Parameters and Quasi-Periodic Variability of Sgr A* Accretion Flow from GRMHD Simulations

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Galactic Center Black Hole Sgr A*

Closest to us – easier to study?

Variability timescale – 20 min

Keck-UCLA
GC group

Monitoring of stellar orbits
=> black hole inside

Ghez et al. 2008; Gillessen et al. 2009

$M = 4.3 \cdot 10^6 M_{sun} \qquad d = 8.3 kpc$

Dramatically underluminous

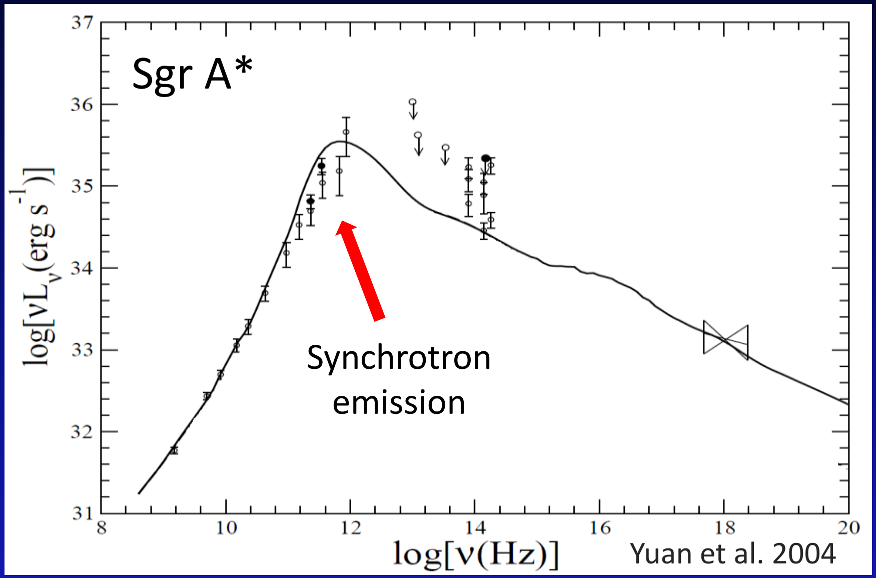
$L < 10^{-8} L_{Edd}$

Narayan et al. 1998

vs

Sub-mm radiation from near the BH

Quiescent SED



Electron T_e and magnetic field B increase steeply towards the BH

Synchrotron emissivity and peak ν rise closer to the BH

The synchrotron peak is produced near the event horizon

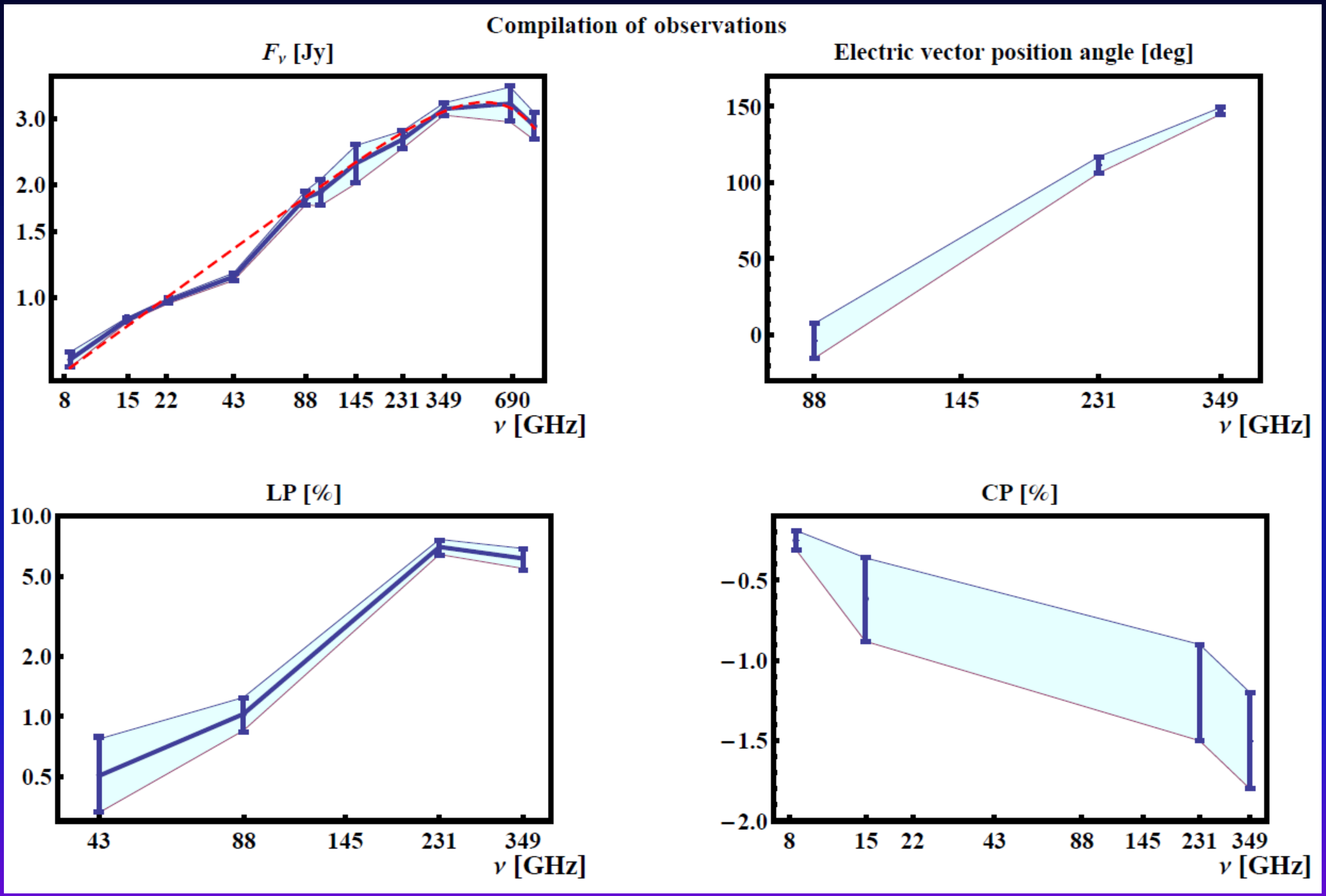
Model sub-mm spectrum

Can find BH spin a*, inclination angle θ, electron temperature T_e, accretion rate $\dot{M}$

Model flow image + phases (obs: Event Horizon Telescope)

Mean polarized radio/sub-mm spectrum

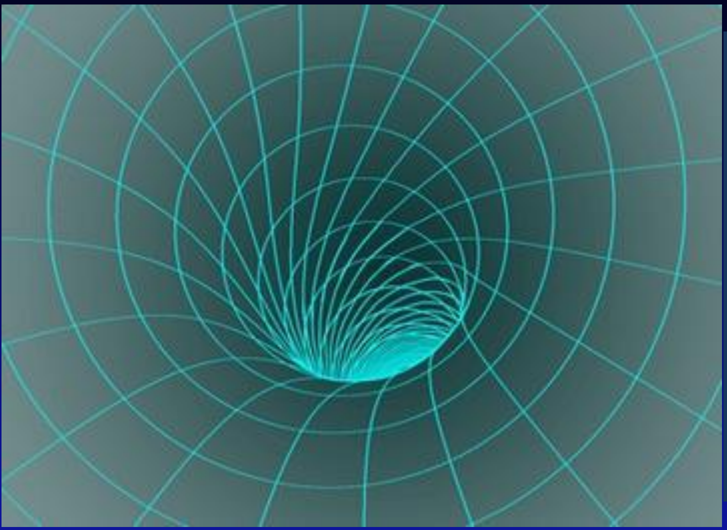
Means and standard errors in sub-mm (all observations)



