# Relativistic MHD
# And
# Radiative Transfer

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with
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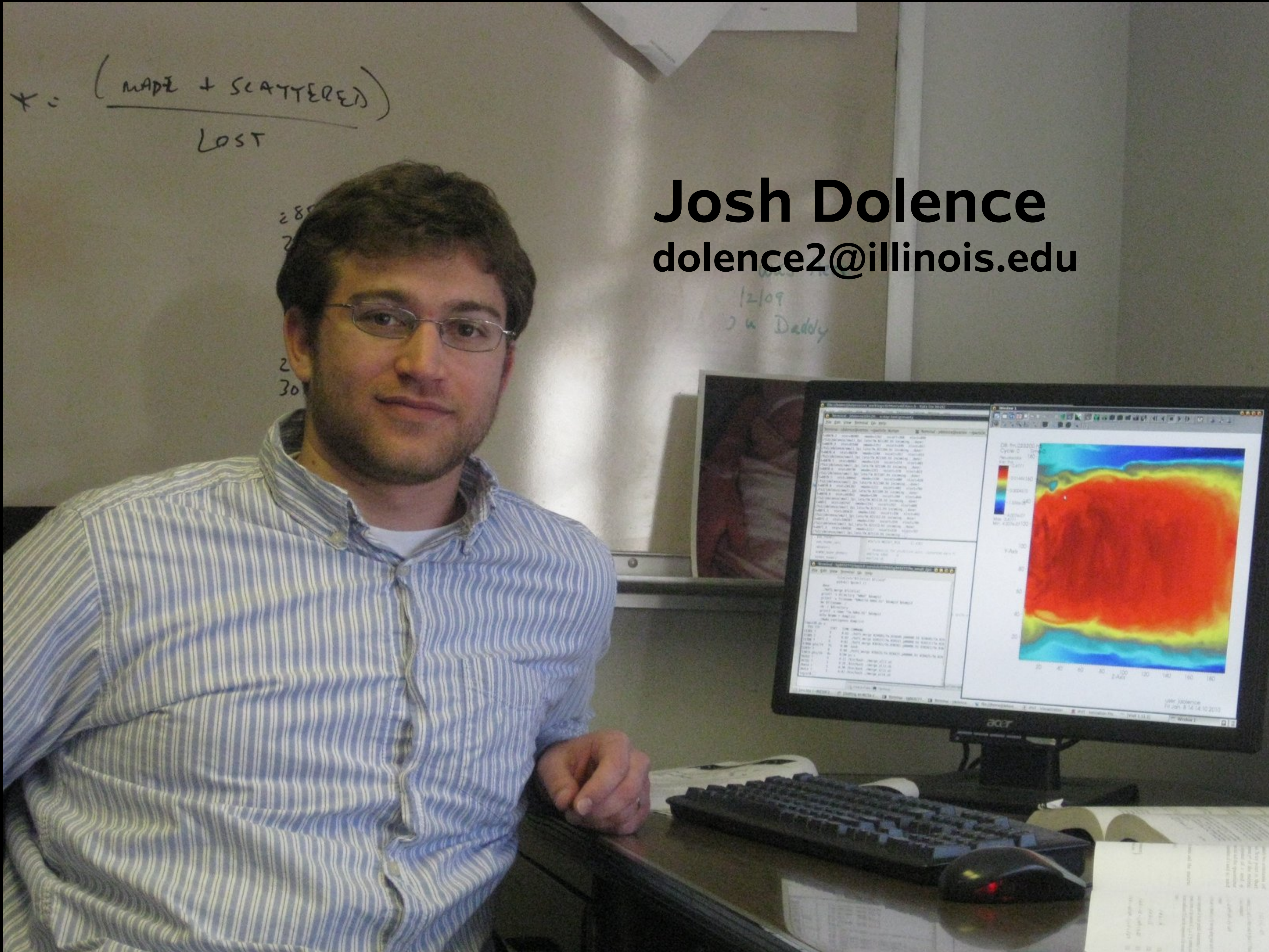
MADE + SCATTERED
LOST
Josh Dolence
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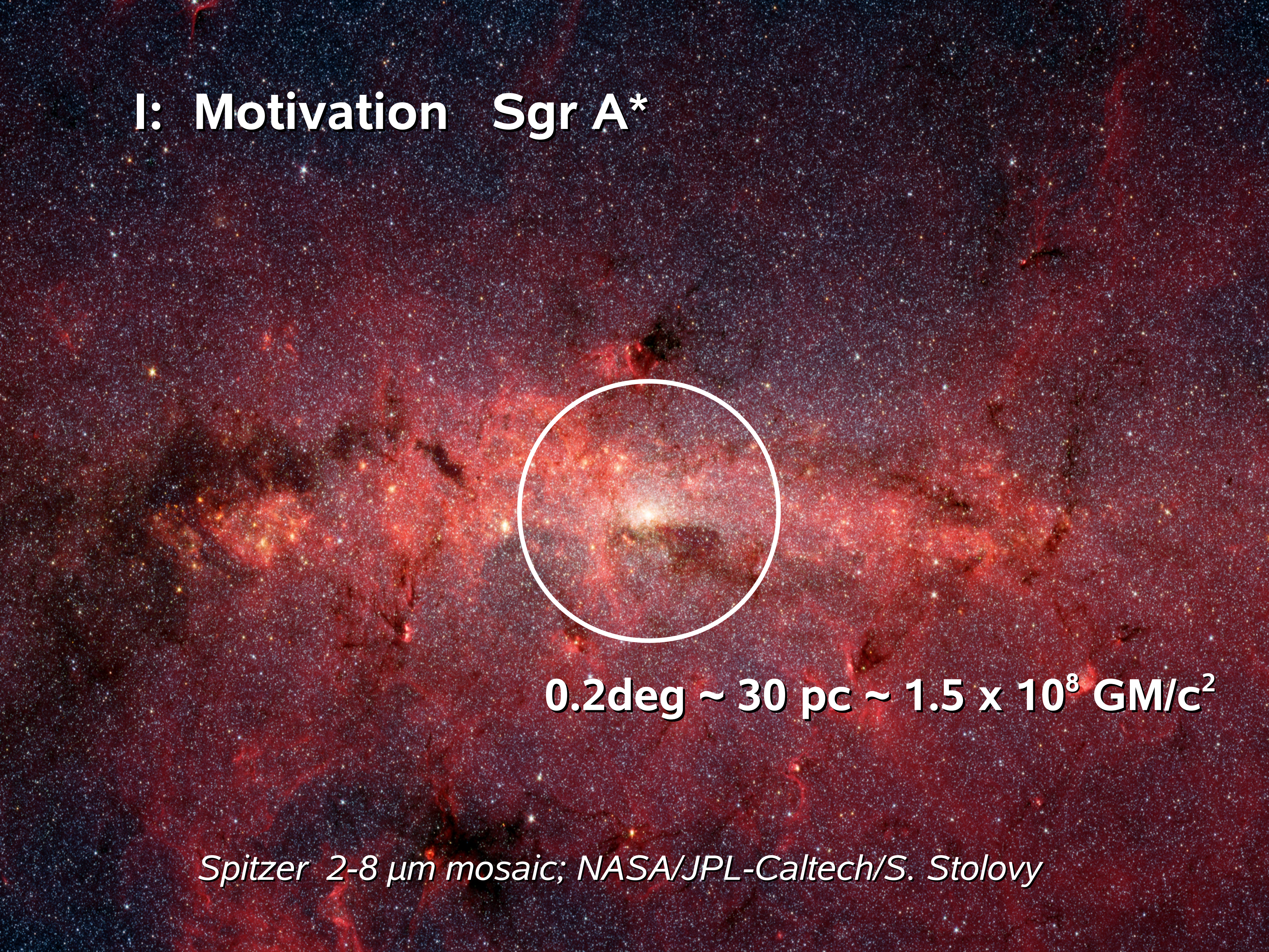
# I: Motivation Sgr A*



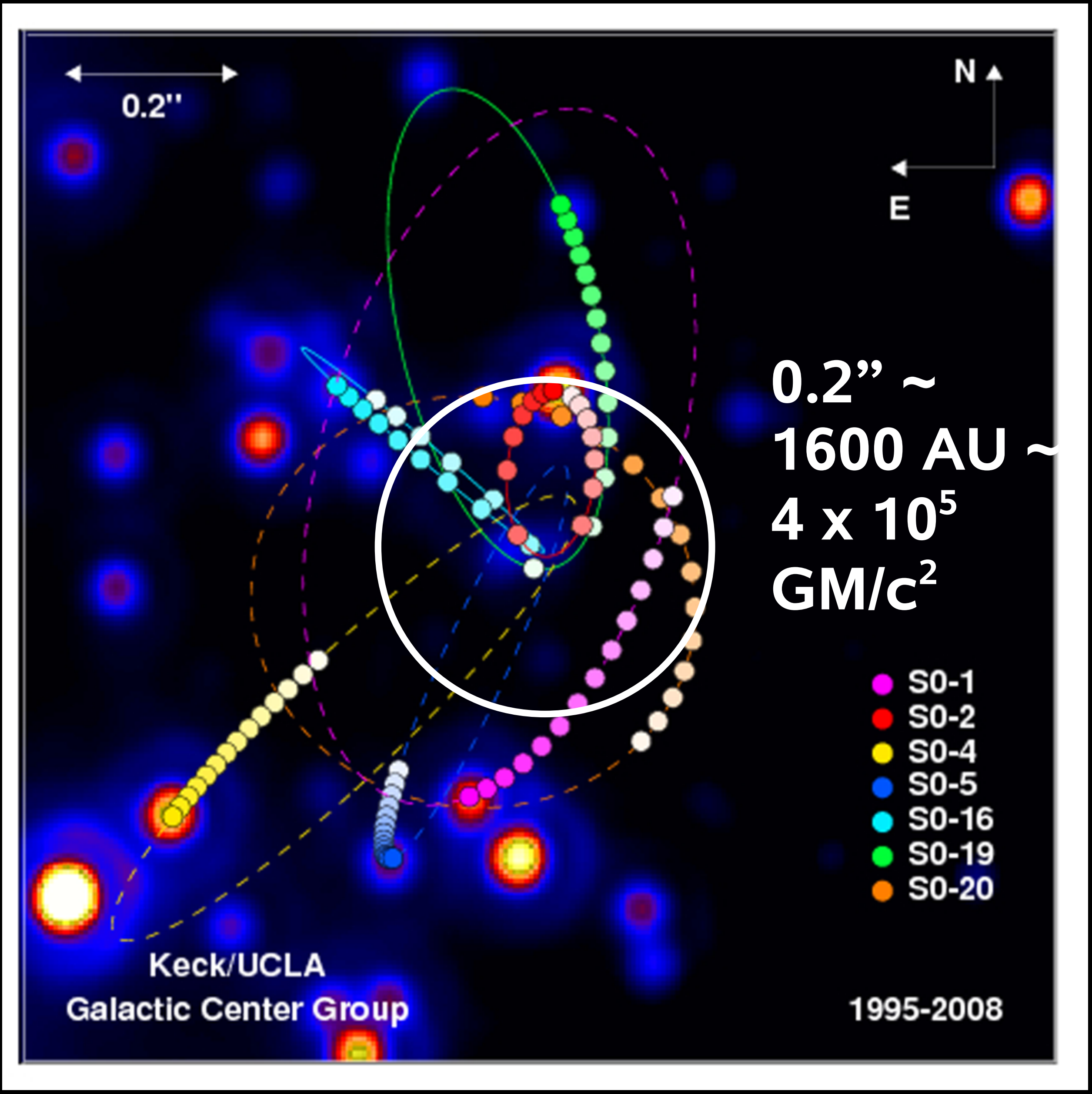

*Spitzer 2-8 µm mosaic; NASA/JPL-Caltech/S. Stolovy*


I: Motivation Sgr A*
90" ~ 4 pc ~ 2 x $10^7$ GM/$c^2$
Spitzer 2-8 µm mosaic; NASA/JPL-Caltech/S. Stolovy

