Prospects for detection of extragalactic magnetar giant flares tails with future X- and gamma-ray satellites

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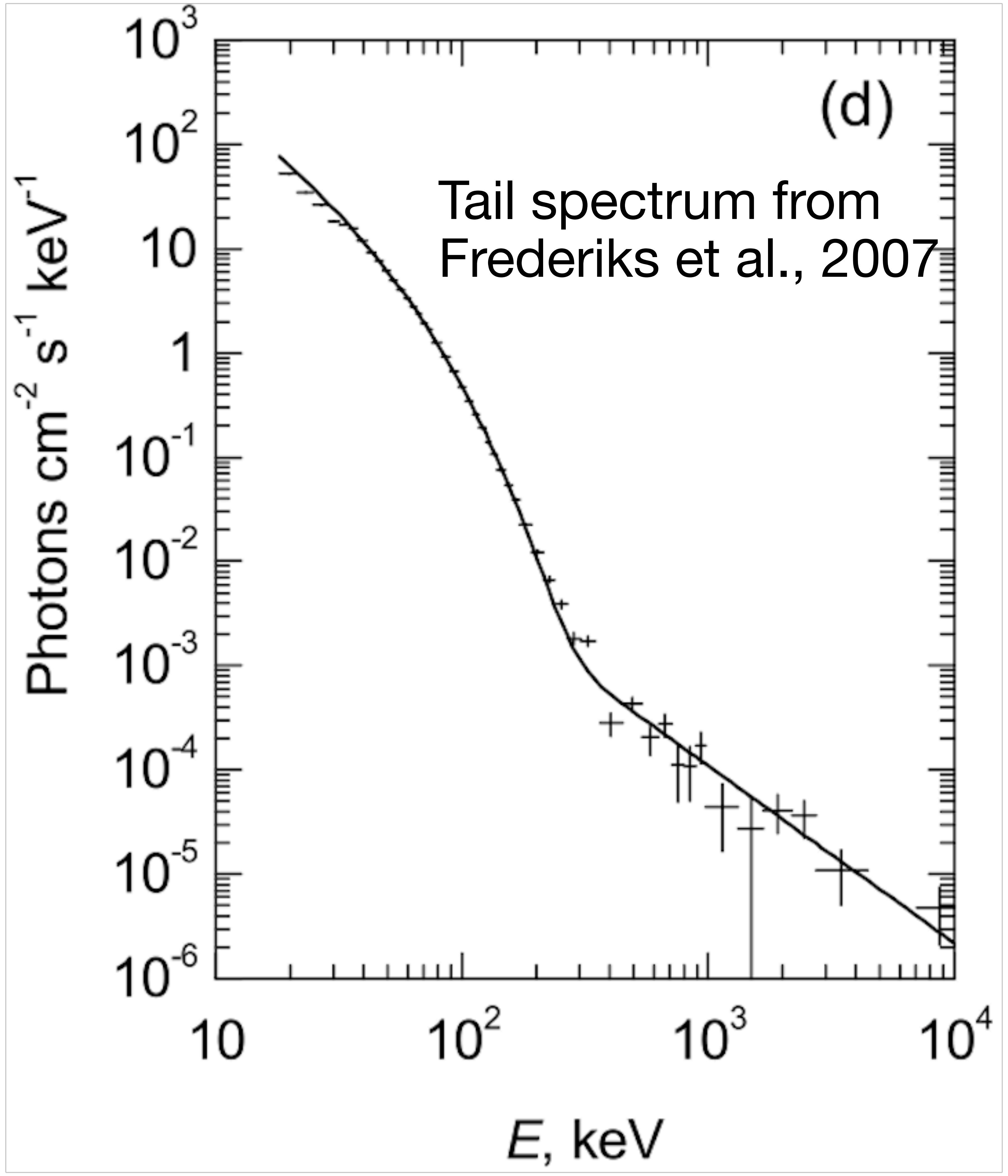
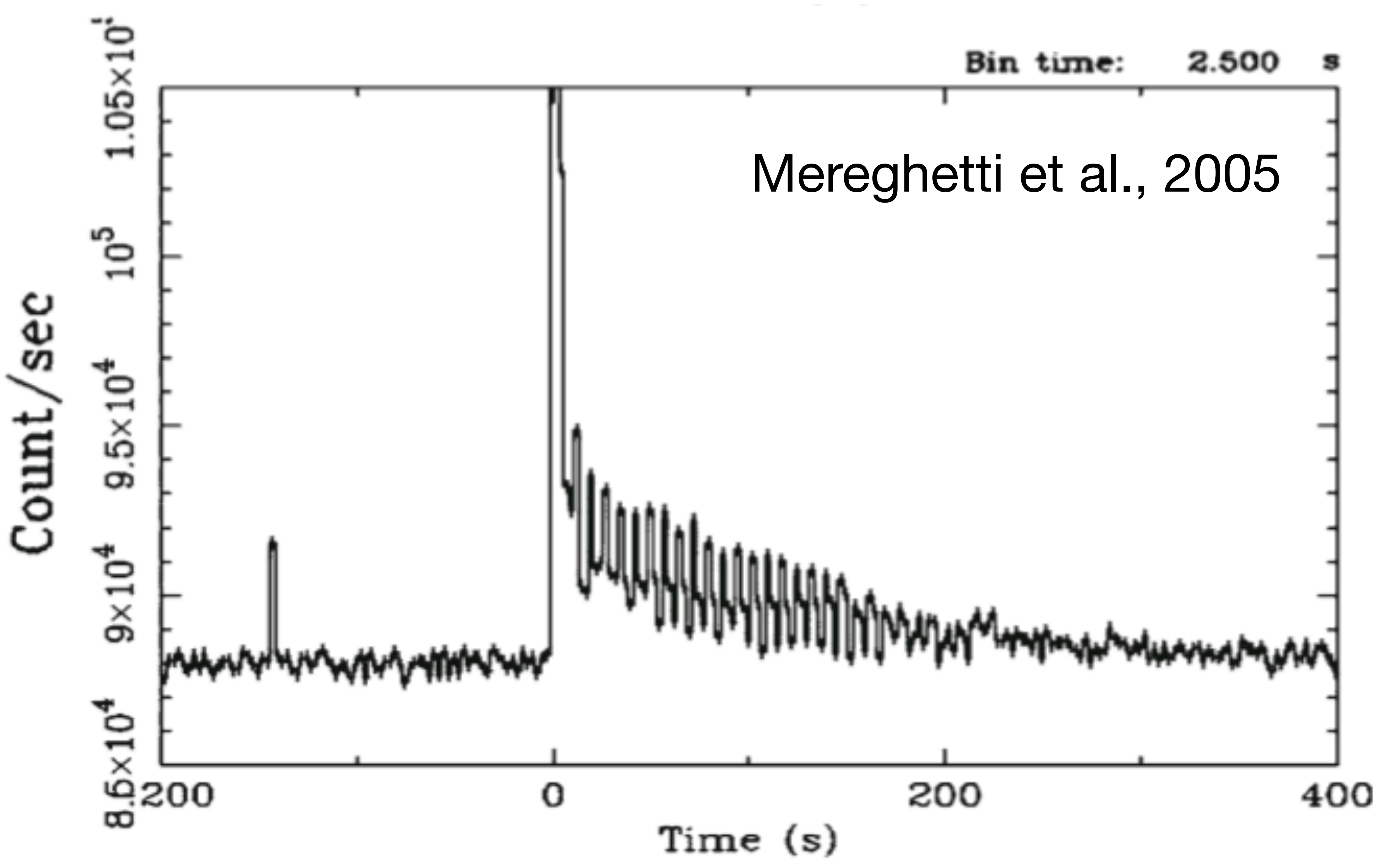
Magnetar Giant Flares

