

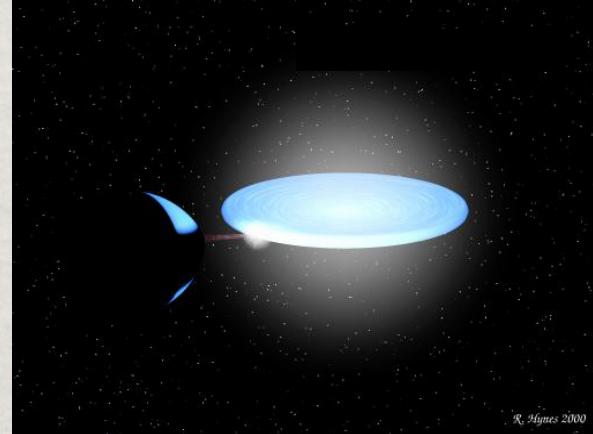
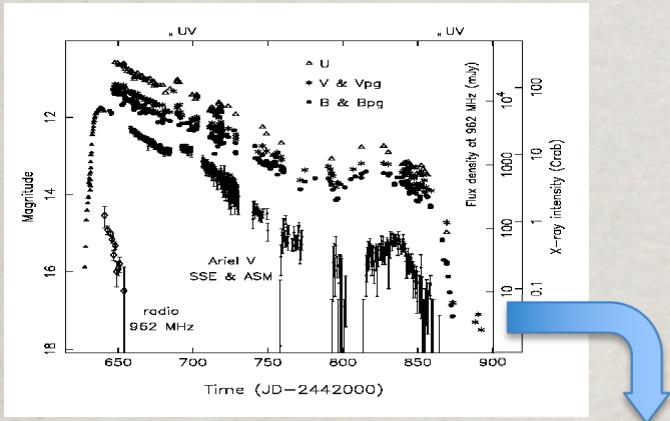
# **HAWKs: a DECam Survey to unveil quiescent BHs**

**J. Casares (IAC)**

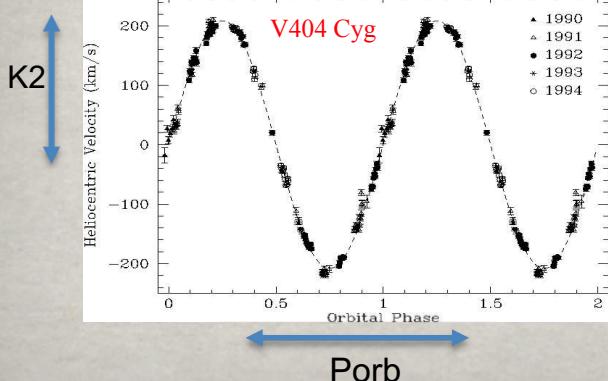


# Context: X-ray transients

**OUTBURST:** thermal-viscous instability in the accretion disc

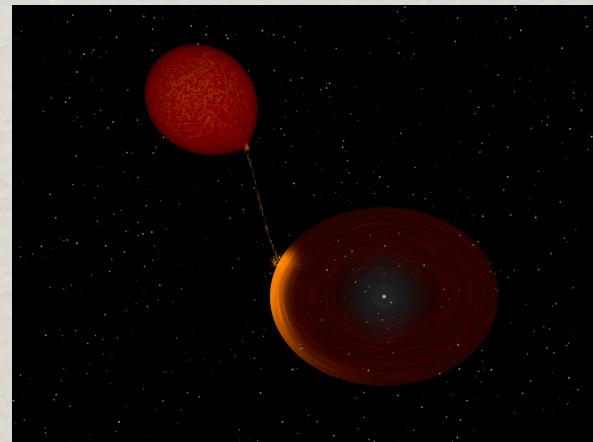


**QUIESCENCE ( $L_X/L_{\text{Edd}} < 10^{-5}$ ):**  
companion dominates optical flux →  
dynamical studies



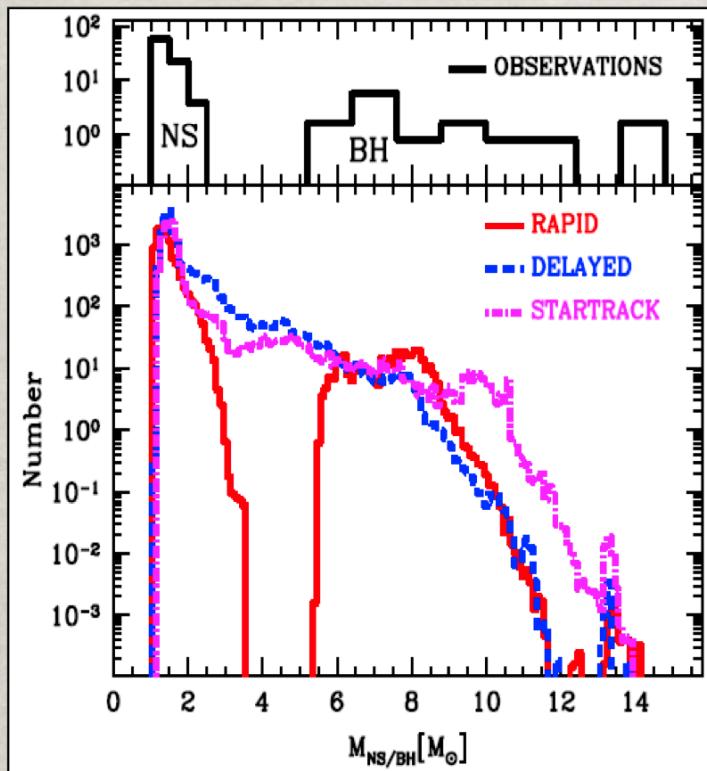
$$f(M) = \frac{P_{\text{orb}} K_2^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1+q)^2}$$

$f(M) > 3 M_{\odot}$  → dynamical BH



# Distribution of Remnant Masses

XRTs give insights into binary evolution and fate of massive stars



Mass gap at  $\sim 2\text{-}5 M_{\odot}$  (Bailyn+ 98, Özel+ 10, Farr+ 11) reproduced by some recent SNe models (Belczynski+ 12, Ugliano+ 12)

