GRMHD simulations & radiative models of Sgr A*

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Sgr A* mode of accretion and jet?

- Sgr A* under-luminous ($10^{-8}\ L_{Edd}$), emits synchrotron radiation, (relativistically hot $T>5\cdot10^{9}$ K, magnetized), inverted radio spectrum

PROPOSED MODELS

- ***Advection Dominated Accretion Flows*** (Ichimaru 1977, Narayan 1995, Narayan et al. 1998, Quataert et a. 1998, Ozel et al. 2000)
  - optically thin
  - radiatively inefficient
  - geometrically thick disk

- ***Jet*** (Falcke & Biermann 1995, Falcke & Markoff 2000, Markoff et al. 2001)
  - because other LLAGN with flat spectrum radio cores where we resolve jets
  - jet outflow is suggested by observations of variability lags and size-frequency relation
- ***Combined ADAF + jet*** (Yuan, Markoff, Falcke 2002)

Sgr A* mode of accretion and jet?

- Hard to remove ***jet vs. disk model degeneracy***
  - Given low luminosity/accretion rate onto the BH any jet/disk has small angular size
  - scattering screen in radio affects intrinsic structure of the source (smearing and adding substructure)

- Last decade ***improvements*** to models and observations:
  - Semi-analytical ADAF/JET models advanced to GRMHD simulations
    - sim. naturally produce jets
    - we model radiation from simulations in self-consistent first-principles calc. all they way down to the event horizon of the BH
  - VLBI observations move towards millimeter λ (**EHT**): scattering reduced but not completely gone, imaging more compact emission region

- Possibly ***similar mode of accretion*** (ADAF+jet) operates in M87 (also EHT target), M81 (also jet, nearest LLAGN), and possibly other LLAGN

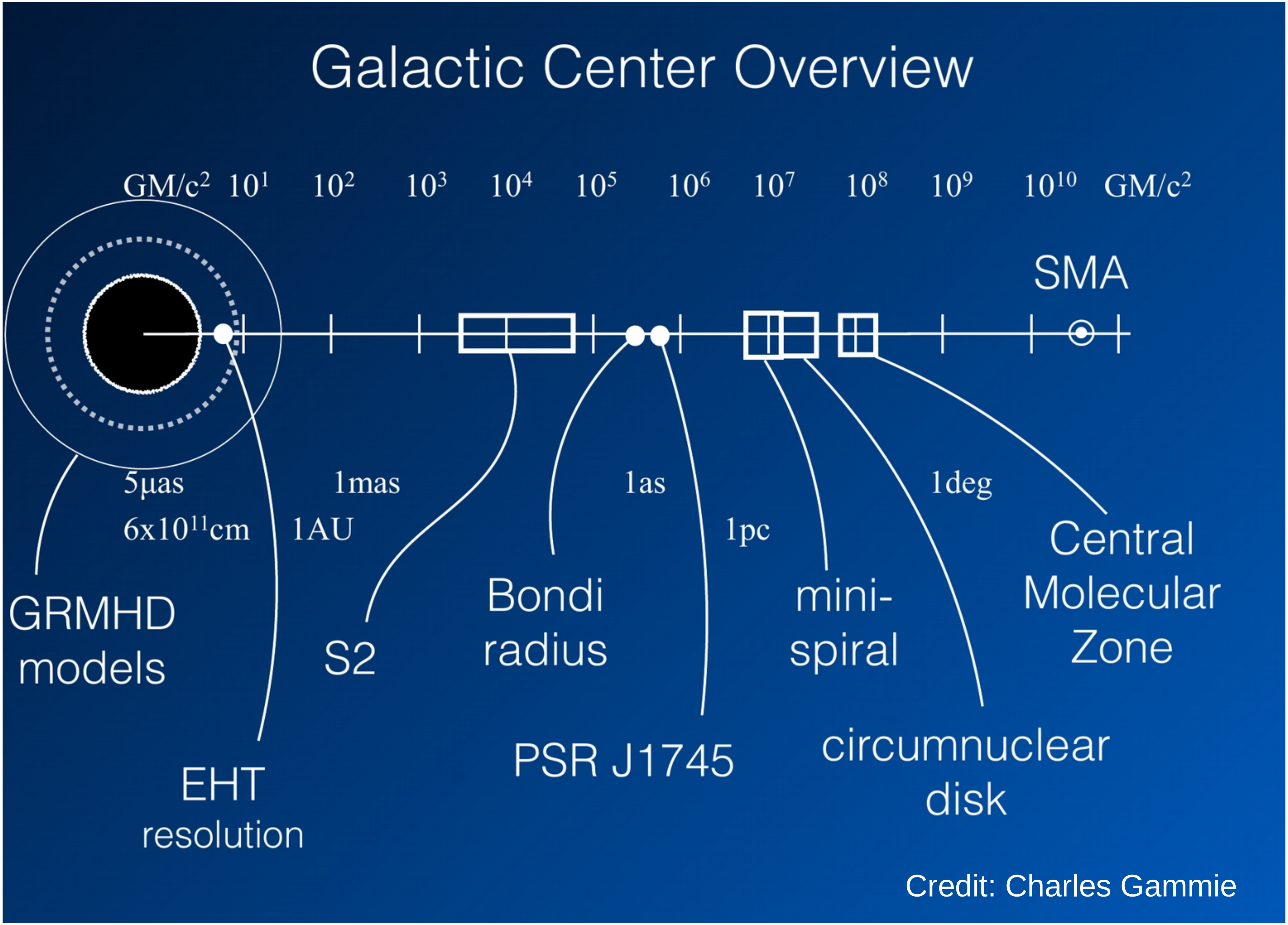
GRMHD models of Sgr A*

- Fixed parameters: $M_{BH}=4 \cdot 10^6\, M_{sun}$, D=8.5 kpc

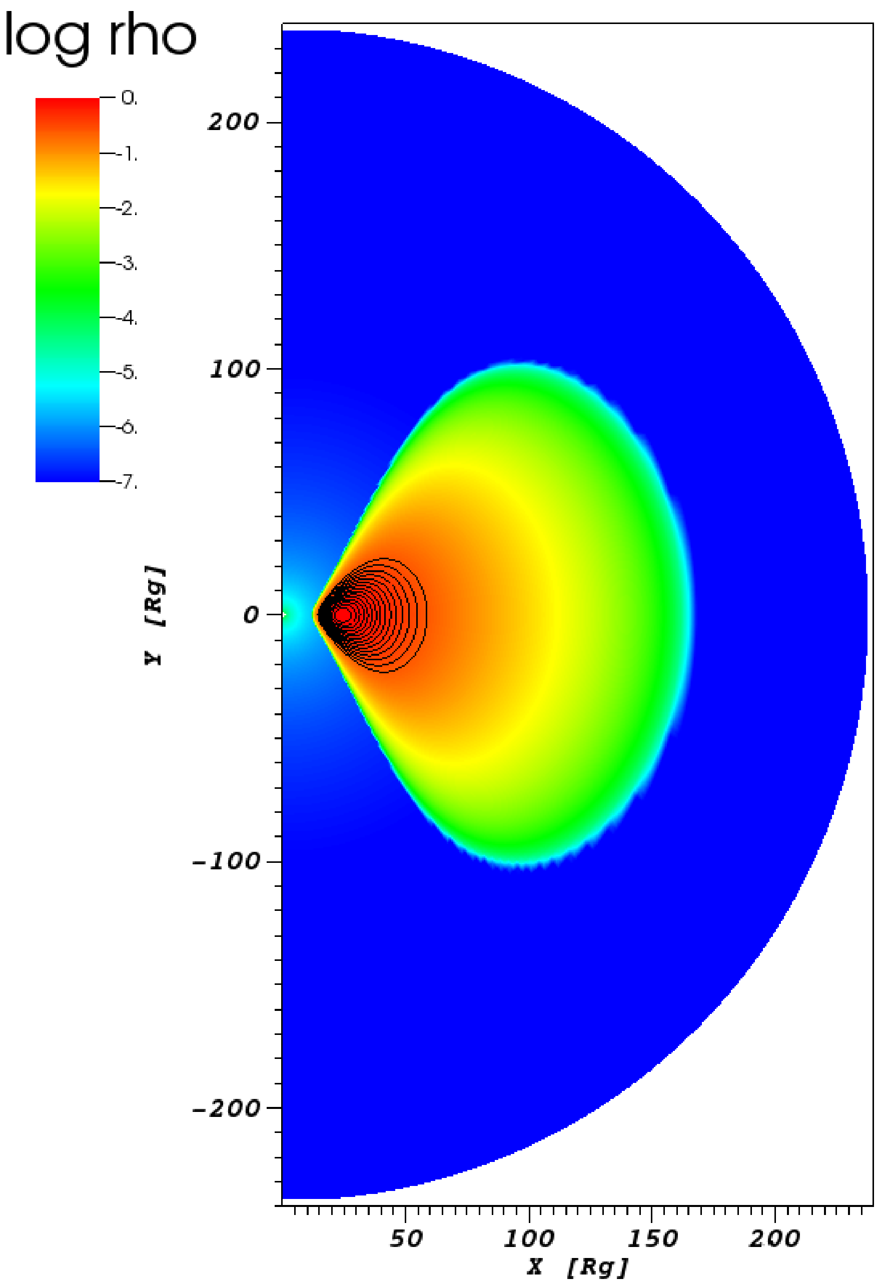
- Free parameters:
  - Space-time (often Kerr is assumed)
  - black hole spin
  - structure of accretion disk
  - accretion rate (rather low 10^{-9}-$10^{-7}\, M_{sun}$/yr, collisionless plasma)
  - magnetic fields (geometry and strength)
  - e- distribution function $f(t,x,y,z)$ - thermal T_e (notice crude approximation for the collisionless plasma)
  - viewing angle (observer wrt. BH spin axis)

