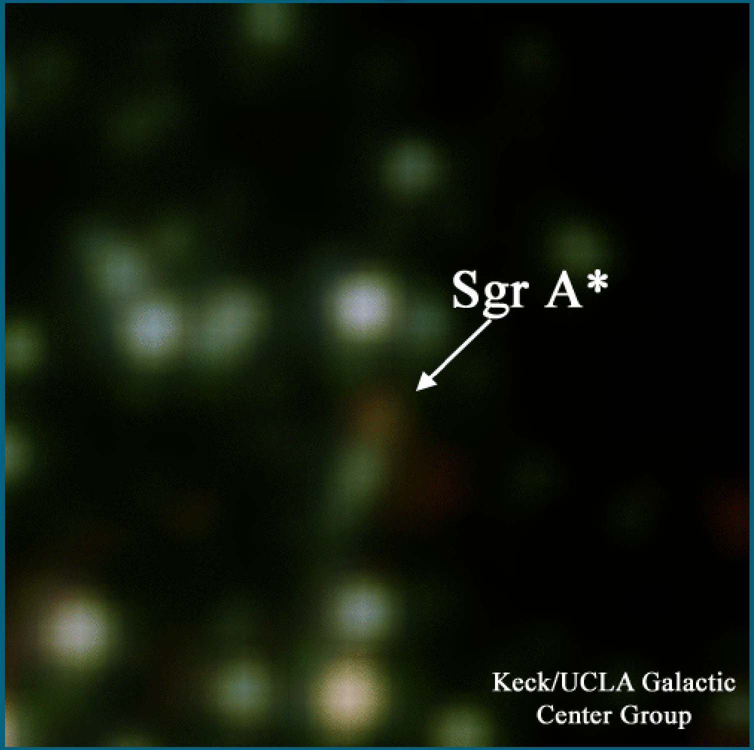
Unified accretion model for Sgr A*



Roman Shcherbakov (Harvard),
rshcherb@cfa.harvard.edu ; http://www.cfa.harvard.edu/~rshcherb/
Frederick K. Baganoff (MIT), Robert Penna (Harvard)

Thanks Ramesh Narayan, Charles Gammie

Washington, DC, 4 Jan 2010

Multitude of observational data

inefficient accretion onto supermassive black hole

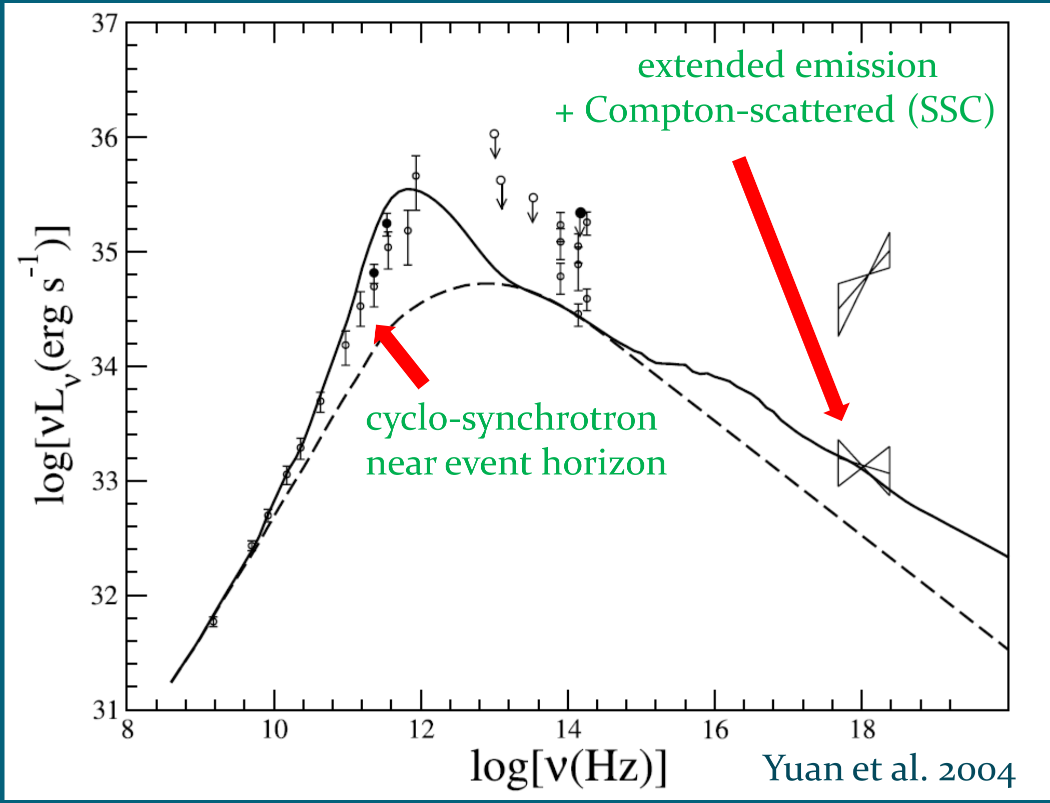
X-Rays
1Ms of Chandra obs.

IR

sub-mm + radio
VLBI, SMA; polarization data

spatially resolved X-Rays & sub-mm

quiescent SED



Idea of the model

Goal:

1. explain X-Ray surface brightness within 5''
2. fit sub-mm SED + linear polarization fractions
3. reproduce image size at 230GHz

Minimum set of physical effects

✓ conduction/outflows for BH feedback
✓ feeding by stellar winds (arcsec scales)
✓ entropy production (viscosity)
✓ electron heating mechanism
✓ GR dynamics near Kerr BH (μas scales)

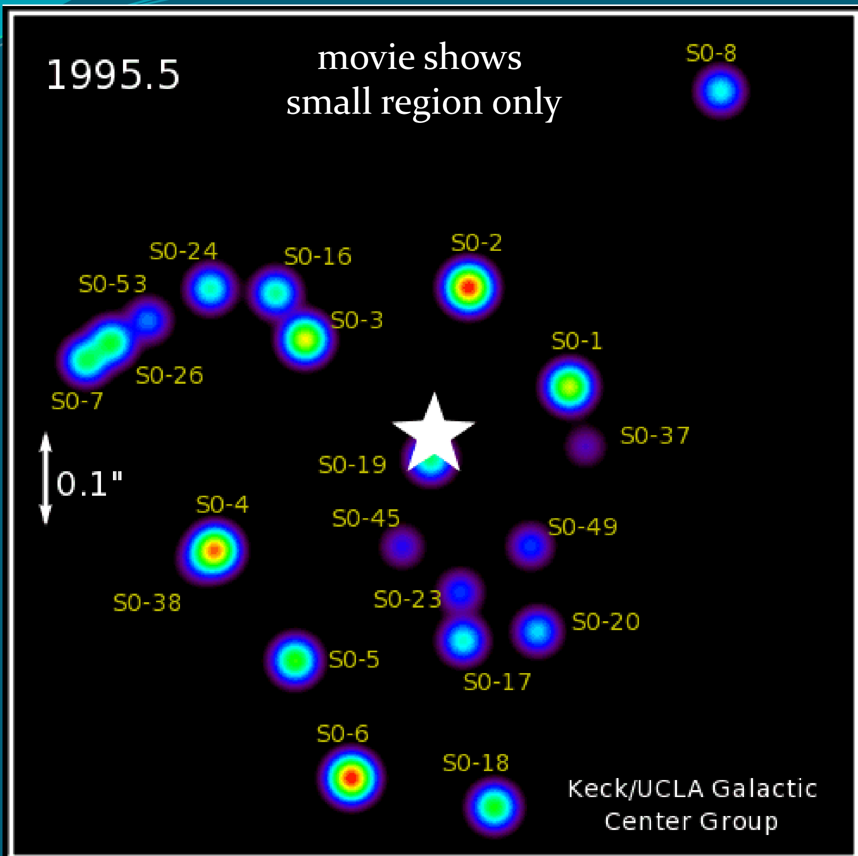
Radial model at large radius
with GRMHD simulations at small radius

✓ precise bremsstrahlung & cyclo-synchrotron emissivities
✓ GR polarized radiative transfer

