Theory, Simulation and Observation: Piecing Together Black Hole Accretion

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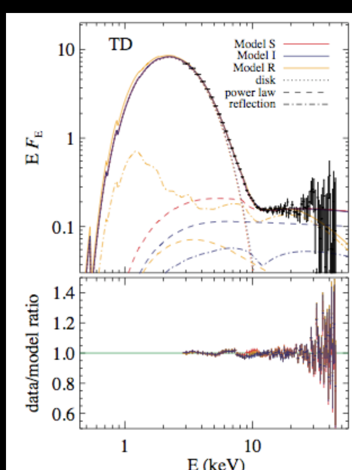
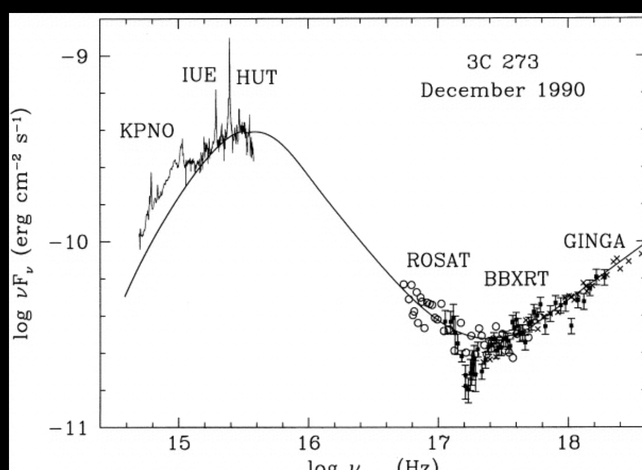
Black Hole Accretion Disks

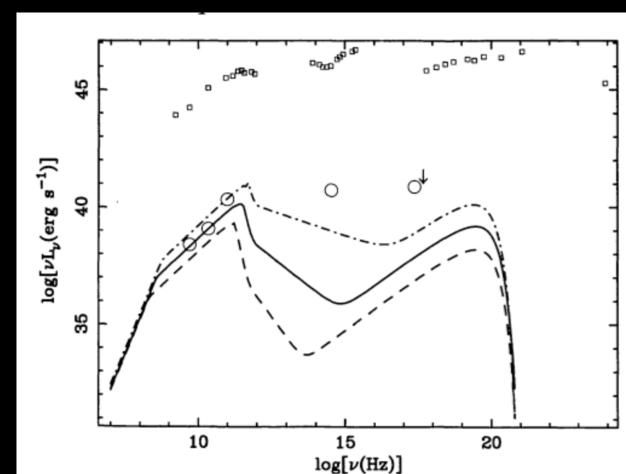
- Thin Disk Accretion (‘α - Model’, Shakura & Sunyaev 1973)
  - Cold & Bright: AGN, high/soft X-ray binaries
  - Theoretically inconsistent & fail to explain AGN spectra, light curves and microlensing sizes
- ADAF → RIAF (Narayan & Yi 1994, Yuan et al. 2003)
  - Sgr A*, M87, LLAGN, ‘quiescent’ state
- No accretion physics, variability or outflow mechanism



Steiner et al. (2010)



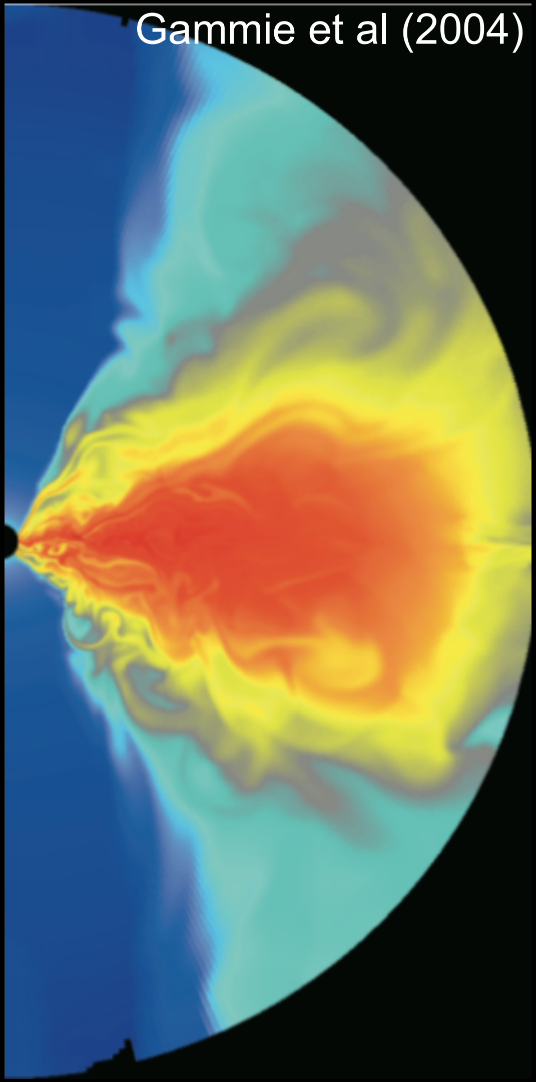
Kriss et al. (1999)



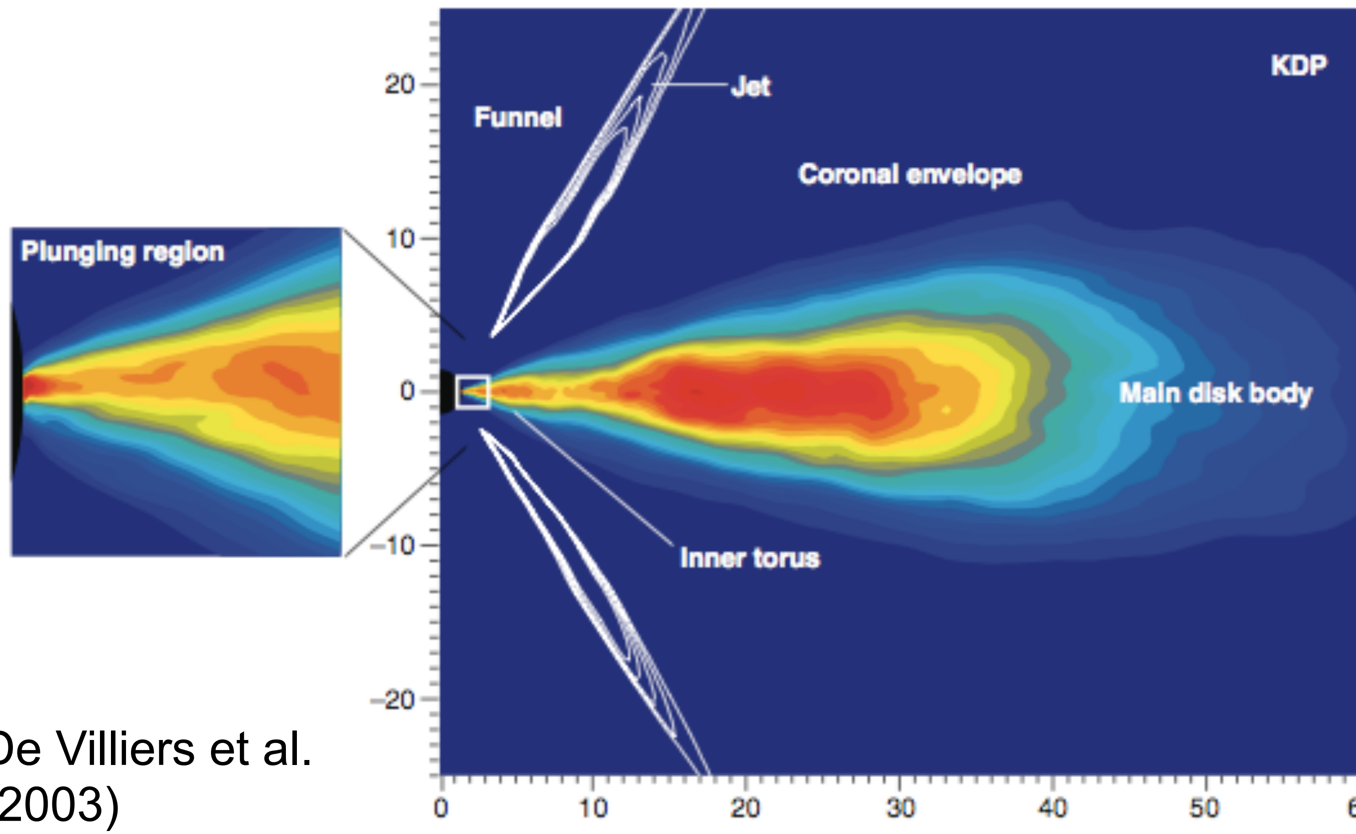
Reynolds et al. (1996)

The MRI & GRMHD

- MRI (Balbus & Hawley 1991):
  - Weakly magnetized fluid with Keplerian rotation is unstable
  - Ang mom transport & accretion
- GRMHD simulations
  - Physical accretion theory
  - Time-dependent, fully relativistic
  - Limitations:
    - Numerical & difficult
    - Radiation & thermodynamics
    - Spatial extent & shape



Black Hole GRMHD



De Villiers et al. (2003)