- There are a few realizations of an *ADAFs* with *GRMHD* simulations

Typical *GRMHD* models size

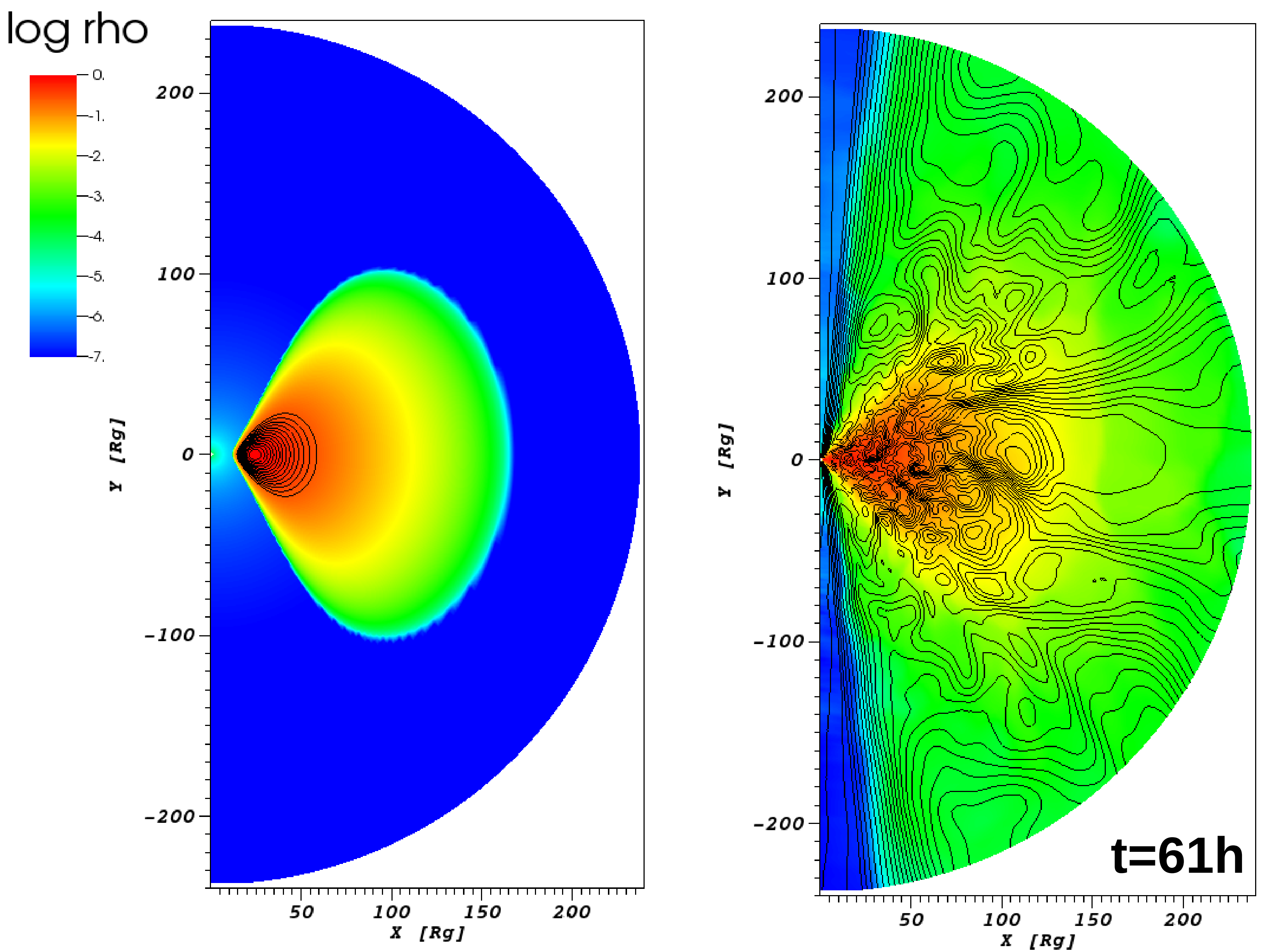


I. Standard and normal evolution (SANE) ADAFs



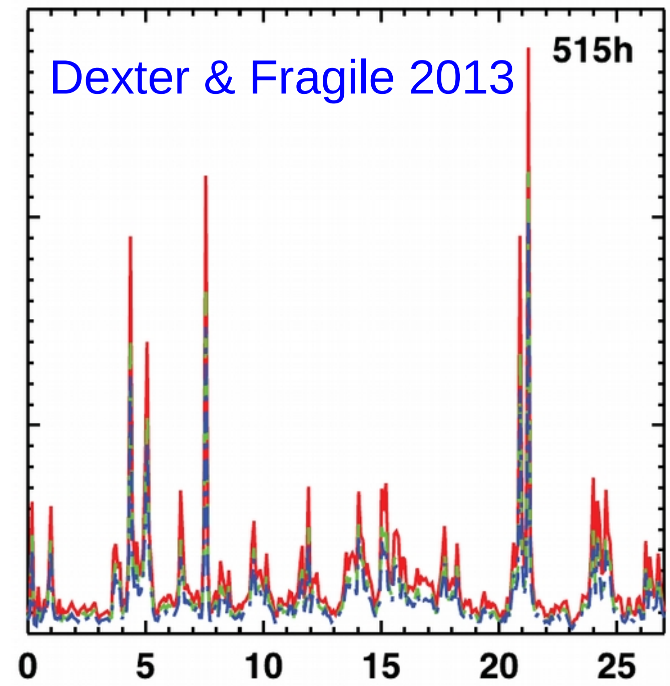
- ADAF initiated with weakly magnetized torus
- Analytical solution of gas in hydrodynamic equilibrium found in 70' (Abramowicz et al 76', Fishbone-Moncrief 78')
- 80', 90' Wilson, Hawley et al.
- Weak B fields → MRI → turbulence → viscosity → accretion
- Forms winds and jets , Blandford-Znajek 77' jets
- Adiabatic, diluted, fluid approach is an approximation, plasma effects (particle acceleration) not captured in this approach

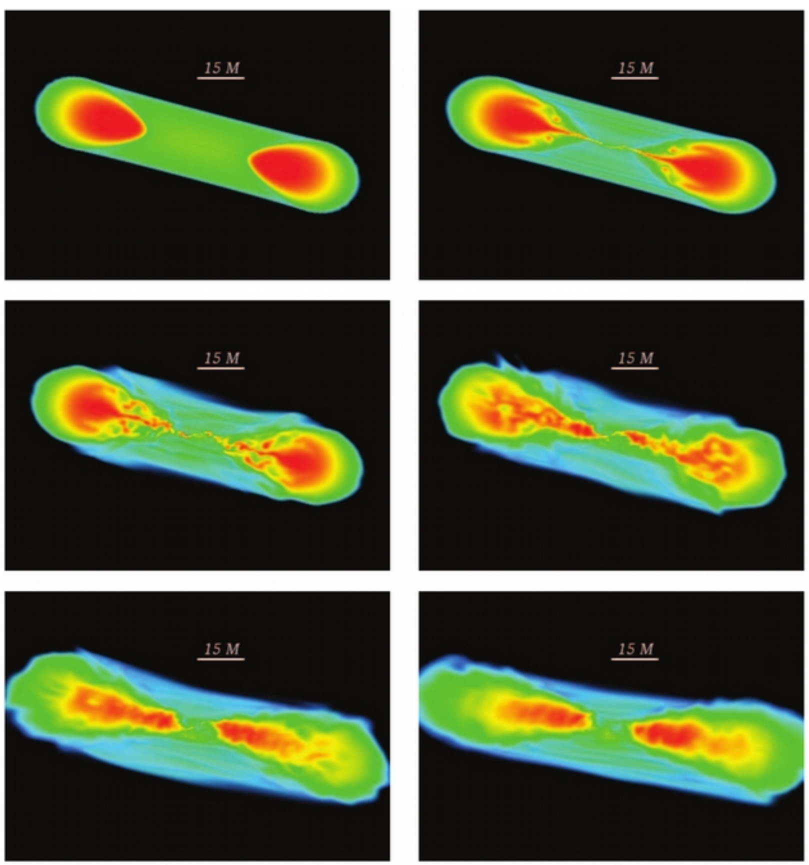
I. Standard and normal evolution (SANE) ADAFs