We fit: F_ν(87-857GHz) – 7 points; LP(87,230,349GHz); CP (230,349GHz)

Hard to get simultaneous data due to fast variability

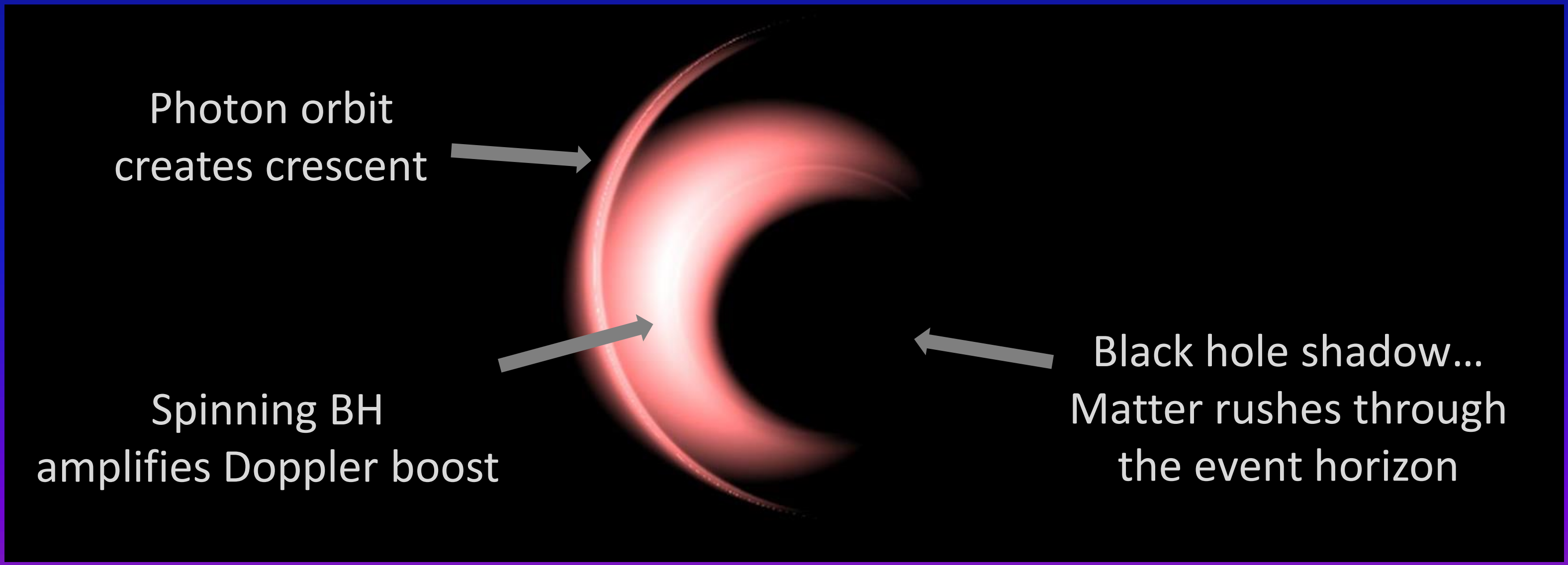
Spacetime distortions near the BH



Credit: Avery Broderick

Black holes:

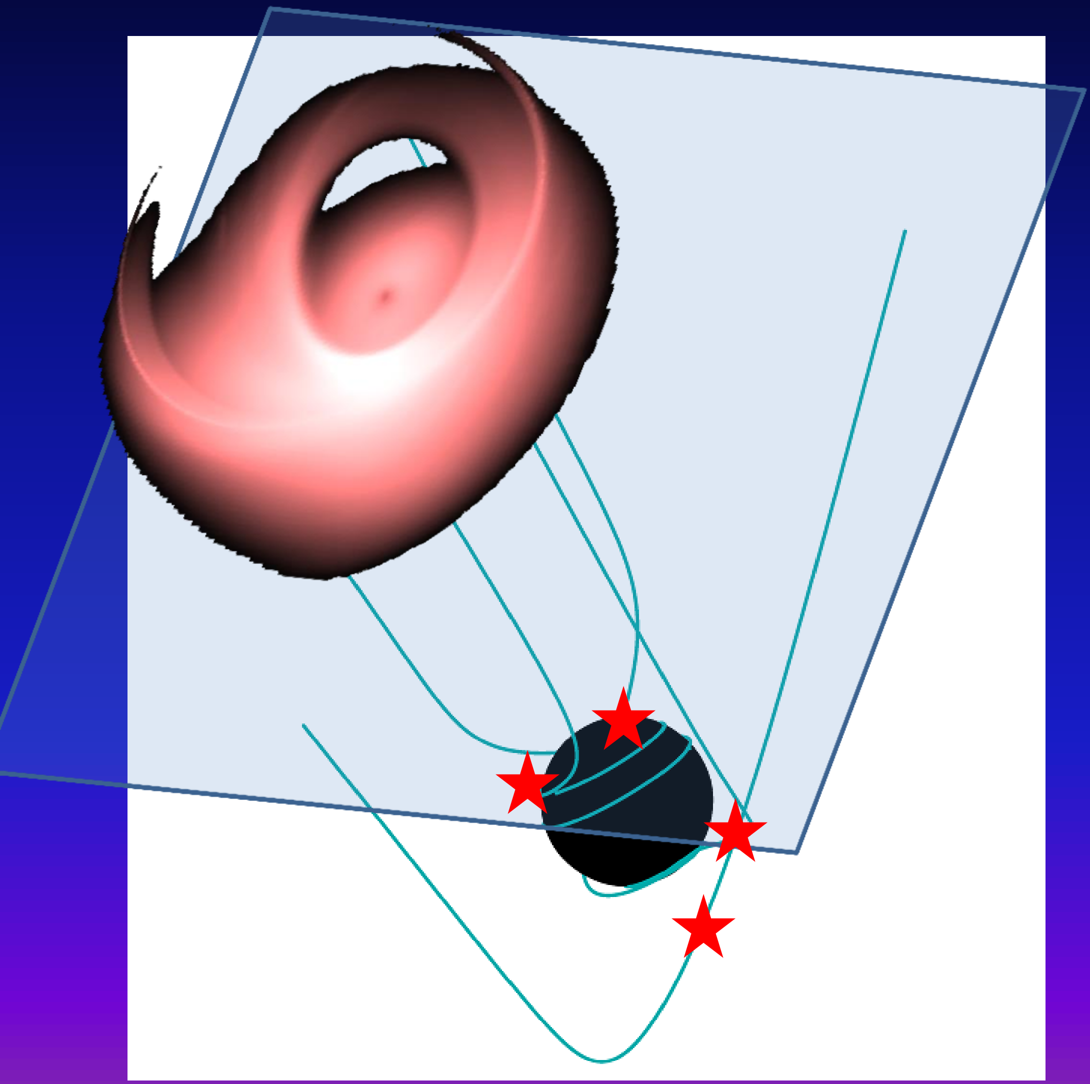
- ✓ Bend light rays (curved geodesics)
- ✓ Spin => extra Doppler boost
- ✓ Pull gas through the event horizon, so that it stops radiating out



