Particle Acceleration and the Quiescent and Flare Emissions in Sgr A* (*and other AGNs?)*

In collaboration with

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and graduate students

Huatulco, April 2007

Outline

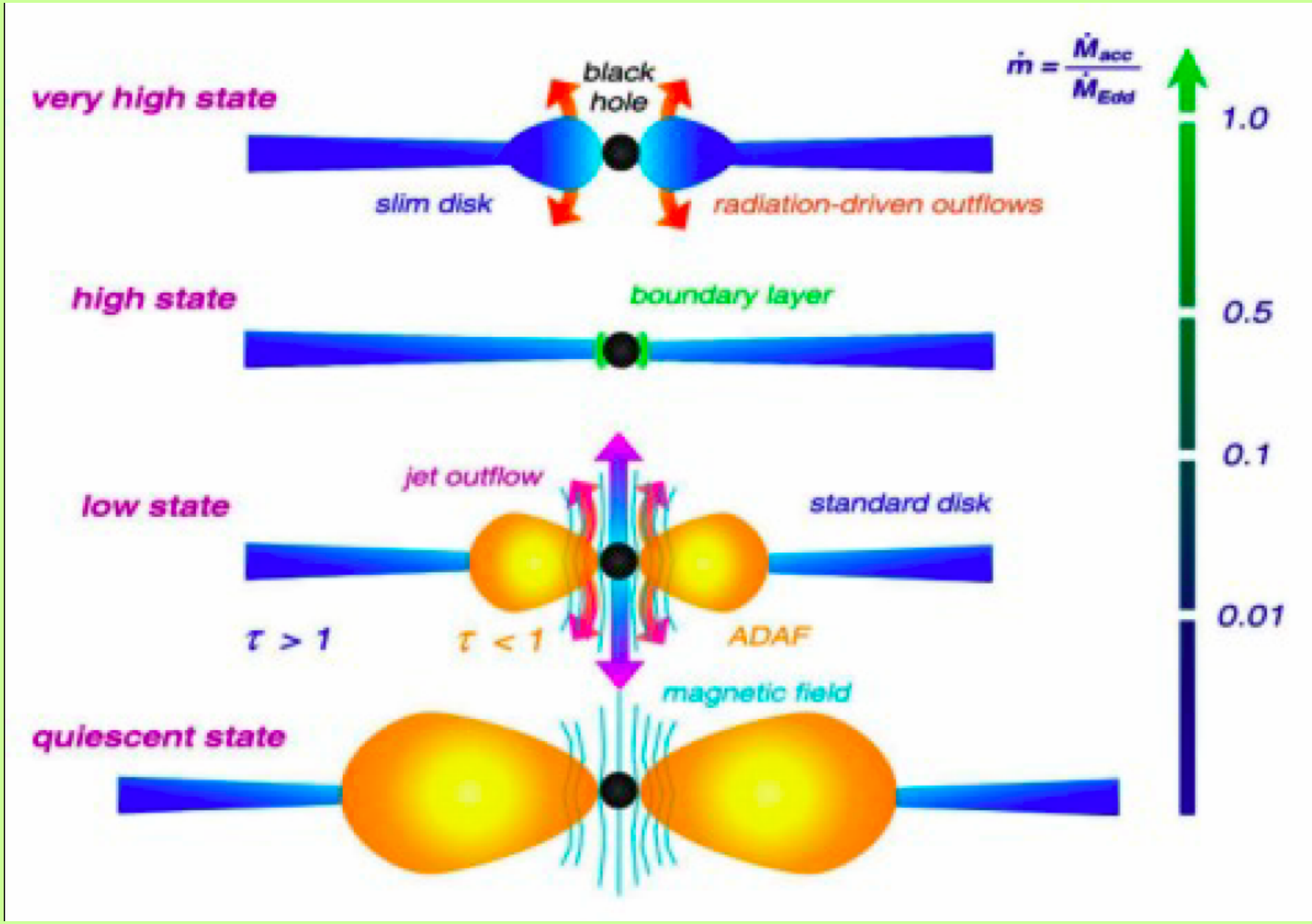
Accretion in Black Holes
Observations of Sgr A*
Emission Mechanisms
Stochastic Acceleration
Quiescent Emission *(Radio and TeV)*
NIR and X-ray Flares

Accretion in Black Holes

Luminosity $\sim L_{edd}$	Luminosity$<<L_{edd}$
High Accretion Rate	Low Accretion Rate

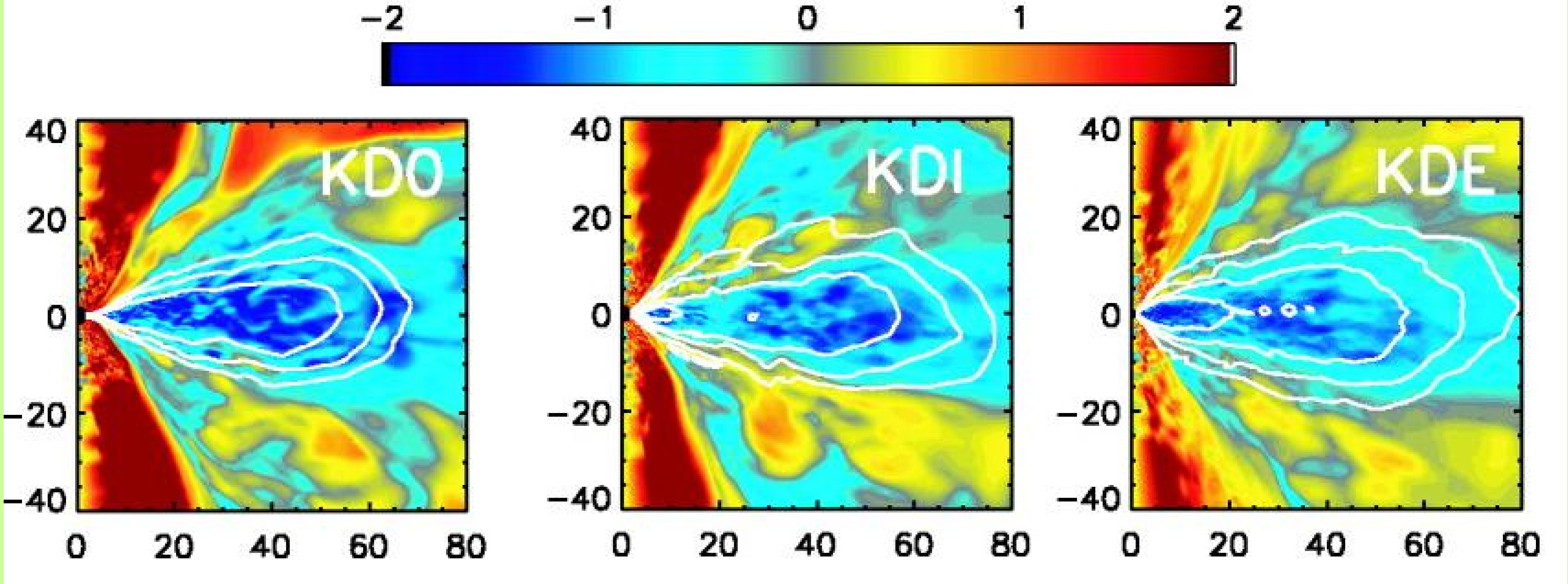
Optically Thick	Optically Thin
High Density	Low Density
Thermal Equilibrium	?
High Efficiency	Low Efficiency
Cold	Hot
Geometrically Thin	Geometrically Thick

Accretion in Black Holes

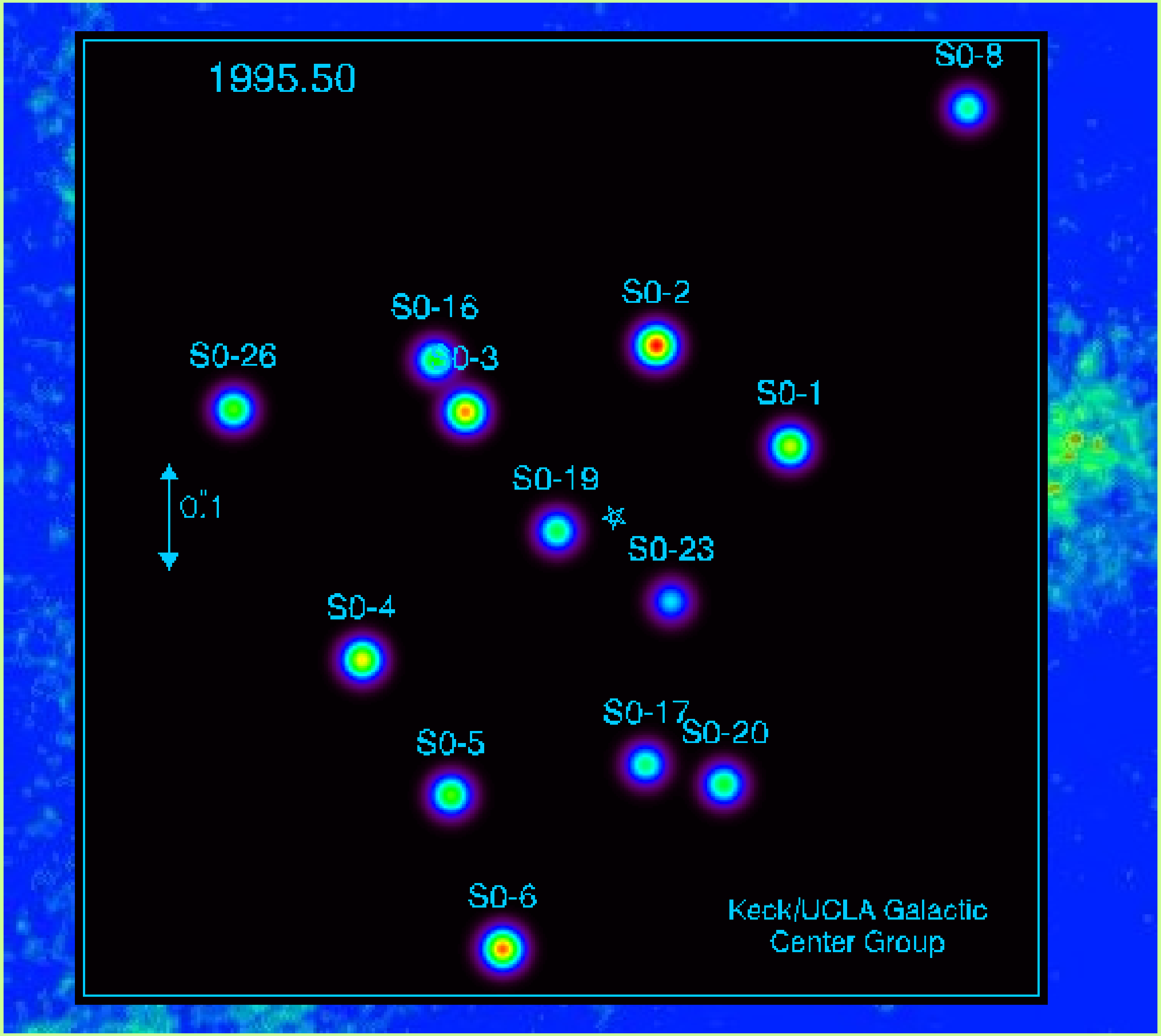


Muller 2004

Accretion in Black Holes



De Villiers et al. 2003 ApJ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S0-6
Keck/UCLA Galactic
Center Group

Some Basic Parameters for Black Hole in Sgr A*

- Distance $D \approx 8 \ \text{kpc}$
- Black Hole Mass $M_{BH} \approx 4 \times 10^{6} M_{sun}$
- Schwarzschild Radius $r_s = 1.2 \times 10^{12} \ \text{cm}$
- Angular size $\vartheta_s = r_s / D = 10^{-5} \text{arcsec}$
- Timescales: $\tau_s = 40(R / r_s) \ \text{sec}$

$$\tau_{Kep} \approx 400(R / r_s)^{3/2} \ \text{sec}$$

Energy Flow During the Flares

Gravitational Energy Release of Protons and Ions

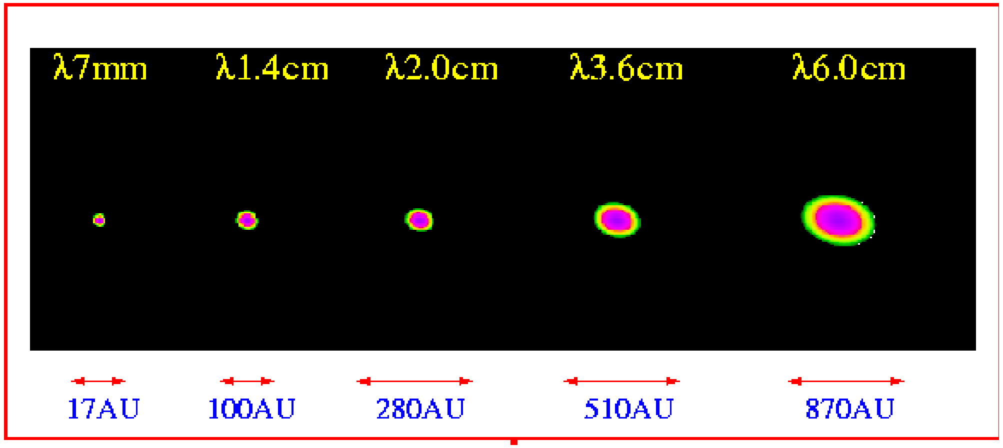
Generation of Turbulence via Instabilities

Electron Acceleration by the Turbulence

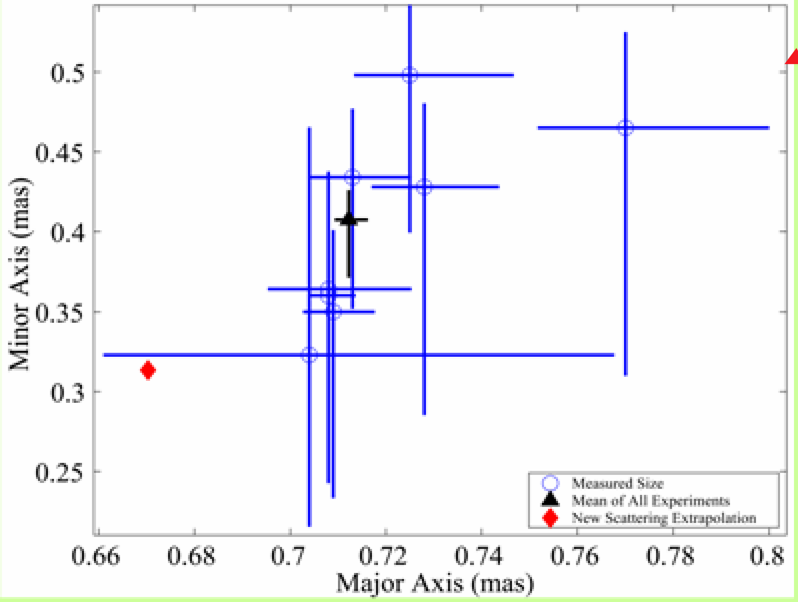
Radiation Produced by Electrons and Protons

