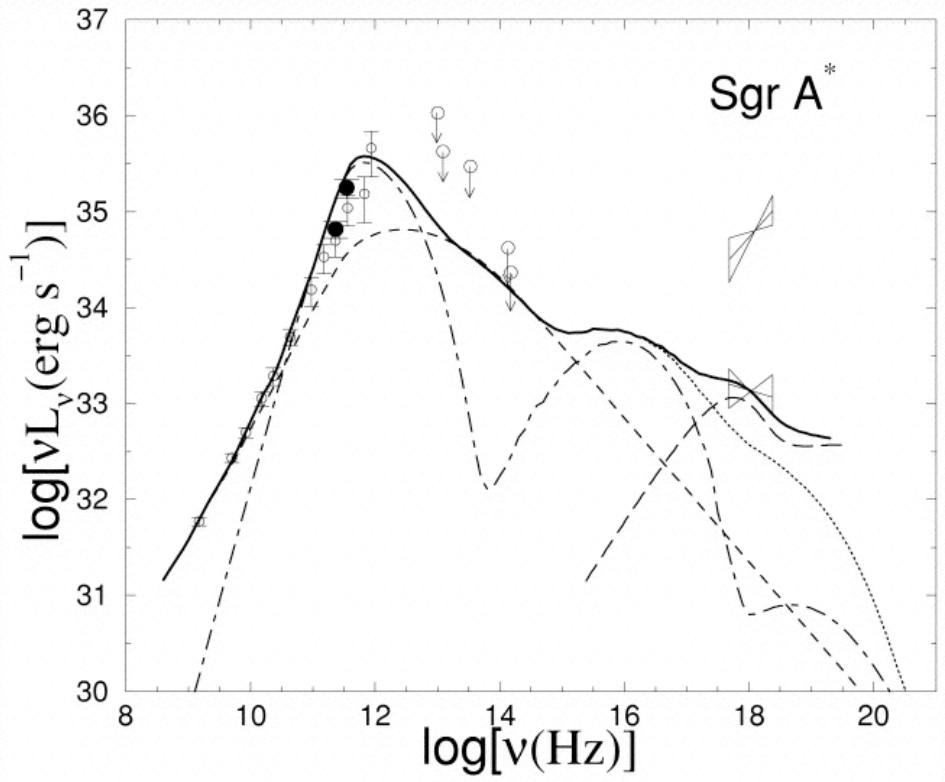
Spectrum of Sgr A*

Radio Sub-mm NIR X-ray

- Wide range of ν 's
- Peaks in sub-mm
- Extremely faint sub-Eddington
- Variability detected in almost all wavelengths but not simultaneous
  - Is the variability correlated?
    - Will it address the emission mechanism?



Yuan et al. 2003

Outline

- Light curves in NIR, X-rays & sub-mm wavelengths
- Cross correlation:
  - NIR vs X-ray
  - NIR vs. sub-mm
- Explain:
  - X-ray /soft γ-ray emission by ICS
  - NIR and sub-mm by Synchrotron

The Nature of Simultaneous near-IR and X-ray Flares from Sgr A* at the Galactic center

F. Yusef-Zadeh

X-Ray
(XMM)
- G. Belanger
- A. Goldwurm
- F. Melia
- B. Warwick

Radio
(VLA+ATCA+BIMA)
- D. Roberts
- G. Bower

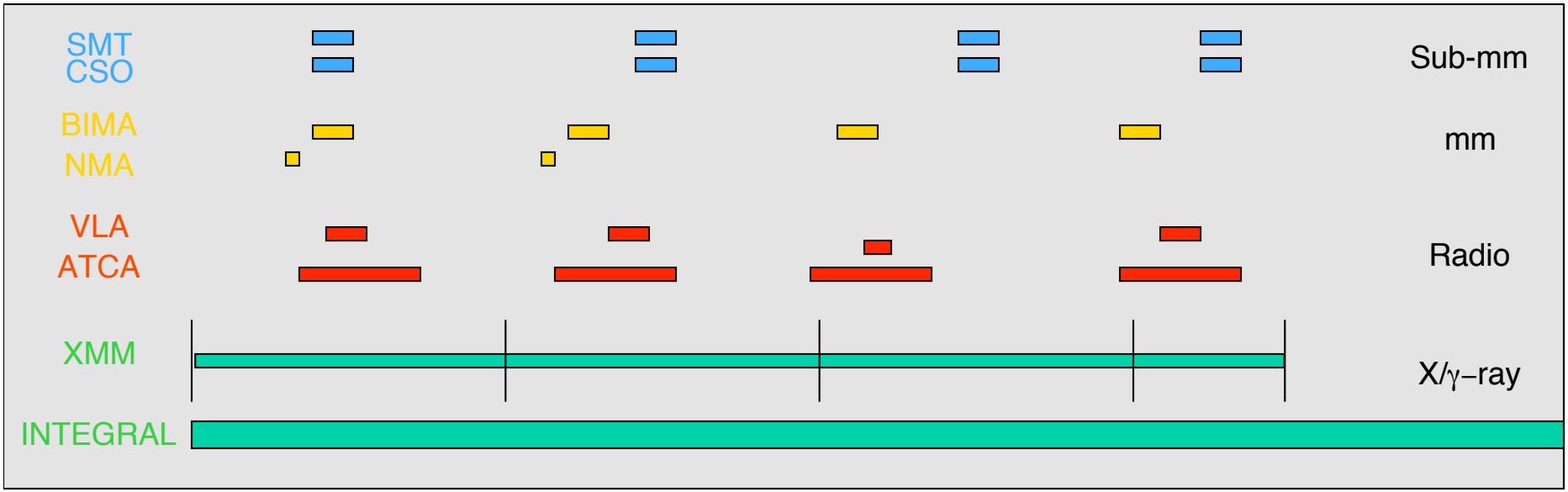
Near-IR
(HST)
- H. Bushhouse
- C. Heinke
- M. Wardle
- S. Shapiro
- A, Goldwurm

Sub-millimeter
(CSO, SMT)
- D. Dowel
- B. Vila Vilaro
- L. Kirby
- G. Novak

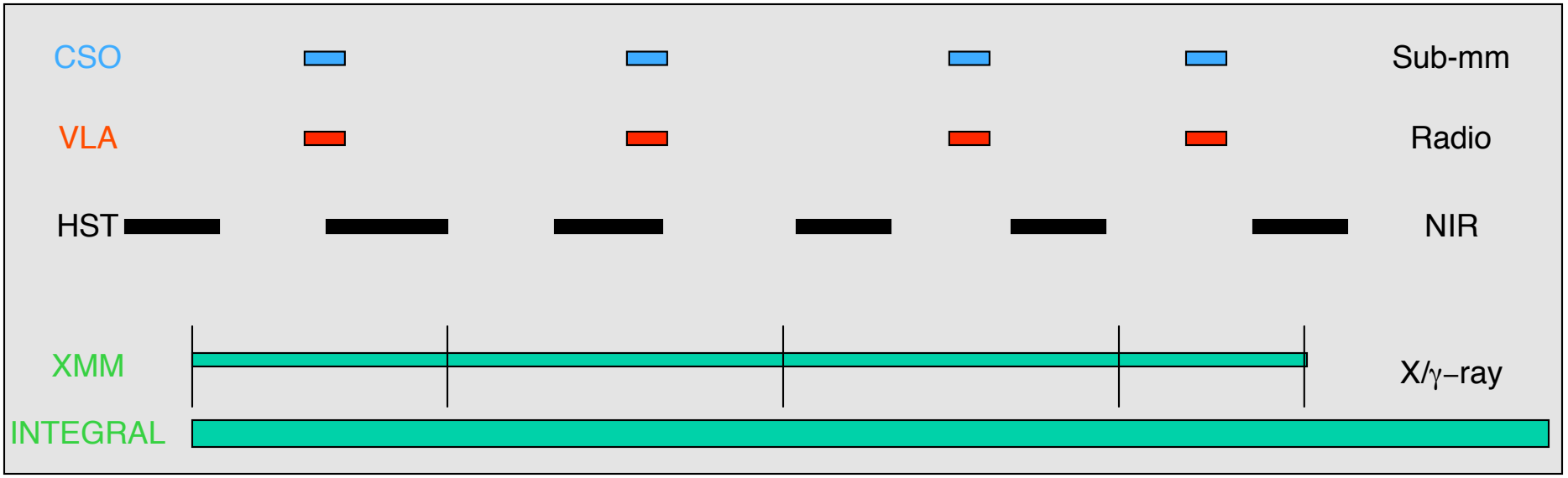
Soft γ-Ray
(INTEGRAL)
- G. Belanger
- A. Goldwurm
- M. Renaud
- R. Terrier
- F. Melia
- N. Lund
- J. Paul
- G. Skinner

