# Equivalence Principle, Decoupling Principle, And Information Loss Paradox

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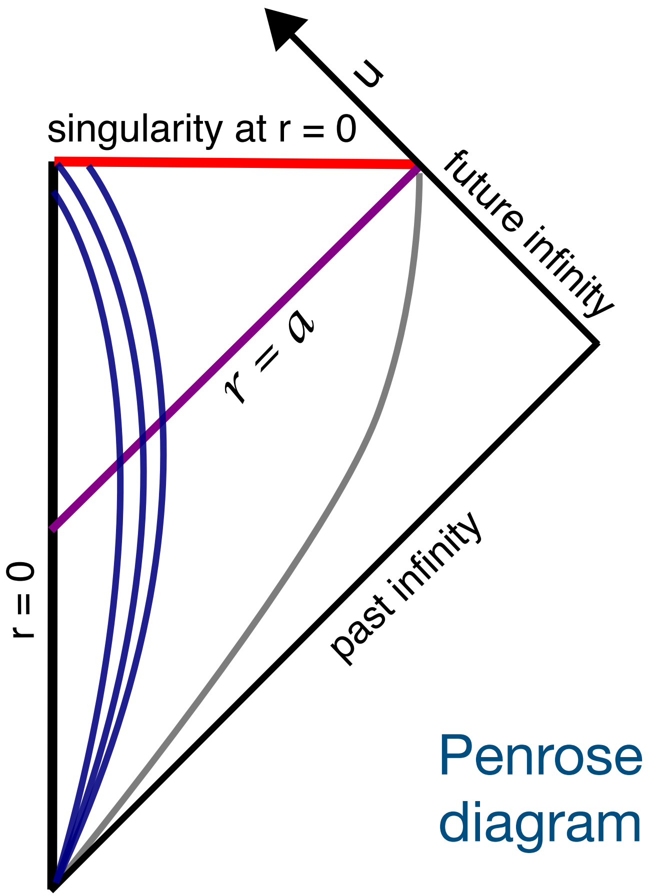
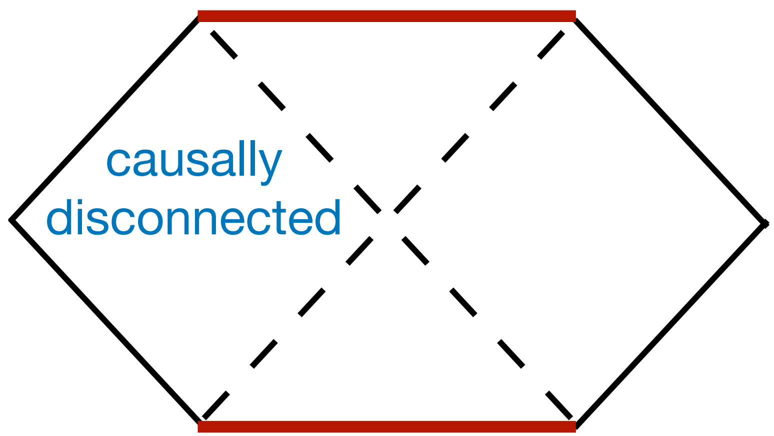
# classical black hole



