Extremely Faint & Incredibly Close: the Physics of Accretion onto Sgr A*

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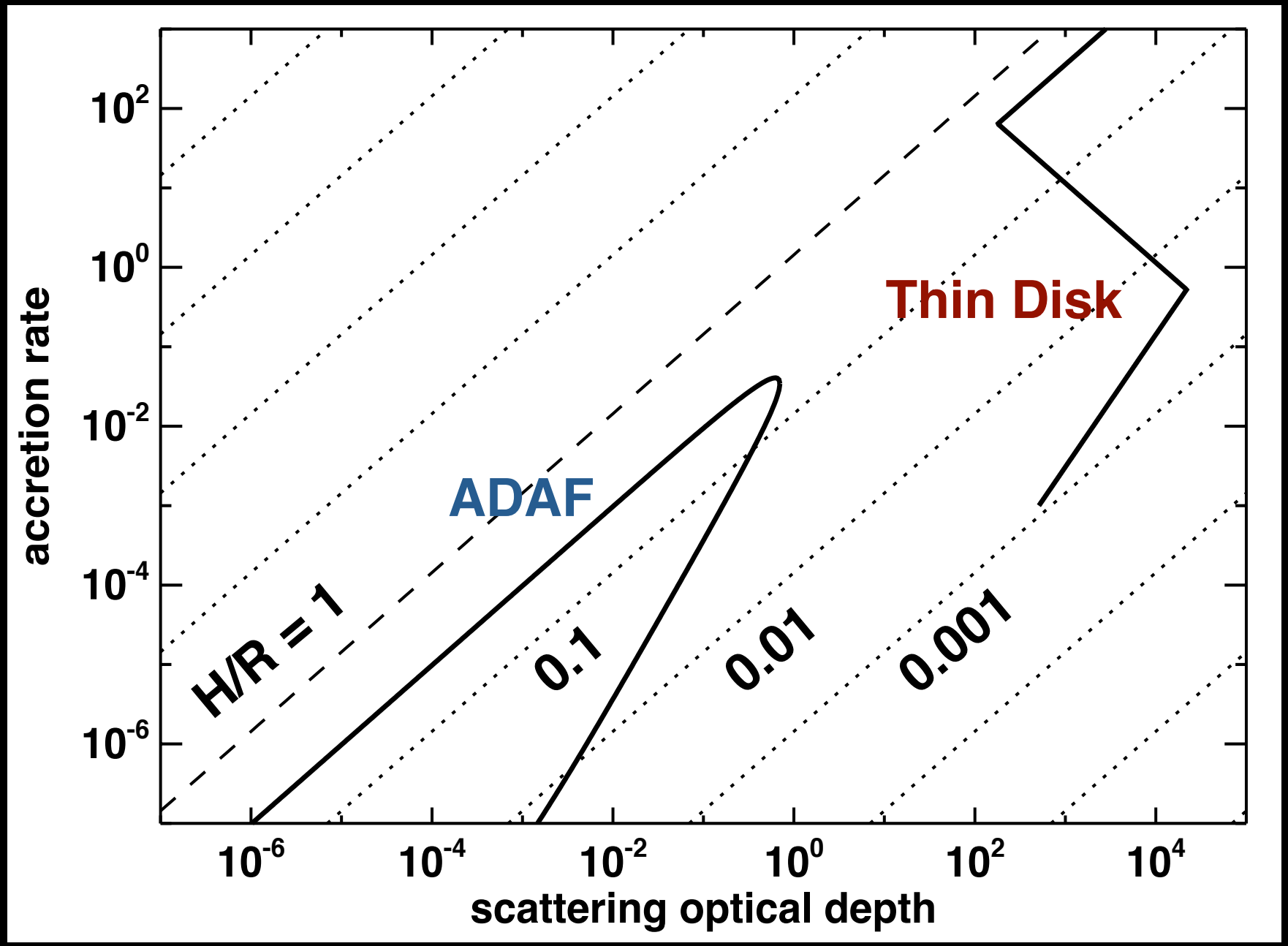
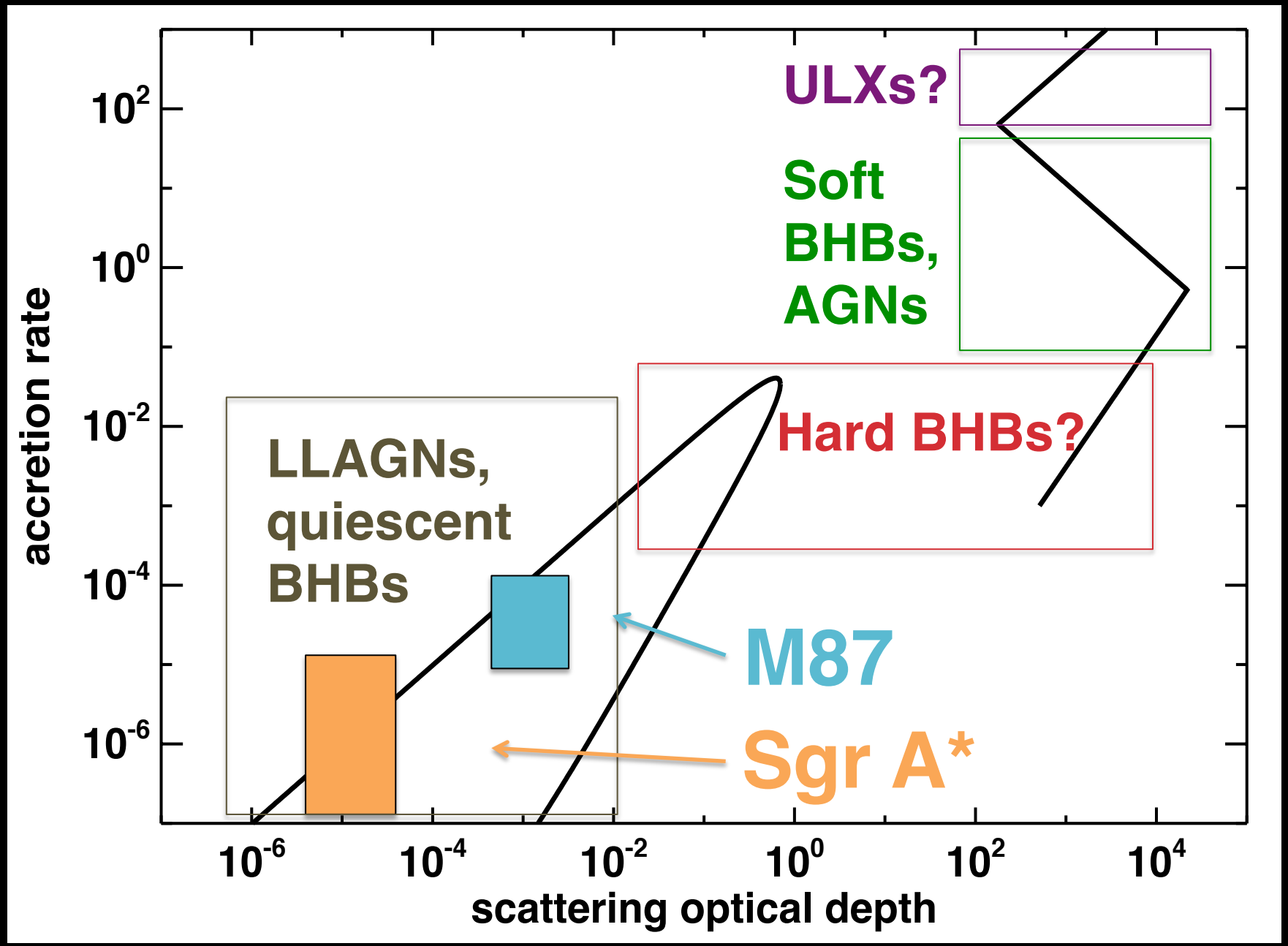
With Eric Agol, Chris Fragile, and Jonathan McKinney

Standard Accretion Theory

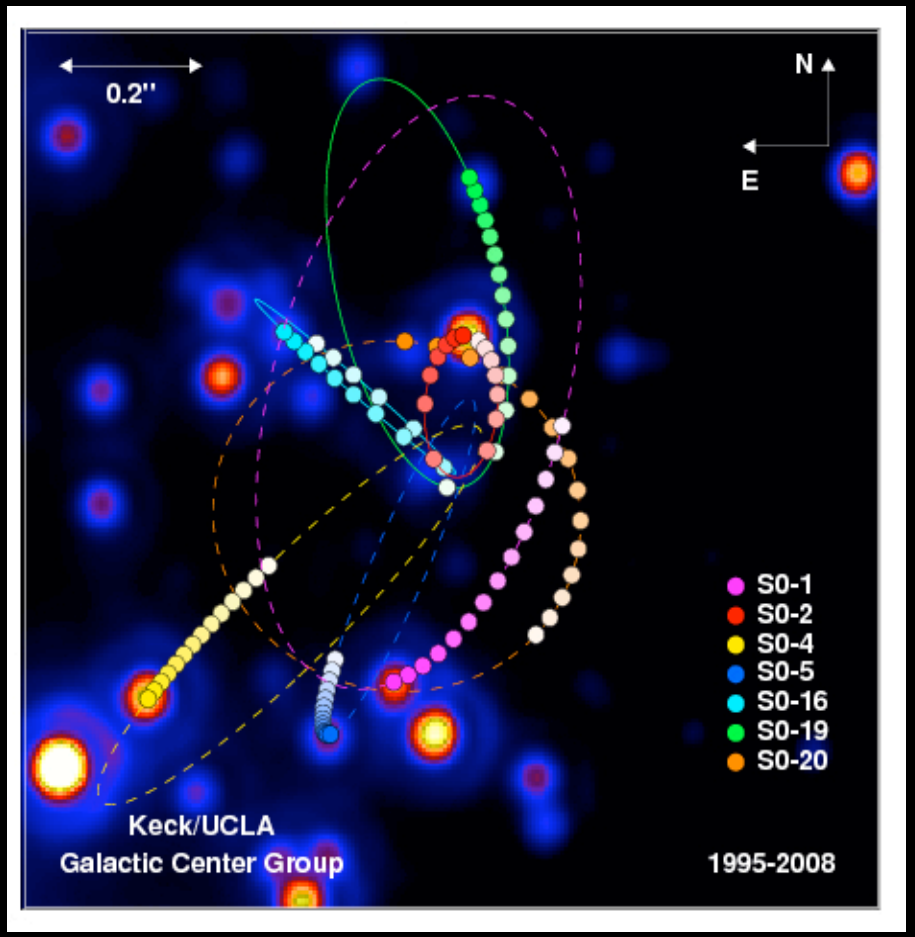


Standard Accretion Theory



Galactic Center Black Hole

- S2 orbit: $M_{BH} \approx 4x10^6\ M_{sun}$
- Proper motion: Sgr A* is $> 4x10^5\ M_{sun}$ (Reid & Brunthalter 2004)
- Fed by stellar winds ($dM/dt \sim 10^{-3}\ M_{sun}$ / yr)



Ghez et al., Genzel et al.