Two Epochs of Observations of SgrA* in 2004

March Campaign

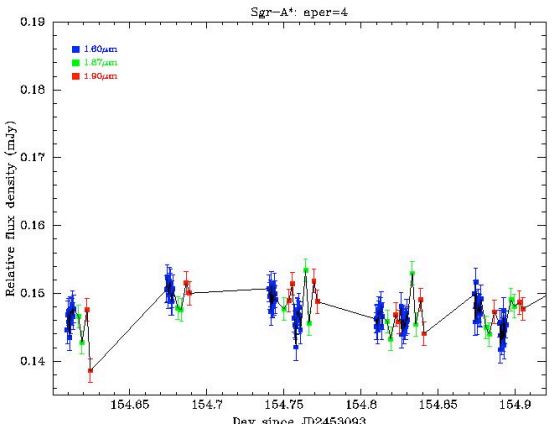


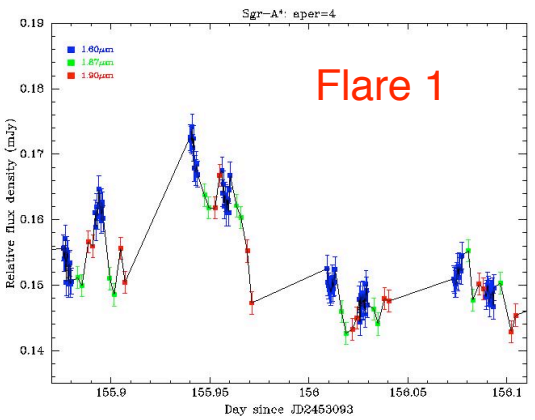
September Campaign

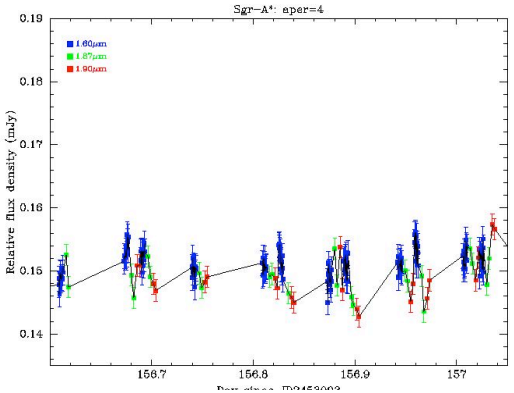


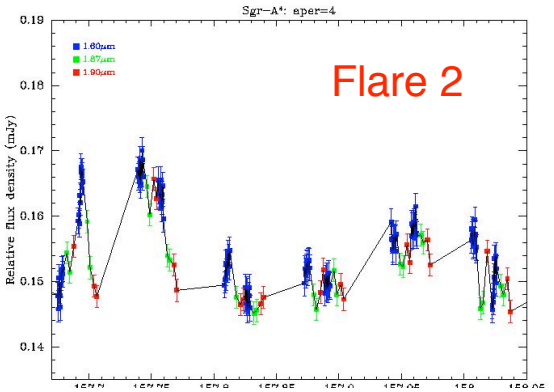
NIR variability in 1.6, 1.87 (Paα line), 1.9μm

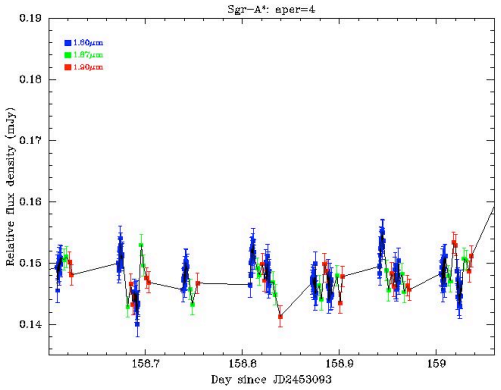
- NIR Light Curves of SgrA* (blue, red, green)
- **Amp**: 10 % to 25% or 3 to 4 times the quiescent flux (2.8mJy at 1.6μm)
- **Duration**: multiple peaks, lasting from 20 minutes to hours
- **Flare activity**: overall fraction of activity is about 30-40% of the observed time
- **Spectrum:** Unknown