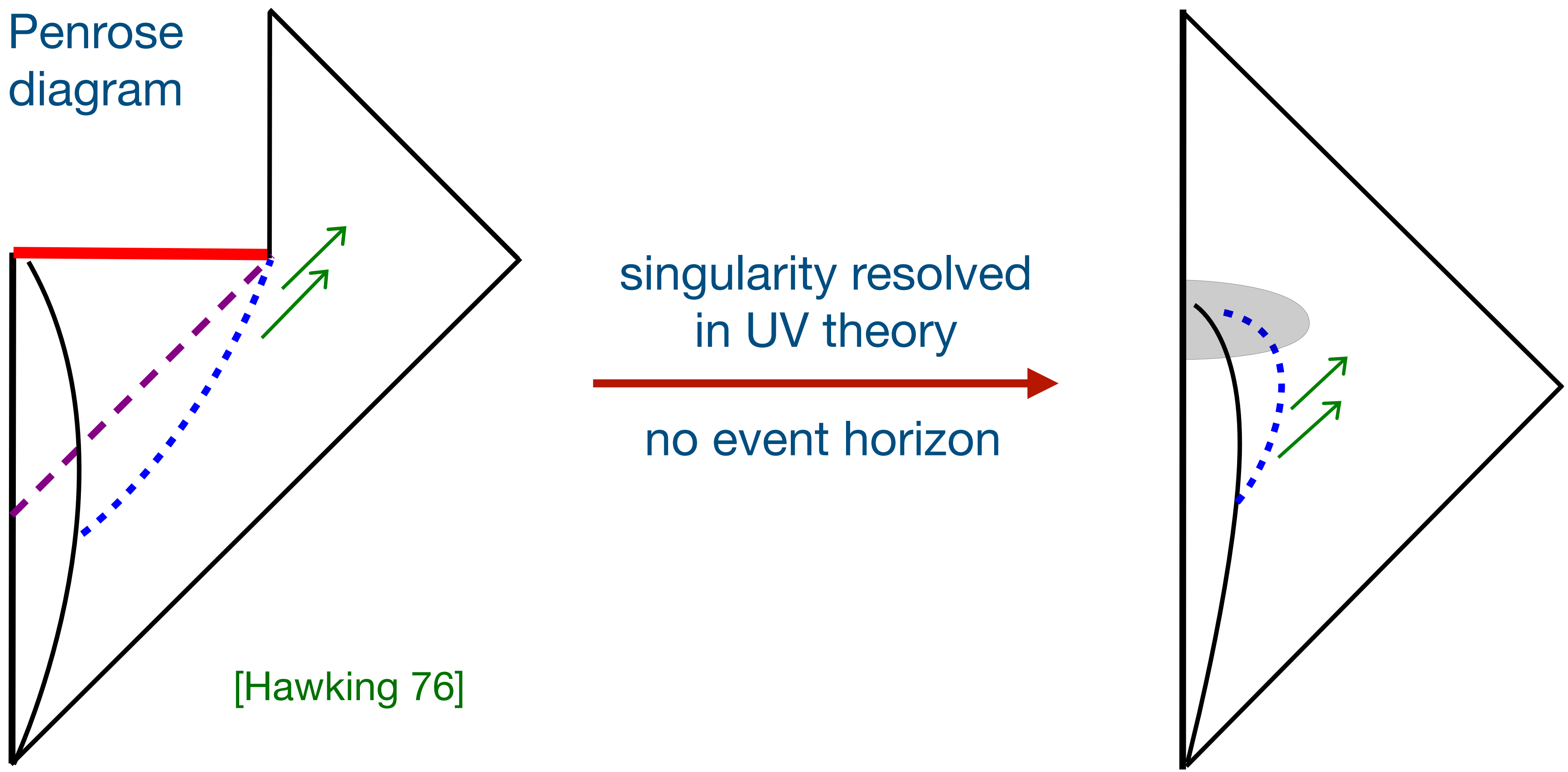

Event horizon has no local meaning.

Collapsing matter feels nothing at horizon.



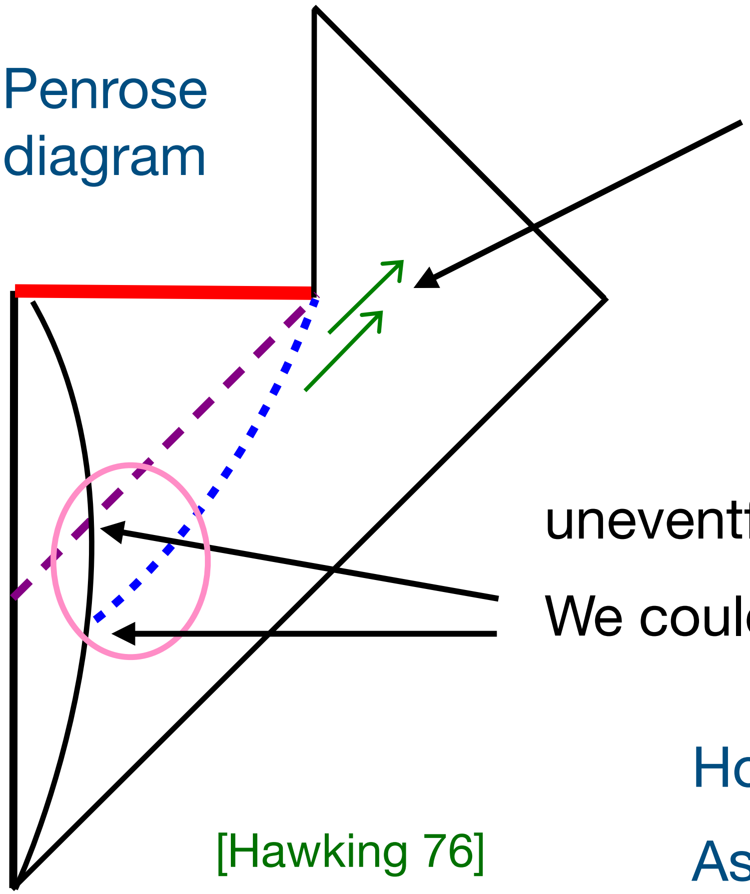

Not this one!

