The Jet in the Galactic Centre – mm-VLBI

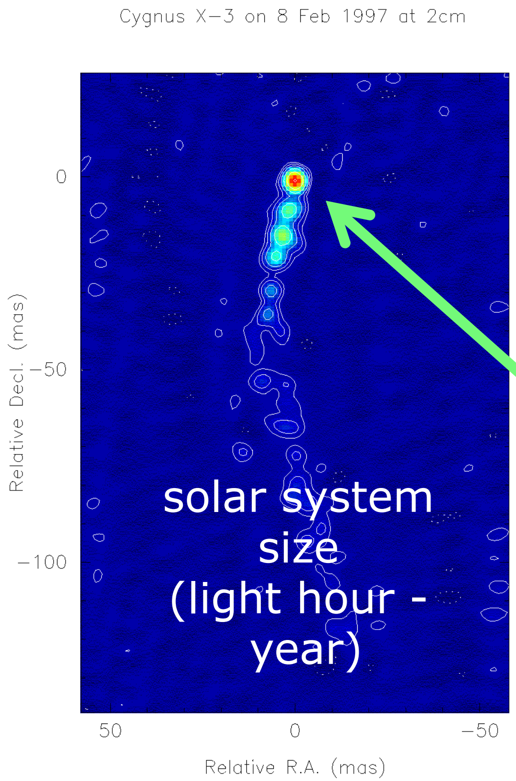
Heino Falcke

Radboud University, Nijmegen

& ASTRON, Dwingeloo

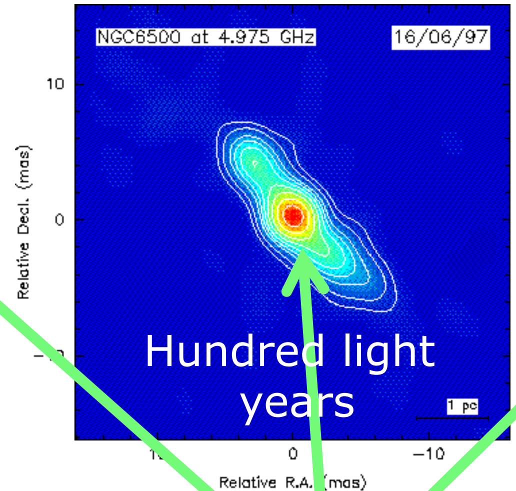
Jets exist on all scales

stellar mass black holes
(x-ray binaries)



Cyg X-3
VLBI: Mioduszewski et al. (2003)

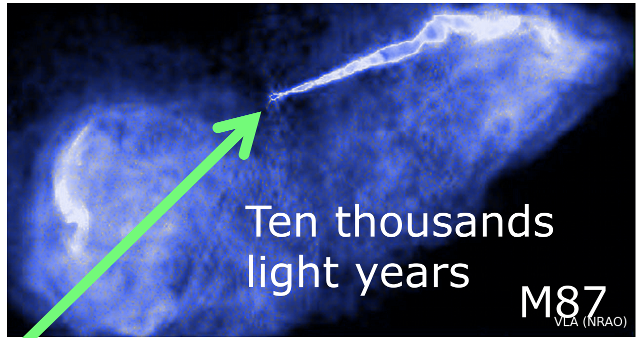
Low-luminosity AGN
(starving supermassive BHs)

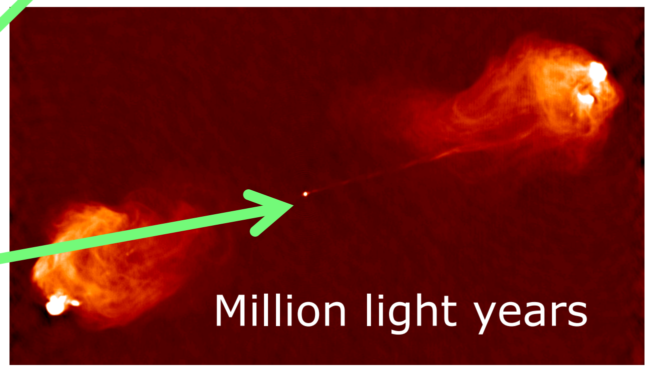


VLBI: Falcke et al. (2000)

Flat-spectrum
radio cores

powerful supermassive
black holes
(quasars, radio galaxies)





Cyg A: VLA/NRAO

The Spectrum of Jets (Cores): Synchrotron Emission

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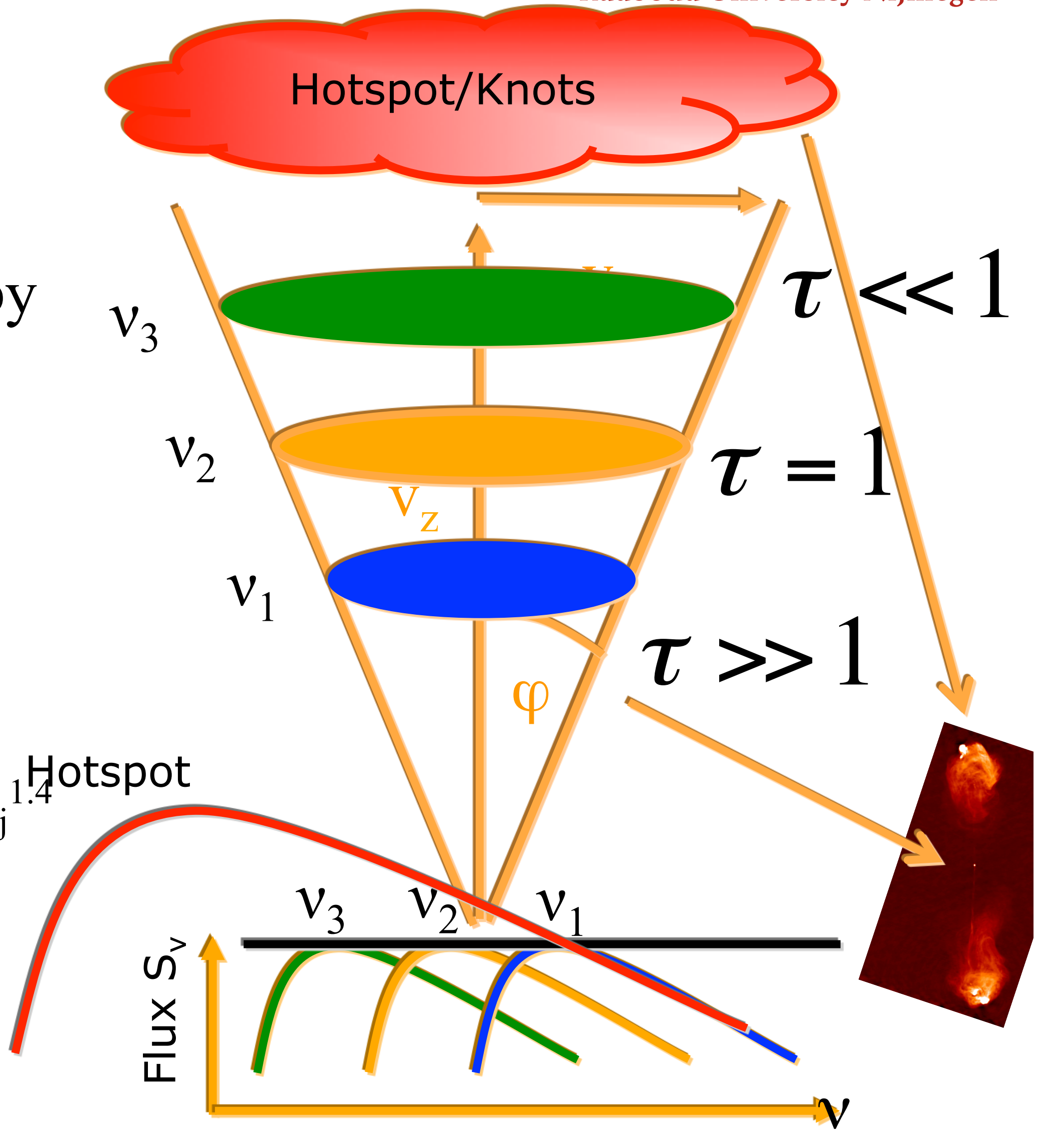
- Conical flow with constant speed (Mach cone):
  - $n \propto R^{-2}$ & $B \propto R^{-1}$
- The emission is dominated by the $\tau=1$ surface.
- Synchrotron emission with equipartition naturally predicts:
  - A flat spectrum: $S_\nu \propto$ const
  - A core shift: $R_{core} \propto \nu^{-1}$
  - Scaling with jet power: $S_\nu \propto Q_j^{1.4}$



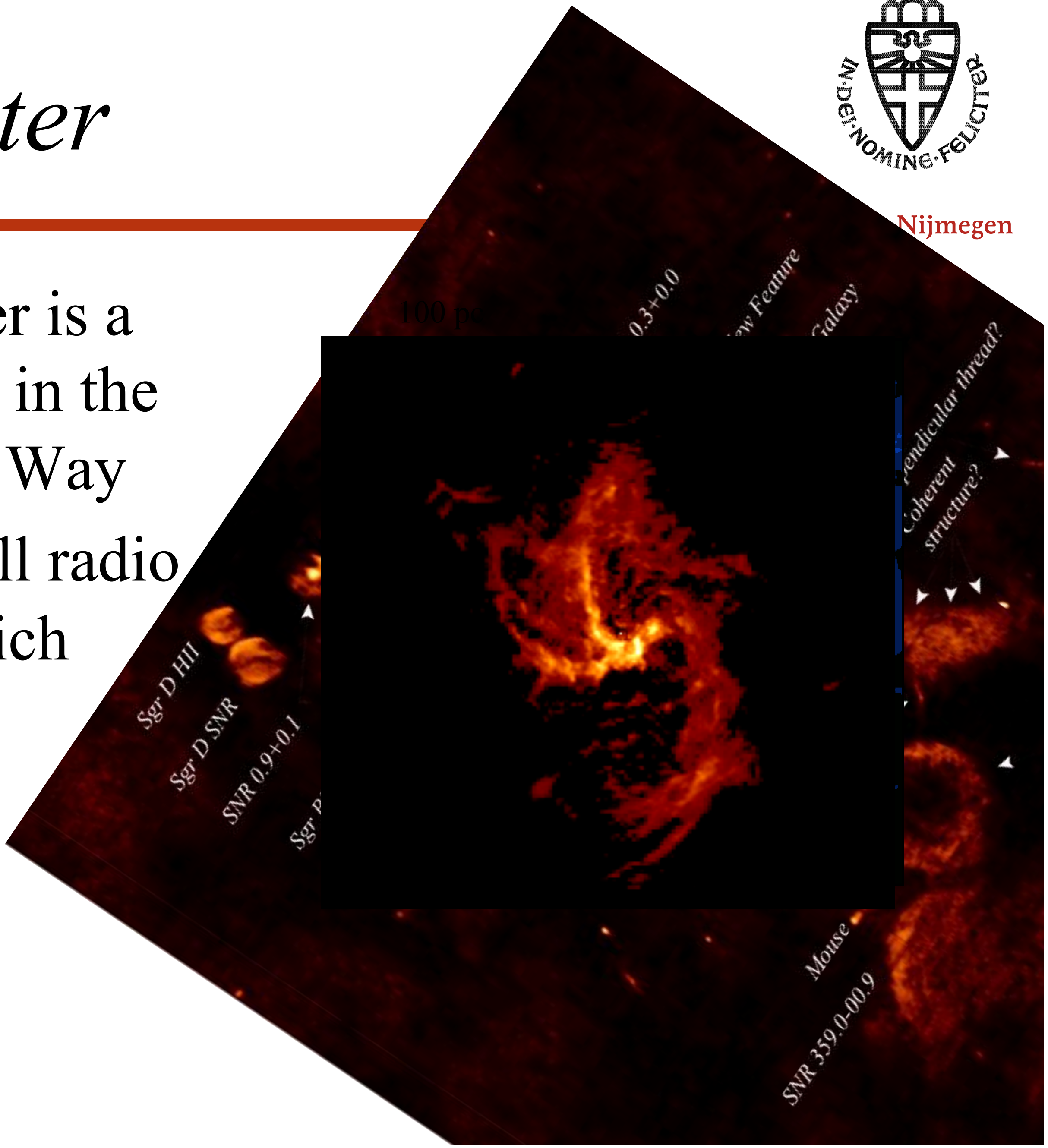
Blandford & Königl (1979)
Falcke & Biermann (1995)

IN·DEI·NOMINE·FELICITER

Nijmegen

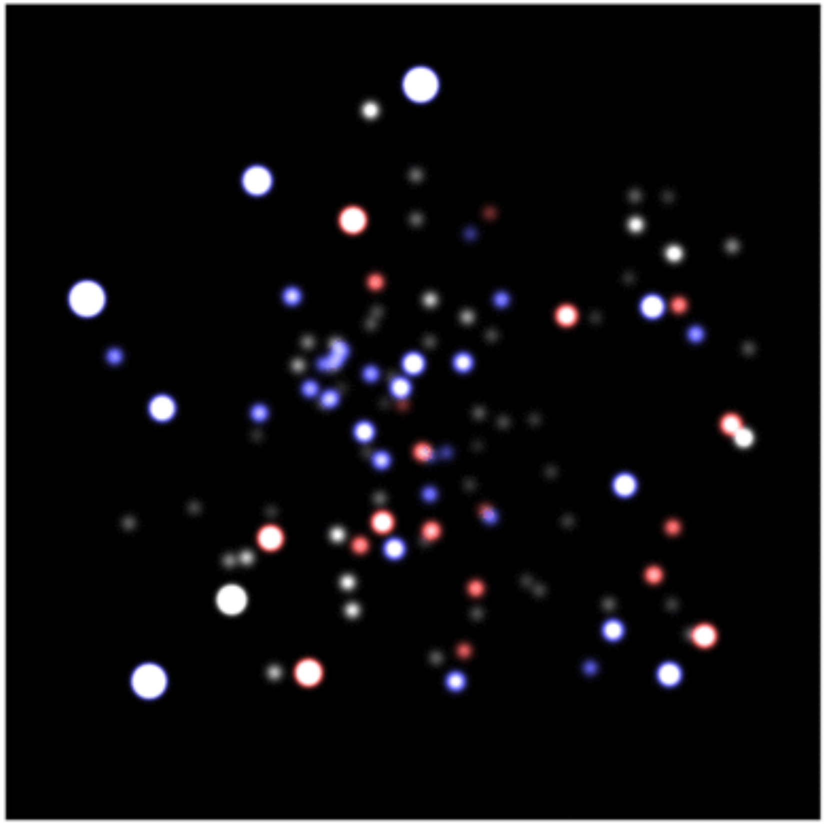
Galactic Center

- The Galactic Center is a bright radio source in the plane of the Milky Way
- It contains the small radio source Sgr A*, which is suspected to be THE central black hole in the Milky Way.



Dark Mass in the Galactic Center

- Stellar proper motions have revealed a dark mass in the Galactic Center of 4 Million solar masses within the size of the solar system.
- The center of gravity coincides with Sgr A* within 215 R_s (15 AU).