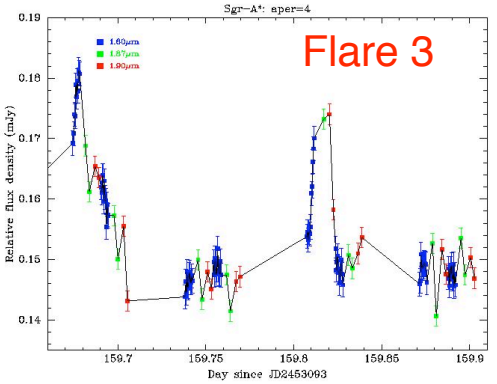




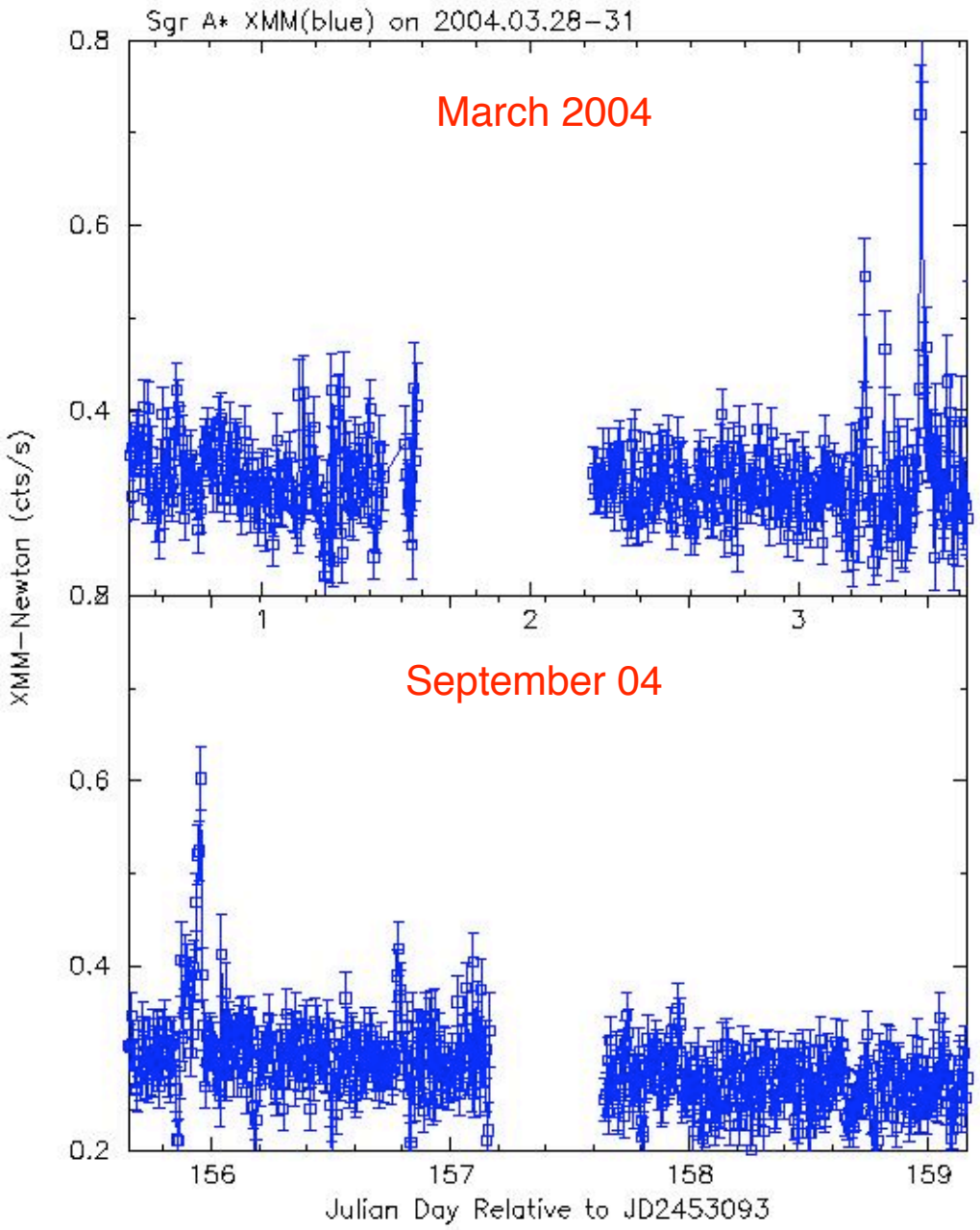






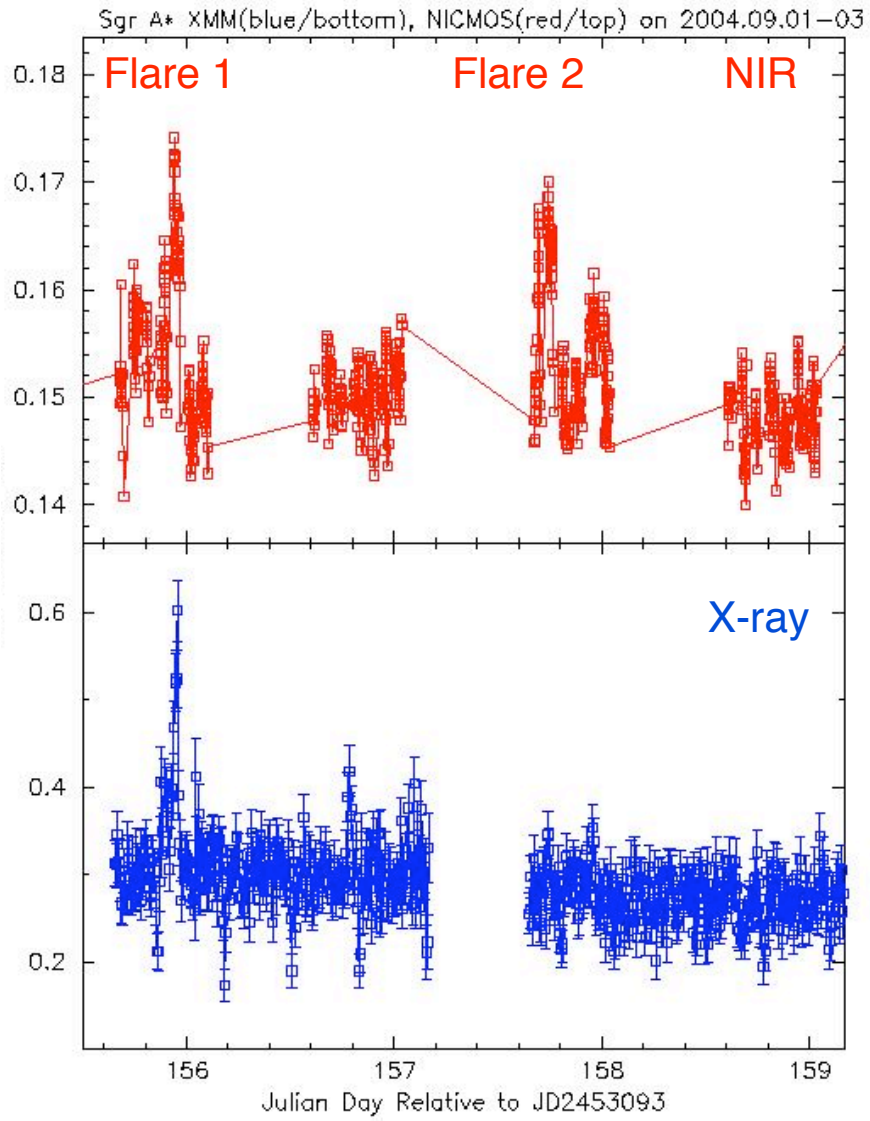


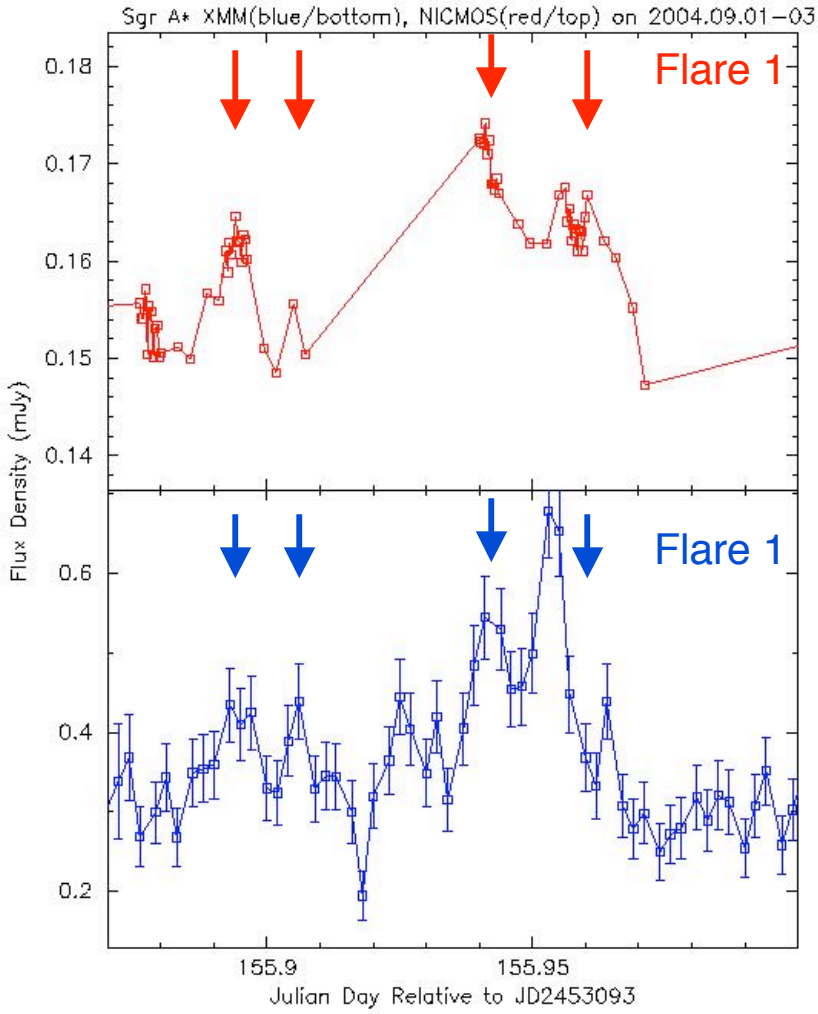
- X-ray Light Curves of Sgr A* (2-10 keV)
- **Amp**: 35 times the quiescent X-ray flux
- **Duration**: multiple peaks, lasting from 10 minutes to 3 hours
- **Spectrum:**
  - Power-law with α = 0.6+/0.5
  - L(2-10 keV)=7.7 x10^{35} erg/s
- **Flare activity**: Two clusters of flares in one week



