NUMERICAL MODELS OF BLACK HOLE ACCRETION FLOWS

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with

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CCP 2006

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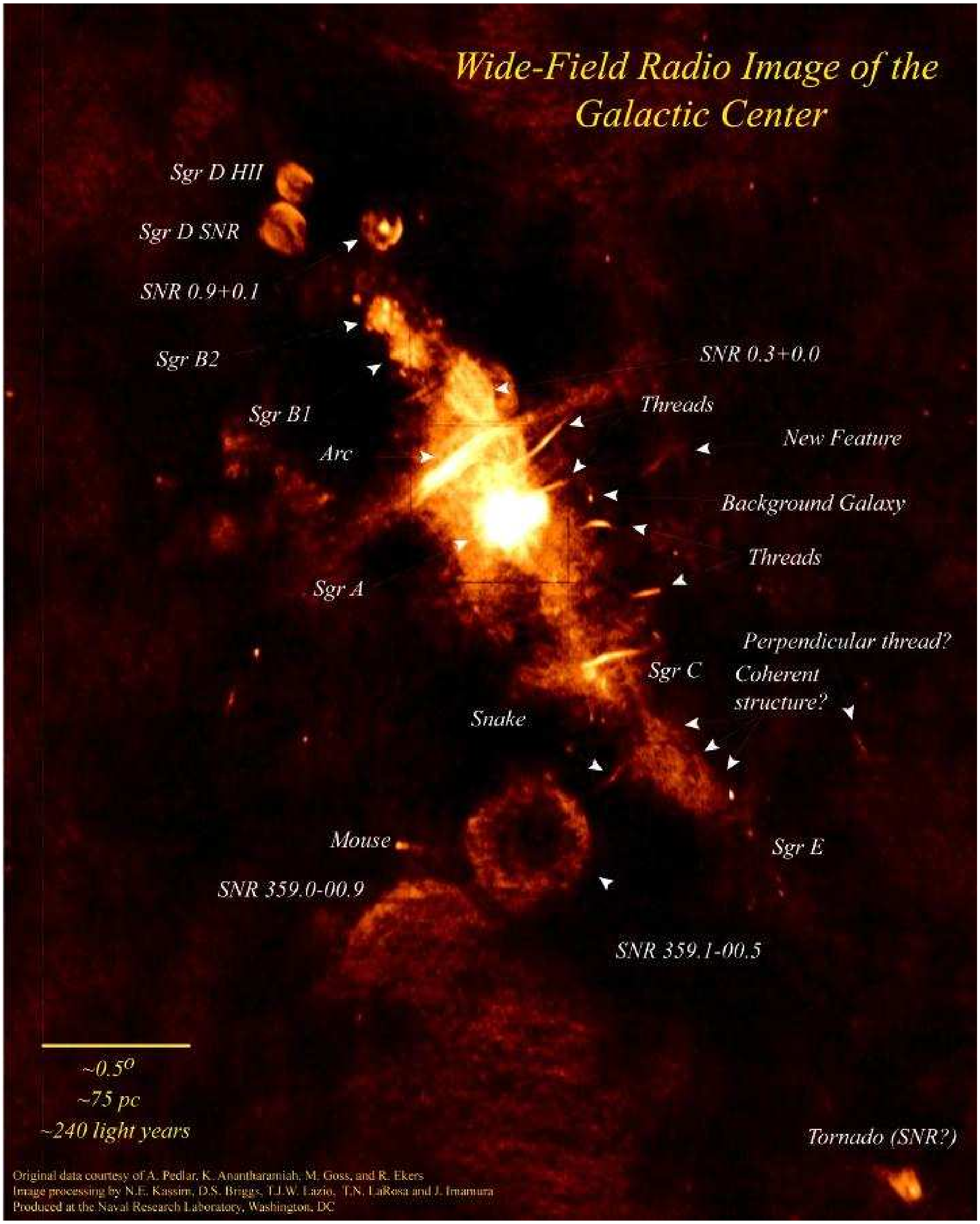
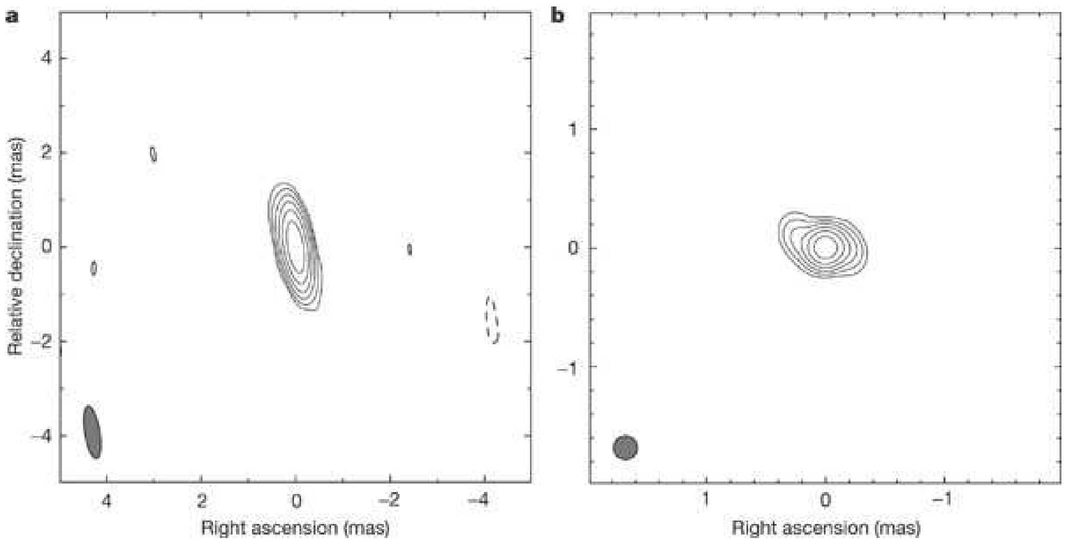
Closing in on Sgr A*



