ANTON PANNEKOEK INSTITUUT

Netherlands Organisation for Scientific Research

Outflows from X-ray Binaries

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University of Amsterdam

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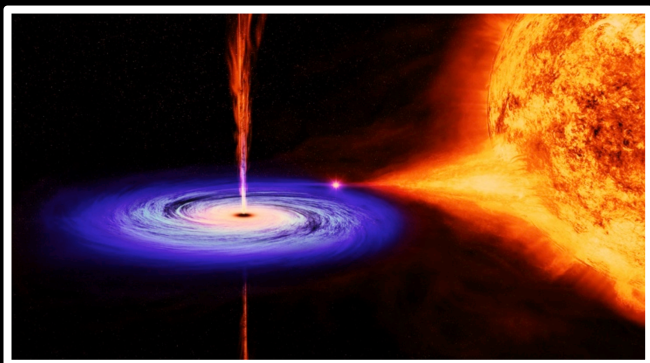
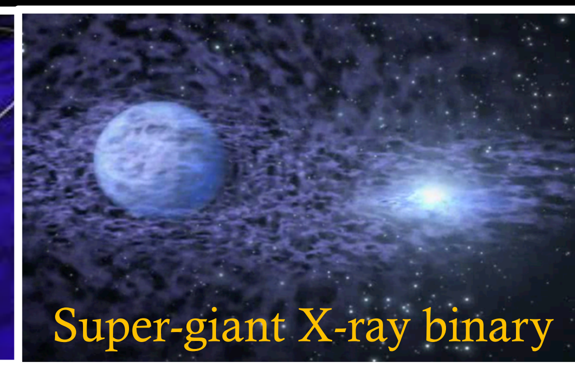
X-ray Binaries





Low-mass X-ray binaries

Roche-lobe overflow
Accretion via disk
~200 sources
~50 black holes

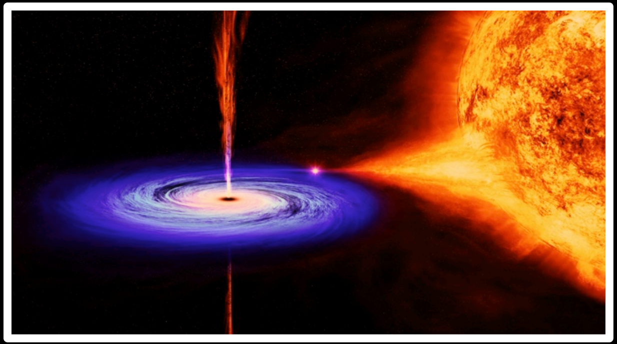
High-mass X-ray binaries

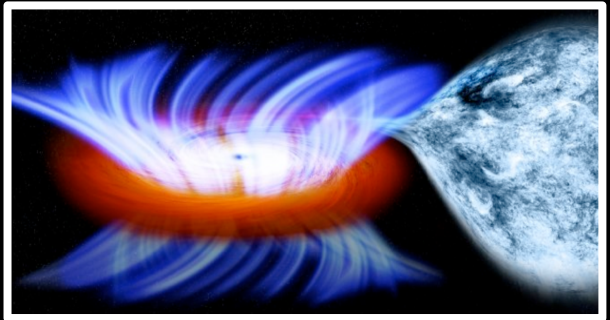
Equatorial disk Be star (majority)
or wind supergiant companion
~200 sources
few black holes

X-ray Binary Outflows

Intro: Connection accretion & outflows

- ◇ Jets: new discoveries
- ◇ Outflows @ extremes of accretion
- ◇ Nebulae around X-ray binaries





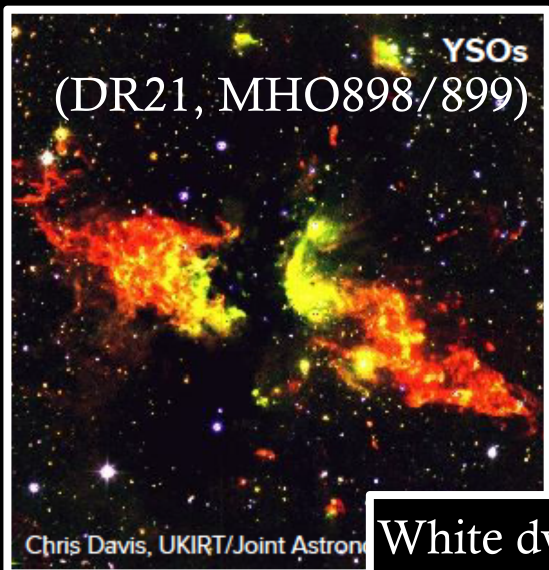
How are outflows launched?

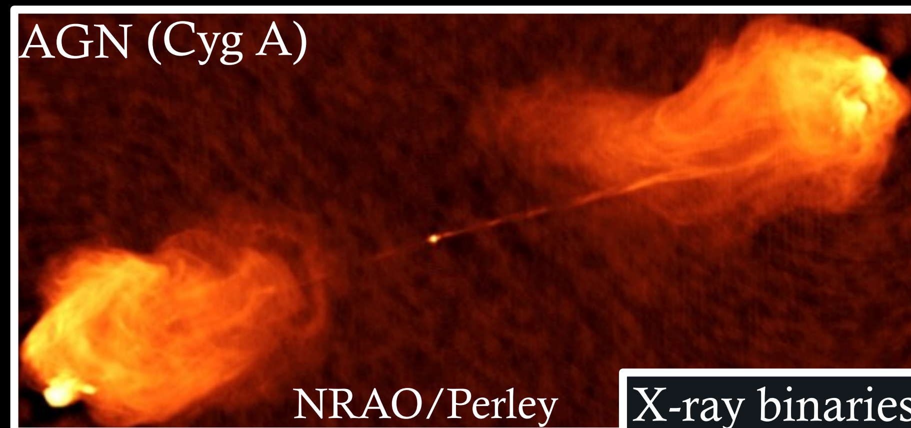
How much mass is lost in outflows?

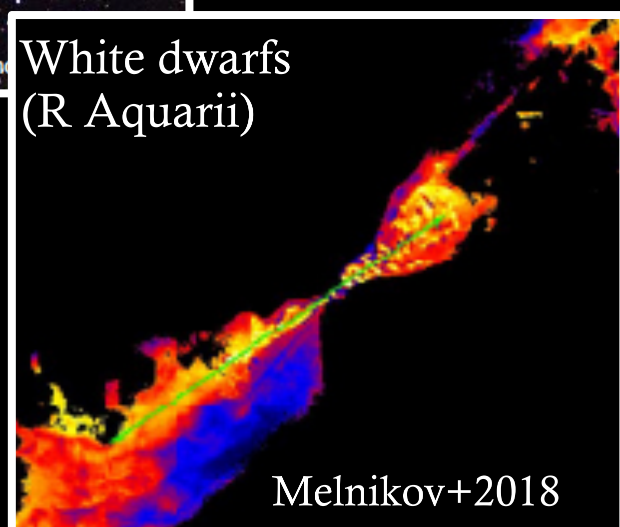
How do outflows impact the environment?

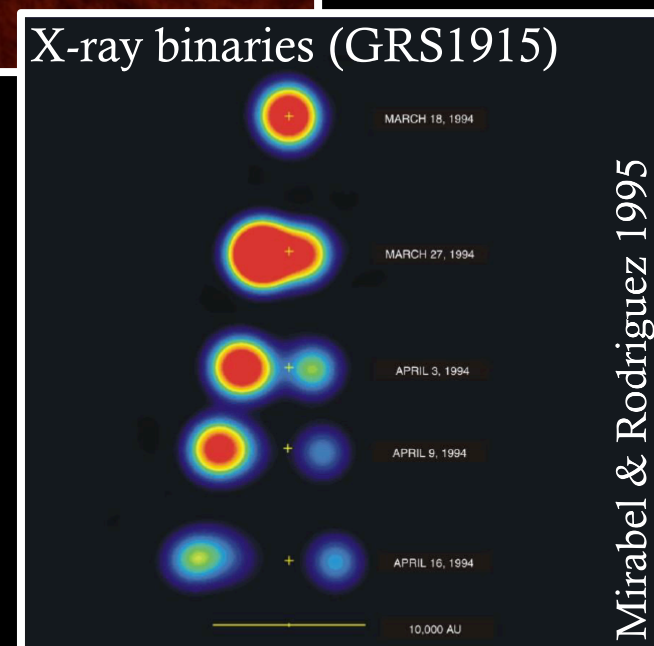
Importance of Outflows

Integral part of accretion flows: Accretion physics



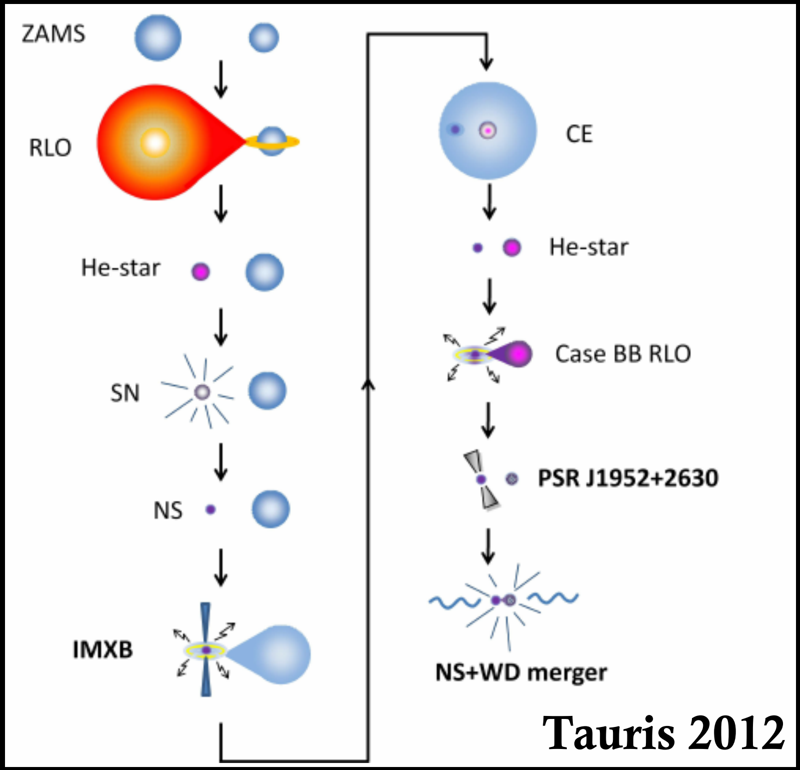




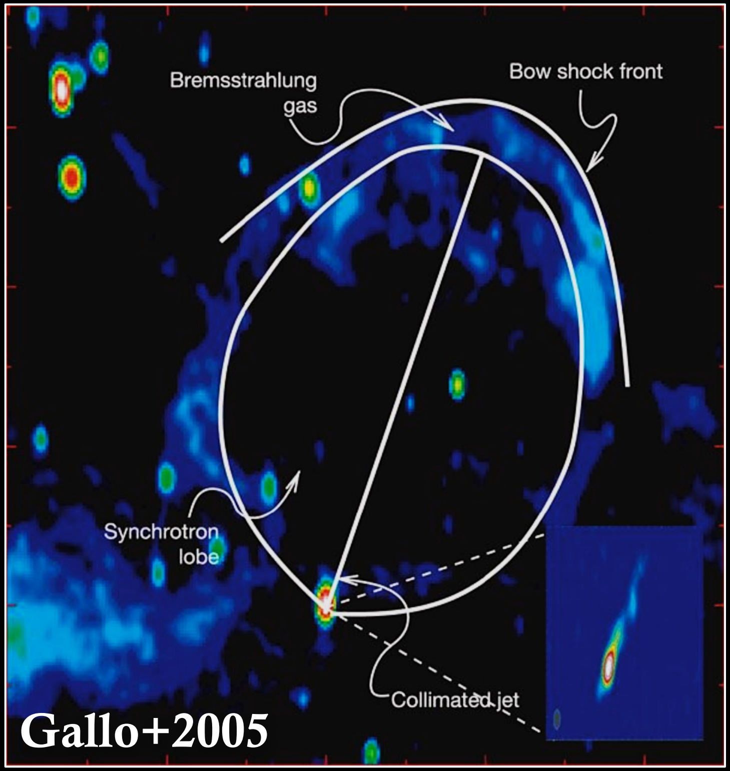


Importance of Outflows

Integral part of accretion flows: Accretion physics
Non-conservative mass-transfer: Binary evolution
Impact on environment: Feedback