This is NOT a fit to Sgr A* – just a sample image

GR polarized radiative transfer

ASTRORAY – ray tracing code



Procedure is outlined in

Shcherbakov, Huang 2010

Propagation effects of polarized radiation

Shcherbakov 2008

Huang & Shcherbakov 2011

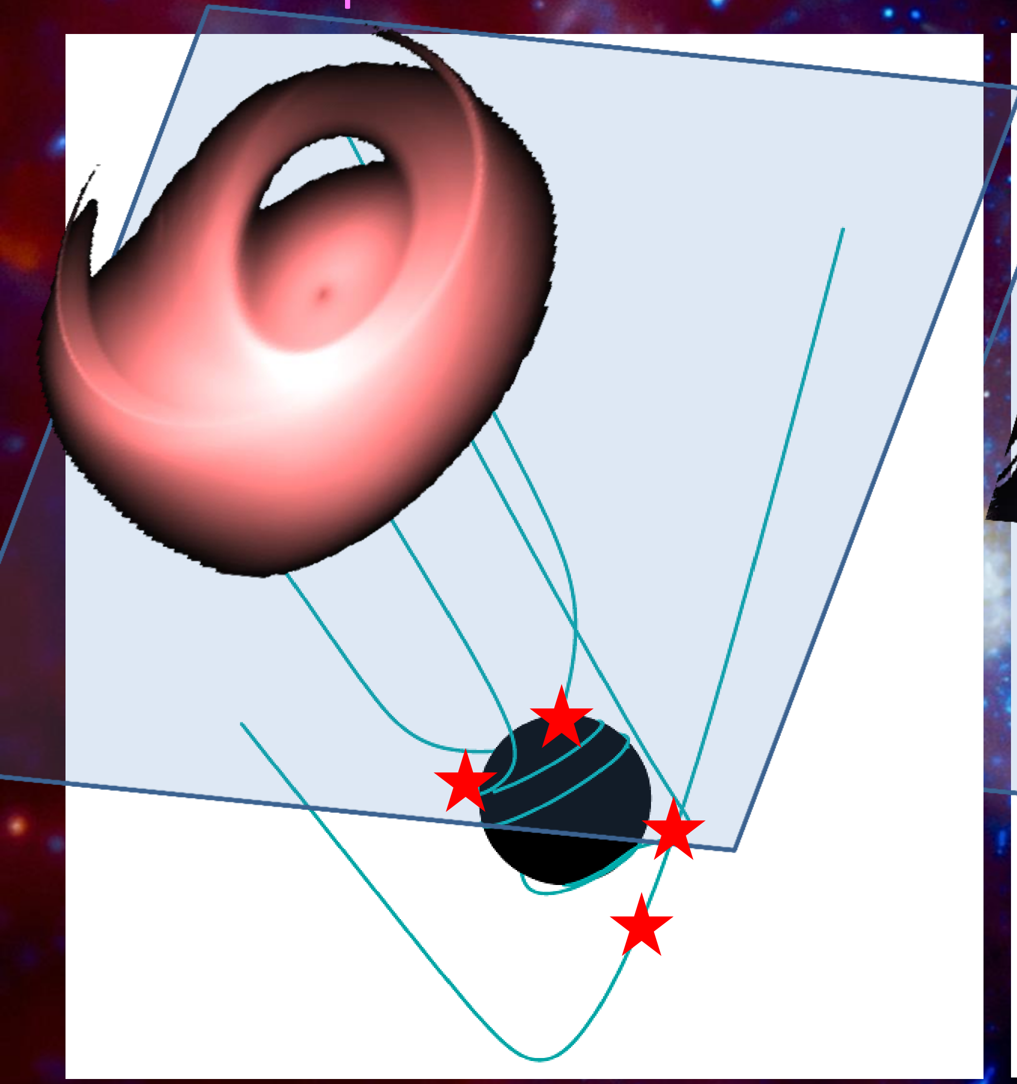
Implemented in C++, ran on a supercomputer

