Title: Two-temperature disk + isothermal jet model for Sgr A* and M87

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Abstract: The super-massive black hole in the center of the Milky Way, Sgr~A*, displays a nearly flat radio spectrum which is typical for jets in Active Galactic Nuclei. Indeed, time-dependent, magnetized models of radiatively inefficient accretion flows, which are commonly used to explain emission of Sgr A* also often produce jet-like outflows. However, the emission from these models so far has failed to reproduce the flat radio spectrum. We show that current GRMHD simulations can naturally reproduce the flat spectrum, when using a two-temperature plasma in the disk and a constant electron temperature plasma in the jet. This assumption is consistent with current state-of-the art simulations, in which the electron temperature evolution is not explicitly modeled. The model images and spectra are consistent with the radio sizes and spectrum of Sgr~A*. The model can also reproduce the radio images of the jet base in M87.

Two-temperature disk + isothermal jet model: Sgr A* and M87

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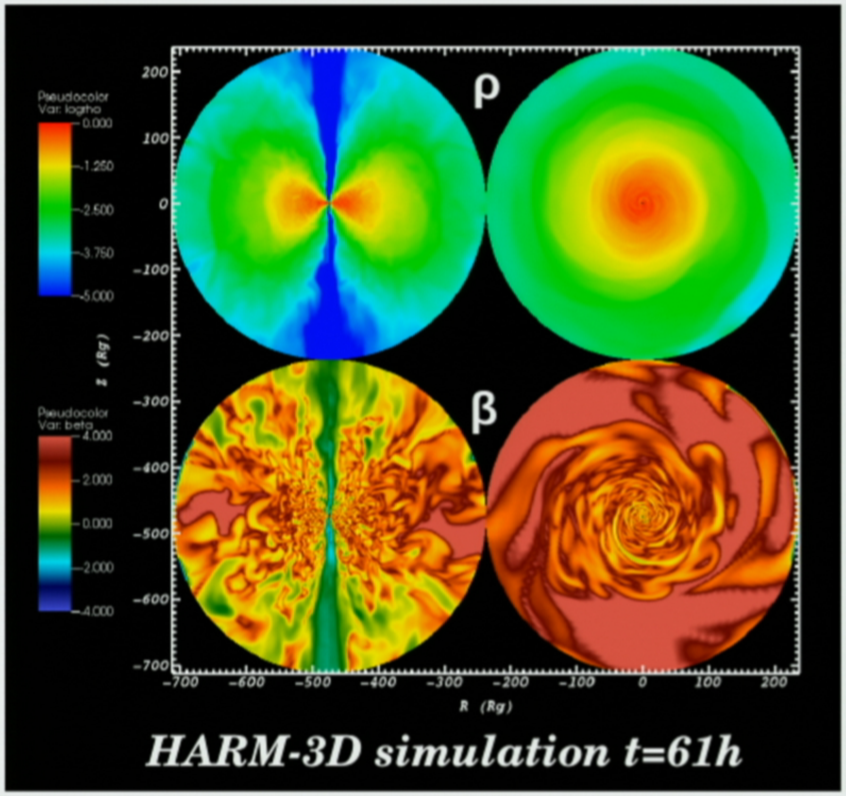
Waterloo, Canada 11 Nov 2014

Modeling plasma close to Sgr A* & M87 core

- General Relativistic MHD simulations
- Simulations comparison to broadband (radio, mm, X-rays) observations of Sgr A* and M87
- The link: modeling electromagnetic radiation produced by the simulations but
  - Emission is produced by e-
  - e- DF not followed in the simulations (collisionless plasma) – lots of degrees of freedom in translating the simulation data to EM signal
  - e- DF controlled by sub-physics that is not “resolved” in the global simulations
- This presentation: address the e- problem using phenomenological approach

A 3-D GRMHD simulation

- black hole in the center, a~0.9
- BH surrounded with rotating torus/ring/donut (bigger size of torus & domain w/ diameter=480 Rg=2.4mas on the sky)
- B fields – weak, initially 1 loop ("SANE" acc. disk w/ steady jet ...)
- dynamics of plasma and B fields after relaxation from initial data



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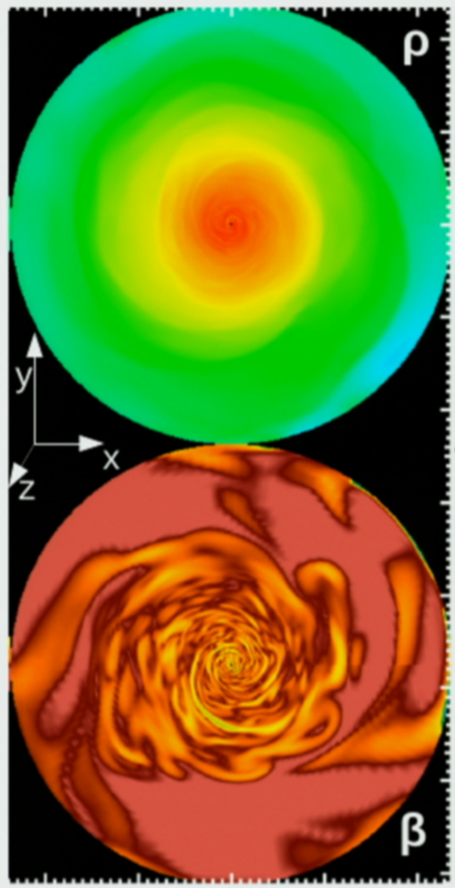
The radiative transfer model free parameter: Te



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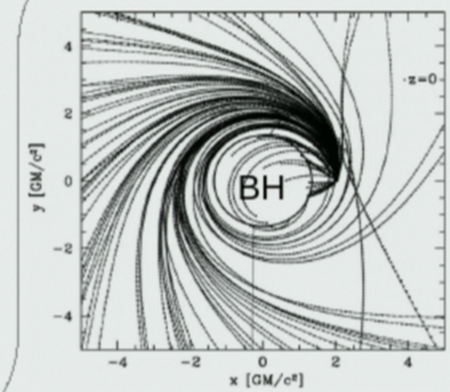
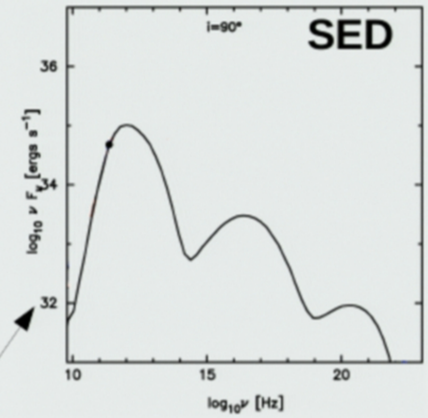
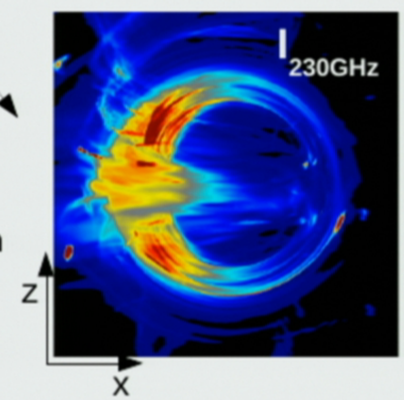


$$\frac{d}{d\lambda}\left(\frac{I_\nu}{\nu^3}\right) = \frac{j_\nu}{\nu^2} - \nu\alpha_\nu\left(\frac{I_\nu}{\nu^3}\right)$$

j_ν - synchrotron emissivity
$(\nu, \rho, B, T_e, \theta, u^\mu)$
α_ν - synchrotron self-absorption
$(\nu, \rho, B, T_e, \theta, u^\mu)$
Inverse Compton process

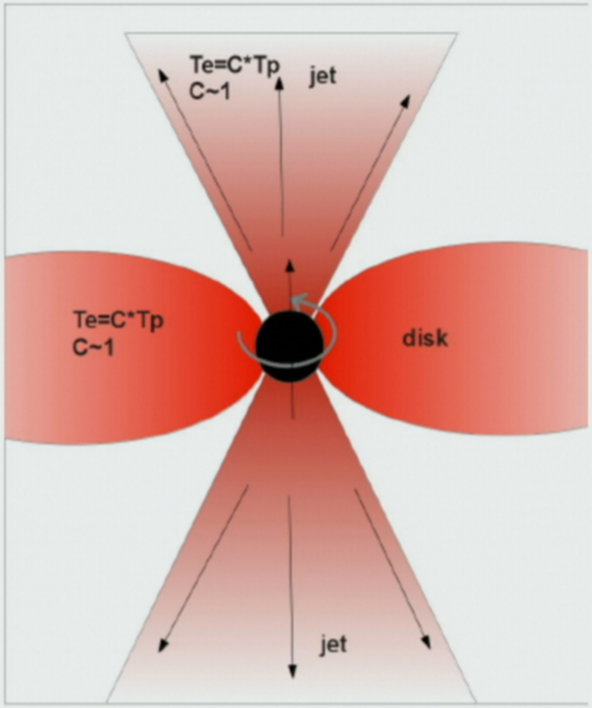
=





What is the electron temperature?

