Anatomy of the horizon-scale structure of Sgr A* with a resolution of \( \sim 3 \) Rs

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in collaboration with

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& the EHT collaboration

1. Max Planck Institute for Radio Astronomy
Sgr A*: the best for imaging a black hole

- Largest apparent event horizon among any black holes in the universe: $R_s = 10 \ \mu\text{as}$

- Horizon-scale structure exists
- A place that allows to test GR in strong fields
- Close enough to watch materials swirling towards the horizon

(global 1.3mm-VLBI provides well-matched resolution!)

$\sim 20-30 \ \mu\text{as}$

Size:
- Maximally spinning ($a=1$): $4.5 \ R_s = 45 \ \mu\text{as}$
- Non-spinning ($a=0$): $5.2 \ R_s = 52 \ \mu\text{as}$

(Bardeen 1973, Falcke, Agol & Melia 2000)
Current development of 1.3 mm-VLBI
-EHT collaboration

- SMA & JCMT, Hawaii
- SMT, Arizona
- LMT, Sierra Negra, Mexico
- APEX & ALMA, Chile
- Pico Veleta, Spain
- Plateau de Bure/NOEMA
- South Pole Telescope
- Greenland Telescope

EHT as viewed from Sgr A*
1.3mm-VLBI observations of Sgr A* before 2013:

![Image of Earth with SMT, CARMA, and SMT-Hawaii labeled]

- CARMA
- SMT
- SMT-Hawaii

**uv-coverage before 2013**

- **6Rs×26Rs**

![Graph showing uv-coverage before 2013]
1.3mm-VLBI observations of Sgr A* in 2013:
- APEX detected Sgr A*: 3 Rs resolution achieved

Baseline length:
92m (intra-site) — 9447 km (with APEX)
Amplitude “gain” calibration

1. Identify zero-spacing flux $S_0$ (measured by connected interferometer)

2. Calculate residual gain factors to make the calibrated parallel hand visibilities on intra-site baselines approximately equal to $S_0$.

“pseudo-closure amplitude relationship”

```
\[ g_F \times g_D \times FD_{\text{obs}} = S_0 \quad \text{and} \quad g_F \times XF_{\text{obs}} = g_D \times XD_{\text{obs}} \]
```

(e.g., for FD baseline, one finds: $g_F \times g_D \times FD_{\text{obs}} = S_0$ and $g_F \times XF_{\text{obs}} = g_D \times XD_{\text{obs}}$ (in practice, this could involve multiple `X' stations)

3. Residual gains for SMT, APEX are not set in an “absolute” sense, but assuming not too far from unity.

![Diagram of baselines E, D, X, FD, and X]
1.3mm-VLBI observations of Sgr A* in 2013
-new signatures seen

Lu et al., in prep.

APEX doubles the uv-range to 7000Mλ!
1.3mm-VLBI observations of Sgr A* in 2013
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APEX doubles the uv-range to 7000Mλ!
1.3mm-VLBI observations of Sgr A* in 2013
-new signatures seen
1.3mm-VLBI observations of Sgr A* in 2013
-Non-zero closure phase

Closure phase (degree)

average: 0.4±0.5 deg.
average: 7.8±1.2 deg.
average: 7.0±3.5 deg.

-non-zero closure phase (consistent with Fish+2016)
-Structure is asymmetric and non-pointlike!
1.3mm-VLBI observations of Sgr A* in 2013

2-component Gaussian ($\chi^2_v=1.22$)

-very compact structure (1Rs ~10 µas)

Crescent model ($\chi^2_v=1.21$)

-not a sharp crescent!

<table>
<thead>
<tr>
<th>flux (Jy)</th>
<th>r (Rs)</th>
<th>$\Theta$ (deg)</th>
<th>$\Phi$ (Rs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>2.37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(B)</td>
<td>0.77</td>
<td>4.6</td>
<td>-128.3</td>
</tr>
</tbody>
</table>

-component separation comparable to the expected diameter of the black hole “shadow”!
Zoo of theoretical models: what do we see?

- **disk+jet**
  - Moscibrodzka et al. 2014

- **“tilted” disk**
  - Dexter & Fragile, 2013

- **semi-analytic RIAF**
  - Broderick et al. 2011

- **magnetically arrested disk (MAD)**
  - Chan et al. 2015
Looking forward

Assumed stations: Pico Veleta (PV), SMT, Hawaii, ALMA, LMT
Millimeter-VLBI is a unique tool to study horizon-scale structures of Sgr A*

The (sub)mm-VLBI array (EHT) is growing fast (new fringes, higher data rates…)

New observations point towards “complex” and extremely compact structures in Sgr A*

Imaging black hole shadow in Sgr A* will be within reach in next few years