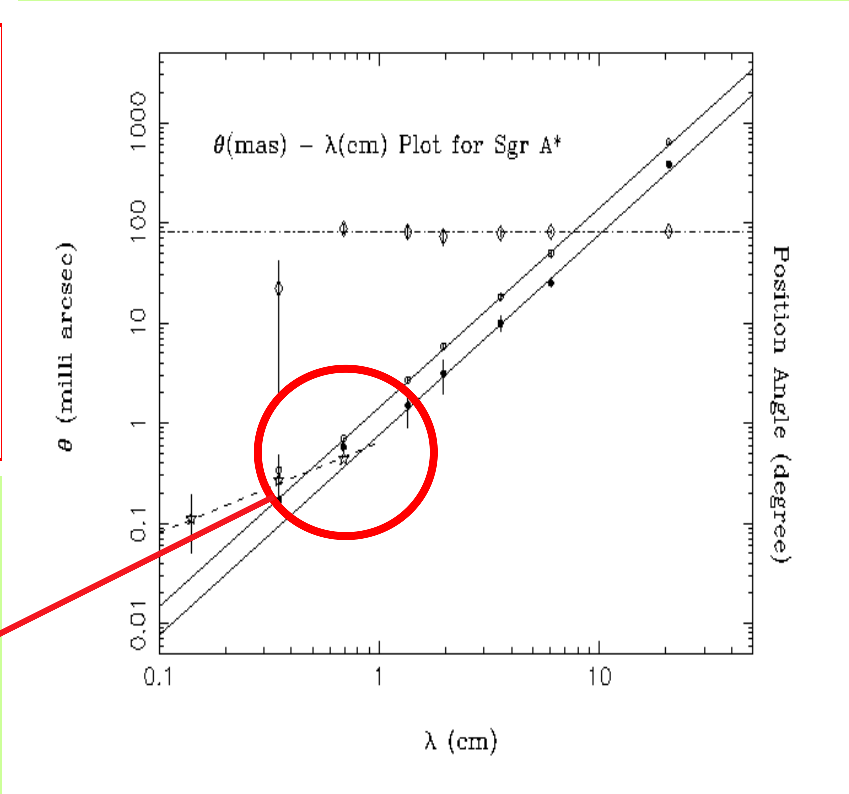
Observation of Sagittarius A*

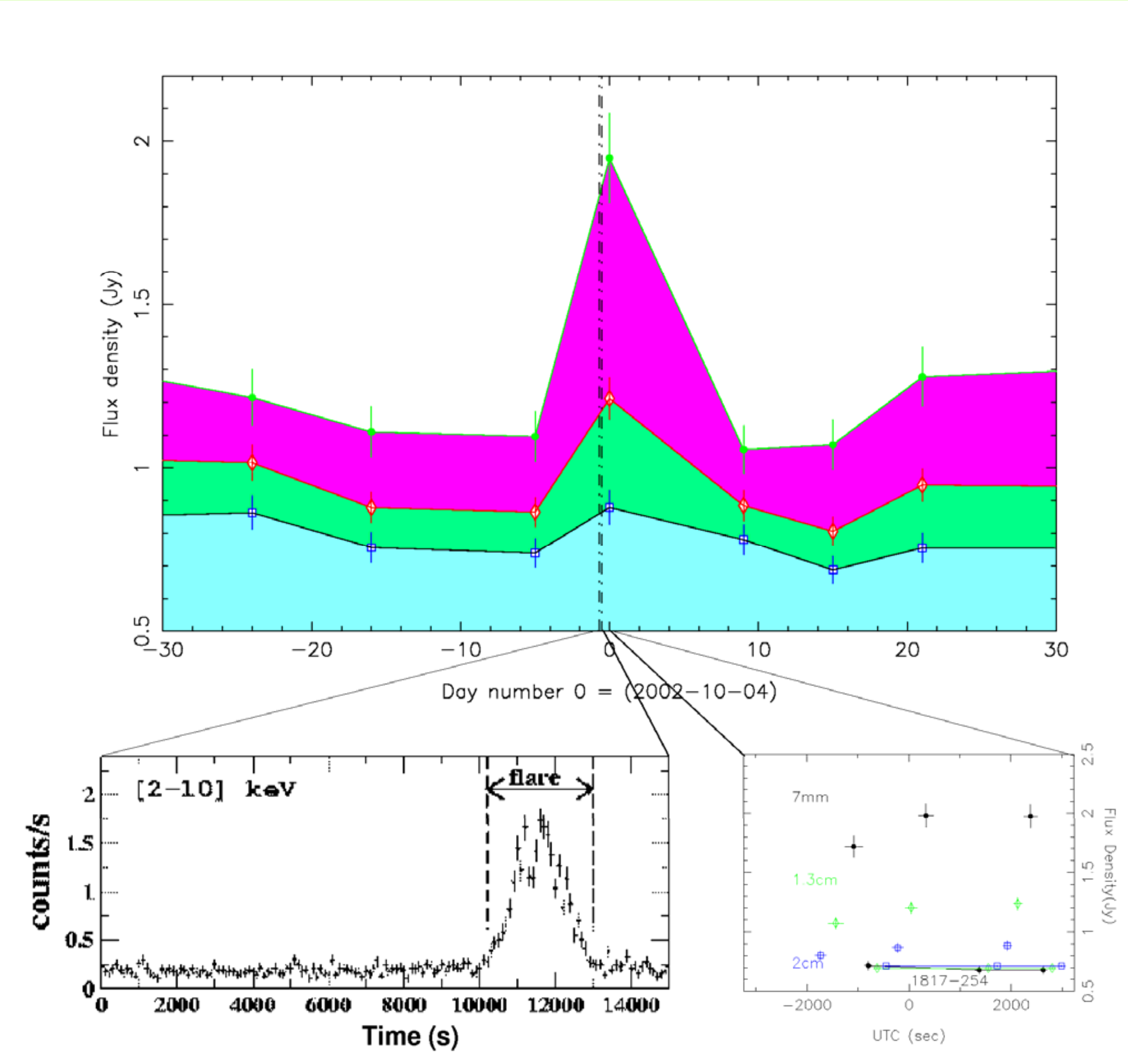
Radio Observations, VLA



Lo et al. 1998, ApJ, 508, 61

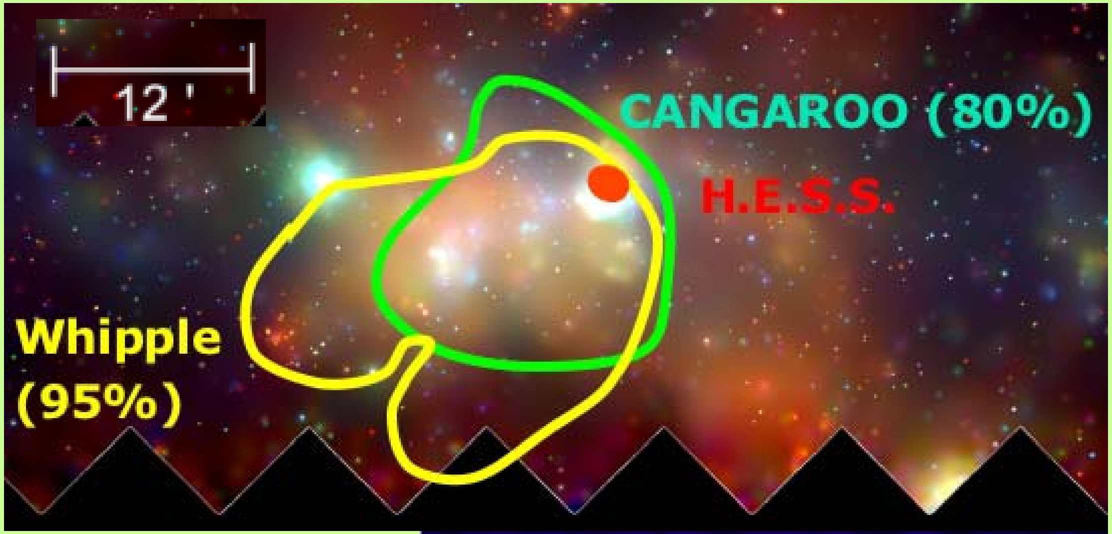


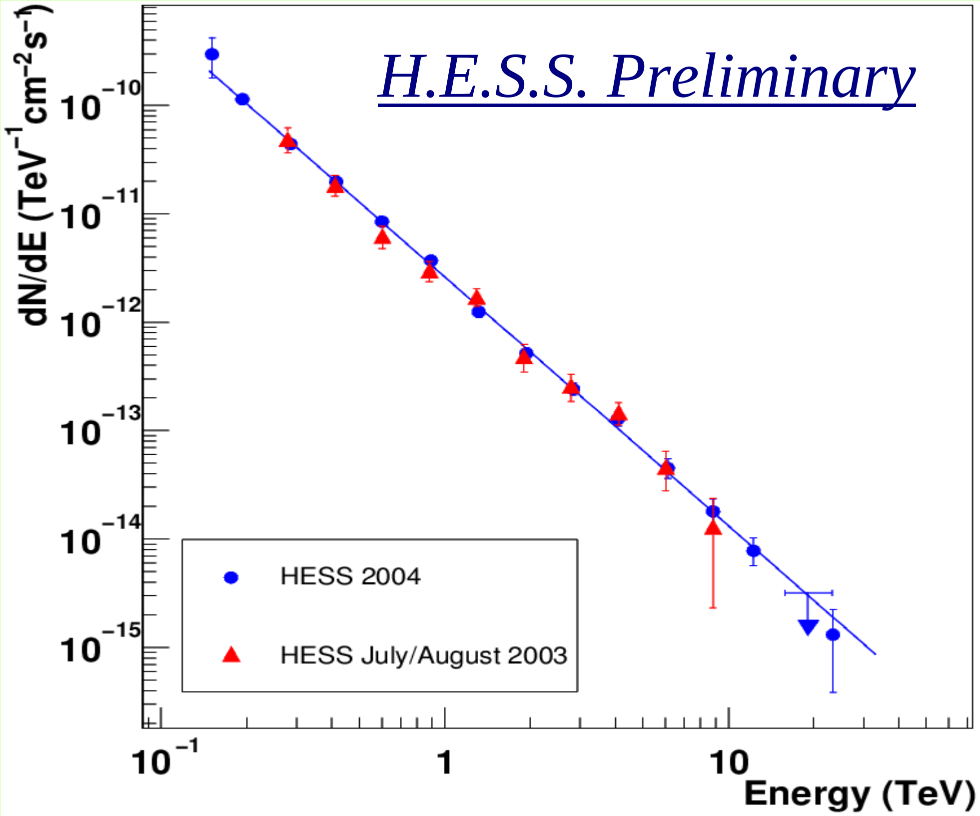


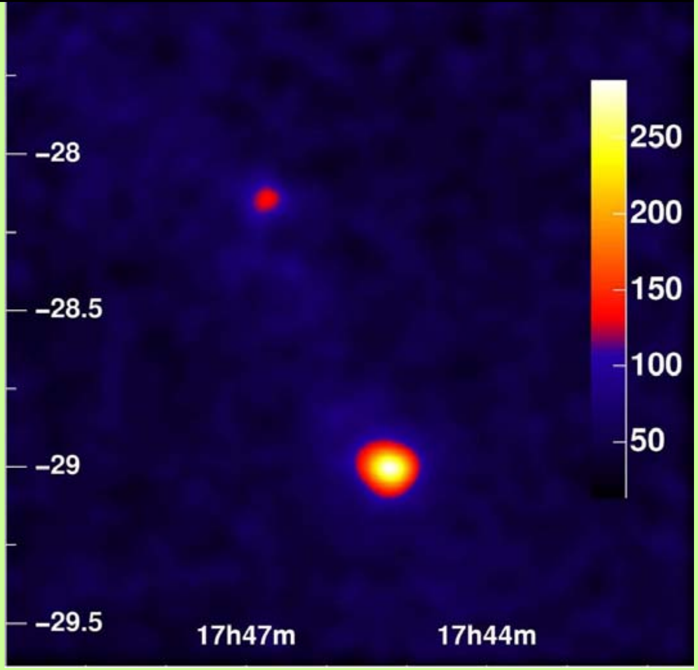


(From Zhao et al.

HESS



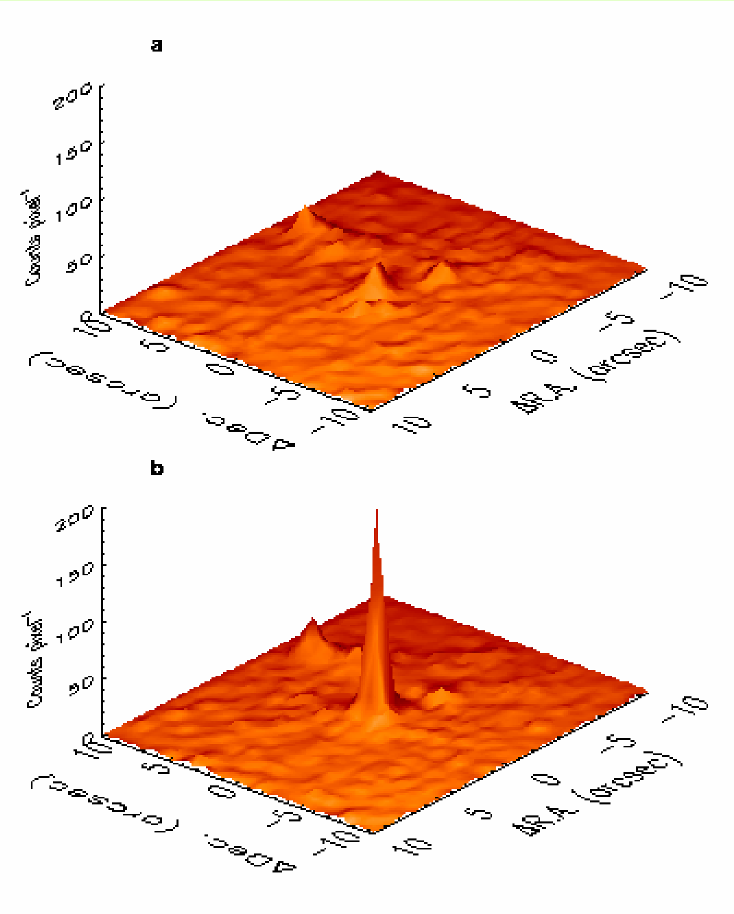


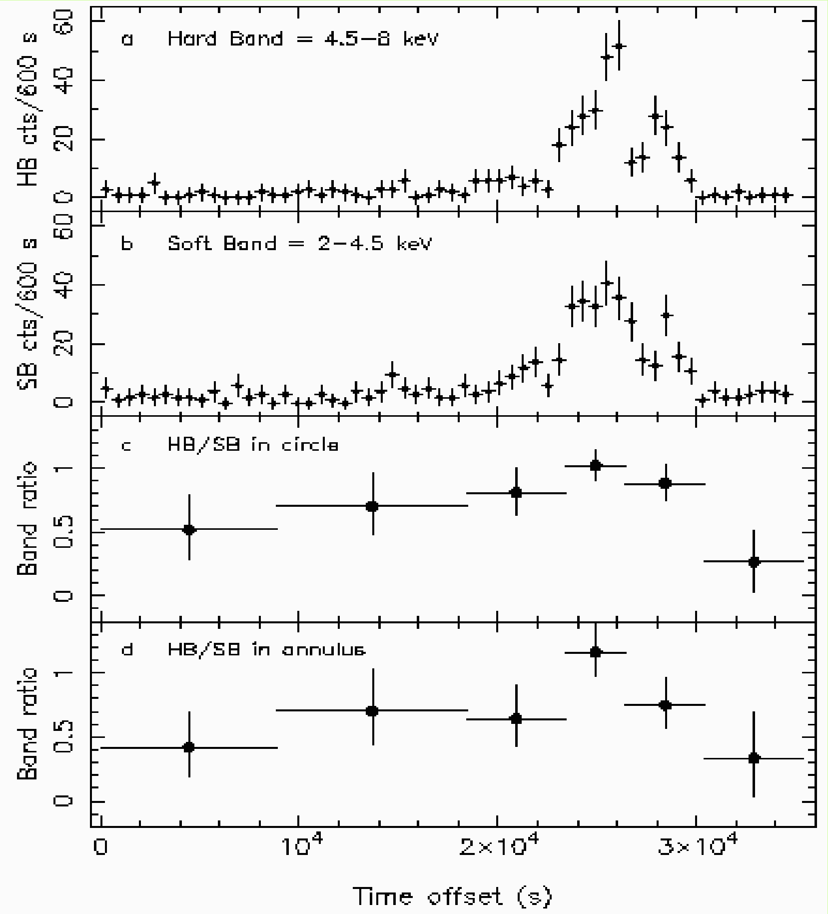


HESS Collaboration 2004

X-ray Flares from Sgr A*

(Baganoff et al. 2001)