NRAO/AUI and Kassim et al.

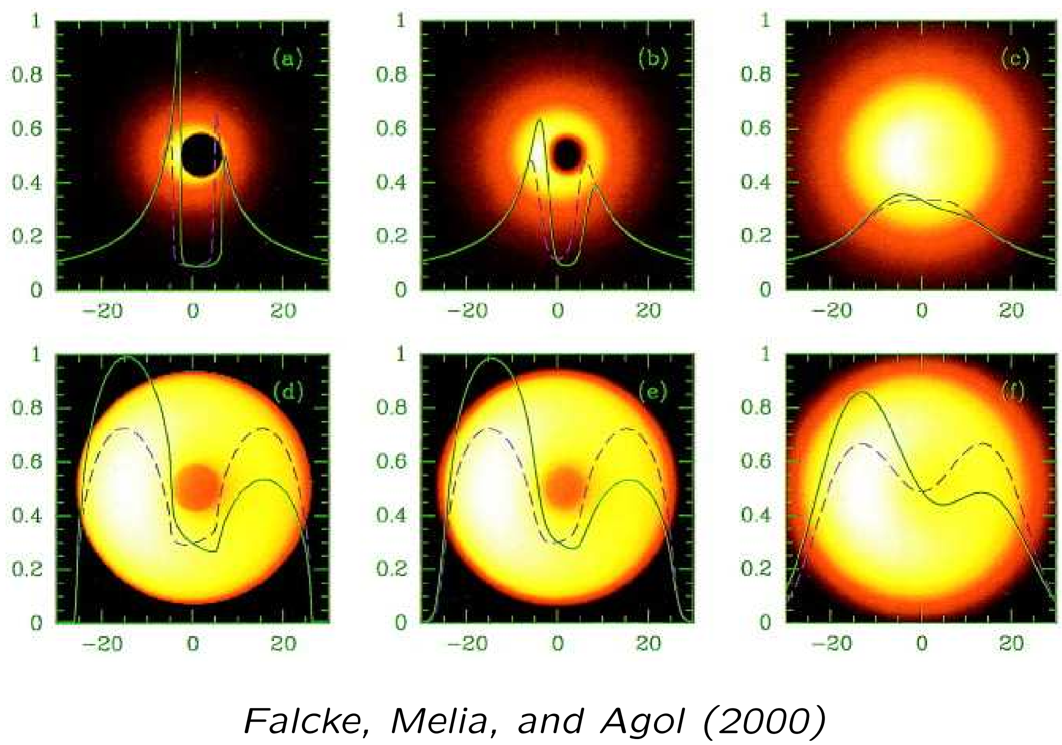
VLA, $\lambda = 90cm$

Closing in on Sgr A*



Shen et al. (2005)

VLBA, $\lambda = 3.5mm$



Falcke, Melia, and Agol (2000)

VLBI at $\lambda \simeq 1mm$?

Magnetohydrodynamic Models in Full General Relativity

General Relativistic MHD Equations

Particle number conservation:

$$\partial_t(\sqrt{-g}\,\rho_o u^t) = -\partial_i(\sqrt{-g}\,\rho_o u^i) \qquad \partial_t\rho = -\nabla\cdot(\rho\mathbf{v})$$

Ideal MHD:

$$u_\mu F^{\mu\nu} = 0 \qquad \mathbf{E} + \mathbf{v}\times\mathbf{B}/c = 0$$

Momentum and energy conservation:

$$\partial_t\left(\sqrt{-g}\,T^t{}_\nu\right) = -\partial_i\left(\sqrt{-g}\,T^i{}_\nu\right) + \sqrt{-g}T^\kappa{}_\lambda\Gamma^\lambda{}_{\nu\kappa}$$

$$\partial_t(\rho\mathbf{v}) = -\nabla\cdot\mathbf{T} - \rho\nabla\phi$$

$$T_{\mu\nu} = (\rho_o + u + p + \frac{b^2}{4\pi})u_\mu u_\nu + (p + \frac{b^2}{8\pi})g_{\mu\nu} - \frac{b_\mu b_\nu}{4\pi}$$

$$T_{ij} = \rho v_i v_j + (p + \frac{B^2}{8\pi})\delta_{ij} - \frac{B_i B_j}{4\pi}$$

Induction equation:

$$\partial_t(\sqrt{-g}B^i) = -\partial_j(\sqrt{-g}(u^j b^i - b^j u^i)) \qquad \partial_t\mathbf{B} = \nabla\times(\mathbf{v}\times\mathbf{B})$$

$$= -\nabla(\mathbf{vB} - \mathbf{Bv})$$

No monopoles constraint:

