13 - 15 November 2023
Valencia

Fourth European Physical Society Conference on Gravitation: Black Holes

Observations of Galactic Black Holes

J. Casares (IAC)

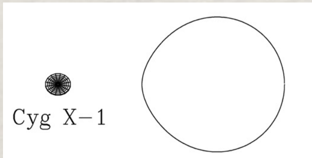
GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

1972: 1st BH: Cyg X-1 (Webster & Murdin; Bolton 1972)

Wind fed from
O9.7 Iab star



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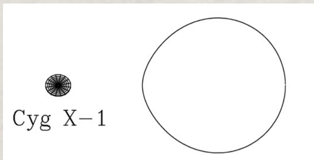
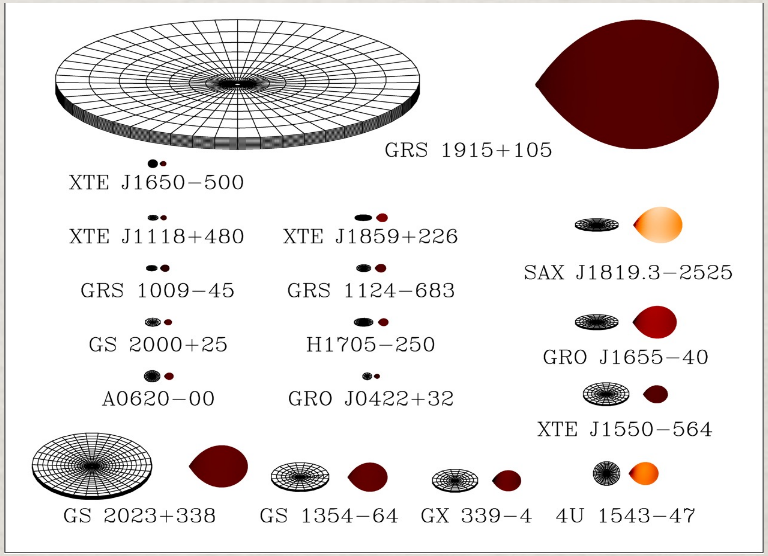


Disc fed from K-type V star



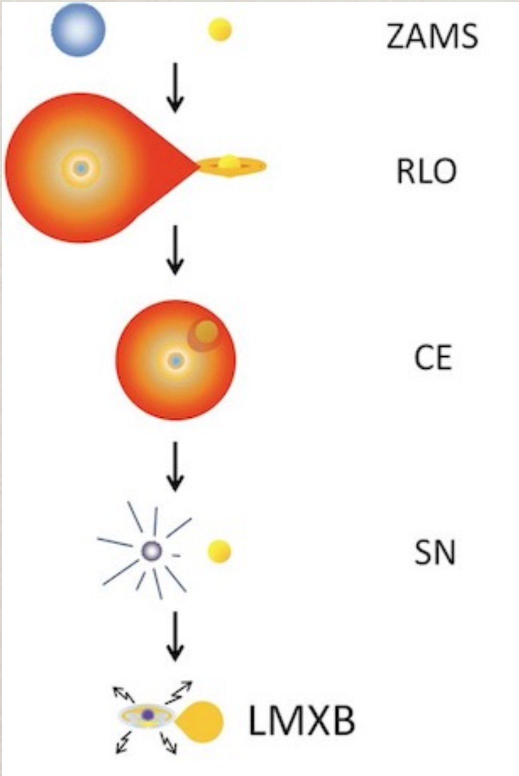
McClintock et al. 2011

2023: 19 “confirmed” BHs in the Galaxy

Why so few??

WHY BLACK-HOLES IN X-RAY BINARIES?

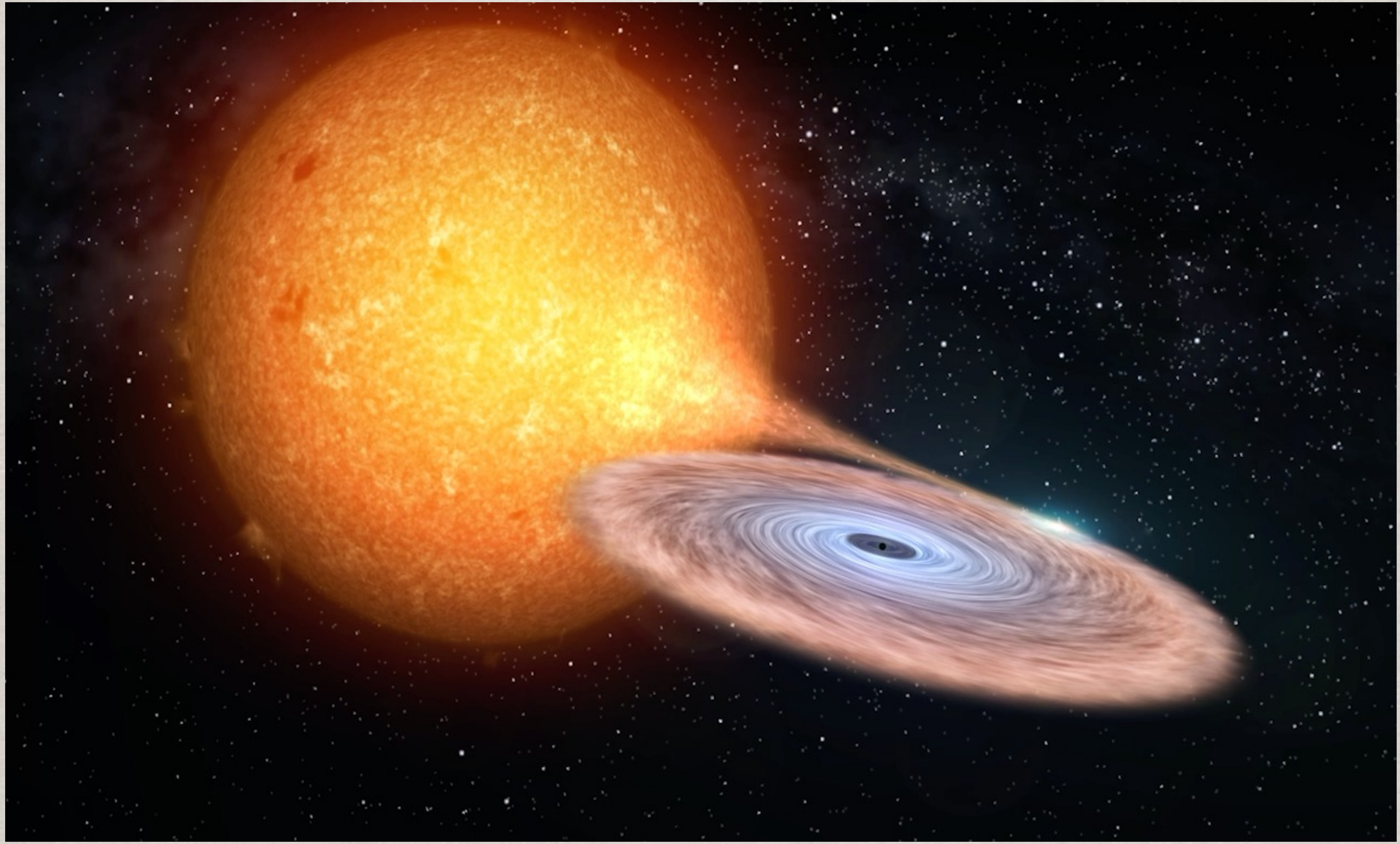
1. **Study accretion/outflows** → repeatedly & in human timescale
2. **Galactic distribution/proper motions** → **Kick velocities & SN models**
3. **Single formation channel but difficult to form** (e.g. Portegies Zwart+ 97)



- **CE phase essential** to reduce binary separation and expel massive star envelope, but **merger difficult to avoid**
- **SN explosion** may disrupt binary

≈ 10 predicted by standard model but
≈ 10^3 expected from observations
(Romani 92, Corral-Santana+ 16)

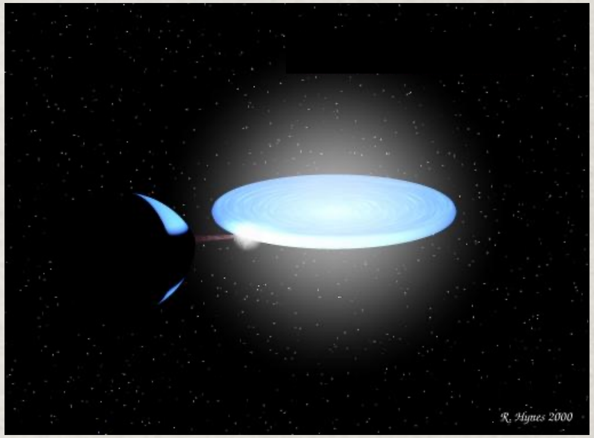
X-ray Transients



Credit: G. Perez (IAC)

