From UV completeness to black hole physics:

Lessons from Asymptotic Safety and Hořava Gravity

Quantum spacetime and the Renormalization Group
Heidelberg - April 1, 2025

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Outline

Motivations

Hořava Gravity: modified causality vs BH thermodynamics

Asymptotic Safety: two predictions on the IR landscape

Conclusions

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Many approaches to QG

There are many ways to achieve a "good" (UV complete) Quantum Gravity

QFT

- Hořava Gravity (non-Lorentz invariant)
- Asymptotic Safety (non-perturbative)
- Quadratic Gravity (unitarity?)
- ….

Beyond QFT

- String theory
- Loop quantum gravity
- Group field theory
- ….

Many approaches to QG

A conservative approach would select a QFT description

QFT	Beyond QFT
• Hořava Gravity (non-Lorentz invariant)	• String theory
• Asymptotic Safety (non-perturbative)	• Loop quantum gravity
• Quadratic Gravity (unitarity?)	• Group field theory
• ….	• ….

Ok the UV, but…

Many approaches to QG

Q: how does the UV physics impact the low-energy regimes?

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Hořava Gravity

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Hořava Gravity

ArXiv:**0901.3775**, P. Hořava

Dropping Local Lorentz Invariance can be employed to build a *power counting renormalizable* theory of gravity. We assume an anisotropic scaling between space and time

$$\mathscr{M} \simeq \mathbb{R} \times \Sigma_d \,, \qquad \{\vec{x} \to \lambda \vec{x}, \quad \tau \to \lambda^d \tau\}$$

The full diffeomorphism invariance is broken into the foliation preserving one

$$FDiff = \{\tau \to \tau'(\tau), \;\; \vec{x} \to \vec{x}'(\vec{x}, \tau)\}$$

Hořava Gravity

ArXiv:0901.3775,
P. Hořava

The Lifshitz scaling allows the insertion of higher (spatial) derivatives. Within the ADM decomposition

$$S[\gamma_{ij}, N, N_i] = \frac{1}{16\pi G}\int_{\mathscr{M}} N\sqrt{\gamma}\,[K_{ij}K^{ij} - \lambda K^2 - \mathscr{V}(a_i, R)]$$

$$K_{ij} = \frac{1}{2N}(\dot{\gamma}_{ij} - 2\nabla_{(i}N_{j)})$$

$$a_i = \nabla_i \log(N)$$

$$\{R, a_i a^i, R^2, a_i a_j R^{ij}, \dots\}$$
up to $(\nabla_i)^{2d}$

$a_i = 0$ Projectable HG

$a_i \neq 0$ Non-projectable HG

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ArXiv:**1512.02250**,
A. Barvinsky, D. Blas, M. Herrero-Valea, S. Sybiriakov, C. Steinwachs

$$a_i = \nabla_i \log(N)$$

In progress,
D. Blas, FDP, M. Herrero-Valea, S. Sybiriakov, J. Radkowsky

$a_i = 0$ Projectable HG

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Hořava Gravity

ArXiv:**0901.3775**,
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The higher derivatives operators modify the dispersion relations

See
ArXiv:**2307.13039**
M. Herrero-Valea,

$$\omega_{TT}^2 = \beta k^2 + \mu_2 k^4 + \nu_5 k^6$$

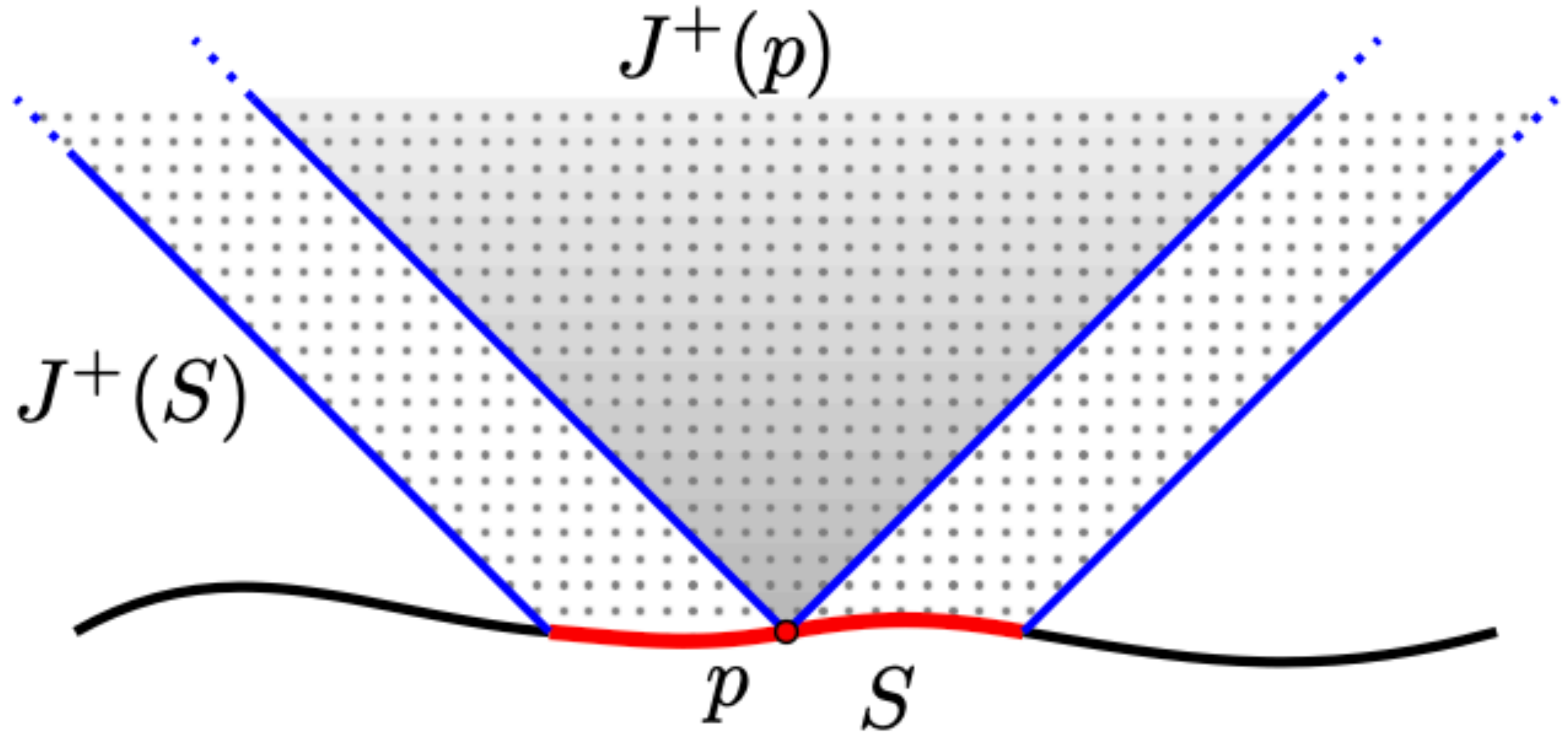
$$\omega_S^2 = (-\tilde{\beta}k^2 + (8\mu_1 + 3\mu_2)k^4 + (8\nu_4 + 3\nu_5)k^6)$$