Black Hole GRMHD

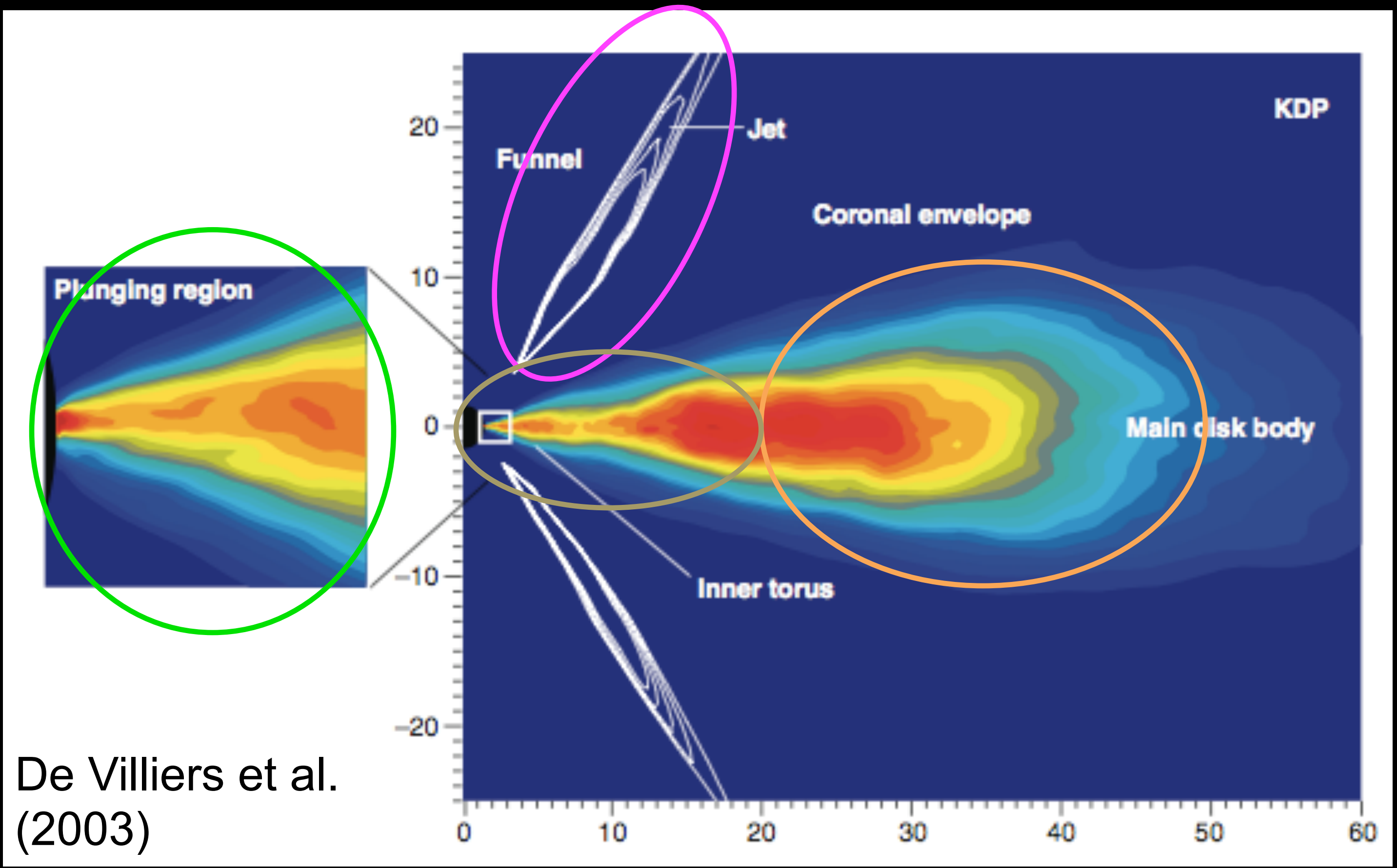
Jet formation, acceleration, stability?
(McKinney et al., De Villiers et al., Tchekhovskoy et al.)

Radiation pressure?
(Turner et al., Hirose et al.)

Plunging region?
(Shafee et al., Noble et al., Penna et al.)

Inner disk edge?
(Krolik & Hawley, Fragile)

Tilted disks?
(Fragile et al.)

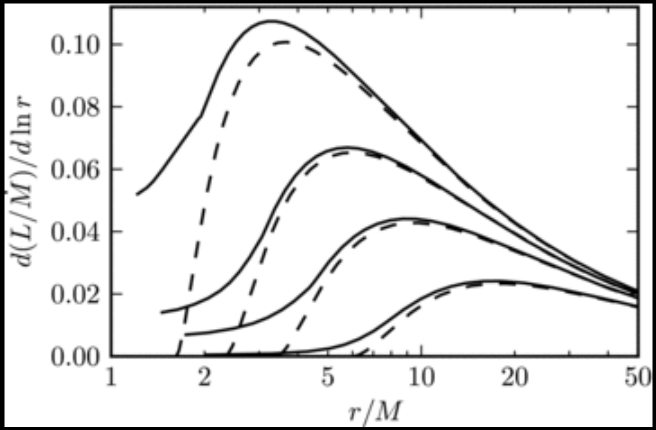


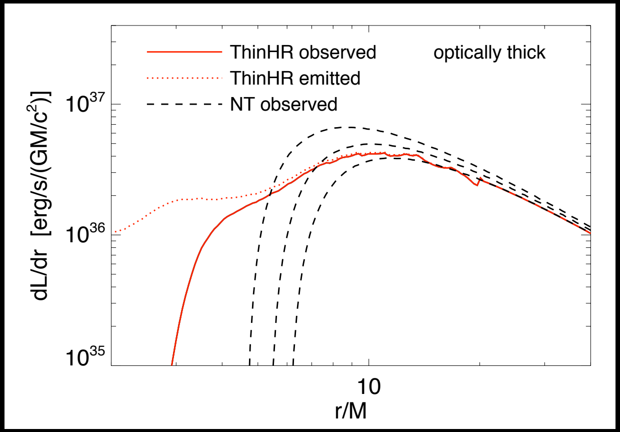
De Villiers et al. (2003)

Applied Black Hole GRMHD

- General
  - Radiation edge? (Beckwith et al. 2008, Dexter & Fragile 2011)
  - Plunging region? (Kulkarni et al. 2011, Noble et al. 2011)
  - Quasi-periodic oscillations? (Schnittman et al. 2006, Dexter & Fragile 2011)
- Individual Sources
  - Sagittarius A* (Goldston et al. 2005, Noble et al. 2007, Huang et al. 2009, Moscibrodzka et al. 2009; 2011, Dexter et al. 2009; 2010, Shcherbakov et al. 2011)

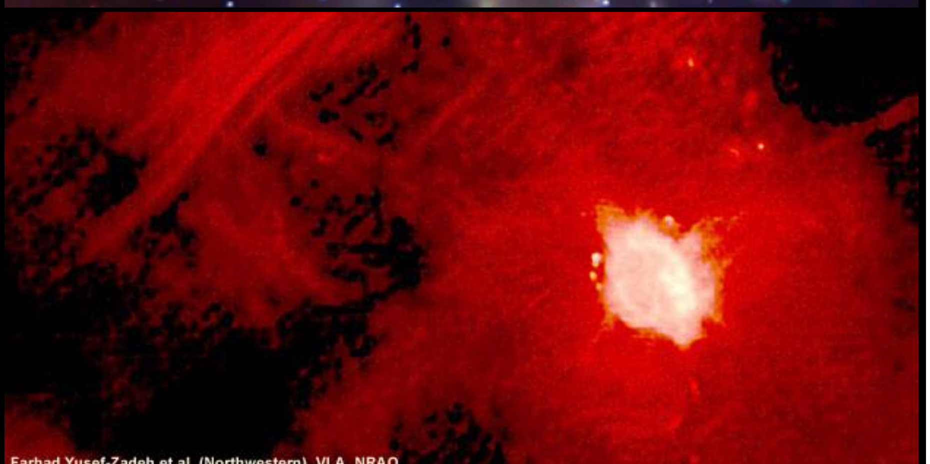
Kulkarni et al. (2011)

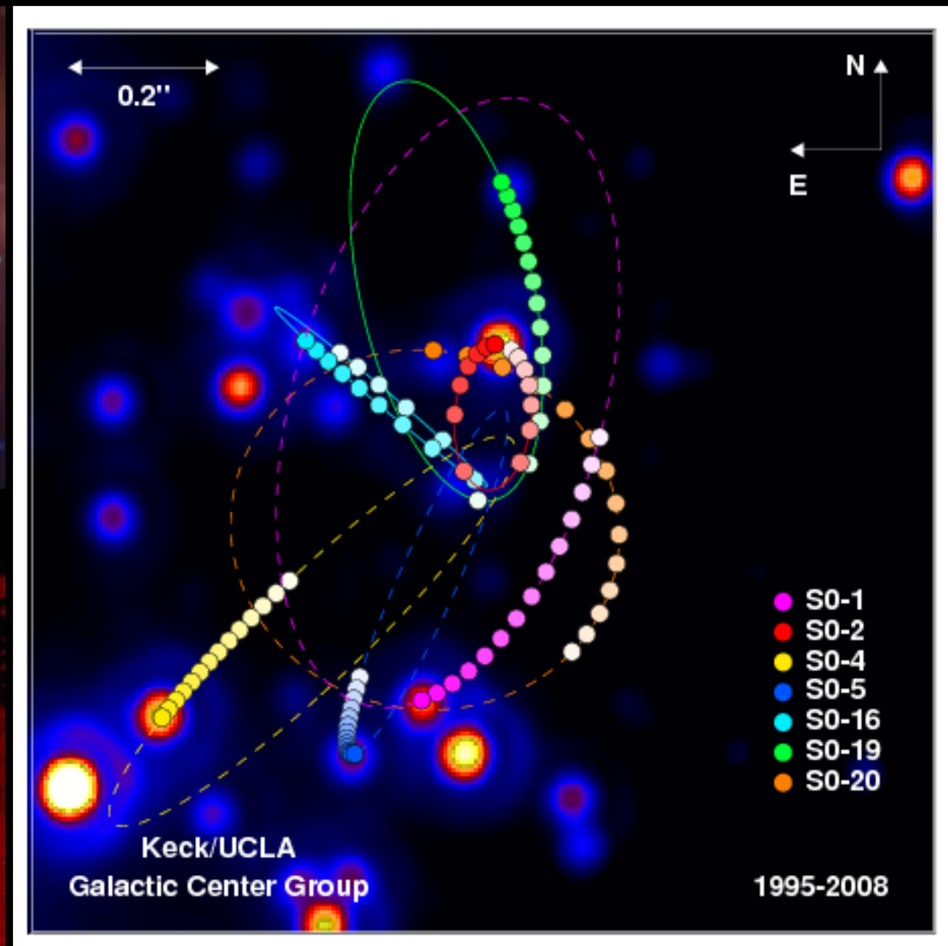




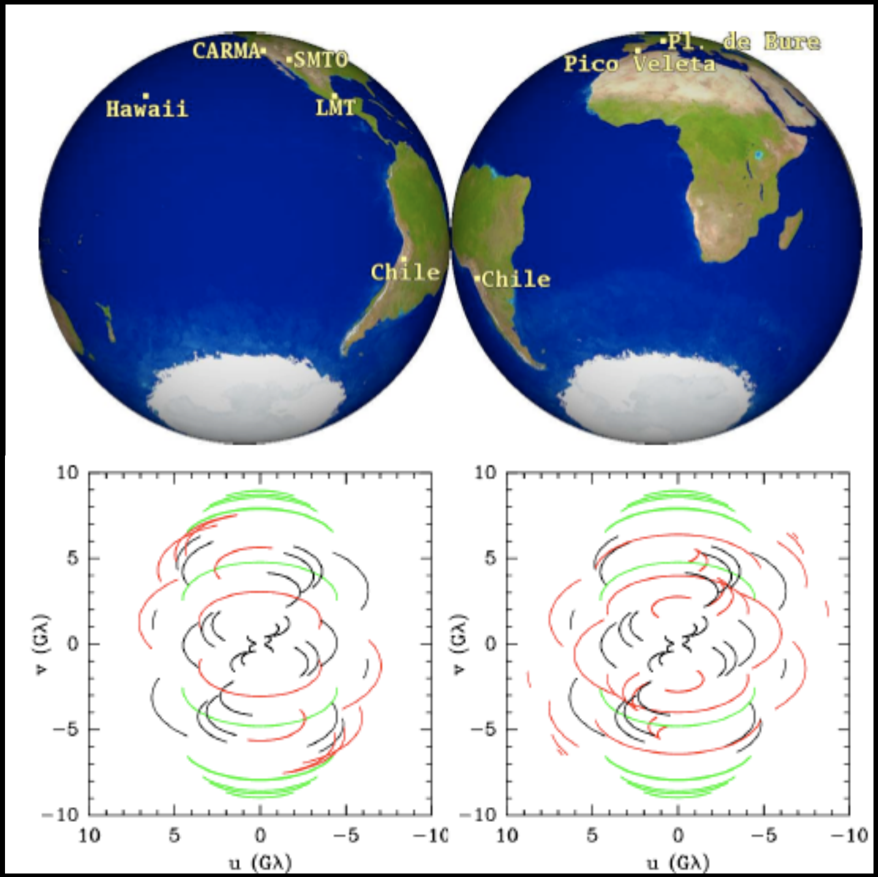
Noble et al. (2011)

