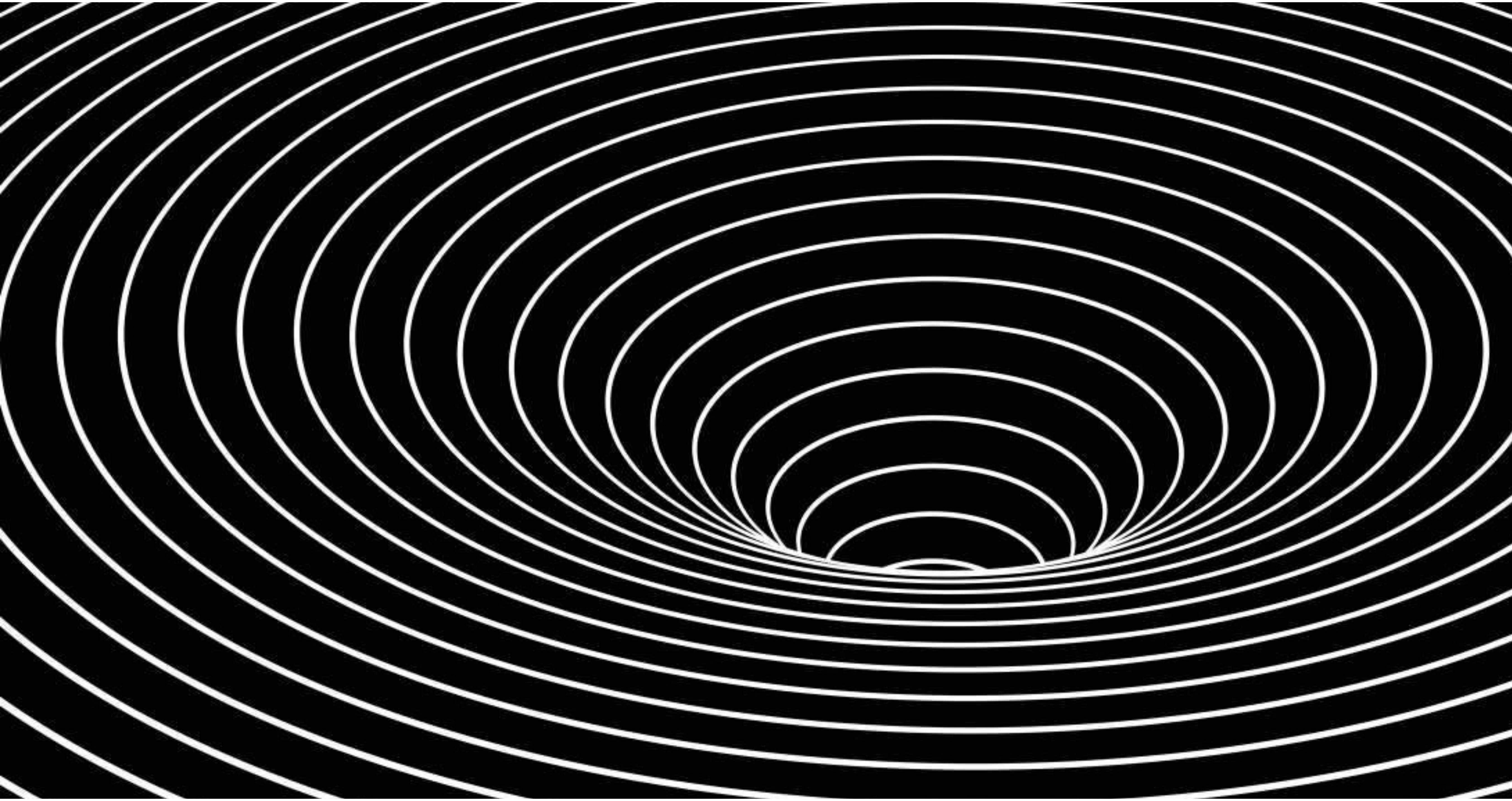
Data challenges for black-hole image reconstruction and feature identification



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HAMLET-PHYSICS 2024,
København