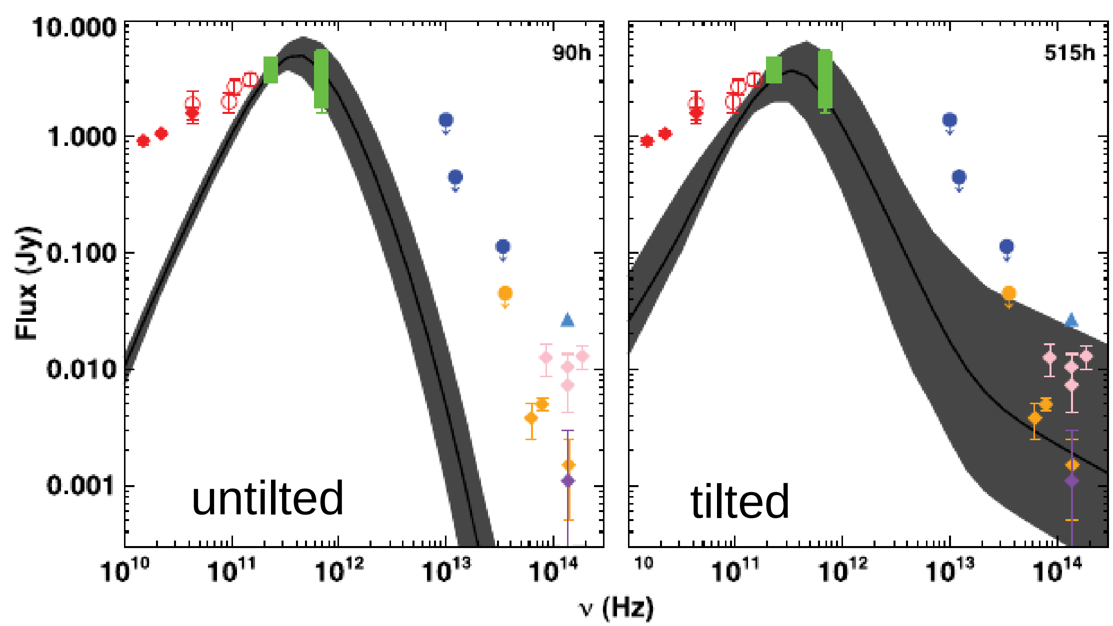
II. Standard and normal tilted ADAFs

- BH and disk angular momentum alignment - free parameter
- models with small tilt 15°-30°
- could explain NIR flares of Sgr A*: precessing plunging streams/shocks beamed towards observer → more variability in NIR compared to untilted case
- please notice: e- are thermal here

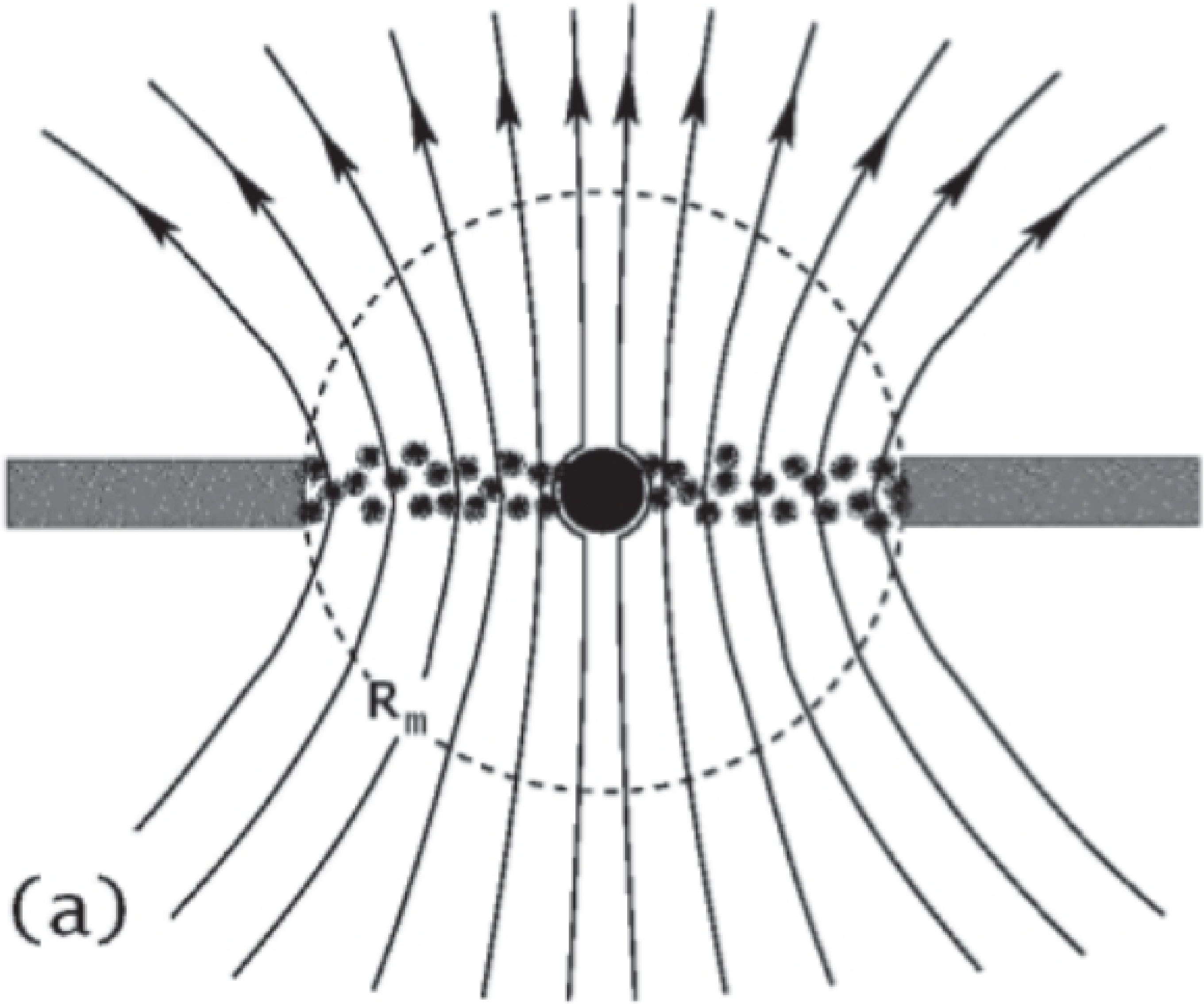




Fragile 2007, 2009



III. Magnetically-Arrested Disk (MAD)

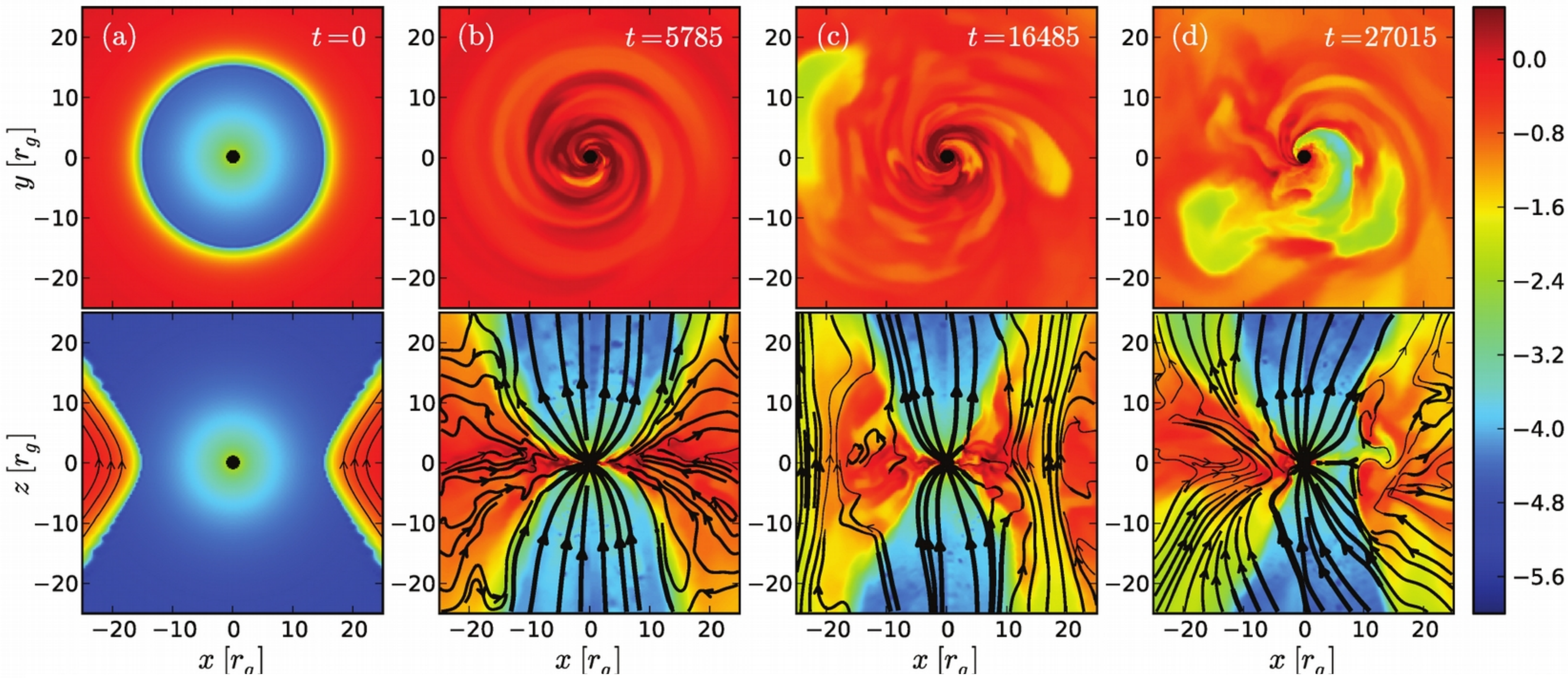


Narayan et al. (2003)

