Relativistic imprints on observed black hole light curves

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ATPEM Days
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LIRA Observatoire de Paris | PSL

LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

Sgr A* VARIABILITY

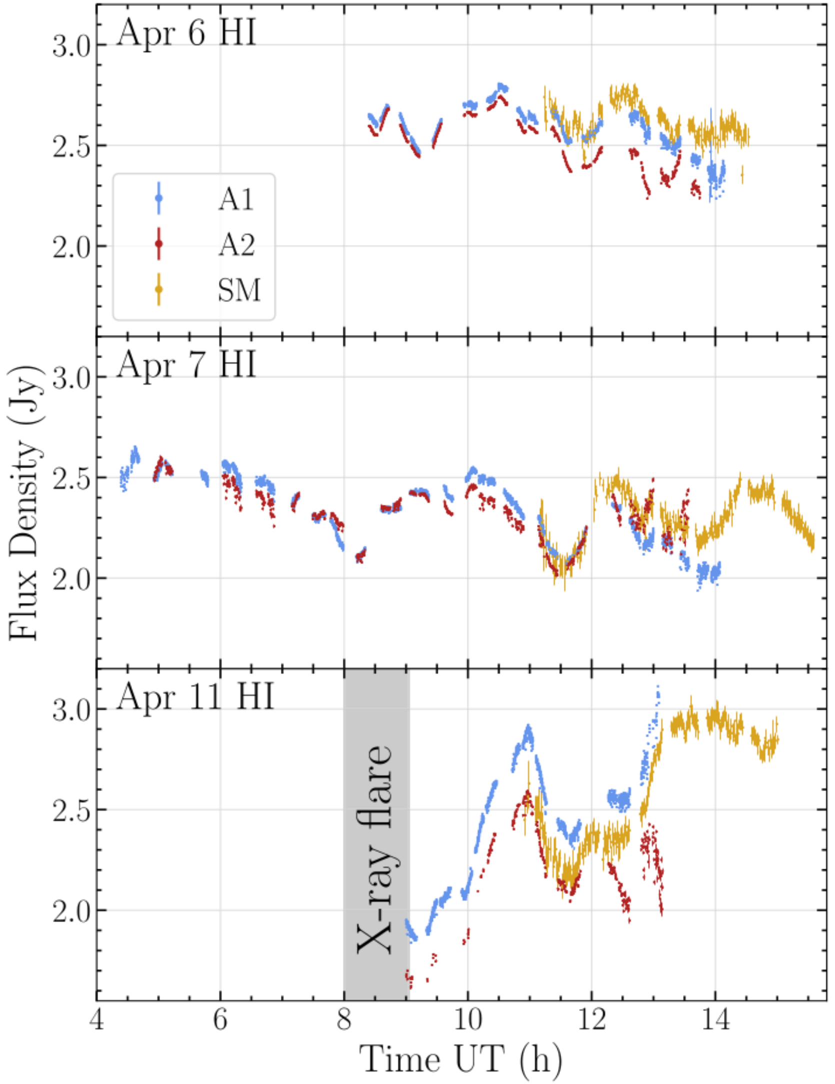
- Broadband **brightness fluctuations**

- Large range of **timescales**

→ Long: variable stellar wind feeding
→ **Short**: **turbulence**, shocks, magnetic reconnection

- **Horizon-scale** timescale:
  $t_g = GM/c^3 \simeq 20$ s

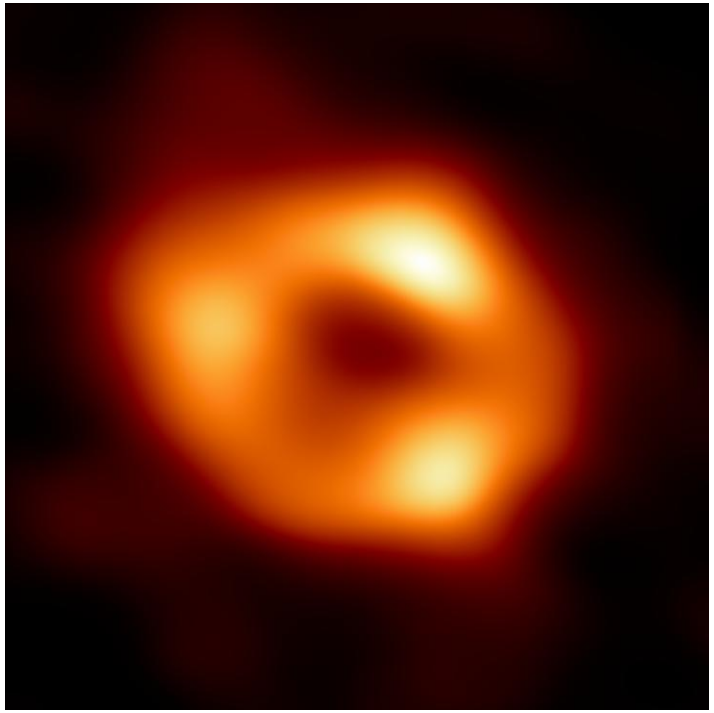
- **Millimetre** 230-GHz ALMA observations confirm timescales as short as **few minutes**

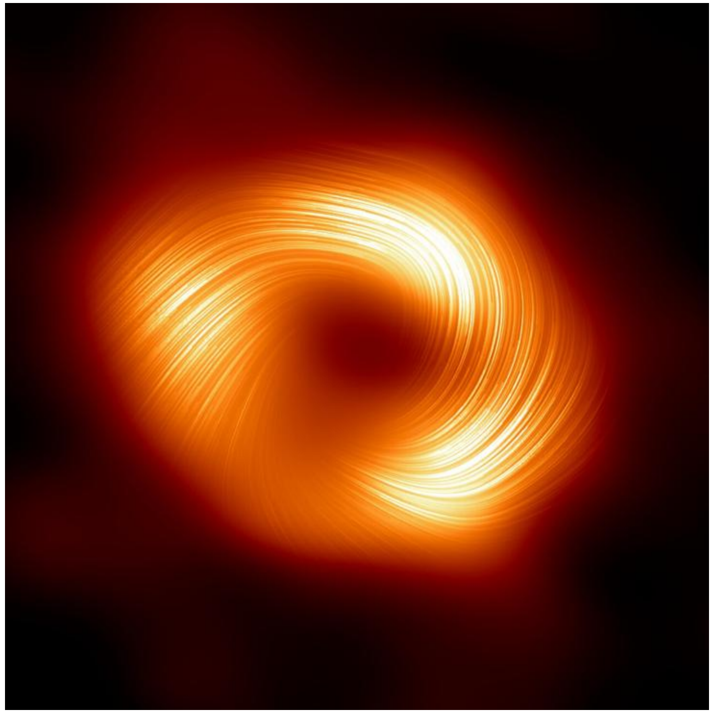


Credits: Wielgus et al. 2022

BLACK HOLE IMAGES

- **EHT V**ery **L**ong **B**aseline **I**nterferometry
- **Angular resolution**: $R \simeq \lambda/B \simeq 20\ \mu\text{as}$
- 8–11 **ground-based** telescopes
- **230-GHz** observing frequency

