Acceleration of Electrons and Protons by Plasma Waves in Sgr A*

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Outline

Observations of Sgr A*

Evidence for Electron Acceleration

A: radio emission

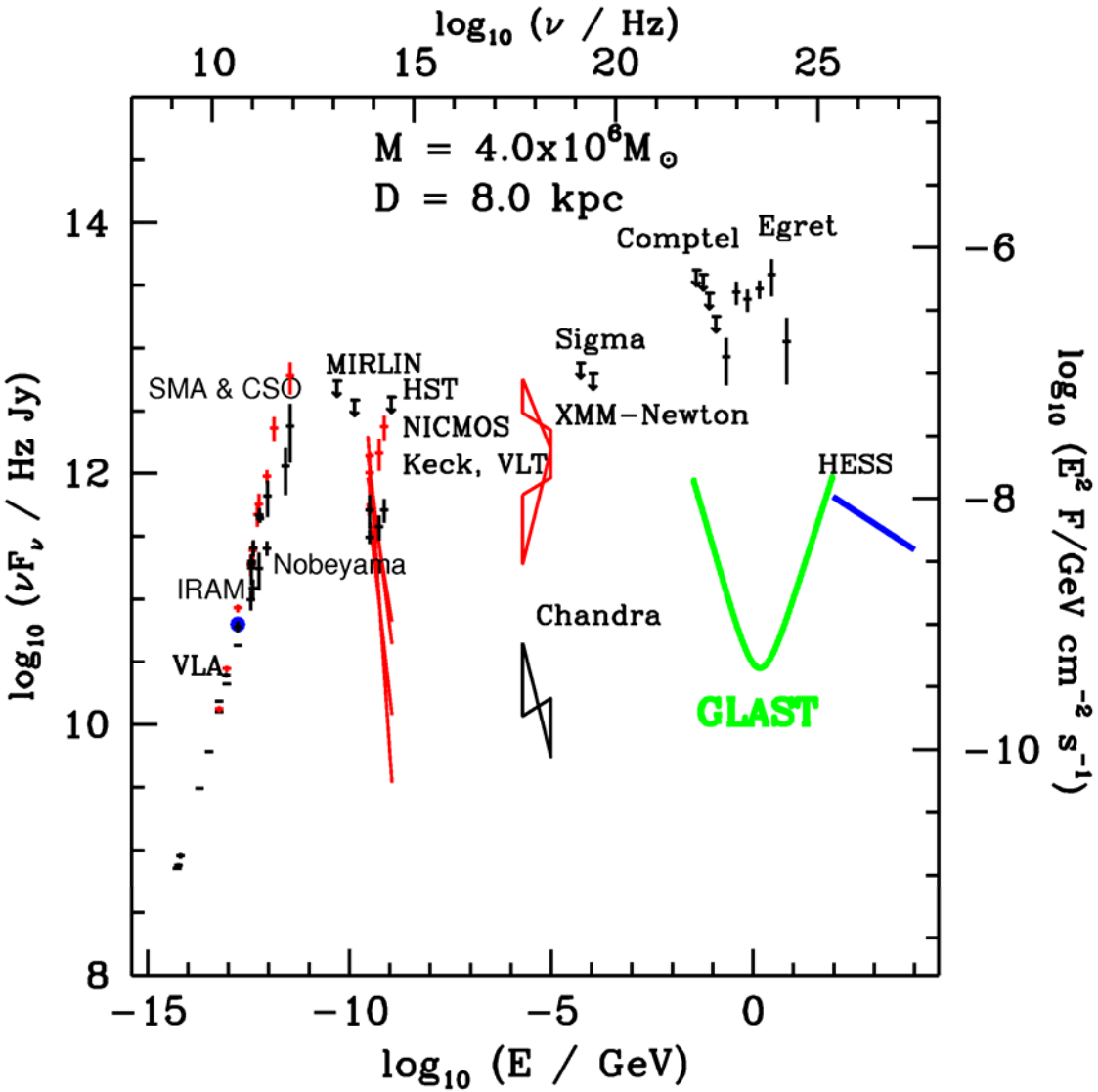
B: NIR and X-ray flares.

Evidence for Proton Acceleration

Stochastic Acceleration by Plasma Waves

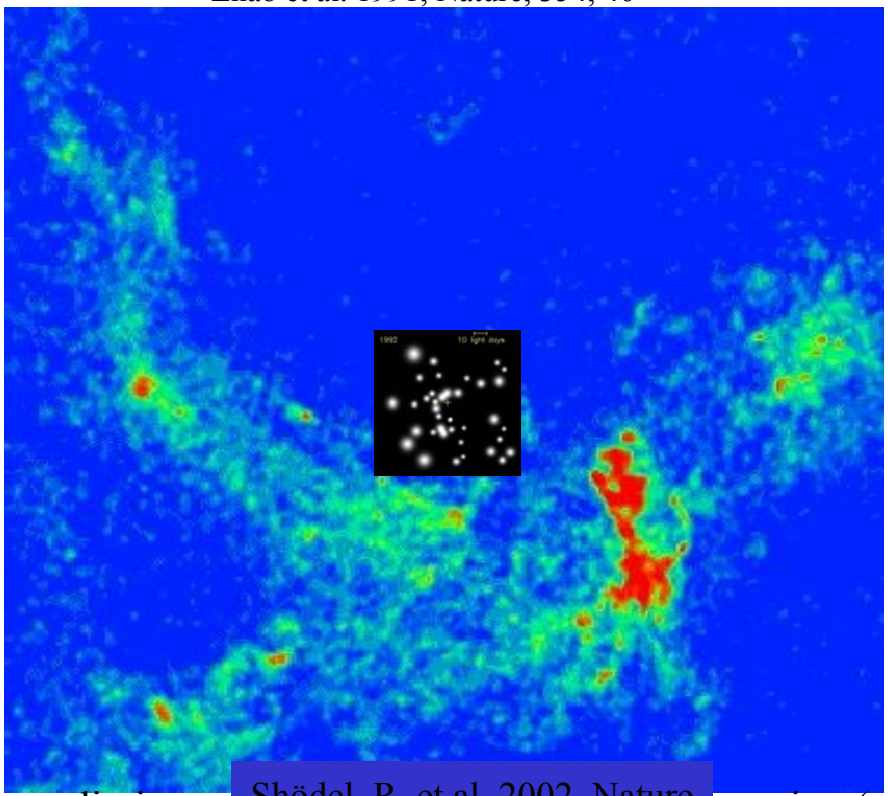
Structure of the Accretion Flow in Sgr A*

Broadband Spectrum



VLA

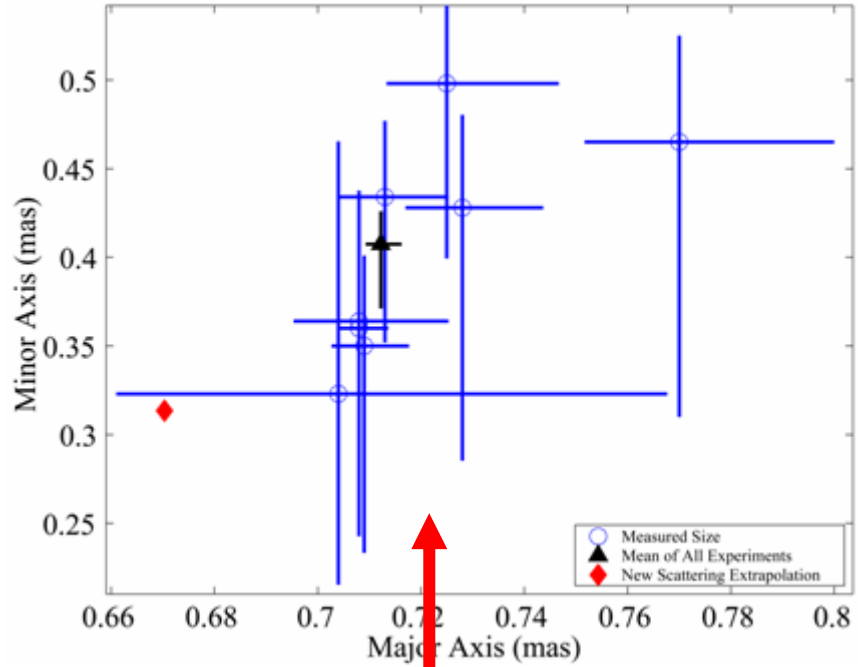
Zhao et al. 1991, Nature, 354, 46

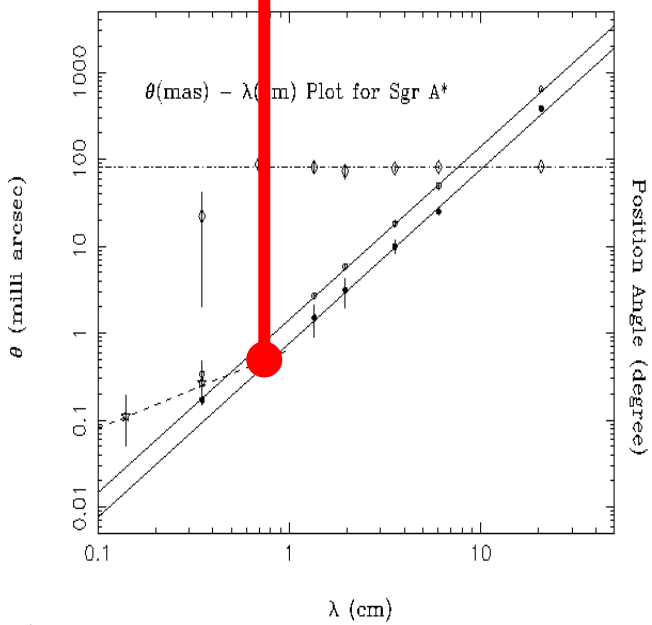


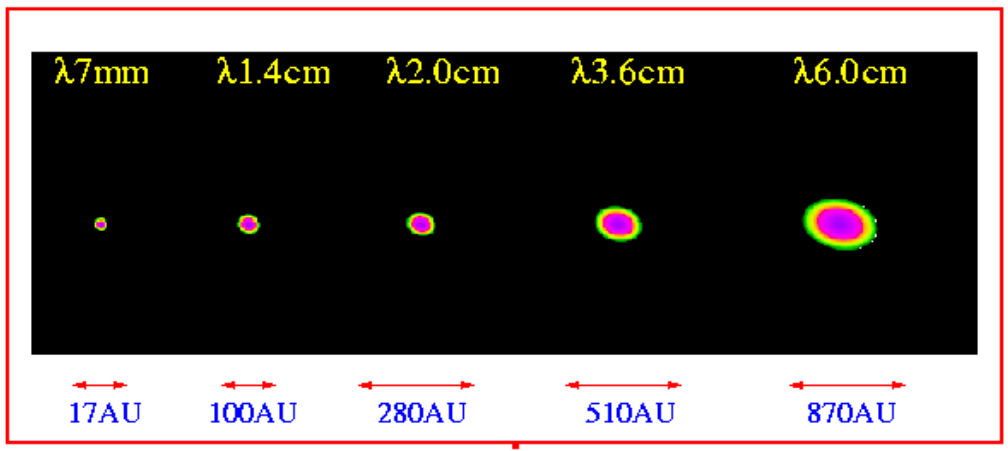
Shödel, R. et al. 2002, Nature

2 cm radio image r region (~20").

