Spacetime-emergent ring toward tabletop quantum gravity experiments

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Based on arXiv: 2211.13863
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Holographic quantum gravity experiment?

True QG theory?

We need QG experiments

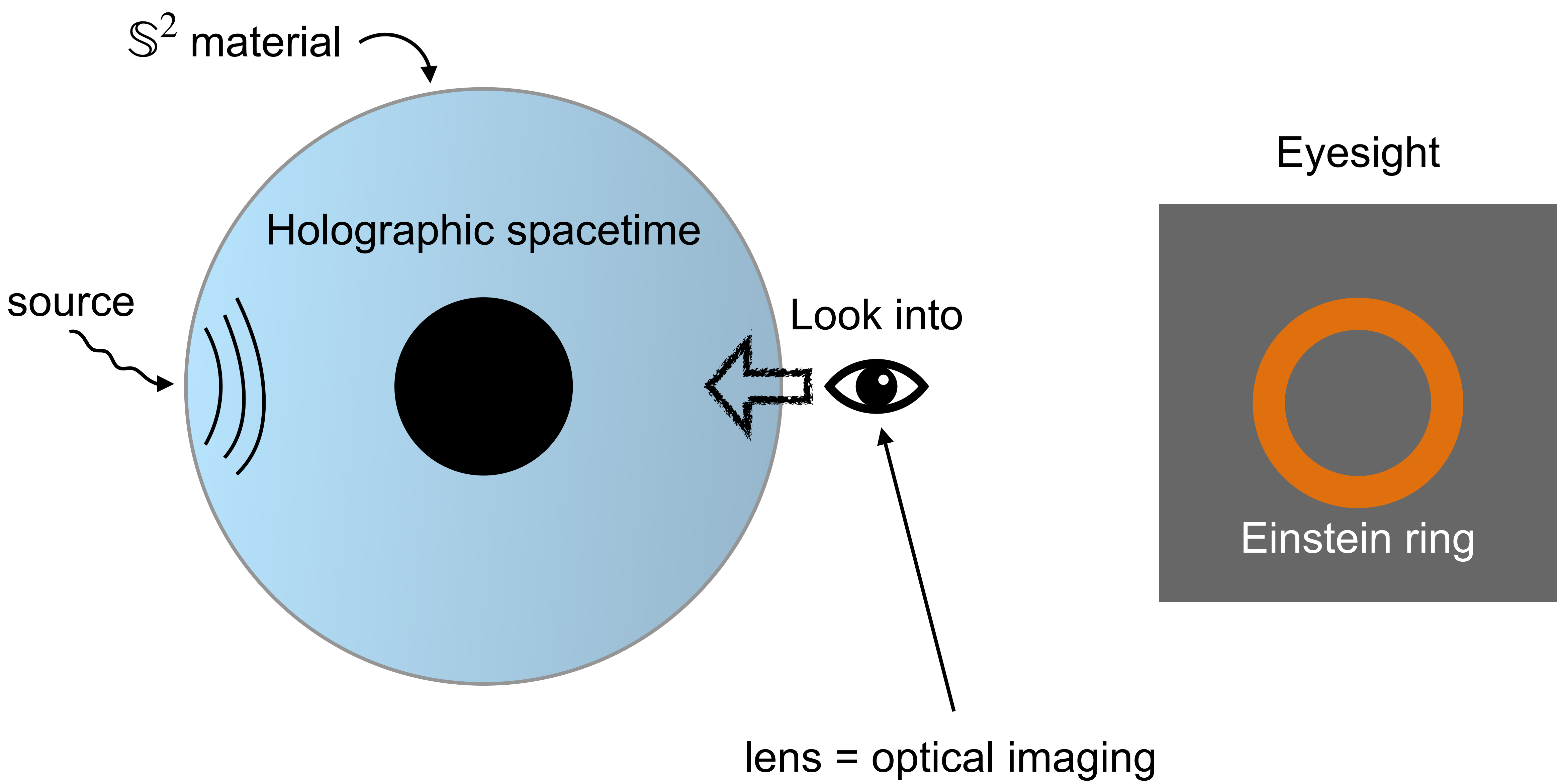
One direction: AdS/CFT

Find materials following the AdS/CFT

How to find?

Seeing the holographic spacetime

Hashimoto, Kinoshita, Murata (2018)