Magnetic analogue of Eddington limit

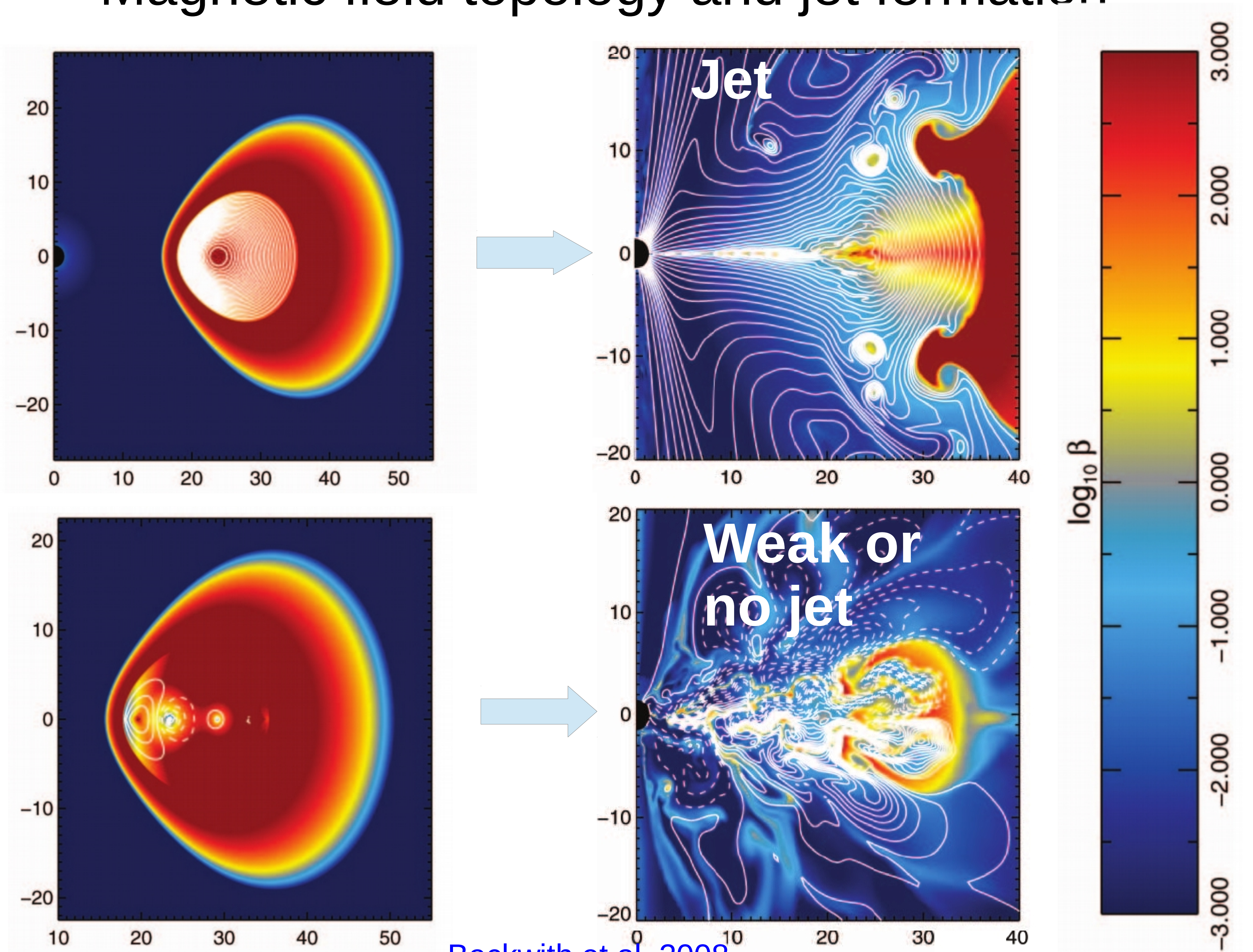
III. Magnetically Arrested Disk (MAD) ADAFs

- when large amount of coherent magnetic field Φ_B is accumulated at the black hole
  - it produces barrier (magnetic pressure) – variability
  - produces very powerful jets, $P_j \sim a^2\, \Phi_B^2$ (60xSANE, M87?)
  - not clear if MADs are applicable to Sgr A* (magnetization possibly affects electron heating hence it is unclear if they are still RIAFs)



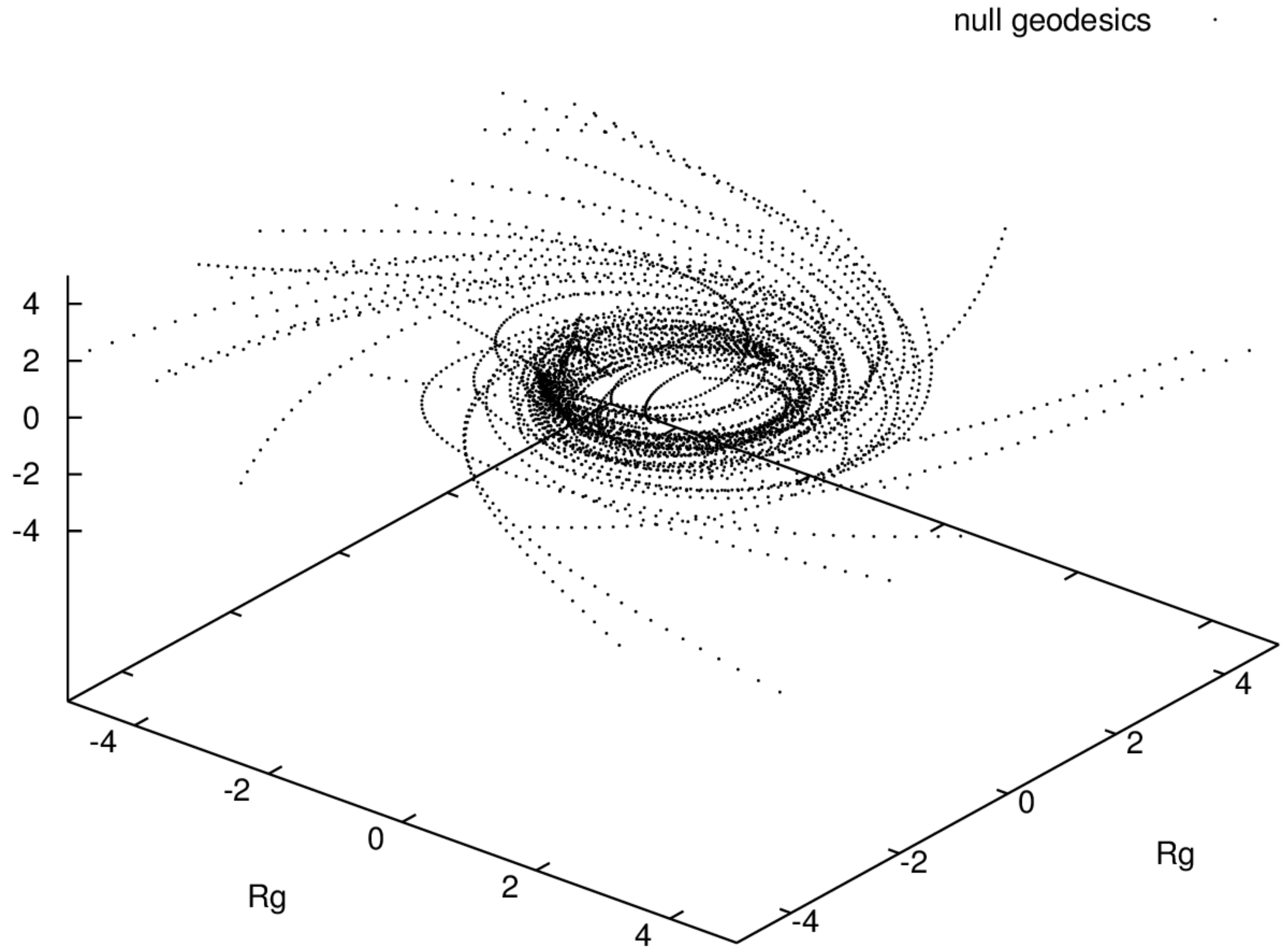
Tchekhovskoy, Narayan, McKinney 2012, McKinney et al. 2012