Bower et al. 2004, Science, 304, 704

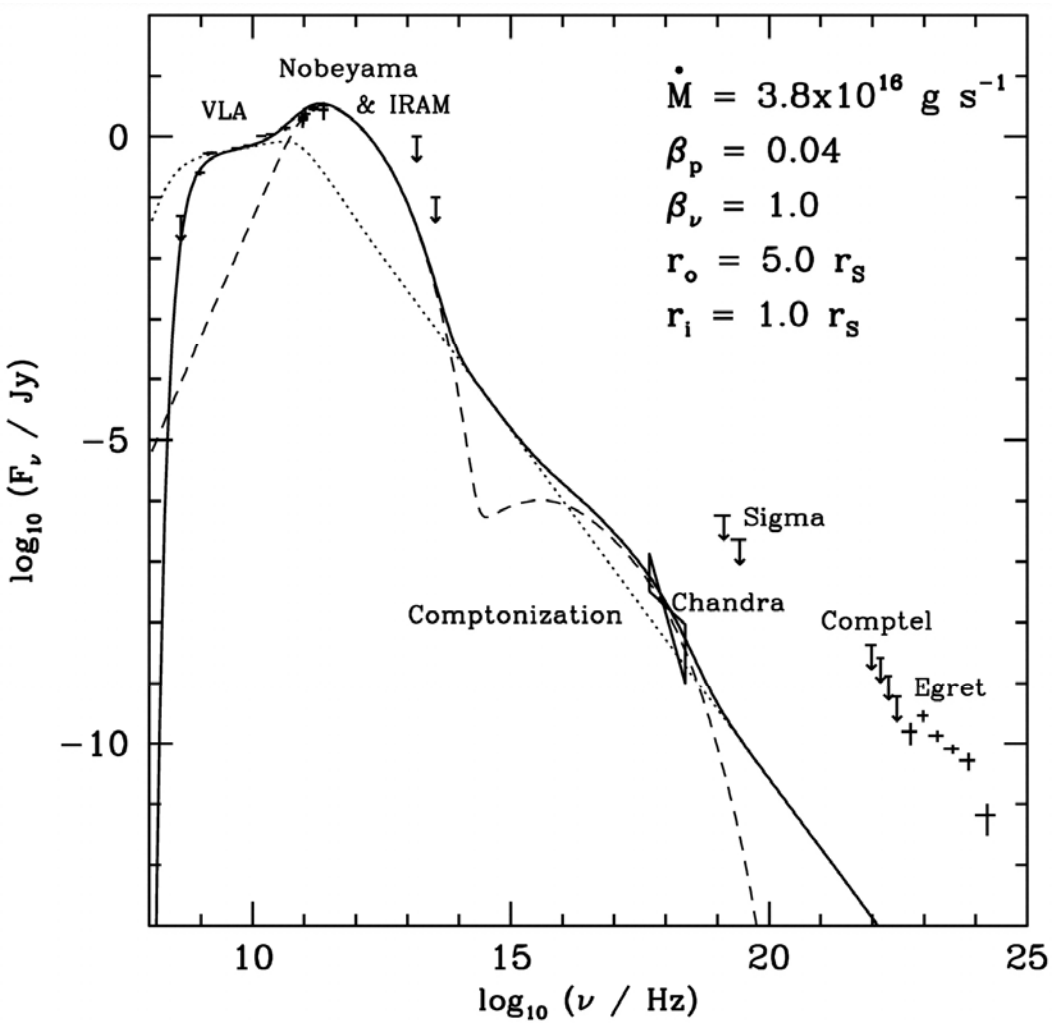






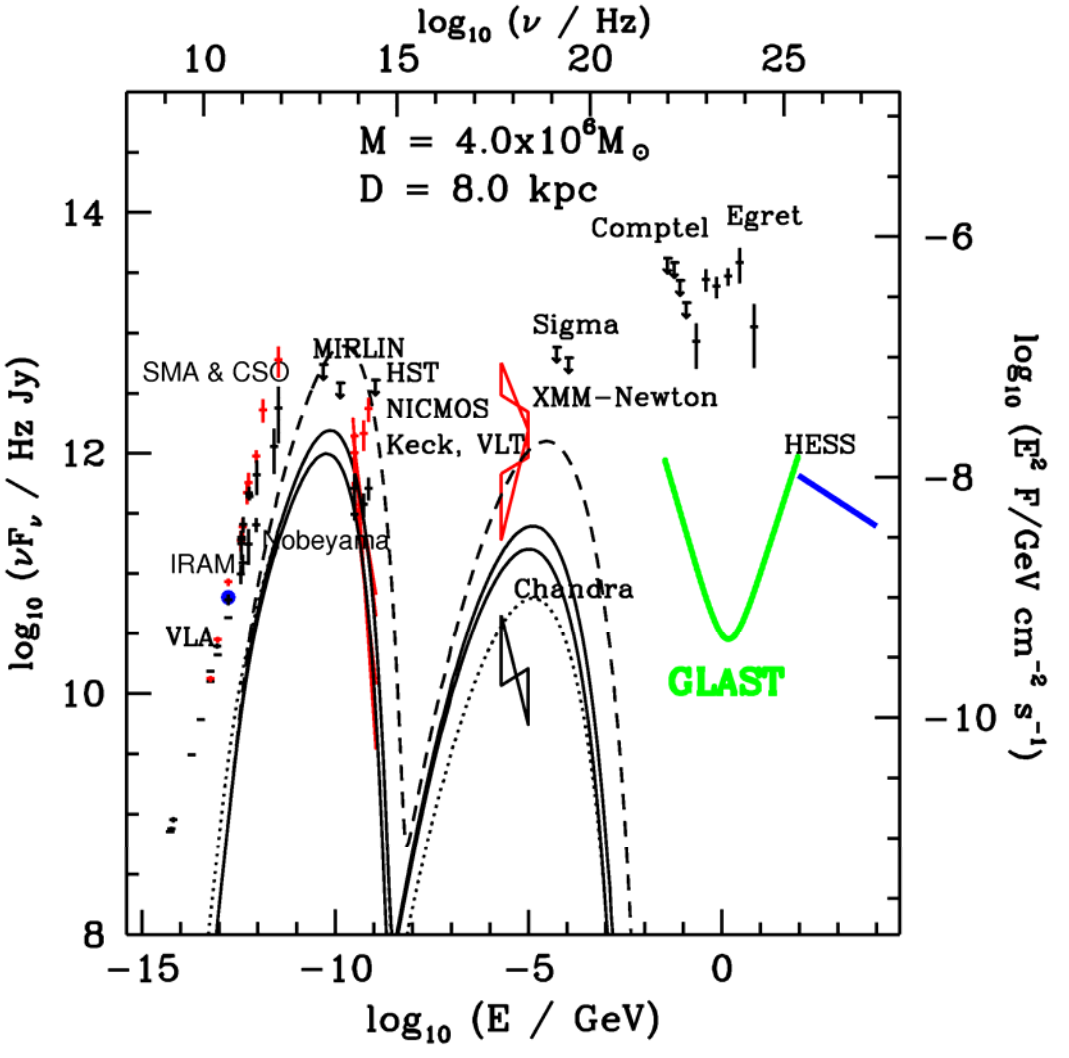
Lo et al. 1998, ApJ, 508, 61

Evidence for Energetic Electrons



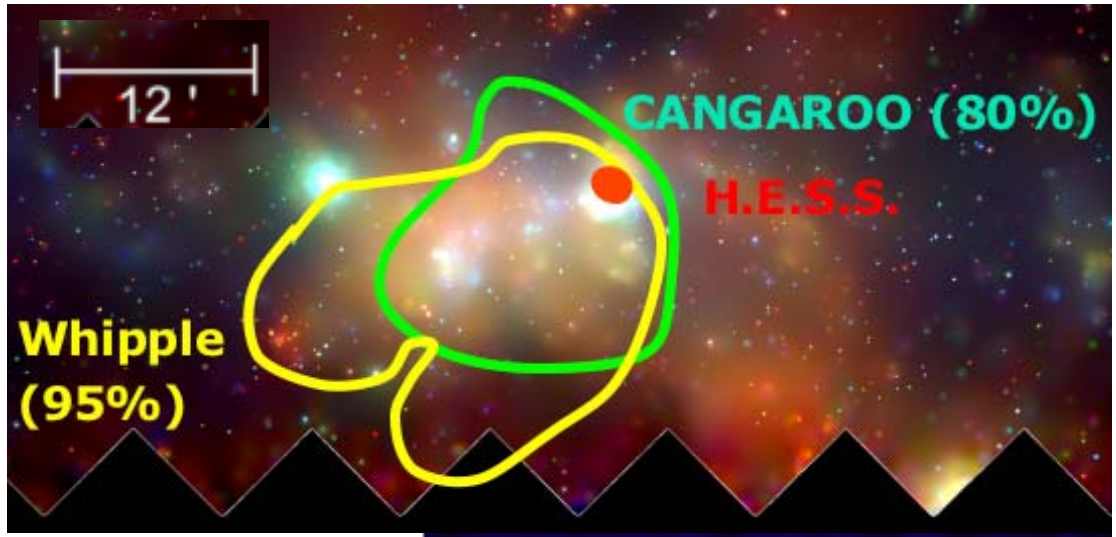
Liu and Melia 2001, ApJ, 561, 77

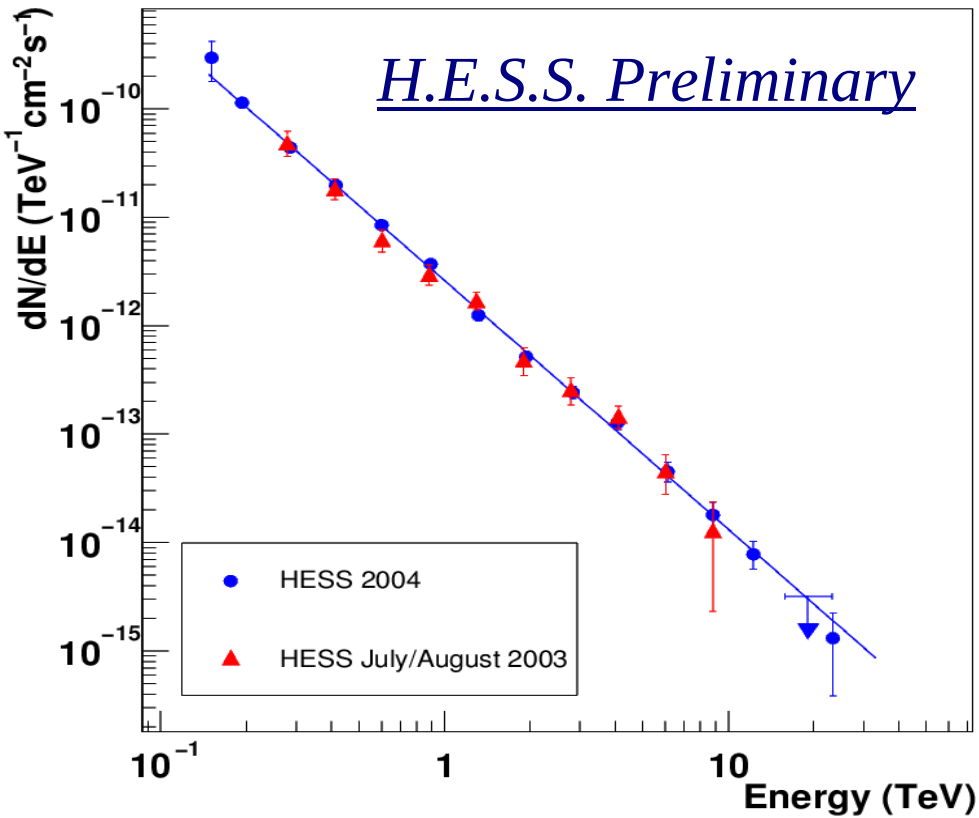
Evidence for Energetic Electrons

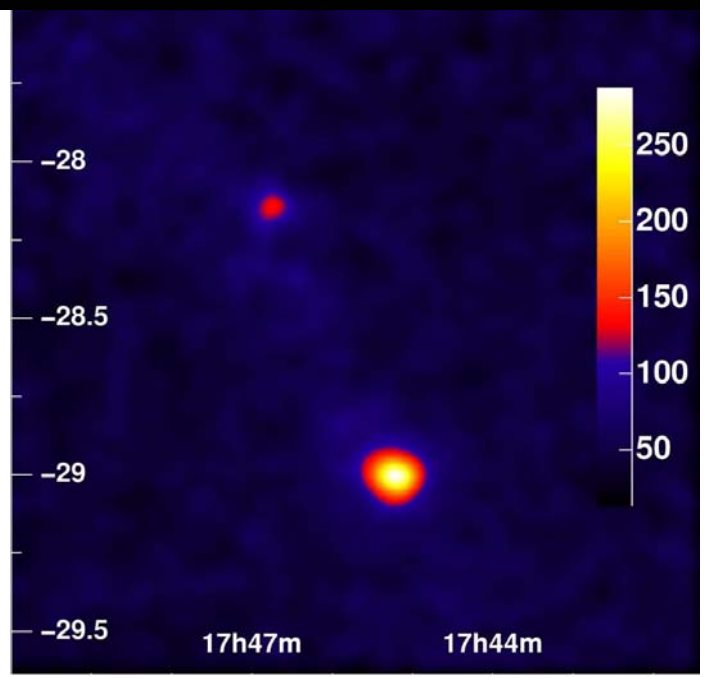


Liu et al. 2005, ApJ

HESS

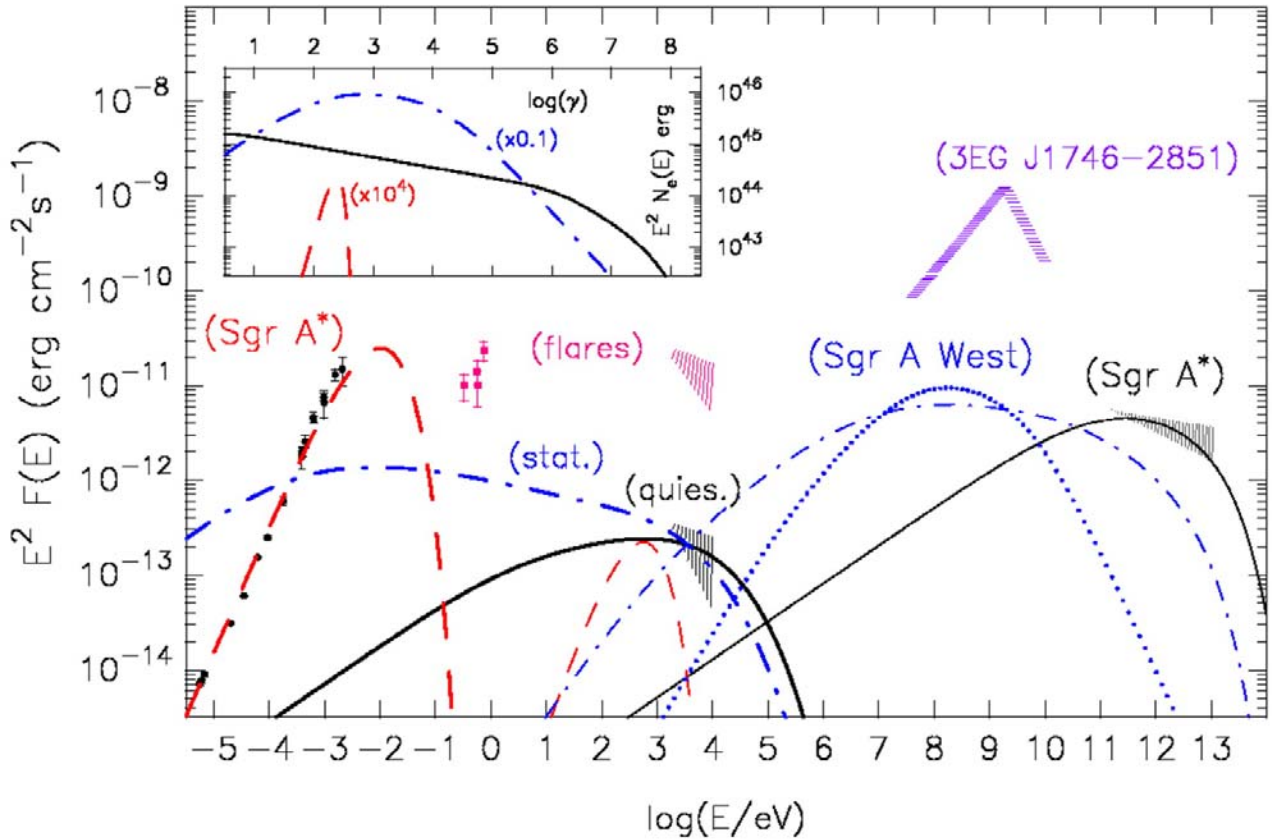






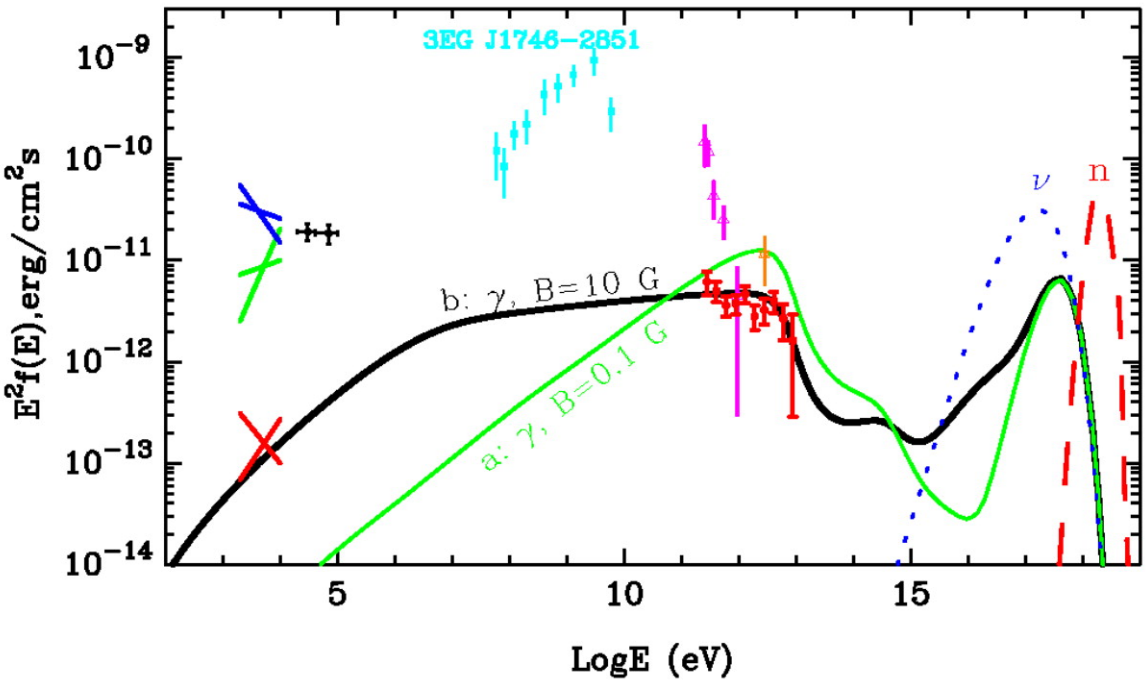
HESS Collaboration 2004

Possible Explanations
Synchrotron Self-Comptonination



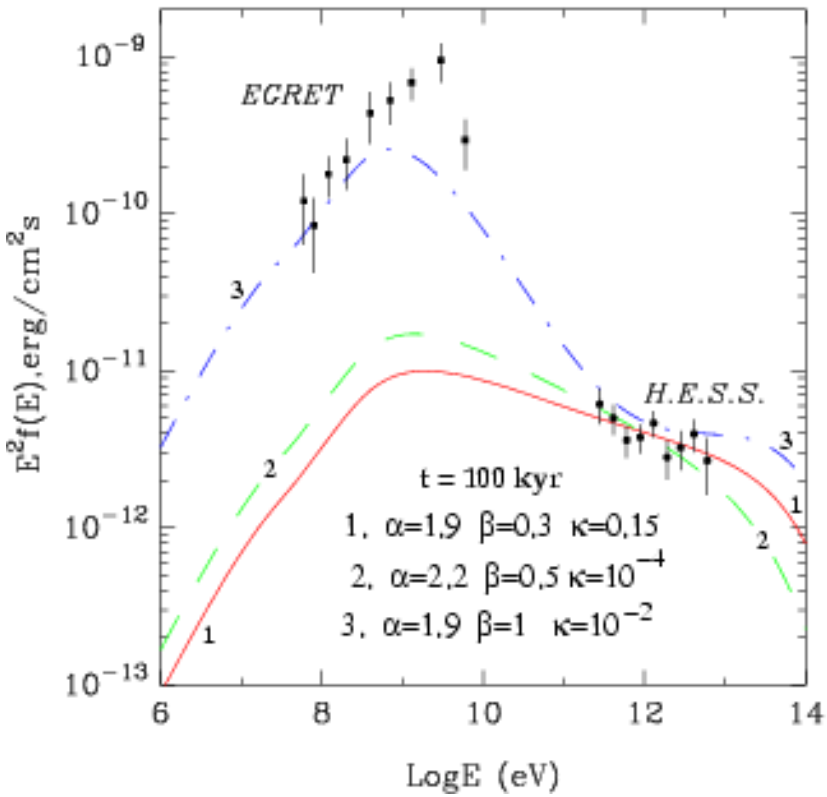
Atoyan and Dermer 2004, ApJ, 617, 123