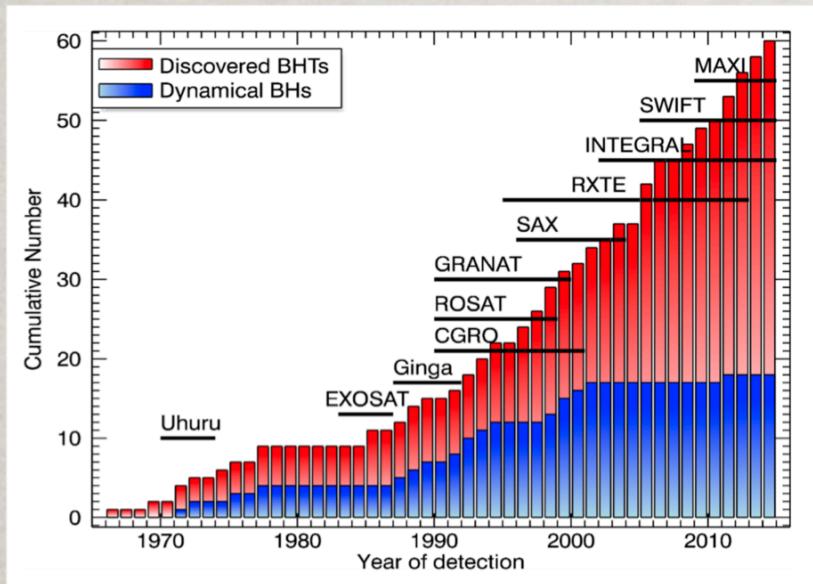
But BH masses could be biased high because of systematics in inclination (Kreidberg+ 12)

Mass cap at  $\sim 15 M_{\odot}$ ? (Belczynski+ 10)

Need to increase statistics by a factor  $\sim 10$  !!

# Black-Hole discoveries

Corral-Santana et al. 16 ([www.astro.puc.cl/BlackCAT](http://www.astro.puc.cl/BlackCAT))



60 XRTs with BH candidates discovered  
in ~50 yr of X-ray astronomy, but only  
~30% dynamically confirmed

18 dynamical BHs

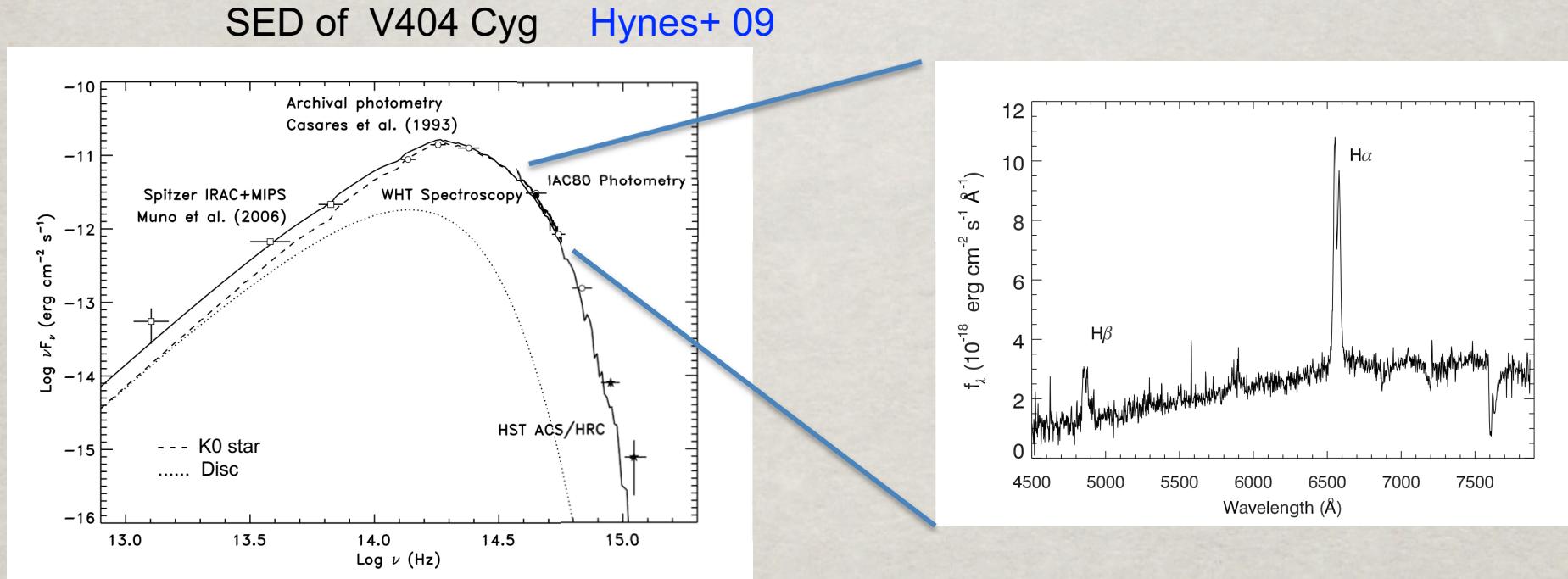
Remaining XRTs are “lost” in quiescence because become too faint  
( $R \gtrsim 22$ ) for dynamical studies with 10m-Telescopes

Tip of the iceberg of a large hidden population of  $\approx 10^3$  quiescent BHs.  
**New strategies required**, otherwise  $\approx 200$  years required to increase  
a factor  $\sim 10$  the number of dynamical BHs

# Signatures of Quiescent Black Holes?

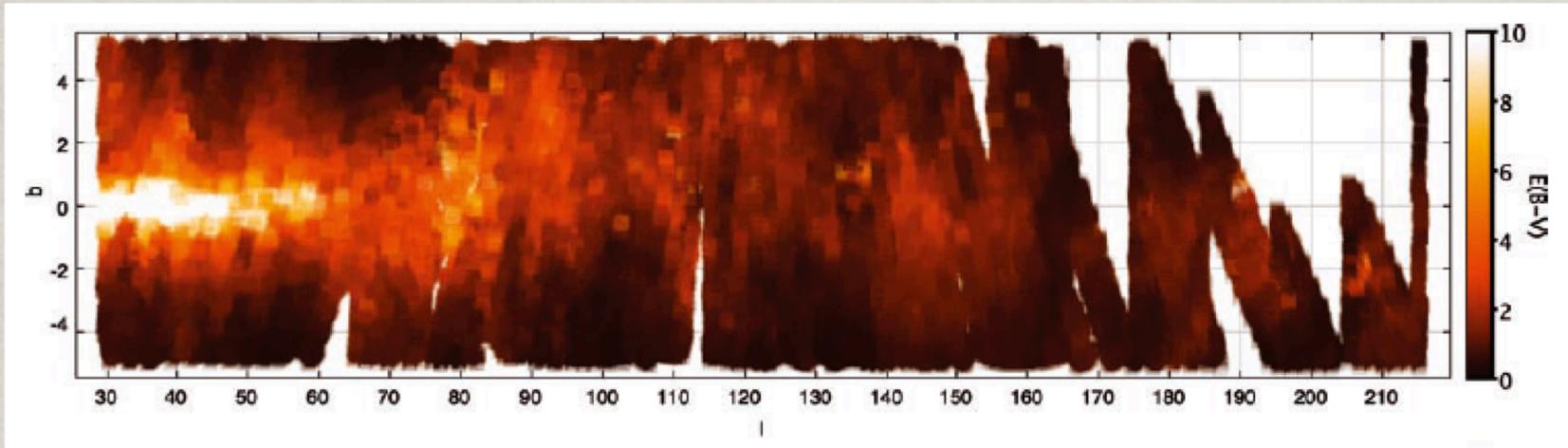
Quiescent BHs are extremely weak in X-rays ( $L_x \sim 10^{31}$  erg/s), UV and radio  
(Narayan & McClintock 2008, Gallo+ 2006, Miller-Jones+ 2011)

