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

Siming Liu
Physics Department, Stanford University
Vahé Petrosian
Dept. of Physics and Applied Physics, Stanford University
Fulvio Melia
Dept. of Physics, University of Arizona

GLAST Sym. Sep.1 2005

Outline

Observations of Sgr A*

Evidence for Electron Acceleration

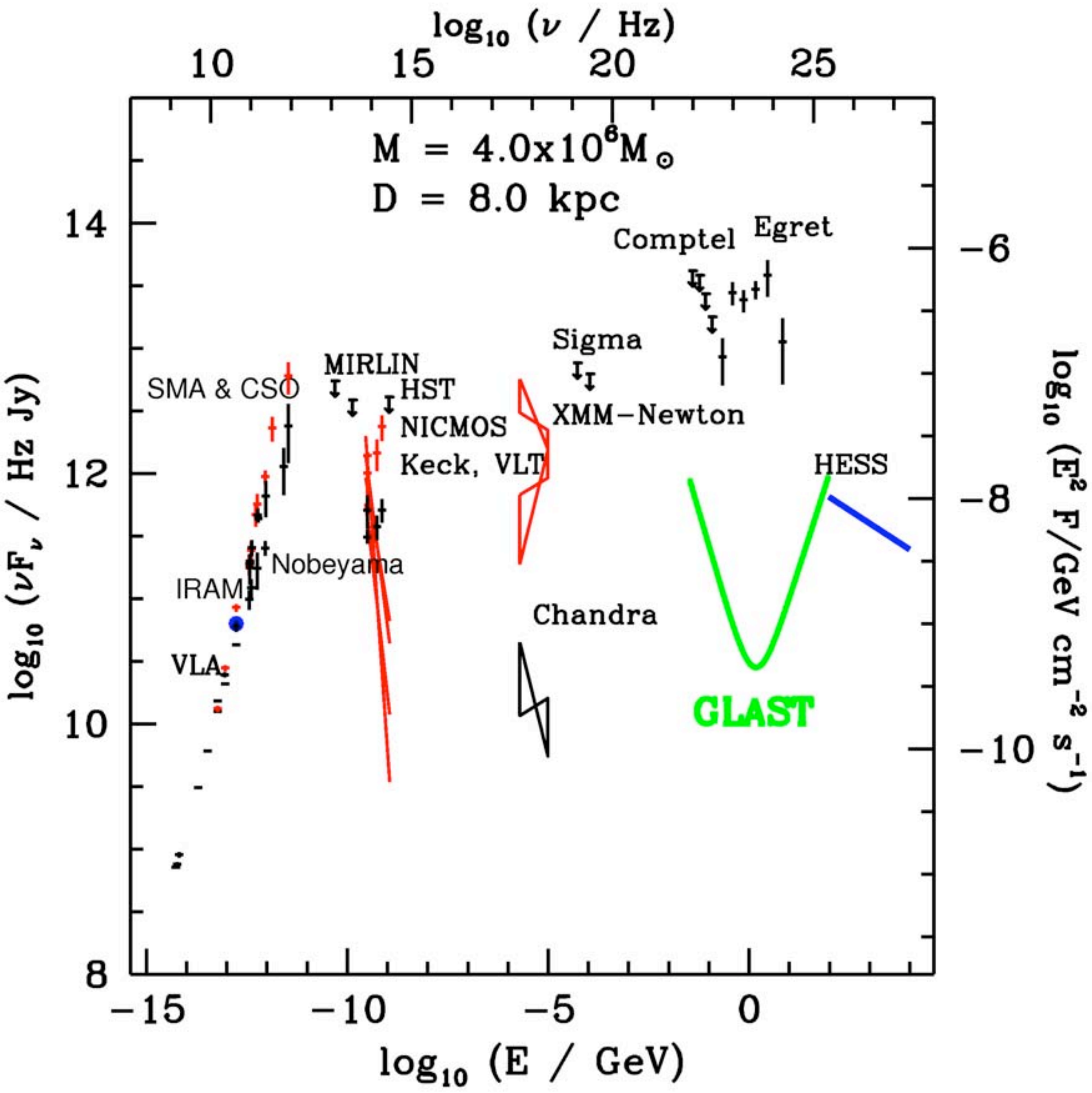
A: radio emission
B: NIR and X-ray flares.

Evidence for Proton Acceleration

Stochastic Acceleration by Plasma Waves

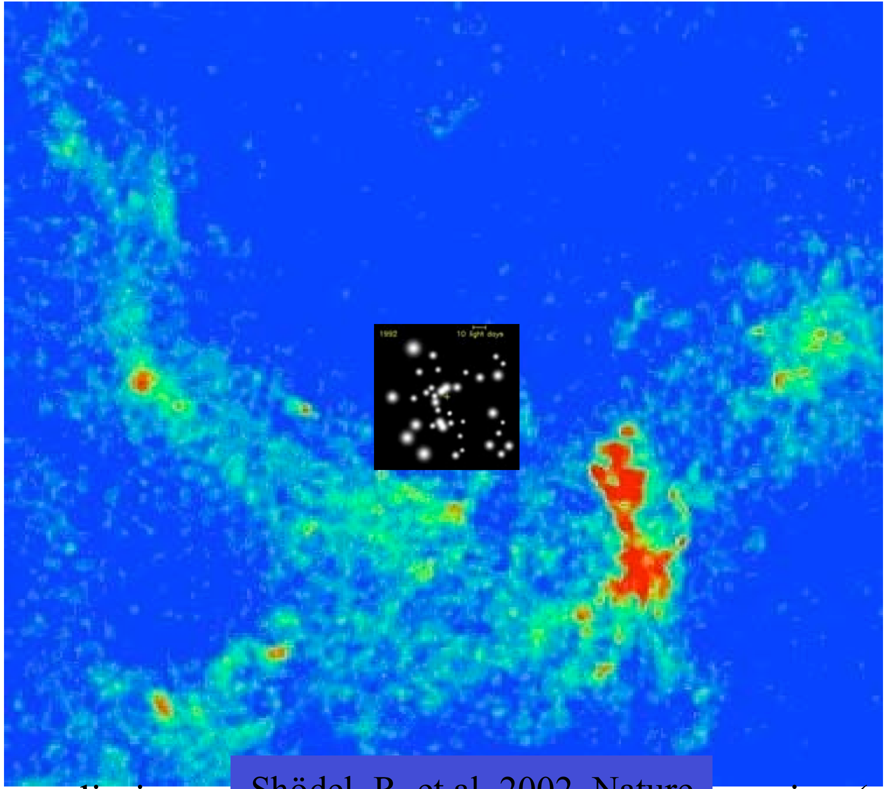
Structure of the Accretion Flow in Sgr A*

Broadband Spectrum



VLA

Zhao et al. 1991, Nature, 354, 46

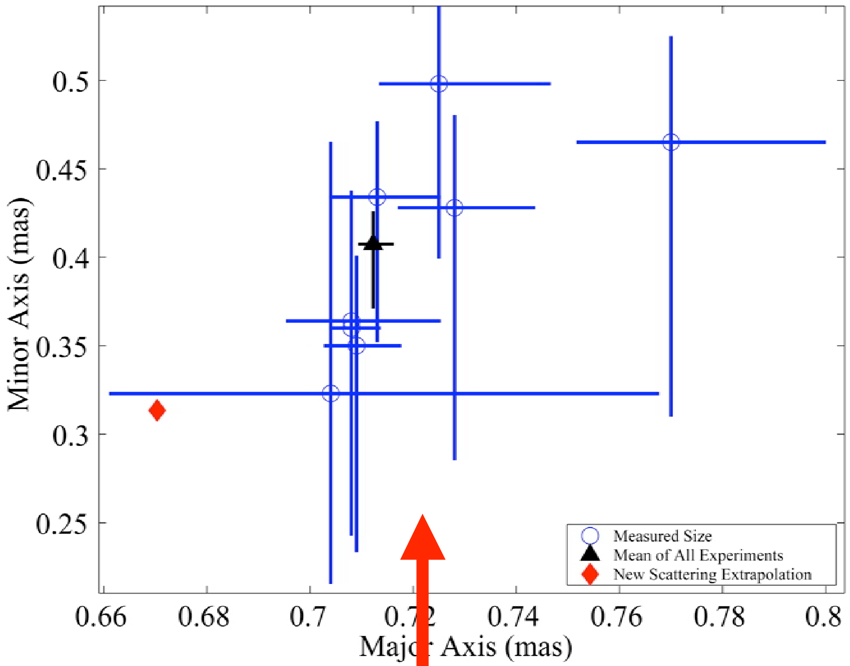


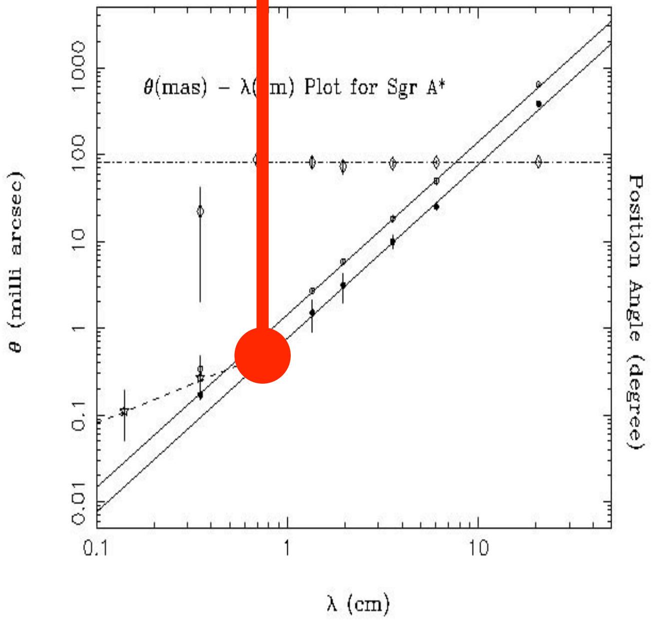
Shödel, R. et al. 2002, Nature

2 cm radio image

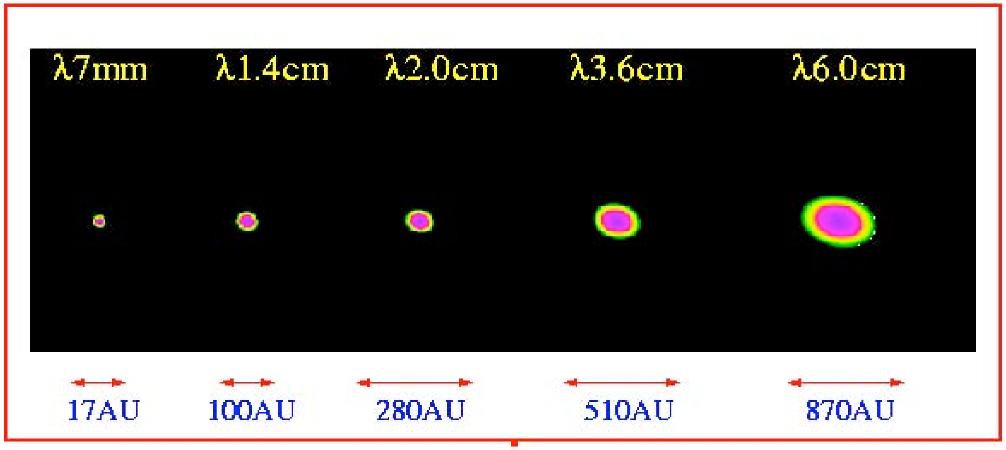
r region (~20”).