Code testing, application to Sgr A*

Shcherbakov, Penna, McKinney 2012

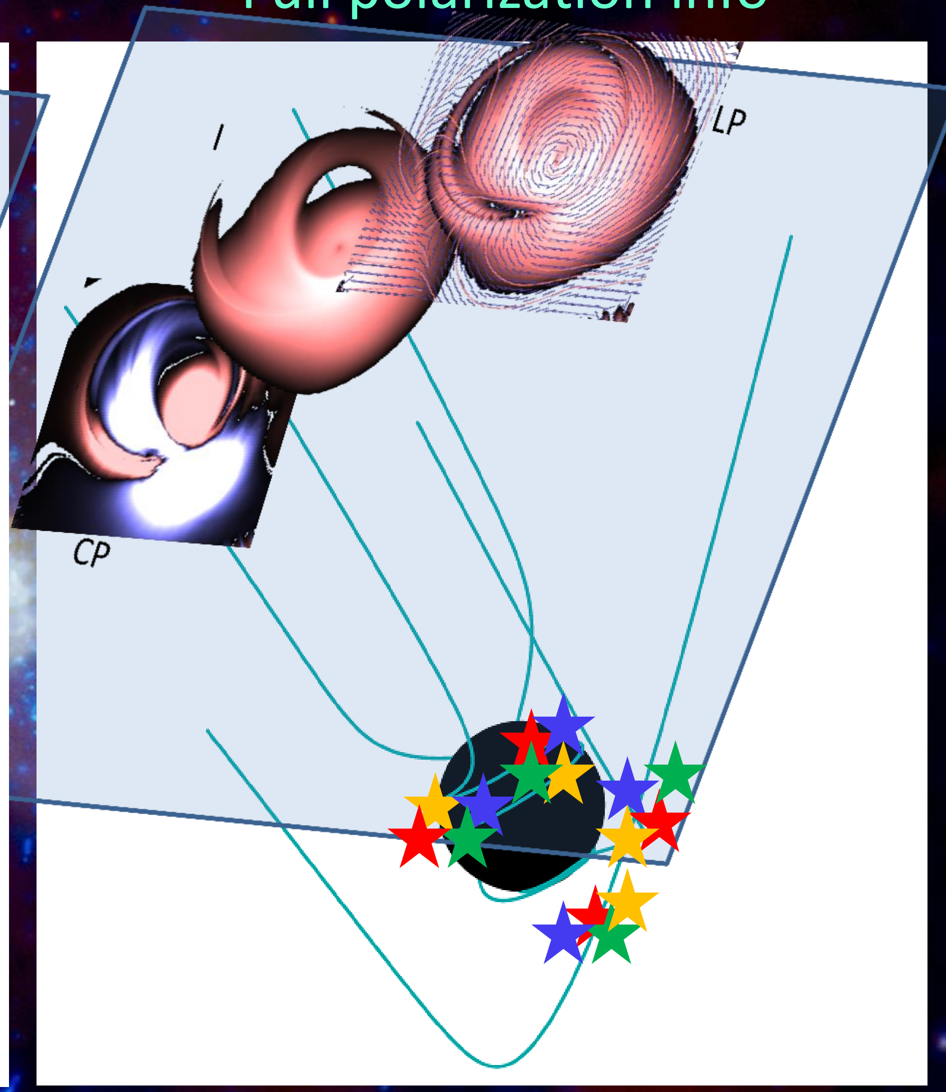
Polarization => 4x information

No polarization info



I – total intensity

Full polarization info

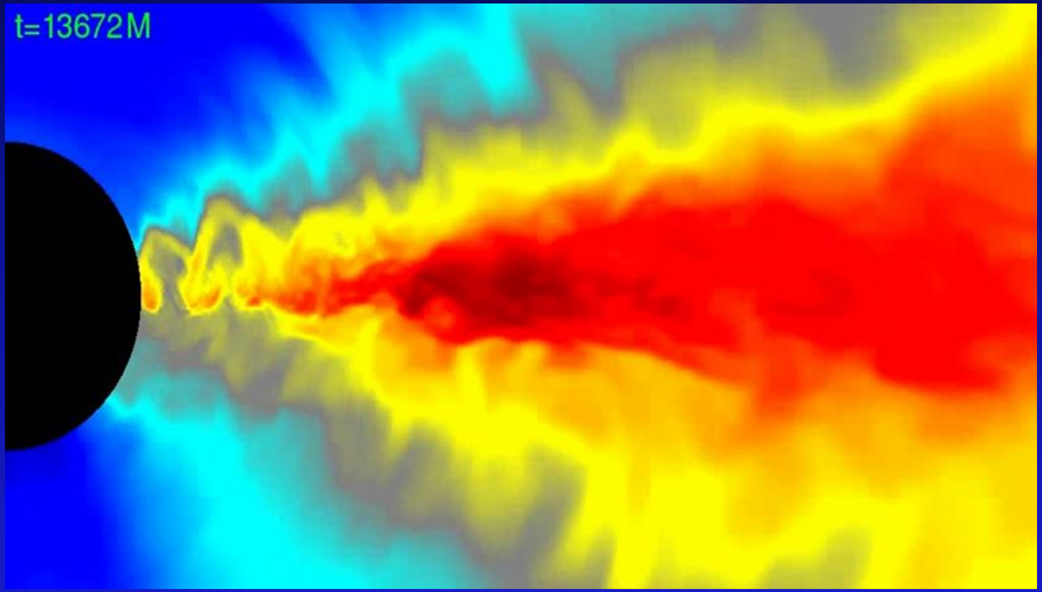


+ linear polarization (LP)
+ circular polarization (CP)
+ electric vector position angle (EVPA)

Modeling flow onto BH:
3D GRMHD simulations + thermal electrons

- Simulate BH accretion for a set of spins a*=0; 0.5; 0.7; 0.9; 0.98 without cooling

similar to Penna et al. 2010



- Assume thermal electrons, (almost) constant ratio Tp/Te
- Perform fully self-consistent radiative transfer post-processing; find time-averaged spectrum
- Fit time-averaged observed spectrum
- Find best spin a*, inclination angle θ, ratio Tp/Te, accretion rate $\dot{M}$

Sgr A*: modeling results

1. No clear preference on spin value a*, high spins look better
2. Spin inclination angle θ=55-70deg (closer to edge-on)
3. Electron temperature $T_e=(3\text{-}4)\cdot 10^{10}$K near BH regardless of spin
4. Accretion rate
   from $7\cdot 10^{-8} M_{\odot}$ /yr for spin a*=0
   to $1.4\cdot 10^{-8} M_{\odot}$ /yr for spin a*=0.9

Accretion rate much below Bondi accretion rate ($10^{-3}\dot{M}_B$)!
Electrons are mildly relativistic

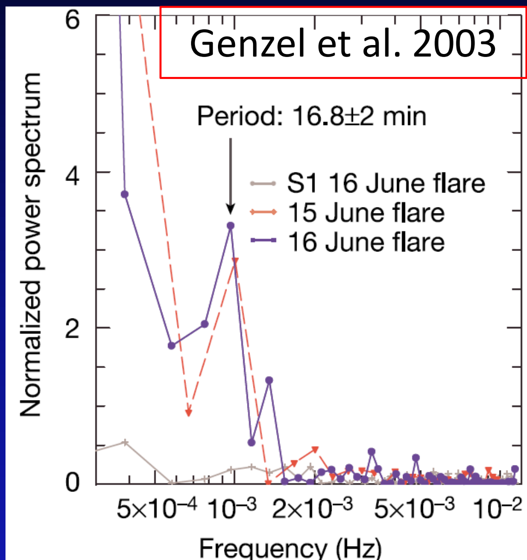
Shcherbakov, Penna, McKinney 2012

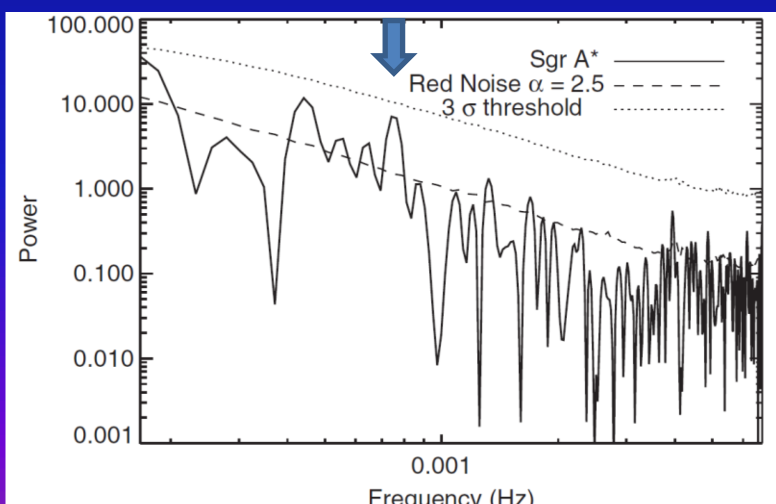
Update: about the same $T_e=3.2\cdot 10^{10}$K near the BH,
accretion rate $1.0\cdot 10^{-8} M_{\odot}$ /yr, but inclination angle θ=37deg
for spin a*=0.9375 (Jon's latest simulations McKinney et al. 2012)