# quantum black hole



# information loss paradox

Penrose diagram



[Hawking 76]

information about *EVERYTHING*

A black hole can be arbitrarily large so that surface gravity is smaller than that on earth.

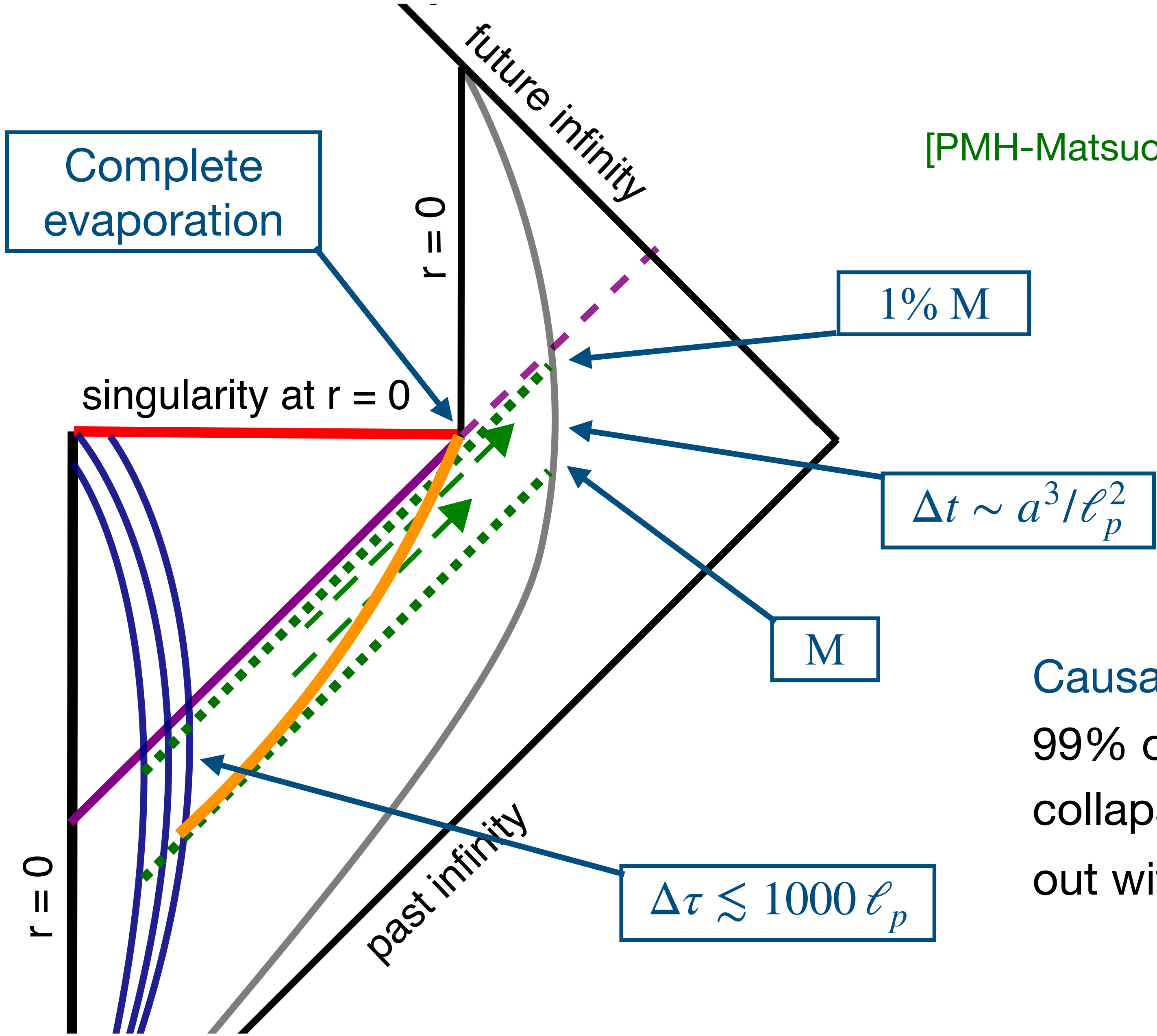
uneventful horizon ⇒

We could be passing through the horizon right now!

How is info transferred into Hawking radiation?

Astrology can be true?  Stringy effect?