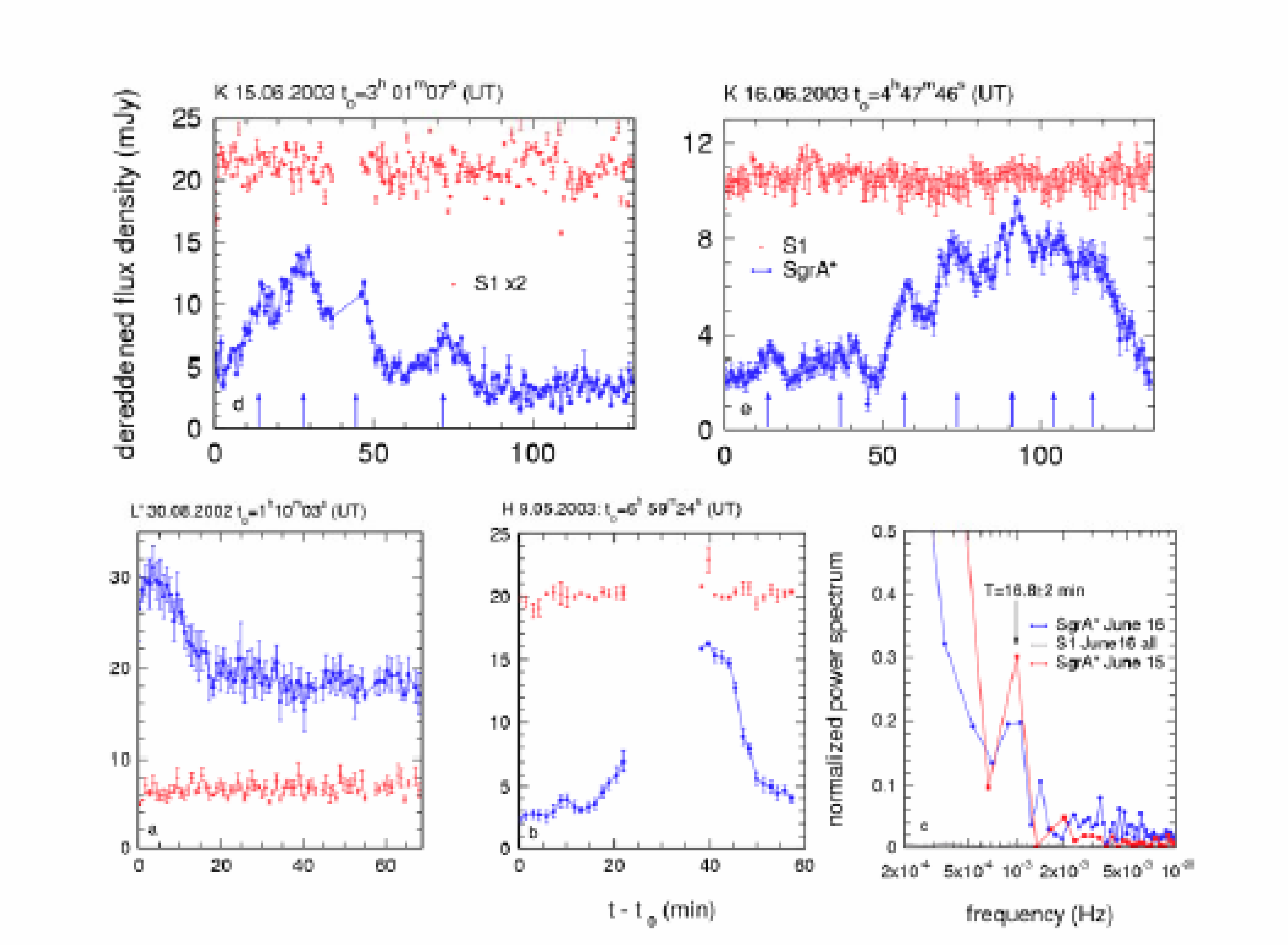


In flare-state, Sgr A*'s X-ray luminosity can increase by more than one order of magnitude.

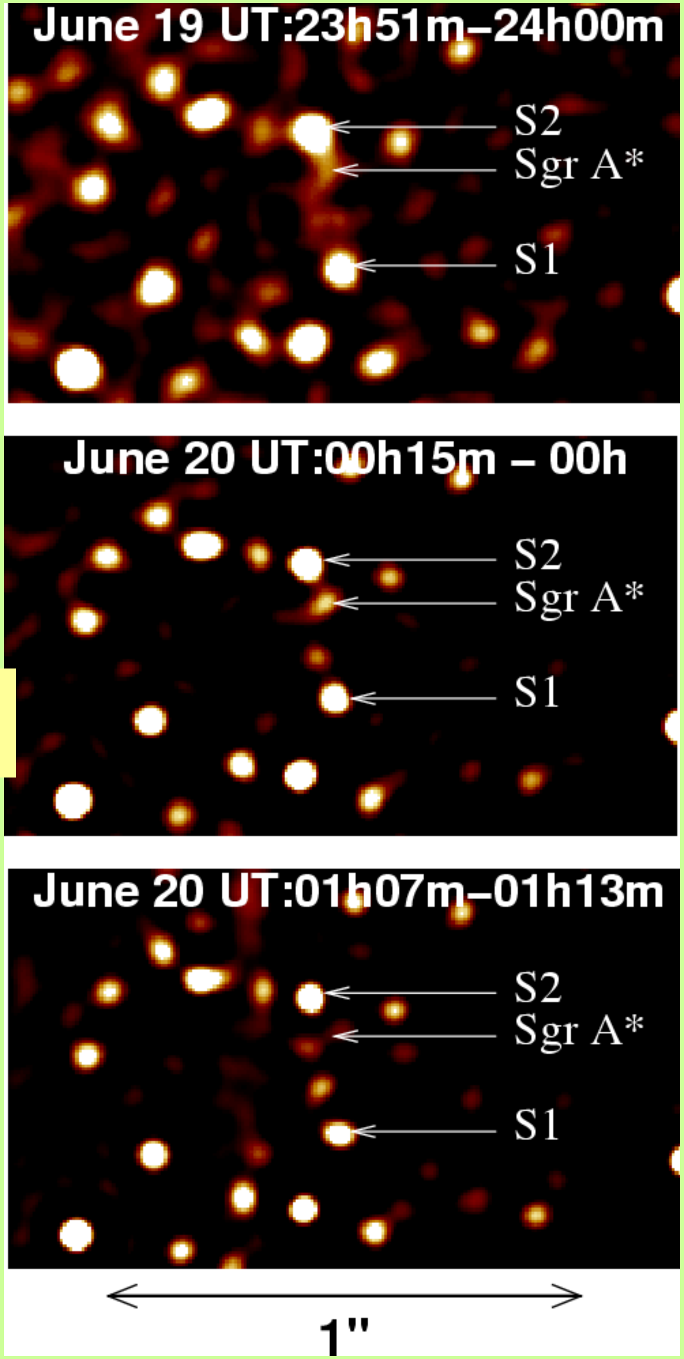
The X-ray flare lasted for a few hours. Significant variation in flux was seen over a 10 minute interval.

NIR Flares From Sgr A*

Quasi-periodic Modulation



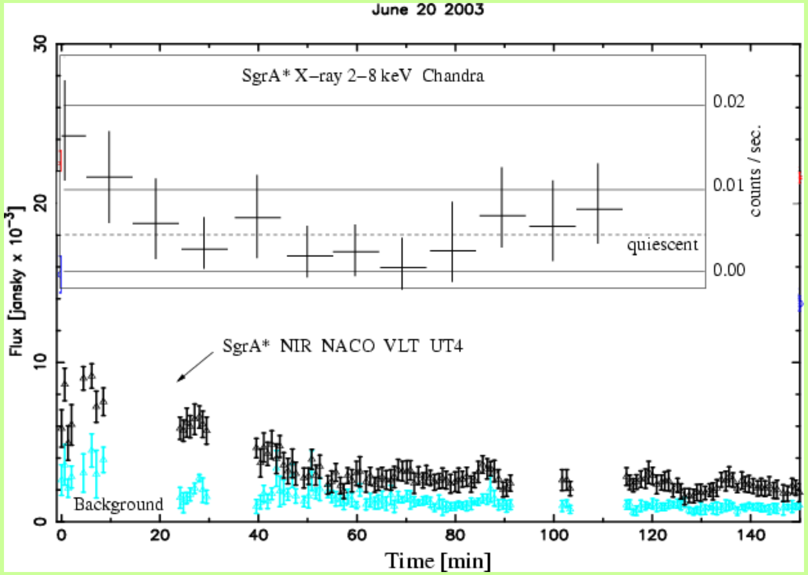
Genzel et al. 2003

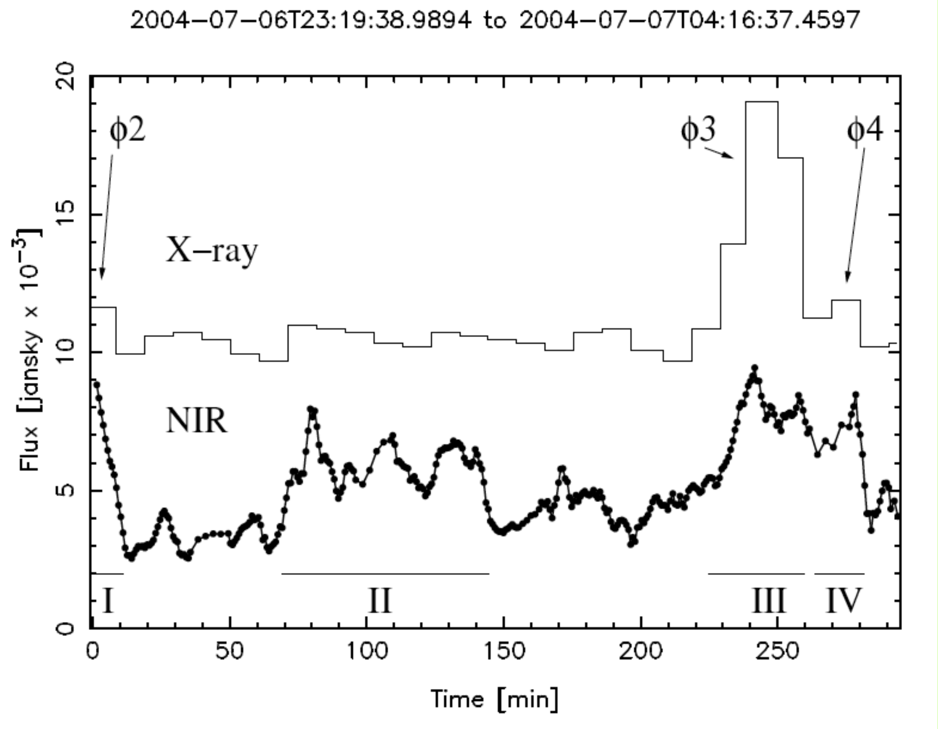


Ghez et al. (2003)

Sgr A* June 2003, NIR/X-ray Flare

Eckart et al. (2004)





Baganoff 2005

$$L_{X-ray} \approx 6\times 10^{33}\ \text{erg/s},\ \ L_{NIR} \approx 5\times 10^{34}\ \text{erg/s}$$