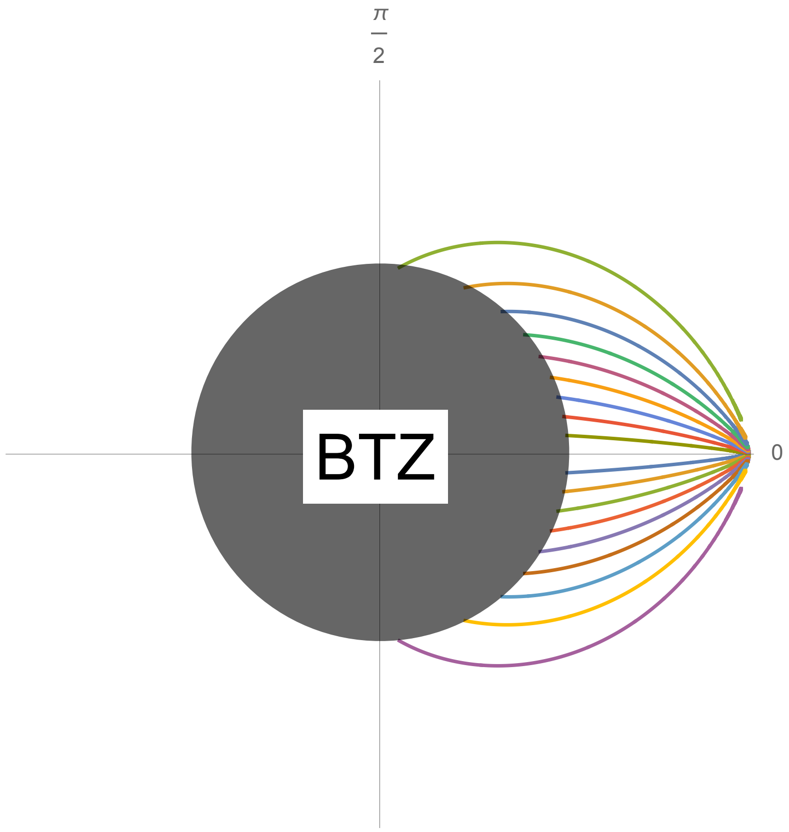


Difficulty: processing material to sphere

Processing materials near QCP is not easy

If only it's ring…

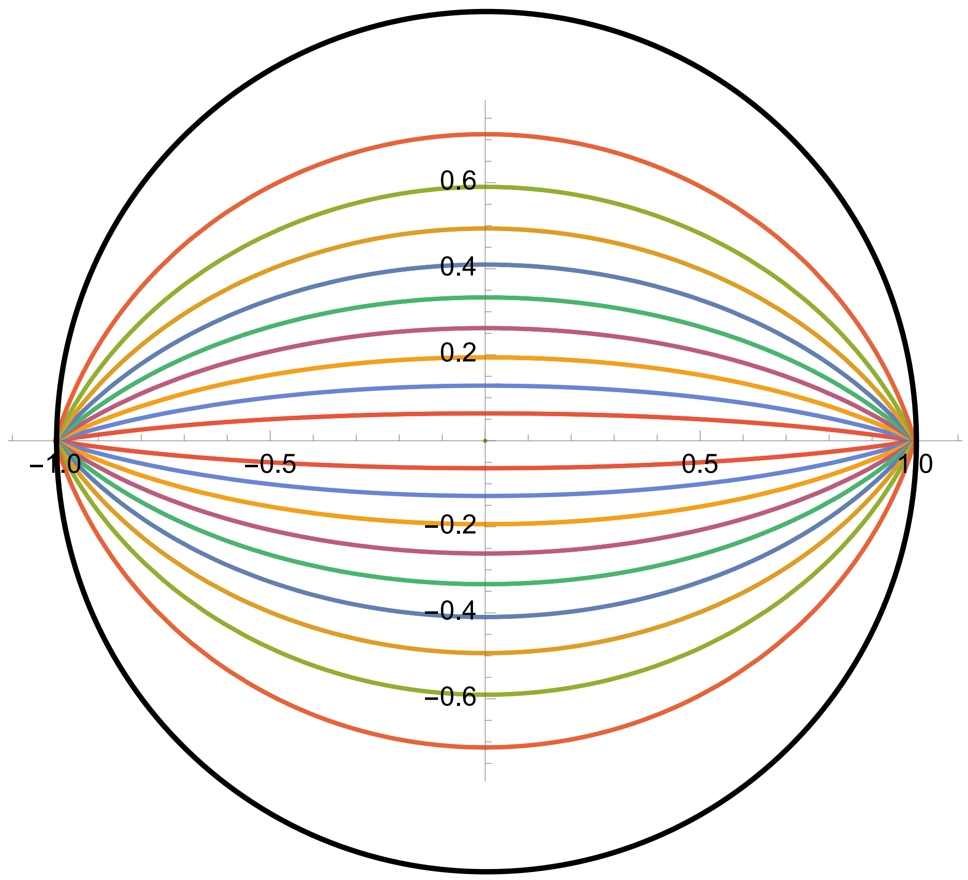
But if it's ring …



No Einstein ring

Giving up BH, let's find AdS_3

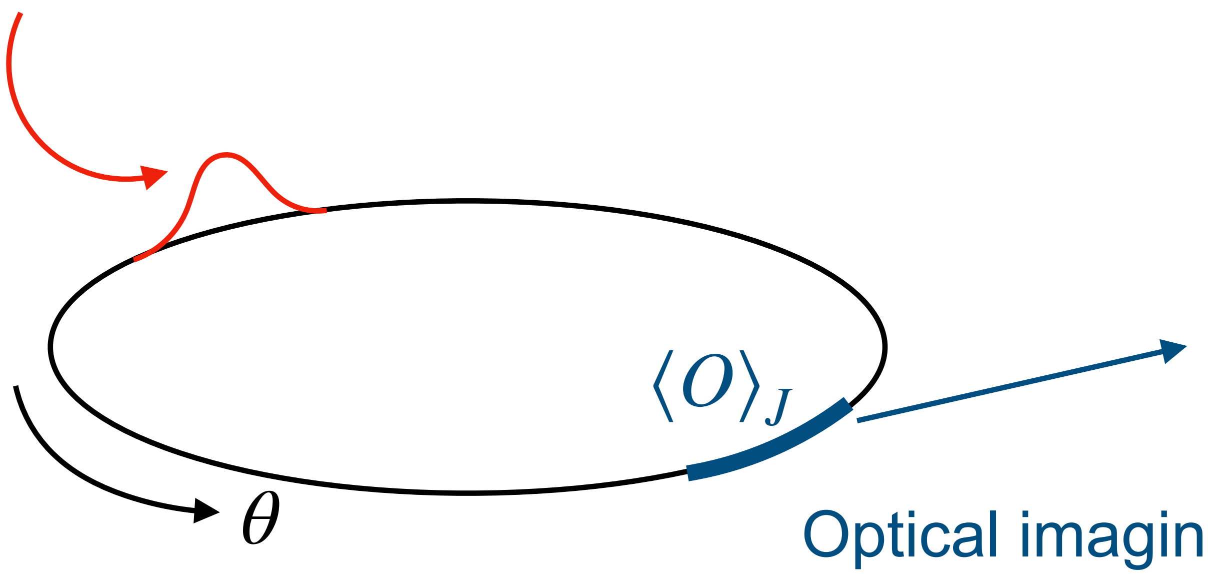
Null geodesics in pure AdS_3



Source J

Observe image

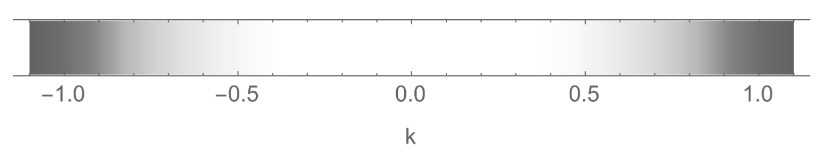
$$J \sim \exp\left[-\frac{\theta^2}{2\sigma^2} - i\omega t\right]$$



$$\psi(t,k) \propto \int_{-d}^{d} d\theta \, \langle O(t,\theta)\rangle_J e^{-i\omega k\theta}$$

Optical imaging
(lens)

Your eyesight at $\theta = \pi$



-90° 0° $+90^\circ$

AdS!

Optical imaging reveals spacetime emergence

1. Demonstration with bulk scalar

2. Any bulk field will do

3. Experiment seems technically feasible

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The model: Einstein + probe scalar

$$S = \frac{1}{16\pi G}\int d^3x\sqrt{-g}\,(R - 2\Lambda) + \int d^3x\sqrt{-g}\left(-\frac{1}{2}\partial_M\Phi\partial^M\Phi\right)$$

Hawking-Page transition

$g_{\mu\nu}$: fixed

$$T > \frac{1}{2\pi L} \qquad ds^2 = -\frac{r^2 - r_h^2}{L^2}dt^2 + \frac{L^2}{r^2 - r_h^2}dr^2 + r^2 d\theta^2$$

$r_h = 2\pi L^2 T$

$$T < \frac{1}{2\pi L} \qquad ds^2 = -\frac{r^2 + L^2}{L^2}dt^2 + \frac{L^2}{r^2 + L^2}dr^2 + r^2 d\theta^2$$

