Multiwavelength observations of ULXs

Mar Mezcua

University of Montréal

Ultraluminous X-ray sources (ULXs)

- Extragalactic, off-nuclear, point-like X-ray sources with $L_X > L_{Edd}$ for a stellar-mass black hole:

$$L_{Edd} = 1.3 \times 10^{38}\ M_{BH}/M_{\odot}\quad \mathrm{erg/s}$$

Ultraluminous X-ray sources (ULXs)

- Extragalactic, off-nuclear, point-like X-ray sources with $L_X > L_{Edd}$ for a stellar-mass black hole:

$$L_{Edd} = 1.3 \times 10^{38}\ M_{BH}/M_\odot \quad \mathrm{erg/s}$$

$$\boxed{L_X \gtrsim 10^{39}\ \mathrm{erg/s\ for\ a\ 10}\ M_\odot\ \mathrm{BH}}$$

Ultraluminous X-ray sources (ULXs)

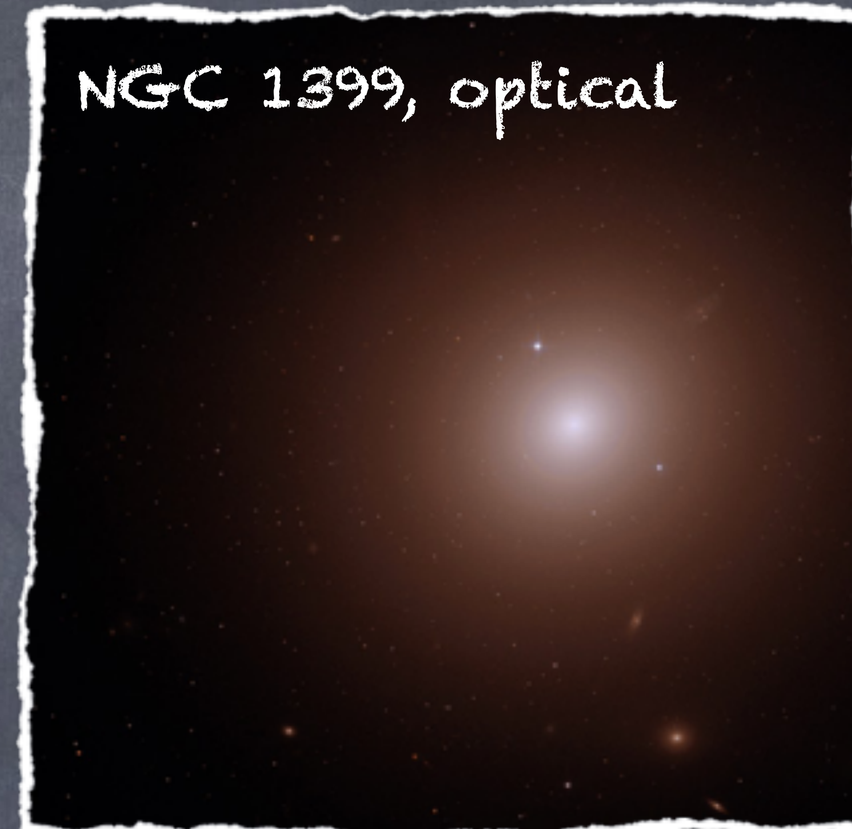
- Extragalactic, off-nuclear, point-like X-ray sources with $L_X > L_{Edd}$ for a stellar-mass black hole:

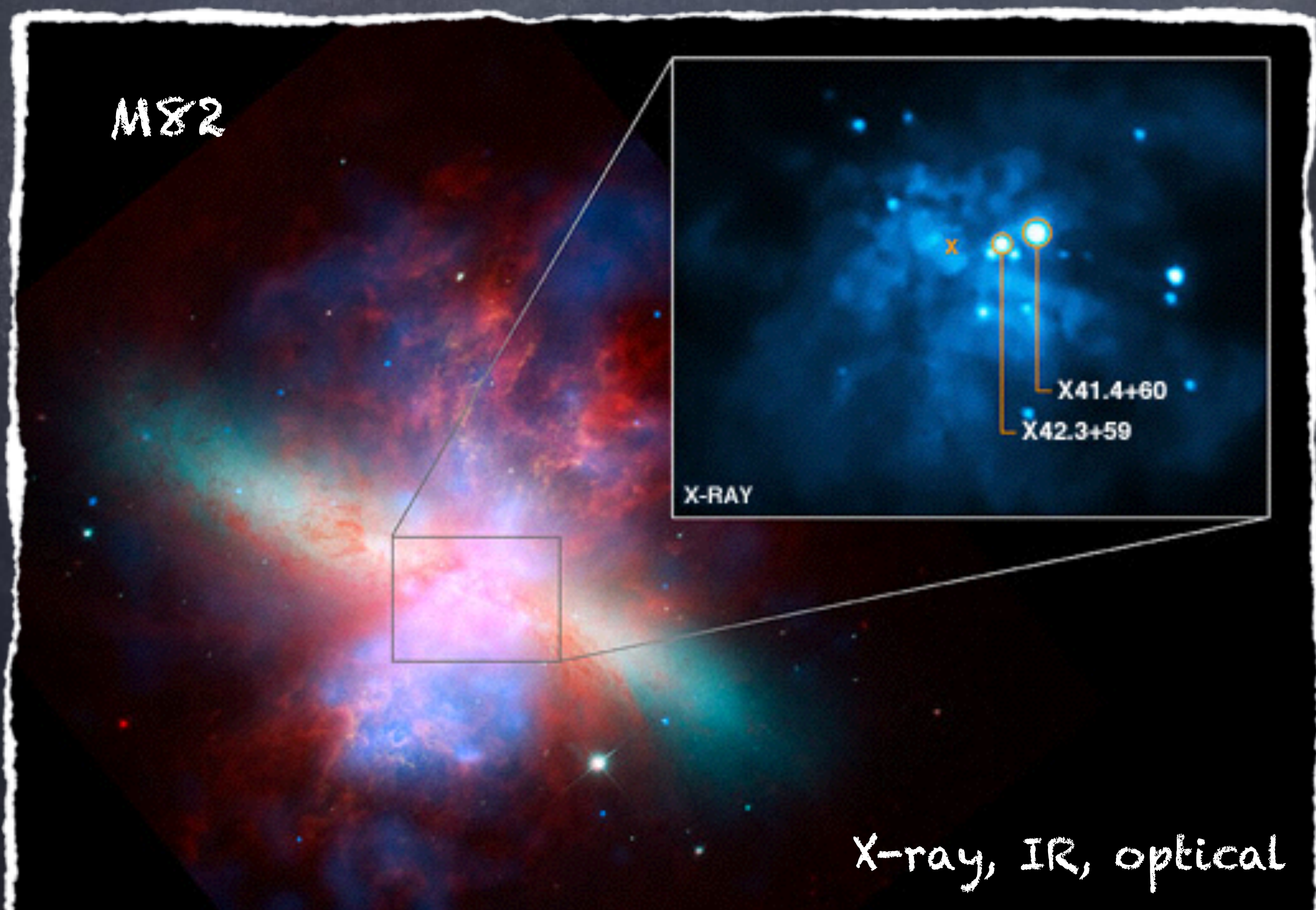
$$L_{Edd} = 1.3 \times 10^{38}\ M_{BH}/M_{\odot}\quad \mathrm{erg/s}$$

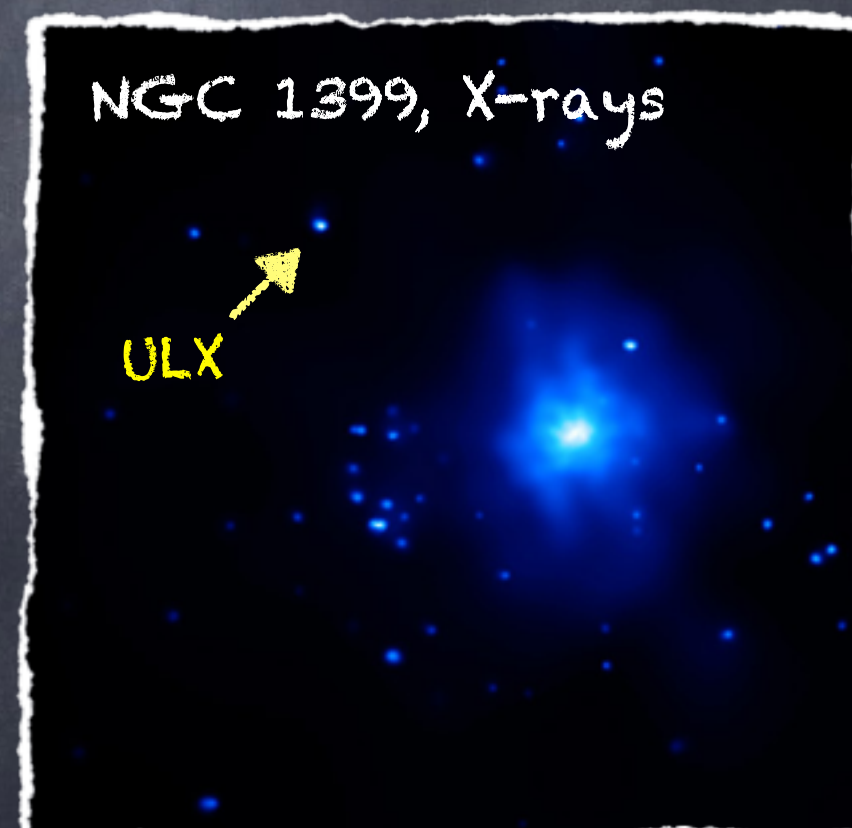
$$\boxed{L_X \gtrsim 10^{39}\ \mathrm{erg/s\ for\ a\ 10}\ M_{\odot}\ \mathrm{BH}}$$

- Most ULXs: $L_X \sim 10^{39} - 10^{40}$ erg/s
  Extreme ULXs: $L_X > 2 \times 10^{40}$ erg/s
  Hyperluminous X-ray sources (HLXs): $L_X \gtrsim 10^{41}$ erg/s

Gladstone (2013)

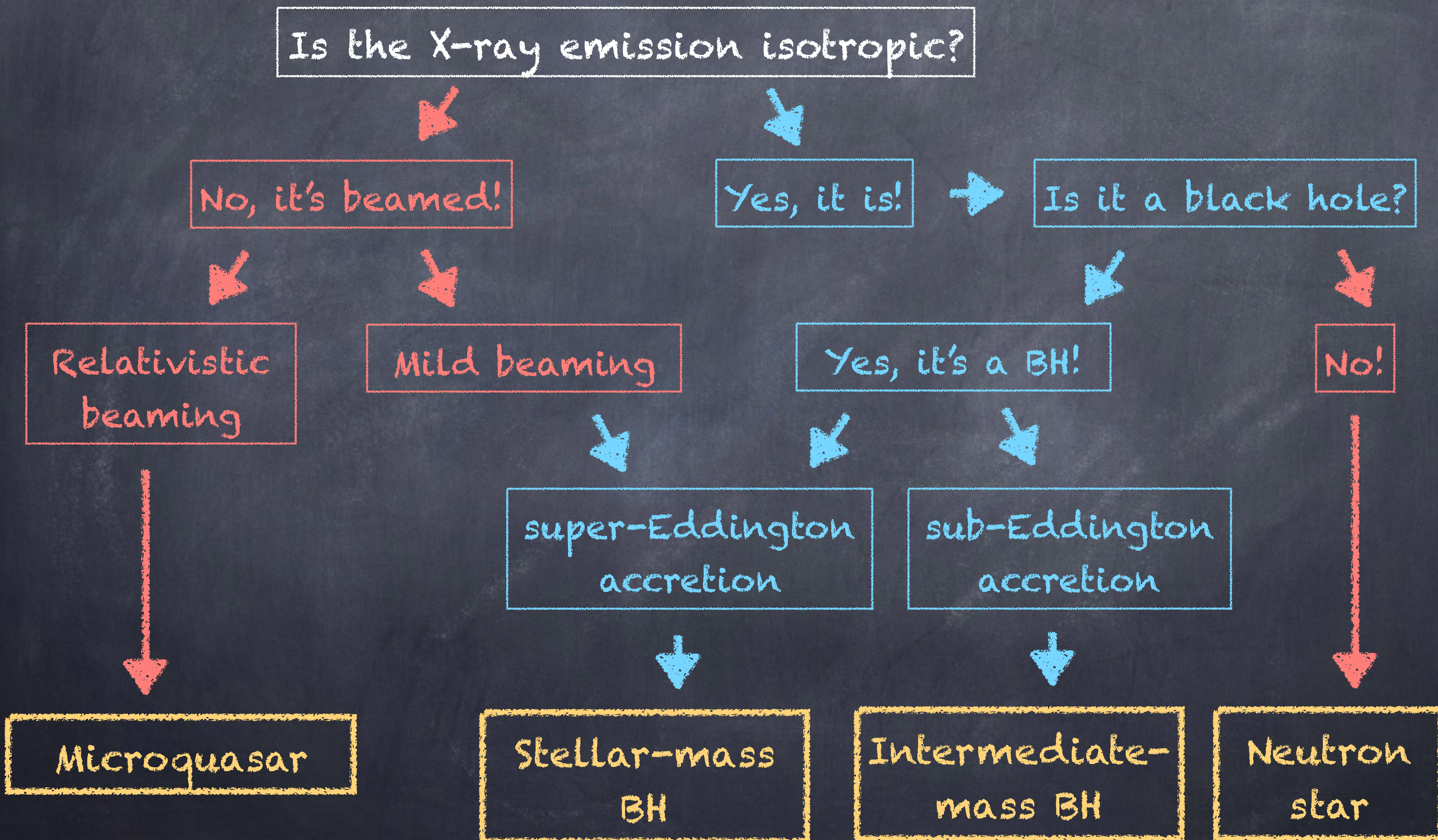






NASA Chandra, HST, Spitzer

The nature of ULXs



The nature of ULXs

Is the X-ra ?

No, it's beamed!

Is it a black hole?

Relativistic beaming

Mild b

s a BH!

No!

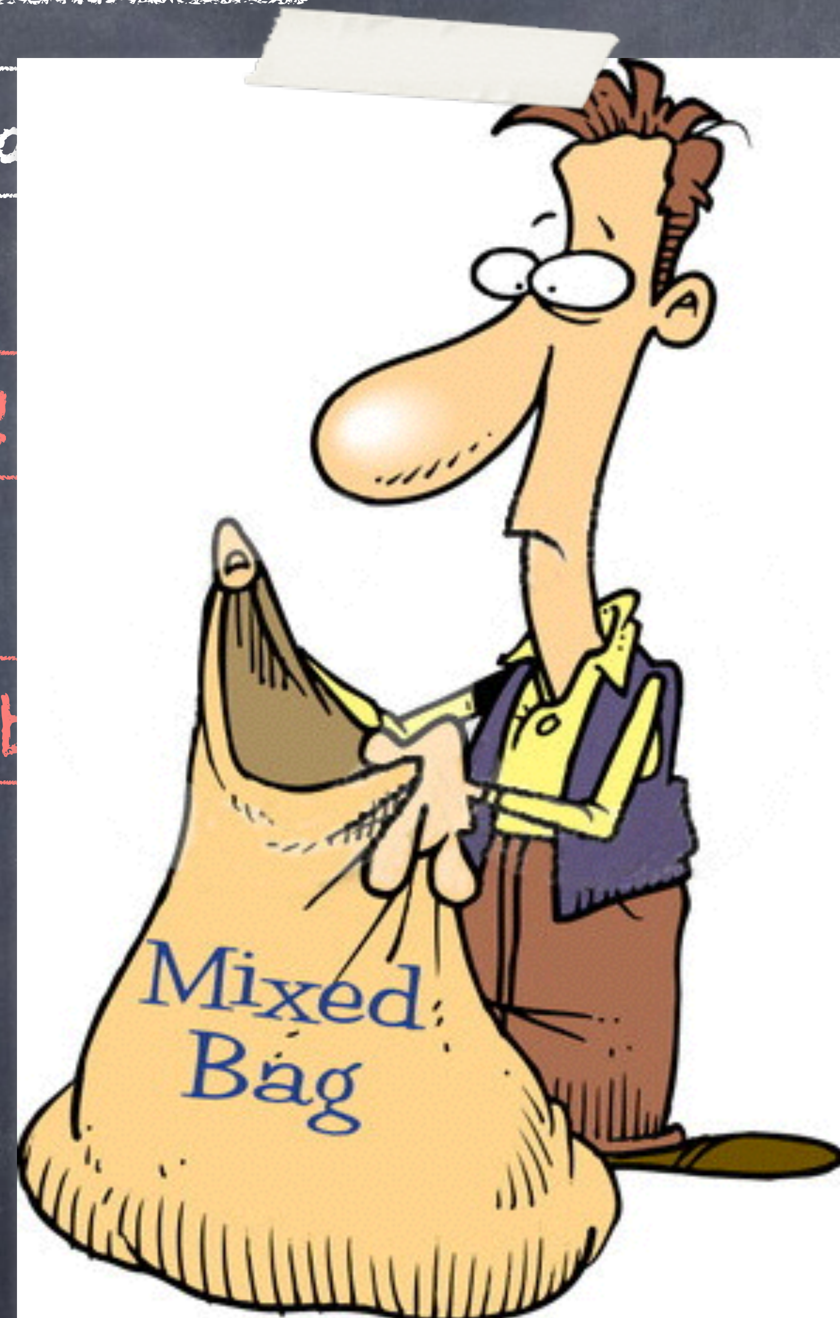
ub-Eddington accretion

Microquasar

Stellar-mass BH

Intermediate-mass BH

Neutron star



CHECKLIST

- ☐ Spectral analysis
- ☐ Variability
- ☐ Timing analysis
- ☐ Distance
- ☐ Mass measurement
- ☐ Environment
- ☐ Jets/outflows
- ☐ Monitoring

CHECKLIST

- [x] Spectral analysis
- [x] Variability
- [x] Timing analysis
- [ ] Distance
- [ ] Mass measurement
- [ ] Environment
- [ ] Jets/outflows
- [ ] Monitoring

X-rays

CHECKLIST

- [x] Spectral analysis
- [x] Variability
- [x] Timing analysis
- [x] Distance
- [x] Mass measurement
- [x] Environment
- [x] Jets/outflows
- [x] Monitoring

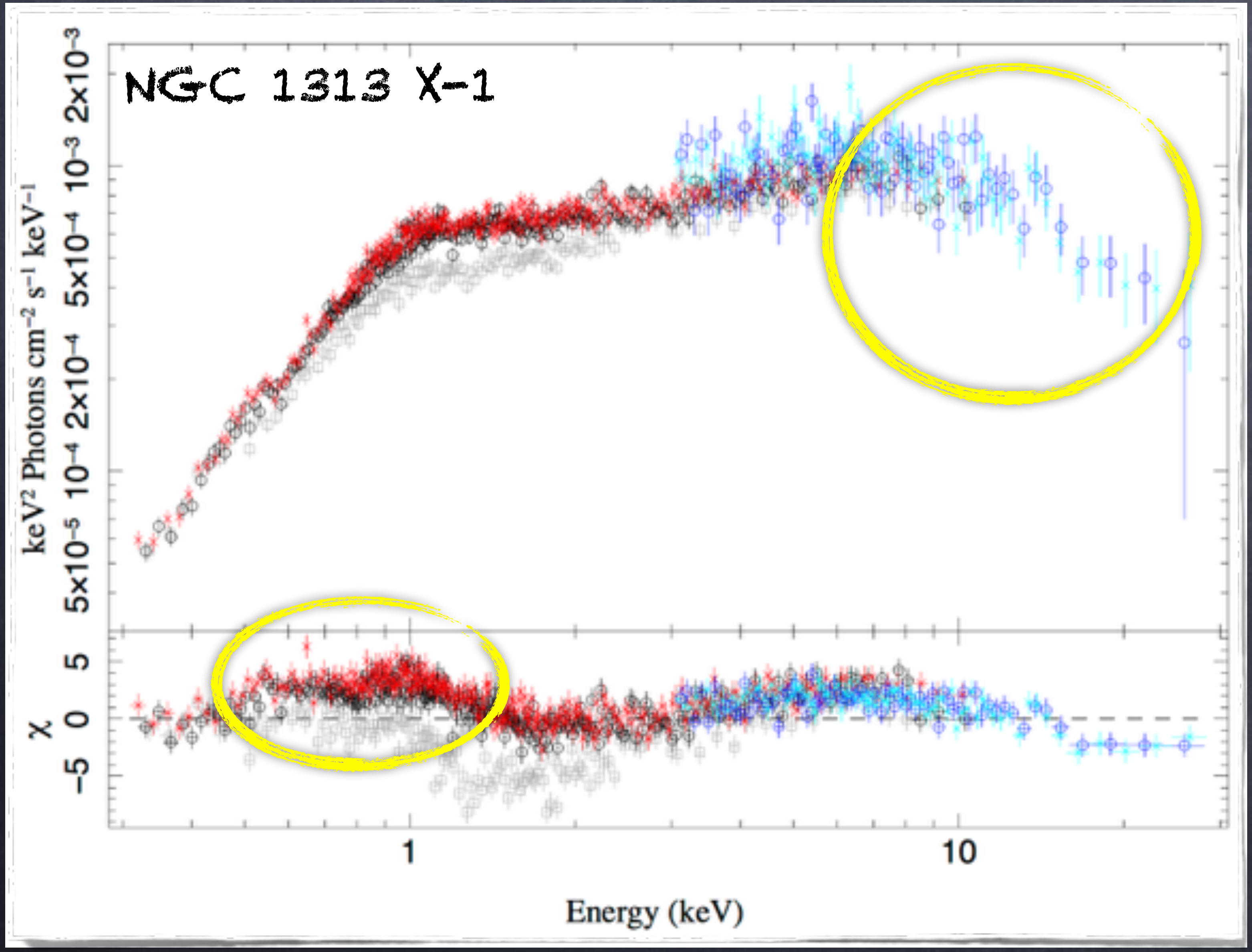
X-rays

Optical, IR
radio

Spectral analysis

Most ULXs spectra:

- soft excess at low energies
- power-law cutoff above ~ 3 keV

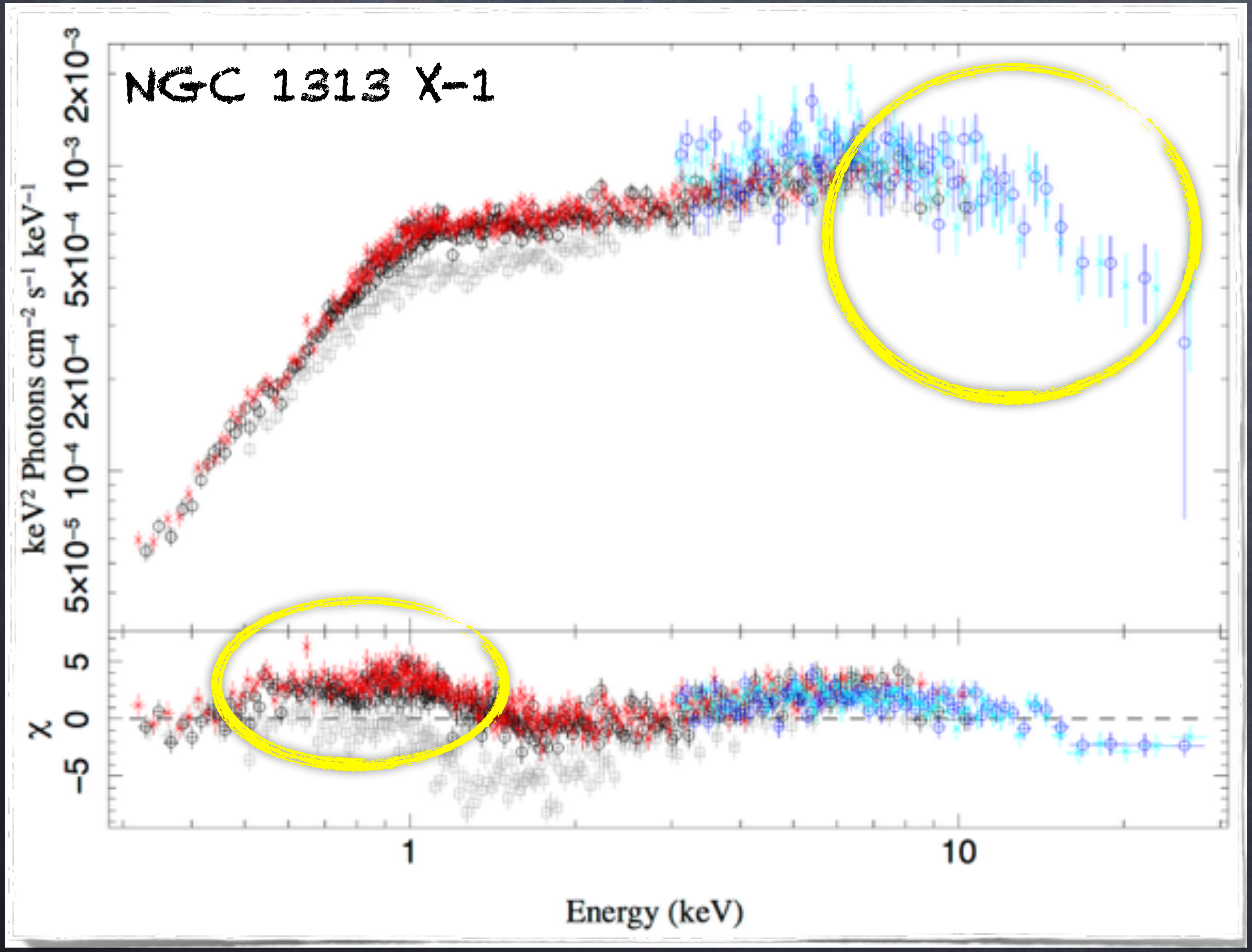


Bachetti et al. (2013)
Also e.g., Stobbart et al. (2006), Walton et al. (2011, 2013, 2014, 2015), Rana et al. (2015)