Optical spectra dominated by K-type donor star + broad H $\alpha$  emission from the accretion disc

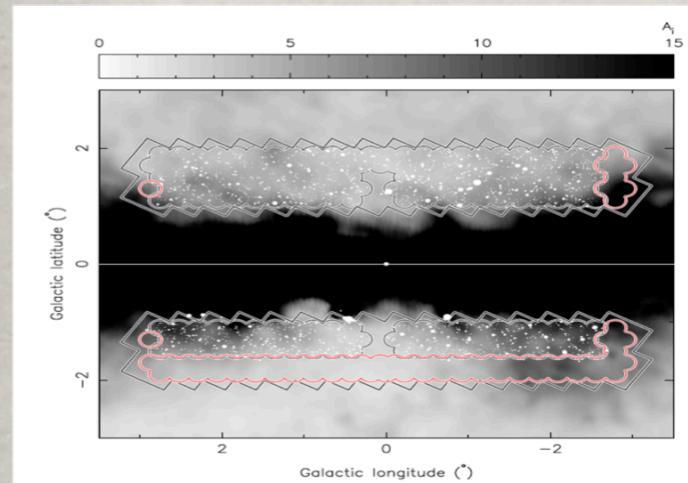


Traditional H $\alpha$  surveys might contain new BHs but outnumbered by other H $\alpha$  emitting populations (CVs, T Tauri, Be...)

# Previous H $\alpha$ Surveys



- **IPHAS/VPHAS+:** H $\alpha$  Surveys of Northern/Southern Galactic plane ( $|b|<5^\circ$ ) in H $\alpha$ , r' and i' down to r'=20 (Drew+ 05,14): ~1800 sq. deg with 200 Mill objects and **10.000 H $\alpha$  emitters: CVs, YSOs, Symbiotics, PNe...**

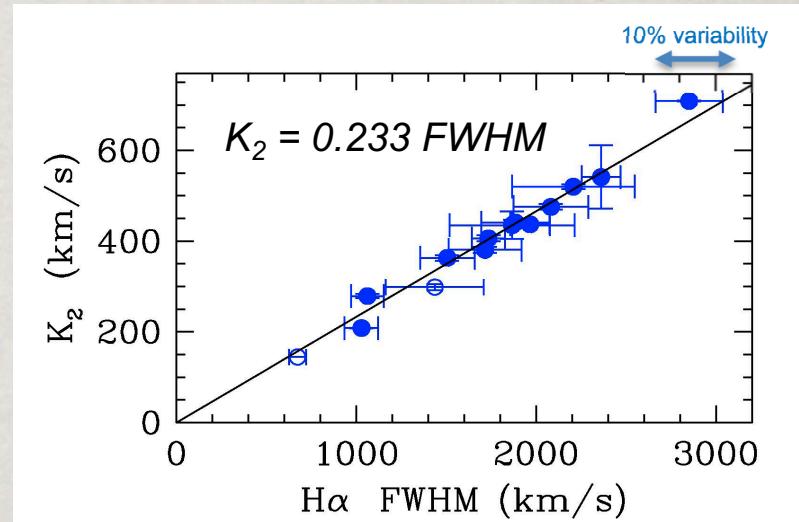
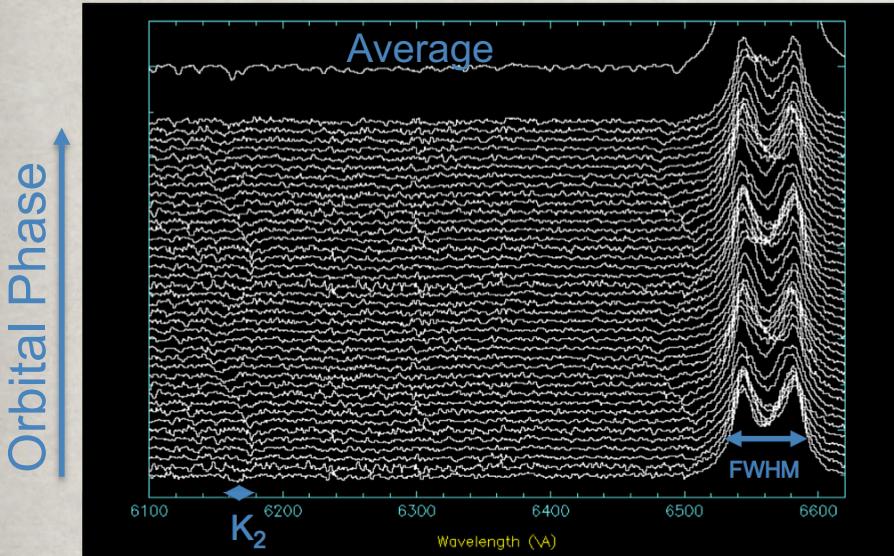


- **GBS/CHAMPlane:** H $\alpha$  Surveys of Galactic Bulge and Southern Plane down to r'=22.5, cross-matched with shallow Chandra detections (Grindlay+ 05, Jonker+ 11): **AGNs, coronal stars & magnetic CVs**

**Contamination from other (dominant) populations of H $\alpha$  emitters not efficiently removed by broad-band/H $\alpha$  color cuts**

# $FWHM-K_2$ correlation for quiescent XRTs

Casares 2015 ApJ 808 80



$$K_2 = 0.233 (13) FWHM$$



$P_{orb}$  (e.g. from light curves)