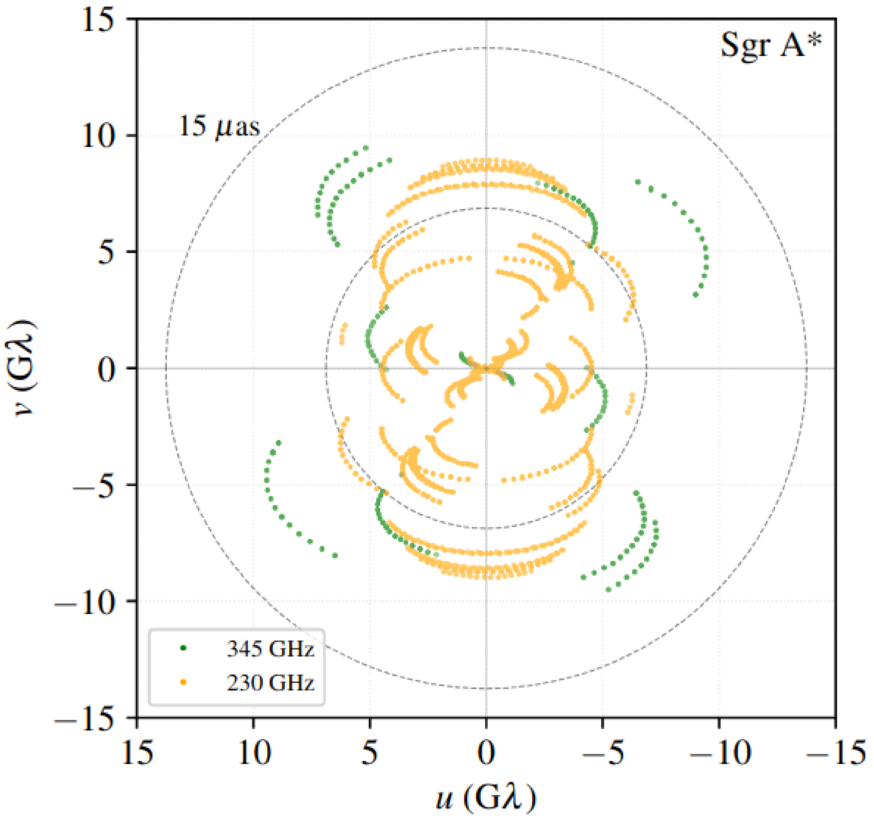


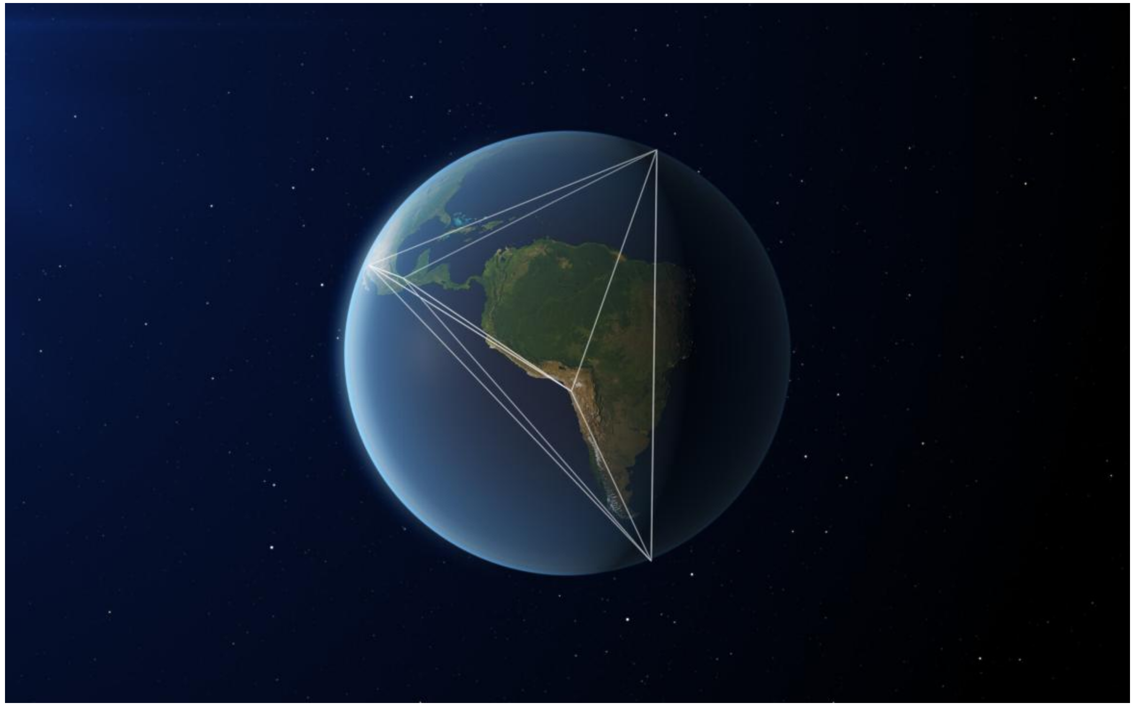


Credits: EHT collaboration

BLACK HOLE MOVIES

Credits: Doeleman et al. 2023



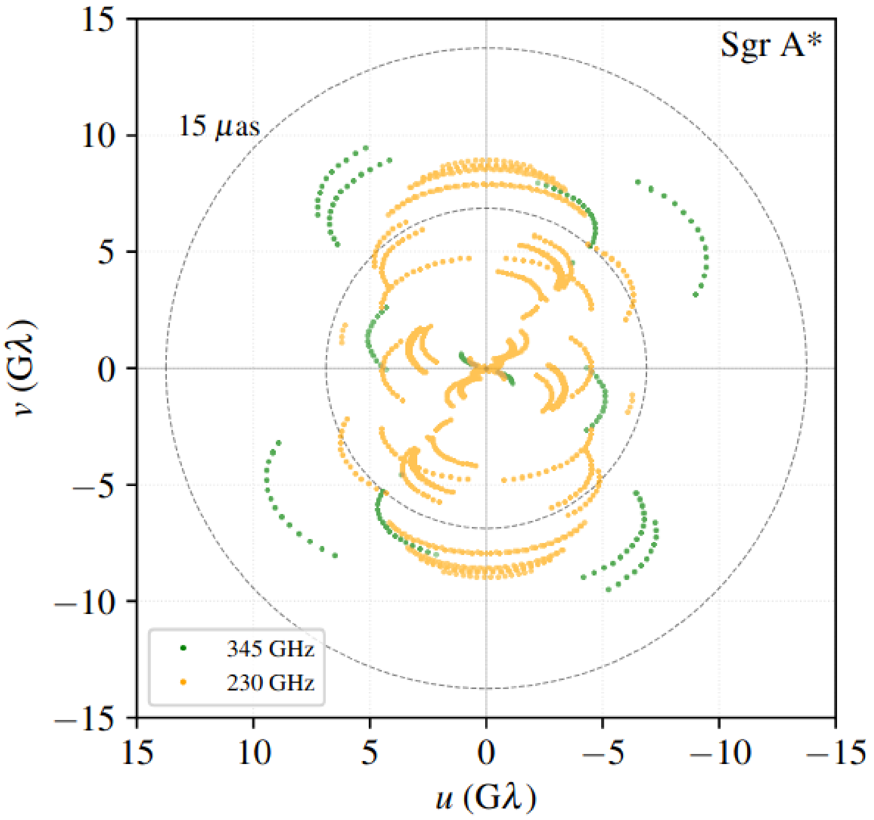


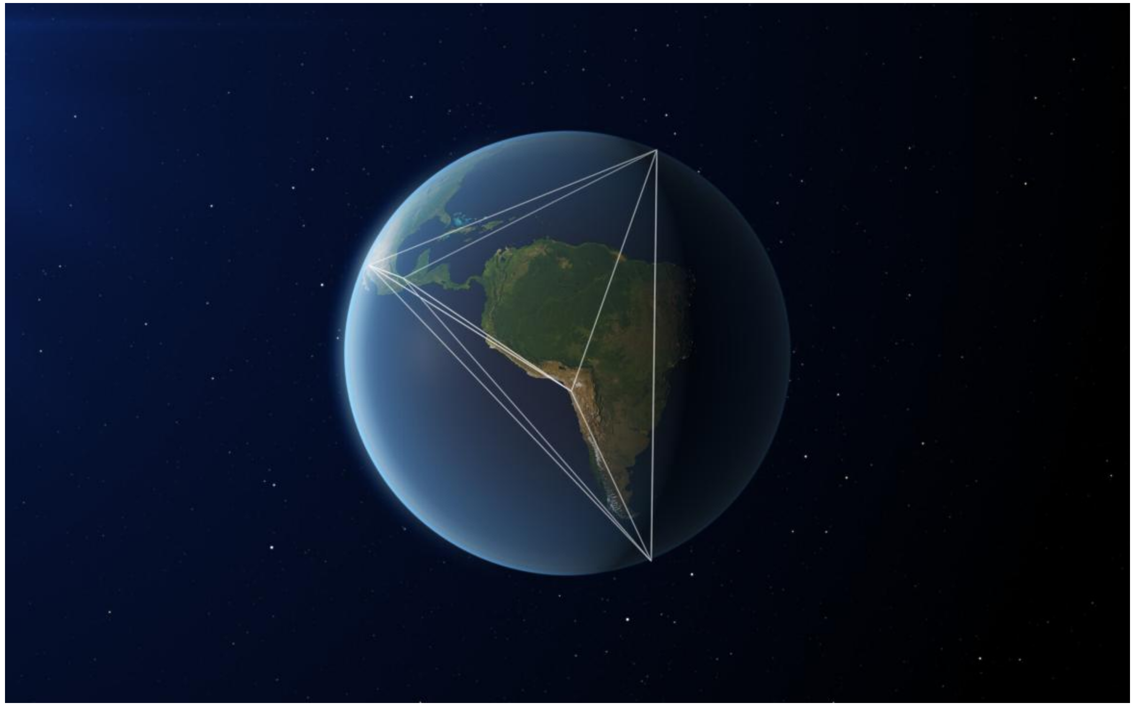
Credits: ESO

BLACK HOLE MOVIES

- **Better** baseline **coverage**
- **Faster** interferometric **sampling**

Credits: Doeleman et al. 2023





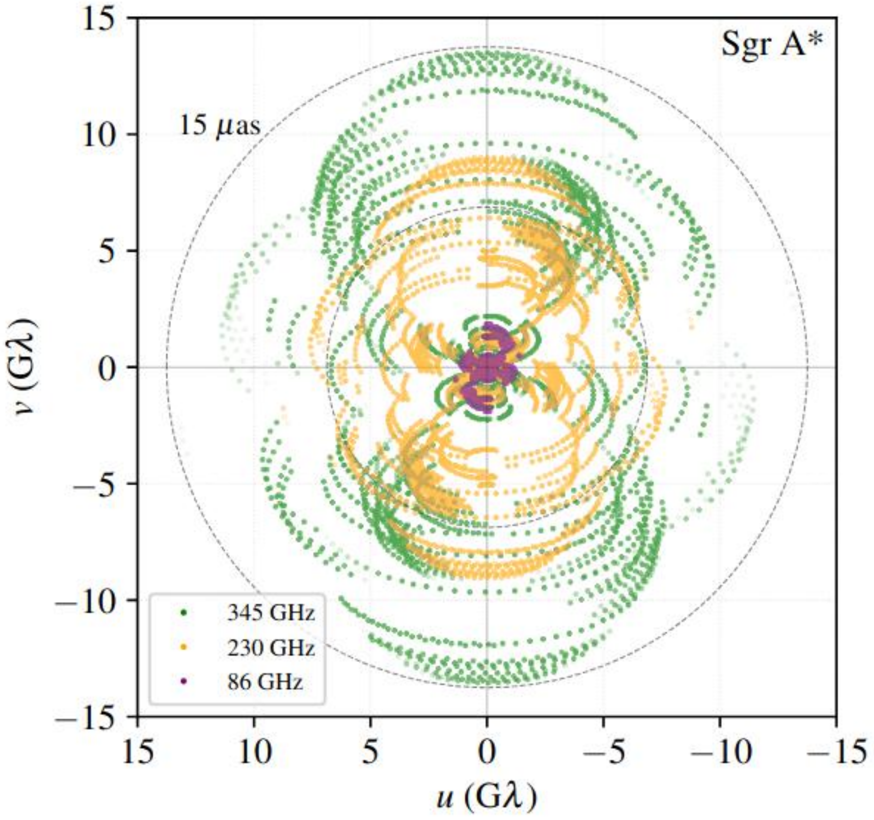
Credits: ESO

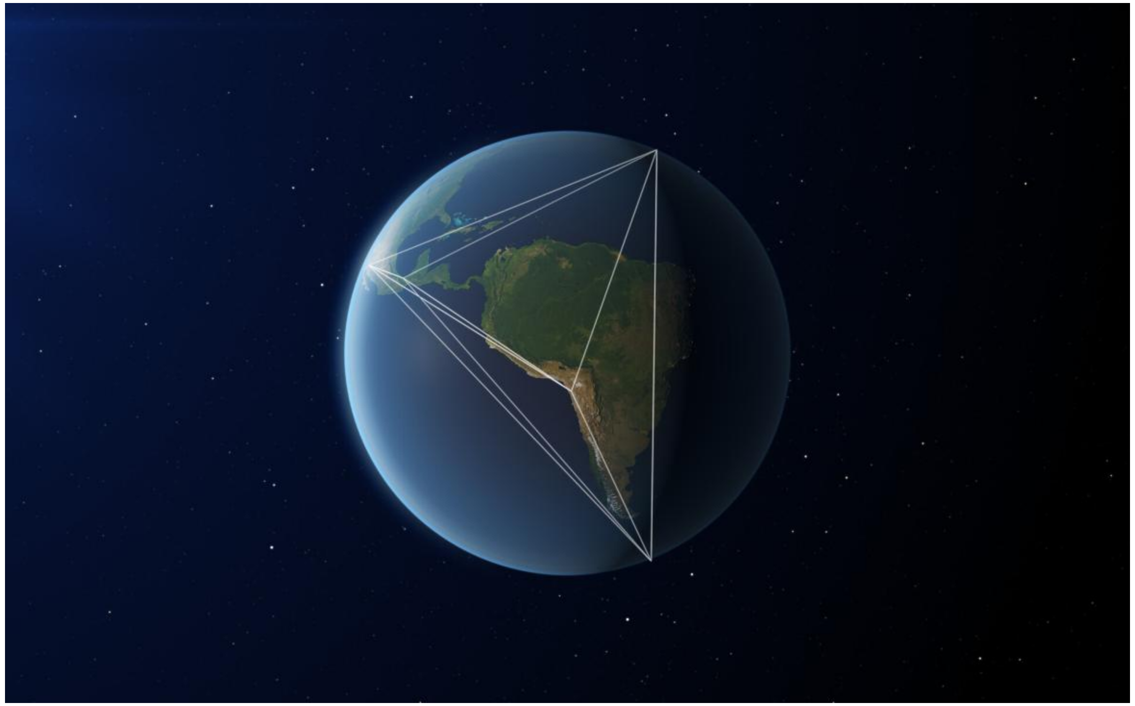
BLACK HOLE MOVIES

- **Better** baseline **coverage**
  → About 10 **additional dishes**
  → **Multi-frequency:** 86, 230, 345 GHz

- **Faster** interferometric **sampling**

Credits: Doeleman et al. 2023





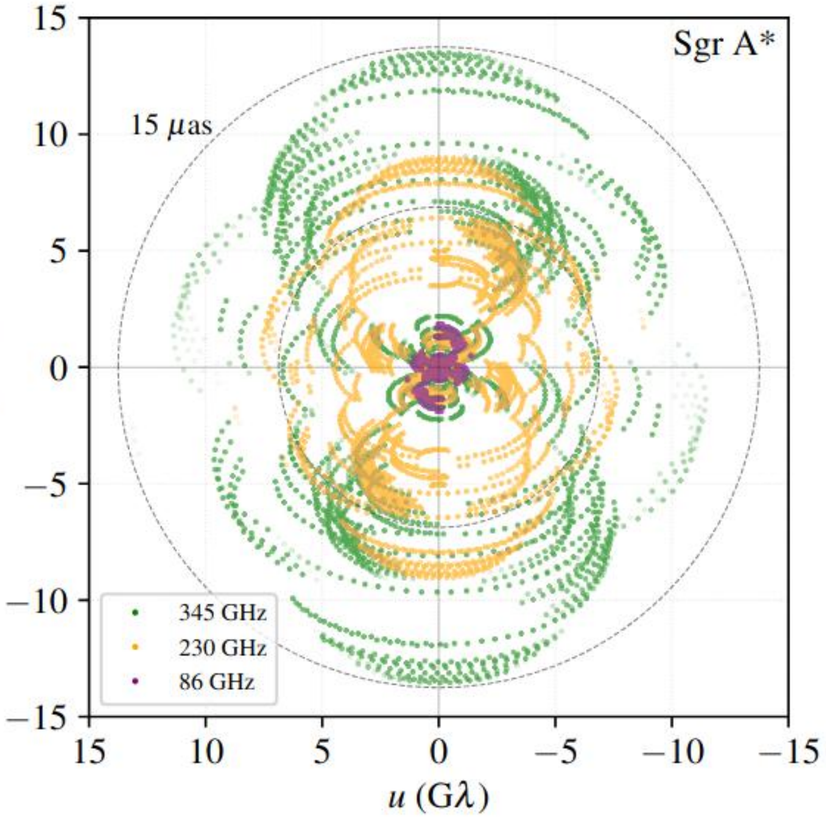
Credits: ESO

BLACK HOLE MOVIES

- **Better** baseline **coverage**
→ About 10 **additional dishes**
→ **Multi-frequency:** 86, 230, 345 GHz

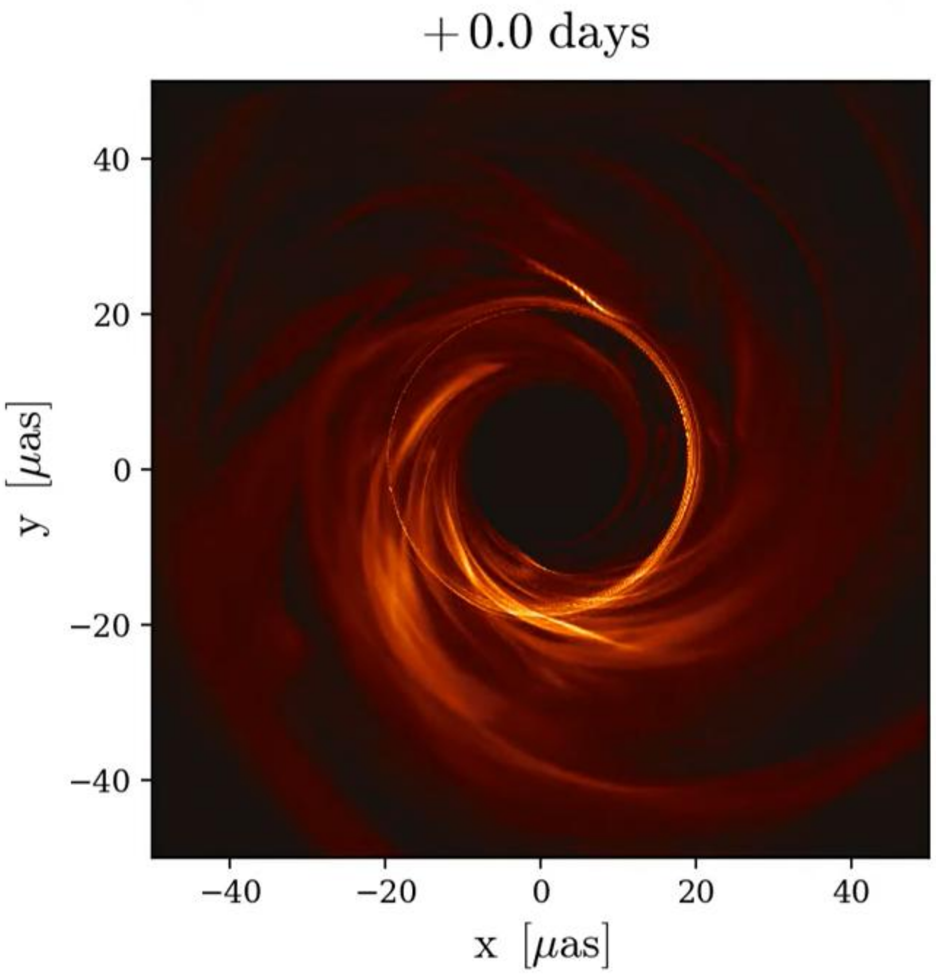
- **Faster** interferometric **sampling**
→ Medium-orbit (20 000 km) **space-based** telescope

Credits: Doeleman et al. 2023



Credits: Black Hole Explorer

SPACETIME PROBES



Credits: Wong, Prather and Gammie

- **Lensed** secondary **images** produce **echoes** (Gralla & Lupsasca 2020, Hadar et al. 2021)

→ **Autocorrelations** of fluctuations in intensity in the **total image light curve** (Wong 2021)

