Test Theories of Gravity via BH Shadows and Modeling of Relativistic Jets

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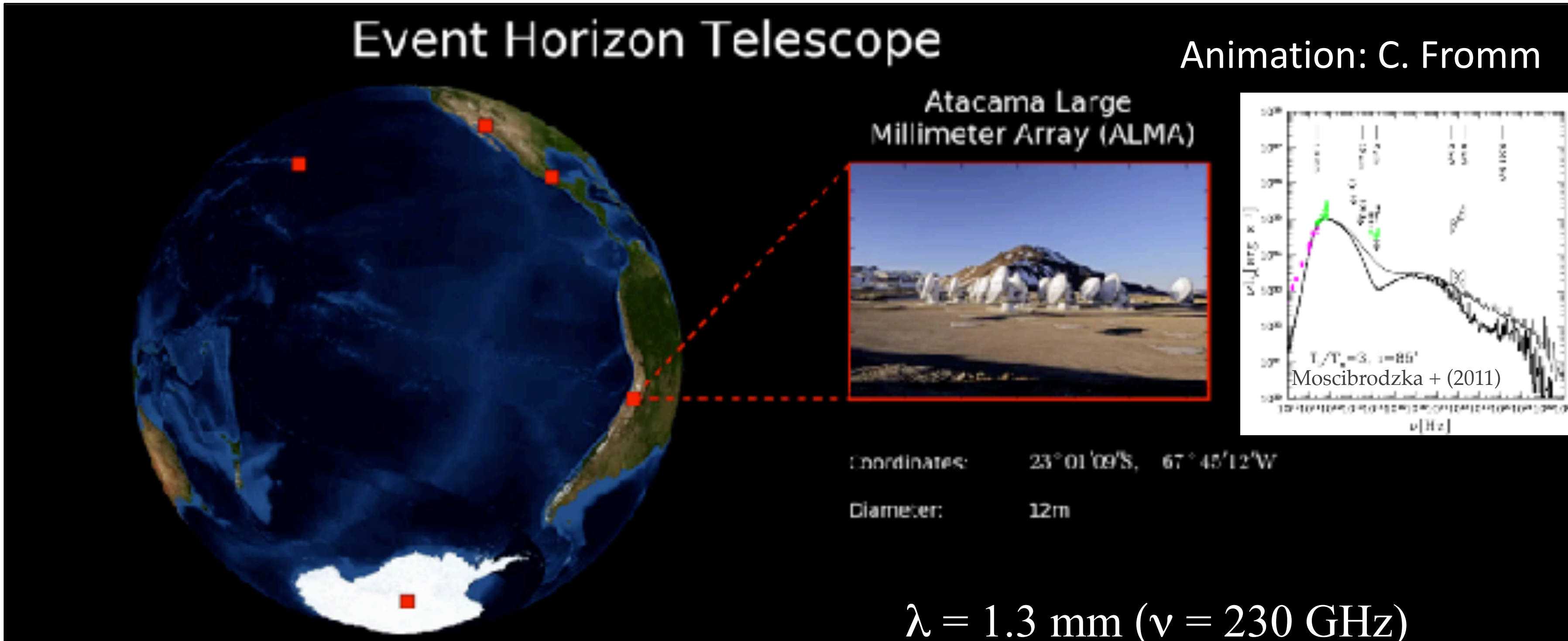
Event Horizon Telescope

International collaboration project of Very Long Baseline Interferometry (VLBI) at mm (sub-mm) wavelength

Event Horizon Telescope



Create a virtual radio telescope the size of the earth, using the shortest wavelength

λ = 1.3 mm (ν = 230 GHz)
D ~ 10,000 km
=> $\lambda/D \sim 25\ \mu as$

Two main targets: Sgr A* & M87

Predicting the realistic BH shadow image

- Milimetre (submm)-VLBI of EHT will be achieved the event horizon scale observation (BH shadow image) in near future
- Ingredients for realistic theoretical image of BH shadow

1. Plasma behaviour surrounding BH

   Consider time evolution of accreting matter onto BH and formation of relativistic jets

2. Radiation process

   Consider GR effects (geodesic, redshift), thermal/non-thermal radiation process, optical thickness etc.

3. BH spacetime
4. VLBI array configuration and schedule

- Tools: General Relativistic MHD code + General Relativistic Radiation Transfer code + synthetic imaging

Which gravitational theory?

- Future mm/sub-mm VLBI observation of EHT will provide the first images of the BH shadow in our galactic centre, Sgr A* & M87.

- If the observations are sufficiently accurate, it will provide
  - the evidence for the existence of an event horizon
  - Testing the no-hair theorem in GR
  - Testing of GR itself against a number of alternative theories of gravity.

- Reasonable to use a model-independent framework which parametrises the most generic BH geometry though finite number of adjustable quantities.
- Recently new parametric framework of generic metric is proposed in spherically symmetric BH (Rezzolla & Zhidenko 2014) and in axisymmetric BH (Konoplya et al. 2016)

Dilaton Black Holes

- For first test, consider non-rotating Dilaton black hole.
  (coming from Einstein-Maxwell-dilaton-axion (EMDA) gravity which is the low energy limit of the bosonic sector of the heterotic string theory)

- When both the axion field and the BH spin vanish, such a BH is described by spherically symmetric metric

$$ds^2 = -\left(\frac{\rho - 2\mu}{\rho + 2b}\right) dt^2 + \left(\frac{\rho + 2b}{\rho - 2\mu}\right) d\rho^2 + (\rho^2 + 2b\rho) d\Omega^2$$ (Exact form)