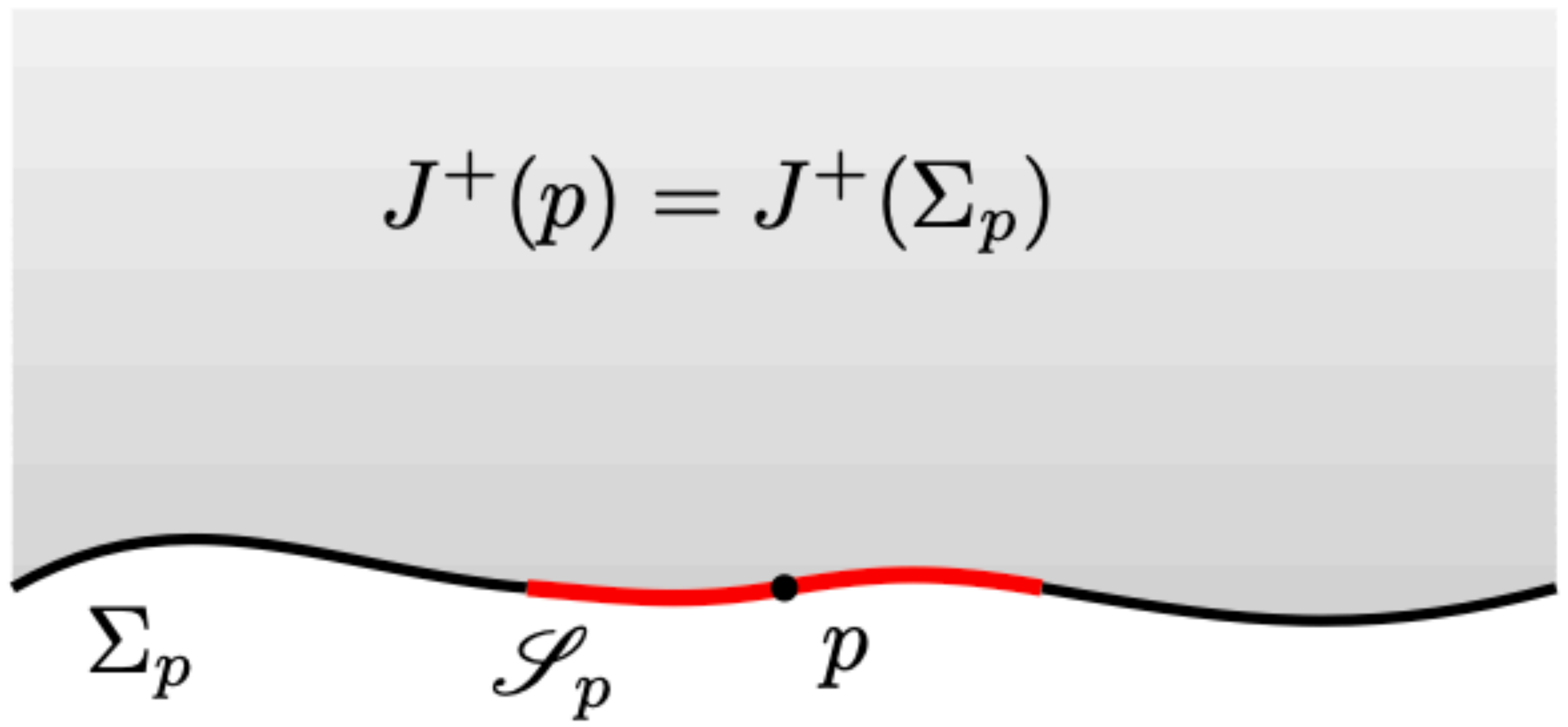
Ok the UV, but…

Causality

Perturbations with modified dispersion relations feel a different causal structure

$$\omega^2(k) = k^2 \left(1 + \sum_{j=1}^{n} \beta_{2j} \frac{k^{2j}}{\Lambda^{2j}}\right) \qquad \beta_{2j} \geq 0$$



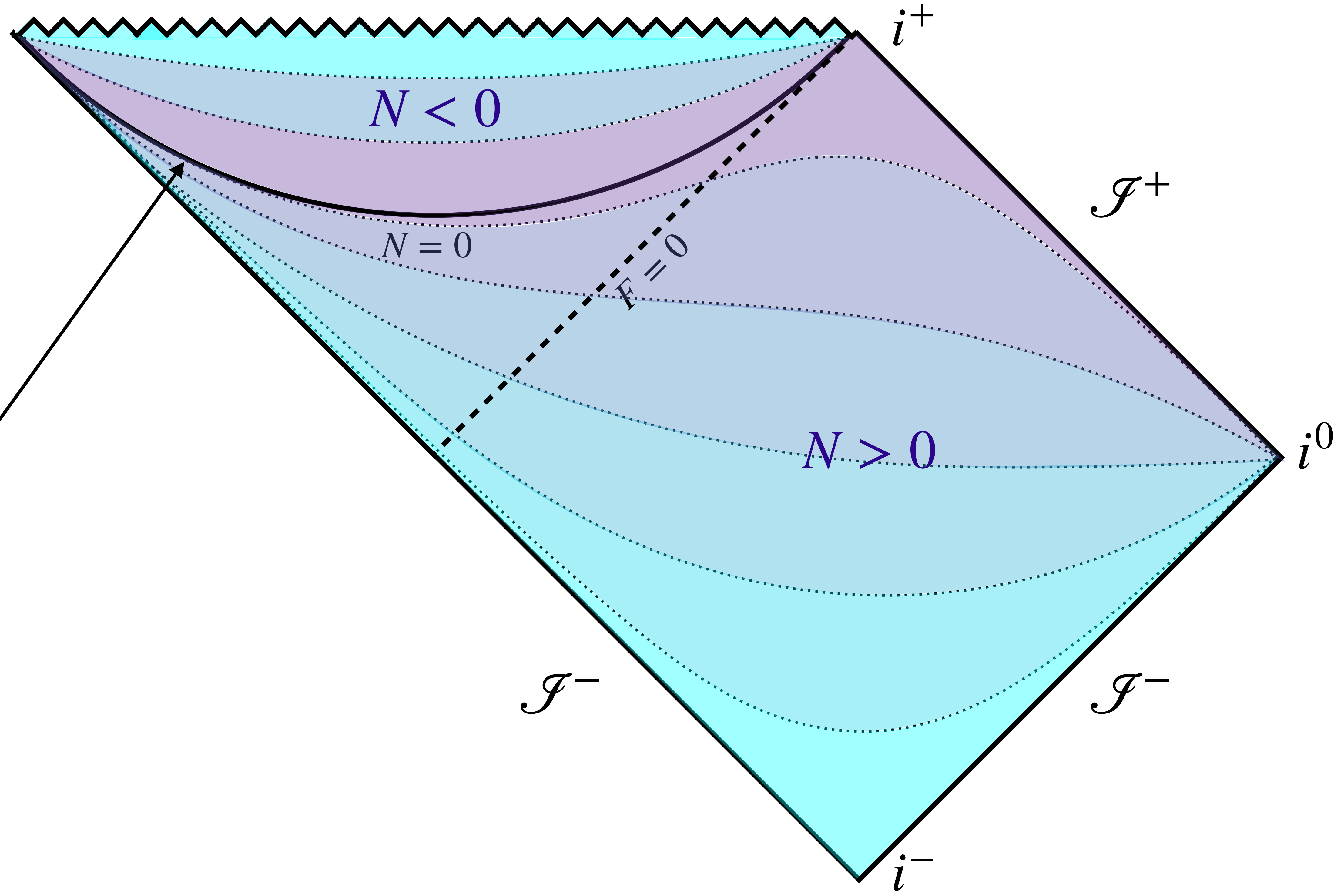


J. Bhattacharyya, M. Colombo, T. Sotiriou
ArXiv: **1509.01558**

Black holes in Hořava gravity

Perturbations with modified dispersion relations feel a different causal structure

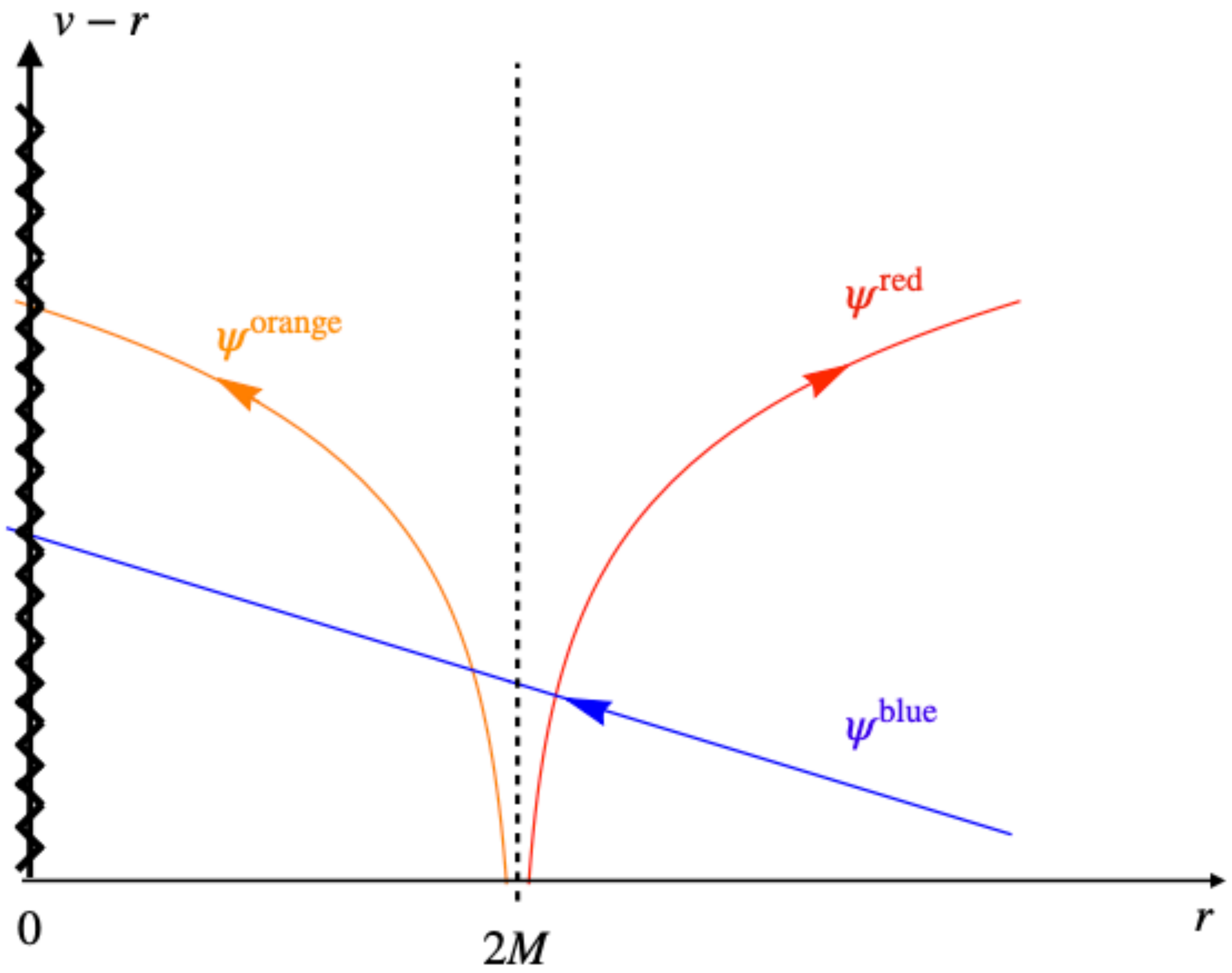
$$u_a = \frac{\partial_a \tau}{\sqrt{\partial_c \tau \partial^c \tau}}$$