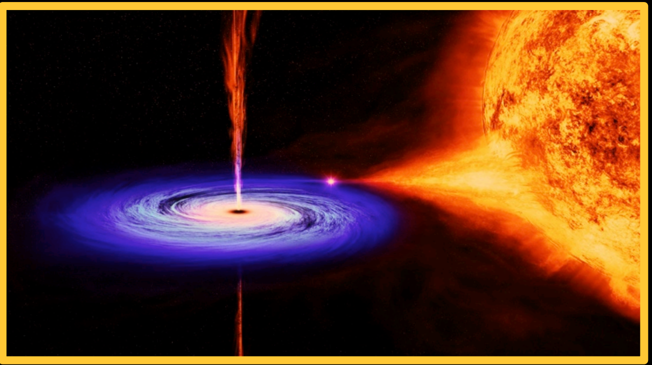
Tauris 2012



Gallo+2005

Accretion and Outflows in X-ray Binaries

X-ray Binaries



Low-mass
X-ray binaries

Roche-lobe overflow
Accretion via disk

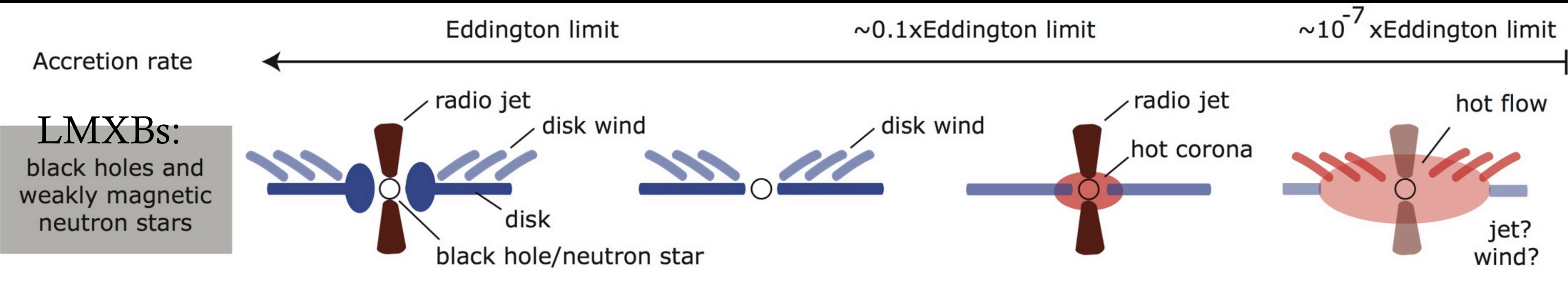
High-mass
X-ray binaries

Equatorial disk Be star (majority)
or wind supergiant companion

Some systems accrete continuously: persistent

In many active accretion switches on/off: transients

Accretion Regimes



Near/super Eddington

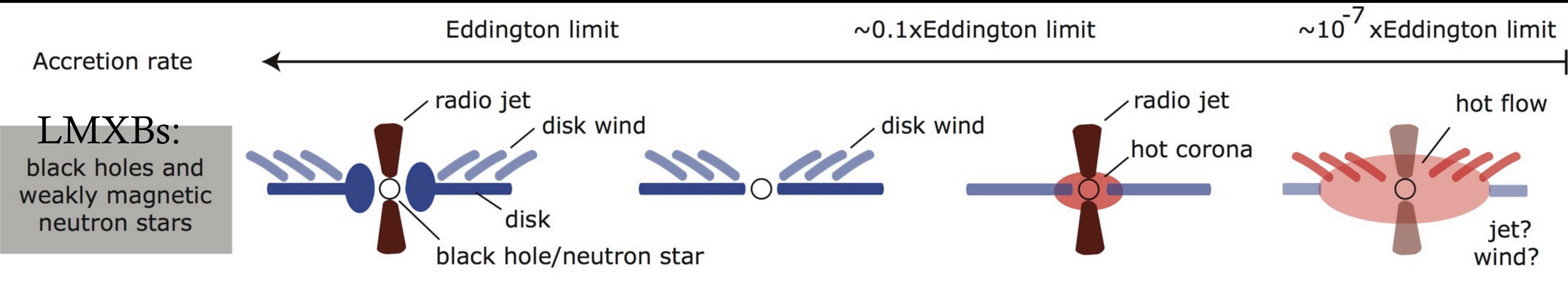
Soft State

Hard State

Quiescence

Wide range of accretion rates possible
Accretion geometry + outflows change with accretion rate

Accretion Regimes



Near/super Eddington

Soft State

Hard State

Quiescence

Most easily studied

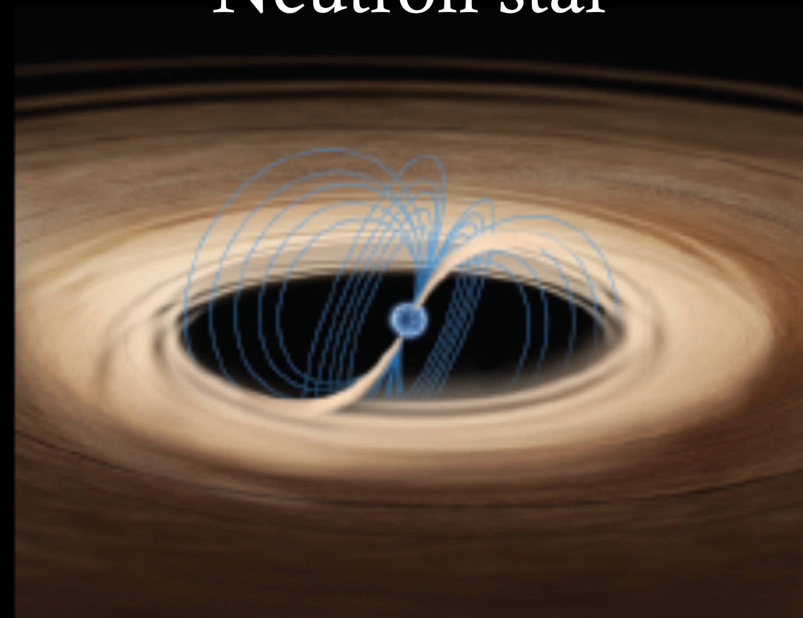
Relatively rare

Common but difficult to study

Black Holes versus Neutron Stars

Black hole

Neutron star

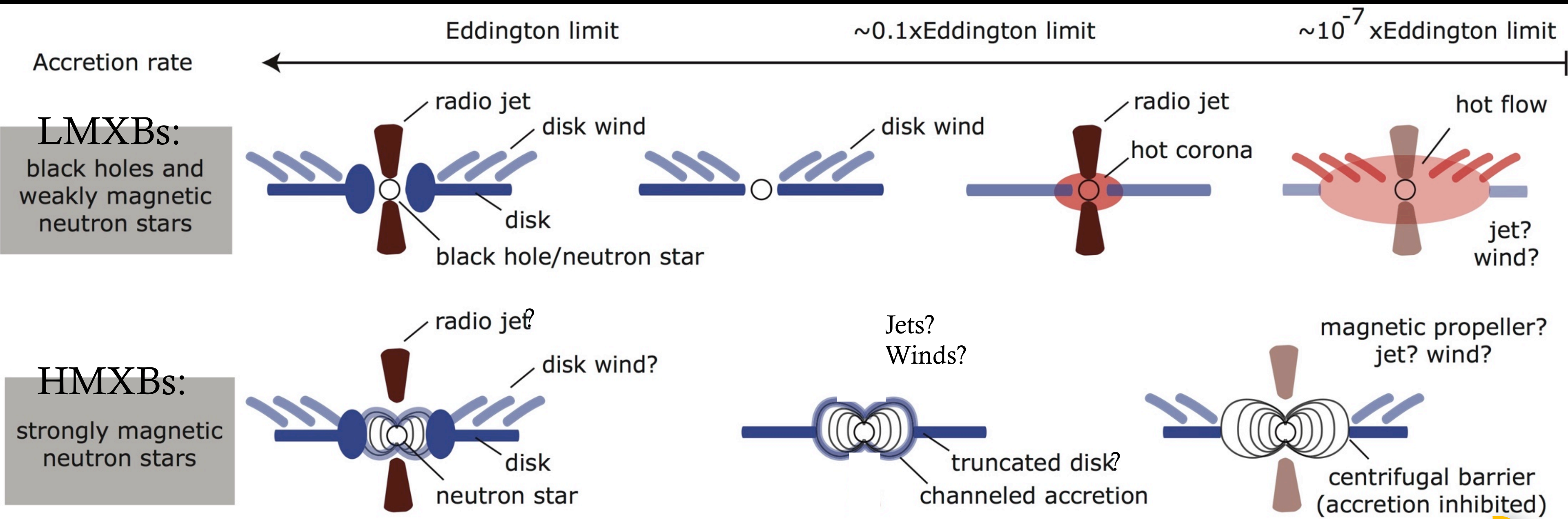


Many aspects of accretion are similar

But: neutron stars have a solid surface + magnetic field

→ Strong magnetic field can truncate the accretion flow

Effect of Strong Magnetic Field



Neutron stars in X-ray binaries come in two classes:

Weakly magnetic ($B < 10^9$ G), high spin (millisec)

Strongly magnetic ($B \sim 10^{12}$ - 10^{13} G), slow spin (sec-min)

A strong magnetic field changes the accretion geometry

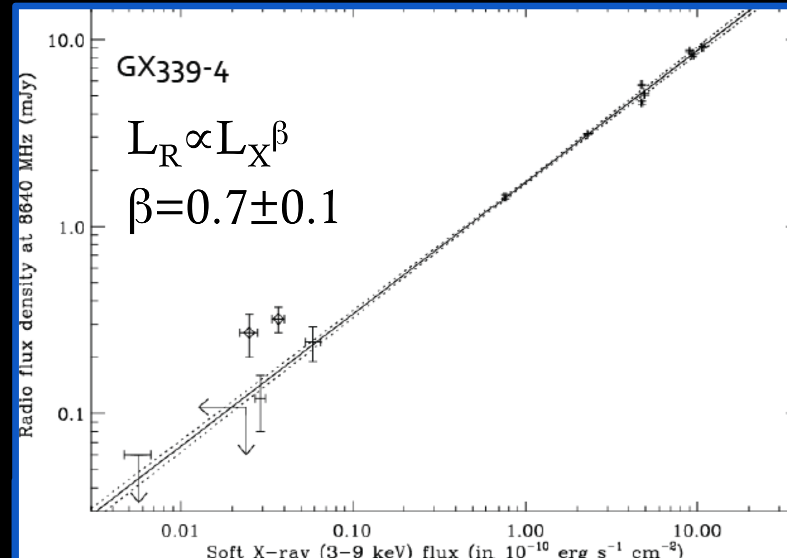
Jets

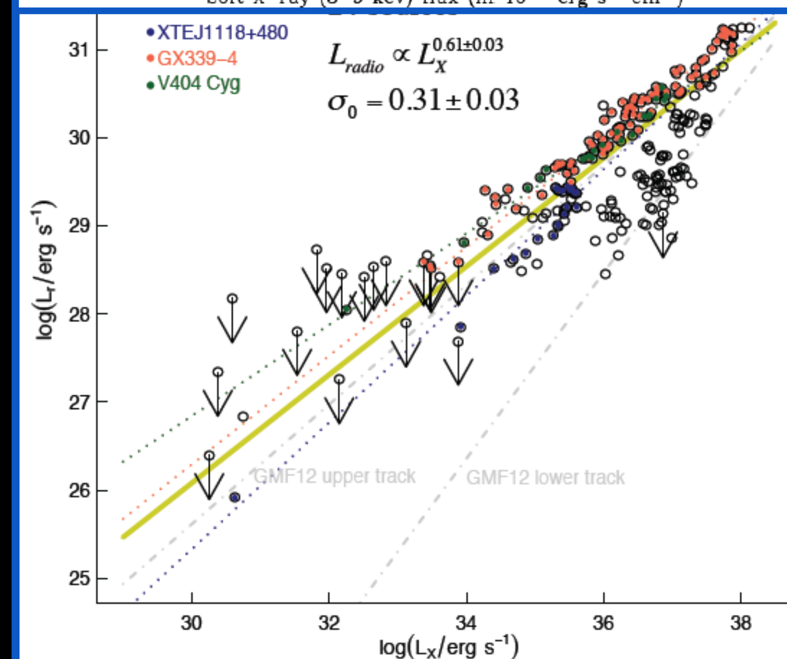
Jet-Accretion Link in Black Holes

Corbel+2003
Tight X-ray/radio correlation of a black hole X-ray binary (multiple outbursts)

Gallo+2014
Confirms relation for 24 black holes, broader Lx range "Universal Correlation"

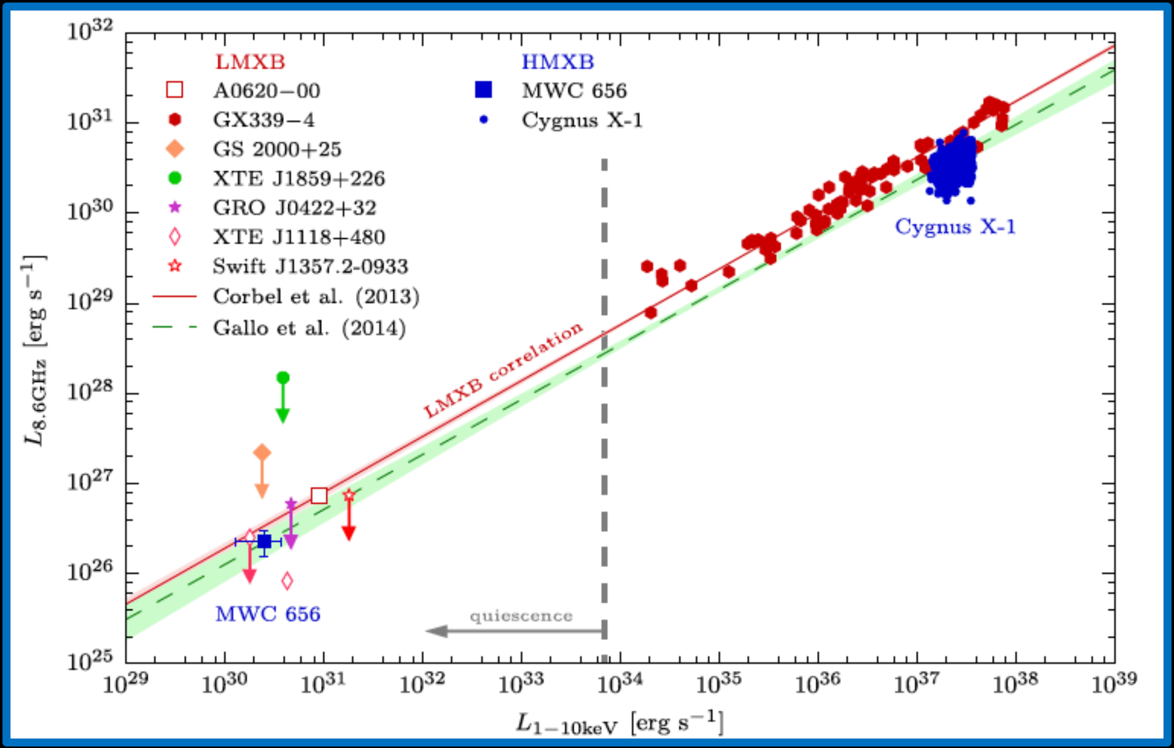
See also Hannikainen+1998; Corbel+2000, 2008, 2013; Gallo+2003, 2012; Jonker+2010; Coriat+2011; Miller-Jones+2011





Jet-Accretion Link in Black Holes

Ribo+2017
Radio detection of first black hole Be X-ray binary (MWC 656)



