Vacuum Energy, Hawking Radiation and Black-Hole Geometry

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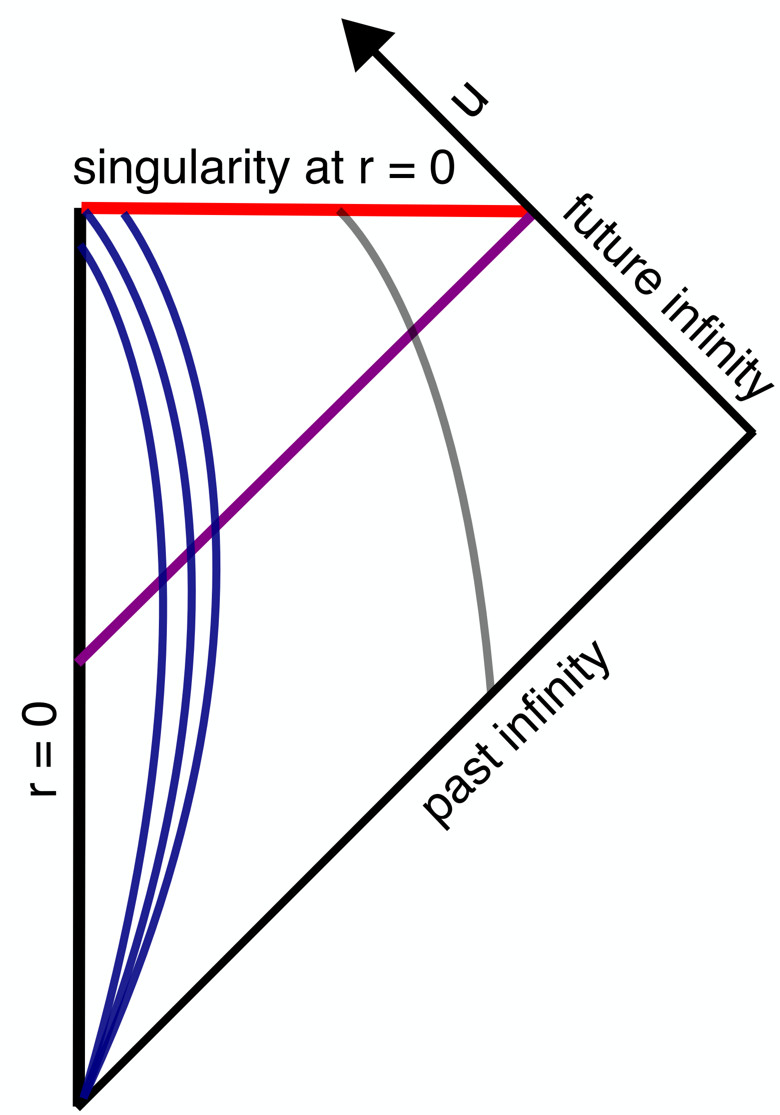
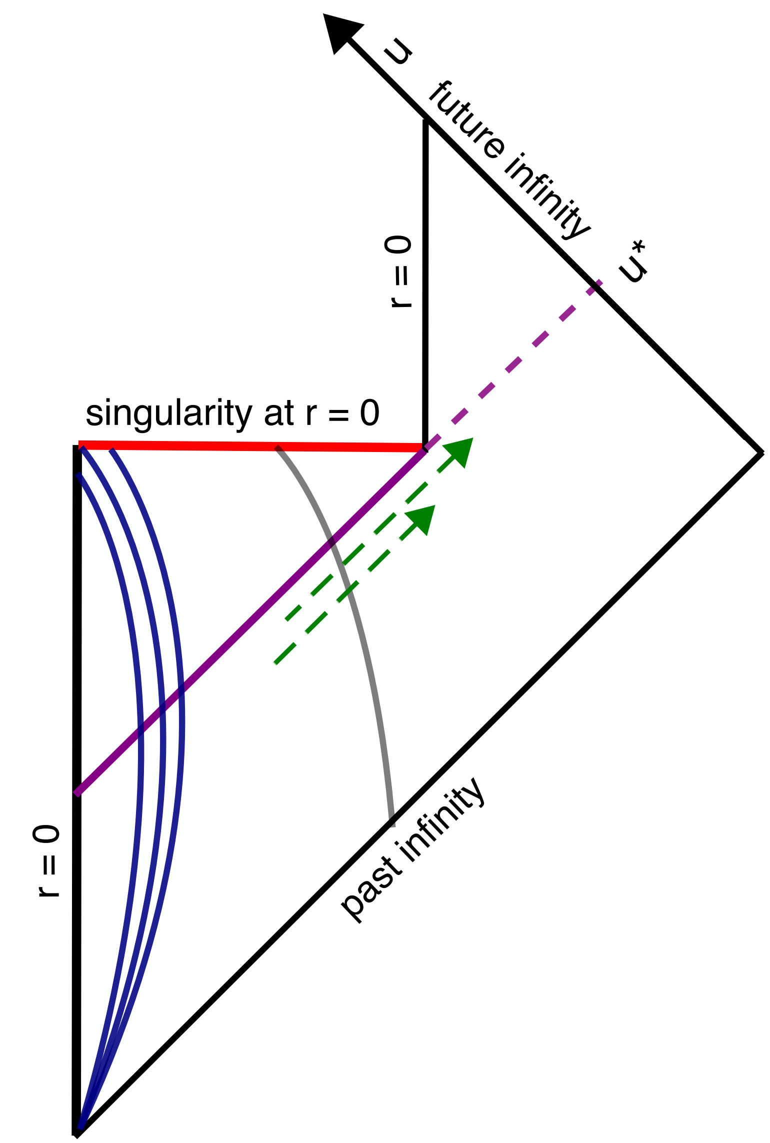
classical BH