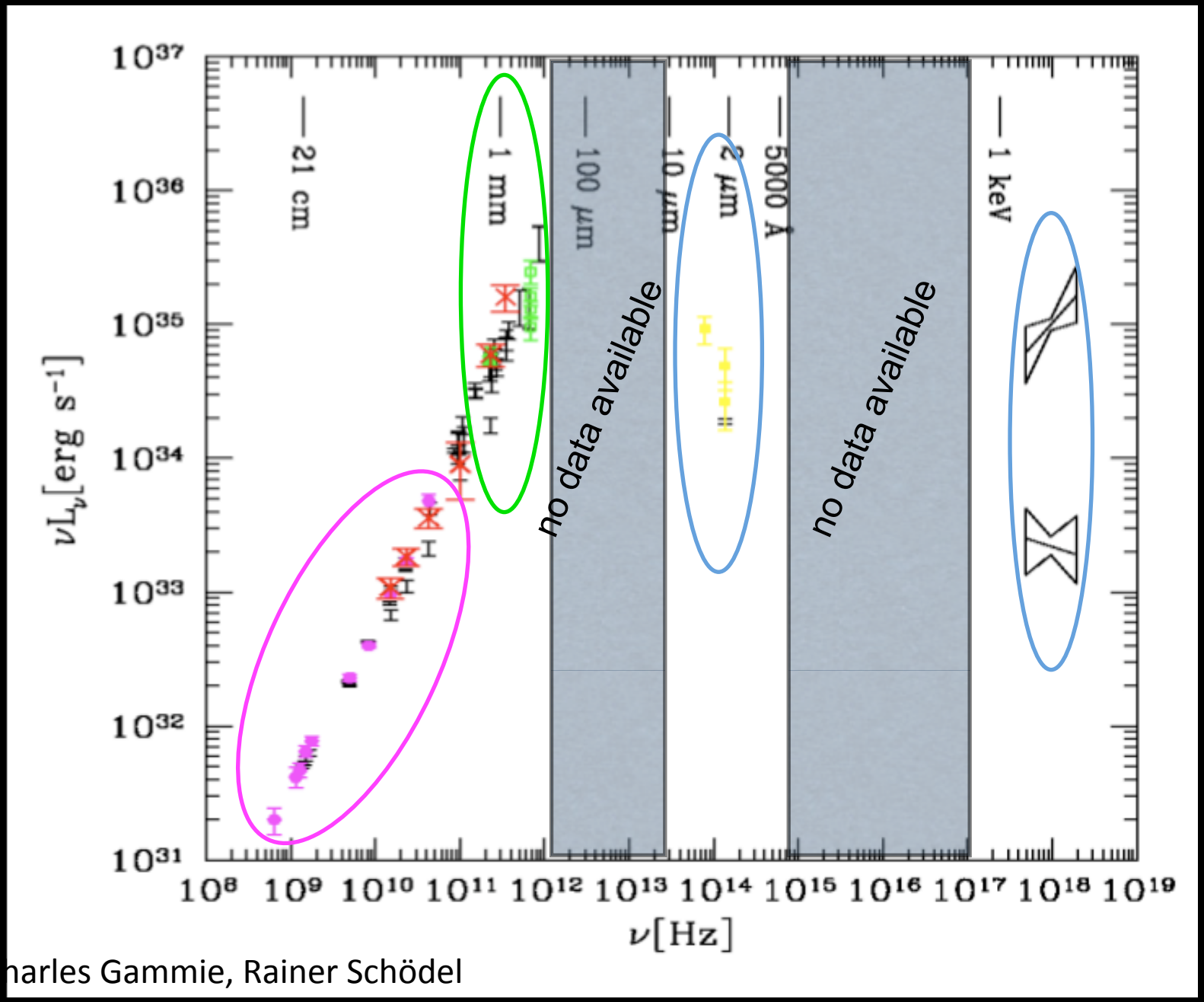
Sagittarius A* SED

Radio: Balick & Brown 1974

mm: Zylka & Mezger 1988

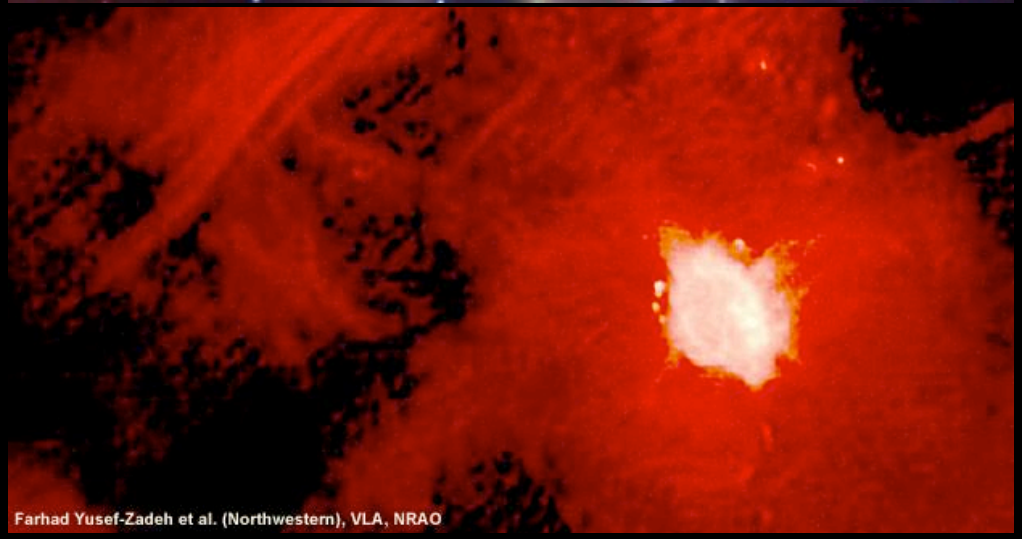
NIR: Genzel+2003; Ghez+2004

X-ray: Baganoff +2001,2003



harles Gammie, Rainer Schödel

Sgr A* Feeding



- L_X: T ≈ few keV, n ≈ 10^2 cm^{-3}

$$- \qquad \odot\ \mathrm{yr}^{-1}$$

- RM: (Marrone et al. 2007)

$$\dot{M} \simeq 10^{-9} r_{NR}^{7/6} M_\odot \mathrm{yr}^{-1}$$

- Most of the mass doesn't accrete!

Sgr A* Size & Polarization

- 230 GHz brightness temp:

$$T_b = \frac{c^2 I_\nu}{2k\nu^2}$$

$$\simeq 6 \times 10^{10}\,\mathrm{K}$$

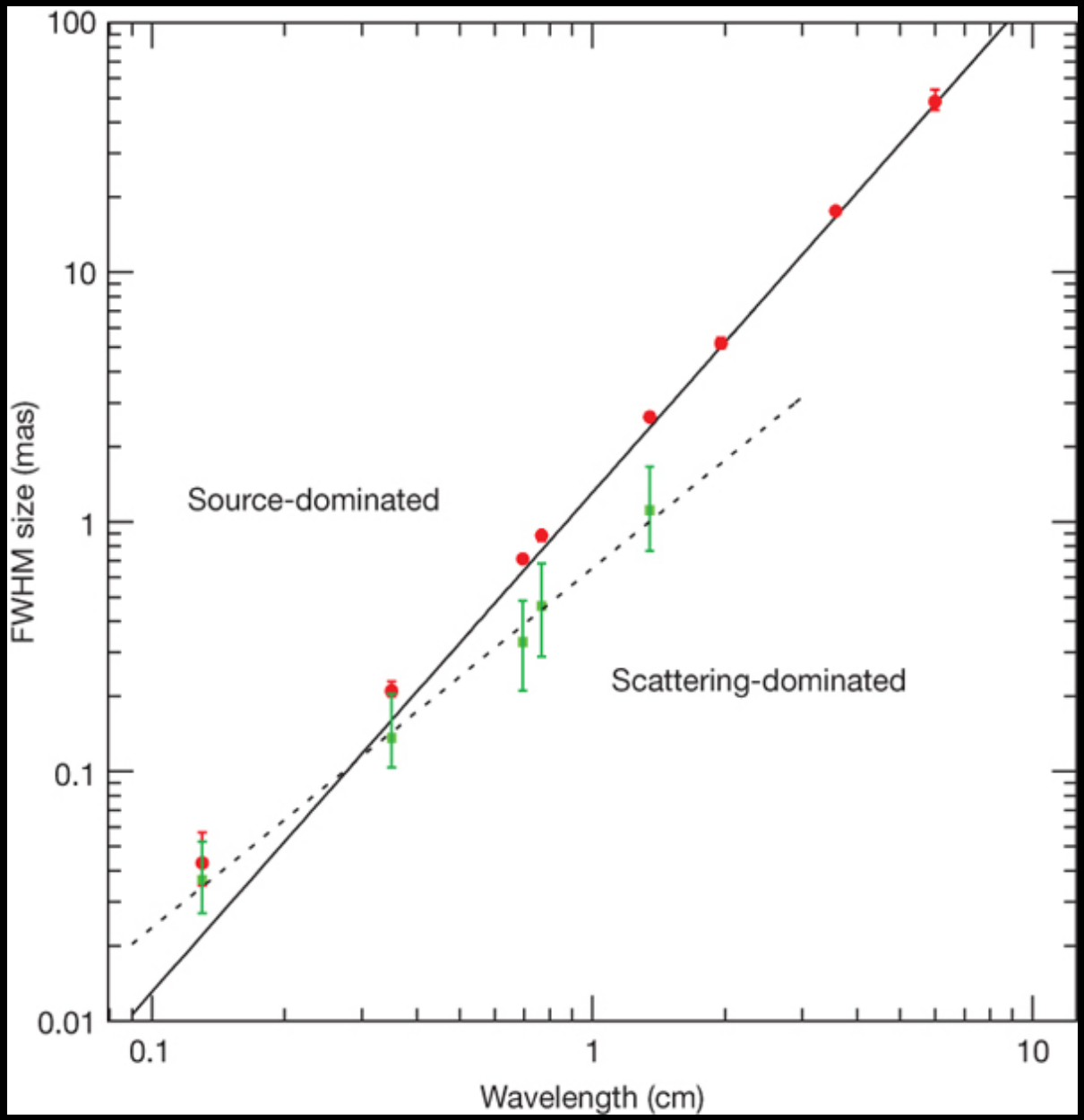
cf. $T_i \approx T_{vir} \approx 10^{12}$ K

- Pol: (Aitken et al. 2000)

$$\delta\theta \simeq 2 \times 10^{-9}\,\mathrm{nB} \lesssim \pi$$

$$n < 10^7 \beta^{1/3}\,\mathrm{cm}^{-3}$$

$$B < 300 \beta^{-1/2}\,\mathrm{G}$$

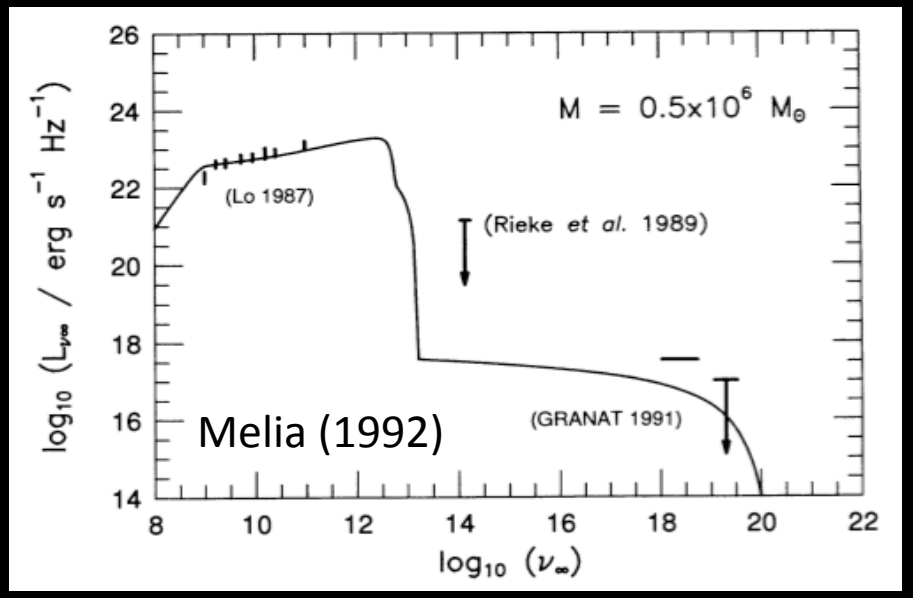


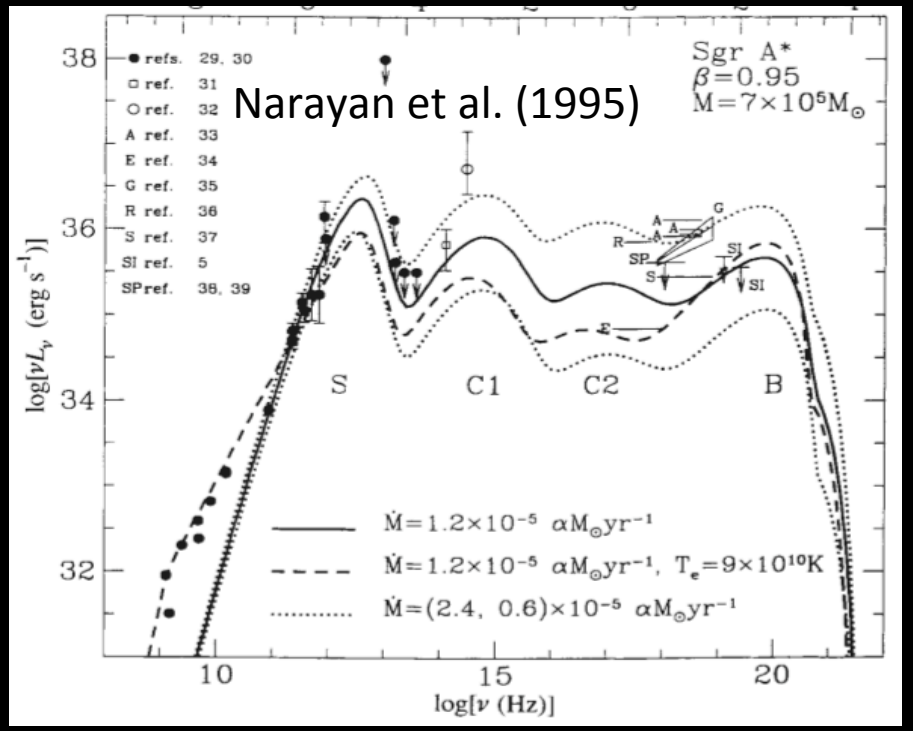
Doeleman et al. 2008

Accretion Flow Models of Sgr A*

- Thin disk:
  - ruled out by T_b, MIR upper limits

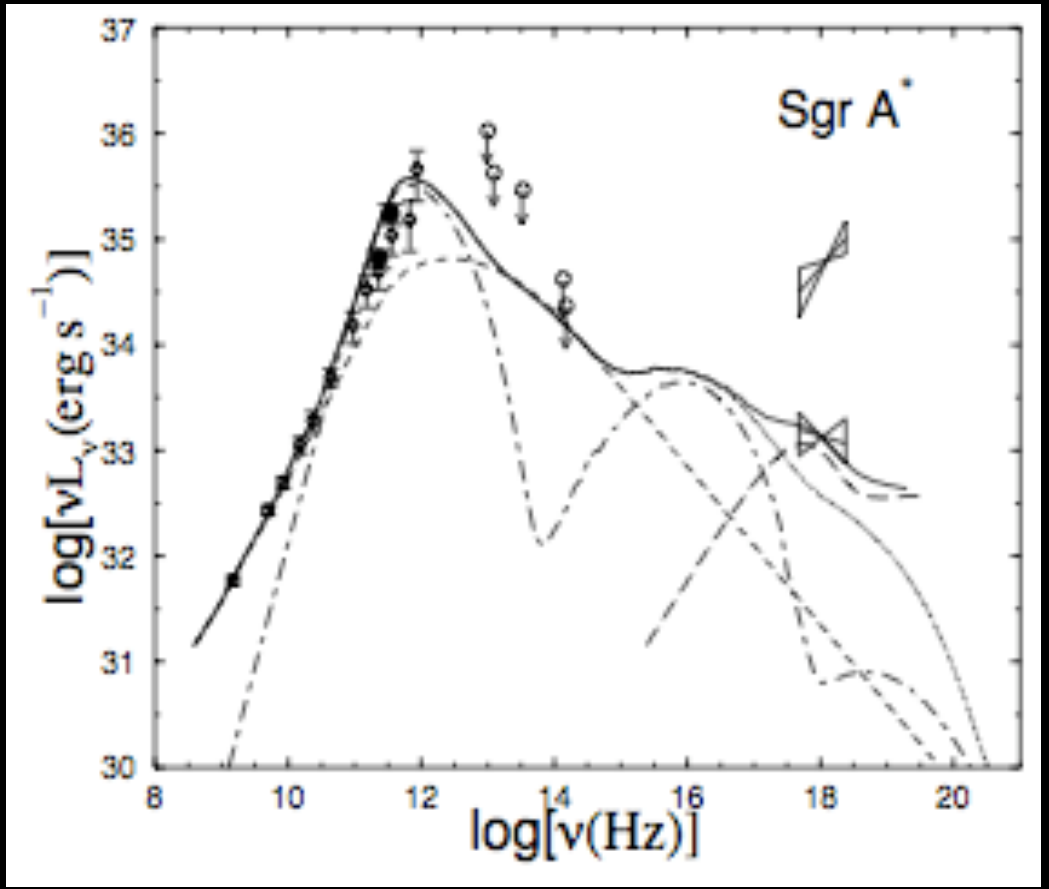
- Spherical accretion / ADAF (Melia 1992, Narayan+1995):
  - $dM/dt \approx dM/dt_{Bondi}$
  - ruled out by T_b, polarization, RM (Quataert & Gruzinov 2000, Agol 2000)