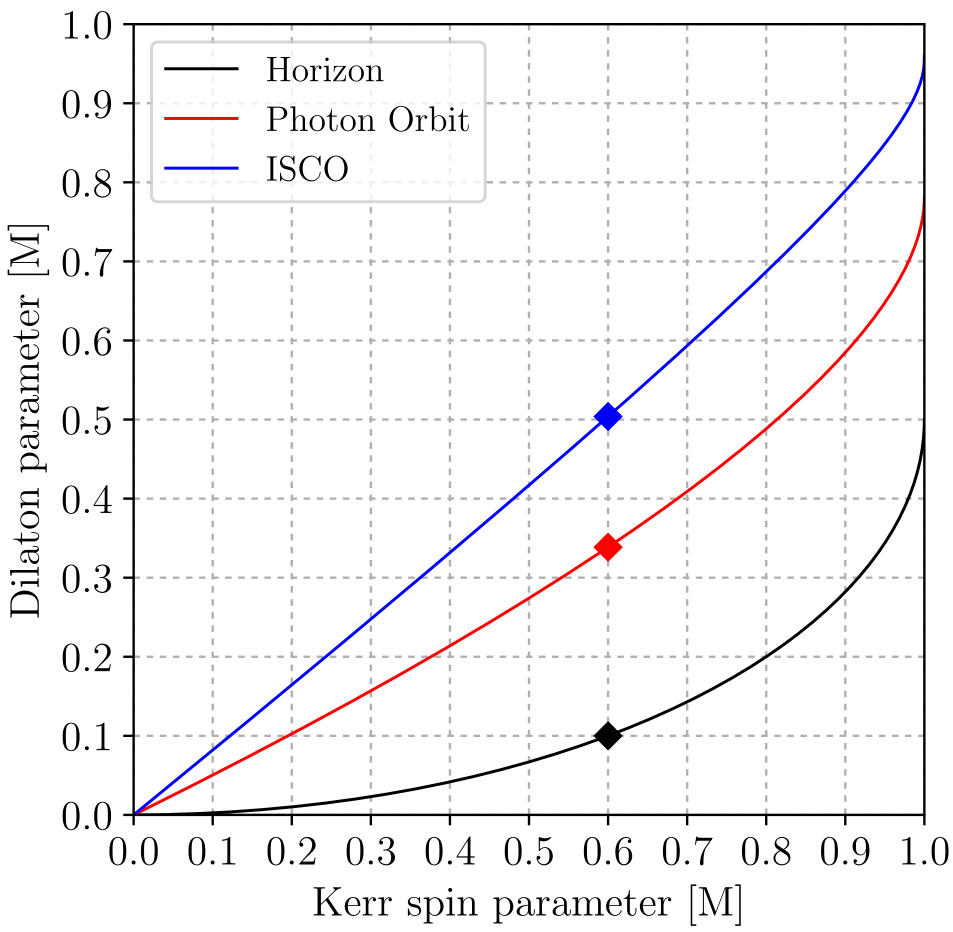
$r^2 = \rho^2 + 2b\rho, \quad M = \mu + b$ r: radial coordinate, M: ADM mass, b: dilaton parameter

- It is clear that if $b=0$, we reproduce Schwarzschild BH metric.

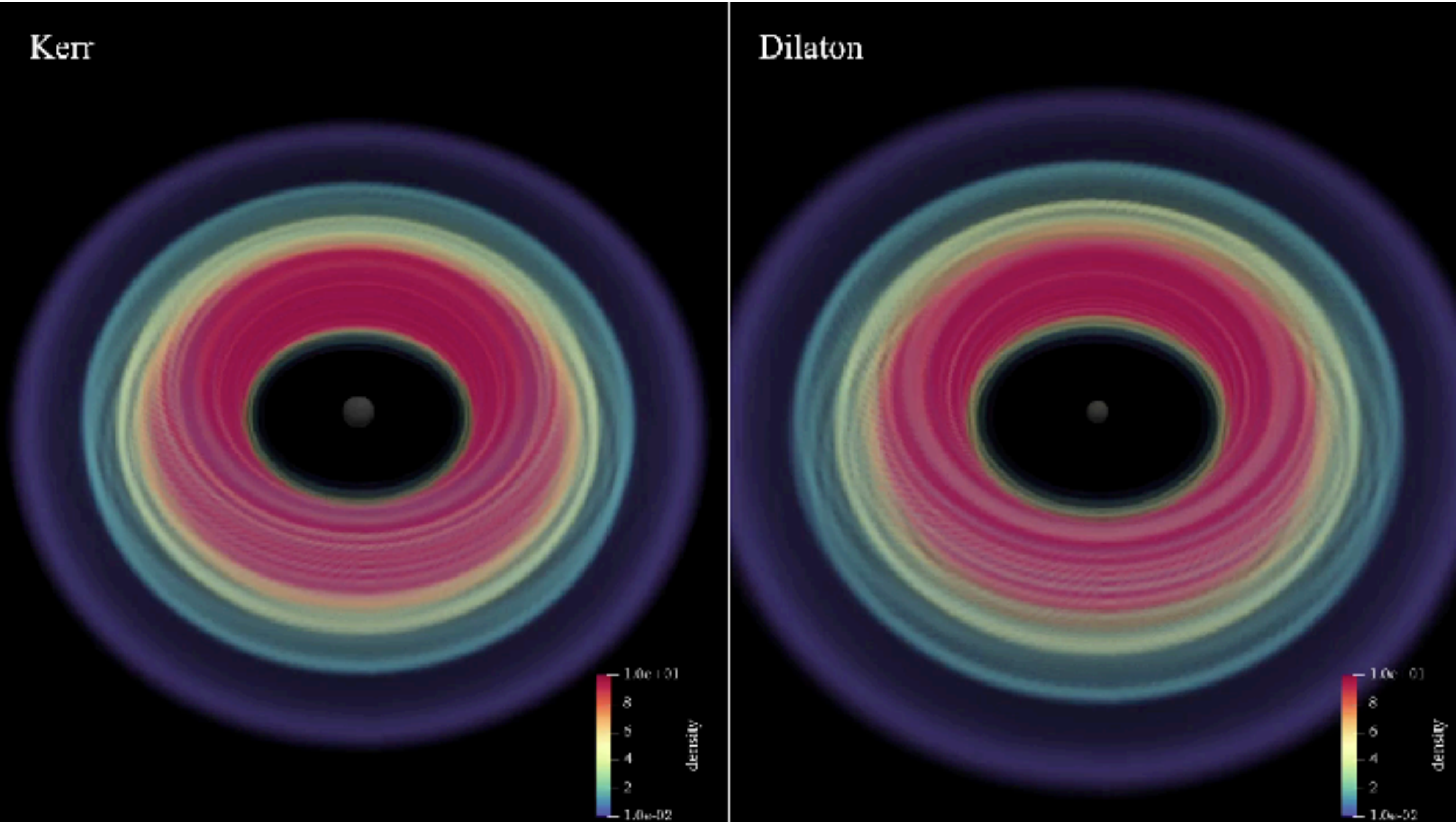
- Use Rezzolla & Zhidenko parameterized metric to describe non-rotating Dilaton BH metric

Dilation vs Kerr

- Does Dilation BH mimics Kerr BH?
- Three characteristic radius: horizon radius, photon orbit, ISCO
- Larger dilation parameter makes smaller horizon radius, Photon orbit, & ISCO
- Similar to Kerr spin parameter.
- How affects for plasma behaviour and radiation signature (BH shadow image)?



