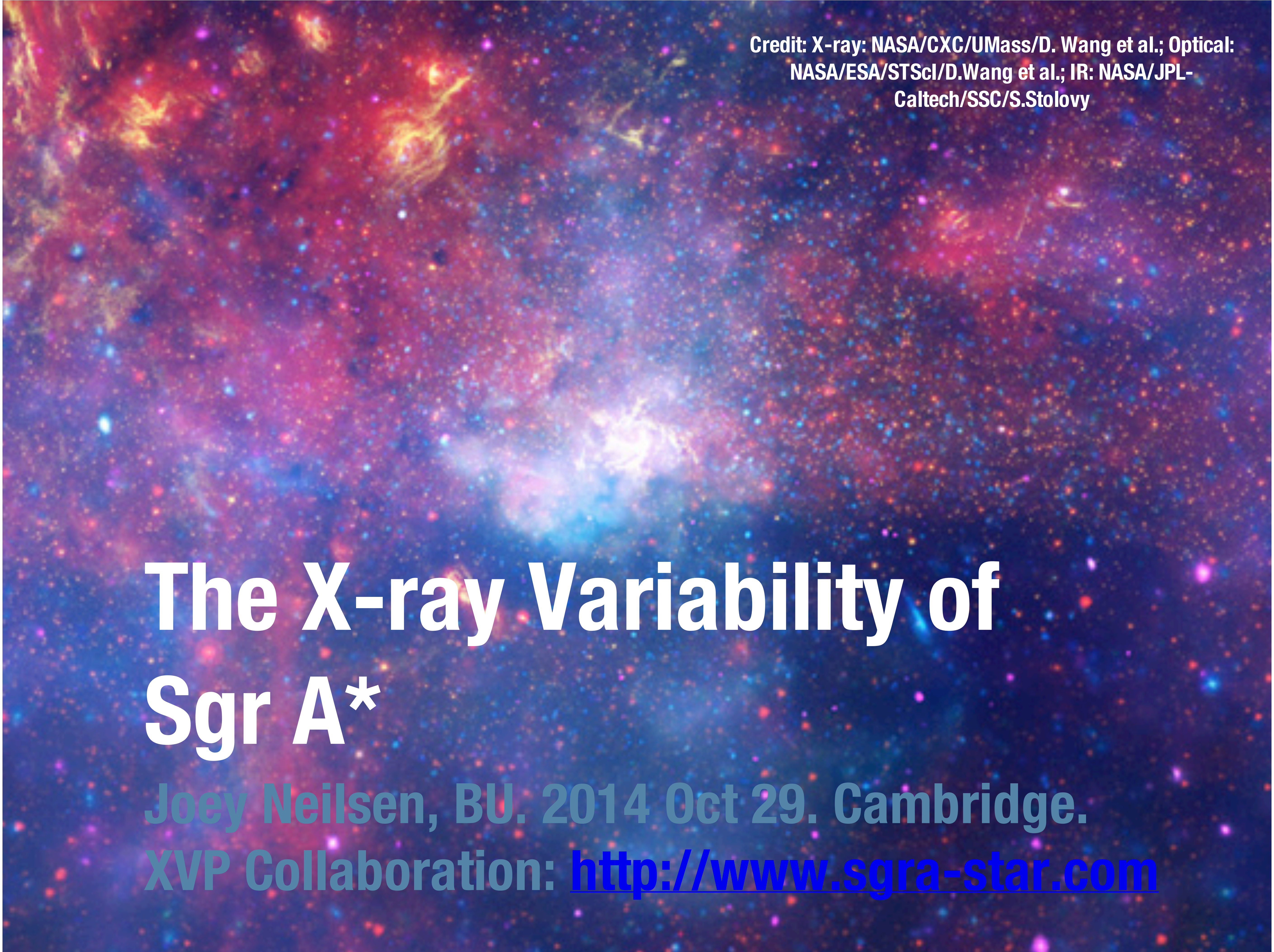


Credit: X-ray: NASA/CXC/UMass/D. Wang et al.; Optical: NASA/ESA/STScI/D.Wang et al.; IR: NASA/JPL-Caltech/SSC/S.Stolovy

The X-ray Variability of Sgr A*

Joey Neilsen, BU. 2014 Oct 29. Cambridge.

XVP Collaboration: http://www.sgra-star.com

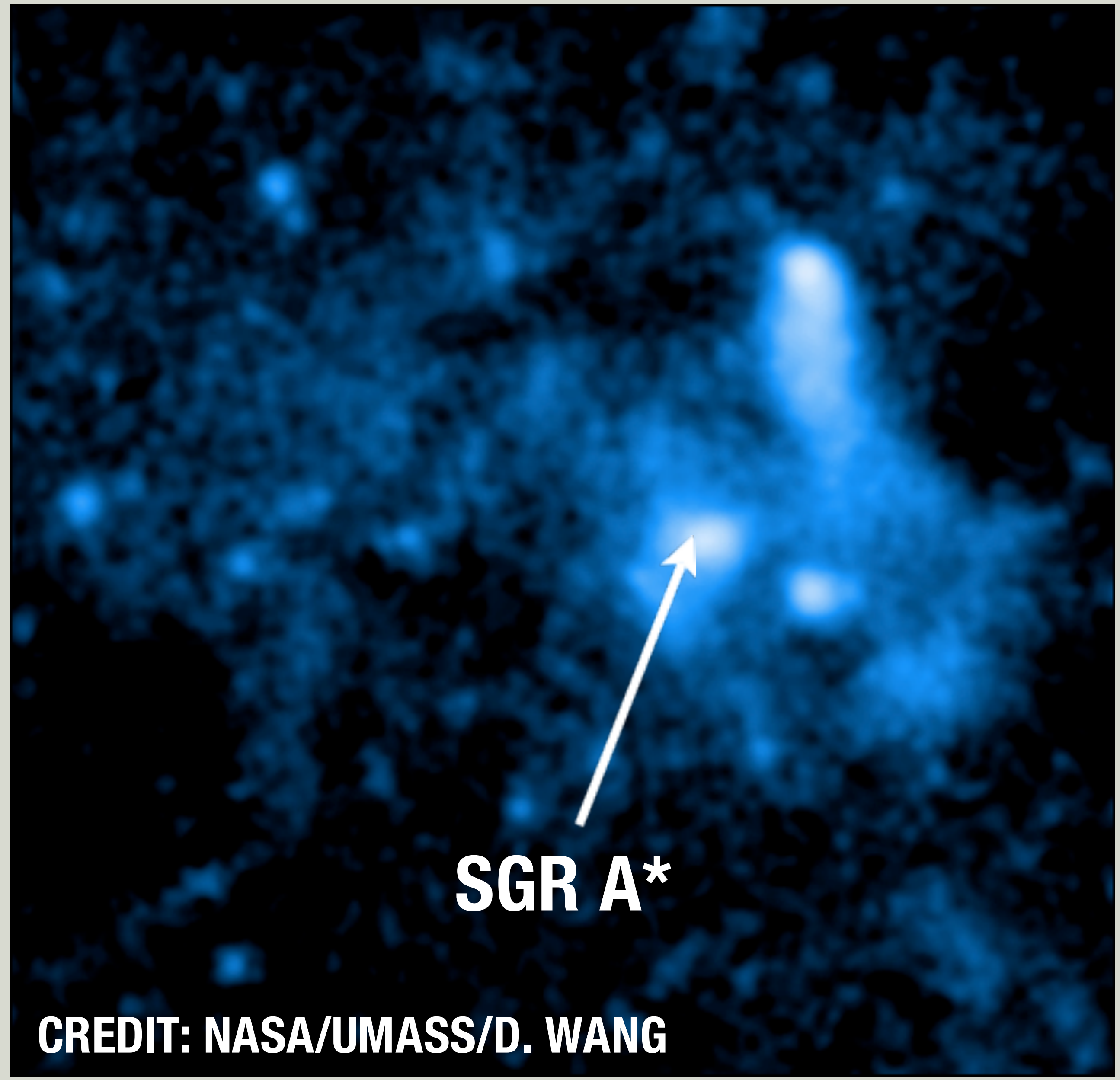
Outline

- Closest example of supermassive black hole variability, and extremely faint!
- Brief introduction to X-ray emission from Sgr A* and the 3 Ms *Chandra* X-ray Visionary Project
- Variability properties, relationship to quiescent emission
  - X-ray flare statistics (Nowak et al. 2012; Neilsen et al. 2013b)
  - X-ray flux distribution (Neilsen et al. 2014b)

