Quantum Behavior of Geometry in Large Systems

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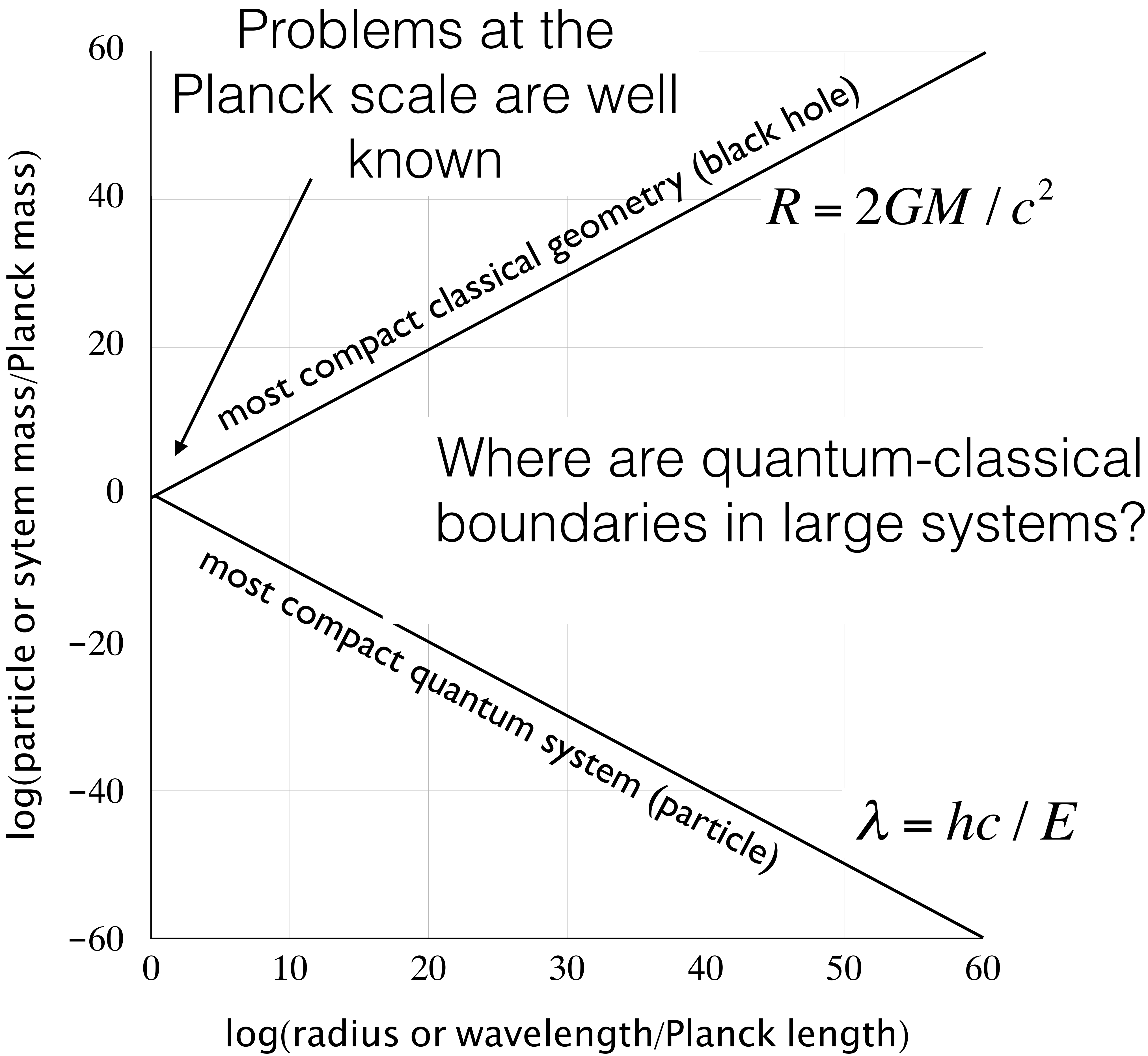

