The rate of optical tidal disruption flares

Featuring implications for jet physics

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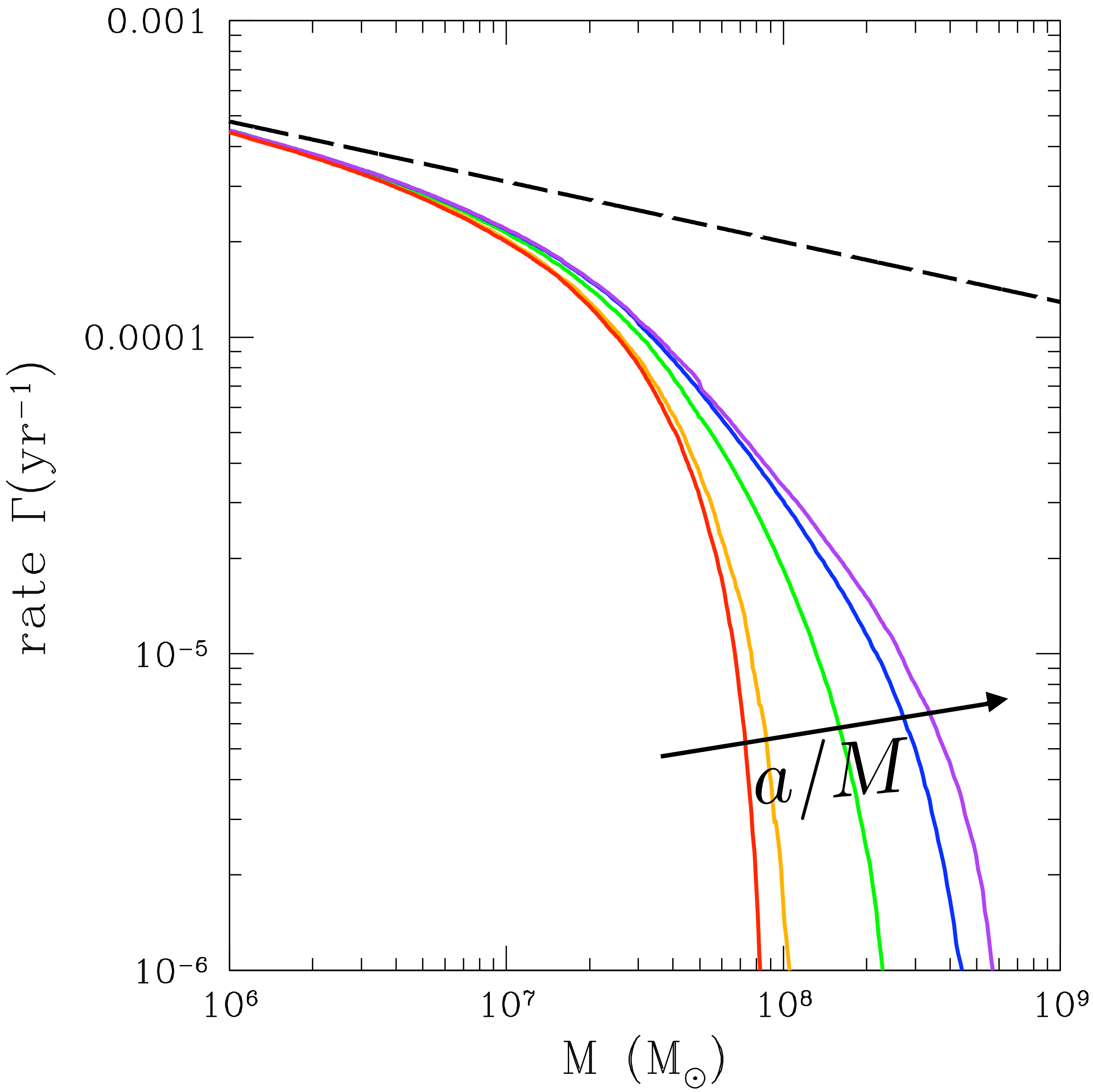
More motivation

- Probing the evolution of stellar orbits:
  - Rate with galaxy mass, redshift, type
  - IMBHs (Hagai Perets talk)
- Connection with the Galaxy:
  - Hyper velocity stars and S-stars (eg, Bromley+ 2012)
- General relativity:
  - Event horizon and spin



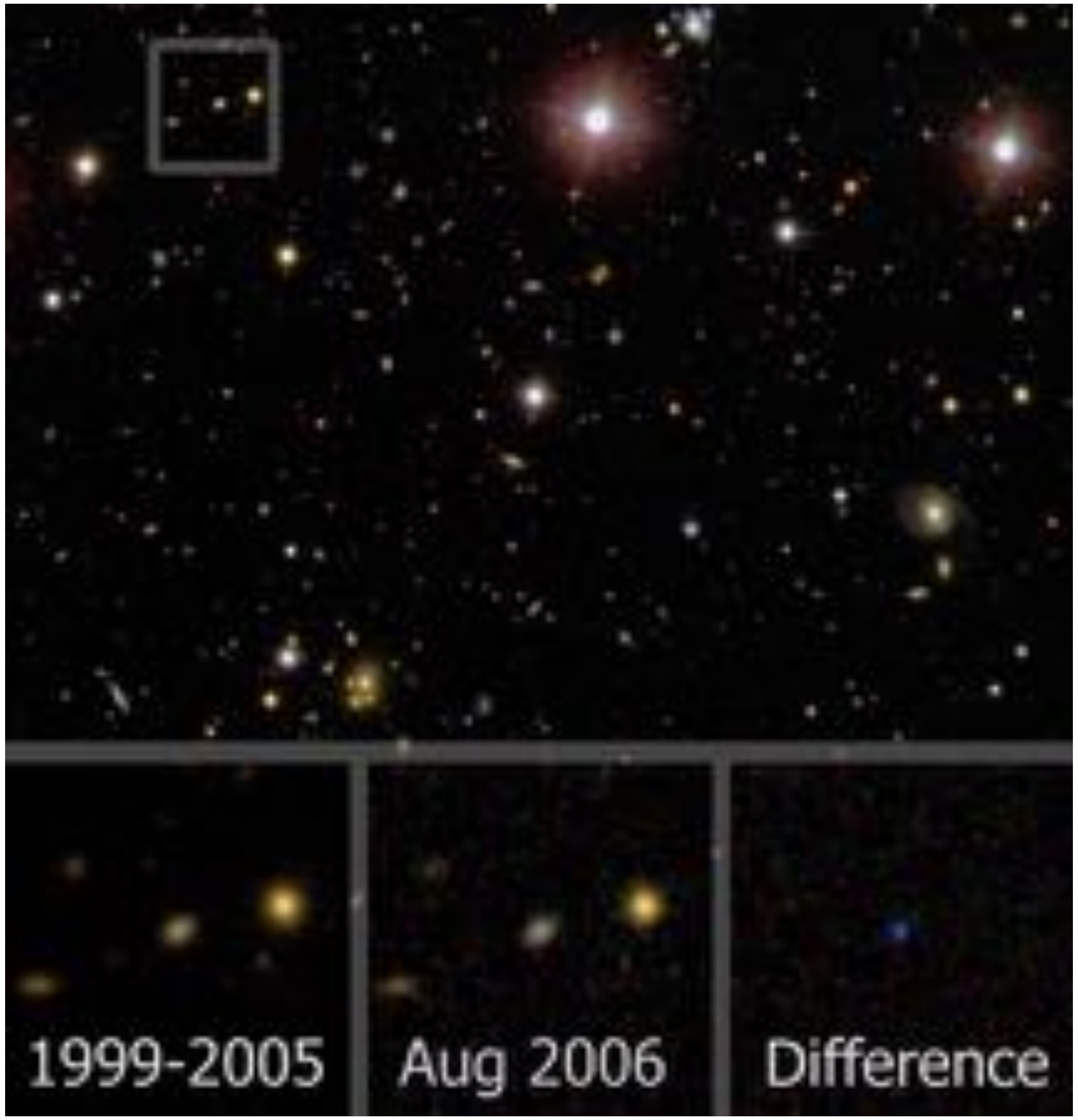
(Kesden 2011)

Non-trivial assignment

- Systematic search
- Well-sampled light curves
- Decent model light curves

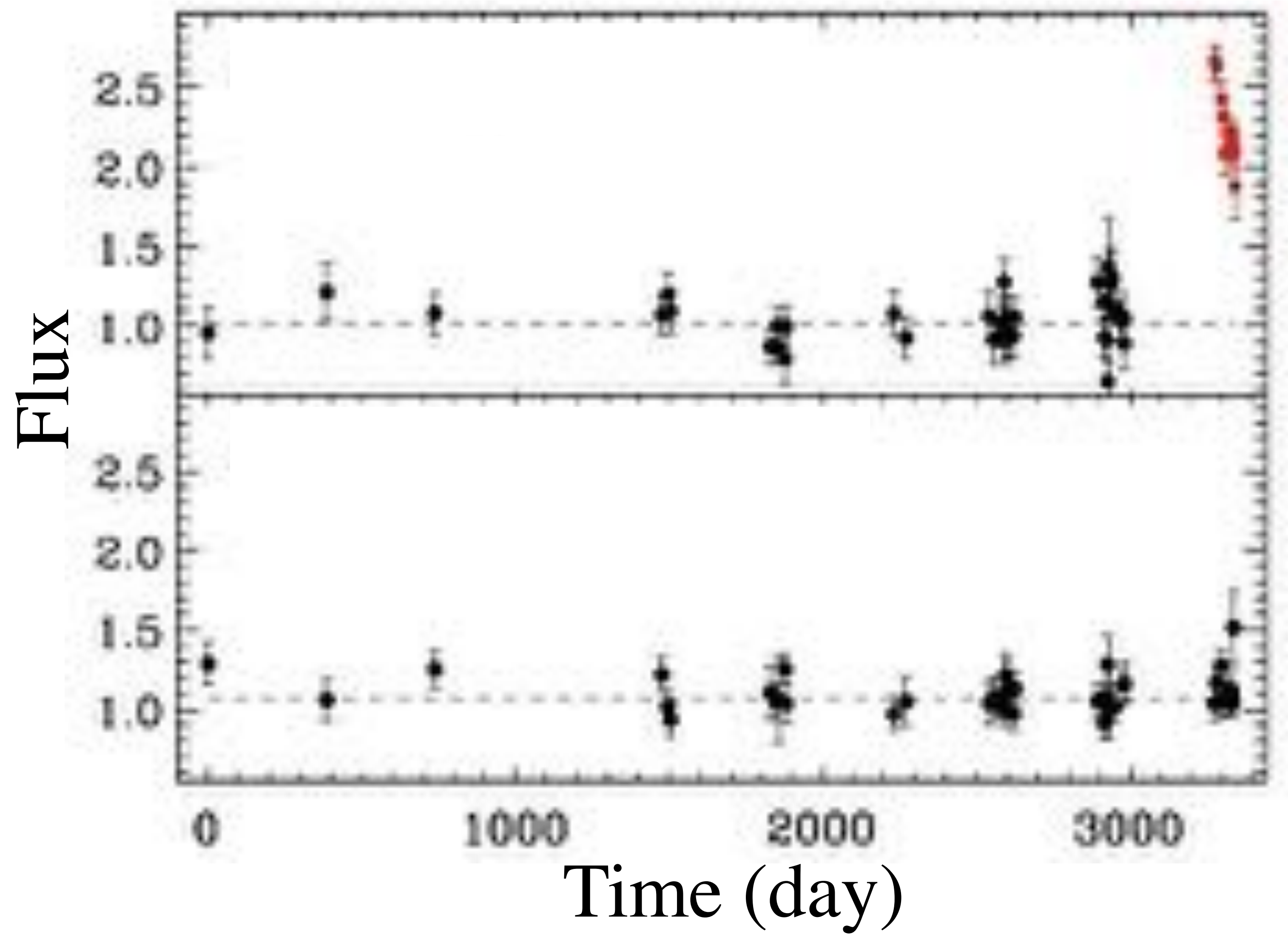
Requirements to measure an event rate

- Completed surveys:
  - ROSAT (3)
  - GALEX (3)
  - SDSS Stripe 82 (2)
- Ongoing:
  - XMM (≈6)
  - PTF (3 or 4)
  - Pan-STARRS (2)
- Future surveys: Gaia, eROSITA, BlackGEM, Atlas, ZTF, LSST