Possible Explanations
Photo-Meson Interactions



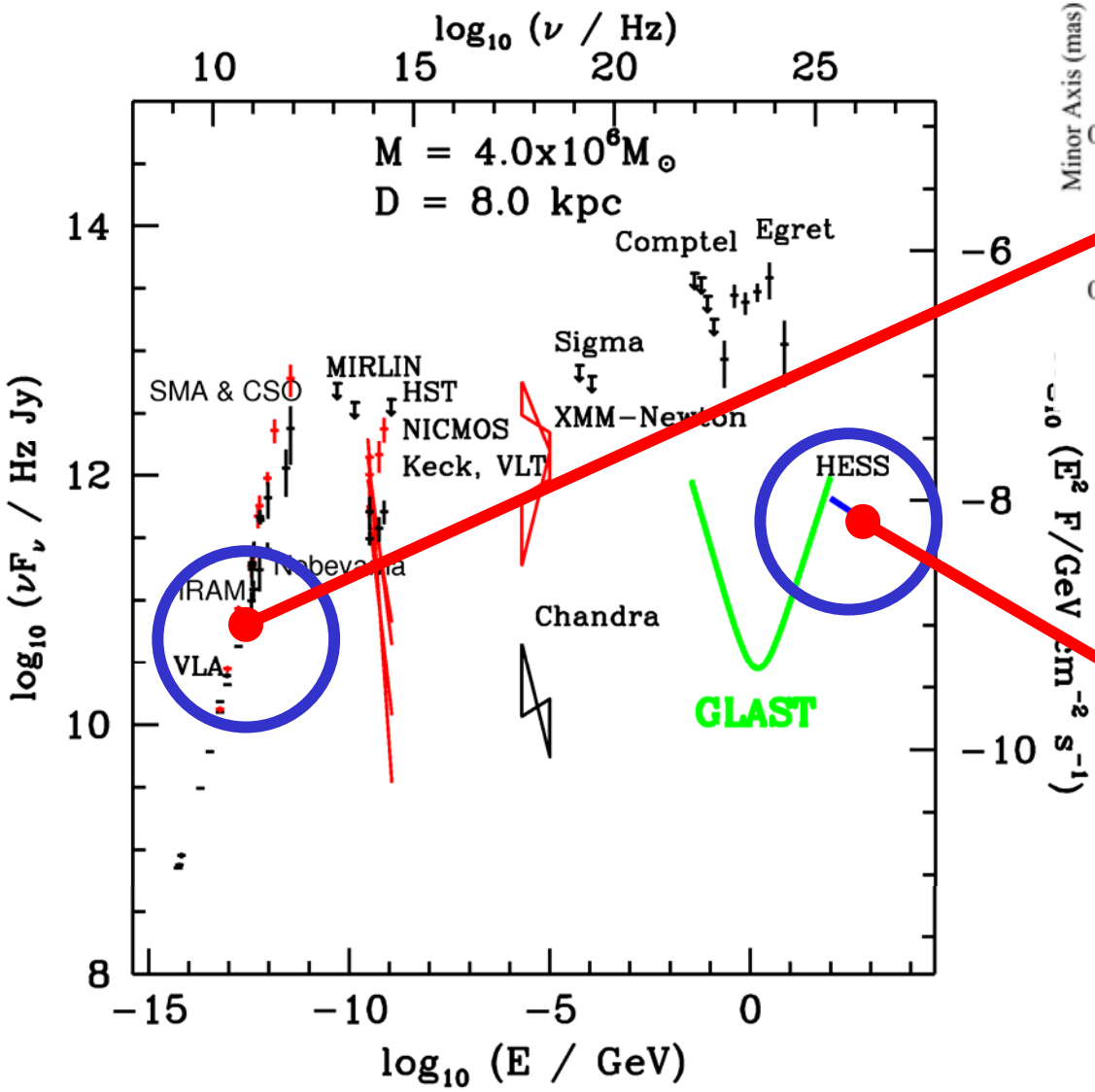
Aharonian et al 2005, ApJ, 619, 306

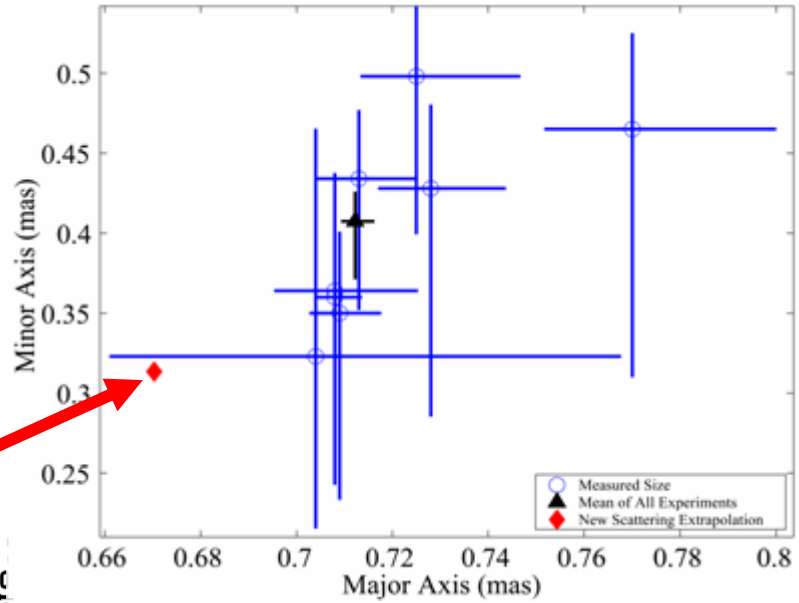
Possible Explanations
Proton-Proton Interactions

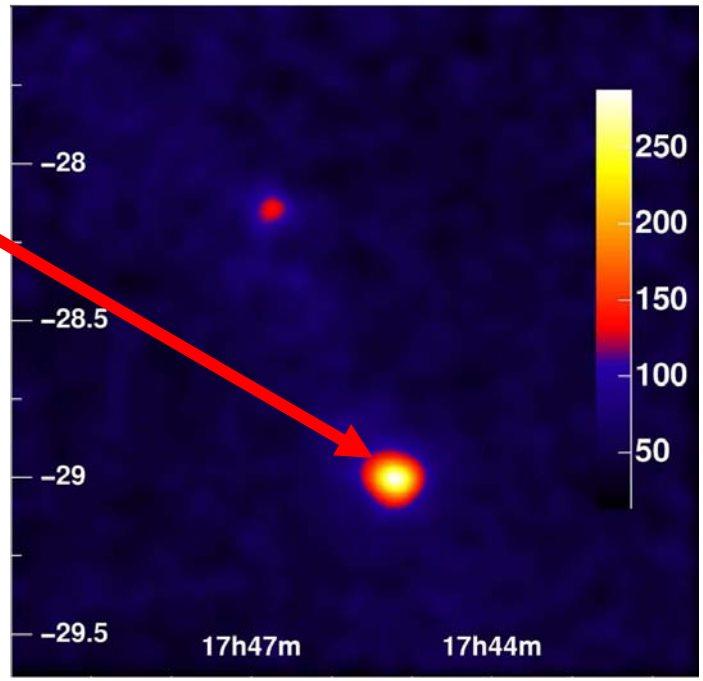


Aharonian et al 2005, ApJ, 619, 306; Liu et al. 2005

Acceleration within $20r_S$







Stochastic Particle Acceleration

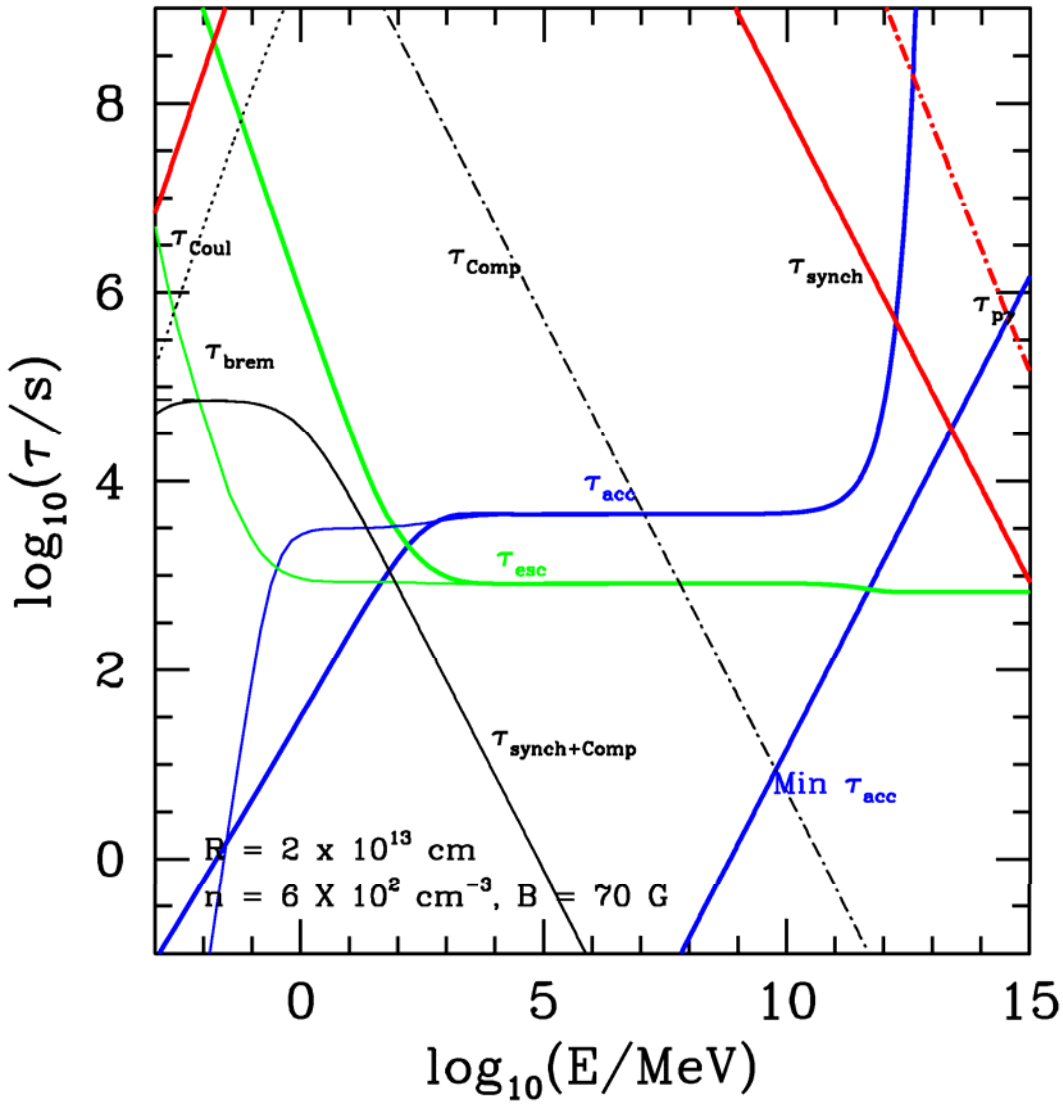
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma}\left[\frac{\partial \gamma^2 N}{\partial \gamma} - \left(4\gamma - \frac{4\gamma^2 \tau_{\rm ac}}{\tau_0}\right) N\right] - \frac{N}{T_{\rm esc}} + \dot{Q}$$