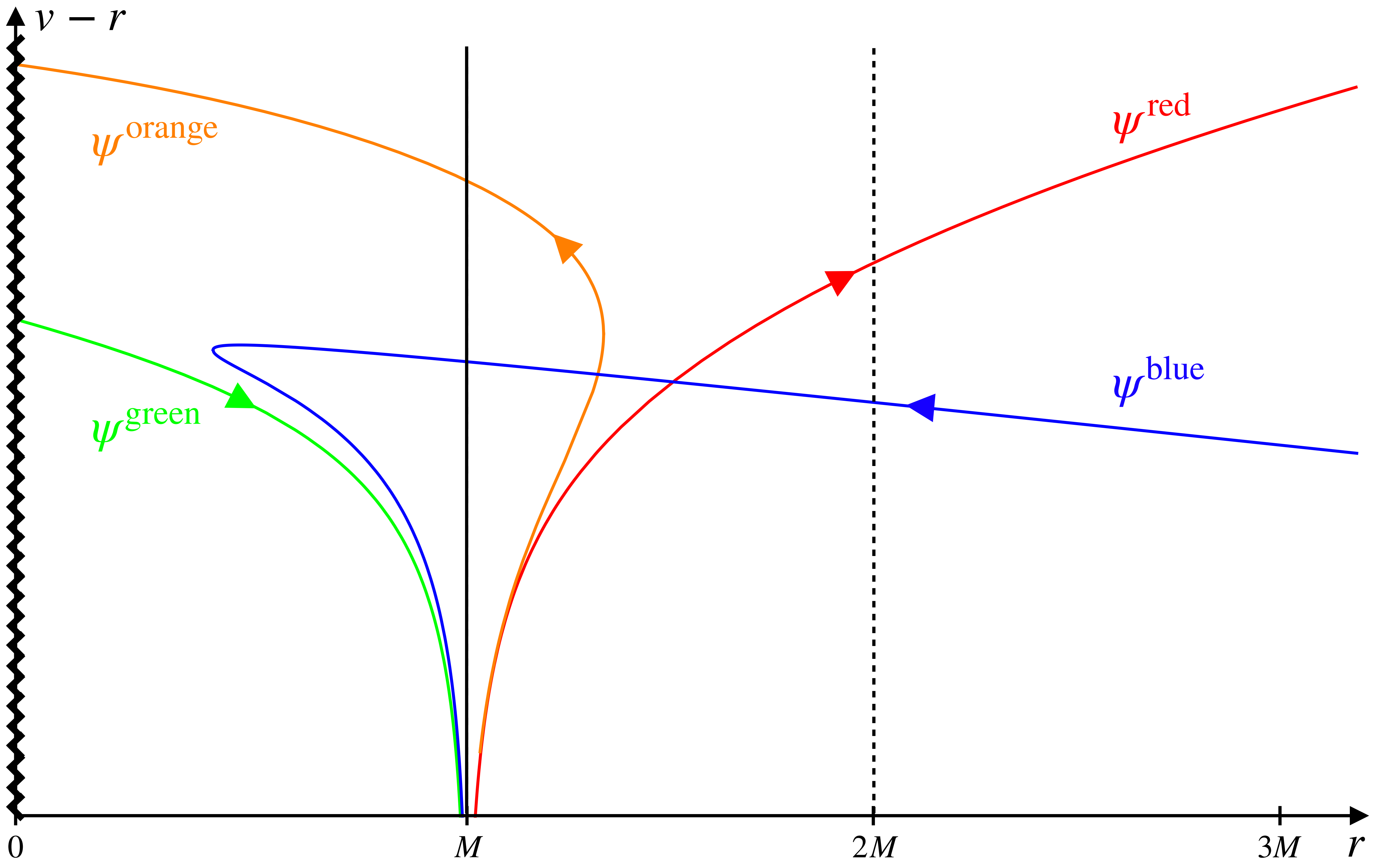
If u_a becomes orthogonal to a compact surface, we have a <u>Universal Horizon</u>

$$\mathrm{UH} = \{(\chi \cdot u) = 0\,, \quad (\chi \cdot a) \neq 0\}$$

Particles with MDRs

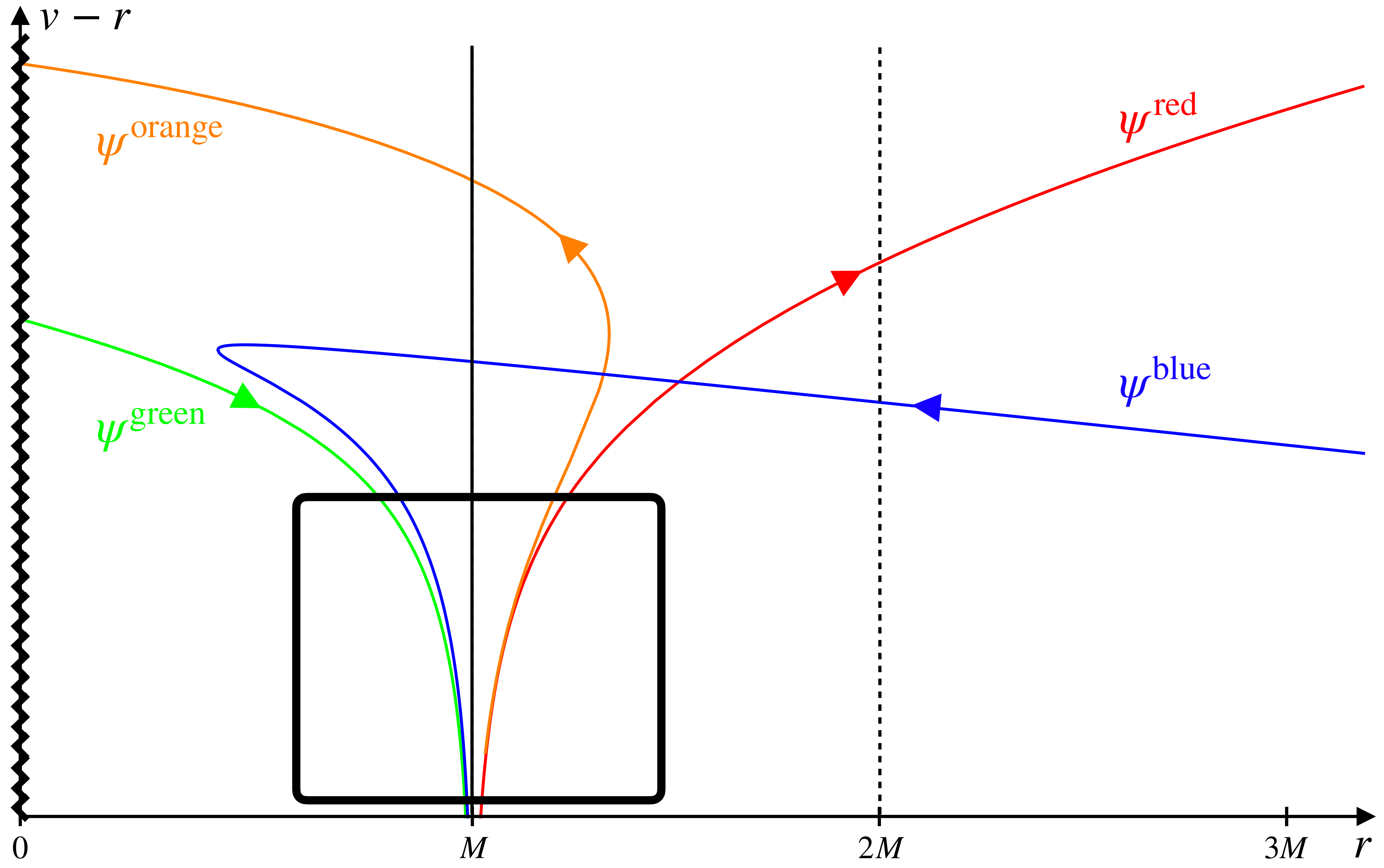


$$\omega^2(k) = k^2$$



$$\omega^2(k) = k^2\left(1 + \sum_{j=1}^{n} \beta_{2j} \frac{k^{2j}}{\Lambda^{2j}}\right)$$

