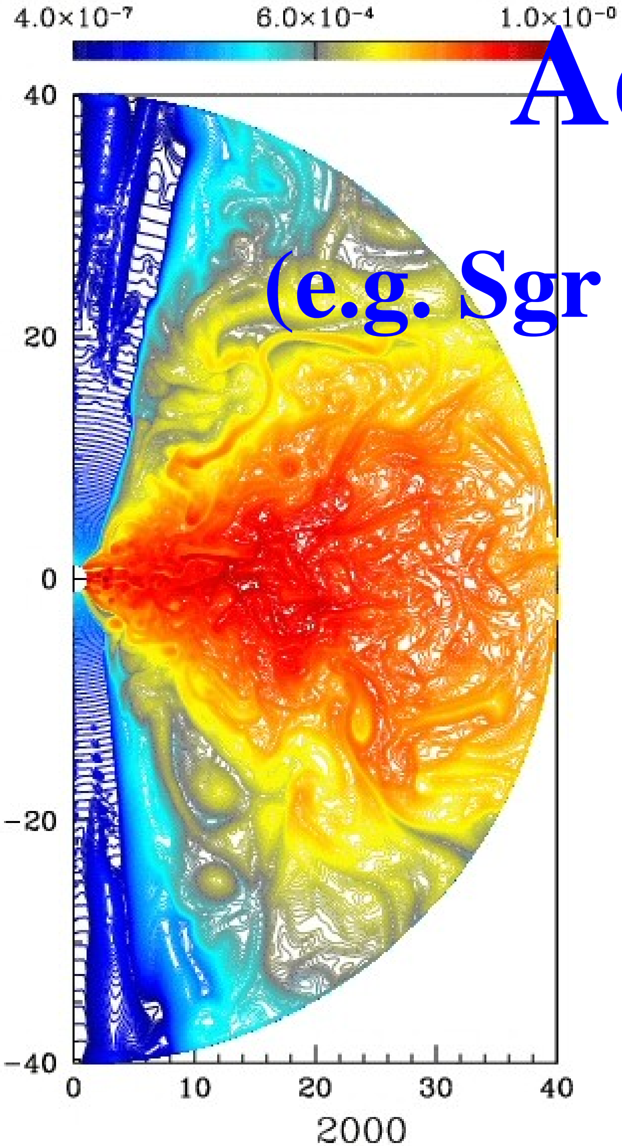
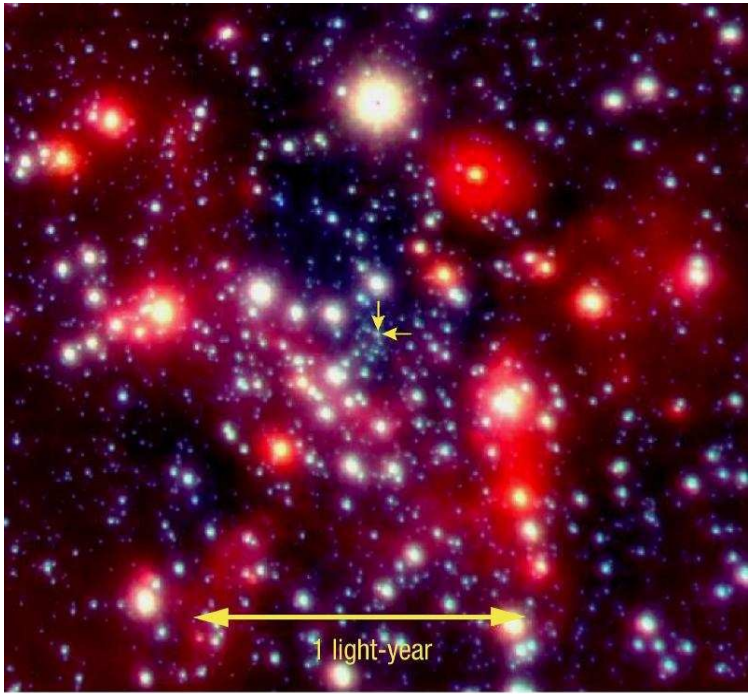
Simulating and Imaging Accretion Disks

(e.g. Sgr A*, i.e. the Galactic Center)



Scott C. Noble

FLAMR 2
Workshop
CITA
June 2, 2006



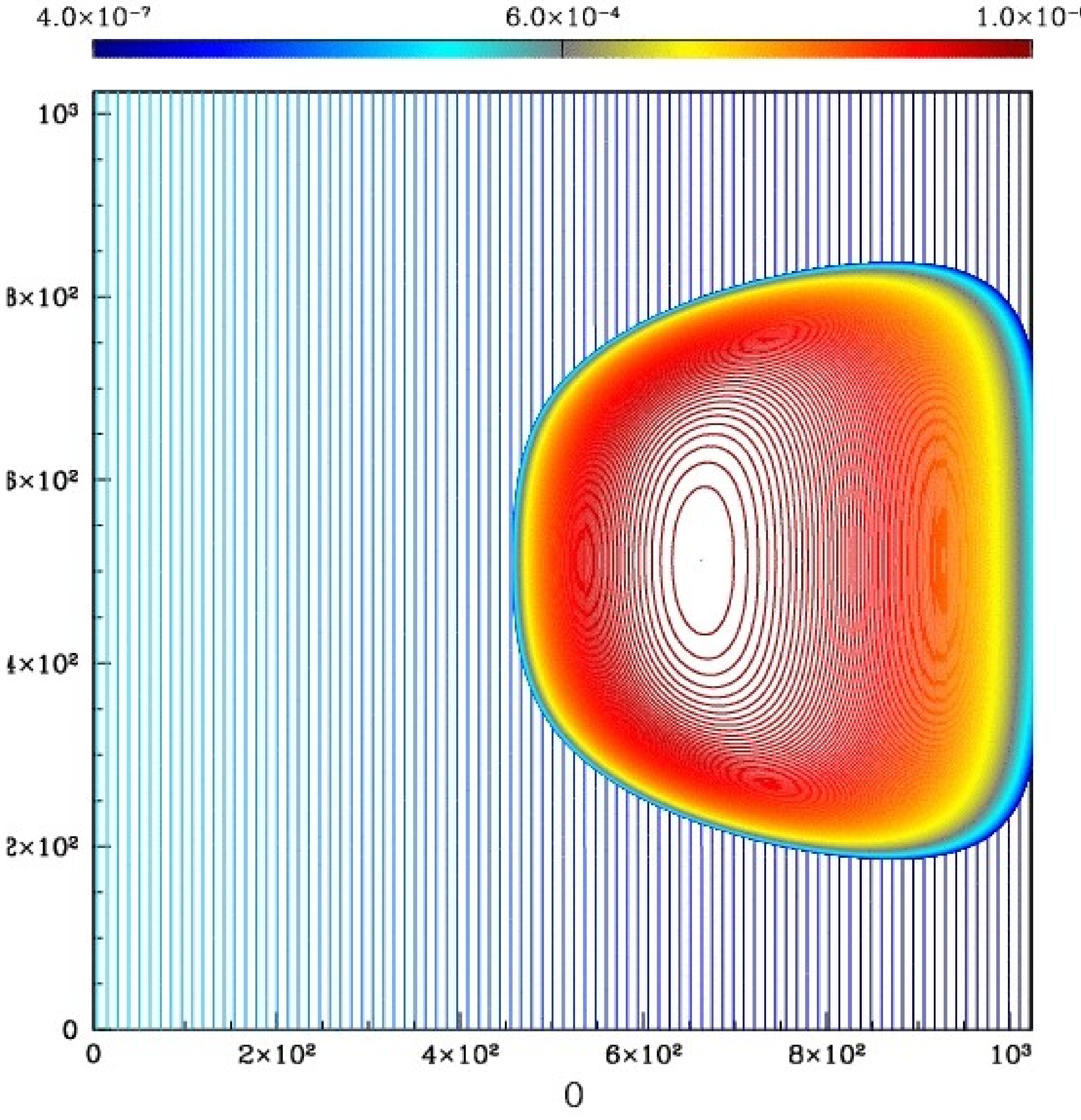
Outline:

- HARM Primer
- When Good Codes go Bad
  - Charles Gammie, Jon McKinney, L. Del Zanna
- Outflow Evolutions
  - Charles Gammie
- Sgr A* Introduction
- Radiative Transfer Calculations of Simulations
  - Charles Gammie, Po Kin Leung, Laura Book

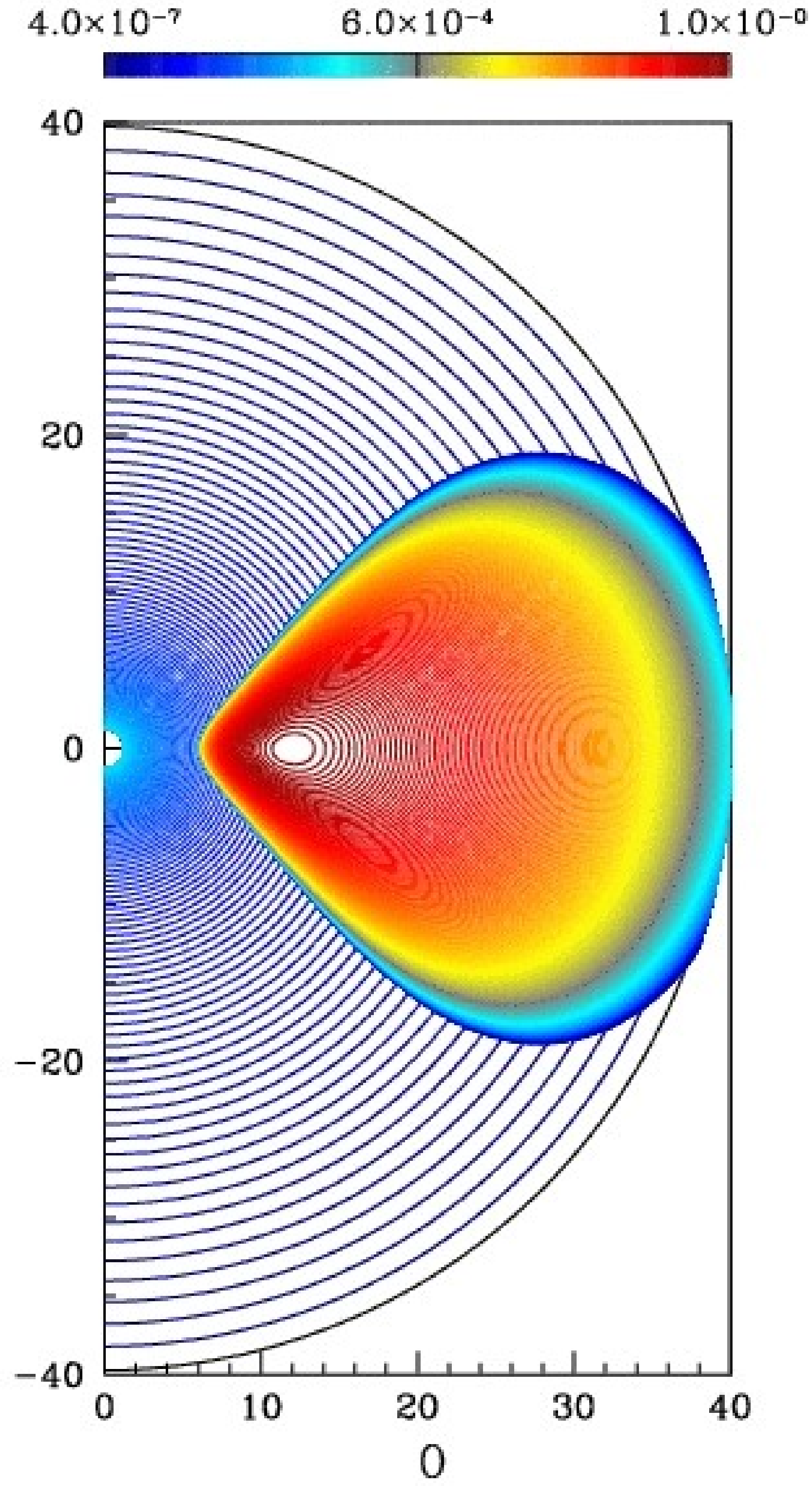
HARM (Gammie, McKinney, Toth 2003)

- Axi., fixed background (Kerr-Schild), MHD
- Conservative (not Zeus-like!)
- HLL, ~~LF~~ KT fluxes, need e. values (good enough)
- 1st-order limiters (minmod, MC)
- Flux-CT scheme imposes divergence constraint
- Parallelization via Domain Decomposition
- "5D" and "Del Zanna" Inversion routines
- Covariant Infrastructure

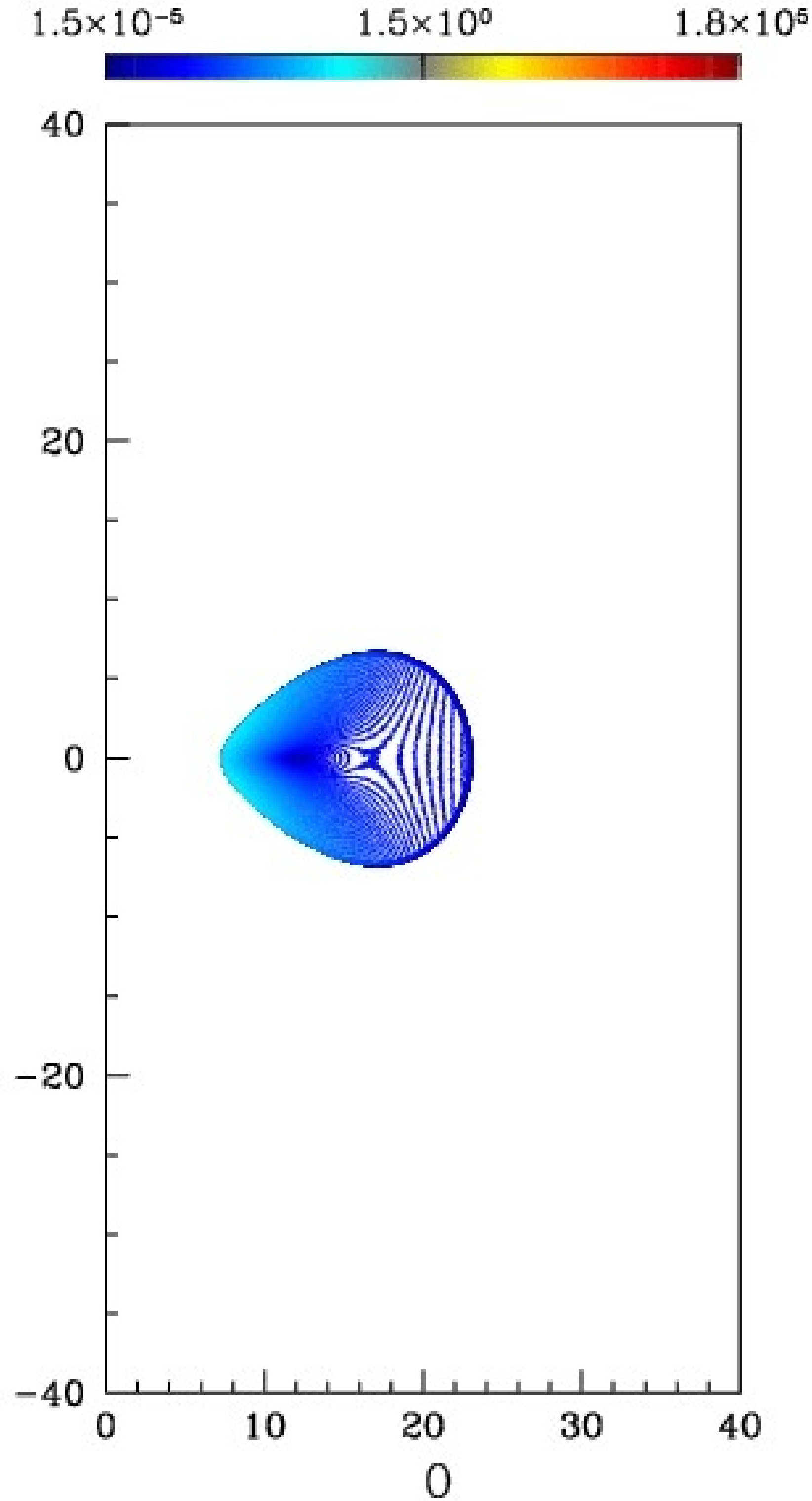
$$\theta = \pi X_2 + h \sin(2\pi X_2) \qquad r = e^{X_1}$$



4.0×10⁻⁷
6.0×10⁻⁴
1.0×10⁻⁰
10³
8×10²
6×10²
4×10²
2×10²
0
0
2×10²
4×10²
6×10²
8×10²
10³
0