Consistent with Lx/Lr correlation of black hole low-mass X-ray binaries

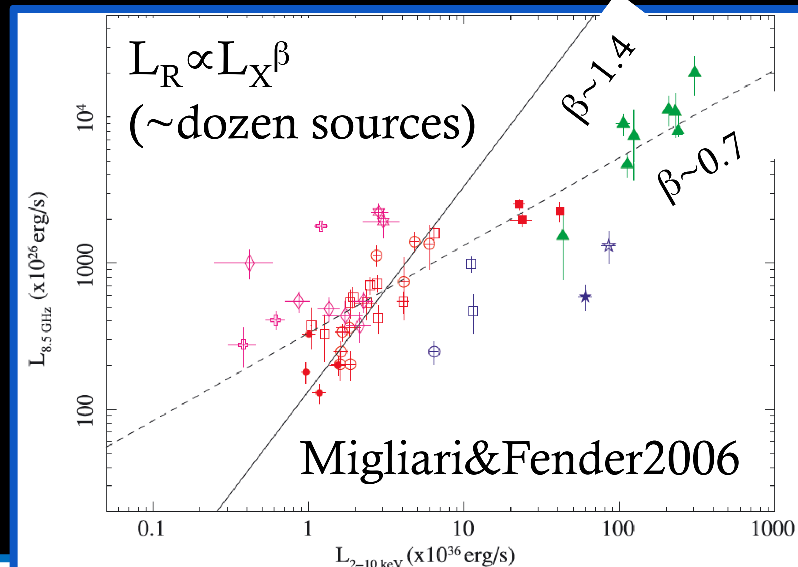
→ Nature of donor star / transfer of matter does not matter for jet production

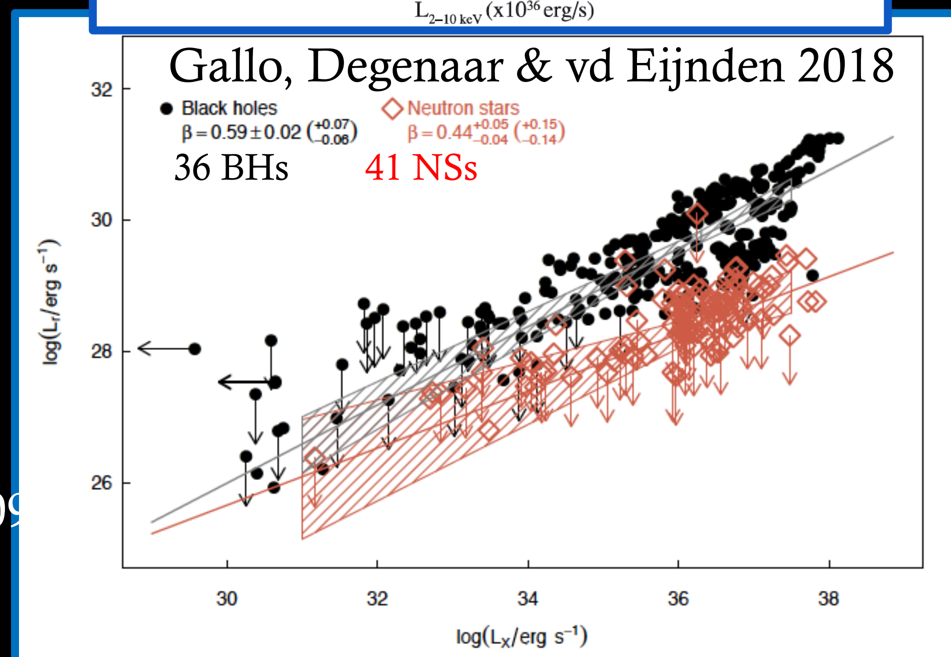
Jet-Accretion in Neutron Stars

Fender & Kuulkers 2001
Neutron stars fainter in radio than black holes

Migliari & Fender 2006
Different couplings NSs?

Gallo+2018
Single coupling index NSs
Coupling similar to BHs
NSs factor 20 radio fainter



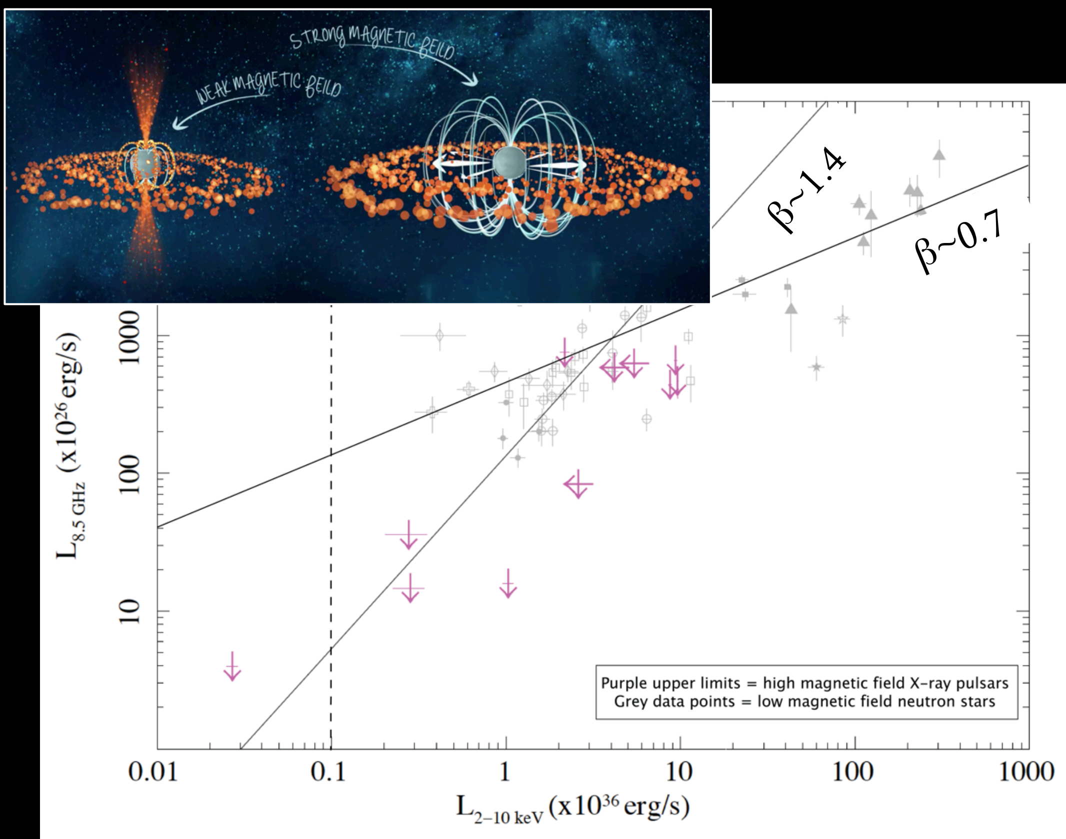


Also Fender+2003; Migliari+2003,2011,2012; Muno+2005; Tudose+2009; Miller-Jones+2009; Deller+2015; DeMartino+2015; Tetarenko+2017; Tudor+2017

Effect of Strong Magnetic Field

Migliari+2012

Compilation of new + old work: No radio detections of neutron stars in high-mass X-ray binaries



Observational paradigm

Strong magnetic fields ($B \sim 10^{12}$-10^{13} G) prevent jet formation

Supported by theory

(Massi & Kaufman Bernadó 2008)

See also Fender & Hendry 2000; Migliari+2006

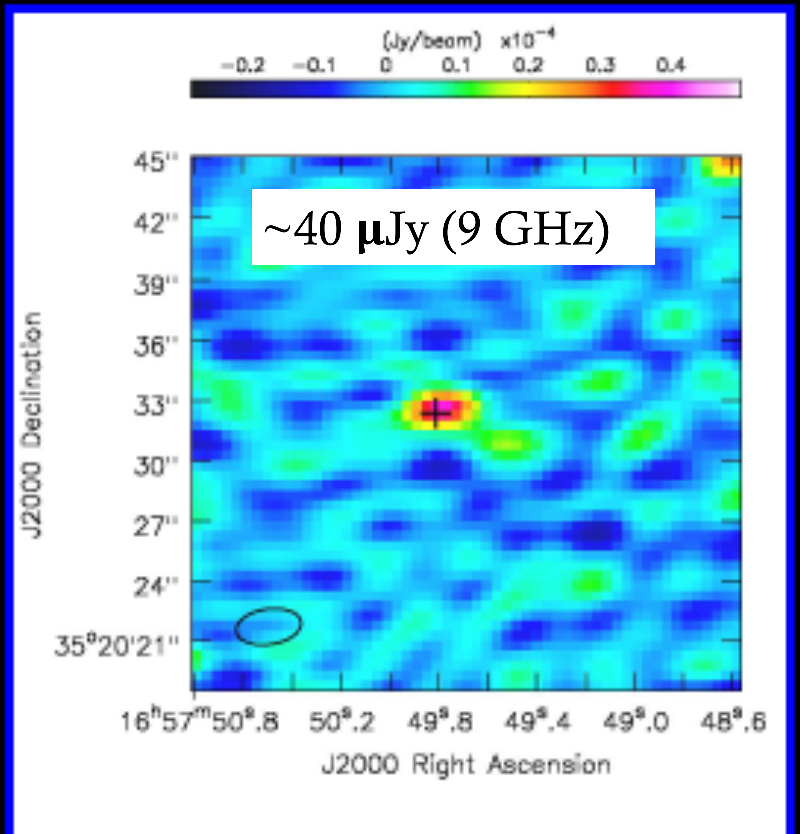
Radio Detections High-B NSs

Van den Eijnden+2018 ab

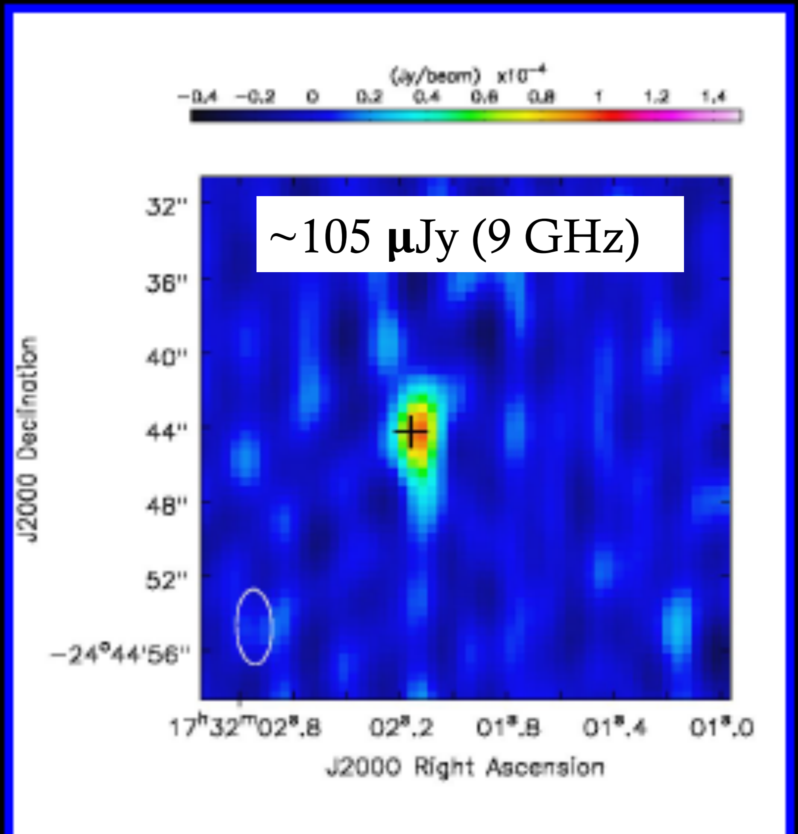
Radio detections of 2 neutron stars with B~10^{11}-10^{13} G

Single band/epoch: Possibly a jet, but not conclusive

Her X-1



GX 1+4



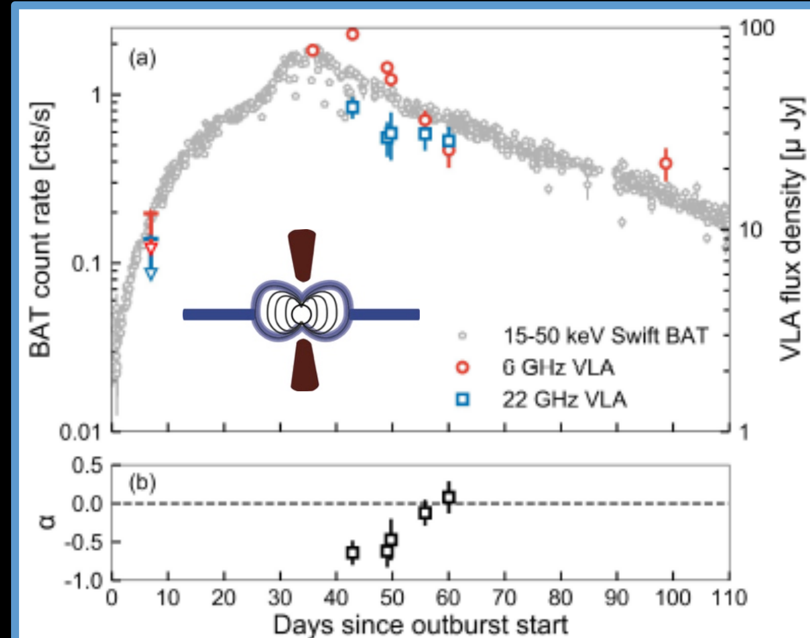
Jet from a Magnetic Neutron Star

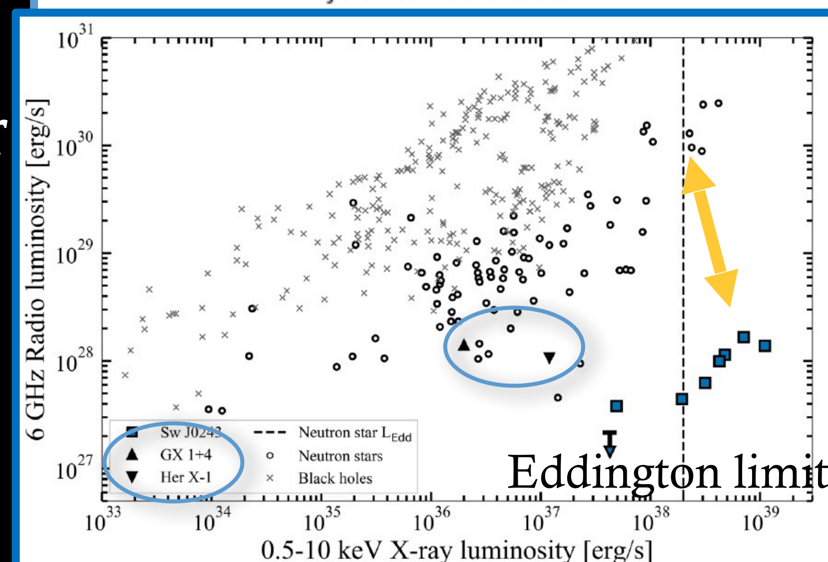
van den Eijnden+2018c (Nature)

- ◇ Unambiguous jet detection neutron star with a strong magnetic field ($B \sim 10^{12}$ G)

- ◇ Much fainter in radio than other neutron stars at similar X-ray luminosity
- ◇ Effect magnetic field? Spin?