Simple scenario: Te ~ Tp



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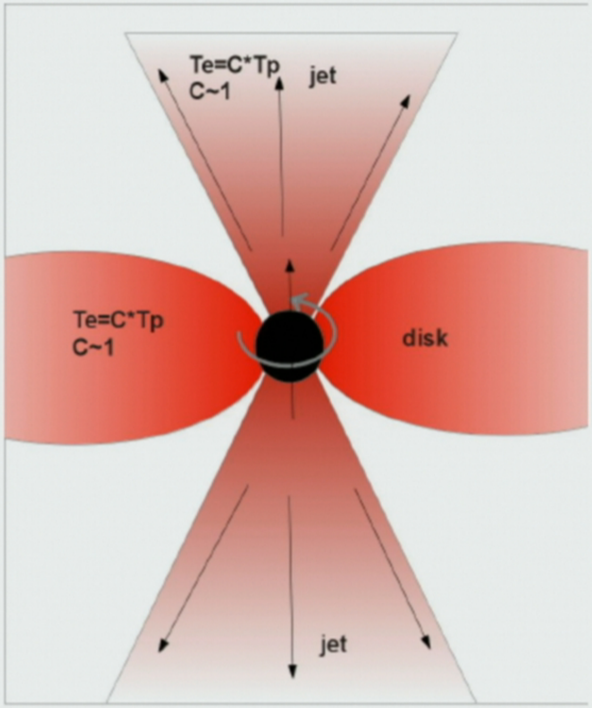
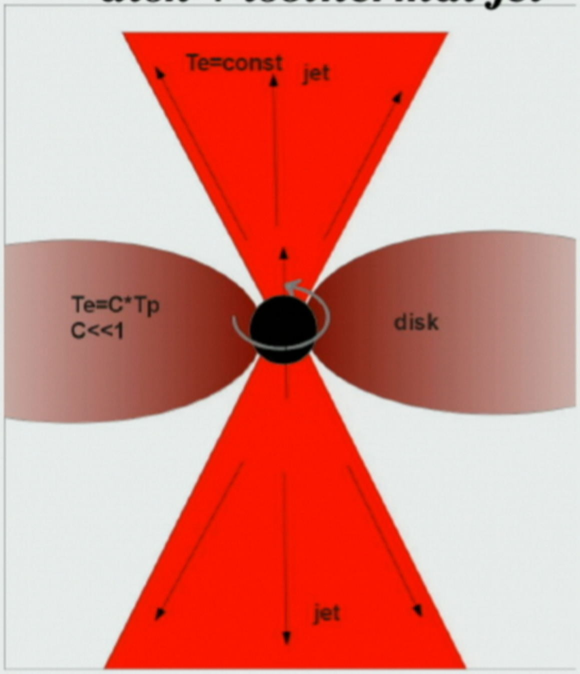


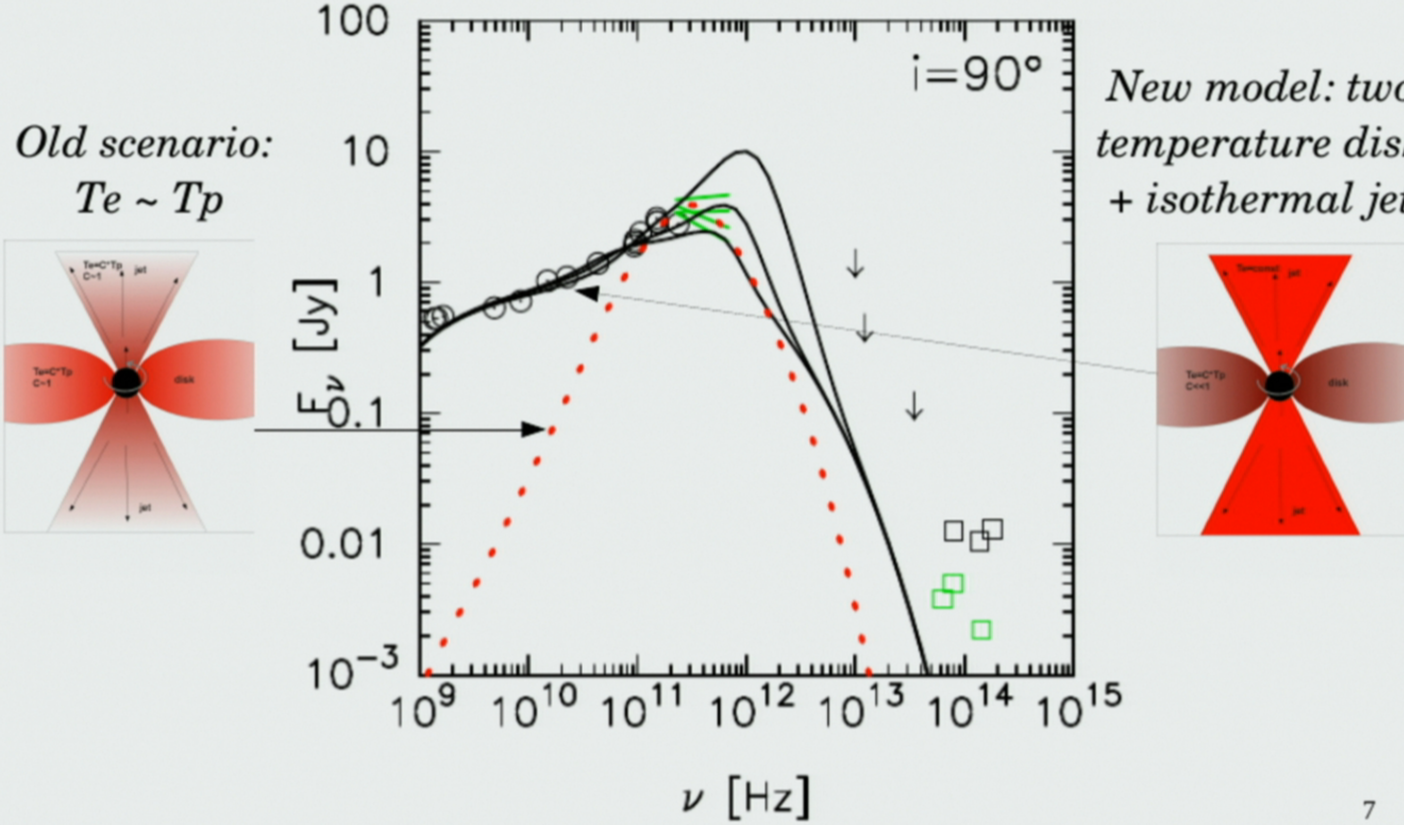
New model: two temperature disk + isothermal jet



SED radio spectral slope is sensitive to the electron temperature in the jet

Old scenario: Te ~ Tp

New model: two temperature disk + isothermal jet



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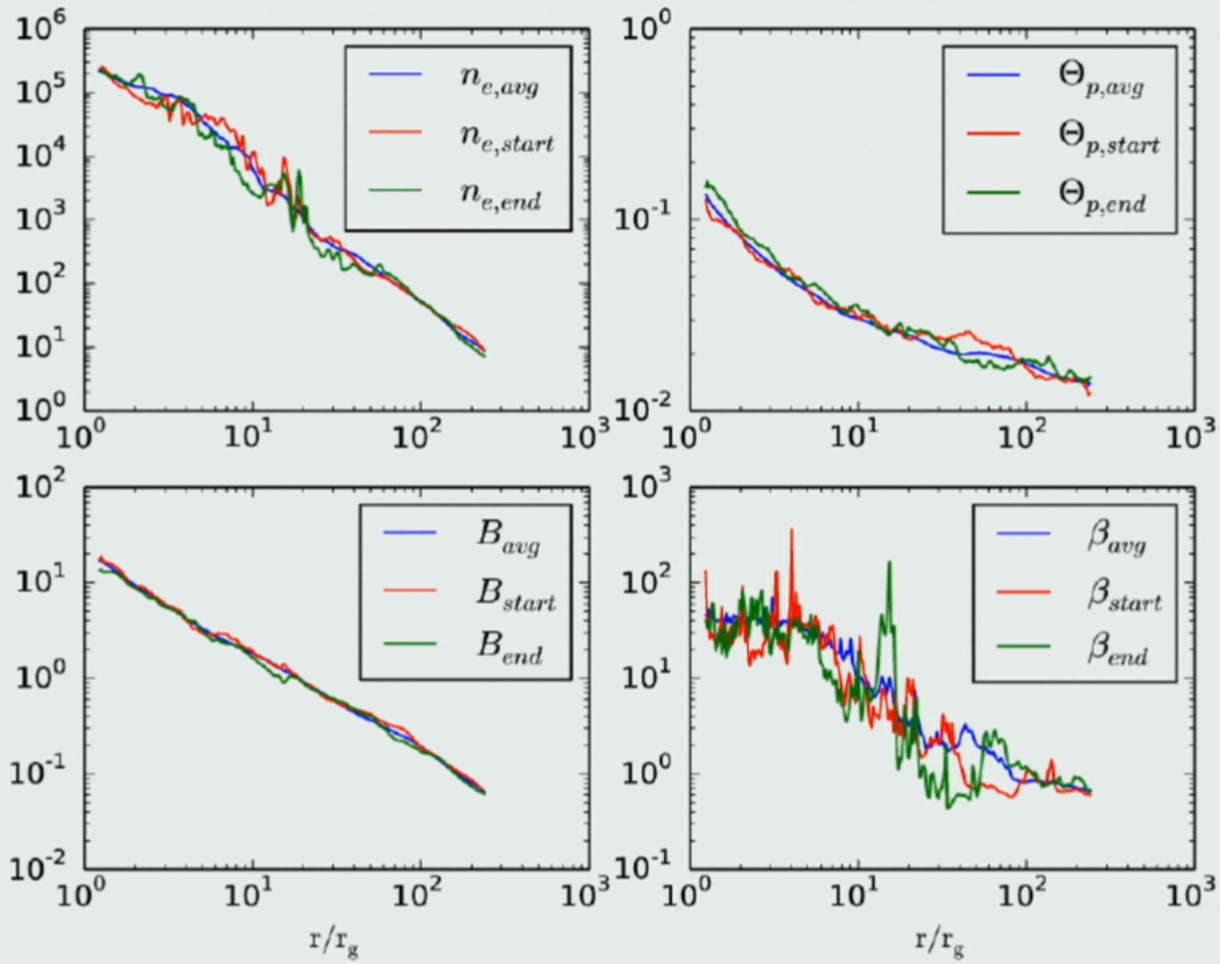
Moscibrodzka & Falcke 2013, based on similar 2-D model

Jet radiation comes from the sheath...the spine is empty.