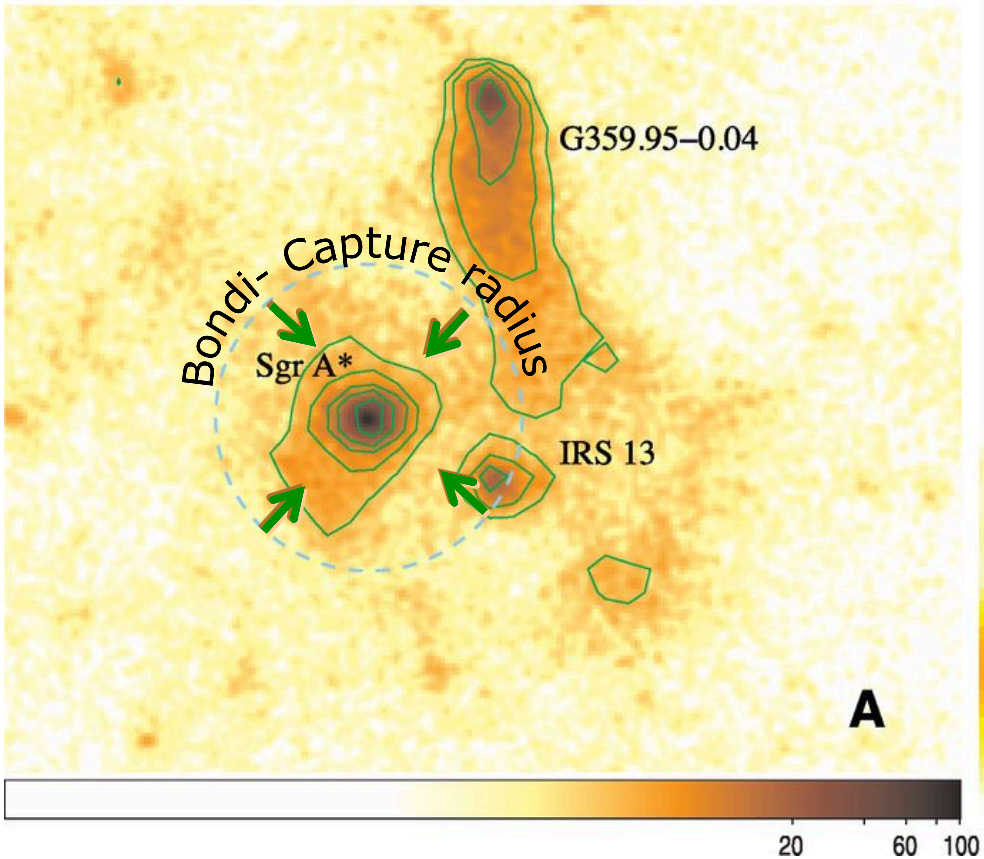


near-infrared

Genzel, Ghez, Eckart ….. (MPE , UCLA, Cologne…)

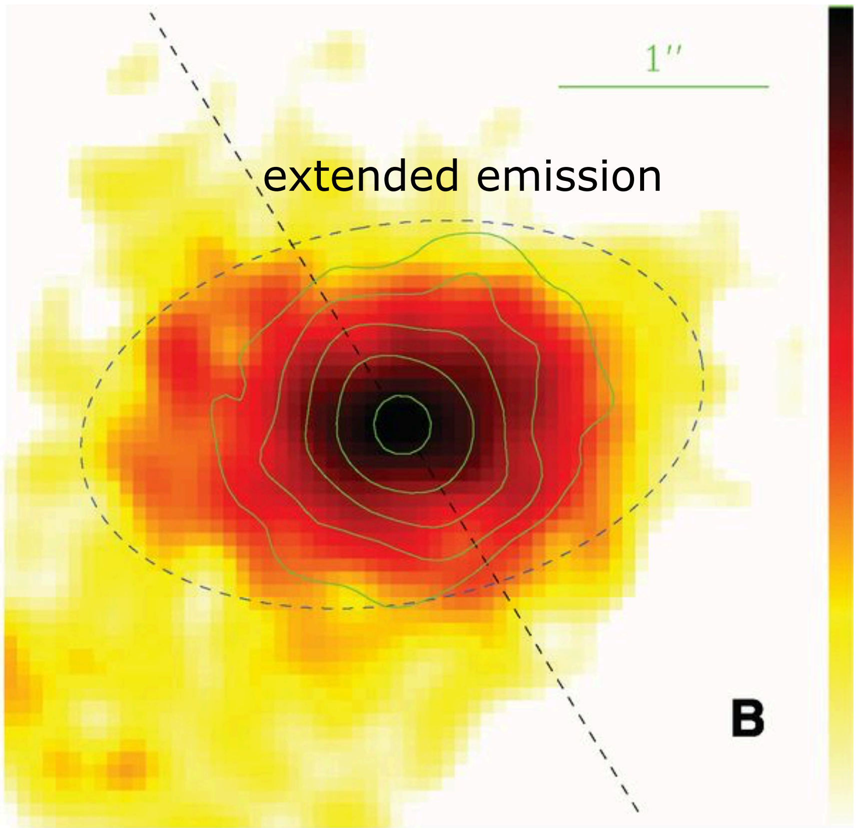
X-Ray View: Flares, Hot Gas, and Accretion

Region around Sgr A*



Chandra, 1-9 keV band

Sgr A* - zoomed view



Wang et al. (2013)

First Galactic Center Pulsar

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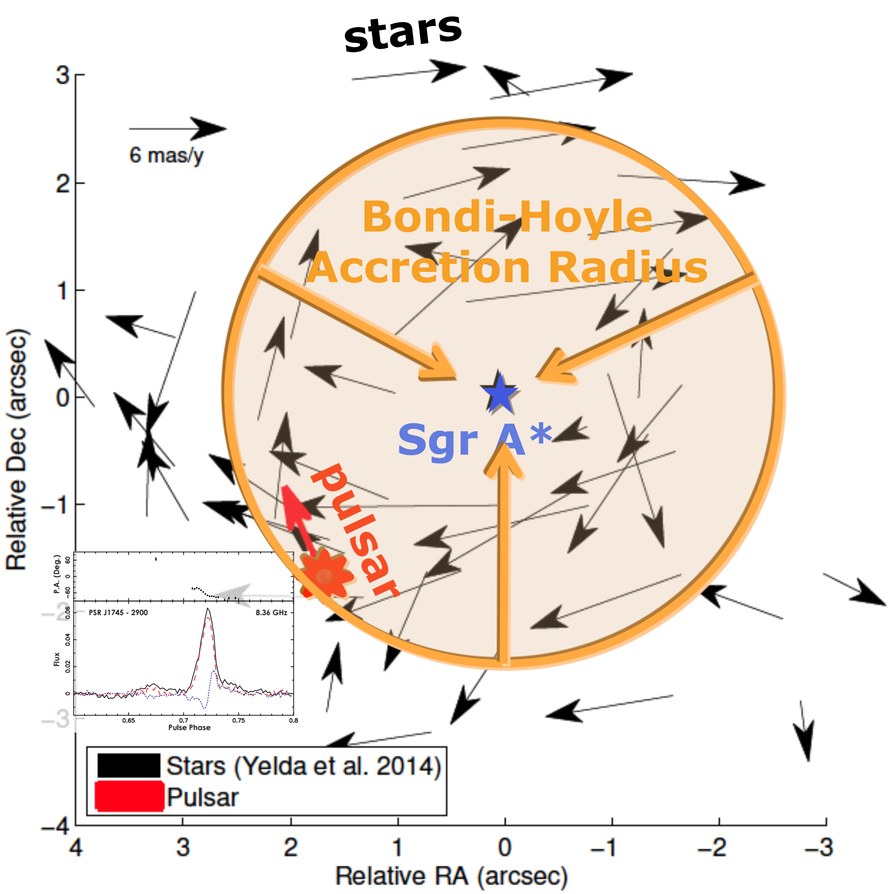


- X-ray transient (NuStar/Swift)
- ~2″ from Sgr A*= Bondi Radius!
- Period: P = 3.76354676(2) s
- Dispersion DM=1778+/-3 cm^{-3} pc
- spectrum ~flat, up to 200 GHz!
- Almost 100% linear polarization
- Rotation Measure:
  RM=-66,960 +/- 50 rad m^{-2}
  Second only to Sgr A*
  (RM=-5×10^5 rad m^{-2})

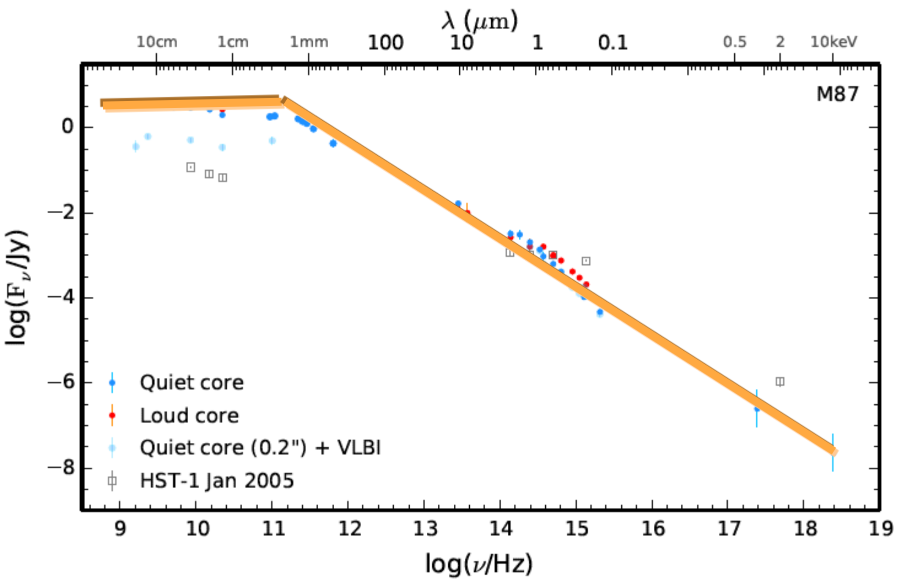
- **Accreting plasma is highly magnetized!**

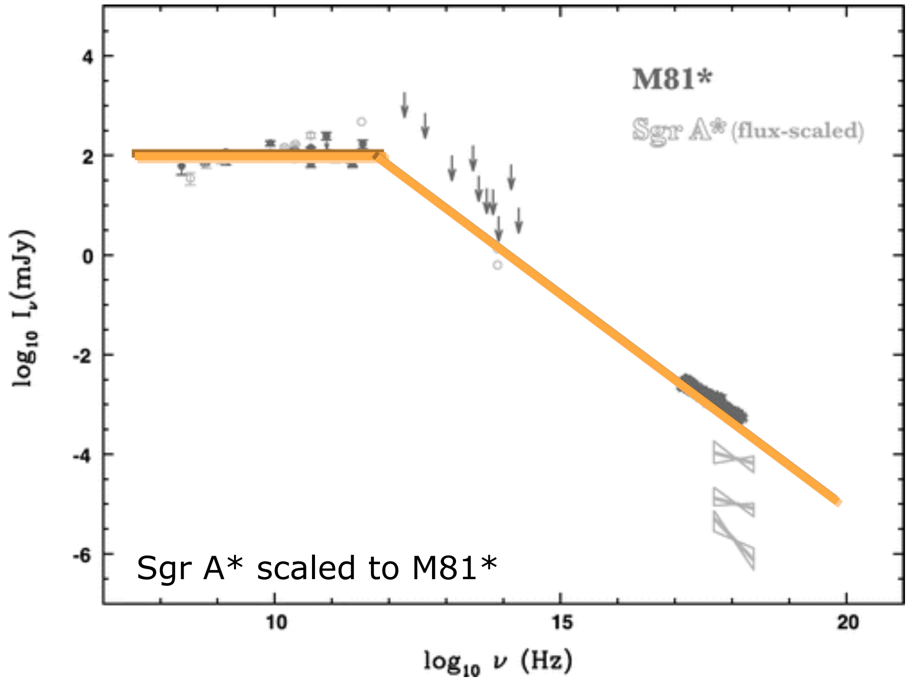
Radio proper motions:
Bower et al. (2015, ApJ)

Radio detection:
Eatough, Falcke et al. (2013, Nature)

Spectrum of M87, M81*, Sgr A*

BlackHoleCam

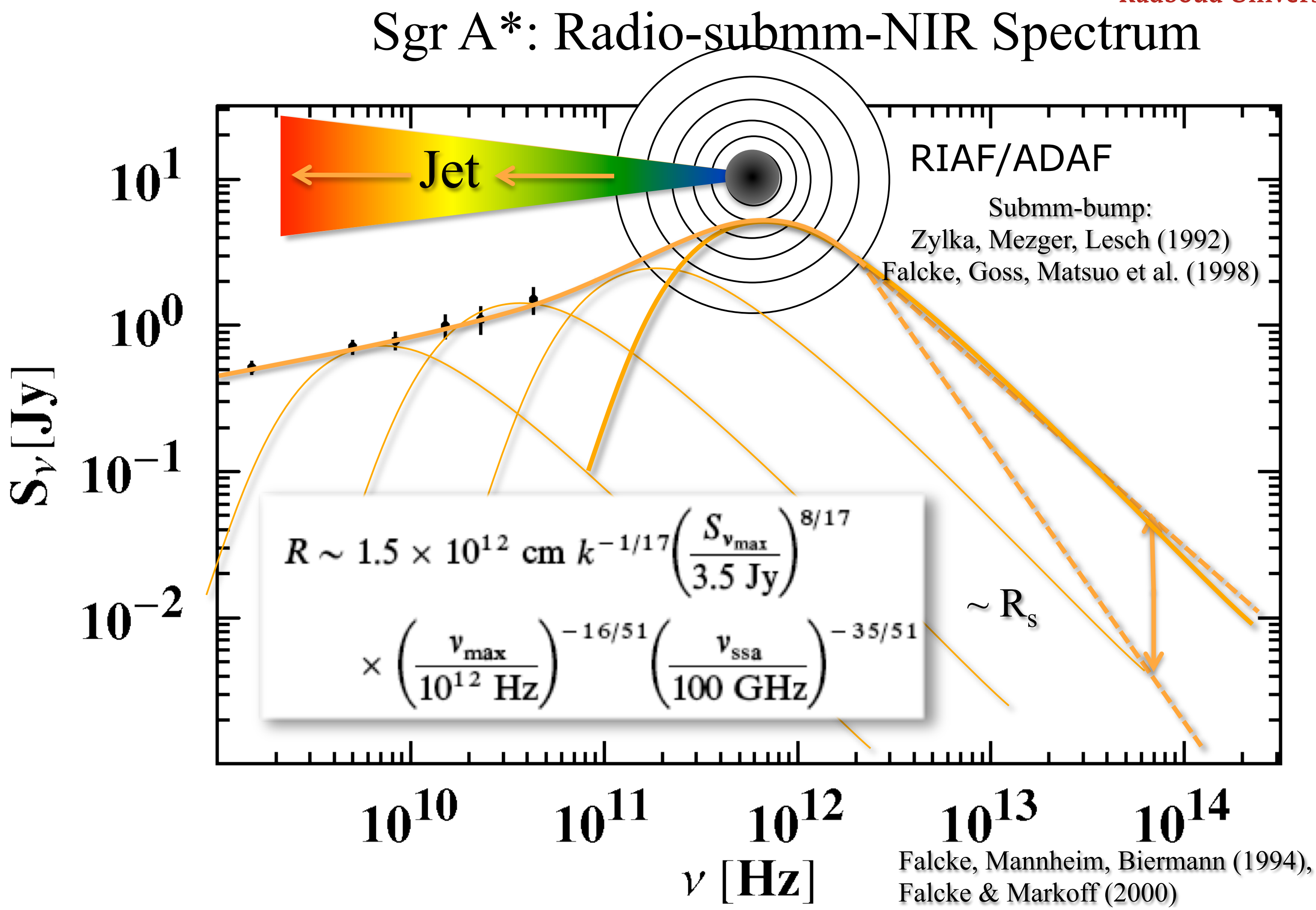




Markoff et al. (2008)

Almudena Prieto

Sgr A Spectrum & Jet Model*



The submm-bump: a compact self-absorbed synchroton component

THE ASTROPHYSICAL JOURNAL, 499:731–734, 1998 June 1

THE SIMULTANEOUS SPECTRUM OF SAGITTARIUS A* FROM 20 CENTIMETER TO 1 MILLIMETER AND THE NATURE OF THE MILLIMETER EXCESS

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Received 1997 November 6; accepted 1998 January 12

ABSTRACT

We report results of a multiwavelength campaign to measure the simultaneous spectrum of the supermassive black hole candidate Sgr A* in the Galactic center from centimeter to millimeter wavelengths using the Very Large Array, the Berkeley-Illinois-Maryland Array (BIMA), the Nobeyama 45 m, and the Institut de Radioastronomie Millimetrique (IRAM) 30 m telescopes. The observations confirm that the previously detected millimeter excess is an intrinsic feature of the spectrum of Sgr A*. The excess can be interpreted as and effect of the presence of an ultracompact component of relativistic plasma with a size of a few Schwarzschild radii near the black hole. If so, Sgr A* might offer a unique possibility to image the putative black hole against the background of this component with future millimeter VLBI experiments.

