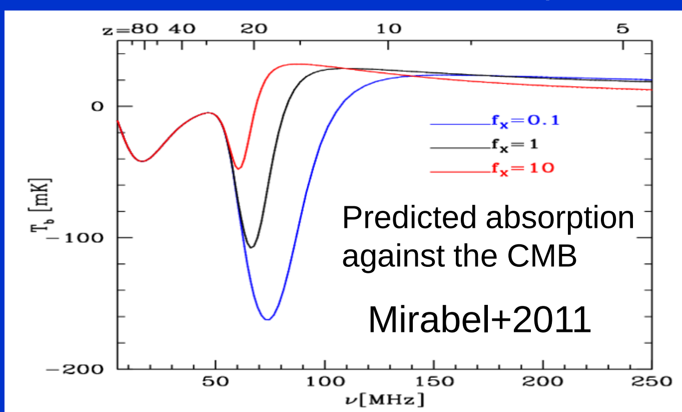
STELLAR BLACK HOLES AT COSMIC DAWN

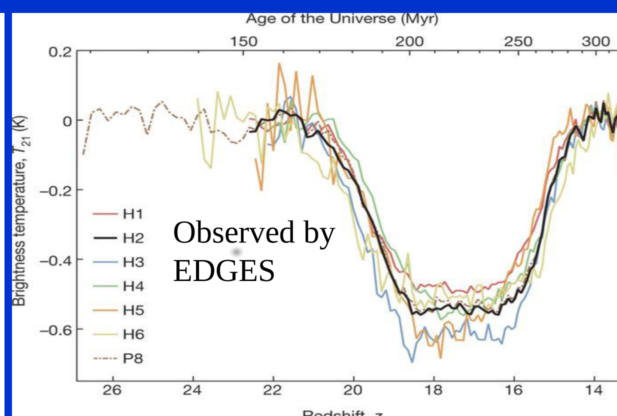
Félix Mirabel (CEA-Paris-Saclay)

The global HI-21cm signal between the dark ages & reionization:

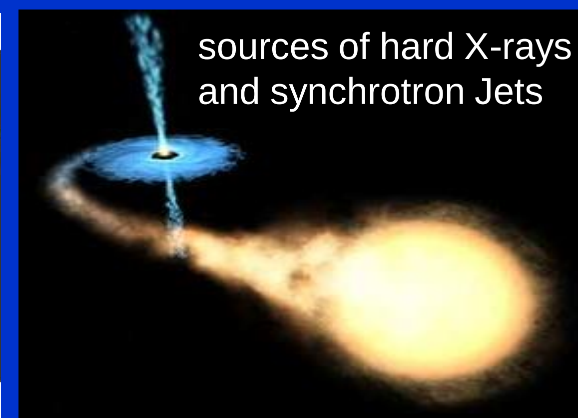
Pritchard & Loeb (Phys. Rev. (2010)
Mirabel+ AA & N&V in Nature (2011)



Bowman+ (Nature 2018)



BH-HMXB-MQs of POP III

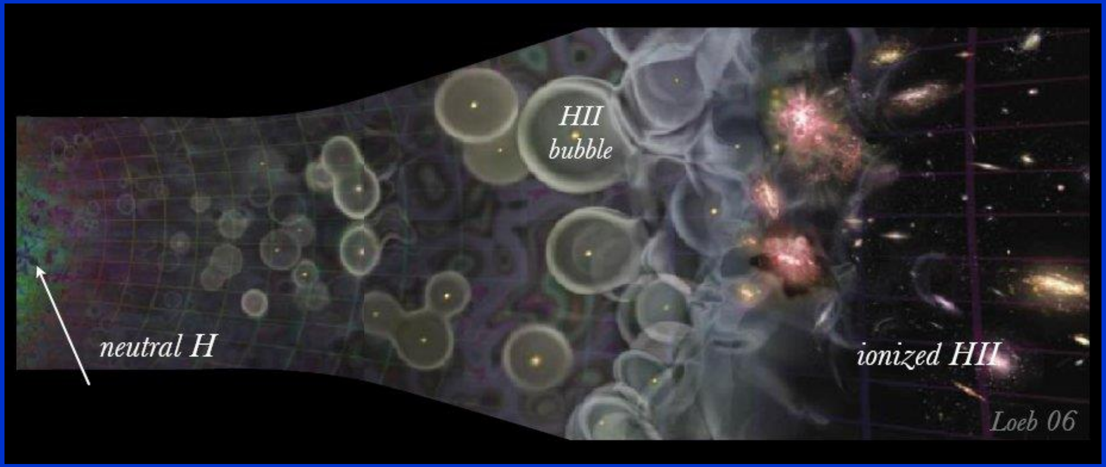


CAN POP III BH-HMXB-MQs ACCOUNT FOR THE TENTATIVE EDGES DETECTION OF λ21cm HI ABSORPTION AT z~17?

Mirabel (2019): Review at IAU Symposium 346 arXiv#1902.00511

Until 2011 the heating & reionization sources of the IGM are the UVs from Pop III/II stars & soft X-rays from SNe…but are absorbed by high dense HI

THE « SWISS CHEESE » MODEL ⇒ A PATCHY STRUCTURE



“Stellar black holes at the dawn of the universe”

Mirabel, Diskra, Laurent, Loeb & Pritchard; A&A & N&V in Nature by Haiman (2011)

- **BH-HMXB-MQs FORMED PROLIFICALLY AS REMNANTS OF POP-III STARS**

⇒

- **HARD X-RAYS FROM POP-III BH-HMXBs PRE-HEATED THE IGM**

⇒A smoother end of cosmic reionization

ASTROPHYSICAL GROUNDS FOR A PROLIFIC FORMATION OF BH-HMXBs AT COSMIC DAWN

THEORETICAL GROUNDS

- **MOST POP III & II STARS WERE FORMED AS MULTIPLE SYSTEMS**
  Turk+Science 2009; Krumholz+ Science 2009; Clark+ Science 2011; Stacy+…etc.

- **STARS OF LOW Z WITH M > 20 $M_\odot$ END AS BHs BY DIRECT COLLAPSE**
  Fryer,1999;Heger+2003;Georgy+2009;Woosley+2008;Nomoto+2010;Linden,Kalogera+2011

OBSERVATIONAL GROUNDS

- **BHs FORM WITH NO ENERGETIC SNe⇒BHs & DONORS REMAIN BOUND**
  Mirabel & Rodrigues, Science 2003; Mirabel+ Nature 2008

- **MOST ULXs & LGRBs ARE HOSTED IN LOW Z-HIGH-SSFR GALAXIES**
  Feng & Soria,2011;LeFloc'h,Duc,Mirabel;2003;Fruchter+ Nature, 2006; Perley+ 2014

- **IN LOW Z GALAXIES Lx/SFR IS LARGER THAN IN MAIN-S GALAXIES**
  Thuan+ 2004; Kaaret+ 2014; Brobry+ 2018; Douna, Pellizza & Mirabel + 2015, 2018

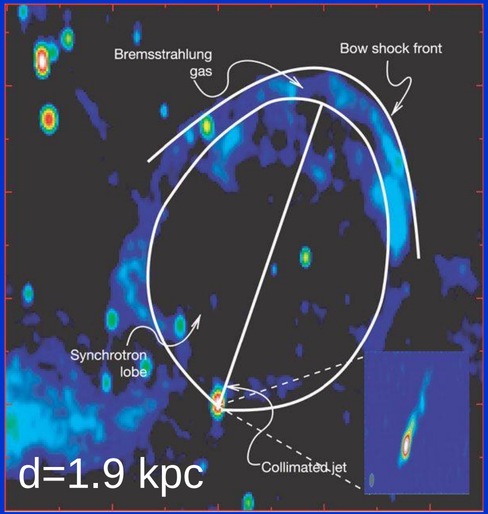
- **Lx/SFR EVOLUTION WITH z IS DRIVEN BY Z EVOLUTION IN HMXBs**
  Fragos+2012; Basu-Zych+2012; Lehmer, Basu-Zych, Mineo et al. (2016)
  up to z~2.5 $L_{2\text{-}10\ \mathrm{keV}}$ (HMXB)/SFR α (1 + z)

- **THE LARGE BH MASSES & MERGER RATES FOUND BY GWs** (LIGO-Virgo Coll.)

