Quantum Twists of Space

Exotic Rotational Correlations from Quantum Geometry,
Their Effects on Interferometer Signals,
and Their Possible Connection with Cosmic Acceleration

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http://arxiv.org/abs/1509.07997

The Problem with Quantum Gravity

General Relativity agrees perfectly with experiments, but only if you ignore the quantum character of matter

The standard quantum theory of matter agrees perfectly with experiments, but only if you ignore dynamical geometry

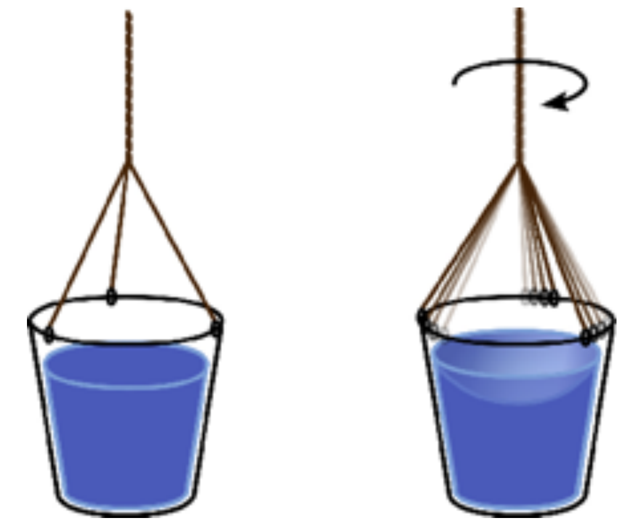
So every experiment is OK with one theory or the other

But a blend of the two theories makes crazy predictions

How does dynamical geometry reconcile with the quantum?

Can experiments help guide theory?

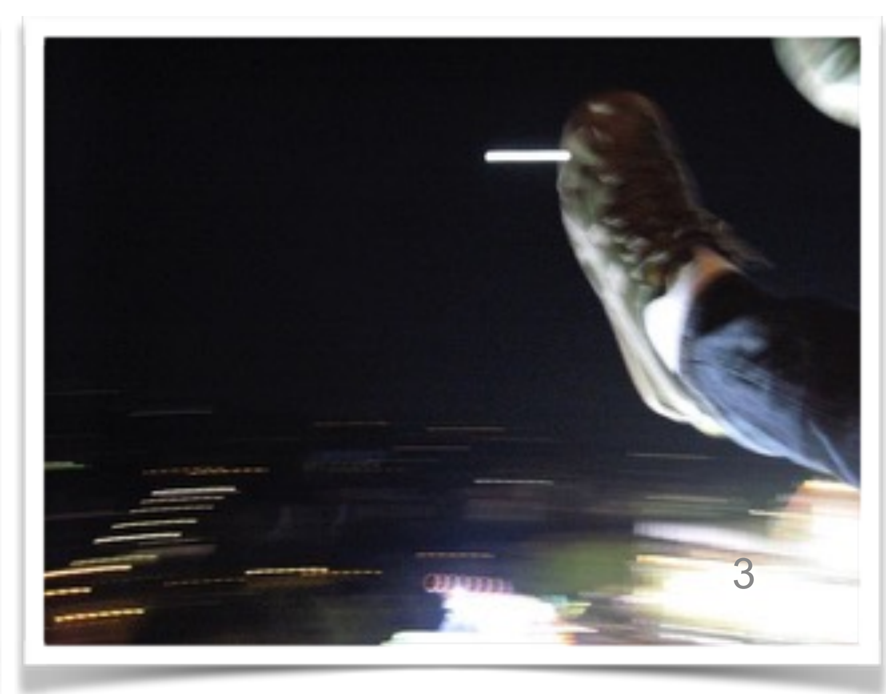
Rotation in Standard Theory



Newton's thought experiment: a rotating vessel of water proves the physical reality of absolute space

Mach asked why this local rotation agrees with distant stars

Einstein's general theory of relativity explains why: local and global frames are connected



Absolute Space and Rotation in General Relativity

There is an absolute local inertial frame at every event

GR answers Mach's question

- GR gives a complete and exact account of the relationship between space and classical matter, including rotation
- "Frame dragging" is measured and agrees with GR
- (Sometimes space rotates a lot, e.g., Kerr black holes)

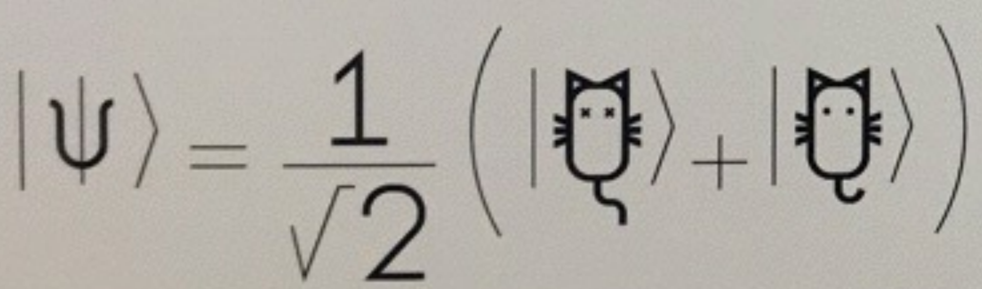
The issue is settled, except for quantum mechanics!

Apache Point Observatory lunar laser ranging

Gravity Probe- B

Schrödinger's Cat

is a famous illustration of the principle of quantum superposition.



Quantum systems, entanglement, and correlations

Matter is a quantum system

Whole system = superposition of states

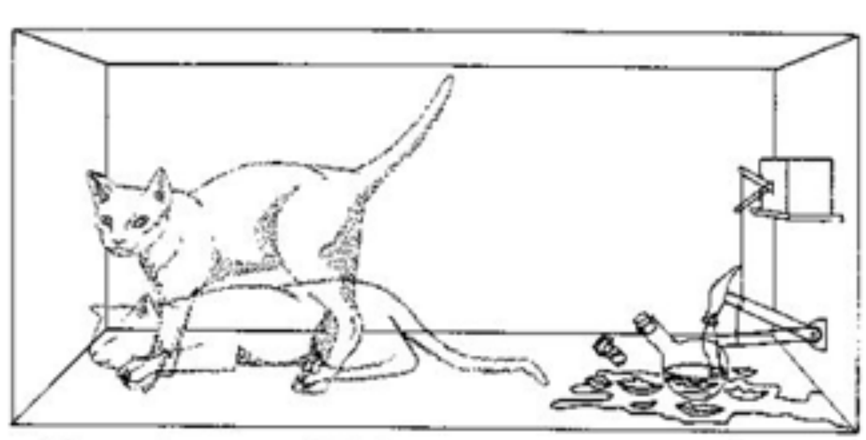
Every subsystem of a whole is *entangled* with every other

- A measurement projects onto a subspace
- A measurement of one subsystem projects all the others

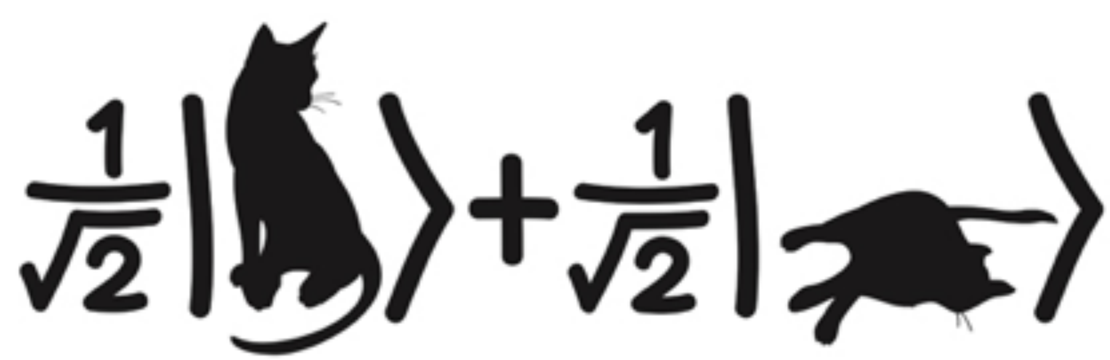
Theory only predicts correlations among observables

- Nothing “happens” at a definite place or time: no “locality”
- (although correlations obey causality)

entangled subsystems: cat and poison



state of the cat subsystem

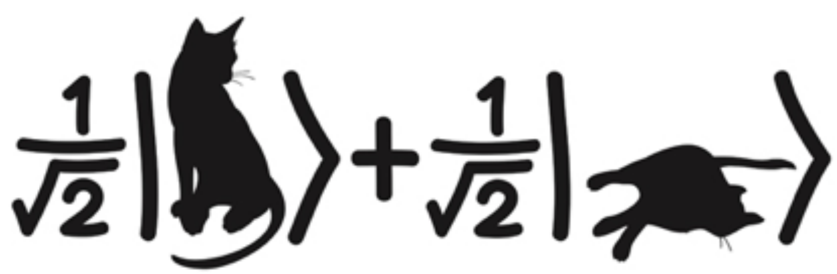


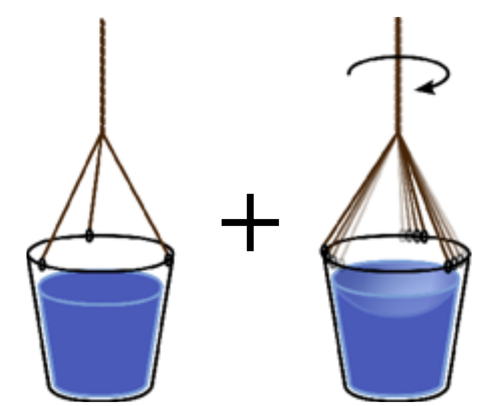
Absolute Space and Quantum Matter

In GR, the local inertial frame is absolute and deterministic, even for infinitesimal volumes

Quantum particles “know about” classical absolute space —- the local inertial frame—- which itself is not a quantum system

But matter states are quantum superpositions:

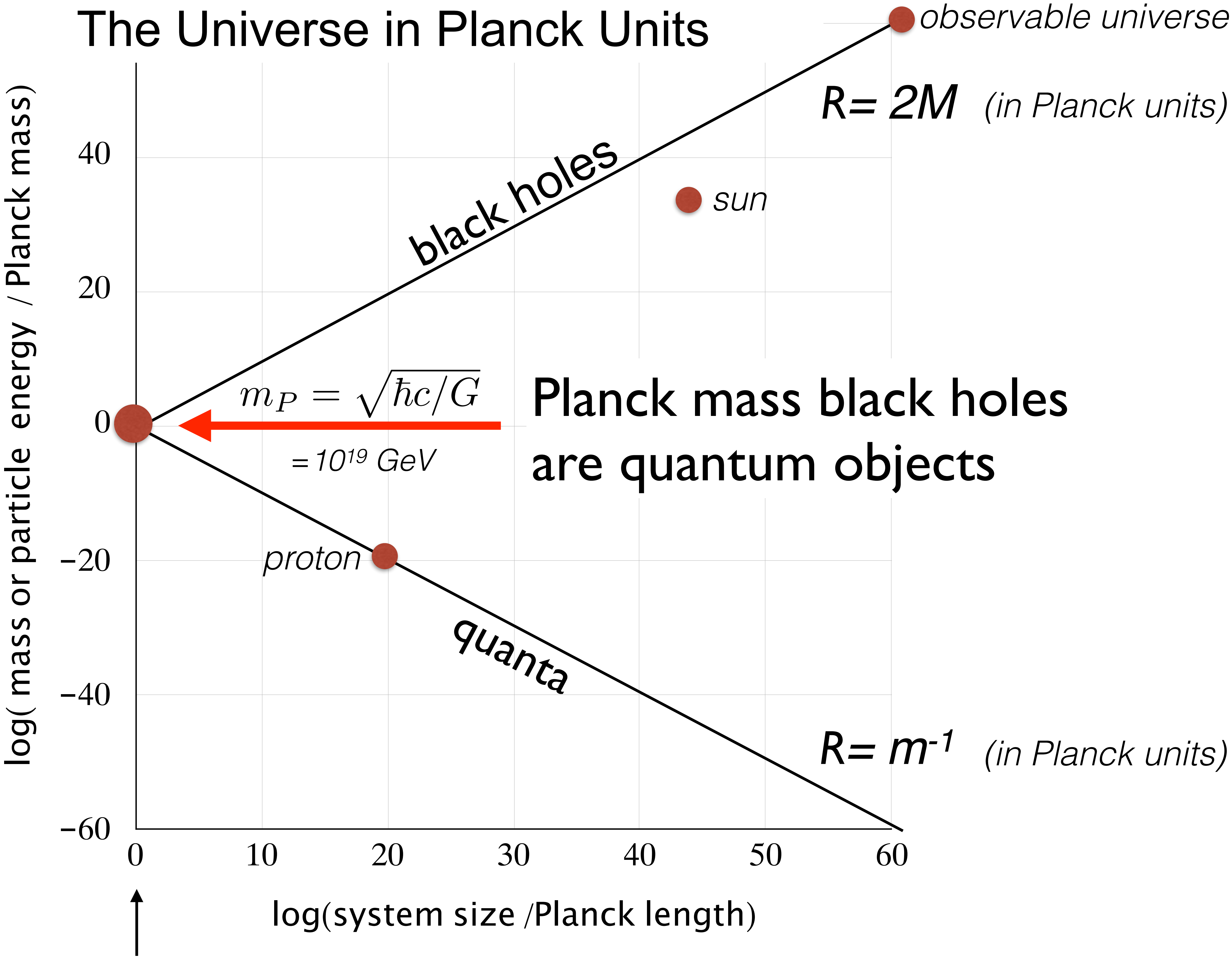




In GR, space interacts with a classical model of matter, even though real matter is quantum

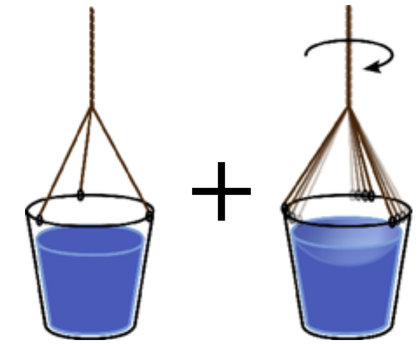
This standard approximation works well on scales much larger than the Planck length, but it cannot be exact

The Universe in Planck Units



$$\ell_P = \sqrt{\hbar G/c^3} = 1.616 \times 10^{-35} \text{ m}$$

No Absolute Space at the Planck Length Scale



Imagine a quantum Newton bucket a Planck length across

- It is a superposition of spin states, like an atom
- Components of spin do not commute
- Rotational indeterminacy ~ one radian per Planck time
- *Frame dragging by a quantum bucket makes it impossible to define determinate, classical local rotation at the Planck scale*
- The local inertial frame does not exist at small scales

This is radically different from standard absolute space

Frames become nearly classical in larger, longer-lived systems

But small, exotic quantum-gravitational rotational correlations must exist that do not occur in standard theory

Conflict of Quantum Fields with Gravity on Large Scales

Consider a standard quantum field in a volume of size R

Its general state is a superposition of excitations

Some of these have ~1 particle per independent mode of energy m

Mass of this state exceeds black hole mass for

$R>m^{-2}$ in Planck units

This field state is impossible in General Relativity

The paradox occurs for large R, even at well studied values of m

Very large R ==> cosmological constant catastrophe (more later)

Conflict could simply be an artifact of disregard for exotic correlations with geometry on large scales

Entanglement reduces independent degrees of freedom

Effect not included in “UV completions” (e.g., string theory)

Exotic Correlations of Quantum Geometry

Suppose space is a quantum subsystem, as well as matter

- There is no background absolute space or time
- Geometry is indeterminate— a superposition of states
- Geometry is entangled with the matter subsystem

Finite information ==> finite number of degrees of freedom

- ==> new, exotic correlations not in standard theory

What is the character of exotic correlations on large scales?

How can we study them?