The Shadow of a Black Hole

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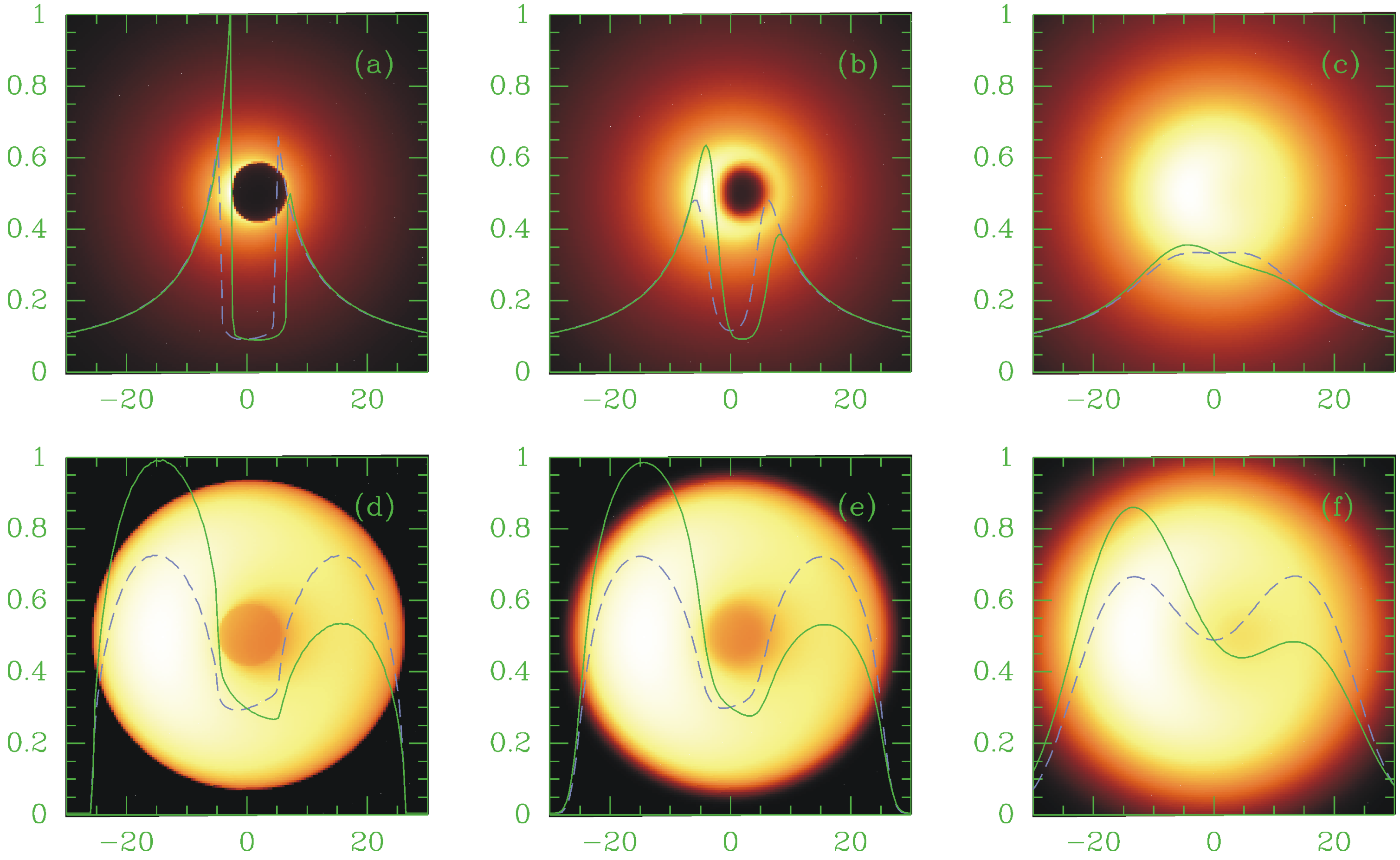
GR Model | λ0.6mm VLBI | λ1.3mm VLBI

a=0.998

$I=r^{-2}$

a=0

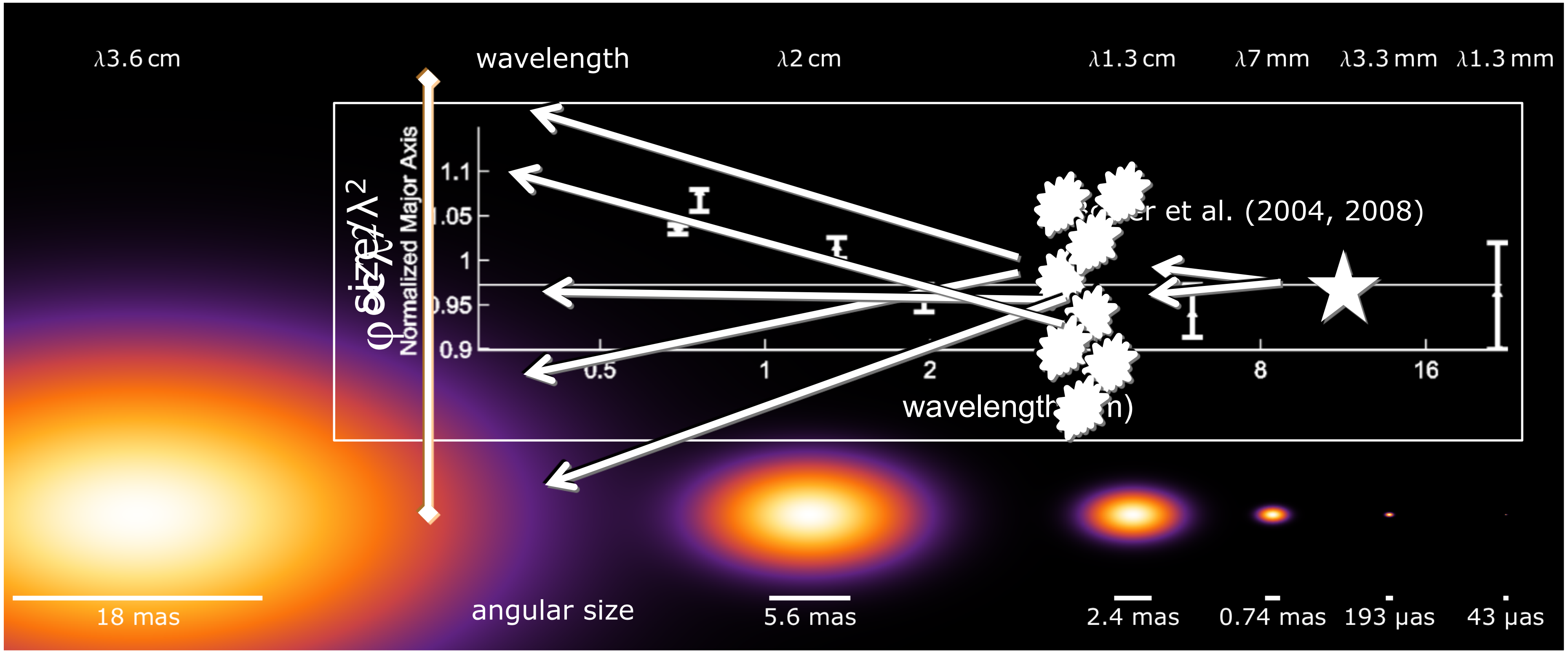
I=const



(Falcke, Melia, Agol 2000, ApJL)

H. Falcke

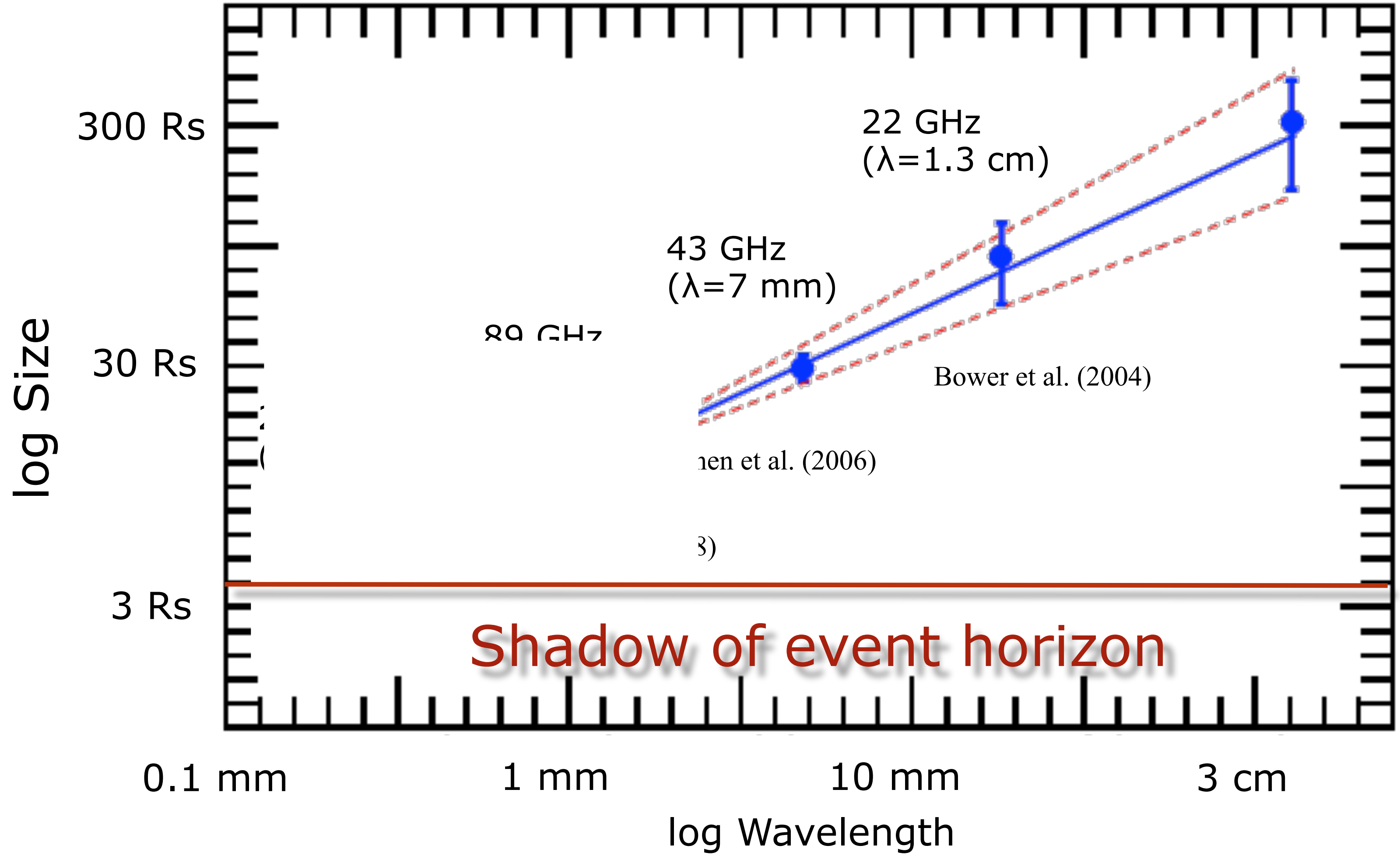
*Structure of Sgr A**



- The shorter the wavelength, the smaller the radio source.
- At low frequencies the structure is blurred by scattering with λ^2-law.
- At λ7 mm the radio source becomes slightly larger than the scattering.
- Intrinsic size at λ7 mm seems elliptical as well (~3:1 ratio, Bower+ 2014)

*Intrinsic radio size of Sgr A**

The higher the radio frequency – the closer to the black hole.
At 230 GHz the emission comes from the event horizon scale.

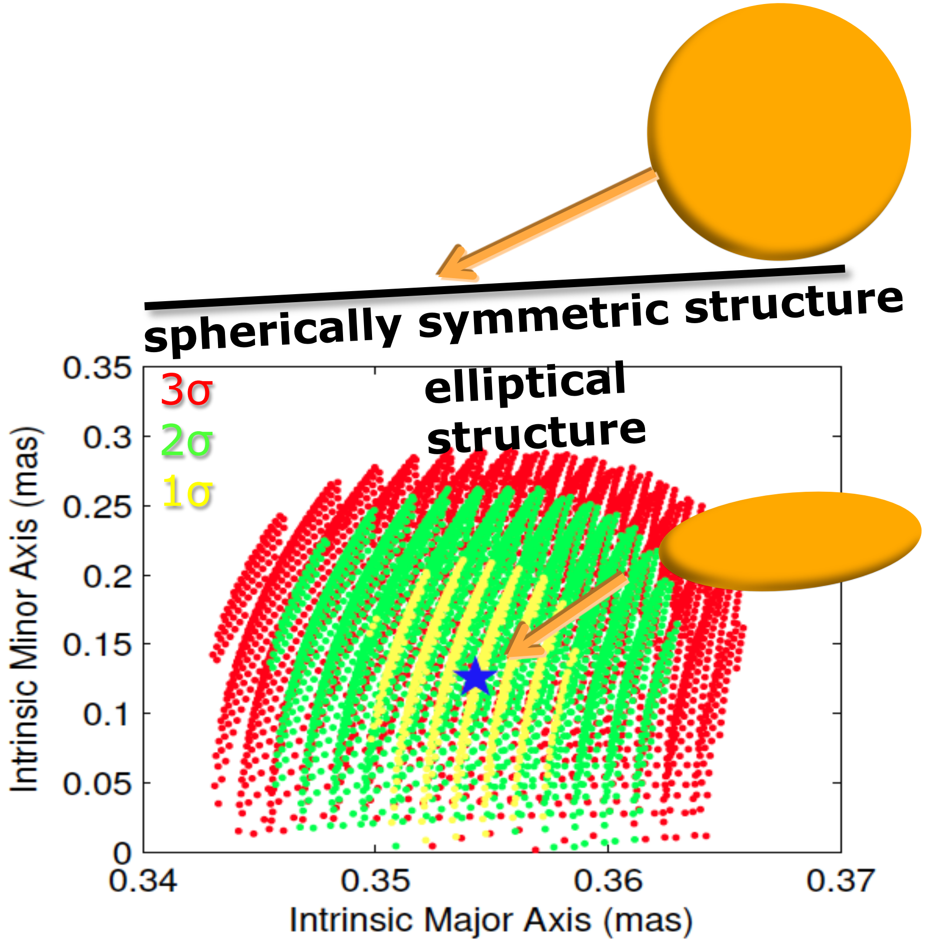


Falcke & Markoff, Class. & Quant. Gravity (2013)

Two-dimensional structure of Sgr A: fairly elongated*

Radboud University Nijmegen

- Accurate closure amplitude measurements of 2D-size of Sgr A* with the VLBA.
- Size at 43 GHz: (35.4 ±0.4) Rs × (12.6±5.5) Rs at PA (95±4)°



Bower et al. (2014, ApJ)

43 – 22 GHz Time Lag: inside-out (20-40 min)