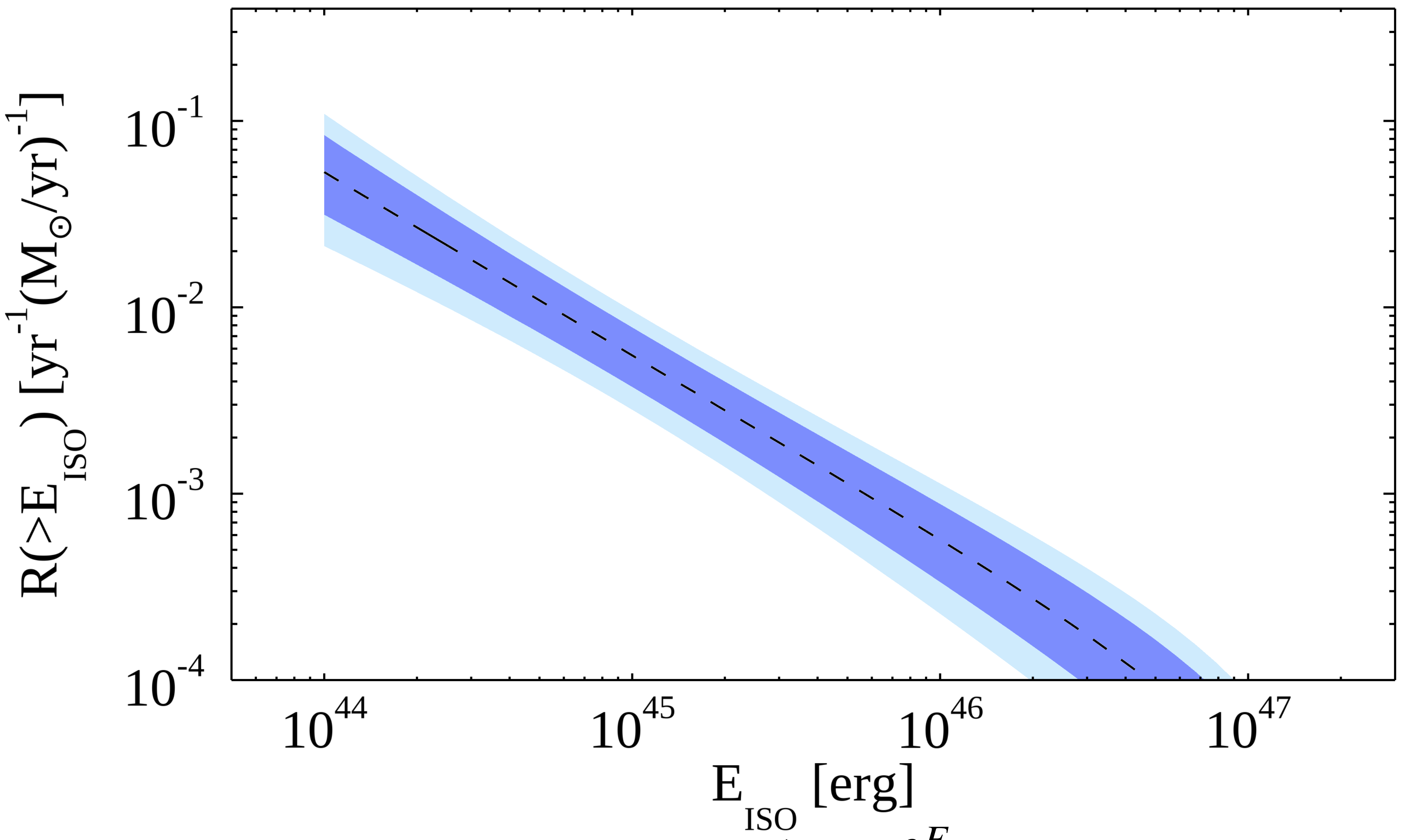




- 2 components
  - Spike: large scale magnetic reconnection, 10^{44} erg $< E_{\rm iso} < 10^{47}$ erg, harder spectrum
  - Pulsed tail: Trapped fireball, $E_{\rm iso} \sim 10^{44}$erg, softer spectrum but measured only above ~20keV (fit with BB, thermal bremsstrahlung)

How many?

- Galactic observations:
    - 3 MGF in 50 years
    - Large statistical uncertainties
- Extragalactic MGF candidates:
    - IPN observations over the last 30 years (complete over the whole sky above $2\ 10^{-6}\ \mathrm{erg/cm^2}$)
    - Using galaxies star formation rate as tracer for the number of magnetars
    - Bayesian analysis to reconstruct energy distribution



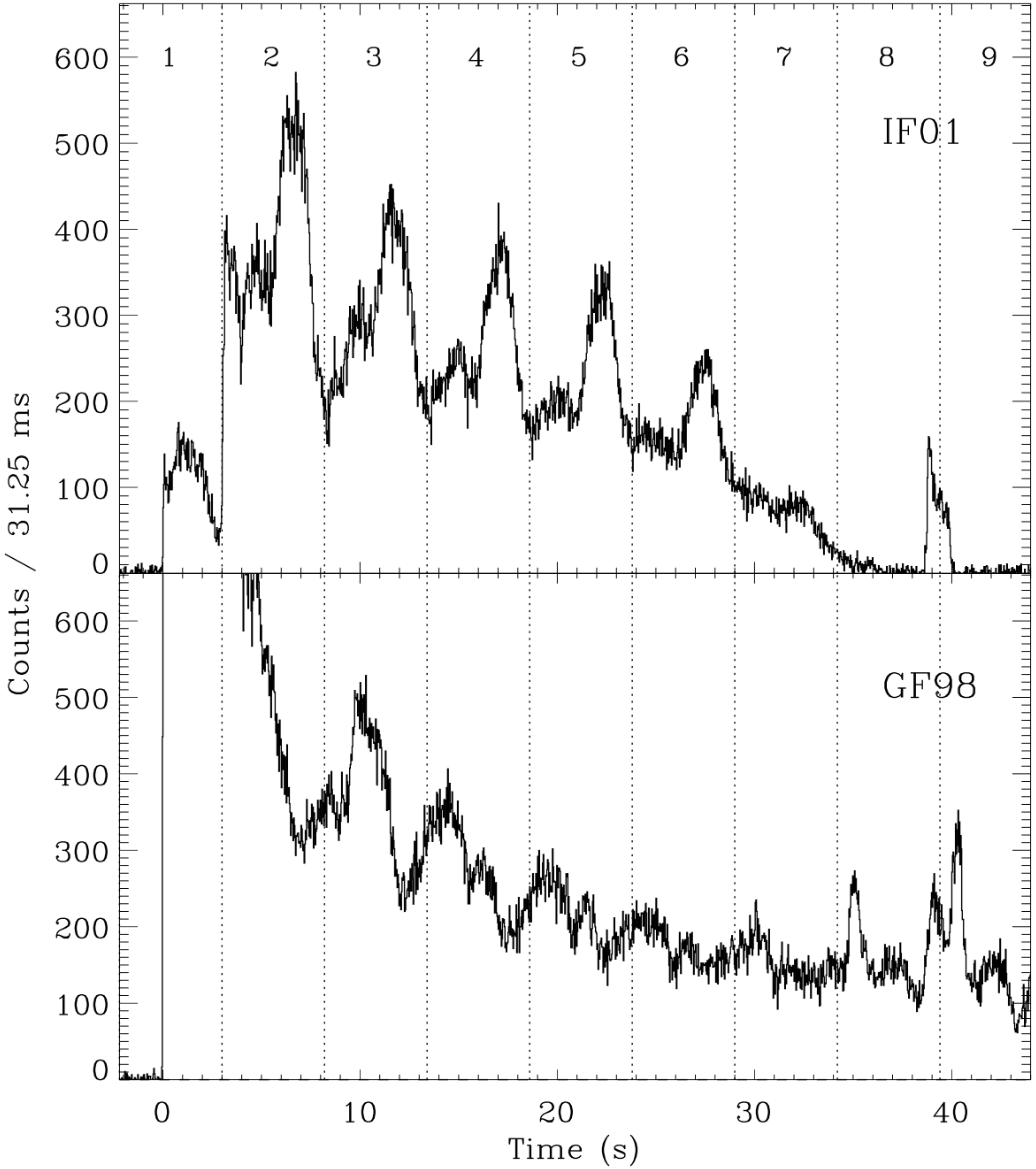
$$R(>E_{\rm ISO}) = k\frac{\gamma-1}{E_{min}^{1-\gamma}-E_{max}^{1-\gamma}}\int_{E_{\rm ISO}}^{E_{max}} E^{-\gamma}\ \mathrm{d}E$$

with parameters (see Pacholski et al., 2024):

$$k = 5.7^{+5.2}_{-3.6}\cdot 10^{-2}\ \mathrm{yr^{-1}(M_\odot/yr)^{-1}},\ \gamma = 1.97\pm0.24$$

Orphan tails

- Initial spike is geometrically beamed
    - Not always oriented towards our telescopes
- Pulsed tail (orbiting trapped fireball) visible from any direction
    - $R(>E_{\rm ISO})$ underestimated by factor $B = \Omega/4\pi$
- The three galactic MGF tails showed similar properties despite significantly different spikes: $R_{\rm tails} = R_{\rm MGF}(>10^{44}{\rm erg}) \cdot B$



Guidorzi et al., 2004: light curves of 2001 flare (top) and 1998 giant flare (bottom) from SGR1900+14 observed with BeppoSAX