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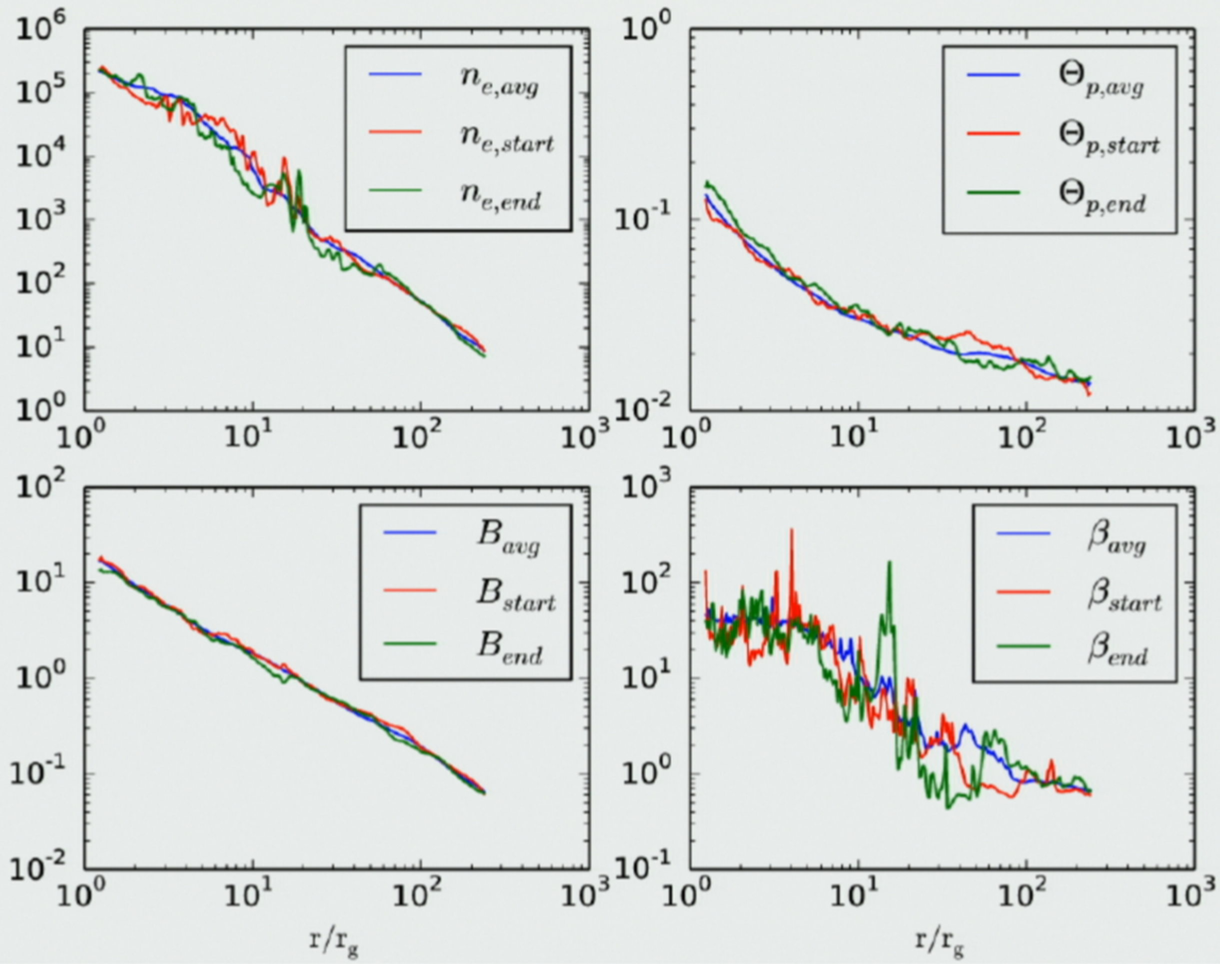
Jet radiation comes from the sheath...the spine is empty.



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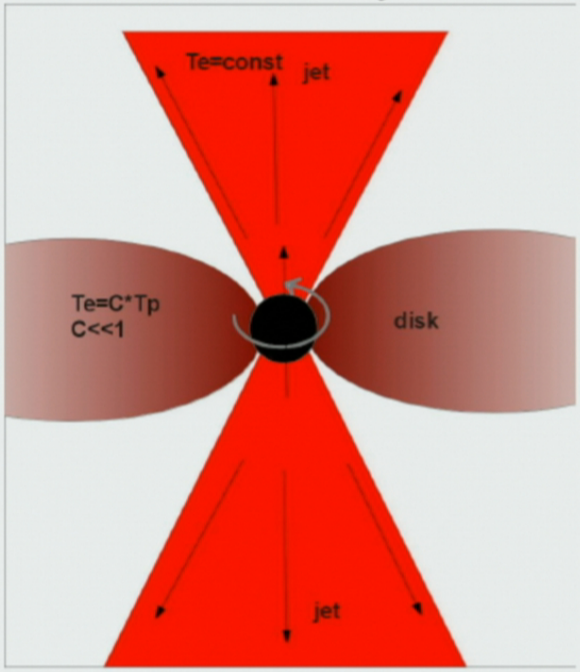
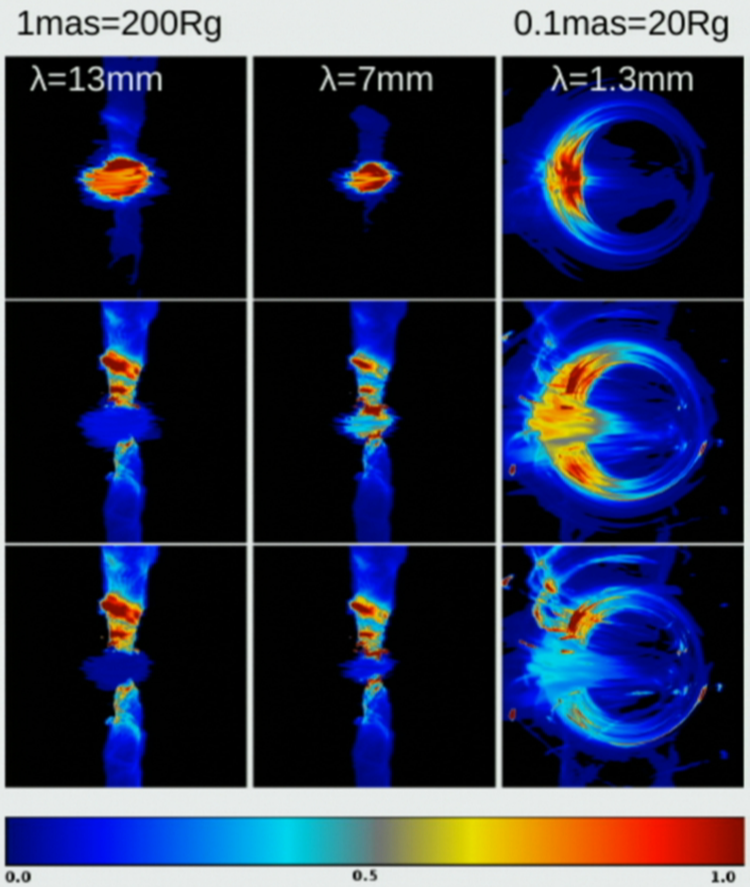
Images and SEDs for various parameters: Tp/Te(disk), Te(jet), i

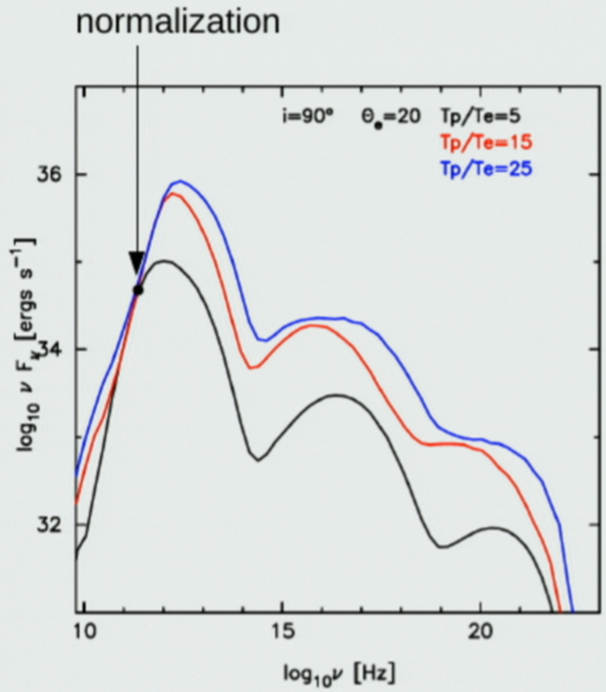
model #	i	$\Theta_{e,jet}$	$(\frac{T_p}{T_e})_{disk}$	$\dot{M}[M_\odot yr^{-1}]$
1			5	4.0×10^{-9}
2			10	1.3×10^{-8}
3	90°	10	15	3.7×10^{-8}
4			20	7.2×10^{-8}
5			25	1.0×10^{-7}
6			5	3.9×10^{-9}
7			10	1.2×10^{-8}
8	90°	20	15	2.9×10^{-8}
9			20	4.6×10^{-8}
10			25	5.7×10^{-8}
11			5	3.9×10^{-9}
12			10	1.1×10^{-8}
13	90°	30	15	2.4×10^{-8}
14			20	3.6×10^{-8}
15			25	4.3×10^{-8}
16			5	3.9×10^{-9}
17			10	1.3×10^{-8}
18	60°	10	15	3.2×10^{-8}
19			20	6.1×10^{-8}
20			25	9.0×10^{-8}
21			5	4.4×10^{-9}
22			10	1.2×10^{-8}
23	60°	20	15	2.7×10^{-8}
24			20	4.2×10^{-8}
25			25	5.4×10^{-8}
26			5	4.3×10^{-9}
27			10	1.2×10^{-8}
28	60°	30	15	2.4×10^{-8}
29			20	3.5×10^{-8}
30			25	4.2×10^{-8}
31			5	5.6×10^{-9}
32			10	1.4×10^{-8}
33	30°	10	15	1.0×10^{-8}
34			20	5.7×10^{-8}
35			25	8.4×10^{-8}
36			5	5.6×10^{-9}
37			10	1.37×10^{-8}
38	30°	20	15	2.7×10^{-8}
39			20	4.1×10^{-8}
40			25	5.2×10^{-8}
41			5	5.6×10^{-9}
42			10	1.3×10^{-8}
43	30°	30	15	2.4×10^{-8}
44			20	3.4×10^{-8}
45			25	4.1×10^{-8}

