Extended X-ray emission around an ultra-luminous X-ray pulsar

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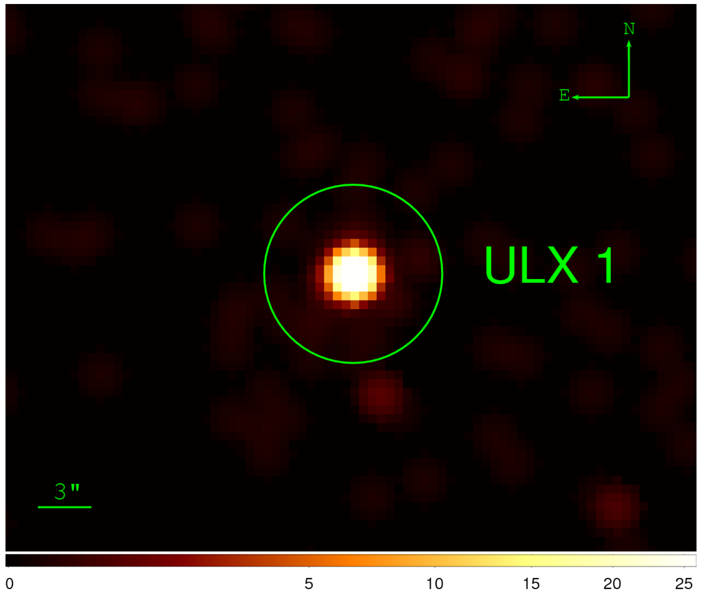
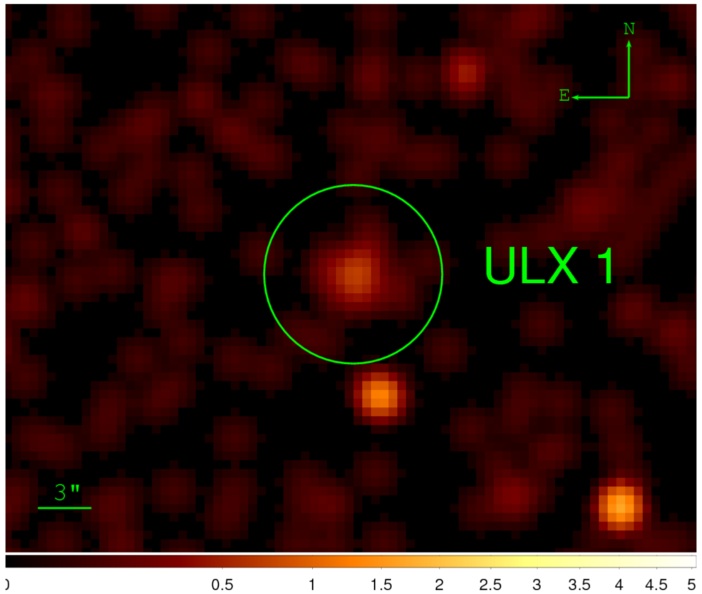
20 Years of Chandra Science - Boston - Dec 3-6 2019

outline

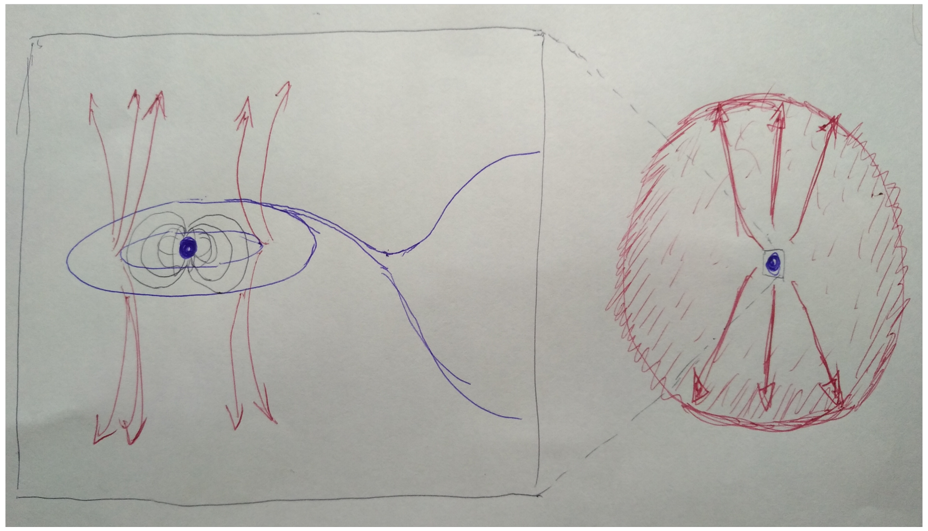
- NGC 5907 ULX1



- Extended emission



- An X-ray bubble



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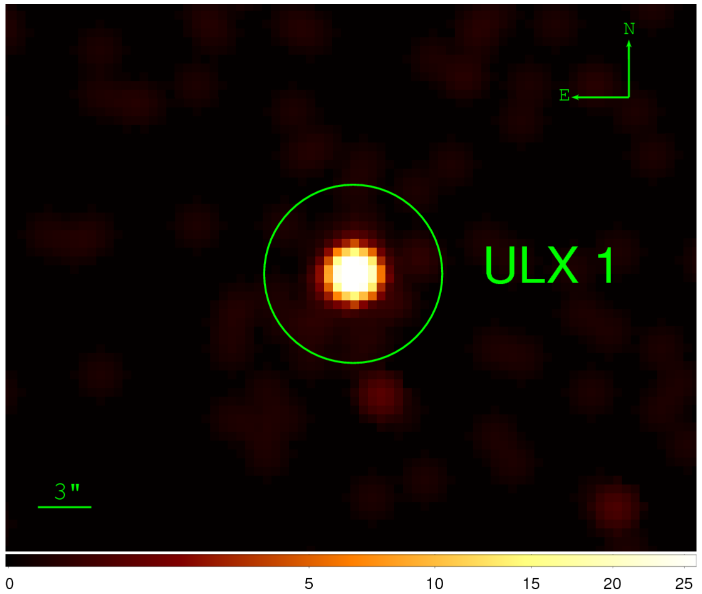

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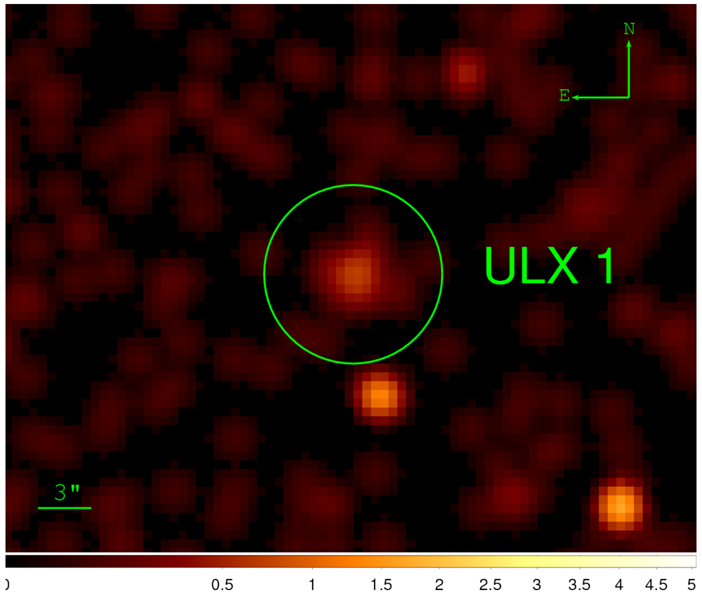

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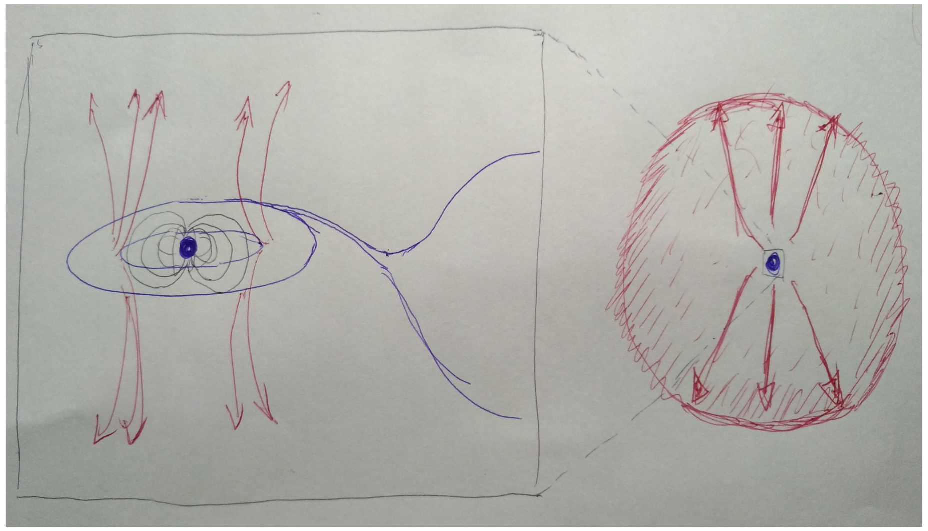
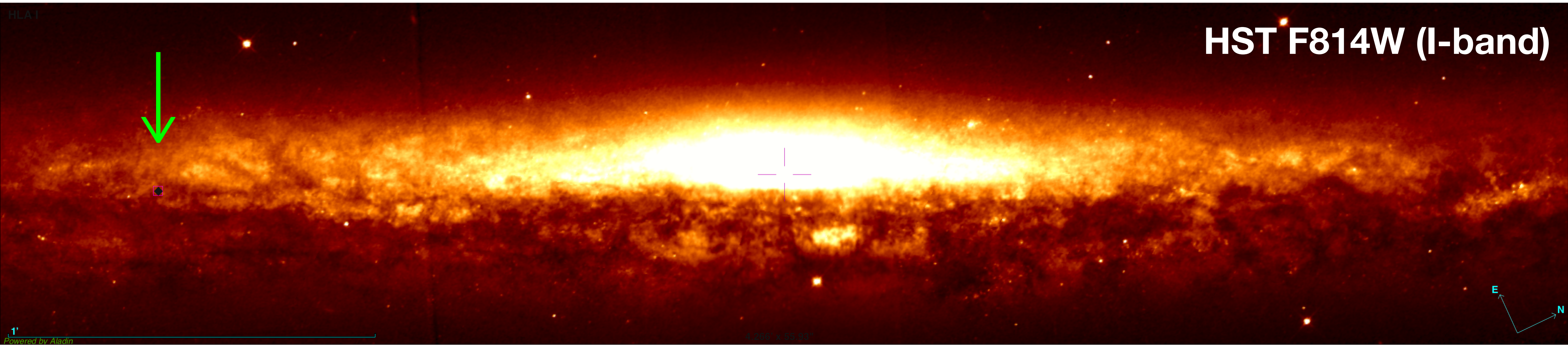
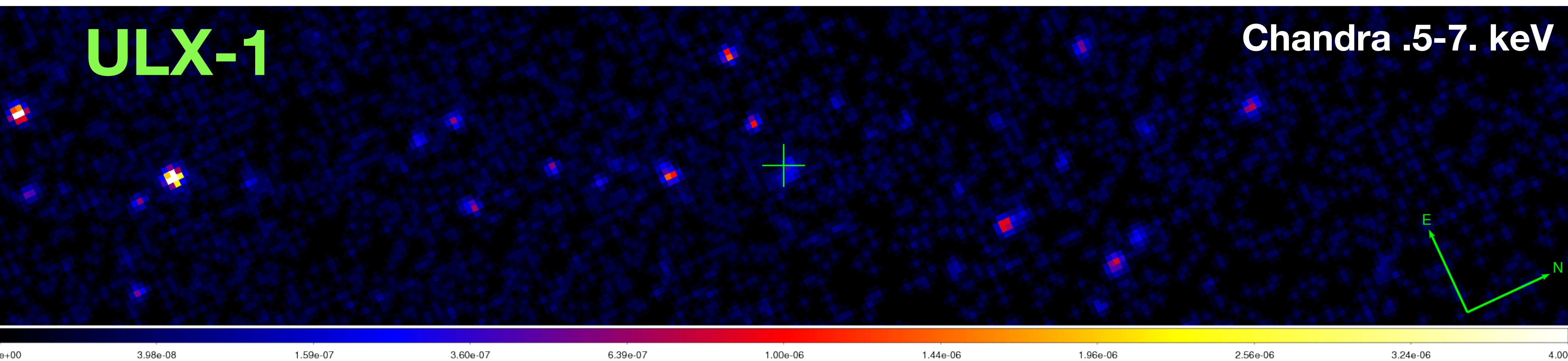


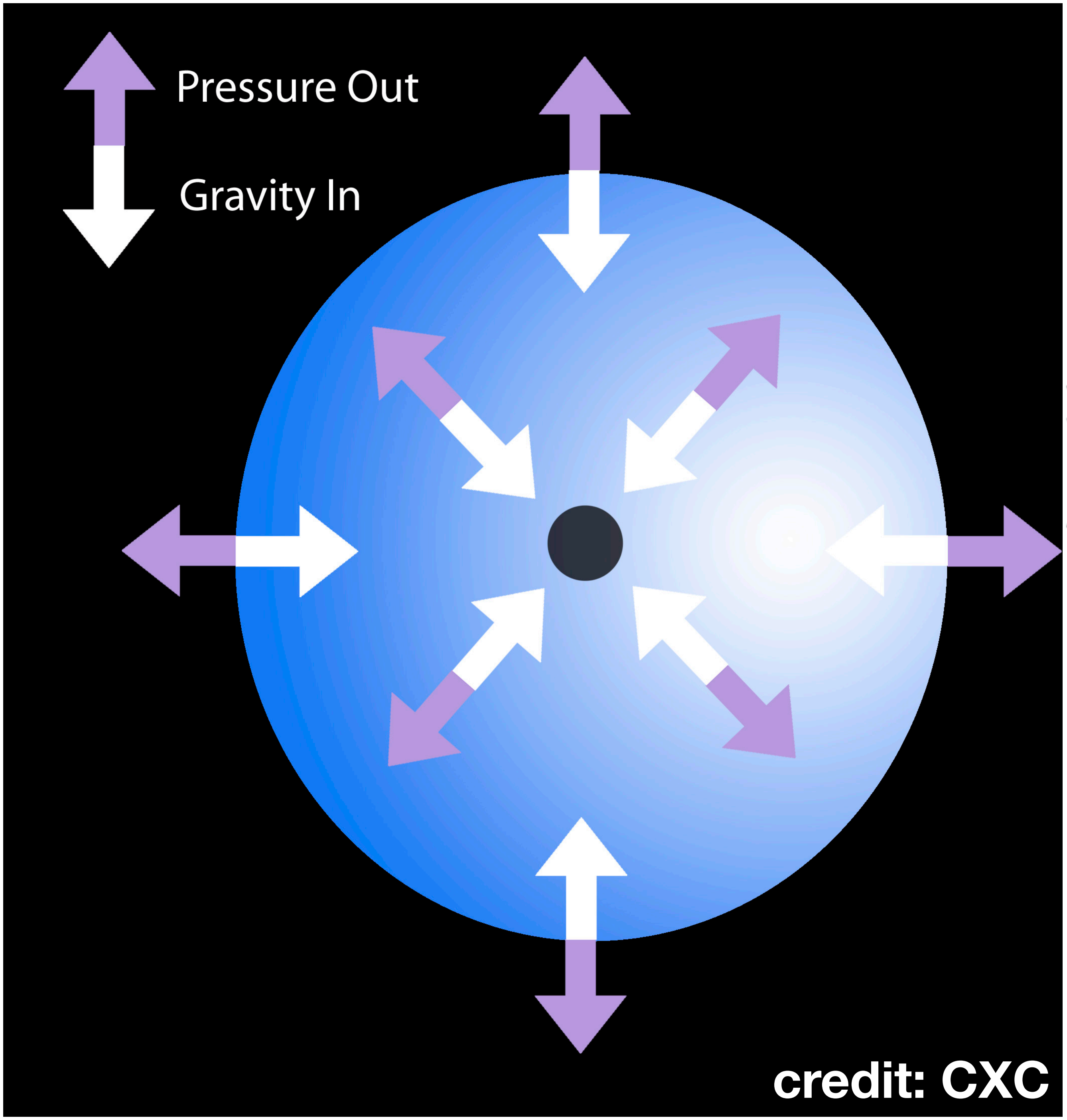
NGC 5907

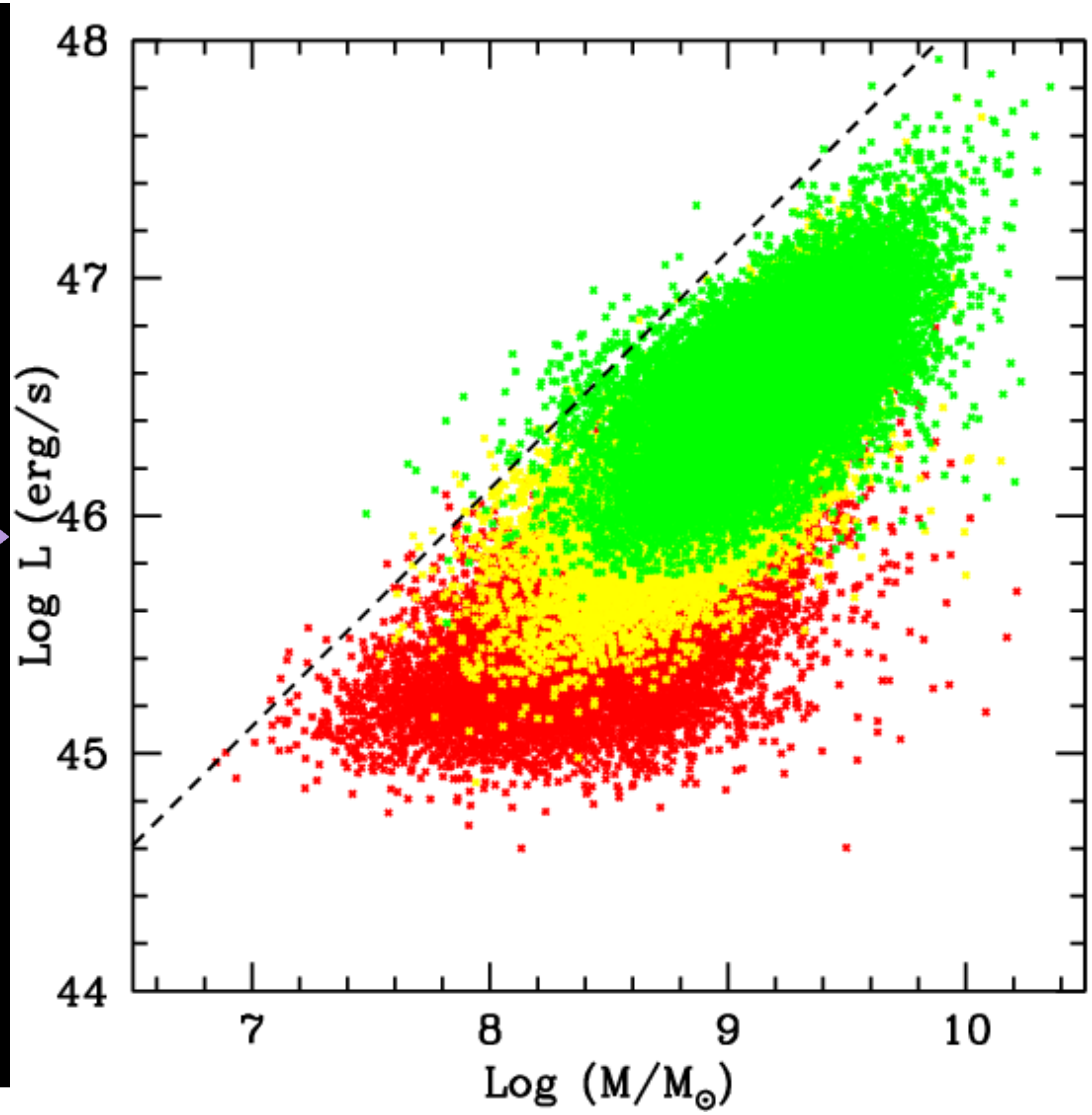




- spiral galaxy type=Sbc (Ann et al 2015 - SDSS)
- distance d=17.1+/-.1 Mpc (Tully et al 2013 - TRGB)
- inclination i=87.2+/-.2 deg (Xilouris et al 1999)