X-ray Transients

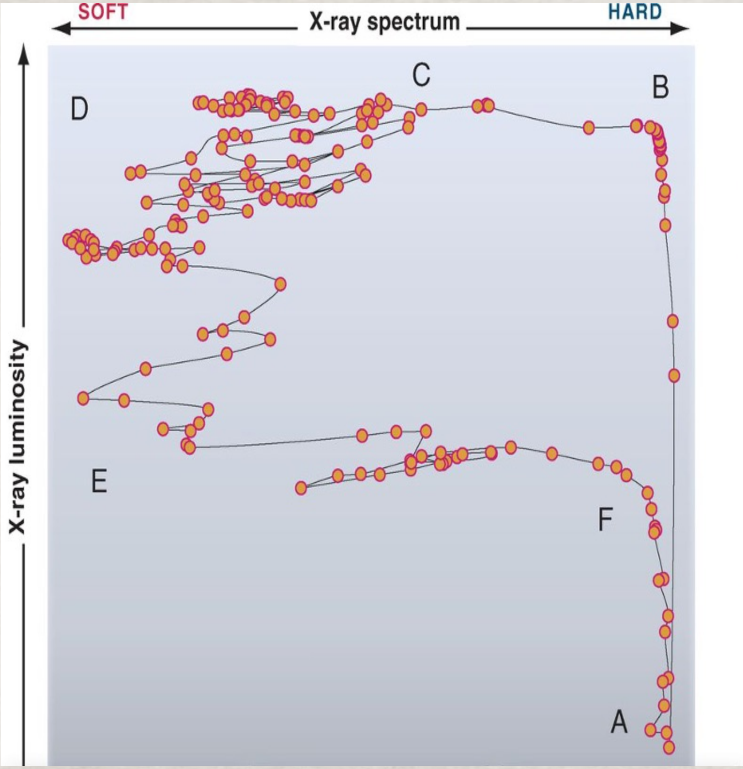
OUTBURST: thermal-viscous instability in the accretion disc



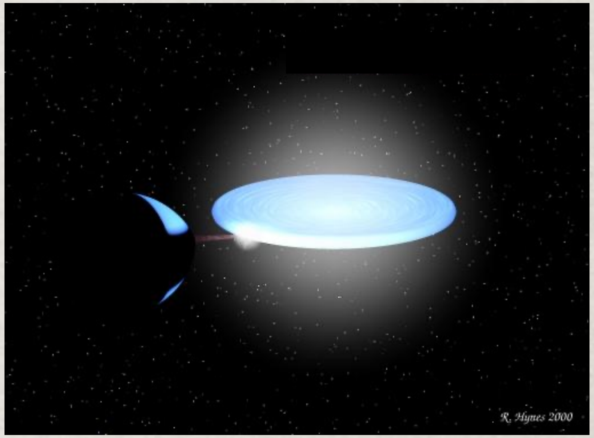
X-ray Transients

OUTBURST: thermal-viscous instability in the accretion disc

Hardness-Intensity Diagram



Fender & Belloni 2012 Science 337 540



X-ray Transients

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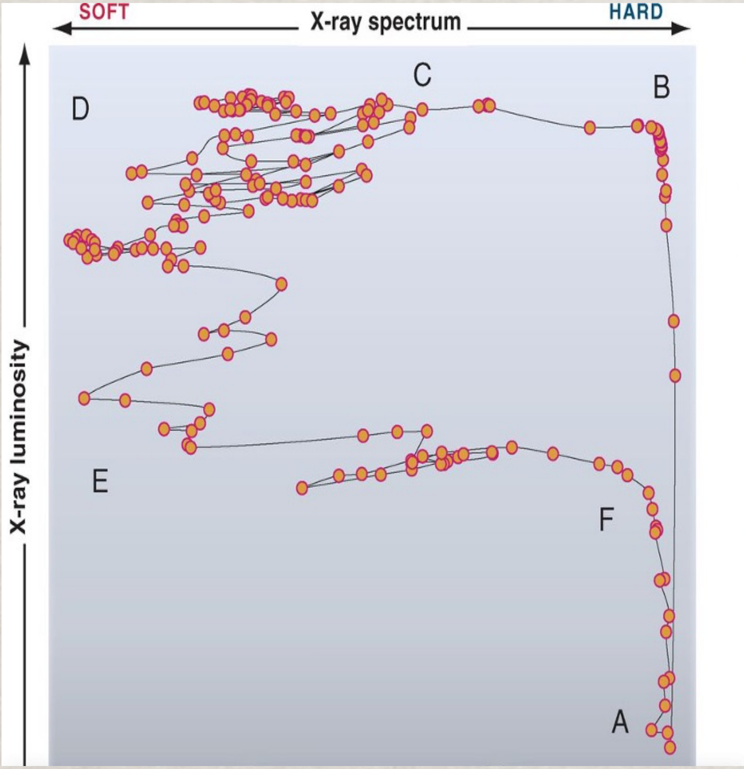

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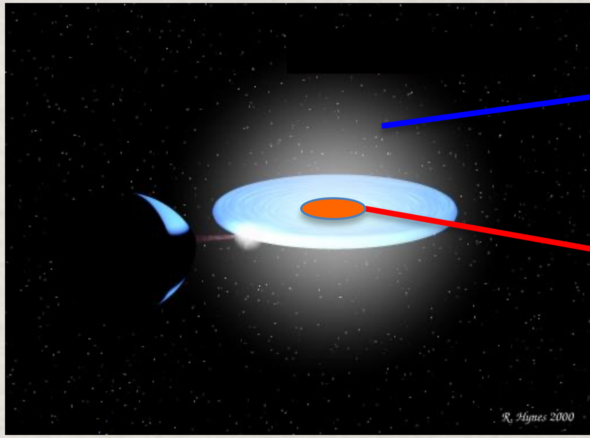
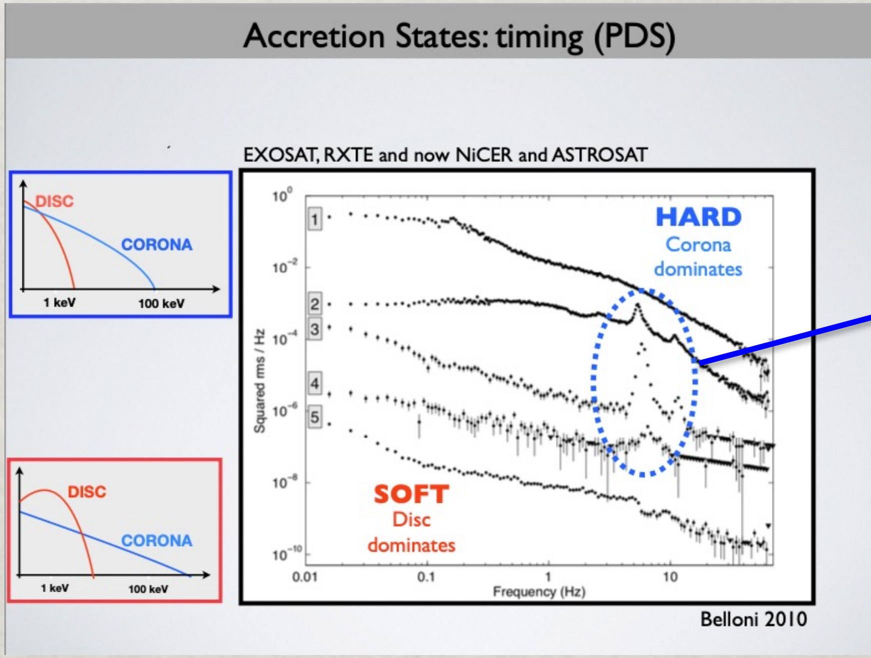