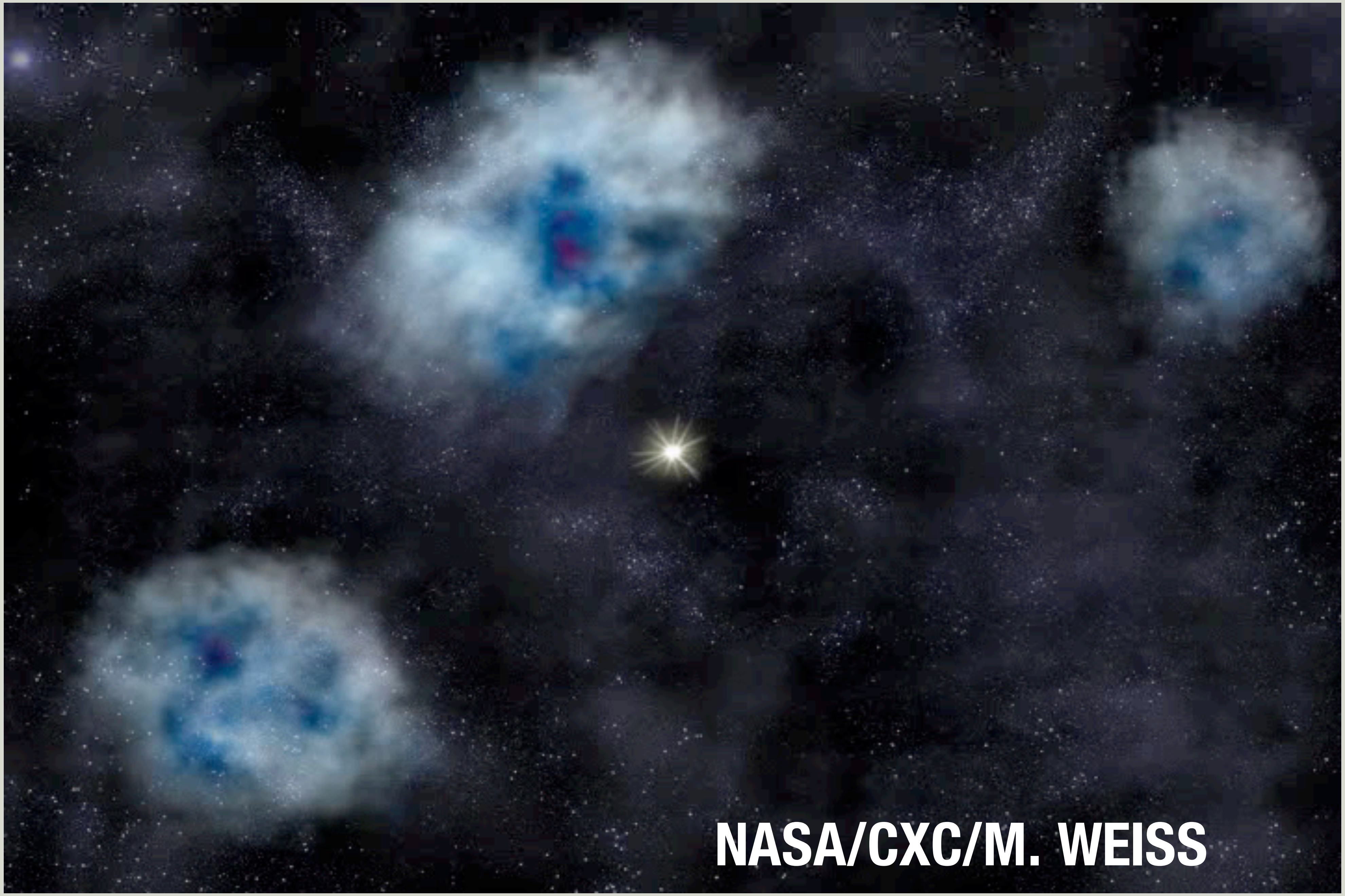
How Variable is Sgr A*?

How Bright is Sgr A*?

- Not very!!!!
- Actually extremely faint: $L_X \sim 3.5 \times 10^{33}$ erg s$^{-1} \sim 10^{-11}$ L_{Edd}
- Undergoes ~daily X-ray flares, few$\times 10^{34}$ erg s^{-1}



An Active Past?



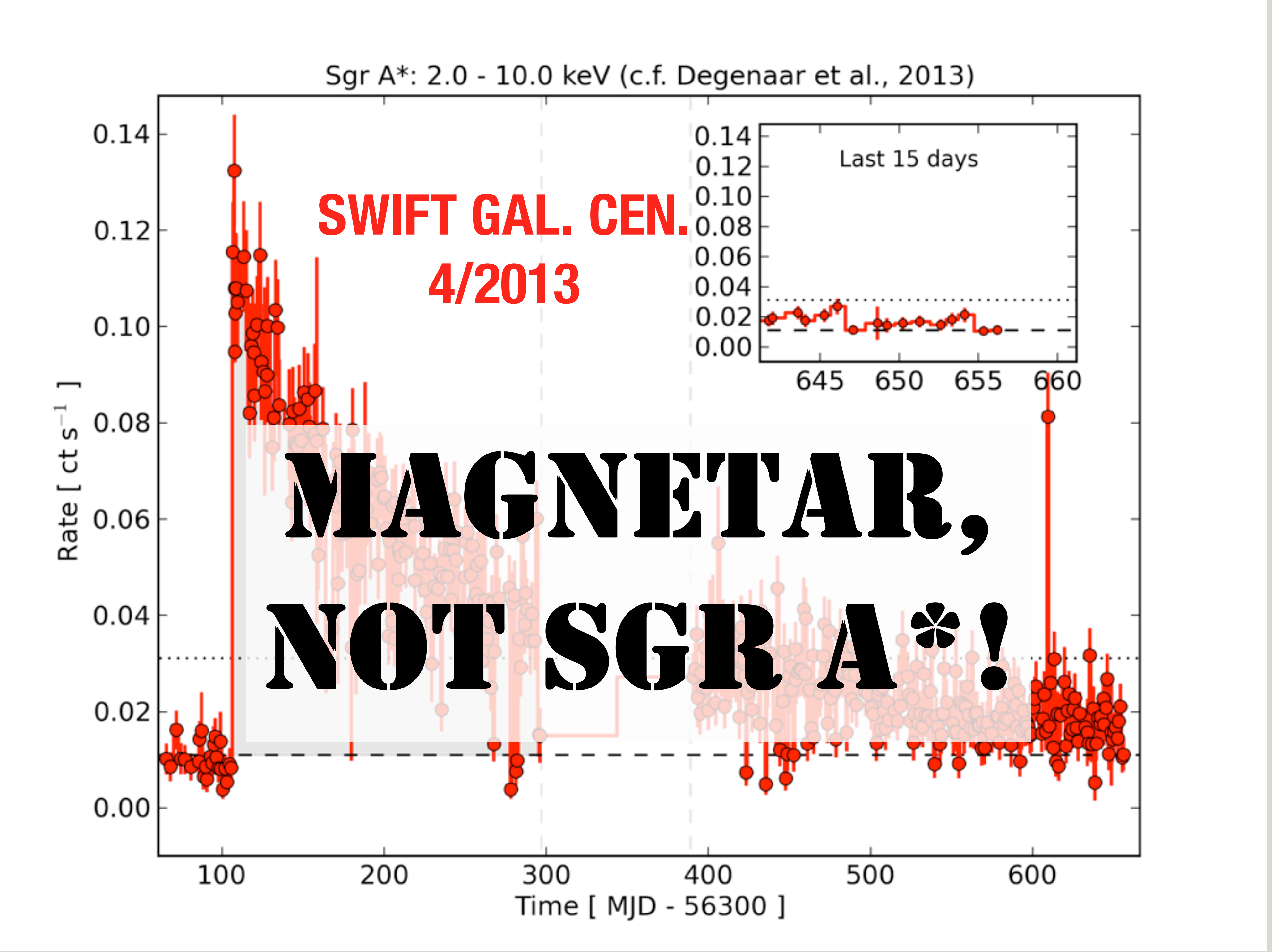
Giant flares from Sgr A* illuminate molecular clouds

How Faint is Sgr A*?

The scattered flux must exist, and therefore the observed flux, even if it is not due to Thomson scattering, imposes an upper limit on the averaged X-ray luminosity from the GC region in the recent past. From the present day X-ray data, it is evident that the total energy release in this region in the 5–20 keV energy band over the past 400 yr cannot be greater than $\sim 10^{48}$ ergs. The nucleus (and its neighborhood) was not brighter than $\sim 10^{38}$–10^{39} ergs s^{-1} during at least the last several hundreds of years. Moreover, the nucleus has not emitted the Eddington luminosity for even a day over the last 400 yr, since otherwise this would be noticeable in the X-ray images of the diffuse emission.

SUNYAEV ET AL. 1993

Bang!



Sgr A*: 2.0 - 10.0 keV (c.f. Degenaar et al., 2013)
SWIFT GAL. CEN.
4/2013
Last 15 days
MAGNETAR,
NOT SGR A*!
Rate [ct s^{-1}]
Time [MJD - 56300]

How Little We Know

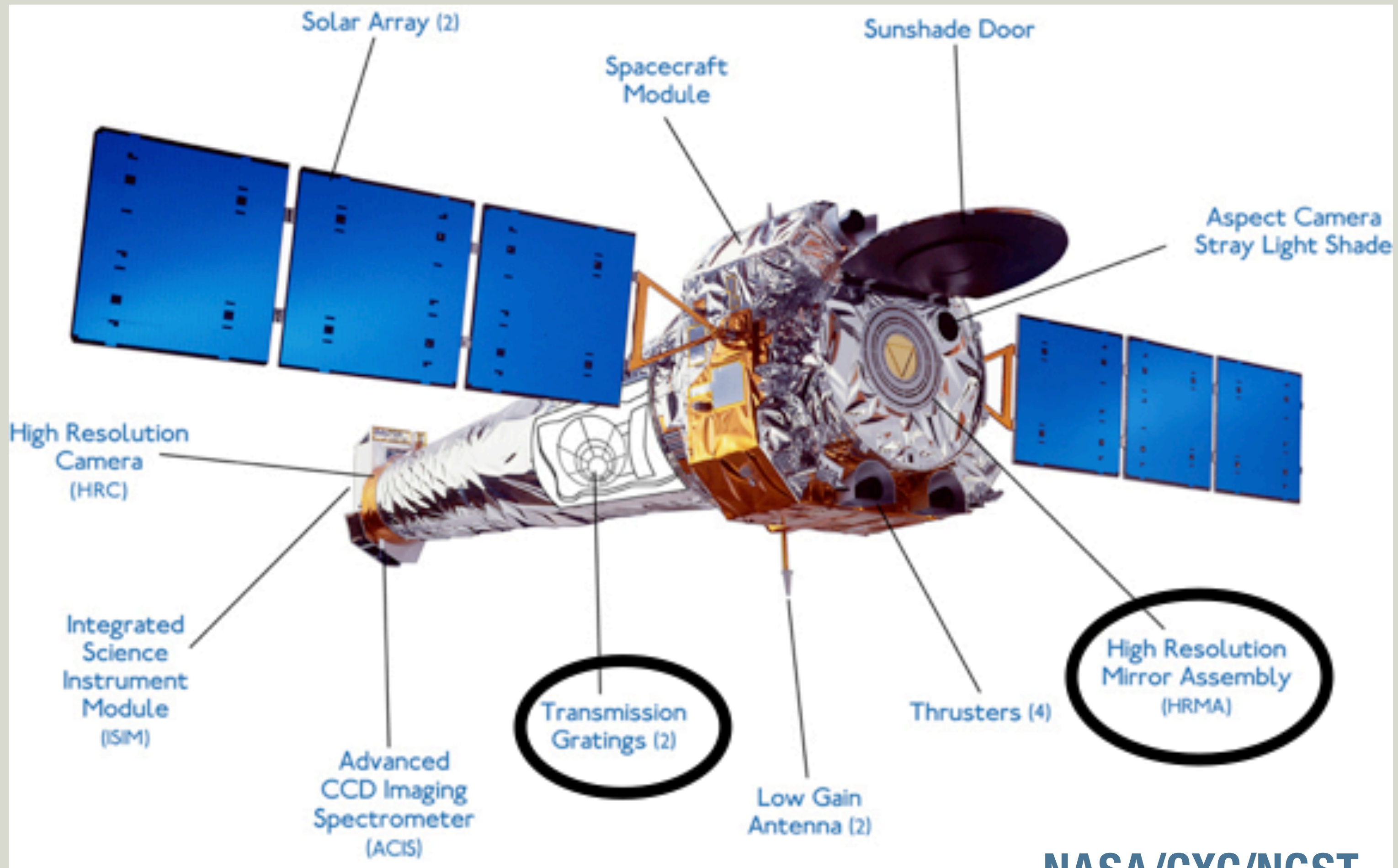
- Whole industry devoted to supermassive black hole accretion: blazars, quasars, LLAGN; variability, spectral energy distributions (SEDs), outflows