# I: Motivation: Sgr A*

$M = 4.1 \times 10^6 M_\odot$

D = 8 kpc




0.2” ~
1600 AU ~
$4 \times 10^5$
$GM/c^2$

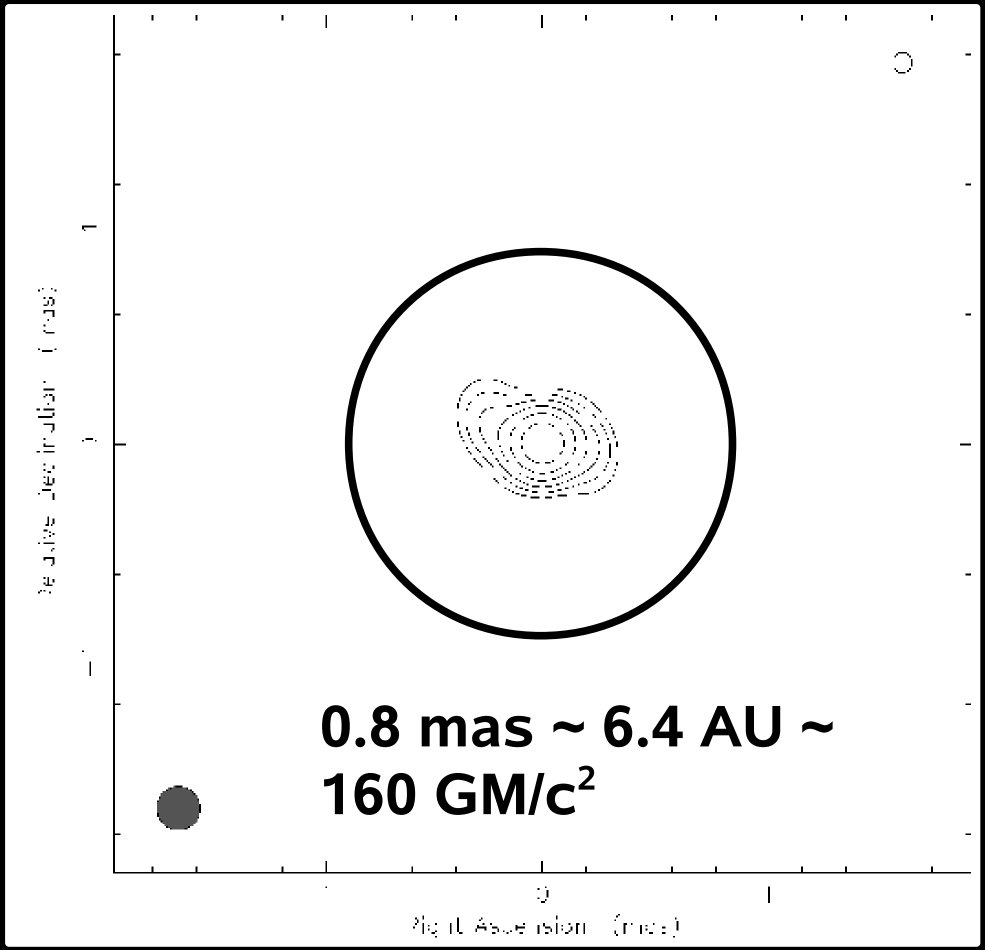
# I: Motivation Sgr A*

**$GM/c^2 = 6 \times 10^{11}$cm**
**5 $\mu$as at 8 kpc**

**Unique!**
**M87: 2 $\mu$as**

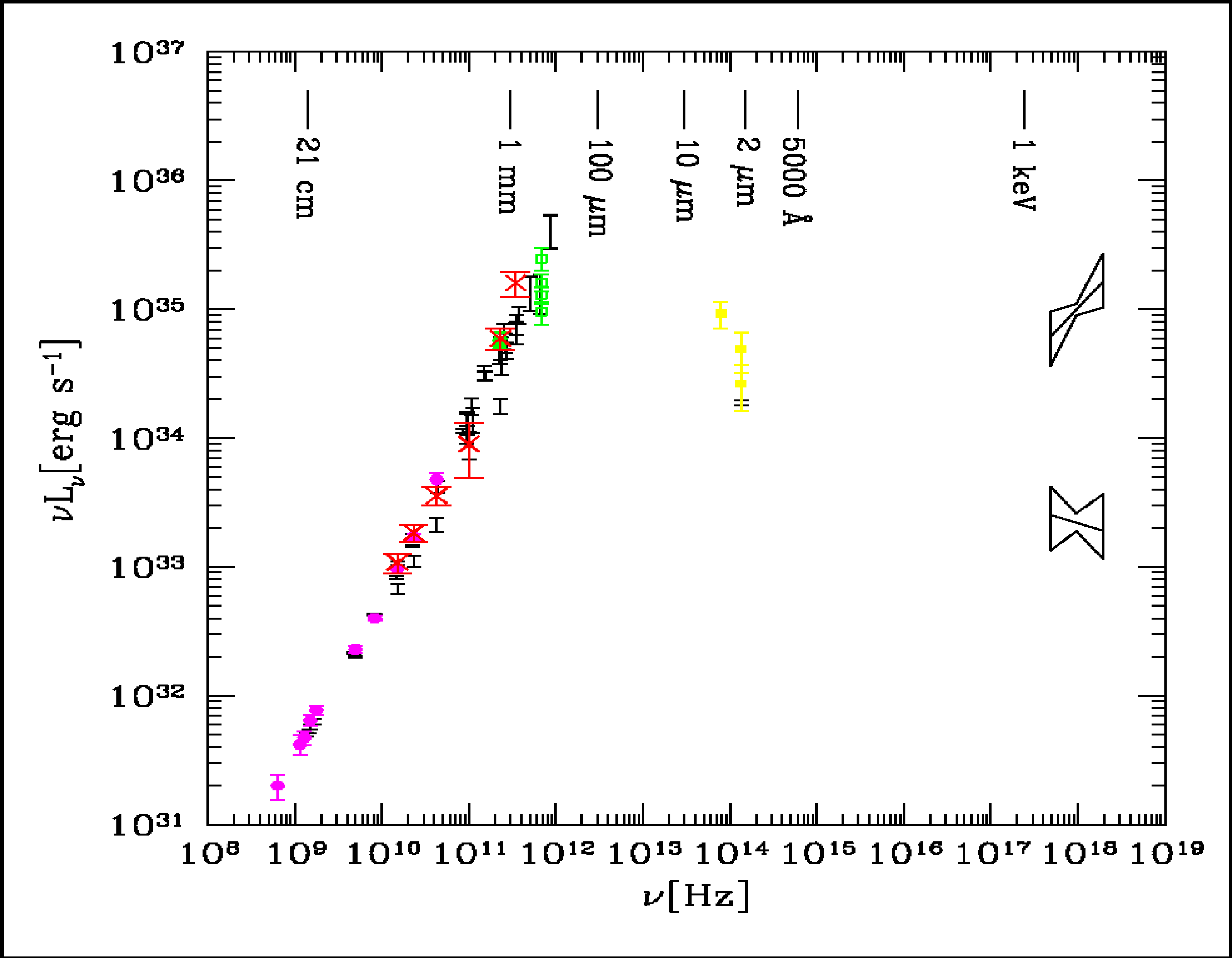
**Stellar mass BH**
**At 4000 AU**

**Doeleman et al. 2008**
**1.3mm VLBI**
**HWHM ~ 20 $\mu$as**




*Shen et al., 2005: VLBI image at 3.5mm*

# I: Motivation Sgr A*



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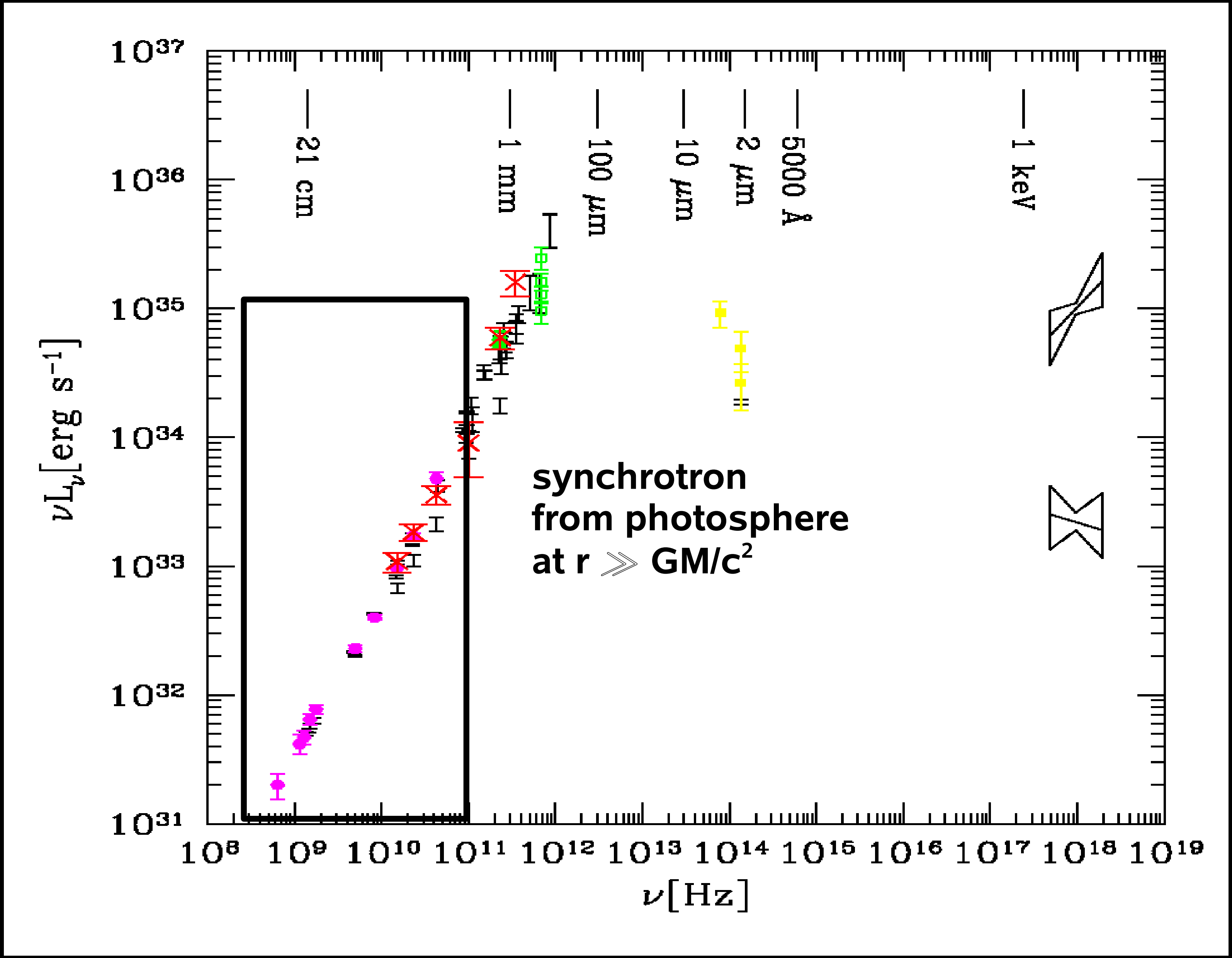