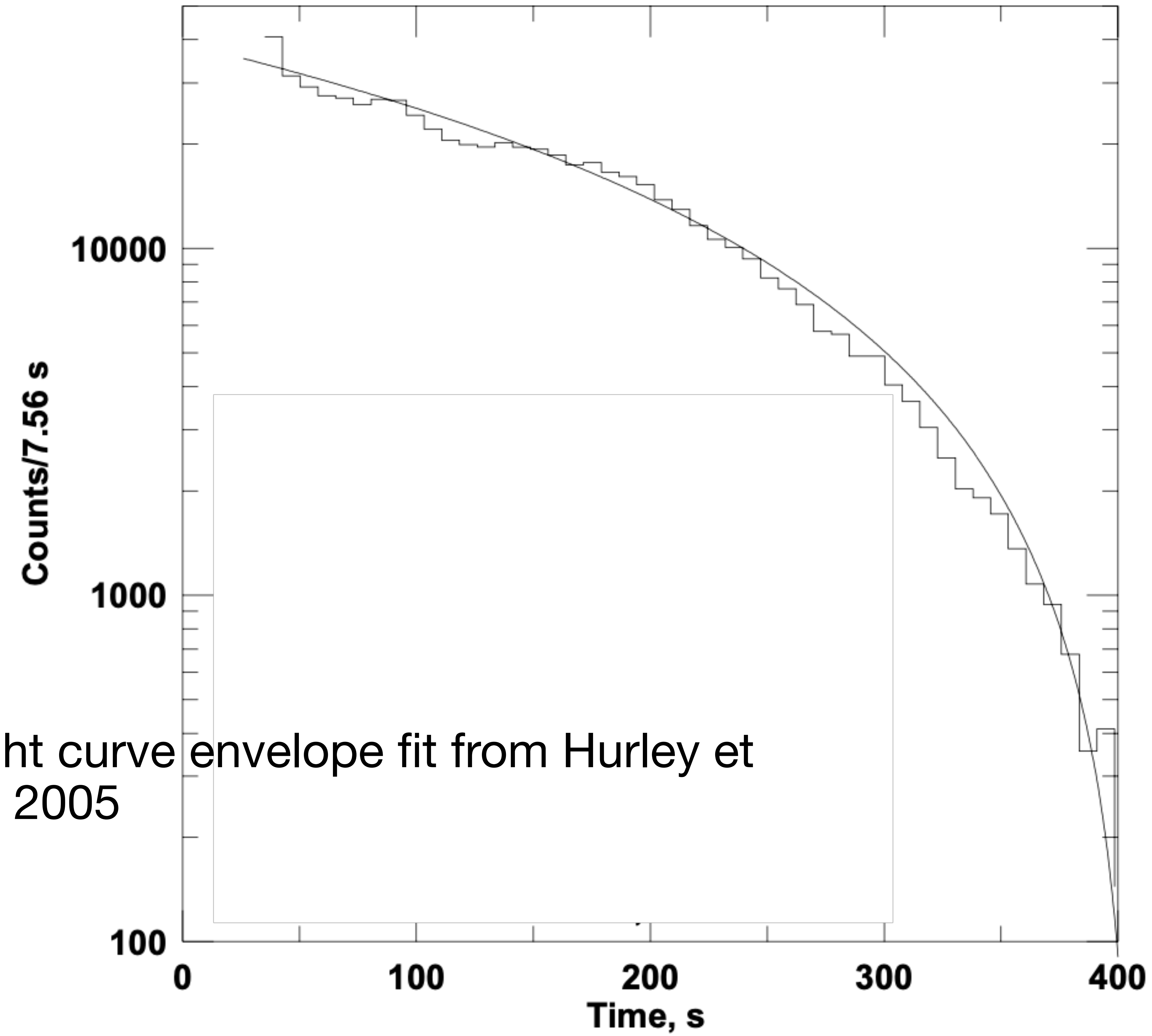
MGF tail model: light curve

- Evaporating fireball model for MGF tail light curve envelope (see Thompson & Duncan, 2001)

- SGR 1806-20 (27 December 2004) event parameters

  - $L(t) = L_0[1 - (t/t_{evap})]^{a/(1-a)}$, with $L_0 = 10^{42}$ erg/s, $t_{evap} = 382$ s, $a = 0.6$

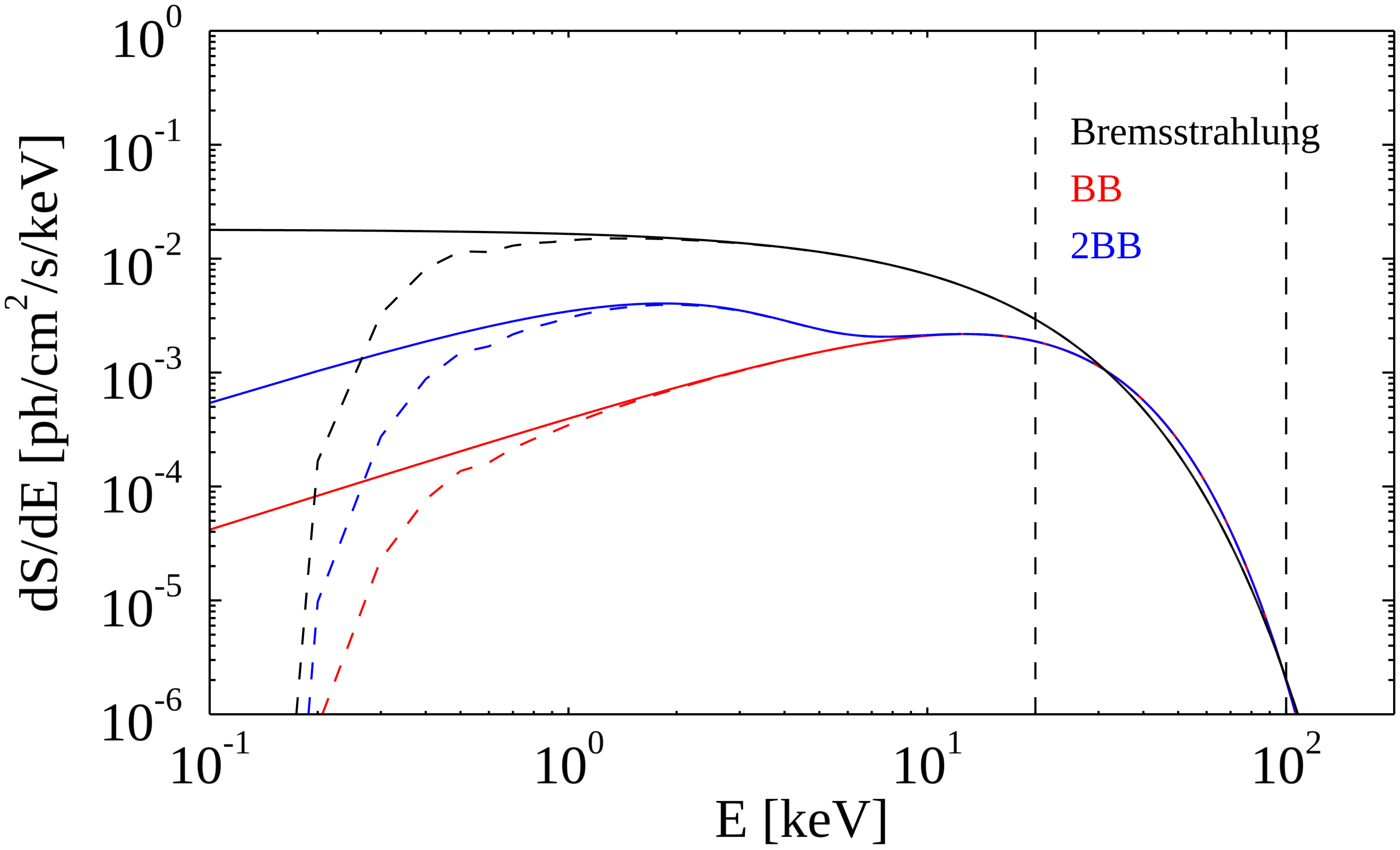
  - Steeper than exponential decay for $t \to t_{\rm evap}$



