The X-ray properties of Compact Symmetric Objects

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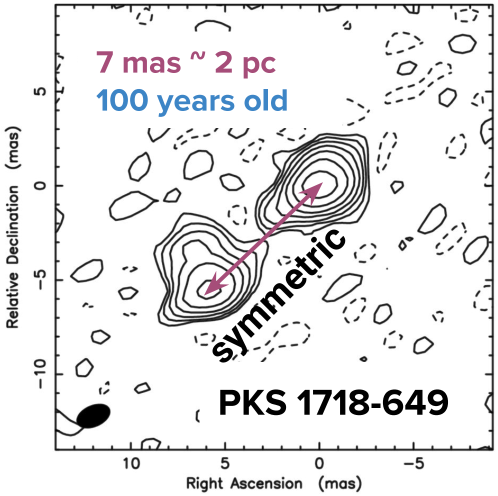
Why study compact radio jets?

AGN / galaxy feedback process

- conditions in a galactic center at the time of radio jet lunch and initial expansion
- impact of a young expanding jet on the innermost regions of its hosts galaxy

Tingay, de Kool (2003), 22 GHz VLBI



vs.

Cygnus A
Hot spot separation
300,000 light years

X-ray
Optical
Radio

e.g. Phillips & Mutel 1982, Pearson & Readhead 1988, Wilkinson+ 1994, O'Dea 1998, Owsianik+ 1998, Stanghellini 2003, Polatidis & Conway 2003, Labiano+ 2007, An & Baan 2012, Edwards & Tingay 2017, Callingham+ 2017

Compact radio jets in the X-ray band

- X-rays are an important puzzle in the broadband radio-to-γ-ray view of AGN activity
- What are the origin of the X-ray emission in young radio sources and implications for the radio source evolution and AGN feedback?
    - AGN disk/corona -- accretion
    - Inner jet/core -- ejection
    - Inverse Compton scattering of soft photons in radio lobes -- ejection
    - Hot gas shocked by the expanding radio source -- jet/ISM interactions
- ISM diagnostics through X-ray spectroscopy
    - Temperature of any soft thermal components detected in the spectra
    - X-ray absorbing column -- an estimator of the gas mass available to fuel an AGN
- **Reminder:** spatial resolution of X-ray images taken with Chandra
  1” = 2 kpc at z=0.1 and 200 pc at z=0.01

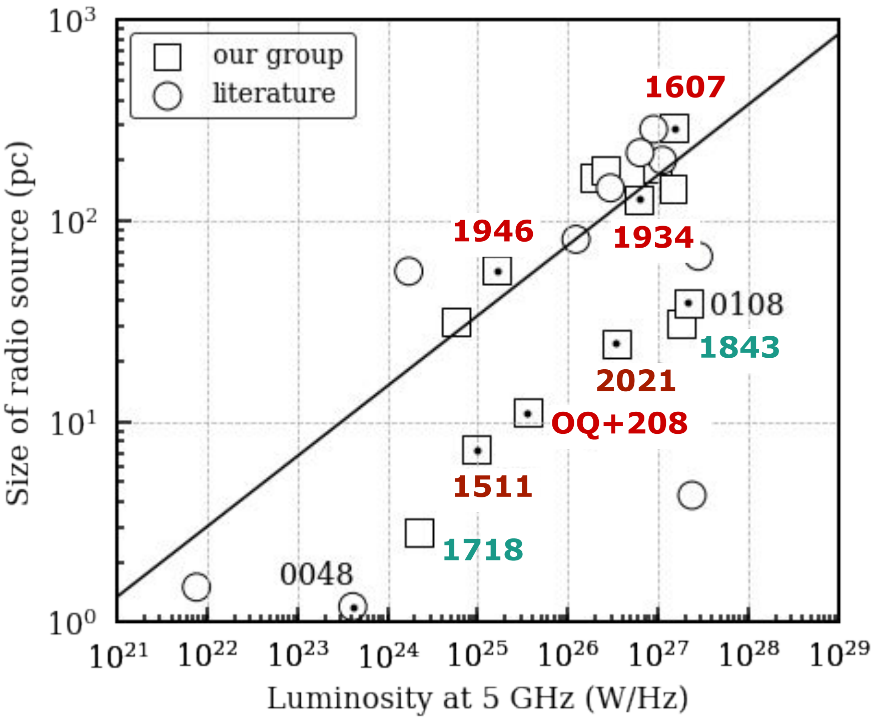
Highlights

- X-ray properties of Compact Symmetric Objects:
    - X-ray absorption properties, the relation between the X-ray absorbing column in CSOs and their radio size and radio luminosity
    - The first observations of CSOs at hard X-ray energies above 10 keV with NuSTAR
    - Compact radio sources at high redshift, $4.5 < z < 5$
- Broadband perspective and radio-to-X/gamma-ray modeling of CSO spectral energy distribution

CSO sample

X-ray observations:
O'Dea et al. 2000
Risaliti et al. 2003
Guainazzi et al. 2006
Vink et al. 2006
Green et al. 2009
Tengstrand et al. 2009
Young et al. 2009
Younes et al. 2010
Singh et al. 2011
Siemiginowska et al. 2016
Beuchert et al. 2018
Sobolewska et al. 2019a
Sobolewska et al. 2019b

Radio data:
An & Baan 2012
Tremblay et al. 2016



General properties of the sample:

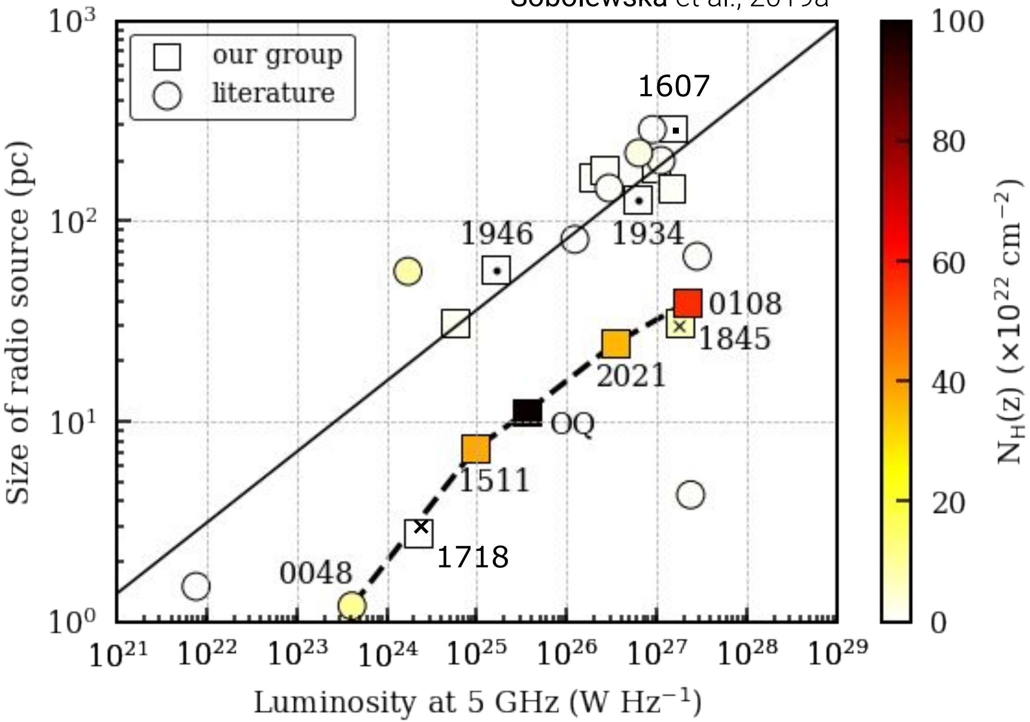
- Low redshift, $z < 0.6$ except for one source with $z = 1.6$
- A range of X-ray photon indices, Gamma as low as 1
- Relatively faint in X-rays, F(2-10 keV) = 10^{-14} - 10^{-13} erg s^{-1} cm^{-2}