Magnetic field topology and jet formation

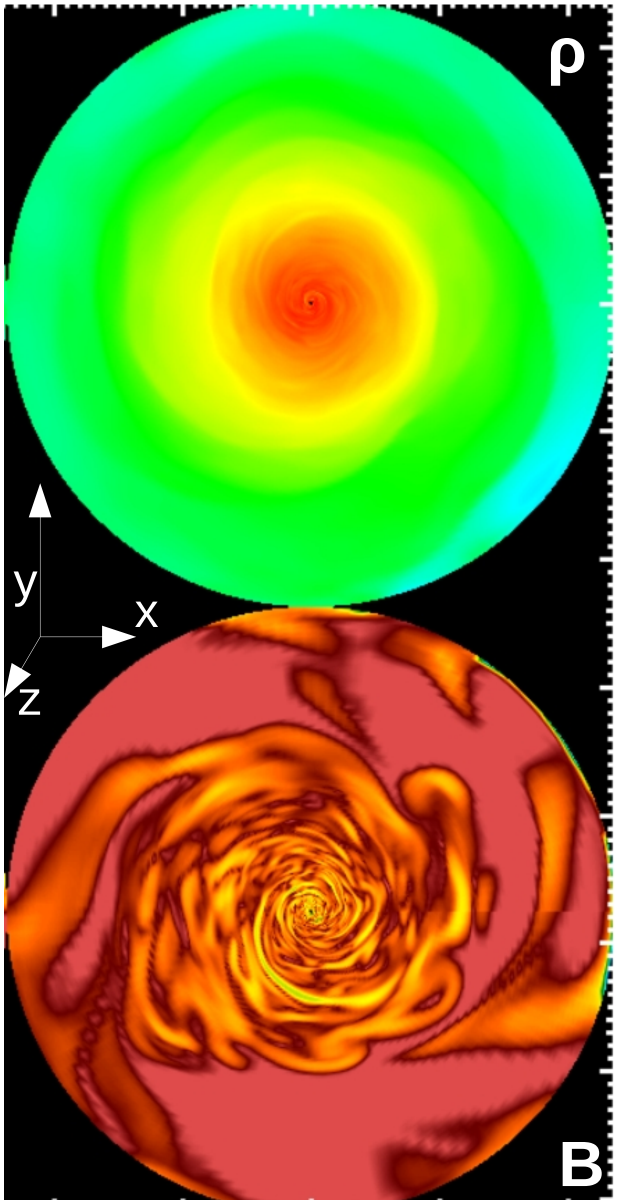


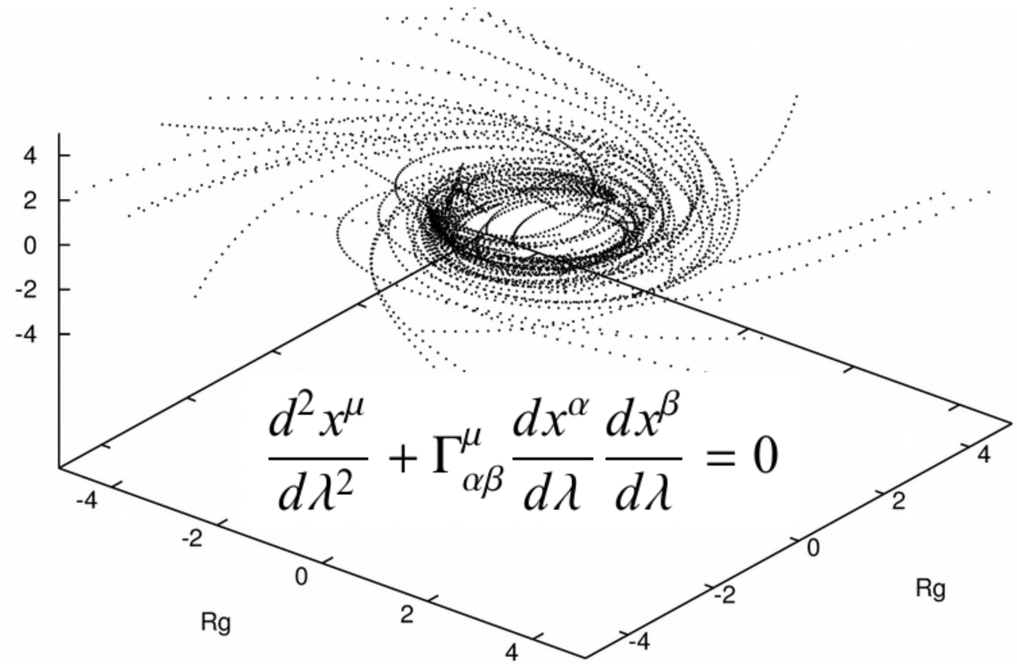
Beckwith et al. 2008

The radiative transfer models based on *GRMHD*



The radiative transfer models





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

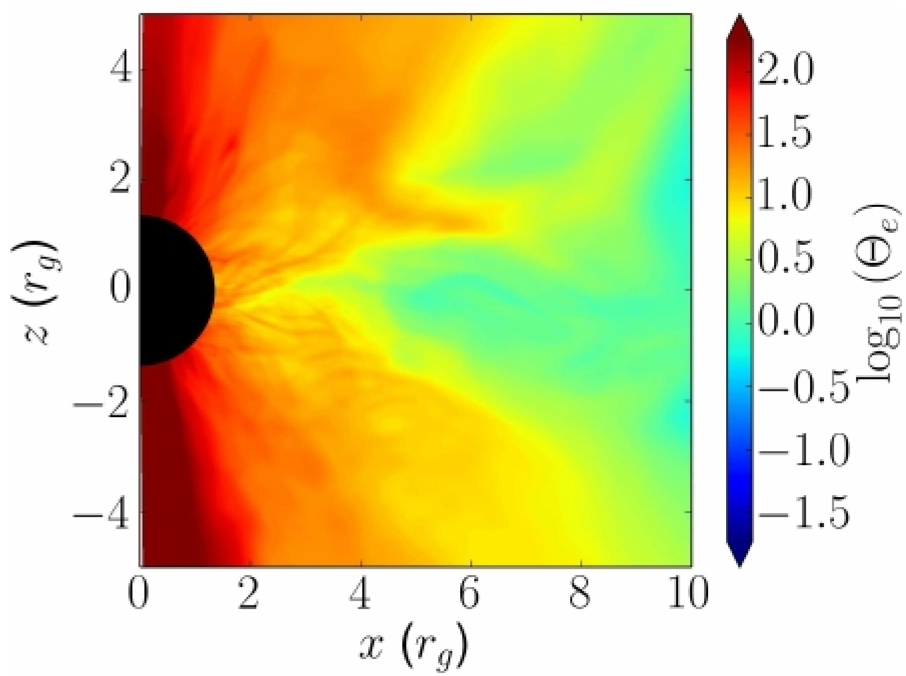
j_ν - synchrotron emissivity
$(\nu, \rho, B, T_e, \theta, u^\mu)$

α_ν - synchrotron self-absorption
$(\nu, \rho, B, T_e, \theta, u^\mu)$

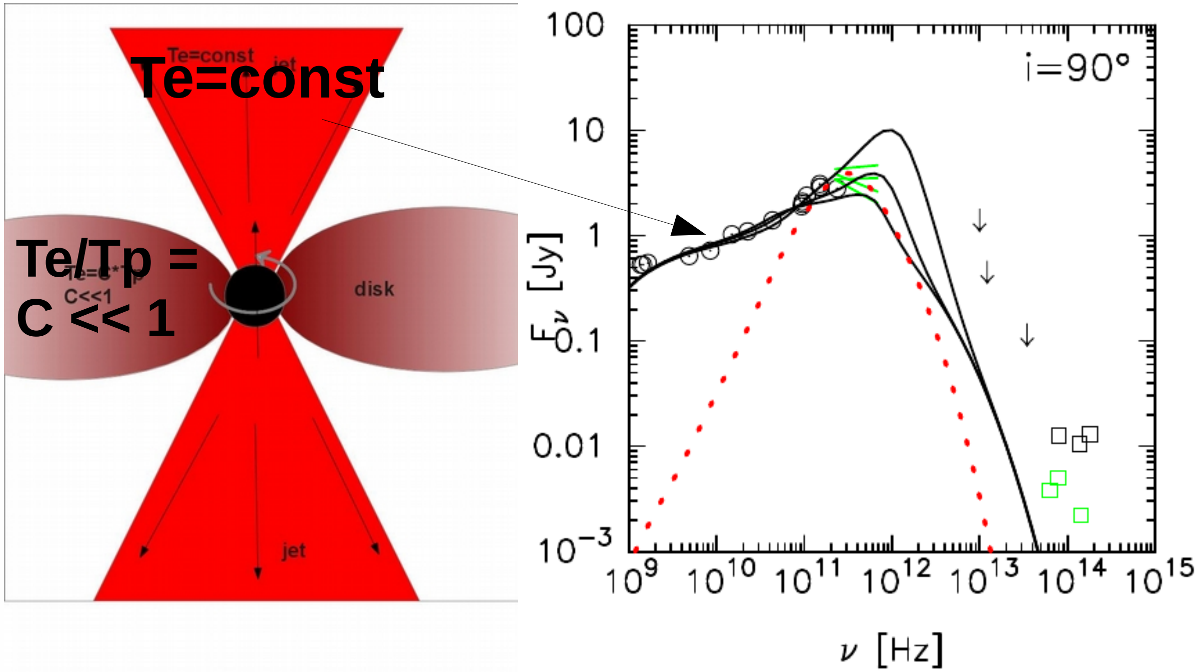
Inverse Compton process

Electrons in *GRMHD* simulation (extension of traditional GRMHD models)

- ADAF at low accretion rates is collisionless: two-temperature plasma: T_p,T_e
- Very recent models include two-temperature plasma in 'extended'-MHD formulation, explicitly following T_e , in jet spine and sheath T_e higher compared to the disk
- Jets are more magnetized: more dissipation expected
- Or a simple model with parameters from observations

