Measurement of Black Hole Spin with the Event Horizon Telescope: Theory of Radiative Echoes and VLBI Observational Approaches

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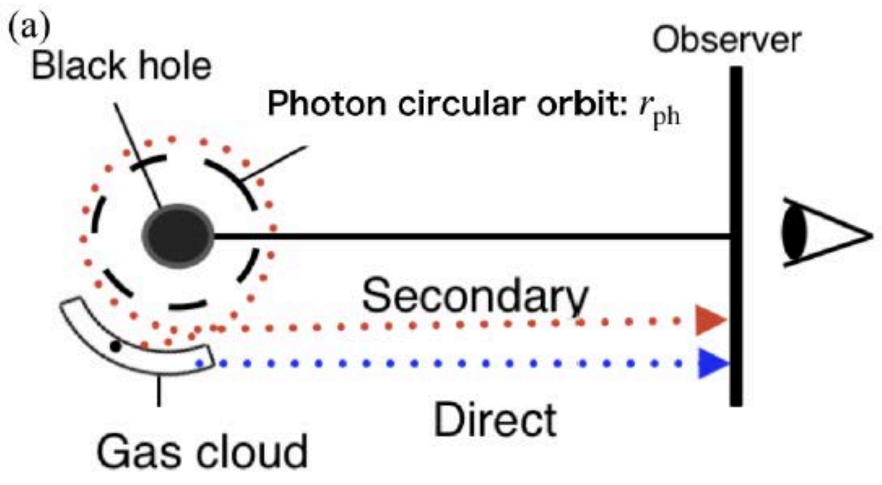
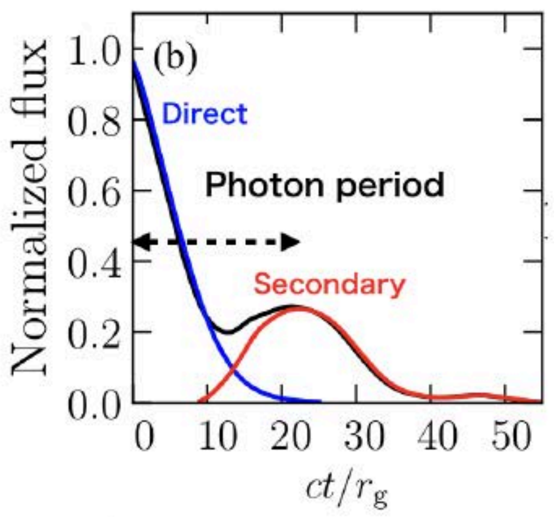
1. Introduction

The measurement of black-hole spacetime is a substantial topic for probing the theory of general relativity. General relativity predicts that the spacetime around a black hole is uniquely described by its mass and spin parameter. The black hole mass can be accurately measured by orbits of stars or gas dynamics inside the sphere of its gravitational influence extending up to ~ 105 rg, where rg is the gravitational radius. On the other hand, the spin measurement requires capturing horizon-scale emission from the black hole, since general relativistic effects of the spin significantly appear only at the immediate vicinity of the black hole (~ rg). EHT observations of the horizon-scale emission provide the spatial and temporal information of the accretion flow in the black hole's vicinity[2-7]. However, it is not easy to extract the spin information from the emission because it depends on both the complexity of accretion properties and spacetime effects.

