Probing Black Holes with Gravitational Lensing

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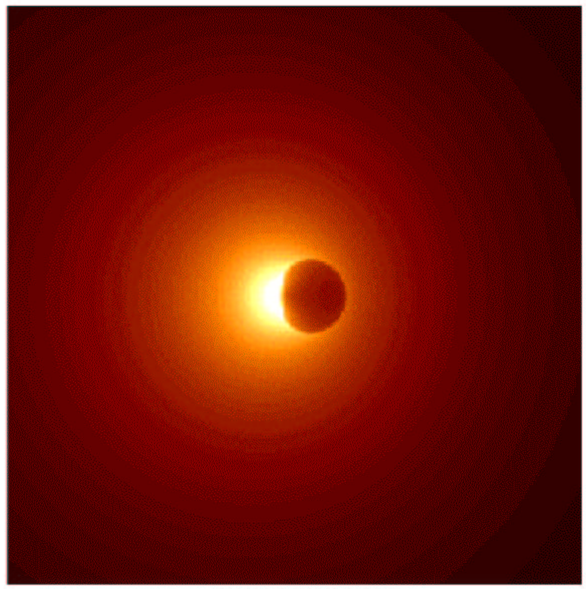
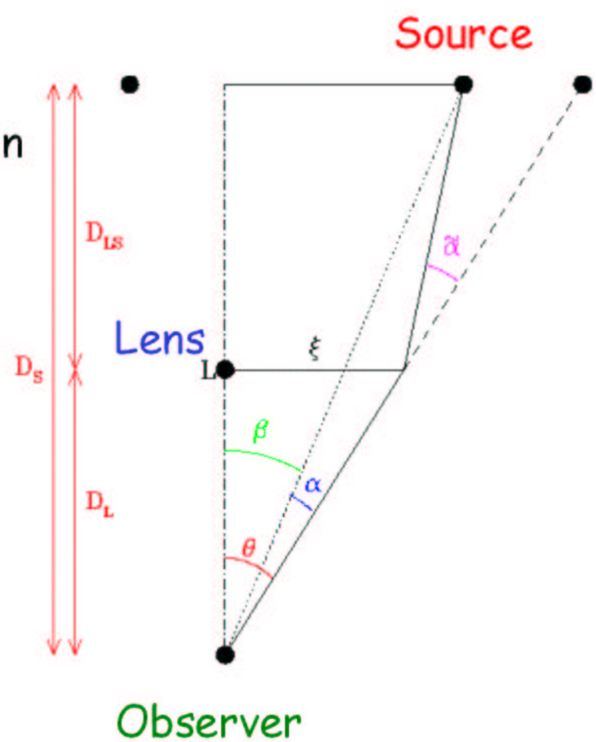


(ITP 1999)

Outline of talk:

- Stellar mass black holes as Lenses - How many black holes in Milky Way disk? Can we weigh SMBH with lensing?
- Black hole accretion disks as Sources - What are Quasars?
- A black hole as a *Lens and Source* - Can we "see" a black hole? Measure its spin, mass?



$$R_E = 1.4_{AU}\, D_S^{1/2}\, m^{1/2}\, \sqrt{x(1-x)}$$

(m=mass of lens in $M_\odot$, D_s in kpc, $x=D_L/D_S$)

Black Holes as Lenses: Isolated Black Holes in the Milky Way

How many black holes reside in our Galaxy? What are their masses? How are they distributed?

- Estimate ~10^{7-9} (e.g. Samland 1997) - depends on mass function, cutoff mass, SF history - large uncertainties in predictions

$$N_{BH} \sim 10^{10} \text{ years} \times 0.01/\text{yr} \sim 10^8$$

How can we detect black holes?

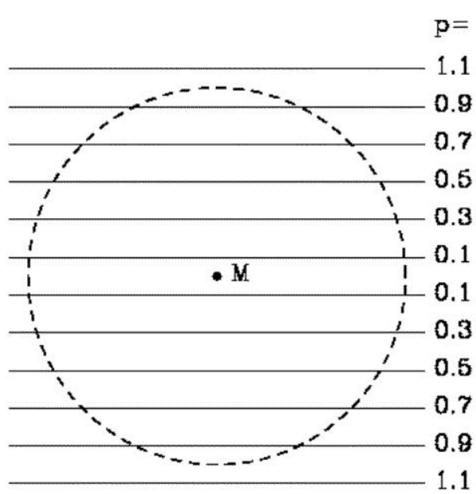
- Black-hole X-ray binaries - 15 with masses
- Accretion from the interstellar medium
- Microlensing (Gould 2001, Alcock et al. 2001)