Accretion Flow Models of Sgr A*

- ADAF/CDAF/ADIOS/ … → RIAF!
  - Need significant mass loss for RM
  - Need non-thermal e- for polarization
- Also: Jet model (Falcke & Markoff 2000)



Yuan et al. (2003)

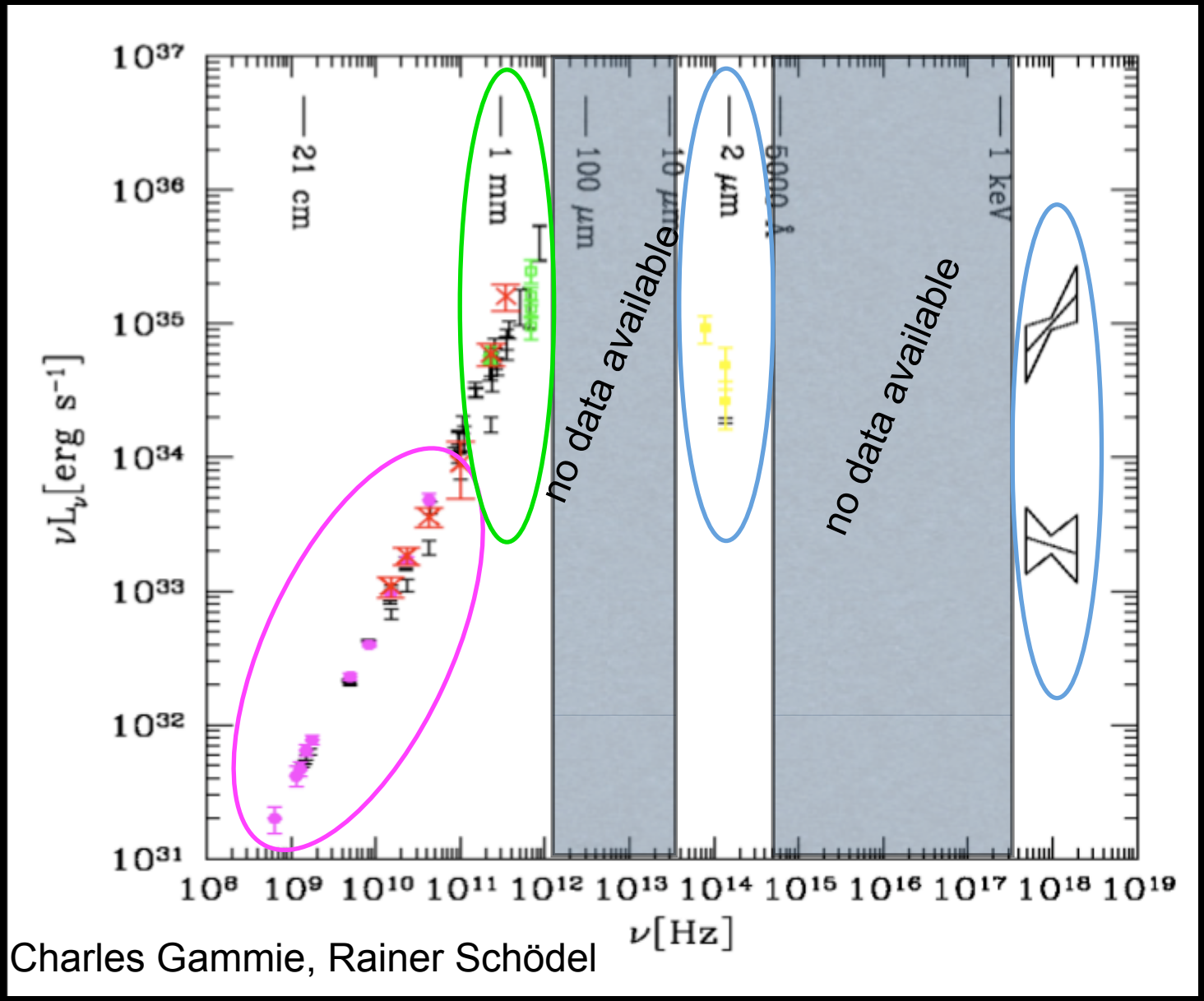
- Stationary, no outflows, no B, no GR

Sagittarius A* SED

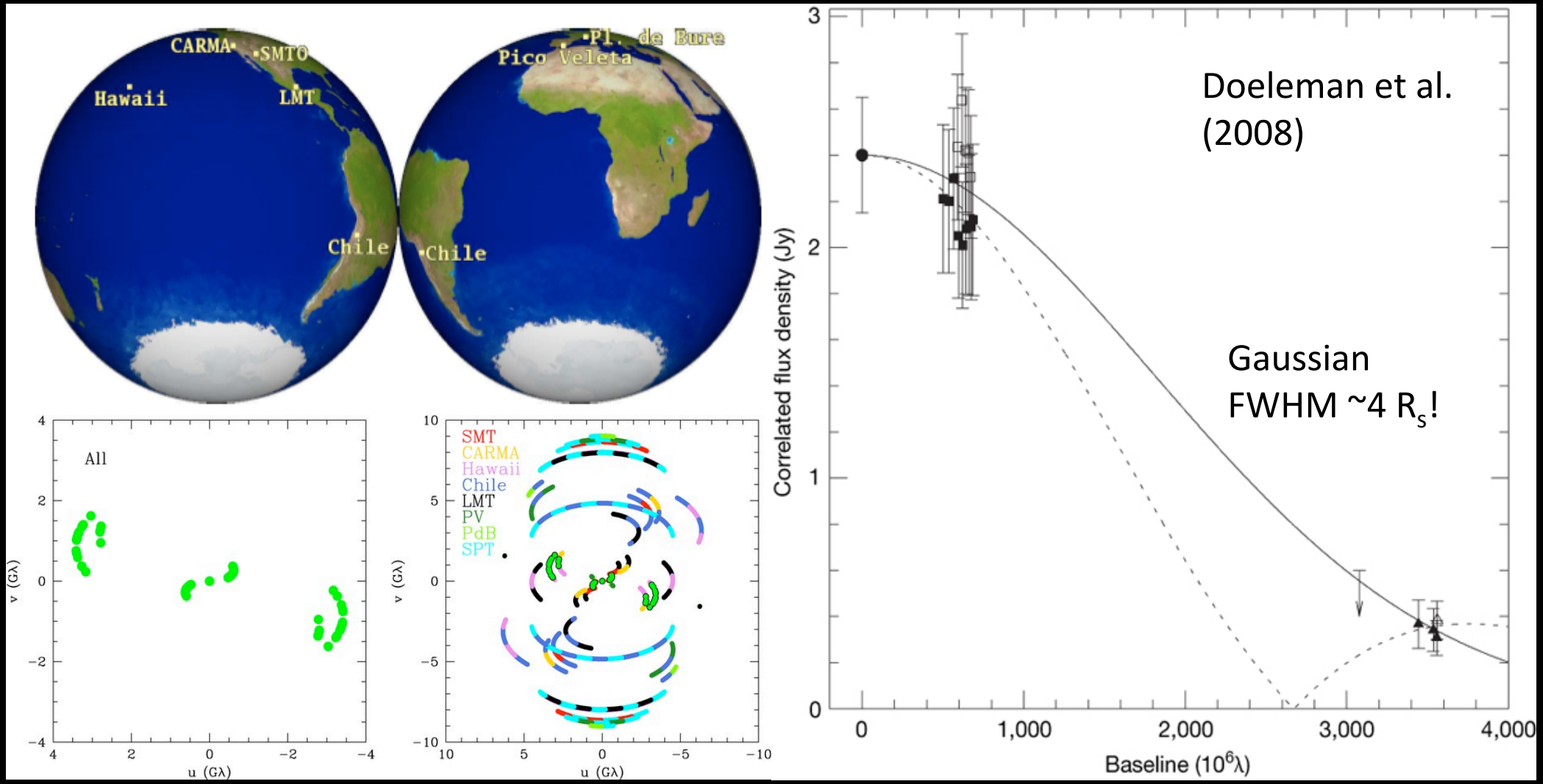
Non-thermal electrons far from BH

Thermal electrons at BH

Simultaneous IR/X-ray flares close to BH?



Millimeter VLBI of Sgr A*

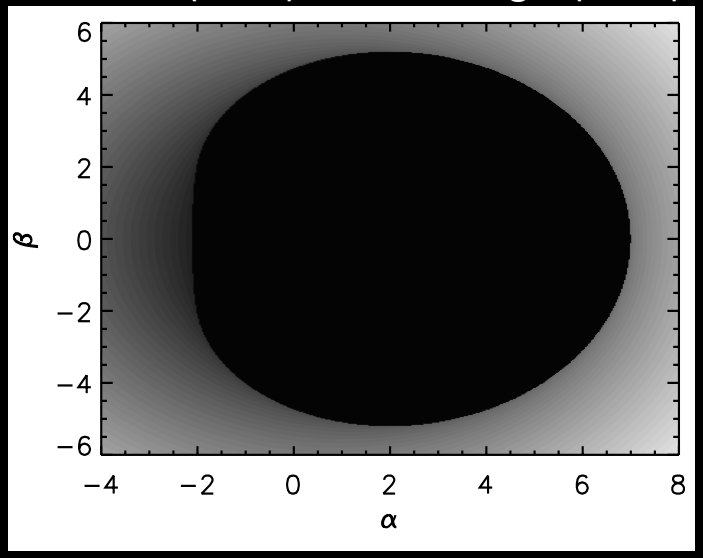


Doeleman et al. (2009), Broderick et al. (2011)

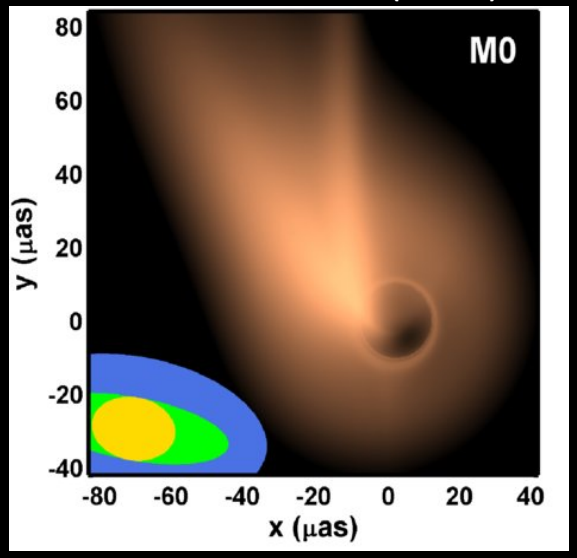
- Event Horizon Telescope (eventhorizontelescope.org, arXiv: 0906.3899)

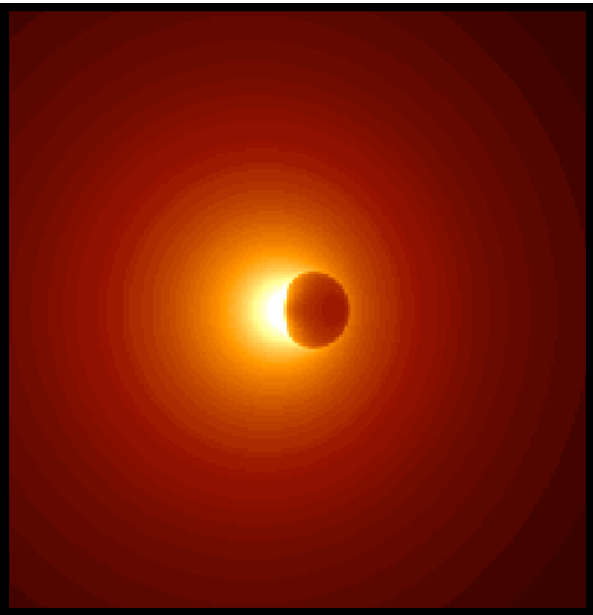
Black Hole Images & Shadows

Bardeen (1973); Dexter & Agol (2009)

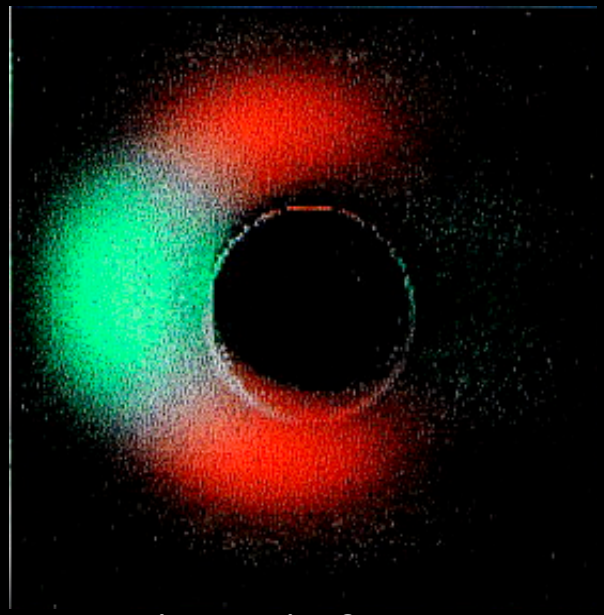


Broderick & Loeb (2009)