4.0×10⁻⁷
6.0×10⁻⁴
1.0×10⁻⁰
40
20
0
−20
−40
0
10
20
30
40
0



1.5×10⁻⁵
1.5×10⁰
1.8×10⁵
40
20
0
−20
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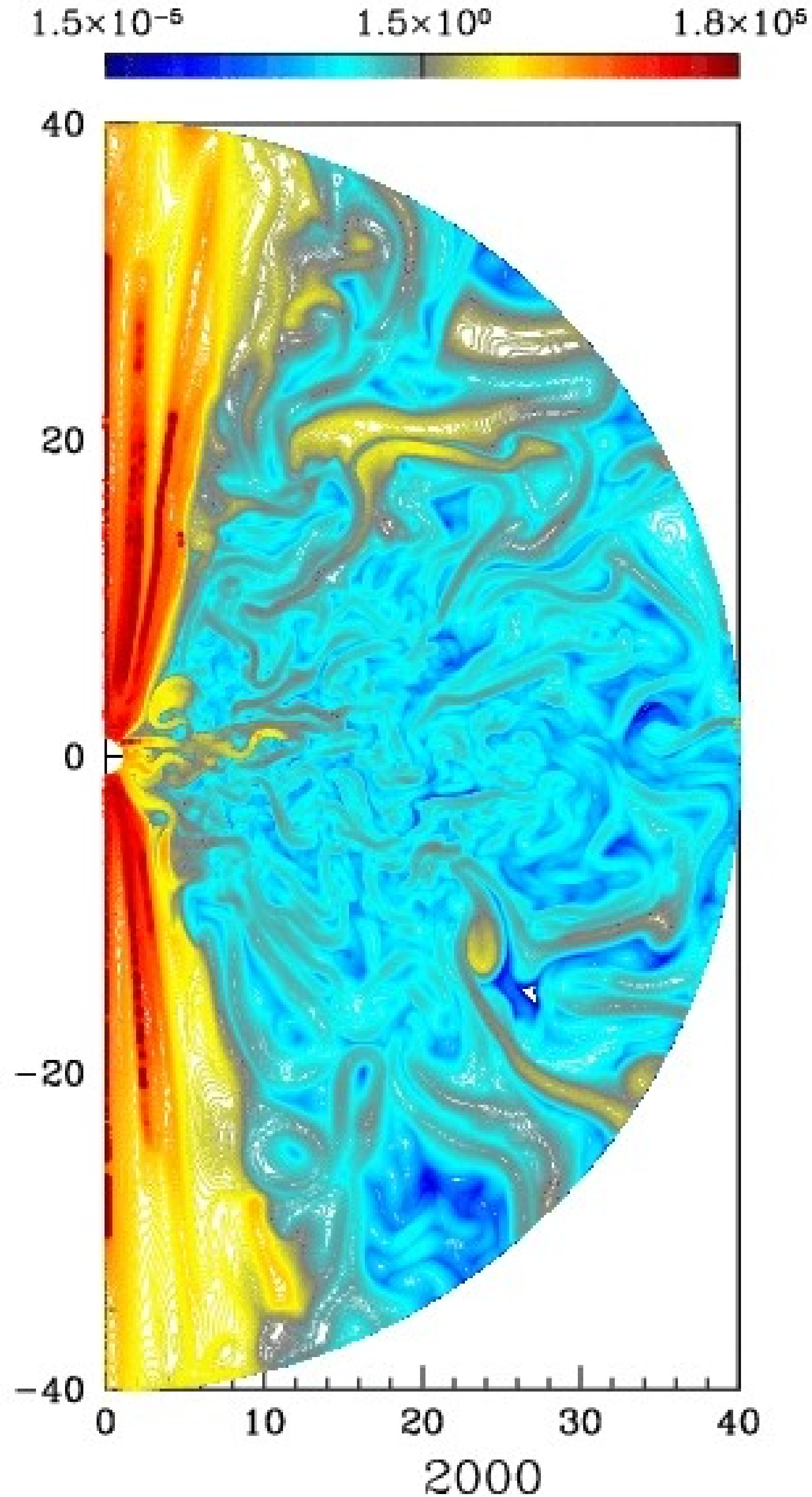
10
20
30
40
0



1.5×10⁻⁵
1.5×10⁰
1.8×10⁵
40
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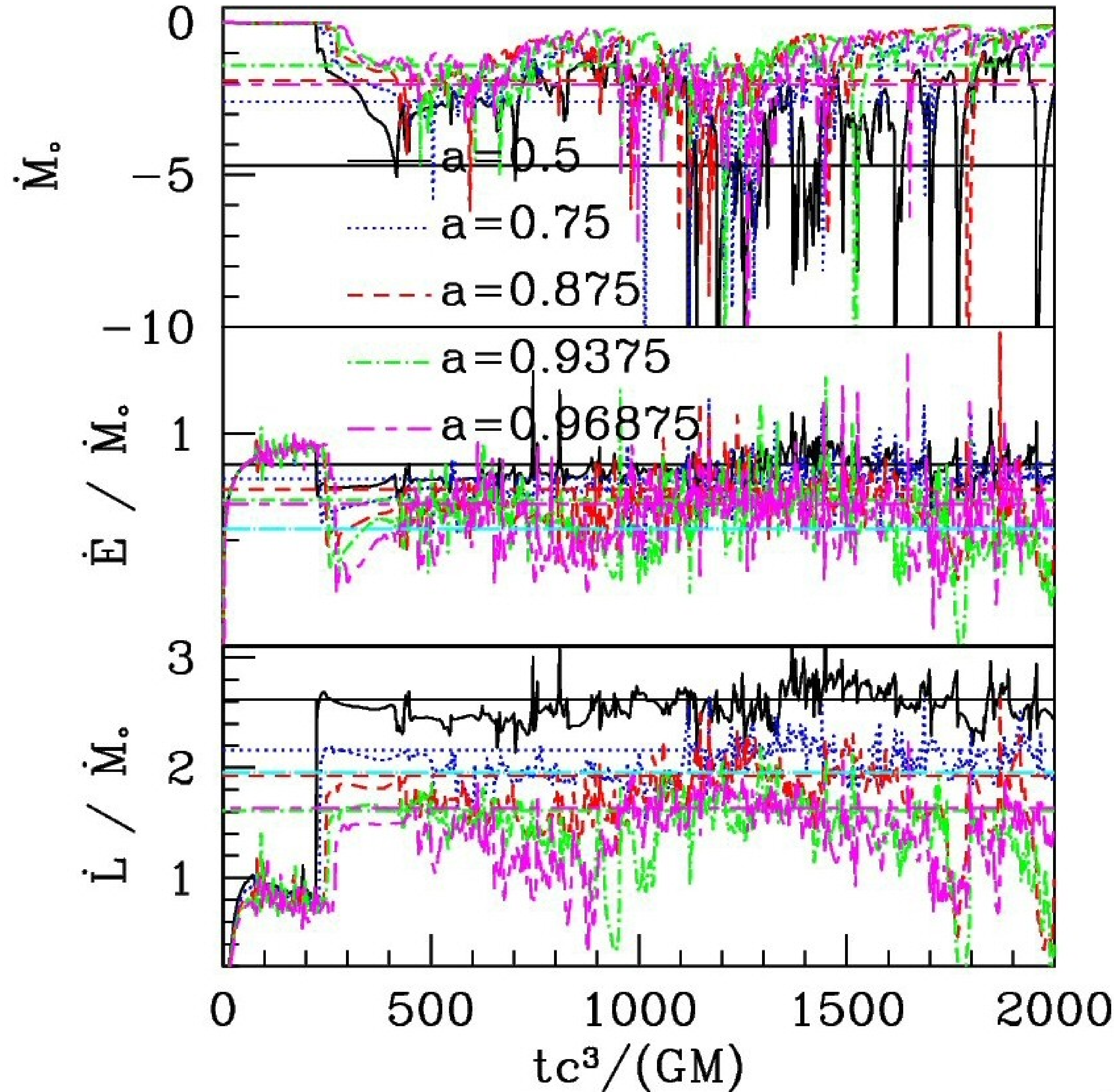
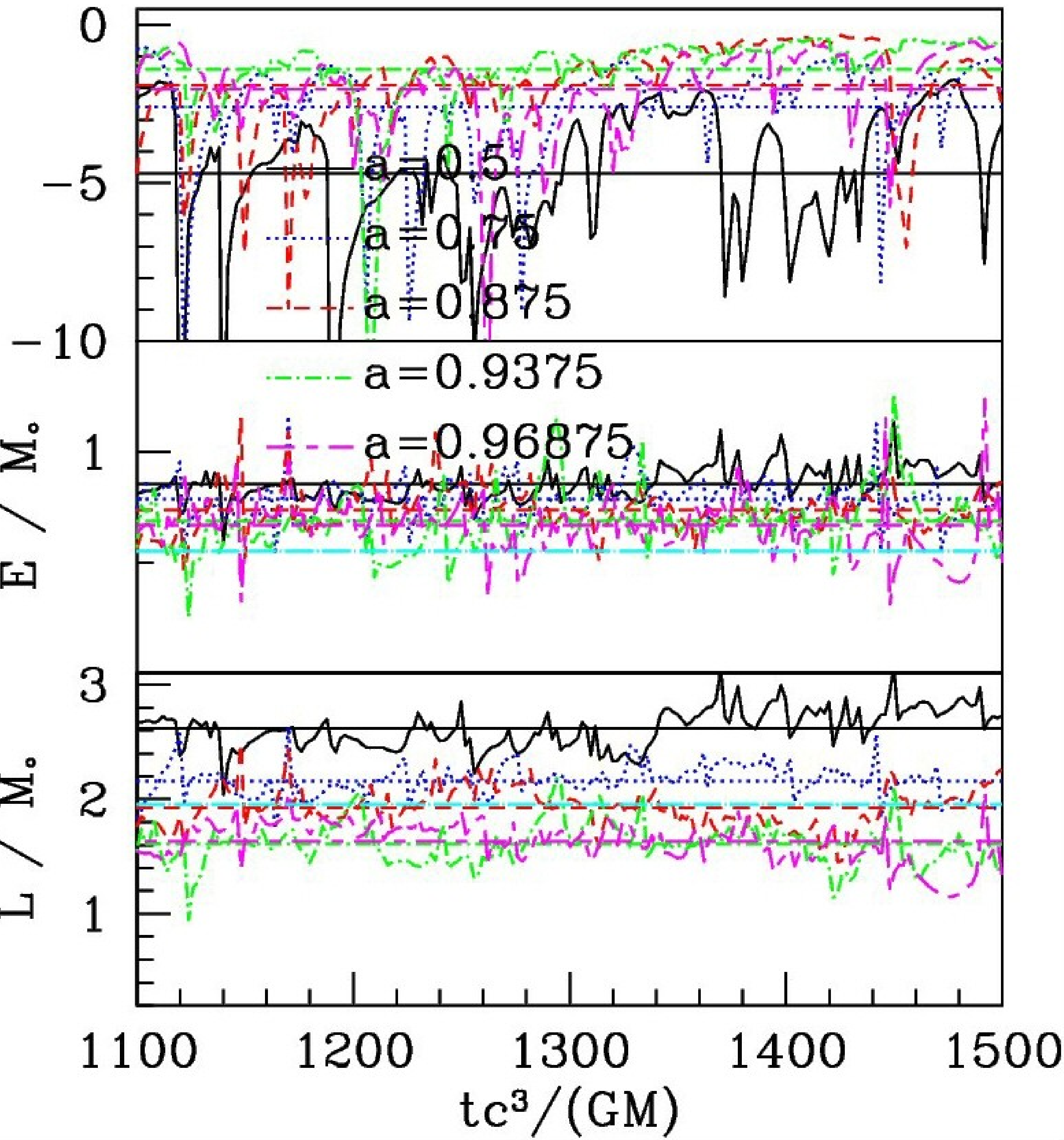
40
2000



$\dot{M}_\circ$
0
−5
−10
a=0.5
a=0.75
a=0.875
a=0.9375
a=0.96875
$\dot{E}\ /\ \dot{M}_\circ$
1
$\dot{L}\ /\ \dot{M}_\circ$
3
2
1
0
500
1000
1500
2000
$tc^3/(GM)$



$\dot{M}_\circ$
$\dot{E}\ /\ \dot{M}_\circ$
$\dot{L}\ /\ \dot{M}_\circ$
a=0.5
a=0.75
a=0.875
a=0.9375
a=0.96875
0
−5
−10
1
3
2
1
1100
1200
1300
1400
1500
$tc^3/(GM)$

Failure Modes

- Most failures along axis and horizon, especially both: Pmag >> Pgas,   v~1
  - Leads to "stiff" PDE's where $Trunc(B) \sim p, \rho$

- Large gradients/velocities lead to large changes in dU/dt --> bad for P(U)
  - --> Need better inversion routines... ?

Inversion Methods

$$Q_\mu = -n_\nu T^\nu{}_\mu \qquad Q_\mu n^\mu = -\frac{B^2}{2}(1+v^2) + \frac{(Q.B)^2}{2W^2} - W + p$$

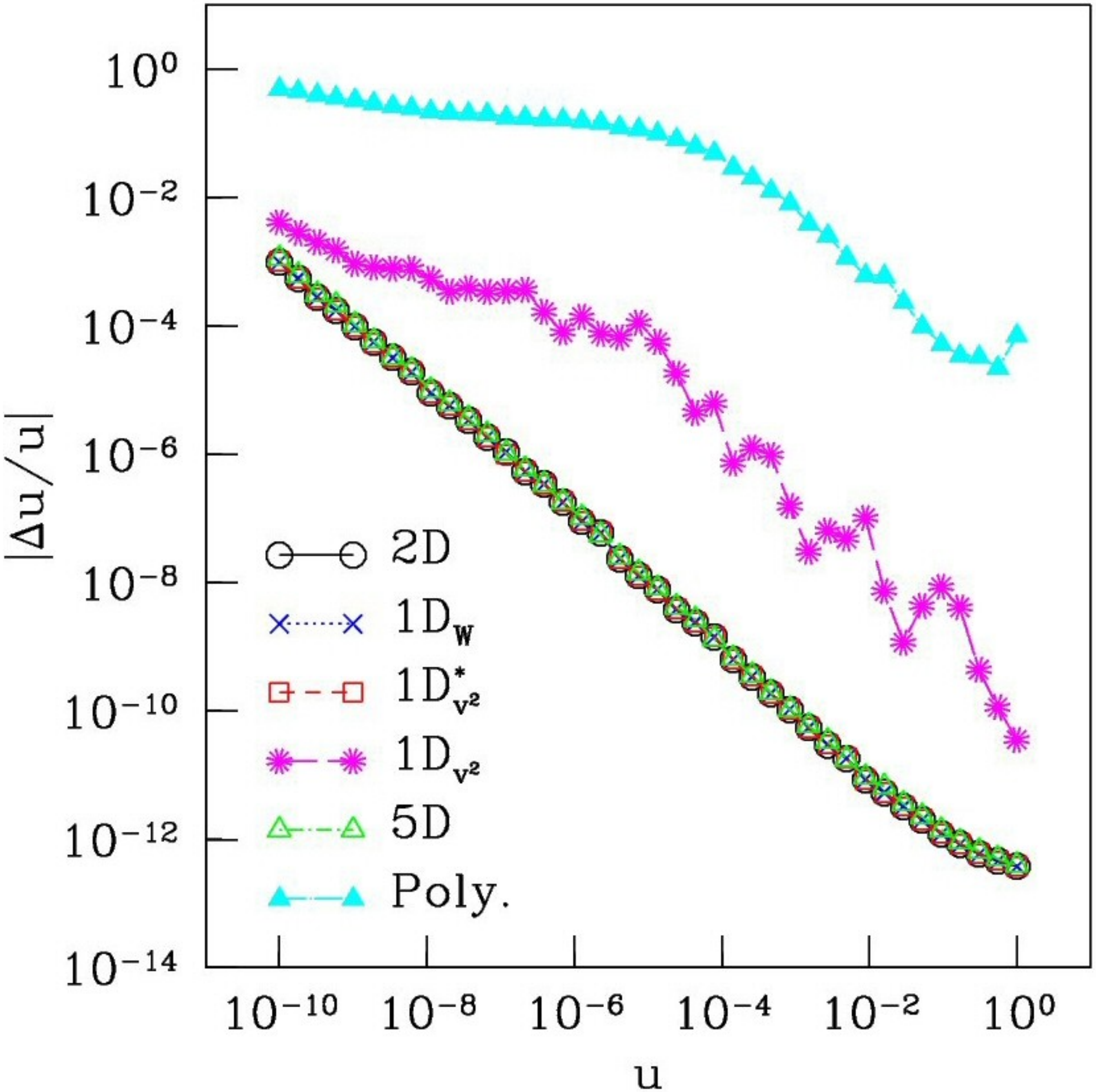
$$\tilde{Q}_\mu = (g_{\mu\nu} + u_\mu u_\nu) Q^\nu \qquad \tilde{Q}^2 = v^2 (B^2 + W)^2 - \frac{(Q.B)^2 (B^2 + 2\mathrm{W})}{W^2}$$