I. Galactic Center Black Hole

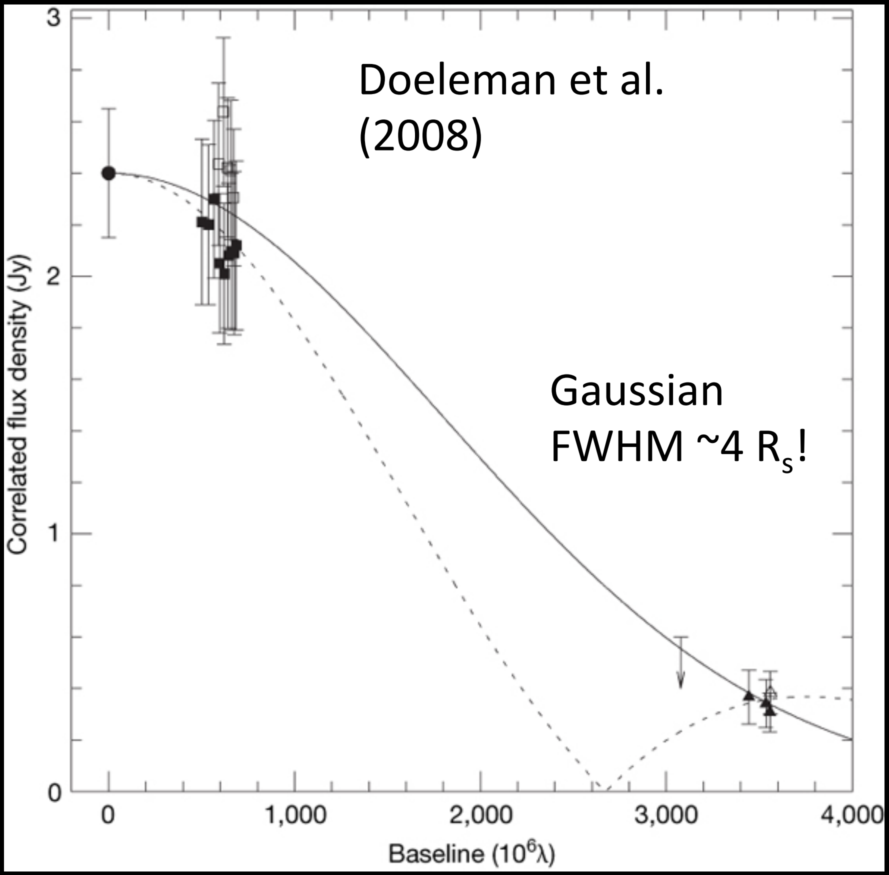




Millimeter VLBI of Sgr A*



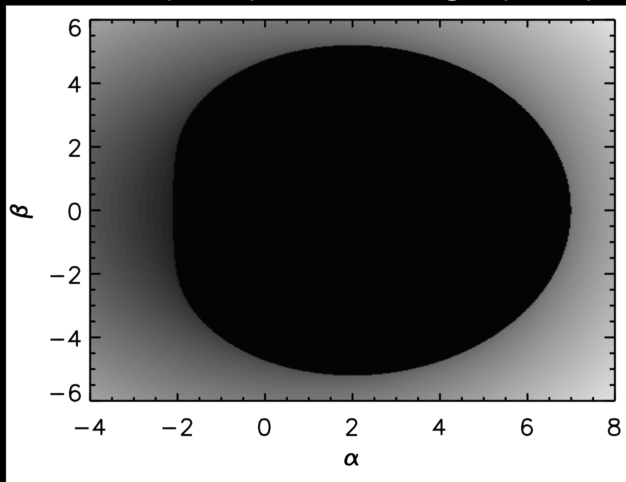
Doeleman et al. (2009)



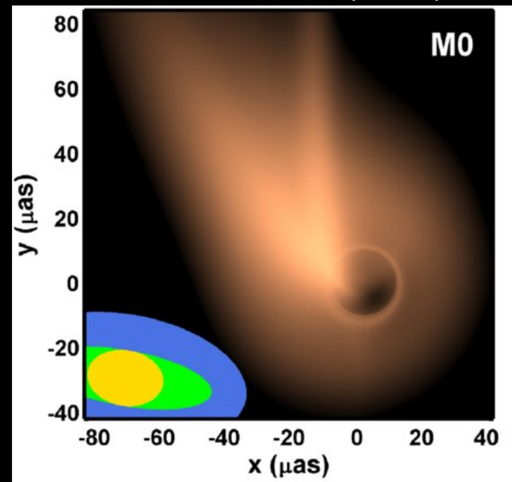
- Event Horizon Telescope (arXiv: 0906.3899)

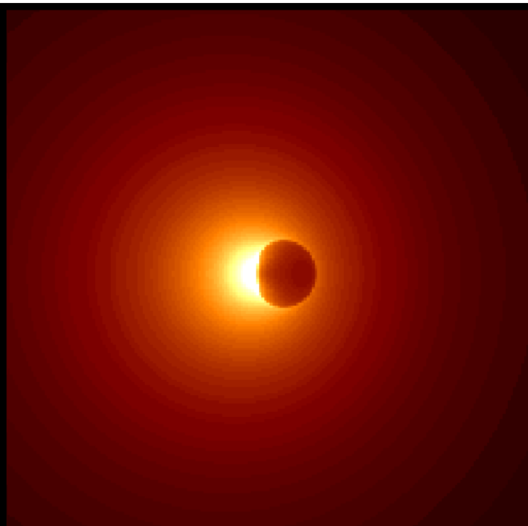
Black Hole Images & Shadows

Bardeen (1973); Dexter & Agol (2009)

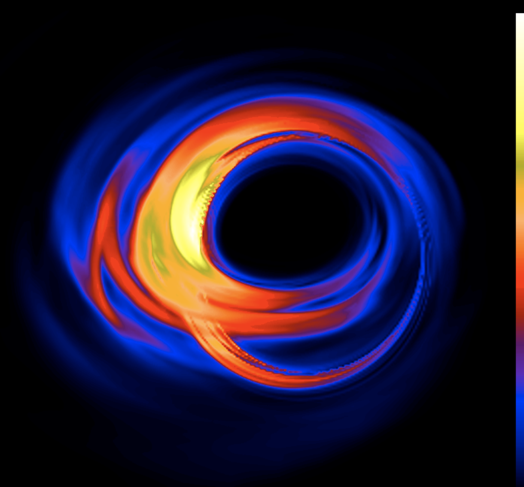


Broderick & Loeb (2009)





Falcke, Melia & Agol (2000)



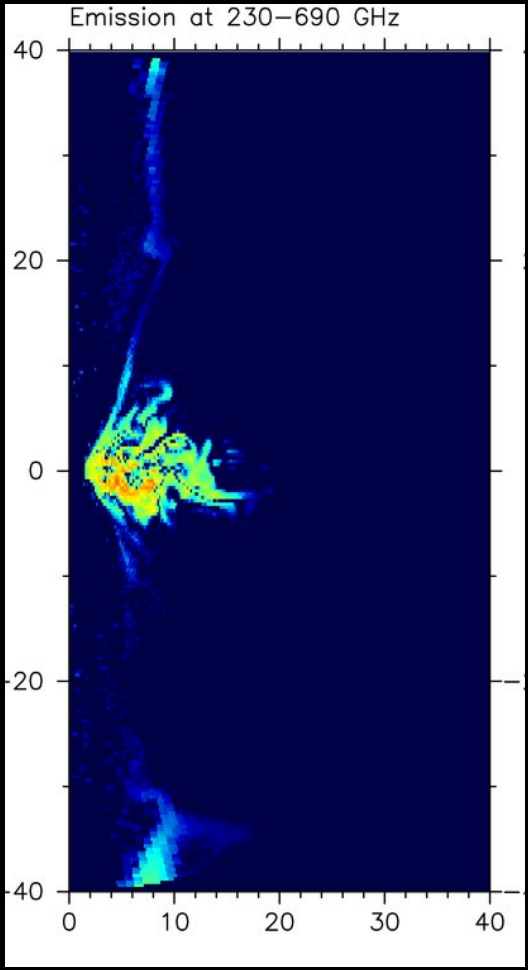
Dexter et al. (2009, 2010)

- Sensitive to viewing geometry & details of accretion flow
  - Need accurate theoretical predictions!