JCAP 05 (2024) 103, arXiv:2312.11351

Héloïse Delaporte

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arXiv:2312.02130

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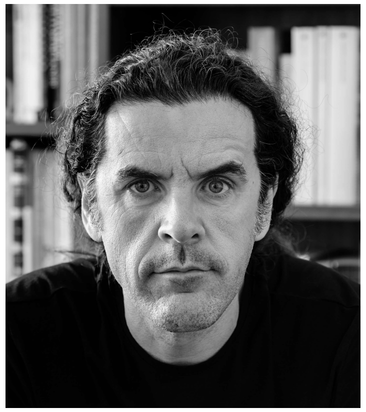


Vitor Cardoso

Ziri Younsi

+ ...

Observing black holes

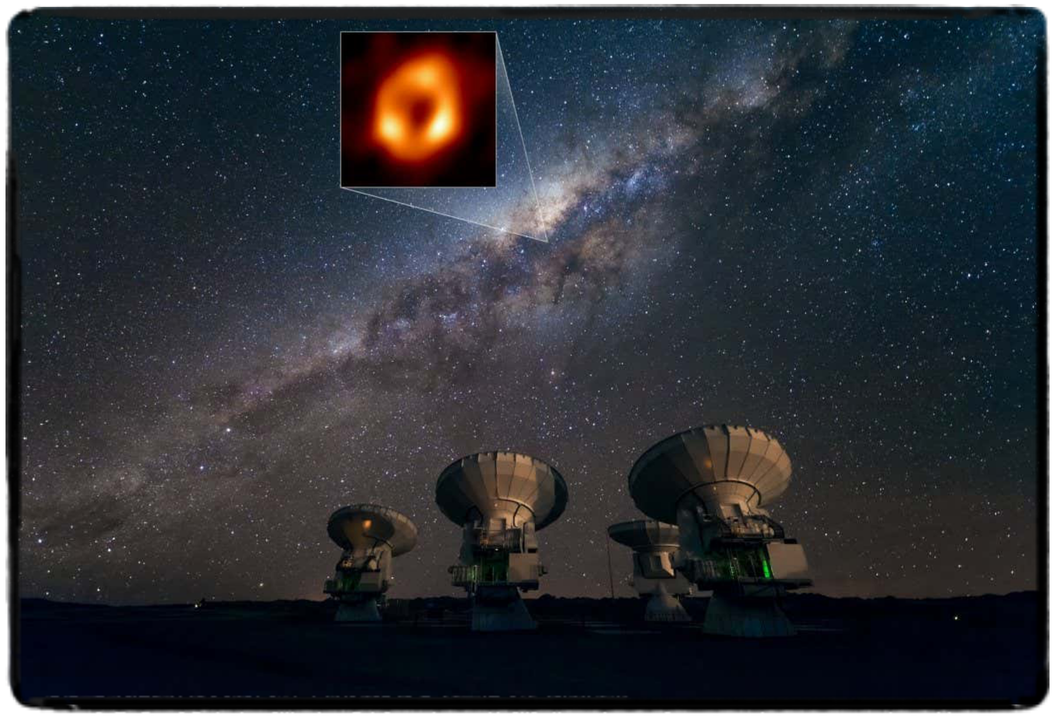


Image credit: EHT Collaboration

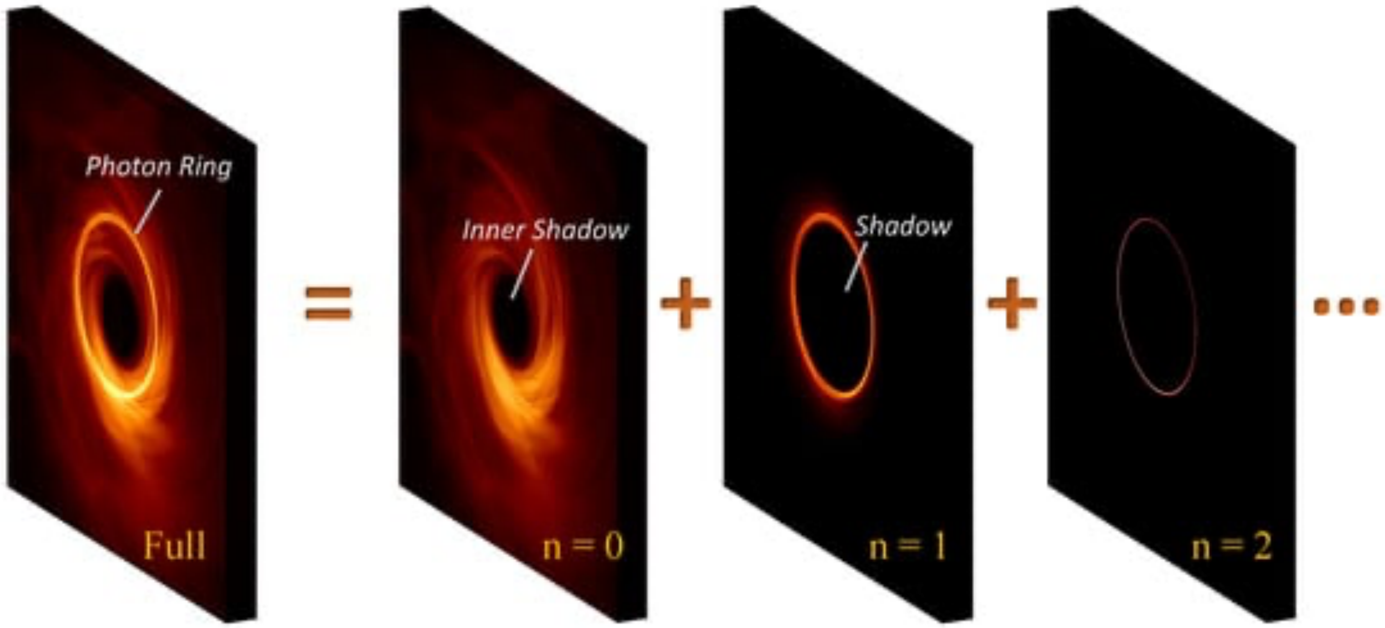
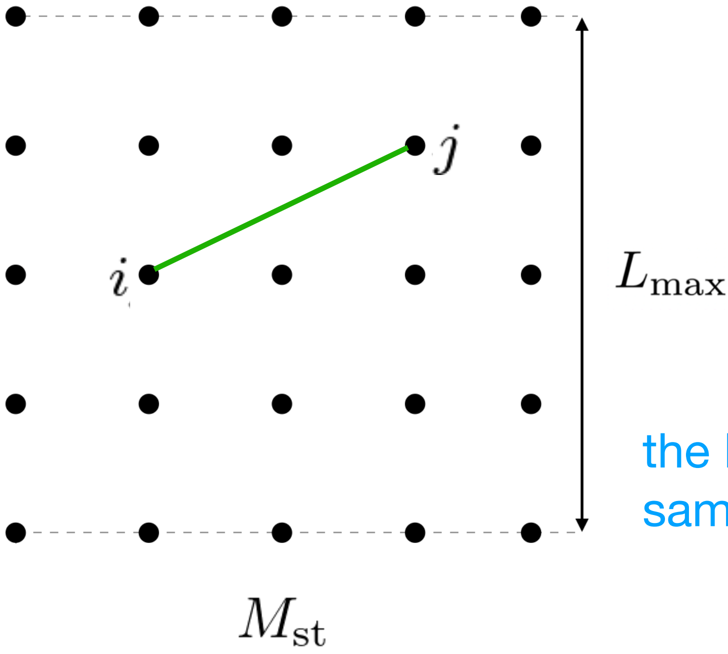