Bower et al. 2004, Science, 304, 704



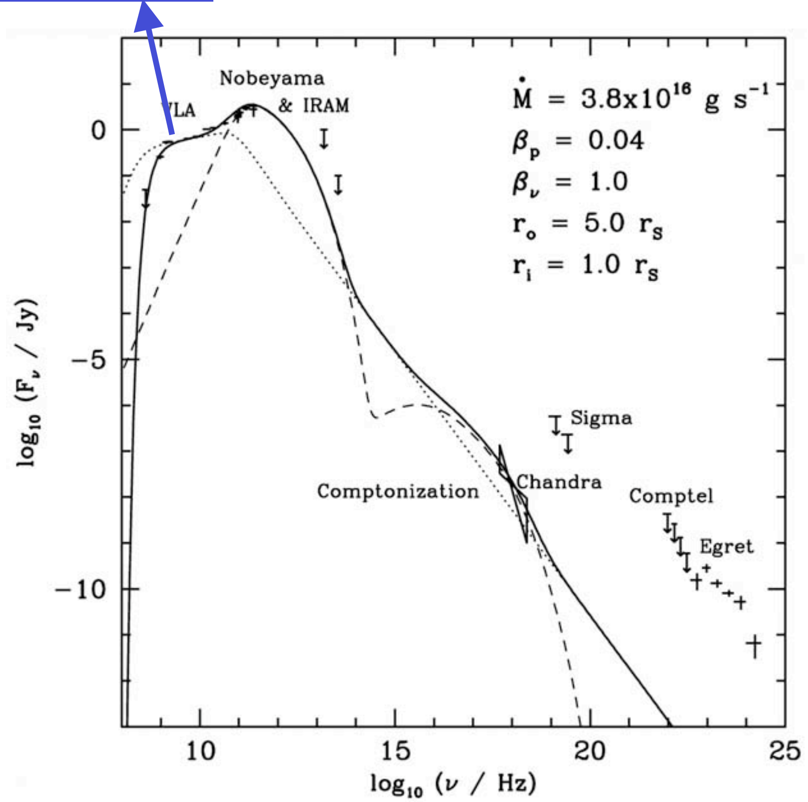


Lo et al. 1998, ApJ, 508, 61

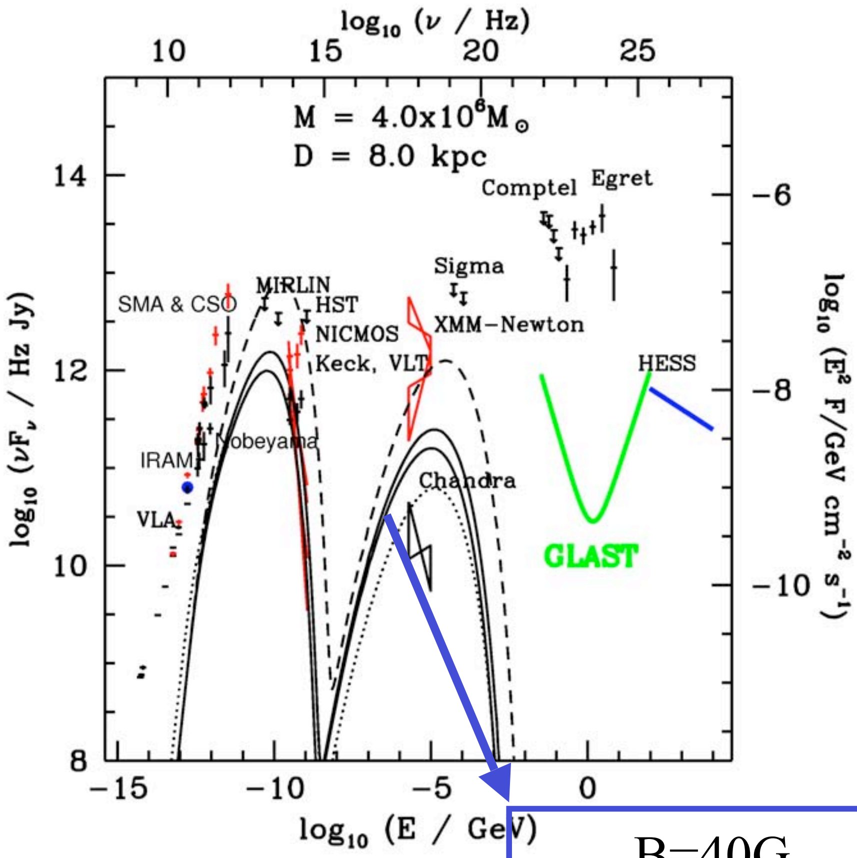


Evidence for Energetic Electrons

Nonthermal



Liu and Melia 2001, ApJ, 561, 77



Liu et al. 2005, ApJ

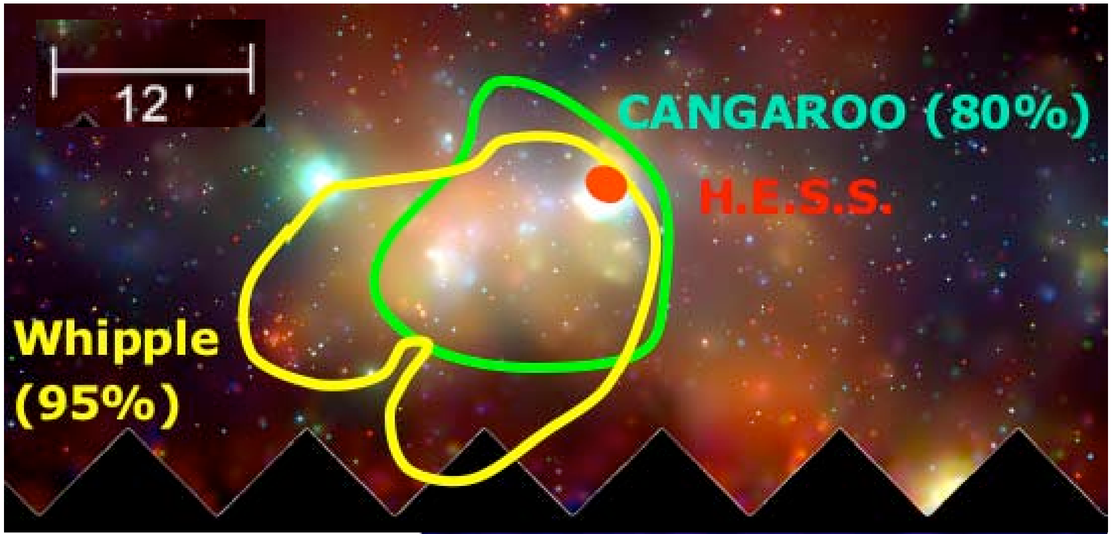
B=40G

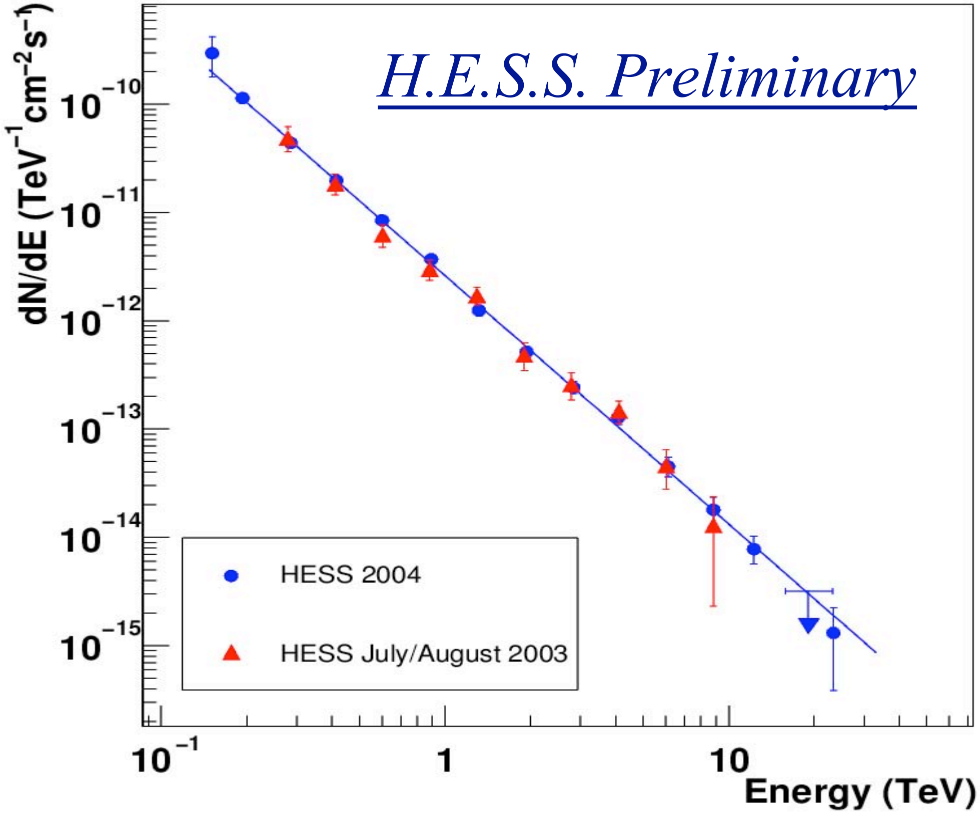
$k_BT=75m_ec^2$

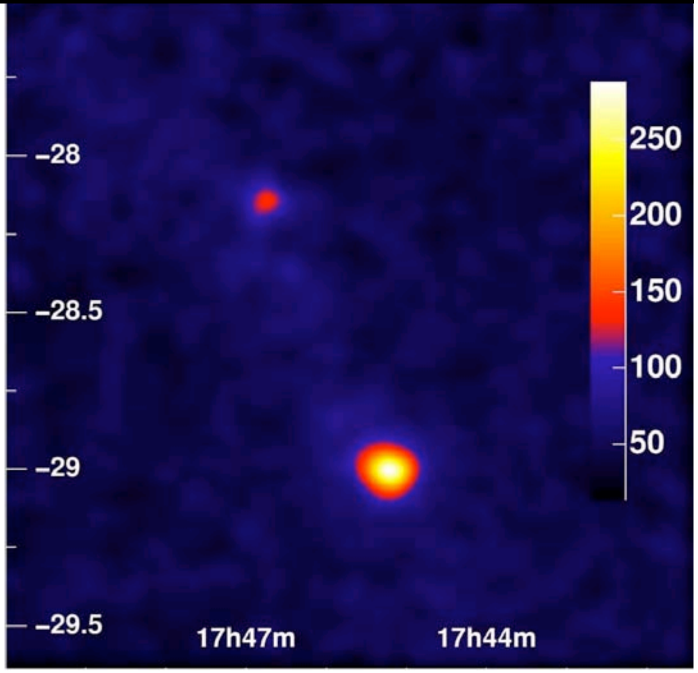
R=0.4 r_s

N=3.8x10^{42}

HESS



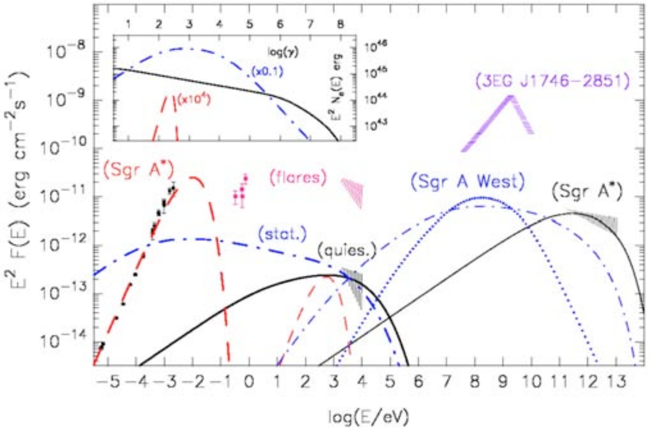




HESS Collaboration 2004

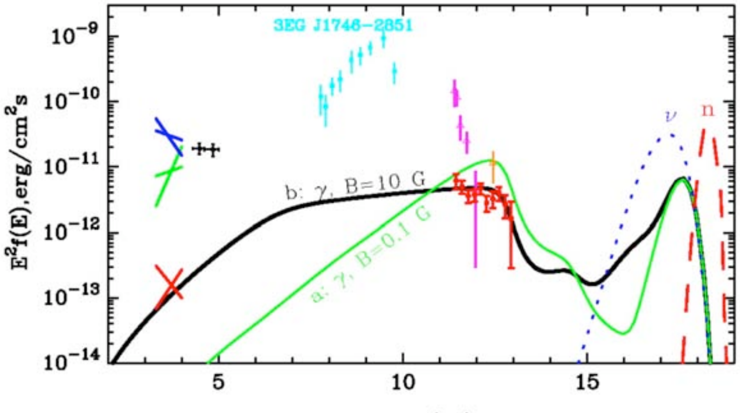
Possible Explanations

Synchrotron Self-Comptonination



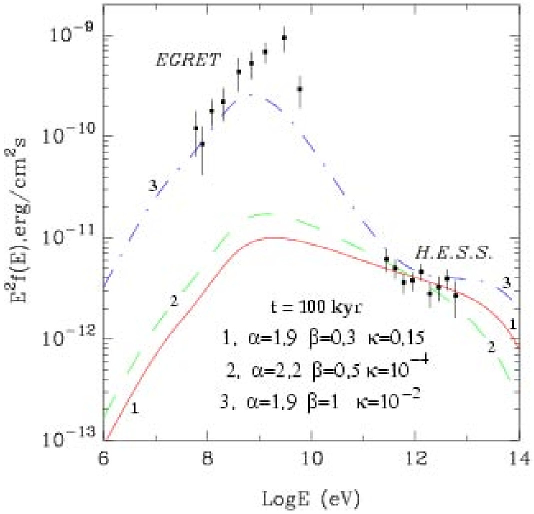
Atoyan and Dermer 2004, ApJ, 617, 123

Photo-Meson Interactions



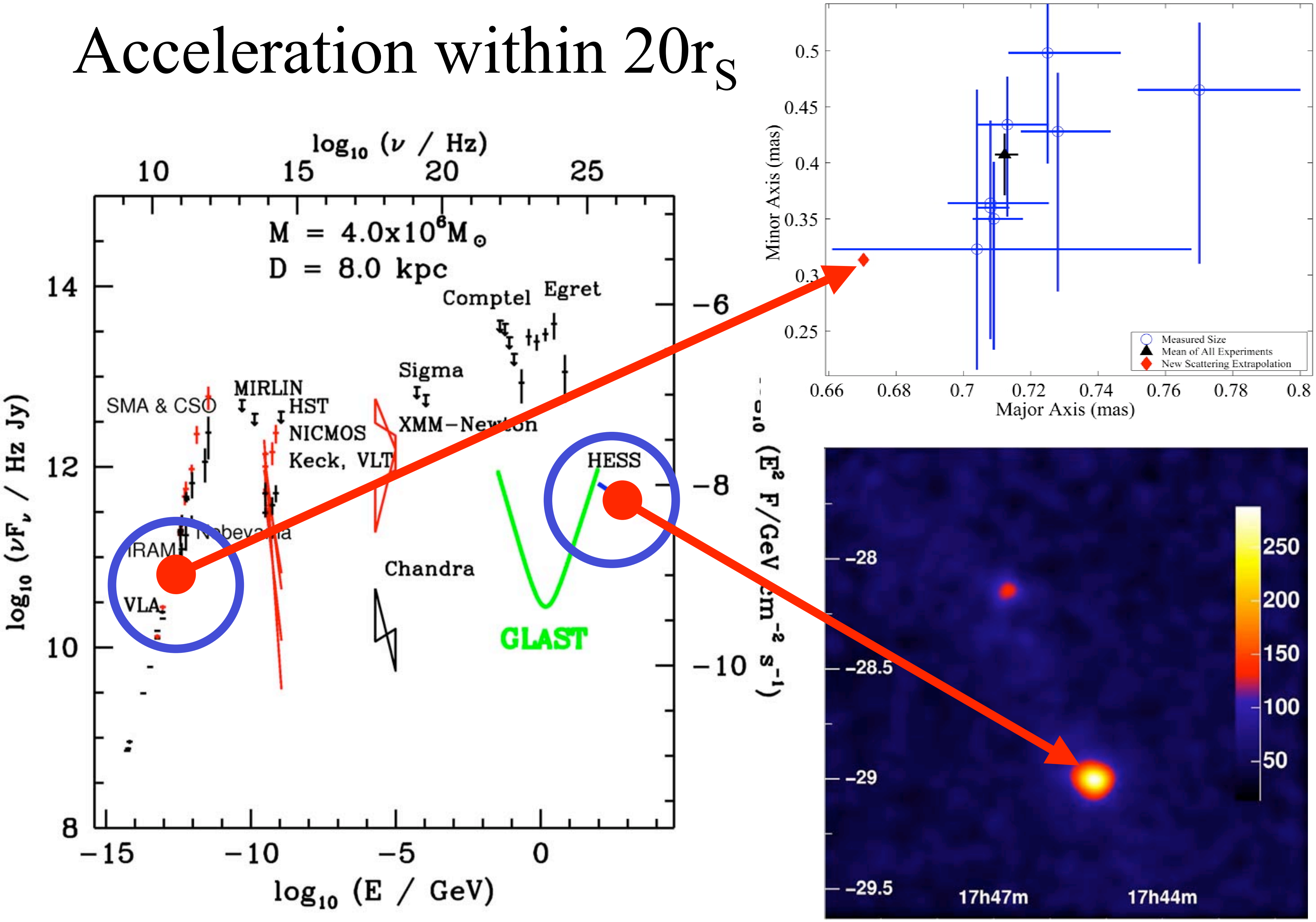
Aharonian et al 2005, ApJ, 619, 306

Proton-Proton Interactions



Aharonian et al 2005, ApJ, 619, 306

Acceleration within 20r$_S$



Stochastic Particle Acceleration