$$\tau_{\rm ac} = \frac{cR}{\pi^2 v_{\rm A}^2 f_{\rm turb}}$$

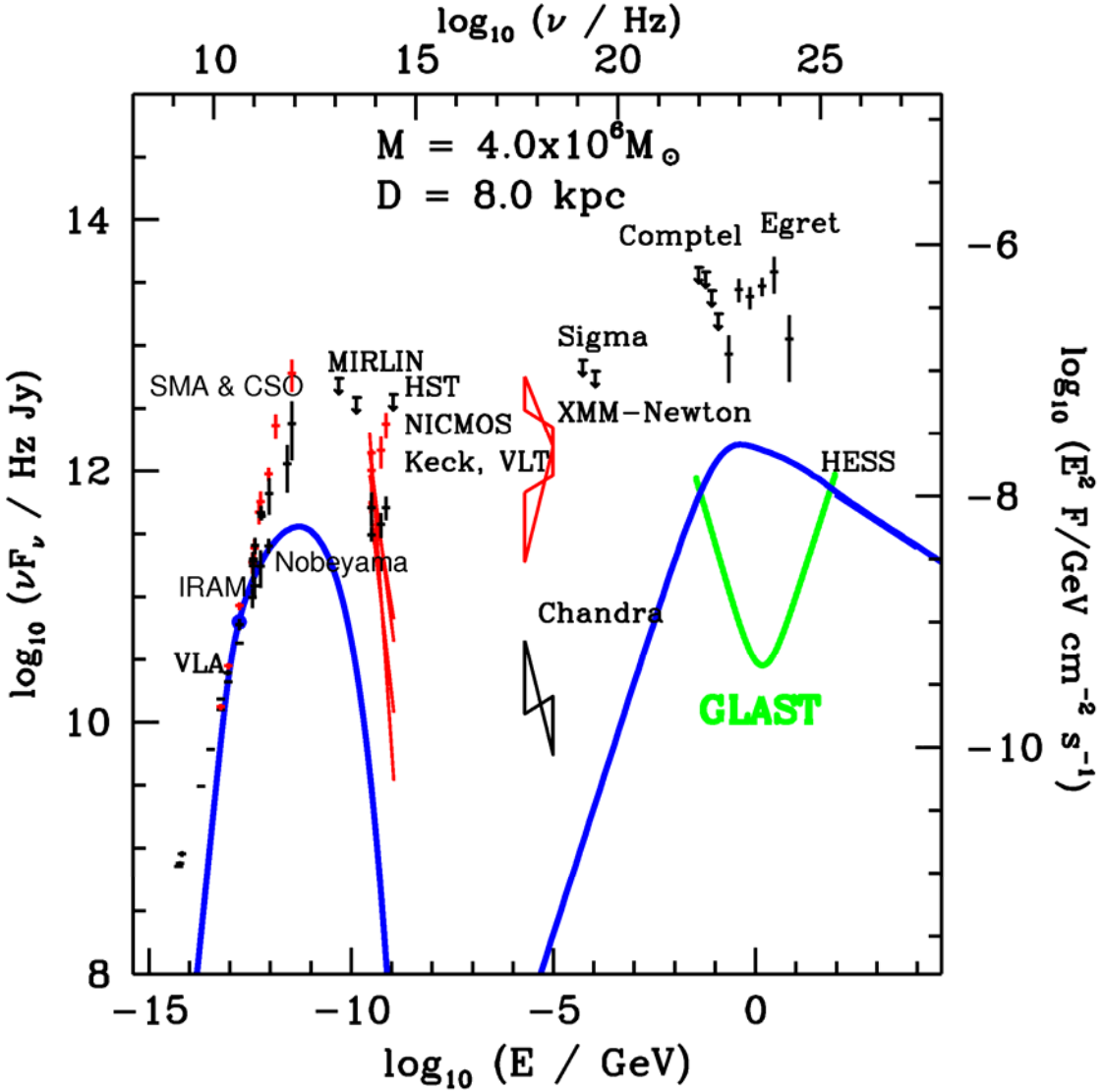
$$\tau_{\rm syn}(\gamma) = 9 m_e^3 c^5 / 4 e^4 B^2 \gamma = \tau_0 / \gamma$$

$$\gamma_{cr} = \frac{\tau_0}{4\tau_{\rm ac}} = \frac{9\pi^2 m_e^3 c^4 v_{\rm A}^2 f_{\rm turb}}{16 e^4 R B^2} = 30 \left(\frac{R}{r_S}\right)^{-1} \left(\frac{n}{10^7\ {\rm cm}^{-1}}\right)^{-1} \left(\frac{f_{\rm turb}}{0.1}\right)$$

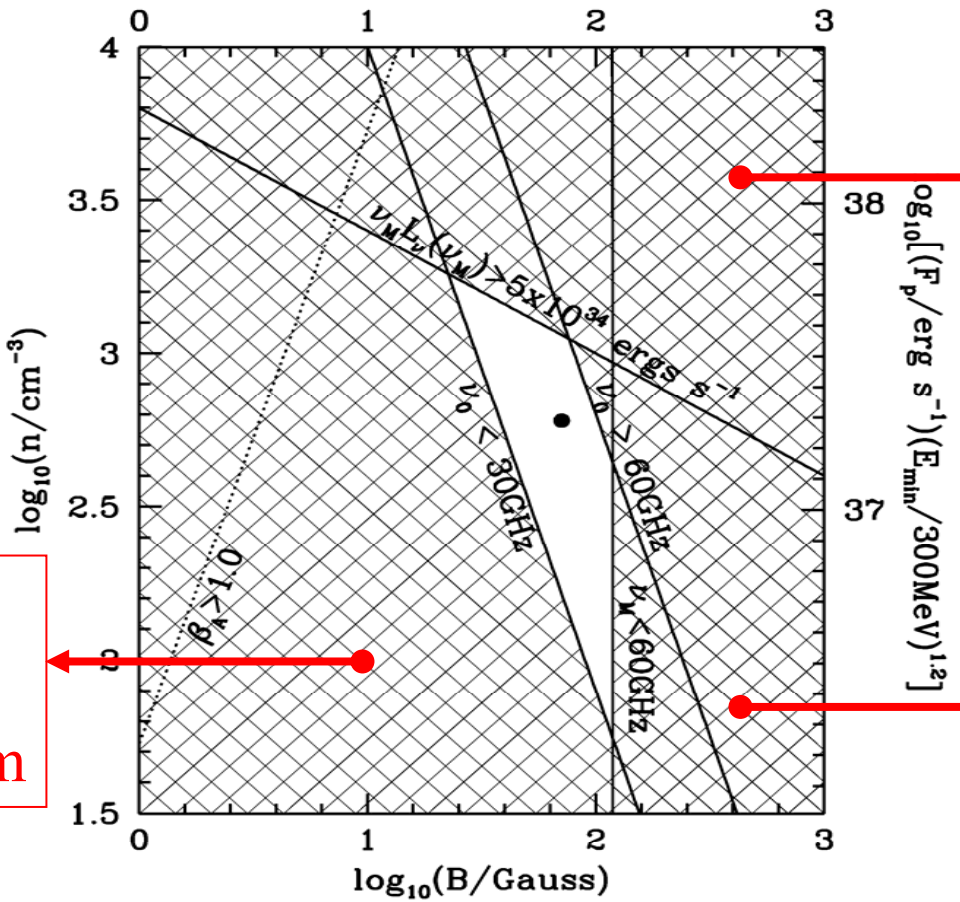
Stochastic Particle Acceleration



Stochastic Particle Acceleration



Proton Acceleration



Source is too bright in the radio band.

Source is optically thin at 7mm

Cooling is too efficient to produce 7 mm emission

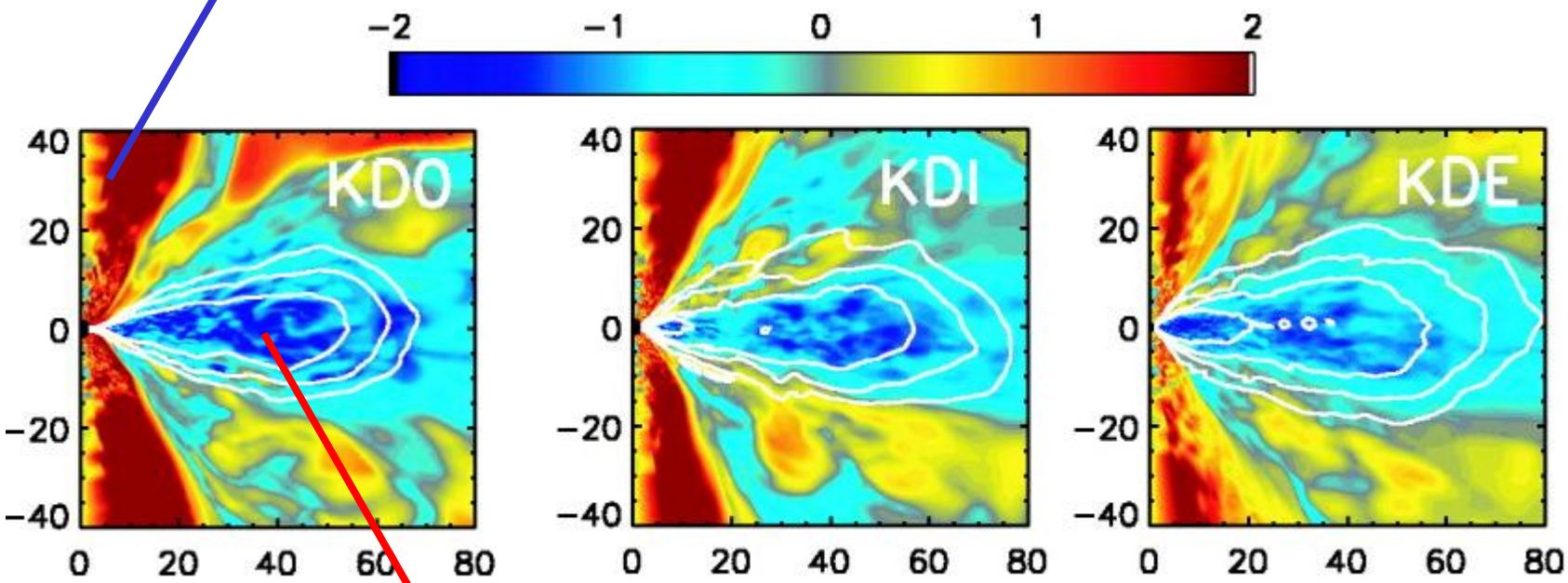
$$\beta_{\rm A} \equiv \frac{v_{\rm A}}{c} = 7.3 \left(\frac{B}{1{\rm G}}\right) \left(\frac{n}{1{\rm cm}^{-3}}\right)^{-1/2} .$$

The HESS source is likely produced via pp scatterings by protons accelerated near the black hole and diffusing toward large radii.

Should the 7mm emission be produced by electrons in the acceleration region, the acceleration region must be strongly magnetized.

Structure of the Accretion Flow

cm and mm via Synchrotron and proton acceleration



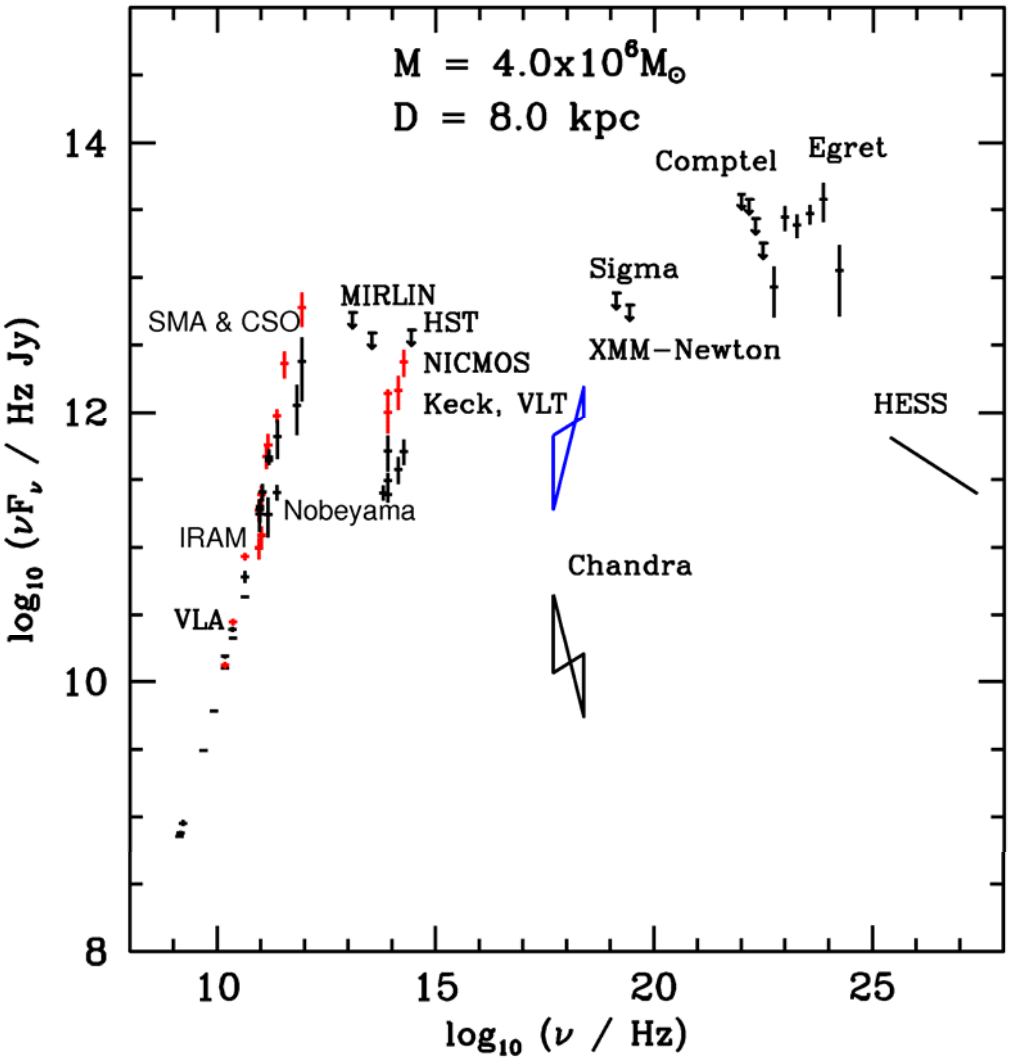
Sub-mm, NIR, and X-ray via Synchrotron and SSC

De Villiers et al. 2003 ApJ

Conclusions

In combination with the theory of Stochastic Acceleration by plasma waves and MHD simulations, observations over a broad energy range can be used to detect the properties of accretion flows

Emission Spectra



Emission Processes During Flares

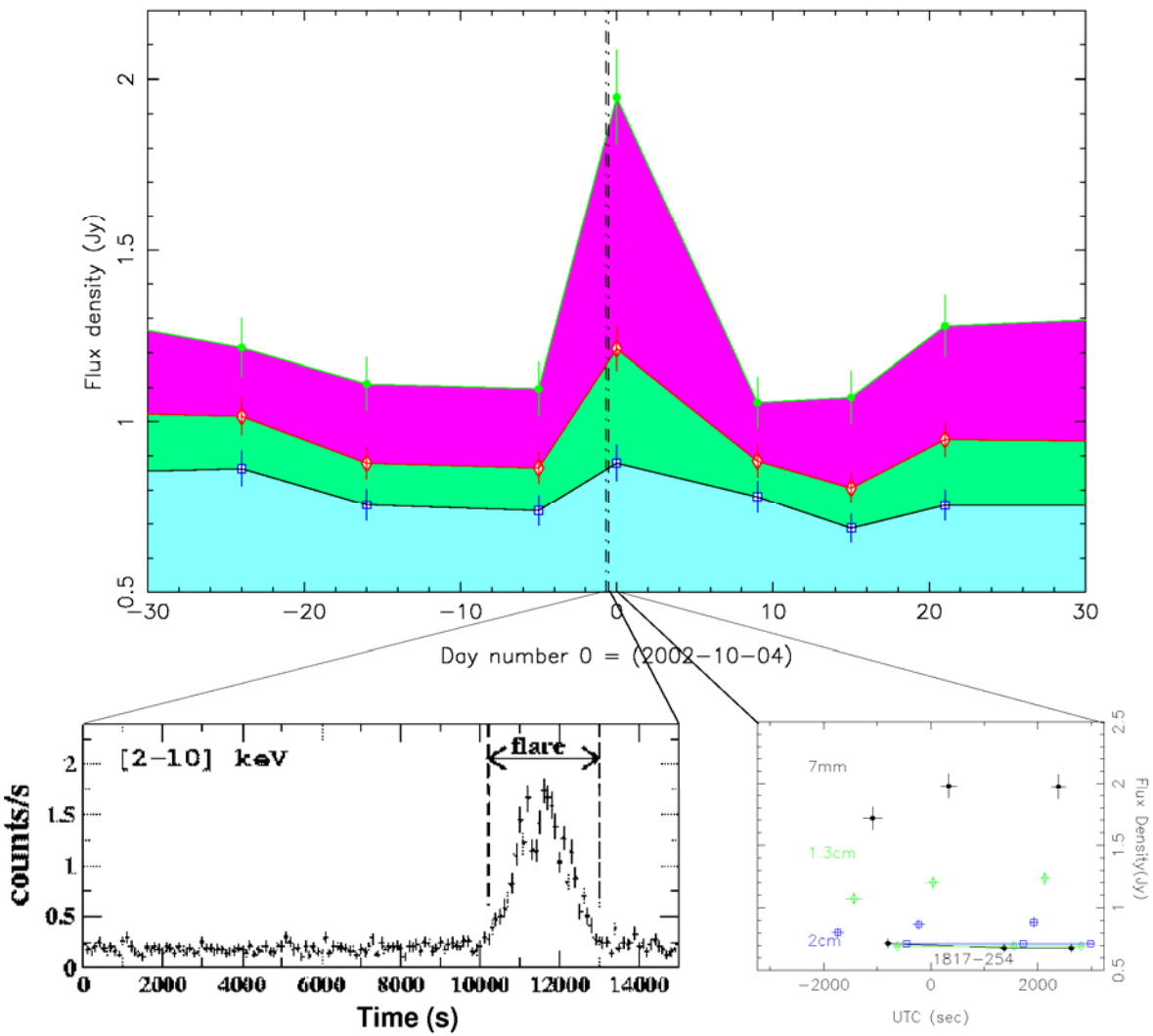
Thermal Synchrotron and SSC:
Four Parameters
B, $k_B T = \gamma_{cr} m_e c^2$, $\mathcal{N}$, $A \approx R^2$