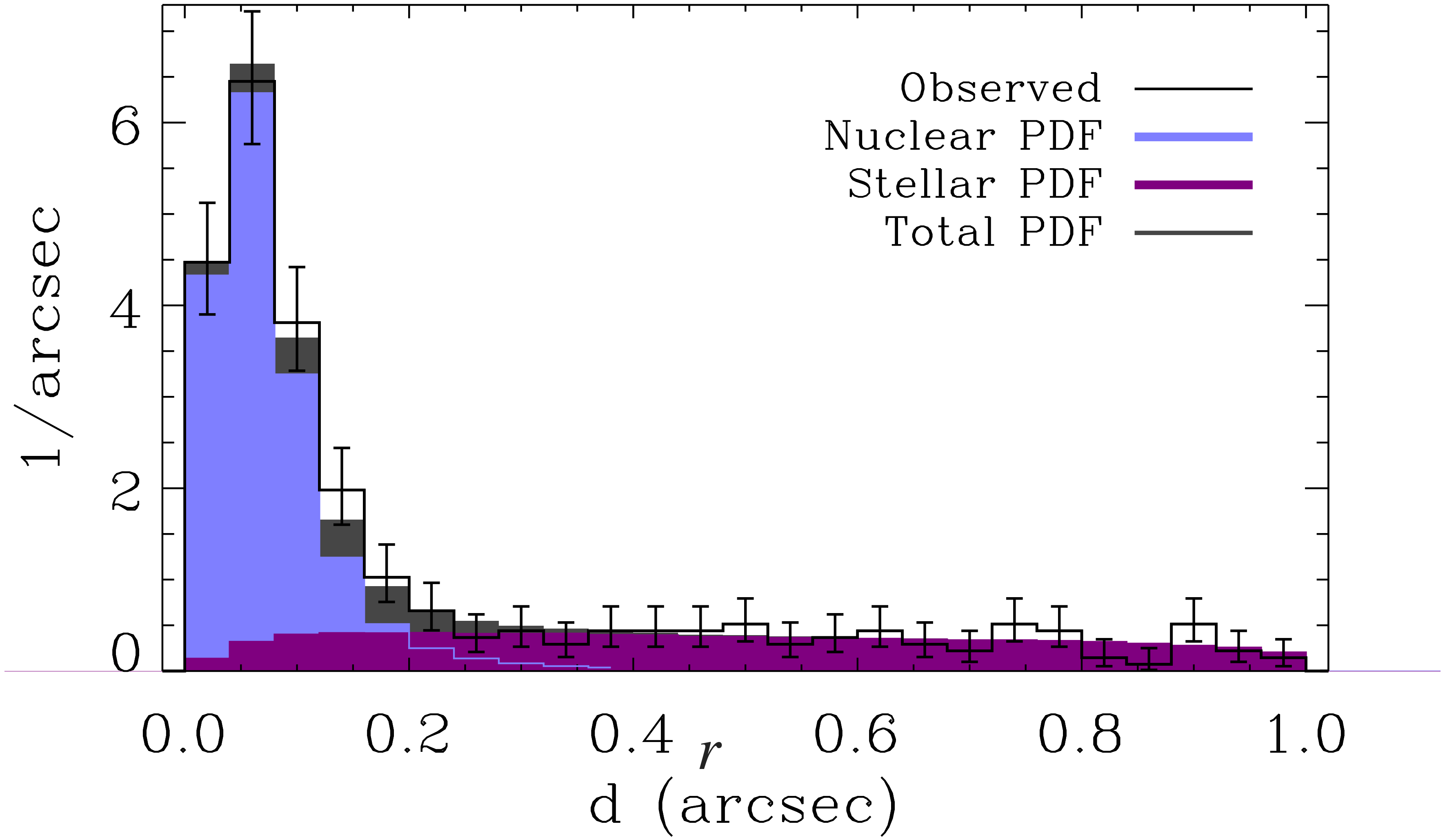
SDSS Stripe 82

- 300 deg^2, 10 yr, *u,g,r,i,z*
- m < 22.5
- ~2 million galaxies
- 70 observations per galaxy
- Systematic search for all nuclear flares in galaxies



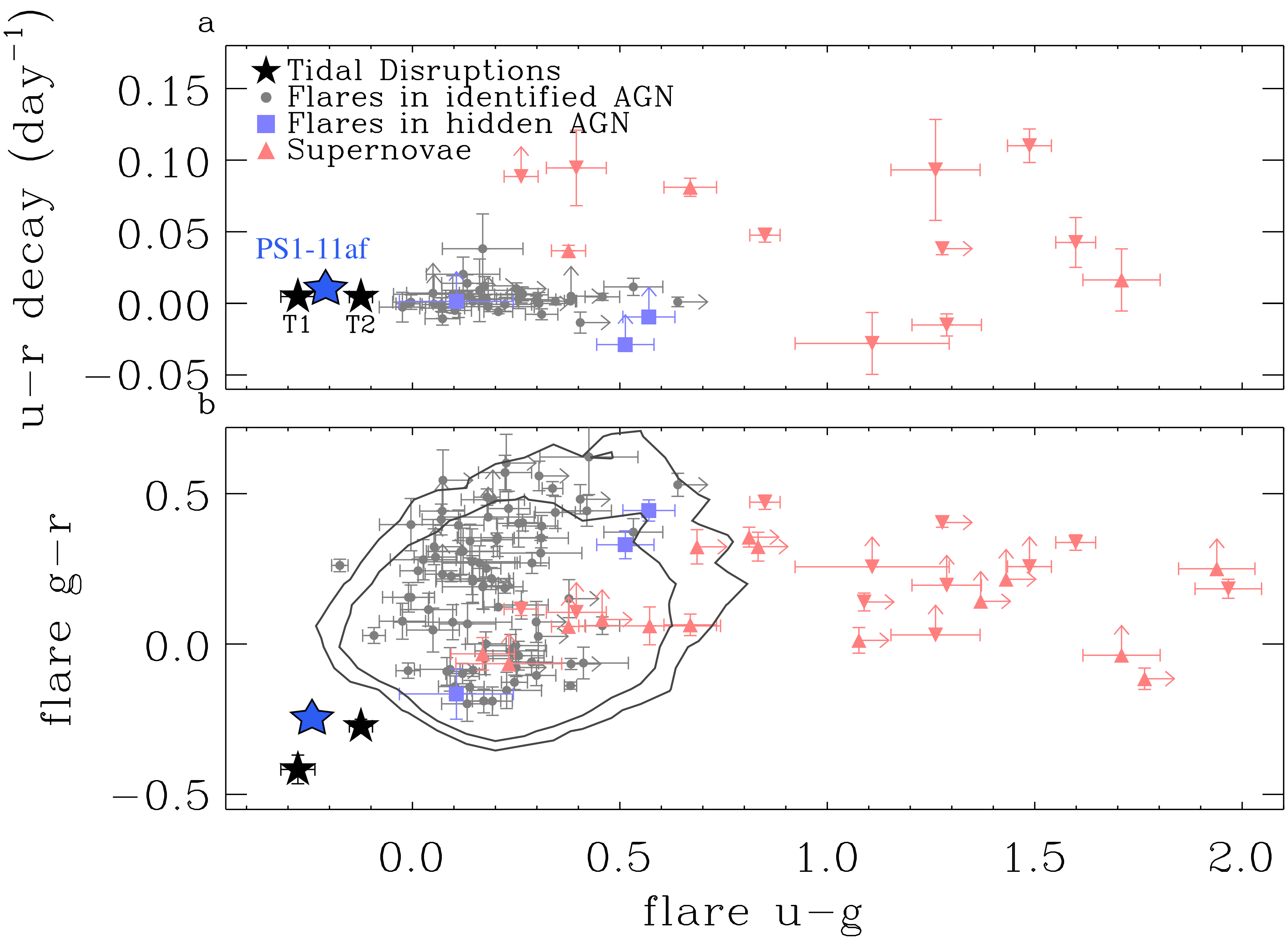
Background removal: supernovae

- Cut for nuclear flares: *r* < 0.2”
- Quality cut: 3 detections in *u*,*g*,*r*
- 42 nuclear flares
- No additional variability: 2 flares



(van Velzen+ 2011)

The SED of TDE is hot and slows little/no cooling



Cooling

Spectral energy distribution

(van Velzen+ 2011)

Detection rate in other surveys

$$\dot{N}_{\rm obs} \propto f_{\rm sky}\, F_{\rm lim}^{-3/2}$$

Survey	$F_{\rm lim}$ (mag)	$f_{\rm sky}$	$N_{\rm obs}$ (1/yr)
GAIA	19	1	4
PTF	21.5	0.2	13
PS1 MD	24.5	0.0012	10
LSST	24.5	0.5	4000

(van Velzen+ 2011)

Theoretical setup for finding the rate

$$N_{\rm TDF} = \tau \sum_{i}^{N_{\rm gal}} \epsilon_i \dot{N}_i$$

$$\dot{N} = \frac{N_{\rm TDF}}{N_{\rm gal} \tau \, \epsilon}$$

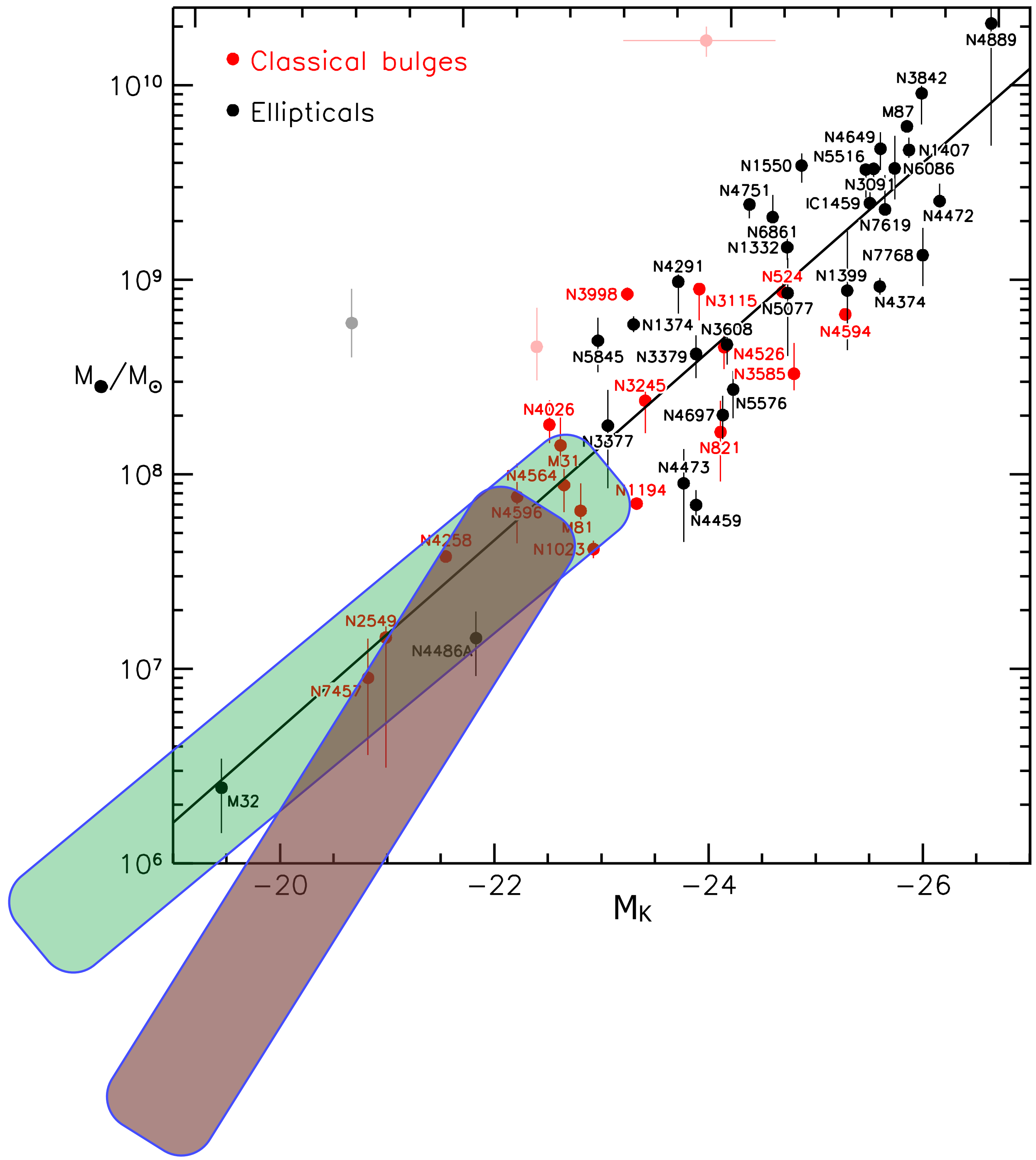
"Effective-galaxy-year"

