Inflow-Outflow Solution with Stellar Winds and Conduction near Sgr A*

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Thanks Ramesh Narayan, Li Ji

Galactic Center Workshop 2009

General idea

Explain extended X-Ray emission within 5’’

Correct bremsstrahlung emissivity

Convolution with Chandra ACIS response

SSC point source

Line-of-sight absorption

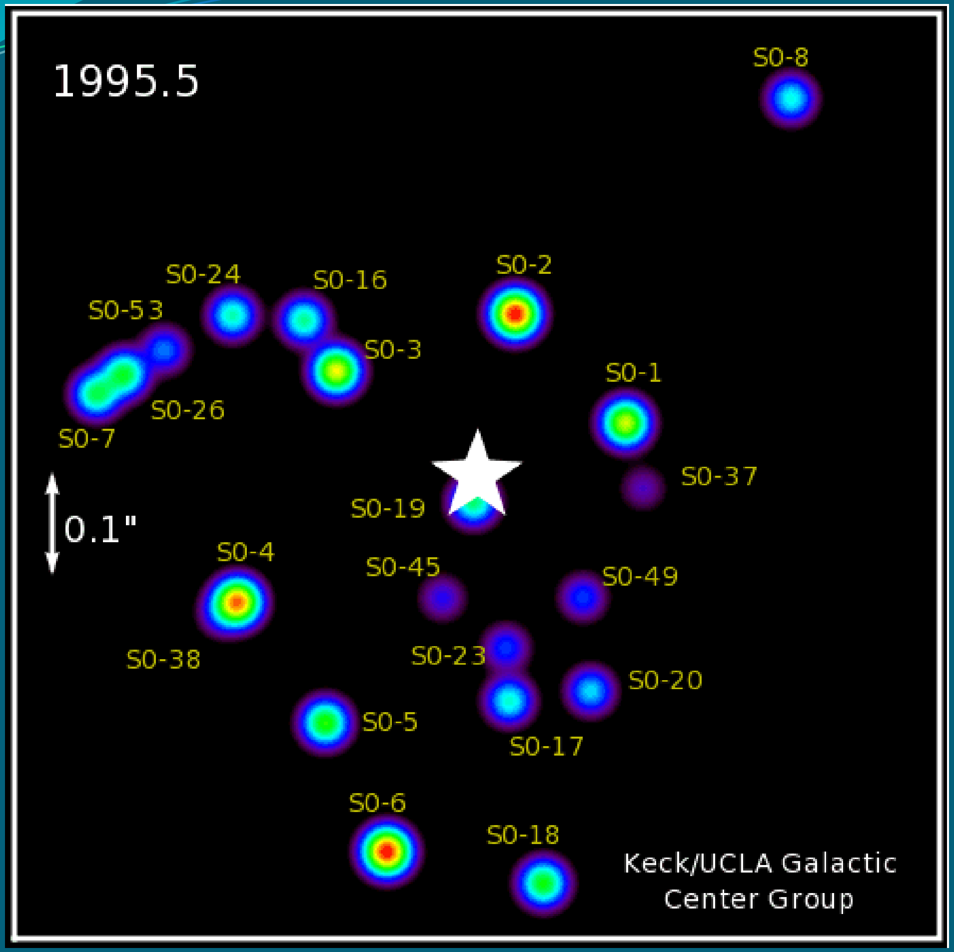
Dynamical model of gas flow

Feeding by stellar winds

Electron heat conduction,
Superadiabatic heating

Proper relativistic effects

Dynamical model: Feeding Mechanism



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

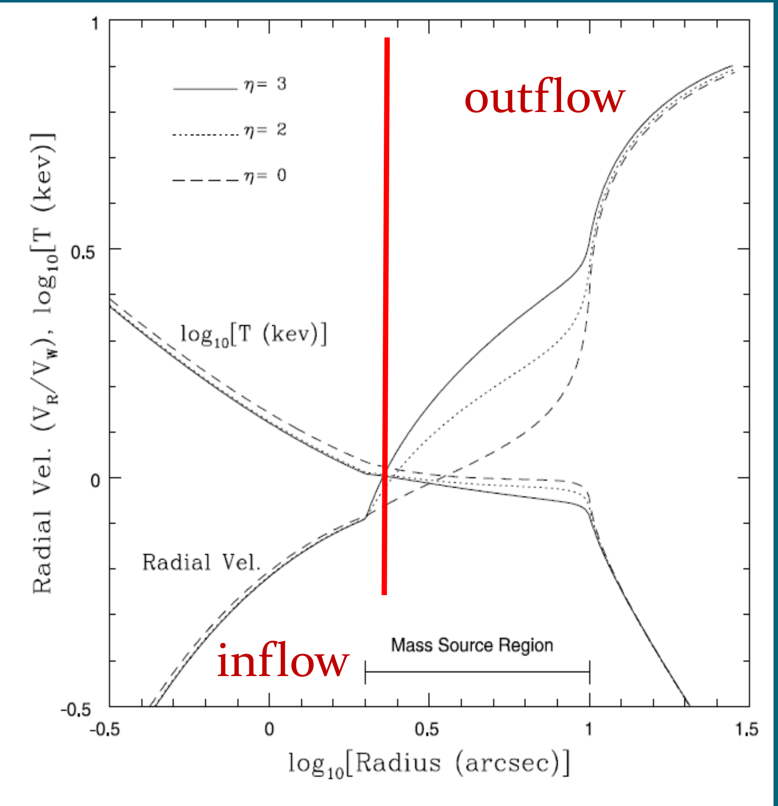


FIG. 1.—Steady state radial velocity and gas temperature as a function of

Quataert, 2004

1. Simplistic feeding
2. No diffusion/conduction

- Implement realistic feeding, accounting for each star
- Add conduction

Dynamical model: Improved Feeding

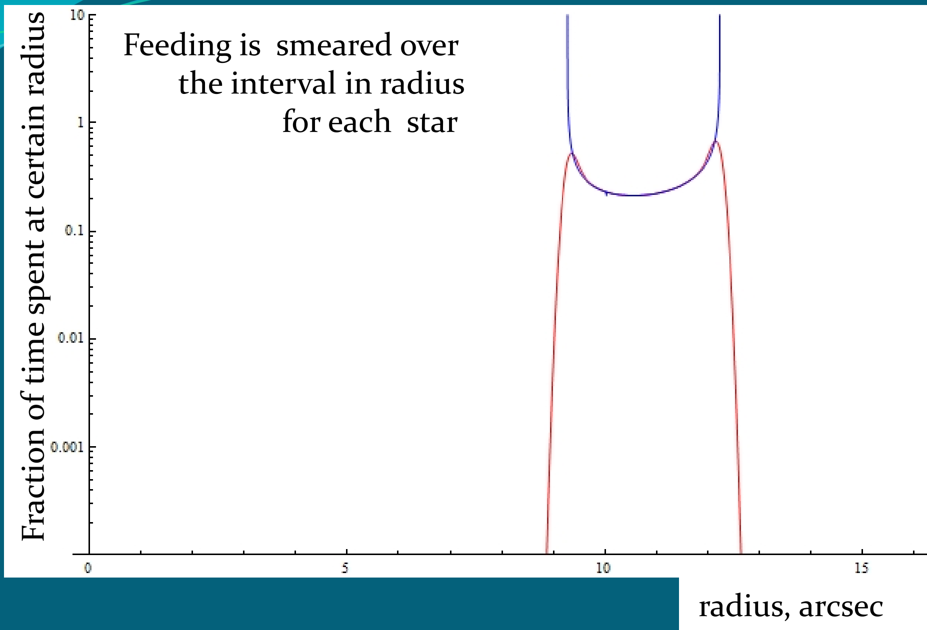
Table of 31 most important wind emitters