Problems at the Planck scale are well known
most compact classical geometry (black hole)
$R = 2GM / c^2$
Where are quantum-classical boundaries in large systems?
most compact quantum system (particle)
$\lambda = hc / E$
60
40
20
0
−20
−40
−60
0
10
20
30
40
50
60
log(particle or sytem mass/Planck mass)
log(radius or wavelength/Planck length)

Quantum matter and quantum geometry

Matter is a quantum system (e.g., field theory)

Geometry is dynamical but classical (general relativity)

Standard approximations: ignore geometrical dynamics in small systems, or ignore quantum behavior in large systems

Whole quantum system actually includes matter and geometry

Matter and geometry are “emergent” subsystems

Their degrees of freedom are entangled, beyond standard theory

Entanglement can have observable consequences on large scales

Standard quantum position uncertainty in macroscopic systems with gravity

Standard quantum kinematic uncertainty: wave function of position compared at two times increases with time interval,

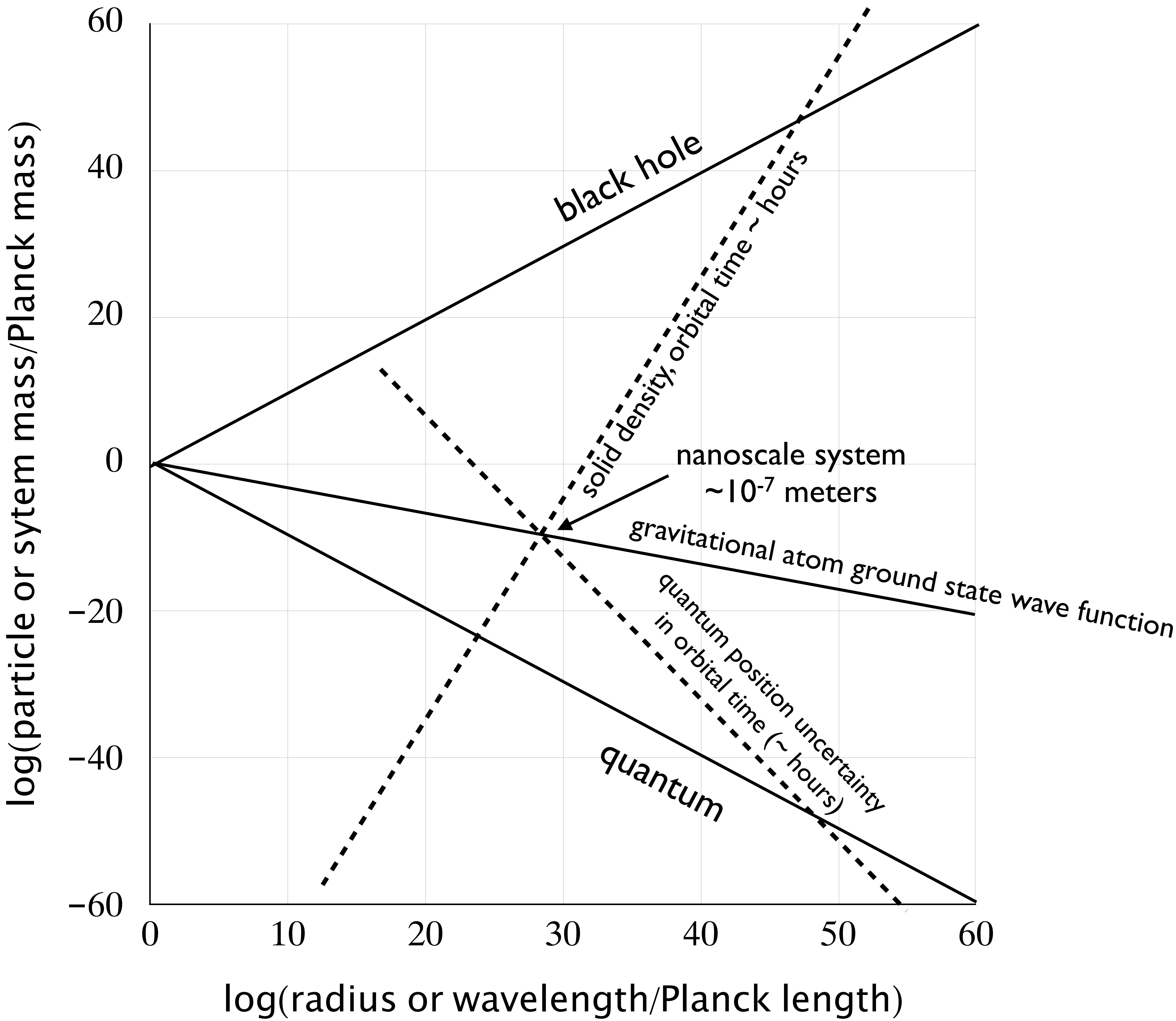
$$\Delta x_q(\tau)^2 \equiv \langle (\hat{x}(t) - \hat{x}(t+\tau))^2 \rangle|_t > 2\hbar\tau/M$$