$$\epsilon \equiv N^{-1} \sum_{i}^{N} \epsilon_i$$

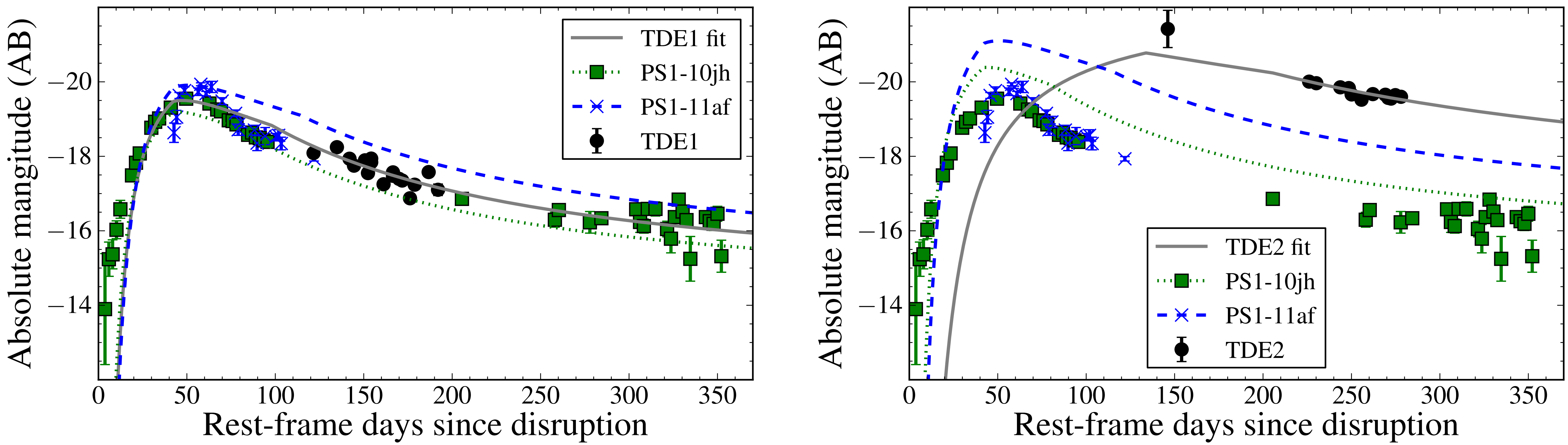
Efficiency for given light curve: Monte Carlo

Models & Scenarios

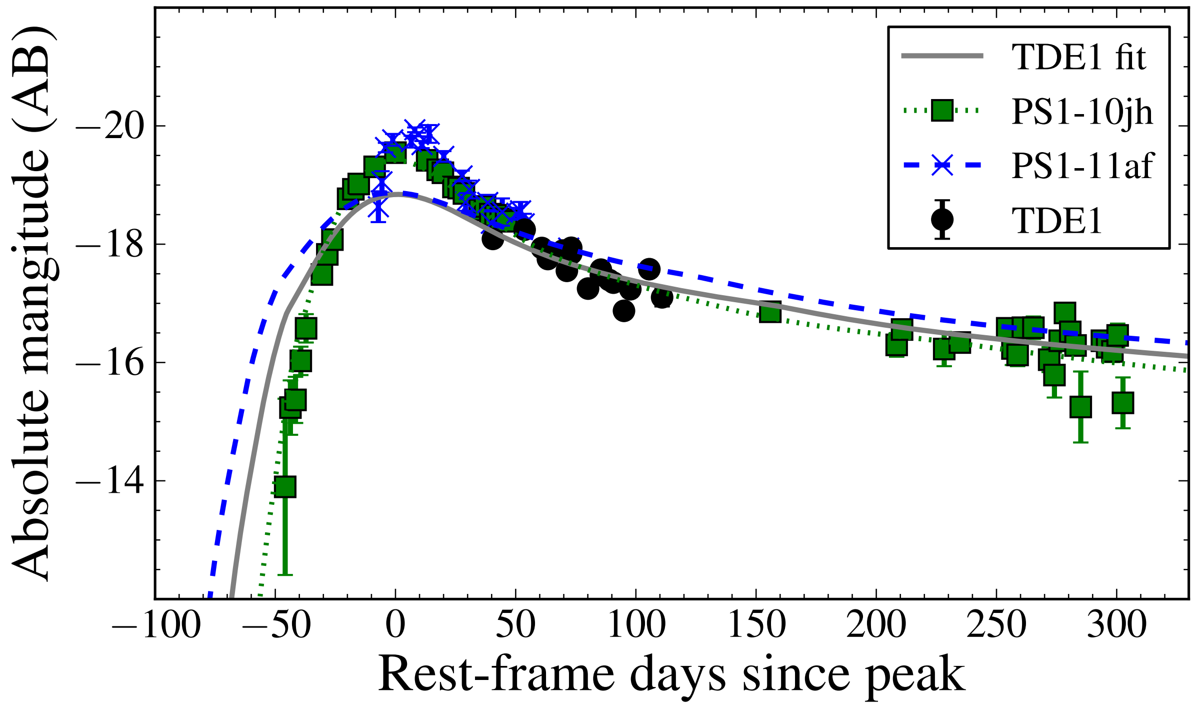
- Correction for captures:
  - Exponential (a≈0.5)
  - Step-function at $10^8\,M_\odot$
- M_{BH} scaling:
  - “Standard” (Harning & Rix 2008)
  - “Broken” (Graham 2012)
- Model light curves:
  - Empirical: SDSS and PS1
  - Model light curves

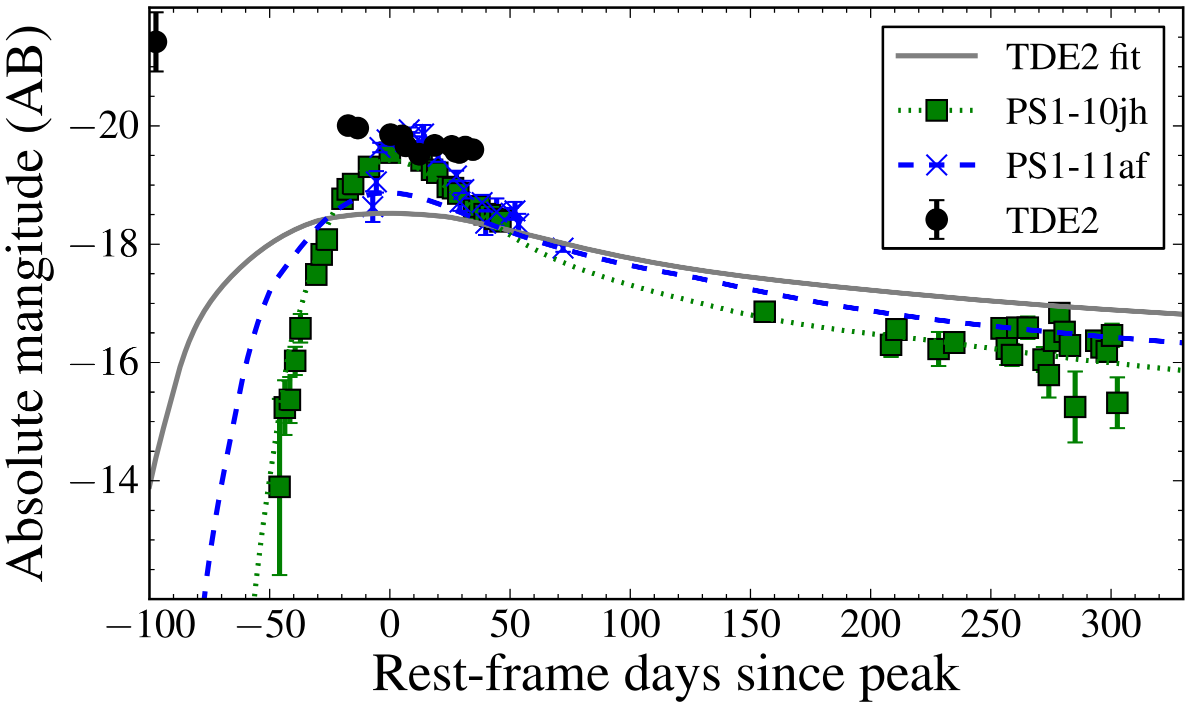


Lodato & Rossi (2011)

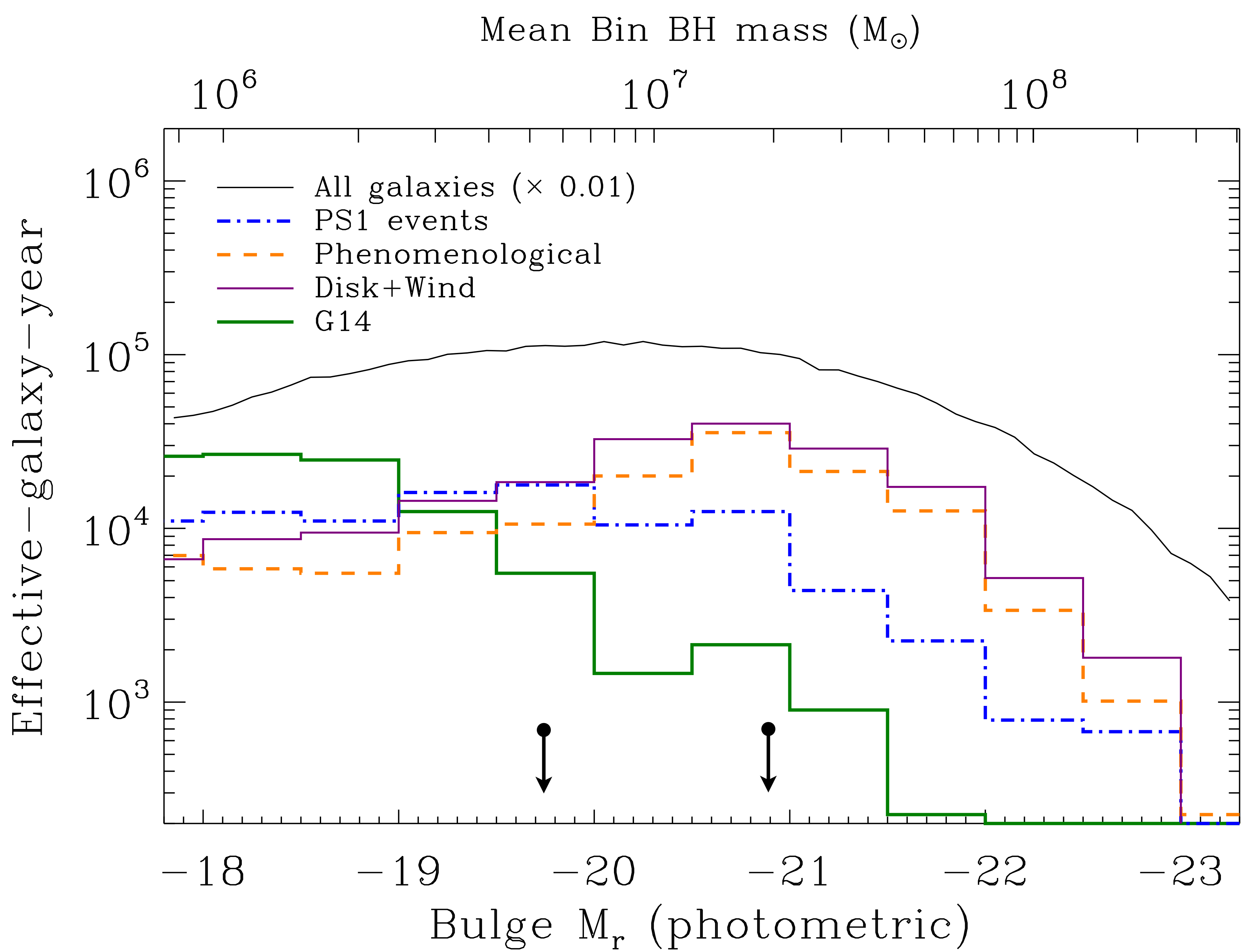


Guillochon, Manukian, and Ramirez-Ruiz (2014)