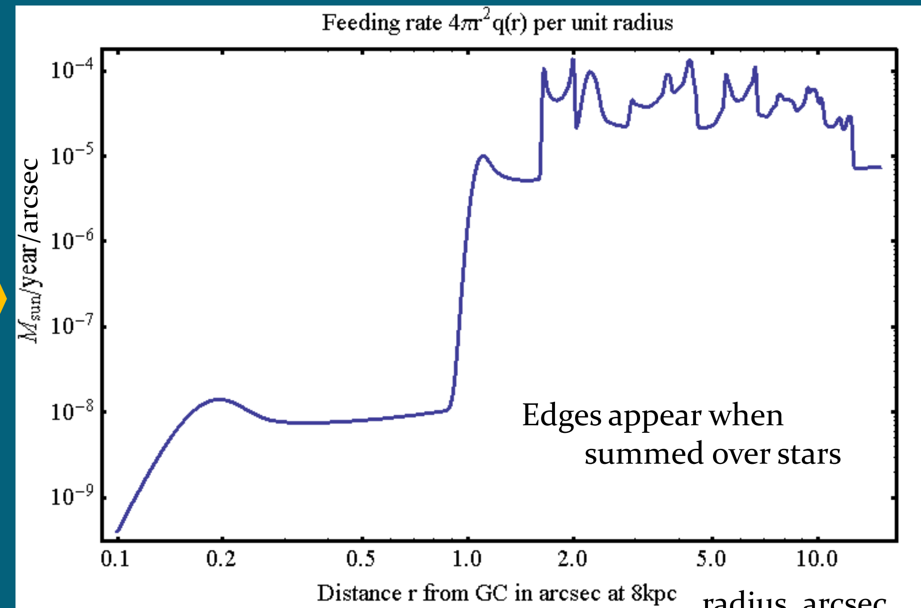
N	Ident	ΔRA,''	ΔDecl,''	Δz,''	v_{RA},km/s	v_{Decl},km/s	v_z,km/s	eccentr	Log[$\dot{M}$,M_S/year]	v_{wind},km/s
1.	S2,S02	0.04	0.12		9.	1830.	-1060.	0.876	-7.2	1000
19.	IRS16NW	0.029	1.221		238.392	32.9208	-44.	0.898	-4.95	600.
20.	IRS16C	1.121	0.497		-330.722	280.773	125.	0.5	-4.65	650.
23.	IRS16SW	1.051	-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.

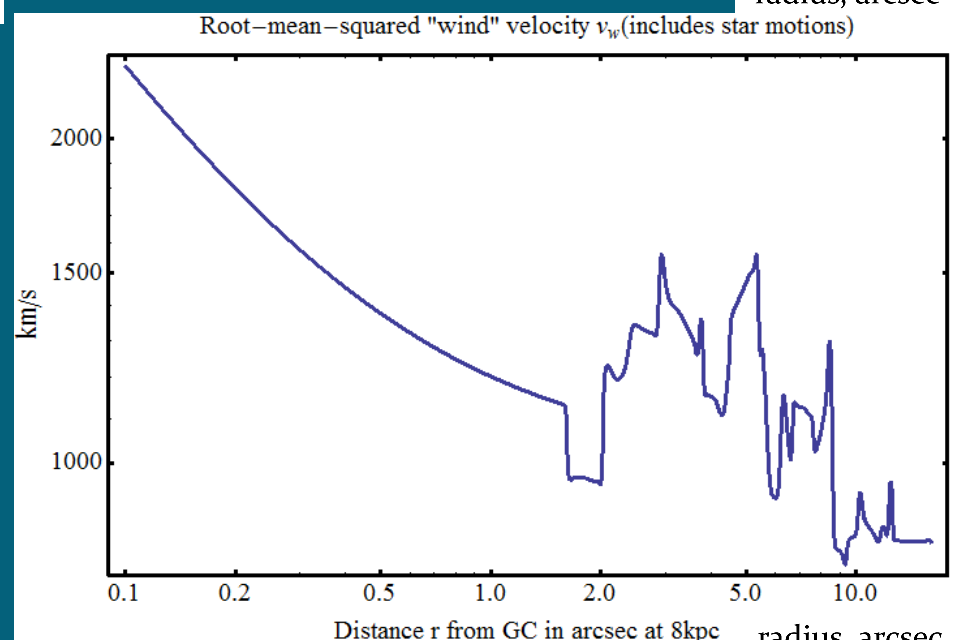
- Orbital data – Paumard et al. (2006)
- Numbers are updated from Lu, Ghez et al.(2009)
- S2 star – Martins, Gillessen (2008)

- 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)

Dynamical model: Improved Feeding





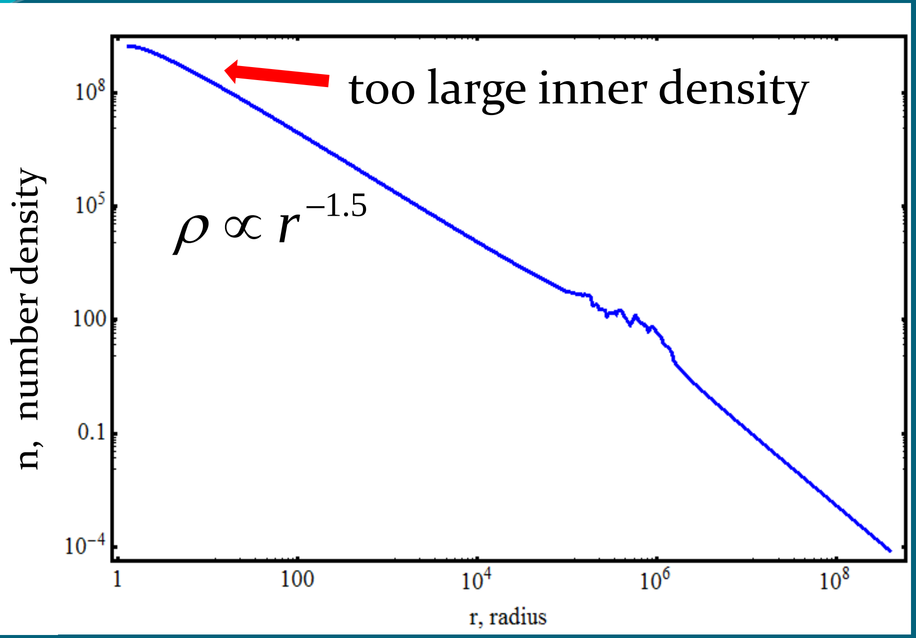


- ✓Gaussian filter is used to smear out orbits
- ✓ Though orbits are ellipses/hyperboles in 3D, only radial info is retained
- ✓ Slow inflow/outflow + energy equilibration by conduction =>

Radial model is reasonable

Dynamical model: shallow density profile

Adiabatic model without conduction



Overproduction of X-Rays, Faraday RM by HUGE factor

Entropy production (next slide)

Outflows

Blandford, Begelman 1999
Yuan et al. 2003

No 1-st principle model

Conduction makes density very shallow

Johnson, Quataert 2007

Why and how electron heat conduction?