2.1 Relativistic Echoes from Infalling Gas Clouds

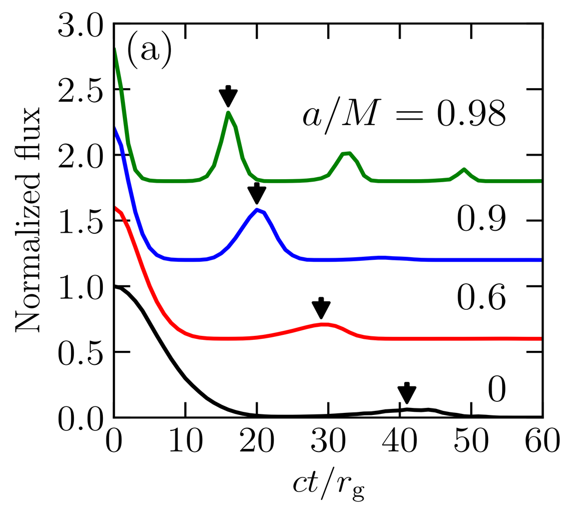




Photons directly reach a distant observer

Photons reaching the observer after more than one rotation around the black hole

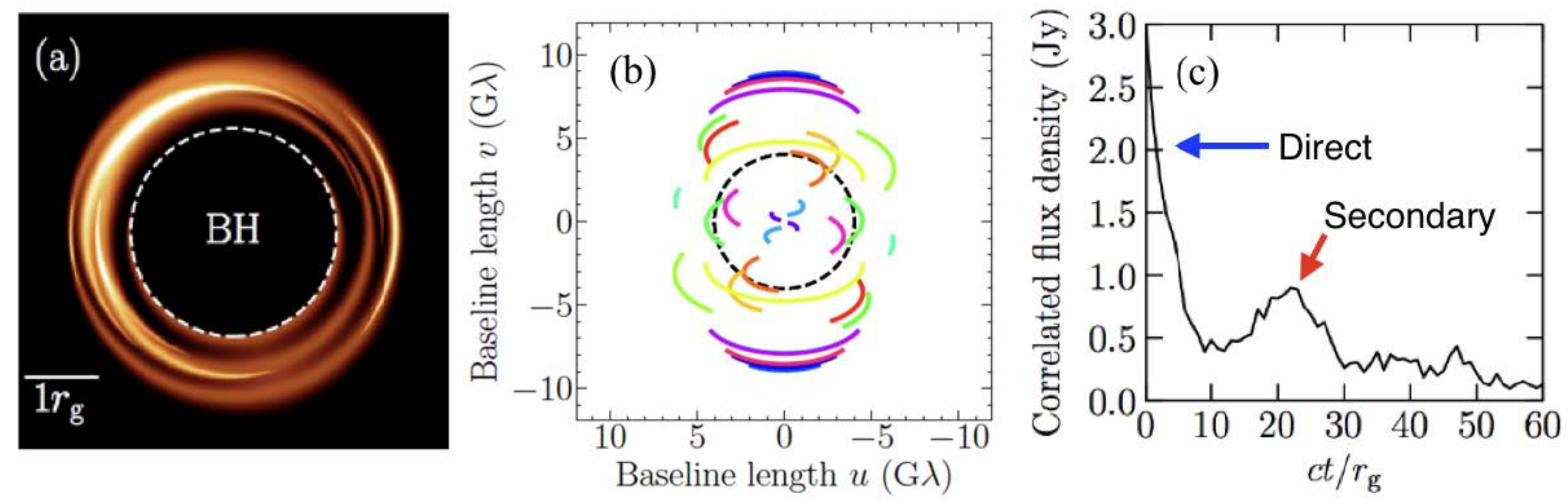
Situation: gas clouds are tidally stripped off from the innermost parts of an accretion disk and intermittently fall toward the black hole [10-13].



Time interval of the echo ~ photon rotation period $\propto a/M$ (spin value)

Time interval of echoes is not significantly affected by the parameters of gas clouds.