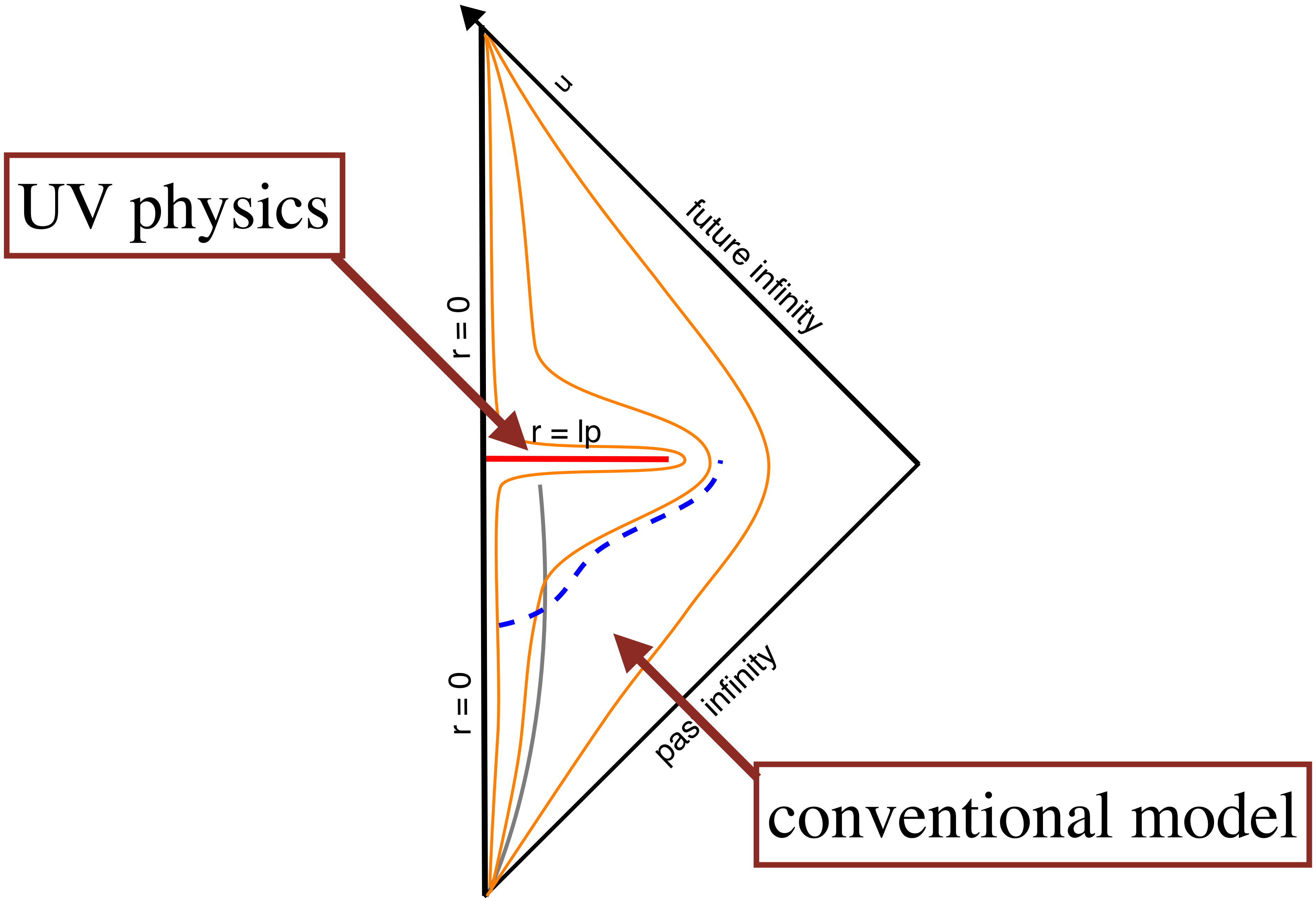


conventional model



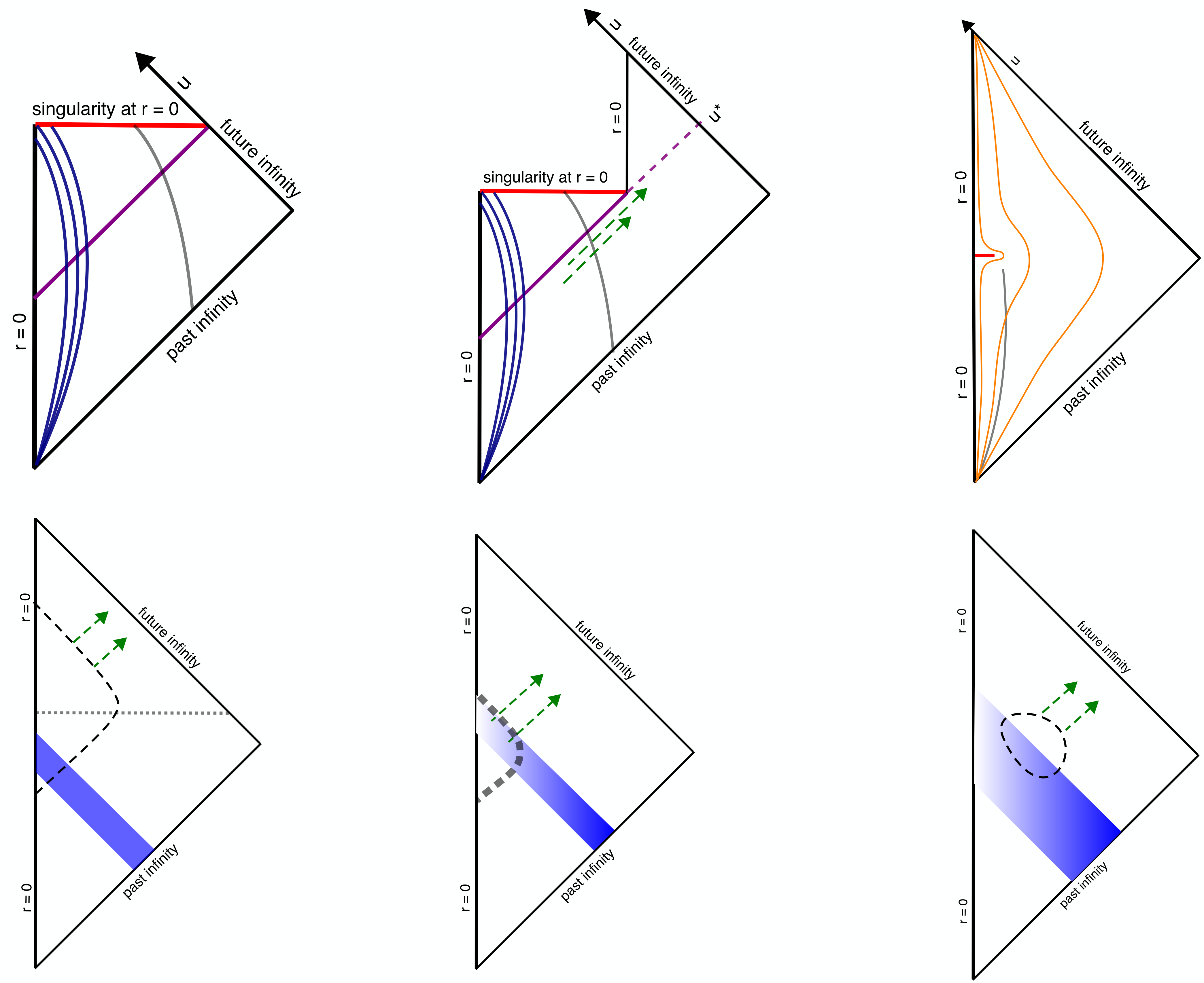
assuming no back reaction
for Hawking radiation.
[Hawking 1976]