**Tight correlation:** fundamental scaling between dynamics of disc and donor

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

**Mass Function**

Use width of H\alpha line as proxy of deep gravitational fields of BH

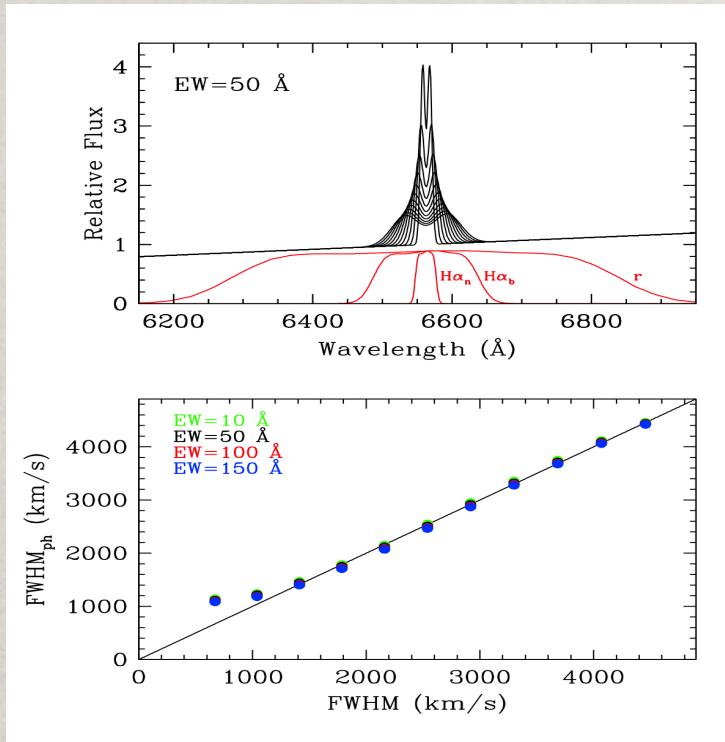
Analogous to reverberation mapping techniques to measure  $M_{BH}$  in AGNs (Peterson+ 2004)

# New concept: “Photometric” Mass Function

Discover & weigh new BHs in large FOVs

Proof-of-concept presented in Casares 2018 MNRAS 473 5195

3 custom filters centered at  $H\alpha$  : *r-band*,  $H\alpha$ -broad,  $H\alpha$ -narrow



SYNTHETIC SPECTRA

“Photometric Width”

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

with

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

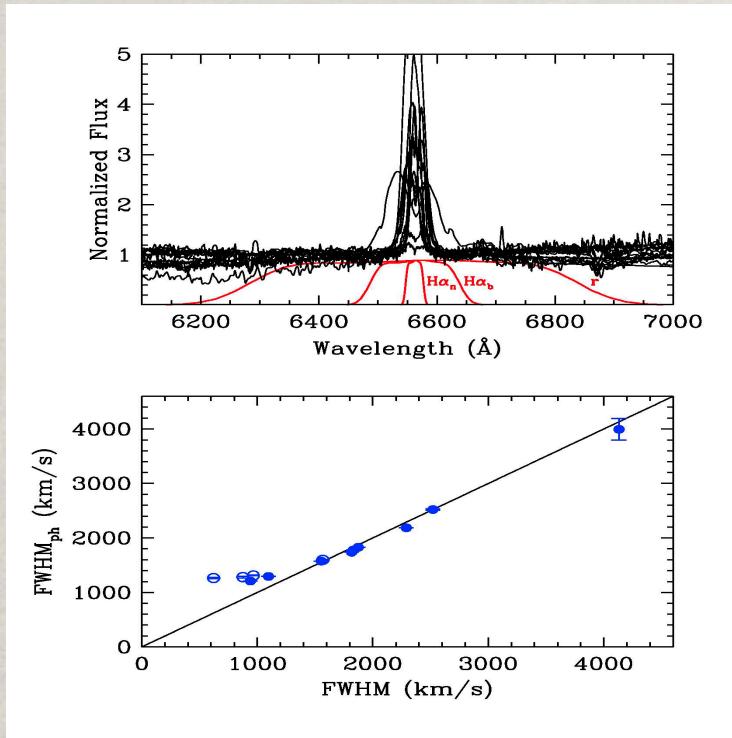
$F_r, F_{Hab}, F_{Han}$ : filter fluxes  
 $W_{H\alpha n}, W_{H\alpha b}, Wr$ : filter's EWs  
 $C_1, C_2$ : calibration constants

# New concept: “Photometric” Mass Function

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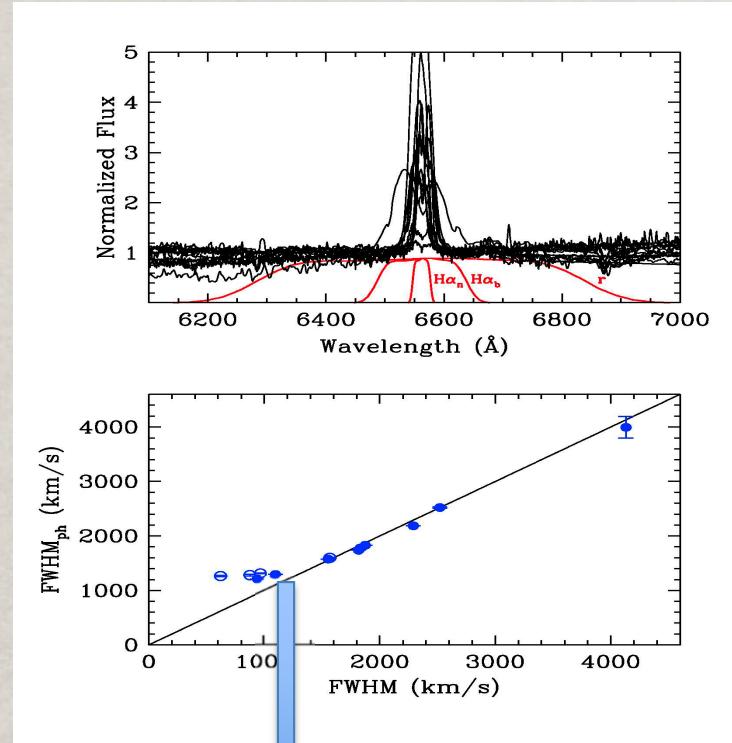