Physics of the material

$$\frac{1}{\sqrt{-g}}\partial_M(\sqrt{-g}\,g^{MN}\partial_N\Phi(x)) = 0$$

with GKPW dictionary

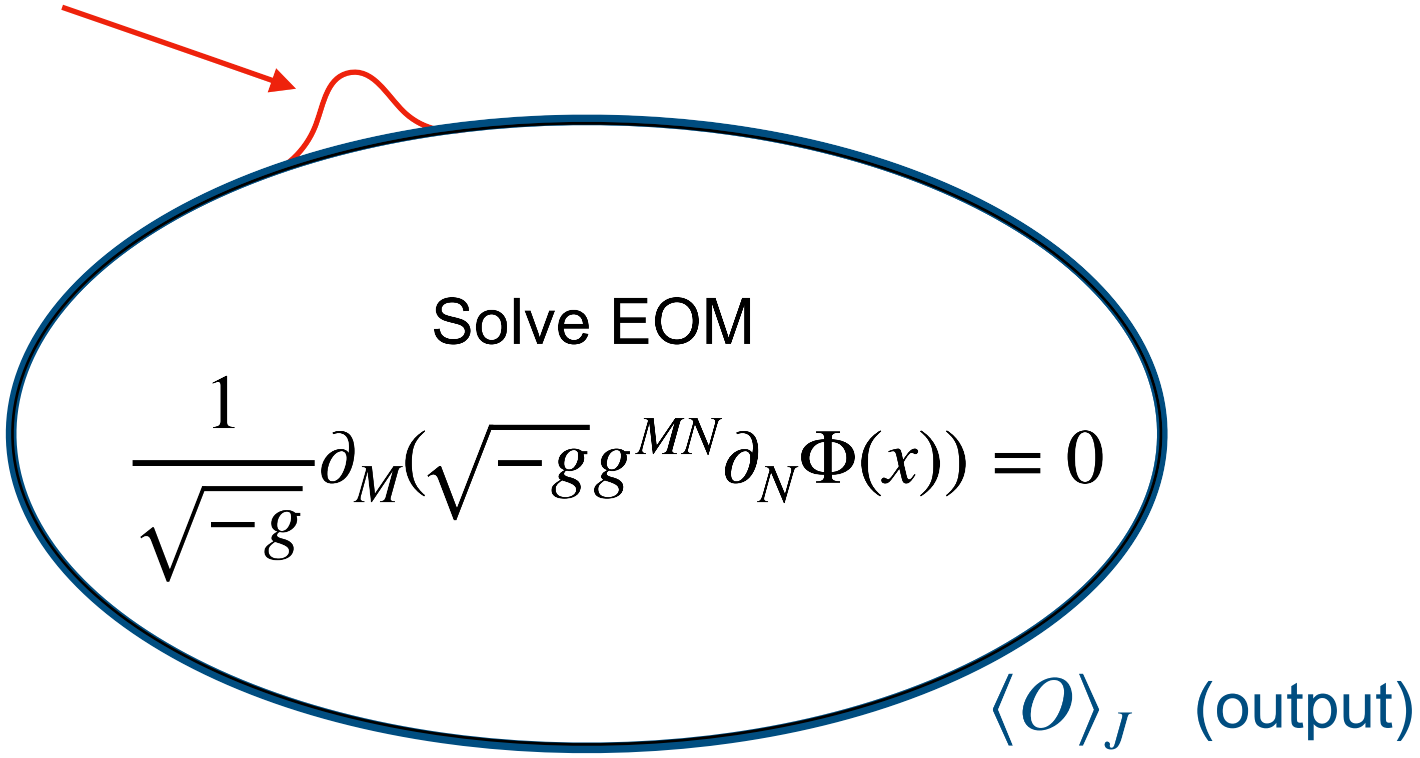
J is leading, $\langle O \rangle_J$ is subleading

GKPW formula

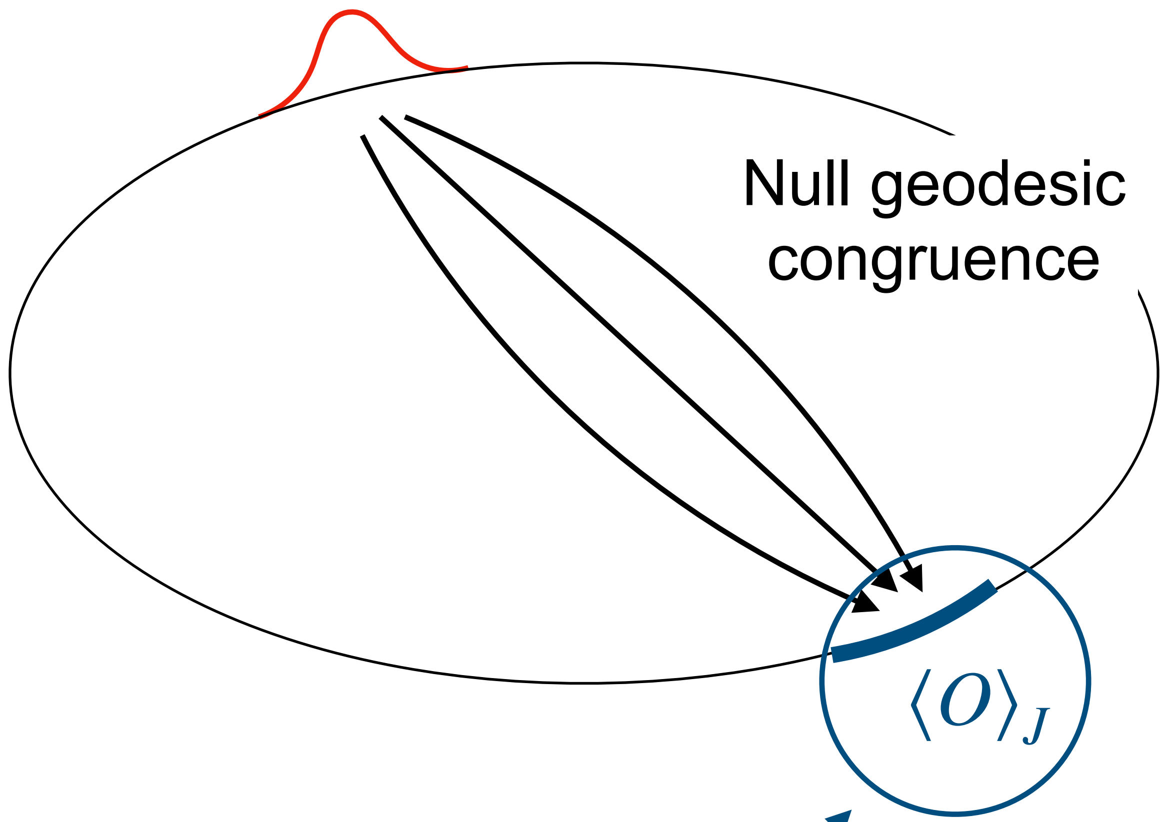
$$\Phi(x) \sim J(t,\theta) + \frac{\langle O(t,\theta)\rangle_J}{r^2} \qquad (r \to \infty)$$

$$J \sim \exp\left[-\frac{\theta^2}{2\sigma^2} - i\omega t\right]$$

Boundary condition (input)