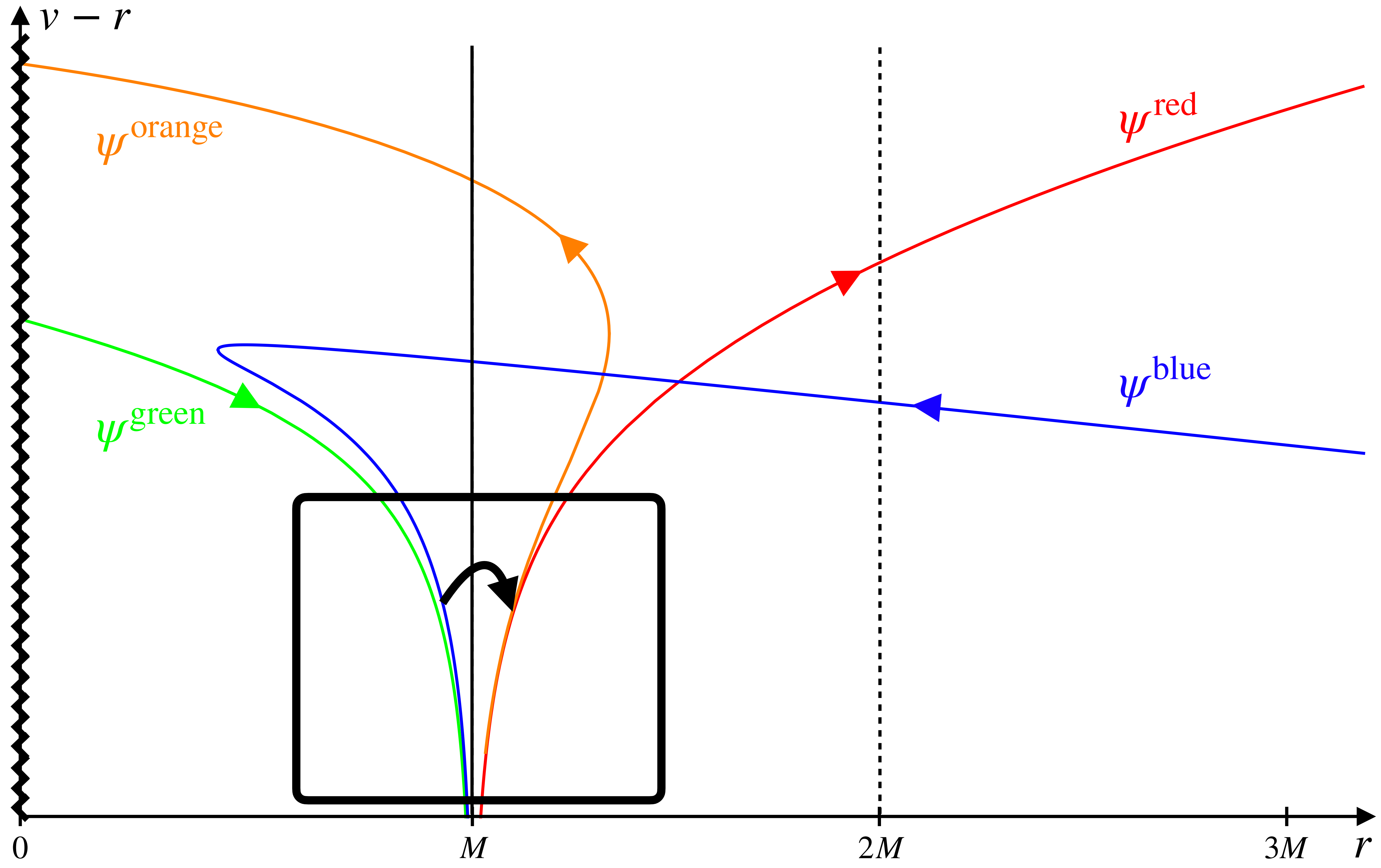
Hawking radiation



Hawking radiation

$$\Gamma = e^{-\Omega/T_{\text{UH}}}$$

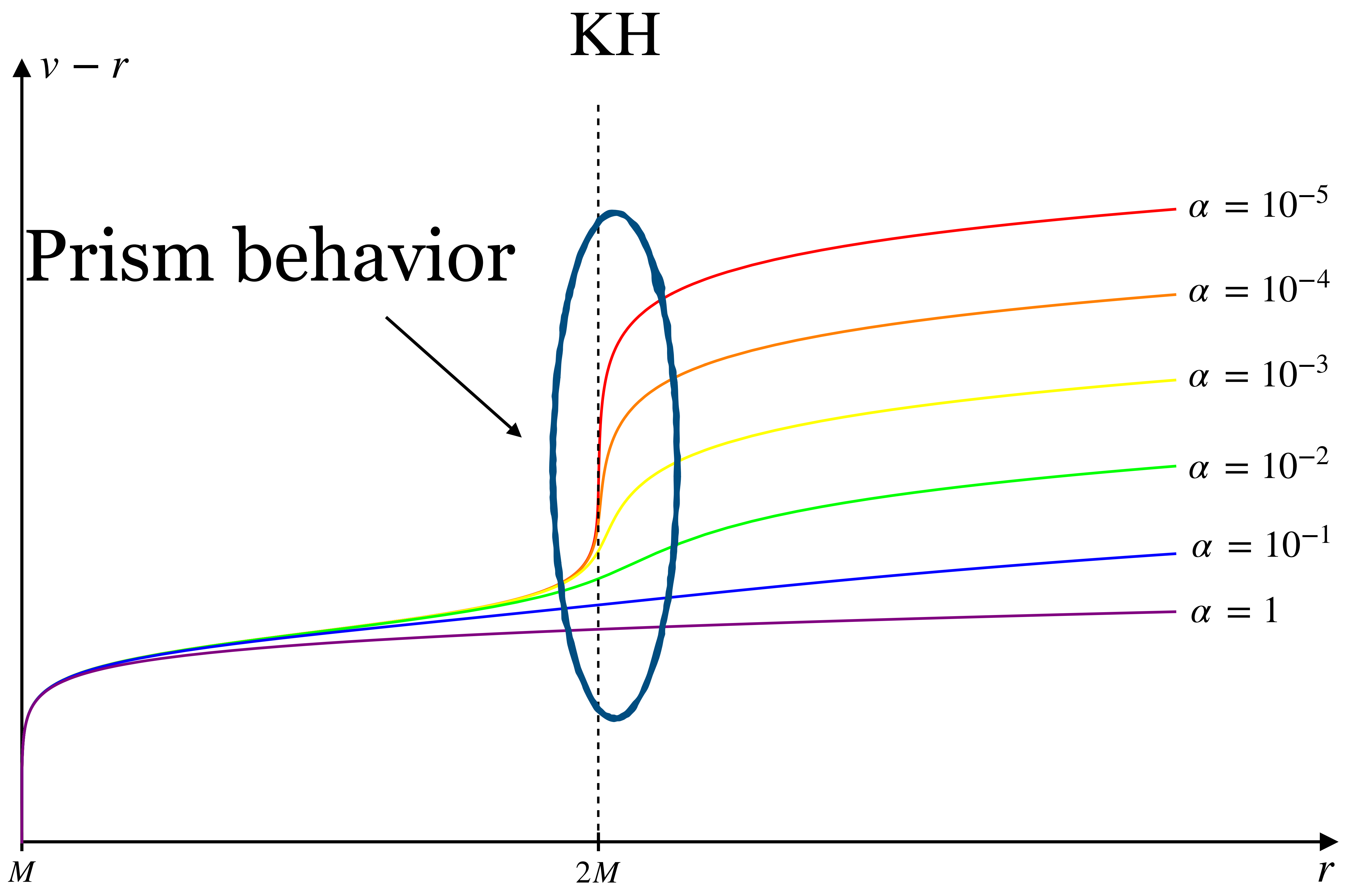
$$T_{\text{UH}} = \frac{(a \cdot \chi)}{2\pi} = \frac{\kappa_{\text{UH}}}{\pi}$$



Propagation

The emission at the UH is insensitive to Λ. However we expect something to happen when $\Lambda \to \infty$

The rays for which $\underline{\alpha = \Omega/\Lambda \ll 1}$ linger at the KH for long time