3D GRMHD simulations



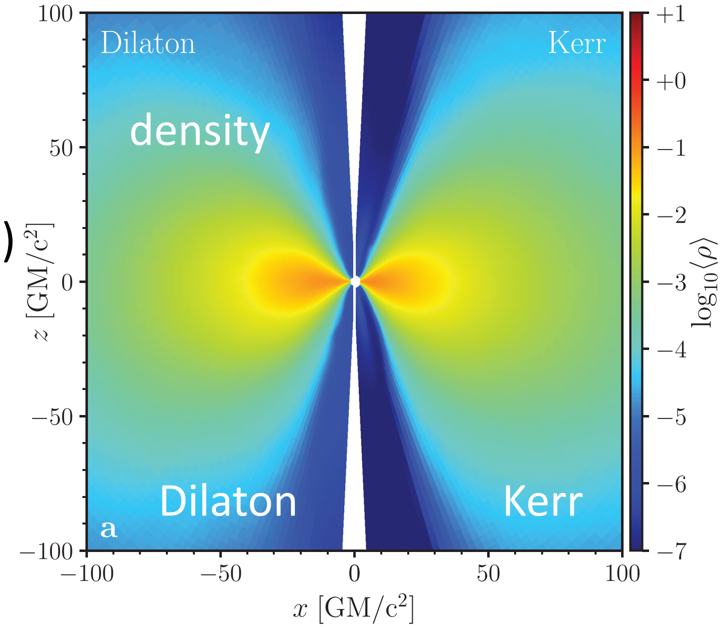
- 3D GRMHD simulations of magnetized torus with a weak poloidal magnetic field loop accreting onto Kerr BH (a=0.6) & ISCO-matched dilaton BH (b=0.5)

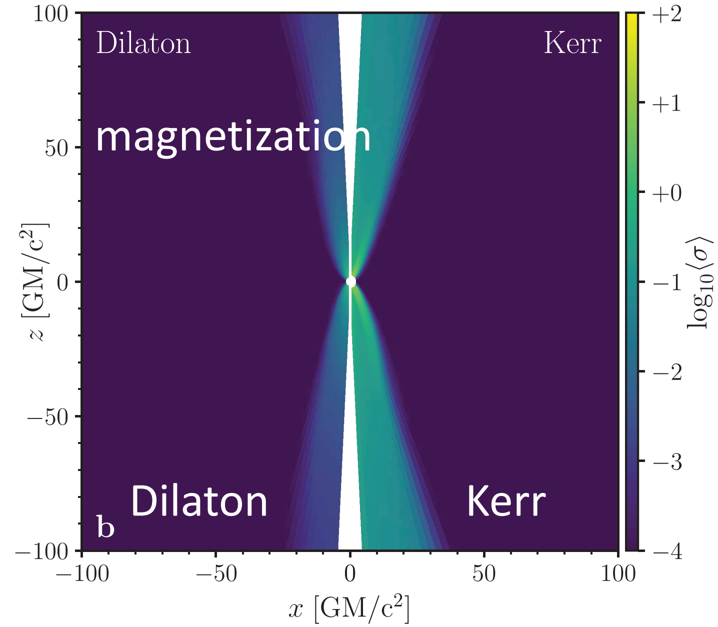
3D GRMHD simulations

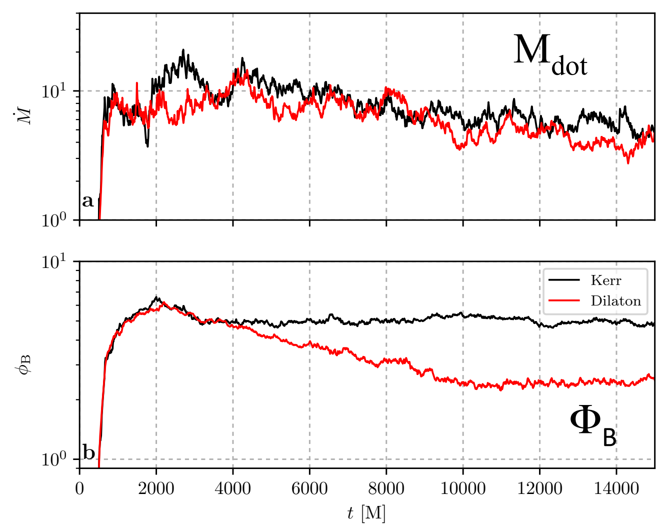
- 3D GRMHD simulations of magnetized torus accreting with a weak poloidal magnetic field loop onto Kerr BH (a=0.6) & ISCO-matched dilaton BH (b=0.5) by *BHAC*

- Azimuthal & time-averaged density (left) and magnetization (right)

- Time averaged over the interval t=11000-12000M which is reached quasi-steady state (turbulence is fully developed)



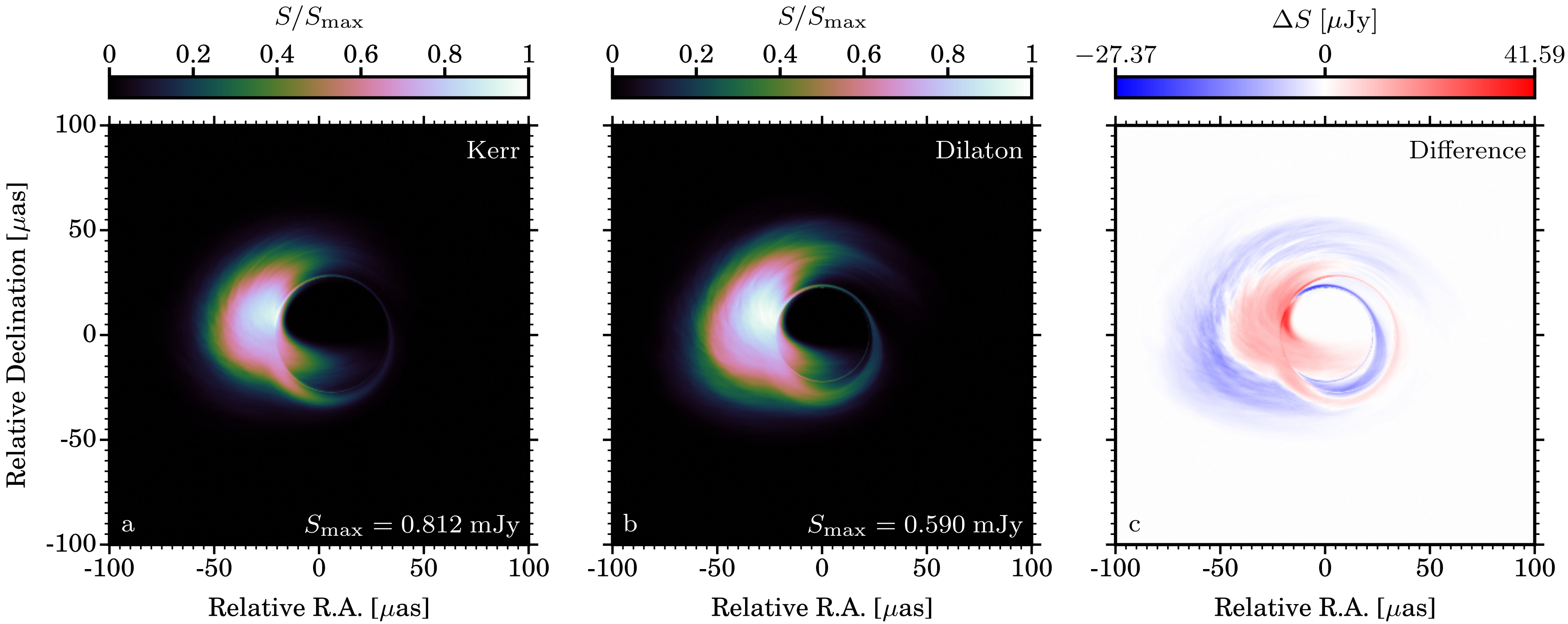




- Overall plasma behaviour is very similar in both cases but high magnetized jet spine region is different (dilaton BH is weaker than Kerr BH).