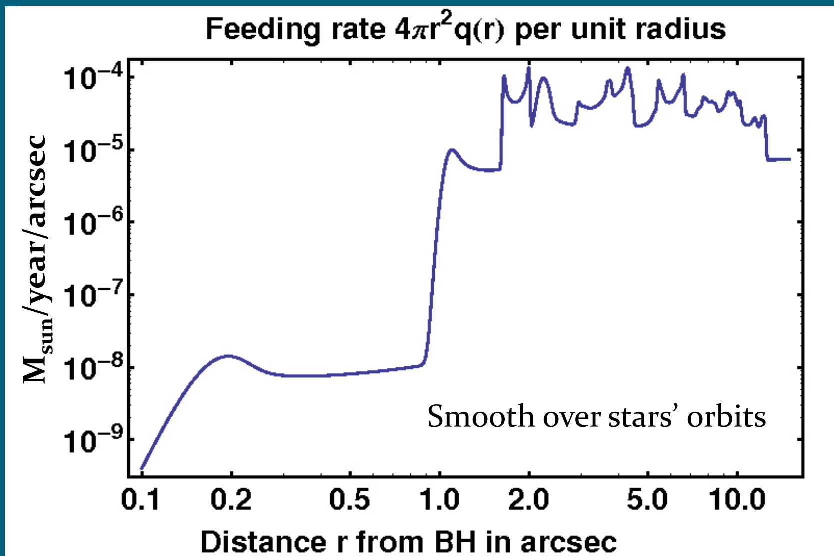
I. Radial model at large radius

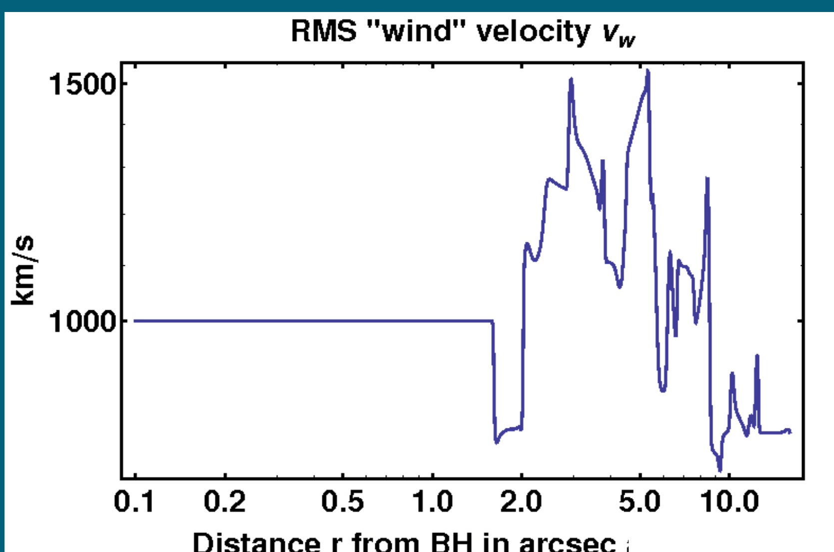
Shcherbakov, Baganoff 2009, ApJL, submitted

Radial model: Feeding Mechanism



Realistic feeding:
sum over 31 main emitters





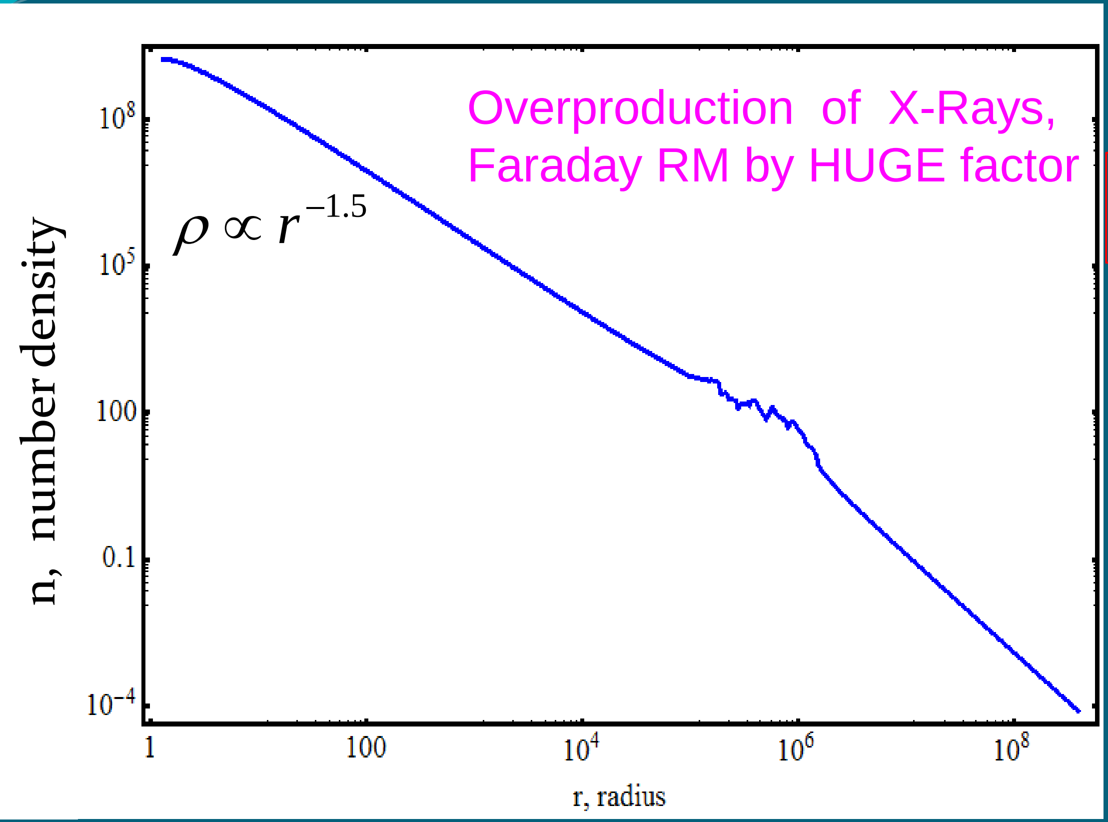
Stars emit wind at 300÷1200km/s
ejection rate $\sim 10^{-3} M_{Sun} / year$

Winds collide, heat the gas,
provide seed magnetic field

Most of gas flows out, some accretes

Radial model: black hole feedback

Adiabatic model (no feedback)



→ Outflows → No 1-st principle model

Blandford, Begelman 1999
Yuan et al. 2003

→ Radiation feedback is negligible

→ Conduction

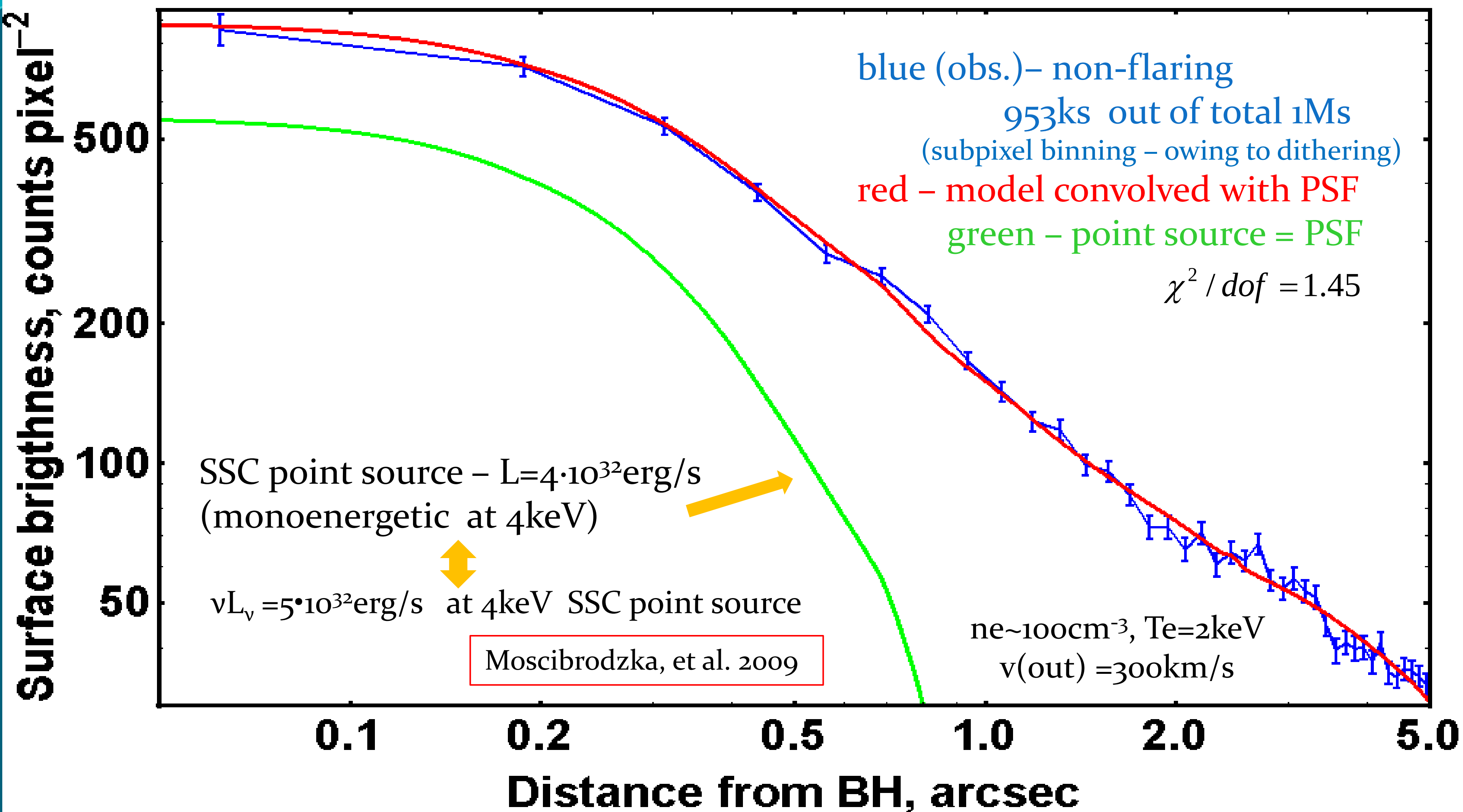
Johnson, Quataert 2007

- ❖ electron conduction dominates convection etc.
- ❖ damped by a factor 3 to 5 in tangled magnetic field