Magnitude of Exotic Correlations in Large Systems

There is no standard theory of quantum gravity

But estimates of exotic correlation follow from simple thought experiments using standard quantum mechanics and gravity

Estimate from standard quantum theory: the **Planck diffraction scale**

- This is much larger than the Planck length (following slides)
- Agrees with current experiments
- Also about the right amount of correlation needed to resolve conflicts of dynamical space-time and quantum matter

Standard Quantum Correlations in Extended States

Schrödinger wave equation for position of a free body of mass *m:*

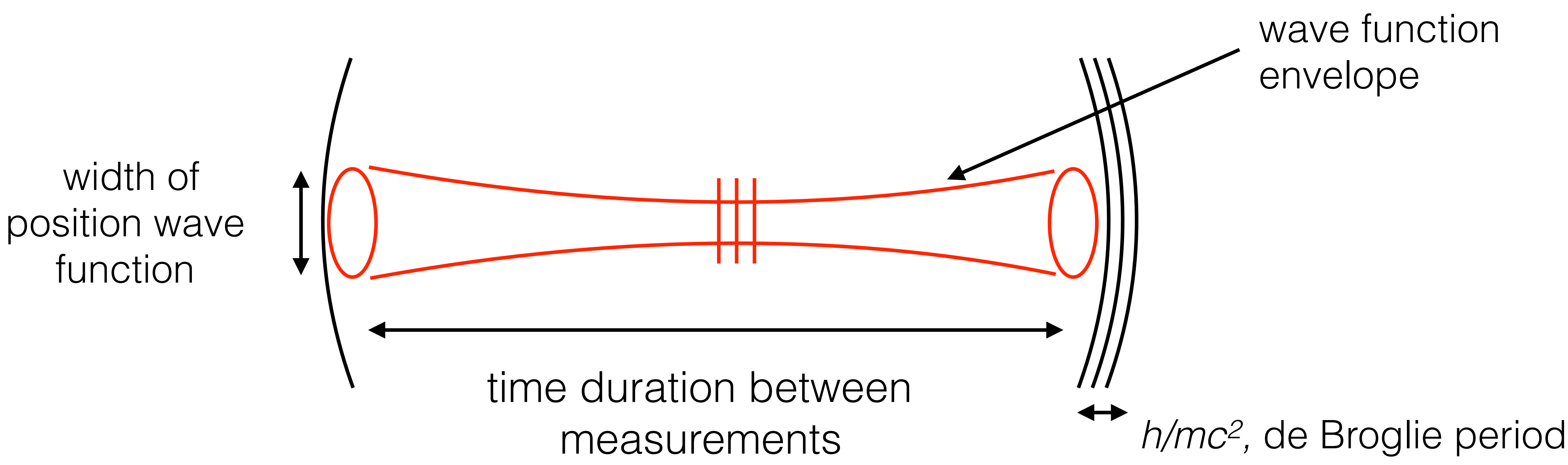
$$(\partial_i \partial^i - 2i(m/\hbar)\partial_t)\psi = 0$$

Extended waves obey a form of the Heisenberg uncertainty principle

Express as a bound on position correlation in the time domain:

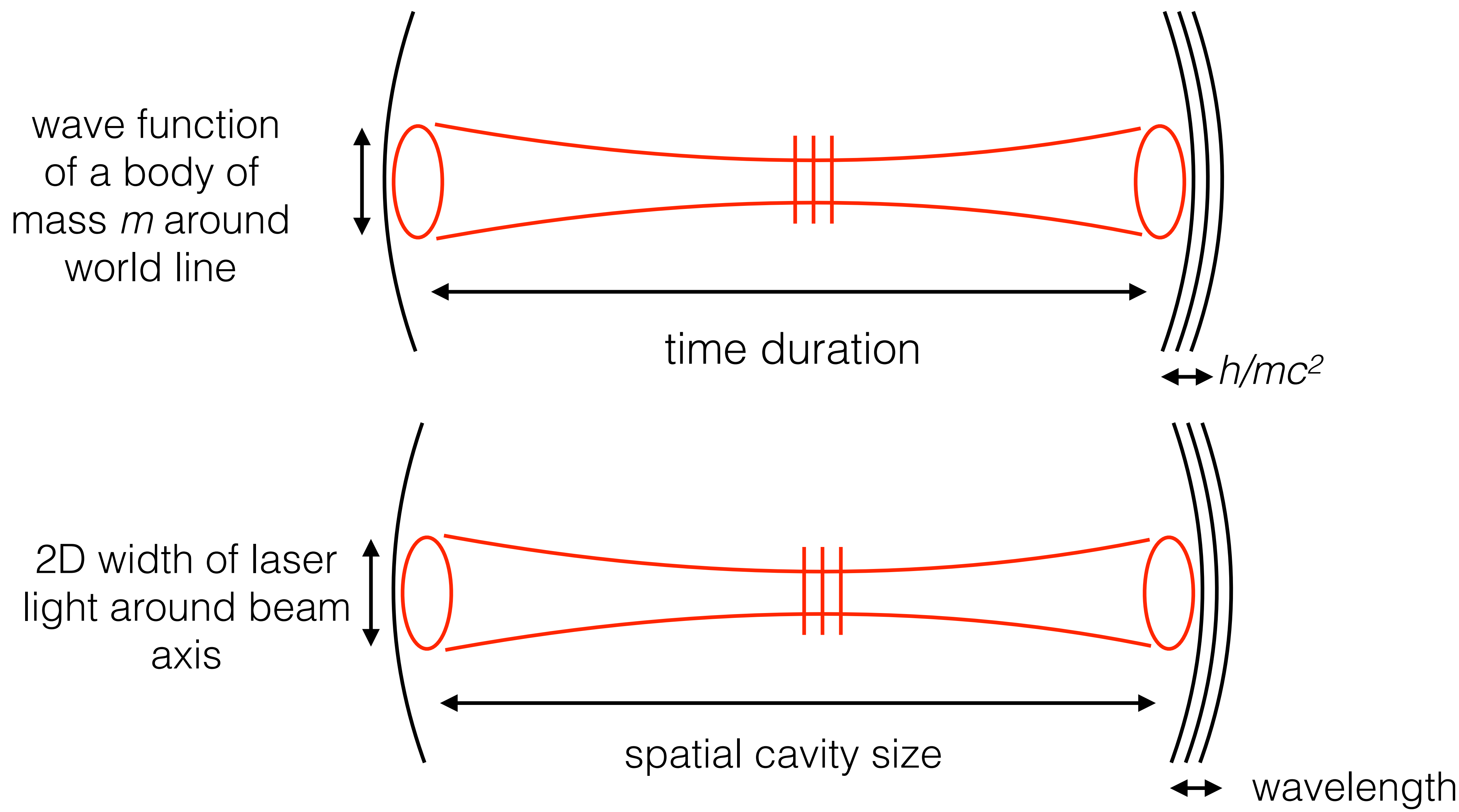
$$\langle (r(t+\tau) - r(t))^2 \rangle = \sigma_0^2(\tau) > \hbar\tau/2m$$

Minimum departure from classical body at rest grows linearly with time



Mathematical equivalents: wave function and laser beam

wave equation for a massive body <=> paraxial wave equation for light
quantum wave function of a body <=> field amplitude in a cavity
body at rest <=> gaussian mode of cavity
spreading of wave function in time <=> transverse spreading of beam
preparation and measurement of state <=> curvature of mirrors



Planck Diffraction Scale: variance of extended Planck state

Model the geometrical quantum state as a Planck variance wave

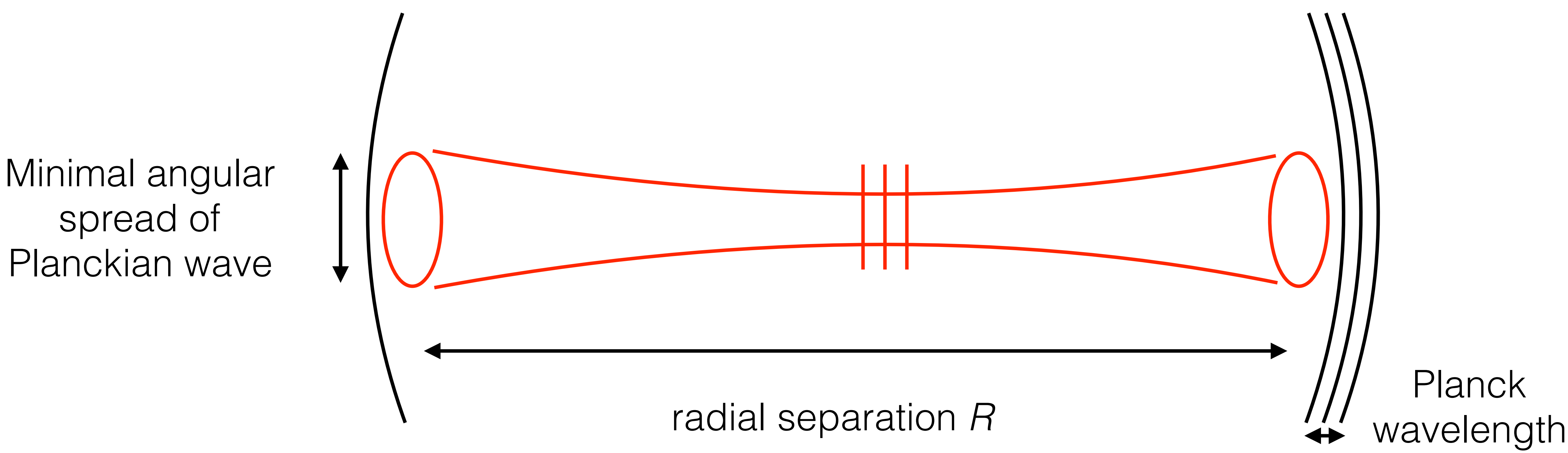
classical ray <=> expectation value of wave direction

actual state is a superposition:

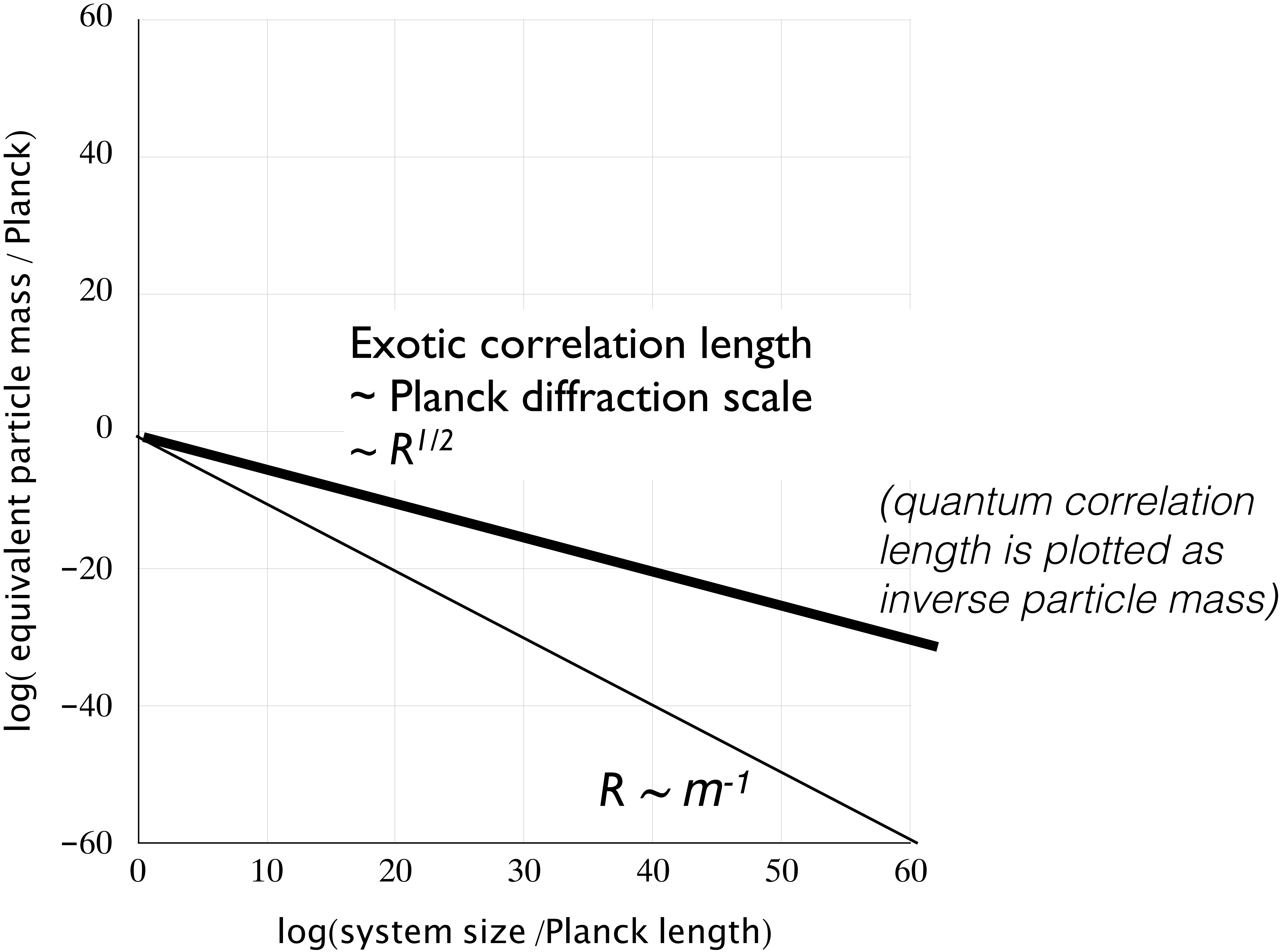
wave function variance <=> exotic correlation

Posit that exotic correlation at separation ~R is set by the directional resolution of a Planck wave function:

$$\langle \Delta\theta_P^2 \rangle_R \approx \langle \hat{x}_\perp^2 \rangle_R / R^2 = \ell_P / R$$



Scale of Exotic Correlation in Planck Units



Character of Exotic Correlations: shared displacement

Base a model on a radical assumption:

quantum geometrical phase entangles with quantum field phase

==> quantum superpositions of shared spatial displacement

Displacement on Planck diffraction scale is shared by all fields and massive bodies

3+1D structure is not known but is constrained by general principles

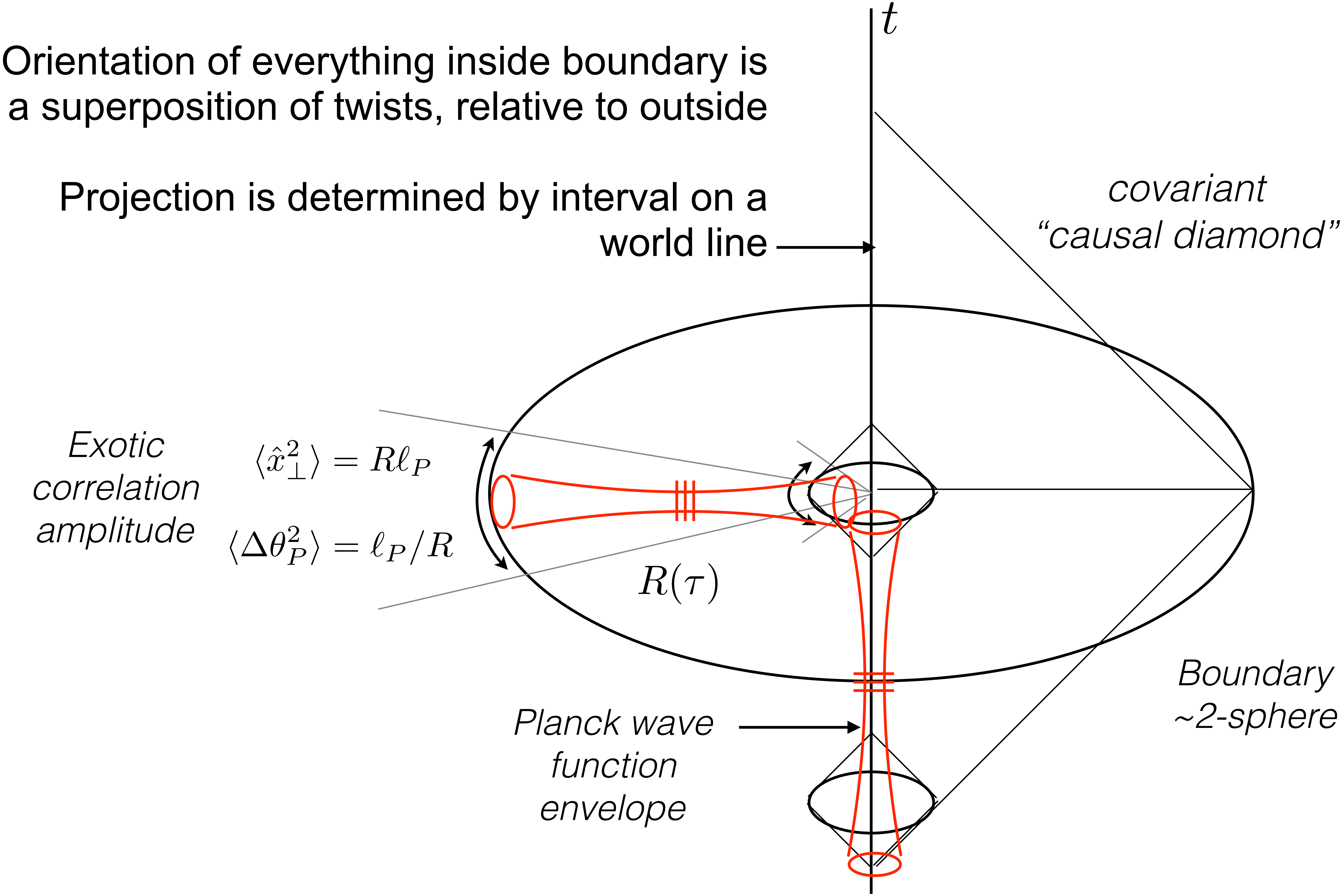
- Covariance between directions ==> strain, rotation and/or shear
- Time projection: “Collapse of wavefunction” on covariant causal boundaries

Unlike all classical geometry since Euclid!