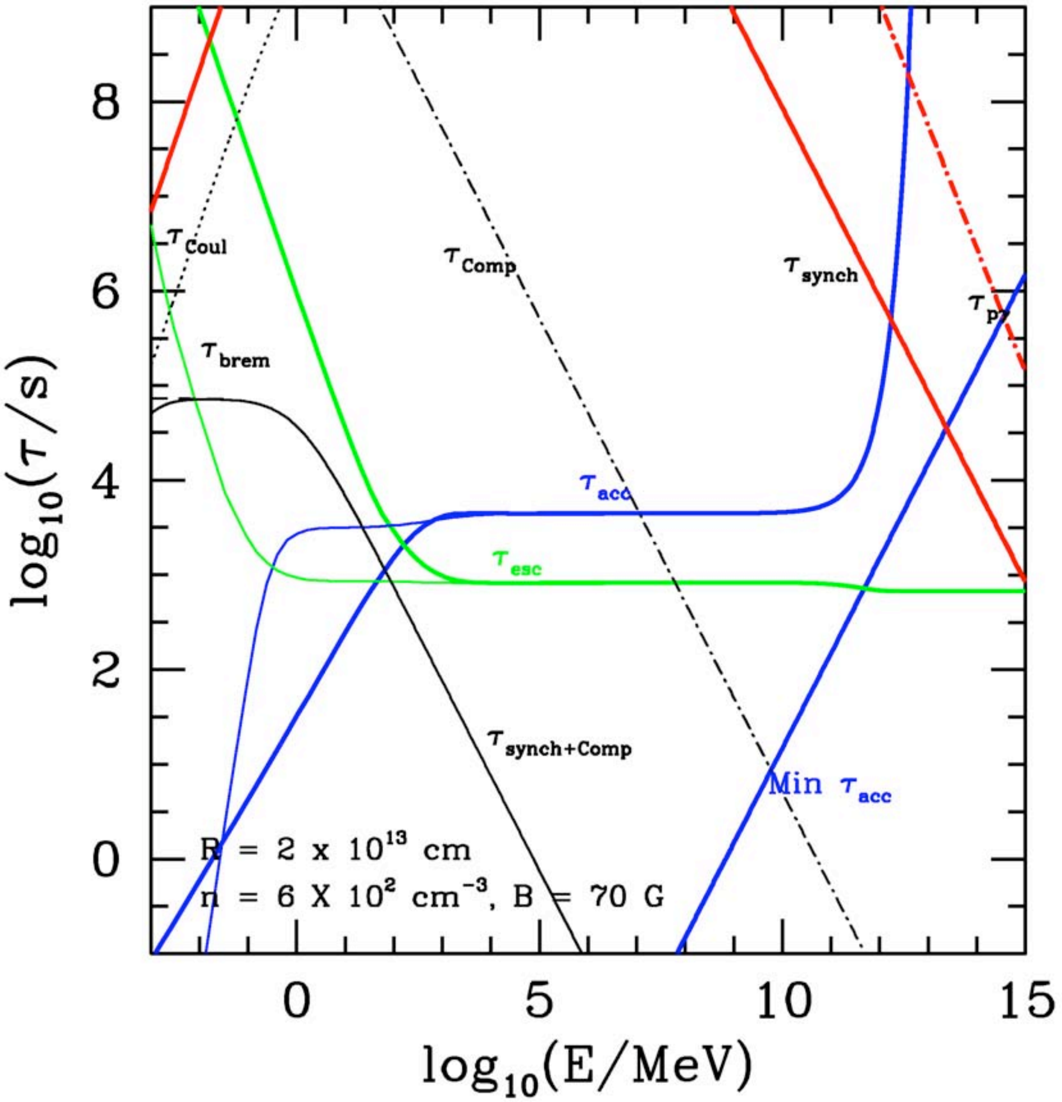
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma}\left[\frac{\partial \gamma^2 N}{\partial \gamma} - \left(4\gamma - \frac{4\gamma^2 \tau_{\mathrm{ac}}}{\tau_0}\right) N\right] - \frac{N}{T_{\mathrm{esc}}} + \dot{Q}$$

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

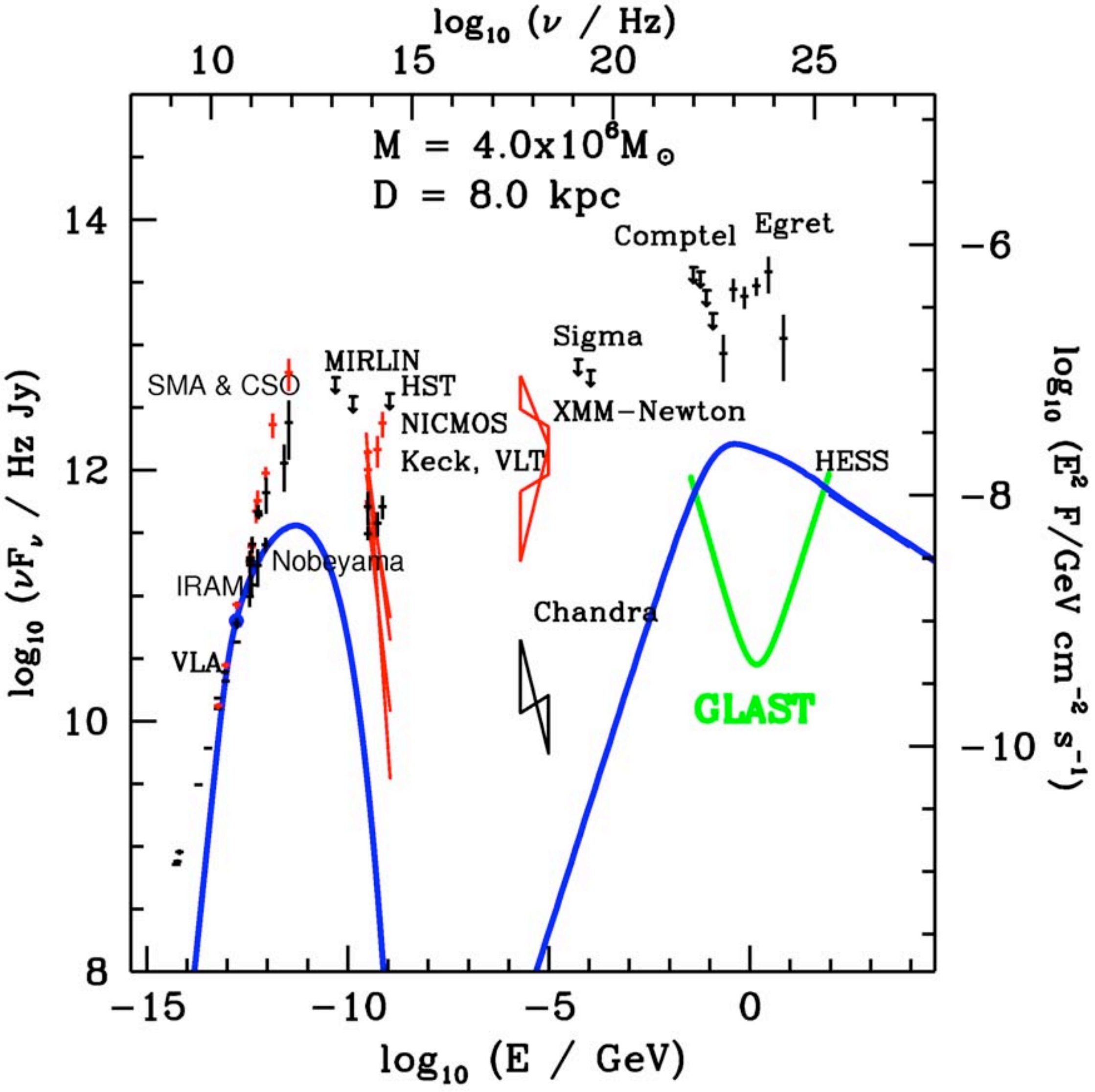
$$\boxed{\tau_{\mathrm{syn}}(\gamma) = 9m_e^3 c^5/4e^4 B^2 \gamma = \tau_0/\gamma}$$

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

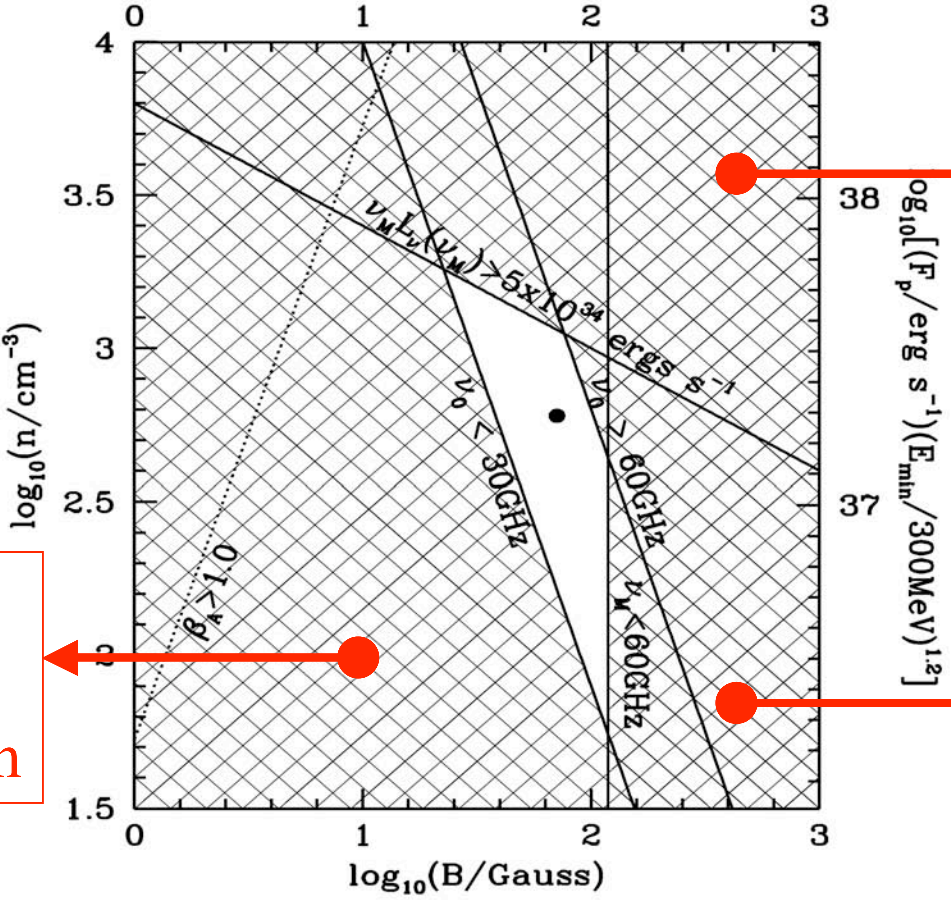
Stochastic Particle Acceleration



Stochastic Particle Acceleration



Proton Acceleration



Source is too bright in the radio band.

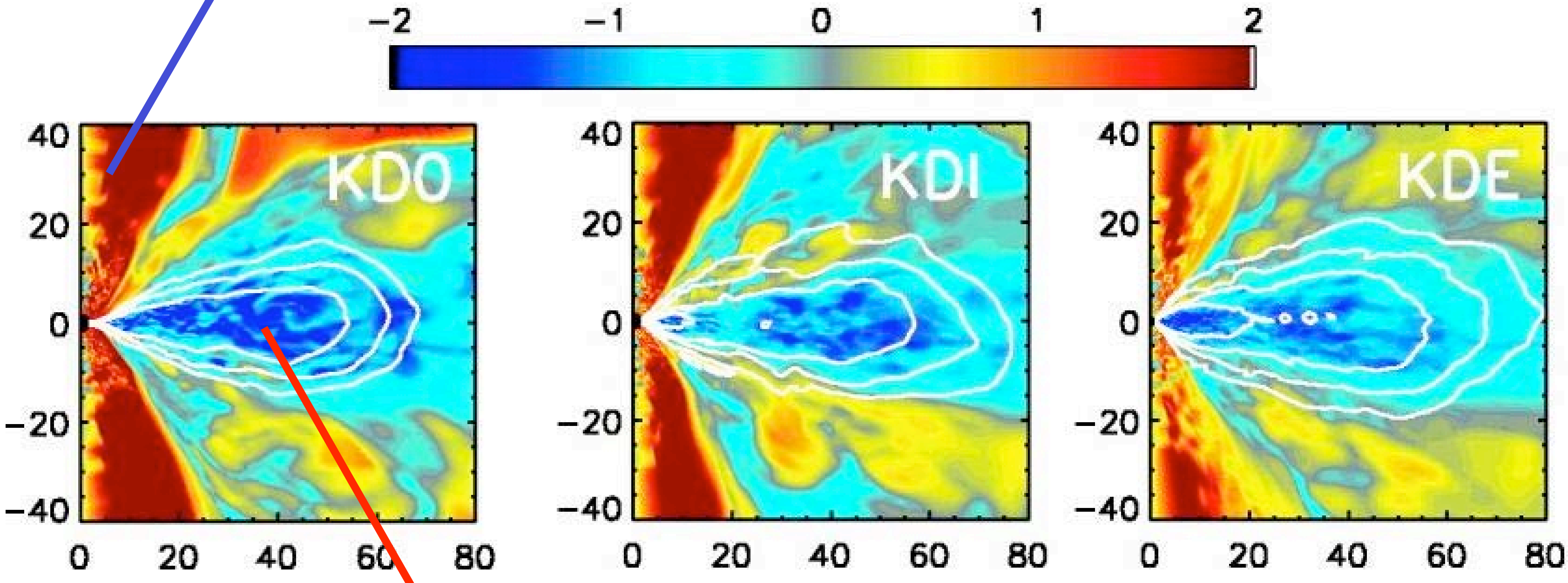
Source is optically thin at 7mm

Cooling is too efficient to produce 7 mm emission

$$\beta_A \equiv \frac{v_A}{c} = 7.3\left(\frac{B}{1\mathrm{G}}\right)\left(\frac{n}{1\mathrm{cm}^{-3}}\right)^{-1/2} .$$

