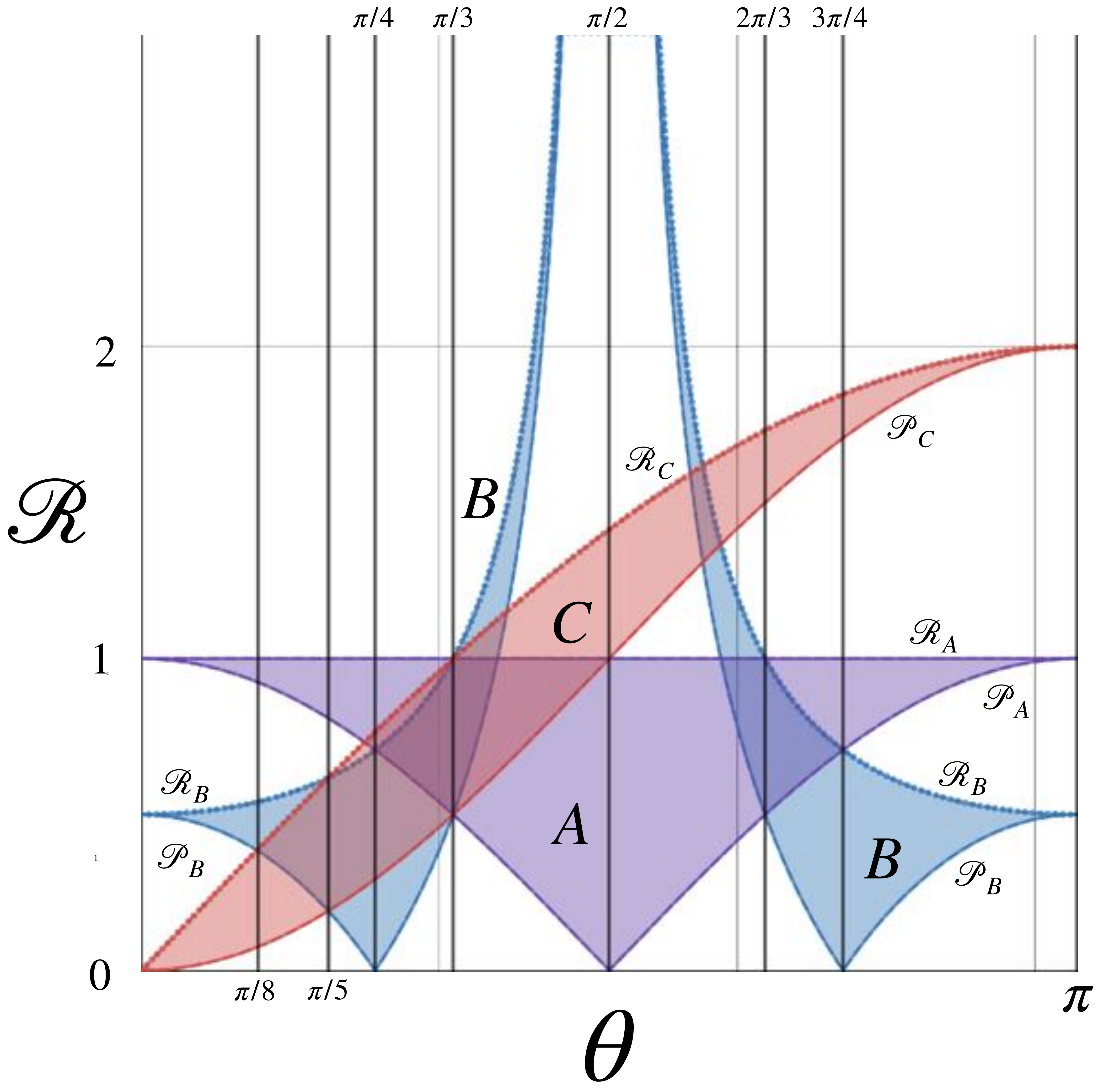
Projected displacements at the intersection are determined by *A,B,C* horizon footprints



Angles map onto times during inflation via comoving radii of horizon footprints



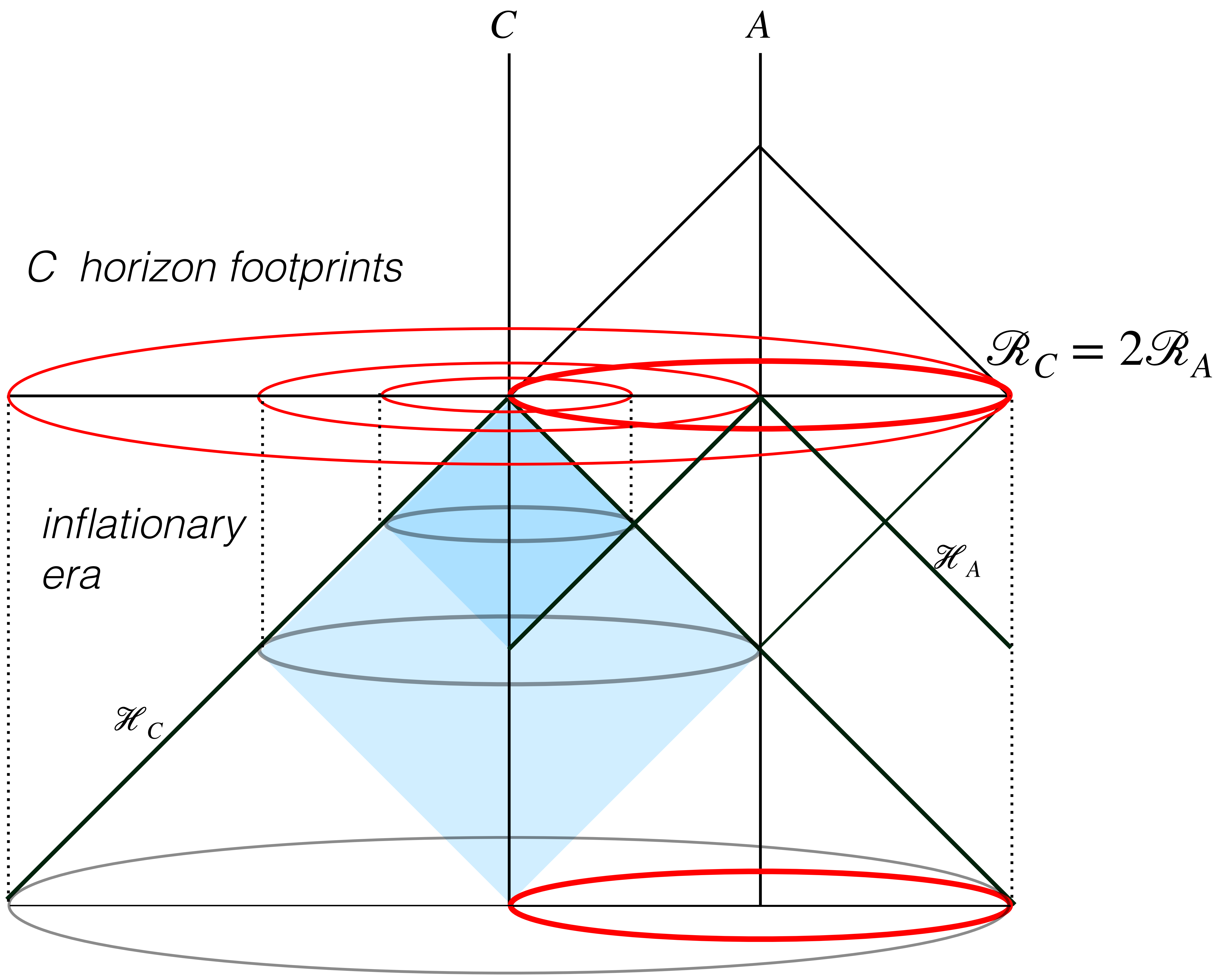
Comoving radii of footprints where they intersect, as a function of axial angle viewed from A