Corona

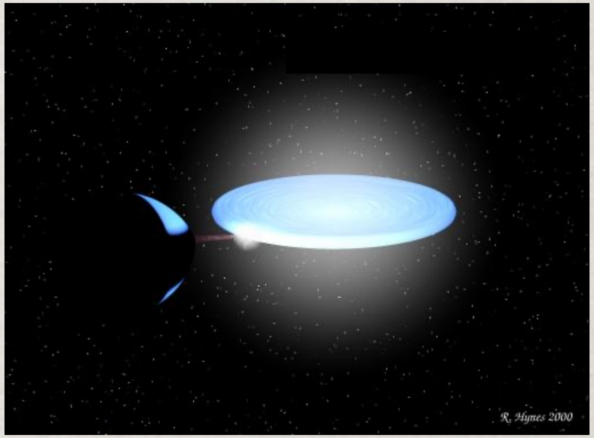
Inner disc



QPOs

X-ray Transients

OUTBURST: thermal-viscous instability in the accretion disc



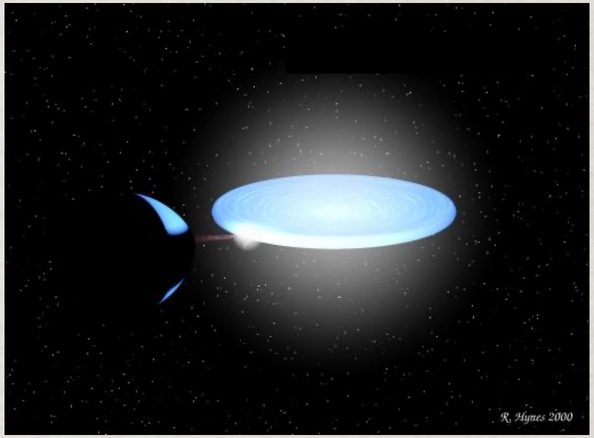
X-Ray Spectral/timing BH signatures

- PL tail without cutoff beyond 100 keV
- Soft multi-BB component
- Type C Low-Frequency QPOs (~Hz)
- Absence of ~2 keV thermal component
- **No pulsations nor bursts**

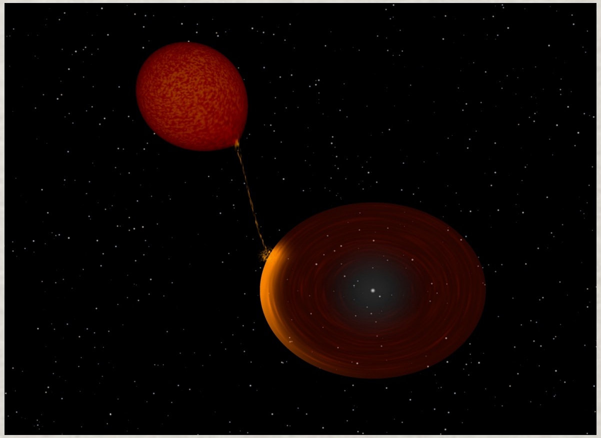
…

X-ray Transients

OUTBURST: thermal-viscous instability in the accretion disc



QUIESCENCE ($L_X/L_{Edd}<10^{-5}$): companion dominates optical flux → **dynamical studies**

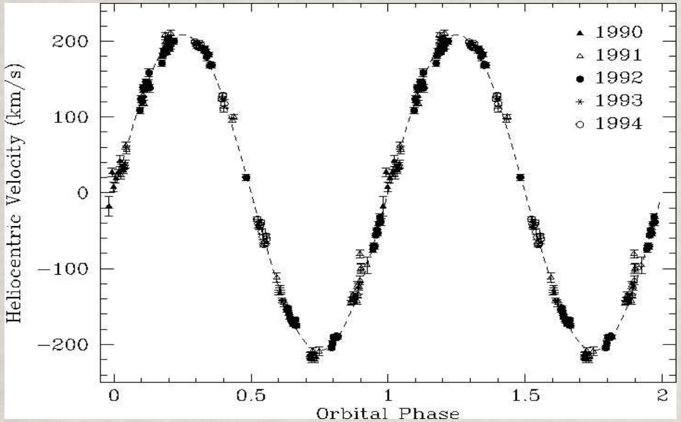


Quiescence: Dynamical Masses

Spectroscopy: **mass function**

M_1: BH mass
M_2: companion's mass

V404 Cyg



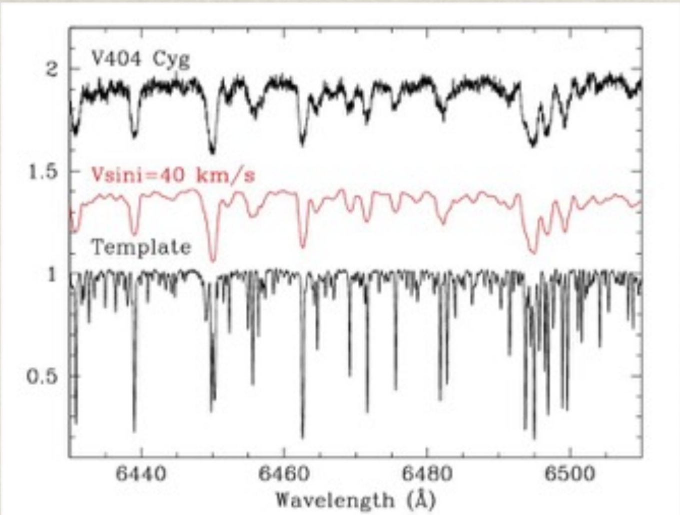
$$f(M) = \frac{P_{\rm orb} K_2^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1+q)^2}$$

$q=M_2/M_1$

$f(M)>3\ M_\odot$ → **dynamical BH**

$f(M)=6.08\pm0.06\ M_\odot$ in V404 Cyg
(Casares et al. 1992; 1994)

Mass ratio ($q=M_2/M_1$) from rotational broadening ***Vsin i***



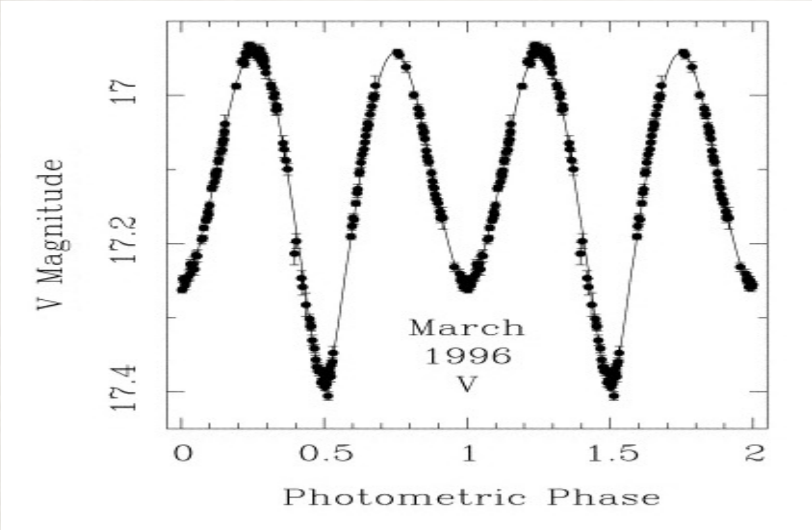
Vsin i* scales with *q because companion fills its Roche lobe and is tidally locked

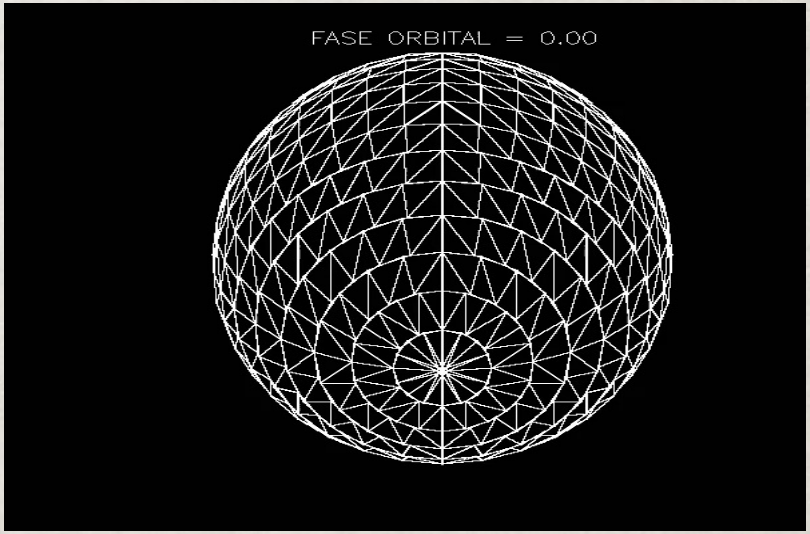
Challenging because demands $\Delta\lambda\approx5000$ & high S/N

