ULX jets, outflows and bubbles

Roberto Soria
(UCAS/NAOC)

Also thanks to:
Ryan Urquhart *(Michigan State University)*
James Miller-Jones *(ICRAR-Curtin)*
Manfred Pakull *(Strasbourg Observatory)*
Christian Motch *(Strasbourg Observatory)*
Jifeng Liu *(NAOC)*

Outline

1. Kinetic and radiative power from accretion

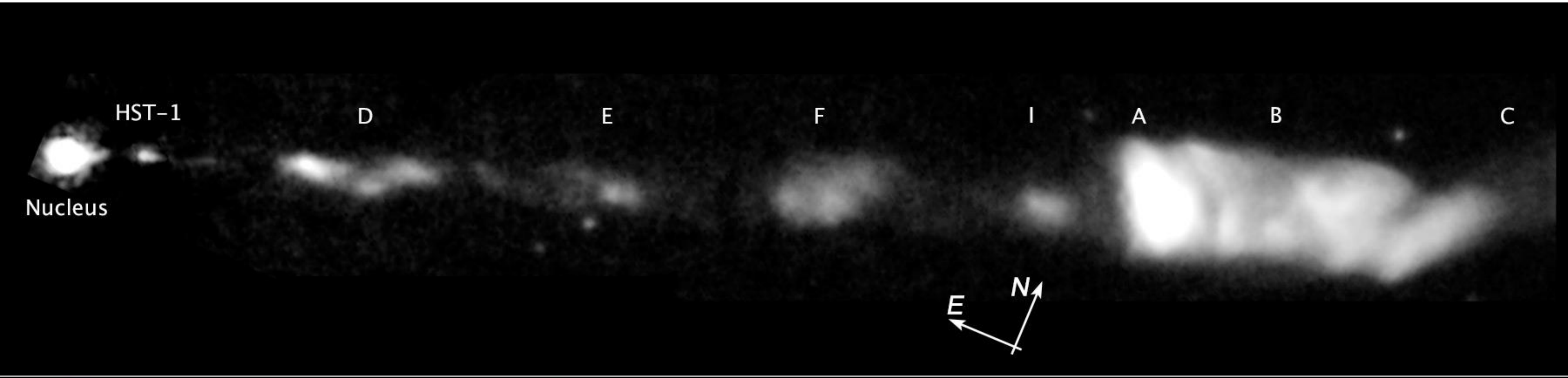
2. Signature of outflows in the photon output

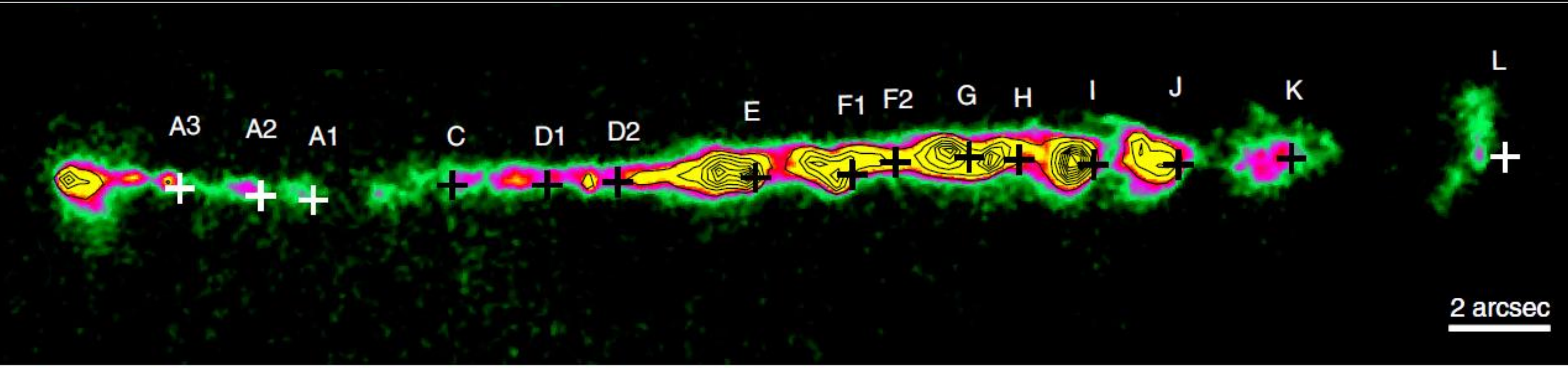
3. Interaction of outflows with surrounding gas

4. Difference between BH and NS outflows?

Accretion ⟷ jets, outflows

M87 jet (HST image; Perlman et al 2001)





Herbig-Haro source 34 in Orion (HST [SII] image; Antoniucci et al 2014)

Accretion ⟷ jets, outflows

Jet produced at all scales (compact object + accretion)

Jet velocity ~ escape velocity from the compact object

Protostars (Herbig Haro objects)
White dwarfs
Neutron stars
Stellar-mass BHs
Gamma-ray bursts
Supermassive BHs in: Tidal disruption events
AGN
Quasars

In this talk I will focus on the super-critical regime

Definitions

Eddington limit

luminosity at which radiation pressure force = gravitational force

Critical mass accretion rate (mdot = 1)

rate at which $L = L_{Edd}$ for standard efficient accretion

Super-critical accretion

when accretion rate mdot > 1

↓

may result in

- Super-Eddington luminosity
- Jets, outflows
- Inefficient accretion (photon trapping)

Open problems of super-critical accretion

1. Inflow structure near ISCO

- Temperature, geometry, wind emission & abs lines
- Difference between magnetic/non-magnetic accretors

2. Jets in the super-Eddington regime

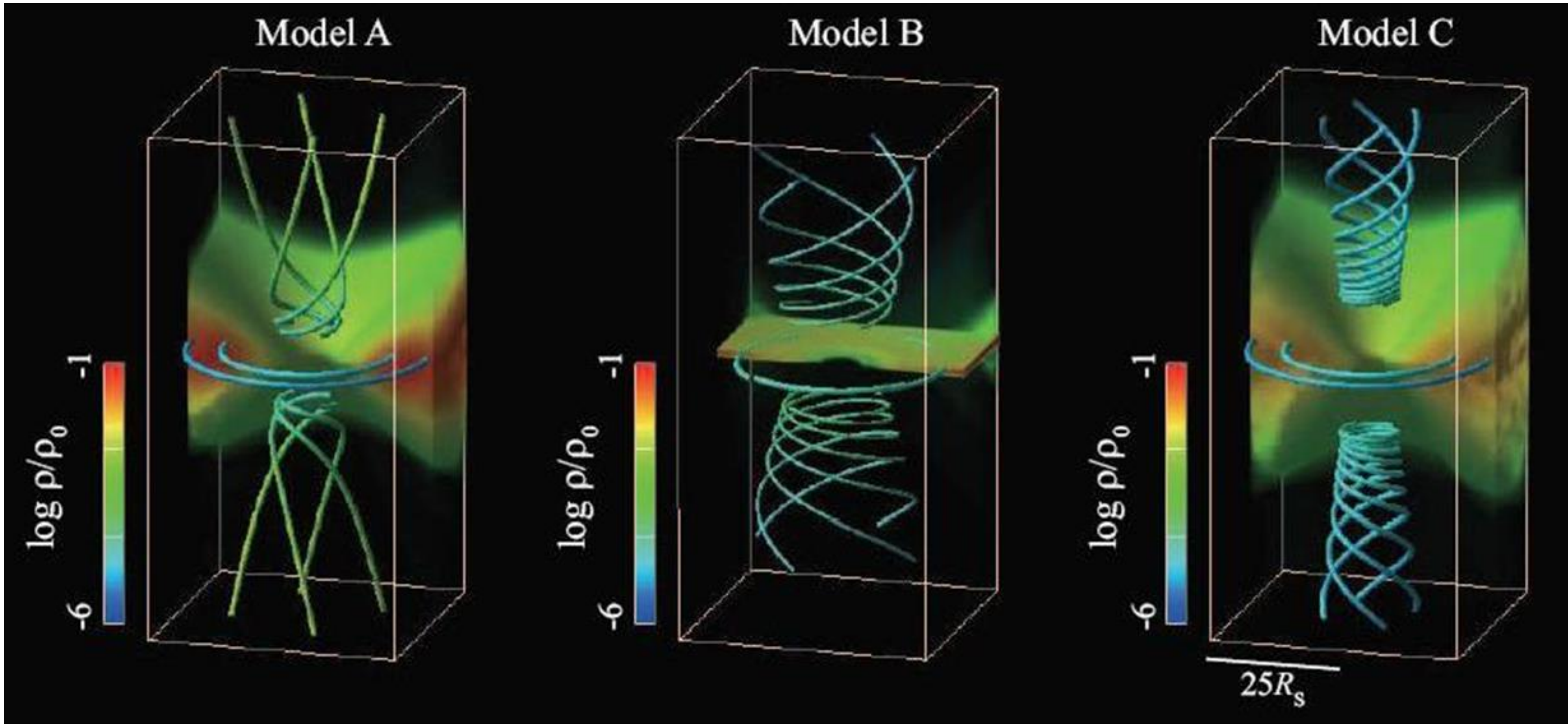
- Powered by accretion or by BH spin?
- Steady or flaring?
- Co-existing with slower, denser winds?

3. Jets/ISM interaction

ULX bubbles, hot spots, optical nebular lines

MHD simulations of accreting stellar-mass BHs

(Ohsuga & Mineshige 2011)

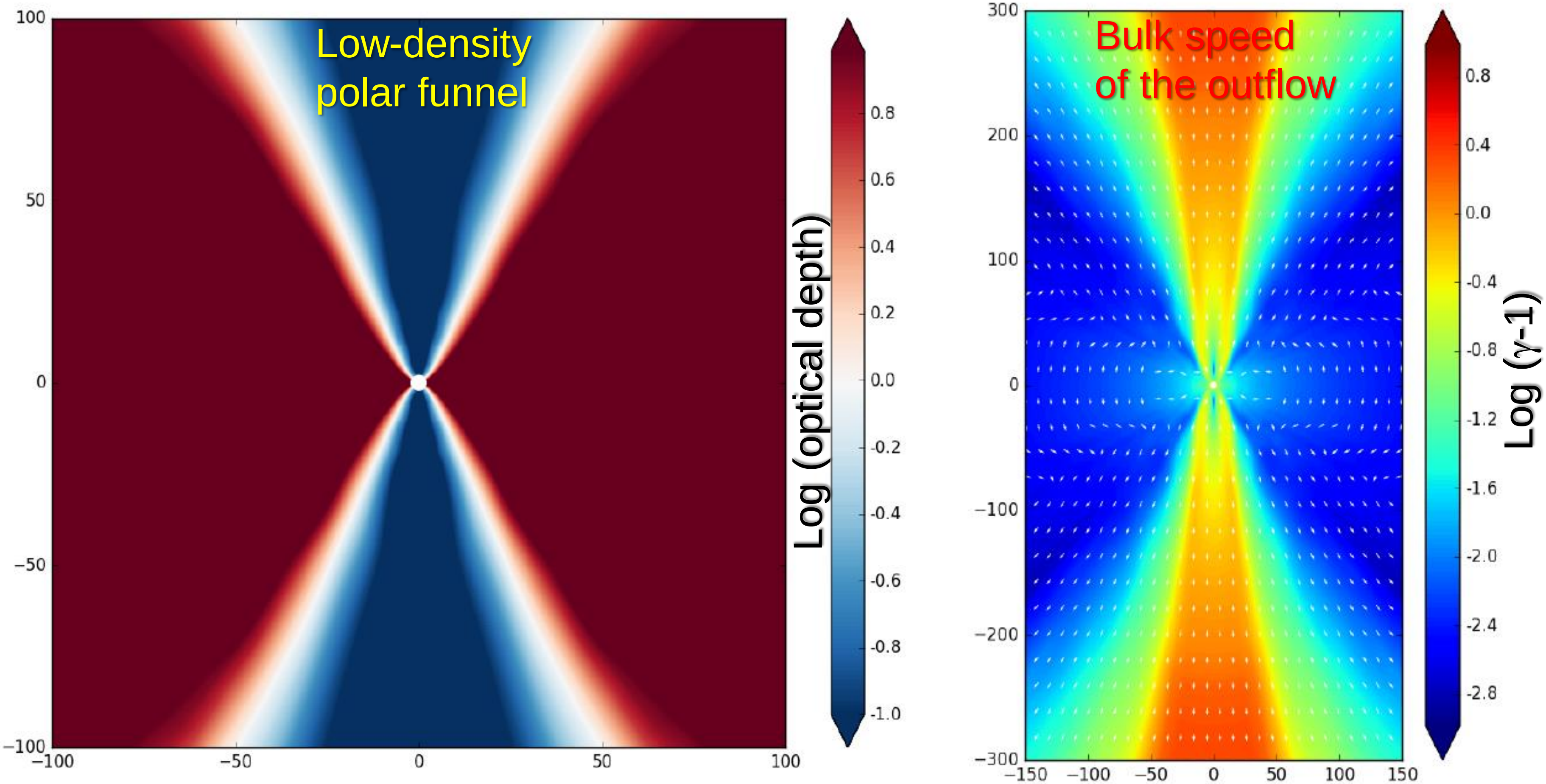


Super-critical ("ultraluminous")	High/soft	Low/hard
Jets (?)	No jets	Jets

L_X ~ 1E39 – a few E40 erg/s

Jets in the super-critical regime?

Theoretical models always predict jets



(Narayan, Sadowski & Soria 2017, MNRAS)

Jets in the super-critical regime?

Observations still inconclusive

Evidence of jets in some sources but not in others

Often difficult to prove super-critical accretion

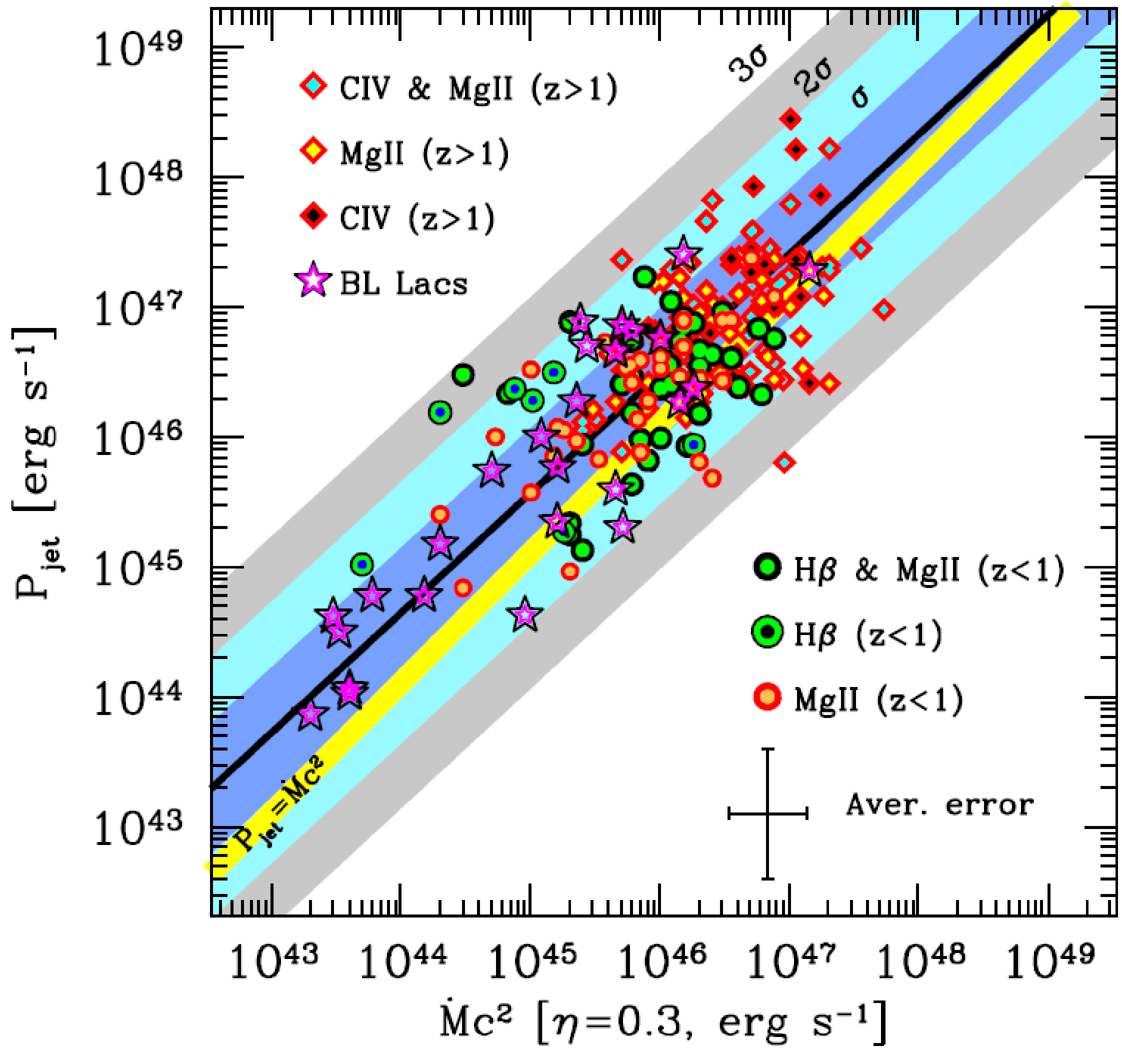
Testing jet models is important for understanding

- Early growth of nuclear BHs
- Feedback and removal of gas from galaxies
- BH mass range in X-ray binaries
- Tidal disruption events

Most important parameters remain untested

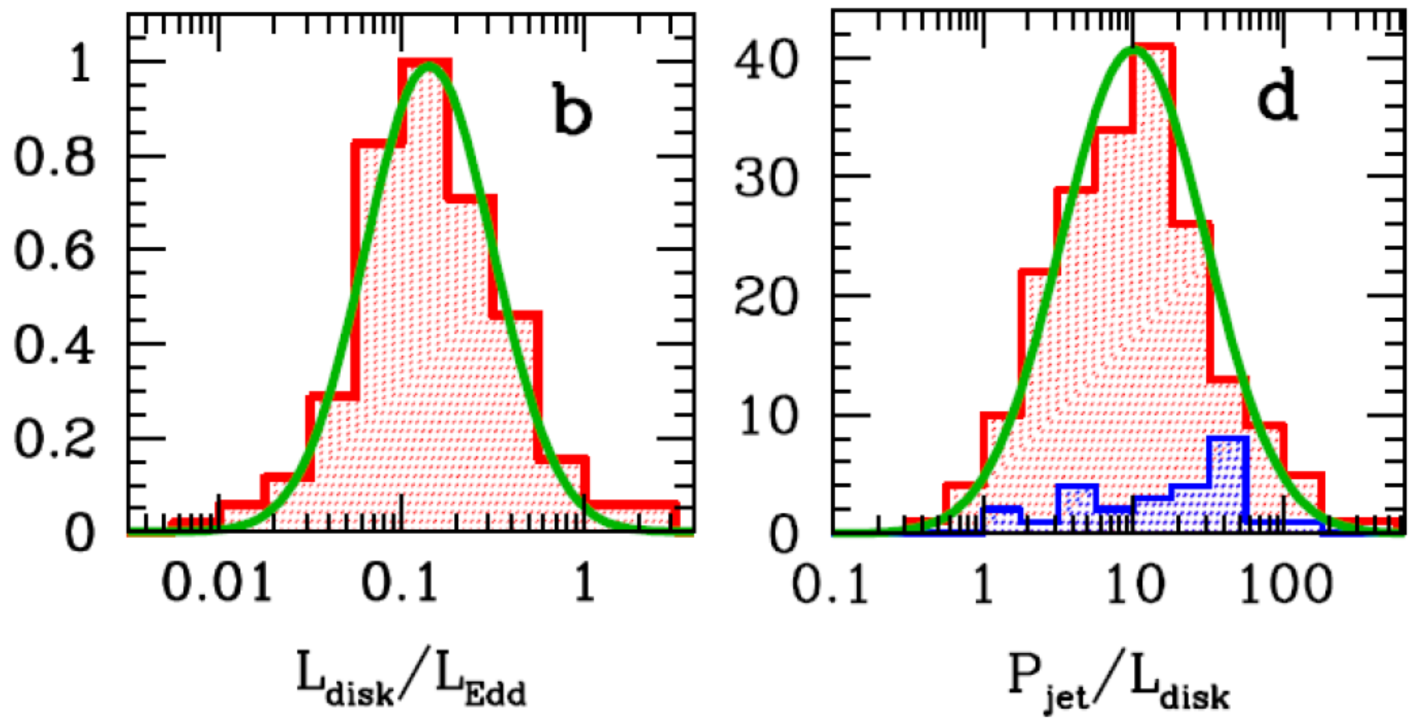
P_{Jet} / L_X $P_{Jet} / (\dot{M} c^2)$

Jet power can be > radiative power



Sample of jet-dominated blazars (Ghisellini et al 2014)

Jet power can be > radiative power



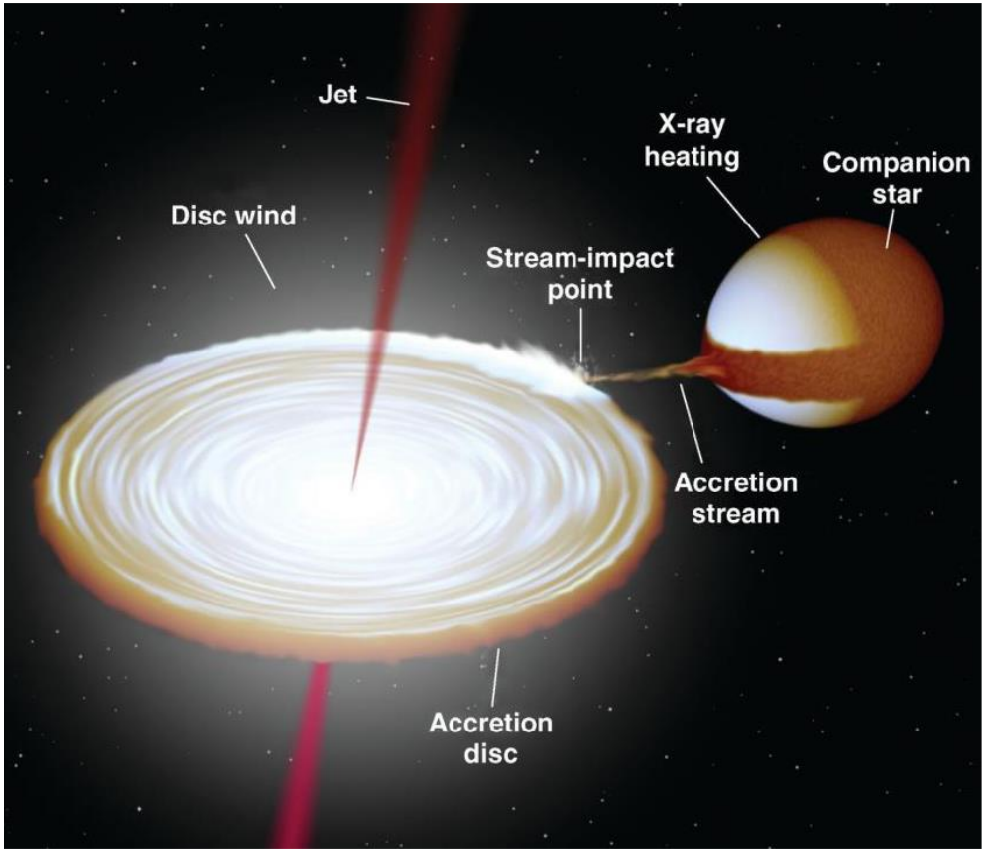
But blazars are mostly sub-Eddington (Ghisellini et al 2014)

What happens in the super-Eddington regime?

How to test jets in the super-Edd regime?

Some tidal disruption events

Ultraluminous X-ray sources (ULXs)
= highest luminosity class of X-ray binaries



How to detect jets near a BH or NS

Two possible ways to detect a jet near its launching radius

1. Core (flat-spectrum) radio emission

Standard technique in Galactic X-ray binaries

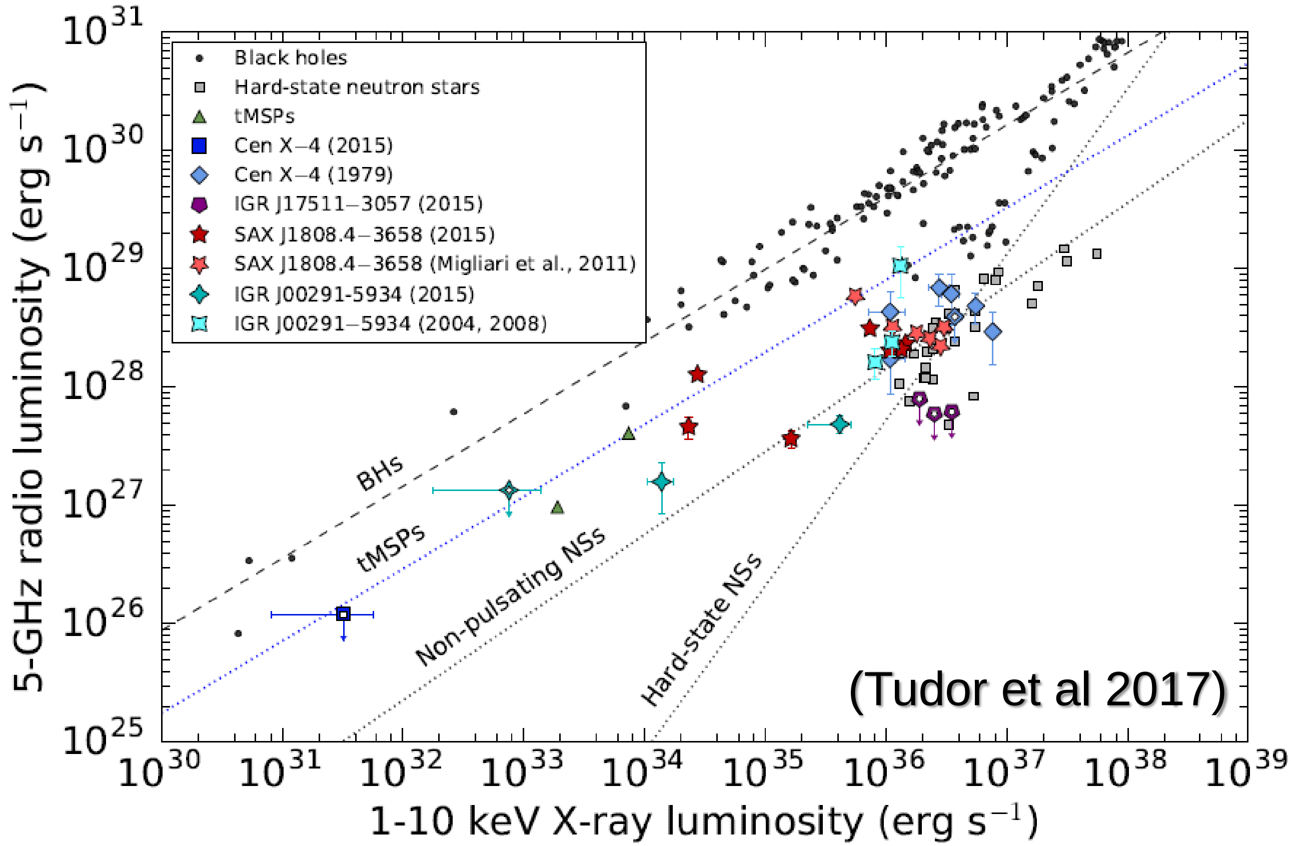
Scaling relations between L_R and L_X

2. Relativistic Doppler-shifted (optical/X-ray) lines

Discovery of jets in Galactic BH SS433 and in M81 ULX

How to detect jets near a BH or NS

Core radio emission

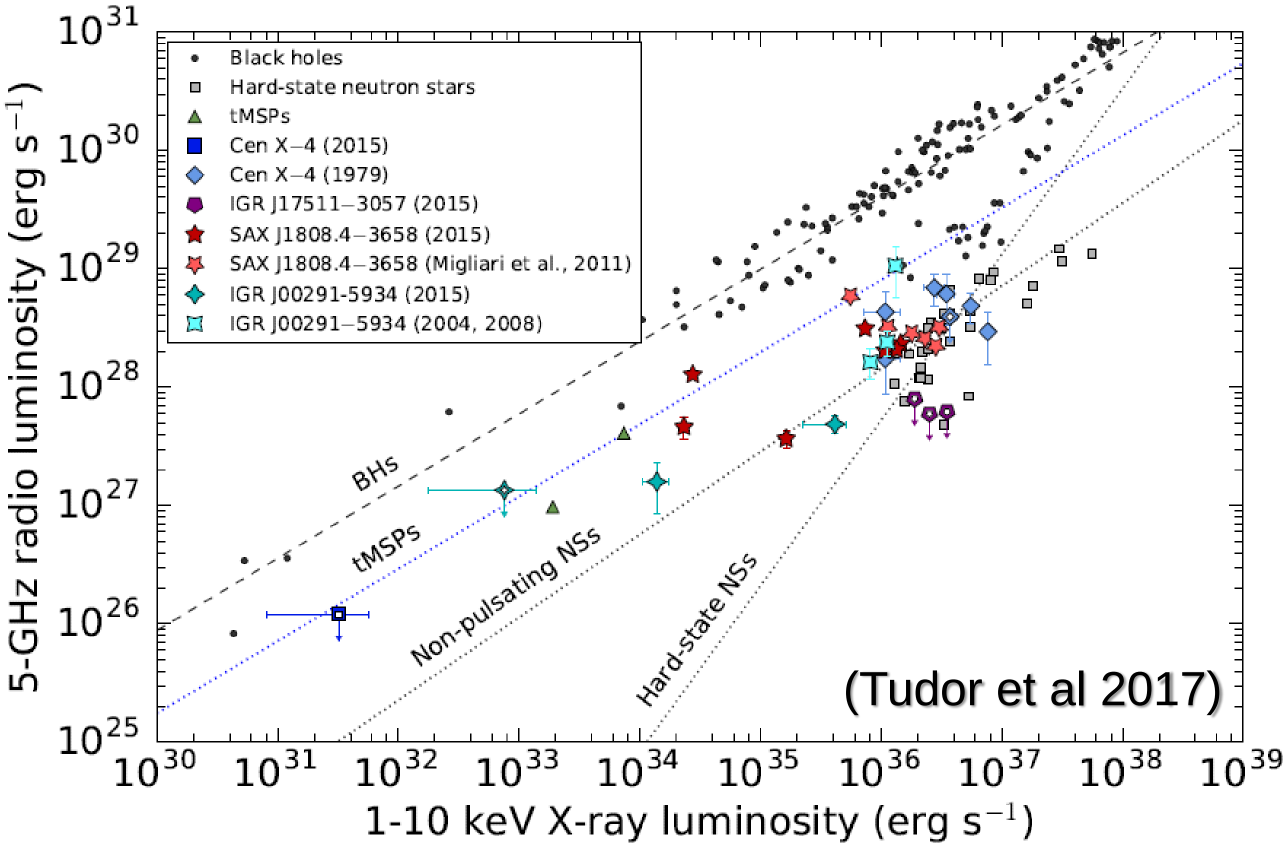


Steady jets too faint to be detected in other galaxies

S_{5GHz} ~ 1 μJy at 5 Mpc ⟶ requires SKA

How to detect jets near a BH or NS

Core radio emission



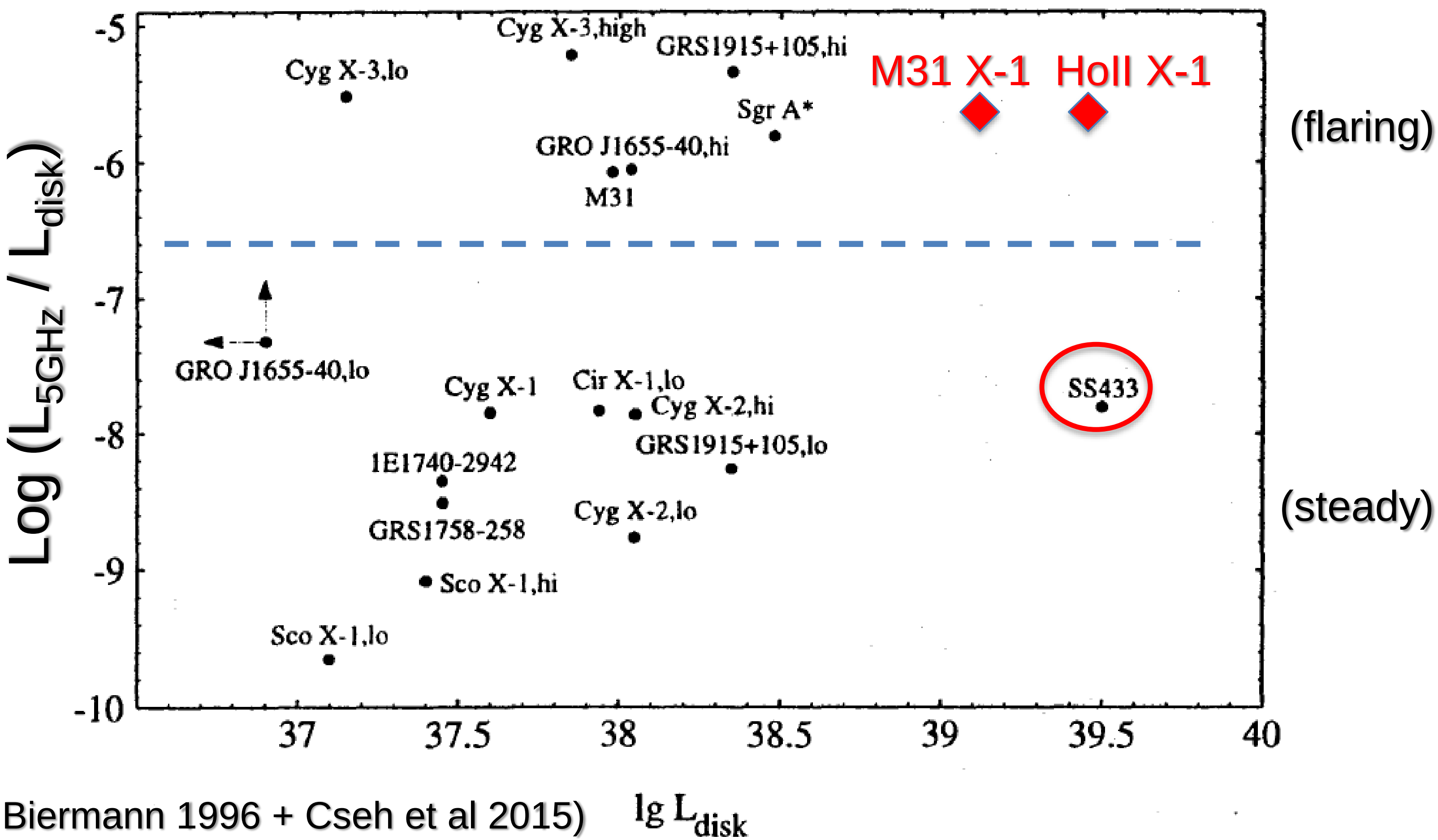
Flaring jets can be detected in other galaxies