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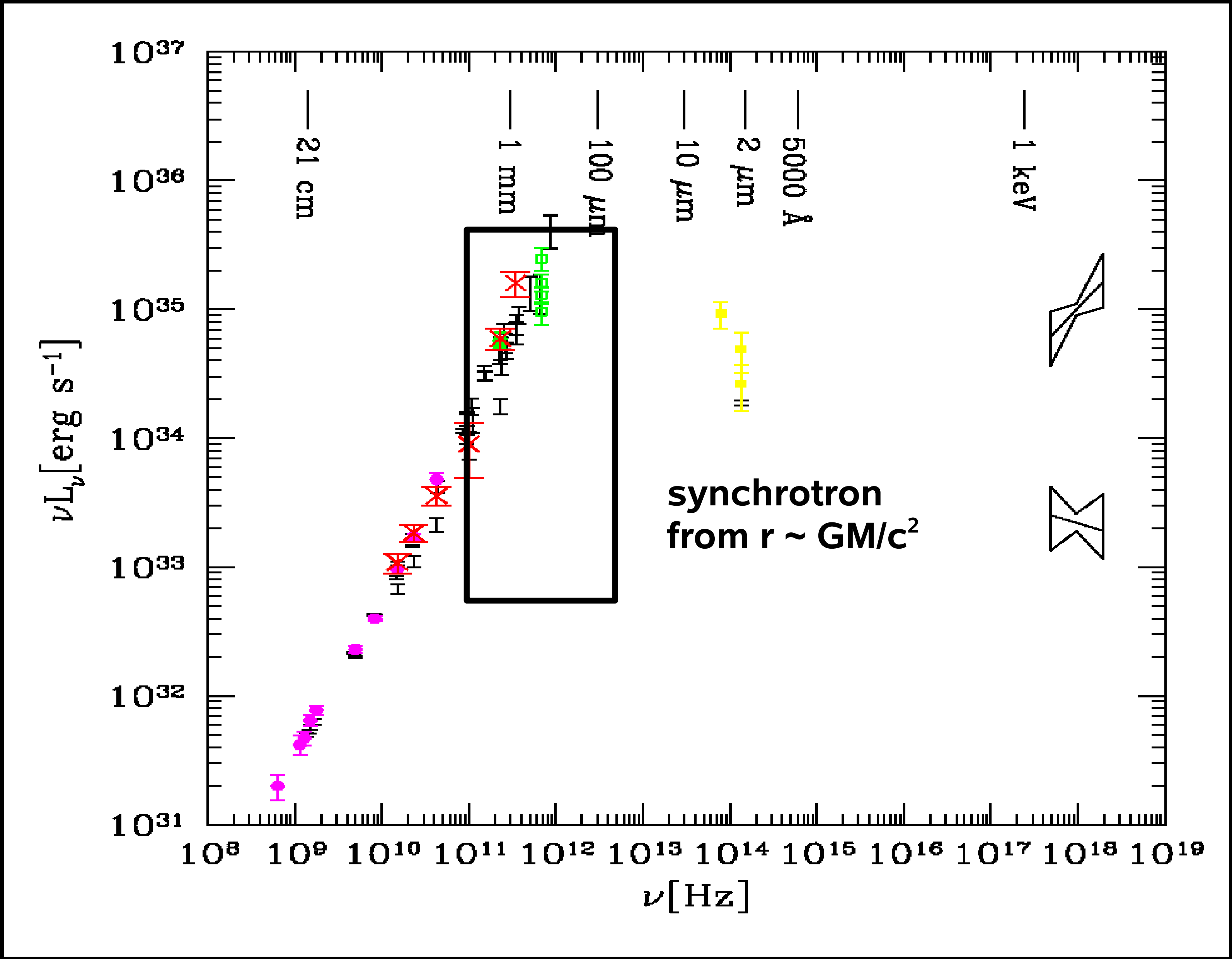
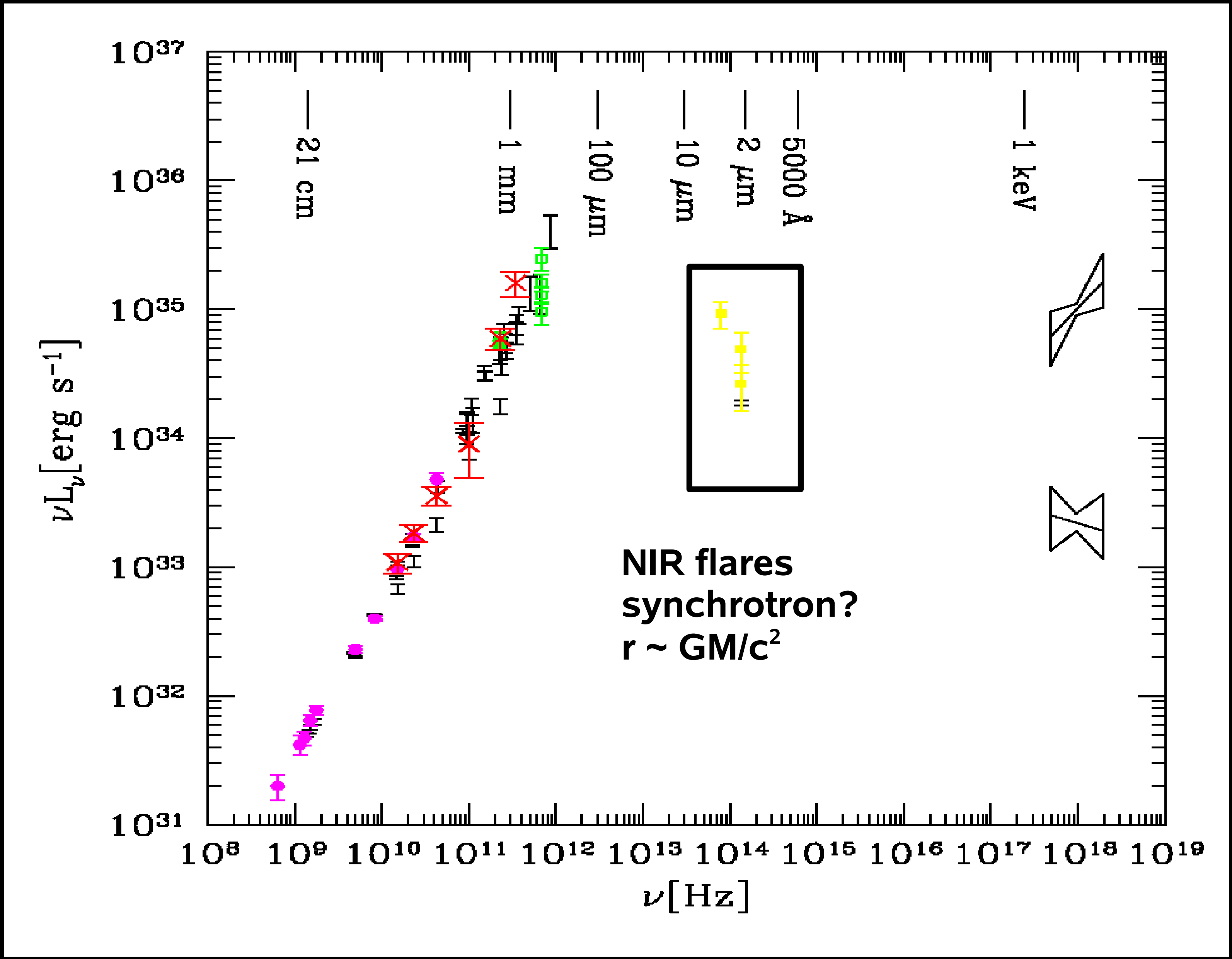
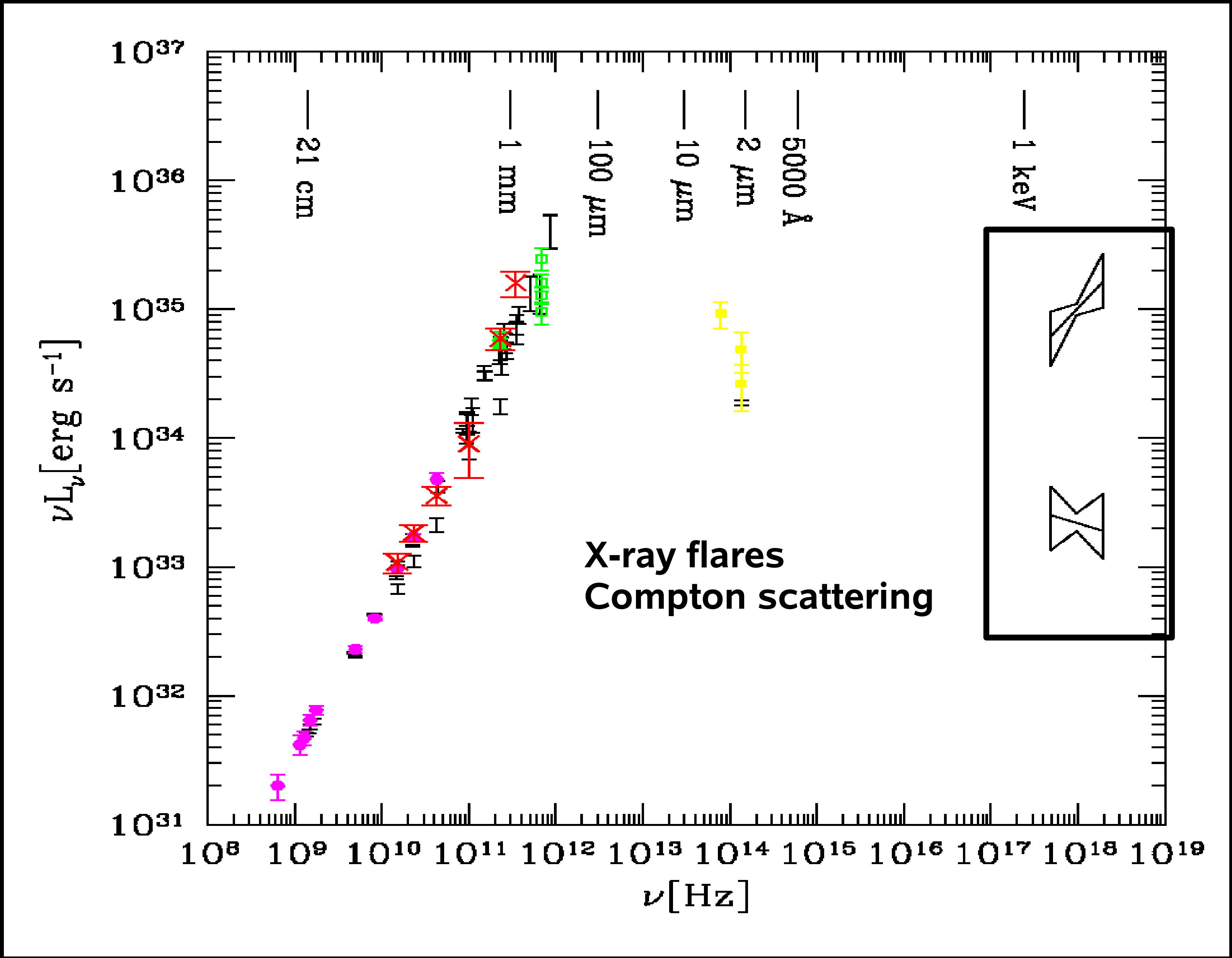