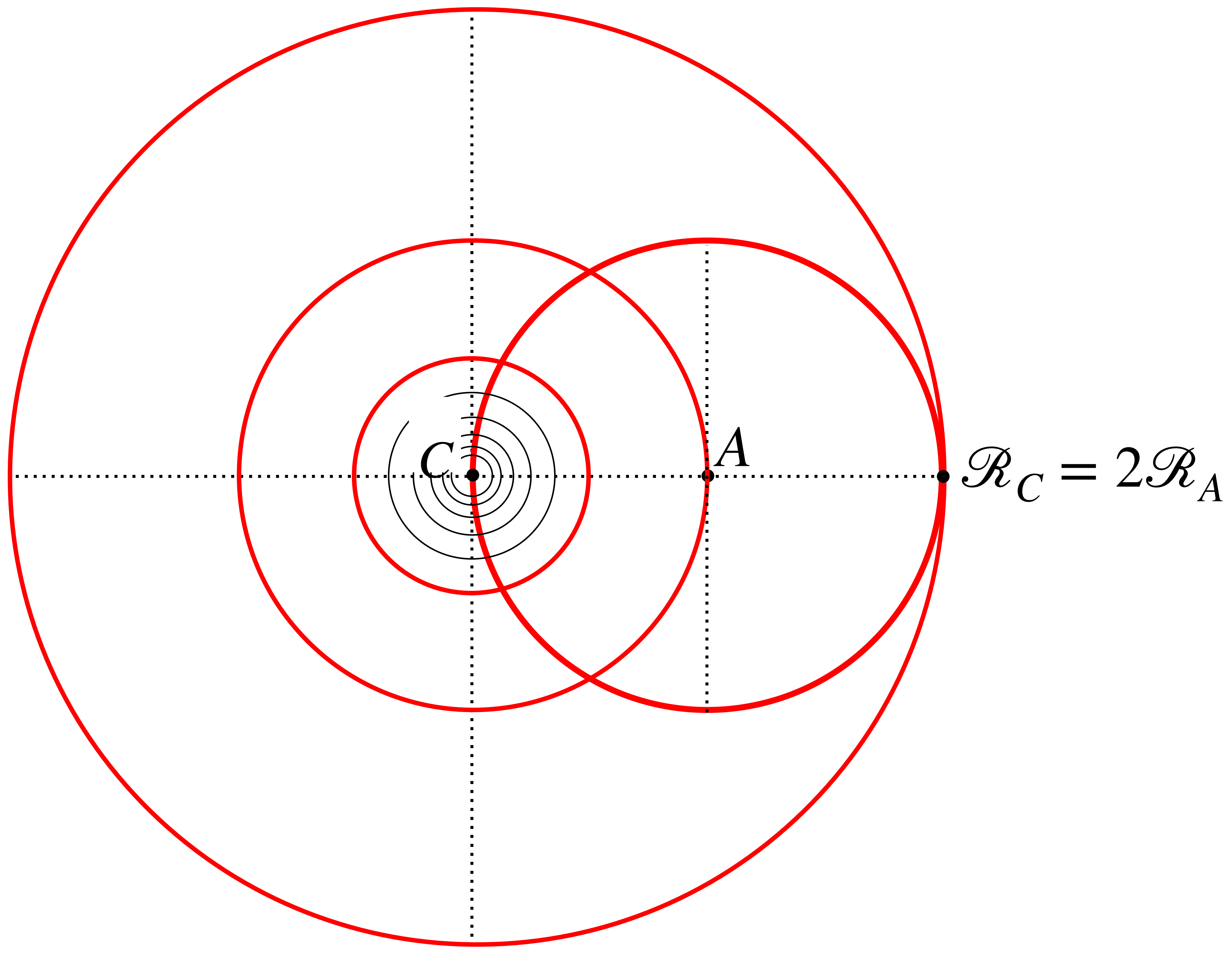


C lies on *A* footprint

Fluctuations on *C* horizons continue to end of inflation: dominate small angular scale distortion

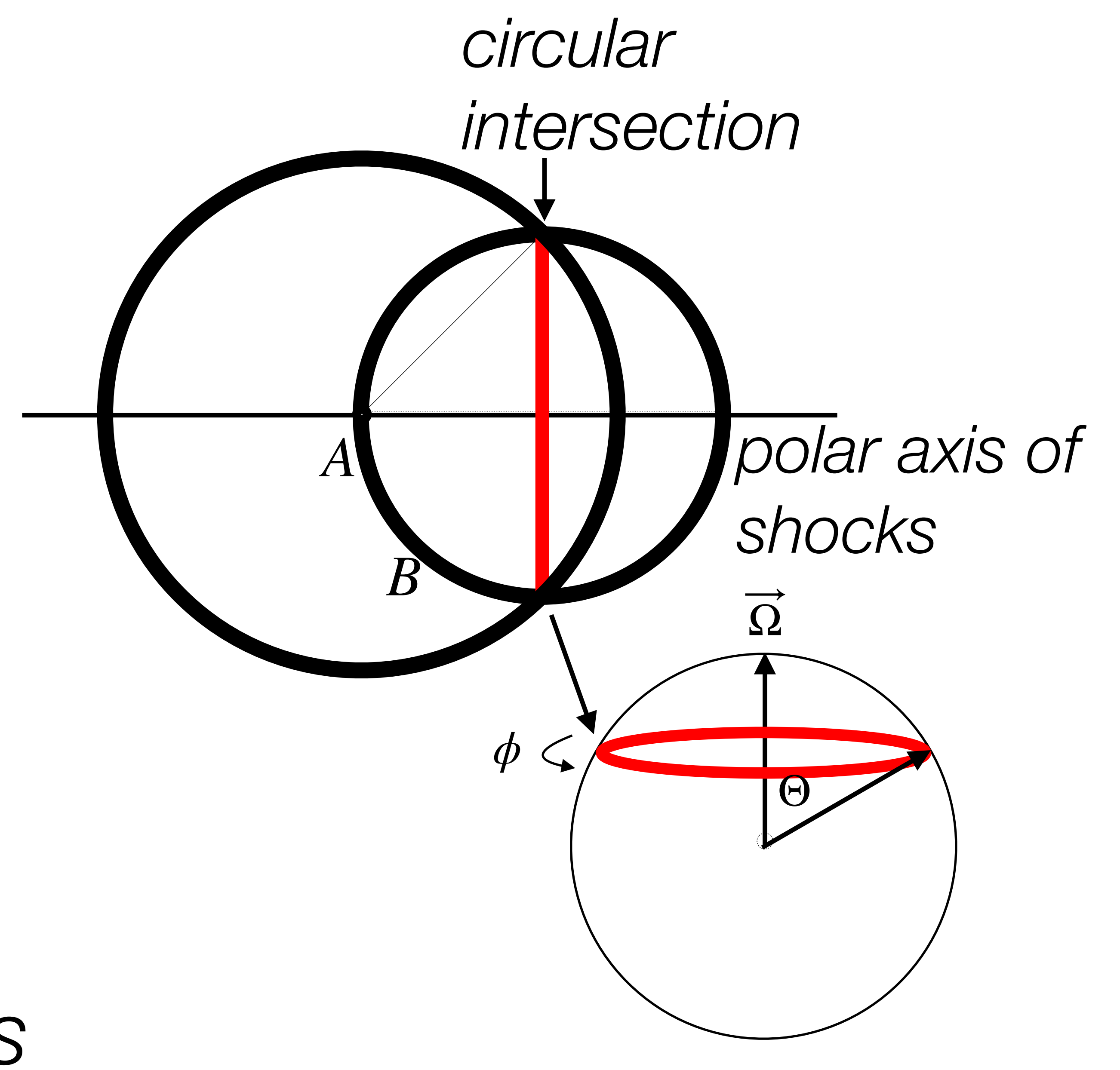
Horizon footprints of a point C on A's CMB surface at the end of inflation