2.2 Detectability of Radiative Echoes

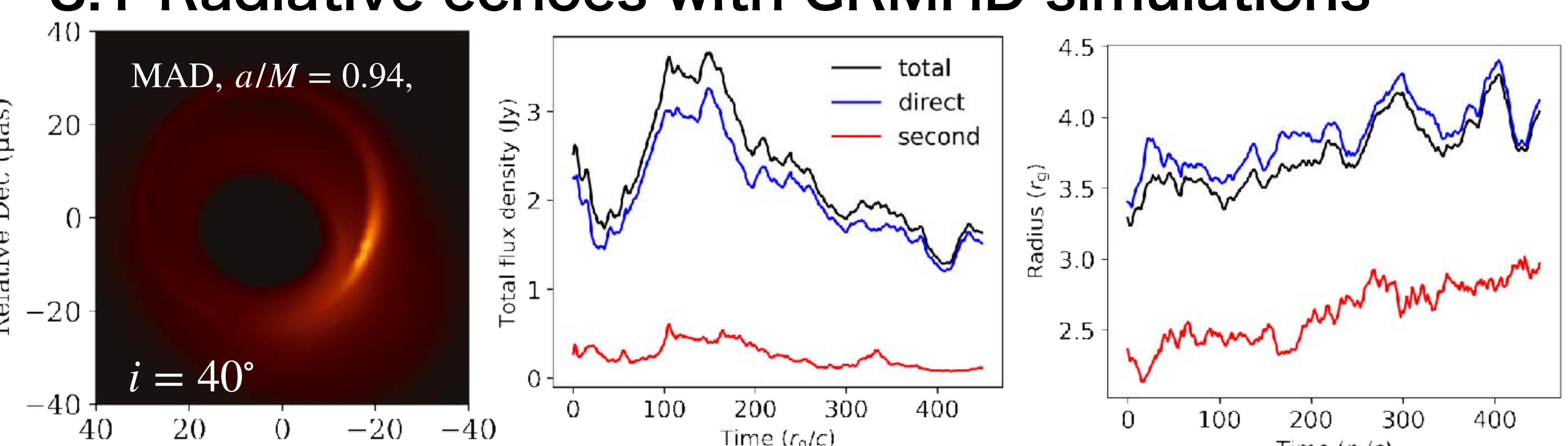


(a) Synthetic observations for Sgr A* under a situation that a number of gas clouds intermittently fall towards the black hole with various initial parameters.

(b) Possible (u, v) tracks for 16 baselines expected near-future EHT observations for Sgr A*(2017-2021).

(c) Detectability of relativistc echoes in EHT observations of Sgr A* since 2017 [13]

3.1 Radiative echoes with GRMHD simulations



$\dot{M} \sim 10^{-8} M_{\odot} yr^{-1}$ (e.g., Bower et al. 2018)

$\langle F_{total} \rangle \sim 2$ Jy $\langle F_{second} \rangle \sim 0.2$ Jy

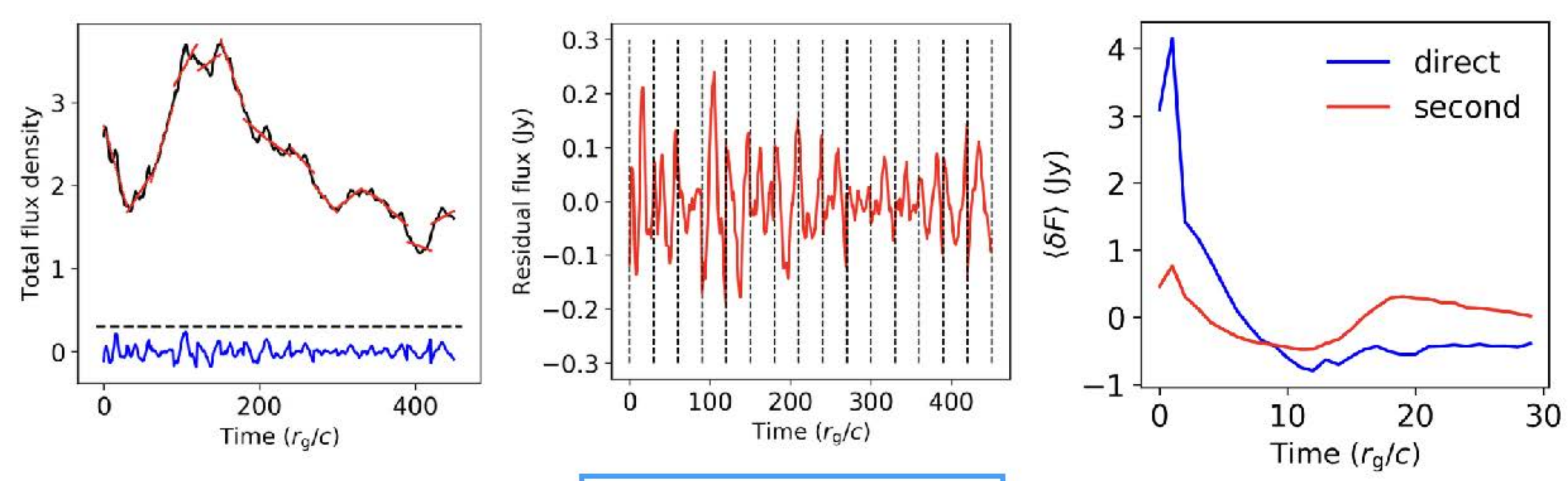
$\langle r_{total} \rangle \sim 3.5 r_g$ $\langle r_{second} \rangle \sim 2.5$ Jy