$$\mathcal{L}_{\rm syn} = \frac{16 e^4}{3 m_e^2 c^3} \mathcal{N} B^2 \gamma_{cr}^2$$

$$= 2.0 \times 10^{36} \left(\frac{\mathcal{N}}{10^{43}} \right) \left(\frac{B}{40\,{\rm G}} \right)^2 \left(\frac{\gamma_{cr}}{100} \right)^2 {\rm ergs\ s^{-1}}$$

$$\mathcal{L}_{\rm SSC} = \frac{U_{\rm syn}}{U_B} \mathcal{L}_{\rm syn} \simeq \frac{8\pi \mathcal{L}_{\rm syn}^2}{cAB^2}$$

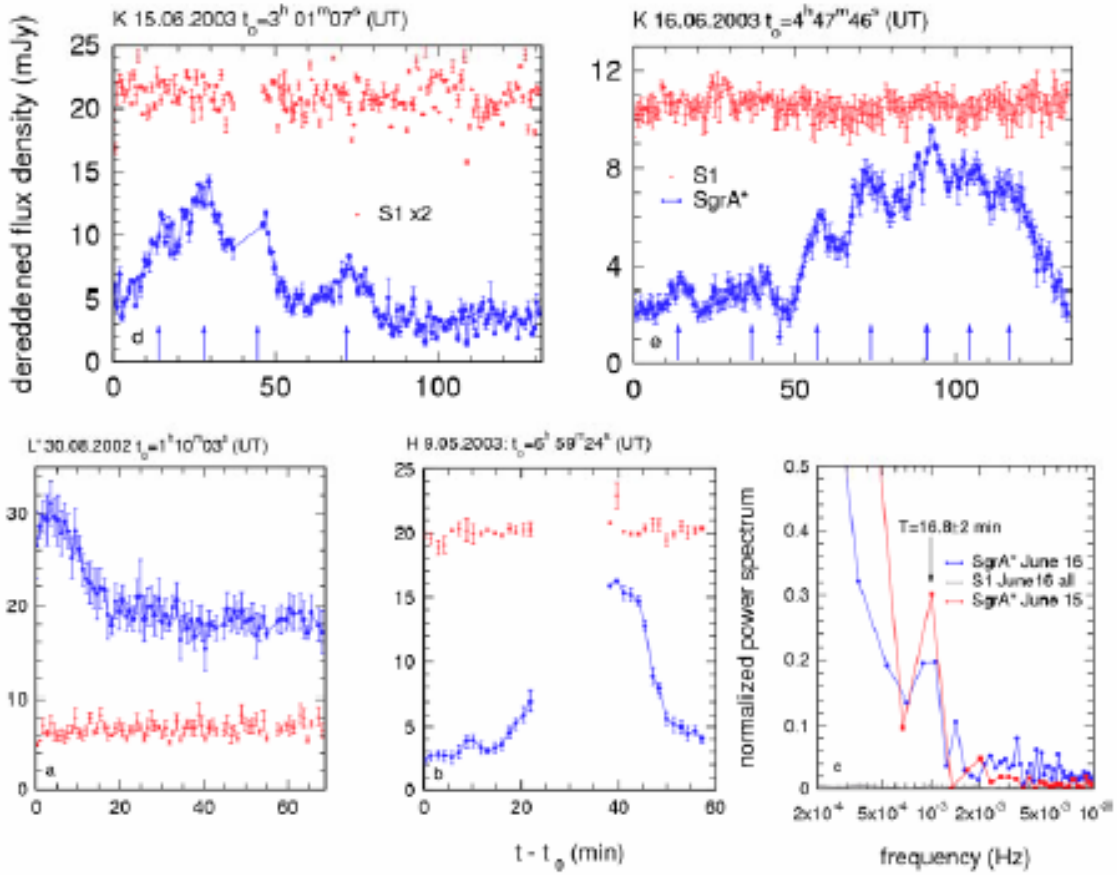
$$= 5.2 \times 10^{35} \left(\frac{\mathcal{L}_{\rm syn}}{10^{36}\,{\rm ergs\ s^{-1}}} \right)^2 \left(\frac{B}{40\,{\rm G}} \right)^{-2} \left(\frac{A}{r_S^2} \right)^{-1} {\rm ergs\ s^{-1}}$$



(From Borozdin et al. 2004)

NIR Flares From Sgr A*

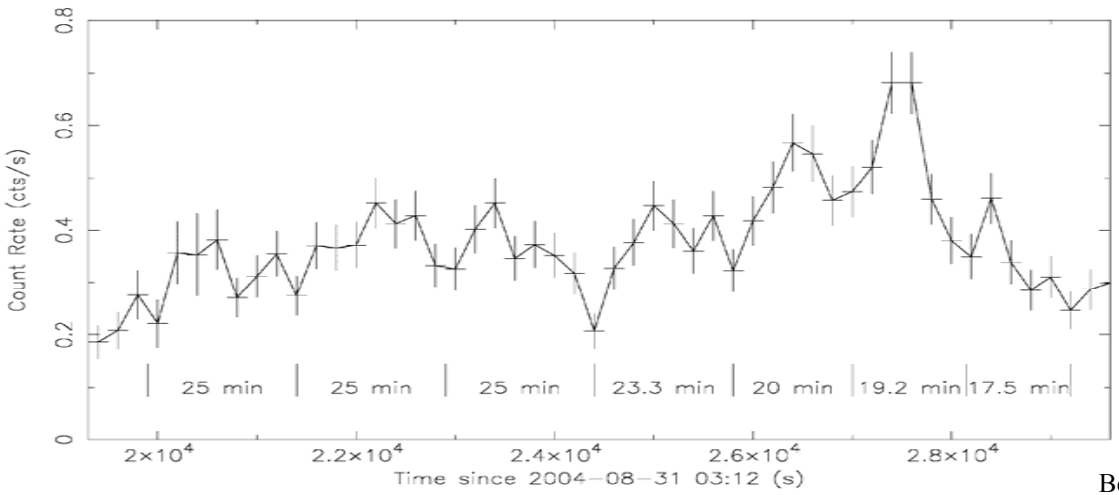
Quasi-periodic Modulation



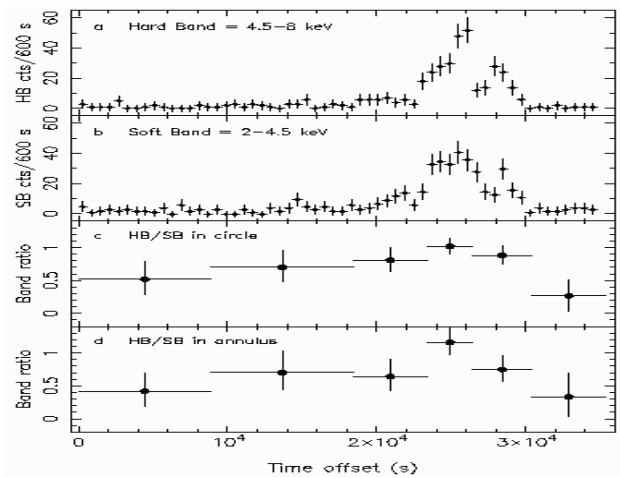
Genzel et al. 2003

X-Ray Flares From Sgr A*

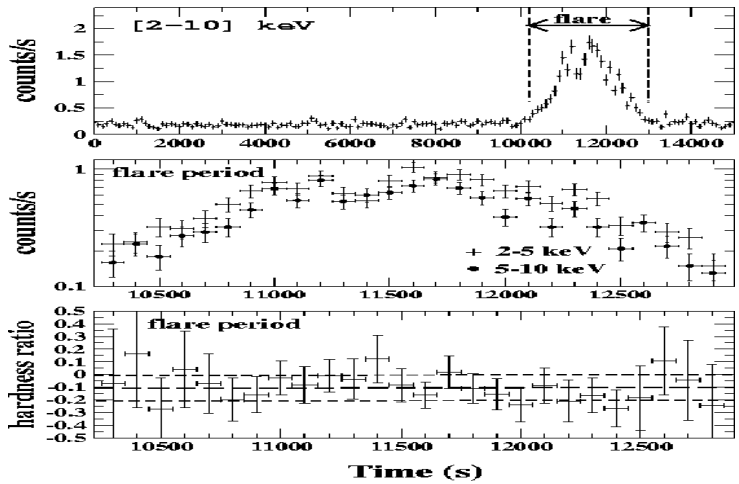
Quasi-periodic Modulation



Belanger et al. 2005



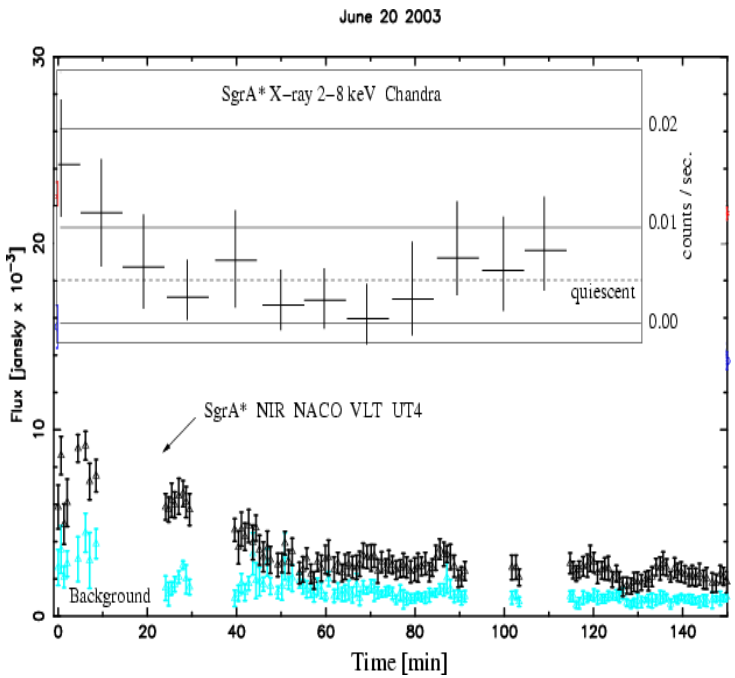
Baganoff et al. 2001

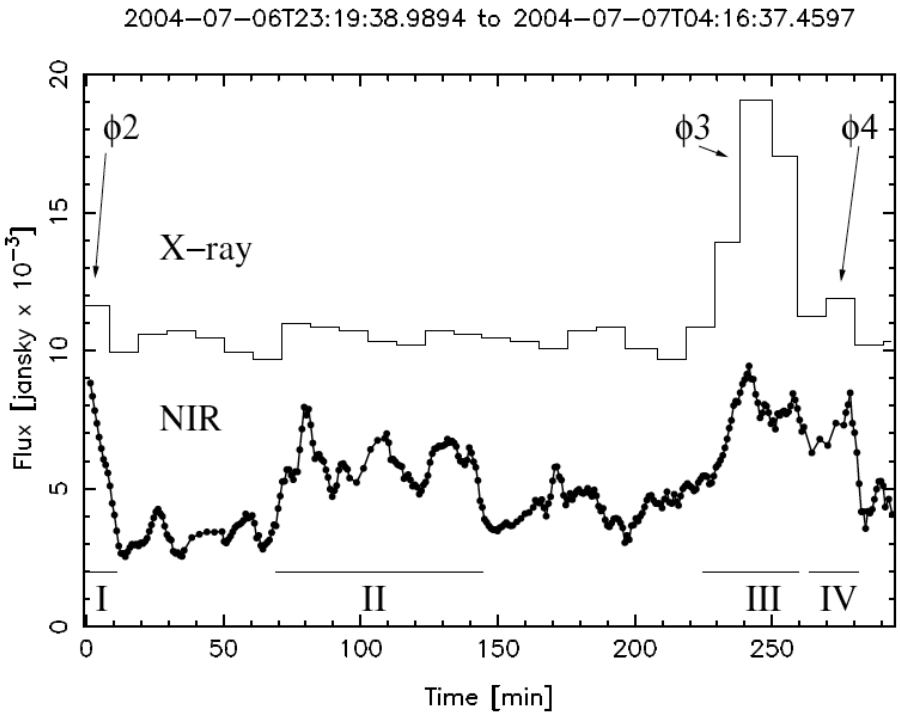


Porquet et al. 2003

Sgr A* 19-20 June 2003 – NIR/X-ray Flare

Eckart et al. (2004)