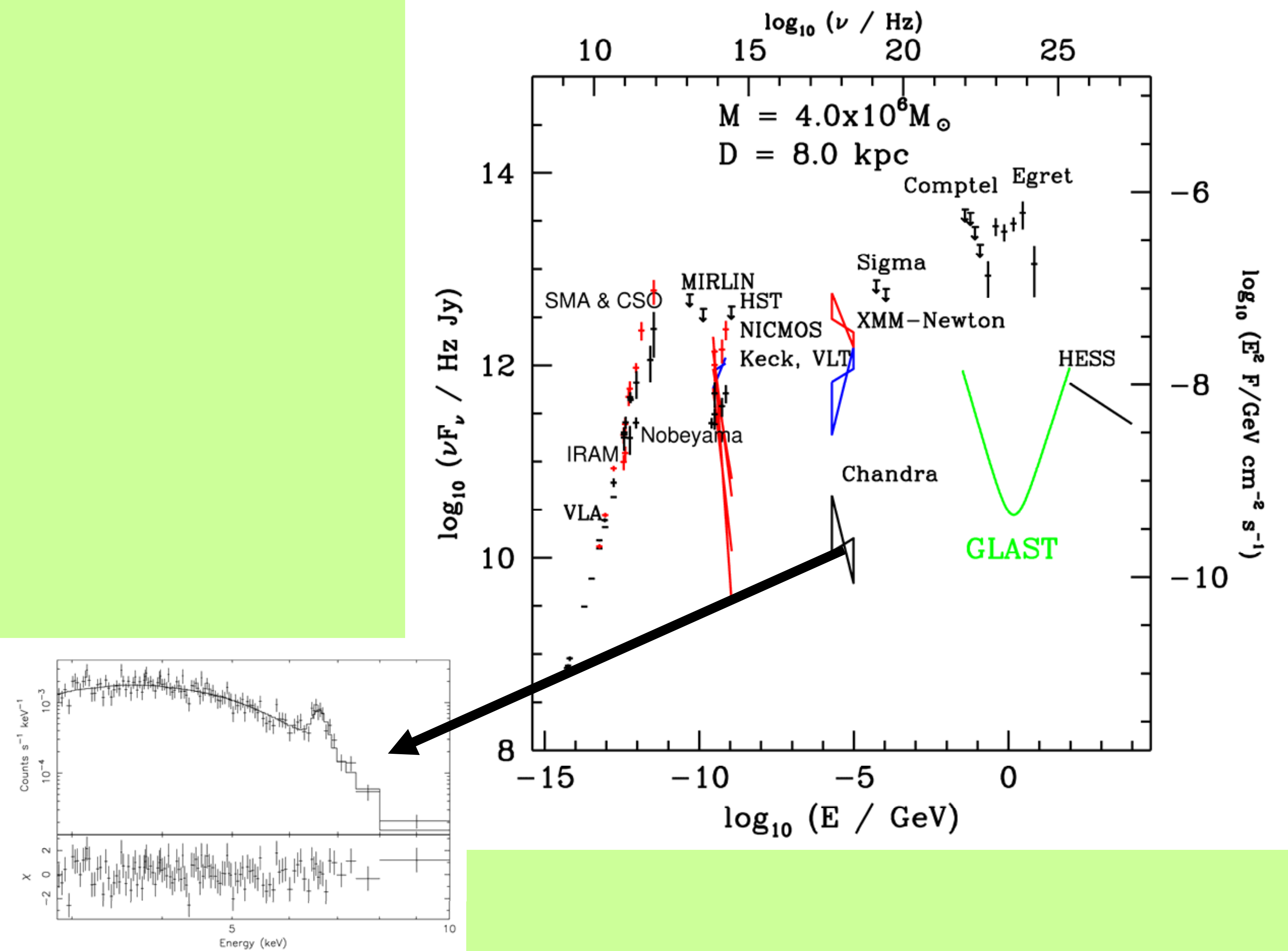
while $L_{EDD} \approx 10^{44}$ erg/s

Emission Mechanisms

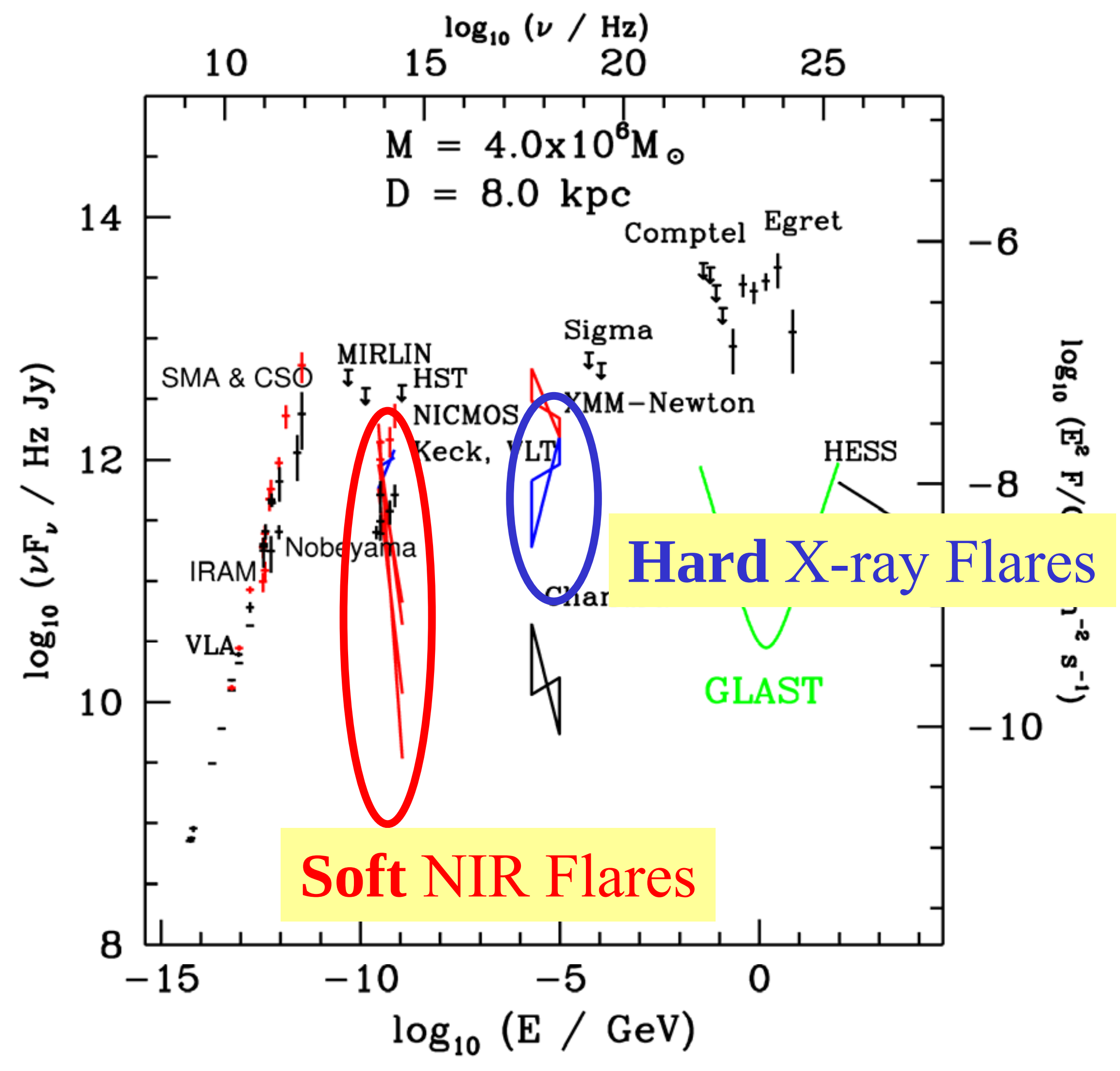
in

Sagittarius A*

Broadband Spectrum



Broadband Spectrum



Hard X-ray Flares

Soft NIR Flares

Emission Mechanisms in General

"Thermal" Synchrotron and SSC:

Four Parameters

B, $k_BT = \gamma_{cr} m_e c^2$, $\mathcal{N}$, $A \approx R^2$

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

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

Thermal Synchrotron Spectrum

$$F_\nu = \frac{4\pi R^3}{3D^2}\mathcal{E}_\nu\,,$$

$$\mathcal{E}_\nu = \frac{\sqrt{3}e^3}{8\pi m_e c^2} B n x_M I(x_M)$$

$$I(x_M) = \frac{4.0505}{x_M^{1/6}}\left(1 + \frac{0.40}{x_M^{1/4}} + \frac{0.5316}{x_M^{1/2}}\right)\exp(-1.8899 x_M^{1/3})$$

$$x_M = \frac{\nu}{\nu_c} = \frac{4\pi m_e c \nu}{3eB\gamma_c^2} = 1412\; C_1^2\; \nu_{14} R_{12}^2\; n_7^2\; B_1^{-1}\,,$$

Thermal Synchrotron and SSC

Details

$$\alpha \equiv \frac{\mathrm{d}\ln(\nu F_\nu)}{\mathrm{d}\ln\nu} = 1.833 - 0.6300 x_M^{1/3} - \frac{0.1000 x_M^{1/4} + 0.2658}{x_M^{1/2} + 0.4000 x_M^{1/4} + 0.5316},$$

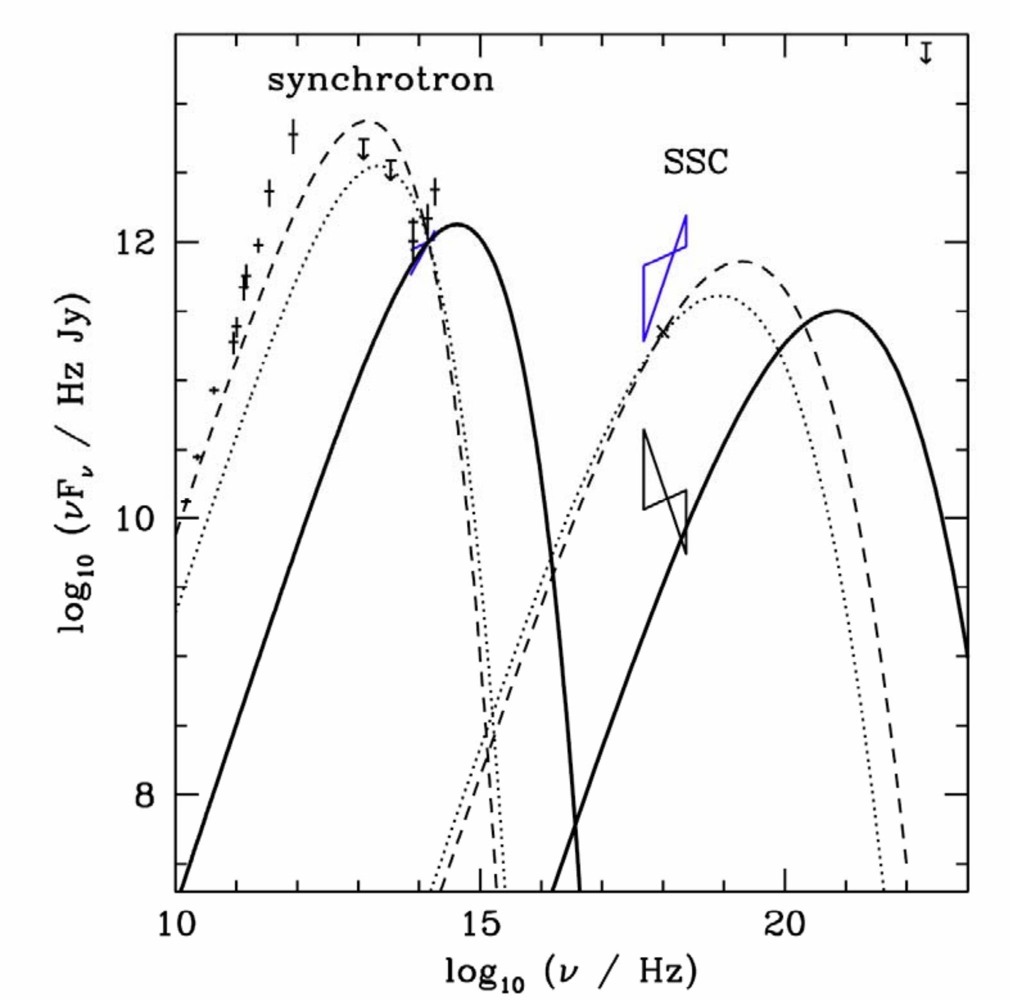
$$F_\nu = \frac{e^3}{2\sqrt{3} m_e c^2} \frac{B n R^3}{D^2} x_M I(x_M) = 639.7\ R_{12}^3\ n_7\ B_1\ D_8^{-2} x_M I(x_M)\ \mathrm{mJy}\,.$$

$$F_X(\nu) \ = \ \frac{2\pi e^7 n^2 B R^4}{3\sqrt{3} m_e^3 c^6 D^2} \frac{\nu}{4\nu_c\gamma_c^2} \int_{\gamma_c^{-1}}^{\infty} \mathrm{d}x \int_0^1 \mathrm{d}y \exp(-x) I\left(\frac{\nu}{4\nu_c\gamma_c^2}\frac{1}{x^2 y}\right)\left(2\ln y + 1 - 2y + \frac{1}{y}\right)$$

$$\simeq \ \ 2.121\ n_7^2\ B_1\ R_{12}^4\ D_8^{-2} G\left(\frac{\nu}{4\nu_c\gamma_c^2}\right) \mu\mathrm{Jy}\,,$$

$$G(z) = z \int_0^\infty \mathrm{d}x \int_0^1 \mathrm{d}y \exp(-x) I\left(\frac{z}{x^2 y}\right)\left(2\ln y + 1 - 2y + \frac{1}{y}\right)$$

Some Example Spectra



Four Observables

Radio Flux

Radio Index

X-ray Flux

X-ray Index

PARTICLE ACCELERATION

in

Galactic Center Quiescent and Flare Sources

ACCELERATION MECHANISMS
General

A: Electric Fields: **Parallel to B Field**

Unstable leads to TURBULENCE

B: Fermi Acceleration

1. Shock or Flow Divergence: **First Order**

   Shocks and Scaterers; i.e. TURBULENCE

2. Stochastic Acceleration: **Second Order**

   Scattering and Acceleration by TURBULENCE

TURBULENCE

PLASMA TURBULENCE AND STOCHASTIC ACCELERATION

1. Generation

$R_e = LV/\nu >> 1,$ $R_m = LV/\eta >> 1$

PLASMA TURBULENCE AND STOCHASTIC ACCELERATION

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2. Cascade: *Nonlinear wave-wave int.*

$$\omega(k_1) + \omega(k_2) = \omega(k_3); \quad k_1 + k_2 = k_3$$

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3. Interactions with Particles: *Resonant int.*

$$\omega = k_{\|} v \mu + n\Omega_i / \gamma$$

Wave-Particle Interactions

- Dominated by Resonant Interactions

$$D_{ij} = \pi e^2 \sum_{n=-\infty}^{+\infty} \int d^3k \langle d_{ij} \rangle \delta\left(\boldsymbol{k} \cdot \boldsymbol{v} - \omega + \frac{n\eta_0}{\gamma} \Omega_0 \right),$$

- Lower energy particles interacting with higher wavevectors or frequencies

2. PLASMA TURBULENCE AND STOCHASTIC ACCELERATION

1. Generation $R_e = LV/\nu >>> 1,$ $R_m = LV/\eta >>> 1$

2. Cascade: *Nonlinear wave-wave int.*

$$\omega(k_1) + \omega(k_2) = \omega(k_3); \quad k_1 + k_2 = k_3$$

3. Interactions with Particles: *Resonant int.*

$$\omega = k_{\|} v\mu + n\Omega_i/\gamma$$

A. Damping of Waves

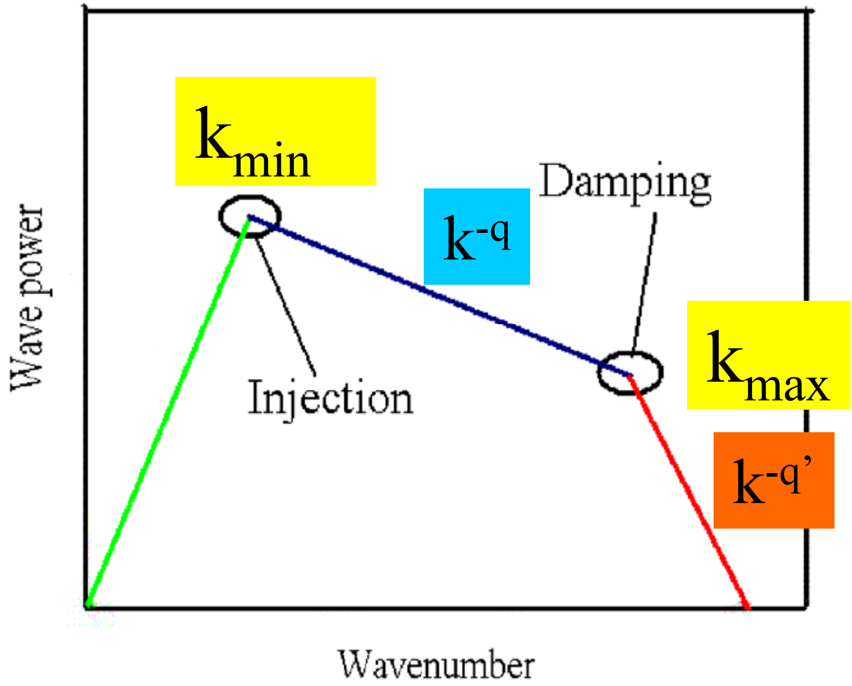
B. Acceleration of Particles

Turbulence Spectrum

$W(k) = ?$

General Features:

- Injection scale: $k_{\min}$
- Cascade and index q
- Damping scale or $k_{\max}$



Kinetic Equation:

$$\frac{\partial W(\mathbf{k},t)}{\partial t} = \dot{Q}_p(\mathbf{k},t) - \gamma(\mathbf{k})W(\mathbf{k},t) + \nabla_i\left[D_{ij}\nabla_j W(\mathbf{k},t)\right] - \frac{W(\mathbf{k},t)}{T^W_{\rm esc}(\mathbf{k})}$$

$\dot{Q}_p(\mathbf{k})$: Rate of wave generation.