Sgr A*

- Why is it so faint?
- How does it vary?
    - ~Daily flares; what causes them?
- What sets the duty cycle of large outbursts?

Chandra and Sgr A*

- To understand X-ray emission from Sgr A*, need high <u>spatial</u> resolution, high <u>spectral</u> resolution, and lots of exposure time!
- *Chandra* X-ray Visionary Project with gratings!
- 3 Ms on Sgr A* in 2012, plus multiwavelength campaigns and theory



NASA/CXC/NGST

1. Why is Sgr A* so faint? Wang et al. (2013)
2. What causes the ~daily flares?

To Make a Flare

Energy Source

Magnetic reconnection

Shocks

Stochastic acceleration in a jet

Asteroid/planetesimal disruption

Radiation Mechanism

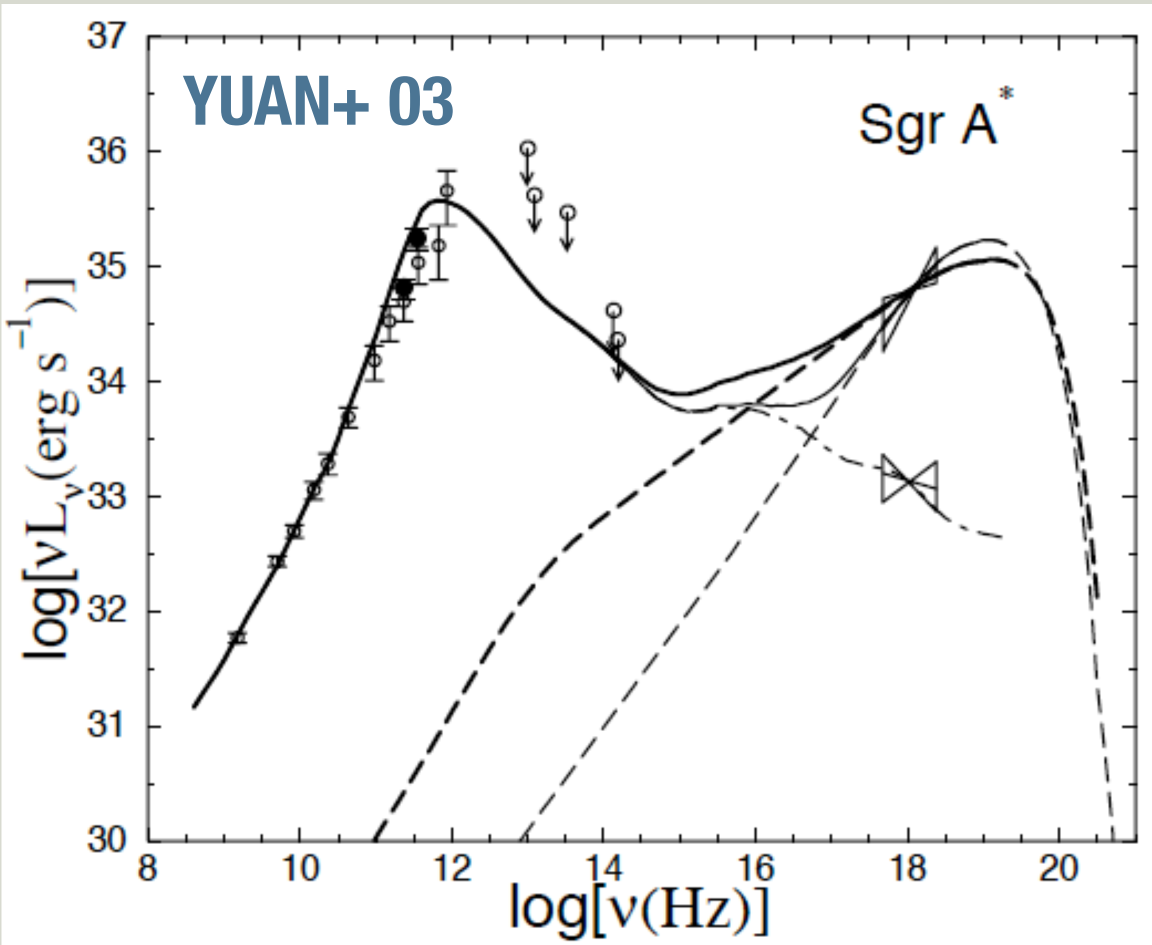
Direct synchrotron (does IR extrapolate to X-rays?)

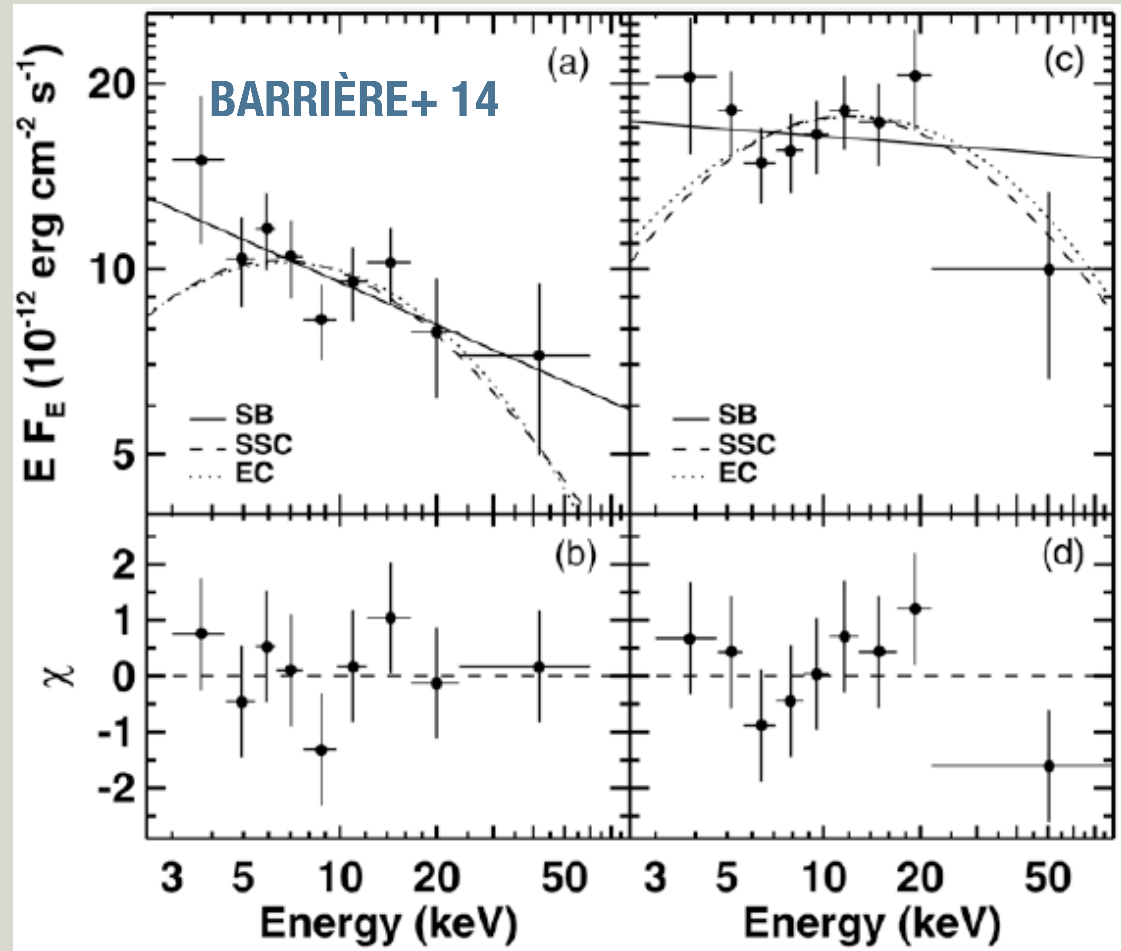
Inverse Compton

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; Hamers & Portegies Zwart 2014