We obtained deep X-ray observations of the labeled CSOs

- $N_H(z) > 10^{23}$ cm^{-2} reported in several sources

CSO environment probed through X-ray absorption

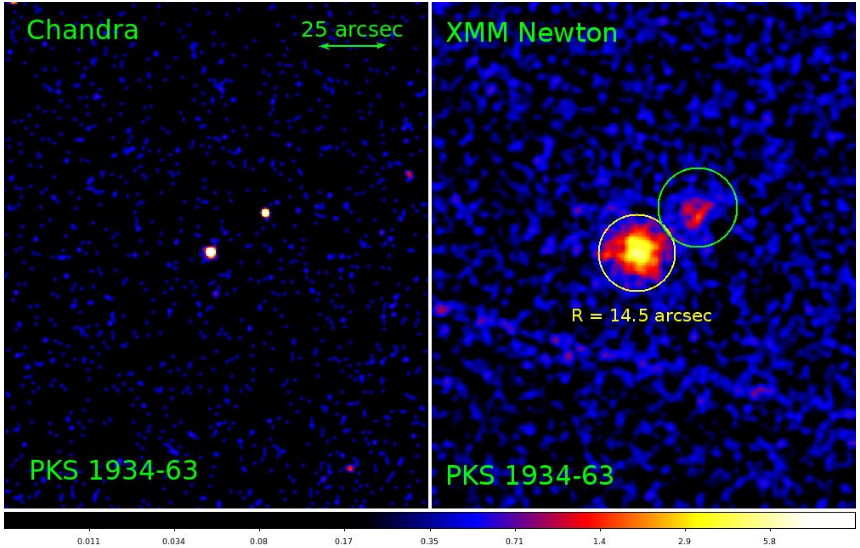
Sobolewska et al., 2019a

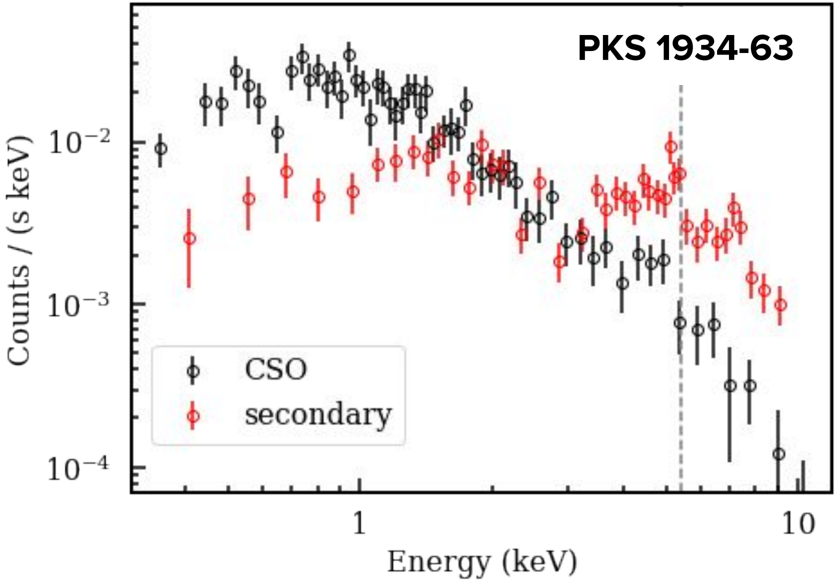


- **X-ray absorbed sources have**
  - **smaller radio size** than X-ray unabsorbed sources with the same radio power, OR
  - **larger radio power** than X-ray unabsorbed sources with the same radio size

- **So far, no detection of NH > 10^{23} cm^{-2} in CSOs with radio size exceeding ~ 50 pc**
  Implications:
  - Size of the region responsible for the X-ray obscuration?
  - Torus destruction by an expanding jet?

Resolved contamination from a serendipitous X-ray source

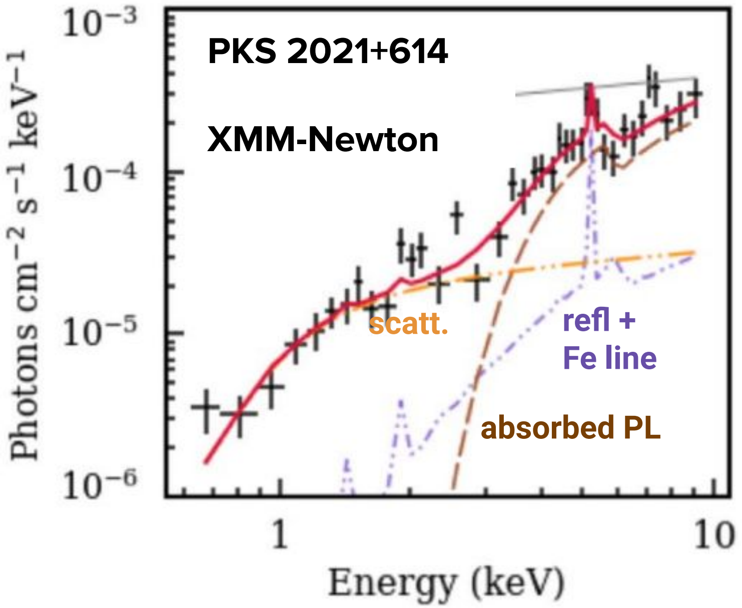


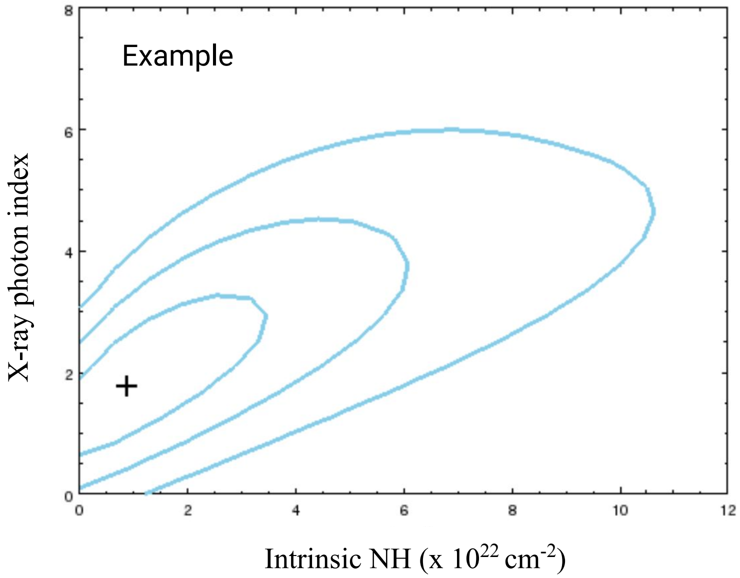


PKS 1934-63, z = 0.181, LS ~ 130 pc

- Serendipitous source seen in the Chandra and XMM images, contaminated the Beppo-SAX observation (Risaliti et al. 2003)
- Iron line emission comes from the extraction region of the secondary source (Sobolewska et al. 2019a)