Narayan, Medvedev 2001

❖heat flux Q_e proportional to T_e gradient

Results for X-Rays



accretion rate = $6 \cdot 10^{-8} M_{Sun}$/yr – <1% of the naïve model estimate

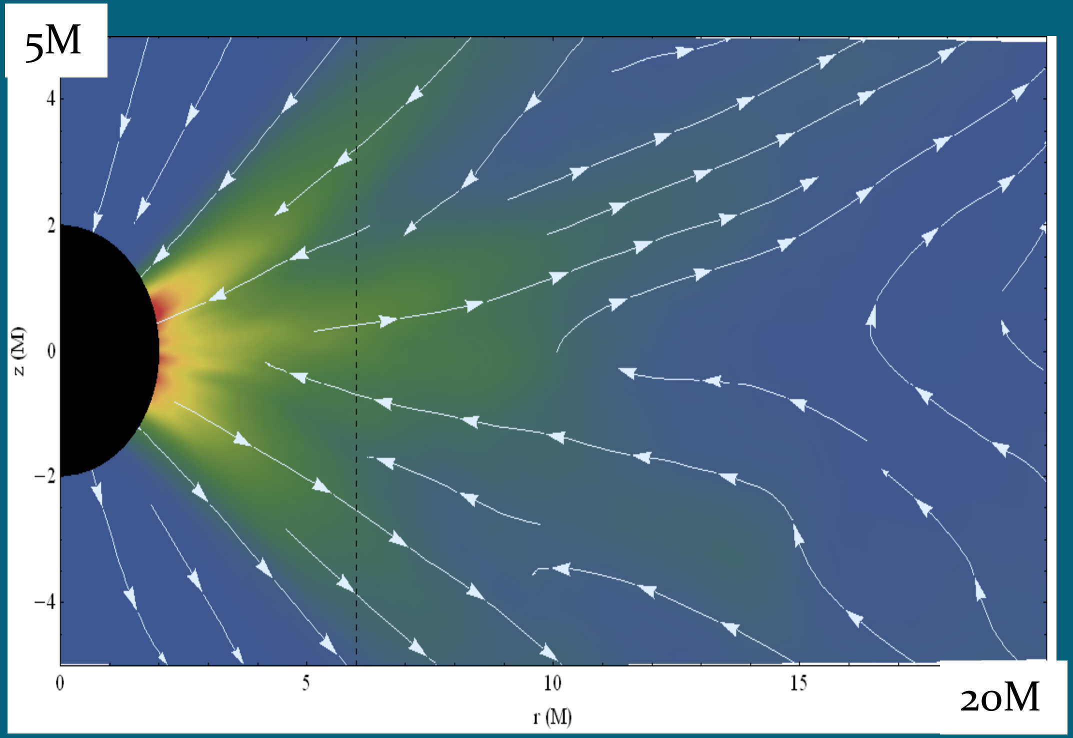
II. 3D GRMHD simulations close to the BH

Shcherbakov, Penna 2010, in preparation

GRMHD simulations

Initial setup and features

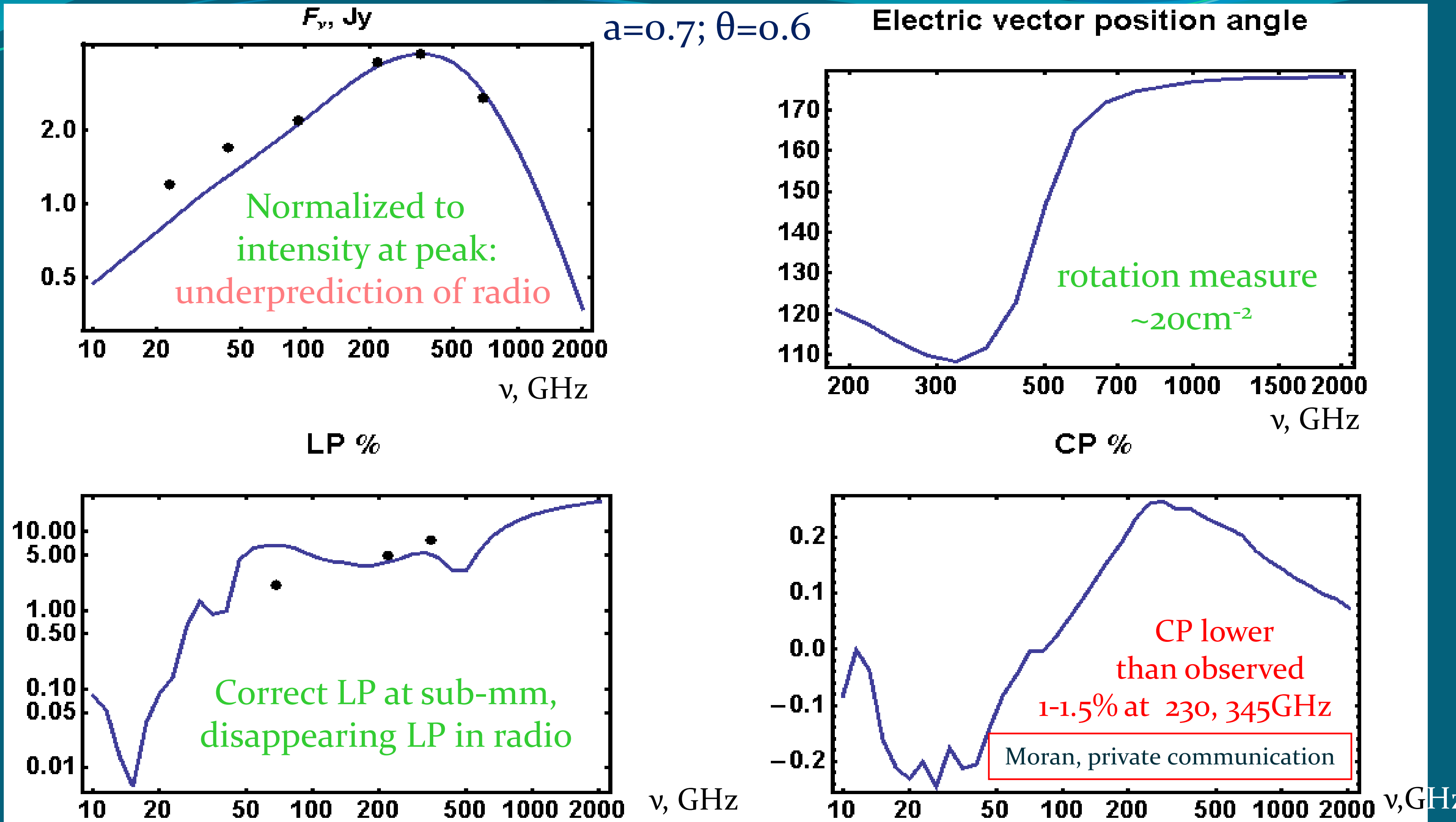
- start from torus w/ inner edge at 20M
- spins 0; 0.7; 0.9; 0.98
- no cooling



VectorPlot of <B> and DensityPlot of <B²>

Azimuthal and t average
in “steady” accretion for each of 4 spins

Fitting sub-mm data



obs: Yuan,2004 Macquart, 2006, Marrone,2007

Conclusions

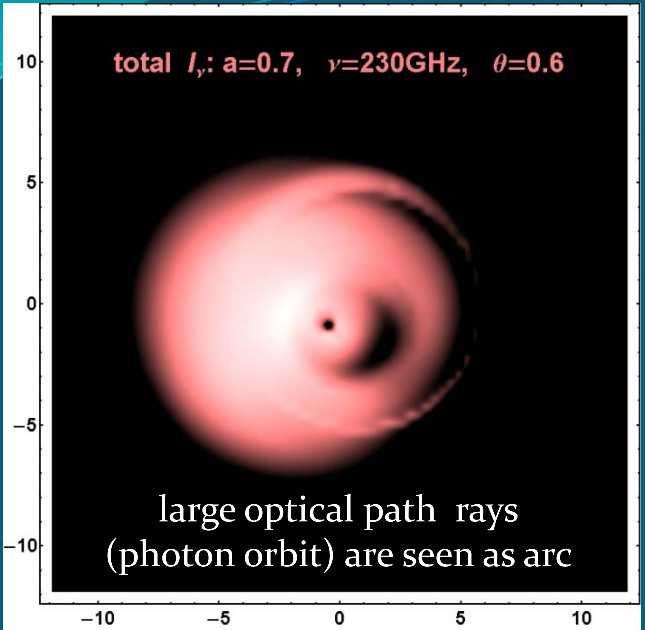
I. High a>0.7 bad: lower density => weak beam depolarization and high LP at lower ν