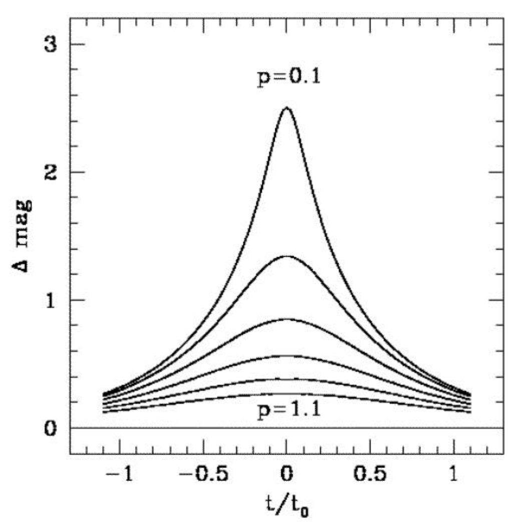
"Isolated black holes"

Microlensing Lightcurves

$$\tau = \frac{2R_E}{v_\perp}$$

$$M = \frac{(v_\perp \tau c)^2}{16 G D_s} \frac{1-x}{x}$$



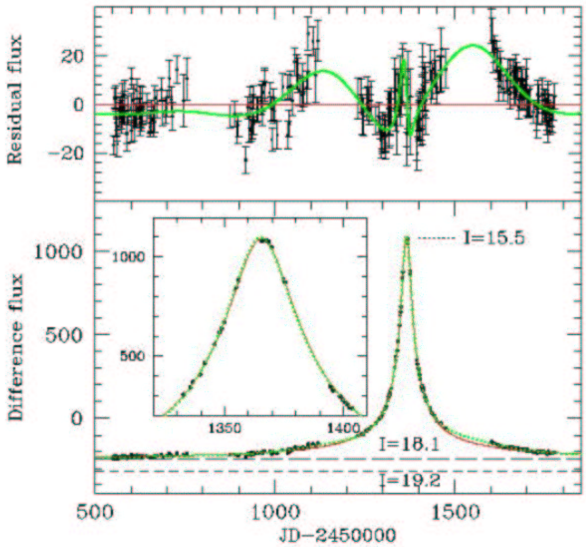


Paczyński (1986)

The Longest Events: Black Holes?

OGLE-1999-BUL-32
τ=1282 days

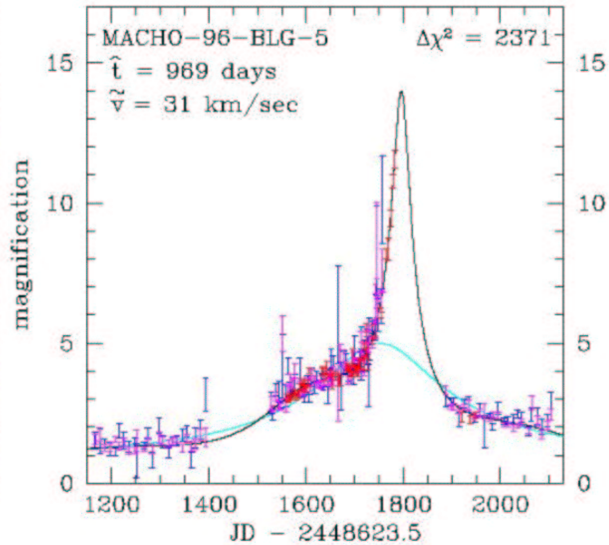
Mao et al. (2002)



v=79 km/s, M~36$M_\odot$

MACHO-96-BLG-5
τ=969 days

Bennett et al. (2001)



v=31 km/s, M~6$M_\odot$

Are Long-Timescale Events Black Holes?

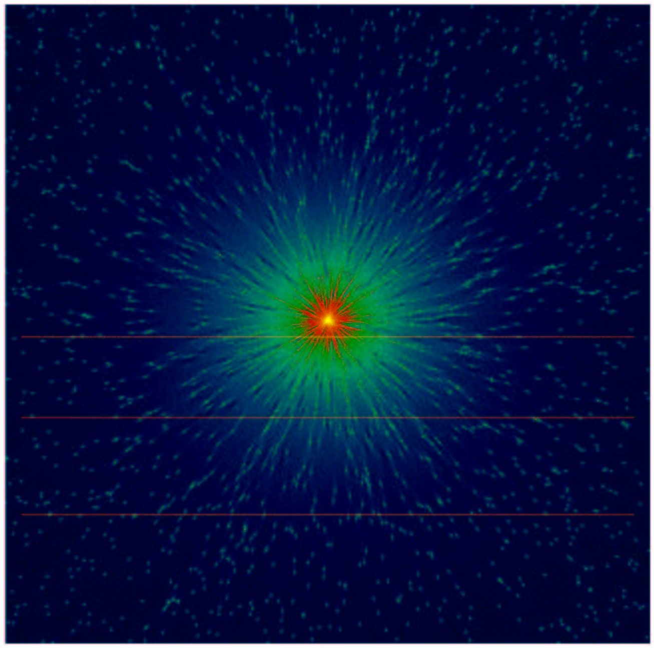
(Agol, Kamionkowski, Koopmans & Blandford 2002)