BH shadow image

Intensity map @ 230GHz, i=60 deg, time-averaged (t=11000-12000M) by *BHOSS*

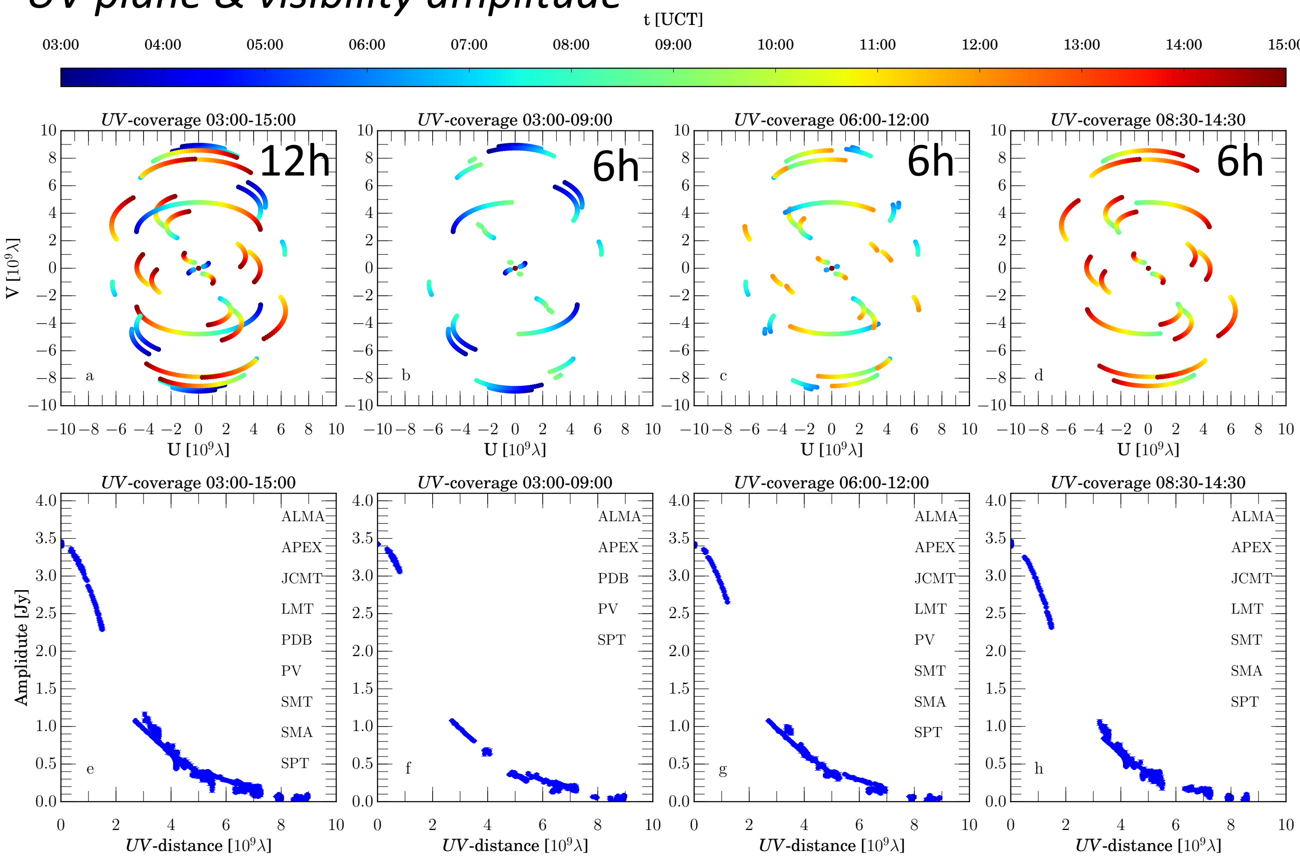


- Emission model (fixed $T_i/T_e = 3,\ \dot{M} \sim 10^{-9} M_{\odot}\,\mathrm{yr}^{-1}$)
- BH shadow image is quiet similar … but we see some difference
- Pixel-by-pixel difference shows smaller shadow size by dilaton BH (blue ring), and offset & asymmetry of shadow by Kerr BH (red ring)
- But this is "infinite-resolution images"

Synthetic Imaging (VLBI array)

- Consider realistic properties of VLBI array & stations adjusting April 2017 EHT observations
- For the synthetic images we use 6h observation time, 420s scan length, 12s integration time, and include interstellar scattering.