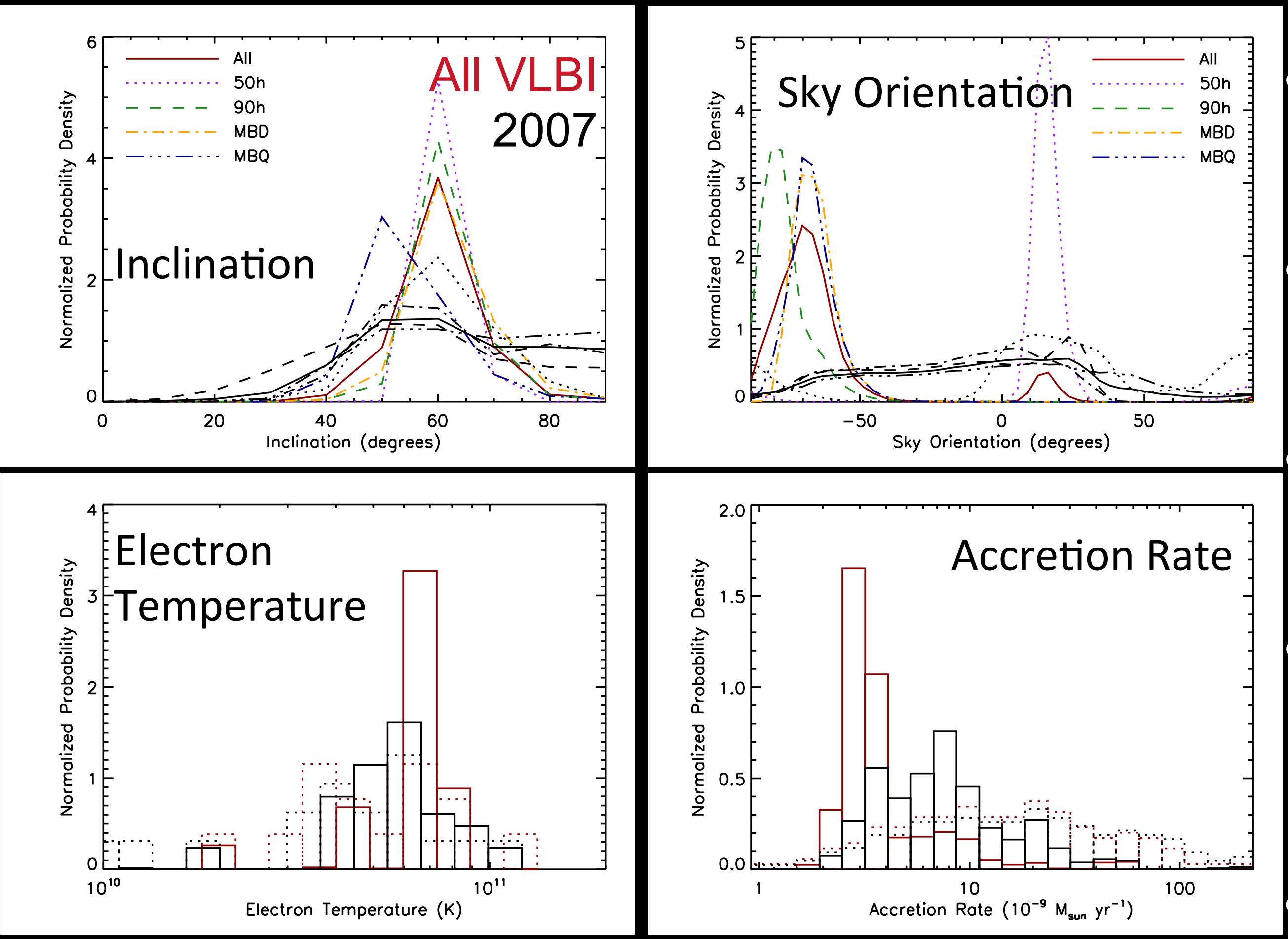
GRMHD Models of Sgr A*

- Sgr A* great for GRMHD
  - Thick, MRI-driven accretion flow
  - Insignificant cooling(?)
  - Synchrotron radiation near BH
- Not perfect…
  - Collisionless plasma (mfp = 10^4 R_s)
  - No electrons
    - Assume constant T_i/T_e

Moscibrodzka et al. (2009)



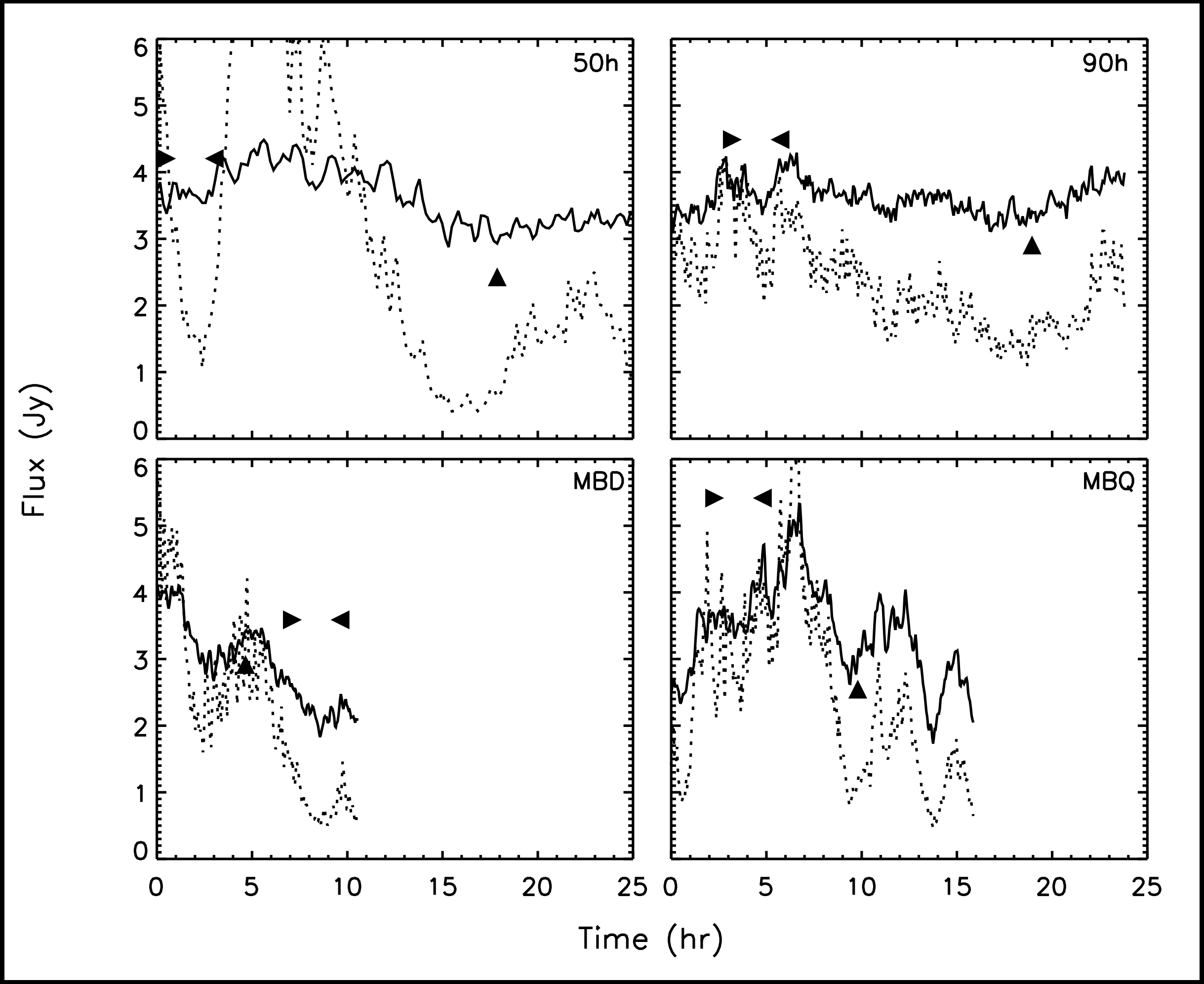
Sgr A* Parameter Estimates



Dexter et al. (2010, 2011)

- $i = 60^{+15}_{-15}$ degrees
- $\xi = -70^{+86}_{-15}$ degrees
- $T_e/10^{10}\,K = 6 \pm 2$
- $dM/dt = 3^{+7}_{-1} \times 10^{-9}$ $M_{sun}\ yr^{-1}$
- All to 90% confidence

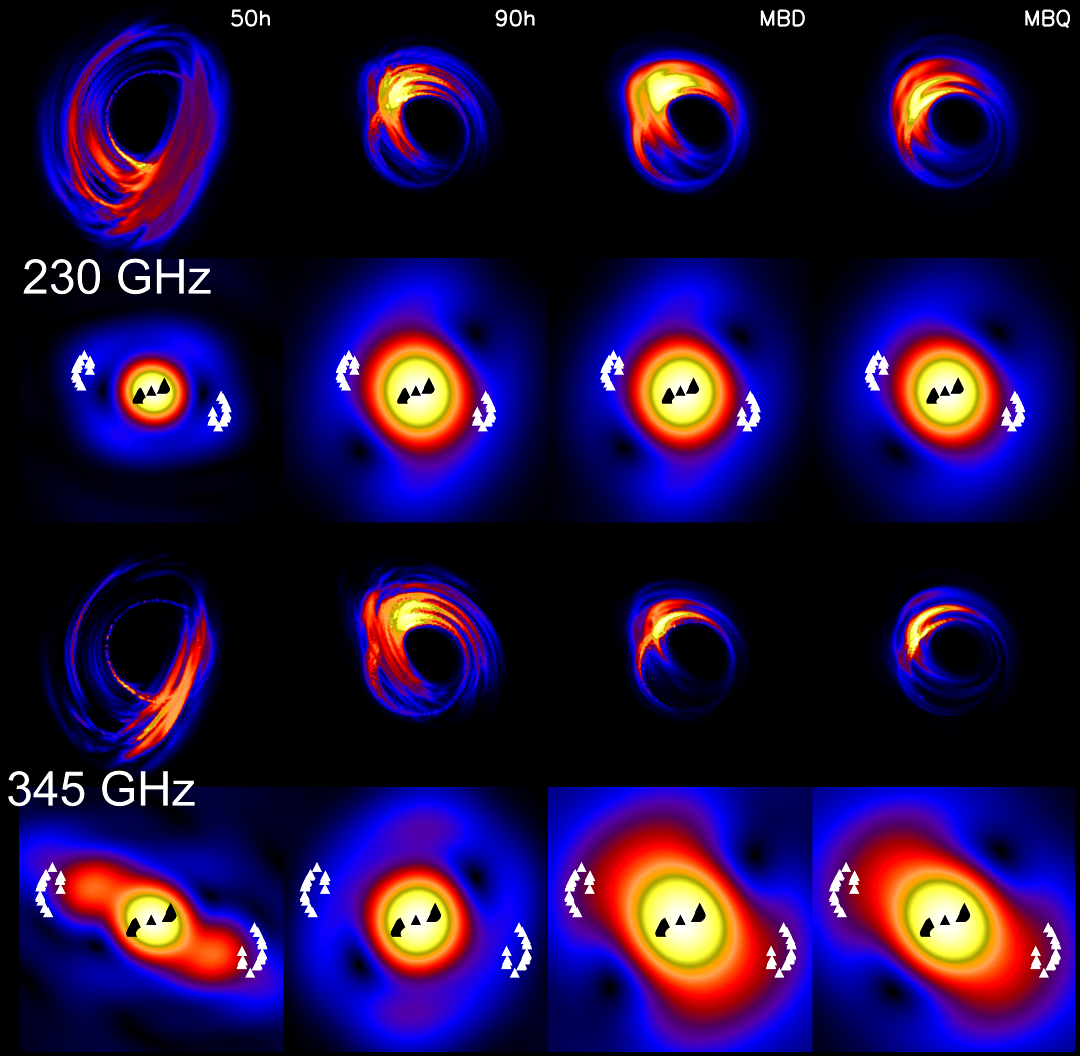
Sgr A* Millimeter Flares

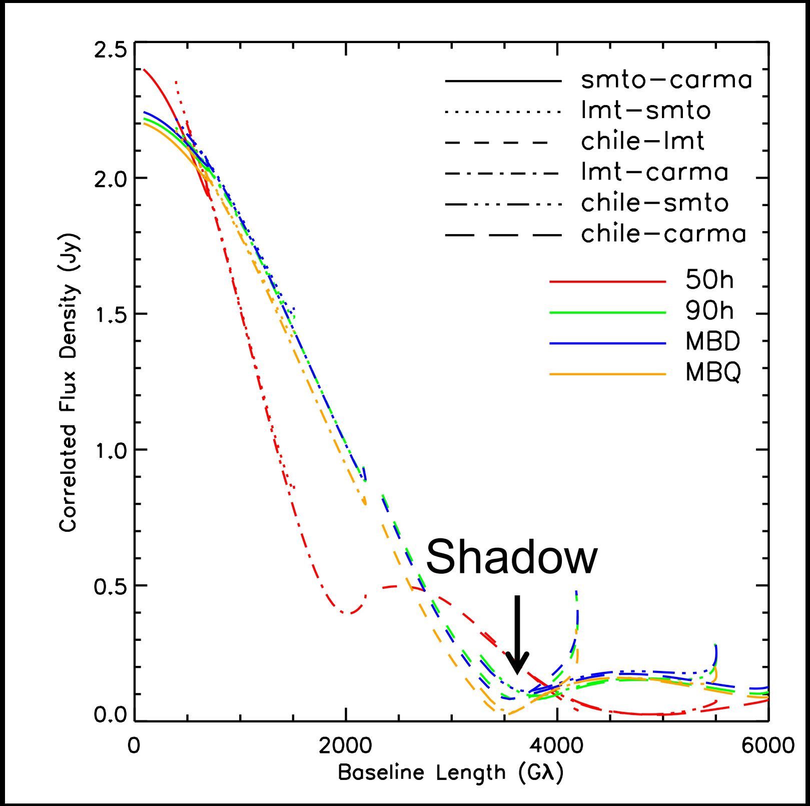


Solid – 230 GHz (1.3mm) Dotted – 690 GHz (0.4mm)