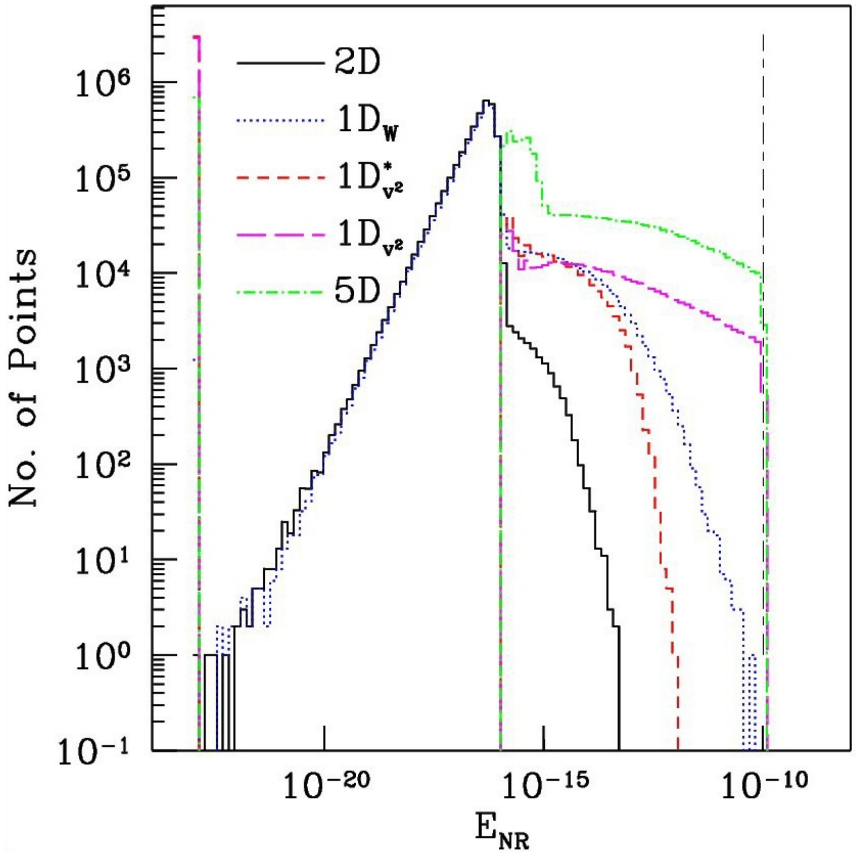
- 5D: Num. Inv. U(P)
- 2D: solve both for v^2 and W
- 1DW: eliminate v^2 by Q^2, solve Q.n
- 1Dvsq: solve quartic Q.n for W, NR Q^2 for v^2
  - Only relevant for ideal-gas EOS
- Poly.: Q^2 -> Q.n -> 8th order poly. (EOS)

Phase Space Survey

$$\log_{10}\rho_\circ \in [-7,1]\ ,\ \log_{10}u \in [-10,0]\ ,\ \log_{10}\gamma \in [0.002, 2.9]\ ,$$

$$\log_{10}B^2 \in [-8,1]\ ,\ \cos\Phi \in [-1,1]\,.$$





Phase Space Survey

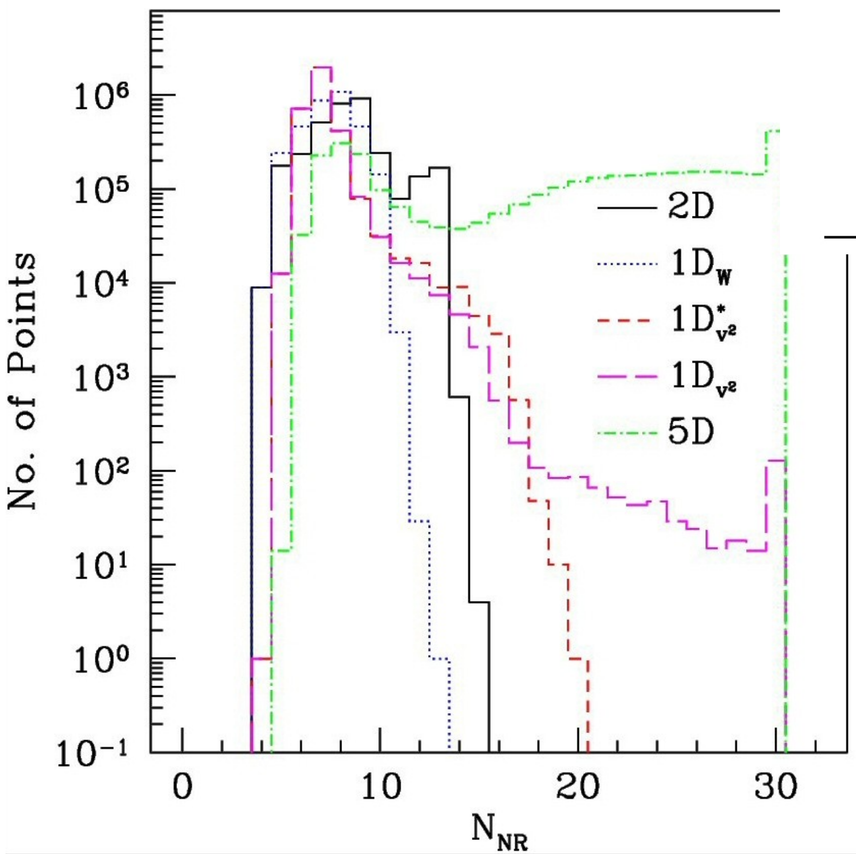
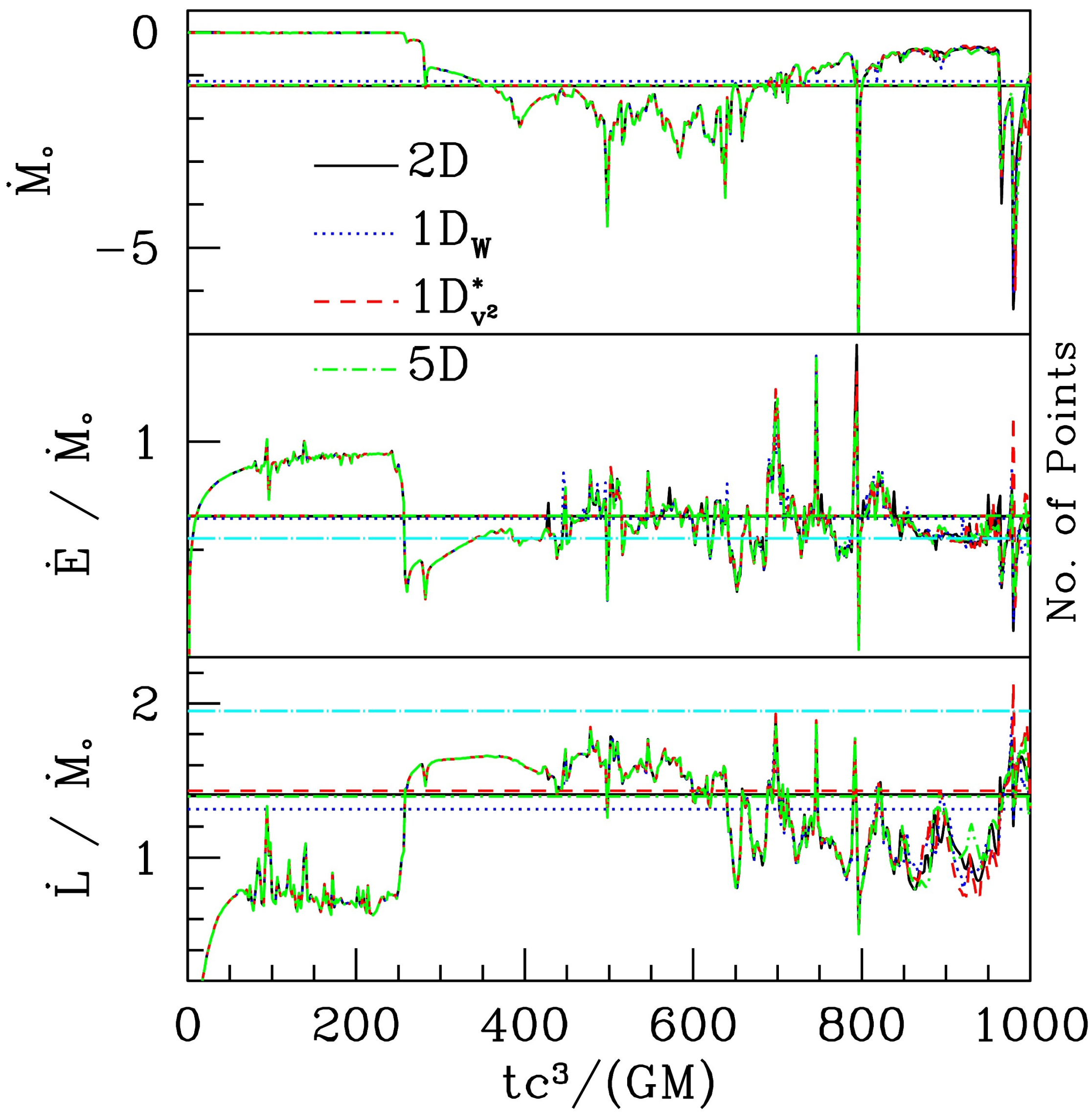
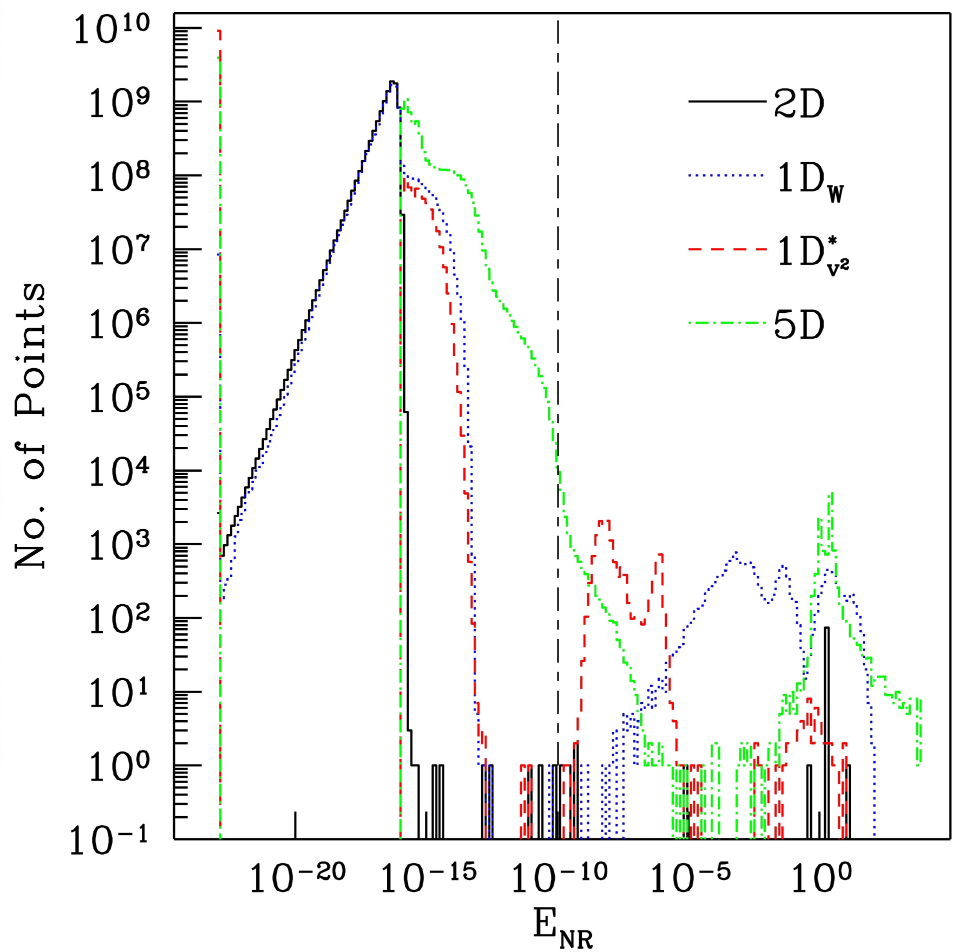


Table 3. Parameter Space Efficiency Comparison

Method	NR steps per sol.	Sol. per sec.	Failure Rate
2D	8.45	1.66×10^5	8.7×10^{-7}
$1D_W$	7.45	1.68×10^5	8.8×10^{-4}
$1D^\star_{v^2}$	7.08	1.06×10^5	3.6×10^{-4}
$1D_{v^2}$	7.05	1.24×10^5	2.0×10^{-2}
5D	19.3	1.89×10^4	4.2×10^{-1}
Poly	—	9.21×10^3	4.1×10^{-2}

Accretion Disk Evolution





Accretion Disk Evolution

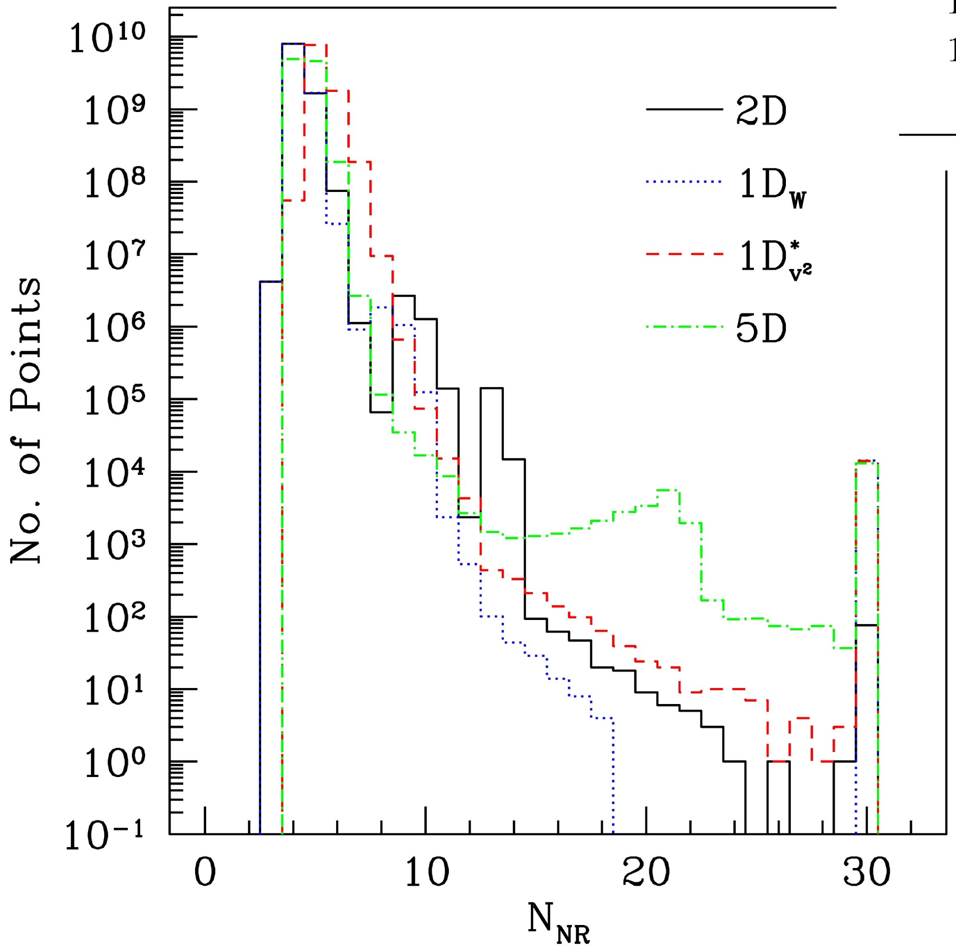
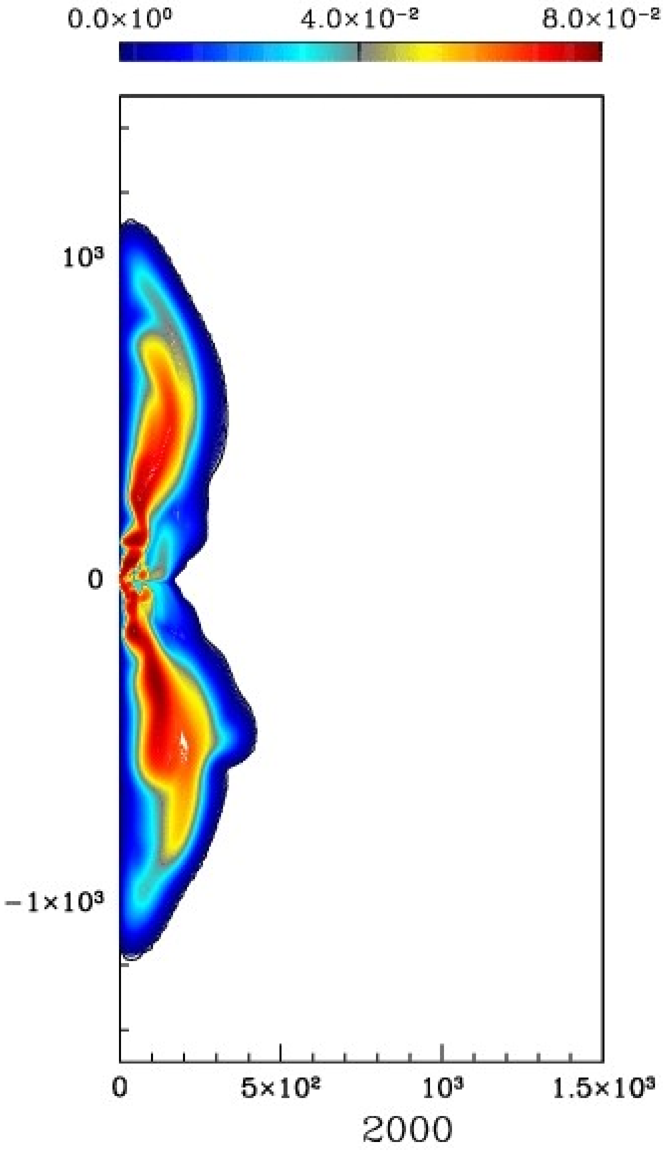