Belanger et al. 2005

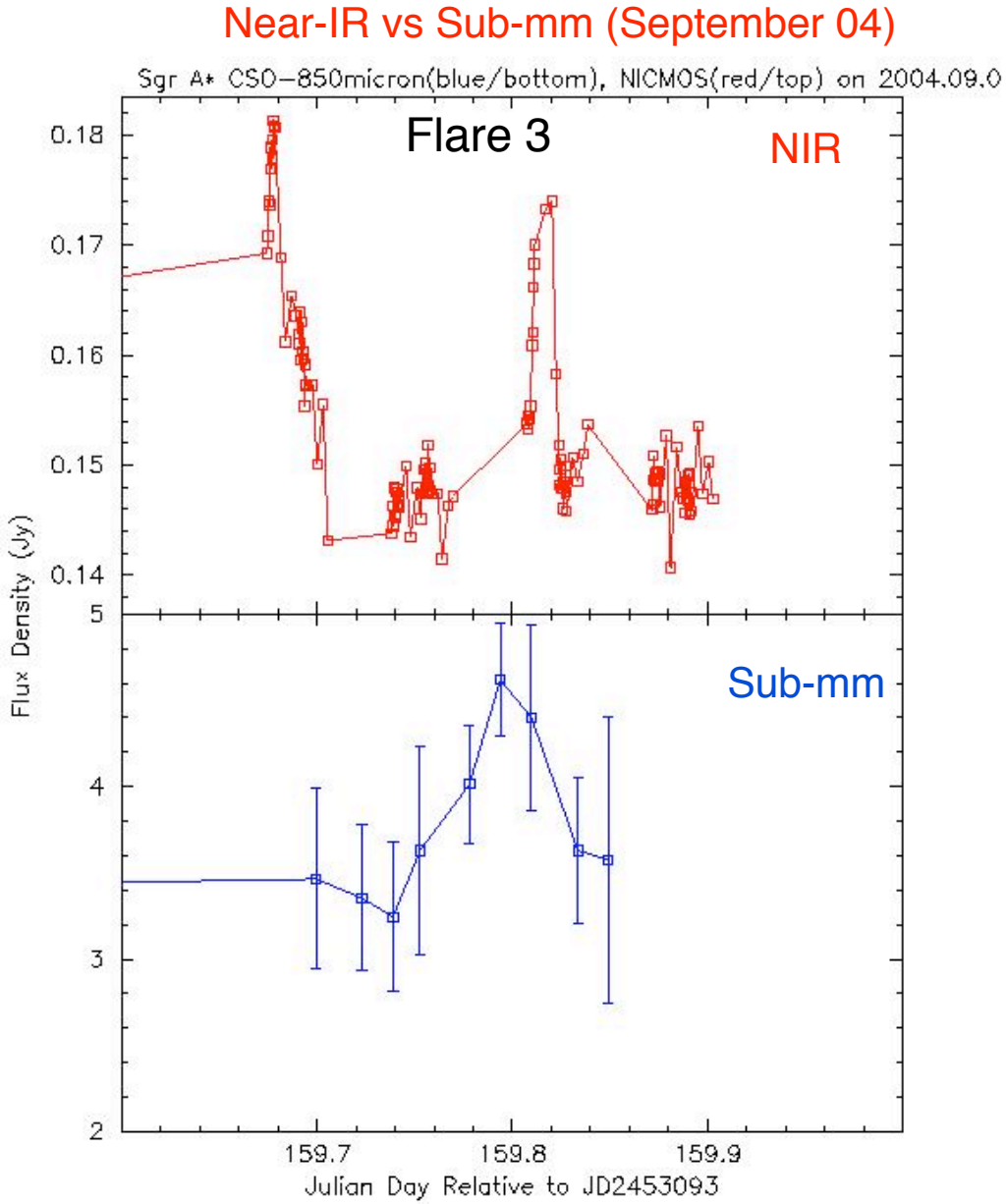
NIR (1.6-1.9μm) vs. X-Ray (September Campaign)





No time delay

- Simultaneous NIR and sub-mm light curves of Sgr A*
- **Amp**: 11 mJy at 1.6micron; 4.7Jy at 350 micron
- **Duration**: multiple peaks in near-IR lasting for 40min;
- One peak lasting for two hours
- **Spectrum:**
  - First evidence of variability in submm



Simultaneous X-ray, NIR & Sub-mm Flares

Near-IR

- Due to Synchrotron: E_e=1.1 GeV, Beq=10G, τ_{nir}= 40min

Sub-mm

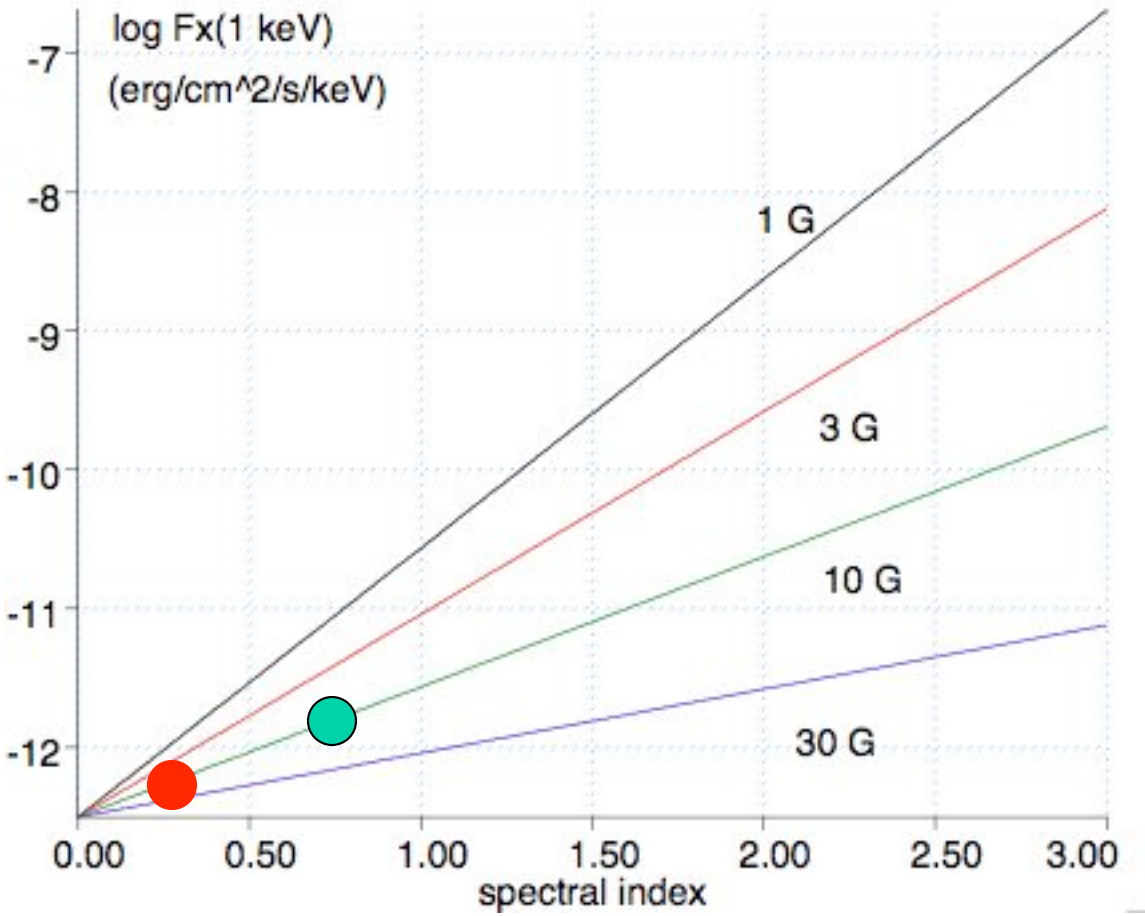
- Due to Synchrotron τ_{nir}= 12h
  - Similar to NIR (the same population of electrons)
  - $F_{850\mu m}$=0.6 Jy, E_e=50 MeV, $F_{1.60\mu m}$=11 mJy, E_e=1GeV, $\alpha = 0.6$

X-rays

- X-Rays cannot be due to Synchrotron: (E_e proportional sqrt (ν / B))
  - τ_{nir}=1min, B=10G, E_e=10 GeV
  - Spectral index between NIR and X-ray is steep
- X-Rays due to ICS: ($E_{photons}$ proportional E^2_e x $\nu_{\text{seed photons}}$)
  - (a) diameter=10R_{sch}, $F_{850\mu m}$=4Jy, E_e=1GeV
  - (b) diameter=10$R_{sch,}$ F_{nir} =10 mJy, E_e=50 MeV
  - $E_{predict}$=2x10^{-12} erg/cm2/s/keV, E_{obs}=1.2x10^{-12} erg/cm2/s/keV
- Lack of one-to-one X-ray detection:
  - Spectral index
  - Magnetic field