# I: Motivation   Sgr A*



# I: Motivation Sgr A*



# I: Motivation Sgr A*

## Some recent Sgr A* models:

Dexter, Agol, & Fragile 2009
Hilburn et al. 2009
Moscibrodzka et al. 2009
Huang et al. 2009
Yuan et al. 2009
Chan et al. 2009
Broderick et al. 2009
Huang, Takahashi, & Shen 2009
Markoff, Bower, & Falcke 2007
Huang et al. 2007
Loeb & Waxman 2007
Broderick & Loeb 2006
Goldston, Quataert, & Igumenshchev 2005
Ohsuga, Kato, & Mineshige 2005
Yuan, Quataert, & Narayan 2003

# I: Motivation  Sgr A*

## Some recent Sgr A* models:

| Some recent Sgr A* models | Flow model: |
|---|---|
| Dexter, Agol, & Fragile 2009 | Rel. Simulation |
| Hilburn et al. 2009 | Rel. Simulation |
| Moscibrodzka et al. 2009 | Rel. Simulation |
| Huang et al. 2009 | Steady (RIAF) model |
| Yuan et al. 2009 | Steady (RIAF) model |
| Chan et al. 2009 | Nonrel. Simulation |
| Broderick et al. 2009 | Steady (RIAF) model |
| Huang, Takahashi, & Shen 2009 | Steady (RIAF) model |
| Markoff, Bower, & Falcke 2007 | Jet |
| Huang et al. 2007 | Steady (RIAF) model |
| Loeb & Waxman 2007 | Jet |
| Broderick & Loeb 2006 | Steady (RIAF) model |
| Goldston, Quataert, & Igum. 2005 | Nonrel. Simulation |
| Ohsuga, Kato, & Mineshige 2005 | Nonrel. Simulation |
| Yuan, Quataert, & Narayan 2003 | Steady (RIAF) model |

# I: Motivation  Sgr A*

| Some recent Sgr A* models: | Radiative transfer: |
|---|---|
| Dexter, Agol, & Fragile 2009 | Rel. Ray Tracing |
| Hilburn et al. 2009 | Nonrel. Monte Carlo |
| Moscibrodzka et al. 2009 | Rel. Ray Tracing, MC |
| Huang et al. 2009 | Rel. Ray Tracing |
| Yuan et al. 2009 | Rel. Ray Tracing |
| Chan et al. 2009 | Nonrel. Rays + corrections |
| Broderick et al. 2009 | Rel. Ray Tracing |
| Huang, Takahashi, & Shen 2009 | Rel. Ray Tracing |
| Markoff, Bower, & Falcke 2007 | Nonrel. Rays + corrections |
| Huang et al. 2007 | Rel. Ray Tracing |
| Loeb & Waxman 2007 | Analytic scaling |
| Broderick & Loeb 2006 | Rel. Ray Tracing |
| Goldston, Quataert, & Igum. 2005 | Nonrel. Rays |
| Ohsuga, Kato, & Mineshige 2005 | Nonrel. Monte Carlo |
| Yuan, Quataert, & Narayan 2003 | Nonrel. Rays |

# Outline

I: Motivation

II: Fluid Dynamics

III: Radiative Transfer

IV: Results

V: Summary

# II: Fluid Dynamics

**Physical processes:**

Rotating (Kerr) black hole $a^* = J\,c/(G\,M^2)$

*Accreting, magnetized plasma*

No cooling, radiation forces (yet)

Collisionless plasma

Approximation: plasma ~ perfectly conducting fluid

$\Rightarrow$ Ideal magnetohydrodynamics (MHD)

**Parameters:**

M black hole mass
a* black hole spin
*Plasma initial conditions: torus model for extended flow*

# II: Fluid Dynamics

## General Relativistic Magnetohydrodynamics Equations

### 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:

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

# II: Fluid Dynamics

Numerical approach:

`HARM`: Gammie, McKinney, Toth 2003, (2D)
Noble et al. 2006 (variable inversion)
Noble, Krolik, & Hawley 2009 (3D)

conservative, finite volume scheme

local Lax-Friedrichs fluxes

constrained transport: $\nabla \cdot B = 0$

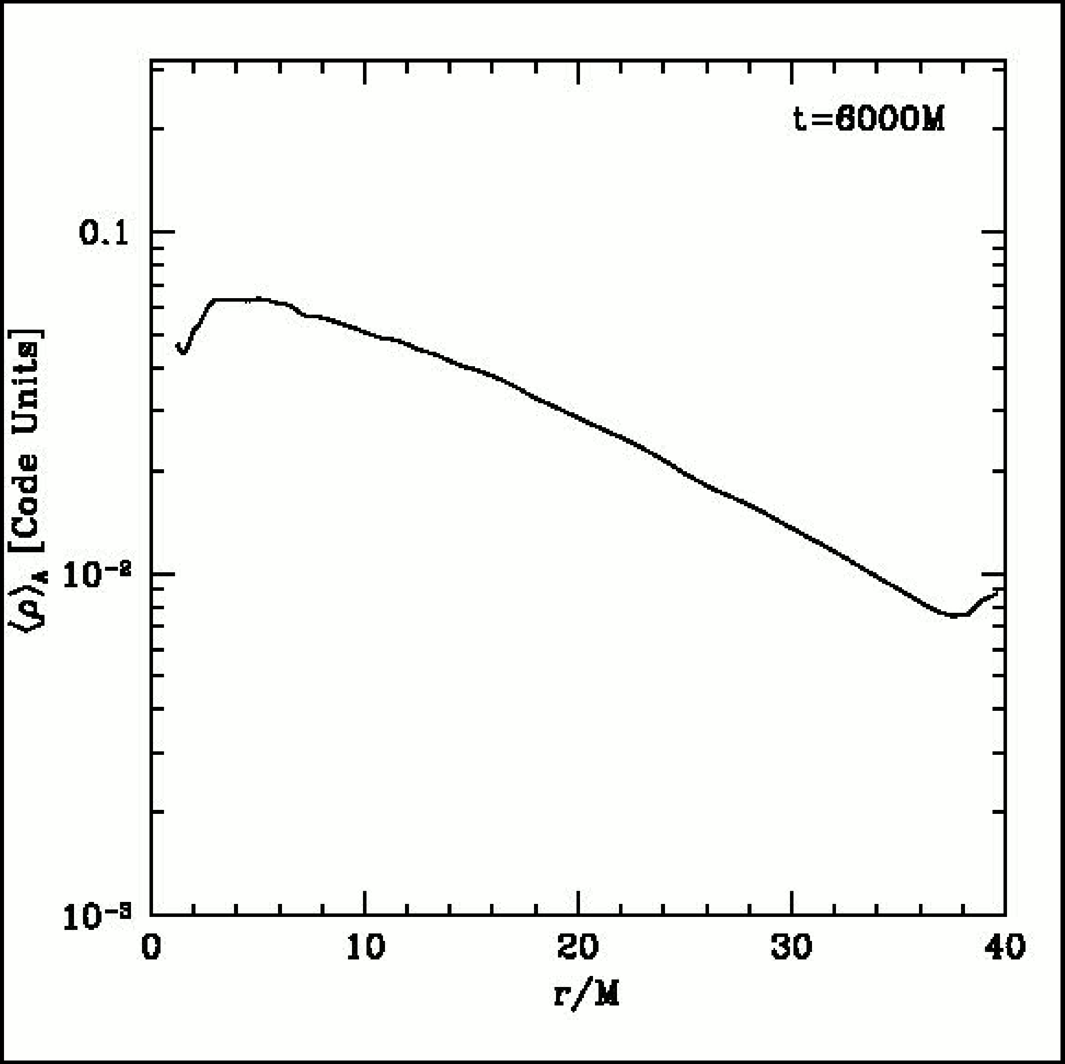
2D, single core (Xeon E5520): 161,000 zc/s