Falcke, Melia & Agol (2000)

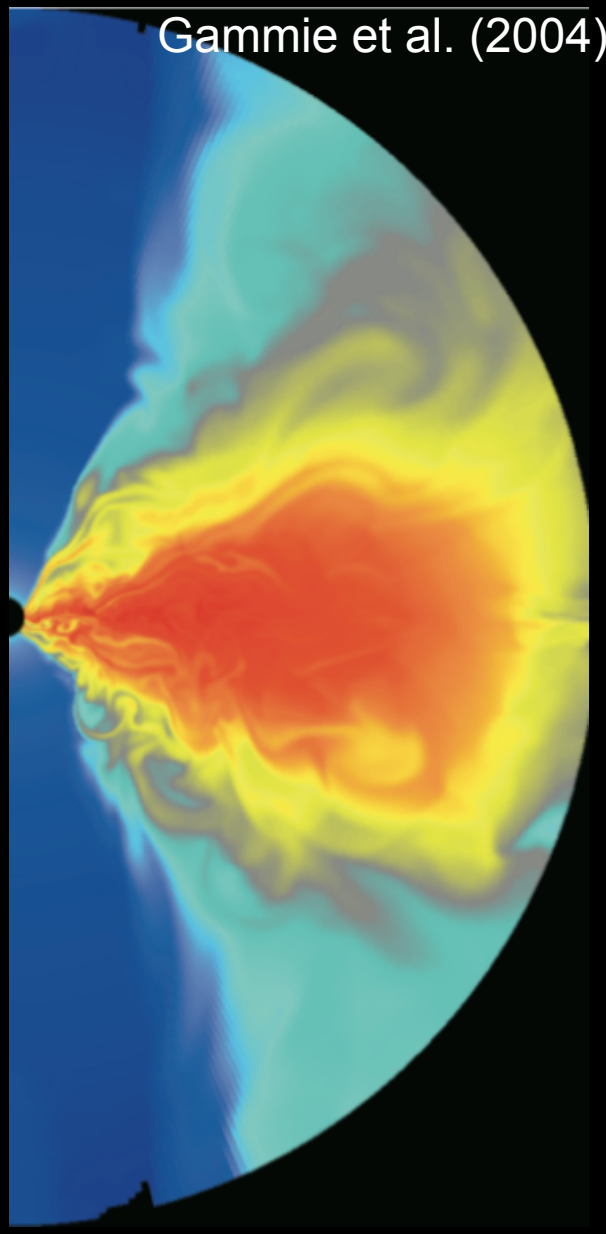


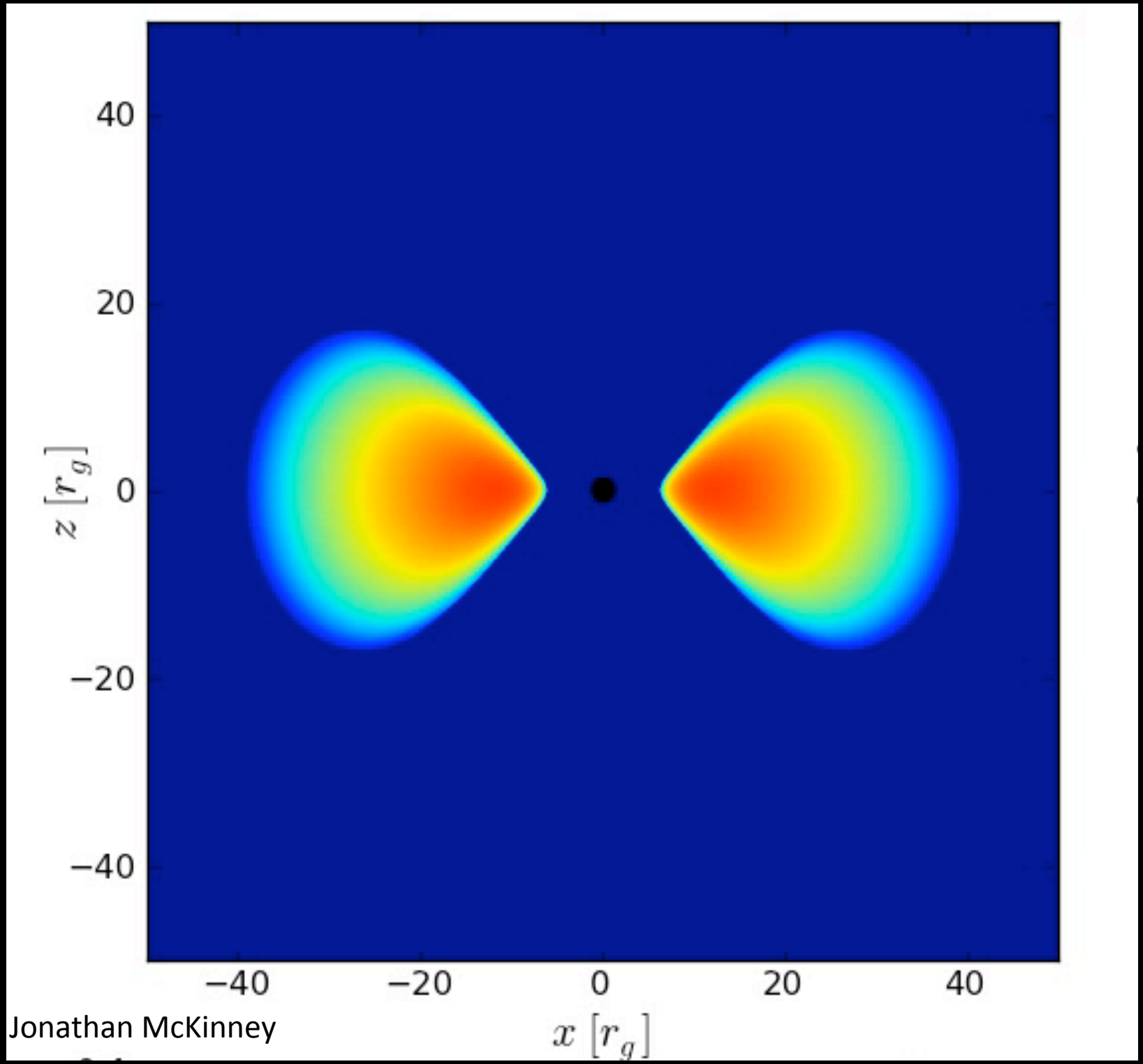
Bromley, Melia & Liu (2001)

- Sensitive to viewing geometry & details of emission region
  - Need accurate theoretical predictions!

GRMHD Simulations

- Ideal theoretical model:
  - Time-dependent (variability / flares)
  - Relativistic (images / BH shadow)
  - Magnetic fields (accretion / synchrotron)
- GRMHD simulations
  - Physical accretion theory
  - Time-dependent, fully relativistic
  - Limitations:
    - Numerical & difficult
    - Radiation & thermodynamics
    - Dynamic range & duration
    - Initial conditions



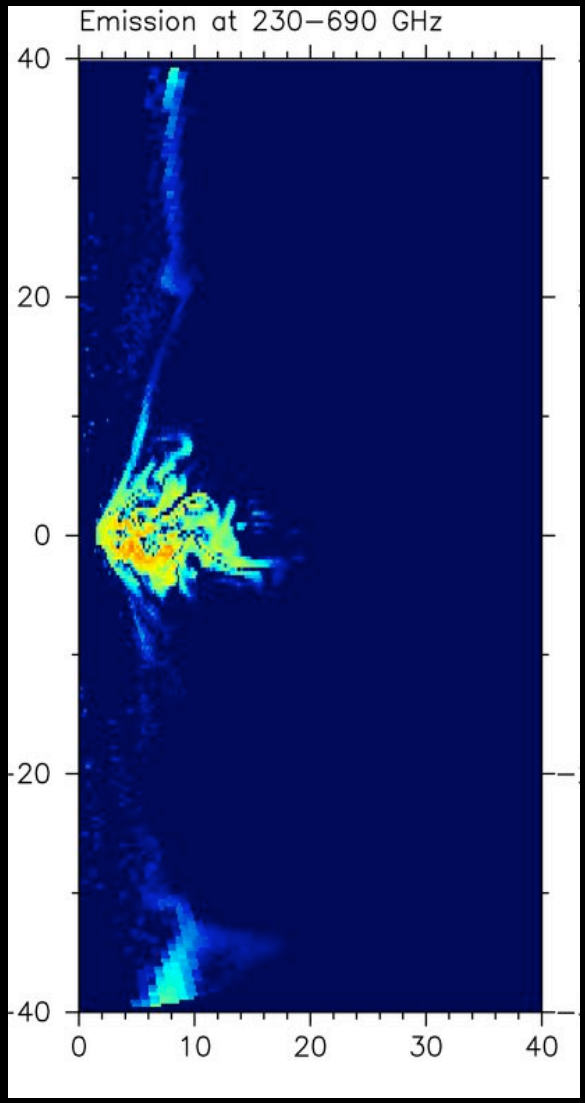


Jonathan McKinney

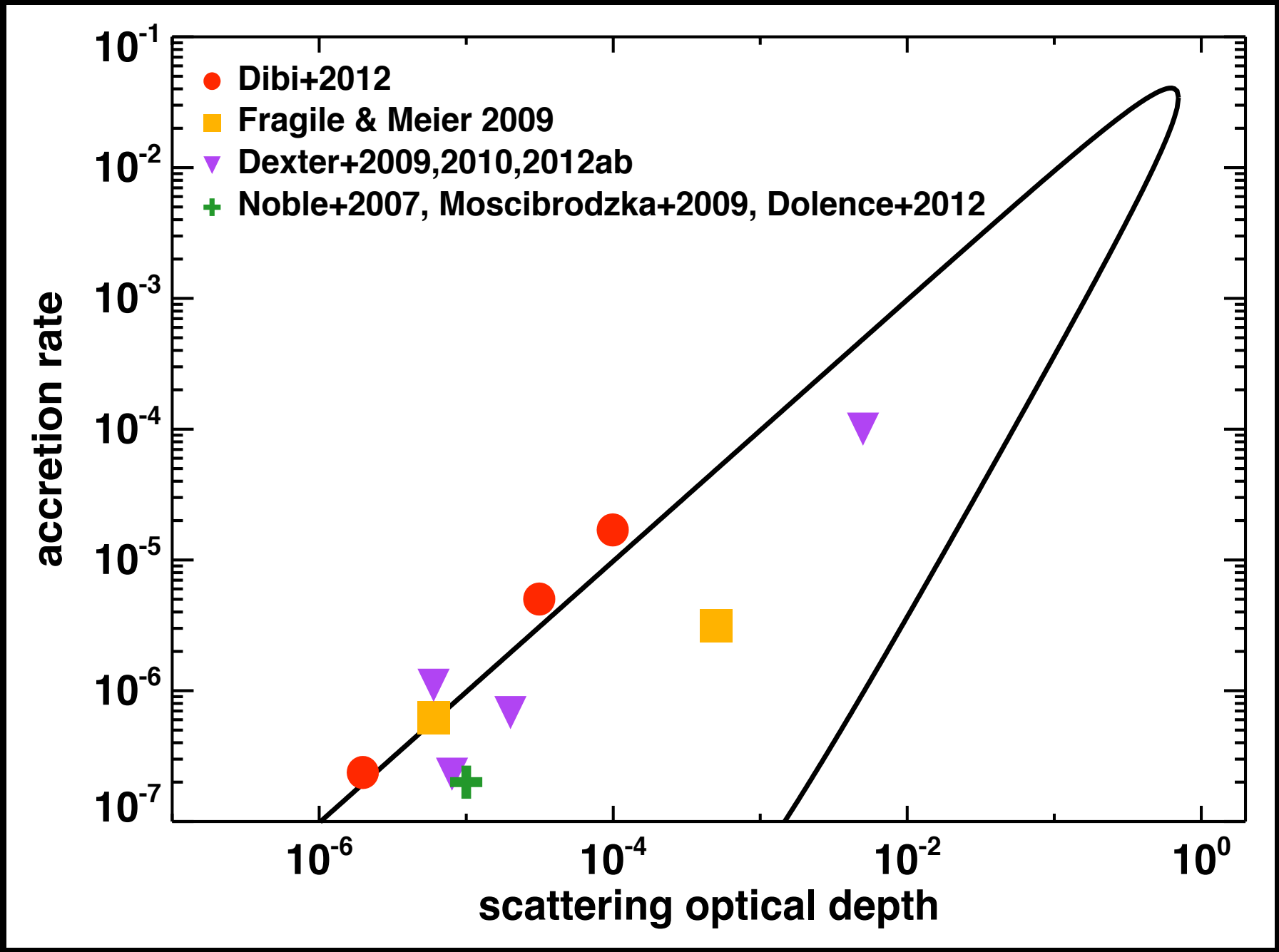
GRMHD Models of Sgr A*

- GRMHD great for Sgr A*
  - Insignificant cooling (Dibi+2012)
  - Synchrotron radiation near BH
- Not perfect…
  - Collisionless plasma (mfp = 10^4 R_s)
  - No electrons
- Add radiation:
  - Scale dM/dt, constant T_i/T_e
  - Observables from ray tracing (Dexter & Agol 2009, Dexter 2011)

Moscibrodzka et al. (2009)