Inner disk radius at ~850 km





Follow up

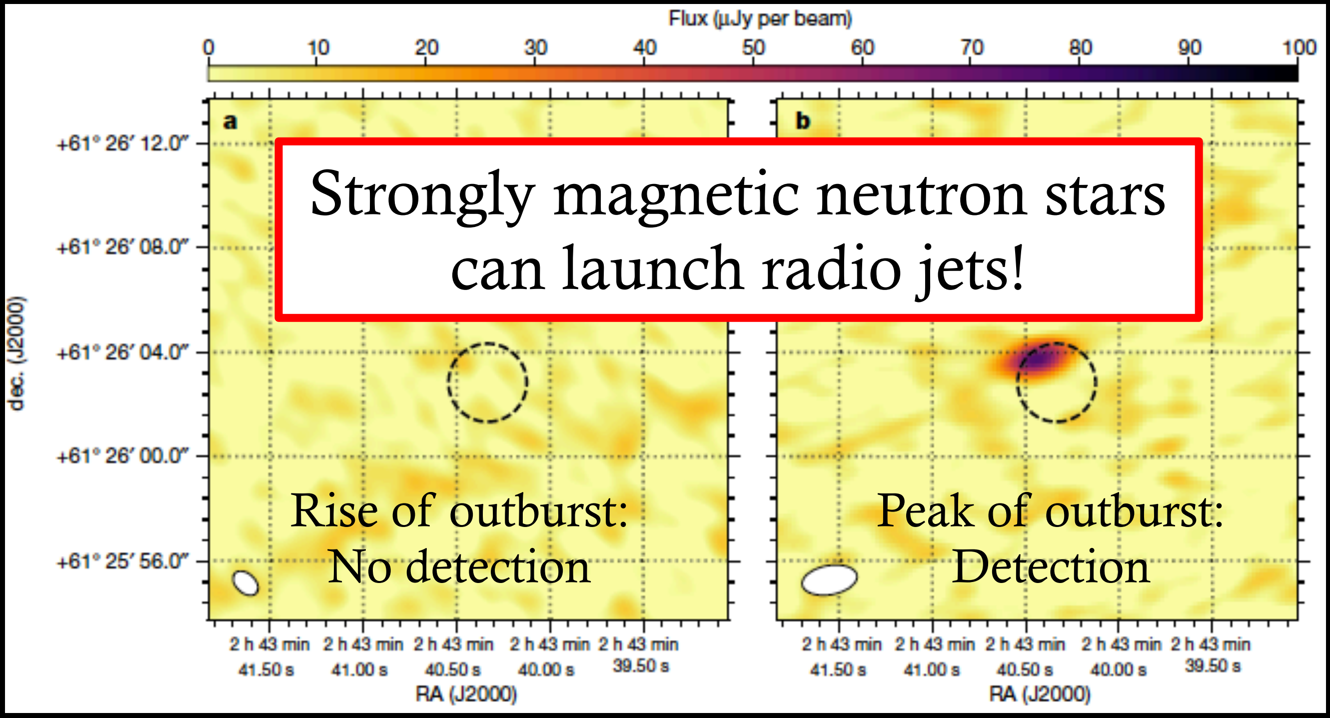
Van den Eijnden+ in prep.

Radio spectral index for GX 1+4: consistent with jet

Sample of 12 persistent neutron stars with B~10^{11}-10^{13} G

Unbiased (no distance/Lx selection): ~6 radio detections

(likely jet detections: Vela X-1, 4U 1700-37, IGR J16318-4848)



van den Eijnden+2018c (detection of transient radio jet in Swift J0243)

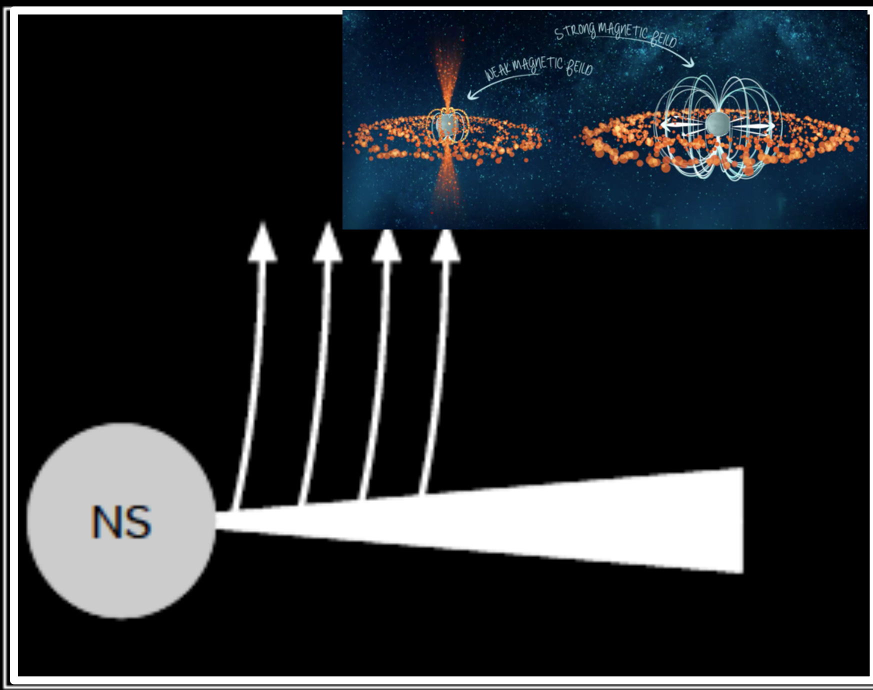
Impact: New Views Jets & Accretion

- ◇ Very different accretion geometry (location inner disk)
- ◇ Test effect of spin on jet Spin dependance: range ~1-1000 s

- ◇ Revise/expand jet models

Impact: Jet Launching

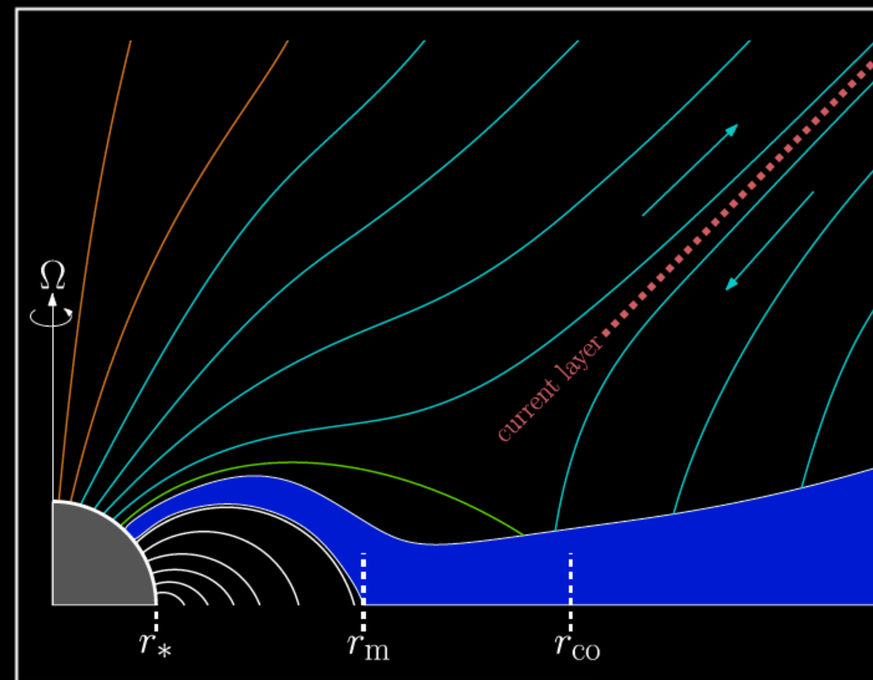
Blandford-Payne (1982)



Massi & Kaufman Bernadó (2008)

Jets cannot form if neutron star has B>10^{10} G (inner disk missing)

Parfrey et al. (2016): alternative mechanism



Parfrey+2016

Jets can form, but… jet power ~$\mu^{6/7}$ spin^2 (expect weaker jets)

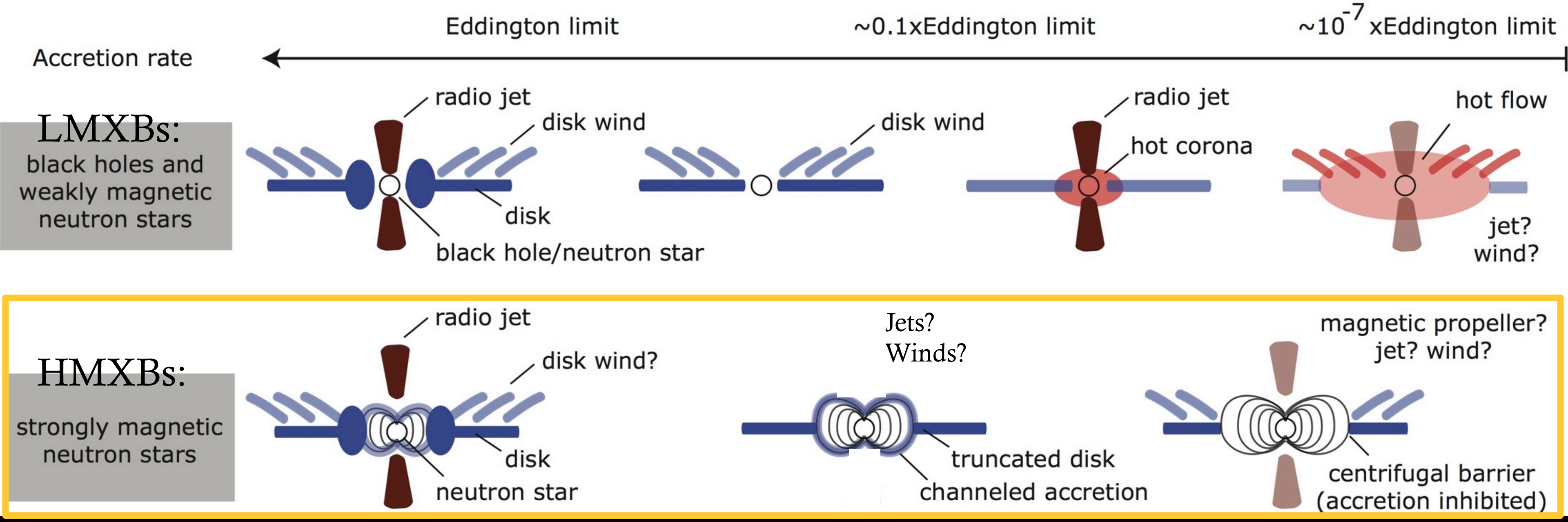
Impact: New Views Jets & Accretion

- ◇ Very different accretion geometry (location inner disk)
- ◇ Test effect of spin on jet Spin
  dependance: range ~1-1000 s

- ◇ Revise/expand jet models

- ◇ New way to probe magnetic accretion
  Accretion morphology in high-mass X-ray binaries?
  → Can be tested through jets

Impact: Magnetic Accretion



Open questions on accretion in HMXBs:

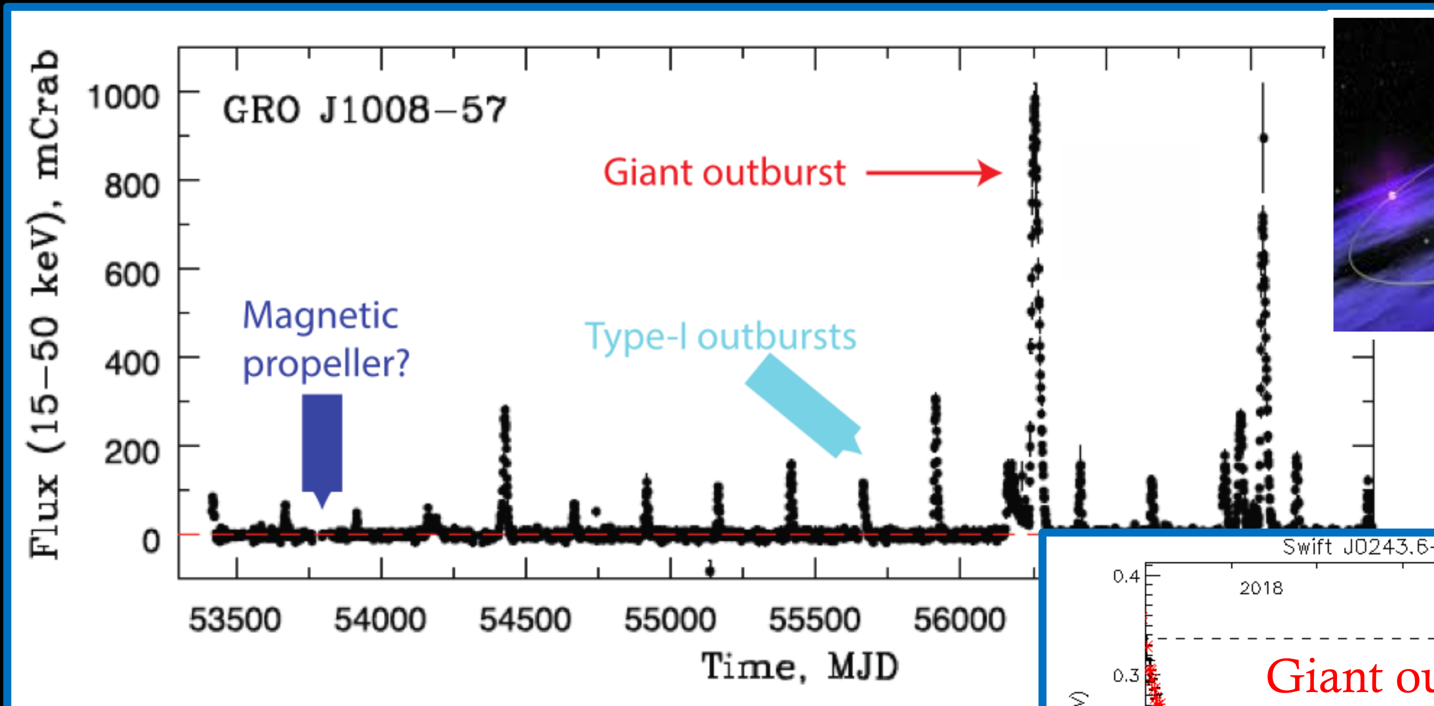
Are jets and winds produced? When?

