3 Ms Chandra Campaign on Sgr A*: A Census of X-ray Flaring Activity in the Galactic Center

Joey Neilsen. 2013 Oct 3. Santa Fe.
XVP Collaboration: http://www.sgra-star.com

Chandra Sgr A* X-ray Visionary Project

- XVP PIs: Fred Baganoff (MIT), Sera Markoff (Amsterdam), Mike Nowak (MIT)
- 3 Ms on Sgr A* in 2012 (see overview talk by F. Baganoff), plus extensive multiwavelength coverage
- Keep up with collaboration at http://www.sgra-star.com
- This work: M. Nowak, F. Baganoff, N. Degenaar, J. Dexter, C. Fragile, D. Haggard, J. Houck, C. Gammie, N. Grosso, S. Markoff, J. Miller, S. Nayakshin, D. Porquet, J. Tomsick, D. Wang, R. Wijnands

(Some of) Sgr A* in 3 Parts

- Introduction to (flaring) X-ray emission from Sgr A*
- First results from campaign: the brightest X-ray flare ever observed from Sgr A* (Nowak et al. 2012)
- Census of X-ray flares from 2012: statistics and relationship to quiescent emission

Why Study X-ray Flares from Sgr A*?

- Flares reveal a connection to weakly accreting black holes at all mass scales
- Origin of flares unknown

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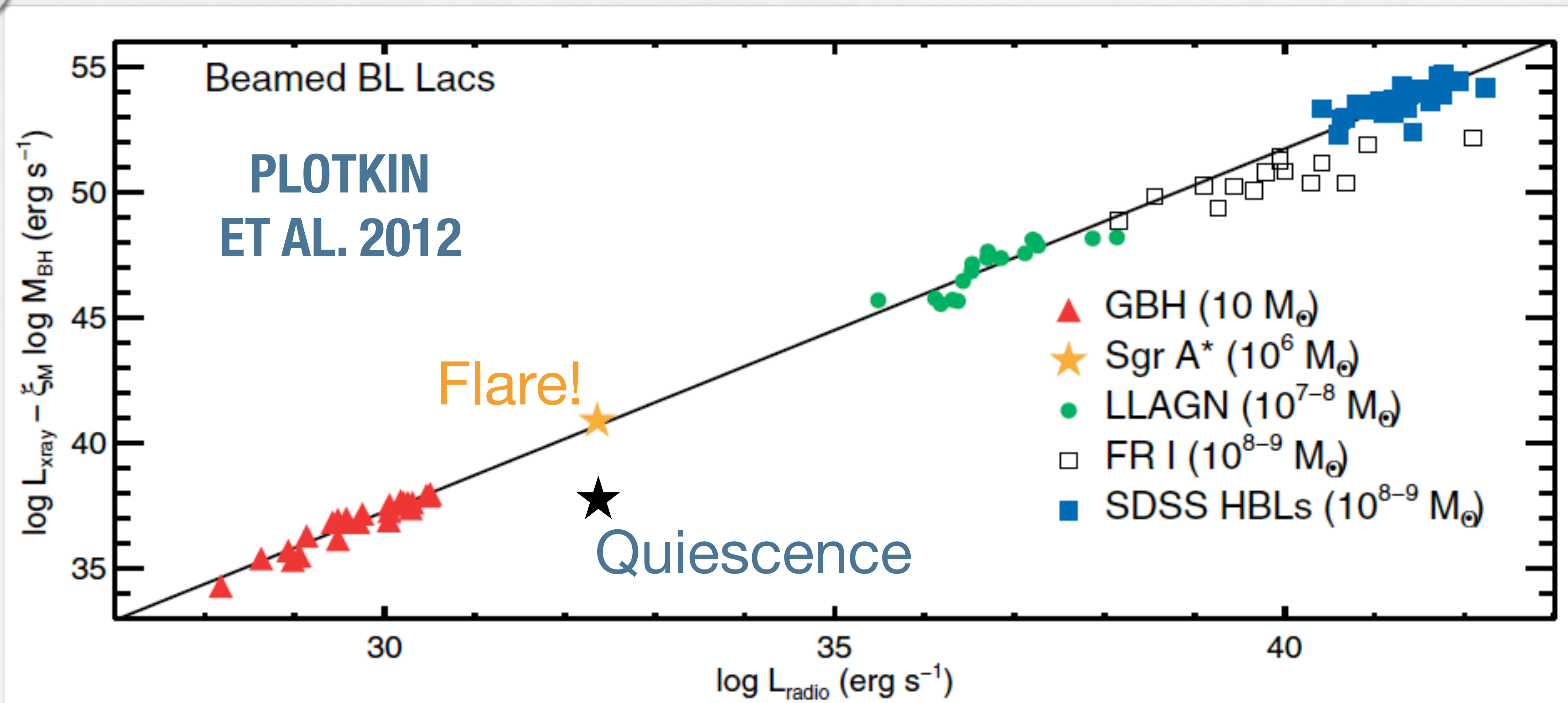
Flares and the Fundamental Plane



- See also Markoff (2005), talk by Salomé Dibi

Why Study X-ray Flares from Sgr A*?

- Flares reveal a connection to weakly accreting black holes at all mass scales

- **Origin of flares unknown**

Some Flare Processes

Physics/Energetics

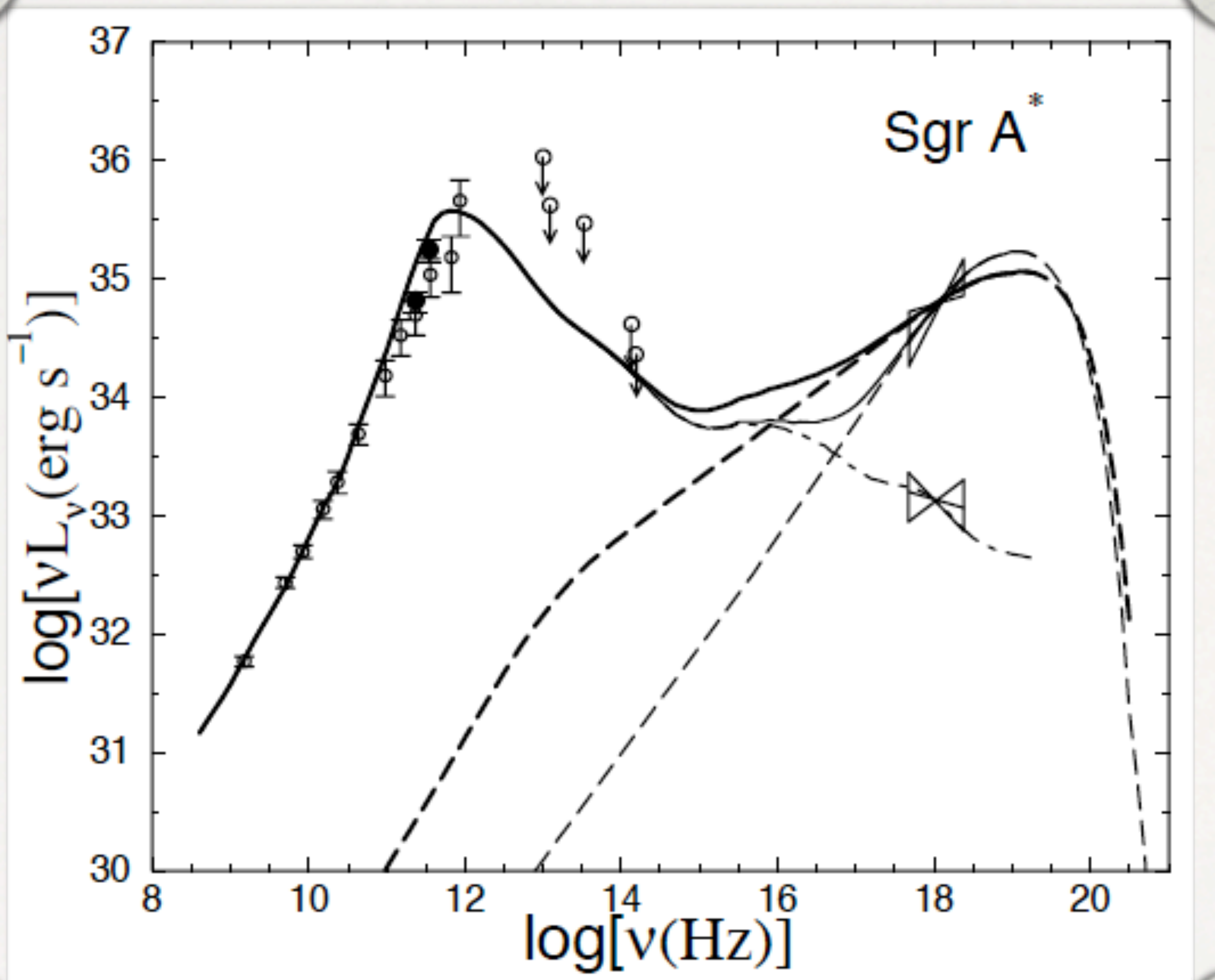
- Magnetic reconnection
- Shocks
- Stochastic acceleration in a jet
- Asteroid disruption