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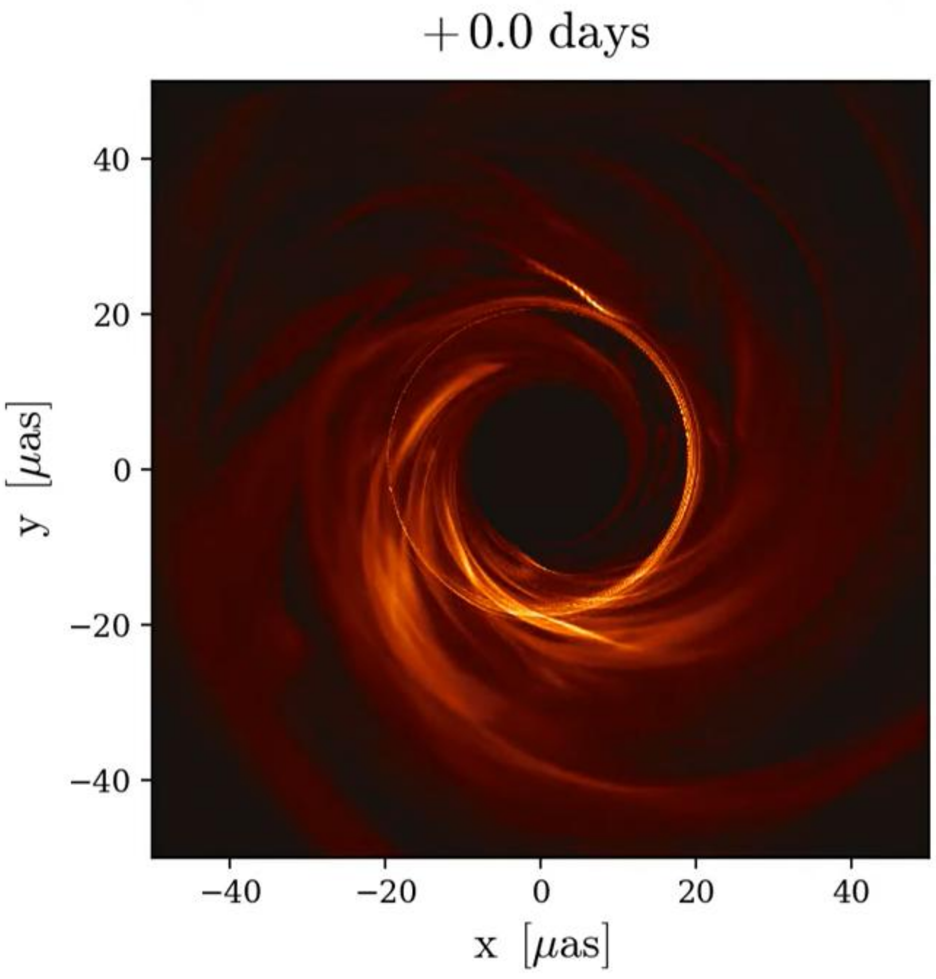
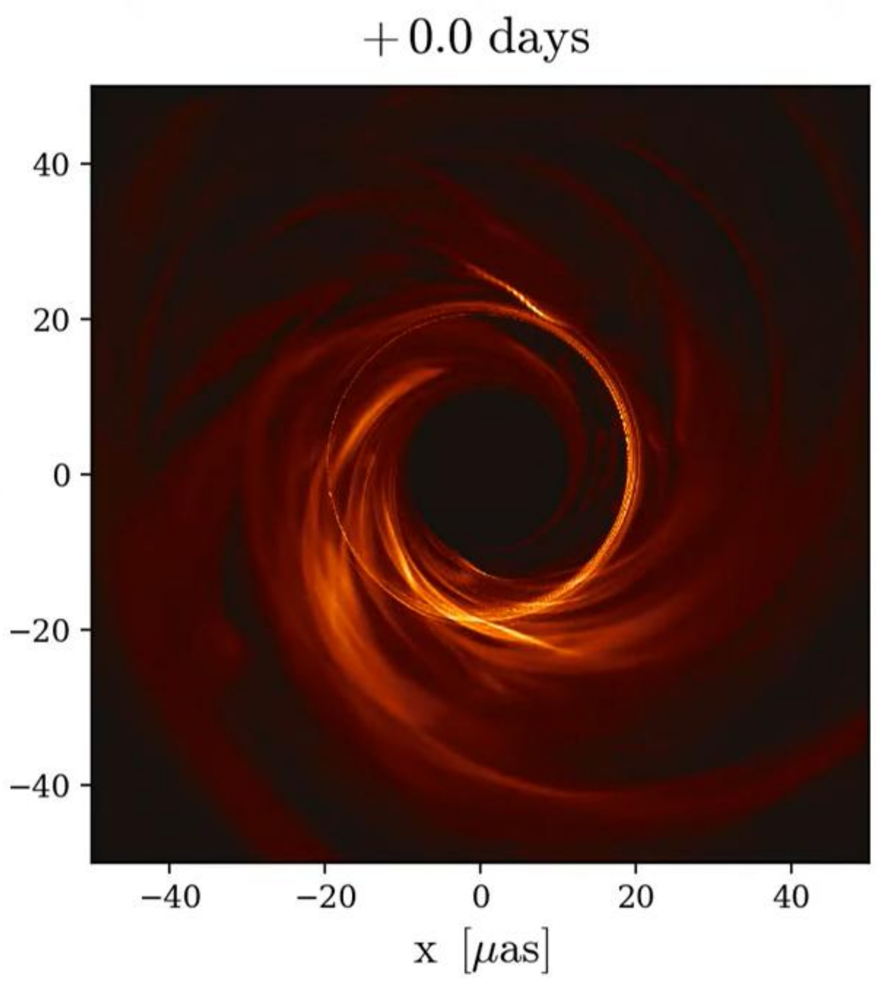


- **Lensed** secondary **images** produce **echoes** (Gralla & Lupsasca 2020, Hadar et al. 2021)

→ **Autocorrelations** of fluctuations in intensity in the **total image light curve** (Wong 2021)

- Exponentially **suppressed power** (Chesler et al. 2021)
- **Source-driven** autocorrelations **absence** (Cárdenas-Avendaño et al. 2024)
- Assumption of **stationarity**

SPACETIME PROBES



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- **Lensed** secondary **images** produce **echoes** (Gralla & Lupsasca 2020, Hadar et al. 2021)

→ **Autocorrelations** of fluctuations in intensity in the **total image light curve** (Wong 2021)

→ **Visibility-space** correlations (Wong et al. 2024)
  - BHEX space-based VLBI

→ **Spectrotemporal** correlations (Hadar et al. 2023)
  - NewAthena X-ray spectroscopy

PROJECT

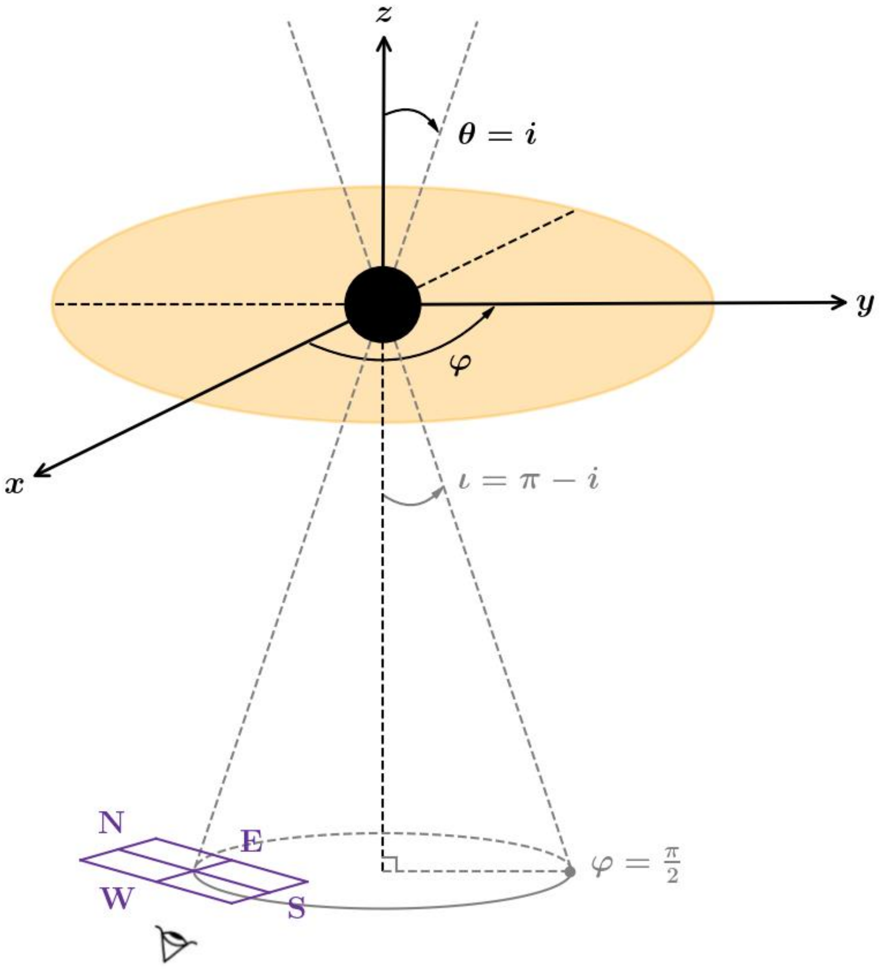
SCIENTIFIC QUESTION

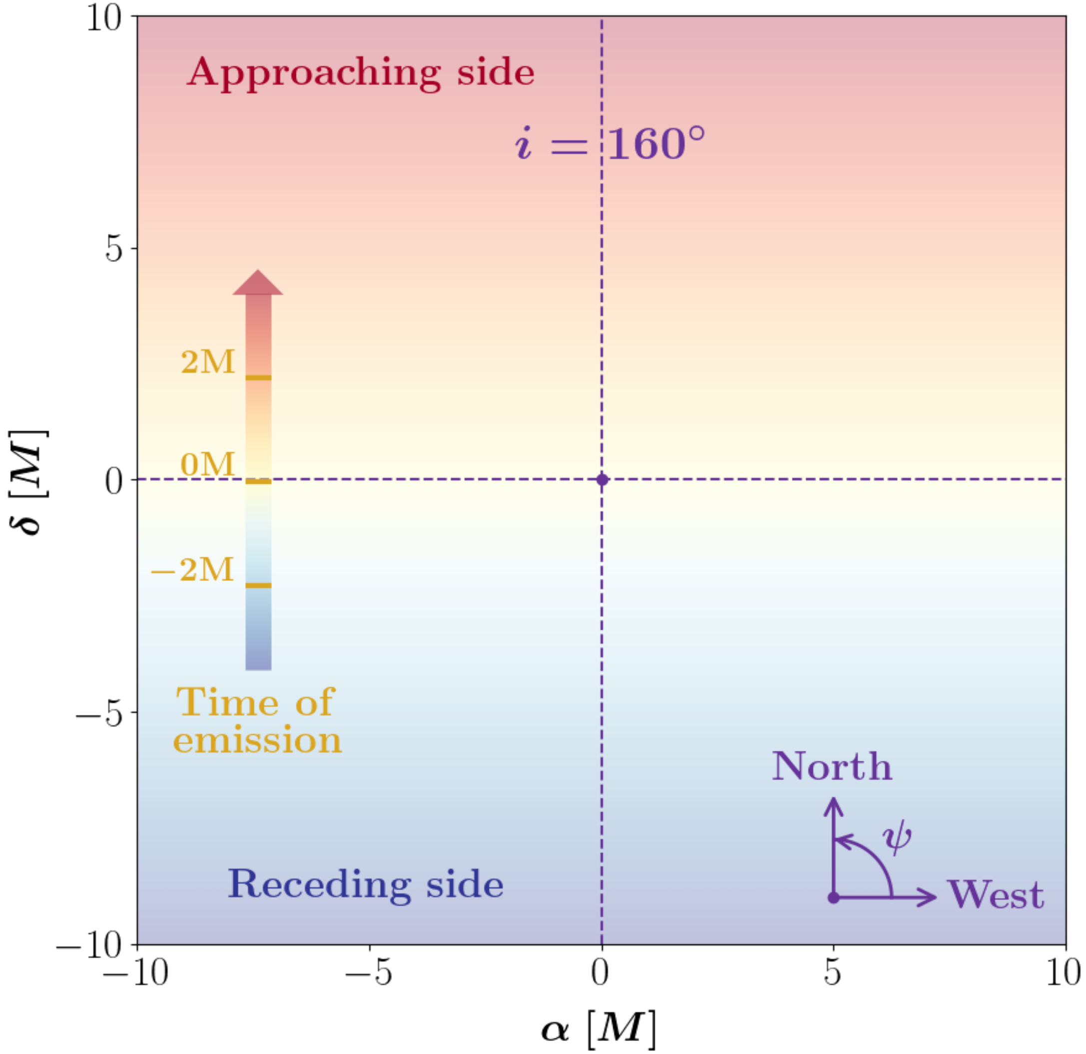
Can we **isolate** special and general **relativistic effects** in **direct** image **black hole movies**?

METHODS

- **Numerical** simulated movies via the **ray-tracing** code GYOTO
- **Analytical** derivations: Minkowski → Kerr
- **Progressive source modelling**: Hot spots → Fluctuating discs
- Consider **image quadrants**

SLOW-LIGHT PARADIGM





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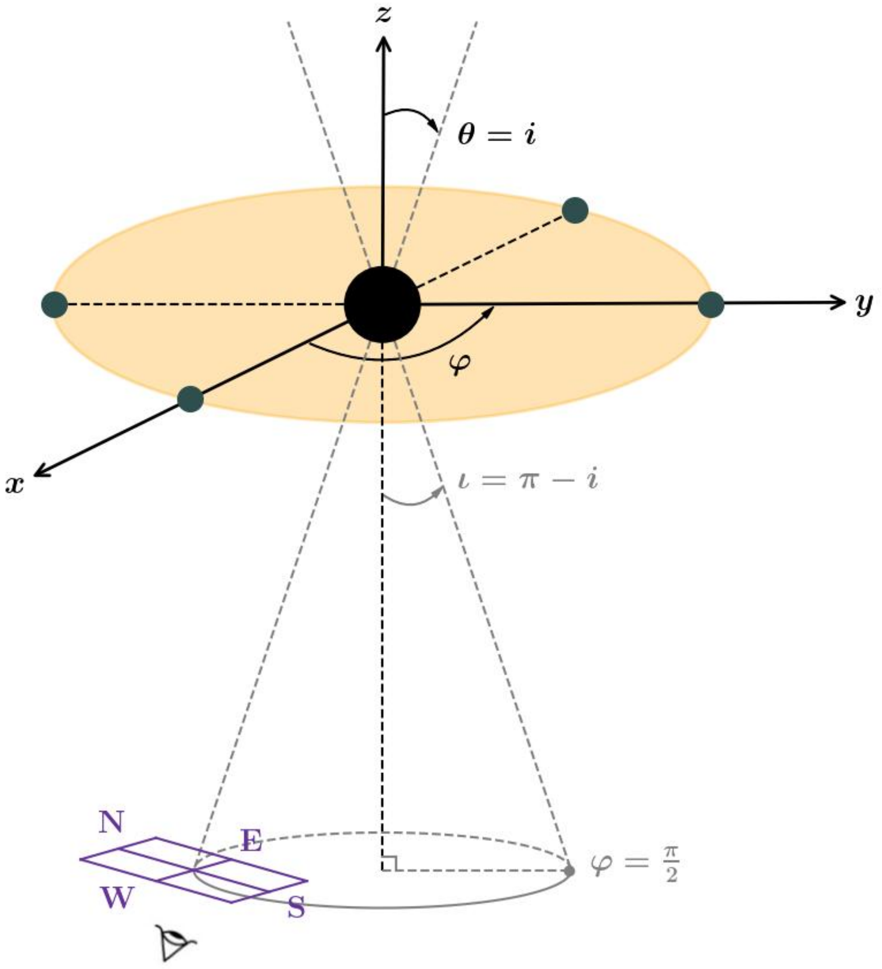