Effective-galaxy-year distribution



van Velzen & Farrar (2014)

Results

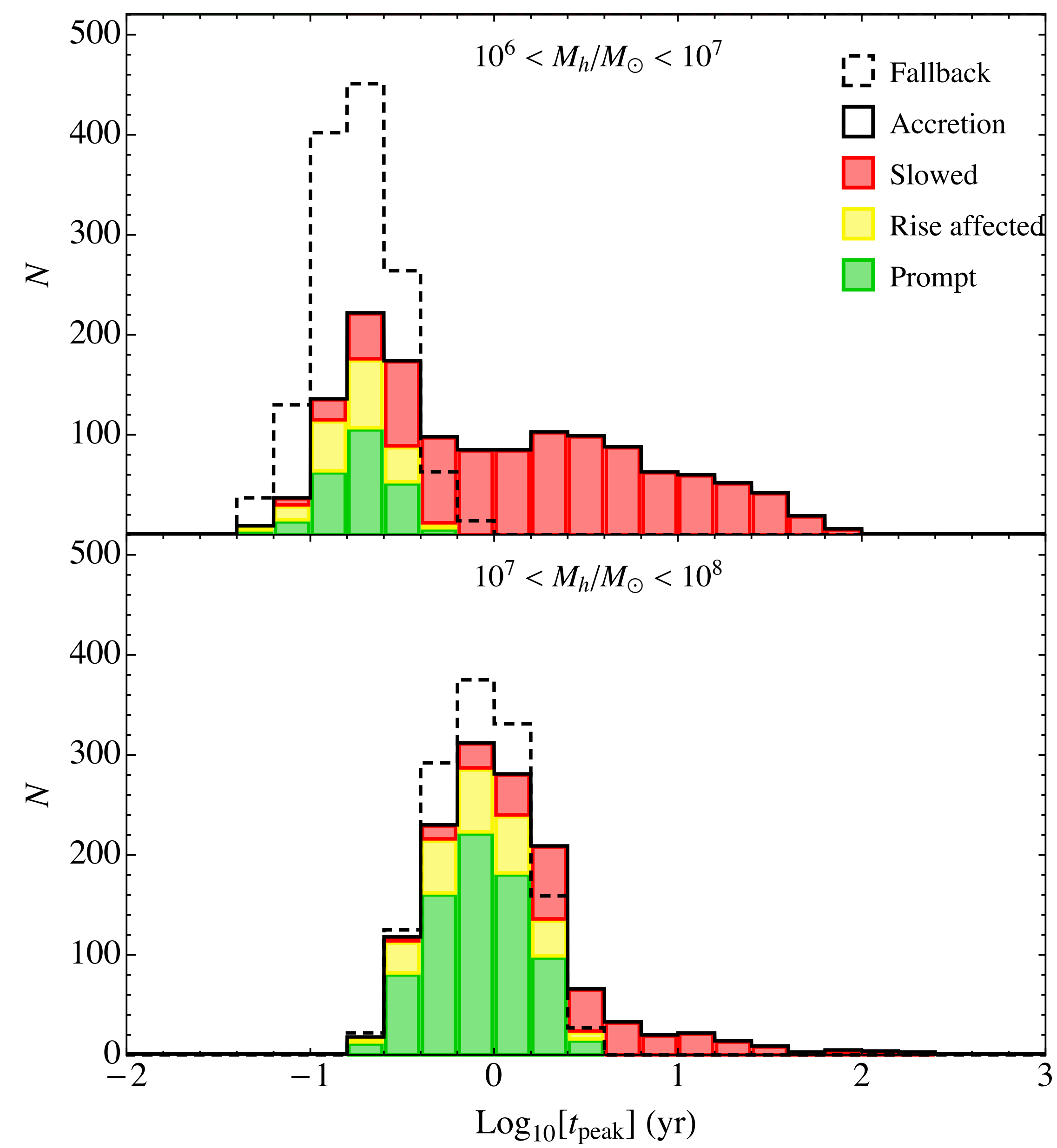
- Uncertainty
  - Poisson: factor ~2
  - Due to M_{BH} scaling: ~2
  - Due to light curves models: 50%
  - Upper limit is model-independent

Model	**Rate (yr^{-1} $galaxy^{-1}$)**
Empirical	$2.0\ 10^{-5}$
Lodato & Rossi	$1.7\ 10^{-5}$
Guillochon et al.	$1.9\ 10^{-5}$
Upper limit	$< 2\ 10^{-4}$

Comparison to theory

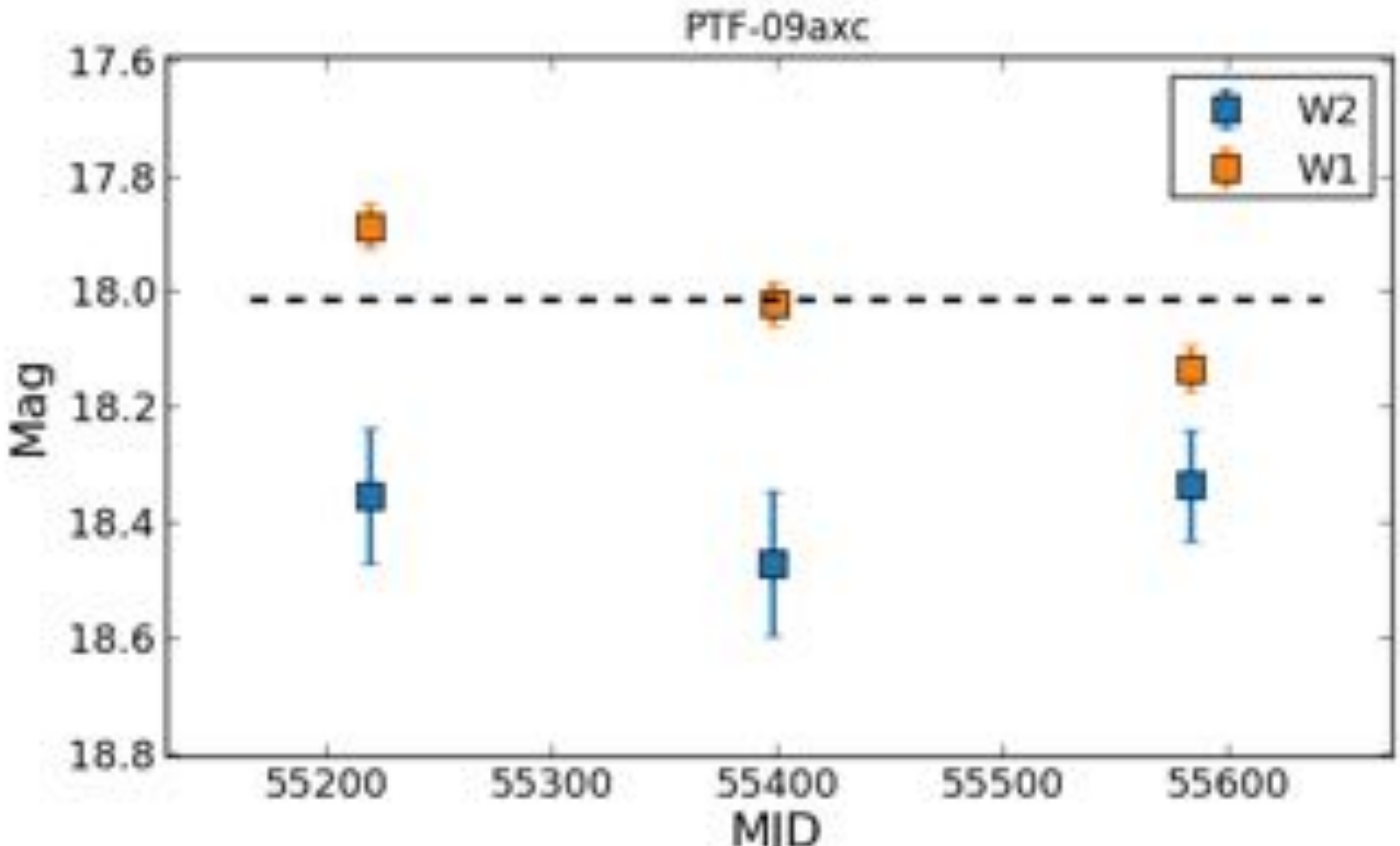
- Theoretical rate ~10 times higher
  - Dust obscuration
  - TDE physics: circularization
  - Occupation fraction (!)

- X-rays could help, however:
  - ROSAT: 9 x 10^{-6} yr^{-1} (Donley+ 2002)
  - XMM: 2 x 10^{-4} yr^{-1} (Esquej + 2009)



Guillochon & Ramirez-Ruiz (tomorrow)

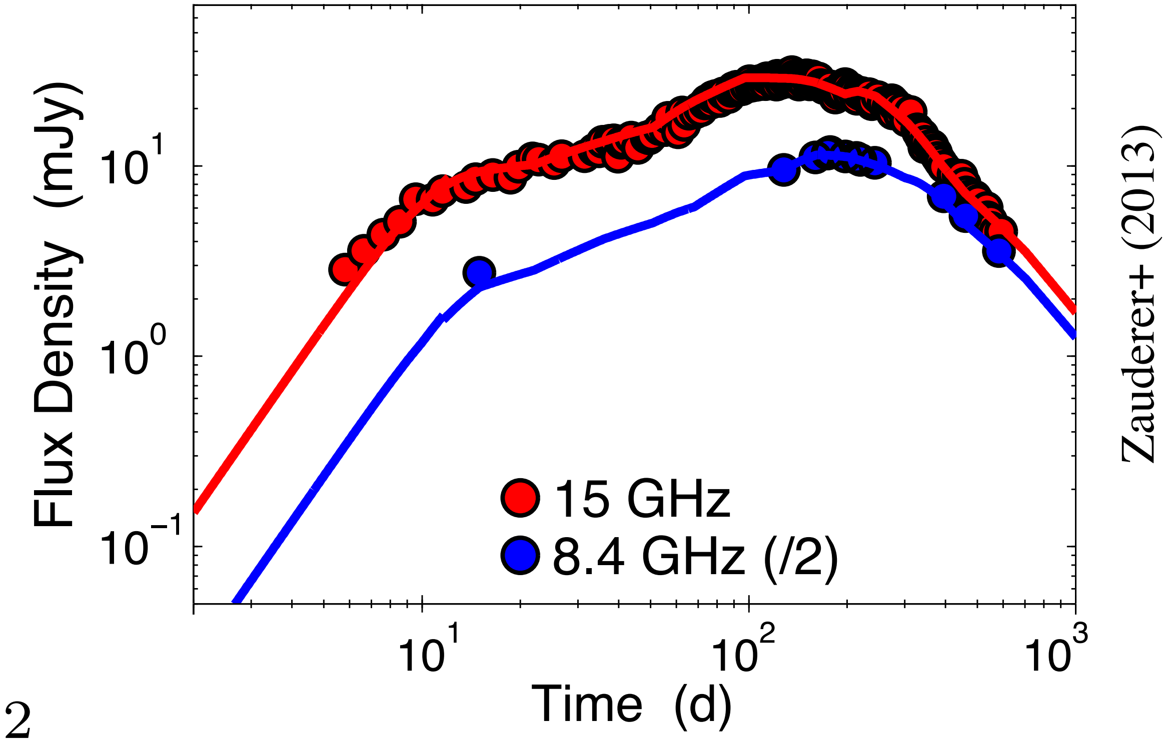
Dust in TDE host galaxies:
Mid-IR light curve, 6 months after optical detection