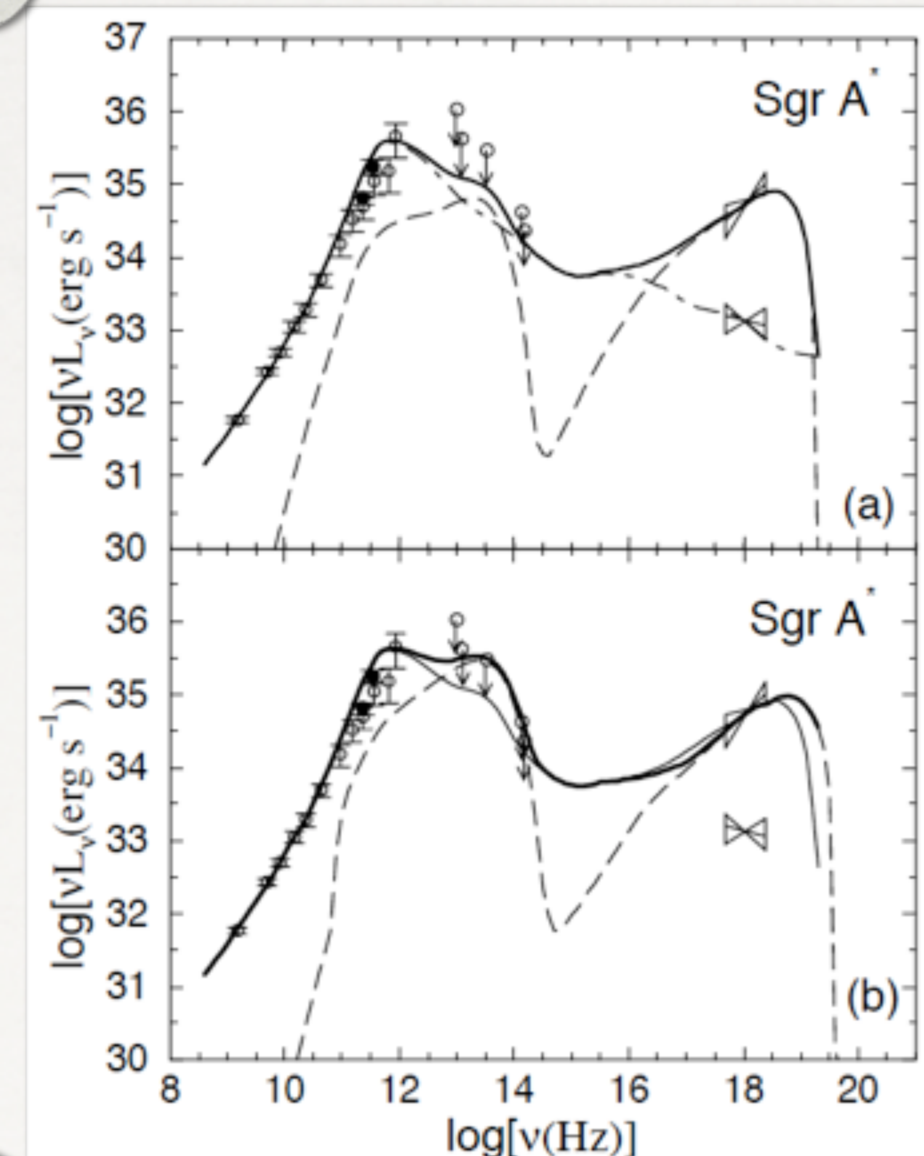
Radiation Processes

- Direct synchrotron (does IR extrapolate to X-rays?)
- Inverse Compton
- Synchrotron self-Compton (SSC)

- e.g. Markoff et al. 2001; Yuan et al. 2002, 2003; Liu et al. 2004; Čadež et al. 2008; Zubovas et al. 2012; Yusef-Zadeh et al. 2012

Multiwavelength Flare Models





- Synchrotron models (left) and SSC models (right) both work, nonthermal electrons (Yuan et al. 2003), but see Dibi et al. 2013

Chandra XVP

What causes the flares from Sgr A*?

All About Flares

- Roughly ~1.1-1.3 X-ray flares per day
- Short: ~1-3 hrs, can be L~10^{35} ergs/s (Baganoff et al. 2001)
- Controversy: do all flares have the same spectra? (Belanger et al. 2005; but see Porquet et al. 2008; but now see Degenaar et al. 2013, talk by N. Barrière)
- Infrared: optically thin synchrotron, Sgr A* variability consistent with a <u>single process</u>, not "flare" and "non-flare" (see talks by L. Meyer, G. Witzel, B. Shahzamanian)

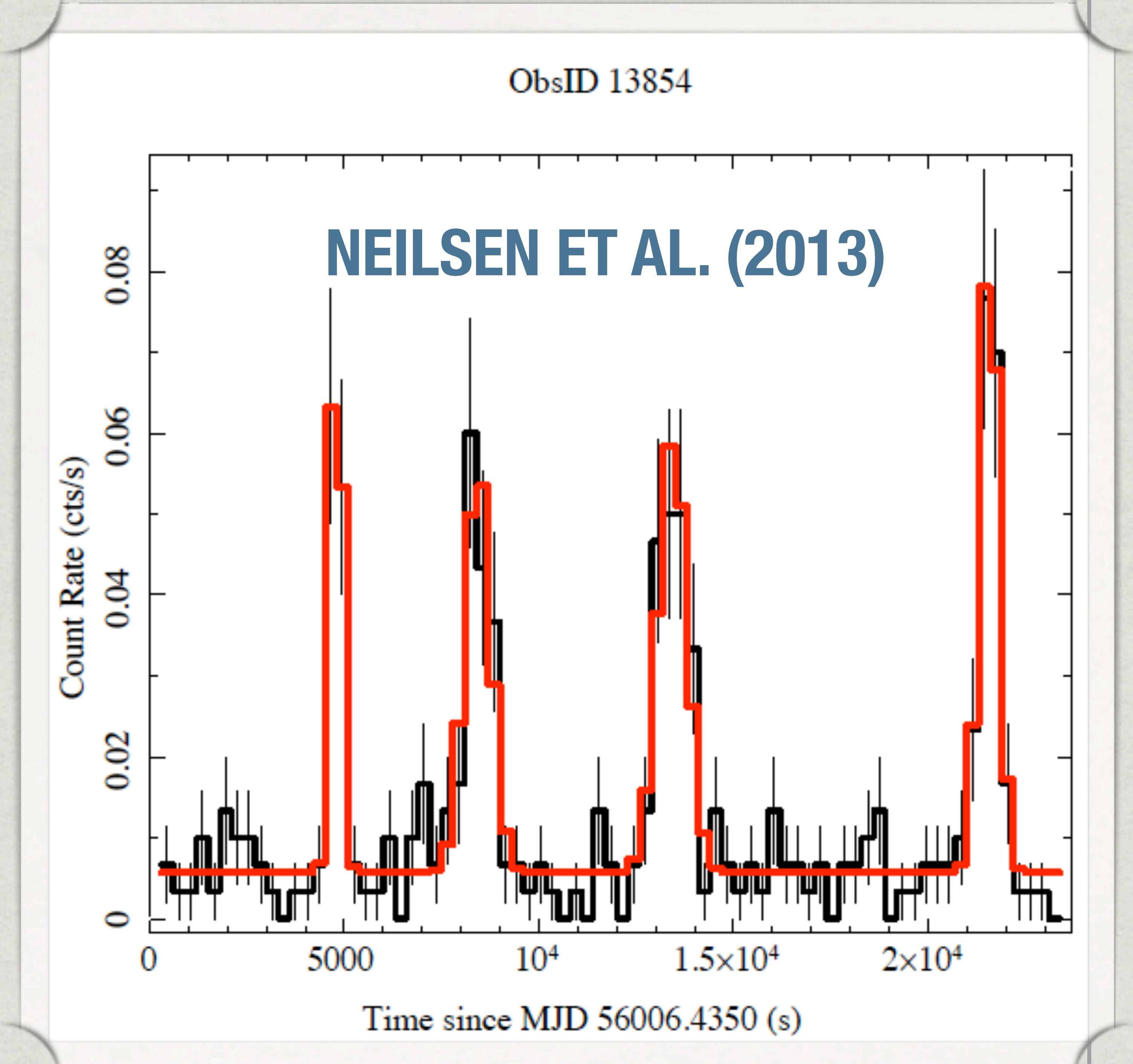
2012 *Chandra* XVP

- X-ray: small number statistics, lingering questions about flare origins, physical significance (but see talk by S. Dibi)

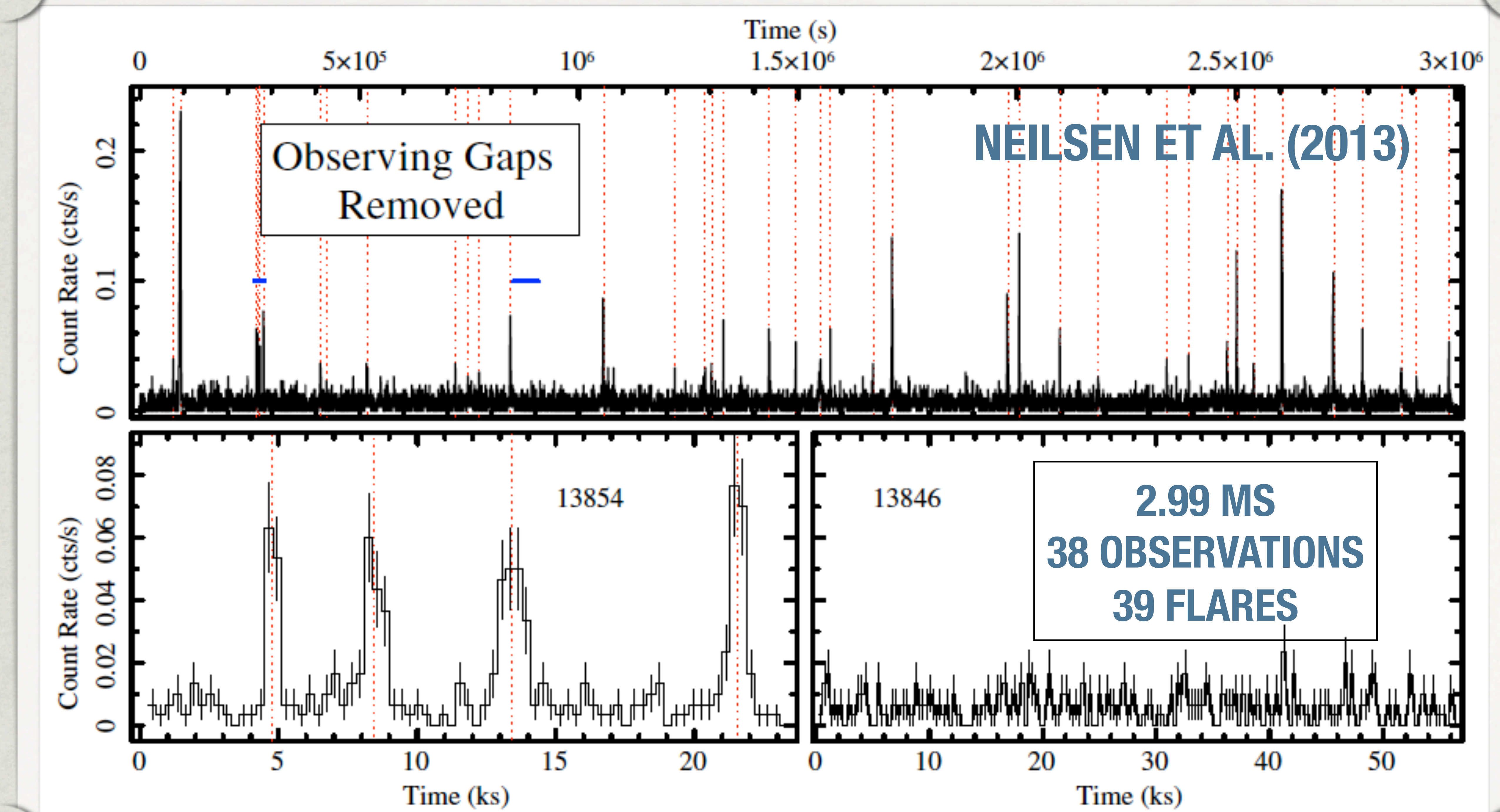
- 3 million seconds of observations with *Chandra* gratings (high spectral resolution), great for studying flare properties/statistics