QPOs

Controversial observed Sgr A* QPOs

17min=53M: in IR flare lightcurves

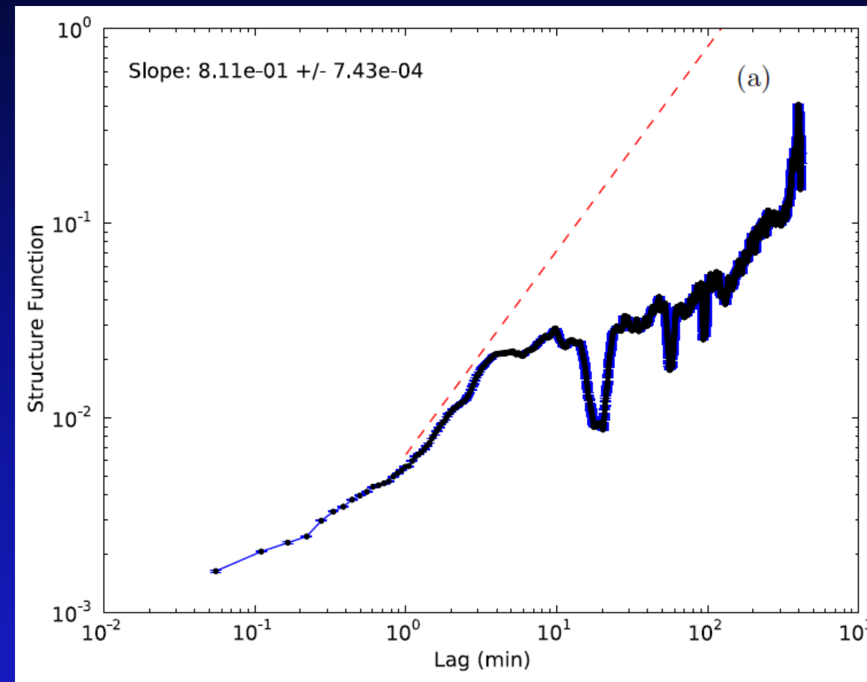




No significant periodicity

Do et al. 2009

20min: in radio lightcurves

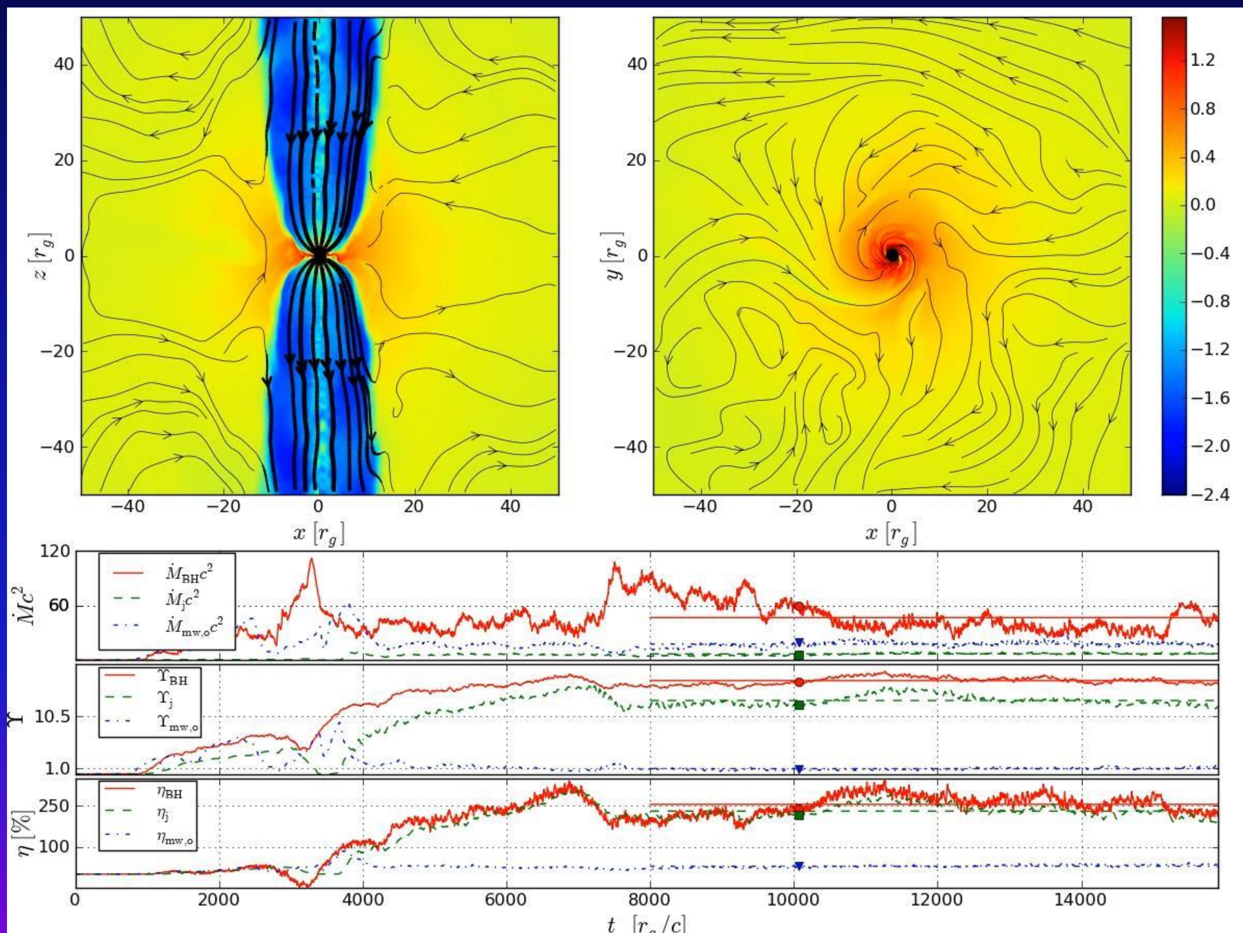


Yusef-Zadeh et al. 2012

QPOs or numerical issues?

Magnetically choked GRMHD simulations

Start w/ an equilibrium very hot torus far from the BH (20-500M)
Start w/ a lot of magnetic flux, which would saturate MRI close to the BH
Let the system evolve for 28,000M

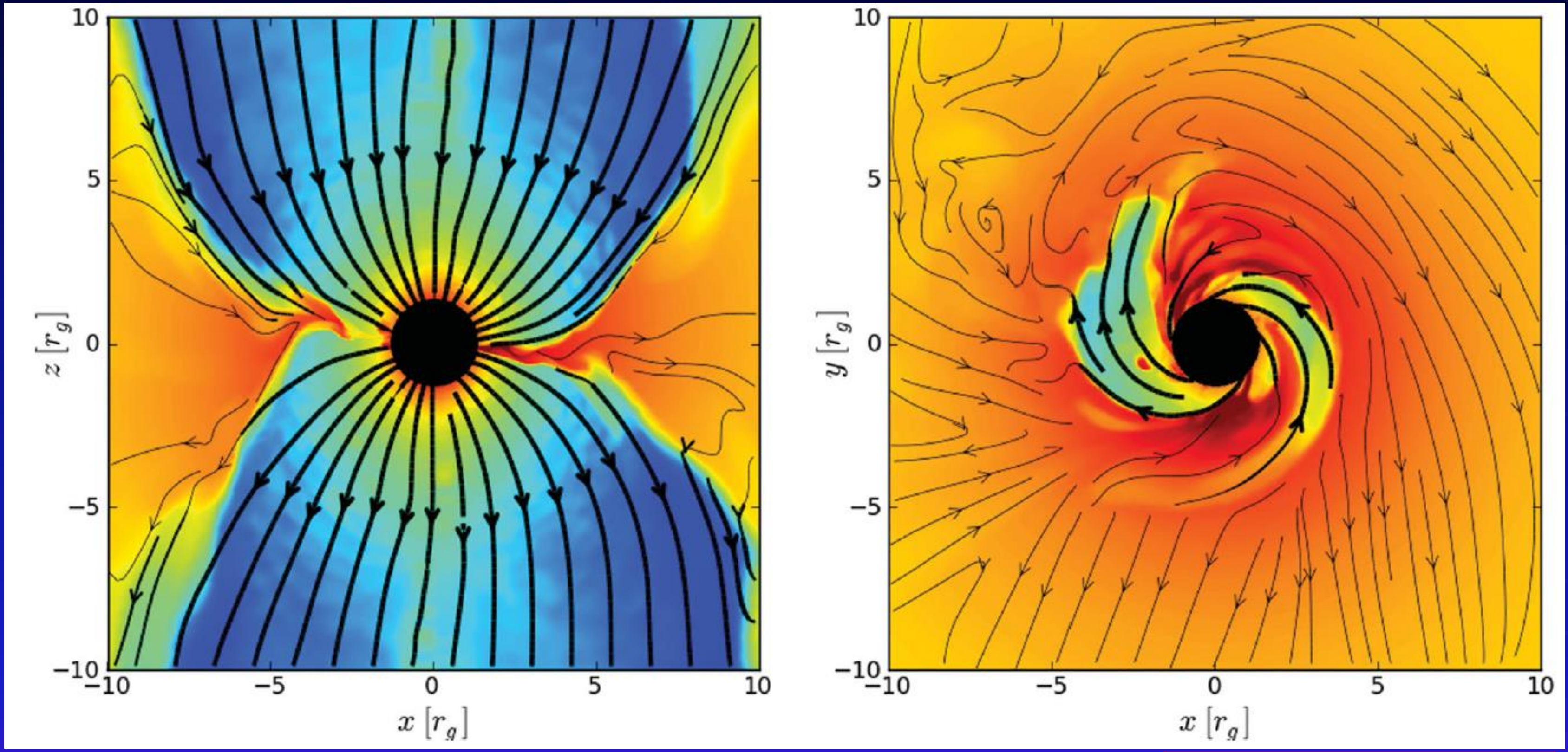


Develop magnetospheric QPOs

McKinney et al. 2012

MCAF magnetosphere and instabilities

Rayleigh-Taylor instability (light under heavy)