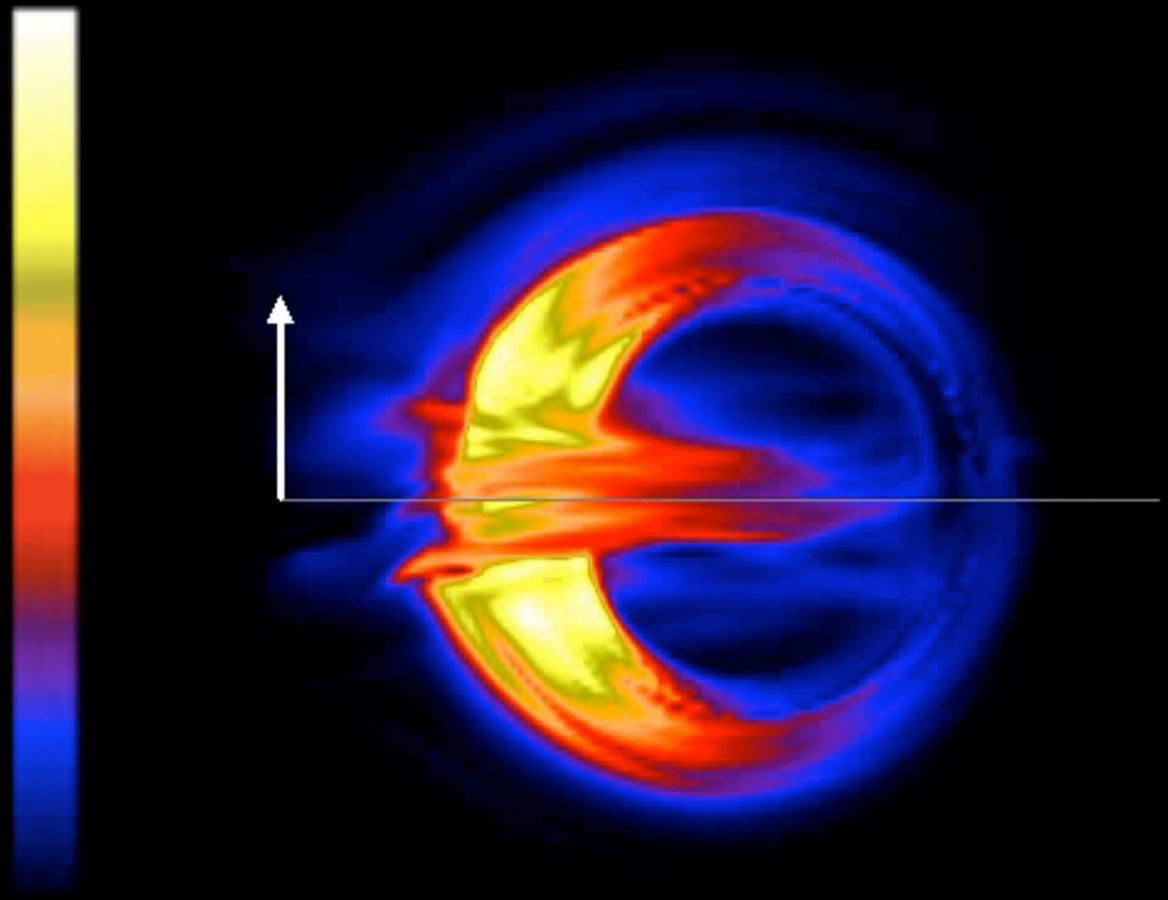


Applied Black Hole GRMHD



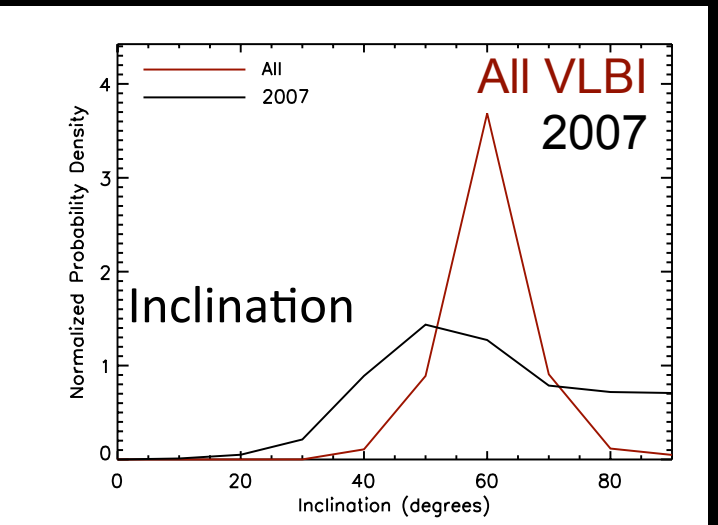
Sagittarius A* Disk Images

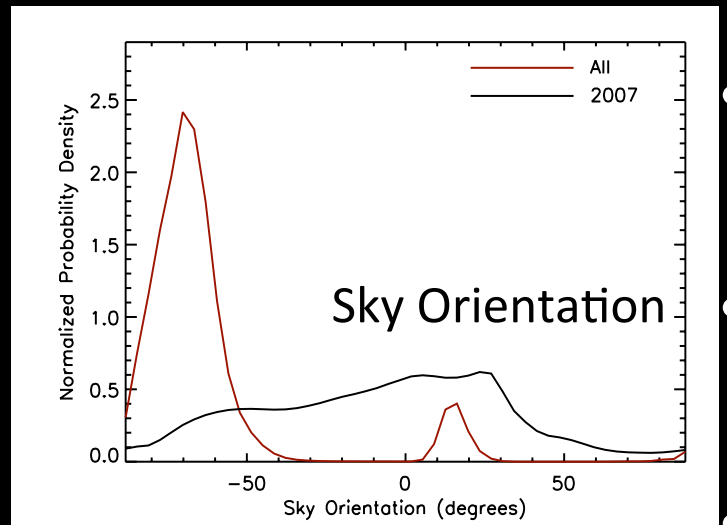
100x100 μas

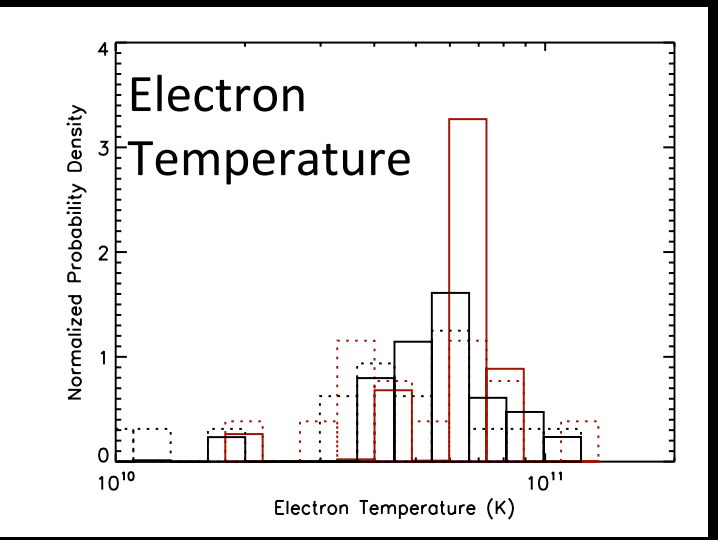


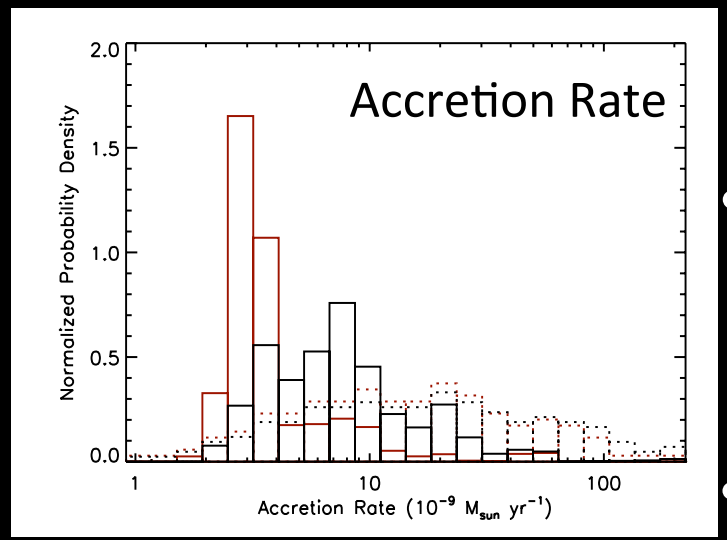
Dexter et al. (2009, 2010)

Parameter Estimates





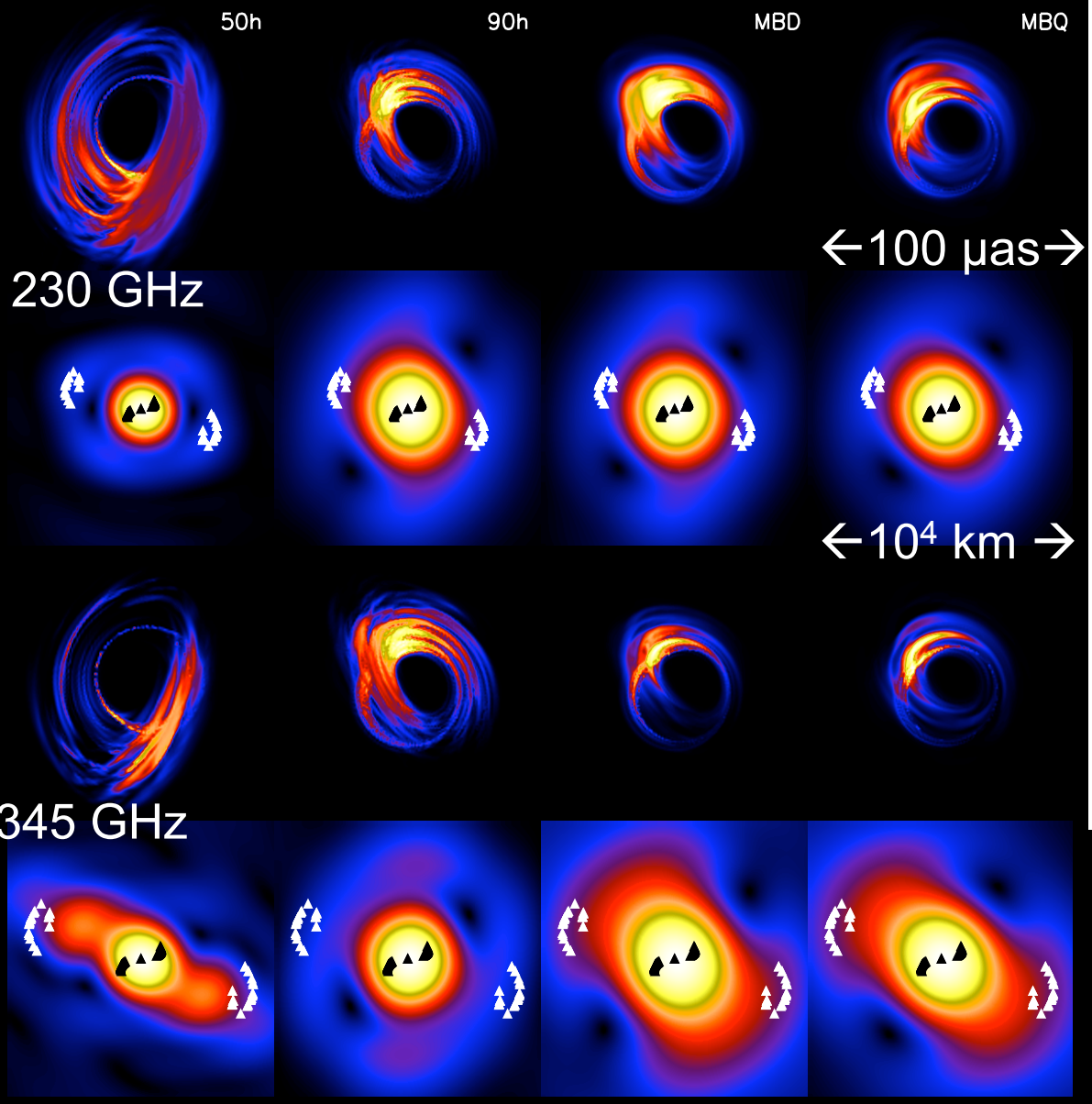


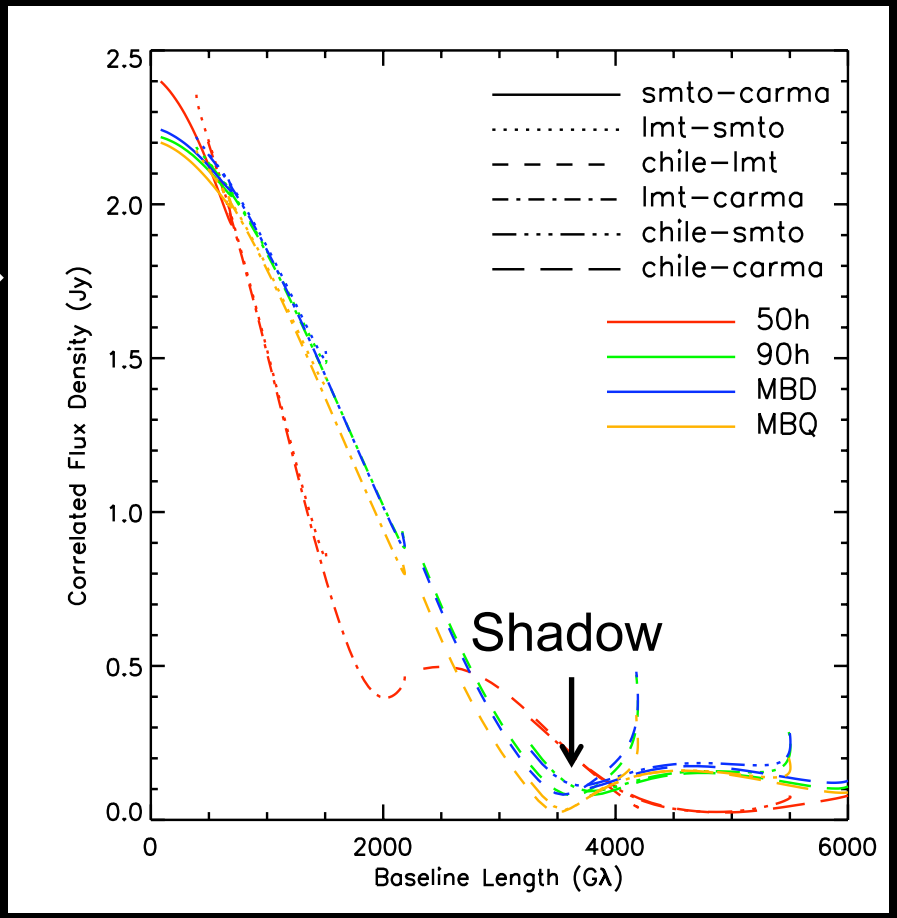


- $i = 60^{+15}_{-15}$ degrees
- $\xi = -70^{+86}_{-15}$ degrees
- $T_e / 10^{10}$ K = 6 ± 2
- $dM/dt = 3^{+7}_{-1} \times 10^{-9}$ M_{sun} yr^{-1}
- All to 90% confidence