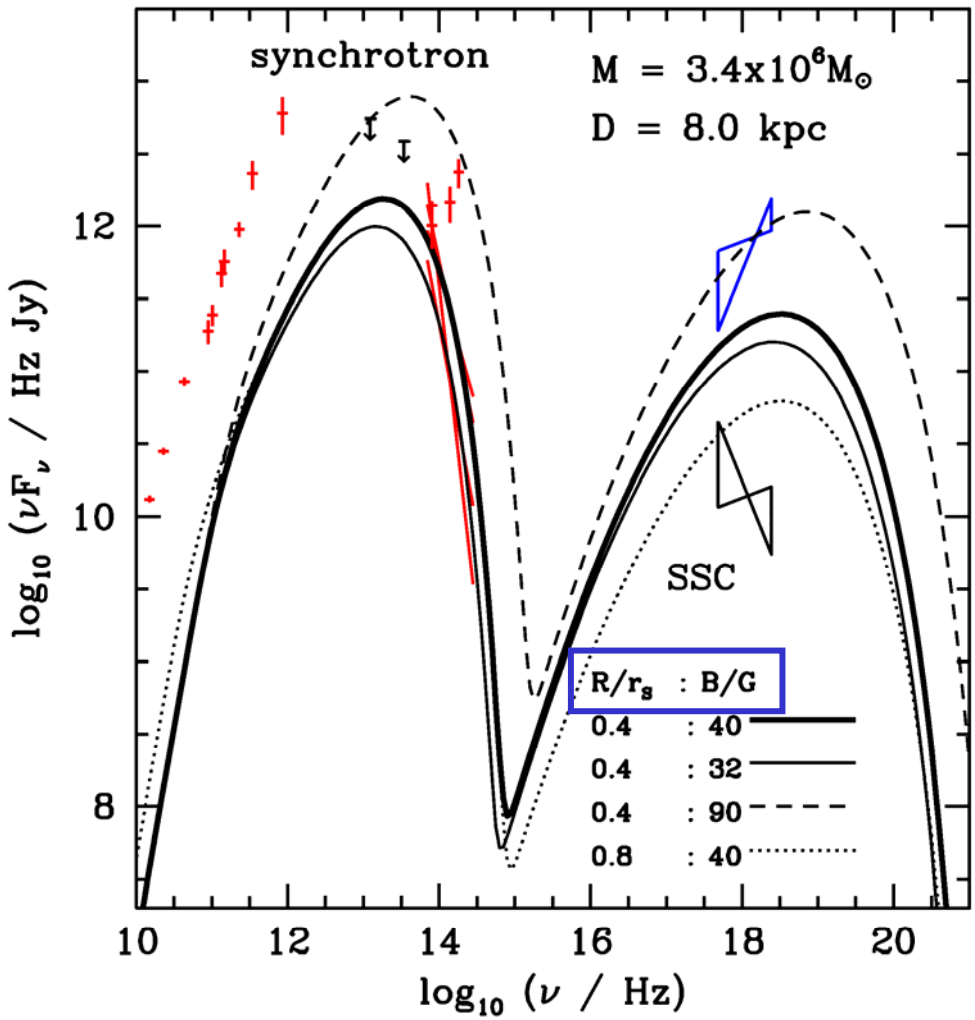


$L_x \sim 6 \times 10^{33}$ erg s^{-1}

$L_{nir} \sim 5 \times 10^{34}$ erg s^{-1}

Baganoff 2005

Emission Processes During Flares

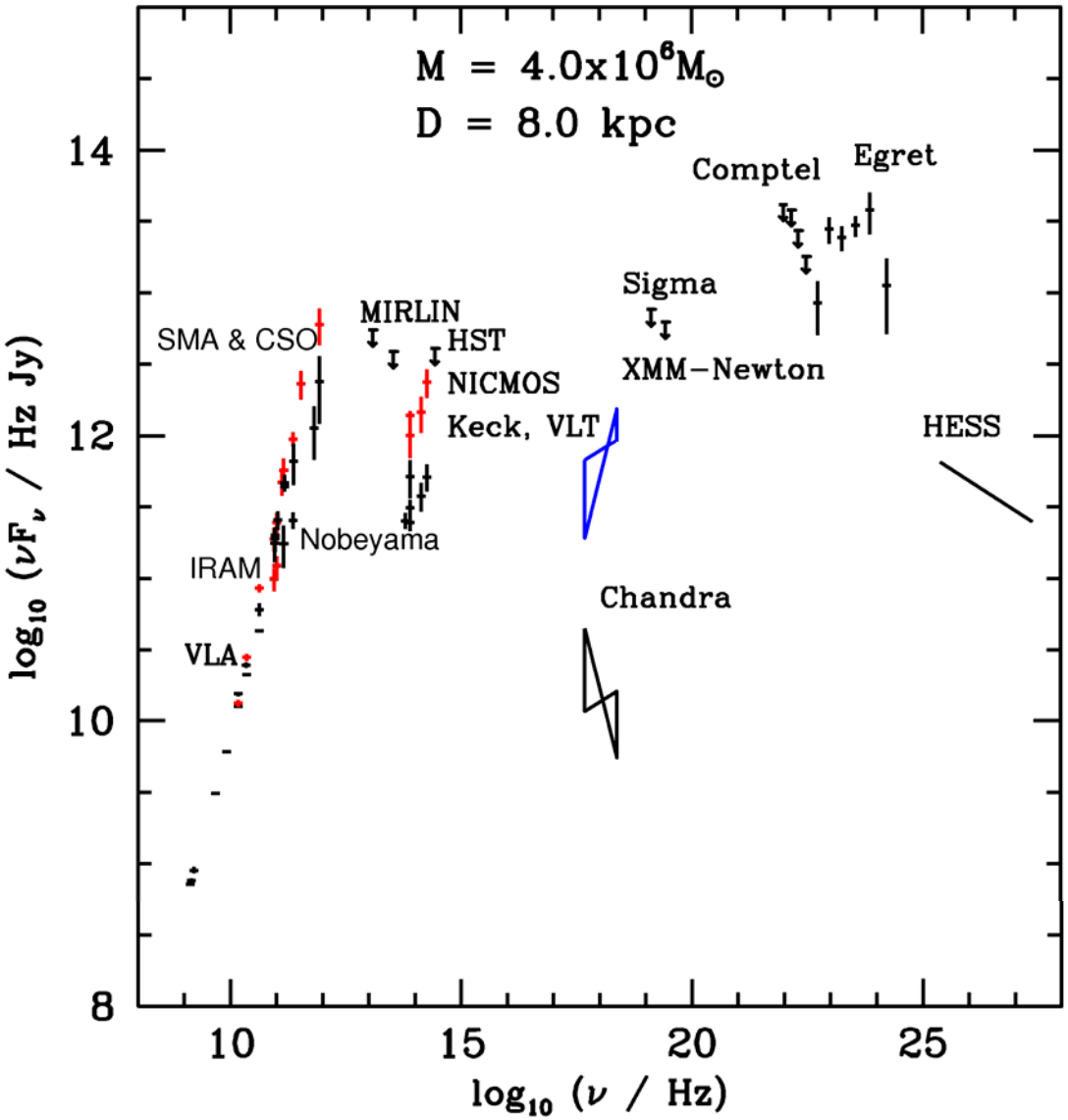


Thermal Synchrotron and SSC: Four Parameters

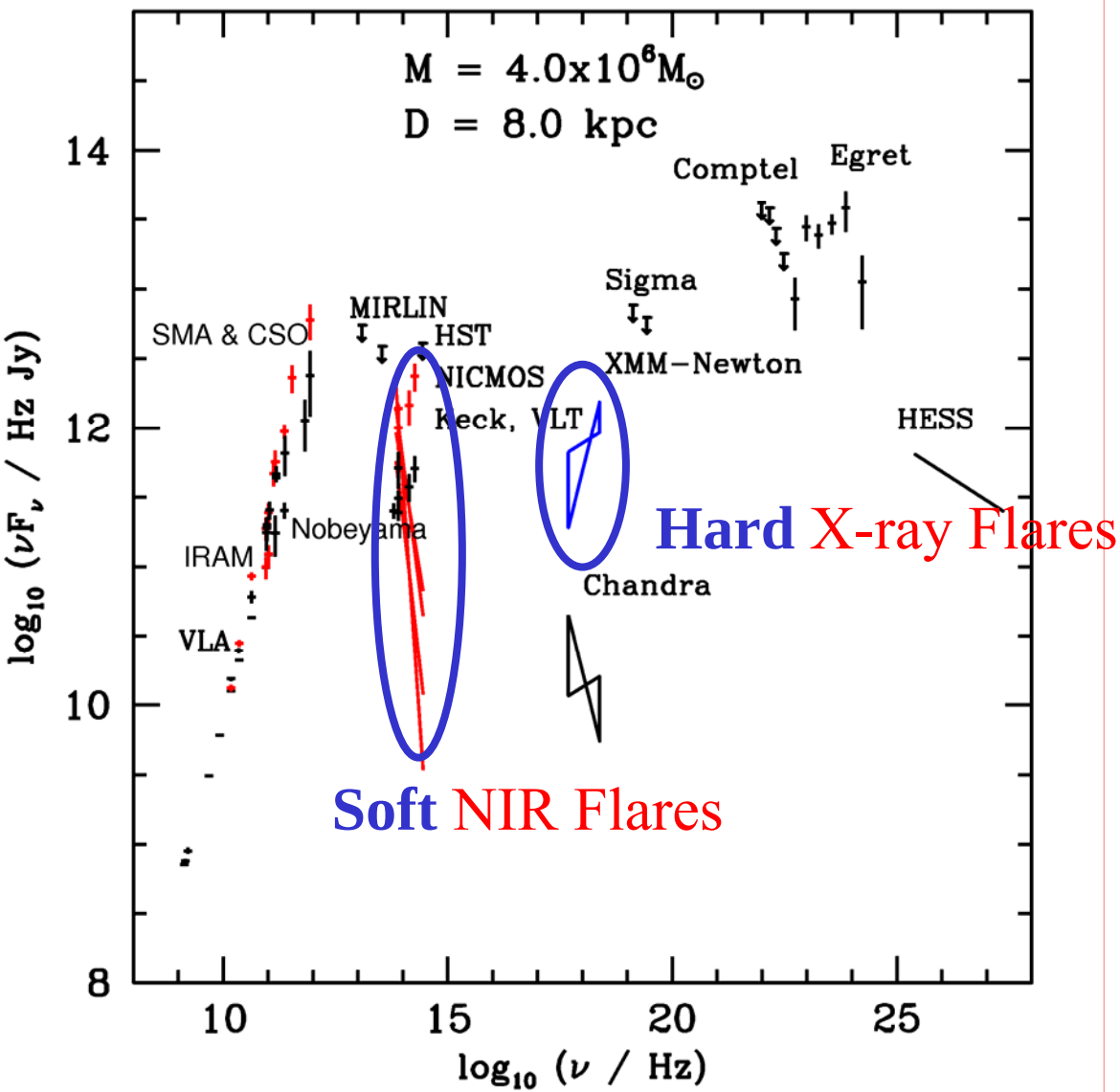
$\mathcal{N}$=3.8x10^{42}

$k_B T = 75 m_e c^2$

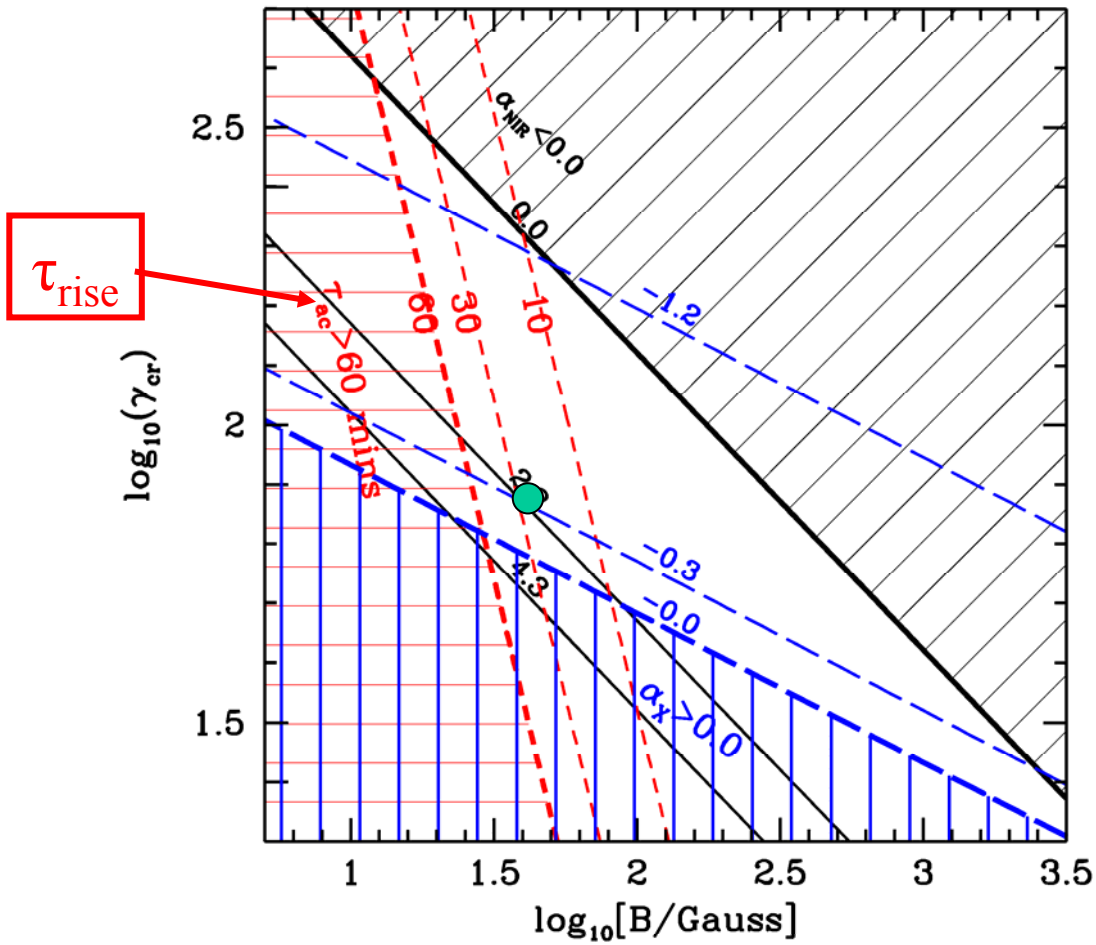
Emission Spectra



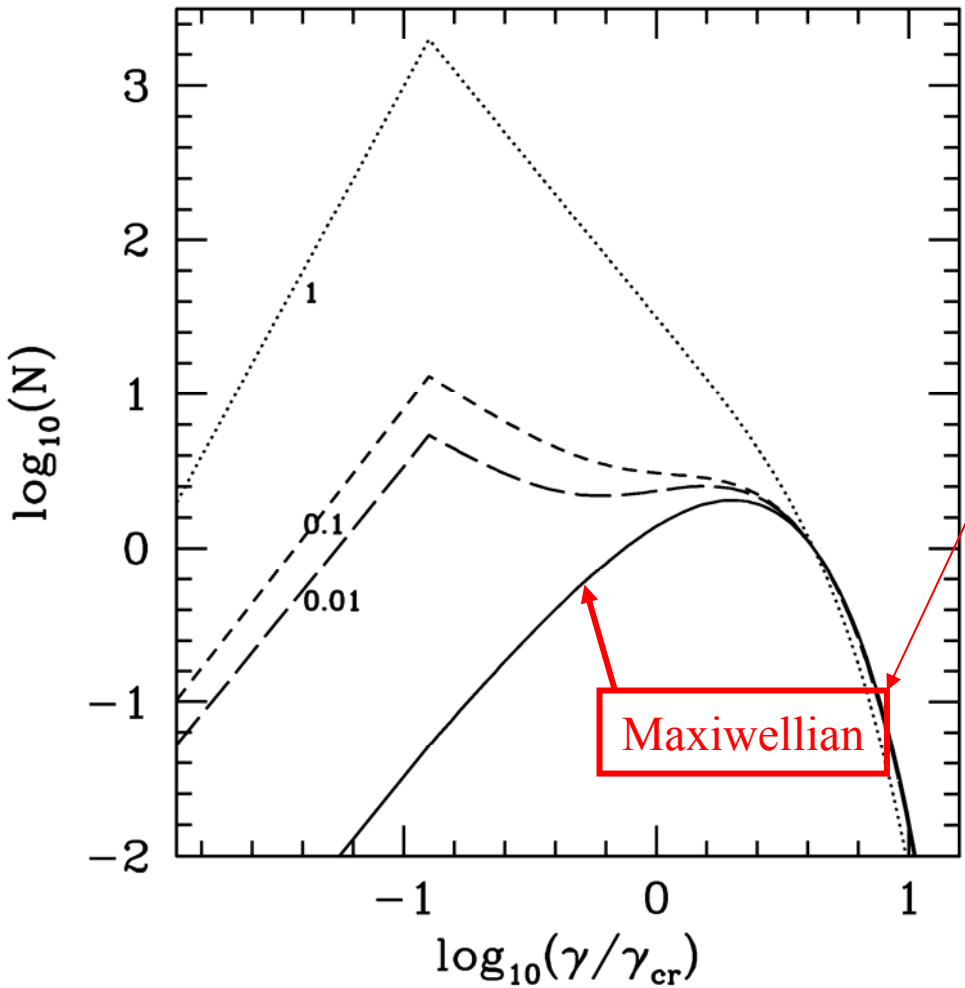
Emission Spectra



