AGNの描像

- 中心にブラックホールが存在
- BHに落ち込むガスが降着円盤を形成。ガスの重力エネルギーを解放して明るく輝く。
- 一部の物質はジェットとして出てゆく

BH＋降着円盤＋ジェット

AGNのVLBI観測

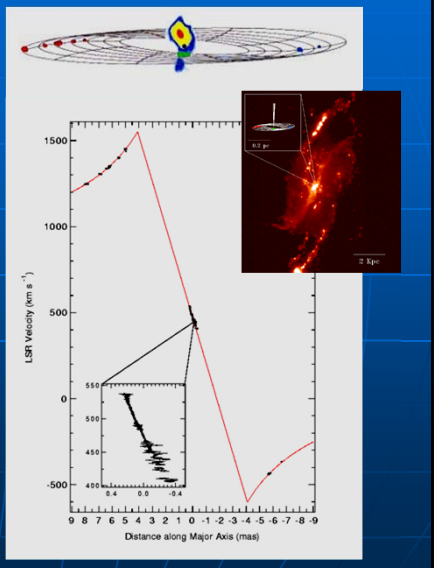
- ジェット
  sub-pcスケールまで分解した例が多数存在）
- 降着円盤
  確実な例はまだ。
  Sgr A*はおそらくそう。M87は（？）
- ブラックホール（シャドウ）
  今後の最重要ターゲット

AGN分子トーラスのメーザー

- VLBAによるイメージング
  ブラックホール周りの回転ガス円盤を検出

その大きさと回転速度か
ブラックホールの質量が
3600万太陽質量と分かった
（精密な距離も同時に決定）

もっとも確からしいブラックホールの証拠
（日米共同研究、1995年）

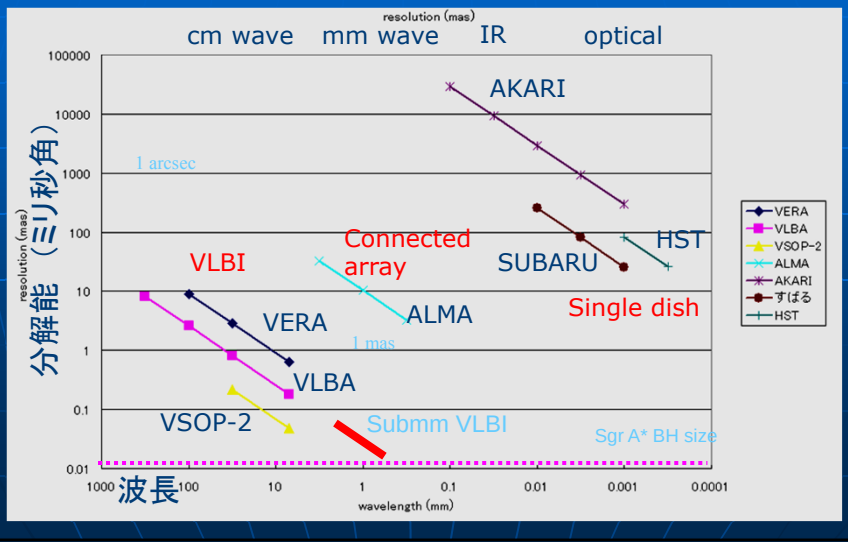


BH周囲観測スケール

N4258分子トーラス	~ 0.1 pc (10^5 R_g)
M87電波ジェットコア	~ 4000 AU (200 R_g)
降着円盤	数 ~ 数10 R_g
Sgr A*のシャドウサイズ	~5 R_g with submm-VLBI?

