ICRAR

International Centre for Radio Astronomy Research

Jets and outflows in ultraluminous X-ray sources

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Curtin University

The University of Western Australia

Achieve International Excellence

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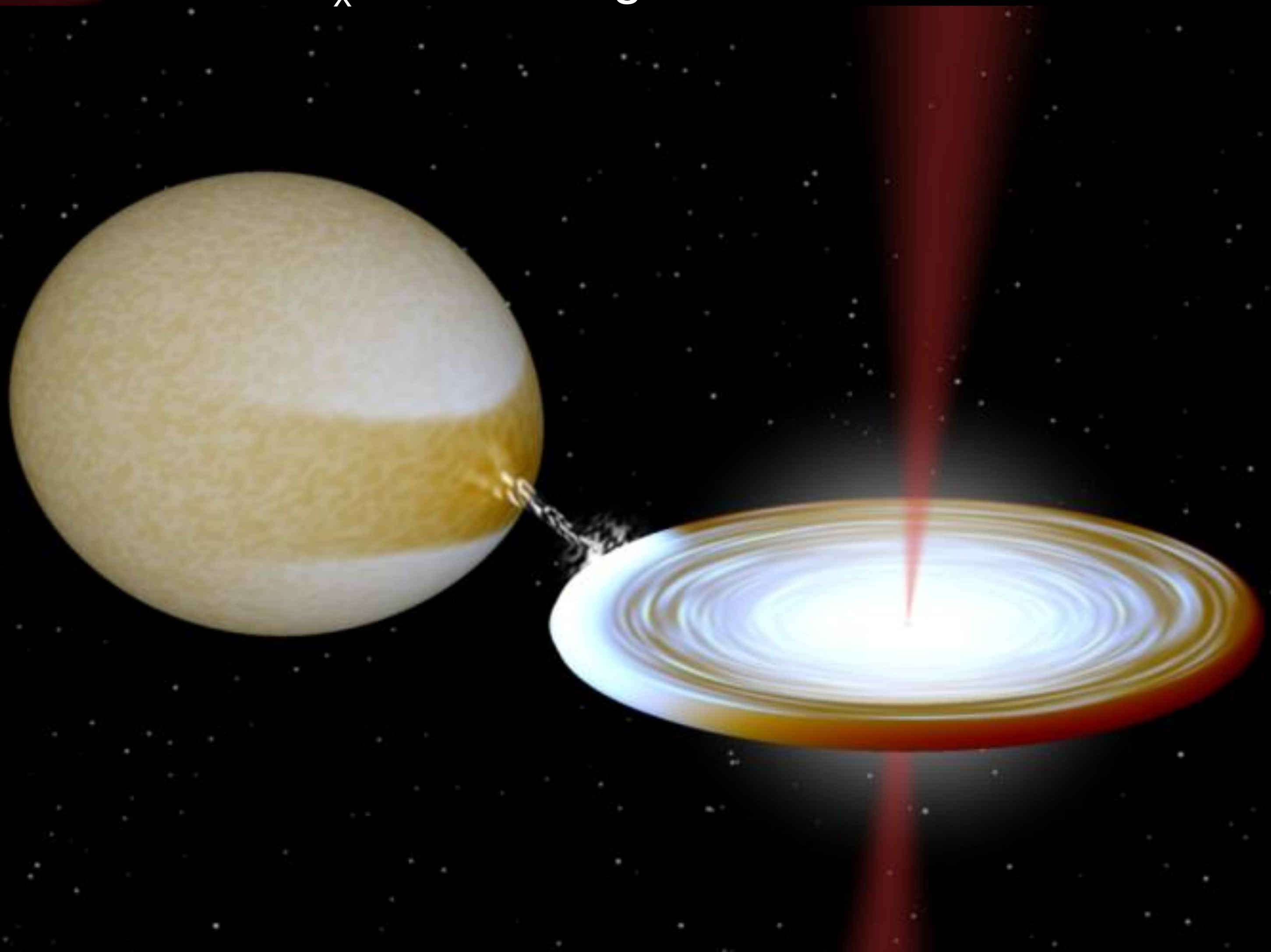
Content

- Introduction: radiative and kinetic power of BHs
- Observational evidence of jets and winds in ULXs
- Measuring BH power from optical/radio bubbles
- Optically thin and optically thick winds

Ultraluminous X-ray sources (ULXs)

= high-luminosity end of X-ray binary population

L_x > 1E39 erg/s



Total power of a BH

Radiation (directly observable in some bands)

Kinetic energy (jets & winds; not directly observable)

Radiation	→	(X-ray) photo-ionized nebulae
Winds	→	shock-ionized nebulae
Jets	→	shock-ionized nebulae (possibly) hot spots synchrotron emission (mostly radio)

1. Select powerful non-nuclear BHs in nearby galaxies
2. Search for evidence of ionized gas around them
3. Use the bubbles as calorimeters for the BH power

Kinetic power measured from:

1. (Flat-spectrum) core radio emission
   → Very difficult to detect in ULXs

2. Direct kinematic study of bubble expansion velocity

3. Fluxes and flux ratios of diagnostic optical/IR lines

   $L(H\beta) \sim (3/1000)\ P_{jet}$

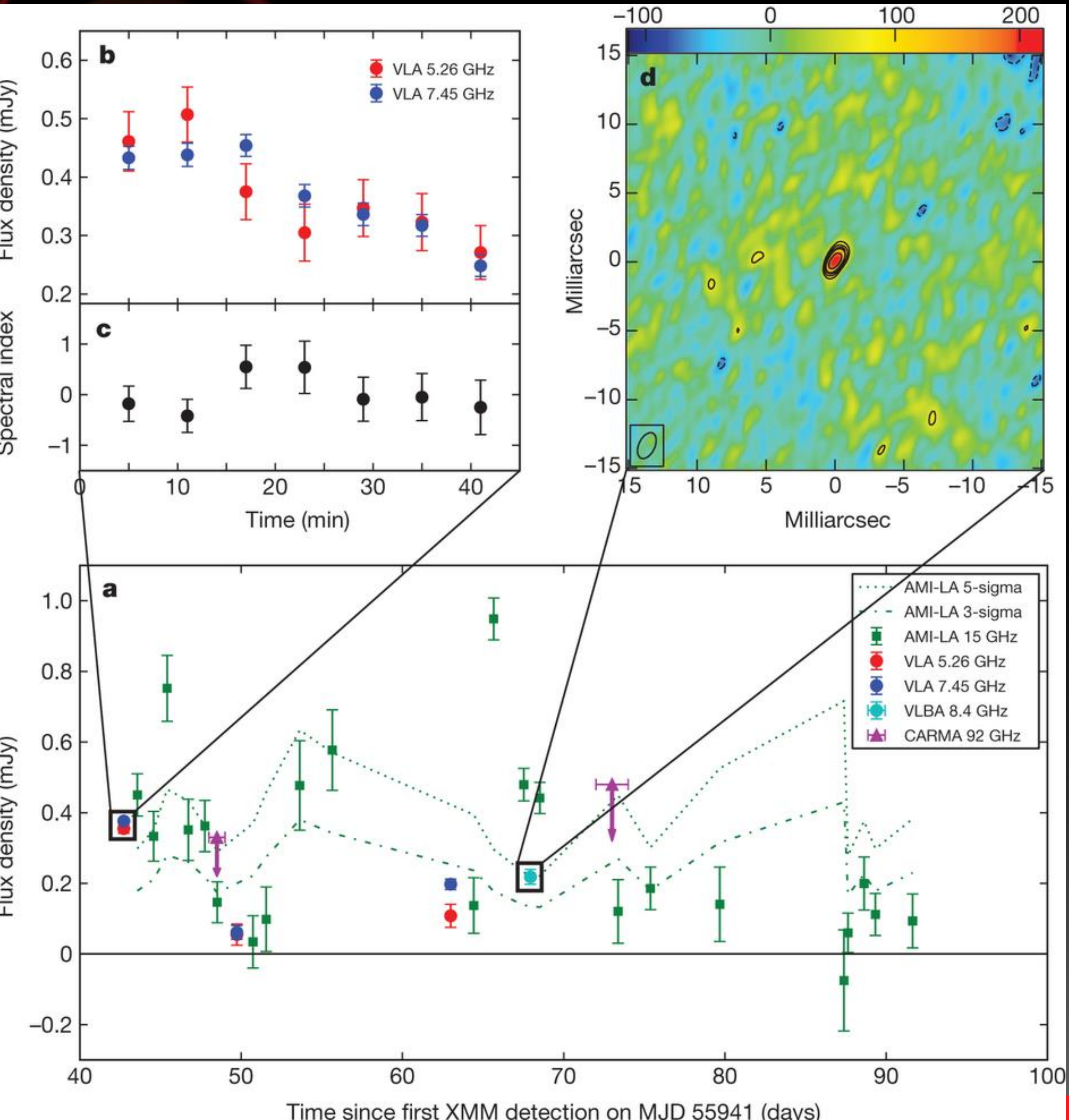
   $L([FeII]1.64) \sim 0.2\text{-}0.4\ L(H\beta) \sim (1/1000)\ P_{jet}$

4. Synchrotron radio emission from the lobes & hot spots

Kinetic power measured from:

1. (Flat-spectrum) core radio emission

→ Very difficult to detect in ULXs



M31
ULX transient

L_X ~ 1E39 erg/s

Radio flaring like in GBHs

(Middleton et al 2013)

Kinetic power measured from:

1. (Flat-spectrum) core radio emission

   → Very difficult to detect in ULXs

2. Direct kinematic study of bubble expansion velocity

3. Fluxes and flux ratios of diagnostic optical/IR lines

   $L(H\beta) \sim (3/1000)\ P_{jet}$

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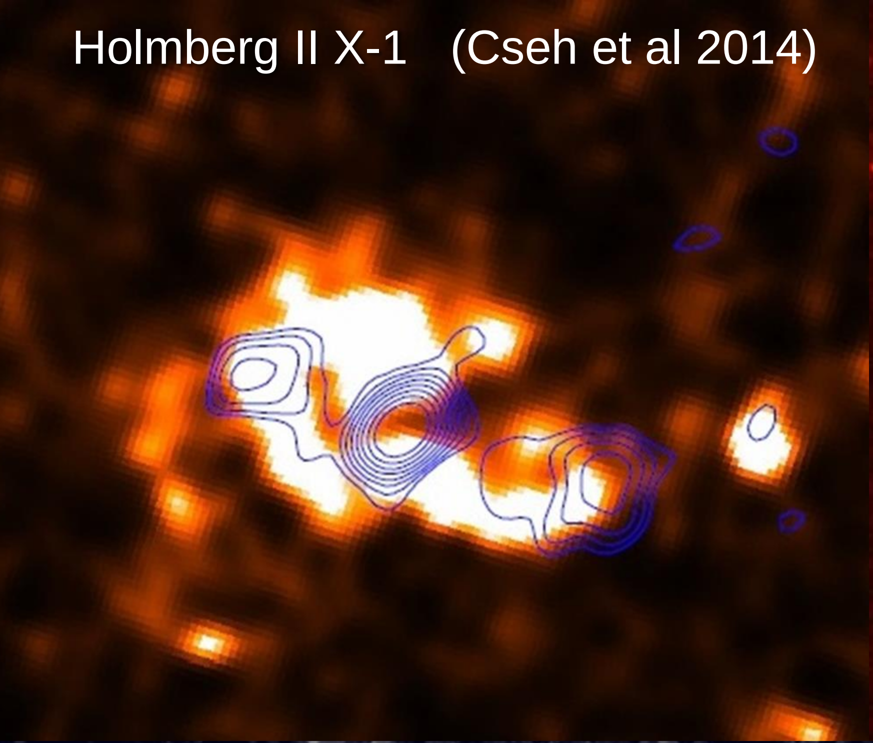
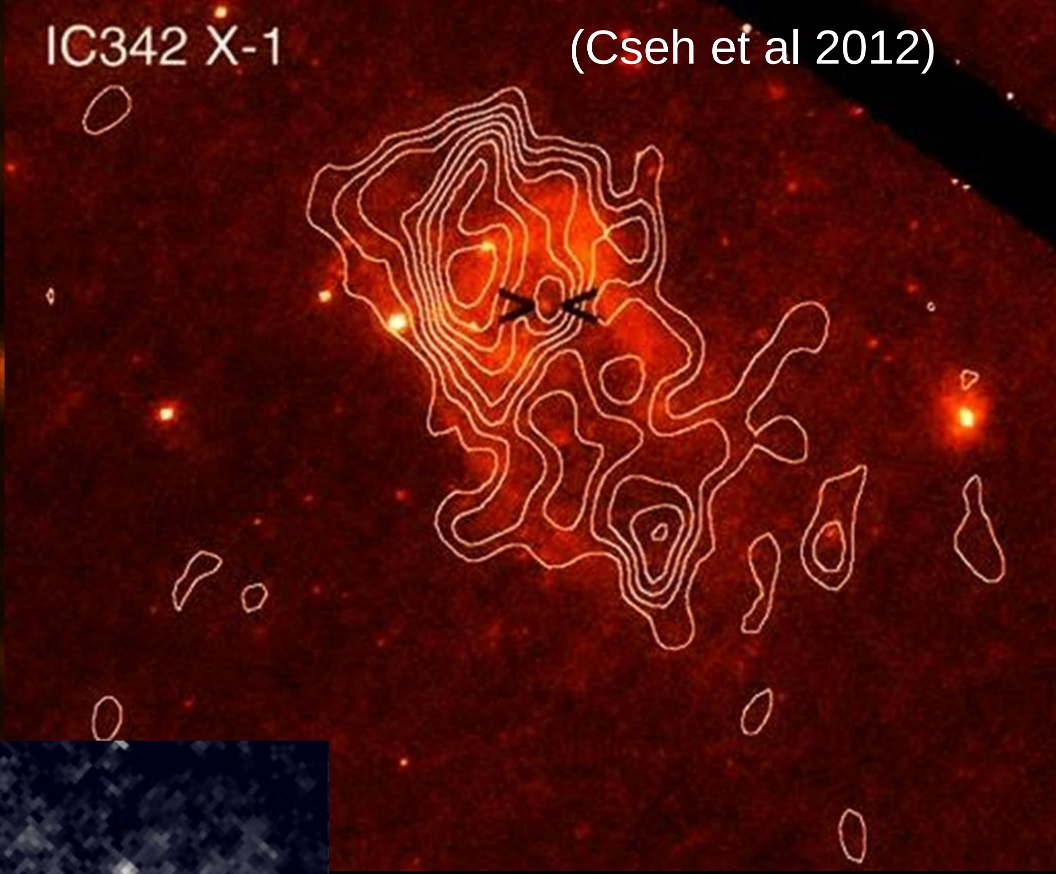
4. Synchrotron radio emission from the lobes & hot spots



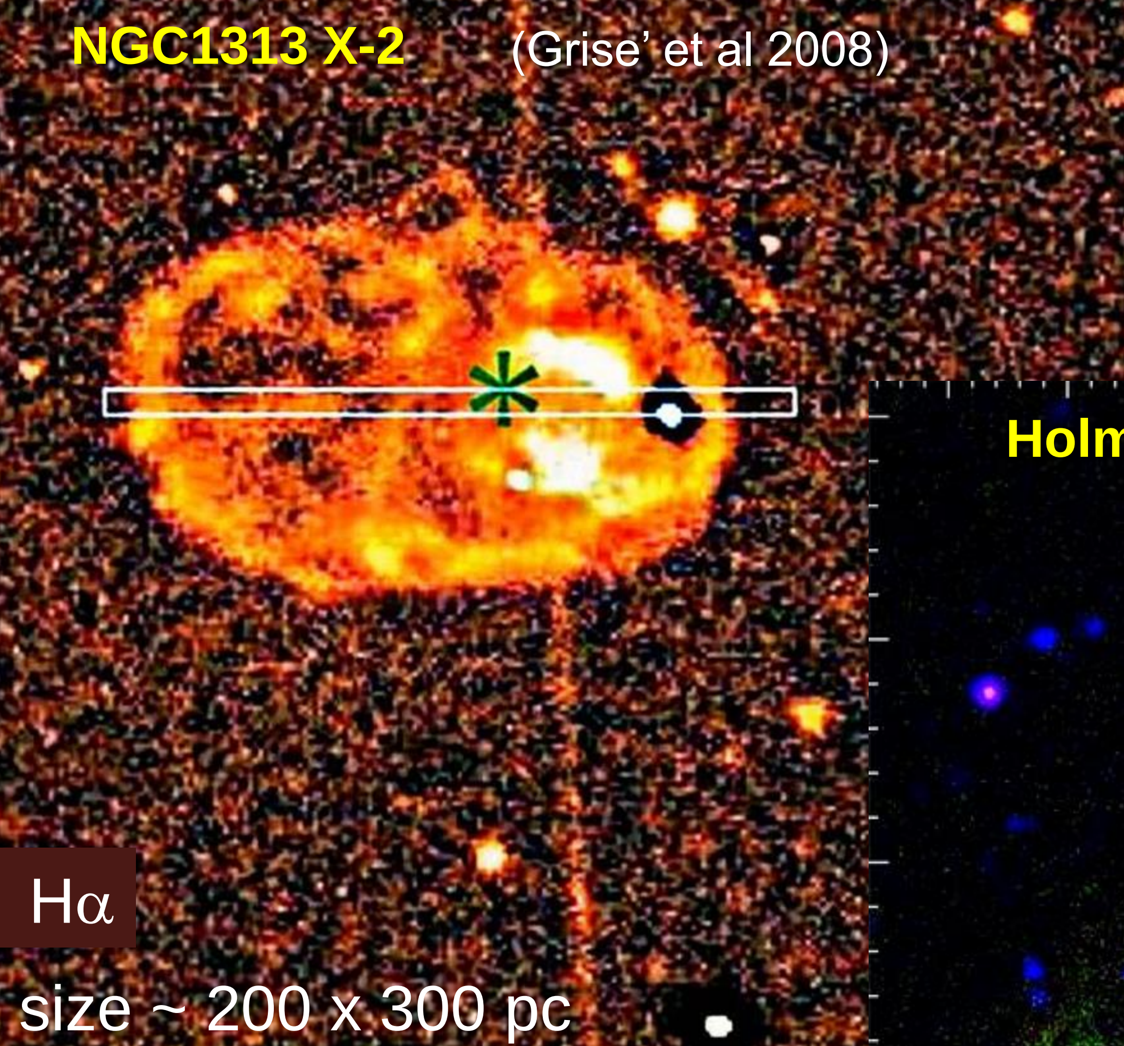


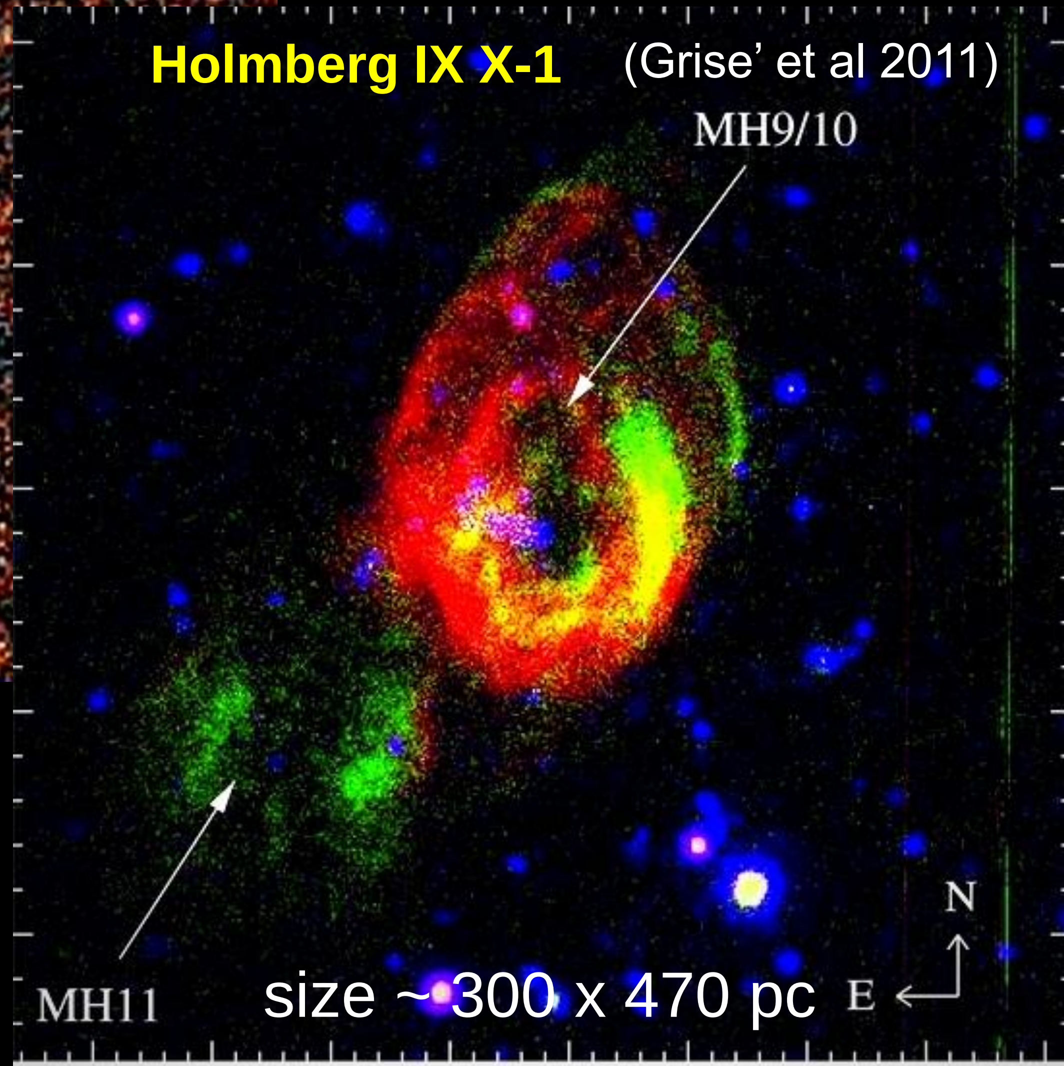
Indirect evidence of jets from optically-thin synchrotron emission

P_{jet} ~ a few 10^{39} erg/s
inferred from the radio emission

Large shock-ionized
ULX bubbles
without radio emission

Winds but no jet?