UV plane & visibility amplitude



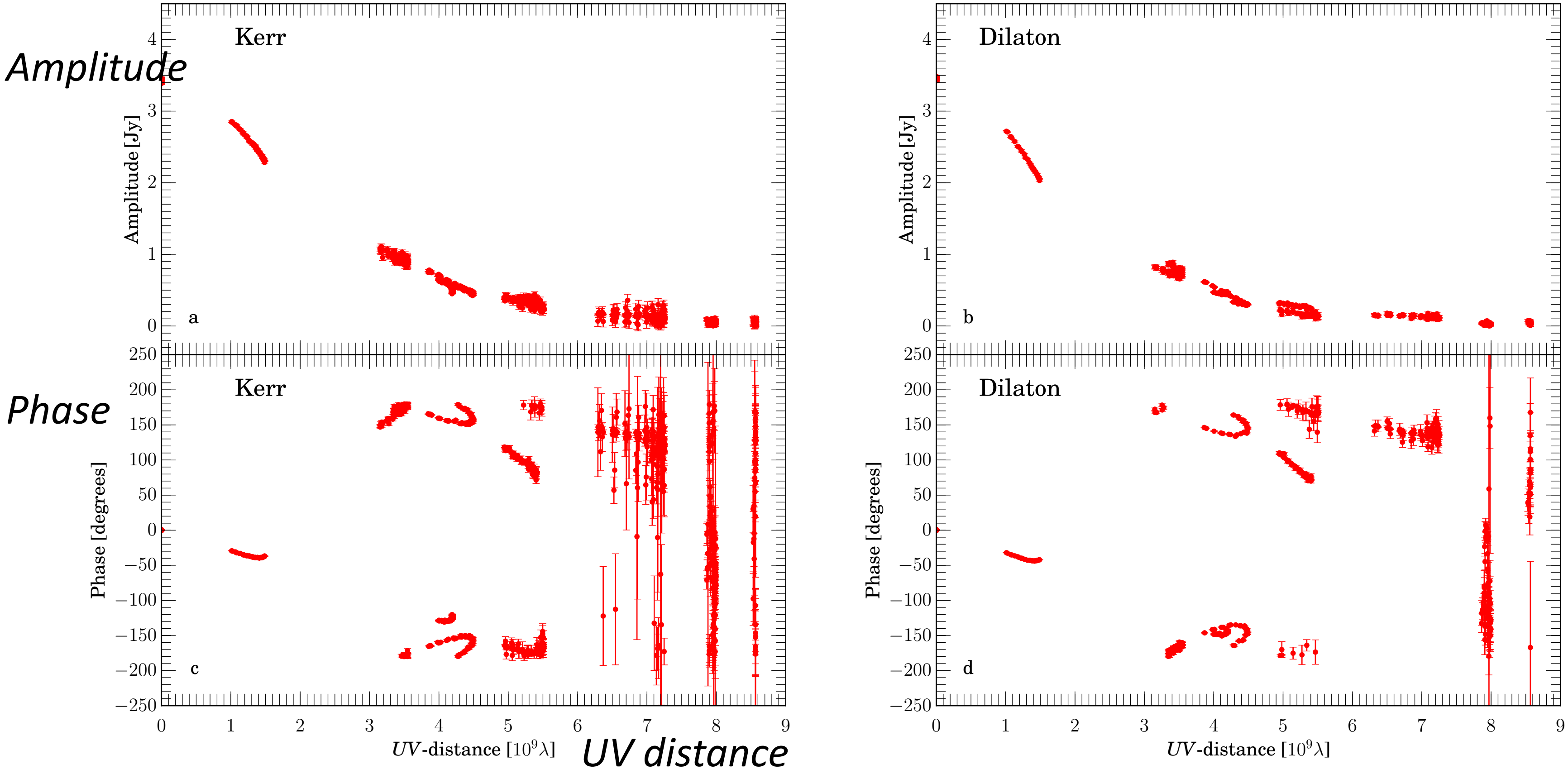
Chosen observation parameter

Parameter	Value
scan length	420 s
integration time	12 s
off-source time	600 s
start time	2017:097:08:30:00 (UT)
end time	2017:097:14:30:00 (UT)
bandwidth	4096 MHz

using *ehtim* python modules

Synthetic imaging (visibility amplitude)

Constrained total flux to 3.4Jy in both cases



Very similar visibility amplitude and phase in Kerr and dilaton BHs

Synthetic Imaging (shadow image)

reconstruction: BSMEM with 50% normal beam size

- Convolved GRRT images: already smeared out of sharp emission features
- Reconstructed images: mapped critical features of BH images (e.g., crescent shape)
- interstellar scattering: increases the blurring of these features

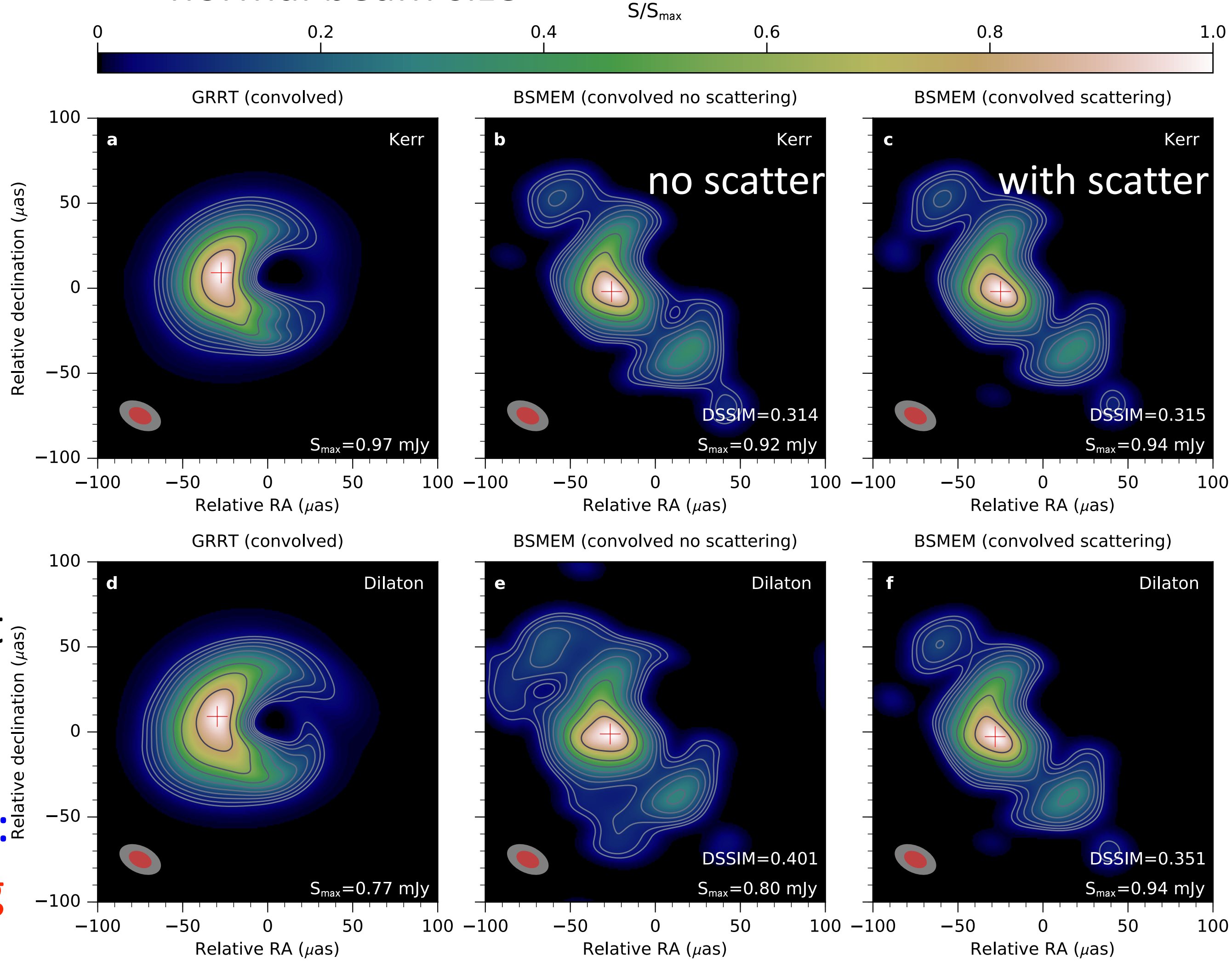


Image-Fidelity assessment

Image 1	Image 2	$MSE_{1,2}$	$DSSIM_{1,2}$
Kerr a	Kerr b [Kerr c]	0.016 [0.016]	0.31 [0.31]
Dilaton d	Dilaton e [Dilaton f]	0.016 [0.016]	0.40 [0.35]
Kerr a	Dilaton e [Dilaton f]	0.018 [0.015]	0.33 [0.30]
Dilaton d	Kerr b [Kerr c]	0.016 [0.016]	0.37 [0.37]