- $v_e >> c_s$ => electron conduction dominates others
- saturated collisionless flux or Spitzer value in collisional case
- damped by a factor 3 to 5 in tangled magnetic field

Narayan, Medvedev 2001

- heat flux Q_e can be well approximated by $Q_e = -\kappa k_B \frac{dT_e}{dr},$

with conductivity $\kappa \sim 0.1\sqrt{k_B T_e / m_e} \cdot n r$

Flow is marginally collisional at 5”

Dynamical 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 → $f_i + f_e = 1$

but we want no cooling

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

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

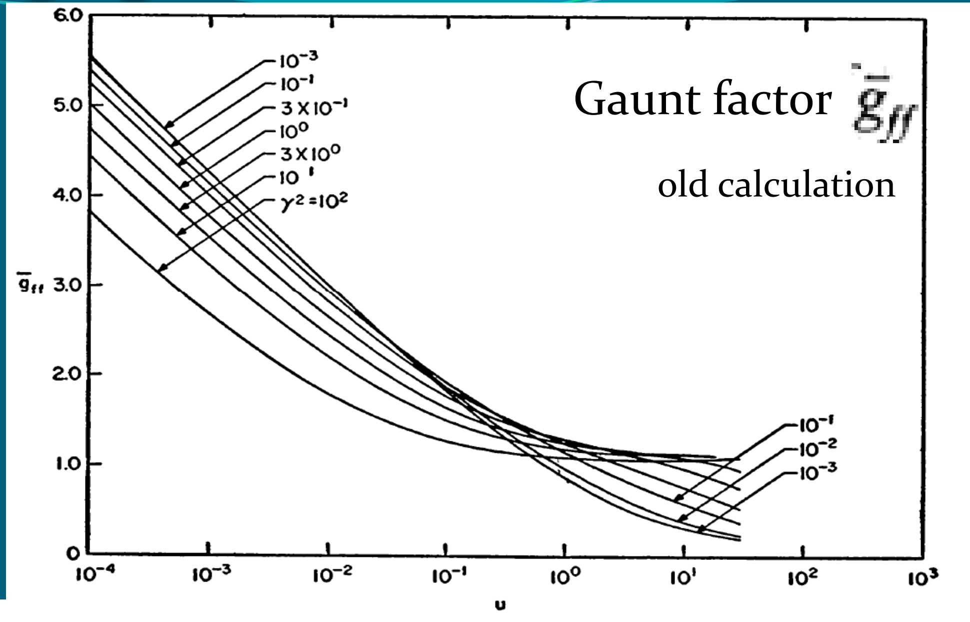
Bremsstrahlung: gaunt factor

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

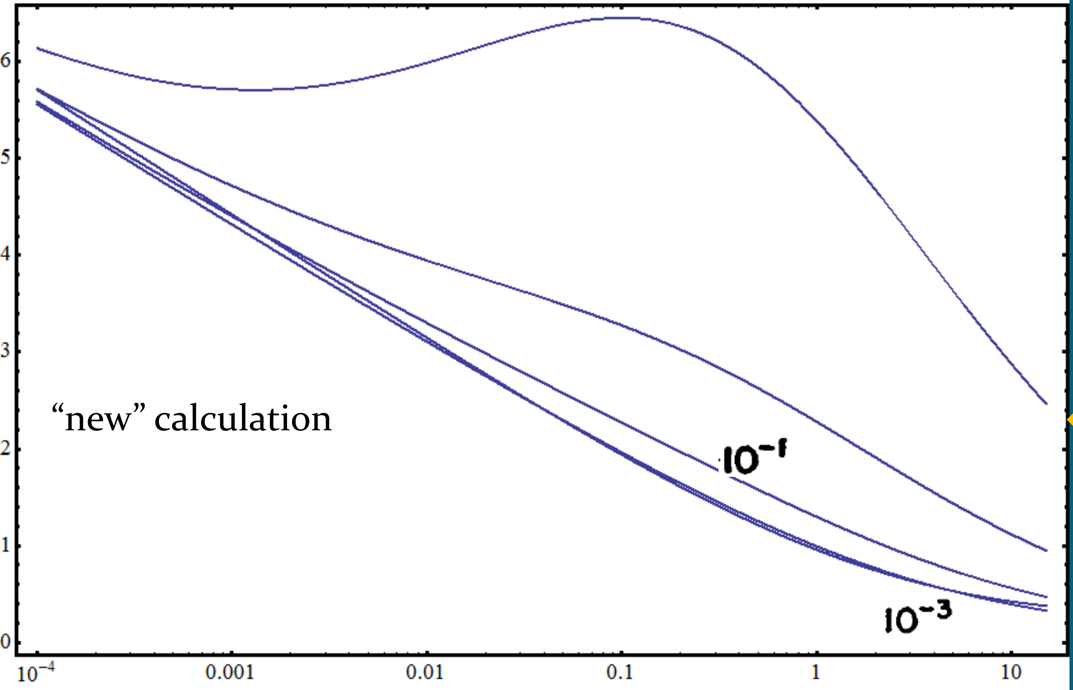
$$u = h\nu/kT$$

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

Gould 1980 (+errata)