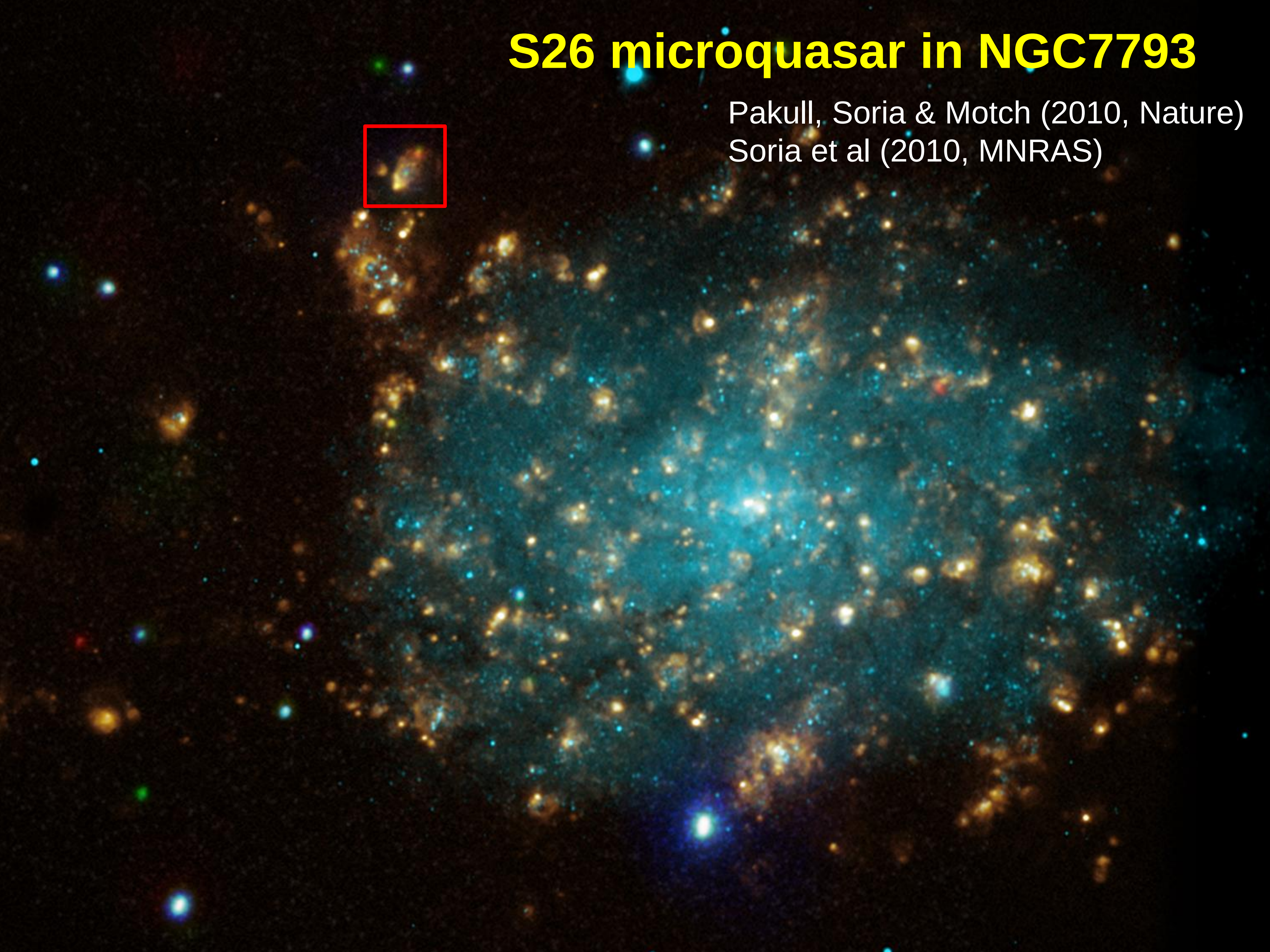




$P_{wind} \sim$ a few 10^{39} erg/s
inferred from the optical bubble

S26 microquasar in NGC7793

Pakull, Soria & Motch (2010, Nature)
Soria et al (2010, MNRAS)



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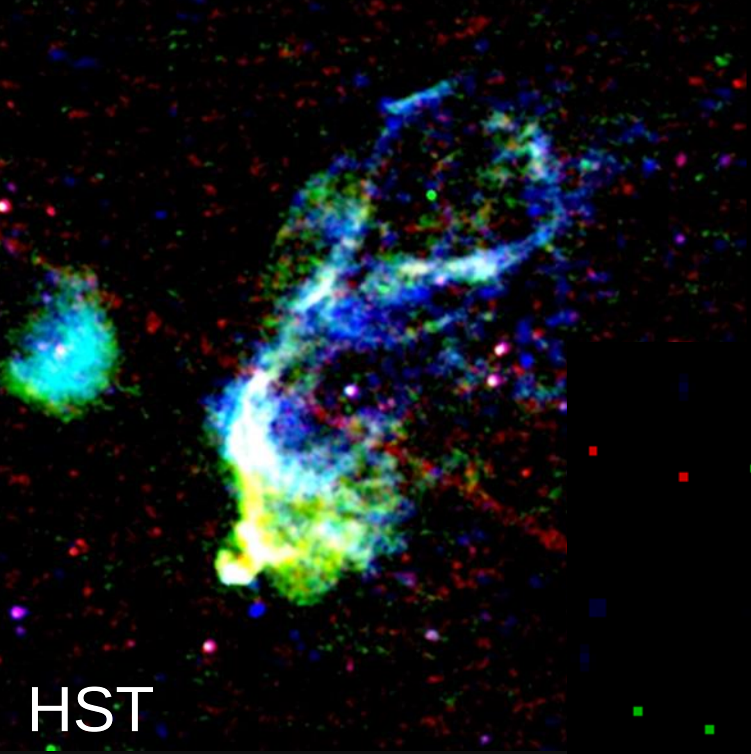
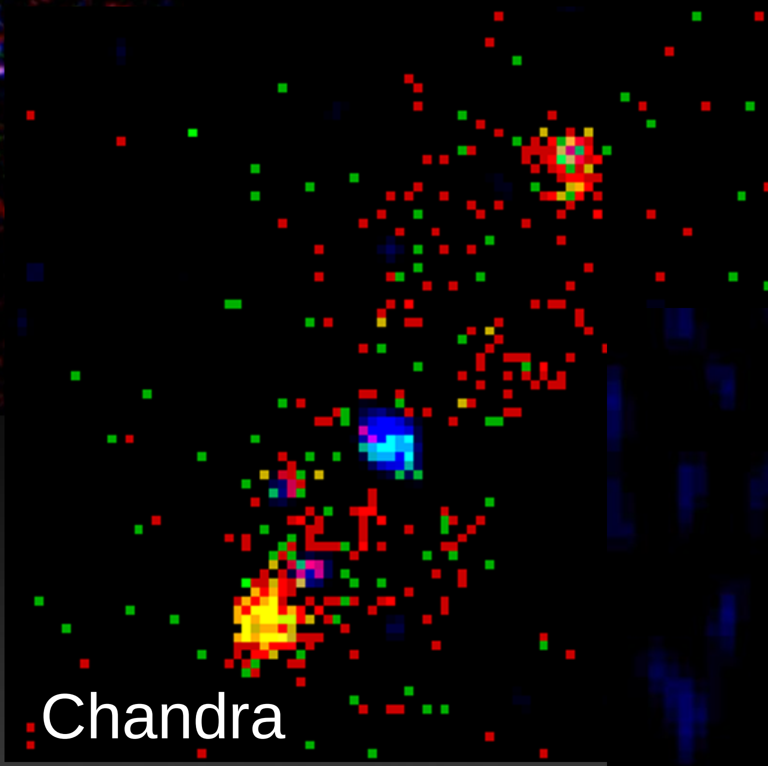
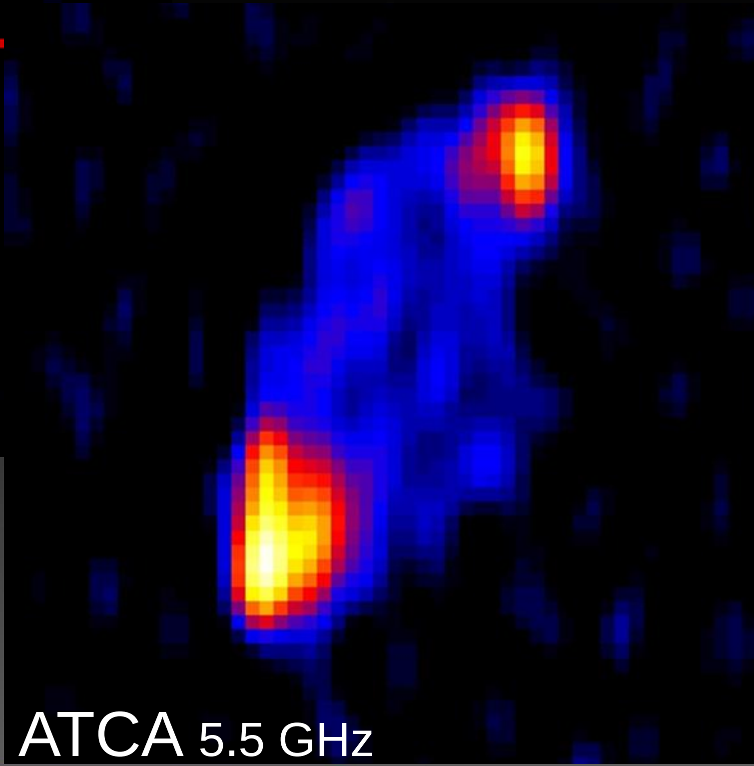