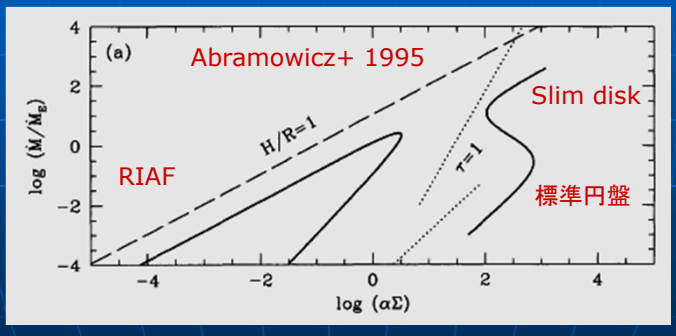
望遠鏡の分解能

- Wavelength – angular resolution diagram



降着円盤

- BH周囲の降着円盤には物理状態の異なるいくつかの状態がある。

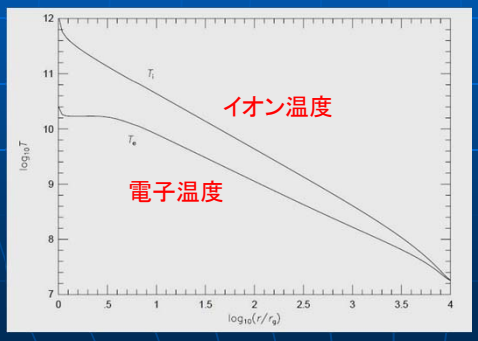


VLBIで円盤を直接観測できる可能性があるのはRIAF円盤
（重力エネルギーを放射で解放しないため、きわめて高温になる）

RIAF DISK

- Radiation Inefficient Accretion Flow

放射が効かず、温度がきわめて高くなる。重力エネルギーはブラックホールの中へ持ち込まれる

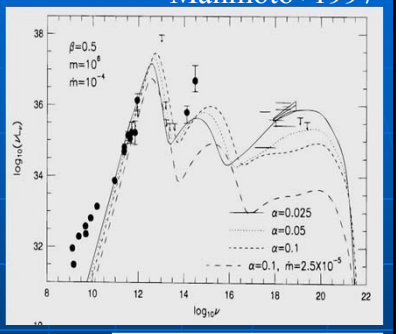


Manmoto+(1997)

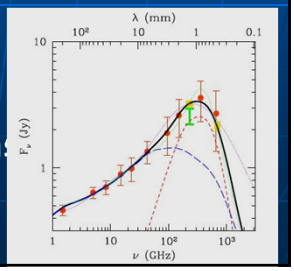
電子温度は
10^9 ~ 10 ^10 K

Sgr A*: RIAF disk source

Manmoto+1997



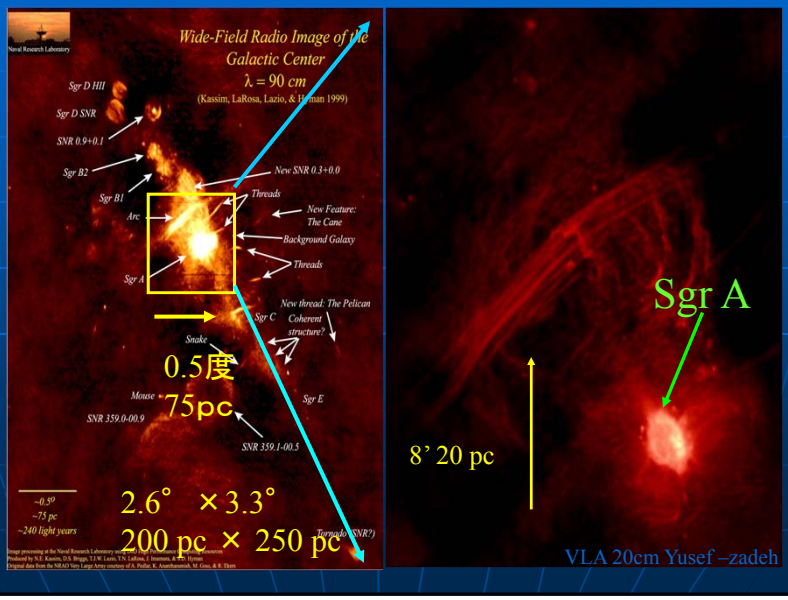
- very compact (< 1mas) radio source at the GC
- Non-thermal source, high brightness
- Dynamical center of the stars around Sgr A*
  mass : 4 x 10^6 solar mass