Karzas & Latter 1960

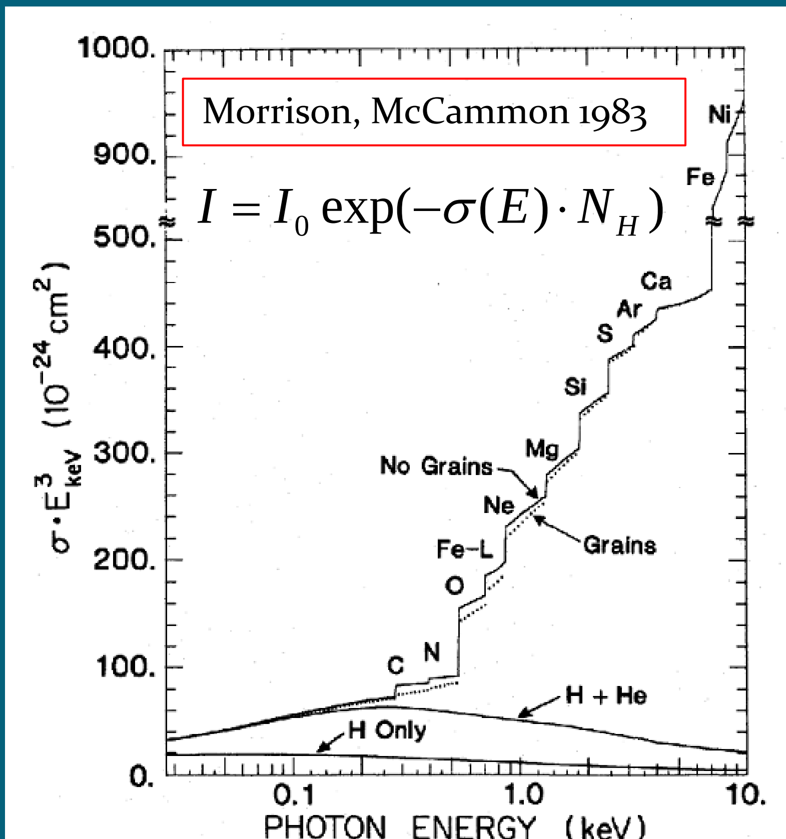


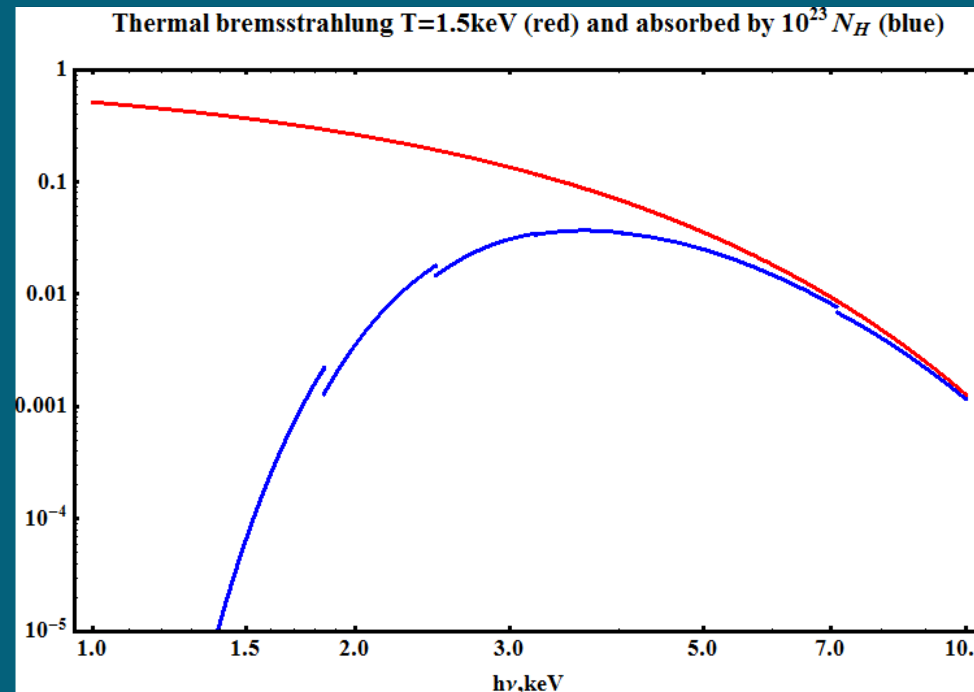
Corrected by
Sommerfeld-Elwert factor
(wave function is not plane wave)