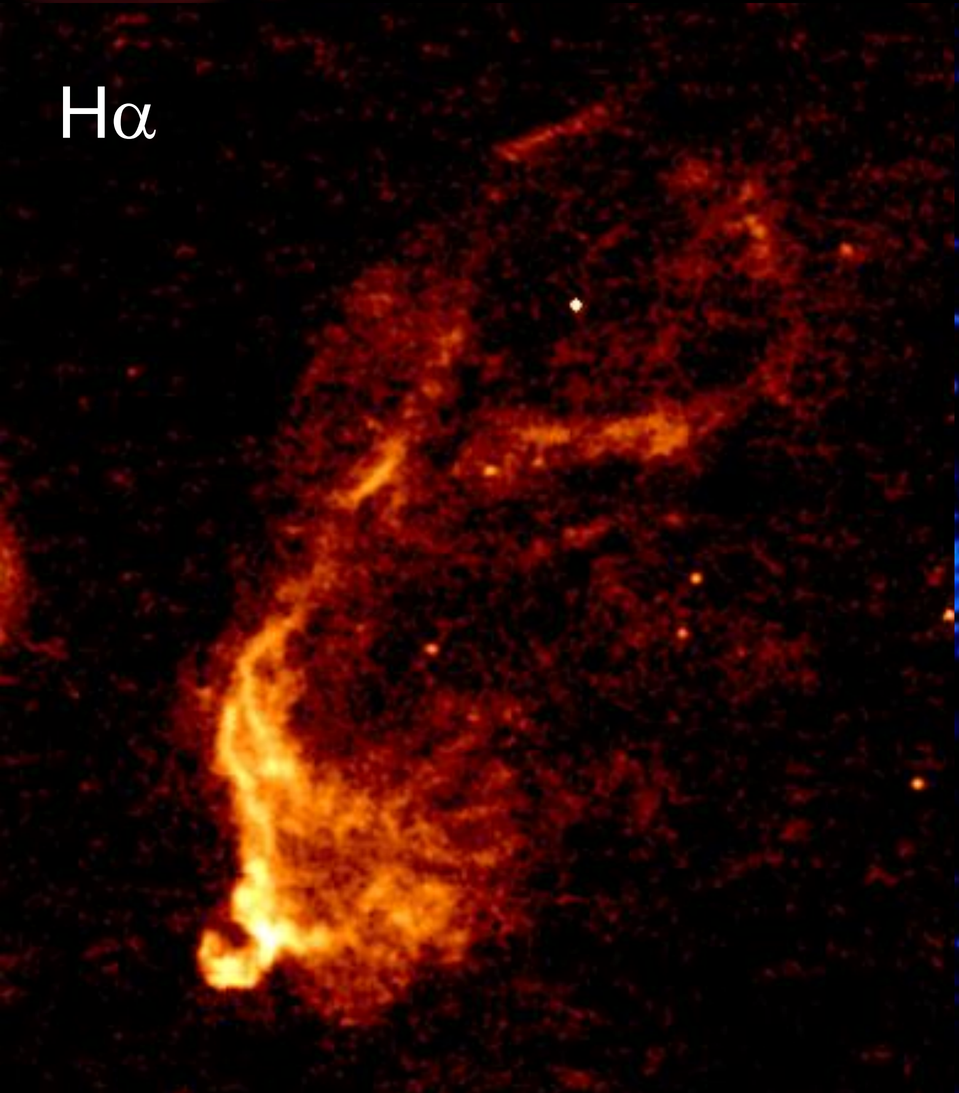
diameter ~ 270 pc

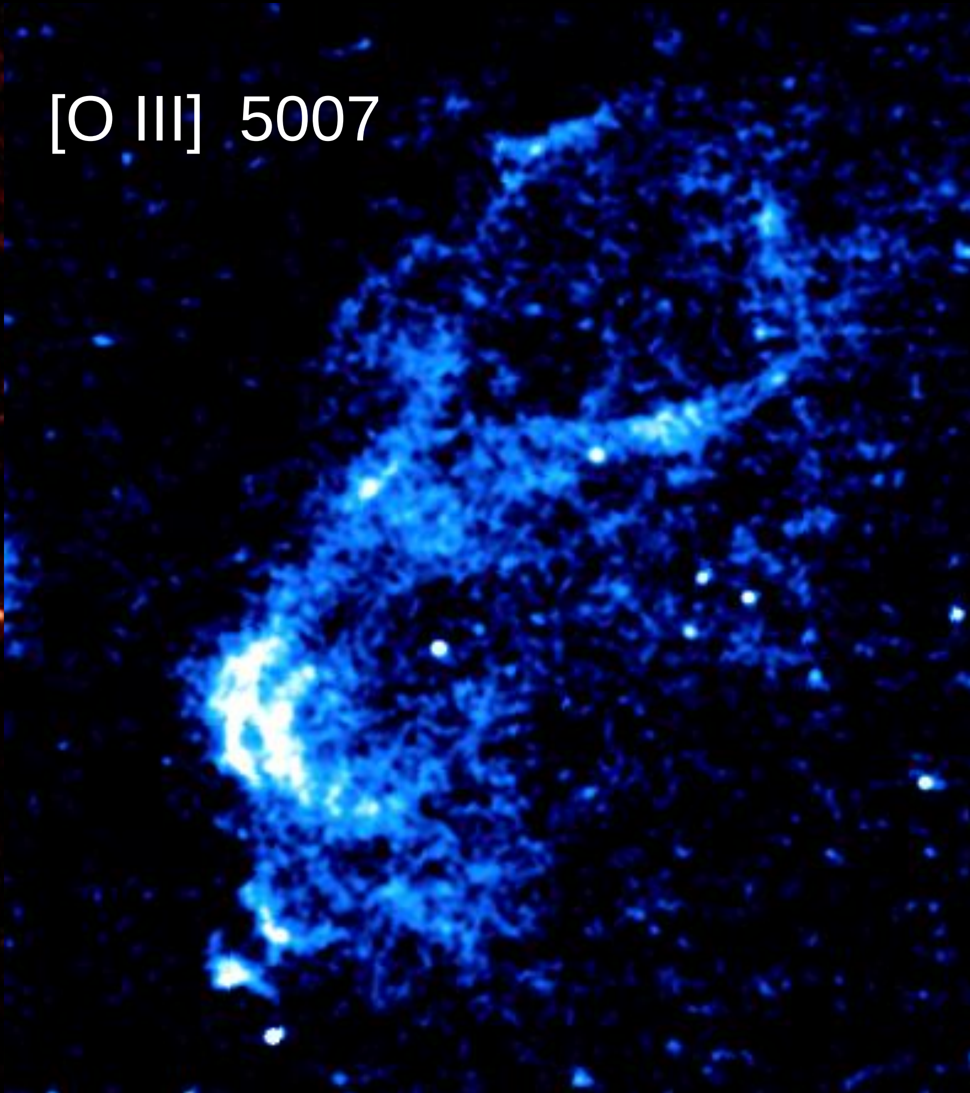
Jet-inflated bubble with hot spots

P_{jet} ~ 1E40 erg/s > L_X

S26 microquasar in NGC7793

P_{jet} ~ 1E40 erg/s > L_X Age ~ 300,000 yrs, v ~ 270 km/s

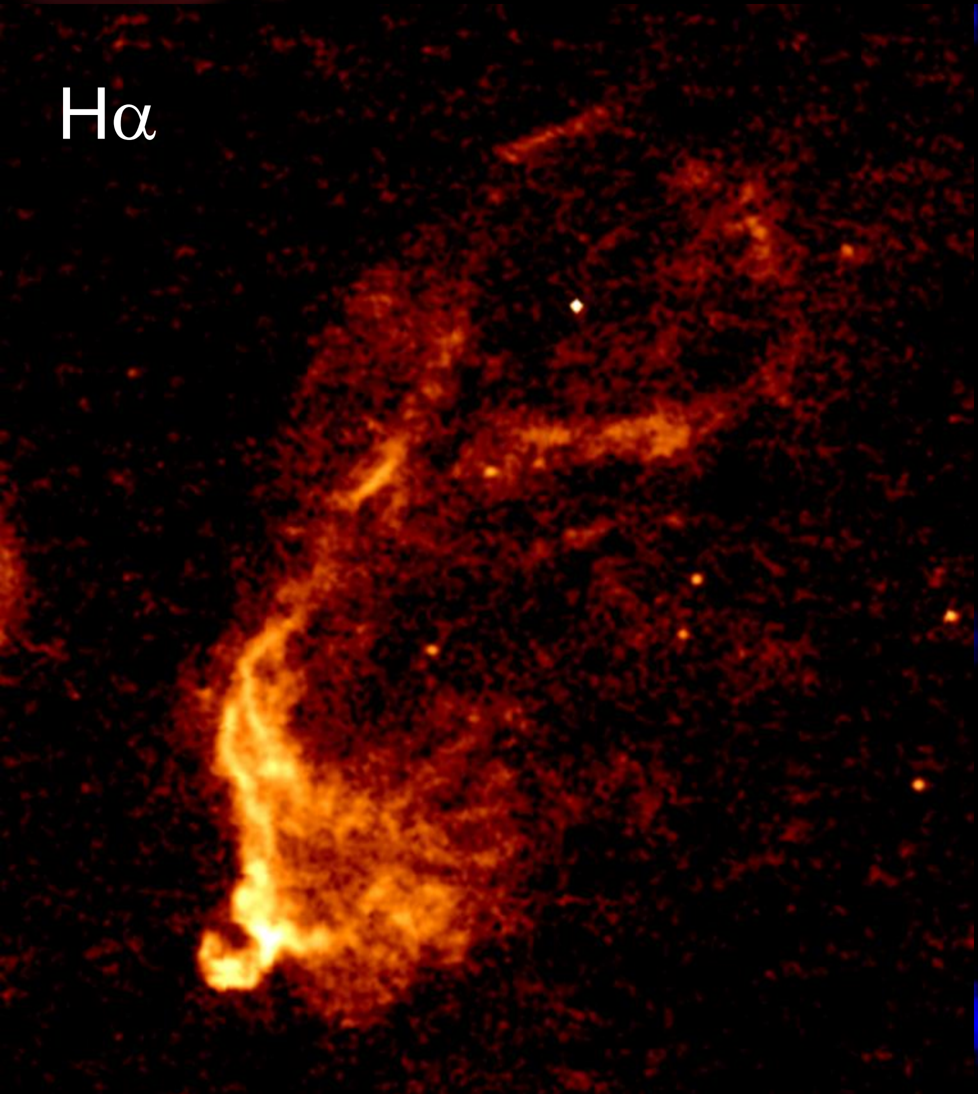


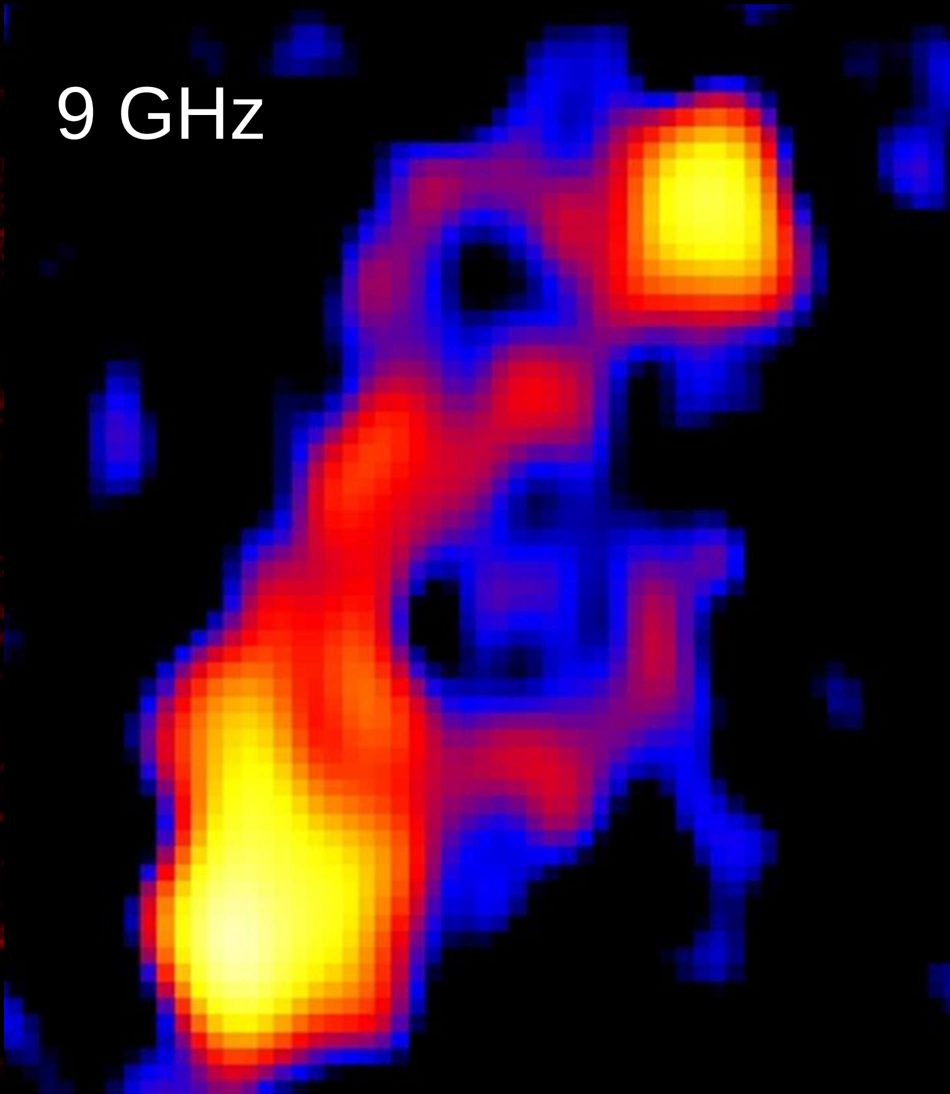


S26 microquasar in NGC7793

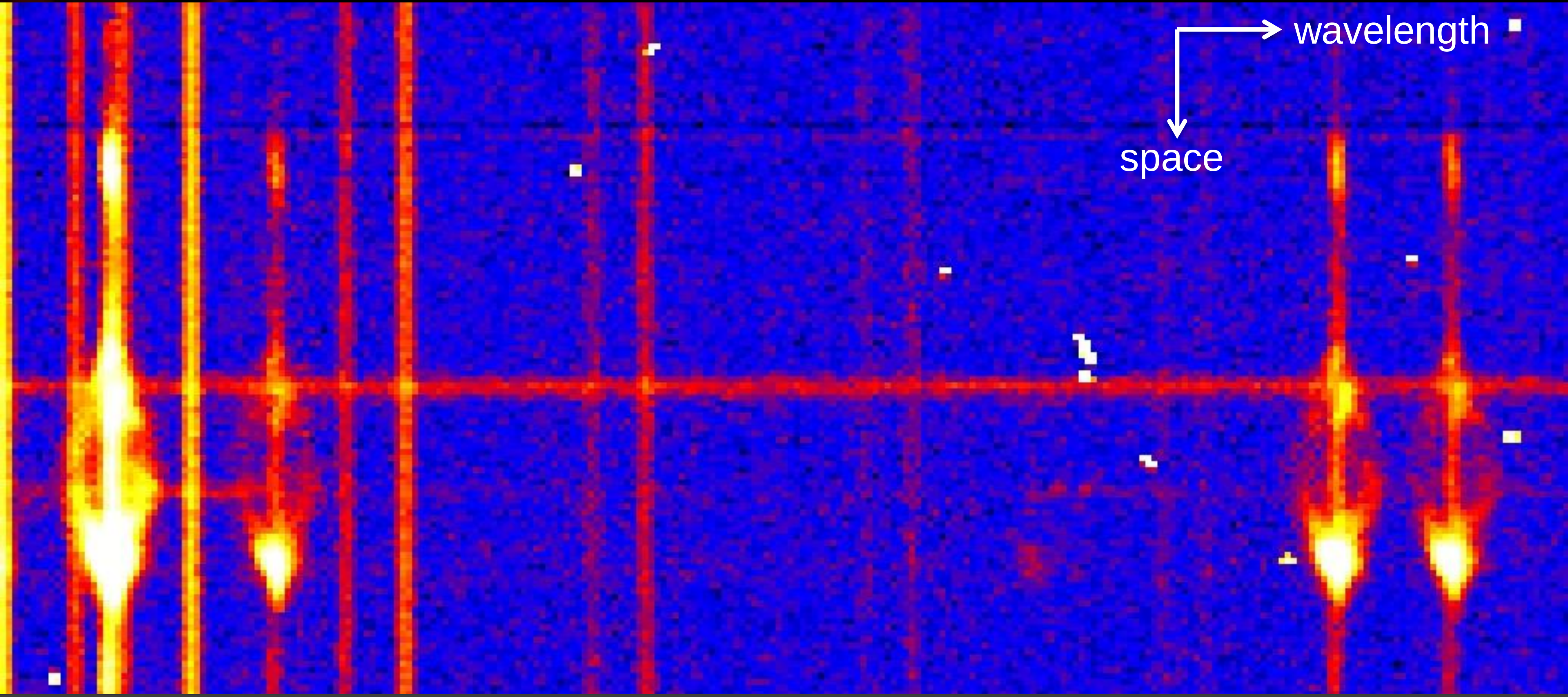
$P_{jet} \sim 1E40$ erg/s $> L_X$

Age ~ 300,000 yrs, v ~ 270 km/s





S26 microquasar in NGC7793

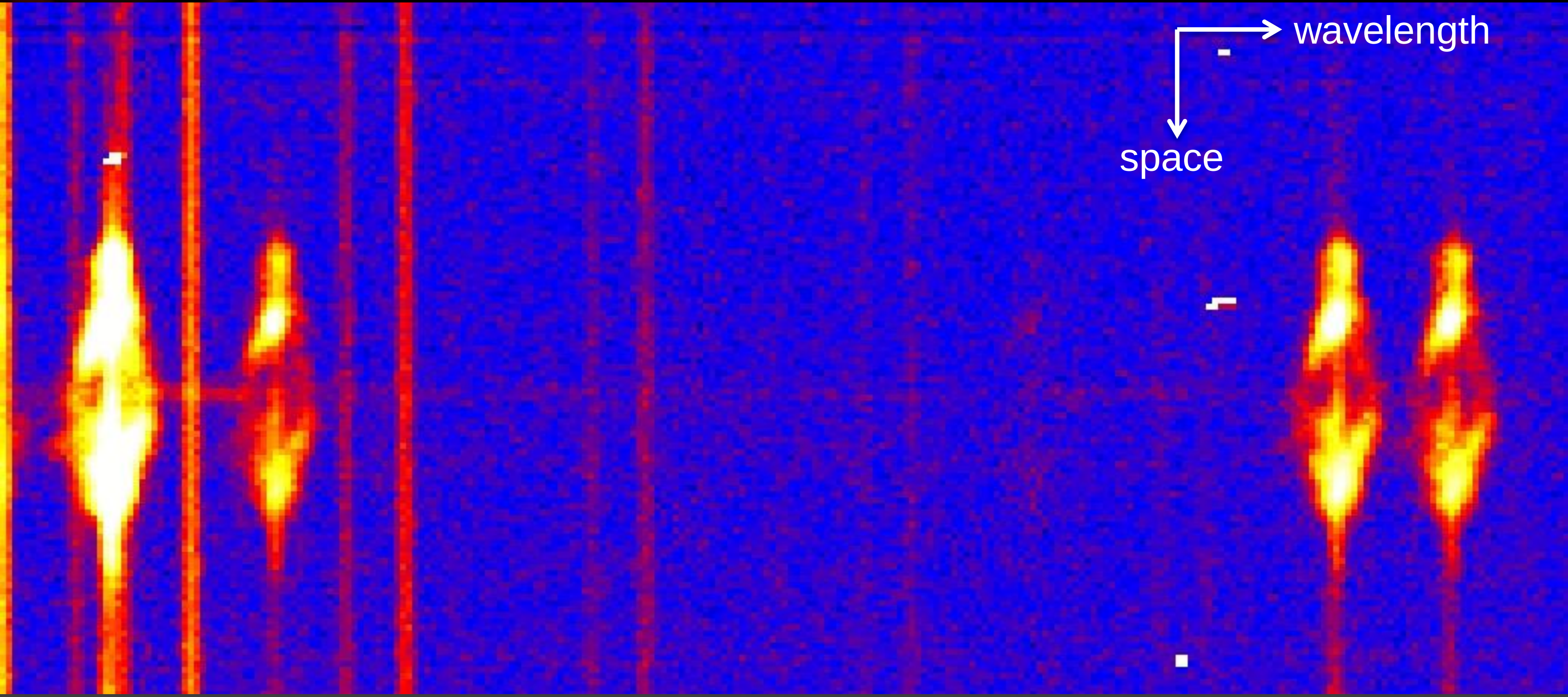


Hα [NII] [SII] [SII]

VLT/FORS2 spectra: slit oriented along the major axis

(Pakull, Motch, Soria & Grise’, in prep)

S26 microquasar in NGC7793



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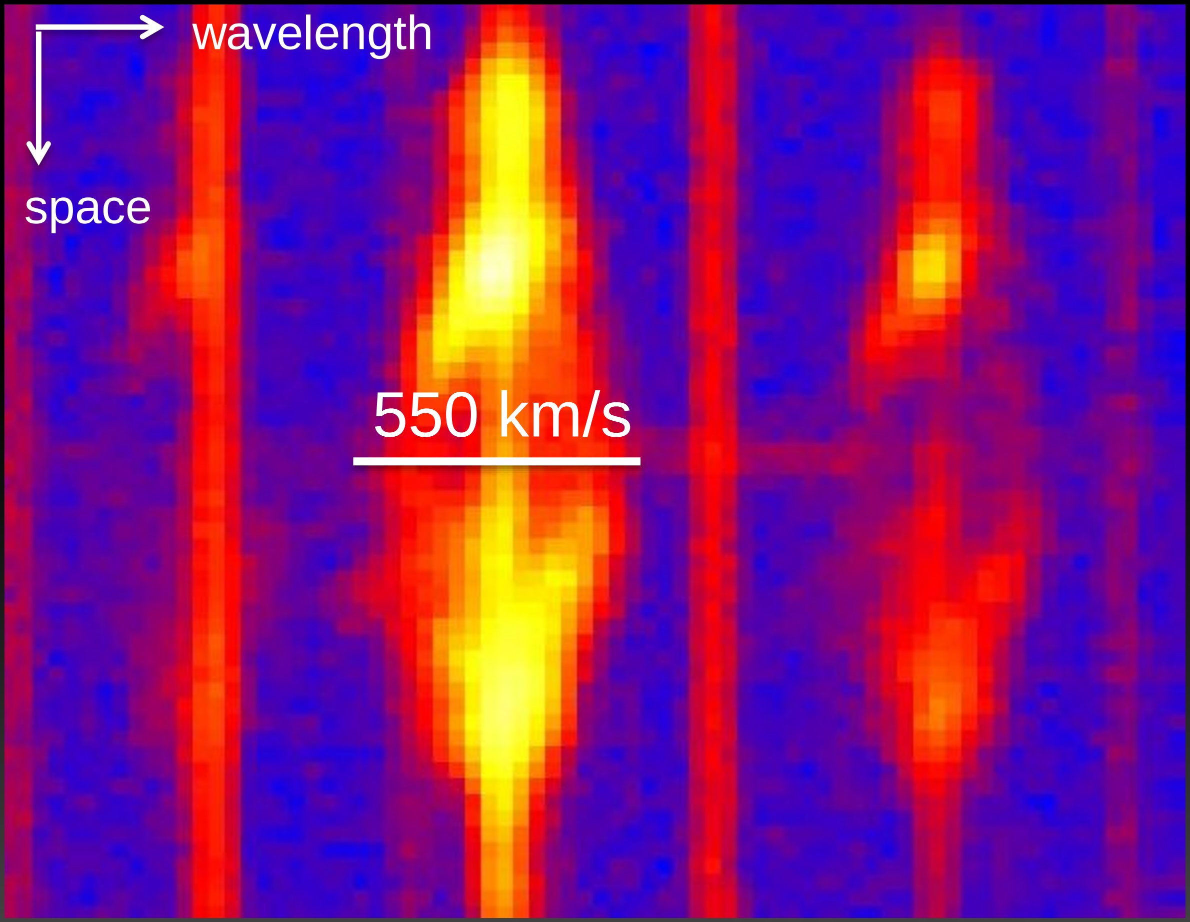
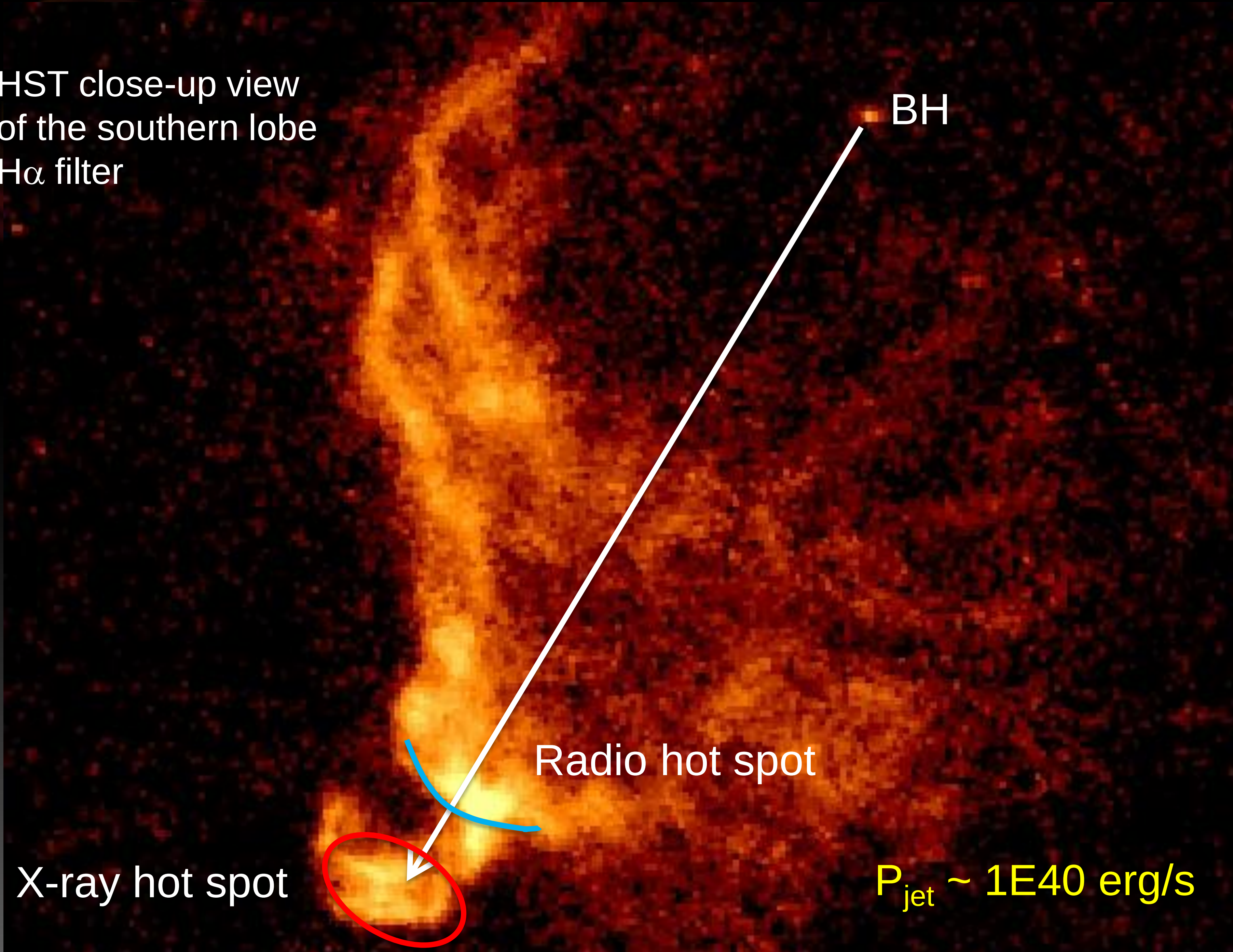
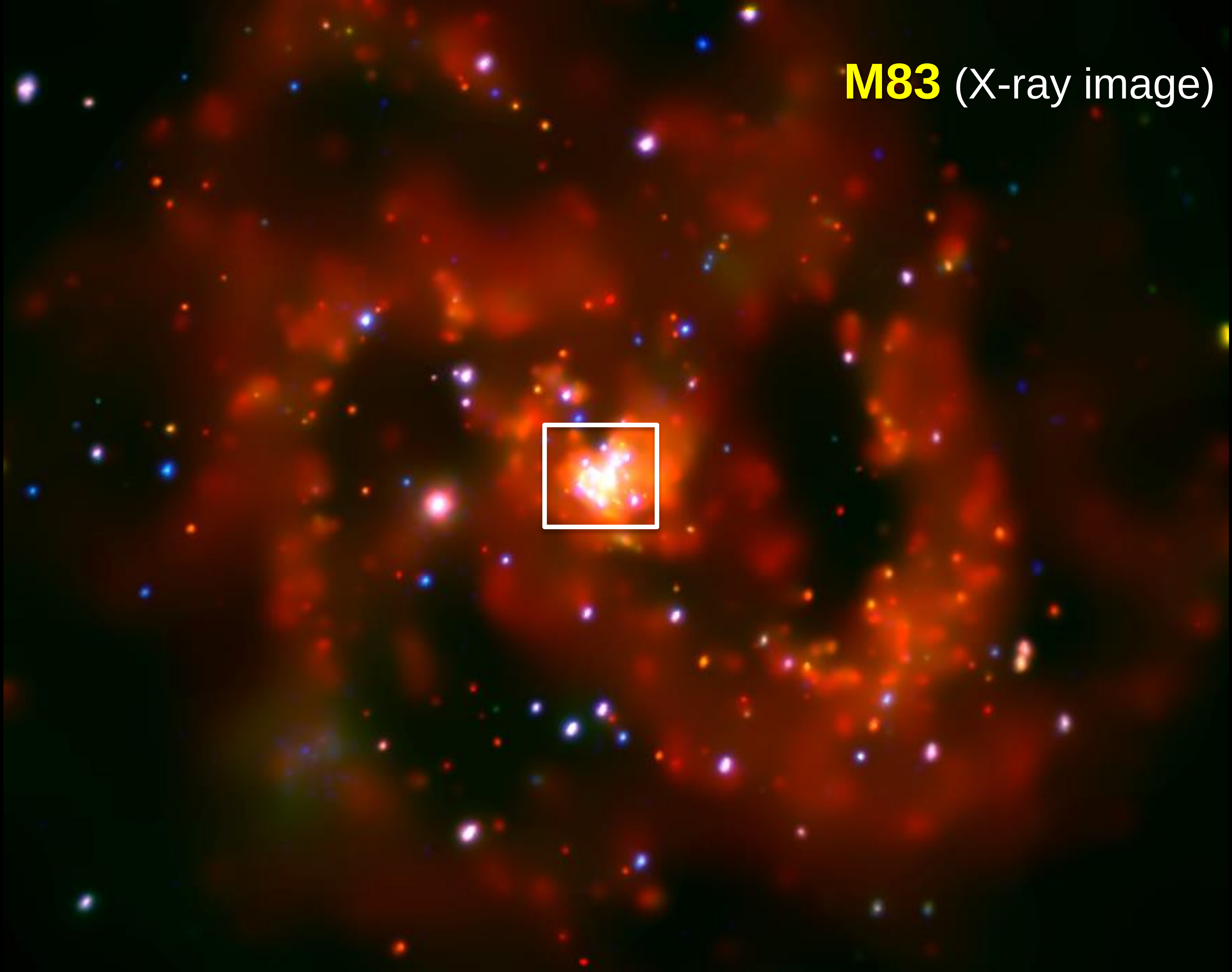