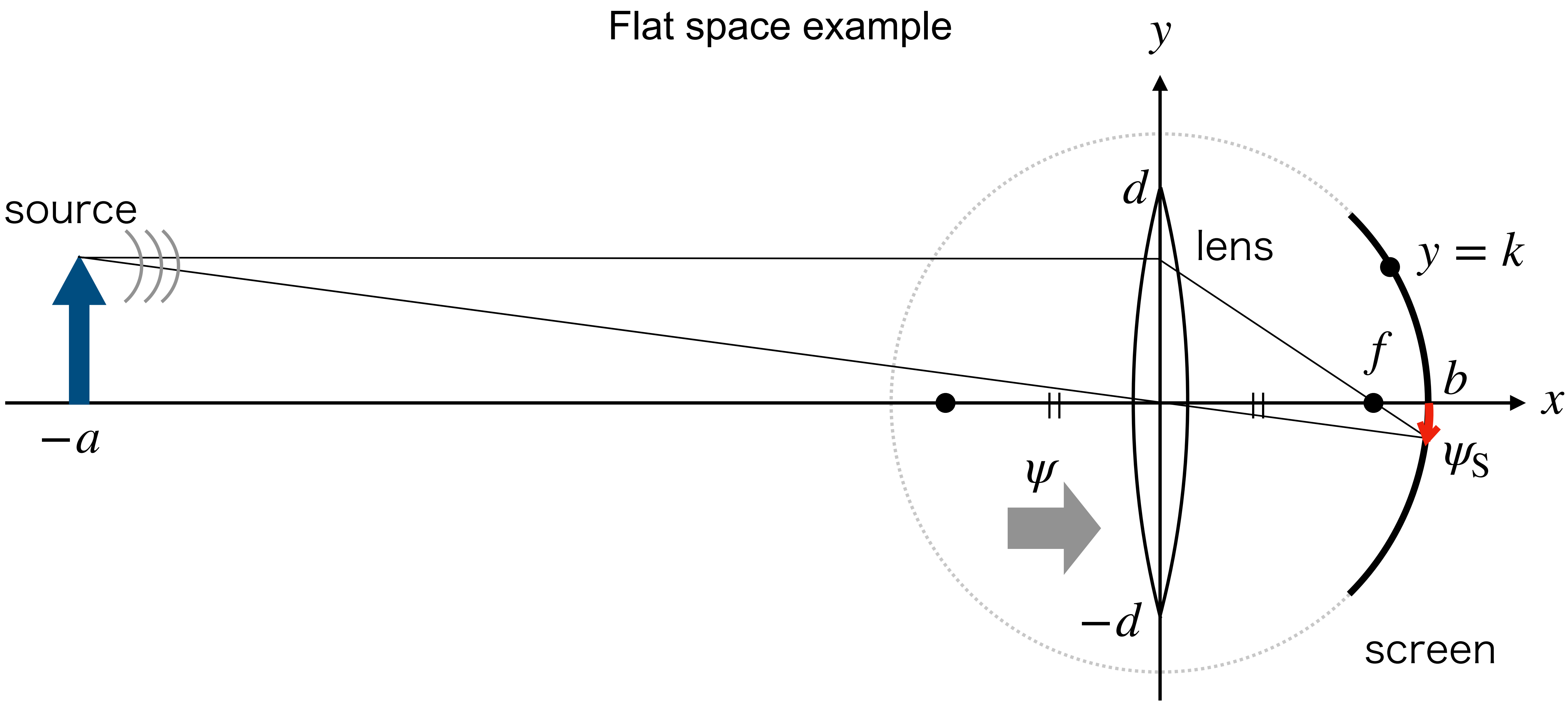
Optical imaging recovers image of J



$$\psi(t,k) \propto \int_{-d}^{d} d\theta \, \langle O(t,\theta) \rangle_J e^{-i\omega k\theta}$$

Optical imaging
(lens)