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

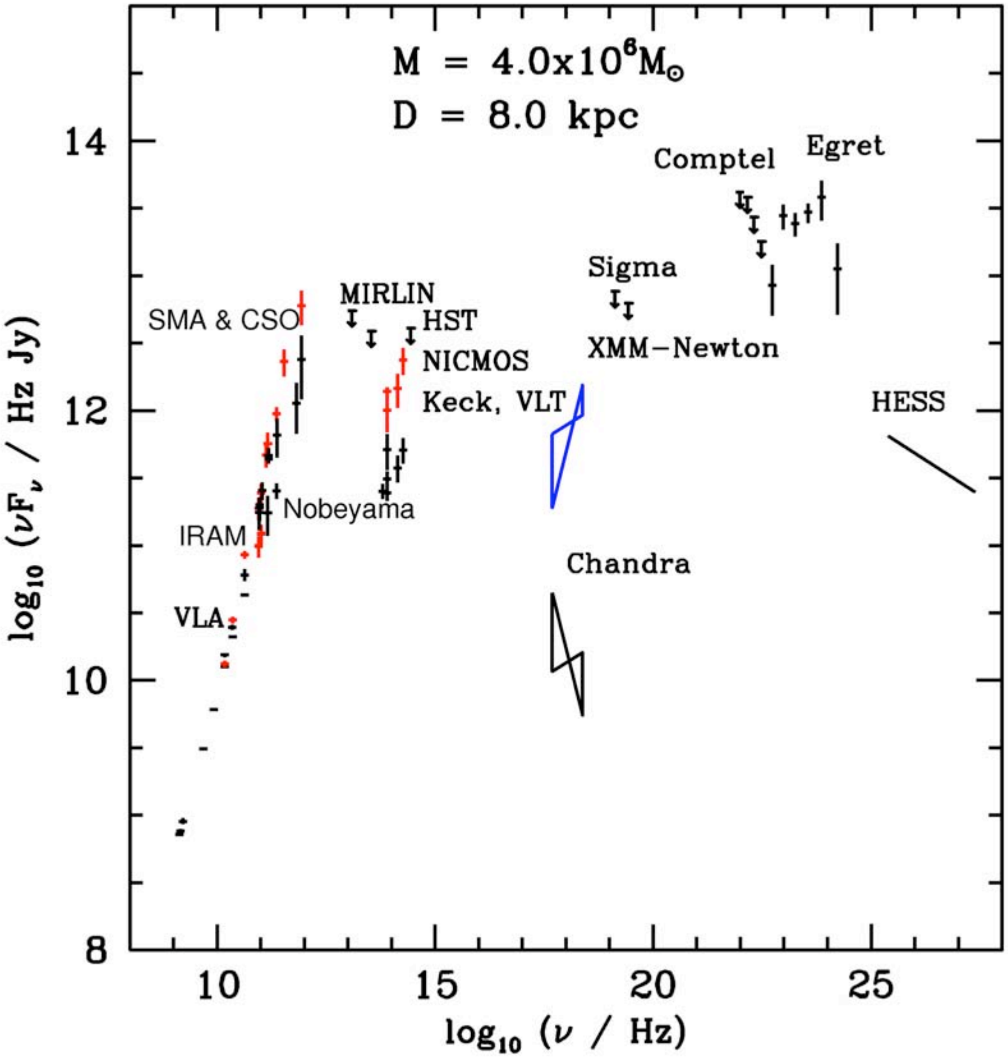
Conclusions

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

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.

Emission Spectra



Emission Processes During Flares

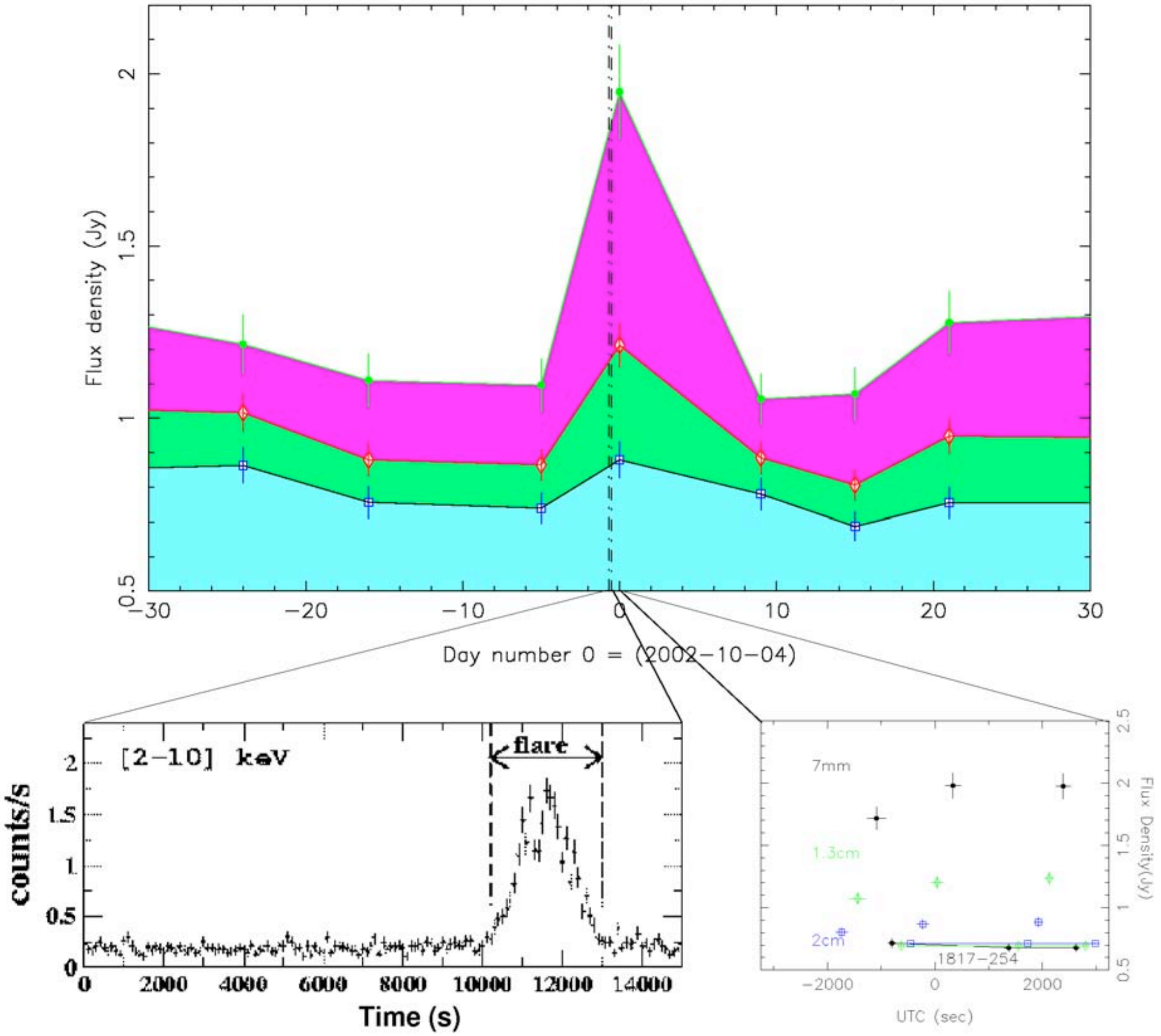
Thermal Synchrotron and SSC:

Four Parameters

B, $k_B T = \_{cr} m_e c^2$, N , A≈R^2

$$
\begin{aligned}
\mathcal{L}_{\rm syn} &= \frac{16e^4}{3m_e^2c^3}\mathcal{N}B^2\gamma_{cr}^2 \\
&= 2.0\times10^{36}\left(\frac{\mathcal{N}}{10^{43}}\right)\left(\frac{B}{40\ \rm G}\right)^2\left(\frac{\gamma_{cr}}{100}\right)^2 \ \rm ergs\ s^{-1}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\rm SSC} &= \frac{U_{\rm syn}}{U_B}\mathcal{L}_{\rm syn} \simeq \frac{8\pi\mathcal{L}_{\rm syn}^2}{cAB^2} \\
&= 5.2\times10^{35}\left(\frac{\mathcal{L}_{\rm syn}}{10^{36}\ \rm ergs\ s^{-1}}\right)^2\left(\frac{B}{40\ \rm G}\right)^{-2}\left(\frac{A}{r_S^2}\right)^{-1} \ \rm ergs\ s^{-1}
\end{aligned}
$$

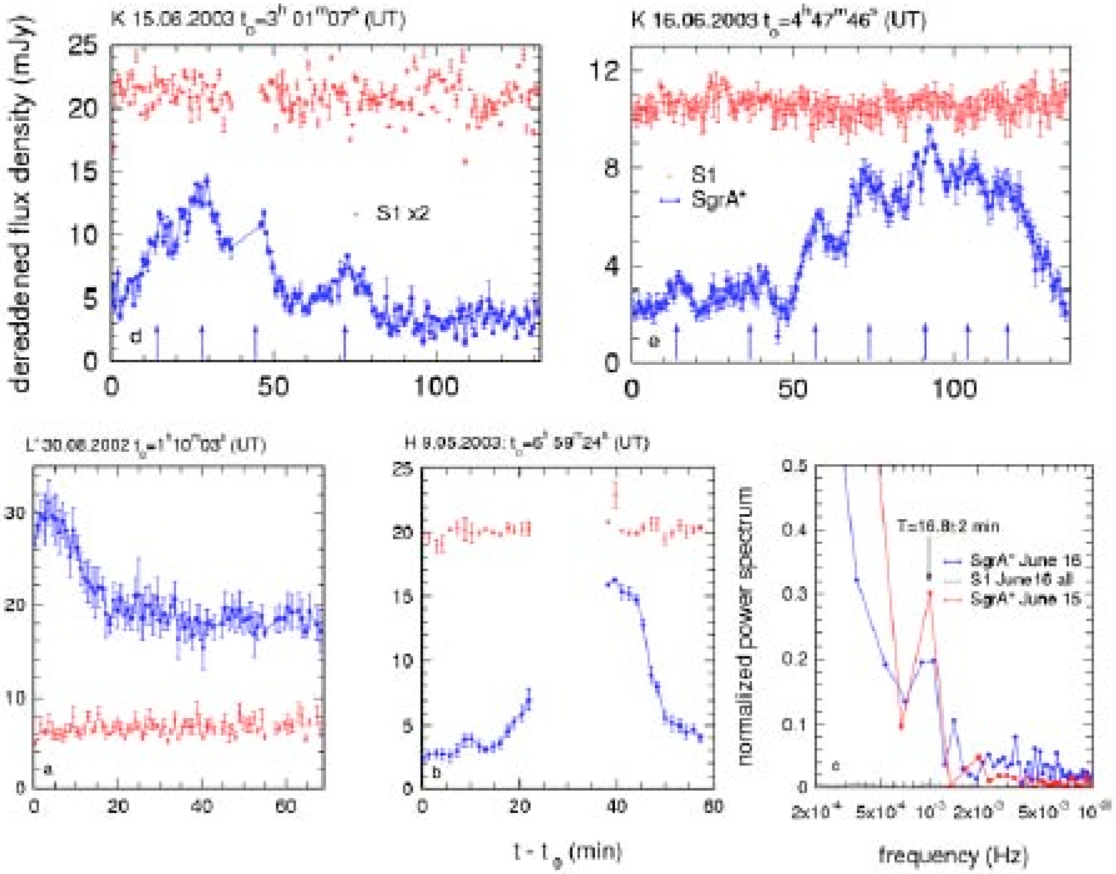


(From Bower, Falcke et al. 2004)

(From Zhao et al. 2004)