Quiescence: Dynamical Masses

Photometry: ellipsoidal light curves ➡ binary inclination

GRO J1655-40





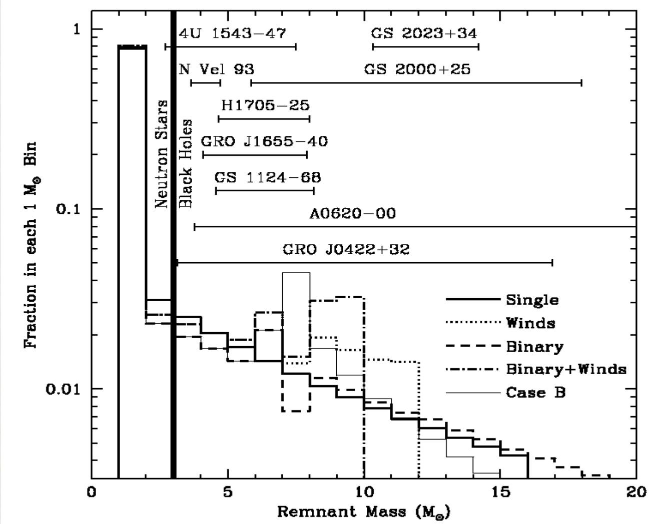
i=69.5±0.1º (Orosz & Bailyn 1997)

i=70.2±1.9º (Greene et al. 2001)

i=68.7±1.5º (Beer et al. 2002)

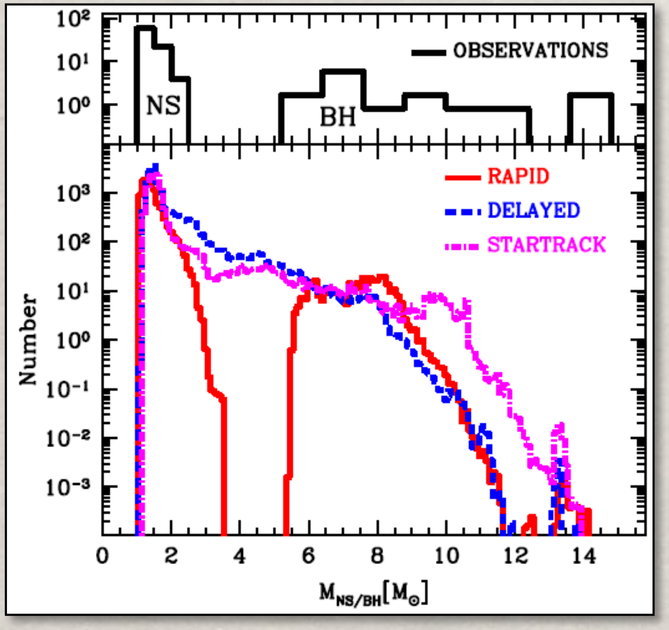
Rad. Vel. Curve + *V sin i* + ellipsoidal light curve ➡
Solve for the mass function eq. and get the BH mass

Distribution of BH Masses



Fryer & Kalogera 2001, Brown et al. 2001

Smooth distribution of progenitor masses drives a continuous distribution of remnant masses

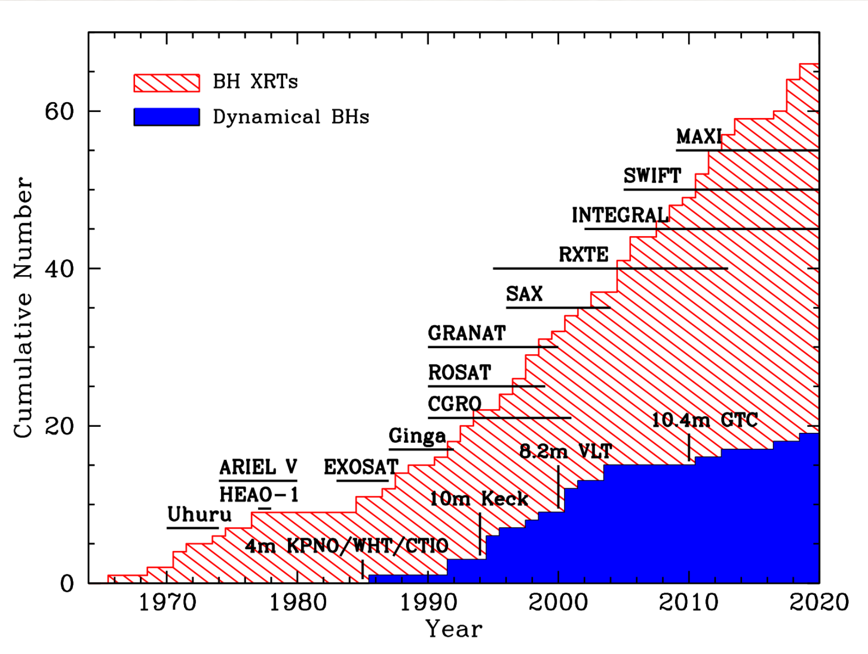


Mass gap at ~2-5 $M_\odot$ (Bailyn et al. 1998, Özel et al. 2010, Farr et al. 2011) reproduced by some recent SNe models (Belczynski et al. 2012, Ugliano et al. 2012)

With a dozen masses we are clearly limited by **low number statistics**

Discovering new Black-Holes

Corral-Santana et al. 2016 (www.astro.puc.cl/**BlackCAT**) => **living edition of BH XRTs**

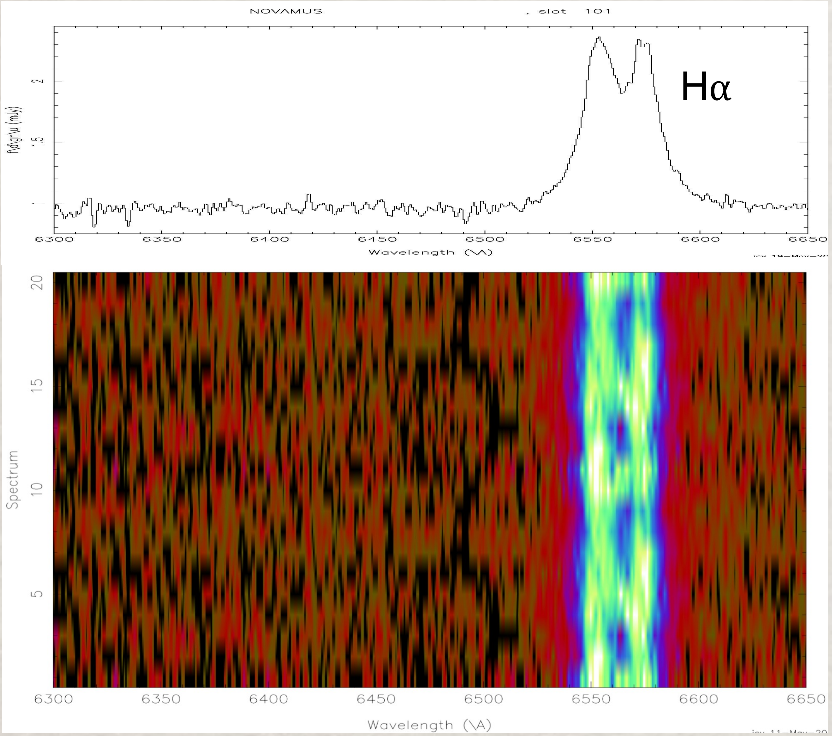


70 XRTs hosting BH "candidates" in ~50 yr of X-ray astronomy, but only ~30% dynamically confirmed

19 dynamical BHs

Remaining XRTs are "lost" in quiescence because become too faint ($R \gtrsim 22$) for dynamical studies, even with 10m-Telescopes