BH-HMXB-MQs IN THE GALAXY

Cygnus X-1

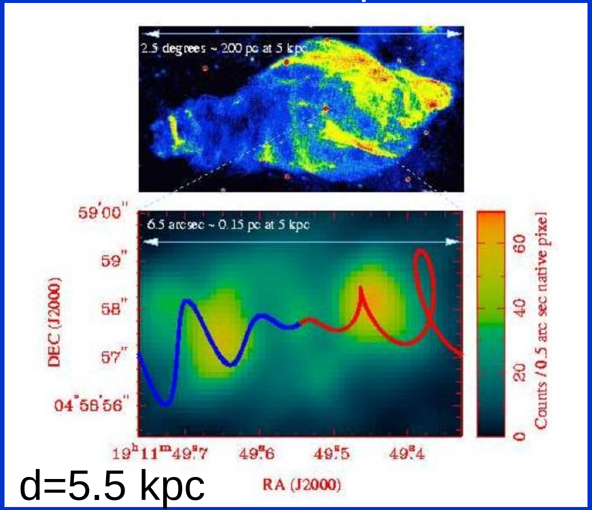
Gallo+ Nature 2005



~15 mJy (1.4 GHz); $\nu = 0.032$

SS 433

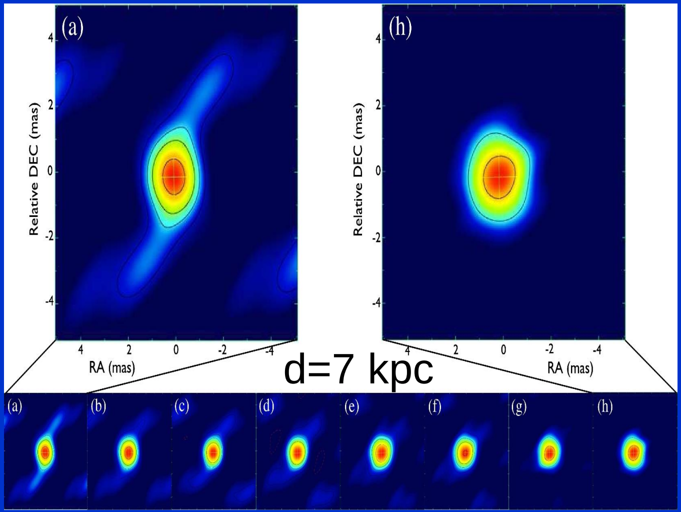
Dubner+; Rupen+ …



~700 mJy (1.4 GHz); $\nu = -0.779$

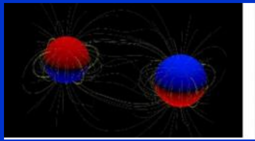
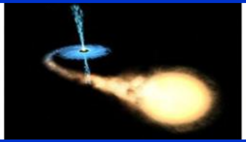
μblazar Cygnus X-3

Ergon+ 2017



~100 mJy (1.4 GHz); $\nu = -0.049$

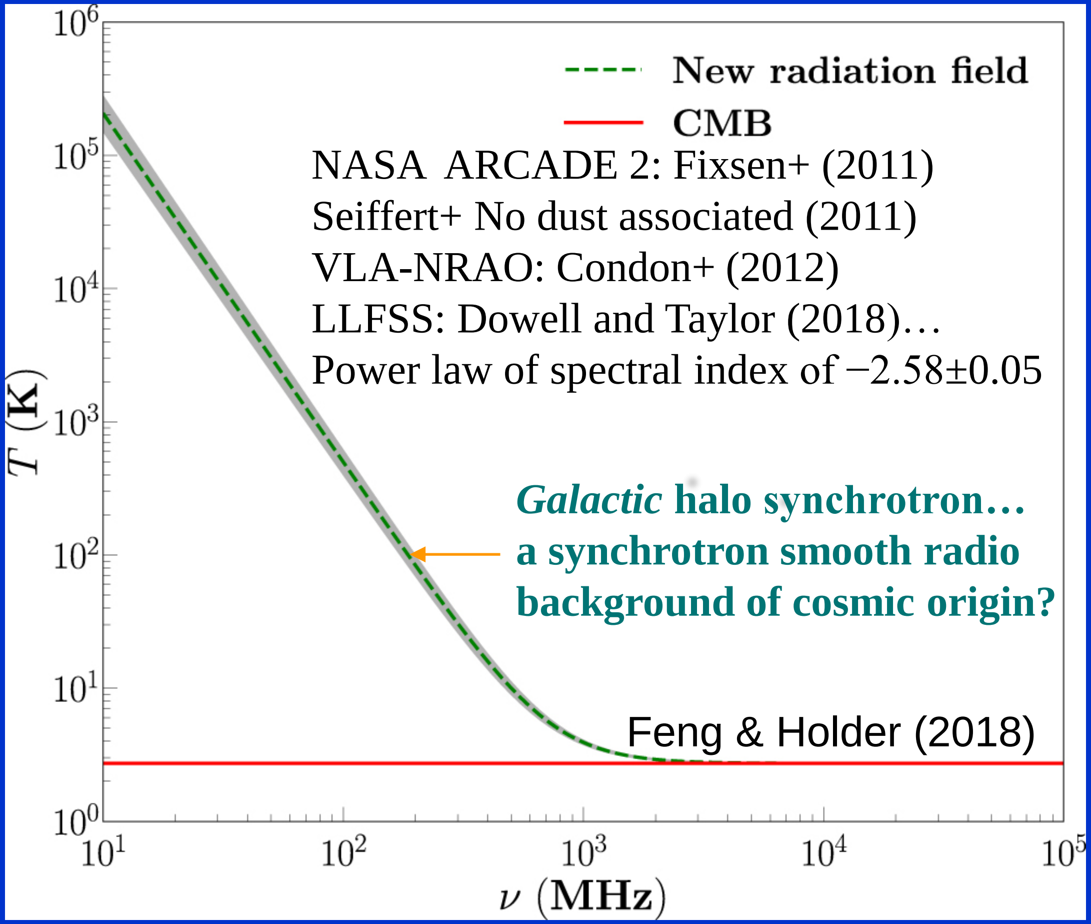
>70% Polarization in Cyg X-1 jets (Laurent+ Science 2011) $\Rightarrow$ B=10^{4-6} G (Zdziarski+2014)


The first astrophysical sources of synchrotron emission in the universe are the remnants of Pop III stars, namely BH-HMXB-MQs

Is there a smooth synchrotron Cosmic Radio Background (CRB)?