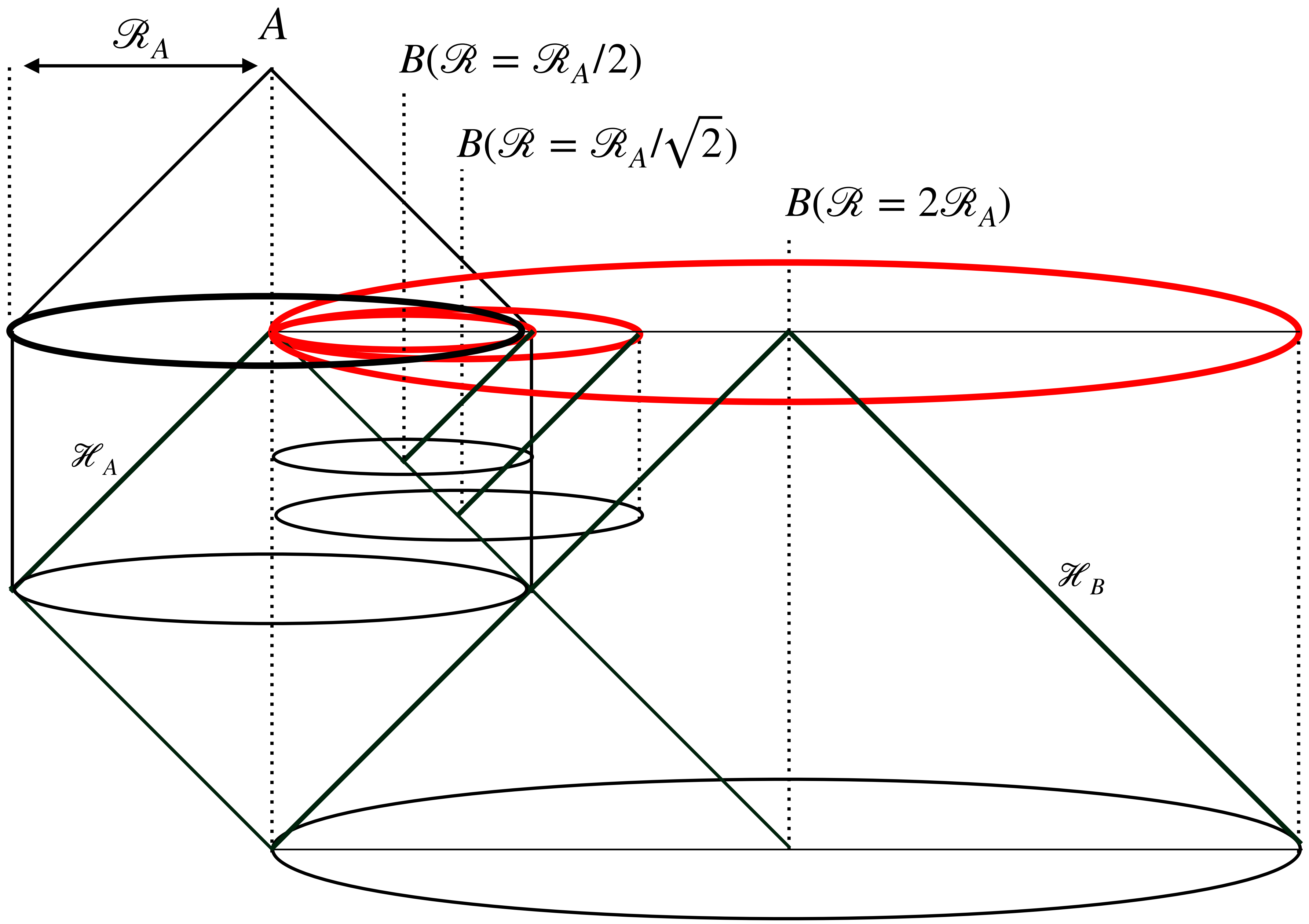




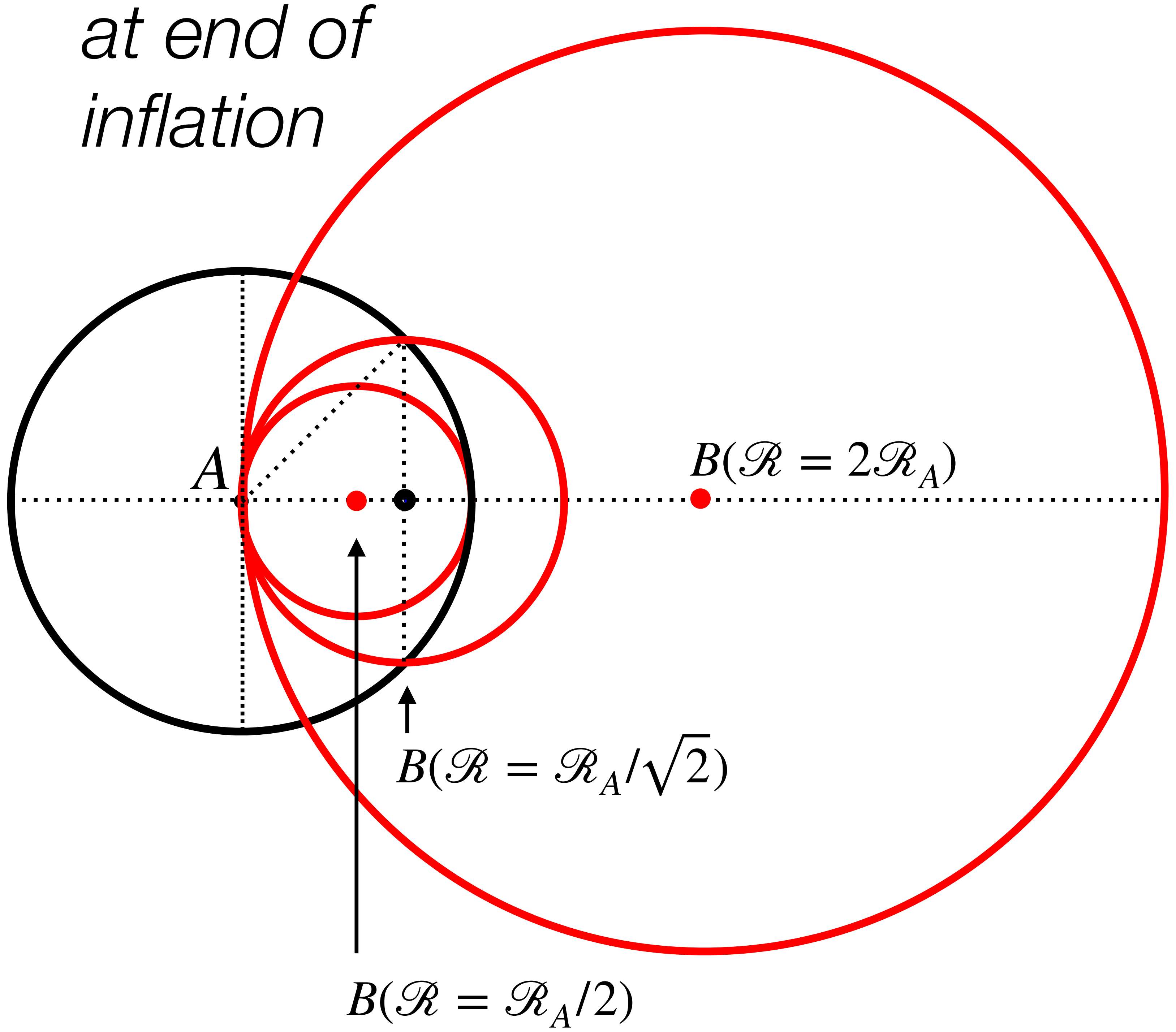
A lies on *B* footprints

In-common displacement of *A* and *B* footprints subtracts from observable distortion