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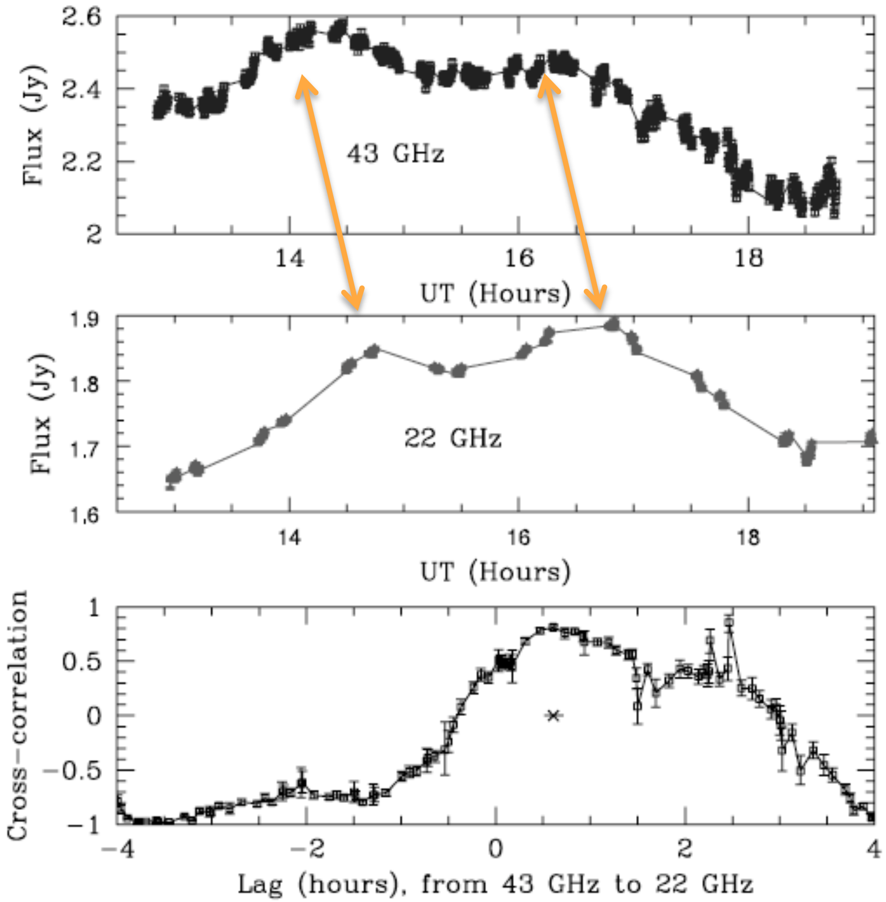
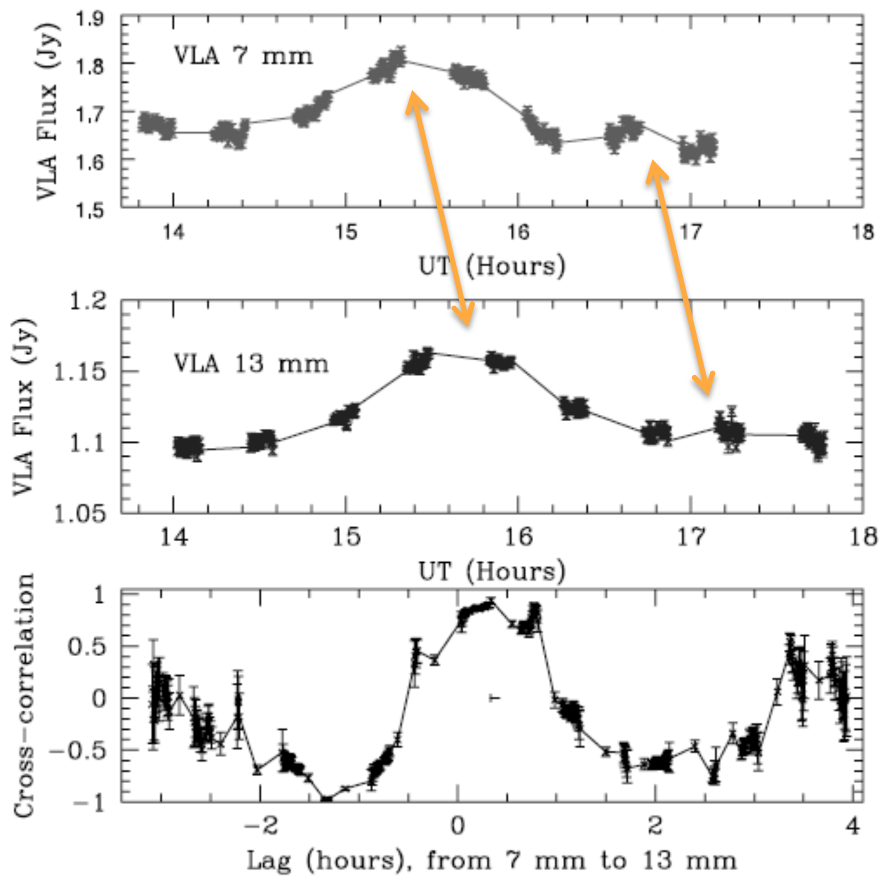
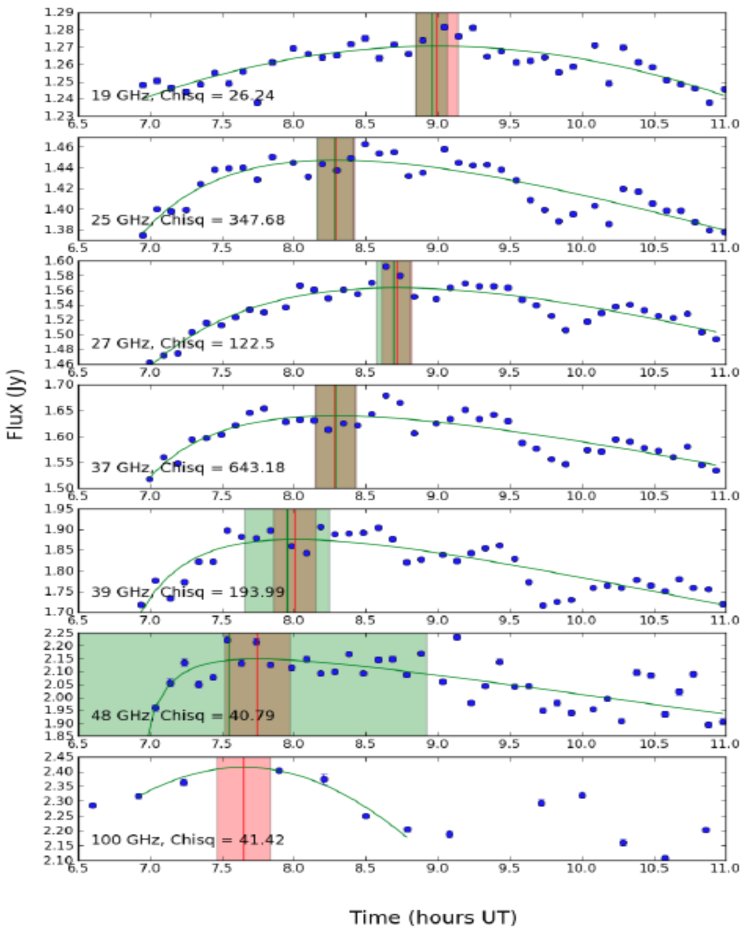


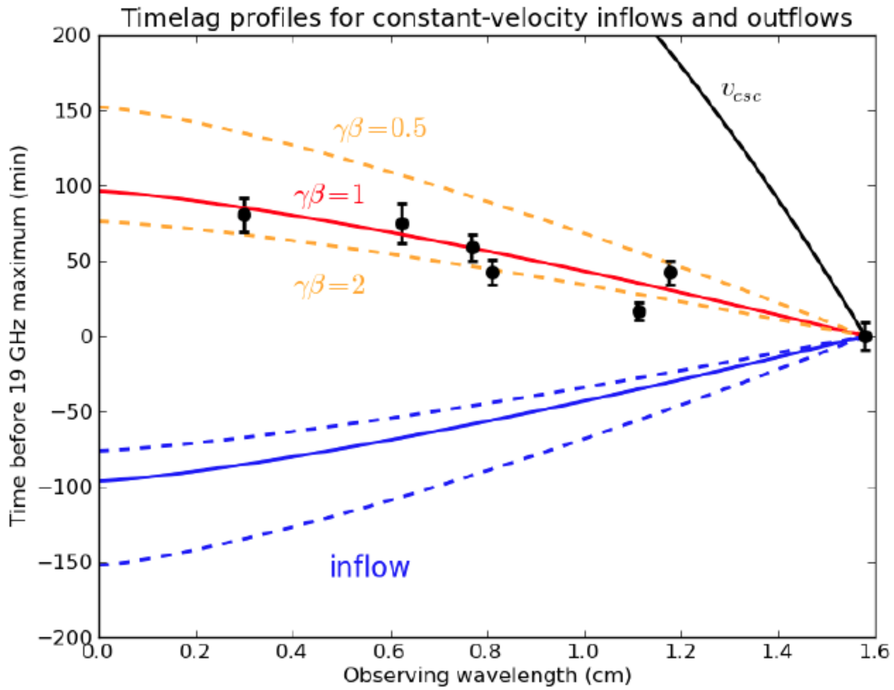


Yusef-Zadeh et al. (2008)

ALMA+VLA Radio Lags

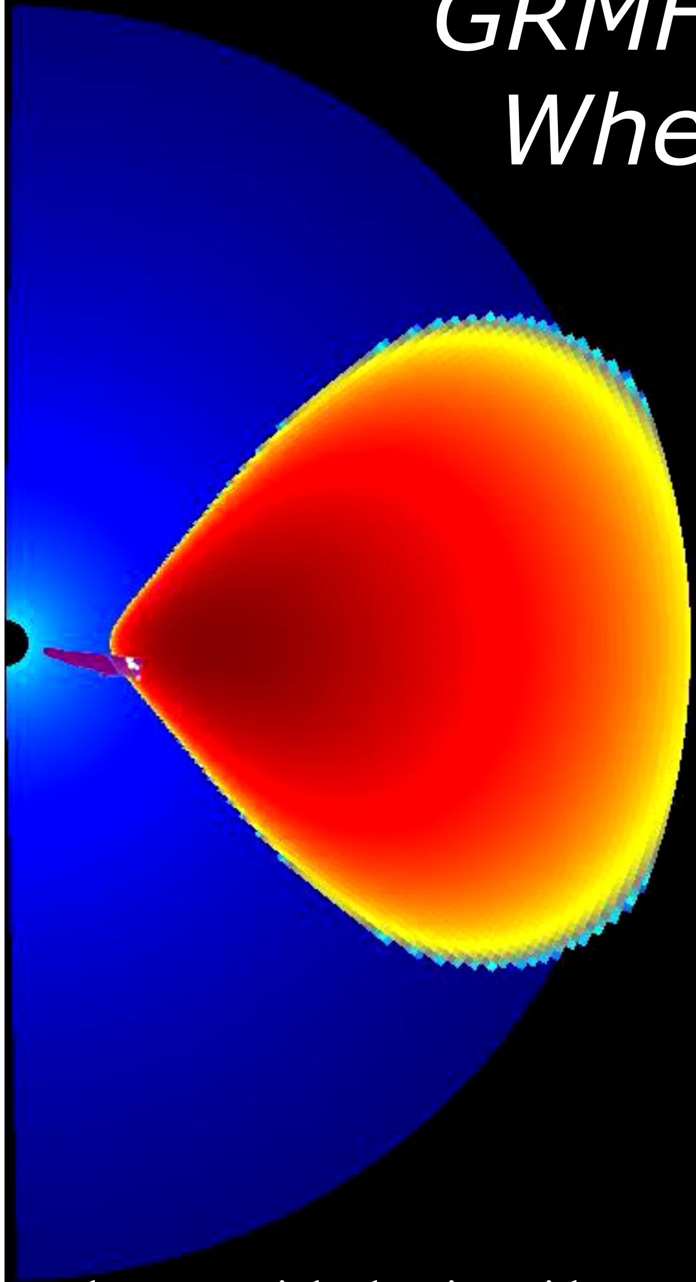


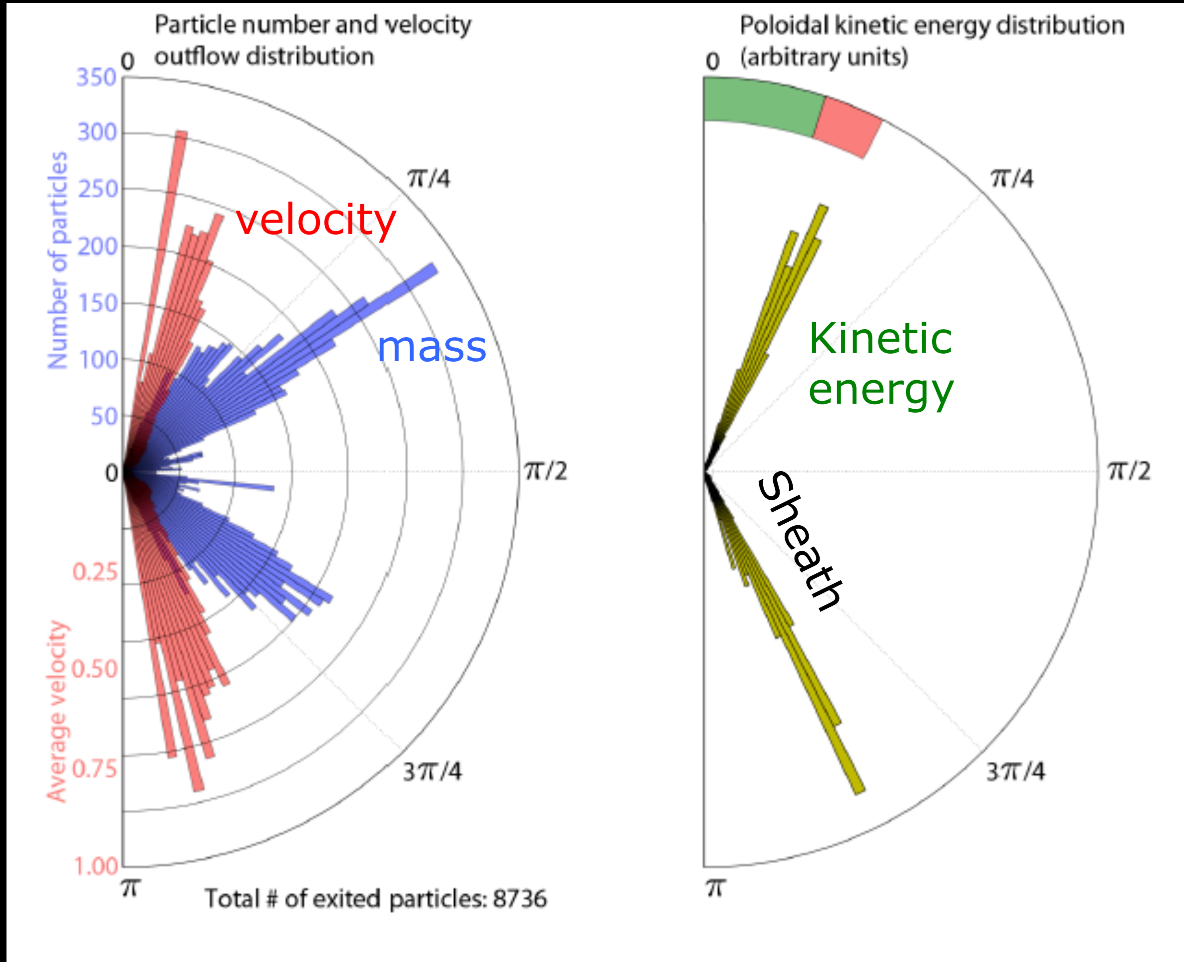
Higher frequencies, lead lower frequencies
⇒ **relativistic outflow**



Brinkerink et al. (2015, A&A)
See also Yusef-Zadeh et al. (2009)