NASA -ARCADE 2 (Fixsen+ 2011) reported at ν < 1 GHz a smooth synchrotron radio background of possible cosmic origin now, confirmed by LLFSS (Dowell & Taylor 2018)



SOME OF THE POSSIBLE ADDITIONAL SYNCHROTRON RADIO EMISSION MAY COME FROM BH-HMXB-MQs OF POP III

TOMOGRAPHY OF HI IN THE EARLY UNIVERSE

Experiments to Detect the Global EoR Signature

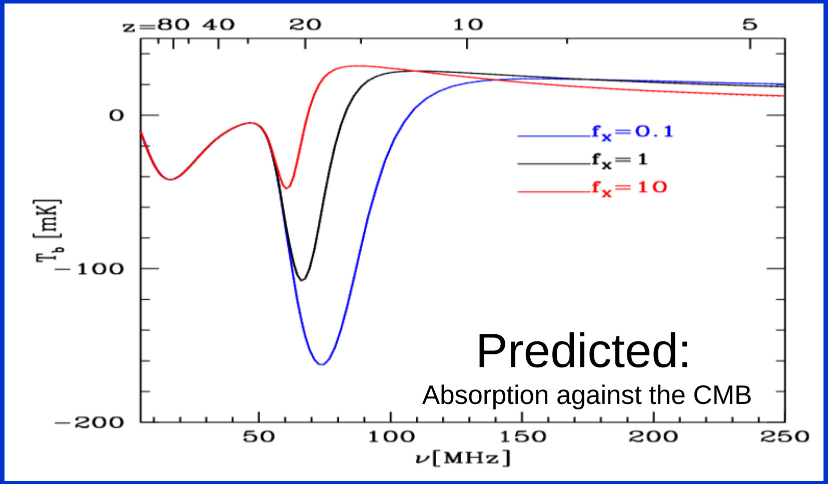
e.g. DARE, EDGES, LEDA

EDGES: Two low-band instruments, each of which has a dipole antenna pointed to the zenith and observing a single polarization

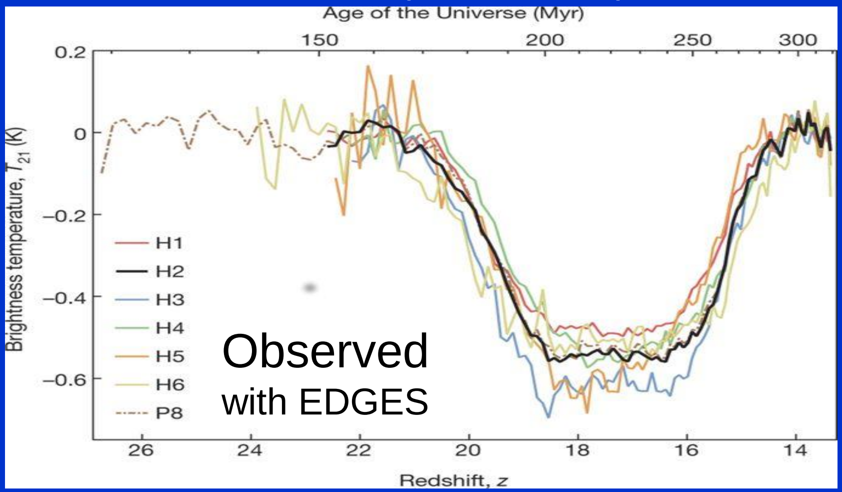
Interferometers for fluctuation measurements

e.g. LOFAR, SKA, HERA

Mirabel+ (2011) + N&V in Nature)



Bowman+ (Nature 2018)



- Absorption at z~17 during 170-270 Myrs, consistent with fx<0.1, but 2-3 times larger amplitude & bottom flat
- Extra amplitude absorption due to cooling by interaction of dark matter with baryons (e.g. Barkana Nature)?

$\Delta T_b \propto \{1 - (T_{CMB} + T_{rad})/T_s\}$; $F_{boost} \sim 1 + T_{rad}/T_{CMB}$ (Feng & Holder; Ewall-Wice+ 2018)

T_{rad} MAY COME FROM POP III RADIO LOUD BH-HMXB-MQs

CONCLUSION

If the EDGES absorption is confirmed by other experiments:

- It would be evidence of a large population of BH-HMXB-MQs of Pop III at cosmic dawn, and therefore **an indirect evidence of stars of Pop III.**

- BH-HMXB-MQs of Pop-III would be **formed before the appearance in the universe of neutron stars, SNe, and large quantities of dust.**

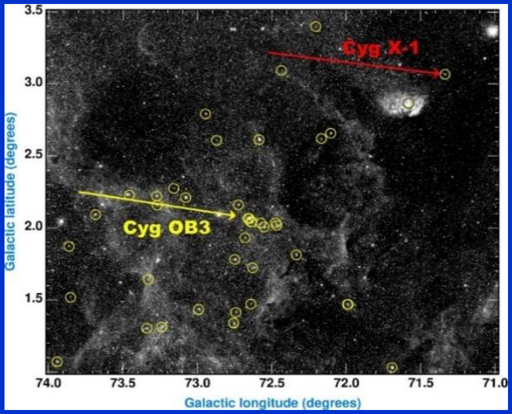
- $f_X < 0.1 \Rightarrow N_H > 5 \times 10^{23}$ $cm^{-2} \Rightarrow$ **UVs & soft X-rays are absorbed close to sources, but the IGM is transparent to the cm radio continuum radiation.** **Radio emission would be the smoking gun of first light in the universe**

Mirabel (2017): New Astronomy Reviews
Mirabel (2019): Review at IAU Symposium 346 (arXiv#1902.00511)

Next step: From the additional amplitude of the λ21cm HI absorption at z~17, will estimate the properties and numbers of stars & BH-HMXBs of POP III (Mirabel & Laurent in progress)

Cygnus X-1

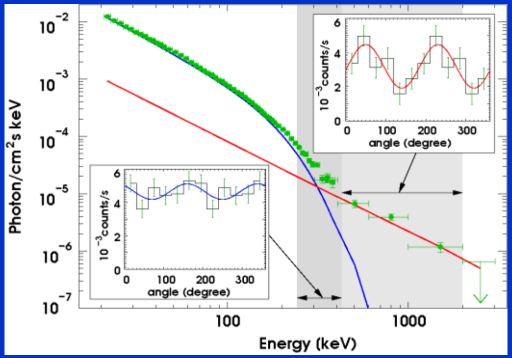
Mirabel & Rodrigues
(Science 2003)



D= 1.86 ± 0.1 kpc ; M_{BH} = 14.8 ± 1.0 $M_\odot$
Donor = O9.7 Iab of 19.2 ±1.9 $M_\odot$
P = 5.6 days; e = 0.018 ± 0.003