Constraining T & B with NIR and X-ray Spectra and flare rise time

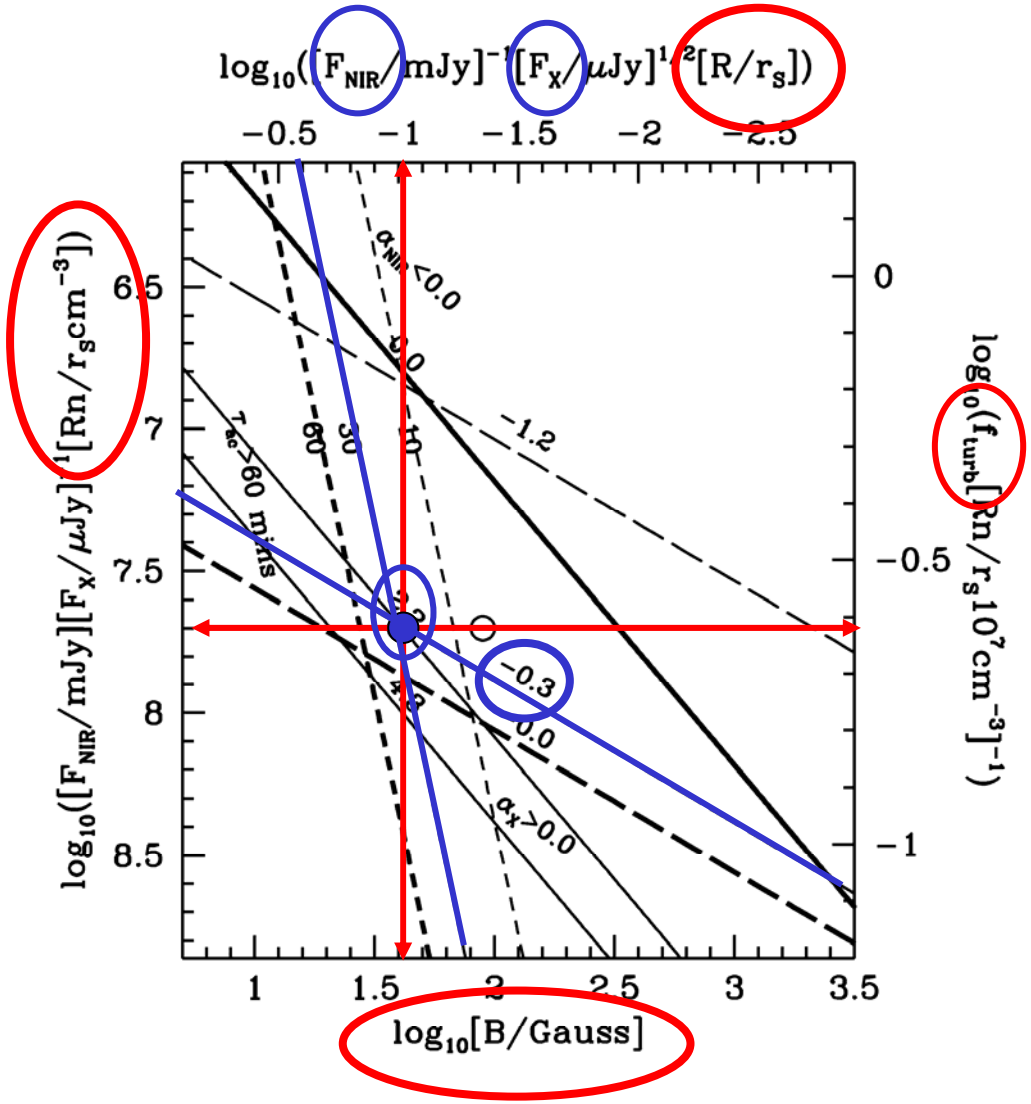


Stochastic Electron Acceleration



Determining the Plasma Properties

Observations

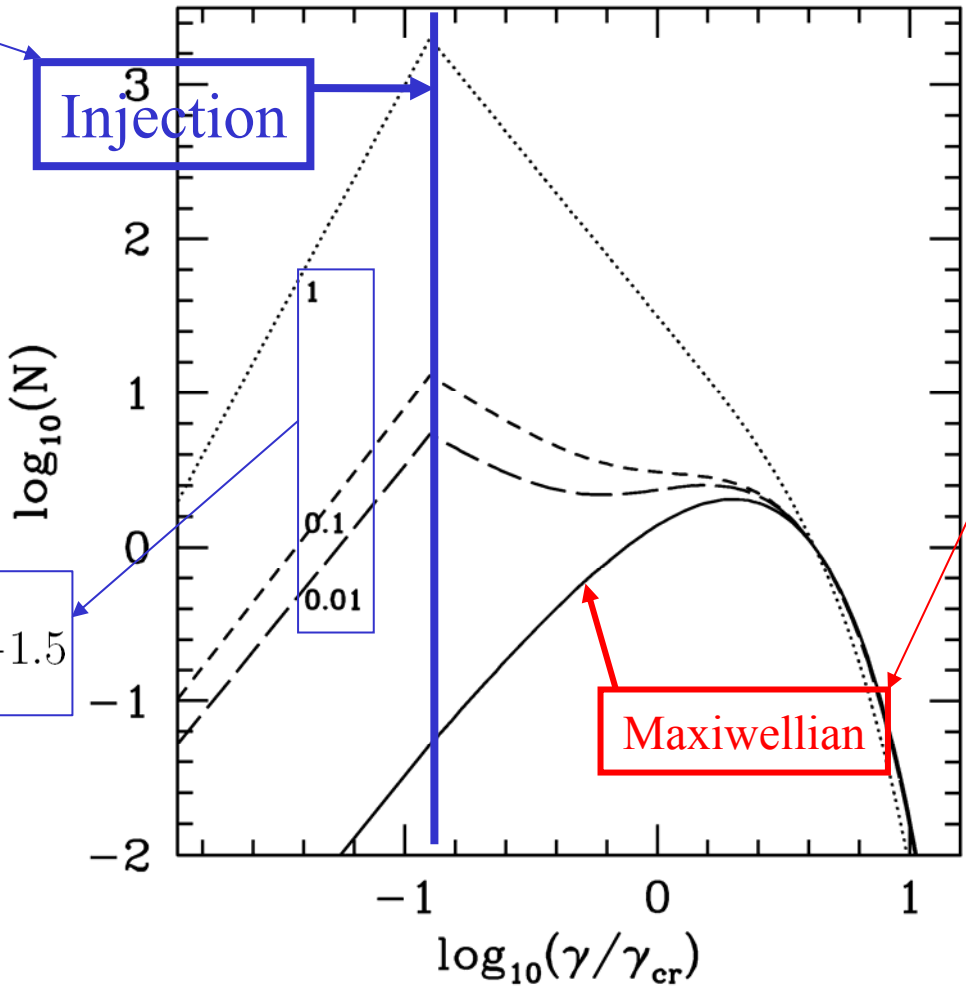


B, R, n, f_{turb}

Stochastic Electron Acceleration

Continuous injection, heating, & cooling.

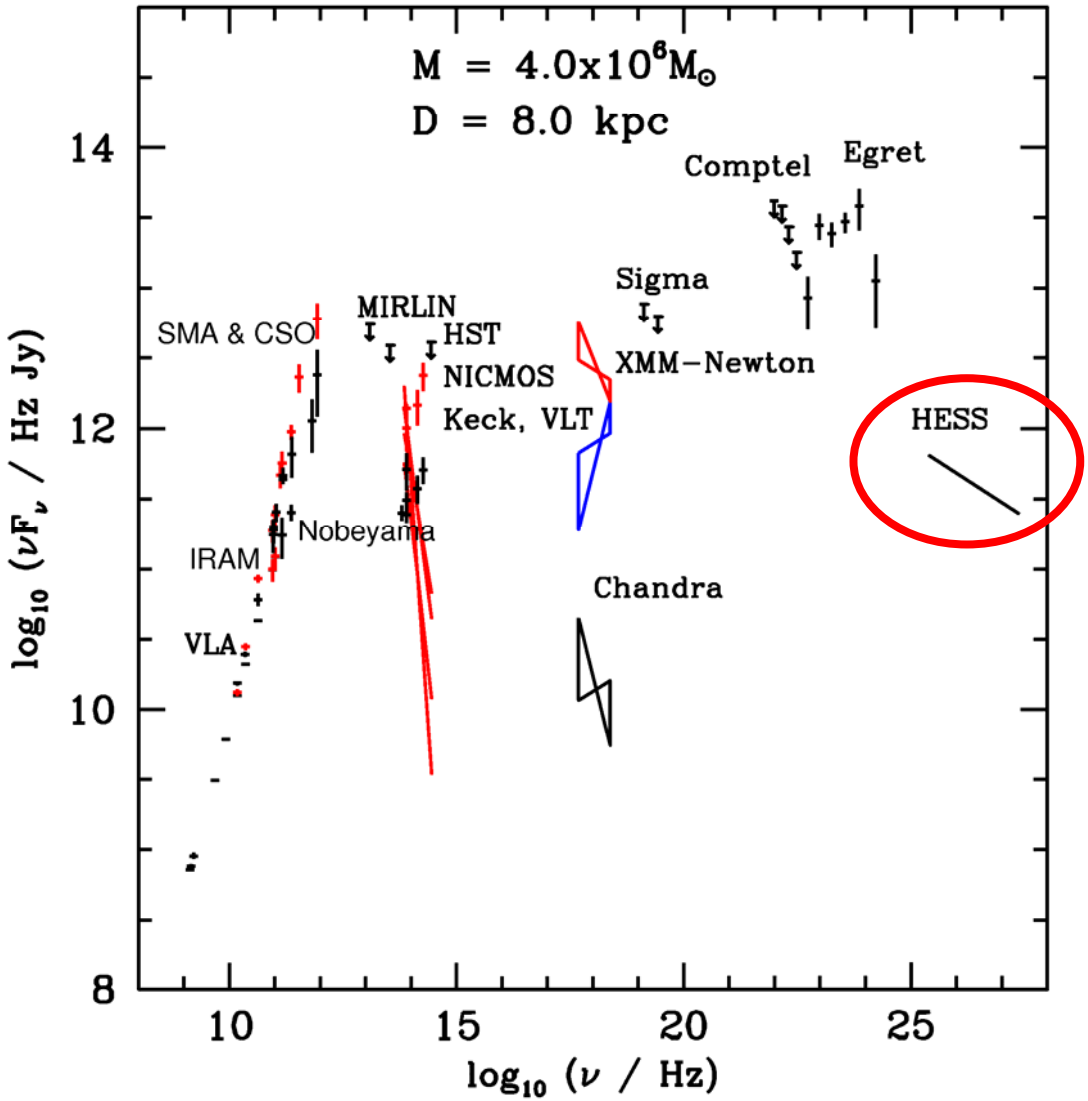
Injection



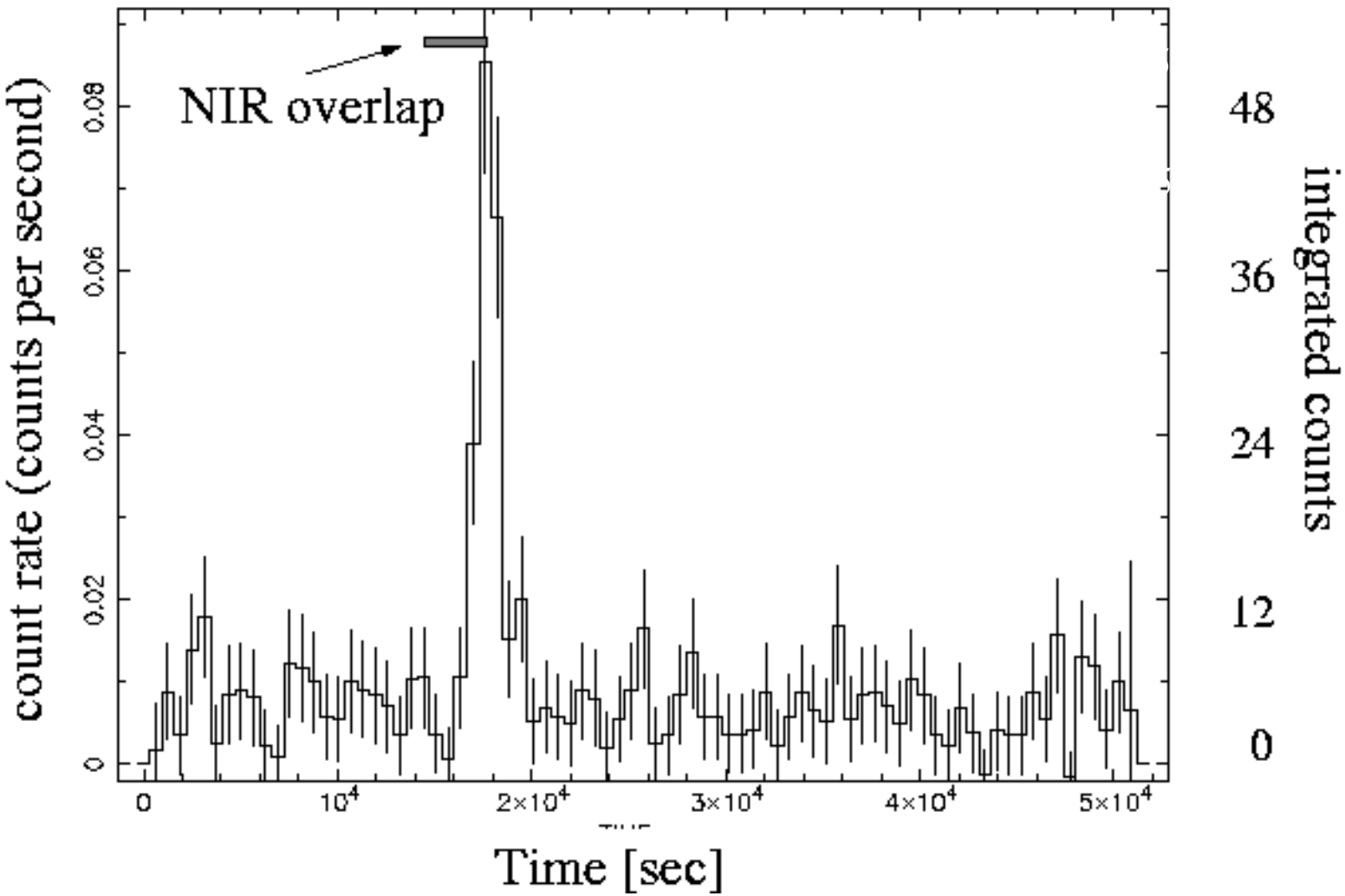
$$\delta = \left(\frac{9}{4} + \frac{2\tau_{ac}}{T_{esc}}\right)^{1/2} - 1.5$$