Gravity also relates mass, size and duration

Quantum-classical boundary is macroscopic at low mass

Gravitational atom: two bodies bound only by gravity

Cosmic Expansion: minimum scale of classical metric



60
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0
−20
−40
−60
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10
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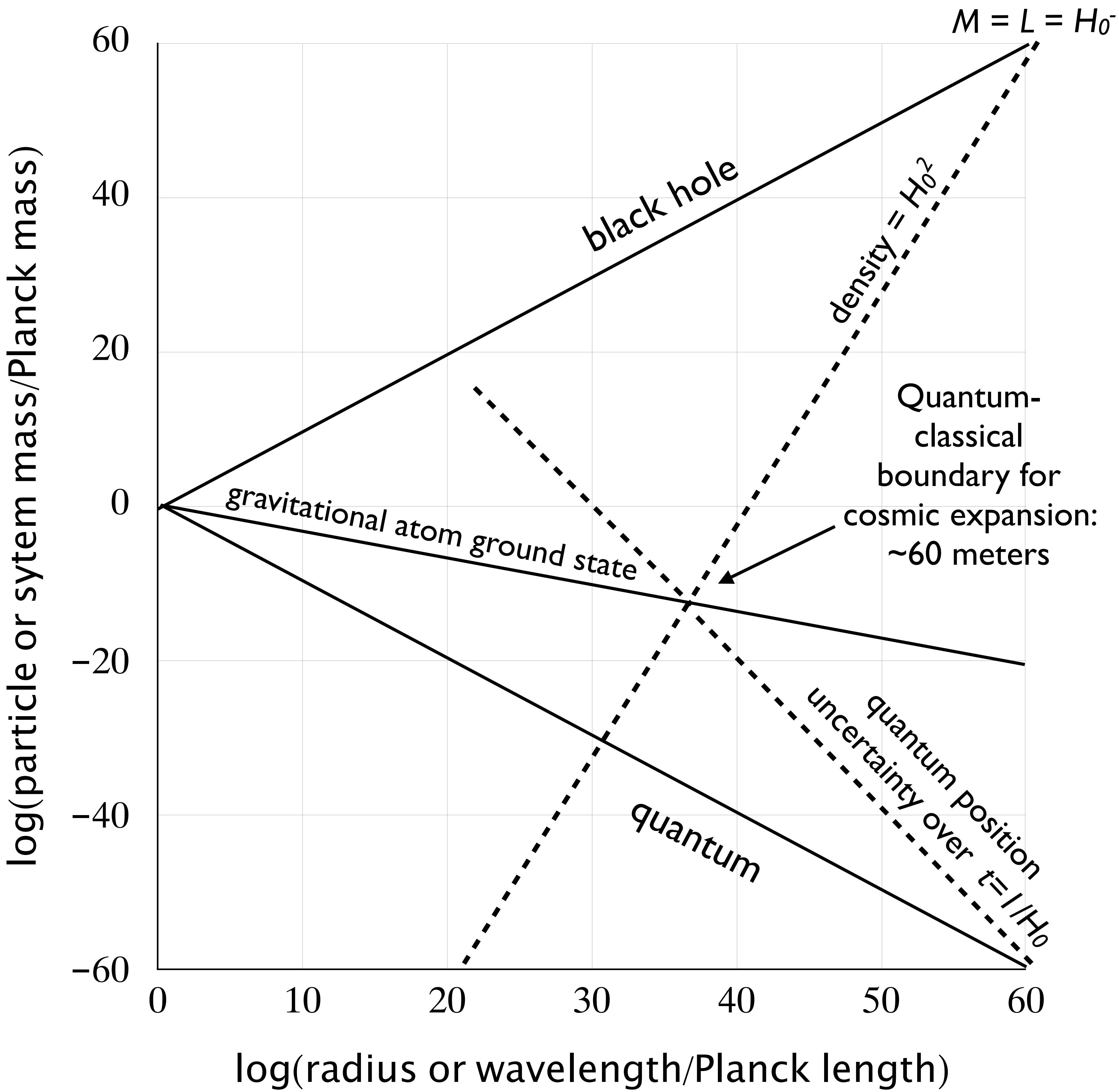
30
40
50
60
black hole
solid density, orbital time ~ hours
nanoscale system
~10-7 meters
gravitational atom ground state wave function
quantum position uncertainty
in orbital time (~ hours)
quantum
log(particle or sytem mass/Planck mass)
log(radius or wavelength/Planck length)



