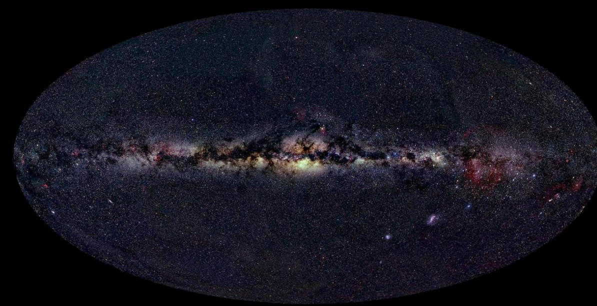
Sgr A*: from 10^0 to 10^{-18} m in 3000 seconds

Mark Wardle

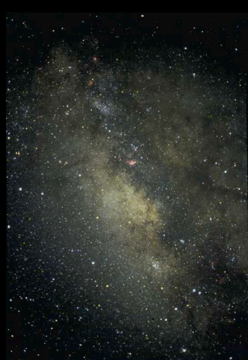
Department of Physics
Macquarie University

Outline

- The Galactic centre and Sgr A*
- Mass determination
- Accretion
- Spectrum: radio to x-ray
- TeV gamma rays
- Summary



Axel Mellinger



Discovery

266 BRUCE BALICK AND ROBERT L. BROWN

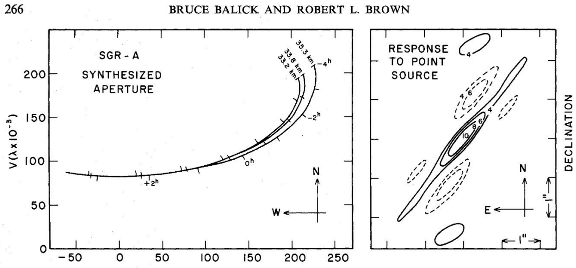
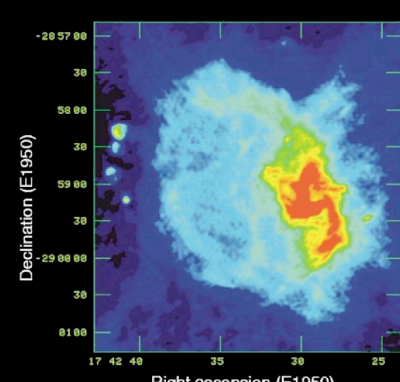


FIG. 1.—The projected baseline coverage and resulting synthesized beam pattern available for Sgr A at 2695 MHz. Hour angles are indicated along the ellipses. The axes are *u*, the east-west, and *v*, the north-south projections of the baseline, measured in wavelengths. At 8085 MHz the ellipses are identical in shape but larger by a factor of 3 so that the resulting synthesized beam is smaller by a factor of three.

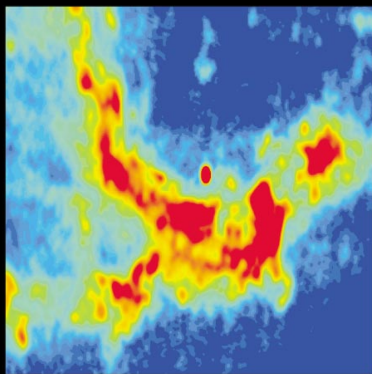
Balick & Brown (1974)

The Sgr A complex



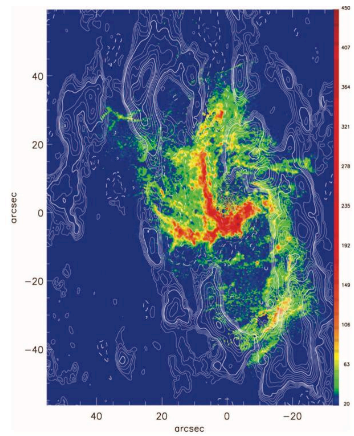
Yusef-Zadeh, Melia & Wardle (2000)