Finding Flares

- First pass: Fit 300-s X-ray lightcurve to estimate baseline emission
  - N.B. Poisson errors, ML fit statistic
- Second pass automated:
  - Look for positive deviations in each 300-s bin
    - If found, try adding a narrow flare (100≤σ≤1600s)
      - If significant at 99%, look for substructure
  - For each flare, record peak count rate, fluence, duration (±2σ)



2012 *Chandra* Campaign

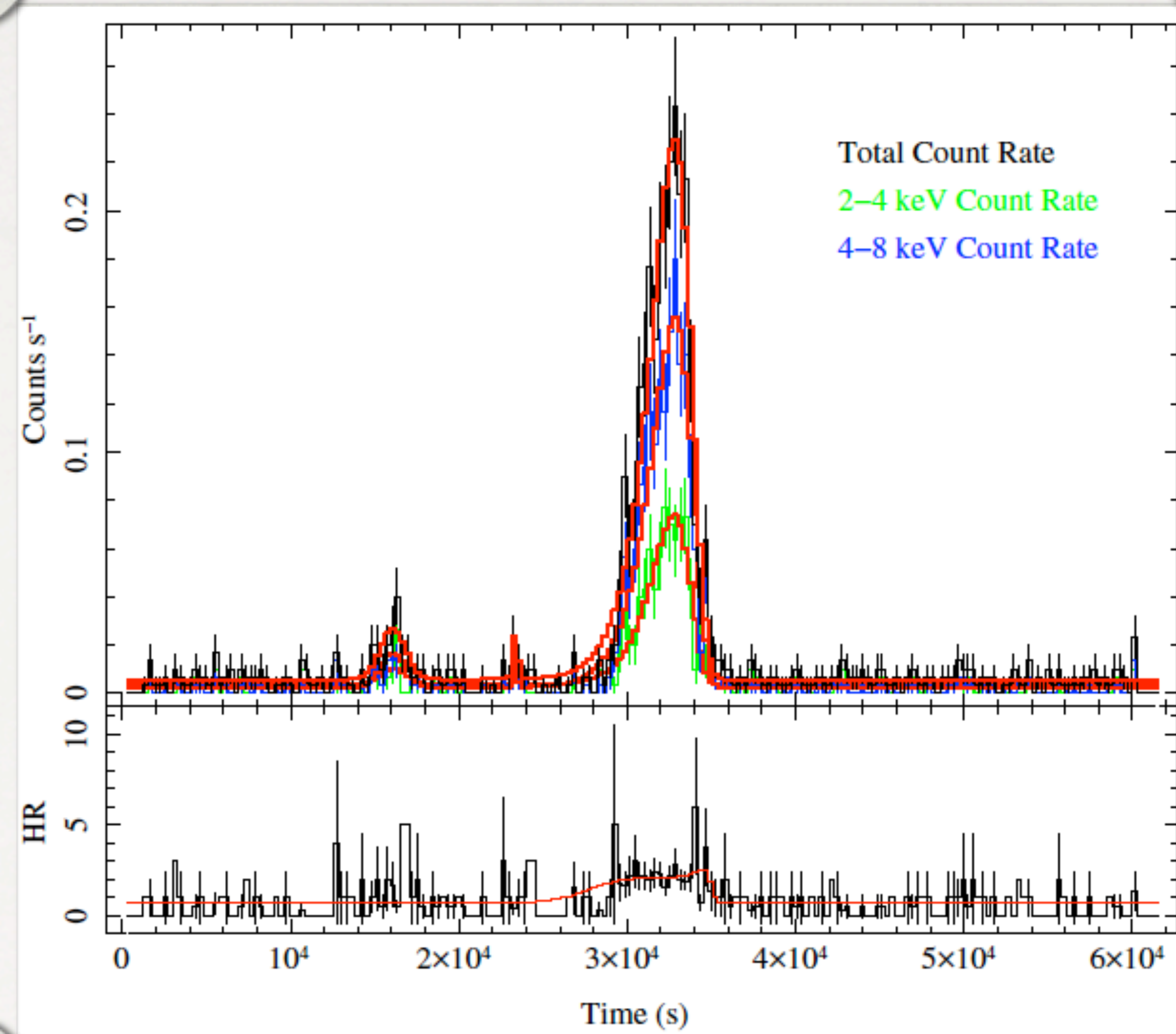


First Results

SECOND?

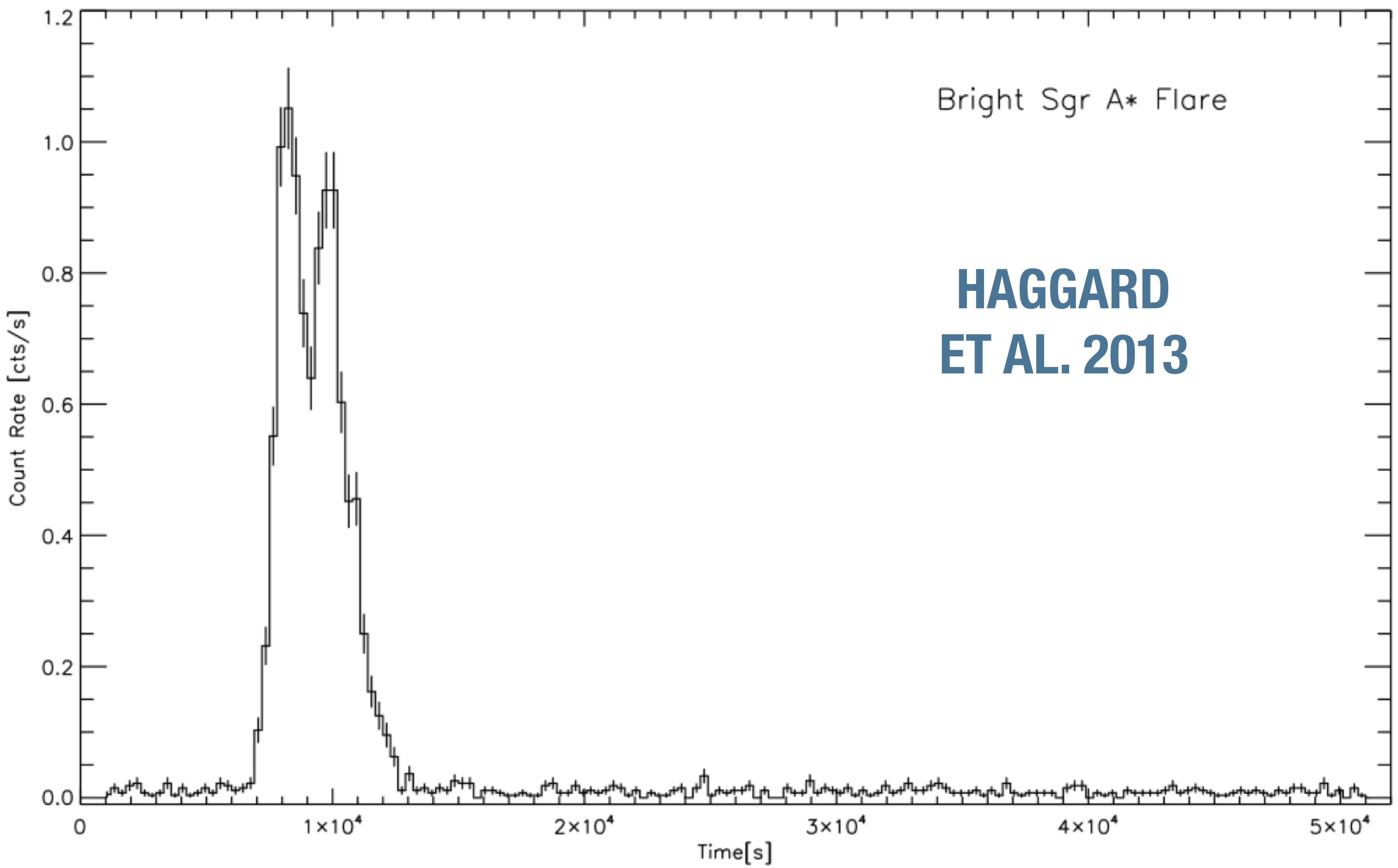
CHANDRA/HETGS OBSERVATIONS OF THE BRIGHTEST FLARE SEEN FROM Sgr A*

M. A. NOWAK[1], J. NEILSEN[1], S. B. MARKOFF[2], F. K. BAGANOFF[1], D. PORQUET[3], N. GROSSO[3], Y. LEVIN[4,5], J. HOUCK[1], A. ECKART[6], H. FALCKE[7,8,9], L. JI[10], J. M. MILLER[11], AND Q. D. WANG[12]