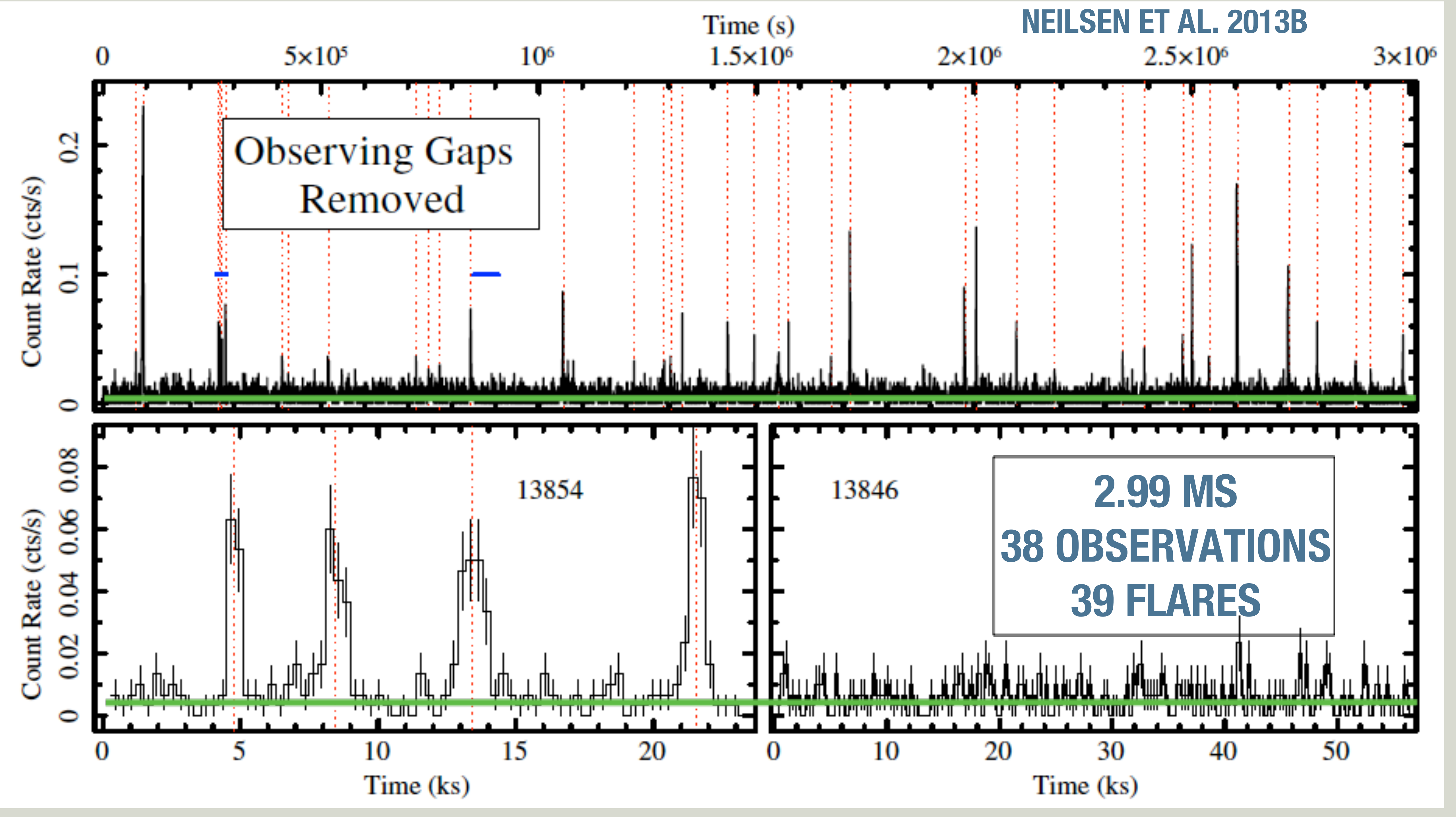
Radiation Models



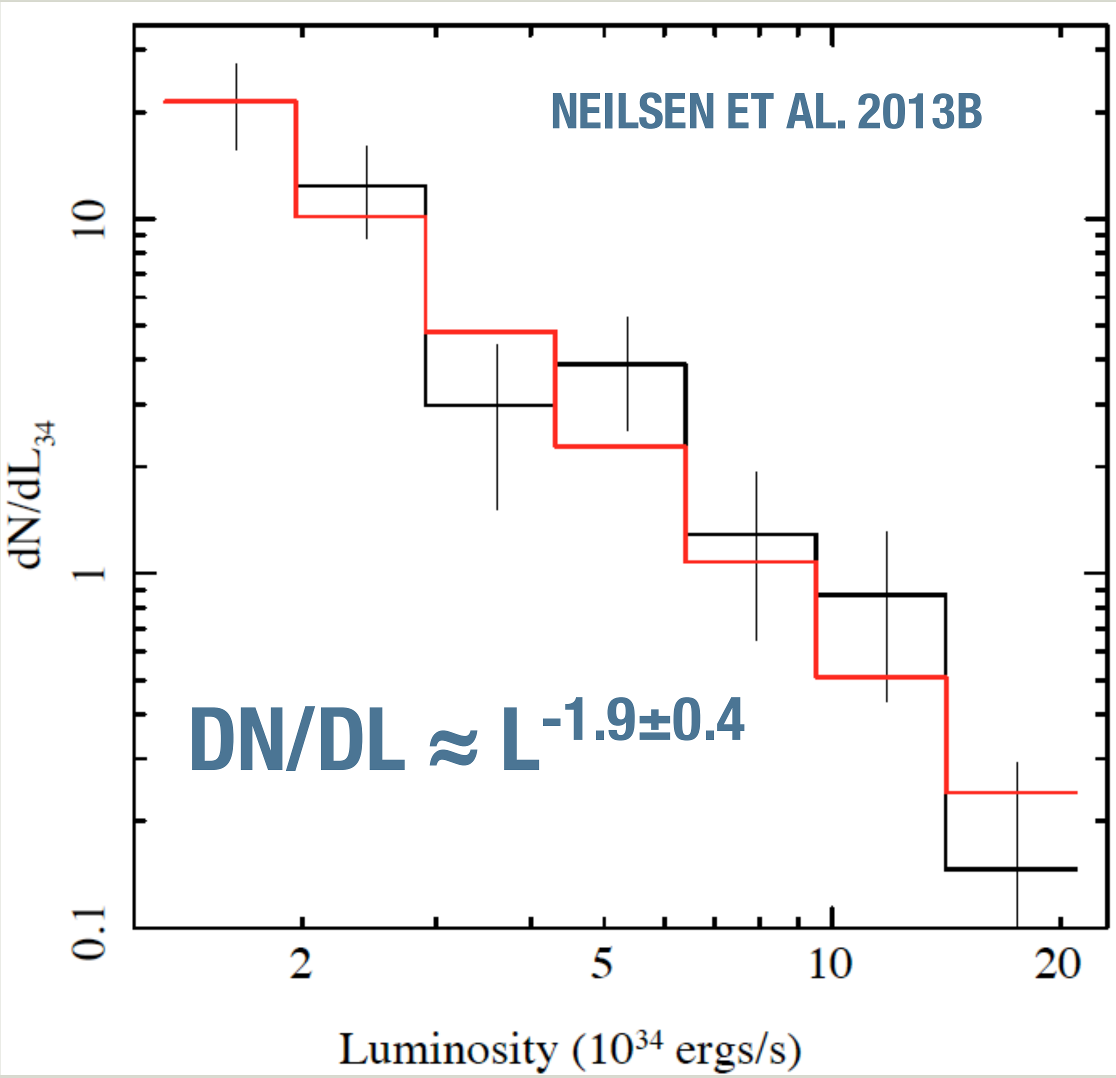


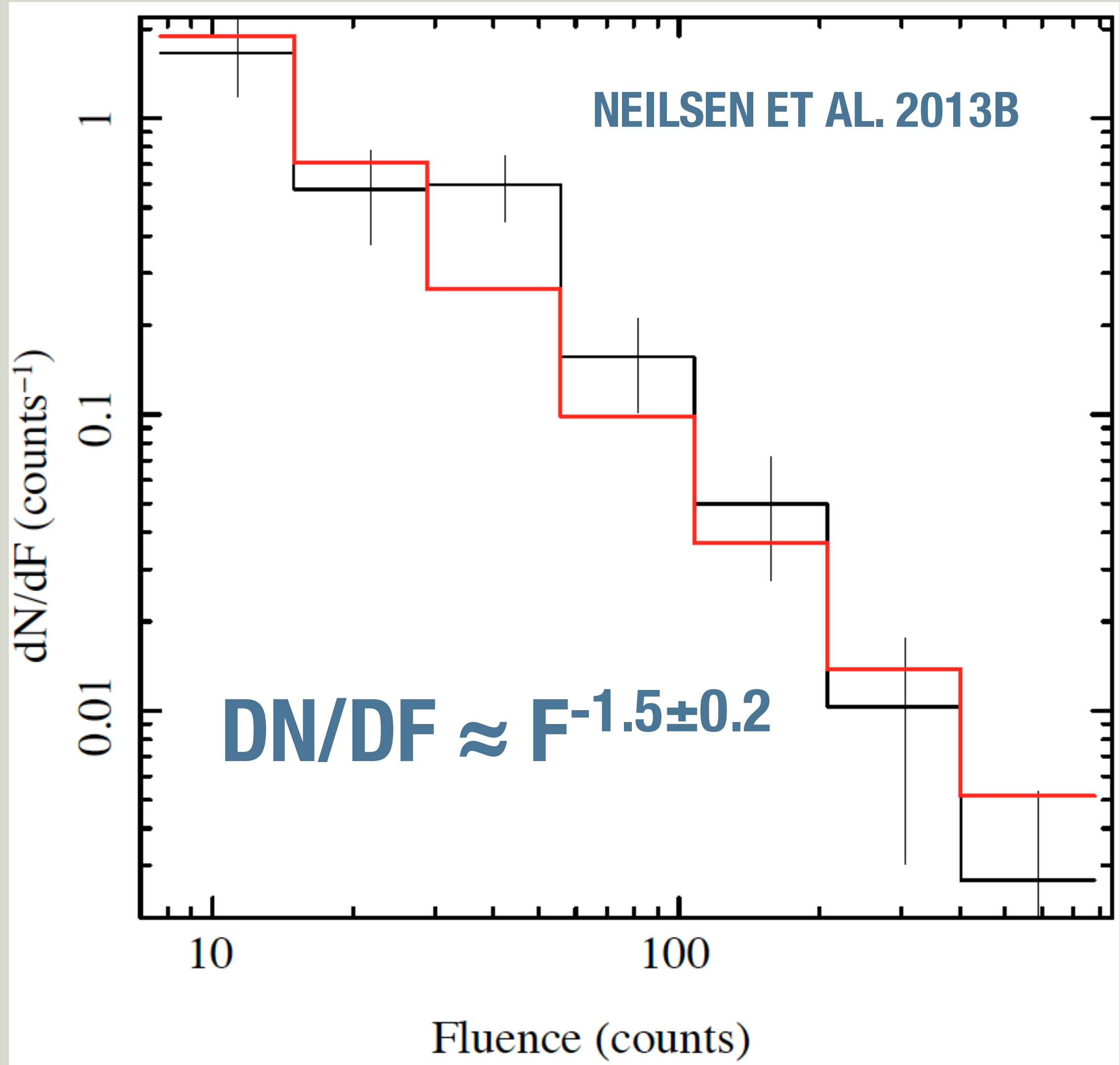
- Multiwavelength flare SEDs haven't ruled out any radiation models
- *NuSTAR* data slightly favor synchrotron models (Barrière et al. 2014; see also Dodds-Eden et al. 2009)
- Complementary approach: statistical analysis of *Chandra* flares