Exotic rotational correlations project twists onto causal boundaries

Orientation of everything inside boundary is a superposition of twists, relative to outside

Projection is determined by interval on a world line



Visualize exotic rotational correlations as fluctuations

Mismatch of “local” and “global” rotation around any observer

“Twists” of local frame <*R* relative to distant frame >*R*

- Planck diffraction scale ~ Planck random walk in transverse position
- Coherent twists on a covariant causal boundary (~2-sphere)
- Mean rotation vanishes, mean square does not

Directional fluctuations get smaller on large scales:

$$\langle \Delta\theta_P^2 \rangle_R \approx \langle \hat{x}_\perp^2 \rangle_R / R^2 = \ell_P / R$$

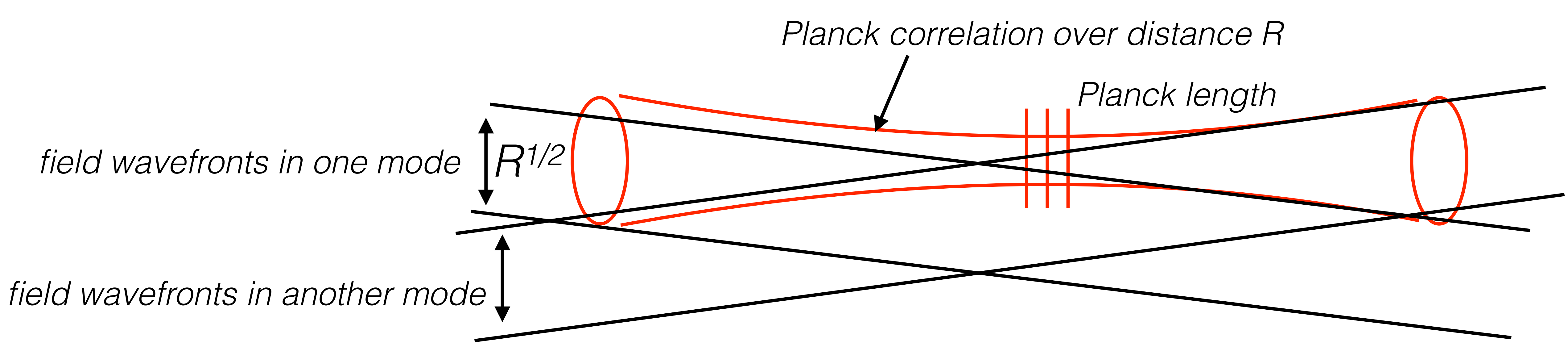
And rotational fluctuations on larger scales get slower*:*

$$\langle \omega_i^2(R) \rangle \approx c^2 \ell_P R^{-3}$$

Quantum geometry entangles field states on large scales

In this model of *quantum geometry,*

- Geometrical correlation ~ Planck diffraction scale
- Field phase is affected by geometric phase
- Propagating field states become less distinct from each other at large R than in standard theory
- This effect is not in standard field theory



Exotic entanglement resolves conflict of field states with gravity on large scales

In-common exotic displacement ~ particle wavelength at

$$R \sim R_C\,(m) = m^{-2}\quad \text{in Planck units,}$$

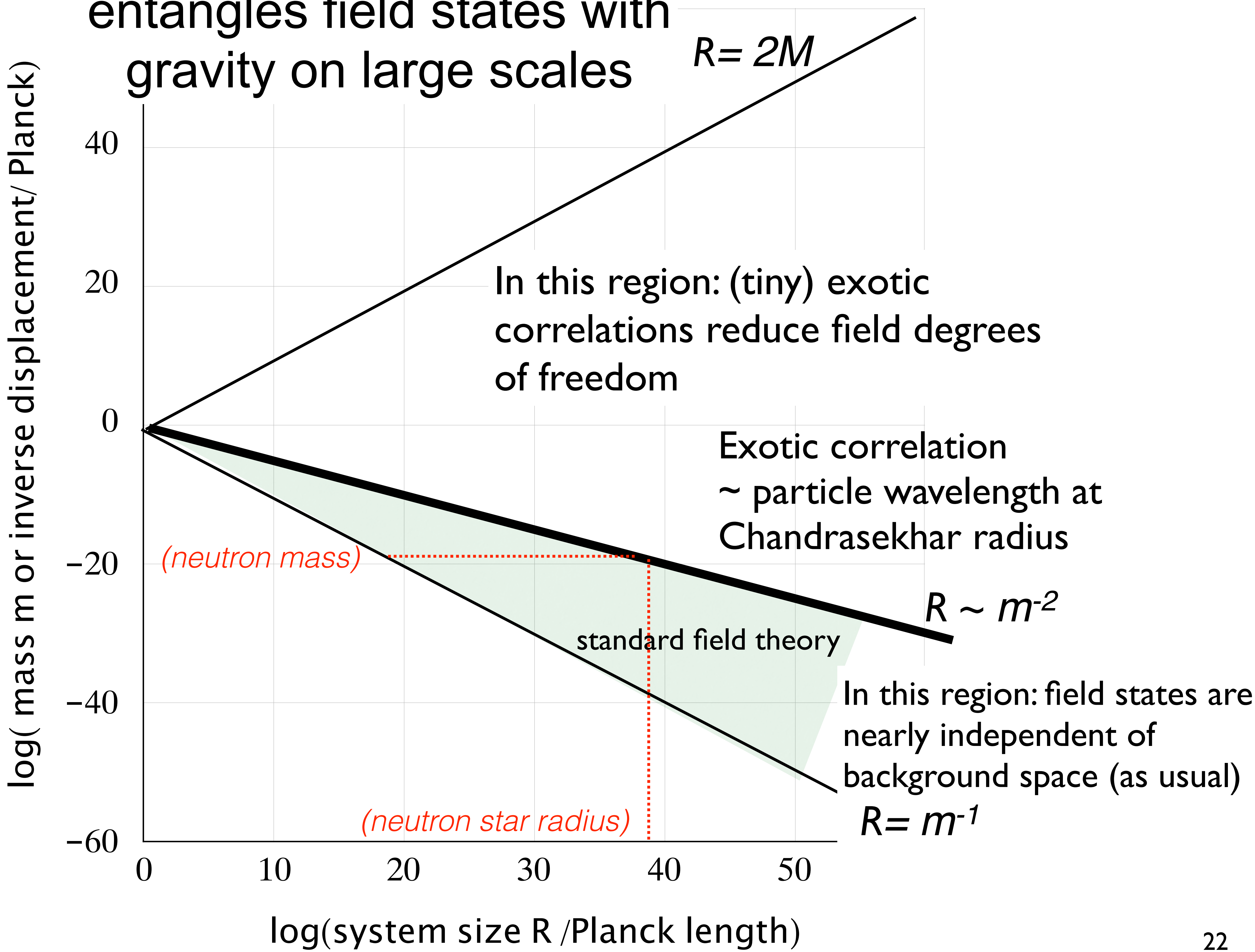
the Chandrasekhar radius for field states of mass *m*

Fewer independent field states: no gravitational catastrophes

Implements previously *ad hoc* "IR cutoff" to field theory at $R>m^{-2}$

Consistent with particle experiments (Cohen et al. 1999)

Exotic quantum geometry entangles field states with gravity on large scales



A radical departure from foundations of field theory

Standard field states: wave packets made of modes of size R describe positions on scale R

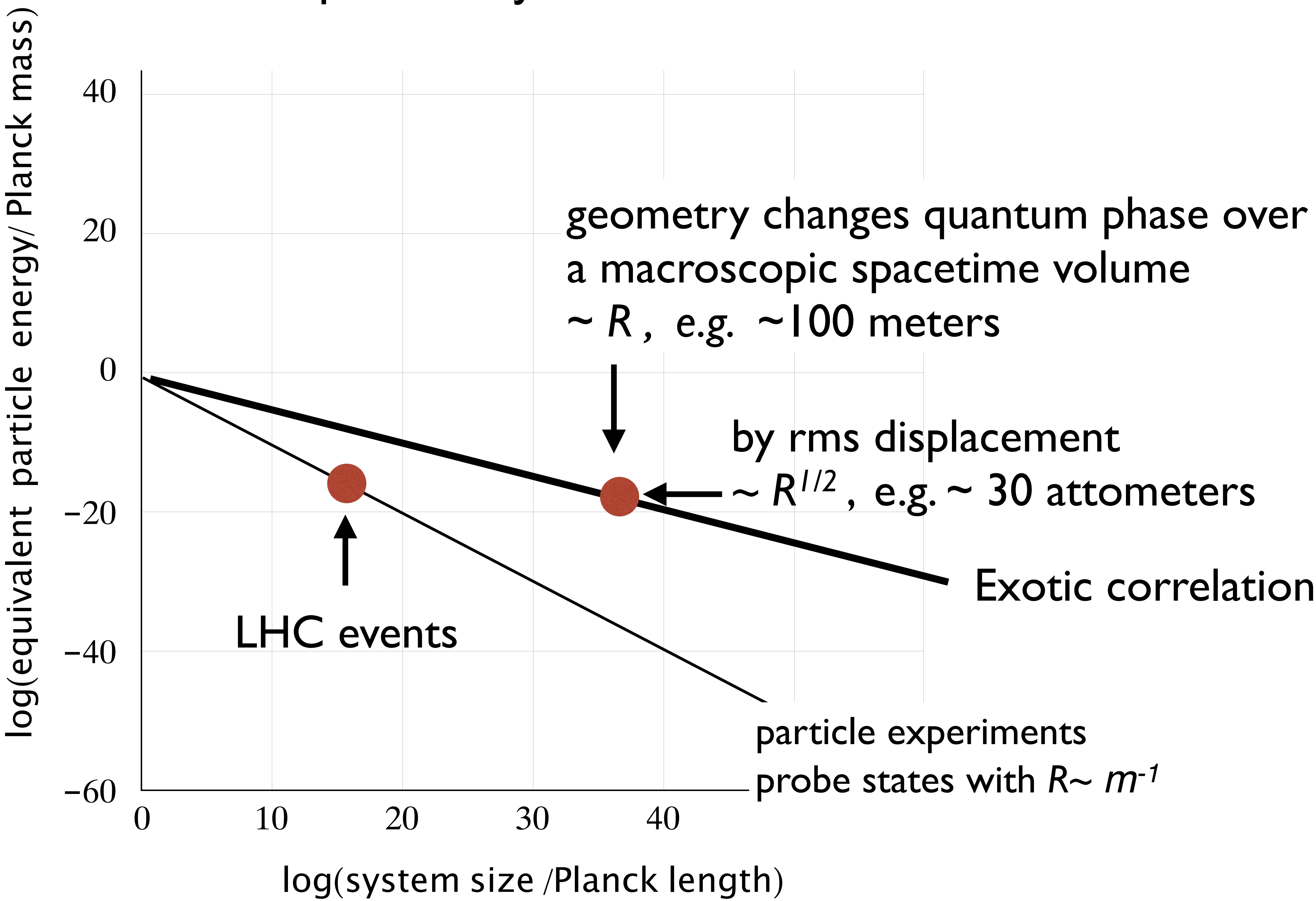
Planck scale correlations entangle field states on scale R

(in-common displacement)$^2 \sim R$

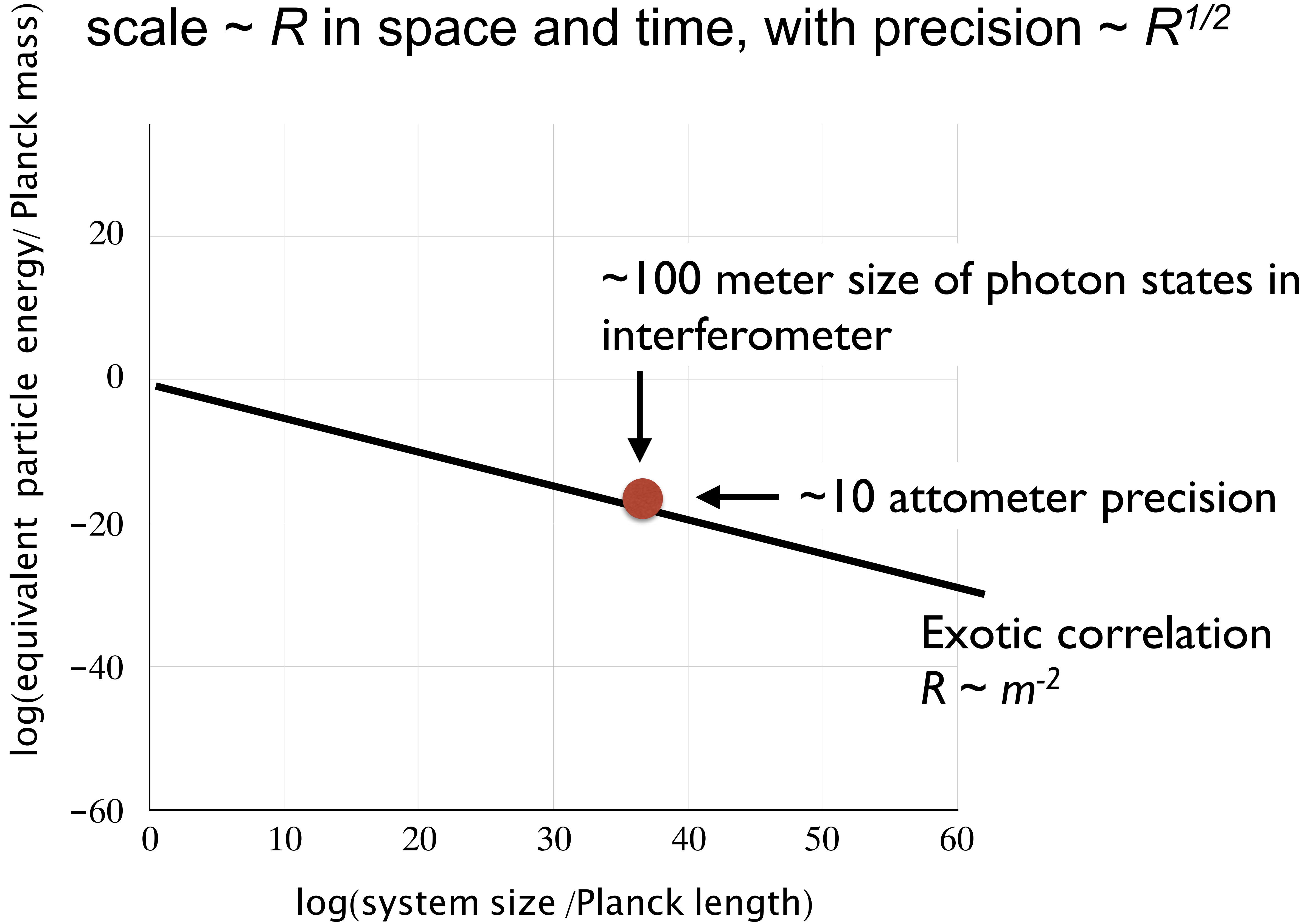
The effect is far too small to detect in local particle experiments