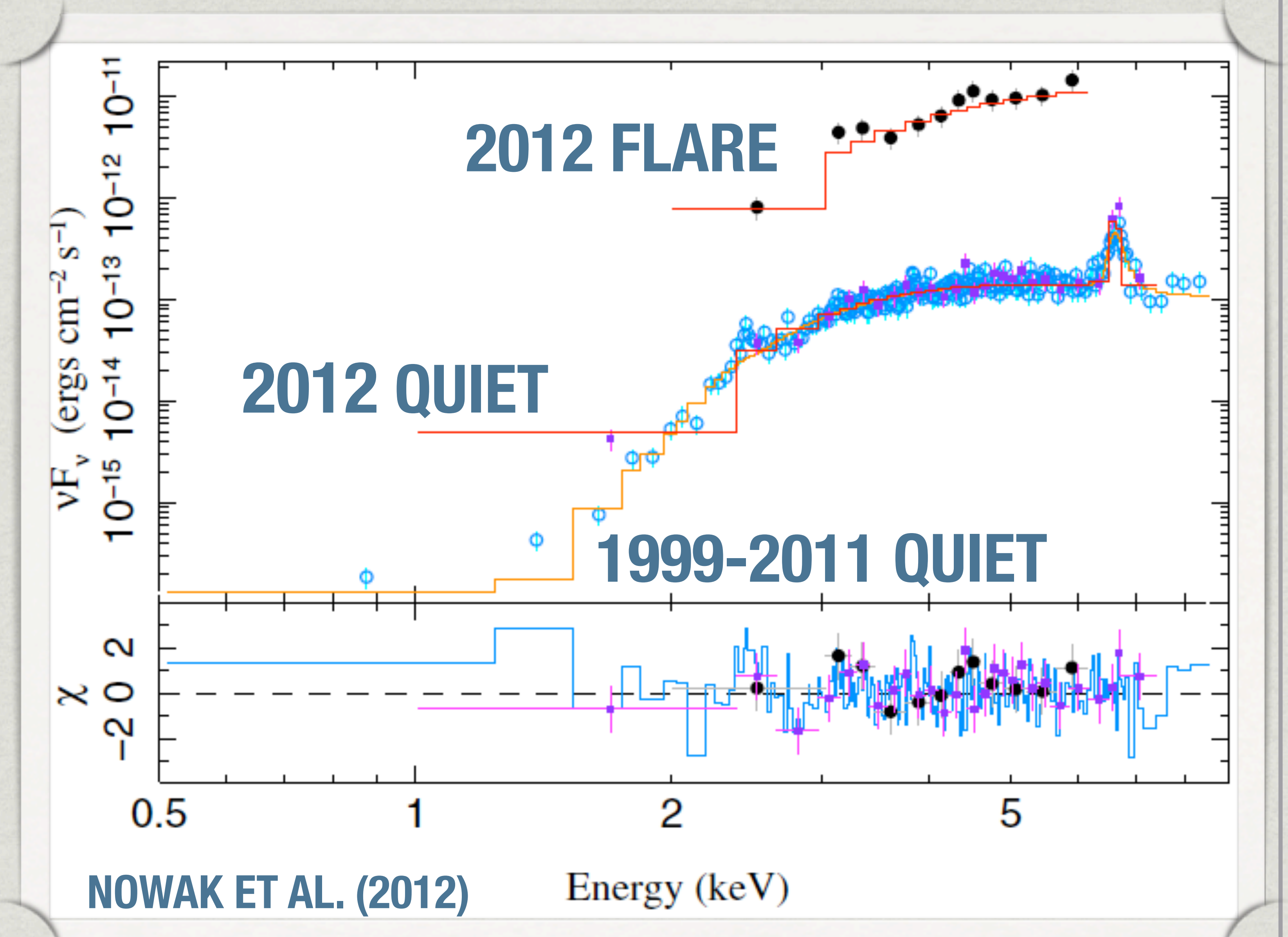
SEE D. HAGGARD'S TALK!

The *New* Brightest Flare EVER!



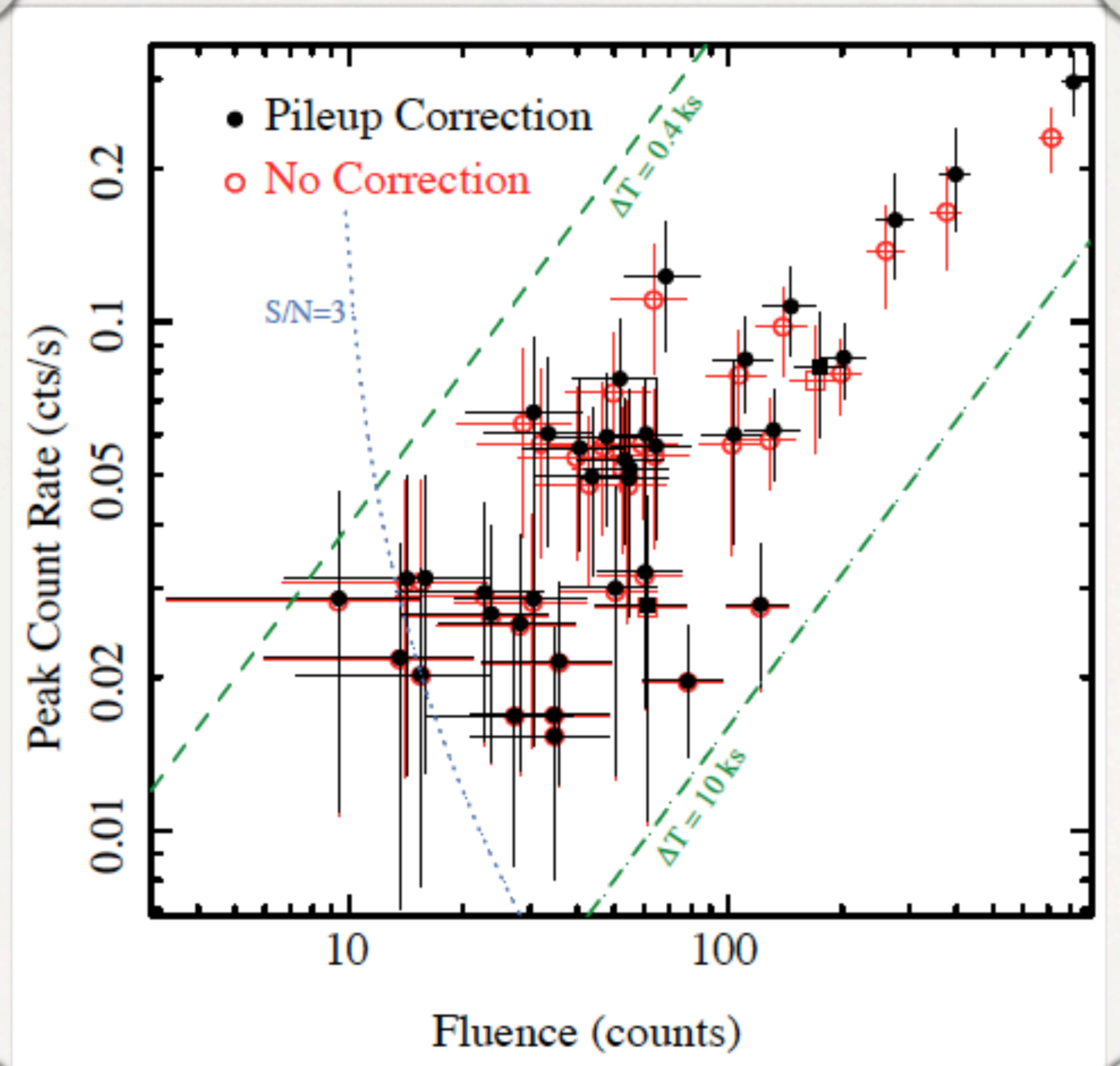
Brightest Flares

- Bright flares seen by *Chandra,* XMM have similar spectra; harder than quiescent spectrum (Nowak et al. 2012)
- Moderate spectral index Γ~2 doesn't rule out any flare models
- What about weaker flares? Statistics of all flares in 2012!



39 Flares: Demographics

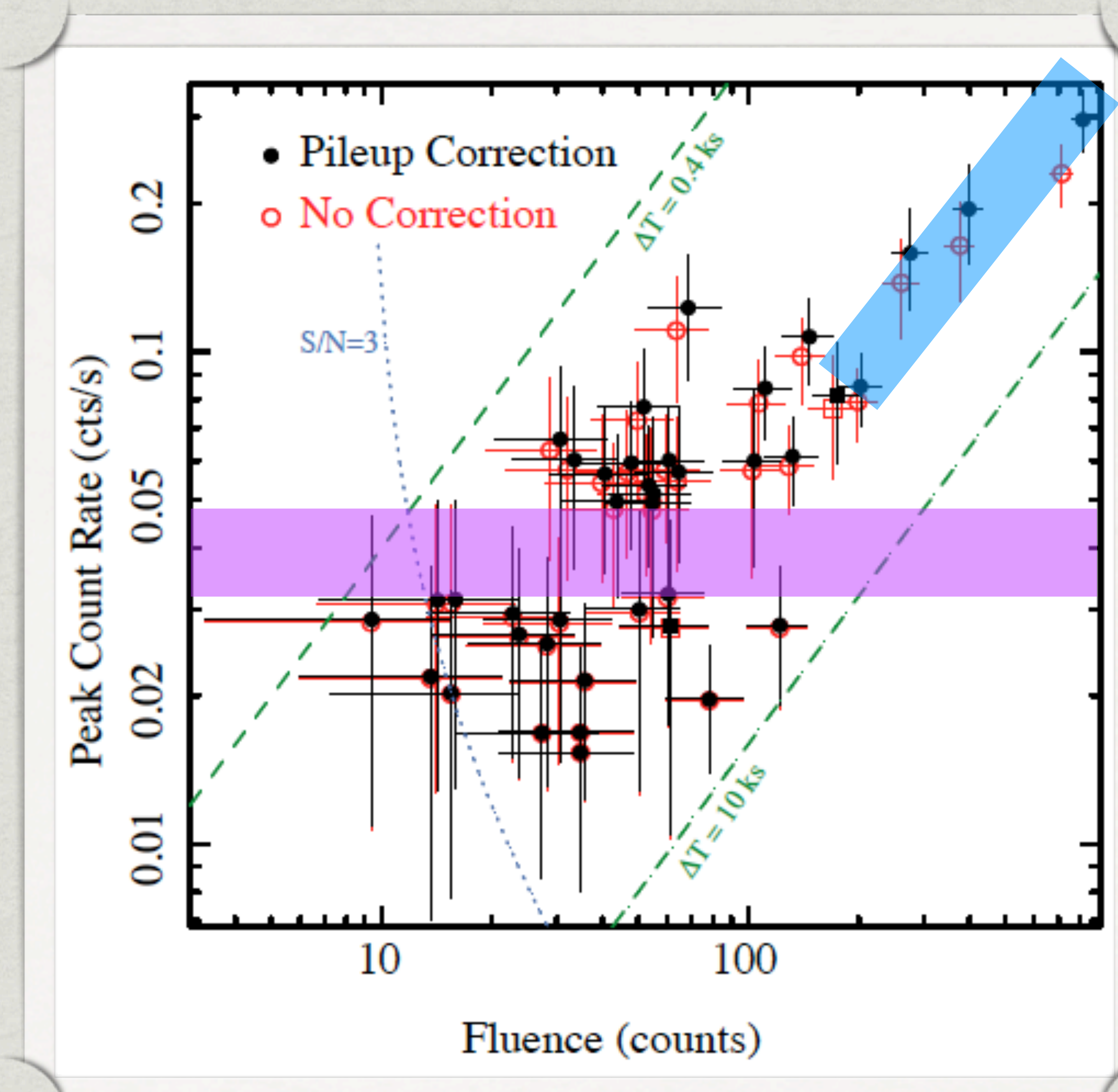
- Strong correlation between peak count rate and fluence
- Sensible/expected if flares have same shape