$T^W_{\rm esc}$: Wave leakage timescale.

$\gamma(k) = \gamma_e + \gamma_p$: The damping coefficients.

D_{ij}: Wave diffusion tensor.

COUPLED EQUATIONS

1. Kinetic Equations

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left[D_{EE}\frac{\partial N}{\partial E} - (A - \dot{E}_L)N\right] - \frac{N}{T^{p}_{\rm esc}} + \dot{Q}^{p}$$

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k_i}\left[D_{ij}\frac{\partial}{\partial k_j}W\right] - \Gamma(\mathbf{k})W - \frac{W}{T^{W}_{\rm esc}(\mathbf{k})} + \dot{Q}^{W}$$

2. Energy Balance

$$\dot{\mathcal{W}}_{nonth} \equiv \int \Gamma_{nonth}(\mathbf{k})W(\mathbf{k})d^3k = \dot{\mathcal{E}} \equiv \int A(E)N(E)dE$$

3. Rate Coefficients

$$A(E) = \frac{d[vp^2D(p)]}{4p^2dp} = \int_{k_{min}}^{\infty} d^3k W(\mathbf{k})\Sigma(\mathbf{k}, E)$$

$$\Gamma_{nonth}(\mathbf{k}) = \int_{E_0}^{\infty} dE N(E)\Sigma(\mathbf{k}, E)$$

Model Parameters

In principle:

Density	n
Temperature	T
Magnetic Field	B
Scale (geometry)	R
Level of Turbulence	

$(\delta B / B)^2$ *or* $(\delta v / v_{Alfven})^2$

Kinetic Equation Coefficients

Acceleration rate or time: τ_{ac}

Loss rate or time: τ_{loss}

Escape rate or time: T_{esc}

Characteristic Times:

$$\tau_p^{-1} \propto \Omega_e (\delta B / B)^2 \text{ and } T_{cross} \approx R / \sqrt{2} v$$

Quiescent radio and X-ray emissions

Timescales

And Spectra

For 3 models

Model A:

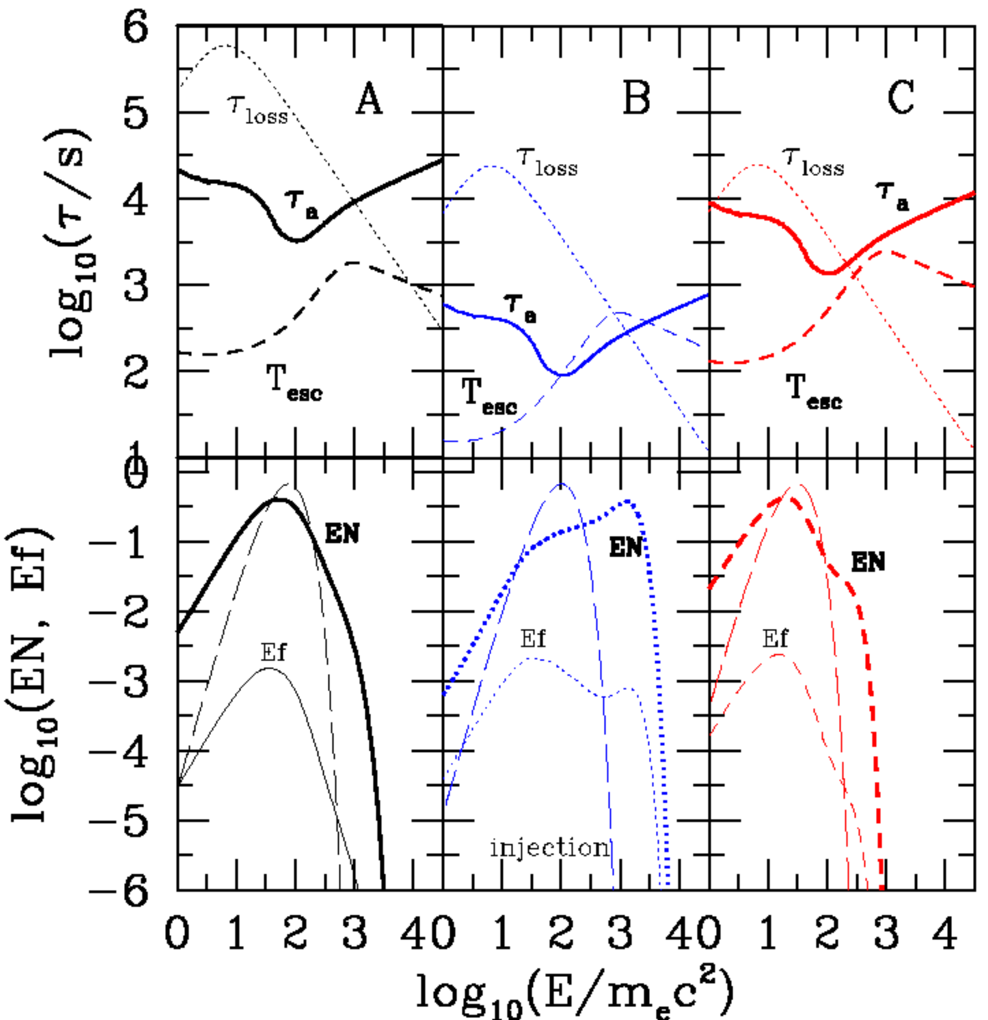
$R / r_s = 2.5$

$n = 0.7 \times 10\char94 7 \text{ cm}^{-3}$

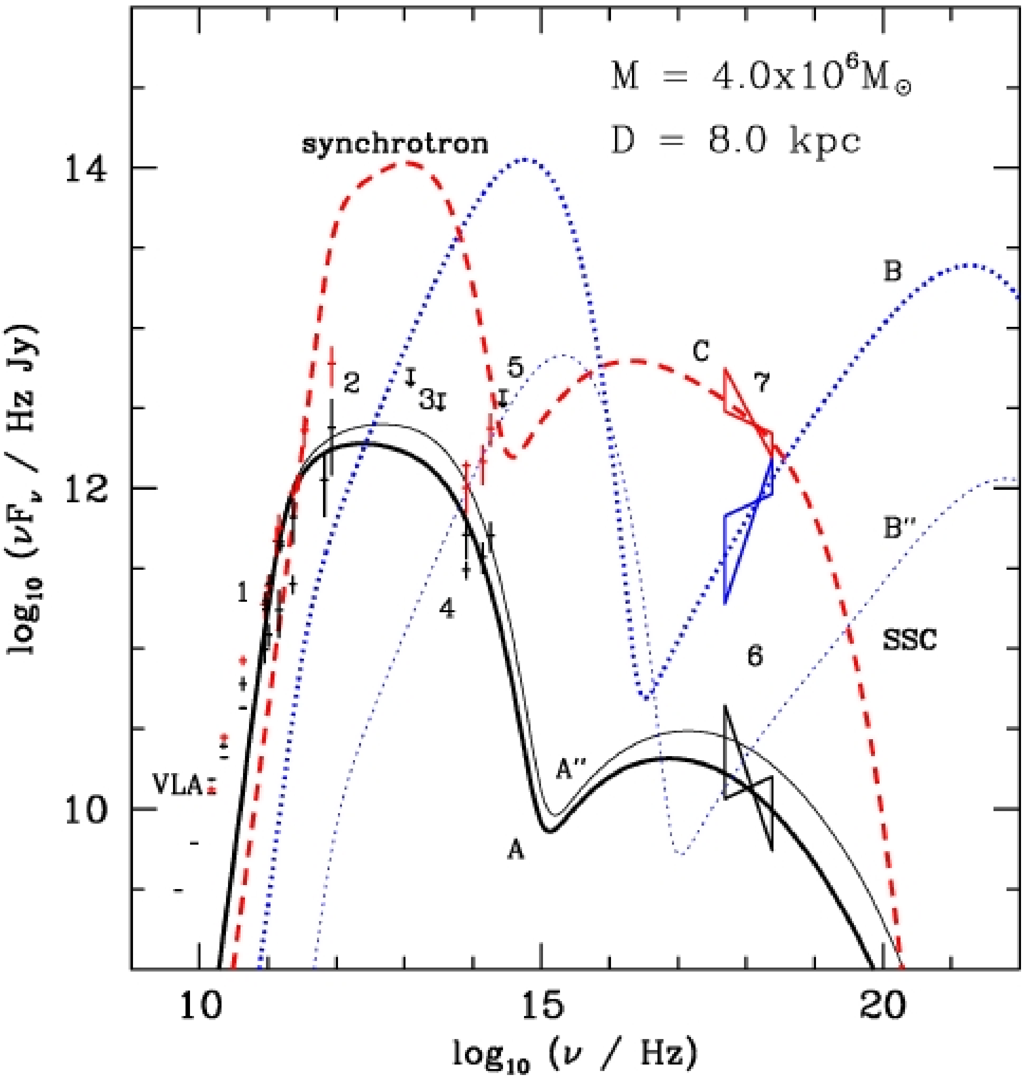
$B = 8.8 \text{ Gauss}$

$\tau_p^{-1} = 0.8 \sec^{-1}$

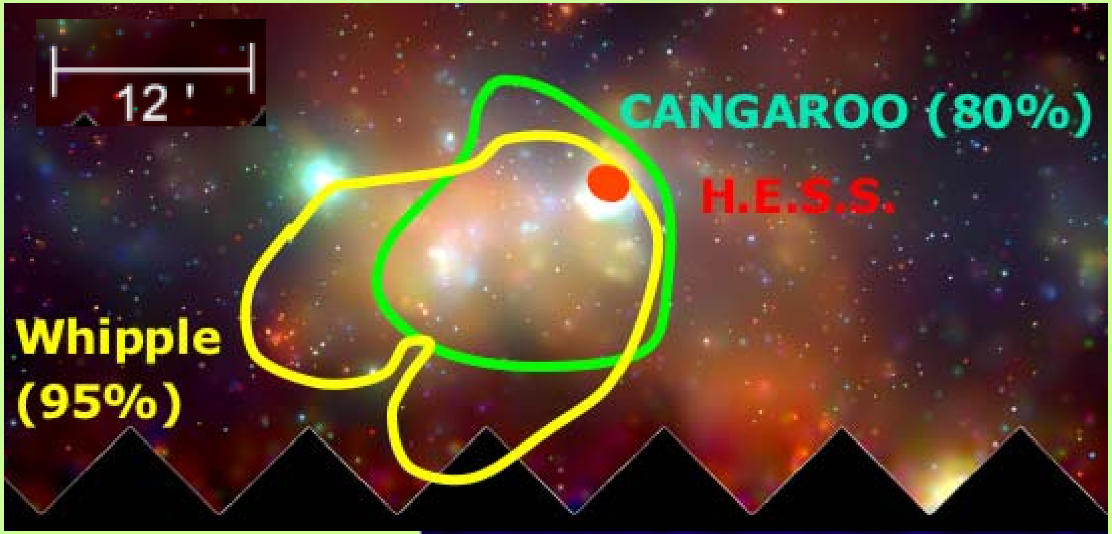
$k_b T = 26 mc^2$

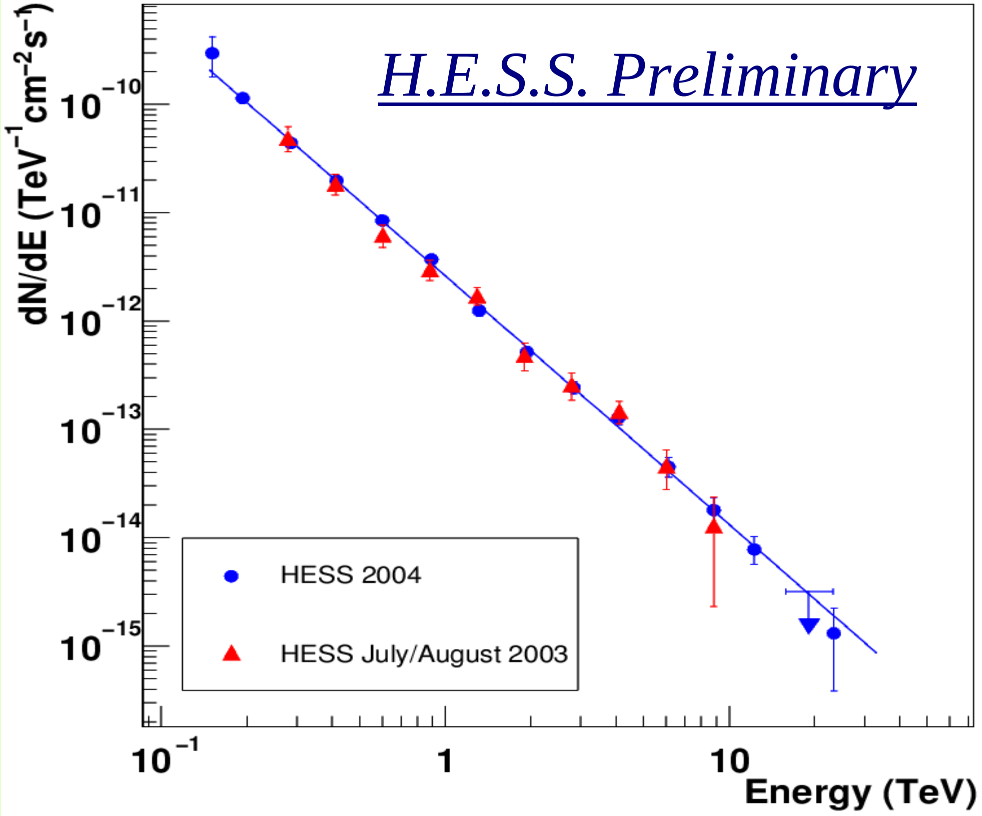


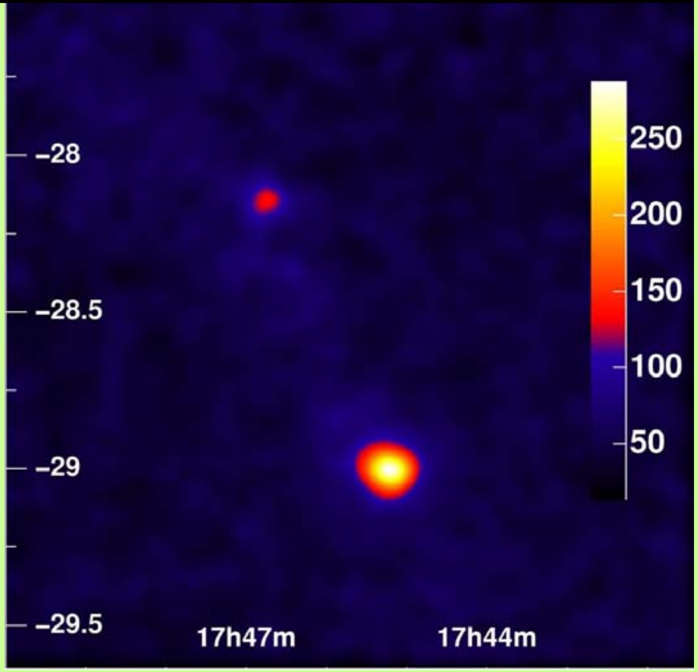
Emission by Accelerated Electrons



HESS

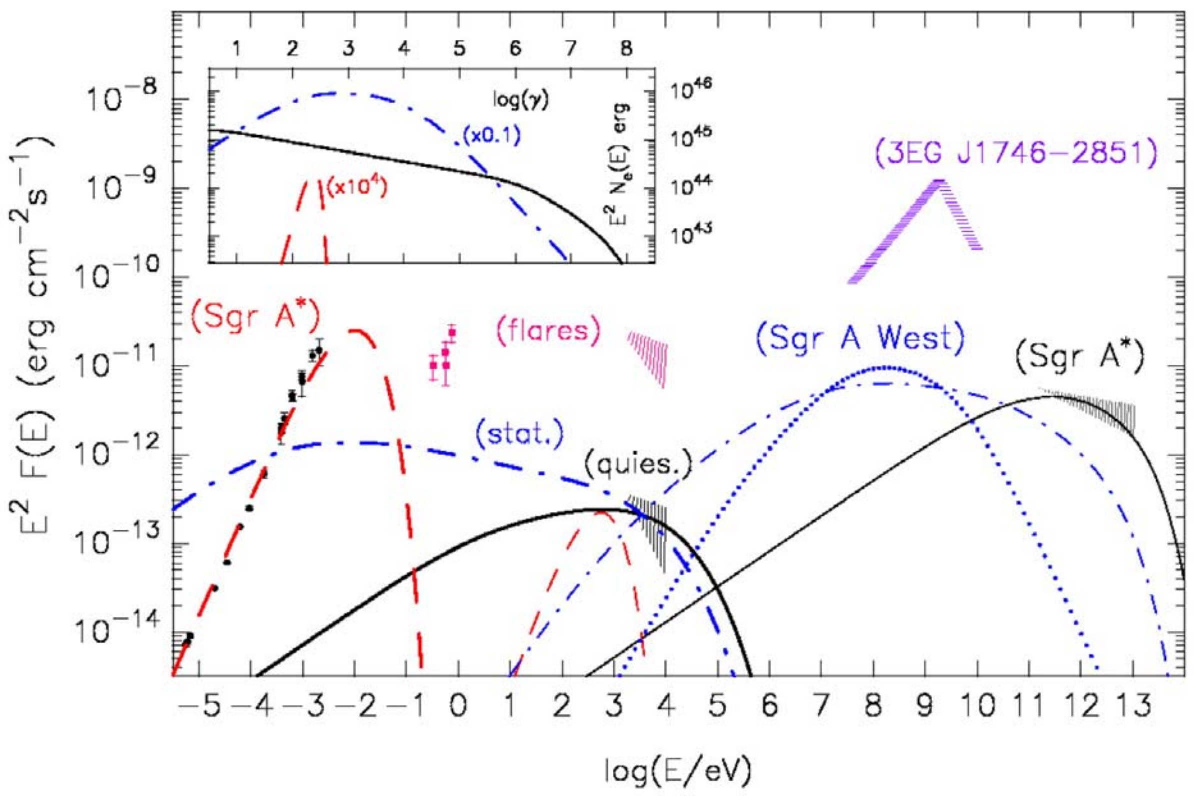






HESS Collaboration 2004

Possible Explanations
Synchrotron Self-Comptonization

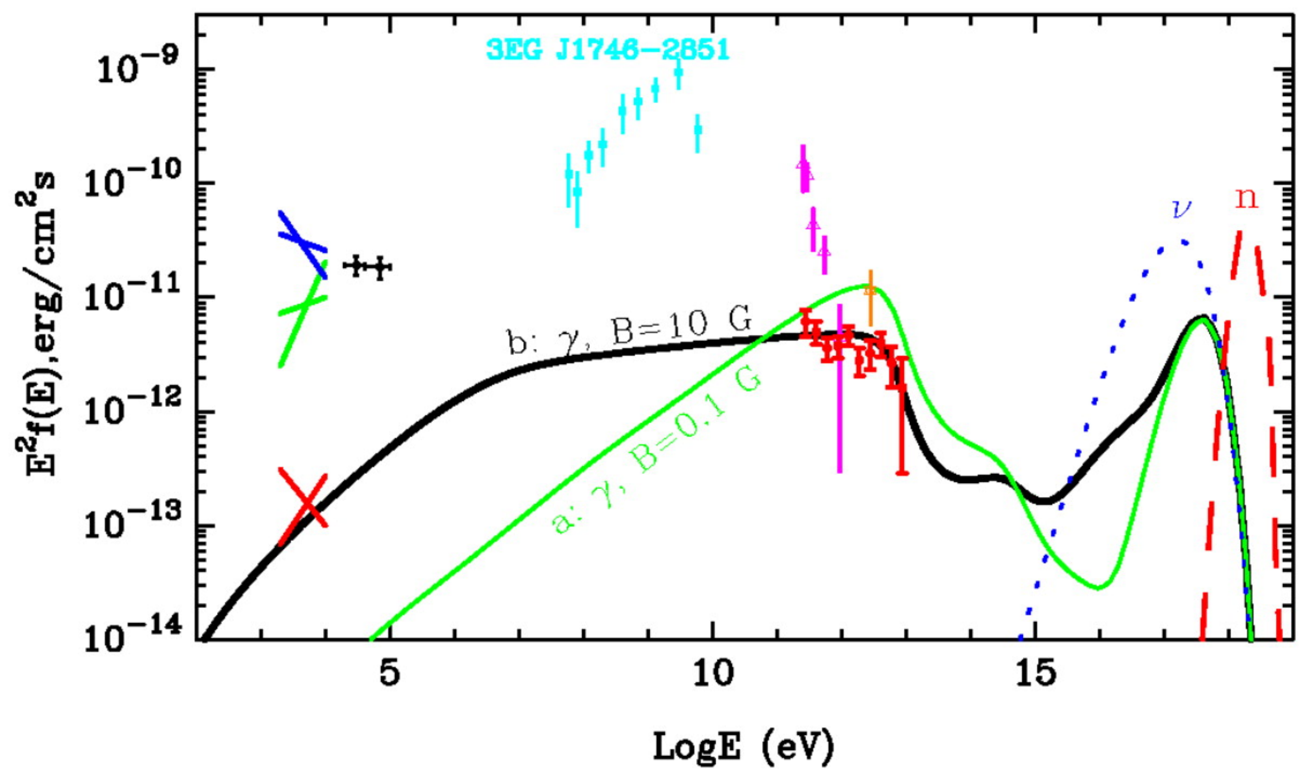


B=90μG

Atoyan and Dermer 2004, ApJ, 617, 123

Possible Explanations

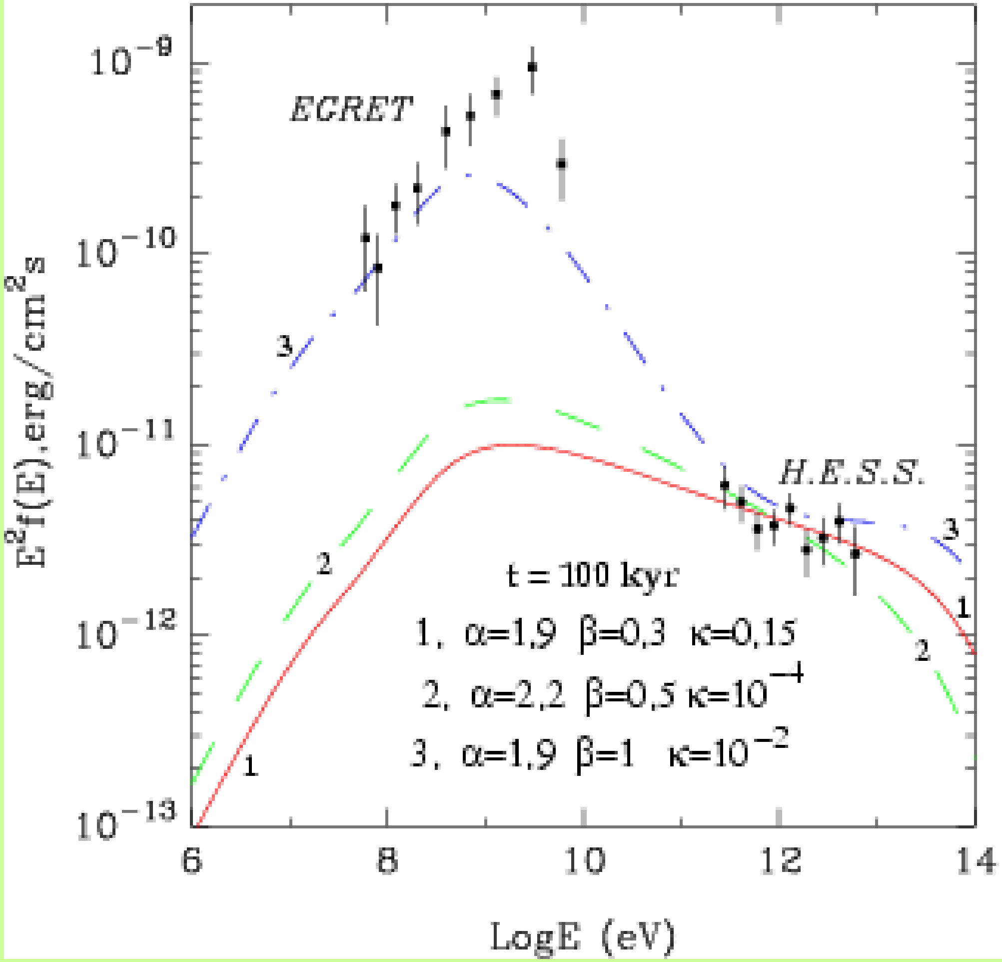
Photo-Meson Interactions



E>10^{18}eV

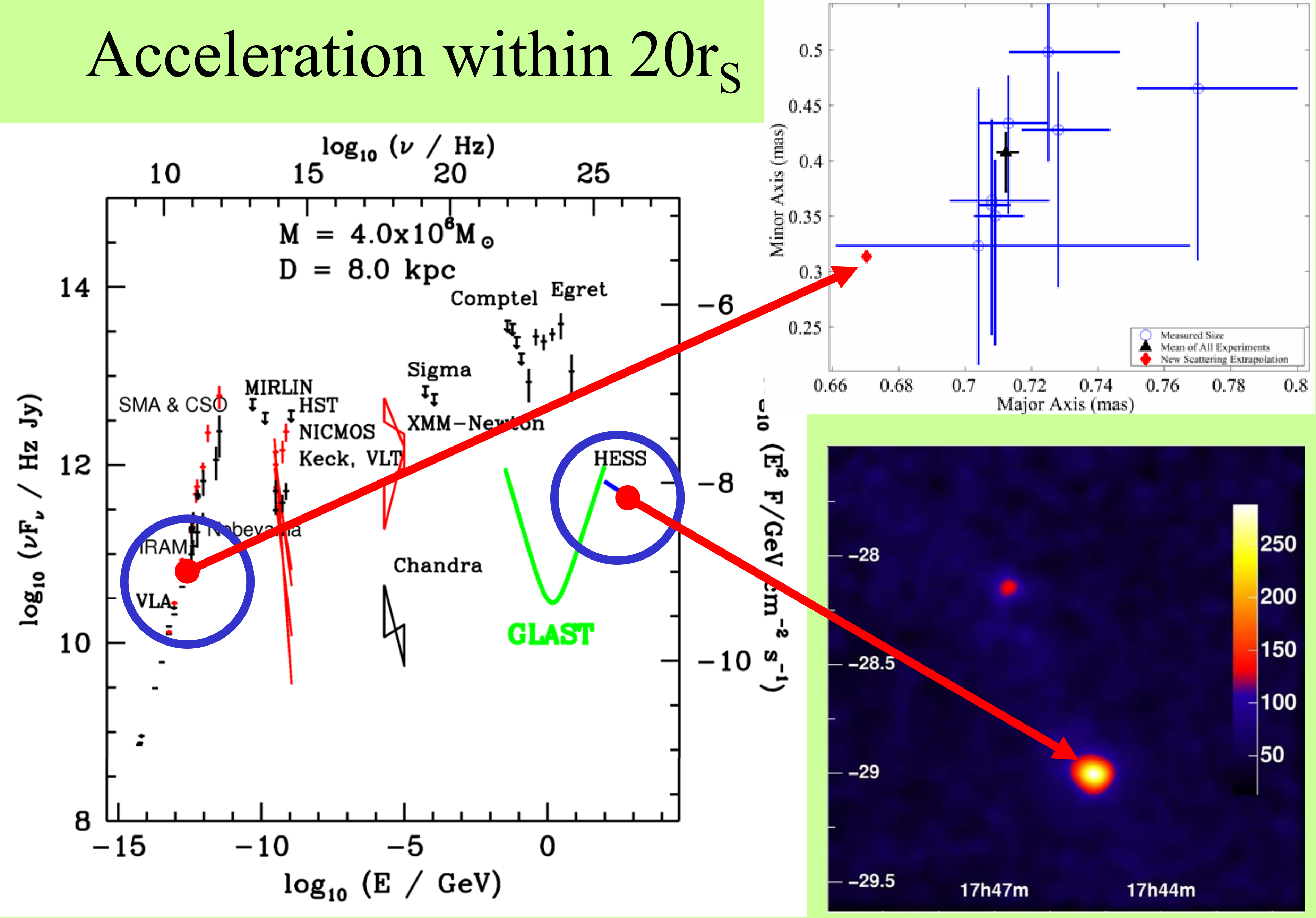
Aharonian et al 2005, ApJ, 619, 306

Possible Explanations
Proton-Proton Interactions

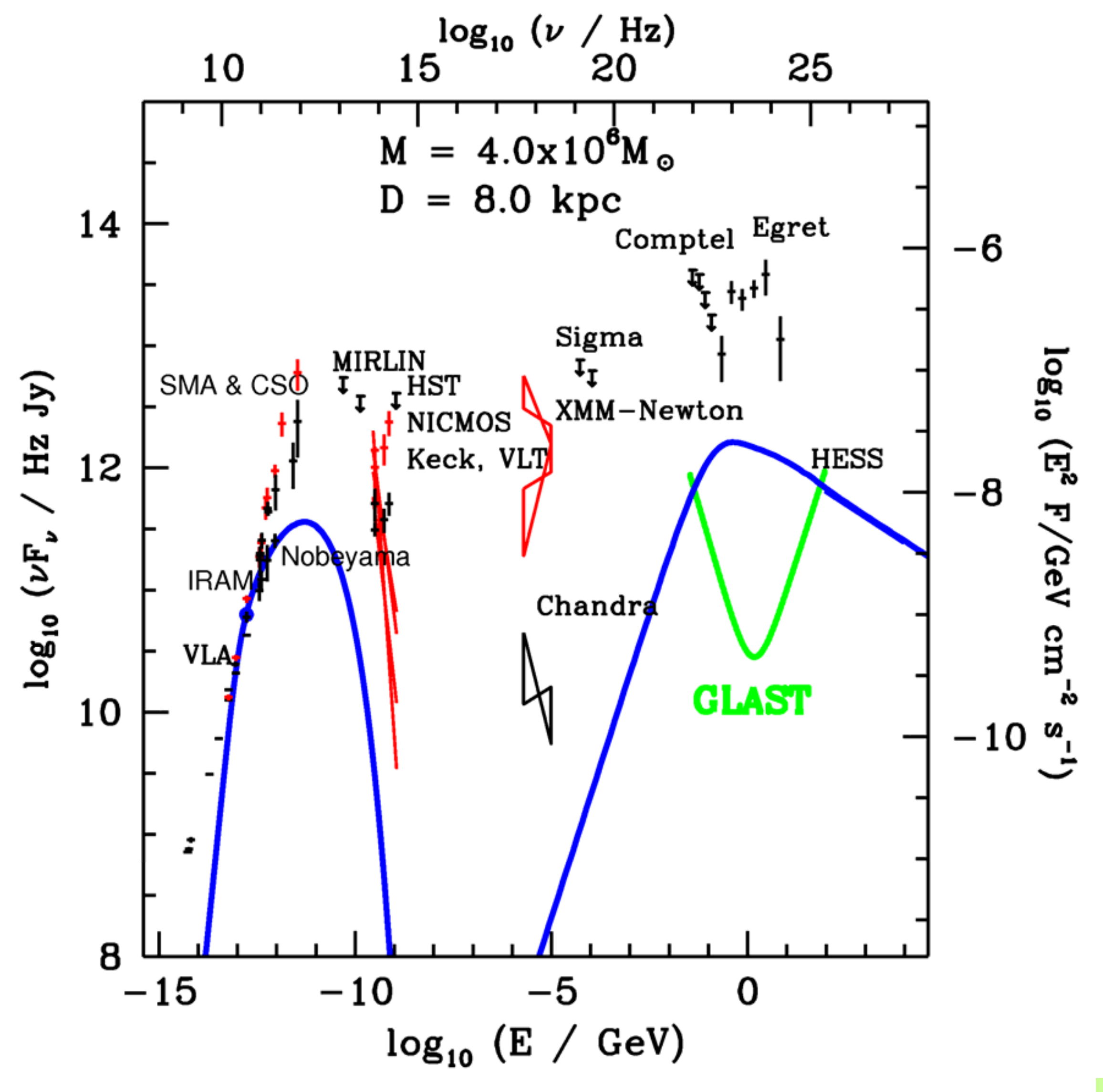


Aharonian et al 2005, ApJ, 619, 306; Liu et al. 2006

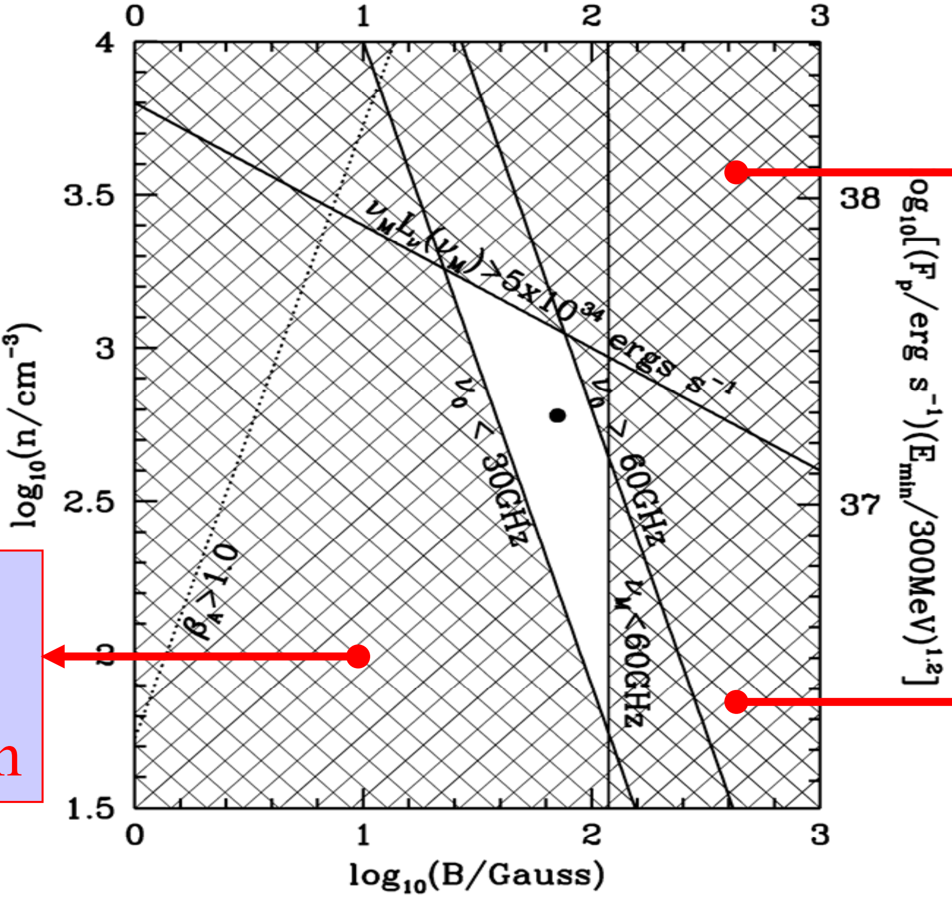
Acceleration within $20r_S$



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

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

Summary

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.

Electron Acceleration

During

NIR and X-ray Flares

Acceleration Scenario for Flares

Simplify the model: Simpler Kinetic Equation

Parametric approach: $\tau_{ac} = \text{const.},\ L_{turb} \approx L_{Synch}$

One less parameter: $f_{turb} = (\delta B / B)^2 \approx 1$

Stochastic Electron Acceleration

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

$$\boxed{\tau_{\rm ac} = \frac{C_1}{f_{\rm turb}} \frac{cR}{v_{\rm A}^2}}$$

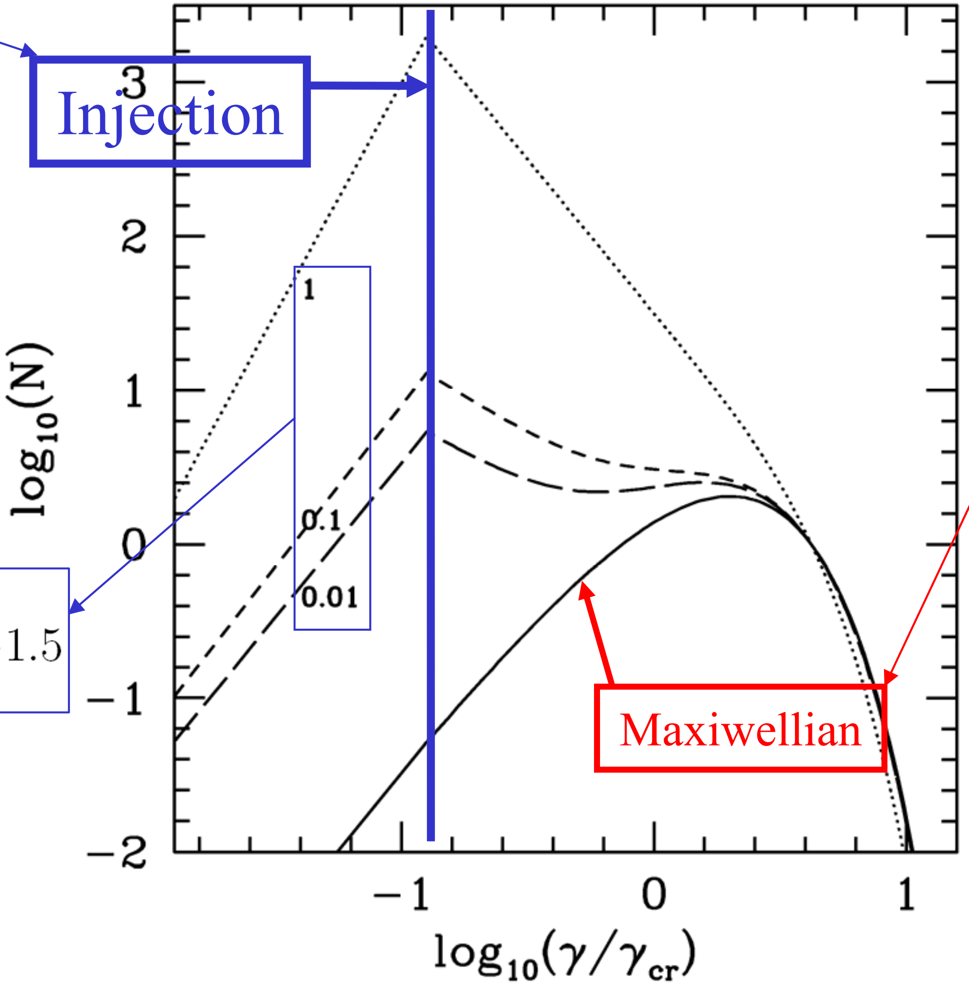