New model: two temperature disk + isothermal jet



Synchrotron maps of the same 3-D GRMHD time slice





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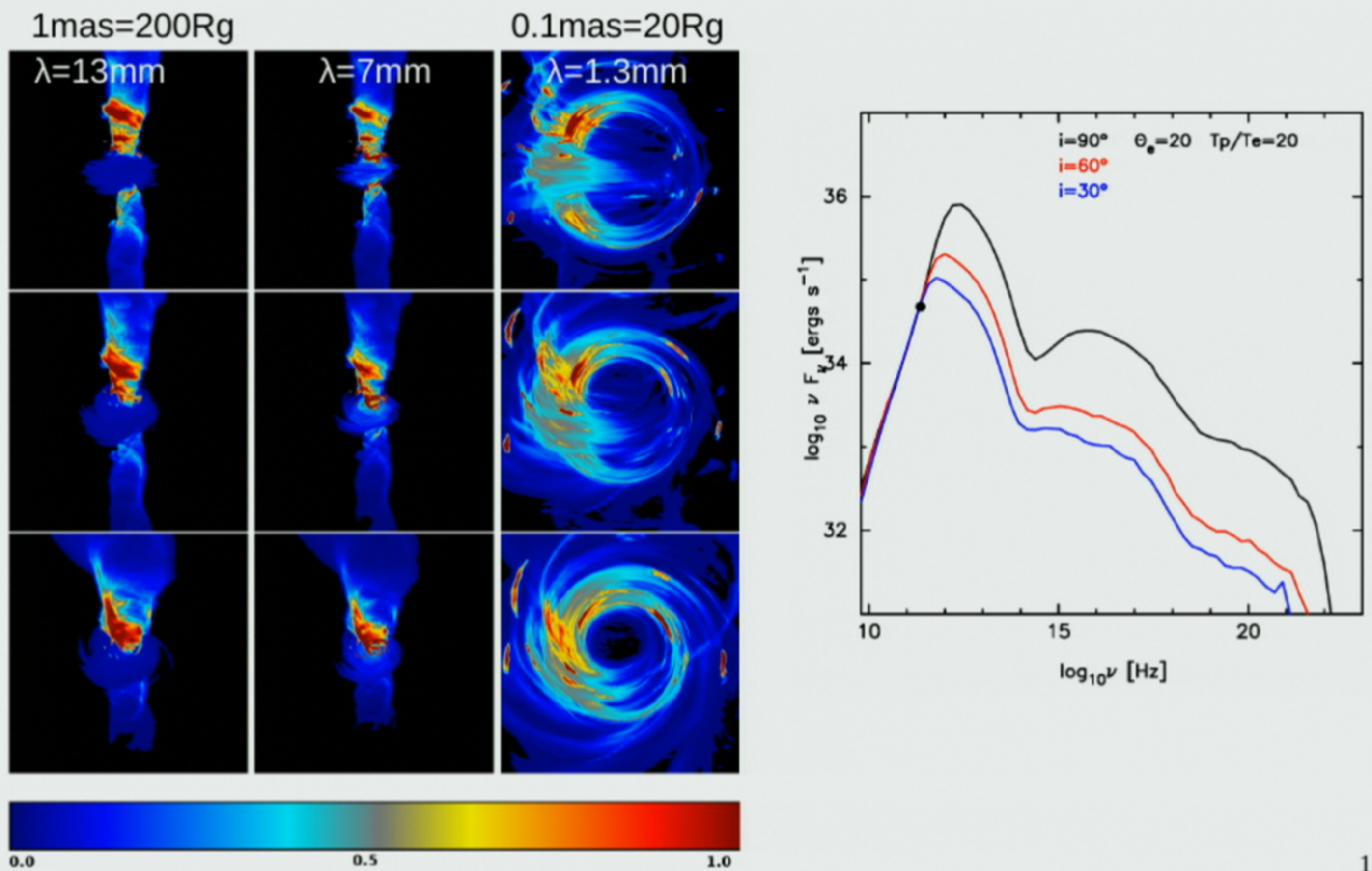
Moscibrodzka et al. 2014

Synchrotron maps of the same 3-D GRMHD time slice



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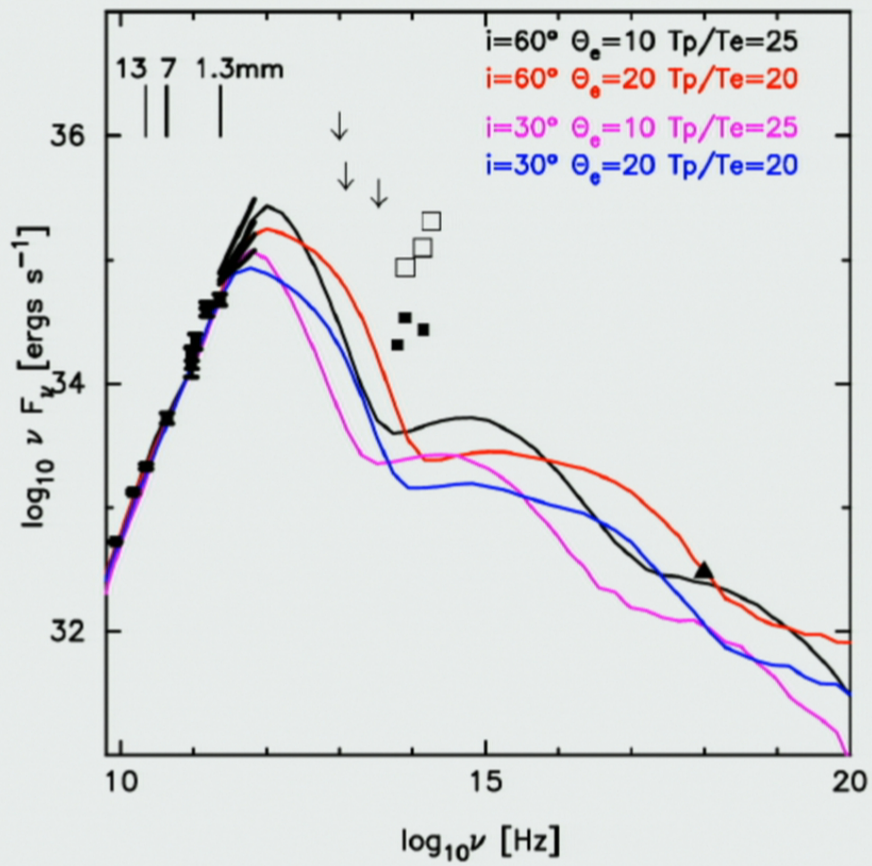
The 3-D GRMHD model SED vs. Sgr A* observed SED (including Chandra XO 3Msec point)



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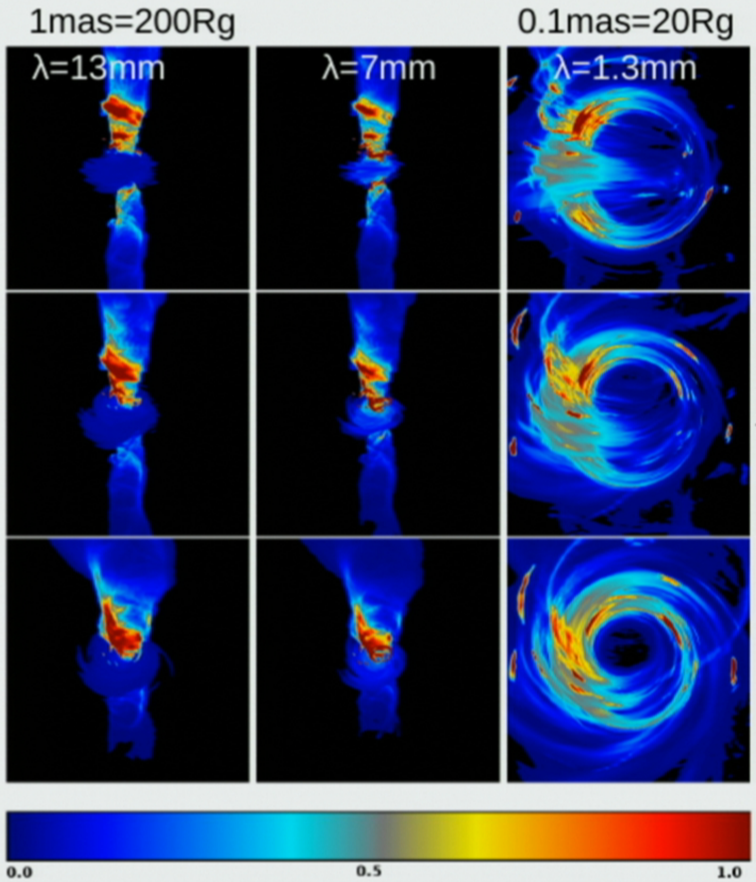
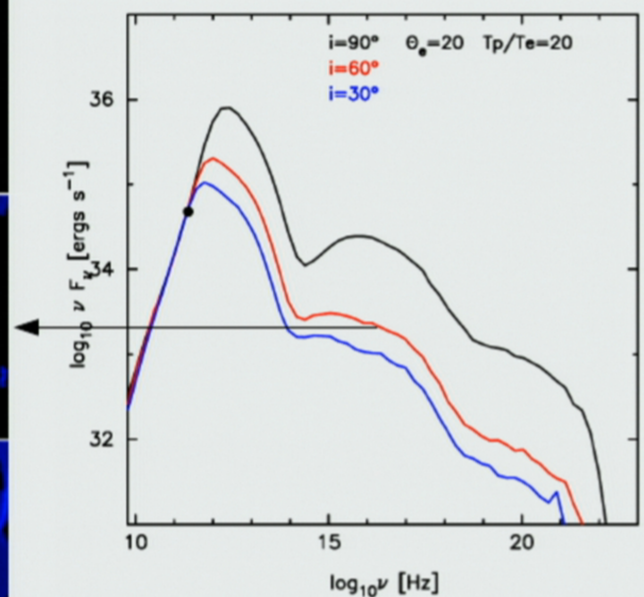
Synchrotron maps of the same 3-D GRMHD slice