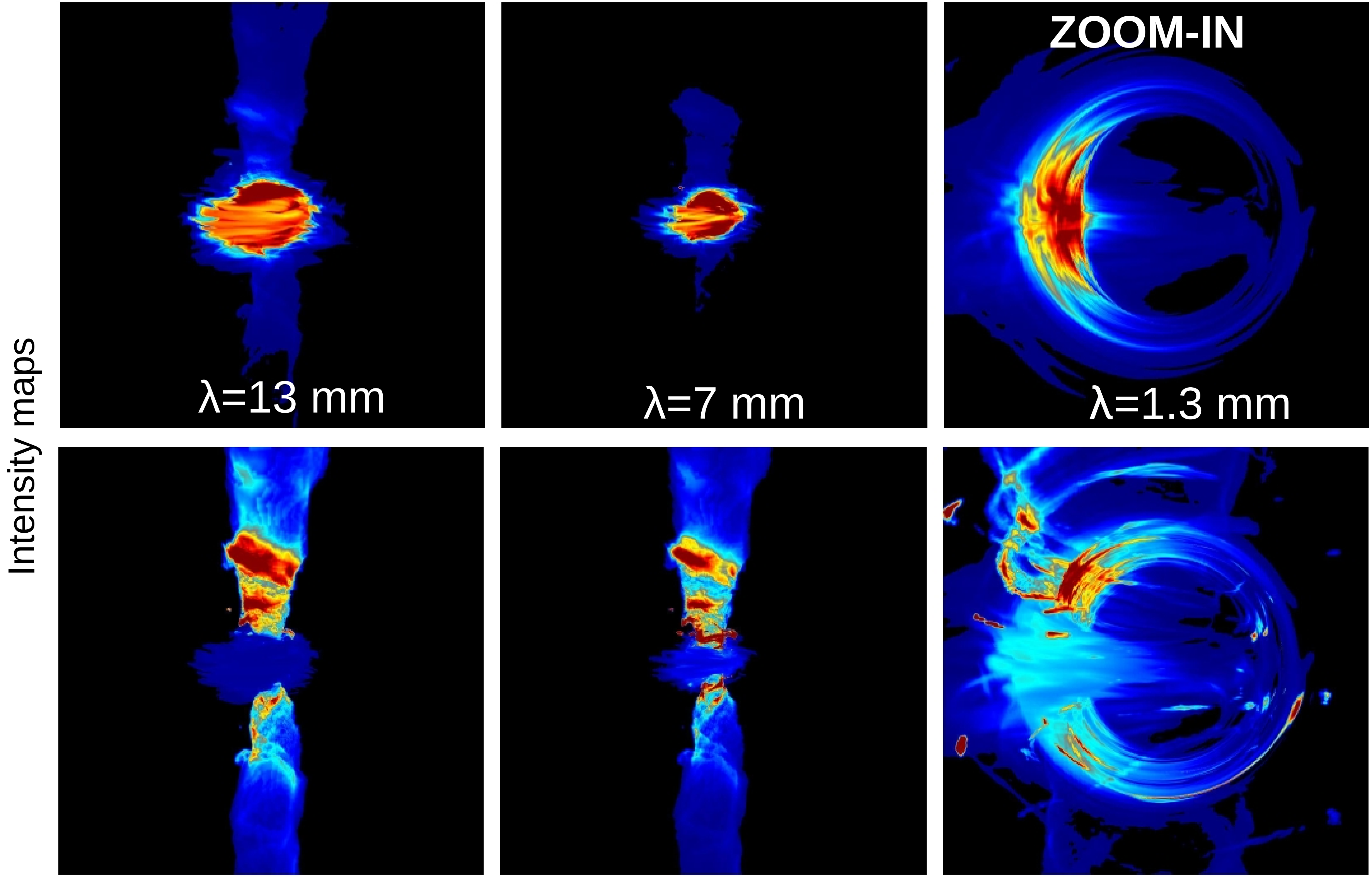


Ressler et al. 2015



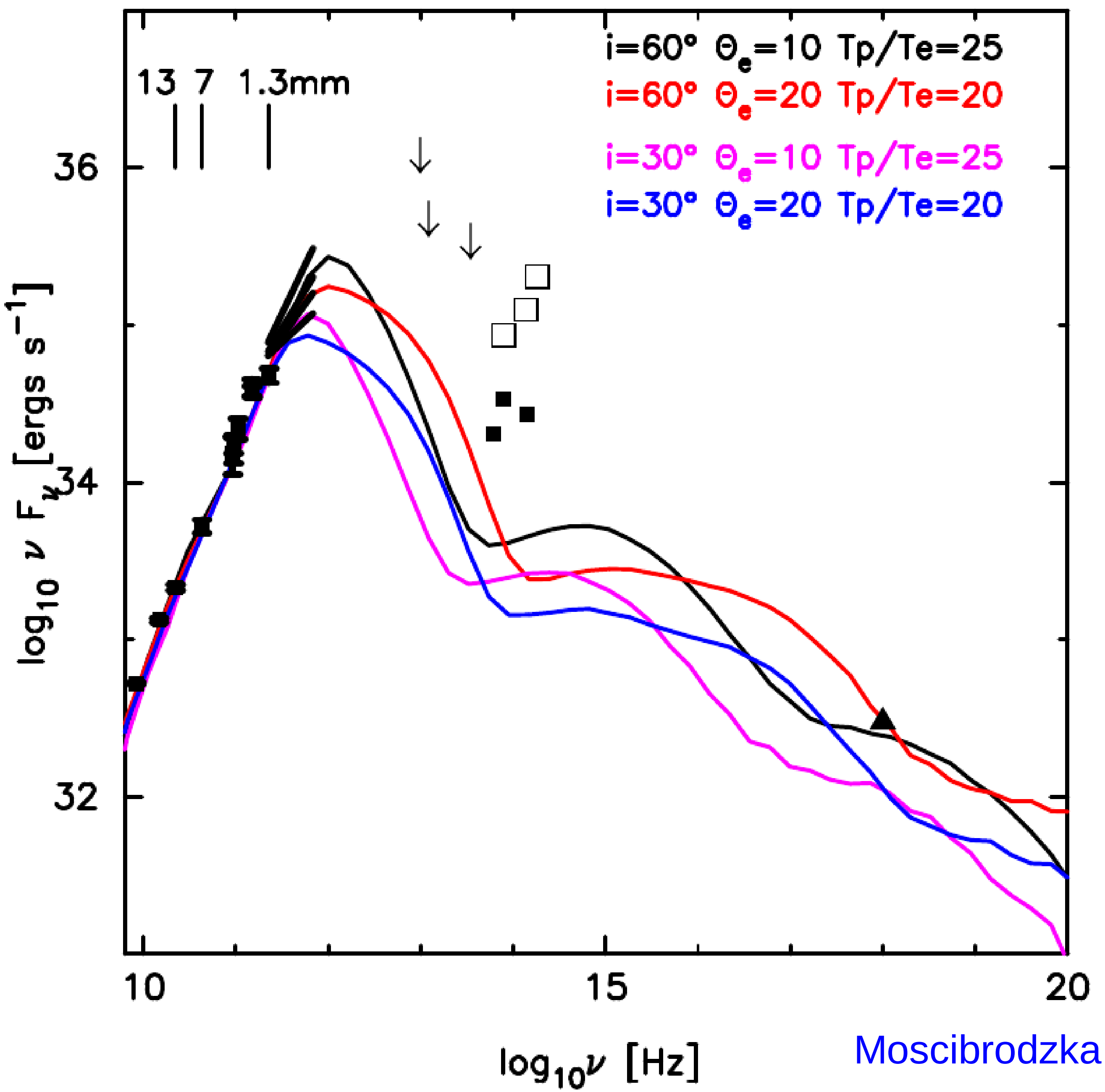
Moscibrodzka & Falcke 2013

Electrons treatment in *GRMHD* simulation make a big difference in a model *appearance*, *SANE* example



Moscibrodzka et al 2014

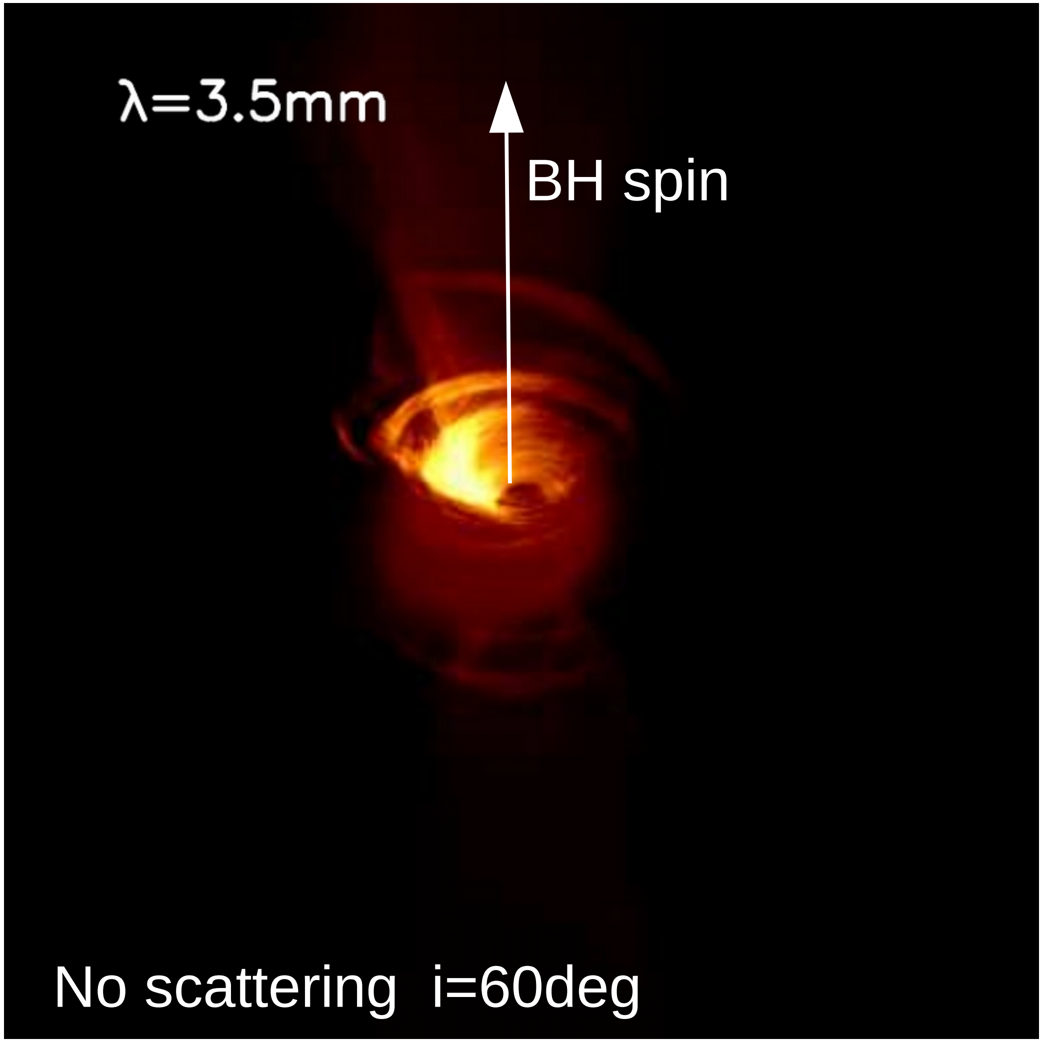
We can find Te in disk and jets by fitting synthetic SED to observational constraints