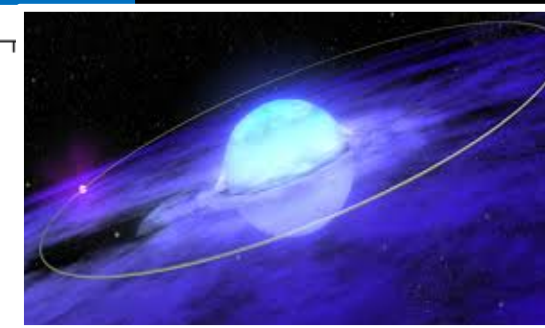
At low accretion rate: magnetic propeller?

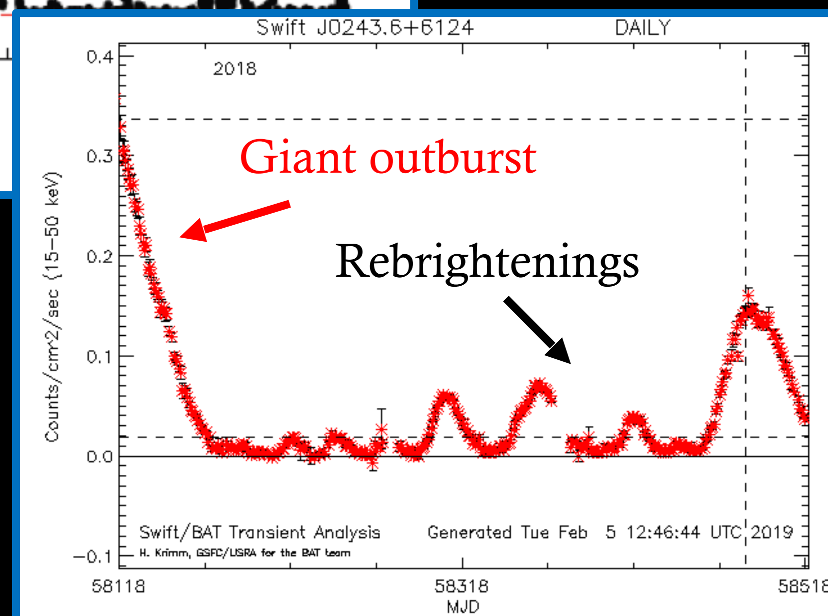
Accretion morphology during different types of activity?

→ Jets can be a new probe of magnetic accretion

Accretion in Be X-Ray Binaries







Type-I outbursts: Periastron passages
Giant outbursts: Mechanism?

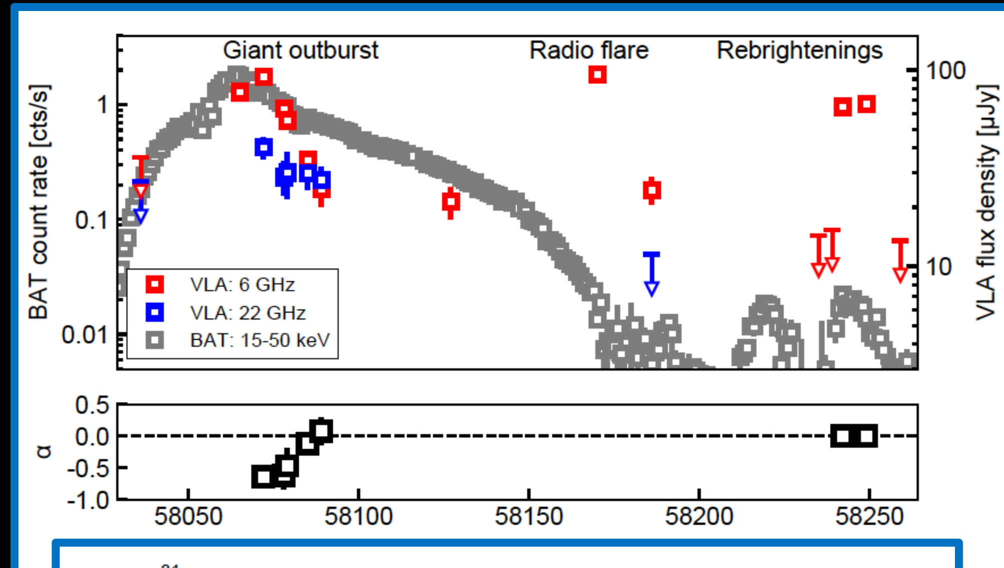
Propeller at low accretion rate?
Rebrightenings: Cool wave in disk?

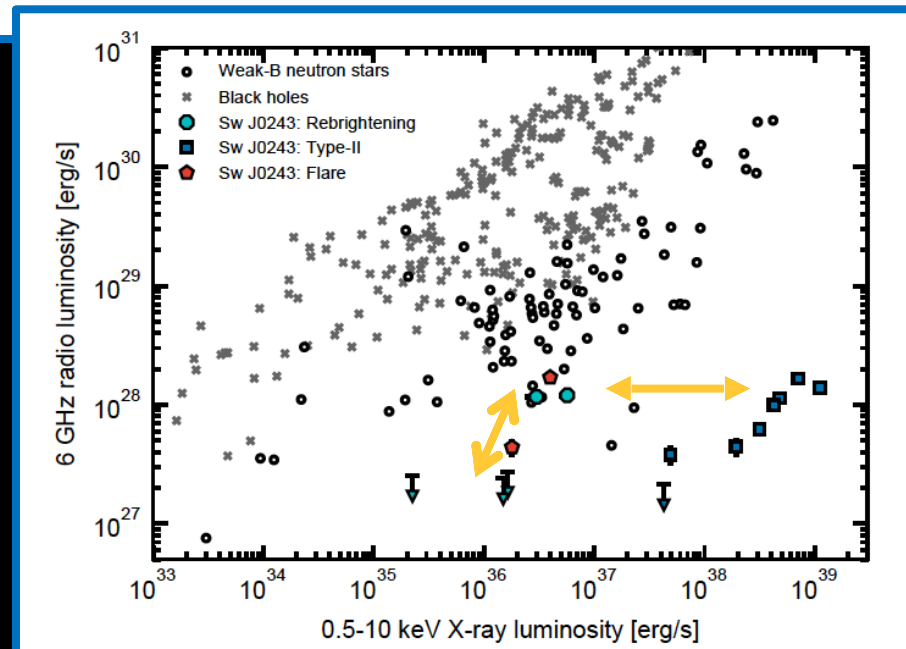
Jet During Rebrightenings

van den Eijnden+2019
Jet switches on during rebrightenings after a giant outburst

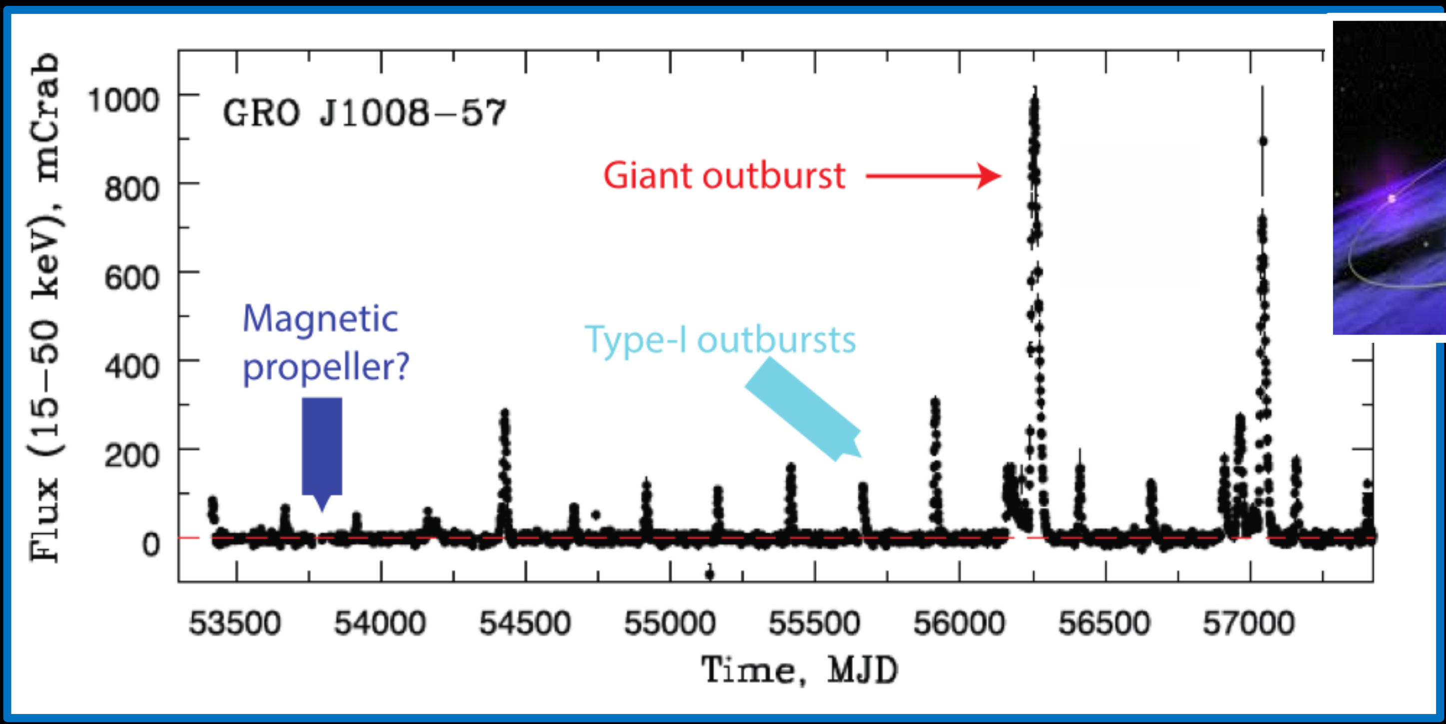
Similar radio brightness despite factor >100 lower X-ray luminosity

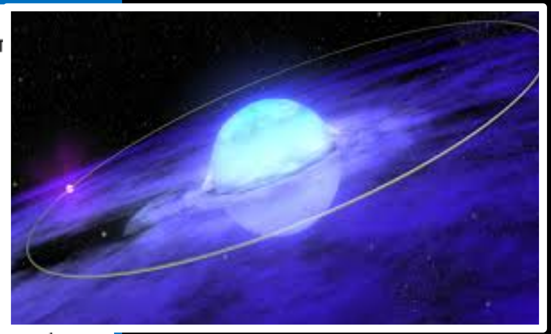
Jet switches on abruptly: Magnetic field interaction?





Jets as Probes of Accretion





Established: radio jet in giant outbursts + rebrightenings

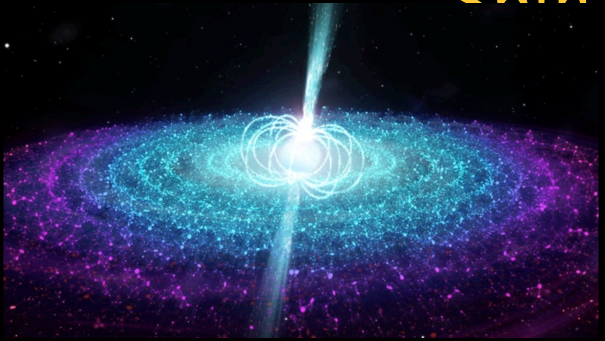
Planned: more dense monitoring jet turn on/off

Planned: radio jets in type-I outbursts + propeller regime?