Dexter et al. (2010)

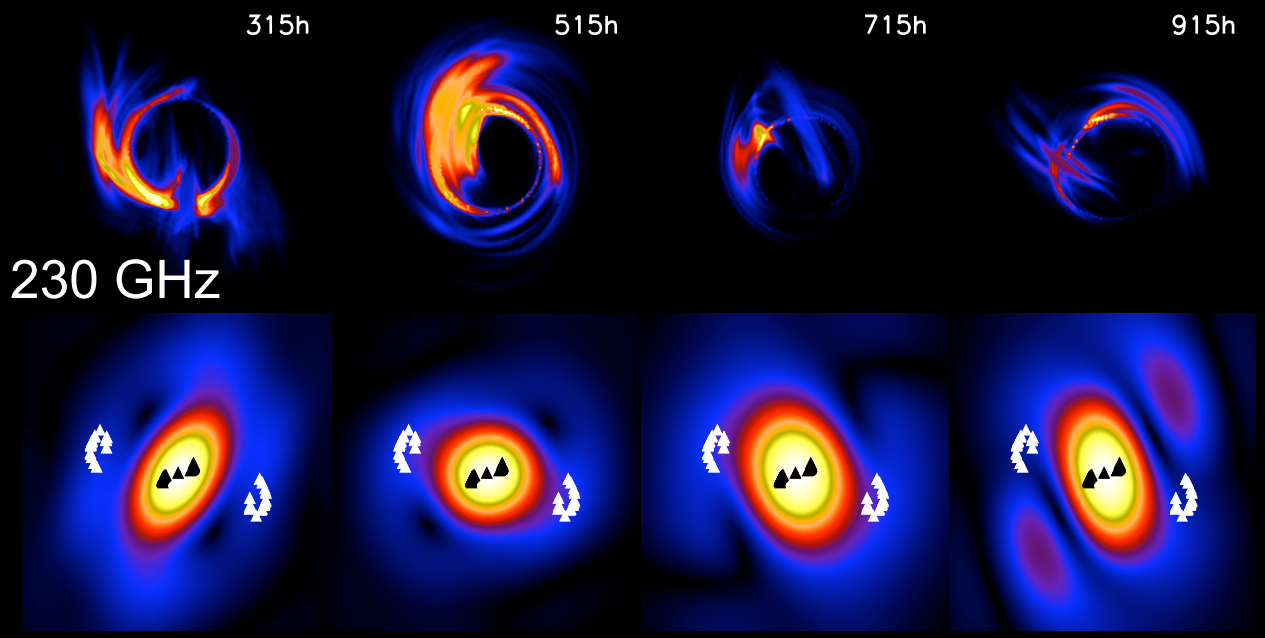
Black Hole Shadow

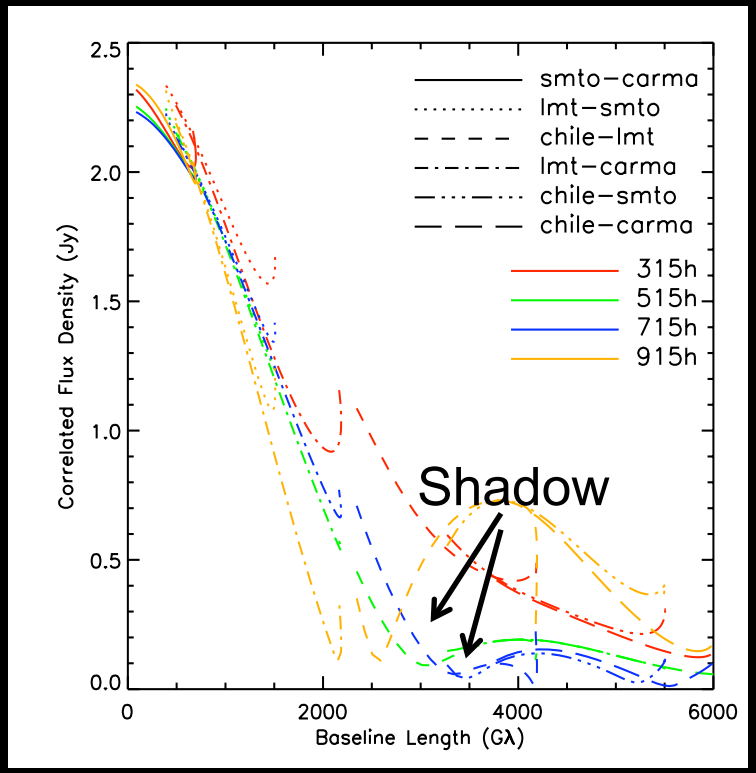




Shadow may be detected on Chile-Mexico baseline (in closure phase too)

But Disk Is Likely Tilted…

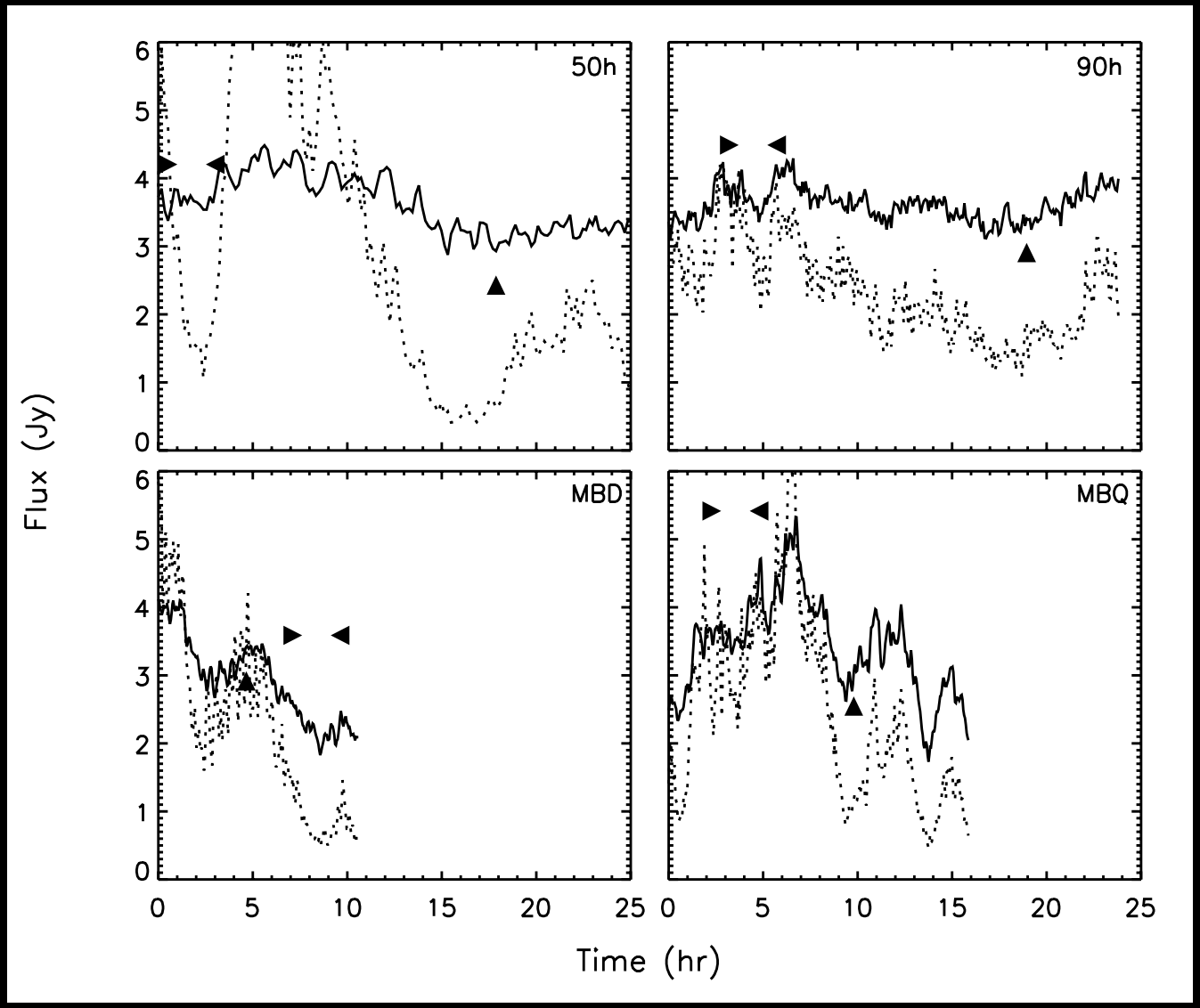




Dexter & Fragile (2012)

- Drastic changes to dynamics! (Fragile et al. 2007-2009, Dexter & Fragile 2011)
- Unconstrained parameters
- Best fit images are still crescents, shadow still visible