Sgr A* at 6 cm



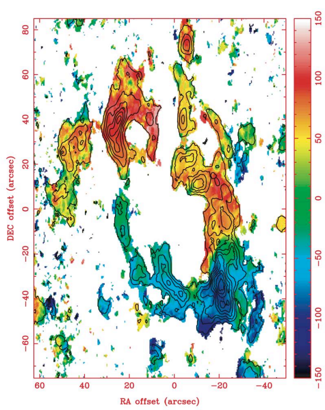
Yusef-Zadeh & Wardle (1993)

HCN vs radio



Christopher et al (2005)

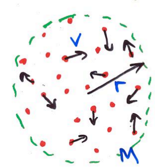
HCN Doppler



Christopher et al (2005)

Mass of Sgr A*

- Mass can be inferred from dynamics of gas or stars

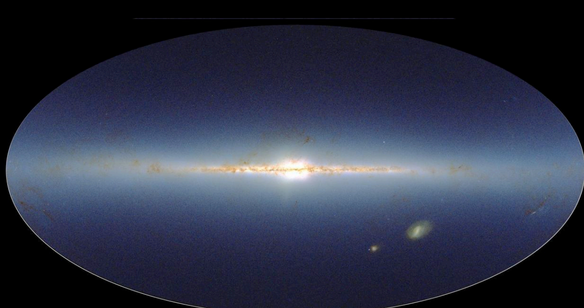


Virial theorem: $2K + W = 0$ (K: kinetic, W: potential)

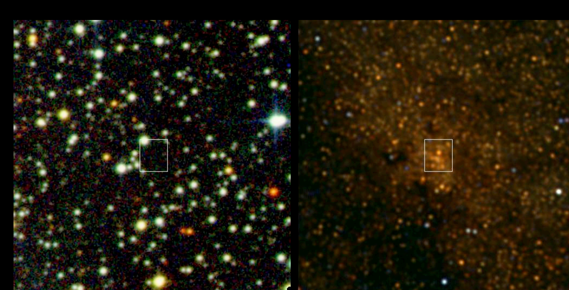
$$\Rightarrow v^2 \sim \frac{GM}{r}$$

$$\Rightarrow M \sim \frac{r v^2}{G} = 2 \times 10^6 M_\odot \, r_{pc} \, V_{100}^2$$