Eddington Limit

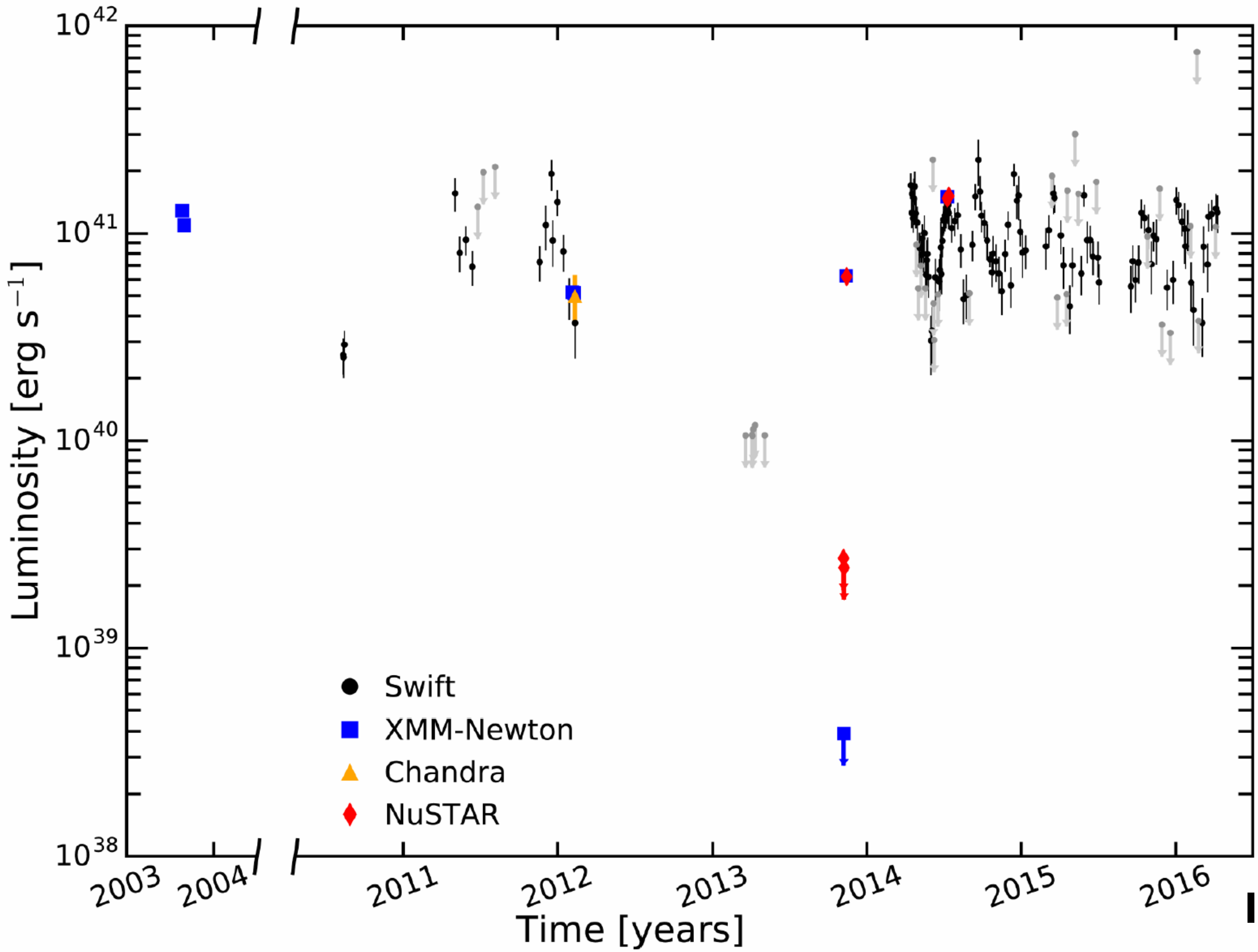




Steinhardt et al 2010

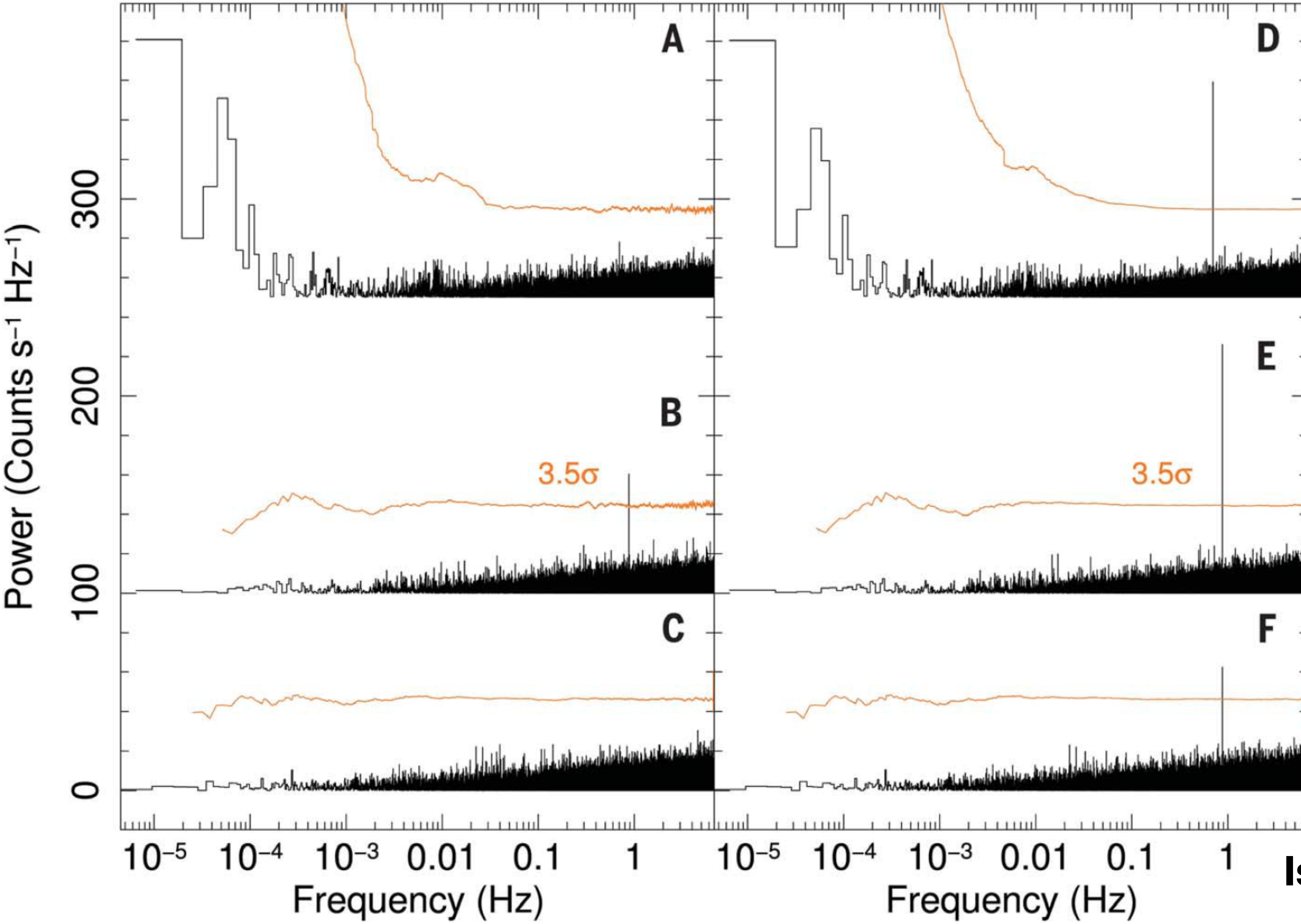
Ultra-Luminous X-ray Sources

- Eddington limit: L_{Edd}=1.3e38 erg/s x (M/M_{sun}) / (σ/σ_T)
- Conventionally ULXs have L_X >1e39 erg/s
- Located off-center their host galaxy (not AGNs)
- Catalogs (various biases) contain ~500 objects
- Using L_X as a mass indicator: candidates for IMBHs
- A handful show pulsations => neutron stars => $M<\sim 2M_{sun}$
- Super-Eddington: anisotropy in the accretion and/or in the emission, photon bubble instability, $\sigma<\sigma_T$ (high B)
- Hard to explain HLXs as extreme super-Eddington sources
- A few of them are associated to ULX nebulae (bubbles)



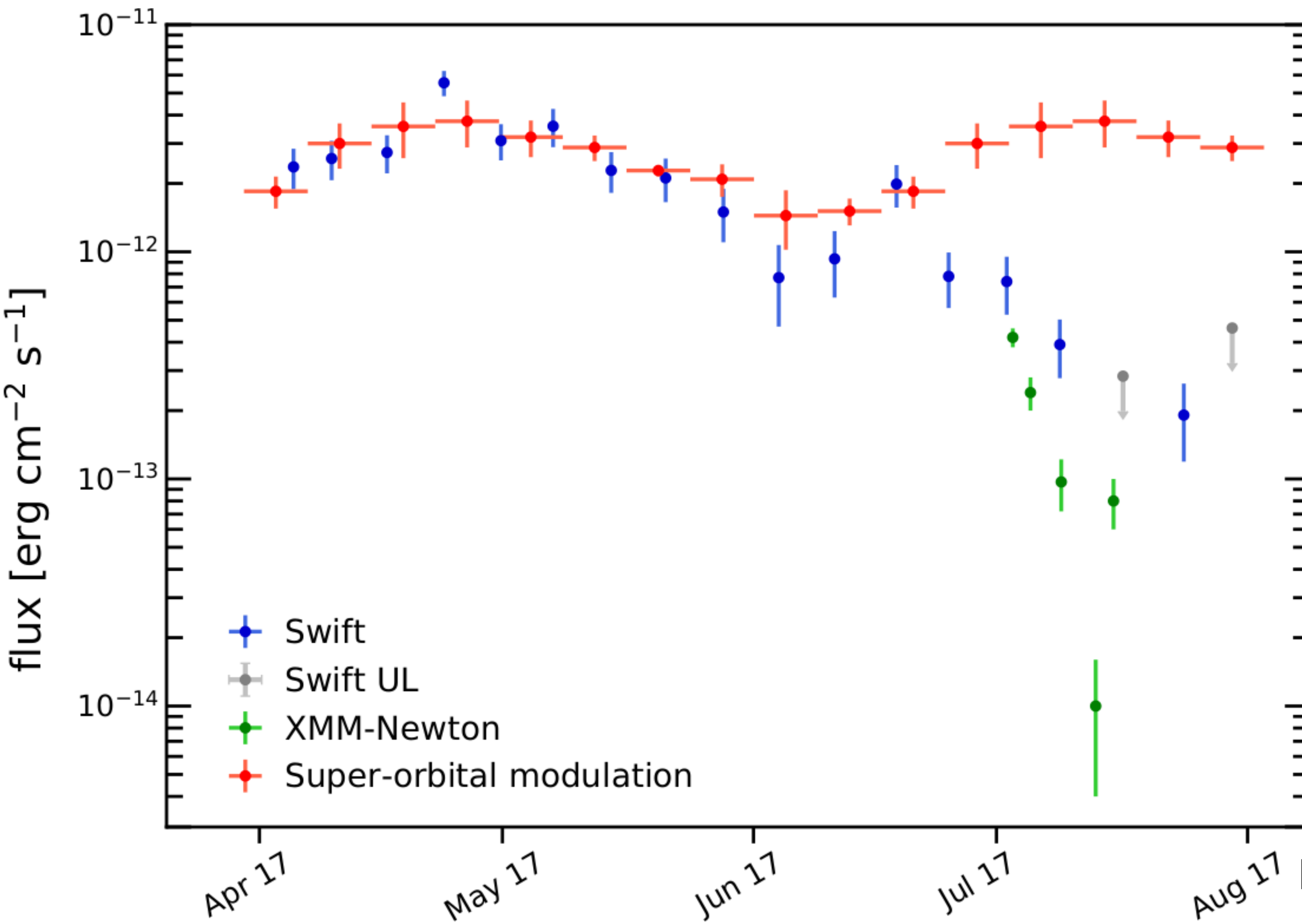
Israel et al 2017

- NGC 5907 ULX (ULX1) peaks at $L_X > 10^{41}$ erg/s
- Quasi periodic modulation 78.1+/-.5d (Walton et al 2016)
- Off state with abrupt switch-on <4d (Walton et al 2015)



Israel et al 2017

- EXTraS: discovery of pulsation => accreting neutron star
- mass < 2.8 M_{sun} => $L_{Edd}<3.4\times10^{38}$erg/s => $L_X>\sim500\ L_{Edd}$
- P(2003)=1.43s   P(2014)=1.13s   => $t_{spinup}<40$ yr



Belfiore et al in prep

- Swift monitoring resumed in Apr 2017
- XMM/NuSTAR LP to refine the orbit observed a switch-off
- Chandra TOO to probe the lowest state in Nov 2017

outline

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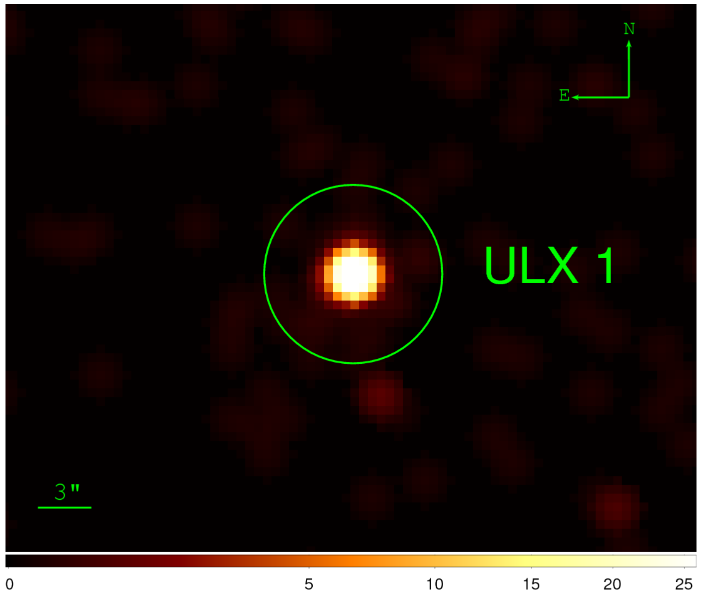
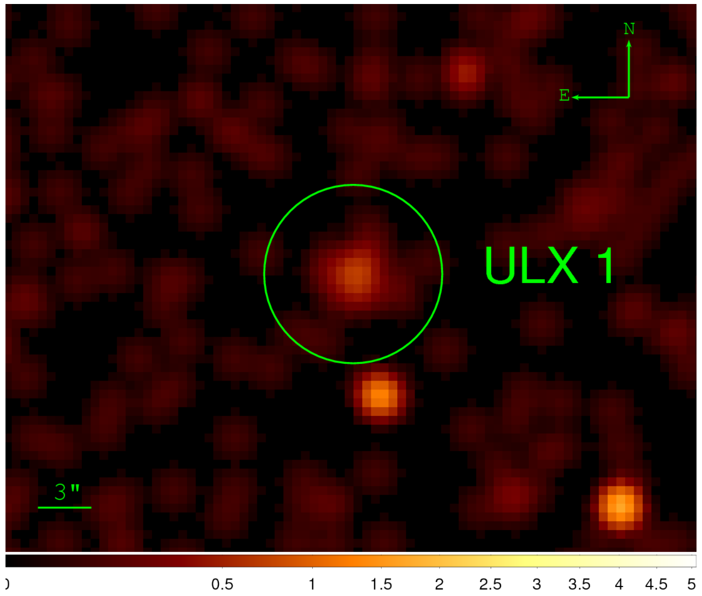
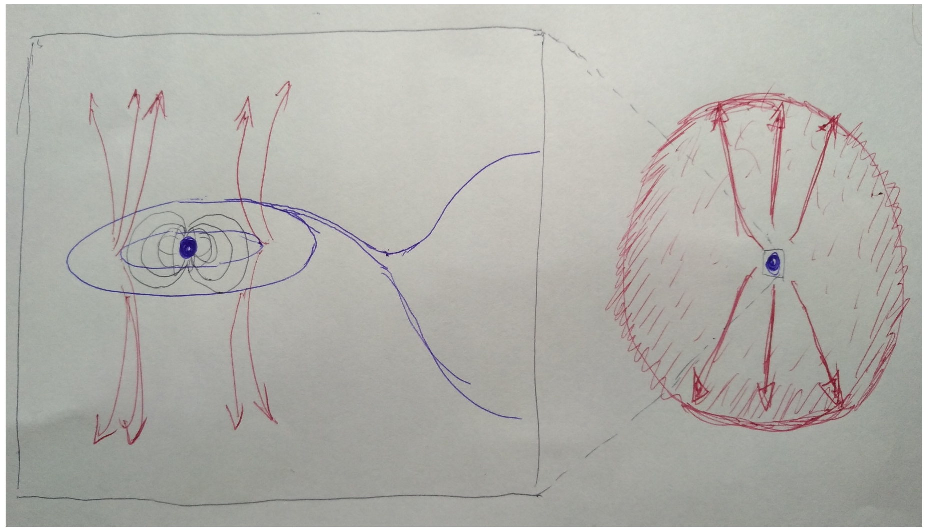
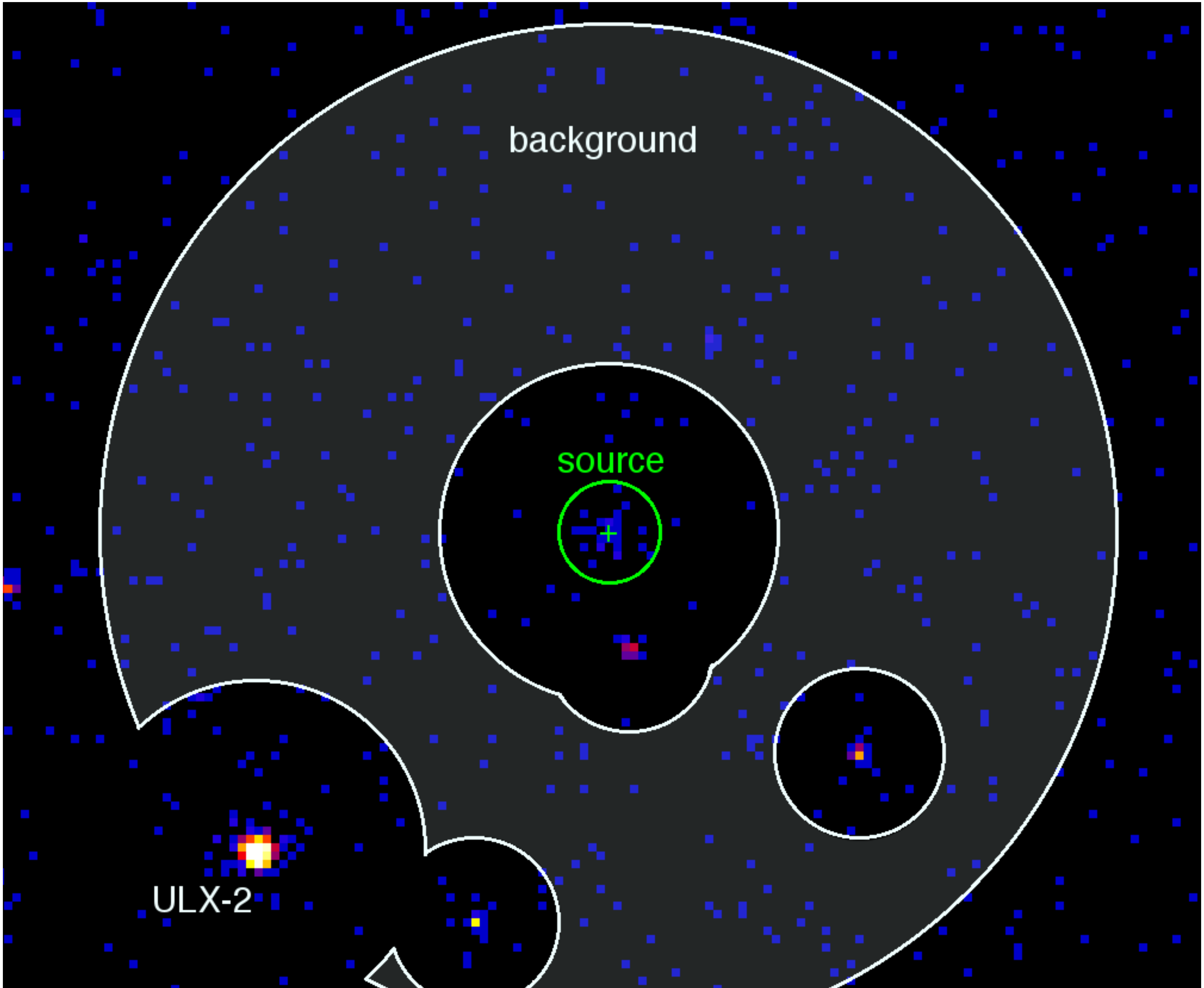
- An X-ray bubble