Table 6. Accretion Disk Efficiency Comparison

Method	NR steps per sol.	Zone-cycles/node/sec. [a]	Failure Rate
2D	4.19	24535	9.57×10^{-5}
$1D_W$	4.18	23860	9.33×10^{-5}
$1D^\star_{v^2}$	5.22	20585	9.46×10^{-5}
5D	4.52	14741	9.22×10^{-5}

Outflow Evolutions



$$r = e^{X_1}$$

$$\theta = \pi X_2 + h(X_1)\sin(2\pi X_2)$$

$$h(X_1) = h_0 \arctan[s(X_1^0 - X_1)]$$

Outflow Evolutions

[show random movies]

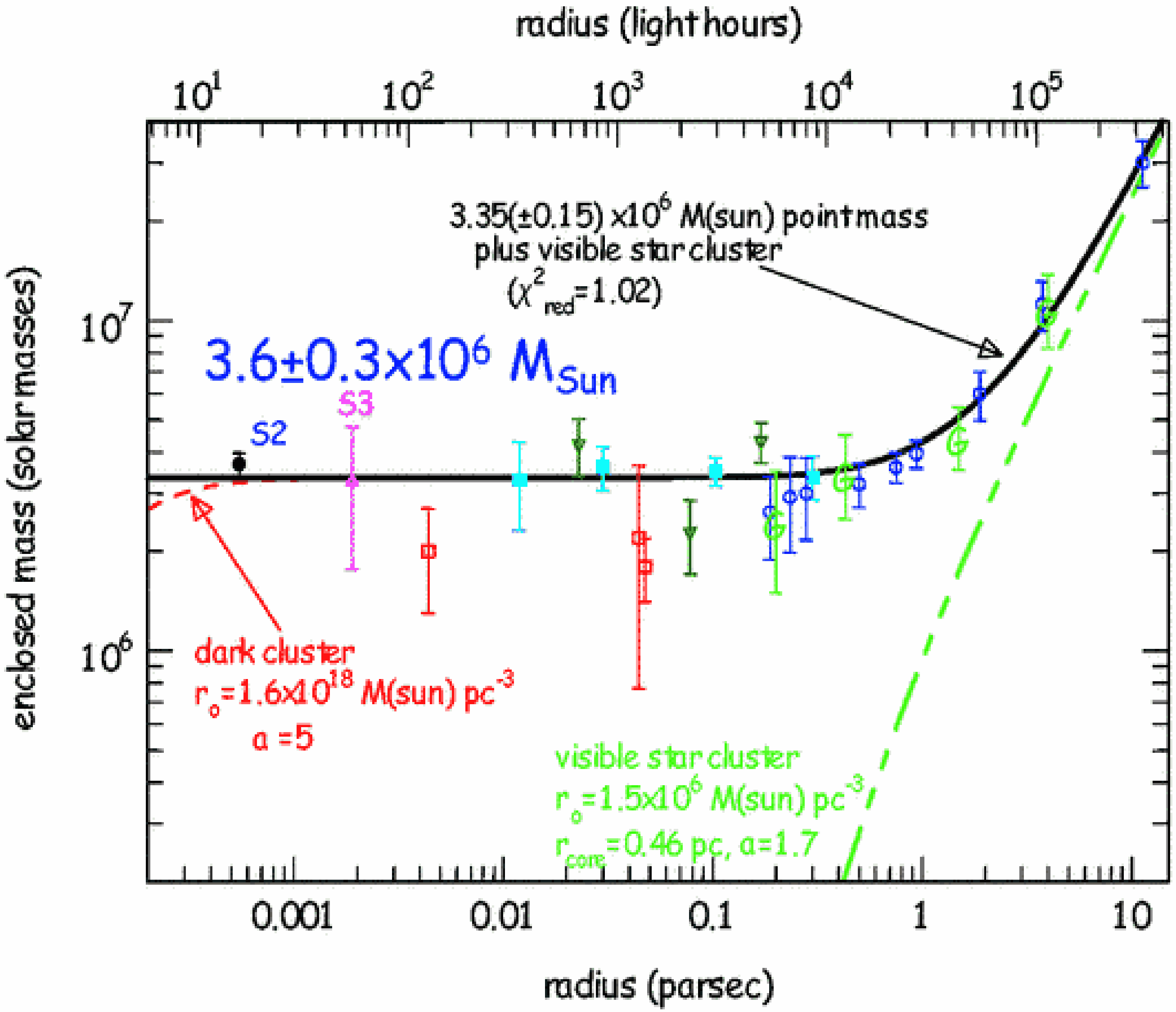
Too much contribution from floor, McKinney (2006) says to use PPM, 3rd-order Runge-Kutta for time-integration and :

$$\rho_{floor} \sim u_{floor} \quad r^{-2.7}$$

Sagitarius A*

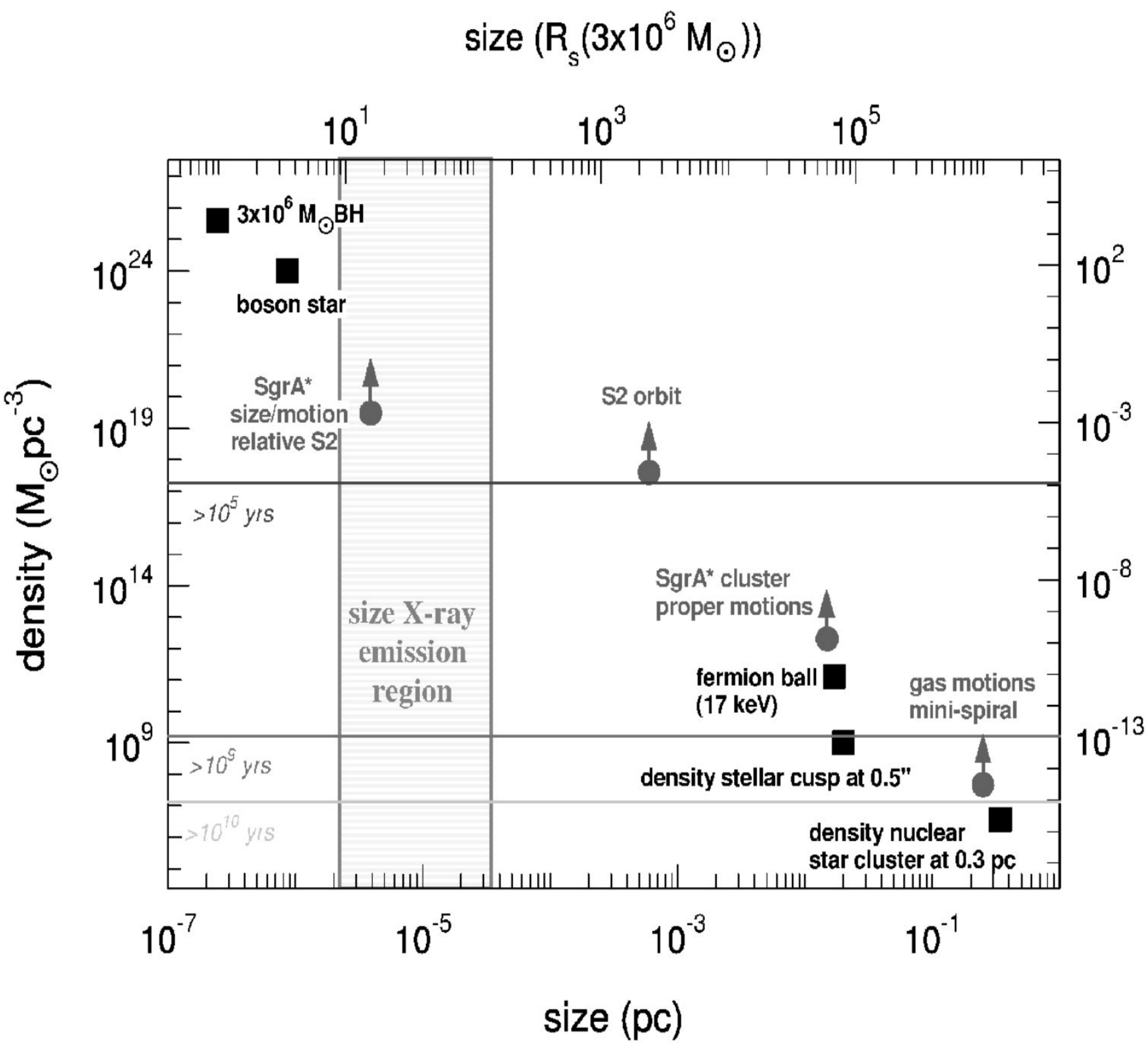
NASA/UMass/D.Wang et al. (Chandra)
120x48 arcmin or 900x400 light-year

It's a Black Hole, ok?



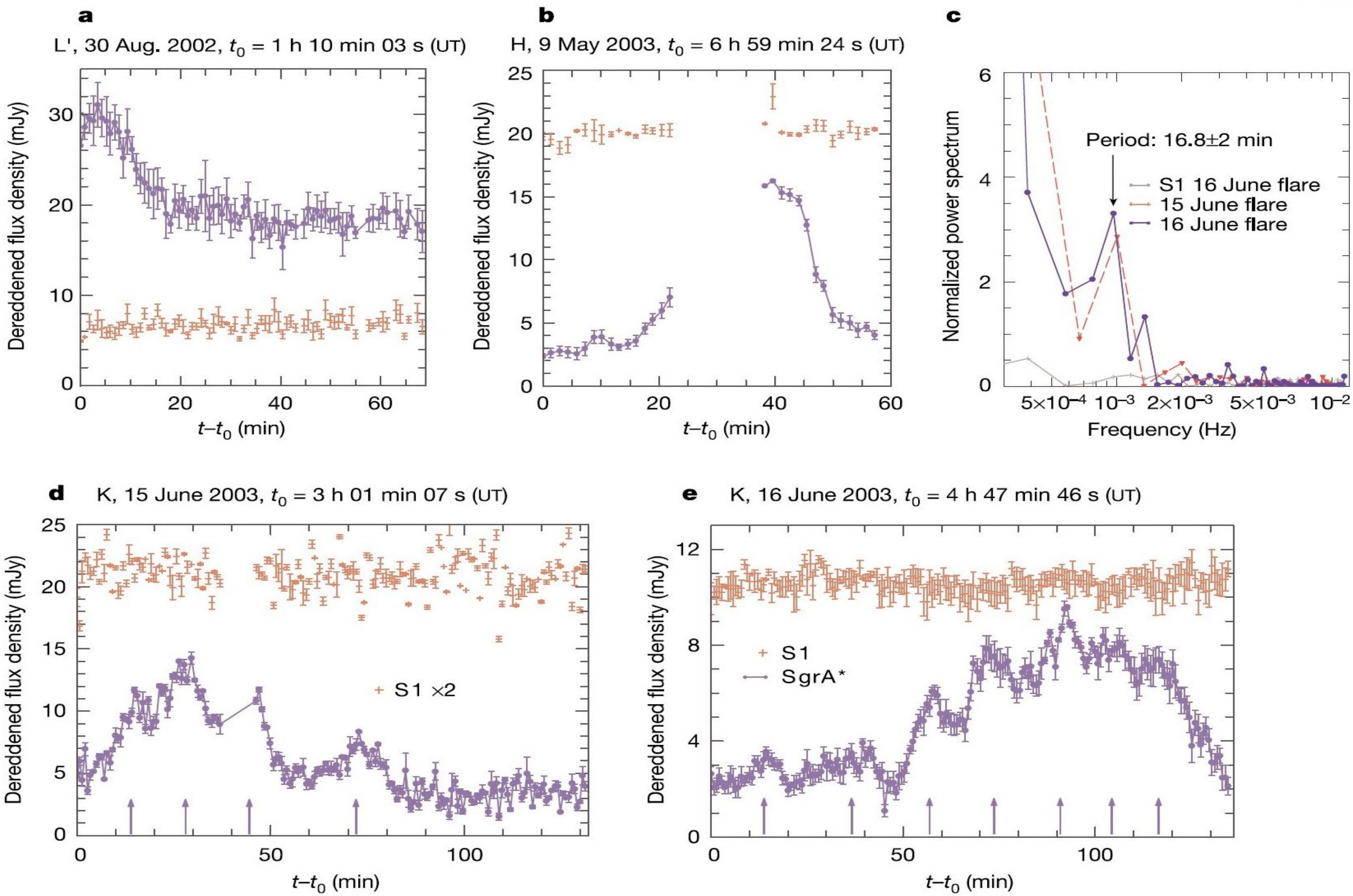
Schödel et al. 2002, 2003, Ghez et al. 2003, Eisenhauer et al. 2003, 2005

It's a Black Hole, ok?



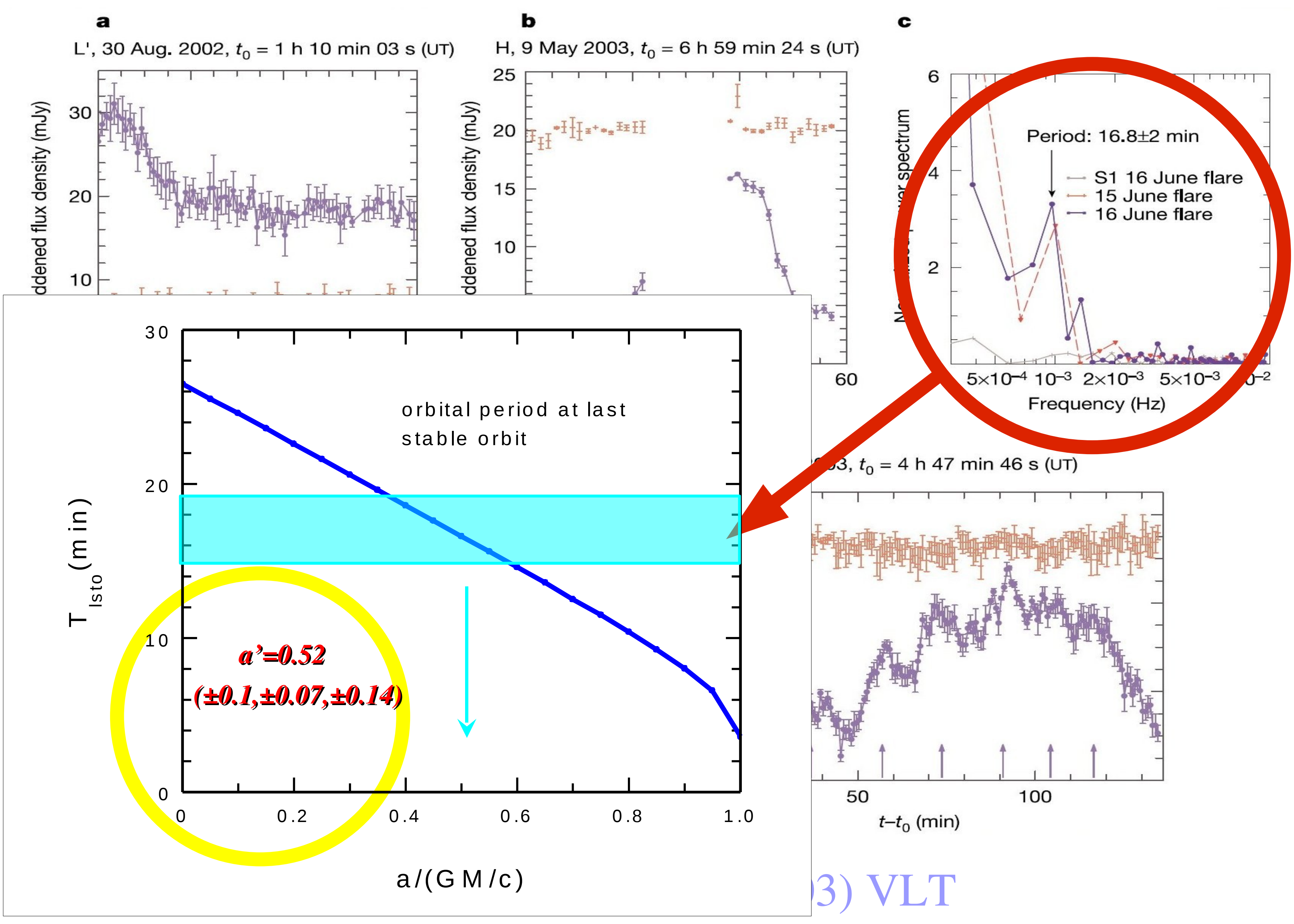
- Very few possible compact sources
- Who's seen a scalar boson anyway?
- Spectra fits well with jet & accretion models
- Some spectra features seem to indicate variability < 10 R_s
- Dark star clusters are short lived