THE BH IN Cyg X-1 WAS FORMED BY IMPLOSION OF A ~45 $M_\odot$ STAR

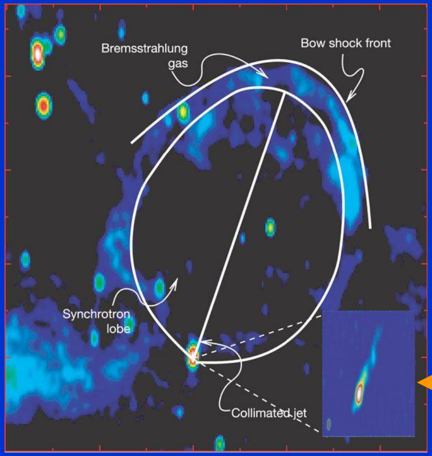
Laurent+
(Nature 2018)



Cyg X-1 IS A SOURCE OF HARD X-RAYS (UP TO ~2 MeV)

with polarized emission
from synchrotron jets

Gallo+
(Nature 2005)



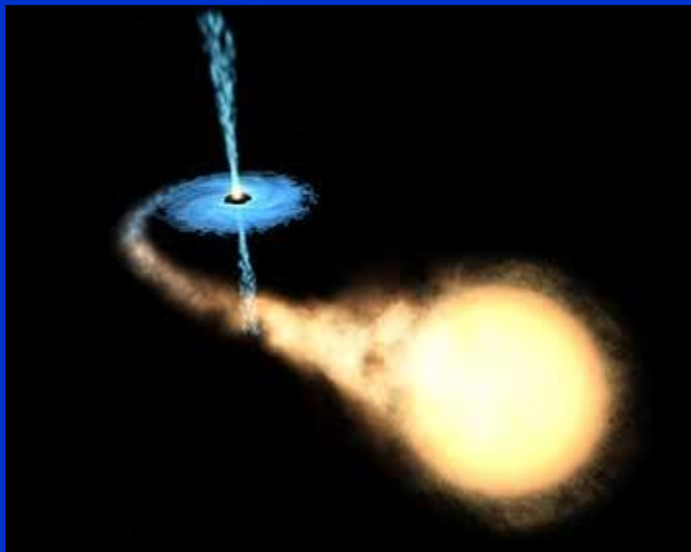
Cyg X-1 IS A SOURCE OF POWERFULL RELATIVISTIC JETS

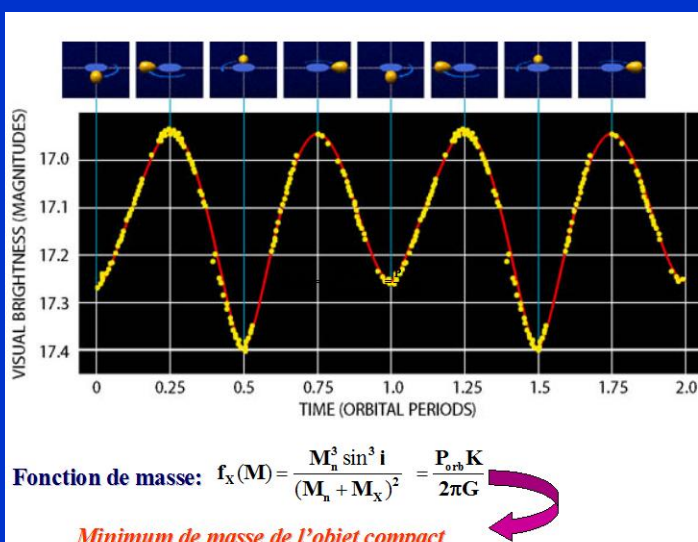
- $10^{36} < P_{jet} < 10^{37}$ erg s^{-1}
- Total energy ~ 10^{48} erg

compact jet

STELLAR BLACK HOLES IN THE GALAXY

Black holes identified by X-rays





IN BINARY SYSTEMS:

$M > 3\ M_\odot \Rightarrow$ BLACK HOLE

~50 known in binaries plus
~30 additional candidates

- **Estimated total population in the Galaxy: ~300 millions**
  Brown & Bethe (1994); Timmes, Woosley, Weaver (1996)

- Assuming ~10 $M_\odot$ this form of dark matter of baryonic origin would be **~4% of the total mass of the baryonic matter in the Galaxy**

- **Its mass is ~10^3 times the mass of the BH of $4\times10^6\ M_\odot$ in Sgr A***

- **Most stellar BHs in the Galaxy are presently in quiescence (dormant)!**

SYNCHROTRON JETS IN BH-XRB-MQs

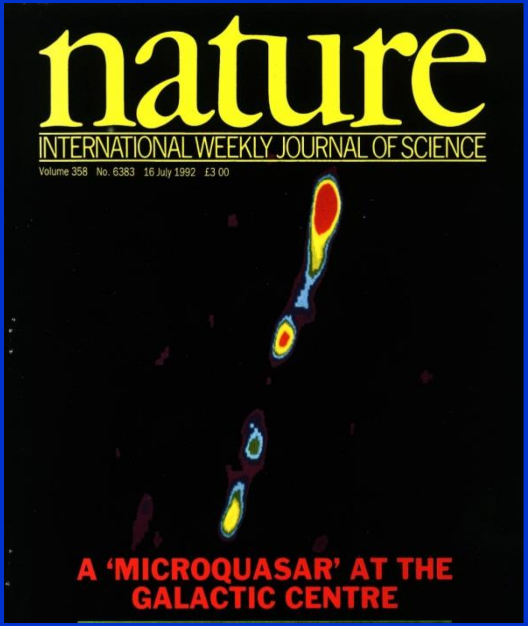
Mirabel, Rodríguez+1992

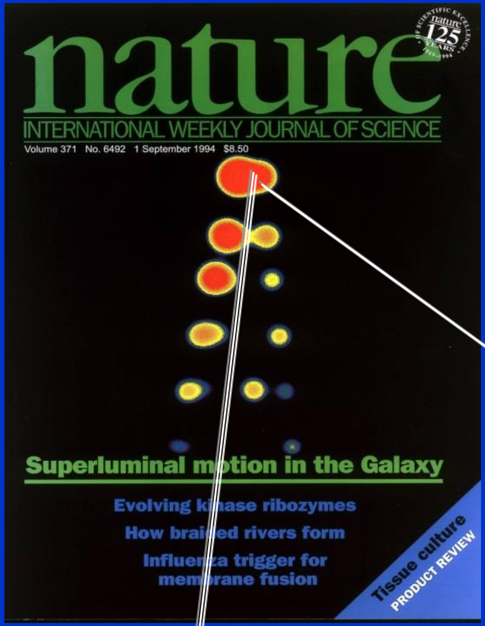
Mirabel & Rodríguez 1994

with VLA

STEADY

JETS

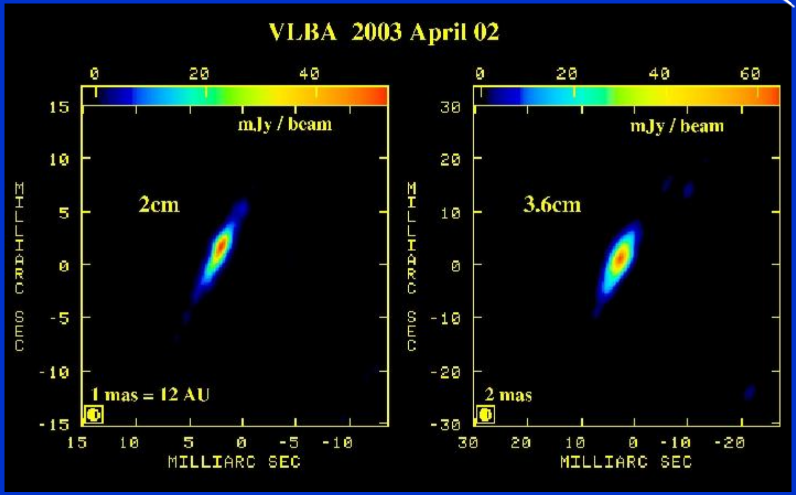




TRANSIENT

JETS

Dhawan, Mirabel, Rodríguez (2007)