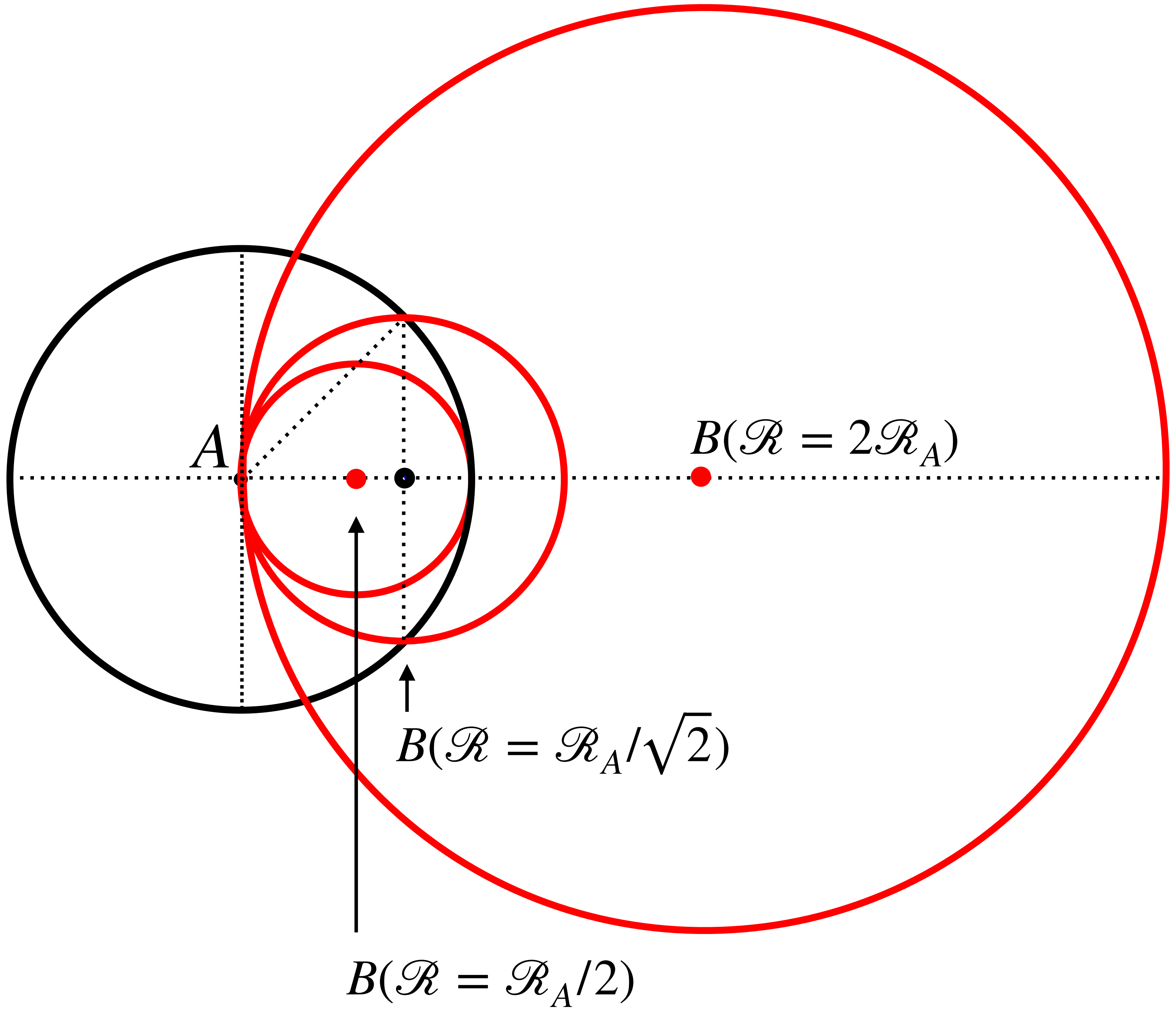
B footprints at end of inflation

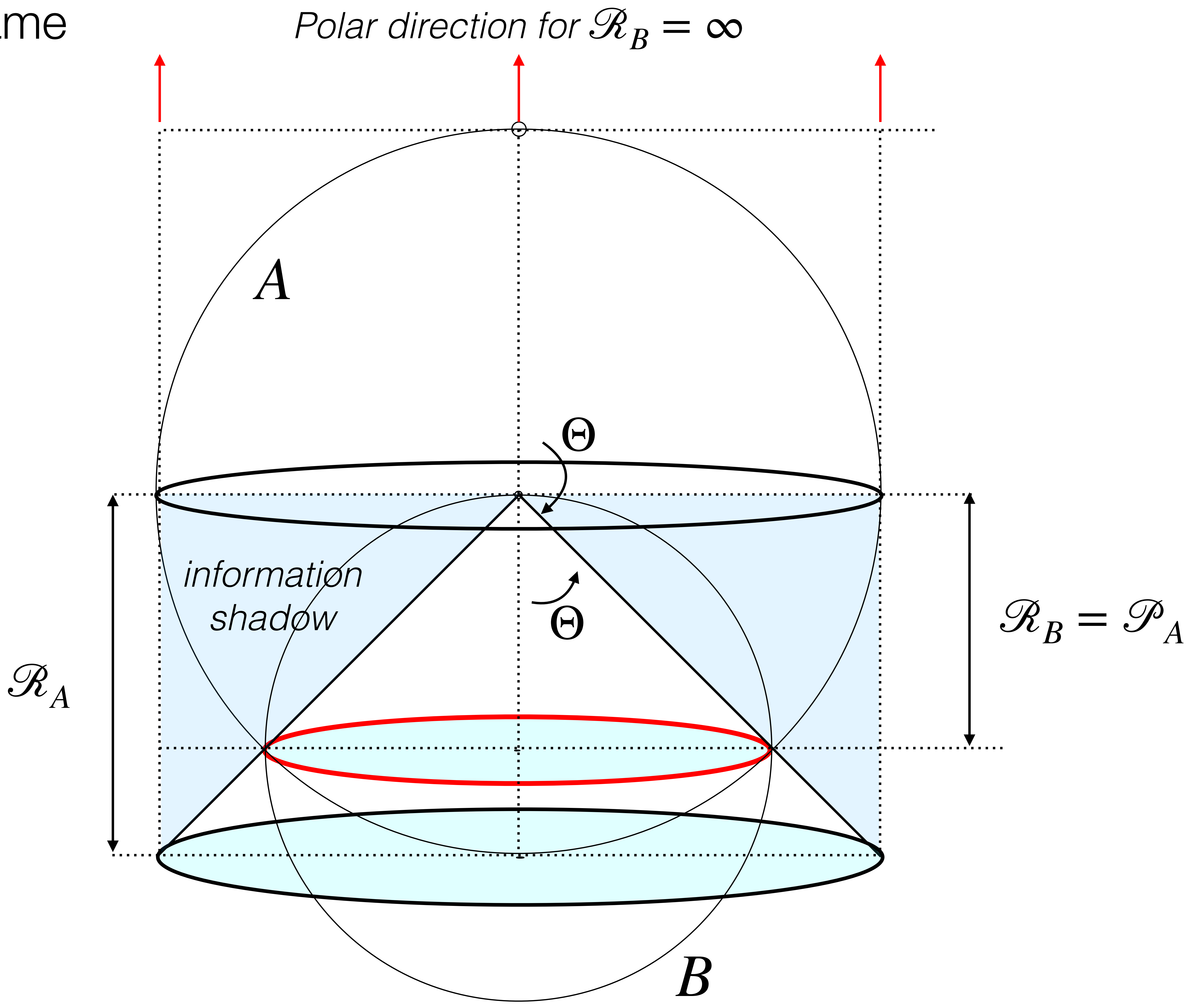


Causal "shadow" from in-common displacement

For $\pi/4 < \Theta < 3\pi/4$, the *A* center lies in the same hemisphere of *B* as the *AB* intersection circle

A and *B* causal diamonds share the same axial displacements: no observable displacement