Light curve envelope fit from Hurley et al., 2005

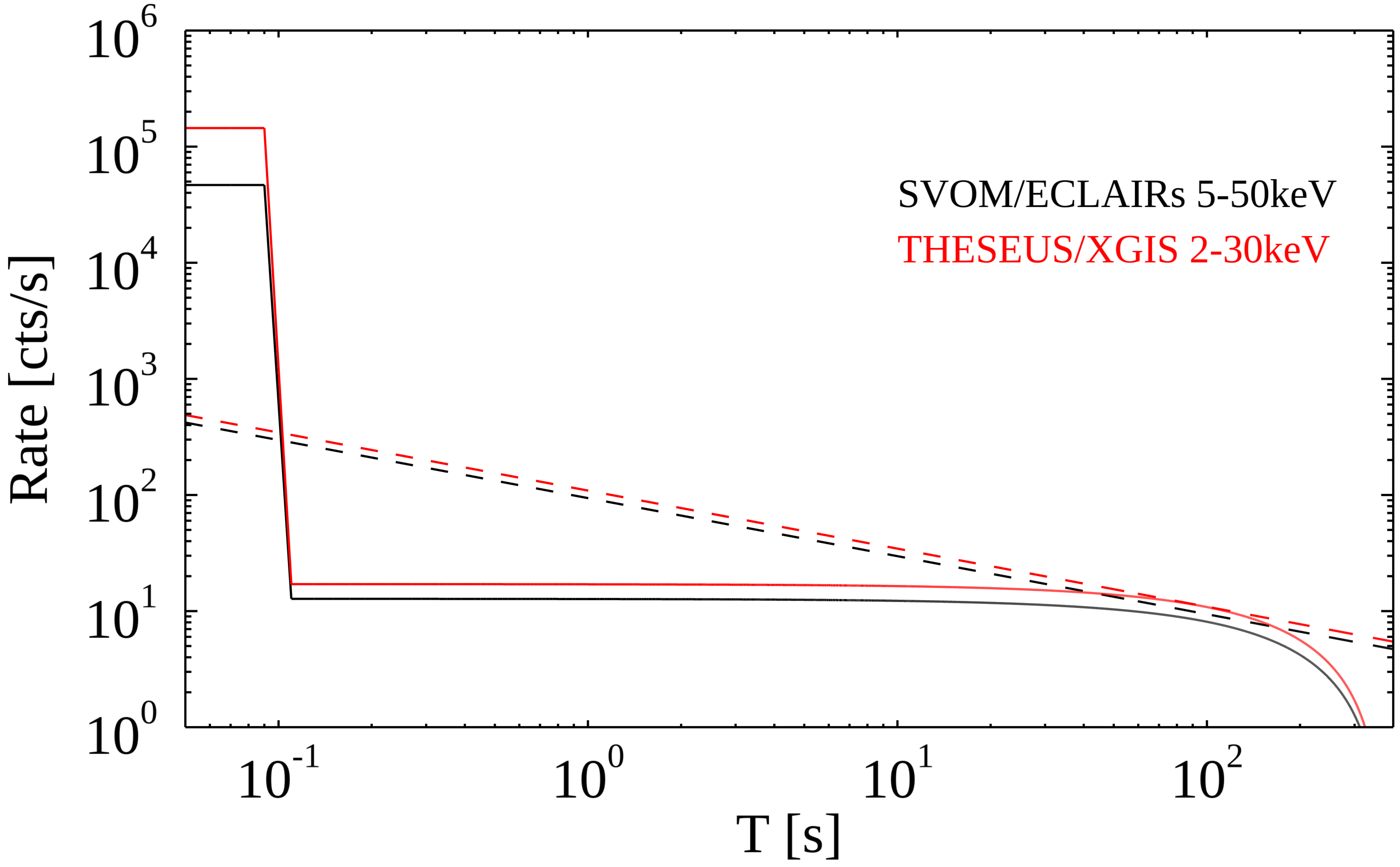
MGF tail model: spectrum

- MGF tail spectrum measured in [20,100] keV range
- Multiple models in agreement
    - Thermal bremsstrahlung $kT \sim 22$ keV
    - Blackbody $kT \sim 8$ keV, double Blackbody (2BB)
- Extrapolation yields different photon fluxes in softer bands