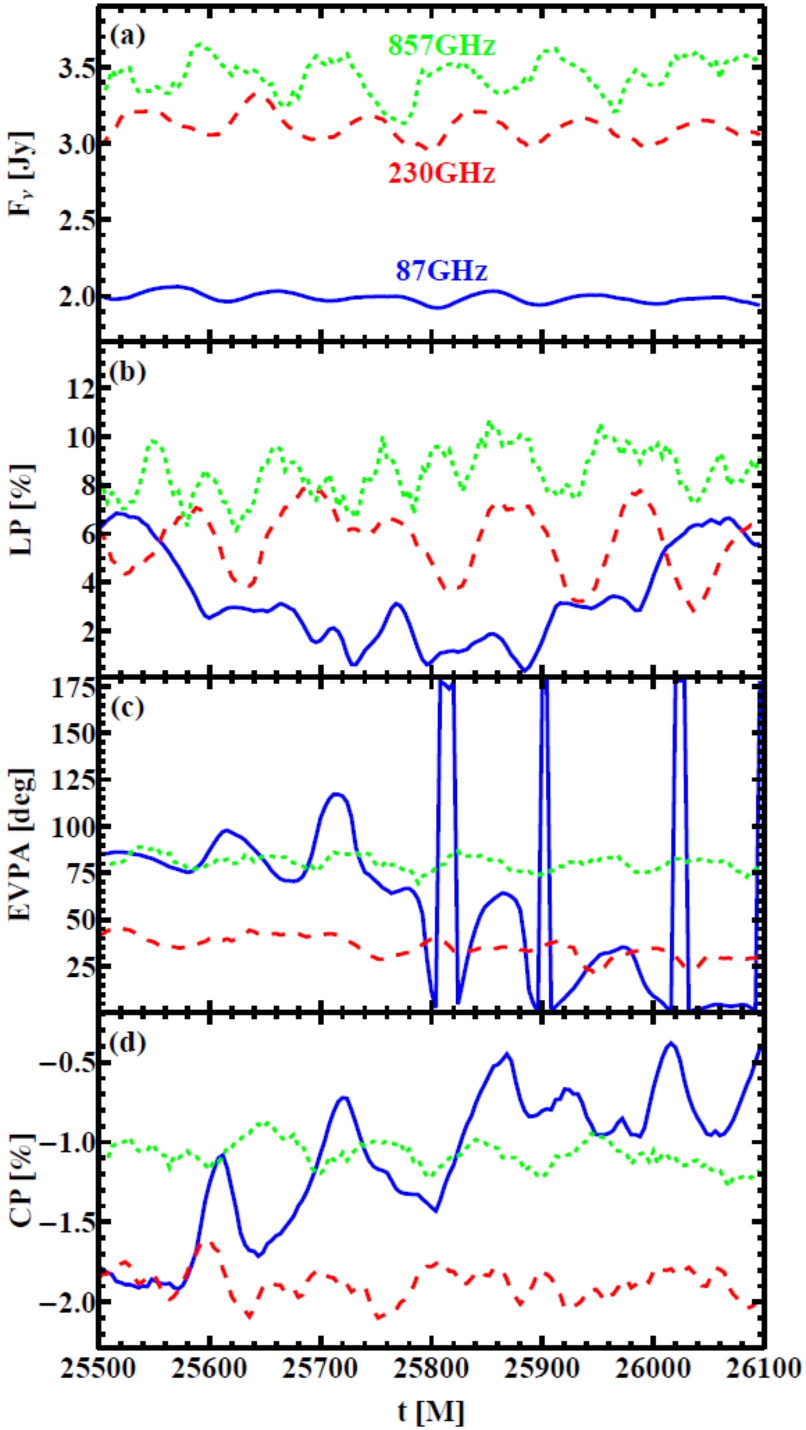
McKinney et al. 2012

Pattern moving around at $\Omega \approx \Omega_H/4$

period 70-100M for a^*=0.9375 => 30min for Sgr A*

Simulated QPOs

Shcherbakov & McKinney, 2013, ApJL, submitted



87GHz – optically thick, produced at 15M radius
230GHz – optical depth 1, produced near the BH
857GHz – optically thin, brightest at the photon orbit

Flux:

1. Amplitude <0.15Jy=5%(observable?)
2. Lower signal at 87GHz.
3. More noise(=microflares) at 857GHz.

LP fraction

1. Amplitude <2%=0.06Jy (observable?).
2. Large fluctuations between 4% and 8%.
3. Not quite periodic at 87GHz.

EVPA angle

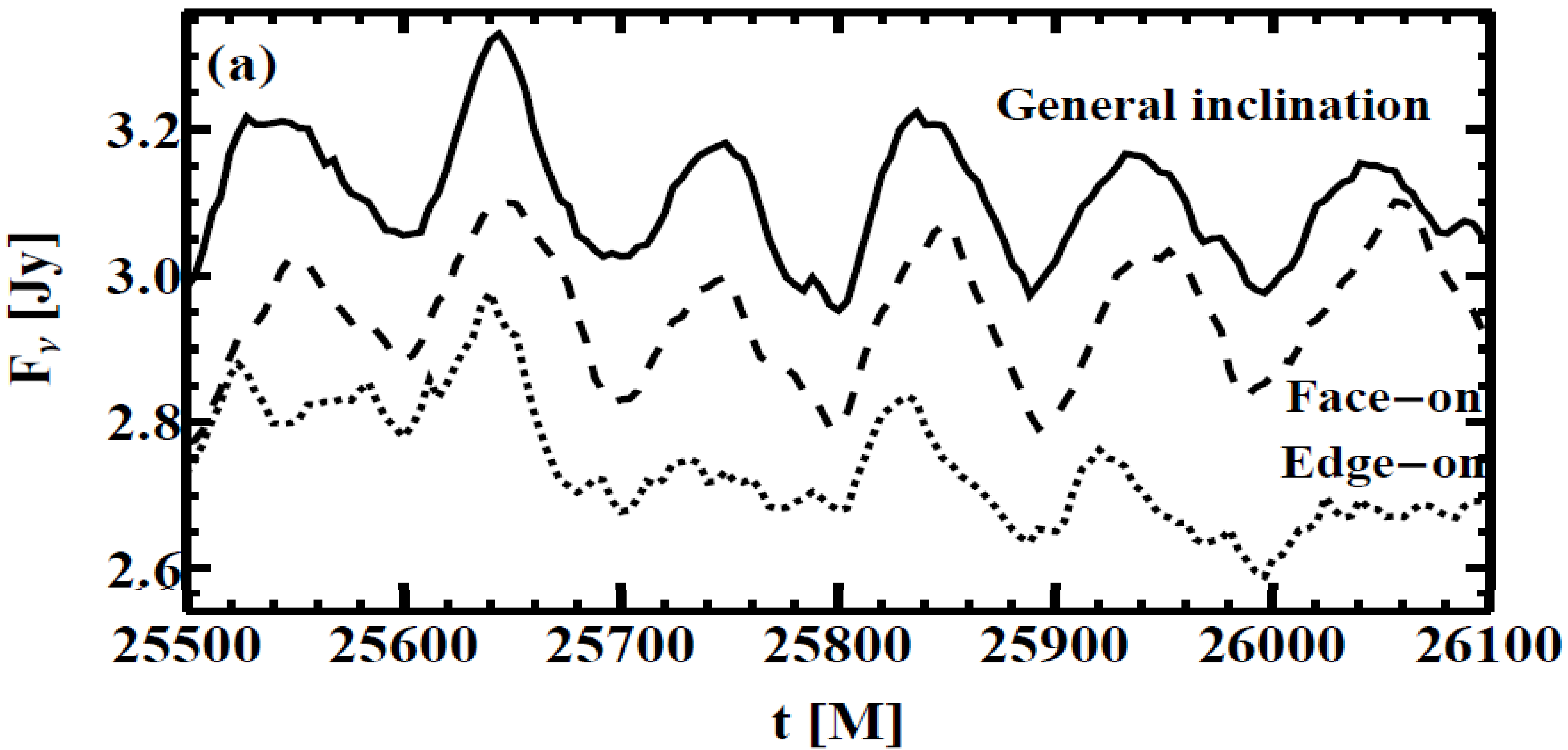
1. Amplitude 8deg.