image 1: convolved
image 2: reconstructed

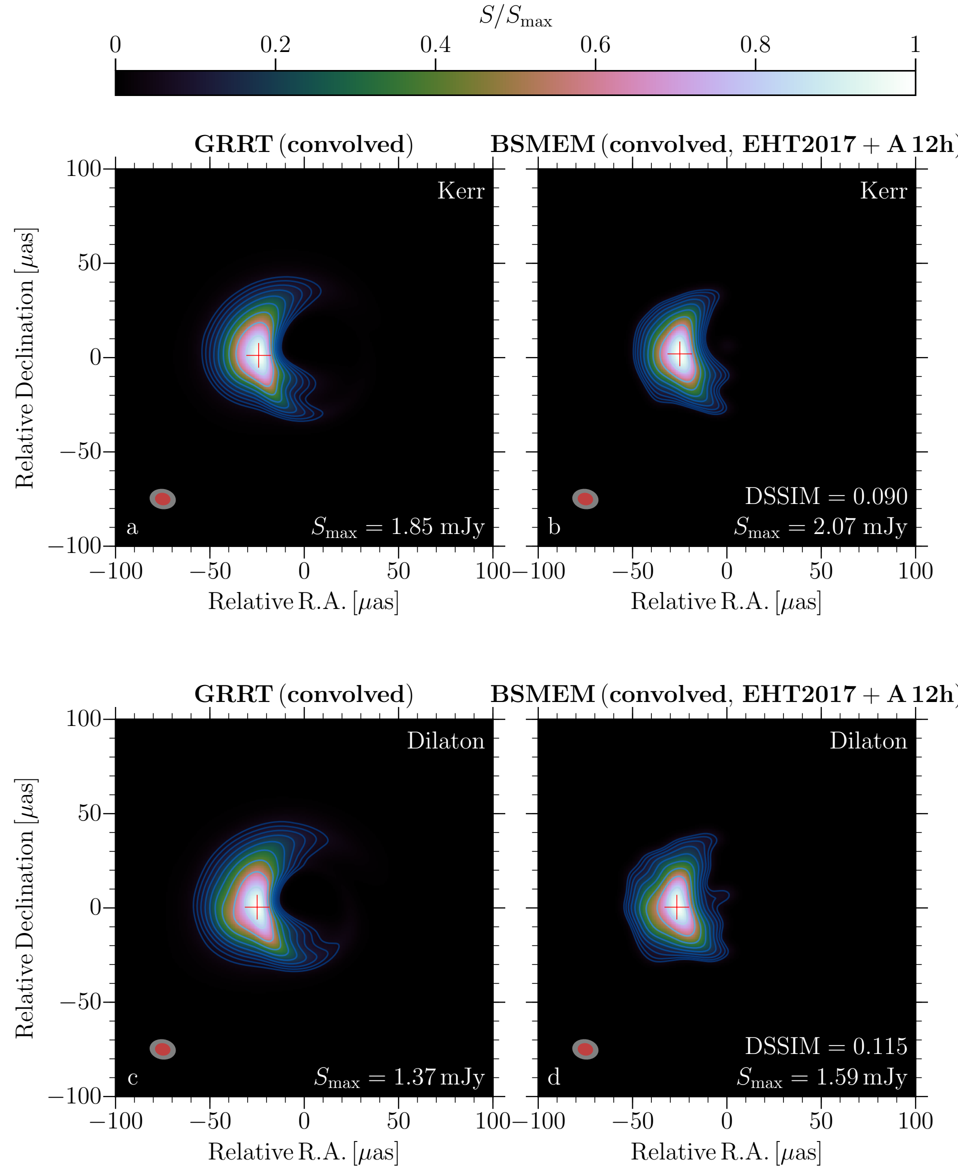
- More quantitative comparison, use two image-comparison metrics; the mean square error (MSE) and the structural dissimilarity (DSSIM) index
- Small values indicate the prominent features of the original convolved images are well-matched in the reconstructed images in both BH cases (*first two lows*)
- *But* similar matches are obtained when comparing the convolved image of a Kerr BH with the reconstructed image of a dilaton BH and vice-versa (*3rd & 4th lows*)
- It is presently difficult to distinguish between a Kerr BH and a dilaton BH on the basis of BH shadow images alone.

Future development: addition two african telescope @ 340 GHz

- Consider addition of two african telescopes + 12 hour observation at 340 GHz with 16GHz bandwidth.

- The reconstructed images agree very well with GRRT convolved images and show very detail features.

- Technological developments will improve the ability to distinguish BH spacetimes from shadow images alone, motivating further work in this direction.