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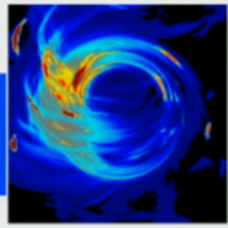

Best model (time averaged) @ 1.3mm

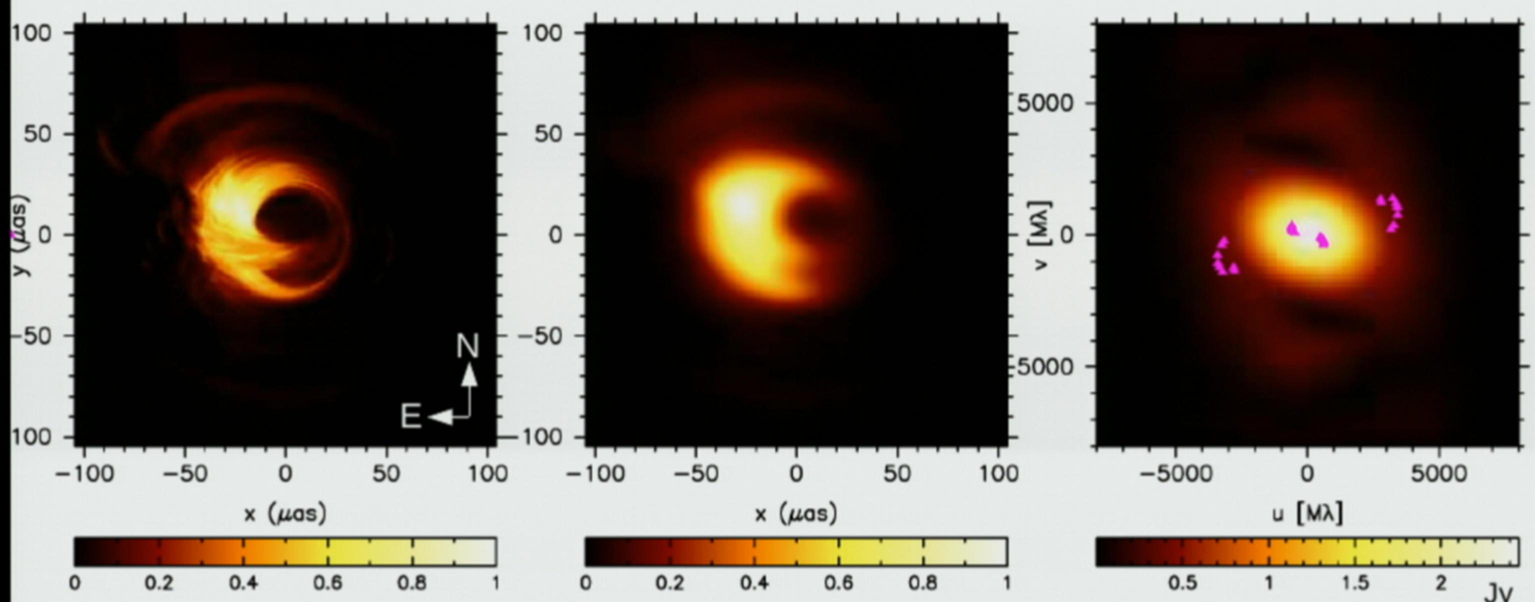

Image w/o ISM

Image w ISM scattering

Visibility amplitude map

Data points from: Fish, Doeleman et al. 2011

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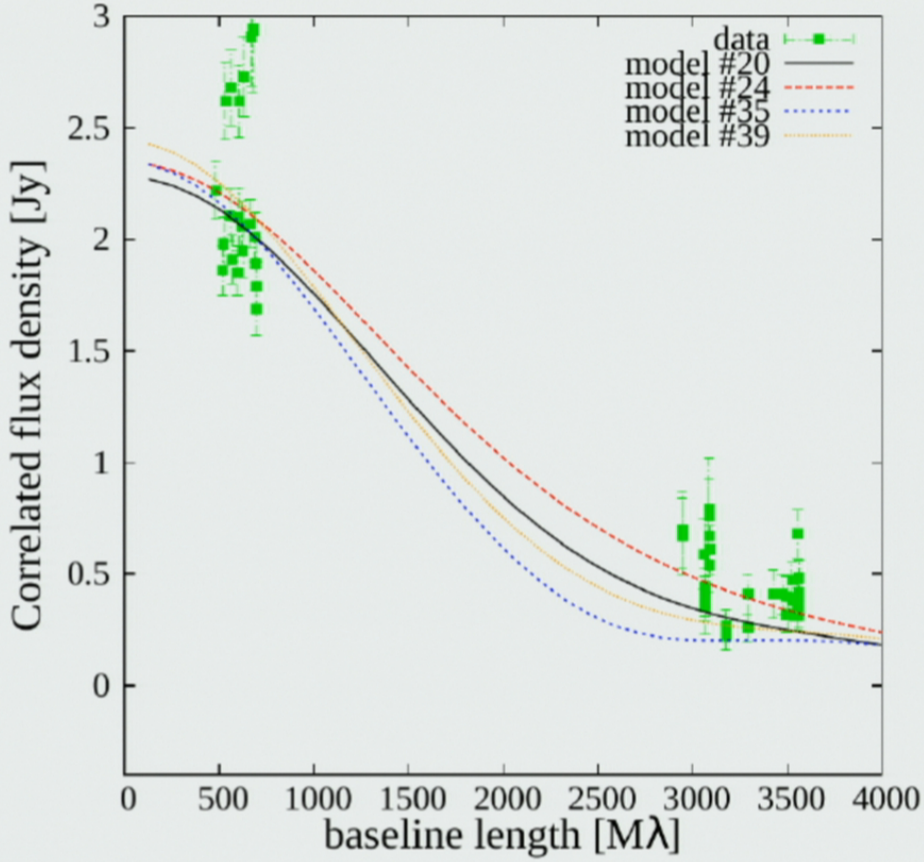
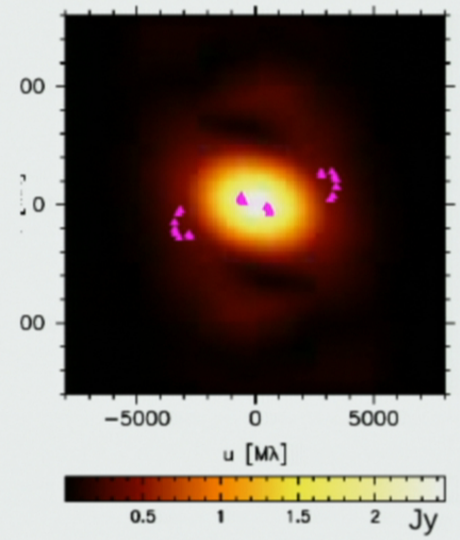
Best model visibility amplitude @ 1.3mm