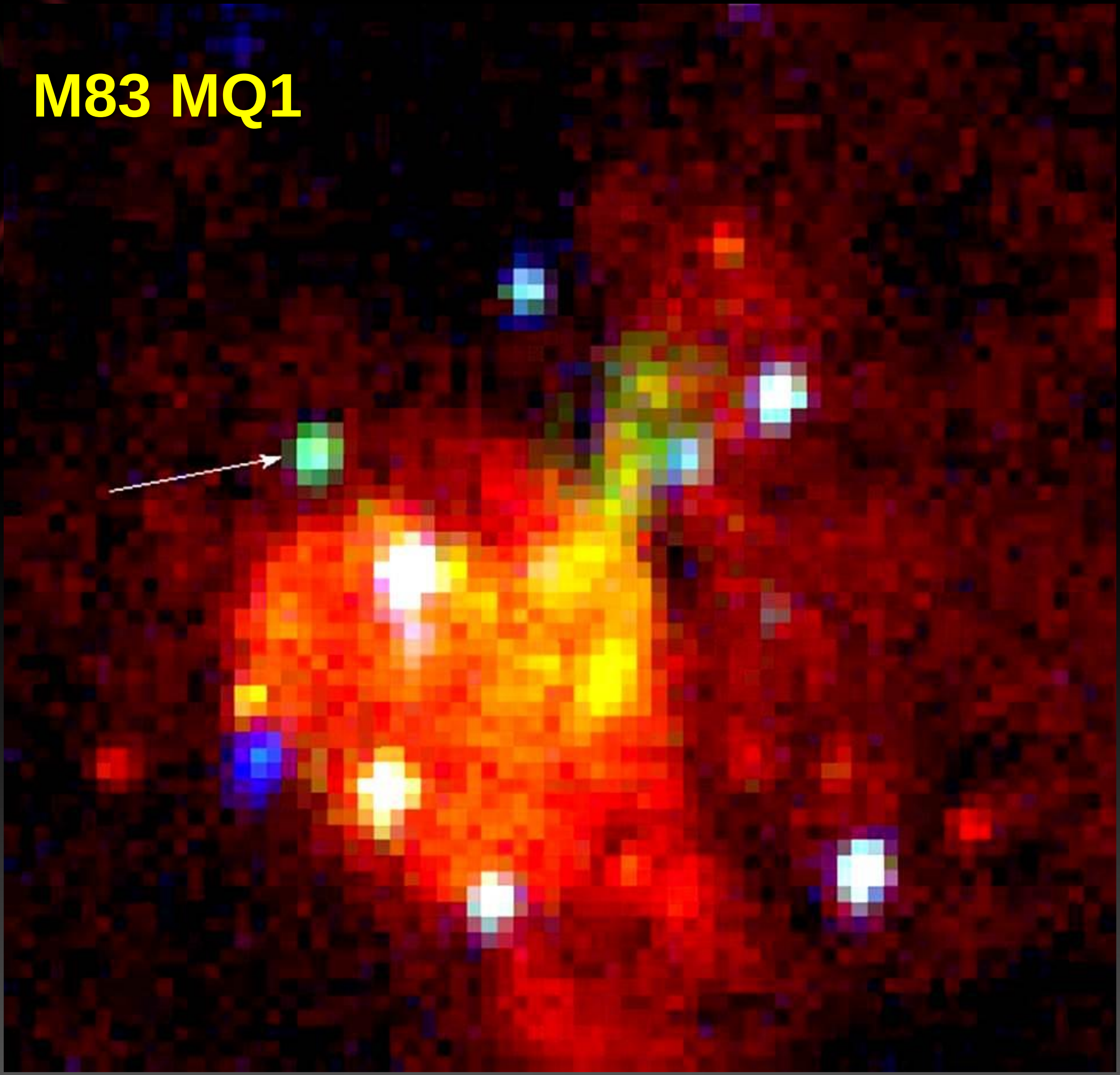
[NII] Hα [NII]

VLT/FORS2 long-sit spectra (Pakull, Motch, Soria & Grise', in prep)


HST close-up view
of the southern lobe
Hα filter
BH
Radio hot spot
X-ray hot spot
P_{jet} ~ 1E40 erg/s

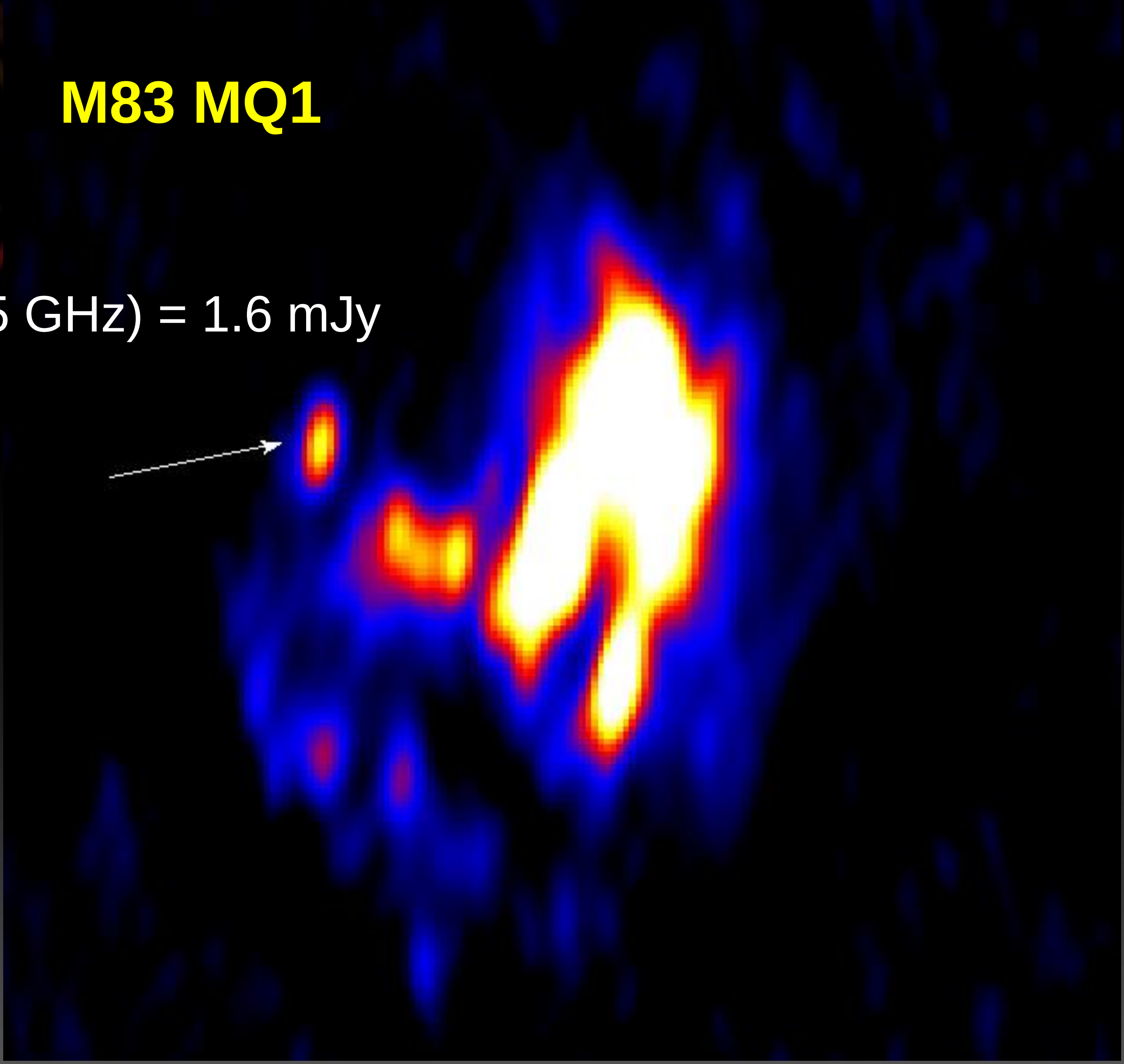

M83 (X-ray image)

M83 MQ1



M83 MQ1

F(5.5 GHz) = 1.6 mJy



M83 MQ1

Shock-ionized hot spots (= powerful jet)
+ photo-ionized core

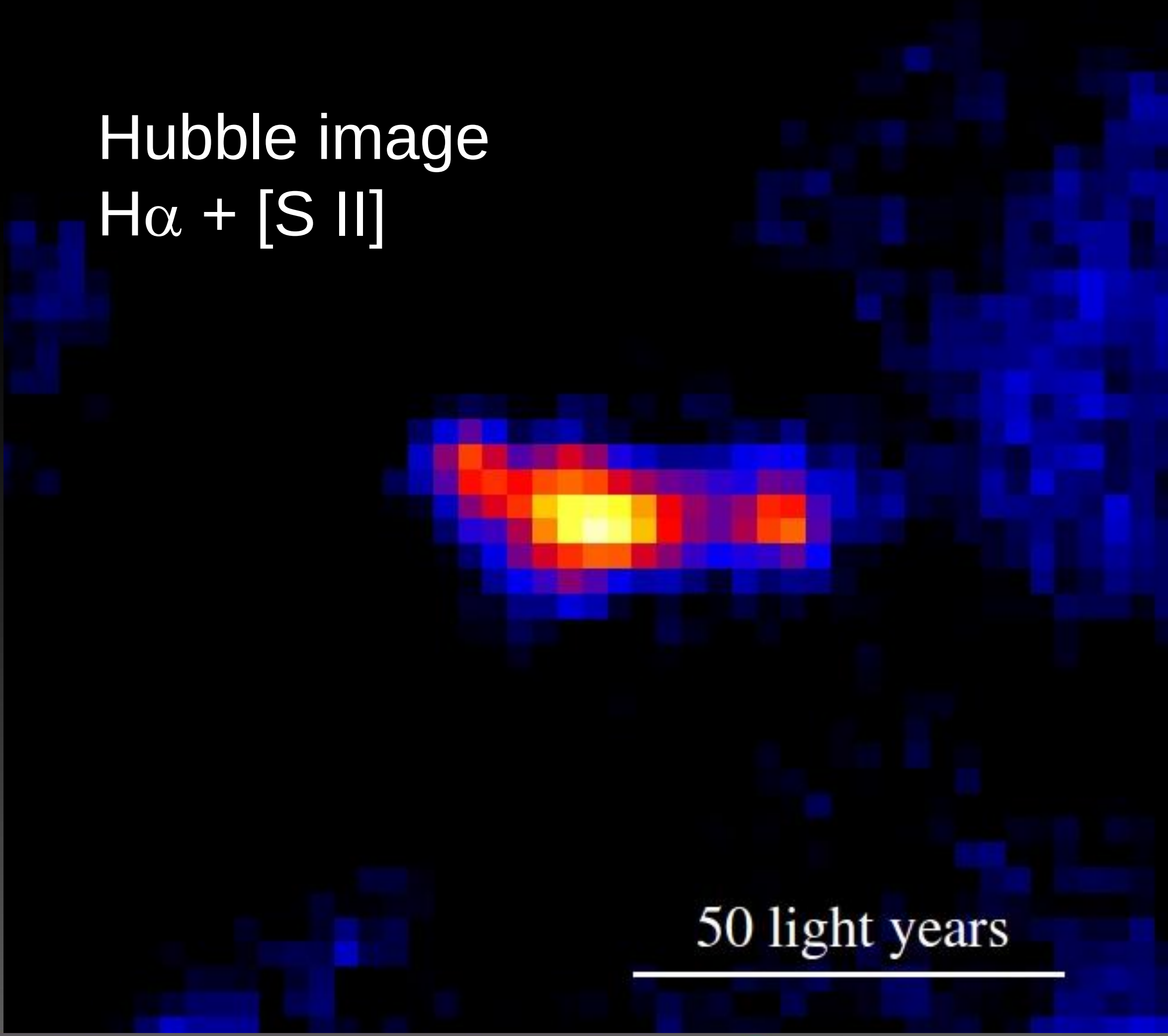
P_{jet} ~ 1E40 erg/s

L_X ~ 1E38 erg/s

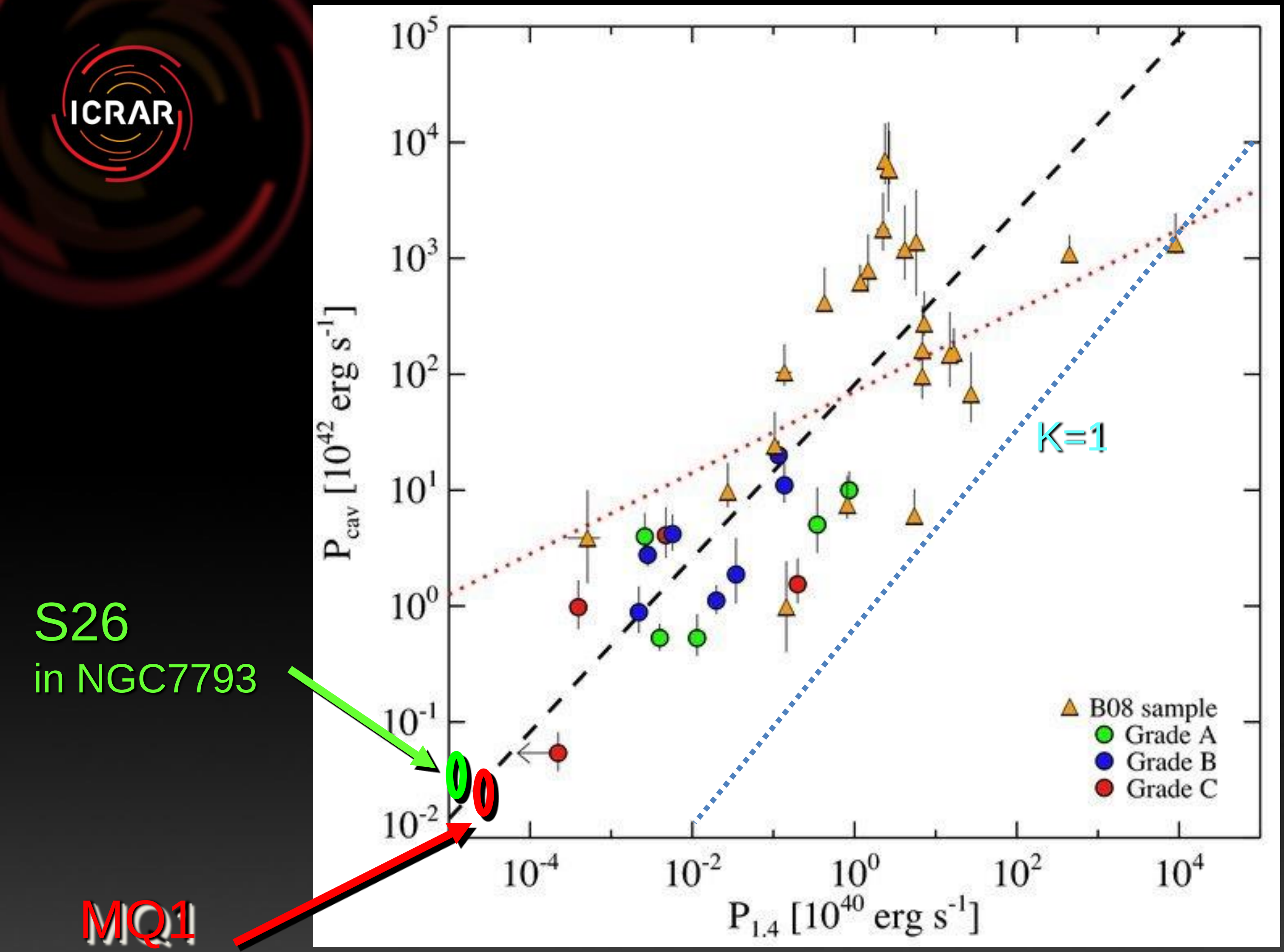
L_{5GHz} ~ 1E35 erg/s

(Soria et al 2014, Science)

Hubble image
Hα + [S II]