In low hard state. Size ~ 100 AU. Same PA

COMPACT JETS

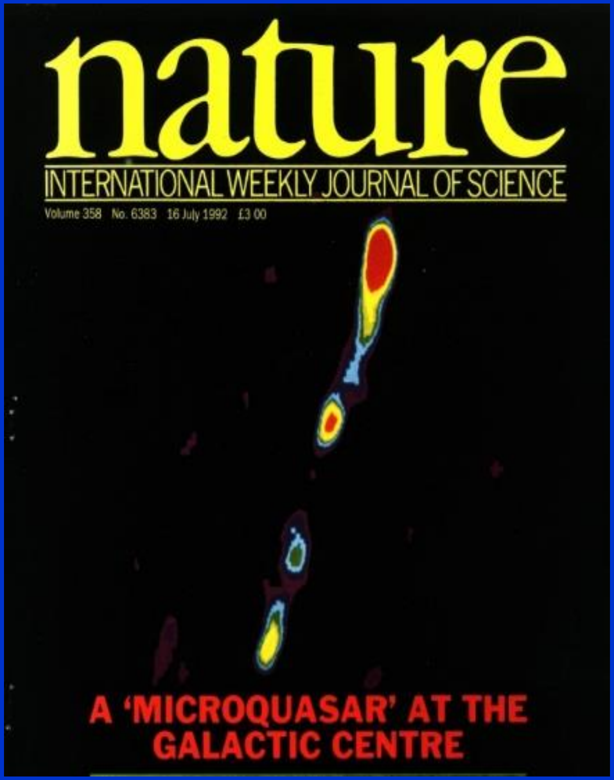
TO DETERMINE PARALAXES & PROPER MOTIONS

(with VLBI to get sub-miliarc sec precision)

with VLBA at $\lambda 3.6$ cm

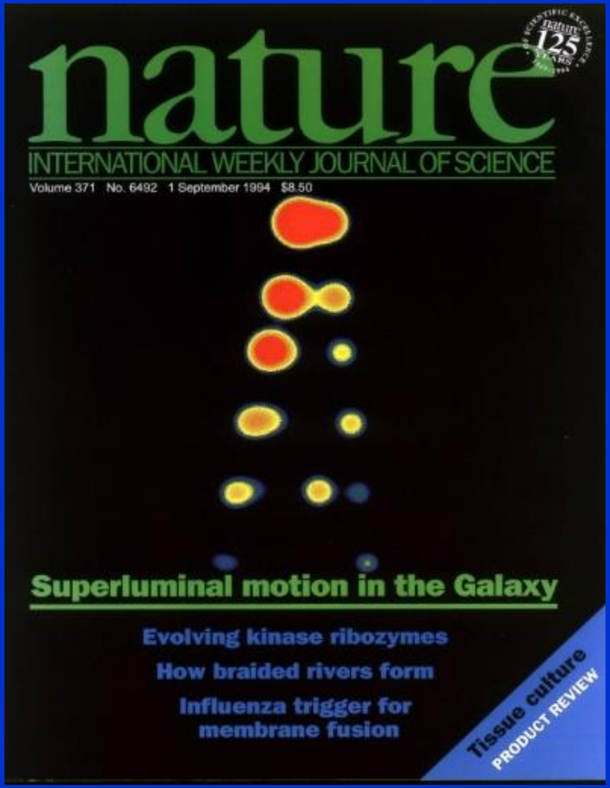
BH-HMXBs ARE MICROQUASARS

Mirabel, Rodríguez+ 1992



STEADY JETS

Mirabel & Rodríguez 1994



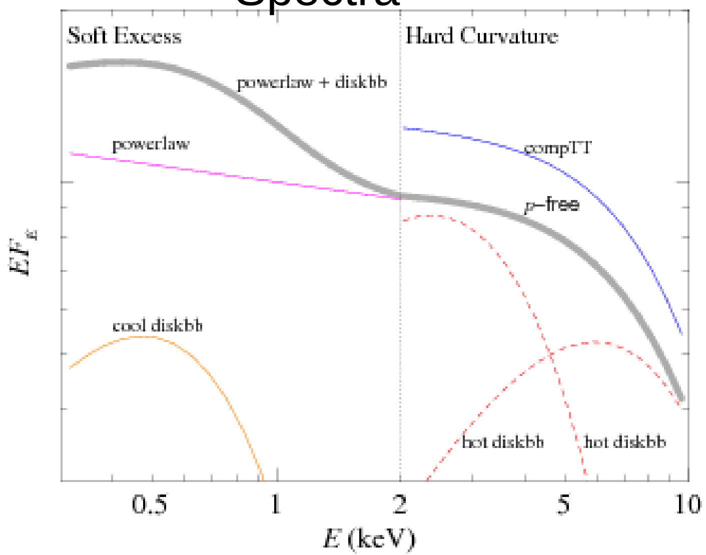
TRANSIENT JETS

SOURCES OF POWERFUL SYNCHROTRON JETS

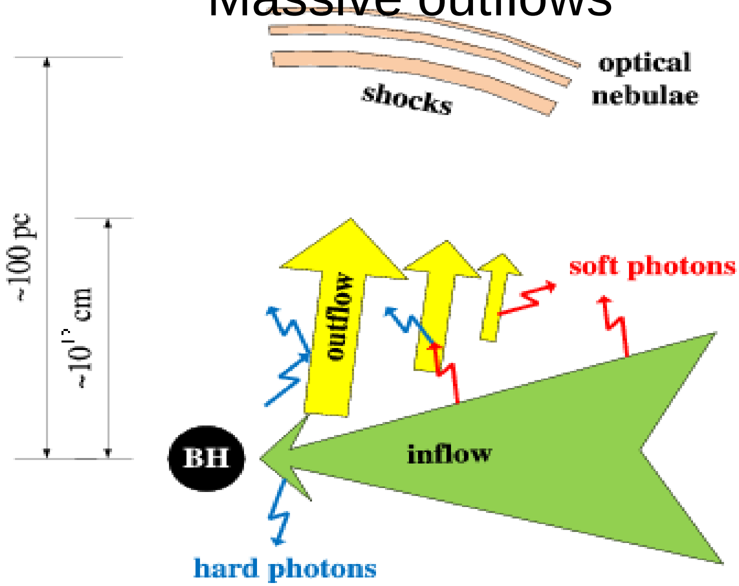
BH-HMXBs IN LOW METAL-STAR-FORMING GALAXIES

From Feng & Soria (2011)