$M = L = H_0^{-1}$
black hole
density $= H_0^2$
Quantum-classical boundary for cosmic expansion: ~60 meters
gravitational atom ground state
quantum position uncertainty over $t = 1/H_0$
quantum
log(particle or sytem mass/Planck mass)
log(radius or wavelength/Planck length)
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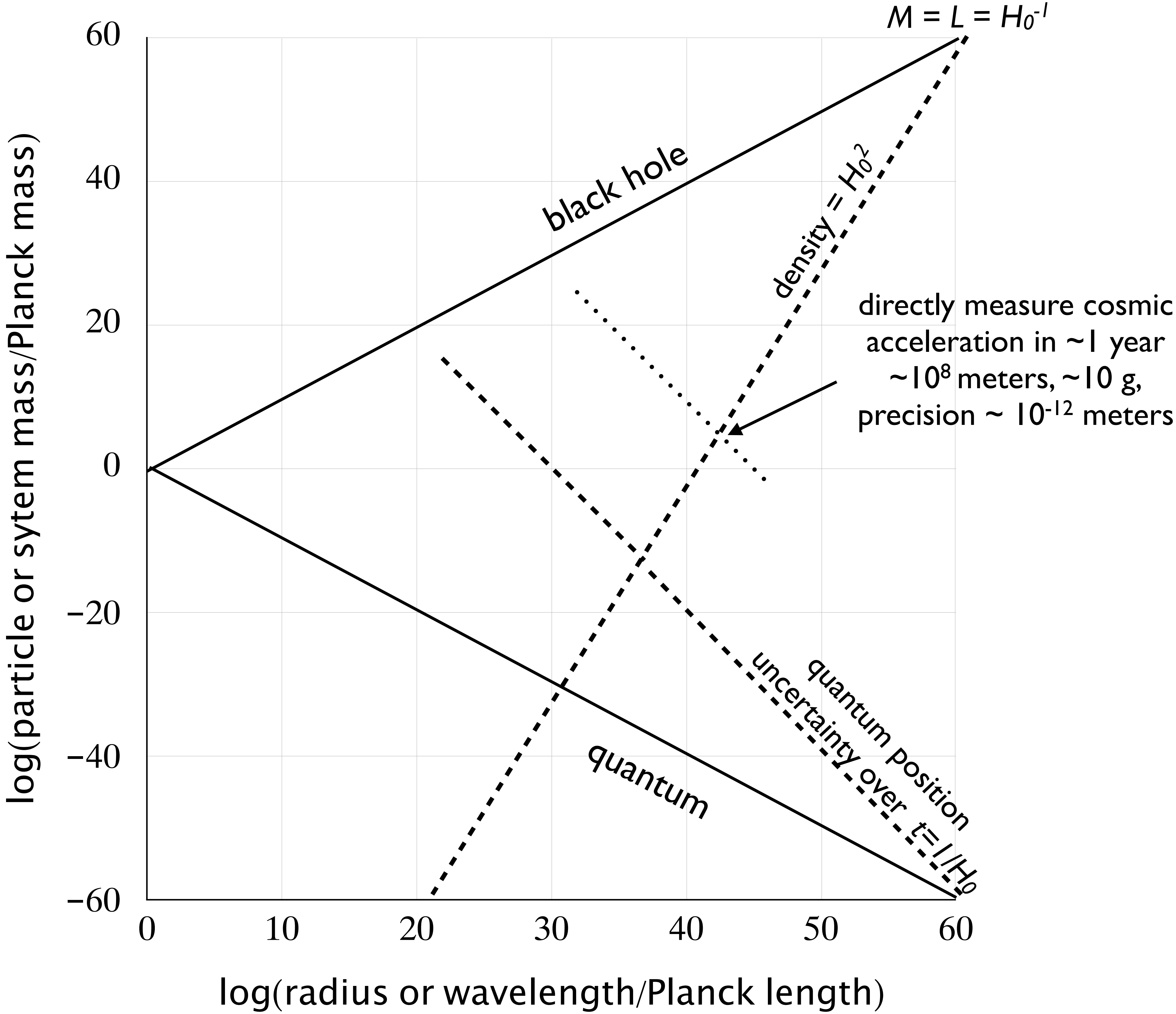