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

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

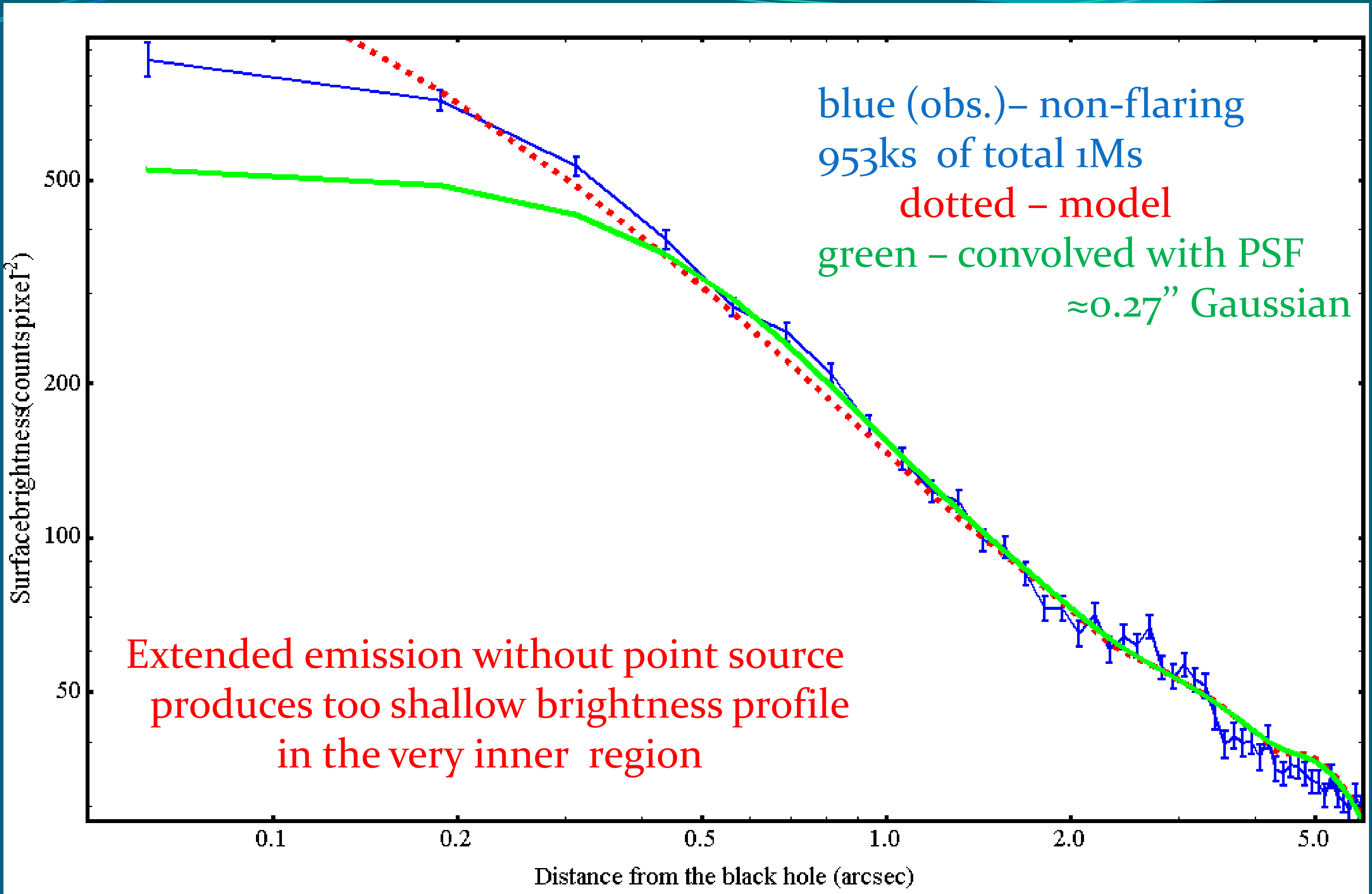
Absorption





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

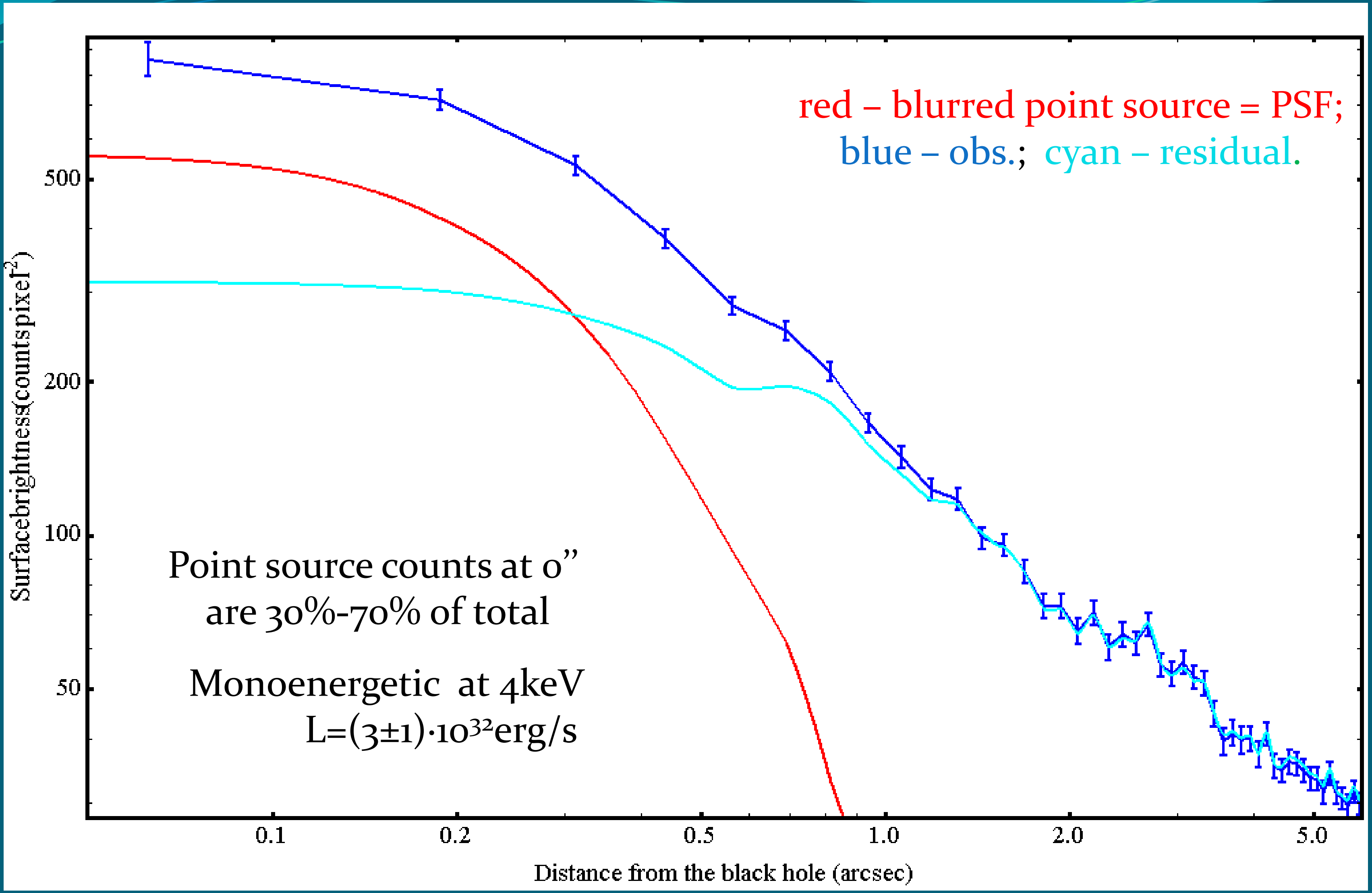
Results: only extended emission



Conduction, f_i=0.15, f_e=0.05,
relativistic heat capacity of e^-

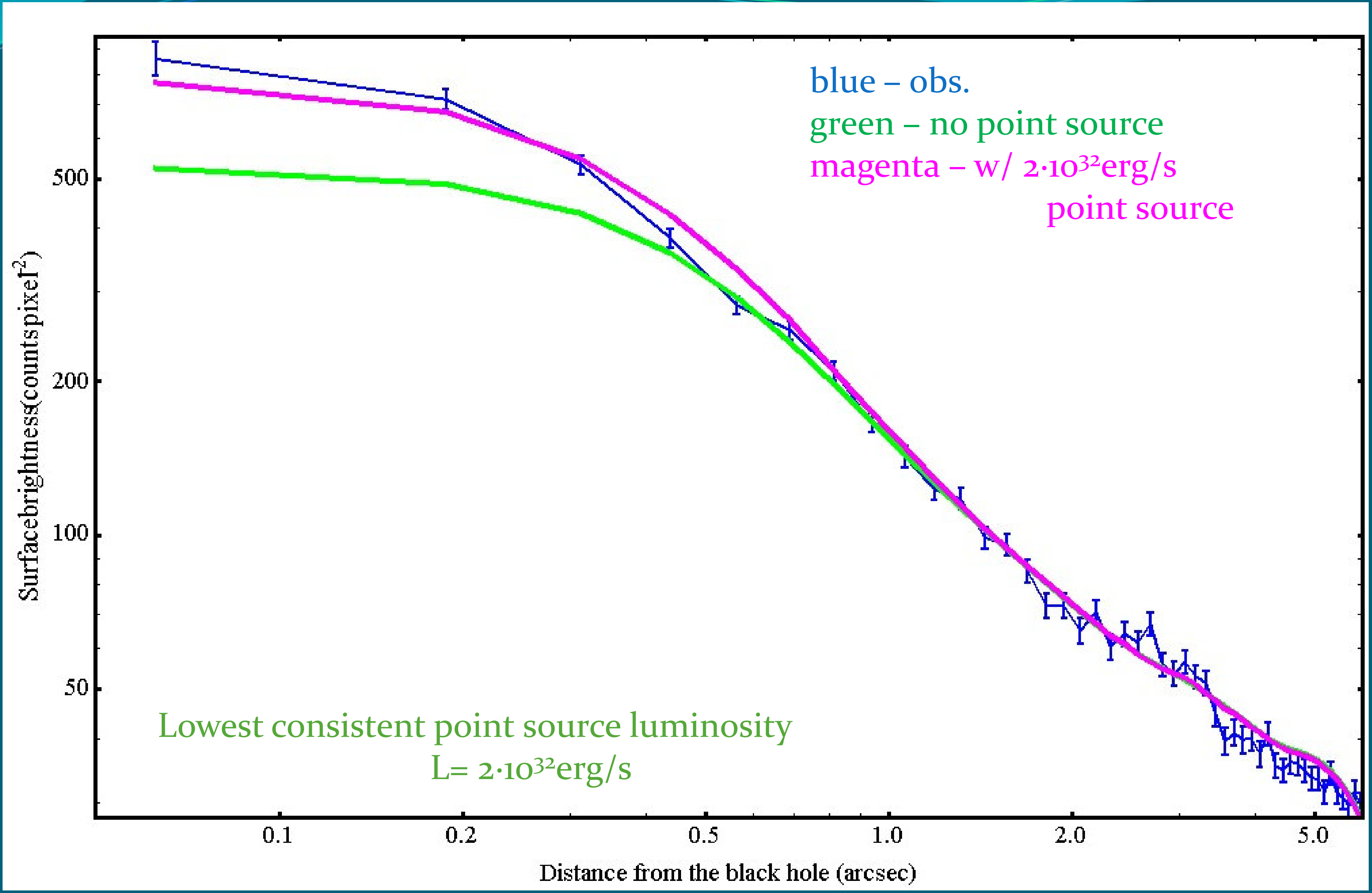
Assumption: emission stops at 7" (line cooling Sutherland, Dopita 1993)