IR Observations

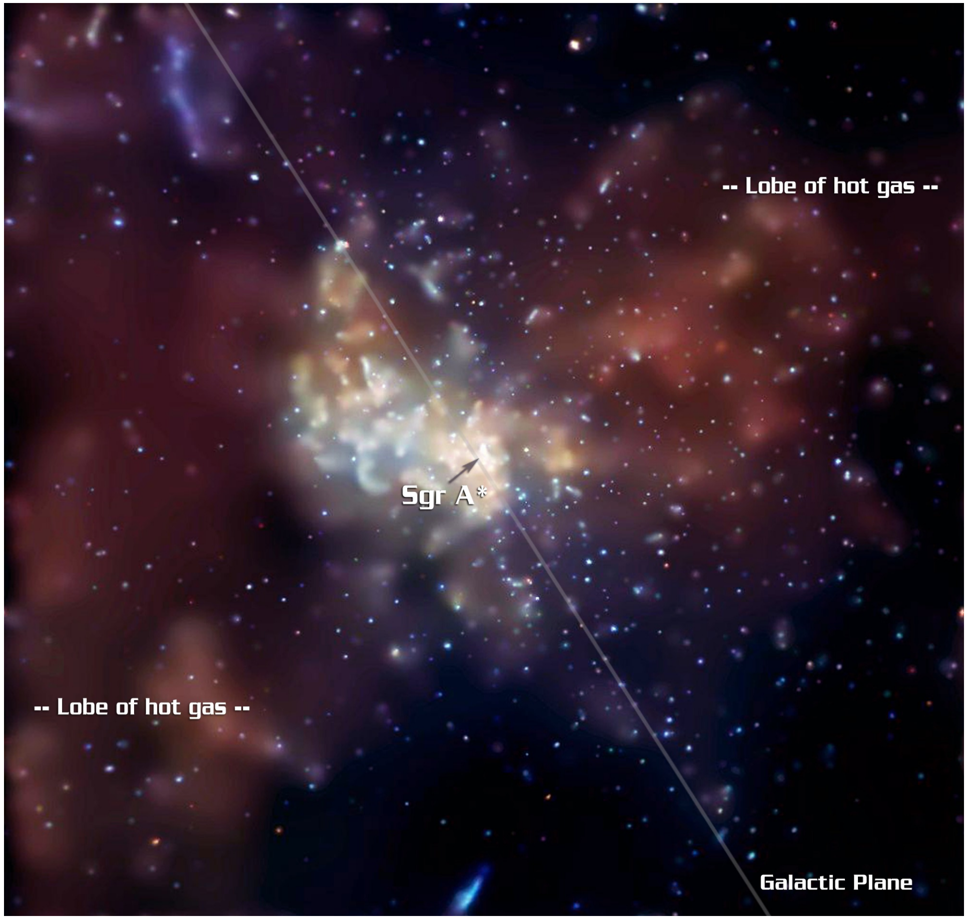


Genzel et al, Nature (2003) VLT

IR Observations

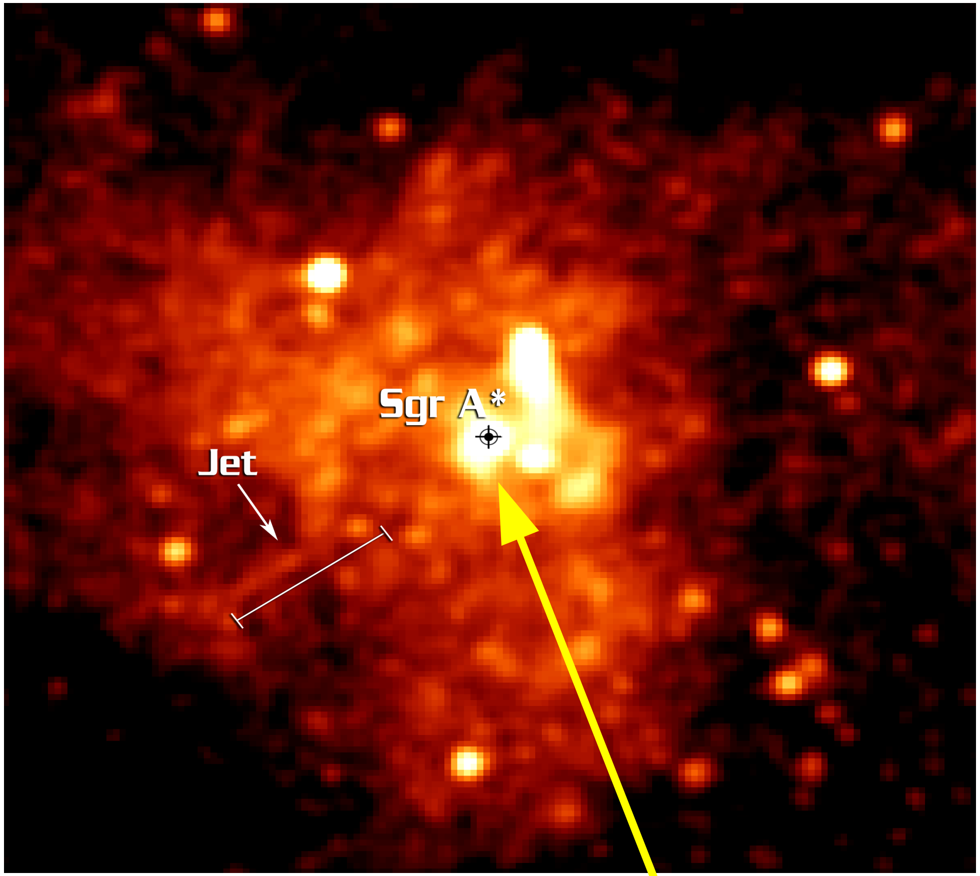


X-Ray Observations



8.4 arcmin

1.23 arcmin



1.4 arcsec

NASA/CXC/MIT/ F.K. Baganoff et al.

X-Ray and Bondi

Modeling it as kT~1.3keV hot, optically-thin emission:

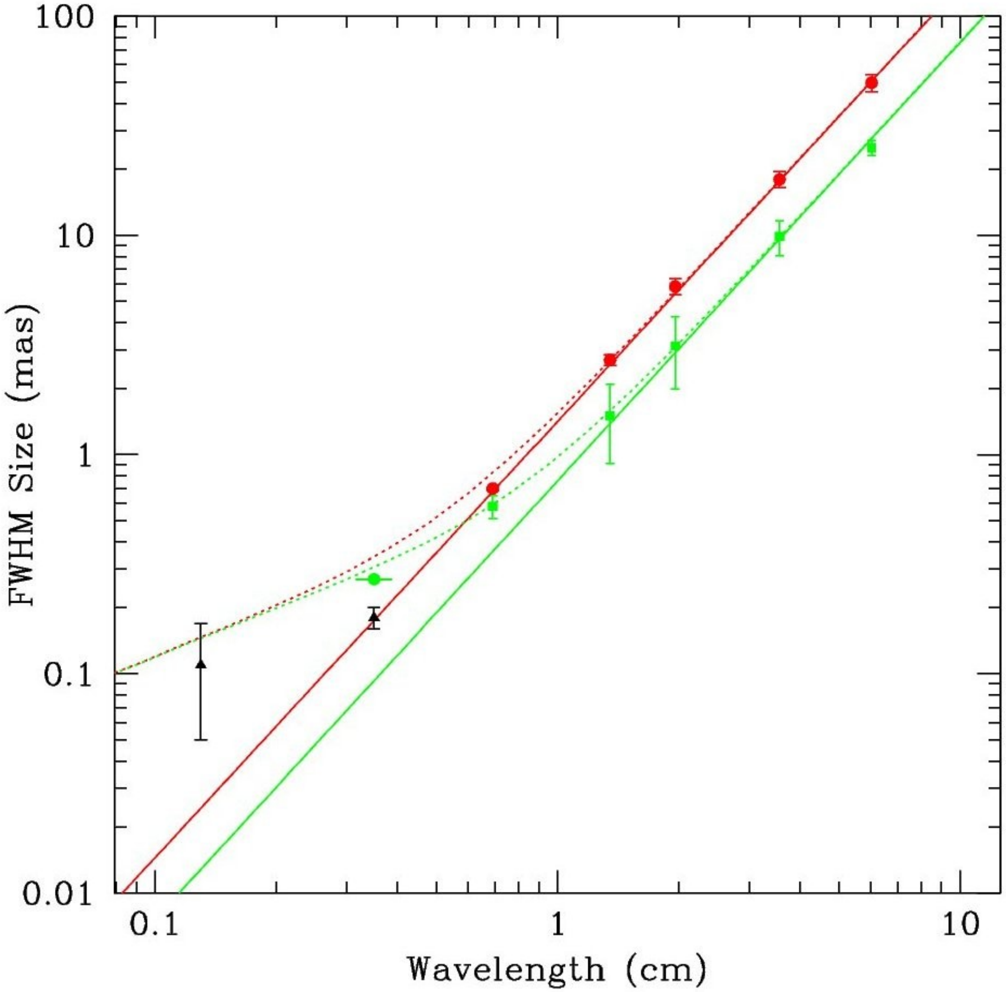
$$n_e = 30\,cm^{-3}$$

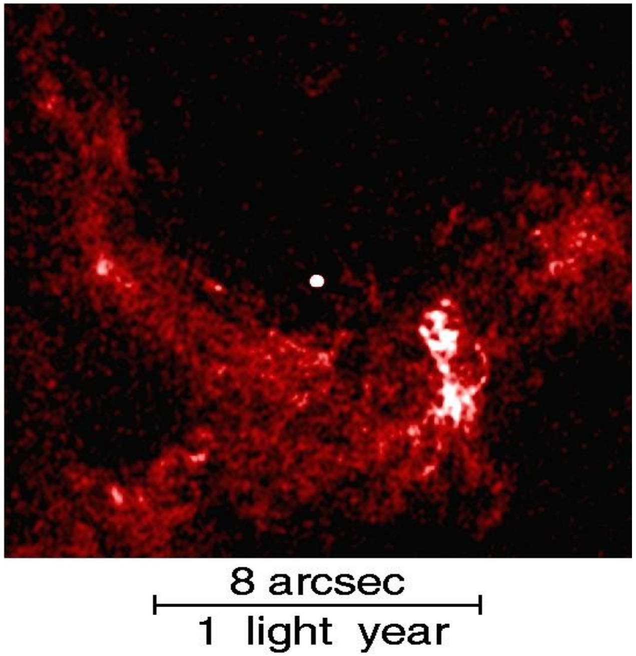
$$c_s^2 = \gamma\,kT/\mu m = 550\,km/s = v_{wind}$$

$$R_B = 2GM_{SgrA}/c_s^2 = 0.1\text{pc} = 2.7\,arcsec.$$

$$\rightarrow \quad R_B = 2R_{X-rays}$$

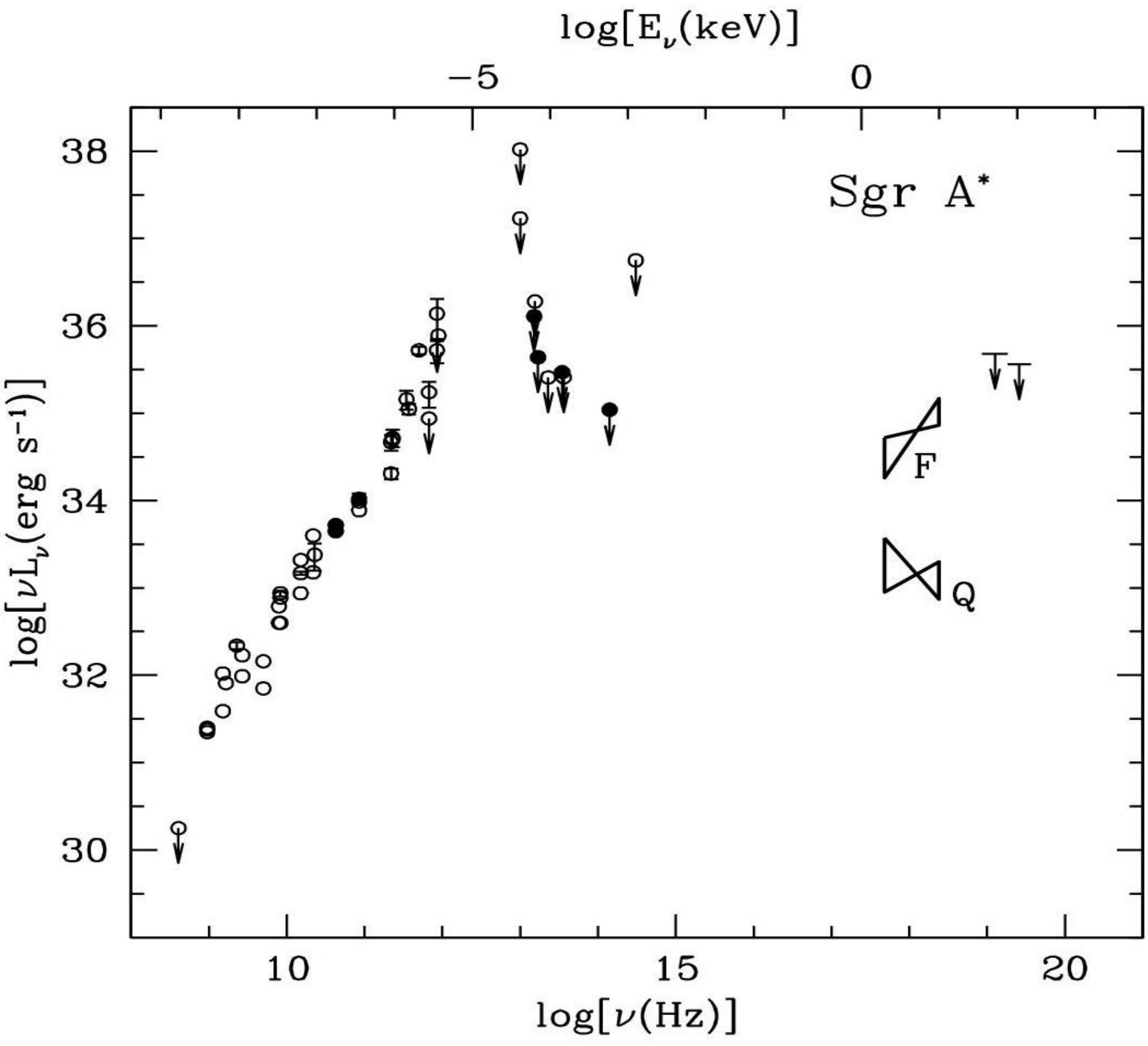
Radio (VLBA)





- Position best determined in radio
  (best res. on the planet)
- Visible Size ~ $1/\nu$
- Optically thin at ~submm λ
  —> horizon images

Composite Spectrum



The Luminosity Problem

$$L_{SgrA} = 10^{36} erg/s$$

$$L_{Edd} = 4\pi c G M \mu_e / \sigma_T = 1.51\times10^{38} (M/M_{sun}) erg/s$$

$$L_{Edd}(M_{Sgr}) = 5.44\times10^{44} erg/s$$

$$\rightarrow \quad L_{Sgr} = 10^{-8} L_{Edd}$$

$$\dot{M}_{X-rays} = 4\pi R_B^2 \rho c_s = 4\times10^{-5} M_{sun}/yr$$

$$\rightarrow \quad L = \eta c^2 \dot{M}_{X-rays} = \eta \; 2.1\times10^{43} erg/s$$