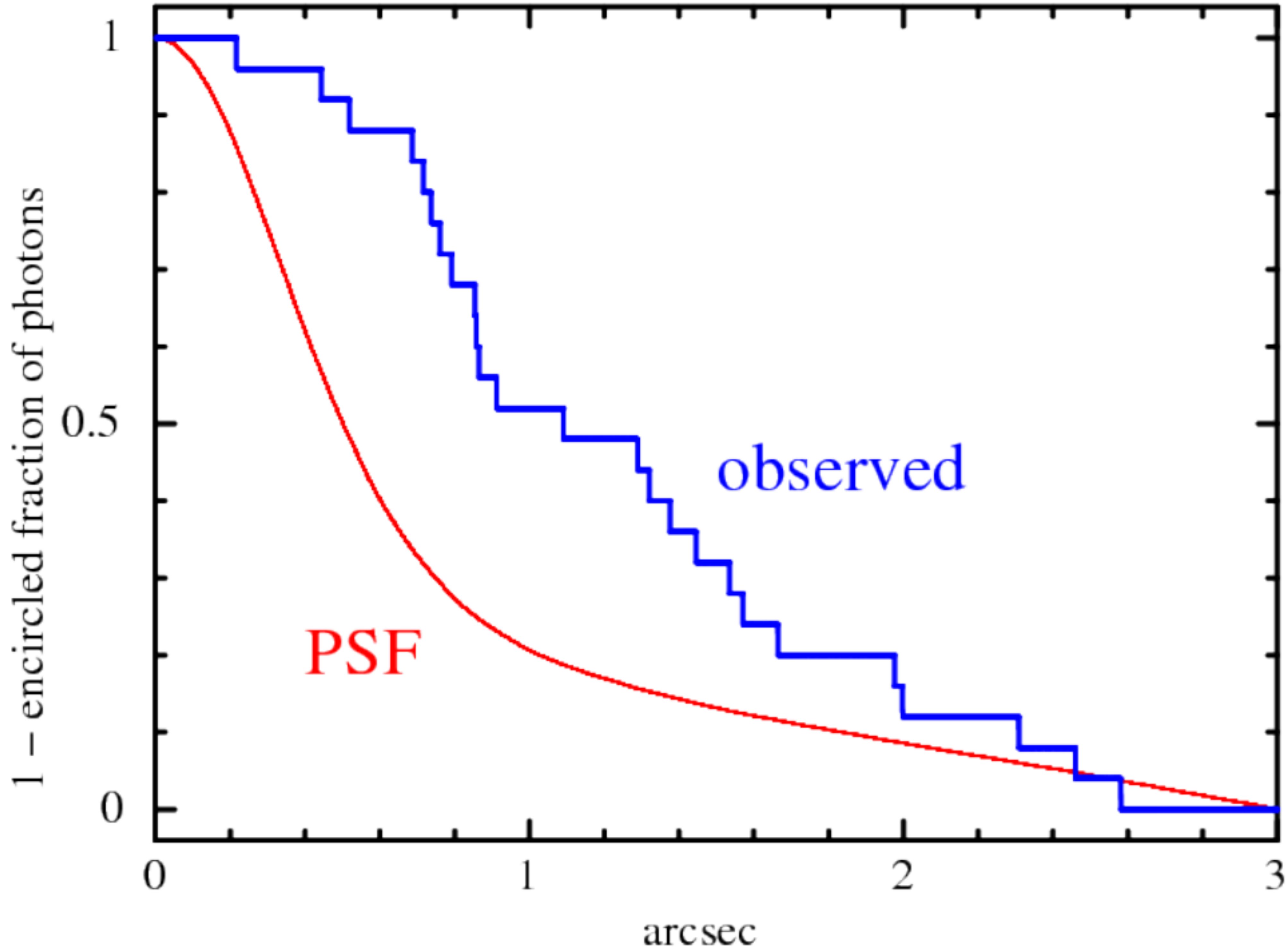




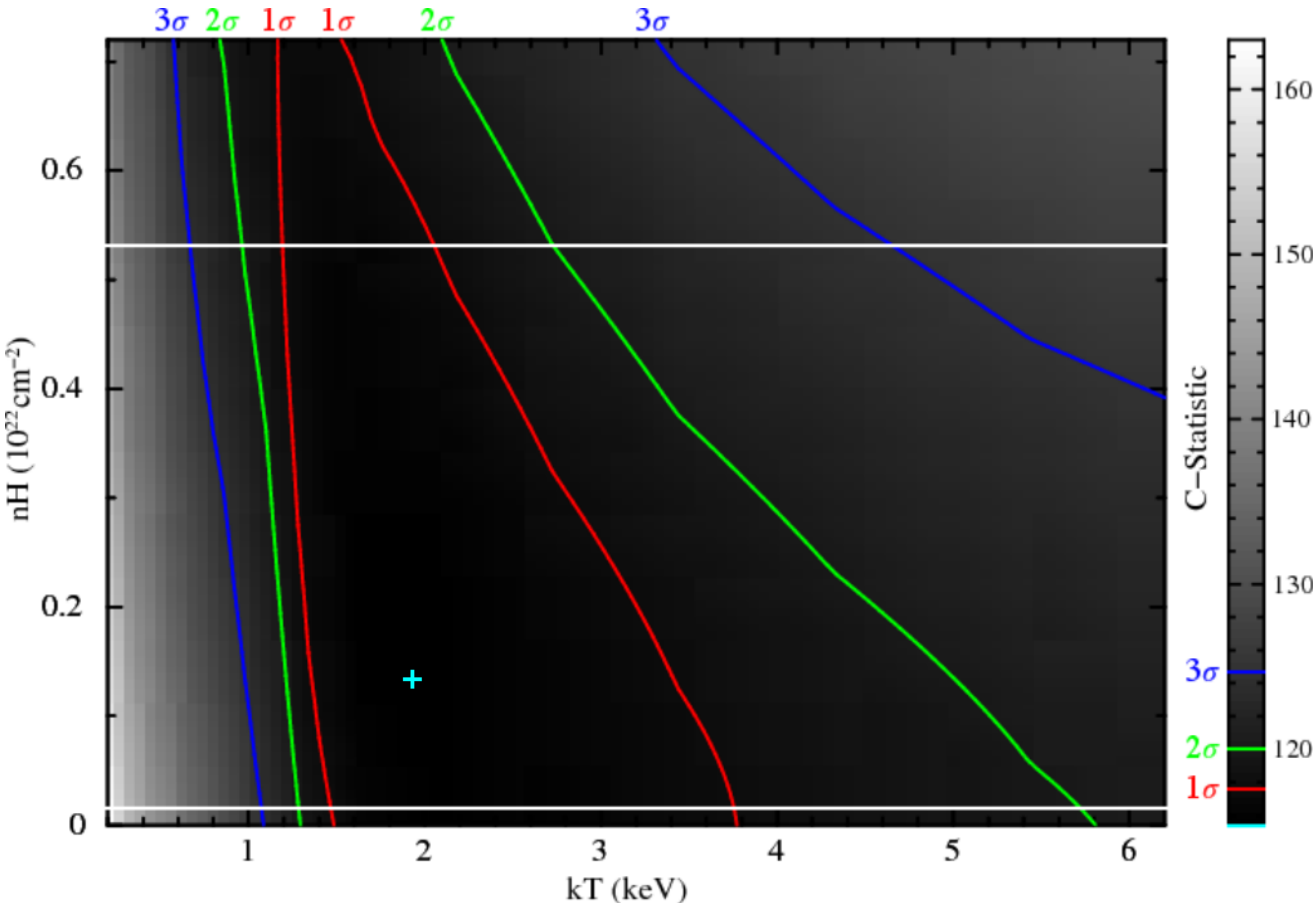


Nov 7 2017: 50ks ACIS observation (Pintore et al. 2018)





- Strong source detection (7.3σ)
- Perfectly aligned with NGC 5907 ULX1 (<.1 arcsec)
- Evidence for extension (5.0σ) (verified with Montecarlo)



- absorbed APEC model in XSPEC weakly constrained
- no photons below 0.8 keV + external constraints on nH
- X-ray luminosity: 1.2×10^{38} erg/s $< L_X < 4.2 \times 10^{38}$ erg/s

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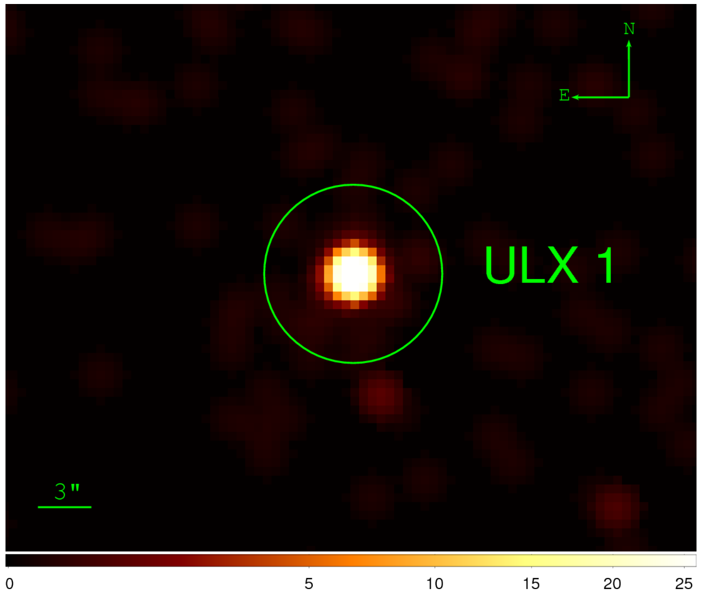
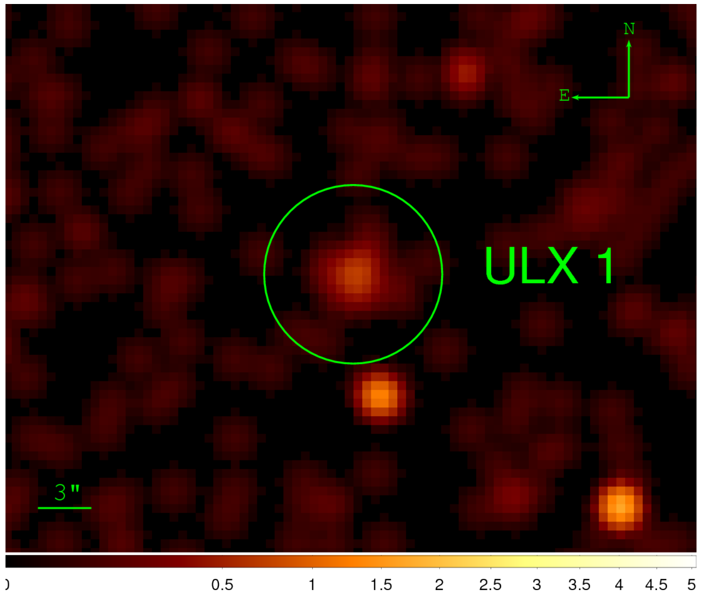
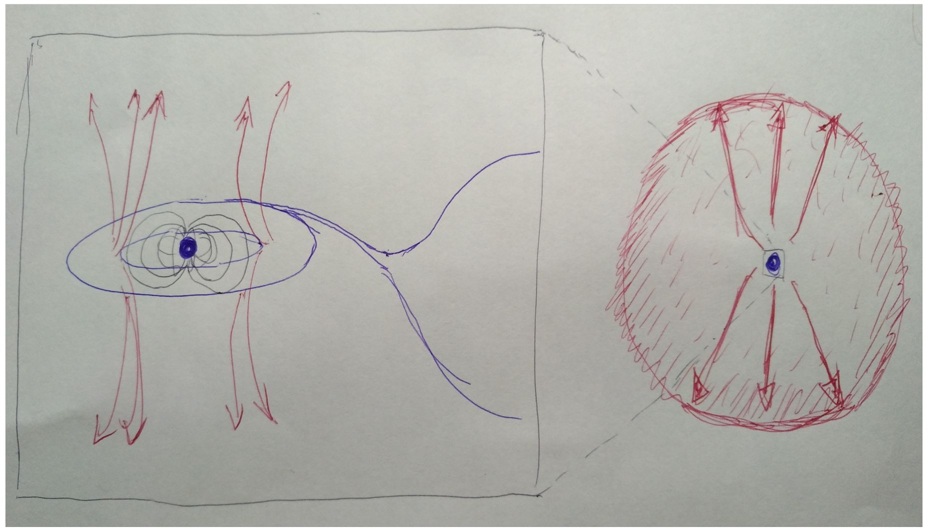
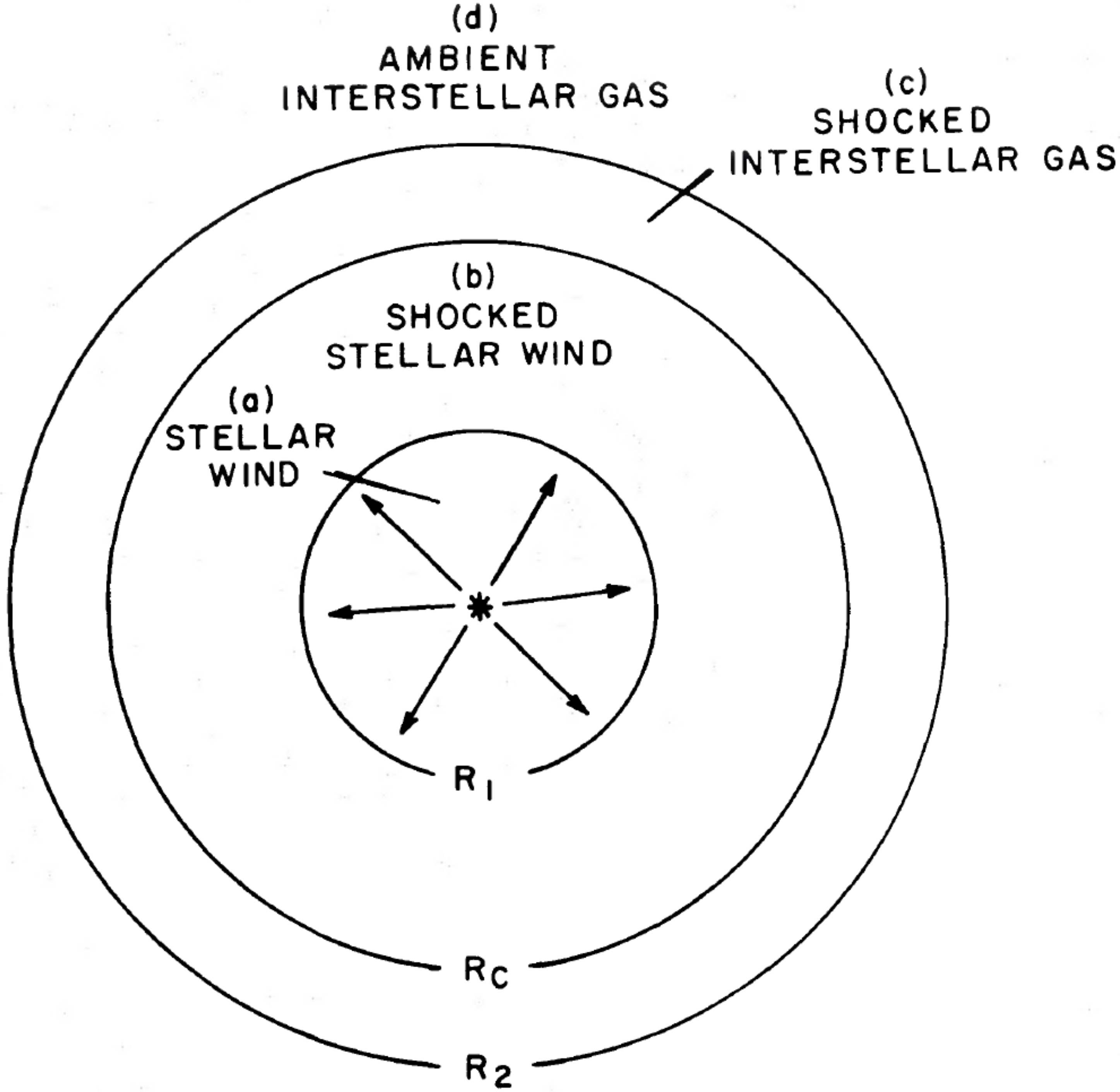


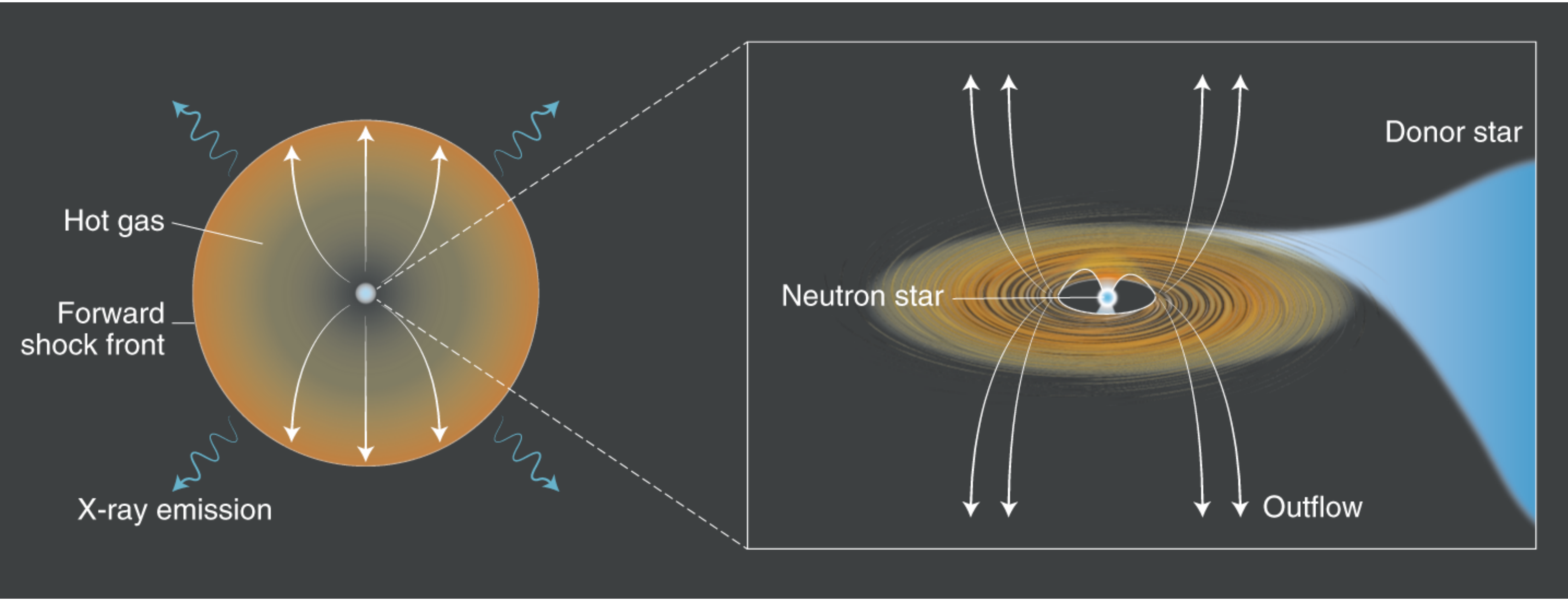






Weaver et al 1977

- standard expansion phases: free - adiabatic - radiative
- mild MWL constraints (radio Halpha) => adiabatic phase
- internal shell has low X-ray efficiency (Siwek et al 2017)



Soria 2019

- The energy does not burst-in but is continuously injected
- The bubble is driven by the wind from the accreting binary
- X-rays come mainly from the outermost shell of the nebula

- @17.1 Mpc the radius of the bubble is 112+/-42 pc

$$v_{\rm sh}^{(0)} = \sqrt{\frac{16}{3}\frac{kT}{m_{\rm p}}} = \left(3.3^{+1.6}_{-0.8}\right) \times 10^{-3} c = \left(9.9^{+4.8}_{-2.4}\right) \times 10^{2}\,{\rm km\,s^{-1}}$$

- bubble theory predicts in this phase a radial evolution:

$$R_2(t) = \alpha \left(\frac{L_{\rm w} t^3}{n_{\rm ISM} m_{\rm p}}\right)^{1/5}$$

- therefore we can estimate the age of the bubble as:

$$\tau = \frac{3}{5}\frac{R_2}{v_{\rm sh}} = \left(6.7^{+3.1}_{-2.8}\right) \times 10^{4}\,{\rm yr} \times \xi^{-1}$$

- the wind power ($n_{\rm ISM}$ comes from the luminosity):

$$L_{\rm w} = \frac{m_{\rm p} n_{\rm ISM} R_2^5}{\alpha^5 \tau^3} = \left(1.3^{+9.8}_{-1.0}\right) \times 10^{41}\,{\rm erg\ s^{-1}} \times \xi^3 \times \left(\frac{W}{4}\right)^{-\frac{1}{2}}$$

- the energy stored in the bubble:

$$E = L_{\rm w}\tau = \left(2.8^{+18}_{-2.2}\right) \times 10^{53}\,{\rm erg} \times \xi^2 \times \left(\frac{W}{4}\right)^{-\frac{1}{2}}$$

- as the ultimate source of energy is accretion, for a NS:

$$M_{\rm accr} = \frac{E}{\eta c^2} \simeq \left(1.8^{+12}_{-1.5}\right) \times 10^{33}\,{\rm g} = 0.9^{+5.9}_{-0.7}\,M_\odot$$

- high: could induce a collapse into a BH, but still plausible

- as the energy is carried by the wind, if we limit its mass, its speed must be mildly relativistic (Pinto et al 2016)

- as $t_{spinup} << \tau$ a very efficient mechanism for dissipating the NS angular momentum must exist (propeller?)