Results: point source & residual

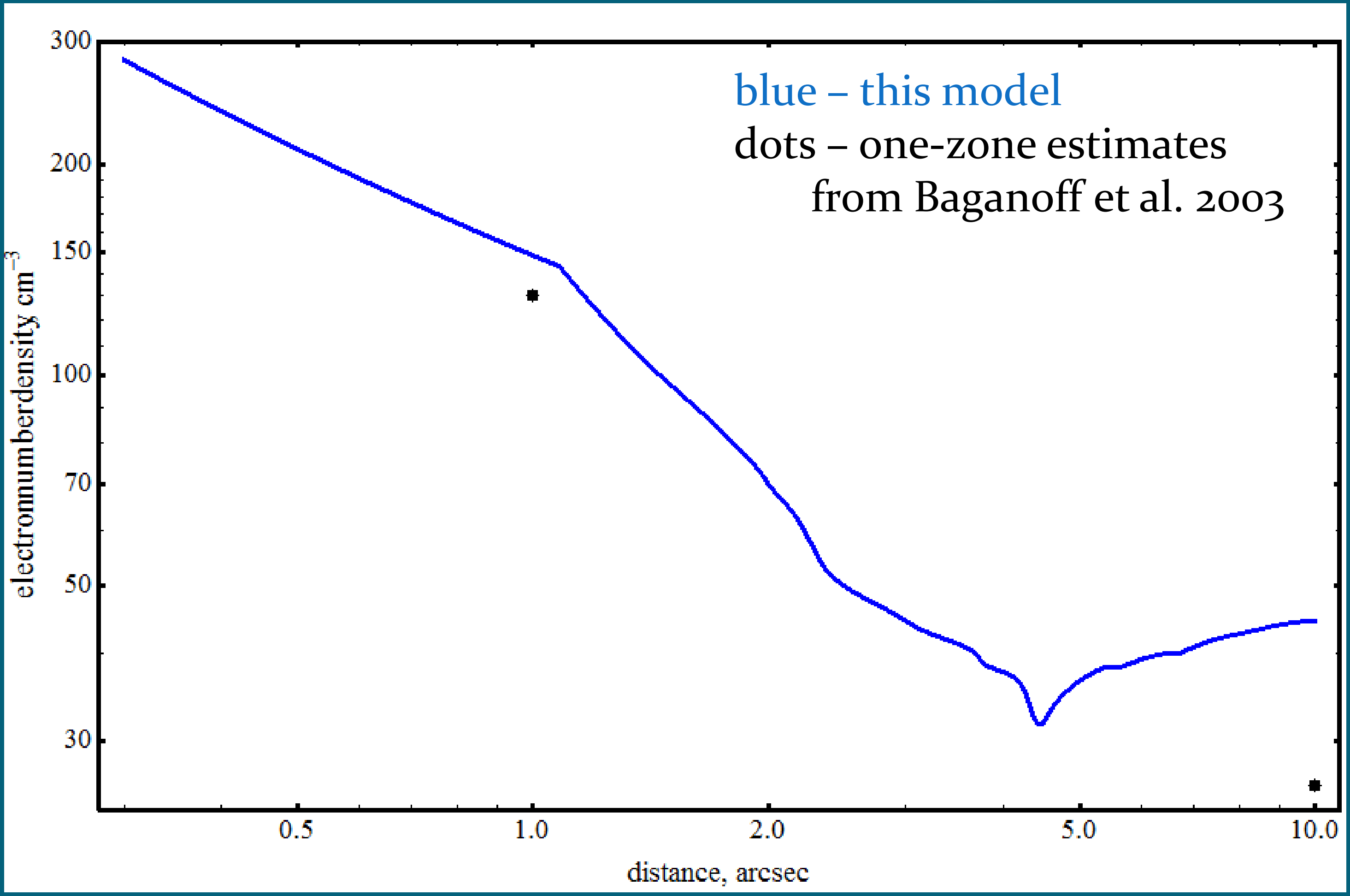


Consistent with Moscibrodzka, et al. 2009
$\nu L_\nu = 5 \cdot 10^{32}$ erg/s at 4keV SSC point source

Results: possible fit



Comparison to previous estimates



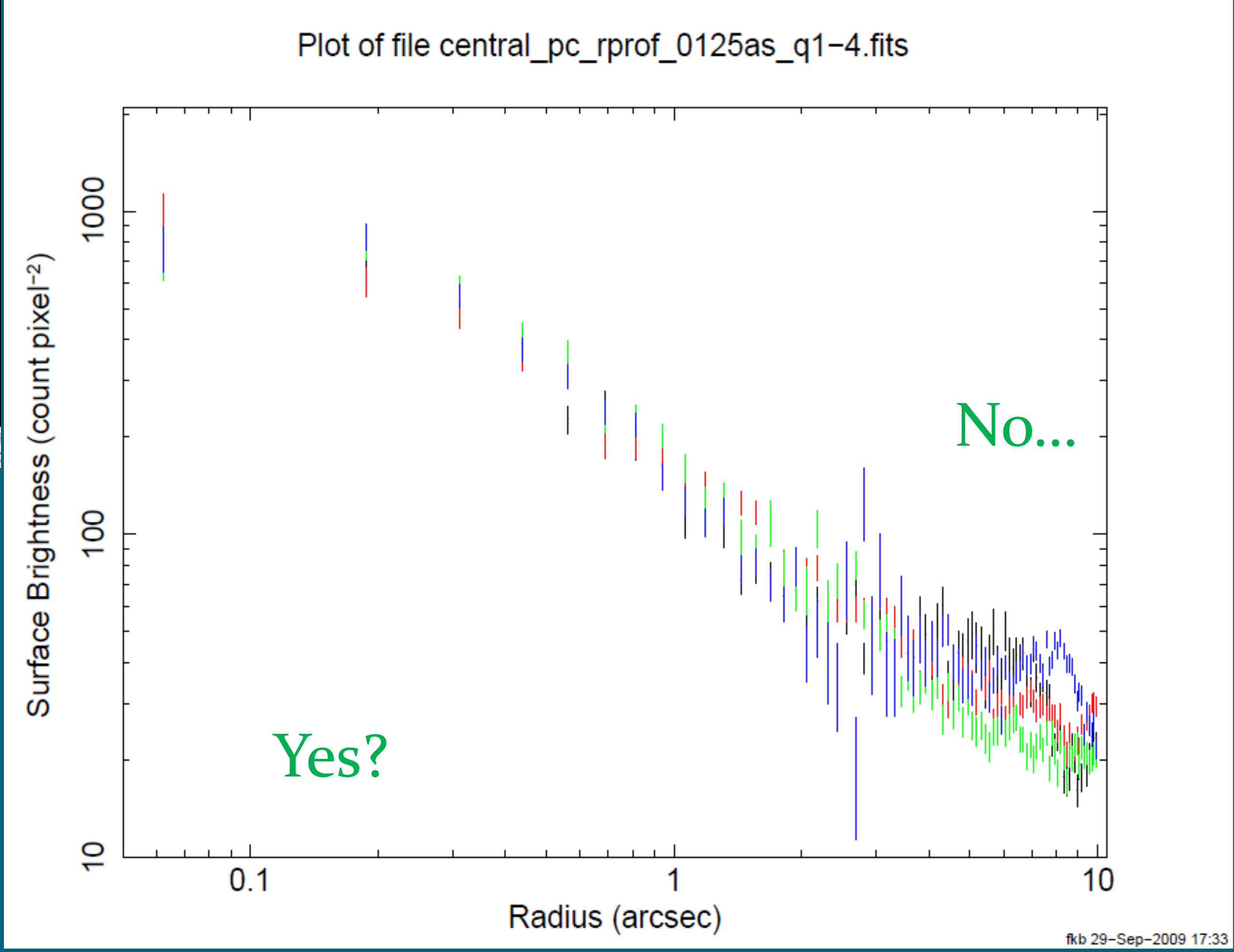
About the same densities in this model
despite bright point sources/extended emission subtracted

Temperature is N_H dependent , around 2.2keV for N_H=10^{23}cm^{-2}

Actually spherically symmetric?