3D, single core (Xeon E5520): 110,000 zc/s

3D, single core (Opteron 2356): 63,000 zc/s

71% efficiency on 1152 cores at TACC `ranger`

# II: Fluid Dynamics




3D model
Fishbone-Moncrief torus
$r(P_{max}) = 13\ GM/c^2$
$a^* = 0.94$

$\Delta\phi = 2\pi$

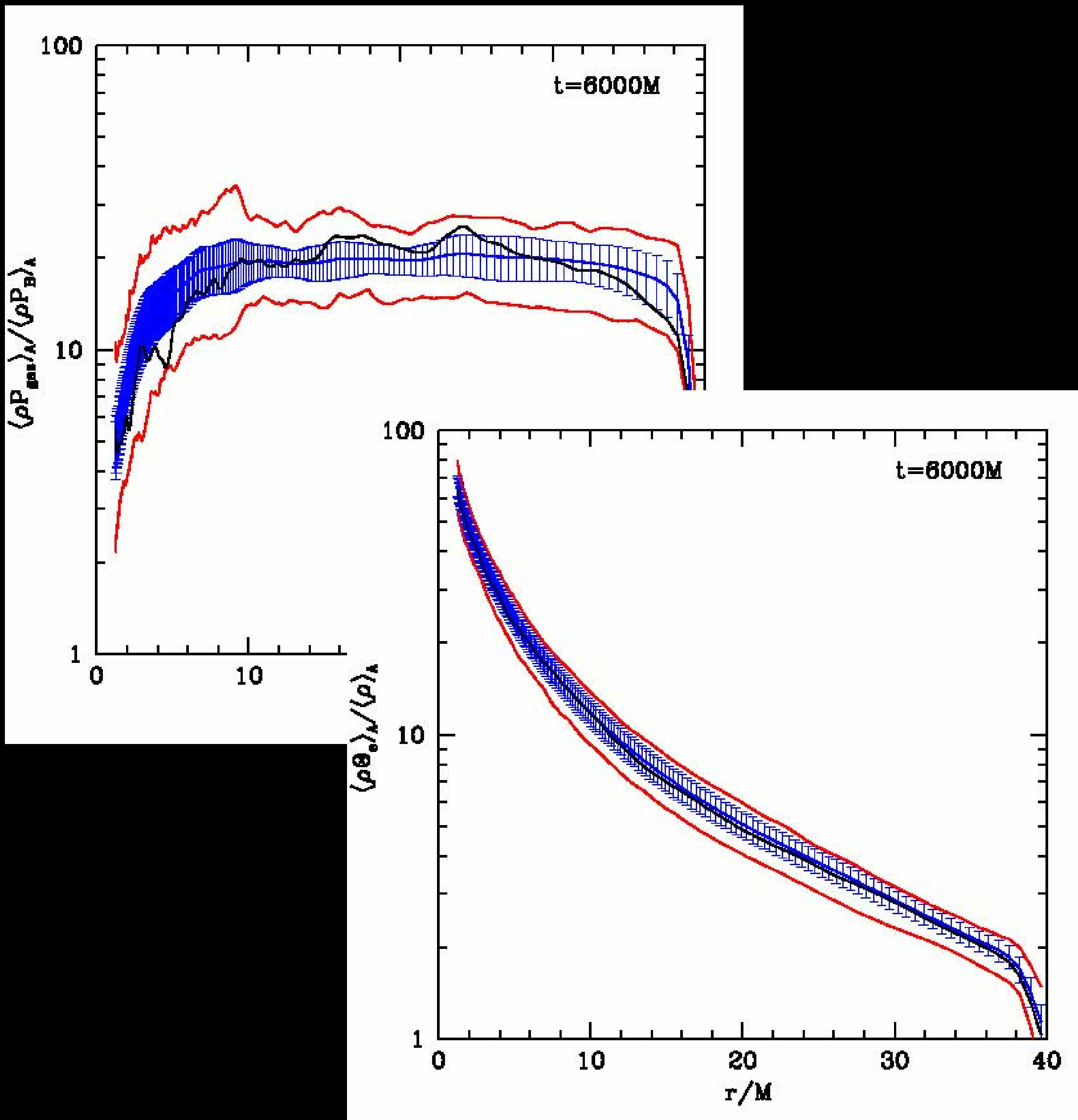
192 x 192 x 128

shell average density

relaxes on viscous
timescale $t_\nu \sim r^2/\nu$

*movie*

# II:  Fluid Dynamics




**3D model**
**Fishbone-Moncrief torus**
**$r(P_{max}) = 13\ GM/c^2$**
**$a^* = 0.94$**

**$\Delta\phi = 2\pi$**

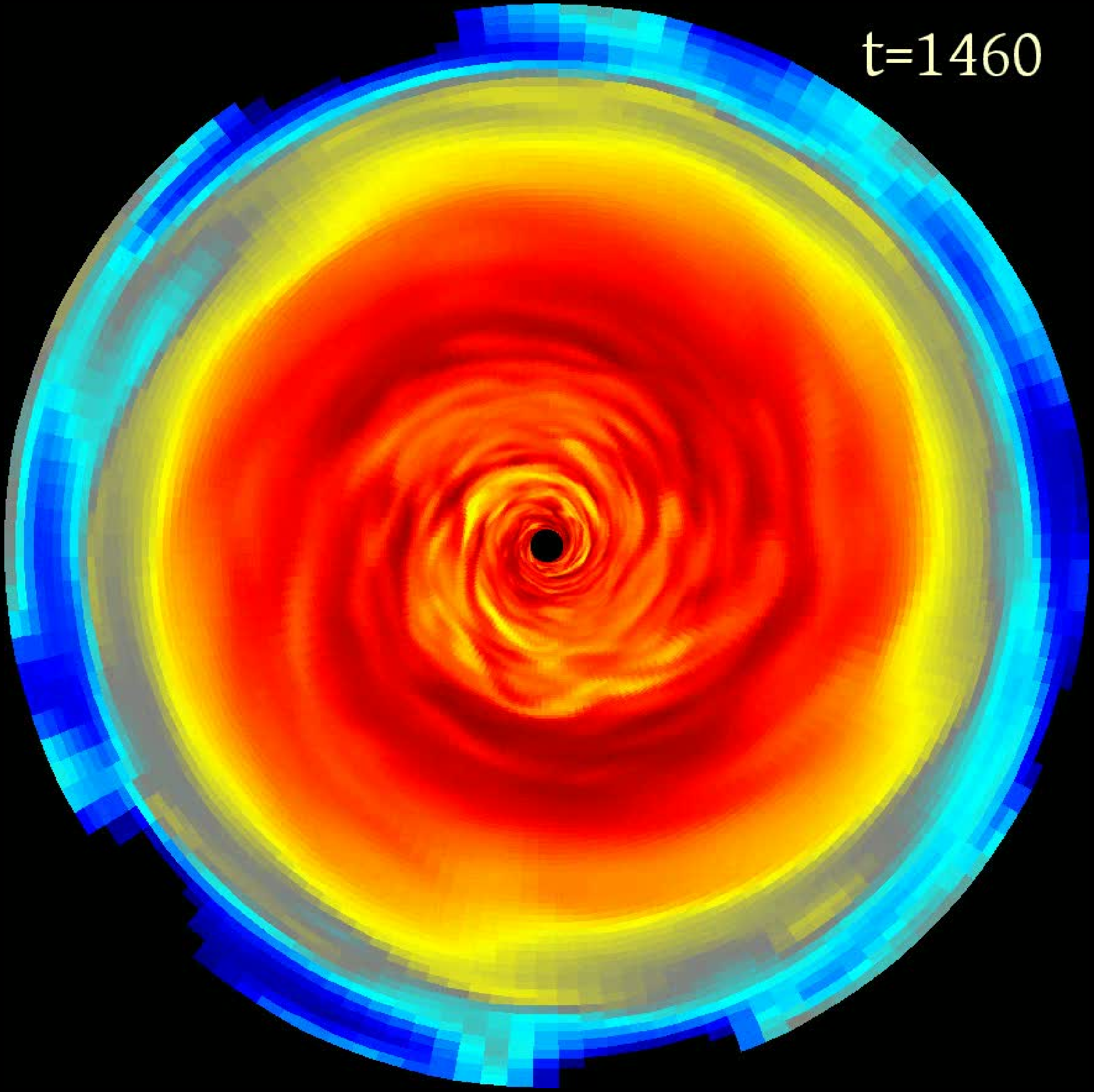
**192 x 192 x 128**

**shell average $\beta$**
**shell average $\Theta_e$**

**converges on viscous timescale $t_\nu \sim r^2/\nu$**

***movies***

# II: Fluid Dynamics




3D model
Fishbone-Moncrief torus
$r(P_{max}) = 13\ GM/c^2$
$a^* = 0.94$

$\Delta\phi = 2\pi$

192 x 192 x 128

midplane density

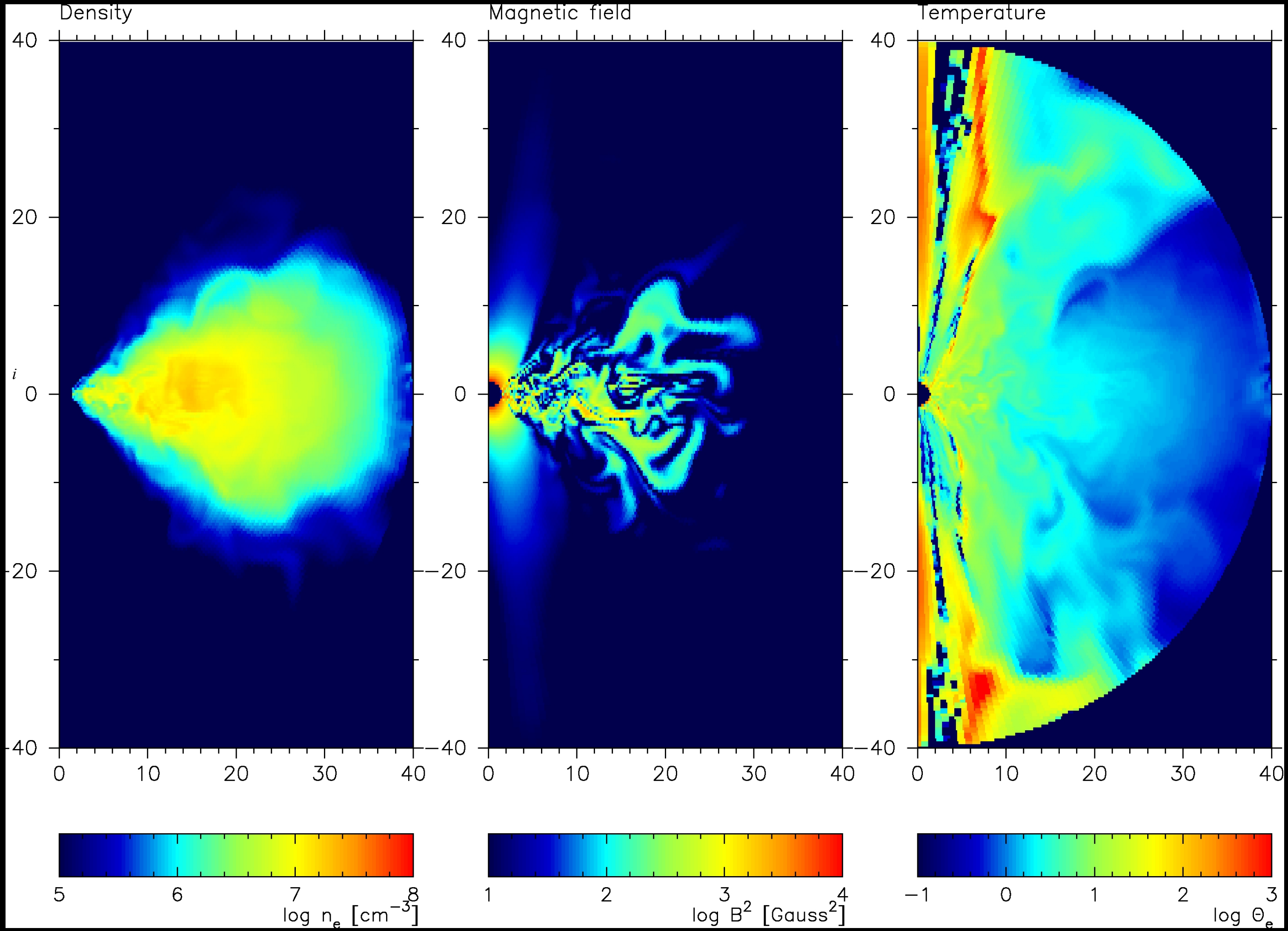
structure at m = 1

$\langle\beta\rangle(\Delta\phi = 2\pi) = 20$

$\langle\beta\rangle(\Delta\phi = \pi/4) = 35$

*movie*

# II: Fluid Dynamics




**Physical conditions in typical model**

***Mosc. et al. 2009***

# Outline

I: Motivation

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# III: Radiative Transfer

**Physical processes:**

- Two temperature plasma
- Thermal synchrotron emission
- Thermal synchrotron absorption
- Compton scattering
- Transport along geodesics

**Parameters:**

| | |
|---|---|
| $\dot{M}$ | mass accretion rate |
| $i$ | inclination |
| $T_p/T_e$ | temperature ratio |

# III: Radiative Transfer

**Numerical Approach:**

`ibothros`: Noble et al. 2007 (ray-tracing)