S_{5GHz} ~ 100 μJy at 5 Mpc ⟶ VLA is enough

Radio emission from flaring ULX jets

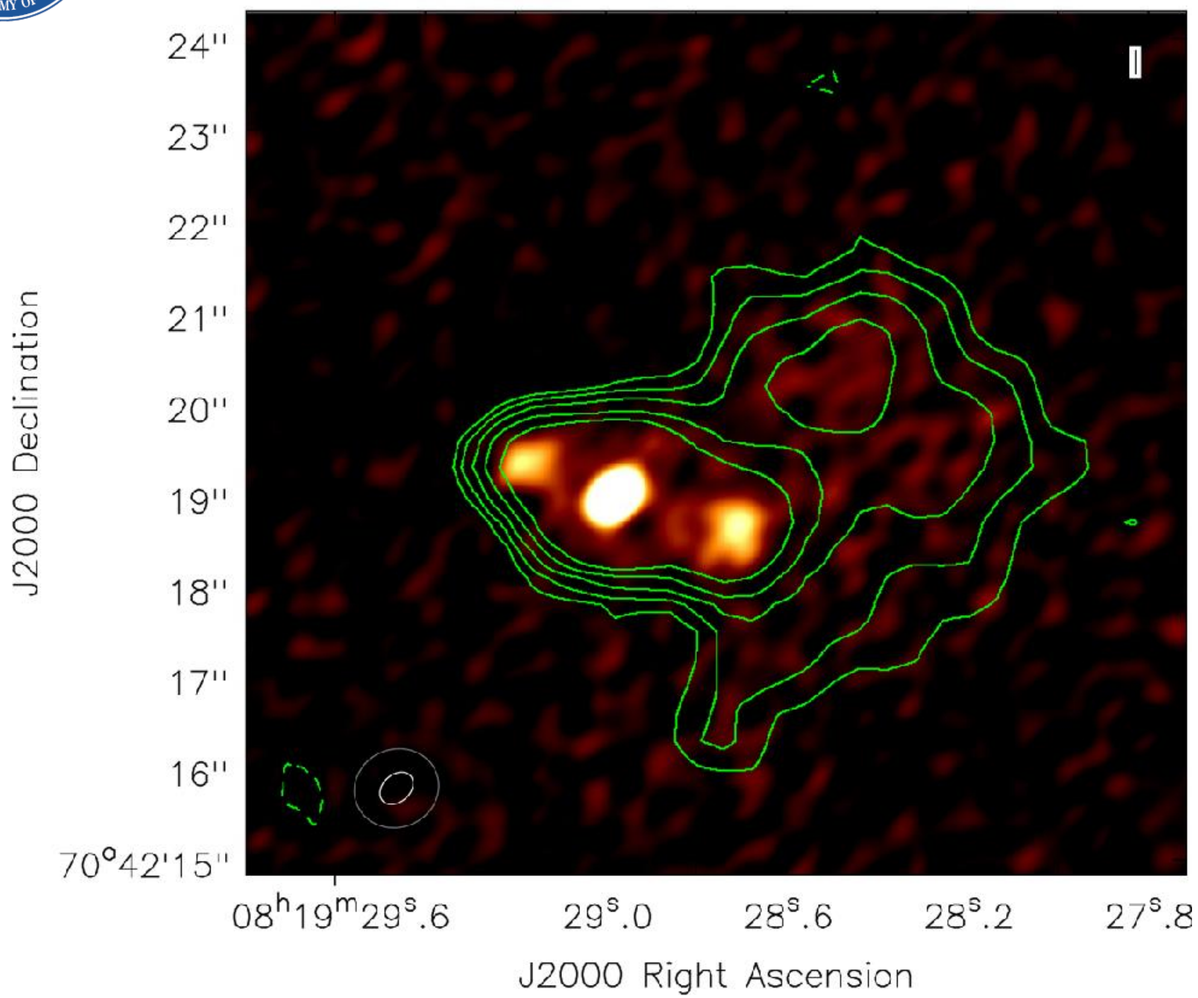
$L_{5GHz} / L_{disk} \sim 10^{-8}$
(steady jet)

$L_{5GHz} / L_{disk} \sim 10^{-6} - 10^{-5}$
(flaring jet)



(Falcke & Biermann 1996 + Cseh et al 2015)

Radio emission from flaring ULX jets



$L_R \sim 1 \times 10^{34}$ erg/s

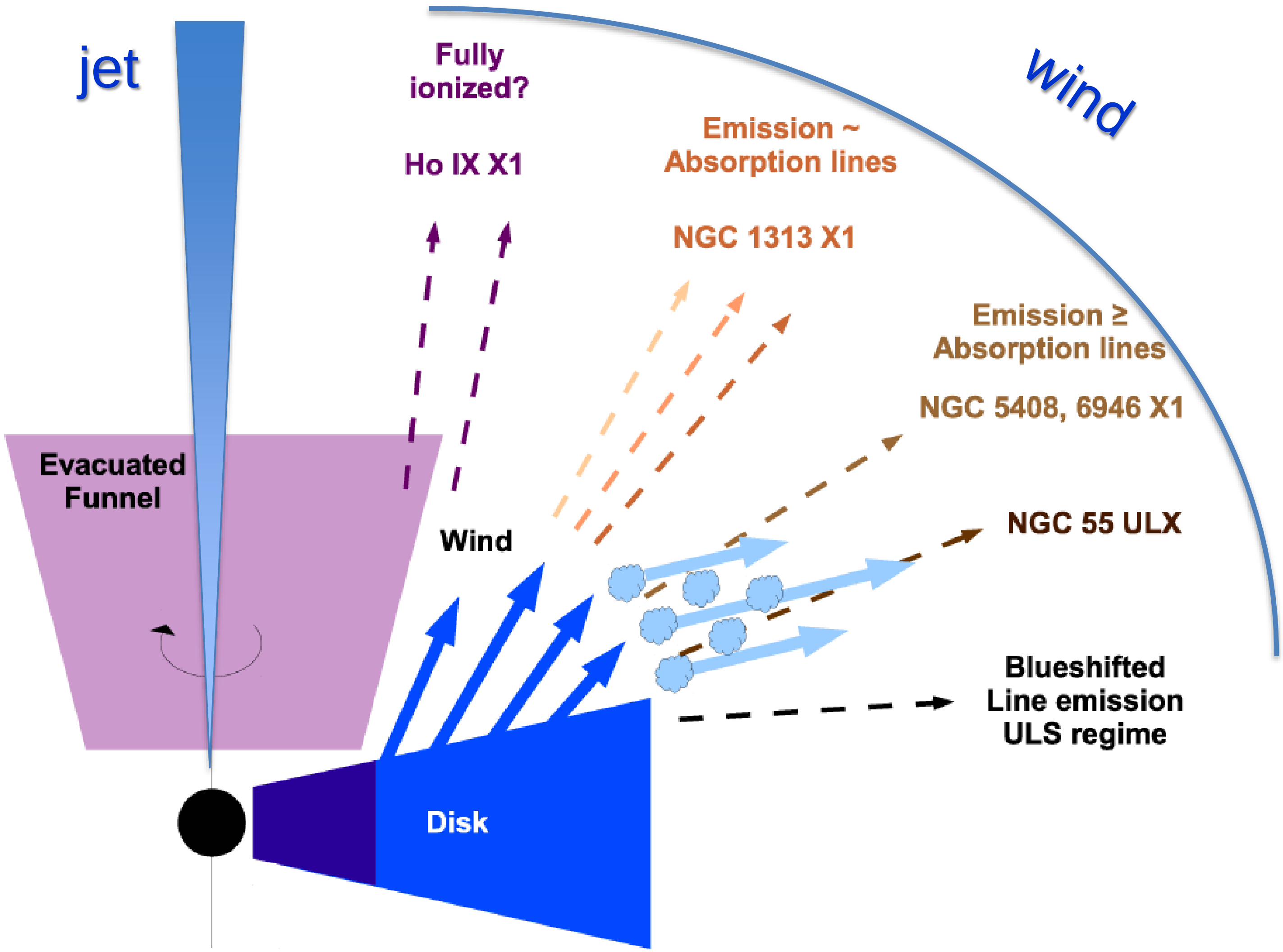
$P_J \sim 2 \times 10^{39}$ erg/s

$L_X \sim 4 \times 10^{39}$ erg/s

Steep radio spectrum

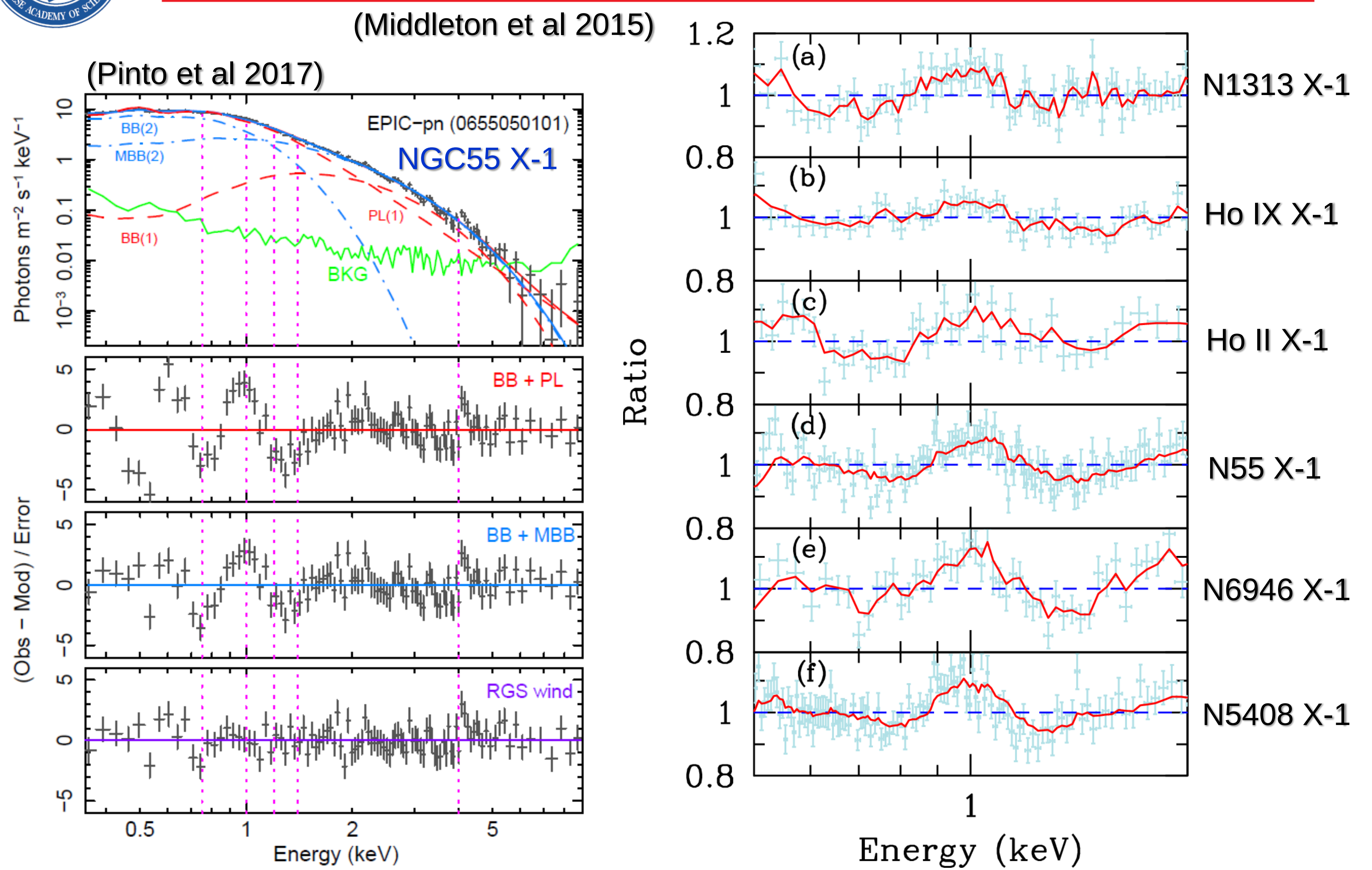
Flaring jet in Holmberg II X-1 (Cseh et al 2014,2015)

Outflow signatures on ULX spectra

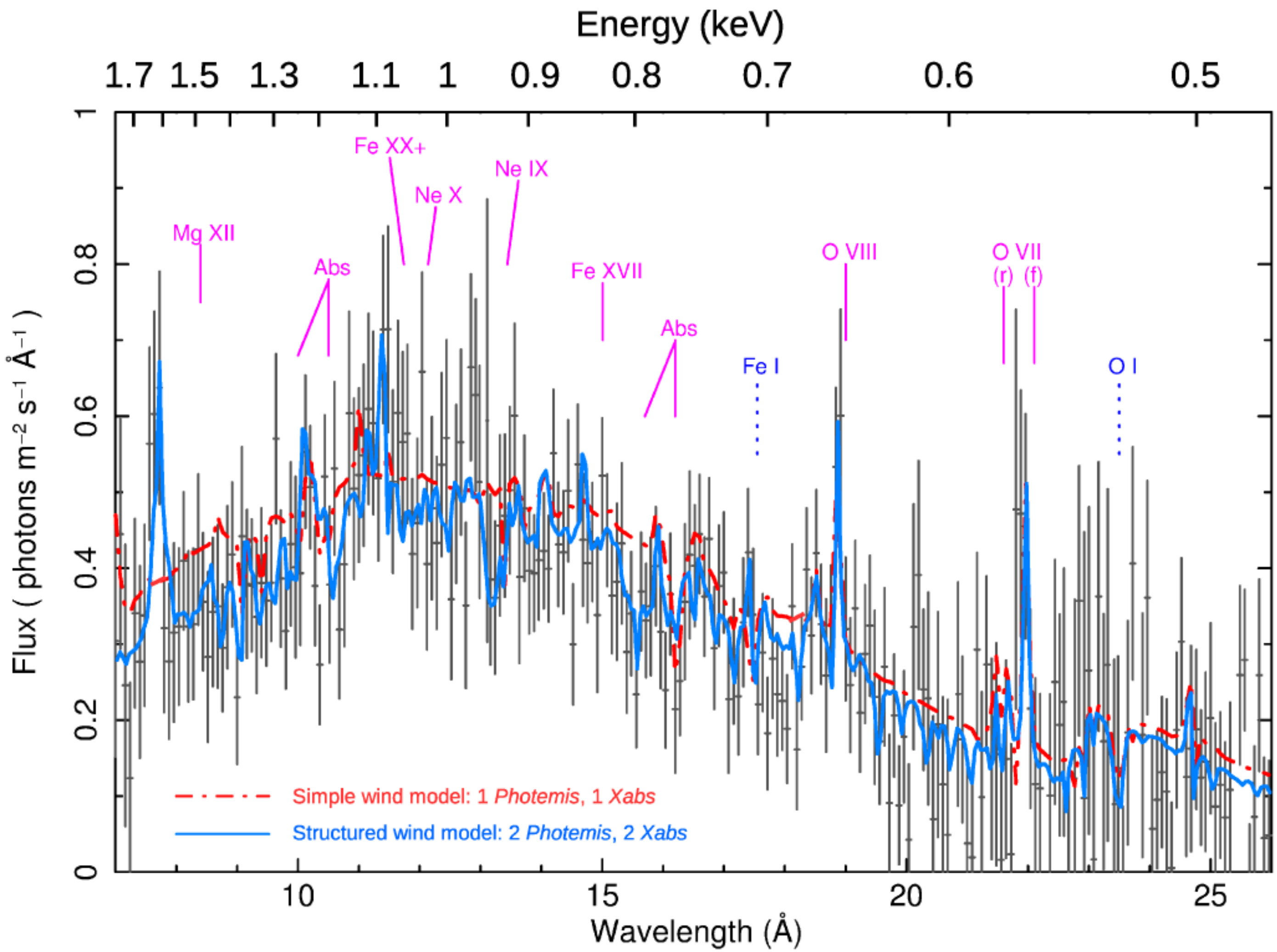


(adapted from Pinto et al 2017)

Outflow signatures on ULX spectra



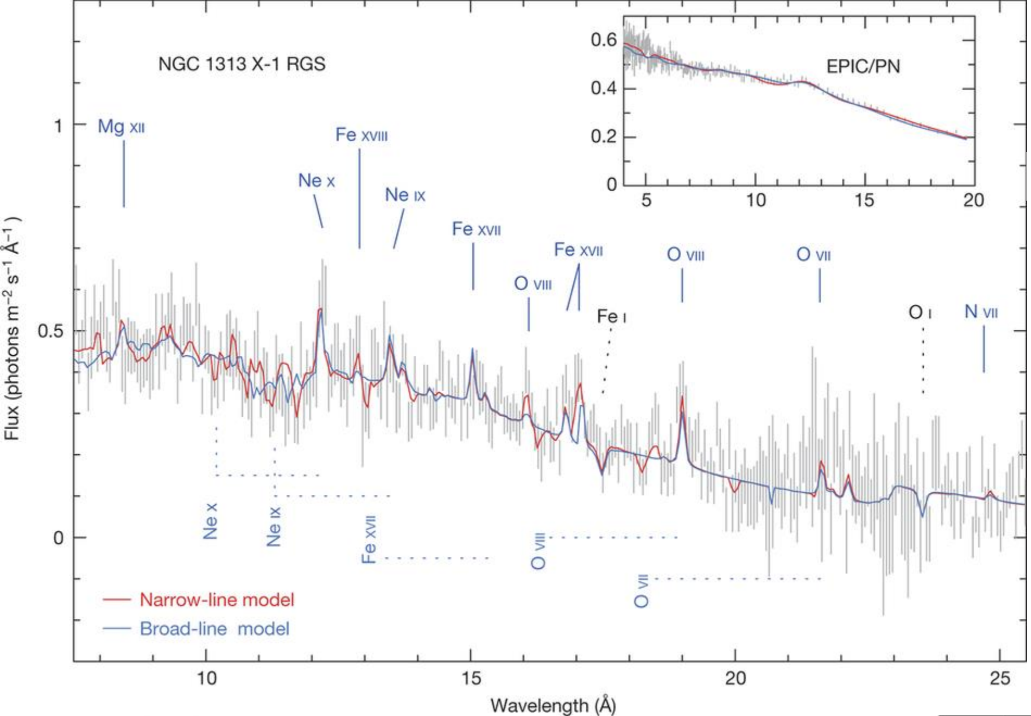
Outflow signatures on ULX spectra



120-ks *XMM-Newton*/RGS spectrum of the ULX in NGC 55

(Pinto et al 2017)

Outflow signatures on ULX spectra

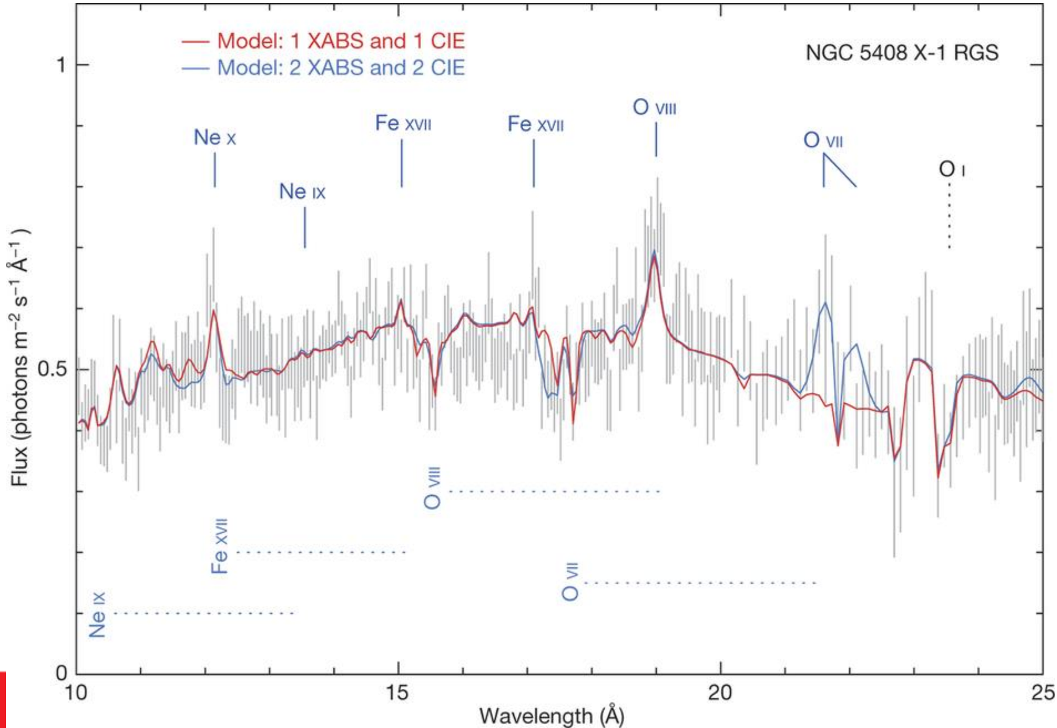


Emission lines
from slow-moving gas
v ~ 0.01—0.1 c

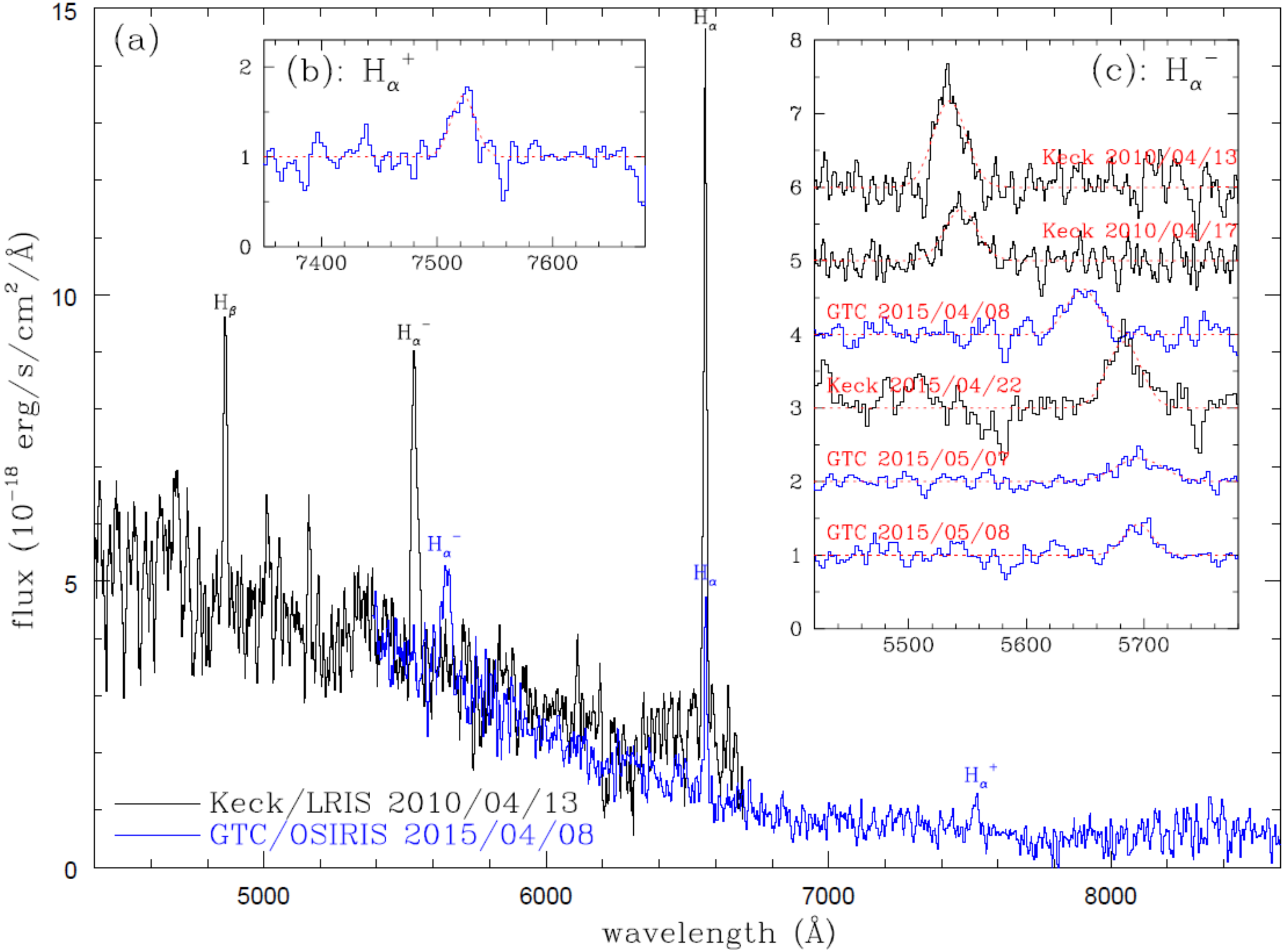
Absorption lines
from fast-moving gas
v ~ 0.1—0.2 c

NGC1313 X-1
350-ks RGS spectrum
(Pinto et al 2016)

NGC5408 X-1
650-ks RGS spectrum
(Pinto et al 2016)