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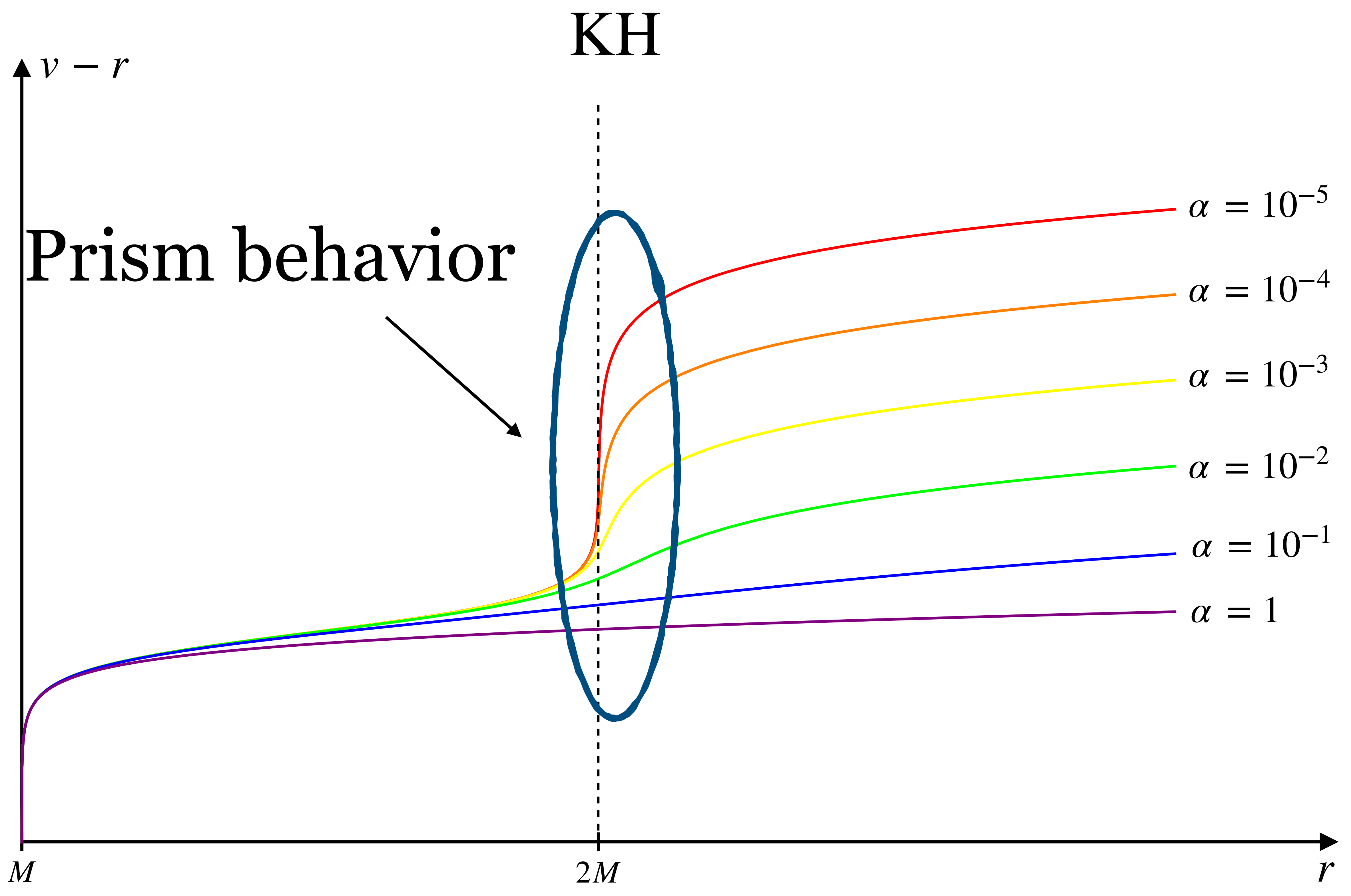
$$T(\alpha) = \frac{\kappa_{\mathrm{KH}}}{2\pi}(1 + 3\alpha^2) + \cdots$$



Predicting the landscape with AS

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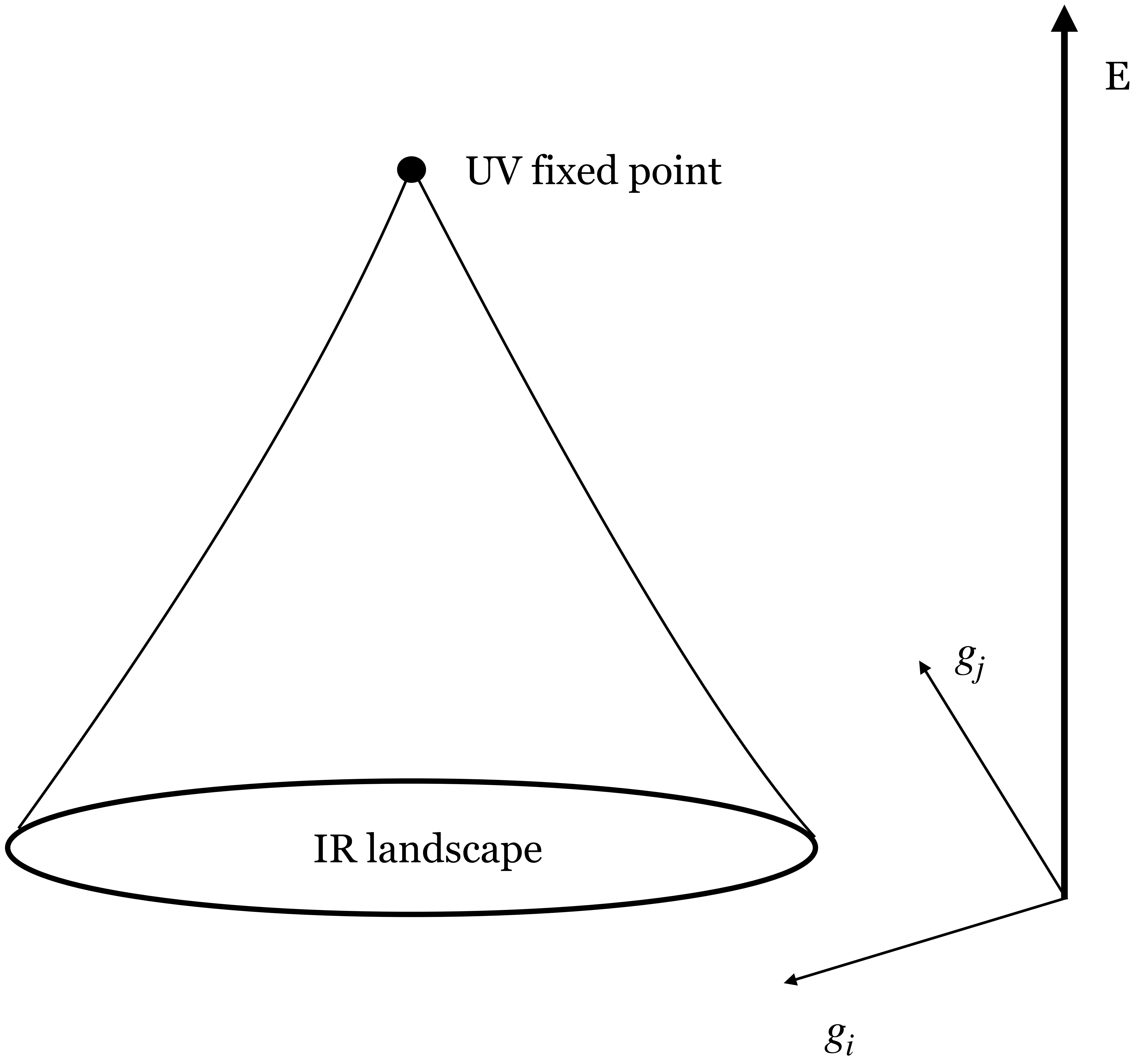
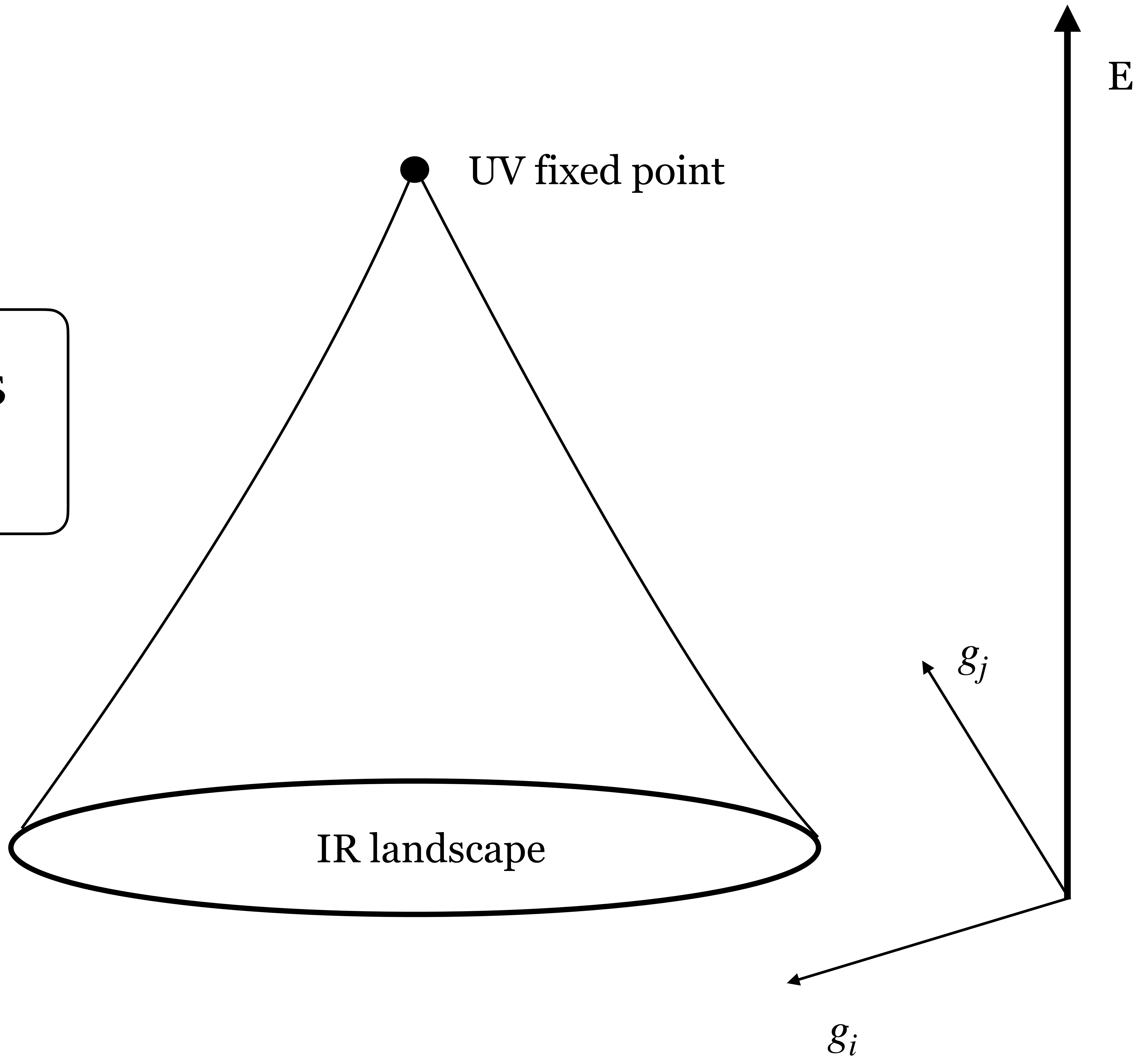
Predicting the landscape with AS