- Most-likely SMBH at MWG center
  for D = 8 kpc, θs = 10 μa

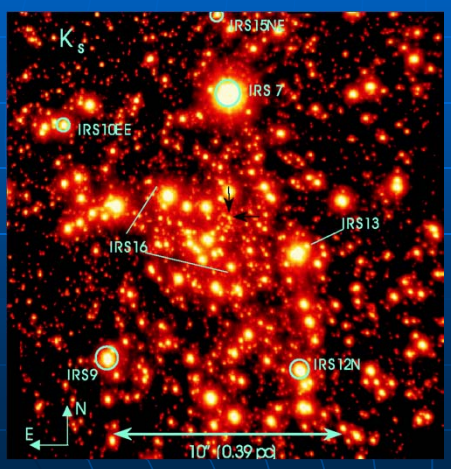
Broderick+2010

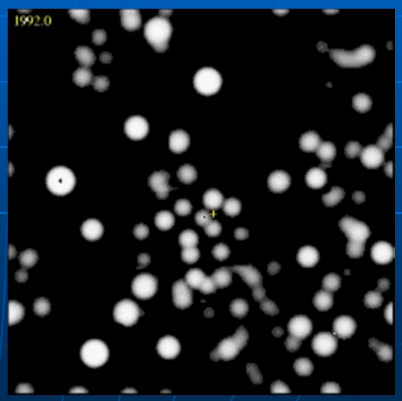
Radio images of the Galaxy Center



Stars' motions around Sgr A*

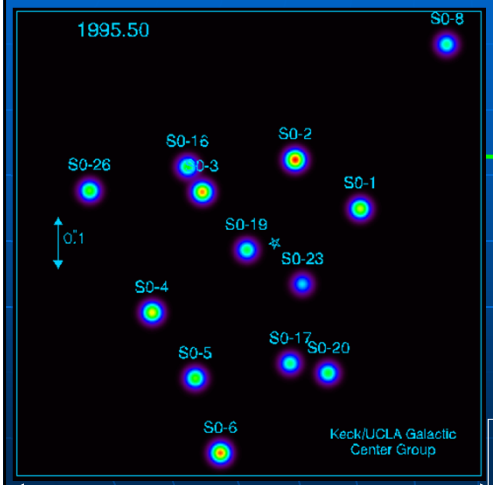
- Deep infrared imaging and astrometry of stars at the G.C.





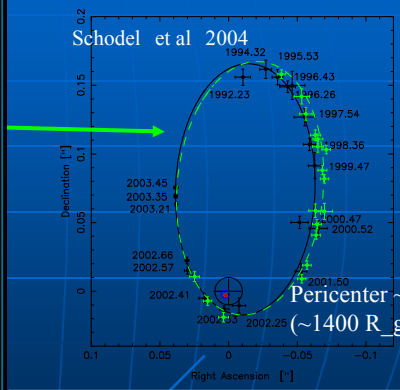
Motion of stars (Genzel et al.)

Orbit of S2 around Sgr A*



Ghez et al. 0.8" 0.032 pc

NTT+VLT black
Keck green



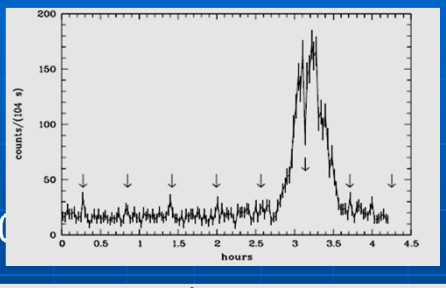
Pericenter ~14 mas (~1400 R_g)

Most likely mass of the BH

~ 4 x 10^6 solar mass

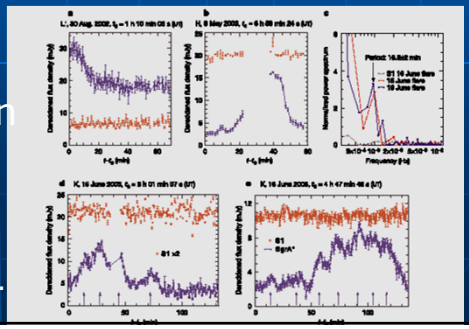
Sgr A* QPO : hot spot in disk ?

