Variable Galactic Gamma-Ray Sources (IV)

Tokyo, 4-7 July 2017

The gamma-ray candidate and Be/BH binary MWC 656 in context: discovery, evolution and recent results

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IEEC

I will present results of **several publications** and **theses**, with different **contributors**:

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The first simultaneous X-ray/radio detection of the first Be/BH system MWC 656
M. Ribó, P. Munar-Adrover, J. M. Paredes, B. Marcote, K. Iwasawa, J. Moldón, J. Casares, S. Migliari, X. Paredes-Fortuny, **ApJ**, 835, L33 (2017)

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OUTLINE

1. Introduction
2. Discovery of MWC 656, the first Be/BH binary
3. Formation and evolution
4. HE and VHE observations
5. Work in progress
6. Conclusions

Introduction

Binary systems with HE (GeV) and/or VHE (TeV) gamma-ray emission:

- Accreting X-ray binaries like **Cygnus X-3** (SED peak at keV).
- Young non-accreting pulsars like **PSR B1259-63** (SED peak at MeV-GeV). We call these systems gamma-ray binaries.
- Colliding wind binaries such as **Eta Carinae**.
- Novae like **V407 Cygni**.
- Transitional millisecond pulsars like **PSR J1023+0038**.
- Recycled non-accreting MS PSRs in binary systems: **Black Widow Pulsar**.

All these systems have been detected at GeV energies by ***Fermi*/LAT** and/or by ***AGILE***, but only the gamma-ray binaries are detected at TeV energies.

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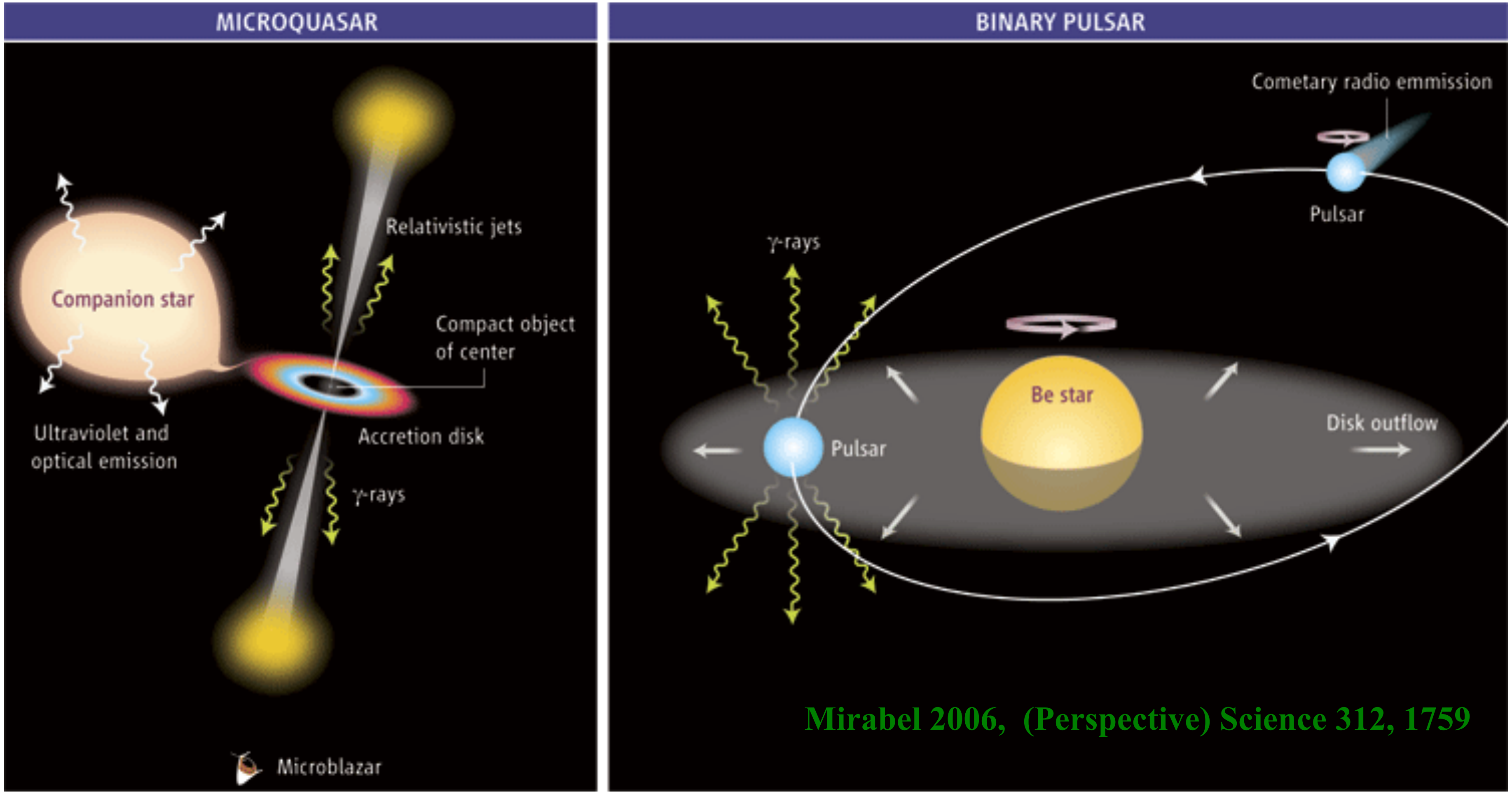
Introduction

Gamma-ray emitting binaries with massive stars and compact objects



Cygnus X-3, Cygnus X-1

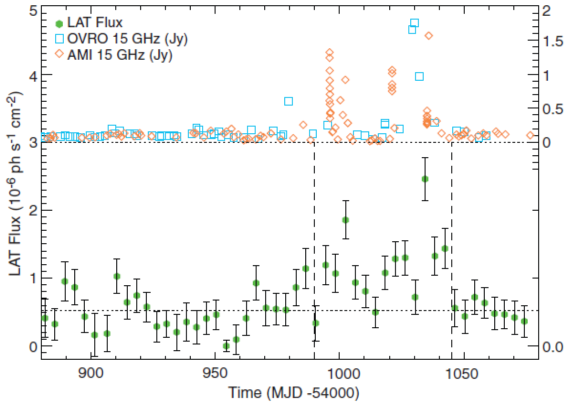
PSR B1259−63
LS 5039 ? LS I +61 303 ?
HESS J0632+057 ? 1FGL J1018.6−5856 ?
CXOU J053600.0-673507 (LMC P3) ?

Introduction

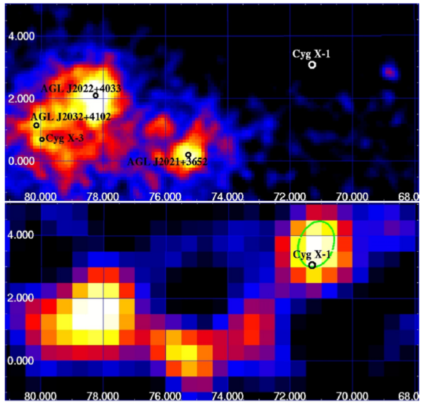
GeV emission:

- **Microquasars**:

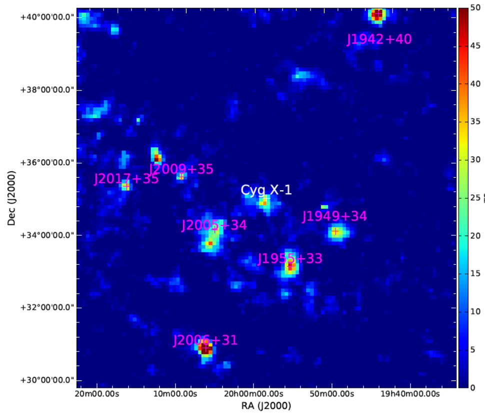
Cygnus X-3
Abdo et al. (2009)



Cygnus X-1
Sabatini et al. (2010)



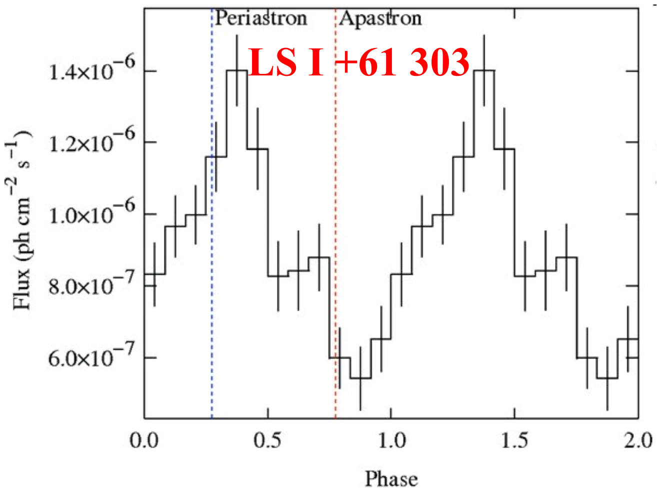
Cygnus X-1
Zanin et al. (2016)



  - **Transient long-term** behavior (Cygnus X-3, 2009 papers).
  - Maybe **short-term flares** (Cygnus X-1, *AGILE*).
  - **Persistent emission** in the low-hard state (Cygnus X-1, *Fermi*/LAT).