[PMH-Matsuo-Yokokura 20, 20]




Causality & Locality ⇒ 99% of the information in collapsing matter comes out within $1000\,\ell_p$

# charge conservation

charge conservation of global symmetries (e.g. baryon number),

Consider particles with the *largest* $q/m$ ratio.

Given $N$ of these particles in gravitational collapse from large distances.

→ radiation during collapse $\rightarrow\ M < Nm$

→ Hawking radiation $M \rightarrow M - \Delta M$

→ total change $< Nq$

→ Charge not conserved!

→ low-energy effective theory breaks down.

→ *There must be high-energy events.*

[Banks-Seiberg 11], [Kawai-Matsuo-Yokokura 13]

# uneventful horizon

spherically symmetric metric

$$ds^2 = -C(u,v)dudv + r^2(u,v)(d\theta^2 + \sin^2\theta d\phi^2)$$

[Davies-Fulling-Unruh 76, Fulling 77, Christensen-Fulling 77]

$$\langle T_{uu} \rangle \sim \mathcal{O}(C^2/a^4), \qquad \langle T_{uv} \rangle \sim \mathcal{O}(C/a^4), \qquad \langle T_{vv} \rangle \sim \mathcal{O}(1/a^4)\,.$$

$$C \sim 0 \quad \Rightarrow \quad \langle T_{uu} \rangle \sim 0, \quad \langle T_{uv} \rangle \sim 0, \quad \langle T_{vv} \rangle \sim -(HR) < 0.$$

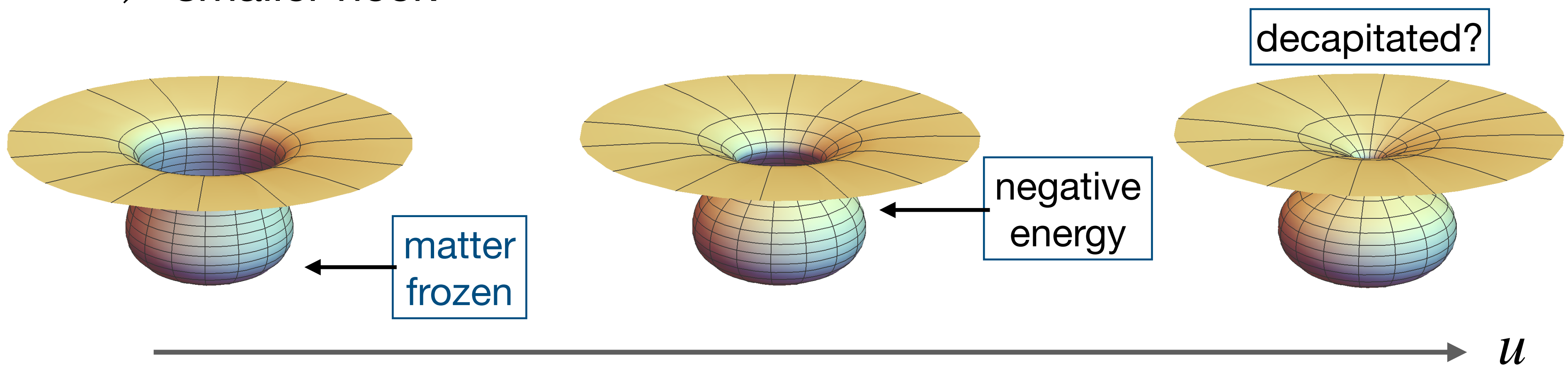
*ingoing negative energy flux around horizon*

[Unruh vacuum vs Boulware vacuum vs Hartle-Hawking vacuum]

# large negative energy

energy of collapsed matter cancelled by large negative ingoing energy

⇒ smaller neck




[Parentani-Piran 94, Ho-Matsuo 18]

remnant = “Wheeler’s bag of gold”, “baby universe”

# information lost?

Remnant? Baby universe?

string theory or holographic principle:

[Strominger-Vafa 96, Maldacena 98, Witten 98, Gubser-Klebanov-Polyakov 98]

Information comes out as Hawking radiation. ['t Hooft, Susskind, …]

Page curve for entanglement entropy [Page 93]

(island, quantum extremal surface, replica wormhole, …)

[Penington 19, Alhmeiri-Mahajan-Maldacena-Zhao 19, Penington-Shenker-Stanford-Yang 19, Almheiri-Engelhardt-Marolf-Maxfield 19, Almheiri-Hartman-Maldacena-Shaghoulian-Tajdini 20]

# Why do we care?

**conflict between principles**

***equivalence principle:***

uneventful horizon (?)