But may affect fields detectably in interferometers

Effect of exotic correlations: quantum fields coherently displaced by distance ~ $R^{1/2}$ on scale R



An experimental program to study exotic correlations: interferometers that measure phase correlations on scale ~ *R* in space and time, with precision ~ $R^{1/2}$



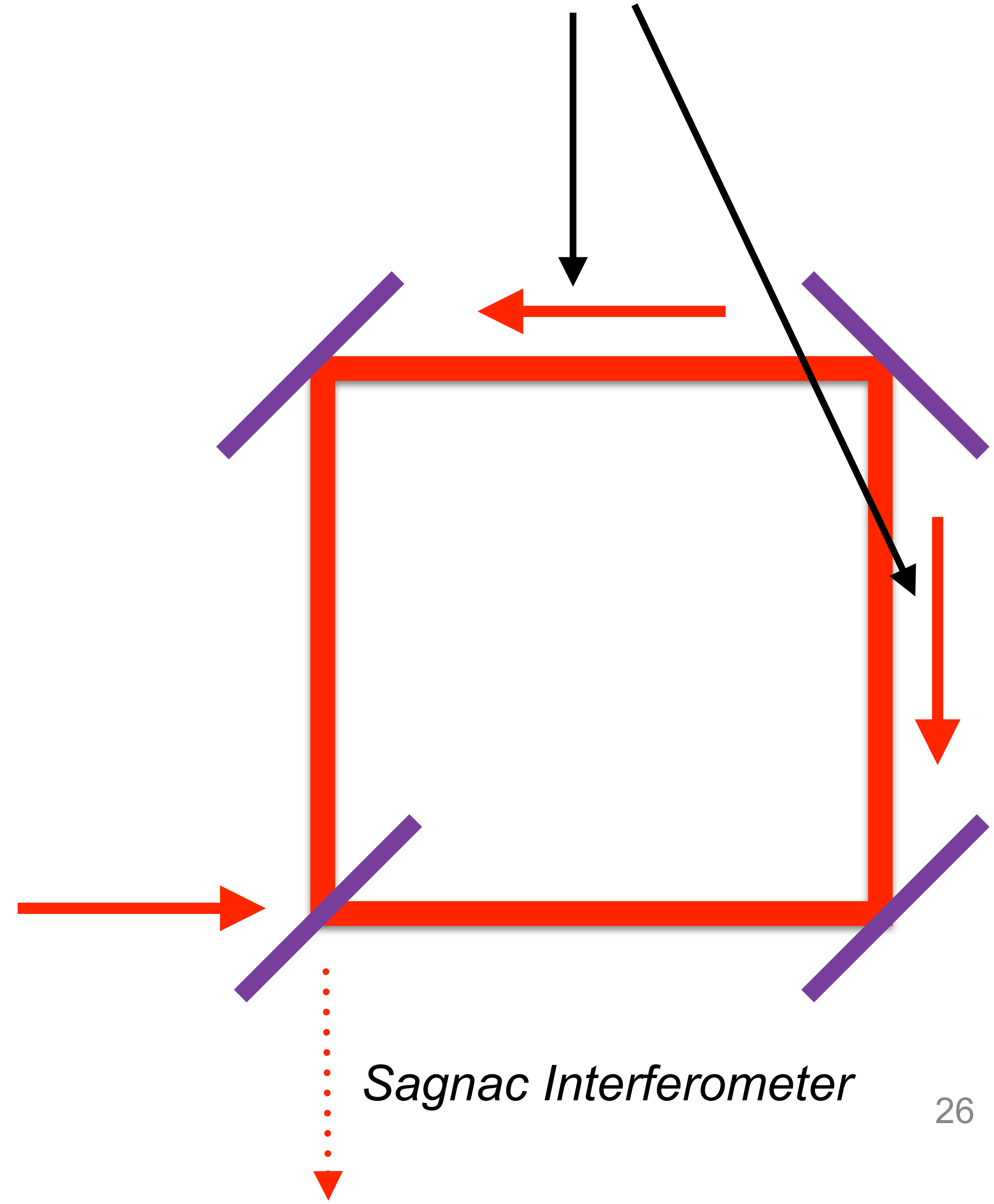
Interferometers measure large coherent quantum states

States inside interferometer cavity are superpositions of two directions

A single photon follows two separated trajectories

Exotic entanglement with geometry means that quantum fields share a geometrical component of path-dependent phase

Direction and location of a photon inside the cavity is indeterminate



Sagnac Interferometer

Sagnac Interferometer

Light path is a closed circuit

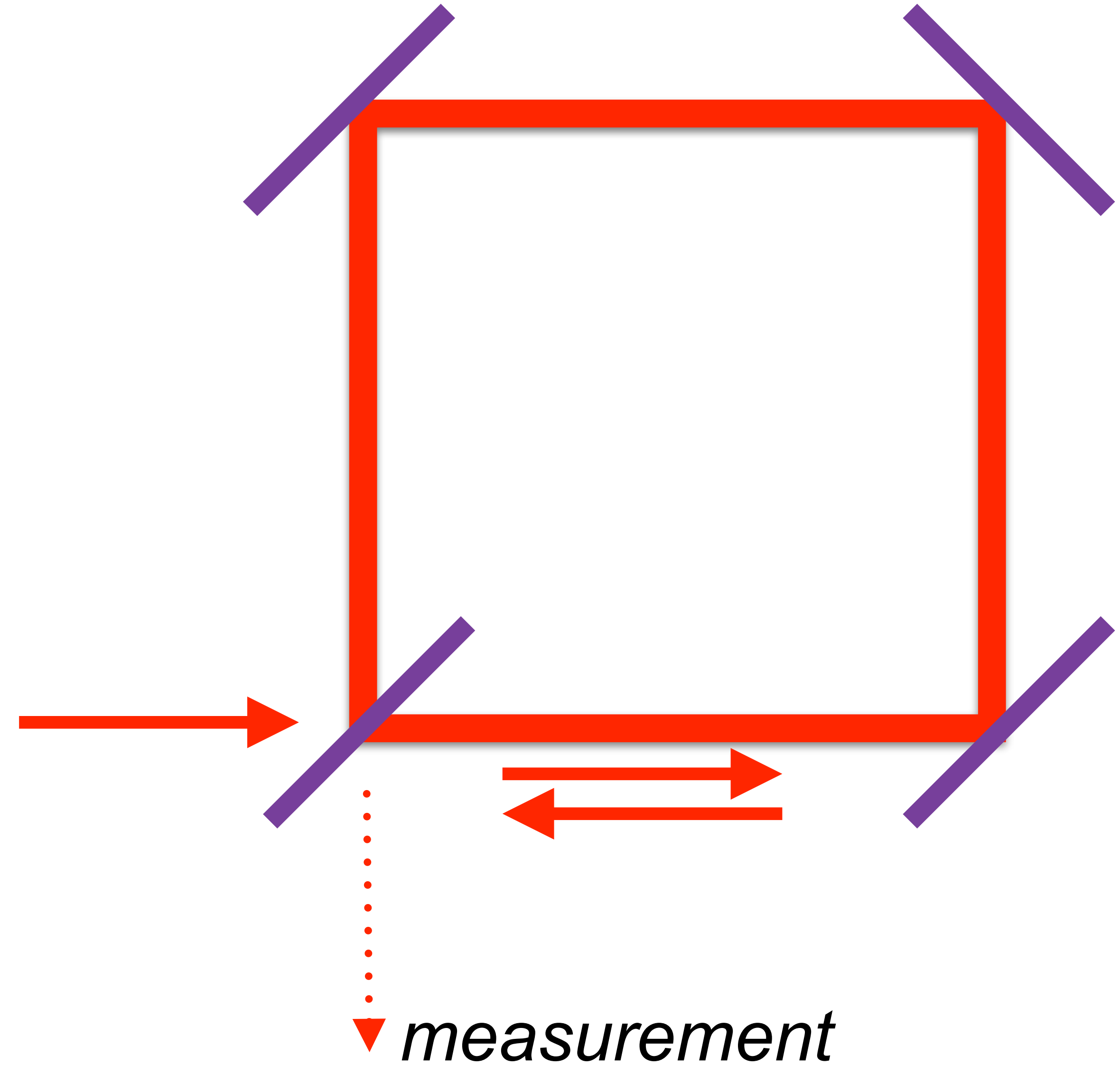
Signal measures classical absolute rotation relative to inertial frame

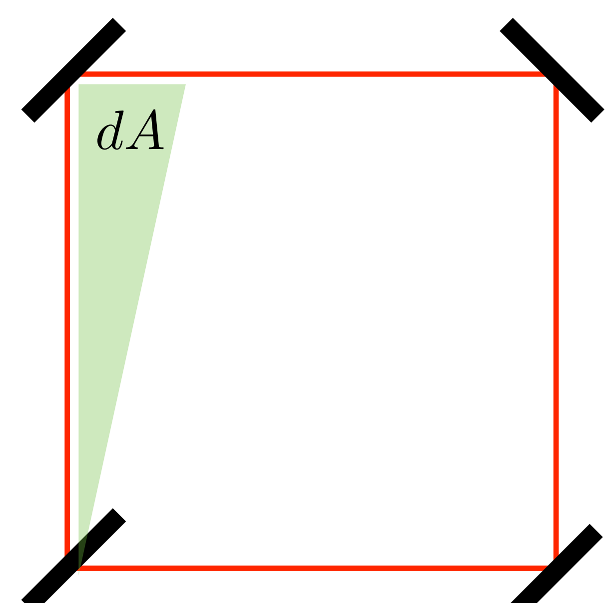
Rotating apparatus has different light path length in opposite directions

Effect on phase in each segment is given by the projected component of rotation on light path

Integral around circuit depends only on total area and rotation rate:

$$\Delta t = 4A\omega/c^2$$





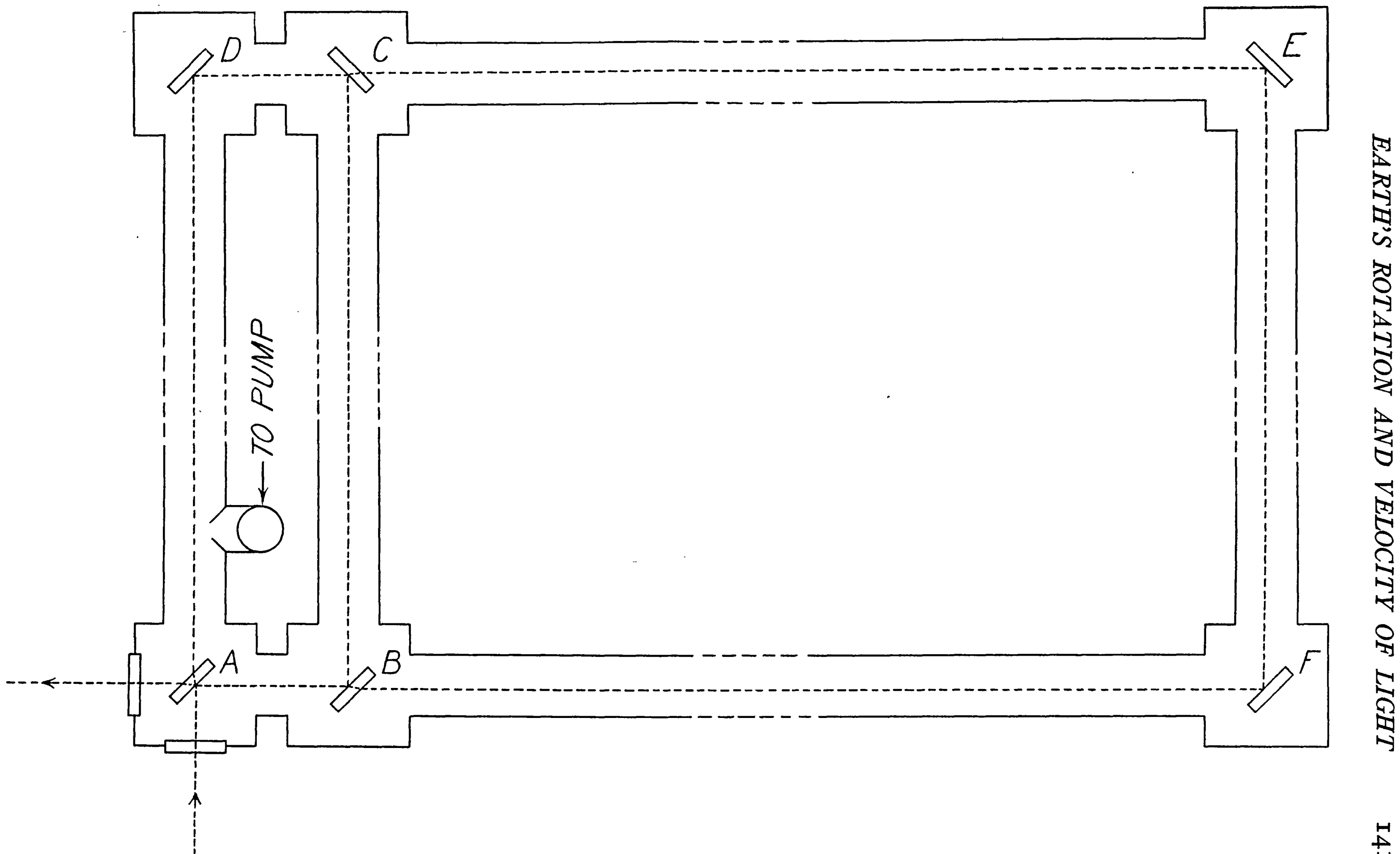


FIG. 1.—Ground plan, showing arrangement of mirrors

Michelson-Gale experiment (1925): Measured rotation of the Earth

Michelson's team in suburban Chicago, winter 1924, with partial-vacuum pipes of 1000 by 2000 foot interferometer, measuring the rotation of the earth with light traveling in two directions around a loop

Exotic Rotational Correlation in Interferometer Signals

If exotic rotational correlations exist, they create “holographic noise” in the signal of any interferometer whose light path encloses an area

Signal responds to twists in the contained inertial frame, with response determined by world lines of mirrors

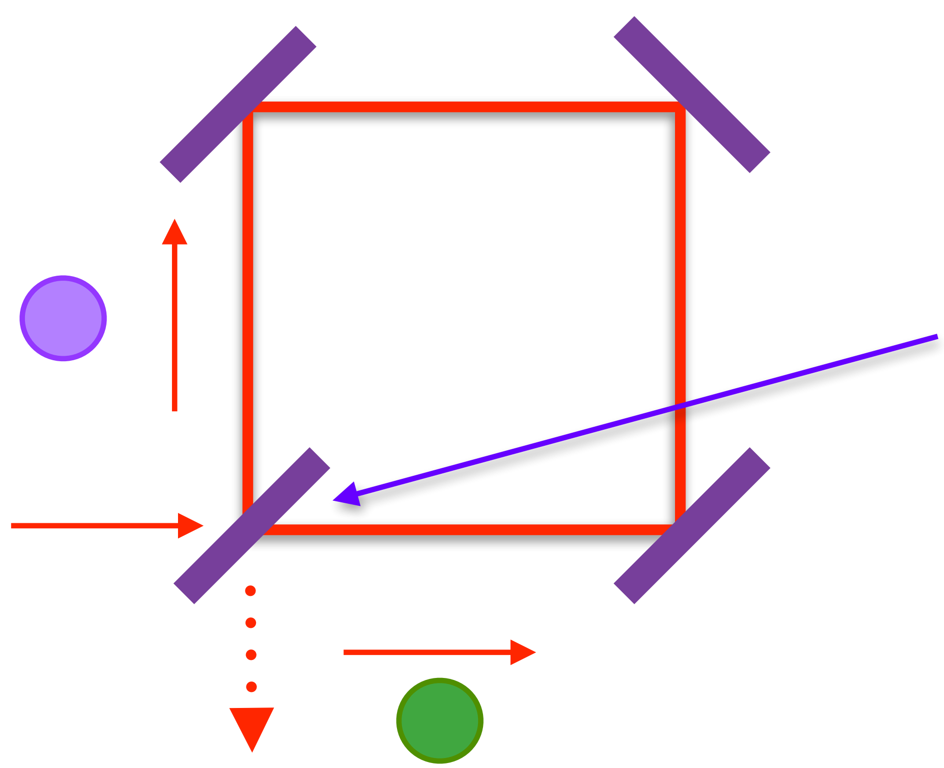
Predicted signal correlations depends on the shape of interferometer, and spatial structure of exotic correlations