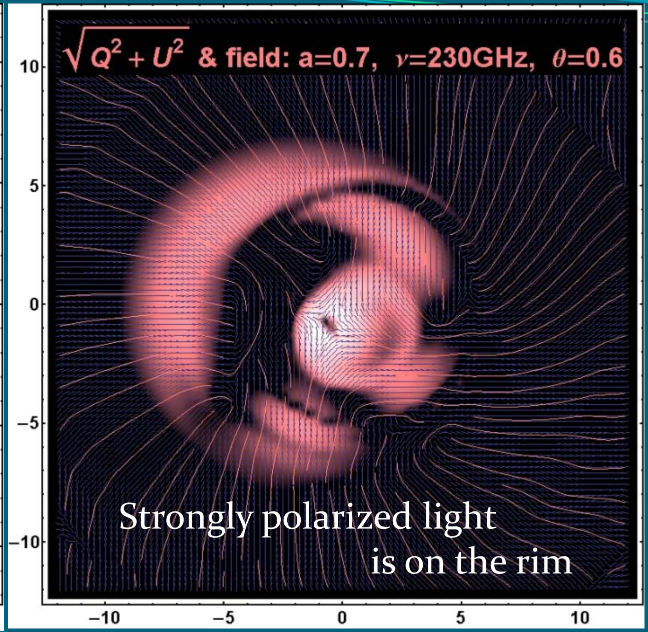
II. CP<0.5%, less radio – need more mildly relativistic e$^-$?

Polarimetric Imaging

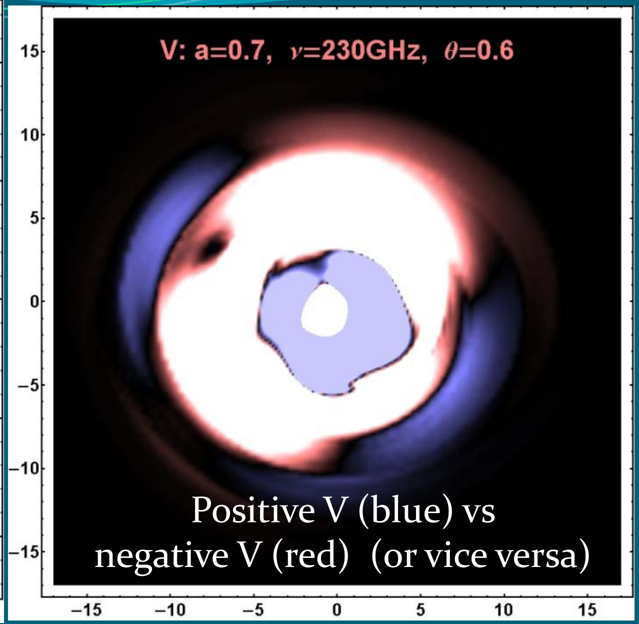
Distances measured in M

White to darkest red – factor of 8

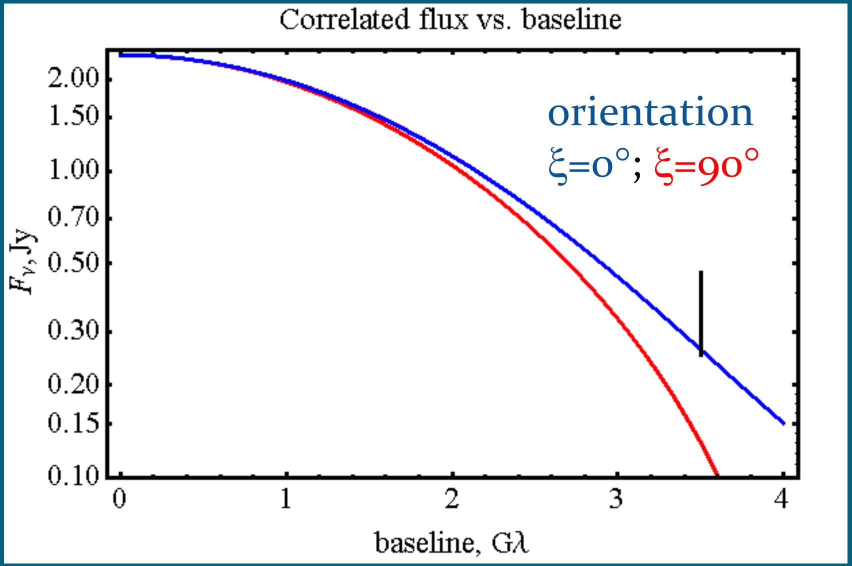




LP up to 70% along each ray
Cancellations lead to CP~8%



CP up to 2% along each ray
Cancellations lead to CP<0.5%



Size at 230GHz is marginally consistent with observed 37μas

Doeleman, et al. 2008

Conclusions

Emphasis on self-consistency

- ✓ Main physical effects captured within arcsec model
- ✓ Realistic 3D GRMHD simulations of rg scales matched to arcsec model

- ✓ Fit to extended X-Ray emission
- ✓ X-Ray point source $L \approx 4 \cdot 10^{32}$ erg/s
- ✓ Reasonable fits to sub-mm total intensity and LP fraction
- ✓ Fit to image size at 230GHz

Future work

- ✓ Include angular momentum into radial model
- ✓ Use X-Ray spectral data for further tests (find N_H)

- ✓ Employ correct cyclo-synchrotron (original calculations done)

Radial arcsec scale model: at a glance

Entropy production

fractions f_e, f_p of grav. energy -> thermal energy

Direct heating of electrons

$$f_e / f_p = \frac{1}{3}\sqrt{T_e / T_p}$$

Sharma et al. 2007

Line cooling is neglected

Sutherland, Dopita 1993

Relativistic heat capacity of e^-:

leads to lower T_e

Fixed large electron conduction

$N_H=10^{23}cm^{-2}$; solar abundance

Najarro et al. 2004

Corrected bremsstrahlung

Gould, 1980 + errata

20% larger emissivity at $T\sim2keV$ and $h\nu \sim 4keV$

Absorption, PSF blurring, effective area

Morrison, McCammon, 1983

PSF is directly extracted from the nearby point source

Fitting surface brightness profile for:

1. Accretion rate $\dot{M}$
2. Luminosity L of SSC point source
3. T_e at stagnation point
4. Heating fraction f_p

GRMHD rg scale model: at a glance

Splitting of internal energy U into Tp and Te

1. Relativistic heat capacity of e-
2. Direct heating mechanism

Sharma et al. 2007

$T_p/T_e \neq const$

Model is extended to larger radii

Smoothly extend B profiles beyond 25M

Match ne, Te to radial arcsec model at 25M

GR polarized radiative transfer

Formalism of GR polarized rad. transfer

Gammie, Leung, Shcherbakov, in prep

full covariant formalism, effects of moving fluid

Exact Faraday rotation/conversion coeff

Shcherbakov, 2008

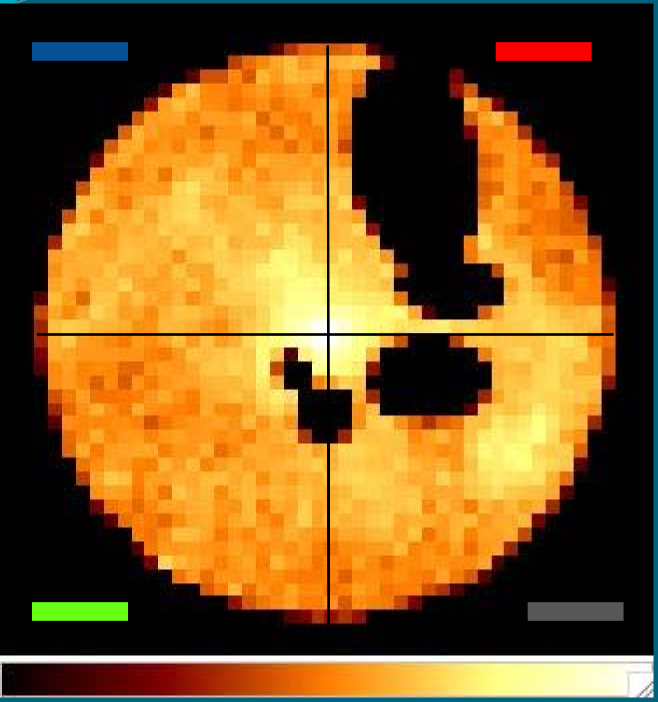
Faraday conversion shuts off at high temperatures!