- as the energy stored in a single bubble is huge, their feedback on the host galaxy could be non-negligible

summary

- NGC 5907 ULX1: extreme super-Eddington X-ray pulsar
- It shows a complex variability behaviour
- In a low state we detected an extended feature
- We can interpret it as a bubble powered by the ULX wind
- This implies extreme energetics and an age ~70kyr
- Still a lot to do to confirm this result, constrain the model, find similar cases in other ULXs, probe their population, understand their evolution and impact on host galaxies

- Israel et al. 2017, Science, 355, 817

An accreting pulsar with extreme properties drives an ultraluminous x-ray source in NGC 5907

Gian Luca Israel[1,*], Andrea Belfiore[2], Luigi Stella[1], Paolo Esposito[3,2], Piergiorgio Casella[1], Andrea De Luca[2,4], Martino Marelli[2], Alessandro Papitto[1], Matteo Perri[5,1], Simonetta Puccetti[5,1], Guillermo A. Rodríguez Castillo[1], David Salvetti[2], Andrea Tiengo[6,2,4], Luca Zampieri[7], Daniele D'Agostino[8], Jochen Greiner[9], Frank Haberl[9], Giovanni Novara[6,2], Ruben Salvaterra[2], Roberto Turolla[10], Mike Watson[11], Joern Wilms[12], Anna Wolter[13]

- Belfiore et al. 2019, Nature Astronomy

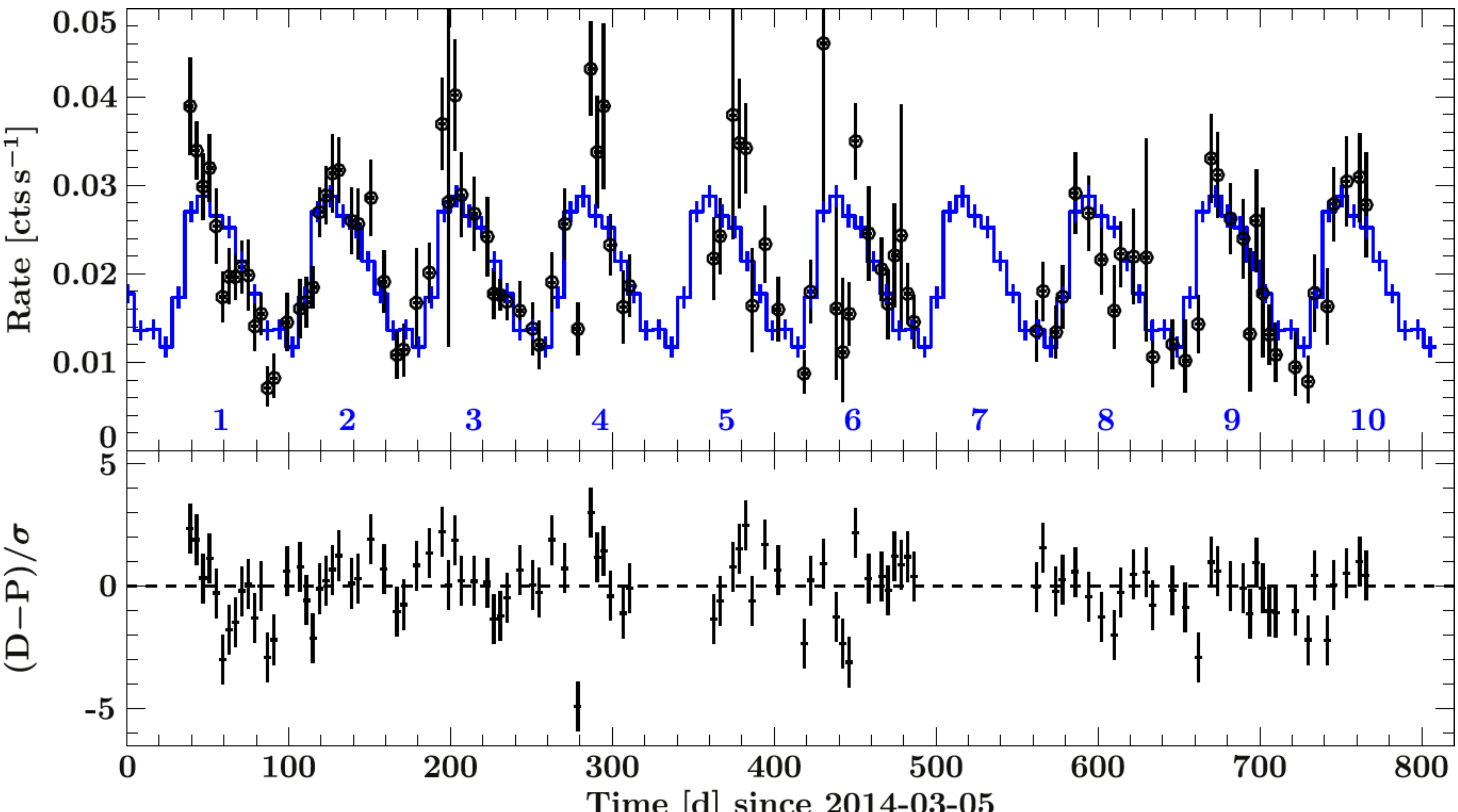
Letter | Published: 28 October 2019

Diffuse X-ray emission around an ultraluminous X-ray pulsar

Andrea Belfiore, Paolo Esposito, Fabio Pintore, Giovanni Novara, Ruben Salvaterra, Andrea De Luca, Andrea Tiengo, Patrizia Caraveo, Felix Fürst, Gian Luca Israel, Danilo Magistrali, Martino Marelli, Sandro Mereghetti, Alessandro Papitto, Guillermo A. Rodríguez Castillo, Chiara Salvaggio, Luigi Stella, Dominic J. Walton, Anna Wolter & Luca Zampieri