GRMHD Simulations Where is the Jet?





shows particle density with tracers
code: harm2d (Gammie)

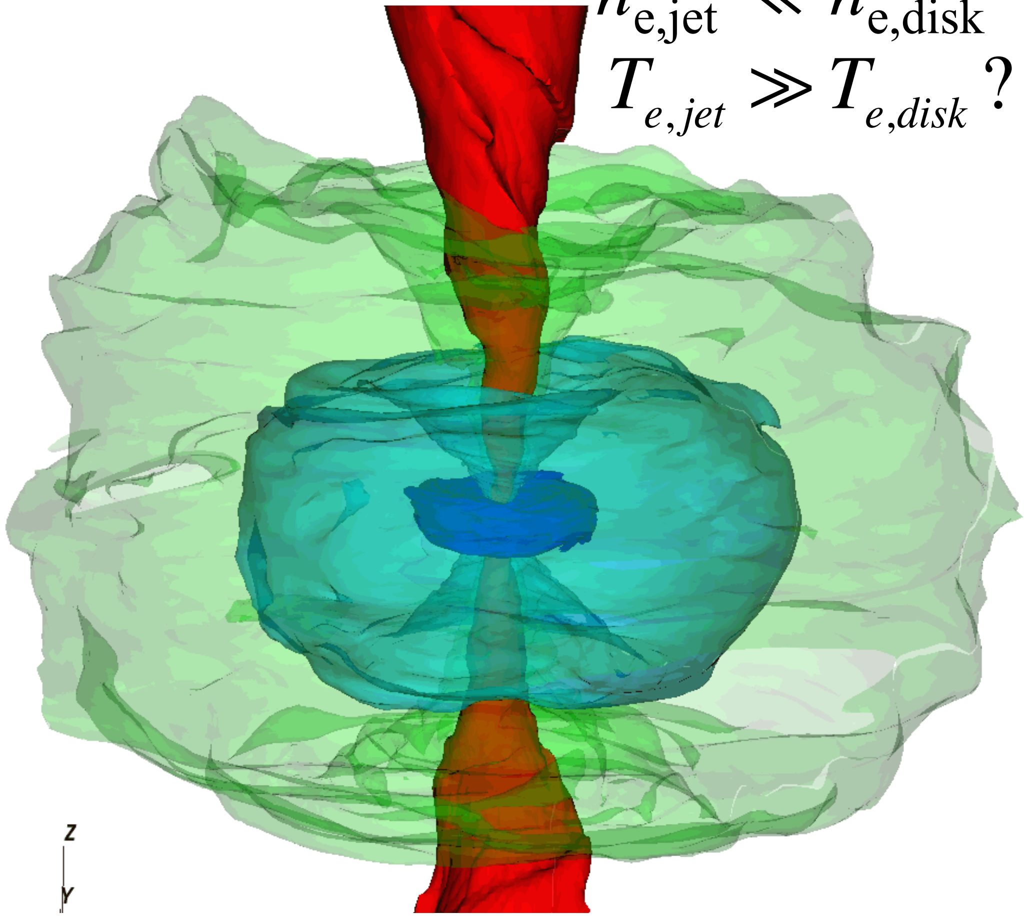
Observable "jet" is the sheath not the spine ...
Brinkerink, Falcke, Moscibrodzka, Gammie

Importance of electron heating

BlackHoleCam

Density regions:
Red = low density
Blue = high density

$$\dot{M}_{jet} \ll \dot{M}_{disk}$$
$$n_{\mathrm{e,jet}} \ll n_{\mathrm{e,disk}}$$
$$T_{e,jet} \gg T_{e,disk}\ ?$$



- **MHD simulations do not treat electrons heating but use arbitrary fudge factor!**
- Only proton temperature fixed.

- Original ADAF/RIAF assumption: $T_e \ll T_p$ everywhere

⇒ **For T(jet)=T(disk) you can never see jets in ADAFs since $n_{e,jet} \ll n_{e,disk}$!**

⇒ Different physical regimes:
- Jet: low n, high B
- Disk: high n, low B

⇒ Unlikely to have same proton-electron coupling mechanisms!

⇒ **Allow for different proton-ion coupling in disk & jet!**

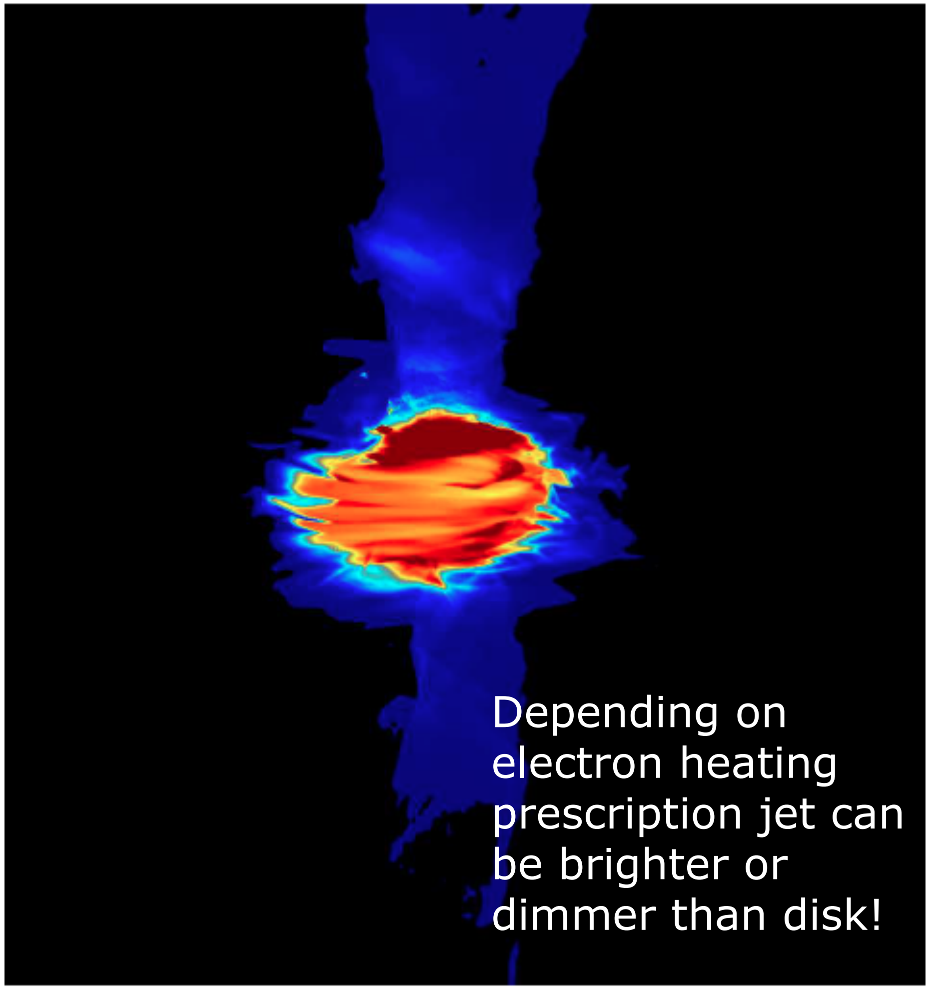
Moscibrodzka & Falcke (2013, A&A)
Moscibrodzka, Falcke, Gammie, Shiokawa (2014, A&A)

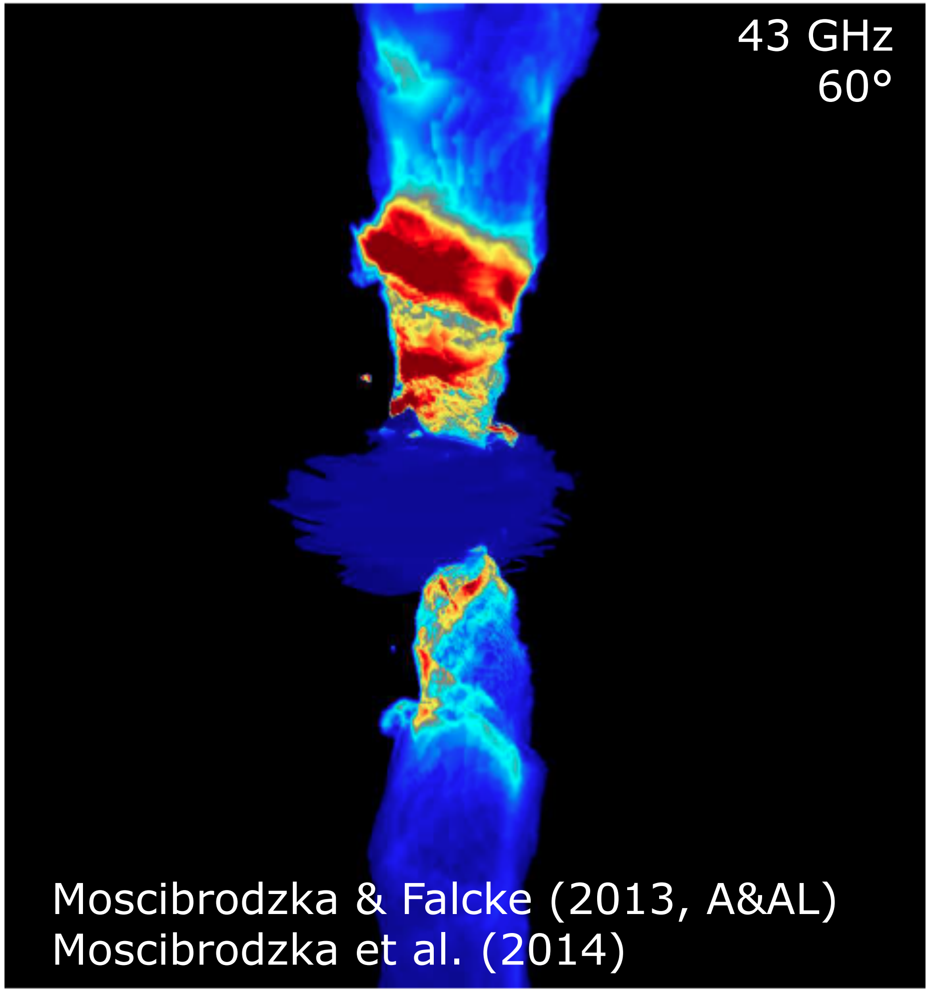
3D GRMHD with isothermal jet

BlackHoleCam

Jet: Tp/Te=1, Te~const
Disk: hot ADAF (Tp/Te~5)

Jet: Tp/Te=1, Te~const
Disk: "classical" 2-temperature ADAF (Tp/Te~25)