REAL DATA

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

$FWHM_{ph}$  recovers  $FWHM$  to < 5% for real data ( $EW=8-250 \text{ \AA}$ ),

# Cut-off width for BH selection



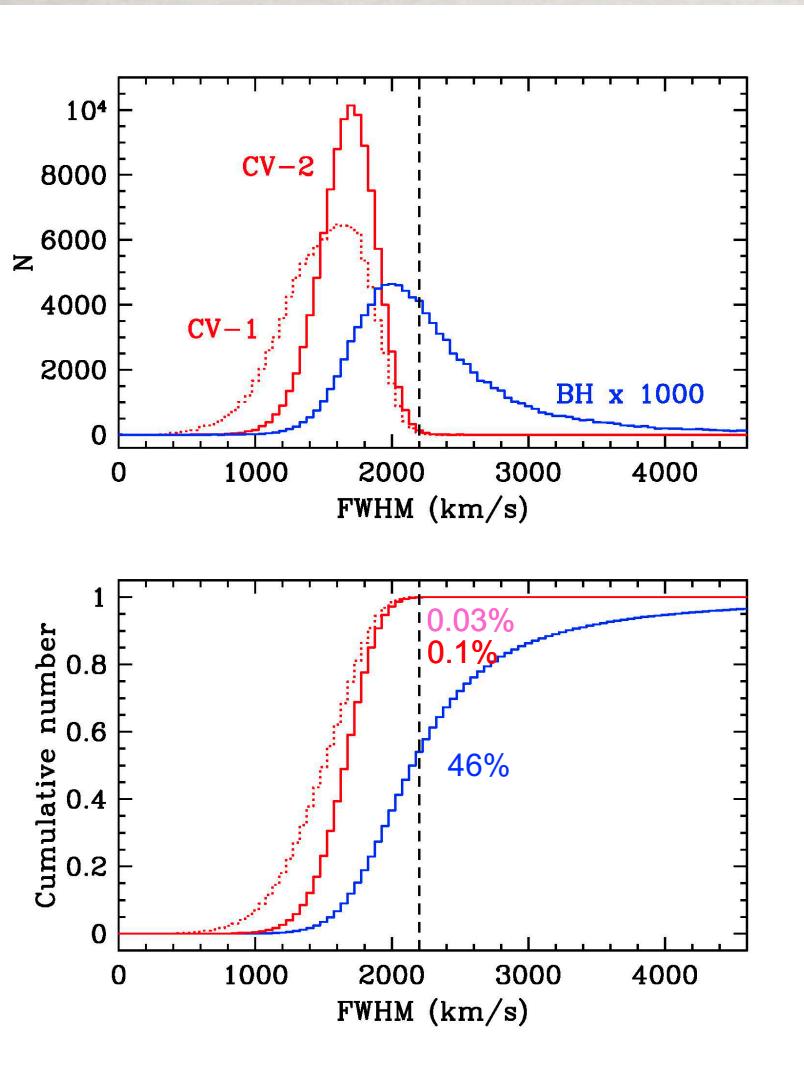
$FWHM > 1500 \text{ km/s}$  would clean most Galactic populations of H $\alpha$  emitters  
**(T Tauri, chromospheric stars, Be-stars, PNe ...)**

Only CVs can produce  $FWHM > 1500 \text{ km/s}$  but they are  $\times 1000$  more abundant than BHs (Pretorius & Knigge12)

width of  $H\alpha_n$  determines the lower limit in  $FWHM$  selection

# Filtering CVs

**$FWHM > 2200 \text{ km/s}$**  allows rejecting 99.9% CVs while still select 46% BHs



## Montecarlo distribution of $FWHMs$

From empirical  **$FWHM-K_2$**  correlation and distribution of **Mass functions** (assuming **isotropic inclinations** )

**BHs:** Gaussian distributions of  $M_1$  (mean=7.8  $M_\odot$ ,  $\sigma=1.2 M_\odot$ ; Özel et al. 10) and  $P_{orb}$  (mean=0.29 d,  $\sigma=0.14$  d),  $q$  (mean=0.05 d,  $\sigma=0.02$ )

**CVs:** Gaussian distribution of  $M_1$  (mean=0.83  $M_\odot$ ,  $\sigma=0.23 M_\odot$ ; Zorotovic et al. 11) and latest distribution of  $P_{orb}$  &  $q$  from Ritter's (**Model 1**) or  $N^o$  CVs below the gap boosted to 98% of total (Kolb 93; Howell et al. 01; Knigge 11; **Model 2**)

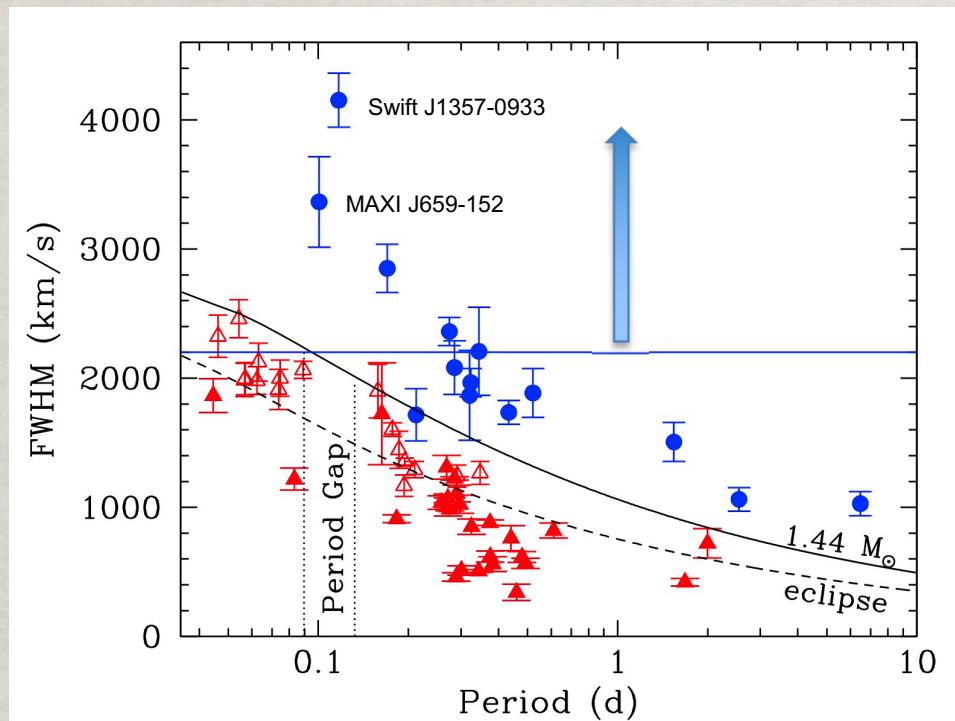
**Implies a discovery rate  $\sim 2$  CV/BH**