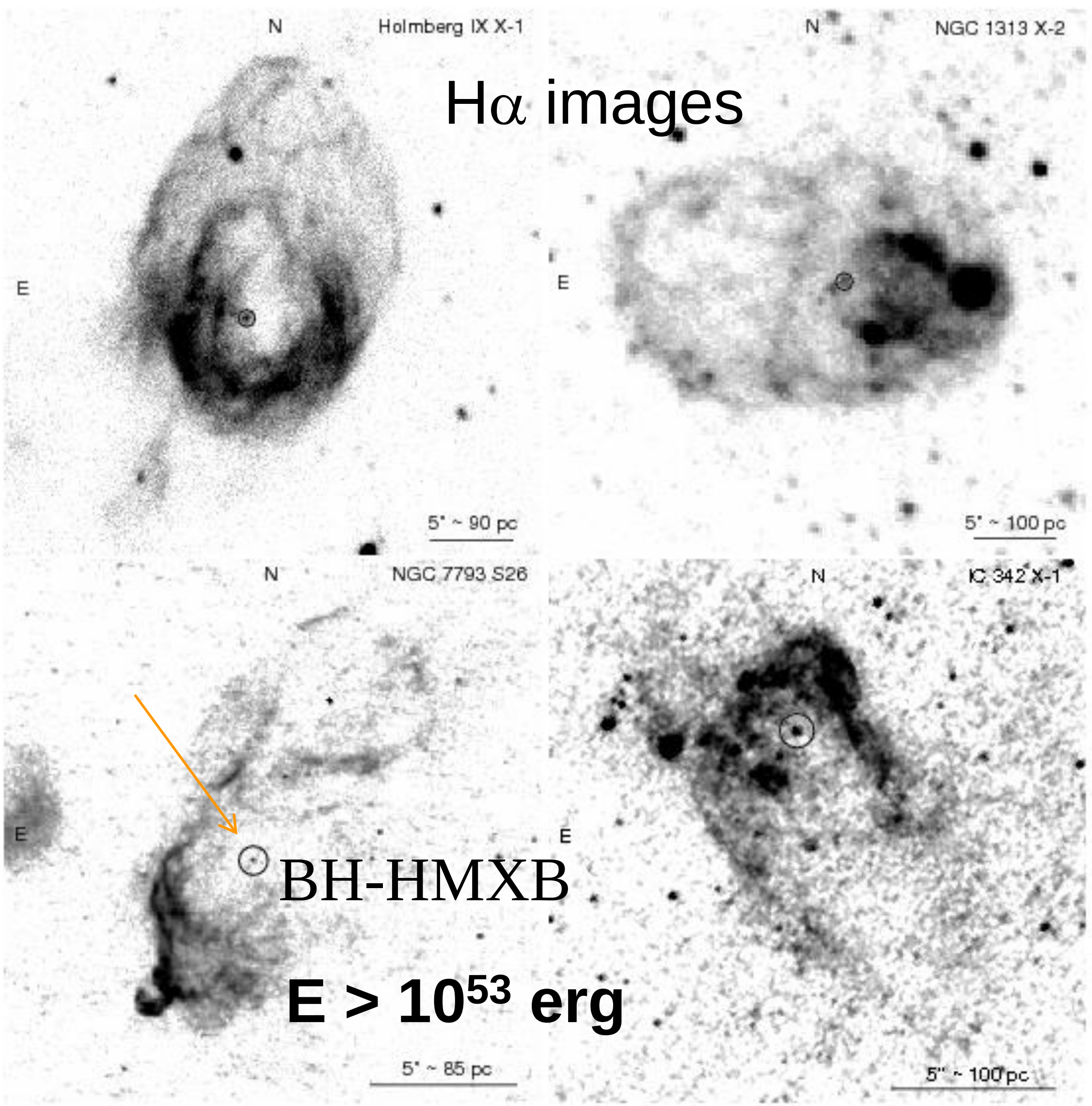
Spectra



Massive outflows



shock & photonionized bubbles of > 100 pc size

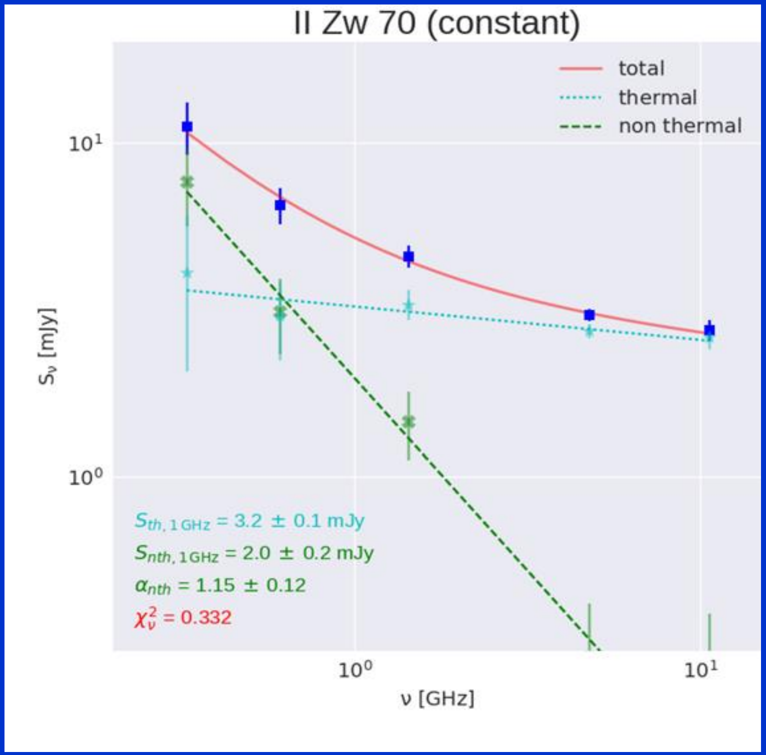


RADIO SYNCHROTRON SPECTRA IN DWARF STAR FORMING GALAXIES OF LOW Z

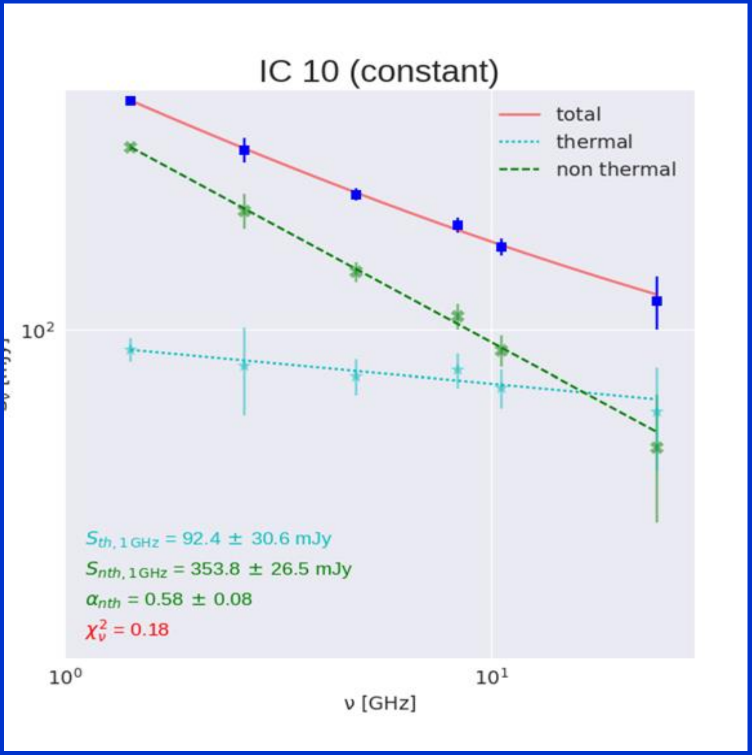
Klein, Lisenfeld and Verley (2018)