- **Gamma-ray binaries**:
  - Persistent/transient but **periodically modulated** (but HESS J0632+057).

Abdo et al. (2009)



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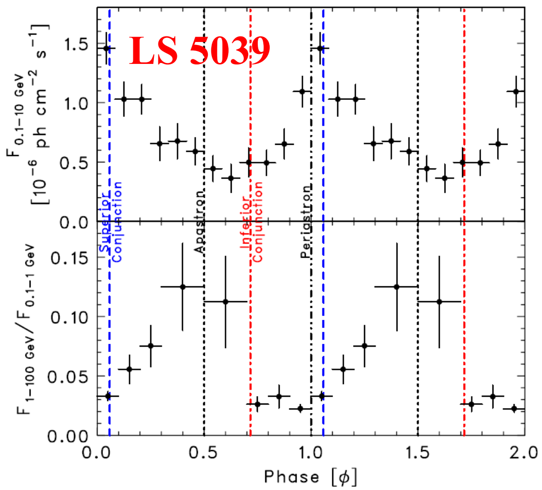

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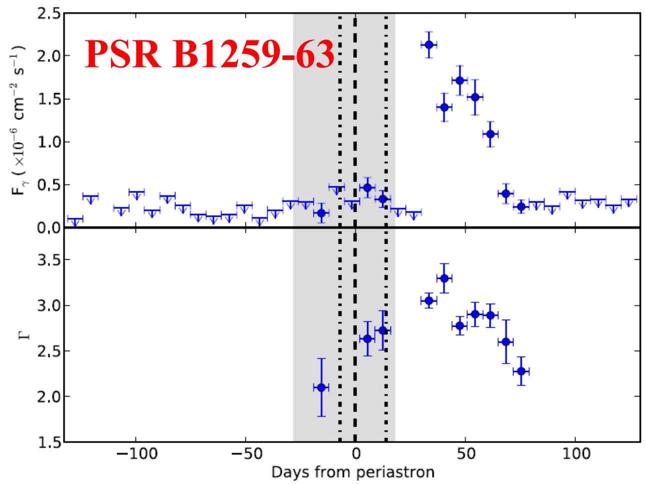


Introduction

X-ray binaries and gamma-ray binaries displaying HE (GeV) and/or VHE (TeV) gamma-ray emission **allow us to study** the following processes depending on black hole states or orbital configurations:

- Particle acceleration
- Anisotropic Inverse Compton Scattering
- Absorption and cascading
- Outflow evolution and energy losses

These are **new laboratories for physics**!

However, there are still lots of **open questions**, and the **study of every new system is important by itself**.

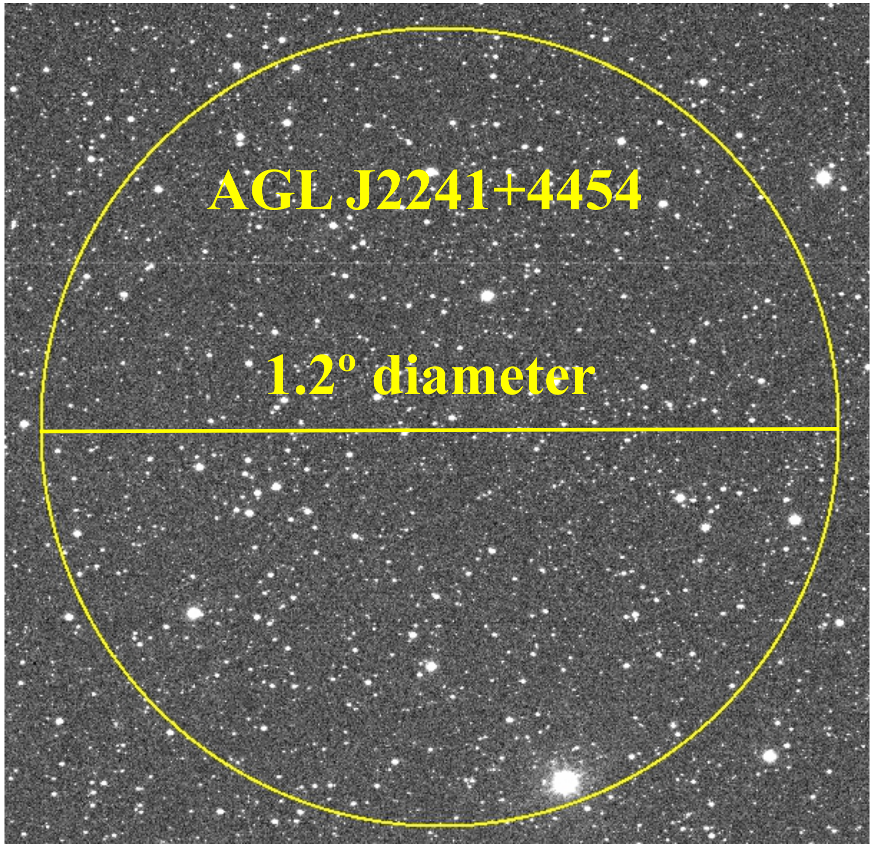
Discovery of MWC 656, the first Be/BH binary

AGILE detected a **new unidentified gamma-ray source: AGL J2241+4454**.

- **Coordinates** $(l,b) = (100.0,$**-12.2**$) \pm 0.6^{\circ}$ (95% stat.) $\pm 0.1^{\circ}$ (syst.).
- **Epoch of detection**: 25-26 July 2010.
- **Flux**: a maximum likelihood analysis yields a detection **above 5 sigma**, and a flux above 1.5×10^{-6} ph/cm^2/s ($E > 100$ MeV) **(Lucarelli et al. 2010)**.

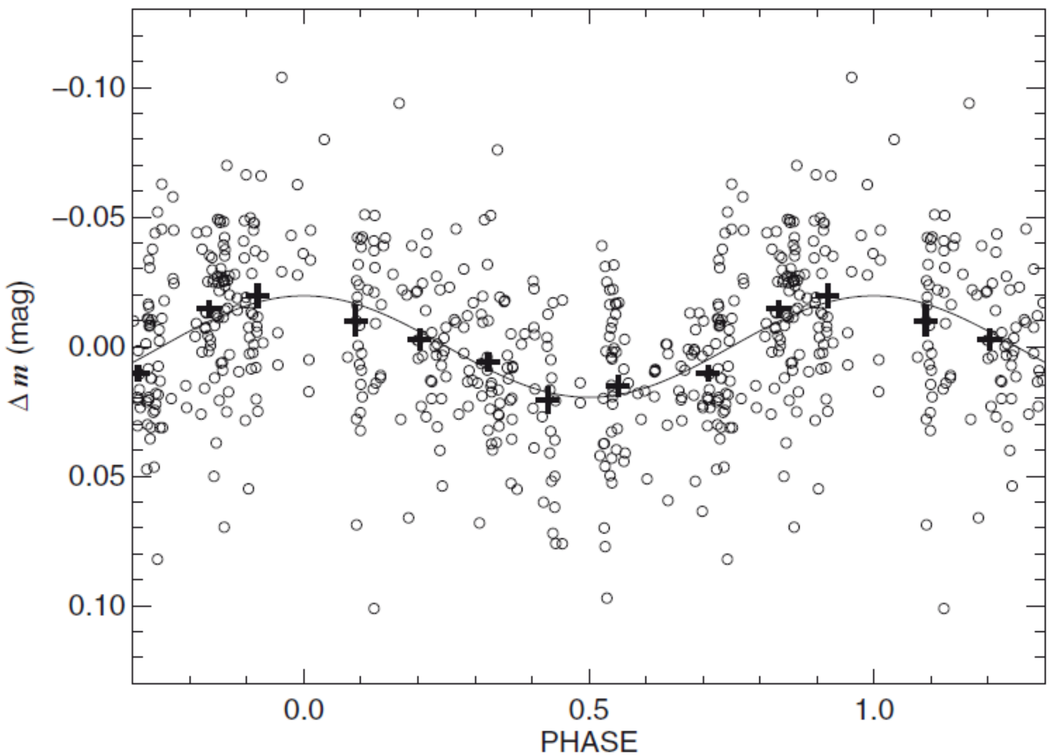
***Fermi*/LAT did not confirm** the detection, with an upper limit one order of magnitude smaller **(http://fermisky.blogspot.com.es/2010/07/extra-note-july-30-2010.html)**.