$\Rightarrow$ no high-energy events

***decoupling principle:***

Why is string theory relevant?

*Need "drama" at horizon.* [Mathur 09]

# conventional model

Assumptions:

1. semi-classical Einstein equation
2. low-energy effective QFT

$G_{\mu\nu} = \kappa \langle T_{\mu\nu} \rangle$

assumption about the theory

3. Semi-classical approximation
4. uneventful horizon condition

assumption about the state

[Unruh vacuum]

→ Hawking radiation

adiabatic process (consistency check)

2D black holes (CGHS model)
3D black holes (JT gravity)
AdS/CFT duality

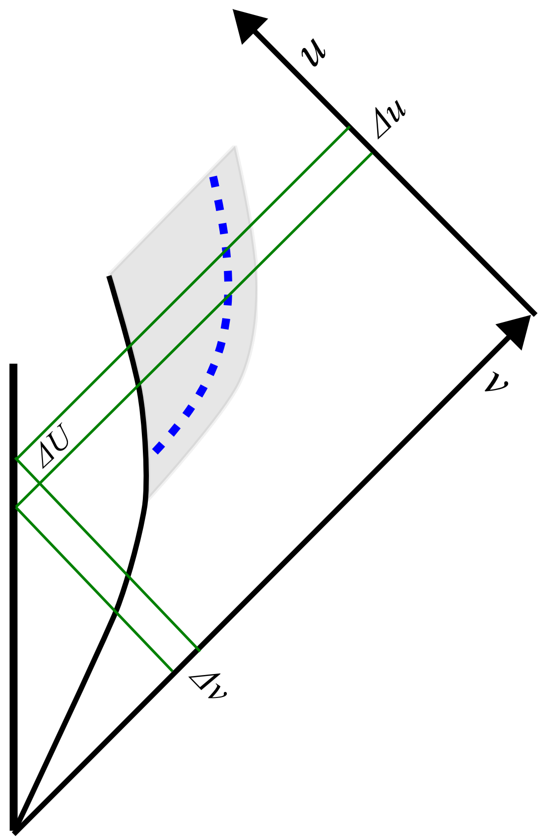
# What could go wrong?

1. trans-Planckian problem of Hawking radiation.

2. vacuum energy-momentum tensor $\langle T_{\mu\nu} \rangle$.

3. stability

# Hawking radiation




Hawking radiation does not need event horizon.

It needs the affine parameters on the past and future null infinities related via an exponential relation.

[Visser 01, Barcelo-Liberati-Sonego-Visser 06,06,10,10]

# trans-Planckian problem

['t Hooft 85] [Jacobson 91, Unruh 95, Brout-Massar-Parentani-Spindel 95, Corley-Jacobson 96]

$\omega_U = \left(\frac{dU}{du}\right)^{-1} \omega_u$ can be *trans-Planckian* since $\frac{dU}{du}$ can be arbitrarily small.

However, due to local Lorentz boosts,

$$u \to u' = \gamma u, \qquad U \to U' = \gamma U,$$
$$v \to v' = \gamma^{-1} v \qquad V \to V' = \gamma^{-1} V$$

The frequency can be arbitrarily large or small.

EFT breaks down if $\left|\omega_u g^{uv} \omega_v\right| > M_p^2$ in the absence of selection rules.

# large invariants

[PMH-Yokokura 20, PMH 20]

$$g^{\mu_1\nu_1}\cdots g^{\mu_n\nu_n}\left(\nabla_{\mu_1}\cdots\nabla_{\mu_{2n}}\phi\right)\left(\nabla_{\nu_1}\cdots\nabla_{\nu_{n-2}}\mathcal{R}_{\nu_{n-1}\nu_n}\right)\left(\nabla_{\nu_{n+1}}\cdots\nabla_{\nu_{2n-2}}\mathcal{R}_{\nu_{2n-1}\nu_{2n}}\right)$$

$$\longrightarrow\quad\left(g^{uv}\right)^{2n}\left(\nabla_u^{2n}\phi\right)\left(\nabla_v^{n-2}\mathcal{R}_{vv}\right)^2$$

$$g^{\mu_1\nu_1}\cdots g^{\mu_{2n}\nu_{2n}}\left(\nabla_{\mu_1}\cdots\nabla_{\mu_{2n}}\phi_1\right)\left(\nabla_{\nu_1}\cdots\nabla_{\nu_n}\phi_2\right)\left(\nabla_{\nu_{n+1}}\cdots\nabla_{\nu_{2n}}\phi_2\right)$$

$$\longrightarrow\quad\left(g^{uv}\right)^{2n}\left(\nabla_u^{2n}\phi_1\right)\left(\nabla_v^{n}\phi_2\right)^2$$

$$g^{-n}\left(\nabla^{m_1}\phi\right)\cdots\left(\nabla^{m_s}\phi\right)\left(\nabla^{p_1}\mathcal{R}\right)\cdots\left(\nabla^{p_r}\mathcal{R}\right)$$

Higher-derivative interactions violate equivalence principle.