Conditions for jet launching, accretion morphology

Impact: New Views Jets & Accretion

- Very different accretion geometry (location inner disk)
- Test effect of spin on jet
  Spin dependance: range ~1-1000 s



- Revise/expand jet models

- New way to probe magnetic accretion
  Accretion morphology in high-mass X-ray binaries?
  → Can be tested through jets

- New way to probe jets at super-Eddington accretion
  Giant outbursts reach super-Eddington rates (ULX)

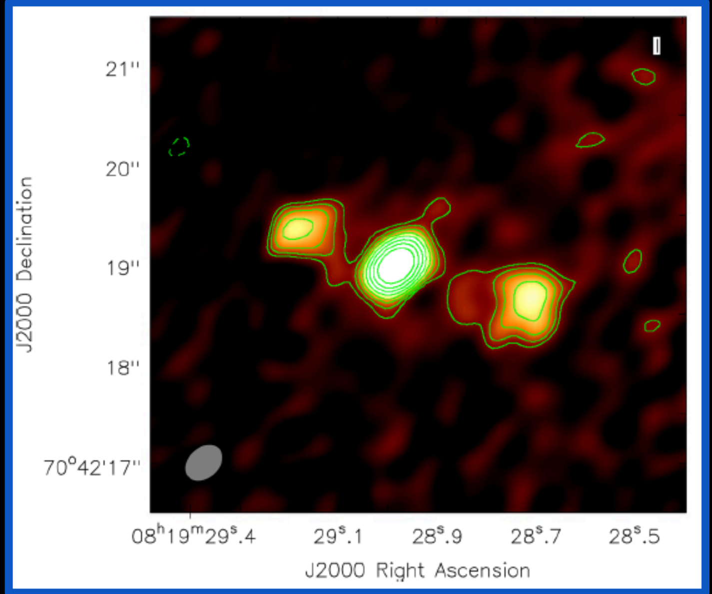
Impact: Jets @ Super-Eddington

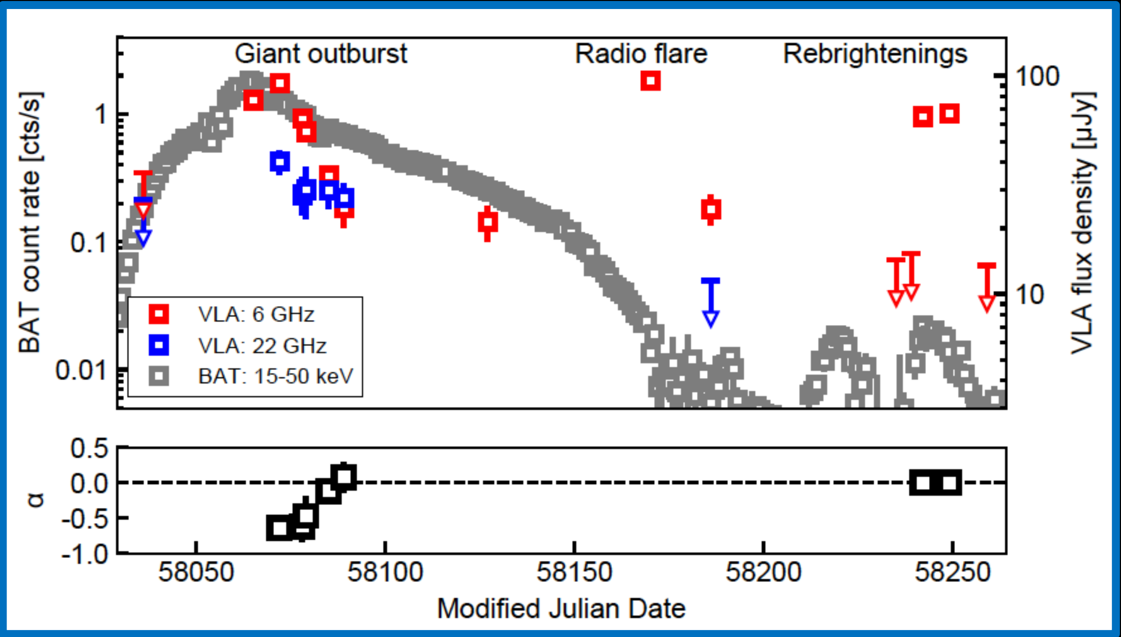
Cseh+2014, 2015

Radio jet ejections from ultra-luminous X-ray sources (ULXs)

What about a steady jet?

See also Soria+2010; Grise+2011

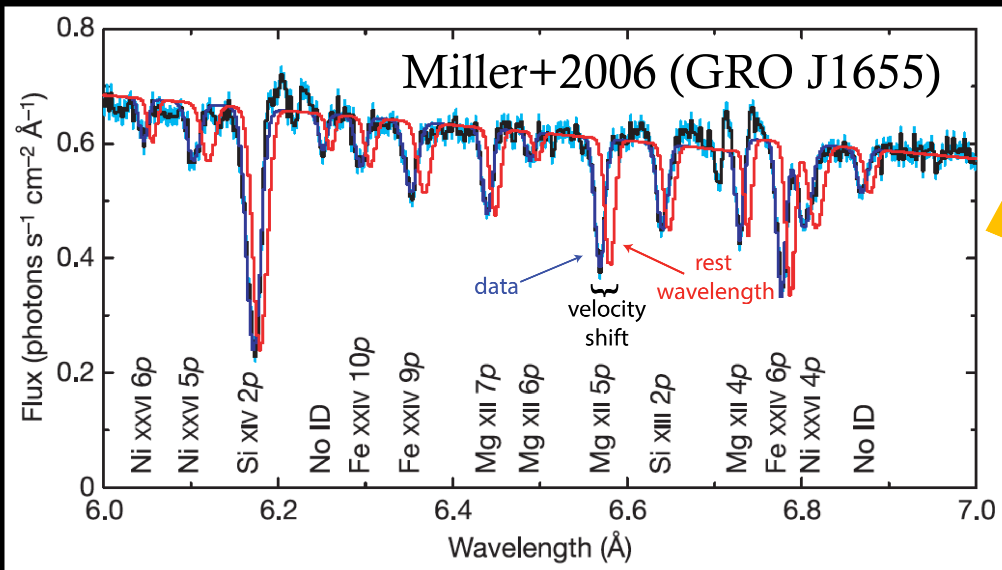


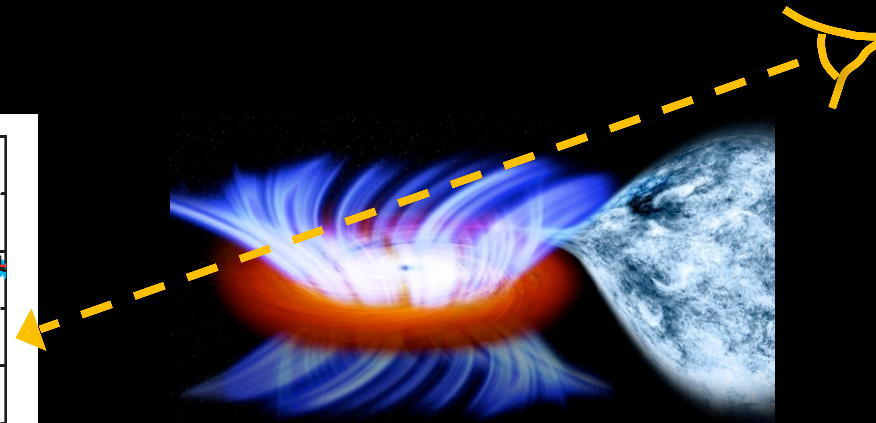


Giant outbursts of Be X-ray binaries: Test jet production in super-Eddington accretion regime

Disk Winds

Observing Disk Winds





Mass content wind
Launching mechanism

Observables
line species
line shift
line width
line depth

→

Physical information
velocity of the plasma
ionization state
(column) density
launch radius

Current Status Disk Winds

Diaz Trigo & Boirin 2016 (review)

Ionized emission/absorption in 19 sources (8 black holes)

Since then 5 more (4 neutron stars, 1 black hole)

Source	P_{orb}	N_H^{Gal} 10^{21} cm^{-2}	NS	Dips	i (°)	log ξ < 3	≥ 3	Flow	References on the warm absorbers
XB 1916−053	0.83 h	2.3	NS	D		x	x	atm	Boirin04, Juett06, Díaz Trigo06, Iaria06, Zhang14
1A 1744-361	1.62 h	3.1	NS	D			x	atm	Gavriil12
4U 1323−62	2.93 h	12	NS	D			x	no grat.	Boirin05, Church05, Bałucińska-Church09
EXO 0748−676	3.82 h	1.0	NS	D		x	x	atm	Díaz Trigo06, van Peet09, Ponti14
XB 1254−690	3.93 h	2.0	NS	D			x	atm	Boirin03, Díaz Trigo06/09 , Iaria07
MXB 1658−298	7.11 h	1.9	NS	D		x	x	atm	Sidoli01, Díaz Trigo06
XTE J1650−500	7.63 h	4.2			> 50	?[a]	?[b]	?[c]	Miller02/04
AX J1745.6-2901	8.4 h	12	NS	D			x	no grat.	Hyodo09, Ponti15
MAXI J1305–704	9.74 h[d]	1.9		D		x		in	Shidatsu13, Miller14
X 1624−490	20.89 h	20	NS	D			x	atm	Parmar02, Díaz Trigo06, Iaria07b, Xiang09
IGR J17480–2446	21.27 h[e]	6.5	NS	D			x	out	Miller11
GX 339−4	1.76 d	3.6			> 45[f]	x		?[g]	Miller04, Juett06
GRO J1655−40	2.62 d	5.2		D			x	out	Ueda98, Yamaoka01, Miller06b/08, Netzer06, Sala07, Díaz Trigo07, Kallman09, Luketic10, Neilsen12
Cir X−1	16.6 d	16	NS	D		x	x	out	Brandt00, Schulz02, , D'Aí07, Iaria08, Schulz08
GX 13+1	24.06 d	13	NS	D			x	out	Ueda01/04, Sidoli02, Díaz Trigo12, Madej14, D'Ai14
GRS 1915+105	33.5 d	13		D			x	out	Kotani00, Lee02, Martocchia06, Ueda09/10, Neilsen09/11/12
IGR J17091–3624	>4 d[h]	5.4			> 53[i]		x	out	King12
4U 1630−47		17		D			x	out	Kubota07, Díaz Trigo13/14, King13/14, Neilsen14
H 1743−322		6.9		D			x	out	Miller06a

Degenaar+2015;

King+2016;

Miller+2016;

van den Eijnden+2017;

Raman+2018

Current Status Disk Winds

Diaz Trigo & Boirin 2016 (review)

Ionized emission/absorption in 19 sources (8 black holes)

Since then 5 more (4 neutron stars, 1 black hole)

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AX J1745.6-2901	8.4 h	12	NS	D			x	no grat.
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IGR J17480–2446	21.27 h[e]	6.5	NS	D			x	out
GX 339−4	1.76 d	3.6			> 45[f]	x		?[g]
GRO J1655−40	2.62 d	5.2		D			x	out
Cir X−1	16.6 d	16	NS	D		x	x	out
GX 13+1	24.06 d	13	NS	D			x	out
GRS 1915+105	33.5 d	13		D			x	out
IGR J17091–3624	>4 d[h]	5.4			> 53[i]		x	out
4U 1630−47		17		D			x	out
H 1743−322		6.9		D			x	out

Velocities: ~200-3000 km/s

Extreme cases: ~ 0.04 c

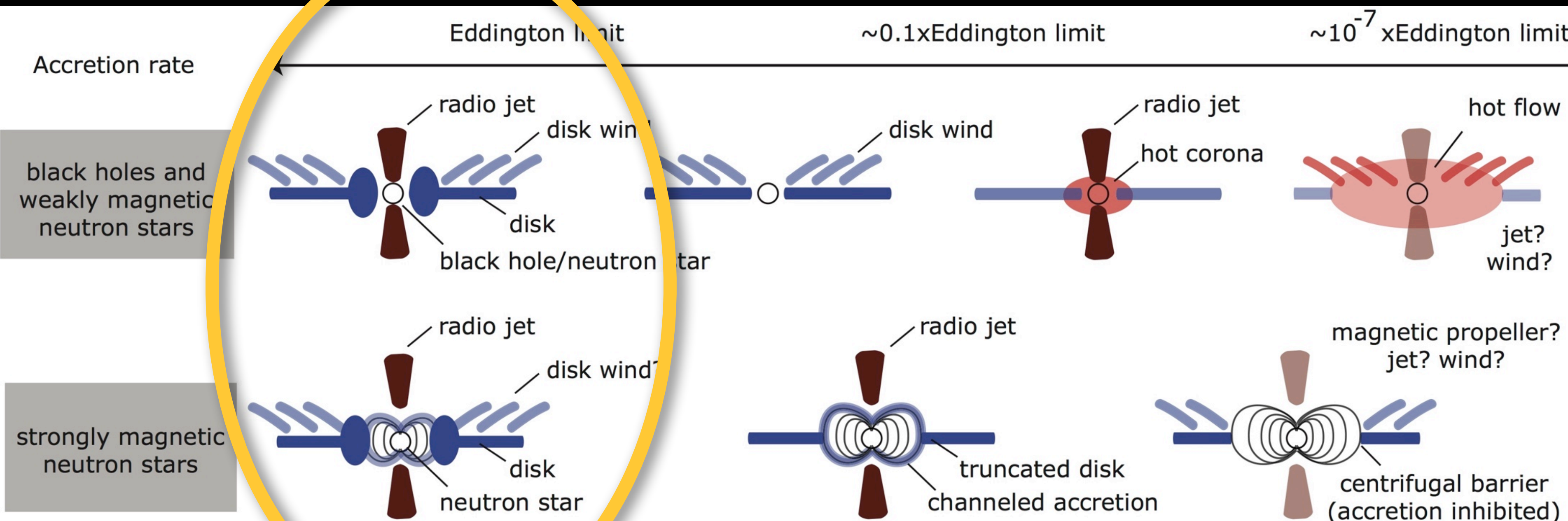
Mass loss rate wind:

~0.01 – 1x inferred accretion rate

Significant mass loss!