Spectral analysis

Most ULXs spectra:

- soft excess at low energies
- power-law cutoff above ~ 3 keV



Characteristic of 'ultraluminous' state
Interpreted as super-Eddington accretion

Gladstone et al. (2009)
Sutton et al. (2013)

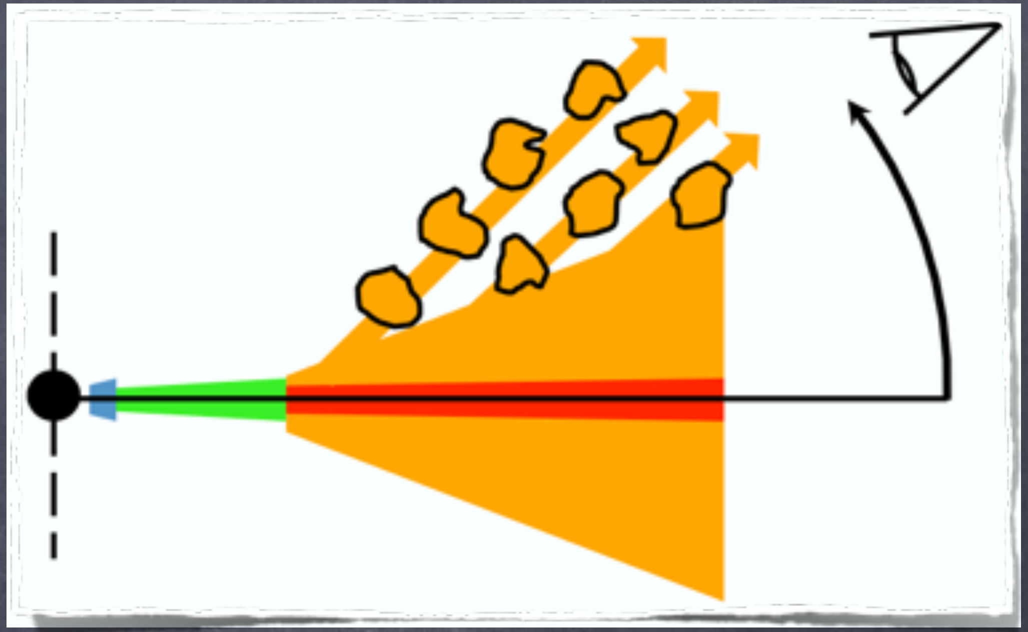
Bachetti et al. (2013)
Also e.g., Stobbart et al. (2006), Walton et al. (2011, 2013, 2014, 2015), Rana et al. (2015)

☑ Variability

- Short-term variability observed in many ULXs
- Explained by super-Eddington wind

More by Matt Middleton!

Middleton et al. (2011)

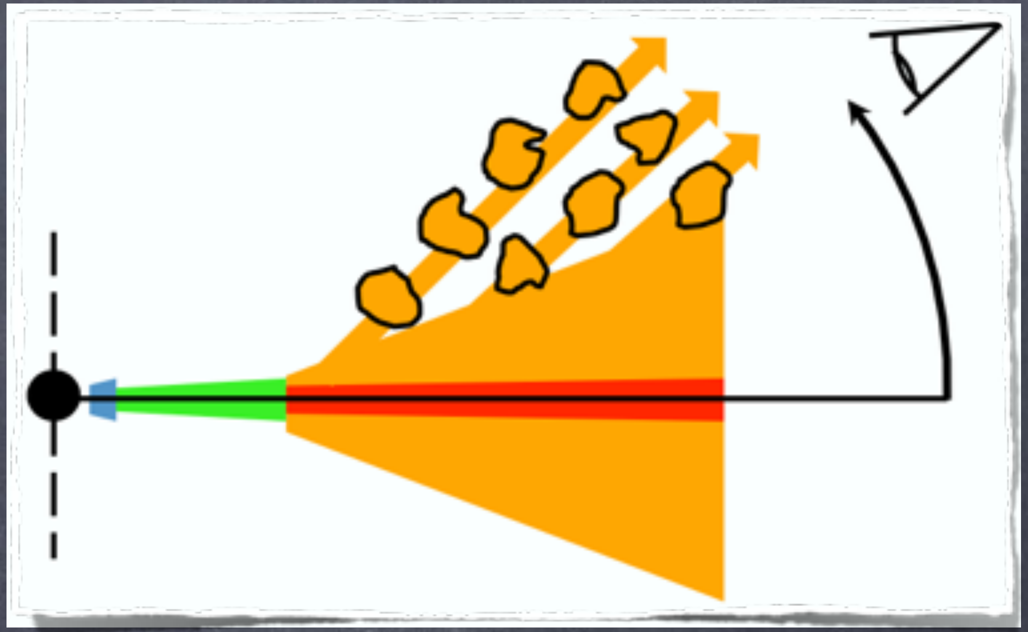


Also e.g., King (2004, 2009)
Poutanen et al. (2007)
King & Pounds (2003)
Middleton et al. (2014, 2015)
Sutton et al. (2013)

Variability

- Short-term variability observed in many ULXs
- Explained by super-Eddington wind

Middleton et al. (2011)



More by Matt Middleton!

- Observational evidence of outflow wind at 0.2c!!

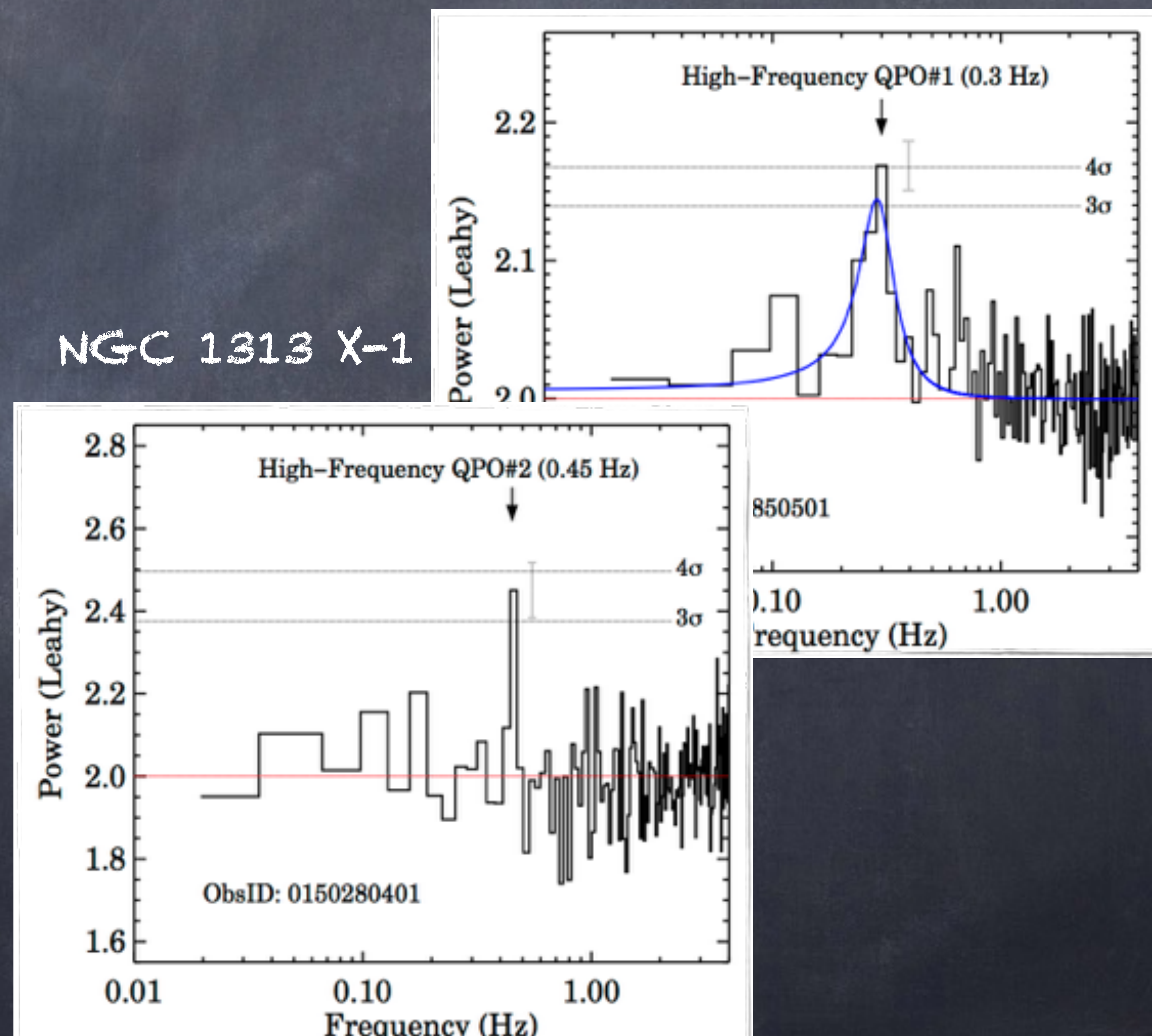
Talk by Ciro Pinto!

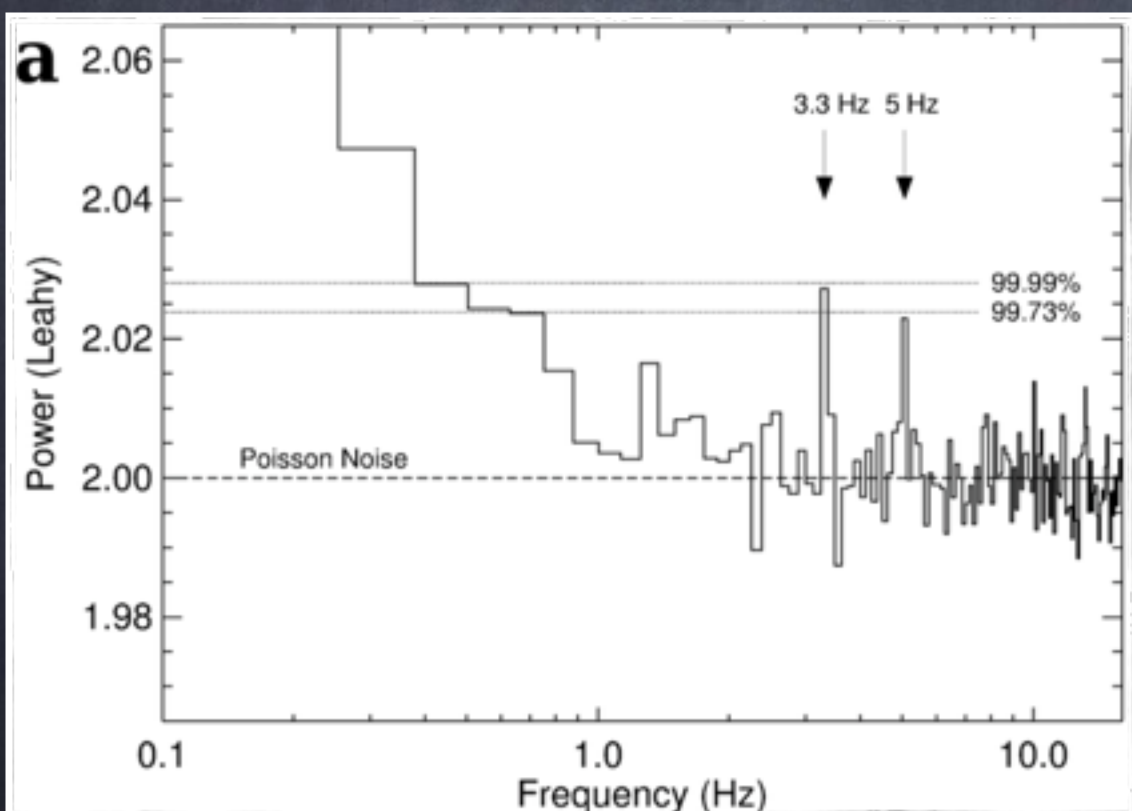
Also e.g., King (2004, 2009)
Poutanen et al. (2007)
King & Pounds (2003)
Middleton et al. (2014, 2015)
Sutton et al. (2013)

Timing analysis

- Twin-peak high-frequency QPOs found in some ULXs

NGC 1313 X-1





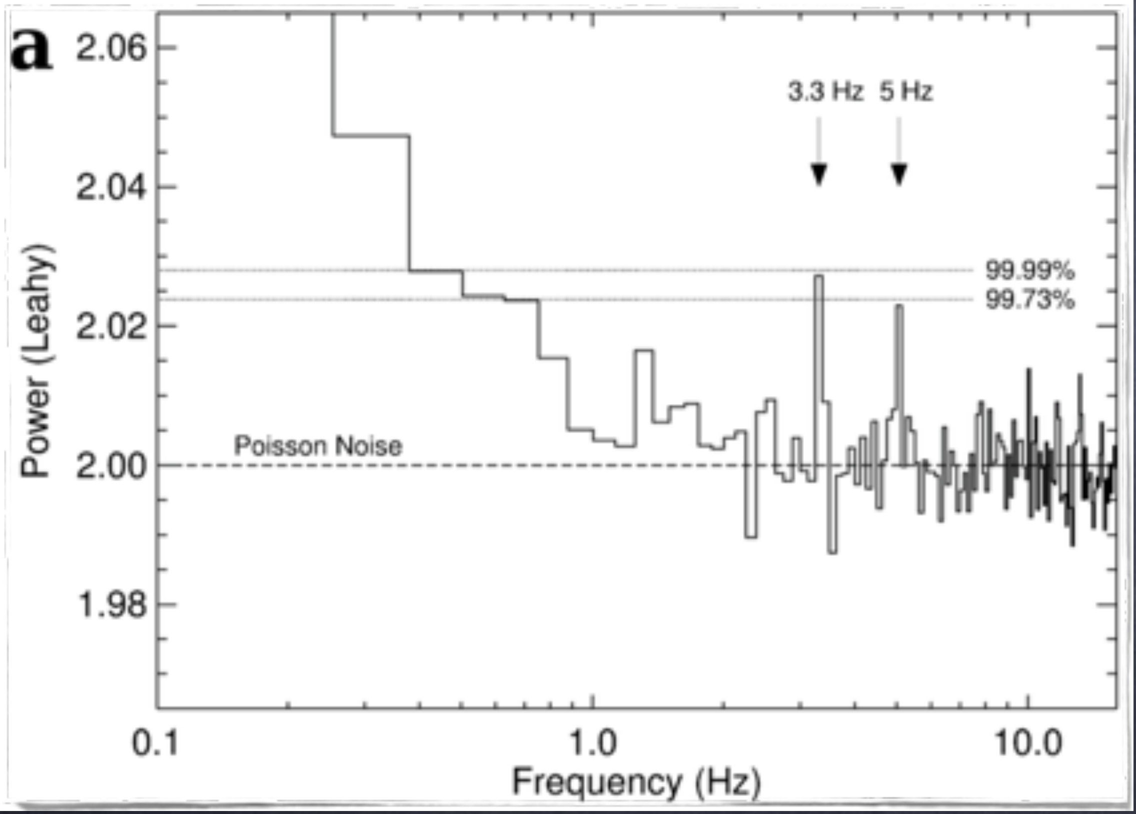
M82 X-1

Pasham et al. (2014, 2015)

Timing analysis

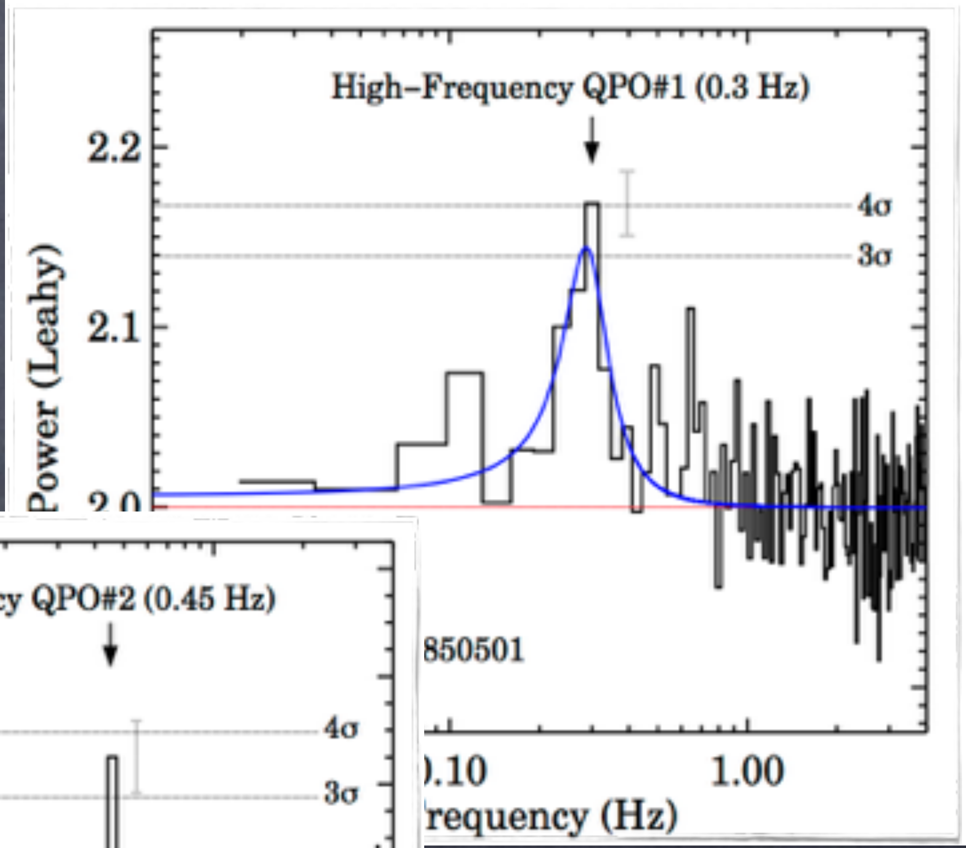
- Twin-peak high-frequency QPOs found in some ULXs
- Frequency ~ 1/M_{BH} in stellar-mass BHs

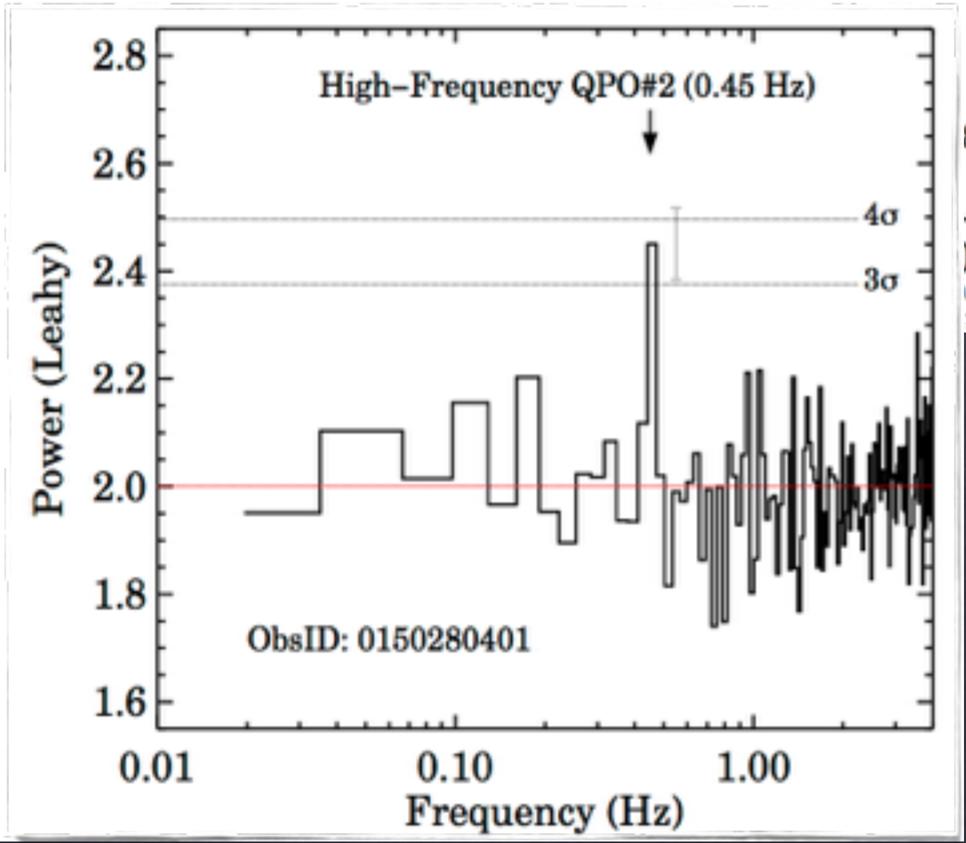
Extrapolating.... ⇨ IMBH!



M82 X-1

NGC 1313 X-1

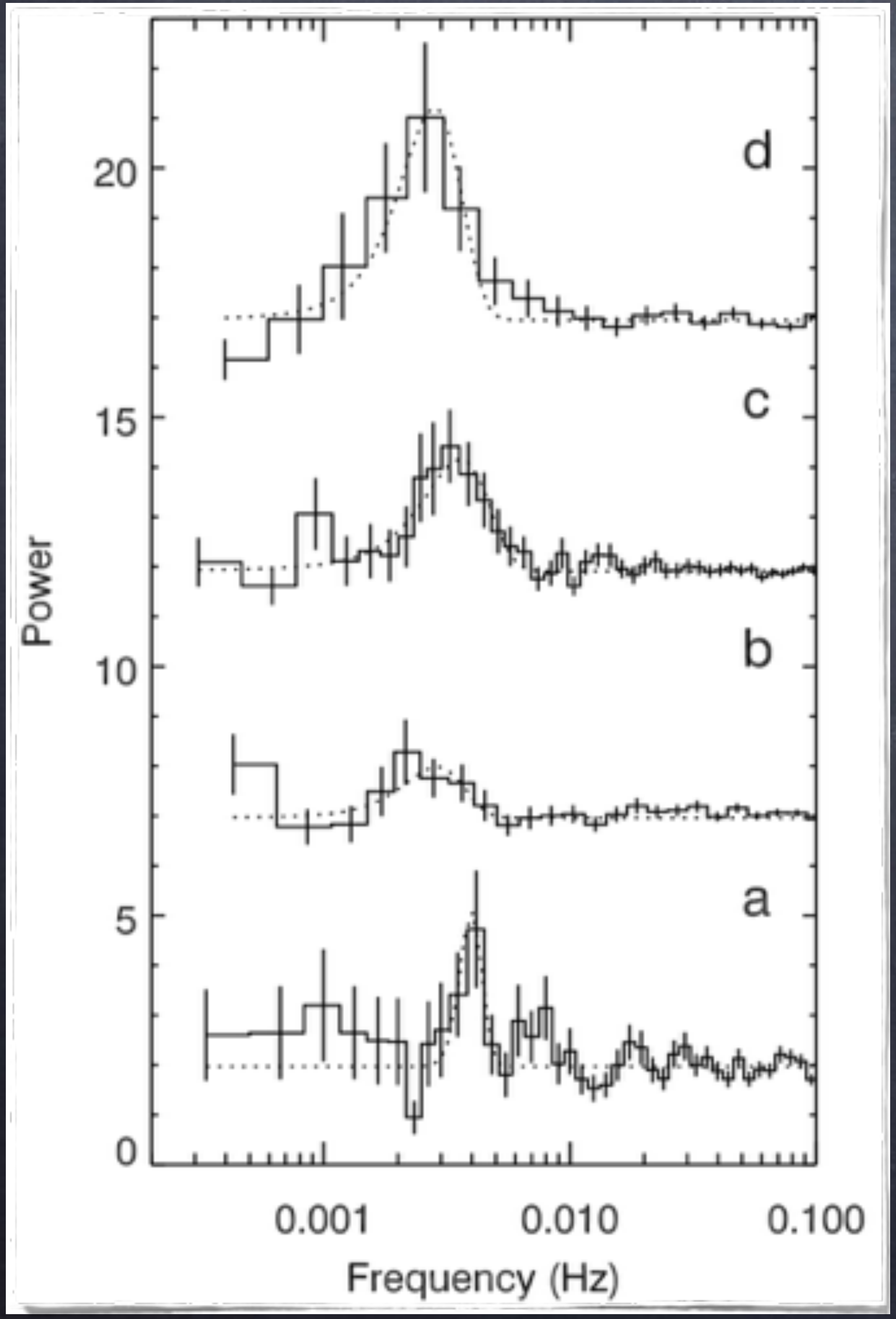




Pasham et al. (2014, 2015)

☑ Timing analysis

- Low-frequency QPOs found in some ULXs
- Frequency scaling from stellar-mass BHs ⇨ IMBH!