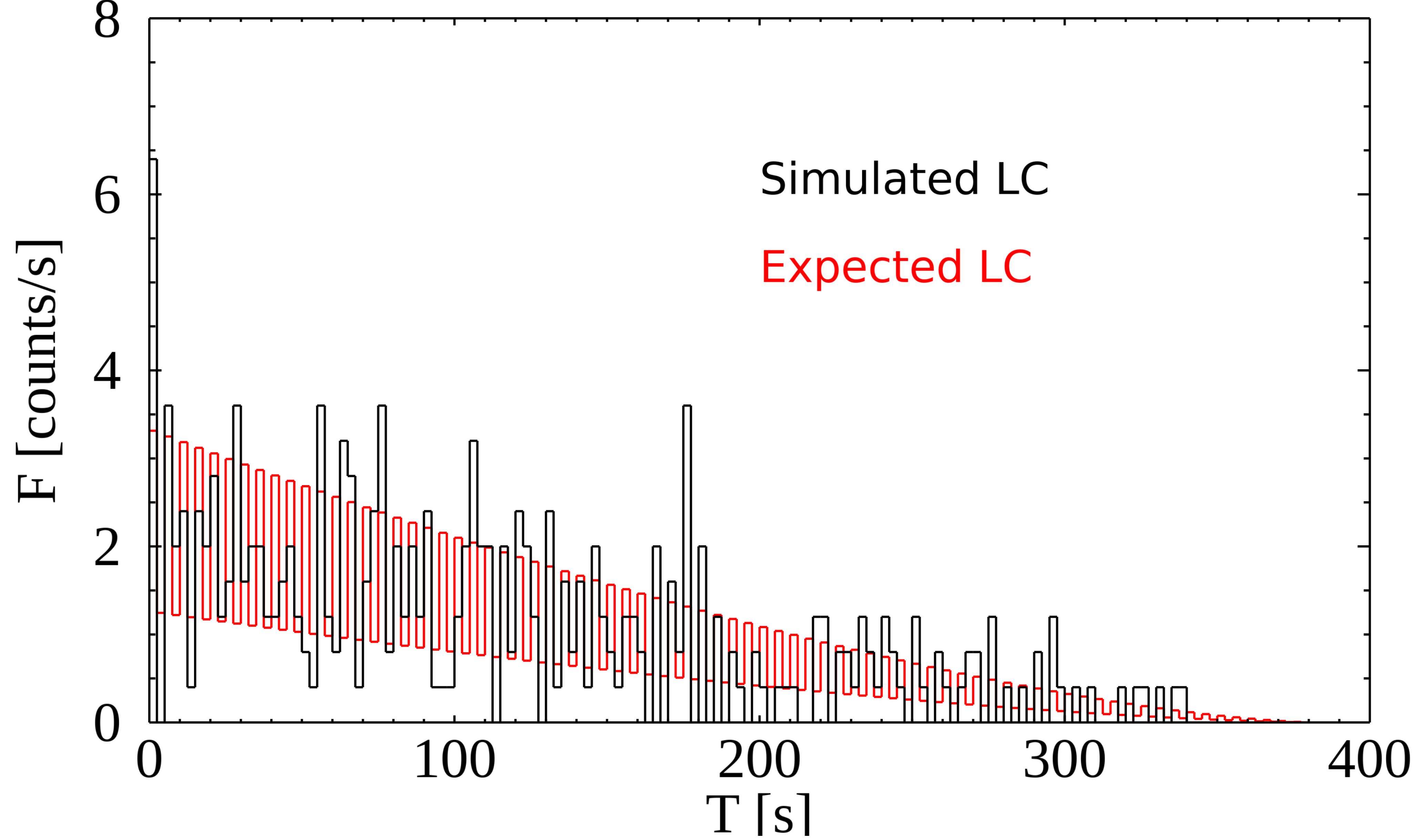
MGF light curve in M82

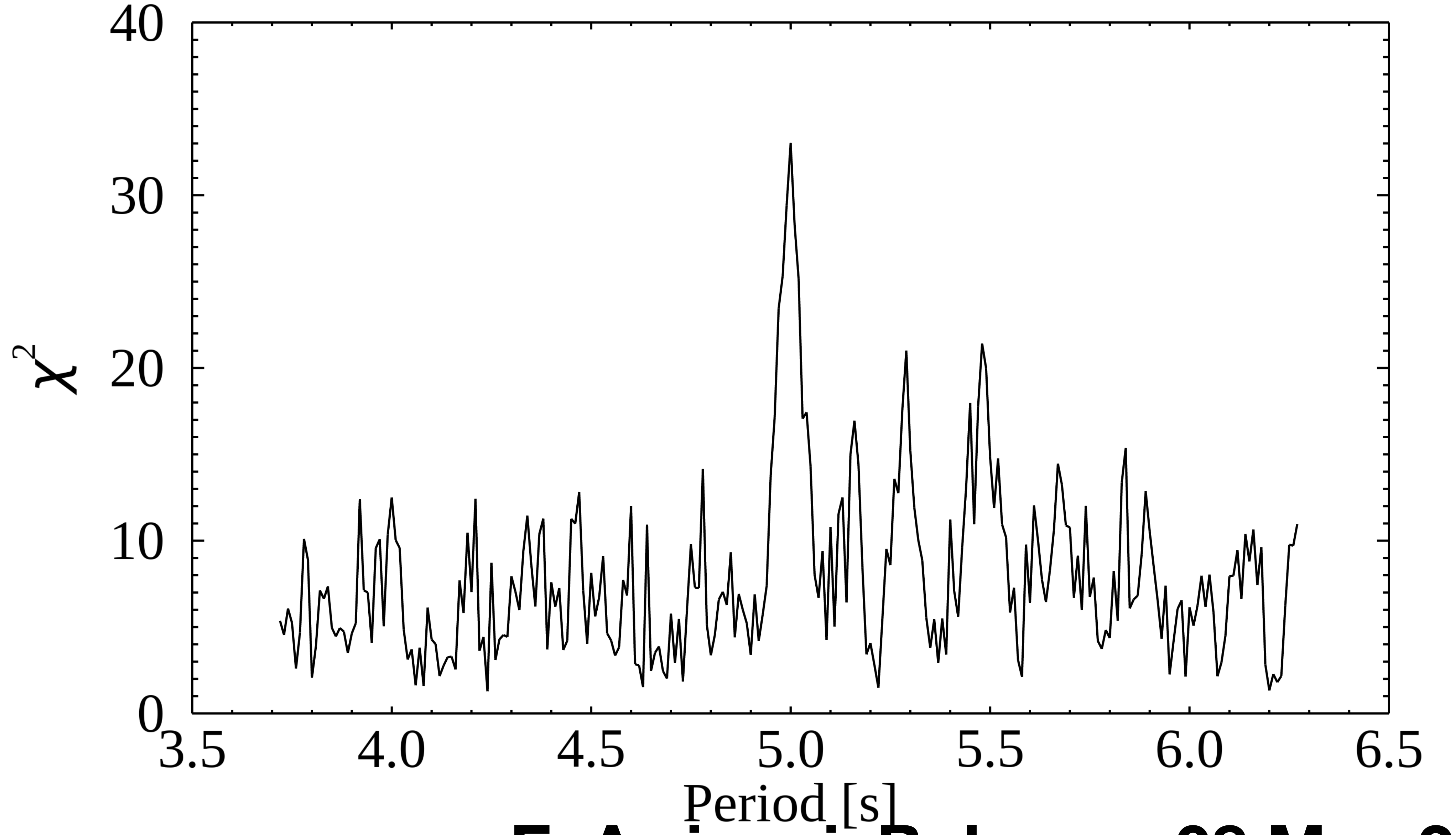
- Coded mask instruments can detect initial spike up to tens of Mpc
- MGF light curve at $D \sim 3.6$ Mpc
  - Tail visible with long observation time and low significance (2σ in figure)
  - Only significant after spike trigger
  - We have to observe in softer energy band



Swift/XRT simulated observation

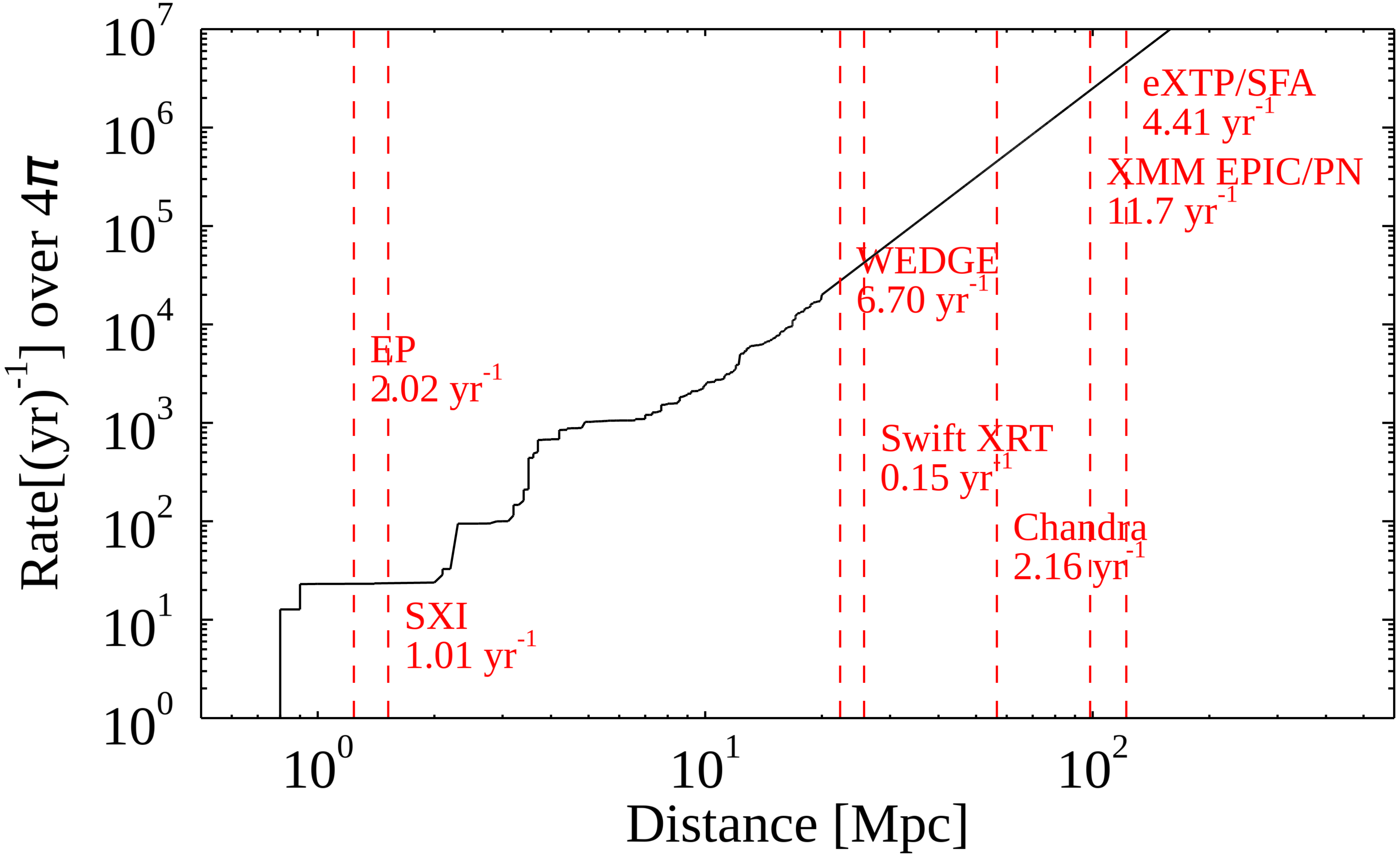
- Typical tail in M82 with absorption $N_H = 5.4\ 10^{20}\ \mathrm{cm}^{-2}$
- Assumptions:
  - Spectrum: Thermal bremsstrahlung $kT = 22\ \mathrm{keV}$
  - Pulsed fraction: $f = 0.45$, Period: $\mathrm{Per} = 5\mathrm{s}$
- XRT parameters:
  - Time resolution Photon Counting mode ~2.5 sec
  - Energy band: [0.3,10] keV