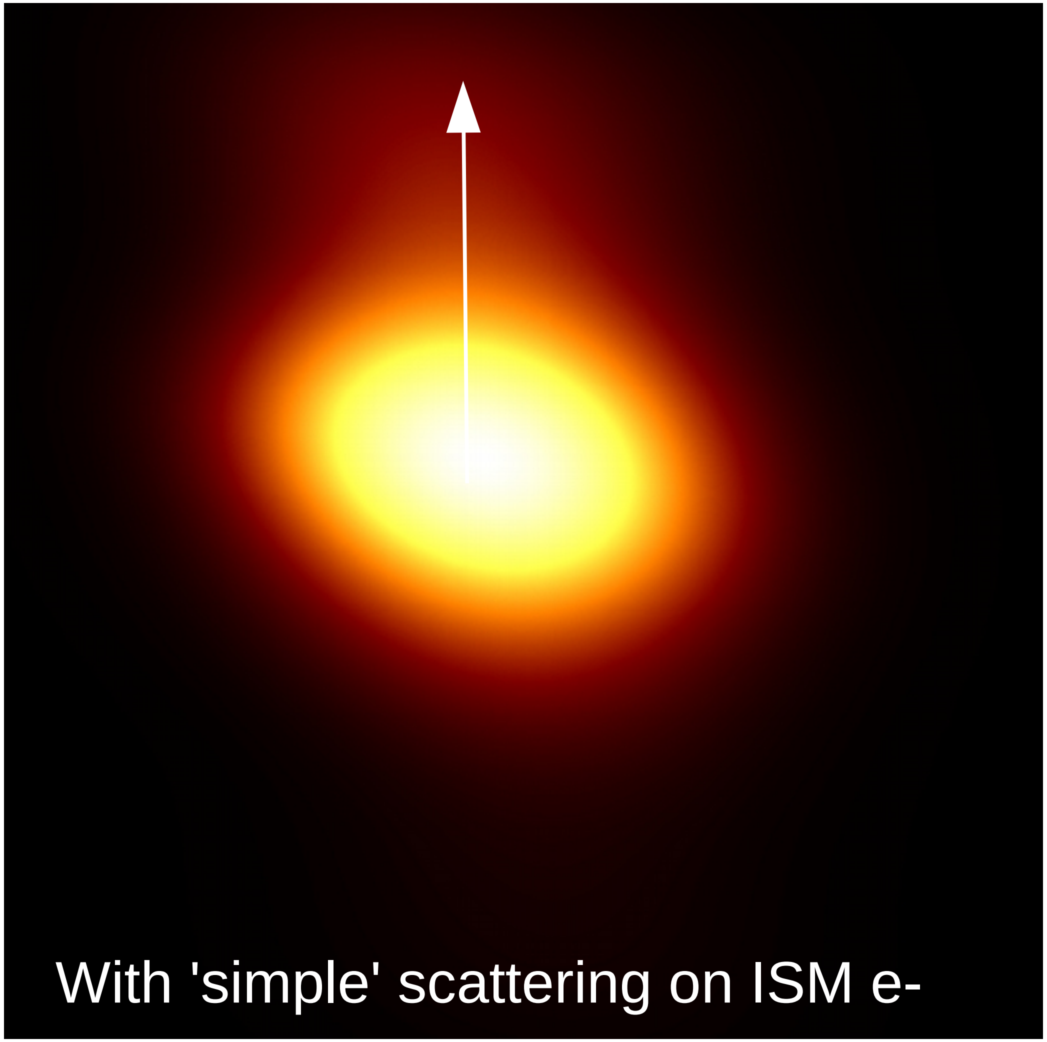


Moscibrodzka et al. 2014

Can we observe the jet?