Predicting the landscape with AS

Q: what can this teach us about BHs?



Example 1: BH in Einstein-Weyl

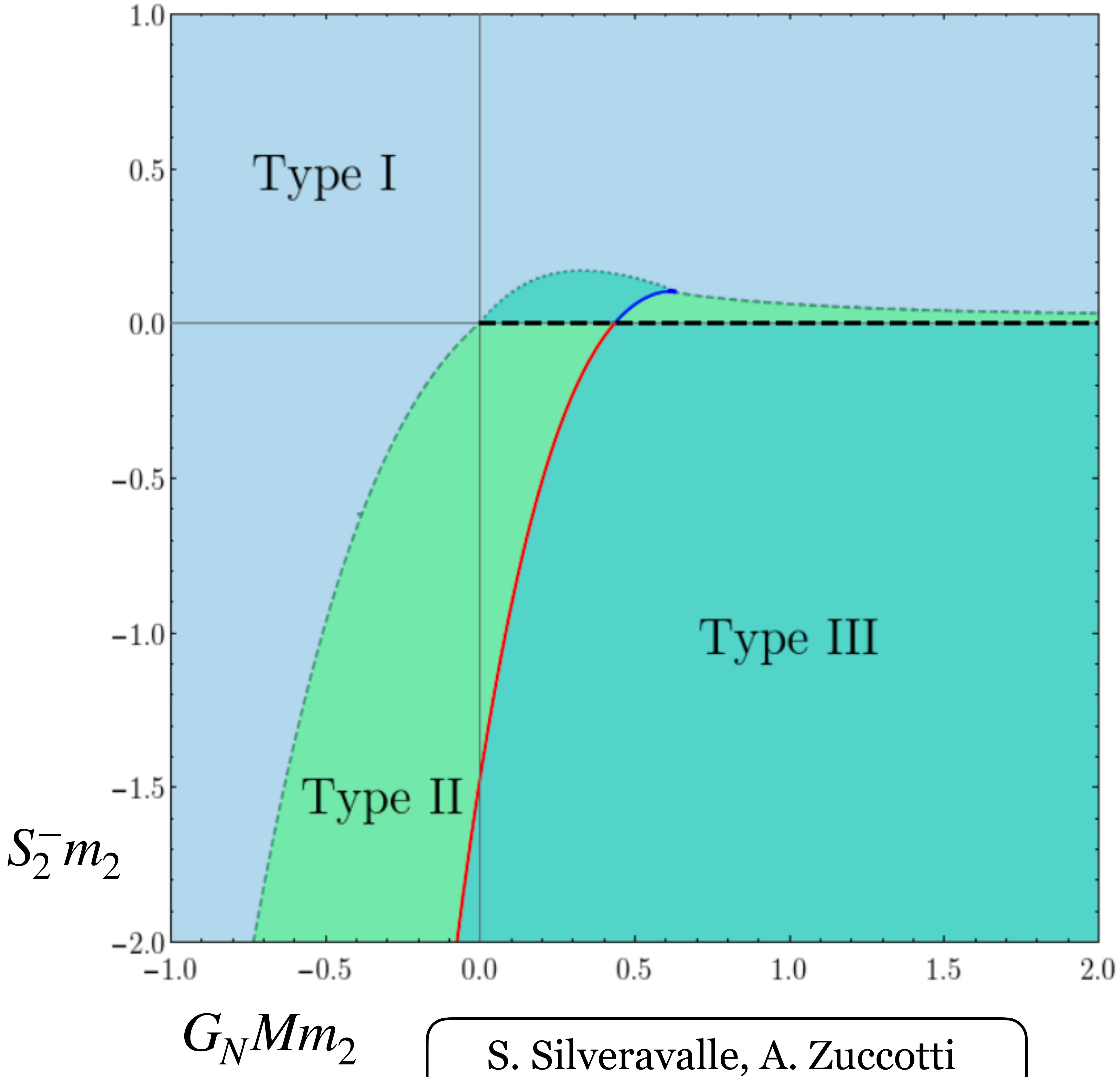
$$S_{\rm EW} = \frac{1}{16\pi G_N}\int \sqrt{-g}\left[R - \frac{\alpha}{2} C_{abcd}C^{abcd}\right]$$

$$\mathrm{d}s^2 = -h(r)\,\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{f(r)} + r^2\mathrm{d}\Omega_2 \qquad m_2 = \alpha^{-1/2}$$

Asymptotically:

$$h(r) \simeq 1 - \frac{2G_N M}{r} + 2S_2^- \frac{\mathrm{e}^{-m_2 r}}{r}$$

$$f(r) \simeq 1 - \frac{2G_N M}{r} + S_2^- \frac{\mathrm{e}^{-m_2 r}}{r}\left(1 + m_2 r\right)$$