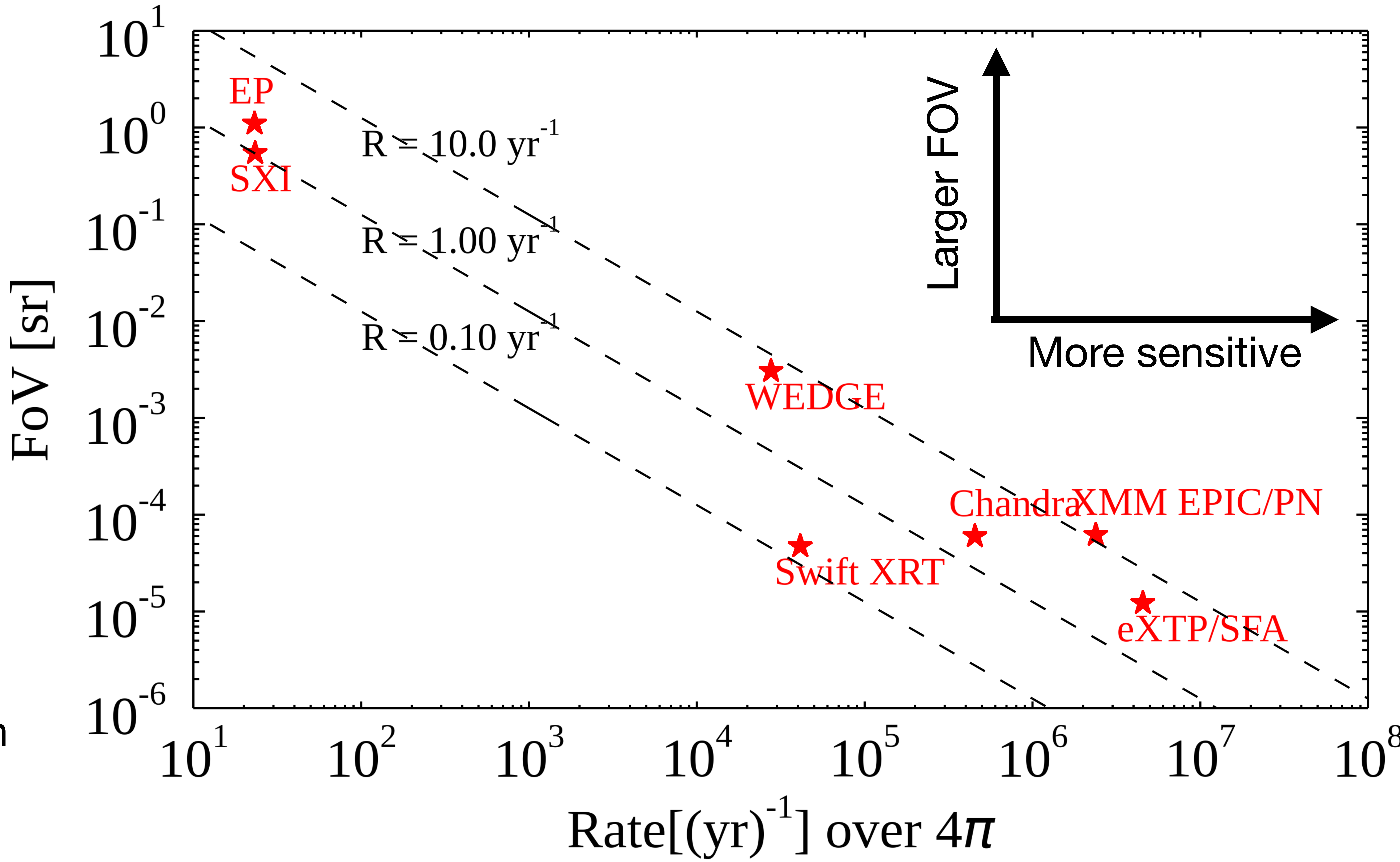
Blind search

- Look for MGF tails independently of spike detection
  - Promising for large B values
- Trade off between sensitivity and field of view
- Assuming $B \sim 500$, uniform sky coverage and SFR distribution from Leroy et al., 2019 below 20 Mpc



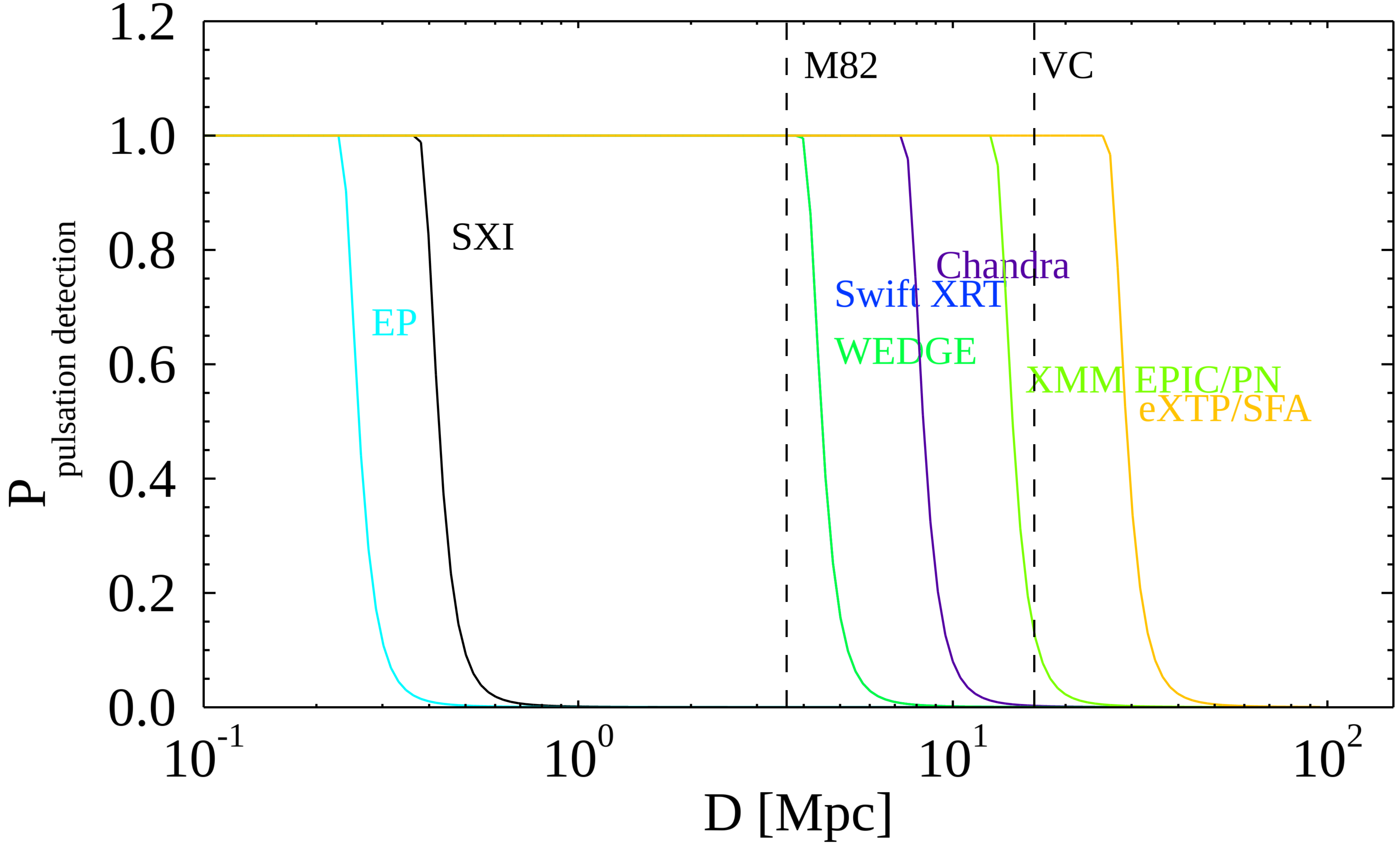
Blind search

- EP, SXI: large FoV but low sensitivity
- Swift, Chandra, XMM, eXTP: small FoV but high sensitivity
- WEDGE: more balanced design
- Less sensitive instruments detections are more dependent on observational strategy
- Not enough to confirm MGF origin
    - GRB afterglow / extended emission



Blind search: pulsations detection

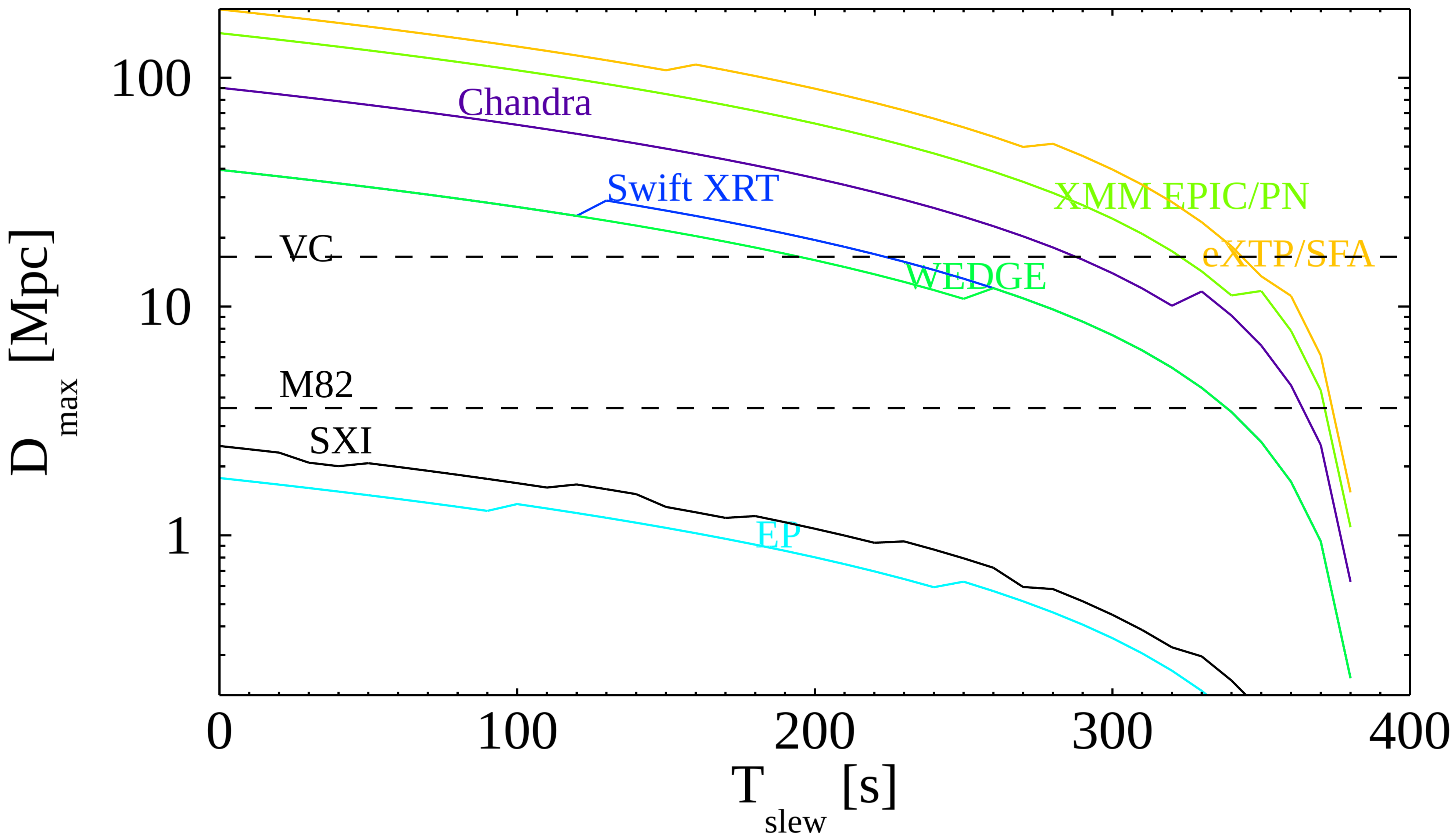
- Look for periodicity as distinguishing feature
    - Significant detection if χ^2 with less than 1% of being caused by noise with epoch folding
- Much more restrictive condition
- Expected $0.2\ \mathrm{yr}^{-1}$ pulsation detections from best performing telescopes (WEDGE)