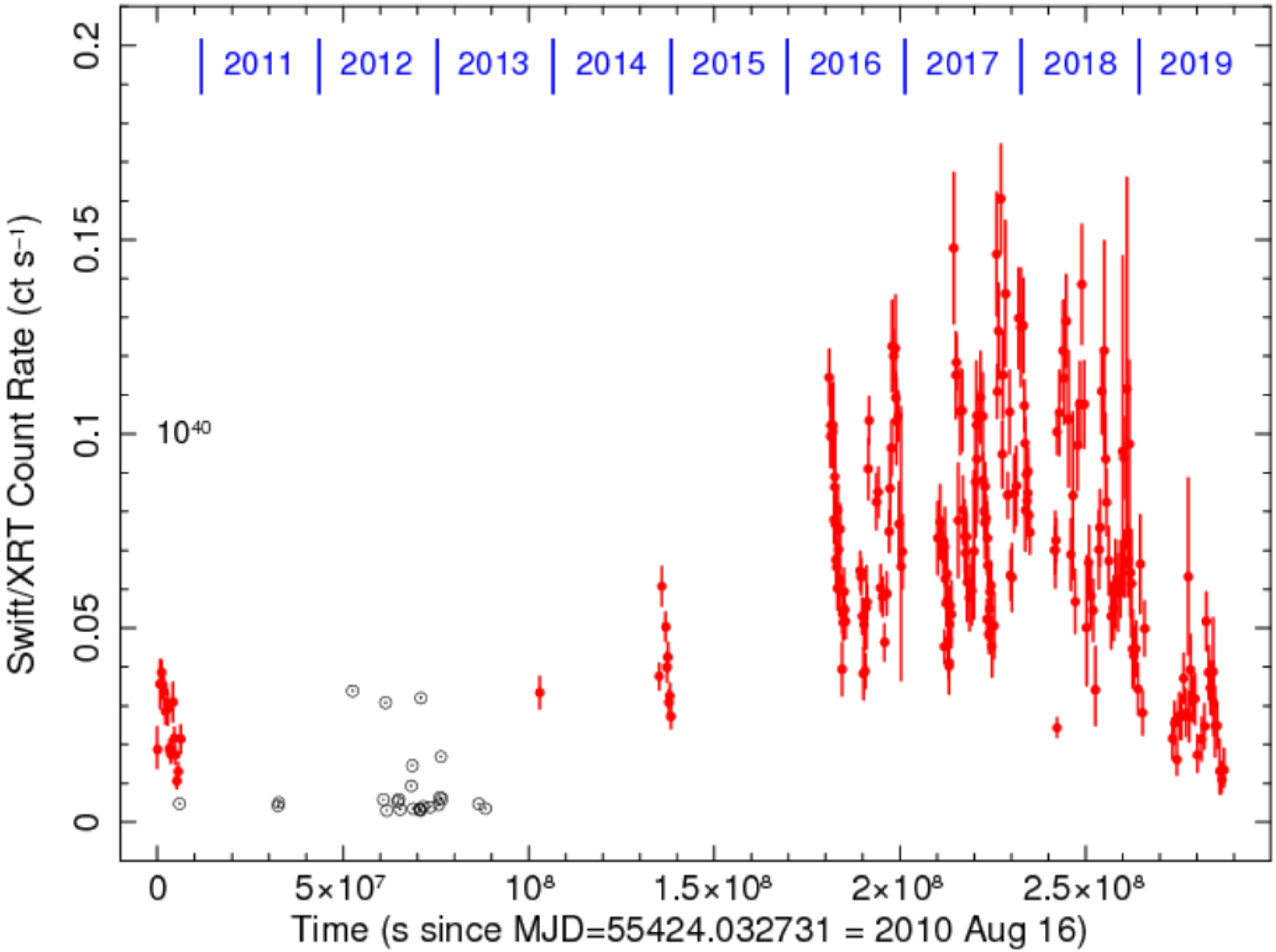


Outflow signatures on ULX spectra

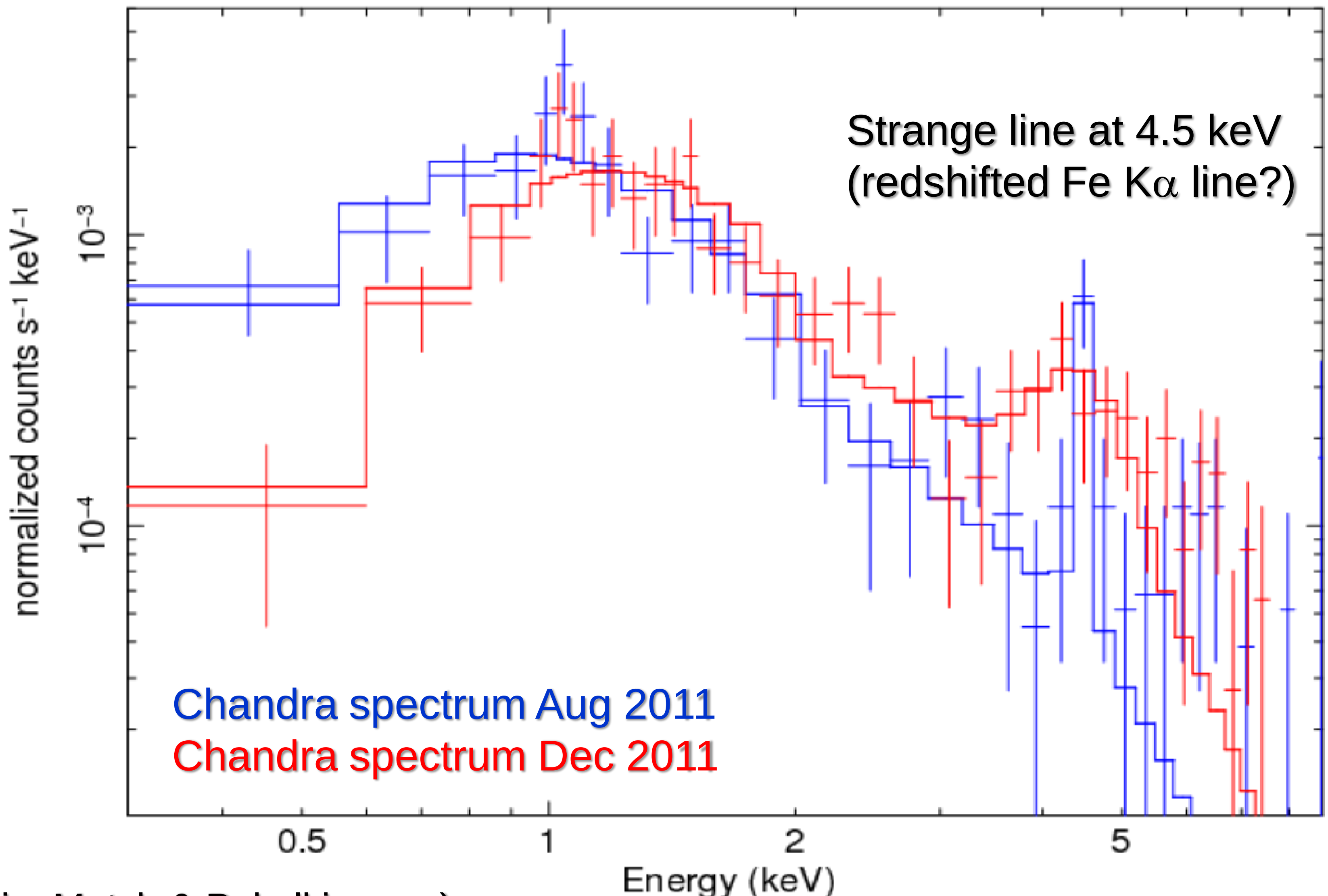


Relativistic jet lines at v = 0.17c in M81 ULS (Liu et al 2015)

Jet signature in the pulsar ULX P13

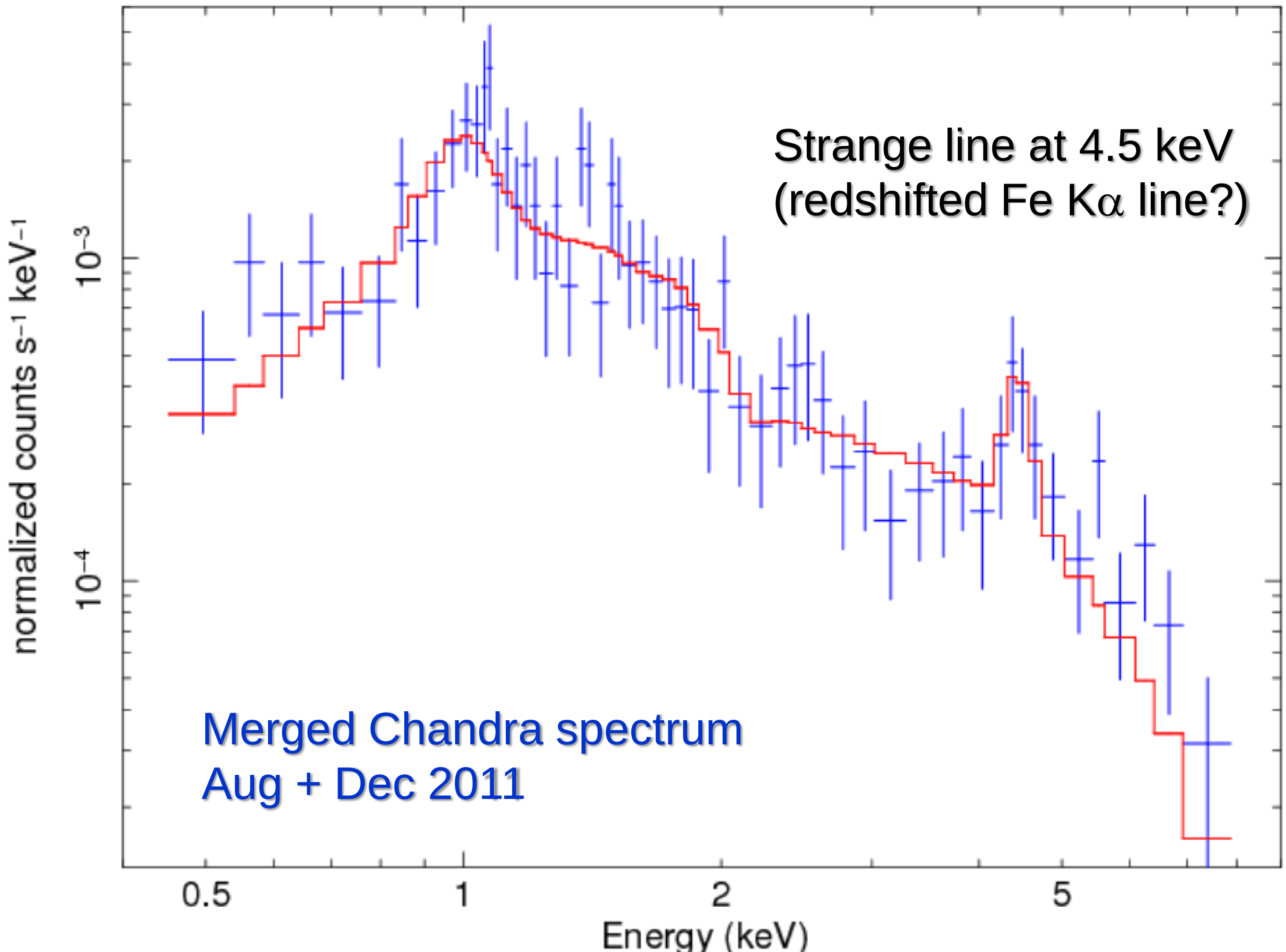


Jet signature in the pulsar ULX P13



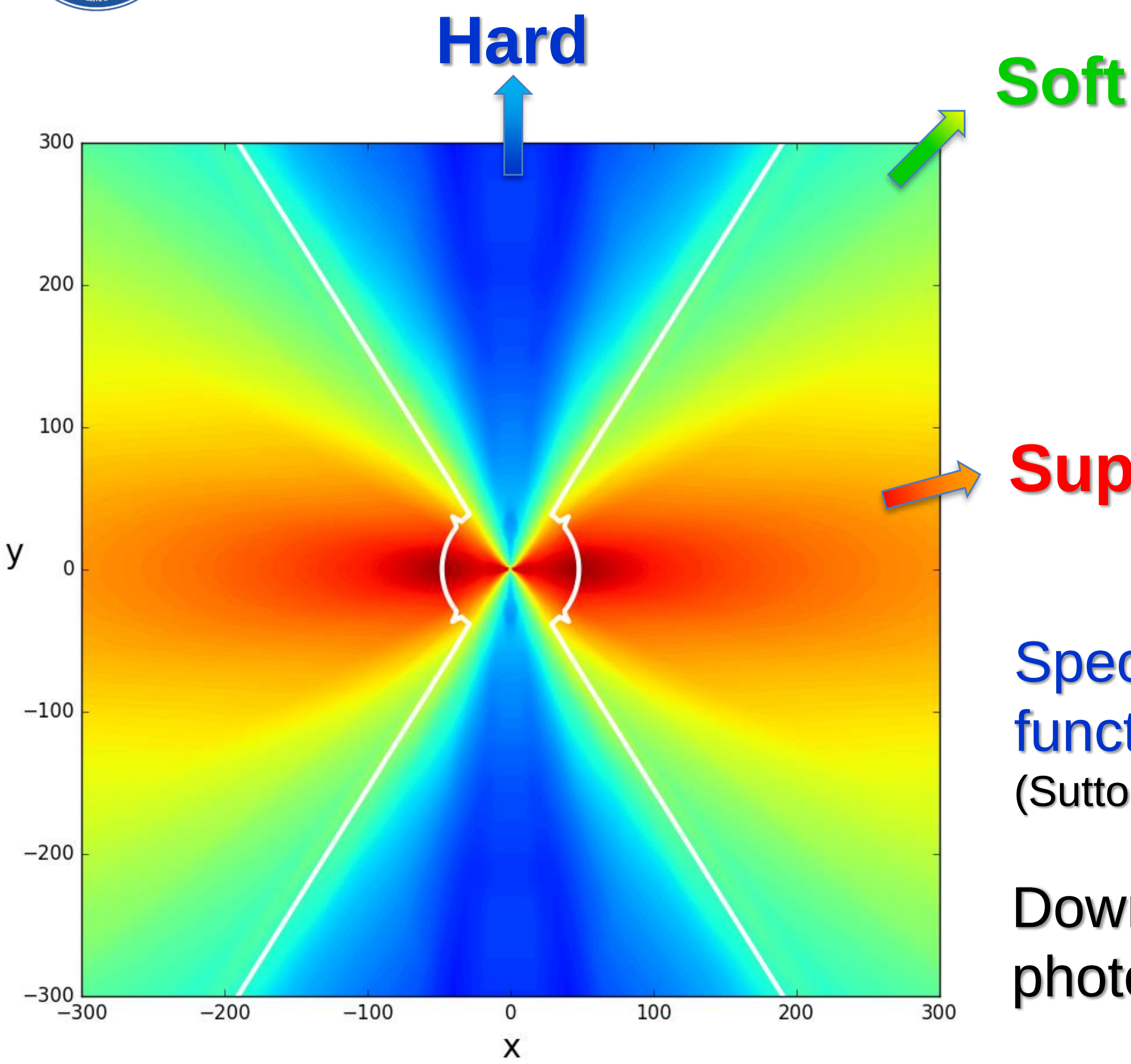
(Soria, Motch & Pakull in prep)

Jet signature in the pulsar ULX P13



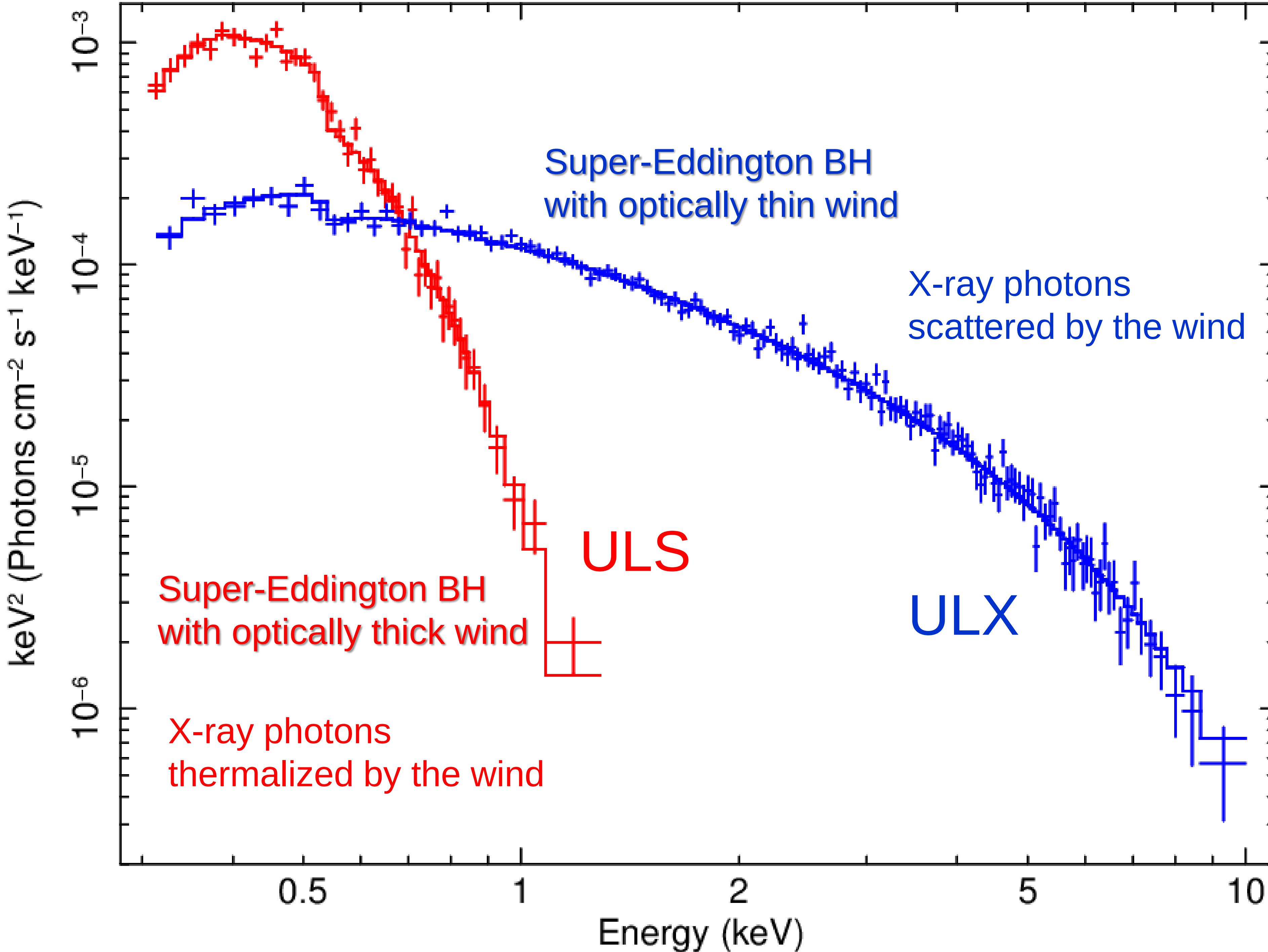
(Soria, Motch & Pakull in prep)

ULX unification model

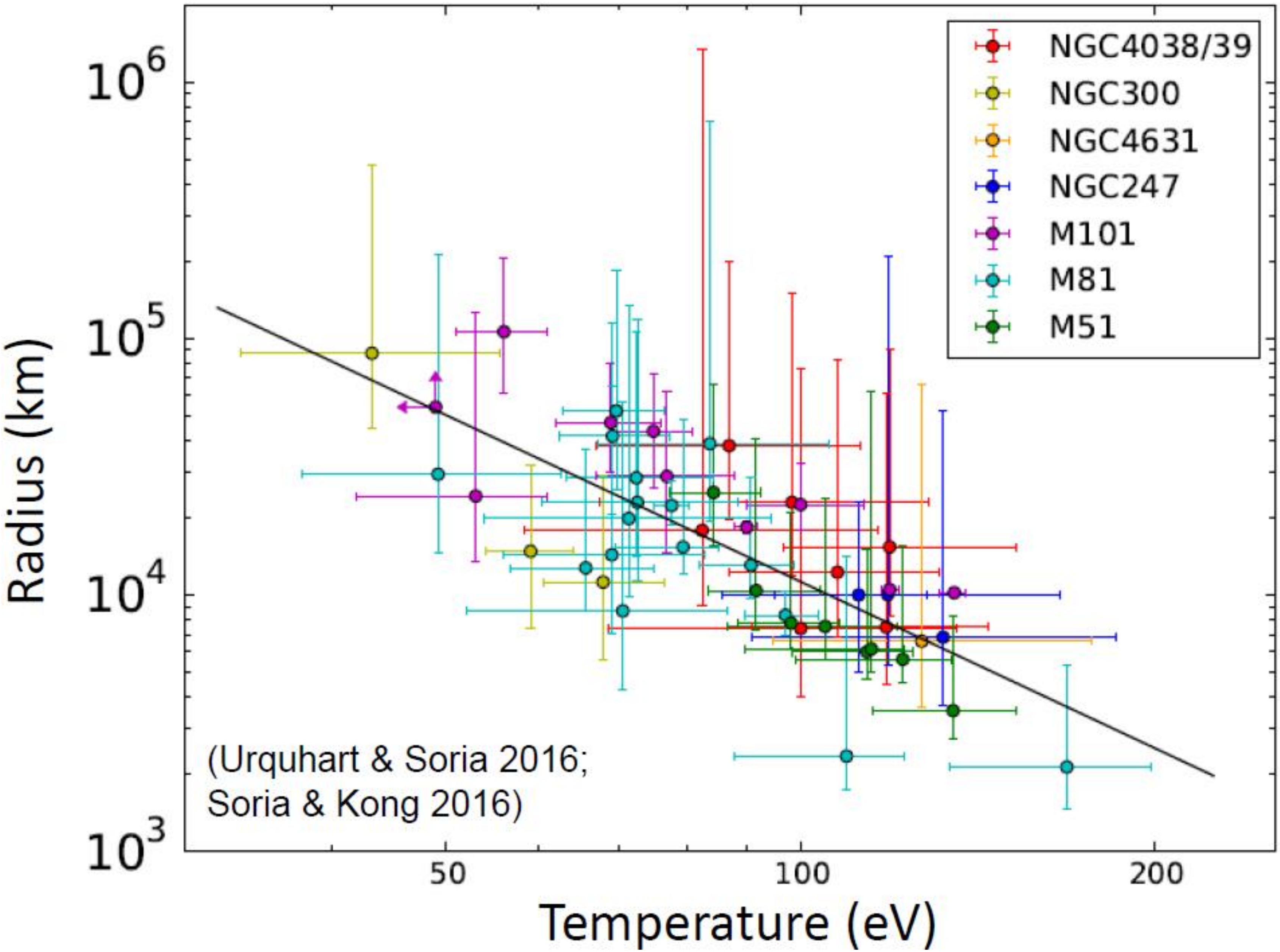


Spectral hardness function of viewing angle (Sutton et al 2013)

Downscattering of X-ray photons through the wind


Super-Eddington BH
with optically thin wind
X-ray photons
scattered by the wind
ULS
ULX
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)

$R_{bb} \sim (T_{bb})^{-2}$ as expected from a ULS photosphere



Recap so far

PART 1

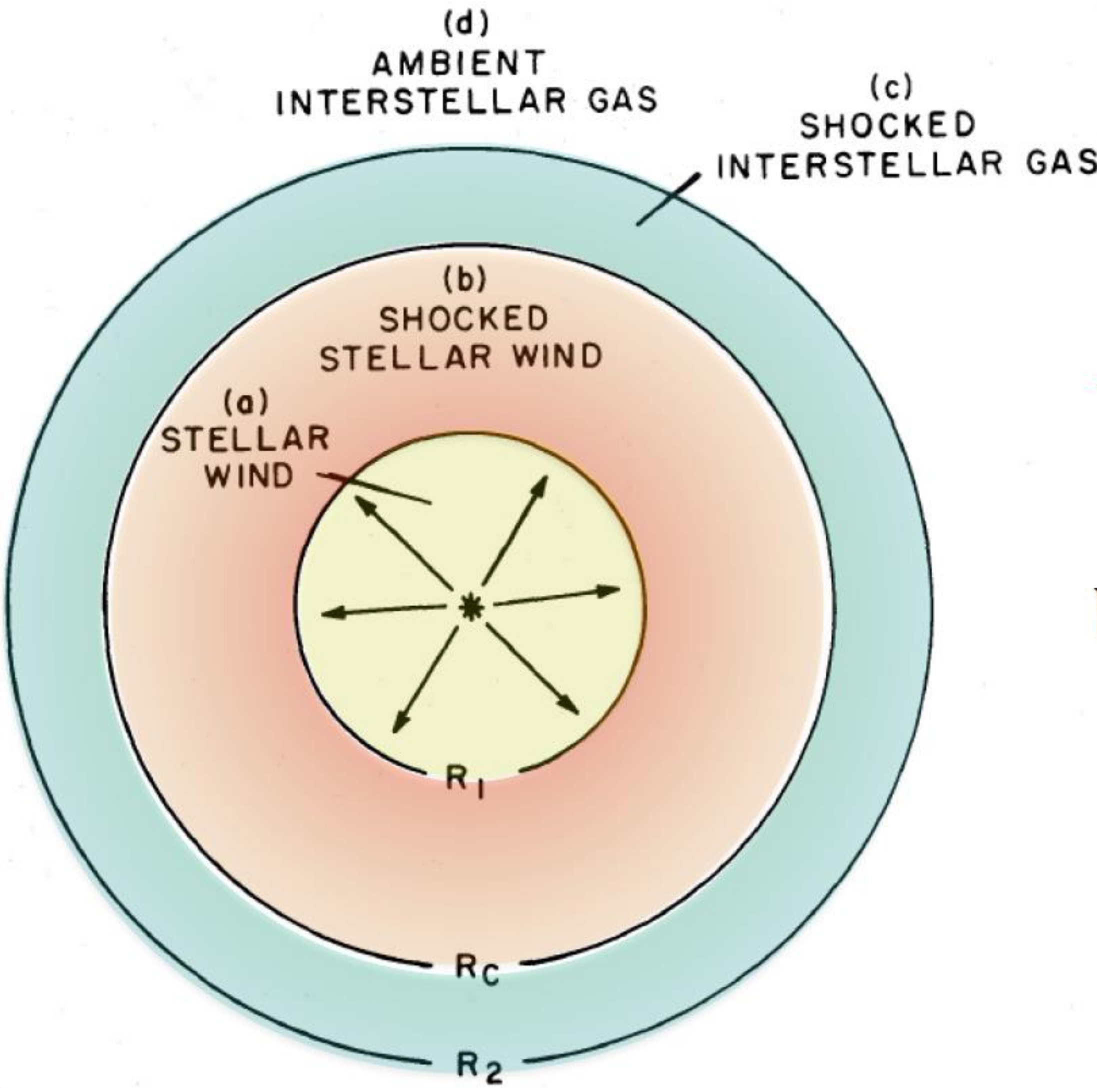
Evidence of jets/winds near the compact object
(d ~ 10—10,000 km)

Next: PART 2

Evidence of jets/winds at large distances
(d ~ 100 pc)

Outflow / ISM interaction

Standard bubble theory (Weaver et al 1977)



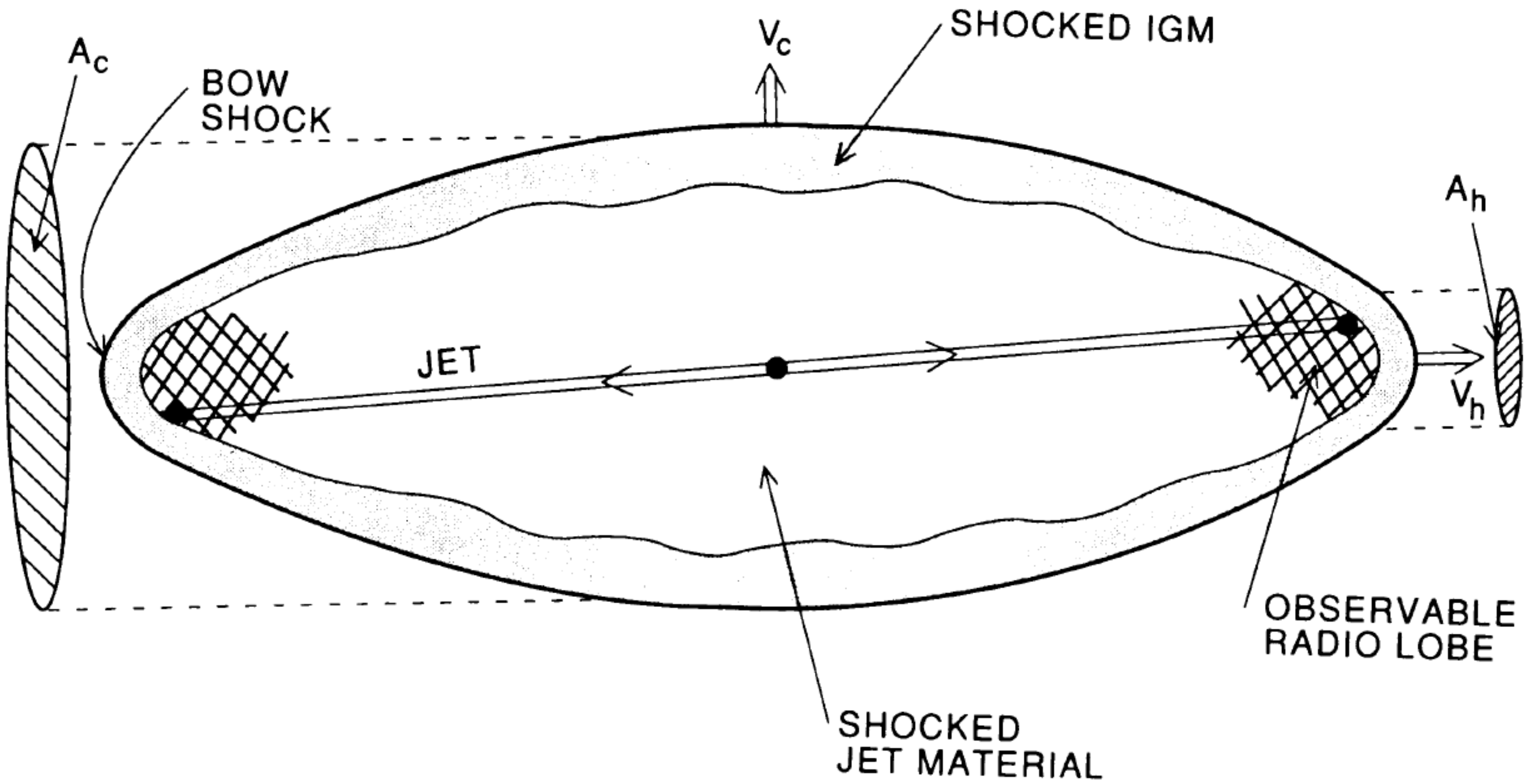
$$R = 0.76\left(\frac{Pt^3}{n}\right)^{1/5}$$

$$V_s = \frac{dR}{dt} = \frac{3}{5}\frac{R}{t}$$

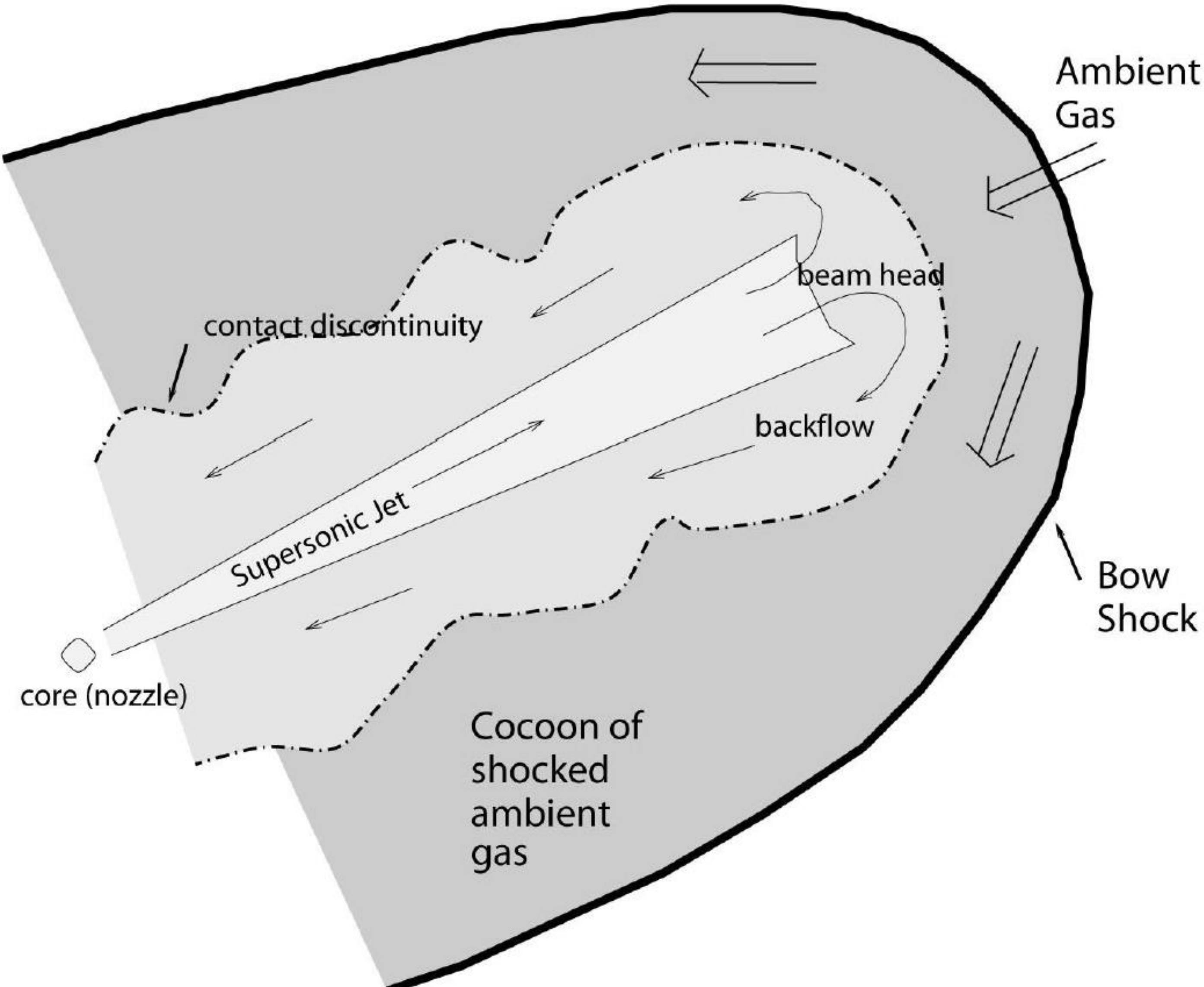
$$P \sim R^2 V_s{}^3 n$$

Outflow / ISM interaction

Overpressured cocoon (Begelman & Cioffi 1989)