The Luminosity Problem

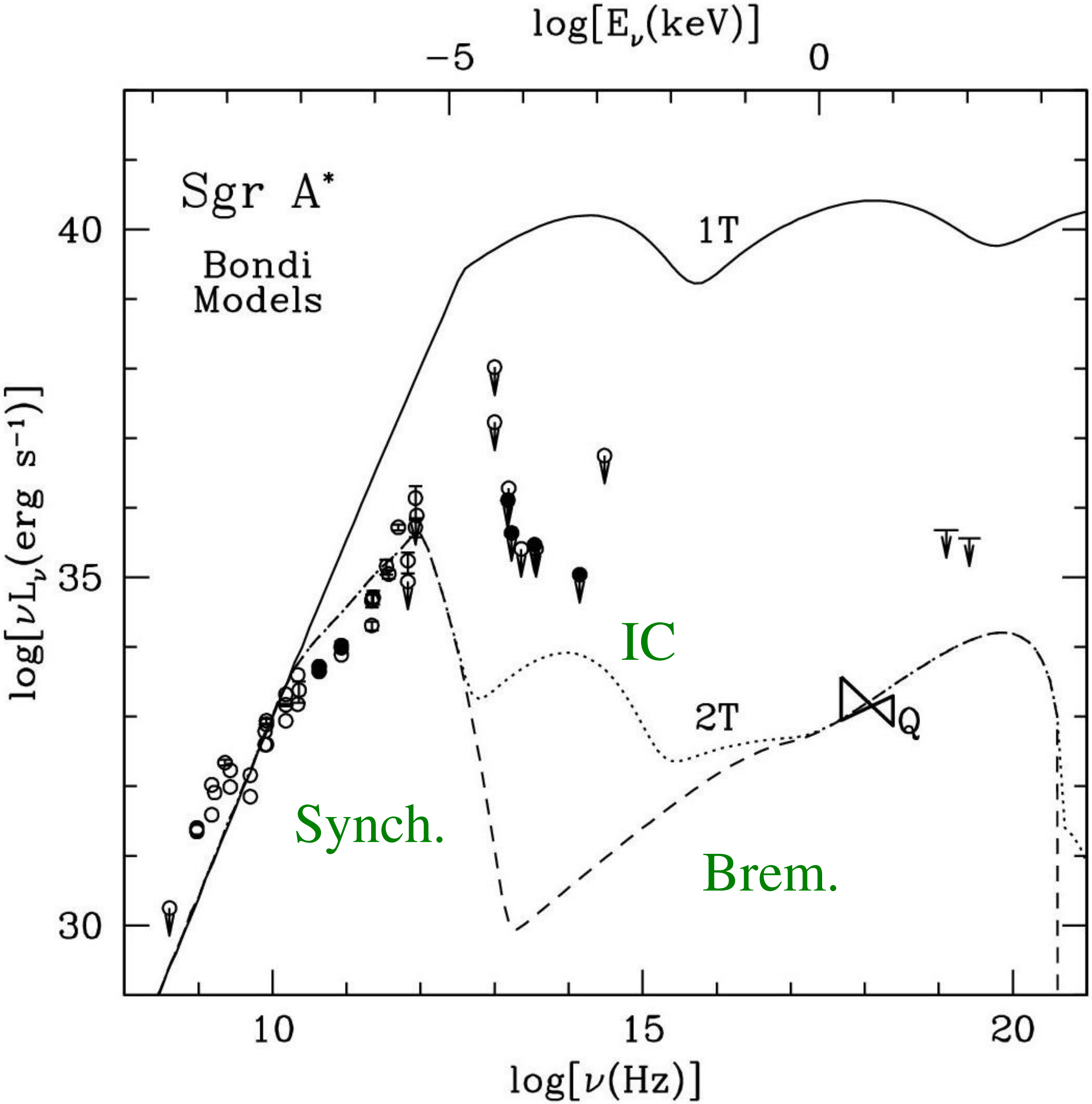
$$\rightarrow \quad L_{SgrA} = 5 \times 10^{-6} L_{thin}$$

Radio Linear Polarization constraints:

$$\dot{M} = 10^{-3} \dot{M}_{X-rays} \rightarrow \eta = 10^{-3} \eta_{thin}$$

$$\rightarrow \quad \dot{M} = 4 x 10^{-8} M_{sun} / year$$

Realistic Bondi Spectrum



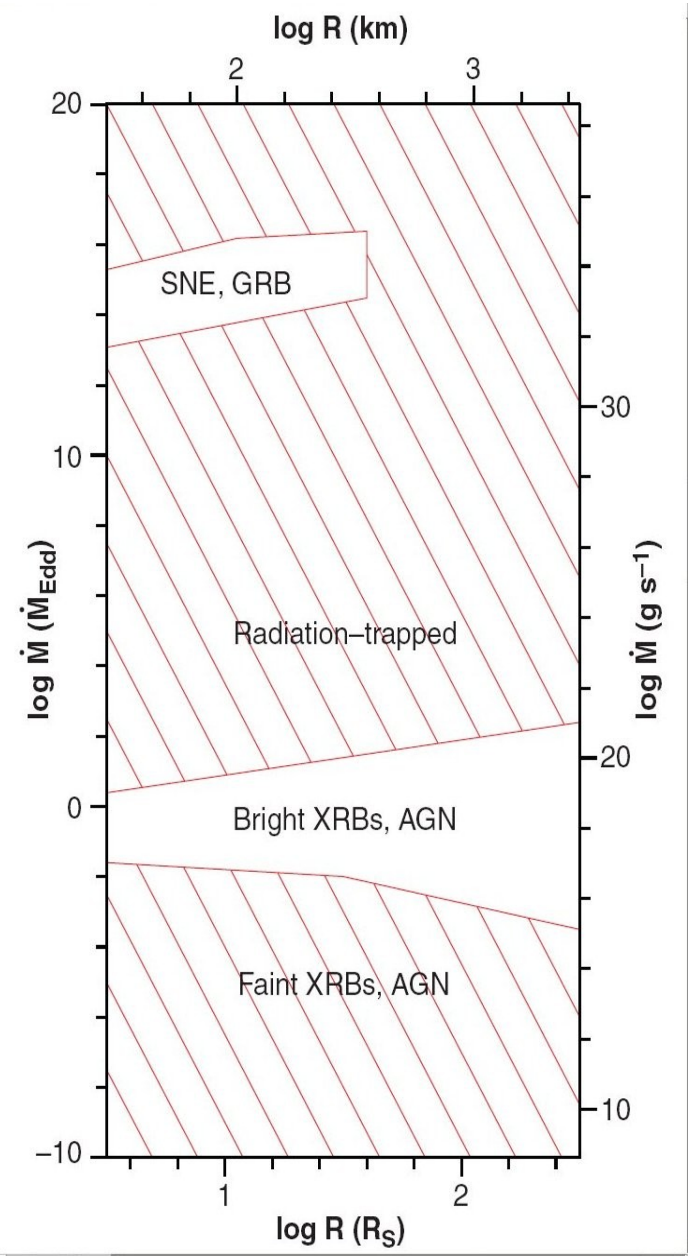
- Including Synch., Bremsstrahlung (+IC)
- At low ρ, e's & ions decouple since

$$t_{Coulomb} > t_{infall}$$

- Shapiro, Lightman, & Eardley (1976)

Narayan astro-ph/0201260

RIAF's (Radiatively Inefficient Accretion Flows)



- **ADAF's (Advection Dominated Accretion Flows)**:
- Narayan & Yi (1994-5), Yuan et al. (2003-4)
  - "At least I didn't name them Type II accretion flows!", Narayan, KITP SgrA* Conf. 2005

$$Q_{diss} > Q_{rad.} \qquad \rho \;\alpha\; r^{-3/2}$$

  - 2-T flows, ala Shapiro et al., advection stabilizes
  - Thick disks, ~spherical
  - Convectively unstable

CDAF's & ADIOS's

$$\rho \;\; \alpha \;\; r^{-3/2+s}$$

$$\dot{M}_{in} = \dot{M}_{out} \left(R_{in} / R_{out} \right)^{s}$$

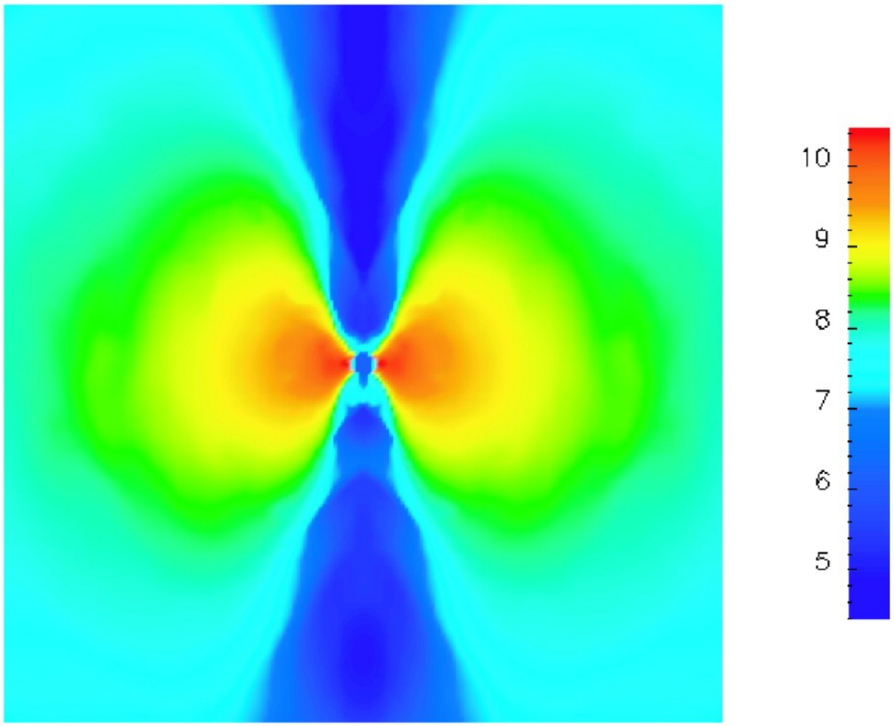
$$0 < s < 1$$

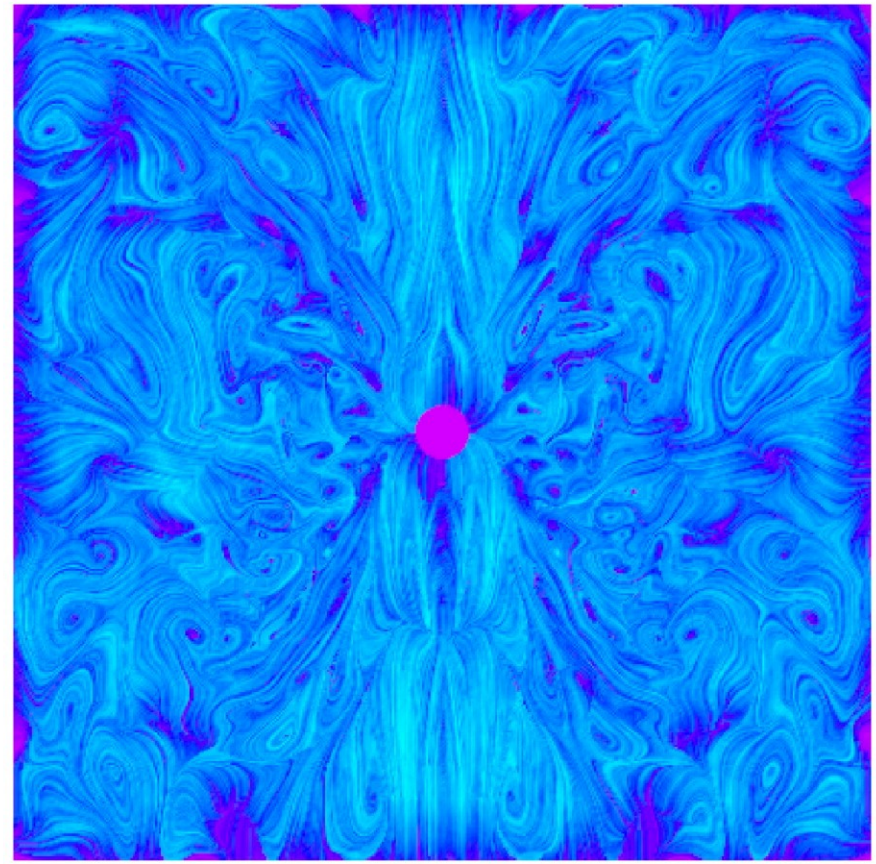
- **ADIOS (Advection Dominated Inflow/Outflow Sol's)**
  - Blandford & Begelman (1999)
    - Much of the energy is blown away in a wind

$$s = 1$$

- **CDAF (Convection-Dominated Accretion Flows)**
  - Quataert & Gruzinov (2000)
    - Ang. Mom. Transported inward
    - Energy Transported outward
    - Weakest accretion of the RIAF's