- Bennett et al. (2001) & Mao et al. (2002) claim $M>3M_\odot$ at >68% confidence; BUT, they neglected the fact that there are *more* lenses at small mass
- Black holes are only 3%, 8% and 20% likely for 3 longest τ for Salpeter IMF, 40 $M_\odot$ NS cutoff -more stars at small mass
- Total number of events $\propto M^{1/2} dn/dM$, while long events $\propto M^2 dn/dM$ ➔ black hole probability greater by factor of 10-100 for τ>2 yr (depends on dn/dM)
- Measuring astrometric shift (~3mas) with ACS (\`02), VLTI (\`04), or SIM (\`09) and parallax from ground yields M, D_L, and v
- Out of ~300 events, ~1 is a black hole (but which one?). OGLE III will have 10^3 events per year, so one can measure mass function with longest events; M^2 weighting means black holes make ~25% of the τ>2 yr events (expect N_{BH} ~ 3 per yr).

Black Holes as Lenses: Galactic Center

(Alexander & Loeb 2000, Chaname, Miralda-Escudé, Gould 2000, 2001)

Requires K=21 observations to detect lensing by massive black hole plus black-hole cluster - CELT or 20/20



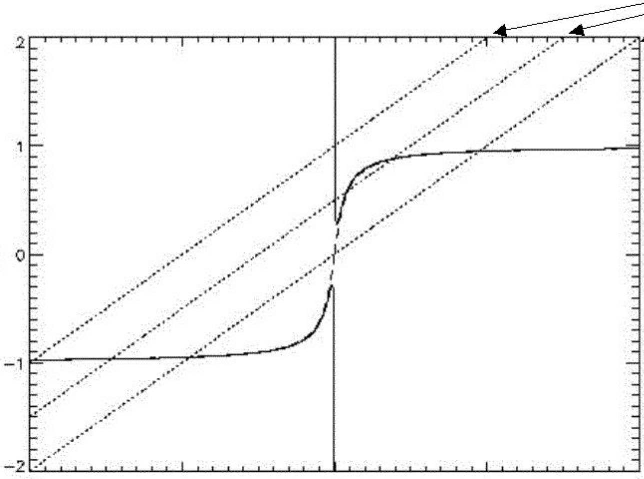
Magnification by Sgr A* and surrounding cluster of 300 $M_\odot$ black holes

(figure courtesy of Joachim Wambsganss)

Black Holes as Lenses: SMBH in Lenses

(Mao, Witt & Koopmans 2001)

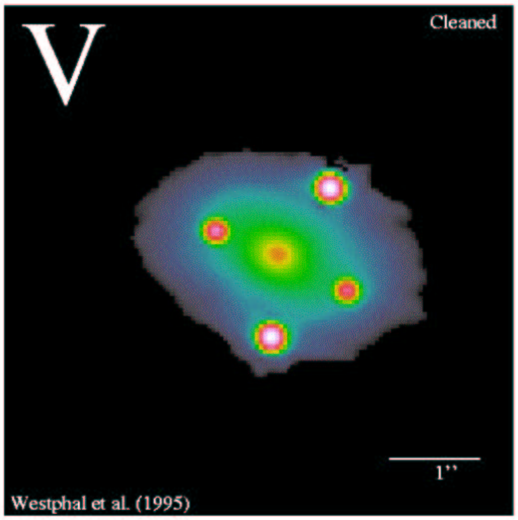
- Black hole creates or destroys central image(s) in grav lens
- Requires high dynamic range in radio - factor of 10 better VLBI- will constrain black hole masses in some massive galaxies

