Constraining the Accretion Flow in Sgr A* by General Relativistic Dynamical and Polarized Radiative Modeling

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$M = 4.3\cdot10^{6} M_{Sun};\ d = 8.3kpc$

Gillessen 2009; Ghez, 2008

Sgr A* - black hole in the center of the Galaxy

Accretion of hot stellar winds ⟶ extremely low accretion rate ~$10^{-8}M_{sun}$/yr

My talk on Tuesday

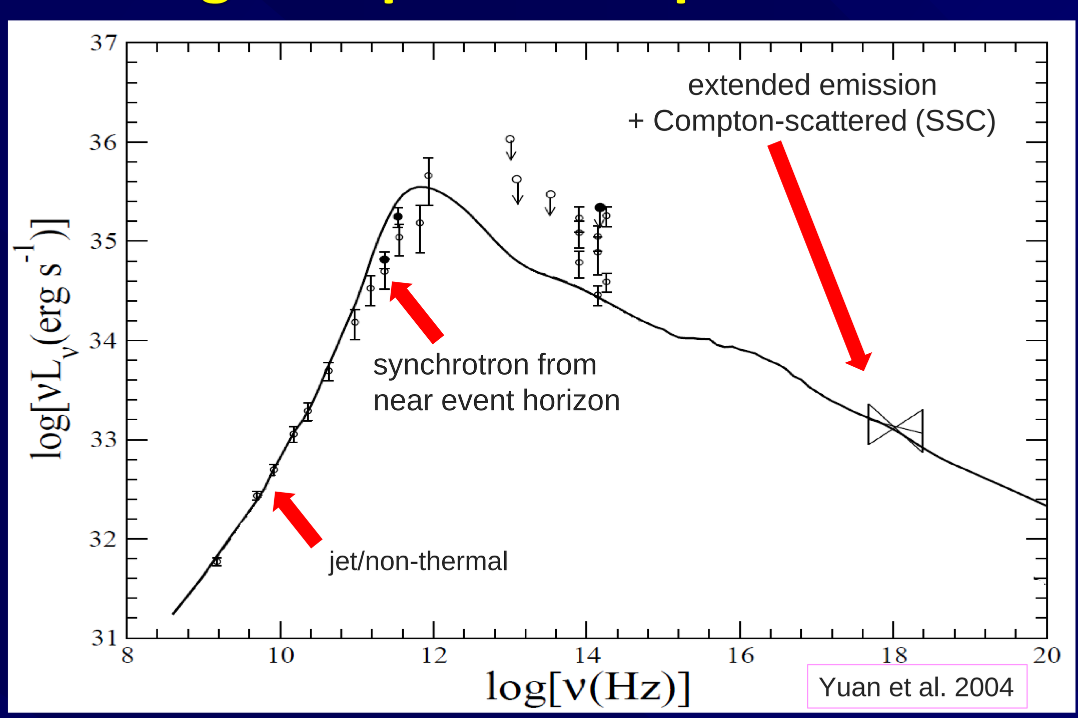
Radiatively inefficient accretion flow has hot electrons