- Correlation with accretion rate
- Driven by magnetic turbulence
- Models reproduce observed mm flares

Sgr A* Black Hole Shadow

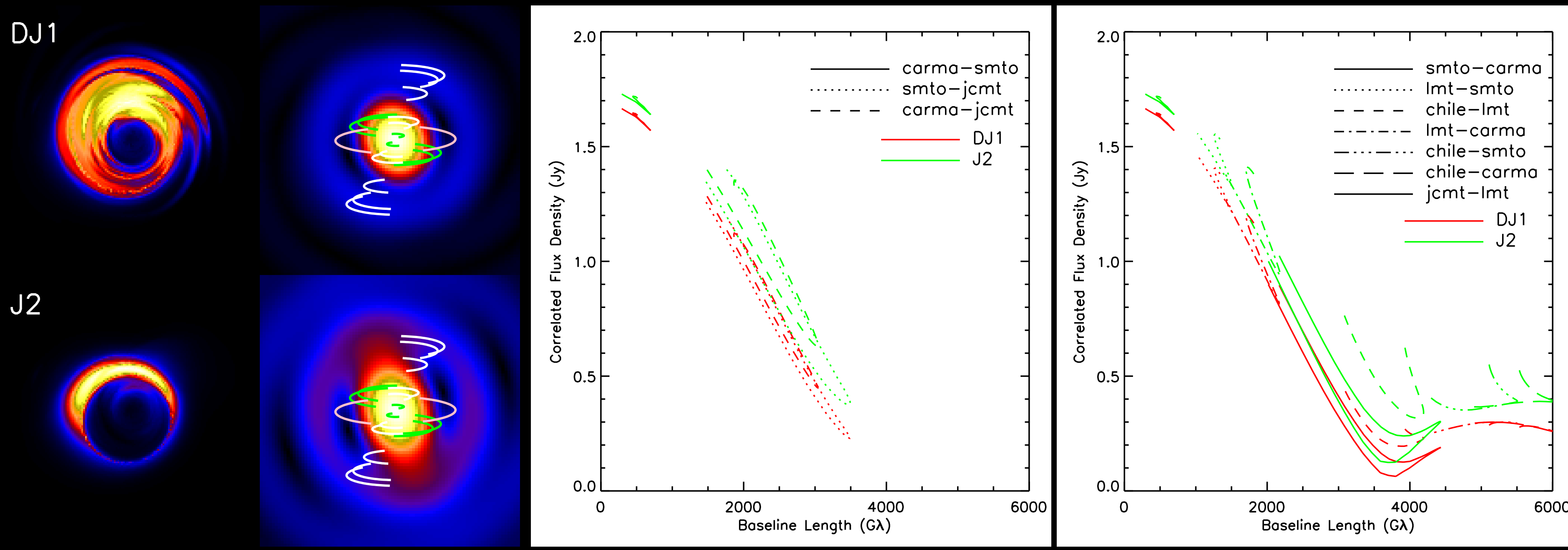




Shadow may be detected on Chile-Mexico baseline (in closure phase too)

M87 Images & Visibilities

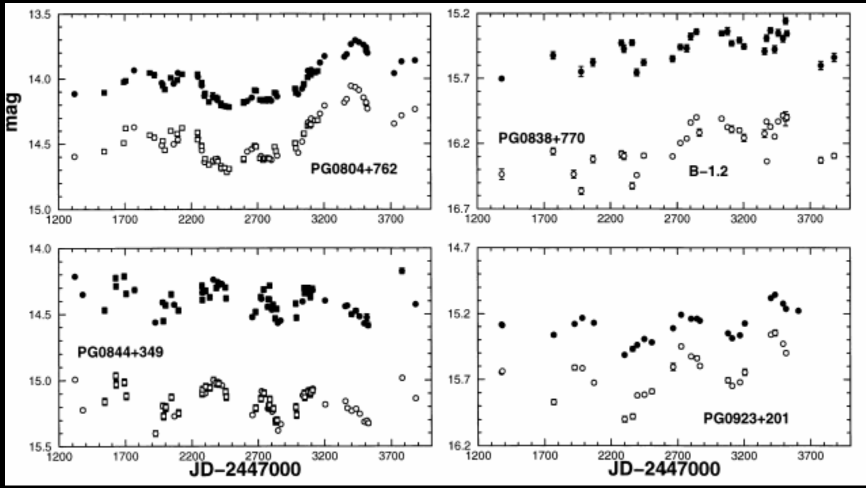
- Images are still crescents!
- Gaussian size: 36-41 μas
- Shadow on Hawaii-Mexico or Mexico-Chile



Dexter et al. (2011)

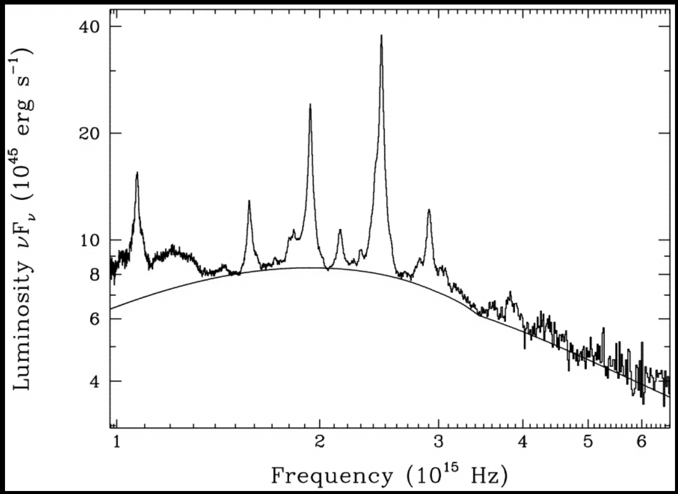
II. Inhomogeneous Quasar Accretion Disks

Giveon et al. (2002)



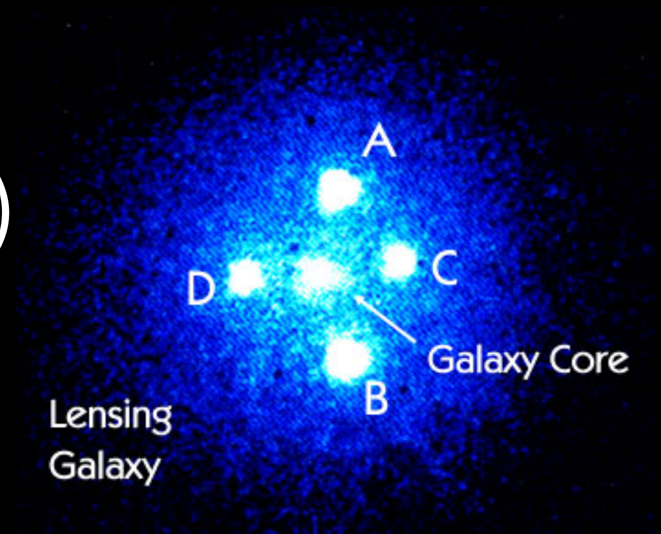
- α - Model Issues:
- Thermal & inflow instabilities
- Observations:
  - High levels of UV
  - Simultaneous variability
  - Microlensing Sizes

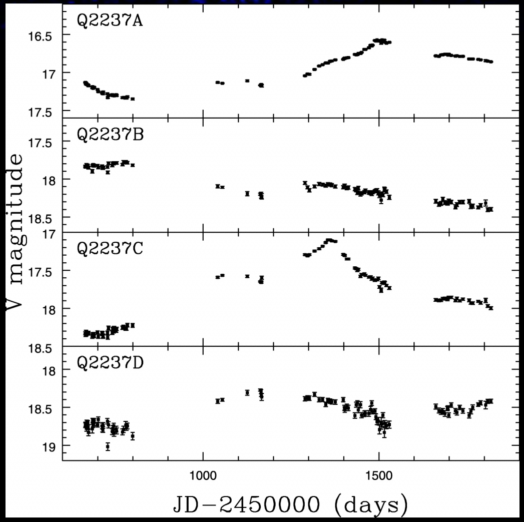
Zheng et al. (1997)



Quasar Microlensing Disk Sizes

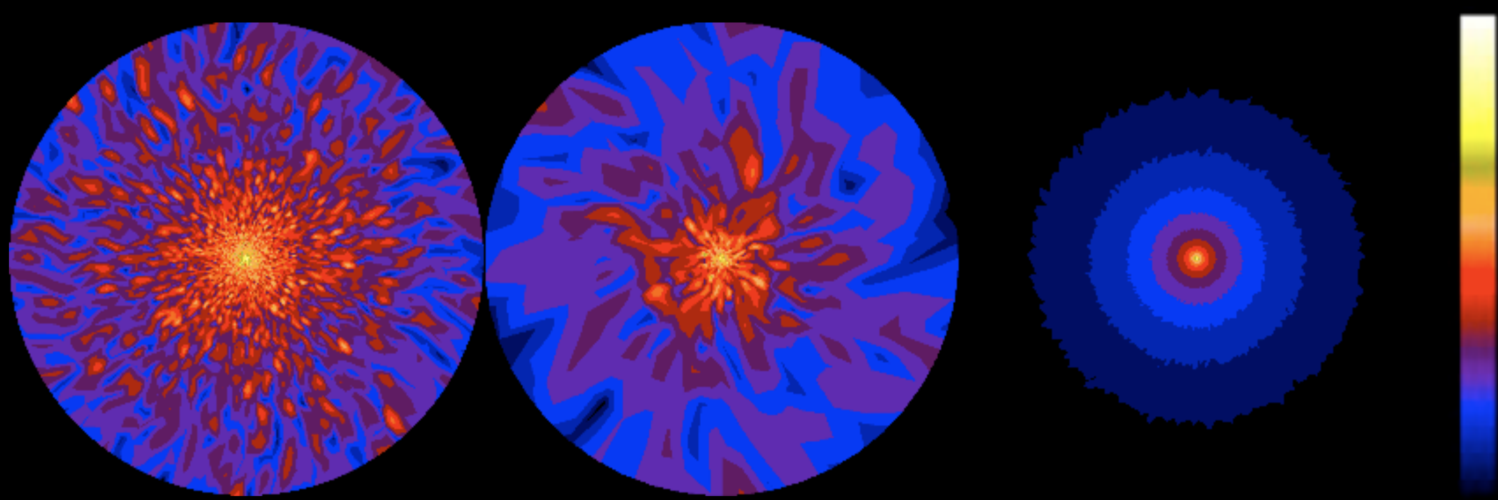
- "Micro" – unresolvable image separations (microarcseconds)
- Uncorrelated variations between images of strongly lensed quasars
- Optical size discrepancy: 0.6 ± 0.3 dex! (Morgan et al. 2010)
- X-ray size / optical size << 1