`grmonty`: Dolence et al. 2009 (monte carlo)

direct integration of geodesics

Leung et al. 2010 emissivities/opacities

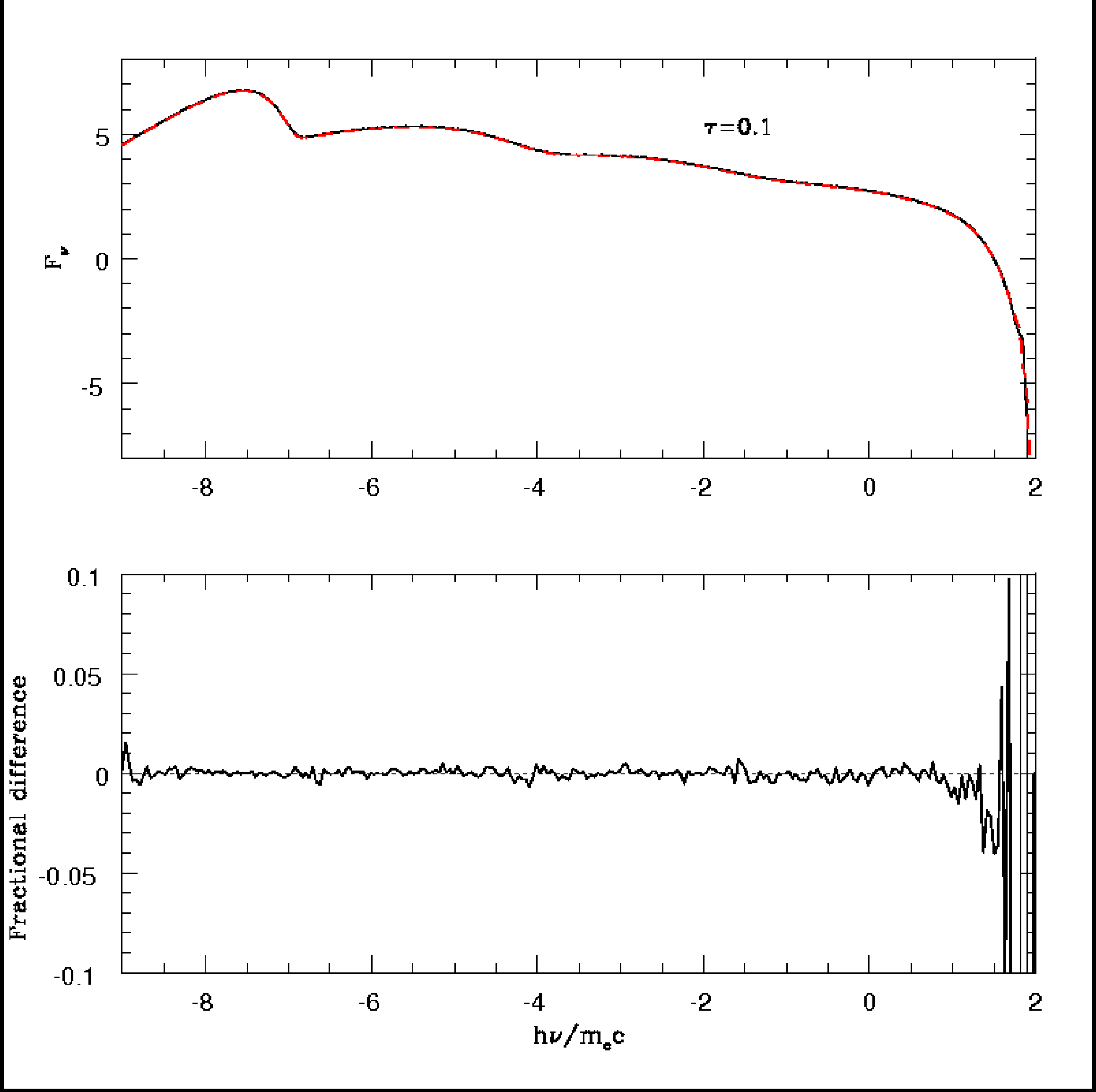
**Tests:**

- synchrotron emitting sphere (thick and thin)
  `grmonty` vs quasi-analytic solution