Point sources and
hot streams were subtracted

Counts from
4 sectors 90° each



No...

Yes?

Conclusions

- ✓ Data extracted from extensive Chandra observations (non-flaring)
- ✓ Model constructed with
  electron conduction and superadiabatic heating

⬇

- ✓ Shallow density profile => fit to extended part of emission
- ✓ Point source of $(3\pm1)\cdot10^{32}$erg/s must be present
- ✓ χ^2 search in the parameter space continues

Future work

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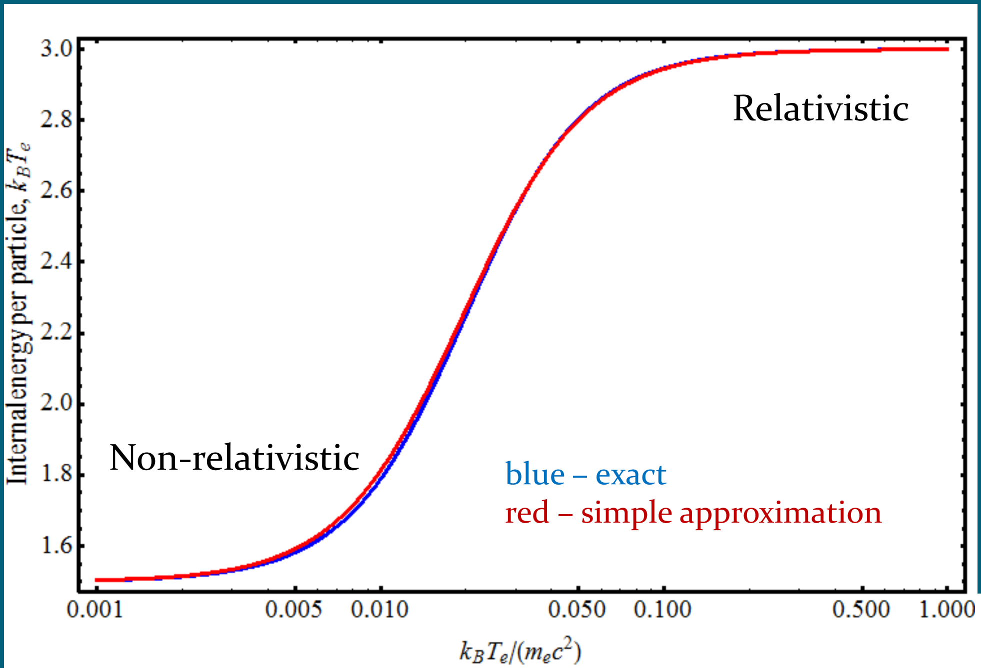
- ✓ Use spectral data
- ✓ Include angular momentum
- ✓ Fit optically thick sub-mm luminosity (86GHz)

Dynamical model: relativistic effects

Proper heat capacity of relativistic electrons



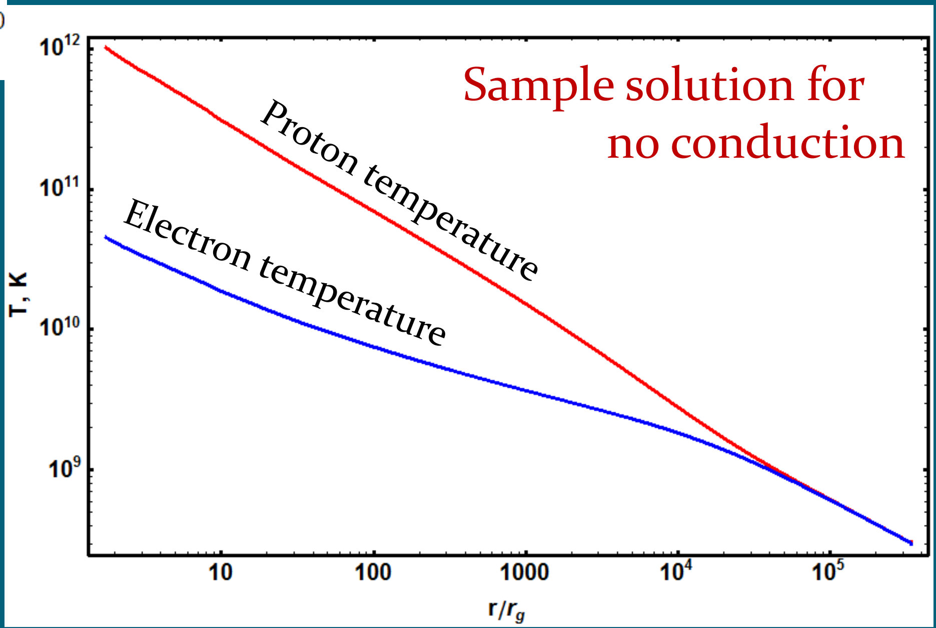
Non-relativistic heating

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

relativistic heating is slower!