$$\boxed{\tau_{\rm syn}(\gamma) = 9 m_e^3 c^5 / 4 e^4 B^2 \gamma = \tau_0 / \gamma}$$

$$\boxed{\gamma_{cr} = \frac{\tau_0}{4\tau_{\rm ac}} = \frac{9 m_e^3 c^4 v_{\rm A}^2 f_{\rm turb}}{16 e^4 R B^2 C_1} = 30 \left(\frac{R}{r_S}\right)^{-1} \left(\frac{n}{10^7\ {\rm cm}^{-1}}\right)^{-1} \left(\frac{f_{\rm turb}}{C_1}\right)}$$

Stochastic Electron Acceleration

Continuous injection, heating, & cooling.

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



Without injection: Continuous heating and cooling

Stochastic Electron Acceleration

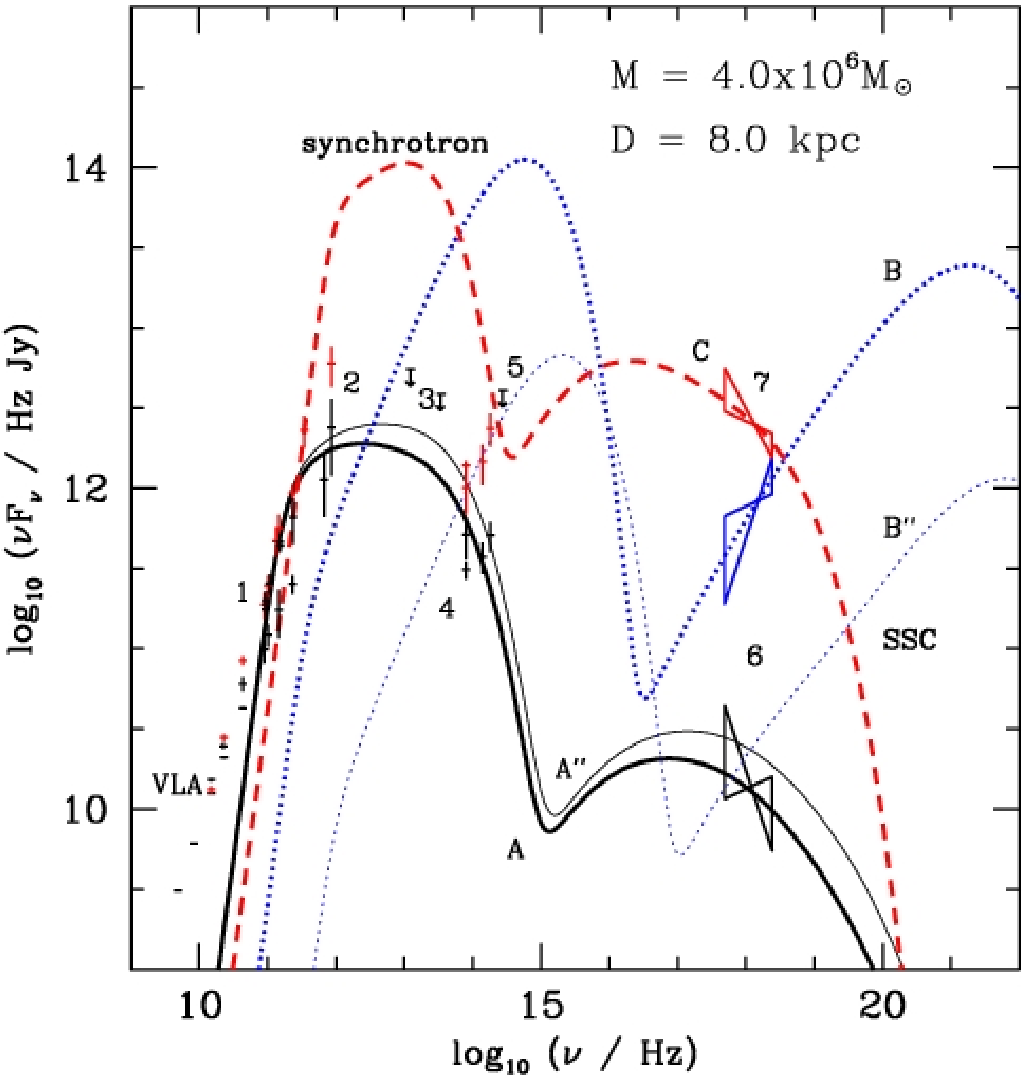
$$\mathcal{L}_{\rm Turb} = C_2 v_{\rm A} B^2 R^2 = 6.901 \times 10^{34} C_2 \; R_{12}^2 \; n_7^{-1/2} B_1^3 \;{\rm ergs\ s}^{-1}$$

$$\mathcal{L}_{\rm syn} = \frac{64\pi e^4}{9 m_e^2 c^3} \; n \; R^3 B^2 \gamma_c^2 = 8.949 \times 10^{34} C_1^{-2} R_{12} \; n_7^{-1} B_1^2 \;{\rm ergs\ s}^{-1}$$

$$R_{12} \; n_7^{1/2} B_1 = 1.297 \; C_1^{-2} C_2^{-1} \,,$$

$$\gamma_c = \tau_0 / \tau_{\rm ac} = 41.08 \; C_1^{-1} R_{12}^{-1} n_7^{-1}$$

Emission by Accelerated Electrons



Example

$\alpha = 0.5,\ \nu_{14} = 1.429,$ $F_\nu = 7\ \mathrm{mJy}.$

$$R_{12} = 0.08471\, C_1^2 C_2^{6/7} D_8^{10/7}$$

$$n_7 = 2.266\, C_1^{-4} C_2^{-10/7} D_8^{-12/7}$$

$$B_1 = 10.17\, C_1^{-2} C_2^{-8/7} D_8^{-4/7} \left(\frac{x_{Mo}}{7.311}\right)^{-1/7}$$

$$\gamma_c = 214.0\, C_1 C_2^{4/7} D_8^{2/7}$$

Example

$$\tau_{\rm ac} = 5.845 C_1^3 \, C_2^{12/7} \, D_8^{6/7} \ {\rm mins}$$

$$\tau_\nu = 1.784 \times 10^{-7} C_1^{-5} C_2^{-16/7} D_8^{-8/7}$$

$$U \simeq \frac{\mathcal{L}_{\rm syn}}{4\pi c \, R^2} = 127.9 C_1^{-4} C_2^{-12/7} D_8^{-6/7}$$

$$\begin{aligned} \alpha_X(z) &= 1.1\,, \\ F_X(z) &= 0.0033\,\mu{\rm Jy} \end{aligned}$$