$$\partial_i(\sqrt{-g}B^i) = 0 \qquad \nabla\cdot\mathbf{B} = 0$$

GRMHD Code

Basic Model

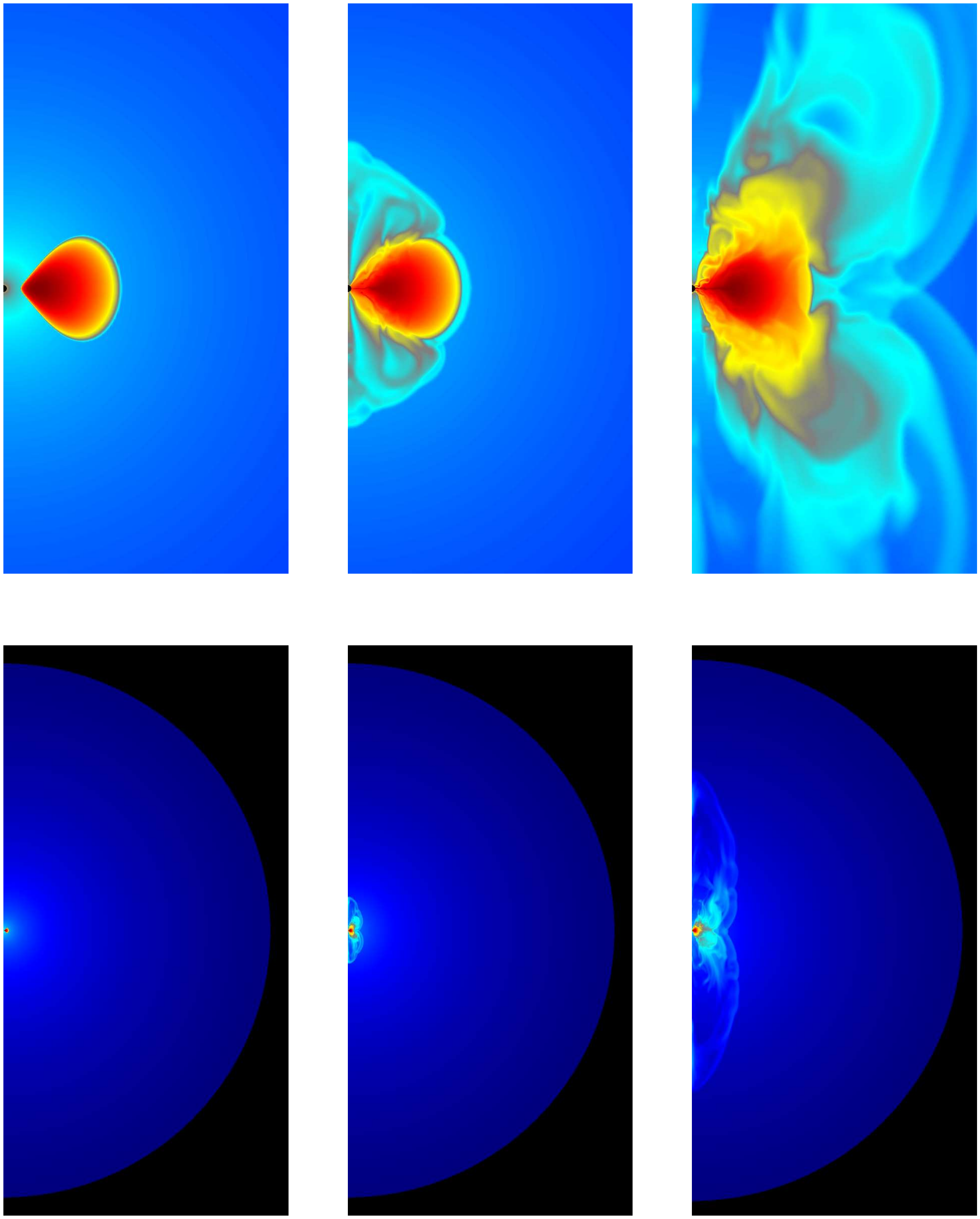
ideal MHD
stationary (Kerr) metric
no cooling
no radiative forces

HARM Algorithm

Gammie, McKinney, Tóth (2003)
conservative, LLF or HLL
constrained transport: $\nabla \cdot \mathbf{B} = 0$
axisymmetric (so far)
covariant
extensively tested

Other GRMHD codes

Koide, Meier et al. (Toyama, JPL)
De Villiers, Hawley (Calgary, Virginia)
Komissarov (Leeds)
Fragile, Anninos (Charleston, LLNL)
Duez, Shapiro (Cornell, UIUC)