- comptonizing sphere from Pozdnyakov et al. 1983
  `grmonty` vs `sphere` code

- spherical accretion, turbulent accretion
  `grmonty` vs `ibothros`

# III: Radiative Transfer

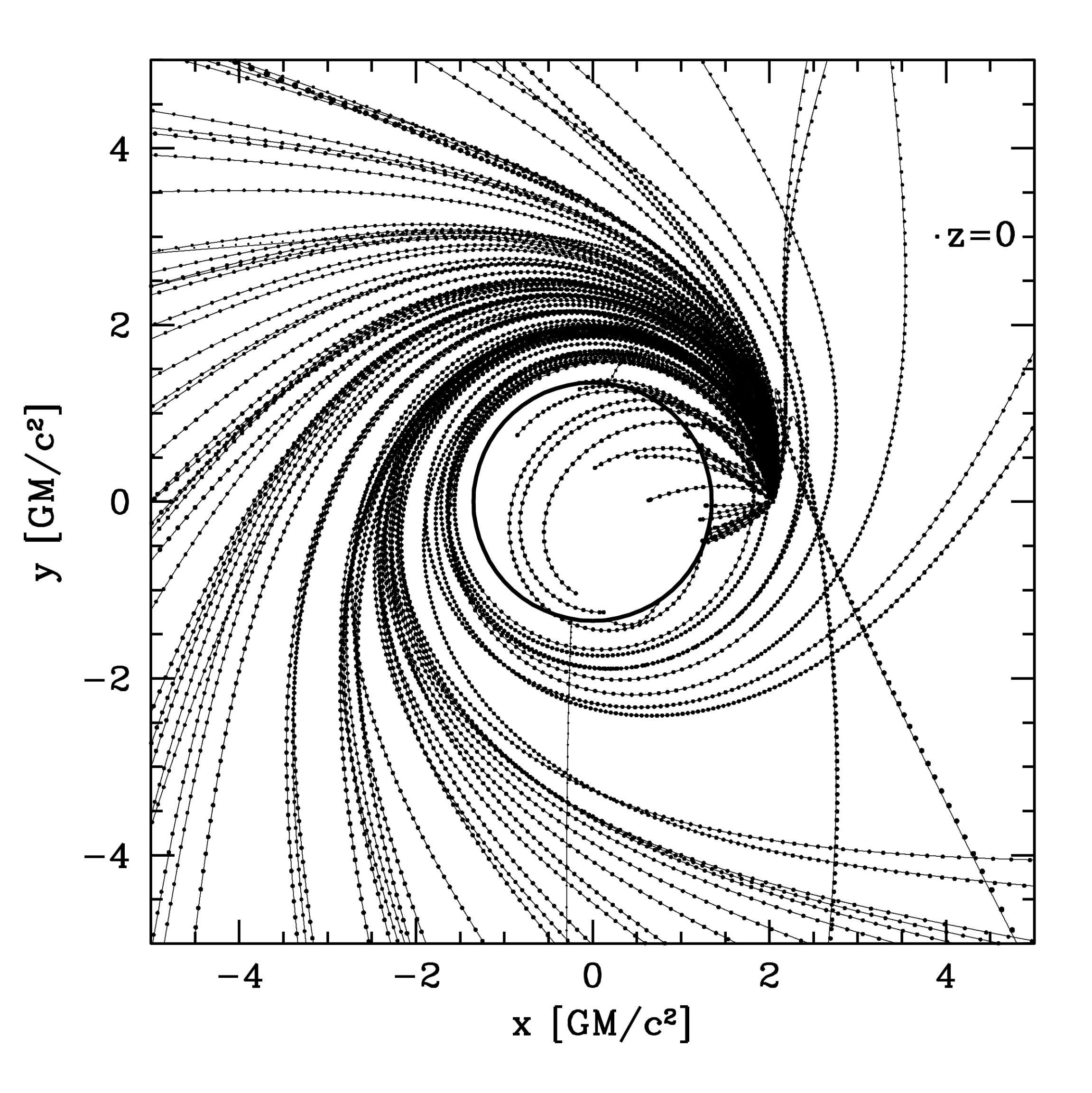



**Comptonizing sphere problem Pozdnyakov et al. 1983**

**`grmonty` vs `sphere`**

***Dolence et al. 2009 thanks to S. Davis***

# III:  Radiative Transfer




**Benchmark problem:**
**photons from source**
**on circular orbit at ISCO**
**a* = 0.9375**

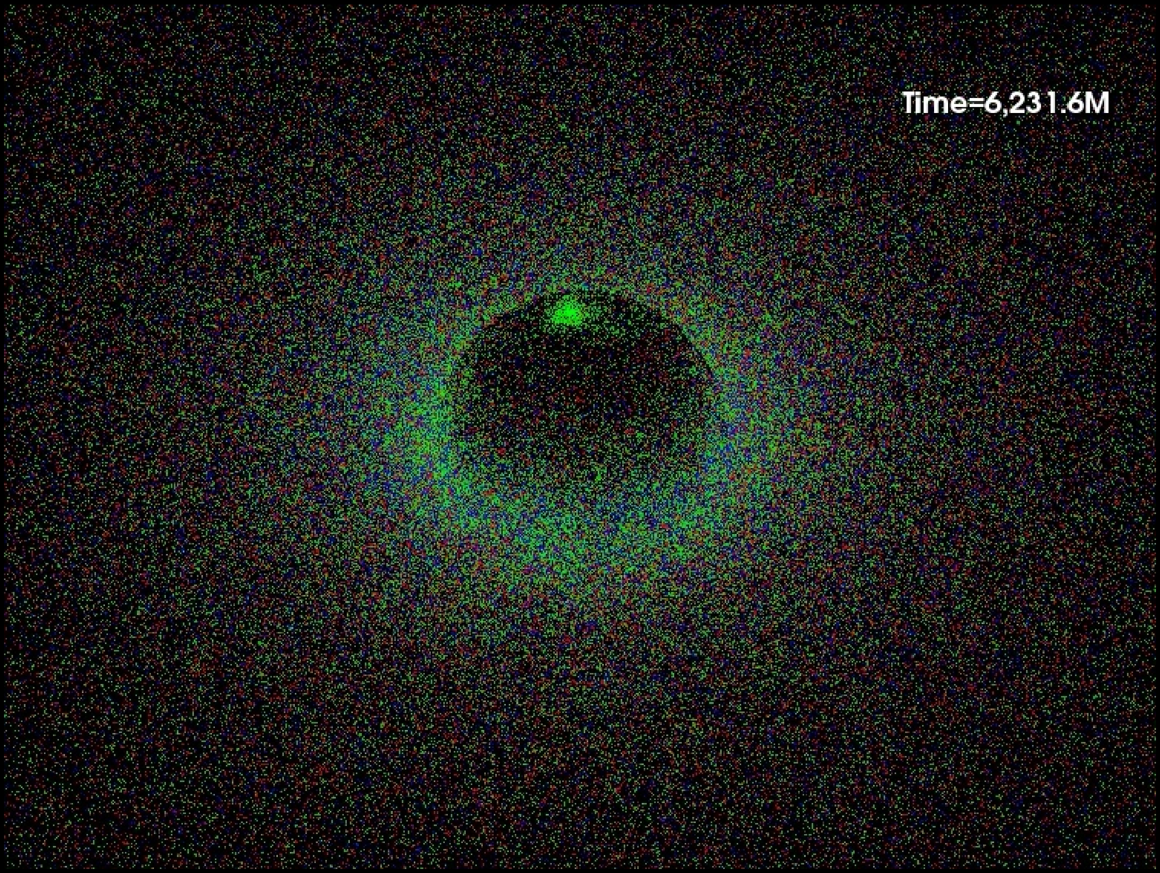
**`grmonty` (dots)**

**`geokerr` (solid)**

***Dolence et al. 2009***

**19,000 geodesics/sec**

# III: Radiative Transfer




Now: time ind. data

Future: time dependent
Monte Carlo

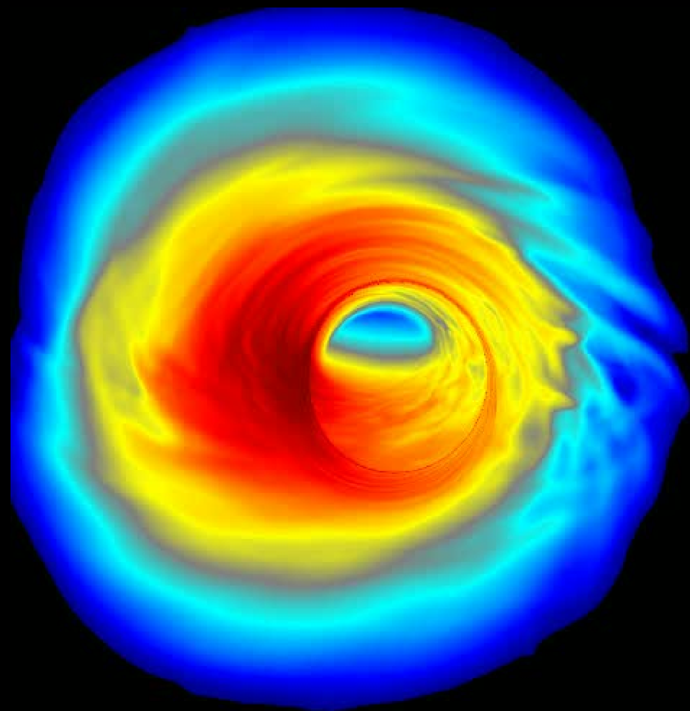
red: radio
green: IR + optical
blue: X-ray

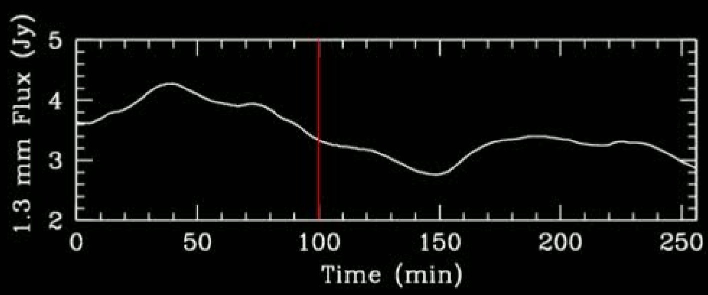
`grmonty`

*Dolence et al. 2010*

*movie*

# III:  Radiative Transfer






**Now: time ind. data**

**Future: time dependent**
**ray tracing**

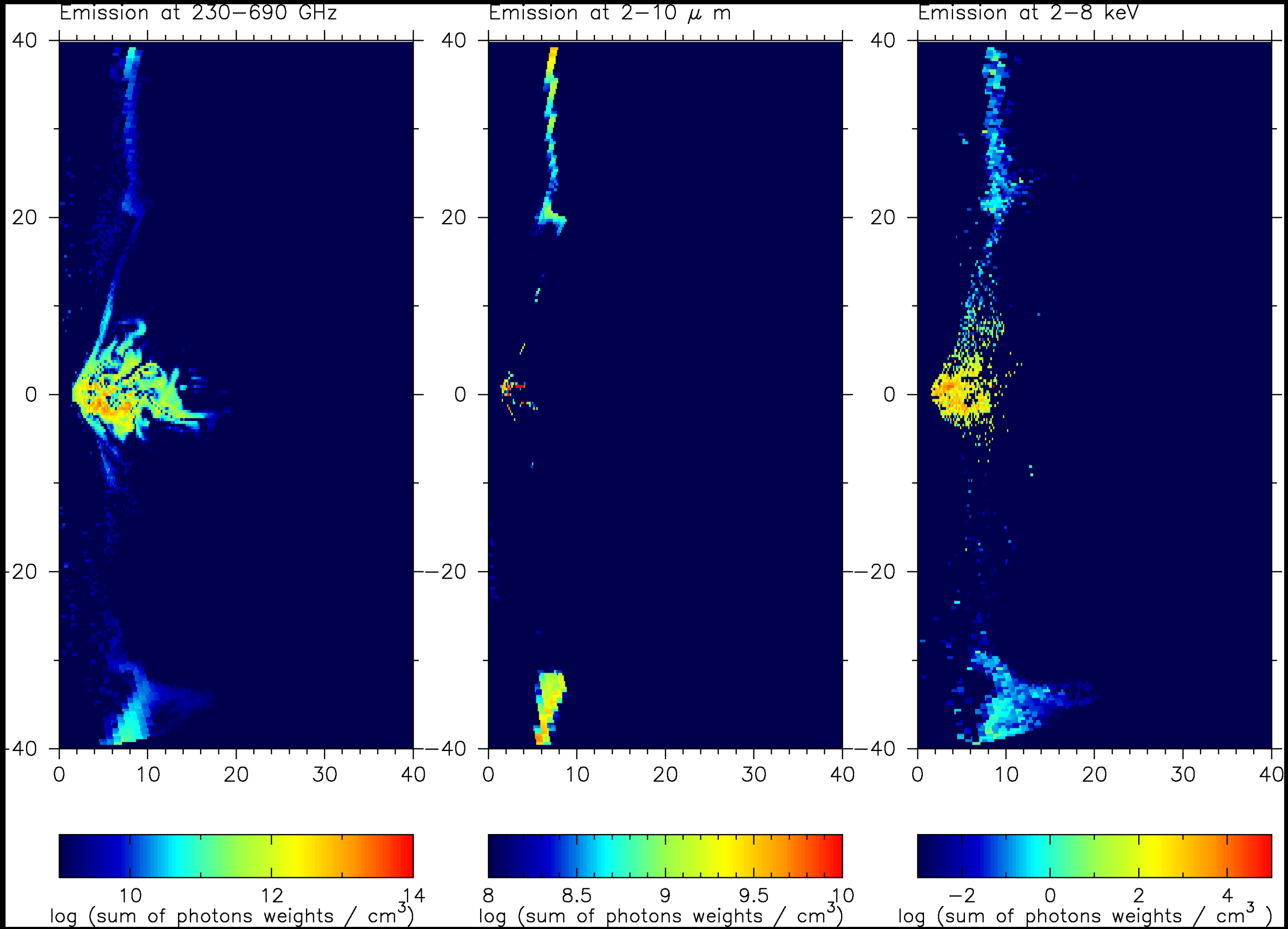
**Sgr A* model at 45deg**
**230 GHz**

**`ibothros`**

***Dolence et al. 2010***

***movie***

# III: Radiative Transfer




***Mosc. et al. 2009***

**Location of emitting regions in typical model**

# Outline

# IV: Results - Parameter Survey

## Parameters

M - black hole mass

D - black hole distance

$a^*$ - black hole spin

i - inclination

dM - accretion rate

$T_p/T_e$ - temperature ratio

(numerical and initial condition parameters)