NEILSEN ET AL. (2013)

39 Flares: Demographics

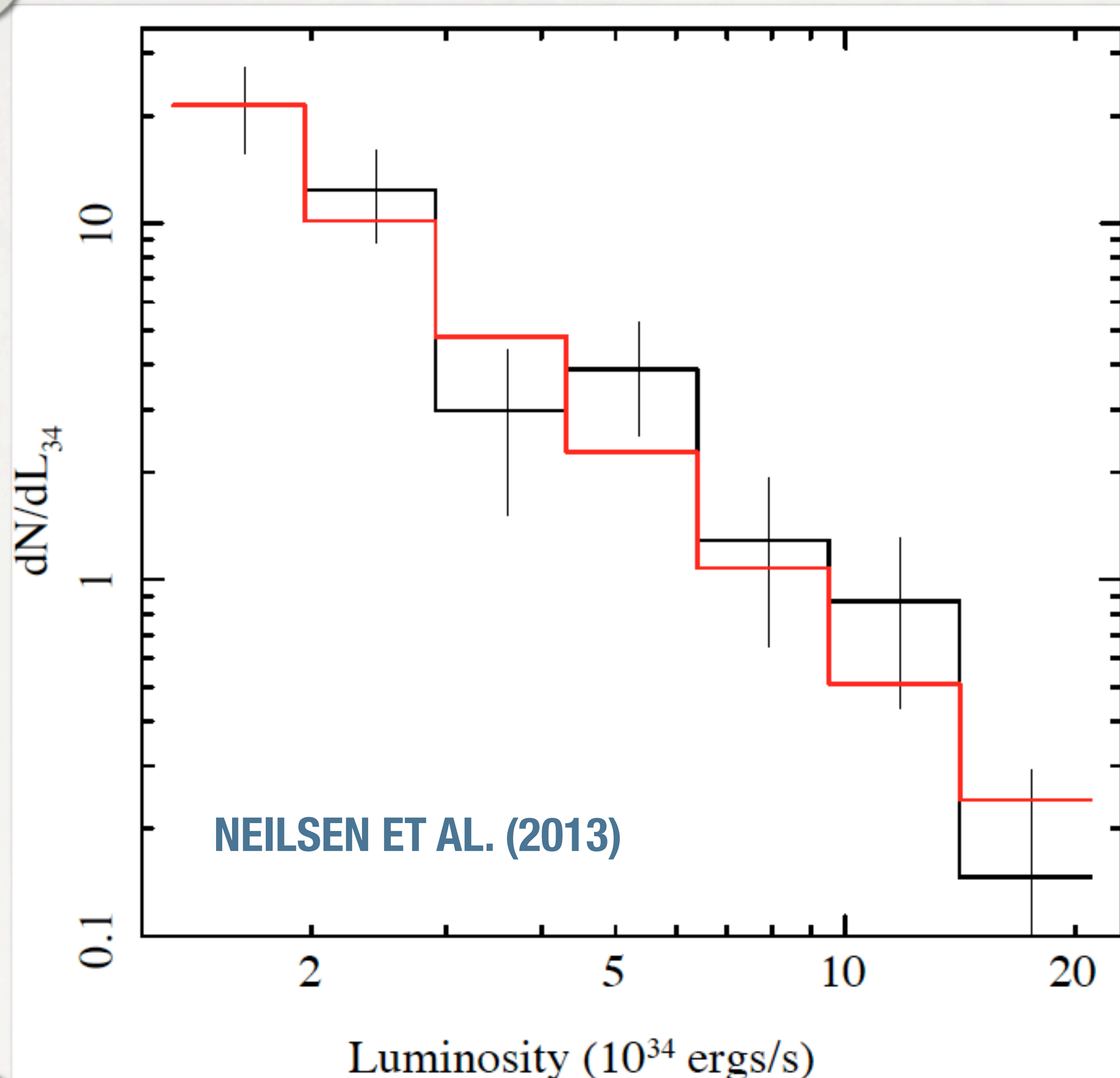
- ~4-6 ks characteristic time scale for the brightest flares? D. Haggard's bright flare too!
- Gap in peak rate around 0.04 counts/s?
    - Significant at ~90%
- Careful treatment of pileup, background: <u>no difference in spectral hardness above/below gap</u>



NEILSEN ET AL. (2013)

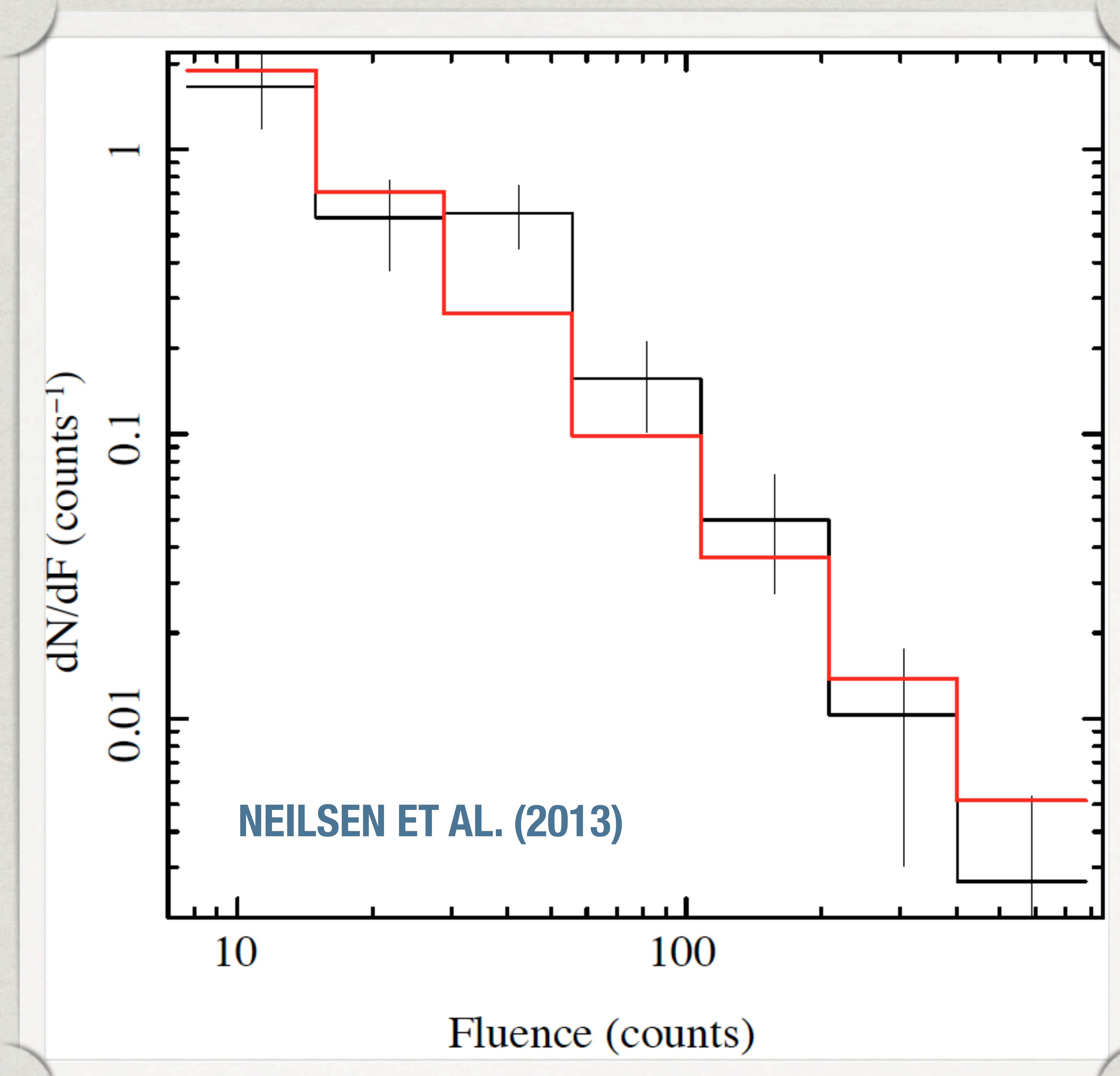
Luminosity Distribution

- Best fit power law: $dN/dL \sim L^{-1.9}$
- Similar to observed solar flares, though not likely stellar in origin
- Asteroid model (e.g. Zubovas et al. 2012) has $dN/dL \sim L^{-(1.6-2)}$
- Other models: difficult to predict from first principles!