BLACK-HOLE CONFIRMATION IN (VERY) FAINT XRTs

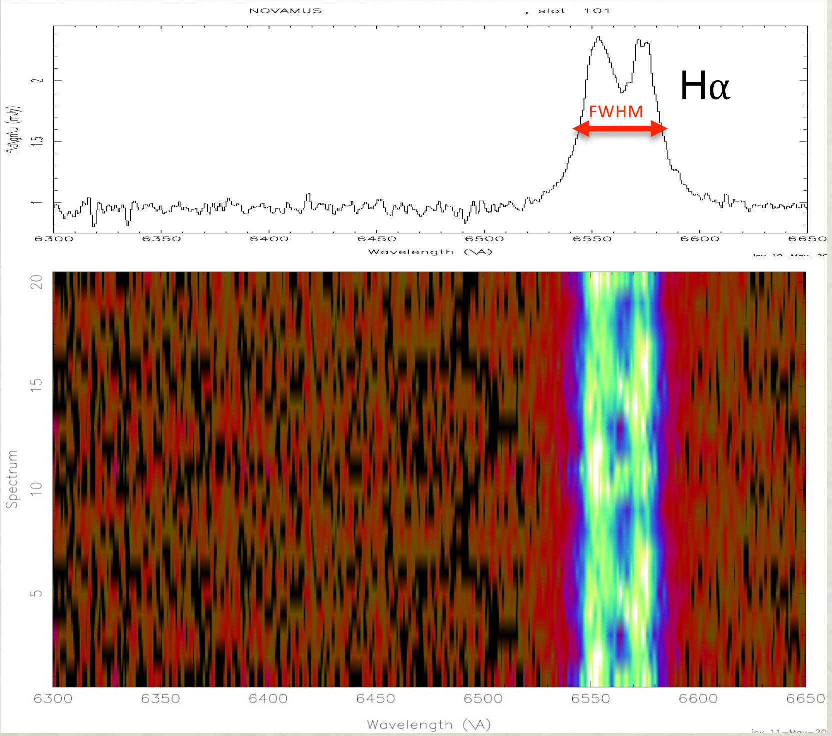


Weak absorption lines hidden in the noise

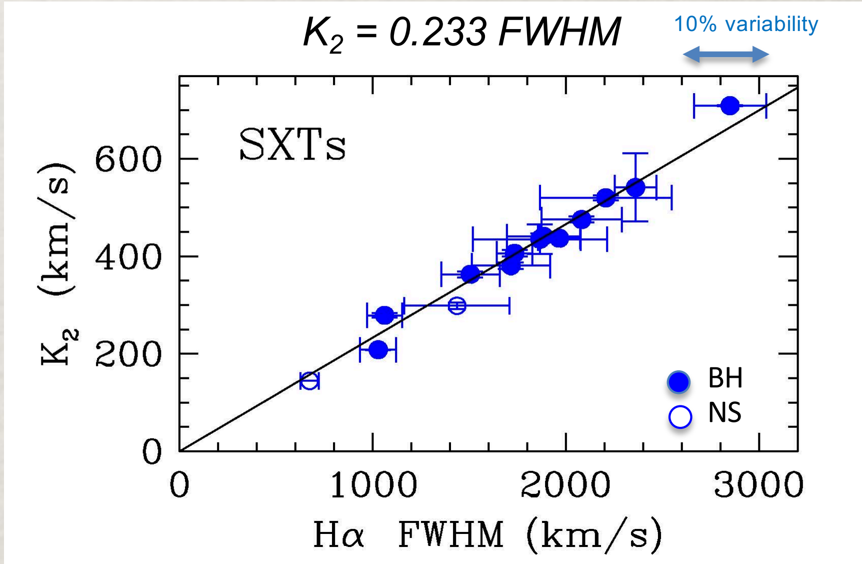
⬇

In most cases not posible to recover the radial velocity curve & K_2

DYNAMICAL BLACK-HOLE CONFIRMATION



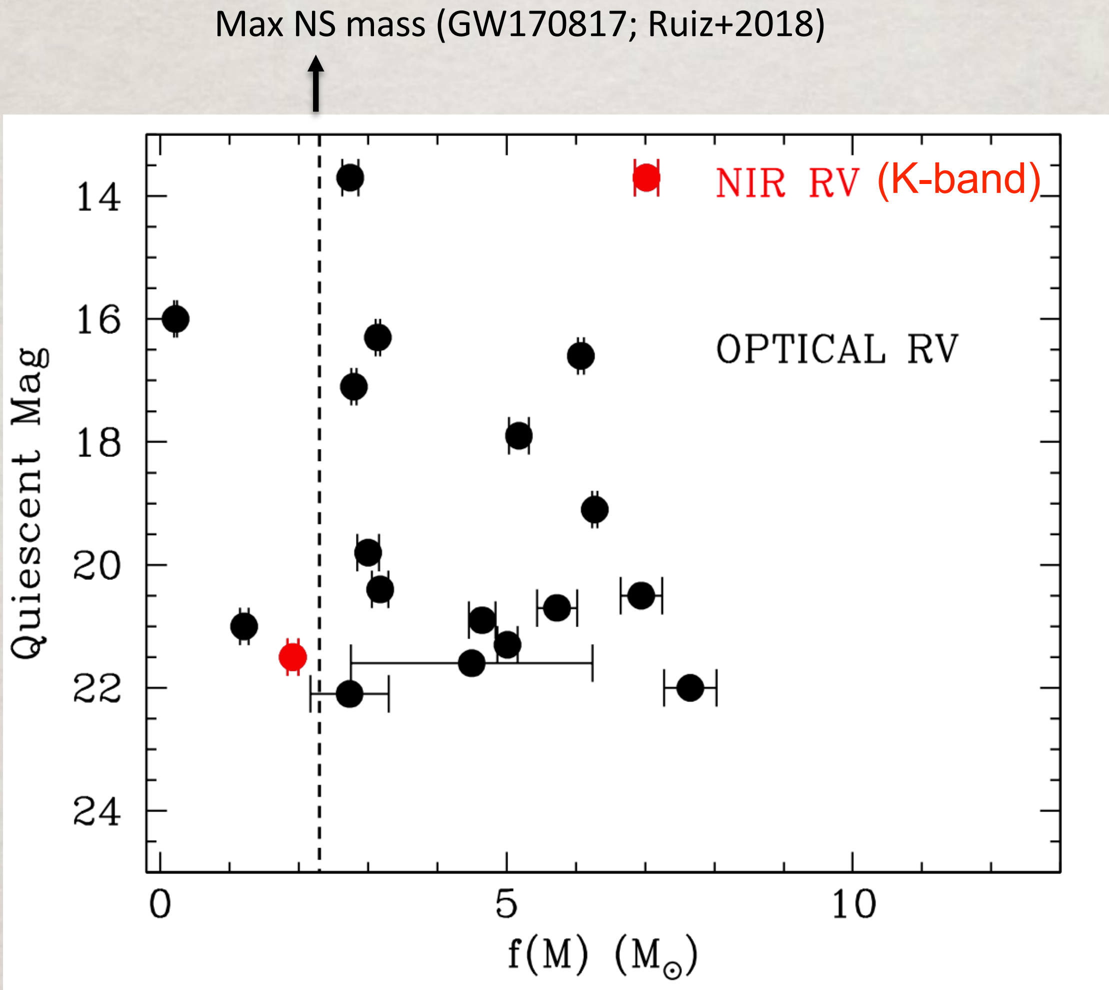
Fundamental scaling between dynamics of disc and donor (Casares 2015)



Extend dynamical studies **~3 mag deeper** than currently possible

→ **Anticipate ELT studies in the next decade**

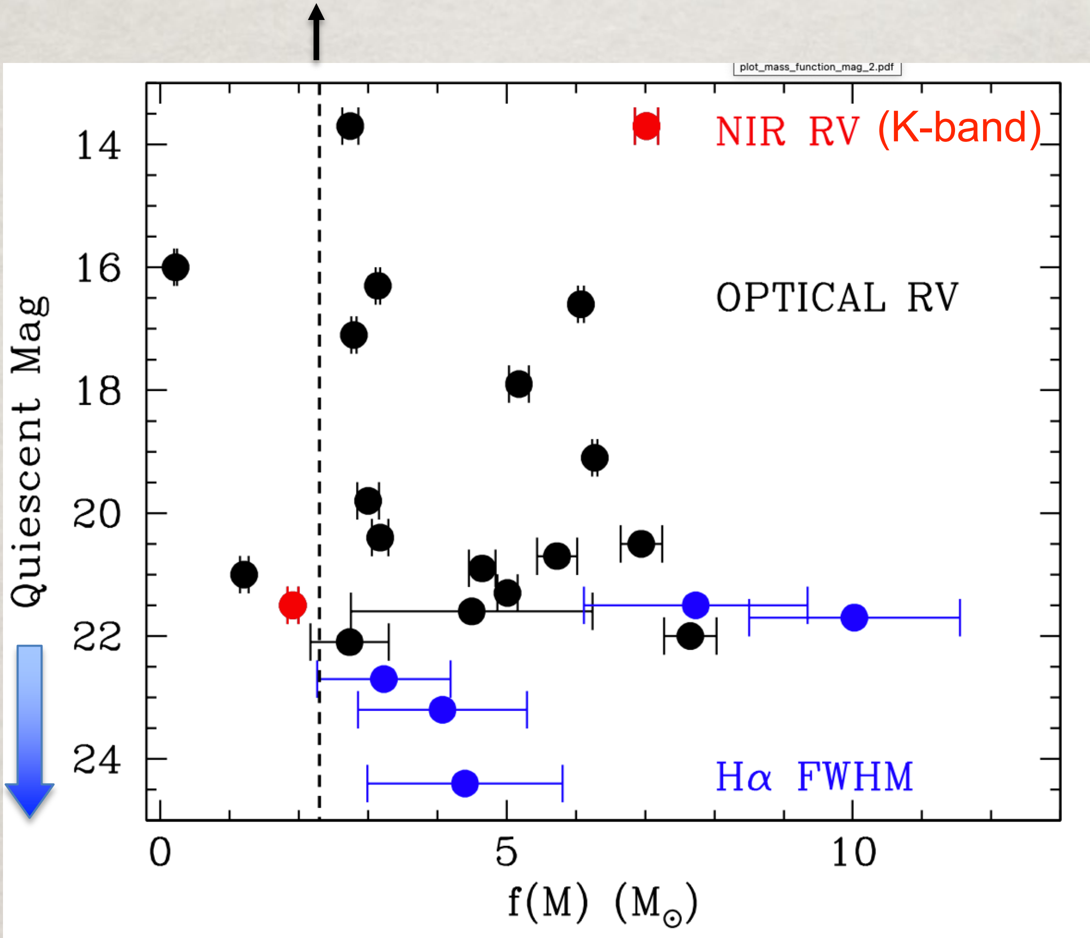
CENSUS OF CONFIRMED BH XRTs



V4641 Sgr
GRS 1915+105
4U 1543-475
GRO J1655-40
V404 CYG
A0620-00
MAXI J1820+070
XTE J1118+480
N MUS 91
N Vel 93
MAXI J1305-704
BW Cir
N OPH 77
GRO J0422+32
GS 2000+25
GX339-4
XTE J1859+226
XTE J1550-564
XTE J1650-500