Winds @ Extreme Accretion

Accretion Regimes



Relatively rare

Most easily studied

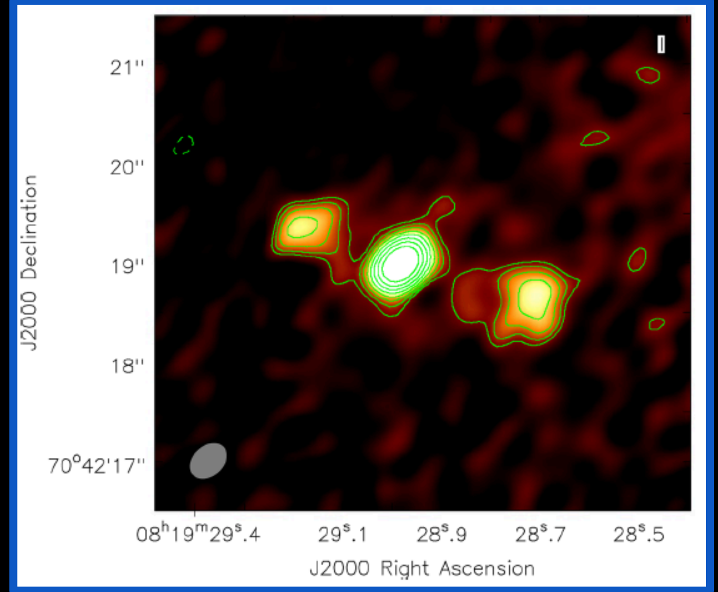
Common but difficult to study

Outflows Super-Eddington Regime

Cseh+2014, 2015

Radio jet ejections from ultra-luminous X-ray sources (ULXs)

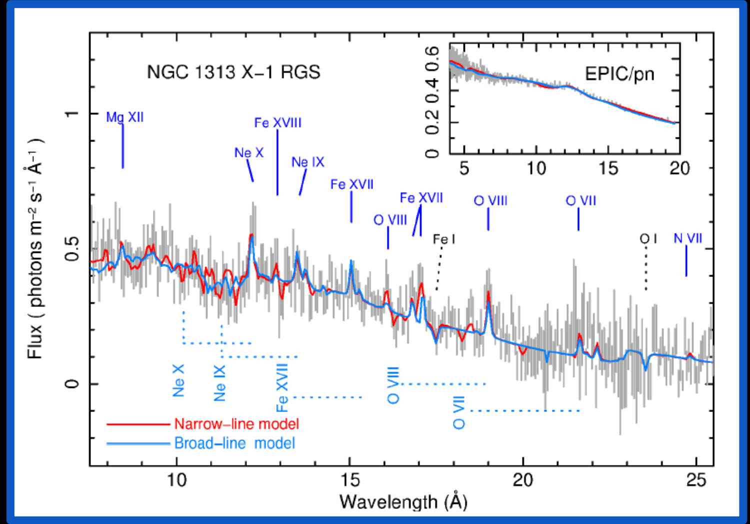
See also Soria+2010; Grise+2011



Pinto+2016, 2017

Wind outflows detected for several <u>other</u> ULXs: v~0.1-0.3c

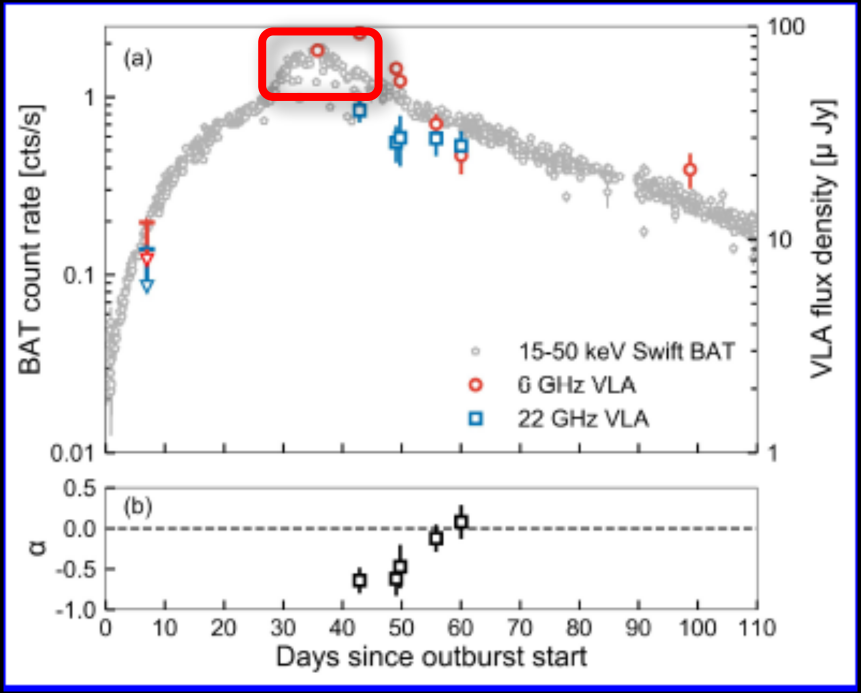
See also Walton+2017; Kosec+2018



Outflows Super-Eddington Regime

van den Eijnden+2018c
Jet detection from Galactic super-Eddington neutron star

van den Eijnden+ submitted
Chandra/HETG at peak of outburst ($L_X > 10^{39}$ erg/s)



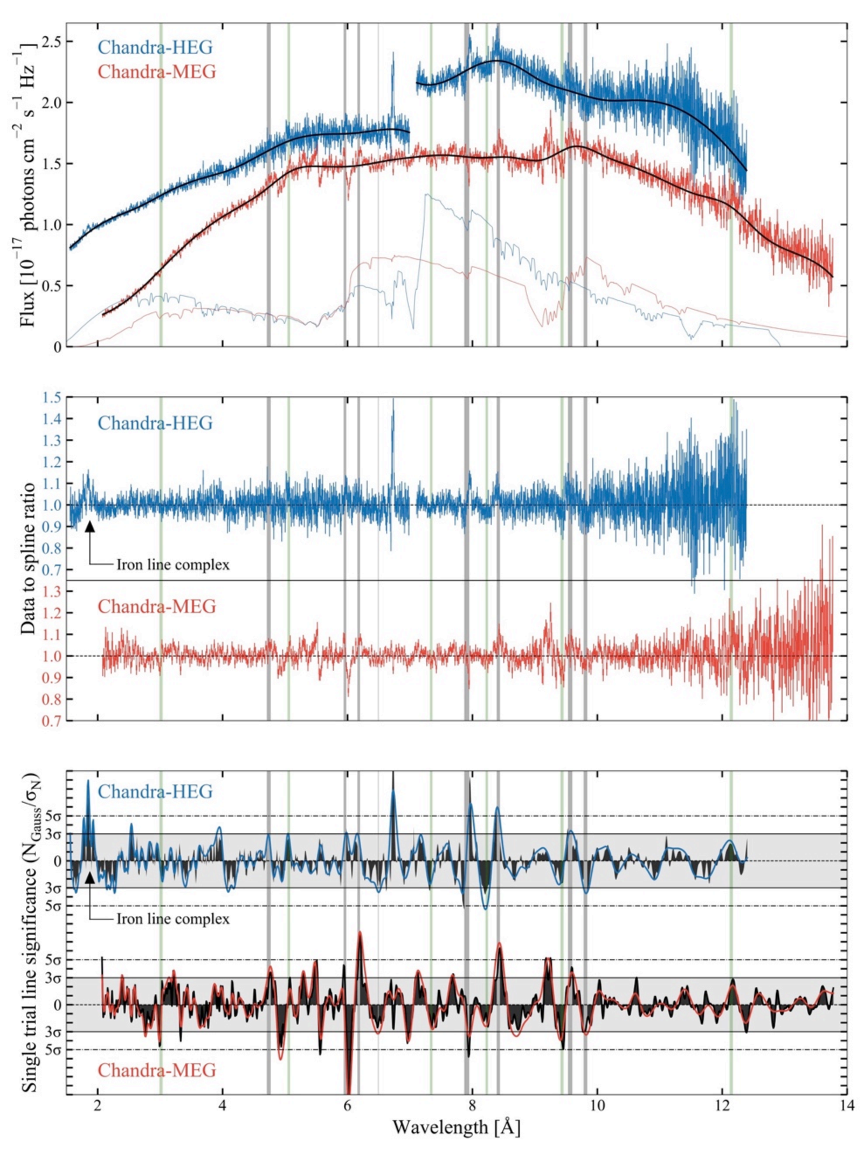
Super-Eddington Jet + Wind

van den Eijnden+2018c
Jet detection from Galactic super-Eddington neutron star

van den Eijnden+ submitted
Chandra/HETG at peak of outburst ($L_X > 10^{39}$ erg/s)

Ionized absorption lines: possible outflow of v~0.2c

Jet + disk wind detection in super-Eddington regime



Impact of Outflows on the Environment of X-ray Binaries

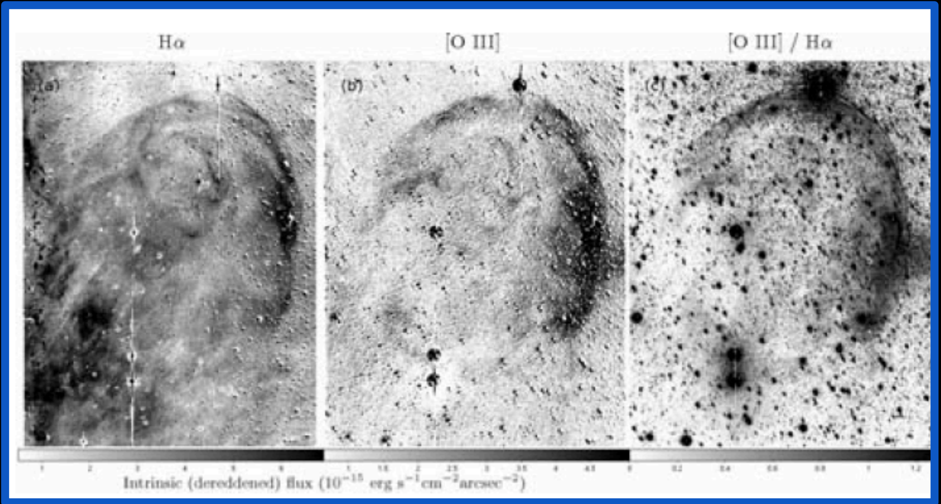
Nebulae Around X-ray Binaries

Gallo+2005

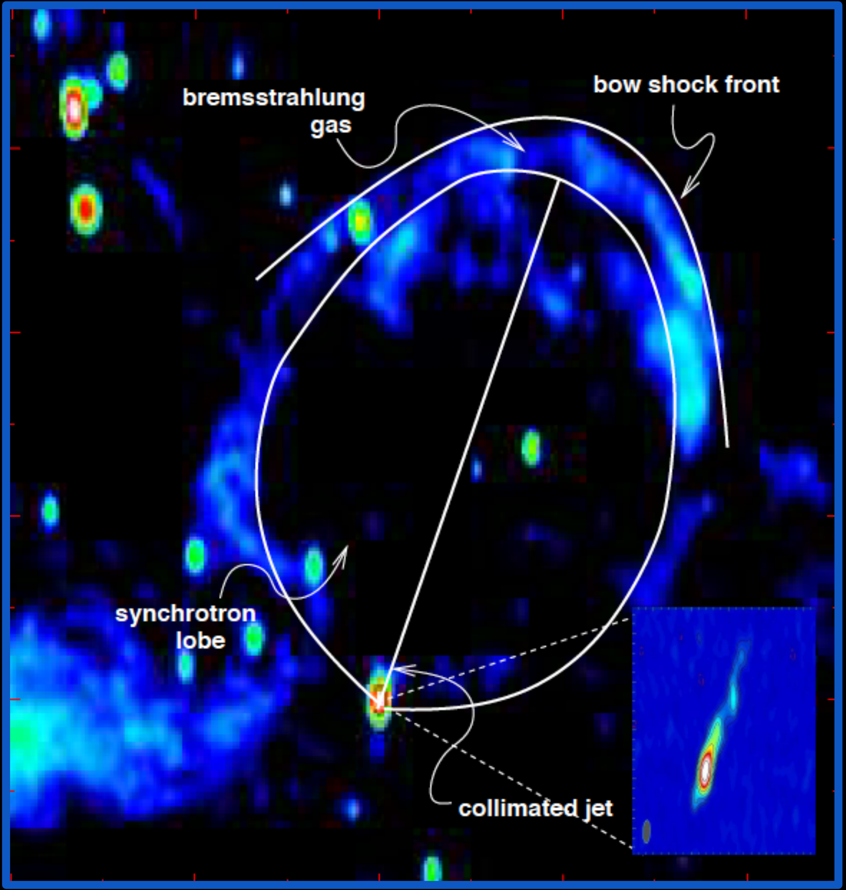
Nebula around black hole Cyg X-1 (radio): Interaction of strong jet with ISM

Russell+2007

Associated optical nebula



Optical images narrow filters

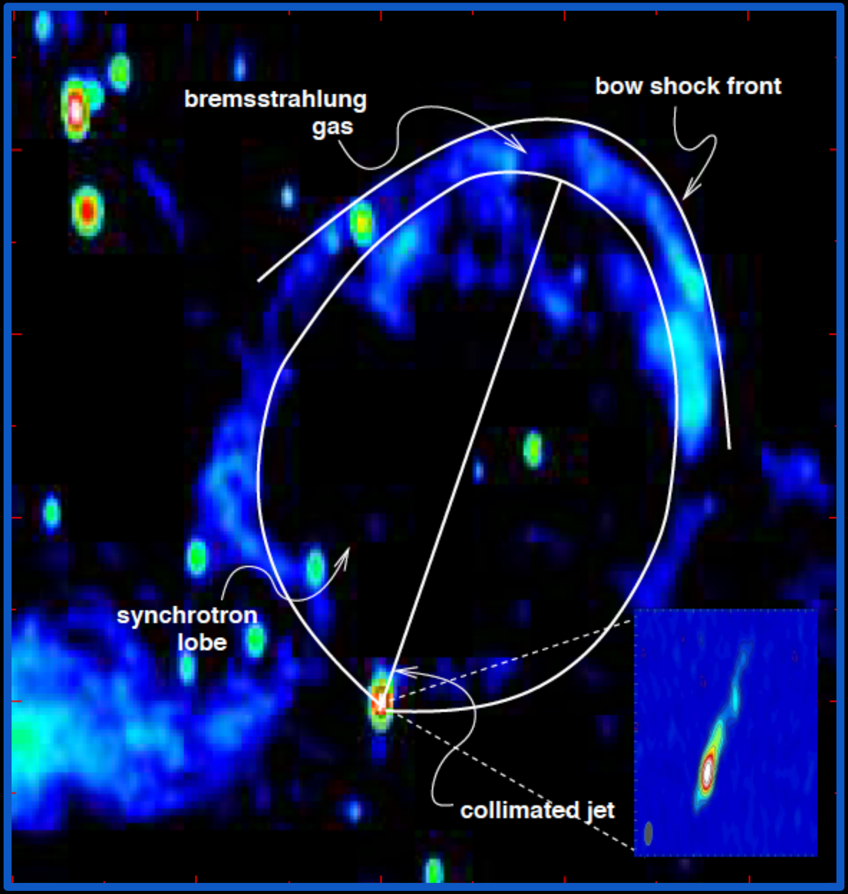


1.4 GHz radio image

Impact of X-ray Binary Outflows

Mirabel & Rodríguez 1999
Fender+2005
Shock fronts may serve as acceleration sides to produce high-energy cosmic rays

Justham & Strawinsky 2012
Feedback of X-ray binaries may rival that of supernova explosions