Mendez & van Velzen (in prep)

A two-minute radio detour…

Implication for jetted TDEs

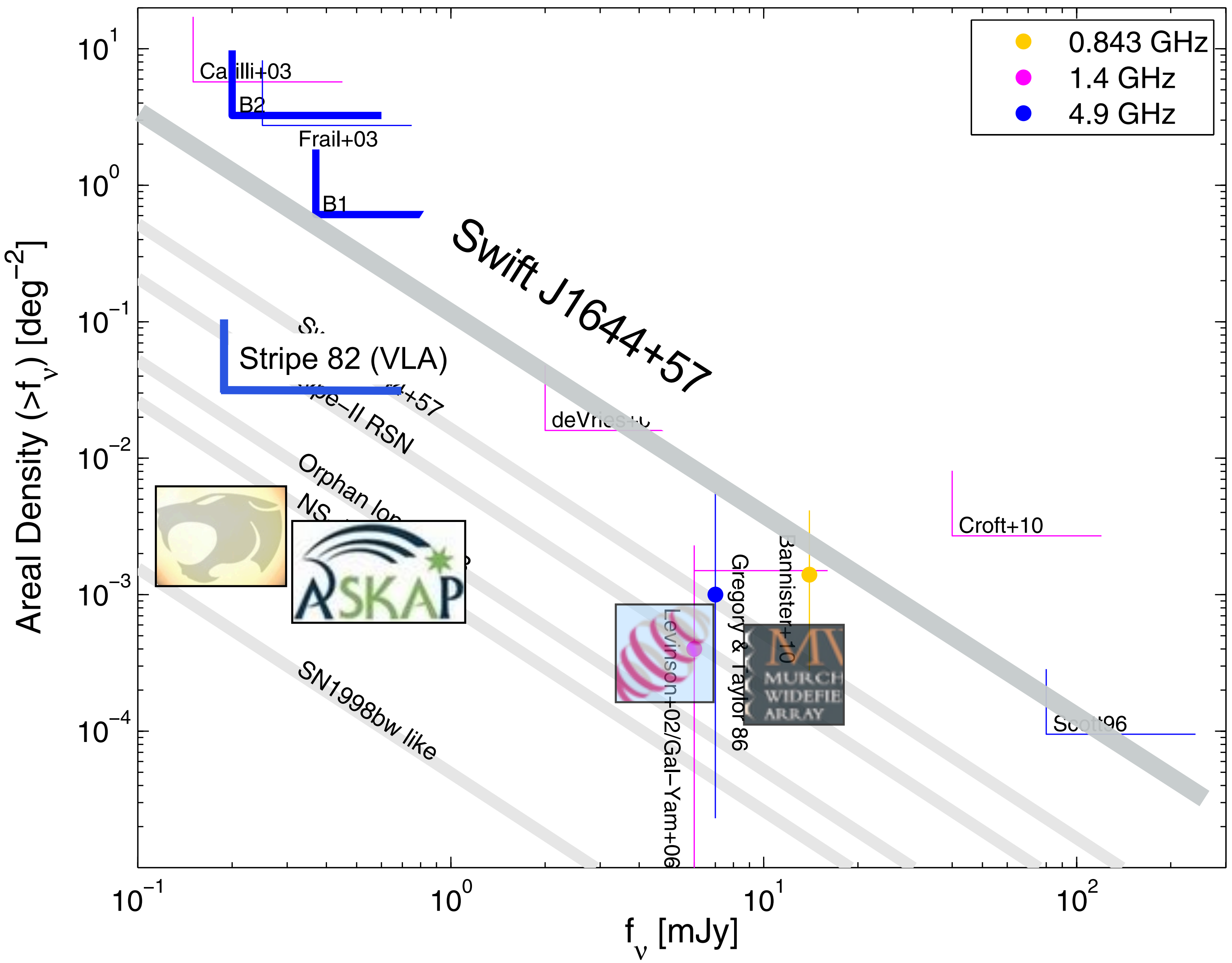


$$R(F_{\nu,\mathrm{lim}}) \sim 8 \times 10^{-3}\,\Gamma_j^{-2} \left(\frac{F_{\nu,\mathrm{Sw}}}{F_{\nu,\mathrm{lim}}}\right)^{3/2}$$

$$\frac{\Delta T \dot{N}_{\mathrm{TDJ}}}{10^{-5}} \frac{\rho_{\mathrm{BH}}}{5 \times 10^{-3}\ \mathrm{Mpc}^{-3}}\ \mathrm{deg}^{-2} \quad .$$

van Velzen+ 2013; Donnarumma+ 2015; Mimica+ 2015

The most common transient on the radio sky?



Frail et al. (2012), TDE jet rate from van Velzen et al. (2013)

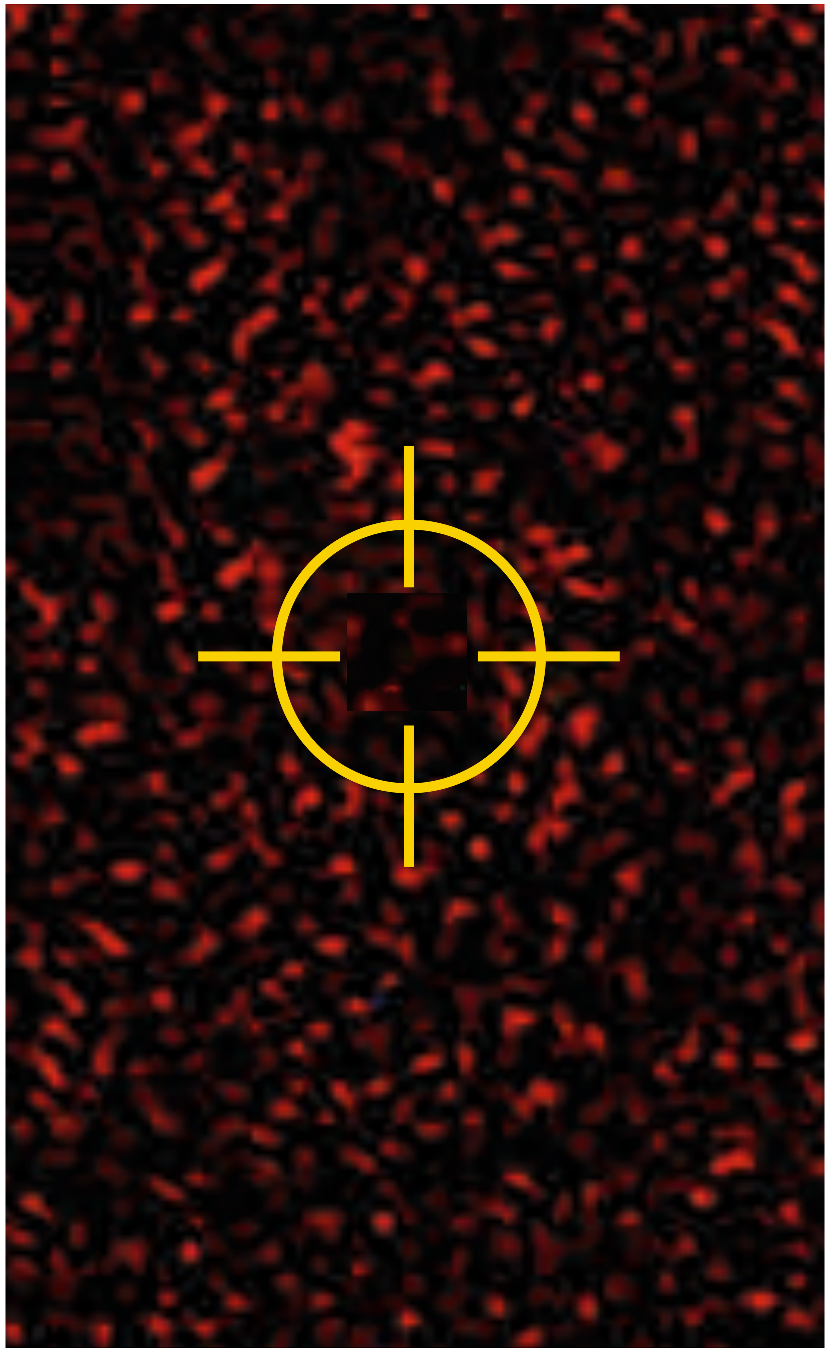
Tidal disruption jets: two models

- External model
  (Giannios & Metzger **2011**; Metzger, Giannios, Mimica 2011)
  - Inspired by GRB jets
    (eg, Granot & Sari 1999)
  - Interaction of forward/reverse shock with environment
  - On-axis or isotropic

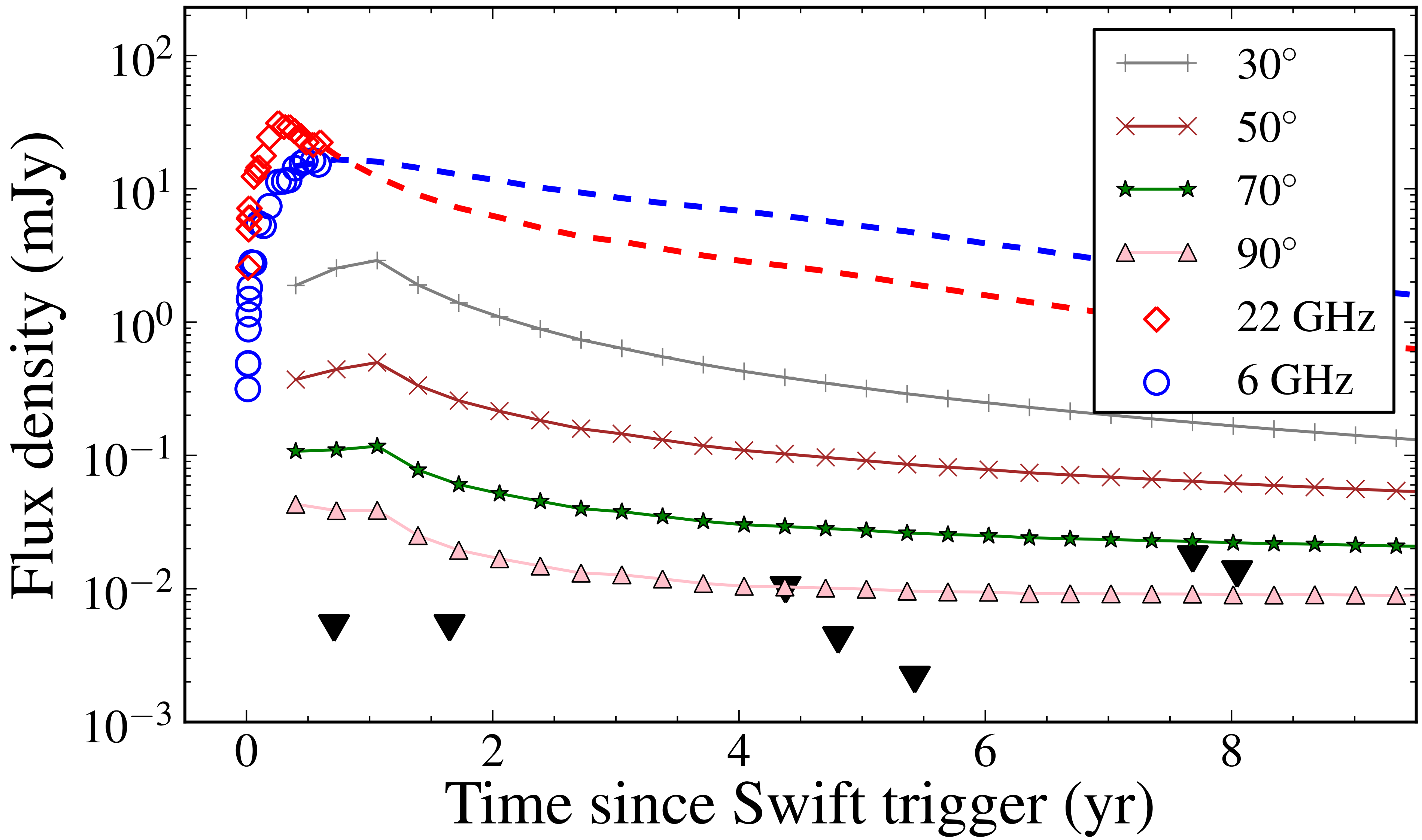
- Internal model
  (van Velzen, Falcke & Farrar **2010**; van Velzen, Körding & Falcke 2011)
  - Inspired by AGN jets
  - Emission from matter injected in the jet from the disk
  - Include accretion state-transitions
  - Function of inclination (Doppler boosting)

