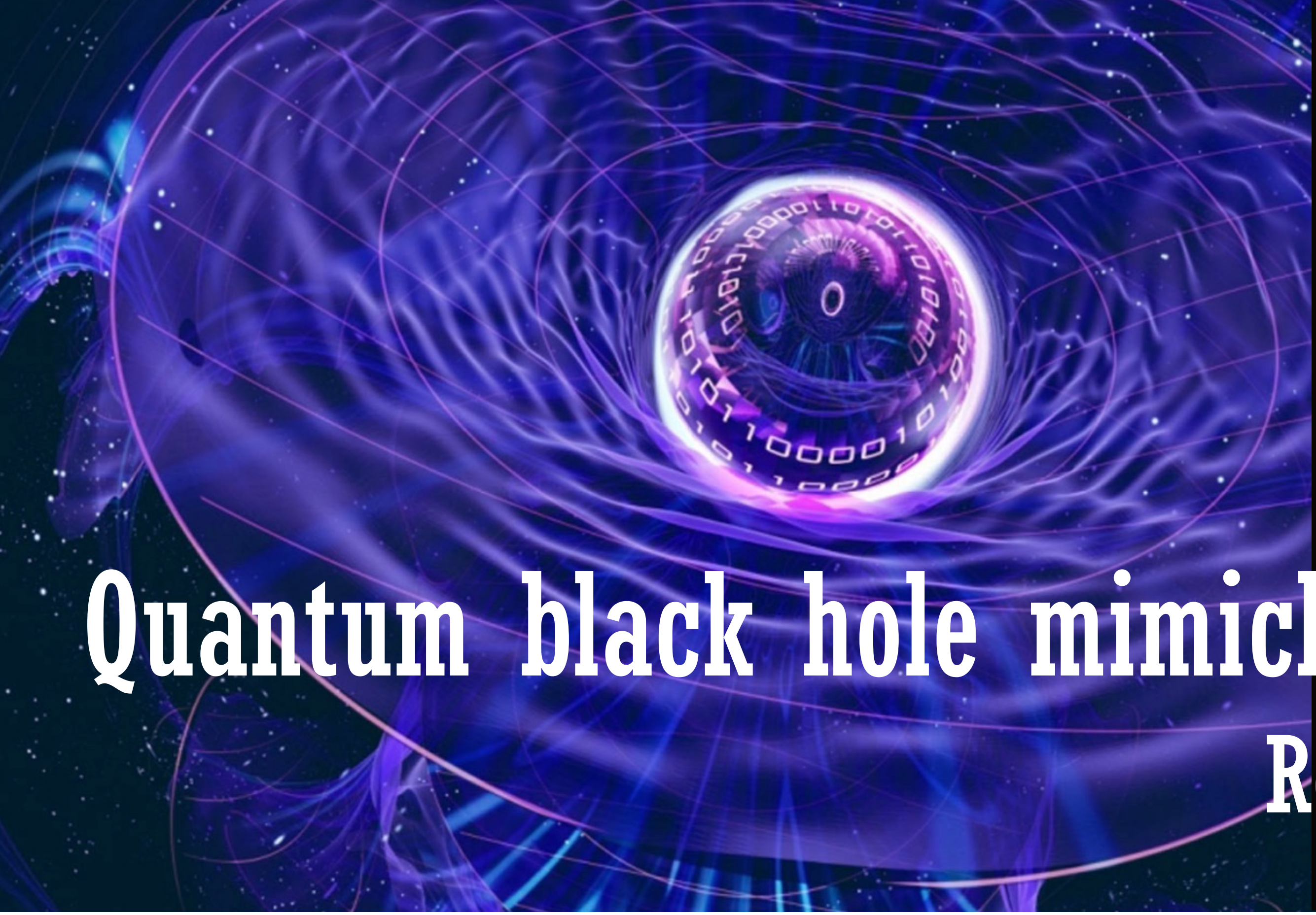


Quantum black hole mimicker:

Redshift plays the role

Che-Yu Chen

iTHEMS (SPDR), RIKEN, JAPAN

- **CYC**, Yuki Yokokura 2403.09388 PRD
- **CYC**, Naritaka Oshita, Yuki Yokokura 25xx.xxxxx

iTHEMS-NCTS 2025 Aug. 18

RIKEN's Programs for Junior Scientists

iTHEMS RIKEN Center for Interdisciplinary Theoretical and Mathematical Sciences

Image features of classical BHs:

- Bright ring
  - Highly lensed images on top of direct emission
  - Spherical photon orbits around the BH (photon sphere)

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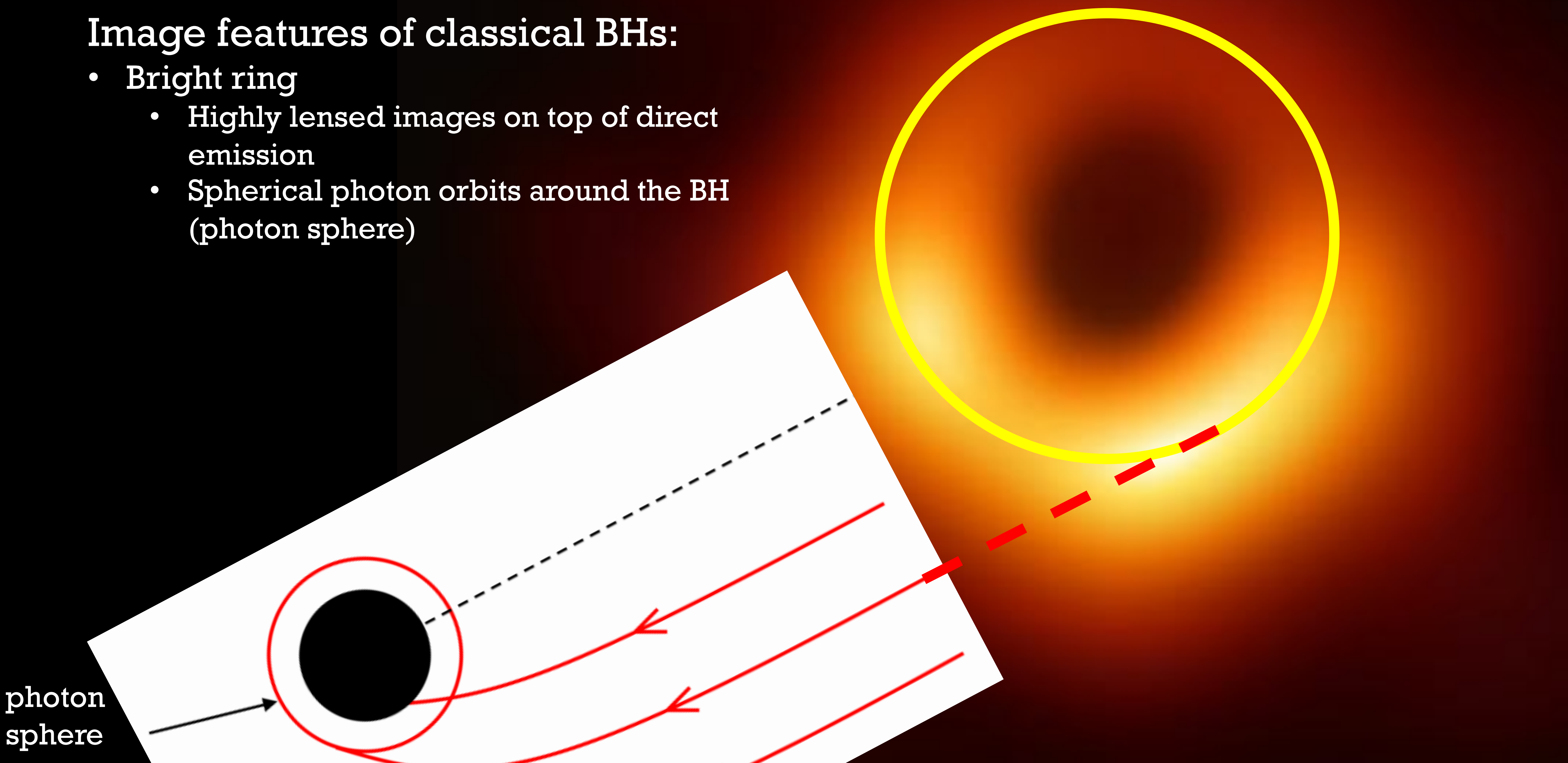