- X-ray QPO
  XMM Sgr A* obs.
  ~30 min QPO ?
  (Aschenbach et al. 20



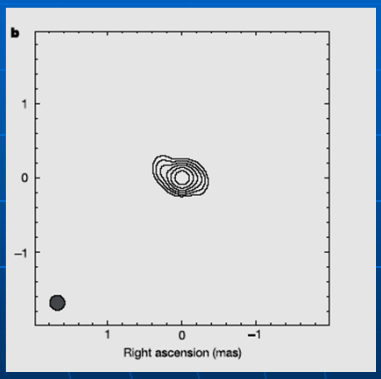
- IR flare and QPO
  periodicity of ~ 15min
  during flare in IR
  (Genzel et al. 2003)

sometimes seen, but not always …

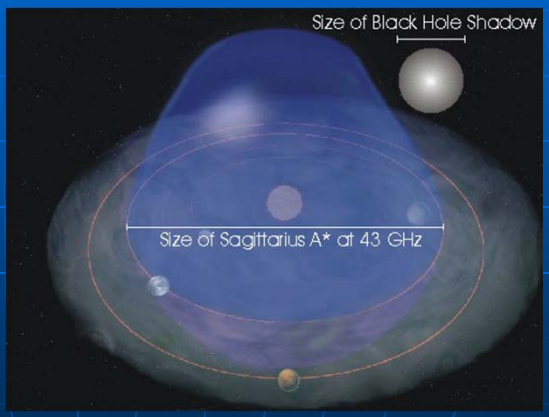


VLBI image of SgrA*

Sgr A* size : < 1mas (< 100 R_g) : c.f. R_g ~ 10 μas



VLBA 86GHz map
by Shen et al.(2005)



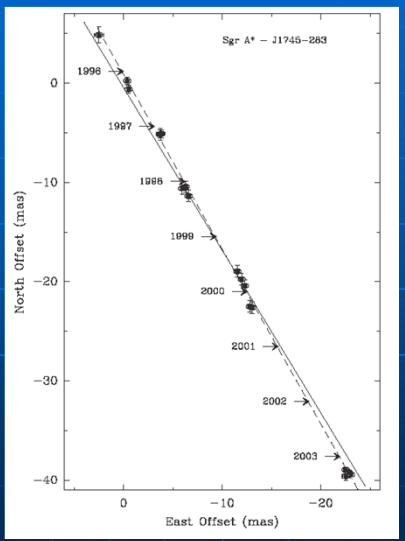
http://www.astro.ru.nl/~falcke/bh/Pictures/sgrastar-size-solarsystem-small.jpg

Astrometry Sgr A* with VLBA

- Reid & Brunthaler (2004)

  Proper motion measurement with VLBA for 8 yr (parallax still difficult)

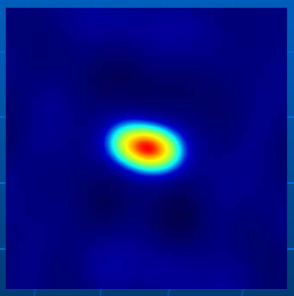
  linear motion (Sun's Galactic rotation)



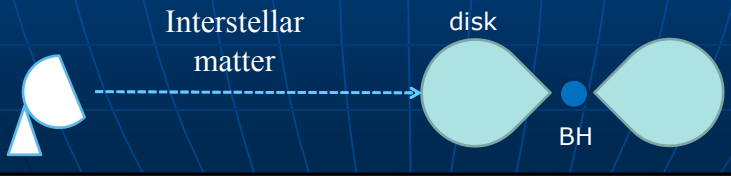
J1745-283に対するSgr A*の動き

Sgr A* at mm wave

- τ=1 surface of RIAF disk ? (scatter-broadened)
- Nearly edge-on ?
- Probably inner part of the disk is invisible at 43G – 86G