CENSUS OF CONFIRMED BH XRTs

Max NS mass (GW170817; Ruiz+2018)



≈ 3 mag deeper

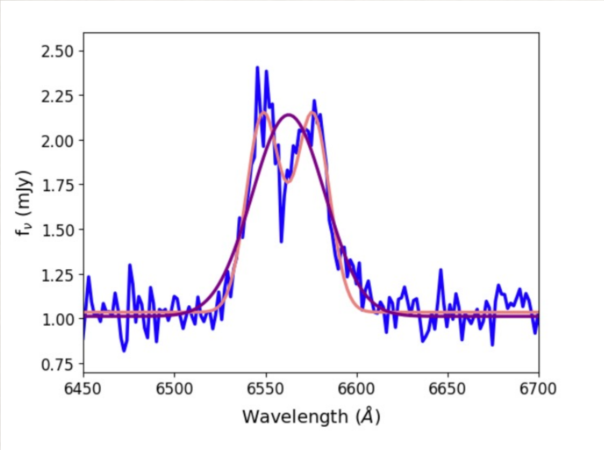
V4641 Sgr
GRS 1915+105
4U 1543-475
GRO J1655-40
V404 CYG
A0620-00
MAXI J1820+070
XTE J1118+480
N MUS 91
N Vel 93
MAXI J1305-704
BW Cir
N OPH 77
GRO J0422+32
GS 2000+25
GX339-4
XTE J1859+226
XTE J1550-564
XTE J1650-500
Swift J1753-0123
Swift J1357-0933
KY TrA
GRS 1716-249
MAXI J1659-152

Swift J1910-0546
MAXI J1828—249
MAXI J1348-630
MAXI J0637-430
...

***FWHM-K*$_2$** allows increasing the **census of dynamical BHs** by ~50%

APPLICATION TO VERY FAINT XRTs

KY TrA
(R=22.7)

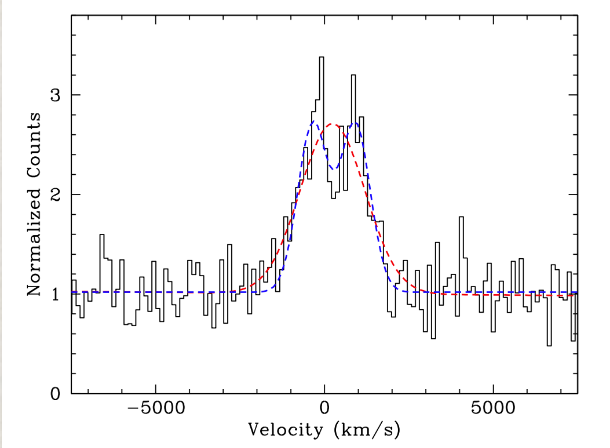


FWHM=2114 ± 211 km/s
P = 6.2 h

***f(M)* = 3.2 ± 1.0 M$_\odot$**

Yanes-Rizo+ 2023 in press

GRS 1716-249
(R=23.2)

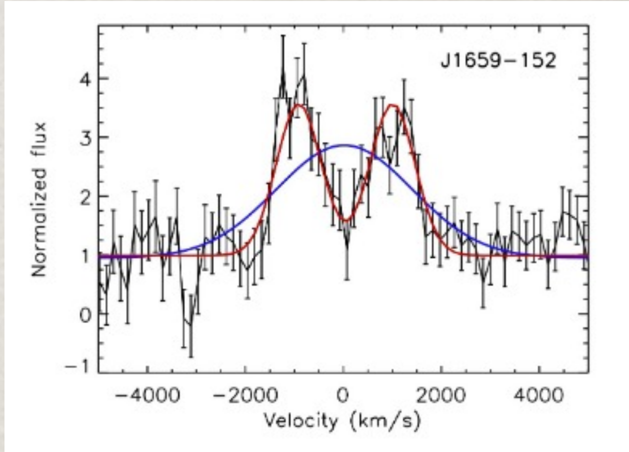


FWHM=2235 ± 224 km/s
P = 6.7 h

***f(M)* = 4.1 ± 1.2 M$_\odot$**

Casares+ 2023

MAXI J1659-152
(R=24.4)