(compared to  $\sim 200$  CV/BH for  $FWHM > 1800 \text{ km/s}$ )

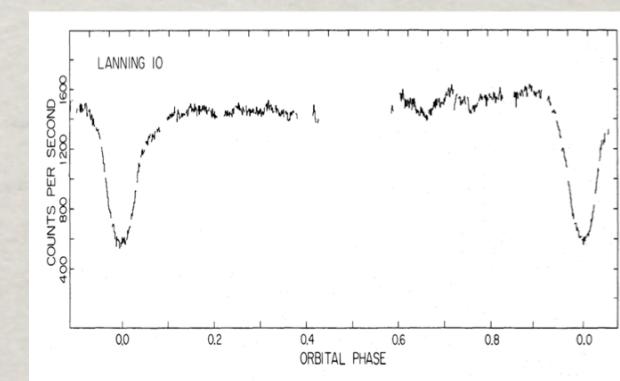
# Filtering CVs

$$FWHM \propto \left( \frac{M_1}{P} \right)^{1/3} \sin i$$

Limit case for  $M_1 < 1.44 M_{\odot}$  and  $i < 90^\circ$   
constrains  $P_{\text{orb}}$  for  $FWHM > 2200 \text{ km/s}$



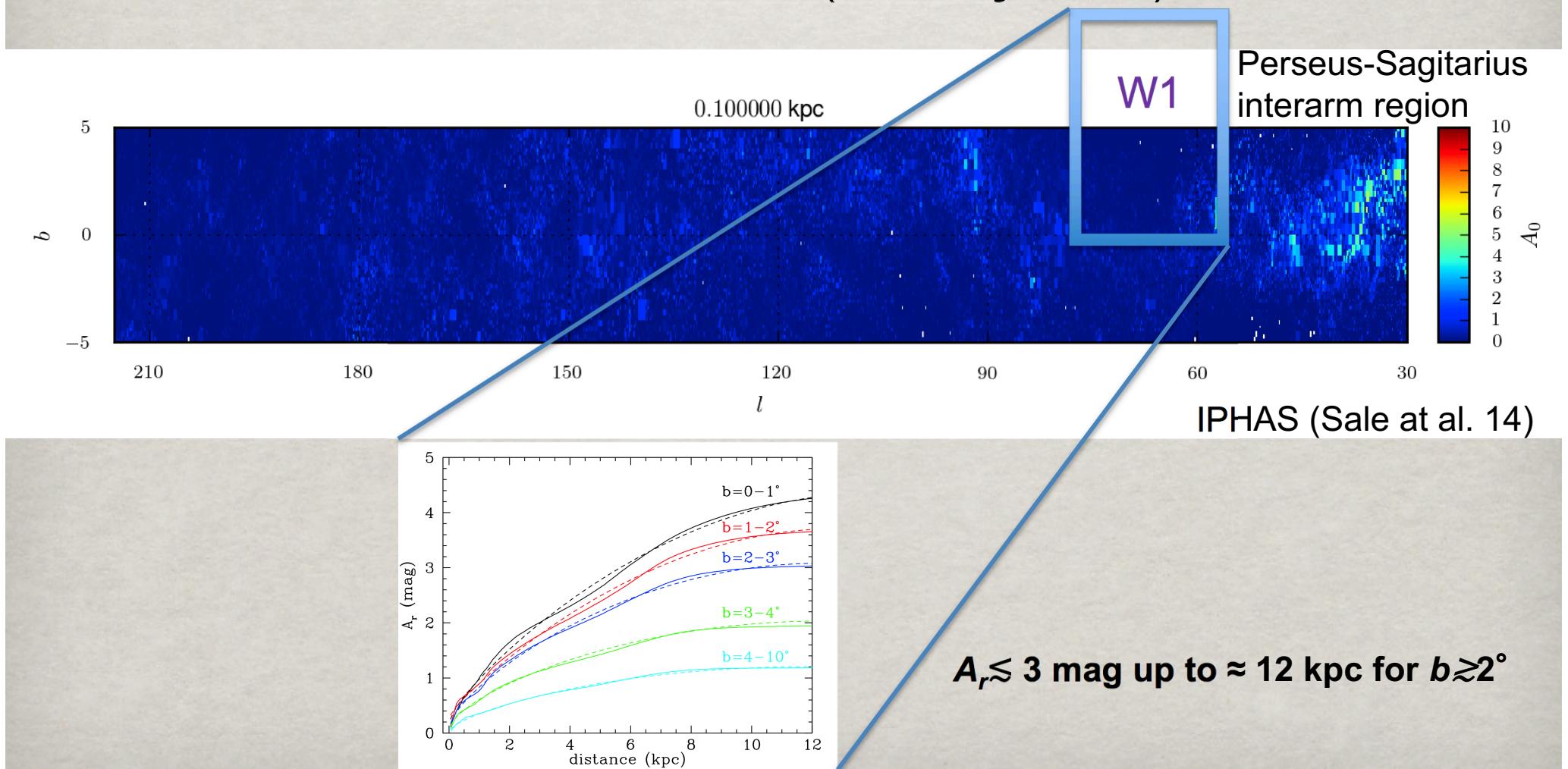
- BHs
- △ Eclipsing CVs
- ▲ Non-eclipsing CVs



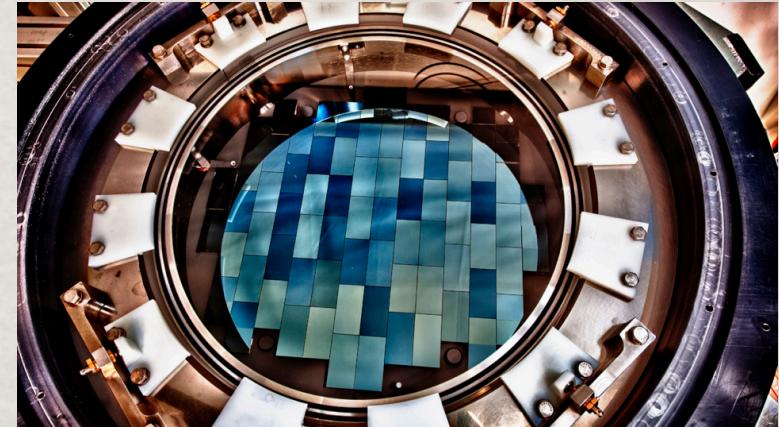
CVs with  $FWHM > 2200 \text{ km/s}$  will have  $P_{\text{orb}} \lesssim 2.1 \text{ h}$  and will all be eclipsing !!