2012 *Chandra* Campaign



Flare Distributions





Difficult to predict from first principles!

Flares contribute ~30% of total radiant energy in 3 Ms

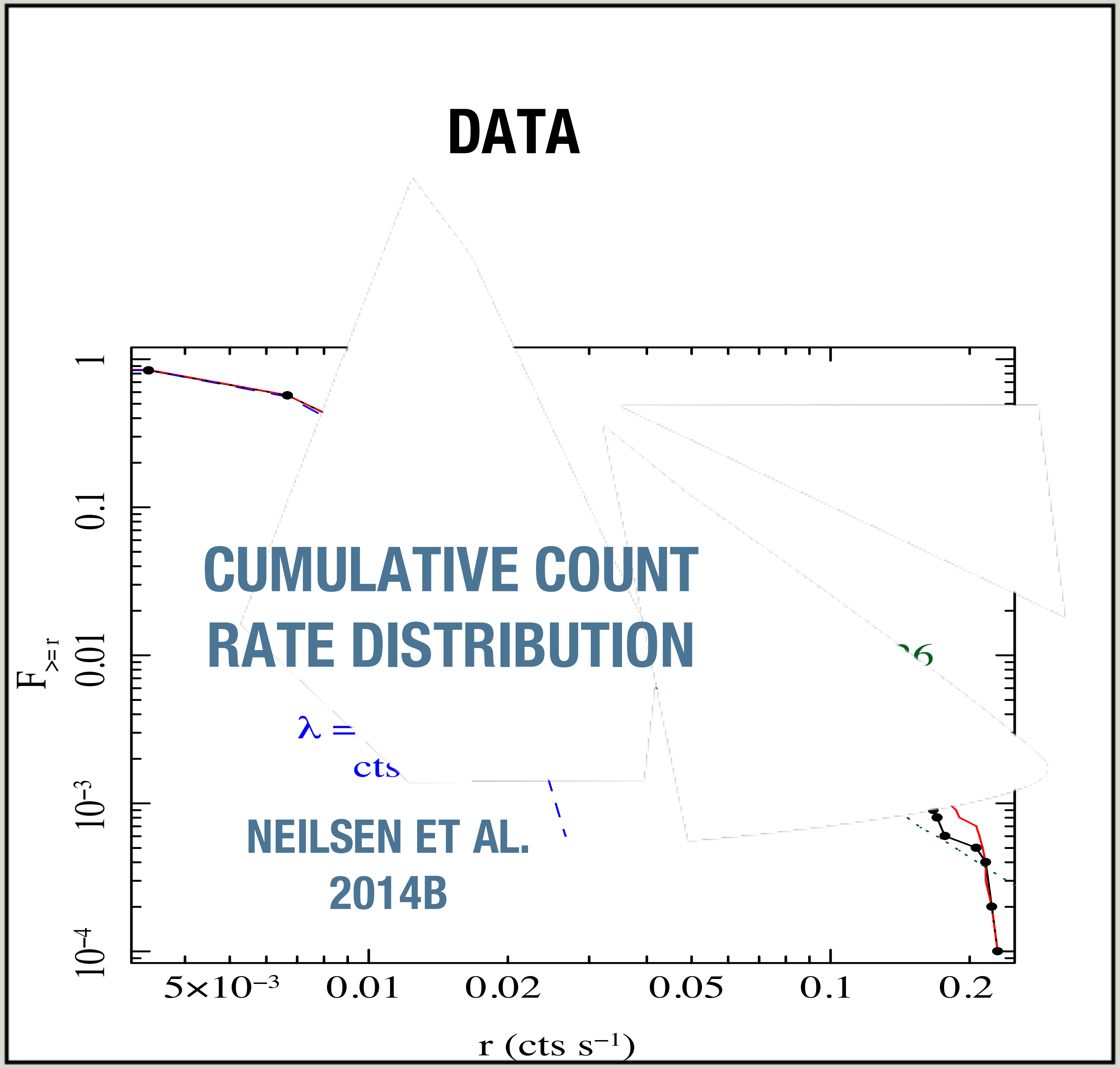
Dominated by brightest flares

Undetected flares contribute ~10% of quiescent flux

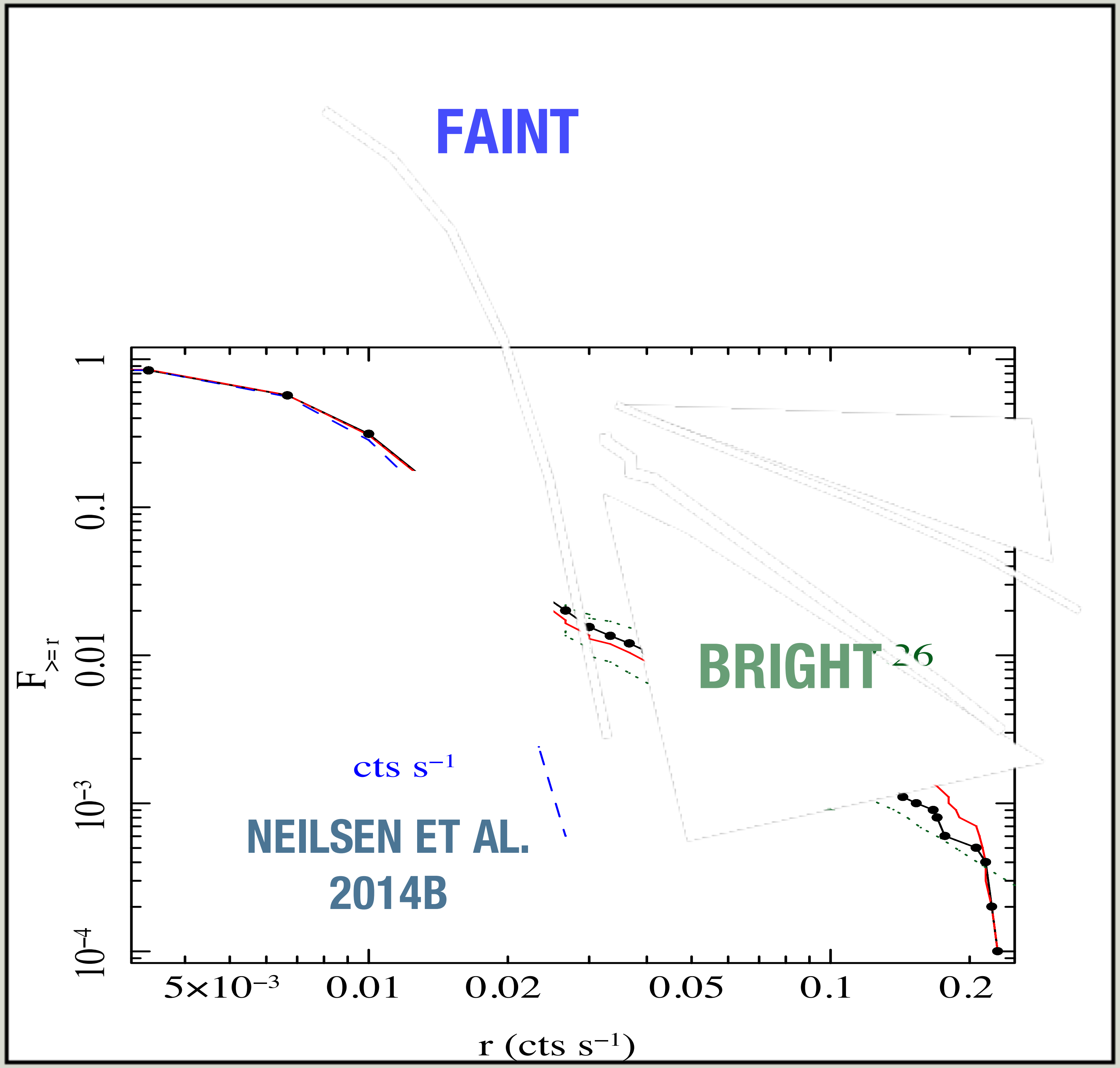
Flux Distribution

- What about the faint flares that we couldn't detect?
    - Want to include all unresolved/undetected flares
- Total X-ray flux distribution: use full 3 Ms X-ray light curve (300s bins, 10,000 data points; Neilsen+ 14b)
- A different perspective: move beyond distinct flares, think about quiescent and variable processes
- Similar work in NIR (Dodds-Eden+ '11; Witzel+ '12)
    - Multi-λ stats: insights into radiation mechanism?