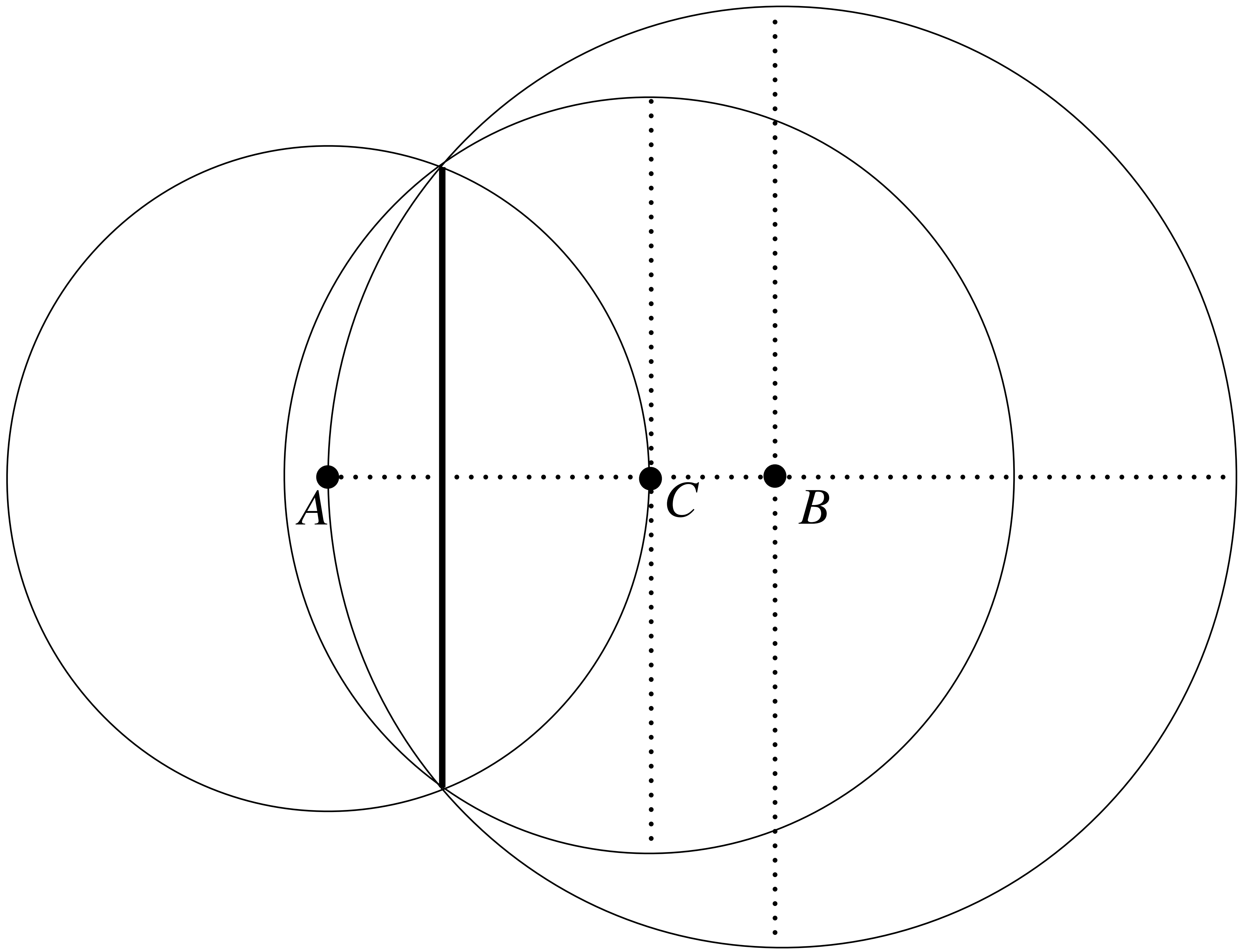
Response kernel for one shock

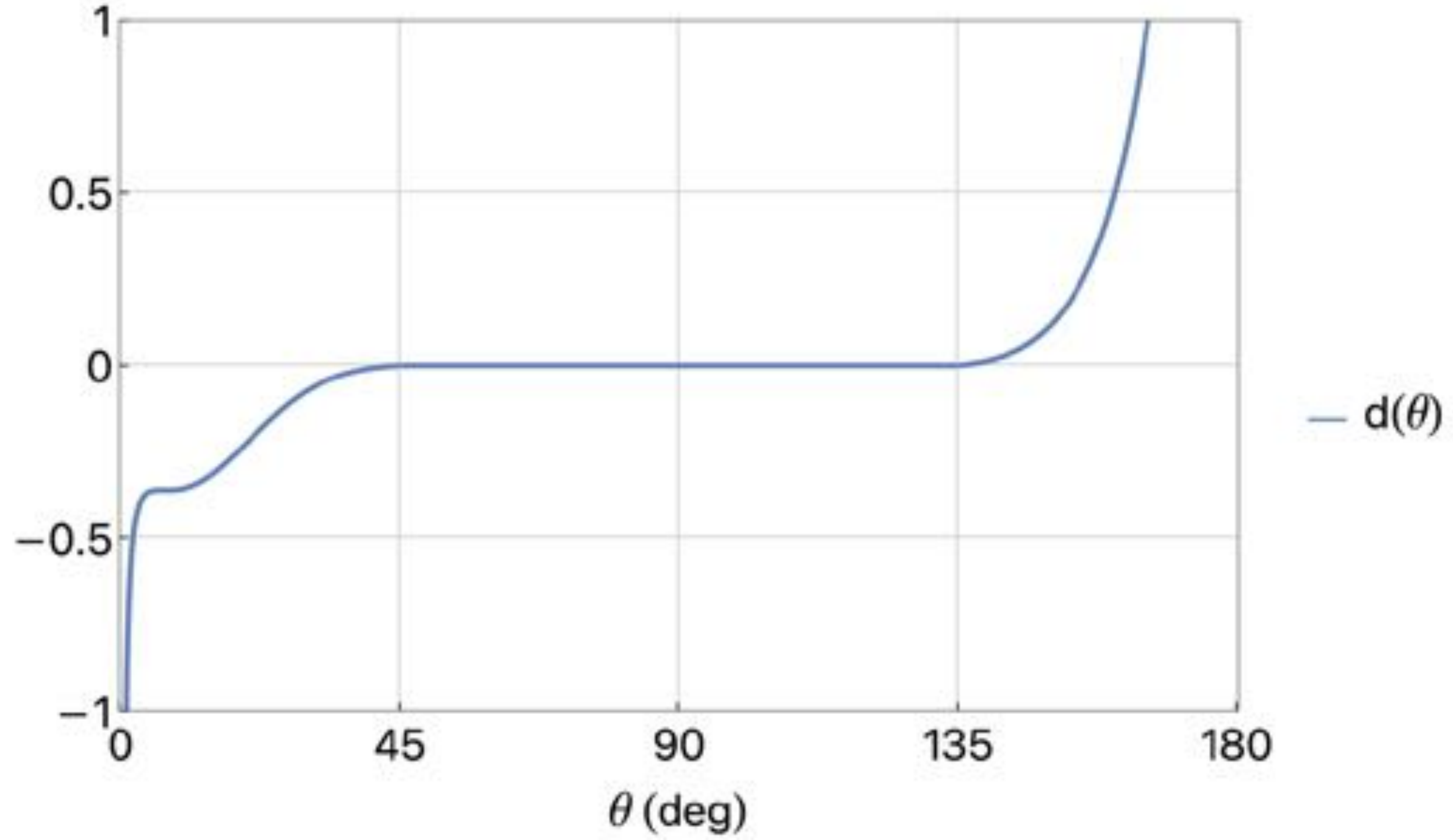
Observable displacement on *A* is the product of:

[accumulated displacement along *ABC* axis]
which is
[difference of *AB* and *AC* displacements]

and

[projection of axial displacement]
which is
[projected difference of *A* and its horizon]





Axially symmetric coherent displacement kernel based on standard horizons in slow-roll inflation

observed *AB* projection (projections onto *A* and *B* footprints, multiplied by difference of *A* and *B* displacements)

$$d_{AB}(\theta) = \cos(\theta)\cos(2\theta)\left[\cos(\theta) - \frac{\sin(2\theta)}{2}\right]$$

Axial displacement (accumulated difference of *A* from *B* and *C* horizons over inflationary history)

$$P_{ABC\mathcal{T}}(\theta) = P_{AB}(\theta)\mathcal{T}_{AB}(\theta) - P_{AC}(\theta)\mathcal{T}_{AC}(\theta)\mathcal{T}_0/\sqrt{2}$$

the terms come from the ratios of horizon footprint radii with a tilted spectrum:

$$P_{AB} = a_A/a_B = 1/2\sin(\theta), \quad P_{AC} = a_C/a_A = 1/2\sin(\theta/2)$$

includes factors for tilted slow roll inflation in opposite directions

$$\mathcal{T}_{AB}(\theta) = 1 - \frac{\epsilon}{2}\ln\left[P_{AB}\right], \quad \mathcal{T}_{AC}(\theta) = 1 - \frac{\epsilon}{2}\ln\left[P_{AC}\right], \quad \mathcal{T}_0 = \mathcal{T}_{AB}(\pi/2)/\mathcal{T}_{AC}(\pi/2)$$

total transfer function: observable displacements in the two hemispheres, allowing for subtraction of projected *B* displacement

$$d_+(\theta) = P_{ABC\mathcal{T}}(\theta)\left[d_{AB}(\theta) - \mathcal{T}_{AB}(\theta)d_{AB}(2\theta)\right]$$
$$d_-(\theta) = P_{ABC\mathcal{T}}(\theta)d_{AB}(\theta)$$

Determines unique angular spectrum and correlation function with no cosmic variance

Result: ***unique angular spectrum of displacement on spheres, with no cosmic variance***

Small-scale power spectrum matches standard theory

Everything in late-time cosmology that only depends on the power spectrum stays the same

Which is to say, the successes of concordance cosmology remain

But directions are not independent: they are causally connected

The pattern is modified at large angles where curvature is important

Causal symmetries are preserved

Angular Spectrum

Holographic model produces universal spectrum with no cosmic variance on a thin sphere

Resembles sky data at large angles

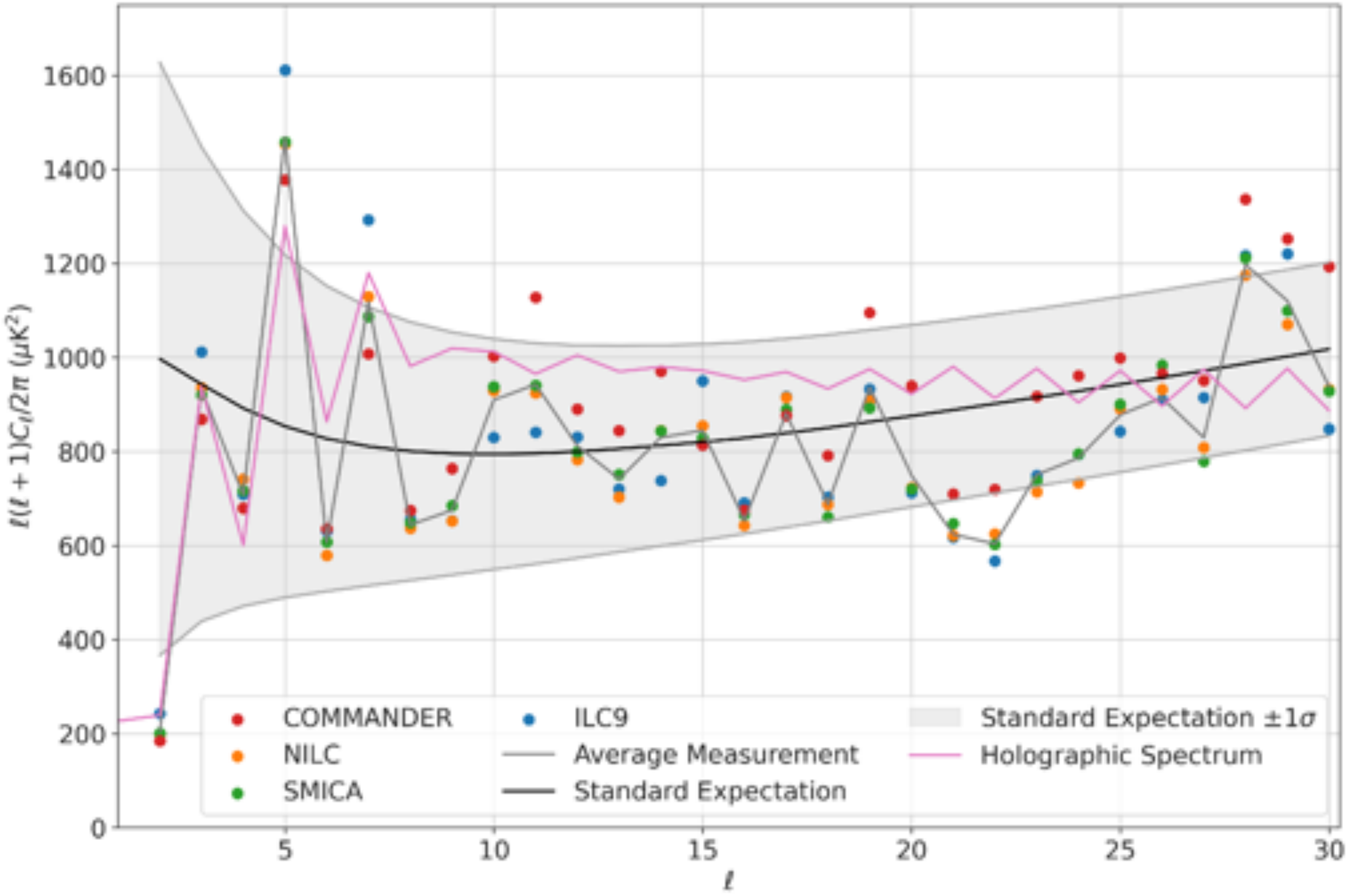
Disagrees with standard picture at $\ell \lesssim 7$ because of causal coherence