## Constraints

Stellar orbits fix M and D

(1) 1.3mm flux – fixes dM

(2) 1.3mm slope – fixes $T_p/T_e$

(3) 1.3mm size – constrains both $T_p/T_e$ and dM

(4) IR upper limits on quiescent flux

(5) X-ray upper limits on quiescent flux

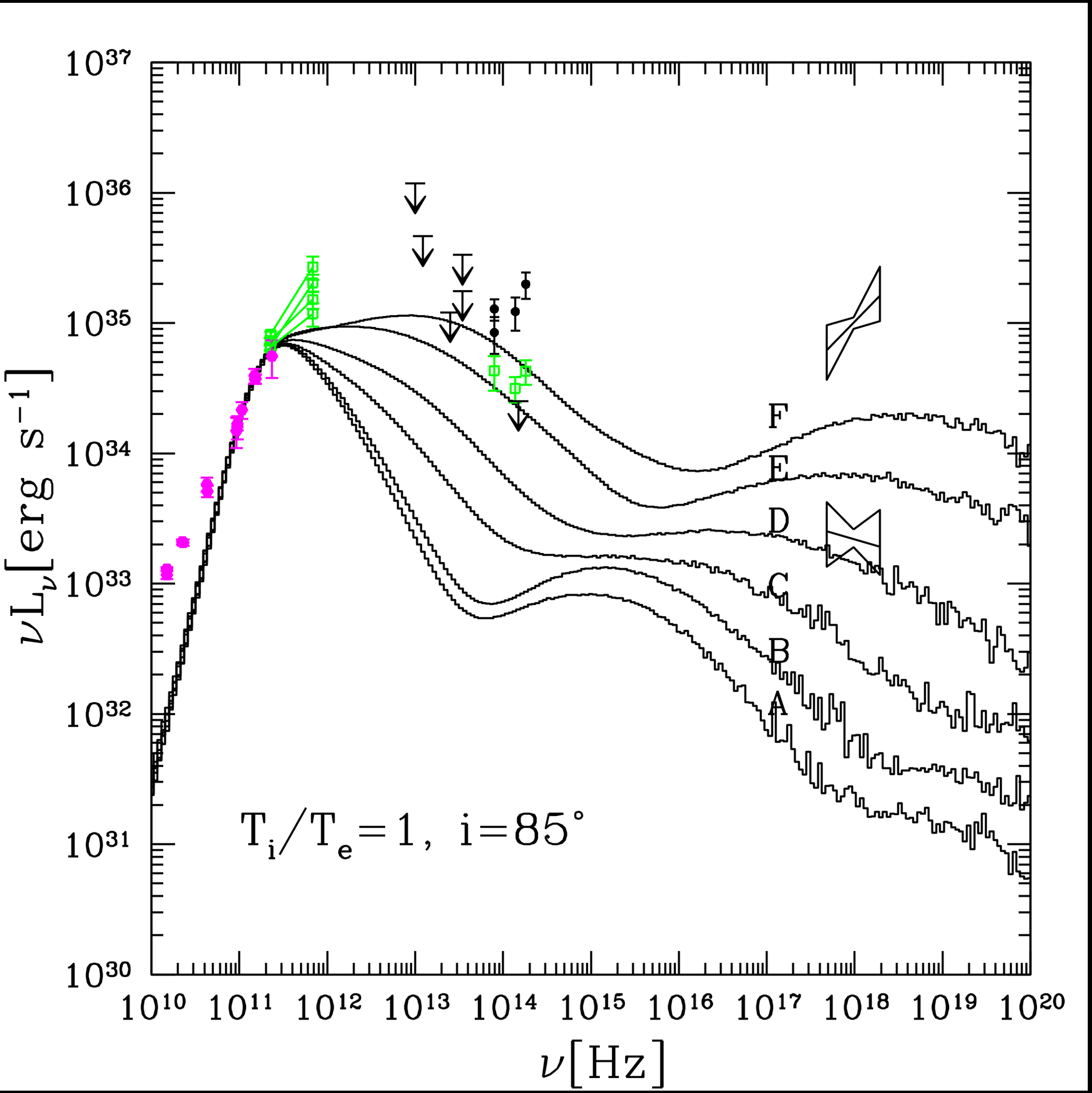
# IV: Results

**All models w/ $T_p/T_e = 1$ ruled out**

**Fail to fit submm slope**
***or***
**Overproduce X-rays**

**A: a* = 0.5**
**B: a* = 0.75**
**C: a* = 0.93**
**D: a* = 0.96**
**E: a* = 0.98**

**Moscibrodzka et al. 2009**



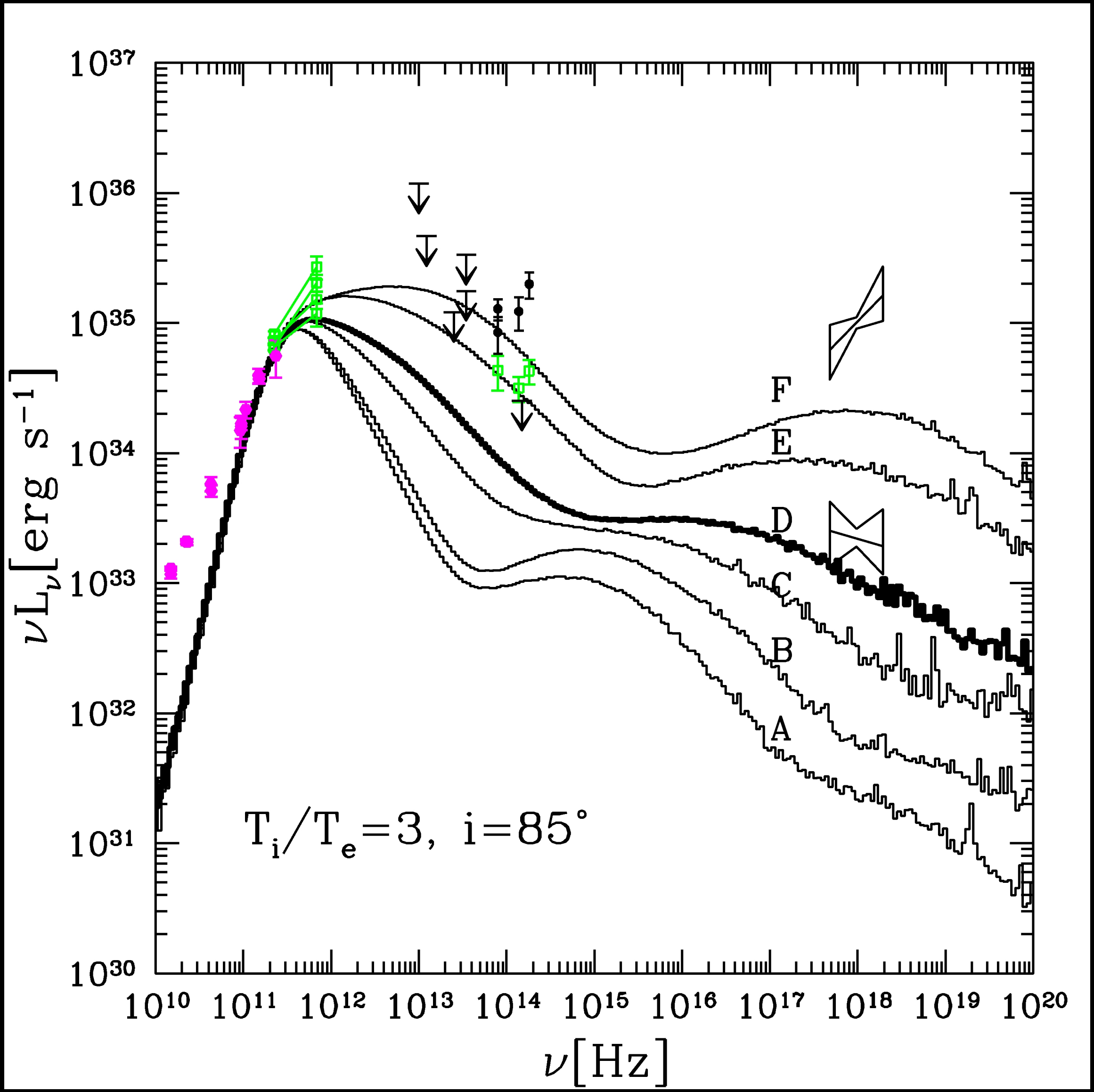
# IV: Results

**Best bet model:**
**$T_p/T_e$ = 3**
**a* = 0.93**
***i* = 85deg**

**Fits submm slope**
**Doesn't overproduce X-rays**

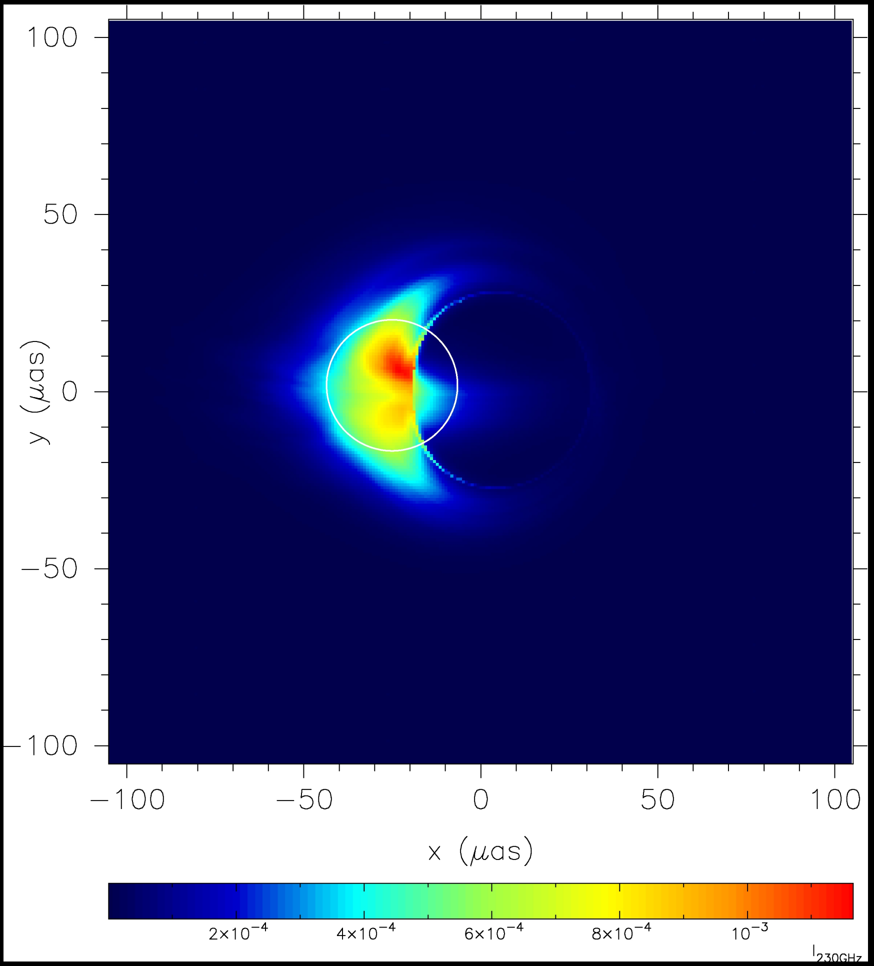
**A: a* = 0.5**
**B: a* = 0.75**
**C: a* = 0.93**
**D: a* = 0.96**
**E: a* = 0.98**

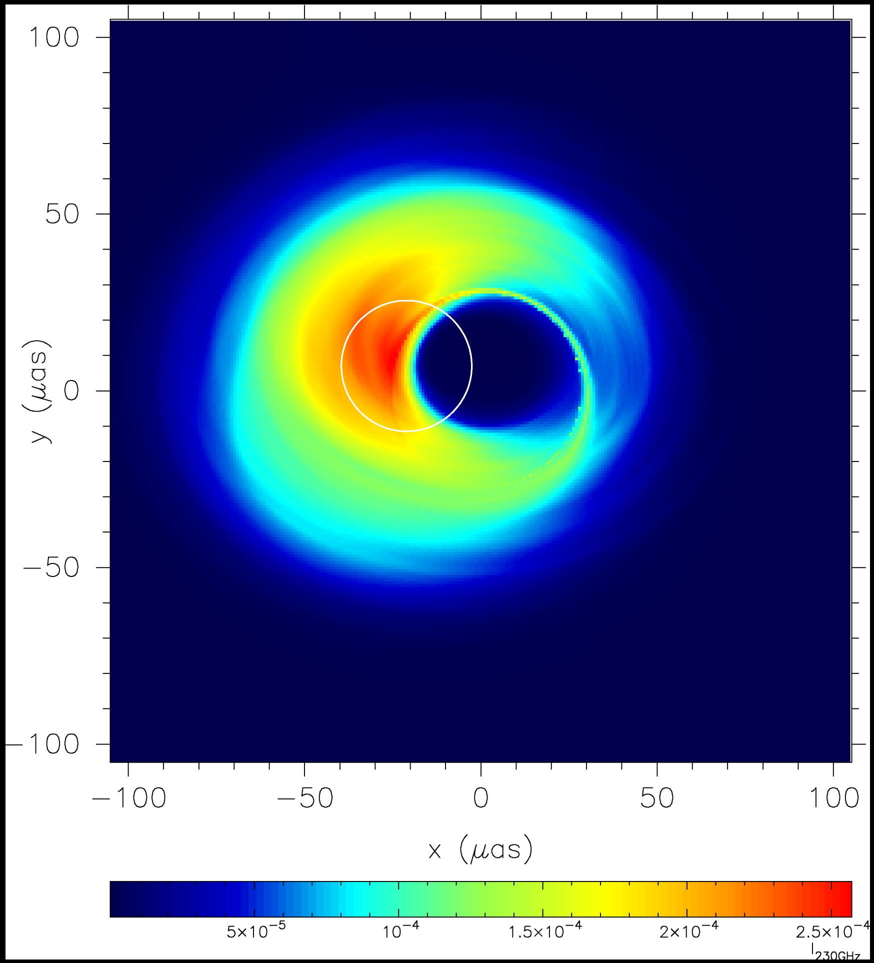
**Moscibrodzka et al. 2009**



# IV: Results

**Models with**
**$T_p/T_e = 3$**
**consistent with 1.3mm VLBI**




**Models with**
**$T_p/T_e = 10$**
**tend to be too large**

**Moscibrodzka et al. 2009**

# V: Summary

**Fully relativistic fluid/radiation models of Sgr A***

**- Submm slope/X-rays rules out models w/ $T_p/T_e = 1$**

**- Best-bet model: a* = 0.93, $T_p/T_e = 3$, i = 85deg**

**- Models w/ $T_p/T_e = 10$ tend to be too large for 1.3mm VLBI constraint.**

**Future:**

***consistent time-dependent polarized spectra,***
***combined fluid - radiation code,***
***pair production,***
***electron heating model***