# HAWKs = HAlpha Width Kilo deg Survey

1. > 90% BH XRTs located in the **Galactic Plane** at  $|b|<10^\circ$
2. Focus on **low extinction windows** to maximize surveyed volume (e.g. **W1** at  $\sim 55-75^\circ$ ). Southern Plane regions will be soon available from **DECAPS** (Schlafly's talk).



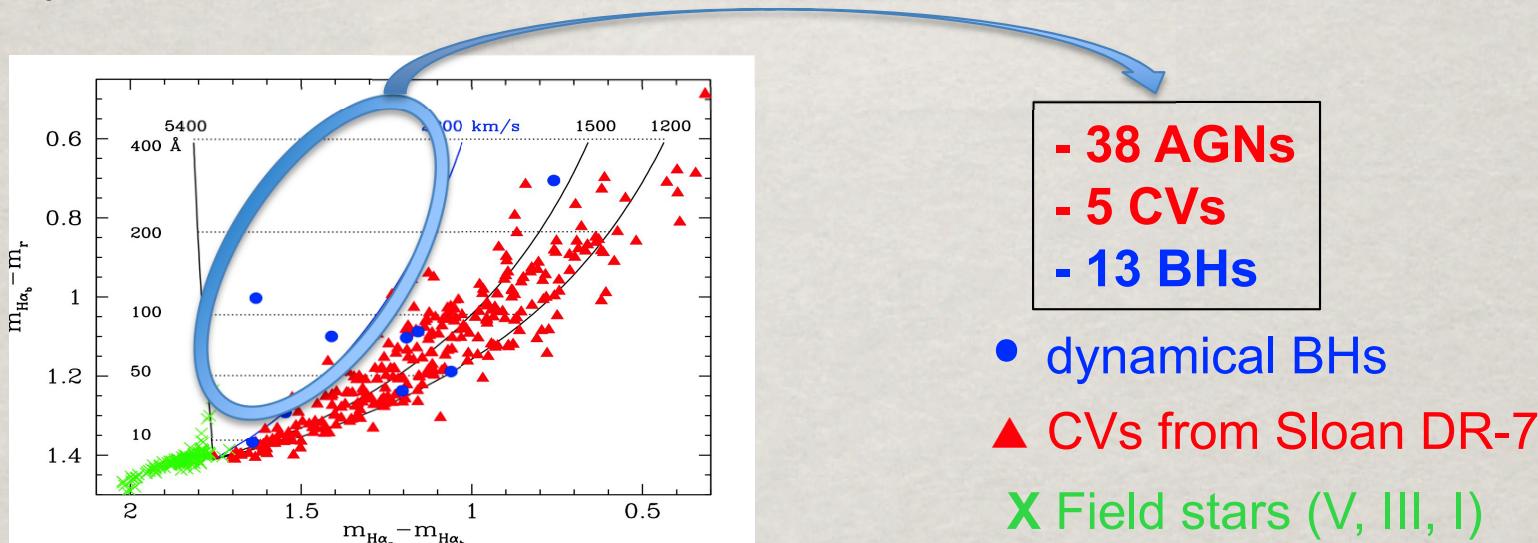
# 4-m Blanco Telescope + 3 deg<sup>2</sup> DECam



- **Single pointing:** 3 h required to reach **SNR=50 for  $r=22$**  in  $r$ ,  $Hab$ ,  $H\alpha$  (or  $r=24$  at 5% photometry) → goal for 10% accuracy in  $FWHM_{ph}$
- Thus ~20 nights required for pilot 200 deg<sup>2</sup> or ~100 nights for ~1 Kdeg<sup>2</sup>
- **Continuous r/Hab/Hα cycles** will yield 3h light curves to (1) average out flickering variability and (2) detect eclipsing targets (all outlier CVs)

# H $\alpha$ Colour-Colour Diagram

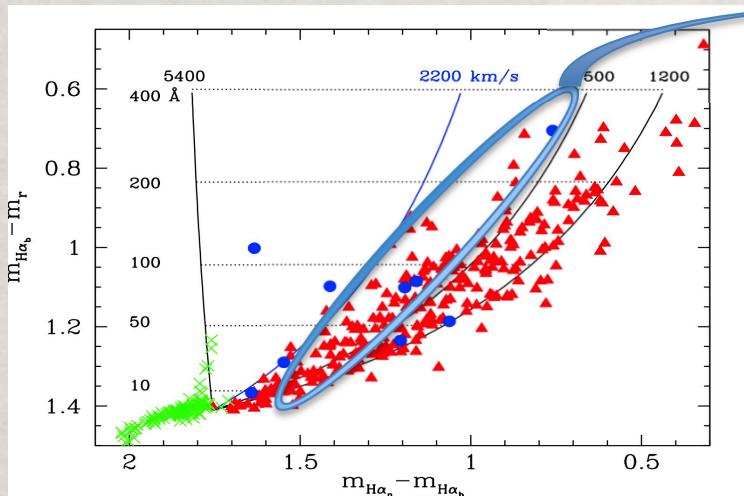
- For an assumed population of  $\sim 5000$  Galactic BHs, a **pilot 200 deg $^2$**  survey at  $r=22$  would unveil  $\approx 56$  H $\alpha$  emitters with  $FWHM > 2200$  km/s



- Outliers** can be singled out through **mid-IR WISE colours (AGNs)** and **photometric variability** in 2 h slots: **non-eclipsing** targets will be prime **BH candidates**

# H $\alpha$ Colour-Colour Diagram

- A survey of  $\sim 1$  Kilo deg $^2$  could discover  $\approx 50$  new dynamical BHs at  $r \sim 22$ , a 3-fold improvement over the existing population ( $\sim 100$  yrs needed at the current discovery rate of XRTs)