NIR Flares From Sgr A*

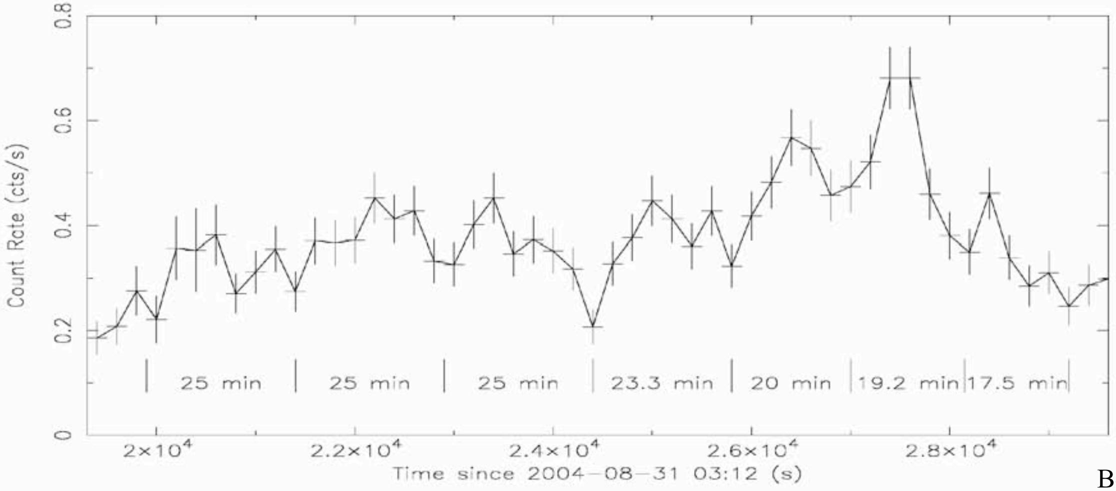
Quasi-periodic Modulation



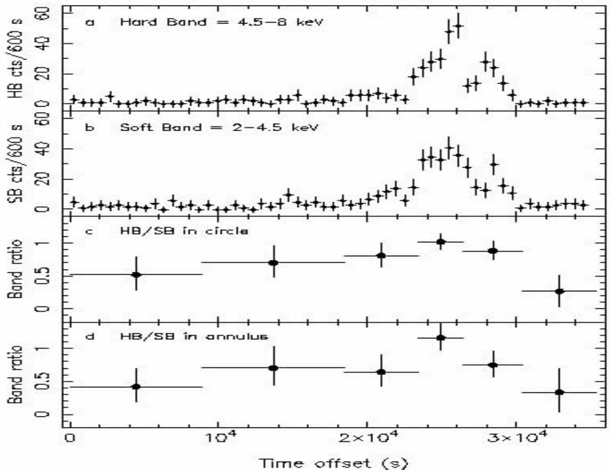
Genzel et al. 2003

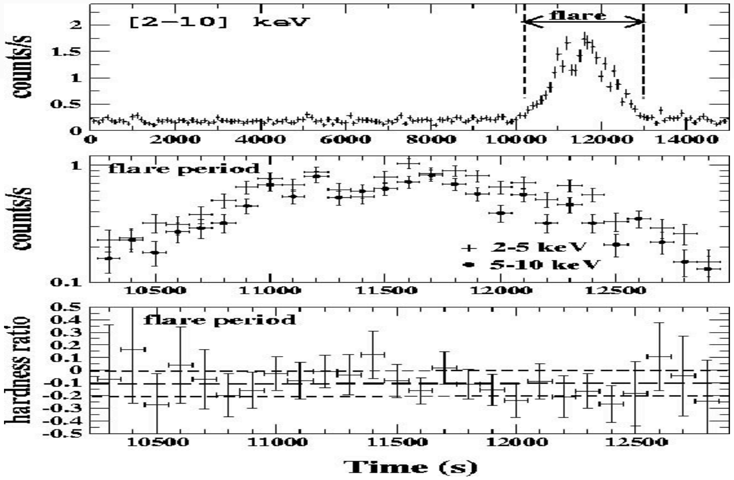
X-Ray Flares From Sgr A*

Quasi-periodic Modulation



Belanger et al. 2005



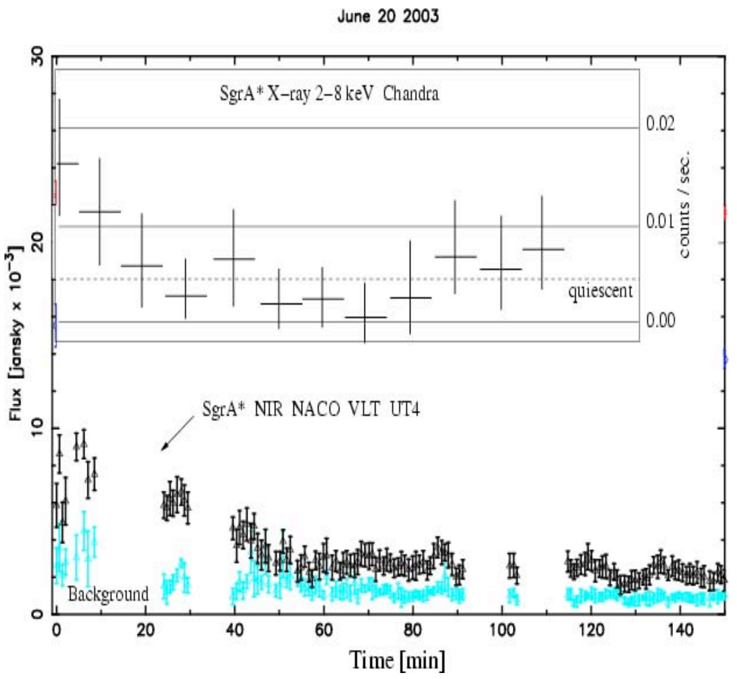


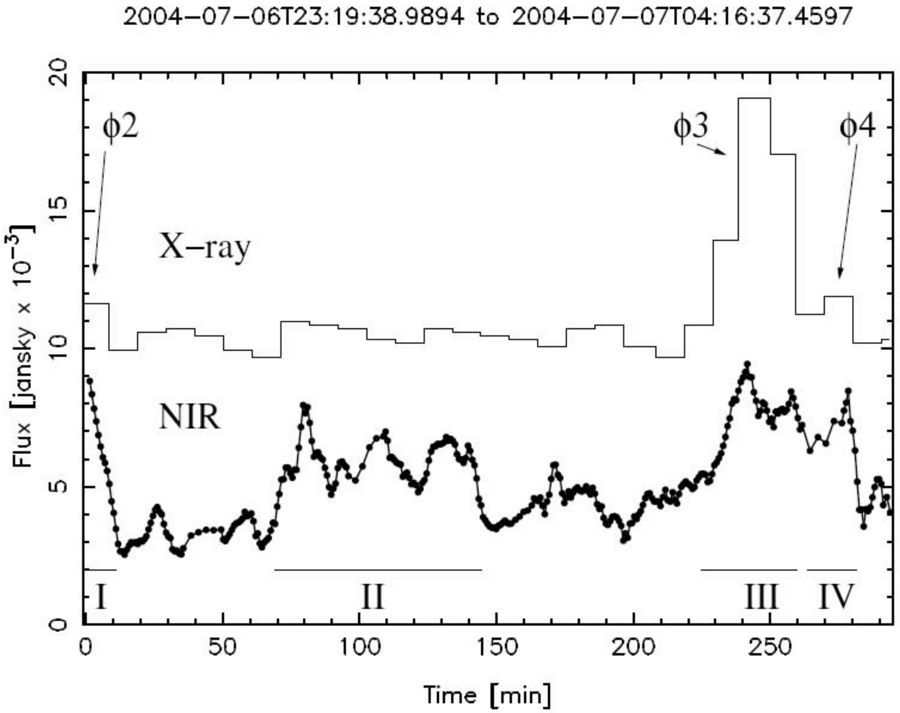
Baganoff et al. 2001

Porquet et al. 2003

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

Eckart et al. (2004)



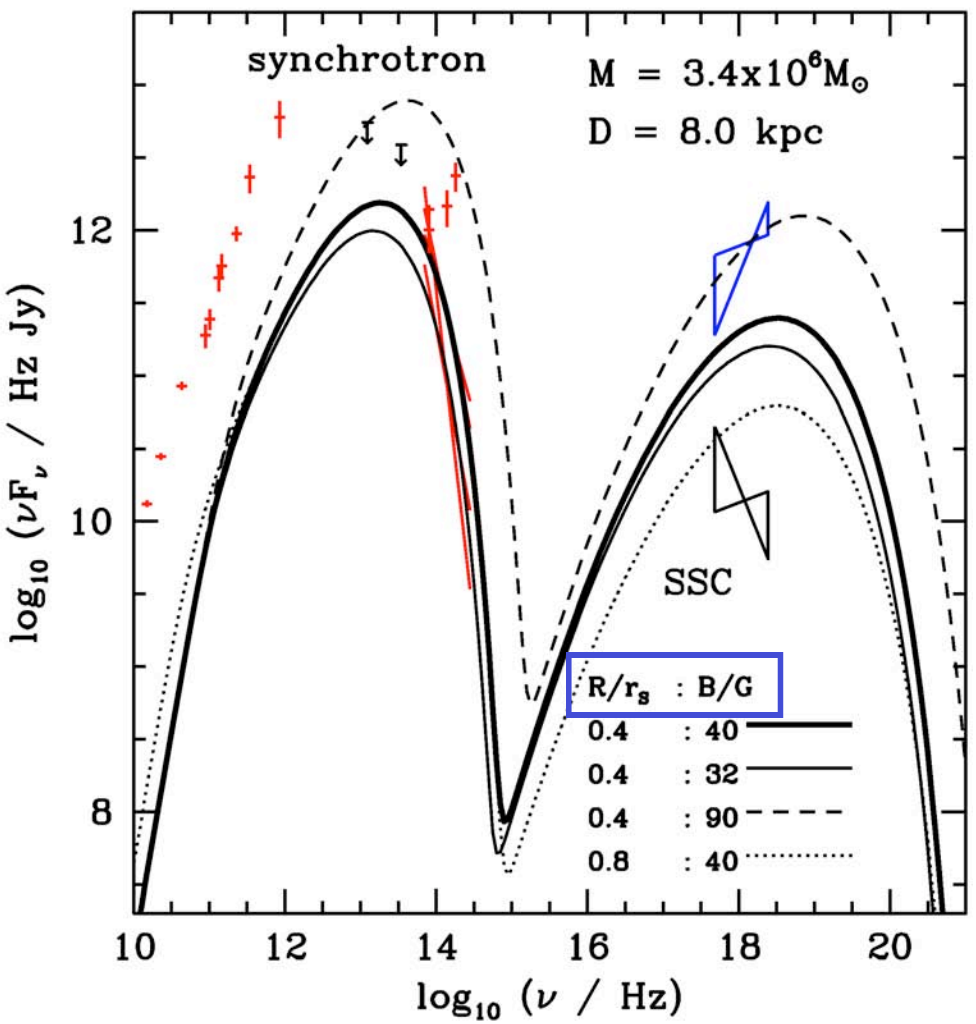


$L_x \sim 6\times10^{33}$ erg s^{-1}

$L_{nir} \sim 5\times10^{34}$ erg s^{-1}

Baganoff 2005

Emission Processes During Flares



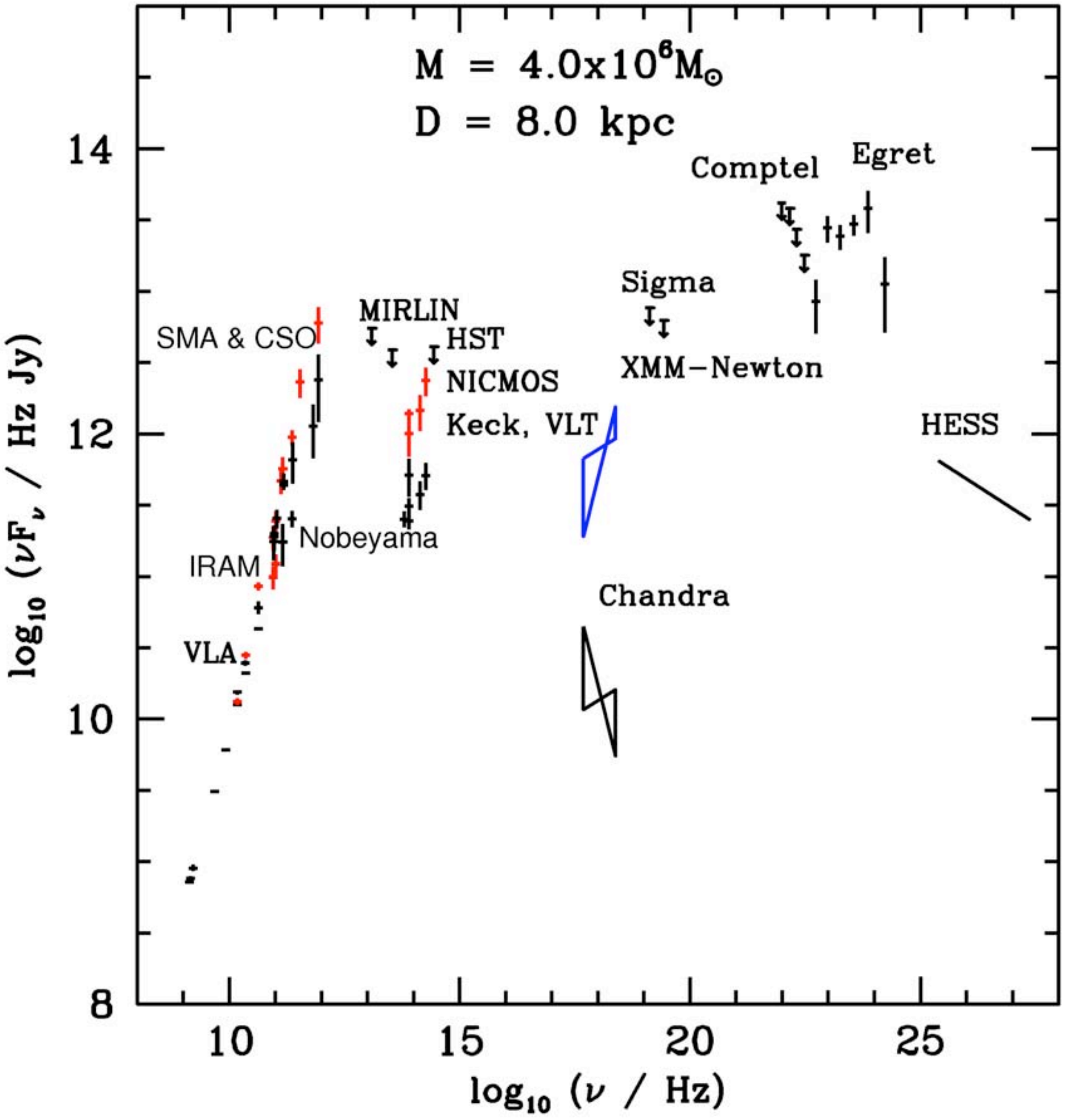
Thermal Synchrotron and SSC:

Four Parameters

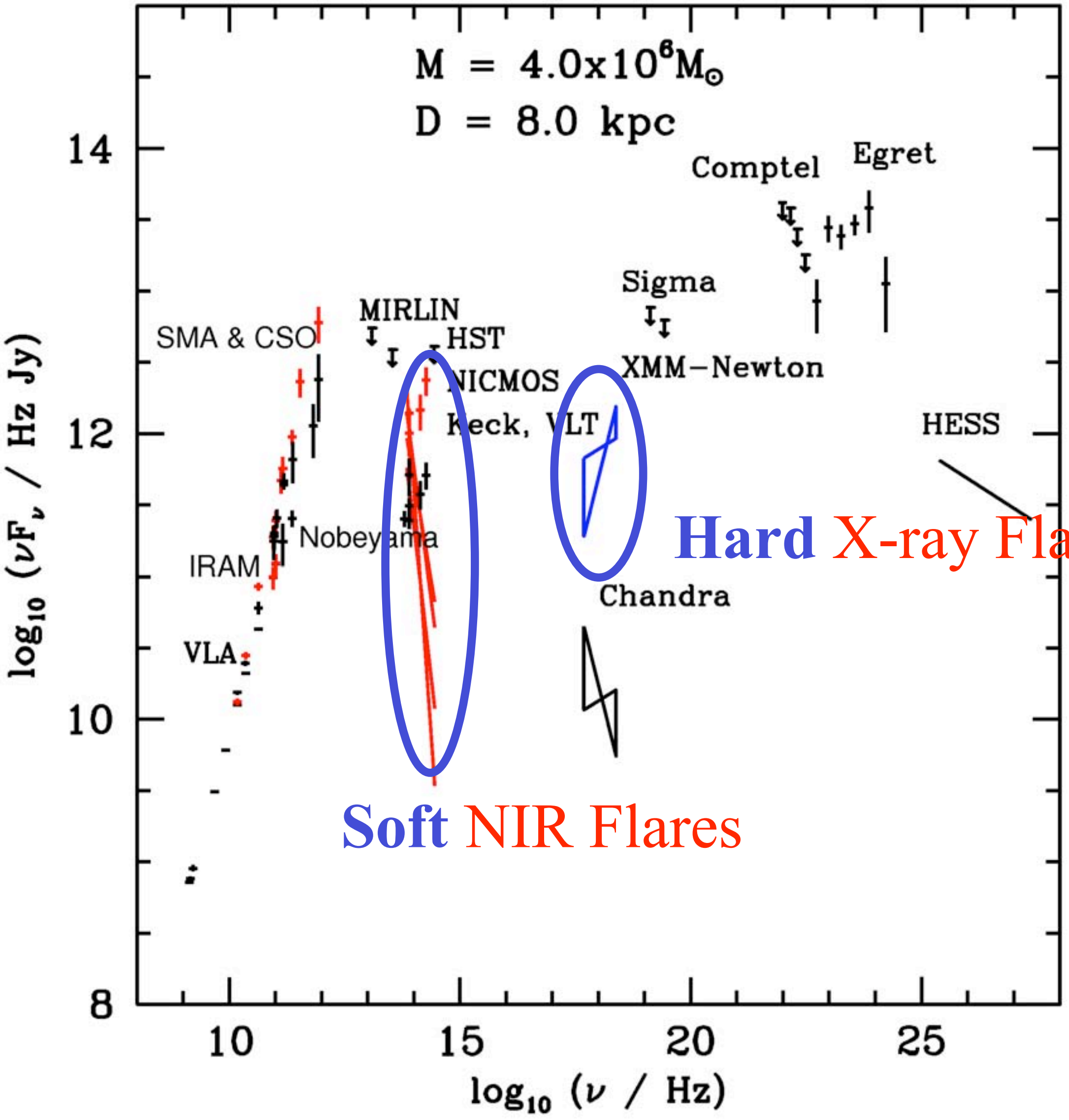
$N=3.8\text{x}10^{42}$

$k_BT=75m_ec^2$

Emission Spectra



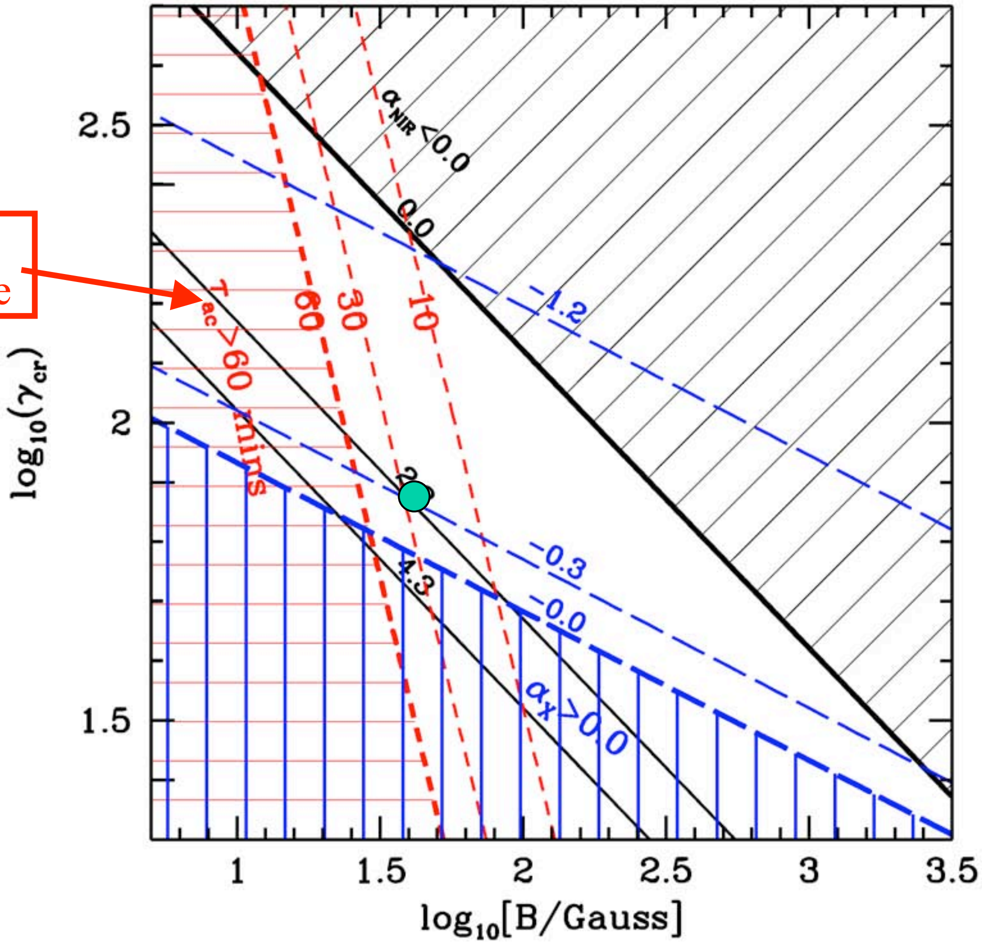
Emission Spectra



Hard X-ray Flares

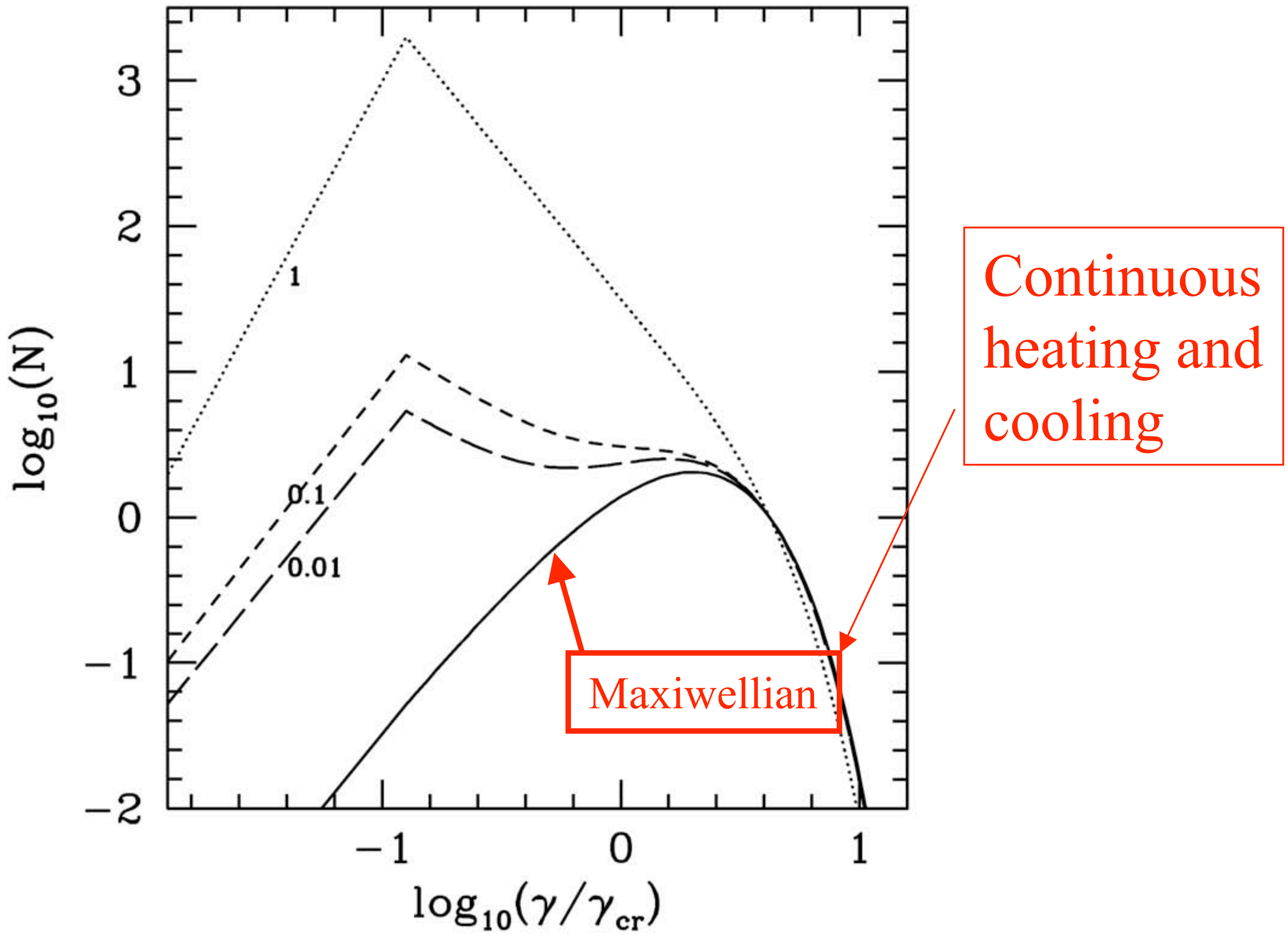
Soft NIR Flares

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



_rise

Stochastic Electron Acceleration



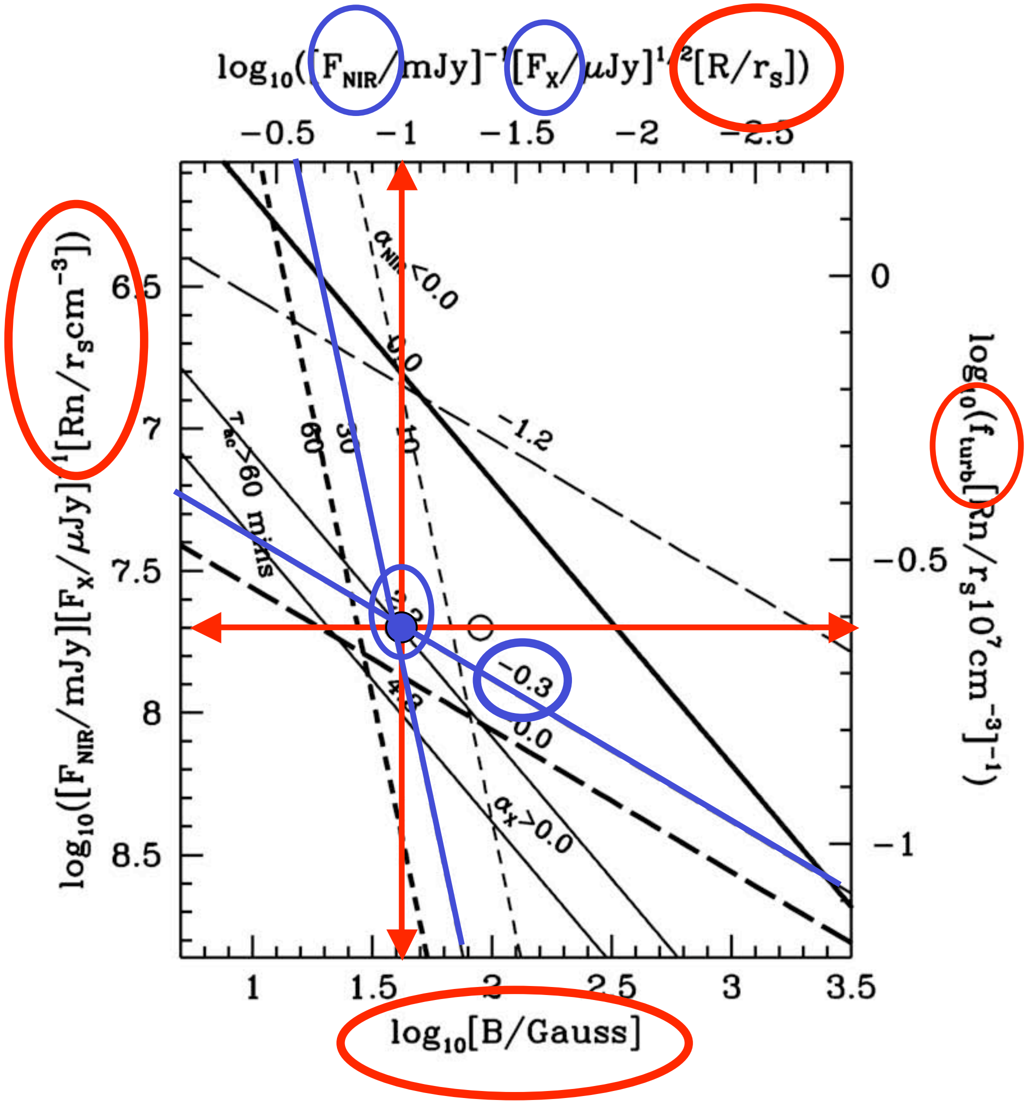
Continuous heating and cooling

Maxiwellian

Determining the Plasma Properties

Observations

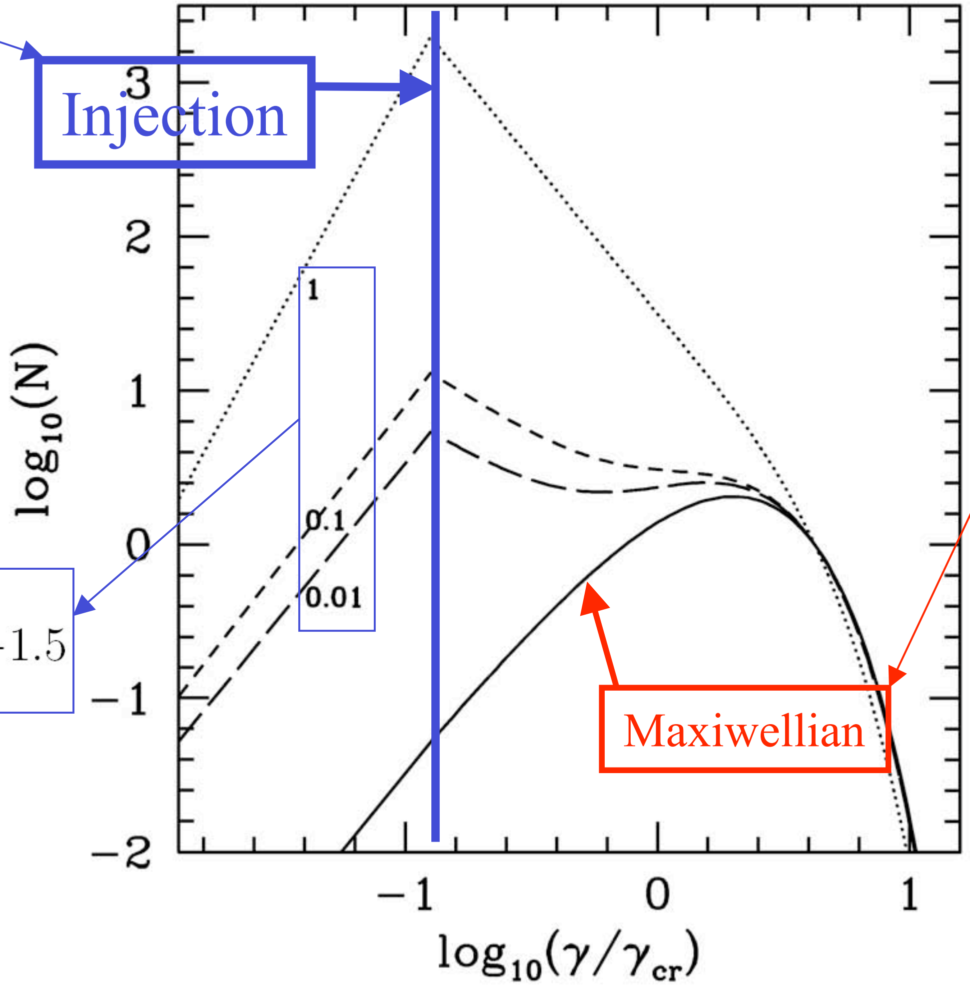
B, R, n, f_{turb}