Approximates gravity-only, thin-sphere standard model on small scales

Reionization will suppress at $\ell \geq 7$

small extra odd parity out to $\ell \sim 30$

Data show systematic measurement error from Galactic modeling: detailed agreement with data is not expected

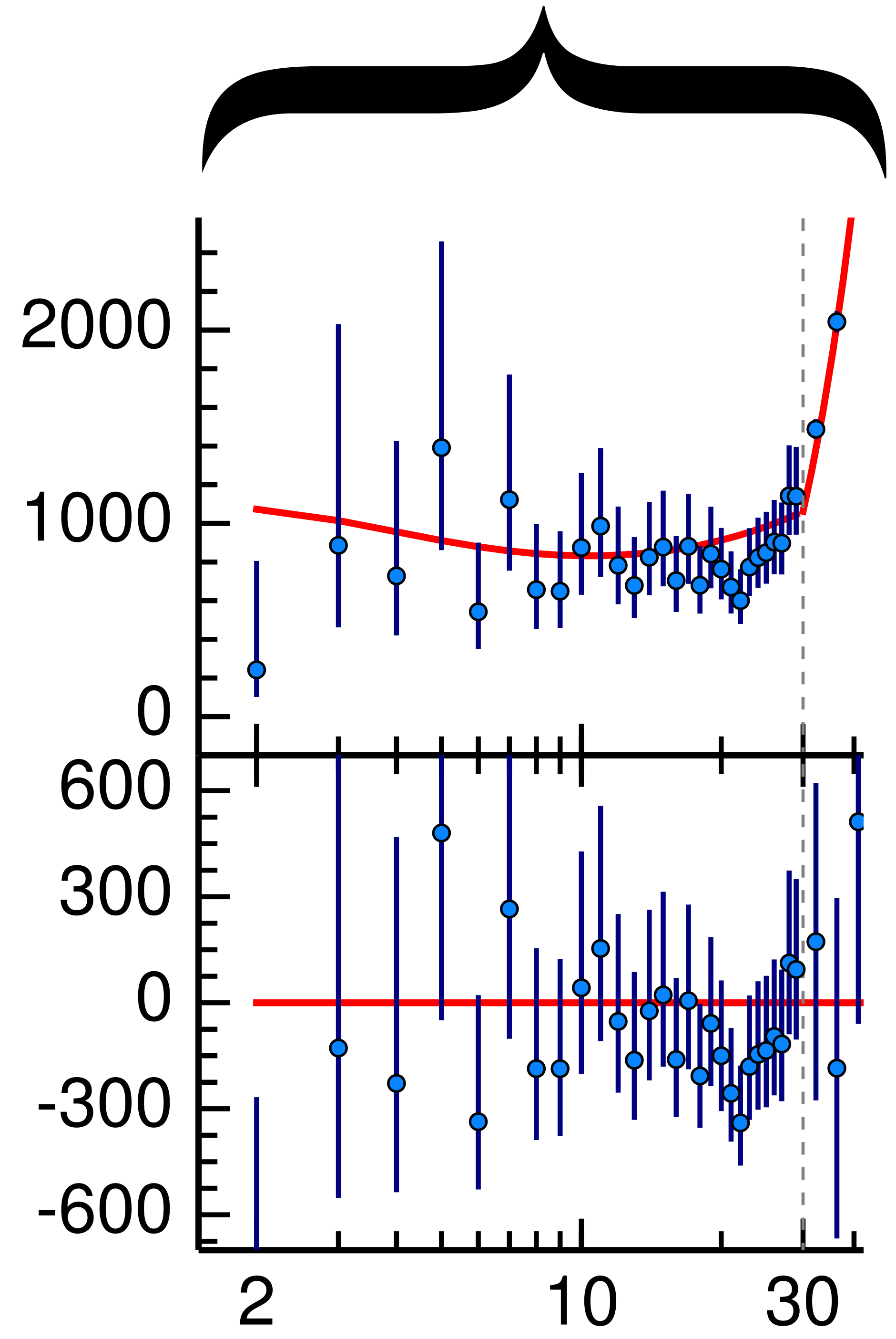


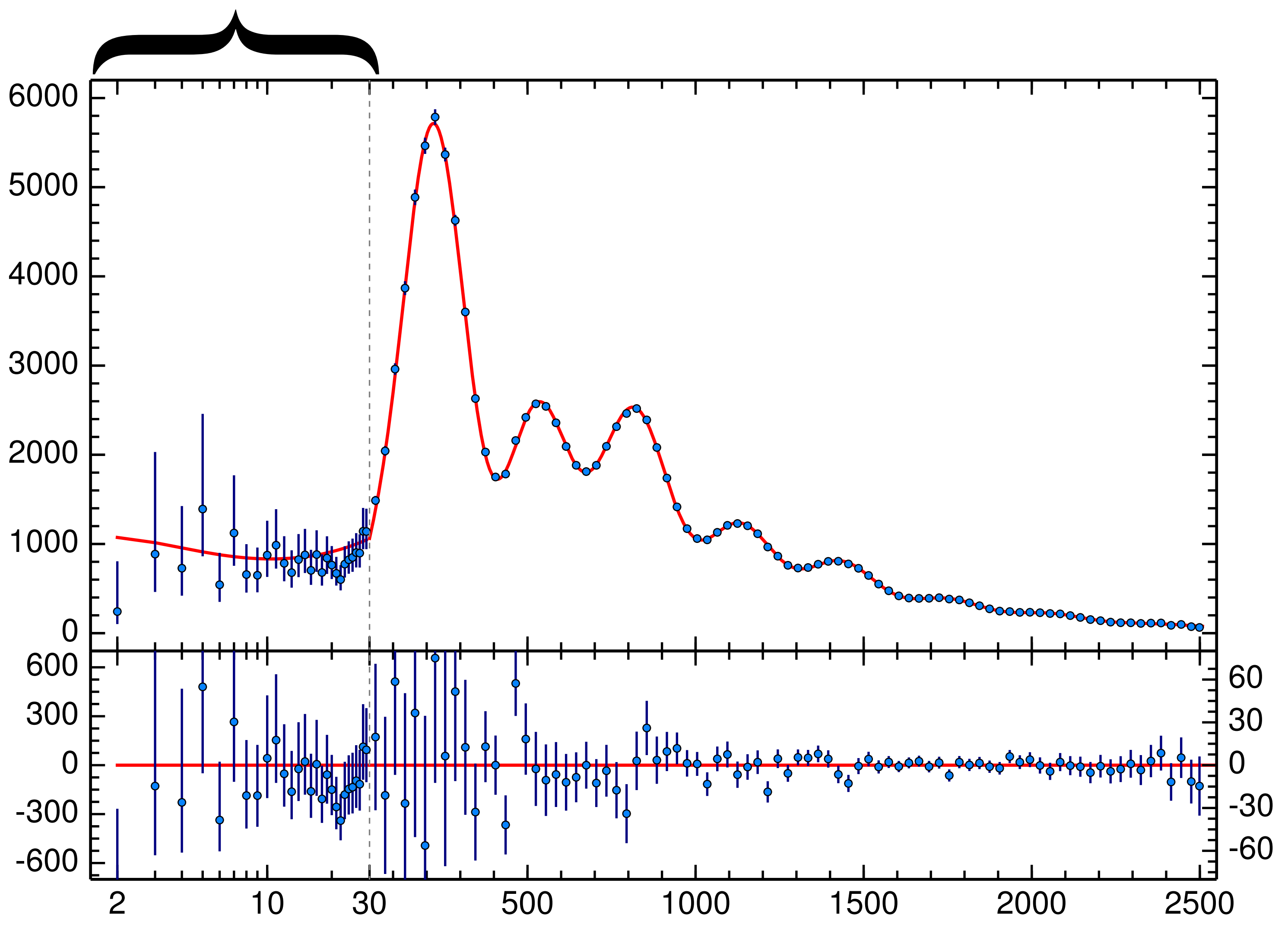
Previously known odd-parity preference seen in harmonics up to $\ell \sim 30$