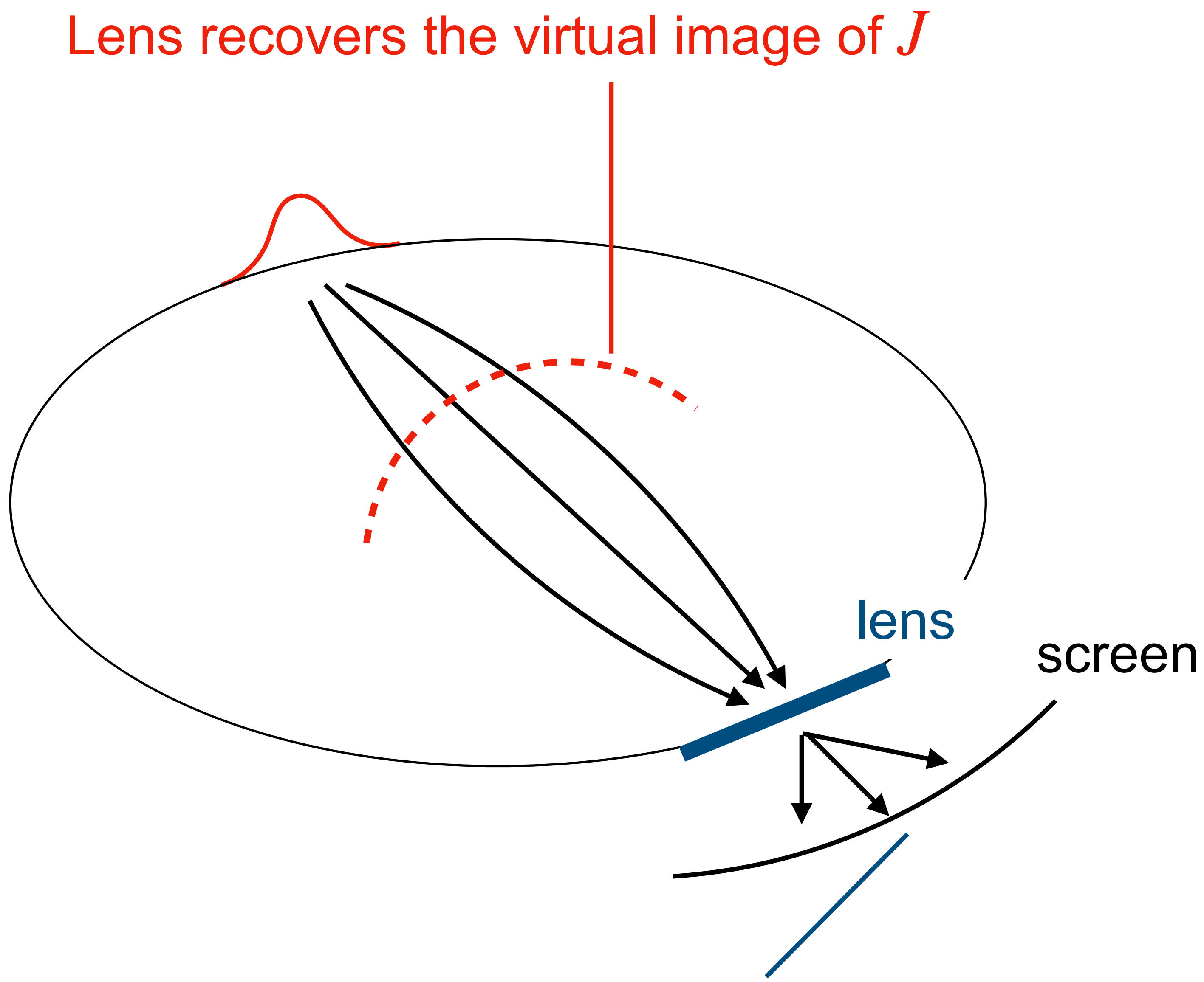
Optical imaging recovers image of J



Lens recovers the source image

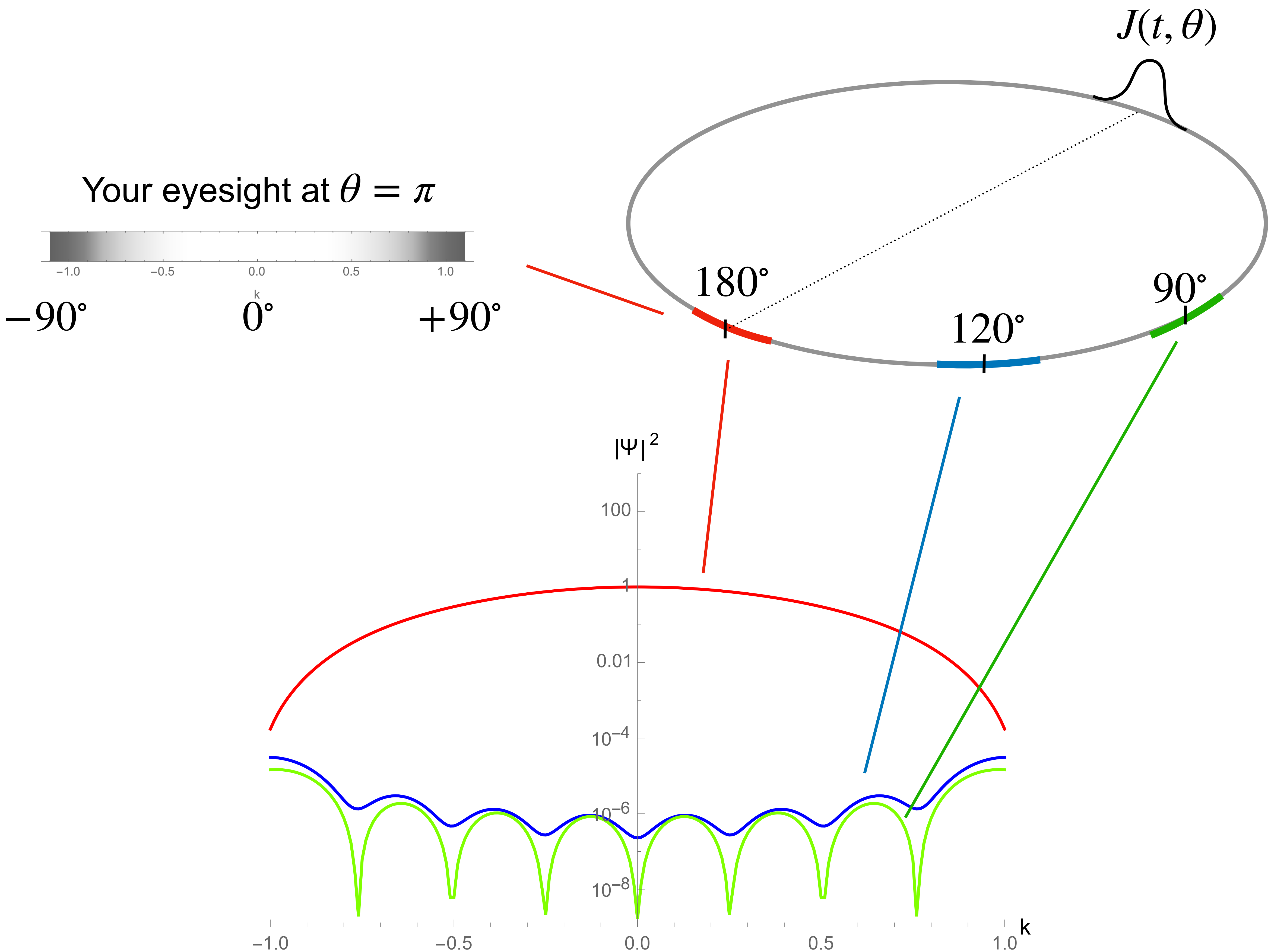
$$\psi_{\rm S}(k) \propto \int_{-d}^{d} dy\ \psi(y) e^{-i\omega k y/f}$$

Optical imaging recovers virtual image of J



$$\psi(t,k) \propto \int_{-d}^{d} d\theta \, \langle O(t,\theta)\rangle_J e^{-i\omega k\theta}$$

Plots



Your eyesight at $\theta = \pi$
−1.0
−0.5
0.0
0.5
1.0
k
$-90°$
$0°$
$+90°$
$J(t, \theta)$
180°
120°
90°
$|\Psi|^2$
100
1
0.01
10^{-4}
10^{-6}
10^{-8}
−1.0
−0.5
0.0
0.5
1.0
k

Comparison with non-holographic model

Real scalar theory on the ring

$$S = \int d^2x \left(-\frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{m^2}{2}\phi^2 + J\phi \right)$$