Visibility amplitude map

Data points from EHT: Fish, Doeleman et al. 2011

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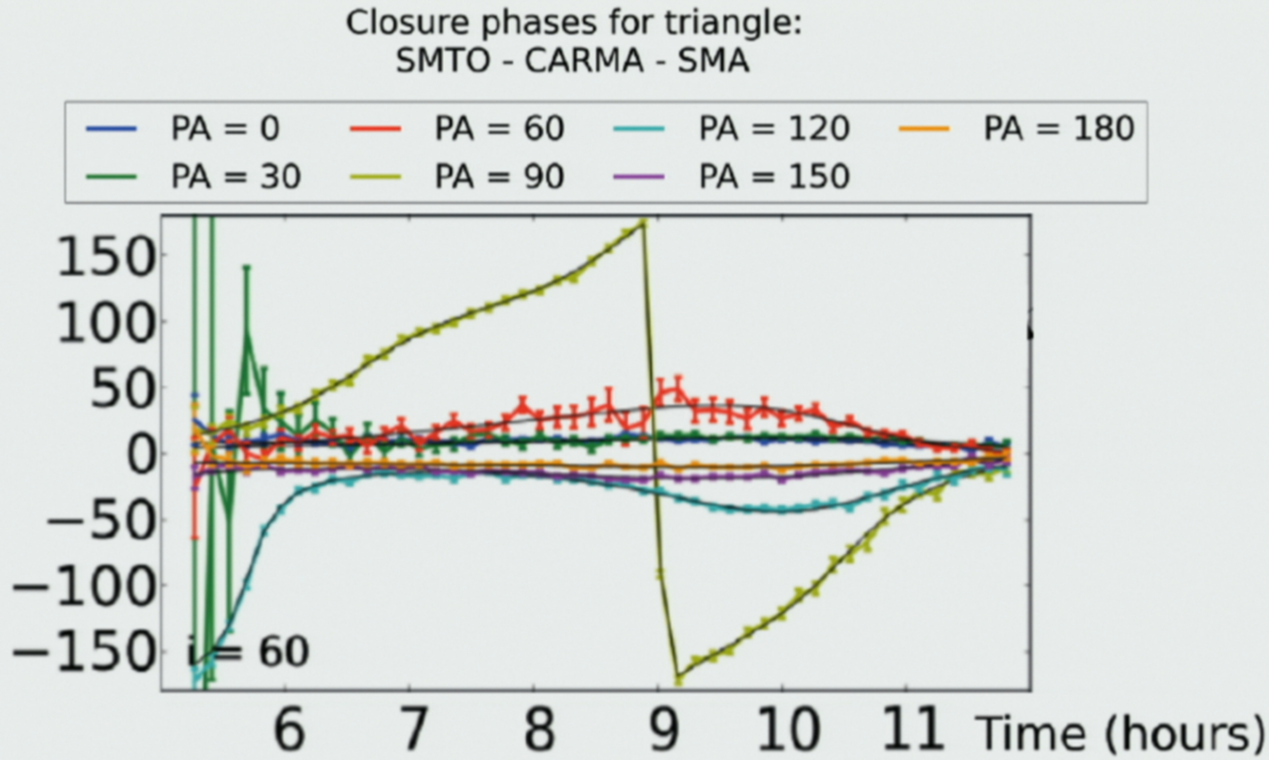
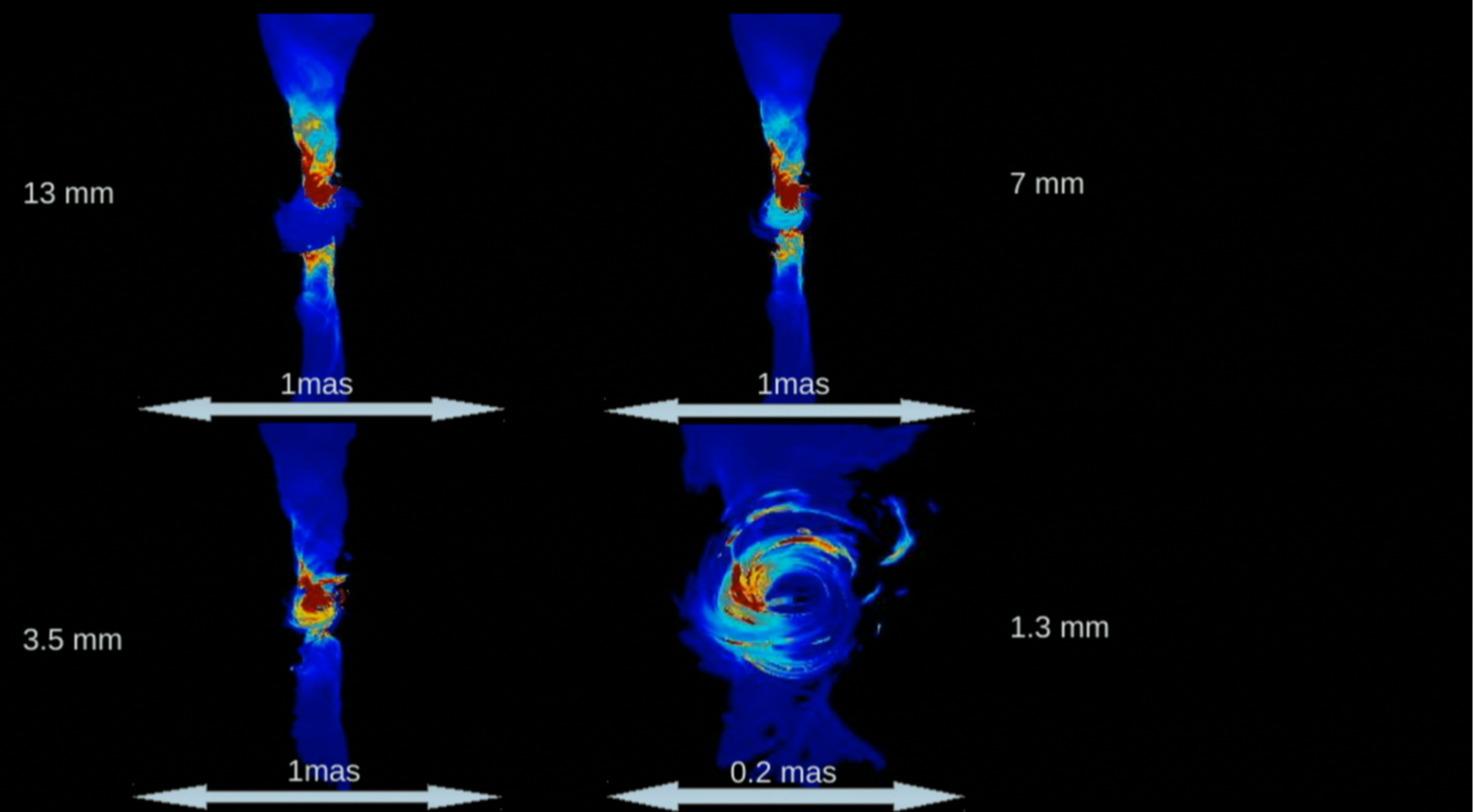
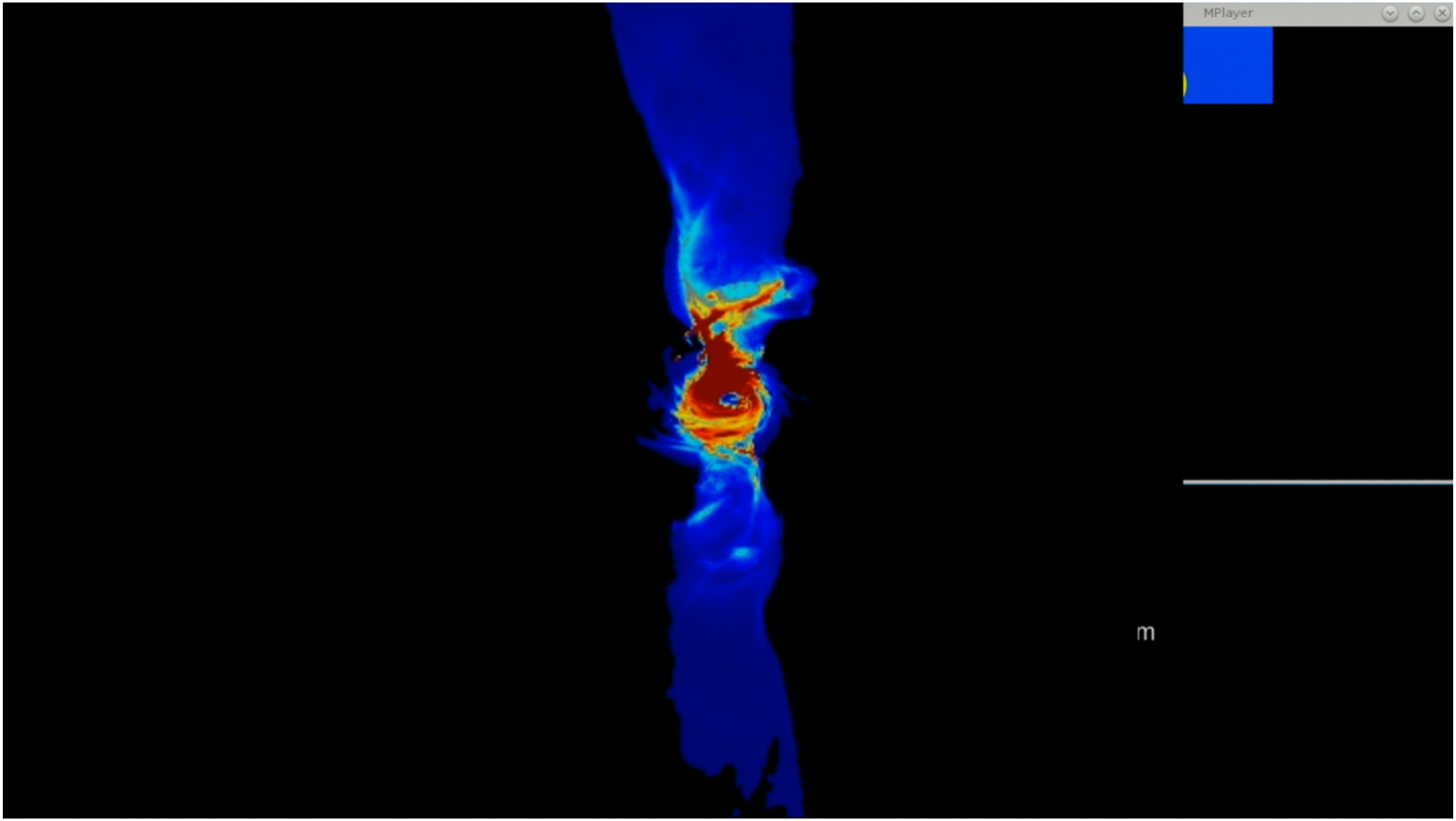
Model closure phase evolution @ 1.3mm