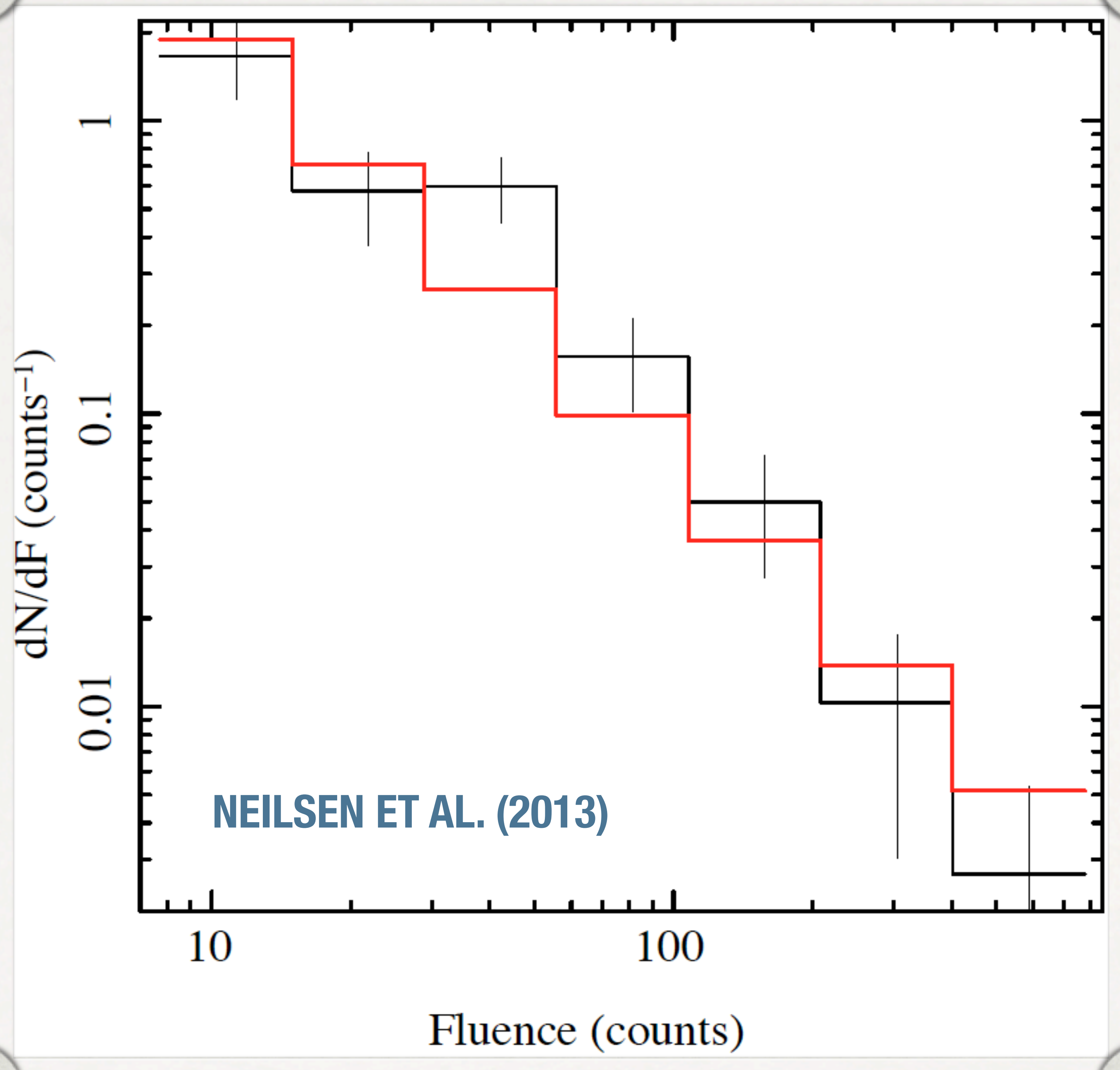
Fluence Distribution

- Flare duty cycle of 3.5%
- Observed flares still contribute 1/3 of the entire radiant energy of Sgr A* in 2012!
- Best fit power law: $dN/dF \sim F^{-1.5}$

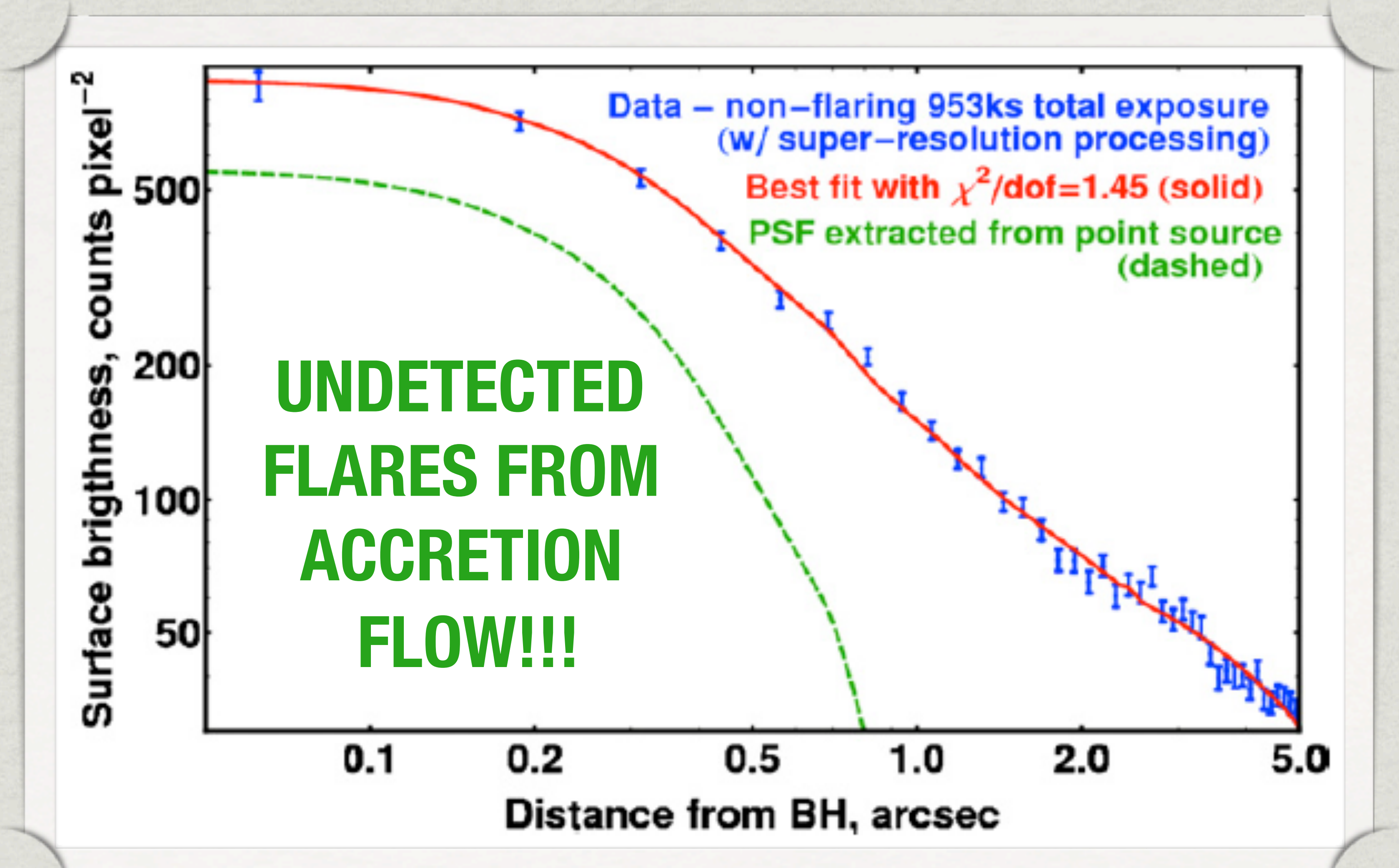


Fluence Distribution

- Is the quiescent emission the superposition of many **undetected** flares?
- Integrate backwards: unobserved flares contribute less than ~10% of underlying quiescent emission
- Power spectral analysis confirms ~10% excess variability above Poisson noise in quiescent emission
- Two emission components in “quiescence”: 1 steady (90%), 1 variable (10%)



What Is This 10%???



- Surface brightness distribution: point source **and** extended emission, 10-20% vs 80-90% of X-ray flux (Shcherbakov & Baganoff 2010; Wang et al. 2013; see D. Wang talk tomorrow!)

Summary

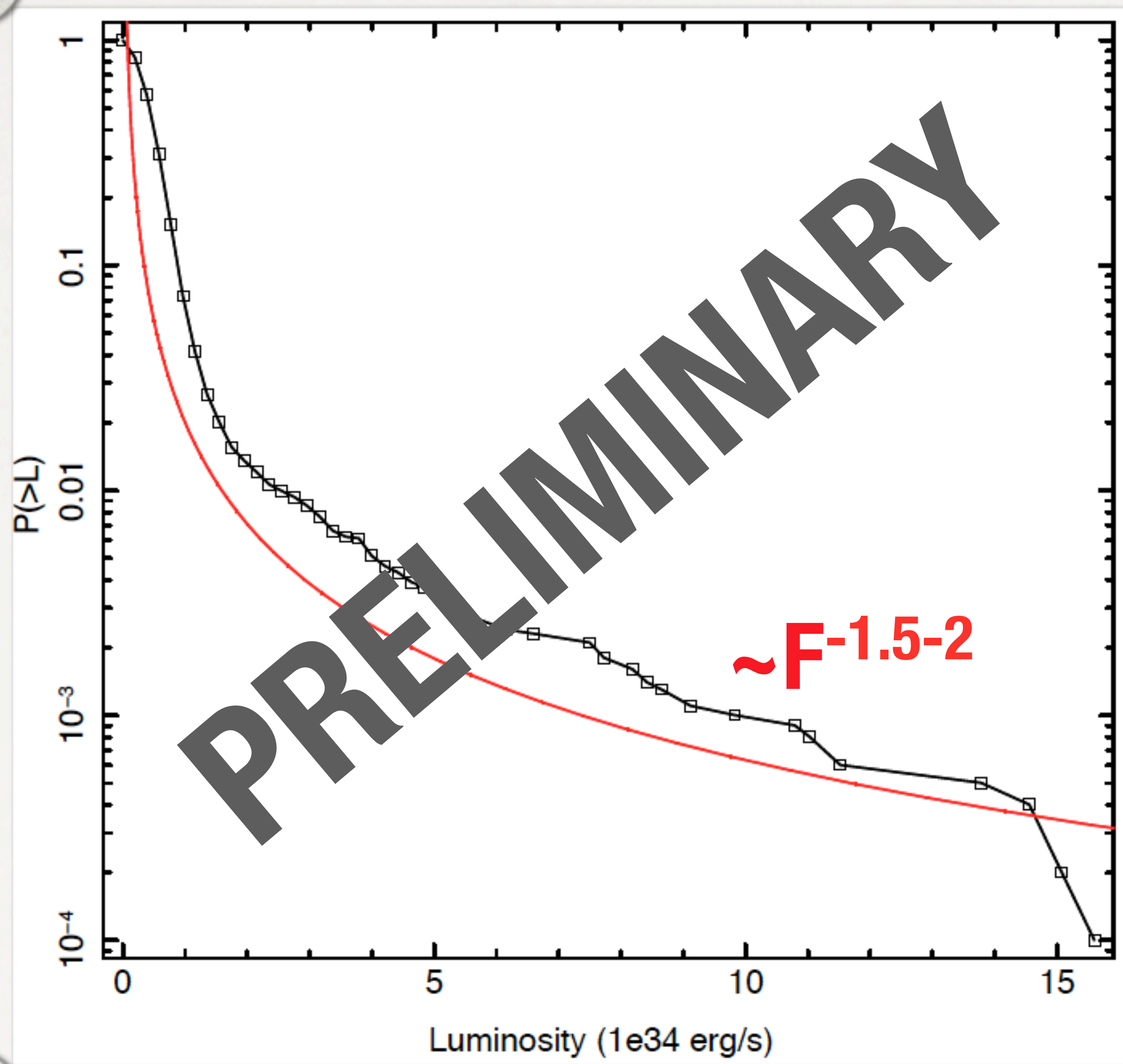
- Flare statistics, surface brightness models, & spectra (Wang et al. 2013) provide a sensible physical decomposition of quiescent emission
    - ~90% of emission is steady thermal plasma on large scales, ~10% is weak flares from the inner accretion flow. See also accretion flow simulations by Dibi et al. (2013), Drappeau et al. (2013)
- Despite a duty cycle of 3.5%, flares contribute 1/3 of radiant output of Sgr A* in 2012!
- No evidence for different flare spectra at different luminosities