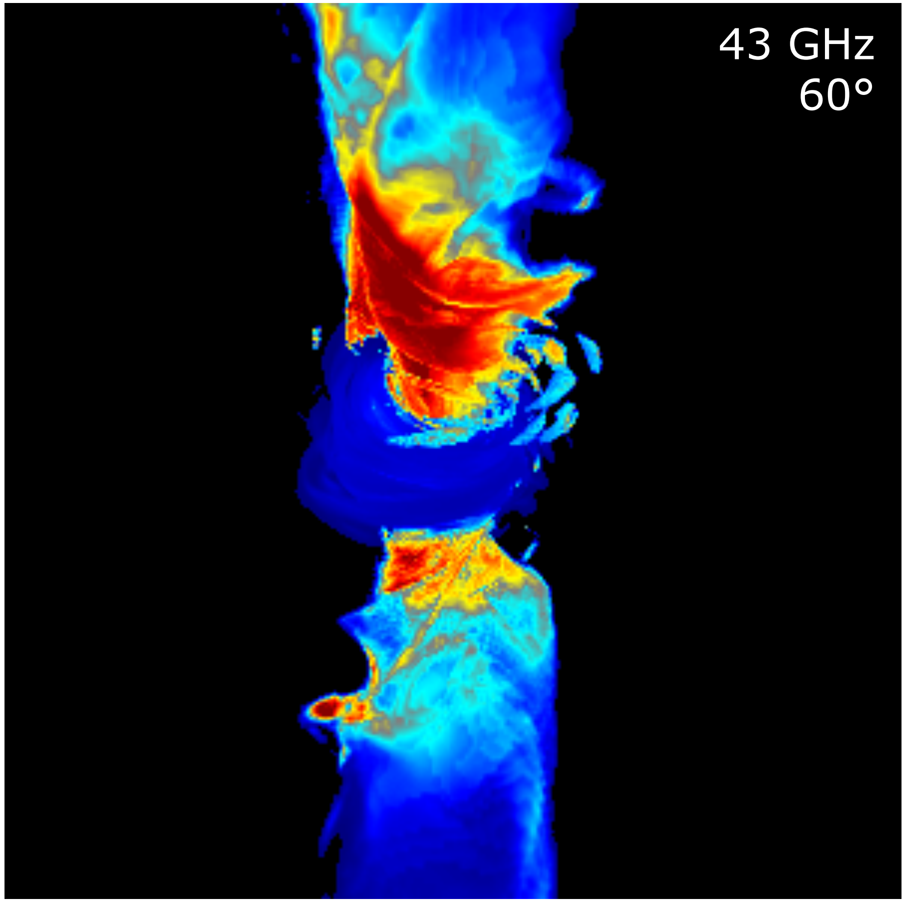


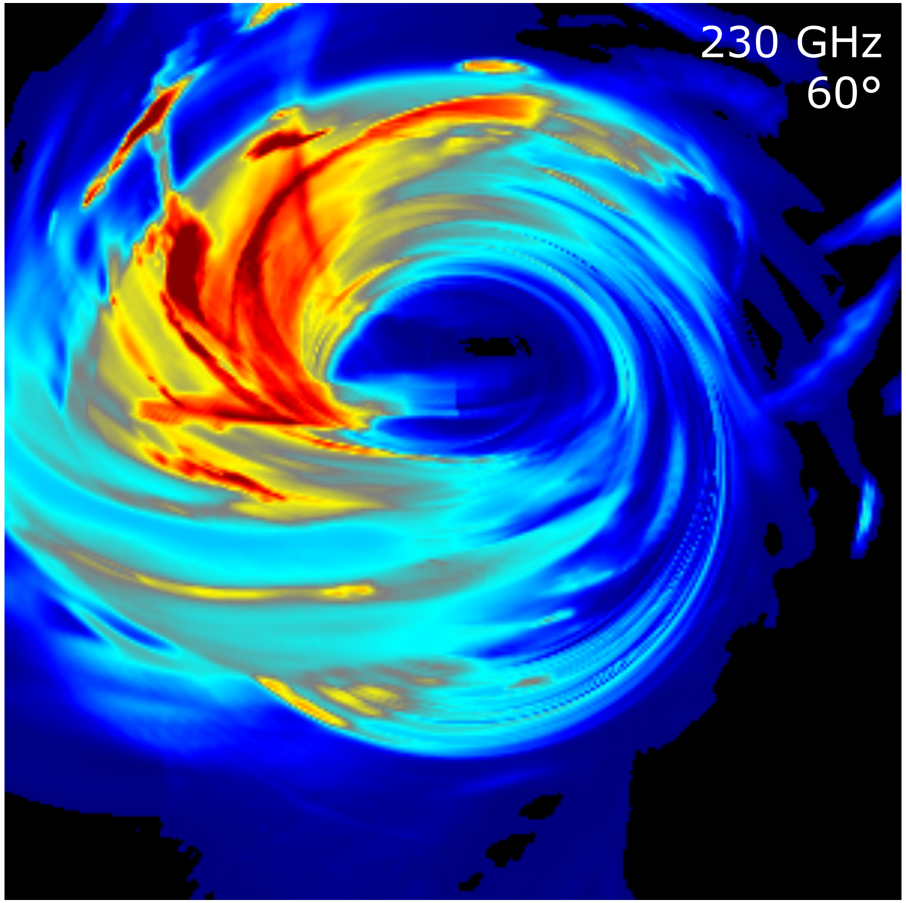


Sgr A* 3DGRMHD with isothermal jet

BlackHoleCam

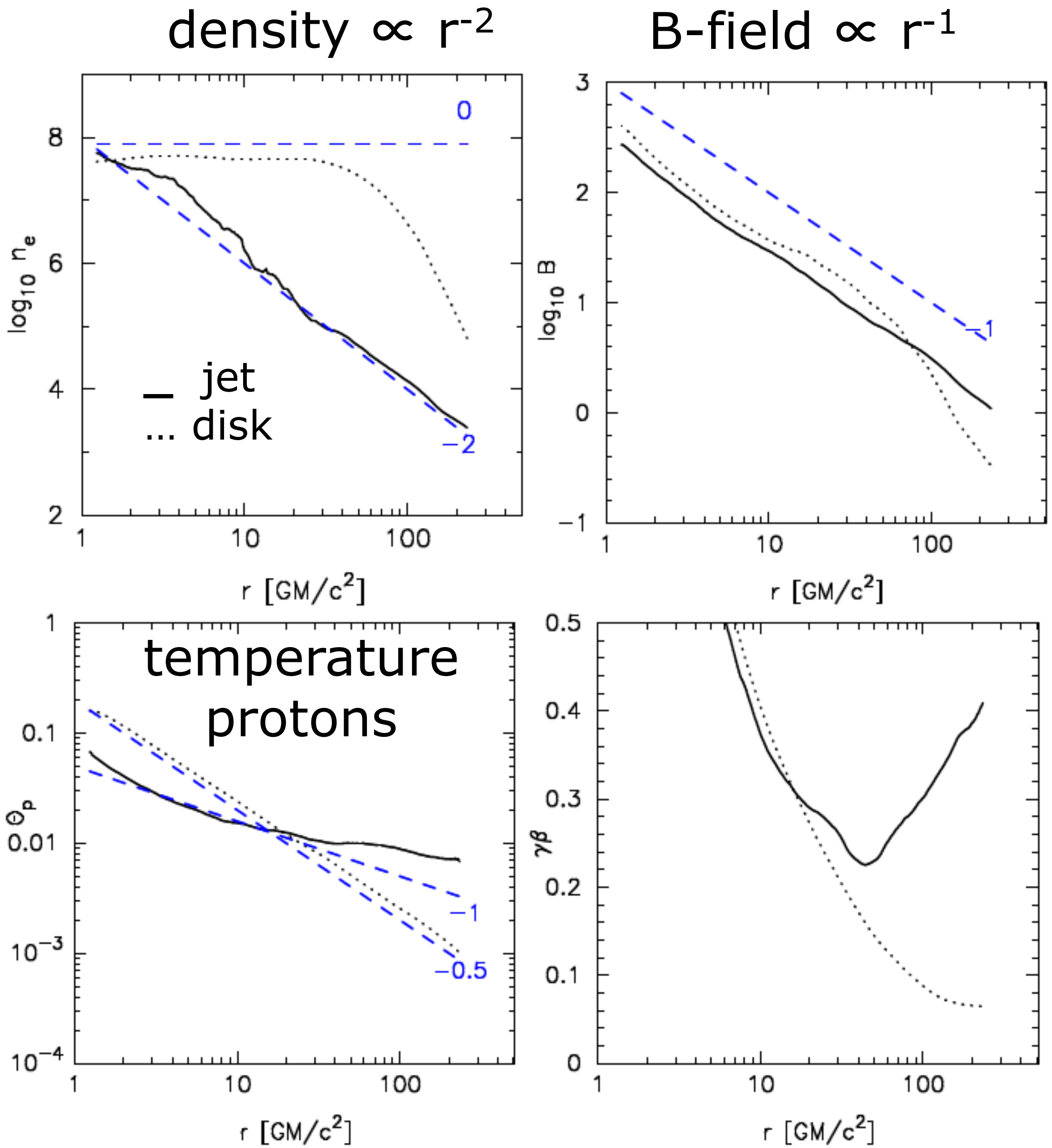
Jet: Tp/Te=1
Disk: two-temperature ADAF (Tp/Te>>1)





Moscibrodzka & Falcke (2013, A&AL)
Moscibrodzka et al. (in prep.)

B-Field and Density Profile



Density and magnetic field in the GRMHD jet sheath **follow the same simple power laws as in Blandford & Königl model** for flat radio cores ….!

⇒ expect flat radio spectrum from (quasi-)isothermal jet.

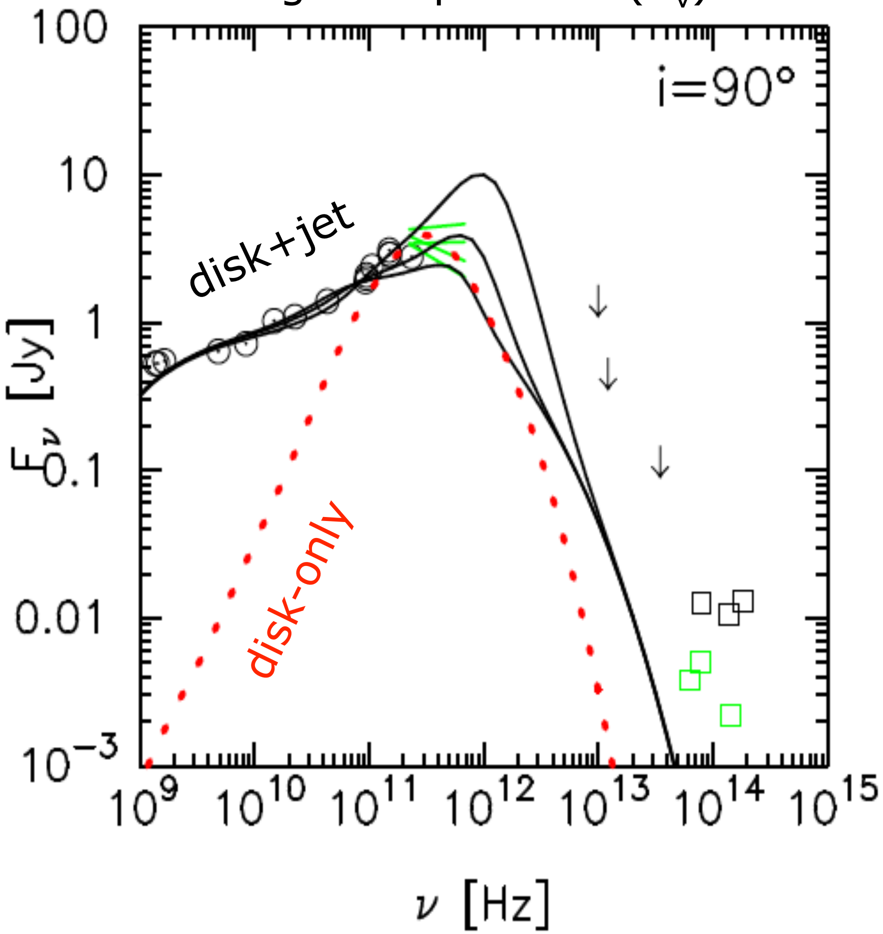
(hollow cone = filled cone)

Moscibrodzka et al. (2014)

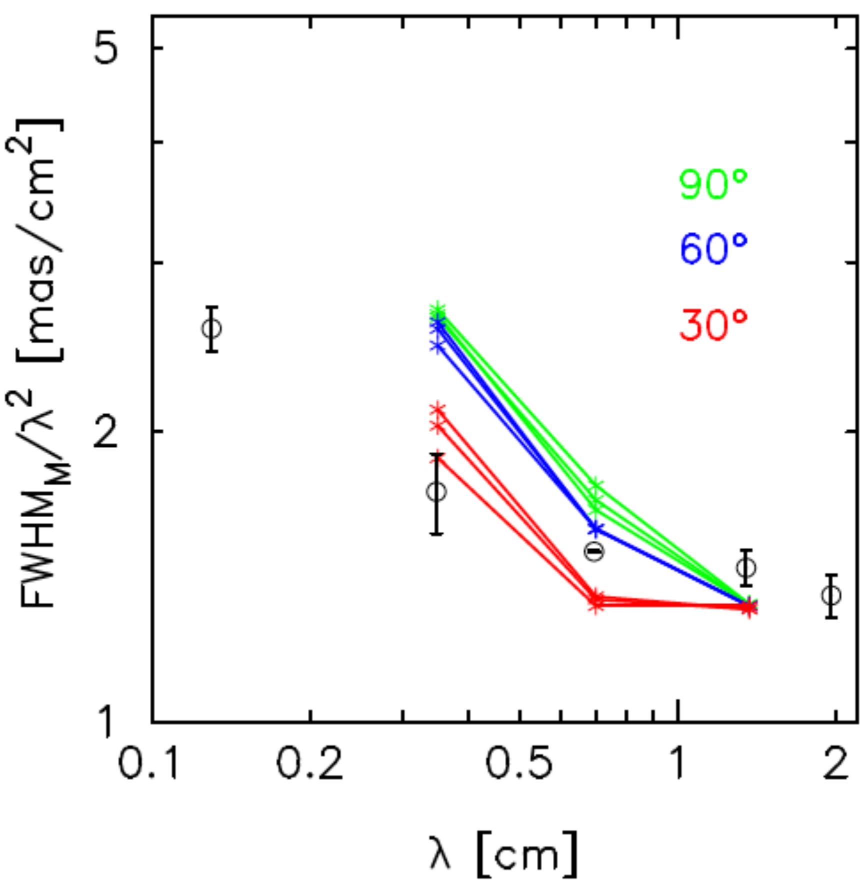
Recovering flat radio spectrum (and size)

GRMHD + GR ray tracing + radiation transport

Sgr A* spectrum (S_ν)

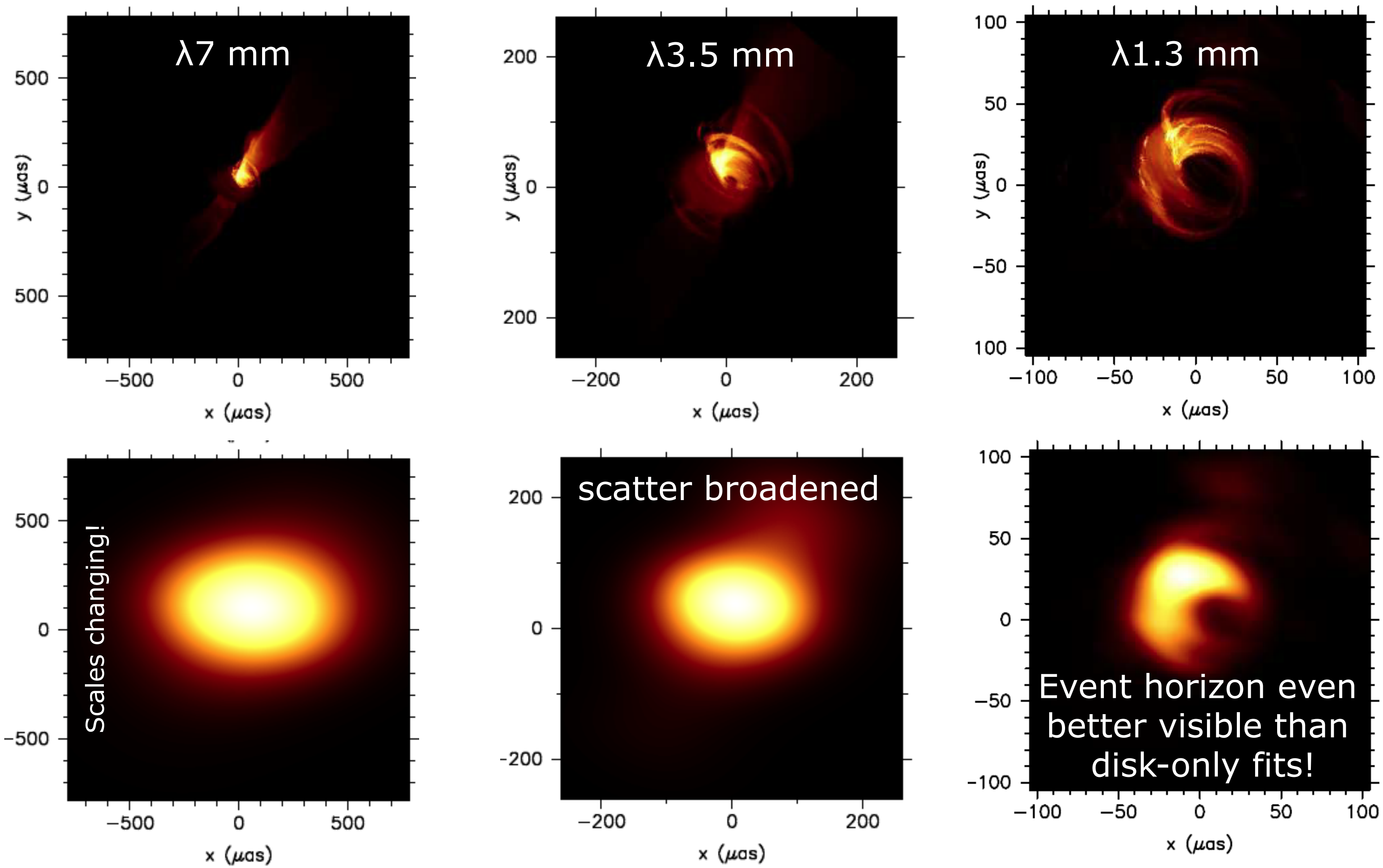


Sgr A* size + scatter broadening



Moscibrodzka & Falcke (2013, A&AL)