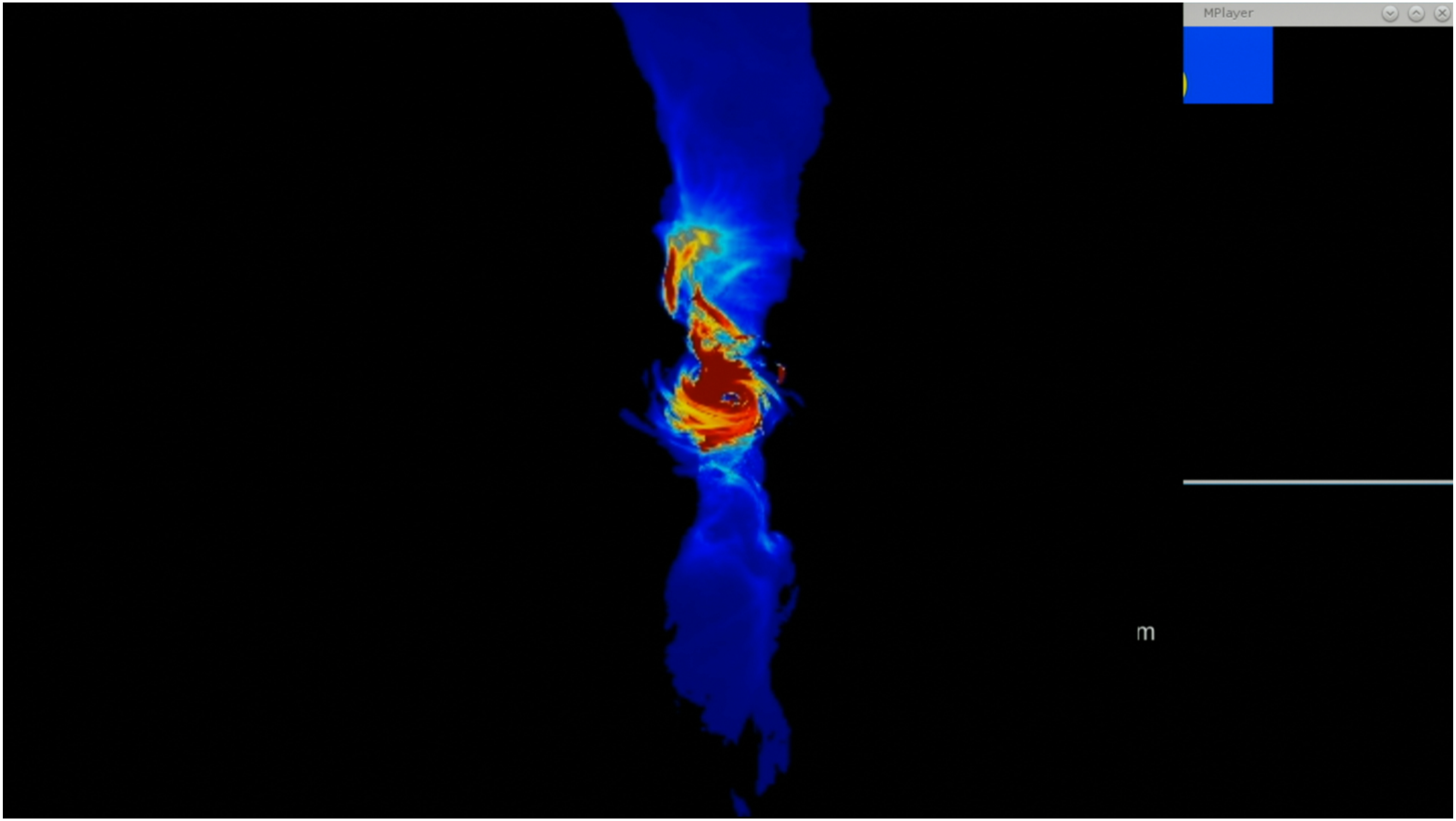


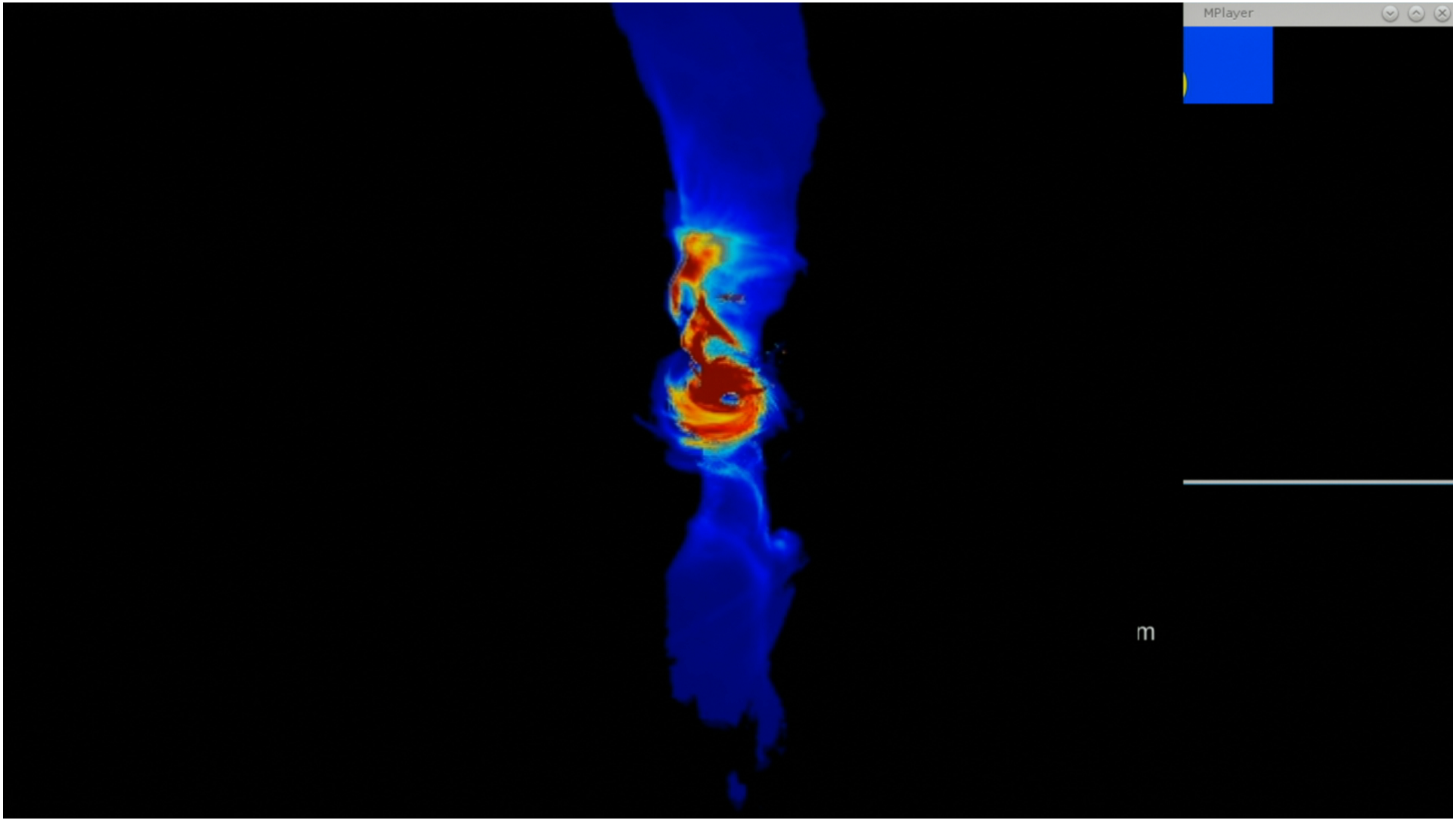
Please see:Fraga-Encinas, Brinkerink (also for λ=3.5mm predictions), and Bronzwaer posters for more

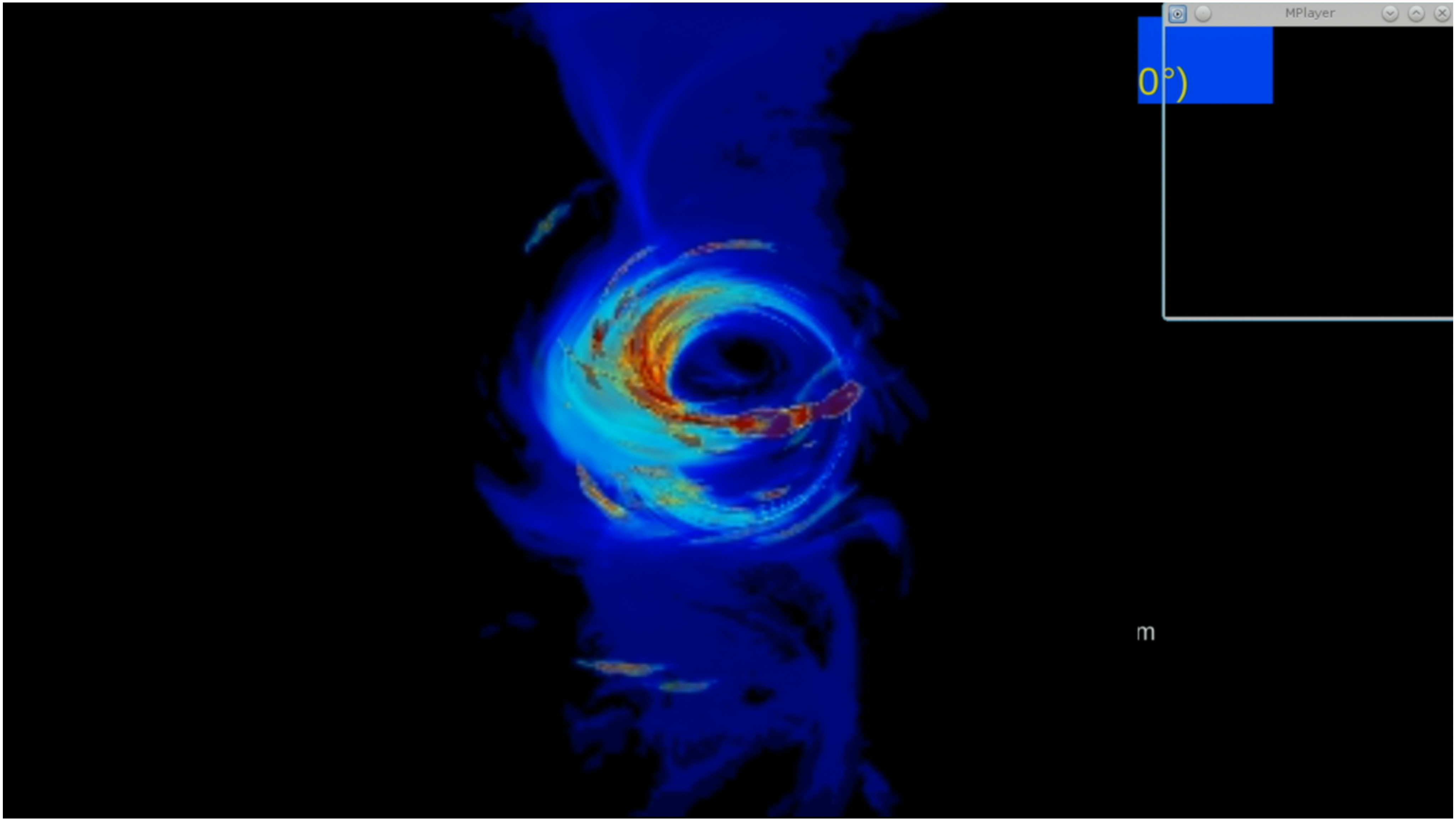
Movies of the model that fits entire SED
(synchrotron radiation intensity w/o scattering at i=60°)