NIR Flares with and without X-ray Counterparts

- The softer (steeper) the particle spectrum, the higher the X-ray flux
- The harder (flatter) the particle spectrum, the weaker the X-ray emission

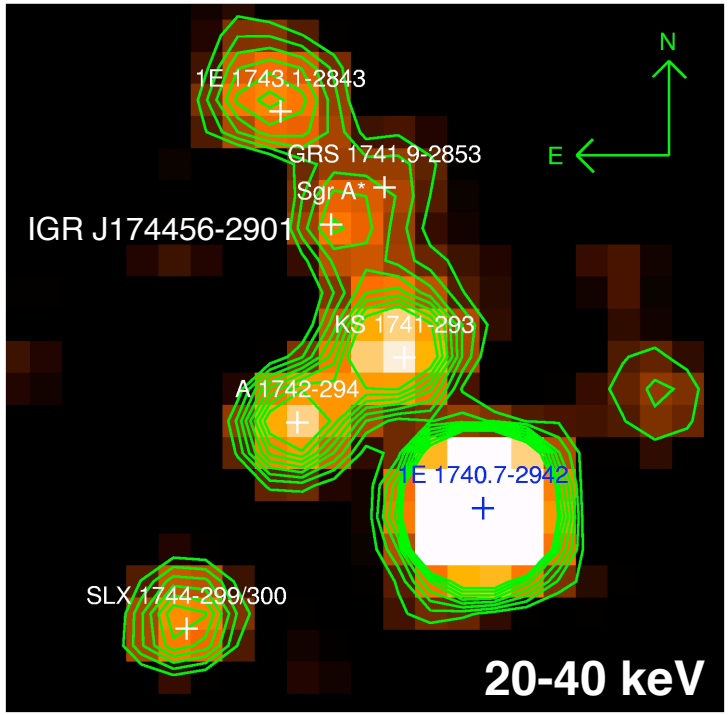


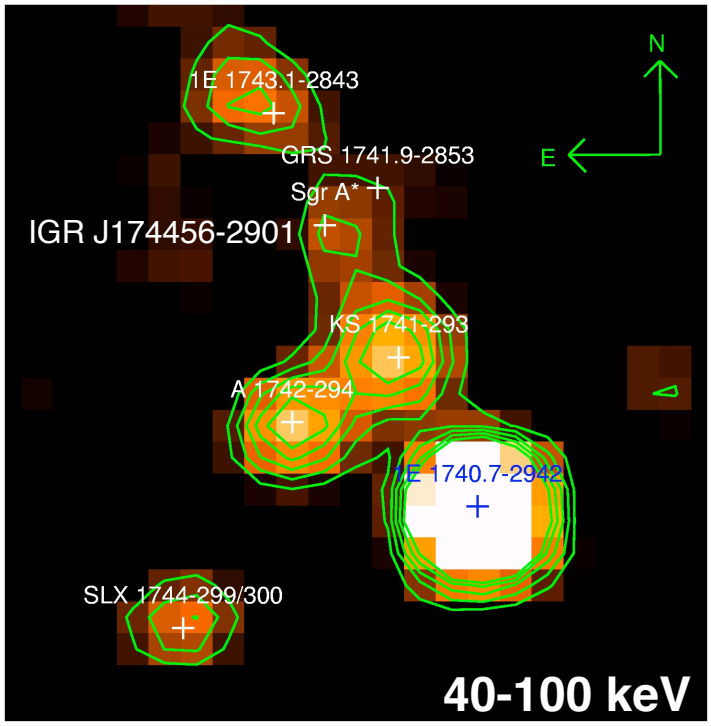
X-ray Flux as a function of spectral index

Flare 1

Flare 2

First IBIS / ISGRI Images of the Galactic Center

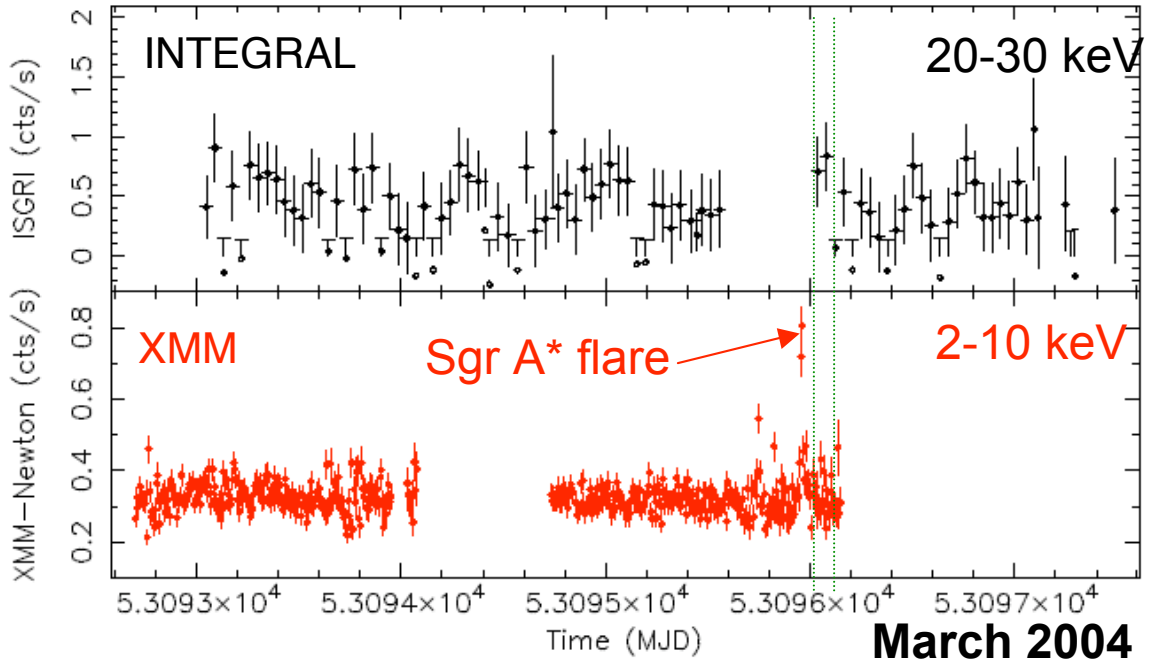




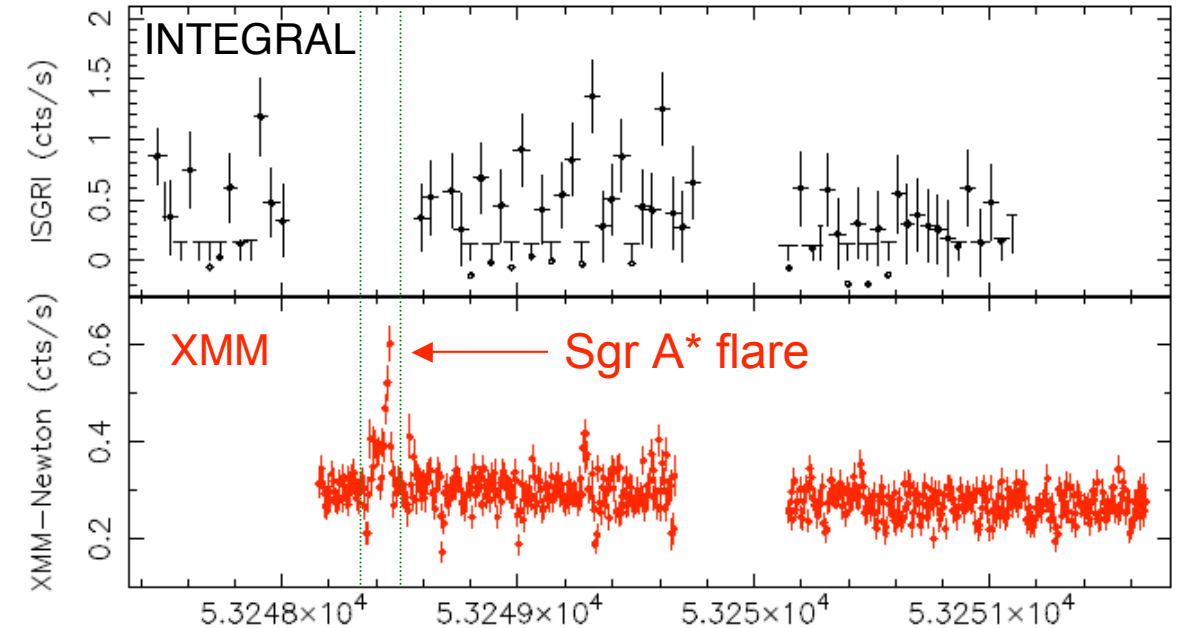
- Six known high-energy sources in the central 2 ° × 2° of the Galaxy
- Detection of IGR J1746-290 coincident with Sgr A*
- A significant excess (8.7 _) at ~ 1' from Sgr A* (4.7 _ in 40-100 keV)
- Power-law α = 2.04 +/- 0.98 and L(20-120 keV) = 4.8 10^{35} erg/s
- Belanger et al. (2005b)