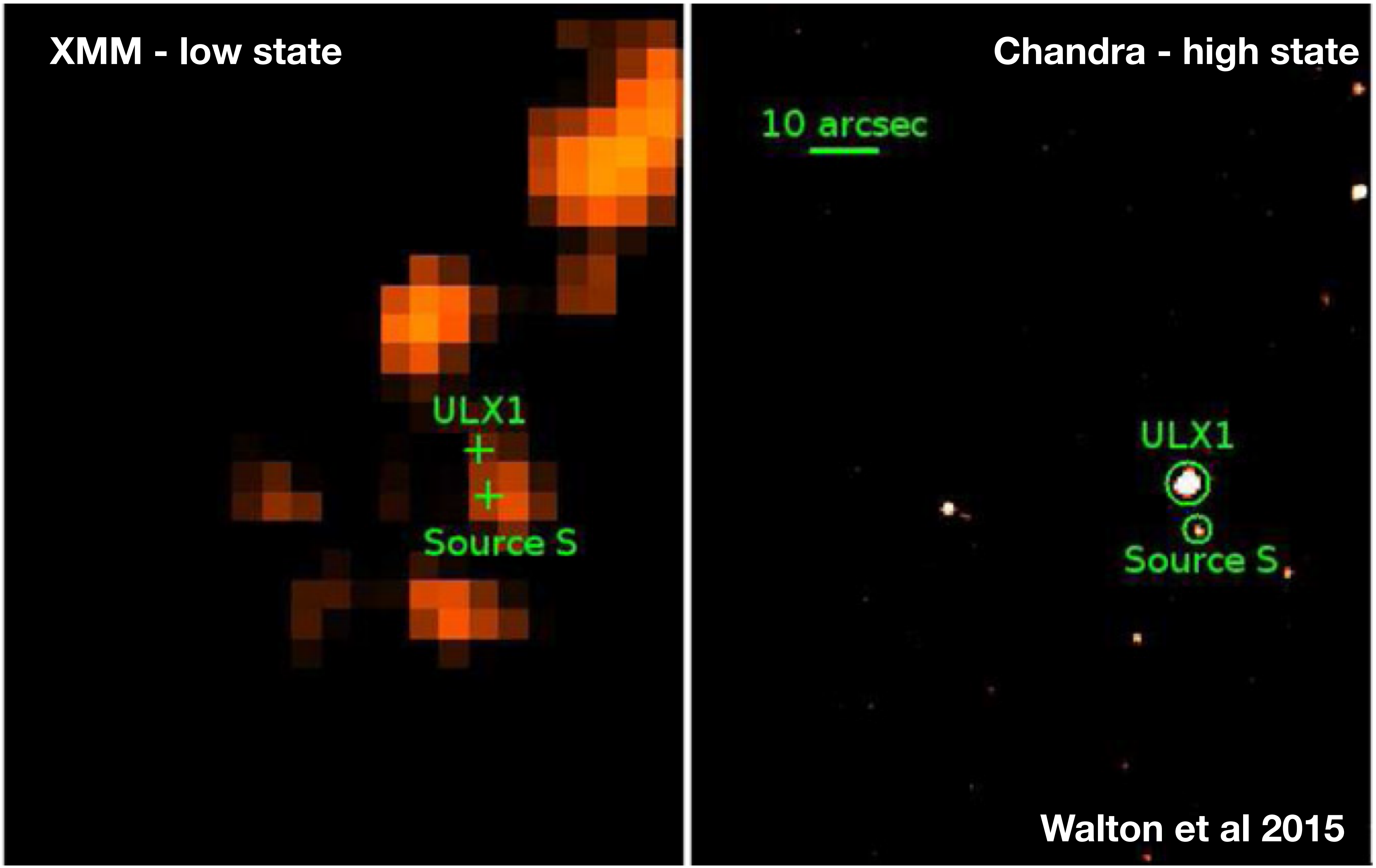
back up slides

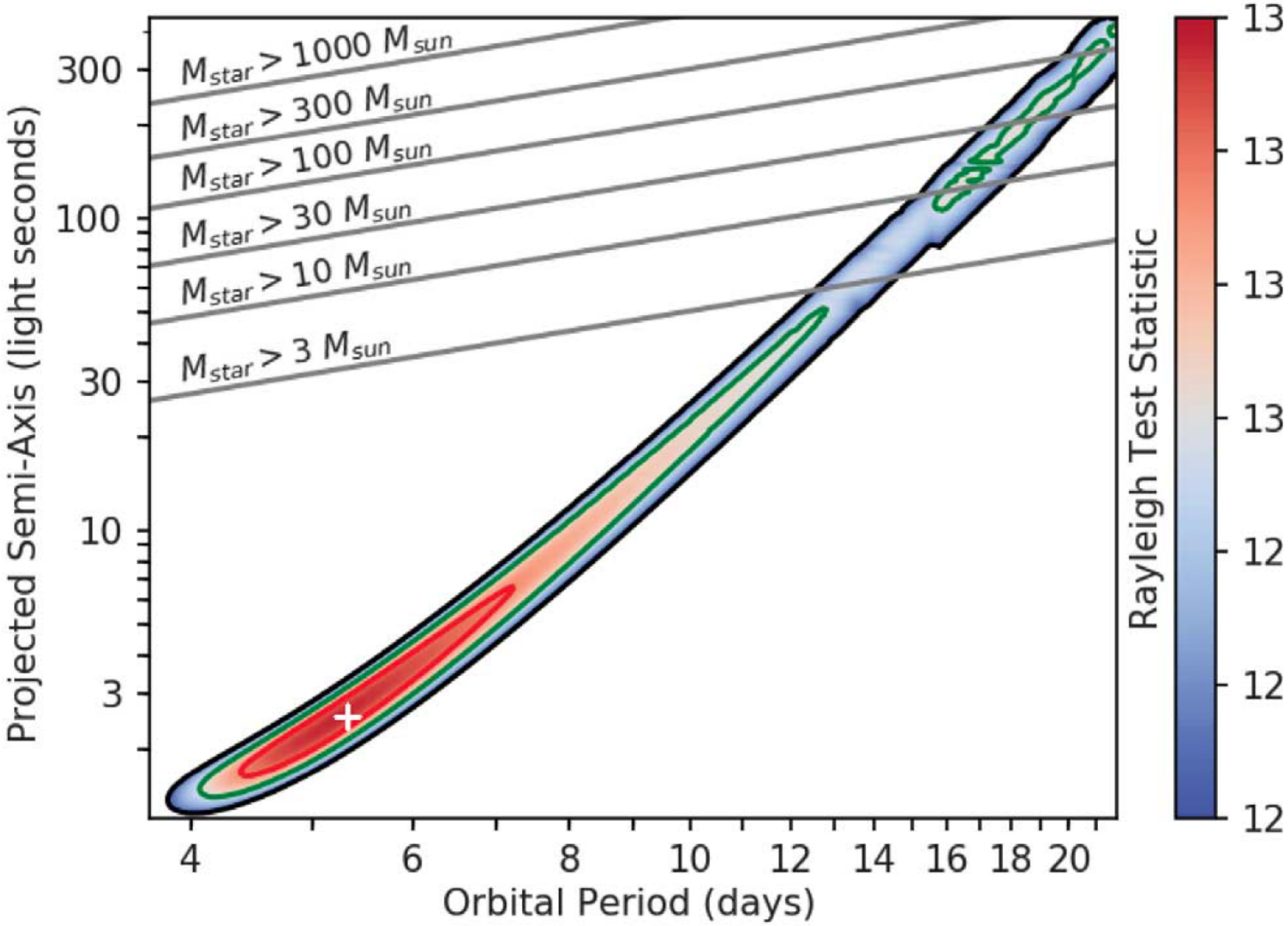
NGC 5907 ULX1



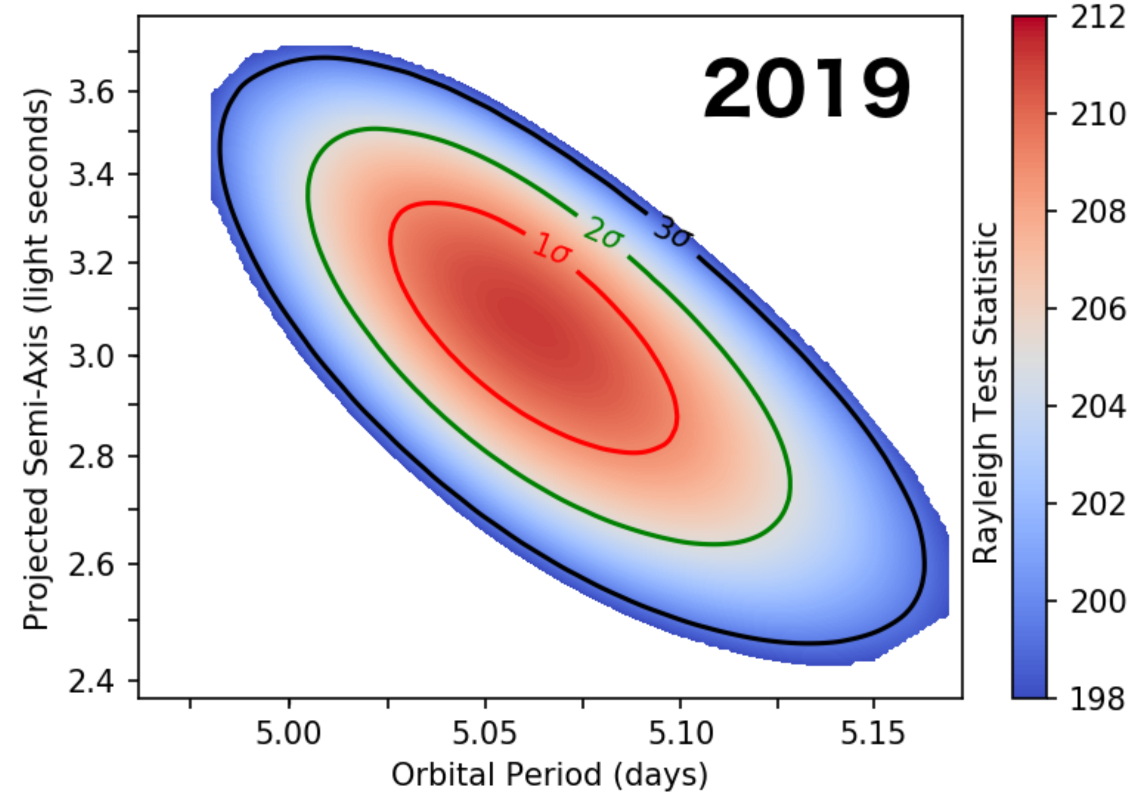
Walton et al 2016

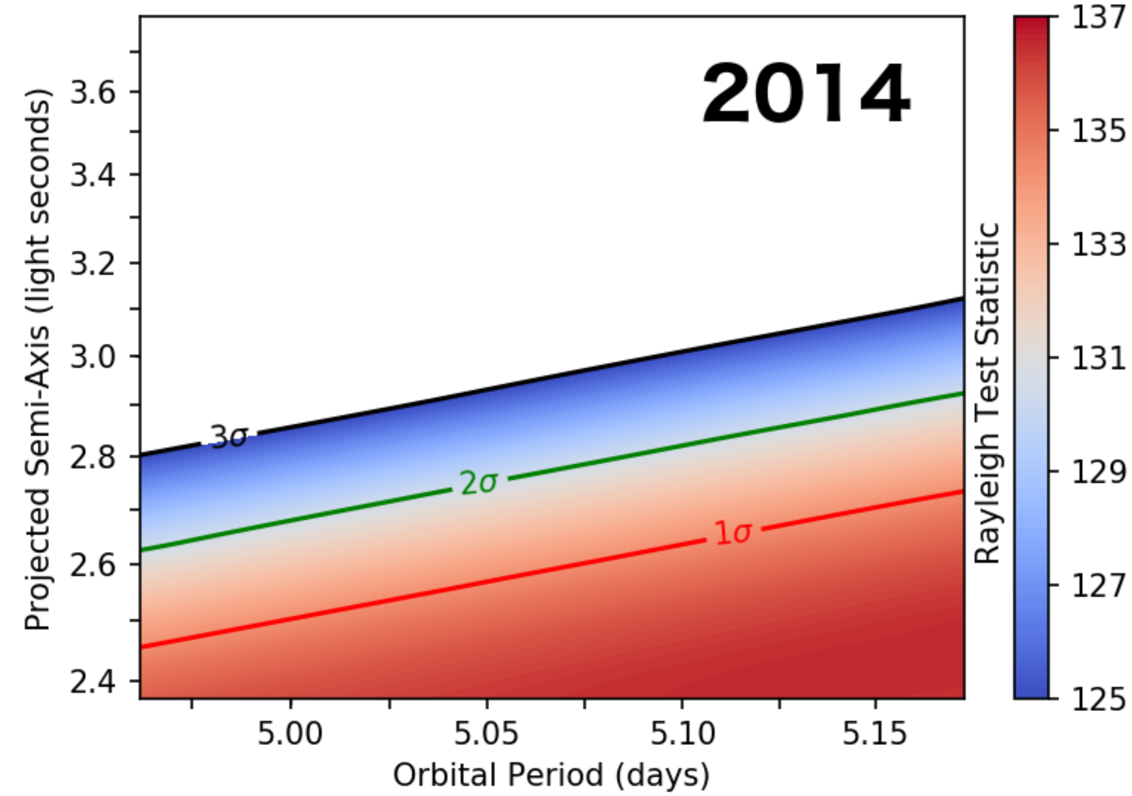
NGC 5907 ULX1



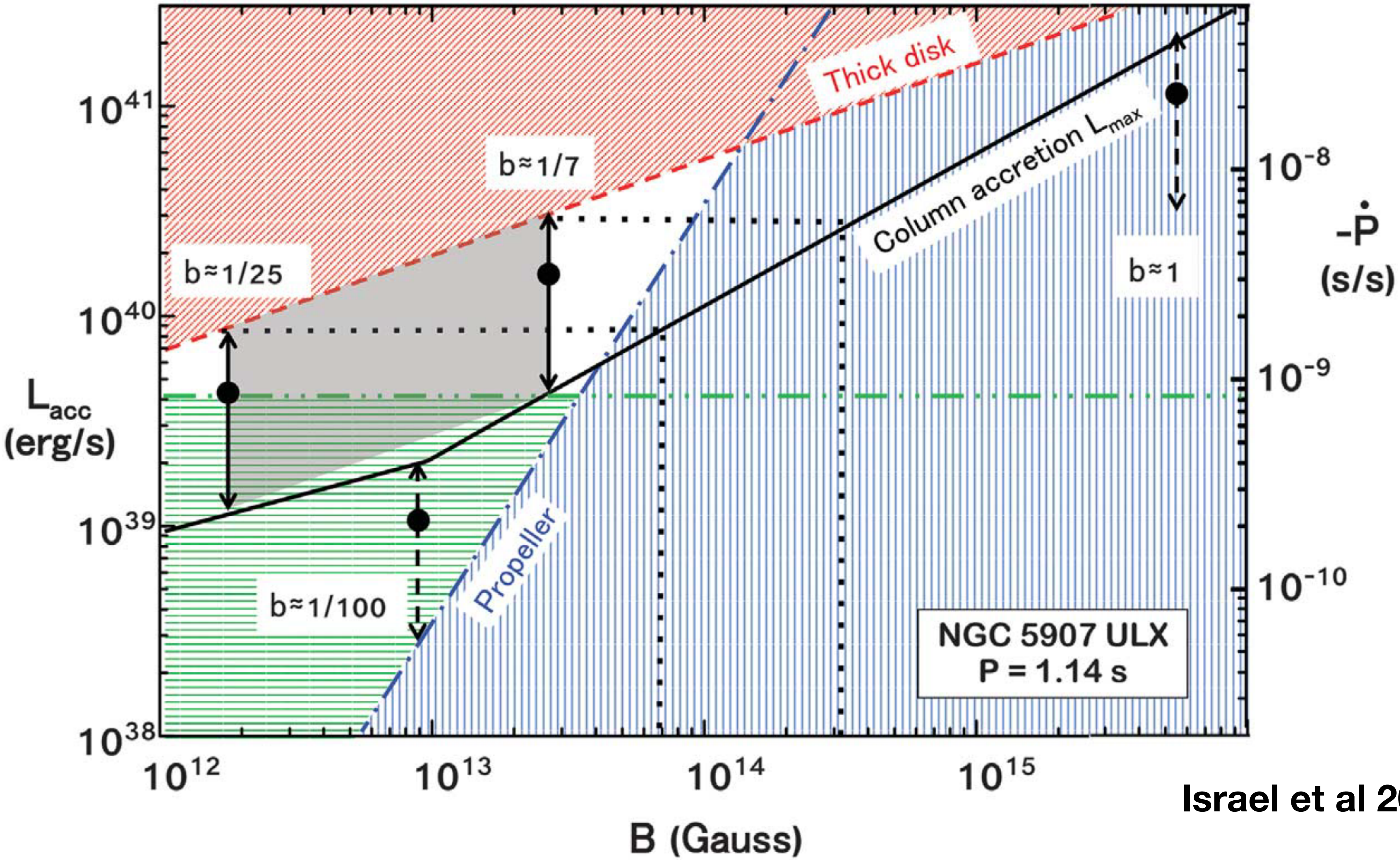


Israel et al 2017





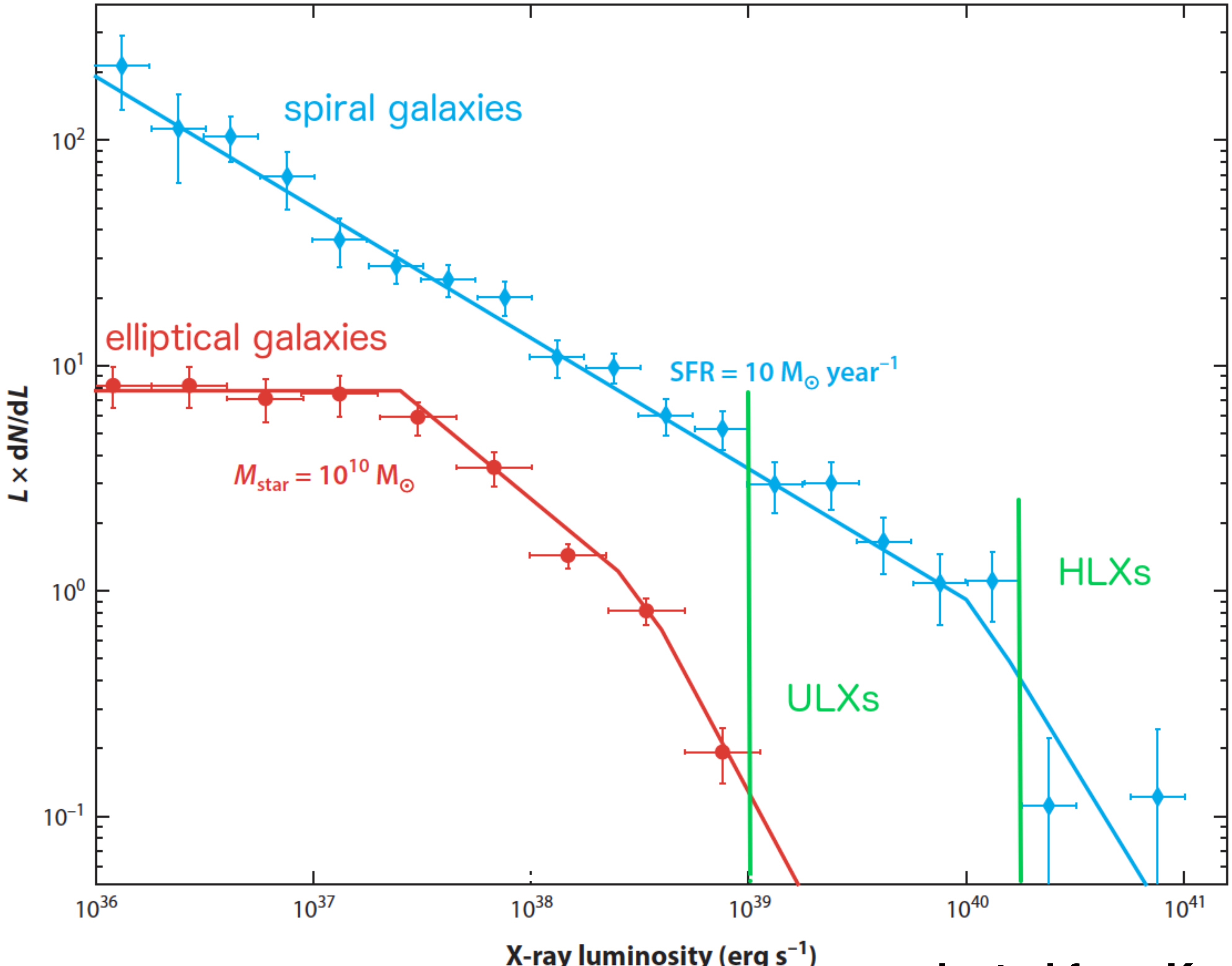
- weak constraints on the orbital parameters from timing
- we run a campaign Swift+XMM+NuSTAR to get the orbit
- recent (2019) XMM observations confirm the 1σ estimate



Israel et al 2017

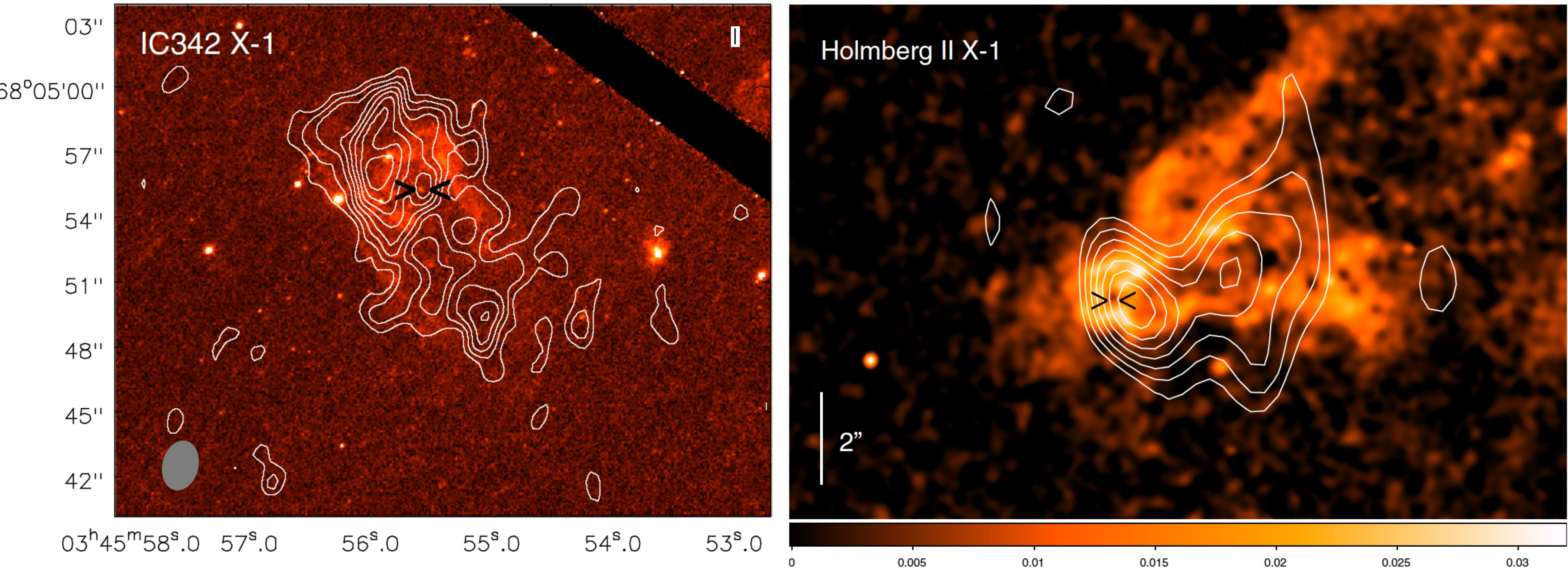
- exclusion plot (propeller, spherization, Ldot-Edot relation)
- points towards mild beaming => $bxL_X >> L_{Edd}$
- evidence for magnetar-like multipolar magnetic field

XRB luminosity function



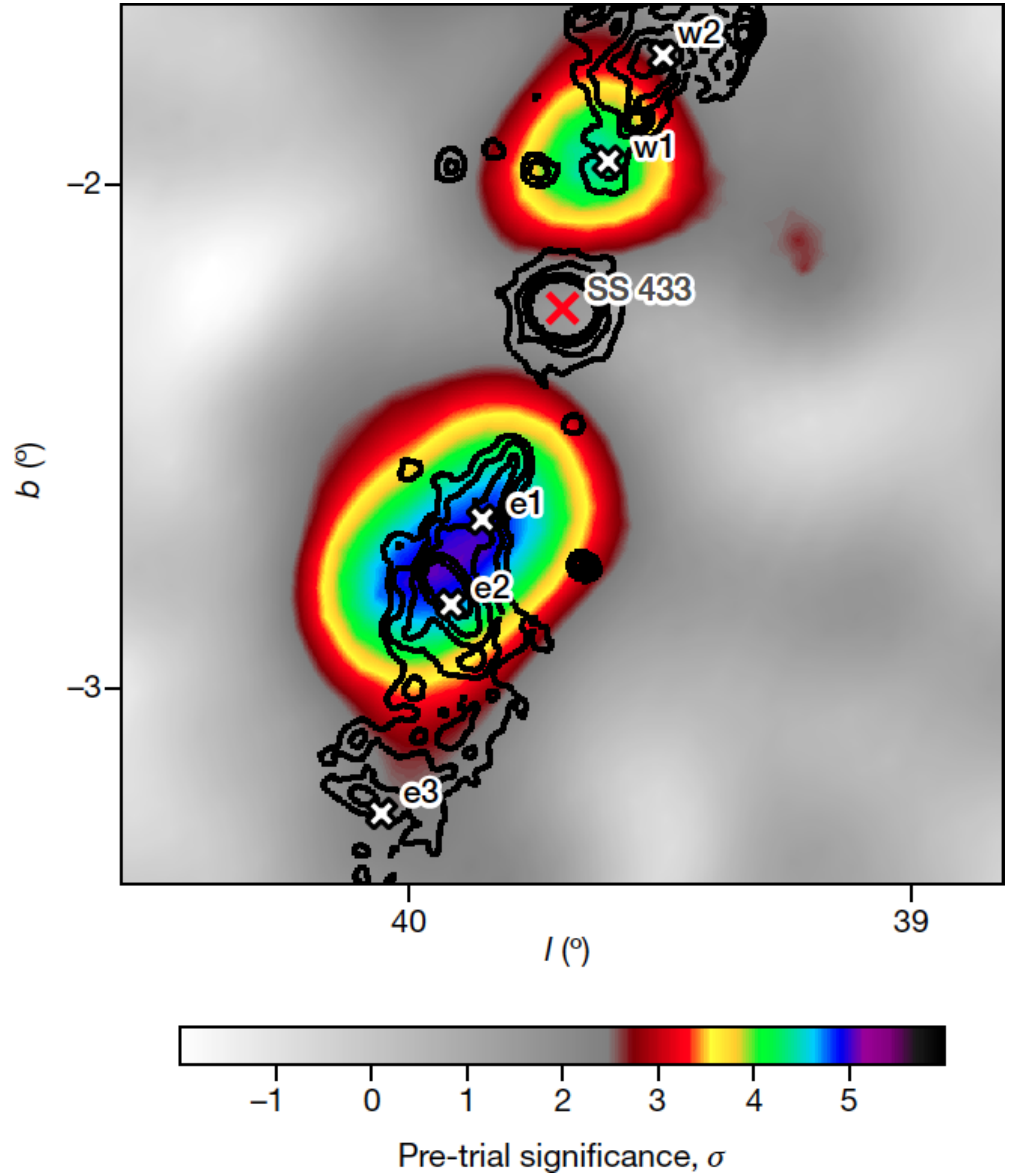
adapted from Kaaret et al 2017

typical ULX bubbles



Cseh et al 2012

- Contours VLA @ 5GHz (integrated to ~600uJy @~3-4Mpc)
- Colors HST Halpha (left) and Hbeta (right)
- They show strong HeII λ4686 emission line (photoionization)
- Physical size ~100-500 pc; age ~1 Myr; power up to 1e41 erg/s



Abeysekara et al 2018

- The microquasar SS433 is a Galactic source very similar to ULXs, has a nebula and jets but no ULX at the center
- HAWC has detected photons >25TeV => electrons >100TeV

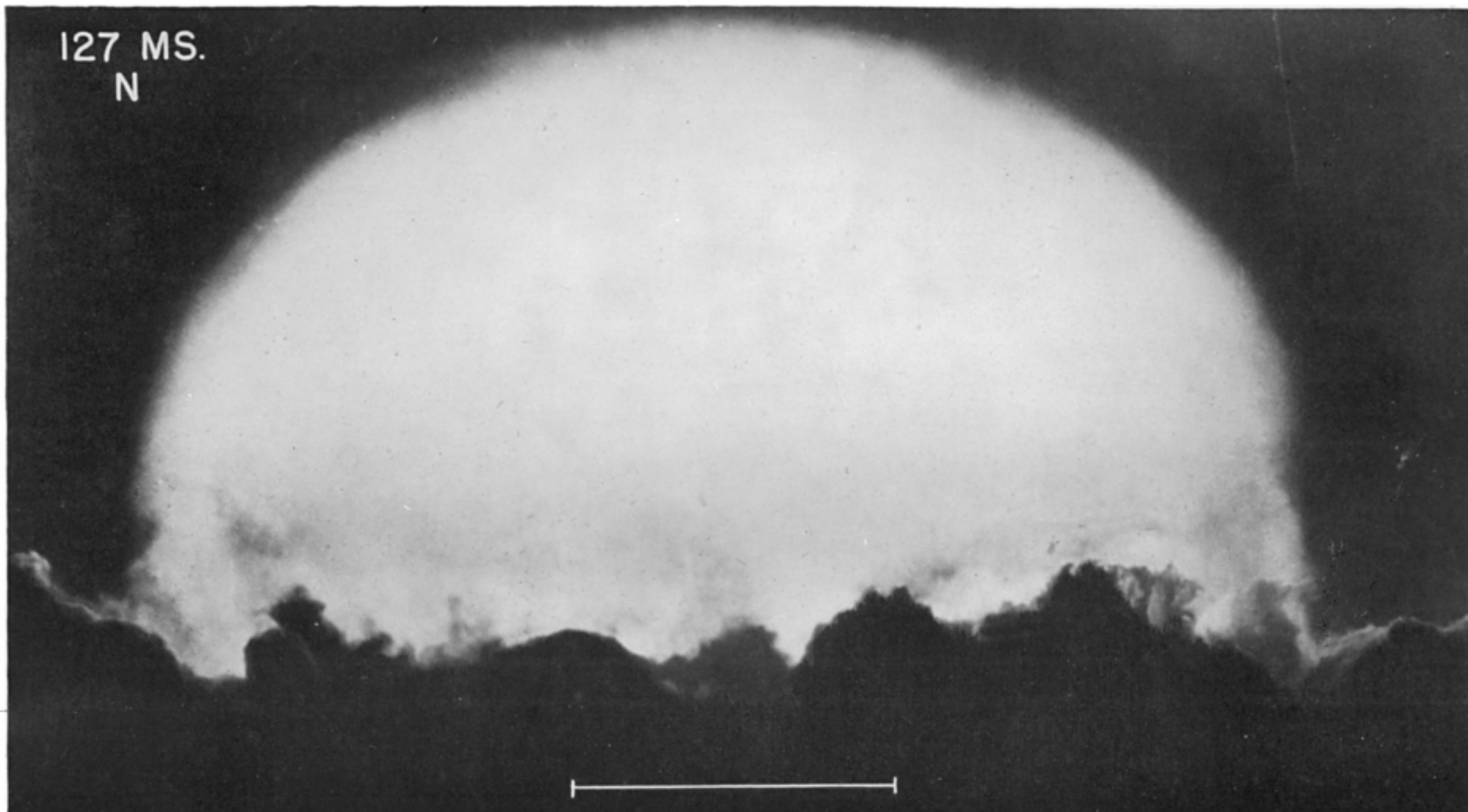
The formation of a blast wave by a very intense explosion. II. The atomic explosion of 1945

By Sir Geoffrey Taylor, F.R.S.