MPlayer
m

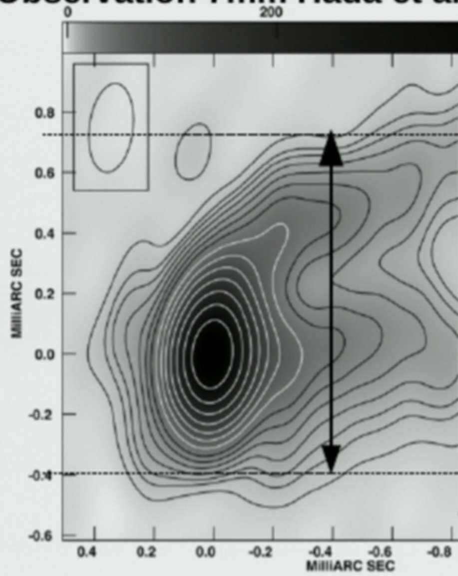

MPlayer
m


MPlayer
m

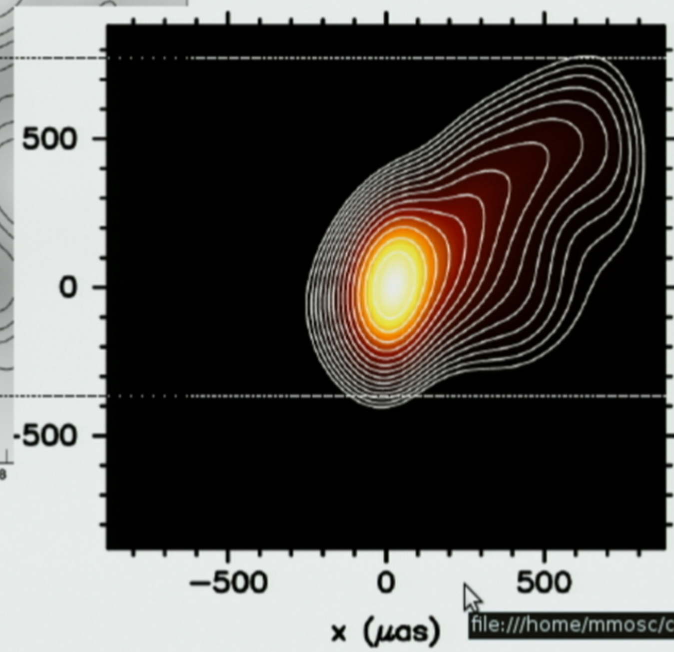

MPlayer
0°)
m

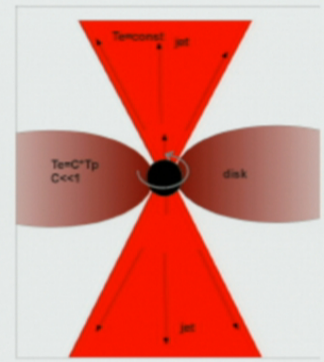
The same model scaled to M87 core

Observation 7mm Hada et al. 2011



Preliminary





New model: two temperature disk + isothermal jet

file:///home/mmosc/conference/BadHonnef/play230.sh

Object data:
M=6x10^9 Msun
D=16.7 Mpc
i=20°
PA=290°
No signatures of scattering

GRMHD model scaled to M87
Synchrotron map at 7mm
(convolved with the telescope beam)

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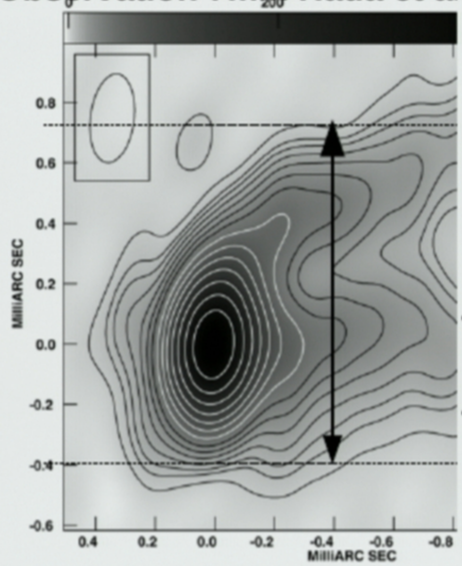
The same model scaled to M87 core

Observation 7mm Hada et al



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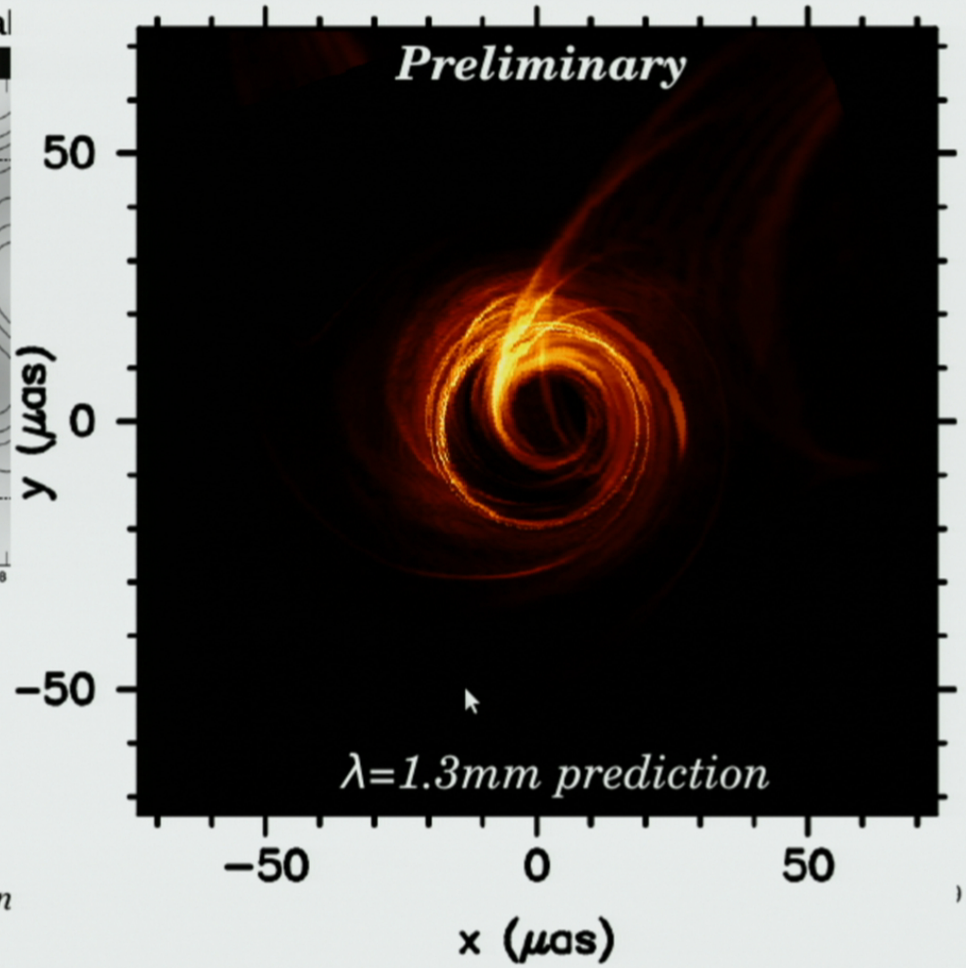
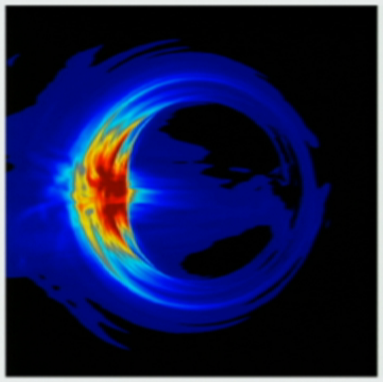
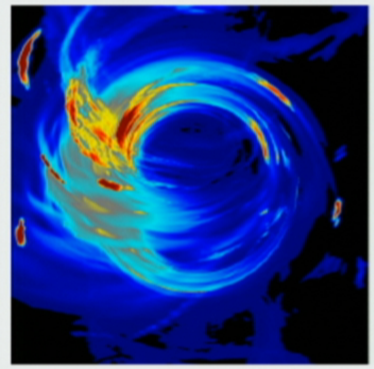


Summary

- Sgr A* appearance may be dominated by the out-flowing plasma, no need of particle acceleration in the jet
- In the "bright" isothermal jet model the mm source geometry looks different in comparison to the old models



e.g. Noble et al. 2007, Moscibrodzka et al. 2009



Moscibrodzka et al. 2014

- Similar model seems to work for M87 (i, possibly the jet is hotter with particle acc.)
- New GRMHD models with self-consistent electron temperatures are needed to interpret mm-VLBI observations of Sgr A* & M87