Signal in an interferometer is a time series on one world line

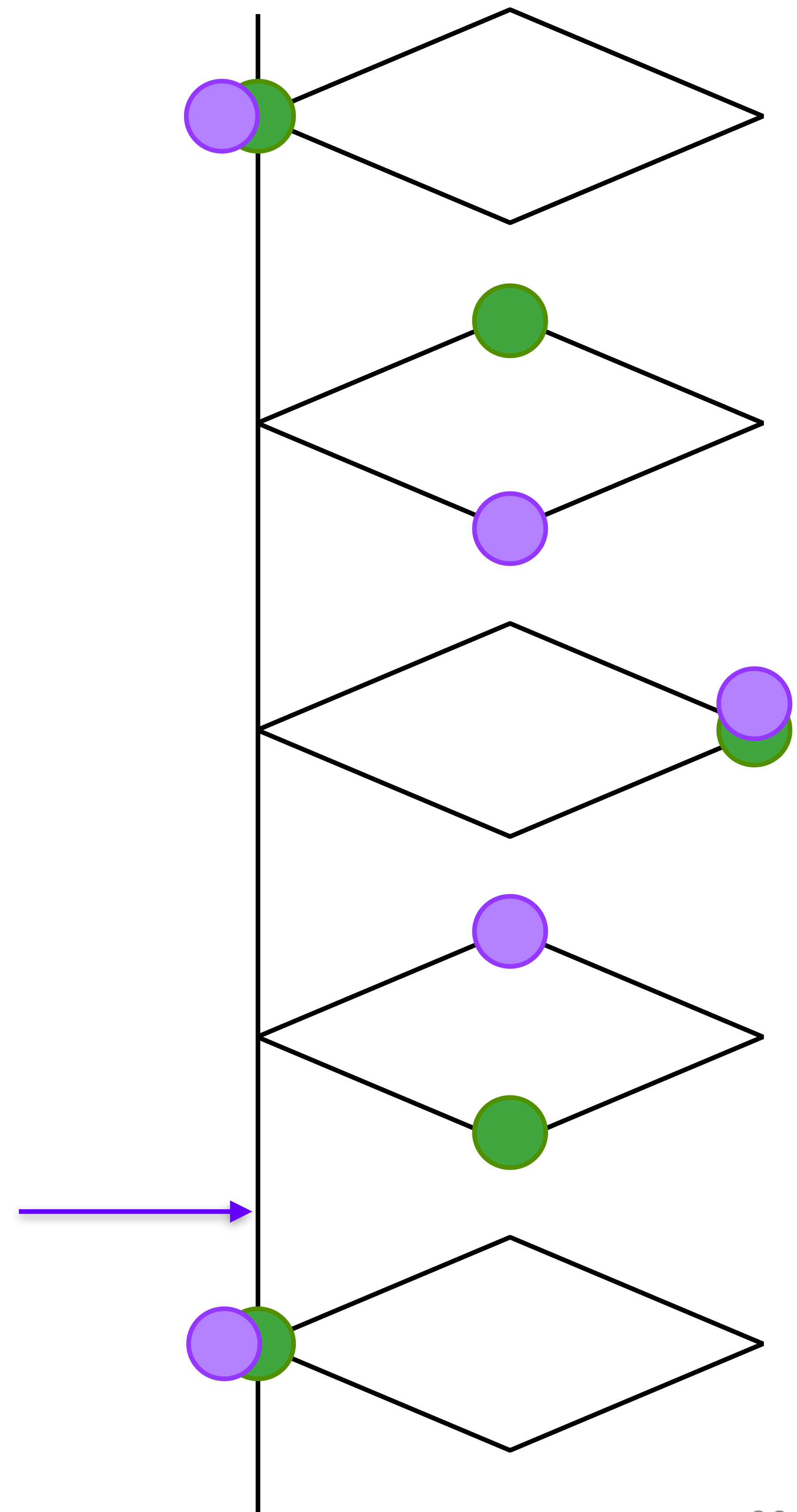
In a (square) Sagnac it depends on events at four world lines connected by null trajectories

The quantum state is delocalized over the whole 4-volume (e.g., Caves 1980)

Photon field state is entangled with geometry on this scale



World line of beamsplitter



Interferometer Signal Exotic Correlation Function

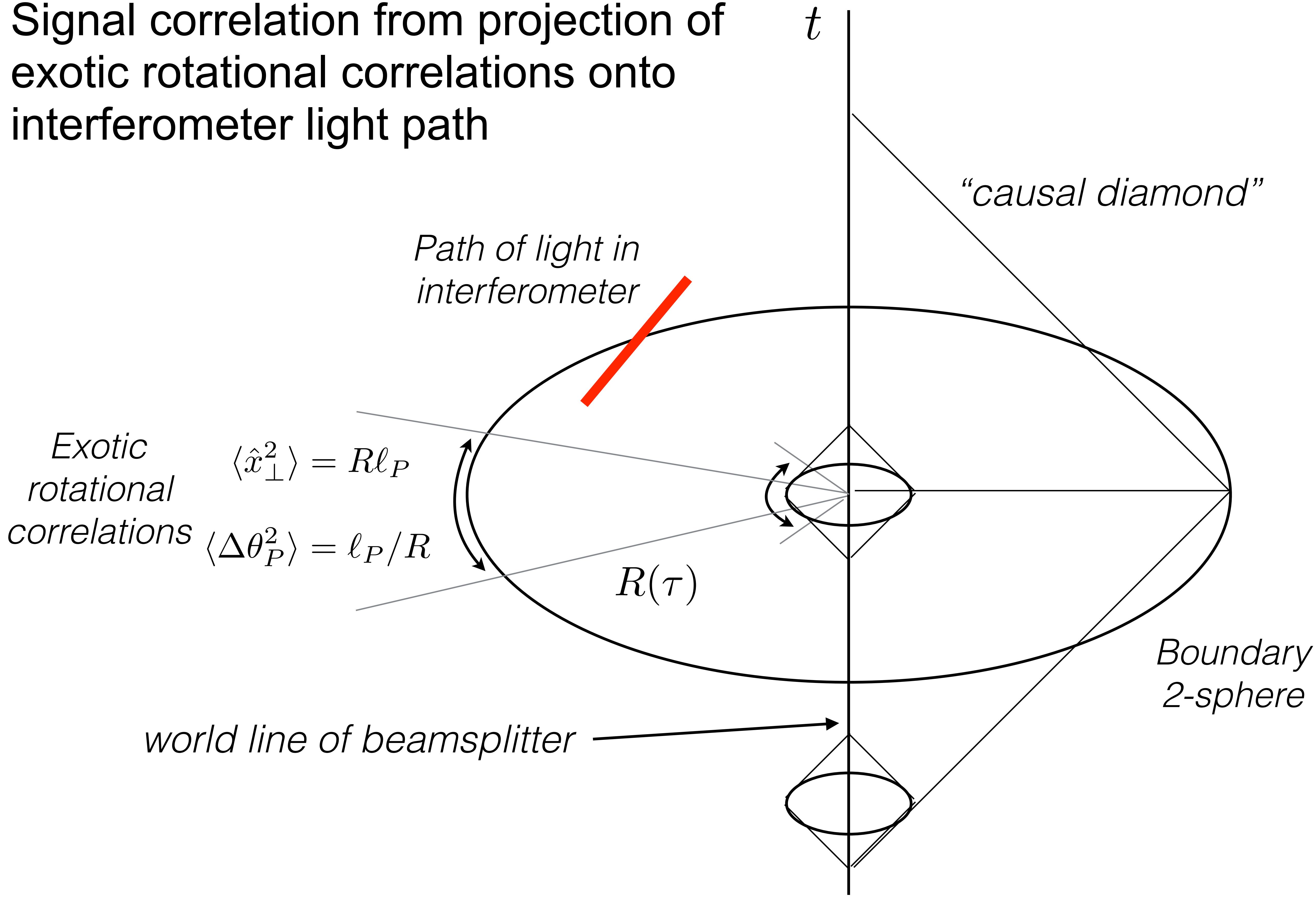
Exotic 3+1D rotational correlations project onto 1D signal correlation

Statistical observable: expressed as a correlation function of differential mirror position,

$$\Xi(\tau) \equiv \langle x(t)x(t+\tau)\rangle_t$$

Signal correlation function must depend only on the path shape

Signal correlation from projection of exotic rotational correlations onto interferometer light path

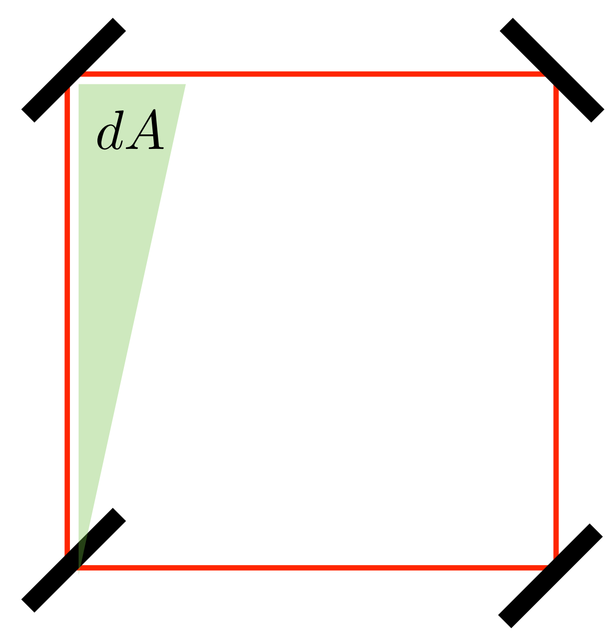


Exotic signal correlation function expressed as swept area

For any shape of circuit, correlation depends only on one function of time lag:

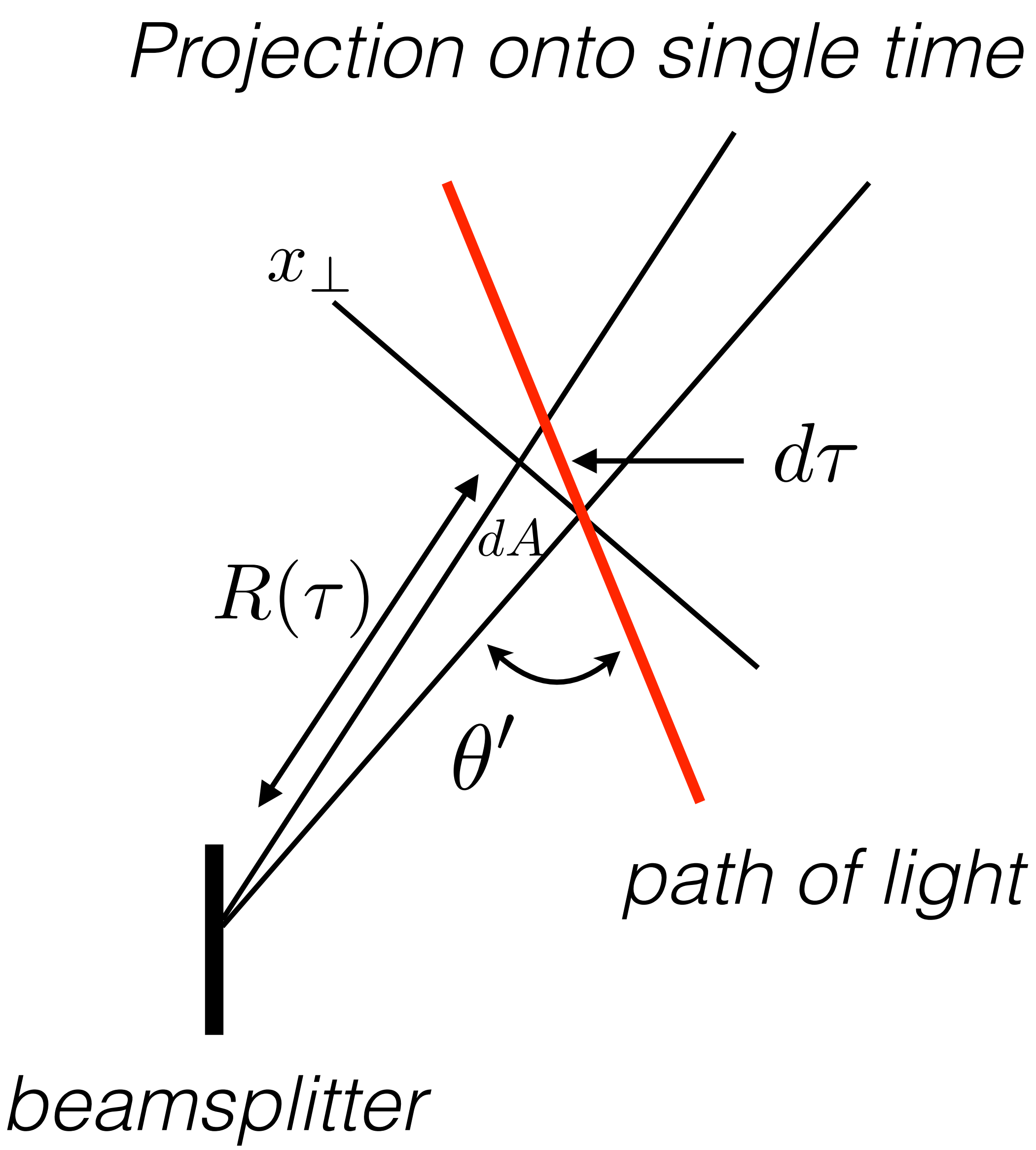
A = area swept out by the light path, as a function of time

Projects exotic 4D rotational fluctuations onto time domain measured in an apparatus



Projection of 3+1D correlation onto 1D signal

Determined by the path of light at the corresponding affine time lag from the beamsplitter, in the rest frame

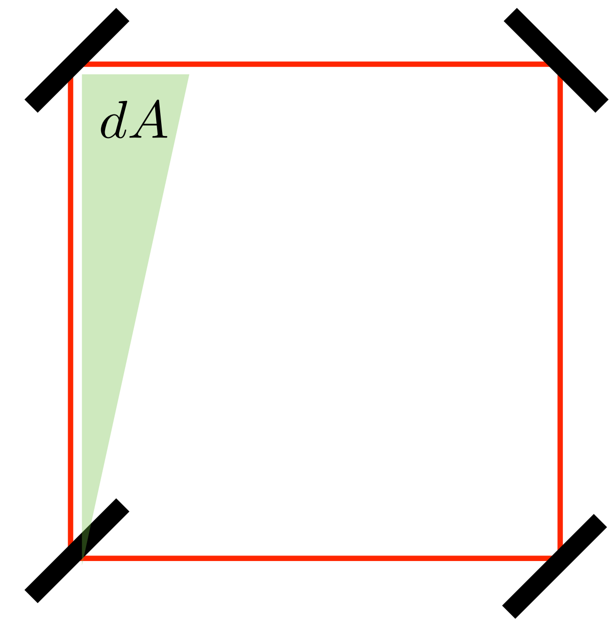


$$dA^{\pm}/d\tau = \sin\theta' dA^{\pm}/dt = R(\tau)\sin\theta'$$

$$\langle \Delta x_\perp^2 \rangle_{R(\tau)} \sin\theta' = \ell_P R(\tau)\sin\theta' = 2\ell_P dA/d\tau$$