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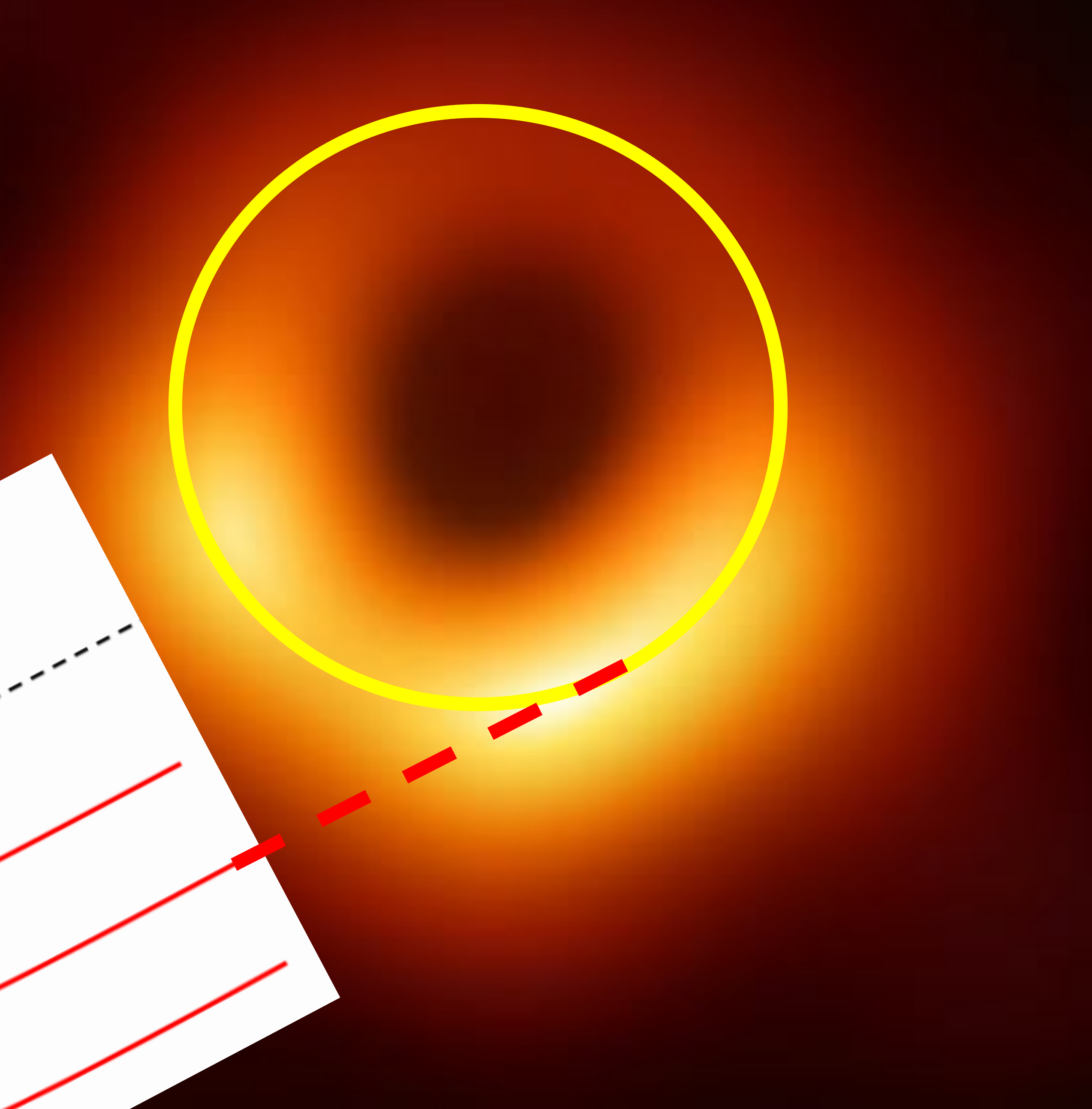
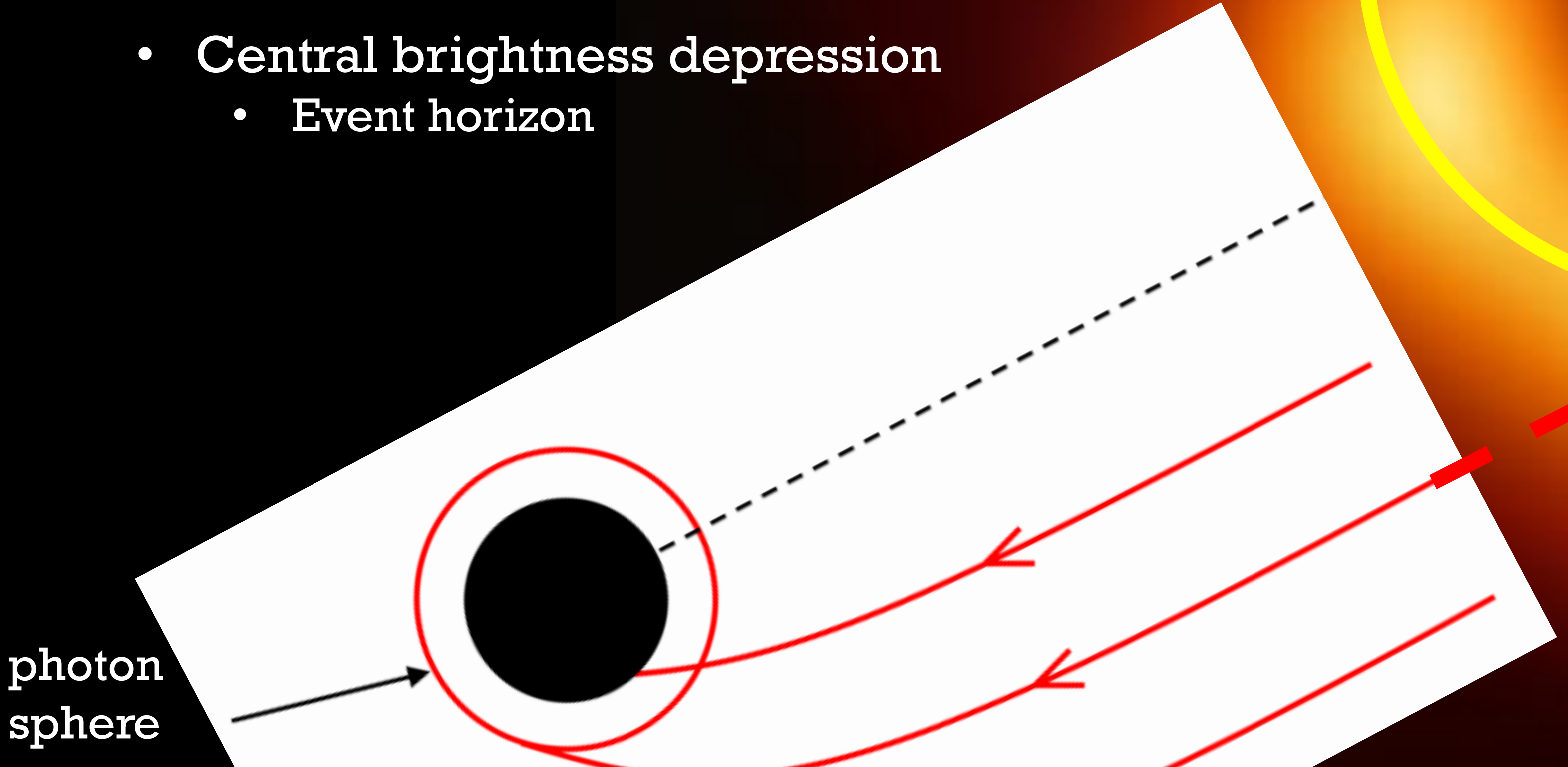
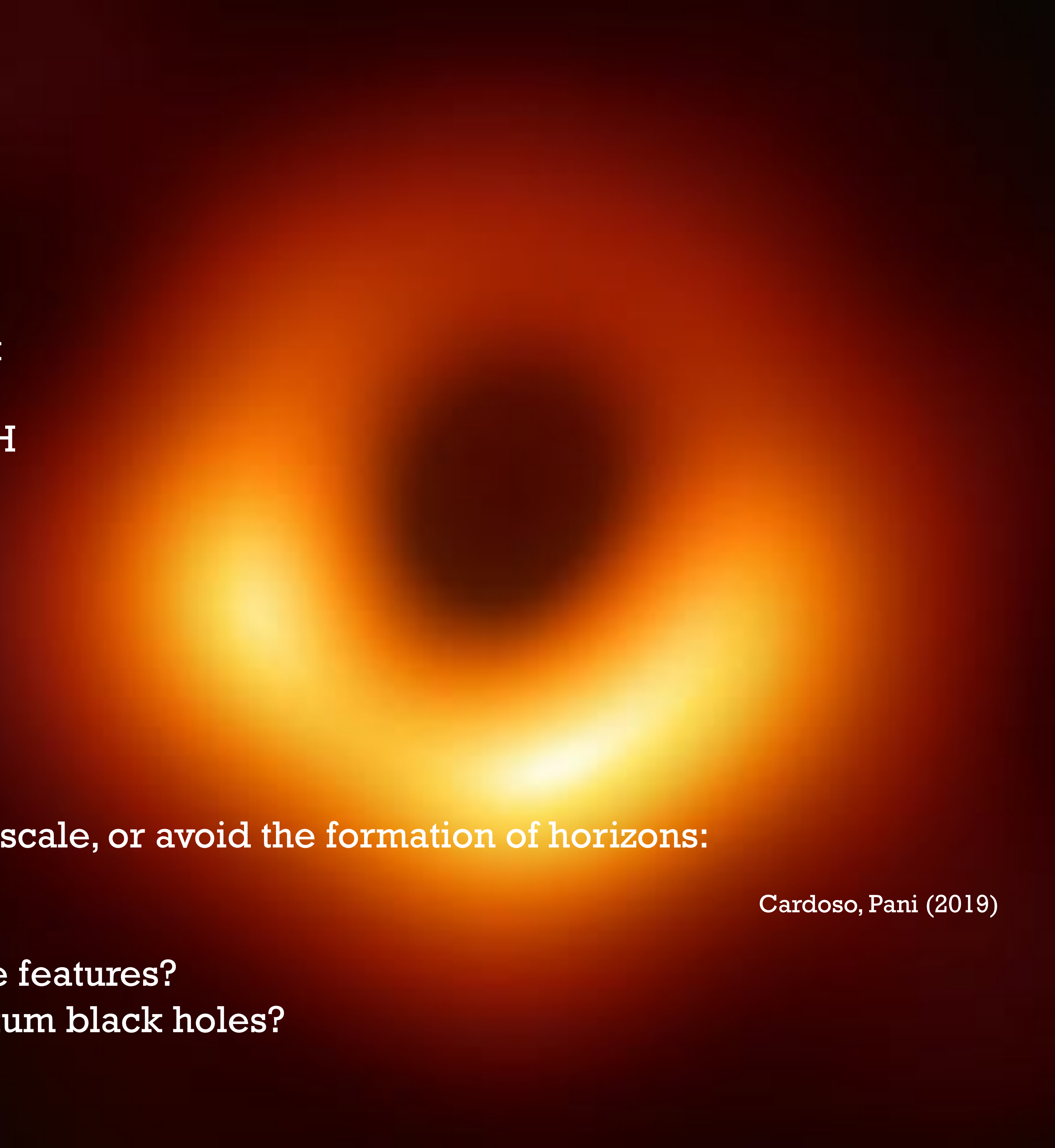
    - Event horizon







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Quantum effects may have horizon-scale, or avoid the formation of horizons:
<u>Horizonless compact object (HCO)</u>

Cardoso, Pani (2019)

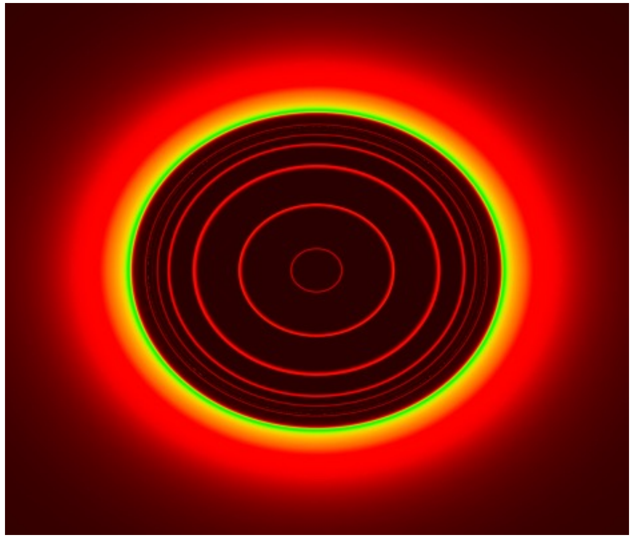
Can such objects cast similar image features?
If so, can it be a candidate for quantum black holes?