Follow-up observations: JVLA, 5 GHz, 10 µJy rms

- van Velzen et al. (2013):
  - followed-up all optical/UV TDE
  - No detections
- Bower et al. (2012):
  - Followed-up all X-ray TDE
  - Two detected, both from ROSAT
    (IC 3599 and RX J1420.4+5334)
  - Very unlikely to be TDE jets
- Soderberg et al. (in prep):
  - No detections

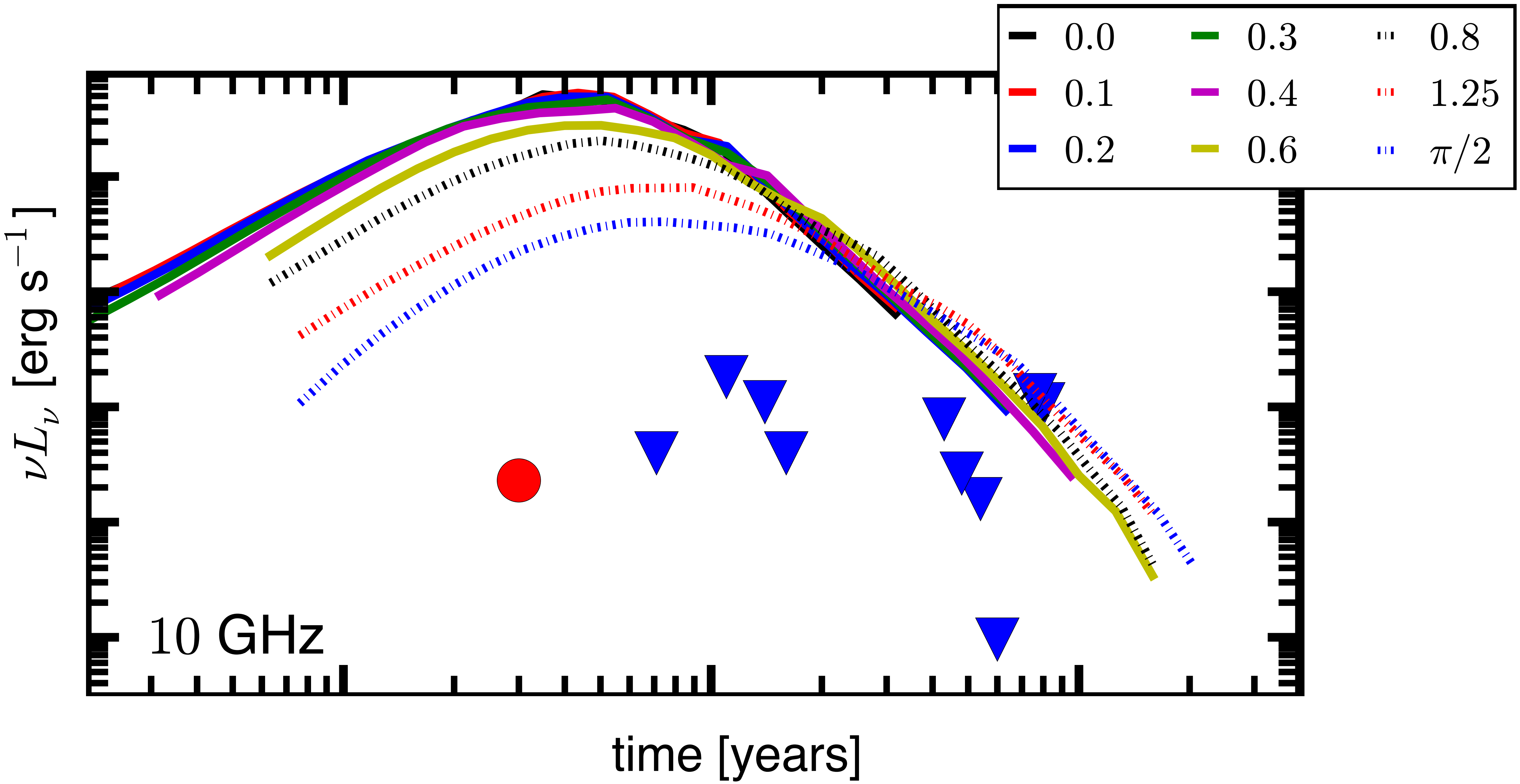


Off-axis light curves: conservative model



van Velzen+ (2013)

Off-axis light curves: simulations

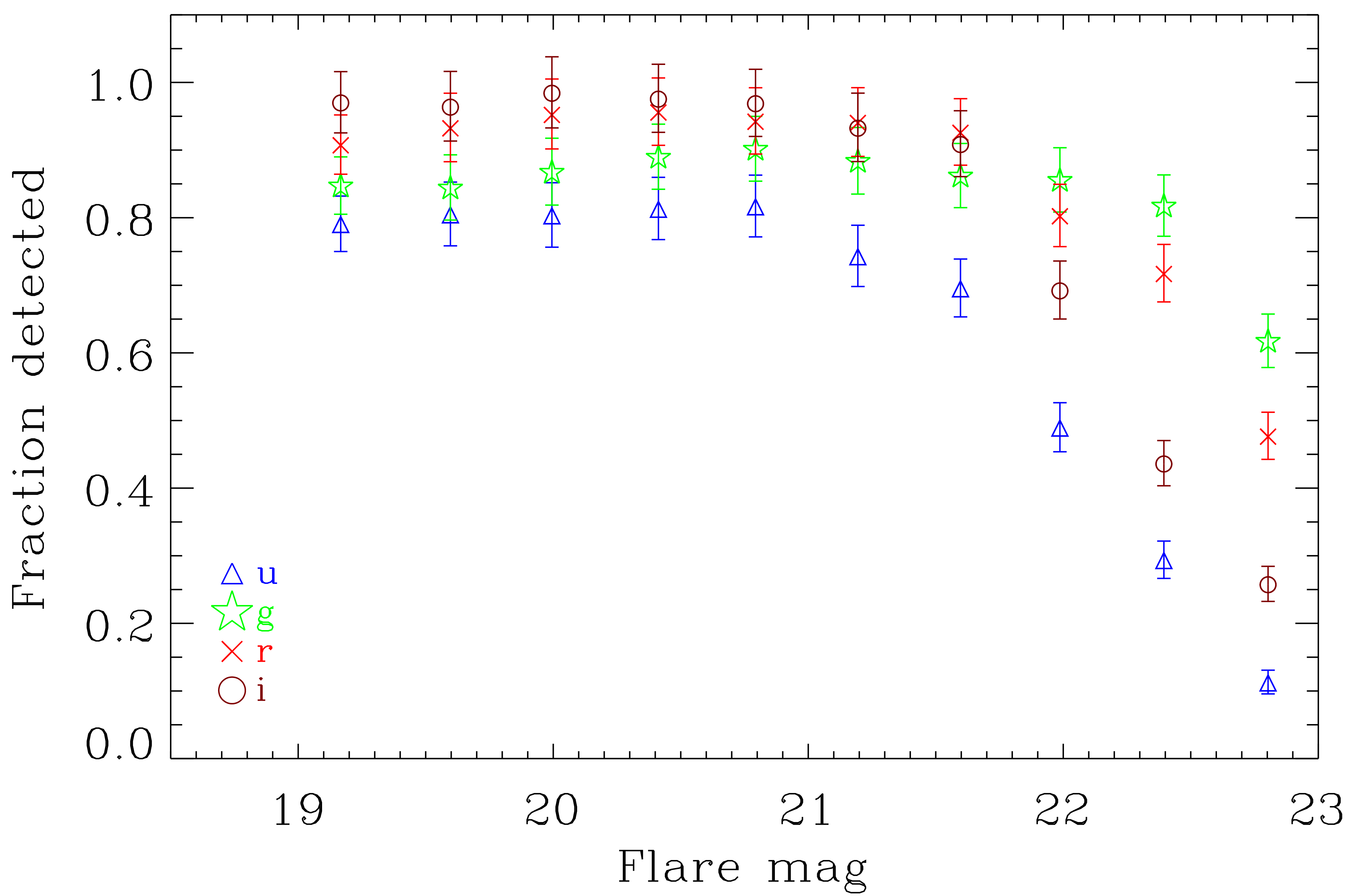


Mimica+ (2015)