Image credit: Galaxies 2023, 11(3), 61

Arrays

idealized array



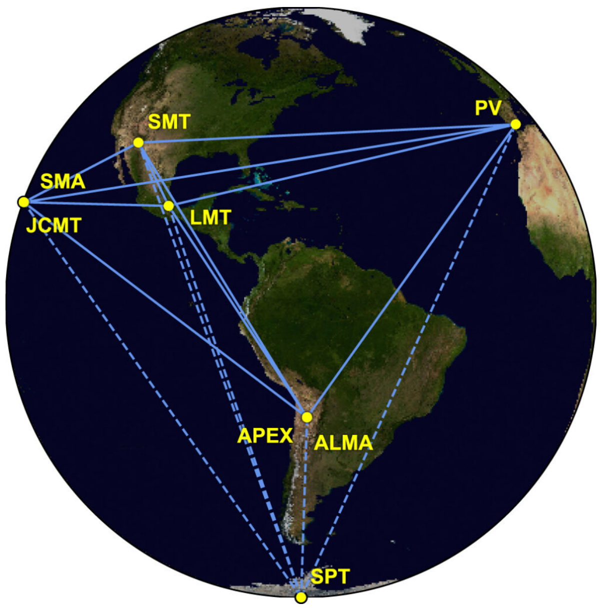


Image credit: EHT Collaboration

the Fourier transform is sampled on a discrete fashion

$$V_{ij} = V(u_{ij}, v_{ij})$$

Intensity profile (proportional to flux)

$$V(u,v) = \int\int dx\, dy\, I(x,y)\, e^{-\frac{2\pi i(ux+vy)}{\lambda}}$$

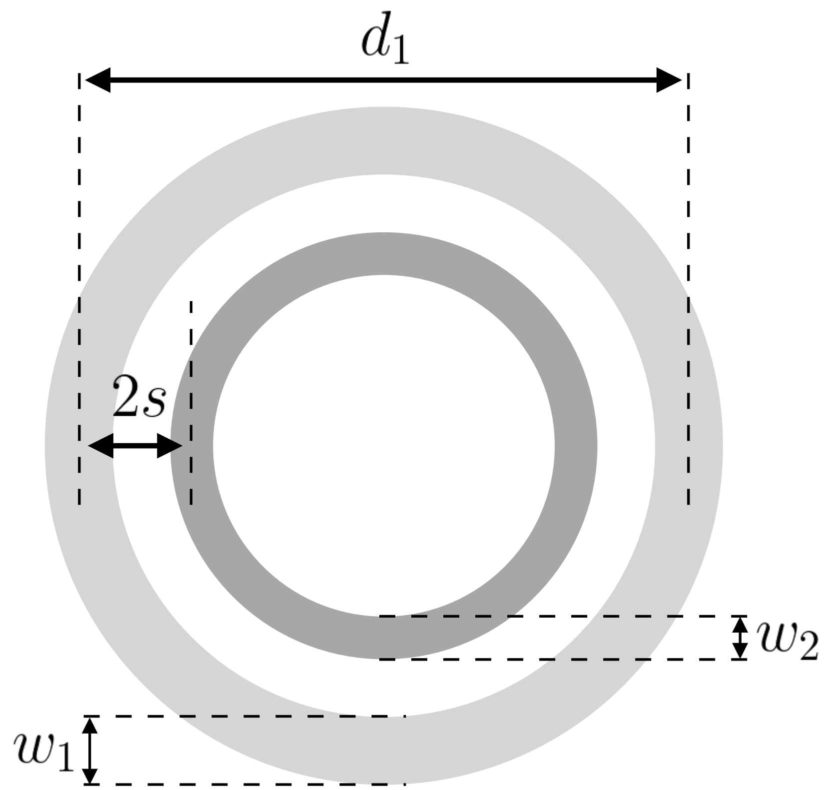
observation wavelength

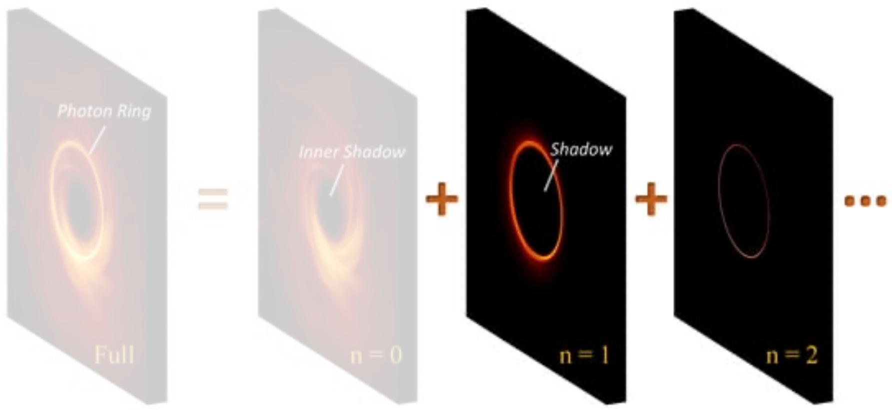
projected (on the plane orthogonal to the line of sight) baseline coordinates