Note: XRT and WEDGE curves overlap

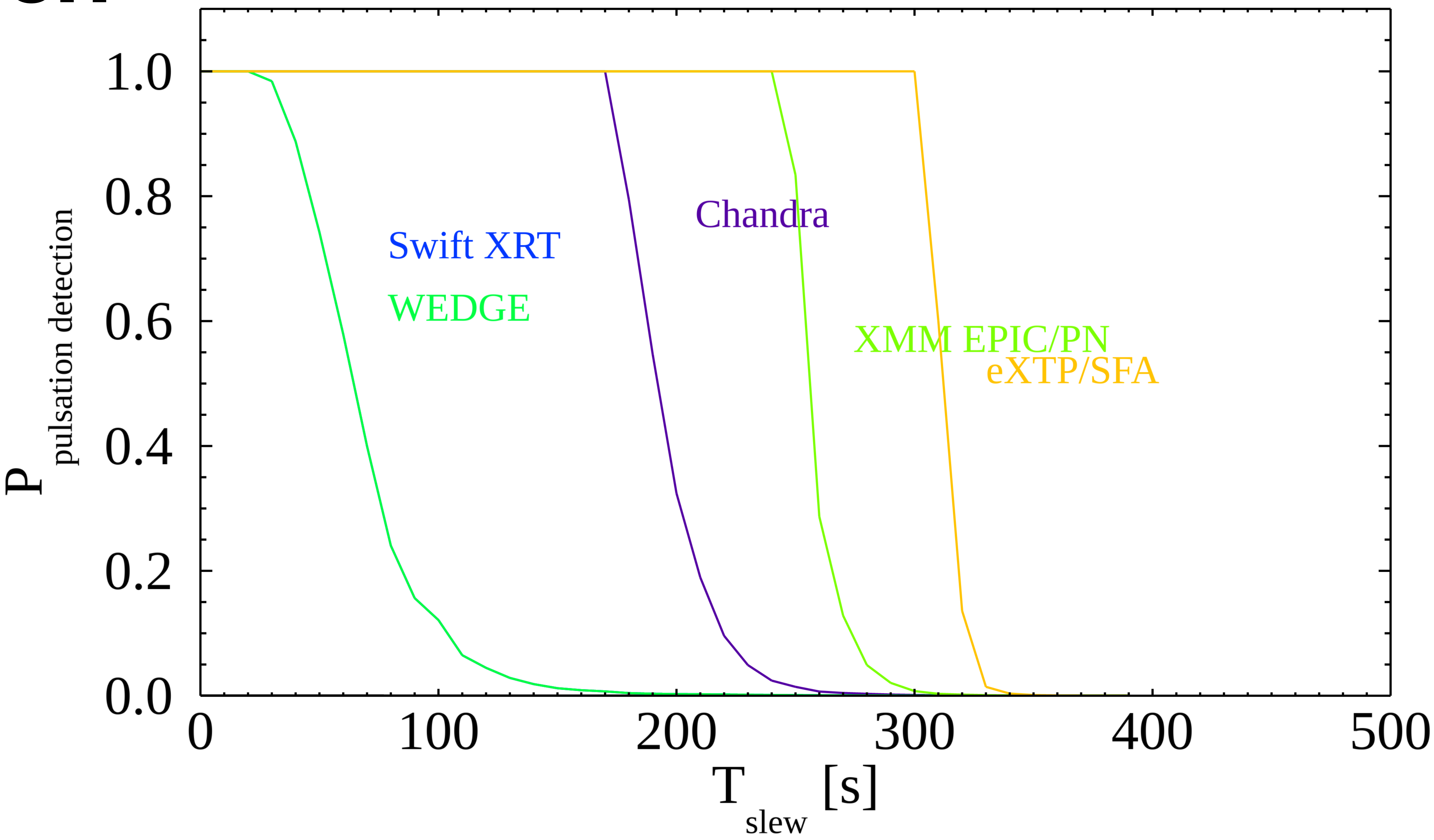
Targeted search

- Follow up of candidate spike detection, need for fast repointing satellites
- Significant detection at several Mpc even after 300s
- At large distances ($\gtrsim 40$ Mpc) only the brightest spikes are visible ($\gtrsim 10^{46}$ erg)
- Assuming $T_{\rm slew} = 100$ s up to ~2 detection per year expected (eXTP)



Targeted search

- Pulsation detection is more challenging
- Can be achieved for MGF in M82 by telescope with XMM sensitivity and Swift repointing capabilities
    - eXTP can do that! (~1 event per 3 year)



Note: XRT and WEDGE curves overlap

Conclusions

- Detection of pulsations fundamental to correctly identify MGF
- Blind searches (untriggered by detection of initial spikes):
  - Can take advantage isotropic emissions tail, but high sensitivity instruments have small FoV
  - Telescopes like WEDGE could observe 1 pulsed tail every ~5 years
- Targeted searches:
  - Only spikes oriented towards us give a trigger: Large FoV at gamma-rays needed (e.g. coded mask cameras like SVOM/ECLAIRs, THESEUS/XGIS)
  - But rapid follow up in X-ray range needed (e.g. $T_{\rm slew} \lesssim 100\ {\rm s}$ with focusing telescopes,   1 pulsed MGF tail per ~3 year with eXTP

Thanks for your attention!