(*Received* 10 *November* 1949)

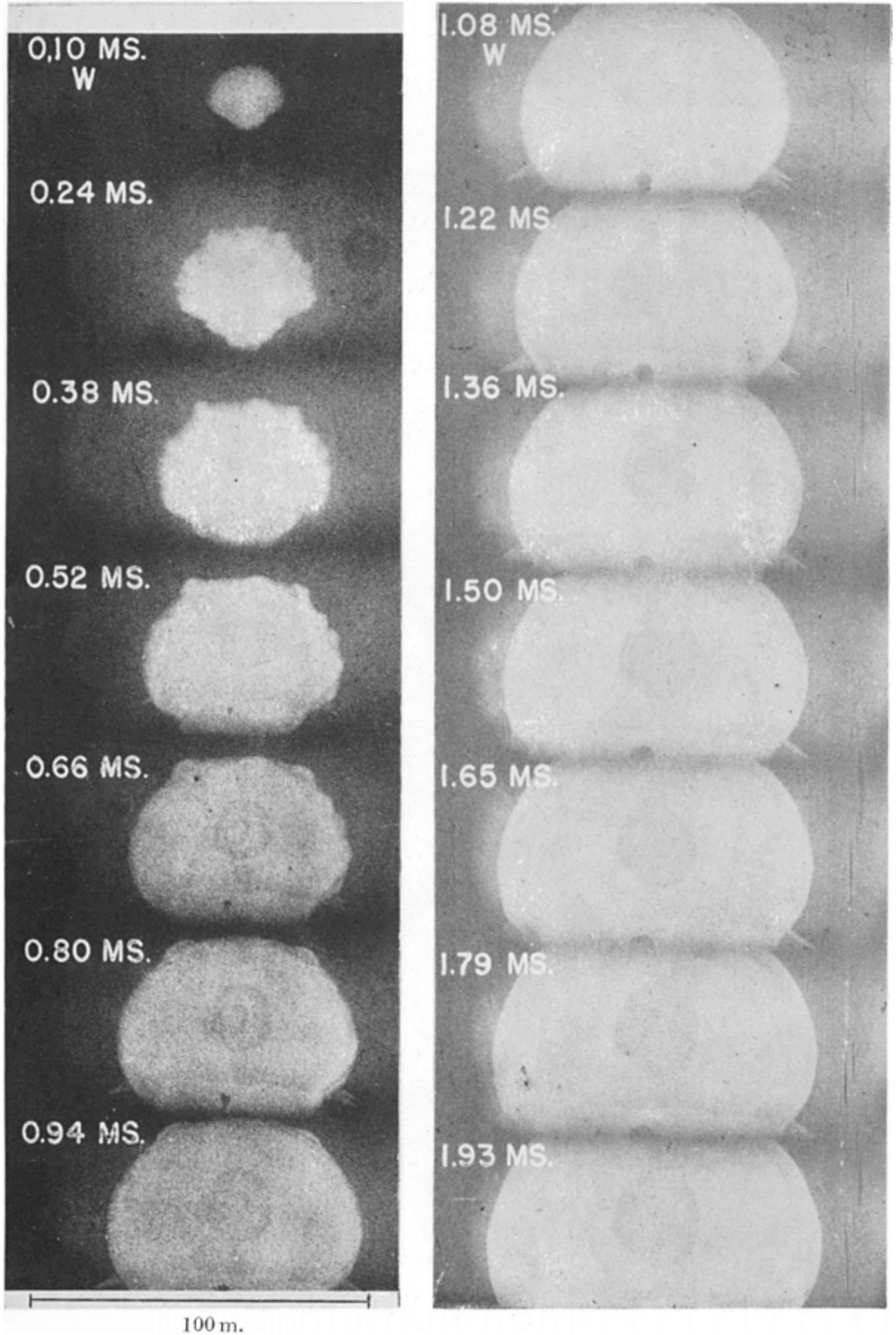
[Plates 7 to 9]

Photographs by J. E. Mack of the first atomic explosion in New Mexico were measured, and the radius, R, of the luminous globe or 'ball of fire' which spread out from the centre was determined for a large range of values of t, the time measured from the start of the explosion. The



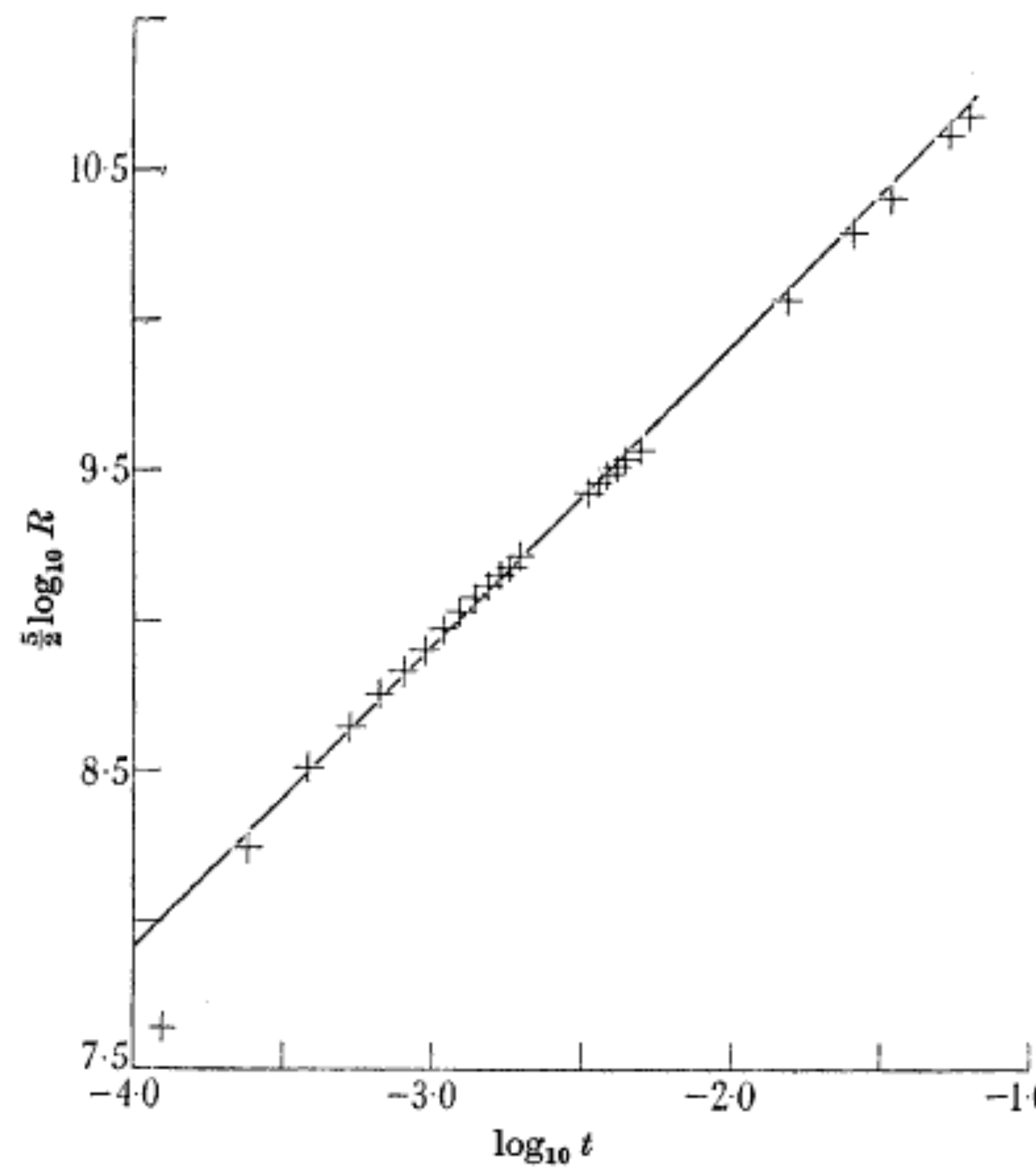
ground — — ground

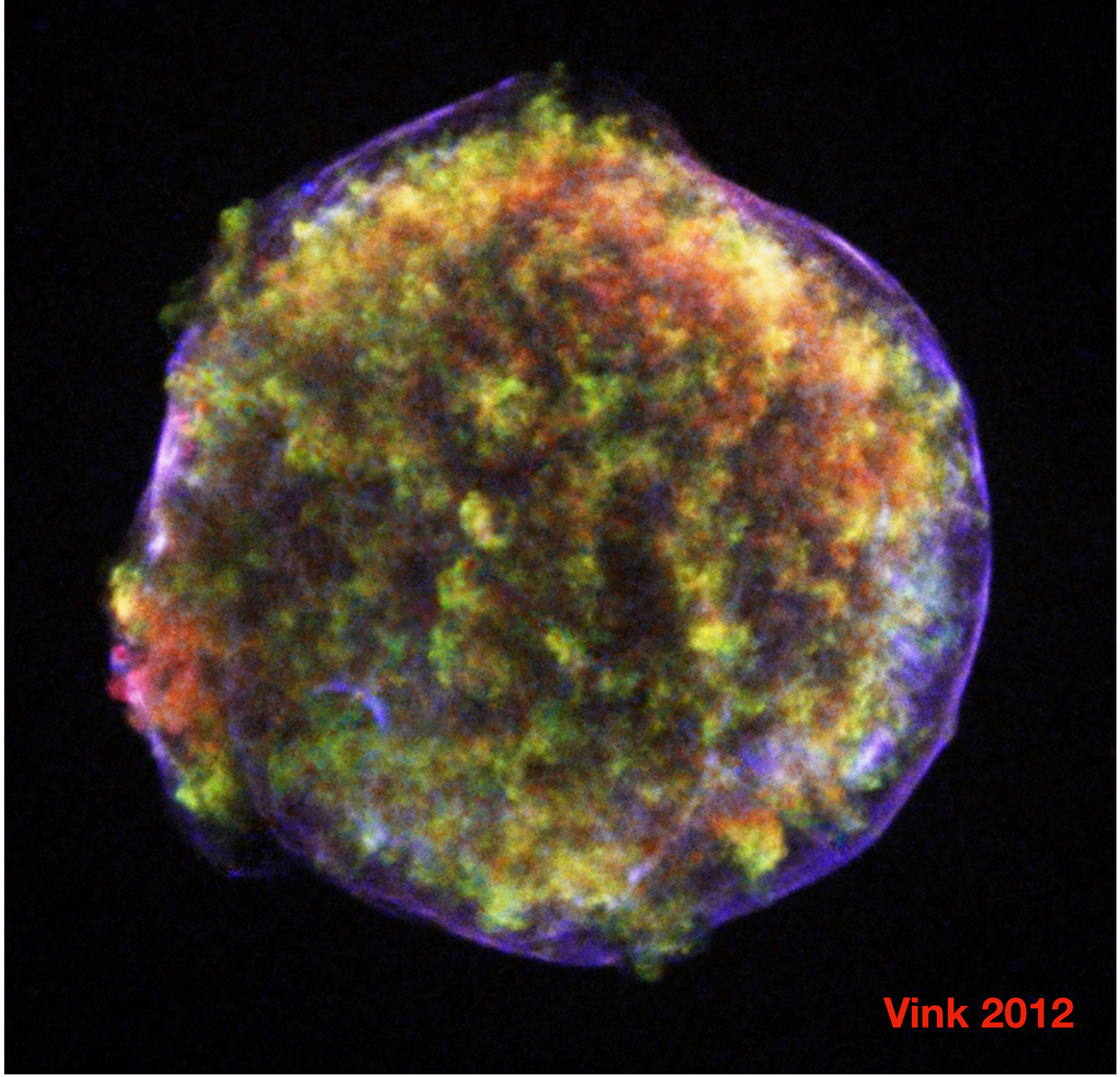
100 m.



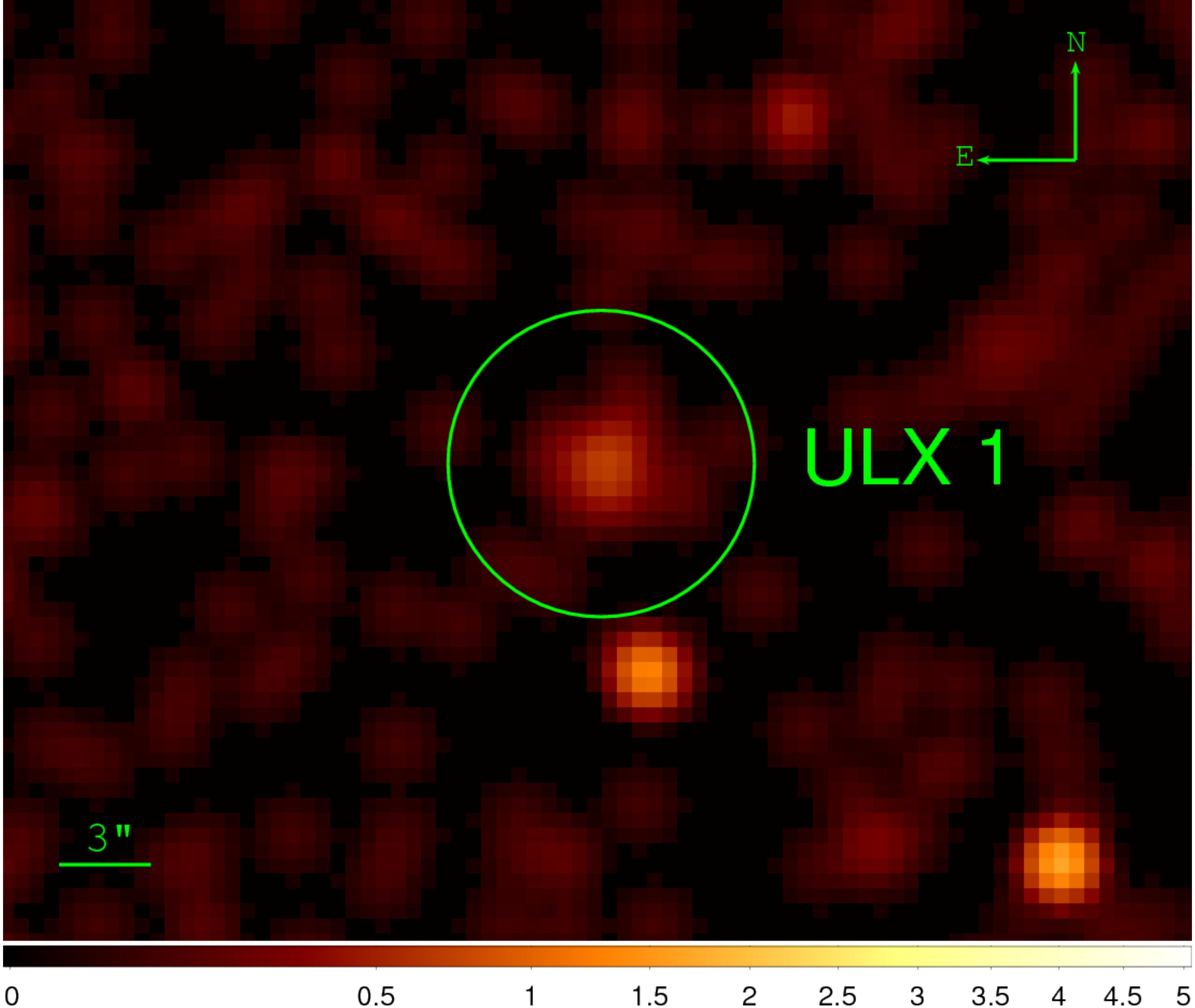
$$r_s \propto E^{\alpha} n^{\beta} t^{\eta}$$

r	E	n	t
[L]	$[ML^2T^{-2}]$	$[ML^{-3}]$	[T]
1	1/5	-1/5	2/5



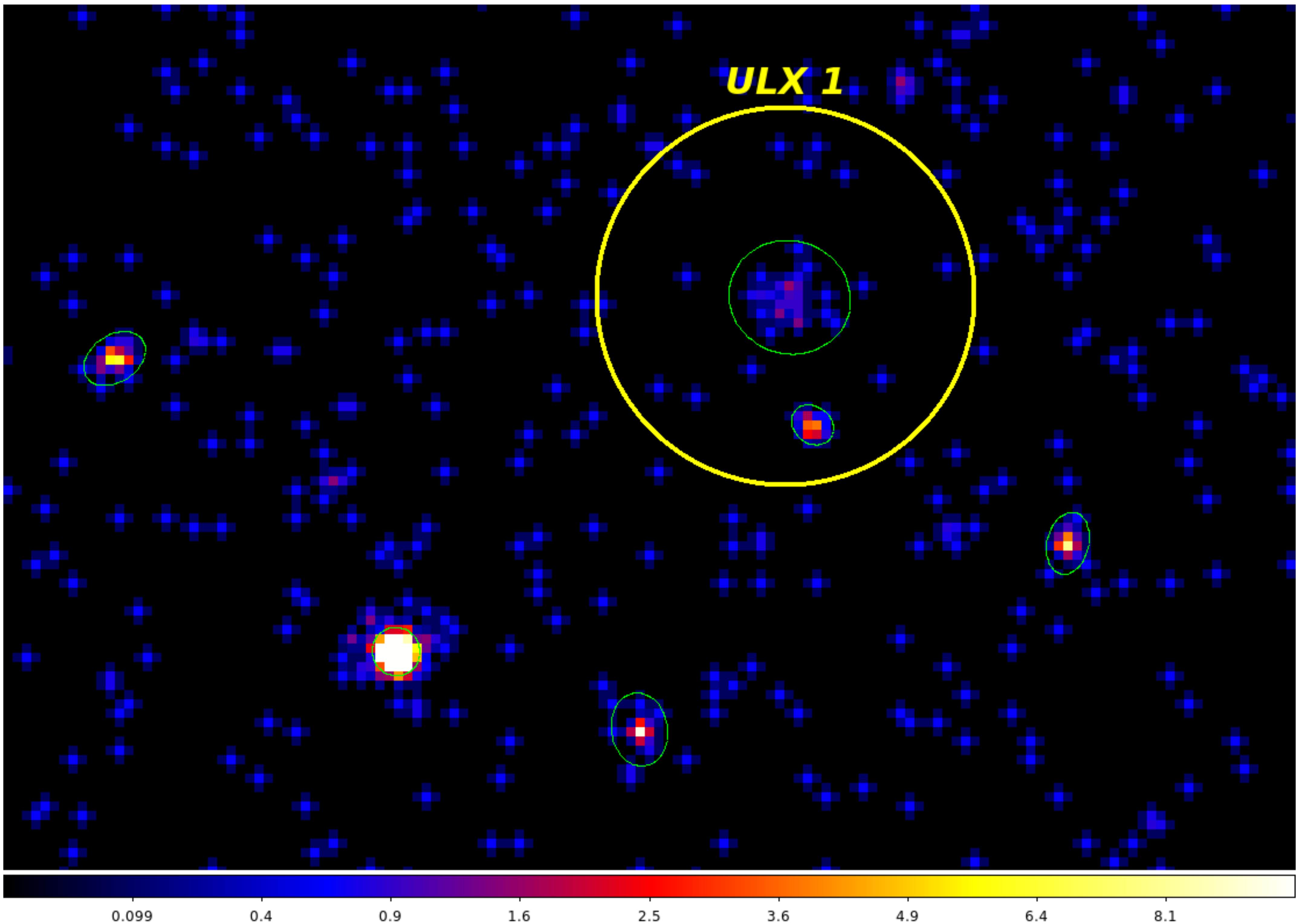


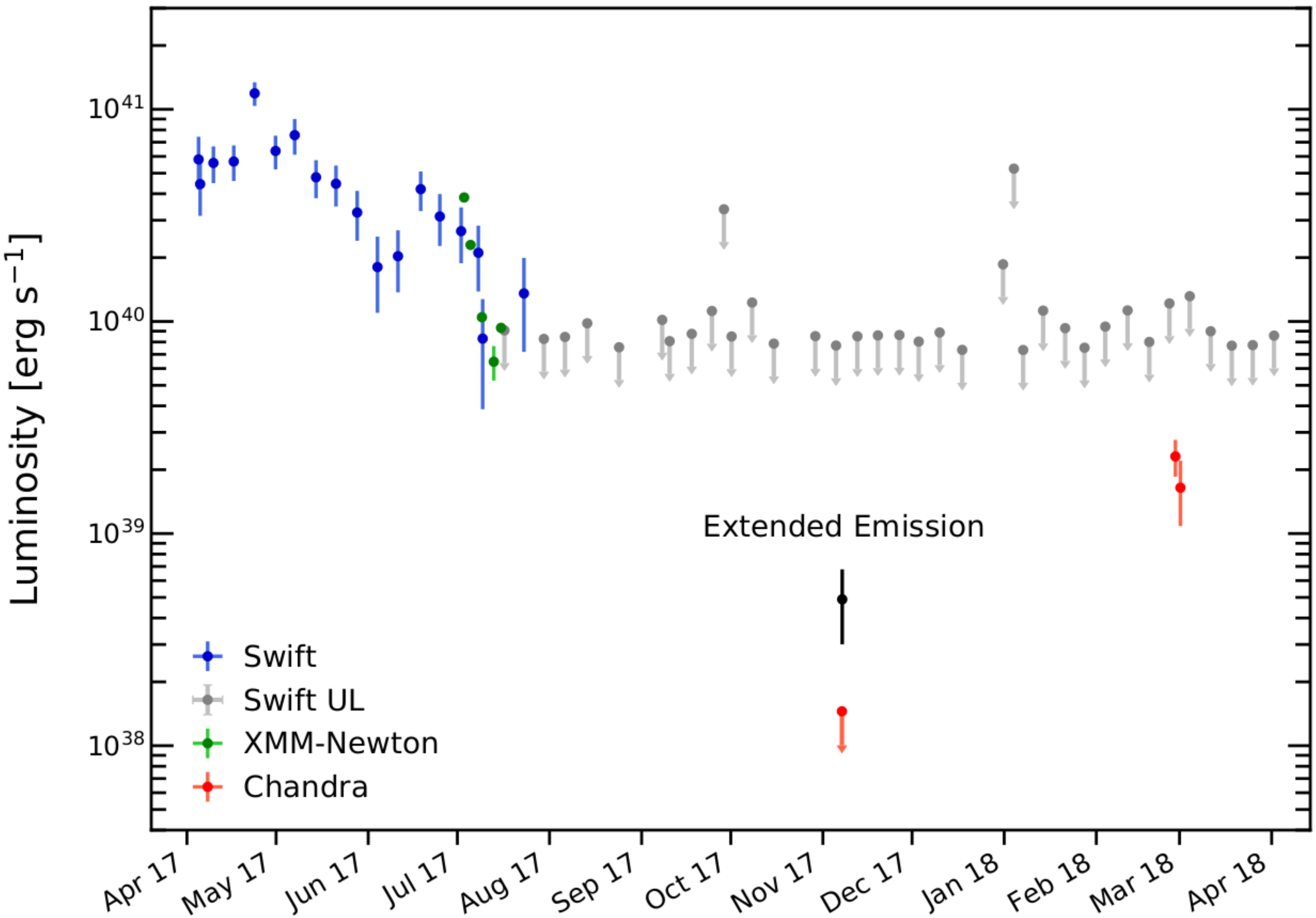
- This model is routinely applied to young supernova remnants
- Here is an example: Tycho SNR (SN 1572) as seen by Chandra