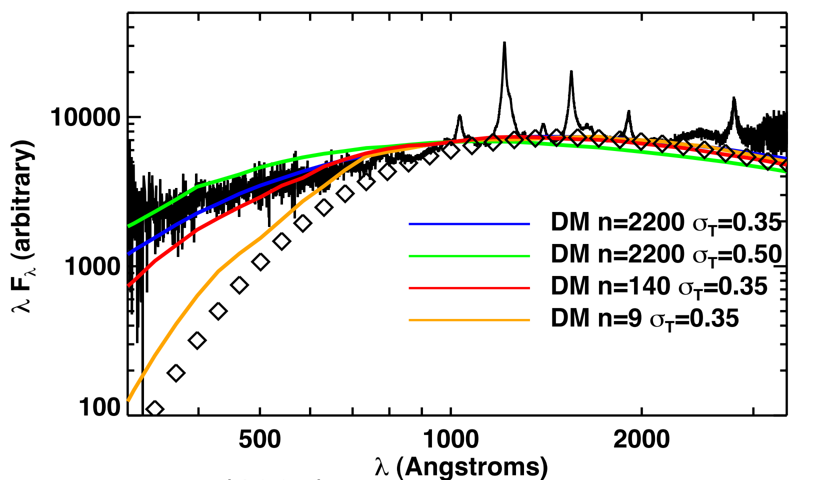


Inhomogeneous Disks

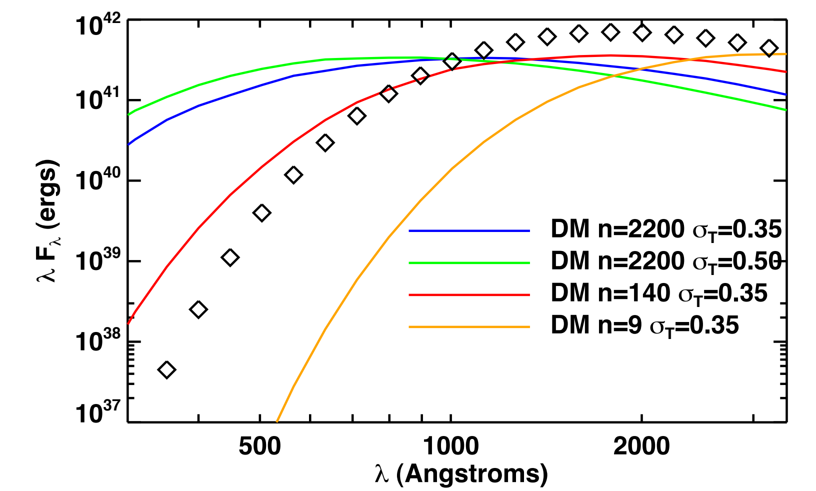
- Quasar var: 10-20%, stochastic
- α on average: $<\sigma T^4>_{\phi,t} = F(r)$
- Let T vary with ϕ & t
- Many possible prescriptions (damped random walk)
- Explain all observations for large fluctuations



Inhomogeneous Disks

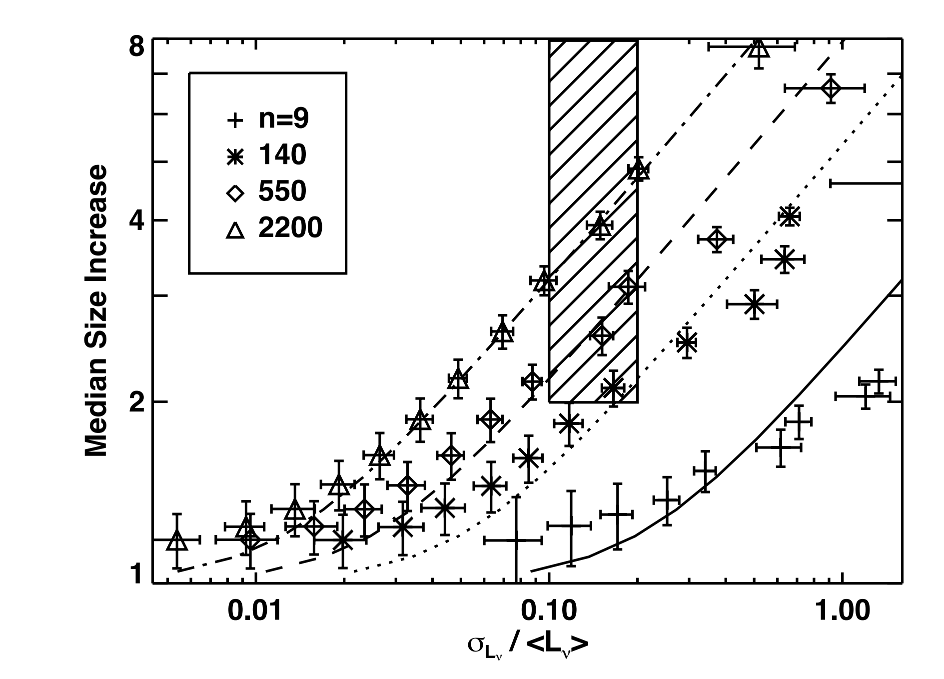


Zheng et al. (1997)



n – number of zones per octave in radius

σ_T - Amplitude of damped random walk fluctations in dex



Dexter & Agol (2011)

Inhomogeneous Disks

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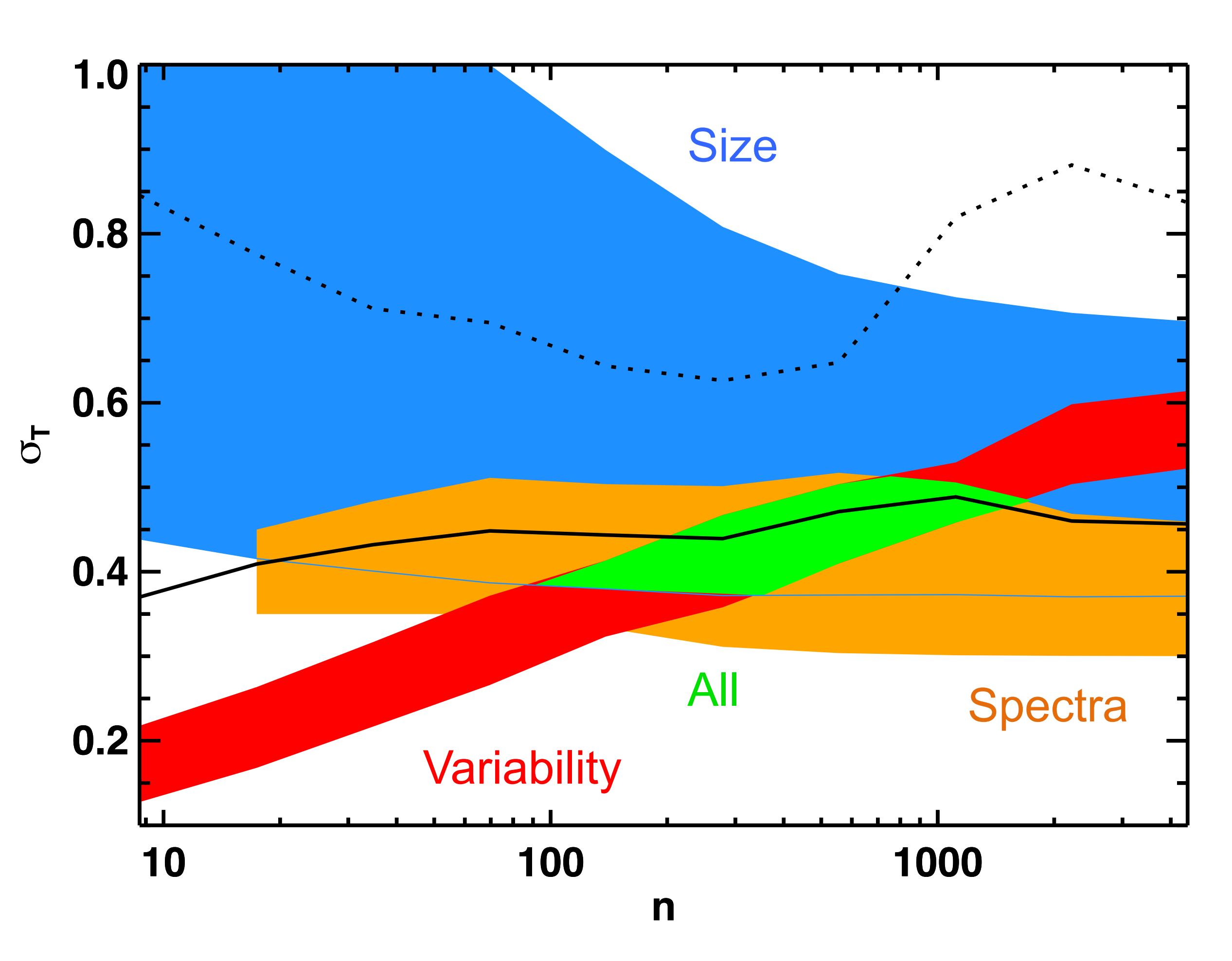
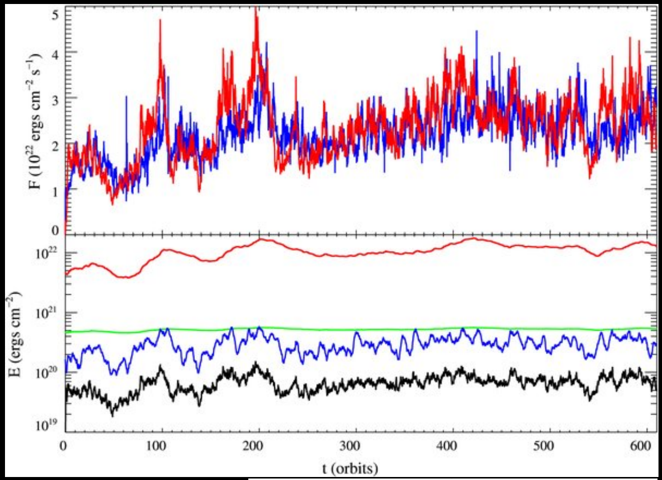


0.35 < σ_T < 0.50, 100 < n < 1000, Dexter & Agol (2011)