S. Silveravalle, A. Zuccotti
ArXiv: **2210.13877**

Example 1: BH in Einstein-Weyl

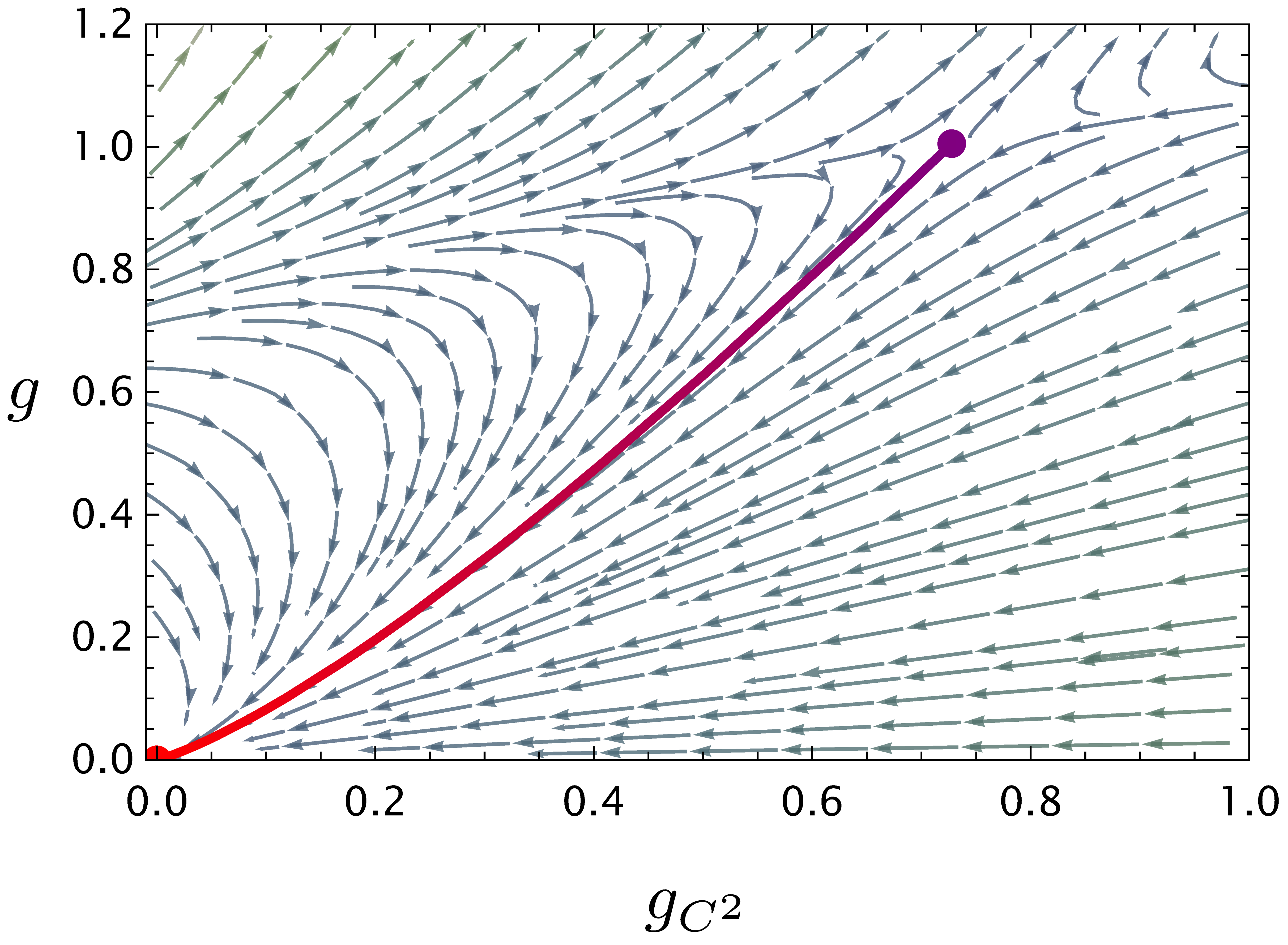
$$S_{\mathrm{EW}} = \frac{1}{16\pi G_N}\int\sqrt{-g}\left[R - \frac{\alpha}{2}C_{abcd}C^{abcd}\right]$$

EW has an UV fixed point. We can give a prediction

B. Knorr
ArXiv: **2104.11336**

$$g_{C^2}(k) = \alpha(k)\,k^2 \qquad g(k) = G_N(k)\,k^2$$

$$\lim_{k\to 0}\frac{g_{C^2}(k)}{g(k)} = \lim_{k\to 0}\frac{\alpha(k)}{G_N(k)} = \frac{M_p^2}{m_2^2}$$



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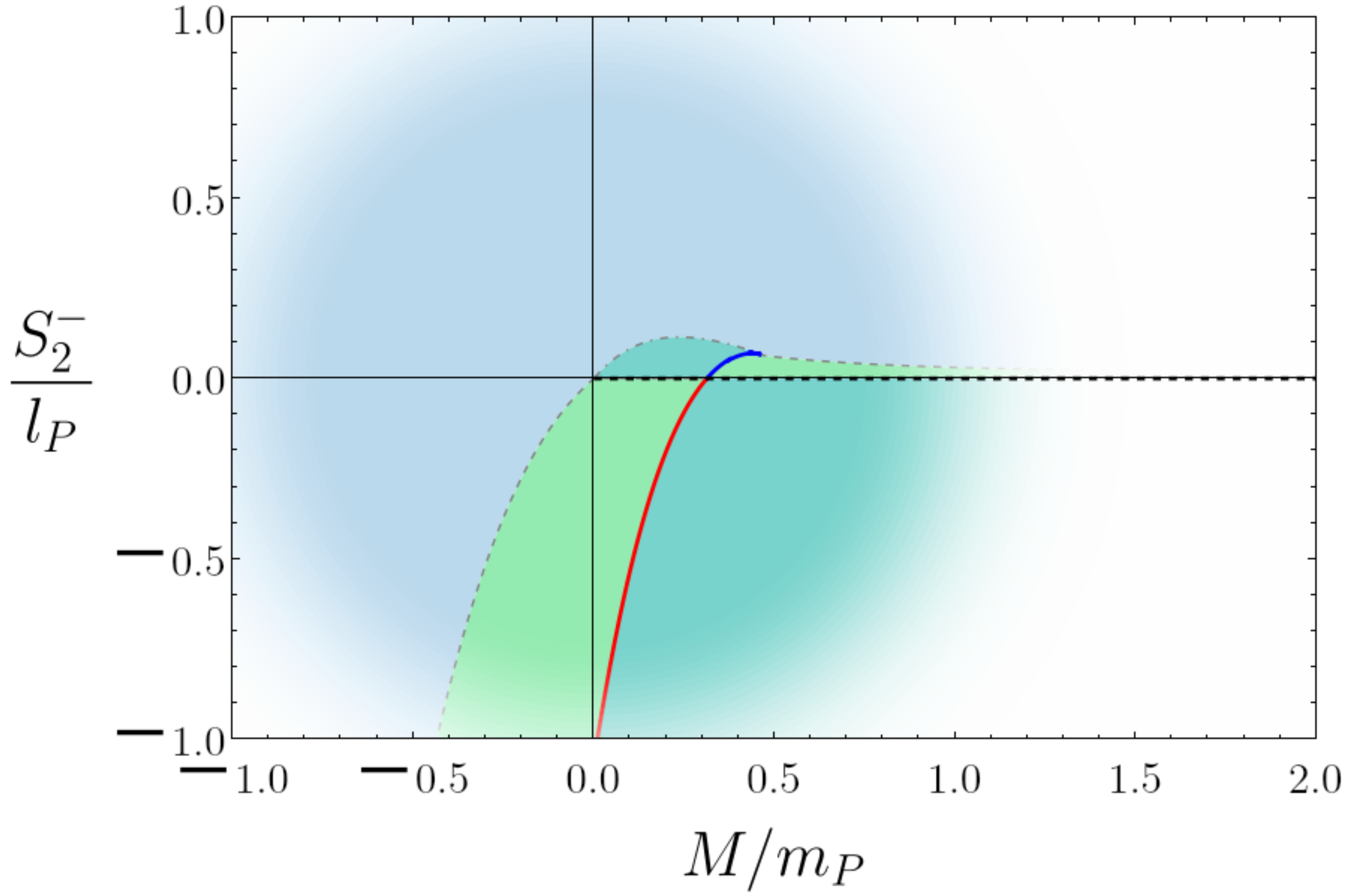
$$m_2^2 \simeq 1.96\, M_p^2$$

For more details → Jonas' Poster!
(work in progress)



Example 2: UV sensitivity of EBH

Extremal Kerr black holes as amplifiers of new physics

Gary T. Horowitz,[1] Maciej Kolanowski,[2] Grant N. Remmen,[1,3] and Jorge E. Santos[4]

[1] *Department of Physics, University of California, Santa Barbara, CA 93106, U.S.A.*
[2] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[3] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, U.S.A.*
[4] *Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK*

We show that extremal Kerr black holes are sensitive probes of new physics. Stringy or quantum corrections to general relativity are expected to generate higher-curvature terms in the gravitational action. We show that in the presence of these terms, asymptotically flat extremal rotating black holes have curvature singularities on their horizon. Furthermore, near-extremal black holes can have large yet finite tidal forces for infalling observers. In addition, we consider five-dimensional extremal charged black holes and show that higher-curvature terms can have a large effect on the horizon geometry.

$$\mathscr{L} = \frac{1}{2\kappa^2}\left[R + \eta\kappa^4\mathscr{R}^3 + \lambda\kappa^6\mathscr{C}^2 + \tilde{\lambda}\kappa^6\tilde{\mathscr{C}}^2\right]$$

$$\delta g_{ab}^{\mathrm{EBH}}(x) \sim (x - x_{\mathrm{H}})^{\gamma}$$

$$g_{ab} = g_{ab}^{(0)} + \eta h_{ab}^{(6)} + \lambda h_{ab}^{(8)} + \tilde{\lambda}\tilde{h}_{ab}^{(8)}$$

$$\gamma = 2 + \eta\gamma^{(6)} + \lambda\gamma^{(8)} + \tilde{\lambda}\tilde{\gamma}^{(8)}$$