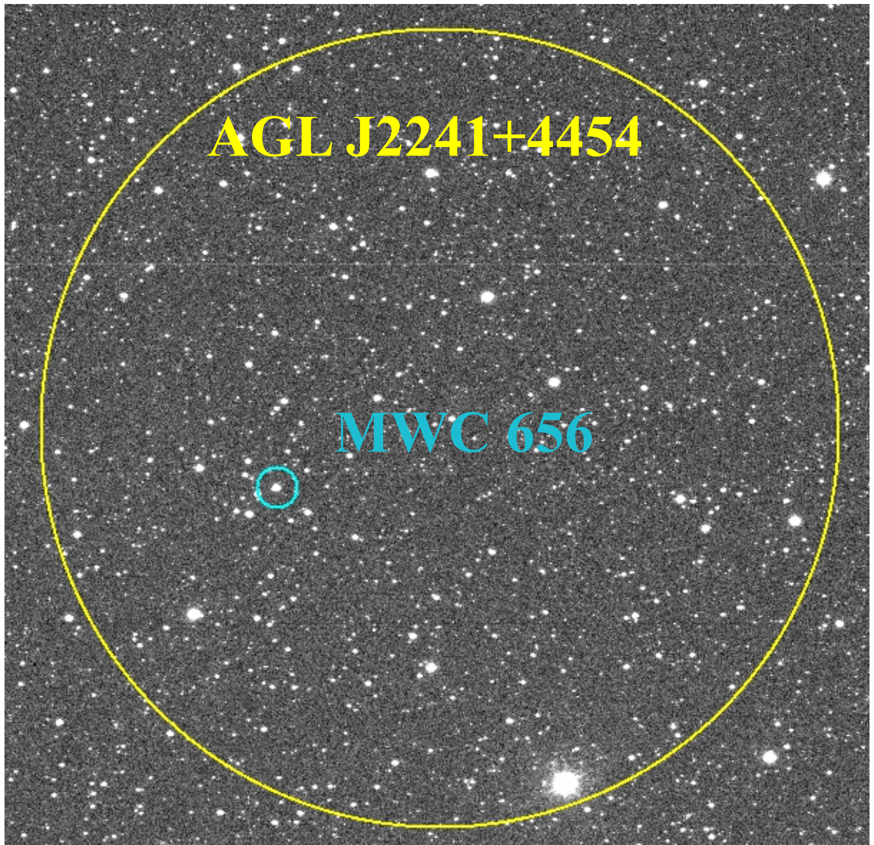
Even if outside the Galactic plane the $\pm 0.6^{\circ}$ includes **lots of possible counterparts**.



Discovery of MWC 656, the first Be/BH binary

- **Williams et al. (2010)** suggested **the Be star HD 215227**, aka **MWC 656**, as possible counterpart.
- Optical photometry (archival data) revealed a **periodicity of 60.37±0.04 d**, suggesting **binarity**.





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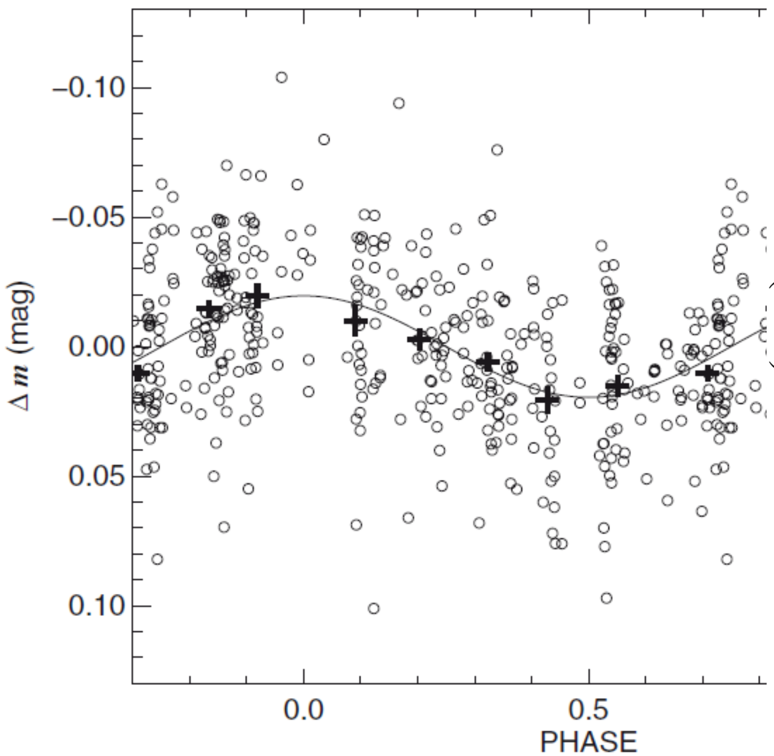
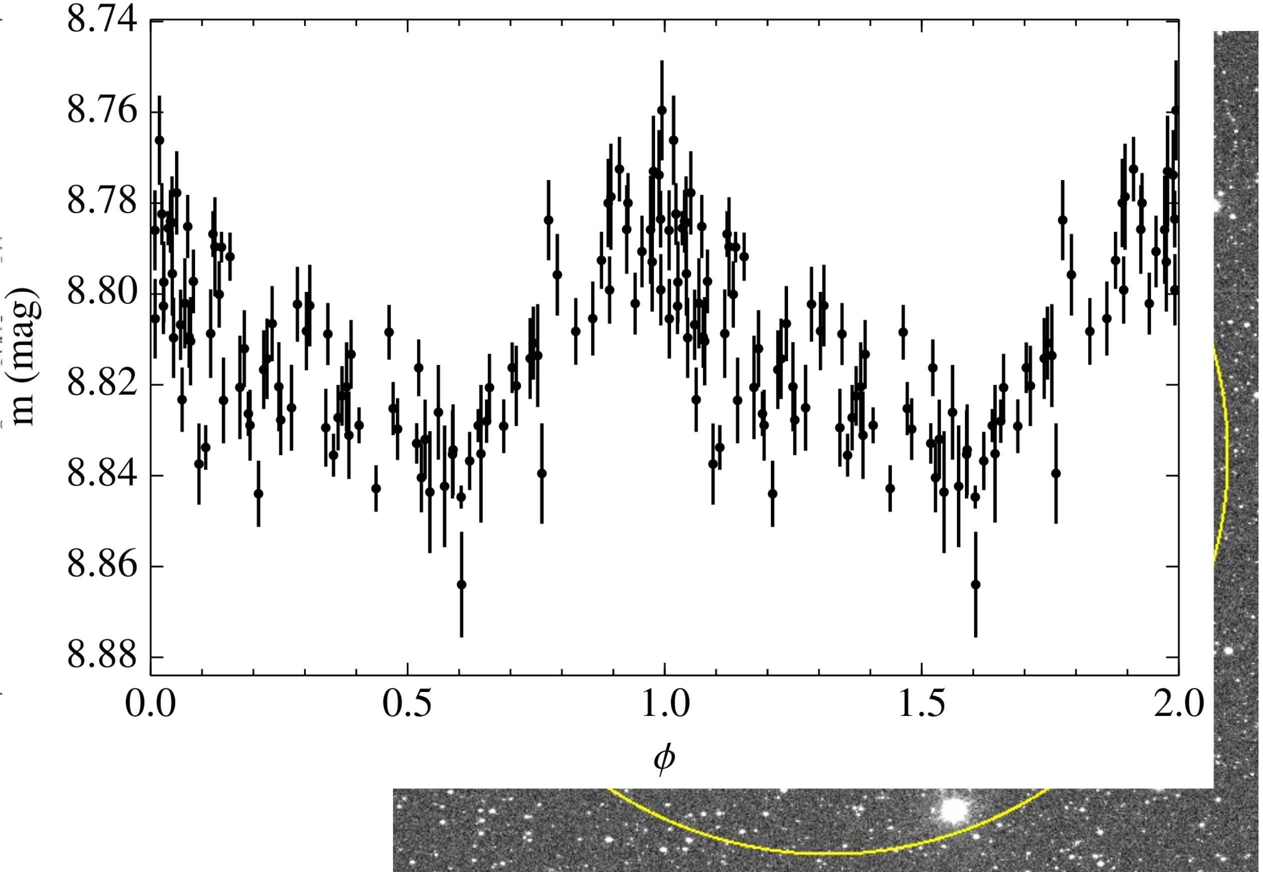
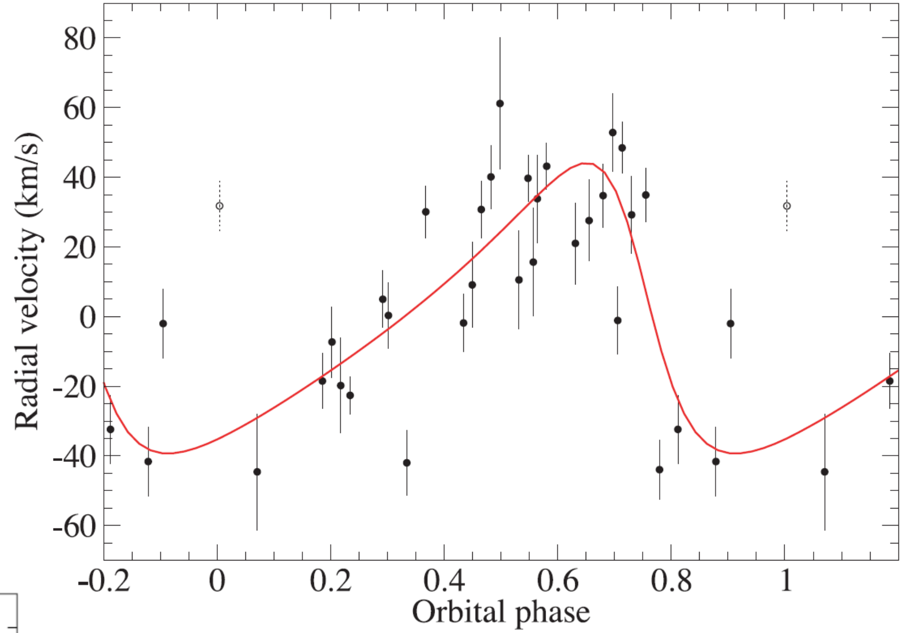
- Optical photometry (archival data) revealed a **periodicity of 60.37±0.04 d**, suggesting **binarity**.
- **Paredes-Fortuny et al. (2012)** confirmed the periodicity with a coherent data set.