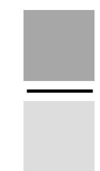
angular coordinates on the sky

A. R. Thompson, J. M. Moran, and J. Swenson, George W., Interferometry and Synthesis in Radio Astronomy, 3rd Edition (2017).

How does the Fourier transform look like?





$$\Delta F = \frac{F_2}{F_1} =$$ 

$$F_1 + F_2 = F_{\rm tot}$$

In this talk we always use:
$d_1 = 42\ \mu$as, $w_1 = 2\ \mu$as,
$s = 5\ \mu$as, $w_2 = 0.5\ \mu$as

$L_{\rm max} = 10\ {\rm G}\lambda$
$M_{\rm st} = 20$

$$V(k) = V_1(k) + V_2(k) = \frac{2\pi I_1}{k}\left[R_{{\rm outer},1} J_1(kR_{{\rm outer},1}) - R_{{\rm inner},1} J_1(kR_{{\rm inner},1})\right] + \frac{2\pi I_2}{k}\left[R_{{\rm outer},2} J_1(kR_{{\rm outer},2}) - R_{{\rm inner},2} J_1(kR_{{\rm inner},2})\right]$$

$$k = 2\pi\frac{\sqrt{u^2+v^2}}{\lambda}$$

- Decaying oscillatory function that has zeroes depending on the parameters of the two-ring model

$$R_{{\rm inner},1},\ \ R_{{\rm outer},1},\ \ R_{{\rm inner},2},\ \ R_{{\rm outer},2}$$

Error budget and closure quantities

R. C. Jennison, MNRAS 118, 276 (1958); R. Q. Twiss, A. W. L. Carter, and A. G. Little, The Observatory 80, 153 (1960)

error budget

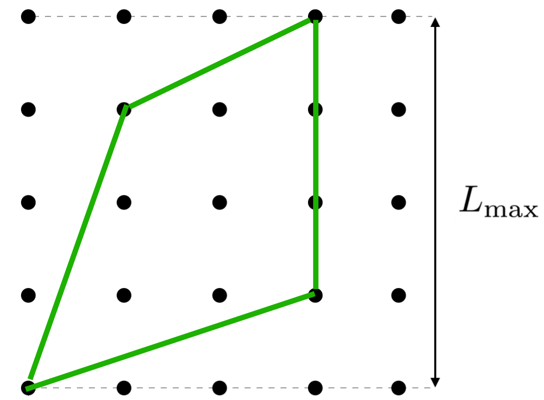
$$\hat{V}_{ij} = g_i g_j^* V_{ij} + \epsilon_{ij}$$

thermal noise: ϵ_{ij}

calibration factors: $g_i g_j^*$
station-based effects
(constituent interferometer
elements, atmospheric
turbulence…)