⬇

Polarized synchrotron emission

$T_e \sim 3\cdot10^{10}K$

Sgr A* quiescent spectrum



Electron T_e and magnetic field B increase steeply towards the BH

⬇

Synchrotron emissivity and peak ν rise closer to the BH

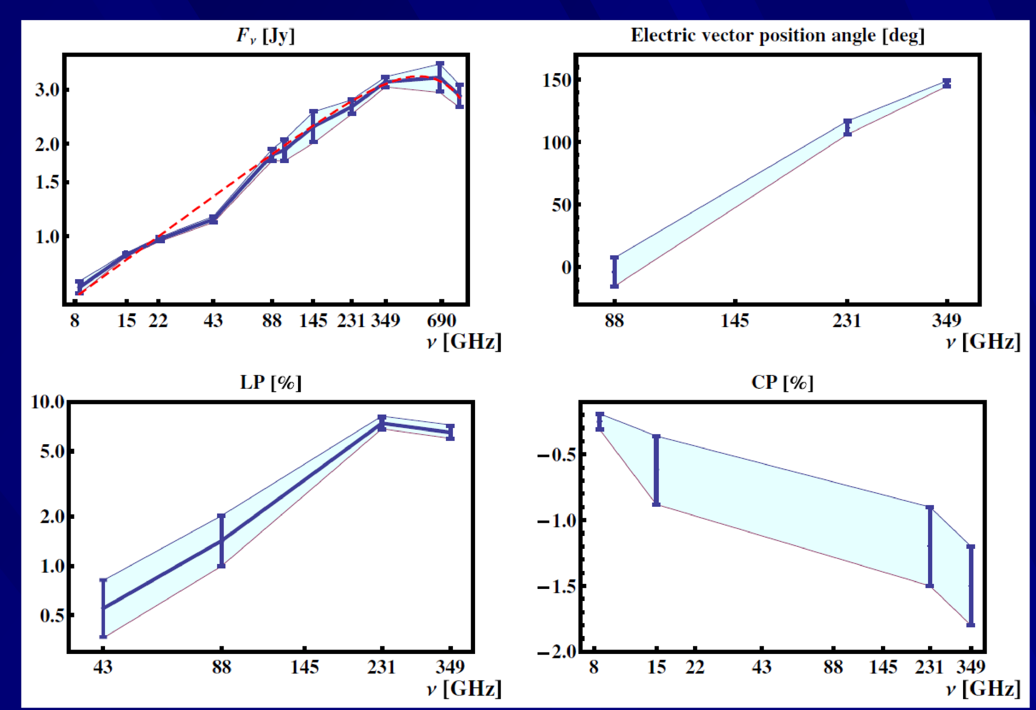
⬇

Sub-mm synchrotron peak is produced near the event horizon

⬇

Allows to probe GR effects

Compilation of mean sub-mm polarized spectrum



- Compilation over 13 yrs of observations
- Shown mean fluxes/polarization fractions
- Error bars – errors of sample means /or/ systematic errors (if larger)
- Total flux peaks at ~500GHz
- Low LP at low frequencies – beam depolarization

Plan:

1. **Simulate accretion flow dynamics near the BH for a set of spins a^***
2. **Construct a set of models with certain electron temperature T_e, accretion rate M_{dot}, viewing angle θ**
3. **Perform GR polarized radiative transfer and simulate mean spectra**
4. **Find the preferred model parameters**

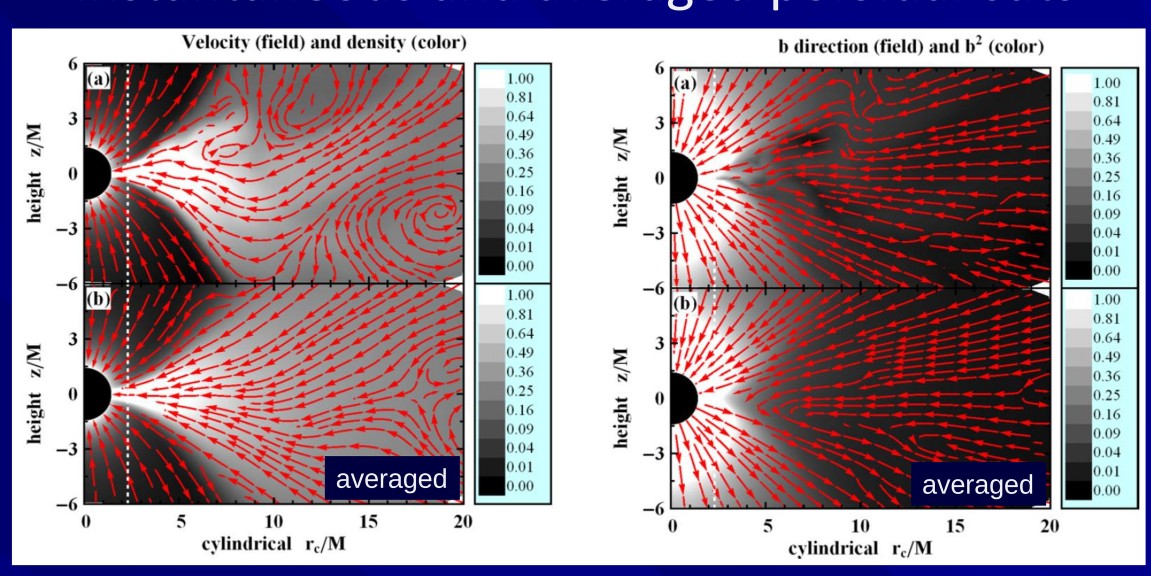
3D GRMHD simulations + extensions

- start with weak-B torus w/ inner edge at 20M
- spins 0; 0.5; 0.7; 0.9; 0.98
- Γ=4/3, no cooling (thick disk)
- disk aligned with spin axis
- resolution 256x64x32
- simulation within Pi wedge
- evolve for 20000M each spin with 3D GRMHD code HARM