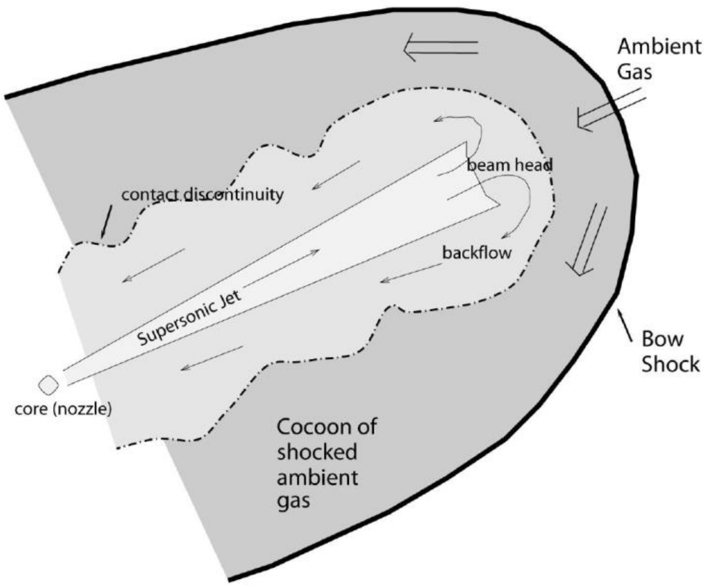


Outflow / ISM interaction



Similar structure for a jet

Outflow / ISM interaction



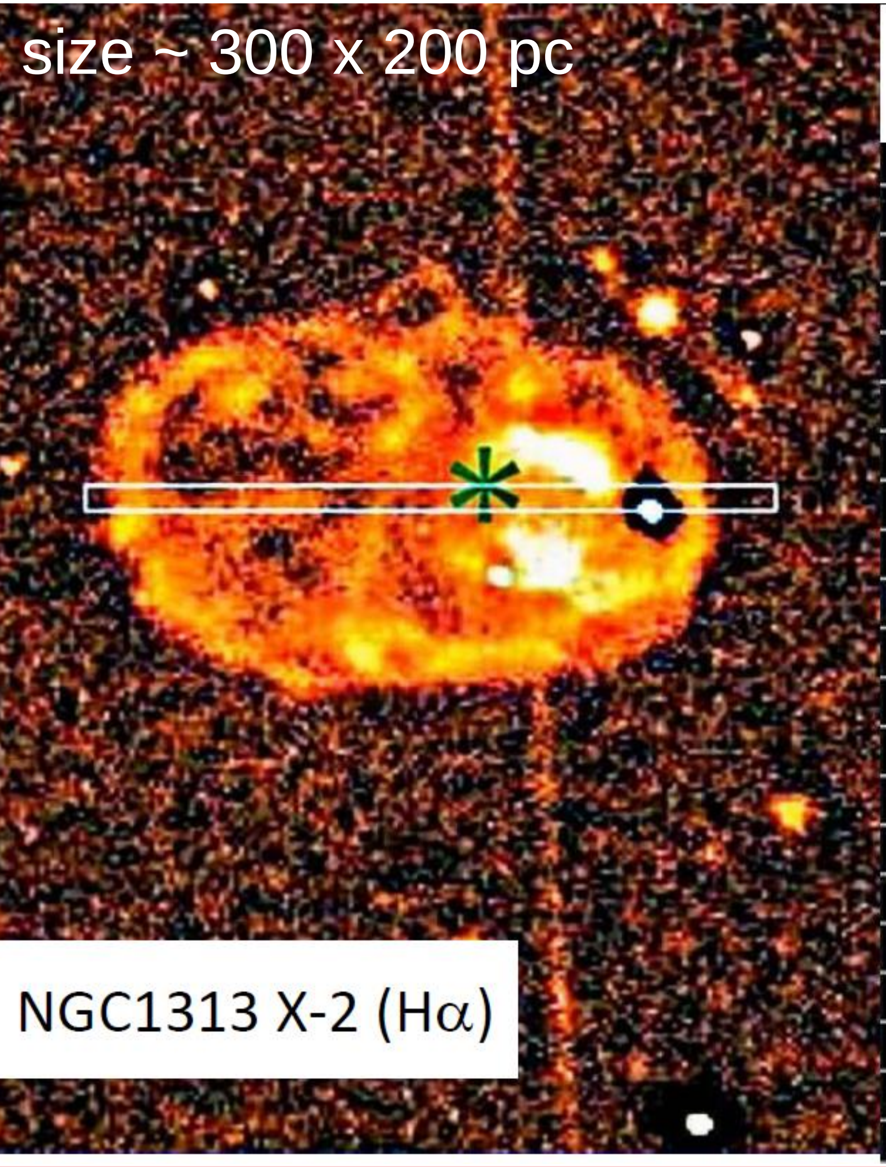
P_J ~ 0.1 Mdot c^2 ~ few 10^{39} erg/s

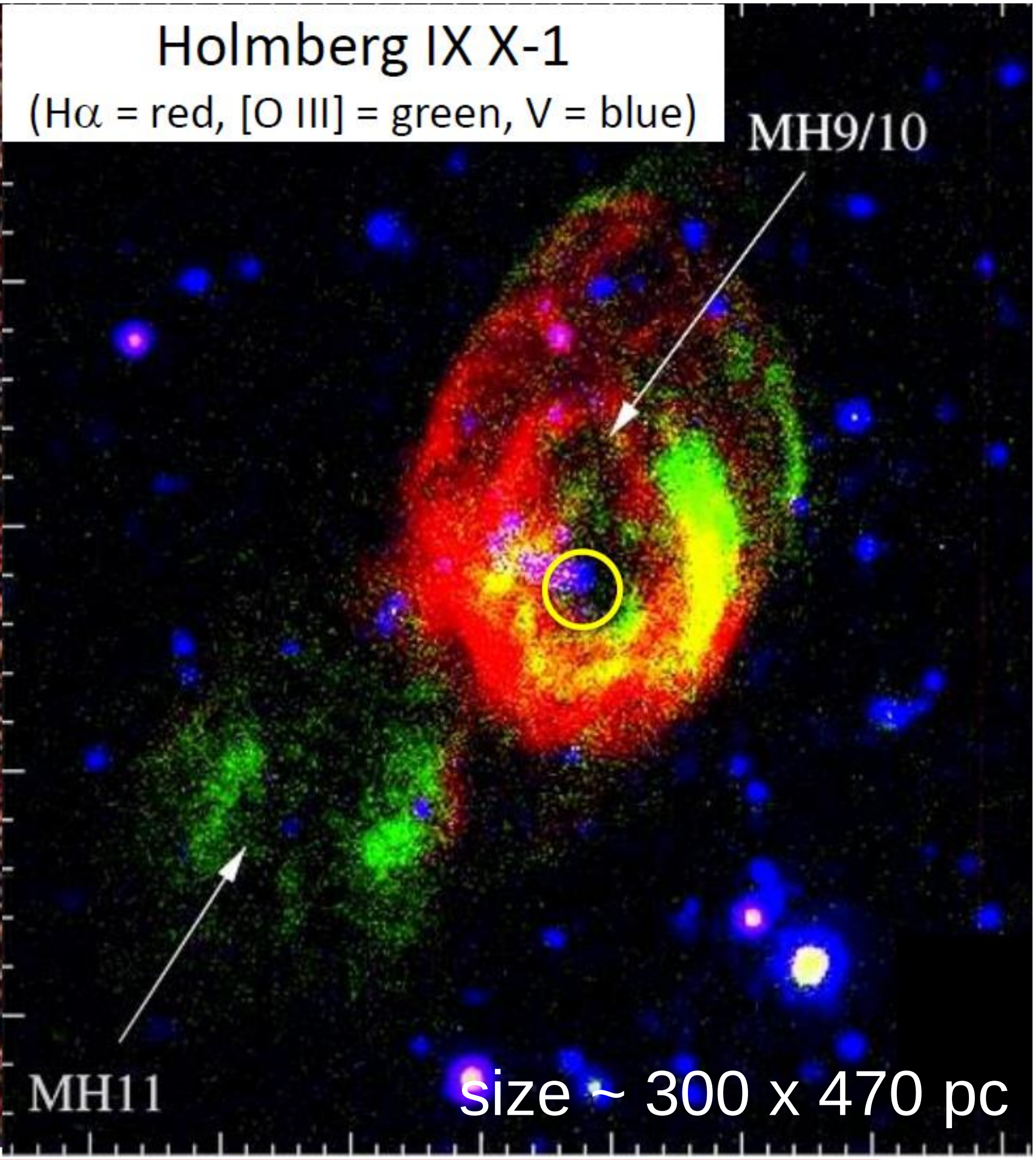
Duration of super-critical phase
t ~ few 10^5 yr

Total energy injected into the ISM
E ~ P_J t ~ 10^{52} erg

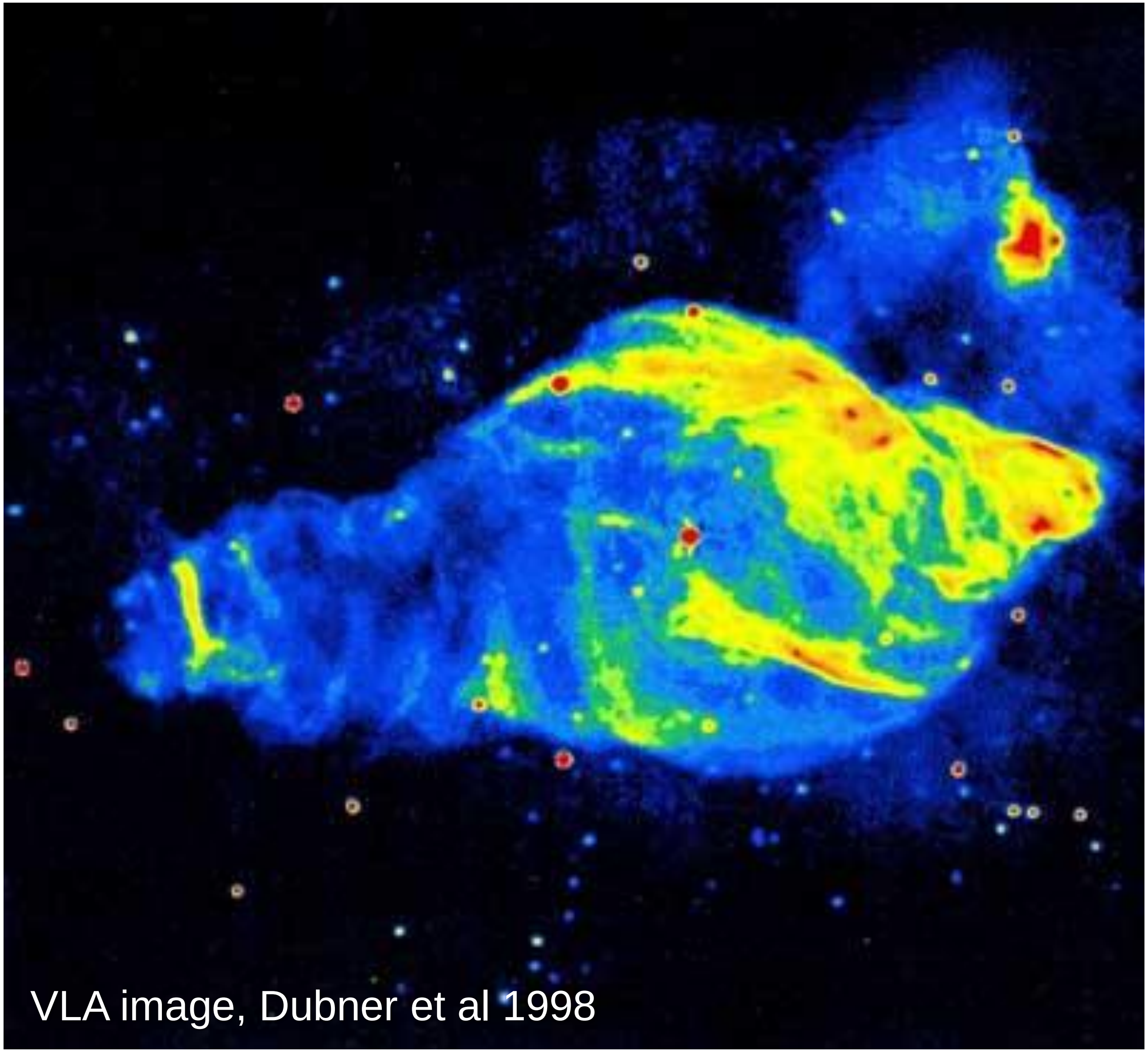
ULX jet bubbles ~ 10 x more energetic than SNRs

ULX bubbles (Pakull & Mirioni 2001)