Millimeter Variability

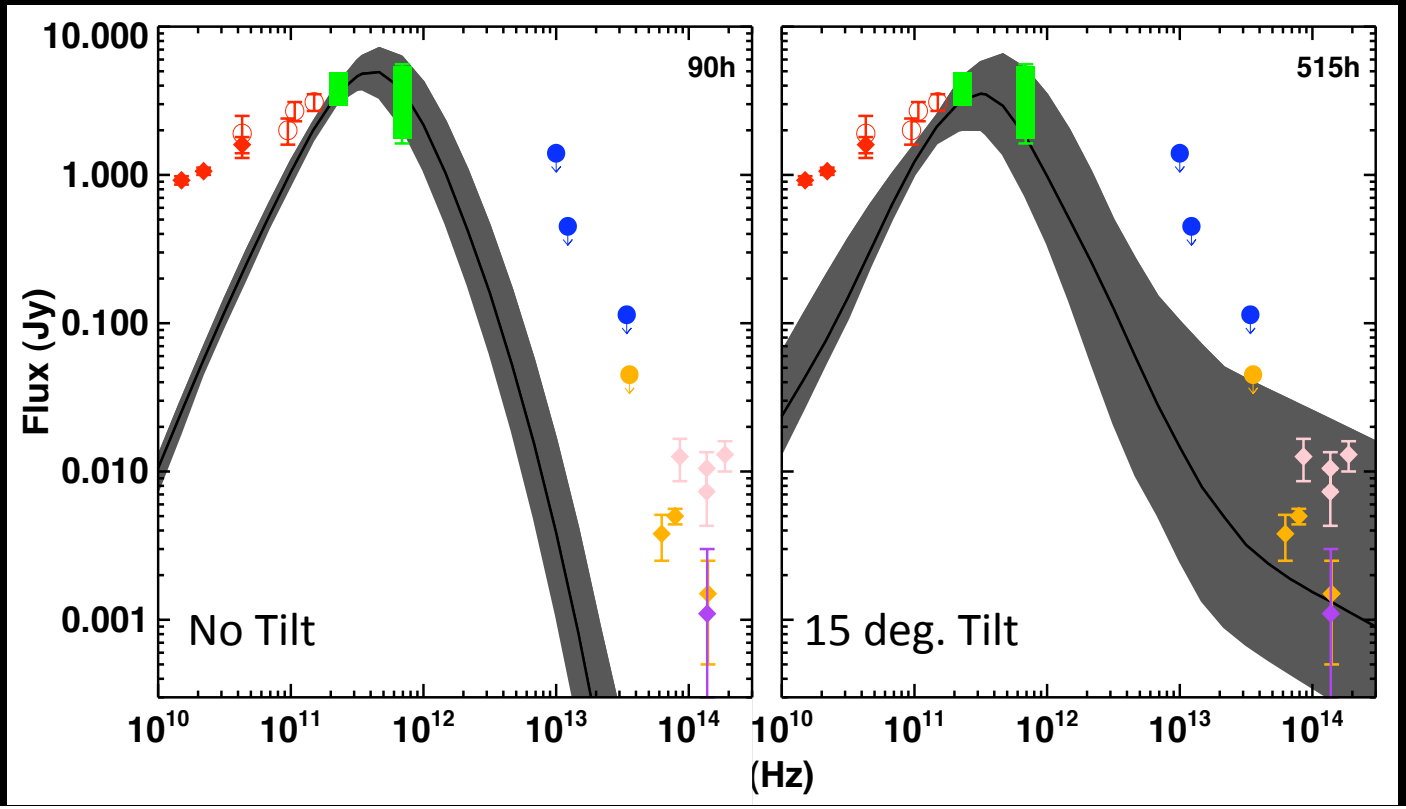


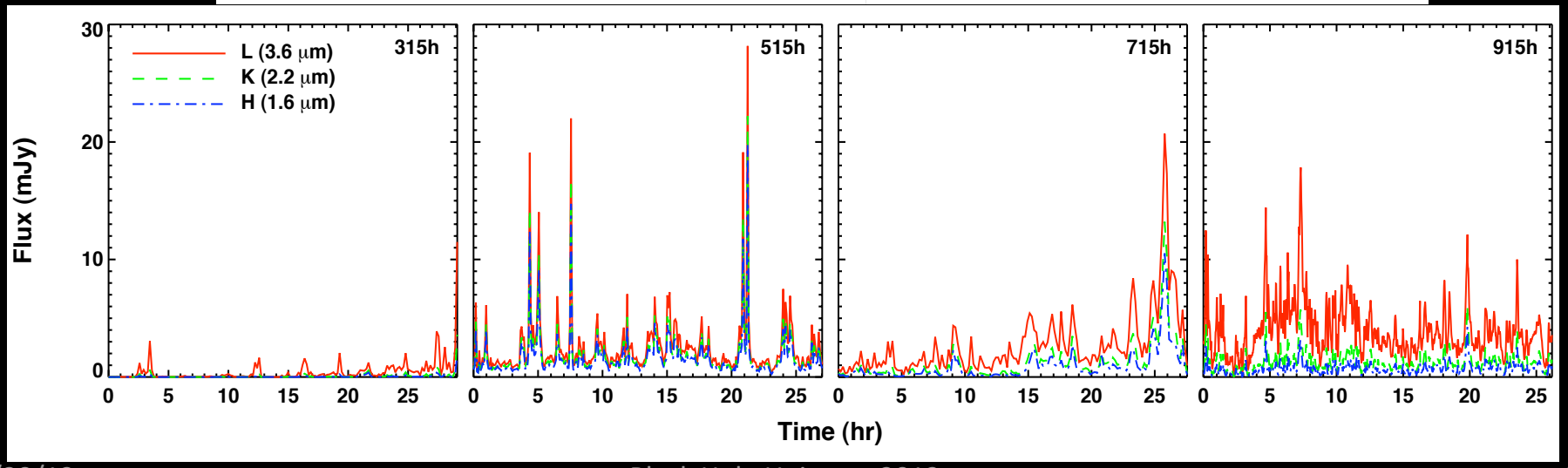
Solid – 230 GHz (1.3mm) Dotted – 690 GHz (0.4mm)

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

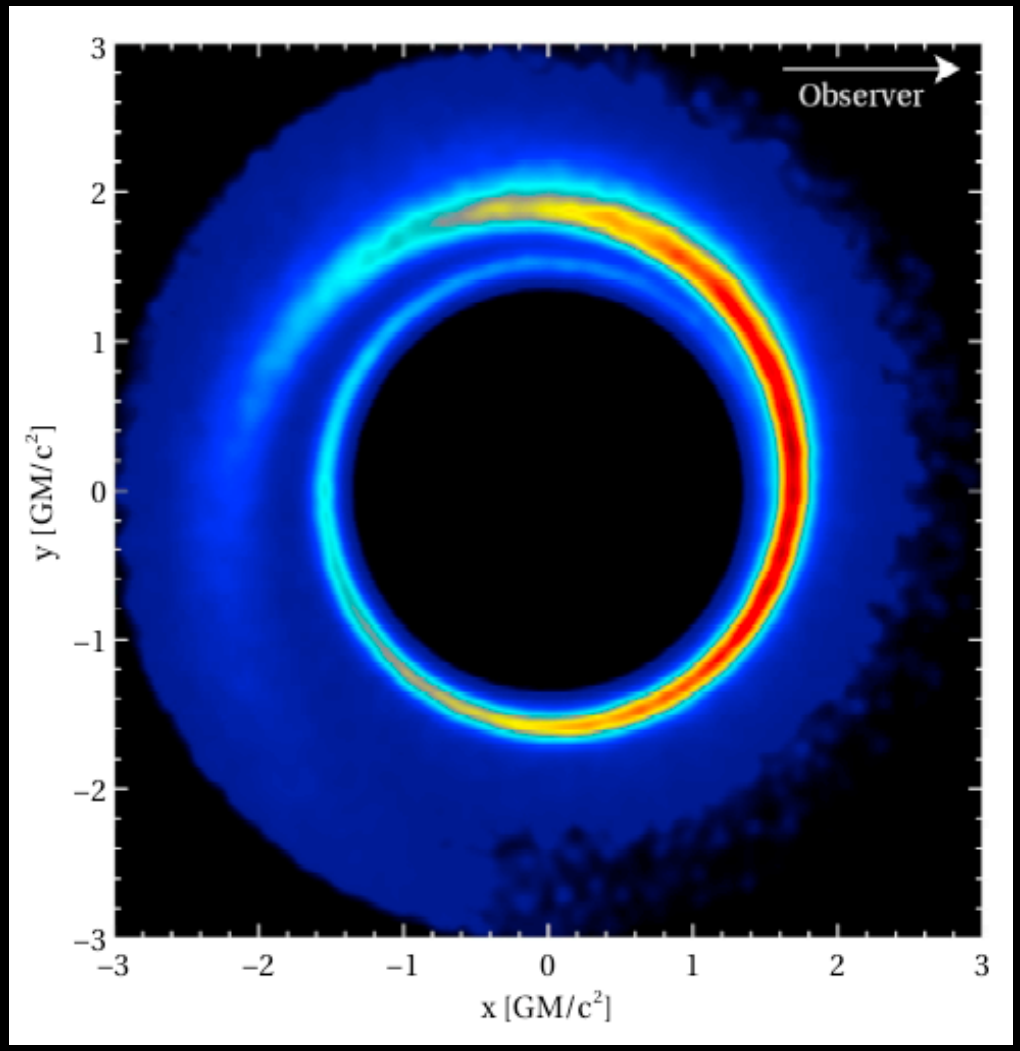
NIR Flares in Tilted Disks

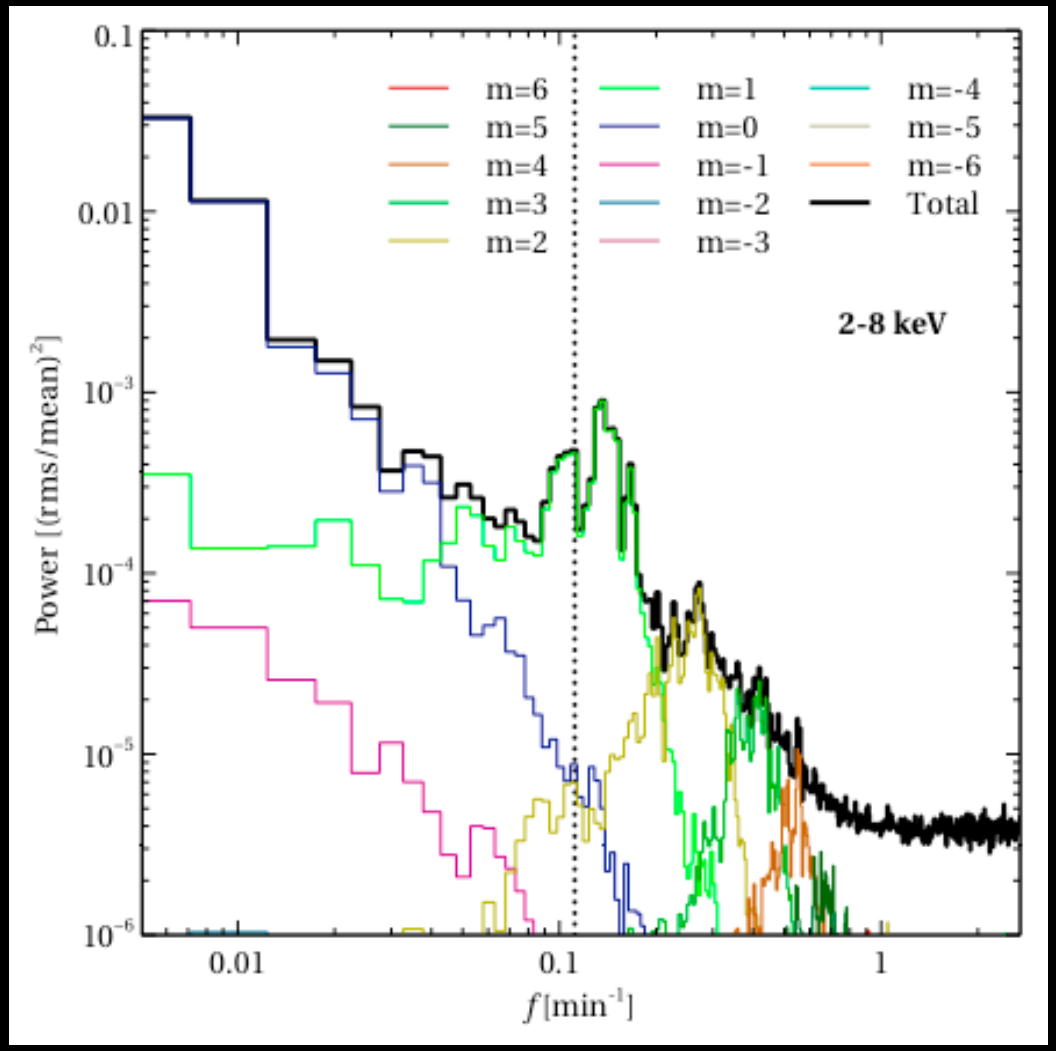
Dexter & Fragile (2012)





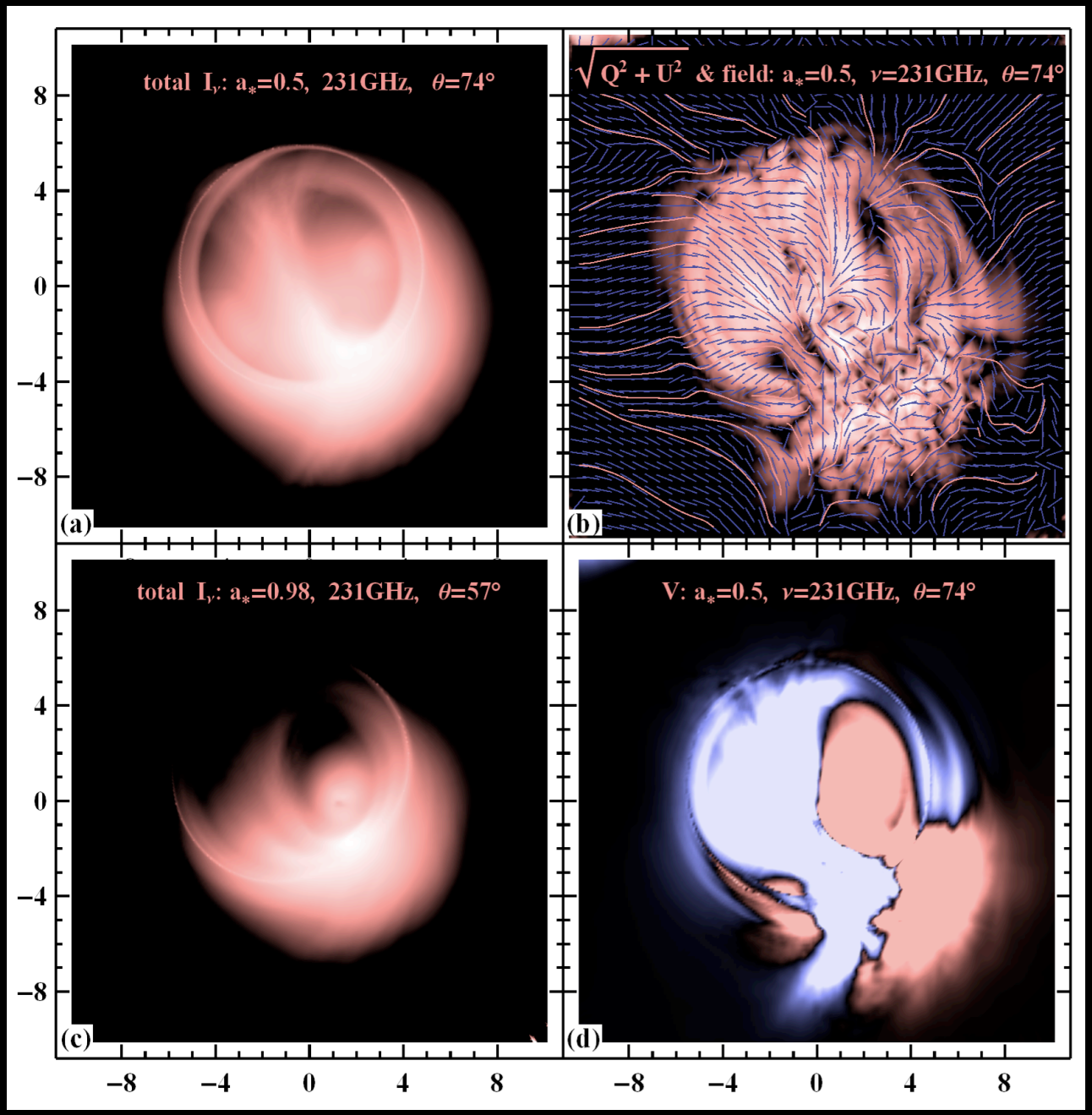
IR/X-ray QPOs





Dolence et al. (2012)