Fitting sub-mm intensity, LP fraction vs ν for

1. Accretion rate $\dot{M}$ (can be fixed by outer flow)
2. Spin of black hole $a=J/M$
3. Inclination θ of BH spin

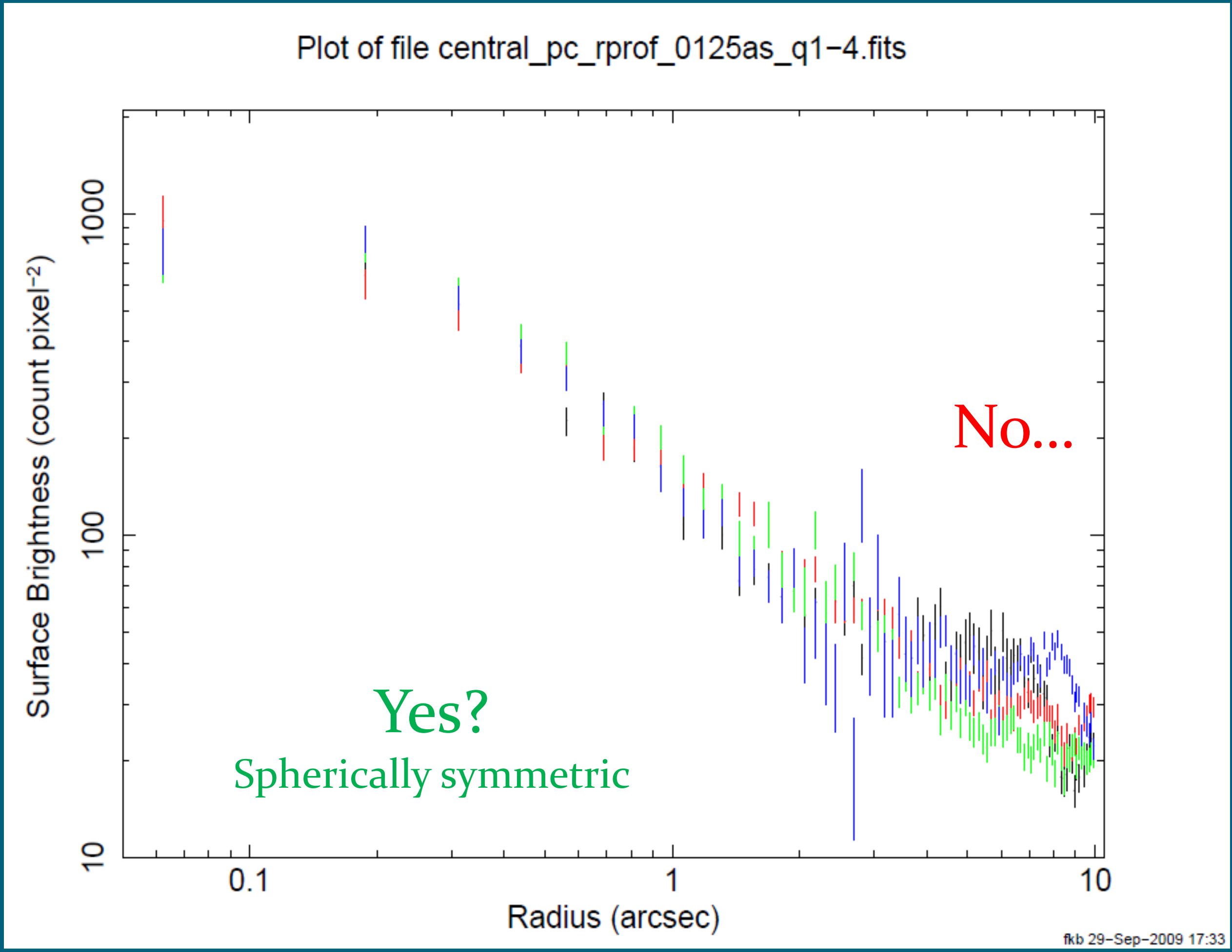
Imaging – fitting image size to VLBI data

Actually spherically symmetric?



Point sources and
hot streams were subtracted

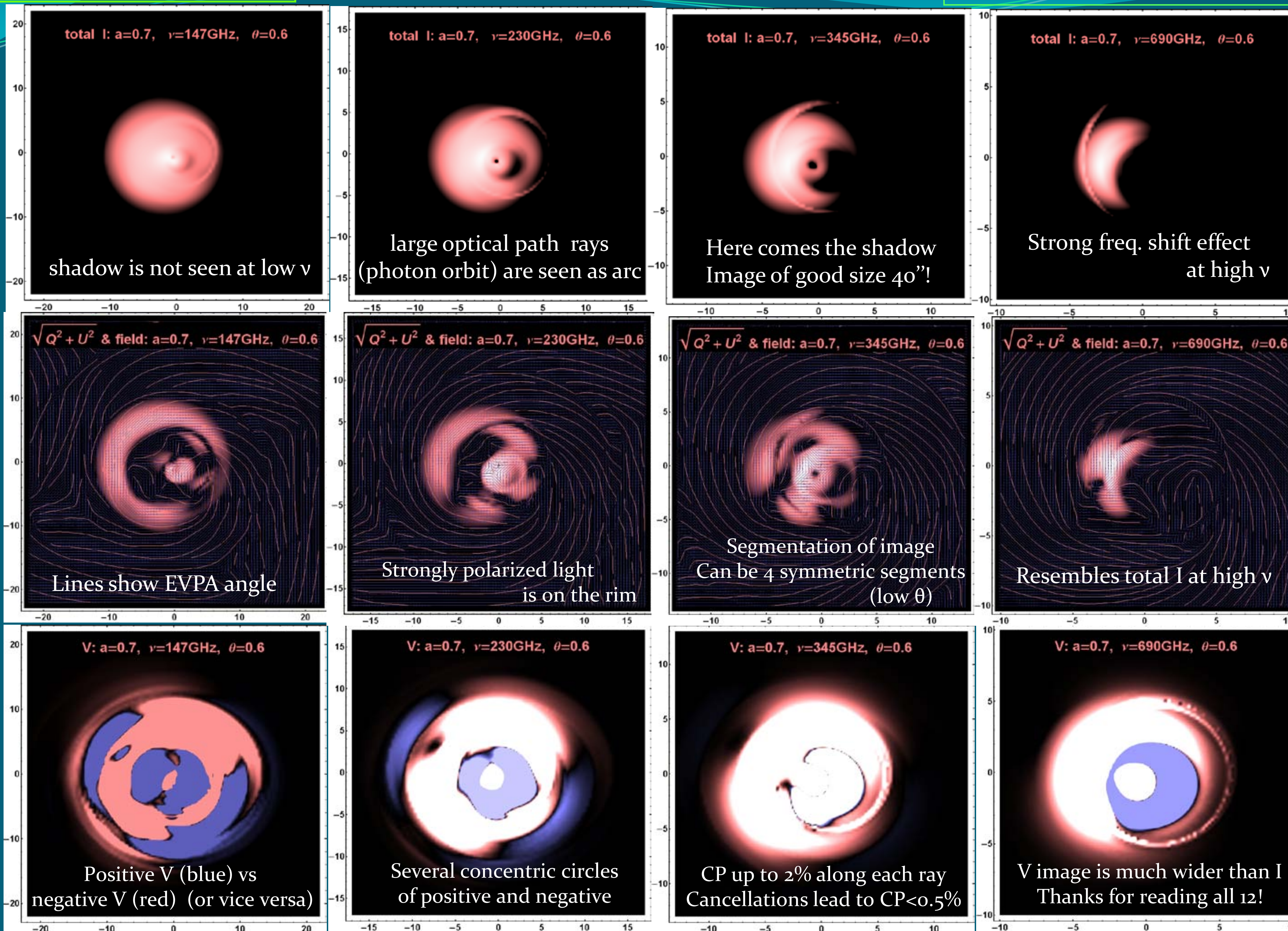
Counts from
4 sectors 90° each



Polarimetric Imaging

Distances measured in M

White to darkest red – factor of 8



Radial model: entropy production

Also called superadiabatic heating:
more effective conversion of gravitational energy into thermal