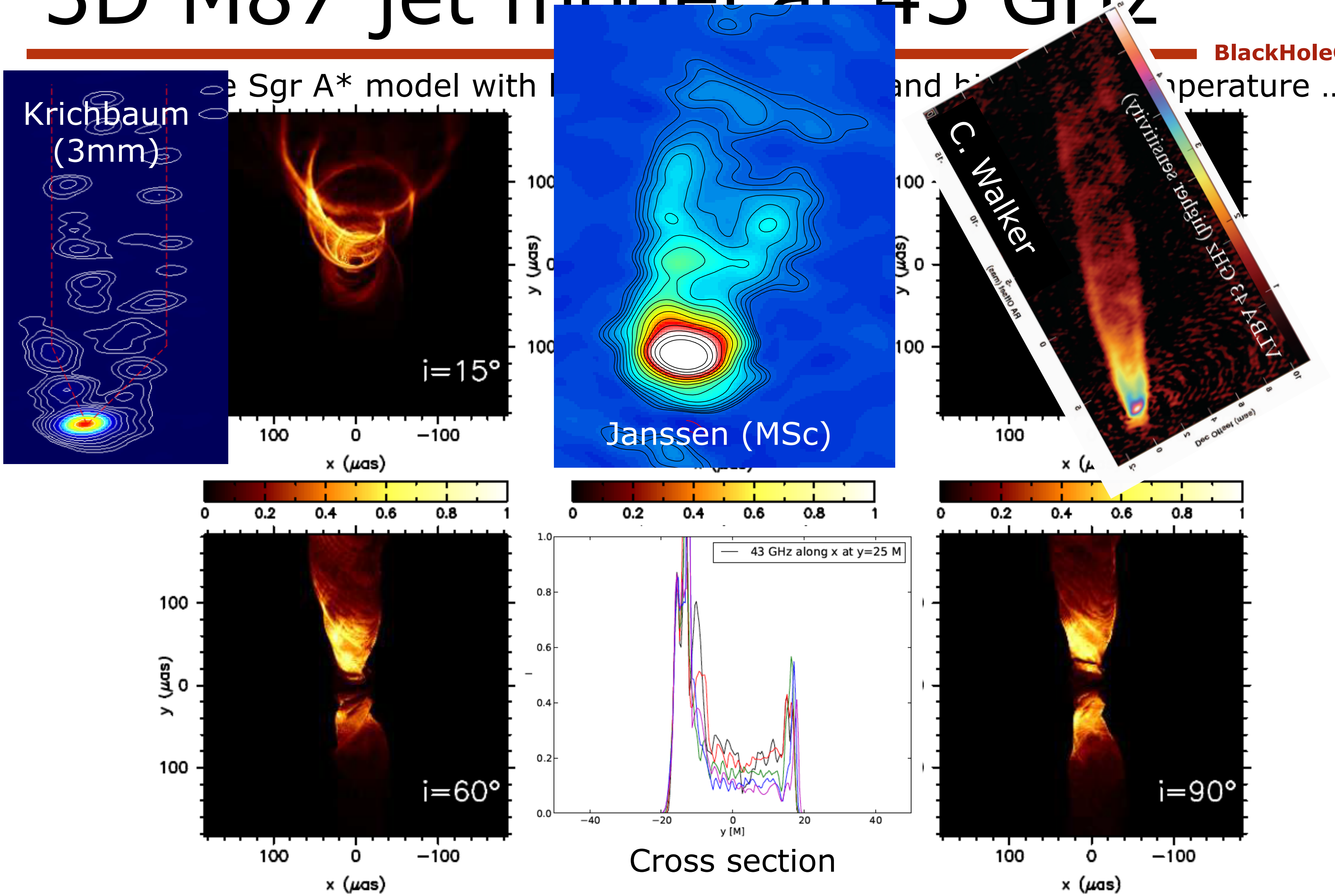
Effect of scatter broadening



3D M87 jet model at 43 GHz

BlackHoleCam

…e Sgr A* model with l… and hi… perature …



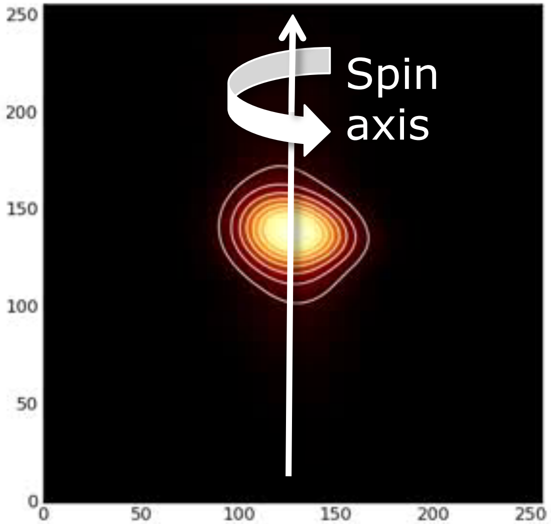
Moscibrodzka et al. (2015, A&A, subm.)

Jet Position Angle & Spin Axis

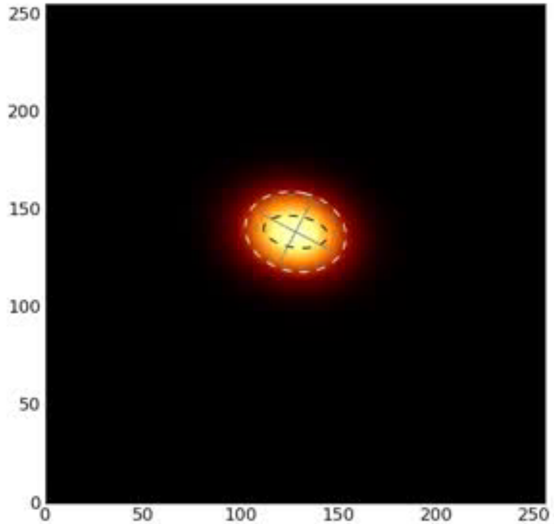
BlackHoleCam

Simulated λ3 mm-VLBI observations

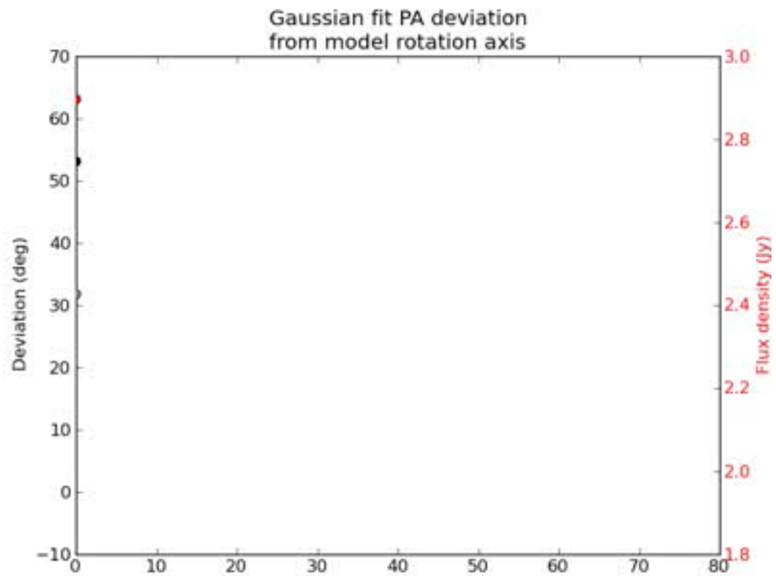
scatter-broadened image



Gaussian fit



Fitted position angle



Good imaging quality is key to get spin axis …

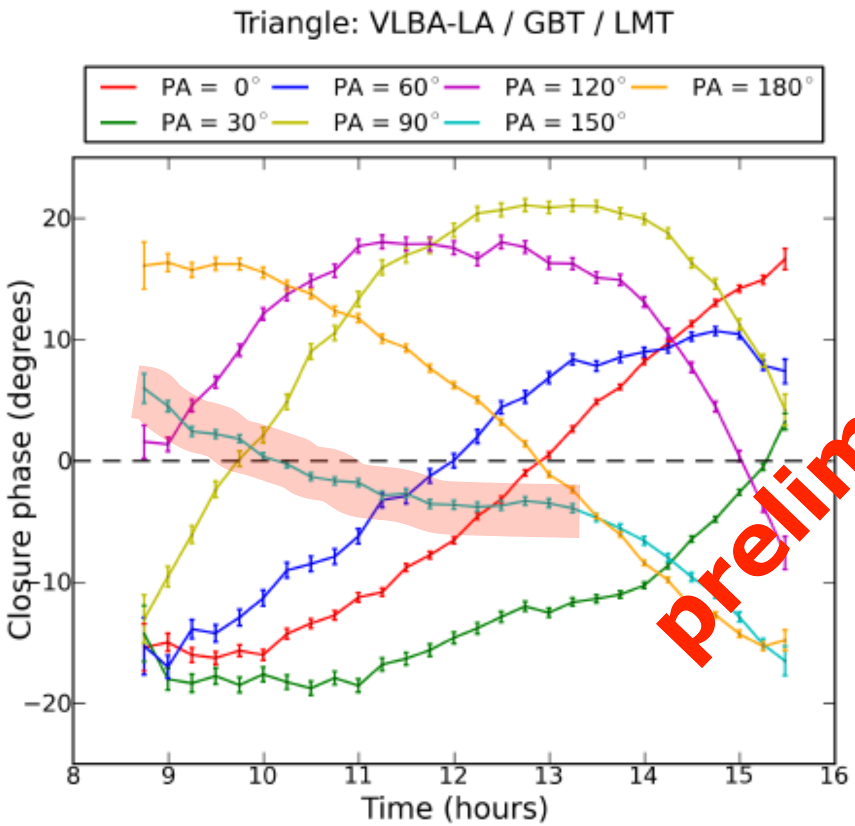
Brinkerink et al. (in prep.)

To be tested with recent VLBA+LMT+GBT VLBi run at 3mm …

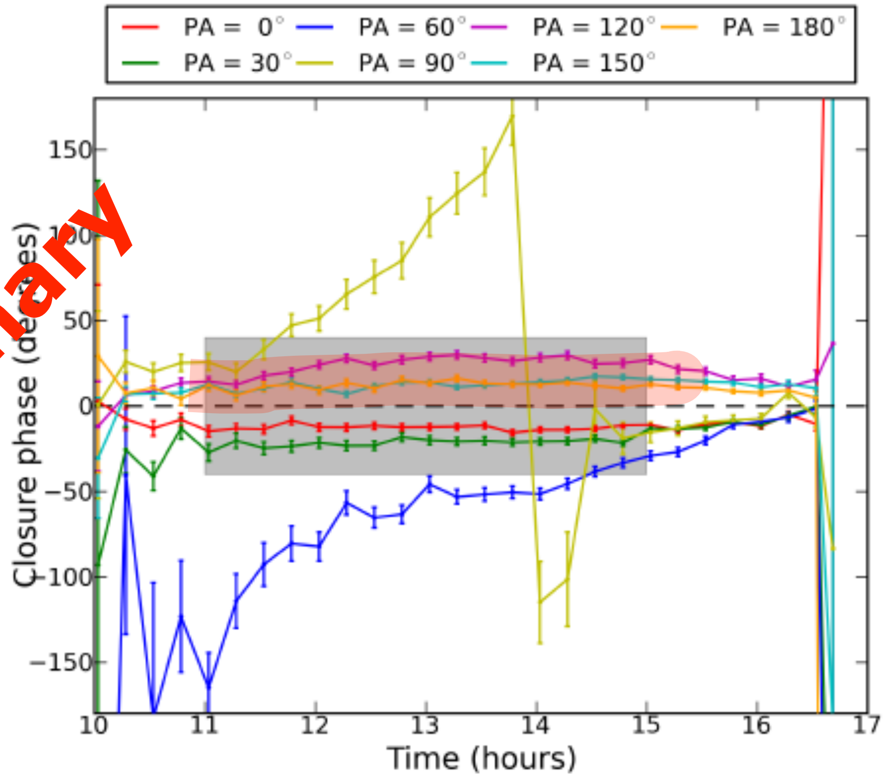
Closure phases for jet model

BlackHoleCam

3 mm VLBI: HSA
(VLBA_LA-GBT-LMT)

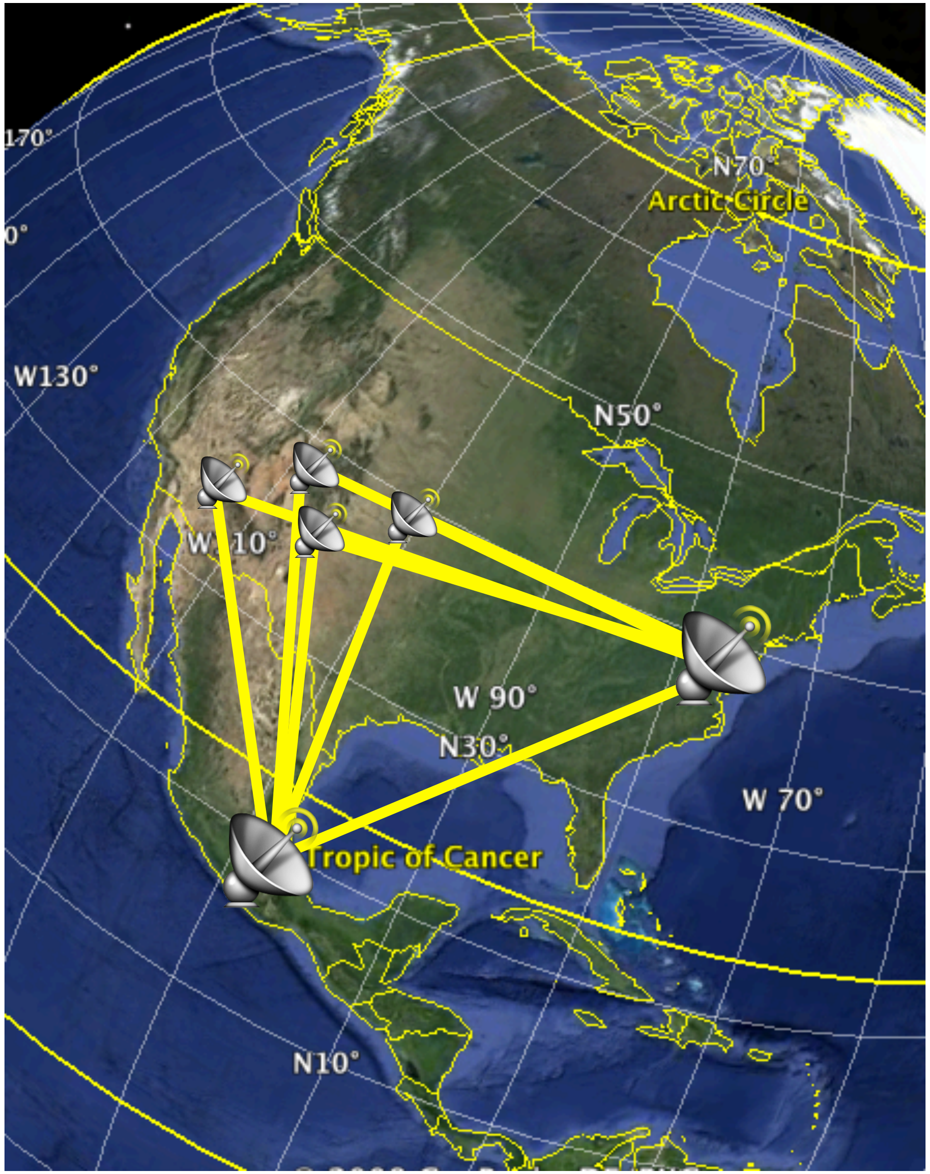


1 mm VLBI: EHT2013
(Hawaii, California, Arizona)



Brinkerink et al., in prep.