Stochastic Electron Acceleration

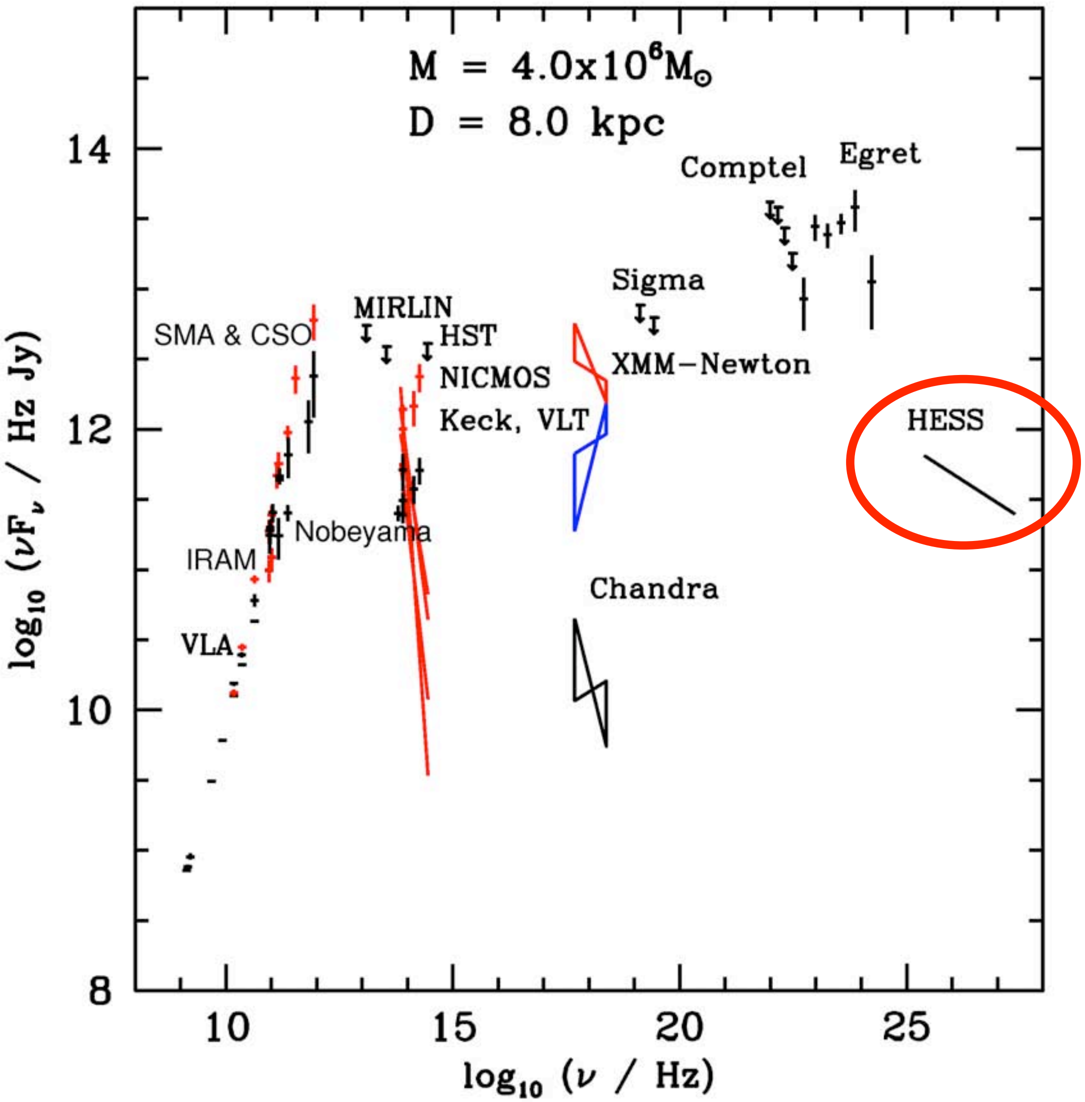
Continuous injection, heating, & cooling.

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



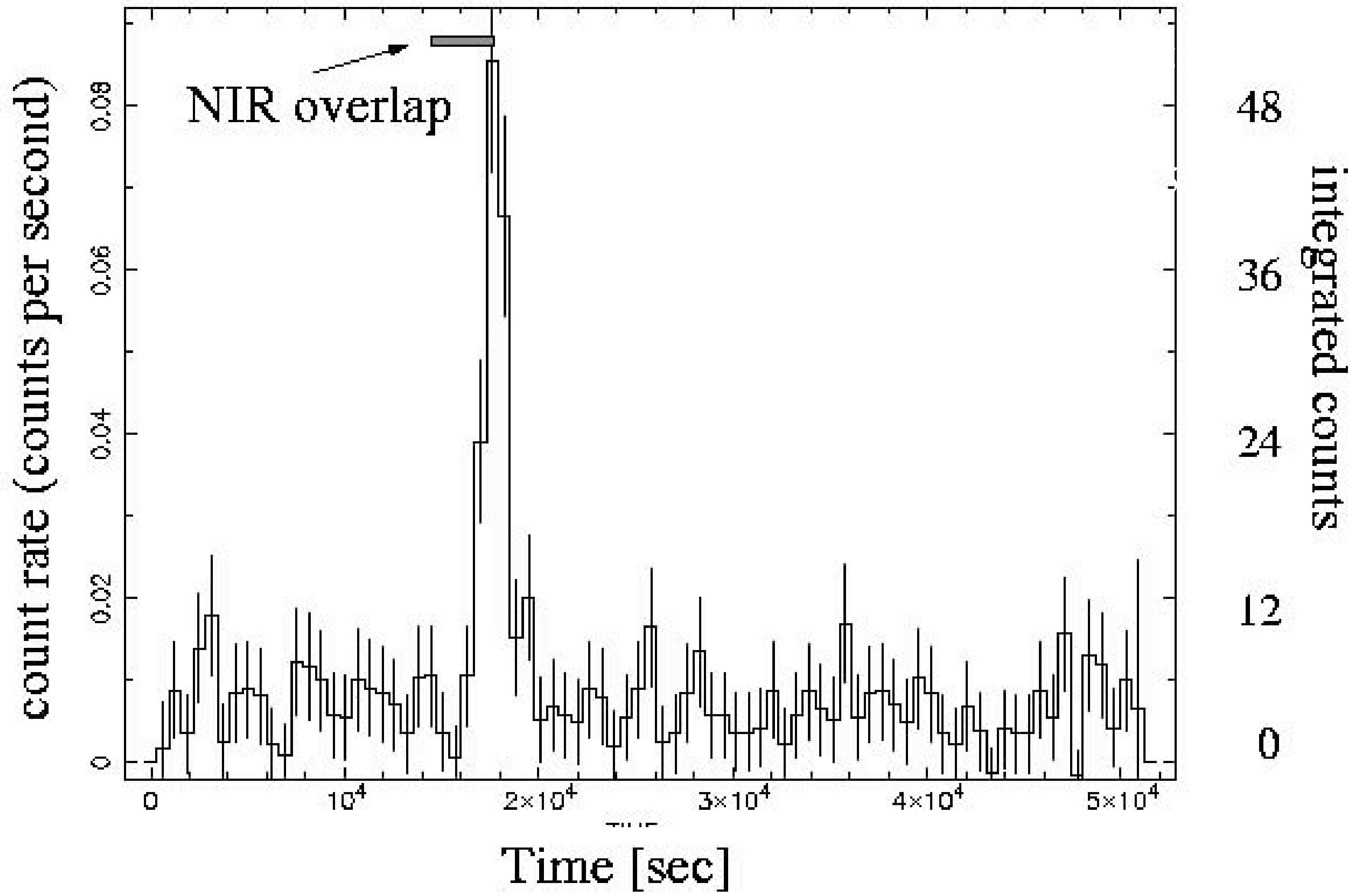
Without injection: Continuous heating and cooling

HESS Source

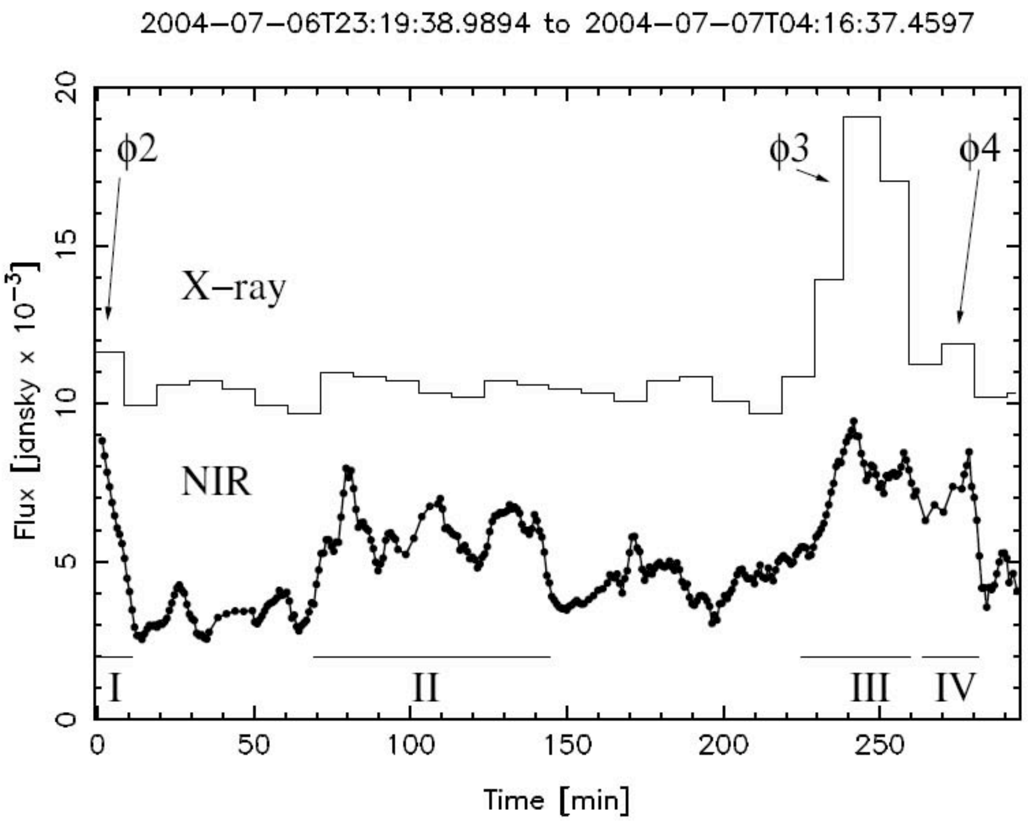


$M = 4.0 \times 10^6 M_\odot$
$D = 8.0$ kpc
Comptel
Egret
Sigma
MIRLIN
SMA & CSO
HST
NICMOS
XMM−Newton
Keck, VLT
HESS
Nobeyama
IRAM
Chandra
VLA
14
12
10
8
10
15
20
25
$\log_{10} (\nu F_\nu$ / Hz Jy)
$\log_{10} (\nu$ / Hz)