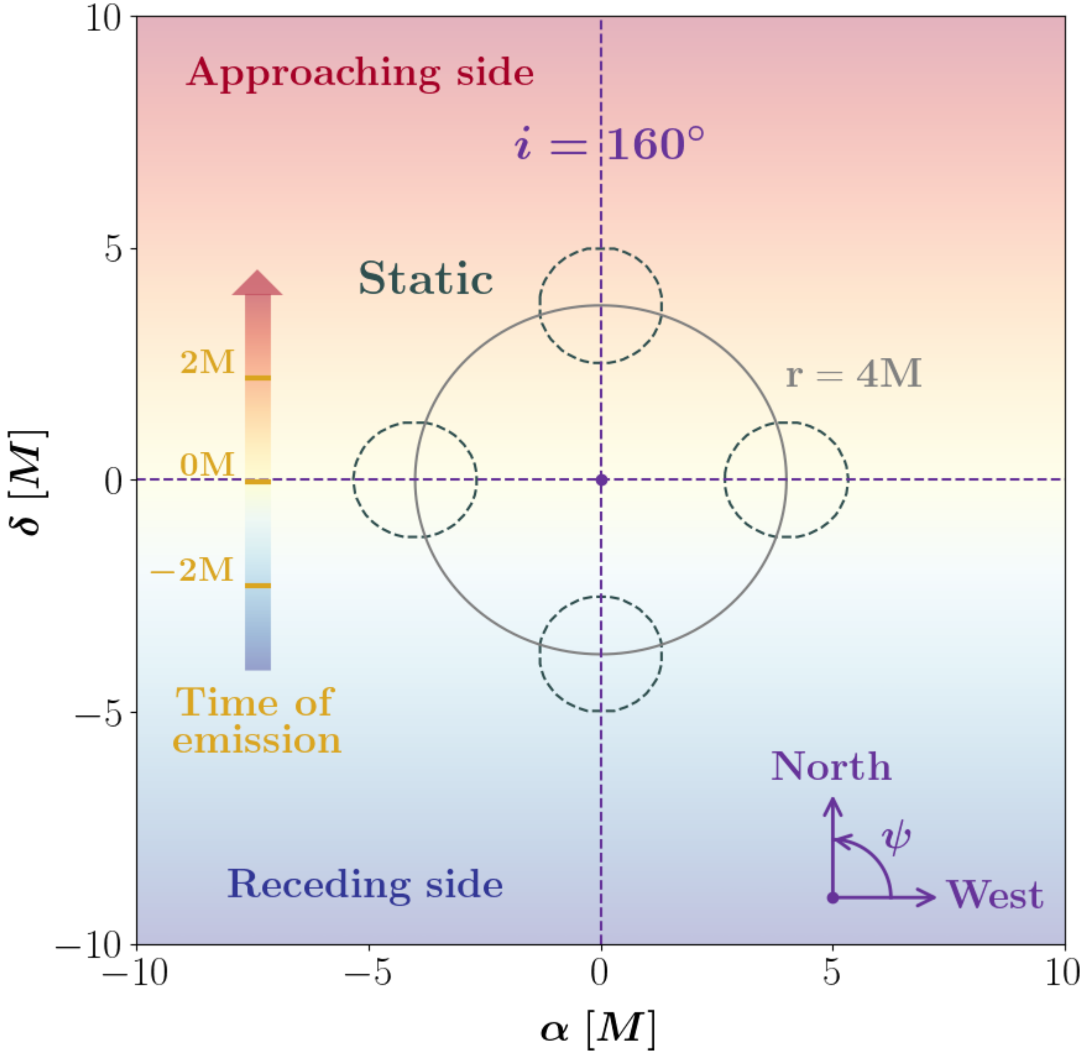

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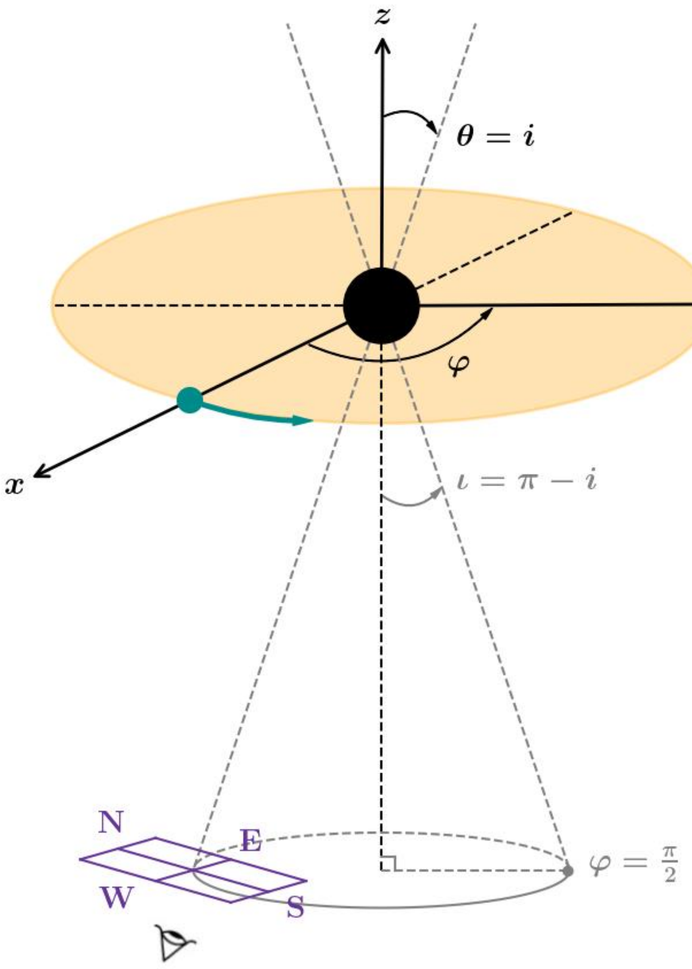

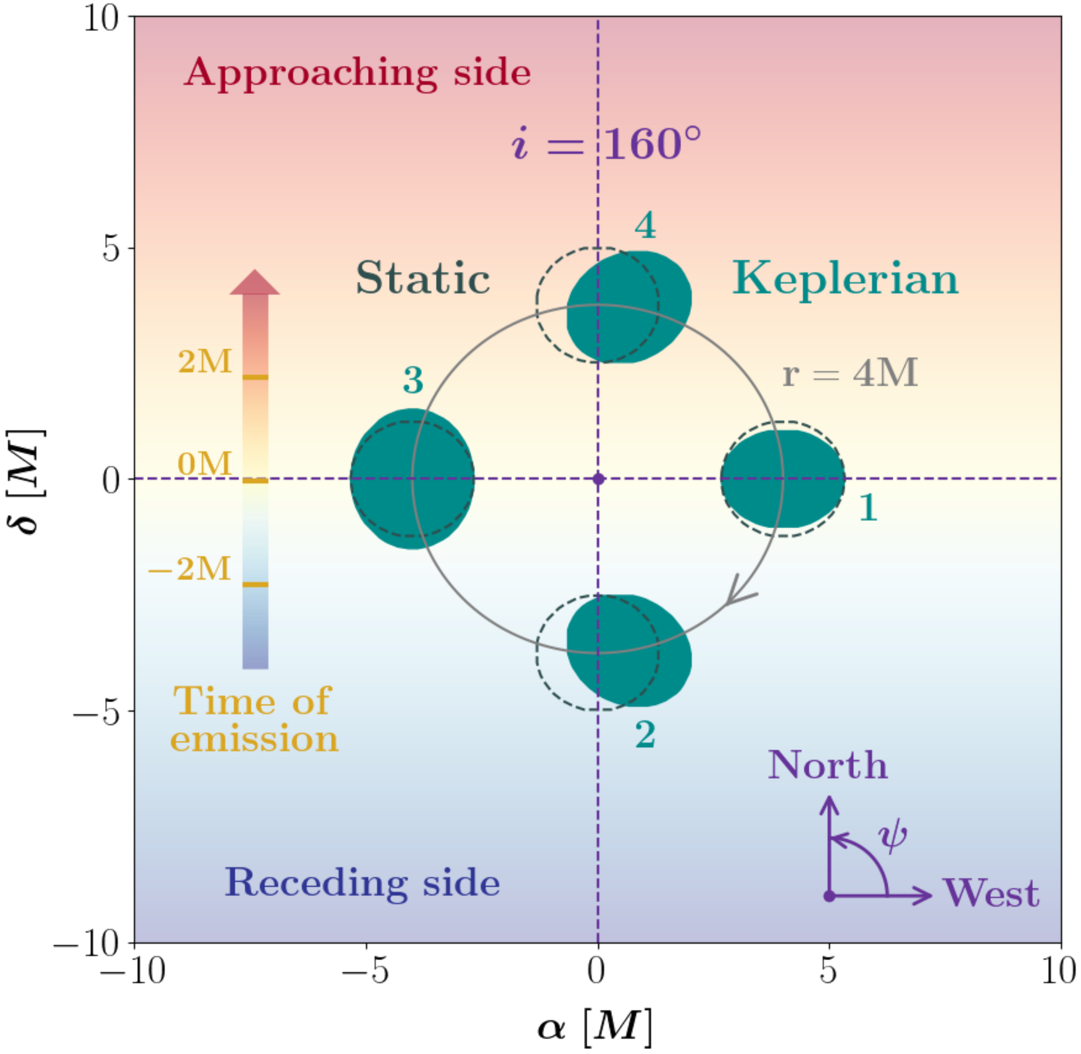

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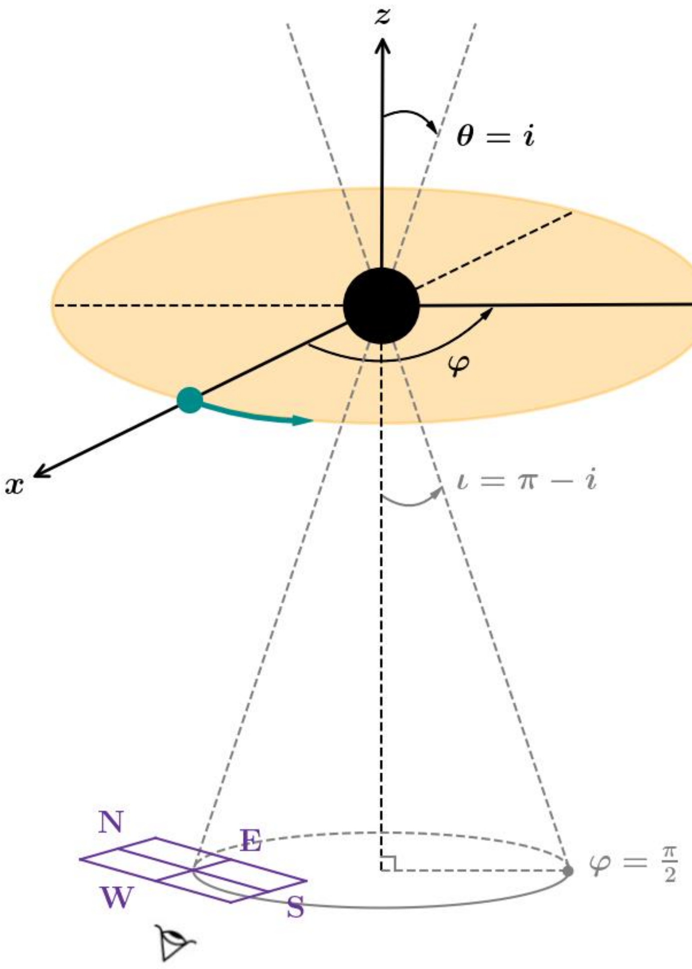
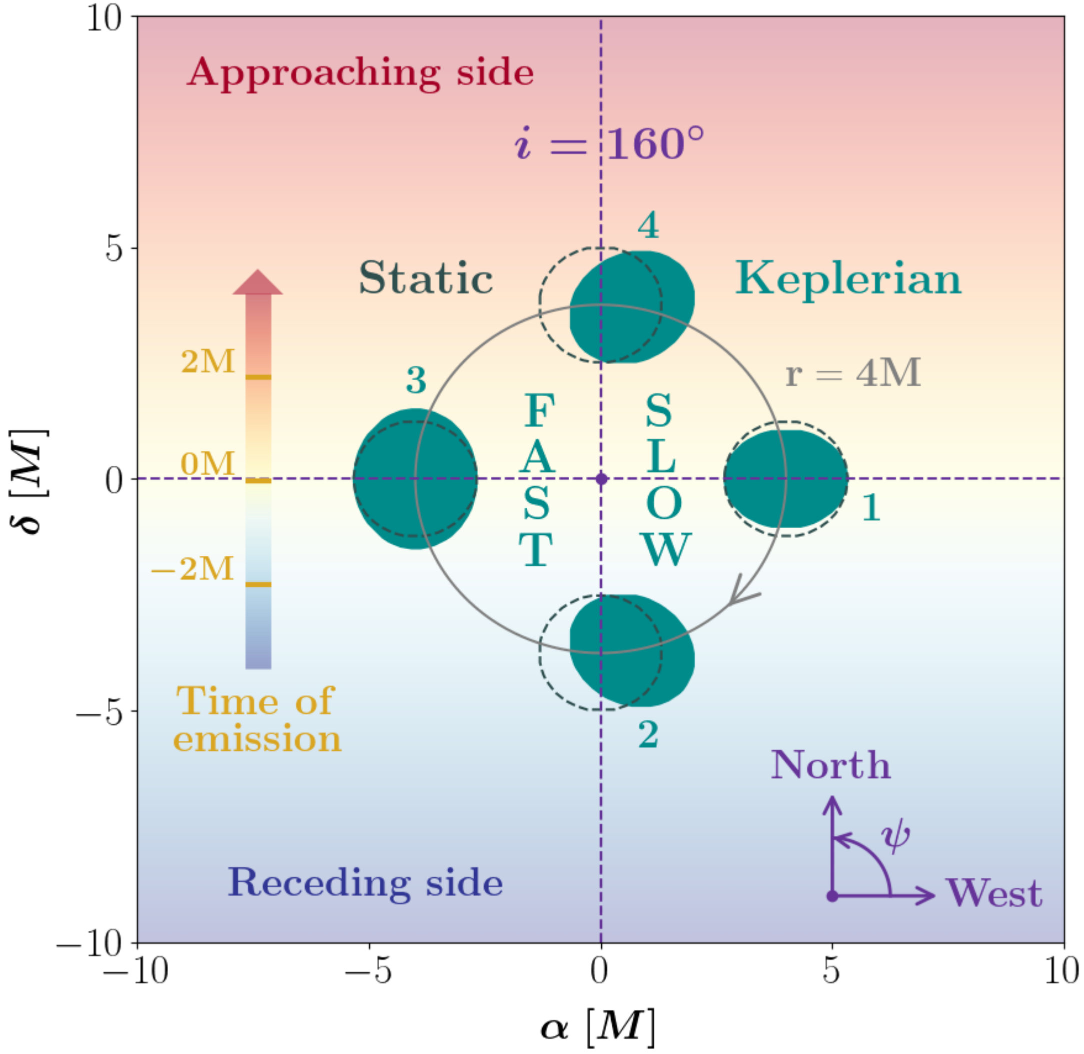
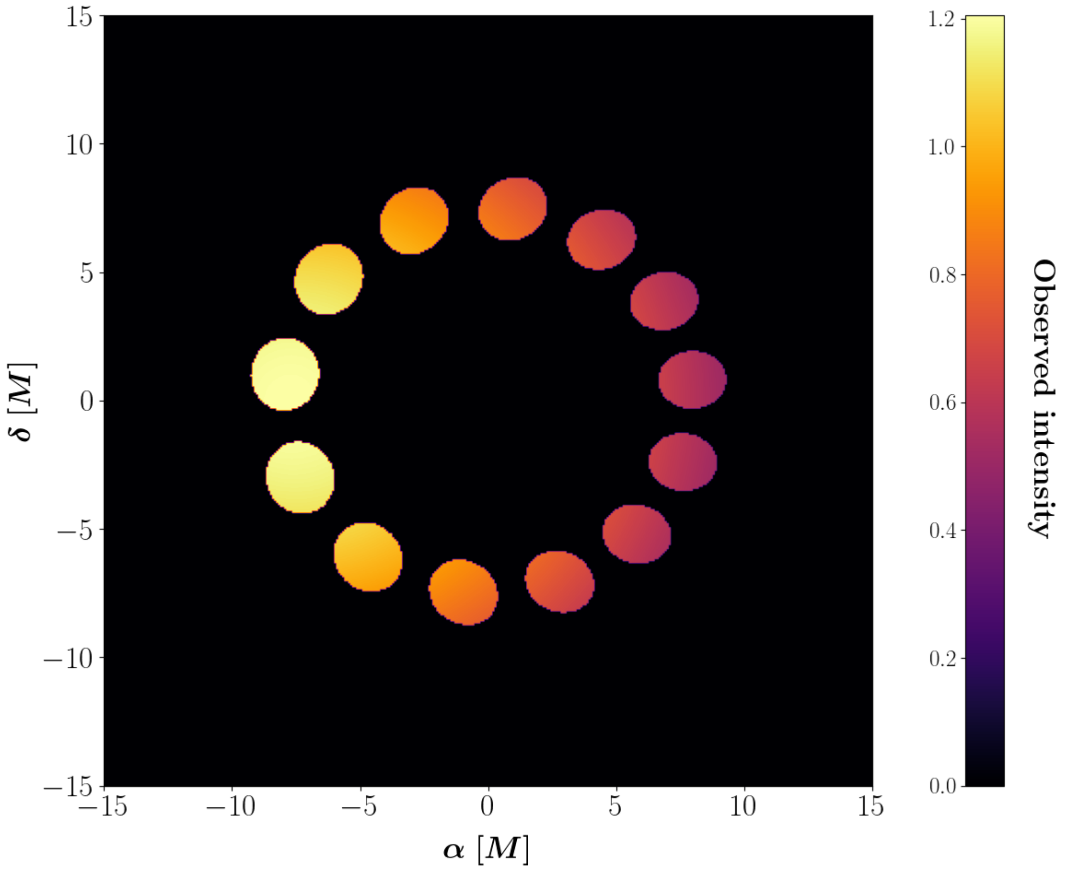