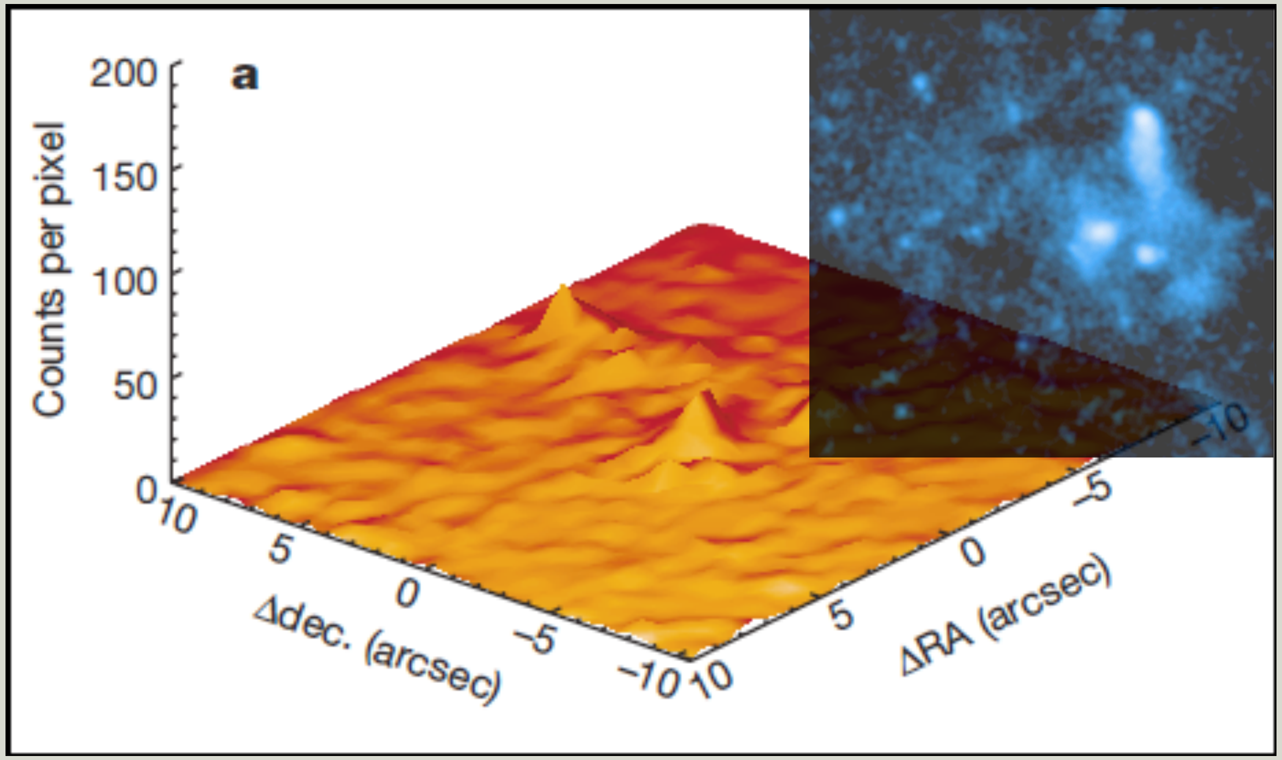
X-ray Flux Distribution

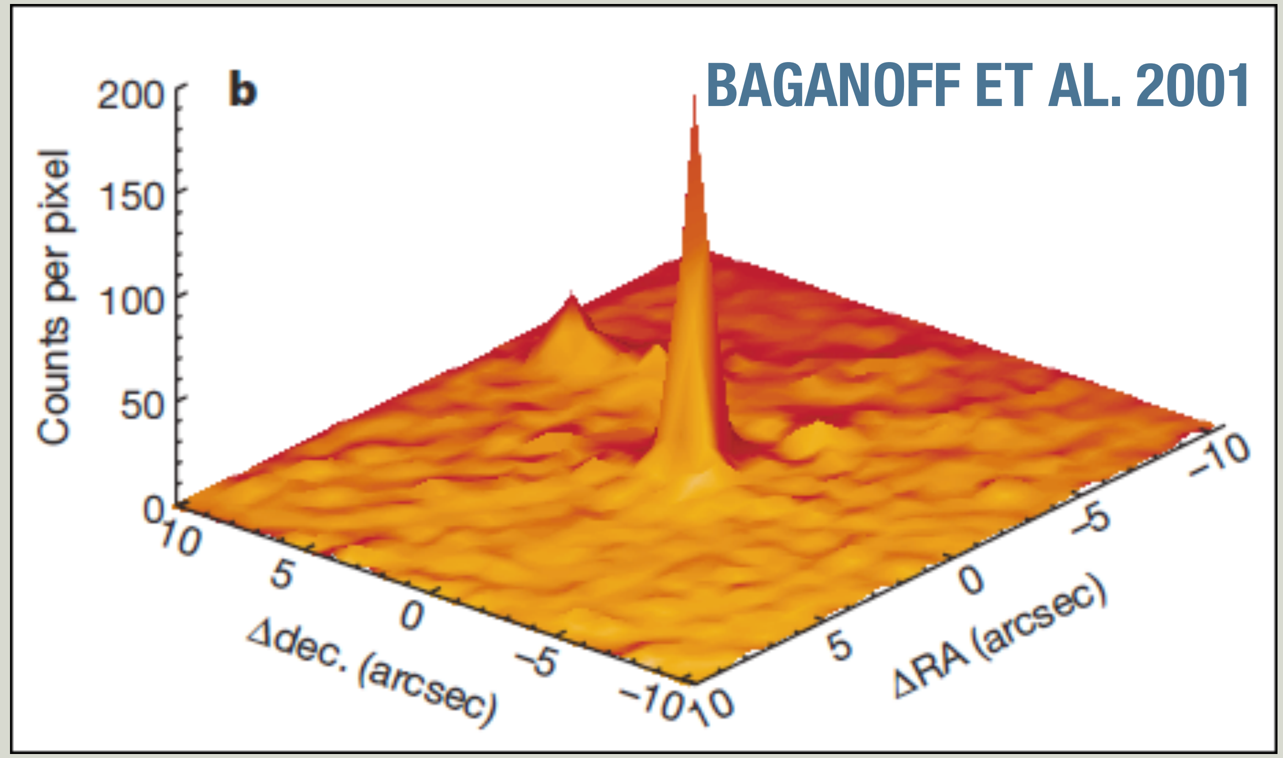


Two Components?



Two Components





Quiescent

Thermal plasma extending to Bondi radius

Model: Constant X-ray flux, Poisson count rate

Variable

Flare emission from inner accretion flow

Model: probability of flux F is power law or log-normal

Strategy: Round 1

- Model: Poisson+variable process (quiescence + flares)
- Use models to generate simulated data sets, including counting noise, photon pileup
- Compare simulated data to observed data with statistical tests (Anderson-Darling test, like K-S)
- See Neilsen et al. (2014b, submitted) for details

Strategy: Round 2

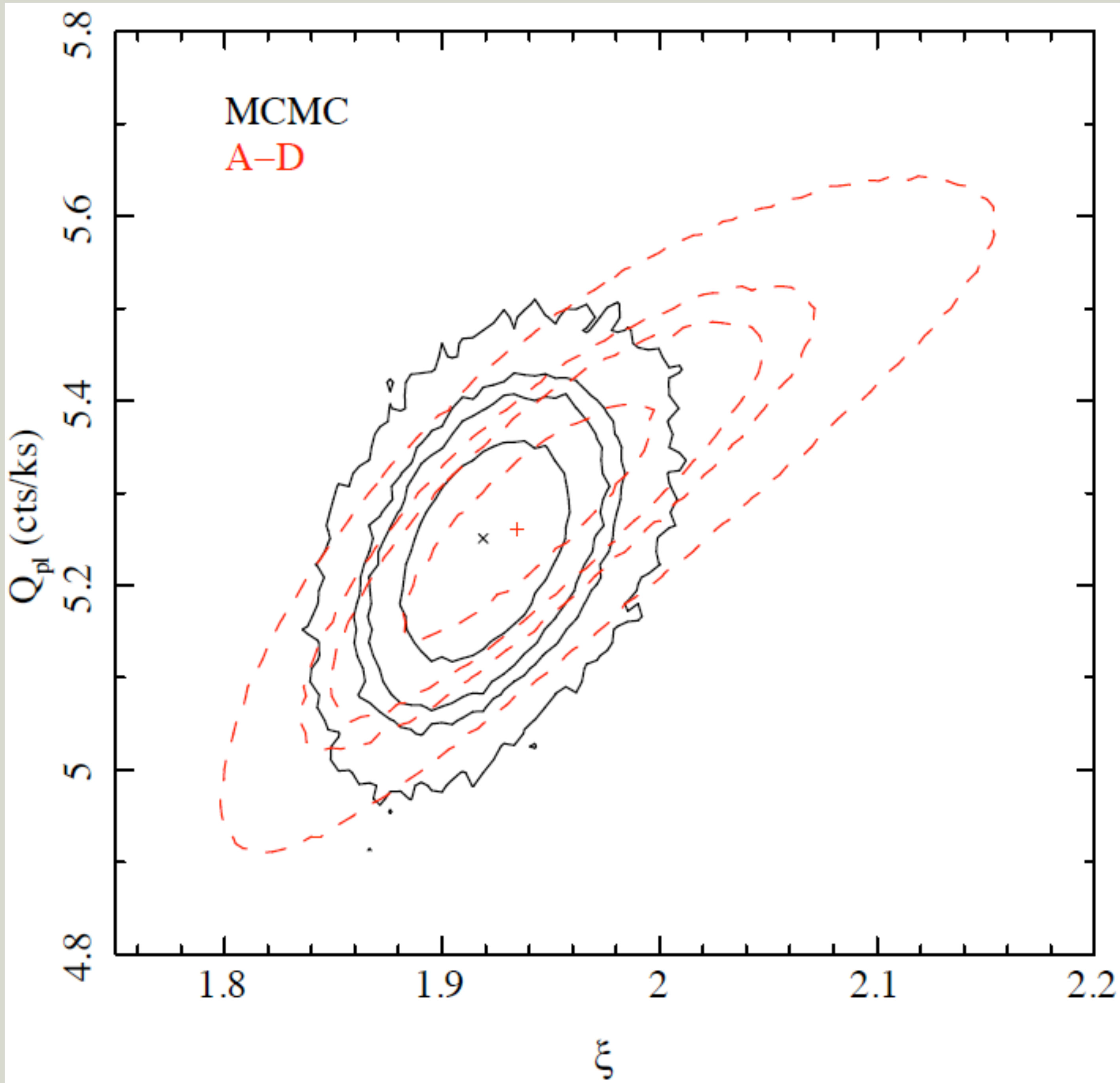
- Model: Poisson+variable process (quiescence + flares)
- Use Markov Chain Monte Carlo (MCMC) to map probability of parameters of X-ray flux distribution

$$\mathcal{P}(n|\theta_Q, \theta_V) = \sum_{j=0}^{n} \mathcal{P}_Q(j|\theta_X)\mathcal{P}_V(n-j|\theta_Y)$$

- P_V includes intrinsic flux distribution plus counting noise, instrumental effects (pileup); can be written analytically in case of power law!