July 2004: Detection of a Strong X-ray flare

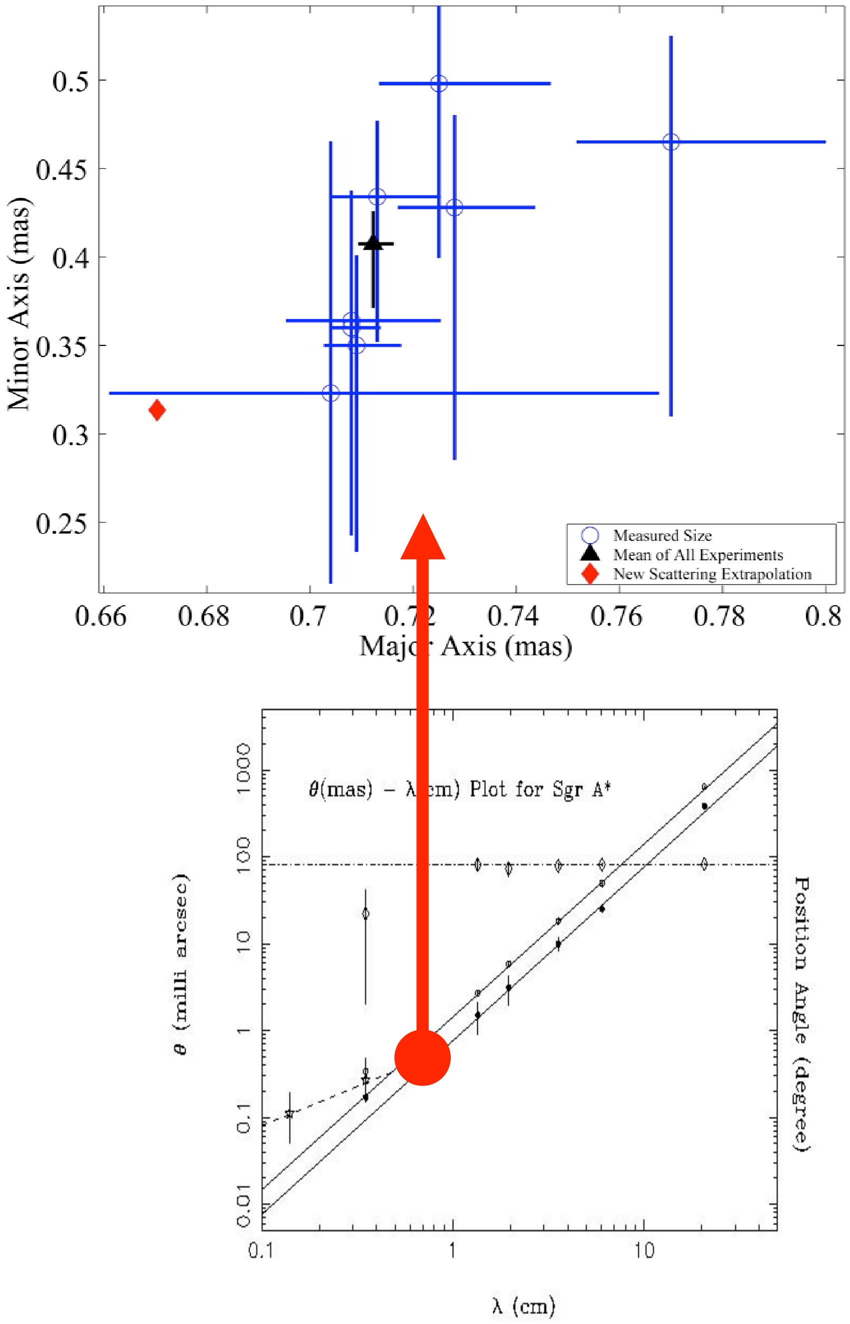


Comparison of X-ray and NIR Lightcurves

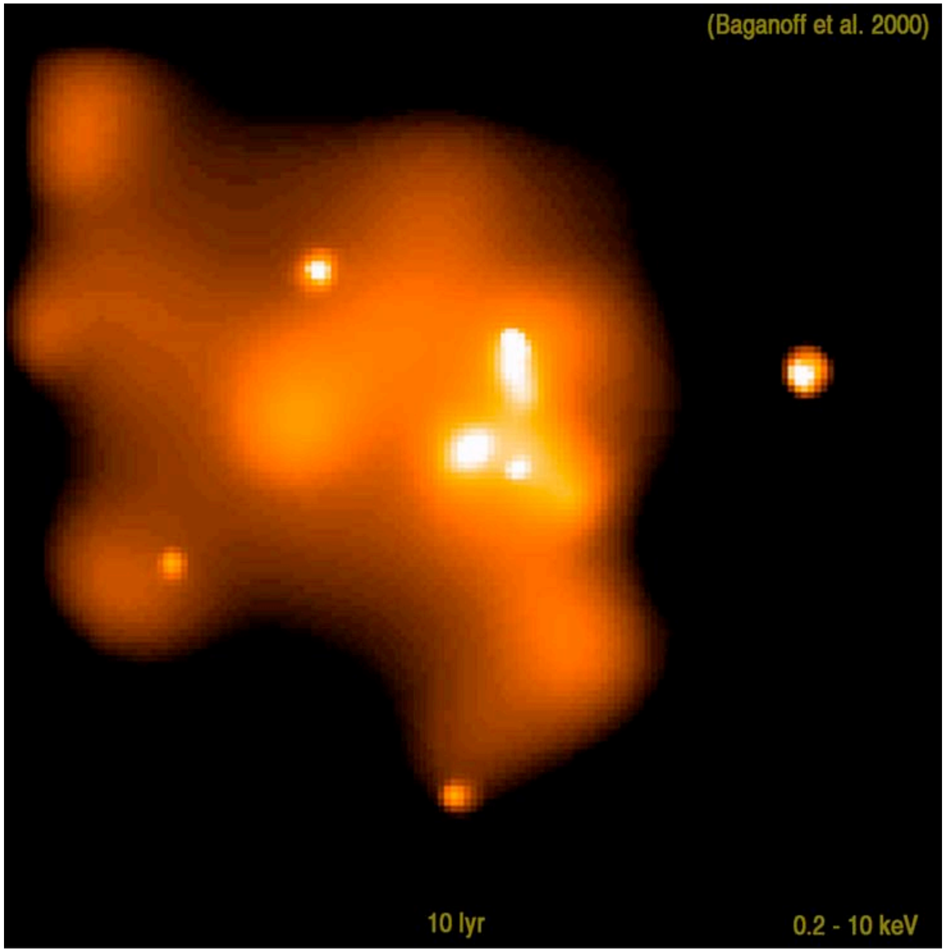


- At least four separate NIR flares were detected at K-band by the VLT with NAOS/CONICA on 2004 July 6/7.
- NIR flare III is correlated with the strong X-ray flare.
- NIR flare I is associated with the possible X-ray event at the beginning of the observations, but the ratio of X-ray to NIR amplitudes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

Baganoff 2005

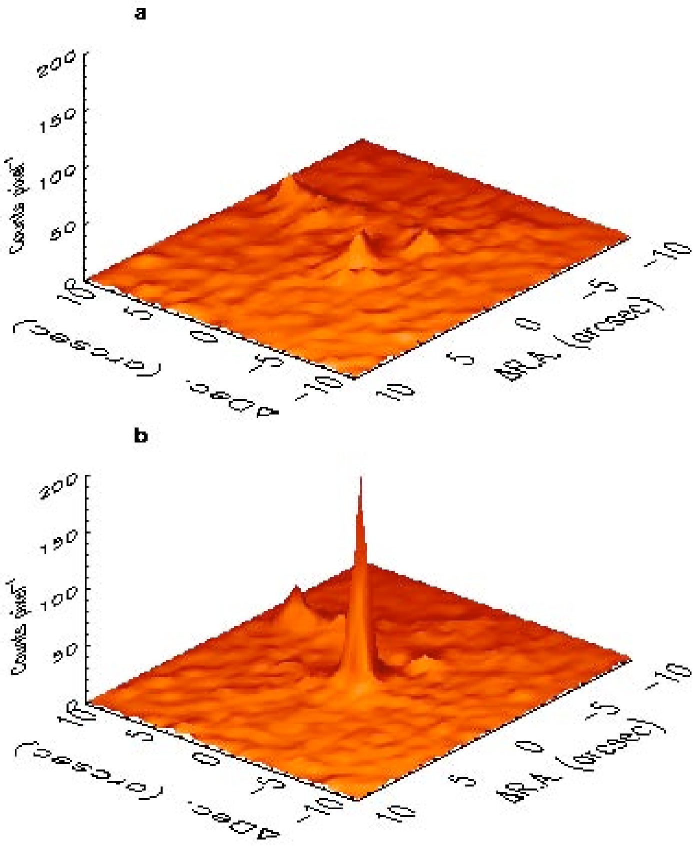

Minor Axis (mas)
0.5
0.45
0.4
0.35
0.3
0.25
0.66
0.68
0.7
0.72
0.74
0.76
0.78
0.8
Major Axis (mas)
Measured Size
Mean of All Experiments
New Scattering Extrapolation
θ(mas) – λ cm) Plot for Sgr A*
θ (milli arcsec)
1000
100
10
1
0.1
0.01
0.1
1
10
λ (cm)
Position Angle (degree)

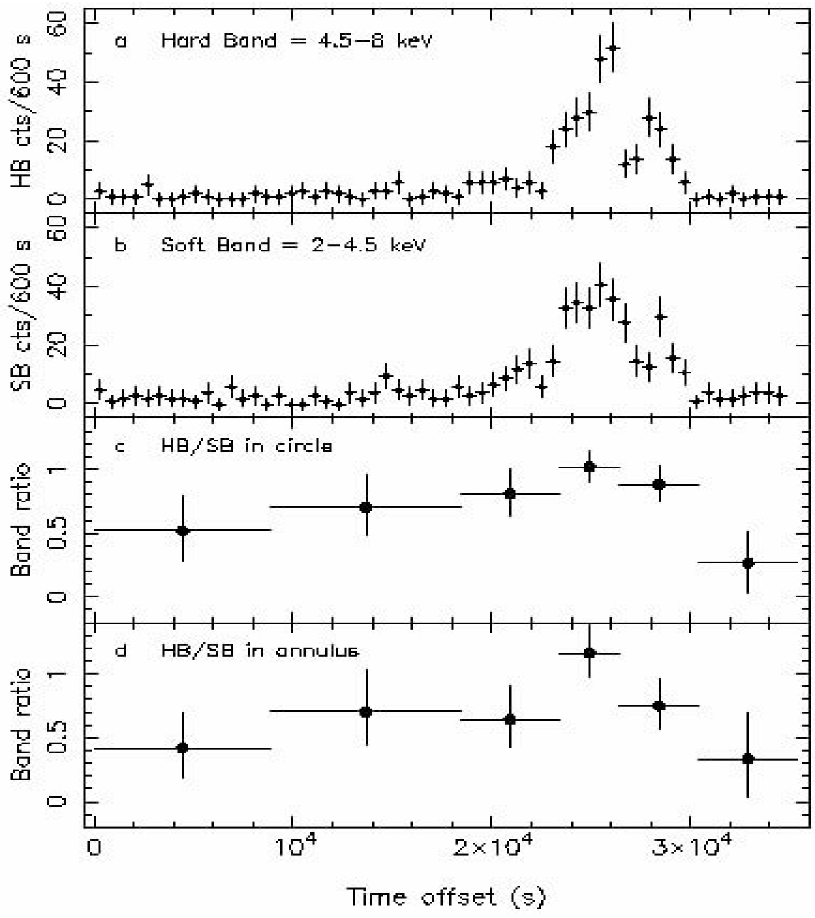
X-ray image of Sgr A*



X-ray Flares from Sgr A*

(Baganoff et al. 2001)

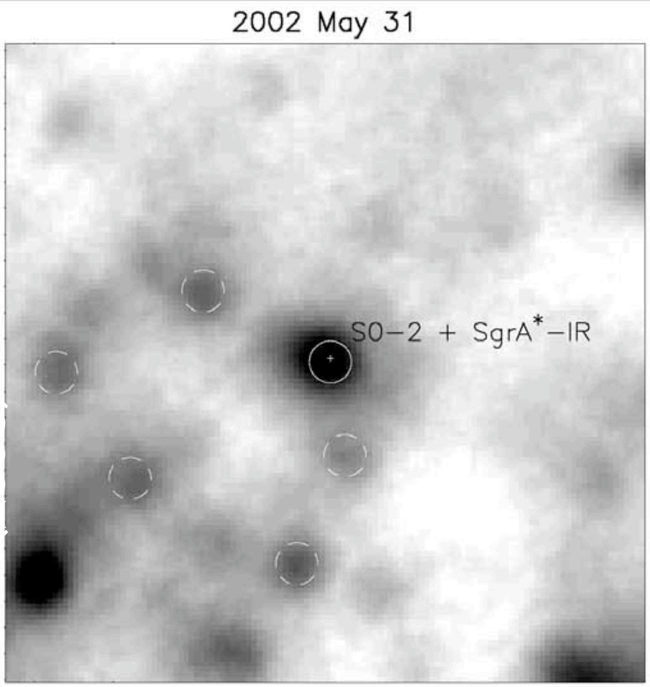


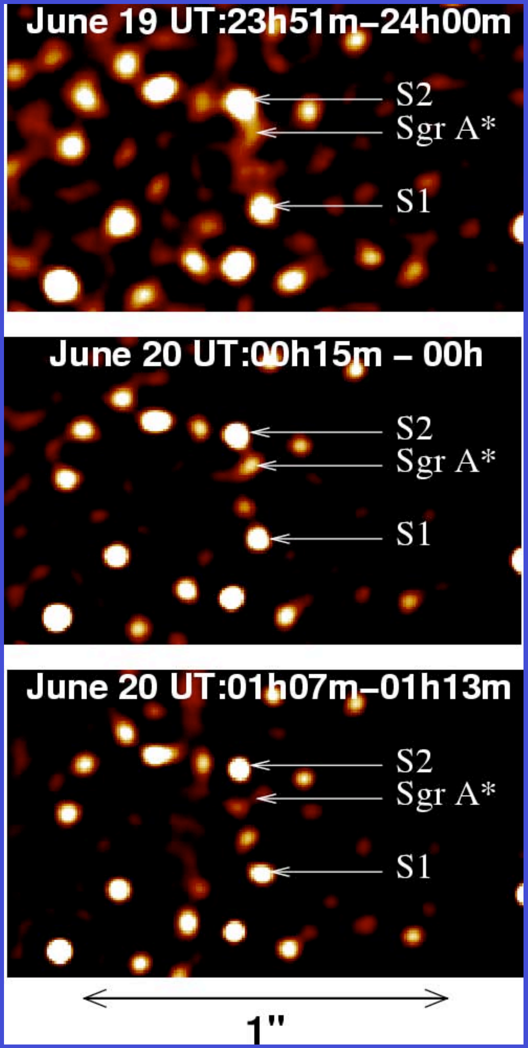


In flare-state, Sgr A*'s X-ray luminosity can increase by more than one order of magnitude.

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

GHEZ ET AL.


2002 May 31
S0−2 + SgrA*−IR


June 19 UT:23h51m–24h00m
S2
Sgr A*
S1
June 20 UT:00h15m – 00h
S2
Sgr A*
S1
June 20 UT:01h07m–01h13m
S2
Sgr A*
S1
1"