Conventional model with singularity resolved



No event horizon if no singularity.

Which is correct?



misconception

"BH has event horizon"

- The notion of event horizon is global.
  No local implication.
- It needs a (to-be-resolved) singularity.
- Penrose diagram ≠ local physics
  10^{20} years $\neq \infty$
  $a^3/\kappa \sim 10^{67}$ years for solar mass

misconception

“Quantum correction too small to remove event horizon”

- Hawking radiation makes a big difference.
- Accumulated tiny local changes can have large effect.
- M vs M^3 argument does not work.
- Quantum vacuum energy is only locally weak.

  Event horizon is not a local property.

misconception

“Apparent horizon must exist.”

- Uniqueness demands spherical symmetry.
- Outer apparent horizon needs ingoing negative energy.
  (violation of weak energy condition)
- Astrophysical BH = huge red-shift factor

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The only thing about a black hole that does not need to be justified.

Information Paradox

- String theory resolves singularity
  → no event horizon → problem solved?
- Mathur:
  "Niceness conditions" must be violated. (e.g. firewall)
  O(1) correction needed at horizon → fuzzball
- How does low-energy effective theory break down?
  Why are the high energy events?

Our Task

- What is really the geometry by time evolution according to semi-classical Einstein equations (with back reaction of vacuum energy)?

$$G_{\mu\nu} = \kappa T^{class}_{\mu\nu} + \kappa \langle \hat{T}_{\mu\nu} \rangle$$

- High energy events?

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- High energy events?

Horizon is not an assumption!

Basic Assumptions

- Semi-classical Einstein equation:

$$G_{\mu\nu} = \kappa T_{\mu\nu}^{class} + \kappa \langle \hat{T}_{\mu\nu} \rangle$$

- Spherical symmetry.

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

areal radius

- Static black hole?

  Black-hole formation/evaporation?

How can there be anything new?

- Nonlinear equations hard to solve exactly.
- conventional approximation:

  classical collapse $\rightarrow$ horizon + evaporation

  ignore back reaction of vacuum energy

  (e.g. Schwarzschild metric outside matter)

What's wrong with naive perturbation

- Schwarzschild metric is good approximation at a few Planck lengths away from the Schwarzschild radius (in vacuum).
- Perturbative expansion in κ is different when

  $r \sim a + O(\kappa/a)$

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$$ds^2 = -(1 - a/r)dt^2 + \frac{dr^2}{1 - a/r} + d\Omega^2$$

Conclusion Preview

- Back reaction of vacuum $T_{\mu\nu}$ is important.
- 3 classes of static black-hole-like solutions with spherical symmetry
- 3 or more classes for gravitational collapses

Static Black Holes

- The energy-momentum operator $\langle T_{\mu\nu} \rangle$ in curved spacetime is different for different QFTs.
- Conformal matters are convenient because of trace anomaly.
- 2D massless field [Davies-Fulling-Unruh 1976][PMH-Matsuo 17 (1)][PMH-Matsuo 17 (2)]
- 4D conformal matter [Christensen-Fulling 1977][PMH-Kawai-Matsuo-Yokokura 18]
- Literature [Solodukhin 04, 06; Fabbri-Farese-Navarro-Salas-Olmo-Sanchis-Alepuz 05 (1), 05 (2)]

Energy-Mom. Tensor in 4D

[PMH-Kawai-Matsuo-Yokokura 18]

- Energy-momentum tensor in 4D is constrained by
  1. Conservation law
  2. Spherical symmetry
  3. Time independence
  4. Trace anomaly
- There is still one functional degree of freedom.
- Conclusion: [PMH-Kawai-Matsuo-Yokokura 18]

  Event horizon needs fine-tuning!