Without injection: Continuous heating and cooling

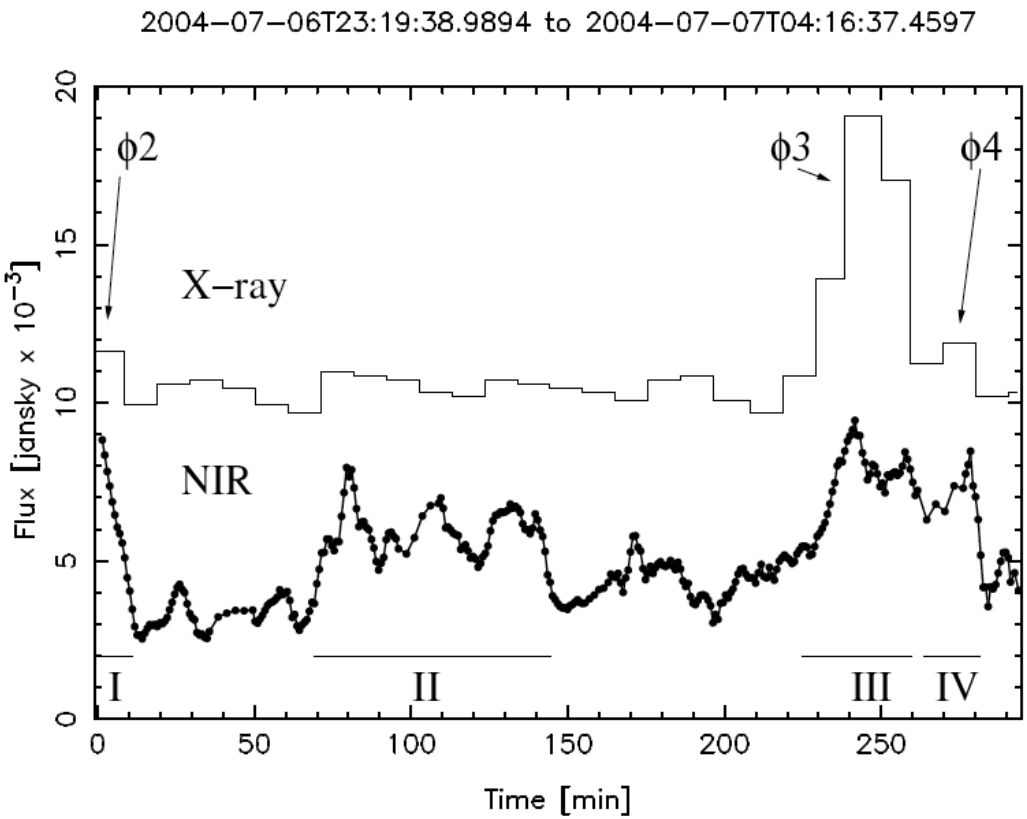
HESS Source


M = 4.0x10^6 M⊙
D = 8.0 kpc
Comptel
Egret
Sigma
MIRLIN
SMA & CSO
HST
NICMOS
Keck, VLT
XMM−Newton
HESS
Nobeyama
IRAM
VLA
Chandra
log10 (νFν / Hz Jy)
log10 (ν / Hz)
14
12
10
8
10
15
20
25

July 2004: Detection of a Strong X-ray flare

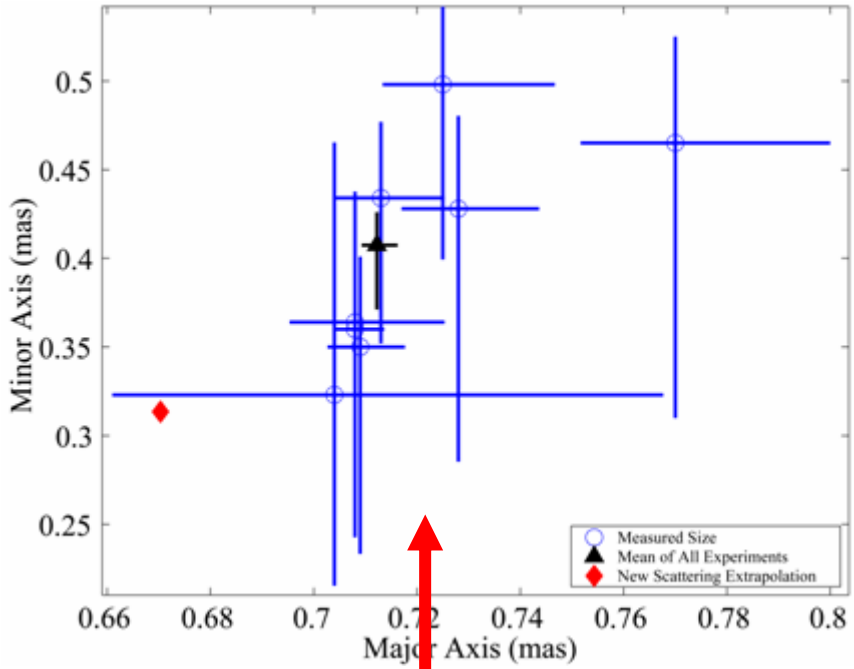


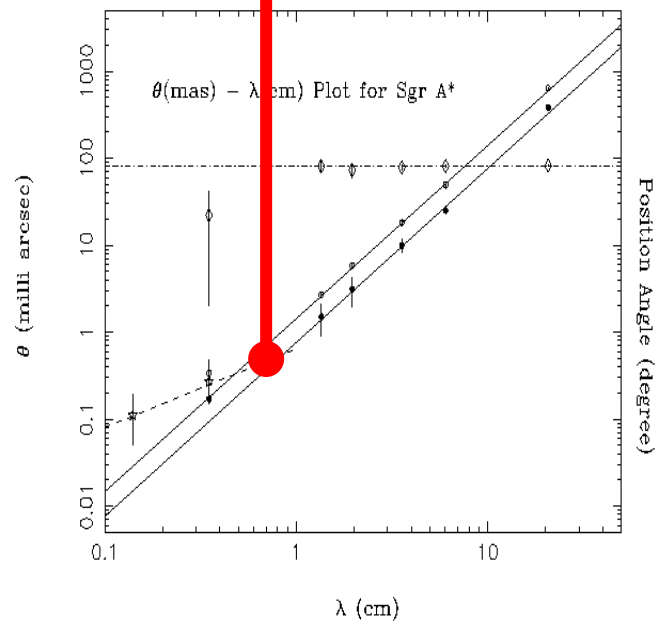
Comparison of X-ray and NIR Lightcurves



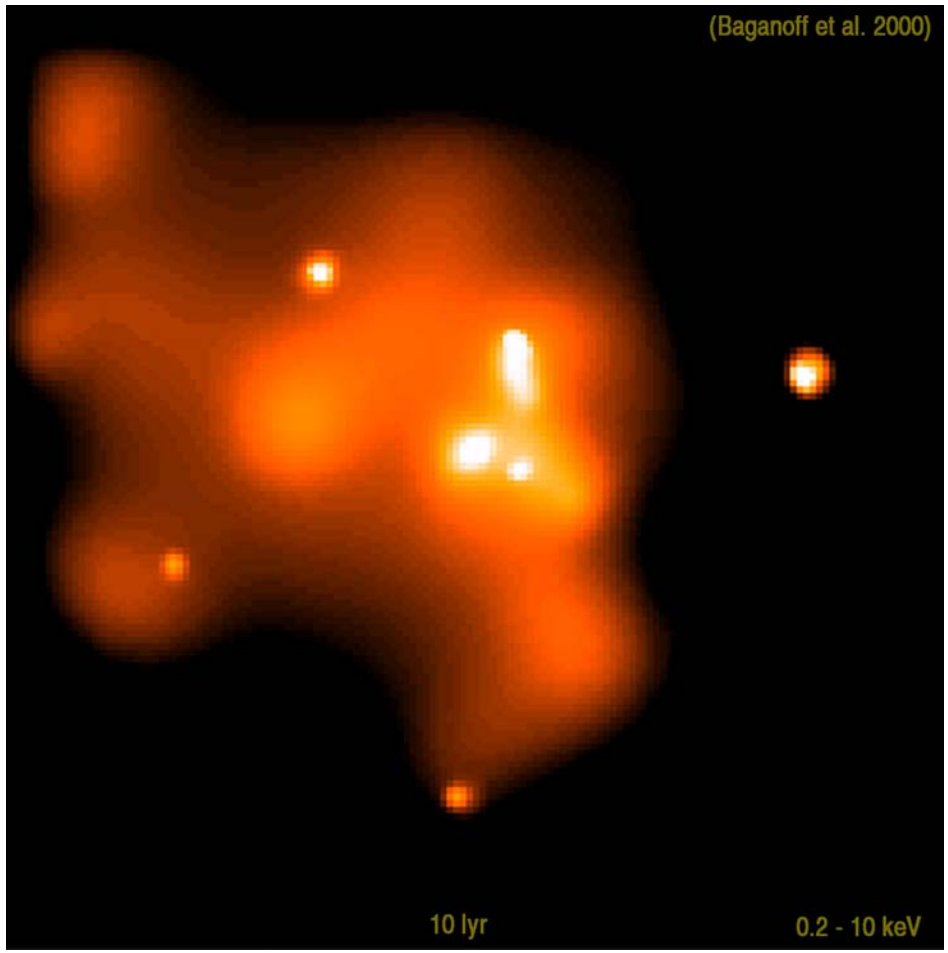
- At least four separate NIR flares were detected at K-band by the VLT with NAOS/CONICA on 2004 July 6/7.
- NIR flare III is correlated with the strong X-ray flare.
- NIR flare I is associated with the possible X-ray event at the beginning of the observations, but the ratio of X-ray to NIR amplitudes is clearly different.
- Additional strong NIR flares (II and IV) have no detected X-ray counterparts.

Baganoff 2005


Minor Axis (mas)
Major Axis (mas)
0.5
0.45
0.4
0.35
0.3
0.25
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
Measured Size
Mean of All Experiments
New Scattering Extrapolation

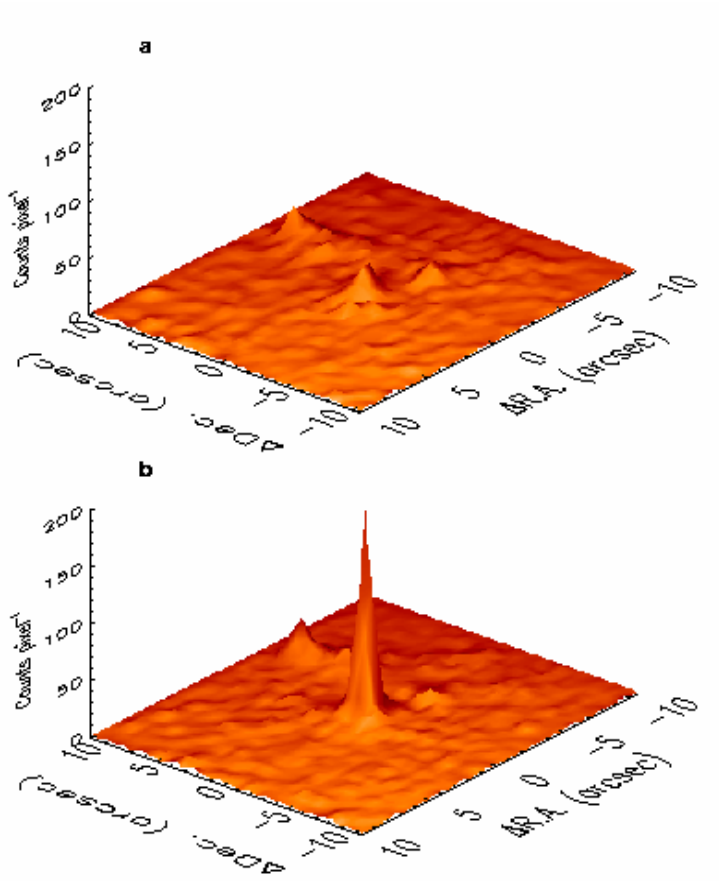

θ(mas) – λ(cm) Plot for Sgr A*
θ (milli arcsec)
λ (cm)
Position Angle (degree)
0.01
0.1
1
10
100
1000
0.1
1
10

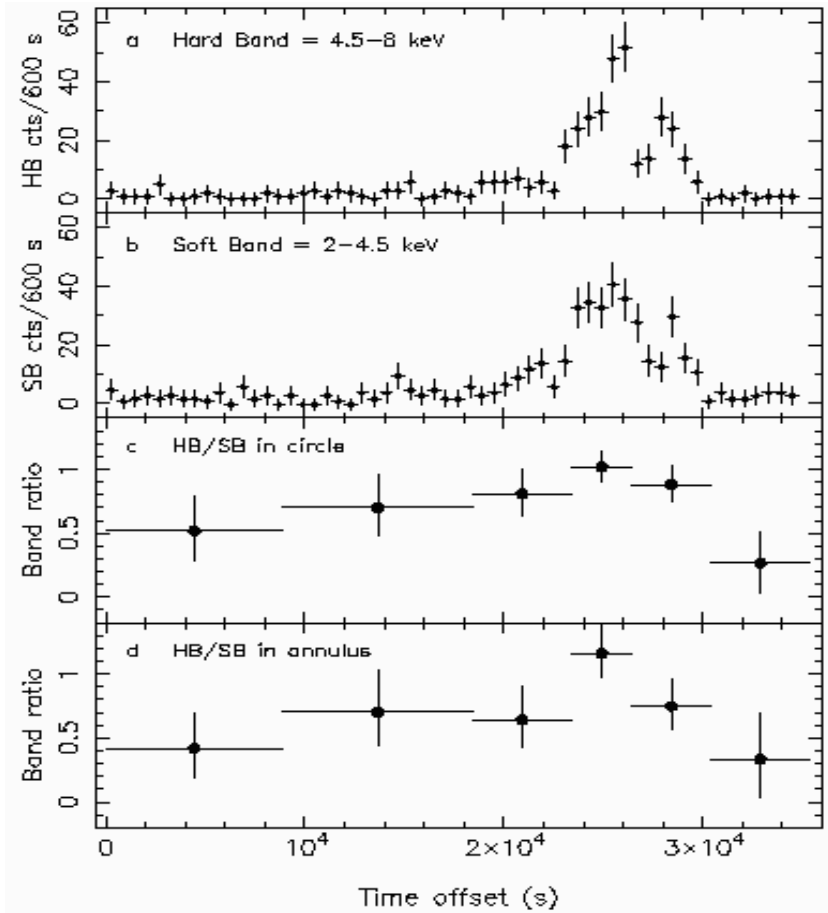
X-ray image of Sgr A*



X-ray Flares from Sgr A*

(Baganoff et al. 2001)





In flare-state, Sgr A*'s X-ray luminosity can increase by more than one order of magnitude.

The X-ray flare lasted for a few hours. Significant variation in flux was seen over a 10 minute interval.

Ghez et al. (2003)