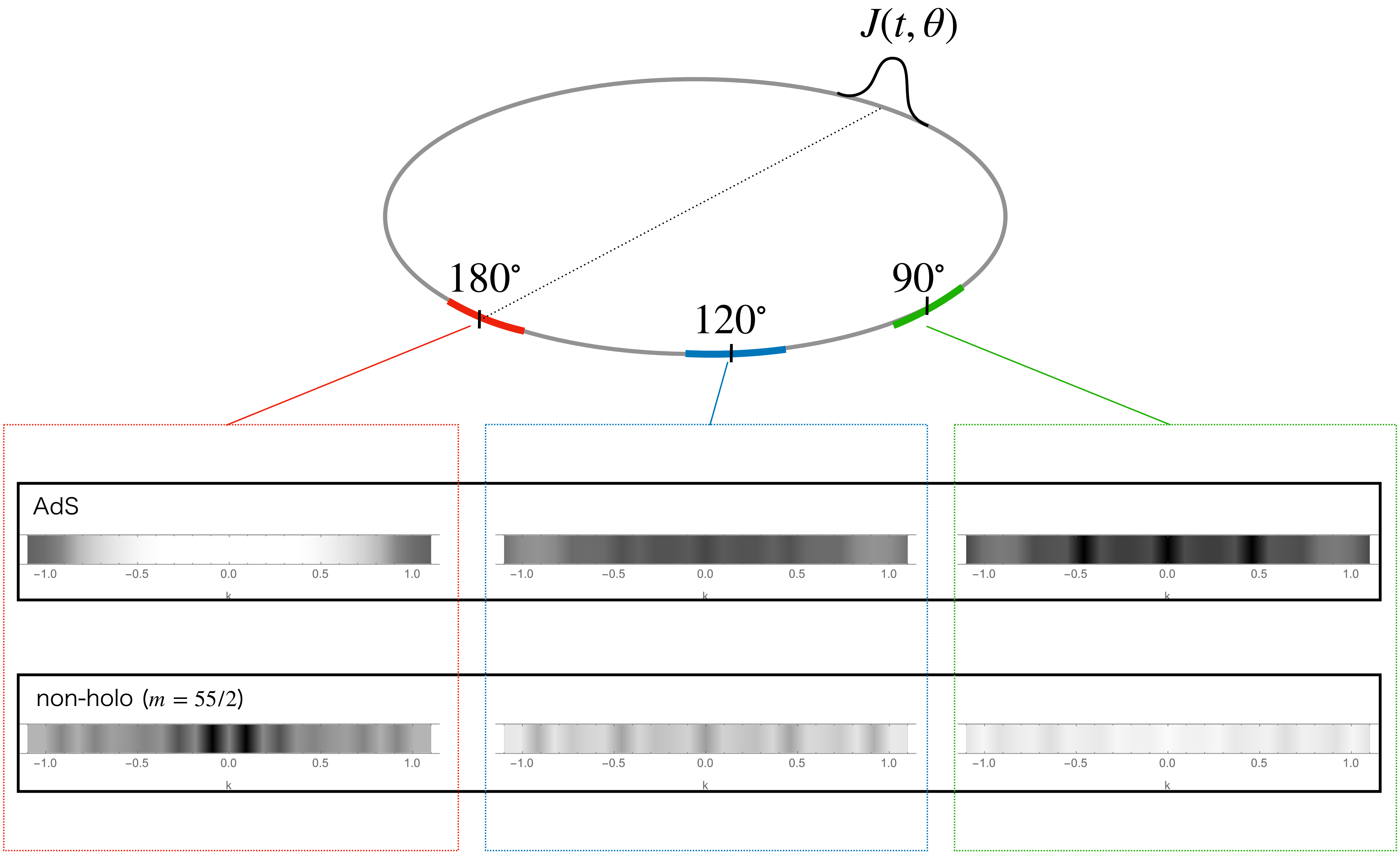
coupling to J

$$J \sim \exp\left[-\frac{\theta^2}{2\sigma^2} - i\omega t \right]$$

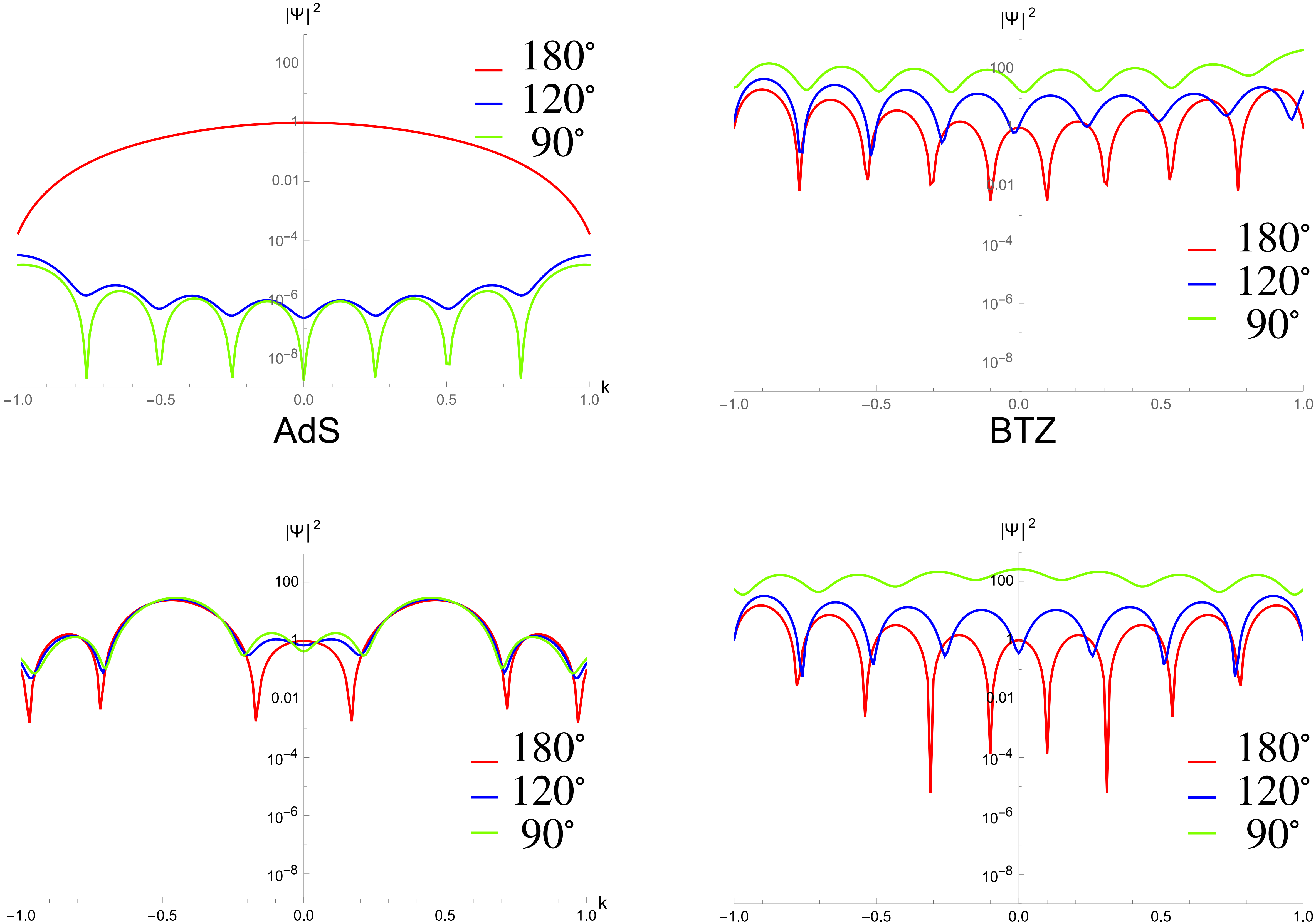
EOM

$$(\partial^2 - m^2)\phi = J$$

Comparison with non-holographic one



Comparison with non-holographic one



AdS

BTZ

non-holo light

non-holo heavy

Optical imaging reveals spacetime emergence

1. Demonstration with bulk scalar

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Eikonal approx: wave $\leftrightarrow$ congruence

If we add mass?