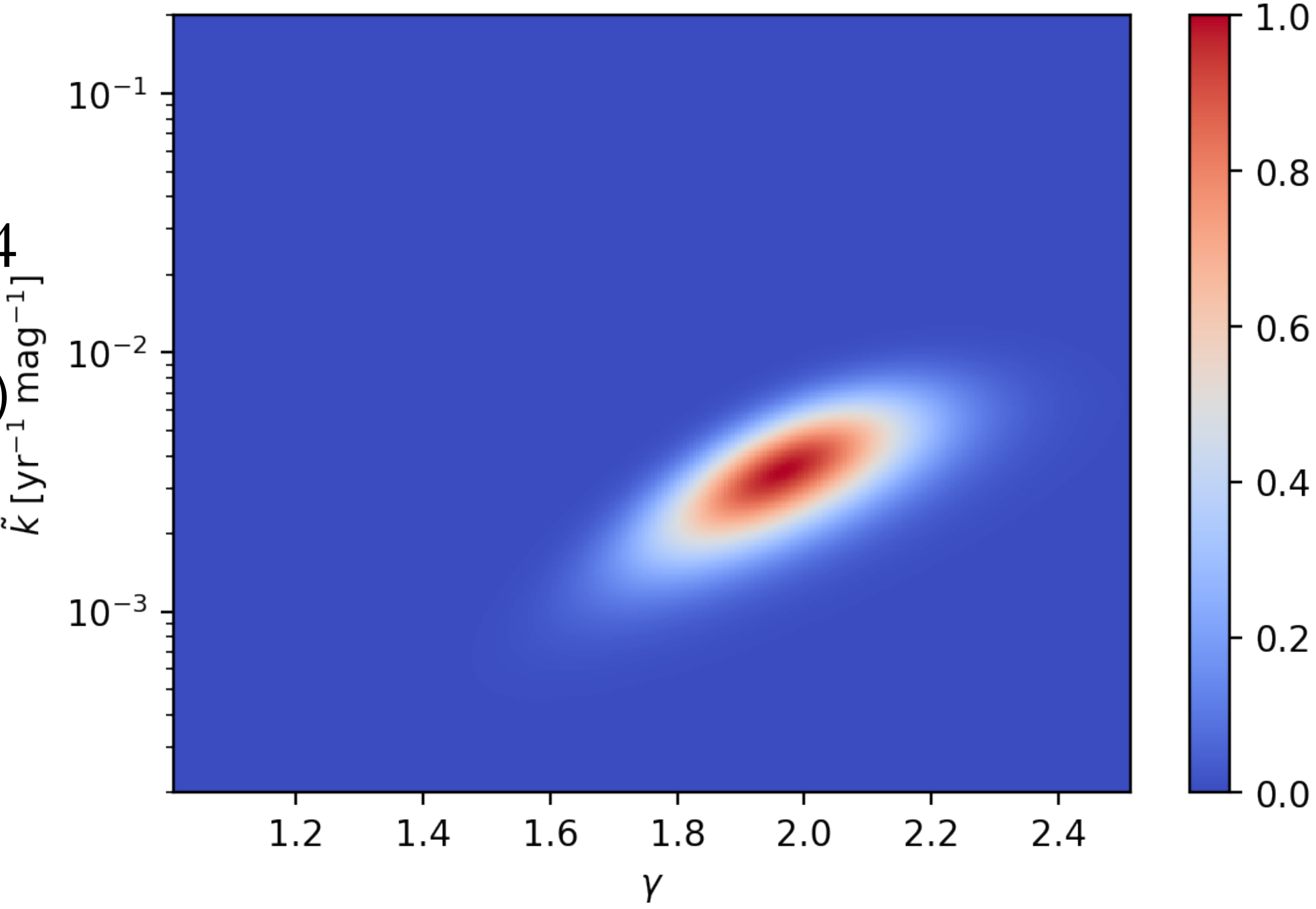
EXTRA SLIDES

MGF energy distribution

- MGF rate parameters optimised with Bayesian analysis on

$$N_{12} = k\frac{\gamma - 1}{E_{min}^{1-\gamma} - E_{max}^{1-\gamma}}\int_{E_1}^{E_2} E^{-\gamma}\ \mathrm{SFR}(E_{\mathrm{ISO}})T_{\mathrm{IPN}}\ \mathrm{d}E$$

- SFR measures from Leroy et al., 2019
- $k = 5.7^{+5.2}_{-3.6} \cdot 10^{-2}\ \mathrm{yr}^{-1}(\mathrm{M}_\odot/\mathrm{yr})^{-1},\ \gamma = 1.97 \pm 0.24$
- $\tilde{k}$ normalisation for rate per magnetar (not unit of SFR)
  - $N_{\mathrm{mag}}^{\mathrm{MW}} = 30, \mathrm{SFR}^{\mathrm{MW}} = 1.85\ M_\odot \mathrm{yr}^{-1}$



X ray telescopes: Blind search numbers

	Sky fraction inside FoV	Energy band [keV]	Bkg flux [cnts/s]	Source flux at T=0s [cnts/s]	Transients [events/yr]	Pulsed [events/yr]
SXI	4.33d-2	[0.3,5.0]	8.31d-3	2.68d-1	1.01d+0	3.8d-5
Chandra	4.76d—6	[0.5,8.0]	4.02d-5	1.04d+2	2.16d+0	7.5d-3
Swift/XRT	3.75d-6	[0.3,10.0]	2.89d-4	2.98d+1	1.55d-1	3.3d-3
EP	8.73d-2	[0.5,4.0]	1.92d-3	1.00d-1	2.02d+0	1.4d-5
WEDGE	2.42d-4	[0.3,10.0]	5.78d-4 *	2.98d+1	6.70d+0	2.1d-1
XMM EPIC/PN	4.91d-6	[0.3,10.0]	6.54d-5	3.11d+2	1.17d+1	3.2d-2
eXTP/SFA	9.70d-7	[0.3,8.5]	2.37d-3	1.25d3	4.41d+0	5.9d-2

* assuming PSF 2x worse than Swift/XRT

X ray telescopes: Targeted search numbers

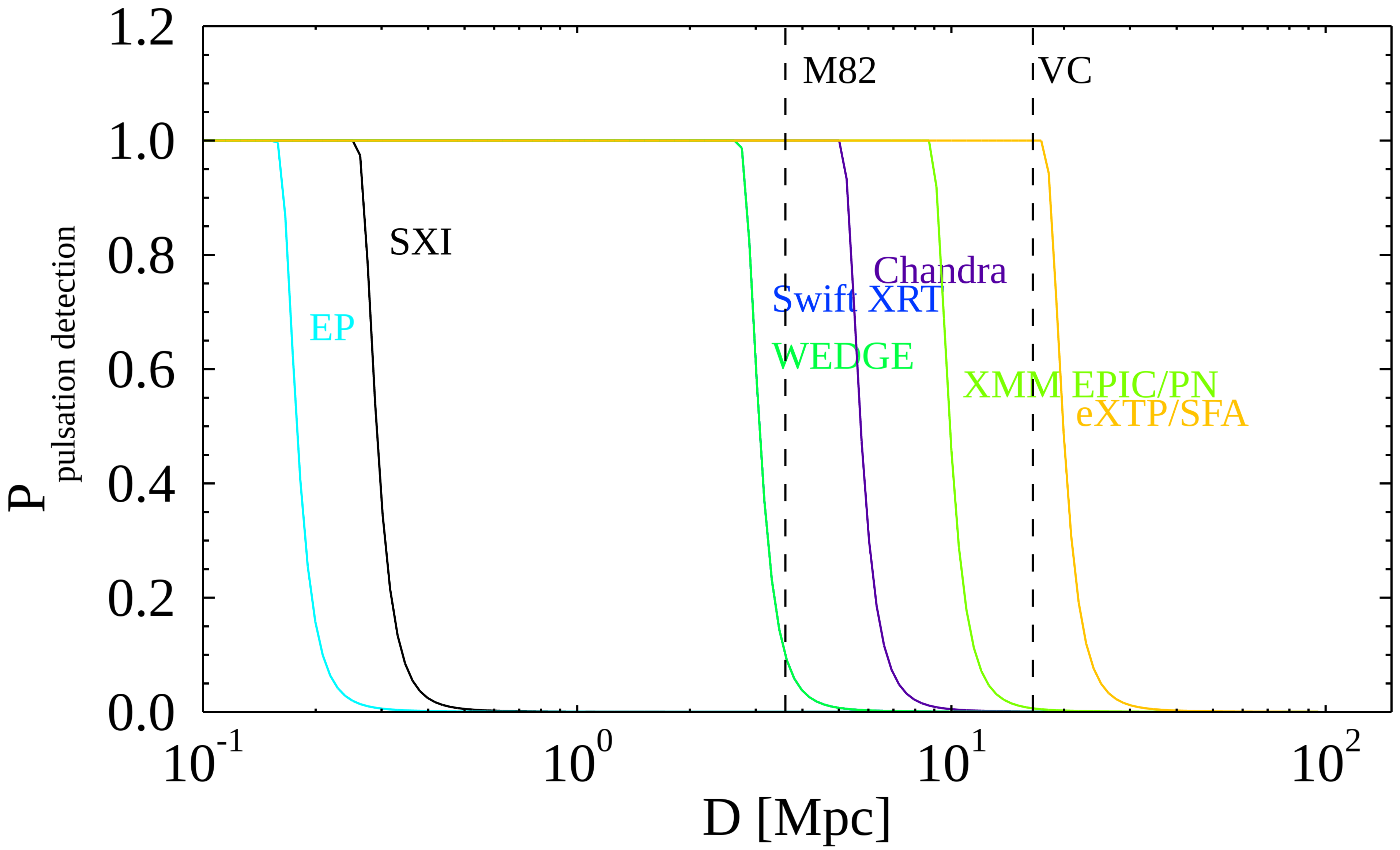
Assuming $T_{\mathrm{slew}} = 100$ s, 3σ detection significance

	Sky fraction inside FoV	Energy band [keV]	Detection distance [Mpc]	Transients [events/yr]	Pulsation distance [Mpc]	Pulsed [events/yr]
SXI	4.33d-2	[0.3,5.0]	1.7d+0	3.1d-3	2.9d-1	2.3d-8
Chandra	4.76d−6	[0.5,8.0]	6.2d+1	1.0d+0	5.7d+0	1.3d-1
Swift/XRT	3.75d-6	[0.3,10.0]	2.7d+1	4.4d-1	3.1d+0	1.3d-2
EP	8.73d-2	[0.5,4.0]	1.4d+0	3.0d-3	1.7d-1	1.5d-8
WEDGE	2.42d-4	[0.3,10.0]	2.7d+1	4.4d-1	3.1d+0	1.3d-2
XMM EPIC/PN	4.91d-6	[0.3,10.0]	1.08d+2	1.6d+0	9.9d+0	1.6d-1
eXTP/SFA	9.70d-7	[0.3,8.5]	1.37d+1	1.9d+0	2.0d+1	3.1d-1

Targeted search

- Maximum detection distances for pulsations

- Assuming $T_{\text{slew}} = 100\ \text{s}$



MGF spectrum

- Spectrum in [3,100]keV from RHESSI
- Low energy increase, not flat as assumed