Image features of HCO

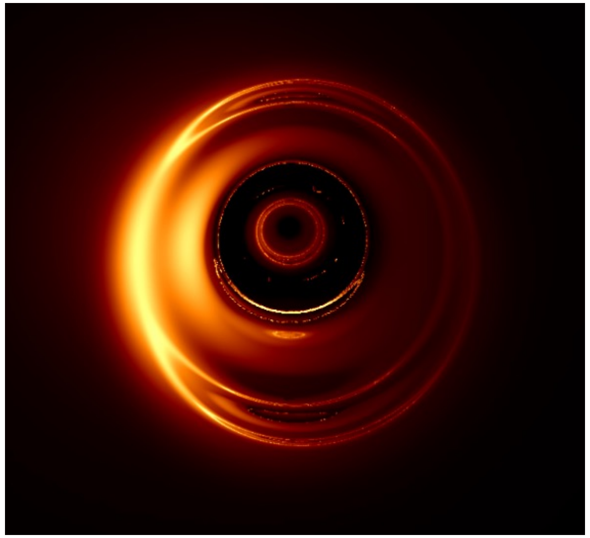
- Bright ring can appear if there is unstable photon sphere

- Additional inner rings
  - Reflection at the surface, internal propagation …

Ohgami, Sakai (2015), Shaikh et al. (2019), Vincent et al. (2021), Wielgus et al. (2020)
Cunha et al. (2017), Rosa (2023) Mayerson, Vercnocke (2023), Shaikh et al. (2019)



Olmo et al. (2023)



Mayerson, Vercnocke (2023)

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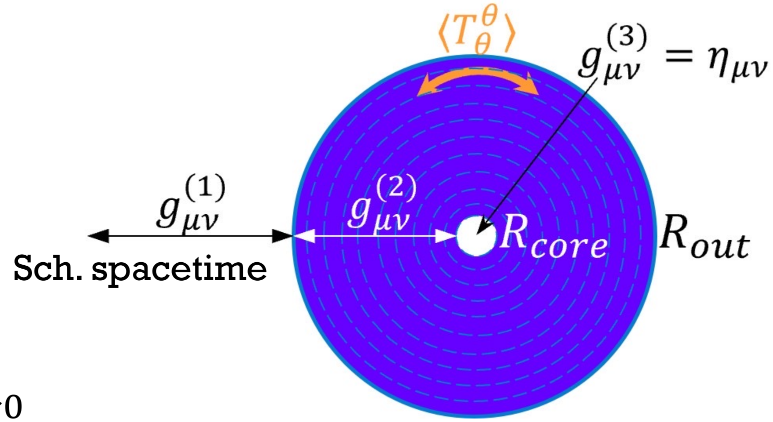
- Two darkening effects may happen inside!!
  - Interaction between light rays and internal quantum structure

    theory-dependent, challenging

  - Delayed by strong redshifts

    depends only on metric, crucial role in darkening images

Quantum Horizonless Compact Object



- A HCO characterized by strong redshift inside

- Exterior (1):

$$g^{(1)}_{\mu\nu} = -\left(1 - \frac{a_0}{r}\right) dt^2 + \left(1 - \frac{a_0}{r}\right)^{-1} dr^2 + r^2 d\Omega^2, \quad r \geq R_{out} > a_0$$

$$R_{out} \approx a_0 \left(1 + \frac{k}{2}\right)$$

- Interior dense region (2):

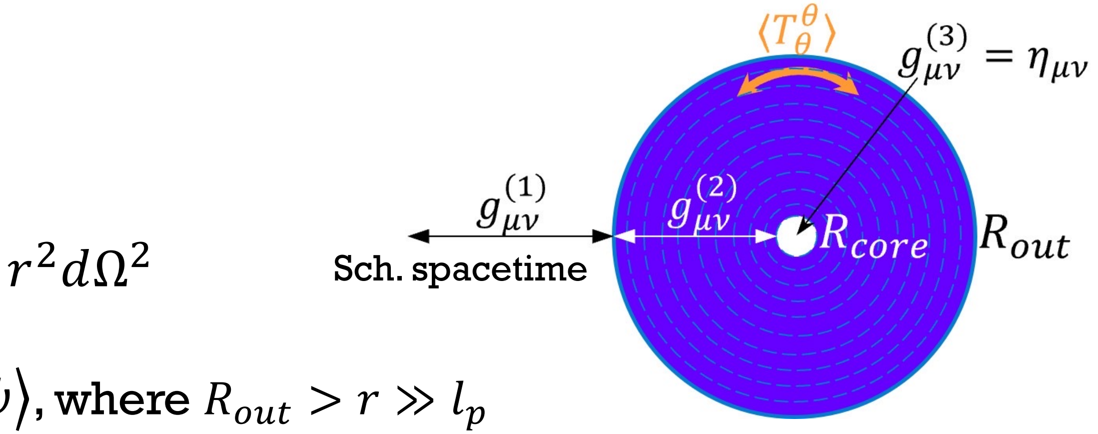
$$g^{(2)}_{\mu\nu} \approx -\frac{k a_0^2}{2r^2} e^{\frac{\eta(r^2 - R_{out}^2)}{2k a_0^2}} dt^2 + \frac{\eta^2 r^2}{2k a_0^2} dr^2 + r^2 d\Omega^2, \quad R_{core} < r < R_{out}$$

Kawai, Matsuo, Yokokura (2013), Kawai, Yokokura (2014)(2015)(2017)(2020)(2021), Yokokura (2022)(2023)

- Central core (3): $g^{(3)}_{\mu\nu} \approx \eta_{\mu\nu}, \quad r < R_{core}$
    - A unified description of regions (2) and (3) has recently proposed

Livine, Yokokura (2025)

Quantum Horizonless Compact Object



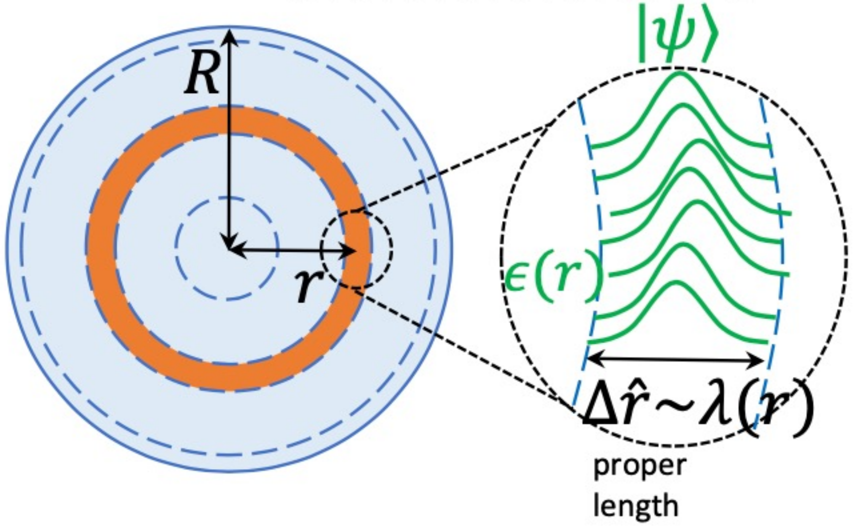
- Interior dense region:

$$g^{(2)}_{\mu\nu} \approx -\frac{ka_0^2}{2r^2} e^{\frac{\eta(r^2-R_{out}^2)}{2ka_0^2}} dt^2 + \frac{\eta^2 r^2}{2ka_0^2} dr^2 + r^2 d\Omega^2$$

- Satisfy semi-classical Einstein eq. $G_{\mu\nu} = 8\pi G \langle \psi | T_{\mu\nu} | \psi \rangle$, where $R_{out} > r \gg l_p$
- Non-perturbative solution in $\hbar$
  - e.g. conformal matter field → Trace anomaly → $R \sim n l_p^2 R^2$ → Non-perturbative branch
  - $k \approx n l_p^2 / a_0^2$ with $n \gg 1$ (semi-classical)
  - $1 \leq \eta < 2$ effectively quantifies internal interactions
- Large tangential pressure
  - Highly anisotropic → extreme compactness

Kawai, Yokokura (2020)

QHCO v.s. classical BH



- Interior dense region:

$$g_{\mu\nu}^{(2)} \approx -\frac{ka_0^2}{2r^2} e^{\frac{\eta(r^2-R_{out}^2)}{2ka_0^2}} dt^2 + \frac{\eta^2 r^2}{2ka_0^2} dr^2 + r^2 d\Omega^2$$

- Maximized entropy configuration

Yokokura (2022)(2023)

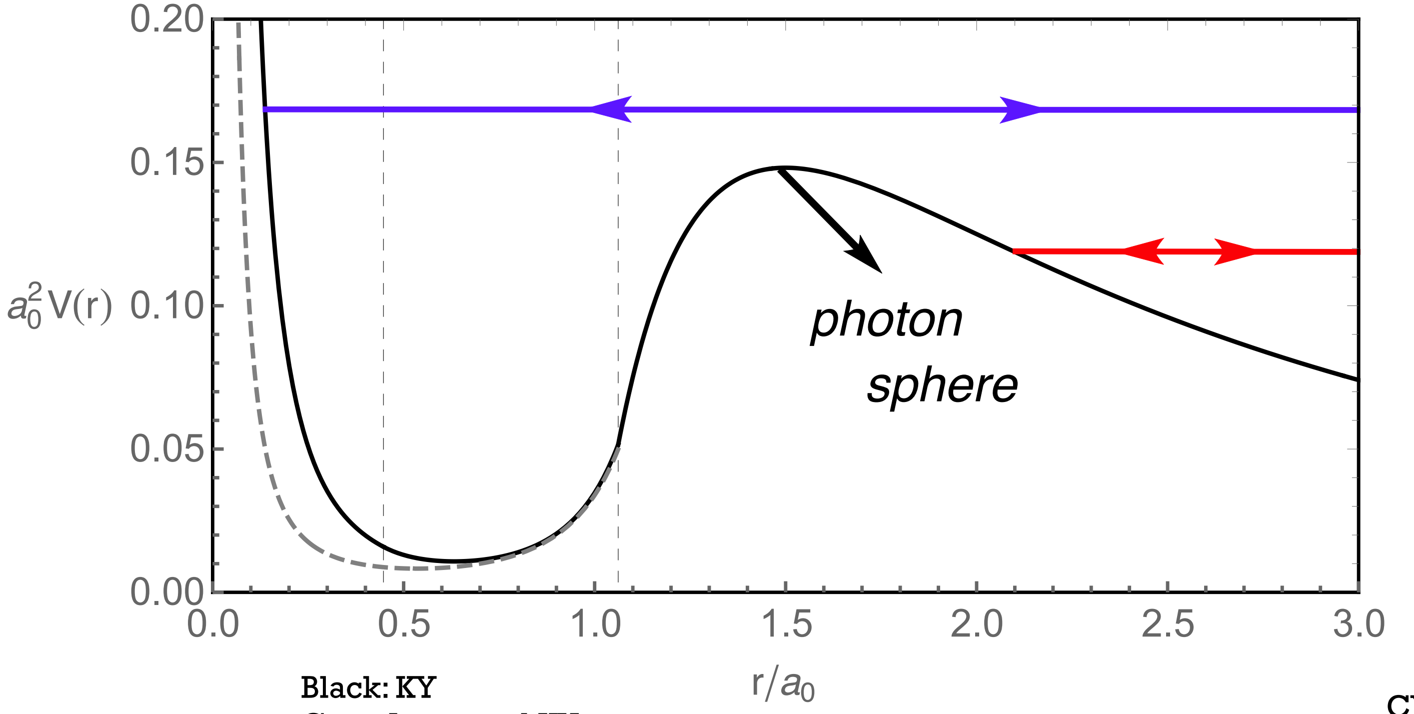
- Saturation conditions of entropy bounds
  - Entropy saturation: fix $g_{rr}(r)$
  - Positive pressure & $O(r^0)$-curvature & Junction at R_{out}: fix $g_{tt}(r)$

- Exponentially strong redshift

- What does it look like?