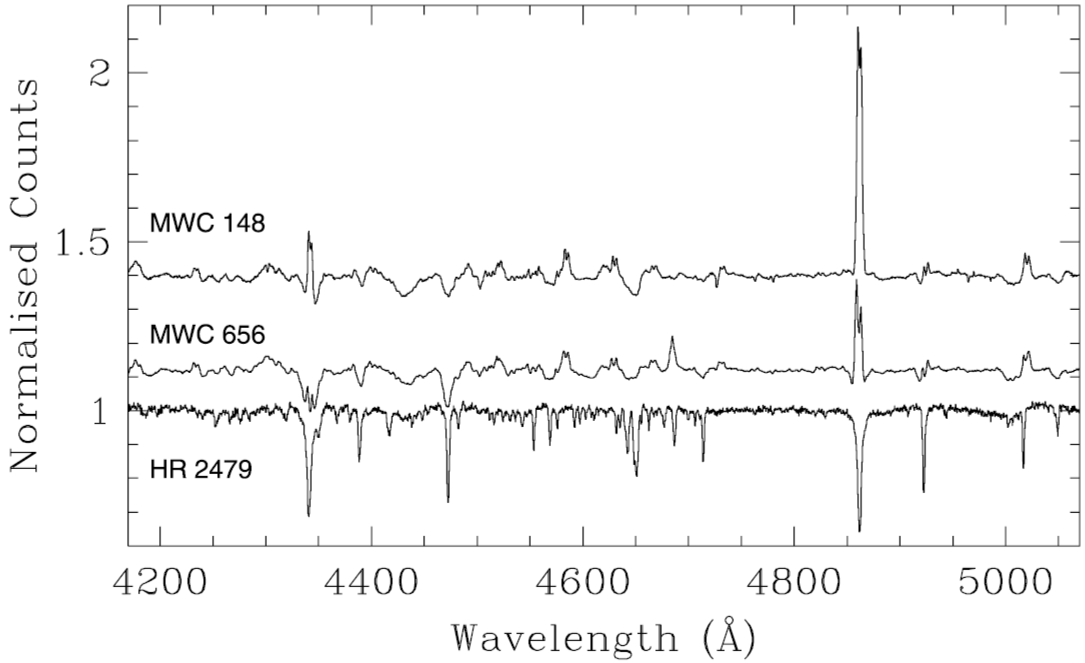




Discovery of MWC 656, the first Be/BH binary

Radial velocity studies of **photospheric absorption HeI lines** of the Be star showed clear variations when folded with the 60.37 d period, **confirming the binary nature** of MWC 656 and allowing for a NS or BH companion **Casares et al. (2012)** .





Parameter	MWC 656
P_{orb} (d)	60.37 (fixed)
T_0 (HJD −2450 000)	3243.3 (fixed)
e	0.4 (fixed)
ω (°)	71 ± 23
γ (km s^{-1})	−2.8 ± 9.4
ϕ_{peri}	0.74 ± 0.05
K_{opt} (km s^{-1})	41.7 ± 6.8
$a_1 \sin i$ ($R_\odot$)	45.6 ± 7.3
$f(M)$ ($M_\odot$)	$0.35^{+0.20}_{-0.15}$
σ (km s^{-1})	20.3

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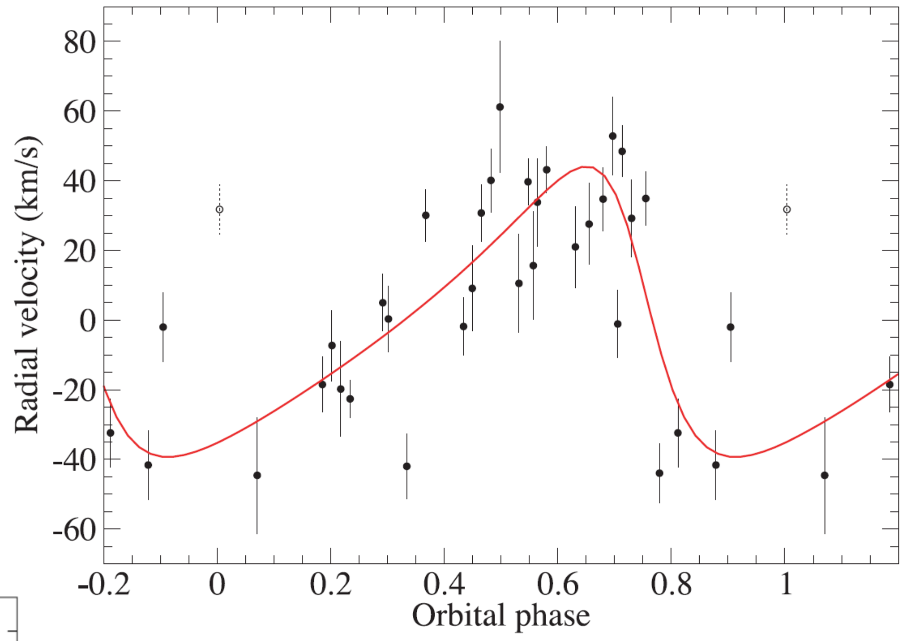