FWHM=3200 ± 300 km/s
P = 2.4 h

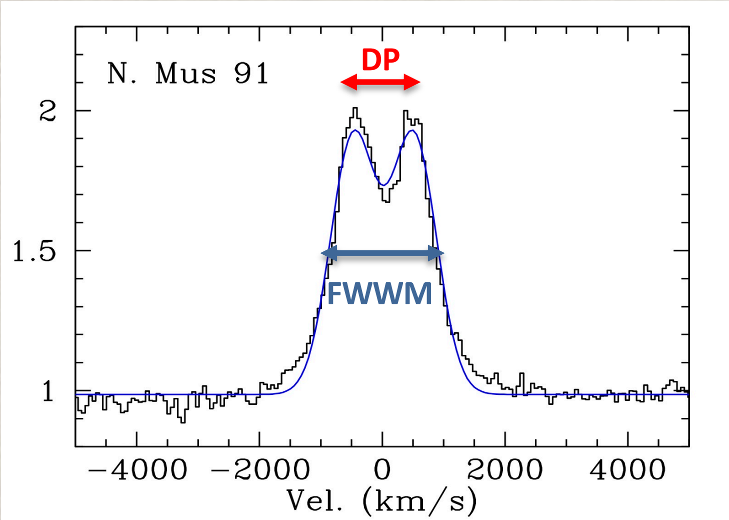
***f(M)* = 4.4 ± 1.4 M$_\odot$**

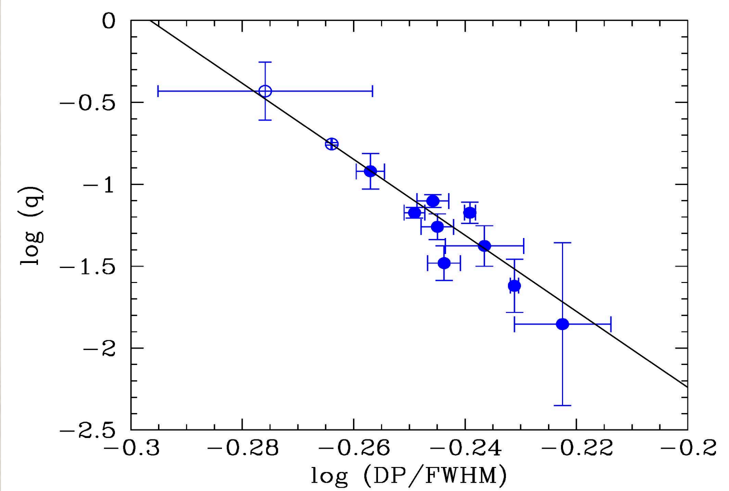
Torres+ 2021

Use width of Hα line as proxy of deep gravitational fields of BH

Mass Ratio $q=M_2/M_1$

Casares 2016



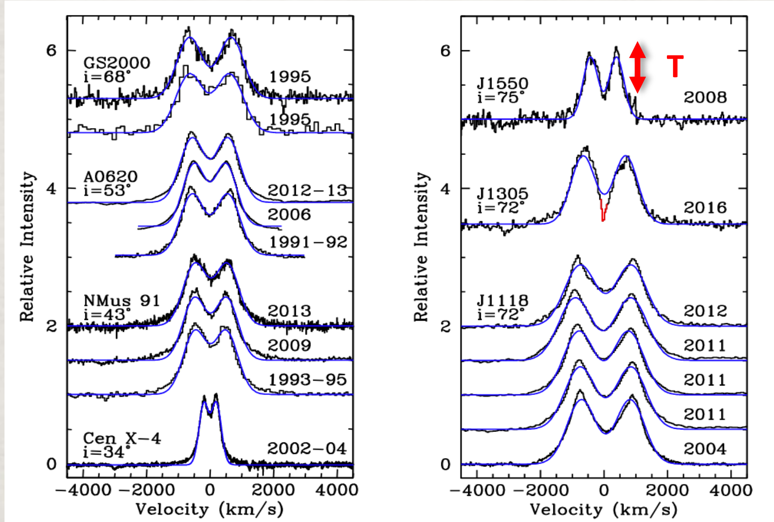


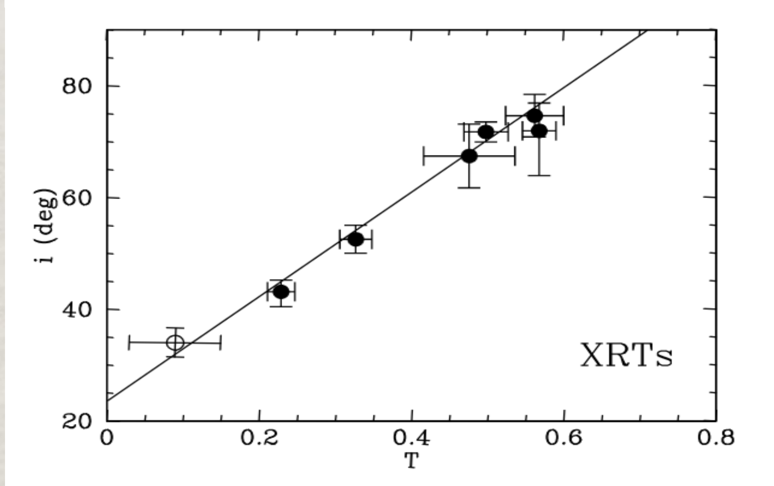
log q = -6.88 –23.2 log (DP/FWHM)

Disc truncated by tidal forces of donor star for $q \lesssim 0.25$

Binary Inclination i

Casares+ 2022



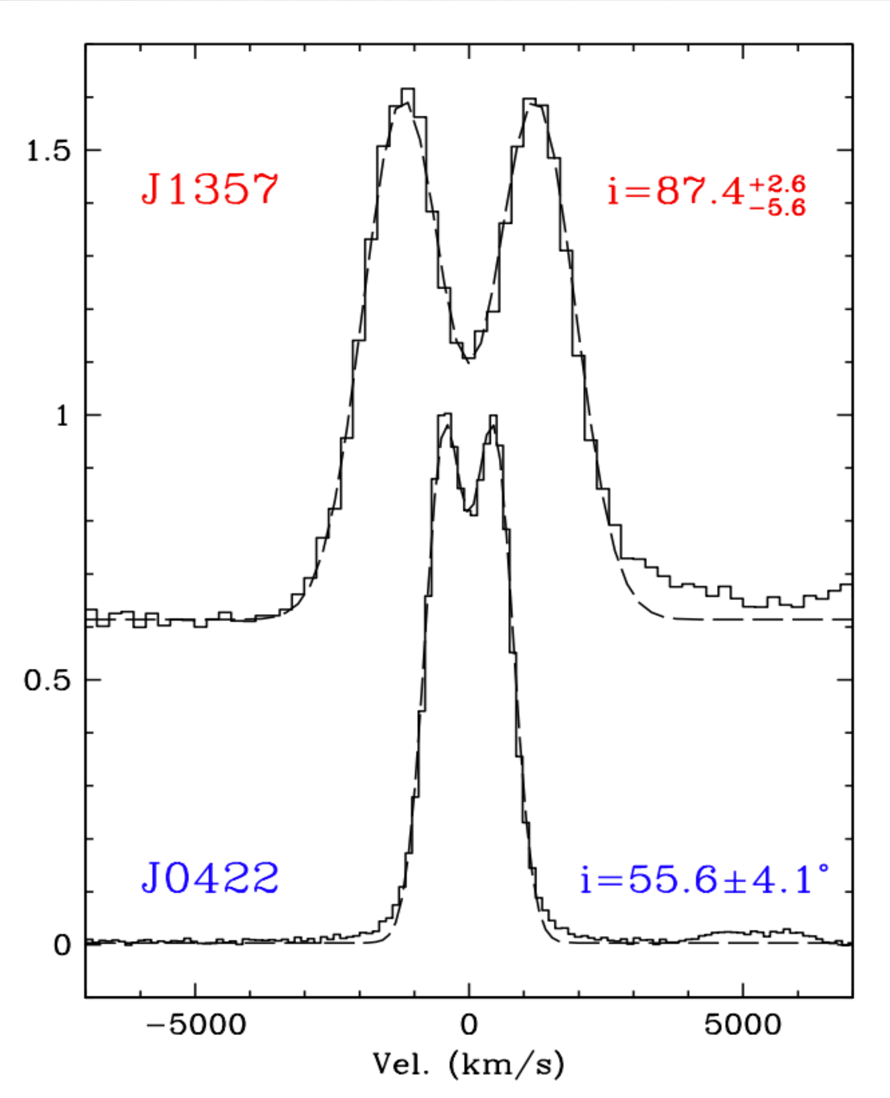


i(deg) = 93.5 T + 23.7

Central trough (T) deepens with i

INCLINATIONS & MASSES IN 2 FAINT BHS

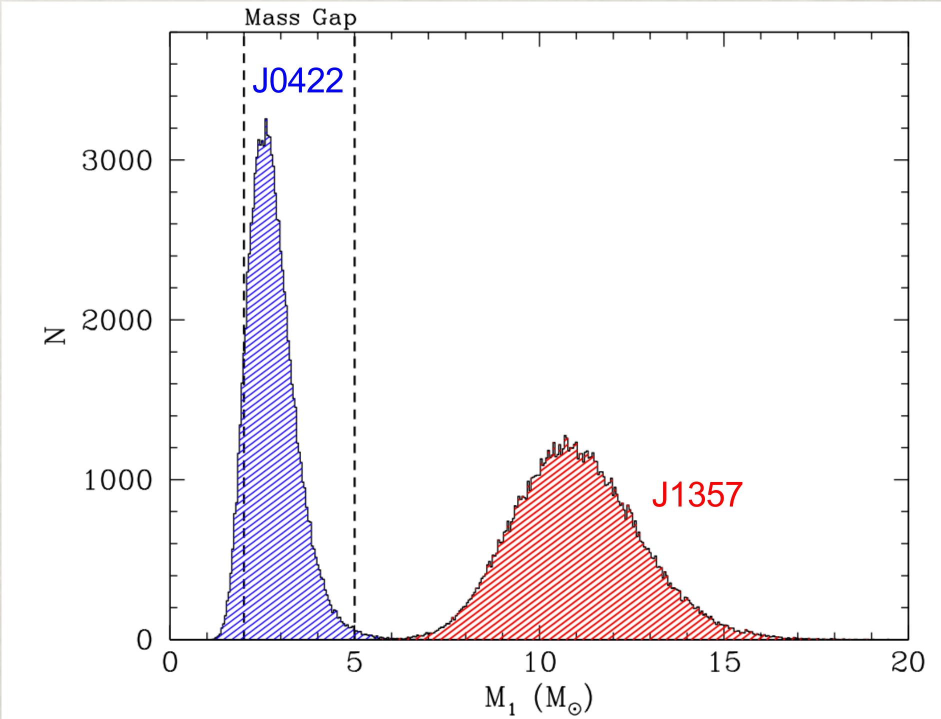
Casares+ 2022 MNRAS 516 2023



BH in **J0422** has M_1=**2.7±0.6** $M_\odot$
(< 5 $M_\odot$ with 99.5% confidence)

It is in the mass gap !!