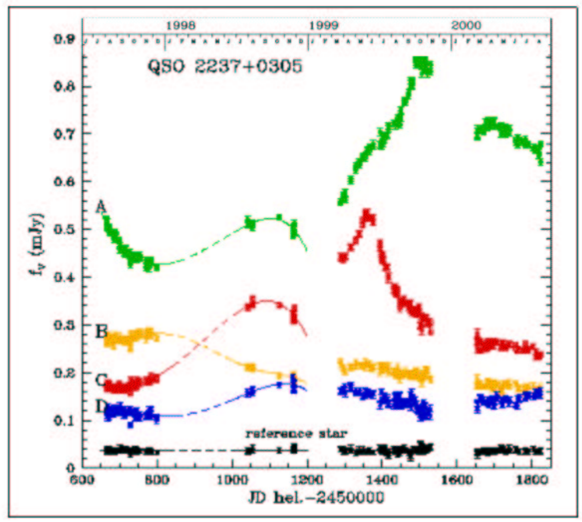


Black Holes as Sources: Imaging a QSO

What powers quasars? What are properties of quasar black holes and accreting gas/jets?

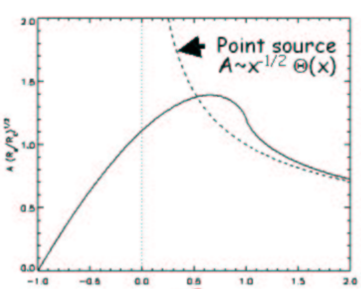
Q2237+0305





Dependence of fluctuations on source size:

Small sources are amplified by as much as $\sim(R_E/R_S)^{1/2}$, while large sources vary by only $\sim(R_E/R_S)$



Refsdal & collabs

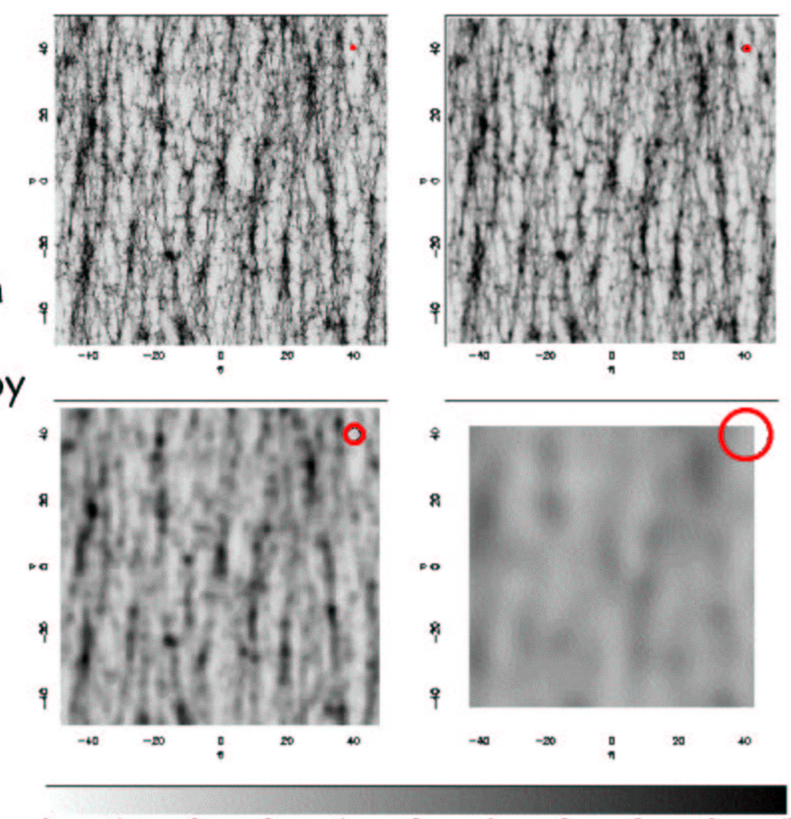
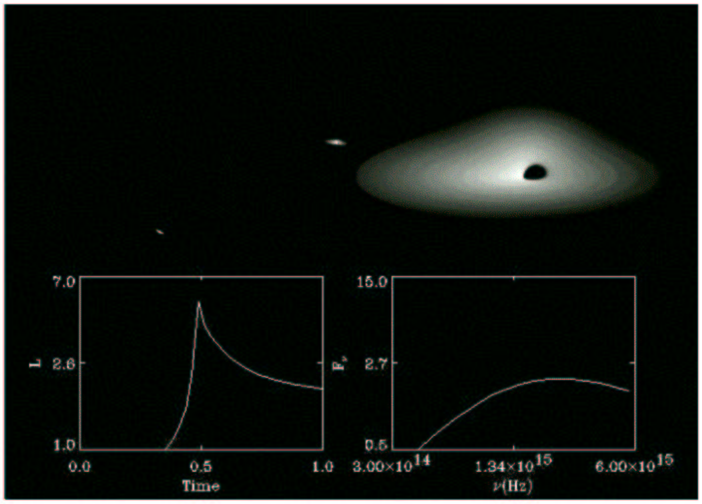


Figure 2. Convolution of a magnification map with source discs of 4 different sizes (shown by the circles in the upper right corner of each panel. The grey-scale bar shows the corresponding magnification. The macrolensing parameters were κ = 0.36, γ = 0.40.