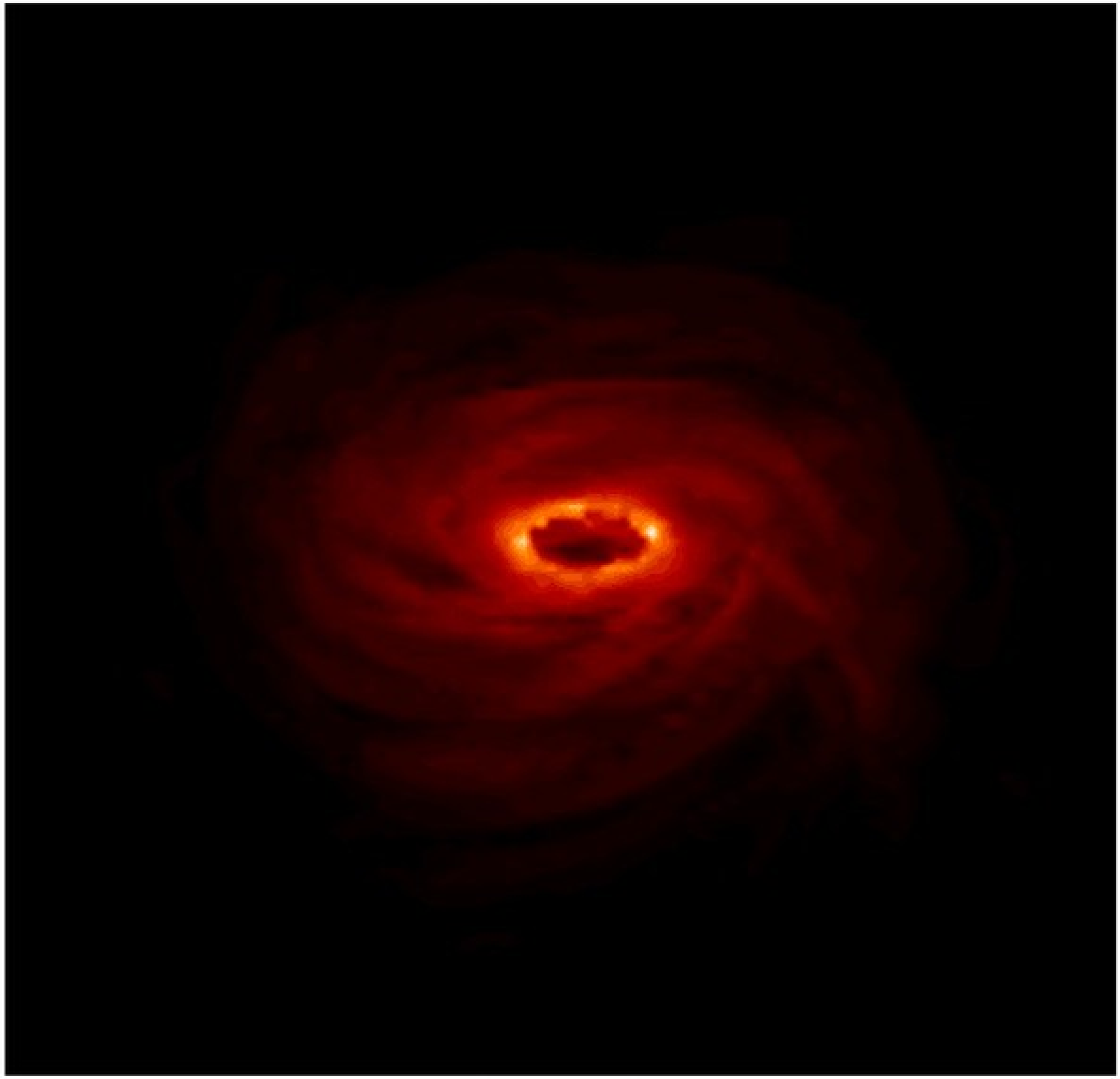
RIAF Simulations





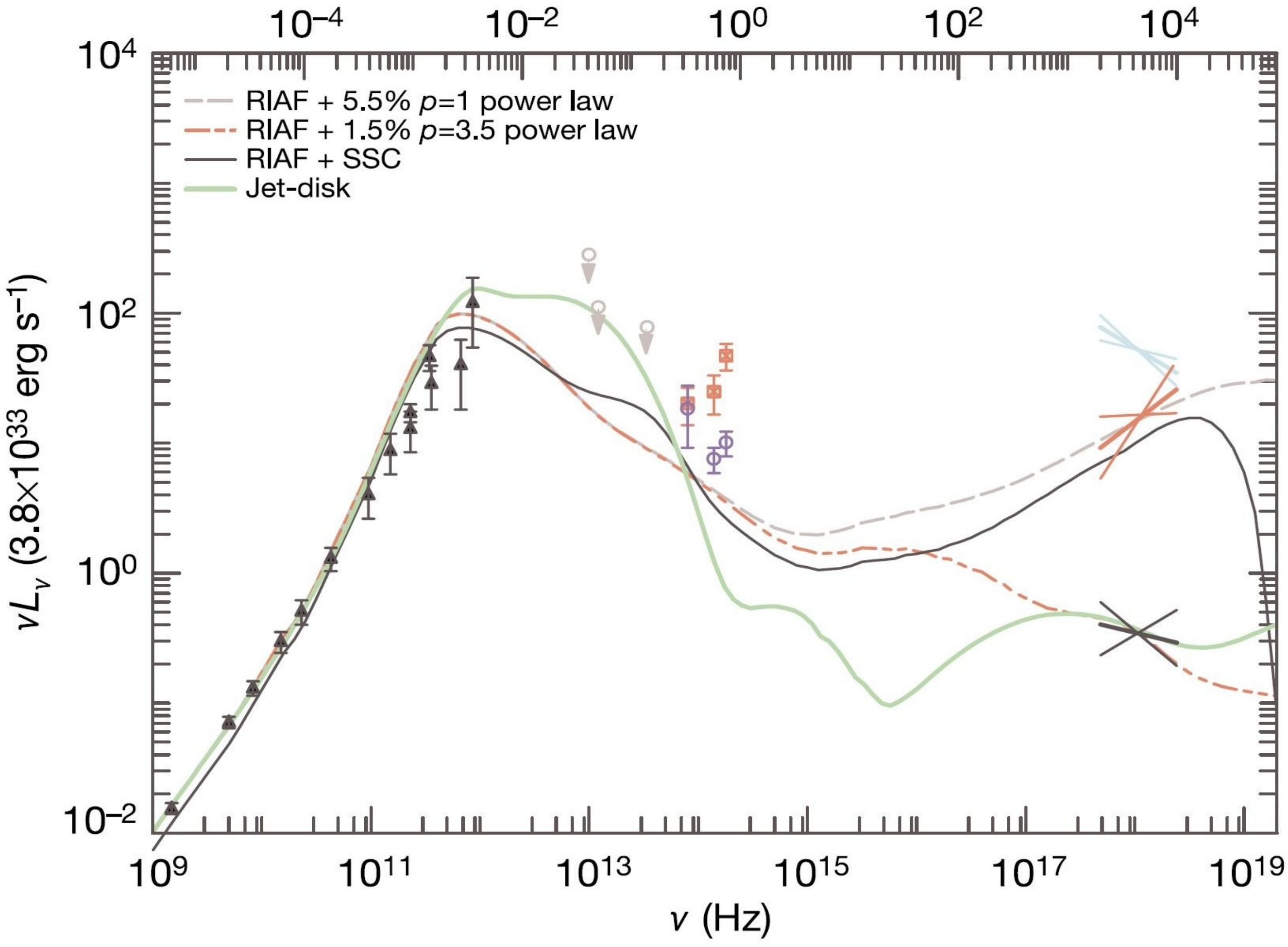
- Igumenshchev, Narayan, Abramowicz (2003)
- 3D, MHD, Paczynski & Wiita Pot., Viscous, Resistive
- Toroidal B fed in from outer boundary
- Similar $\rho \sim 1/R$ close to analytic CDAF

RIAF Simulations



- Goldston, Quataert, Igumenshchev (2005)
- 3D RIAF Sim. as before
- $T_e = a\, T_{tot}$
- n_e ~ Maxwellian + PLT
- Opt. thin at 450 GHz
- t_{orbit} timescale for opt. thin emission
- > t_{orbit} timescale for opt. thick emission

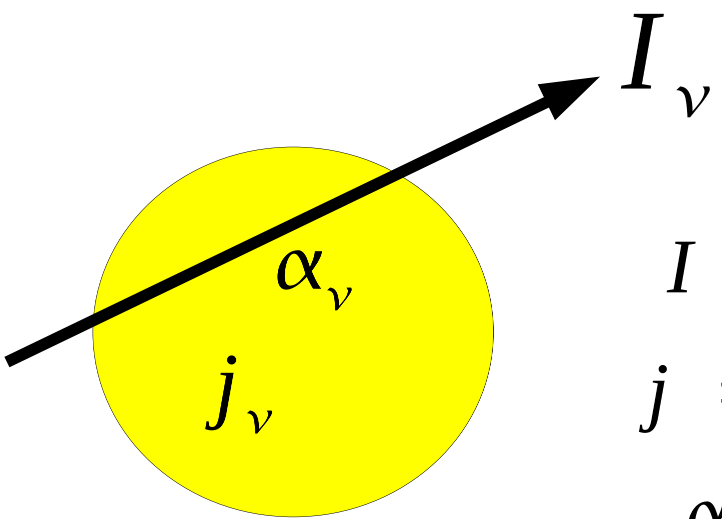
Composite Spectrum (comparison)



- RIAF's have problem with var. of brem. since $R_{brem} \sim 10^5 R_s$
- Instead, add PL n_e gives hard IC/SSC photons
- Solves Radio under-lum.
- Modern RIAF's have many parameters, need better constraints: simult. wide-freq. survey, submm VLBI

- Jets lack a mechanism, no launching mechanism
- Reliant on a disk model of some type
- Can it predict X-ray flare state?
- SgrA* may have been more active in the past...?

Relativistic Radiative Transfer



$$\frac{\partial I_\nu}{\partial s} = j_\nu - \alpha_\nu I_\nu$$

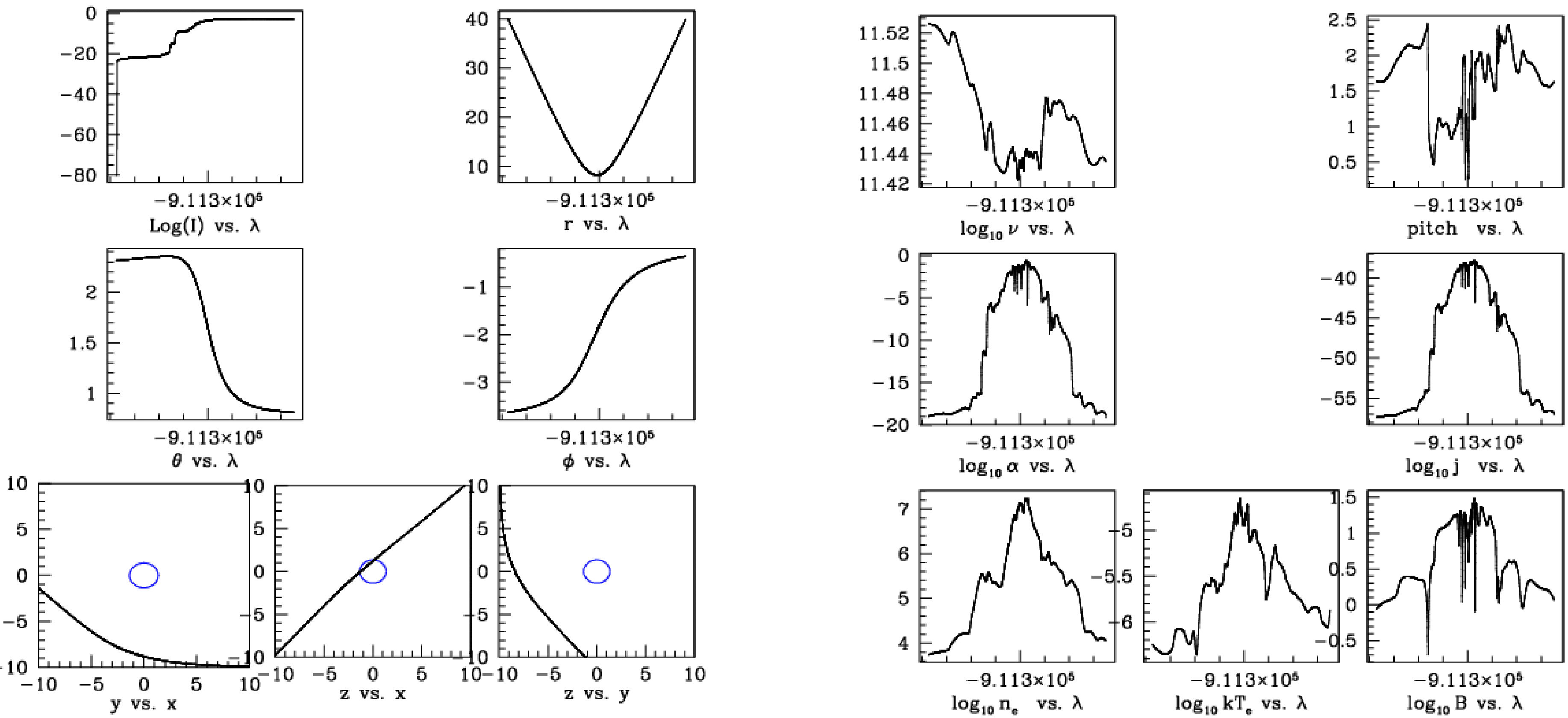
$$I = I_\nu / \nu^3$$

$$j = j_\nu / \nu^2$$

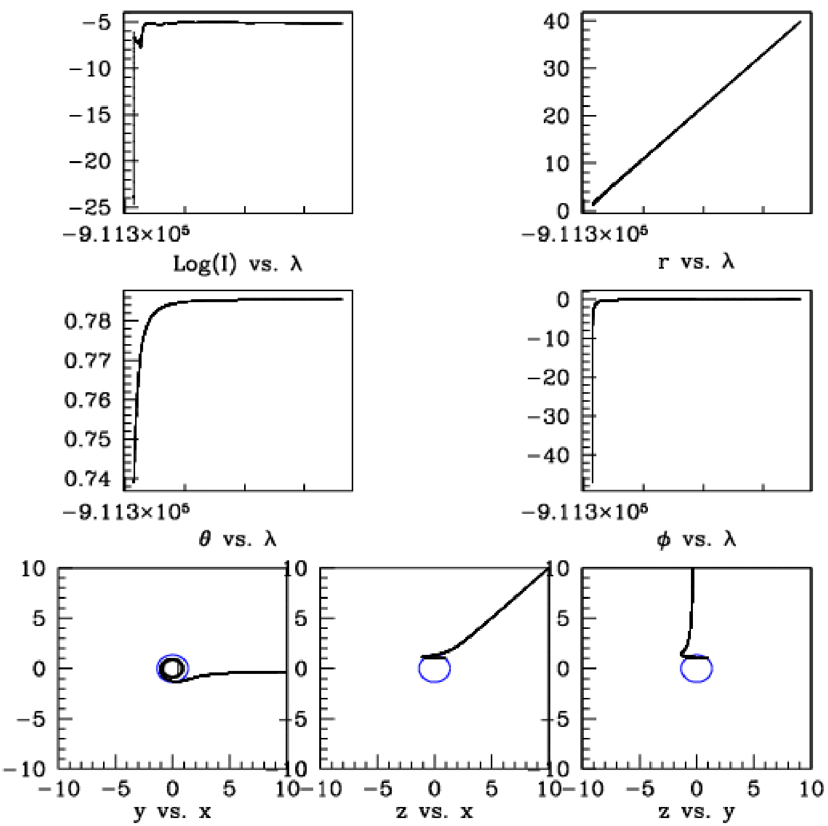
$$\alpha = \alpha_\nu \nu$$

$$\frac{\partial I}{\partial \lambda} = j - \alpha I$$

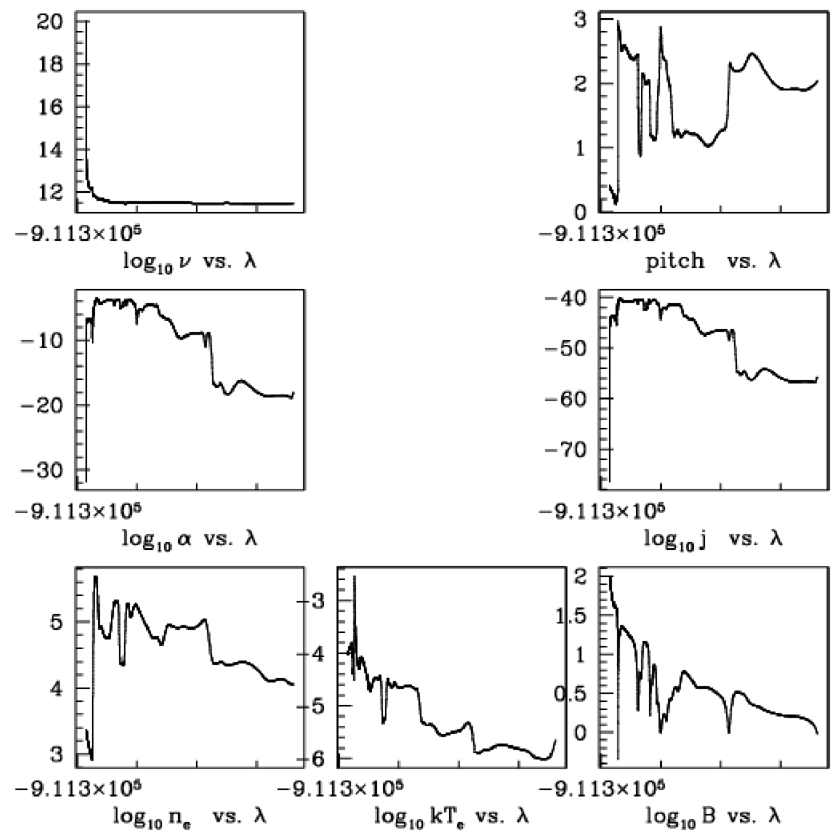
- Calc. Kerr-Schild geod.
- Use geodesics as rays along which to integrate I
  - Interpolate HARM data for density, temperature, B^i, v^i
- Synchrotron and Bremsstrahlung
  - Thermal equilibrium (i.e. No power-law electrons)
- Currently uses “frozen-in” approx.



Log(I) vs. λ
r vs. λ
log10 ν vs. λ
pitch vs. λ
θ vs. λ
ϕ vs. λ
log10 α vs. λ
log10 j vs. λ
y vs. x
z vs. x
z vs. y
log10 ne vs. λ
log10 kTe vs. λ
log10 B vs. λ
−9.113×10^5