Polarization

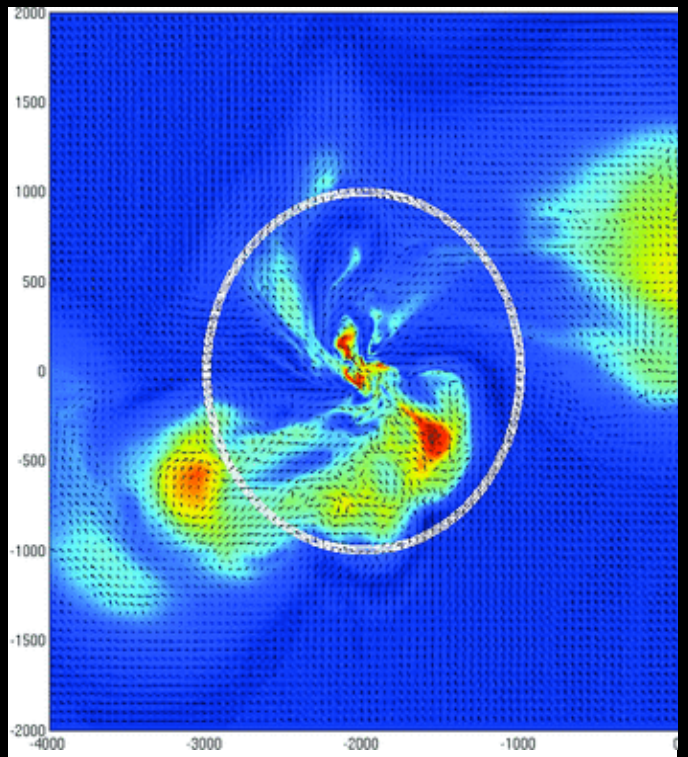


Shcherbakov et al. (2012)

Open Theoretical Questions

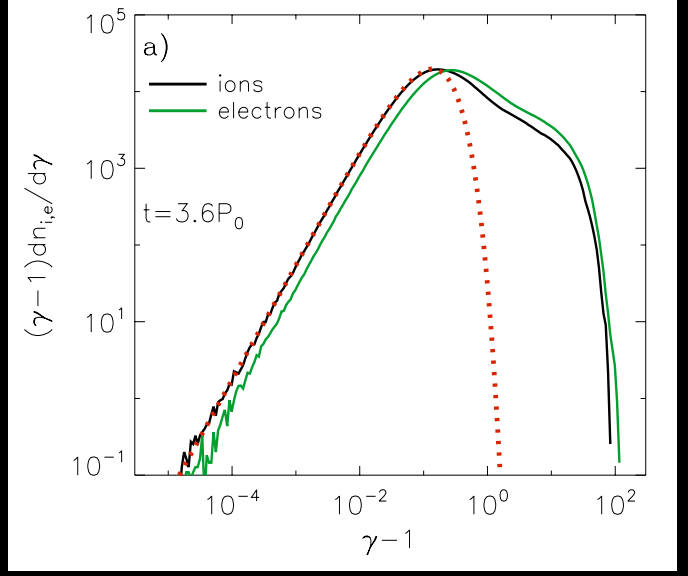
- Initial conditions at r ≈ 100 M
  - Tilt? H/R?
  - Magnetic flux? (Jon's talk)
  - Circularization radius?

Pang et al. (2011)

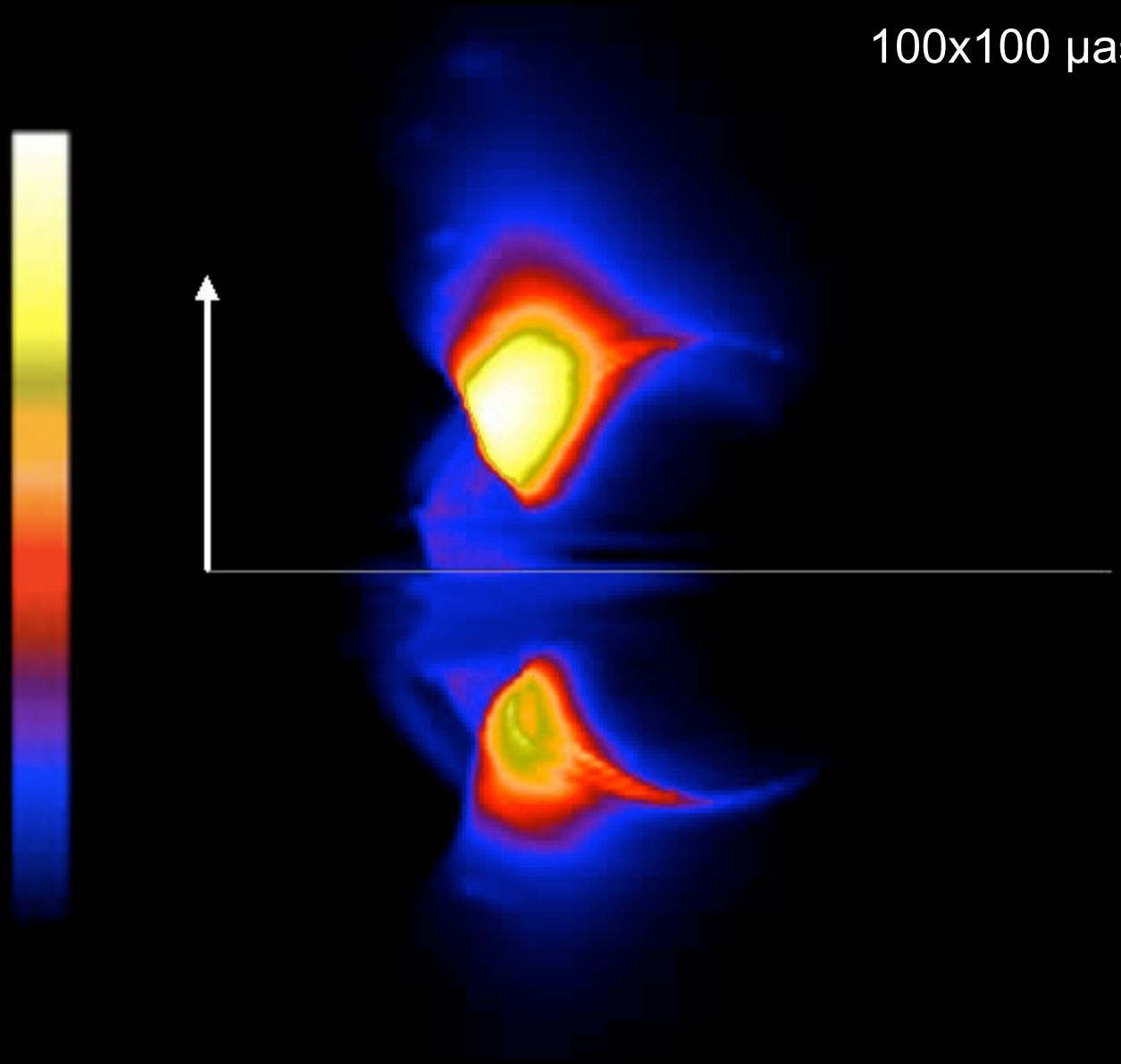


- Electron distribution function
  - Thermal with T_i/T_e (**x**)?
  - Power law tail?

Riquelme et al. (2012)

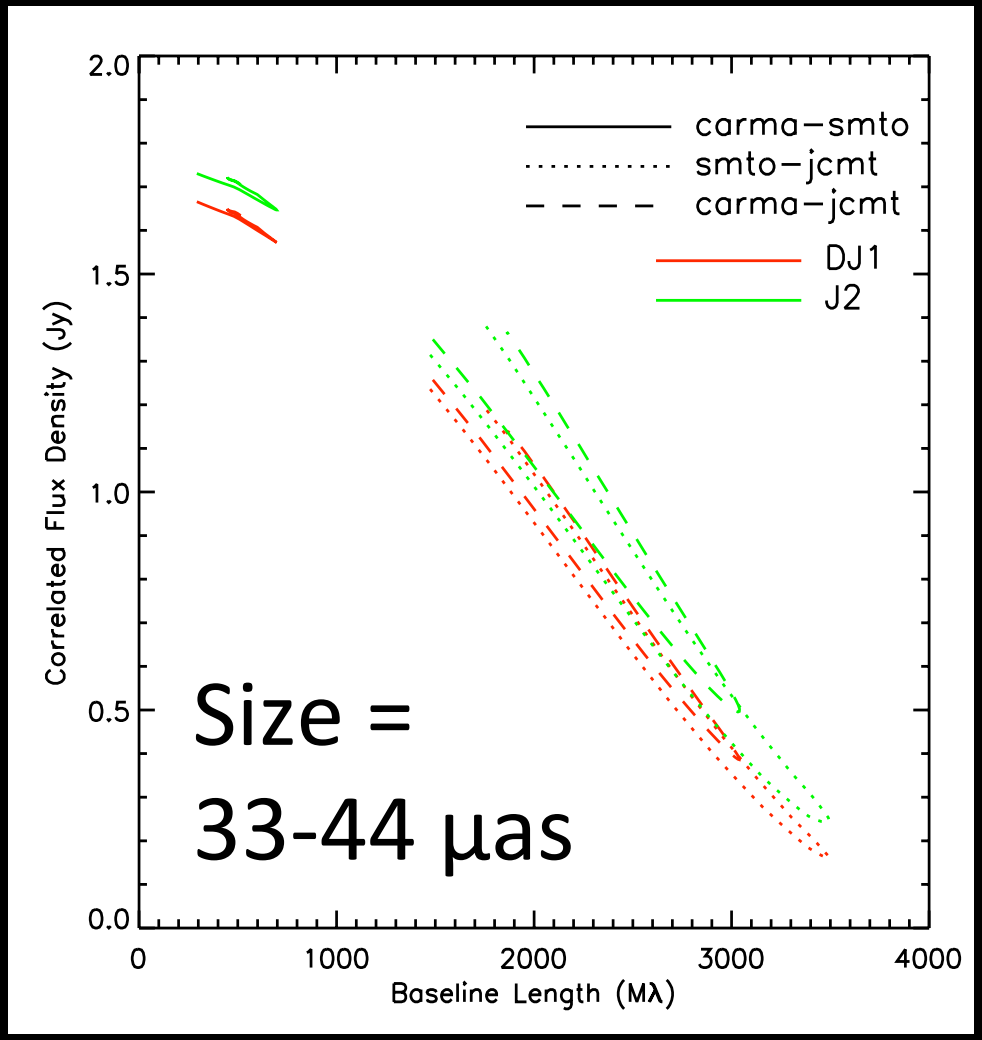


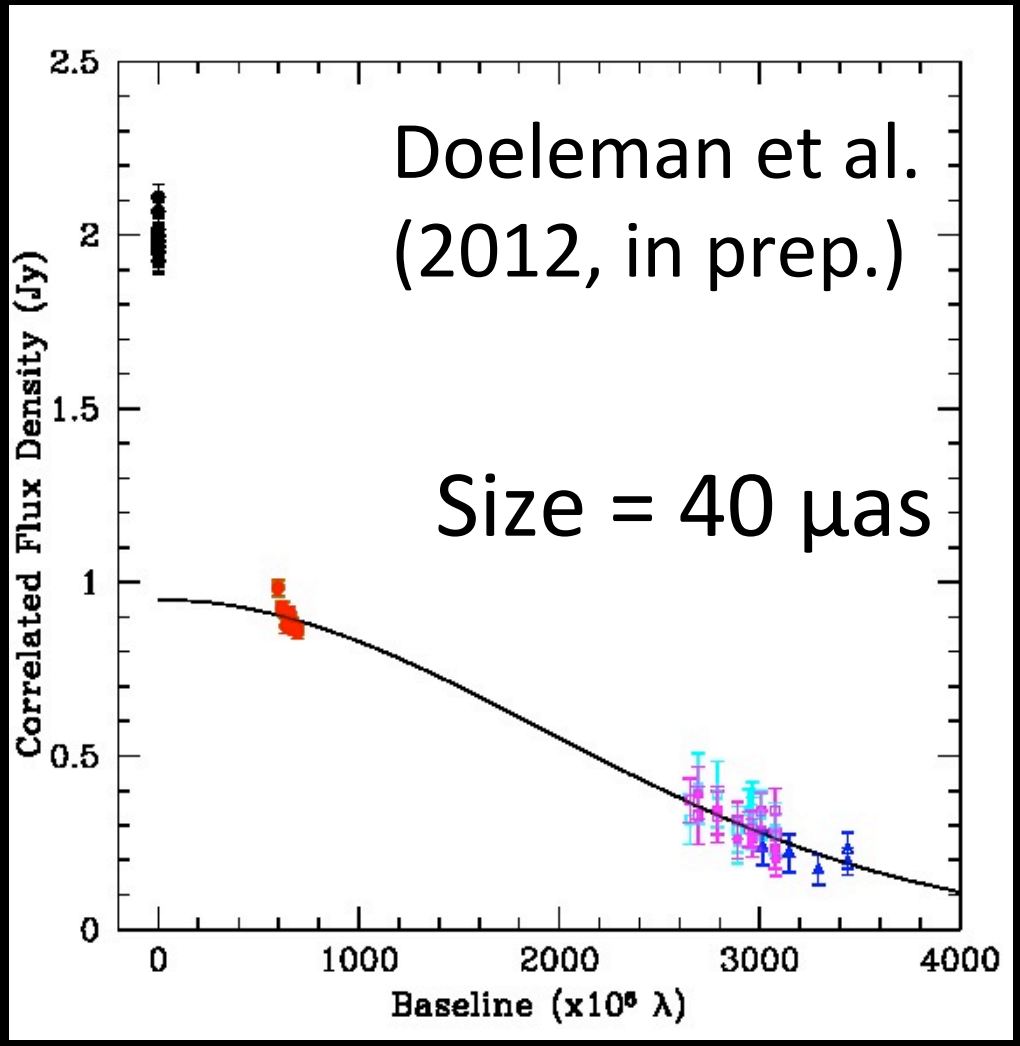
M87 Jet Images



Dexter, McKinney, Agol (2012)

The size of M87





Summary

- Sgr A* excellent lab for testing contemporary accretion theory
- GRMHD simulations provide good description of event-horizon-scale & time-domain observations
- Near future extremely promising (EHT, GRAVITY, Chandra XVP)

Gas Cloud

Gillessen et al. (2012)

- Arrives 2013!
- Accretion rate increase?
- X-rays from 1000 M?