$S_\nu \ \alpha \ \nu^{-\alpha}$ α=0.59+/-0.20

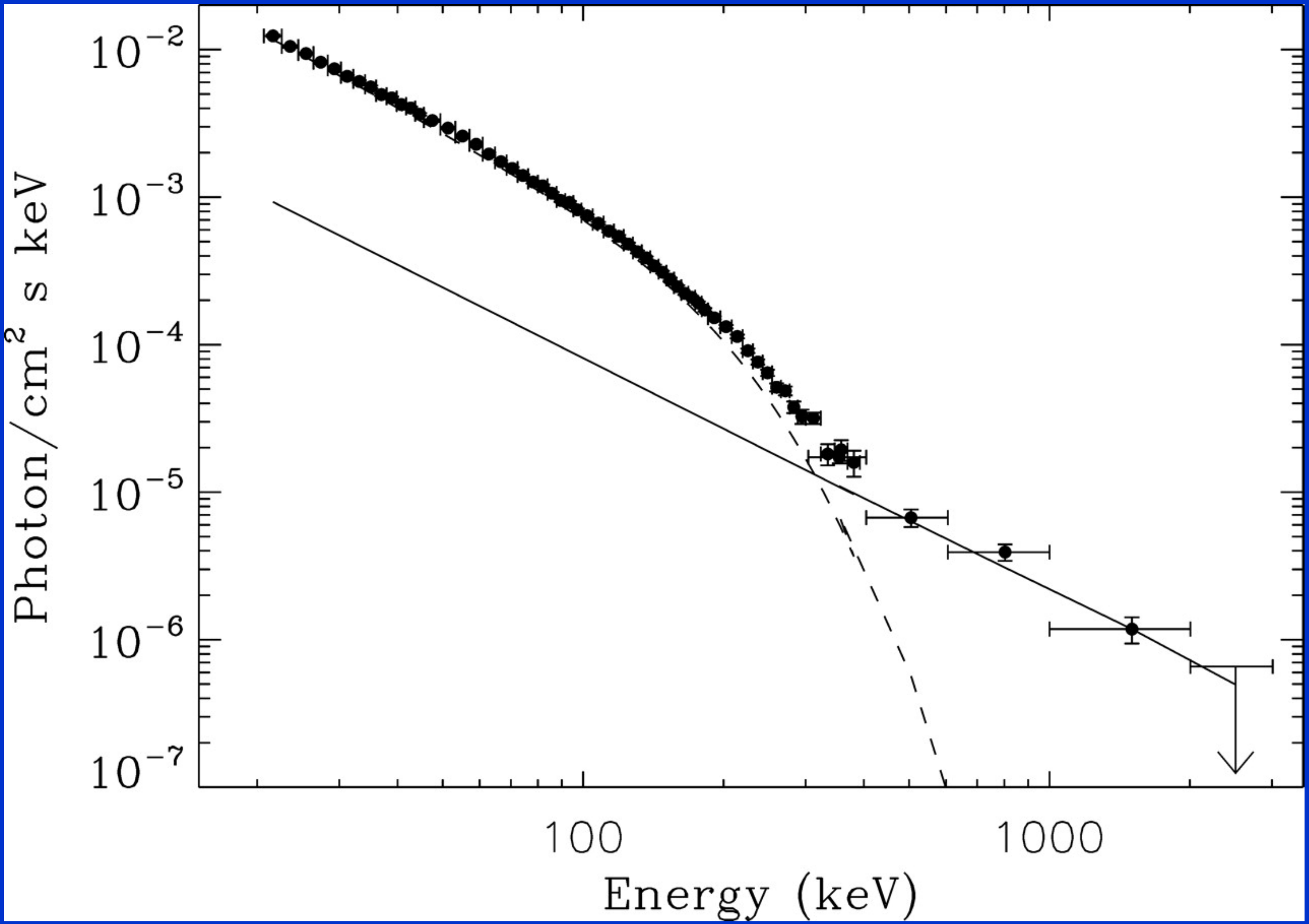
12+Log (O/H) = 7.86



12+Log (O/H) = 8.30



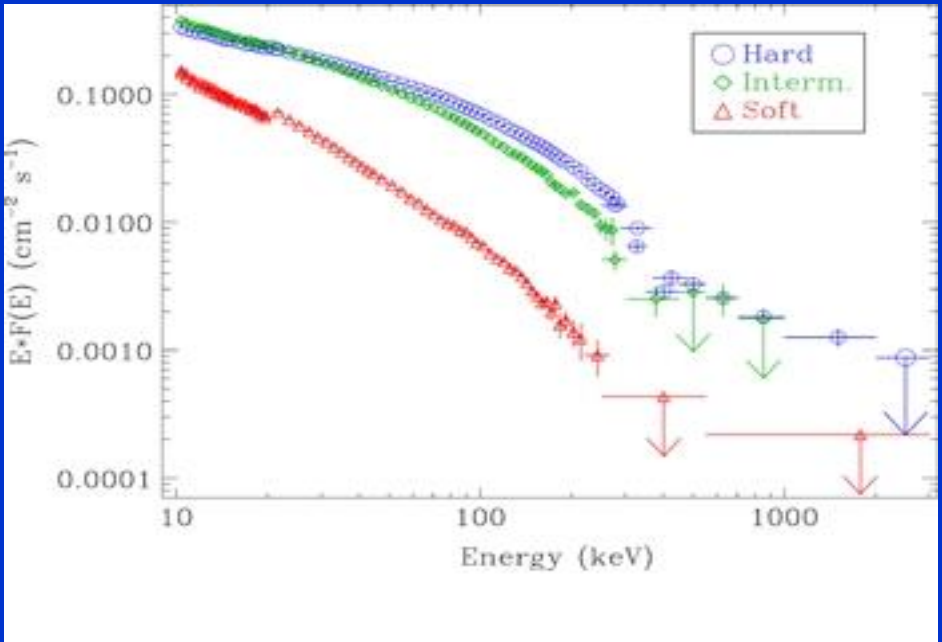
Cygnus X-1 energy spectrum as measured by the INTEGRAL/IBIS telescope and obtained with the standard IBIS spectral analysis pipeline.