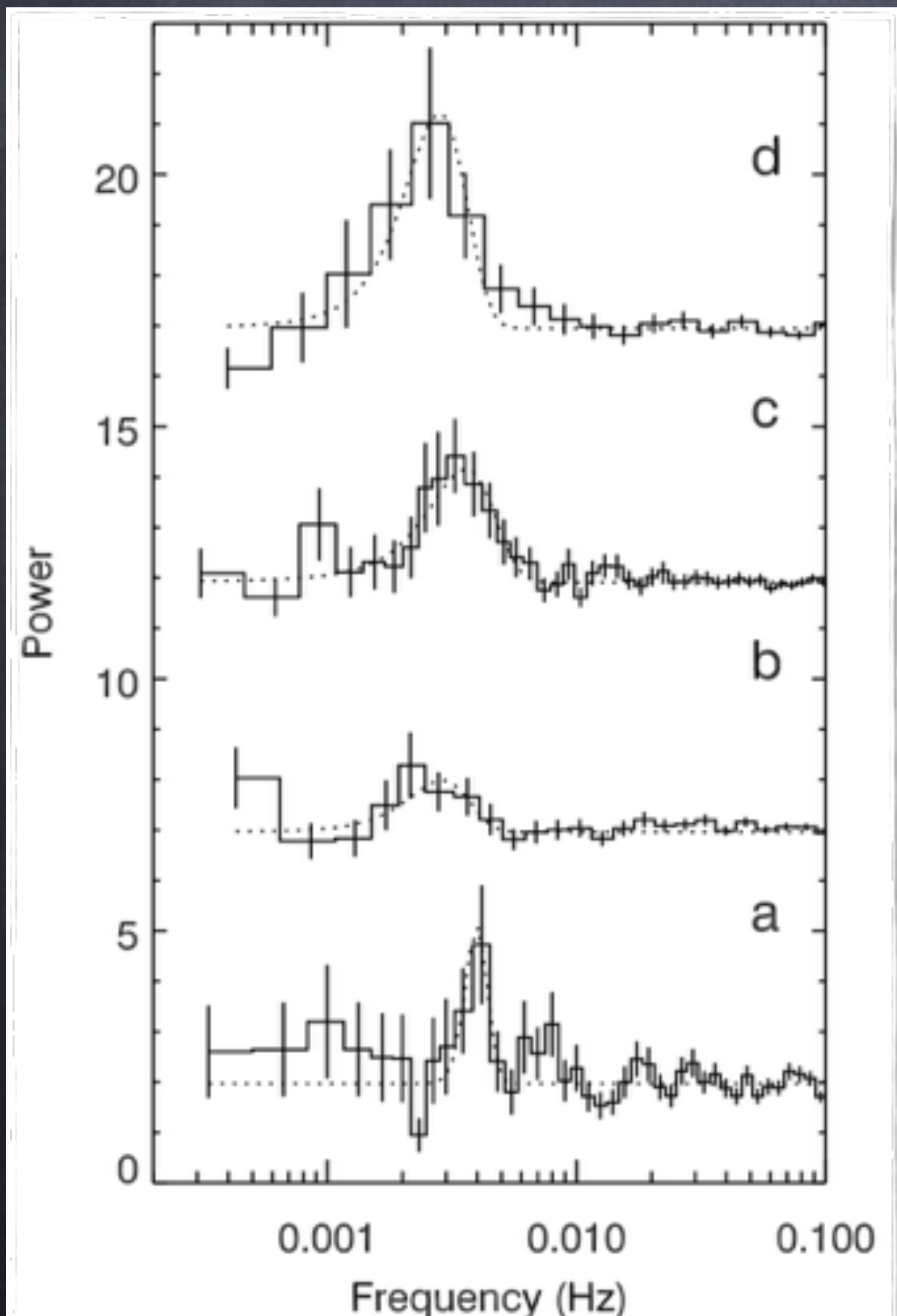


M82 X-2

Feng et al. (2010)

☑ Timing analysis

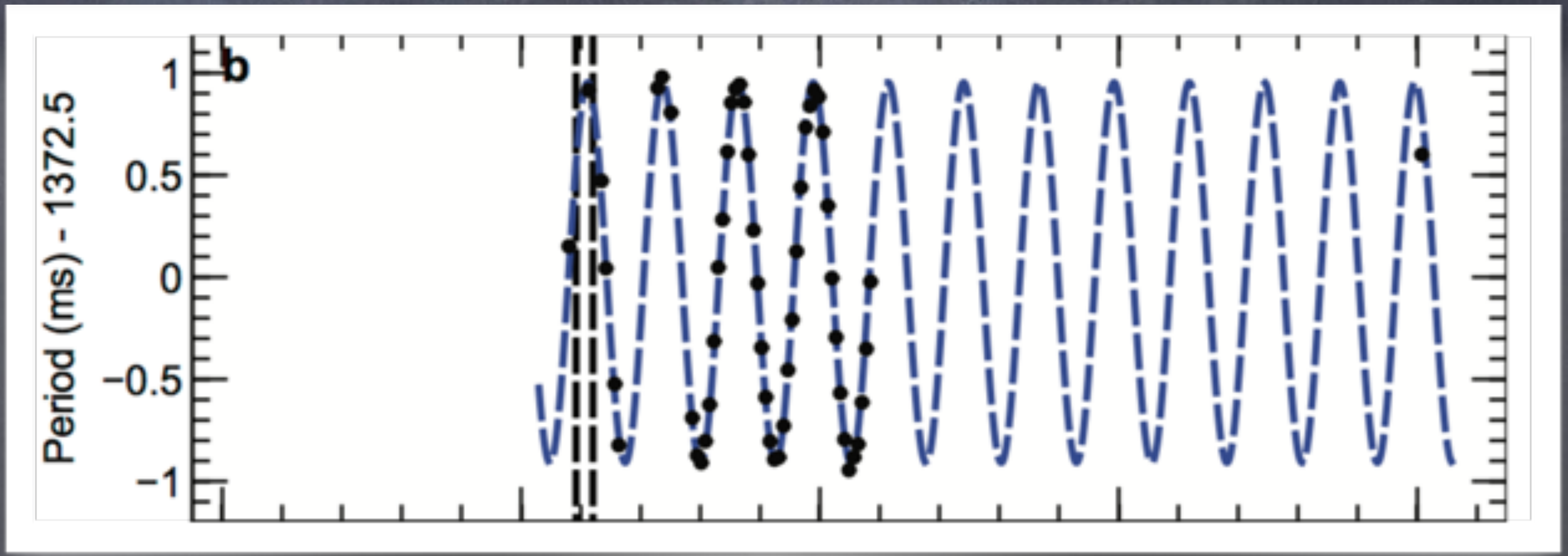
- Low-frequency QPOs found in some ULXs
- Frequency scaling from stellar-mass BHs ⇨ IMBH!



M82 X-2

Feng et al. (2010)

But...pulsations reveal neutron star!



Bachetti et al. (2014)

CHECKLIST

- ☑ Spectral analysis
- ☑ Variability
- ☑ Timing analysis
- ☑ Distance
- ☑ Mass measurement
- ☑ Environment
- ☑ Jets/outflows
- ☑ Monitoring

X-rays

Optical, IR
radio

CHECKLIST

- ☑ Spectral analysis
- ☑ Variability
- ☑ Timing analysis
- ☑ Distance
- ☑ Mass measurement
- ☑ Environment
- ☑ Jets/outflows
- ☑ Monitoring

X-rays

Optical, IR
radio

Optical counterparts

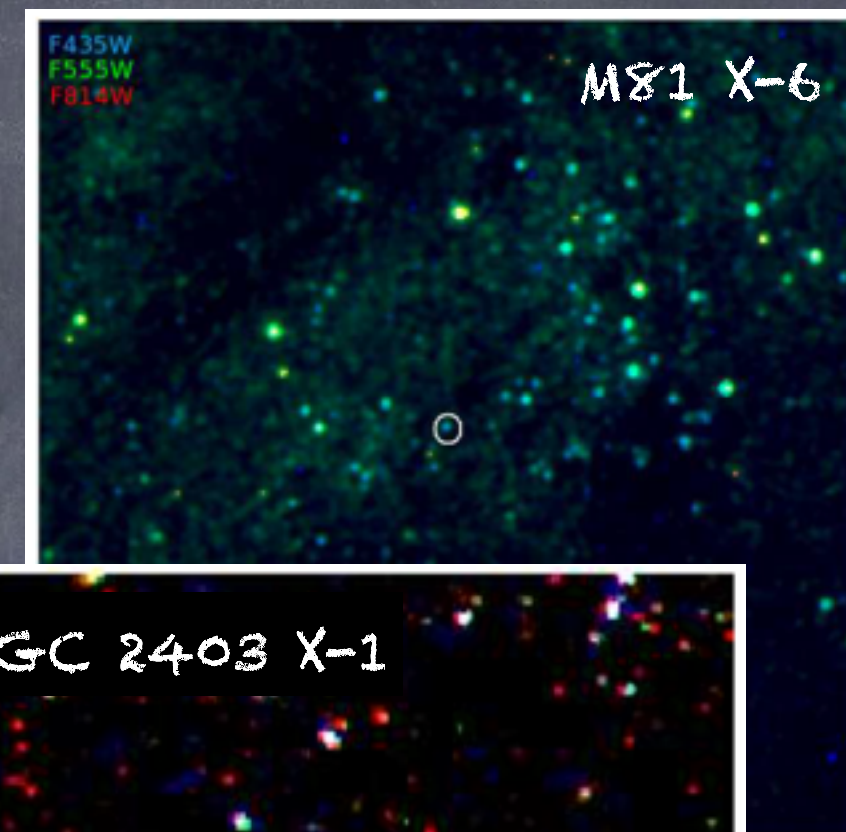
- Tens of ULXs with optical counterpart

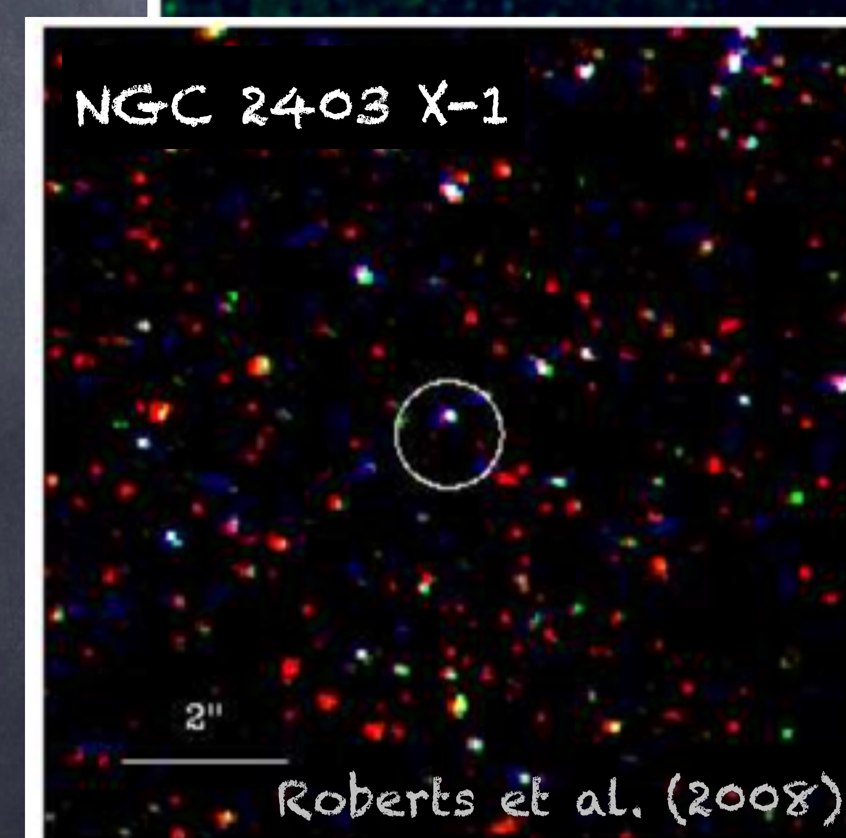
  Thanks to Chandra+HST astrometry

- Emission tends to be blue

  $m_V \sim 20-26$

Gladstone et al. (2013)





Roberts et al. (2008)

Optical counterparts

- Tens of ULXs with optical counterpart

  Thanks to Chandra+HST astrometry

- Emission tends to be blue

  m_V~20-26

BUT optical emission from:

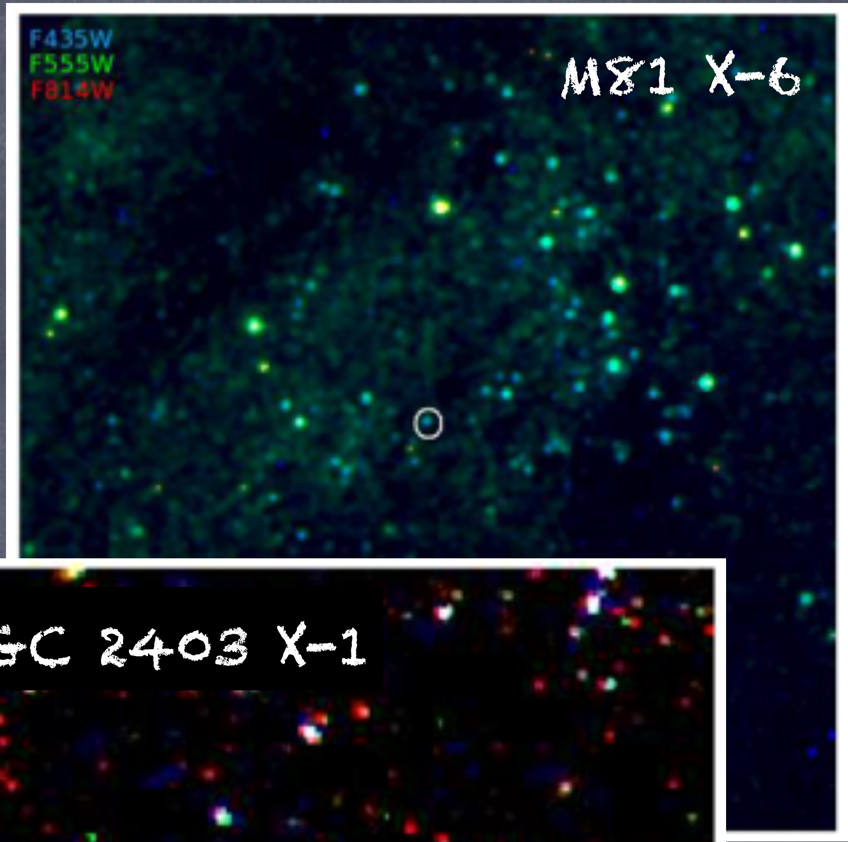
?

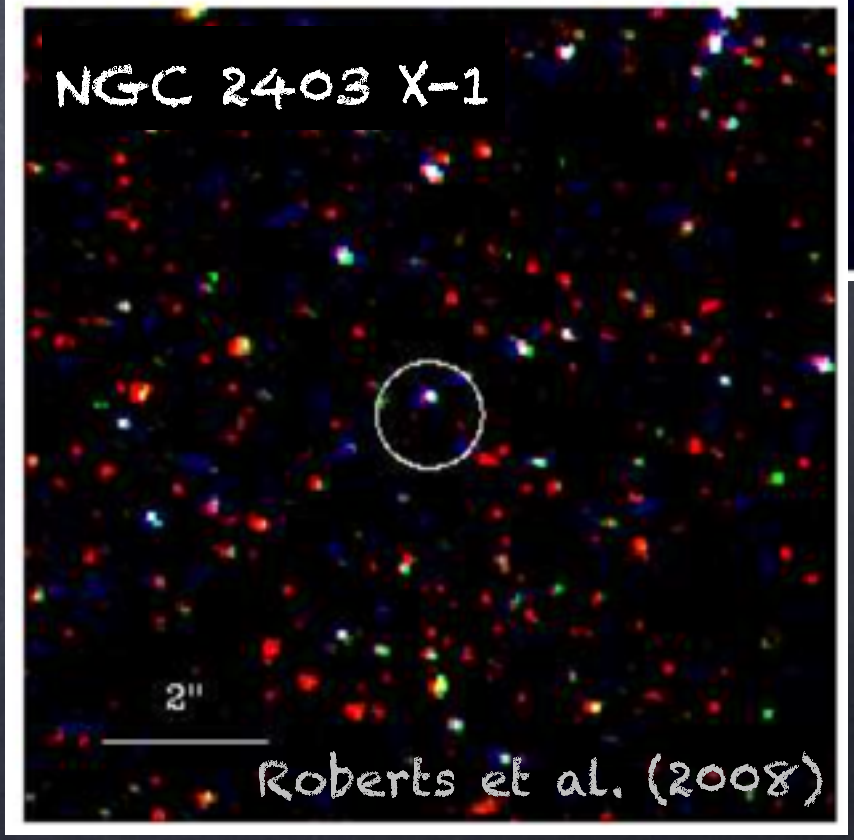
?

?

?

Gladstone et al. (2013)





Roberts et al. (2008)

Optical counterparts

- Tens of ULXs with optical counterpart

  Thanks to Chandra+HST astrometry

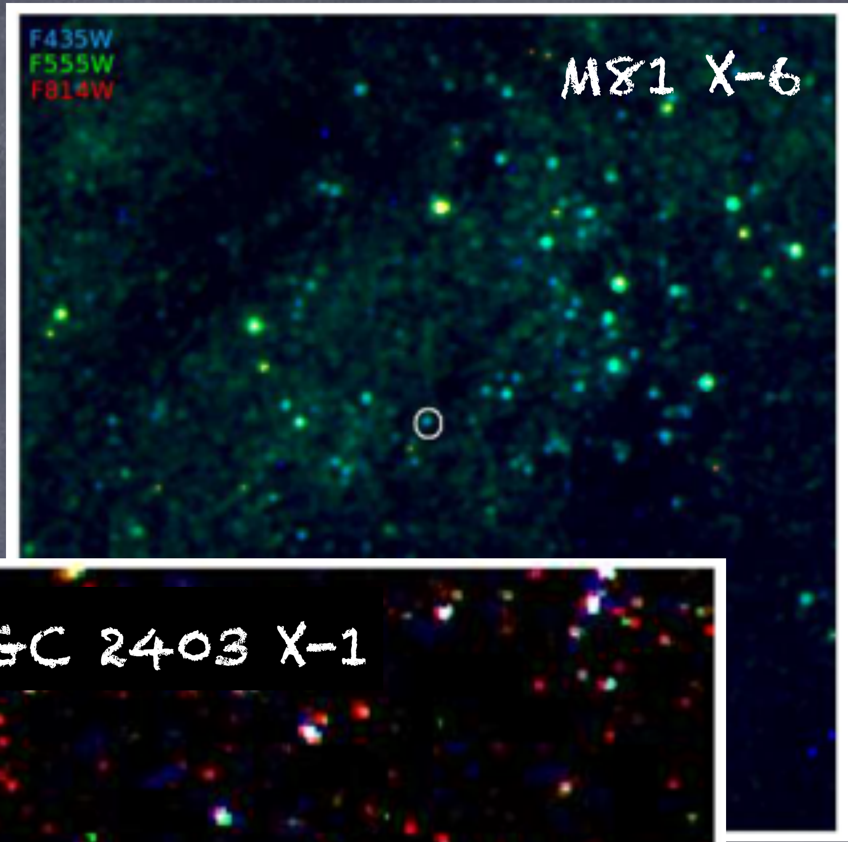
- Emission tends to be blue

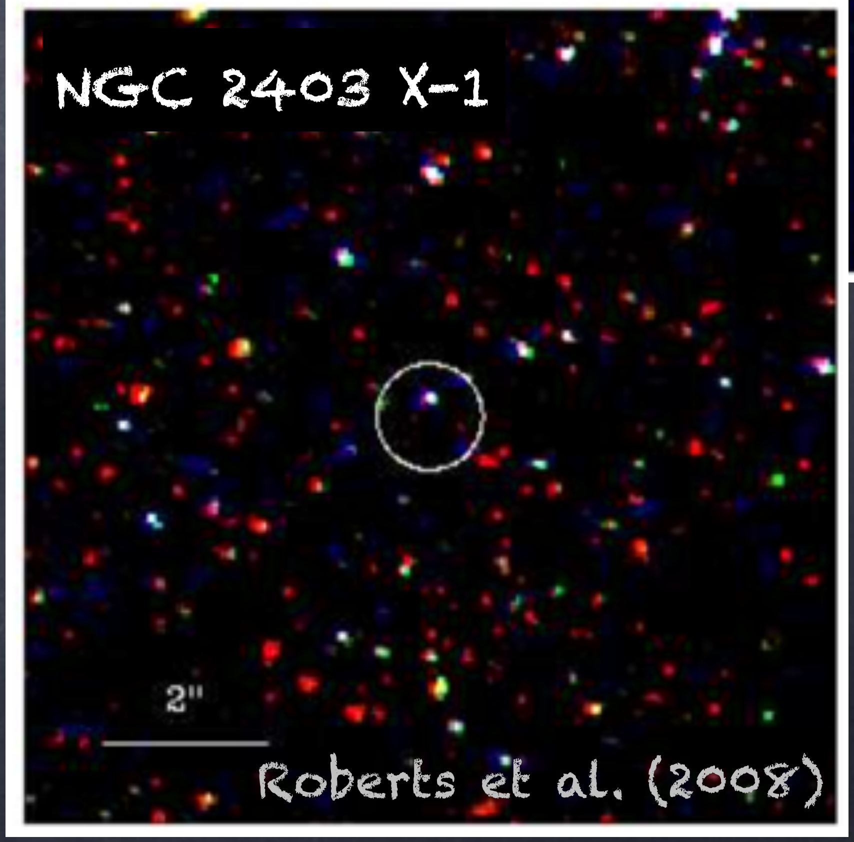
  $m_V \sim 20-26$

BUT optical emission from:

? * companion star? ?
* intrinsic accretion disk?
? * X-ray irradiated outer disk?
* all the above combined? ?