Imaging a Quasar with Microlensing



•Invert spectrum as a function of time to measure spectrum as function of radius at disk, constraining inclination, mass, and spin (Agol & Krolik 1999)

•X-ray continuum size (Mineshige & Yonehara 1999)

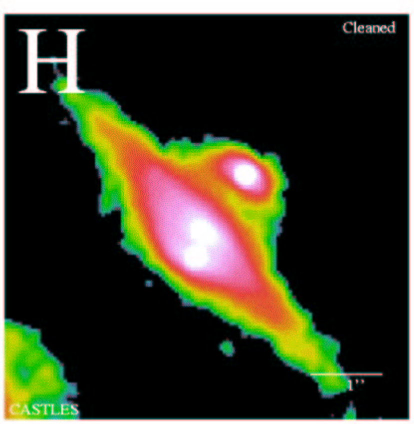
• Polarization (Turnshek's poster)

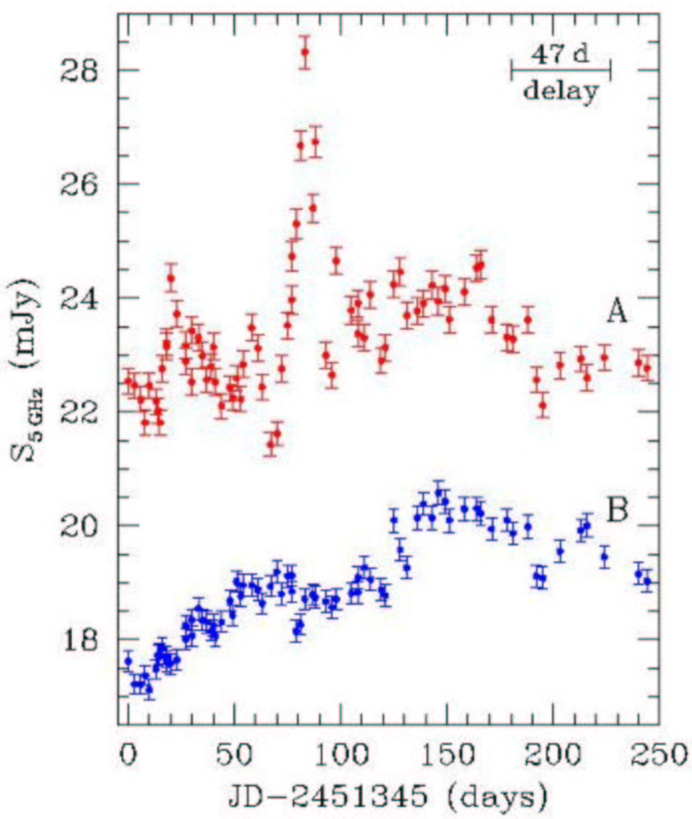
Radio Microlensing

B1600+434

Koopmans et al. (2001)