Light rays trajectories

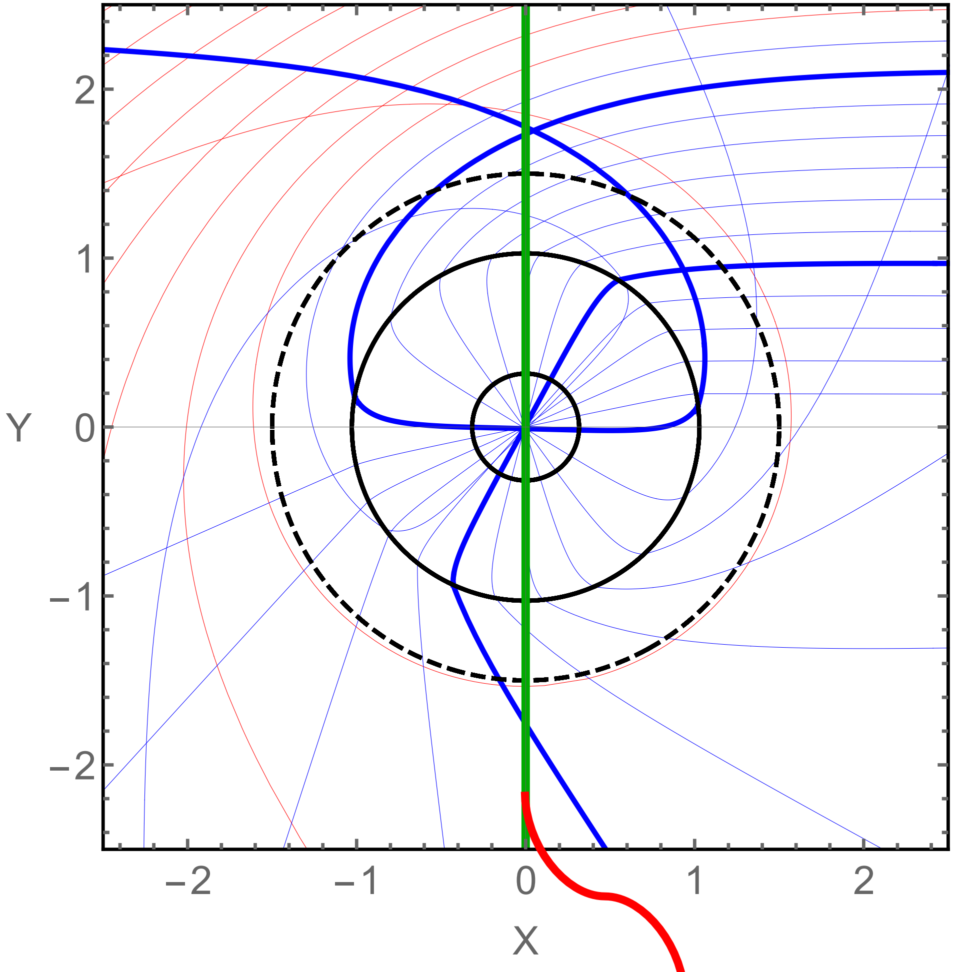
Effective potential: $$\frac{C_i(r)}{L^2}\left(\frac{dr}{d\lambda}\right)^2 + V(r) = \frac{1}{b^2}$$ $b = L/E$: impact parameter



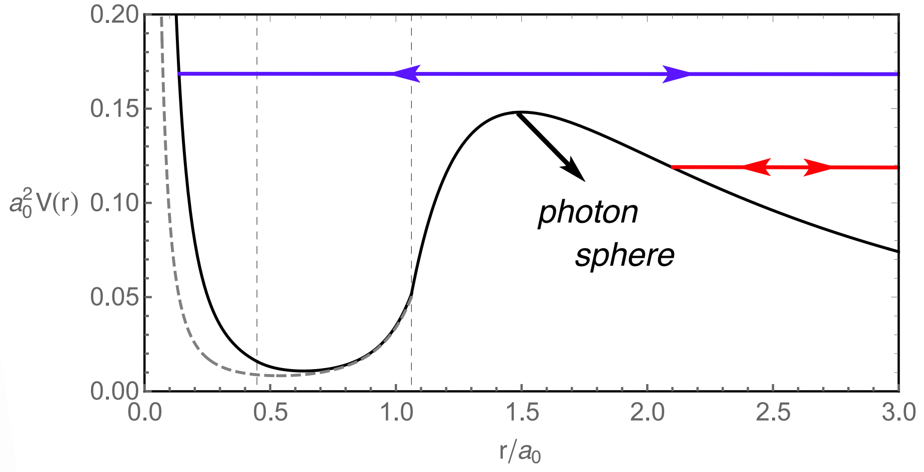
Black: KY
Gray: Improved KY

CYC, Yokokura (2024)

Modeling QHCO images



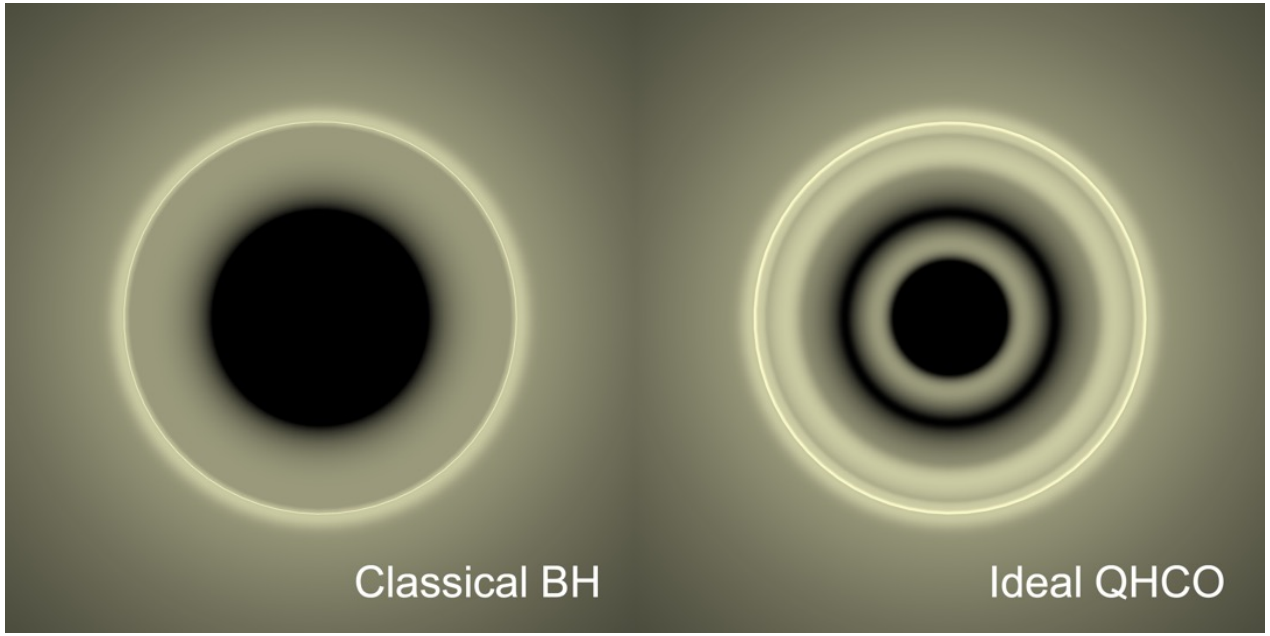
Geometrically thin, optically thin disk



1. Calculate trajectories, which are labeld by the impact parameter b
2. Identify the points where the trajectories cross the disk
3. Assume emission profile of the disk
4. For each trajectory, calculate the observed intensity $I_o(b)$

Ideal images

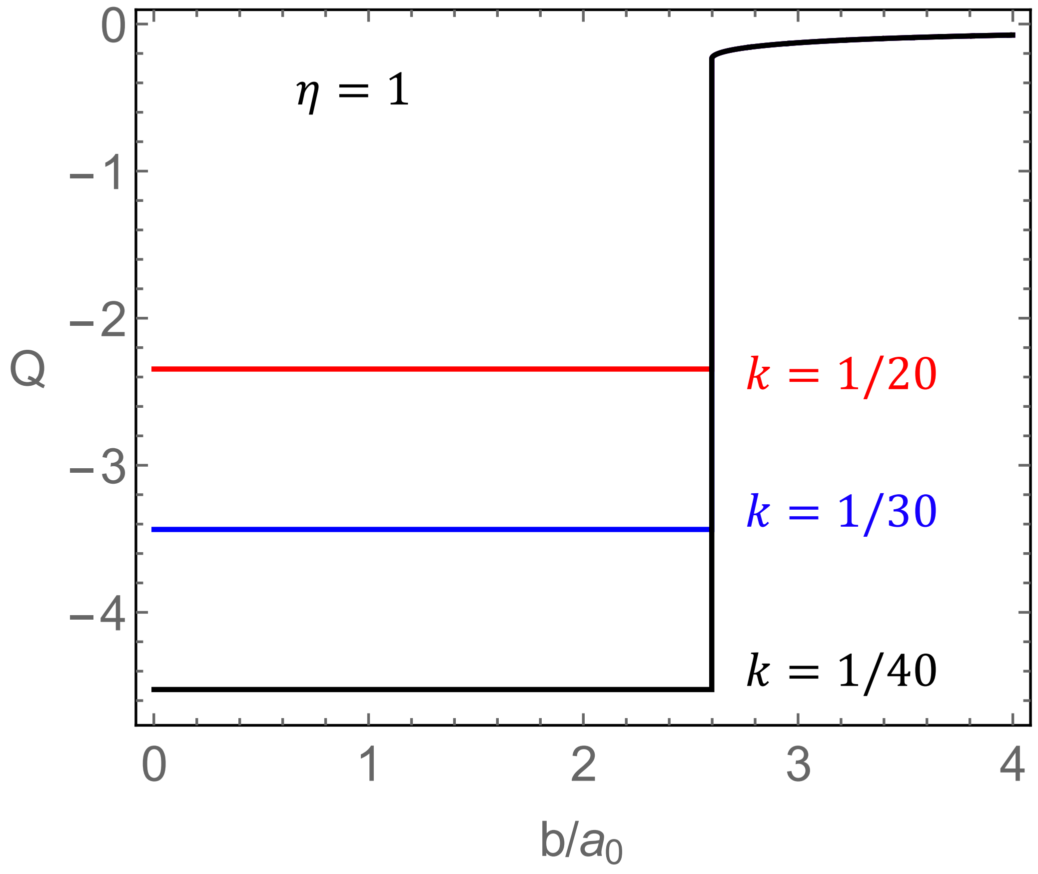
- Emission profile: emission down to the interior
- Assuming that the infalling light rays can be observed, no matter how much time they may take with respect to the observer