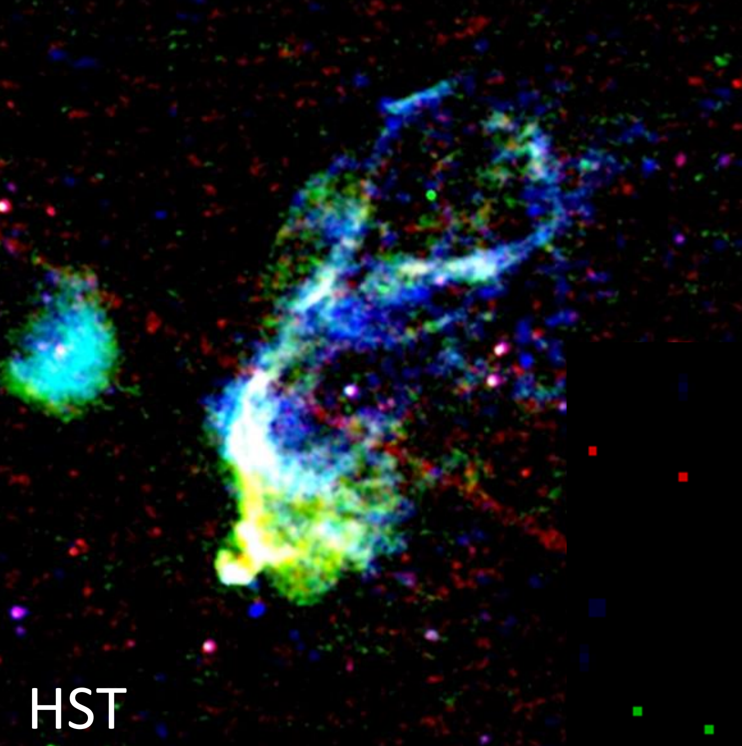


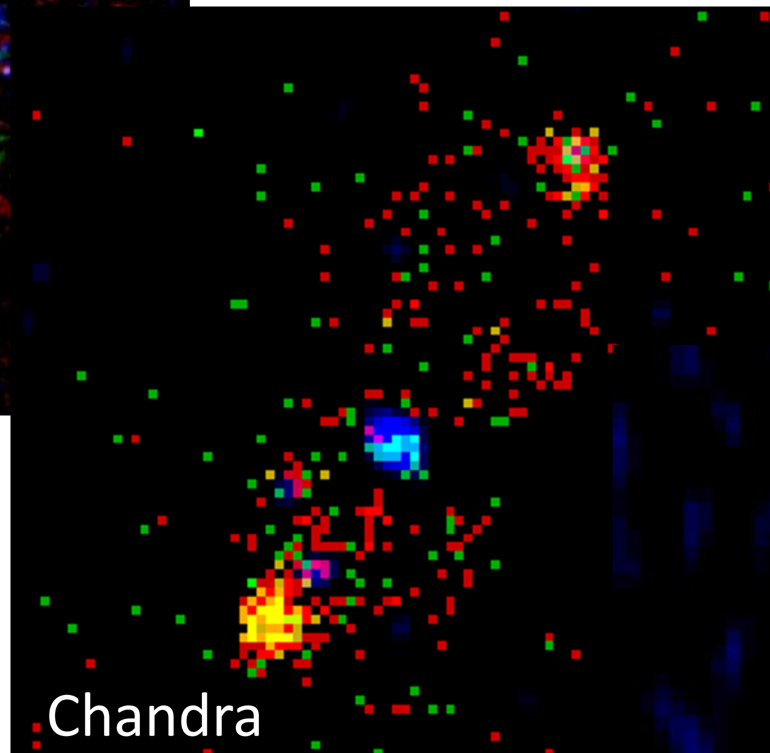
Galactic ULX bubble SS433



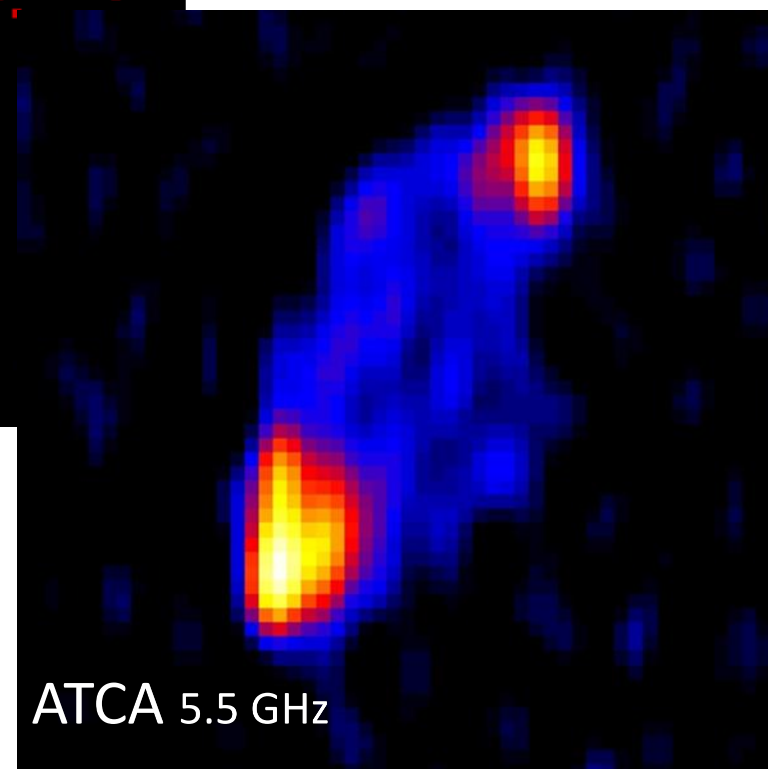
VLA image, Dubner et al 1998

Some jets are easy to identify
S26 in NGC 7793





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



diameter ~ 270 pc

Jet-inflated bubble with hot spots

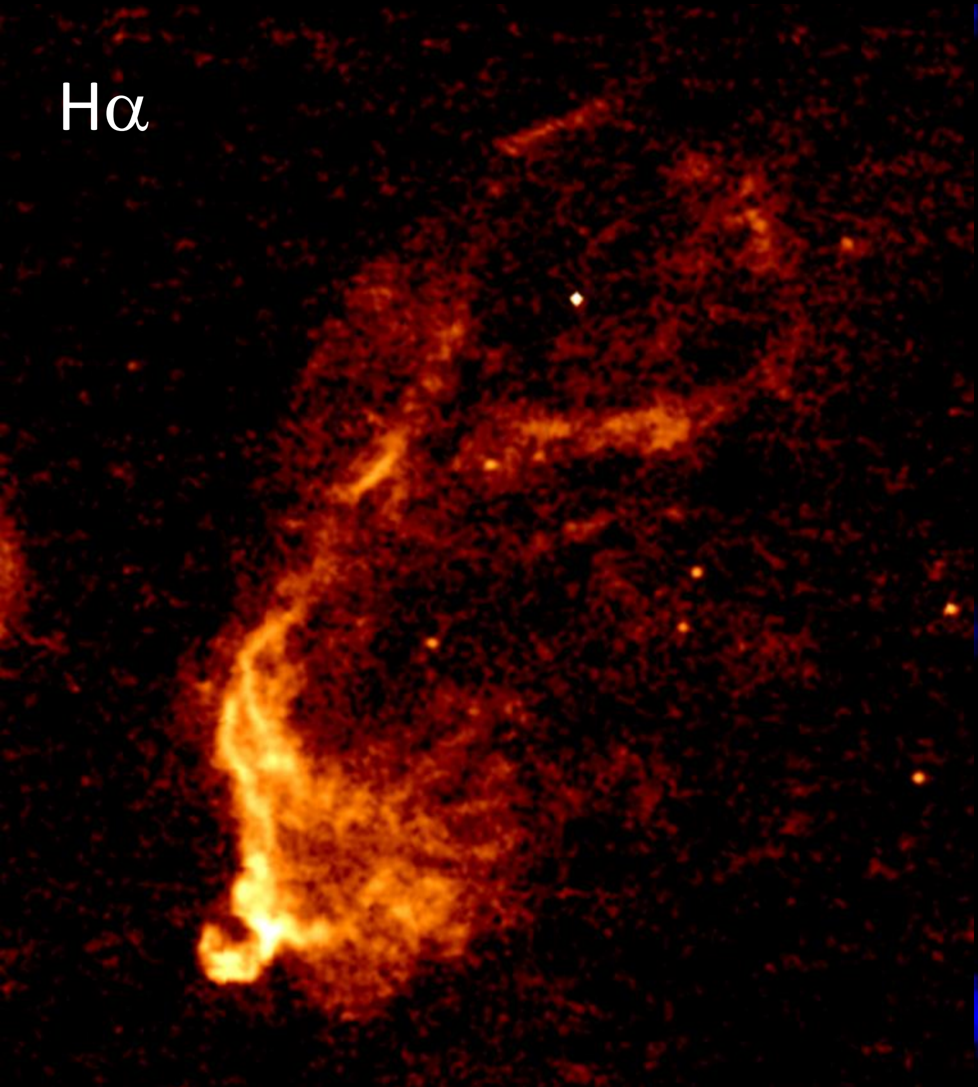
P_J ~ 10^{40} erg/s > (apparent) L_X

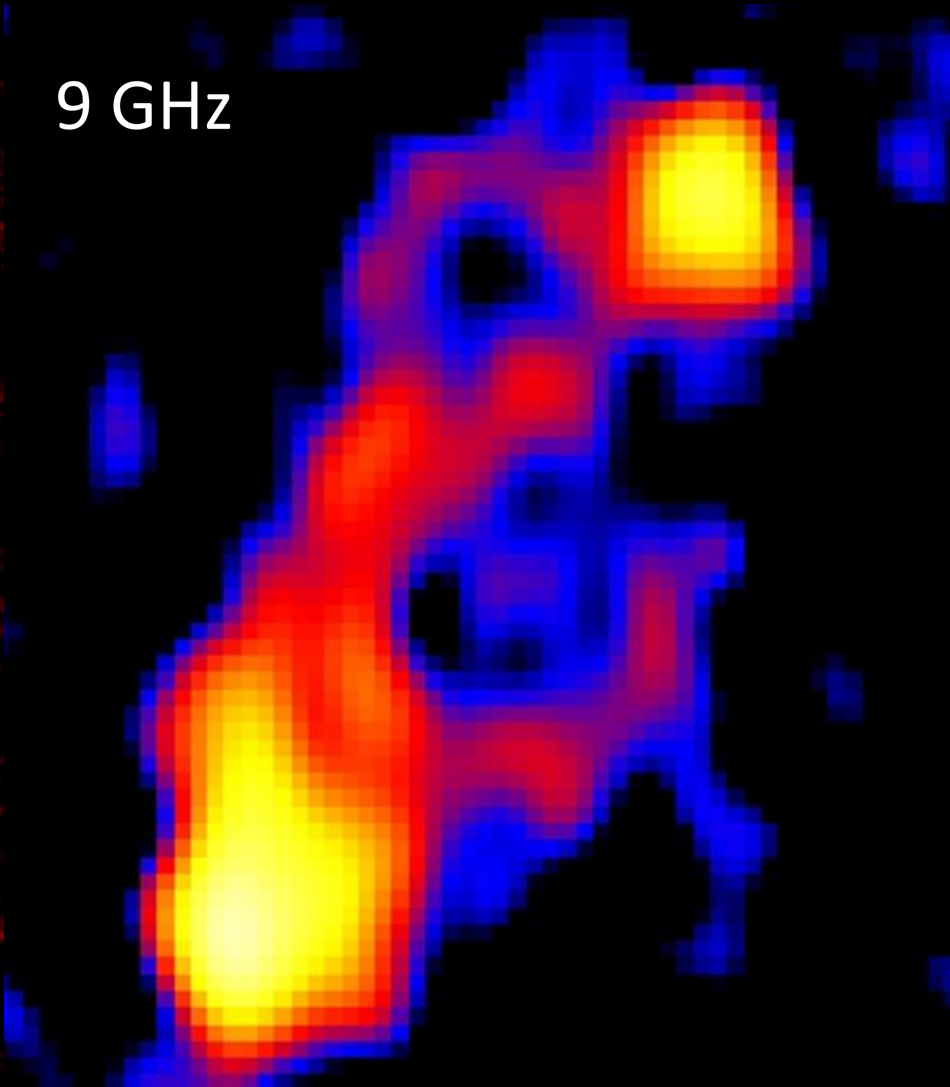
L_{5GHz} (bubble) ~ 10^{35} erg/s

S26 microquasar in NGC 7793

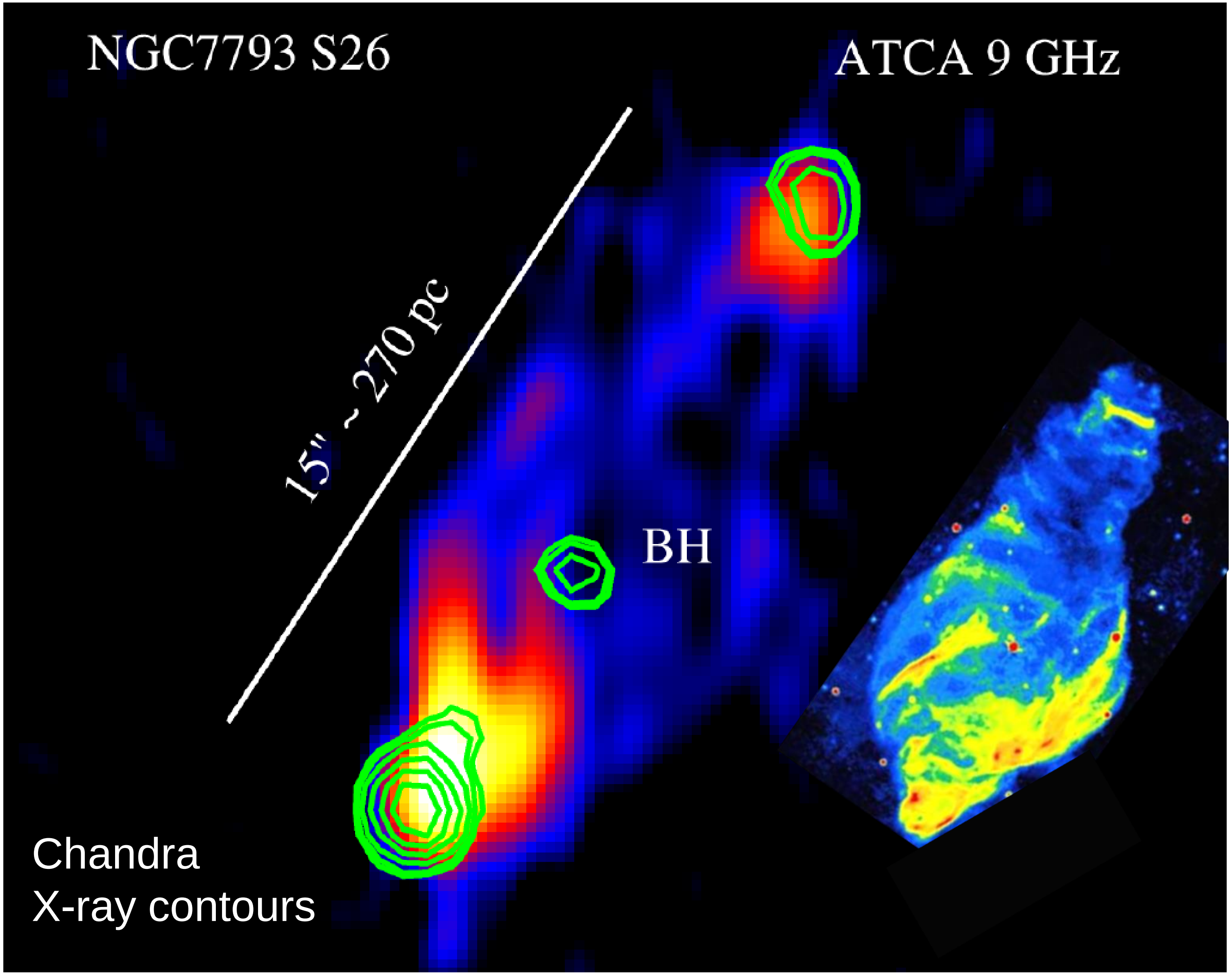
Shock-ionized bubble

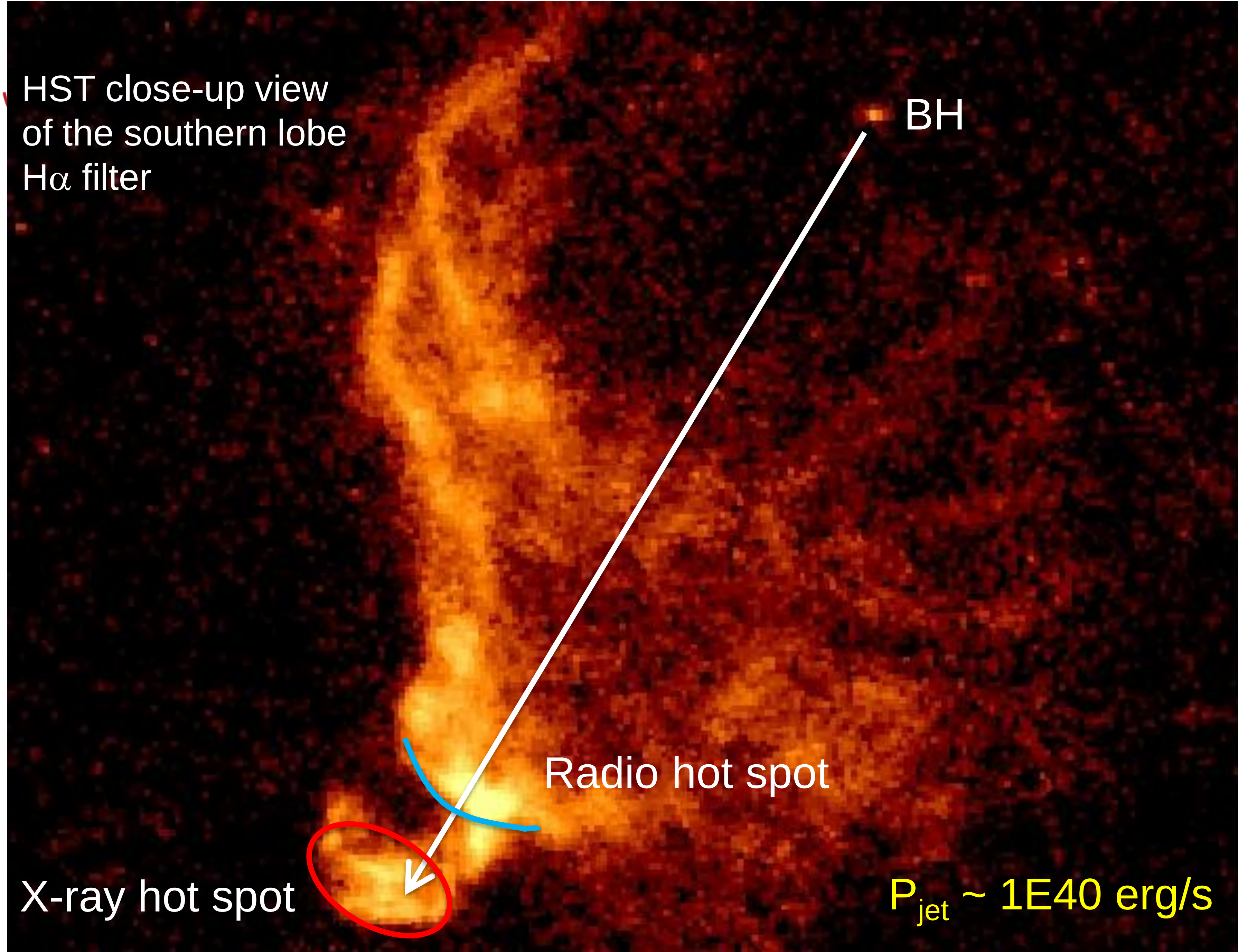
Age ~ 300,000 yrs, v ~ 270 km/s

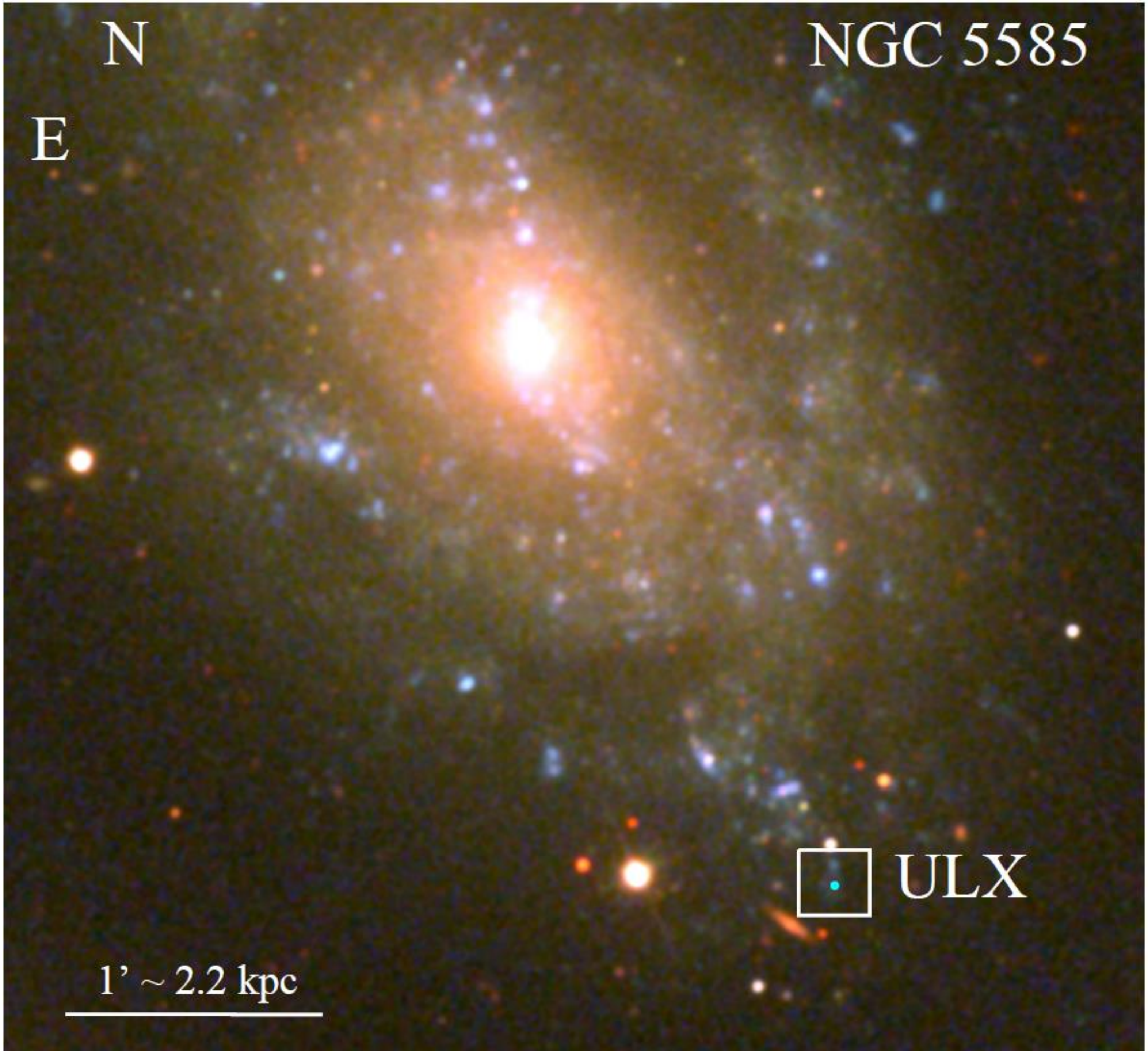


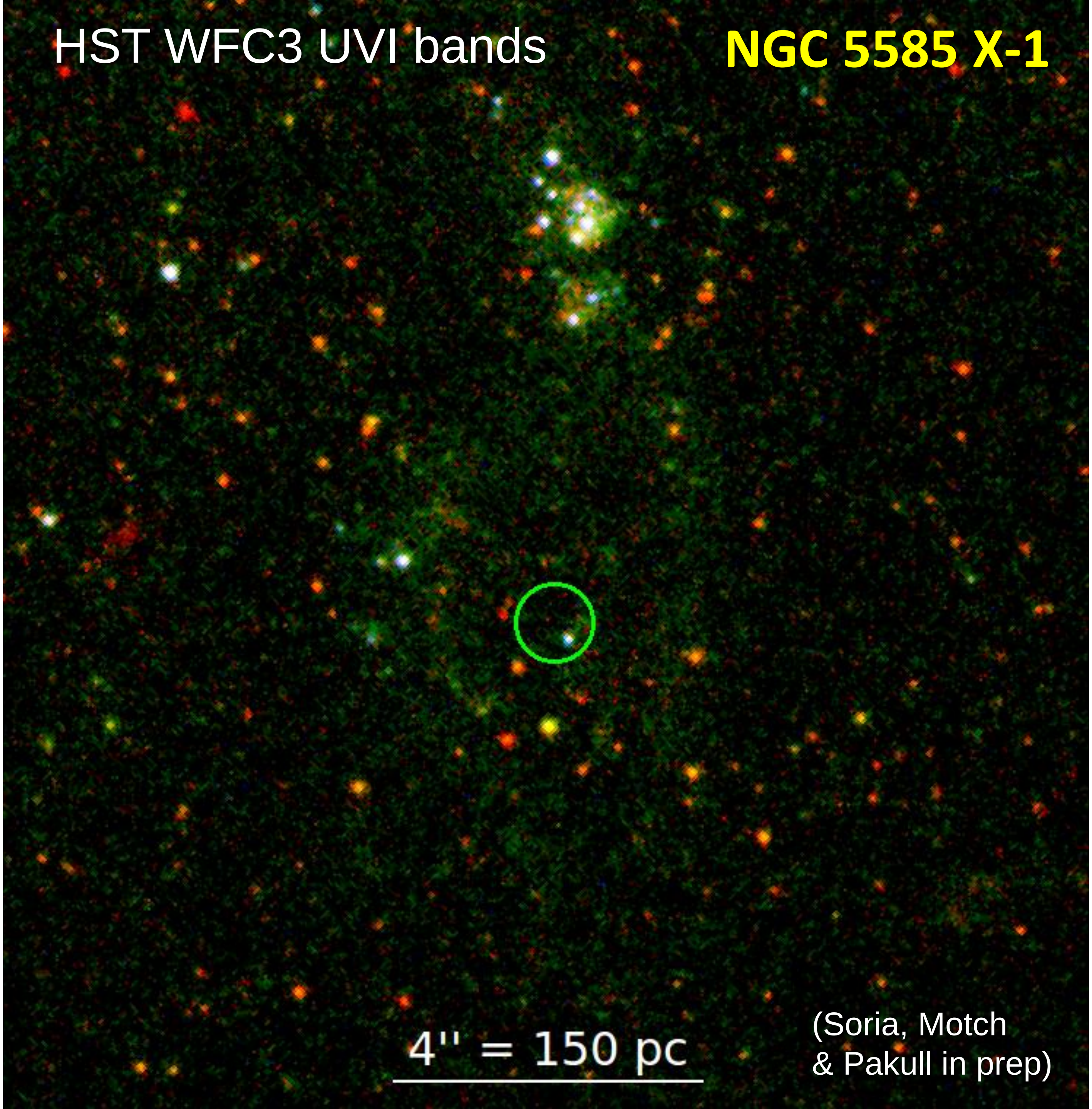


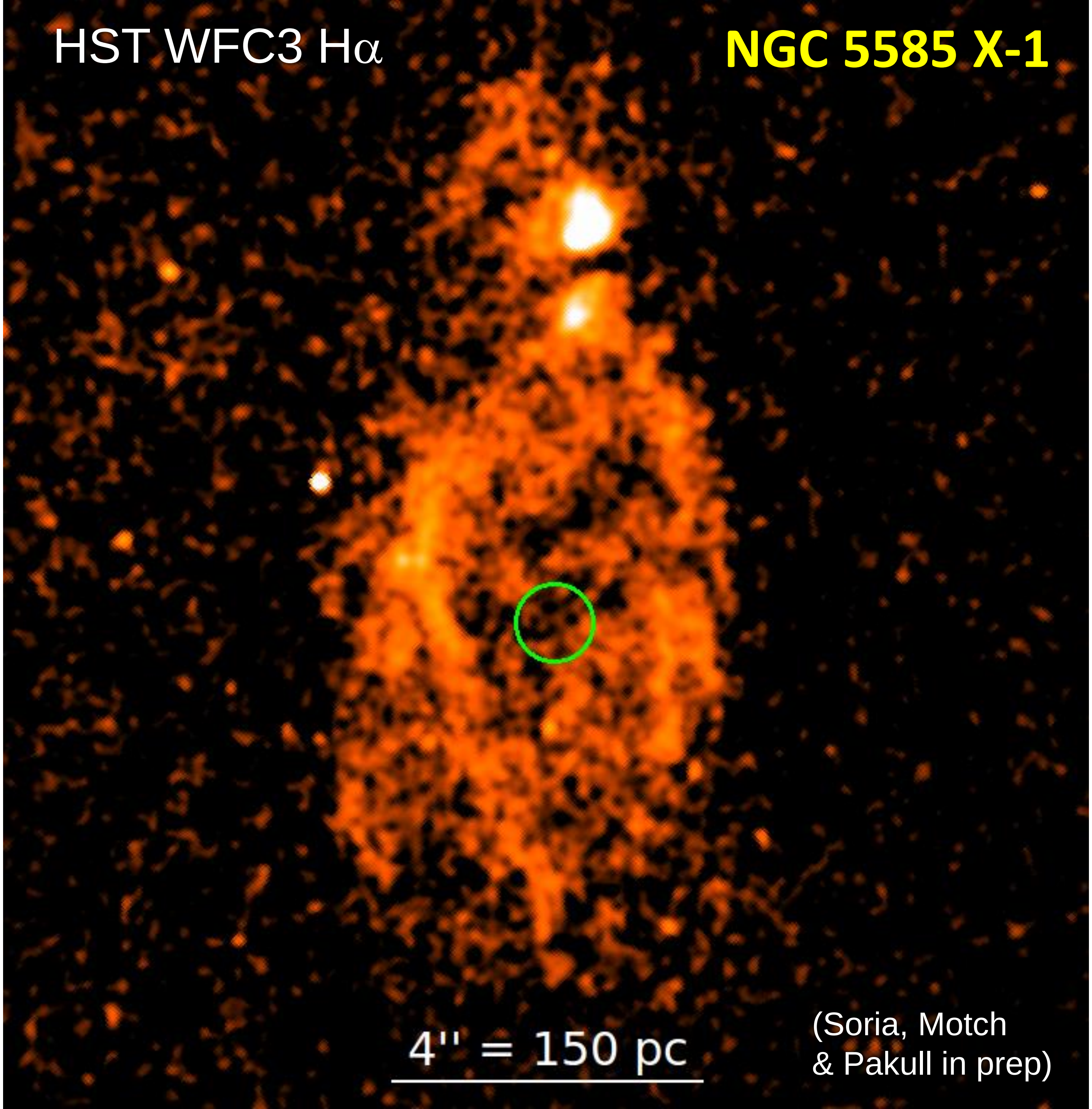
S26 microquasar in NGC 7793

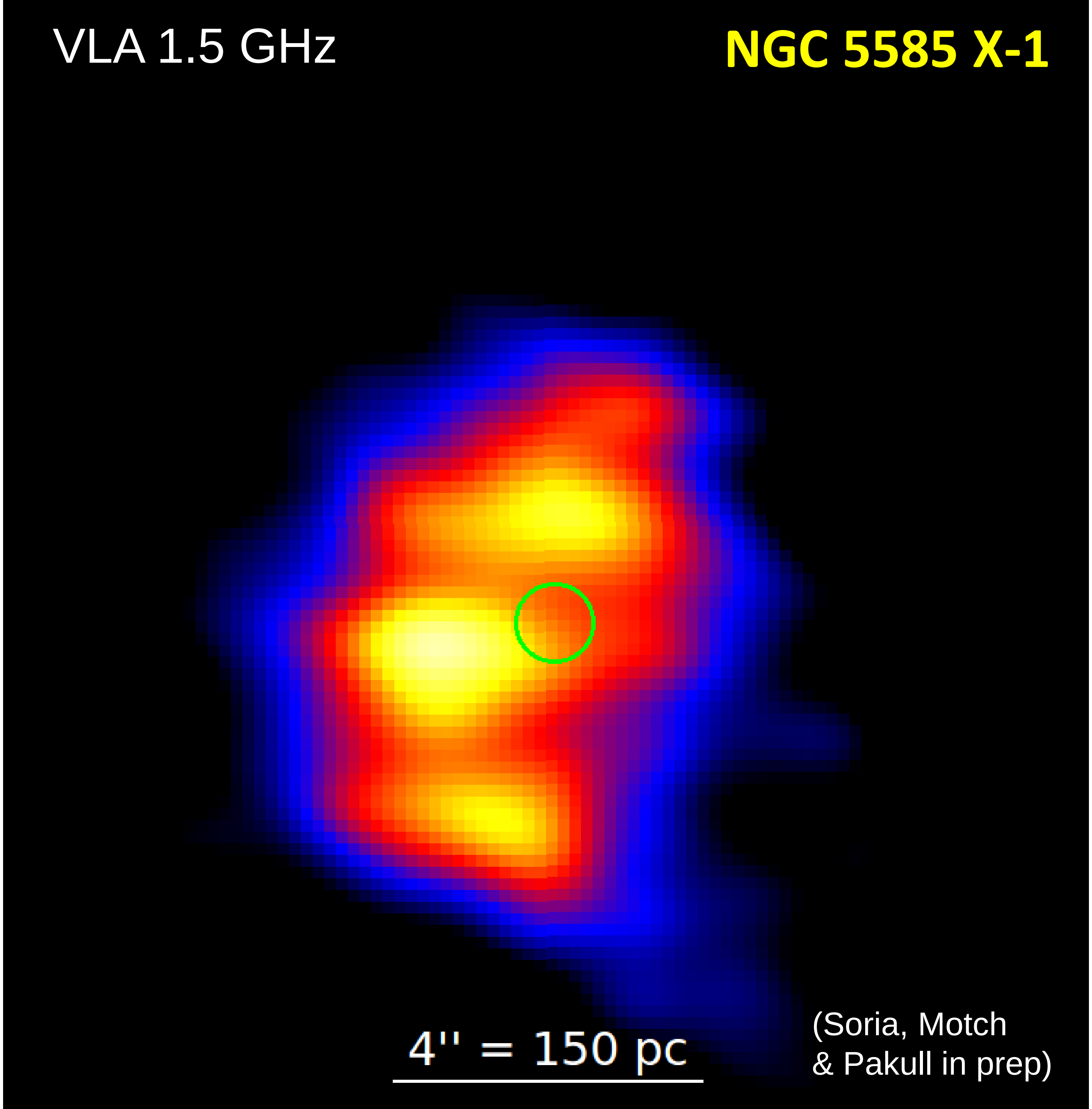



HST close-up view
of the southern lobe
Hα filter
BH
Radio hot spot
X-ray hot spot
P_{jet} ~ 1E40 erg/s


N
E
NGC 5585
ULX
1' ~ 2.2 kpc

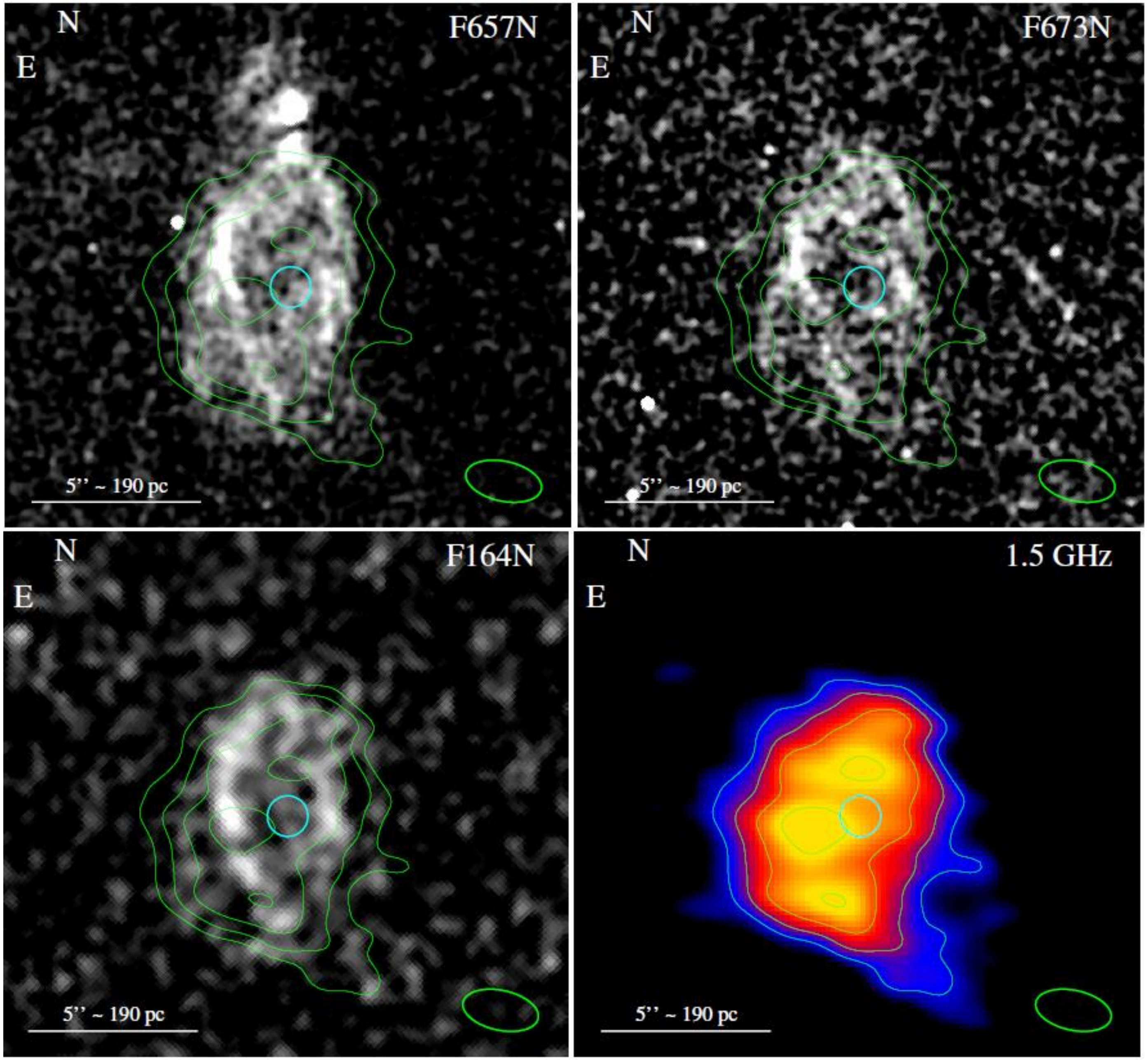

HST WFC3 UVI bands
NGC 5585 X-1
4'' = 150 pc
(Soria, Motch
& Pakull in prep)


HST WFC3 Hα
NGC 5585 X-1
4'' = 150 pc
(Soria, Motch
& Pakull in prep)


VLA 1.5 GHz
NGC 5585 X-1
4'' = 150 pc
(Soria, Motch
& Pakull in prep)

VLA 1.5 GHz

NGC 5585 X-1



Mechanical power in shock-ionized bubbles

Similar to SNRs but larger (100—300 pc) and older

Shock velocity ~ line FWHM ~ 150—250 km/s

Two complementary techniques (M W Pakull et al)

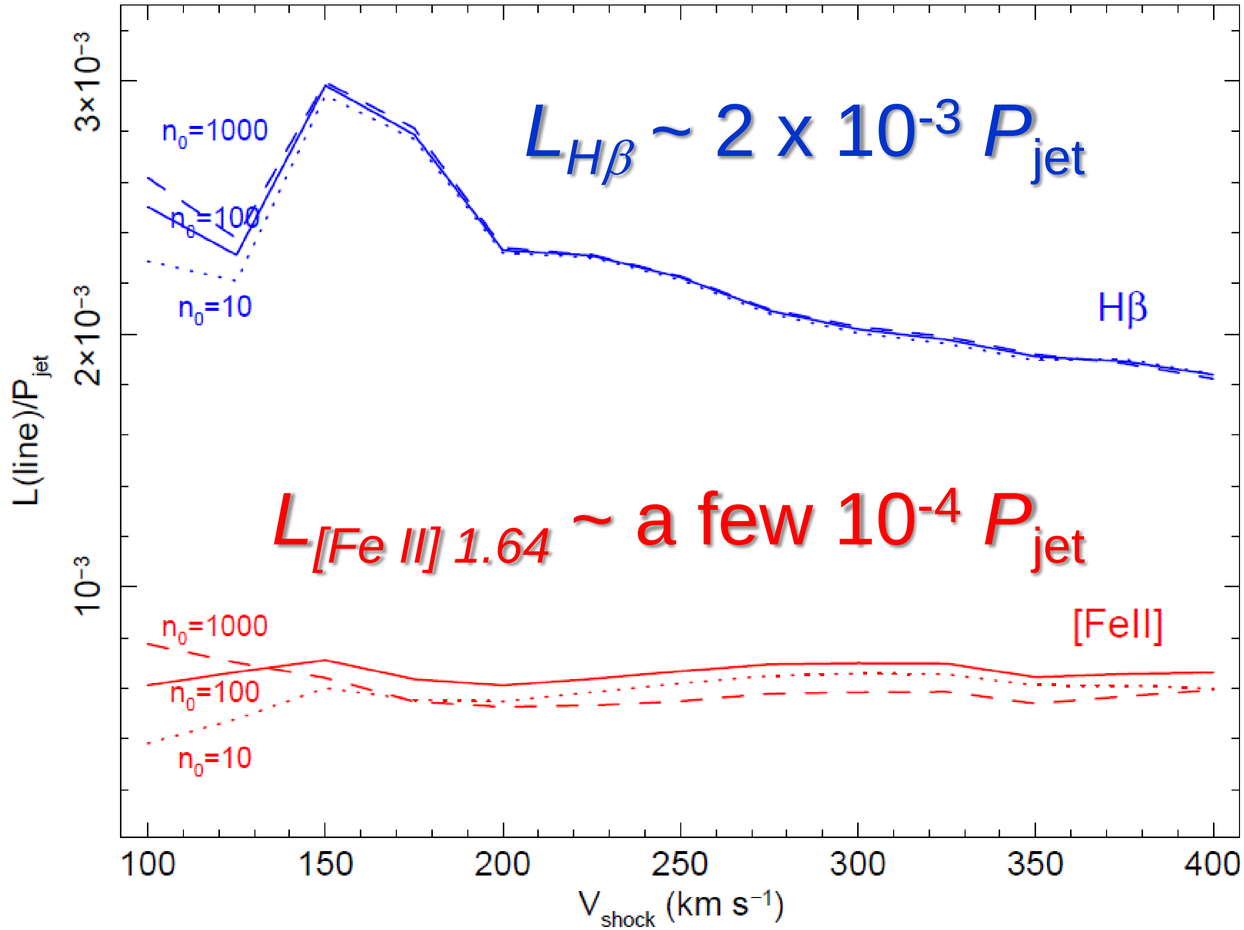
a) Measure bubble size (R) and expansion velocity (V)

$$\longrightarrow \quad P_J \sim nR^2V^3$$

b) Measure flux of diagnostic lines (Hα, Hβ, [Fe II] 1.64μm)

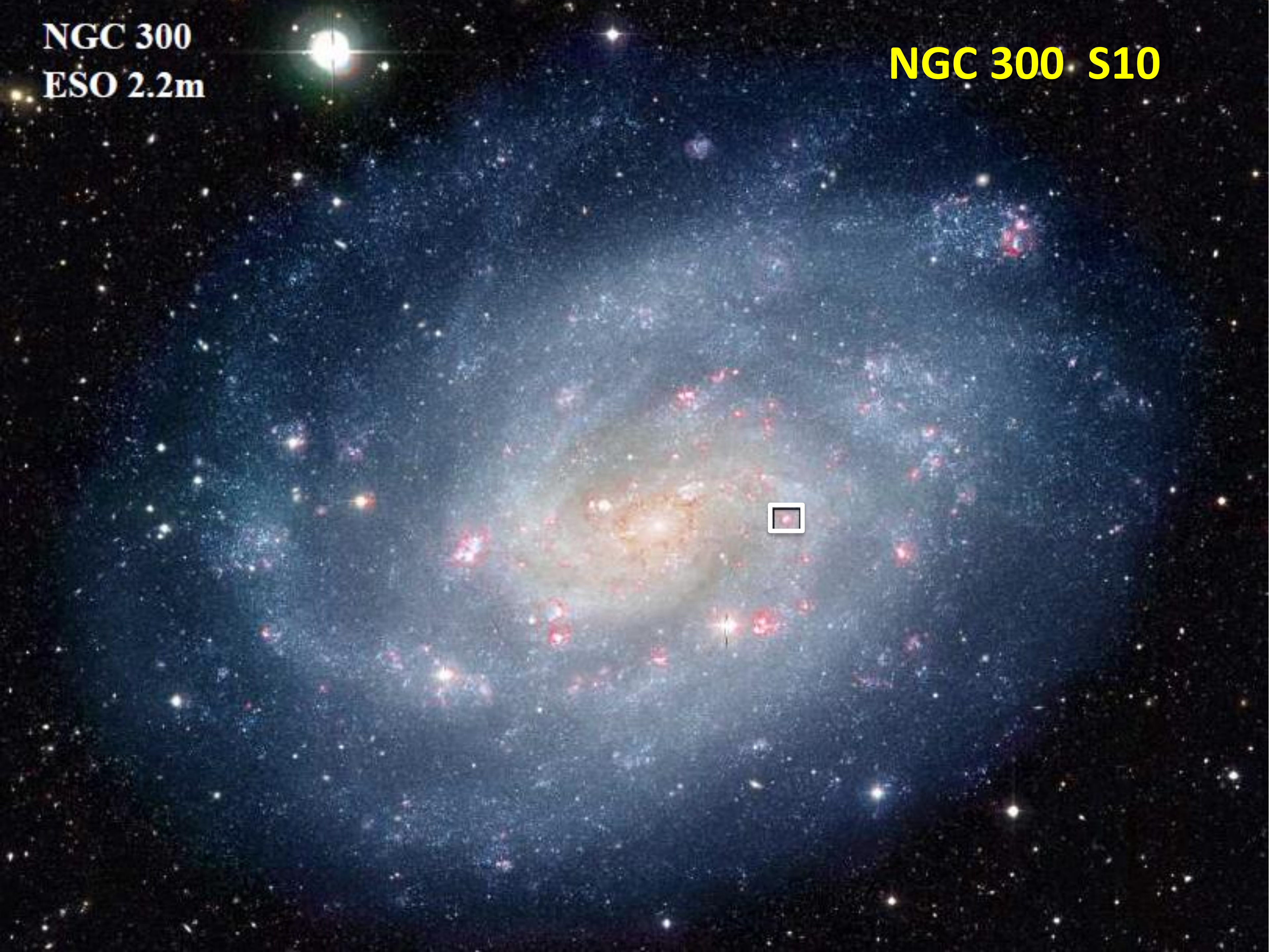
$\longrightarrow$ P_J scales with optical/IR line flux

Hβ and [Fe II] are good proxies for jet power



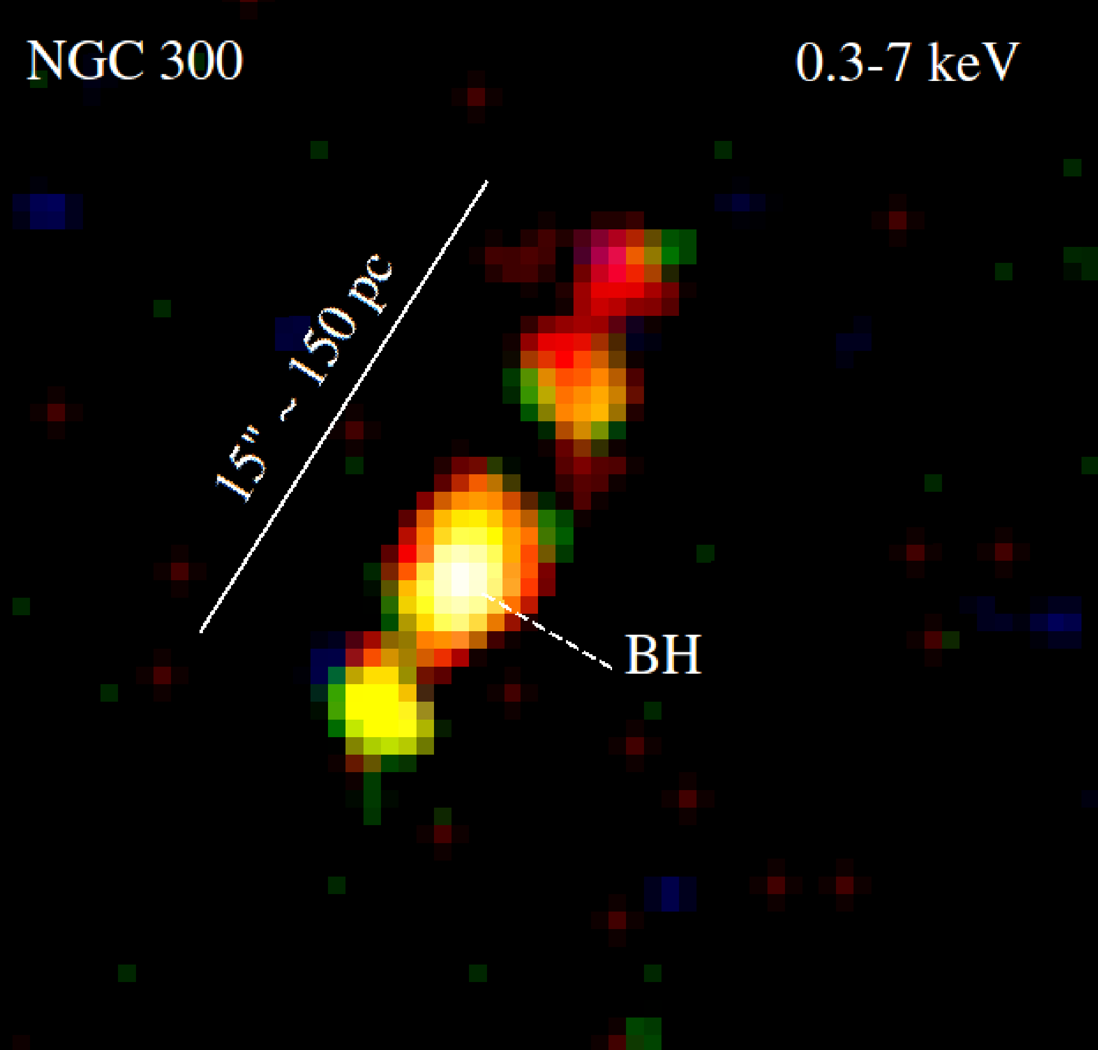
(Soria et al 2014, using Mappings III, Allen et al 2008)