Wave : $\Phi = a(x)e^{iS(x)}$

$$0 = (\nabla^\mu \nabla_\mu - m^2)(ae^{iS})$$
$$= \nabla^\mu \left[e^{iS} \left(\nabla_\mu a + ia\partial_\mu S \right) \right] - m^2 a e^{iS}$$
$$= e^{iS} \left[-a(\partial_\mu S)^2 + 2i\partial^\mu S \nabla_\mu a + \nabla^\mu \nabla_\mu a + ia \nabla^\mu \partial_\mu S - am^2 \right]$$

Eikonal approx : keep $|\partial_\mu S|$ large

In general, in weak coupling theory,

Eikonal approx : $\partial_\mu S \partial^\mu S = 0$

Eikonal approx: wave ↔ congruence

$$\partial_\mu S \partial^\mu S = 0$$

$$\Big\downarrow \nabla^\nu$$

$$\partial_\mu S \, \nabla^\mu \partial_\nu S = 0$$

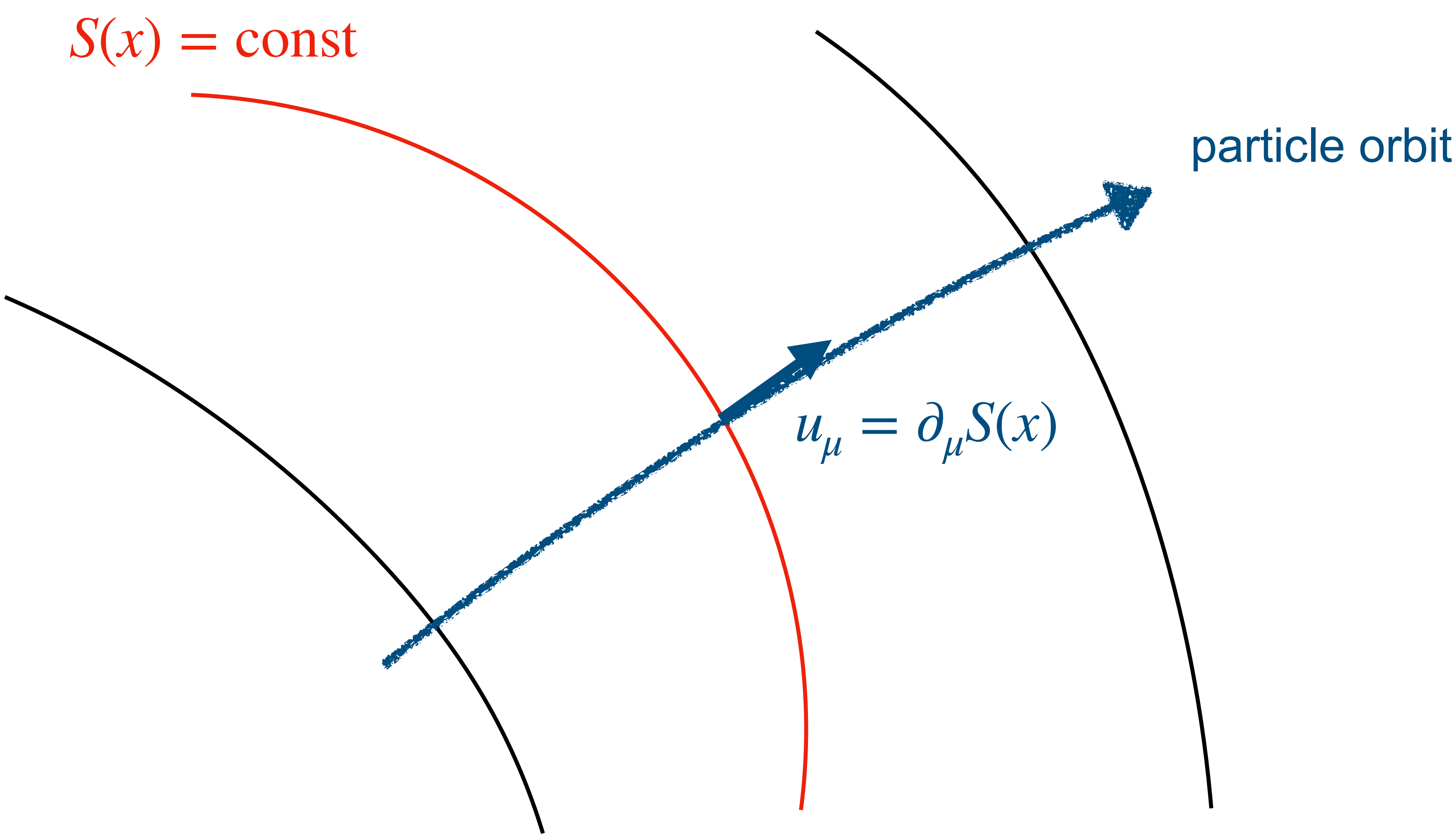
⟺

$$u_\mu = \partial_\mu S$$

Geodesic eq

$$u_\mu u^\mu = 0$$

$$\nabla_u u^\mu = 0$$



Any bulk field is available with ω kept large

$$J \sim \exp\left[-\frac{\theta^2}{2\sigma^2} - i\omega t\right]$$

Boundary condition for $S(x)$

As long as ω is kept large, the wave equation is reduced to

$$\partial_\mu S \partial^\mu S = 0 \qquad \partial_\mu S \, \nabla^\mu \partial_\nu S = 0$$