Gladstone et al. (2013)

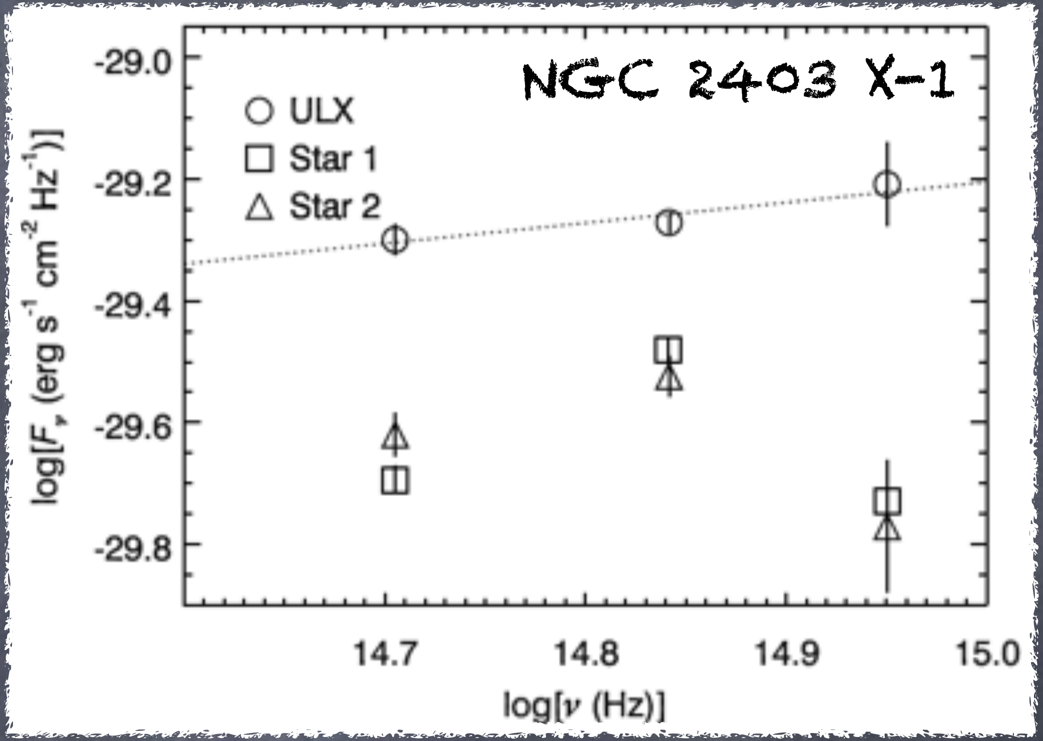




Roberts et al. (2008)

HST data of 13 ULXs:

- SED: no single spectral type match
- SED: power-law fit $\alpha \sim 1$–2 ($F_\nu \sim \nu^\alpha$)
- optical variability
- log(fx/fv) ~ 3 consistent with LMXBs



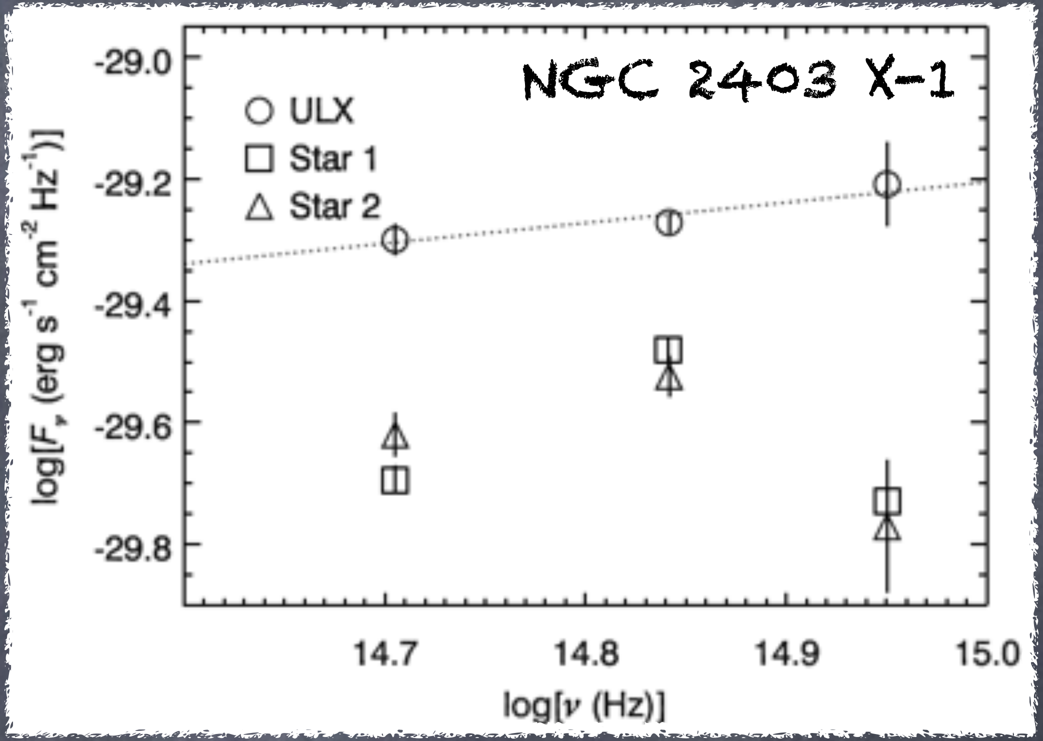
Tao et al. (2011)

optical emission dominated by X-ray reprocessing on the outer disk

HST data of 13 ULXs:

- SED: no single spectral type match
- SED: power-law fit $\alpha \sim 1\text{–}2$ ($F_\nu \sim \nu^\alpha$)
- optical variability
- log(fx/fv) ~ 3 consistent with LMXBs

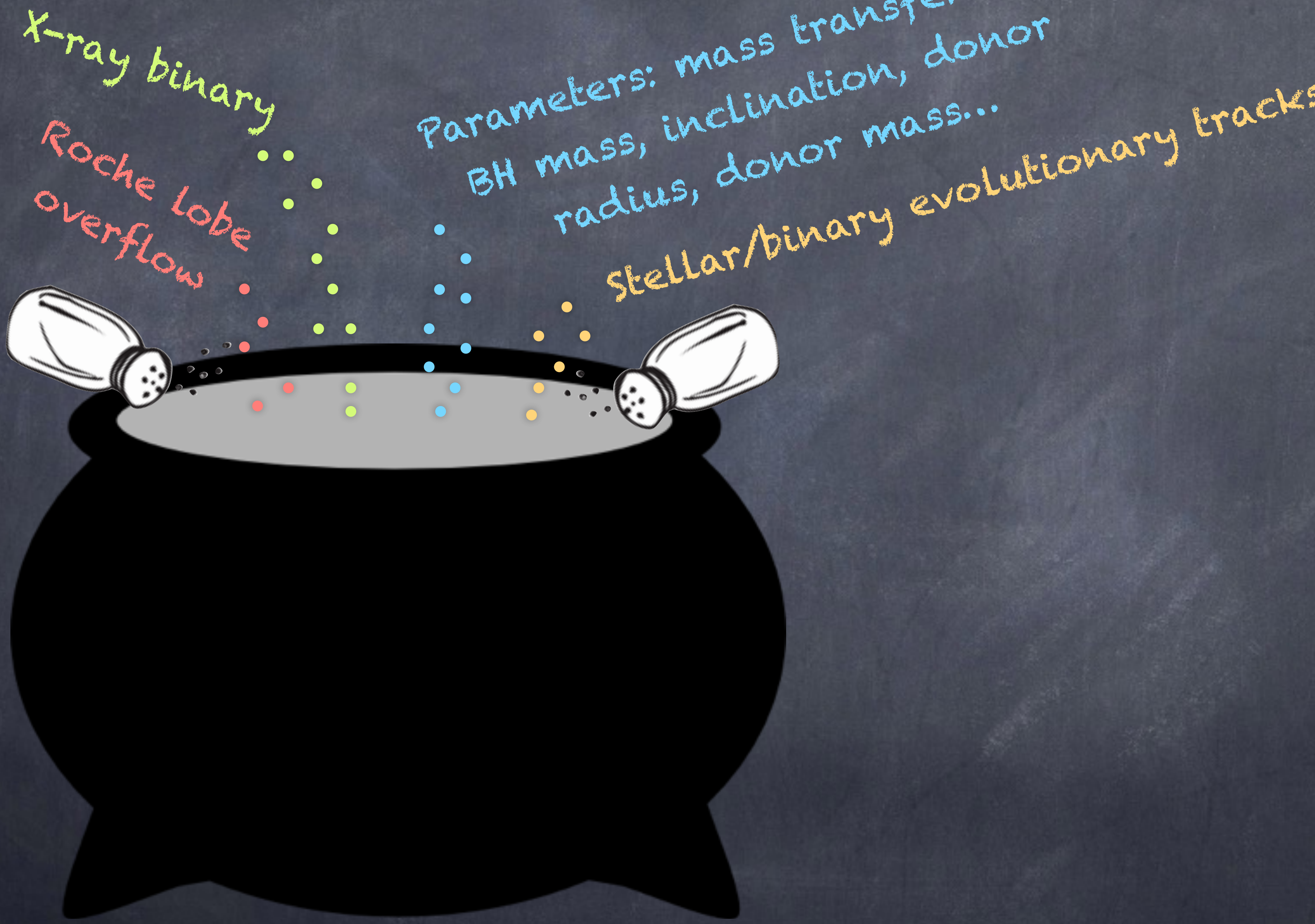
optical emission dominated by X-ray reprocessing on the outer disk



Tao et al. (2011)

Mmmm...
What could we do...?

Apply irradiation models!



e.g., Copperwheat et al. (2005, 2007), Patruno & Zampieri (2008,2010), Madhusudhan et al. (2008), Grisé et al. (2011), Gladstone et al. (2013)

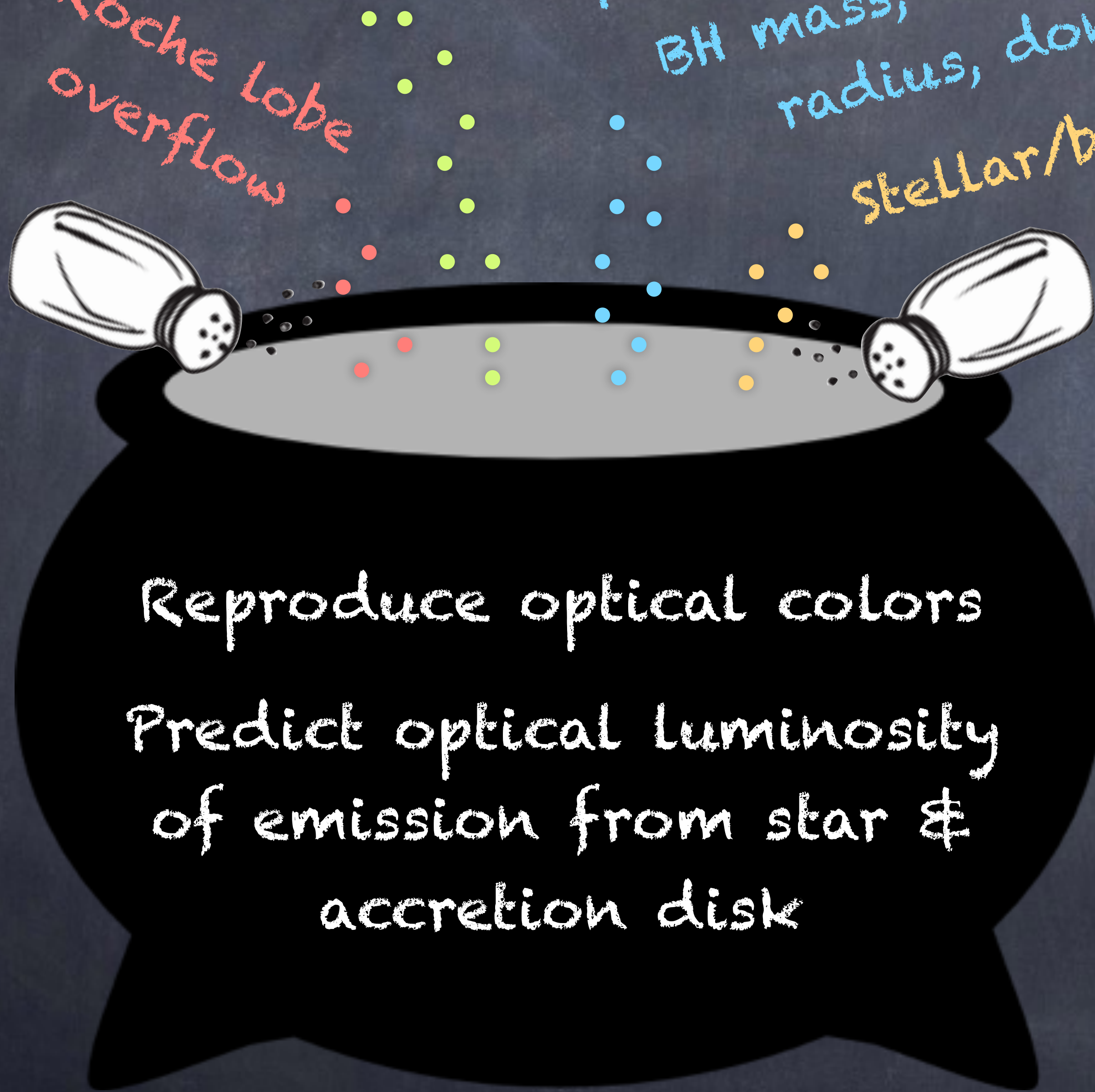
Apply irradiation models!

X-ray binary

Roche lobe overflow

Parameters: mass transfer rate, BH mass, inclination, donor radius, donor mass...

Stellar/binary evolutionary tracks



e.g., Copperwheat et al. (2005, 2007), Patruno & Zampieri (2008,2010), Madhusudhan et al. (2008), Grisé et al. (2011), Gladstone et al. (2013)

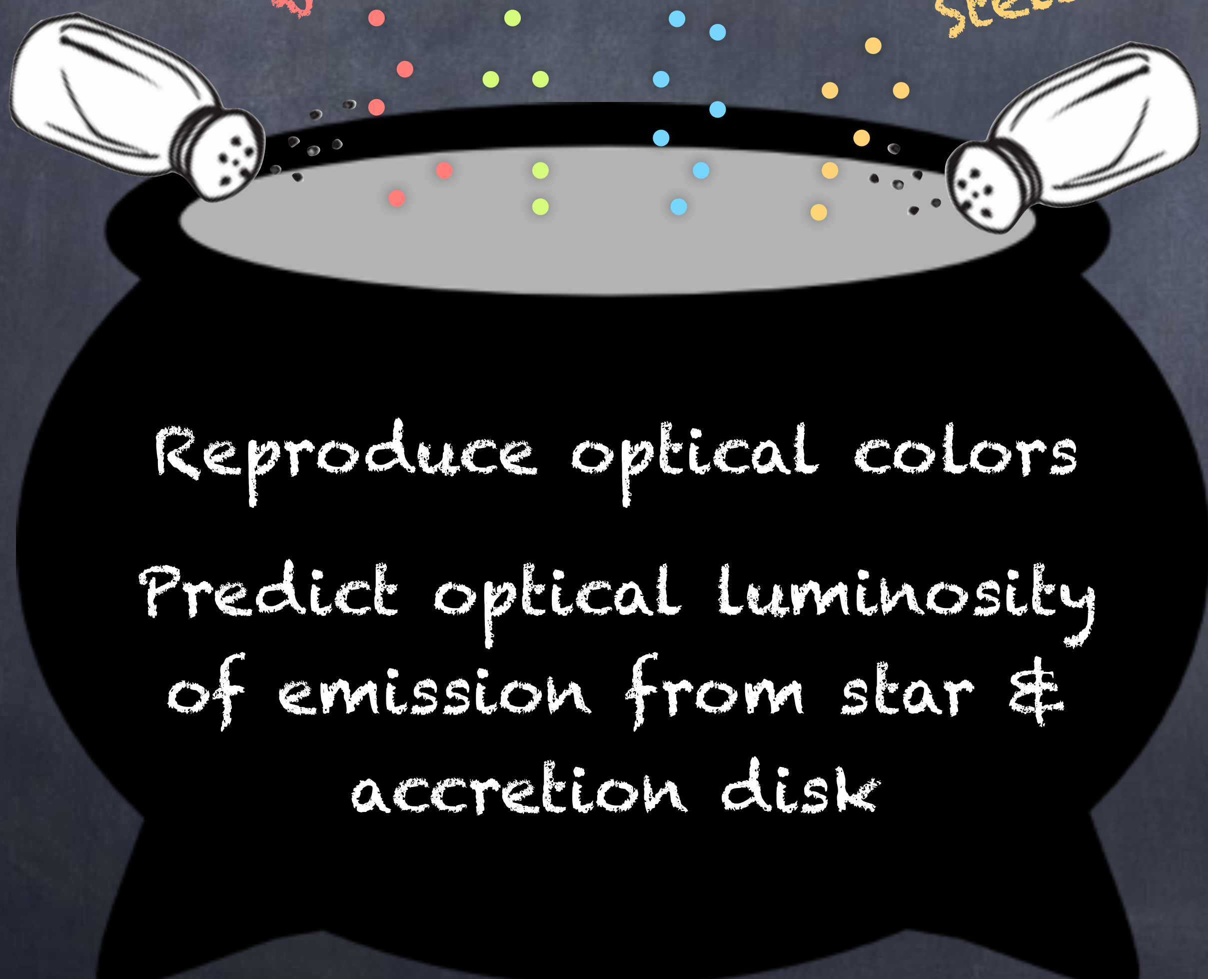
Apply irradiation models!

X-ray binary

Roche lobe overflow

Parameters: mass transfer rate, BH mass, inclination, donor radius, donor mass...

Stellar/binary evolutionary tracks



Most donor stars consistent with B giants

e.g., Copperwheat et al. (2005, 2007), Patruno & Zampieri (2008,2010), Madhusudhan et al. (2008), Grisé et al. (2011), Gladstone et al. (2013)

Distance

Optical counterpart or background AGN?

Spectroscopy needed!

10 ULXs: 2 background AGN

Sutton et al. (2015)

17 ULXs: 15 background AGN

2 foreground stars

Wong et al. (2008)

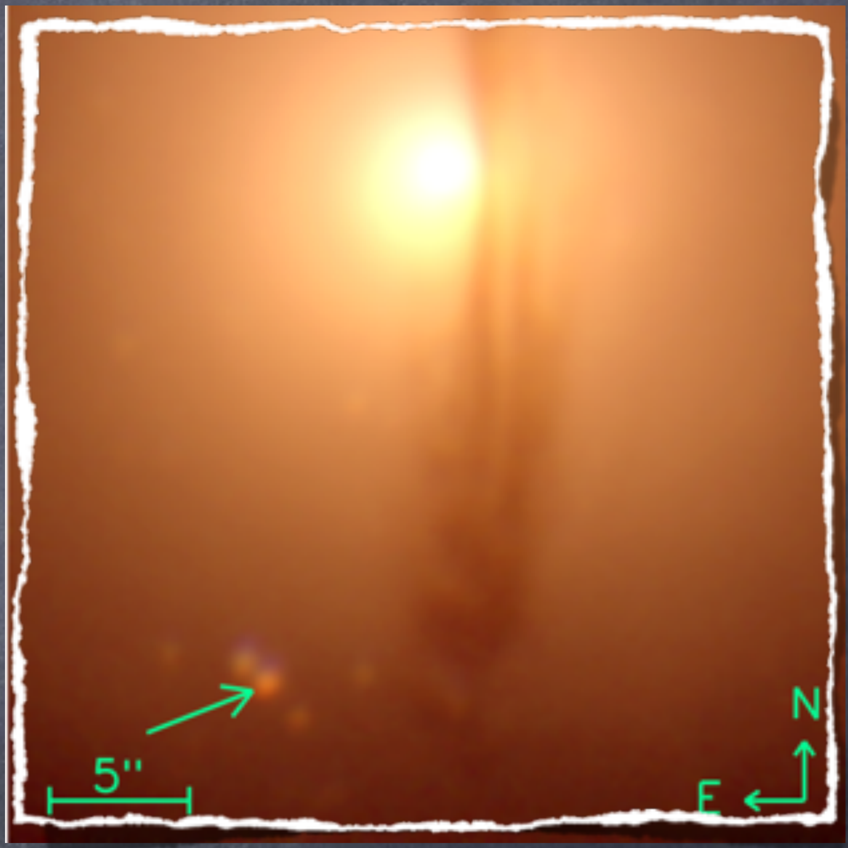
23 ULXs: 20 background AGN

3 foreground stars

Gutiérrez & López-Corredoira (2005, 2007)

Gutiérrez (2006, 2013)

Sutton et al. (2015)



HLX in IC 4320

$m_V = 22.67$

Distance

Optical counterpart or background AGN?

Spectroscopy needed!

10 ULXs: 2 background AGN

Sutton et al. (2015)

17 ULXs: 15 background AGN

2 foreground stars

Wong et al. (2008)

23 ULXs: 20 background AGN

3 foreground stars

Gutiérrez & López-Corredoira (2005, 2007)

Gutiérrez (2006, 2013)

Sutton et al. (2015)

HLX in IC 4320

$m_V = 22.67$

Distance

Optical counterpart or background AGN?

Spectroscopy needed!

10 ULXs: 2 background AGN

Sutton et al. (2015)

17 ULXs: 15 background AGN

2 foreground stars

Wong et al. (2008)

23 ULXs: 20 background AGN

3 foreground stars

Gutiérrez & López-Corredoira (2006, 2007)

Gutiérrez (2006, 2013)

Sutton et al. (2015)

HLX in IC 4320

$m_V = 22.67$

ULX location confirmed for many other ULXs

e.g., Pakull & Mirioni (2002), Lehmann et al. (2005), Grisé et al. (2006), Pakull, Grisé & Motch (2006), Kaaret & Corbel (2009), Wiersema et al. (2010), Motch et al. (2011), Roberts et al. (2011), Soria et al. (2013), Gutiérrez & Moon (2014)

Meanwhile, in the infrared...

Spectroscopy:

- 4 ULXs: 3 background AGN

Heida et al. (2013)

- $\log(f_X/f_V) = -1 - 1$ ⇨ likely AGN

Meanwhile, in the infrared..

Spectroscopy:

- 4 ULXs: 3 background AGN

Heida et al. (2013)

- $\log(f_x/f_v)$= -1 - 1 ⇨ likely AGN

★ Twinkle, twinkle ★
★ ~~little~~ star... ★

Photometry & spectroscopy:

- ULX counterparts consistent with red supergiants
- radial velocity confirms ULX location for a few ULXs
- but no dynamical mass measurement... YET!

Heida et al. (2014, 2015, 2016)

Meanwhile, in the infrared..

Spectroscopy:

- 4 ULXs: 3 background AGN

Heida et al. (2013)

- $\log(f_X/f_V) = -1 - 1$ ⇨ likely AGN

★ Twinkle, twinkle ★

★ ~~little~~ star... ★

Photometry & spectroscopy:

- ULX counterparts consistent with red supergiants
- radial velocity confirms ULX location for a few ULXs
- but no dynamical mass measurement... YET!

Heida et al. (2014, 2015, 2016)

See next talks by Marianne Heida & Kristhell López!