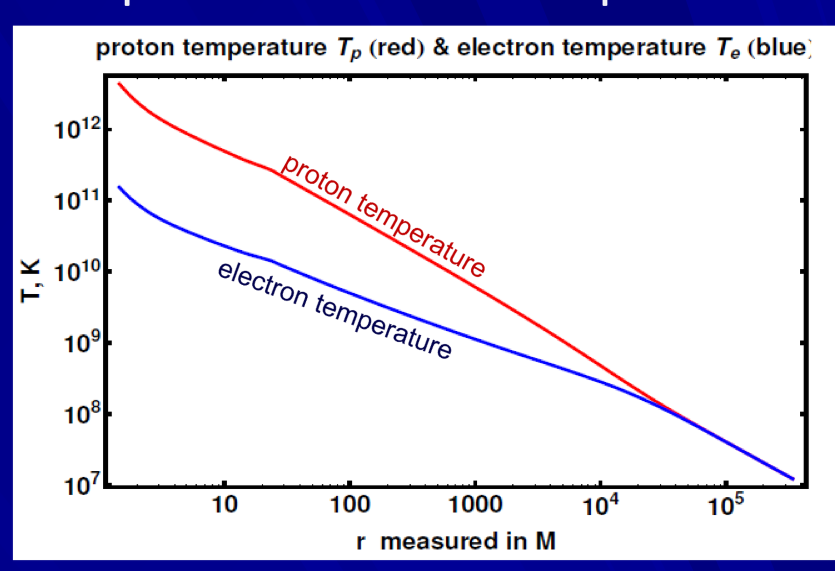
- use quasi-steady late-time accretion flow for radiative transfer: from 14000M to 20000M
- solve for electron temperature profile leaving heating coefficient C – free parameter

magnetic field settles by 14000M into helix (split monopole in projection)

Instantaneous and averaged poloidal cuts



Sample solution for temperatures



General relativistic polarized radiative transfer

Plasma effects:

- Transport of Stokes I, Q, U, V along geodesics
- Cyclo-synchrotron emissivity in thermal plasma
- Faraday rotation Q↔U (between linear modes)
- Faraday conversion Q,U↔V (between linear and circular)
- Circular polarization produced via direction emission and Faraday conversion

Radiative transfer is fully self-consistent

- Simulation is evolved as light propagates through it
- We find the mean simulated spectrum by averaging the spectra at different times
- Then compare the mean observed and mean simulated spectra: CP, LP, total flux in sub-mm