- HCN rotation (100 km/s at 2 pc) $\Longrightarrow 4 \times 10^6 \, M_\odot$



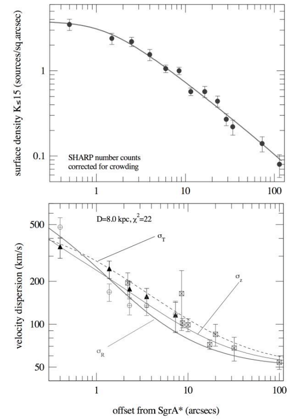
2MASS



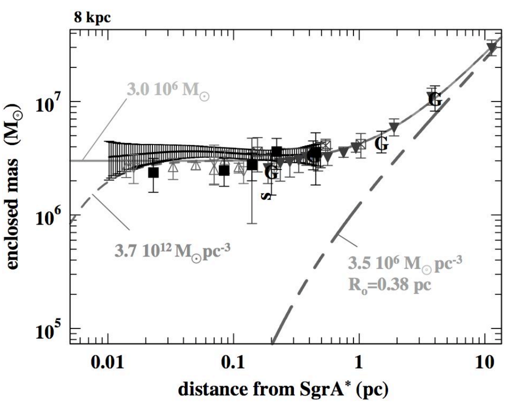
SuperCOSMOS

2MASS

Stellar velocity dispersion

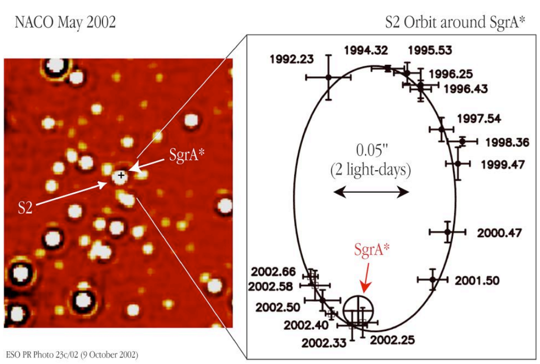


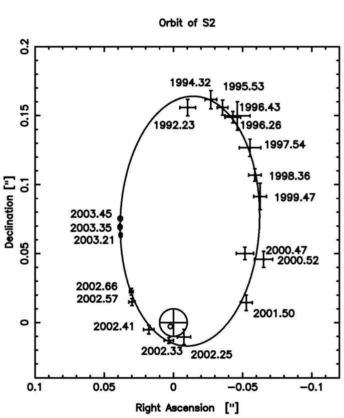
Genzel et al 2000



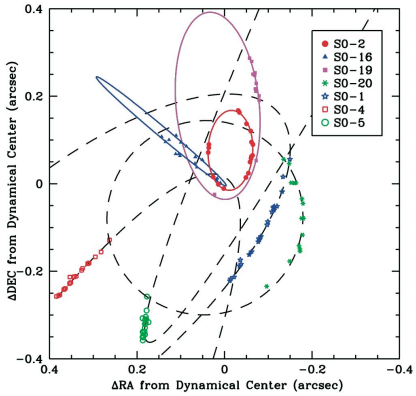
Genzel et al 2000

Stellar orbits





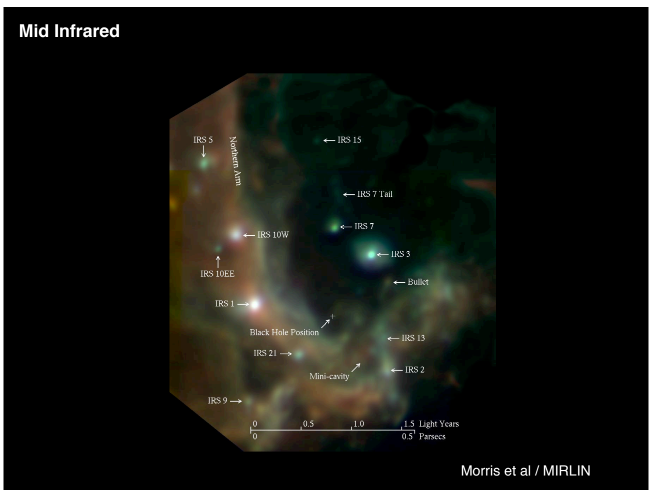
Eisenhauer et al 2003



Ghez et al 2005

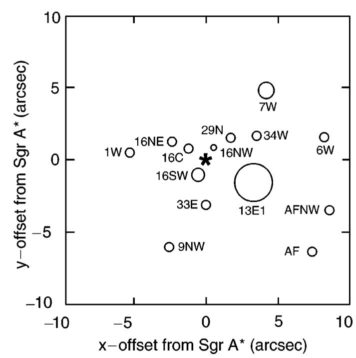
The conservative option

Sgr A* is a black hole with mass $\approx 4 \times 10^6\,\mathrm{M}_\odot$



Stellar winds near Sgr A*

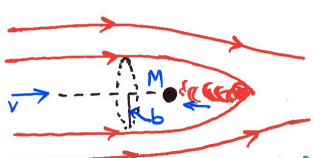
- Total stellar mass loss rate $\dot{M}_w \approx 3 \times 10^{-3}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$



Coker & Melia 1997

Accretion

- Sgr A* accretion rate $\dot{M} \sim 10^{-4}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$