Resolved degeneracy between the X-ray photon index and NH



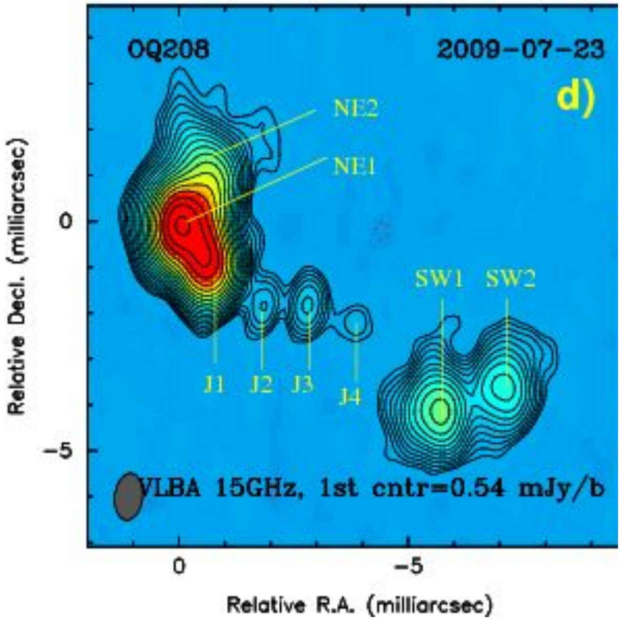


PKS 2021+614, z = 0.227, LS ~ 25 pc

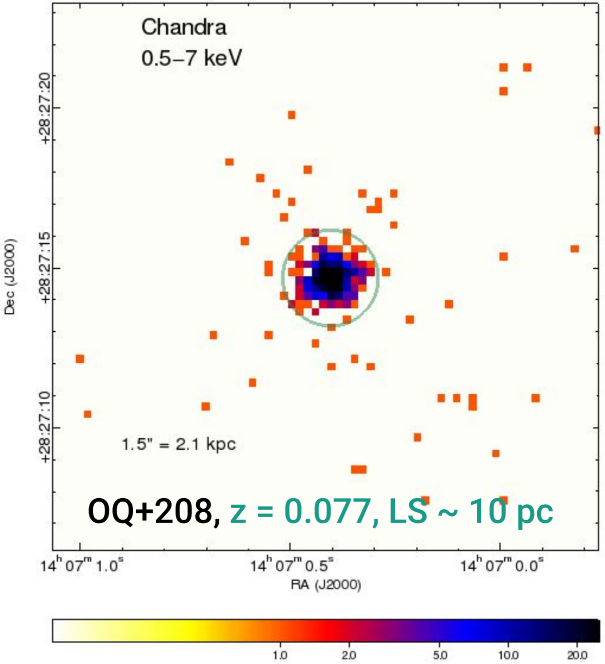
- X-ray absorbed CSO candidate based on Chandra observation (Siemiginowska et al. 2016)
- **XMM** confirmed **X-ray absorption with NH ~ 4 x 10^{23} cm^{-2}** in this CSO (Sobolewska et al. 2019a)