Regardless of spin or mass

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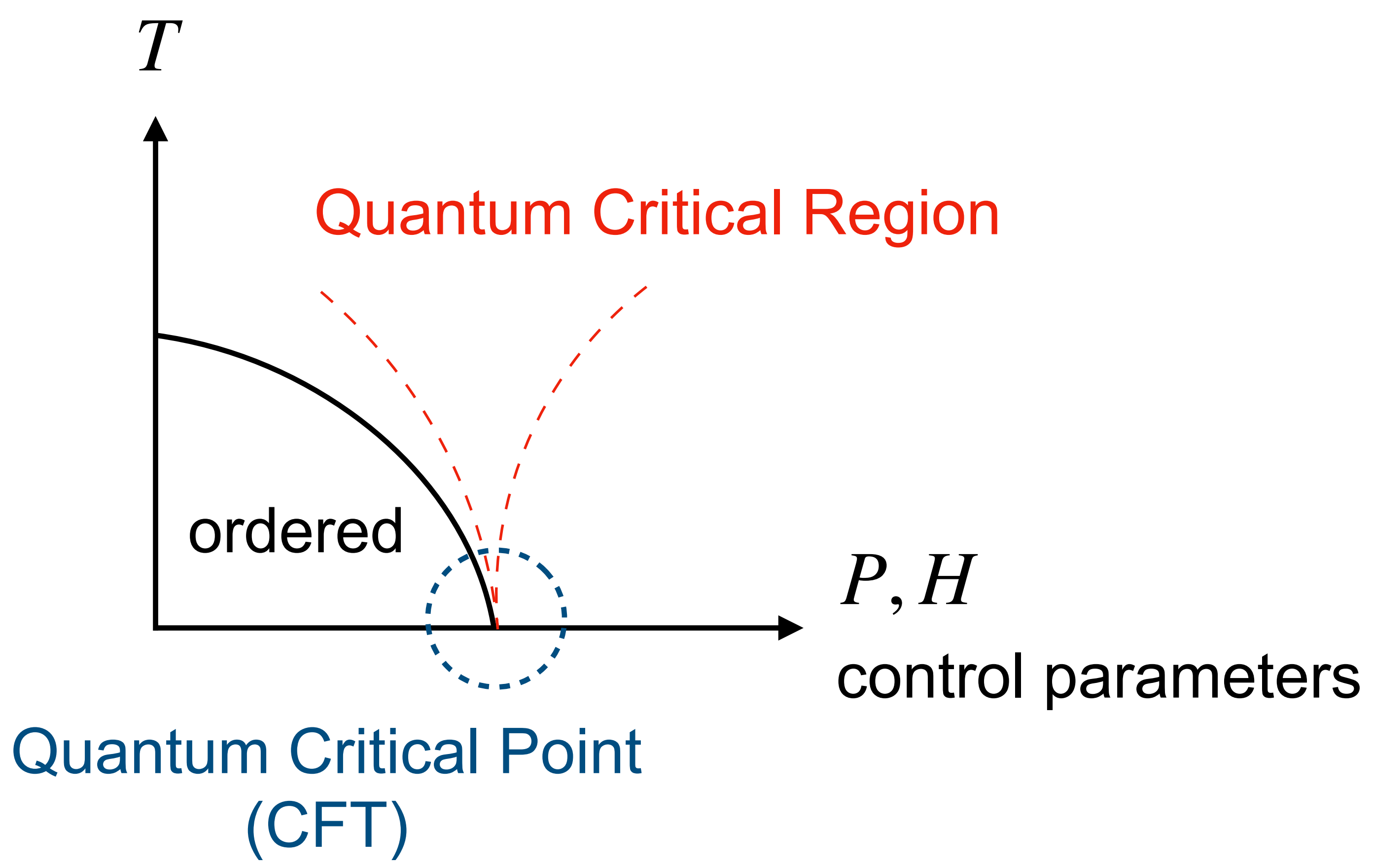
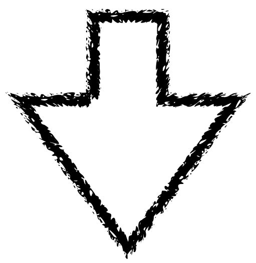
Probing QCP





Process it to ring

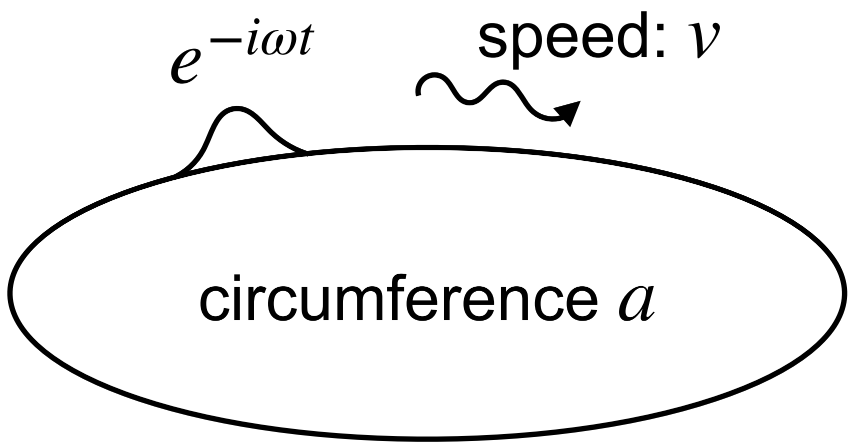
CFT on $\mathbb{S}^1$

Estimation: we can do the experiment

Wavelength ≪ ring size $\quad \omega \gg \dfrac{2\pi v}{a} \quad \omega \sim \dfrac{50\pi v}{a}$

Low temperature phase $\quad \dfrac{v\hbar}{a} > k_B T$

Continuum limit is good $\quad a \gg 1\ \mathrm{nm}$

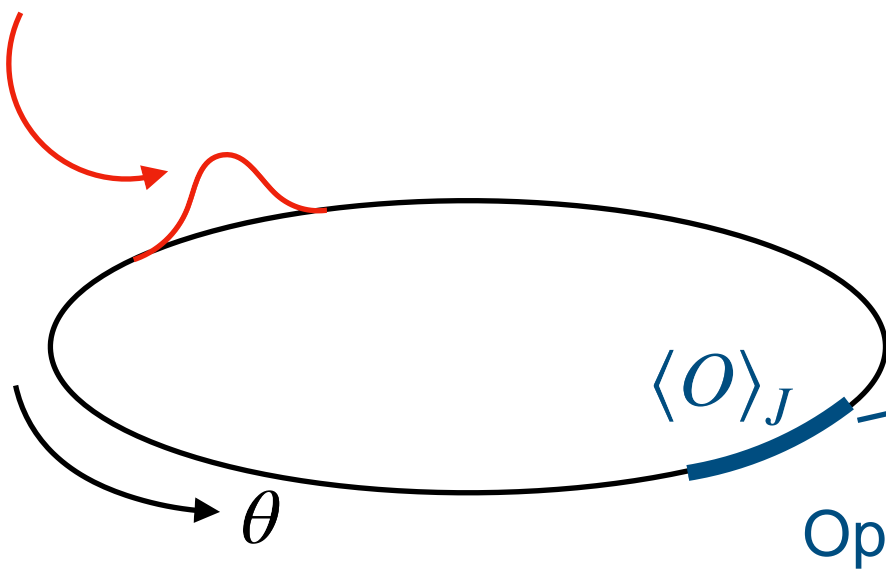


TlCuCl3 $\quad J$: EM field, $\ O$: spin operator

$$v \sim 2.0 \times 10^3\ \mathrm{m/s}$$

$$T \sim 0.1\ \mathrm{K}, \quad a \sim 10\ \mathrm{nm}$$

$$J = \sim \exp\left[-\frac{\theta^2}{2\sigma^2} - i\omega t\right]$$



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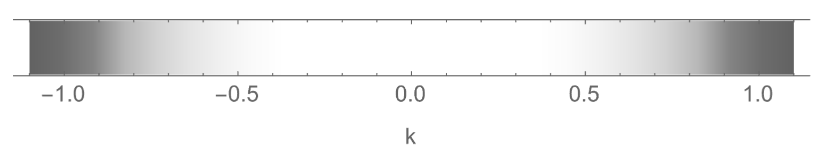

-90° 0° $+90^\circ$

AdS!

Response before imaging