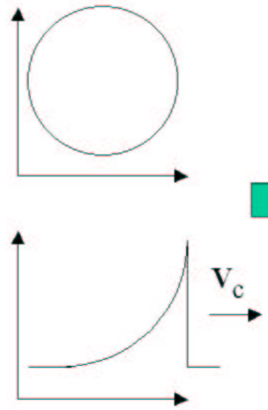
•Probe of μas radio jet structure

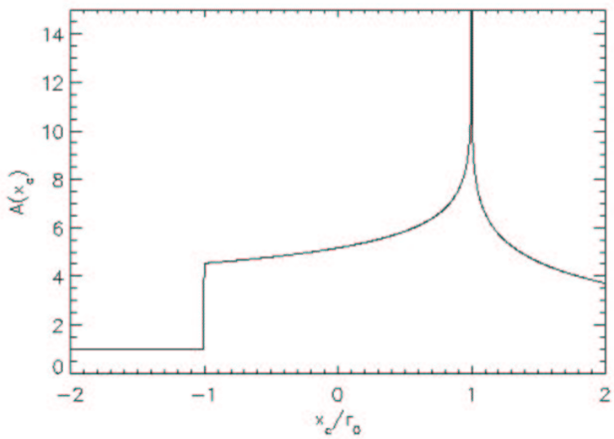




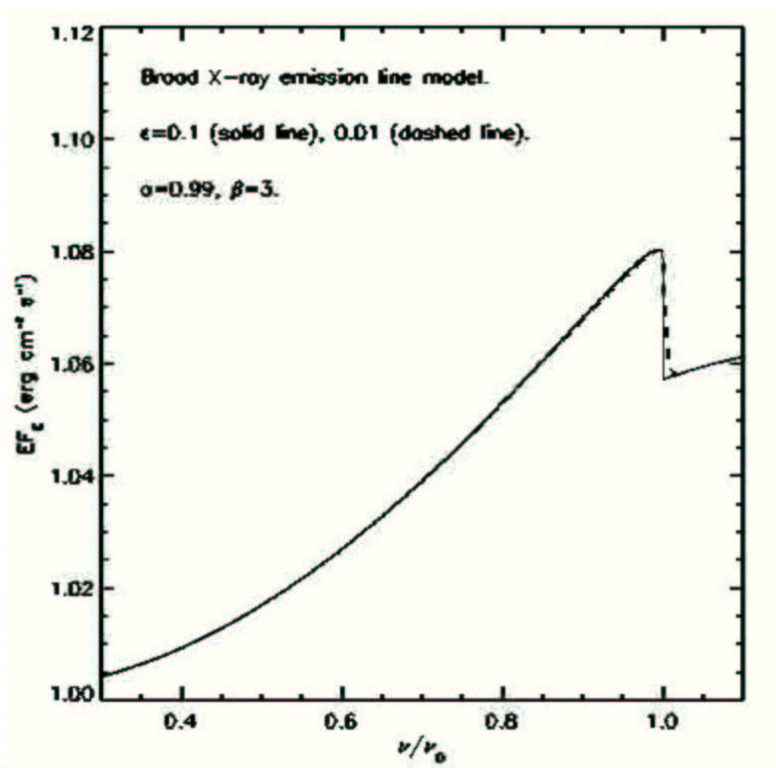
Microlensing of a ring by a caustic

(Agol & Chartas 2002)





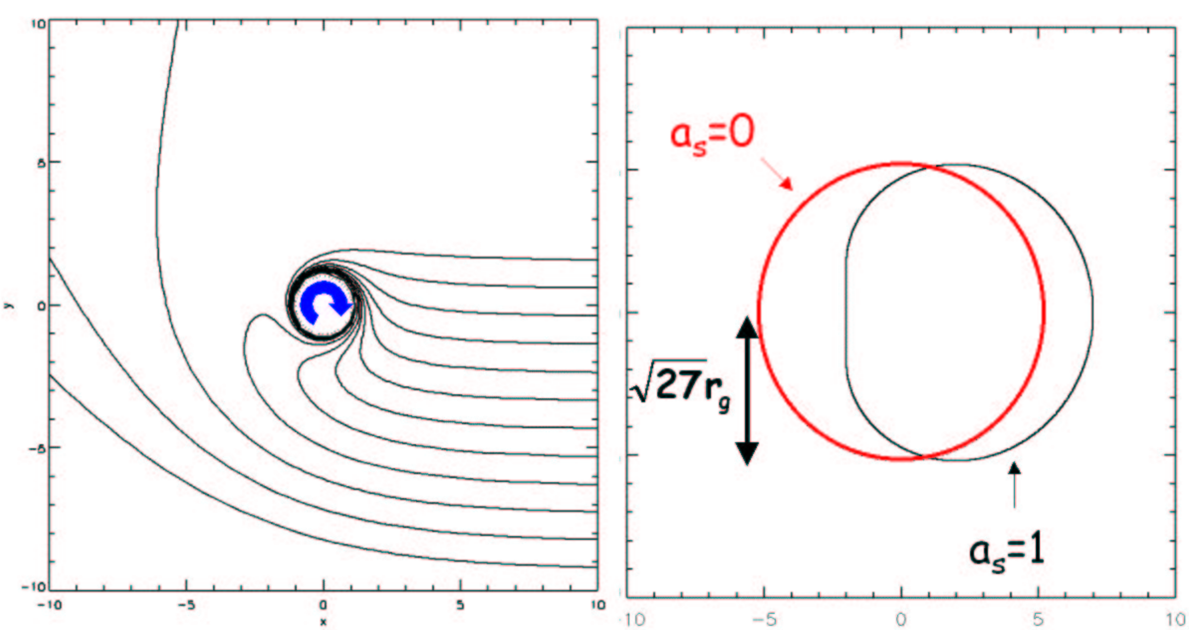
- Step followed by cusp separated by 2r
- Maximum amplification $\propto 1+\ln[64\ r/\Delta r])$