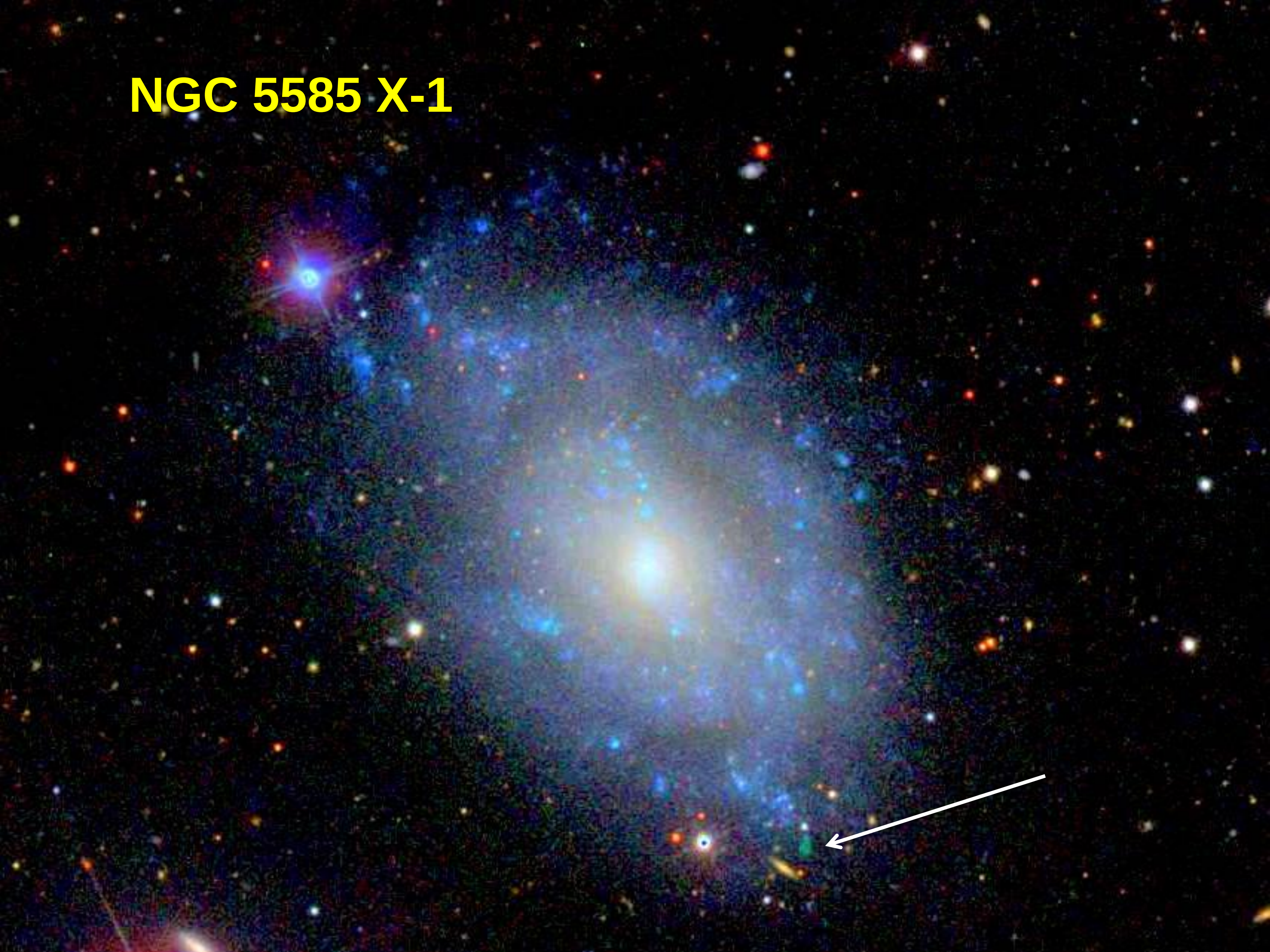
HST/STIS spectrum
approved for 2016

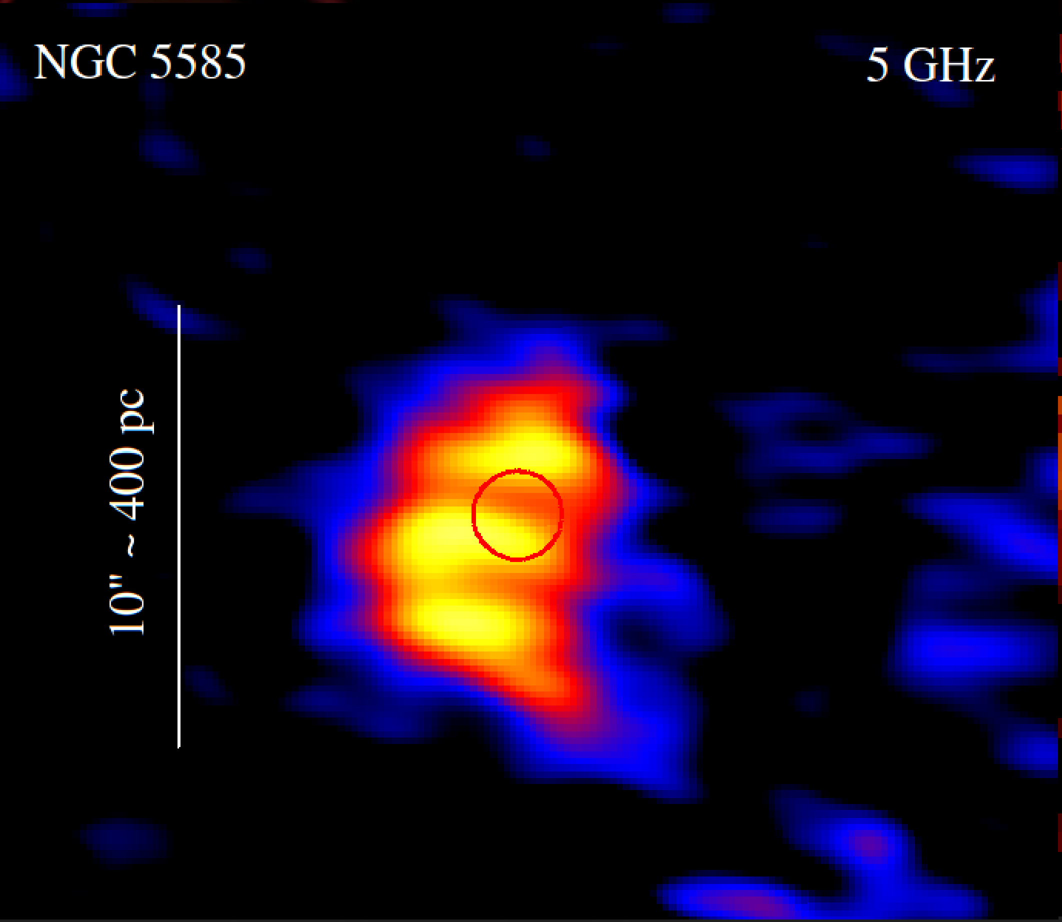


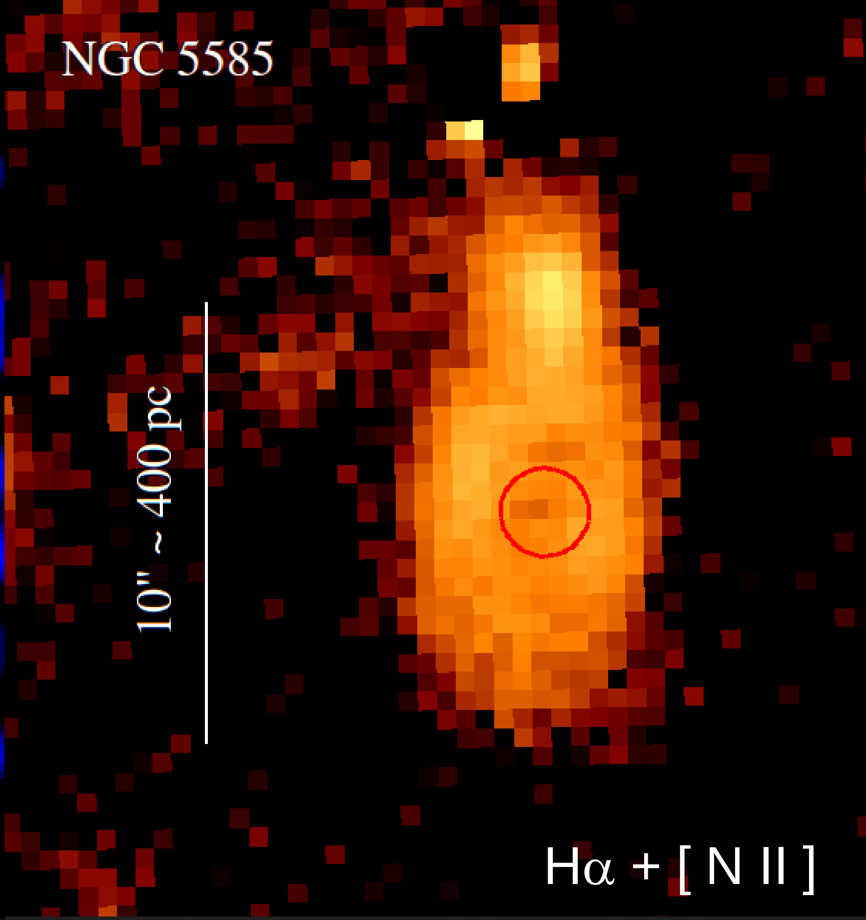
Radio lobe luminosity vs jet power

for a sample of AGN and radio galaxies (Cavagnolo et al 2010)

Power in relativistic electrons ~ (1/100)—(1/1000) of the total jet power


NGC 5585 X-1



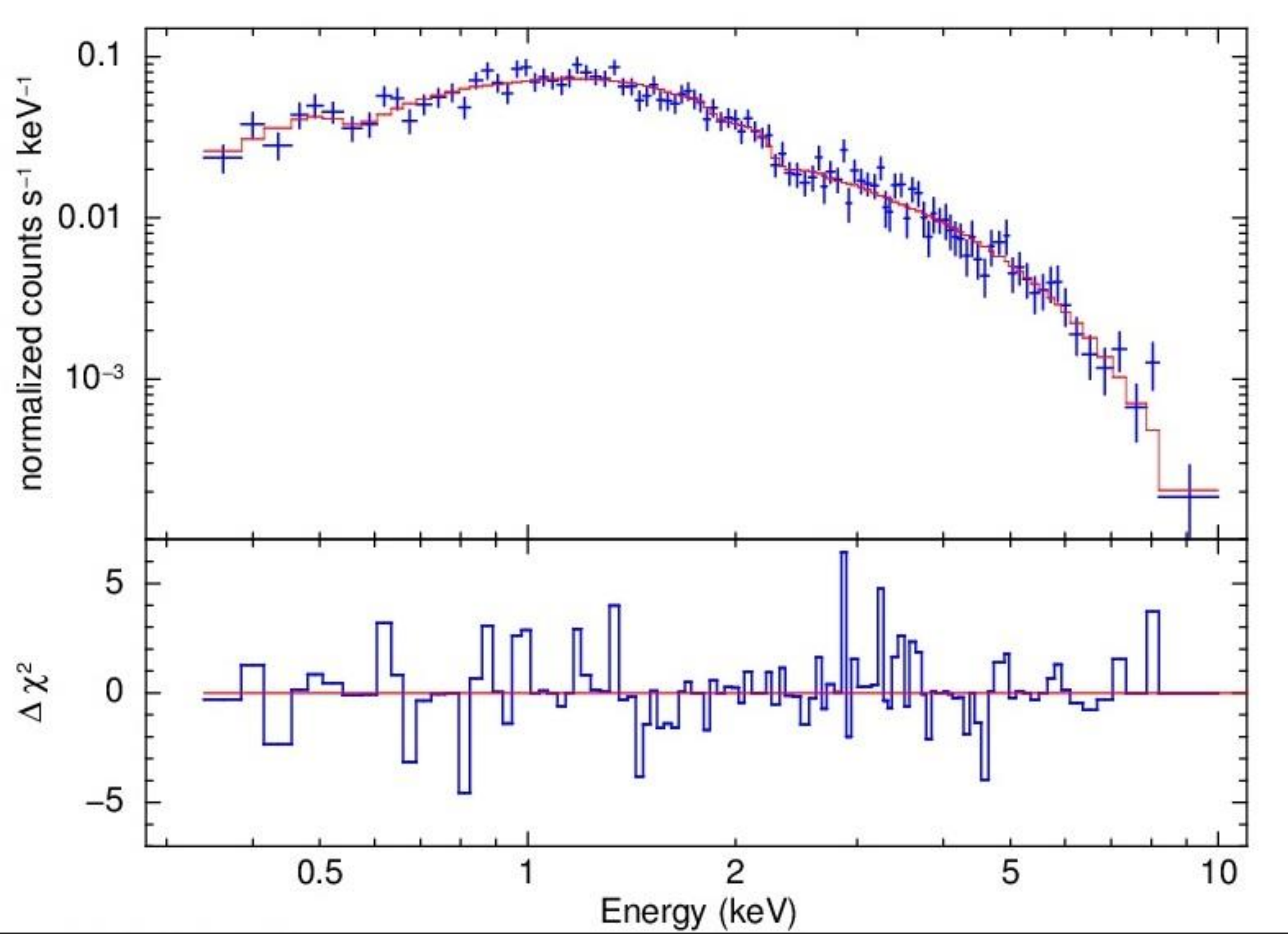


NGC 5585 X-1

$P_{jet} \sim L_X \sim$ 4E39 erg/s

(Soria, Pakull, et al., 2016, in prep.)

Slim-disk ULX
+ shock-ionized bubble



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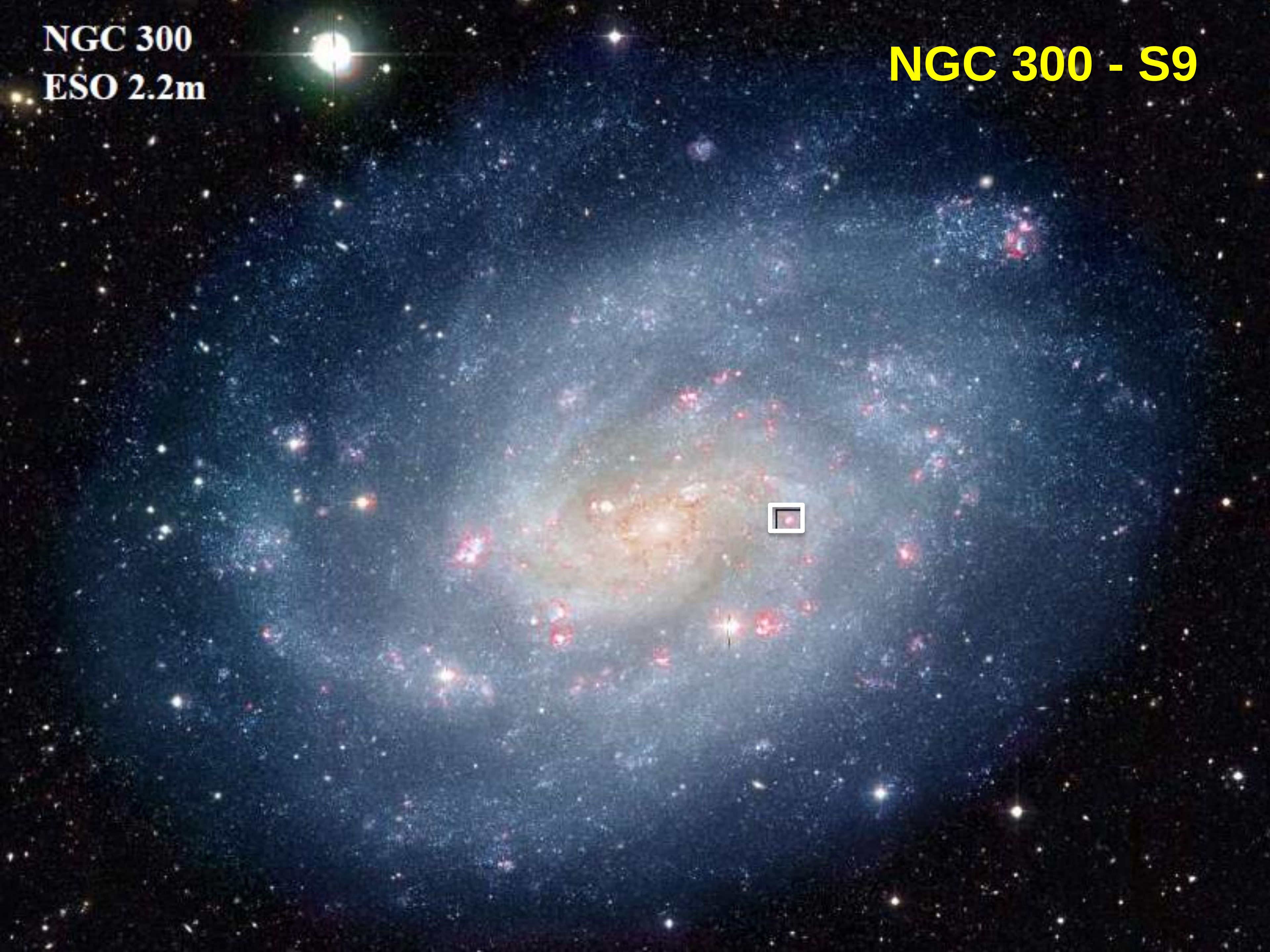
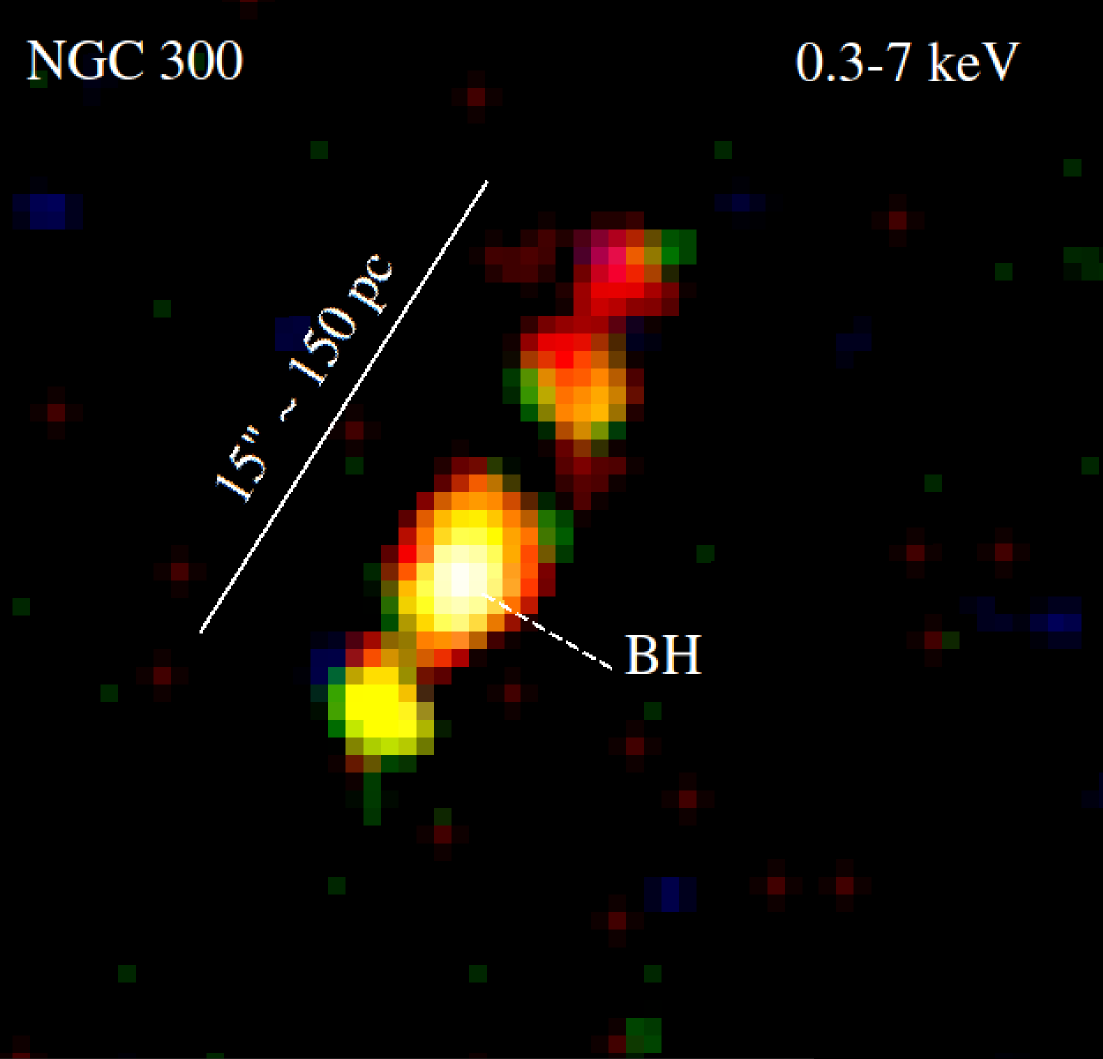
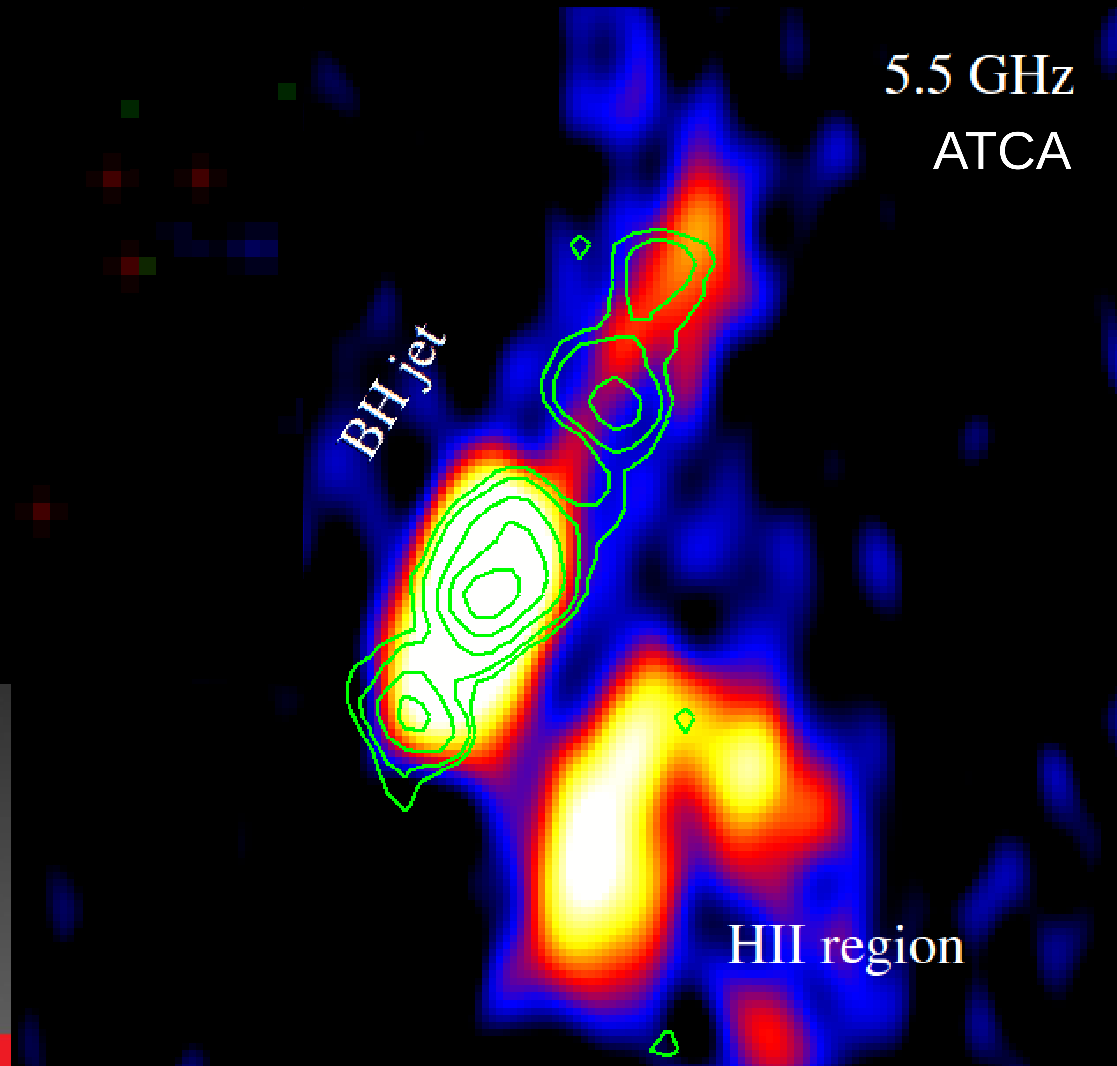