Exotic signal variance

$$\Xi_0 \equiv \Xi(\tau = 0) \approx A_0 \ell_P / c T_0$$



A_0= total enclosed area
T_0= arm length
l_P= Planck length

Valid for any shape of light path

arxiv.org/abs/1509.07997

Design Features of Experiments

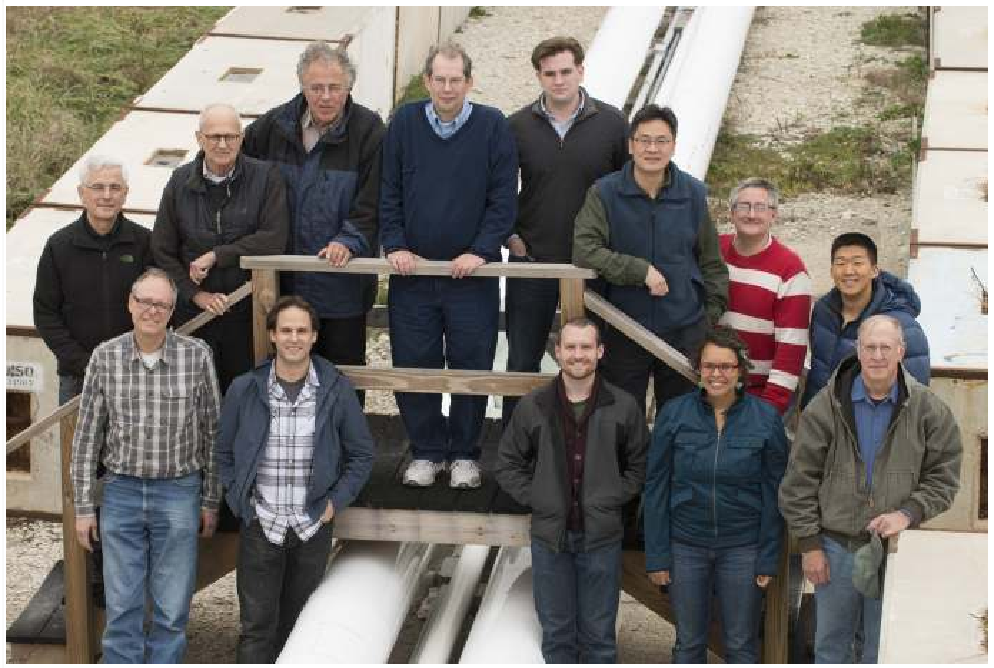
Universal spectrum
- Depends only on Planck scale
- Known dependence on layout of the interferometer

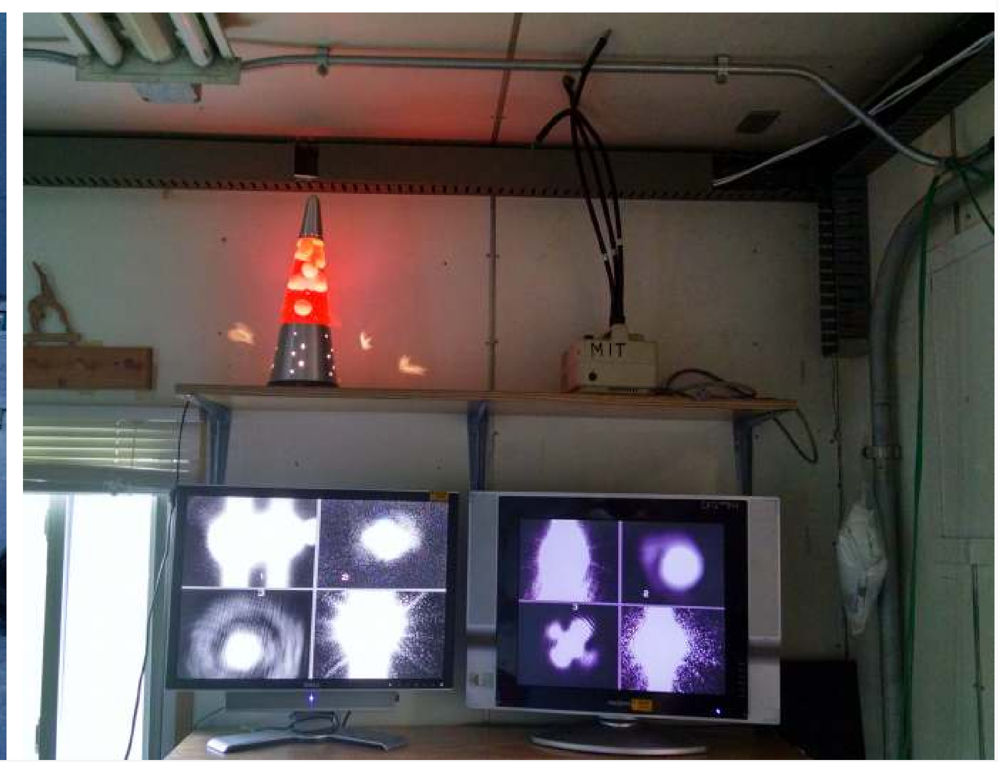
Path must enclose an area to show rotational fluctuations
- No effect from radial propagation

Cross Correlation
- Twists are the same for different instruments that measure the same 4-volume
- Null configurations can be used to control for environment

Noise power is at high frequencies ~ free spectral range
- Optimal experiment measures superluminal correlation
- Time sampling and correlation at high frequency

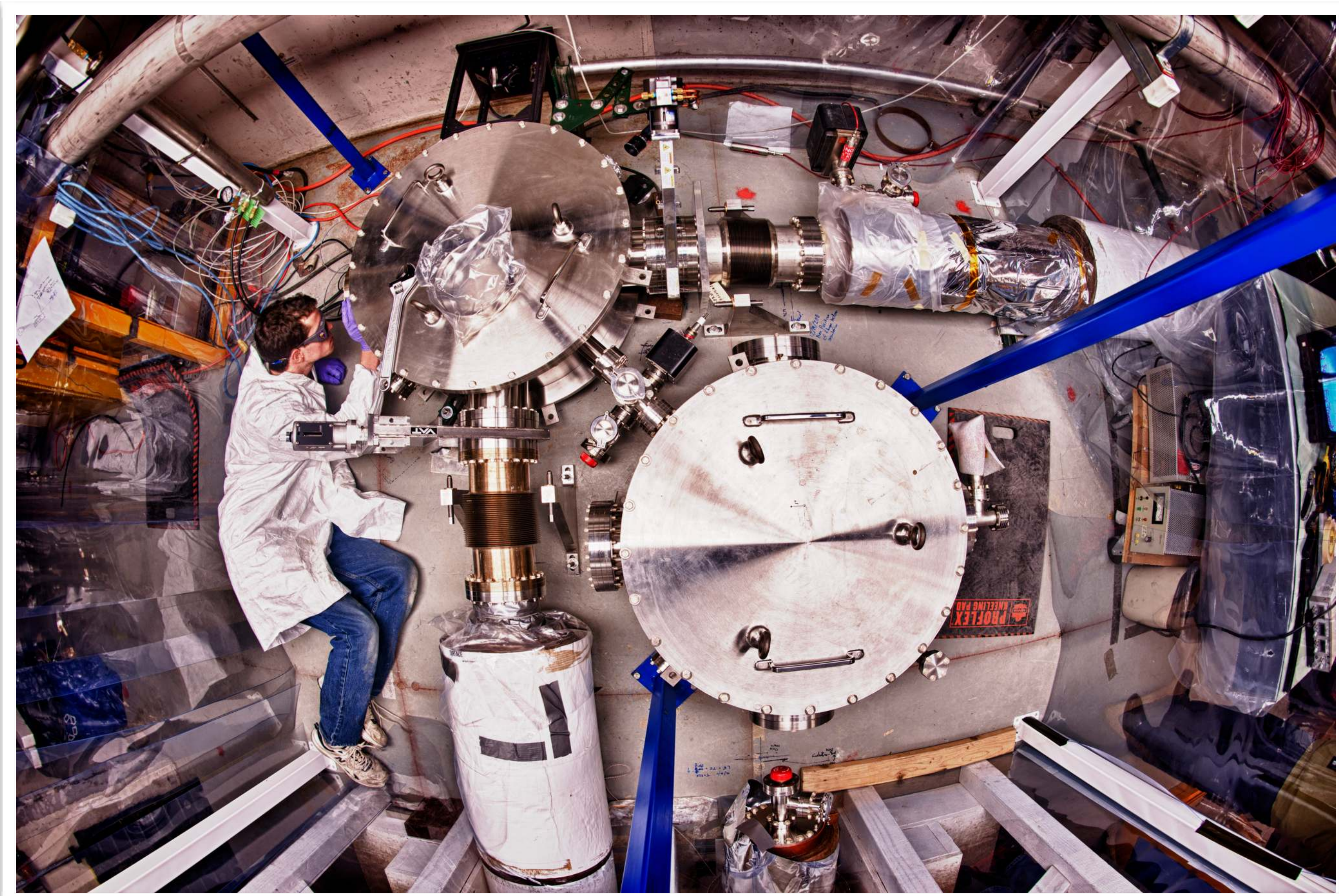
An experiment that studies quantum geometry: the Fermilab Holometer





Location

Construction

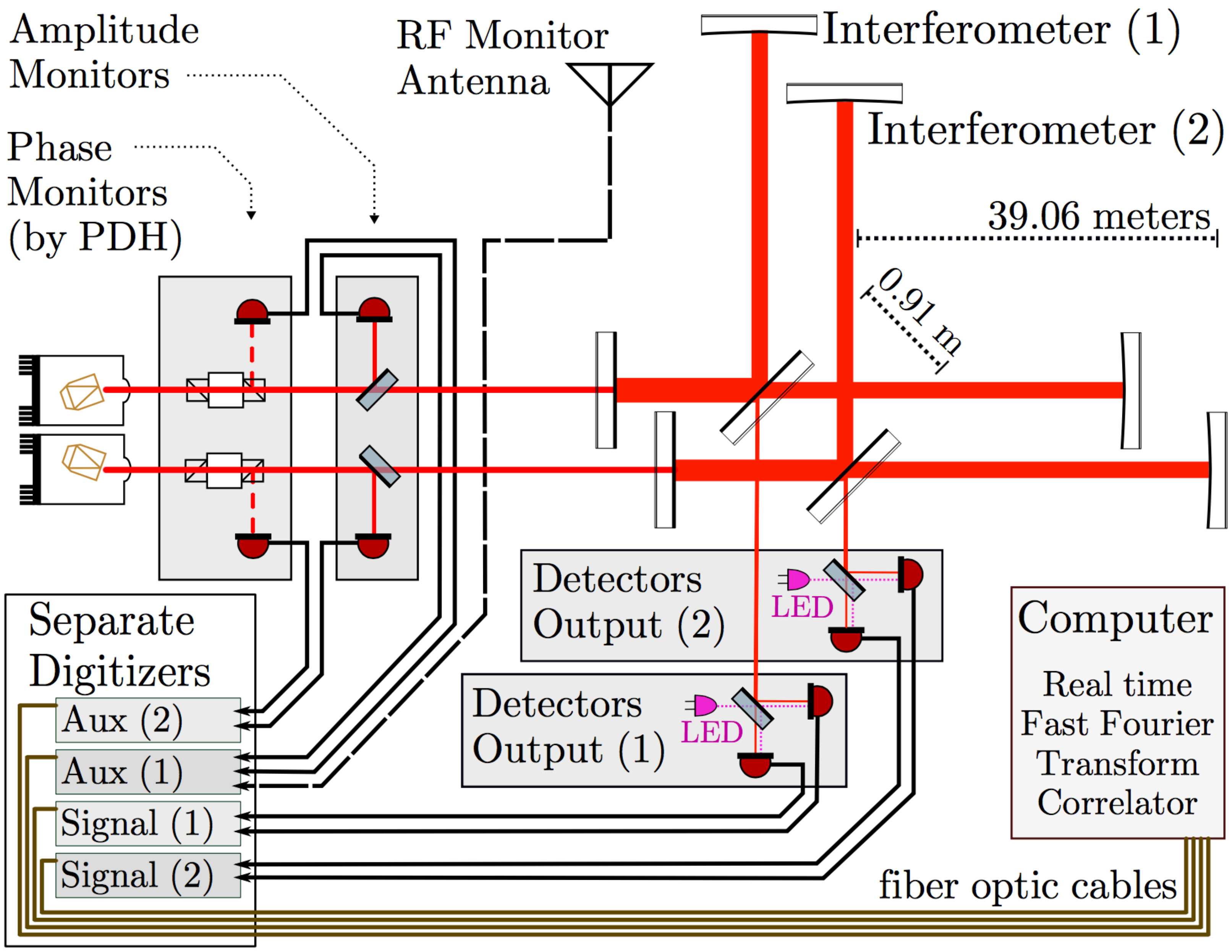


The Fermilab Holometer as currently configured

Two collocated Michelson interferometers with cross correlated signals

~ trillions of independent measurements

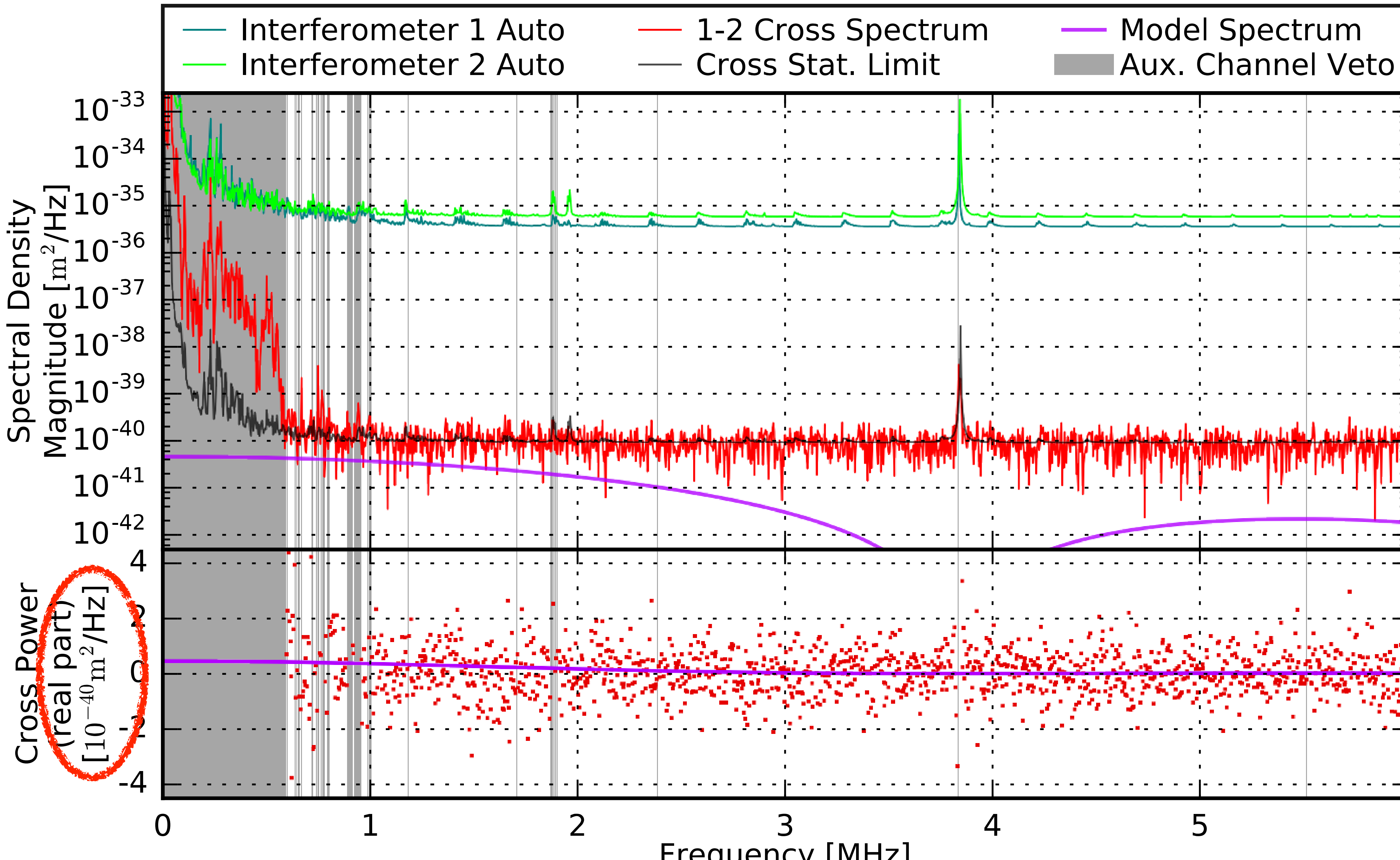
sensitive to well below Planck spectral density