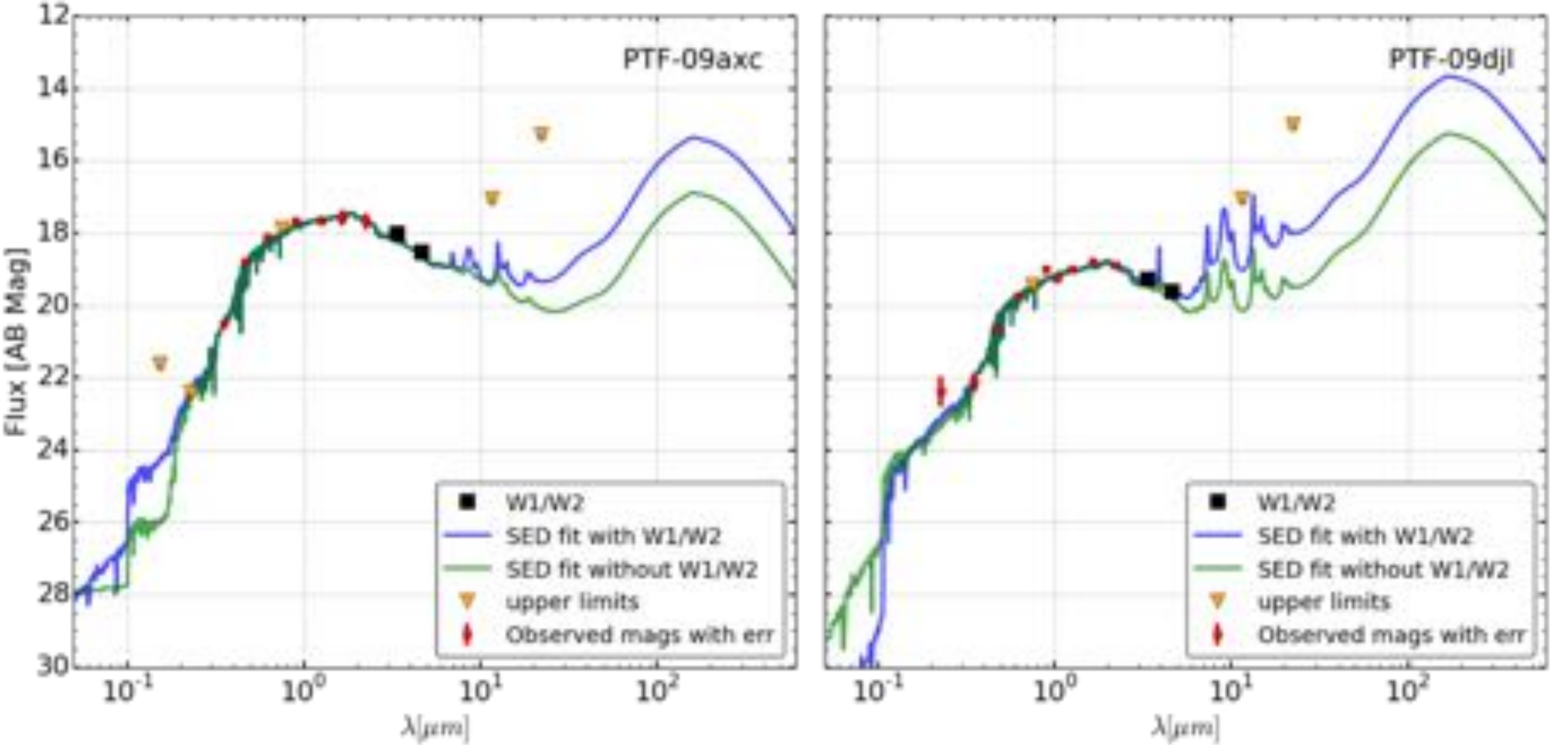
Conclusions & Outlook

- Jets from tidal disruptions:
  - Not common (<10 % of TDE)
  - Upcoming radio surveys could detect few per year
- Rate based on systematic search:
  - ~2×10^{-5} yr^{-1} $galaxy^{-1}$
- Discrepancy with theory
  - Circumnuclear dust or something even more exciting?
- Combine X-ray, UV, optical surveys

Efficiency: catalog selection + difference imaging



Galaxy SEDs



Mendez & van Velzen (in prep)

Could there flares be supernovae?

- Not normal SNe: more blue, little cooling
- UV detection > 2 yr after the flare
- Based on geometry:
  - *P*(SN) < 2%
- New kind of “nuclear” core collapse SN?
  - Never observed before (?)
  - Would require factor 1000 suppression outside nucleus

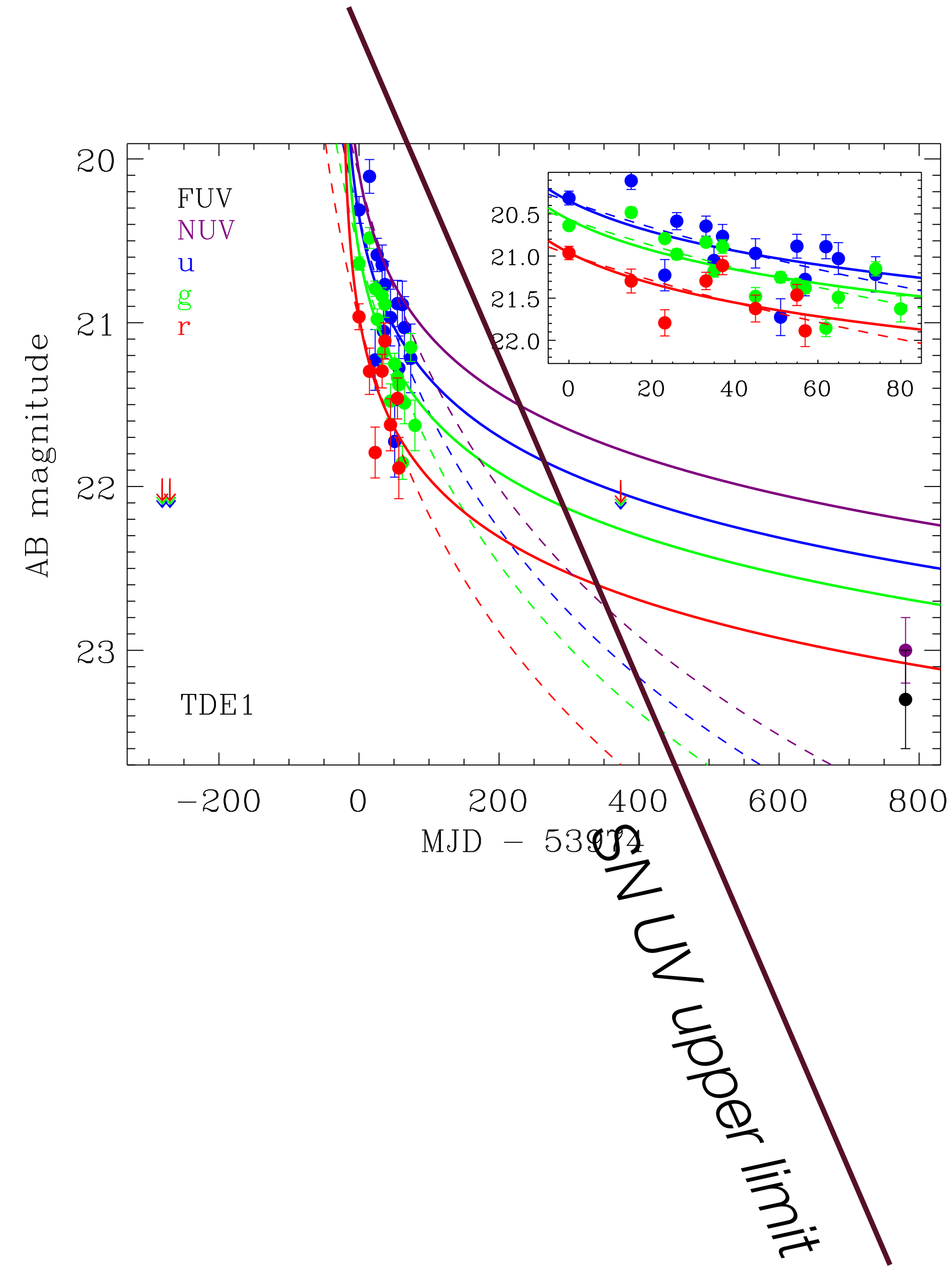


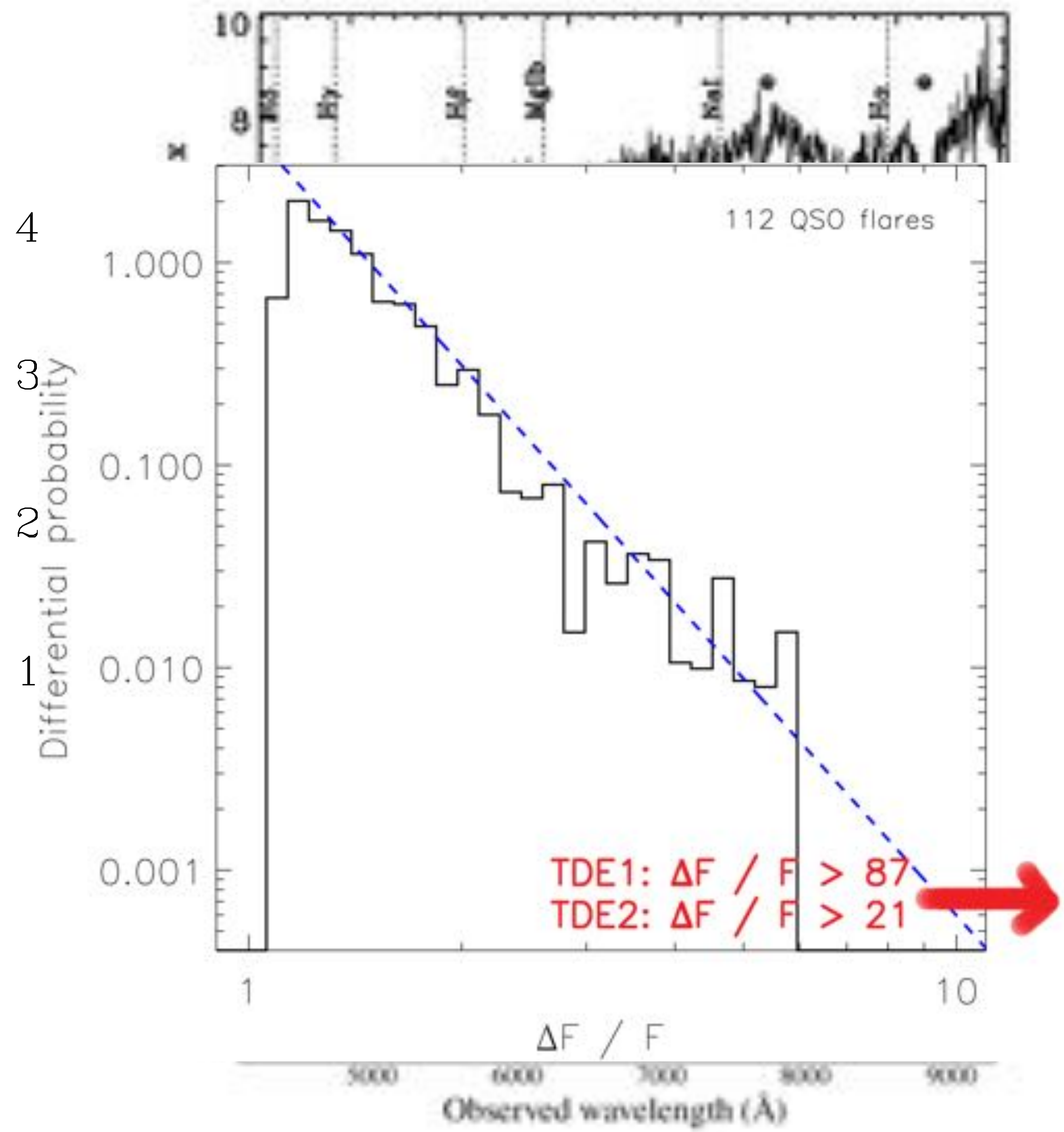
TABLE 1

LIGHT CURVE MODEL EFFICIENCIES & RESULTING OPTICAL TDF RATES.