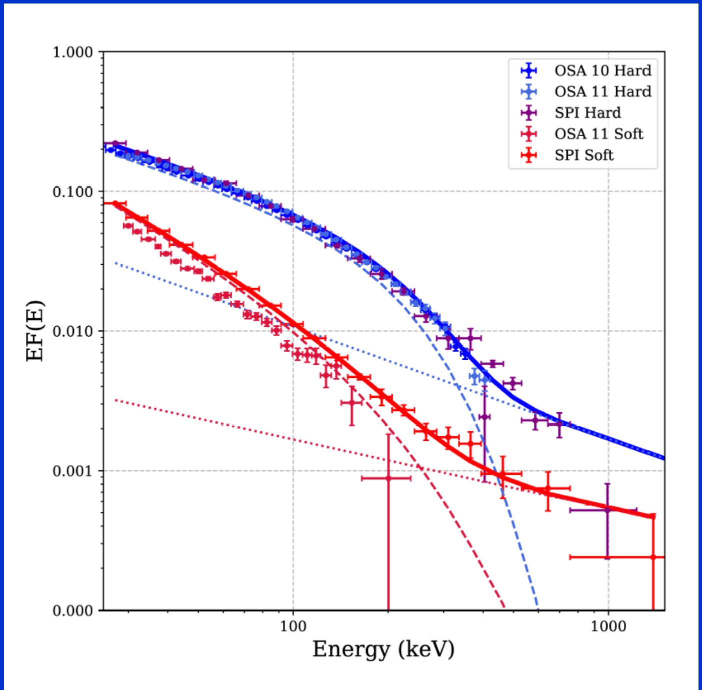
P. Laurent et al. Science 2011;332:438-439

Figure 3 from Spectral State Dependence of the 0.4-2 MeV Polarized Emission in Cygnus X-1 Seen with INTEGRAL/IBIS, and Links with the AMI Radio Data

Jérôme Rodriguez et al. 2015 ApJ 807 17 doi:10.1088/0004-637X/807/1/17



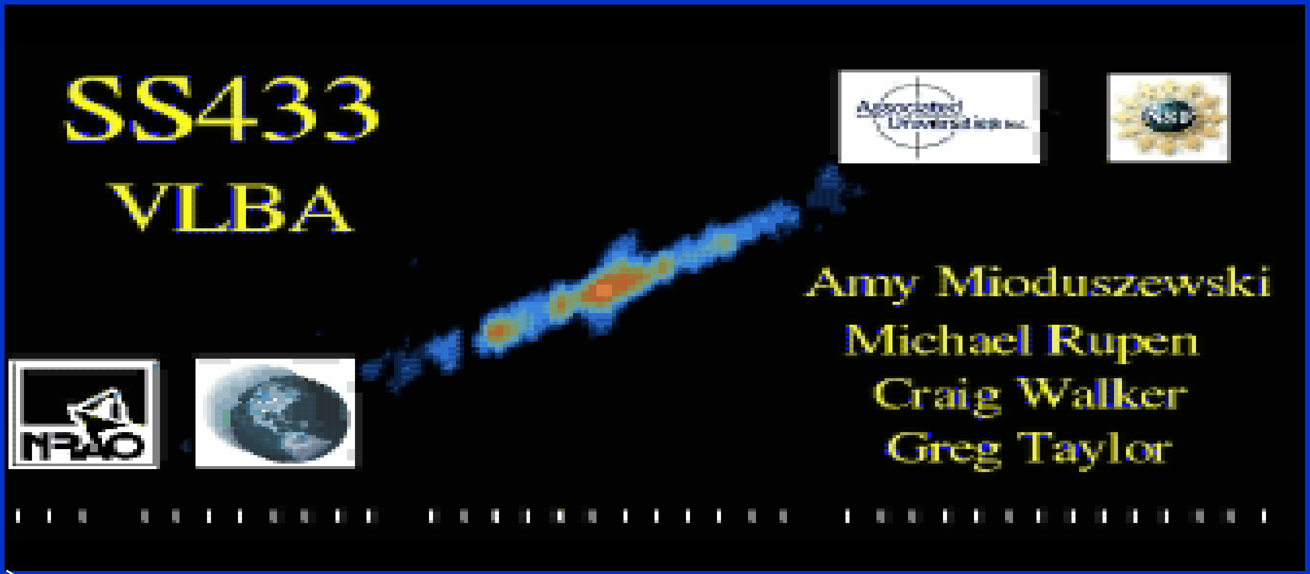
Cygnus X-1 spectra



Issu de Cangemi F. et al., 2019, proceedings of the 12th INTEGRAL conference, Geneve, 11-15 february 2019.
Spectres observés par SPI et IBIS.

Blue points and lines : hard state
Fit : comptonisation + powerlaw : kT = 55 keV, tau =0.95, alpha (PL) = -1.5
Red points and lines : soft state
Fit : cutoff PL + PL : alpha1 = -2.27 , Ecut = 273 keV, alpha2 = -1.5

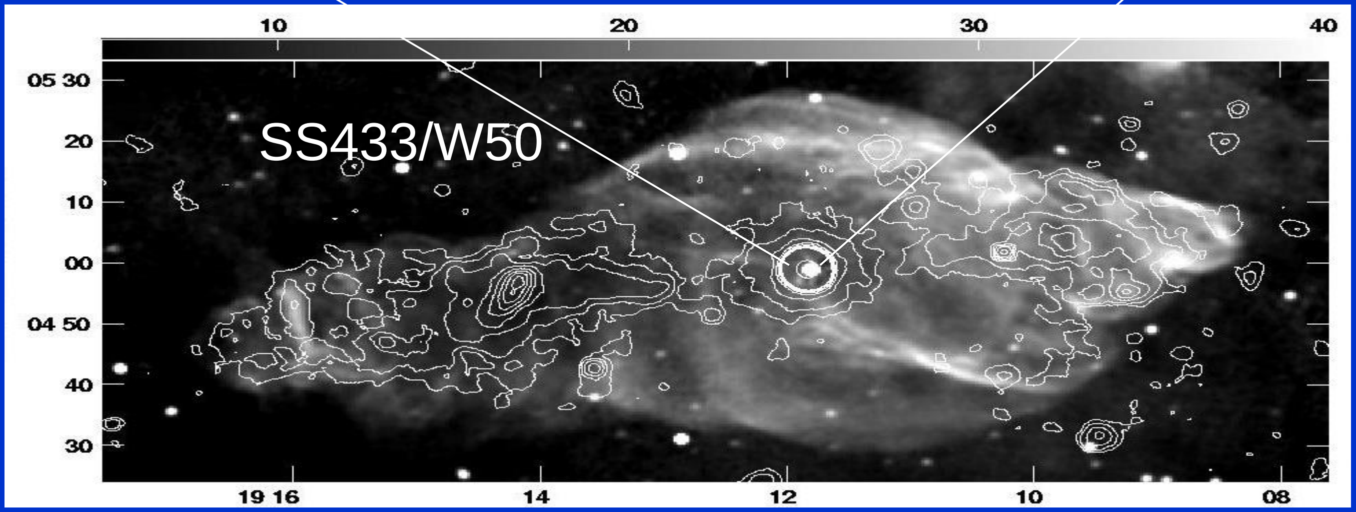
POWERFULL JETS IN SS 433



HAWAC reported detection of gamma-rays in the lobes (Nature 2019)

1 arcsec

1° = 60 pc



Radio:
(Dubner, Goss, Mirabel)

X-rays
(Brinkmann +)

Cygnus X-3

- Probably a BH wind-fed by a Wolf Rayet star
- Short orbital period: 4.8 hr, distance 7.4 kpc
- The brightest galactic X-ray binary in radio $s{-}1$

Giant radio flares of 10-50 Jy. Mean Jet power of 10^{37} erg s^{-1}

Evolution in 4h: (Egron+ 2017)