- Additional inner rings

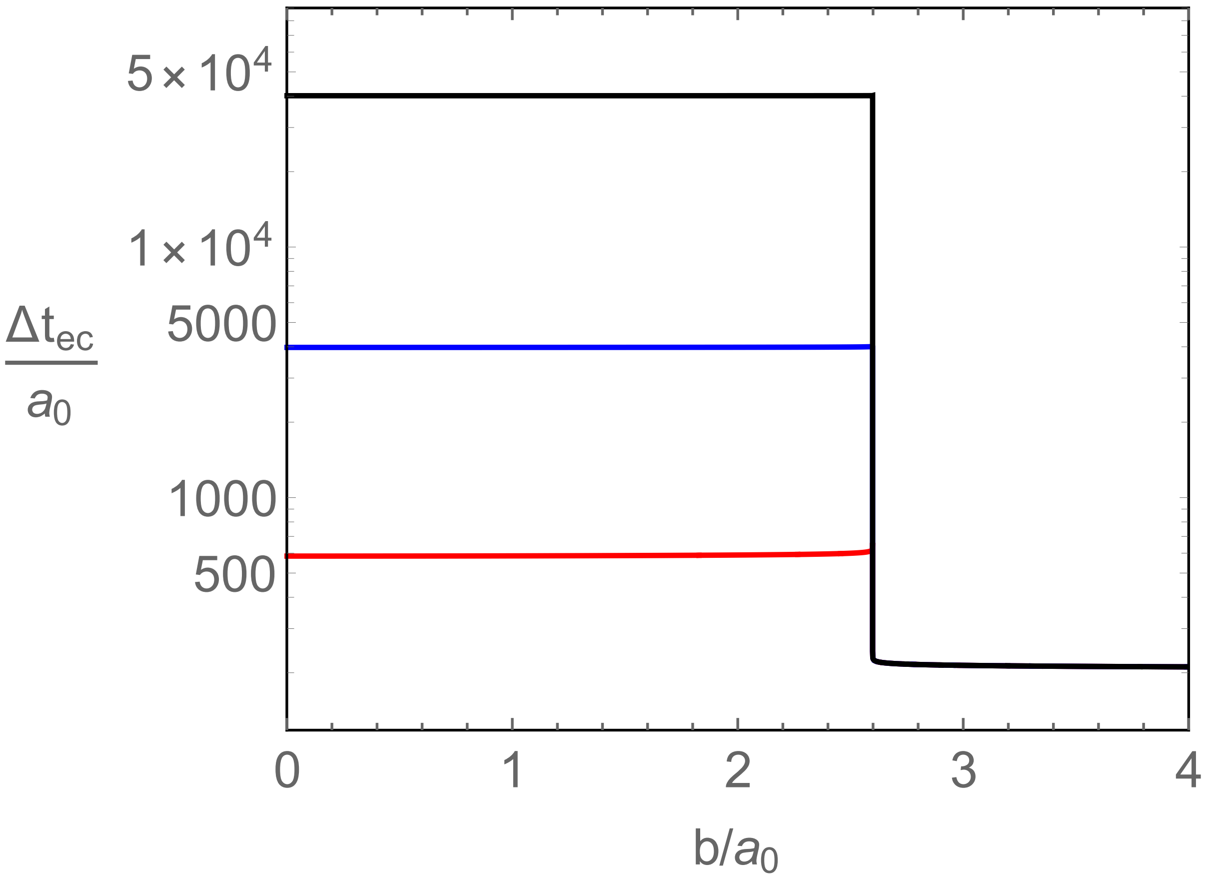
CYC, Yokokura (2024)

Strong redshift and propagation time



$Q \equiv \min[\log_{10}\sqrt{g_{tt}(\boldsymbol{x})/g_{tt}(\boldsymbol{x}_0)}]$

(maximized redshift inside)

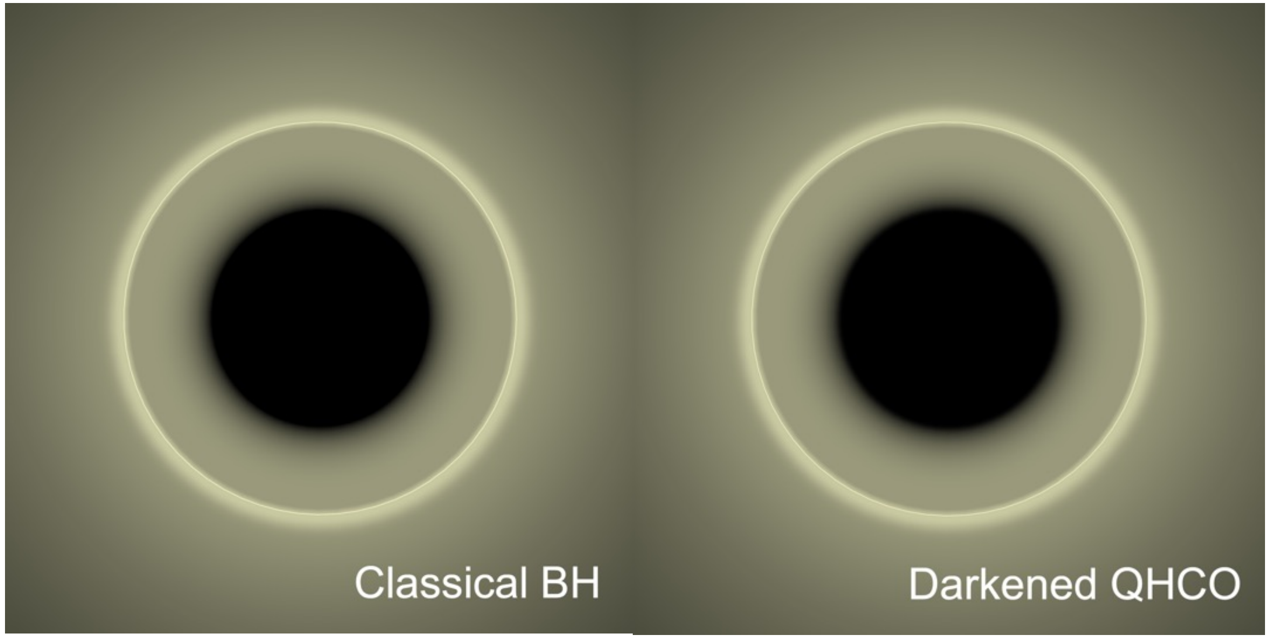


$\Delta t_{ec} \sim a_0 e^{\eta/4k}$: elapsed coordinate time

CYC, Yokokura (2024)

Darkened images

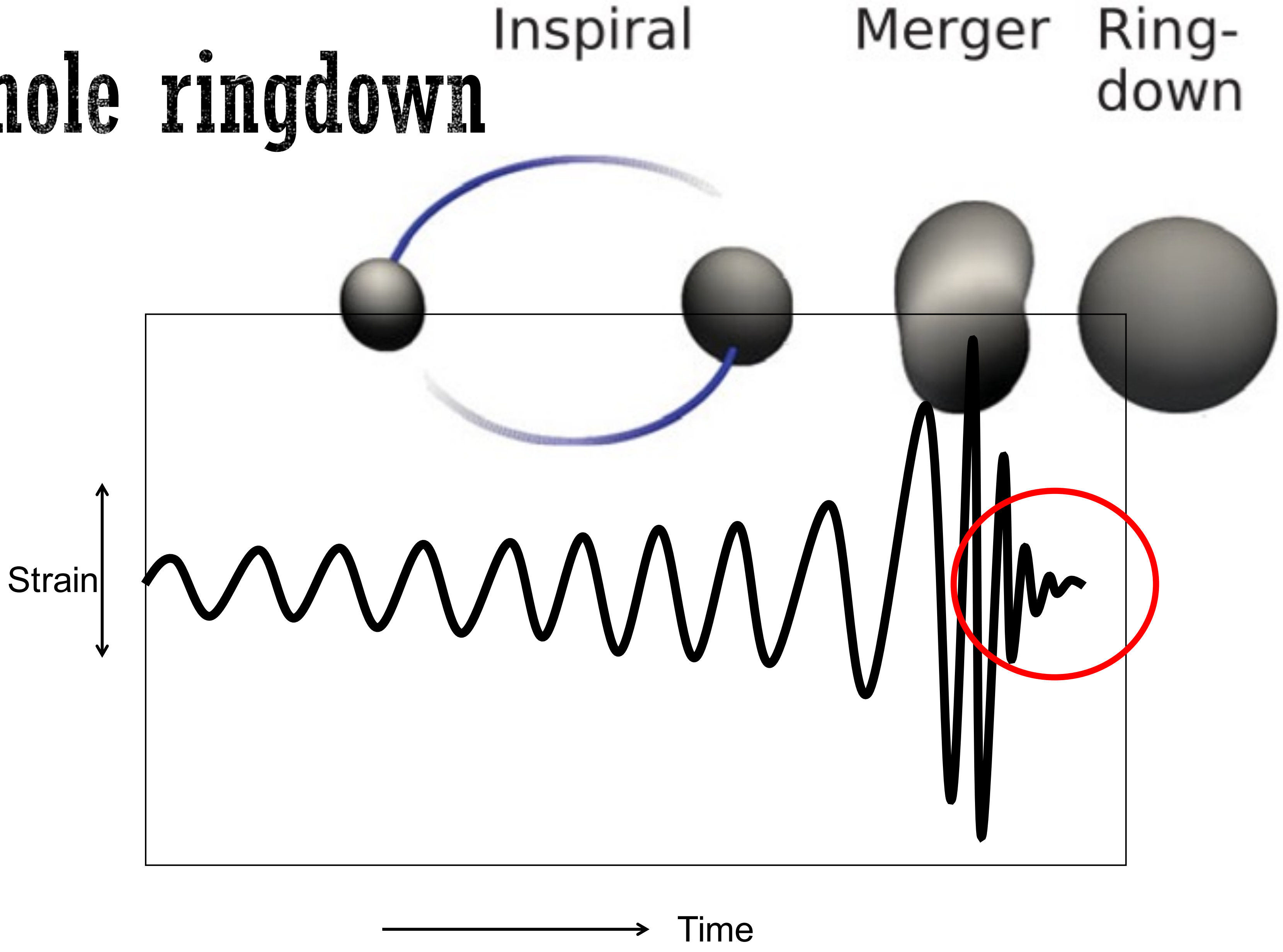
- Δt_{ec}: elapsed coordinate time. We have $\Delta t_{ec}/a_0 \sim e^{a_0^2/nl_p^2}$
- Consider only light rays with $\Delta t_{ec} \leq a_0^3/nl_p^2$ (evaporation timescale)



Perfect black hole mimickers!