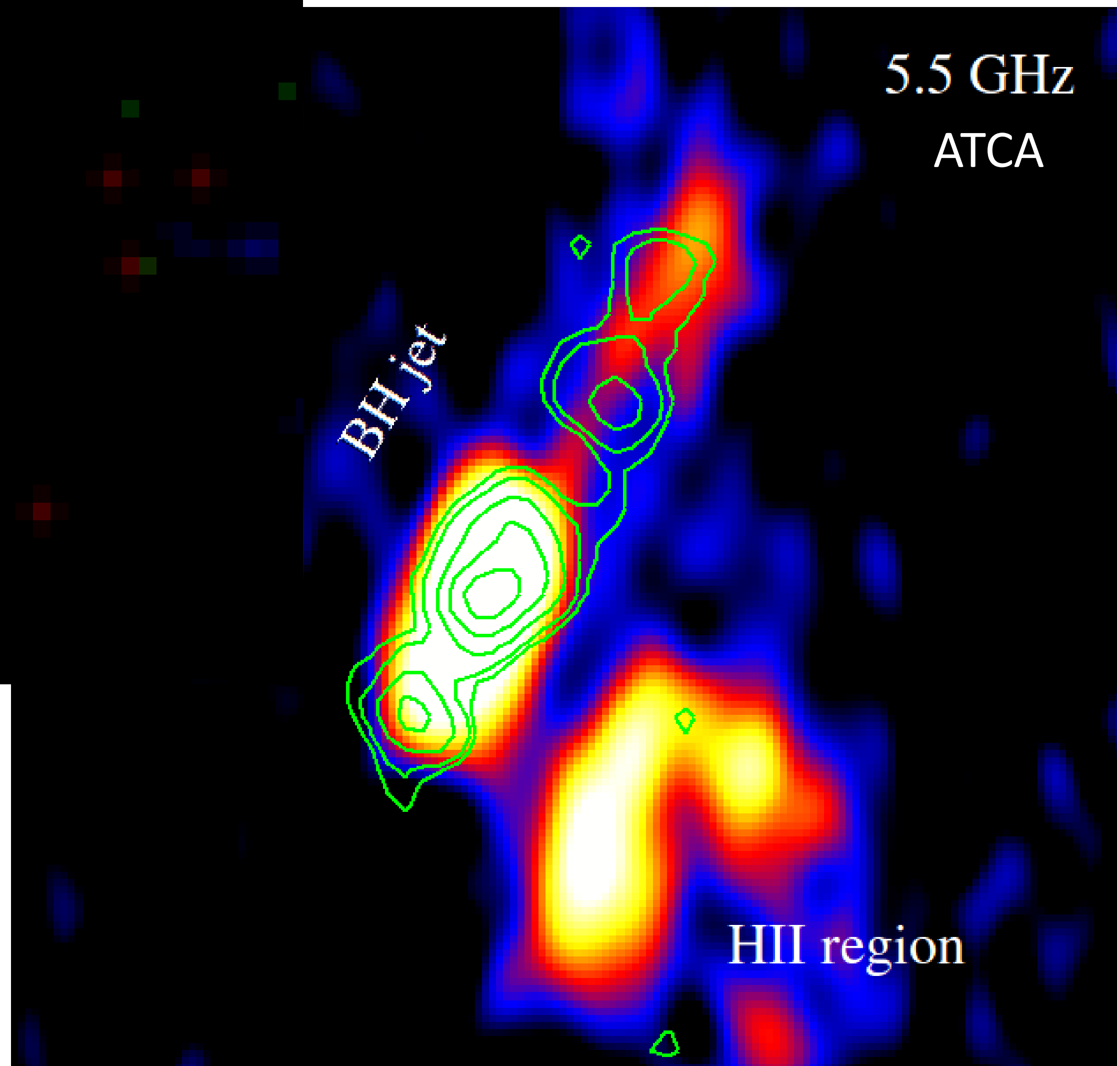
[Fe II] traces gas with $n_e \sim 10^3$—10^5 cm^{-3}, $T_e \sim$ 6,000—15,000 K


NGC 300
ESO 2.2m
NGC 300 S10

NGC 300 S10

Jet with multiple X-ray knots

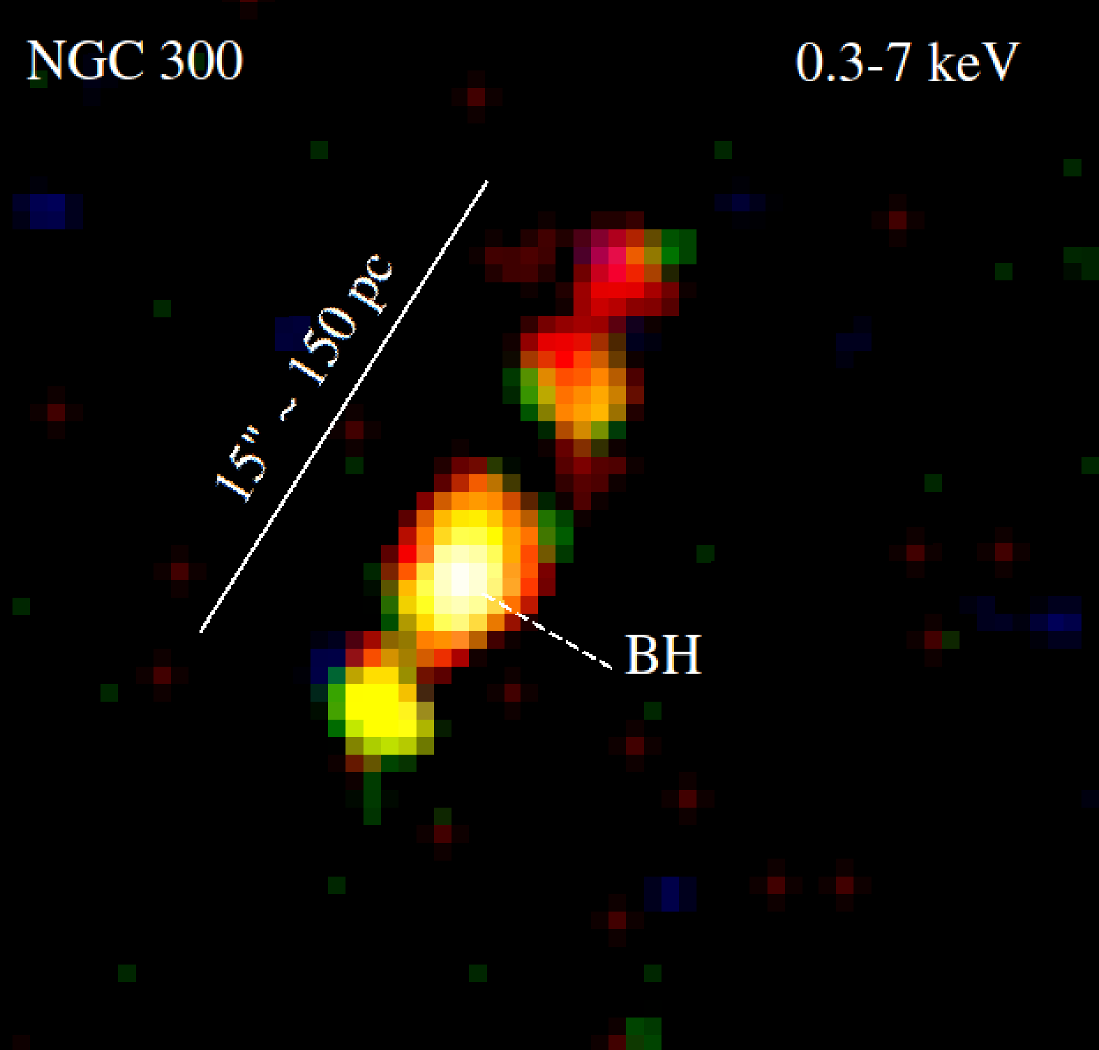




X-ray, Hα and radio detection

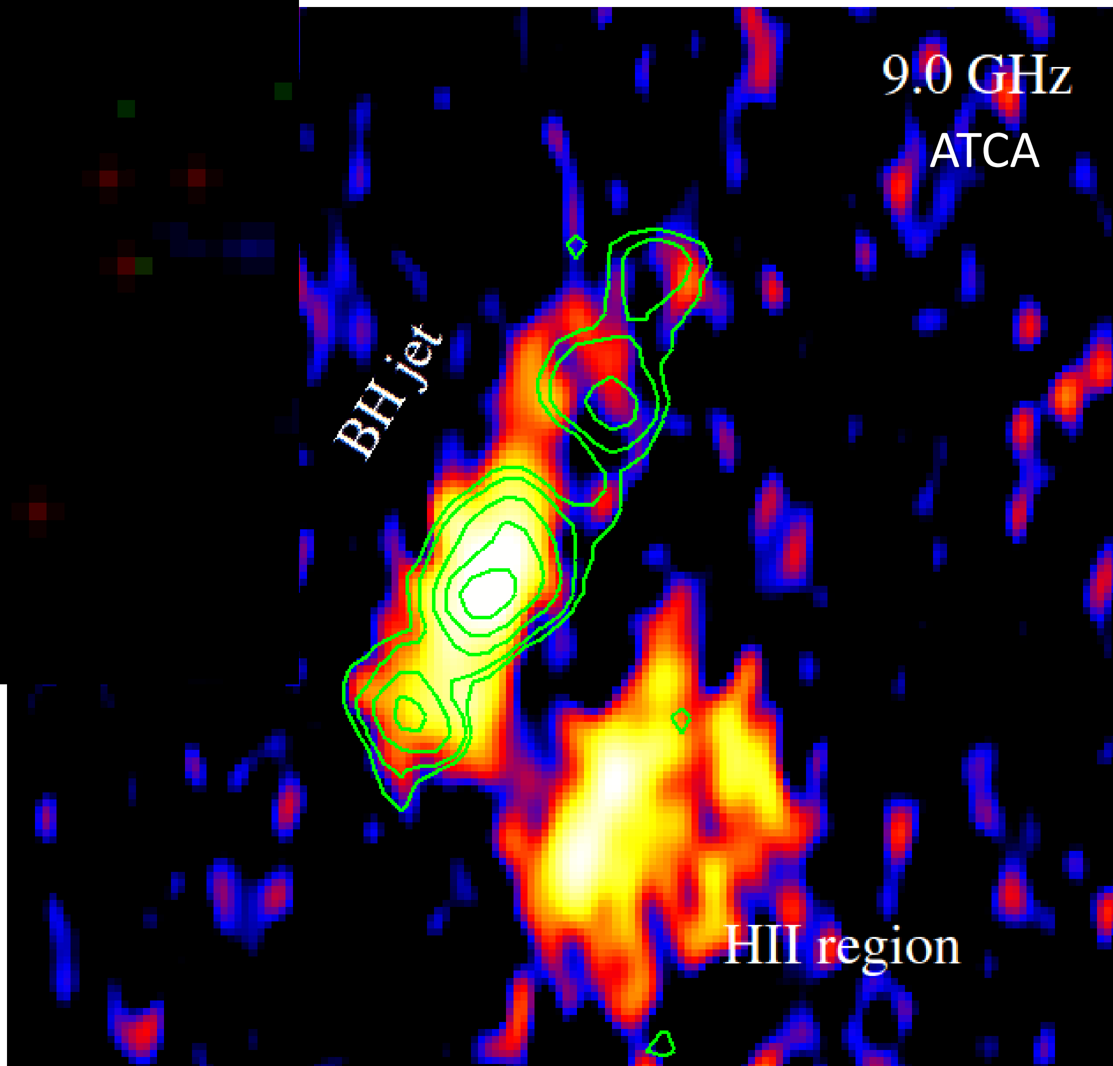
L_{5GHz} (jet) ~ 10^{34} erg/s

(Urquhart, Soria, Pakull et al 2019)



NGC 300 S10

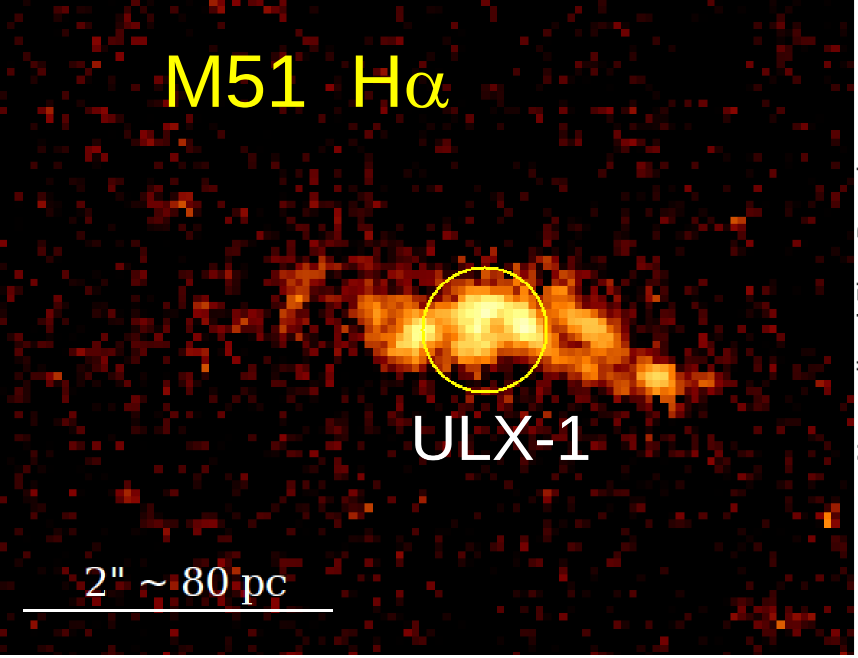
Jet with multiple
X-ray knots

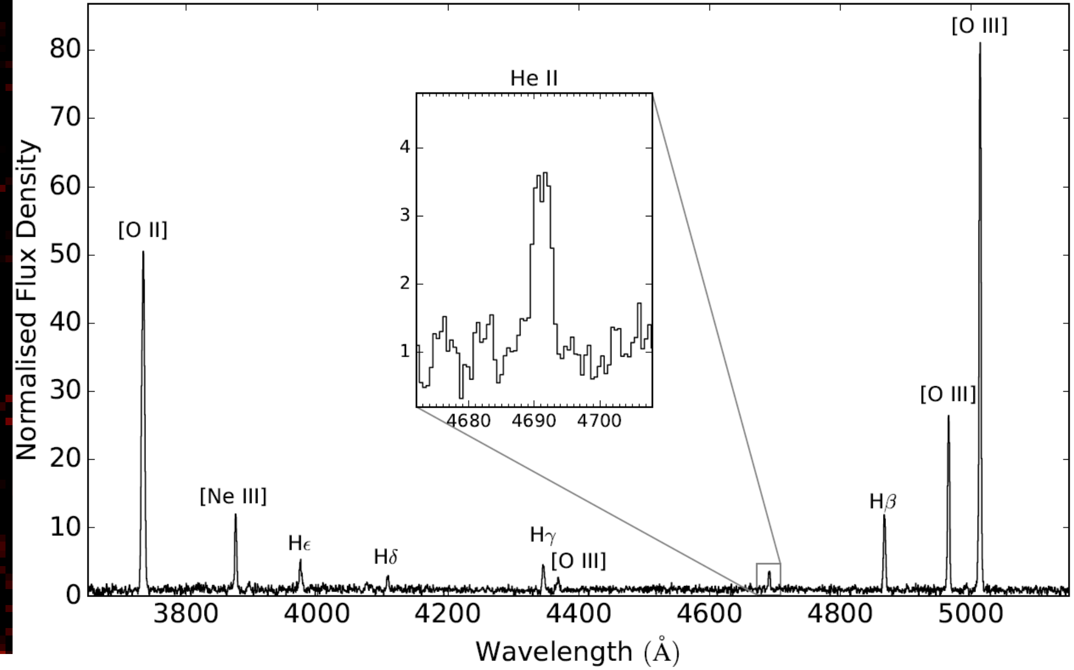


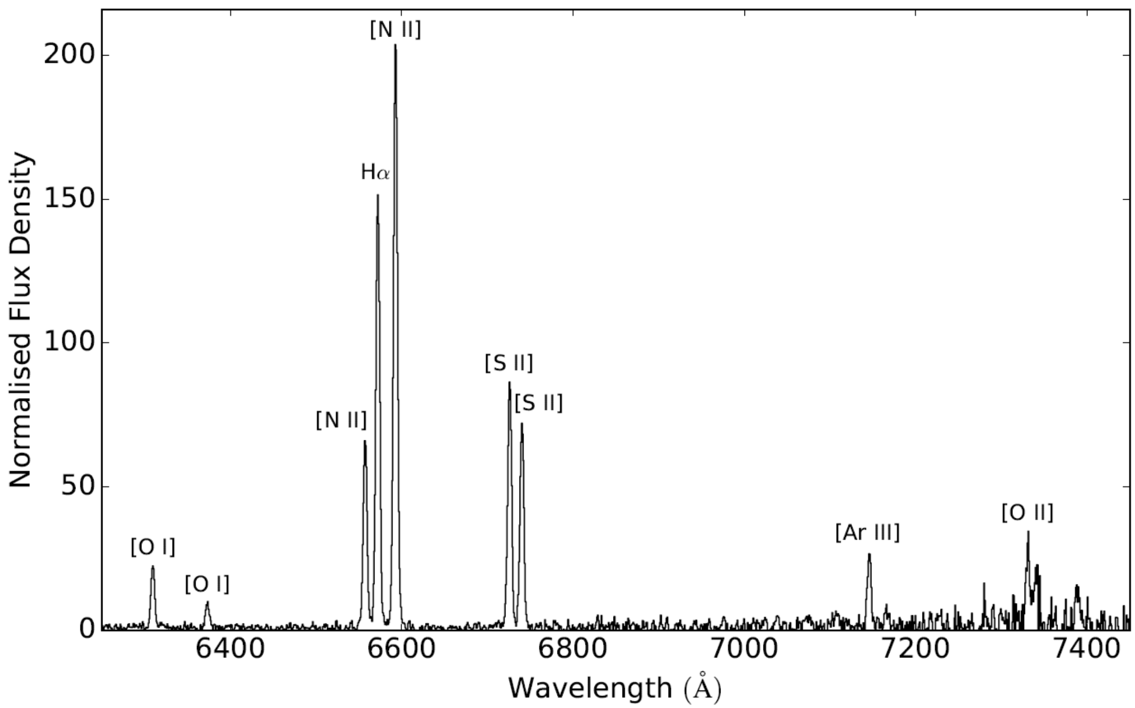
X-ray, Hα
and radio detection

L_{5GHz} (jet) ~ 10^{34} erg/s

(Urquhart, Soria, Pakull et al 2019)







Jet-inflated bubble in M51

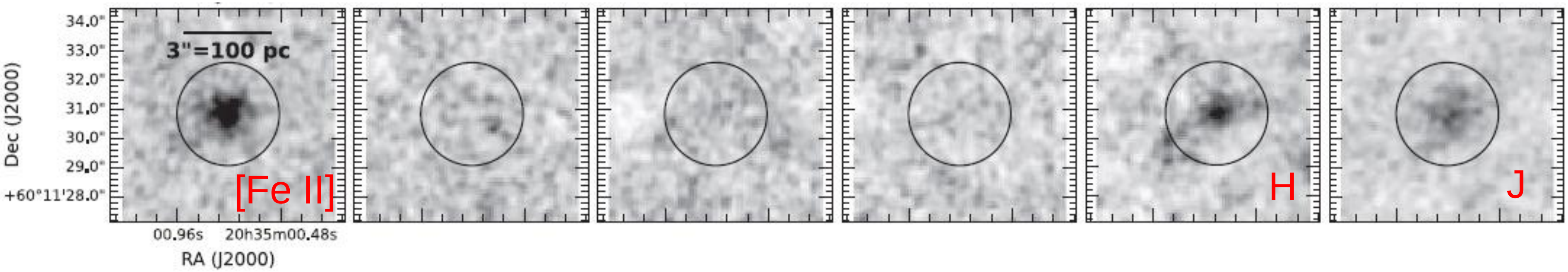
(Urquhart, Soria, et al, 2018)

P_J ~ 2×10^{39} erg/s

L_{5GHz} ~ 2×10^{34} erg/s

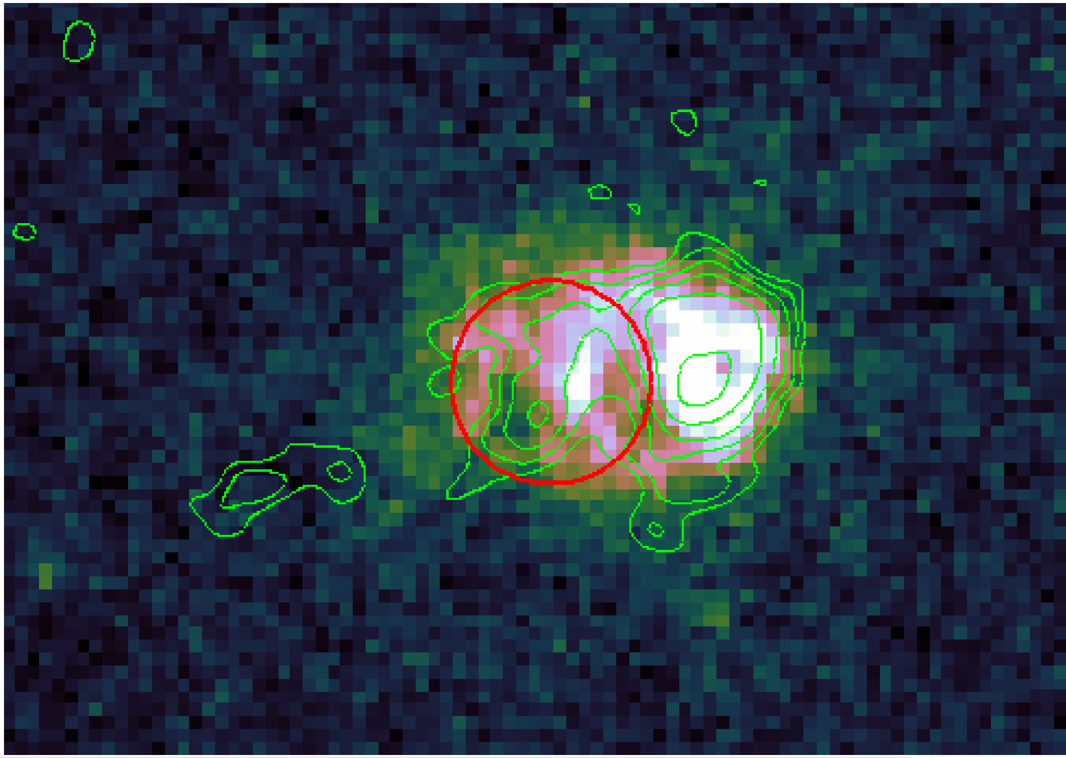
SNR or microquasar bubble?

(Bruursema et al 2014)



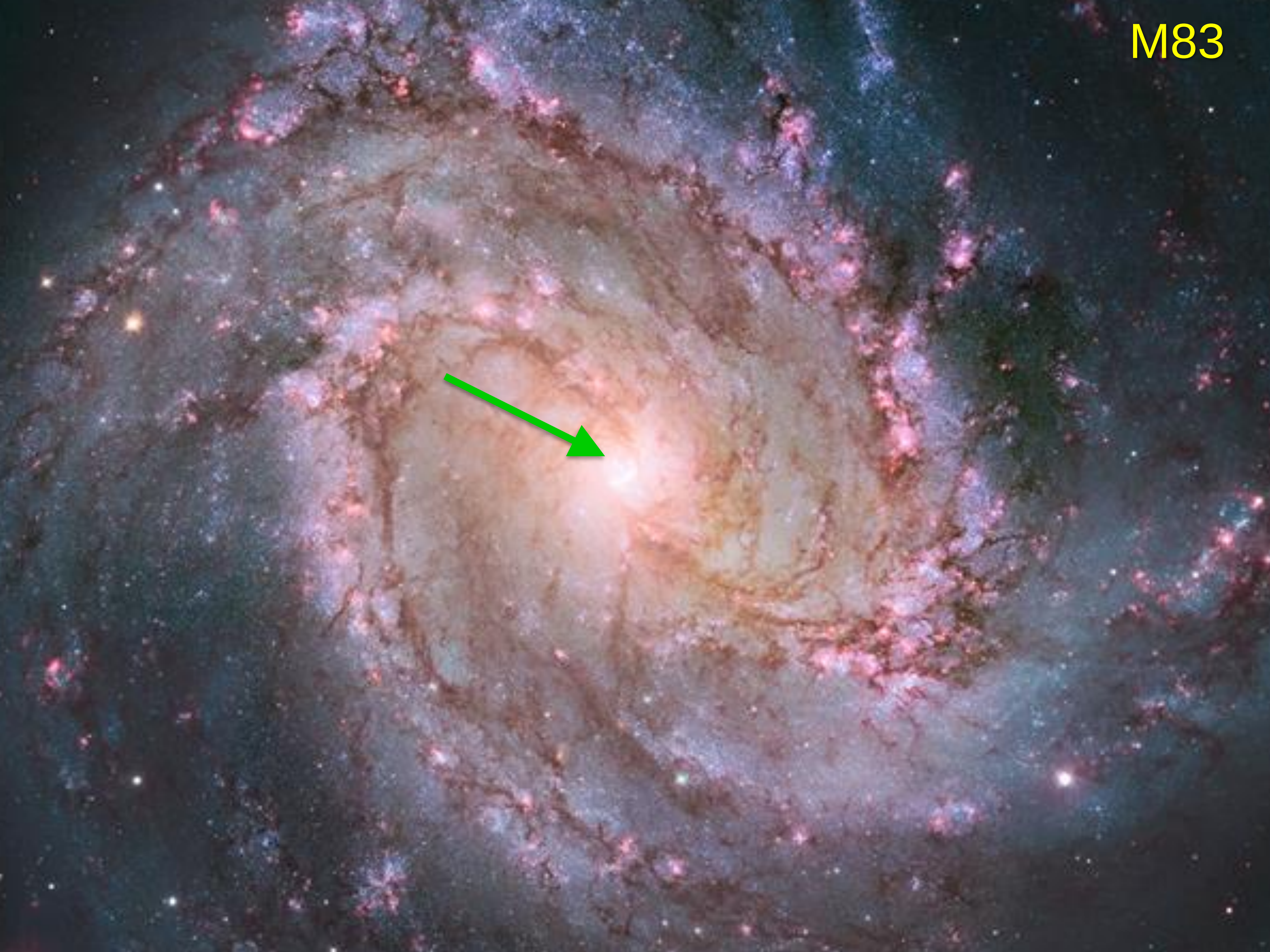
MF16 in NGC 6946

Strongest [Fe II] source in NGC 6946 is in fact a microquasar jet

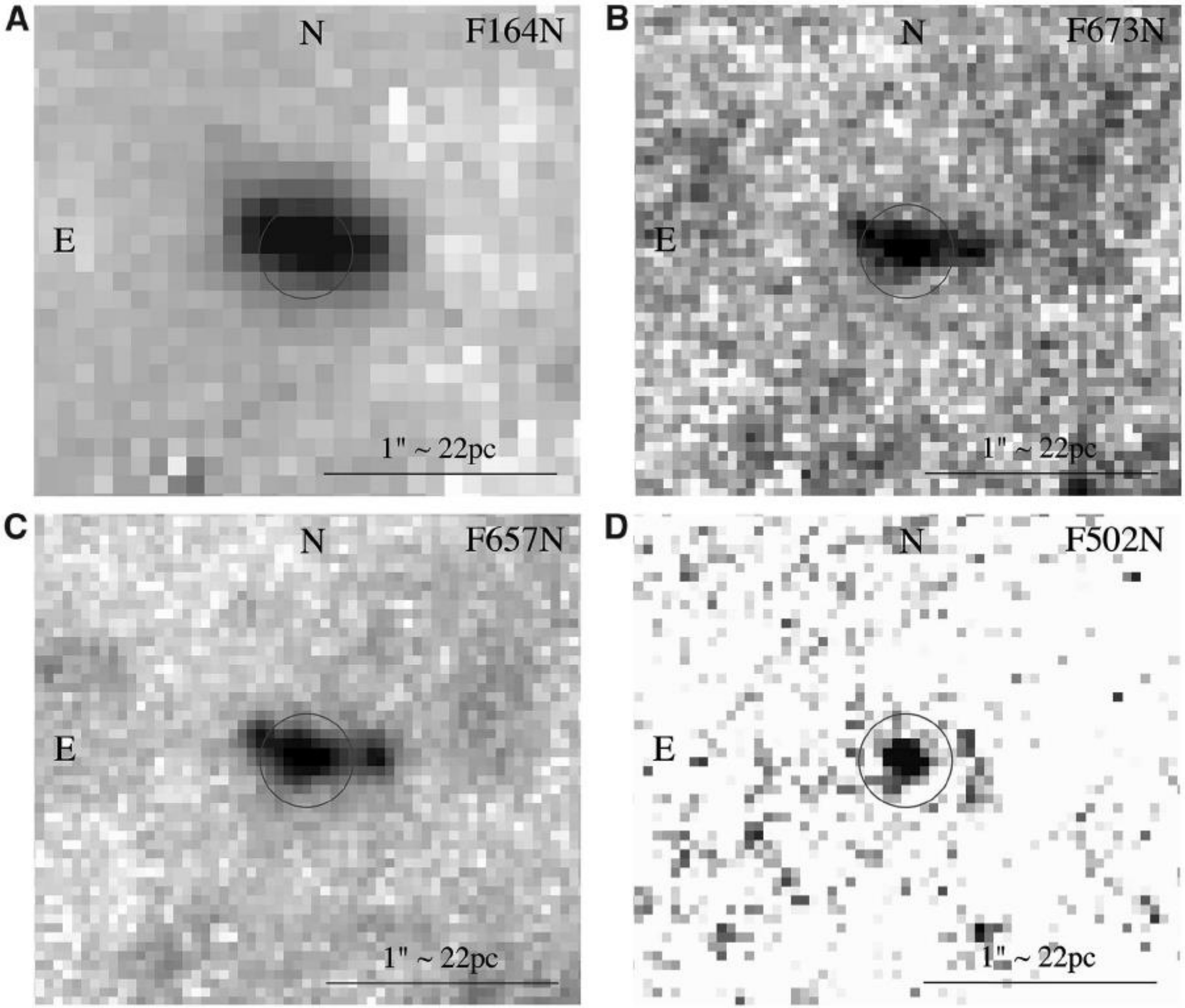


VLA radio contours
HST optical image

(Beuchert et al in prep.)