$$-v_r n T_e \frac{ds_e}{dr} = q_e^+$$

$$q_{e,i}^+ = f_{e,i} \frac{GM\dot{M}}{4\pi r^4}$$

Johnson, Quataert 2007

Thin disk → Shakura, Sunyaev, 1971 → $f_i + f_e = 0.5$

f_i and f_e can be calculated "self-consistently" in turbulent flow

Radial magnetized turbulent flow → Shcherbakov 2008 → $\rho \propto r^{-1.2}$

General idea

Explain observed within 5'' extended X-Rays

Correct bremsstrahlung emissivity

SSC point source

Convolution with Chandra ACIS response

Line-of-sight absorption

Dynamical model of gas flow

Feeding by stellar winds

Electron heat conduction, Superadiabatic heating

Proper relativistic effects

Dynamical model: Improved Feeding

Table of 31 most important wind emitters

N	Ident	ΔRA,''	ΔDecl,''	Δz,''	v_{RA},km/s	v_{Decl},km/s	v_z,km/s	eccentr	Log[$\dot{M}$,M_S/year]	v_{wind},km/s
1.	S2,S02	0.04	0.12		9.	1830.	-1060.	0.876	-7.2	1000
19.	IRS16NW	0.029	1.221		238.392	32.9208	-44.	0.898	-4.95	600.
20.	IRS16C	1.121	0.497		-330.722	280.773	125.	0.5	-4.65	650.
23.	IRS16SW	1.051	-0.966	-1.46	257.312	84.0048	320.	0.41	-4.95	600
31.	IRS29N	-1.595	1.423		199.038	-166.874	-190.		-4.95	1000
32.	MPE+1.6-6.8(16SE1)	1.846	-1.141	-1.52	182.767	112.763	366.	0.26	-4.95	1000
35.	IRS29NE	-0.992	2.073	2.99	-305.369	-10.9736	-100.	0.14	-4.95	1000
39.	IRS16NE	2.868	1.053		117.682	-413.97	-10.	0.	-4.95	1000
40.	IRS16SE2	2.938	-1.183	-1.2	54.4896	130.17	327.	0.206	-4.15	2500.
41.	IRS33E	0.665	-3.126	-3.57	203.579	1.5136	170.	0.63	-4.8	450.
48.	IRS13E4	-3.19	-1.42		-316	76	56.	0.809	-4.3	2200.
51.	IRS13E2	-3.14	-1.74		-303.	68.	40.	0.749	-4.35	750.
56.	IRS34W	-4.05	1.59	1.55	-79.	-166.	-290.	0.217	-4.88	650.
59.	[PMM2001] B9	2.94	3.46		250.	32.	-150.	0.794	-4.9	1000.
60.		-4.36	-1.65		-210.	127.	330.	1.046	-4.95	1000
61.	IRS34NW	-3.73	2.85	3.08	-225.	-112.	-150.	0.	-5.3	750.
65.	IRS9W	2.85	-5.62		167.	135.	140.	0.665	-4.35	1100.
66.	IRS7SW	-3.95	4.93		-5.	-108.	-350.	1.261	-4.7	900.
68.	IRS7W	-2.45	5.99		185.	36.	-305.	0.155	-5.	1000.
70.	IRS7E2(ESE)	4.41	4.97		203.	-7.	-80.	0.714	-4.8	900.
71.		1.59	6.49		-148.	189.	-300.	0.73	-4.95	1000
72.		6.71	-0.5		65.	100.	86.	0.555	-4.95	1000
74.	AFNW	-7.63	-3.57		-67.	-92.	70.	0.932	-4.5	800.
76.	IRS9SW	4.28	-8.03		108.	8.	180.	0.521	-4.95	1000
78.	[PMM2001] B1	9.46	0.31		-161.	-142.	-230.	0.781	-4.95	1000
79.	AF	-6.54	-6.91		68.	50.	160.	0.991	-4.75	700.
80.	IRS9SE	5.65	-8.17		-2.	-131.	130.	0.766	-4.65	650
81.	AFNWNW	-9.63	-2.58		87.	-9.	30.	0.873	-3.95	1800.
82.	Blum	-8.63	-5.33		-53.	249.	-70.	0.646	-5.3	750
83.	IRS15SW	-1.58	10.02		-55.	-32.	-180.	0.863	-4.8	900.
88.	IRS15NE	1.38	11.68		-8.	103.	-65.	0.877	-4.7	800.

- Orbital data – Paumard et al. (2006)
- Numbers are updated from Lu, Ghez et al.(2009)
- S2 star – Martins, Gillessen (2008)
- Δz and Eccentricity – from identification with stellar disks or from minimum eccentr (if not disk)
- Wind speeds/ejection rate – Martins et al.(2007)
- Guesses on wind speeds/ejection rates from similarity – Cuadra et al. (2007)

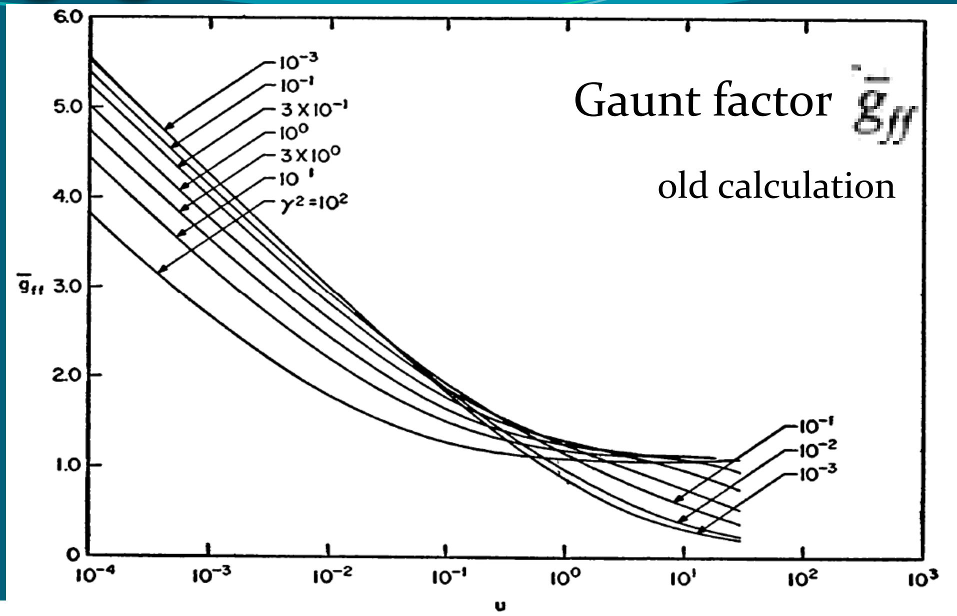
Bremsstrahlung: gaunt factor

$$\frac{dW}{dV\,dt\,d\nu} = \frac{2^5 \pi e^6}{3mc^3}\left(\frac{2\pi}{3km}\right)^{1/2} T^{-1/2} Z^2 n_e n_i e^{-h\nu/kT} \bar{g}_{ff}$$

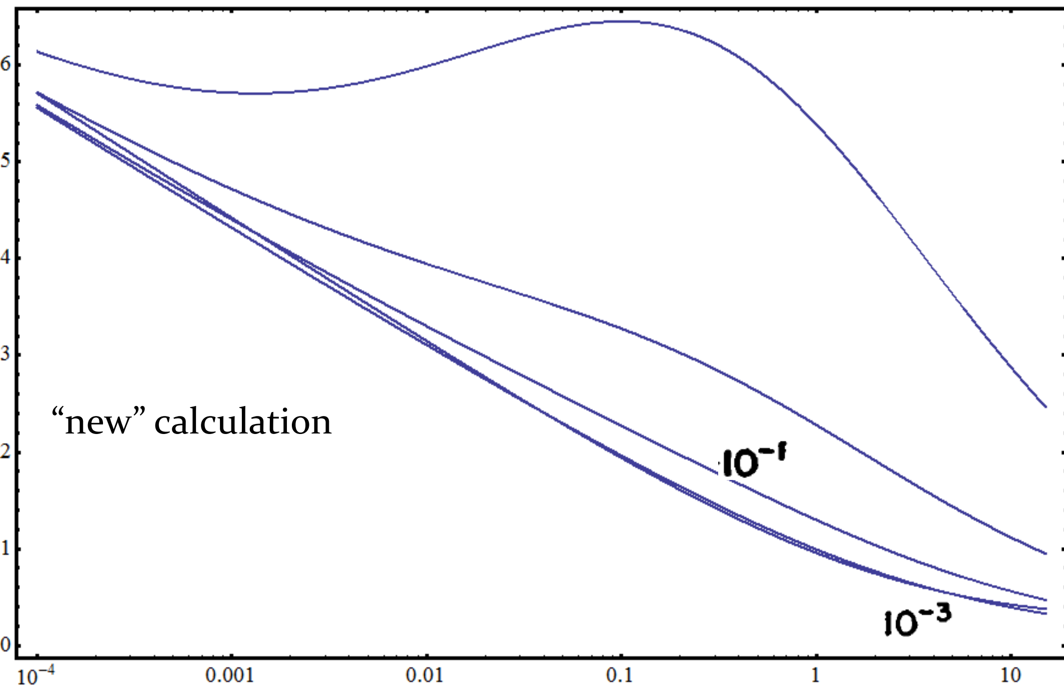
$$u = h\nu/kT$$

$$\gamma^2 = Z^2 Ry/kT$$

Gould 1980 (+errata)