# What could go wrong?

1. trans-Planckian problem of Hawking radiation.
2. vacuum energy-momentum tensor $\langle T_{\mu\nu} \rangle$.
3. non-perturbative effect

# non-conventional models: KMY model

KMY model [Kawai, Matsuo, Yokokura 2013, Kawai, Yokokura 14,15,17]

outgoing energy flux $\langle T_{uu} \rangle \sim \mathcal{O}(a^{-4})$ $\left( \text{or } \langle T_{UU} \rangle \sim \mathcal{O}(\ell_p^{-2} a^{-2}) \right)$

apparent horizon never appears

even for matter collapsing at the speed of light

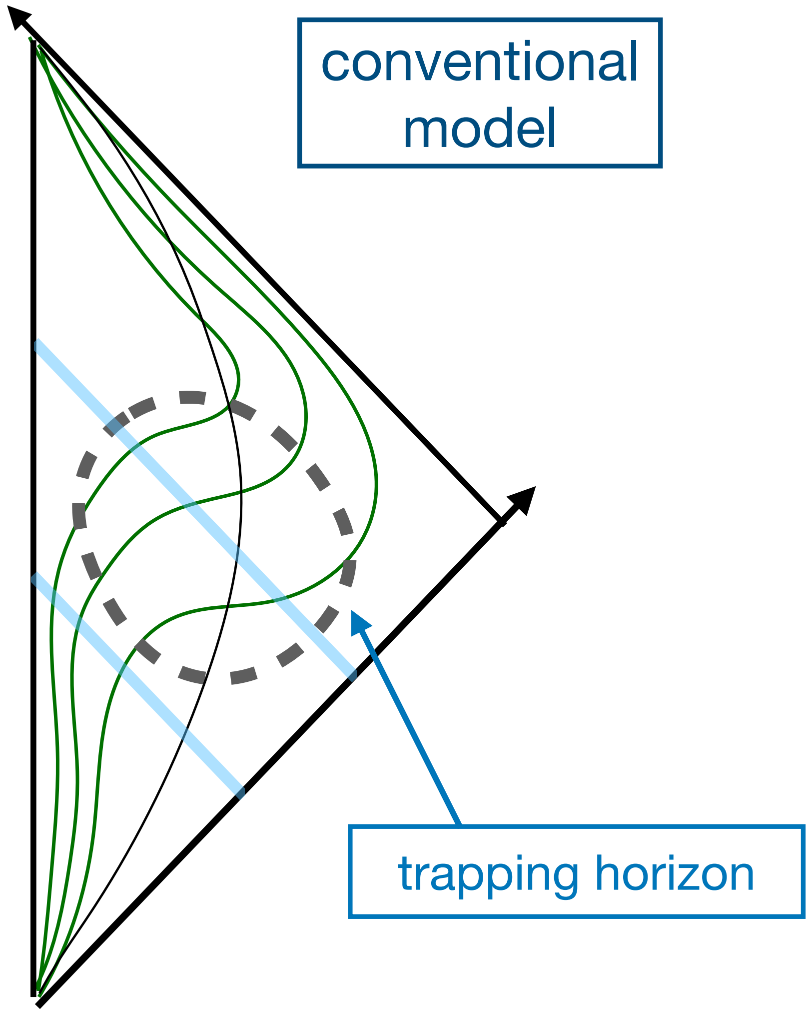
# Einstein equivalence principle

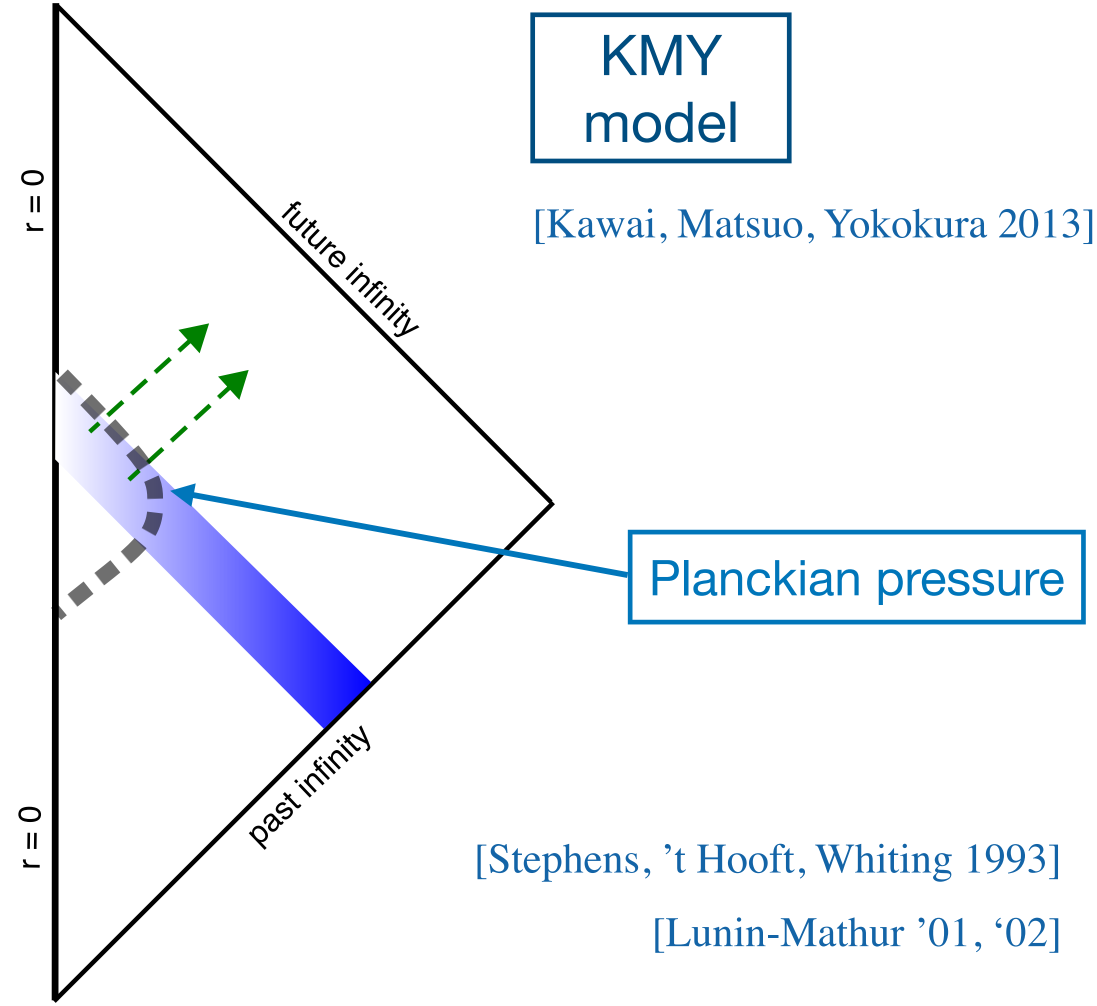
Einstein Equivalence Principle:

*The outcome of any local non-gravitational experiment in a freely falling laboratory is independent of the lab's velocity and location.*

Apart from the energy of the particles,
the vacuum EMT cannot be measured non-gravitationally.

*The Einstein EP restricts particles' EMT,*
*but not vacuum EMT.*




[Kawai, Matsuo, Yokokura 2013]

[Stephens, 't Hooft, Whiting 1993]

[Lunin-Mathur '01, '02]