- 50ks ACIS obs on Nov 7 2017

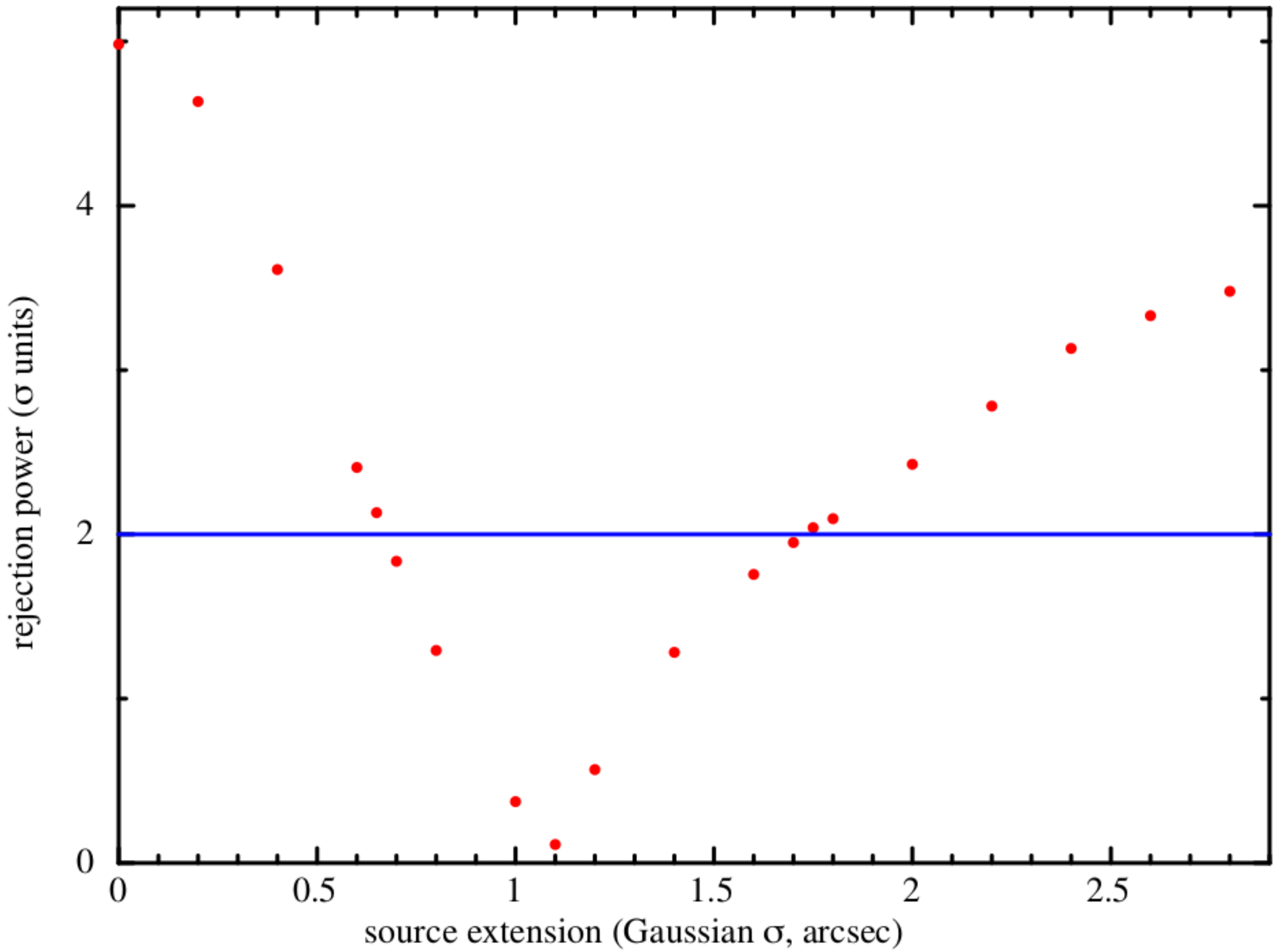
The low state



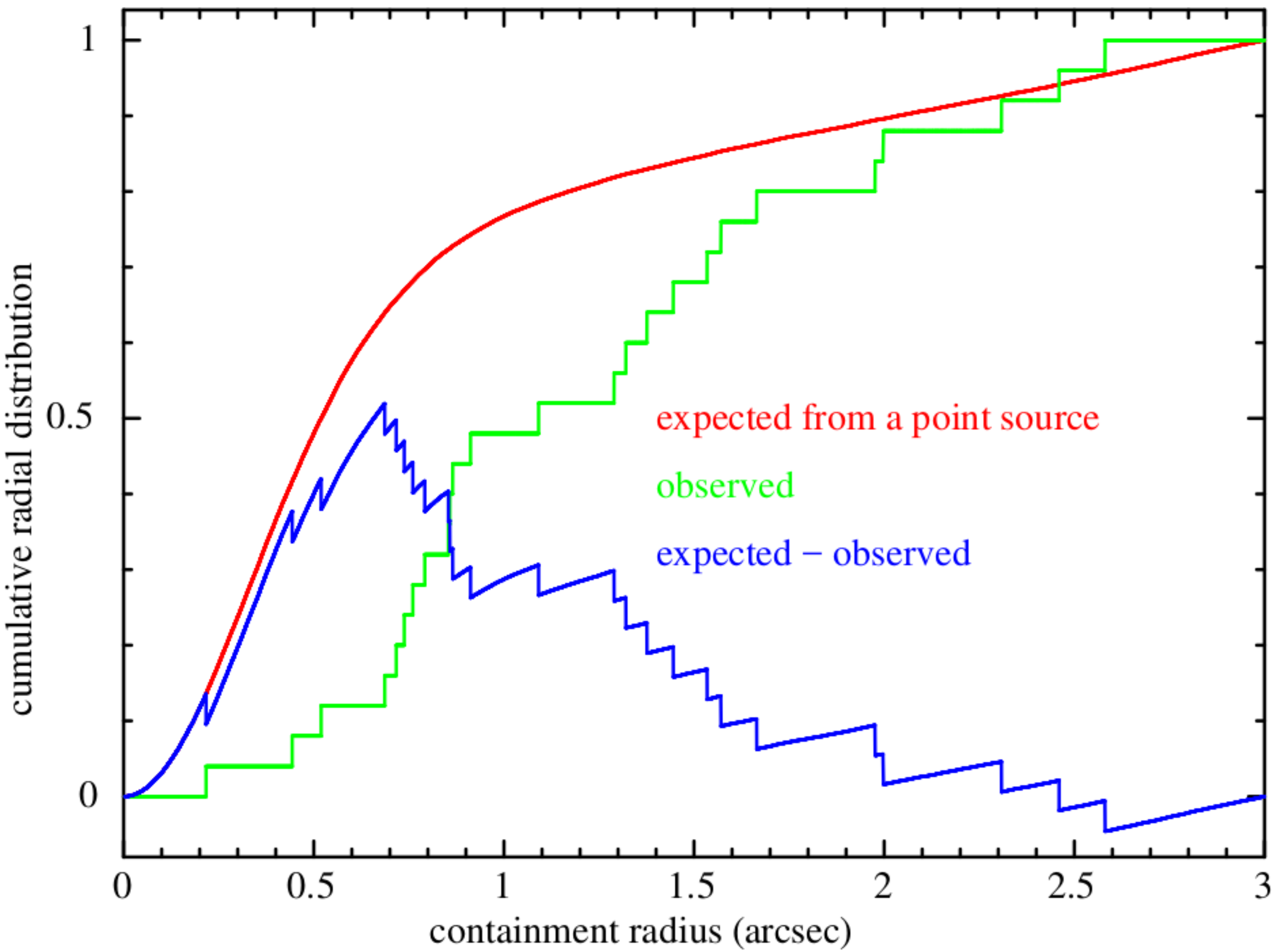


- Deep upper limit on the point source ($L_X < L_{Edd}$)
- Follow-up Chandra TOO caught ULX1 in intermediate state too bright to detect and study the nebula

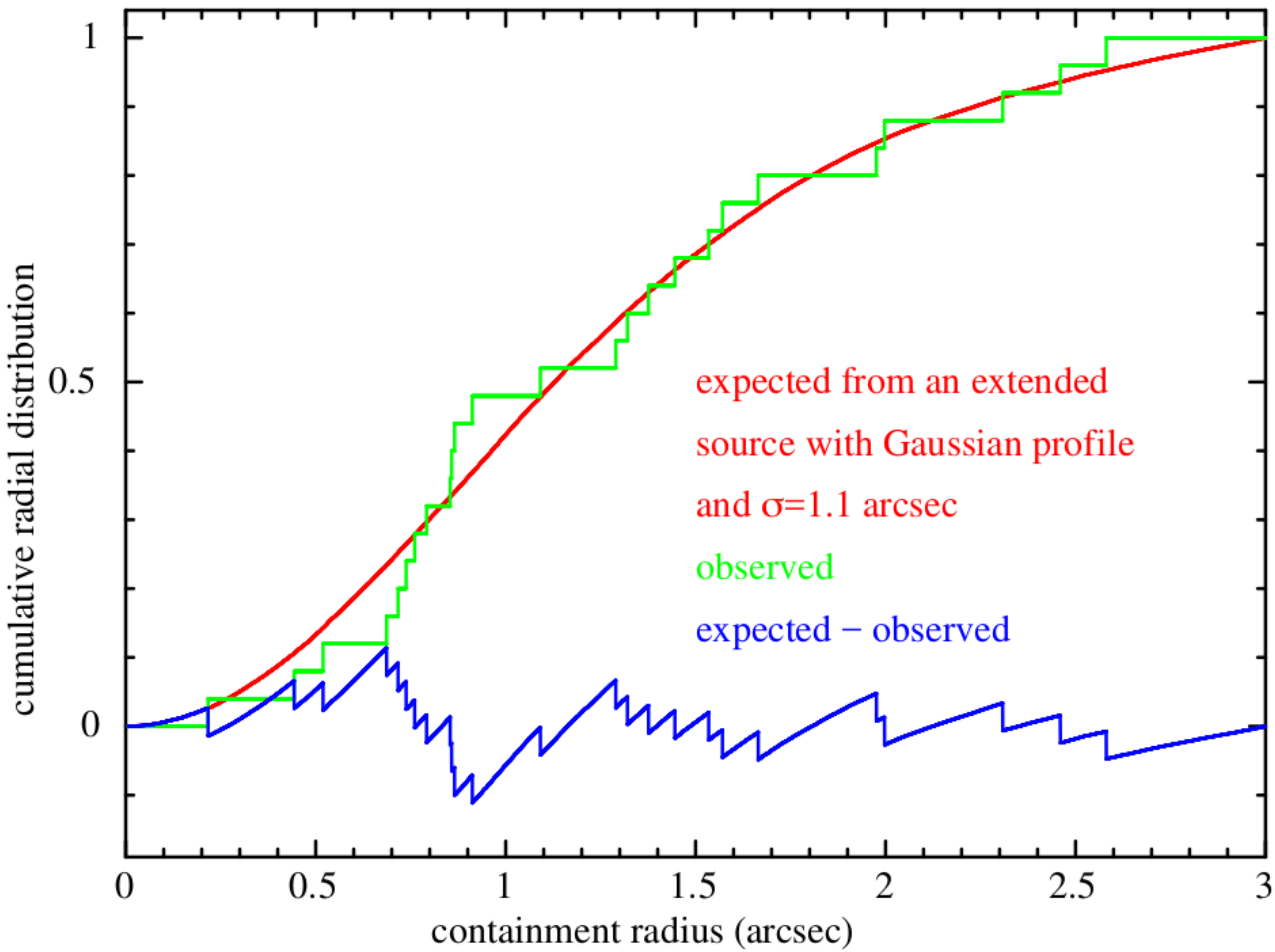
extension estimate



point source - bad



extended source - good

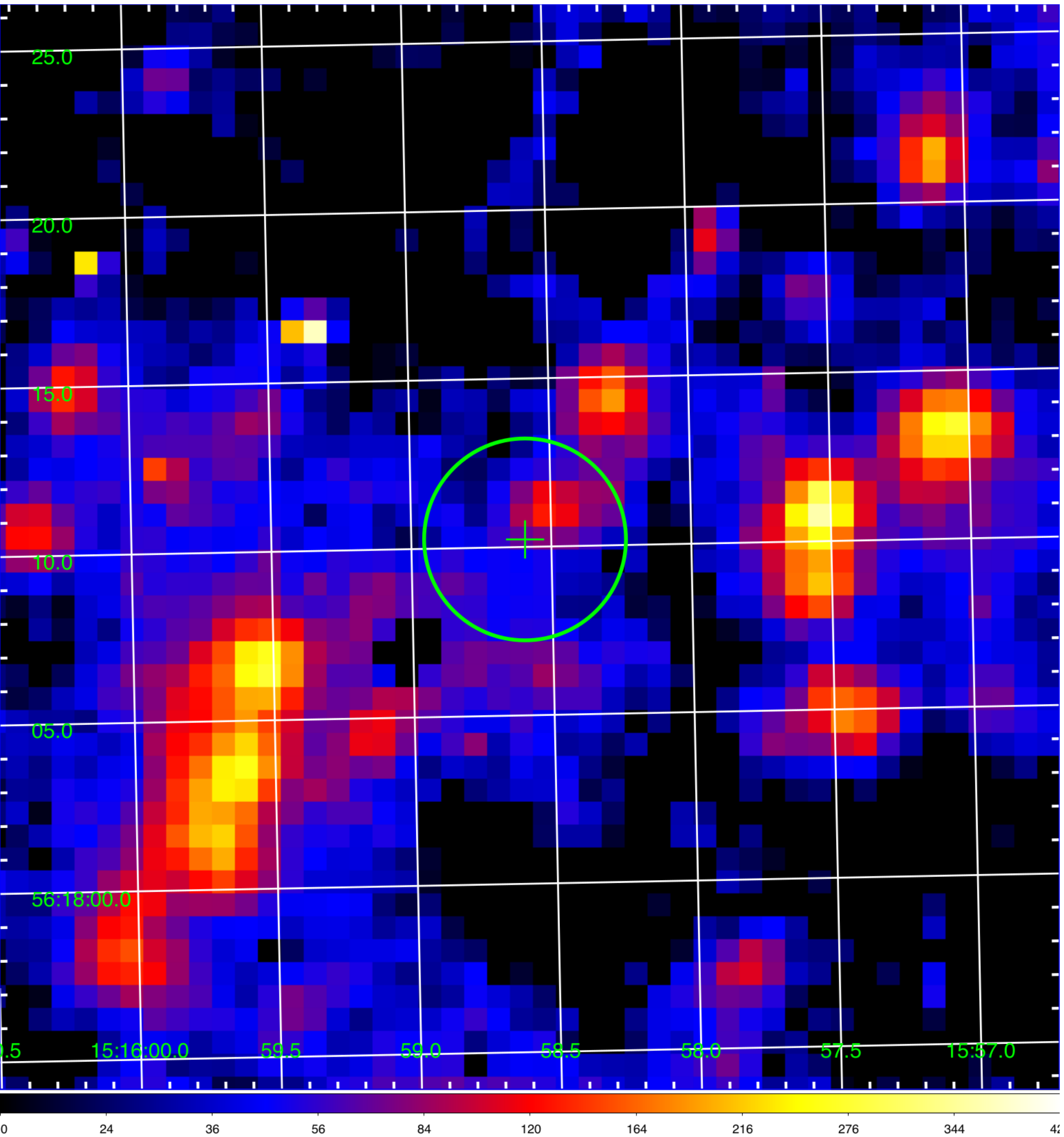


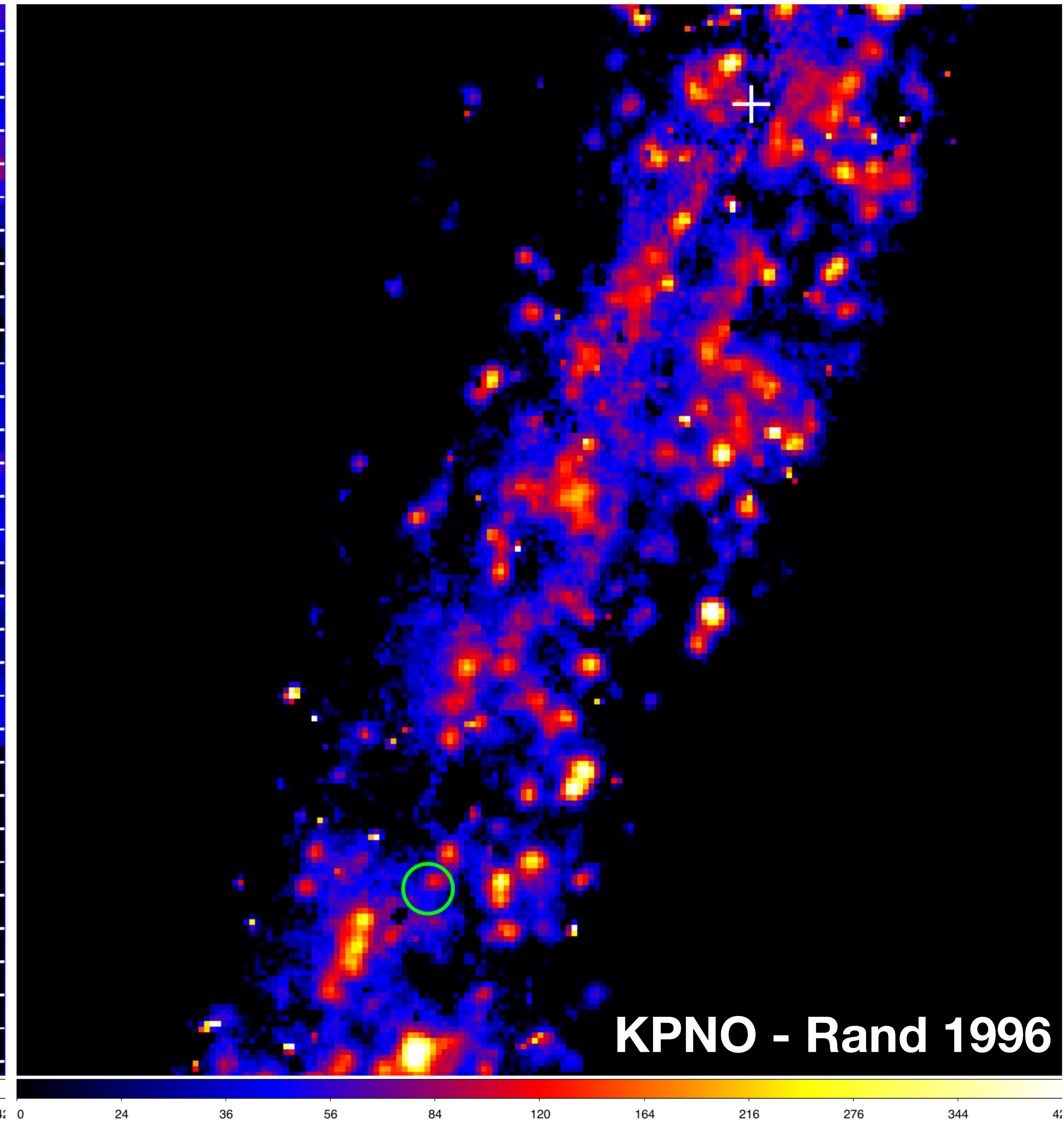
how do we interpret this feature?