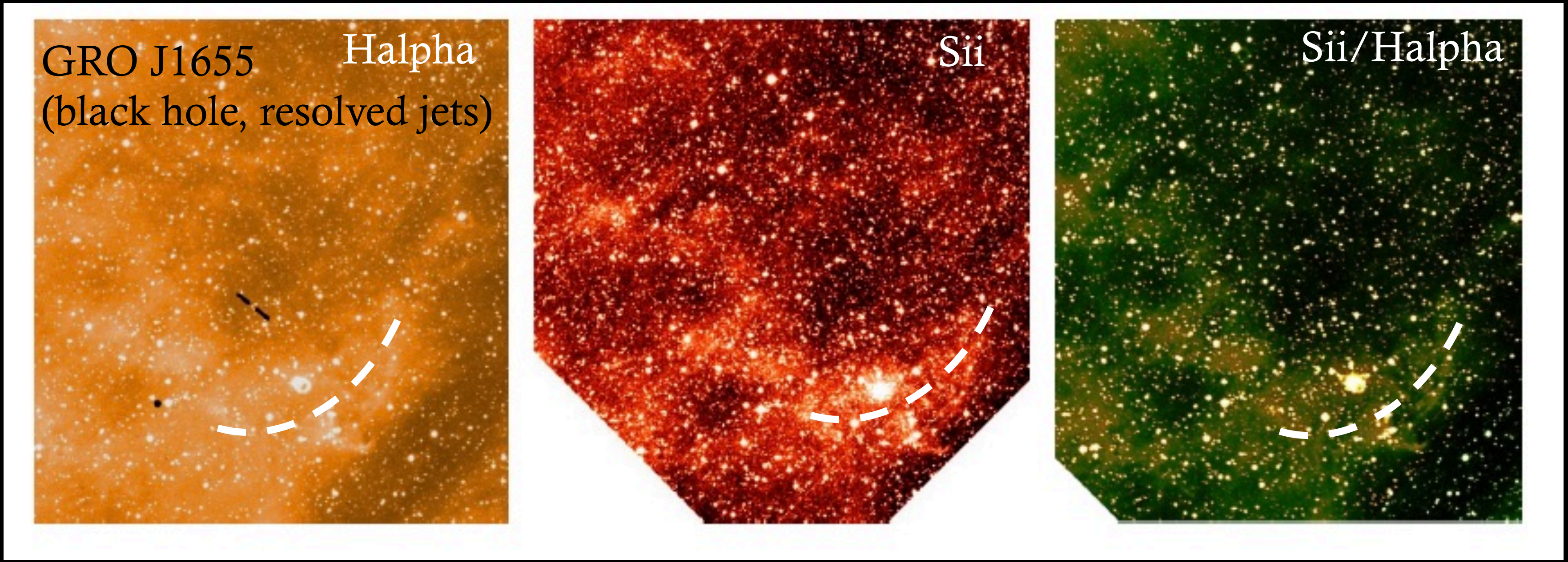
How common are these nebula?
Are all X-ray binaries an important source of feedback?

Nebulae Around X-ray Binaries

Russell+2006; Tudose+2006

Searched (black hole) low-mass X-ray binaries strong jets

Few other candidate nebulae (radio or optical)



What about the feedback potential of disk winds?

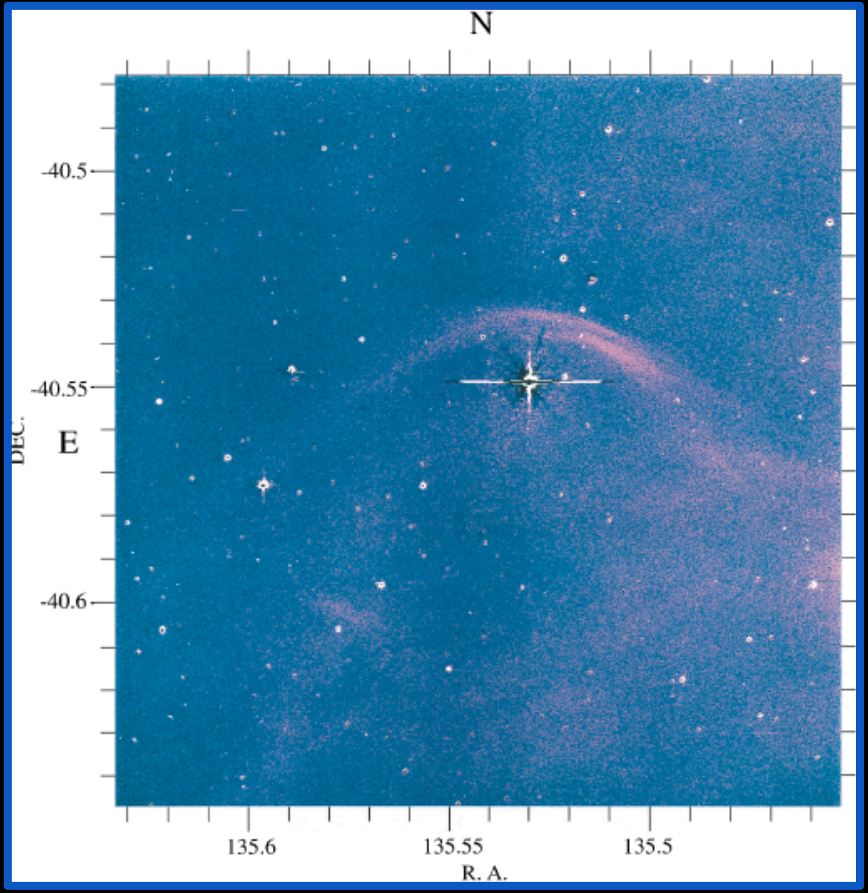
Less powerful but larger subtended angle

Nebulae Around X-ray Binaries

Kaper+1997
Bow-shock nebula high-mass X-ray binary Vela X-1

High proper motion, wind of massive companion interacts with ISM

It also has a radio jet…
Role in nebula production?



R-band corrected H-alpha image (10'x10')

An Unbiased Pilot Study

September 2018:
INT/WFC narrow-band images of 19 X-ray binaries
Various outflows, various companion types

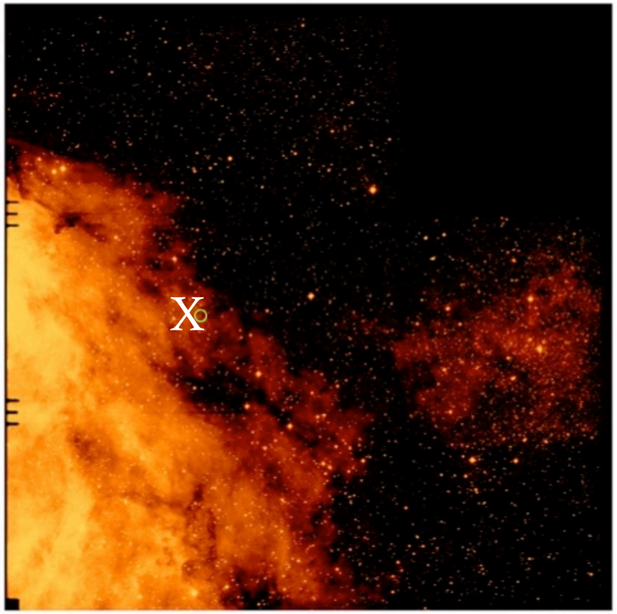
~ 34’x34’ field of view
~1 hr integration times
5 observing nights total
(bright nights)

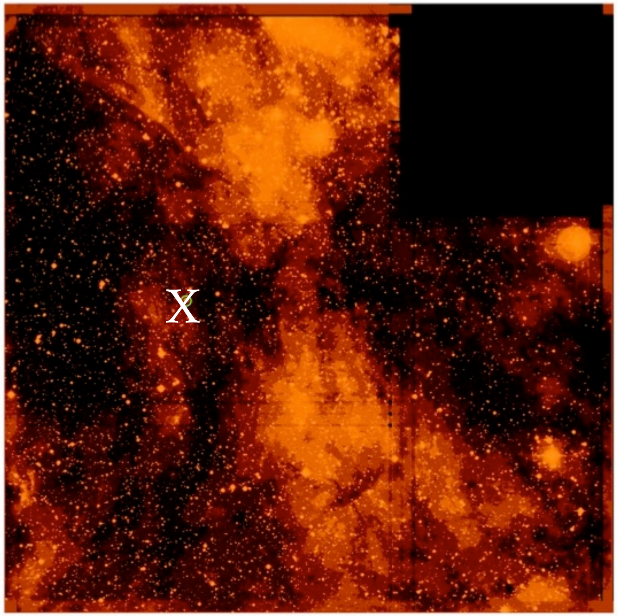
Find the Nebula

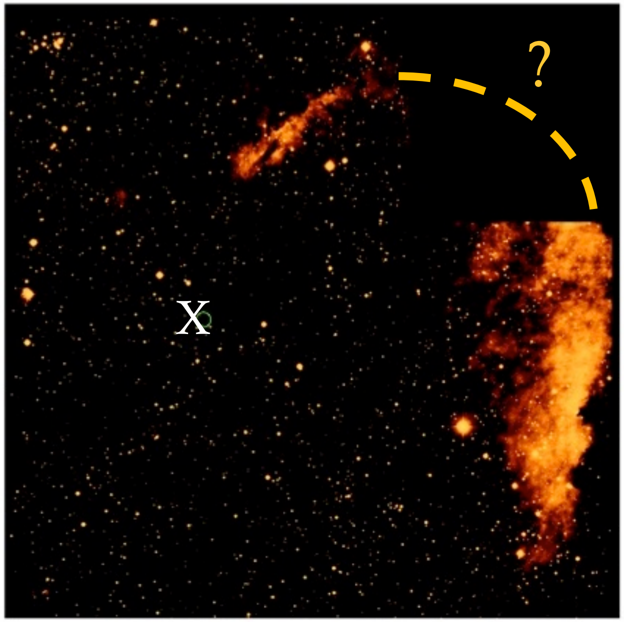
H-alpha images: Quick-look results (Maria Georganti)

Not easy to find! Only one suggestive case jumping out

But… plenty of things to explore for image processing







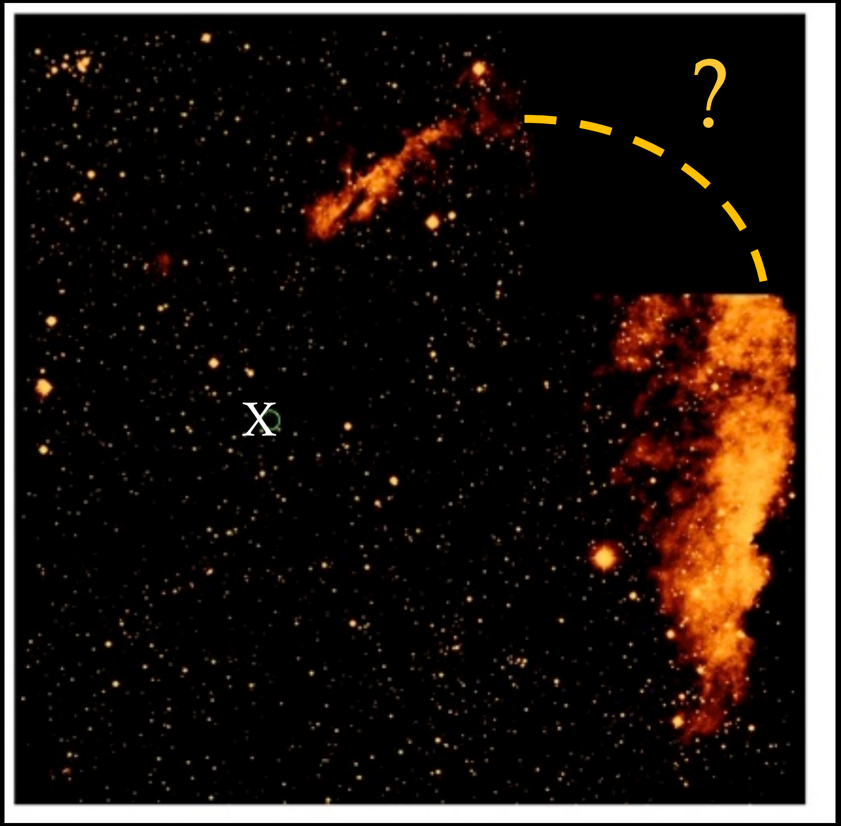
GX 17+1
Bright persistent neutron star near Eddington, jet+wind

Swift J0243
Transient magnetic NS, super-Eddington wind+jet

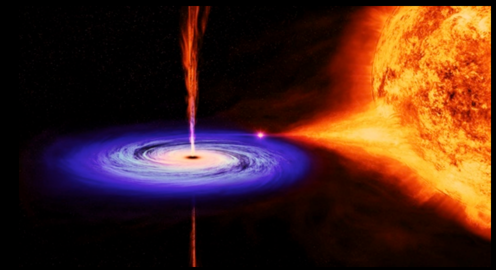
Cyg X-3
Bright persistent black hole, massive companion, jet

To Be Continued

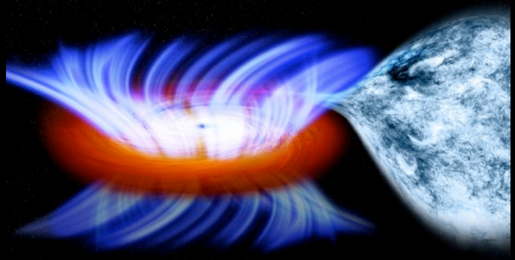
- ◇ Are X-ray binaries overall important for feedback?
- ◇ Unbiased/complete search for nebula warranted
- ◇ <u>Not</u> finding many nebula = important result too



Probe the feedback of different outflows (jets, disk winds) and different types of systems (LMXBs, HMXBs)



To Take Away



- ◇ Accretion is universally linked to jets and winds
  X-ray binaries: study (dynamic) outflows
- ◇ Open questions about X-ray binary outflows
  Launch mechanism, mass loss, kinetic power
- ◇ Mass loss and power of outflows important for
  Regulating accretion, binary evolution, feedback
- ◇ New ways to probe jets and accretion Jets
  from strongly magnetic neutron stars

NOVA

NWO Netherlands Organisation for Scientific Research

LKBF

July 1-3, 2019: From Winds to Jets

A dedicated conference on the important role of outflows in compact binary systems

Abstract deadline: March 15

www.outflows2019.com

SOC & LOC: Nathalie Degenaar, Thomas Russell Juan Hernández Santisteban, Jakob van den Eijnden