Future Work

- Are flares clustered? Are they asymmetric? Periodicities or random? Change over time? Incorporate historical Chandra/XMM observations
- No present evidence for different flare spectra at different luminosity (but see NuSTAR, N. Barrière talk, Degenaar et al. 2013). Need detailed spectral analysis of each flare: any evidence for changing properties with luminosity?
- Detailed multiwavelength modeling of flare SED; how do the IR/X-ray flux distributions compare?

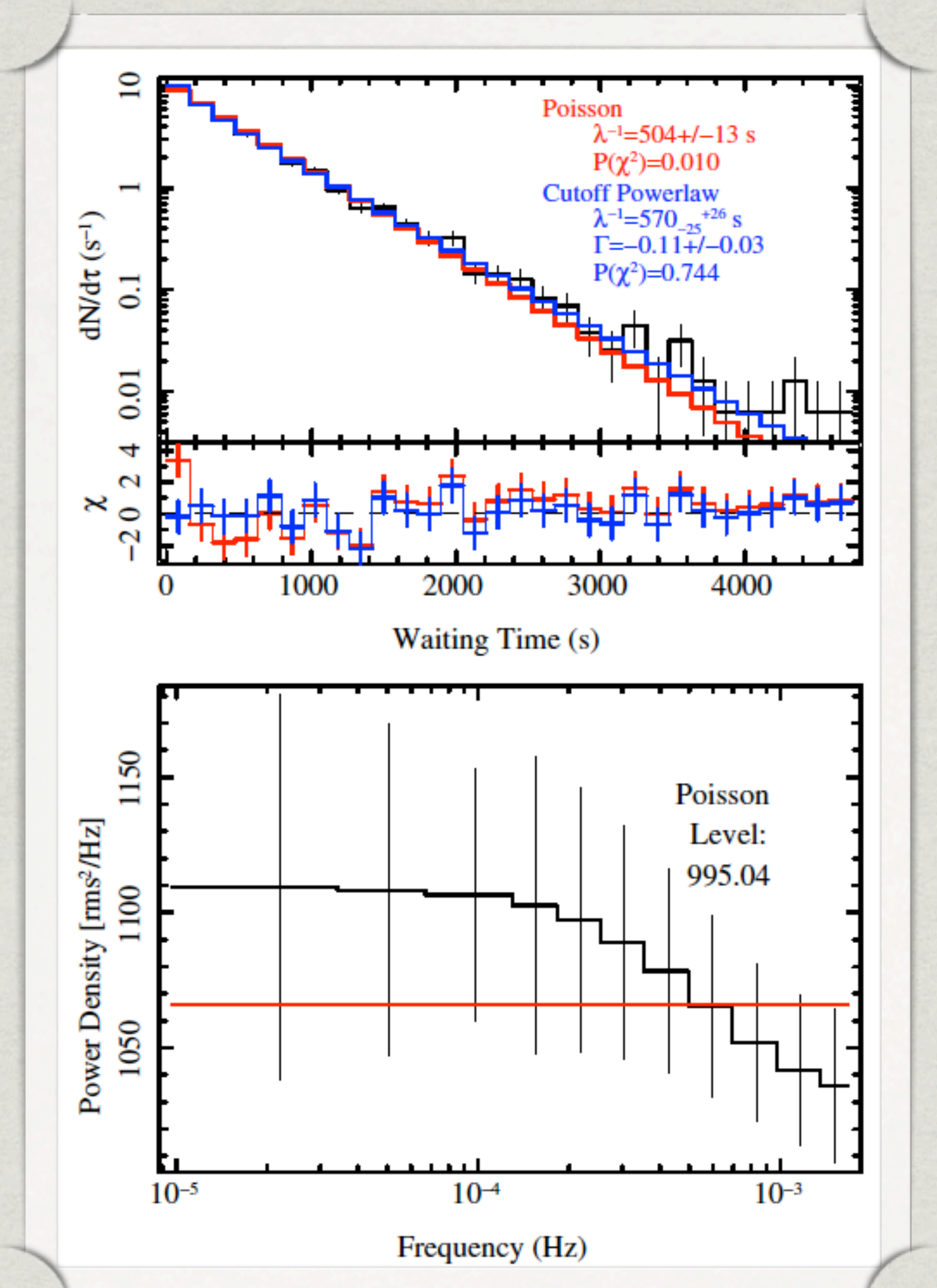
Total X-ray Flux Distribution

- (Preliminary) X-ray flux $\sim F^{-1.5-2}$
- IR flux $\sim F^{-4.2}$ (Witzel et al. 2012)
- High luminosity IR tail? $\sim F^{-2.1}$ (Dodds-Eden et al. 2011)
- Constraining for flare models??!?



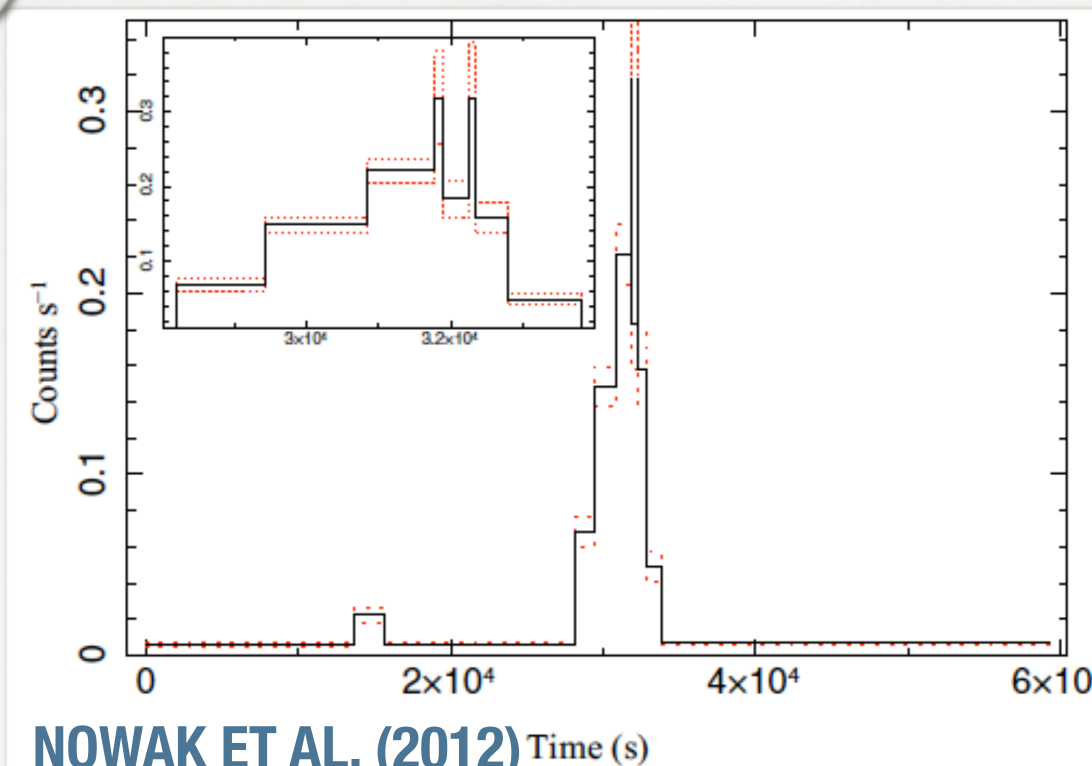
Quiescent Variability

- Waiting times (inter-arrival times) between quiescent photons close to exponential (i.e. Poisson process)
- Small amount of correlated noise
- Power spectral analysis confirms: ~10% excess variability above Poisson!