Measured Spectrum in the Fermilab Holometer

http://arxiv.org/abs/1512.01216

$T = 140$ Hours $\quad\quad \Delta F = 4$ kHz



Holometer Integrated Cross Spectrum

Result rules out a model of exotic shear correlation

But has no sensitivity to exotic rotational correlation

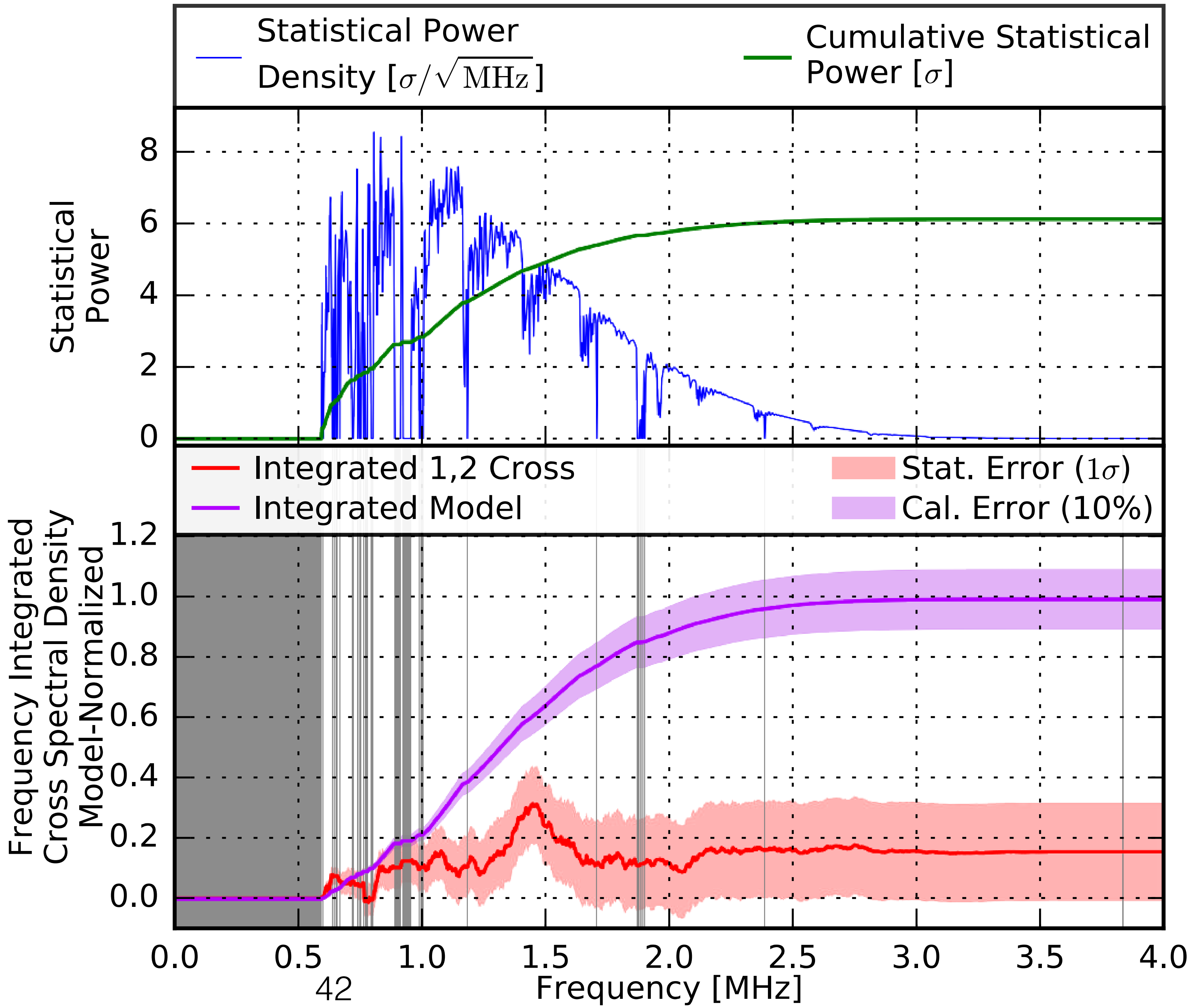
arXiv:1512.01216

Model amplitude
Sets weighting
Function

Shapes statistical
power

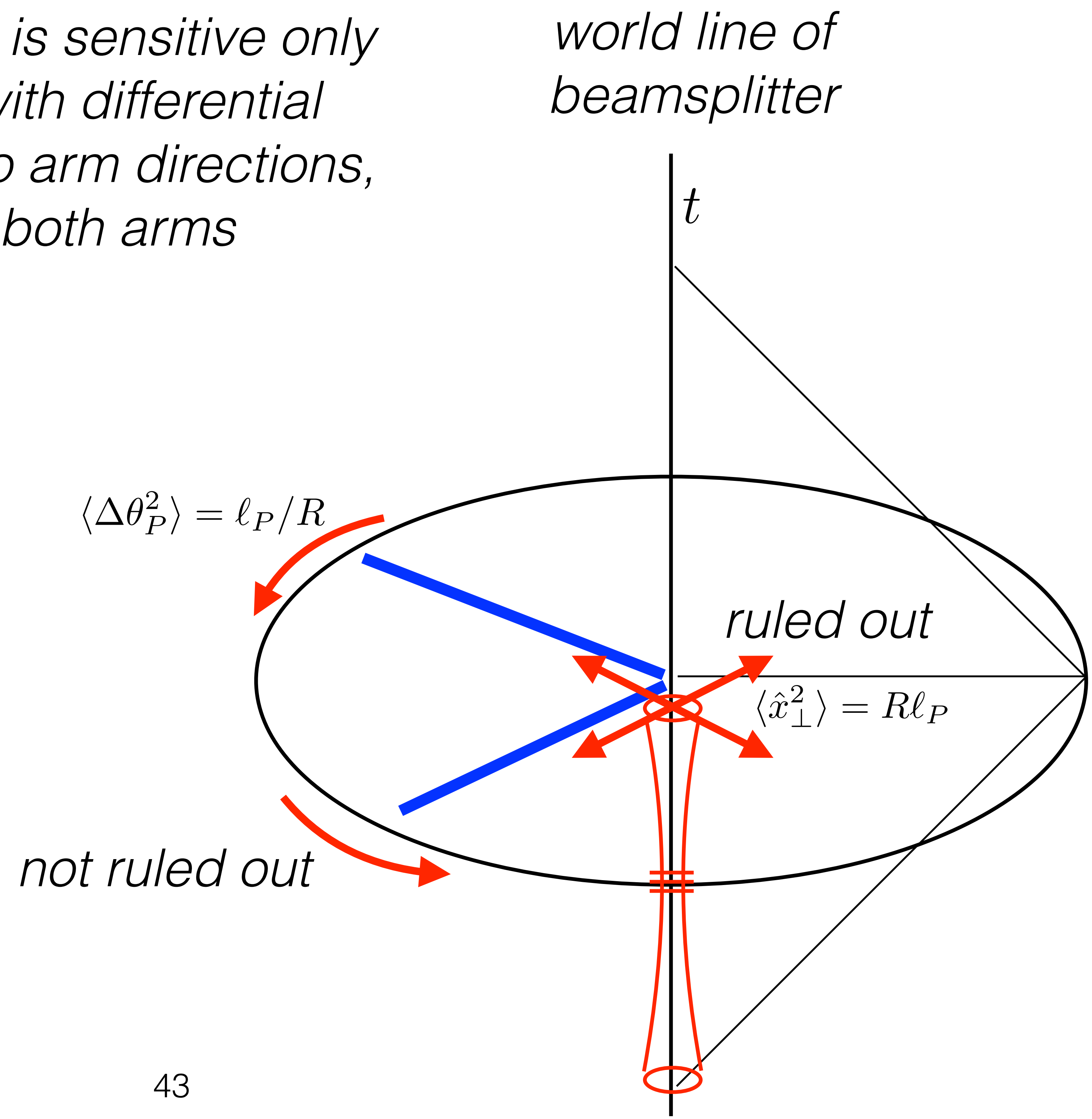
Fully Accumulated
Over Bandwidth

Done as integral
To observe
Narrowband vs.
Broadband
Contributions



First Holometer result rules out exotic *shear* correlation at the Planck diffraction scale, but not a purely *rotational* correlation

Signal of current Holometer is sensitive only to correlations associated with differential jitter of separation in the two arm directions, not to correlated rotation of both arms



A reconfigured Fermilab Holometer could measure exotic rotational correlations

Current results rule out a signal correlation at the predicted amplitude

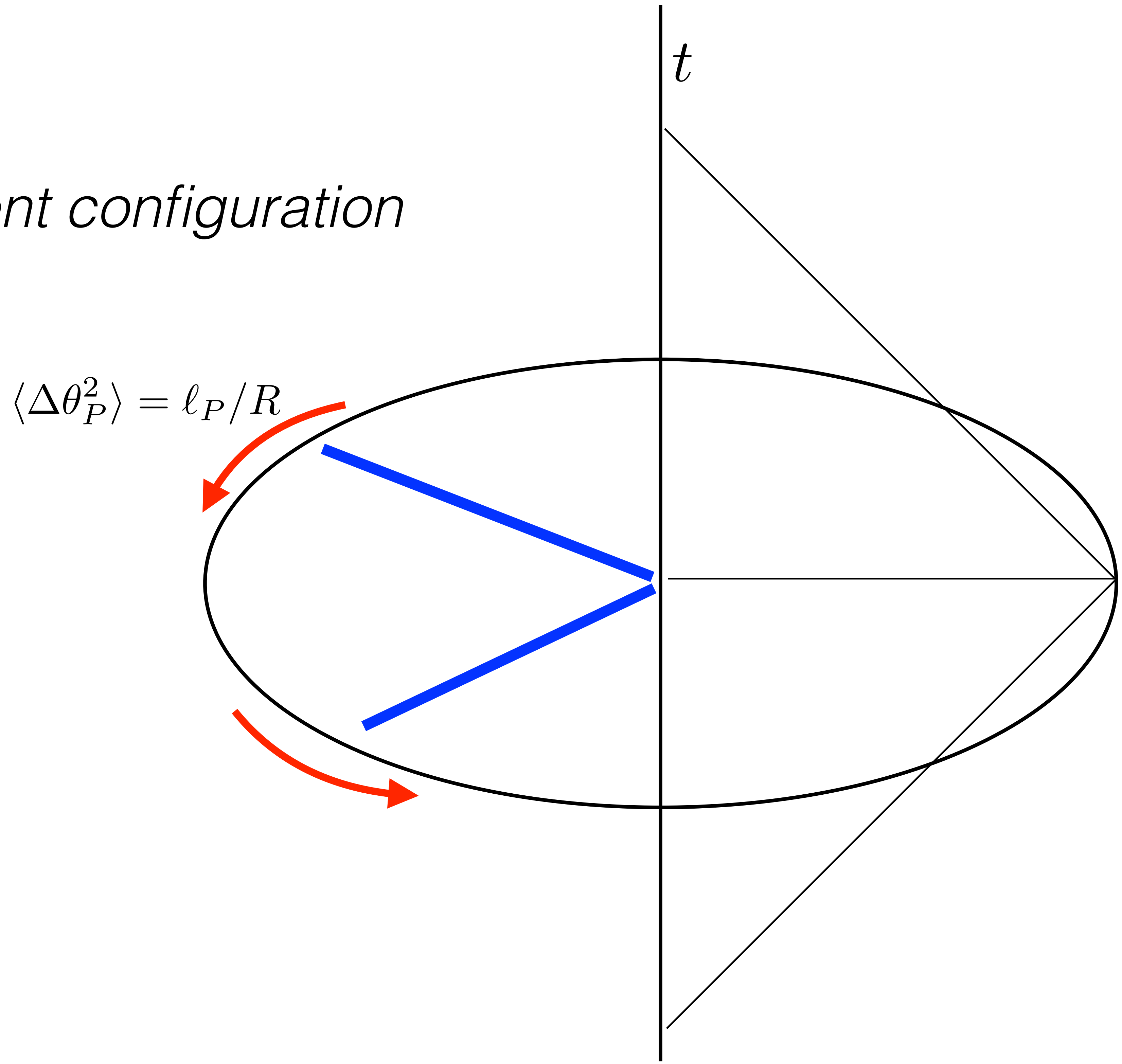
Explores exotic correlations of space and time for the first time

First direct evidence that emergent quantum gravity obeys a symmetry (*i.e.*, little or no “jitter”, or shear degrees of freedom)

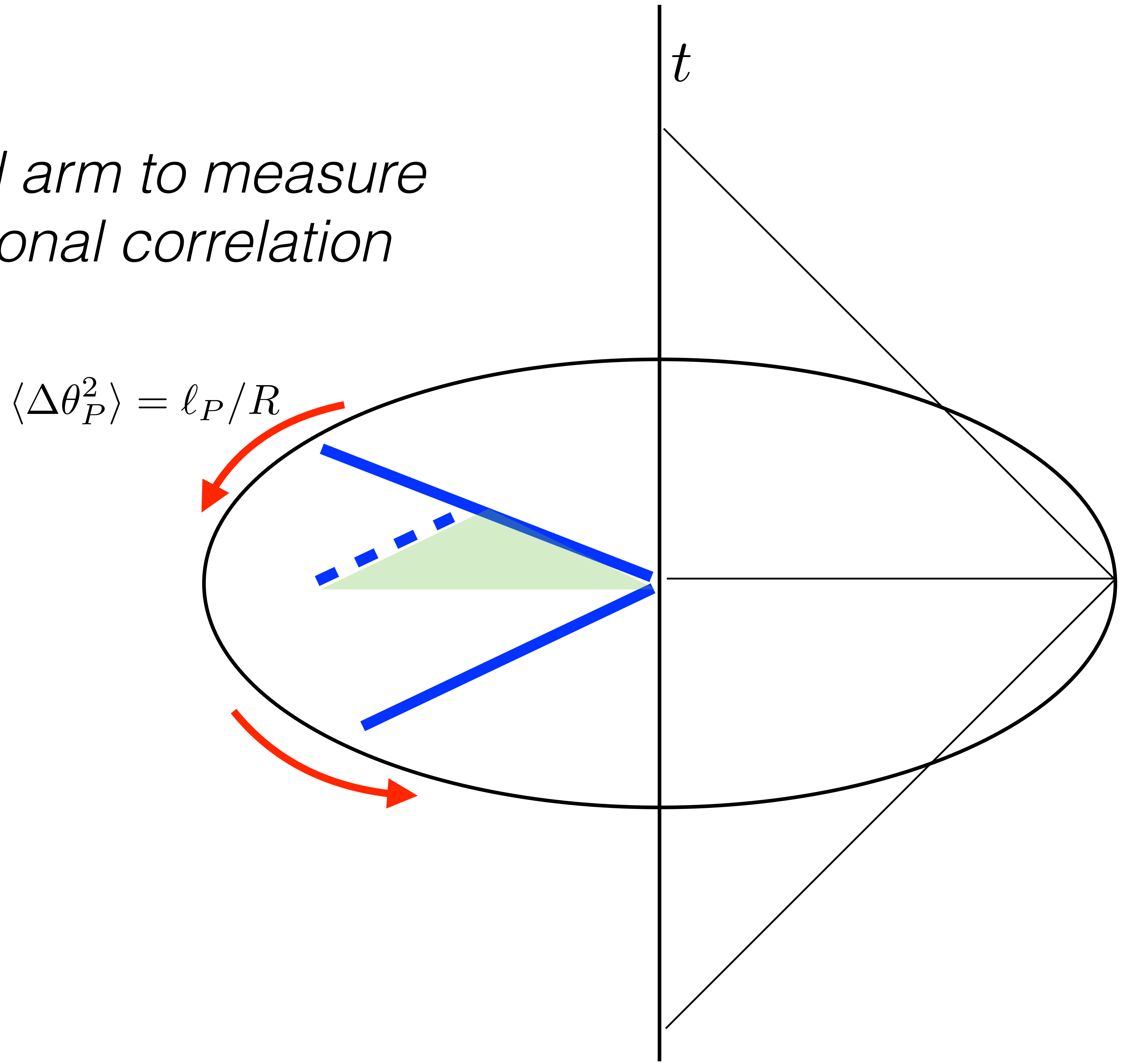
Suggests that causal structure represents an exact symmetry