OBSERVED INTENSITY

- **Redshift:** $I_\nu^{obs} = g^3 I_\nu^{em}$



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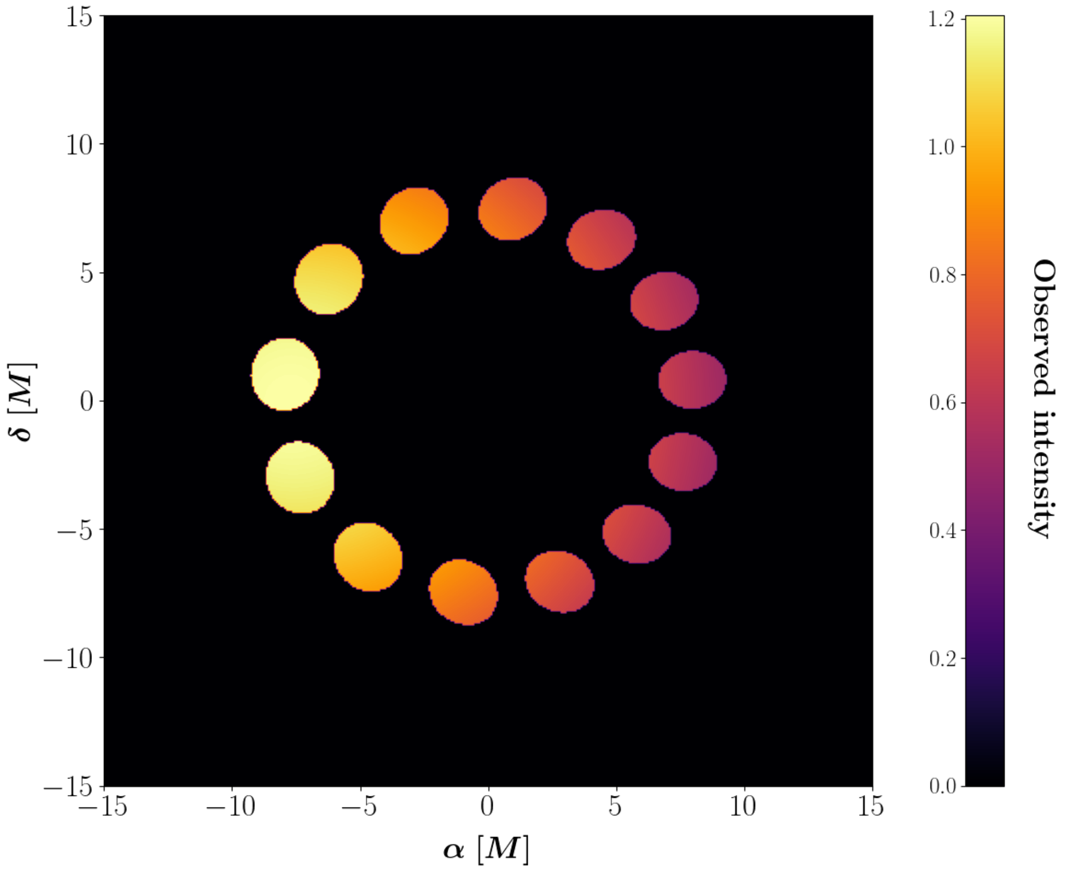
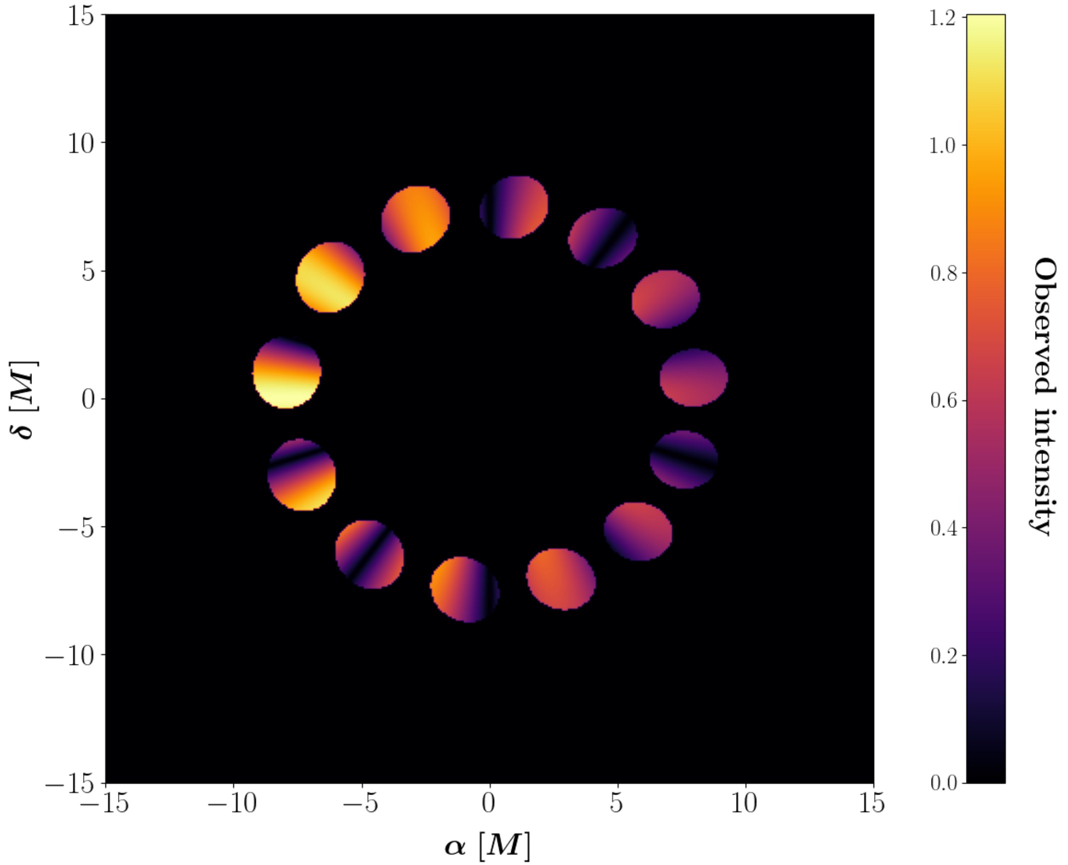
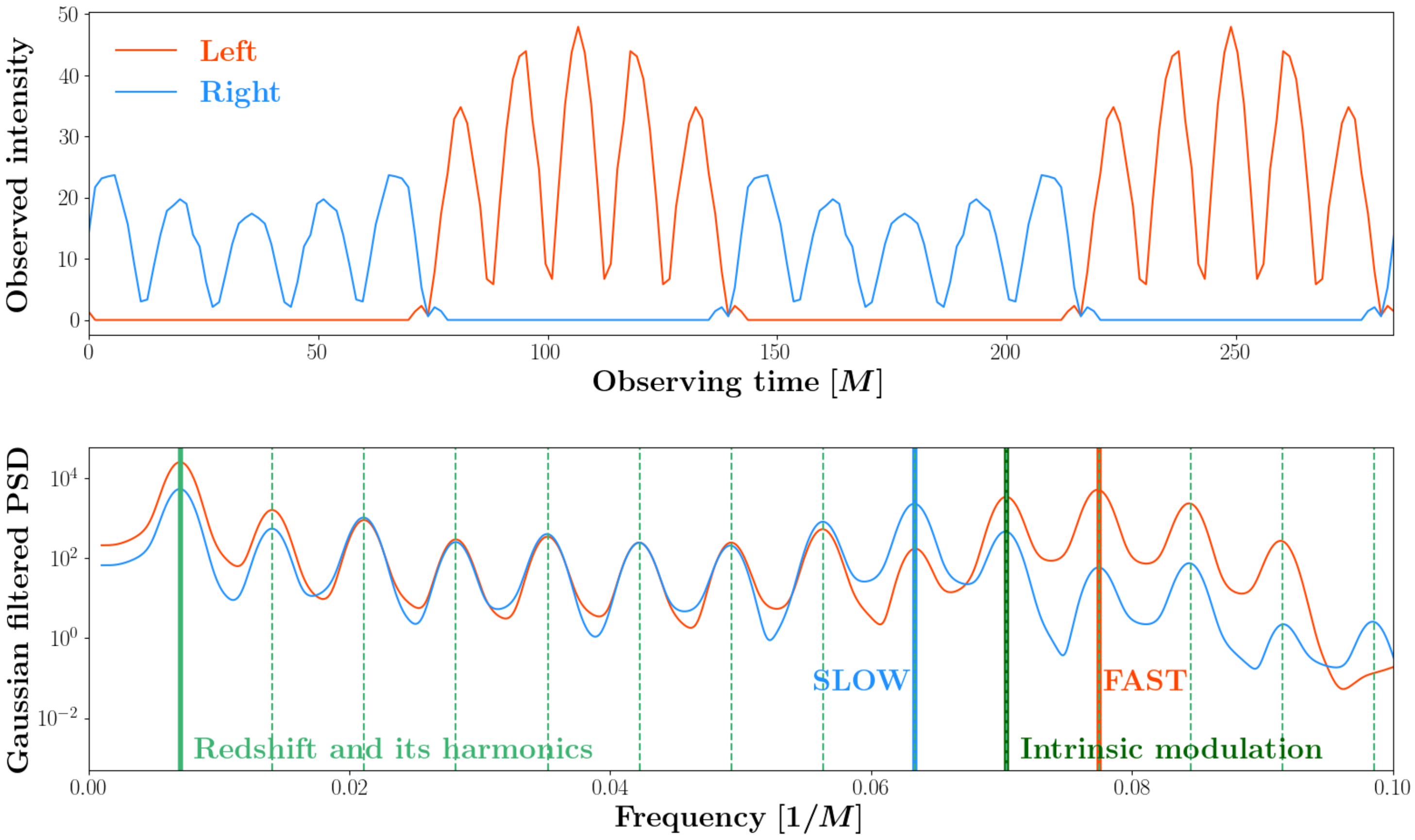