# What could go wrong?

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# non-conventional models: FuzzBall

fuzzball [Lunin-Mathur '01, '02]

Planckian scale structure around would-be horizon

supergravity solutions

tunneling probability $\sim e^{-S} e^{S} \sim \mathcal{O}(1)$

# What do we need?

Reason to call UV theory for help. ✔

Is it sufficient to induce strong UV effect?

Or it stops Hawking radiation?

Mechanism for info transfer & **unique final state**

# final-state problem

$$|\phi\rangle \otimes |\Psi_0\rangle \rightarrow |\phi'\rangle \otimes |\Psi\rangle$$

$$|\phi^{(n)}\rangle \otimes |\Psi_0\rangle \rightarrow |\phi'^{(n)}\rangle \otimes |\Psi^{(n)}\rangle$$

$$\left(\sum_n c_n |\phi^{(n)}\rangle\right) \otimes |\Psi_0\rangle \rightarrow \sum_n c_n |\phi'^{(n)}\rangle \otimes |\Psi^{(n)}\rangle$$

$\rightarrow$ entanglement

The black-hole final state must be unique:

$$|\phi^{(n)}\rangle \otimes |\Psi_0\rangle \rightarrow |\phi_0\rangle \otimes |\Psi^{(n)}\rangle$$

cf: [Horowitz-Maldacena 03]

# conclusion

**challenge for conventional model** (keeping **equivalence principle**)

How is decoupling principle broken?