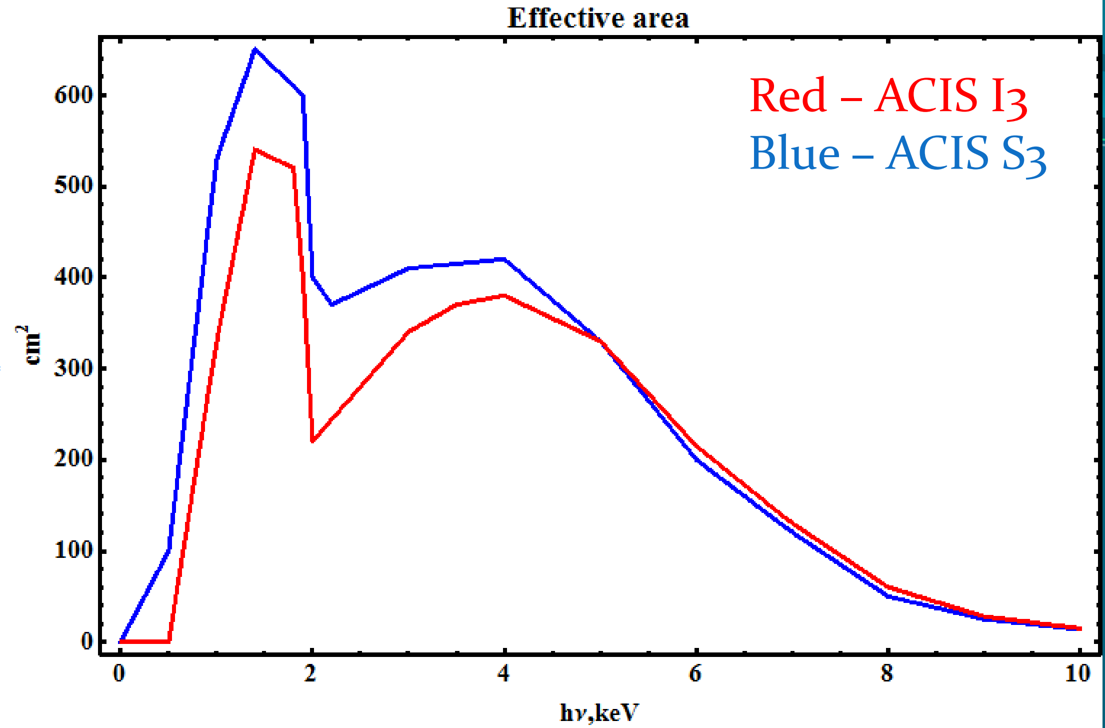
$$T_e \sim \rho^{1/3}$$

Narayan, McClintock 2008



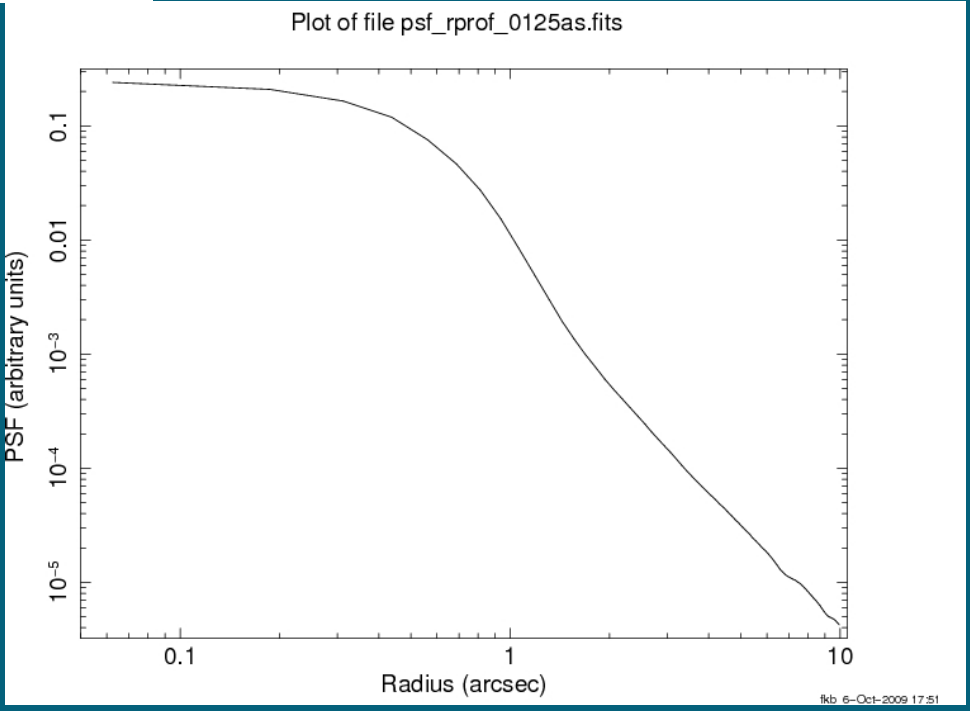
Temperatures start to deviate at $r<10^4 r_g$

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



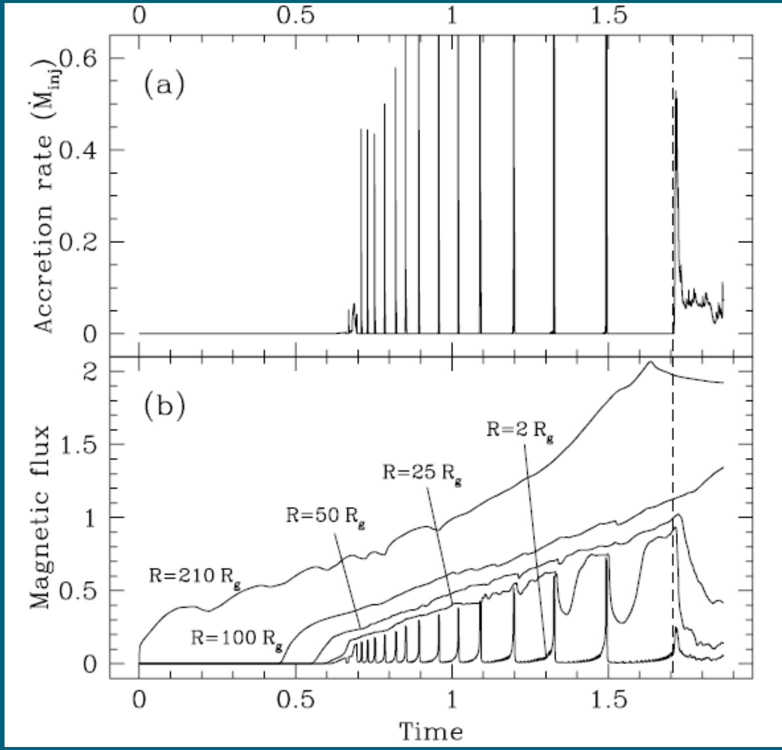
Pixel size 0.492”, but Dithering of spacecraft allows us to go to subpixel scales!

Why 2D GRMHD simulations are bad?

Axisymmetric configurations cannot sustain magnetic field

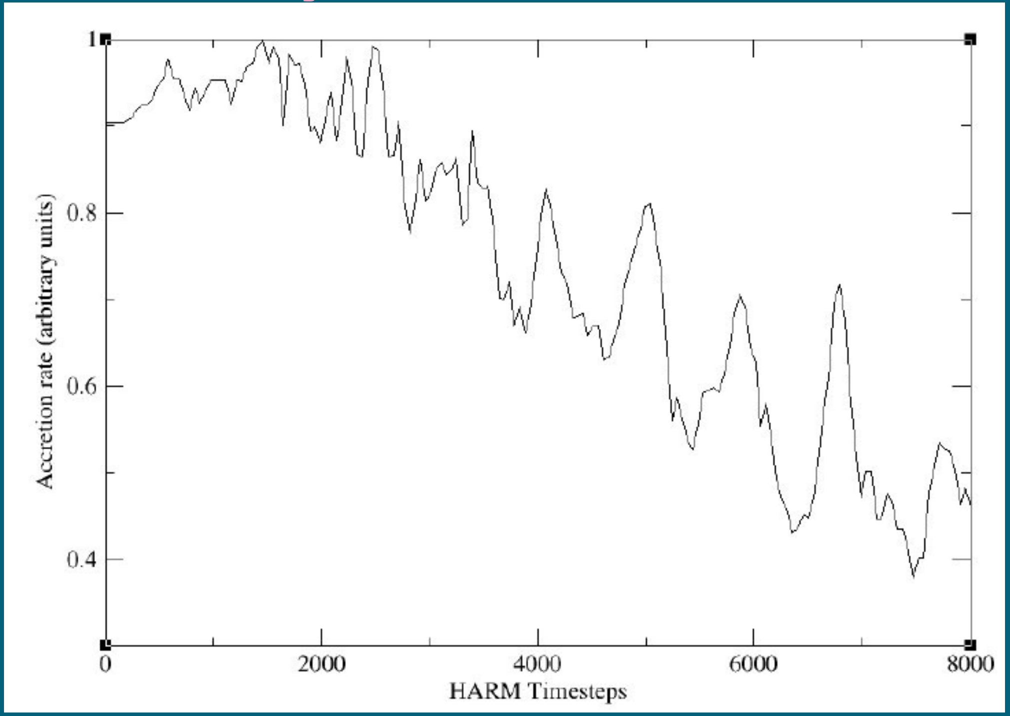
antydynamo Ivers, James 1983

~~Cowling, 1934~~



2D MHD Igumenshchev 2008

2D flow exhibits cyclic accretion



2D GRMHD

Hilburn, Liang et al. 2009, astro-ph