CYC, Yokokura (2024)

Black hole ringdown



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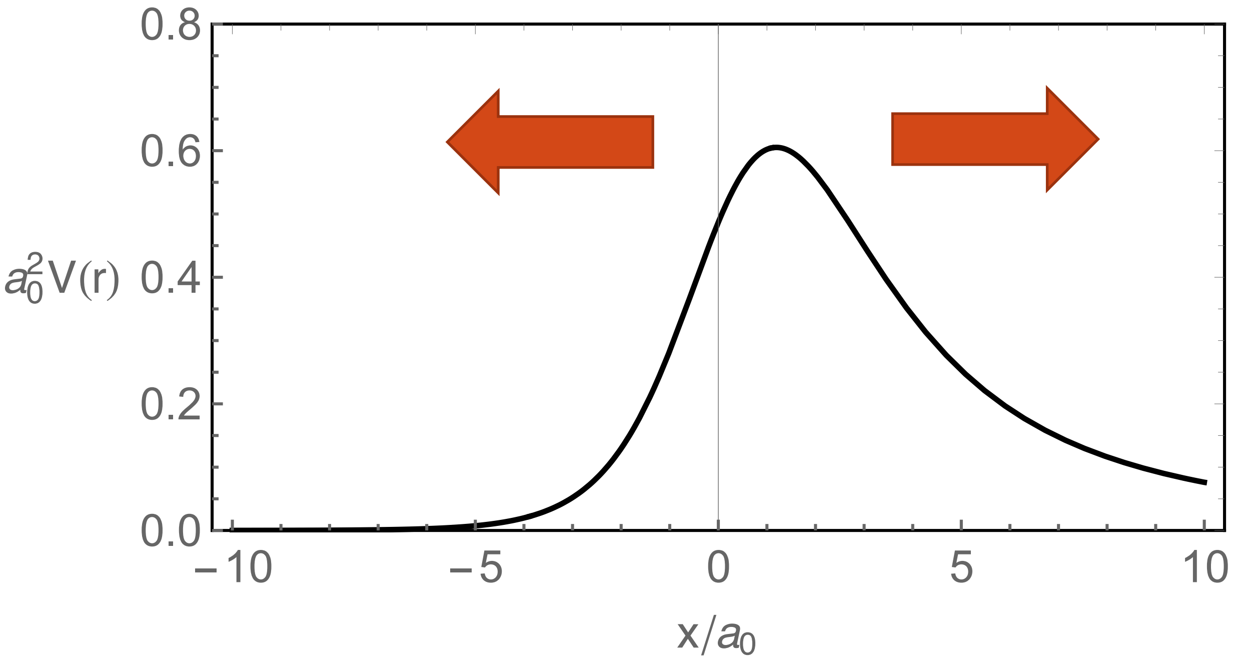
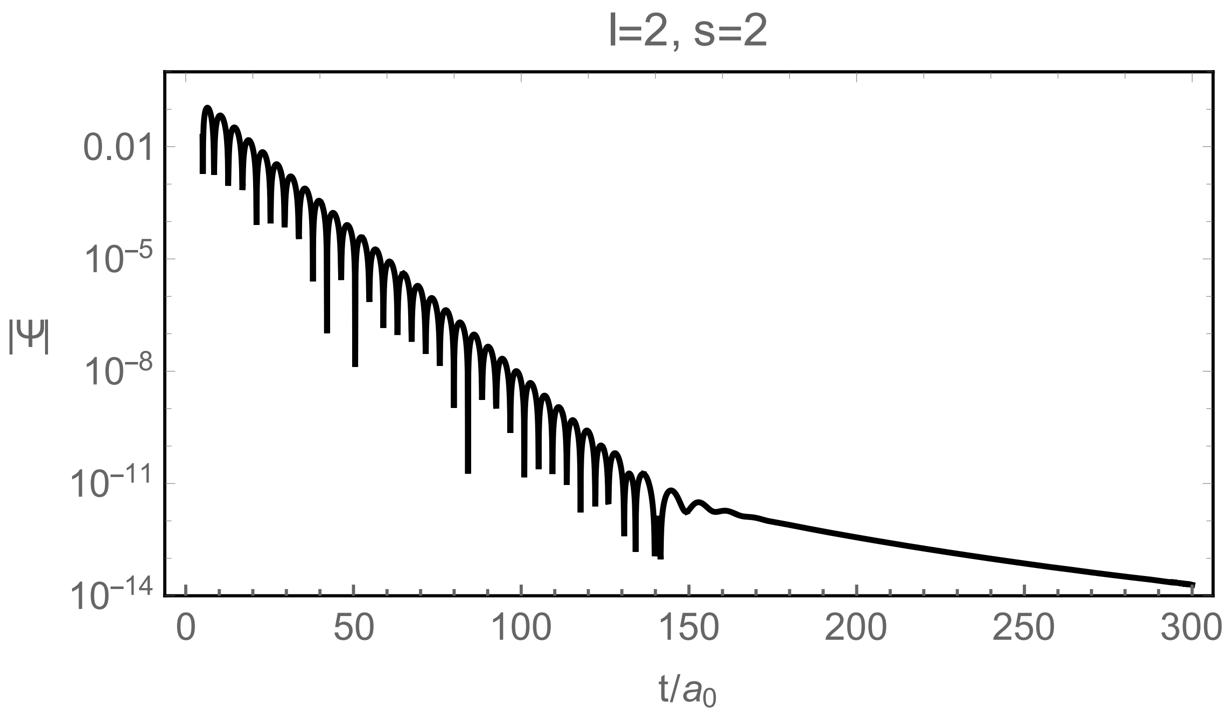
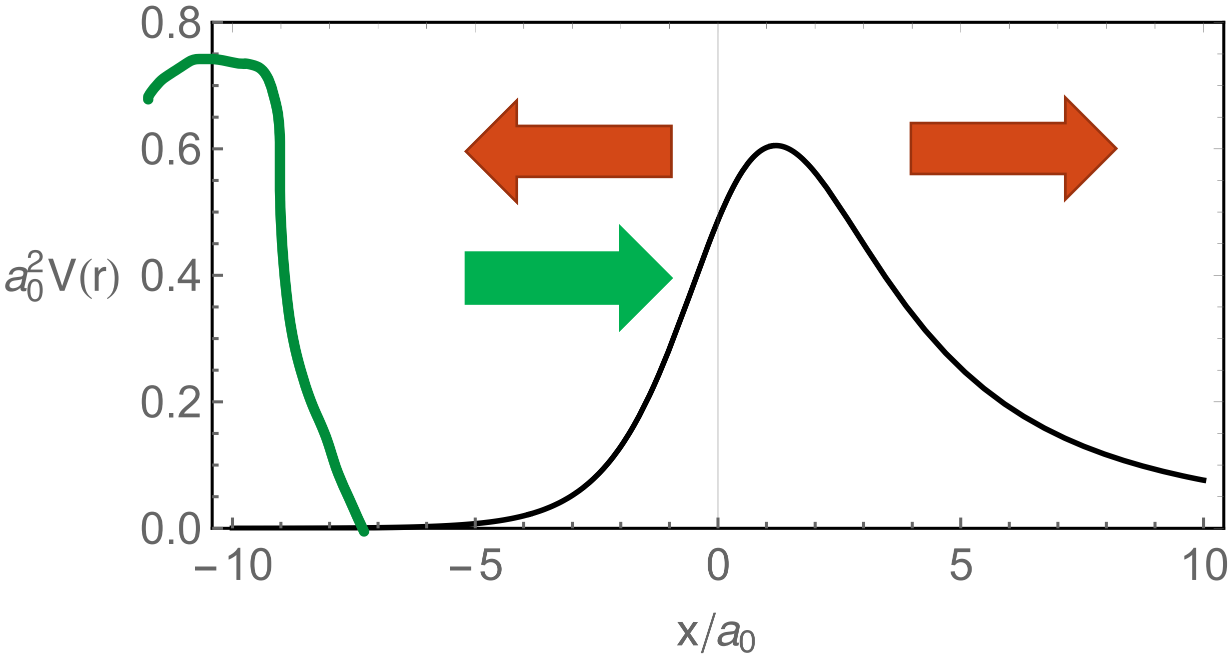
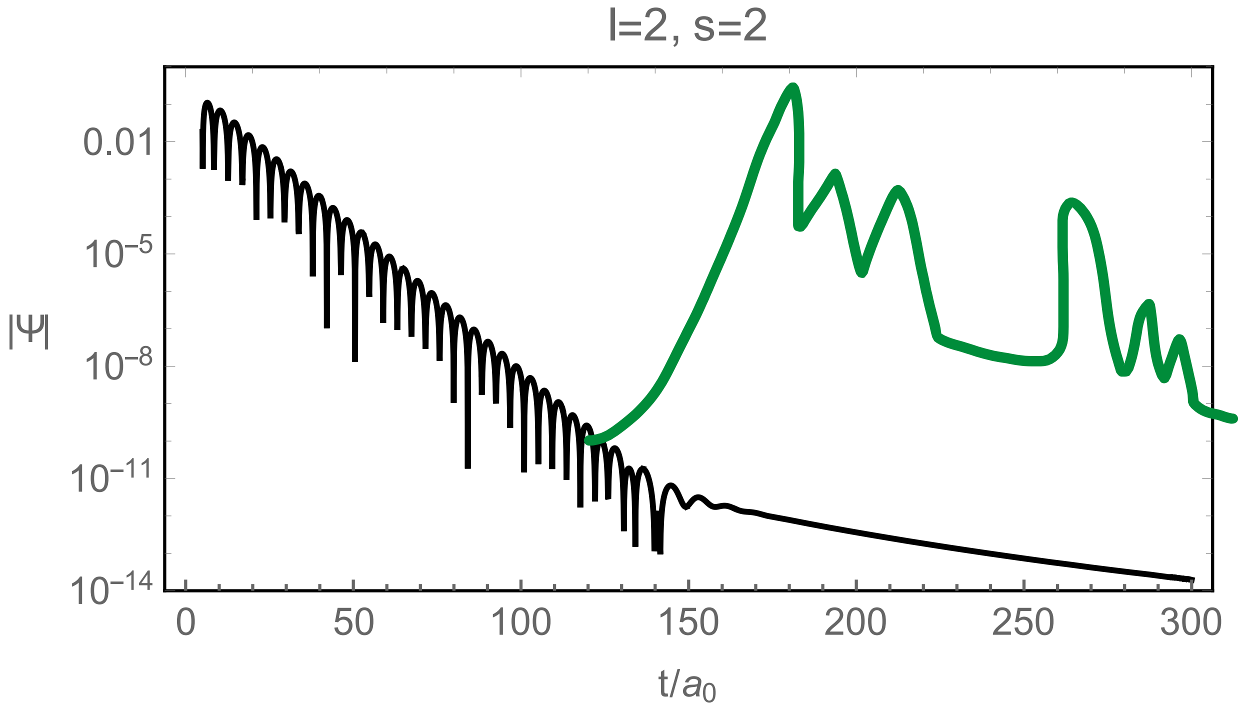