How can we still trust Hawking radiation or Schwarzschild geometry?

(nonlocal effect, microscopic wormholes?)

**challenge for non-conventional models** (keeping **decoupling principle**)

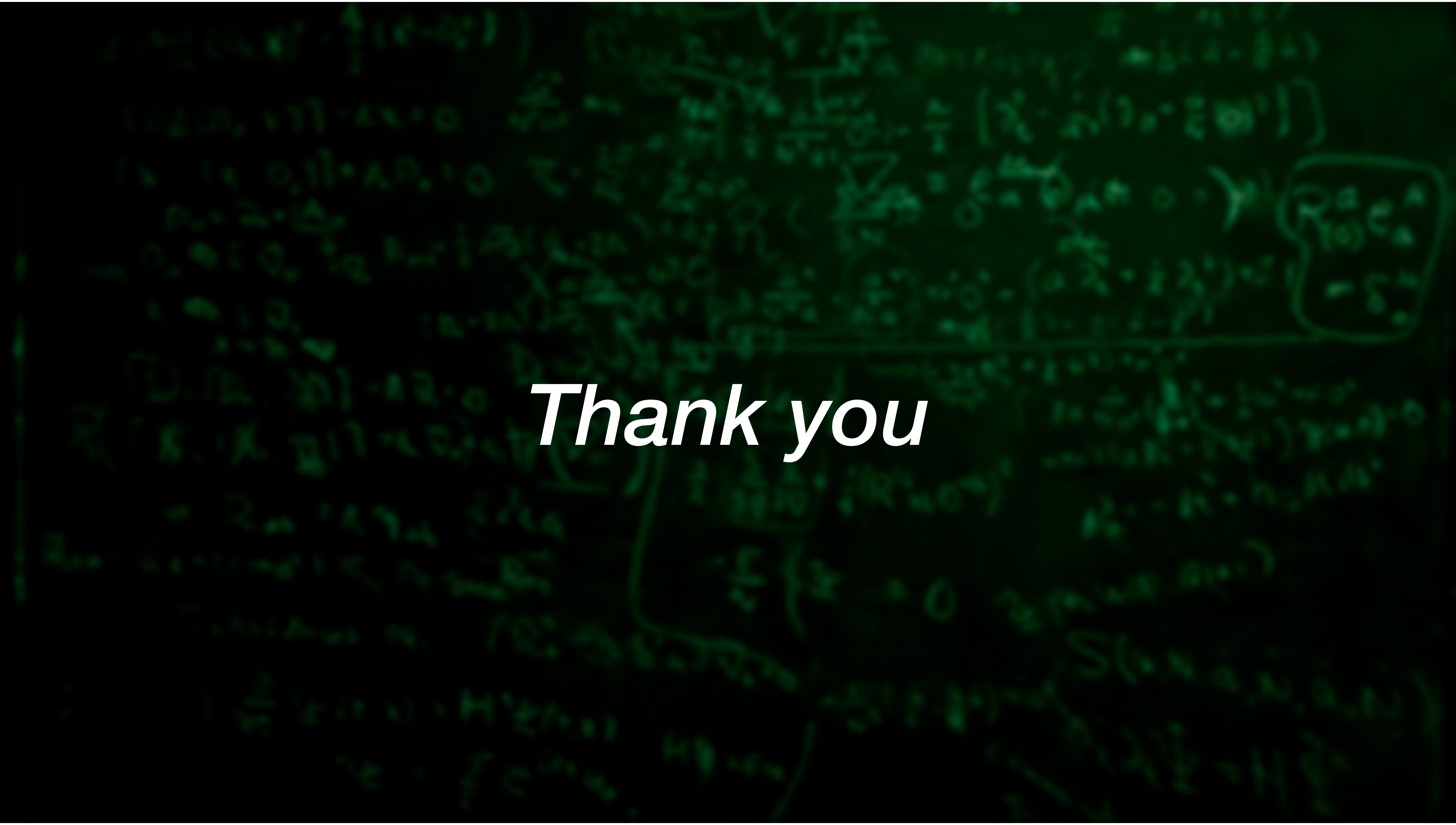
How is equivalence principle broken?

(Einstein's equivalence principle is not broken.)

Experience of freely falling observers may be very similar.

(quantum state is nonlocal, higher-derivative interactions, tunneling?)

[PMH-Yokokura 20, PMH 20]


Thank you