$$\ln Z_{ijkl} = \ln \frac{V(k_{ij})V(k_{kl})}{V(k_{ik})V(k_{jl})},$$

$$k_{ij} = 2\pi \frac{\sqrt{u_{ij}^2 + v_{ij}^2}}{\lambda}$$

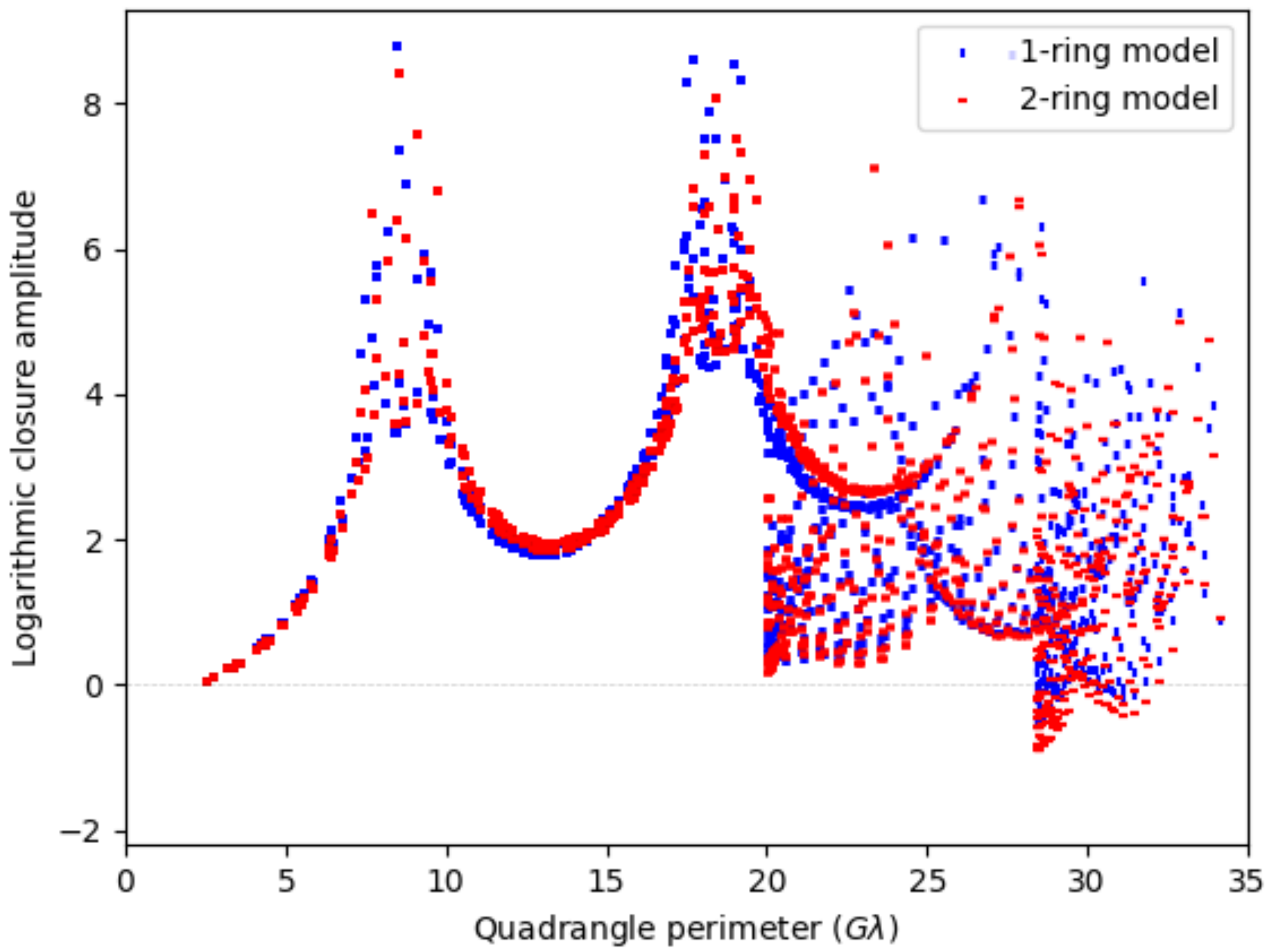


$$\frac{N(N-3)}{2}$$ independent quadrangles

- Independent of calibration factors in the absence of thermal noise
- Higher-dimensional data with natural representation space being 5D, which makes it difficult to visualize

How do closure quantities look like?