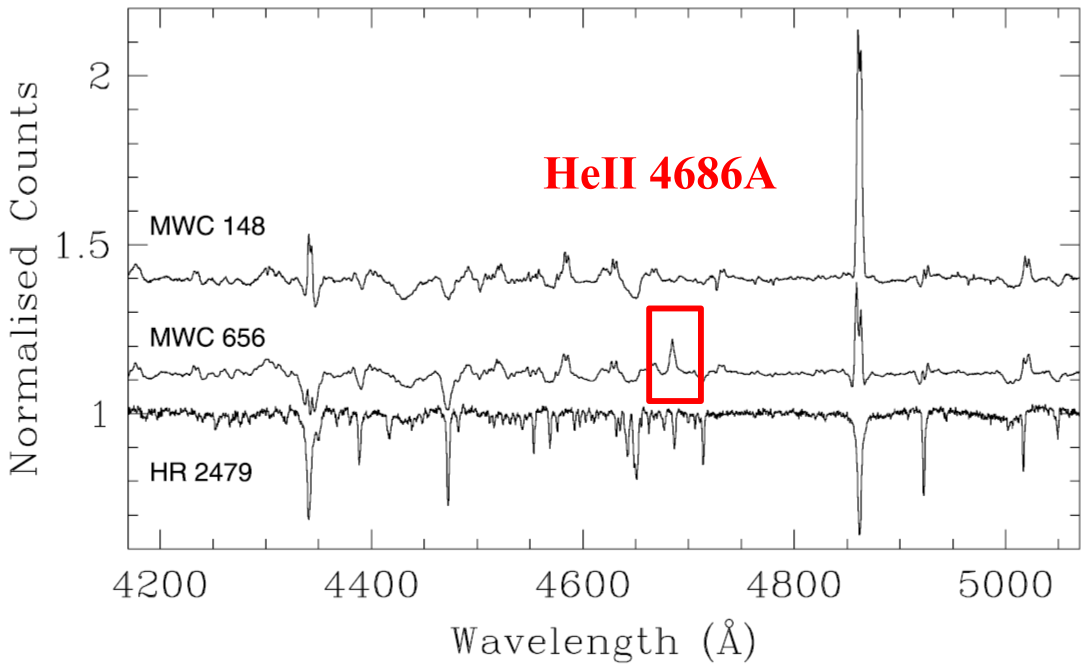

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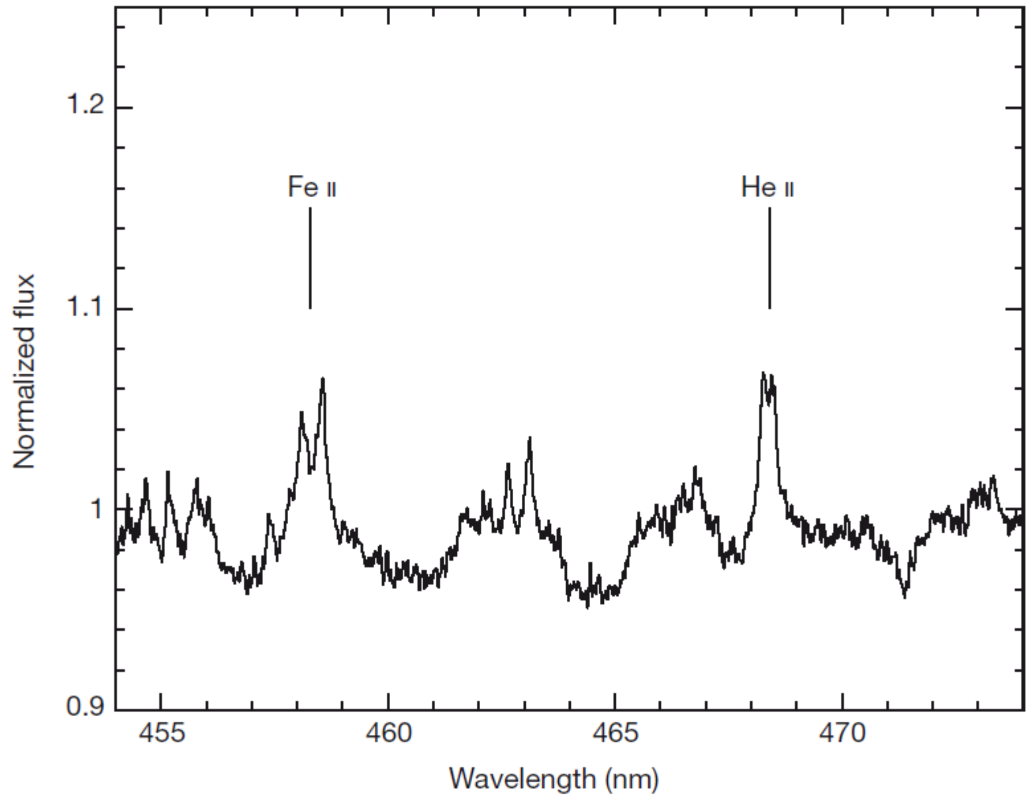
- **HeII 4686 A** emission line too hot to be originated in the Be disk.
- Its double peak suggests gas orbiting in Keplerian motion.
- **FeII** emission lines arise in the Be decretion disk.