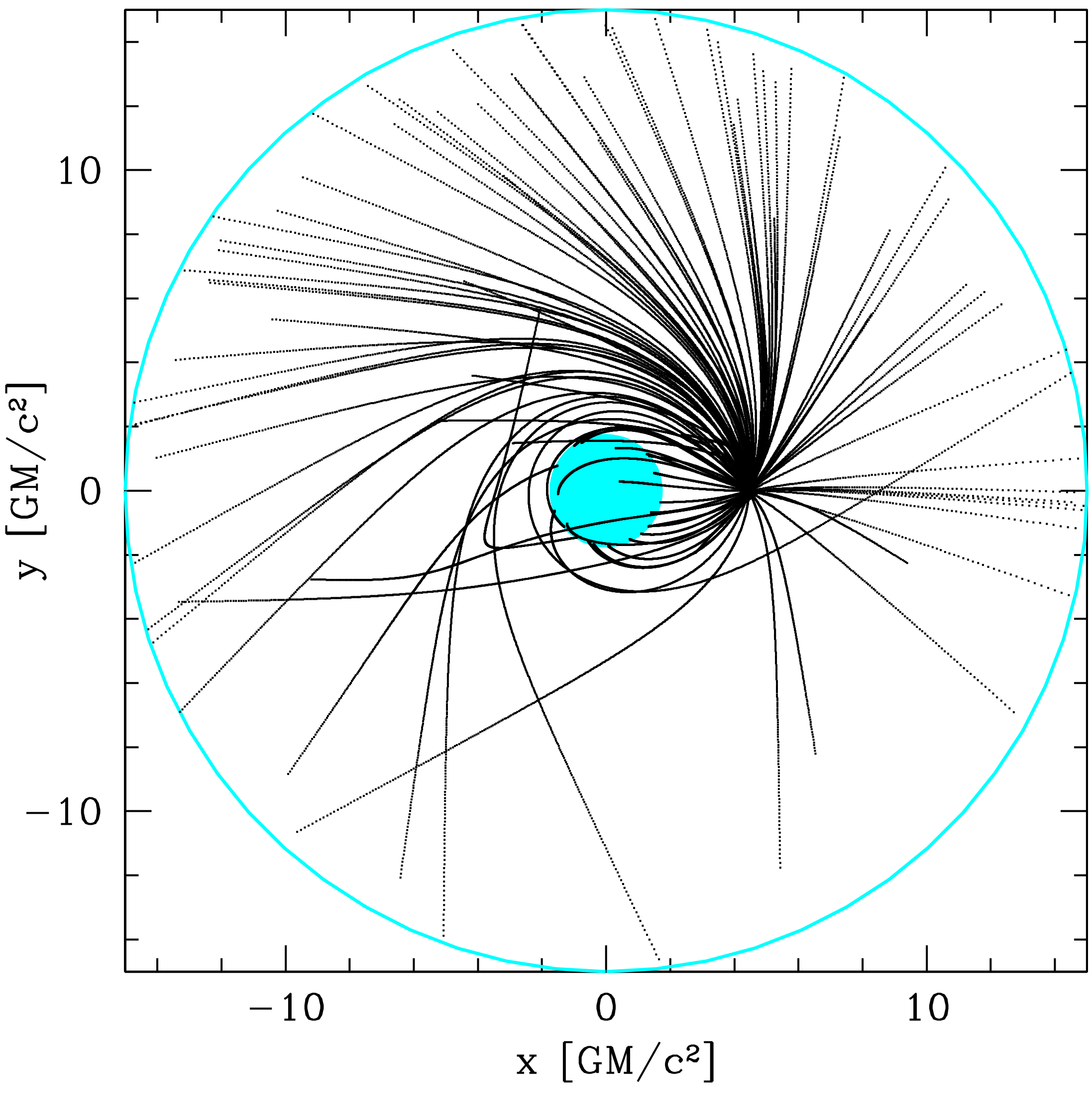


color shows log(density)

movie (small, big)