- **Intrinsic** time modulations

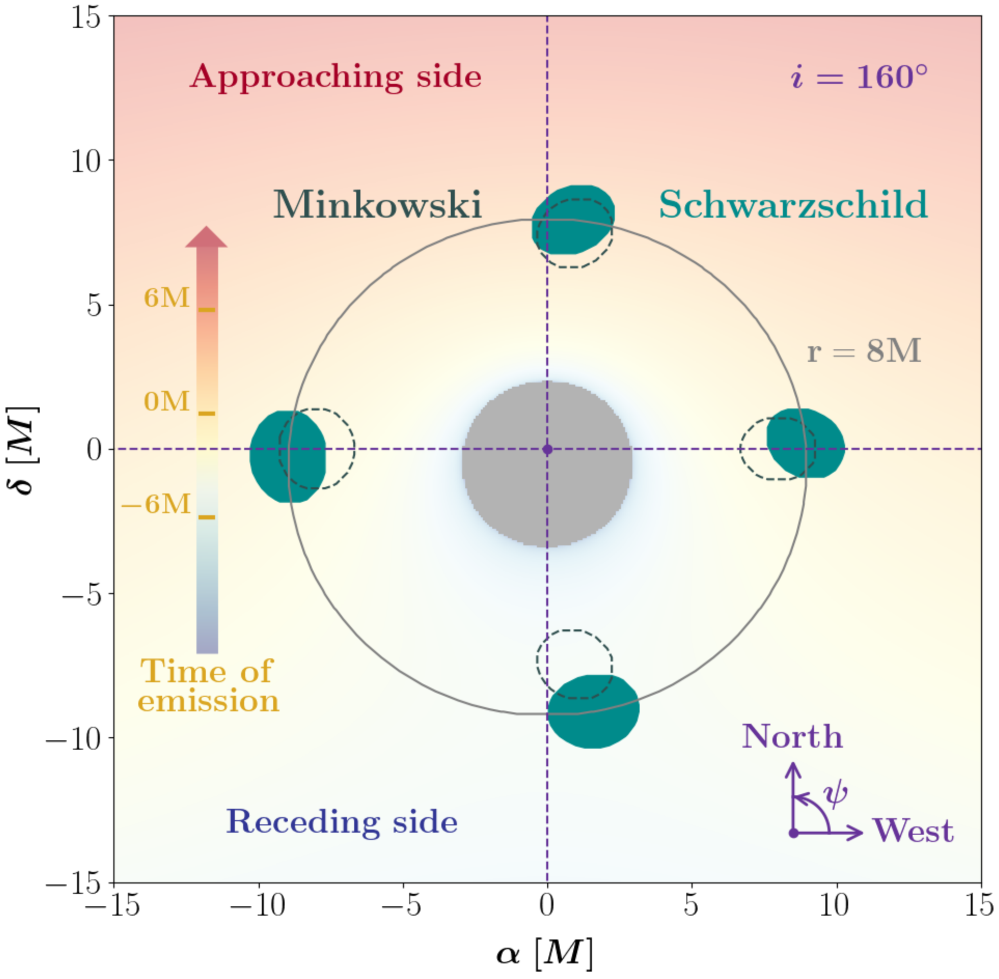


DYNAMICS

- Orbital radius: $r = 8$ M (GRAVITY Collaboration 2021)
- Lomb-Scargle periodiograms
- Observed intrinsic modulation frequencies functions of the **light time of flight** (spacetime + observer's inclination) and of the **velocity of the source**
  - **Analytical** predictions

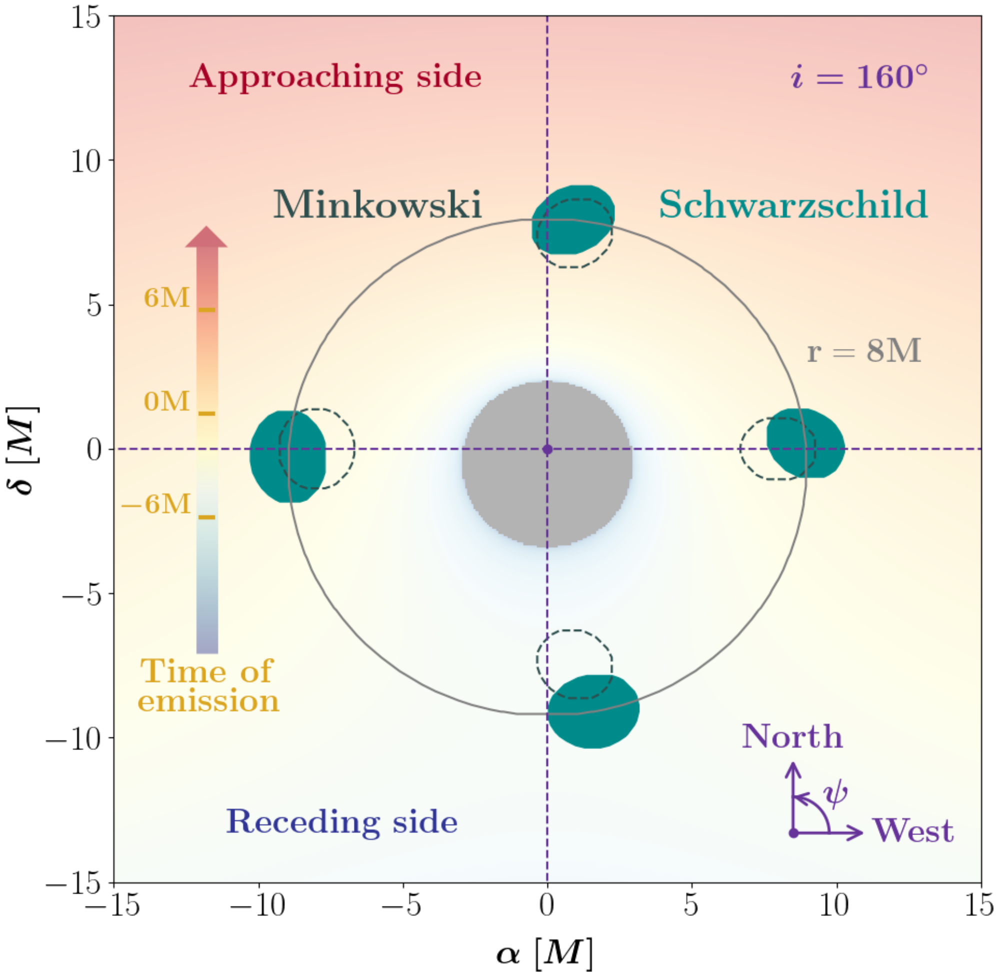


CURVATURE



Approaching side
$i = 160°$
Minkowski
Schwarzschild
6M
0M
−6M
Time of emission
r = 8M
North
ψ
West
Receding side
$\delta\ [M]$
$\alpha\ [M]$
15
10
5
0
−5
−10
−15

CURVATURE



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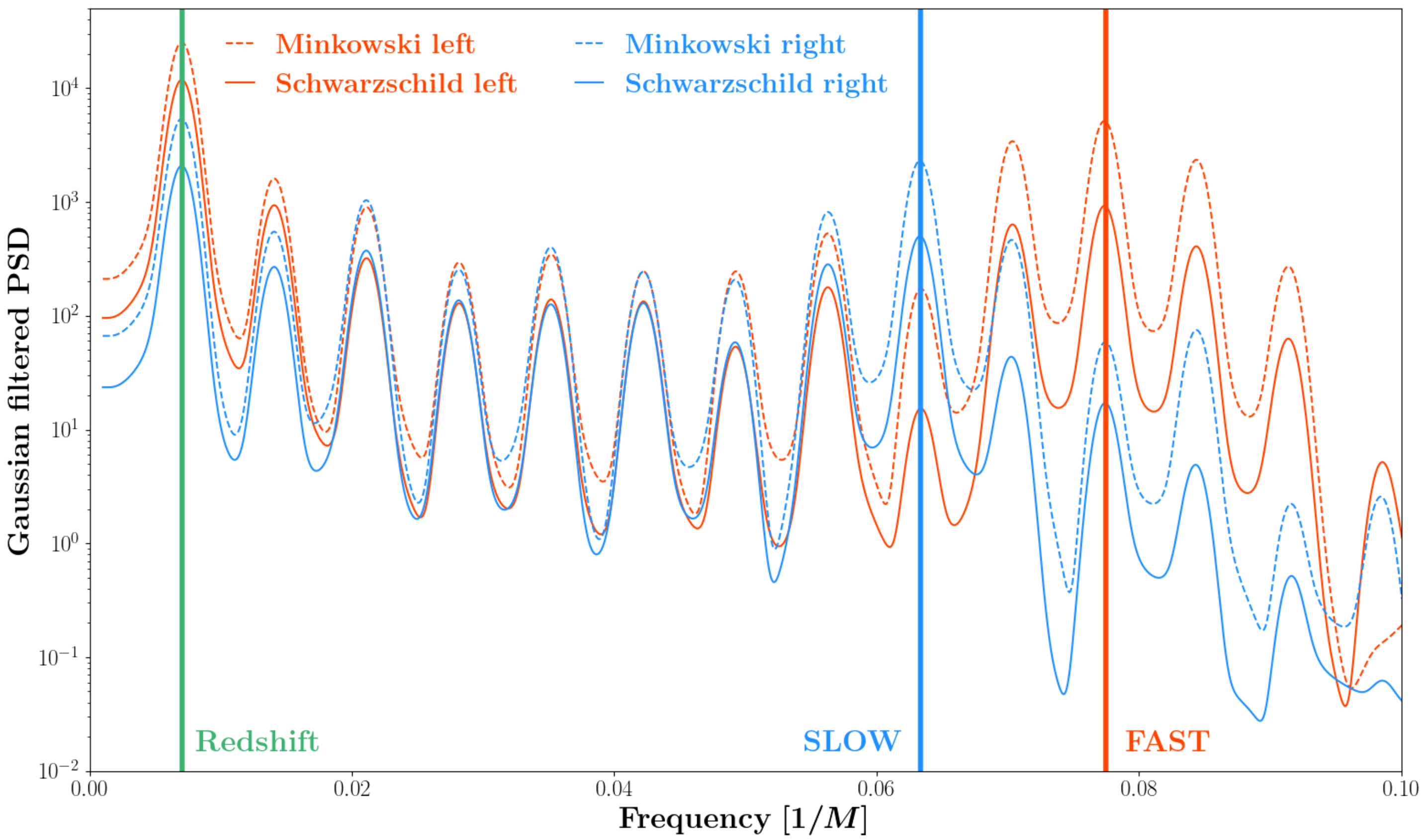
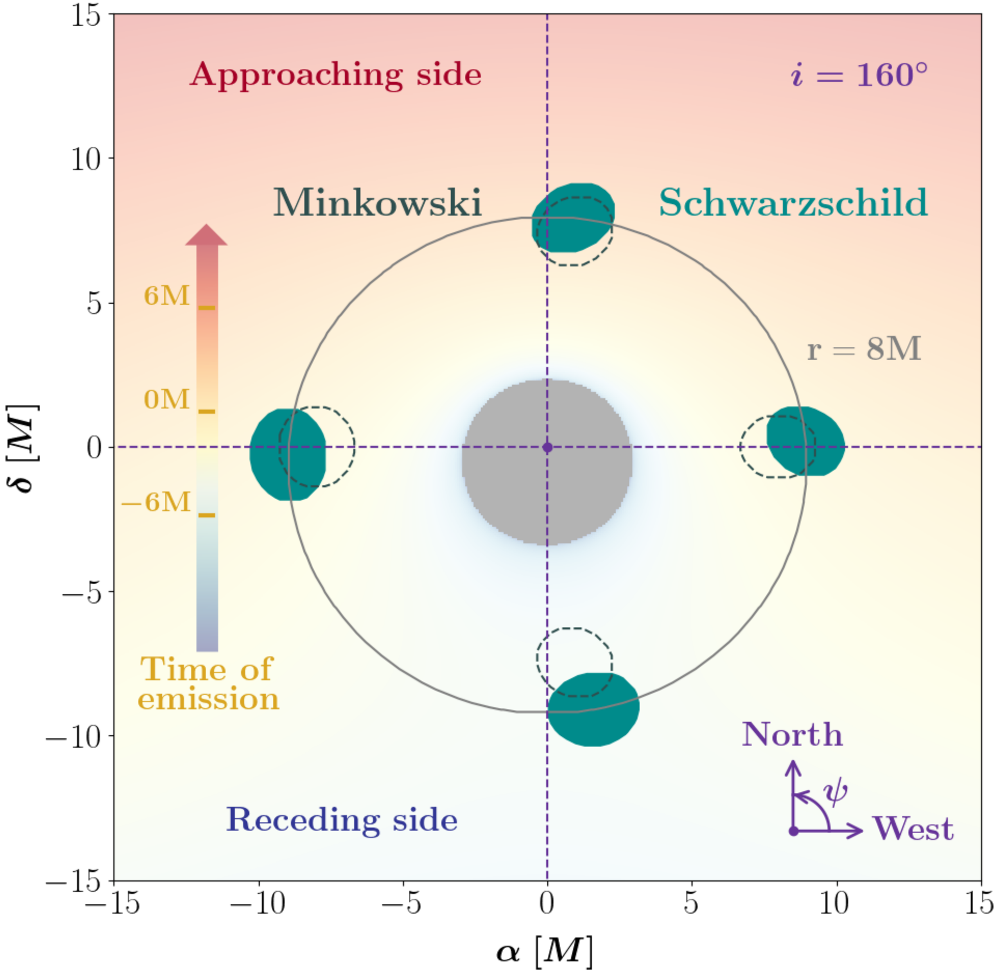
δ [M]
α [M]



Minkowski left
Schwarzschild left
Minkowski right
Schwarzschild right
Redshift
SLOW
FAST
Gaussian filtered PSD
Frequency [1/M]