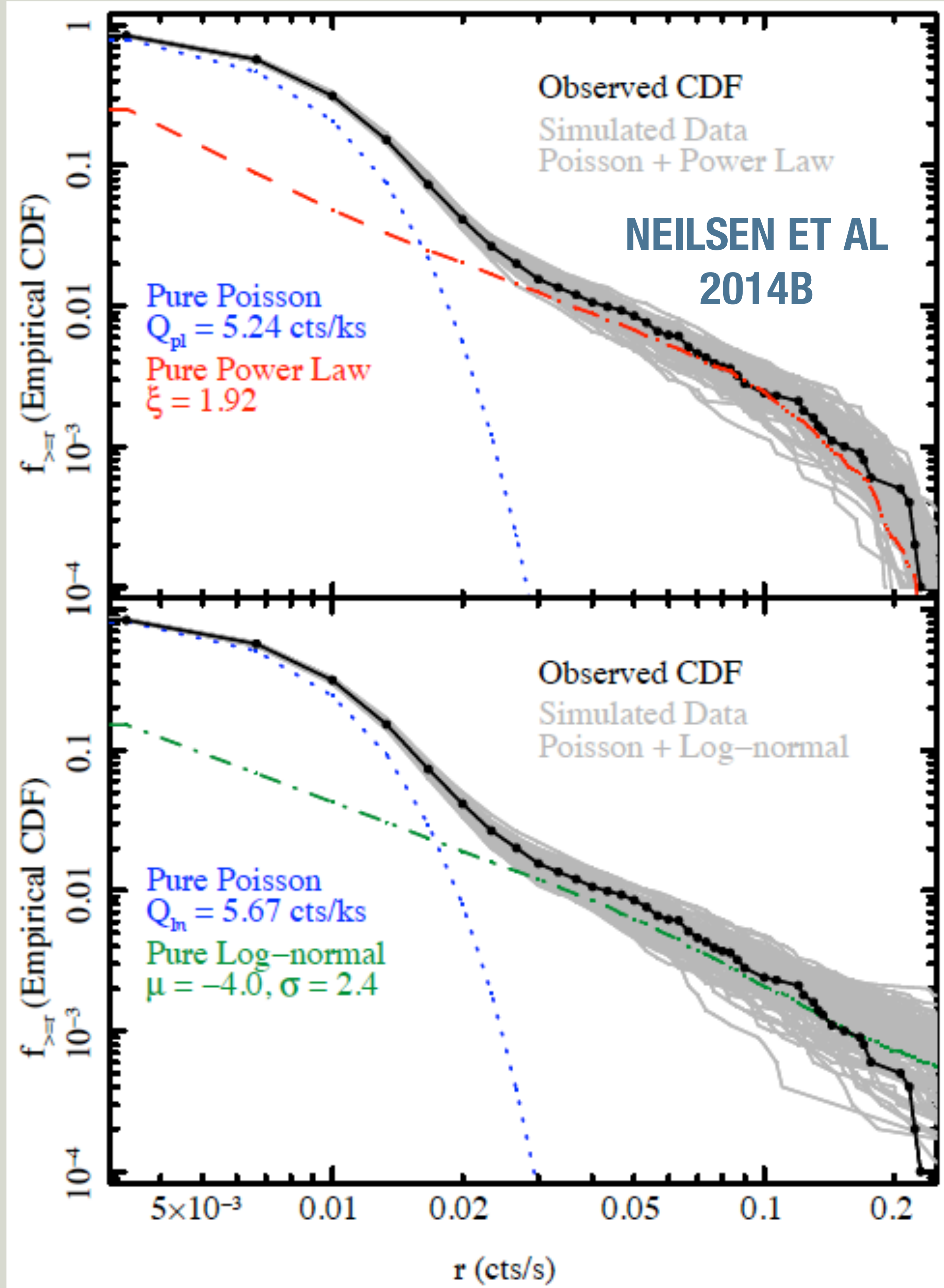
Success!

- Particularly in the case of power law, good quantitative agreement no matter how we calculate the answer!



Results

- Poisson+power law, Poisson+log-normal models describe data well, power law superior!
- Power law: $dN/dF \sim F^{-\xi}$, $\xi = 1.92_{-0.02}^{+0.03}$
- Over 3 orders of magnitude in flux!

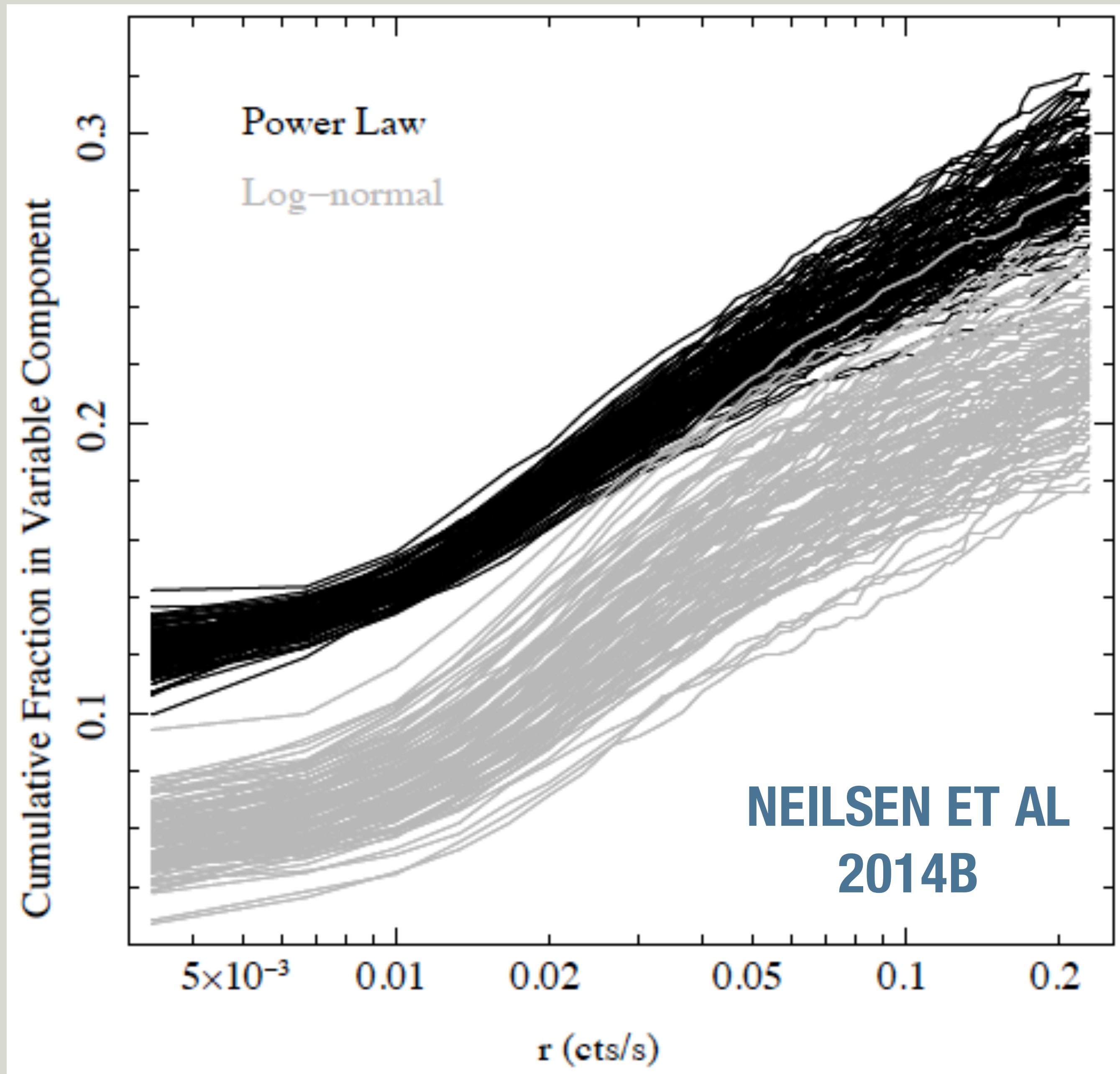


What is a “Flare?”