- A standard representation is in terms of the quadrangle perimeter



In this talk we always use:
$d_1 = 42\ \mu\text{as},\ w_1 = 2\ \mu\text{as},$
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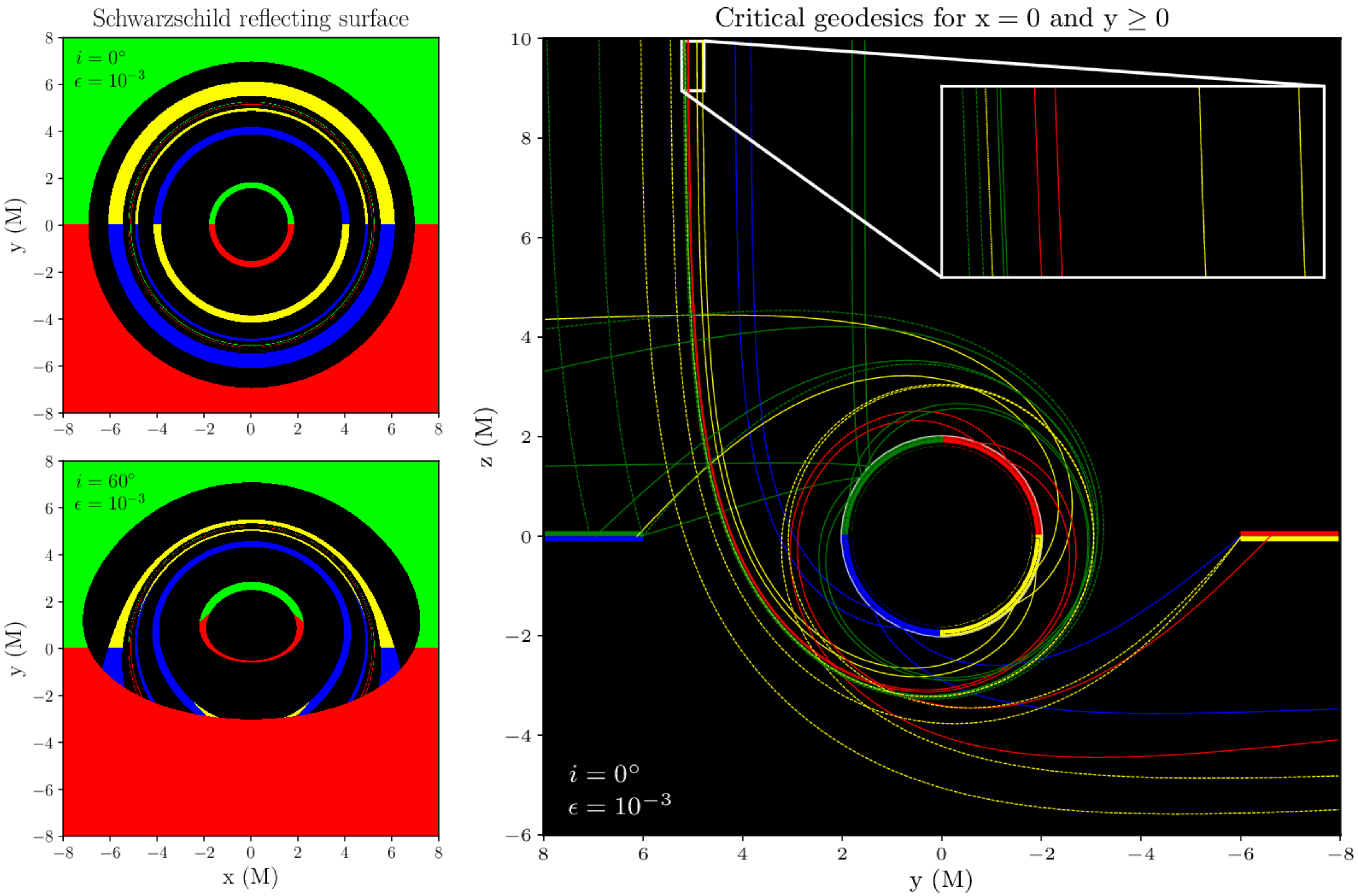
- Challenging to distinguish between one and two rings, specially with sparse (realistic) data

Why is this important? Two rings as a smoking gun of new physics

- The number of rings, their width, and relative separation are essential observables to test general relativity and alternative theories

- Example: physics beyond general relativity leads to additional ring structures in black hole images
  RCR, V. Cardoso and Z. Younsi; Phys.Rev.D 106 (2022) 8, 084038