Karzas & Latter 1960

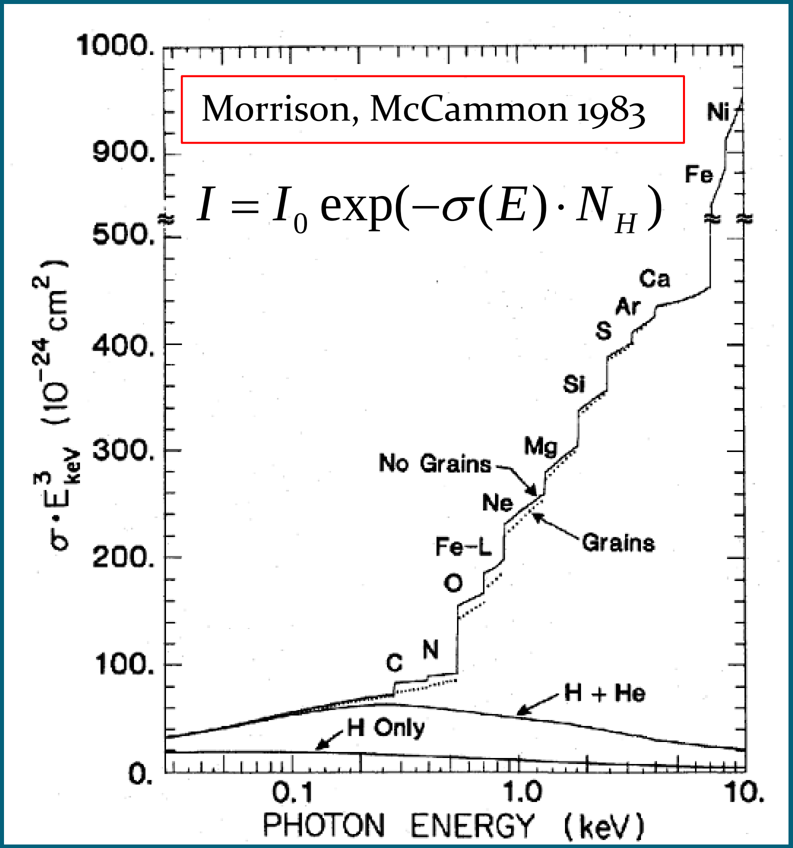


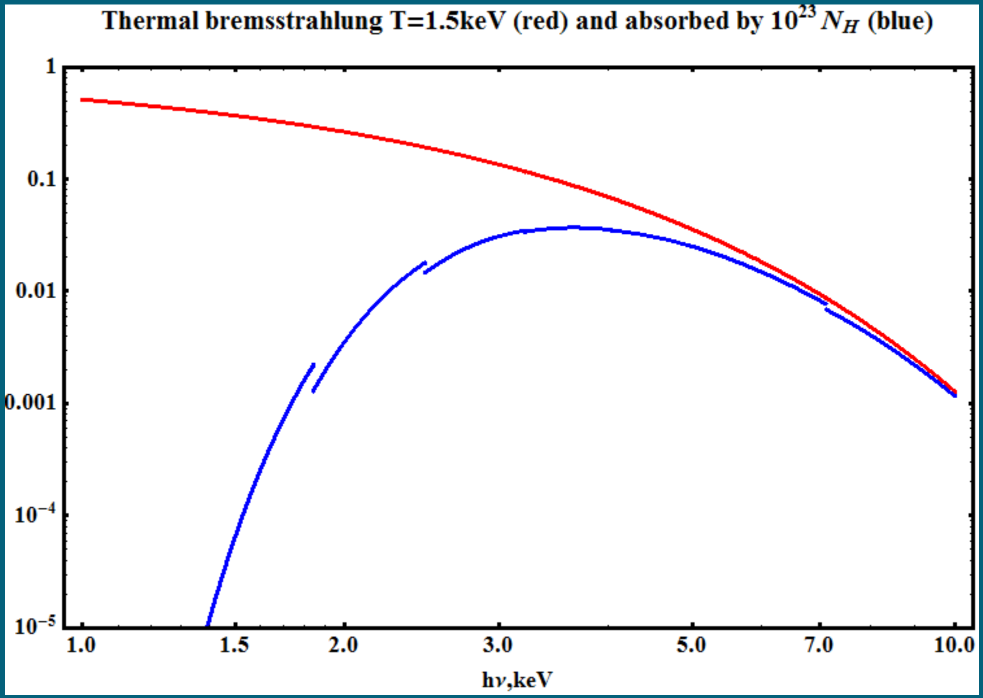
Corrected by Sommerfeld-Elwert factor (wave function is not plane wave)

$$f_S(v_f, v_0) = \frac{v_0}{v_f}\,\frac{1-\exp(-2\pi\alpha c Z/v_0)}{1-\exp(-2\pi\alpha c Z/v_f)}$$

20% larger emissivity at T~2keV and hν ~ 4keV

Absorption

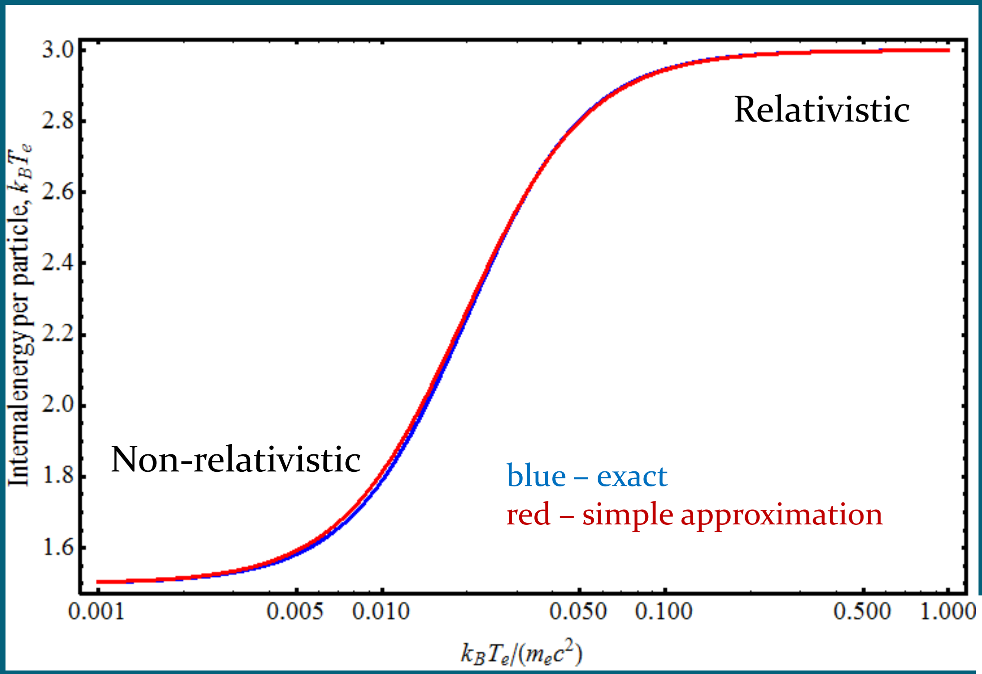




At N_H=10^{23}cm^{-2}, peak energy reaching the detector is ≥4keV

Dynamical model: relativistic effects

Proper heat capacity of relativistic electrons



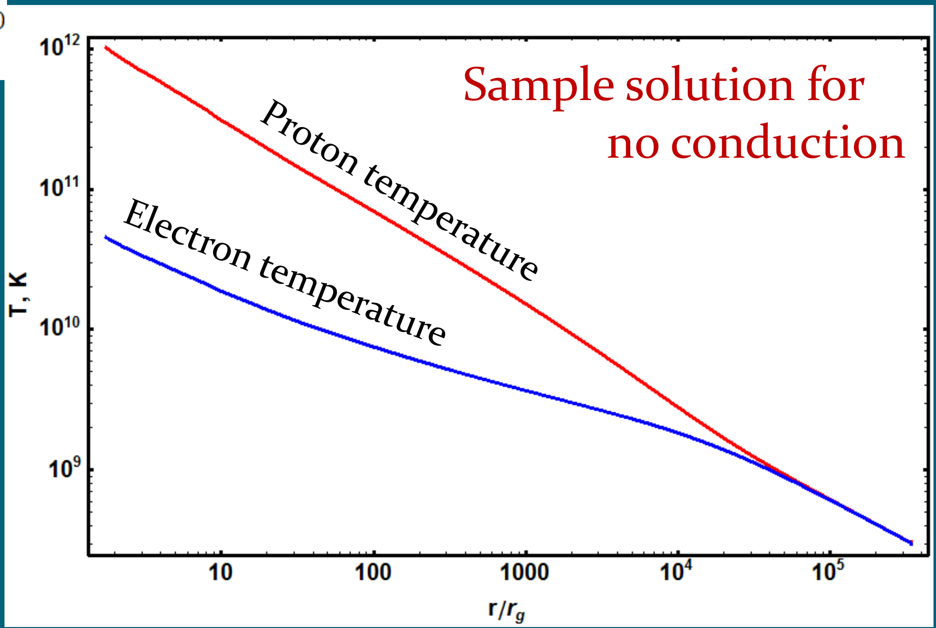
Non-relativistic heating

$$T_i \sim \rho^{2/3}$$

relativistic heating is slower!