Any jet too compact to shine through the scattering screen



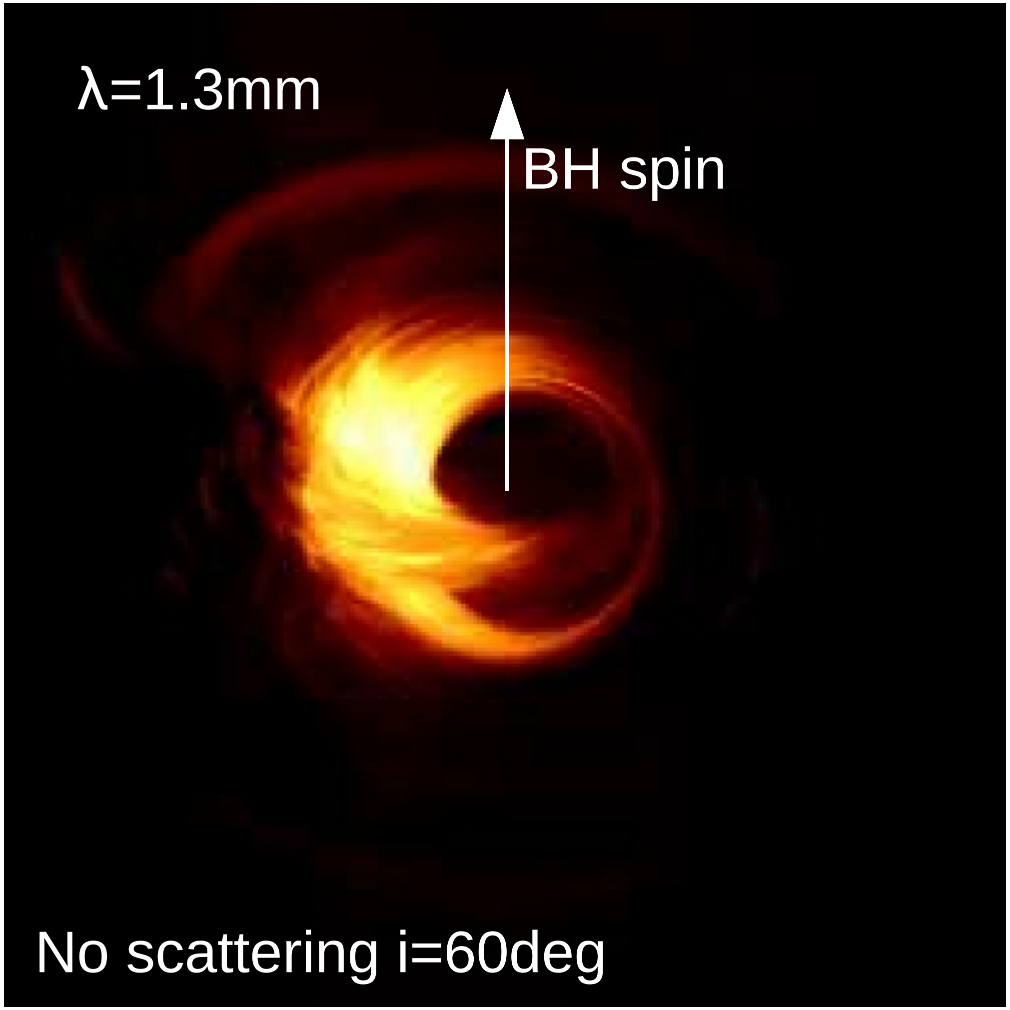


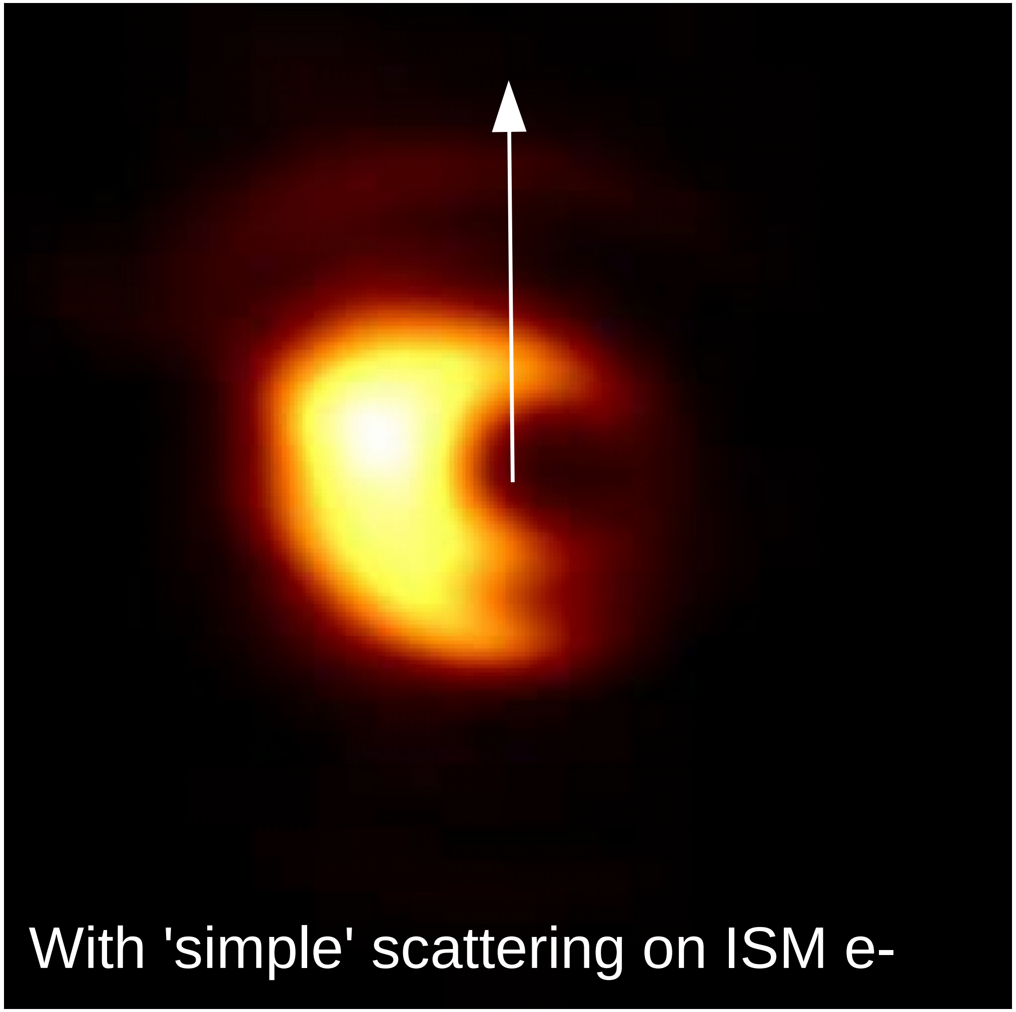
Moscibrodzka et al. 2014

See Ortiz-Leon et al. 2016 and Brinkerink et al. 2016 for detection of asymmetry at 3.5mm

Scattering reduced at λ=1.3 mm
but close to the event horizon the jet is also smaller

ZOOM-IN





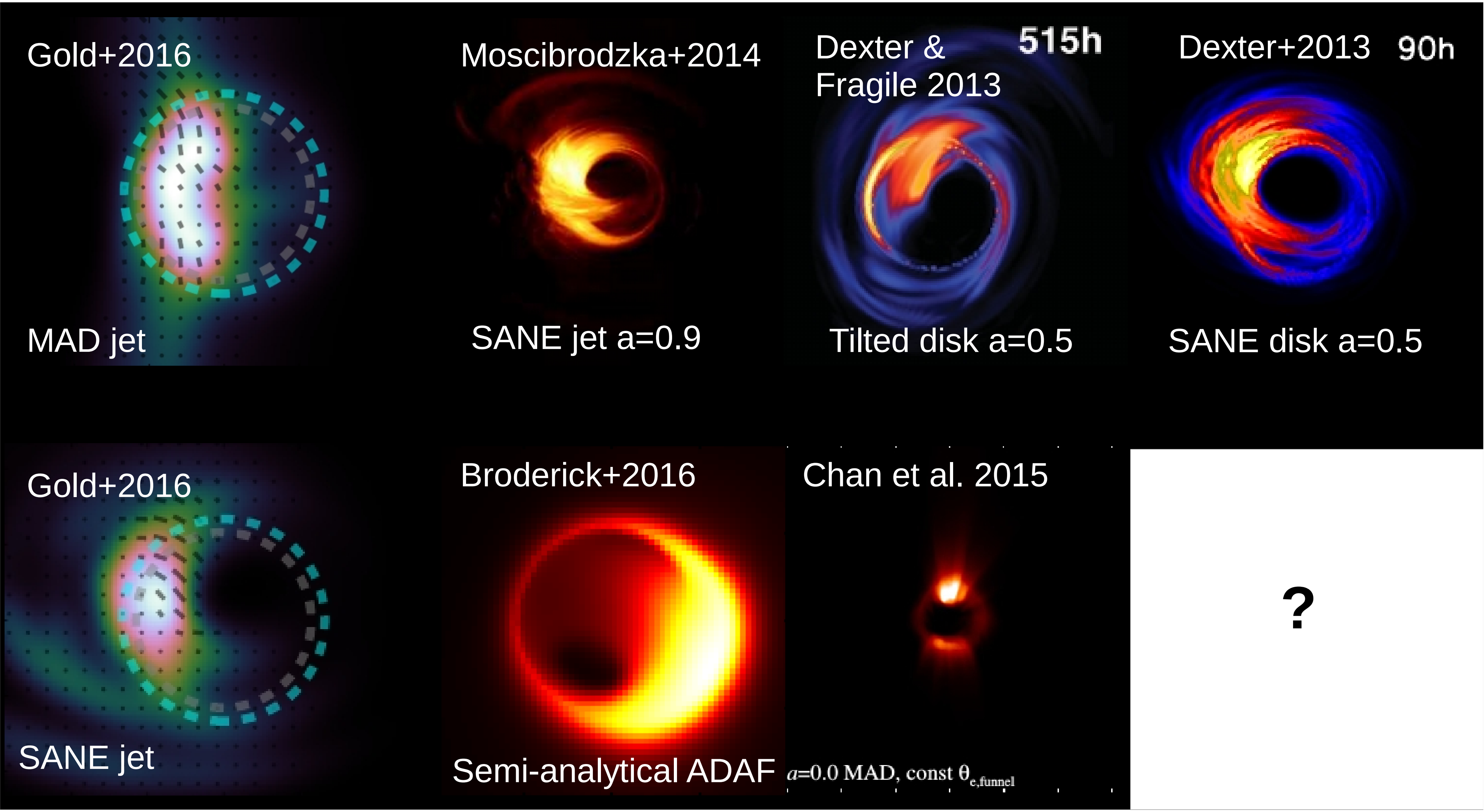
Moscibrodzka et al. 2014
See Fish et al. 2016 for detection of asymmetry at 1.3mm

Sgr A* parameters based on tuning various *GRMHD* simulations to the observations

model type	a_* explored	B_{init} topology	e^-_{disk} $\frac{T_p}{T_e}$	e^-_{jet}	image size[1]	image shape[2]	LP CP	SED all	a_* fit	$\dot{M}$ $[\mathrm{M}_\odot/\mathrm{yr}]$	i	PA	reference
SANE 2D	0-0.97	dipole	1	$\frac{T_p}{T_e} = 1$	✓	-	✗	✓	≤ 0.88	$\sim 1\,10^{-9}$	$\geq 35°$	-	Noble+2007
SANE 2D	0-0.98	dipole	3	$\frac{T_p}{T_e} = 3$	✓	-	✗	✓	0.94	$1\,10^{-9}$	85°	-	Moscibrodzka+20(
SANE 3D	0.9	dipole	3	$\frac{T_p}{T_e} = 3$	✓	-	✗	✗	-	$5\,10^{-9}$	50°	-23°	Dexter+2010
SANE 3D	0-0.98	multipole	15-20	-	✓	-	✓	✗	0.5	$4\,10^{-8}$	75°	115°	Shcherbakov+201
tilted 15°	0.5	dipole	1	-	✓	-	✗	✗	-	$1.8\,10^{-8}$	40°	-81°	Dexter+2013
tilted 15,30°	0.94	dipole	3	-	✓	-	✗	✓	-	-	-	-	Shiokawa+2012
SANE 3D	0.94	dipole	20	$\Theta_e = 20$	✓	-	✗	✓	-	$4\,10^{-8}$	60°	-	Moscibrodzka+20
SANE 3D	0.7,0.9	multipole	100	$\Theta_e = 30$	✓	-	✗	✓	0.9	-	60°	140°	Chan+2015
MAD 3D	0, 0.7, 0.9	dipole	1300	$\frac{T_p}{T_e} = 316$	✓	-	✗	✓	0.9	-	60°	160°	Chan+2015
SANE 3D	0.92	dipole	?	$\Theta_e = 100$	✓	-	✓	✗	-	$2\,10^{-8}$	126°	-	Gold+2016
SANE 3D	0.94	quadrupole	?	$\Theta_e = 50$	✓	-	✓	✗	-	$4\,10^{-8}$	98°	-	Gold+2016
MAD 3D	0.94	fancy	?	$\Theta_e = 35$	✓	-	✓	✗	-	$5\,10^{-9}$	140°	-	Gold+2016
ADAF	0-0.998	-	power-law	-	✓	✓	✗	✗	0.1	-	60°	156°	Broderick+2016
JET	-	-	-	power-law	✓[3]	✗	✗	✓	-	-	$\geq 75°$	105°	Markoff+2007

[1]from visibility amplitudes at 1.3mm in 2008
[2] available at 1.3mm in 2016, based on closue phases
[3]based on 7mm data

Synchrotron 1.3mm maps of various ***GRMHD*** models
Near horizon emission



Summary

- ***JETS*** united with ***ADAFs*** in *GRMHD* simulations: shiny jets are now naturally produced in extended *GRMHD* models

- Various models are used in the community; parameters different but we agree (more or less) about accretion rate level (**$\dot{M}$=fewx10^{-8} Msun/yr**) and the viewing angle (***i>40°***)

- Still to address:
  - particle acceleration (e.g. Ball et al. 2016)
  - alternative (to Kerr) metrics (different images of BH and disk/jets?, Rezzolla+ in prep.)
  - adaptive mesh (better resolution of jet, turbulence, shocks, Rezzolla+ in prep.)
  - onsets of accretion flows (radally extended MHD models, match radio & X-ray observations & models)

- Big picture of Sgr A* brought together by **EHT** and **BHCAM (European partner of EHT):** (observations: (mm)VLBI, ALMA, pulsars in GC, and theoretical interpretation) → see talk by **Heino Falcke**