Dynamical mass measurement

Several attempts in the optical...

e.g., Pakull et al. (2006), Kaaret & Corbel (2009), Pakull, Grisé & Motch (2006), Grisé et al. (2009), Roberts et al. (2011), Liu et al. (2012)

- M101 X-1

$L_X = 3 \times 10^{39}$ erg/s, Wolf-Rayet donor of 19 $M_\odot$

Dynamical mass measurement

Several attempts in the optical...

e.g., Pakull et al. (2006), Kaaret & Corbel (2009), Pakull, Grisé & Motch (2006), Grisé et al. (2009), Roberts et al. (2011), Liu et al. (2012)

- M101 X-1

$L_X = 3 \times 10^{39}$ erg/s, Wolf-Rayet donor of 19 $M_\odot$

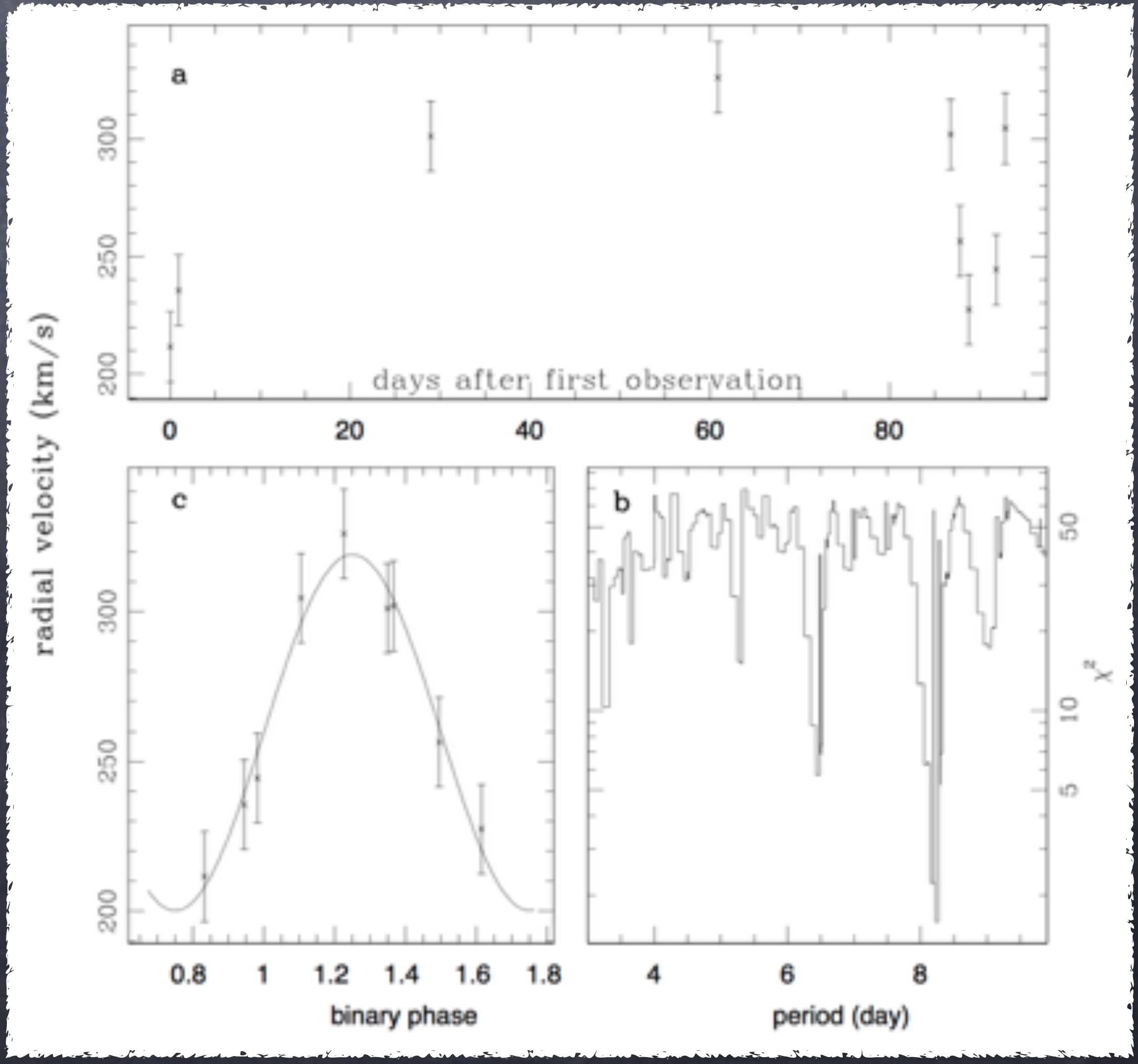
Radial velocity variations:

± 60 km/s over 3 months

Orbital period: 8.2 ± 0.1 days

⇨ $5 < M_{BH} < 20\ M_\odot$
super-Eddington accretion

Liu et al. (2011)



Dynamical mass measurement

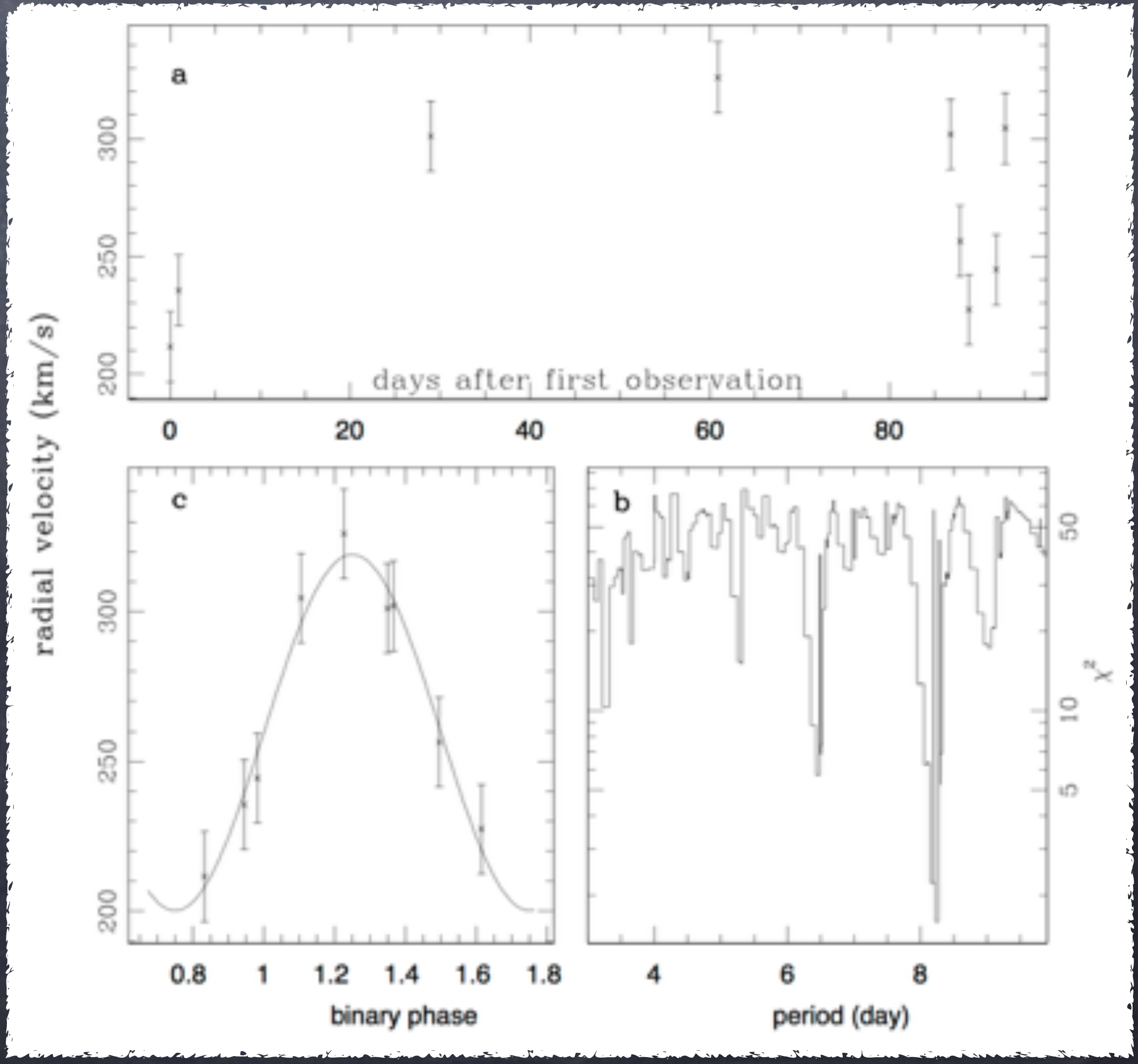
Several attempts in the optical...

e.g., Pakull et al. (2006), Kaaret & Corbel (2009), Pakull, Grisé & Motch (2006), Grisé et al. (2009), Roberts et al. (2011), Liu et al. (2012)

- M101 X-1

$L_X = 3 \times 10^{39}$ erg/s, Wolf-Rayet donor of 19 $M_\odot$

Liu et al. (2011)



Radial velocity variations:

± 60 km/s over 3 months

Orbital period: 8.2 ± 0.1 days

⇨ $5 < M_{BH} < 20\ M_\odot$

super-Eddington accretion

Signatures of optical thick outflow!

Shen et al. (2015), Soria & Kong (2016)

- ULX P13 in NGC 7793

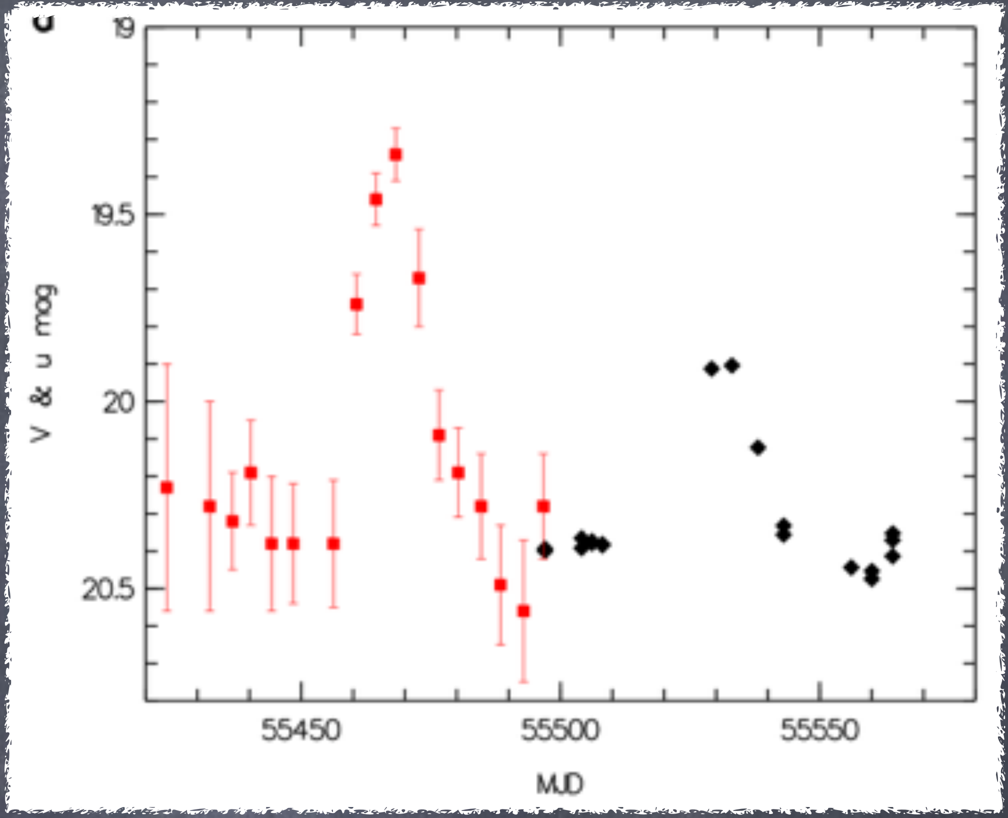
Donor star B9Ia

Optical/UV modulations

Orbital period ~ 64 days

⇨ $M_{BH} < 15\ M_{\odot}$

super-Eddington accretion



Motch et al (2014)

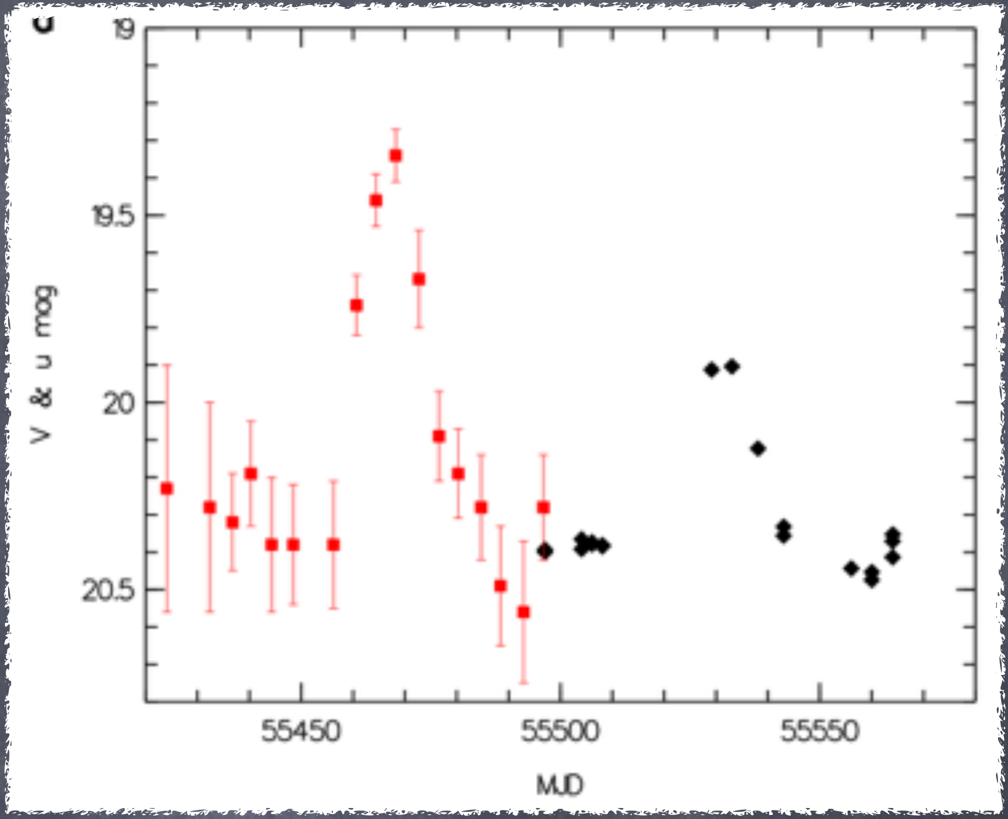
- ULX P13 in NGC 7793

Donor star B9Ia

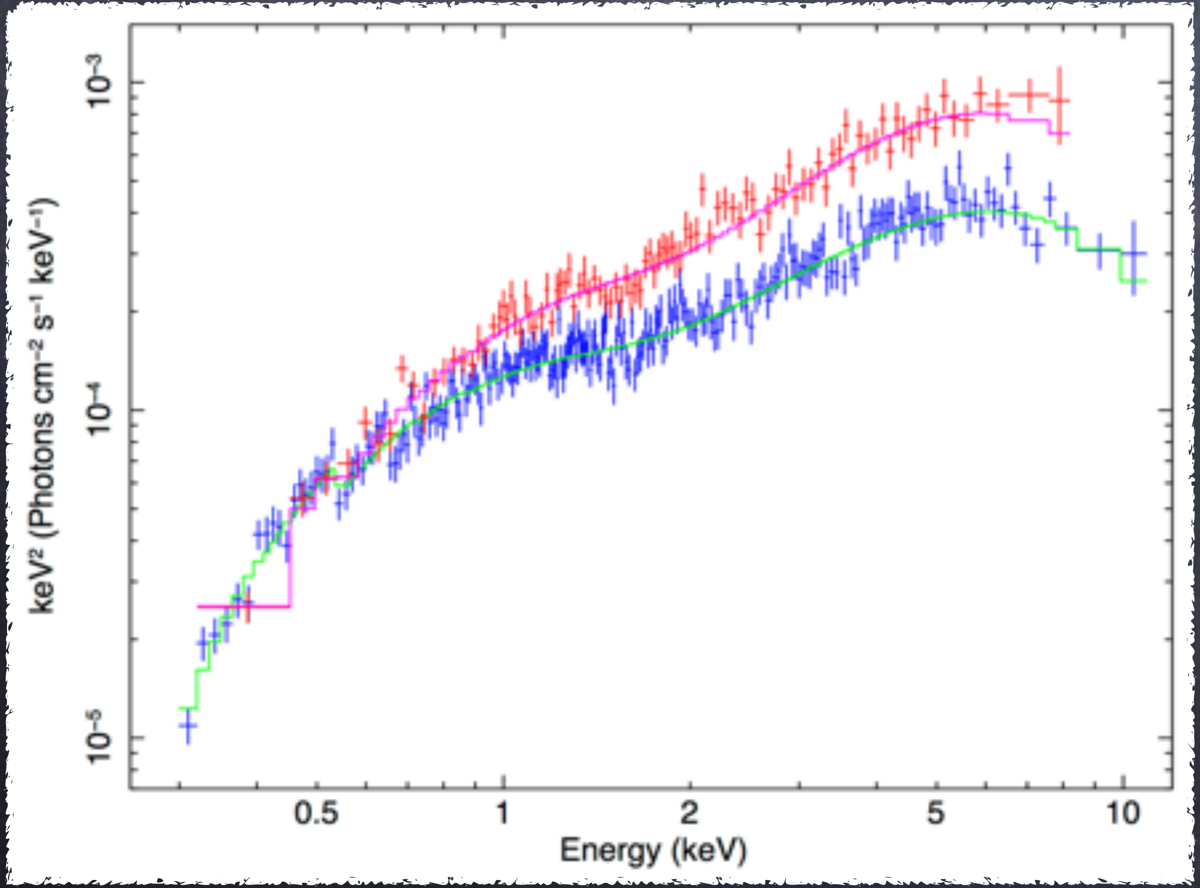
Optical/UV modulations

Orbital period ~ 64 days

⇒ $M_{BH} < 15\ M_\odot$
super-Eddington accretion



Motch et al (2014)



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

Soft excess

Spectral break at ~ 4.2 keV

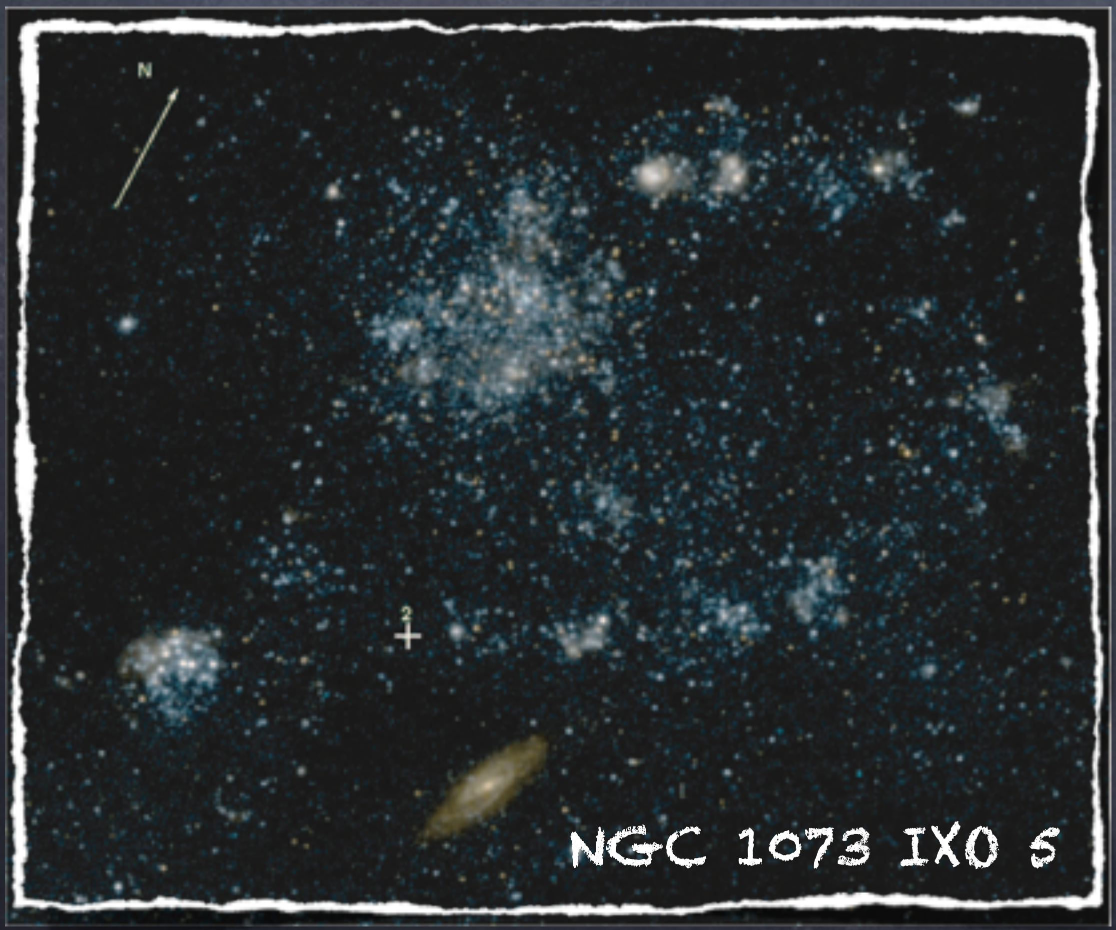
Signatures of
super-Eddington accretion

Environment

- Some ULXs near/within >10 Myr old stellar clusters

- Others near star formation ring

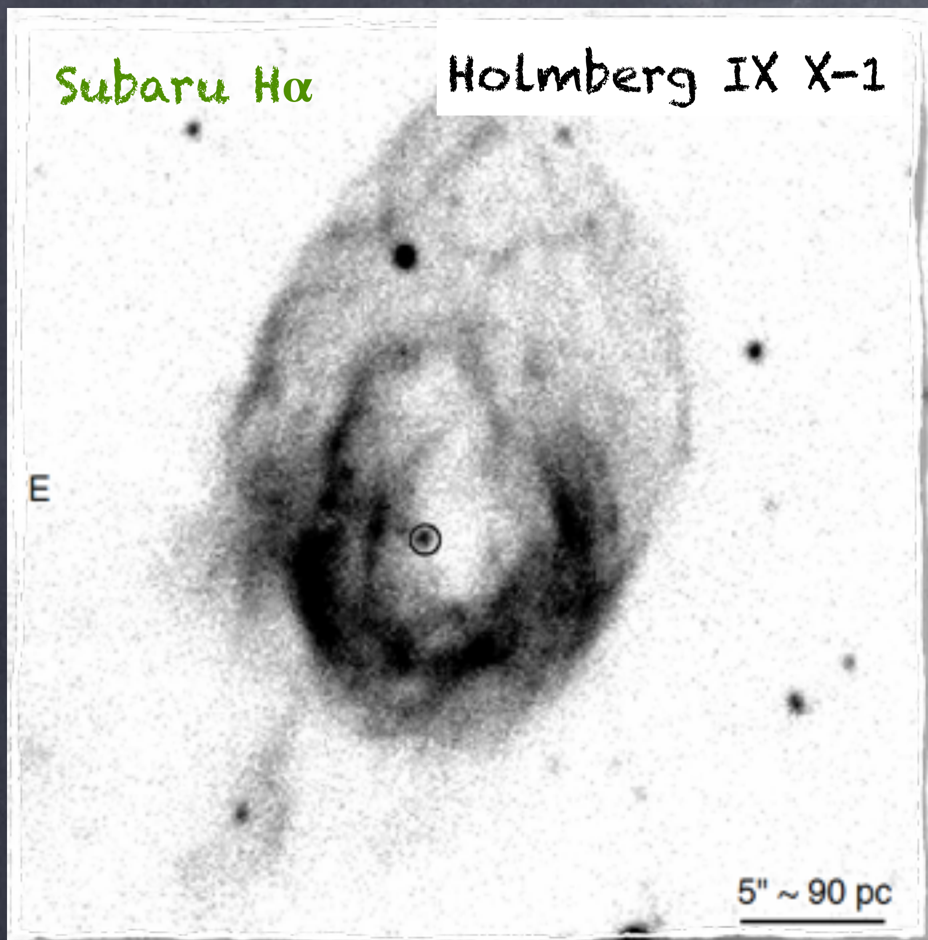
Grisé et al. (2011)



Kaaret (2005)

e.g., Liu et al. (2007), Feng & Kaaret (2008), Grisé et al. (2008, 2011), Yang et al. (2011), Farrell et al. (2012)

- Some ULXs surrounded by nebular emission



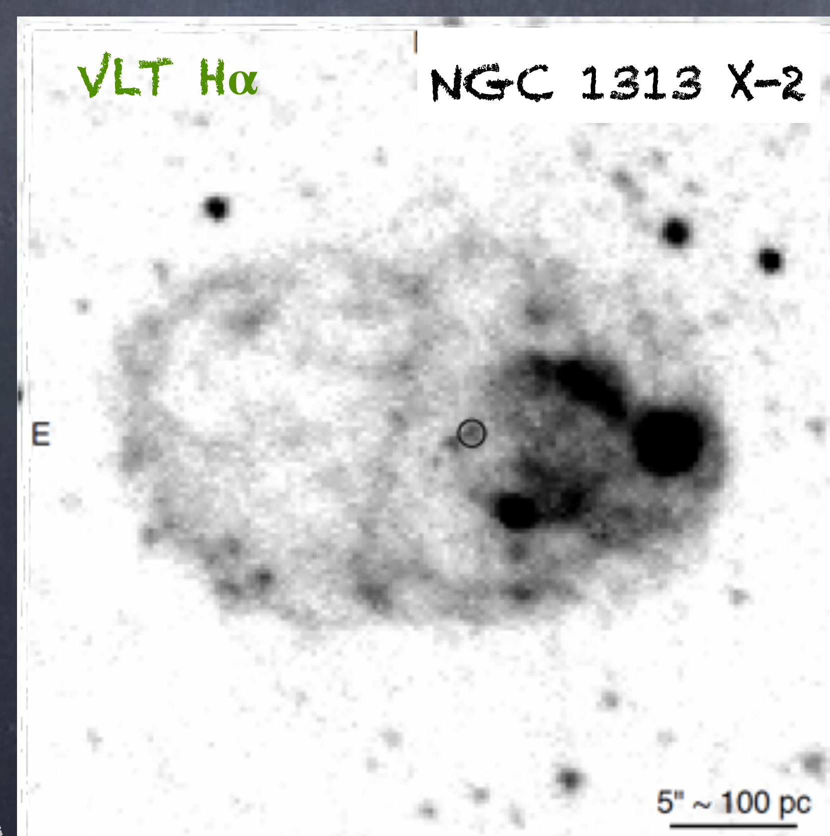
Feng & Soria (2011)