$T_{second} = 15 - 20 r_g/c$

Assumption of gas cloud model: shape and thickness have no time dependence and showed that our spacetime measurement does not depend on these values.
Section 3: Optimize the spacetime measurement by including the effect of the time development of gas-cloud structures with 3D-GRMHD simulations.

3D- GRMHD simulation data from iharm3D [8], Raytracing scheme [12, 13]

3.2 Detection of Radiative Echoes



Procedure of the echo extraction

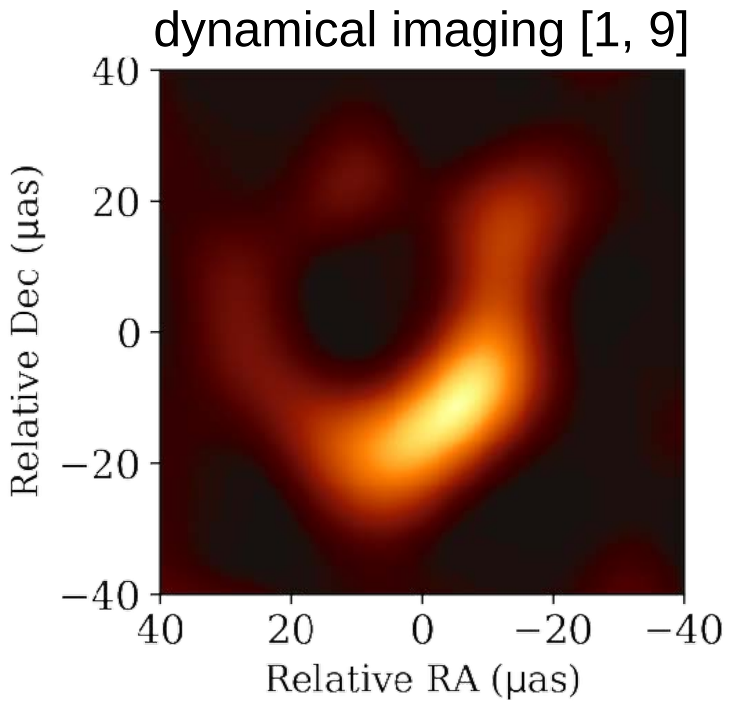
Linear fit to reduce the long timescale variation

Superposed shot analysis:
1. Split residual F into each segment
2. Superpose light curves in each segment by aliging maximum peaks