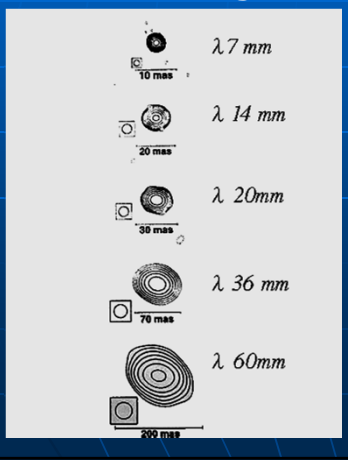


43G Image with VERA

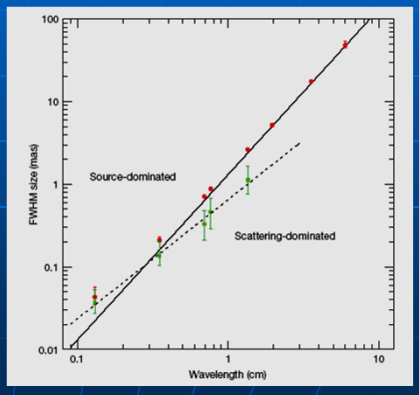


sub-mm VLBI is the key

- Sgr A* suffers from significant interstellar scattering at cm—mm wavelength



Lo et al.1999



Scatter effect ∝ λ^2

Toward BH shadow

Sgr A* is a unique source for black hole study

- bright, compact radio source (observable with VLBI's high angular resolution)
- precise mass measurement
  M_bh ~ 4 x 10^6 solar mass
- Nearby source (D ~ 8 kpc)
  → the largest angular size:θg ~ 10 μas
  it can be resolved in near future !?

Fukue+ 1989

Is BH really a "black hole"?

Sgr A* "black hole" may be observable in sub-mm

Simulated image by Falcke et al. 2000

Rotating (a=0.998)

Non-rotatin (a=0)

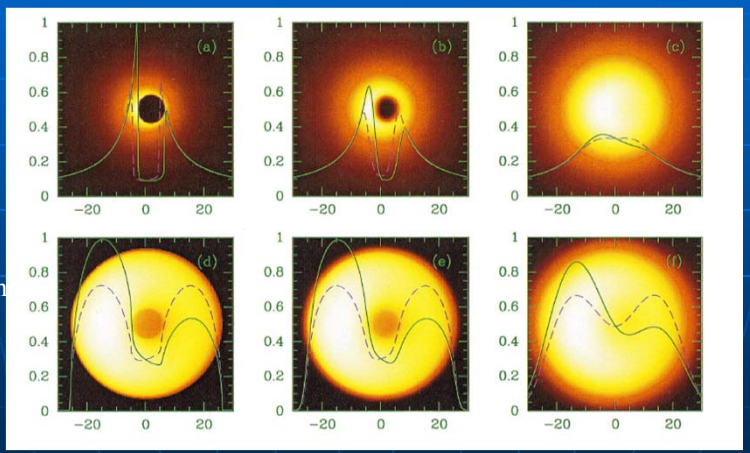


image 500 GHz 230 GHz

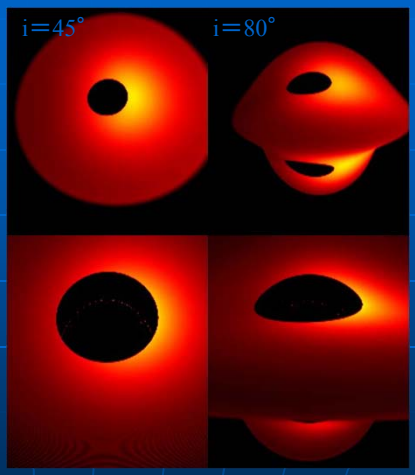
Black hole shadow size : ~ 5 r_g

Simulated image of Sgr A* black hole shadow

Takahashi et al.(2004)

ADAF with different BH parameters
(spin, disk inclination)

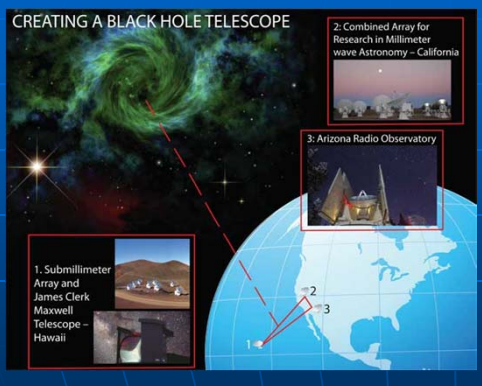
Different metric gives different shape of black hole shadow

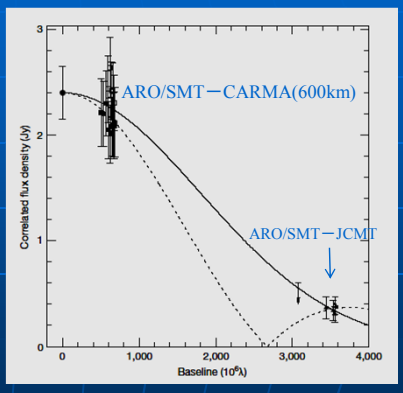


black hole shadow >
provides an ultimate evidence of BH existence
allows us to measure the metric

Event-horizon-scale structure detected !?