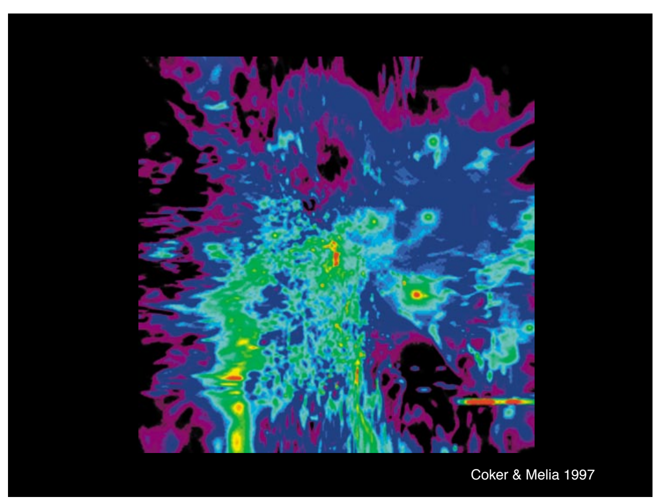


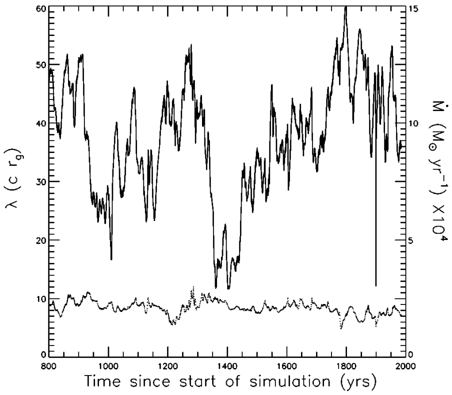
$$\frac{GM}{b} \sim \frac{1}{2}v^2 \Rightarrow b = \frac{2GM}{v^2} = 0.07\,\mathrm{pc}$$

($4\times10^6\,M_\odot$; $700\,\mathrm{km/s}$)

$$\Rightarrow \dot{M}_{BH} \sim \dot{M}_w \frac{\pi b^2}{4\pi R_w^2} = \dot{M}_w \left(\frac{b}{2R_w}\right)^2 \simeq 10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$$

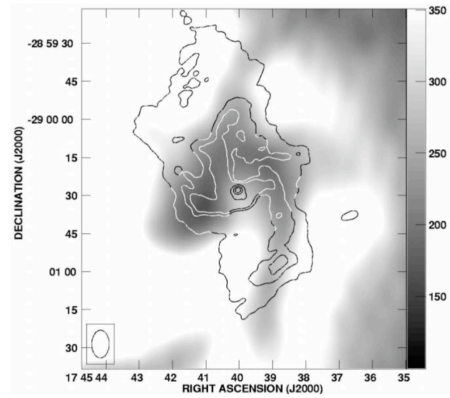
($4_{-3}\,M_\odot/\mathrm{yr}$; $0.2\,\mathrm{pc}$)





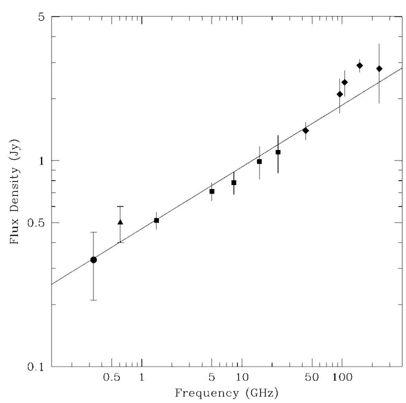
Coker & Melia 1997

Sgr A* at 6 and 90 cm



Nord et al (2004)

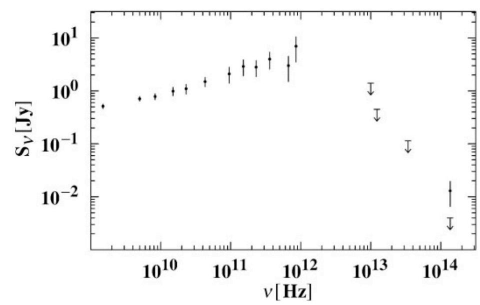
The radio spectrum



Nord et al (2004)