CURVATURE



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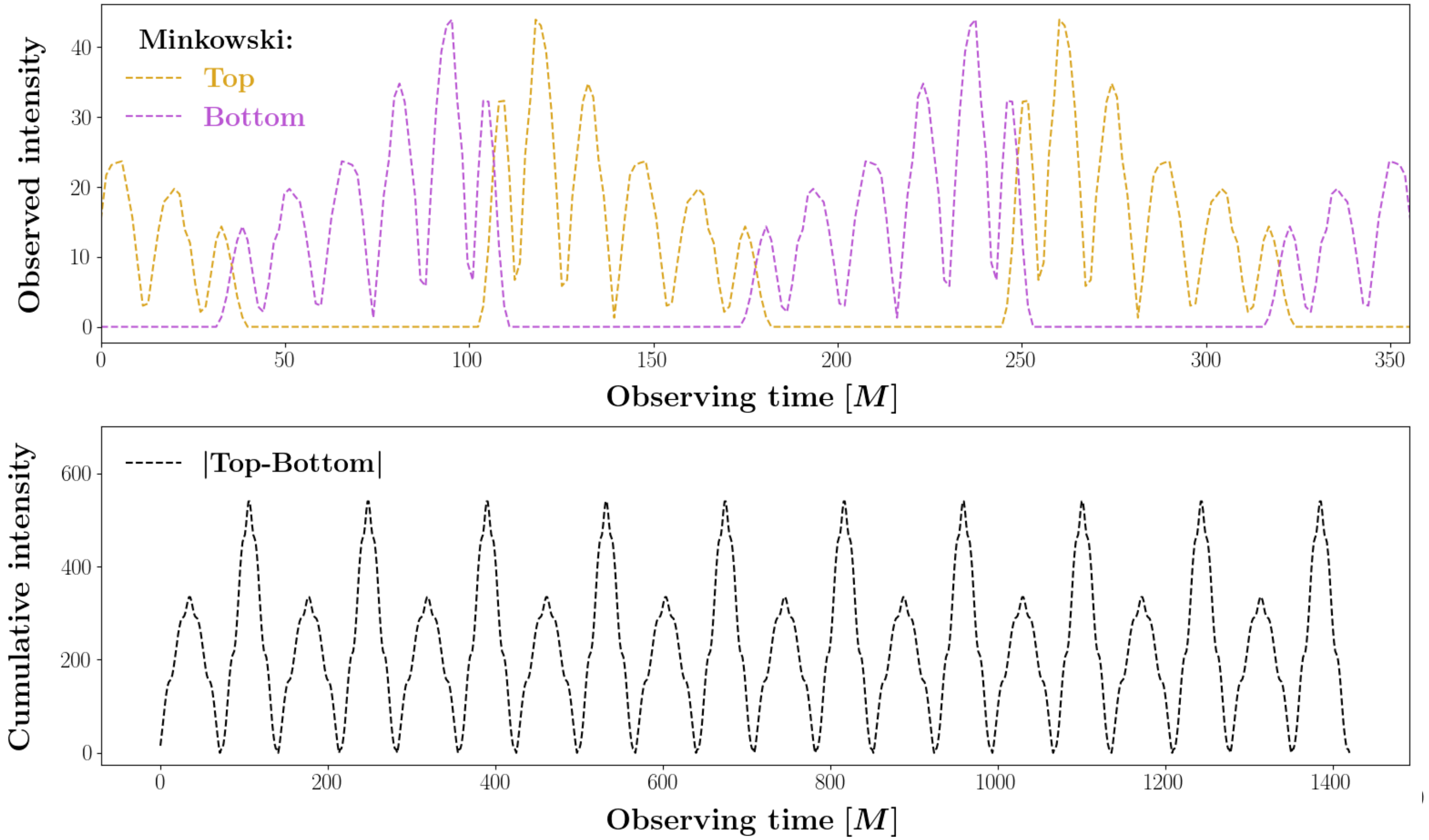
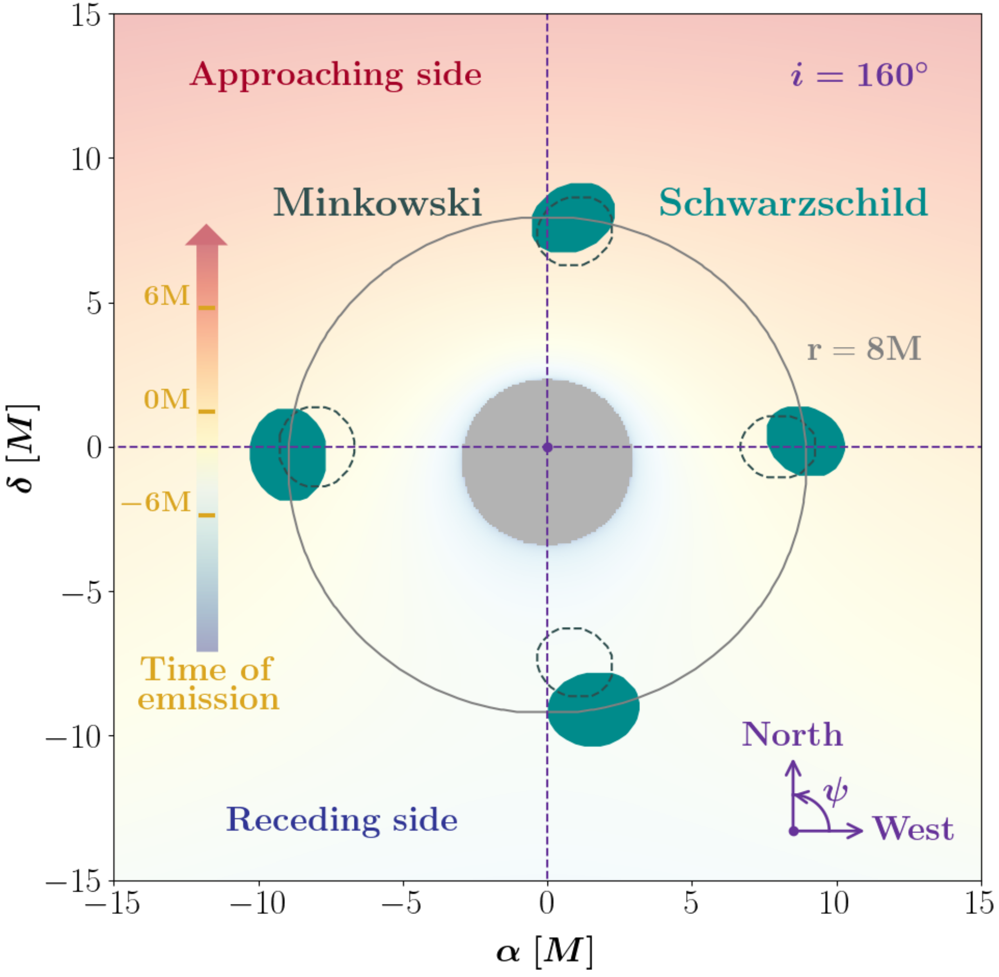
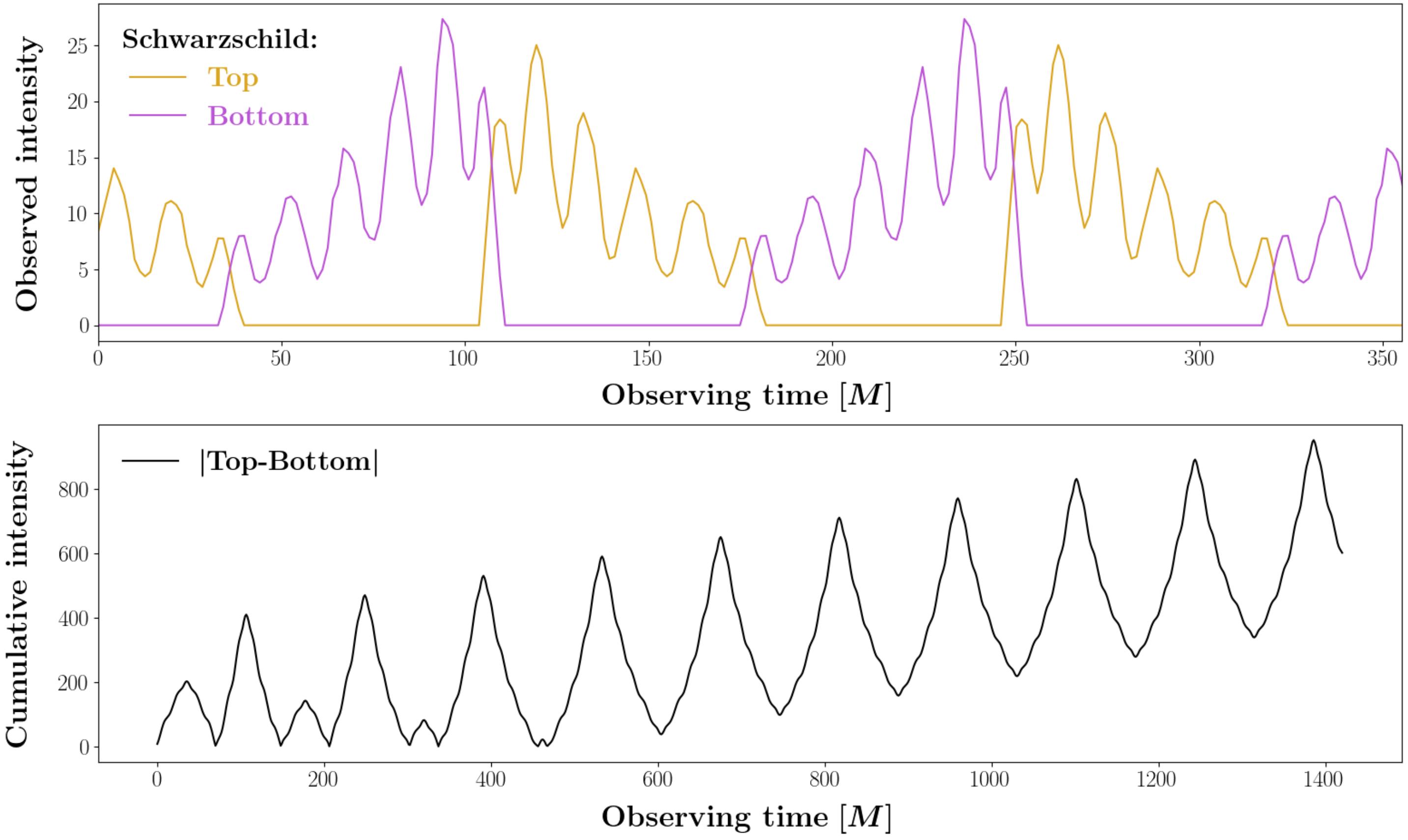


Minkowski:
Top
Bottom
Observed intensity
Observing time [M]
|Top-Bottom|
Cumulative intensity
Observing time [M]

CURVATURE

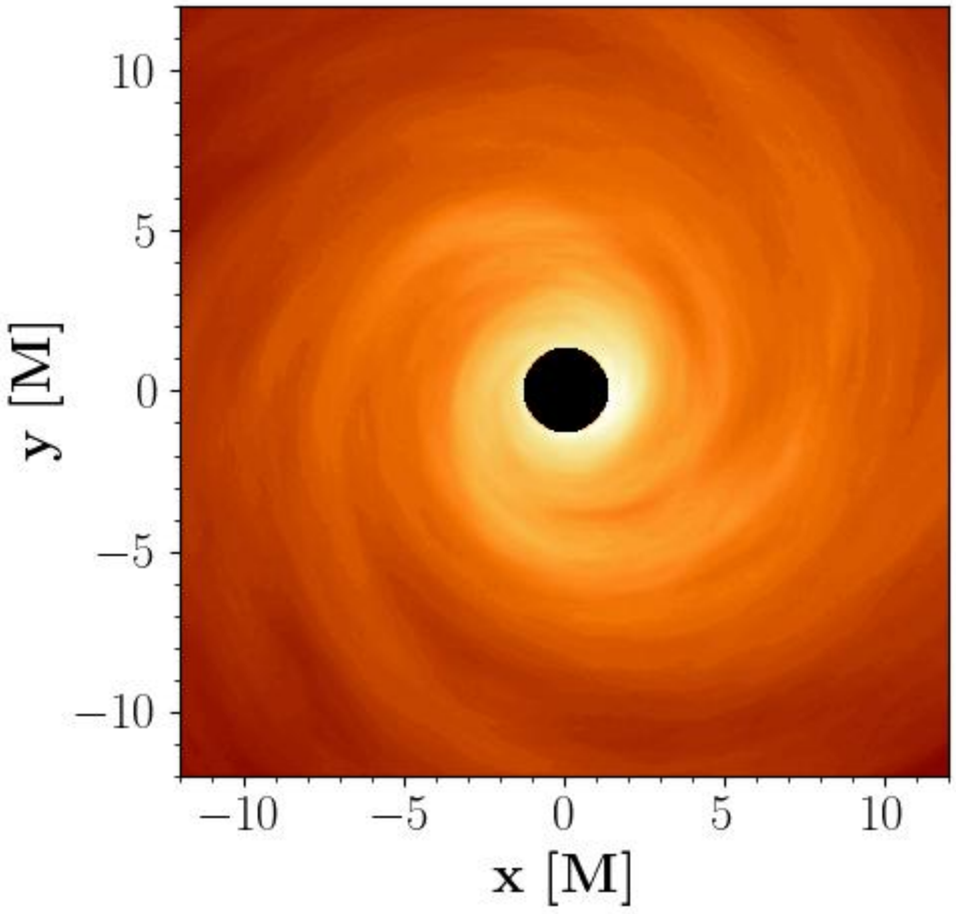
- Top-Bottom **asymmetry** induced by **lensing** effects





STATISTICAL FLUCTUATIONS

- **Semi-analytical statistical** fluctuations of a geometrically thin **Keplerian disc** (Lee & Gammie 2021)
  - Inhomogeneous
  - Anisotropic
  - Covariance of Kolmogorov **turbulence**
- **Fluctuations advected** by the flow
- **Timescale** of the fluctuations directly proportional to the **rotational period**



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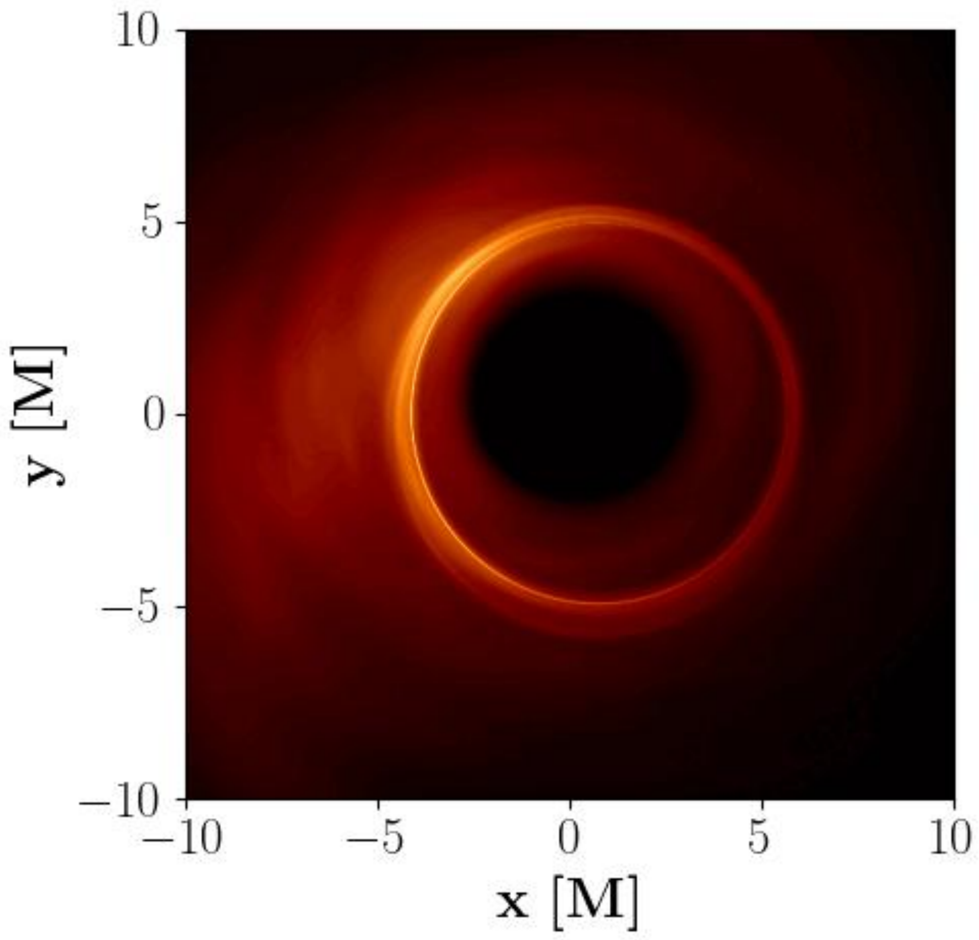