Name	Mean efficiency (%)	TDF Rate ($\mathrm{yr}^{-1}\mathrm{galaxy}^{-1}$)	
SDSS-only	0.13, 0.62	$< 1.5 \times 10^{-4}$	
PS1 events (10jh, 11af)	1.0	2.0×10^{-5}	
Phenomenological	1.4	1.5×10^{-5}	
M_{BH} scaling: Häring & Rix (2004)		Correction for captures:	
		Step-function	Exponential
Disk+Wind	0.83, 3.3	1.2×10^{-5}	1.7×10^{-5}
GMR14	1.2	1.8×10^{-5}	1.9×10^{-5}
M_{BH} scaling: Graham (2012)		Correction for captures:	
		Step-function	Exponential
Disk+Wind	0.22, 1.5	2.1×10^{-5}	3.2×10^{-5}
GMR14	1.6	1.2×10^{-5}	1.3×10^{-5}

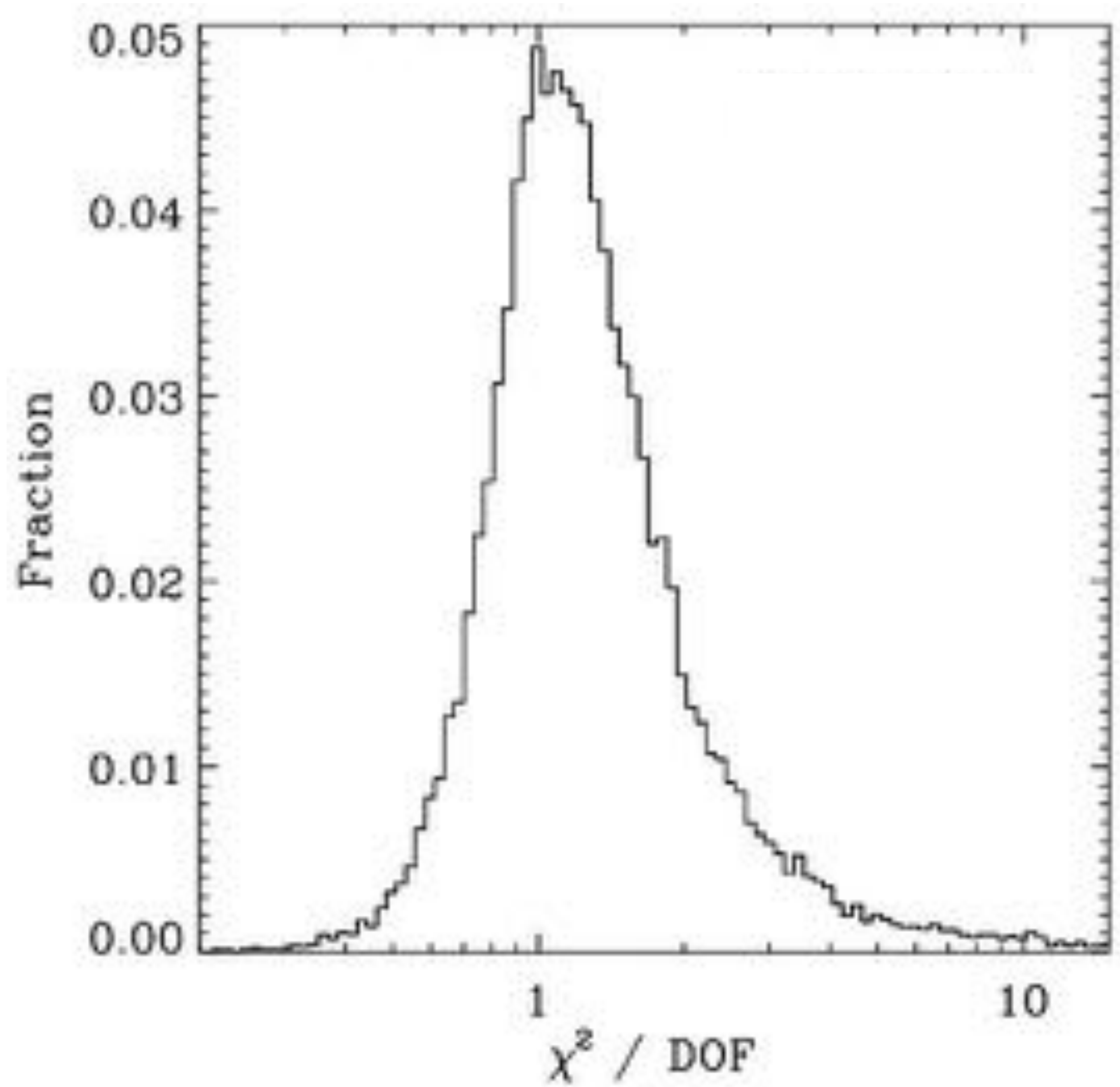
Could these flares originate from AGN?

- Flares are more blue than QSO (in their high-state)
- Host spectra show no sign of active black hole
- Flux increases very large: P(AGN)~10^{-7},10^{-5}
- No additional variability: P(AGN)~10^{-6},10^{-5}
- Radio non-detection: F < 20μJy, < 10^{28} erg $s^{-1}Hz^{-1}$



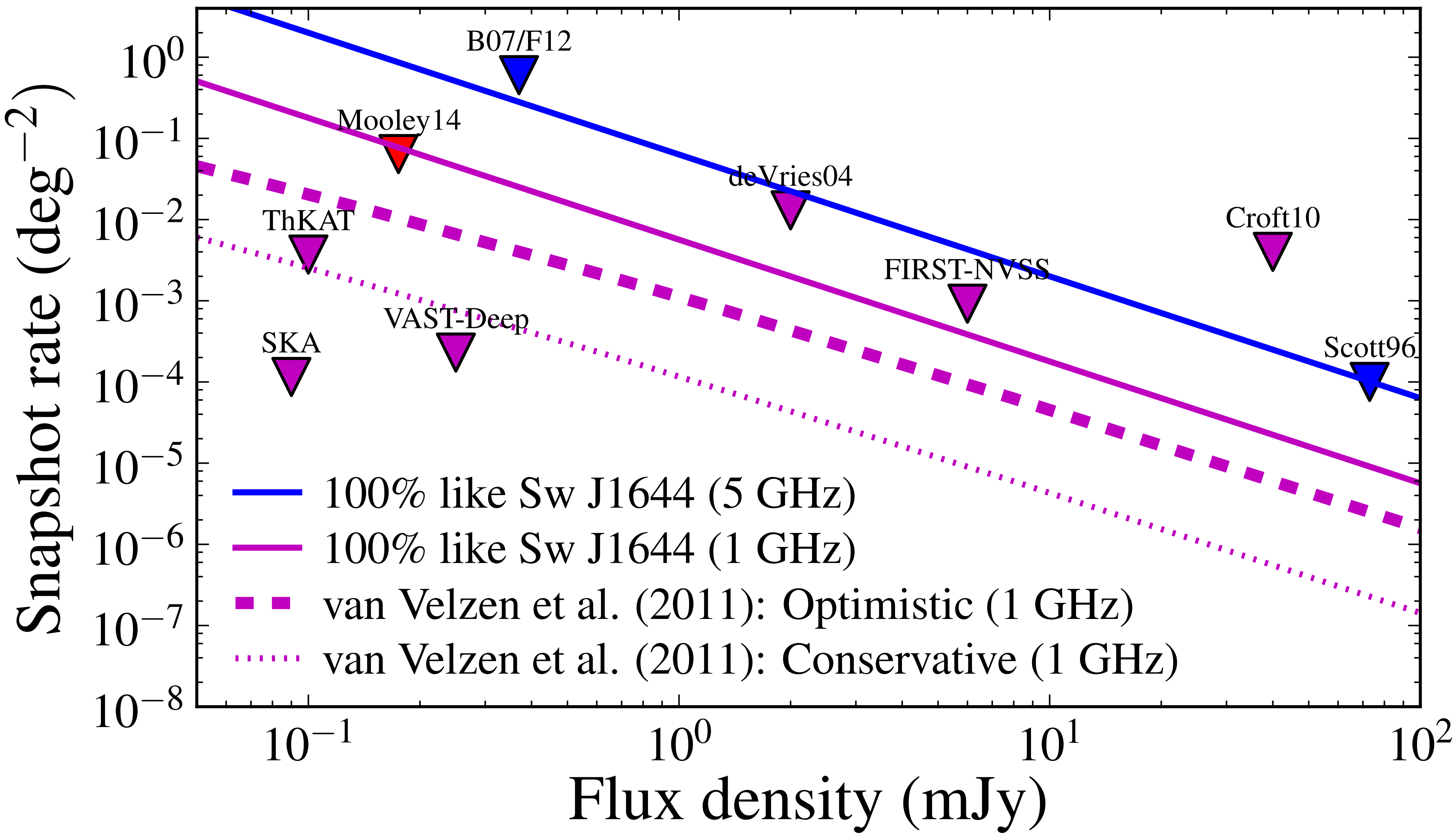
Flare selection: catalog cuts

$$\begin{aligned} \chi^2/\mathrm{DOF} &> 5 \\ \Delta F/F_{\mathrm{mean}} &> 0.1 \\ \Delta F/\sigma &> 7 \end{aligned}$$



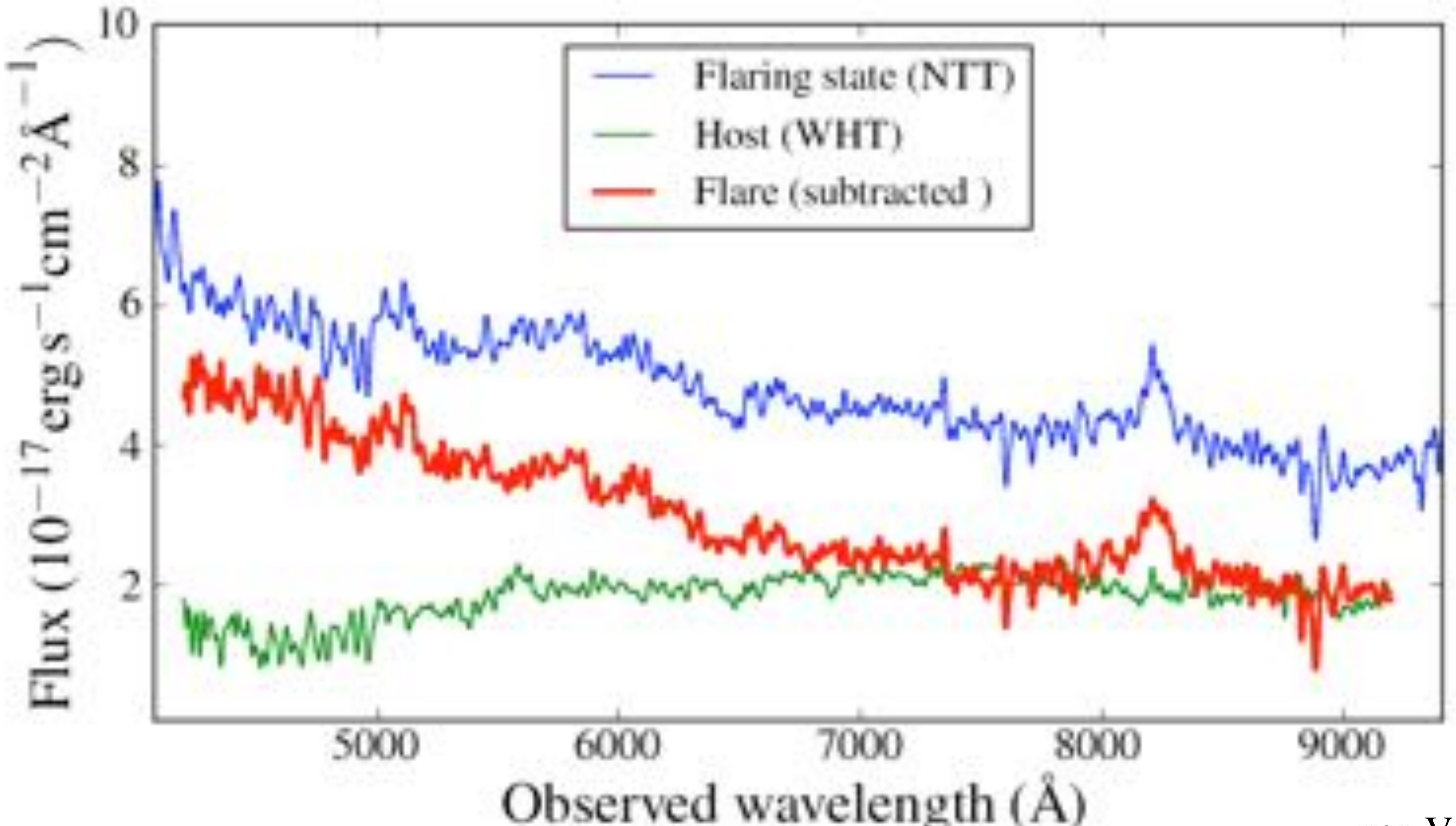
- Factor 100 reduction: 21,383 follow-up candidates

Snapshot rate



Donnarumma+ 2015

Observations: flaring state spectrum (TDE2)



van Velzen+ 2011