$M = L = H_0^{-1}$
black hole
density = H_0^2
directly measure cosmic acceleration in ~1 year
~10^8 meters, ~10 g,
precision ~ 10^{-12} meters
quantum
quantum position uncertainty over $t=1/H_0$
log(particle or sytem mass/Planck mass)
log(radius or wavelength/Planck length)
60
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30
40
50
60

Directional Entanglement of Quantum Fields with Quantum Geometry

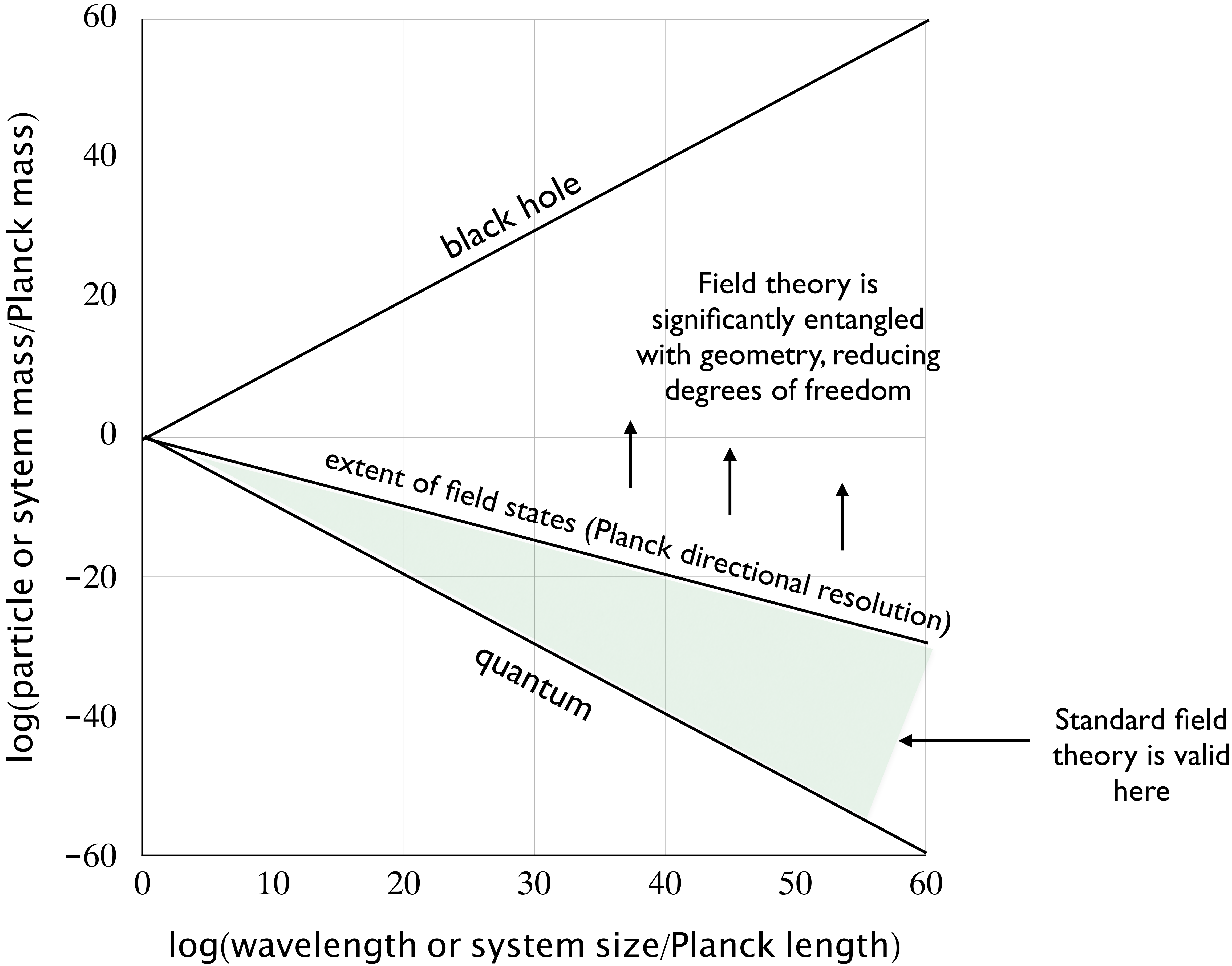
Energy density of of quantum field states is given by the UV cutoff of the theory to the fourth power, independent of volume