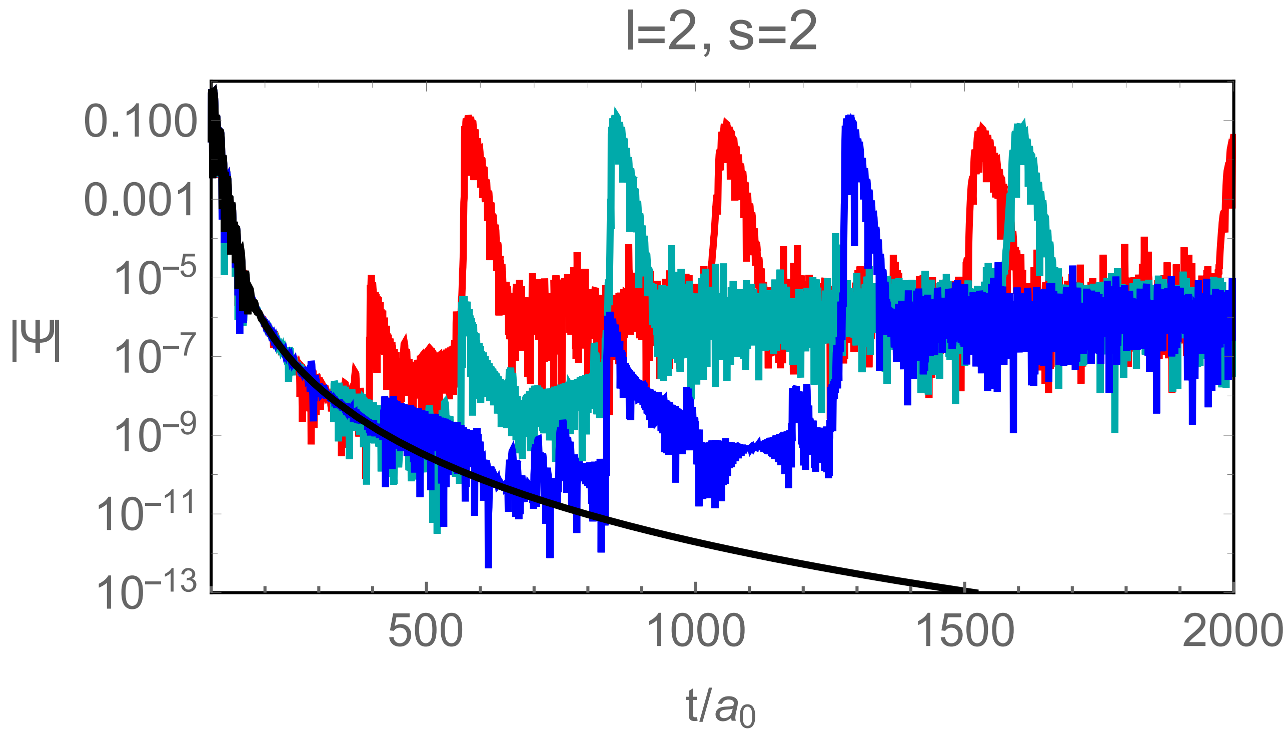
Gravitational wave echoes





QHCO echoes delayed by redshifts

- Series of echoes after typical ringdown
- $\Delta t_{echo}/a_0 \sim e^{a_0^2/nl_p^2}$: time separation between echo peaks



CYC, Oshita, Yokokura (in preparation)

Conclusions

- Bright ring & central darkness do not imply a standard BH

- <u>Darkening effects induced by redshifts are crucial in modeling HCO images</u>
- <u>Redshifts delay GW echoes</u>

- Primordial BHs & dark matter (Shuntaro's talk on early universe)
- QHCO as the end state of evaporation of primordial BHs?
  - e.g. memory burden effects or other UV physics (Pei-Ming's talk)

    Dvali (2024) Ho, Kawai, Shao (2024)
- DM candidates?
- Detection through: microlensing, NS capture, interaction with WD, gravitational waves, etc…

  Kaiser et al (2025) Carr, Kuhnel (2020)(2022), Green, Kavanagh (2021)

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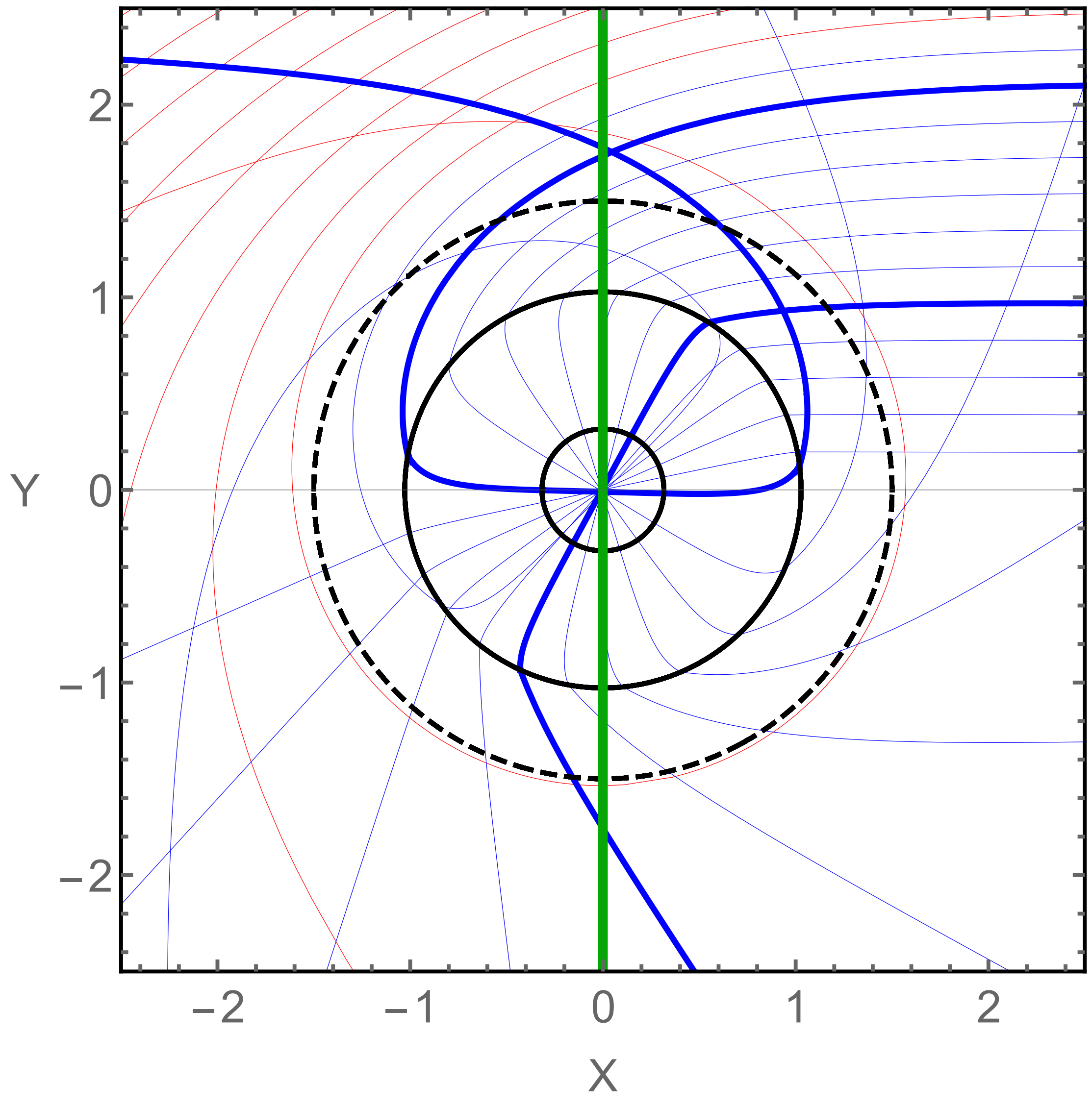
Quantum gravity & Astrophysics & Cosmology & Nuclear physics