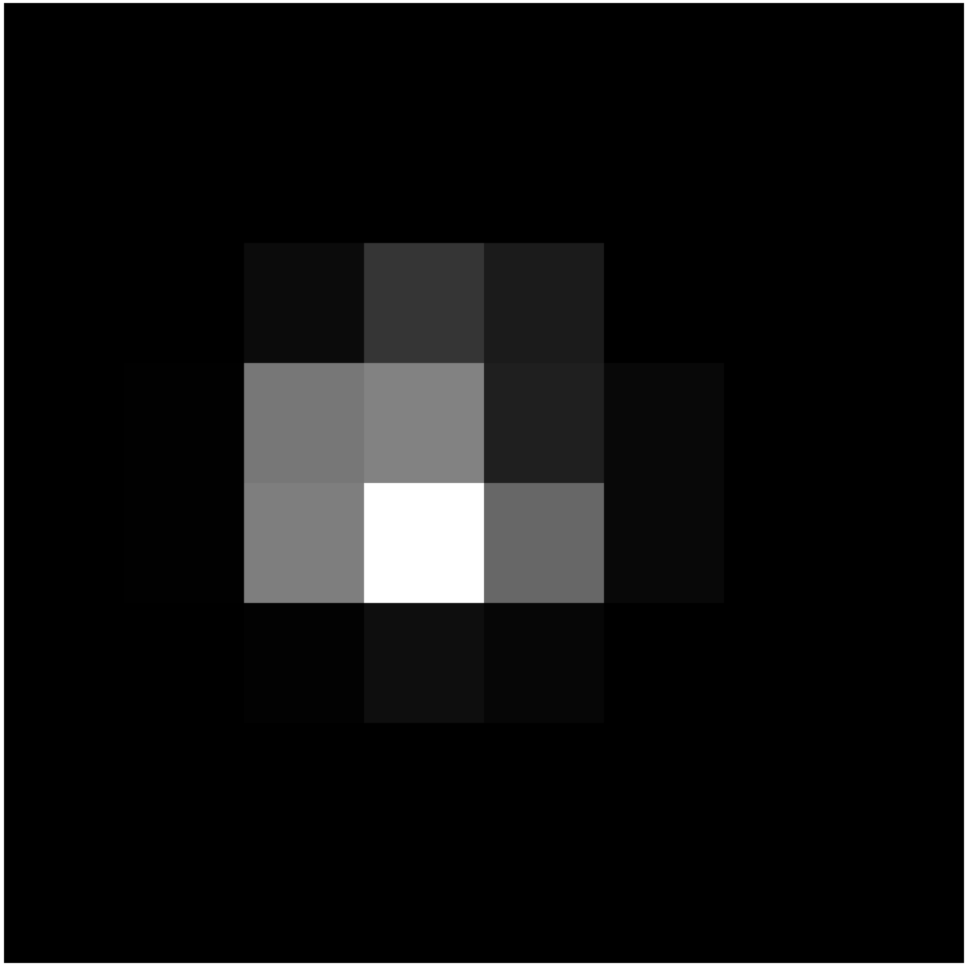


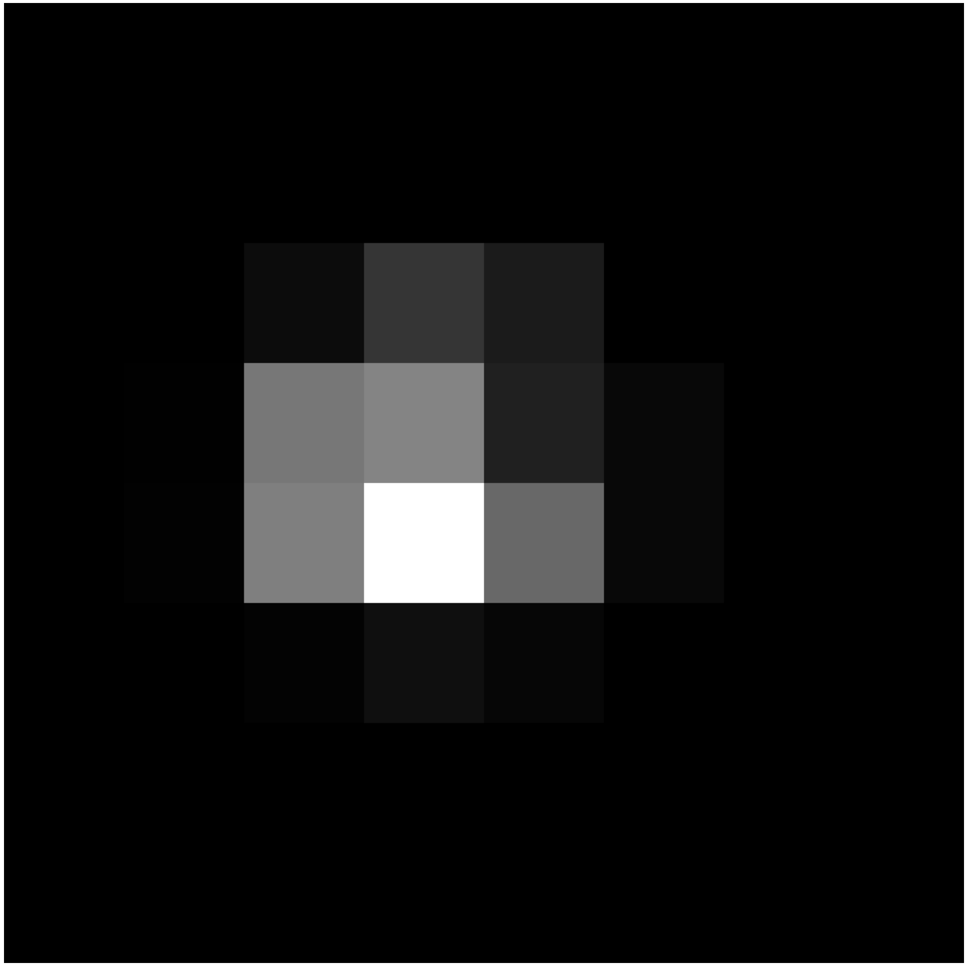
Log(I) vs. λ
r vs. λ
θ vs. λ
φ vs. λ
y vs. x
z vs. x
z vs. y
−9.113×10^5



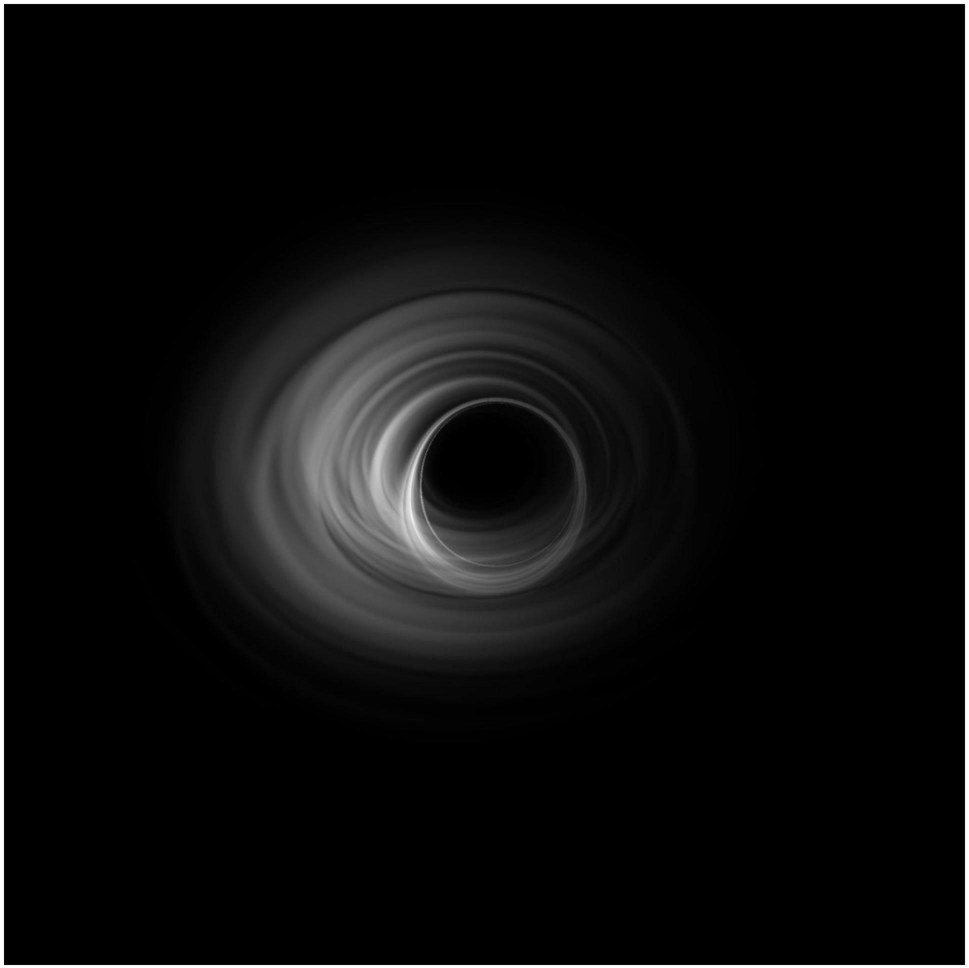
log10 ν vs. λ
pitch vs. λ
log10 α vs. λ
log10 j vs. λ
log10 n_e vs. λ
log10 kT_e vs. λ
log10 B vs. λ
−9.113×10^5

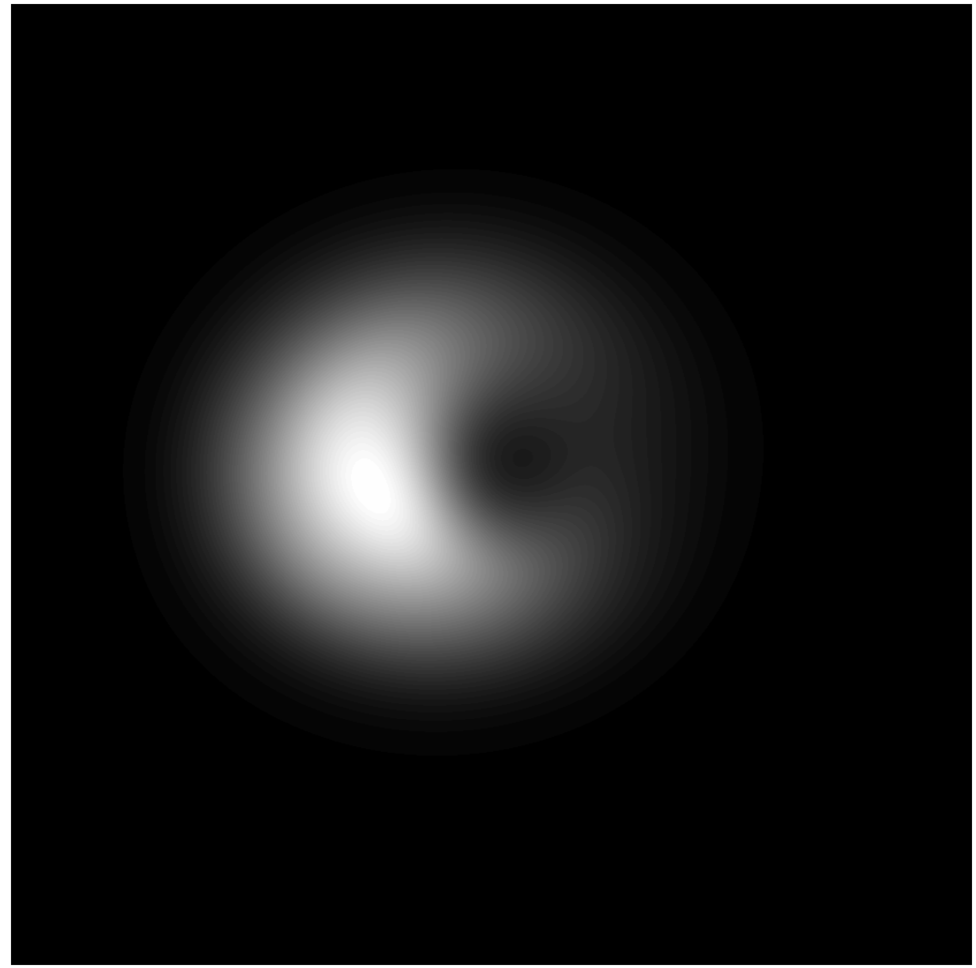
Camera Resolution





Camera Resolution





Inclination

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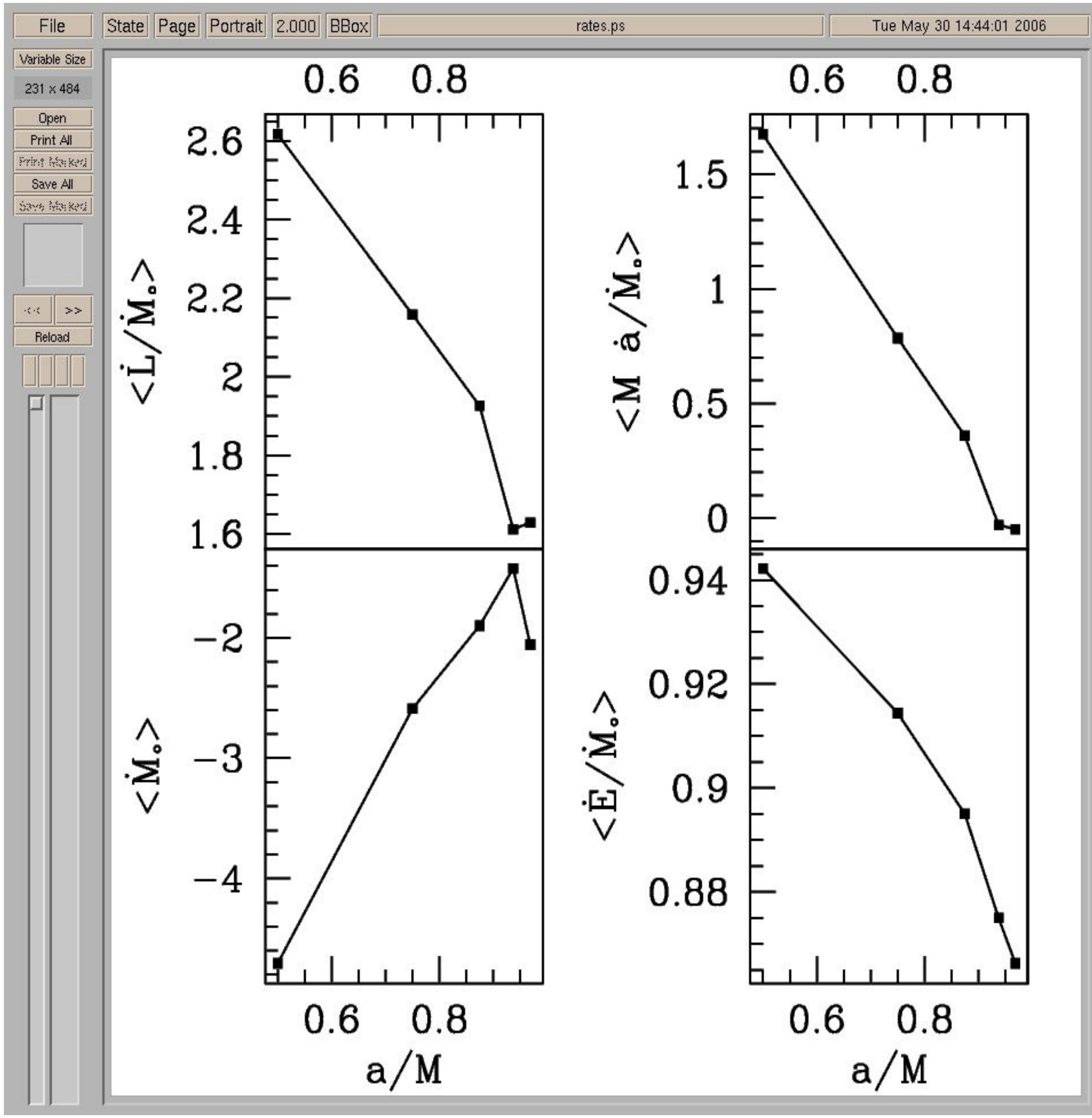
Inclination

Spin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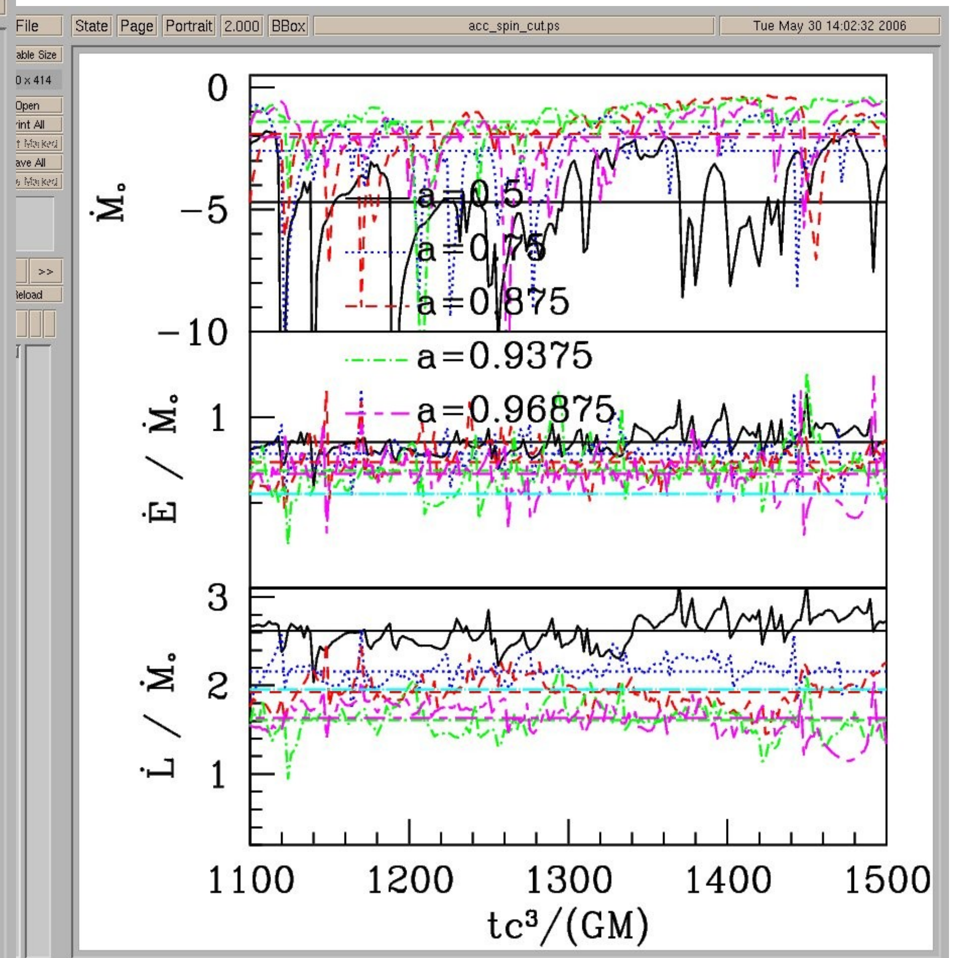
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a=0.875
a=0.9375
a=0.96875
tc³/(GM)

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Spin

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