The radio-NIR spectrum

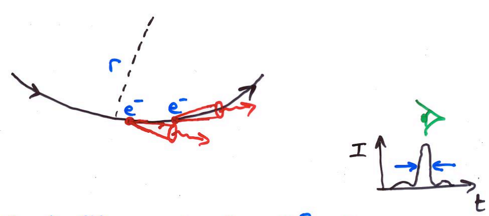
- Spectrum peaks near 10^{12} GHz
- Luminosity $L = 4\pi d^2 \int S_\nu d\nu \approx 4\pi d^2 \nu S_\nu$ (100 GHz) $\sim 80\,L_\odot$



Melia & Falcke 2001

Synchrotron Emission

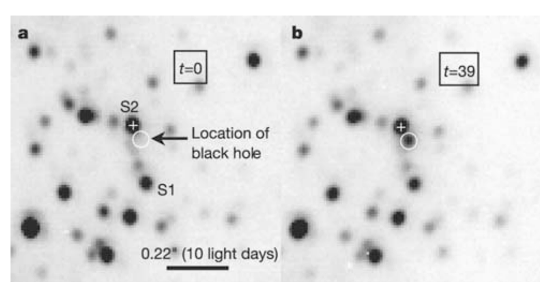
- Size of Sgr A* < 1 AU $\Longrightarrow$ synchrotron emission by relativistic electrons



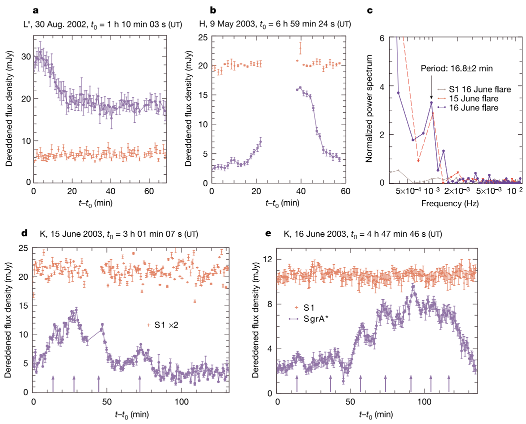
$$\Delta t \sim \frac{1}{\gamma^2}\frac{mc}{eB} \Rightarrow \nu \sim \frac{1}{\Delta t} \sim \frac{eB}{mc}\gamma^2$$

$$\nu = \frac{3eB\gamma^2}{4\pi mc} = 16\,B_{\rm mG}\,E_{\rm GeV}^2\ \text{GHz}$$

NIR flaring



Genzel et al (2003)

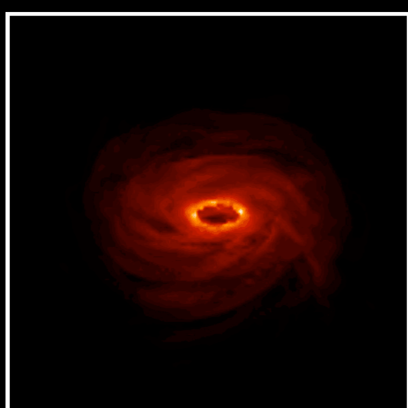


Genzel et al (2003)

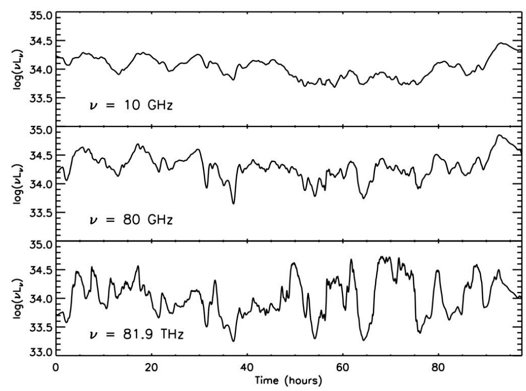
Disk movies. . .