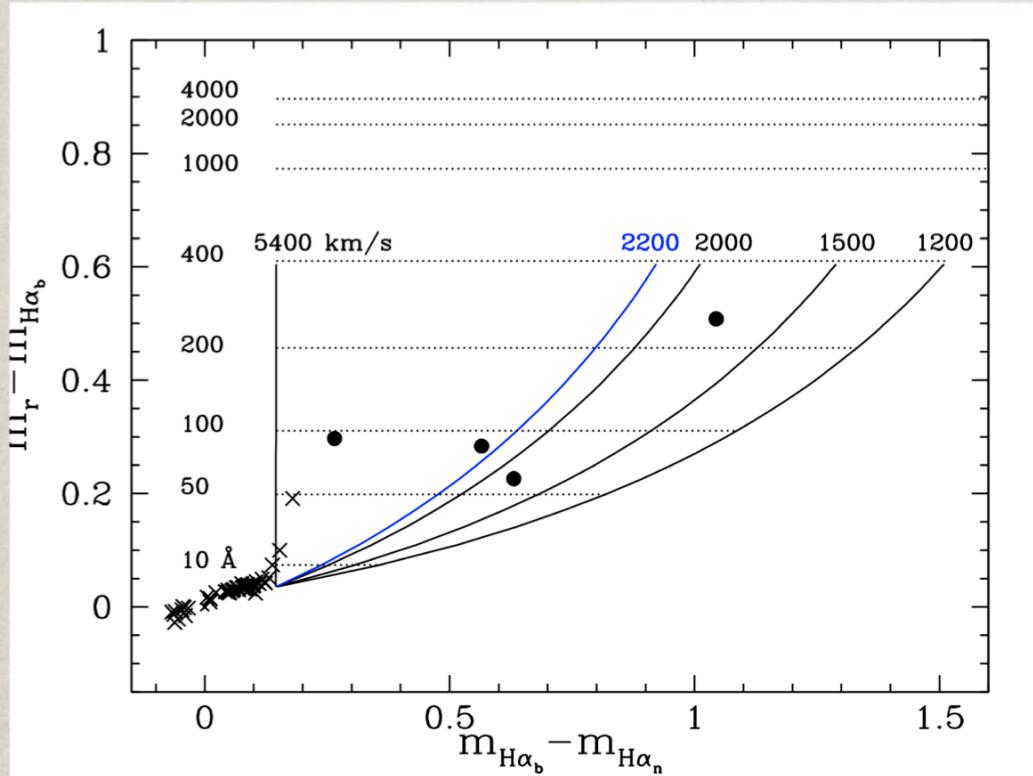


Multi-object spectrographs (e.g. 4MOST, WEAVE) and synoptic surveys (LSST) can recover many more BHs

- The *HAWKs catalogue* will unveil many high-inclination/eclipsing BHs, so far hampered by X-ray selection effects (Narayan & McClintock 2005)
- Plus other ancillary studies:
  - Eclipsing NSs (some could be massive)
  - Several 100 short-period (eclipsing) WZ Sge stars
  - Plus countless numbers of other  $H\alpha$  emitters (more CVs, T Tauri, Symbiotics, Be-stars...)

# HAWKs Legacy Project

BH demographic studies: population size/distribution,  $P_{orb}$ , Masses



x Field stars (V, III, I)

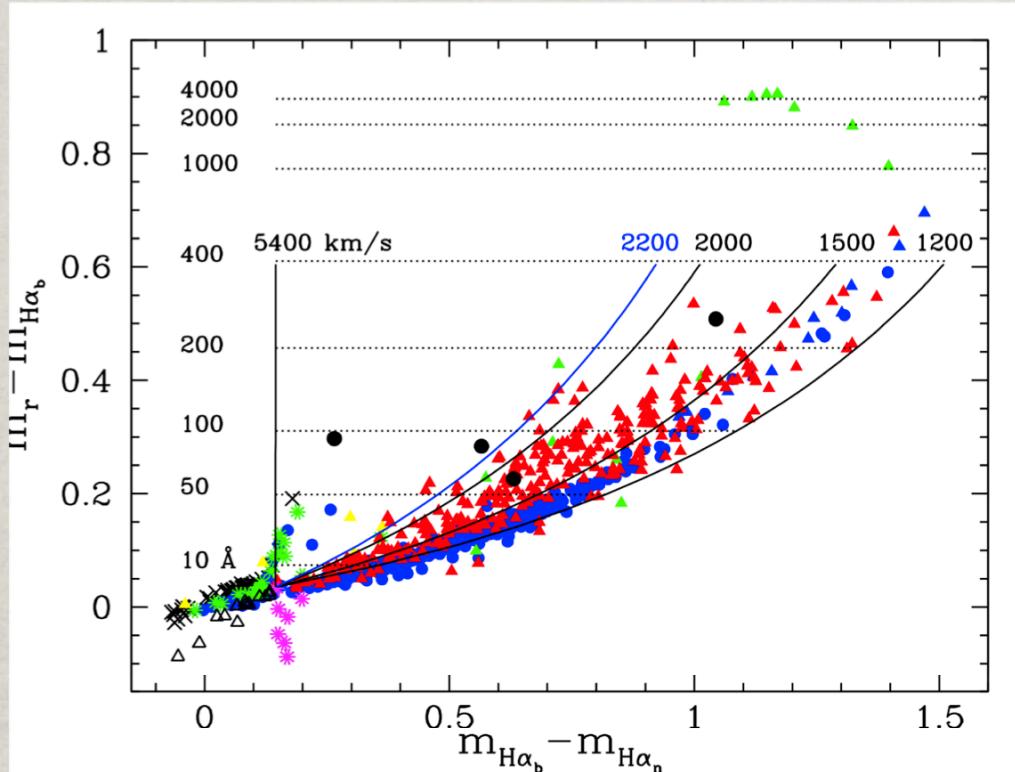
• **BLACK-HAWKs:** dynamical BHs

+ **other coloured/flavoured HAWKs**



# HAWKs Legacy Project

**BH demographic studies:** population size/distribution,  $P_{orb}$ , Masses



x Field stars (V, III, I)

• **BLACK-HAWKs:** dynamical BHs

**YOUNG-HAWKs:** YSO

● T Tauri

▲ Be stars

**SYMBIOTIC-HAWKs:**

● S-type

▲ D-type+PNe

● **CORONAL-HAWKs:** Coronal stars

▲ **CATAclysmic-HAWKs:** CVs

✿ **ULTRACOMPACT-HAWKs:** AM CVn

△ **WHITE-HAWKs:** WDs

LISA calib.  
targets

**SYNERGIES WITH OTHER SURVEYS:** LSST (colours &  $P_{orb}$ ), WISE (MIR colours of AGNs & Symbiotics), VISTA (NIR colours of TTauri & Symbiotics), GAIA (parallaxes of nearby targets), 4MOST, ELT (follow-up spectroscopy), eROSITA ...