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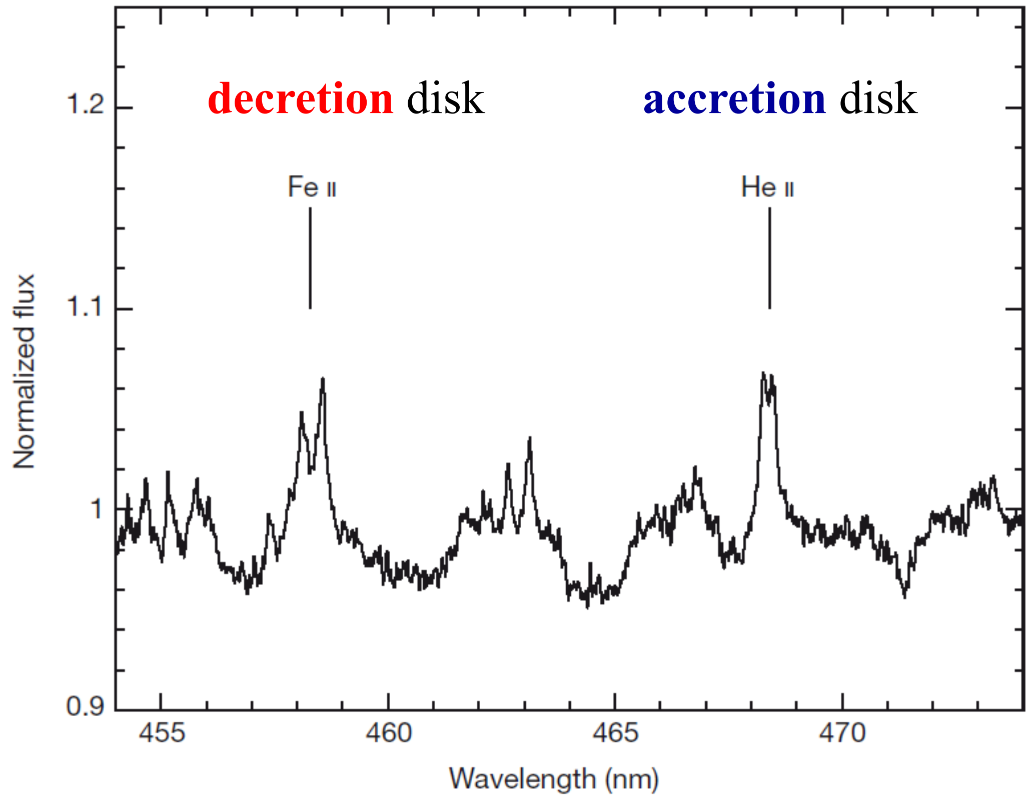
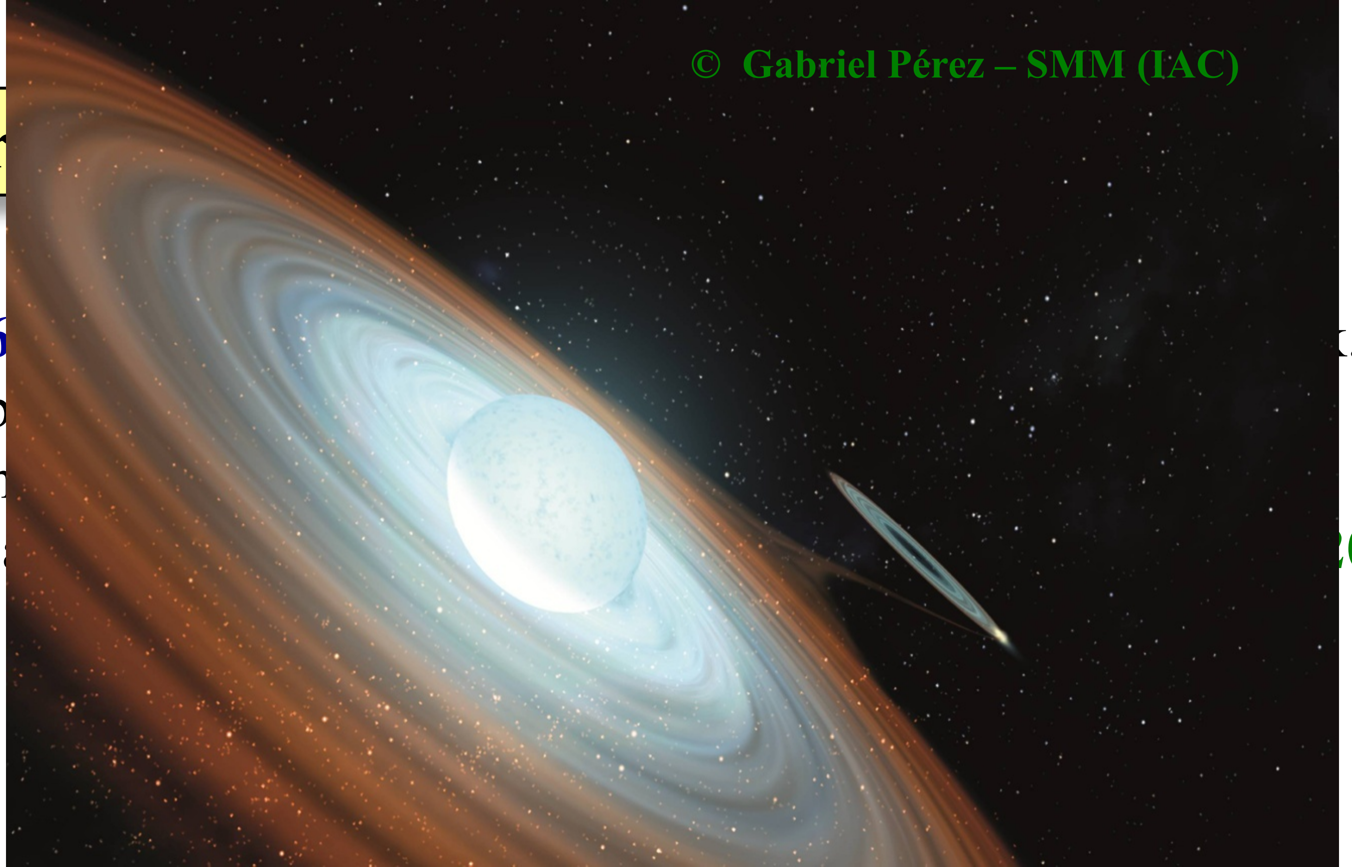
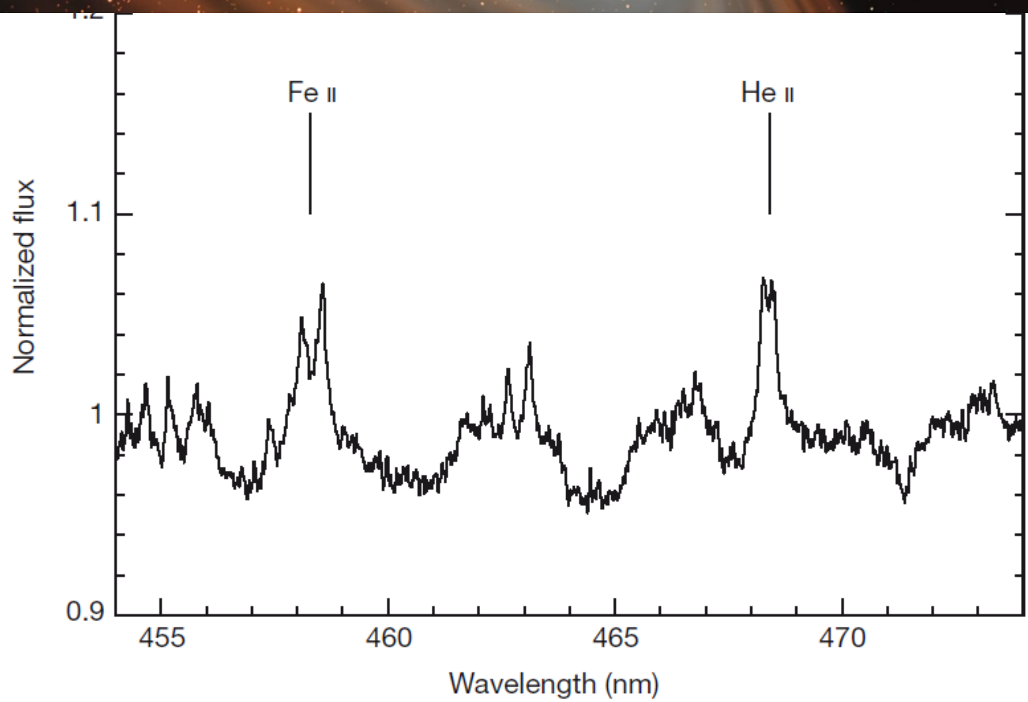
- Its double peak suggests gas orbiting in Keplerian motion.
- **FeII** emission lines arise in the Be decretion disk.
- We see a **decretion** disk and an **accretion** disk! **(Casares et al. 2014)**.



Discover

- **HeII 46** … k.
- Its doub
- **FeII** em
- We see … **2014)**.





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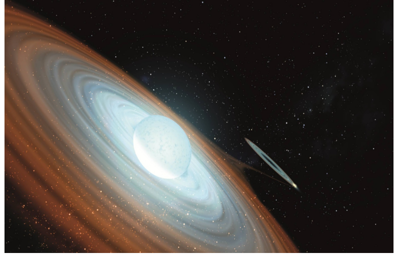
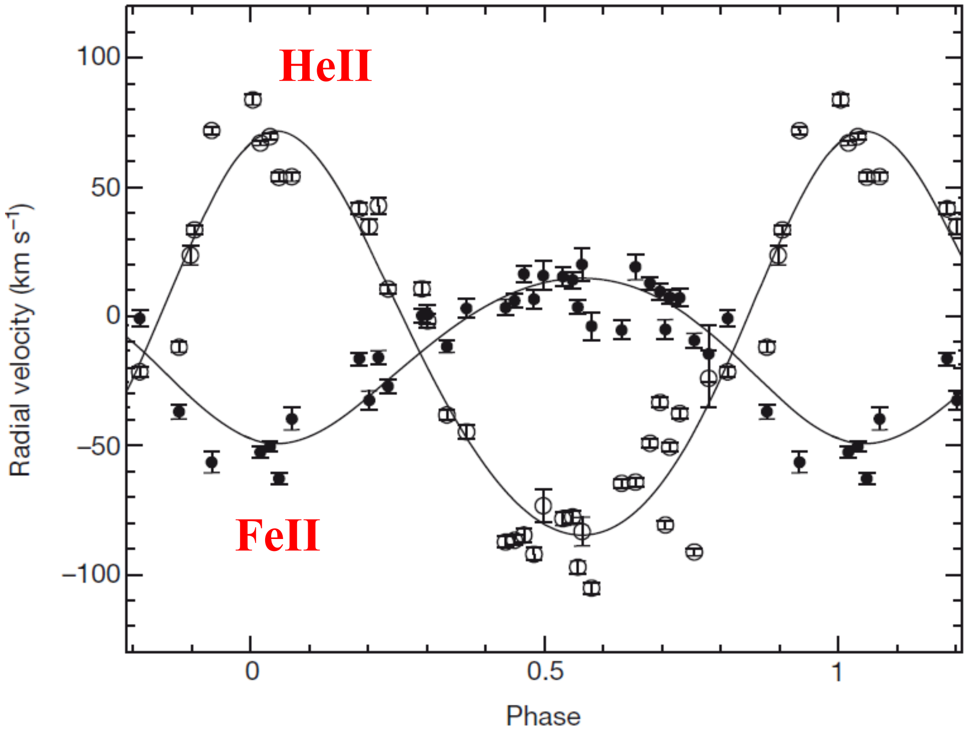