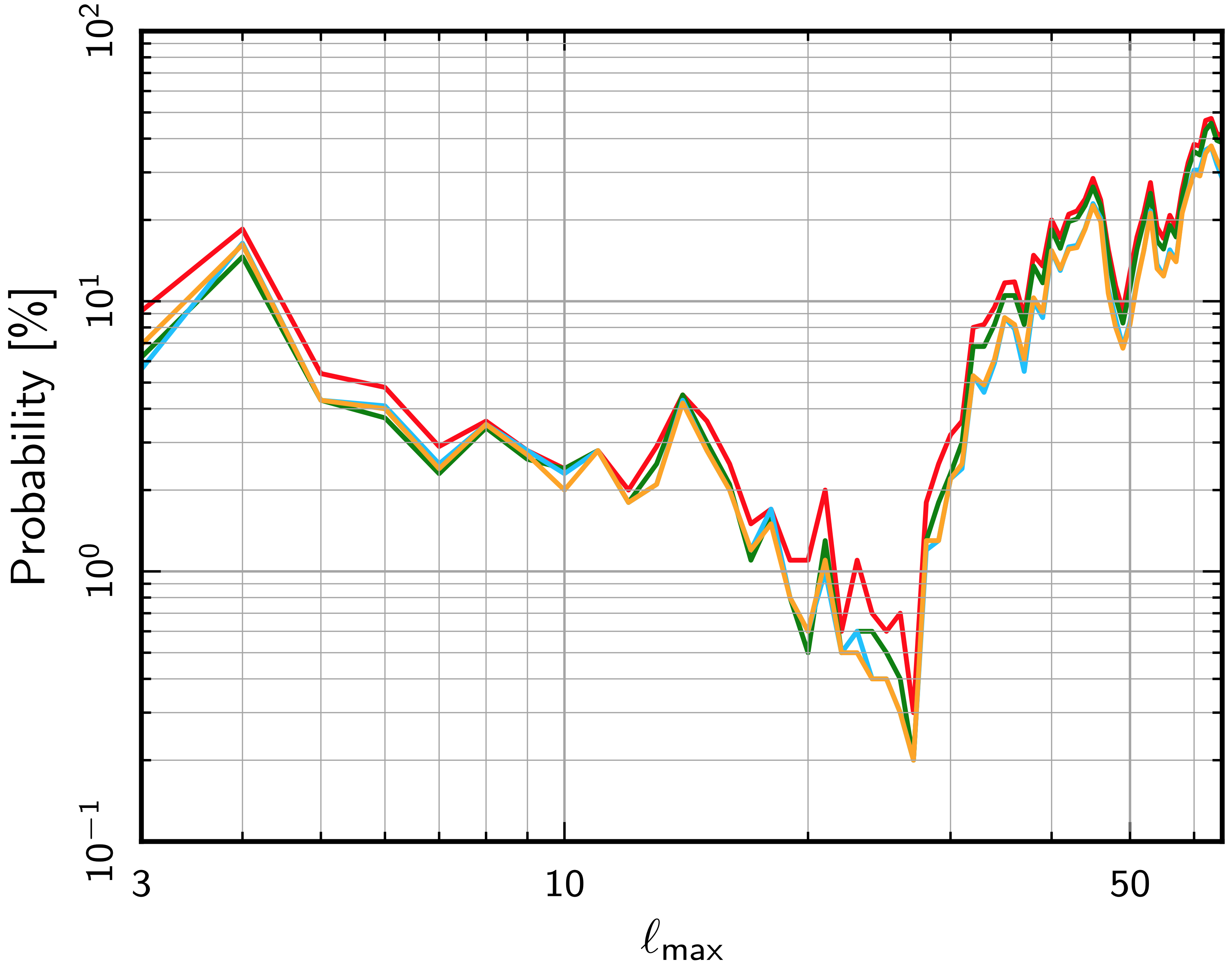
unlikely in standard inflation at ~0.2%

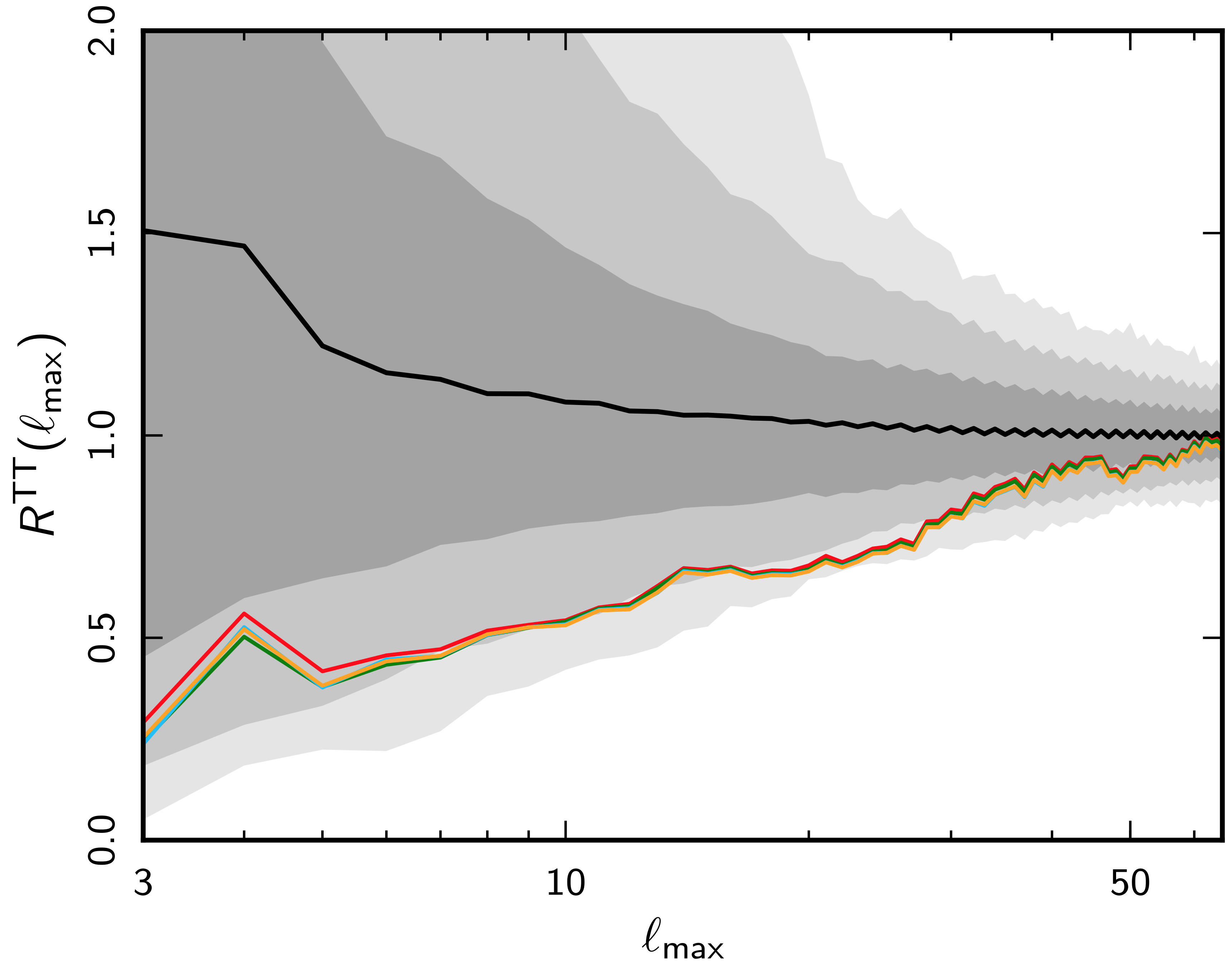
Opposite sides of the sky "know about" each other, even on small scales

In the coherent model, antipodes are connected by causal diamonds even for $\ell >> 1$