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Not surprising?

3 Classes Of Solutions

[PMH-Matsuo 17 (1)][PMH-Matsuo 17 (2)]
[PMH-Kawai-Matsuo-Yokokura 18]

1. event horizon: fine-tuning
2. "wormhole-like": local minimum in areal radius r (no event horizon).
3. neither.

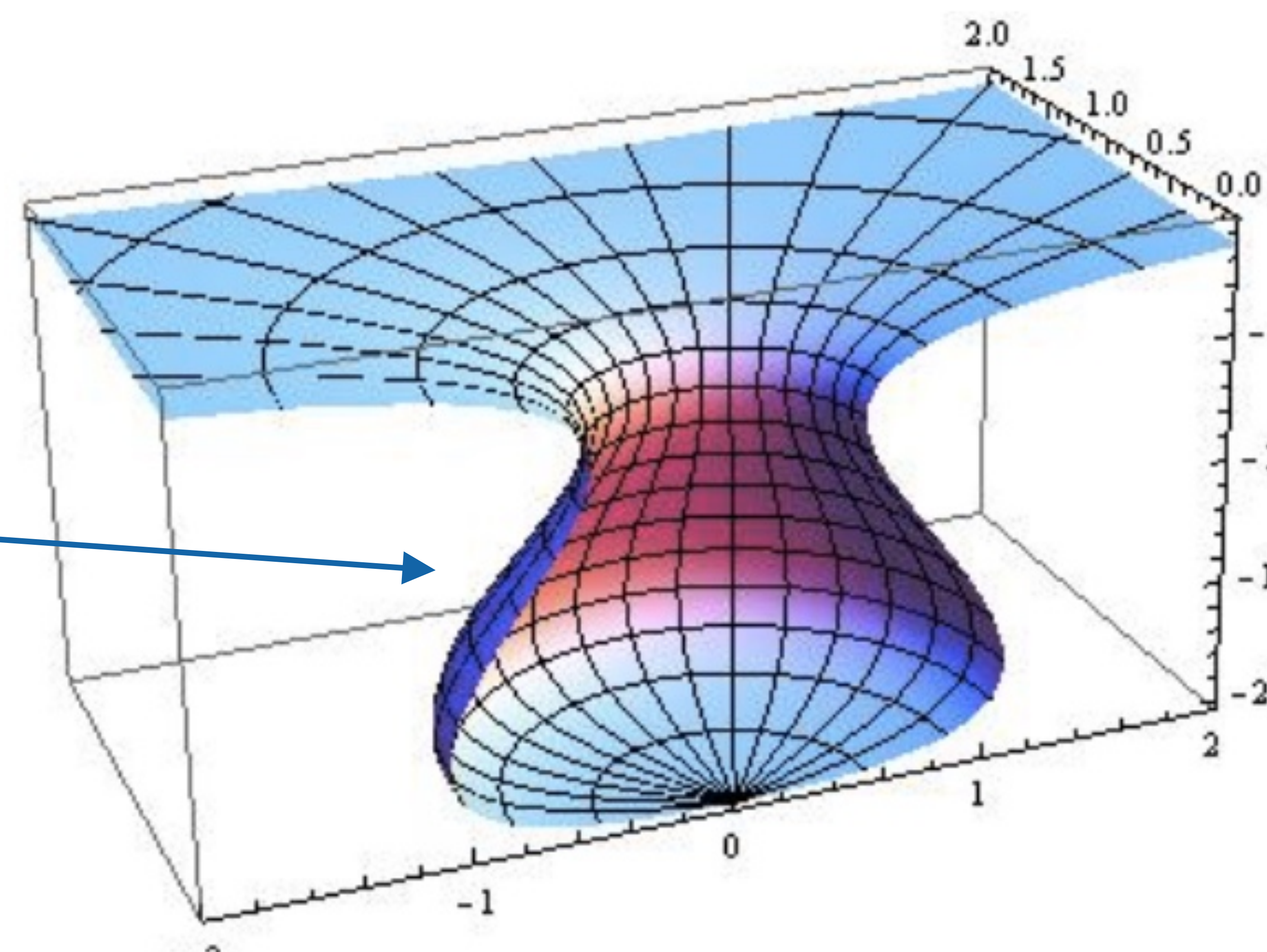
Buchdahl's theorem ($P \to \infty$ if $R < 9a/8$) is in general violated (due to negative energy — weak energy condition violated).