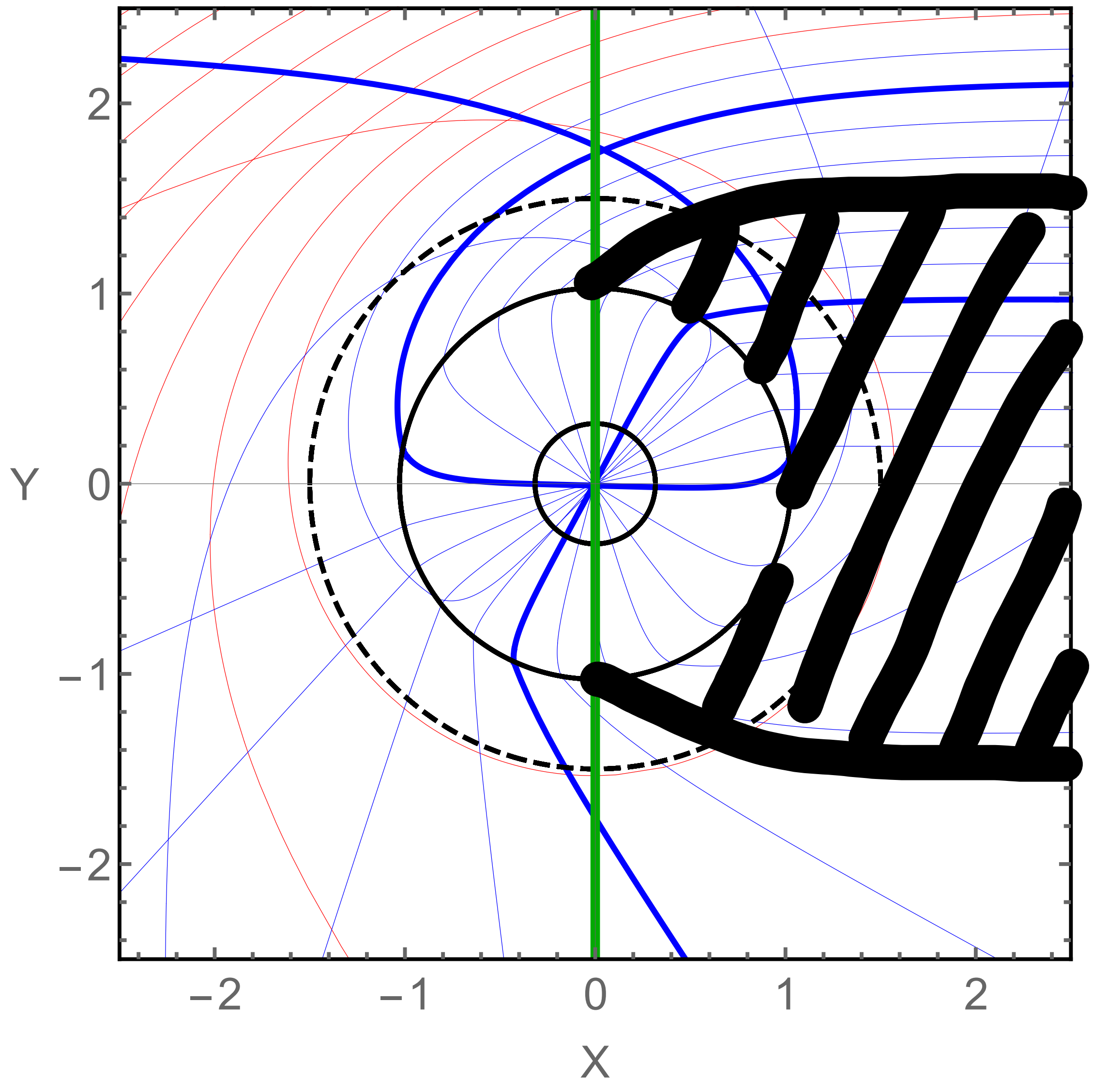
Inner shadow



- Inner shadow boundary:
  Direct emission at the horizon

Chael, Johnson, Lupsasca (2021)

Inner shadow



- Inner shadow boundary:
  Direct emission at the horizon
  - Only valid when emission exists there

Chael, Johnson, Lupsasca (2021)

Darkened images

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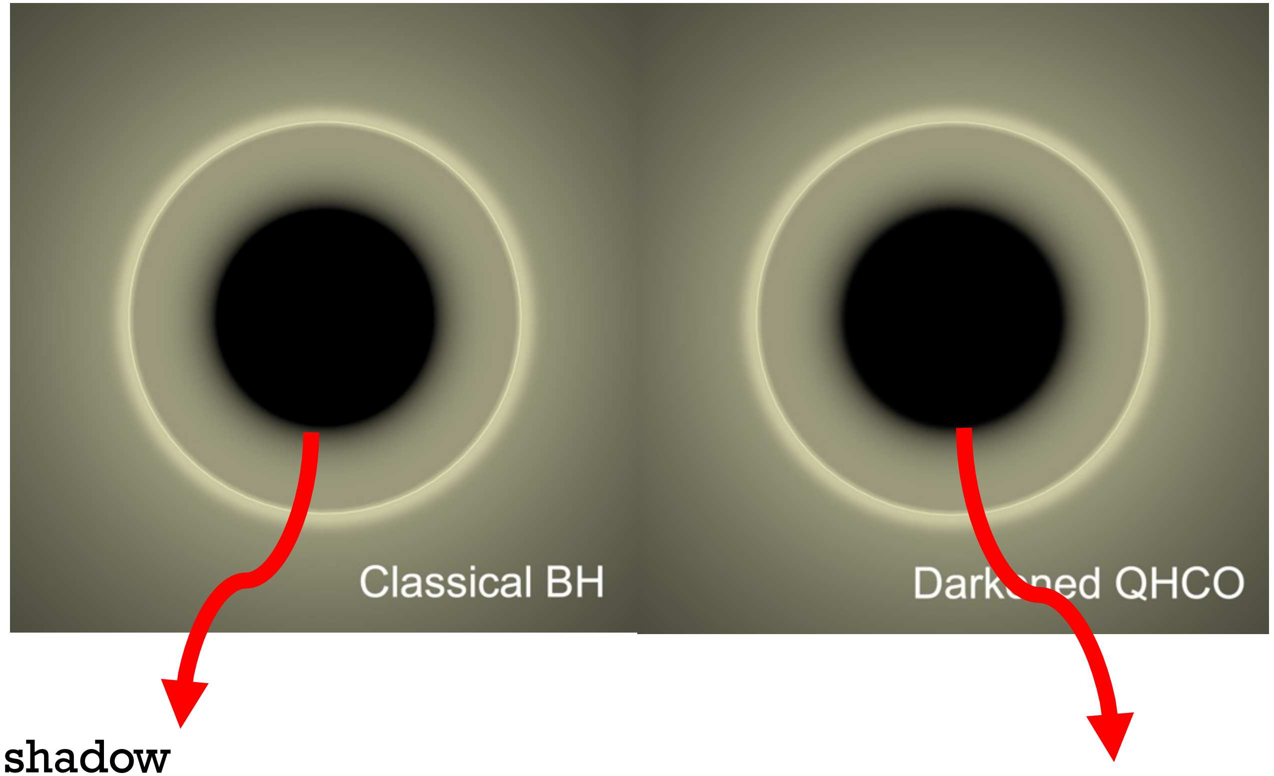


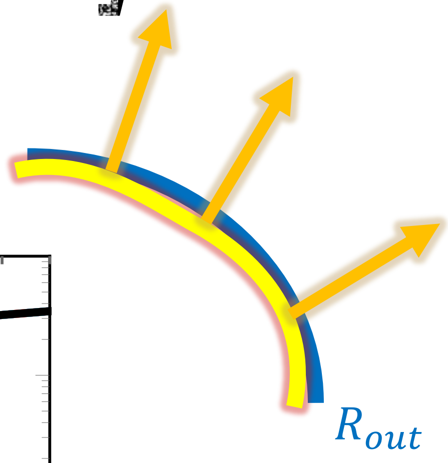
Inner shadow

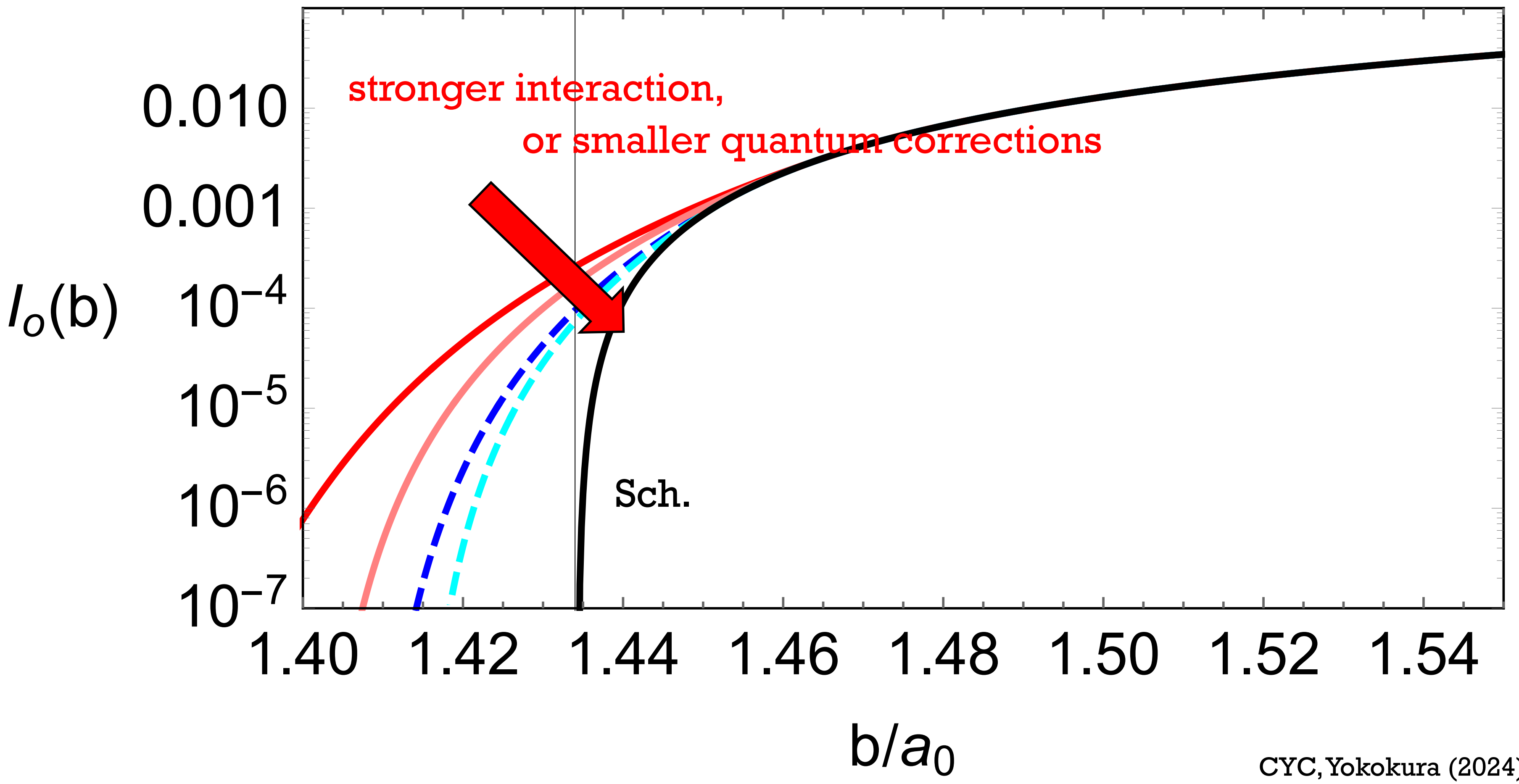
?

CYC, Yokokura (2024)

Near the inner shadow: excess intensity

If the light source extends slightly inside the surface R_{out}:





CYC, Yokokura (2024)