NGC 300
ESO 2.2m
NGC 300 - S9

NGC 300 - S9

Jet with multiple
X-ray knots



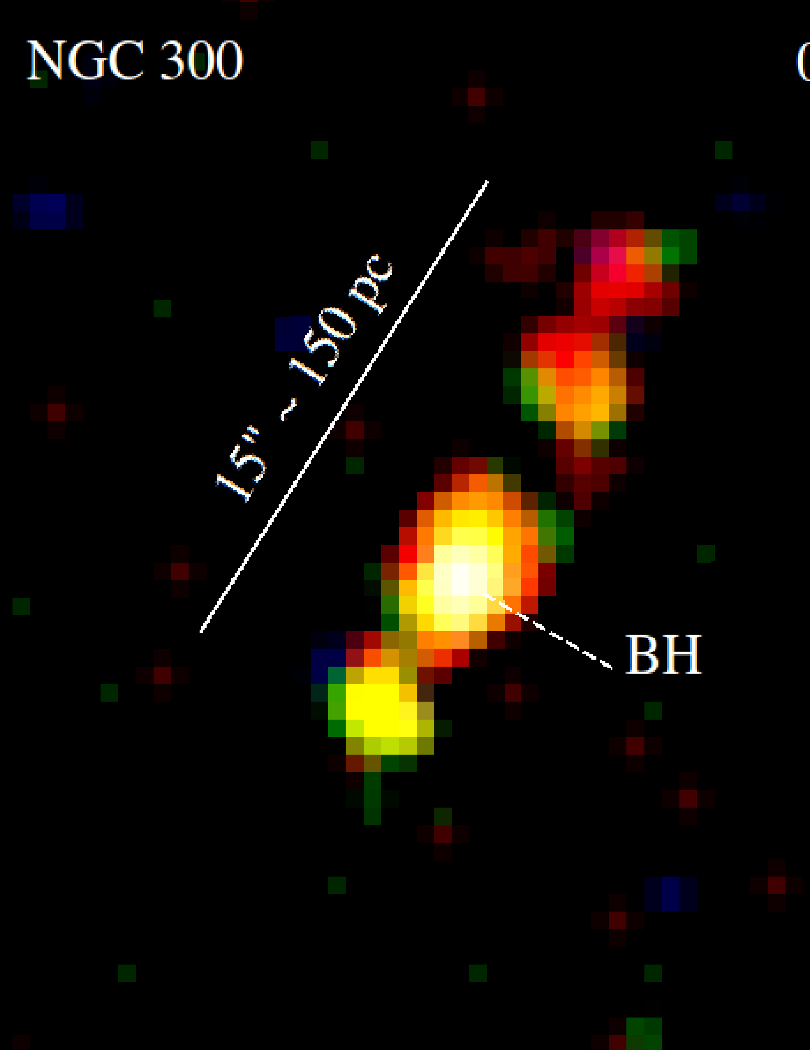


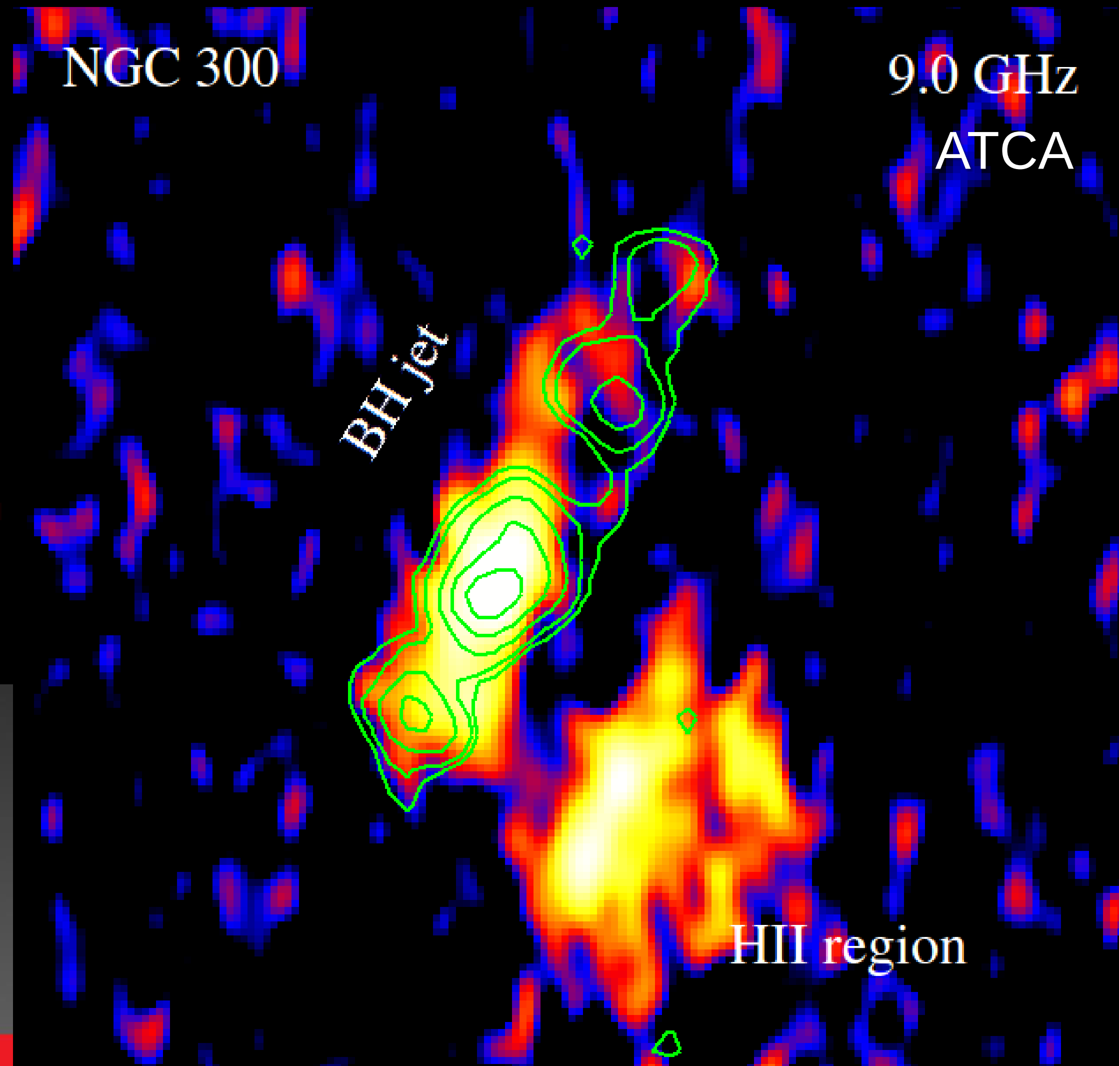
X-ray, Hα
and radio detection

(Soria, Urquhart & Pakull 2016)

NGC 300 - S9

Jet with multiple
X-ray knots





X-ray, Hα
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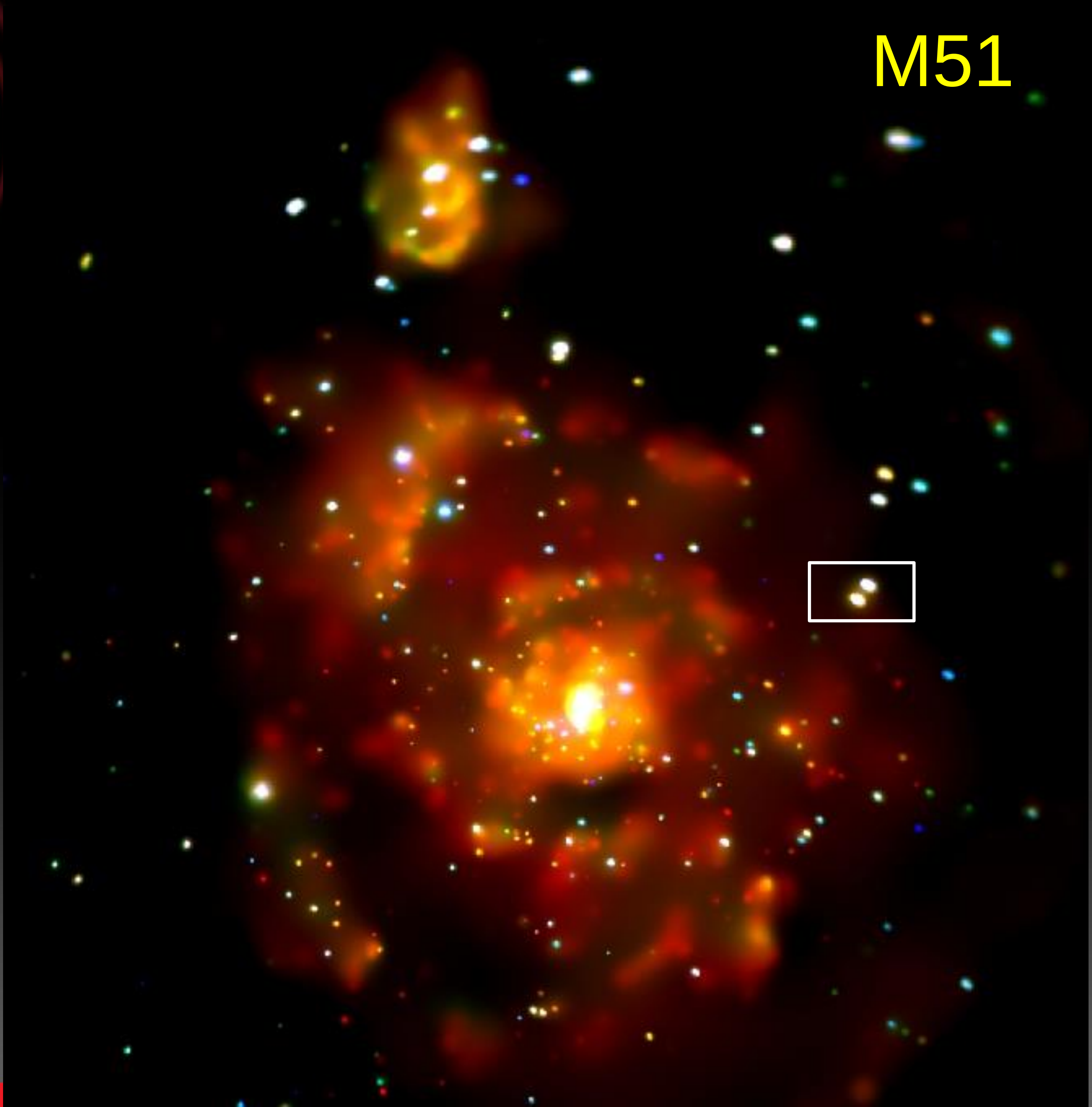
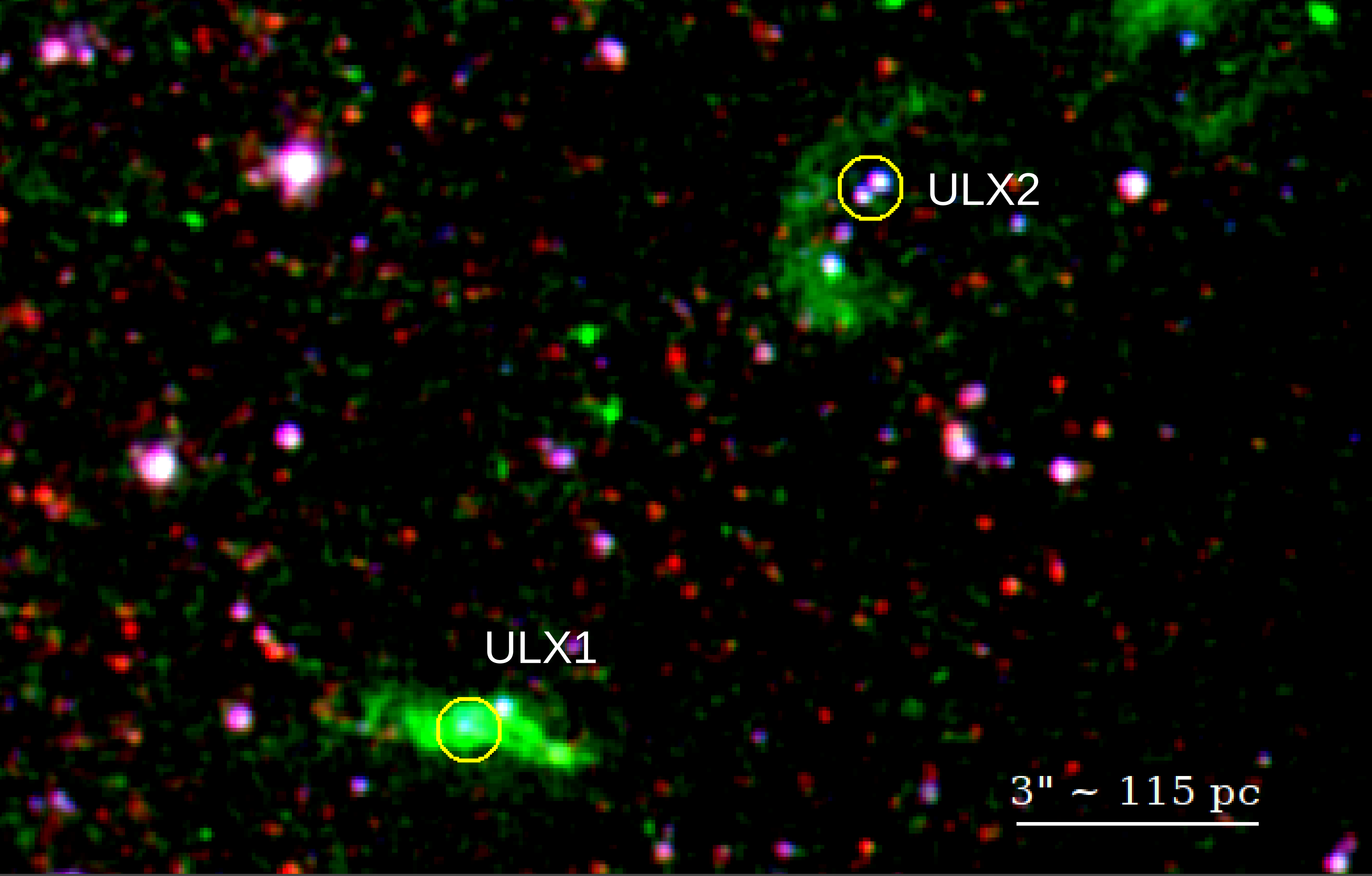
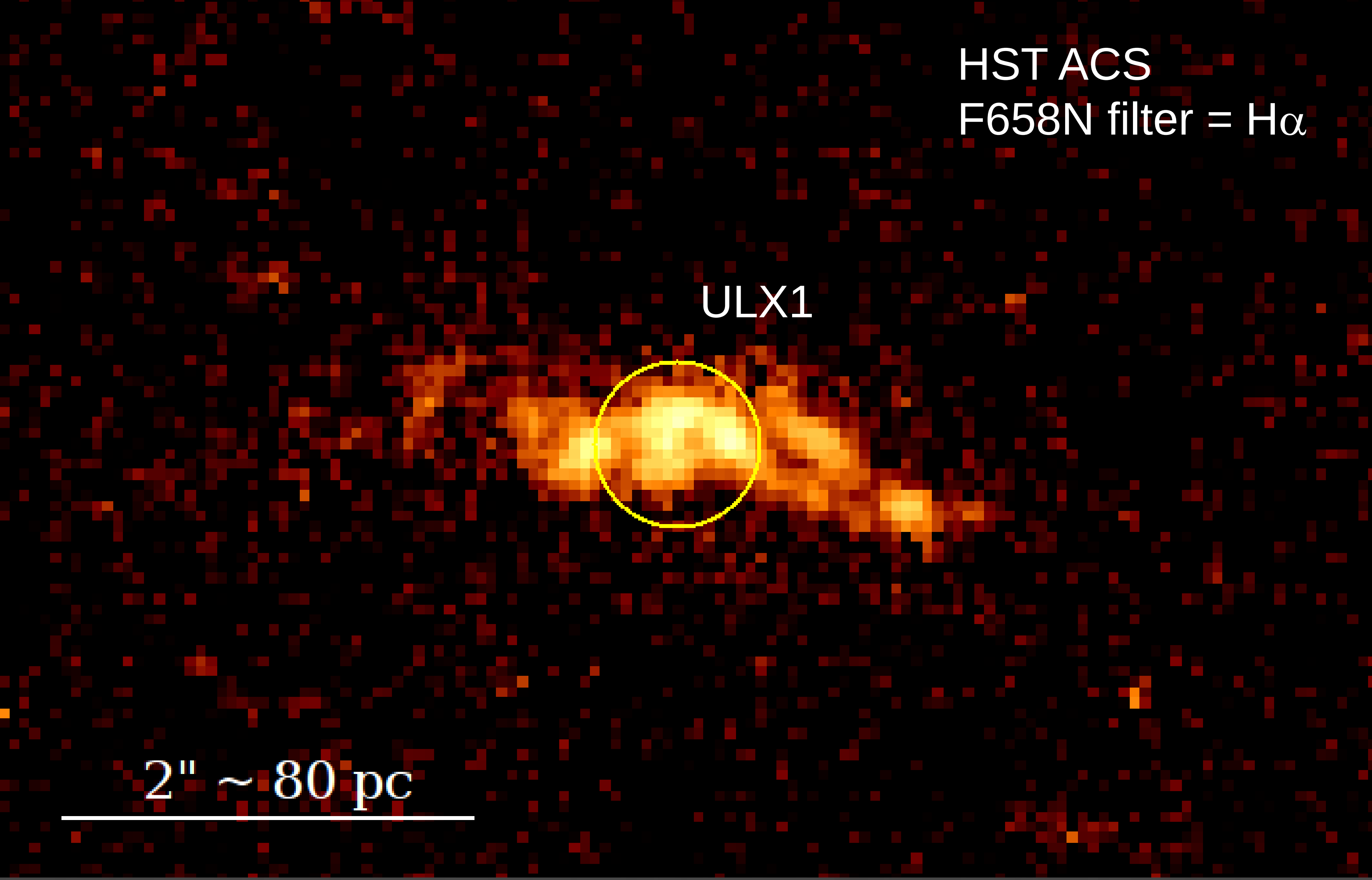

M51



M51

Two ULXs with L_X ~ 1E39 associated with Hα emission

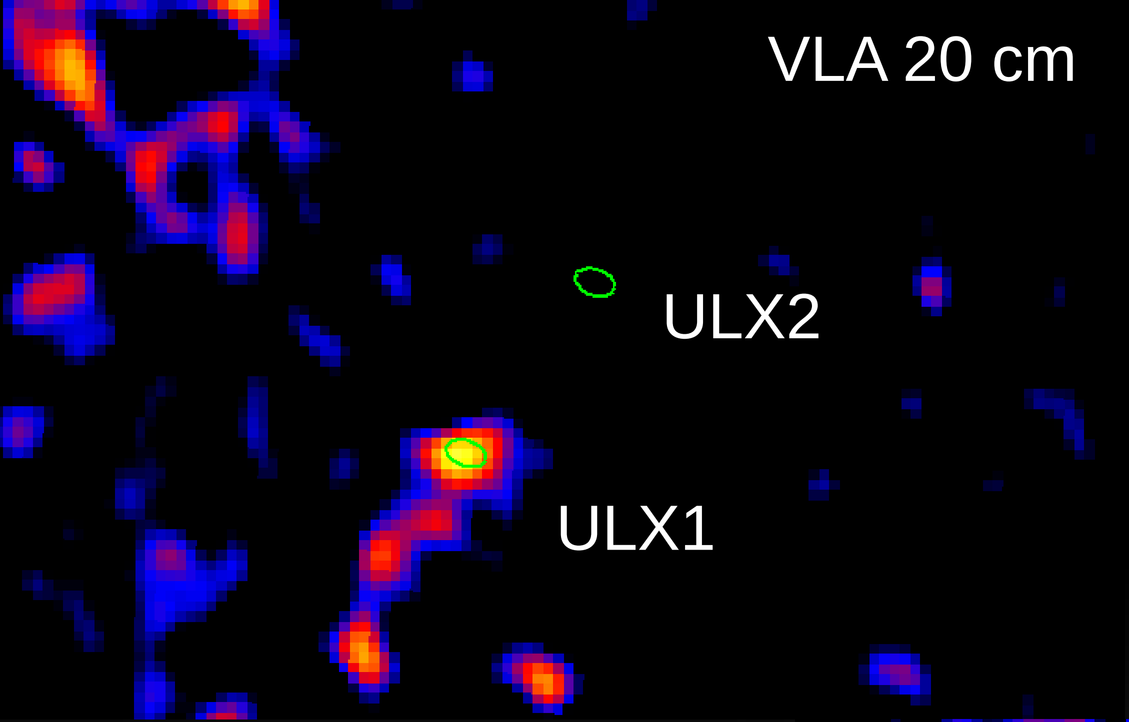
(Soria, Urquhart, et al in prep)