INTEGRAL and XMM Variability

- INTEGRAL:
  - 20-30 keV light curve of IGR J17456-290
- Cross Correlation
  - During the 2 bright SgrA* flares seen with XMM INTEGRAL was in the radiation belts (Belanger et al. 2005b)



March 2004



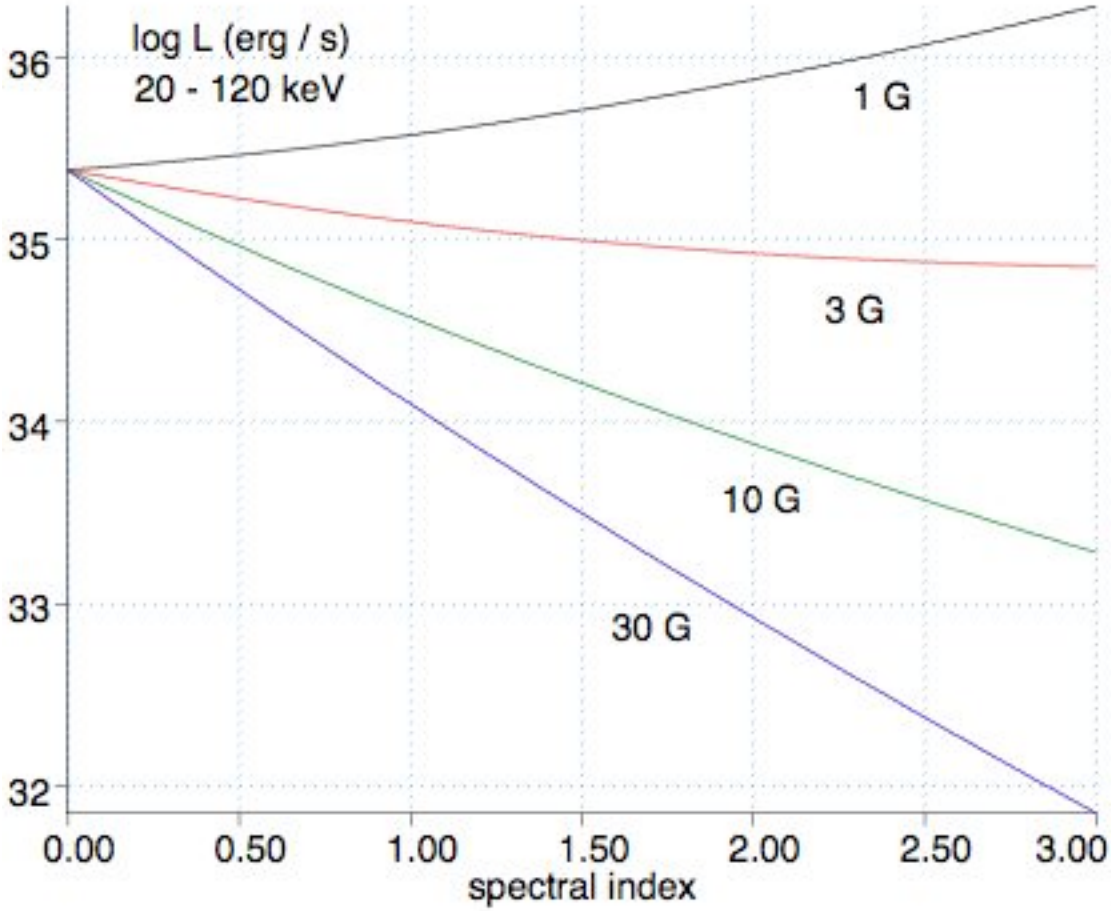
Belanger et al. 2005

Sept 2004

Soft γ–ray Flux as a function of spectral index

- The spectral index in NIR ranges ~ 0.5-4 (Ghez et al. 2005;

- The population of particles producing NIR emission can explain the soft γ-ray emission