M83

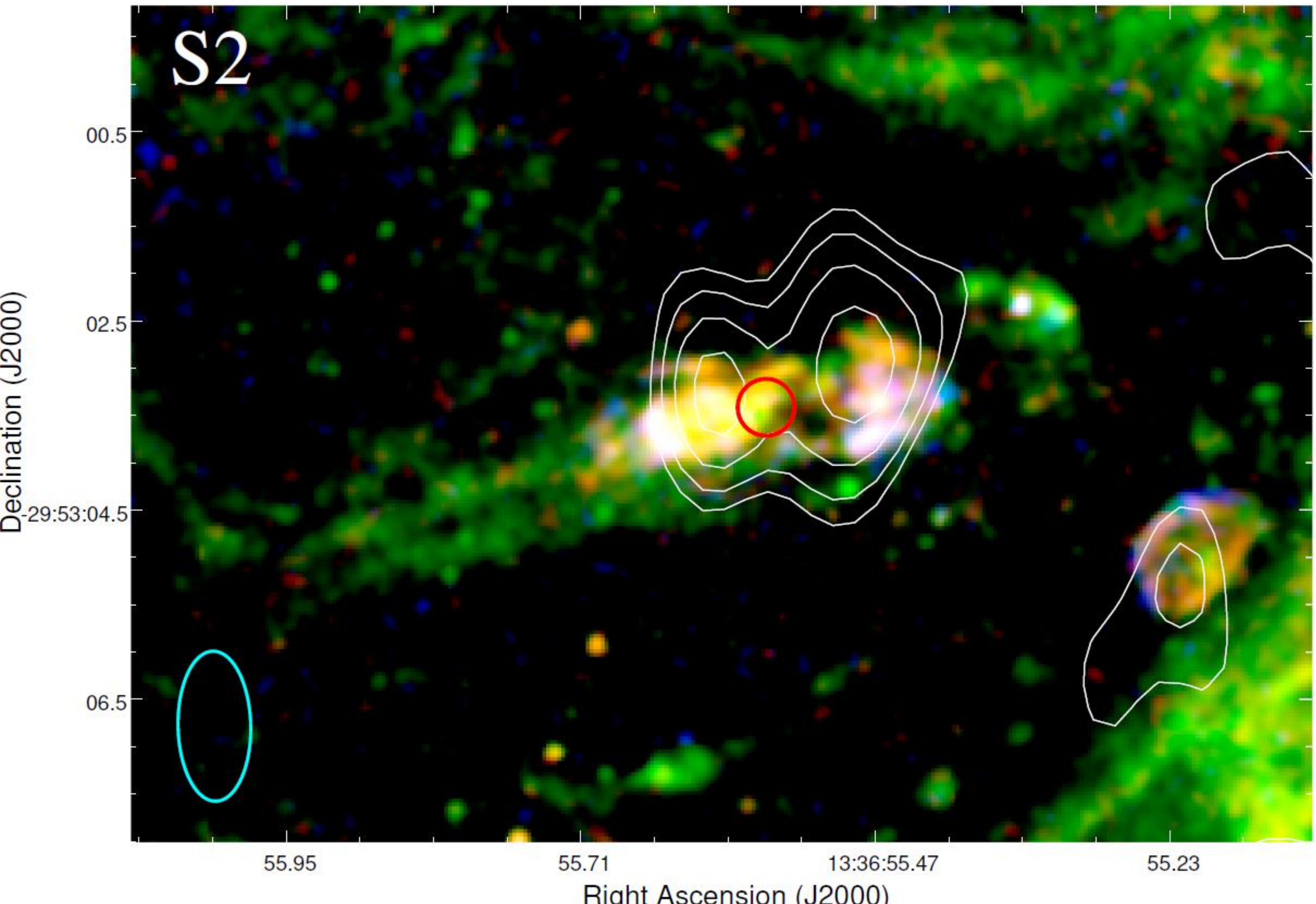
M83 MQ1: jet with super-Eddington power



P_{Jet} ~ 10^{40} erg/s

(Soria et al 2014, *Science*)


M83



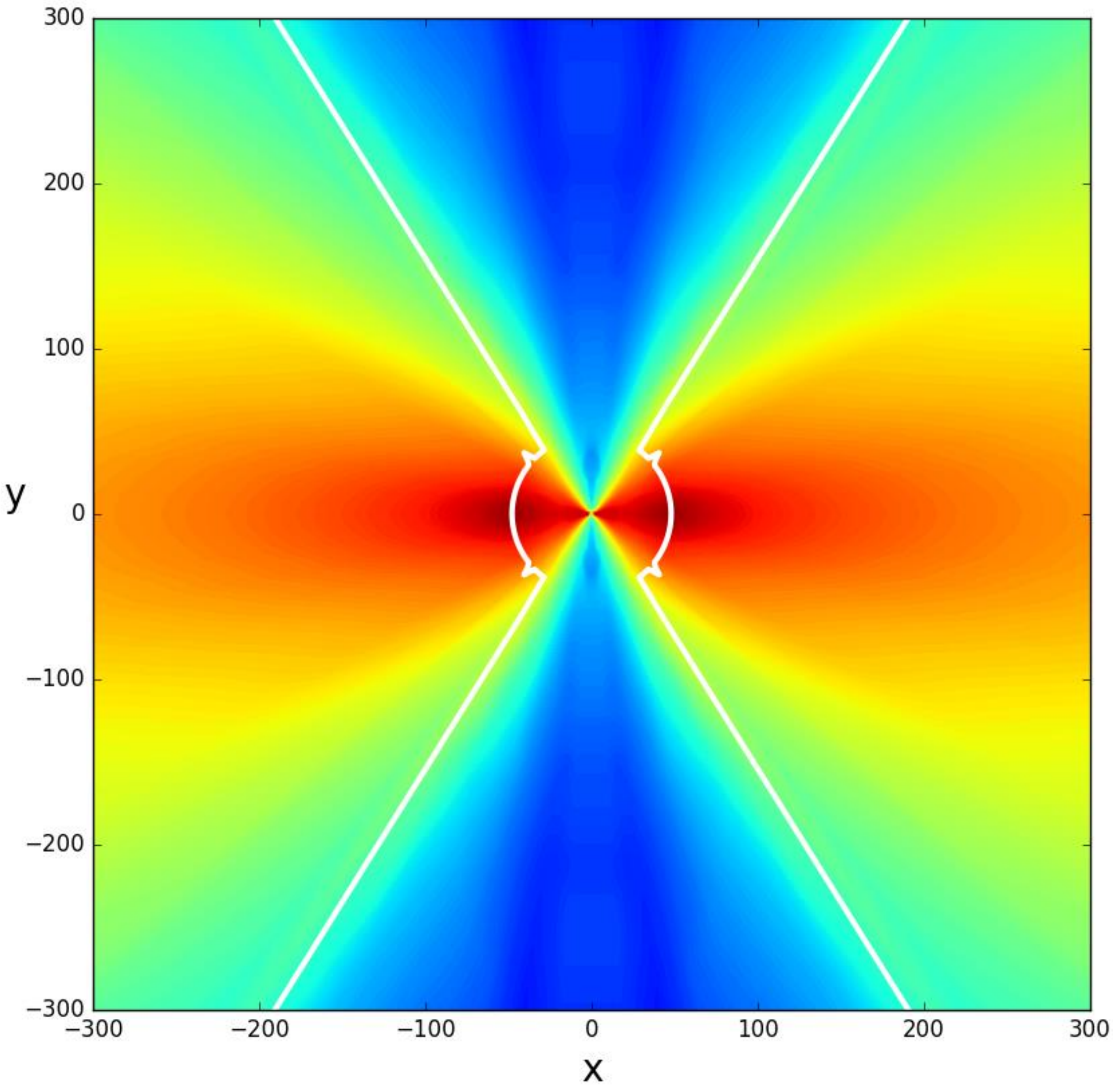
(Soria, Long, Blair et al 2019 submitted)

Putting together our findings so far

- ✓ Several ULXs with jets ($P_{kin} \sim P_{rad} > 10^{39}$ erg/s)
- ✓ Several ULXs with fast and/or dense outflows
- ✓ Typical duration of the super-critical phase ~ 10^5 yr
- Other bright ULXs have no evidence of jets
- Several ULXs have high inclination but hard spectra
- Hard and soft ULXs have similar luminosity range

⟶ *Problems for ULX unification model*

Problems with ULX unification model



Some ULXs have
high inclination
but hard X-ray spectra

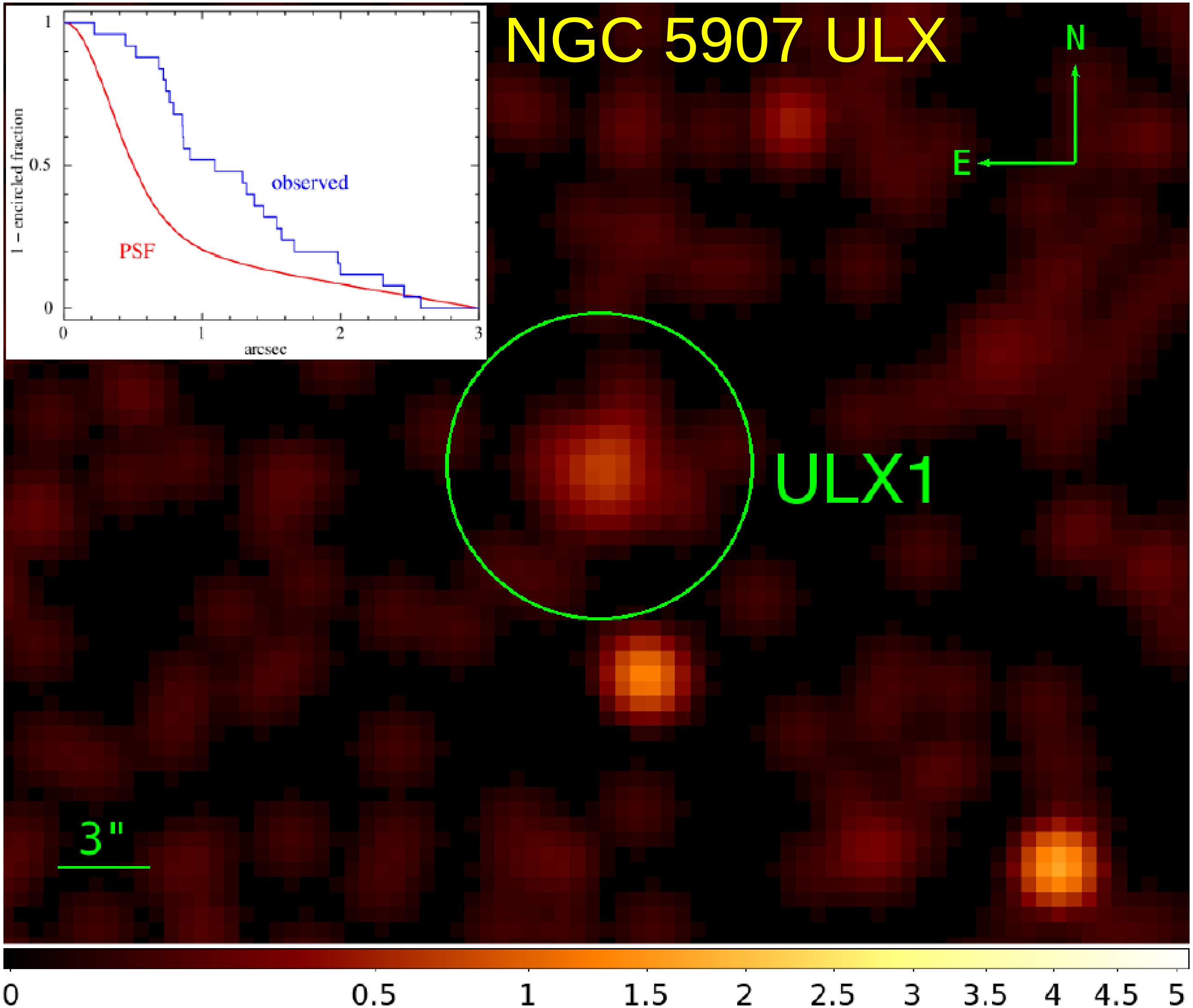
Some ULXs have
stronger jets/outflows
at same accretion rate

An additional parameter: NS vs BH

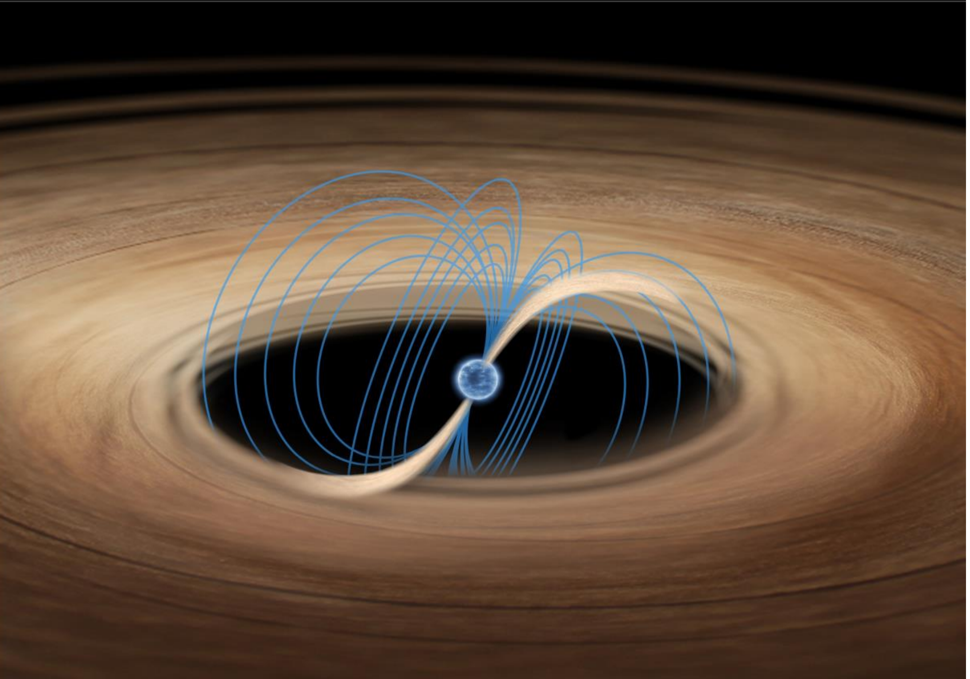
Strongly magnetized vs
weakly-magnetized accretion

- Weaker jets in NSs for same accretion power?
- Different jet launching mechanism in BHs and NSs?
- Can NSs exceed Edd luminosity better than BHs?

First ULX bubble in a NS (Belfiore et al 2019)

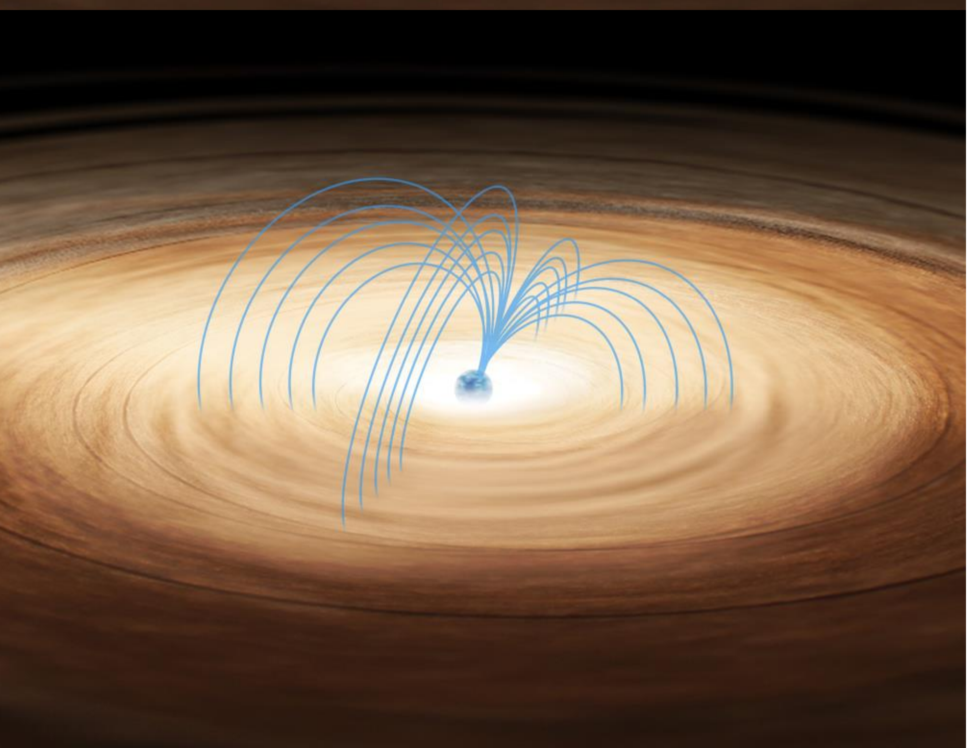


Accretion onto NSs



Strong magnetic field
(for mdot > 1, B > 10^{12} G)

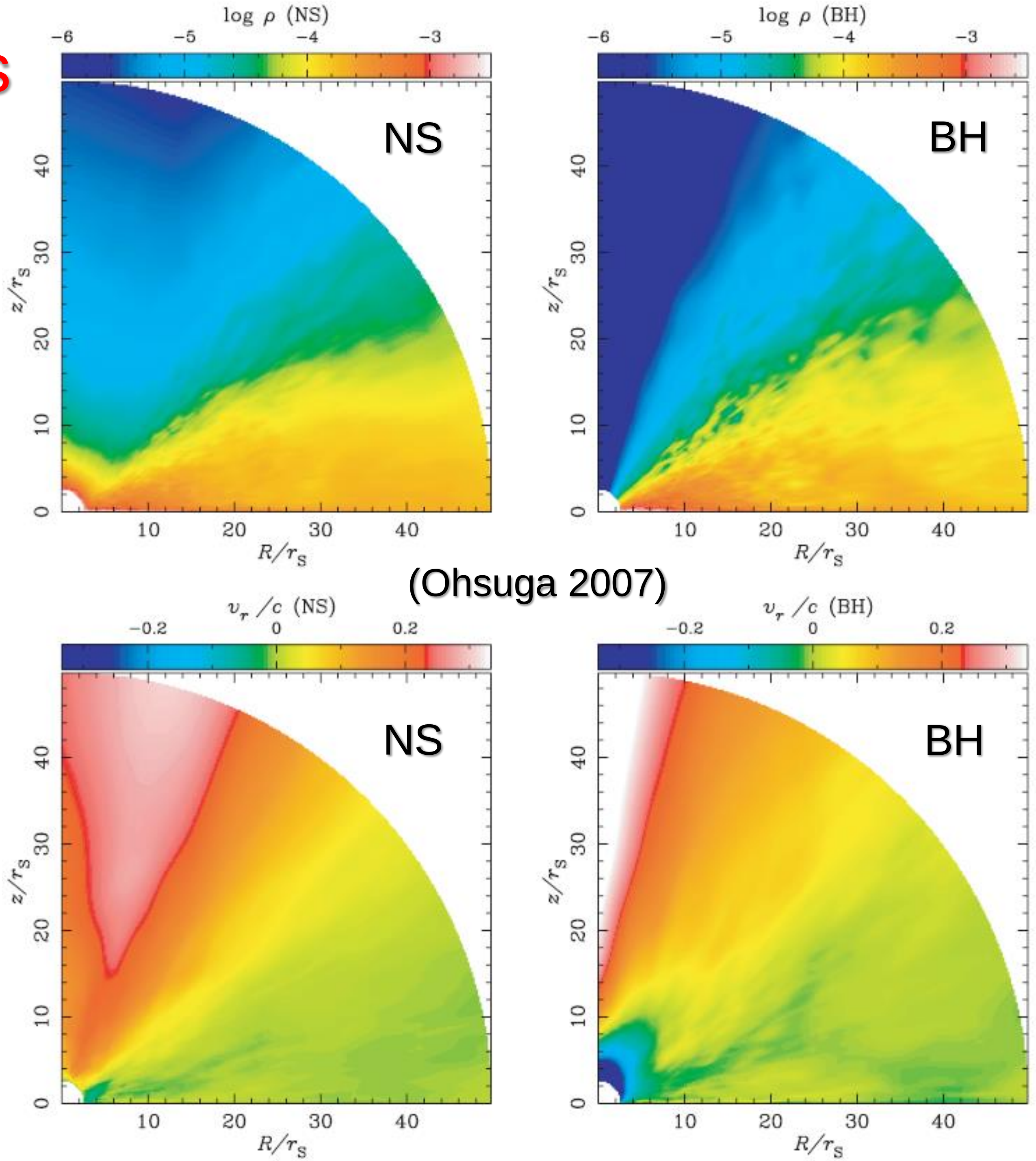
Polar accretion columns
No disk outflows/funnel?



Weak magnetic field
(for mdot > 1, B <~ 10^{12} G)

Disk accretion, strong outflows
BH = NS

Weak-field NSs similar to BHs

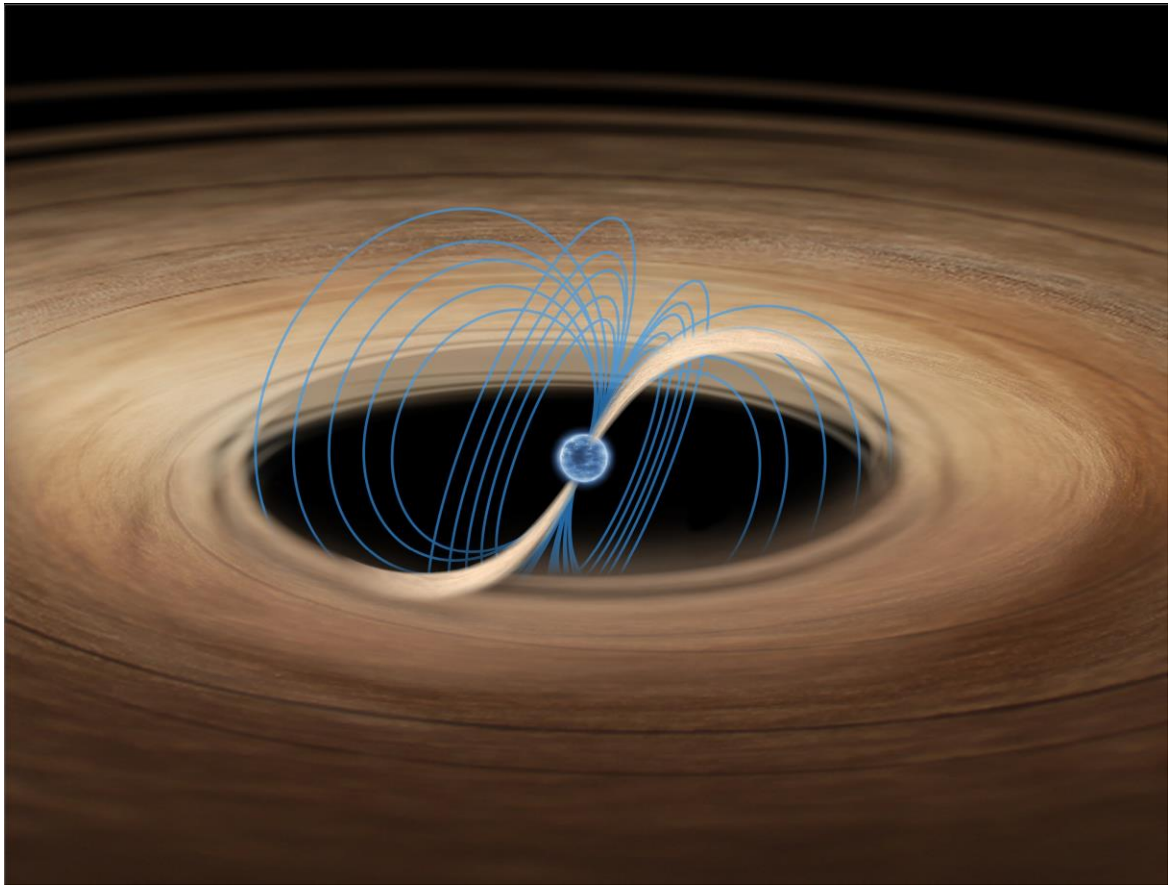


Gas density

(Ohsuga 2007)

Outflow speed

No disk outflow if inner disk is missing

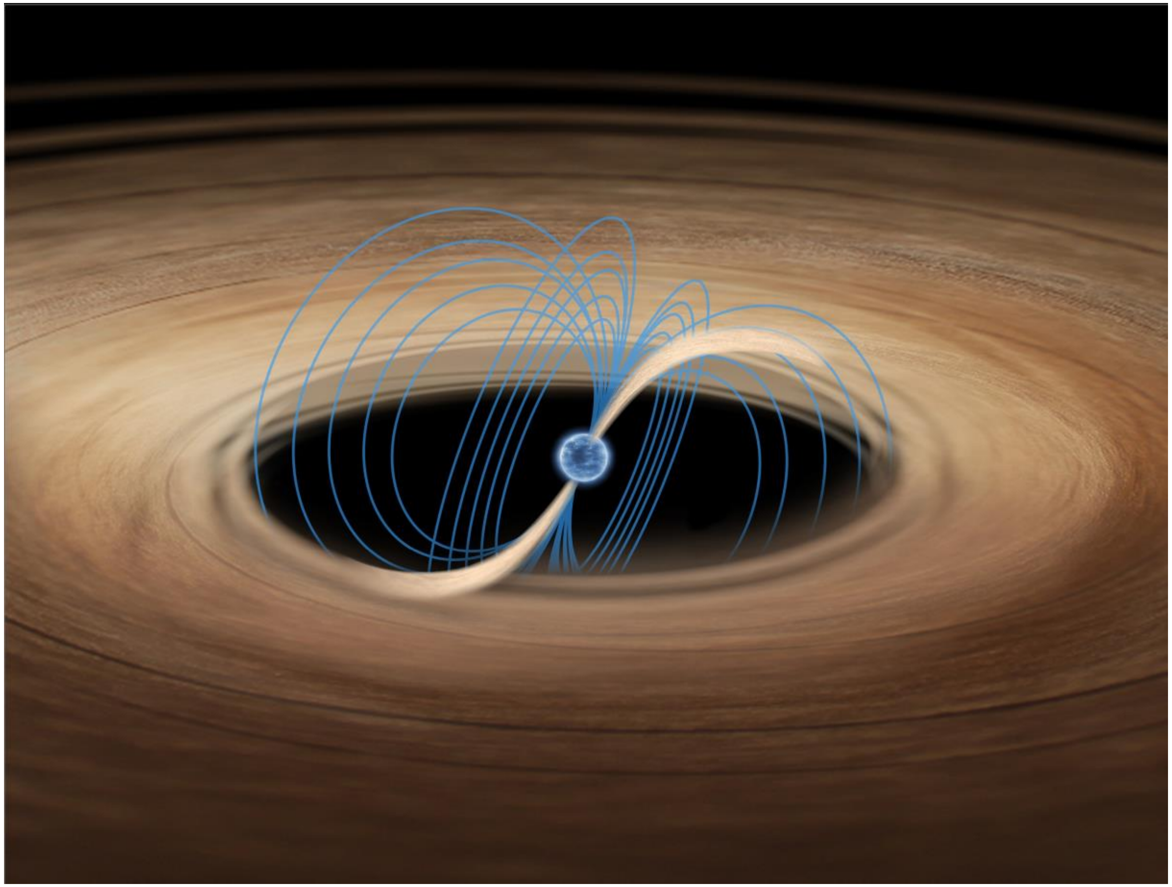


Magnetospheric radius > outflow launching radius

$$B_{10} > 0.5\,\dot{m}^{9/4}$$

$$L_X \approx \dot{m}\left(2 \times 10^{38}\right)\ \mathrm{erg/s}$$

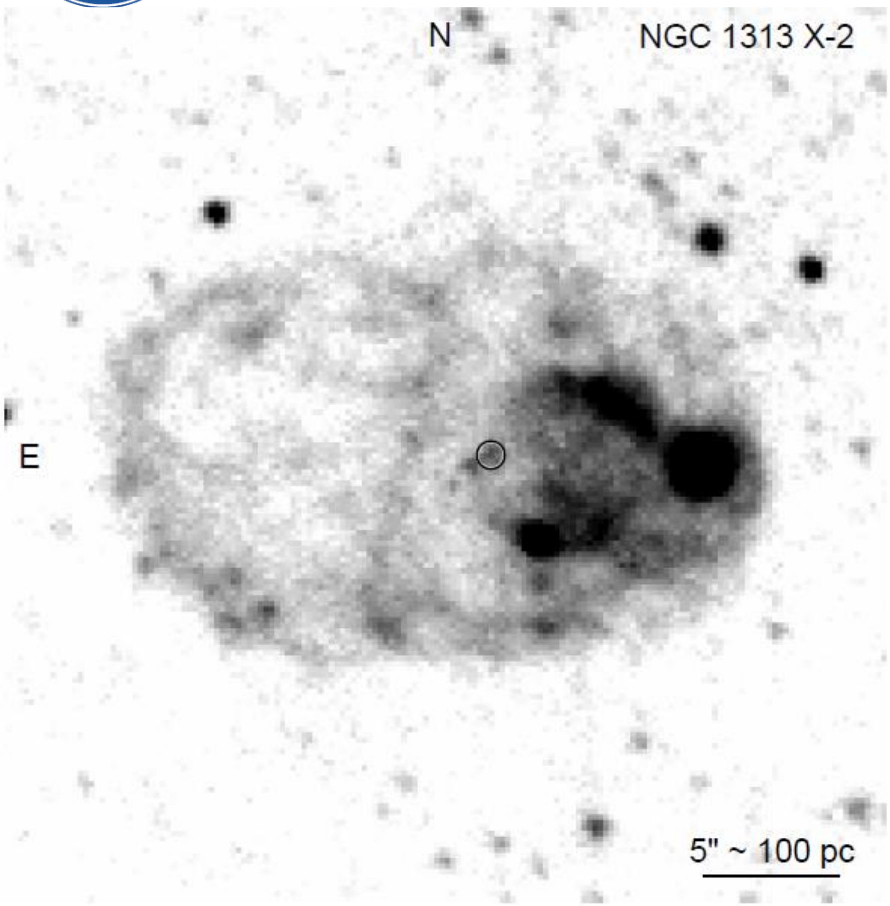
No disk outflow if inner disk is missing

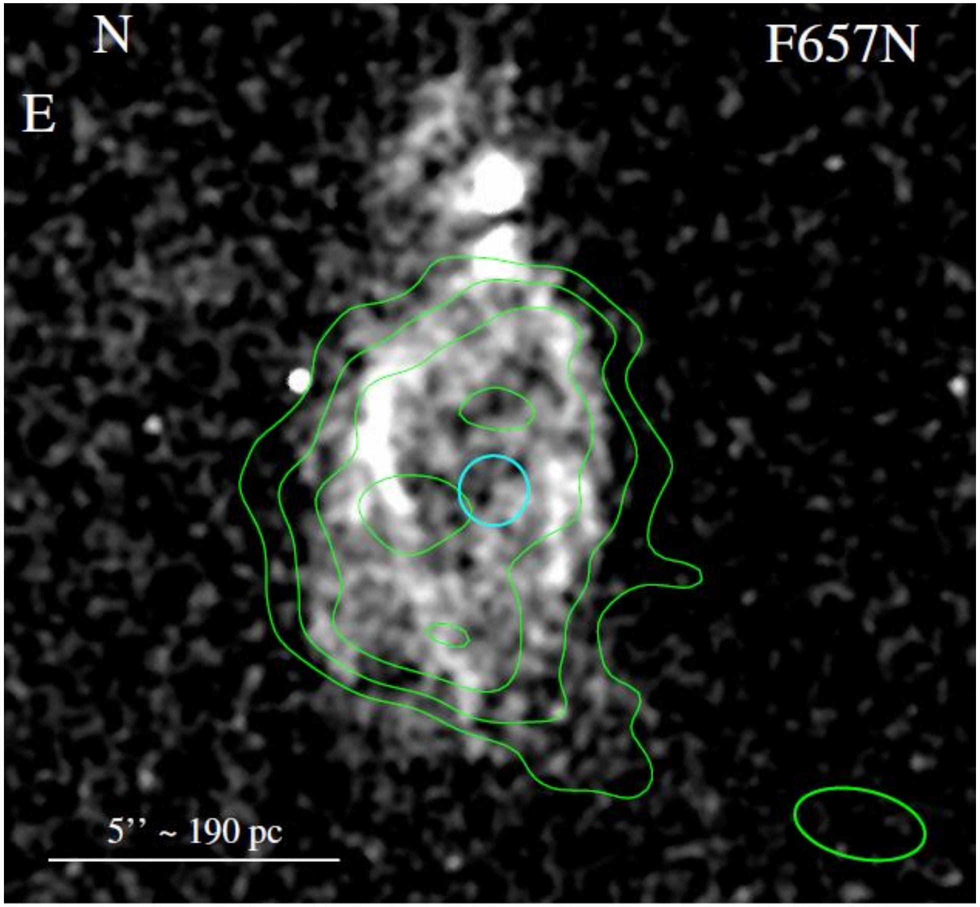


Magnetospheric radius > outflow launching radius

NSs with B ~ 10^{13}—10^{14} G can be hard-state ULXs

Radio loud and radio quiet bubbles





Similar huge bubbles for NGC 1313 X-2 and NGC 5585 X-1
Similar Ha luminosity ~ 10^{37} erg/s
NGC 5585 X-1 at least 100 times more radio luminous