CSOs in hard X-rays. First observations above 10 keV with NuSTAR

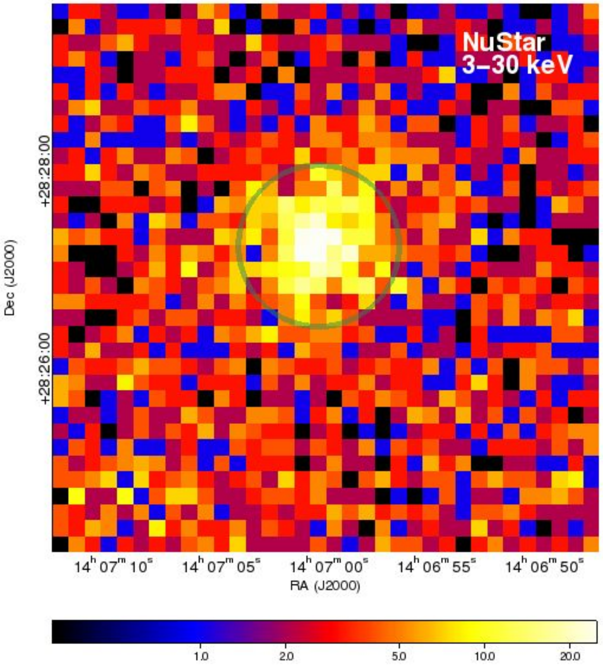
VLBA, miliarcsecs, Wu+ 2003



Chandra, 0.5 - 7 keV, **1.5 arcsec**
Siemiginowska et al. 2016



NuSTAR, 3 - 30 keV, **30 arcsec**
Sobolewska et al. 2019b



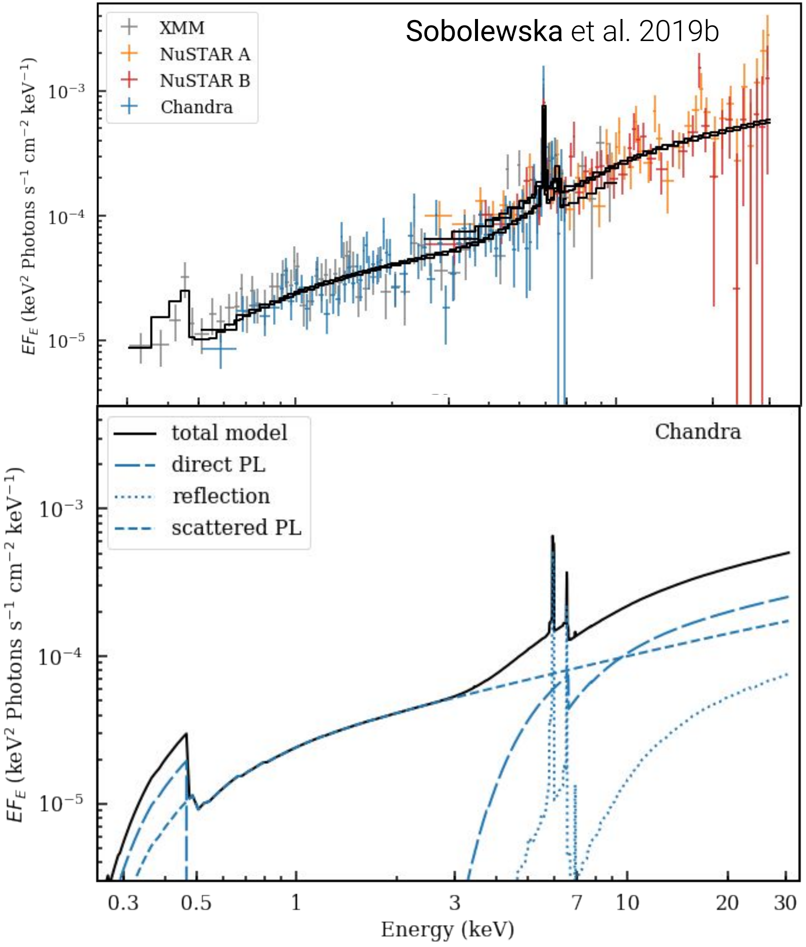
CSOs in hard X-rays

First observations above 10 keV with NuSTAR

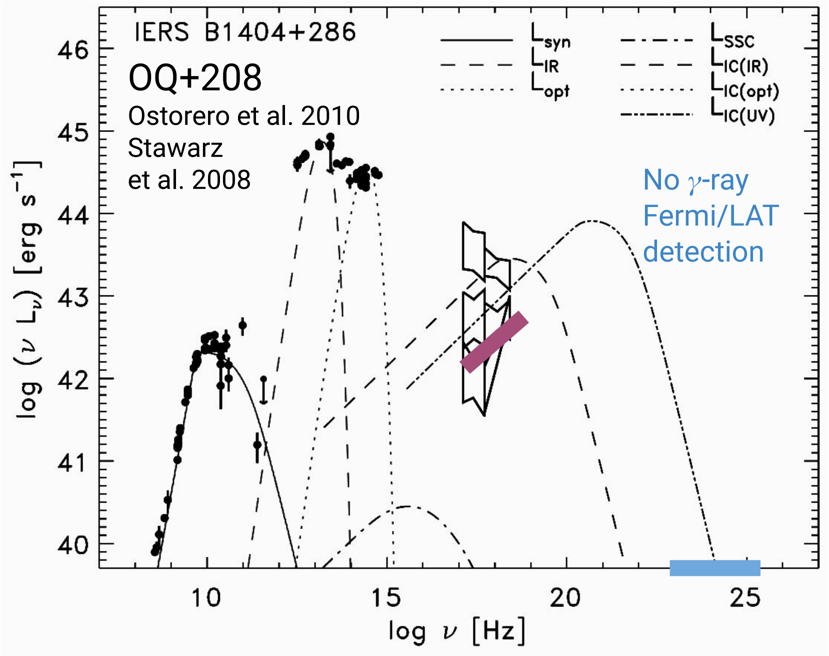
Primary X-ray emission visible at > 10 keV if intrinsic $N_H(z) < 10^{25}$ cm^{-2}

A **power-law emission** modified due to interactions (absorption, reflection, scattering) with a **toroidally distributed, possibly porous, cold matter** (model of Balokovic et al. 2018).

- Intrinsic line-of-sight absorption $N_H(z) = 10^{23}$ cm^{-2}
- Column density of the torus $N_{H,\,torus}(z) = 10^{24}$ cm^{-2}
- X-ray luminosity L (0.3-30 keV) = 10^{43} erg s^{-1}
- Photon index = 1.45 ± 0.10
  (X-ray corona? jet? IC in radio lobes?)



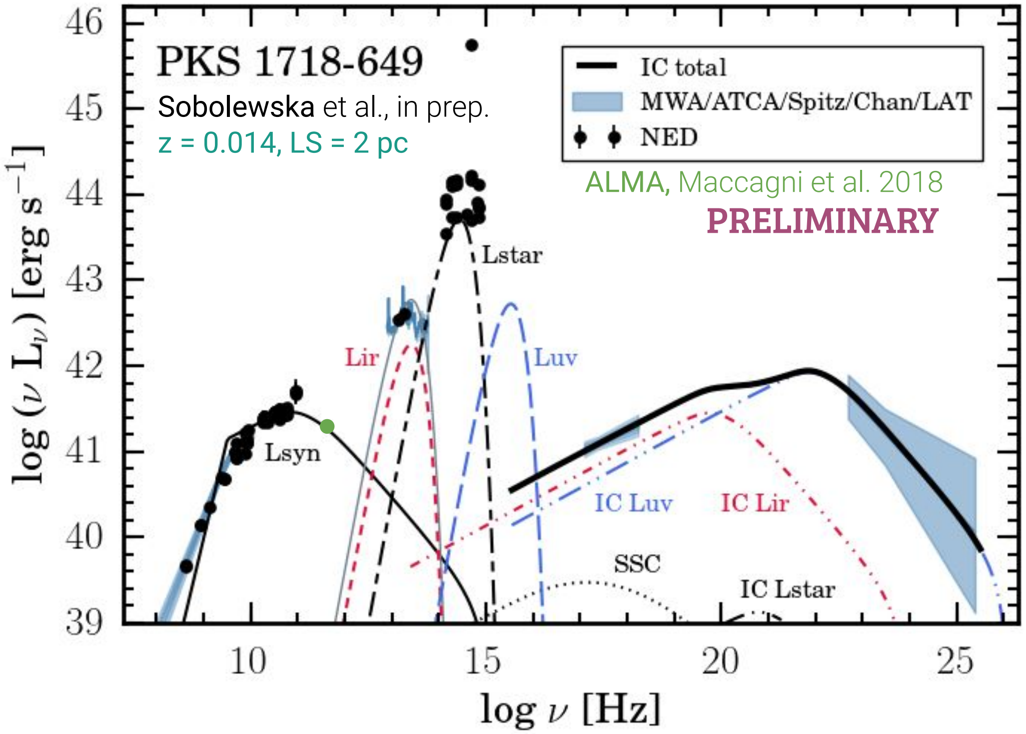
Broadband modeling. Radio to X/γ-ray SED

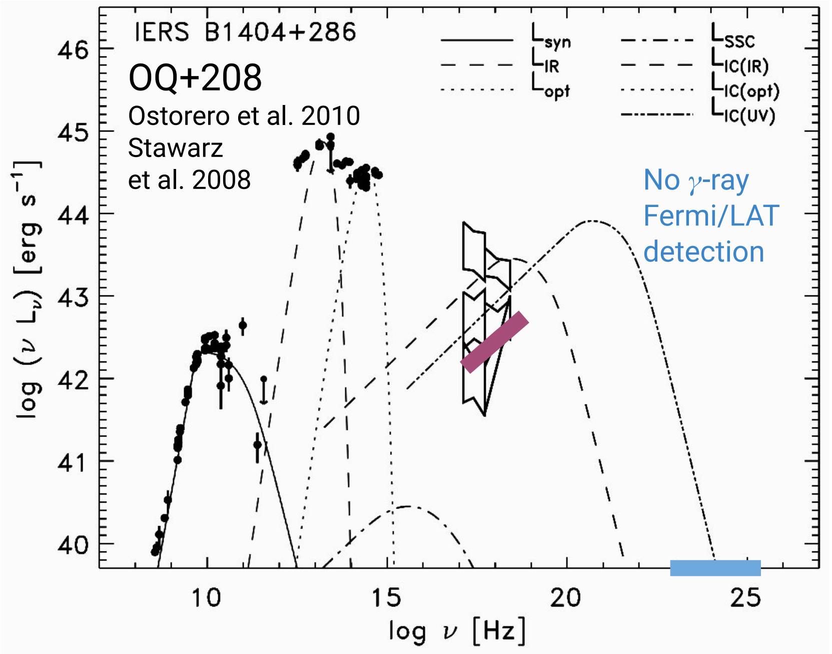


X-ray constraints:
XMM only (Guainazzi et al. 2004)
Chandra/XMM/NuSTAR (Sobolewska et al. 2019b)