CP fraction

1. Small amplitude <0.5%=0.015Jy (too small)

Different inclination angles θ

Computed for 230GHz, general θ=37deg, face-on: θ=10deg, edge-on: θ=80deg.



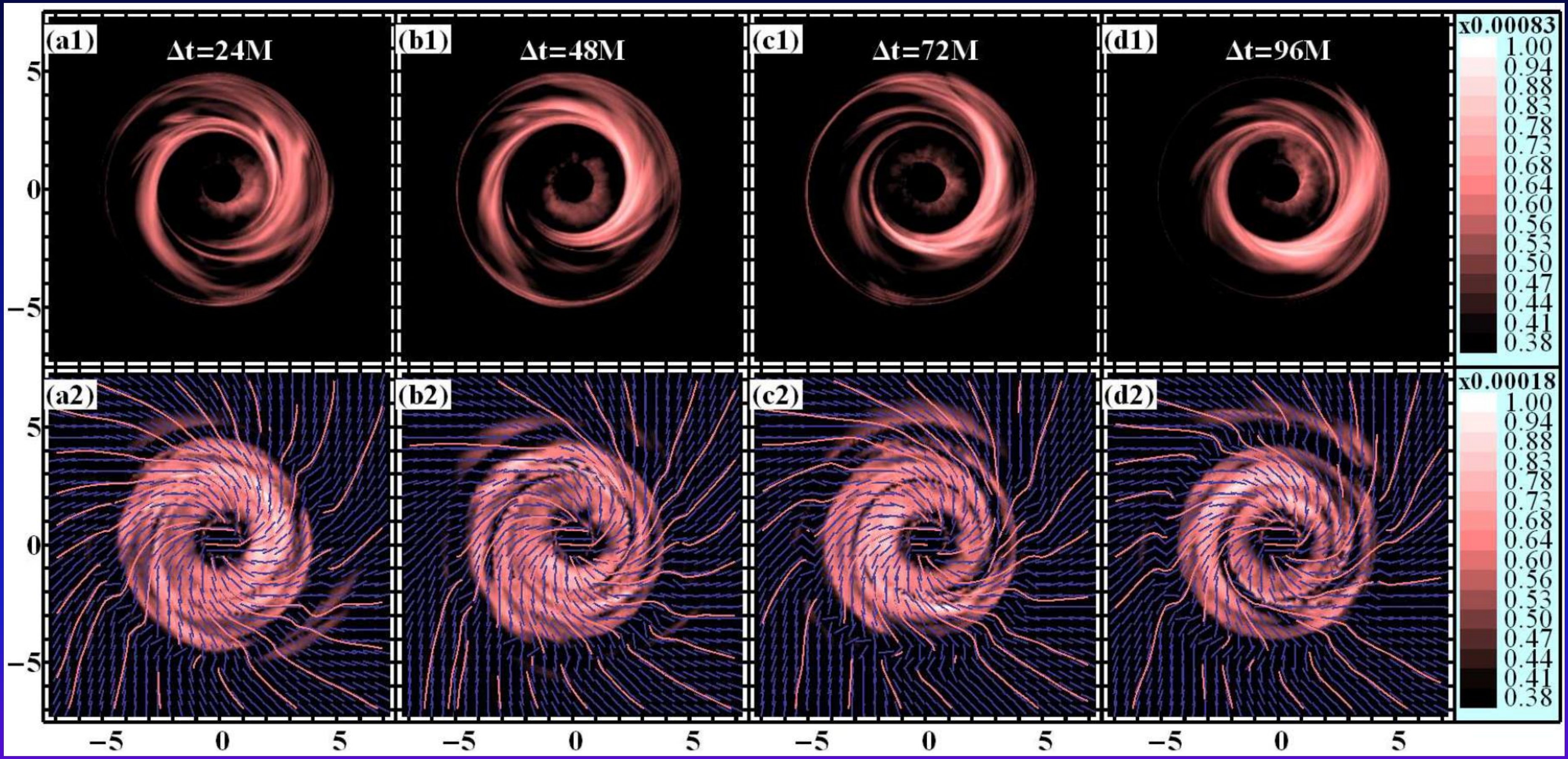
Oscillations are present at all inclination angles (at 230GHz)

but are generally weaker for a face-on orientation.