Implications

Thermal Synchrotron Sources

$$R_{12}\, n_7^{1/2} B_1 = 1.297\, C_1^{-2} C_2^{-1}\,,$$

$$\gamma_c = \tau_0/\tau_{\rm ac} = 41.08\, C_1^{-1} R_{12}^{-1} n_7^{-1}$$

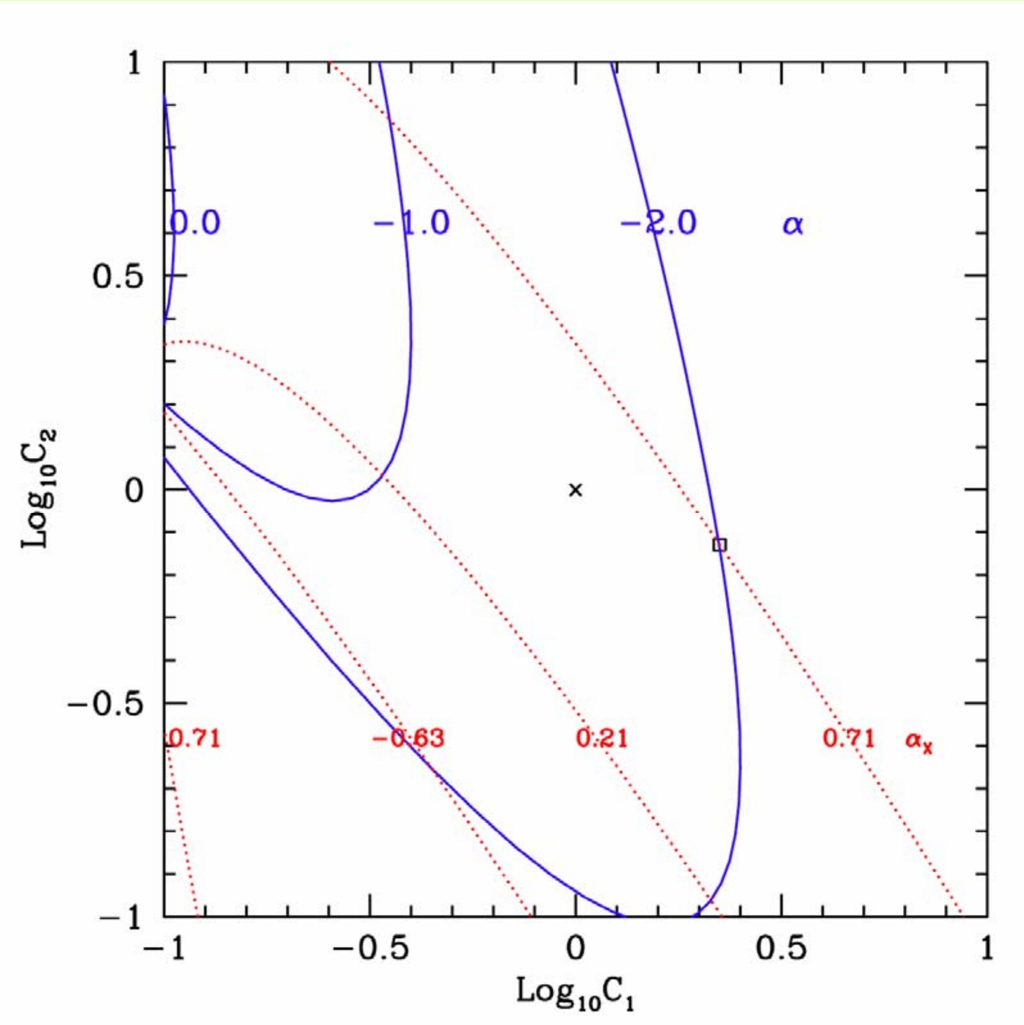
Can be generalized to Comptonization dominant sources e.g., X-ray binaries, to address the coupling of electrons and protons via turbulence

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma}\left[\frac{\gamma^4}{\tau_{\rm ac}}\frac{\partial \gamma^{-2} N}{\partial \gamma} + \frac{\gamma^2}{\tau_0} N\right]$$

Constraining C_1 and C_2

F_ν=12mJy

$F_x = 0.22\mu$Jy

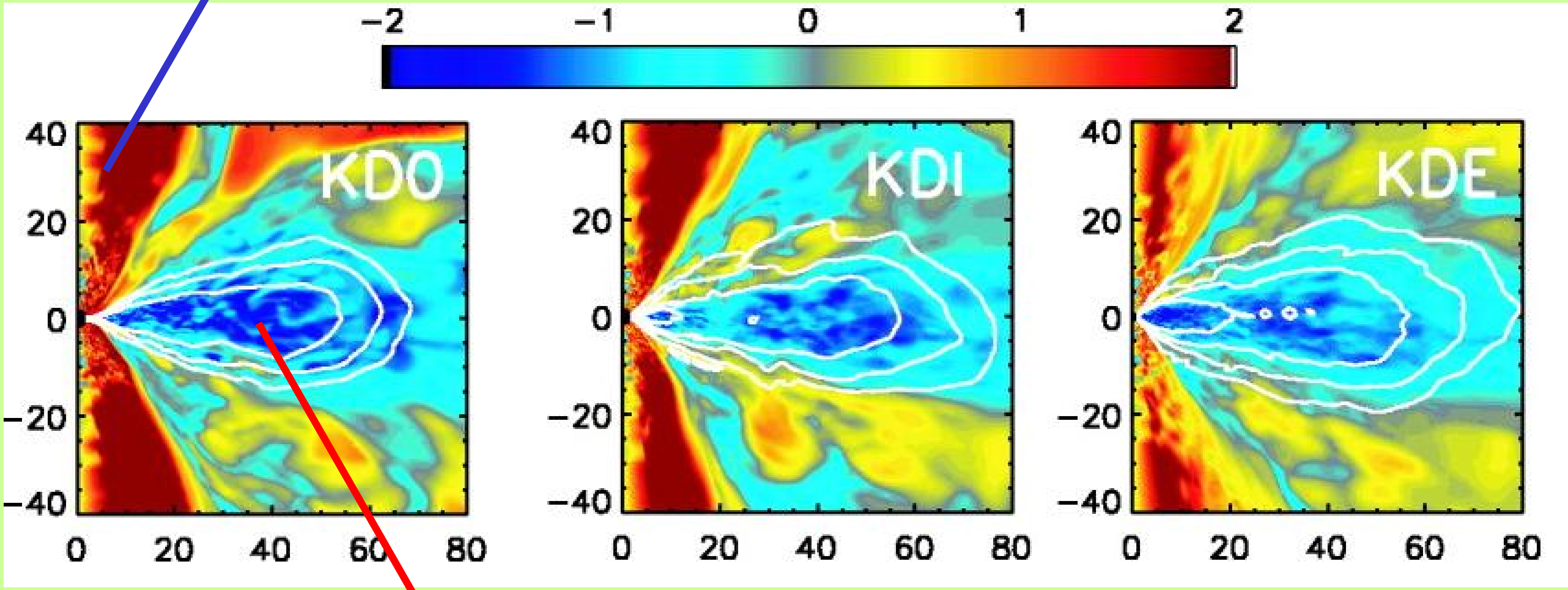


Summary

- Flares from Sgr A* are produced near the event horizon of the black hole
- NIR and X-ray emissions are produced via thermal synchrotron and SSC by energetic electrons accelerated by plasma waves.
- The observed NIR or X-ray fluxes and spectral indexes can be used to measure B, R, n, and T, which will result in a better understanding of the flare energizing mechanism and may lead to a measurement of the black hole spin.

Structure of the Accretion Flow

cm and mm via Synchrotron and proton acceleration



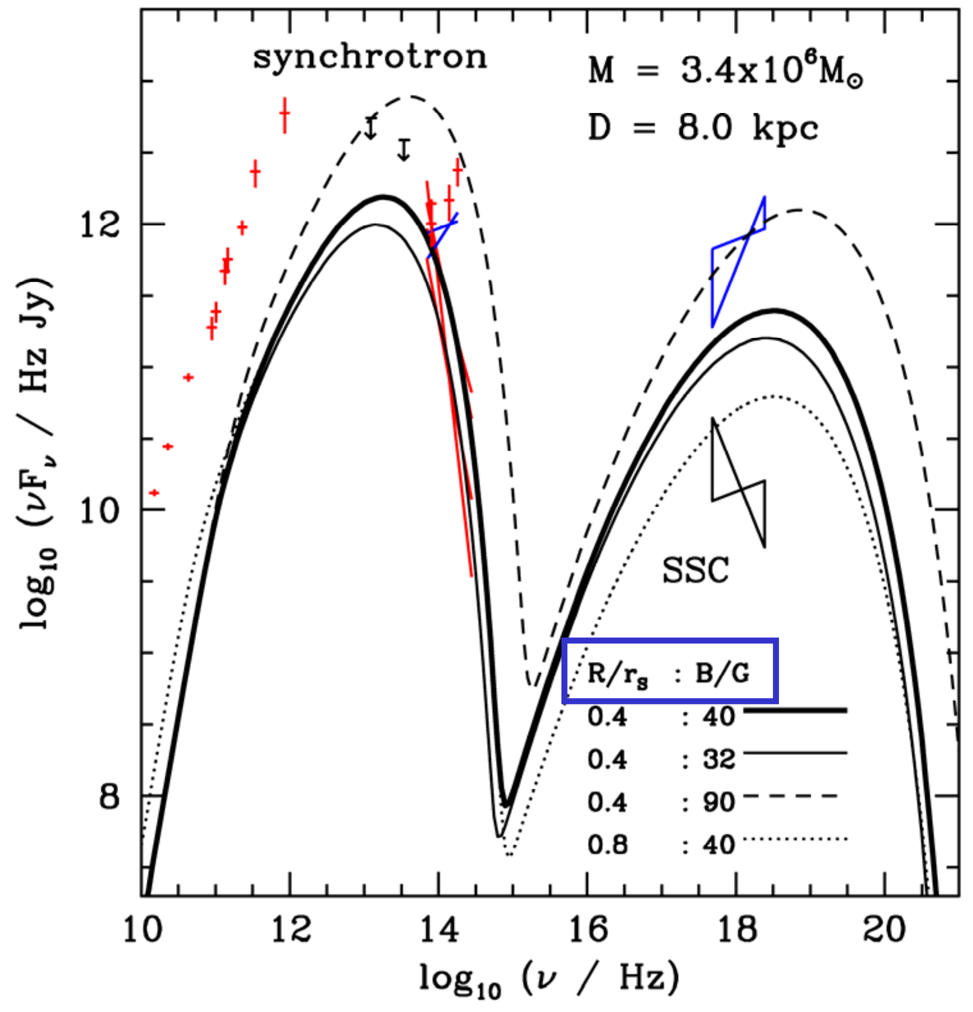
Sub-mm, NIR, and X-ray via Synchrotron and SSC

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 the black hole and its accretion flows.

Emission Processes During Flares



Thermal Synchrotron and SSC:

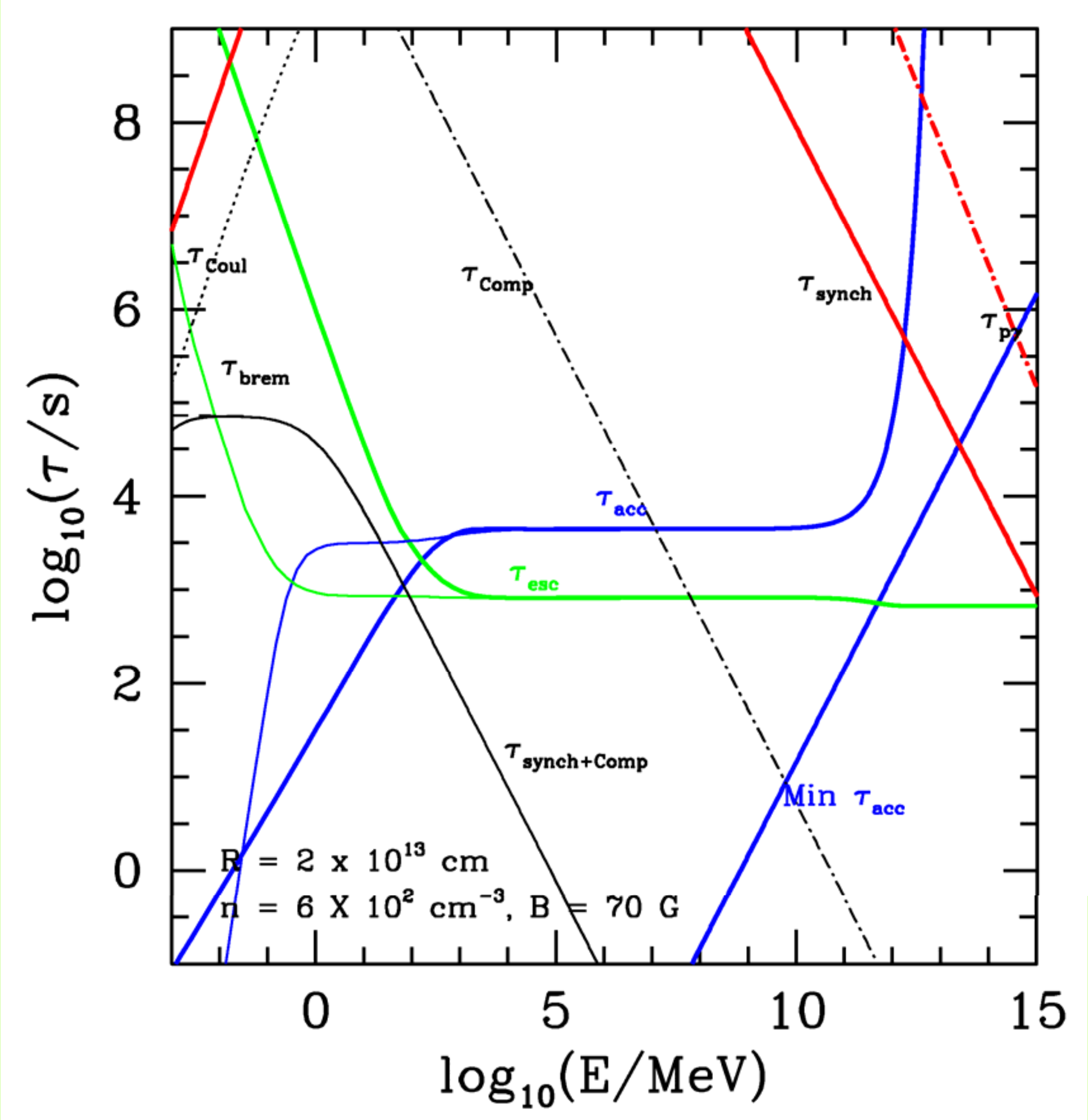
Four Parameters

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

$k_B T = 75 m_e c^2$

Liu et al. 2006

TIMESCALES


τ_{Coul}
τ_{Comp}
τ_{synch}
$\tau_{\mathrm{p\gamma}}$
τ_{brem}
τ_{acc}
τ_{esc}
$\tau_{\mathrm{synch+Comp}}$
Min τ_{acc}
$R = 2 \times 10^{13}$ cm
$n = 6 \times 10^{2}$ cm^{-3}, $B = 70$ G
$\log_{10}(\tau/\mathrm{s})$
8
6
4
2
0
$\log_{10}(E/\mathrm{MeV})$
0
5
10
15