Hawley, Balbus & Stone (2001)

Synchrotron from a turbulent disk

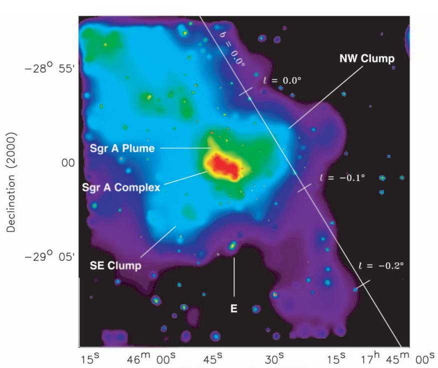


Goldston, Quartaert & Igumenshchev (2005)

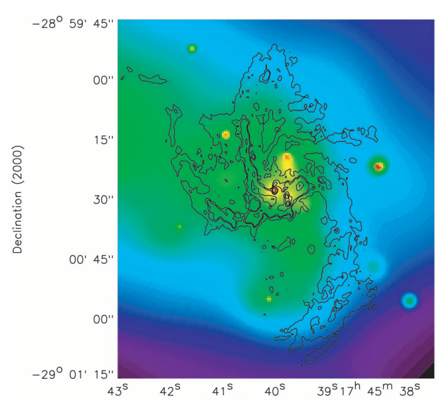


Goldston et al (2005)

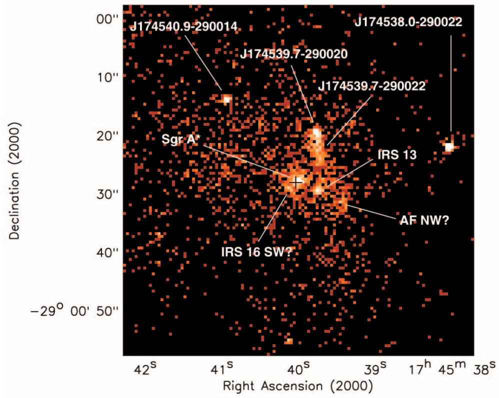
X rays



Baganoff et al (2003)

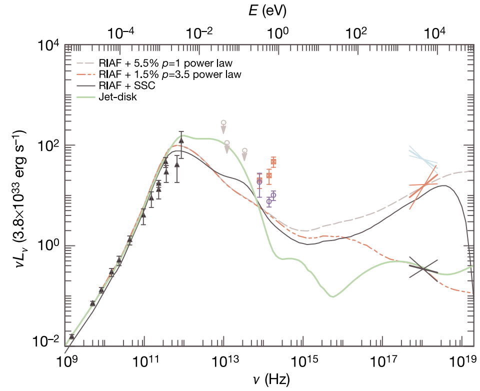


Baganoff et al (2003)



Baganoff et al (2003)

Radio–X-ray spectrum



Genzel et al (2003)

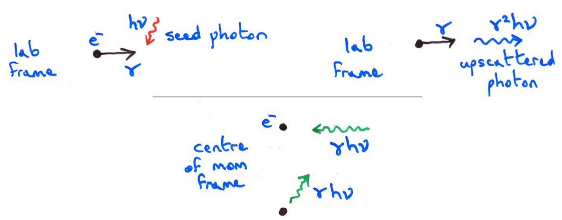
Correlated flaring in NIR and X-rays

- NIR is synchrotron from ∼GeV electrons in ∼10 G magnetic field

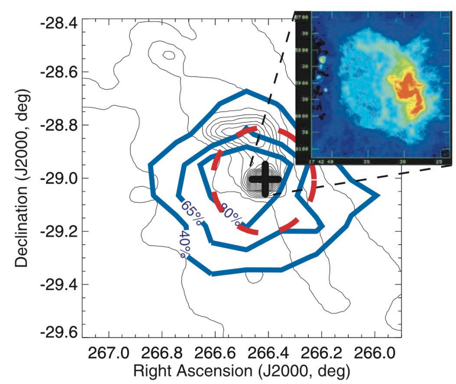
$$\nu = 16 B_{\mathrm{mG}} E_{\mathrm{GeV}}^2 \text{ GHz}$$