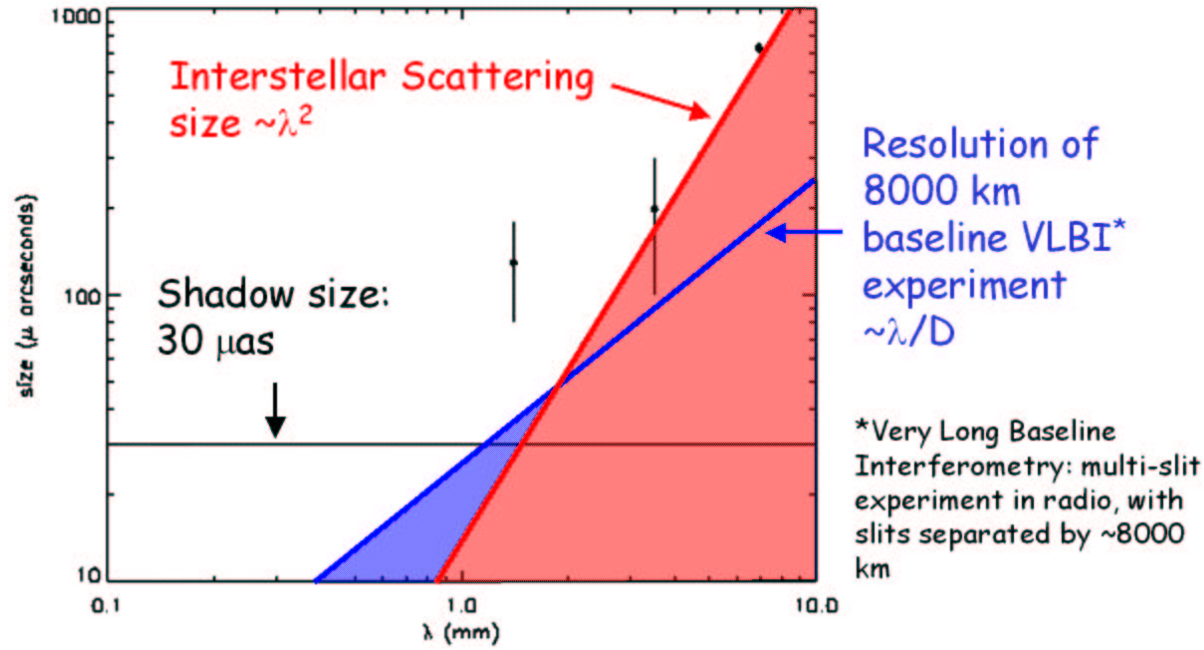
Black Hole as Lens and Source: Imaging a Black Hole

- Why image a black hole?
  - ➔ Test of strong-field relativity - "proof" of event horizon
  - ➔ Constrain mass & spin of black hole
  - ➔ Probe extreme astrophysics - inflow, outflow
- Can see black hole in absorption (Bardeen 1973)
  - ➔ Cosmic Microwave Background (Paczyński 1986)
  - ➔ Accretion flow - Galactic Center Black Hole is massive and close; accreting ~$10^{-5} M_\odot$ /yr (Coker & Melia 1997) - emits faintly in radio and X-ray -> small efficiency or mass loss