Conclusions

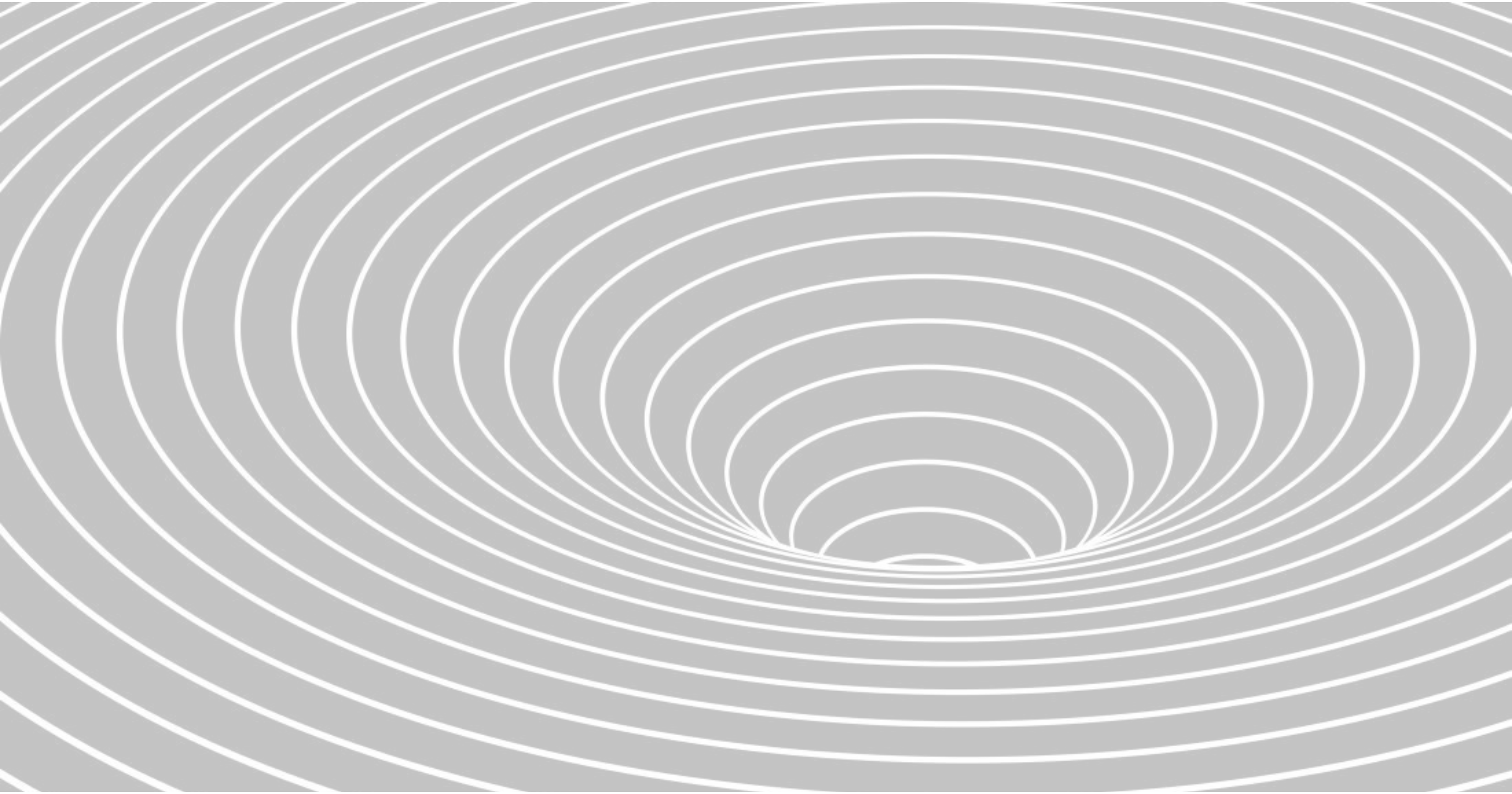
- Physics beyond general relativity can modify specific image features of black holes, in particular changing the number of photon rings and their relative separation

- Closure quantities are used to minimize the impact of noise.

- Closure quantities complicate the extraction of specific features due to being a nonlinear redefinition of Fourier transform and having a higher-dimensional natural representation space.

- Necessary to develop strategies to extract these features from high-quality datasets.

Thank you!



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