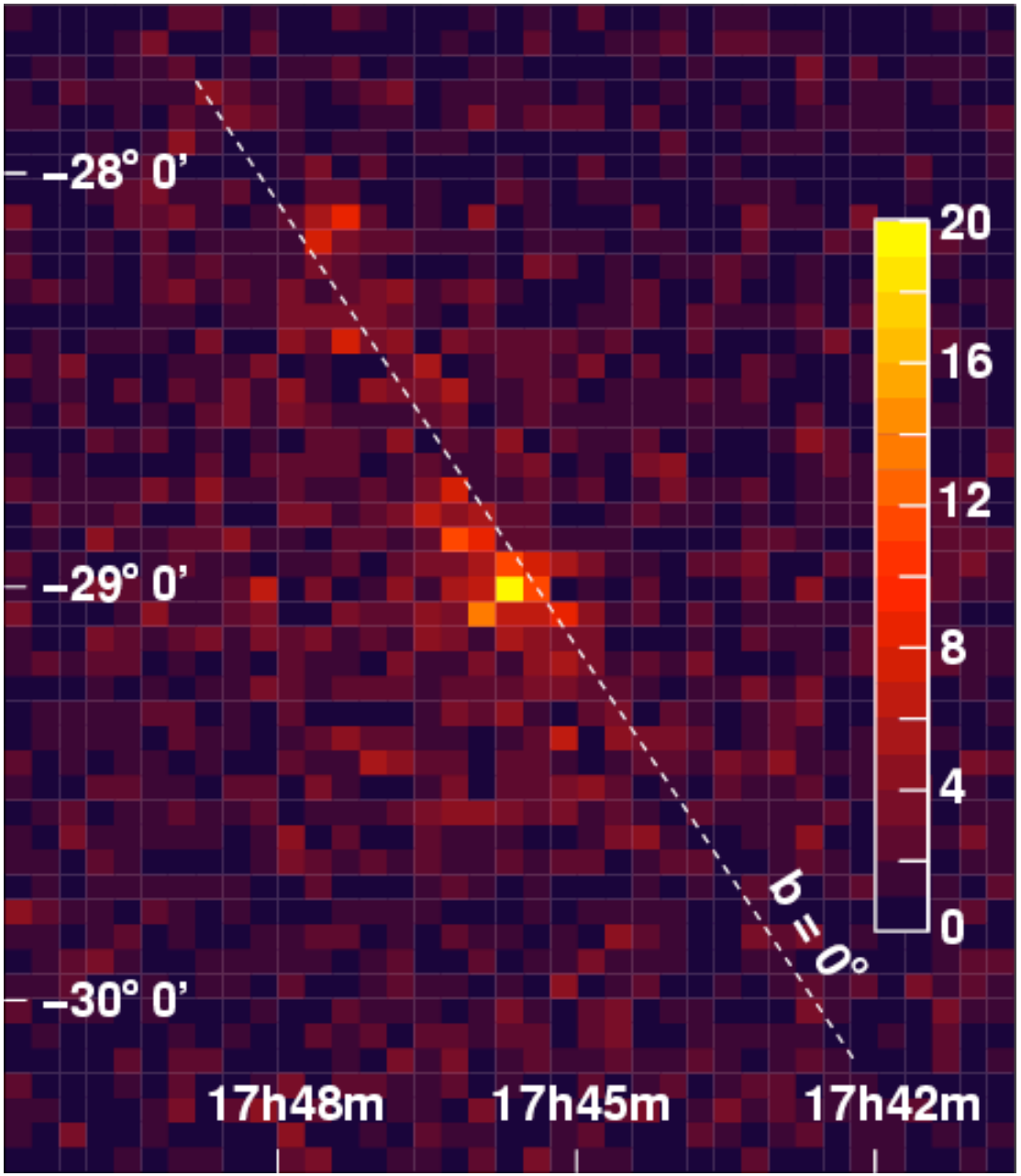


Conclusions

- Correlation between a near-IR and X-ray/soft γ–ray flare: the same population of particles
  - ICS may account for steady X-ray/γ-ray source
- Lack of one-to-one correlation: spectral index and/or magnetic field variation
- Correlation between a near-IR and sub-mm flare: the same population of particles
  - Low-energy component of power-law spectrum
- The flow always fluctuates even in its quiescent phase
- Duration of flaring set by dynamical mechanisms (adiabatic expansion)

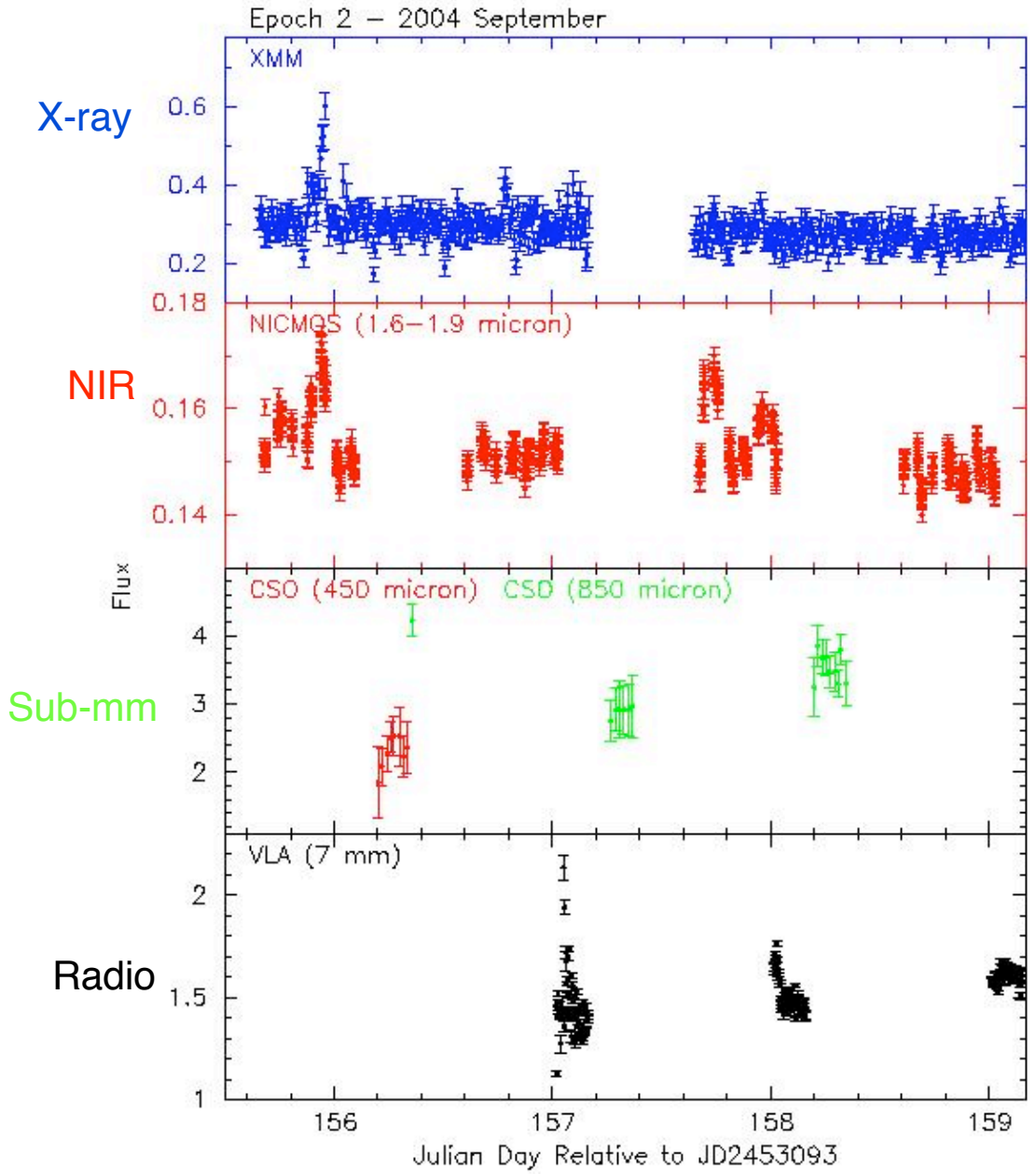
TeV Emission From the Galactic Center

- Aharonian et al. (2004)

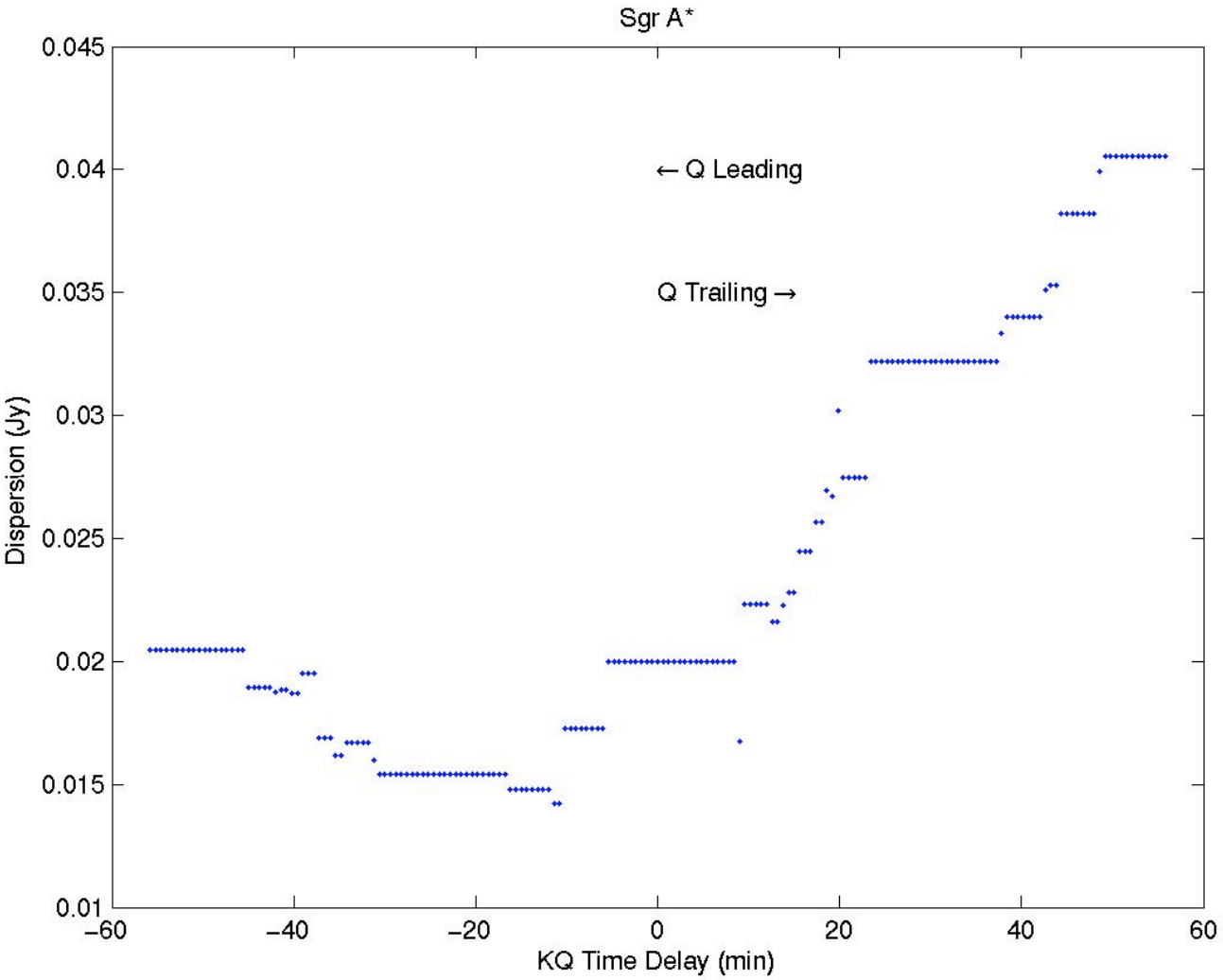


Radio (7mm) vs X-ray (March Campaign)