Photon Paths About Kerr (a_s~1) Black Hole

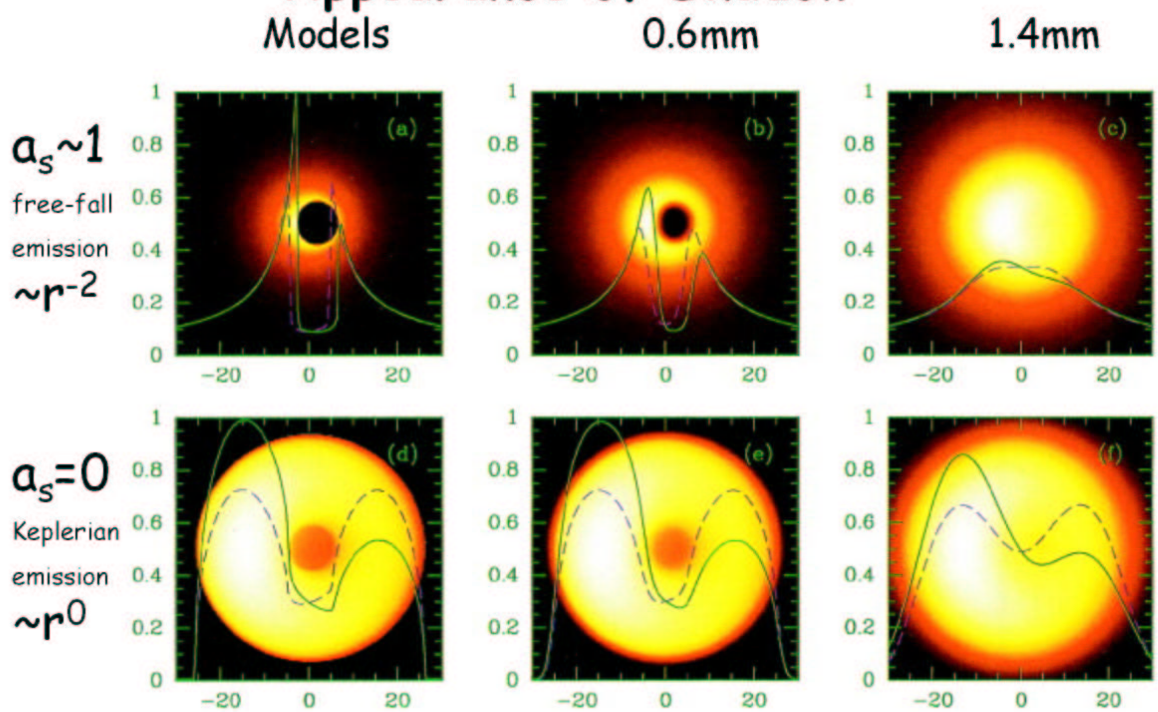


Resolving Galactic Center black hole requires sub-mm radio observations



*Very Long Baseline Interferometry: multi-slit experiment in radio, with slits separated by ~8000 km

Appearance of Shadow



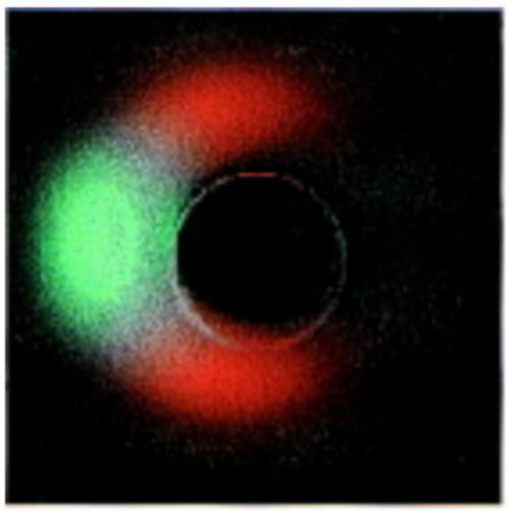
Falcke, Melia, & Agol (2000)

We may "see" a black hole with sub-mm VLBI

Radio Polarization of Sgr A*

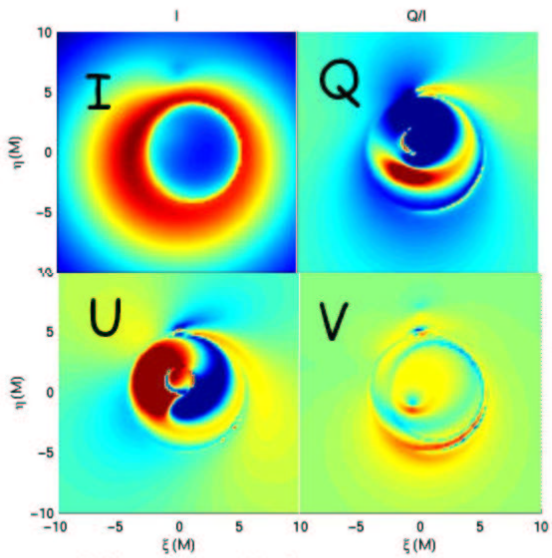
Requires radiation transfer including Faraday rotation, conversion, and magnetoionic modes => 1% circular polarization?

Bromley, Melia, Liu (2001)



Null geodesics

Broderick & Blandford (2002)



Plasma Dispersion

Black Holes as Lenses, Sources, or Both

- Galactic microlensing can allow one to measure number of black holes in MW using long timescale π μ–lens events and ACS, VLTI, or SIM -> M
- SMBH can create faint lensed images
- Quasar μ–lensing probes accretion physics:
  - Can invert spectrum as a function of time to measure local spectrum in an accretion disk
  - Broad emission lines depends on disk turbulence
  - Disk inclination, black hole mass, and spin
- VLBI measurements at sub-mm wavelengths (requires ALMA) may allow us to view the shadow of the Galactic center black hole - spin