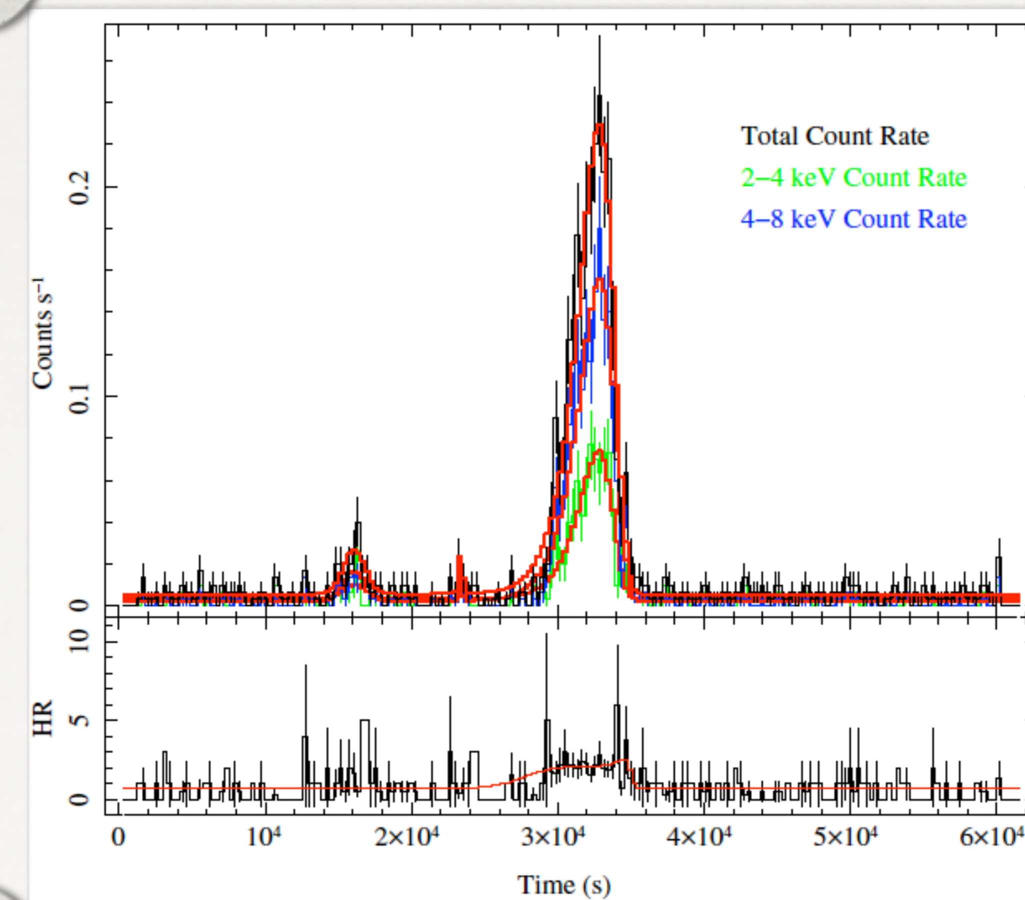


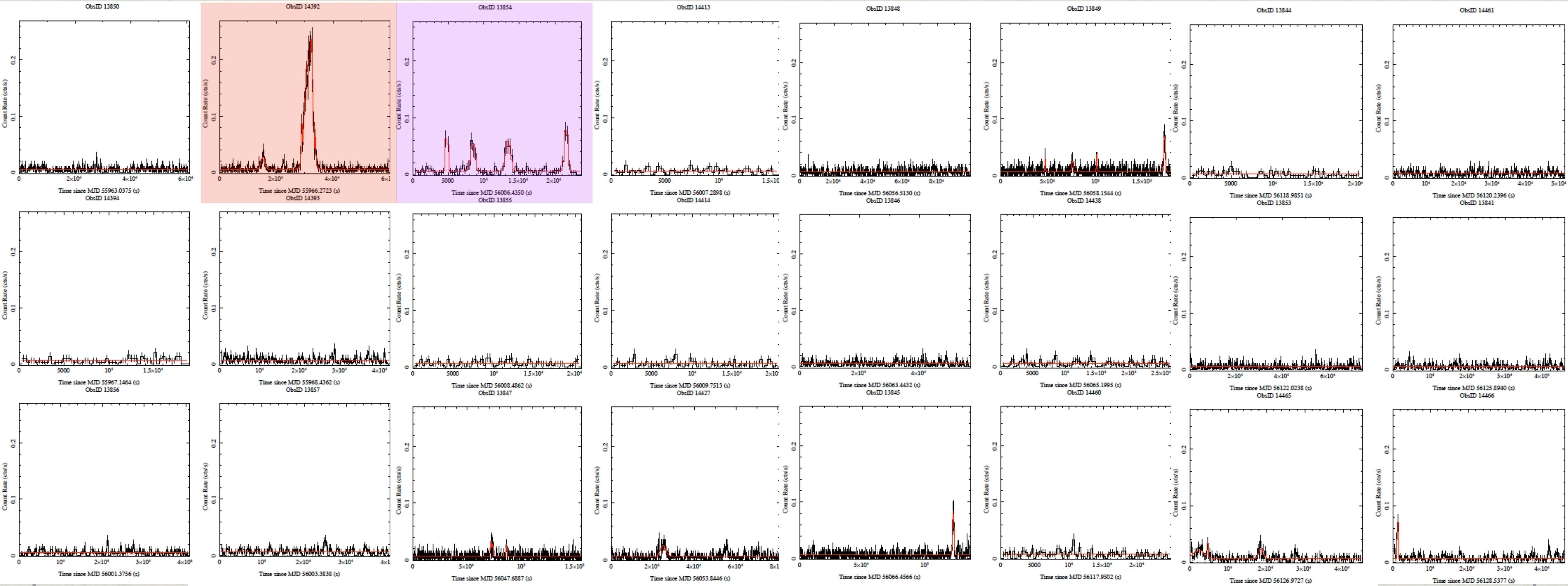
Bright F

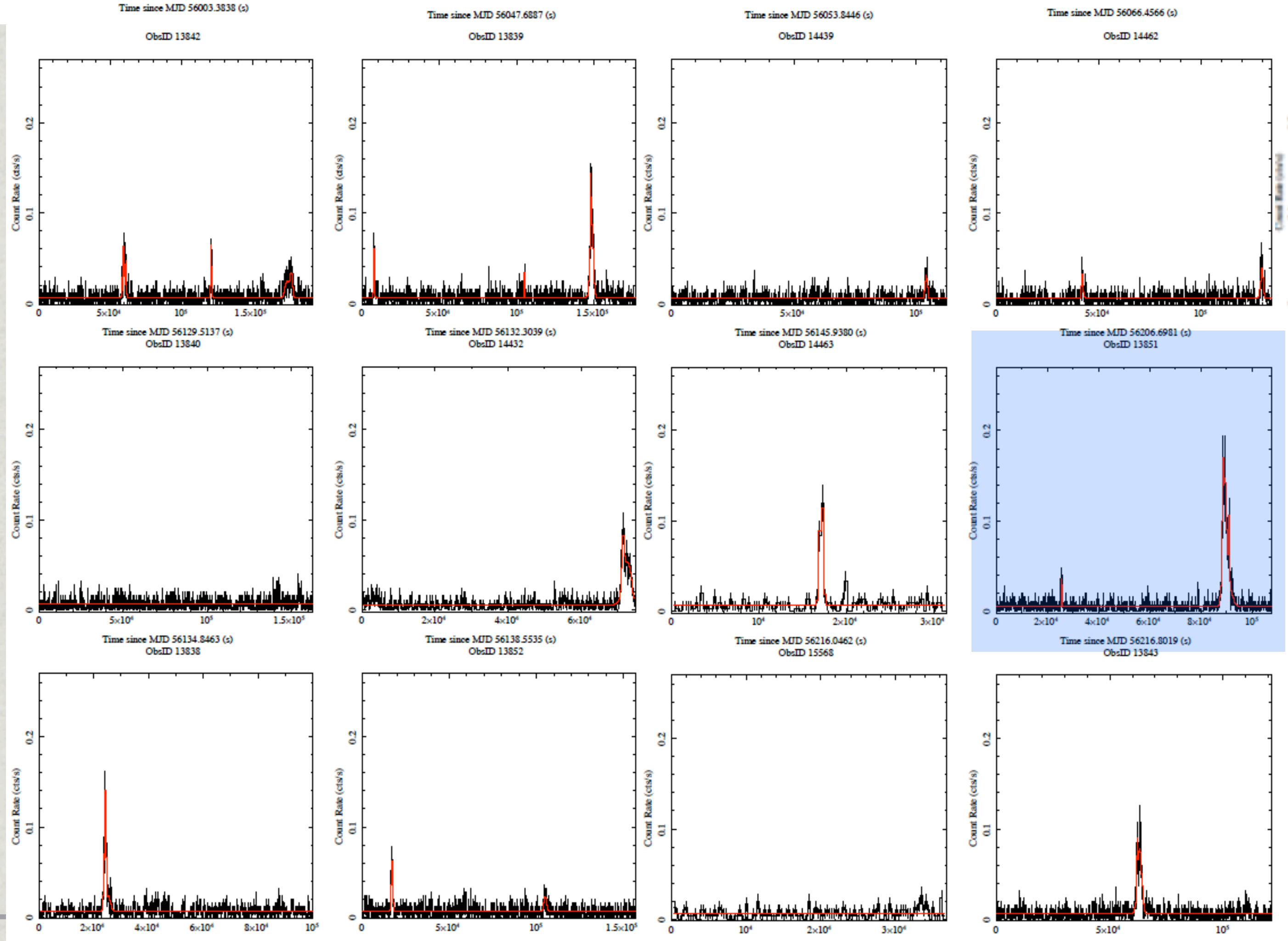
- Brightest flare in 2012 campaign
- Lasted 5600 s, substructure on time scales of 100 s
- Short time scale $\Longrightarrow$ compact emission region!
- Spectral variations?
- HR=(4-8 keV)/(2-4 keV)
- K-S test: flare/quiescence differ at >95% confidence

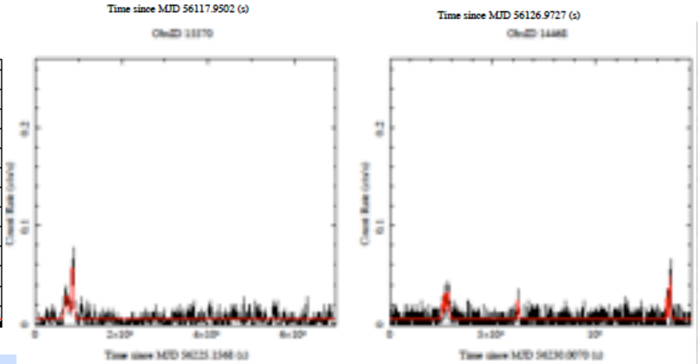


NOWAK ET AL. (2012)









2.99 MS
38 OBSERVATIONS
~22000 PHOTONS
39 FLARES