M51

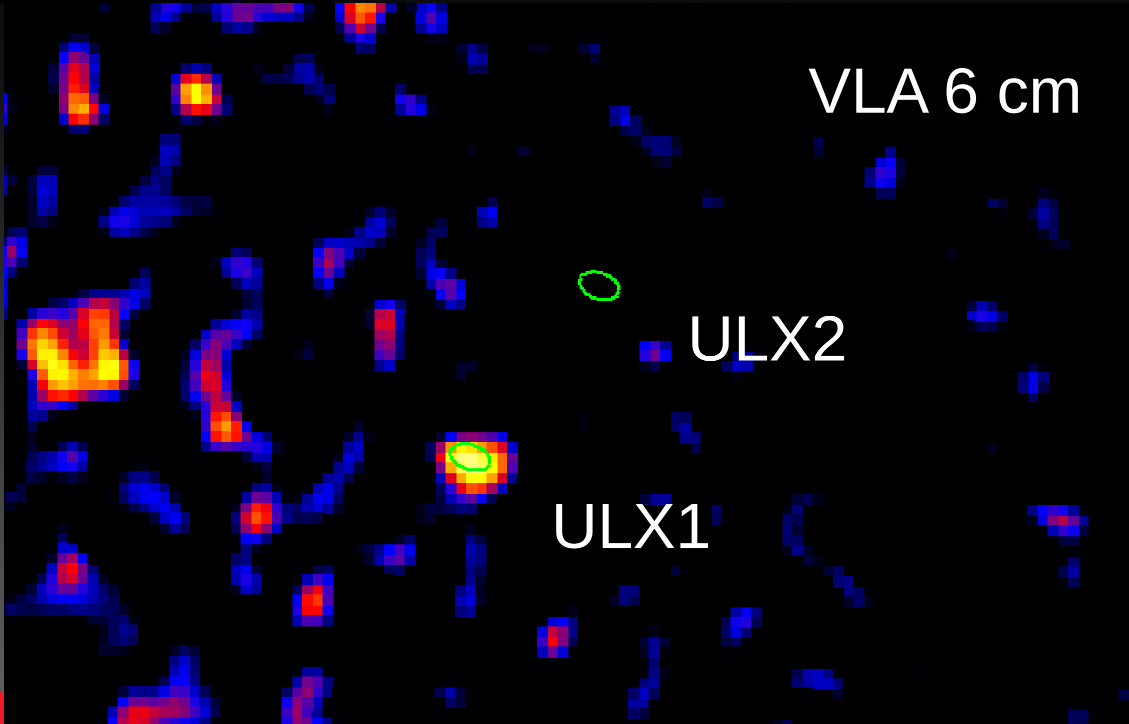
ULX1: evidence of an extended jet

M51



ULX1 is indeed
a strong radio source

(Soria, Urquhart, et al in prep)



Summary of ULX bubble studies

We use BH bubbles as calorimeters for L_X, P_{mech}

We found evidence of powerful BH winds and jets at super-critical accretion rates, P_{mech} > 1E39 erg/s

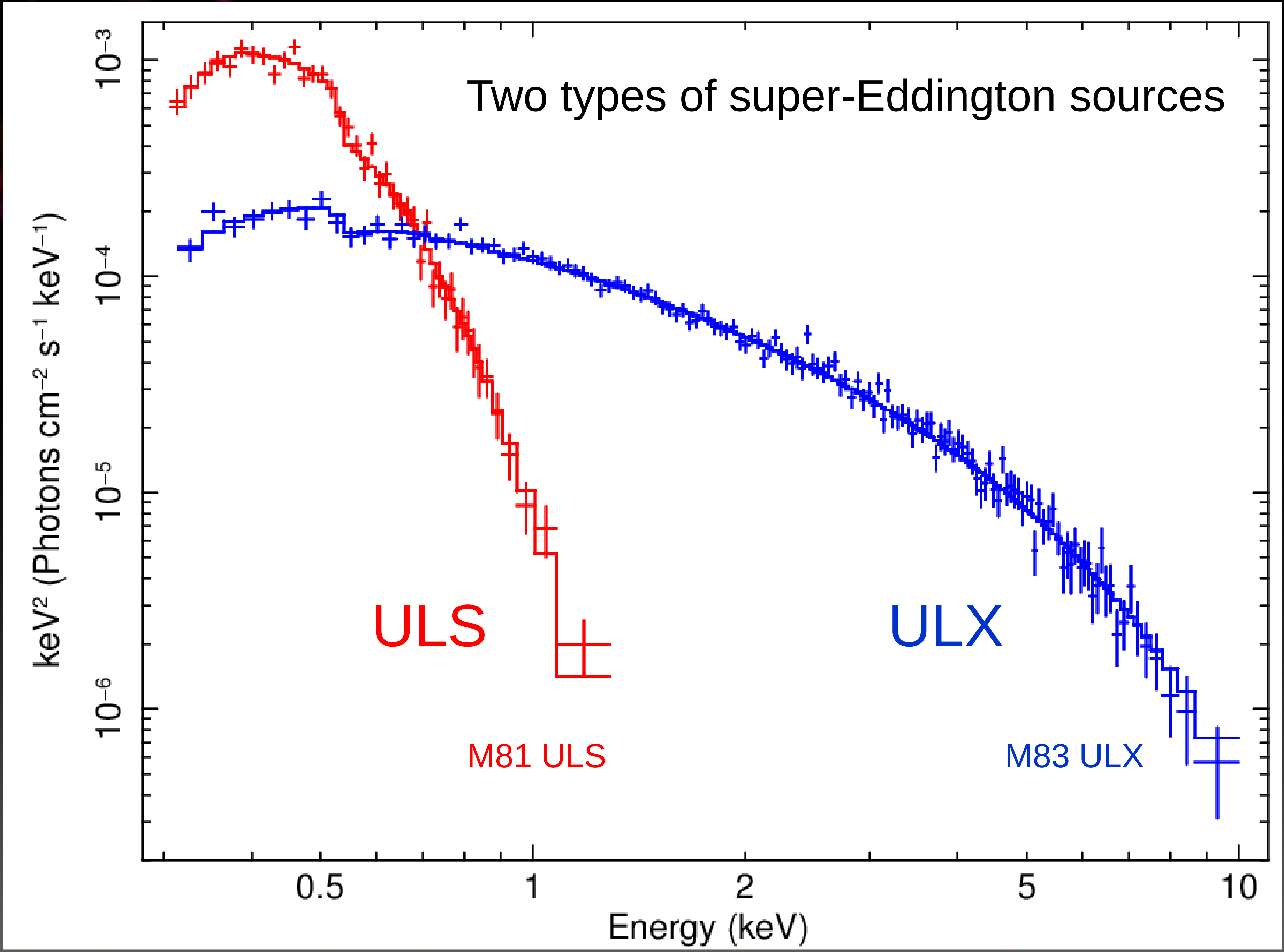
We use L_{radio}/L_{bol} of a bubble to constrain $\varepsilon_e/\varepsilon_p$ = {energy in electrons} / {energy in ions}

Next challenge: find compact radio cores (S_{9GHz} ~ μJy)

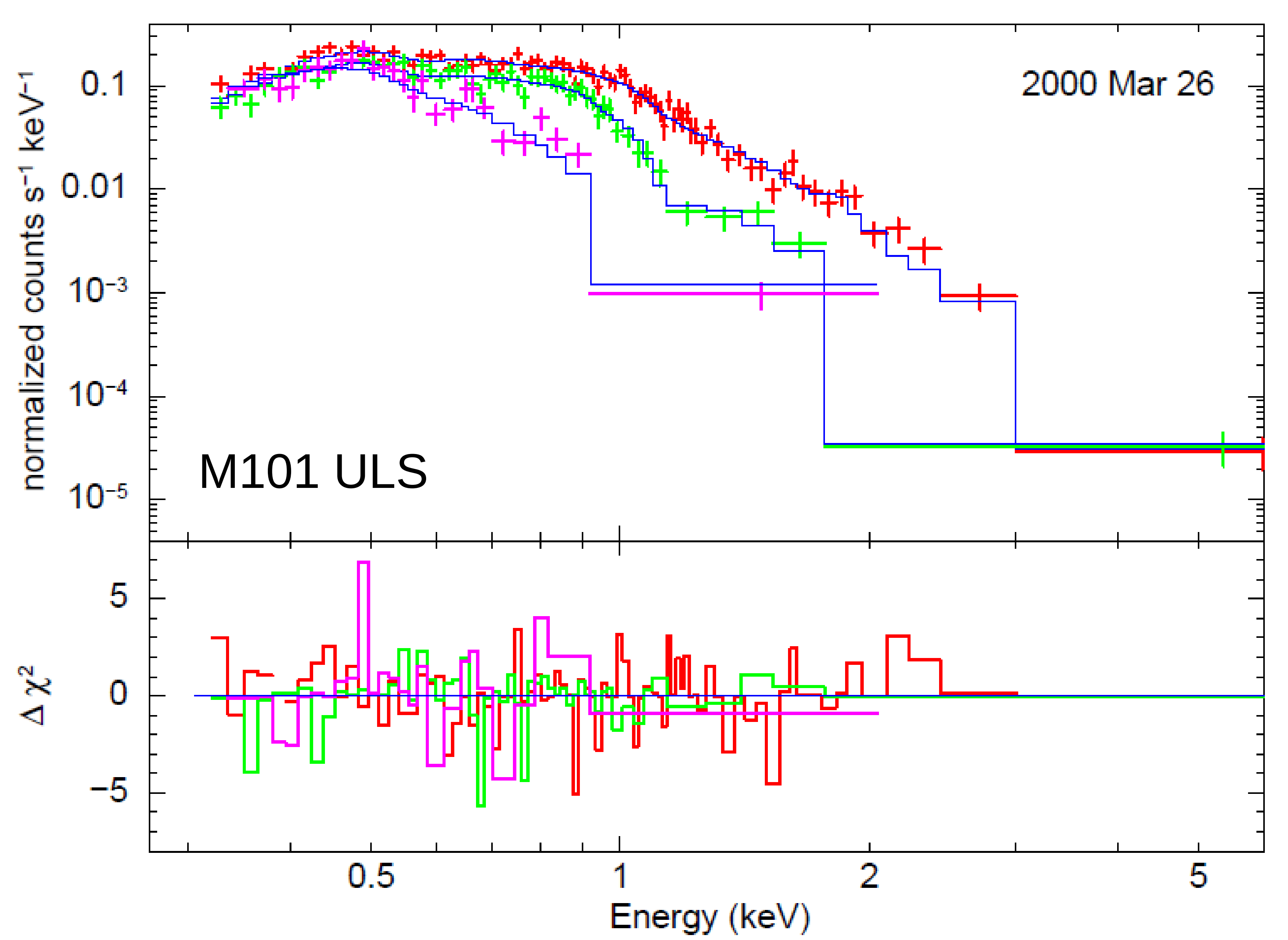
Local-Universe test of feedback & reionization models

Other evidence of outflows in ULXs

Information on outflows from X-ray spectra?



Two types of super-Eddington sources
ULS
ULX
M81 ULS
M83 ULX
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.5
1
2
5
10
Energy (keV)

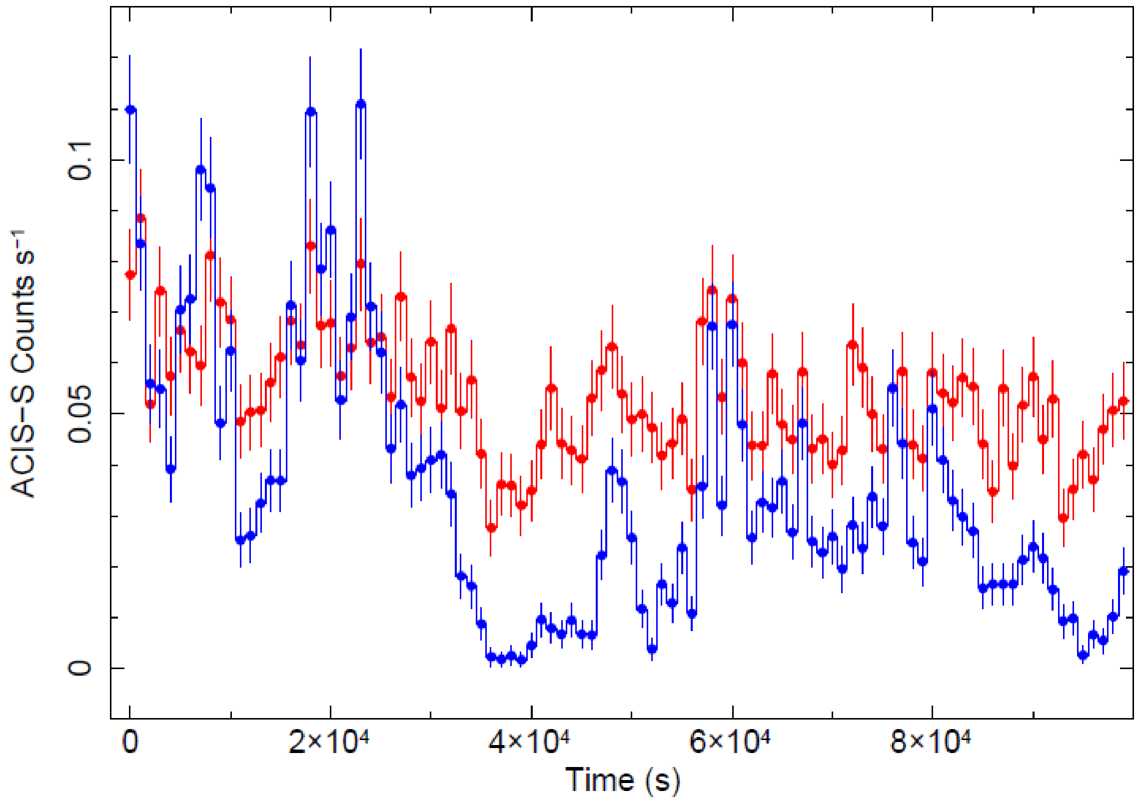


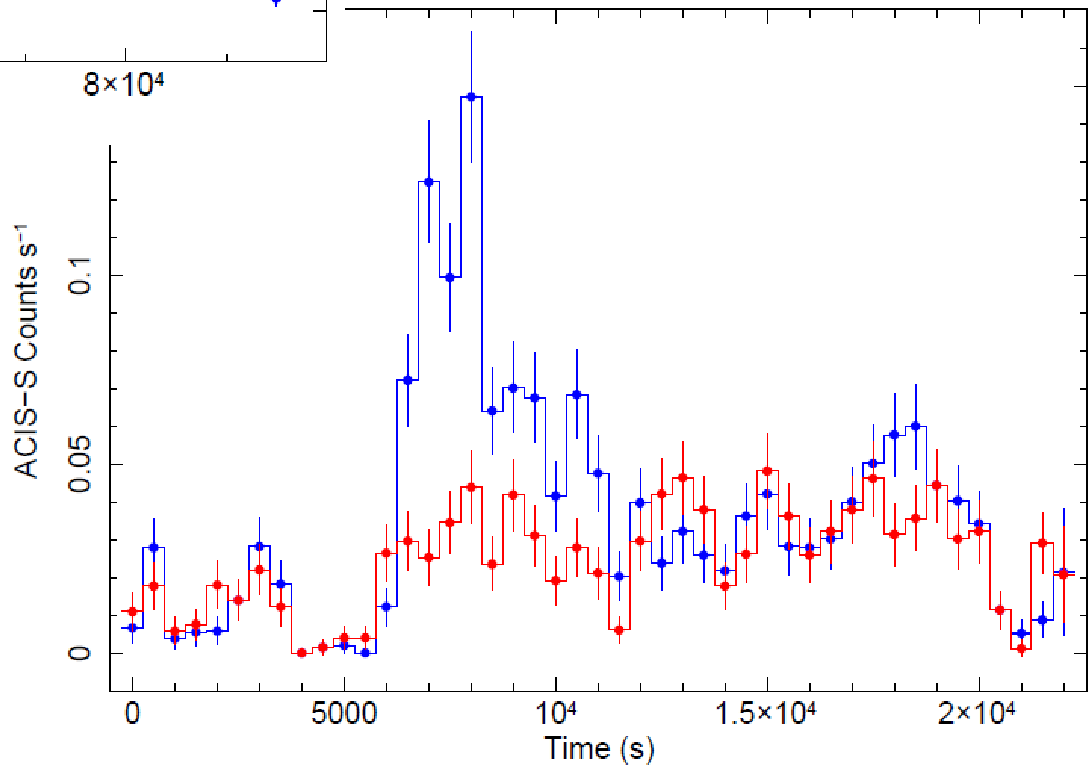
But some ULSs (occasionally) develop a hard tail

(Soria & Kong 2015, MNRAS in press)

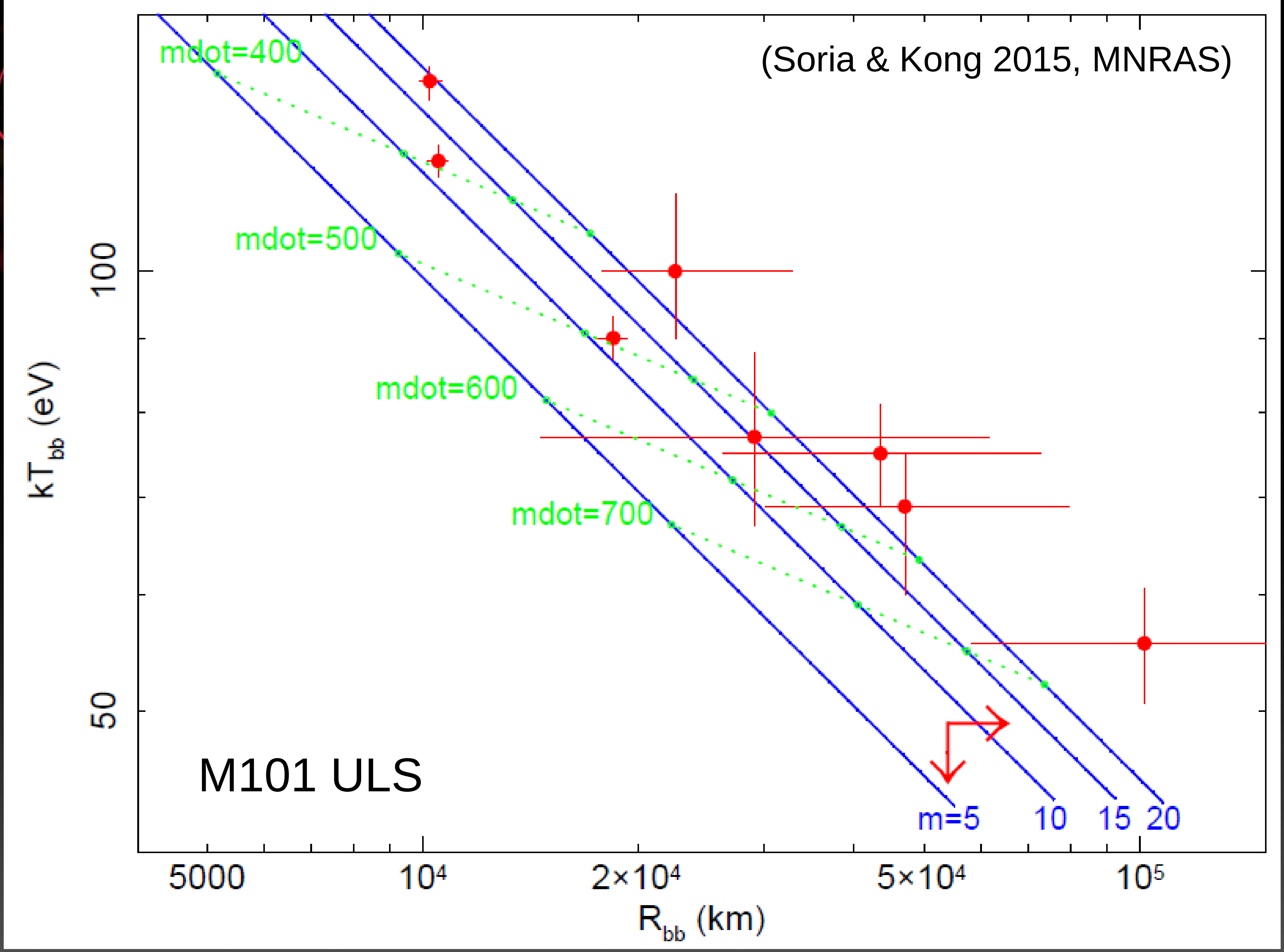
Flaring of the M101 ULS

(Urquhart & Soria 2015, MNRAS, in press)