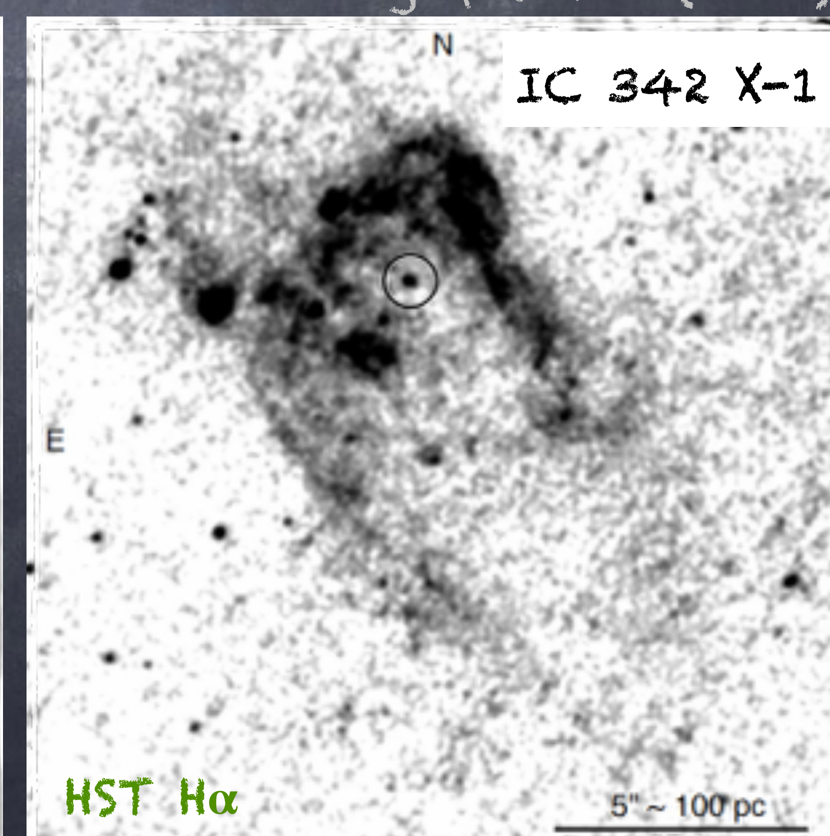
X-ray photoionized nebulae

Shock-ionized nebulae

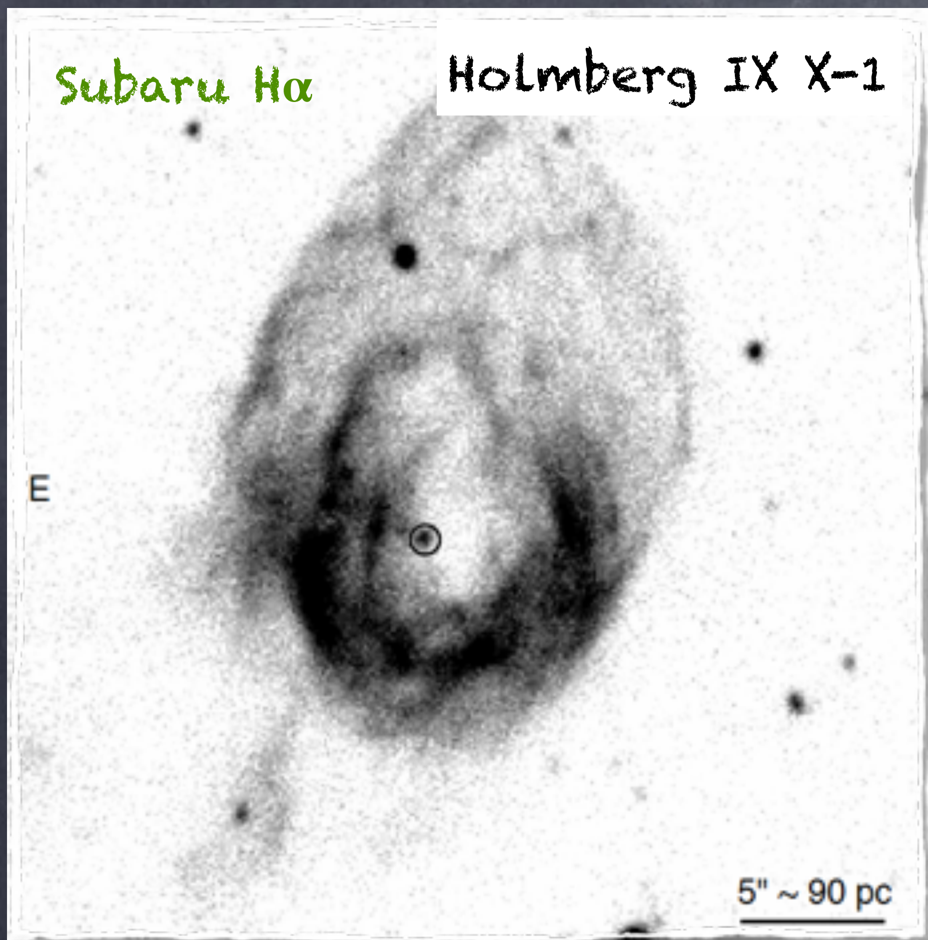
e.g., Pakull & Mirioni (2002, 2003), Pakull & Grisé (2008), Abolmasov et al. (2007), Kaaret & Corbel (2009), Kaaret et al. (2004, 2010), Moon et al. (2011), Cseh et al. (2012)

Feng & Soria (2011)





- Some ULXs surrounded by nebular emission



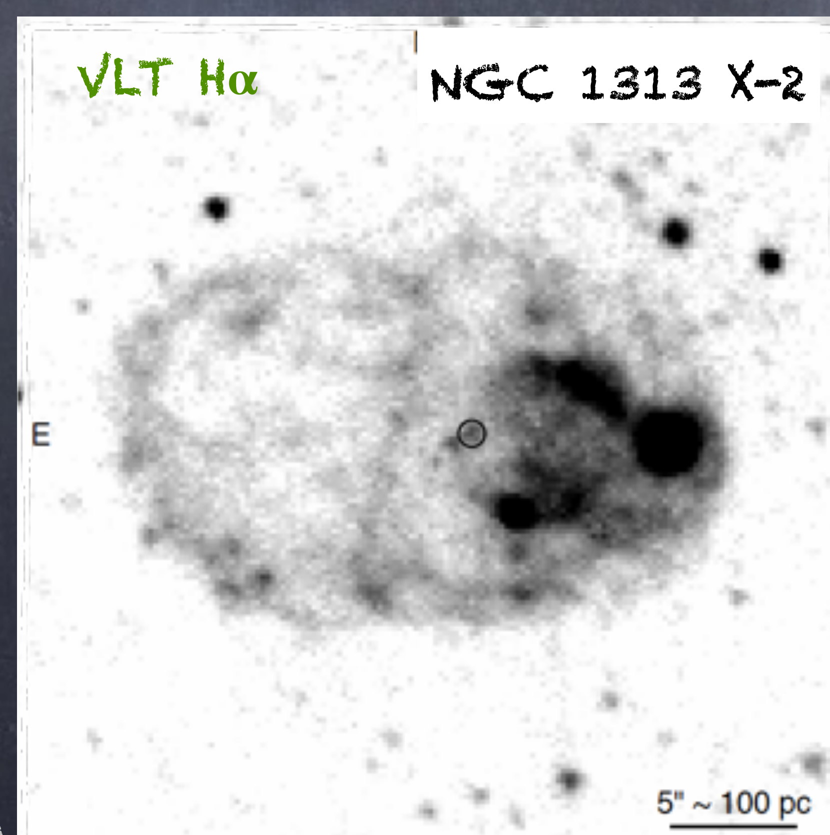
Feng & Soria (2011)

X-ray photoionized nebulae

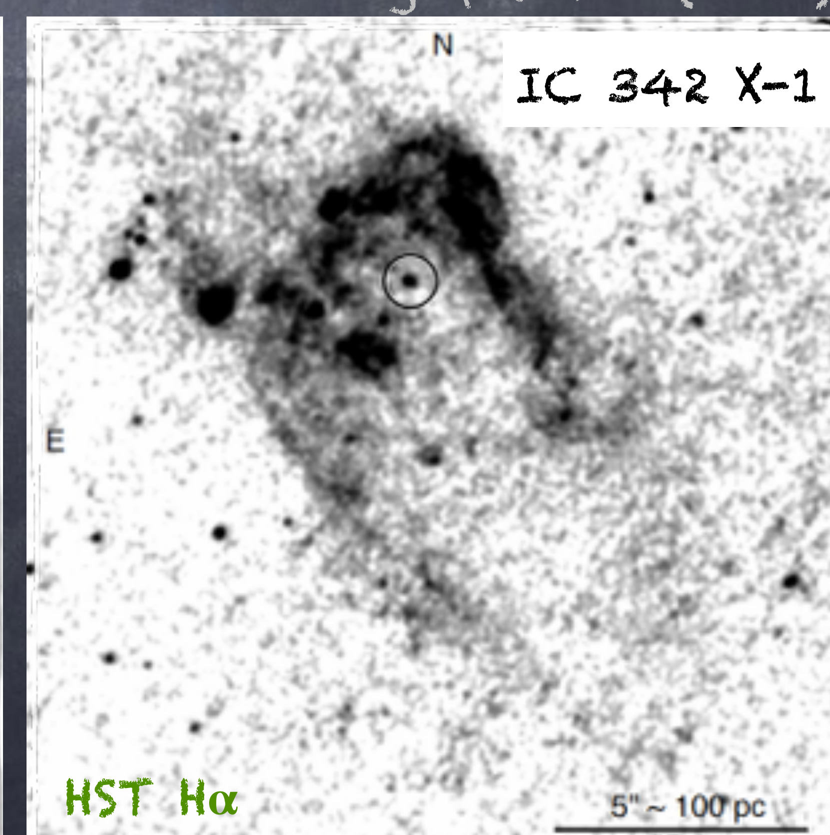
$L_X \sim 10^{39} - 10^{40}$ erg/s required to produce high-ionization (e.g., HeII) line luminosities

Shock-ionized nebulae

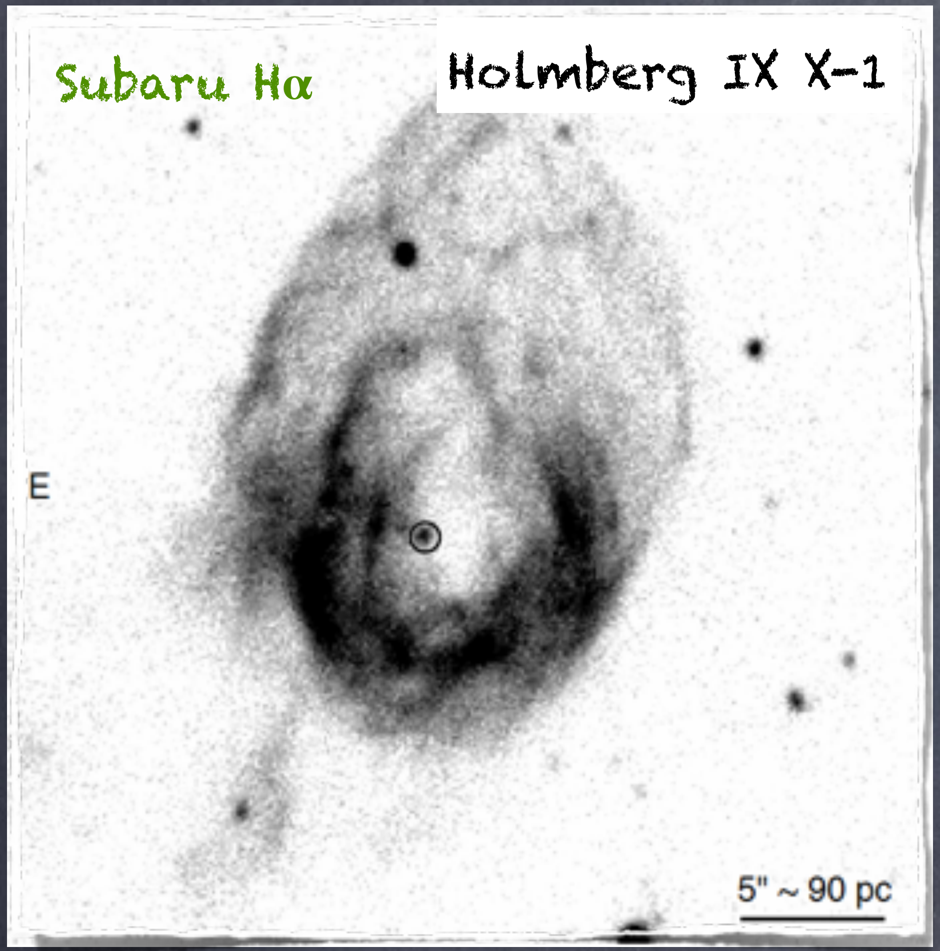
e.g., Pakull & Mirioni (2002, 2003), Pakull & Grisé (2008), Abolmasov et al. (2007), Kaaret & Corbel (2009), Kaaret et al. (2004, 2010), Moon et al. (2011), Cseh et al. (2012)



Feng & Soria (2011)



- Some ULXs surrounded by nebular emission



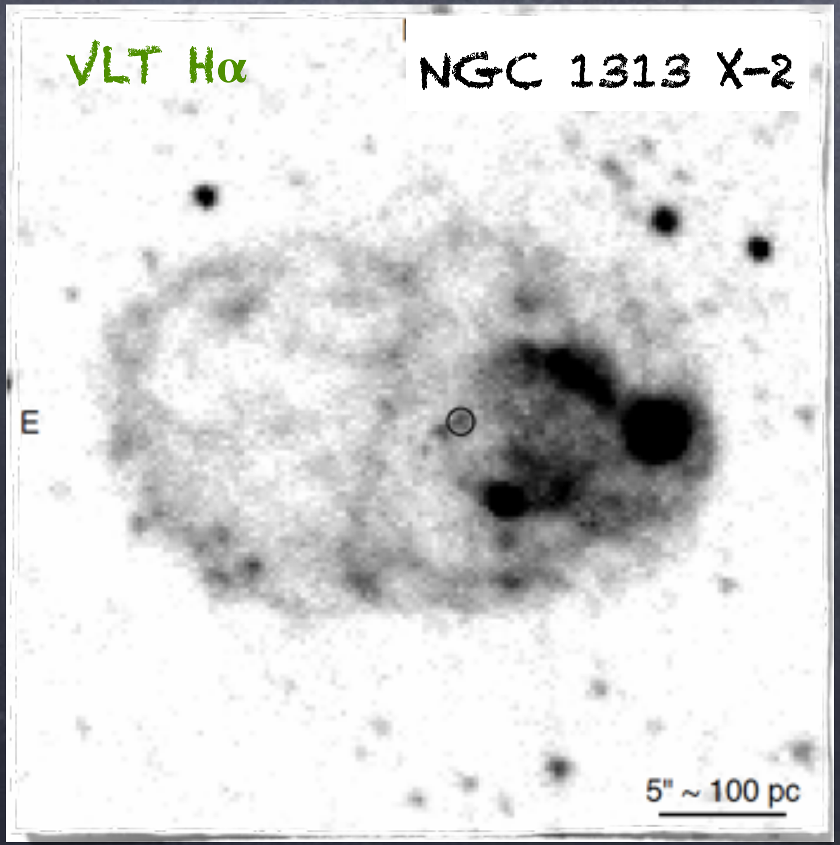
Feng & Soria (2011)

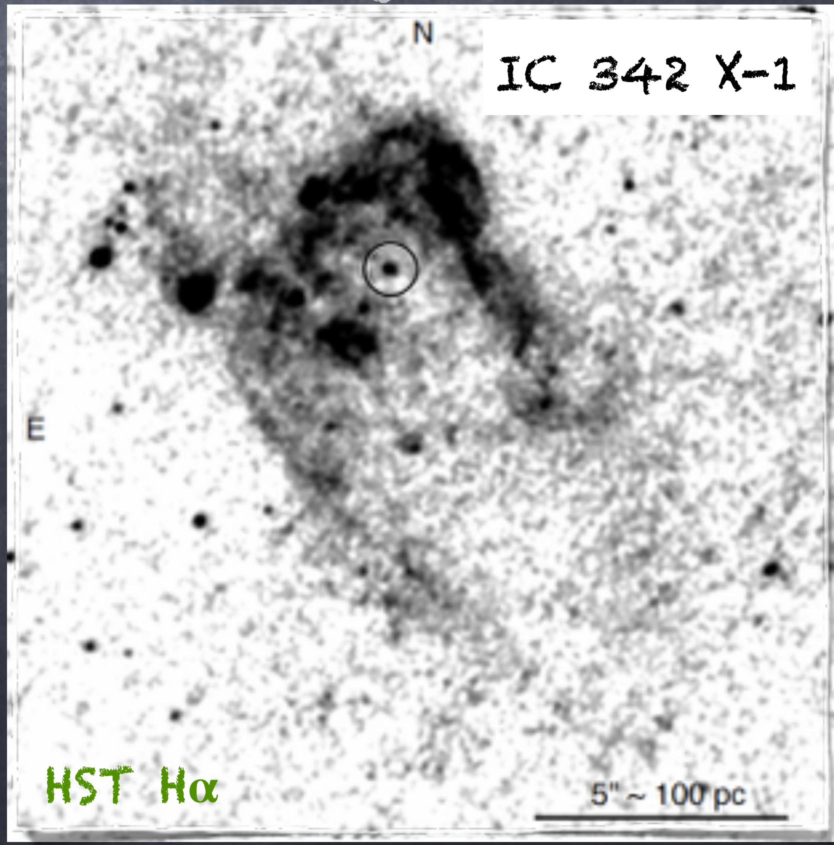
X-ray photoionized nebulae

$L_X \sim 10^{39} - 10^{40}$ erg/s required to produce high-ionization (e.g., HeII) line luminosities

⇨ Isotropic X-ray emission

Feng & Soria (2011)

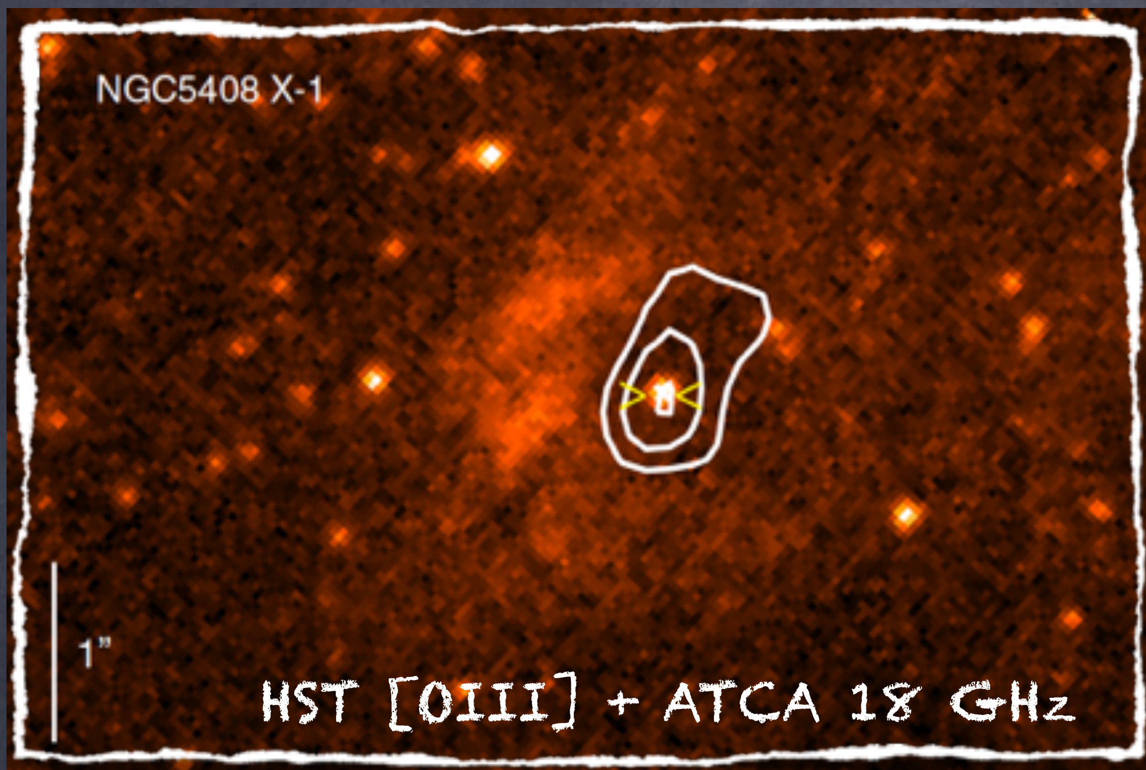


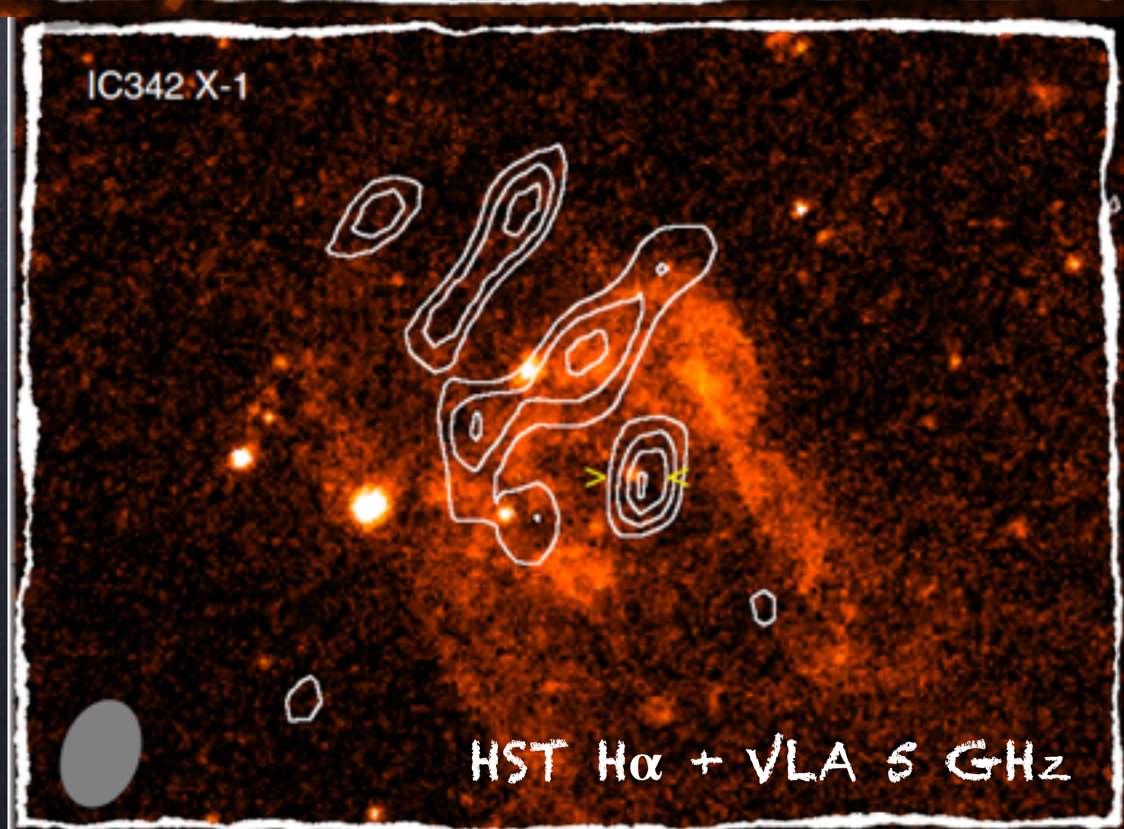


Shock-ionized nebulae

e.g., Pakull & Mirioni (2002, 2003), Pakull & Grisé (2008), Abolmasov et al. (2007), Kaaret & Corbel (2009), Kaaret et al. (2004, 2010), Moon et al. (2011), Cseh et al. (2012)