Broadband modeling. Radio to X/γ-ray SED

MWA/ATCA, Tingay et al. 2015; Spitzer, Willett et al. 2010; Opt/UV, Filippenko 1985;
Chandra, Siemiginowska et al.2016; Fermi/LAT, Migliori et al. 2016





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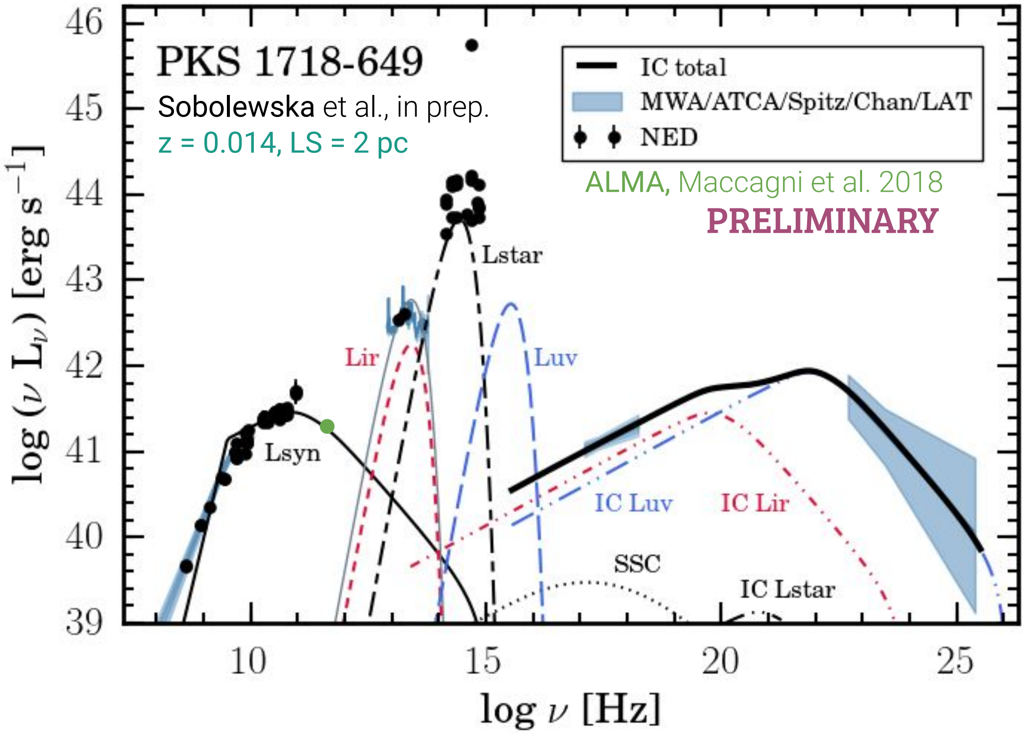
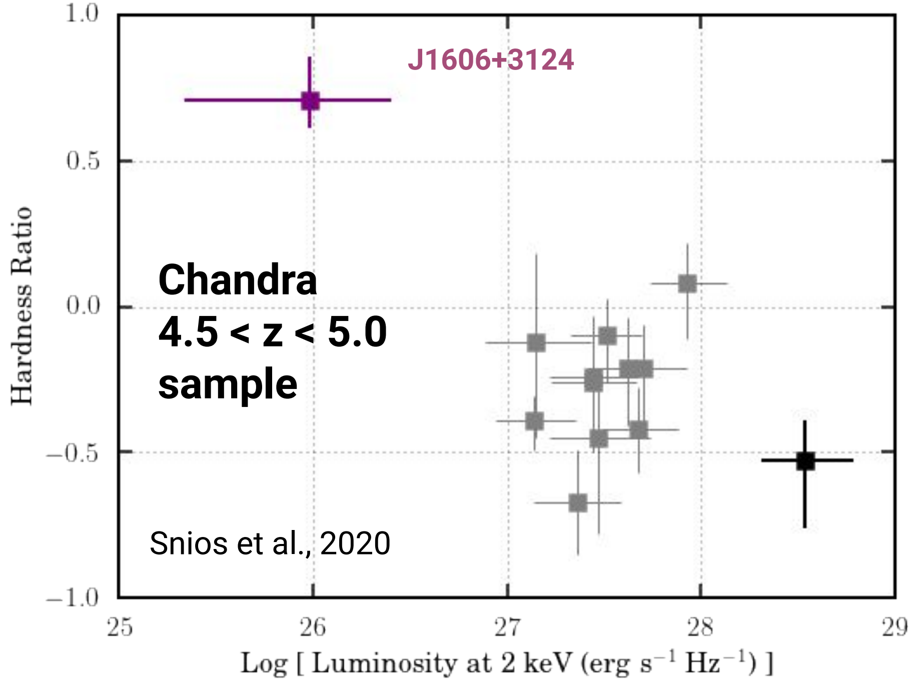


n = 0.3 cm^{-3}
s1 = 2.4, s2 = 3.3
γ_b = 2 m_p / m_e
Lj = 2.3 x 10^{43} erg s^{-1}

- Broken power law electron energy distr.
- X-rays - IC of IR photons (torus)
- γ-rays - IC of UV photons (disk)

Compact radio sources across redshift range



see also eROSITA discoveries:
Medvedev et al. 2020; Khorunzhev et al. 2021

- X-ray observations of compact high-z radio sources with steep or peaked spectra at MHz frequencies (Coppejans et al. 2016, 2017 catalog of compact radio quasars at z > 4.5)
- Compton Thick candidate (based on the high hardness ratio) at redshift z = 4.56
- Rest-frame 5 GHz flux density **466 mJy** (Coppejans et al. 2016)
- Rest-frame turnover frequency **14 GHz** (Coppejans et al. 2016)
- Turnover frequency vs. Linear size relation implies **LS ~ 10 pc**