Wormhole-Like Solution: local minimum in areal radius

- vacuum energy + incompressible fluid
- No horizon
- *Large pressure* when surface is not well outside the neck.

[PMH-Matsuo 17 (1), (2)]

Radial distance is short.



Dynamical Cases: 3 Scenarios

- apparent horizon: Collapsing wormhole evaporated

  [PMH-Matsuo 18]

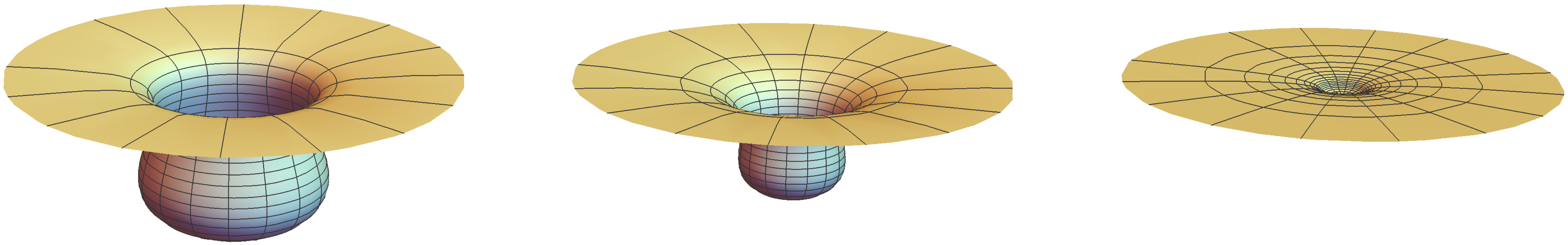
- apparent horizon: Collapsing wormhole (nearly) decapitated [Parentani-Piran 1994]

- no apparent horizon: KMY Model

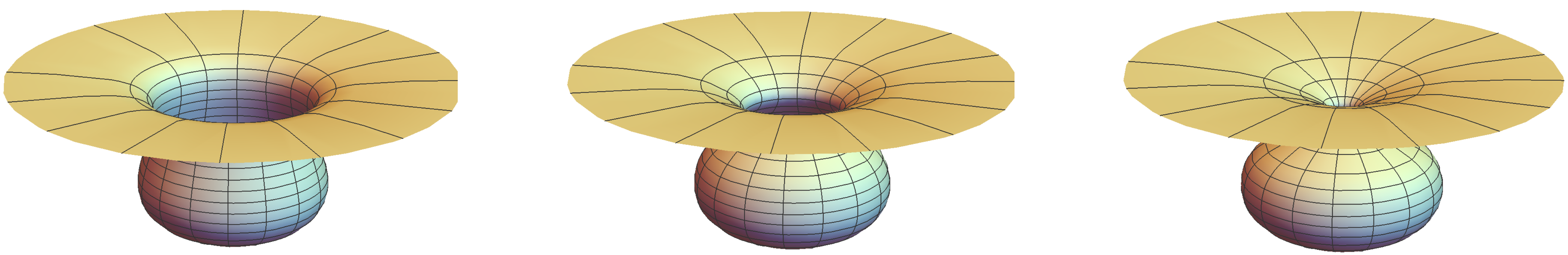
  [Kawai-Matsuo-Yokokura 13][Kawai-Yokokura 14, 15, 17][PMH 15, 15, 16]

- Other scenarios?

Wormhole evaporated [PMH-Matsuo 18]



Wormhole decapitated [Parentani-Piran 94]



information not lost

holography lost <= macroscopic negative energy

Conclusion

- Semi-classical Einstein equations solved …
- Back reaction of vacuum energy

  → different classes of near-horizon geometries
- Near-horizon geometry sensitive to states.
- "High-energy events" for all examples.
- Generic statement about dynamical case?

Thank you.