VLBA+LMT+GBT @ λ3mm

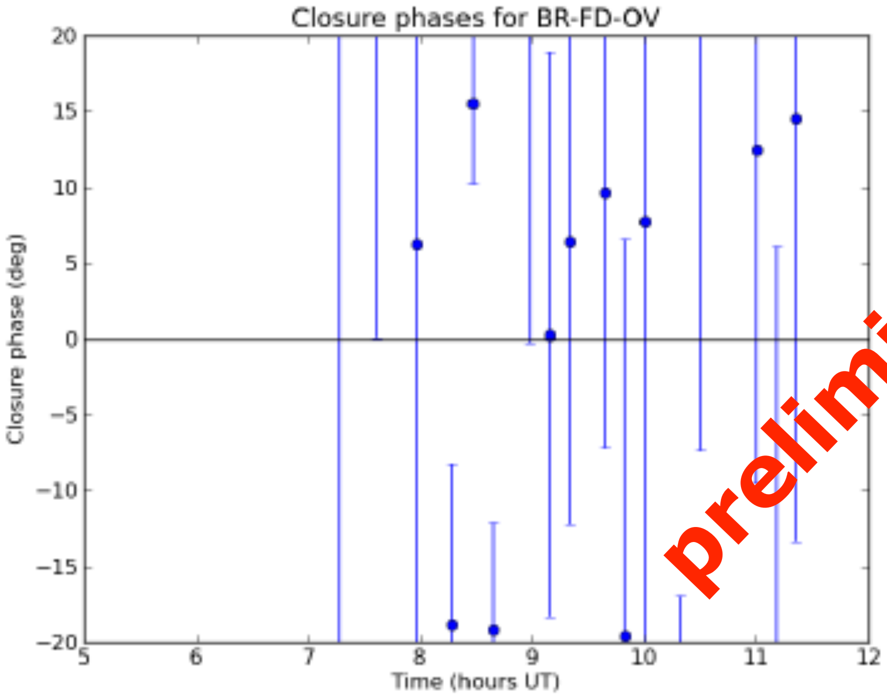


- Interesting baselines between SW-US, East-Coast, Mexico (2000-3000 km)
- Includes “big guns”: LMT & GBT
- Ideal closure-phase triangles
- BF114a&b, May 2015: fringes between VLBA/LMT/GBT

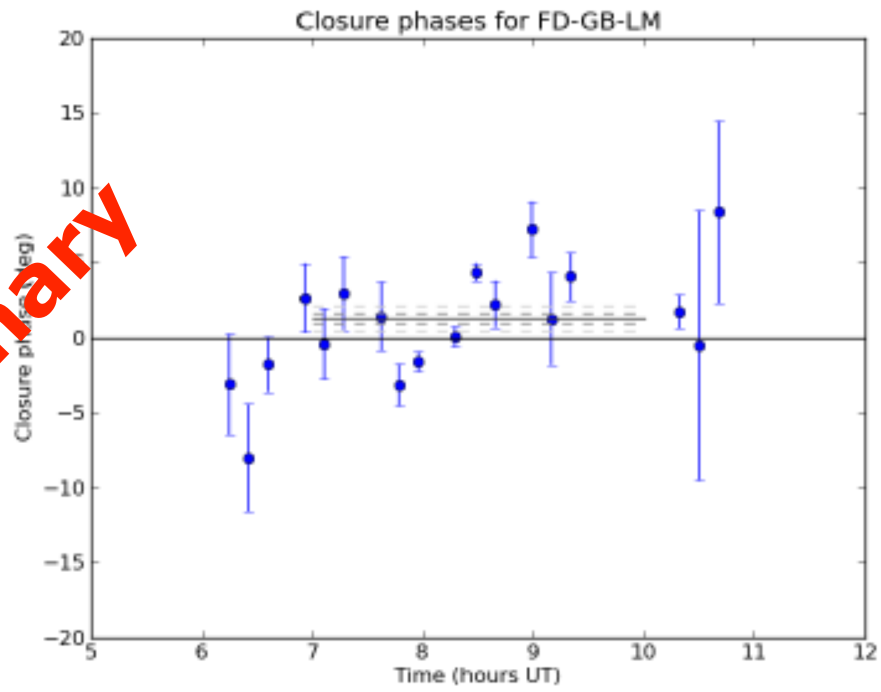
US-Mexican Closure Phases

BlackHoleCam

VLBA only



VLBA_FD + GBT + LMT

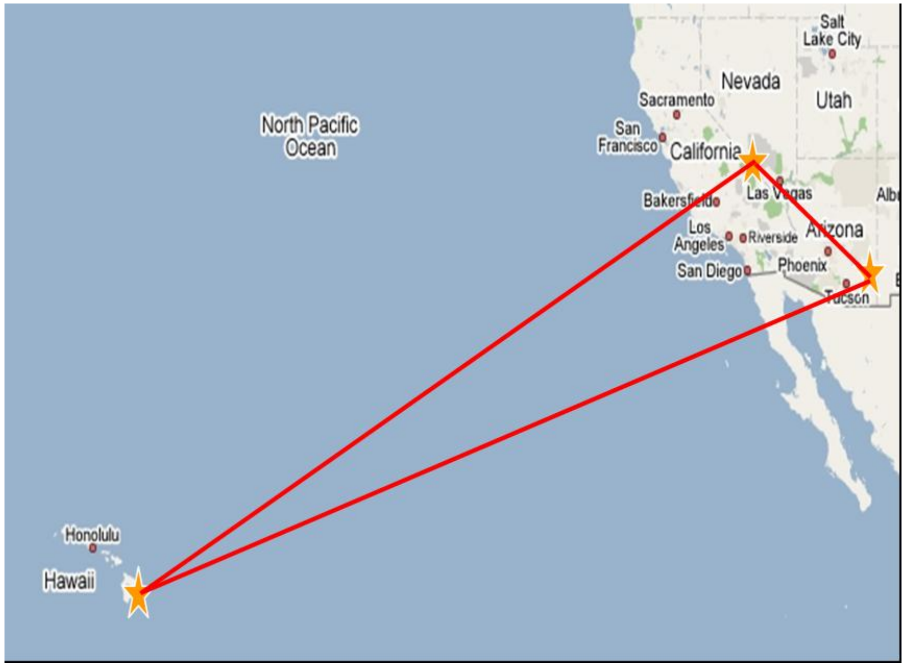


Brinkerink et al., in prep.

EHT Closure phases at 1 mm

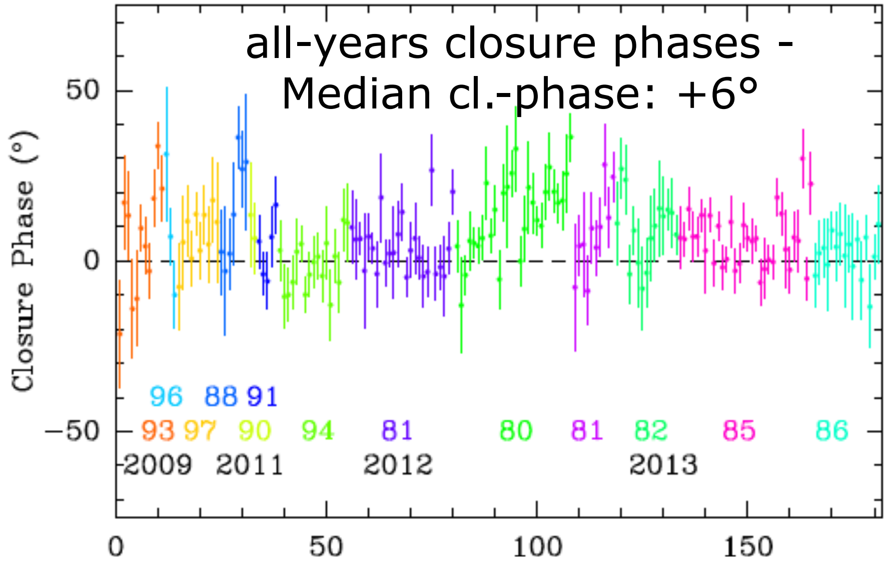
BlackHoleCam

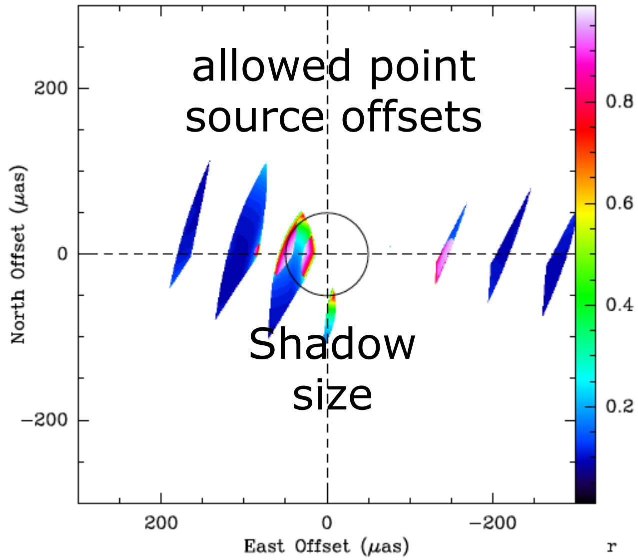
Hawaii-California-Arizona



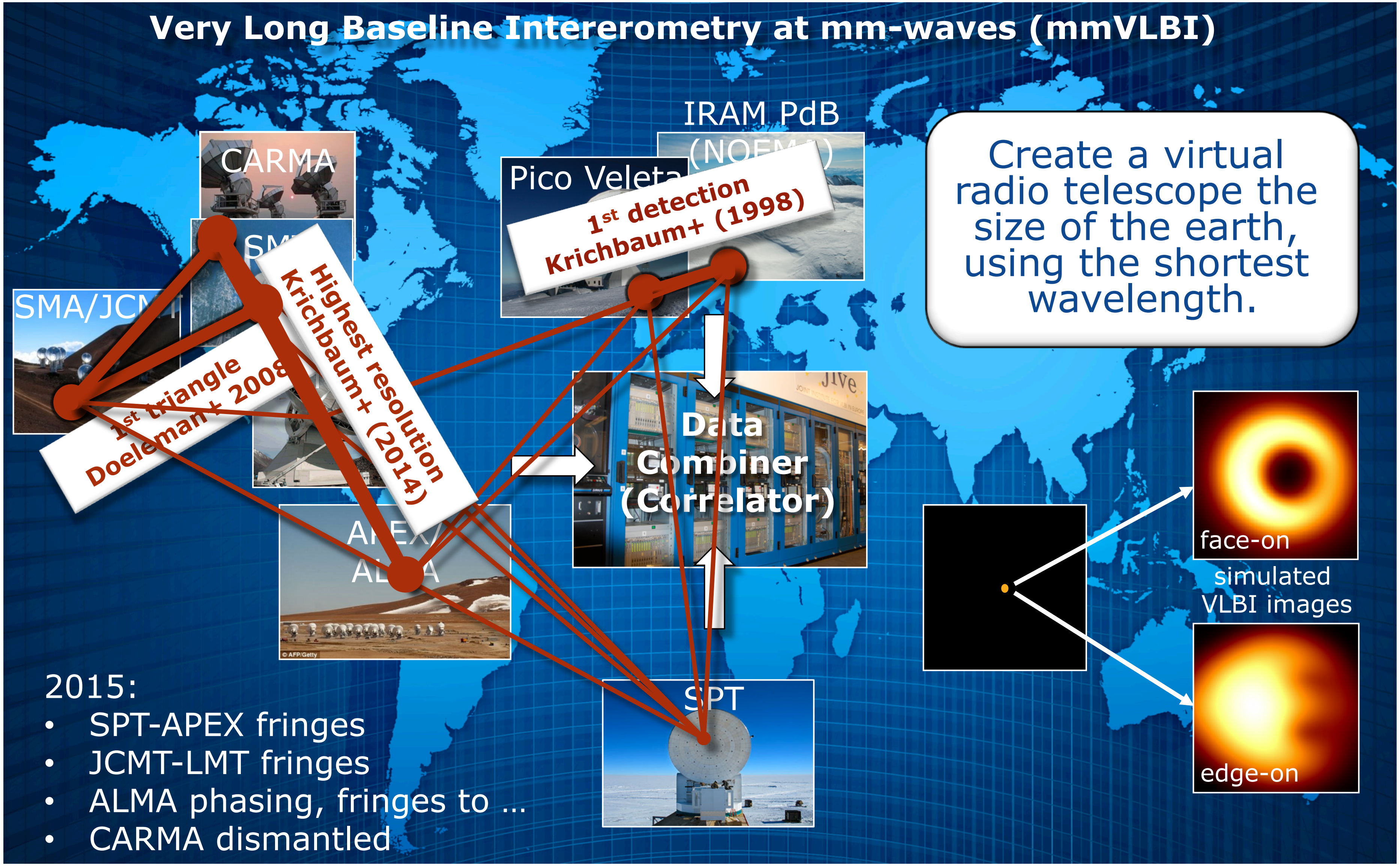
Fish et al. (2015, ApJ subm.)

See also "Polarization on EH scales":
Johnston et al. (2015, Science, in press)





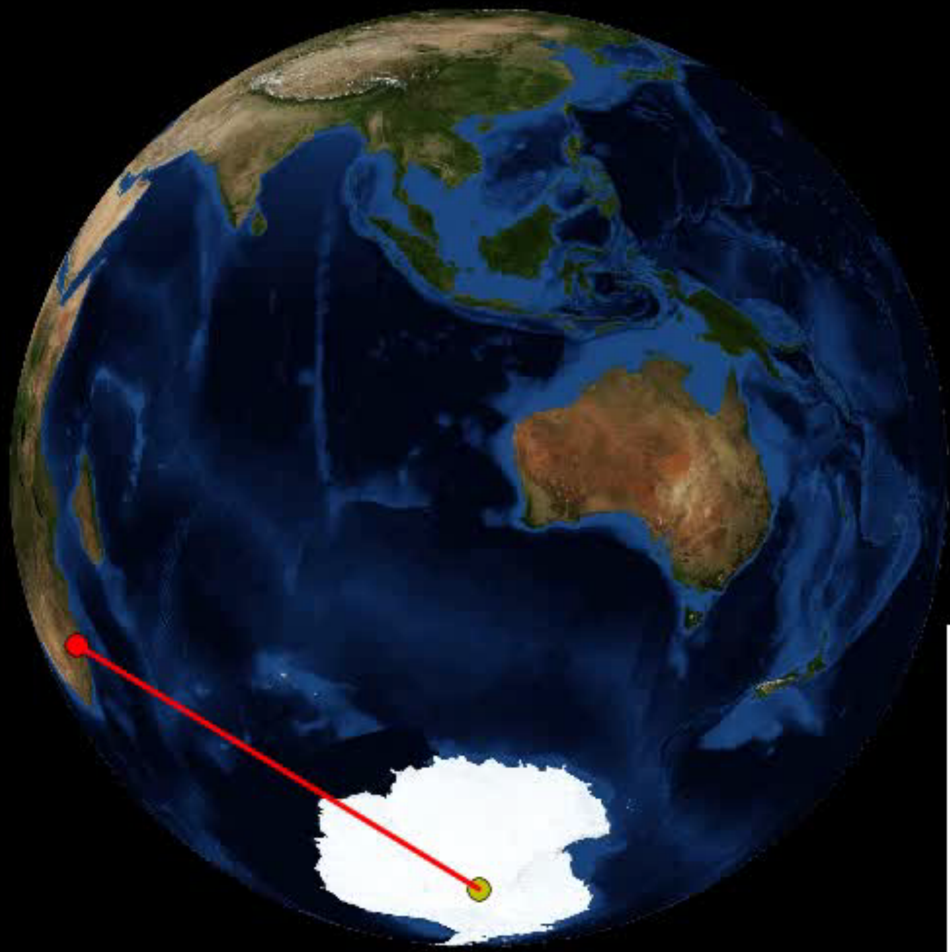
Event Horizon Telescope



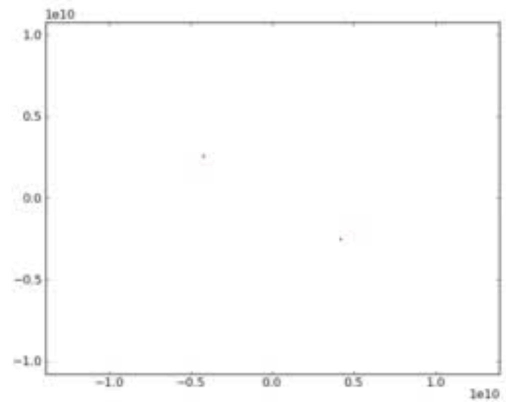
VLBI with Africa mm-telescope?

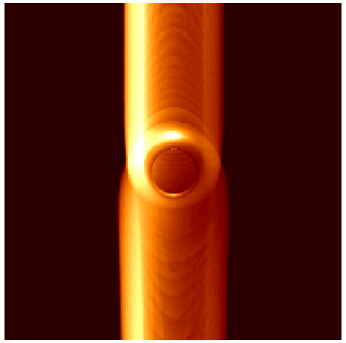
BlackHoleCam

A dedicated African cm and mm-VLBI telescope for EHT/BHC, EVN, & SKA. investment cost: ~8 M€ + operations …



Earth seen from Sgr A*





Conclusions

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- The radio source Sgr A* is the best supermassive black hole candidate:
  - Mass and distance are accurately determined
  - sub-mm waves comes from event horizon scale
- To constrain GR from BH shadow we need to understand the radio source better
- Jet model is currently the only model that naturally describes all characteristics of the radio source Sgr A* (spectrum, size, lags) and also scales to other AGN.
- mm-VLBI strongly constrains jet model orientation – challenge or blessing?
- A jet could fix the BH spin axis, if one can find consistent results.
- Future steps: broad-band equipment (2015+), SouthPole (2017), Alma …??
- Imaging the BH shadow with mm-VLBI will
  - demonstrate that black holes and event horizons exist
  - test GR and also modified GR
  - allow comparison with simulations and probe accretion & jet physics

  ⇒ **black hole astrophysics becomes testable science!**