But in the current Michelson layout, the Holometer is not sensitive to rotational correlations (*i.e.*, “twists” in inertial frame)

It can be reconfigured to detect exotic rotation by bending one of the arms in both interferometers at right angles *current configuration*

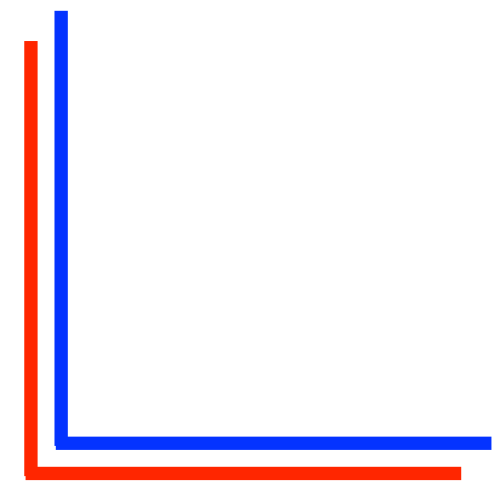


Bend arm to measure rotational correlation



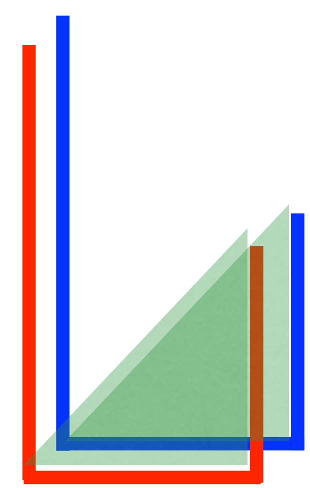
Simplest reconfiguration to measure rotational correlations

Current configuration: no response to a pure rotation



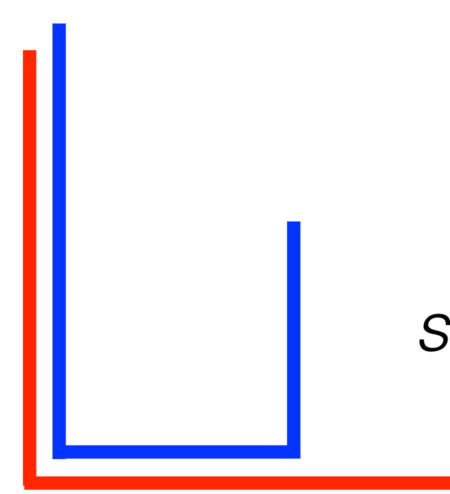
neither path encloses an area

“Half-Bent Michelson”: sensitive to exotic rotational correlations (but not mean rotation)



paths enclose overlapping areas

Null reconfiguration



no correlated signal encloses an area

Completing a comprehensive study of exotic correlations

Basic hypothesis: exotic Planck scale correlations of geometry affect world lines of bodies and phases of fields

- General arguments set the amplitude but not the spatial pattern
- Limited options for spatial patterns: shear, strain, rotation
- Each experiment constrains a symmetry of exotic correlations
- Current result supports a Planck scale symmetry of causality

After the conclusive exclusion of shear by the current Holometer, the rotational mode is the only remaining possibility

- Complete constraints on independent covariances in space

This reconfiguration of the Holometer will complete the survey

- It will either detect the effect or rule out the basic hypothesis
- It will either detect a Planck scale correlation, or provide evidence for Planck scale symmetry of inertia

Wait, there's more: a possible connection between the cosmological constant and the field vacuum

Trace of Einstein equations includes a "cosmological constant", the sum of traces from matter and geometry:

$$\Lambda = \frac{2\pi G}{c^4}(T + 2\mathcal{R})$$

In standard theory it is arbitrary, unrelated to other constants

In holographic gravity, it fixes the total cosmic information in Planck units:

$$H_\Lambda^2 \equiv \Lambda/3$$

~ area of cosmic event horizon

In an emergent universe the cosmological constant must be related to the entanglement of the two quantum subsystems: field vacuum and geometry

Cosmic Acceleration and Rotational Acceleration

Classical kinematic acceleration at distance *r* from an axis of rotation:

$$\ddot{r} = \omega^2 r \qquad\qquad \omega = \text{rotation rate}$$

Cosmic acceleration by cosmological constant at separation *r* :

$$\ddot{r} = H_\Lambda^2 r \qquad\qquad H_\Lambda^2 \equiv \Lambda/3$$

Mean square exotic rotational fluctuation in volume of size *R*:

$$\langle \omega_i^2(R) \rangle \approx c^2 \ell_P R^{-3}$$

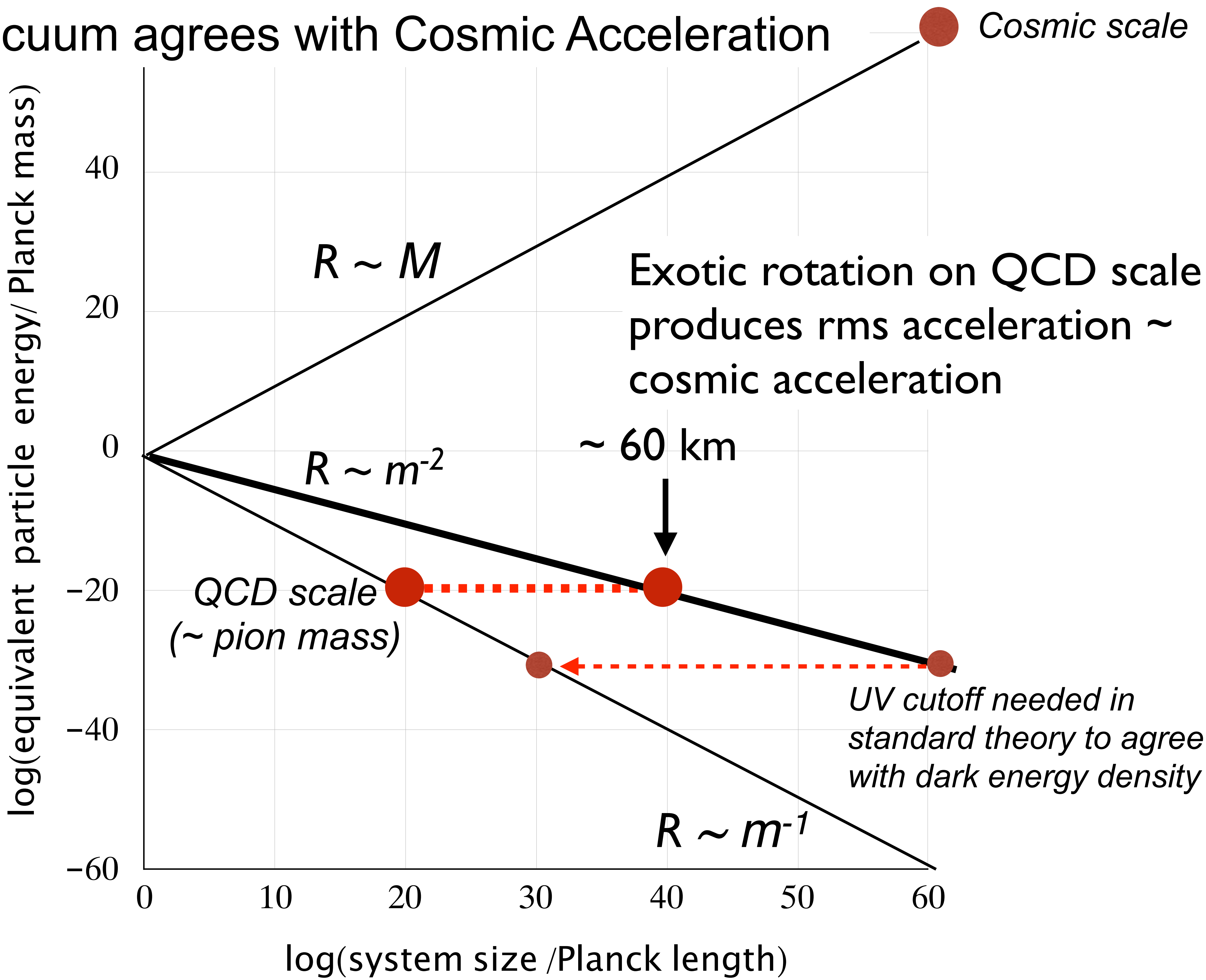
Cosmic and rotational accelerations match at $R \sim H^{-2/3}$ ~ 60 km ~ geometrical entanglement length for standard strong interactions

identify cosmic acceleration ~ rotational mismatch of field vacuum

The universe “shakes apart”: ~ 60 km twists by ~ 1 Fermi, at ~ 5000 Hz

Reprises the Dirac/Eddington/Zeldovich/Bjorken coincidence, $m^3_{pion} \sim H_0$

Rotational Acceleration of Standard Model Vacuum agrees with Cosmic Acceleration



Cosmic information ~ number of QCD field modes

Holographic information in (2D) cosmic horizon equals (3D) information in field modes up to:

$$k_{max} = k_\Lambda \equiv (H_\Lambda 9\pi^2/2)^{1/3}$$

Adopt a current cosmic measurement in Planck units:

$$H_\Lambda = \Omega_\Lambda^{1/2} H_0 = 0.99 \pm 0.018 \times 10^{-61}$$

The corresponding cut off closely matches the QCD vacuum scale:

$$k_\Lambda = 1.65 \pm 0.01 \ \times 10^{-20} m_P = 201 \pm 1.2 \ \mathrm{MeV}$$

Main uncertainty in excellent agreement comes from QCD theory

Entanglement of quantum geometry with field vacuum could explain the value of the cosmological constant from only known scales of physics

Emergent Cosmological Constant

Suppose quantum geometry entangles with the Standard Model field vacuum to produce a cosmological constant in the emergent space-time

Mean rotation vanishes, consistent with statistical isotropy

Not perfectly constant, but fluctuates: coherence scale is about 60 km

Cosmic acceleration fluctuates below ~ 5000 Hz

Radial fluctuations by ~ 1 Planck length— likely unobservable

Cosmic acceleration timescale naturally occurs on astrophysical evolution timescale

They both depend on similar combinations of fundamental constants, related to the Chandrasekhar mass for protons (Planck+ QCD scales)

Explains “why now”

Summary

Planck scale quantum geometry can lead to exotic correlations in displacements of bodies and phases of fields that grow with scale, in the same way as standard quantum correlations in extended systems.

Even without a theory of quantum gravity, basic quantum principles suffice to predict the effect in the signal of an interferometer.

The prediction can be tested with a reconfiguration of the Fermilab Holometer.

Entanglement of these correlations with the Standard Model vacuum might explain the origin of the cosmological constant.

Extra slides

Exotic Correlation Appears in Loop Quantum Gravity

Some theories of quantum gravity have no fixed background space

Discrete spectrum of spatial area states, normalized by black hole entropy:

$$A_n \approx A_Q n^2$$

$$\ell_Q = A_Q^{1/2} = \sqrt{2 \ln 2 \hbar G c^{-3} / \sqrt{3}}$$

Separation of geometrical states grows like $dA \sim A^{1/2} \sim R$

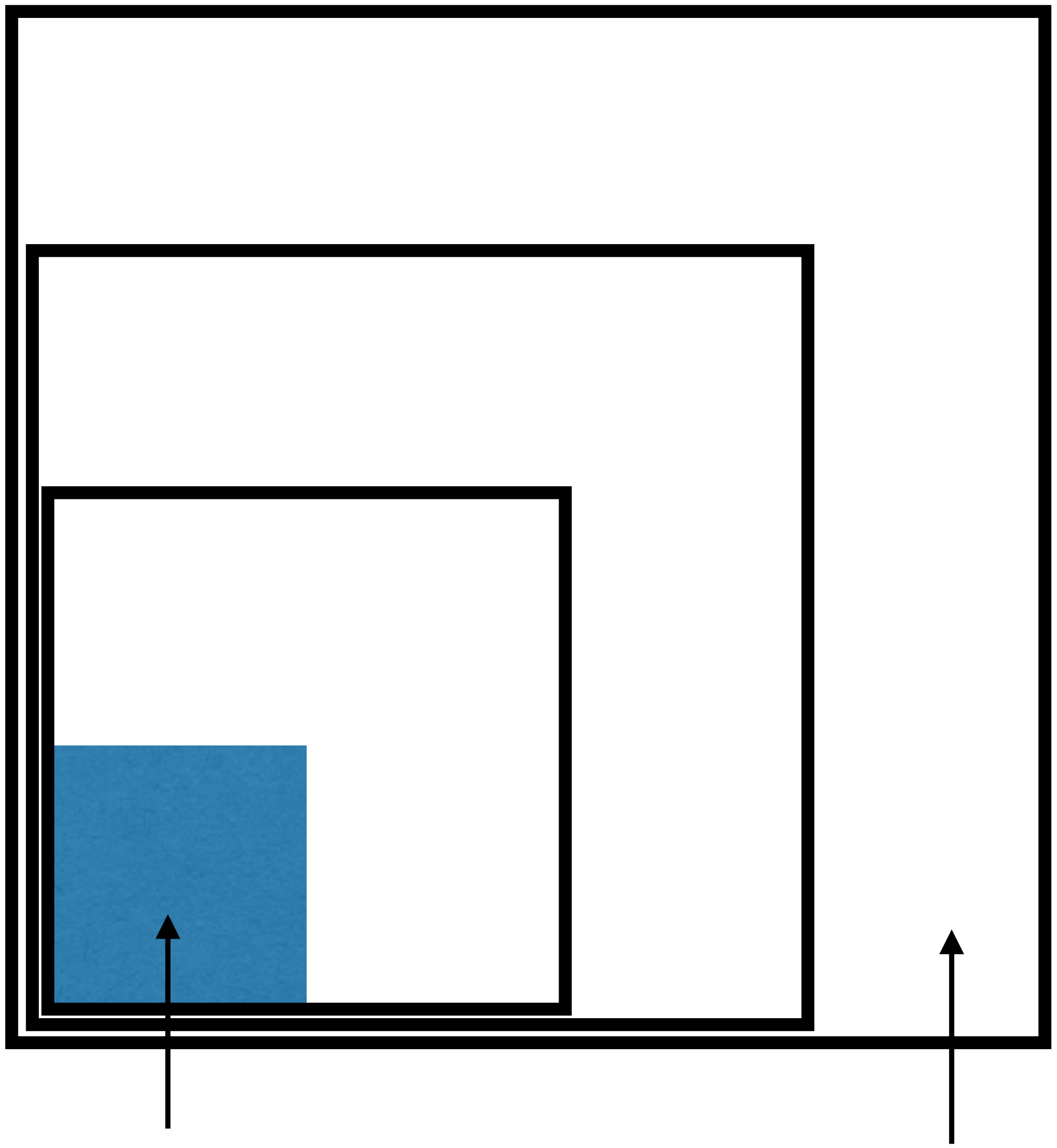
Degrees of freedom scale holographically, like R^2

Exotic variance of position correlations ~ R

…``the fundamental quanta of geometry are one dimensional, polymer-like excitations over nothing, rather than gravitons, the wavy undulations over a continuum background."

1408.4336, Ashketar, Reuter and Rovelli

Discrete area states: spacing increases with size



$$A_n \approx A_Q n^2$$

Planck area

Difference >> Planck area