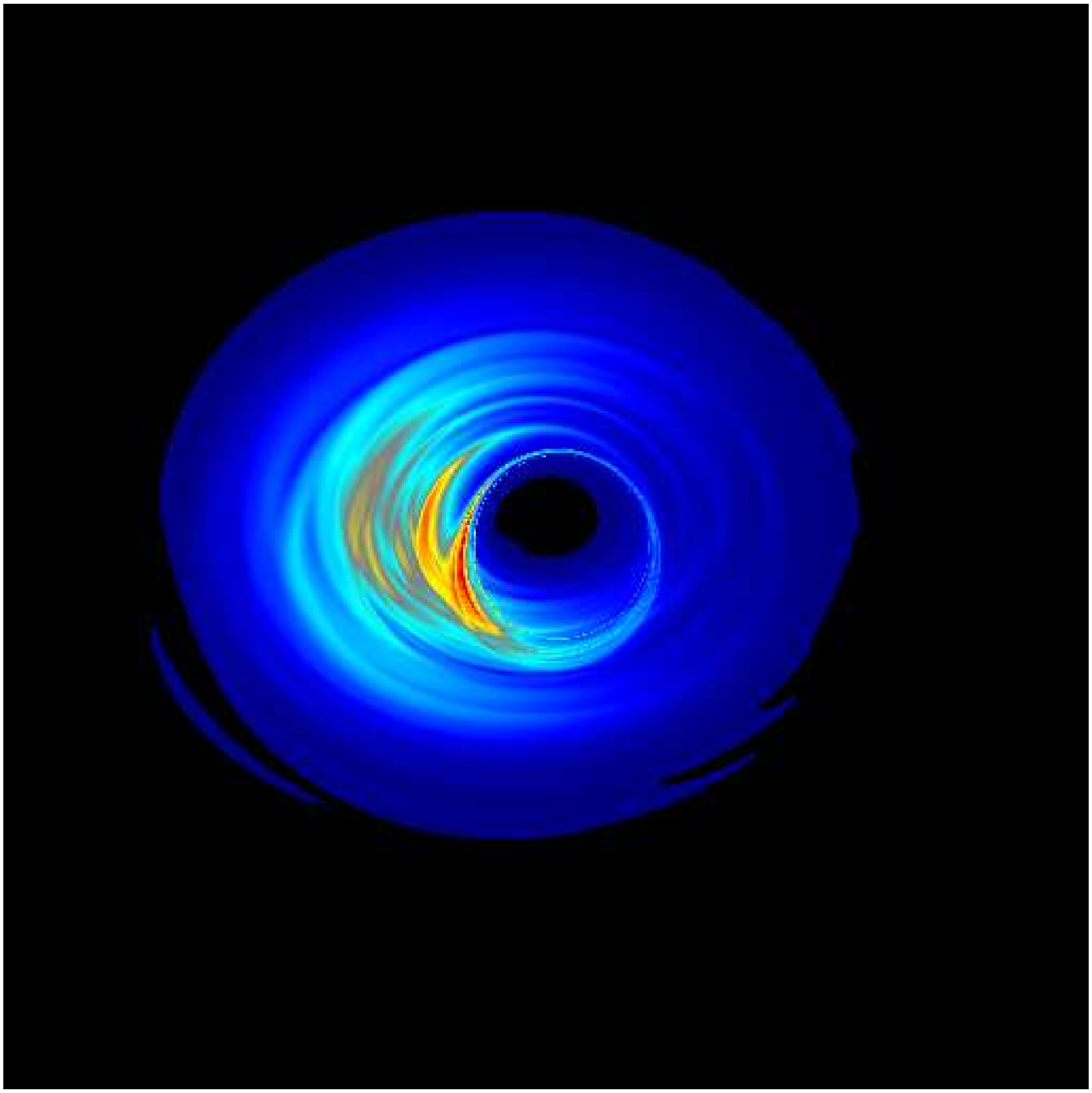
Radiative Models

Isotropic Emission in Plasma Rest Frame



Noble, Leung, & Gammie 2006

Model of Sgr A* at 1mm



synchrotron emission; $\dot{M} = 3 \times 10^{-9} M_{\odot} \mathrm{yr}^{-1}$

Noble, Leung, & Gammie 2006

Summary

Numerical Challenges

Magnetically dominated regions in GRMHD

Accurate treatment of radiative processes

Coupling dynamics to radiative transport

Results

$d\tilde{a}/dt = 0$ at $\tilde{a} \sim 0.9$

Compare Thorne (1974): $\tilde{a} = 0.998$

$L_{jet} \sim L_{acc}$

Predictions for submm imaging of Sgr A*