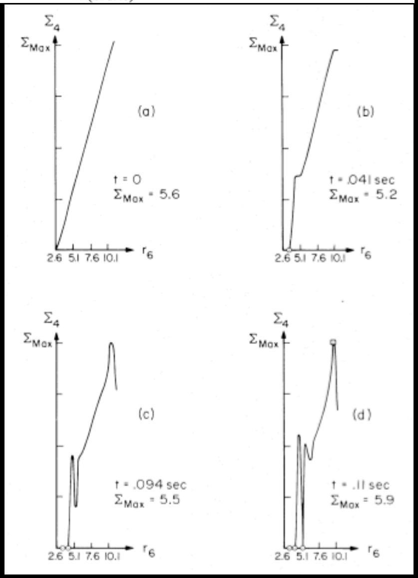
Physical Mechanisms

- Observations: σ_T = 0.35-0.50
- Reasonable? Depends on disk instabilities
  - MRI: Too small?
  - Thermal: Doesn't operate?
  - Inflow: Need to test!
  - Photon bubble: May help
- Or: magnetically supported disk (Begelman & Pringle 2007, Evghenii Gaburov's talk)

Hirose et al. (2009)



Lightman (1974)

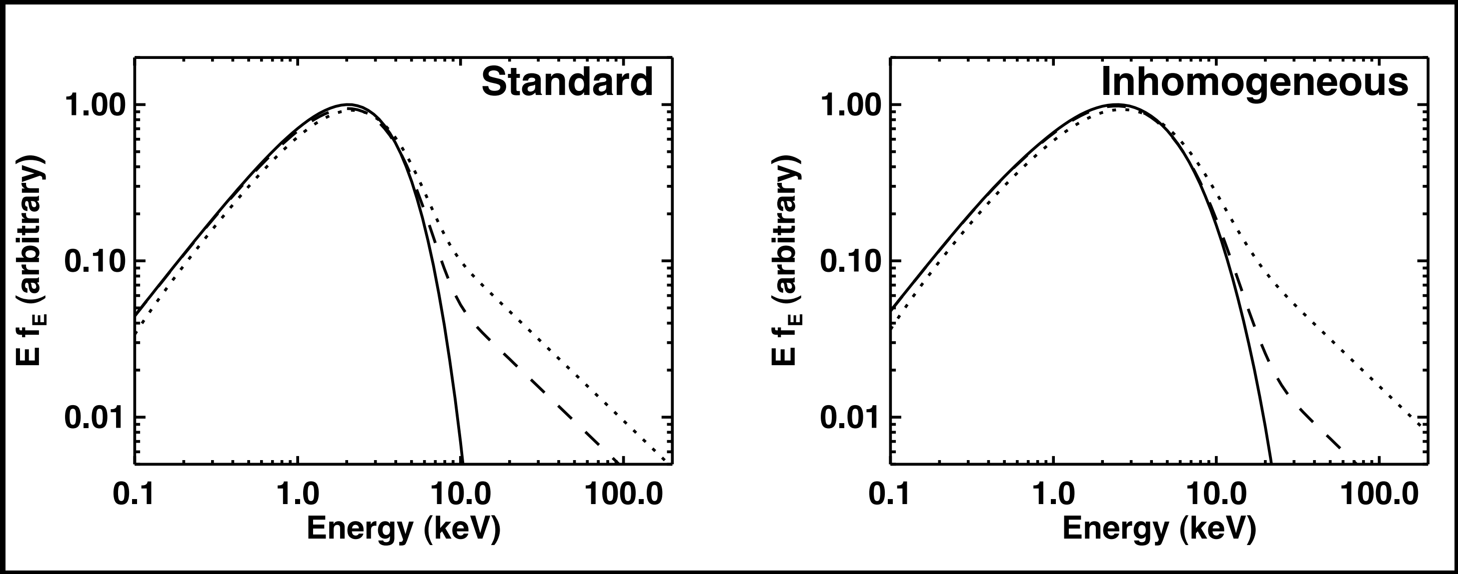


Summary

- Observations moving beyond semi-analytic disk models (EHT, microlensing)
- Numerical simulations based on the MRI provide physically realistic models of black hole accretion disks
- Comparing simulations to observations is feasible for low luminosity sources (Sgr A*)
- Radiation physics is necessary for direct comparisons to AGN & X-ray binaries

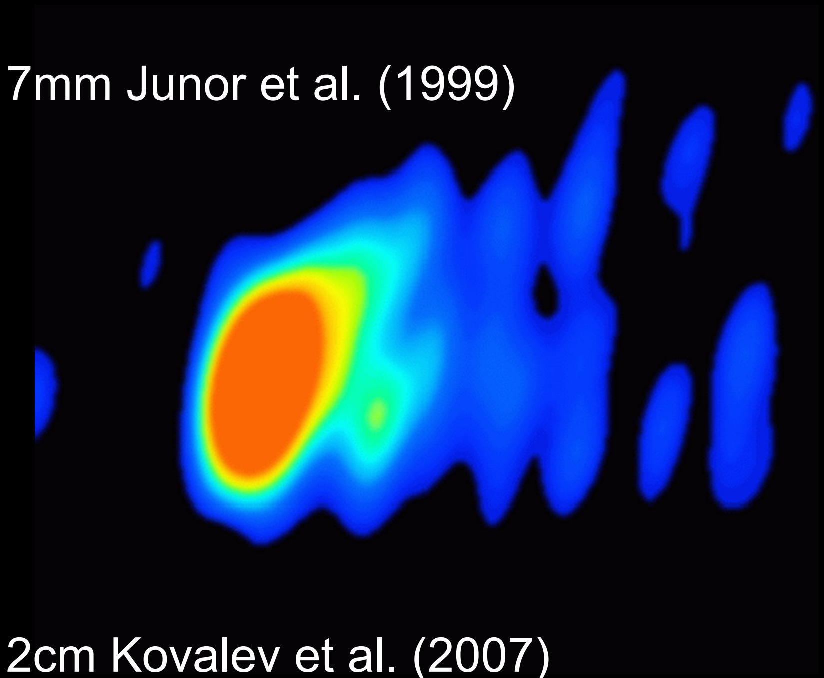
Inhomogeneous disks in BHBs?

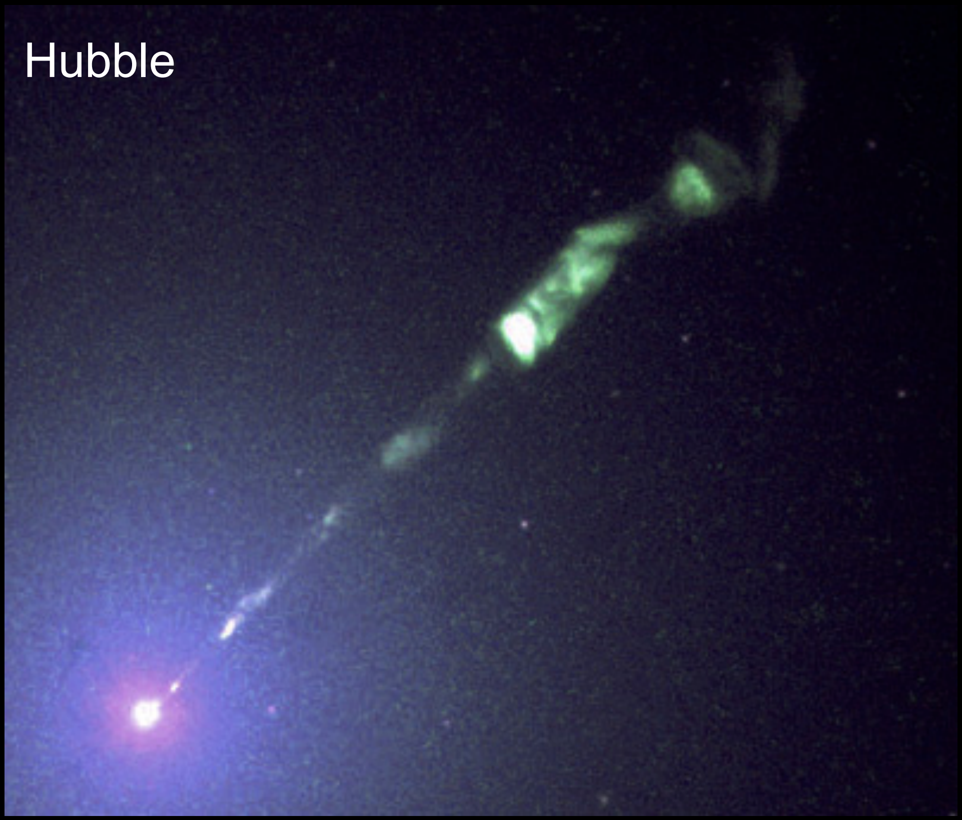
- Disk instabilities would operate in BHBs, but thermal spectra well fit by α disks
- Compact corona & inhomogeneous disk?

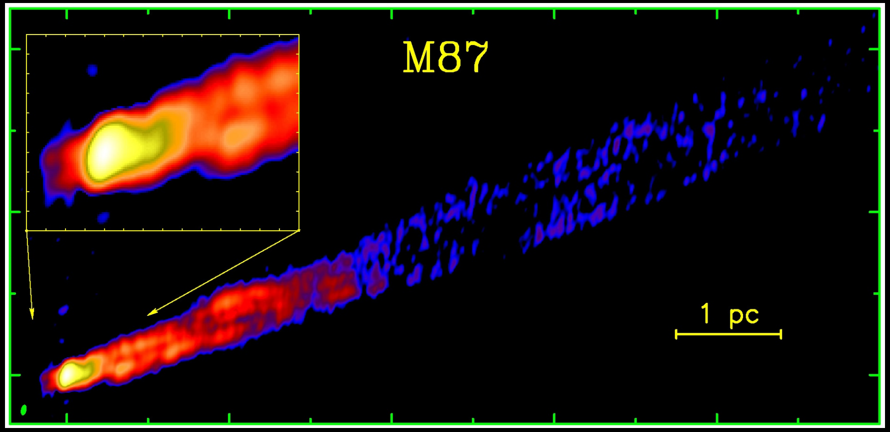


M87

- 1600 $M_{Sgr\ A*}$ at 2000 $D_{Sgr\ A*}$
- Jet launching physics?
- Known viewing geometry?