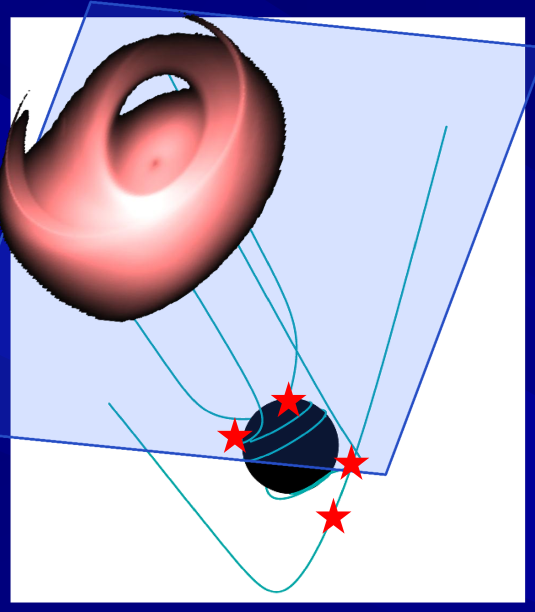
Formalism outlined in

Shcherbakov, Huang 2010, ApJ

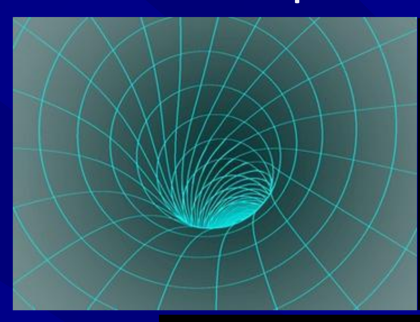
Faraday rotation and conversion

Shcherbakov 2008

Ray tracing procedure

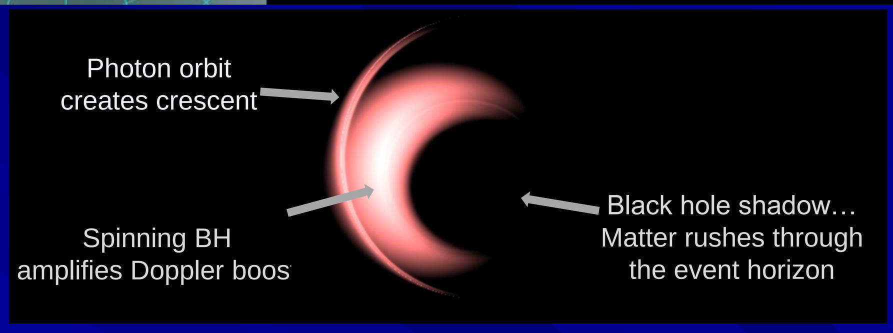


Spacetime distortions near the BH



Black holes:

- ✓ Bend light rays (curved geodesics)
- ✓ Spin => extra Doppler boost
- ✓ Pull gas through the event horizon, so that it stops radiating out



Results: preferred BH and accretion flow parameters

Properties of the Best-fit Models with Different Spins

Model	Inclination Angle, θ (deg)	Spin Position Angle, P.A. (deg)	Heating Constant, C	Ratio T_p/T_e at 6M	Electron T_e at 6M (K)	Accretion Rate $\dot{M}$ ($M_\odot\ yr^{-1}$)
Spin $a_* = 0$	42.0	171.0	0.42107	15.98	3.343×10^{10}	7.005×10^{-8}
Spin $a_* = 0.5$	74.5	115.3	0.37012	20.14	3.087×10^{10}	4.594×10^{-8}
Spin $a_* = 0.7$	64.5	84.7	0.37239	20.16	3.415×10^{10}	2.694×10^{-8}
Spin $a_* = 0.9$	53.5	123.4	0.39849	18.16	4.055×10^{10}	1.402×10^{-8}
Spin $a_* = 0.98$	57.2	120.3	0.41343	17.00	4.190×10^{10}	1.553×10^{-8}
Spin $a_* = 0.5$ short period 1	70.0	79.3	0.38934	18.50	3.334×10^{10}	3.513×10^{-8}
Spin $a_* = 0.5$ short period 2	72.8	113.1	0.40507	17.31	3.541×10^{10}	3.452×10^{-8}
Spin $a_* = 0.5$ short period 3	73.4	57.4	0.37302	19.87	3.125×10^{10}	3.897×10^{-8}
Spin $a_* = 0.5$ short period 4	74.4	115.4	0.36147	20.95	2.978×10^{10}	4.508×10^{-8}
Spin $a_* = 0.5$ short period 5	71.9	95.7	0.37420	19.79	3.137×10^{10}	5.334×10^{-8}
Spin $a_* = 0.5$ short period 6	76.4	116.7	0.38853	18.59	3.320×10^{10}	6.080×10^{-8}
Spin $a_* = 0$ fast light	41.4	187.5	0.41929	16.09	3.322×10^{10}	7.044×10^{-8}
Spin $a_* = 0.5$ fast light	72.7	105.9	0.39804	17.83	3.447×10^{10}	3.957×10^{-8}
Spin $a_* = 0.7$ fast light	59.4	131.8	0.35708	21.62	3.204×10^{10}	2.966×10^{-8}
Spin $a_* = 0.9$ fast light	53.3	123.3	0.40215	17.86	4.116×10^{10}	1.340×10^{-8}
Spin $a_* = 0.98$ fast light	57.7	119.6	0.41720	16.73	4.246×10^{10}	1.515×10^{-8}