In a sufficiently large volume, these states are unphysical because they exceed the mass of a black hole of the same size

(Extreme version of this, with Planck cutoff and Hubble volume, is the classic, factor of $\sim 10^{122}$ dark energy problem)

One proposed solution (Cohen, Kaplan, Nelson): there is a maximum extent of field states (IR cutoff), which depends on UV cutoff

Can be explained by directional entanglement of fields with emergent geometry: angular resolution is limited by Planck diffraction (CJH)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0
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30
40
50
60
log(particle or sytem mass/Planck mass)
log(wavelength or system size/Planck length)
black hole
extent of field states (Planck directional resolution)
quantum
Field theory is
significantly entangled
with geometry, reducing
degrees of freedom
Standard field
theory is valid
here

Information budget suggests that emergent cosmic acceleration rate could be set by the QCD scale

Entanglement connects micro scale of fields to macro scale of geometry

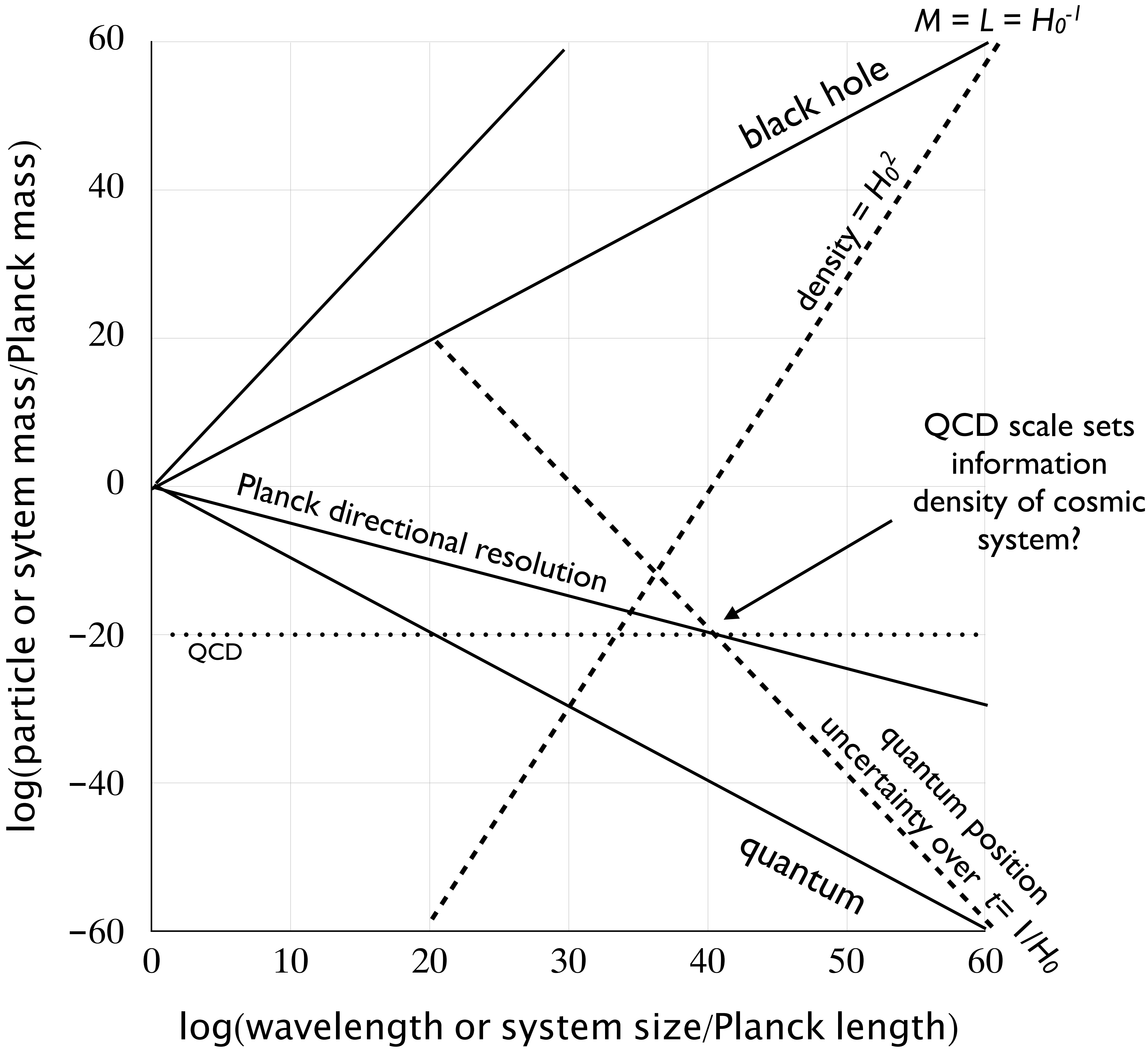
Density of holographic cosmic information ~ density of QCD field information

Standard position uncertainty of pion over a Hubble time ~ extent of QCD field states in entangled scenario (about 100 km)

Dark energy in a volume of this size ~ 1 Planck mass; amount of expansion in this time ~ directional uncertainty~ QCD scale; effect of acceleration in this time ~ 1 Planck length difference

Equipartition of information could explain well known coincidence between QCD scale and Hubble scale, in Planck units (eg, Zeldovich, Bjorken):

$$m_\pi \approx H_\Lambda^{1/3}$$



$M = L = H_0^{-1}$
black hole
density = H_0^2
QCD scale sets information density of cosmic system?
Planck directional resolution
QCD
quantum position uncertainty over $t = 1/H_0$
quantum
60
40
20
0
−20
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Experimental probe of Planckian directional entanglement

Direct laboratory measurement of gravitational indeterminacy or cosmic acceleration is impractical

But interferometers may be able to measure noise from Planckian directional entanglement on lab scale

An operating experiment, the Fermilab Holometer, is designed to measure or rule out this effect