- Also radio nebulae





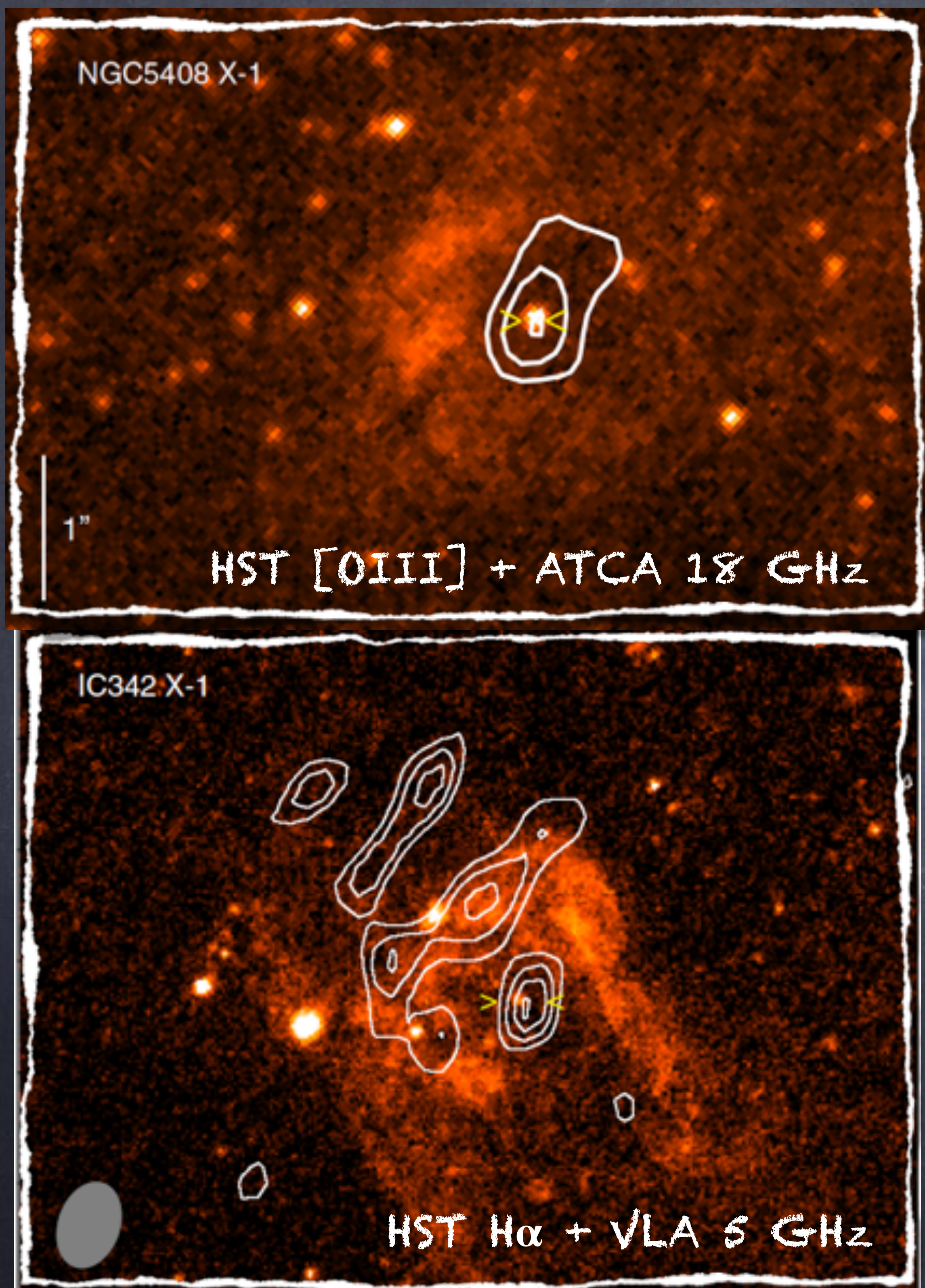
Cseh et al. (2012)

Optically-thin synchrotron emission

Size ~ 40-200 pc

More luminous than SNR

- Also radio nebulae



Cseh et al. (2012)

Optically-thin synchrotron emission

Size ~ 40-200 pc

More luminous than SNR

"ULX bubbles"

Shock-ionized nebulae
Radio nebulae

- Also radio nebulae

Cseh et al. (2012)

Optically-thin synchrotron emission

Size ~ 40-200 pc

More luminous than SNR

"ULX bubbles"

Shock-ionized nebulae

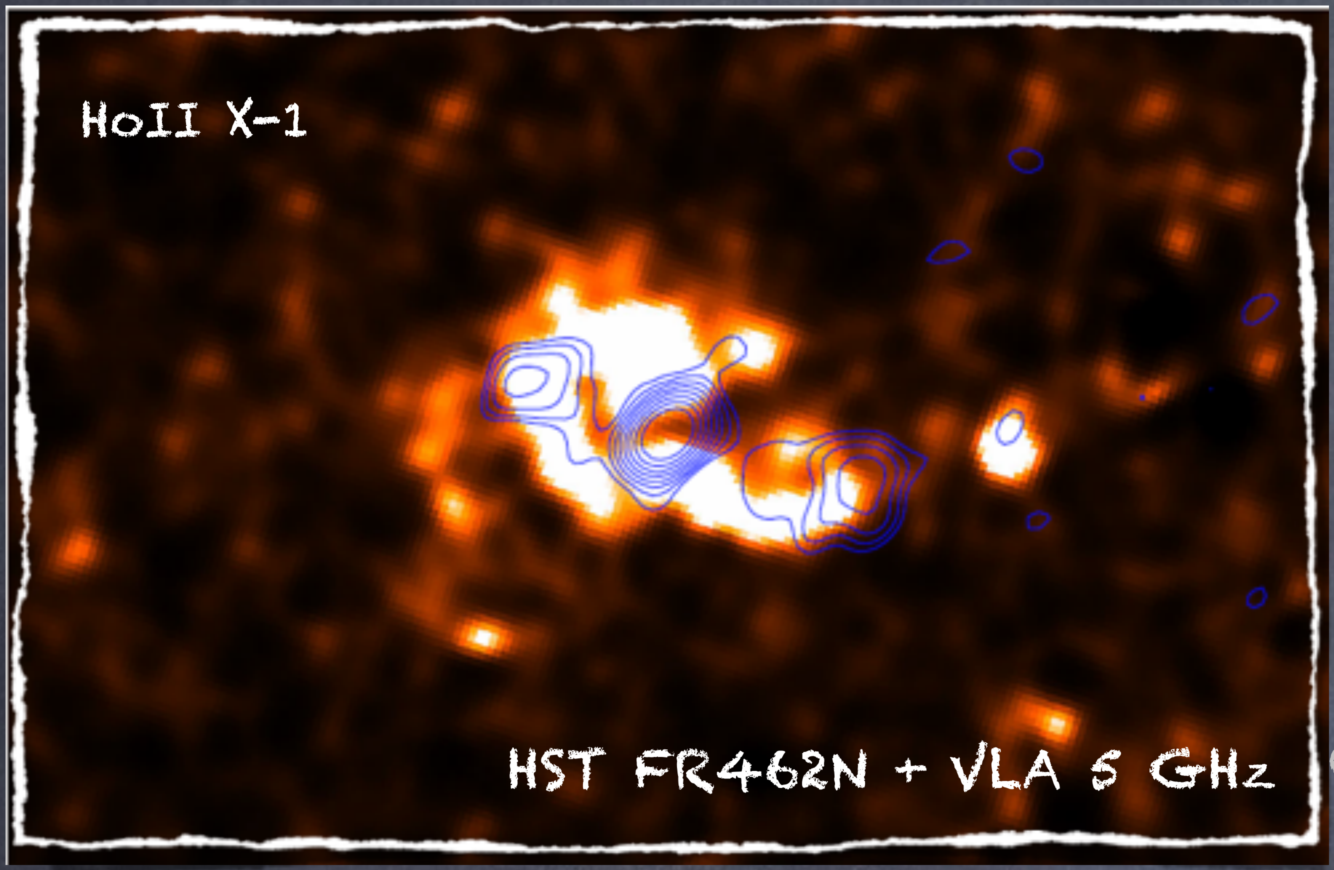
Radio nebulae

Inflated by jets or winds

Energy carried ~ 10^{49} - 10^{53} erg/s

(SS433 ~ 10^{46} erg/s)

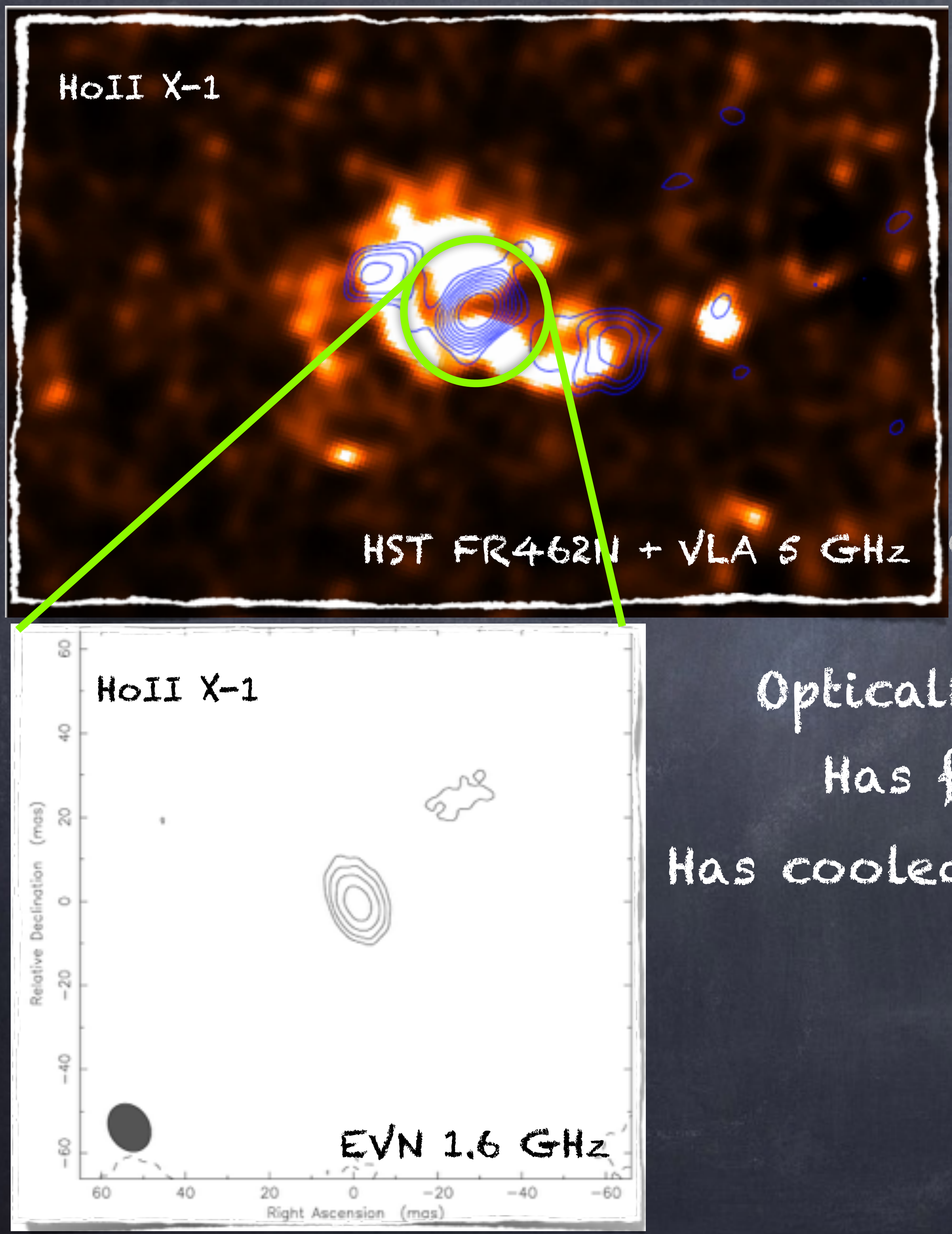
- Radio jets inside nebula



Radio bubble inflated by jet (although optical nebula produced by photoionization!)

Cseh et al. (2014, 2015)

- Radio jets inside nebula



Radio bubble inflated by jet (although optical nebula produced by photoionization!)

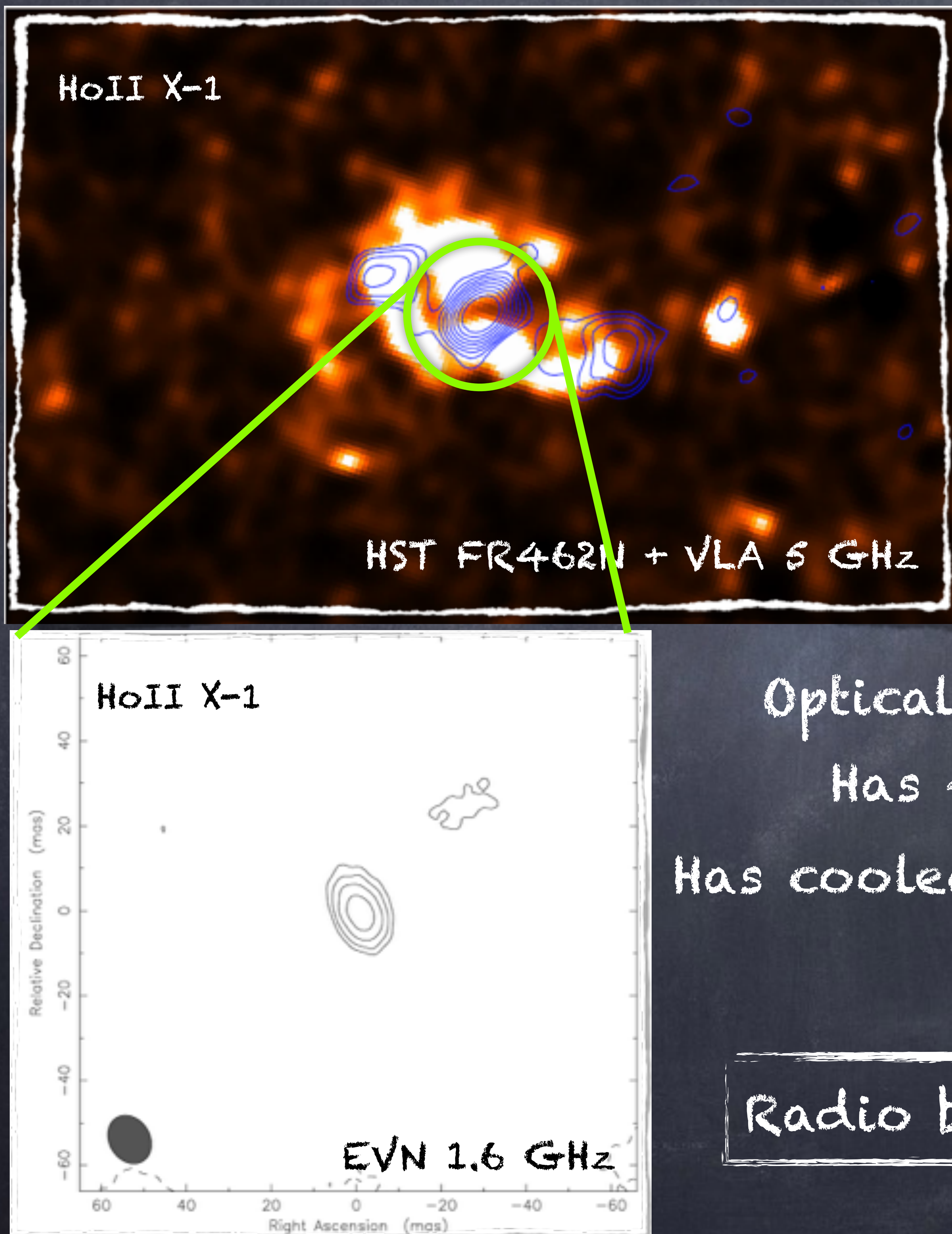
Cseh et al. (2014, 2015)

Optically thin synchrotron emission

Has faded factor ~ 7 in 1.5 yrs

Has cooled faster than outer components

- Radio jets inside nebula



Radio bubble inflated by jet (although optical nebula produced by photoionization!)

Cseh et al. (2014, 2015)

Optically thin synchrotron emission

Has faded factor ~ 7 in 1.5 yrs

Has cooled faster than outer components

⇩

Radio bubble inflated by jet EJECTA

- Radio flares

HLX-1

$L_X \sim 10^{42}$ erg/s

Periodic outbursts ~months

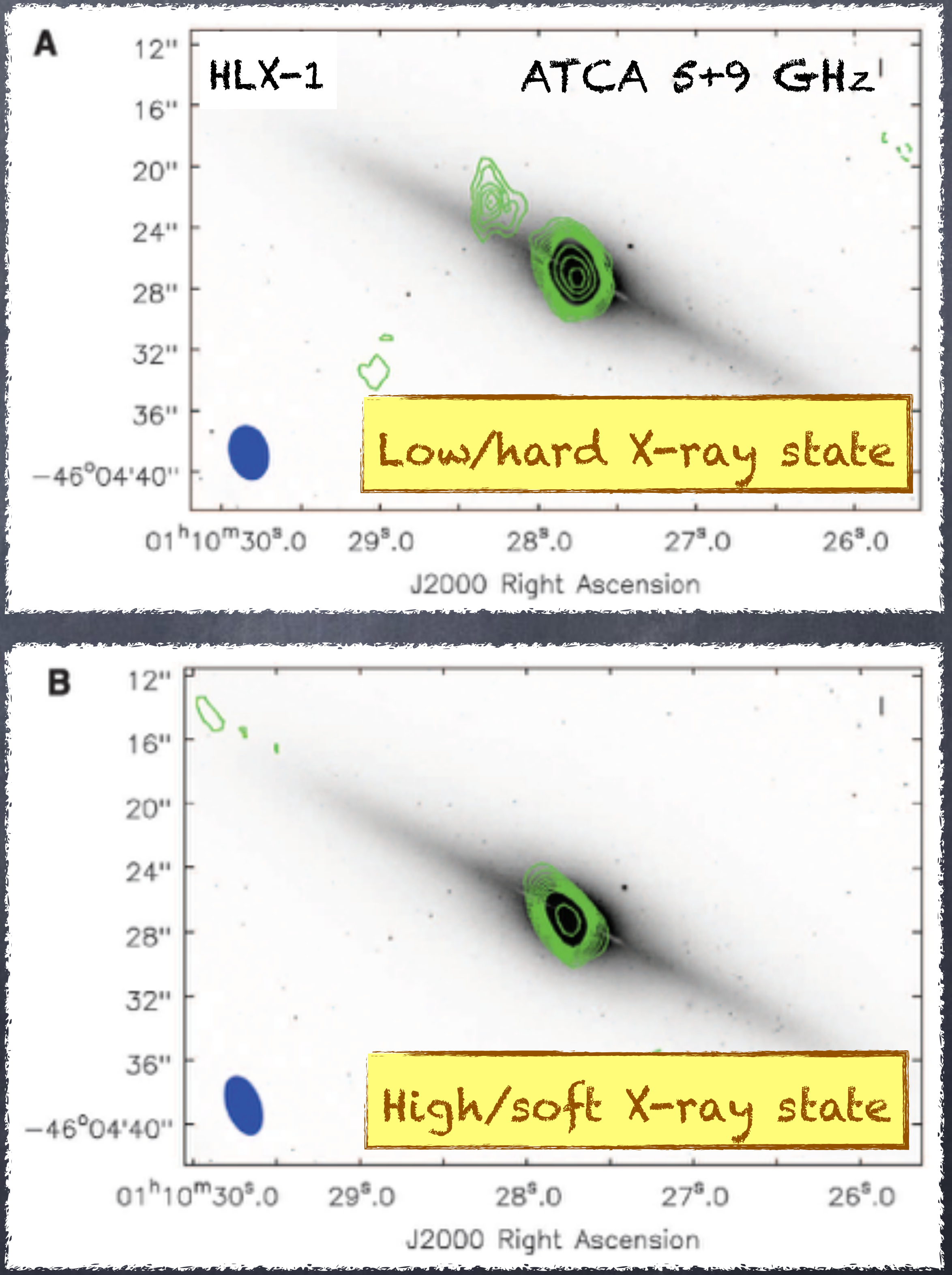
Spectral state transitions ~day

Transient jet radio emission follows X-ray spectral state transitions (as in Galactic XRBs!)

$M_{BH} \sim 10^4 - 10^5\ M_\odot$ ⇨ IMBH

Nucleus of stripped dwarf galaxy?

e.g., Farrell et al. (2009), Davis et al. (2011), Lasota (2011), Servillat et al. (2011), Godet et al. (2009, 2012, 2014), Yan et al. (2015), Cseh et al. (2015)



Webb et al. (2012)

XMMU J004243.6+412519 in M31

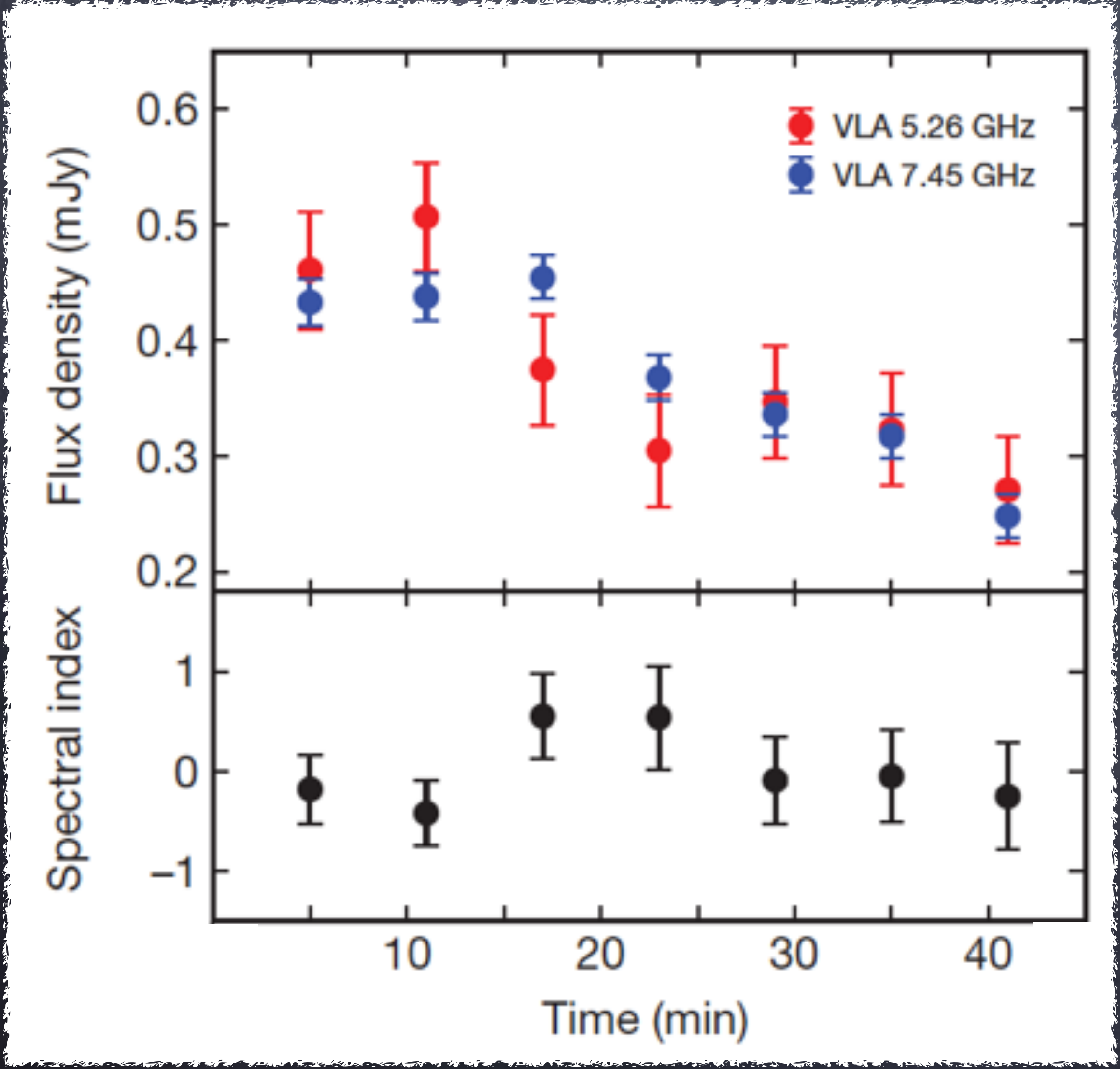
$L_X \sim 2 \times 10^{38}$ erg/s → sub-Eddington regime