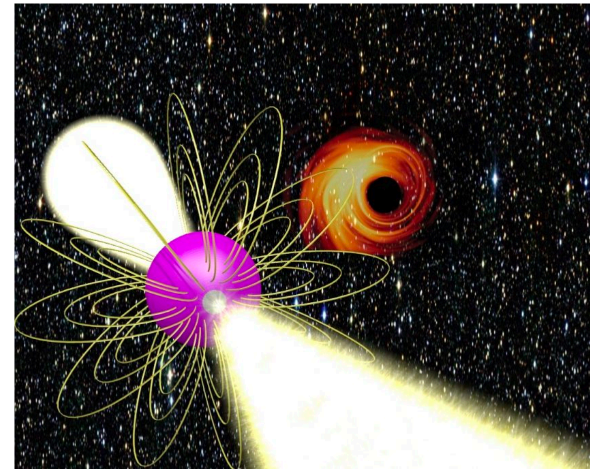


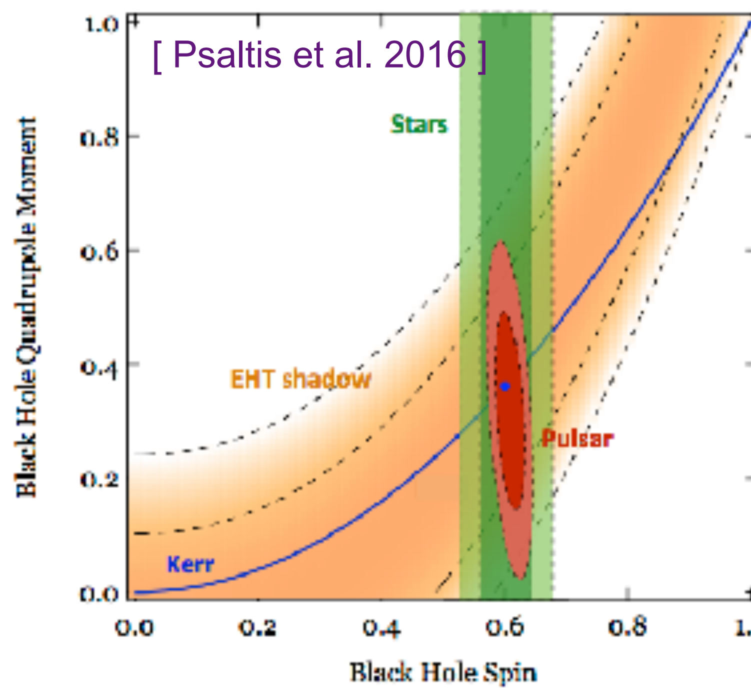
Complementarity to imaging (pulsar timing obs. in the vicinity of Sgr A*)

- Pulsar timing obs. is probing the **far field**,
- BH shadow image is probing the **near field**.

- **Shadow size and shape** depends on BH **mass** and **spin** and inclination angle, a suitable pulsar can provide these parameters with high precision (0.1~ 1%).

- The image itself might not be able to identify deviations from a Kerr **spacetime** due to correlations, a suitable pulsar can help to break such correlations.





Modeling of Relativistic Jets

Evolutionary Algorithms (simulation pipeline)

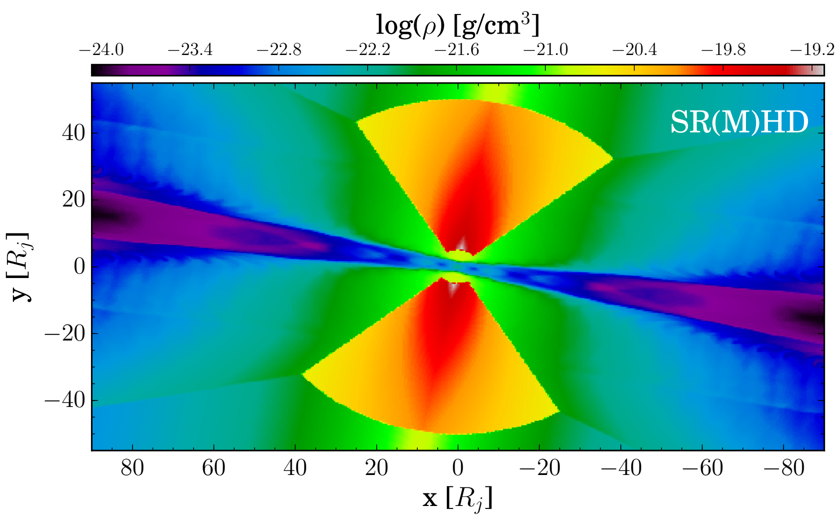
observations (images,SED)

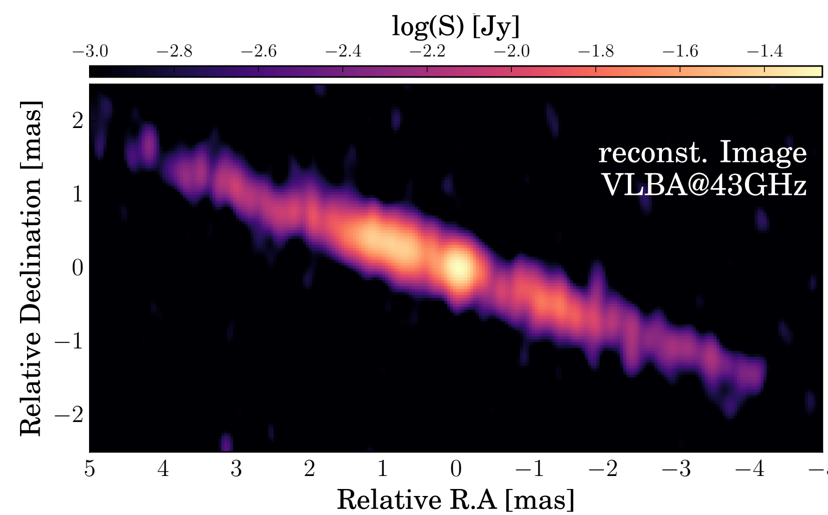
jet model → emission model → synthetic image

SRMHD
(AMR-VAC, BHAC)

thermal, non-thermal +Spev
(synchro.py)

VLBI array, image reconst.
(ehtim, BSMEM,CLEAN)