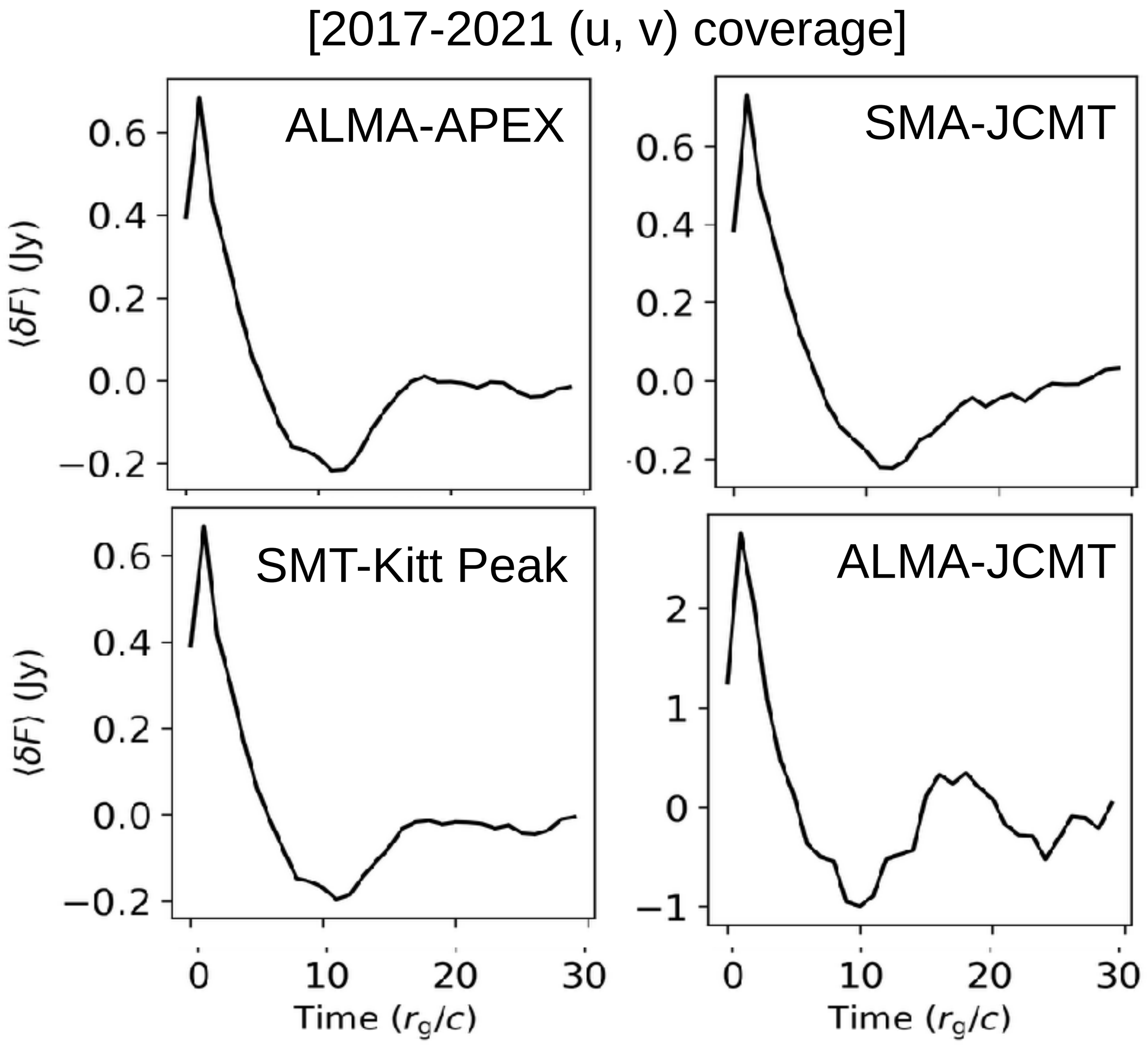
1. Number of shots =125
2. Secondary peak at $ct/r_g \sim 20$
→Detection of echoes with spin dependency

3.3 EHT Synthetic Observation (2017-2021)

Averaged image with dynamical imaging [1, 9]



EHT synthetic observation for Sgr A* [2017-2021 (u, v) coverage]



Relativistic echoes are detectable in the simulated visibility amplitudes accurately calibrated by baselines between sites with redundant stations

4. Summary and Next Issues

Summary:

1. Detection of relativistic echoes in the high spin black hole case
2. Investigate the detectability based on 2017-2020 EHT synthetic observation
3. Accretion flow with GRMHD simulations shows the existence of radiative echoes

Next issues

1. Echo existence in different spin cases
2. Evaluate the accuracy of the spin observations
3. Improveme the method for testing non-GR effects

Reference

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[2] EHT Collaboration 2019a, *ApJ*, 875, L1
[3] EHT Collaboration 2019b, *ApJ*, 875, L2
[4] EHT Collaboration 2019c, *ApJ*, 875, L3
[5] EHT Collaboration 2019d, *ApJ*, 875, L4
[6] EHT Collaboration 2019e, *ApJ*, 875, L5
[7] EHT Collaboration 2019f, *ApJ*, 875, L6
[8] Gammie et al. 2003, *ApJ*, 589, 444
[9] Johnson et al. 2017, *ApJ*, 850, 172
[10] Moriyama & Mineshige 2015, *PASJ*, 67, 6
[11] Moriyama & Mineshige 2016, *PASJ*, 68, 3
[12] Moriyama et al. 2017, *ApJ*, 850, 1
[13] Moriyama et al. 2019, *ApJ*, 887, 227