- Double-line fit to disk lines provides a **mass ratio** of 0.41±0.07.
- Spectral classification B1.5–B2 III implies **10–16 solar masses** for Be star.
- This yields a **companion star of 3.8–6.9 solar masses**, implying a BH.
- Spectro-photometric distance is **2.6±0.6 kpc**
- *ROSAT* provided an **X-ray luminosity < 1.0×10^{32} erg s^{-1} or < 1.6×10^{-7} L_{Edd}**.



First Be/BH binary system to be discovered **(Casares et al. 2014)**.

Formation and evolution of MWC 656

Binary population synthesis models predict a high number of Be/NS systems and a low number of Be/BH systems. **The ratio of Be/NS to Be/BH varies between 10 and 50** depending on the survival after the Common Envelope phase and on the kick velocities for NSs **(Belczynski & Ziolkowski 2009)**.

Simulations: Be X-ray Binary Formation Channels

Formation Channel	Efficiency (%)[a] Model A	(B)	[C]	Evolutionary History[b]
BeNS:01	44.2	(41.8)	[45.3]	CE:a→b, SN:a
BeNS:02	42.3	(43.9)	[45.0]	CE:a→b, NC:a→b, SN:a
BeNS:03	11.9	(13.3)	[8.8]	NC:a→b, SN:a
BeNS:04	1.6	(1.0)	[0.9]	All other
BeBH:01	79.6	(13.2)	[17.2]	CE:a→b, SN:a
BeBH:02	19.8	(85.5)	[82.8]	NC:a→b, SN:a
BeBH:03	0.6	(1.3)	[0.0]	All other
$N_{\rm BeNS}$	579	(517)	[1578]	Galactic number of NS BeXRBs
$N_{\rm BeBH}$	82	(19)	[29]	Galactic number of BH BeXRBs
$F_{\rm NStoBH}$	7	(27)	[54]	Number ratio of NS to BH BeXRBs
	survival	no survival	small kicks	

Notes.
[a] Efficiency for models with standard kicks ($\sigma = 265$ km s^{-1}) in which survival through a CE phase with an HG donor is allowed (A) and not allowed (B). Model C shows results for evolution with small kicks ($\sigma = 133$ km s^{-1}) and the survival in CE with HG donors is not allowed.

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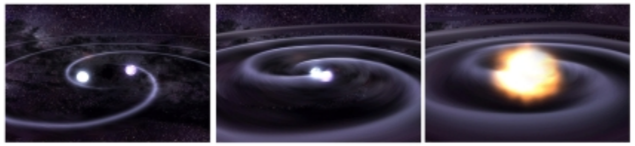
In 2014 there were **81 BeXBs known in the Galaxy with 48 pulsating NS**. The discovery of a BH companion to MWC 656 appears consistent with these model predictions, but there are possible **biases**:

- X-ray spectra of the remaining BeXBs, when available, **suggest NSs**.
- MWC 656 has been identified through a claimed gamma-ray flare and **not by its X-ray activity**.

Implication: the **discovery of Be/BHs seems observationally biased**, in which case **common envelope mergers** would be **less frequent** than commonly assumed **and/or NS kicks** would be best described by the **radio pulsar birth velocity distribution (Casares et al. 2014)**. Models need to be tuned.

Formation and evolution of MWC 656



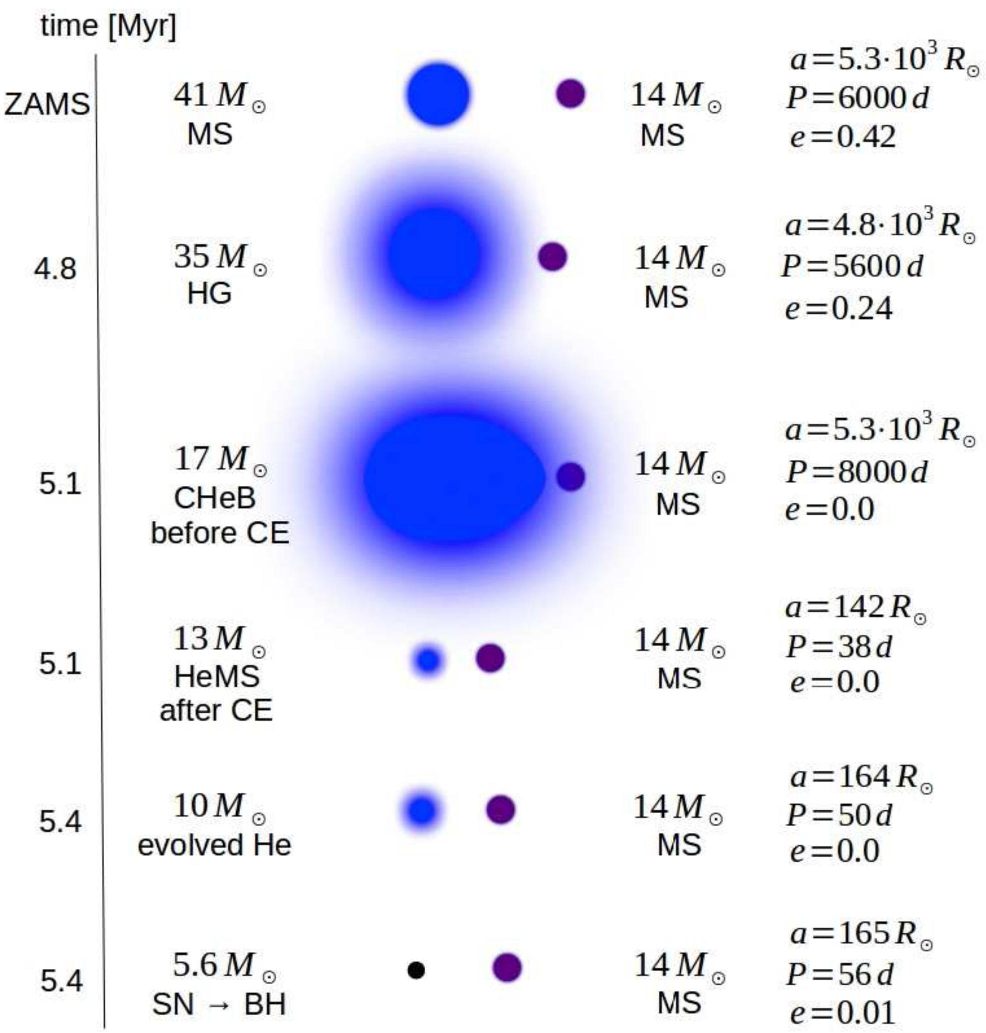
Binary population synthesis models (StarTrack) to:

- **Understand the formation channel** of MWC 656.
- Constrain the **population of Be/BH systems**.
- Study the **fate of MWC 656 as a possible NS-BH merger**.