CSO sample

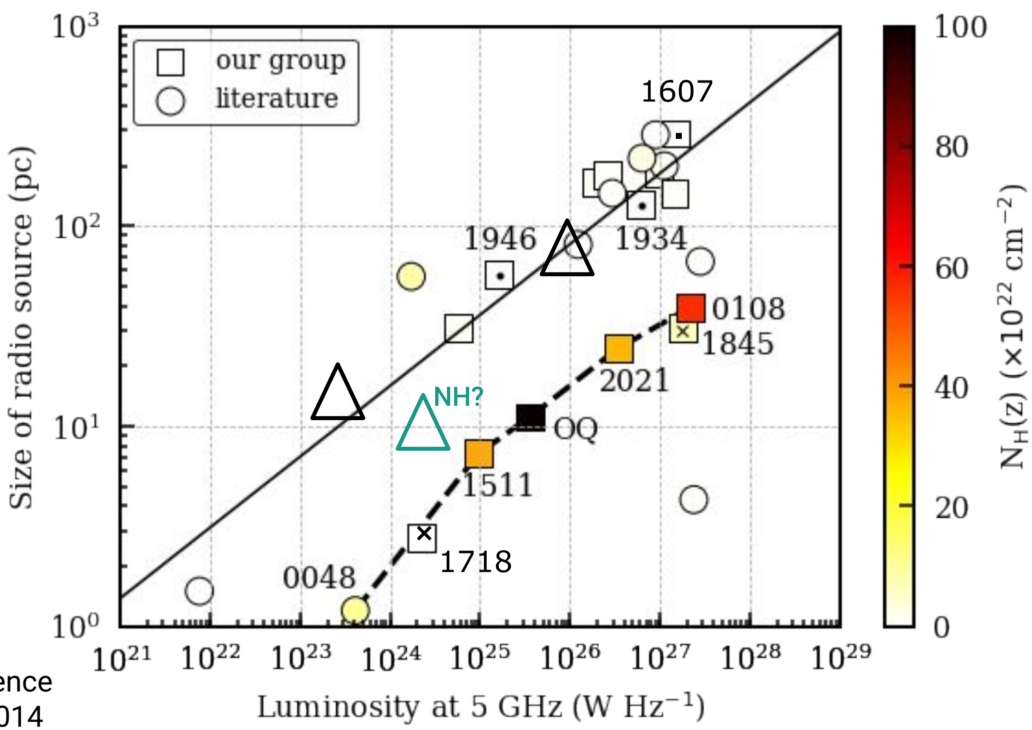
LS > 1 kpc?

X-ray observations:
Siemiginowska et al 2008
Hardcastle et al. 2012
Kunert-Bajraszewska et al. 2014
O'Dea et al. 2017

△ New γ-ray detections

TXS 0128+554, LS = 12 pc
PMN J1603-4904, LS = 56 pc
NGC 3894, LS = 10 pc NH?

Principe et al. 2020, this conference
Lister et al. 2020, Muller et al. 2014



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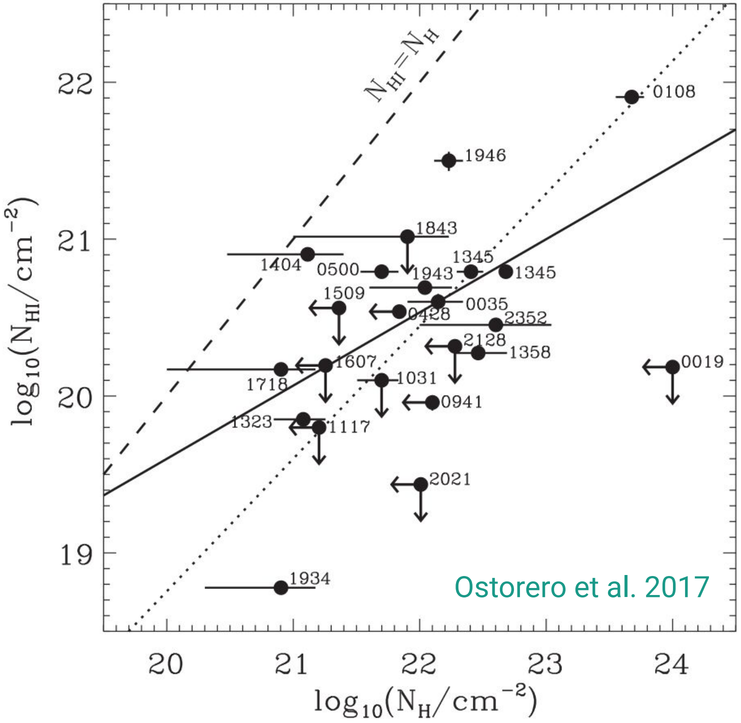
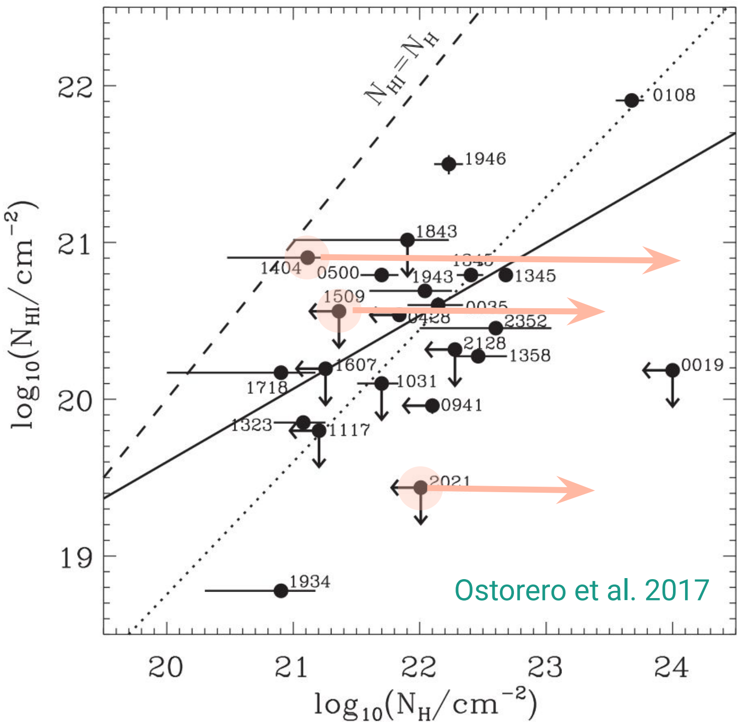
Siemiginowska et al. 2016
Beuchert et al. 2018
Krauss et al. 2018
Sobolewska et al. 2019a
Sobolewska et al. 2019b
Lister et al. 2020

Relation between NHI (radio) and NH (X-rays)



- NHI (radio) provides the column density of neutral hydrogen
- NH (X-rays) provides the total equivalent hydrogen column density: neutral, partially ionised, molecular, dust
- Are the X-ray and radio absorbers co-spatial?
- The correlations has a large spread
- The assumption about the ratio between the spin temperature of the absorbing gas and its covering factor needed to derive NHI can contribute to this spread
- We found evidence that the the X-ray obscuring torus is porous rather than uniform in at least one CSO with high NH (Sobolewska et al. 2019b)

Relation between NHI (radio) and NH (X-rays)



- X-ray NH measurements as an estimator of the mass of gas residing in the galactic center, available for triggering and fueling an AGN
- X-ray derived gas mass can be then compared with other estimators

NH (X-ray)	Radius	The gas mass
4×10^{23} cm^{-2}	1 kpc	10^{10} Msun
4×10^{23} cm^{-2}	50 pc	2×10^{7} Msun
1×10^{21} cm^{-2}	1 kpc	2×10^{7} Msun