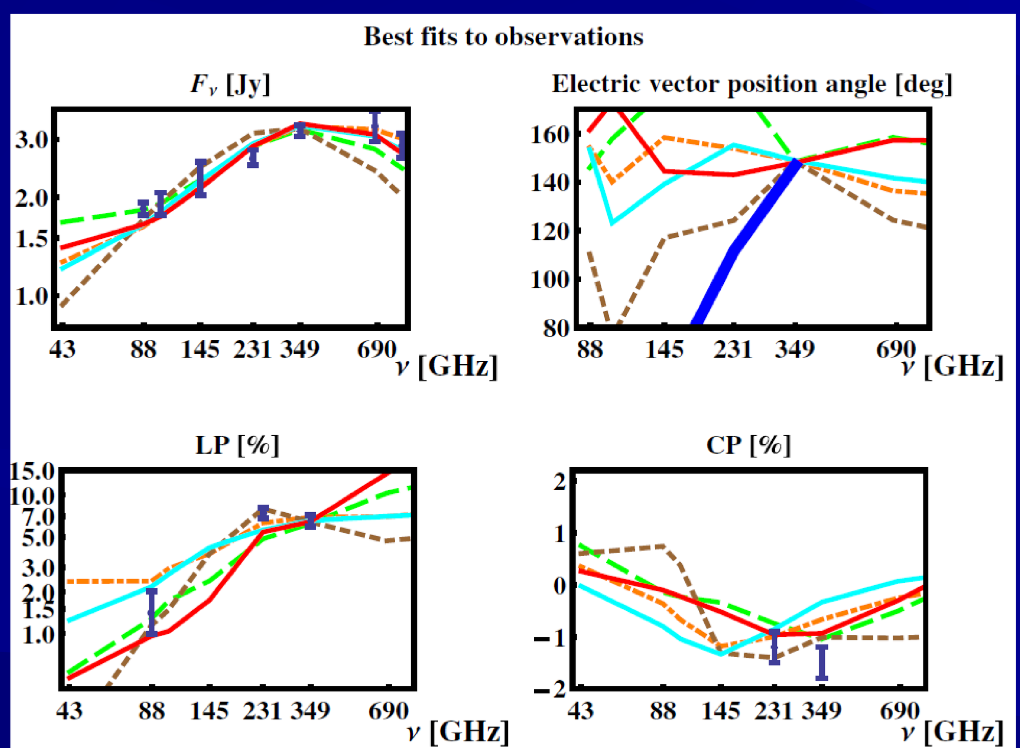
- Reduced χ^2=2-5 for best models with each spin
- Best reduced χ^2 changes by ~1 between realizations => cannot choose a best spin
- Electron temperature at $r=6r_g$ for best-fitting models: $T_e=(3.0\text{-}4.2)\cdot10^{10}K$
- Accretion rate $M_{dot}=(1.5\text{-}7.0)\cdot10^{-8}M_{sun}/yr$, higher spin => lower accretion rate
- Spin inclination angle 40-75°, neither face-on nor edge-on models fit
- "Fast light" approximation (radiative transfer on stationary snapshots) leads to significant variations in the best-fitting parameters

Dozens of caveats

- Is numerical resolution sufficient?
- Did simulation reach the steady state?
- Does red noise change time variability?
- Are plasma effects important for dynamics (conduction)?
- Are plasma effects important for electron distribution?
- How are the electrons heated?