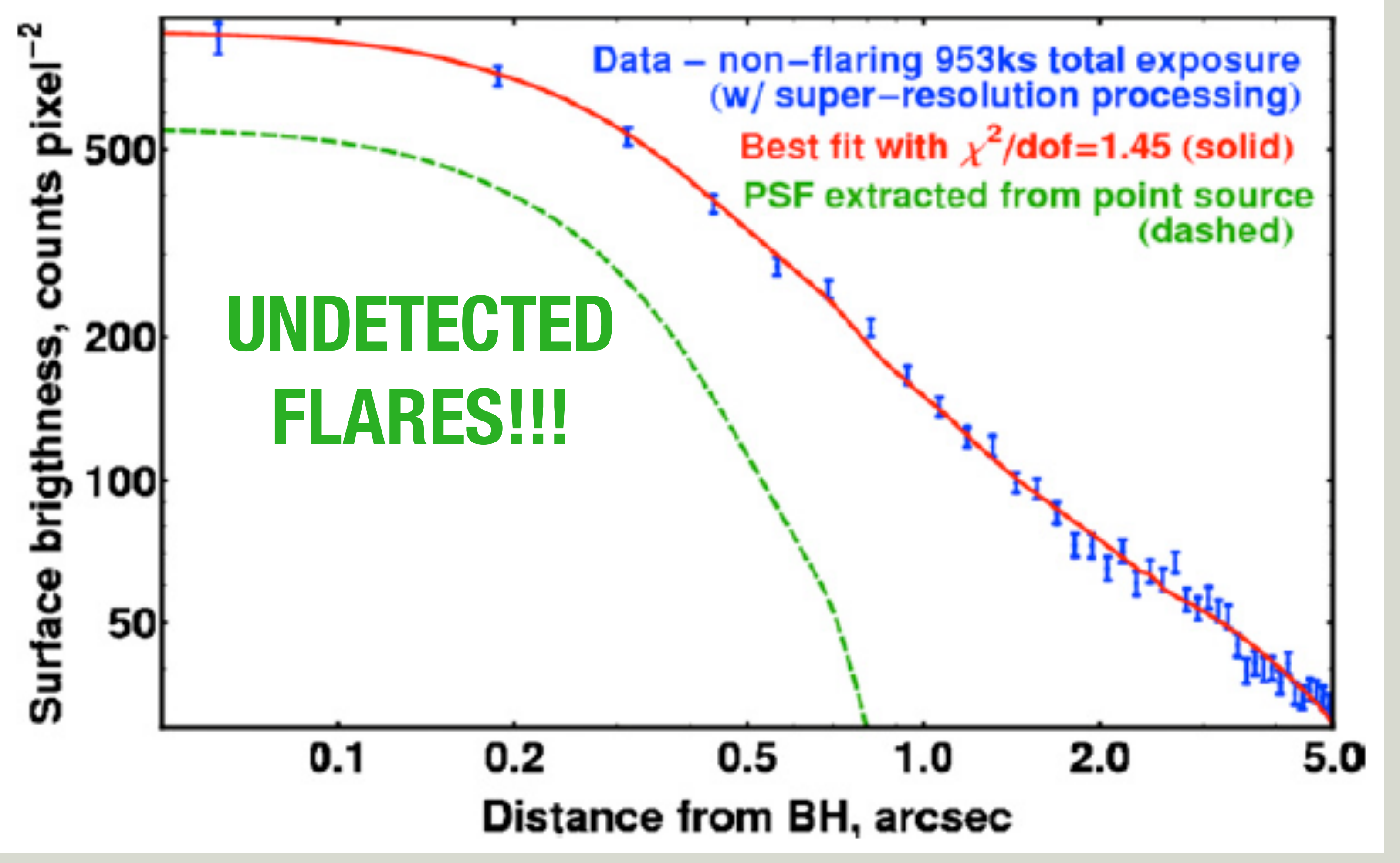
- Variability consistent with a power law process
- Tempting to interpret this as indicating a continuously-variable source, i.e. a “single” emission region with power on all time scales
    - Flare is only defined phenomenologically
- But flux distribution matches flare luminosity distribution
    - Suggests that power law in flux is a superposition of numerous distinct astrophysical events: “flares”

Contribution of Variability

- Variable component contributes 10-15% of quiescent count rates
- ~20-30% of total flux in flares



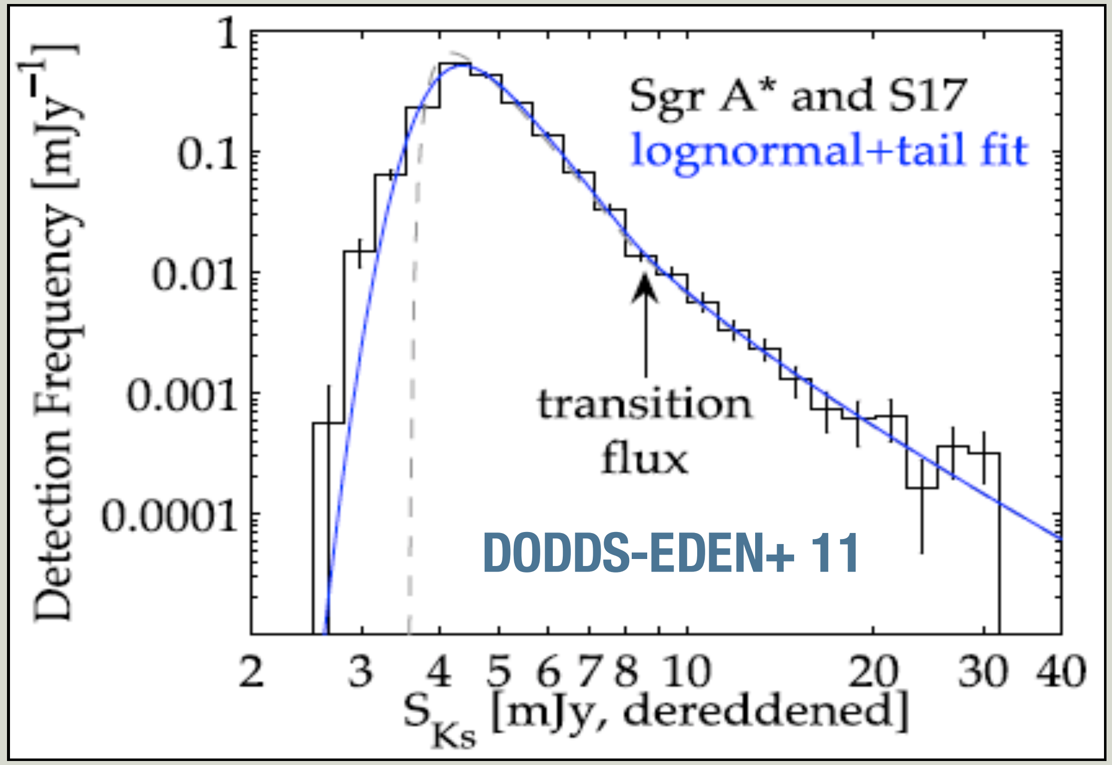
Synergy

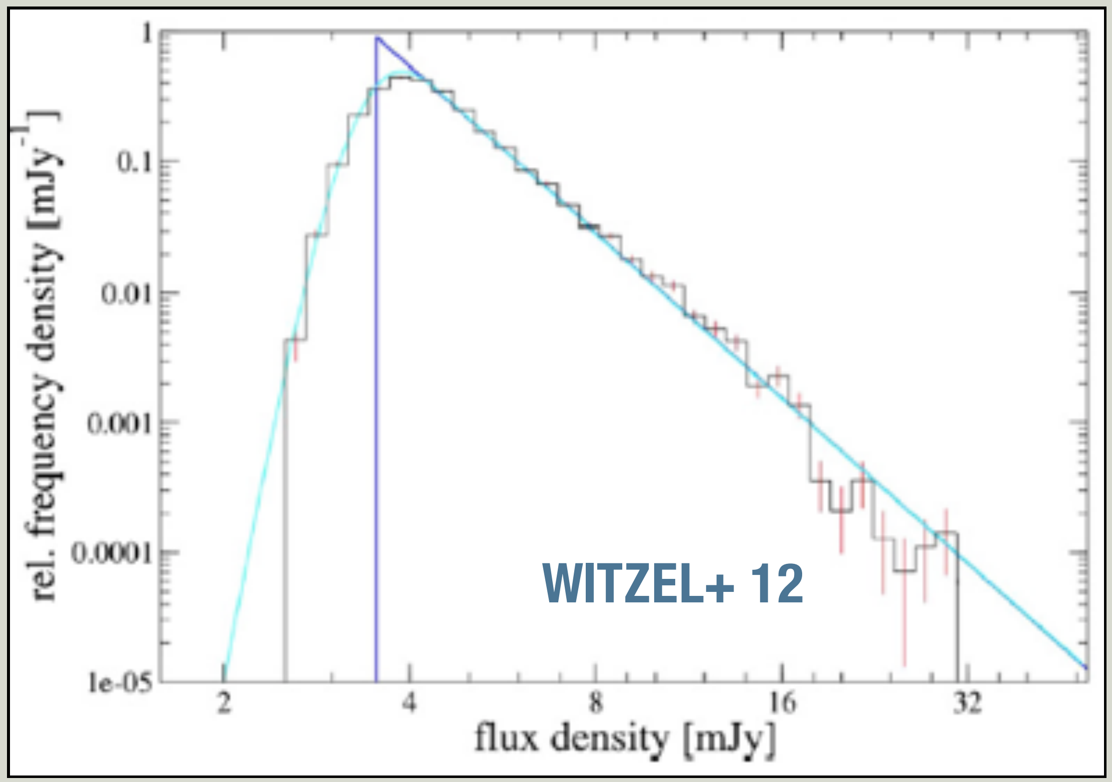


- **Flare distributions** and **power spectra** in quiescence (Neilsen et al. 2013b), **flux distribution** (Neilsen et al. 2014b), **X-ray spectra** (Wang et al. 2013), and **surface brightness profile** (Shcherbakov & Baganoff 2010) all consistent with a ~10% contribution to quiescence!

Radiation Mechanism?

- Sample of X-ray fluxes comparable to what's available in the infrared
- Parallel analyses: total NIR flux distribution (see Dodds-Eden et al. 2011; Witzel et al. 2012)
- X-ray flux distribution: models must be able to reproduce SED and multiwavelength variability





Summary

- Flare statistics, variability, spectra, and surface brightness models 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)
- All intrinsic variability of Sgr A* comes from flares/inner accretion flow!
- Future work: X-ray flux distribution places a strong constraint on models of the radiation from Sgr A*!