It has recently achieved near-Planck sensitivity

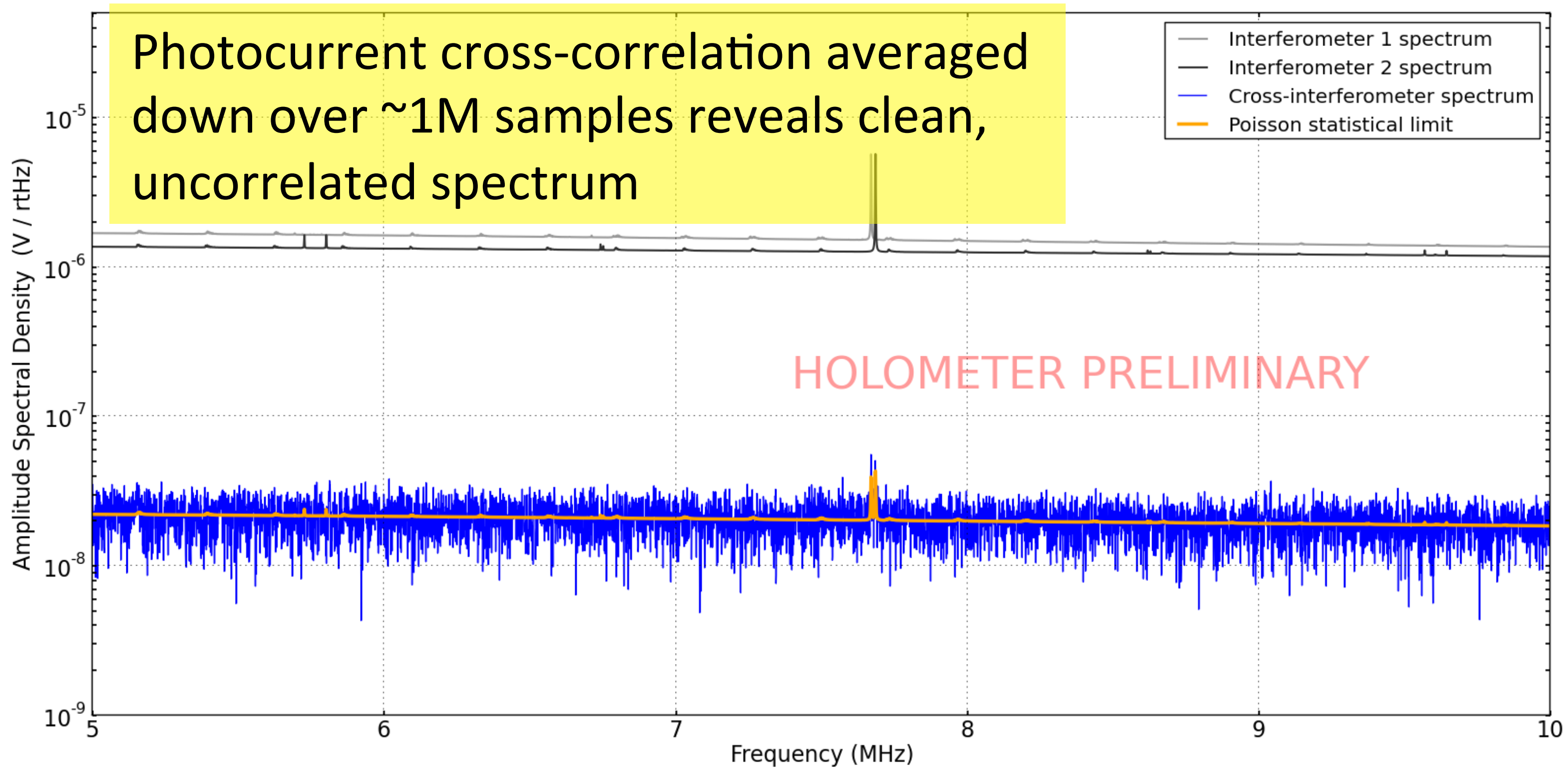
Stay tuned for results in the next year

Report from A. Chou and the Holometer team at Fermilab All-Experimenter's Meeting

7/28/2014

Holometer (E-990) Operations Status:

Real, out-of-signal-band data at near holographic noise sensitivity



- **Beginning 1-year operations phase July, 2014**
  - Interferometers running stably and high quality data being taken at near full power
  - Uncorrelated shot noise is integrating away nicely
- **Operations phase tasks**
  - Develop in situ signal calibration schemes
  - Investigate and mitigate any sources of MHz frequency noise which may be uncovered by increased sensitivity levels
- **Seismic/acoustic stability is still an issue**
  - One of the interferometers still leaks 30% more power than the detectors can handle.
  - Investigating electronic and mechanical fixes (alignment control, tethering hut down)