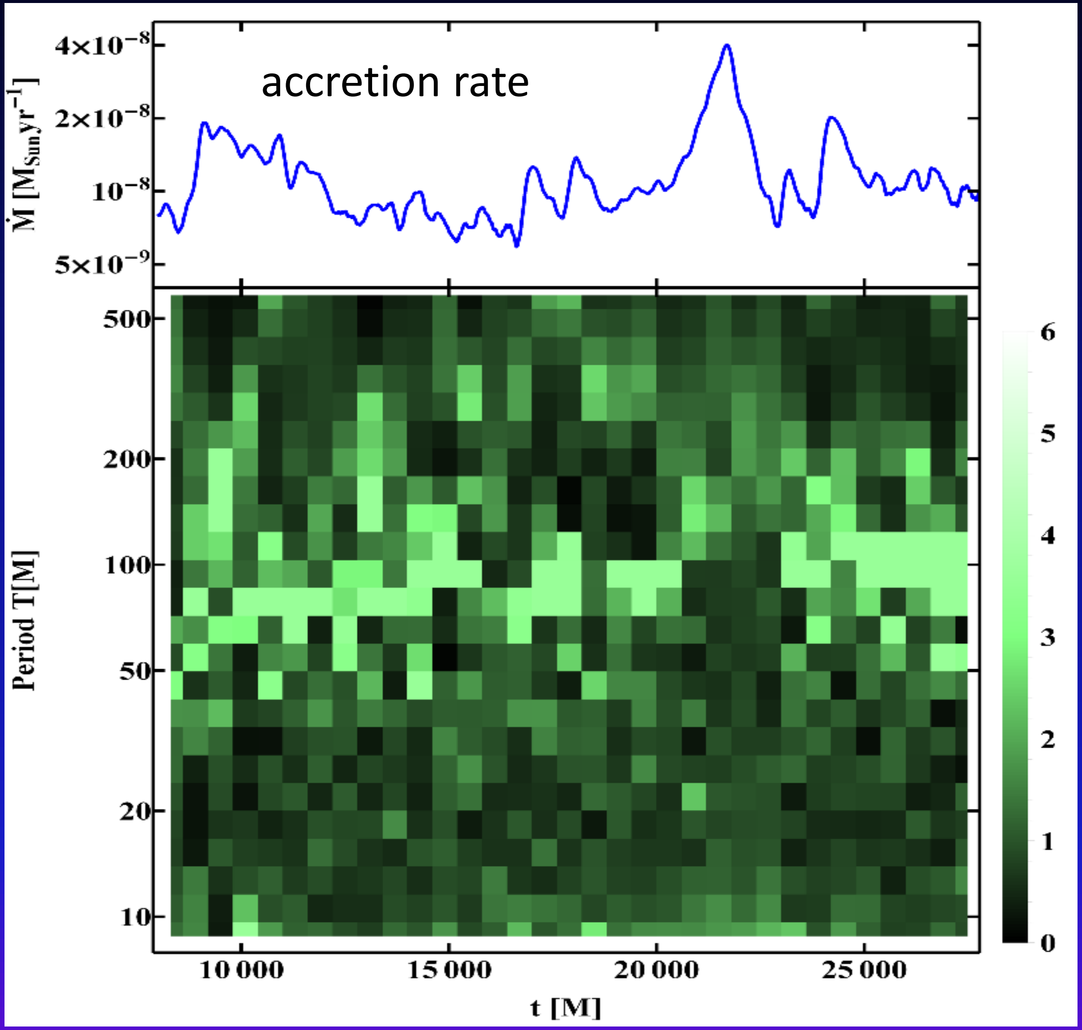
Contribution from vertical m=1 mode?

Rotating pattern is one-arm spiral

Images of face-on disks

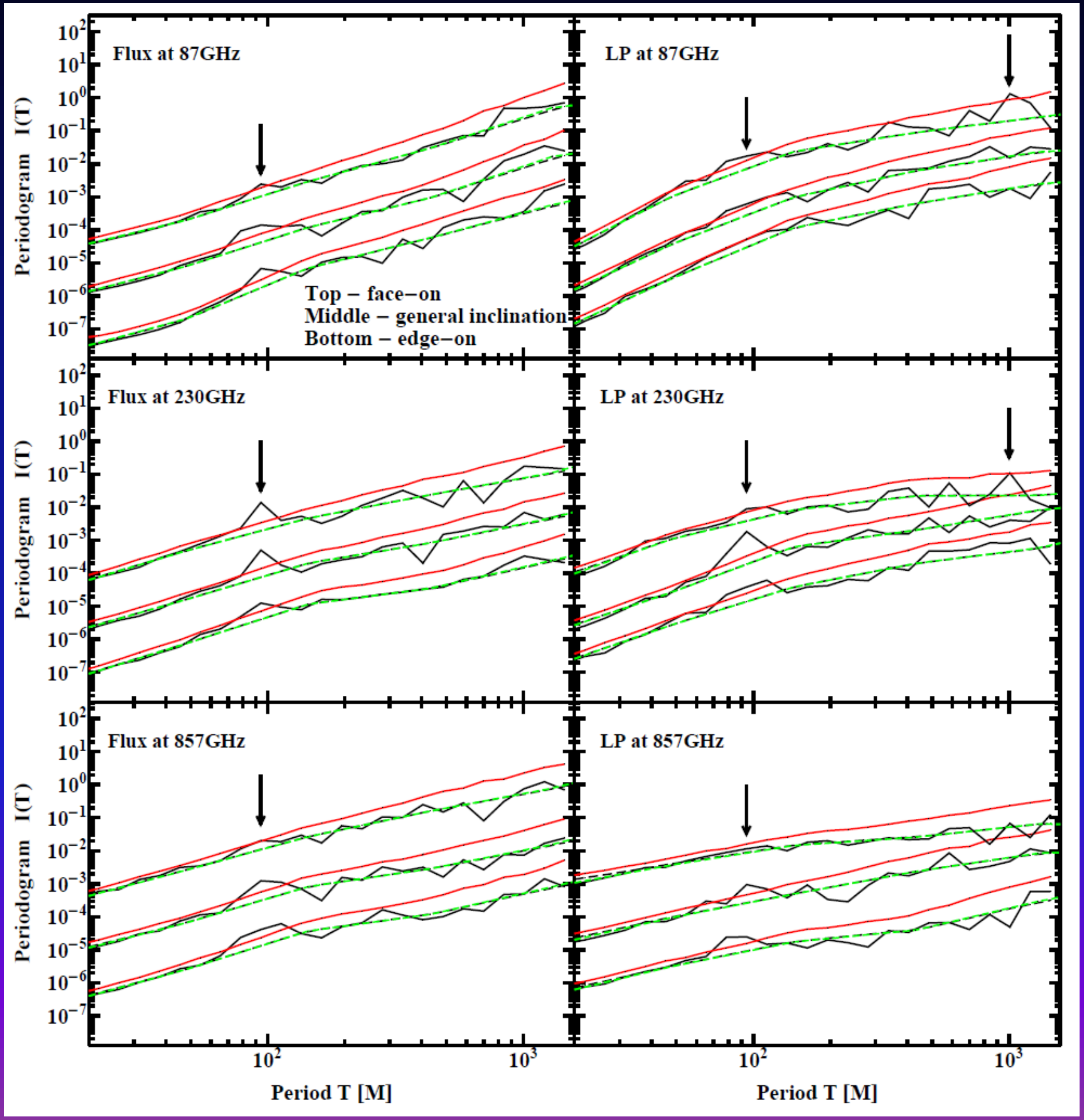


Spectrogram



QPOs disappeared
for the period of active accretion
(happened during field reversal)

Significance of QPOs



Results:

1. Period 90M=30min for Sgr A*.
2. Significance up to 8σ.
3. Quality up to Q=10.
4. Most significant at 230GHz.
5. Most significant at θ=37deg.
6. Second period of 1000M=5hrs.

Observational prospective

Actual QPO signal

Period 30min, flux amplitude 5%, LP amplitude 2%

SMA

sampling every 20min, flux error 1%, LP error 0.3% =>

Non-detection is OK: sampling rate is too low, strong aliasing

ALMA

30x the collecting area of SMA, sampling every few min =>

should detect QPOs

Discussions/conclusions

Can study Sgr A* w/ models based on GRMHD simulations
by performing GR polarized radiative transfer
and fitting the mean spectra w/ simulated spectra
(+ image sizes)

An order of magnitude of BH/flow parameters

Flow parameters: $\dot{M}$=(1-7)·$10^{-8}M_{\odot}$ /yr; T_e=(3-4)·10^{10}K.

BH parameters: spin uncertain… inclination angle uncertain…

Another dimension: can study QPOs (period/amplitude),
which can be seen in ALMA.

A lot of assumptions… => room for much more work (non-thermal)

It's been a gradual progress over the last 20 years.