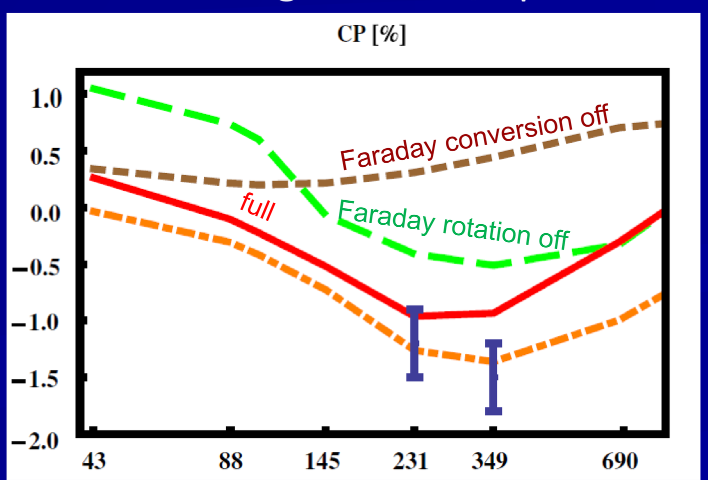
The results should be taken as order of magnitude estimates

Spectra for best models with each spin



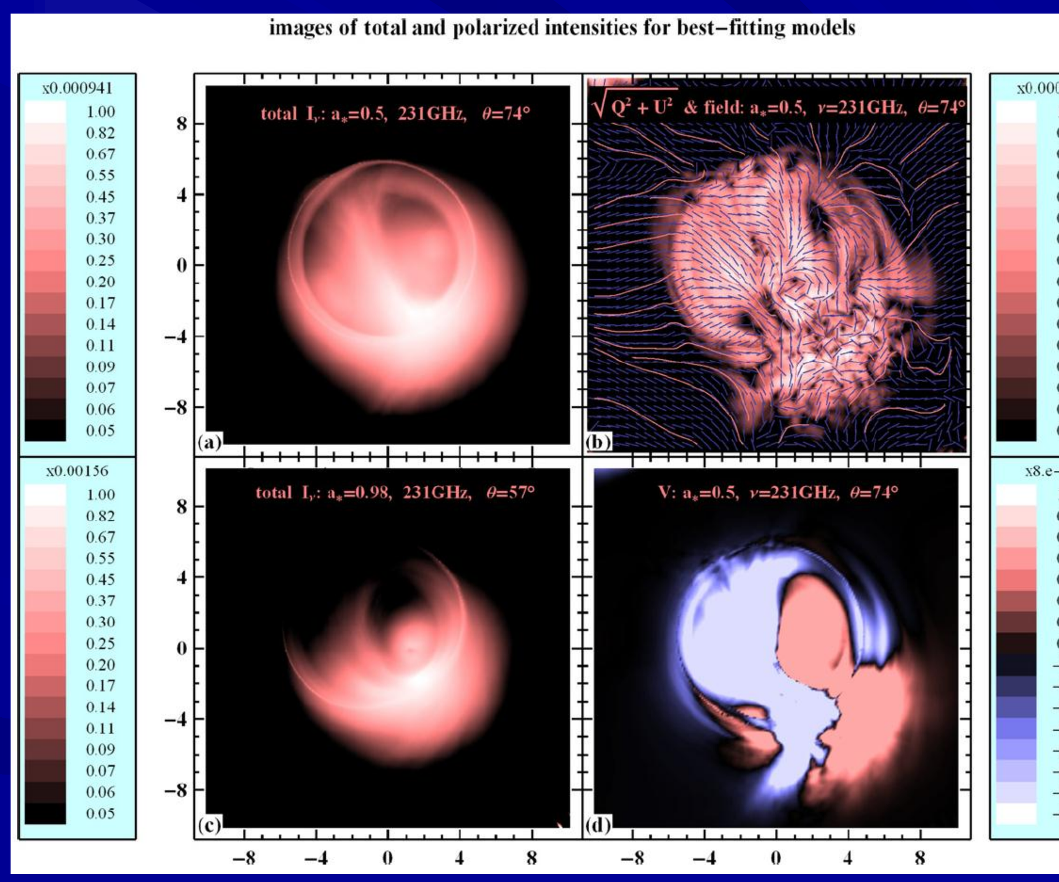
- No obvious discrimination between models

How circular polarization is produced in best-fitting model w/ spin 0.5



Emissivity in V produces some CP(~+0.5%), while stronger negative V is produced via "rotation-induced Faraday conversion"

Producing polarized images/movies



- Emission region size is consistent with observations
- "BH shadow" is observable at 230GHz (at current accretion rate)
- Typical linearly polarized intensity is 15%, which becomes 6% in total LP flux
- Typical circularly polarized intensity is 10%, which becomes 1% in total CP flux