- Local scattering - inconsistent with nH (too low)
- Local diffuse emission - very hot and bright
- Dust scattering within NGC 5907 - requires fine tuning
- A hypernova remnant - hard to get a NS in ULX1
- A ULX bubble - never observed in X-rays before

- We try and go after this last interpretation

H-alpha observation





- @17.1 Mpc the radius of the bubble is 112+/-42 pc
- RH conditions map kT into a shock speed:

$$v_{\rm sh}^{(0)} = \sqrt{\frac{16}{3}\frac{kT}{m_{\rm p}}} = \left(3.3^{+1.6}_{-0.8}\right) \times 10^{-3} c = \left(9.9^{+4.8}_{-2.4}\right) \times 10^{2}\,{\rm km\,s^{-1}}$$

- we allow for a non ideal shock speed: $v_{\rm sh} = v_{\rm sh}^{(0)} \times \xi$
- bubble theory predicts in this phase a radial evolution:

$$R_2(t) = \alpha \left(\frac{L_{\rm w} t^3}{n_{\rm ISM} m_{\rm p}}\right)^{1/5}$$

- therefore we can estimate the age of the bubble as:

$$\tau = \frac{3}{5}\frac{R_2}{v_{\rm sh}} = \left(6.7^{+3.1}_{-2.8}\right) \times 10^{4}\,{\rm yr} \times \xi^{-1}$$

- this is fully consistent with the adiabatic hypothesis

- we derive n_{ISM} from R and the spectral normalisation
- we allow also for a non-ideal compression factor W>4
- the expansion law leads to an estimate of the wind power:

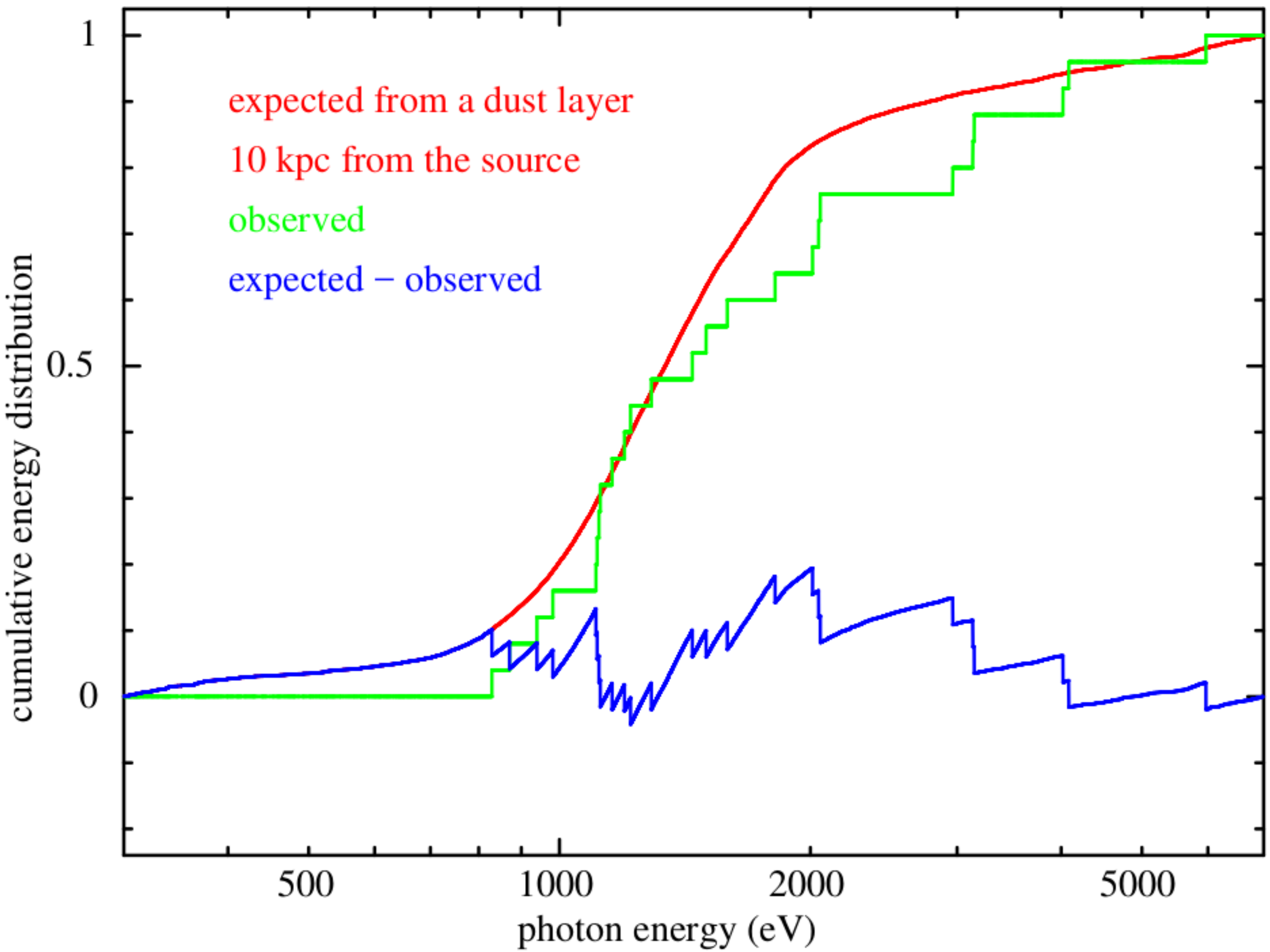
$$L_{\rm w} = \frac{m_{\rm p} n_{\rm ISM} R_2^5}{\alpha^5 \tau^3} = (1.3^{+9.8}_{-1.0}) \times 10^{41}\,{\rm erg\,s^{-1}} \times \xi^3 \times \left(\frac{W}{4}\right)^{-\frac{1}{2}}$$

- as this is fixed by the model, the bubble stores an energy:

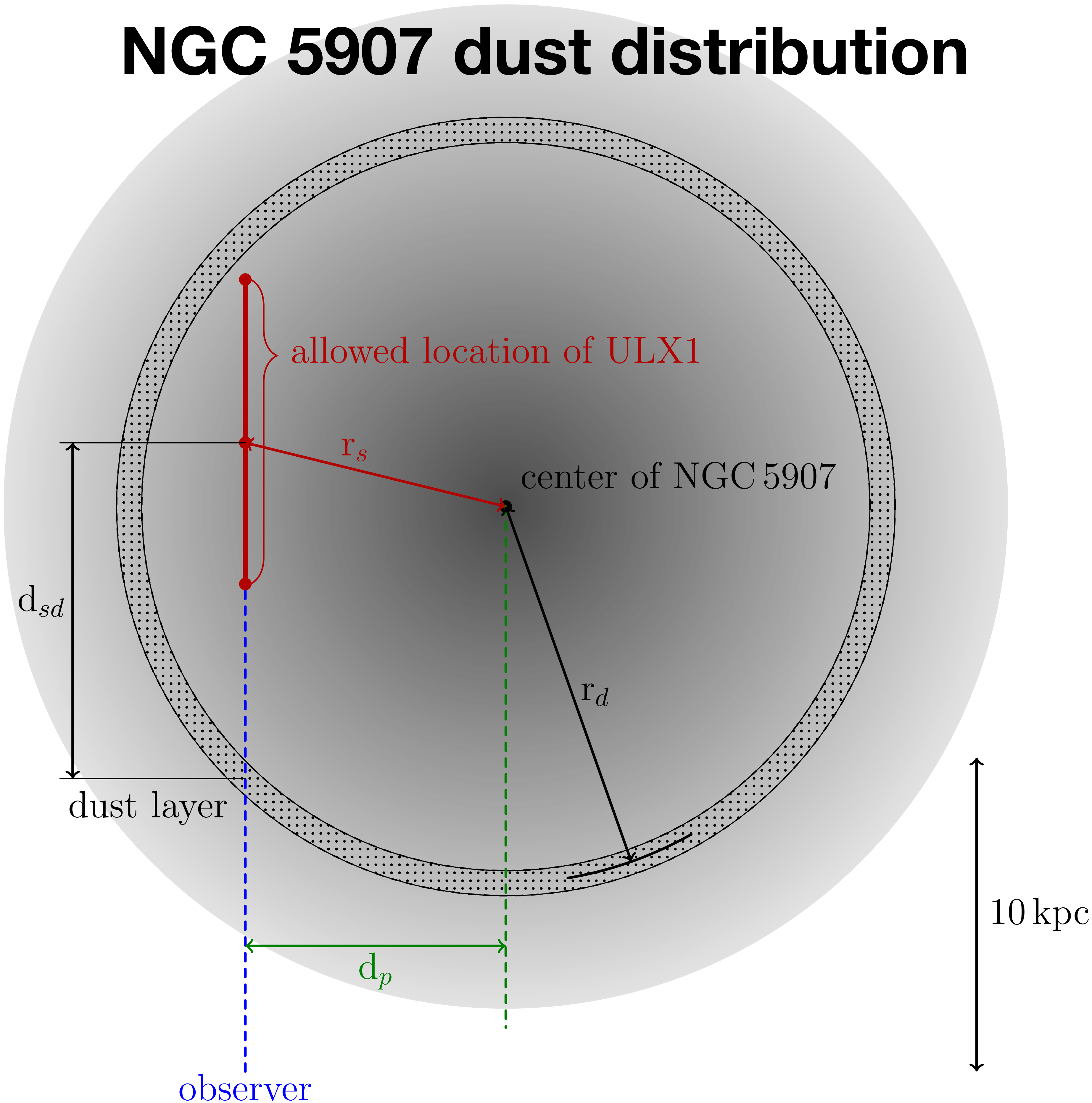
$$E = L_{\rm w}\tau = (2.8^{+18}_{-2.2}) \times 10^{53}\,{\rm erg} \times \xi^2 \times \left(\tfrac{W}{4}\right)^{-\frac{1}{2}}$$

- which is split between bulk motion and thermal energy

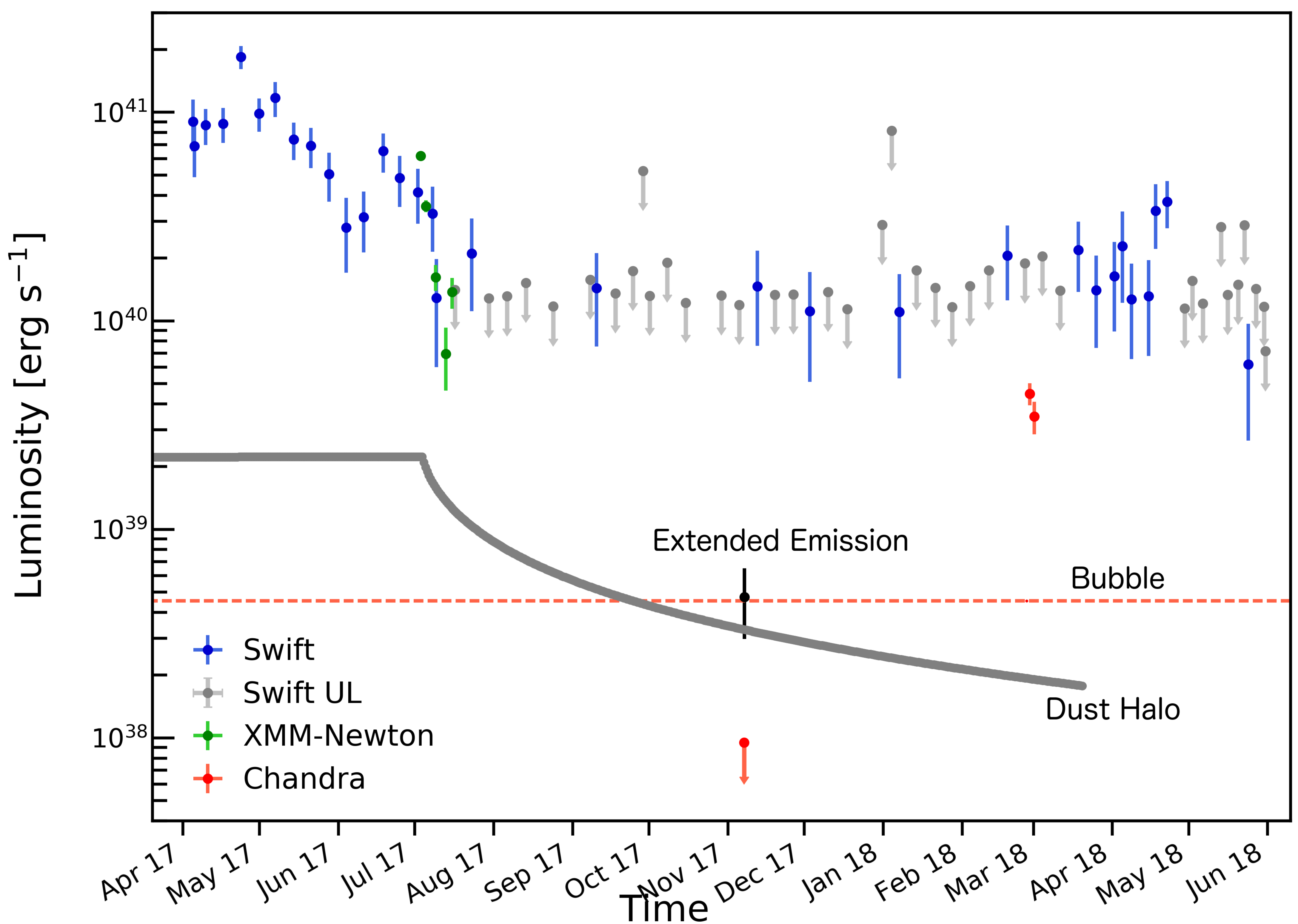
dust scattered spectrum

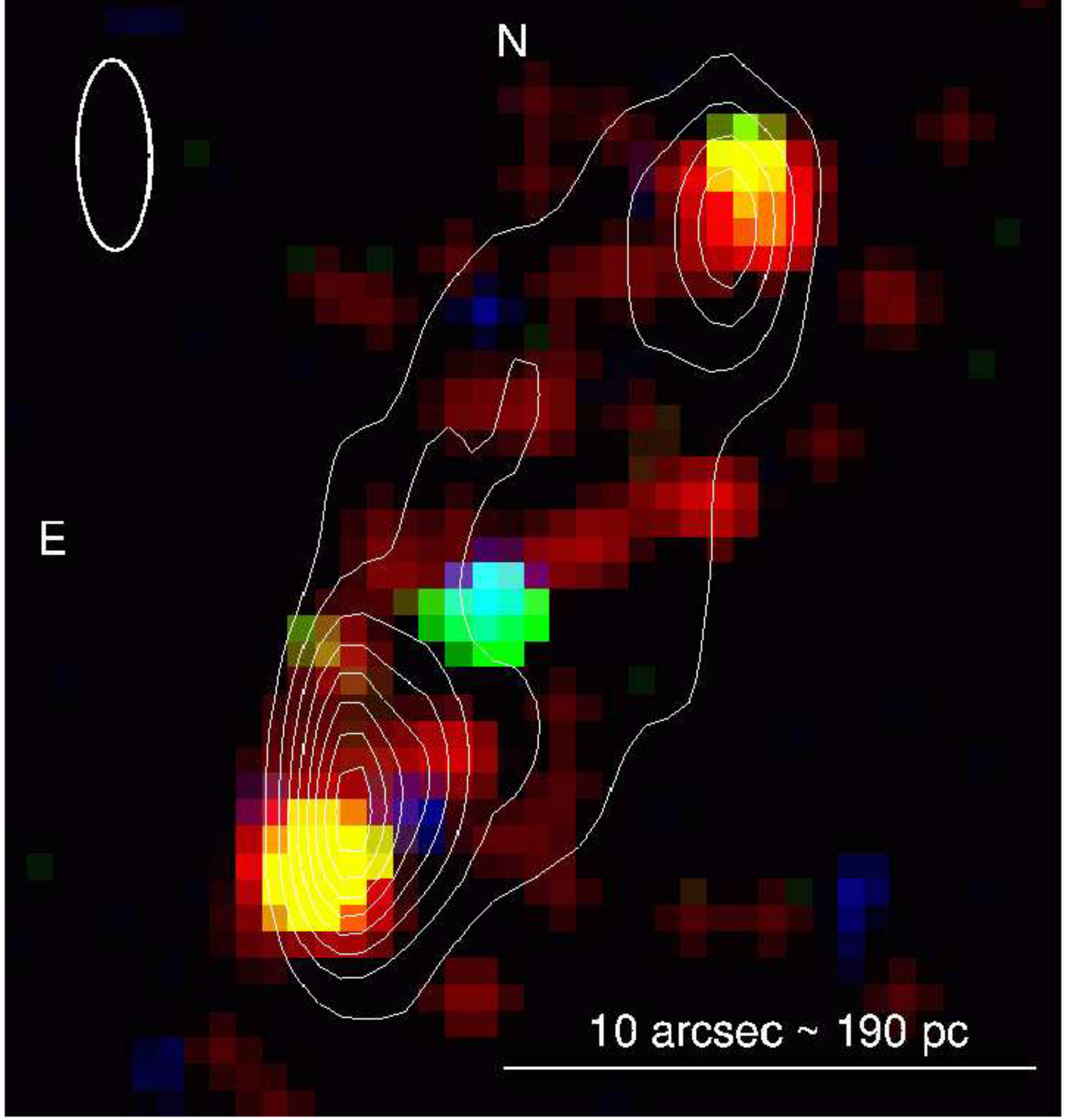


NGC 5907 dust distribution



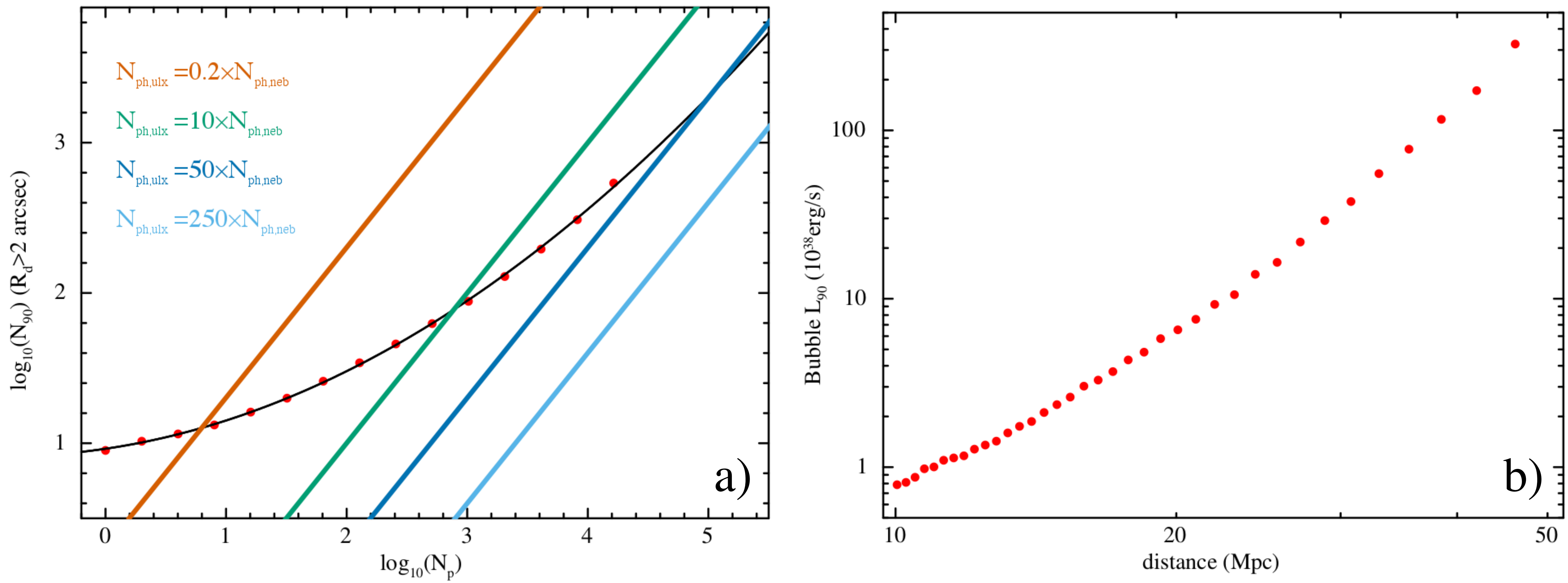
dust halo vs bubble





Soria et al 2010

- S26 in NGC7793 has a similar bubble (jetted) but no ULX
- more time on ULX1 could constrain its anisotropy or variability
- we can dig more into the binary system (orbit, spin evolution)



- Chandra could in principle detect similar structures around other ULXs or orphans as long as the ULX is in a faint state
- Depending on the brightness of the bubble the horizon could be ~20 Mpc (with a source like NGC 5907 ULX1)