Doeleman et al. 2008 in Nature



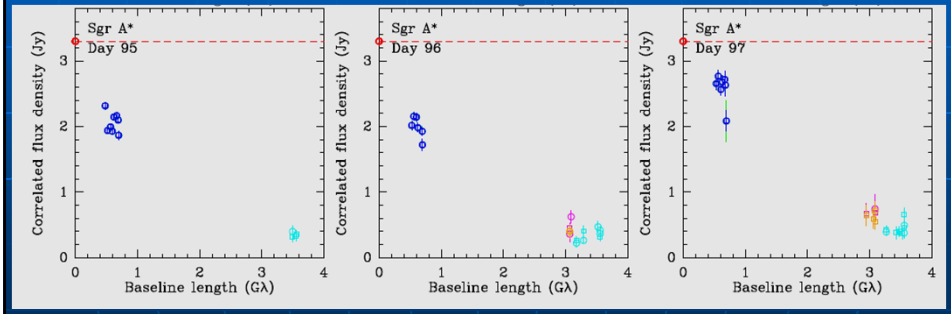


Non-imaging analysis (traditional UV distance plot)

- 37±(16,10) Intrinsic diameter of Sgr A*
- Non detection on the JCMT-CARMA（3075 km）

Sgr A* in 2009 April

- Hawaii-SMTO-CARMAで3日連続観測
- SMTO-CARMAで変動が見えている

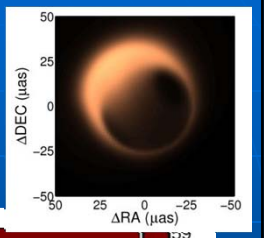


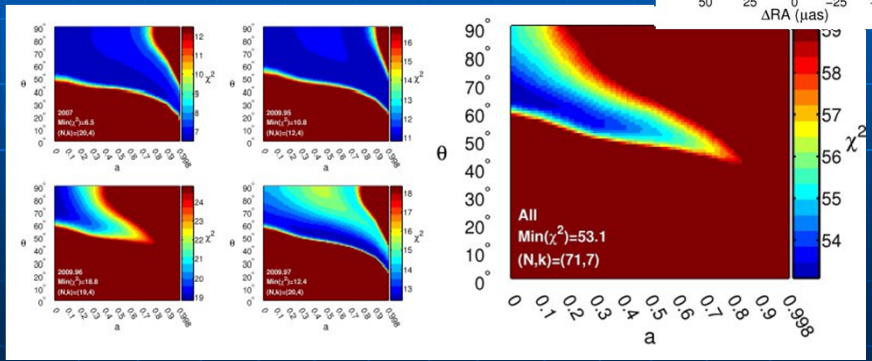
0.4 mas (~ 4 AU, ~ 40 R_g) スケールの構造の変化を示唆？

Doleman et al. ApJL submitted

Sgr A* parameters up-dated

- Broderick et al. (2011) constraining parameters with 4-day data (2007, + 3 days in 2009)

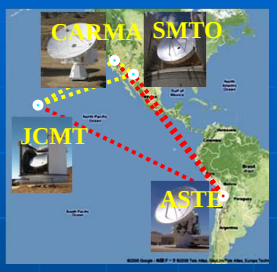


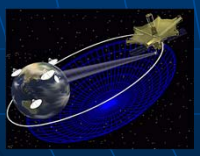


Extreme Kerr case is ruled out ?

Future prospect

- Use Chilean telescope such as ASTE and APEX to have longer baselines
- ACA/ALMA phase-up array will significantly boost the sensitivity of submm VLBI
- VSOP-3 as a submm VLBI satellite (one of the possible candidates) targets : Sgr A* and M87





まとめ

- 降着円盤は見え始めている(?)。しかし、その構造をきちんと分解した例はない。
- BHシャドーももちろんまだ未開拓の領域。
- 今後、ミリ波、サブミリ波のVLBIで分解能を上げることで、ジェットの根元、降着円盤構造、BHシャドーの観測で大きな進展が期待される。