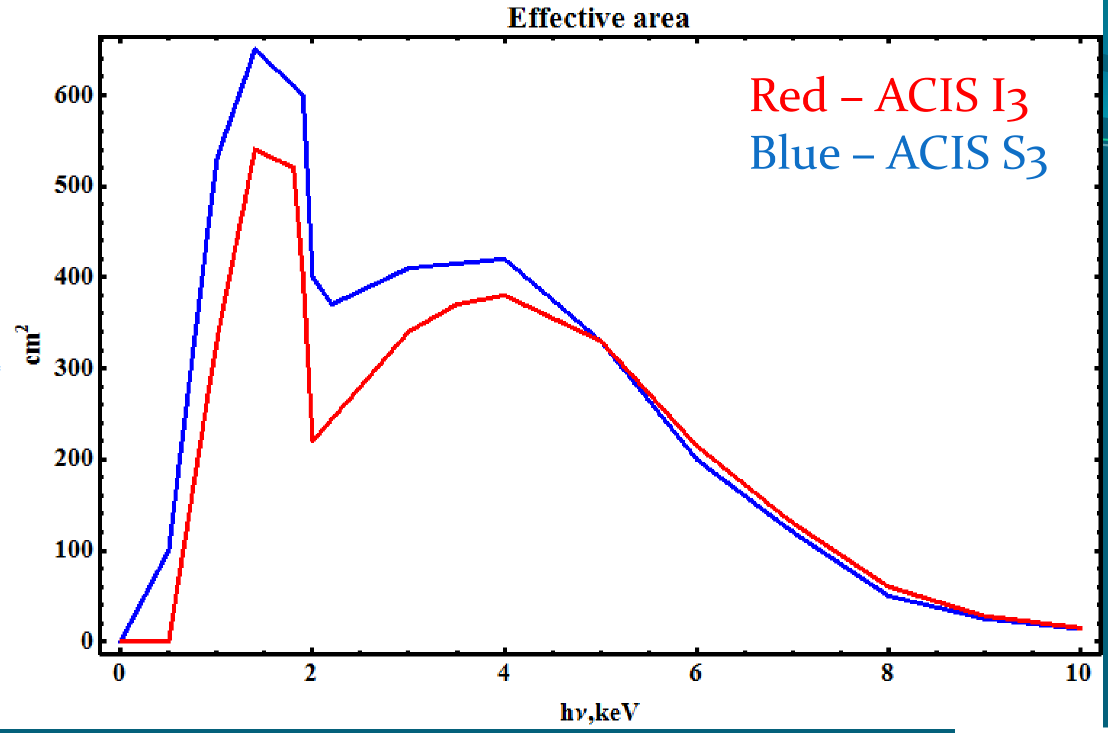
$$T_e \sim \rho^{1/3}$$

Narayan, McClintock 2008



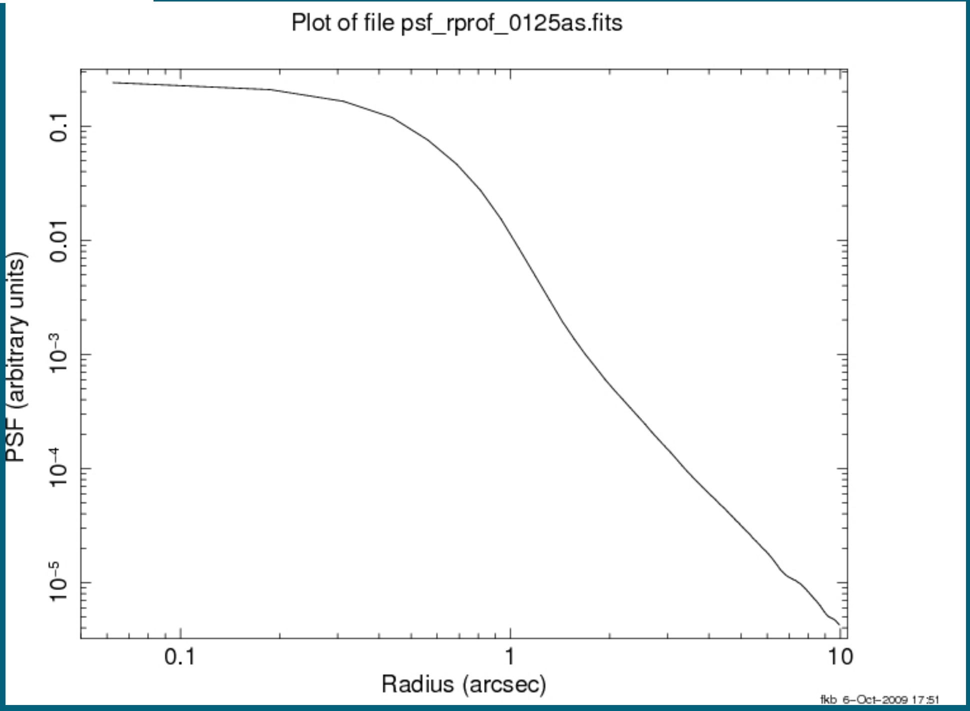
Temperatures start to deviate at $r<10^4 r_g$

For adiabatic heating $T_p/T_e = 15$ near BH



Chandra ACIS response

PSF is well approximated with σ=0.27" Gaussian, but has Lorentzian wings



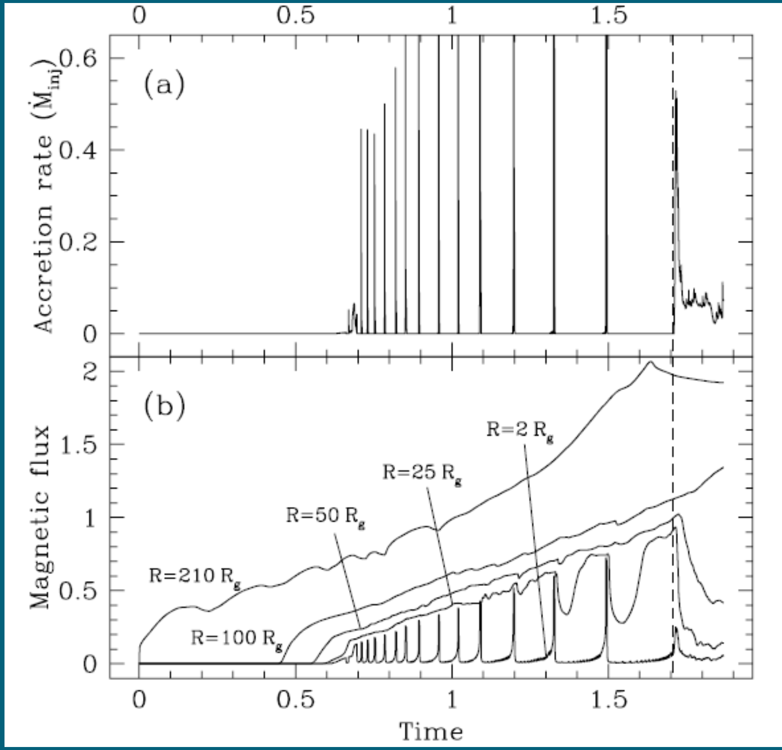
Pixel size 0.492", but Dithering of spacecraft allows us to go to subpixel scales!

Why 2D GRMHD simulations are bad?

Axisymmetric configurations cannot sustain magnetic field

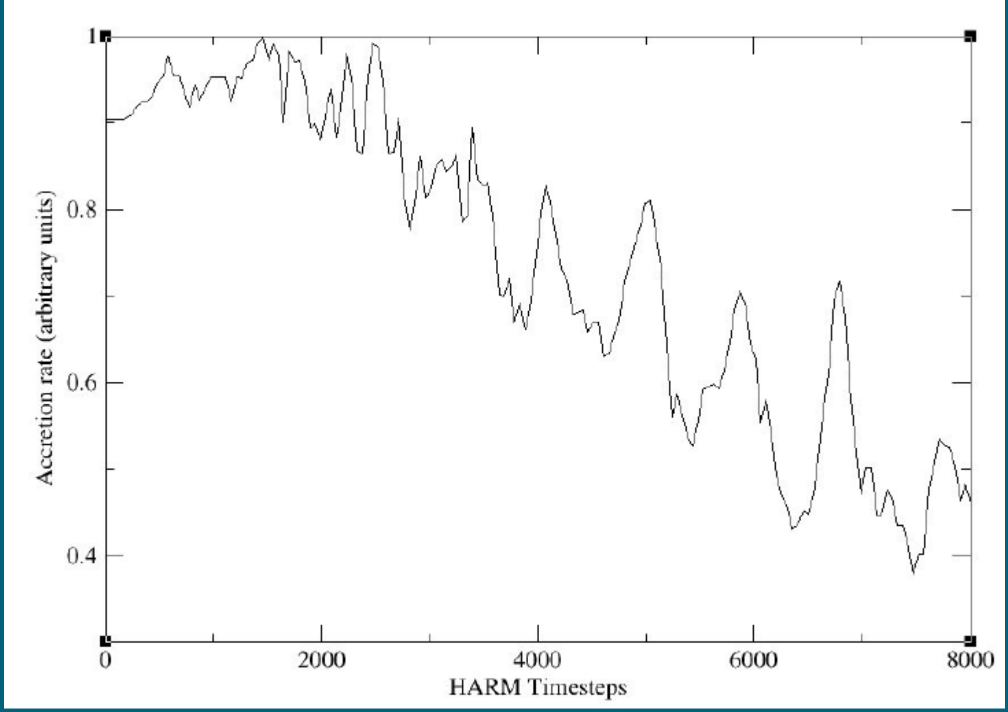
antydynamo | Ivers, James 1983

~~Cowling, 1934~~



2D MHD | Igumenshchev 2008

2D flow exhibits cyclic accretion



2D GRMHD

Hilburn, Liang et al. 2009, astro-ph