- electrons inverse compton scatter mm photons to X-ray energies

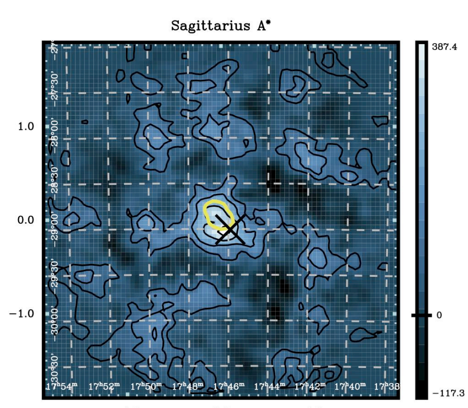
$$E_\gamma = \tfrac{4}{3}\gamma^2 h\nu = 2.1\, \nu_{100\,\mathrm{GHz}} E_{\mathrm{GeV}}^2 \text{ keV}$$



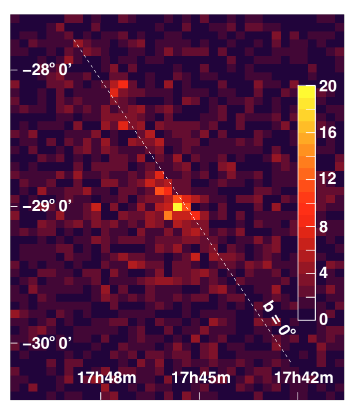
TeV gamma rays (maybe)



Cangaroo II – Tsuchiya et al (2004)

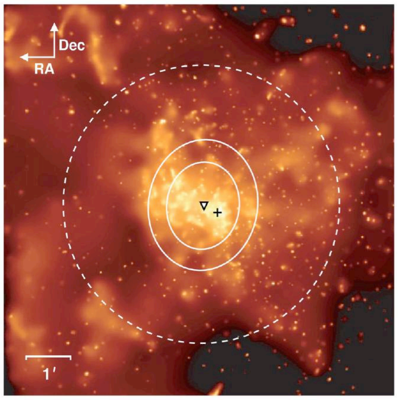


Whipple – Kosack et al (2004)

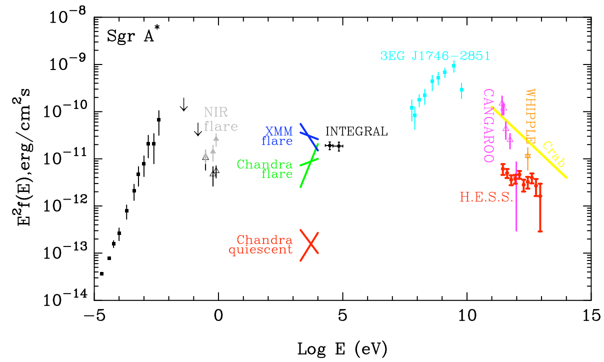


Hess – Aharonian et al (2004)

Hess error ellipses vs x rays



Aharonian et al (2004)



Aharonian & Neronov (2005)

Summary

- Sgr A* is *almost certainly* a black hole with mass $\approx 4 \times 10^6\,M_\odot$
- Sgr A* *probably* accretes stellar wind material, with $\dot{M} \sim 10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$
- Sgr A* *may* be a source of TeV gamma rays
- Flaring from submm to x-rays provides useful constraints on models for the accretion flow and emission mechanisms