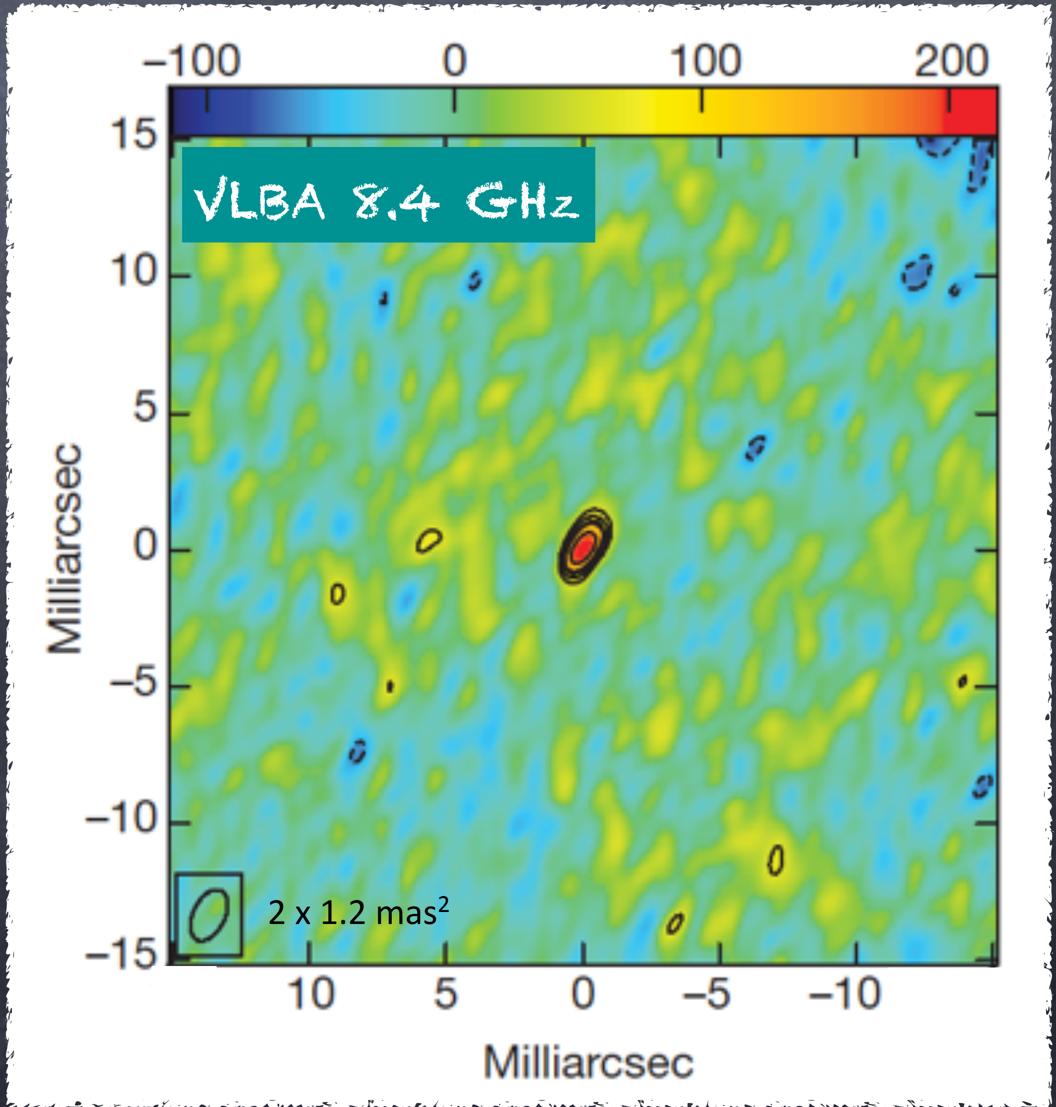
$L_X \sim 1.2 \times 10^{39}$ erg/s → ULX, super-Eddington regime

Radio flares, similar behavior as Galactic XRBs

Radio variability ~days & minutes → size ~5 AU

Middleton et al. (2013)





- Compact radio emission

NGC 5457 X-9

$L_X \sim 3 \times 10^{39}$ erg/s

Short- & long-term X-ray variability

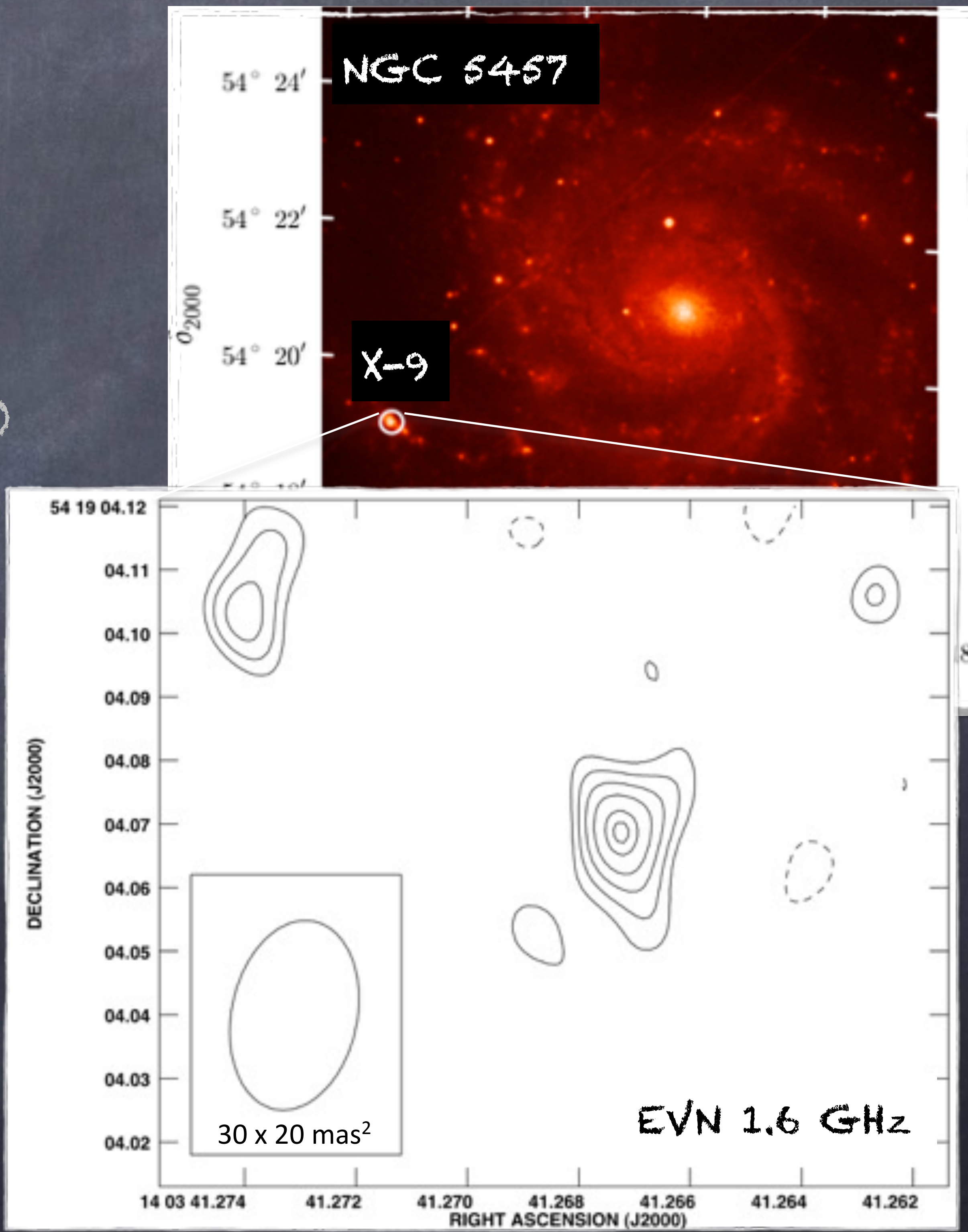
$\Gamma \sim 0.2 - 0.4$ or cool disc?

Jenkins et al. (2004, 2005)

Fundamental plane of BH accretion (if sub-Eddington):

⇩

IMBH



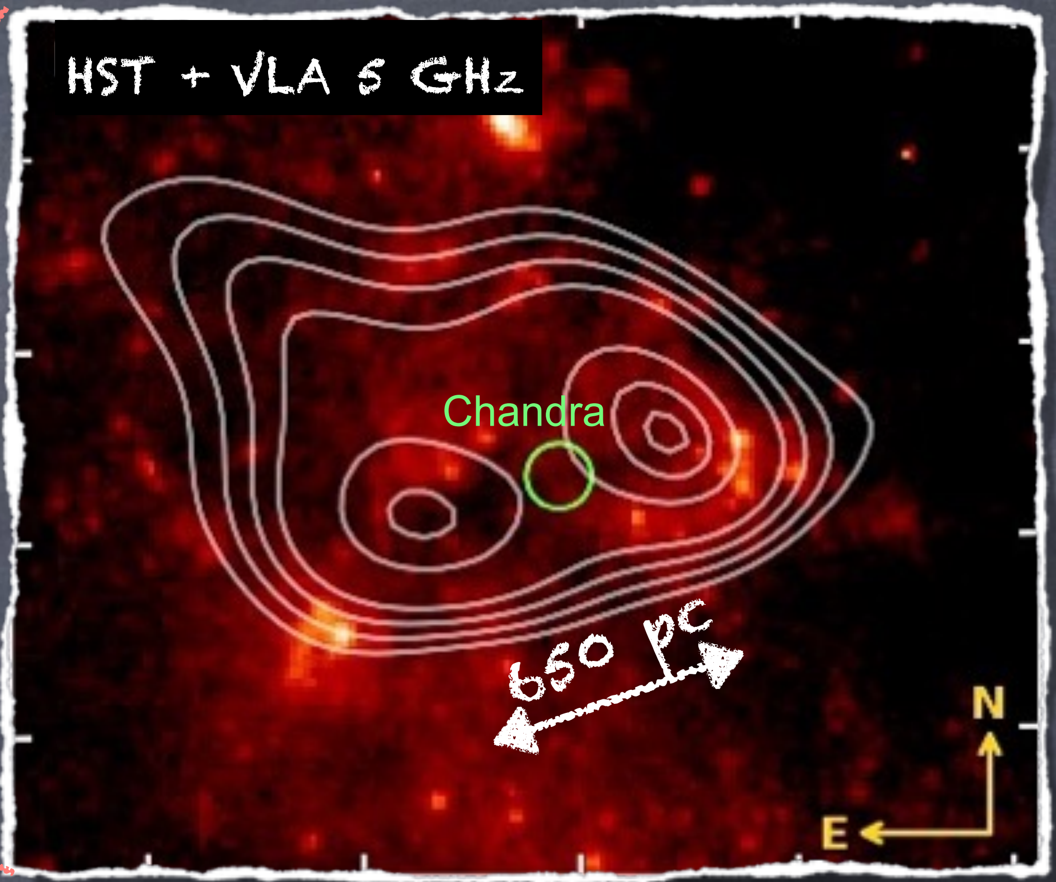
Mezcua et al. (2013a)

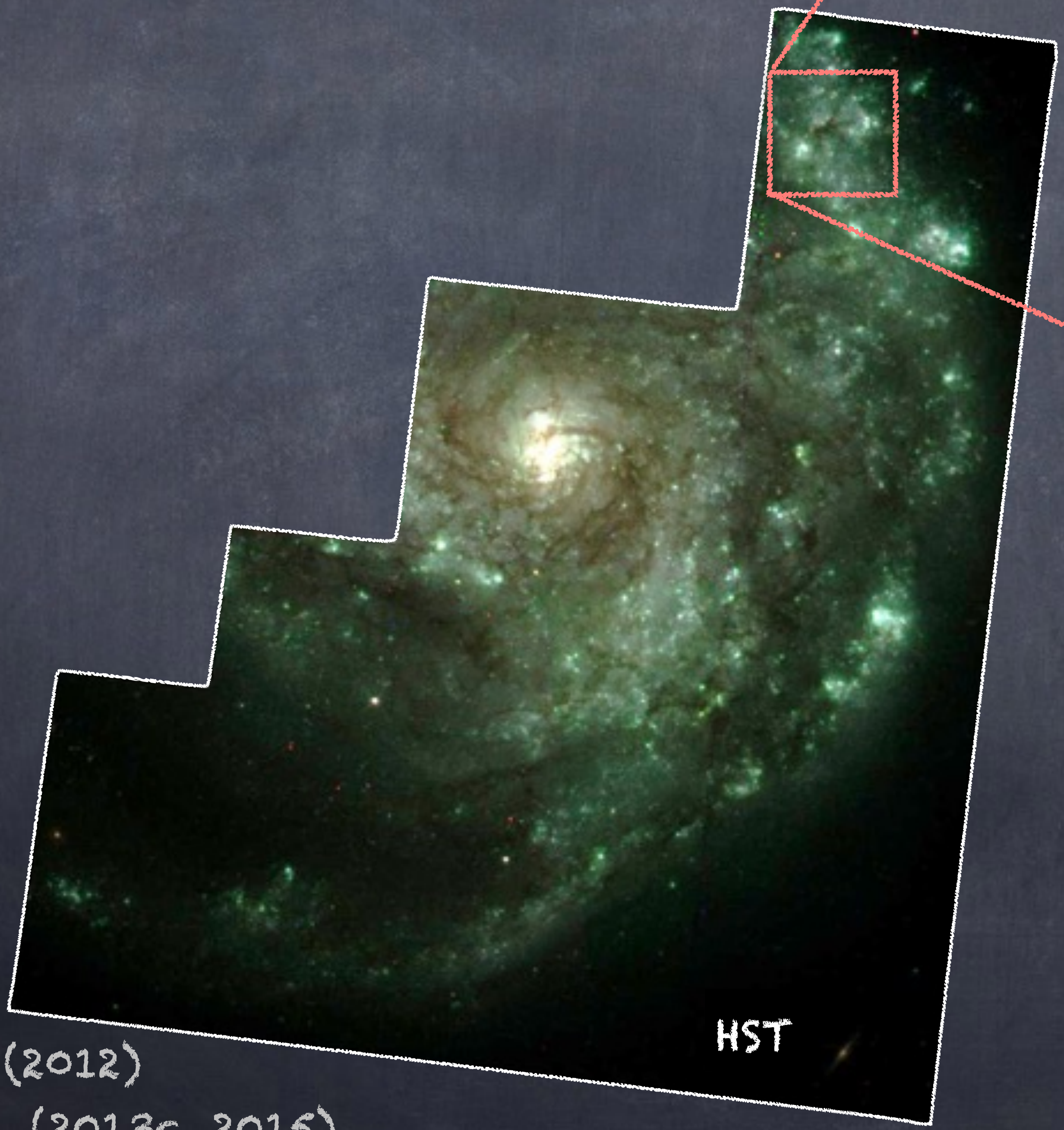
NGC 2276-3c

$L_X \sim 6 \times 10^{40}$ erg/s

Short-term X-ray variability

$\Gamma \sim 1.4$





Sutton et al. (2012)

Mezcua et al. (2013c, 2015)

NGC 2276-3c

$L_X \sim 6 \times 10^{40}$ erg/s

Short-term X-ray variability

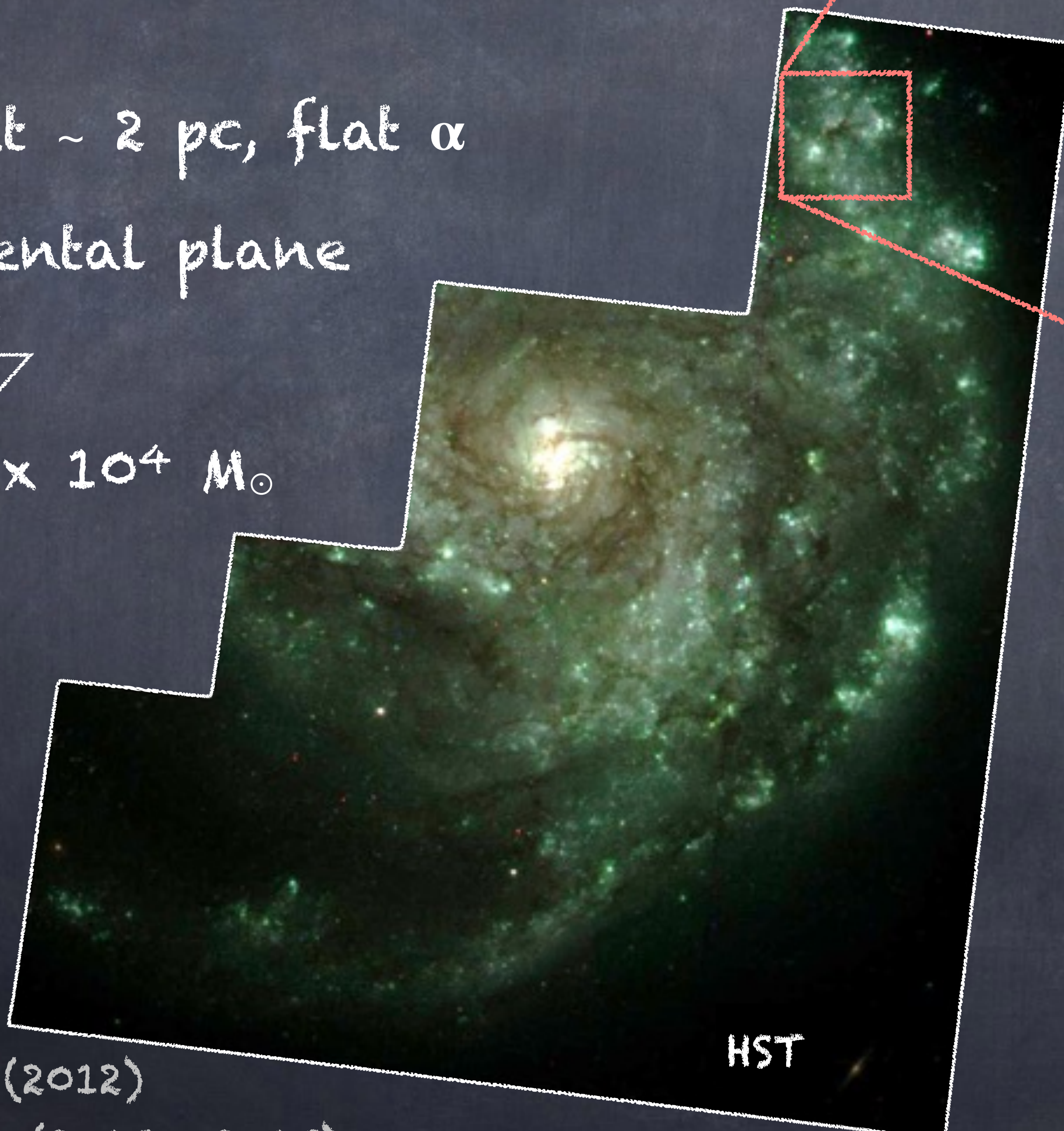
$\Gamma \sim 1.4$

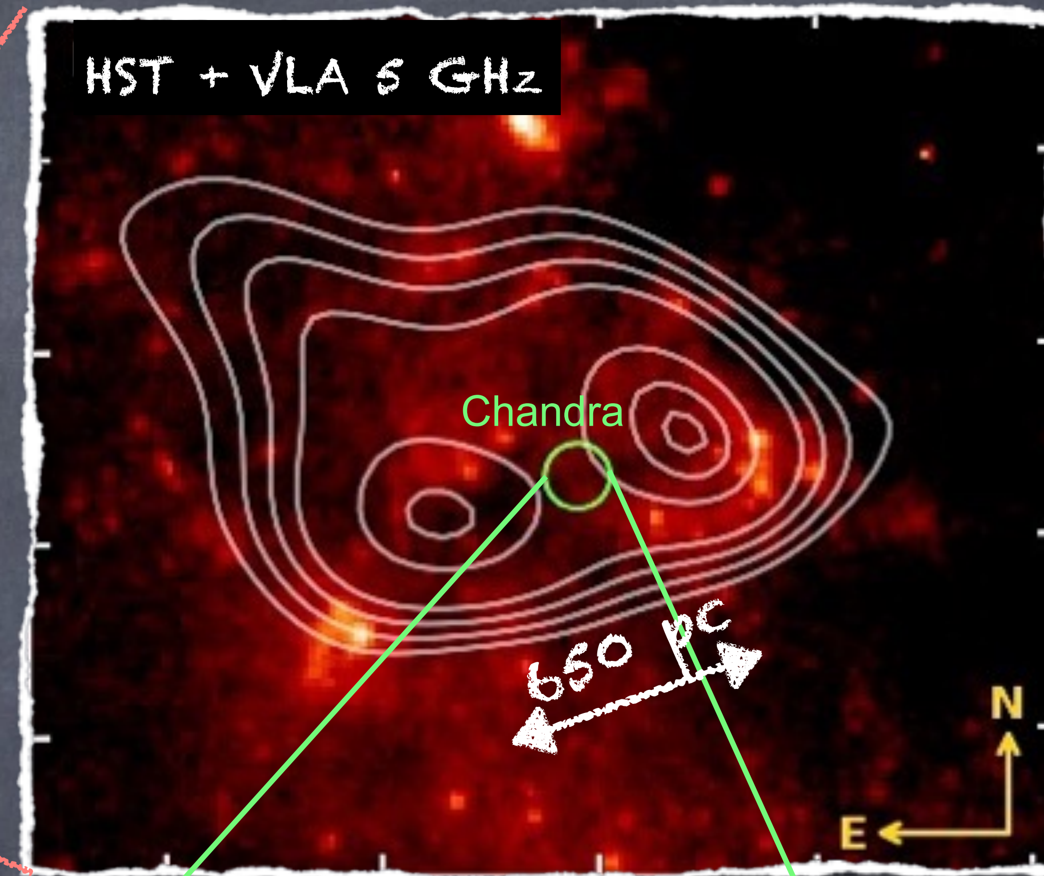
Radio jet ~ 2 pc, flat α

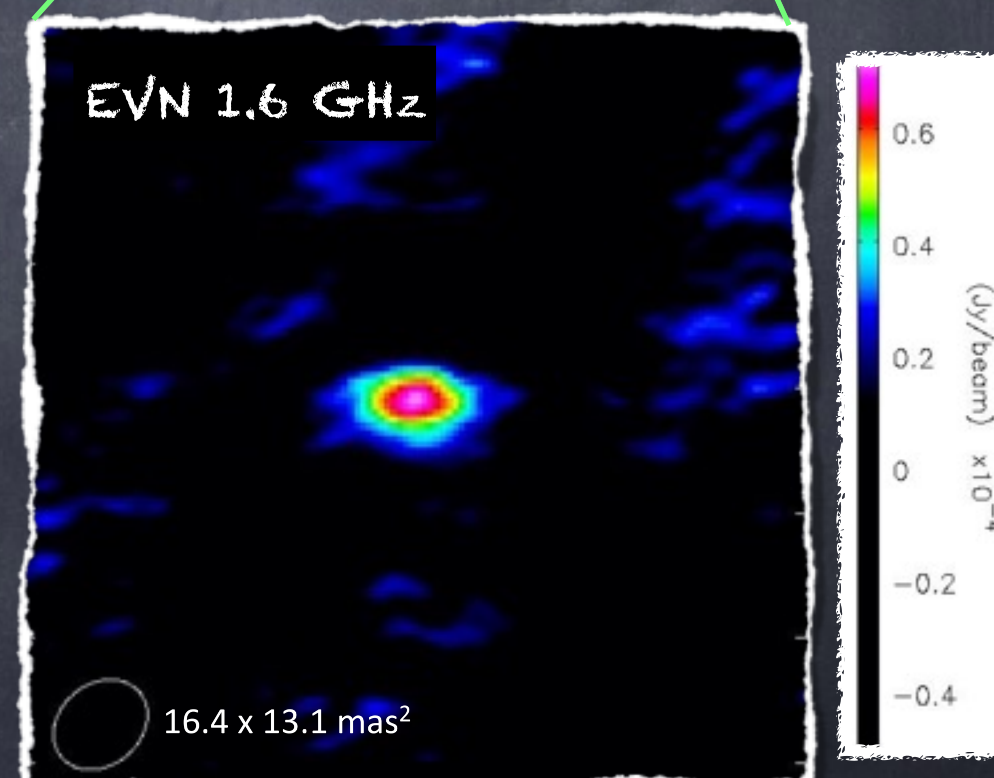
Fundamental plane

⇩

$M_{BH} \sim 5 \times 10^4\ M_\odot$







Sutton et al. (2012)
Mezcua et al. (2013c, 2015)

Summary

ULXs: mixed bag of objects

- X-rays: soft excess, high-energy cut-off
- Optical: dynamical mass measurements

⇒ stellar-mass BHs super-Eddington accretion

Summary

ULXs: mixed bag of objects

- X-rays: soft excess, high-energy cut-off
- Optical: dynamical mass measurements

⇨ stellar-mass BHs super-Eddington accretion

- X-rays: high-frequency QPOs
- Radio: jets, fundamental plane

⇨ IMBHs

Summary

ULXs: mixed bag of objects

- X-rays: soft excess, high-energy cut-off
- Optical: dynamical mass measurements

⇒ stellar-mass BHs super-Eddington accretion

- X-rays: high-frequency QPOs
- Radio: jets, fundamental plane

⇒ IMBHs

- X-rays: pulsations ⇒ neutron star

Summary

ULXs: mixed bag of objects

- X-rays: soft excess, high-energy cut-off
- Optical: dynamical mass measurements

⇒ stellar-mass BHs super-Eddington accretion

- X-rays: high-frequency QPOs
- Radio: jets, fundamental plane

⇒ IMBHs

- X-rays: pulsations ⇒ neutron star

- Optical/IR spectroscopy: background AGN?
- Radio/optical: environment, nebulae
- Radio/X-ray monitoring: similarities with XRBs

THANK YOU!!

www.astro.umontreal.ca/~marmezcua/

@marmezcua_astro