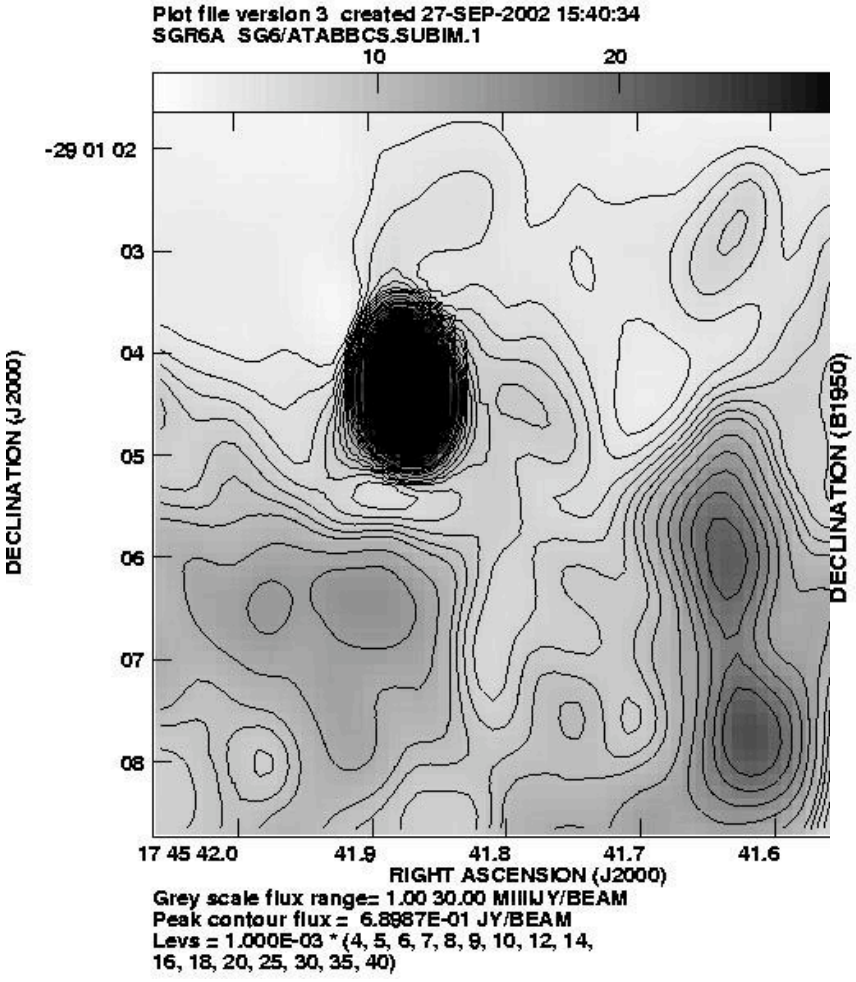
- Lag time between X-ray/NIR flare and sub-mm peak 4-5 hours
- Time delay between X-ray/NIR and radio peak is one day
- An expanding synchrotron source in an optically thick medium
- As the electrons cool, the synchrotron self-absorption frequency moves to longer wavelengths
- Delay as a function of frequency expected

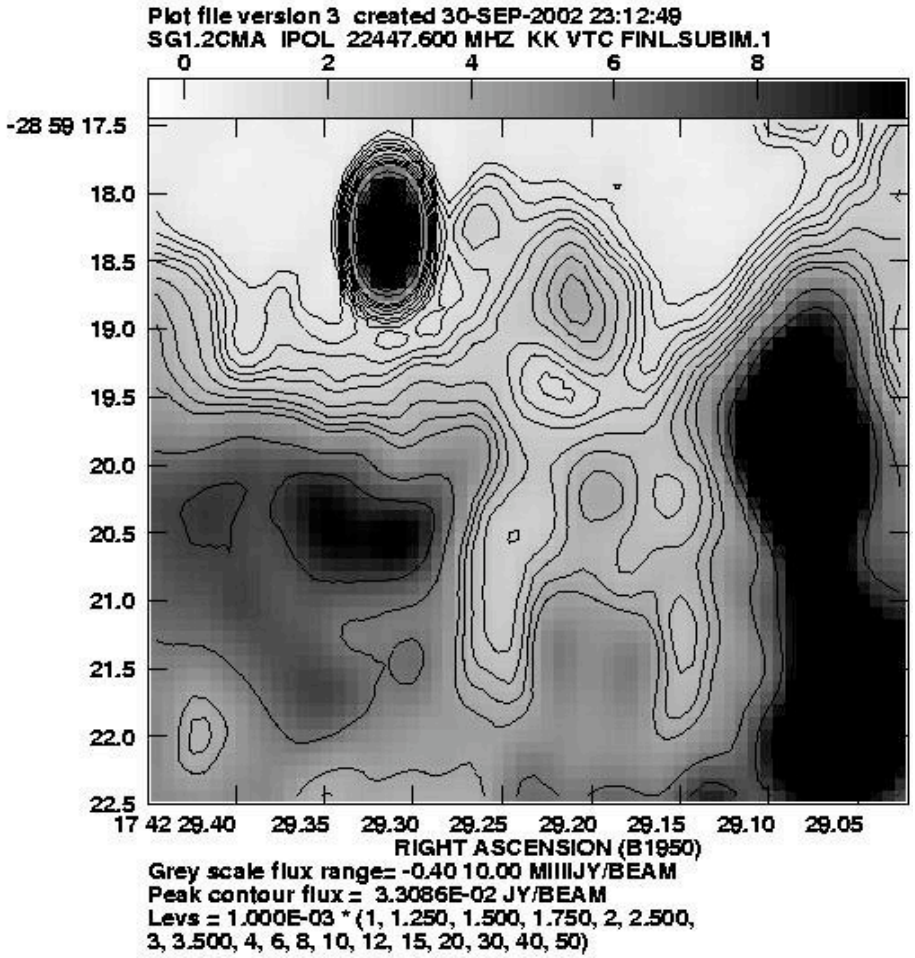


- The dispersion plot is minimum at ~20min
- An expanding self-absorbed synchrotron source with a delay of 20min implies plasma ejection took place 54min before the 7mm peak (van der Laan 1966).
- No near-IR or sub-millimeter data)
- Continuous ejection?



6 and 1.2cm VLA images of the Galactic Center





Conclusions

- Flare correlation: simultaneous vs delayed
- Correlation between a near-IR and X-ray/soft γ–ray flare: the same population of particles
- Evidence for a NIR flare with quasi-periodic 35min behavior
- The flow always fluctuates even in its quiescent phase:
  - ICS may account for steady X-ray/γ-ray source
- An expanding synchrotron self-absorbed blob: outflow

Radio Time Lags Between 7mm and 13mm

- Light curves of SgrA* observed simultaneously at 7mm and 1.2cm
- The spectral index steeper at higher frequencies and during flares consistent with Herrnstein et al. (2004)
- The 7mm peak is leading the 1.2cm peak