Radio loud and radio quiet bubbles

Radio luminosity determined by many physical parameters
(not a simple function of jet power)

$$L_{1.4} \approx 6.7 \times 10^{24} \left(\frac{\epsilon_e}{0.01}\right) \left(\frac{\epsilon_b^u}{0.01}\right)^{0.8} R_2^3\, v_2^{3.6} \text{ erg s}^{-1} \text{ Hz}^{-1}$$

$$L_{1.4} \approx 6.2{\times}10^{23} \left(\frac{\epsilon_e}{0.01}\right) \left(\frac{\epsilon_b^u}{0.01}\right)^{0.8} \left(\frac{P_{39}}{n_0}\right)^{1.32} t_5^{0.36} \text{ erg s}^{-1} \text{ Hz}^{-1}$$

Radio SNRs fade with age, ULX radio bubbles get brighter

SNRs

$$L_{1.4} \propto t^{-0.96}$$

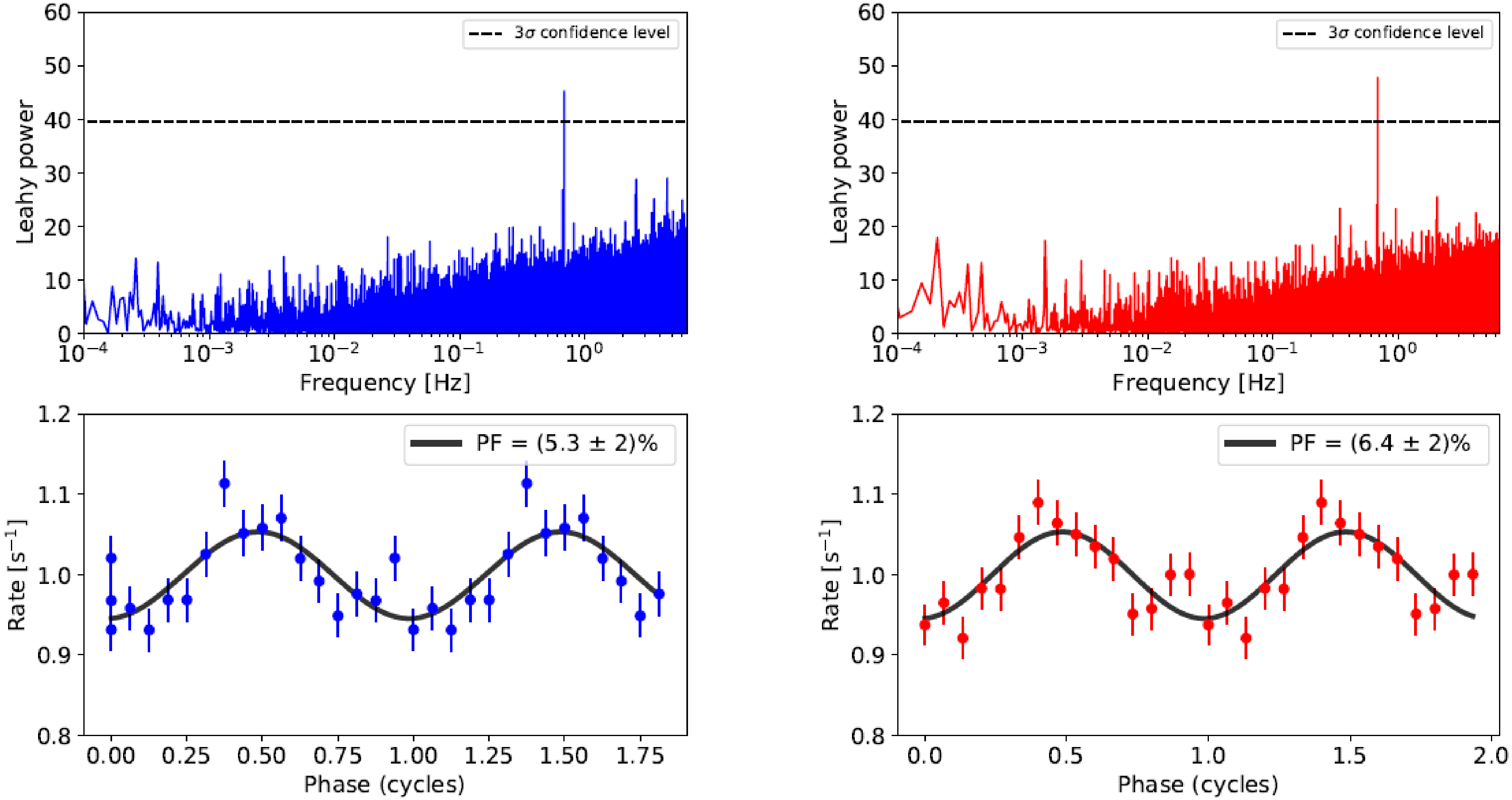
$$L_{1.4} \propto R^{-2.4}$$

ULX bubbles

$$L_{1.4} \propto t^{0.36}$$

$$L_{1.4} \propto R^{0.6}$$

NGC1313 X-2: another NS bubble?



(Sathyaprakash et al 2019)

Conclusions

Jets/outflows are important in super-critical regime

(ULX – quasar comparisons)

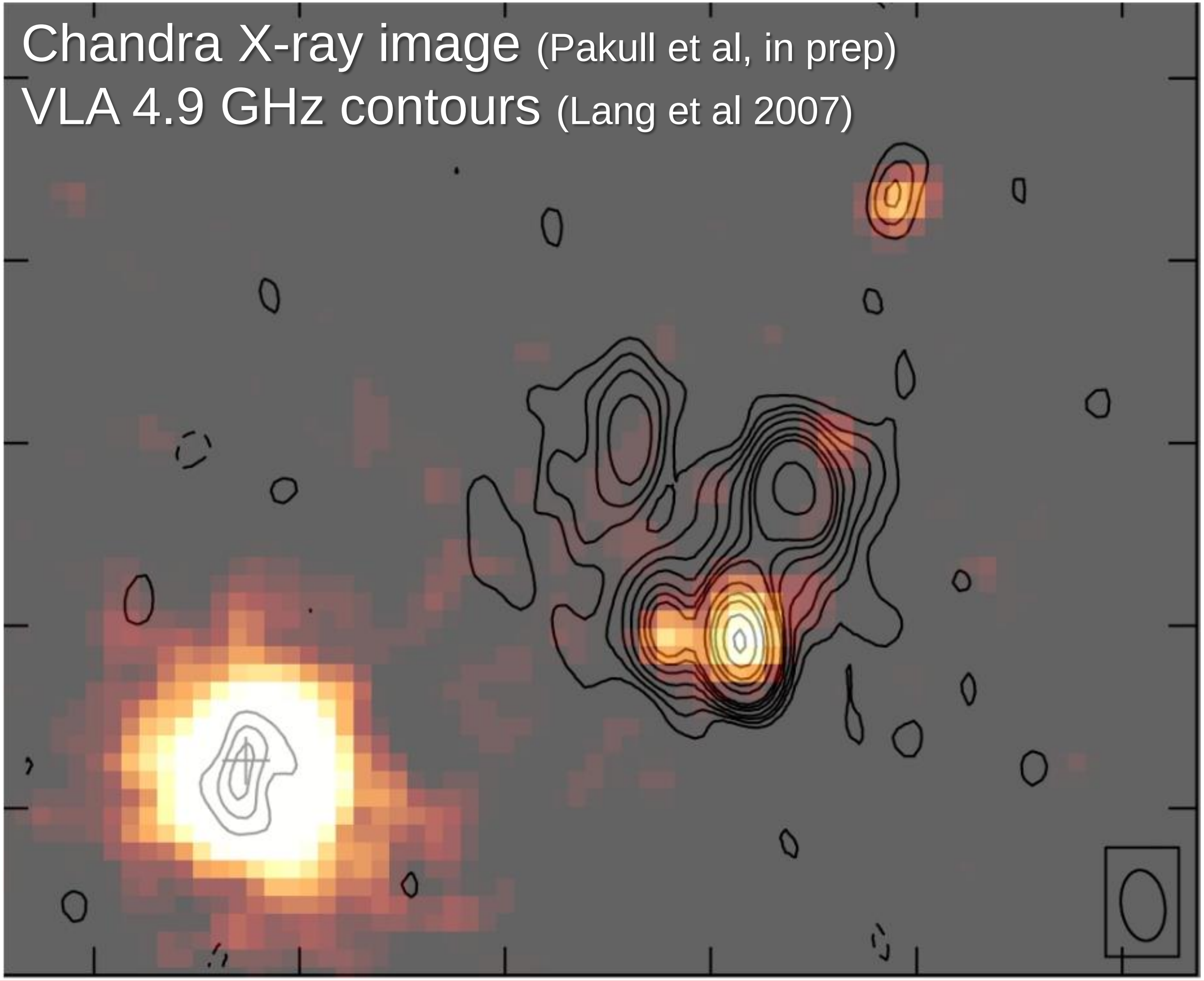
Both NS and BH ULXs produce strong outflows

Difference between strongly and weakly magnetized NSs?

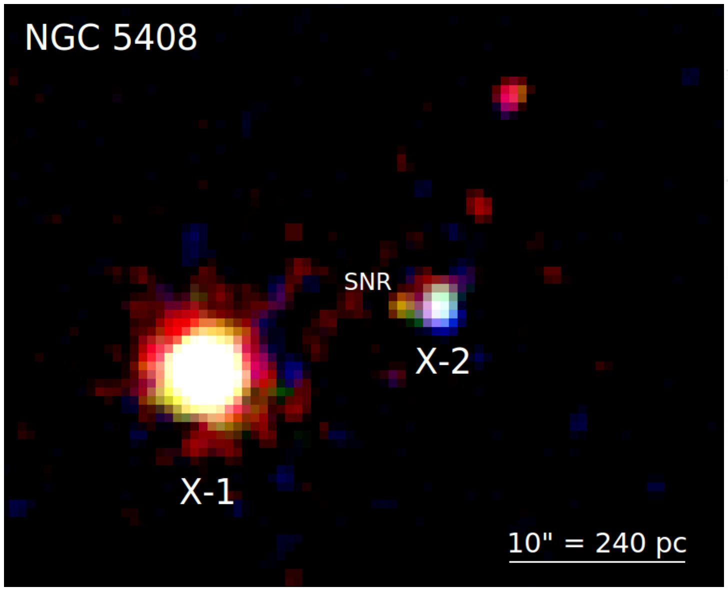
Jet power = accretion power or Blandford-Znajek?

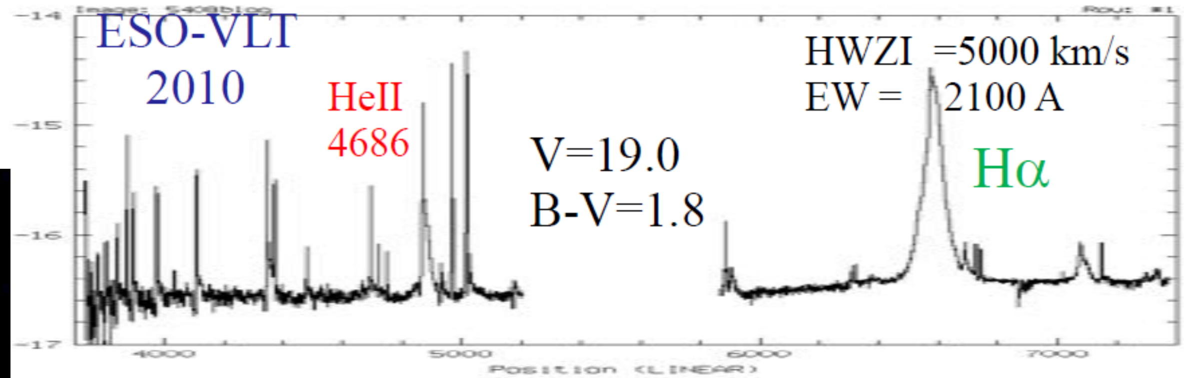
Are NS bubbles less radio luminous?

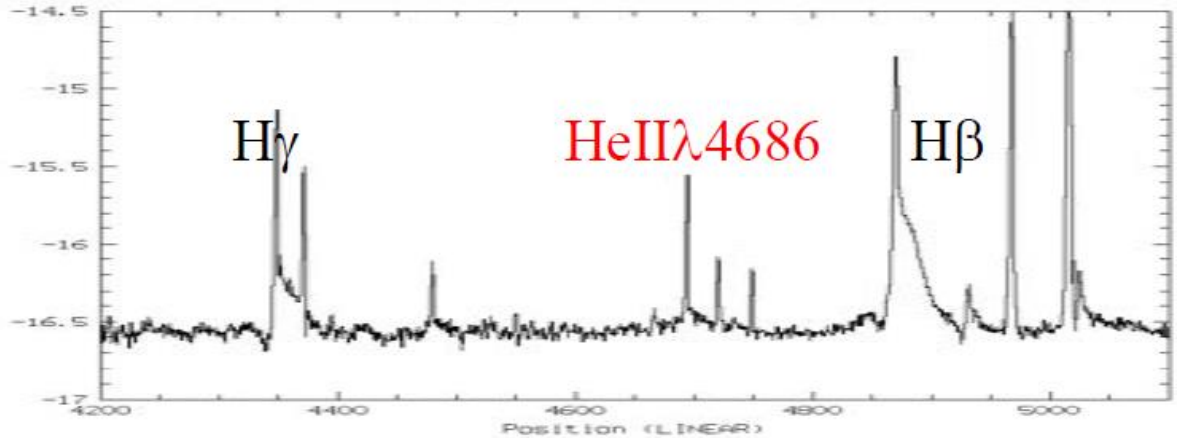
NGC 5408 X-2: BH + LBV star?



NGC 5408 X-2: BH + LBV star?





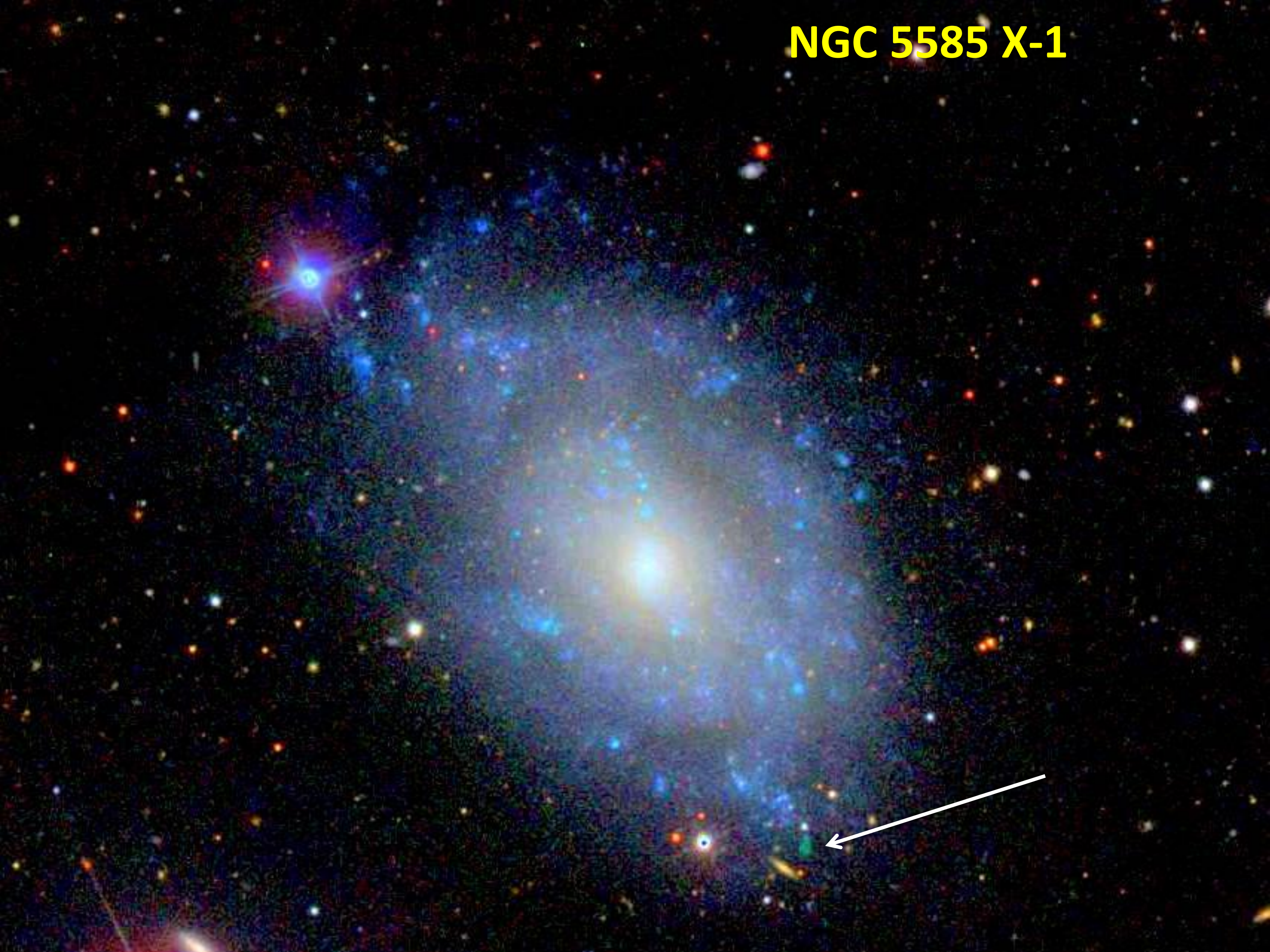


Very broad (HWZI ~ 5000 km/s) and very bright (EW ~ 2000 Ang) Hα emission

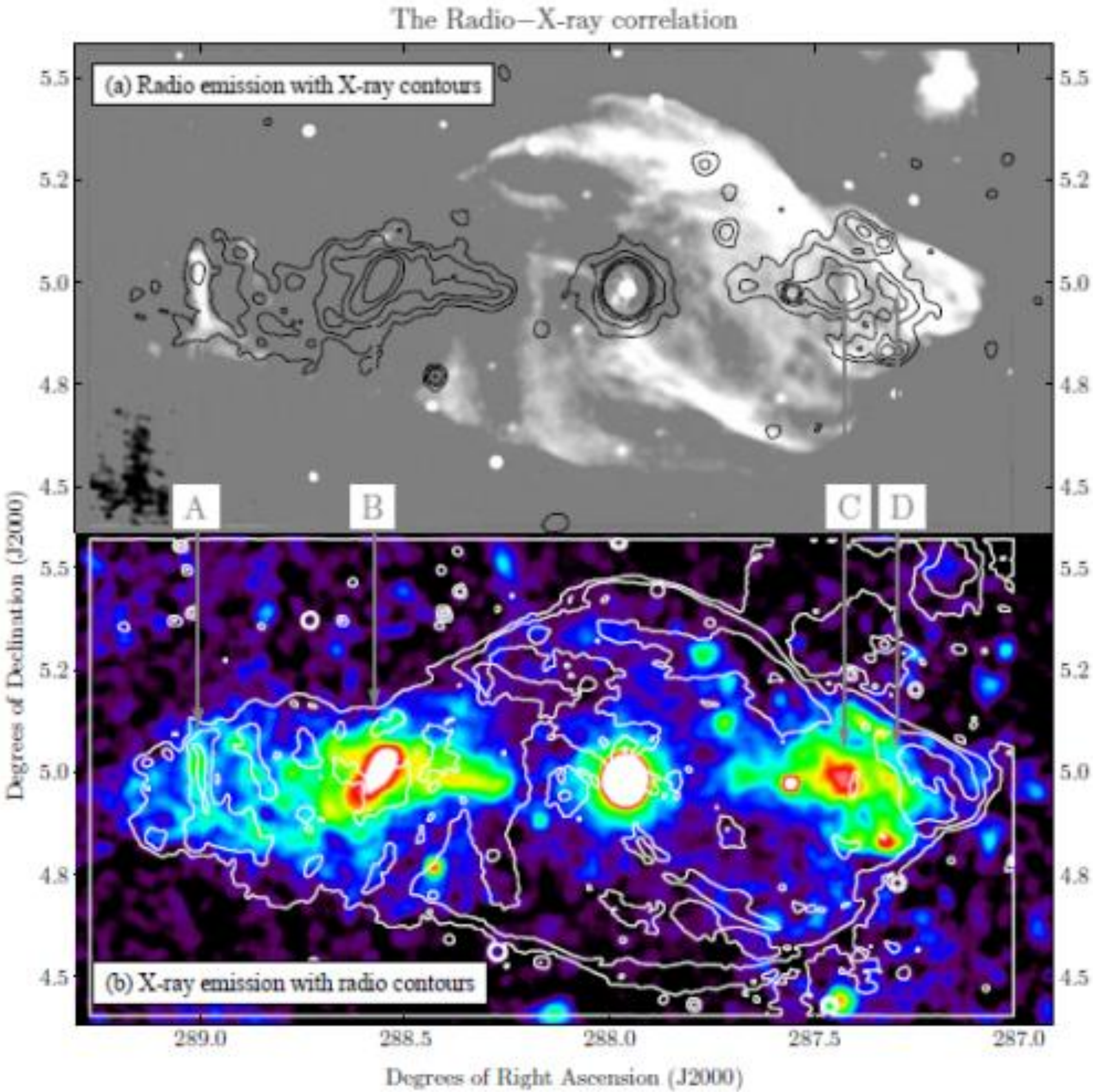
Strong photo-ionized He II 4686

Outflow from super-Eddington BH in a Common Envelope? (Pakull et al in prep)

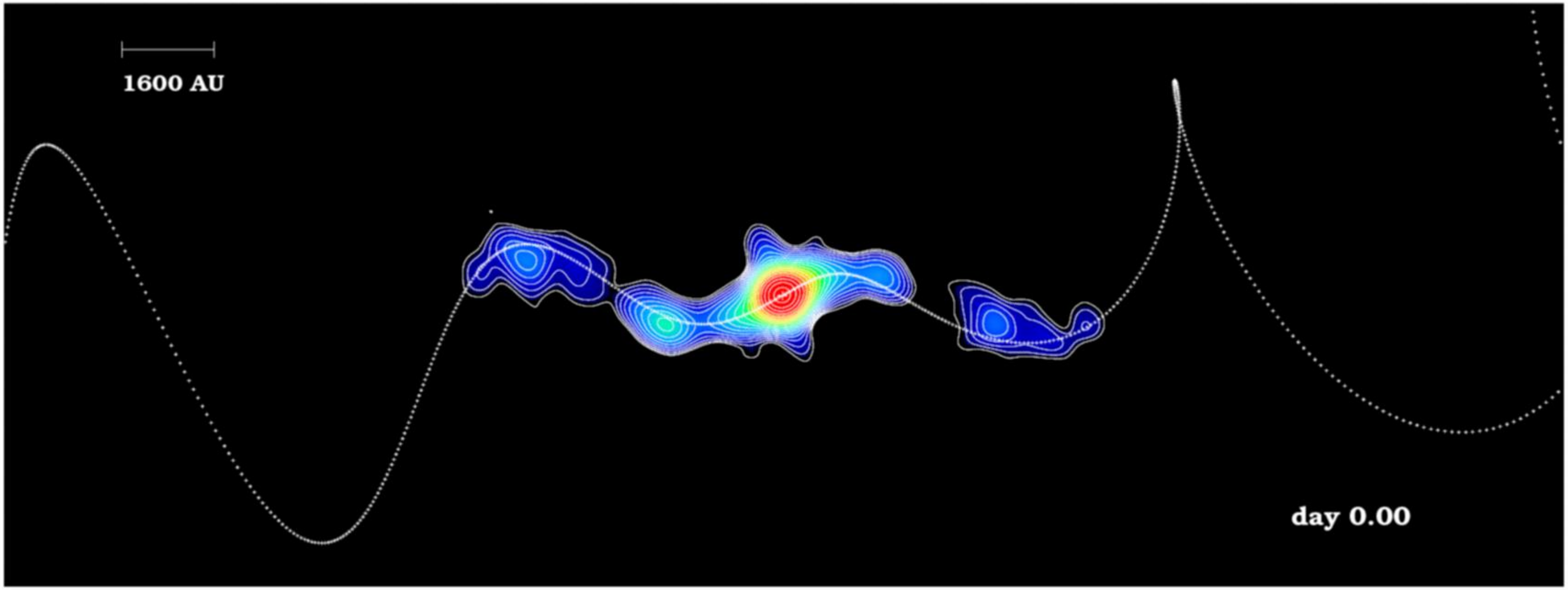
NGC 5585 X-1



SS433: the most powerful BH in our Galaxy?

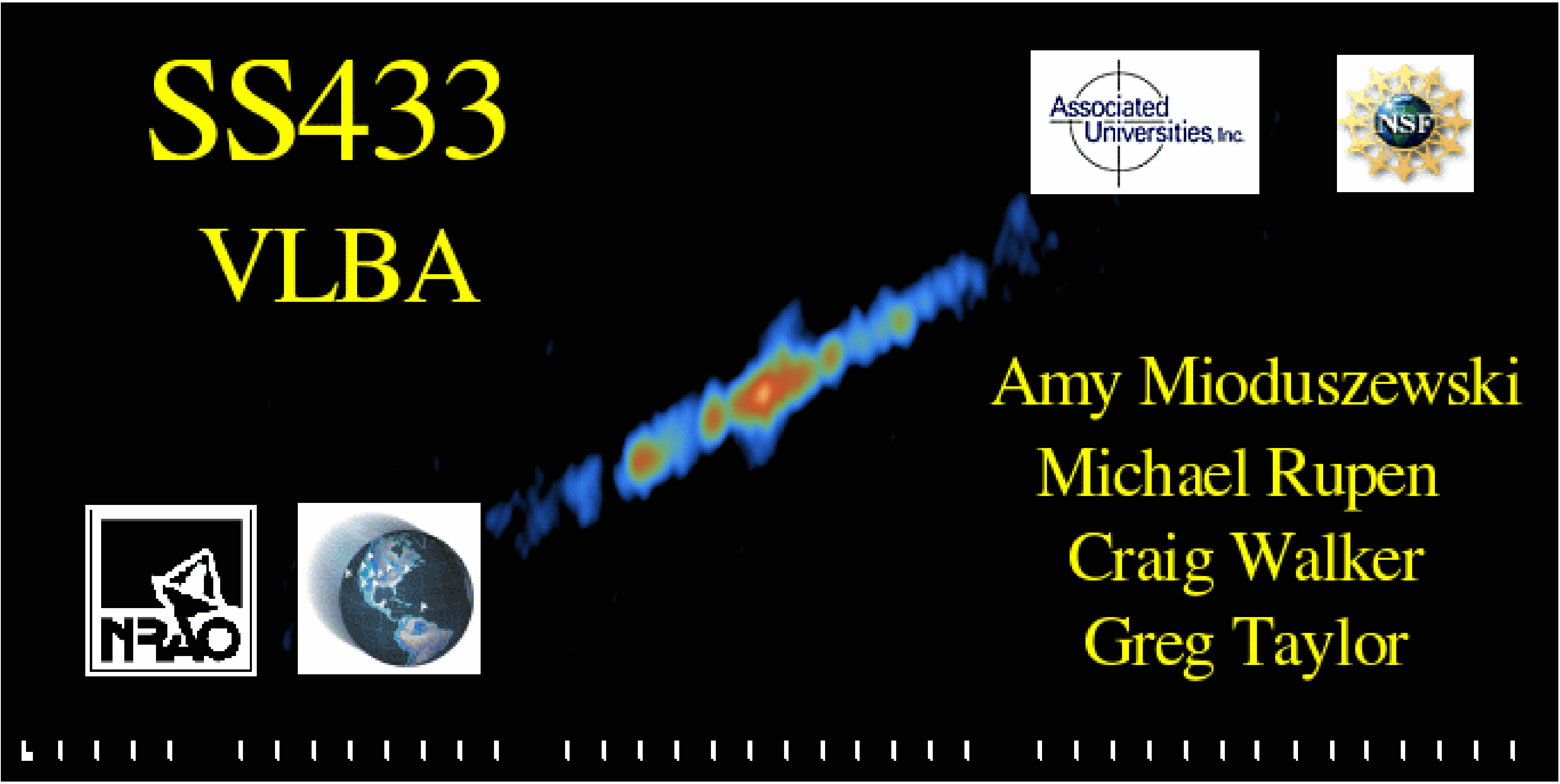


SS433: the most powerful BH in our Galaxy?

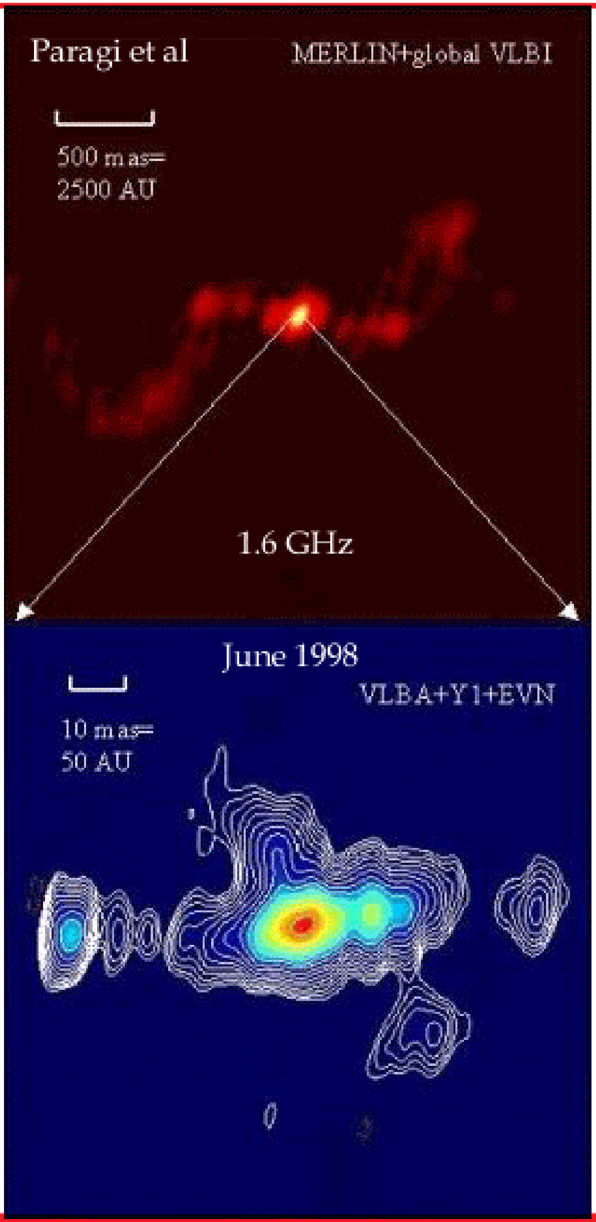


Very Long Baseline Interferometry images of the precessing jet

Galactic ULX bubble SS433



SS433: the most powerful BH in our Galaxy?



SS433: the most powerful BH in our Galaxy?