SUMMARY AND PROSPECTS

- **Apparent** hot spot **acceleration** due to light **time travel** and source **velocity**
  → Left-Right **intrinsic modulation shifts**

  → **Analytical** understanding

  → **Multiple hot spots** and **disc**

- **Curvature** induces additional **lensing** which adds up to the Roemer effect
  → Top-Bottom **asymmetry**

  → Pertinent **measurements**

  → **Spin** effects

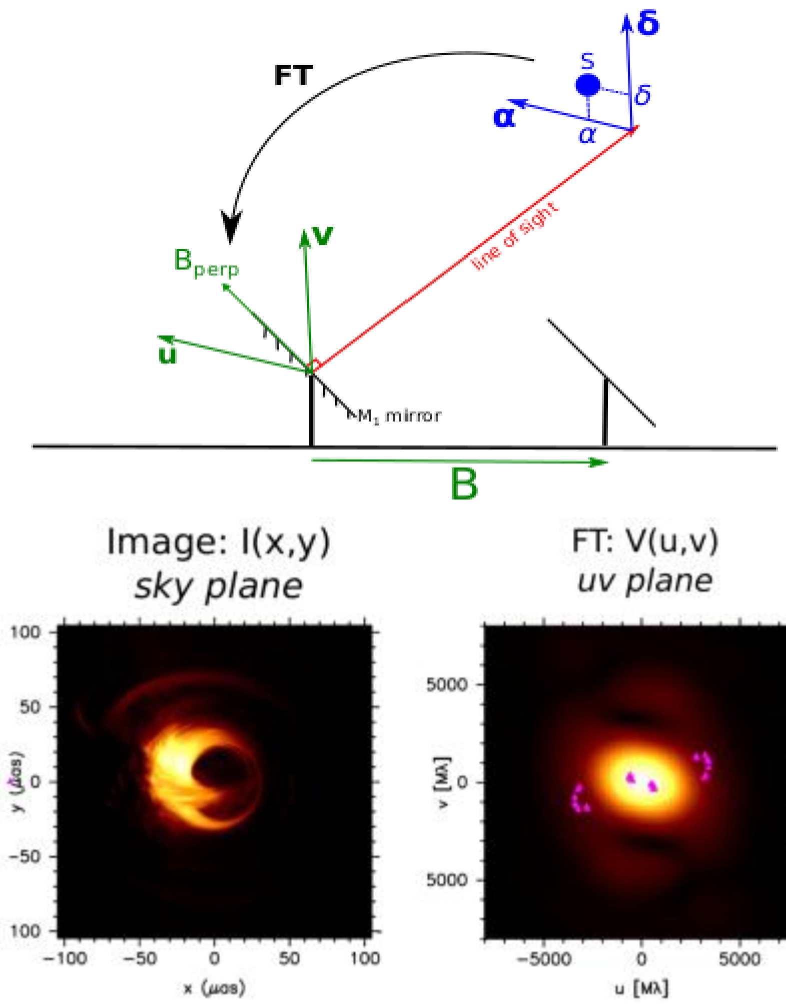
- **Image** decomposition in **quadrants** helps to **isolate relativistic effects**

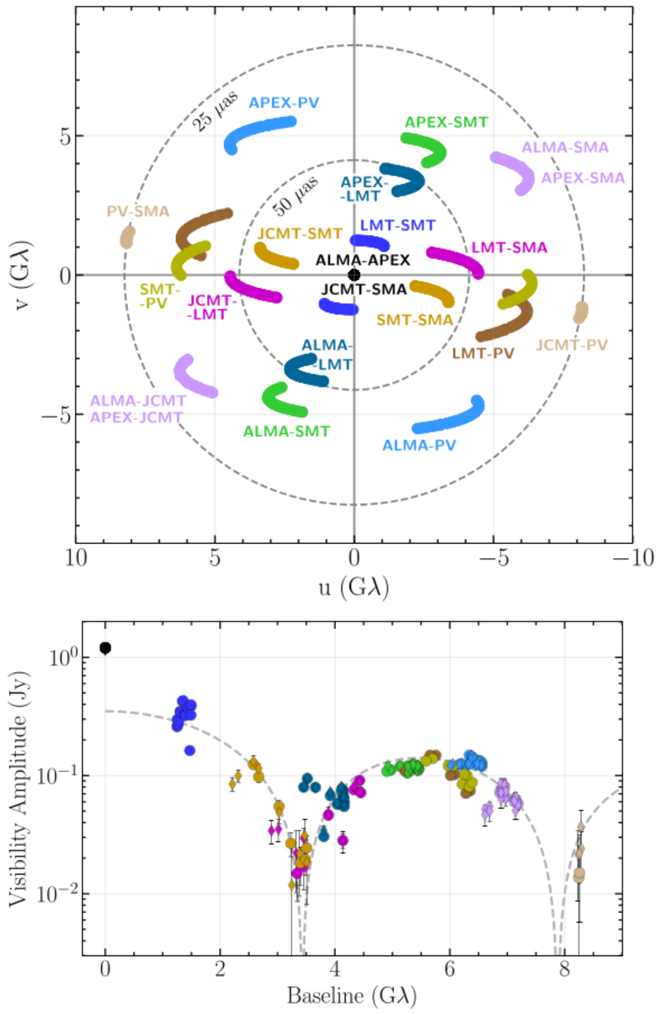
  → **Link** with real **observations**

BACKUP SLIDES

VERY LONG BASELINE INTERFEROMETRY

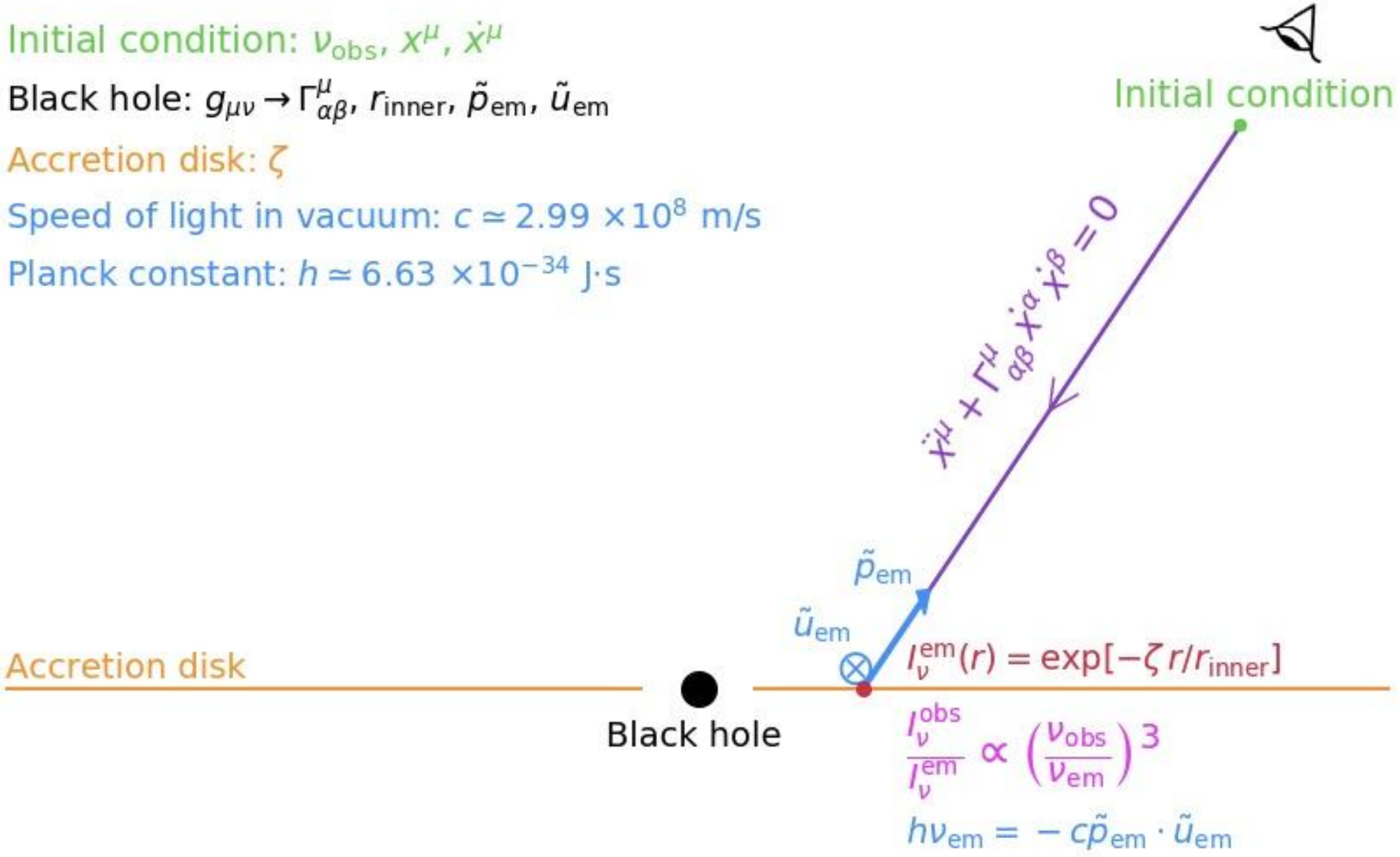
Credits: Frédéric Vincent



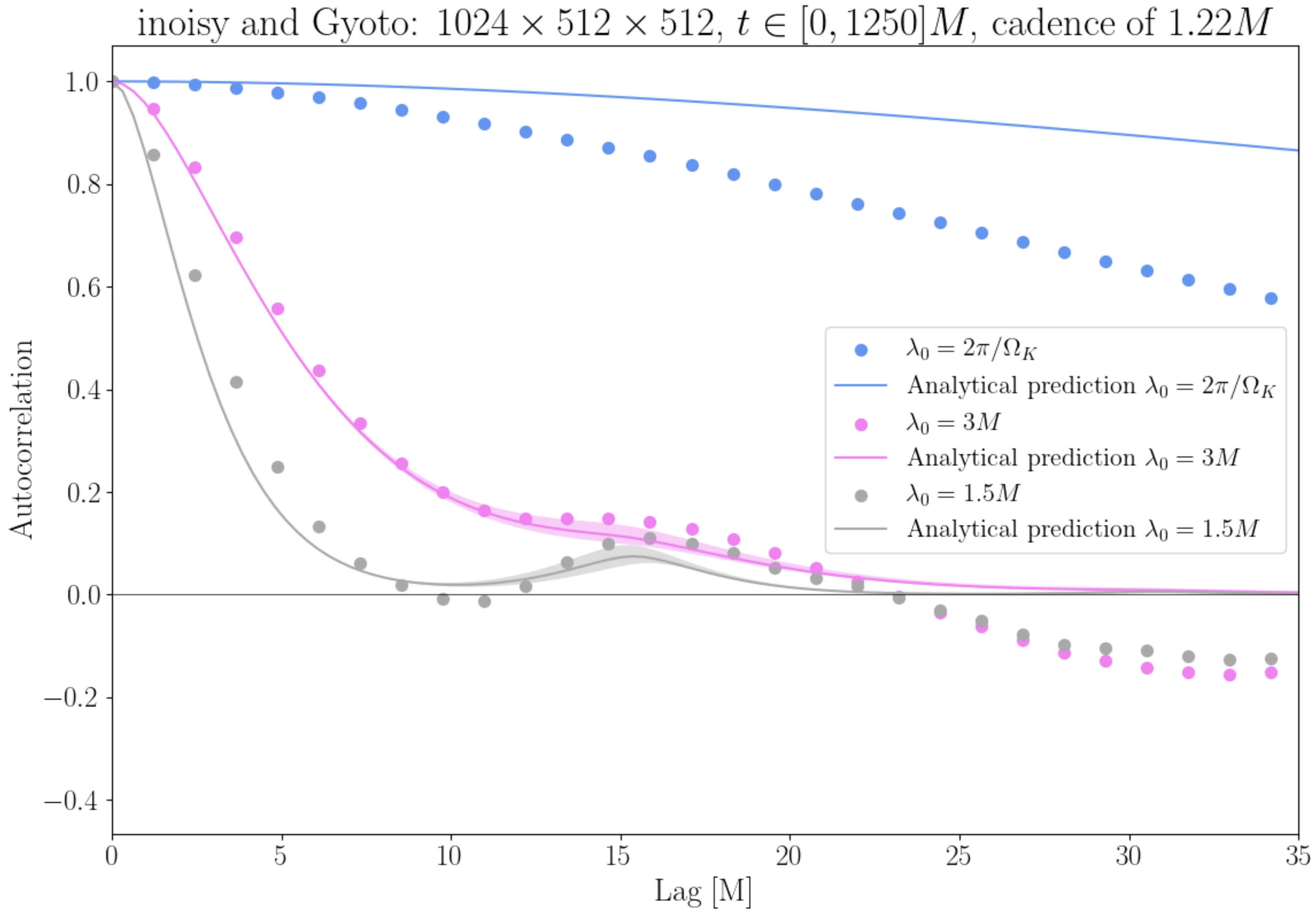


Credits: EHT collaboration

GYOTO


Initial condition: ν_{obs}, x^μ, $\dot{x}^\mu$
Black hole: $g_{\mu\nu} \rightarrow \Gamma^\mu_{\alpha\beta}$, r_{inner}, $\tilde{p}_{\mathrm{em}}$, $\tilde{u}_{\mathrm{em}}$
Accretion disk: ζ
Speed of light in vacuum: $c \simeq 2.99 \times 10^8$ m/s
Planck constant: $h \simeq 6.63 \times 10^{-34}$ J·s
Initial condition
$\ddot{x}^\mu + \Gamma^\mu_{\alpha\beta} \dot{x}^\alpha \dot{x}^\beta = 0$
$\tilde{p}_{\mathrm{em}}$
$\tilde{u}_{\mathrm{em}}$
$I_\nu^{\mathrm{em}}(r) = \exp[-\zeta\, r/r_{\mathrm{inner}}]$
Accretion disk
Black hole
$\frac{I_\nu^{\mathrm{obs}}}{I_\nu^{\mathrm{em}}} \propto \left(\frac{\nu_{\mathrm{obs}}}{\nu_{\mathrm{em}}}\right)^3$
$h\nu_{\mathrm{em}} = -c\tilde{p}_{\mathrm{em}} \cdot \tilde{u}_{\mathrm{em}}$

CODE VALIDATION



- The **longer** the **signal** and **smaller** the **time steps**, better the autocorrelation
- Longer series to ray-trace: **computationally expensive**
- Razor-thin disc: **ray-trace** the geometric quantities **once**
- **Construct** images: $I_\nu^{obs} = g I_\nu^{em}$