Summary and future directions

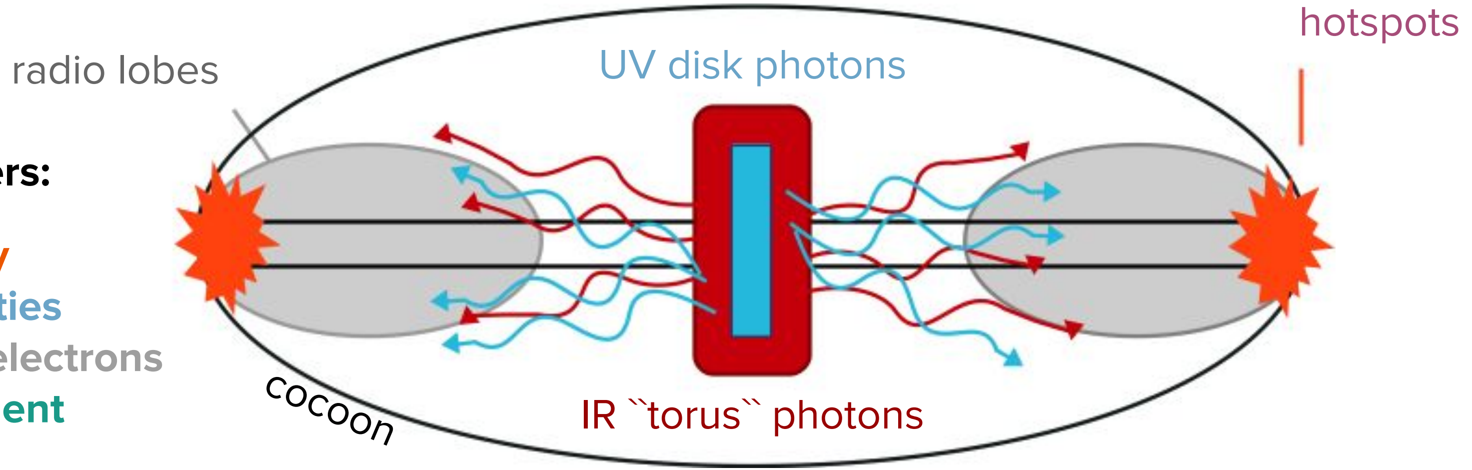
The X-ray properties of Compact Symmetric Objects

- **X-ray absorbed/unabsorbed dichotomy** of CSO jets, needs to be confirmed in a large sample
  - difference in radio size for the same radio luminosity at 5 GHz -- **confinement?**
  - difference in radio L for the same radio size -- **density of the environment? enhanced jet power?**
- **First detections** of CSOs in **hard X-ray band** (NuSTAR), and in **gamma-rays** (Fermi/LAT).
- **Broadband modeling. IC processes in young radio lobes** appear to **overestimate** the X-ray emission in two CSOs and **underestimate** the gamma-ray emission in one CSO. **Inner jet/core in gamma-rays? X-ray corona (accretion) plus jet (ejection) in X-rays?**
- **New compact radio jet candidates** identified in the radio surveys. **X-ray follow-ups needed**
- High-z compact radio sources are being found and observed X-rays (Snios et al. 2020; eROSITA, Medvedev et al. 2020, Khorunzhev et al. 2021)
- **Compare radio/X-ray properties of CSOs and CSS** with sizes > 1kpc

Expanding radio lobes. The site of X/γ-ray production?

Parameters:

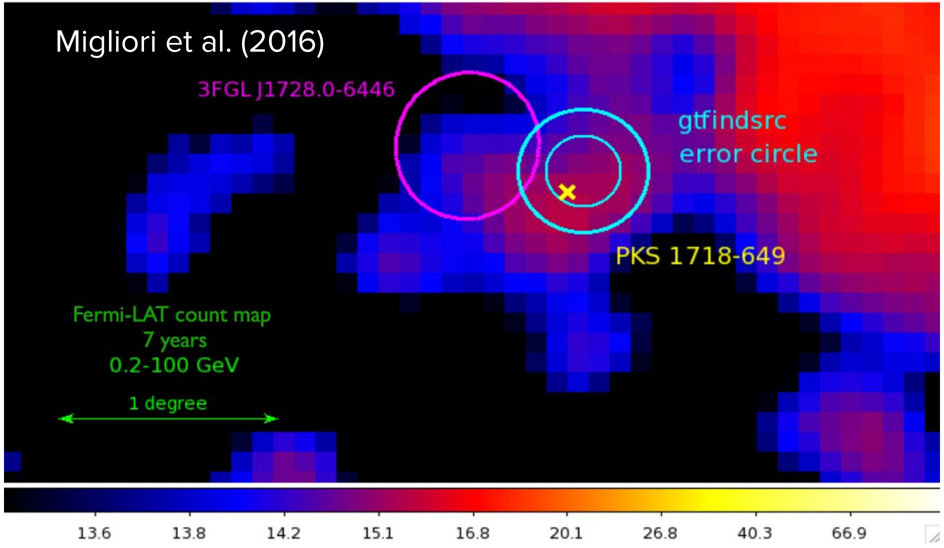
Geometry
Luminosities
Injected electrons
Environment



Model framework (Begelman & Cioffi 1989; Stawarz et al. 2008; Ostorero et al. 2010)

- Follow the evolution of ultrarelativistic electrons injected from terminal jet hot spots to the expanding lobes
- Account for appropriate adiabatic and radiative energy losses
- Electrons Inverse Compton up-scatter the soft photon fields

CSO detections in the γ-ray band

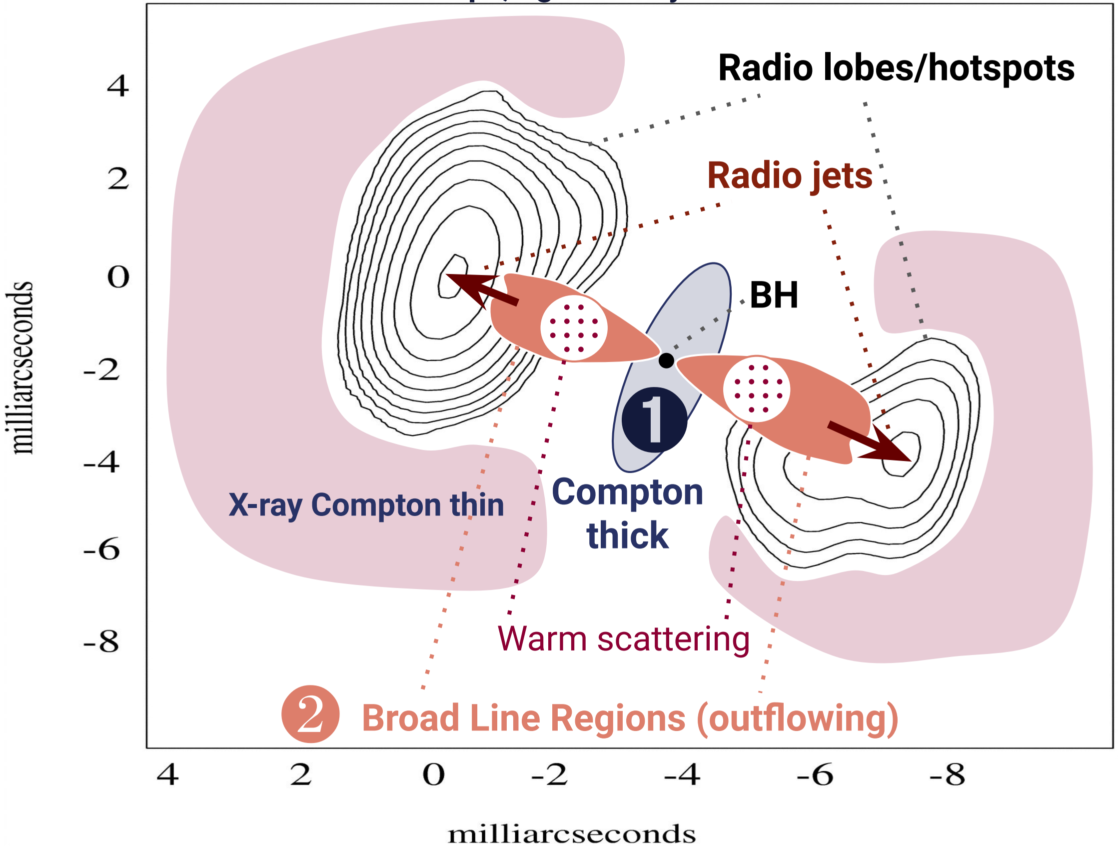


PKS 1718-649 (Migliori et al. 2016)
TXS 0128+554 (Lister et al. 2020)
NGC 3894 (Principe et al. 2020 and talk this morning)
PMN J1603-4904 (Muller et al. 2016)