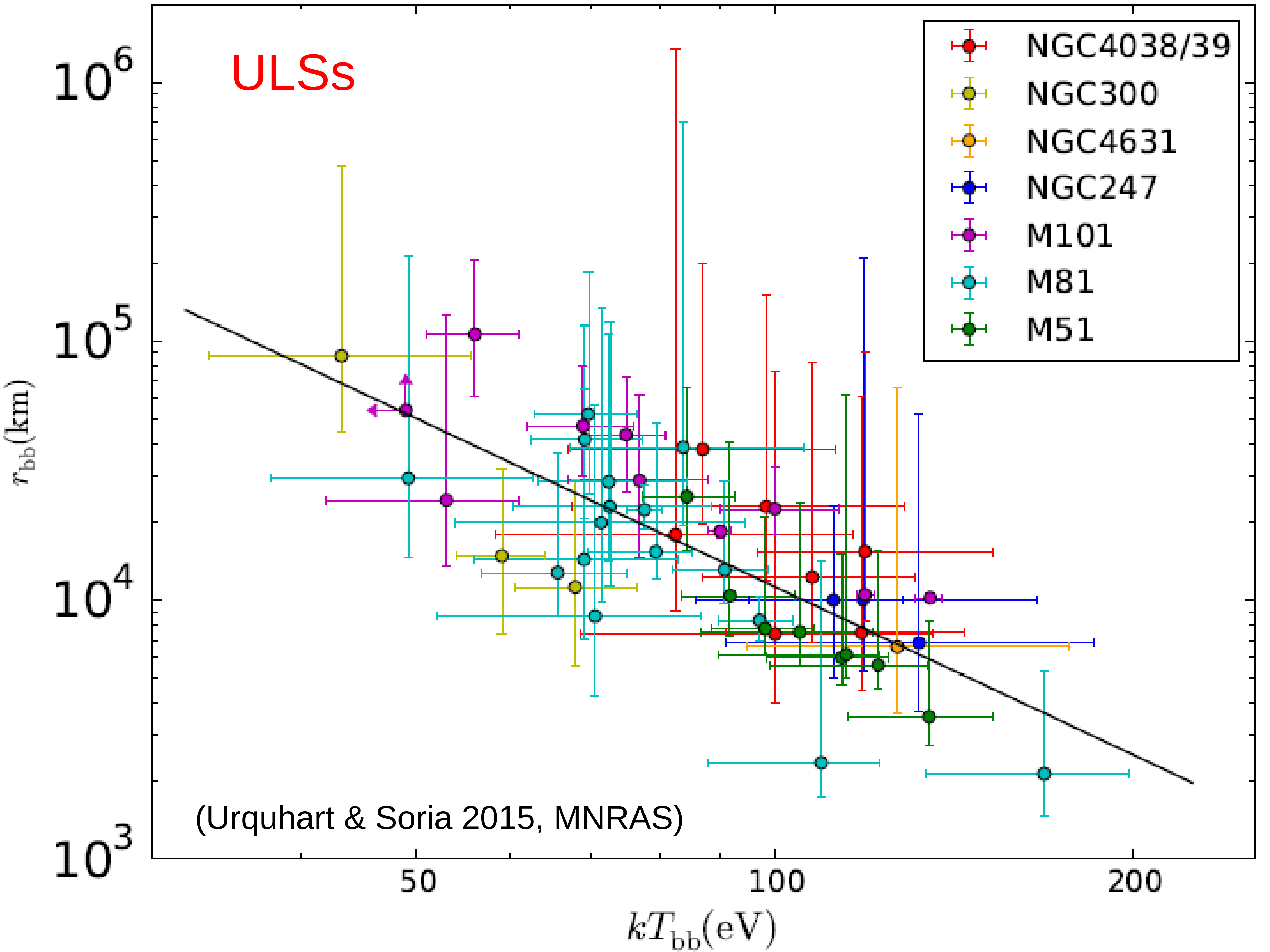




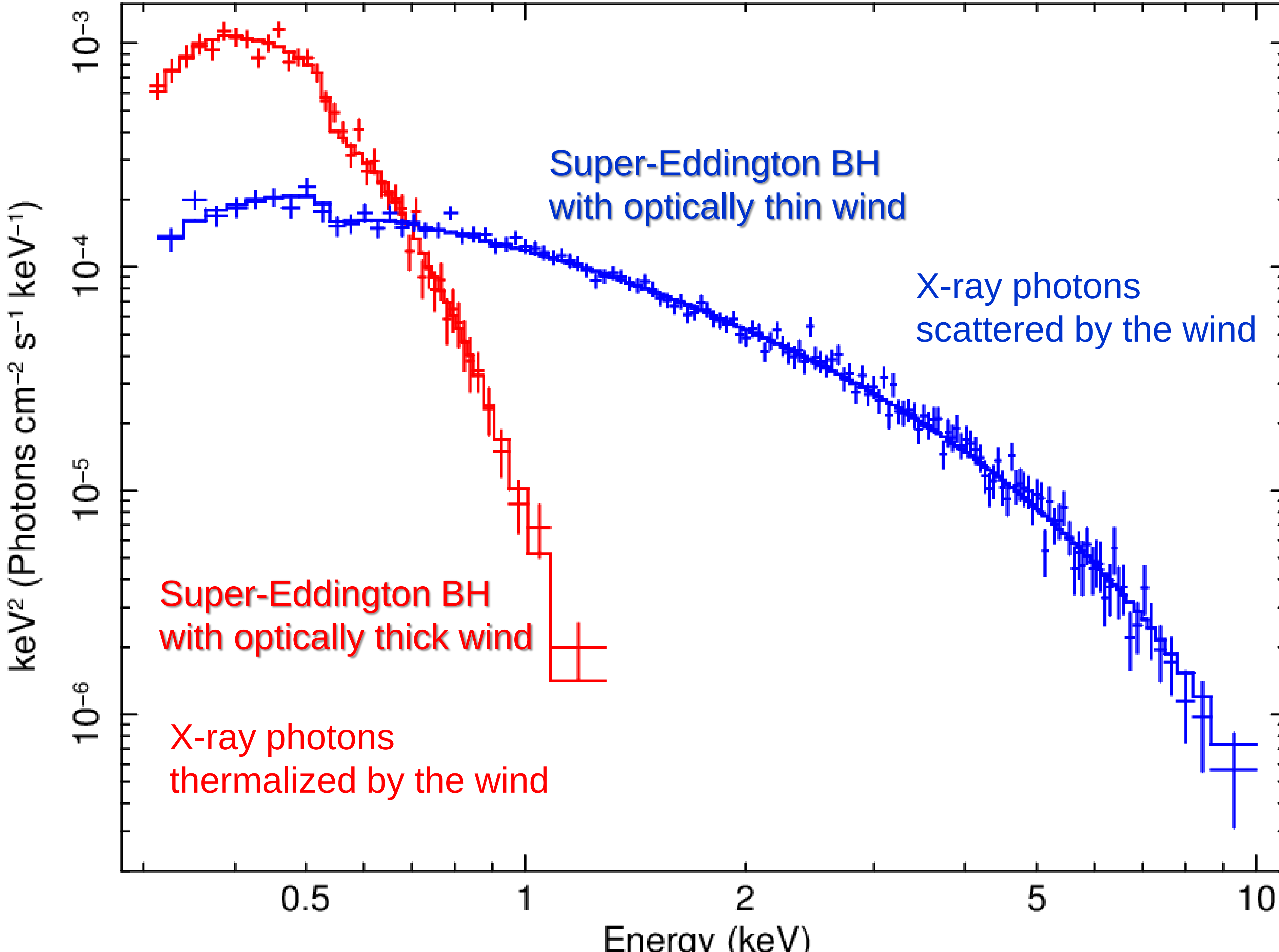
ULS are strongly variables on short timescales



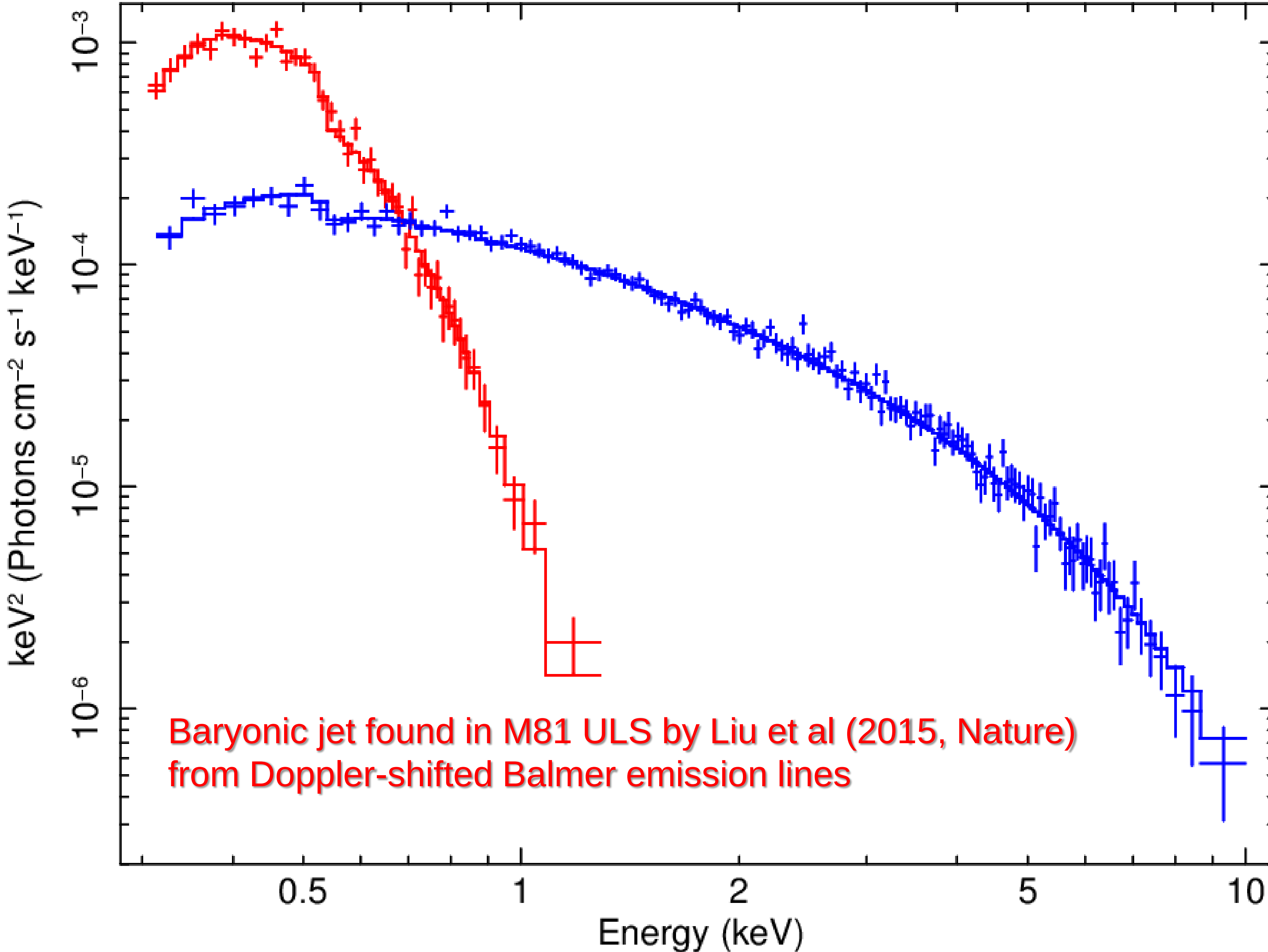
Temperature ~ (Radius)^{-1/2}



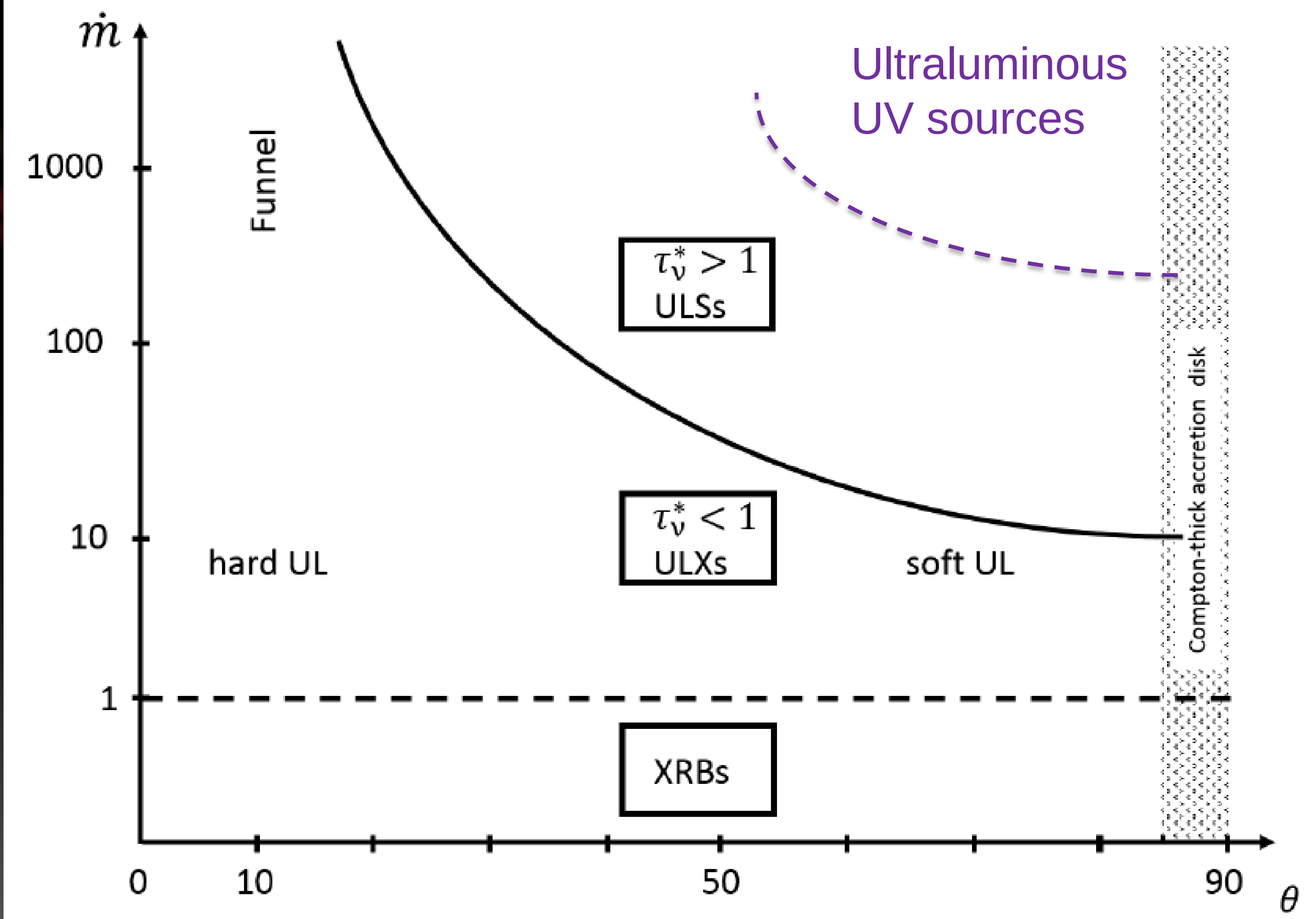
ULSs
NGC4038/39
NGC300
NGC4631
NGC247
M101
M81
M51
10^6
10^5
10^4
10^3
$r_{\rm bb}({\rm km})$
50
100
200
$kT_{\rm bb}({\rm eV})$
(Urquhart & Soria 2015, MNRAS)



Super-Eddington BH
with optically thin wind
X-ray photons
scattered by the wind
Super-Eddington BH
with optically thick wind
X-ray photons
thermalized by the wind
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.5
1
2
5
10
Energy (keV)



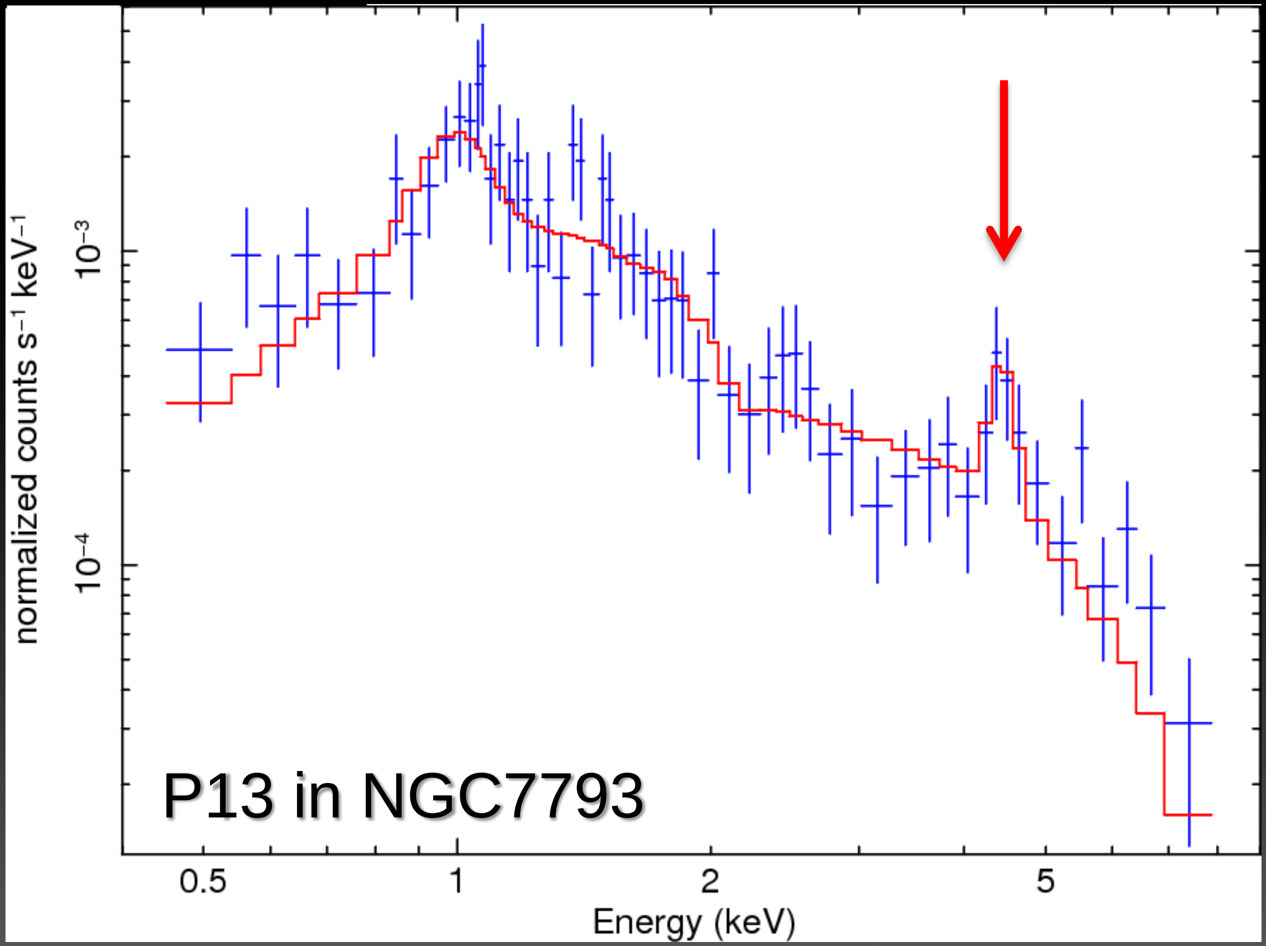
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.5
1
2
5
10
Energy (keV)
Baryonic jet found in M81 ULS by Liu et al (2015, Nature)
from Doppler-shifted Balmer emission lines



(Urquhart & Soria 2015)

Evidence of relativistic baryonic jets in a super-Eddington ULX

Emission line at E = 4.4 keV
Redshifted 6.7-keV Fe line? (v~c, i=70º)



(130 ks on XMM-Newton waiting for trigger)

Conclusions

Super-critical accretion produces strong outflows,
sometimes **also jets**

Outflows observed in radio, optical, X-ray bands

Optical/radio bubbles = calorimeters for kinetic power

P_{mech} >~ a few E39 erg/s ~ L_X

Wind effective $\tau < 1$: Ultraluminous X-ray sources

Wind effective $\tau > 1$: Ultraluminous supersoft sources