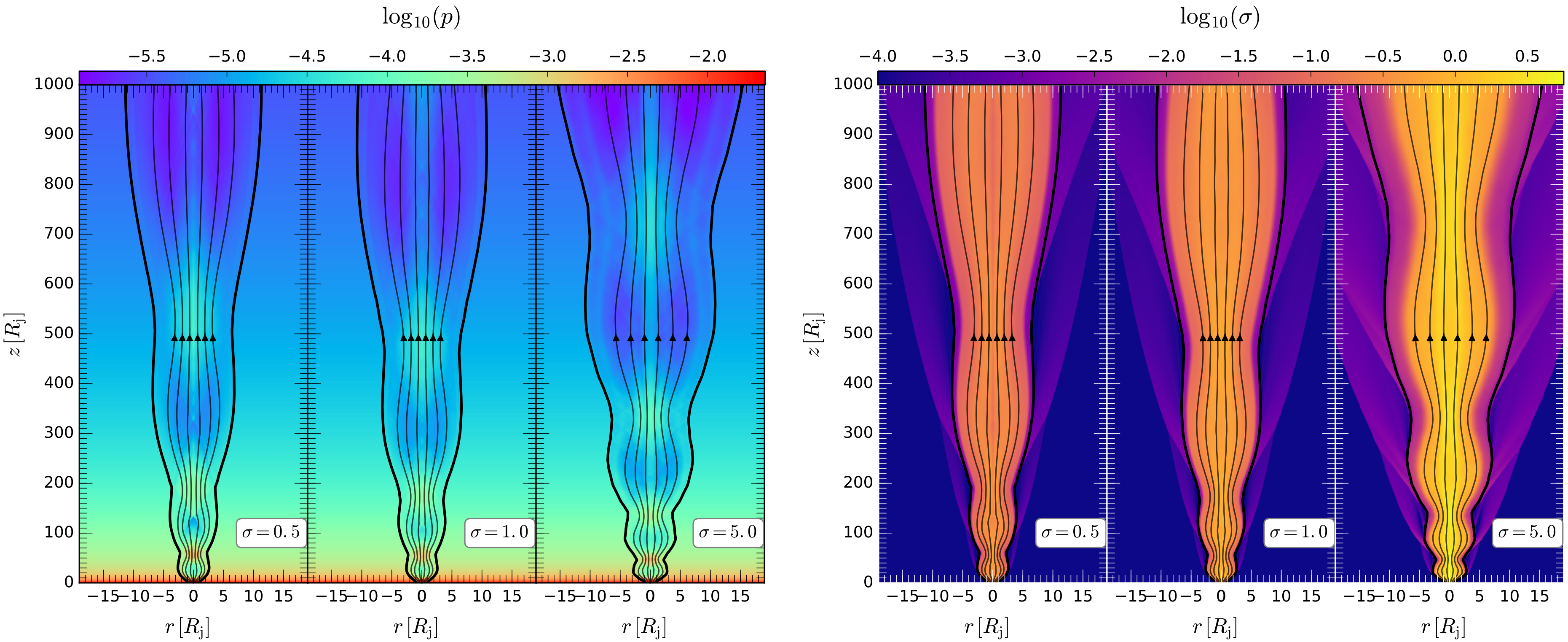




Fromm et. al. (2018)

Jet Model (RMHD simulation)

- Perform 1D RMHD simulations of propagating jets with power-law atmosphere (Porth & Komissarov 2014)
- initial values: $\rho_j = 0.01\rho_a \quad \Gamma = 4 \quad \hat{\gamma} = 13/9 \quad \kappa = 1.0$
- change magnetisaion $\sigma = b^2/w$

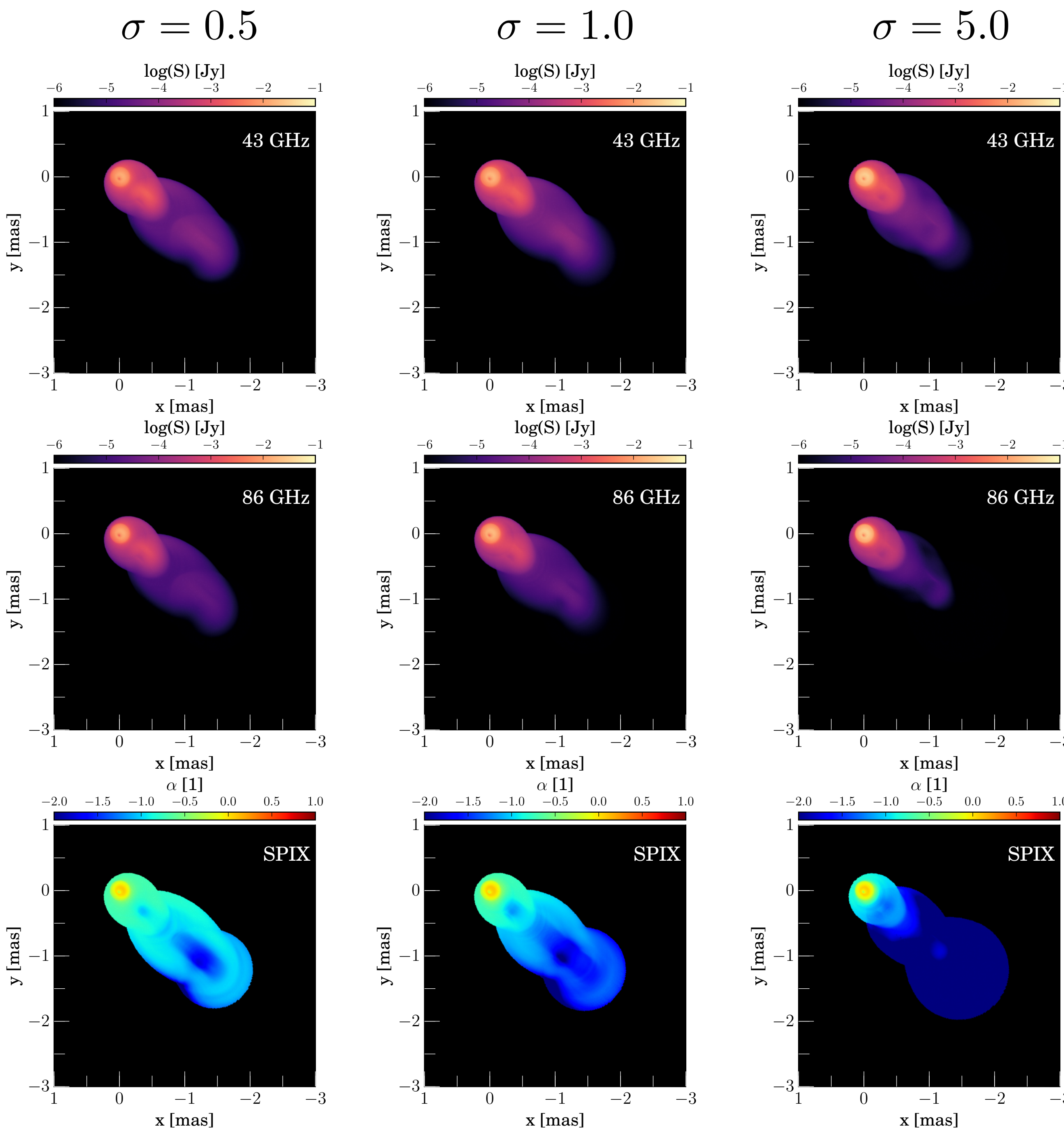


$\sigma \uparrow \quad \Rightarrow v_a \uparrow \quad \Rightarrow r_{\rm jet} \downarrow$

$\sigma \uparrow \quad \Rightarrow$ less recollimation shocks

Synthetic imaging

match 3C279 (z=0.5) :
radio spectrum
+15GHz VLBA image



Summary

- It is presently difficult to distinguish between a Kerr BH and a dilaton BH on the basis of BH shadow images alone.
- The results focus on a specific example of a non-GR BH solution (non-rotating dilaton BH) and do not consider the case of extremal black holes and other exotic objects.
- Several future developments can improve our ability to discriminate between GR and alternative theories of gravity using shadow images
  - Advanced image reconstruction algorithms
  - Increases in observational frequency (e.g., 340 GHz) and bandwidth (e.g., 8GHz)
  - Additional VLBI antennas (e.g., in Africa)
  - Source variability and timing measurements
  - Concurrent multifrequency spectroscopic & spectro-polarimetric observations together with horizon-scale VLBI shadow images
- Pulsar timing observations in the vicinity of Sgr A* also have the potential to impose strict constraints on the underlying theory of gravity
- Theoretical jet simulation pipeline would be useful for modelling various relativistic jets.