- The γ-ray emission from 1718 and NGC 3894 much stronger than the expected emission for the ISM component alone (Kosmaczewski et al. 2020)
- More compact radio jets should be detected in the γ-ray band in the future
  - Longer accumulation of the LAT data
  - Renewed inner jet activity

- The radio lobes model **appears to overpredict the observed X-ray flux** in PKS 1718-649, OQ+208 (in preparation)
- The model **underpredicts the γ-ray flux** observed by Fermi-LAT in TXS 0128+554 (Lister et al. 2020).

Radio source size = 10pc, age = 250 years



Torus in OQ+208

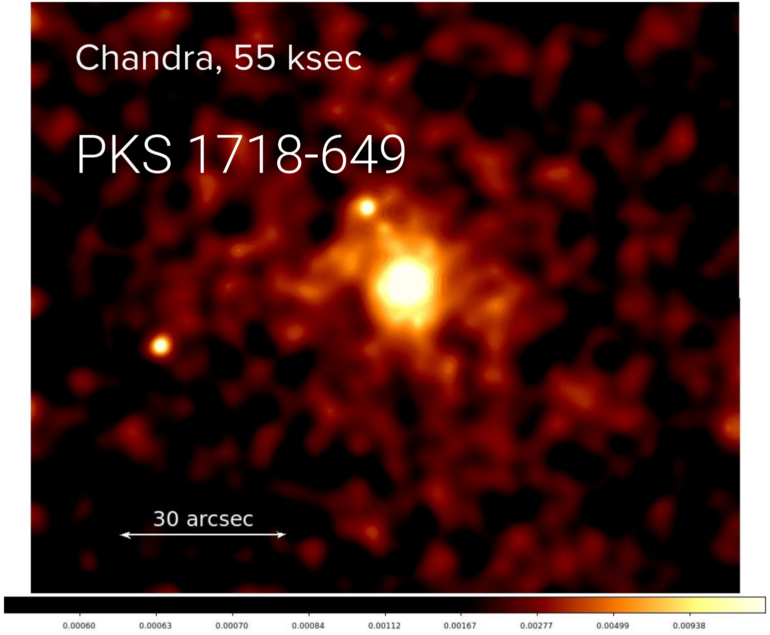
- Optical classification as a broad-line QSO (Stanghellini+1997),
- NHI = 8×10^{20} cm^{-2} in radio (Orienti+2006),
- X-ray signatures of **warm scattering** and Compton thick and thin absorbers (Guainazzi+2004, Sobolewska+2019b).

Compton thick X-ray obscuring torus may have a porous structure allowing some of the broad line emission to reach us. 1

Or the torus is uniform and broad line regions are **outflowing**. 2

Compton thin X-ray absorber is mostly neutral and may be co-spacial with the radio absorber.

Environment probed through extended X-ray emission



Siemiginowska et al. 2016

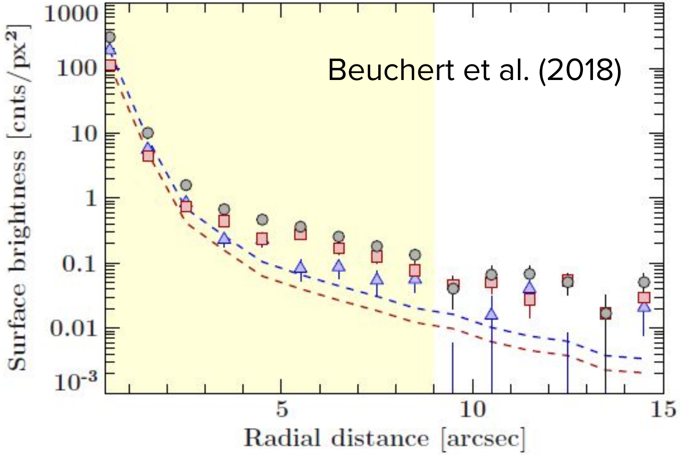
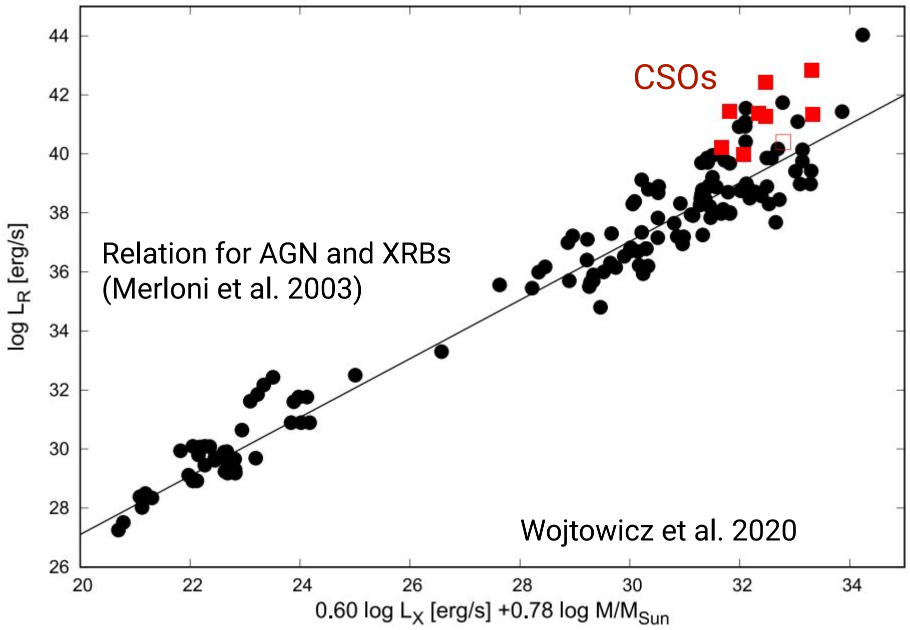


Image: Extended emission on > 3 arcsec scales (1 - 2.8 kpc) while the linear size of the young radio source is ~2 pc

Spectra: Diffuse emission is soft and forms a hot, collisionally ionized medium consistent with being due to supernovae explosions

CSOs and fundamental plane of black hole activity



- **X-axis:** A combination of the 2-10 keV X-ray luminosity and black hole mass
- **Y-axis:** radio luminosity at 5 GHz
- CSO sample, only radio core luminosity
- CSOs located **above** the correlation but not obviously inconsistent with the correlation