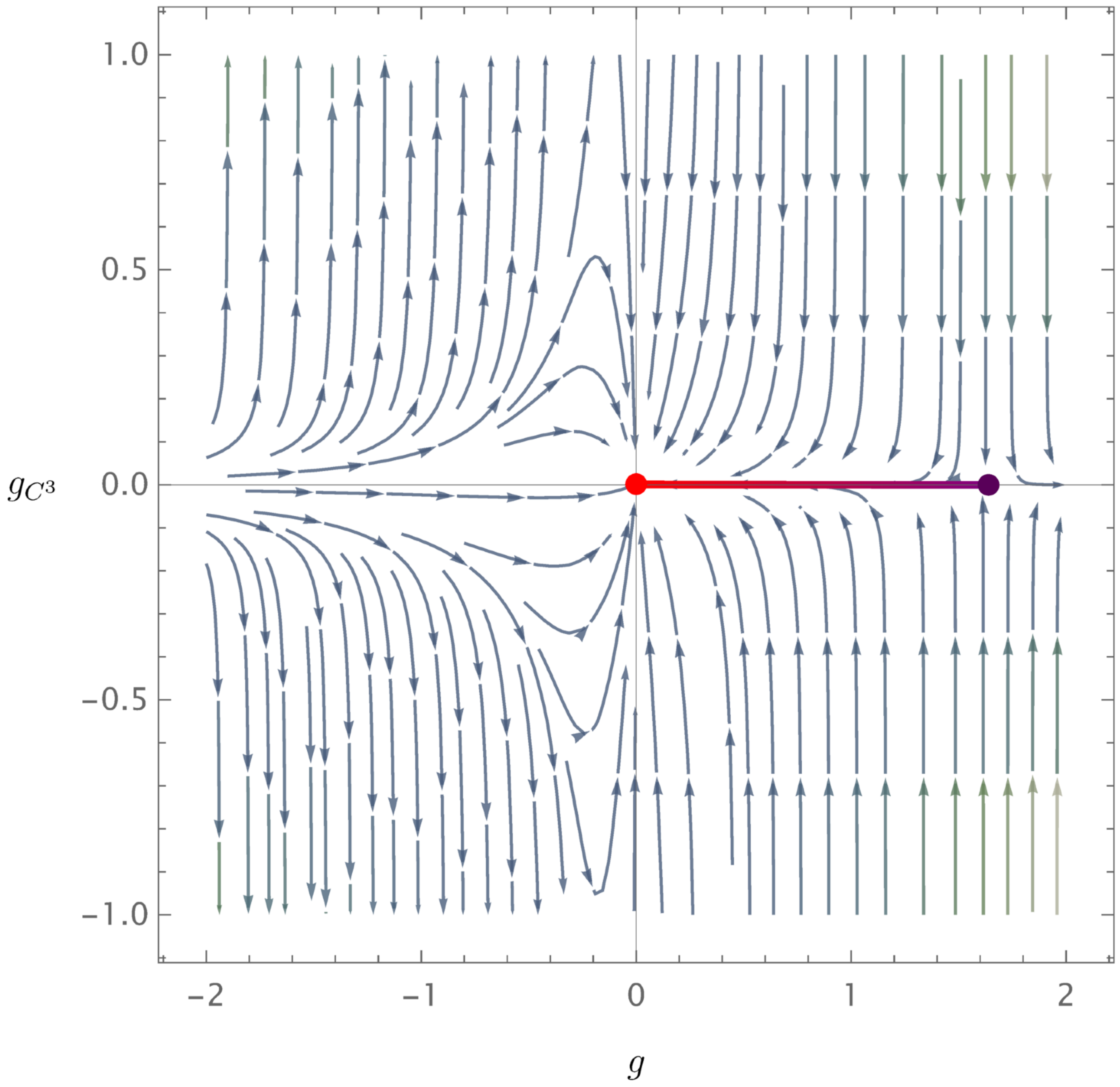
Example 2: UV sensitivity of EBH

Eight derivatives are complicated… But for six derivatives we can say something

$$\mathscr{L} = \frac{1}{2\kappa^2}\left[R + \eta\kappa^4\mathscr{R}^3\right]$$

And again we have

$$\lim_{k\to 0}\frac{g_{C^3}(k)}{g(k)} = \eta_{\mathrm{IR}}$$



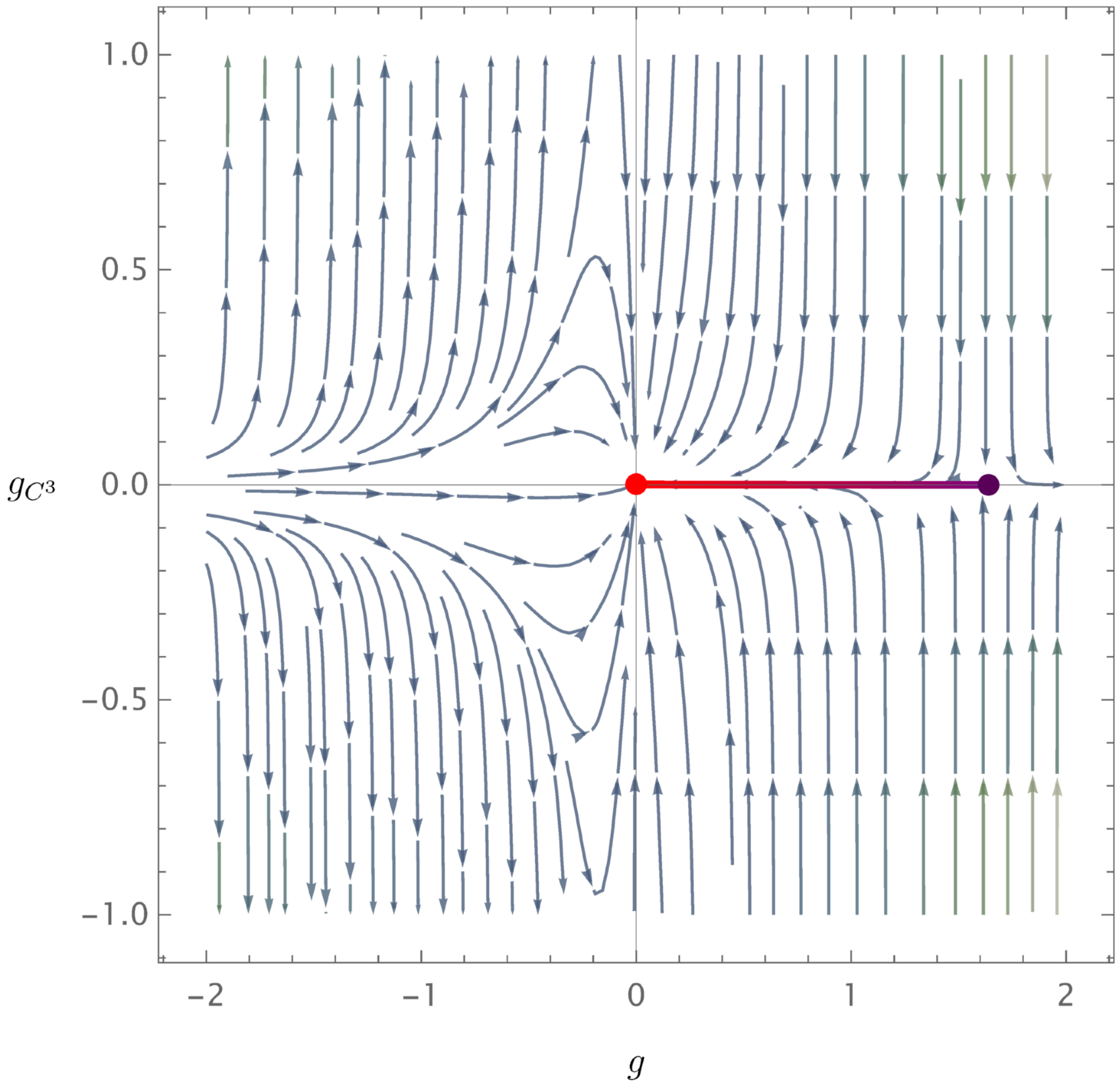
A. Baldazzi, K. Falls, Y. Kluth, B.Knorr
ArXiv: **2312.03831**

Example 2: UV sensitivity of EBH

In this case, AS predicts no UV sensitivity of EBH:

$\eta_{\text{IR}} \simeq 9.4 \times 10^{-3} > 0$ $\quad$ $\gamma = 2 + \eta_{\text{IR}}\gamma^{(6)} > 2$

For more details → Francesco's Poster!
(work in progress)



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- In the case of Asymptotic Safety: the constraint of UV completeness impacts the landscape, solving possible puzzles

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Thank you!