Planck, 1506.07135

Angular correlation function

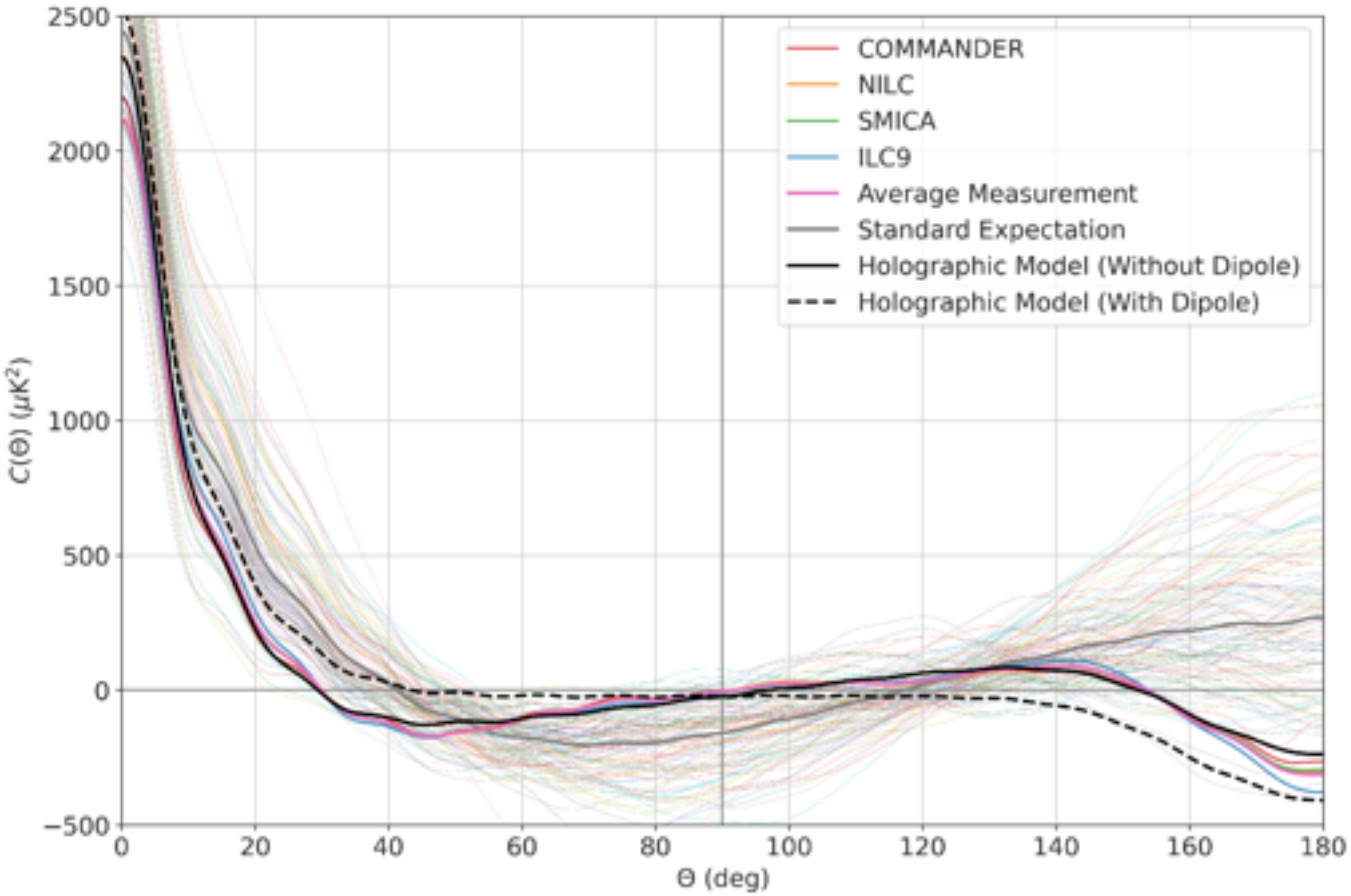
Angular relationships preserve boundaries of primordial causal relationships

Standard realizations seldom resemble the data

Causally coherent model fits the data

Hidden exact causal null symmetry appears when the dipole is included:

$$C(45^\circ < \Theta < 135^\circ) = 0$$



Compare relative agreement of maps with models

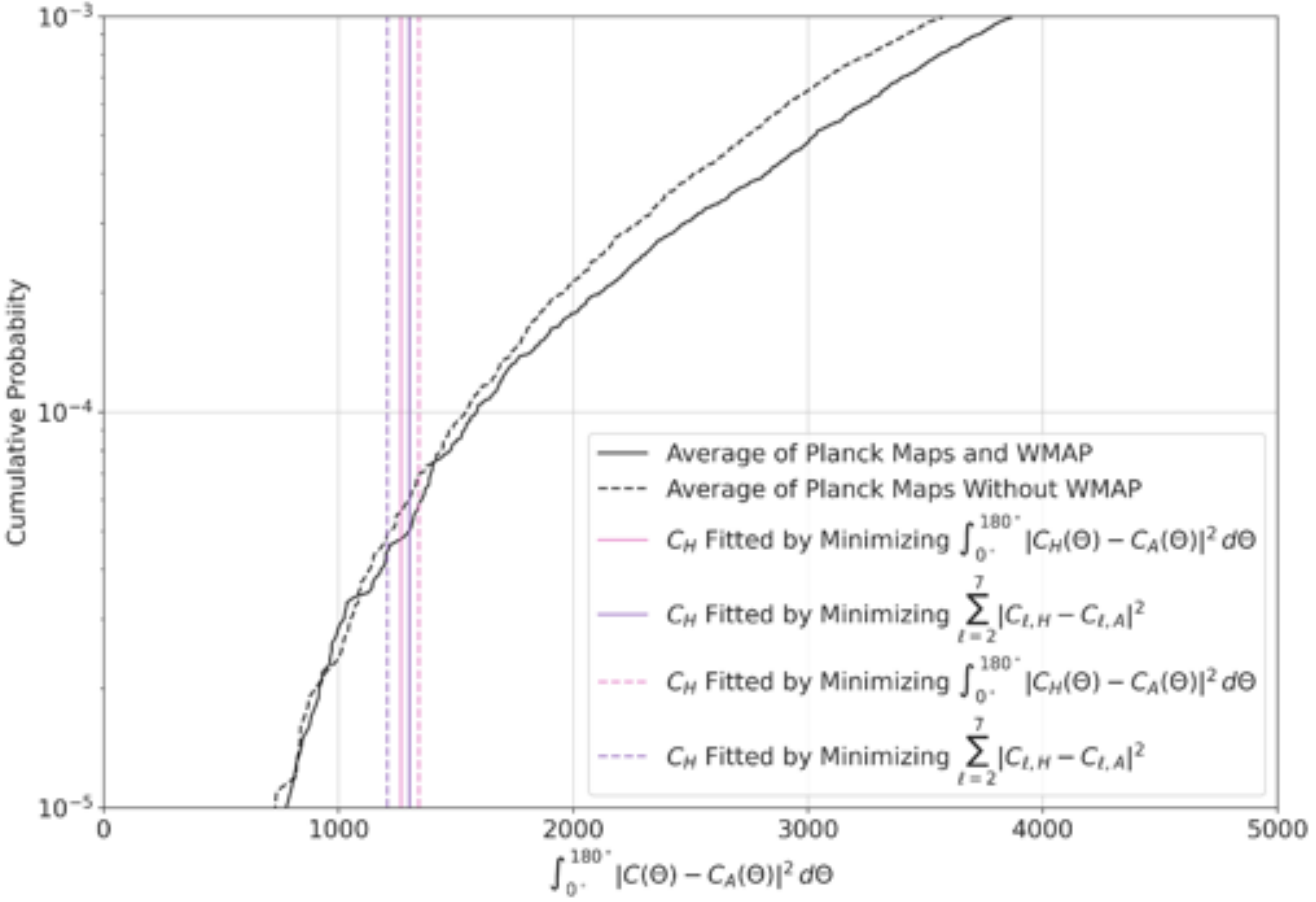
Residue= sum of the squared differences from measured correlations over all angles

Compare maps with the holographic model and with 10^6 standard realizations

Fewer than 7×10^{-5} of standard realizations have residues as small as the holographic model

Evidence for causal coherence

Cumulative histogram of summed residues for standard realizations from average CMB maps



Takeaways

CMB at large angles preserves the primordial pattern of gravitational quantum fluctuations

“Anomalous” small correlations could signify profound holographic causal symmetries

A causal-shock noise model fits the large angle data much better than the standard picture

CMB could show the first direct evidence for causal coherence of quantum gravity

This interpretation would require a radical revision of the quantum model of inflationary fluctuations and initial conditions, but little change in successful concordance cosmology

Laboratory experiments could measure similar holographic noise