(likewise GW100814 & GW200210)



Light BHs exist & lower-mass gap might be a selection effect

DISCOVERY OF NEW DORMANT BHs

Dynamical confirmation of known BH XRTs (even with Hα scaling) is very **inefficient** → **≈ 200 yr required to increase numbers by factor 10**

BLIND PHOTOMETRIC SEARCH for new (dormant) BHs by selecting Hα stars with **broad lines**: ***HαWKS*** **(=Hα W**idth **K**ilo-degree **S**urvey)

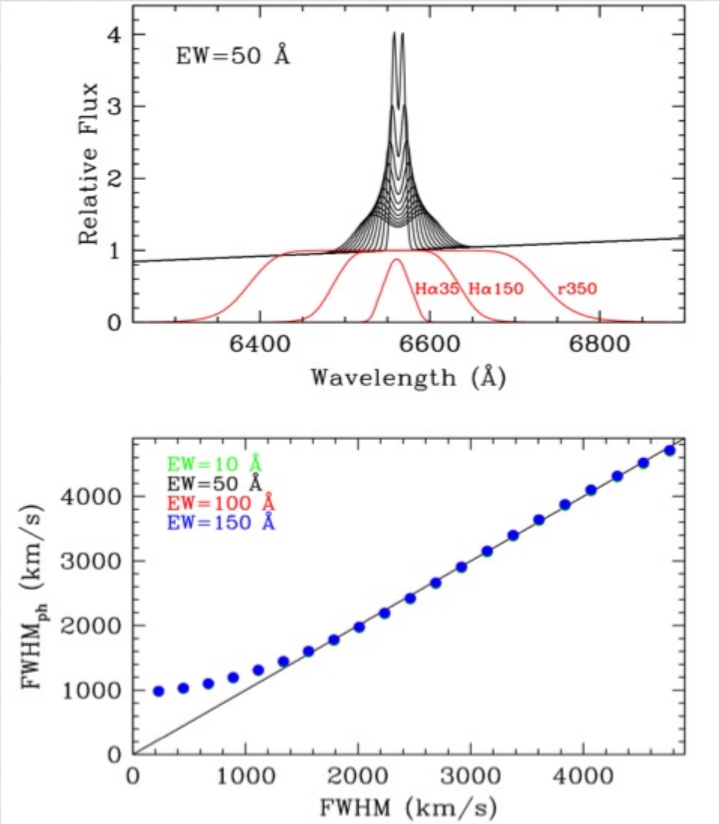
Survey of **~3000 deg²** in the GP down to R~21 will deliver **~150 new BHs** in just a few years → factor 10 increase over known population!!

HαWKs **much more efficient than classic spectroscopy since will** allow discovering (+ weighing) new BHs through **imaging** in large FoV

A PHOTOMETRIC SYSTEM TO MEASURE Hα WIDTHS

FWHM recovered from relative fluxes obtained with **3 custom Hα filters**

Proof of concept (Casares 2018)



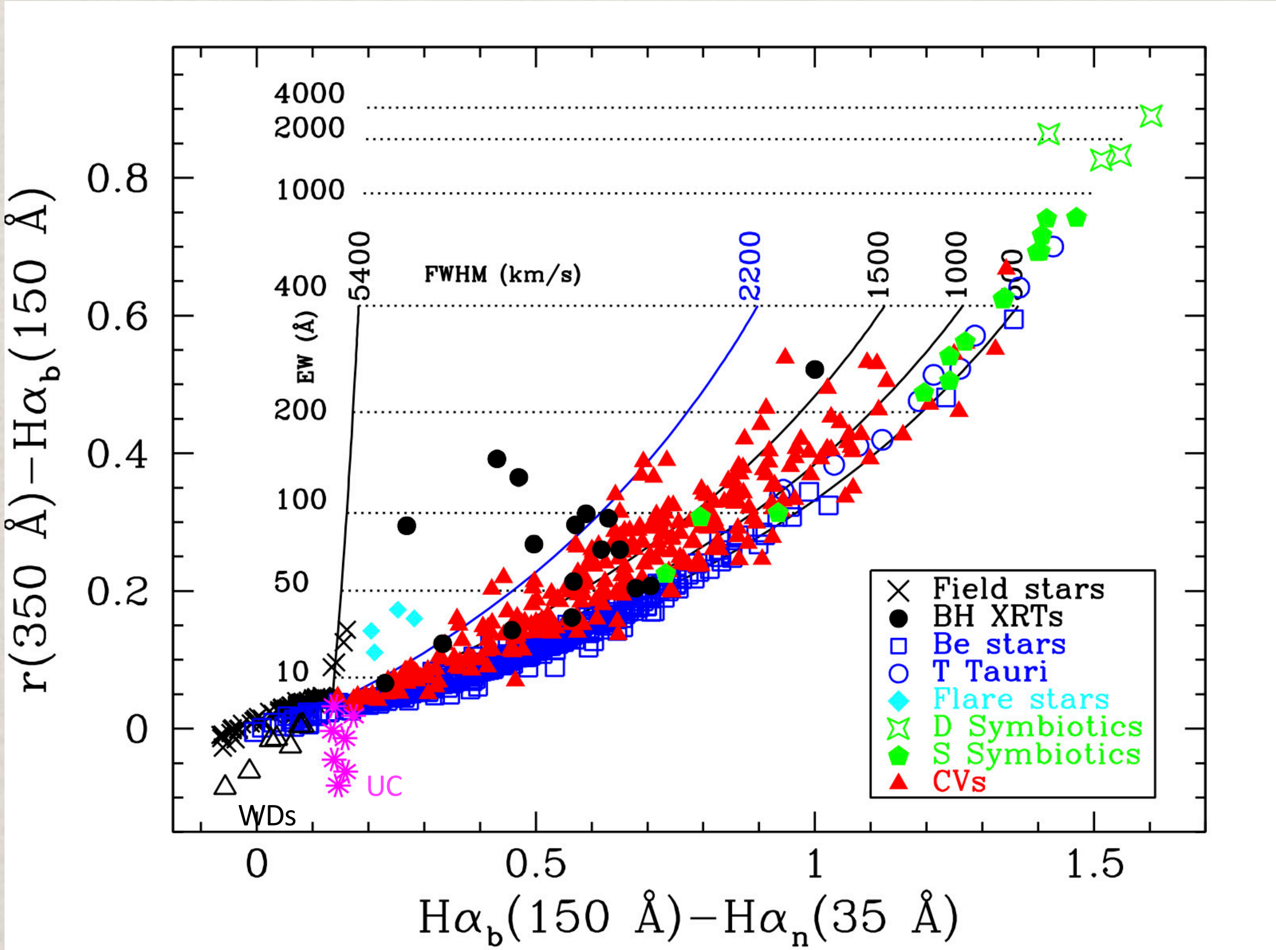
$$EW_{ph} = C_1 \frac{W_r \times \left(\frac{F_{H\alpha_b}}{F_r}\right) - W_{H\alpha_b}}{1 - \left(\frac{F_{H\alpha_b}}{F_r}\right)}$$

$$FWHM_{ph} = C_2 \frac{EW_{ph}}{\left(\frac{EW_{ph}+W_{H\alpha_b}}{W_{H\alpha_n}}\right) \times \left(\frac{F_{H\alpha_n}}{F_{H\alpha_b}}\right) - 1}$$

***$F_{H\alpha n}$* , *$F_{H\alpha b}$* , *Fr* : filter fluxes**
$W_{H\alpha n}$, *$W_{H\alpha b}$* , *Wr* : filter's equivalent widths
C_1, *C_2* : calibration constants

The 3 filters define a New Photometric System tailored to measure line FWHMs (and EWs)

Hα COLOUR-COLOUR DIAGRAM



Efficient separation of **Hα populations** & **BH identification**

Mini-HαWKs pathfinder: Legacy Survey at JAST80

Observatory of Javalambre in Teruel (Spain)

- **3 Hα filters already manufactured** by ASAHI. ***Mini-HαWKs*** will **start in Summer 2024** to survey **~50 sqr deg** with the **2 sqr deg camera** of JAST80 over **2-3 years.**
- **Goal is to reach SNR~50 at *r*=21** in the 3 Hα filters *for a* **10% accuracy in *FWHM*** $_{ph}$
- **40 r/Hαb/Hαn cycles** (90/200/900 sec) will provide **~14h light curves** → Instrumental to measure $\mathbf{P_{orb}}$ and detect **eclipsing CVs**
- ***Mini-HαWKs*** will deliver **≈2-3 BHs, ≈10^2 CVs and ≈10^3 Hα emitters** (Be, T Tauri, Symbiotics, etc.)

Conclusions

- Classic techniques to measure BH masses limited to bright candidates (R≲22) in quiescence. Thus, only **19 dynamical BHs** confirmed in **50 years**

- Hα scaling relations allow probing BHs ≈3 mag deeper => 50% increase

- Novel strategies required for a ten-fold increase in BH XRT population: ***HαWKs***, a 3 Kilo deg^2 photometric survey can potentially discover ≈150 new dormant BHs in only a few years (≈200 yr required at current rate)

- ***Mini- HαWKs***, a pathfinder of ***HαWKs***, will test the observing strategy over a 50 deg^2 footprint, starting Summer 2024

Boost in statistics will allow demographic studies of Galactic BHs and set tight constraints on Population number, P_{orb}, Masses, Kick velocicites …