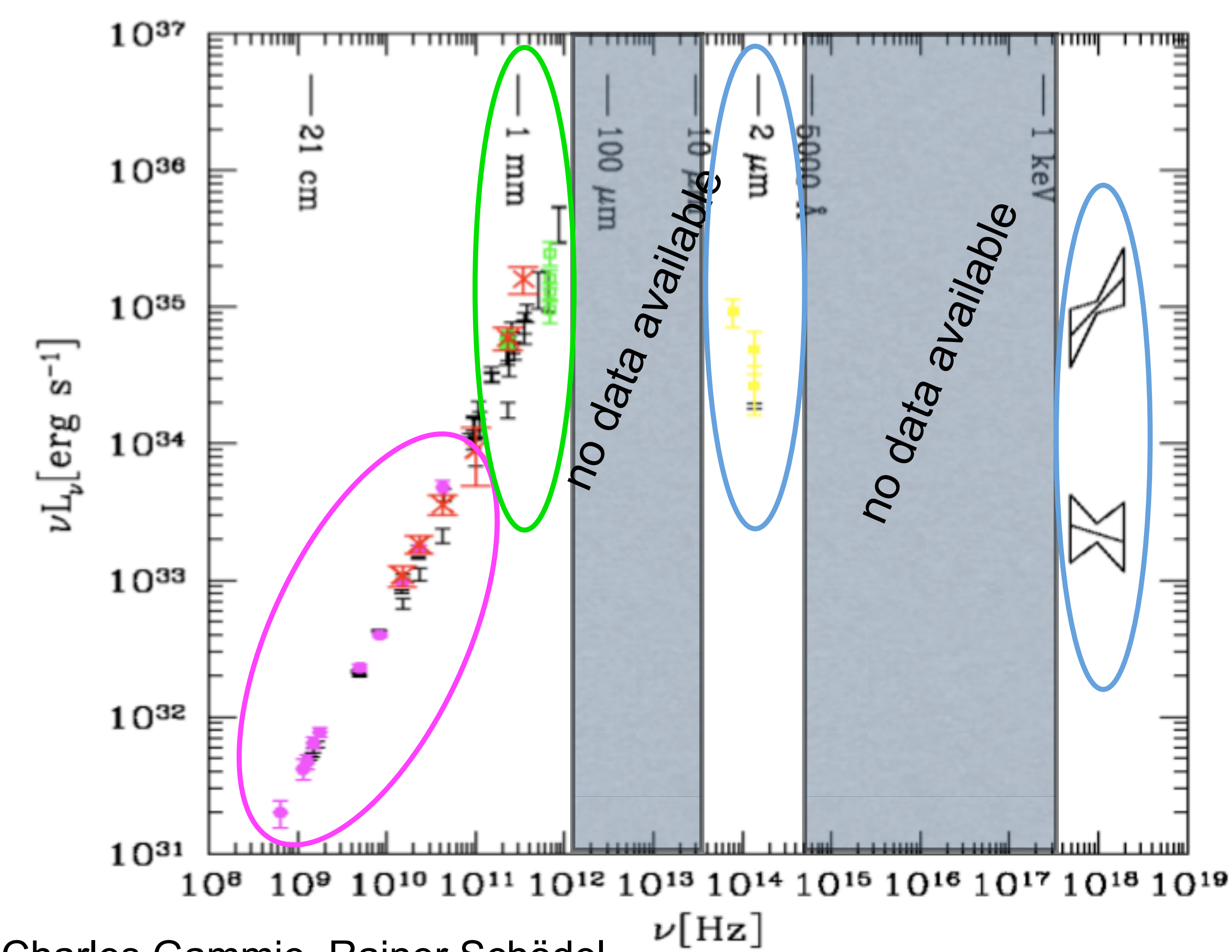


Sagittarius A*

Jet or nonthermal electrons far from BH

Thermal electrons at BH

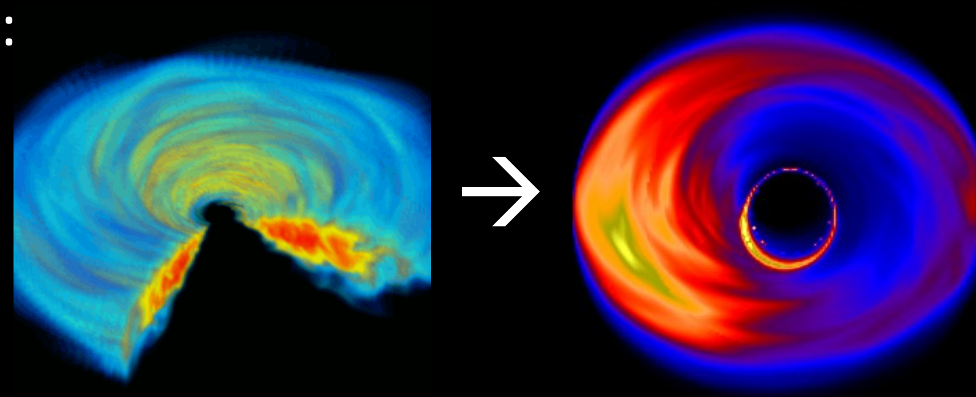
Simultaneous IR/X-ray flares close to BH?

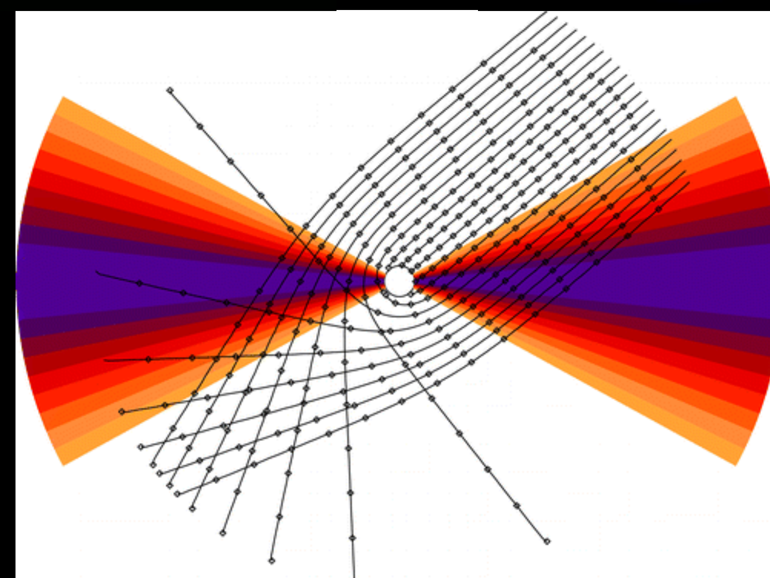


Charles Gammie, Rainer Schödel

Ray Tracing

- Assume light rays are geodesics:
  - `geokerr`, Dexter & Agol (2009)
- 5 (4) Simulations:
  - Fragile et al. (2007, 2009)
  - McKinney & Blandford (2009)
- Synchrotron emissivity:
  - Leung et al. (2011)
- Joint fits to spectral & VLBI data:
  - Marrone 2006, Doeleman et al. 2008, Fish et al. 2011
  - Parameters: dM/dt, i, a, T_i/T_e

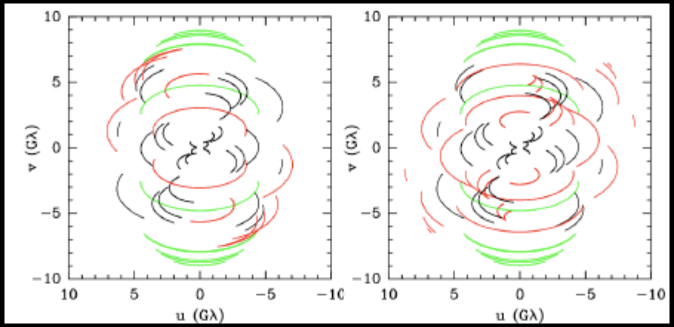




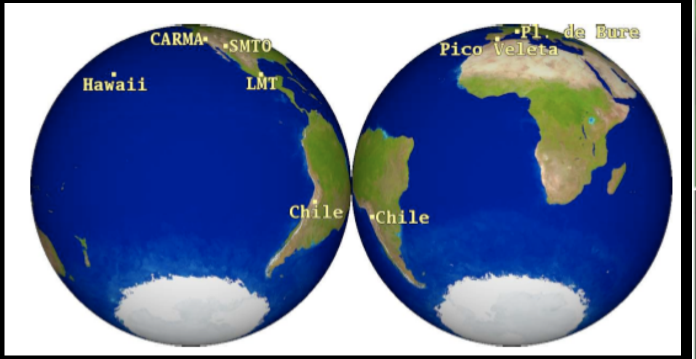
Schnittman et al. (2006)

Event Horizon Telescope

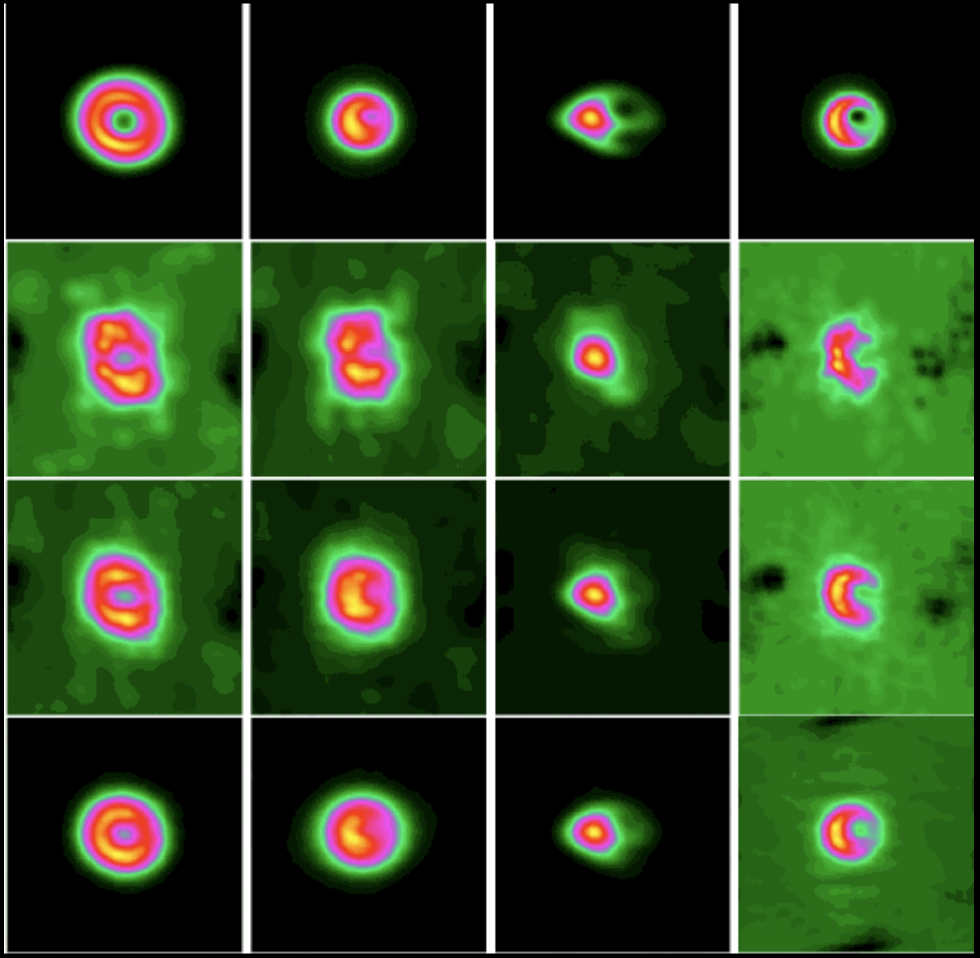
From Shep Doeleman's Decadal Survey Report on the EHT



UV coverage
(Phase I: black)



Doeleman et al (2009)



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