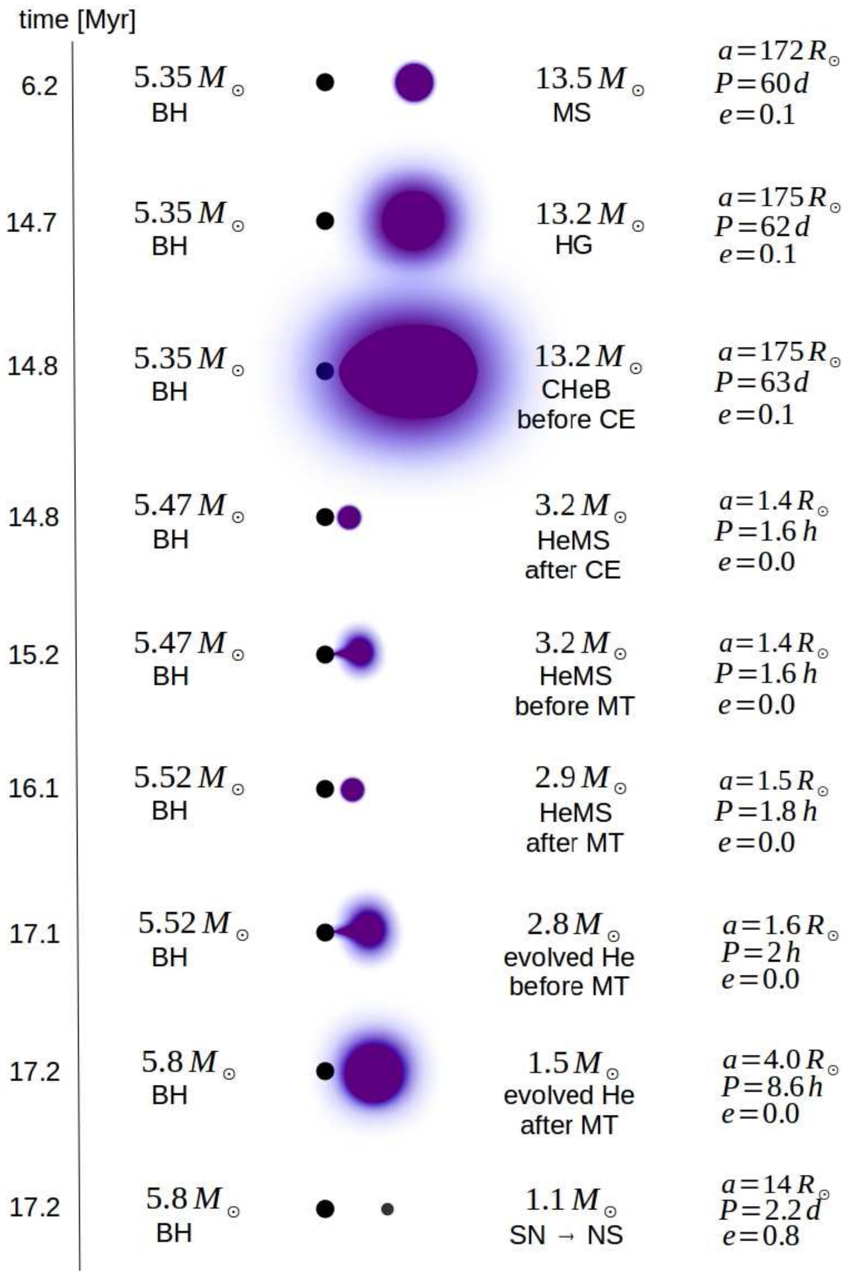
Assumption: all donors beyond main sequence are **allowed to survive the Common Envelope phase** **(Grudzinska et al. 2015)**.

Formation and evolution of MWC 656

Past→ present:

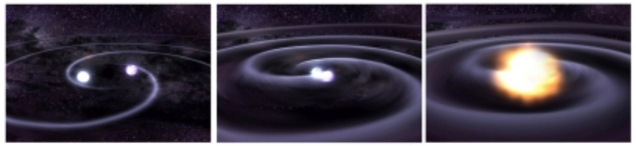


Present→future:



(Grudzinska et al. 2015)

Formation and evolution of MWC 656



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Assumption: all donors beyond main sequence are **allowed to survive the Common Envelope phase (Grudzinska et al. 2015)**.

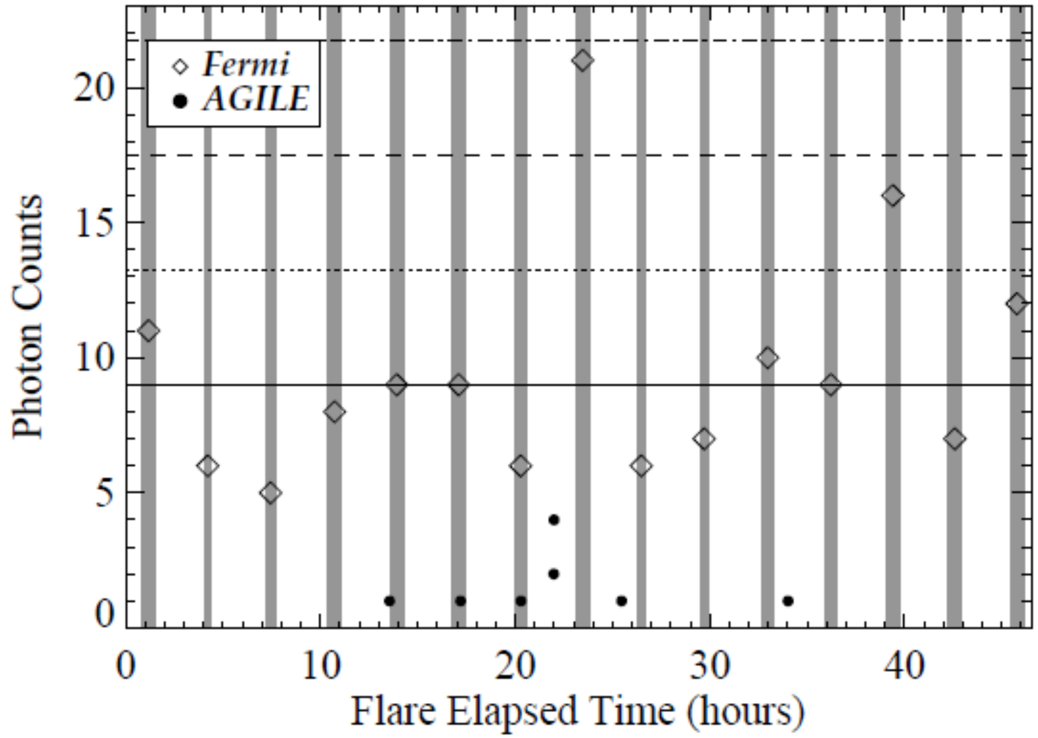
Total number of Be/BH systems formed over entire 10 Gyr of evolution of the Galactic disk is **1.4×10^4**. Only **13 of them** have periods, eccentricities and masses **similar to MWC 656**.

The simulated number of Be/BH systems at present is 26, but **only 0.007** with properties **similar to MWC 656** (probability 1%).

The detection of **gravitational waves** is possible for Advanced LIGO and Virgo, with **detection rate** at the level of **0.1 ± 0.1 yr^{-1} (Grudzinska et al. 2015)**.

HE and VHE observations

- ***AGILE*** claimed a **detection above 5 sigma**, and a flux above 1.5 x 10^{-6} ph/cm^2/s (E > 100 MeV) **(Lucarelli et al. 2010)**.
- ***Fermi*/LAT** provided an **upper limit** one order of magnitude smaller **(http://fermisky.blogspot.com.es/2010/07/extra-note-july-30-2010.html)**.
- A study of the *Fermi* data shows an **enhancement of signal** during the *AGILE* detection, nearly reaching a 3σ deviation with respect to the median **(Alexander & McSwain 2015)**.



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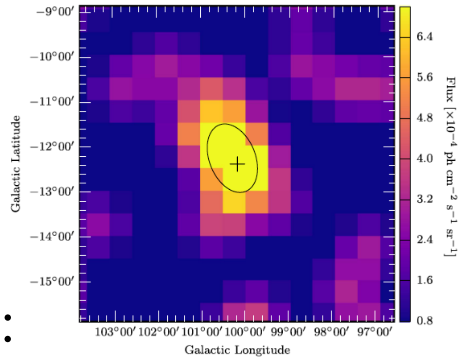
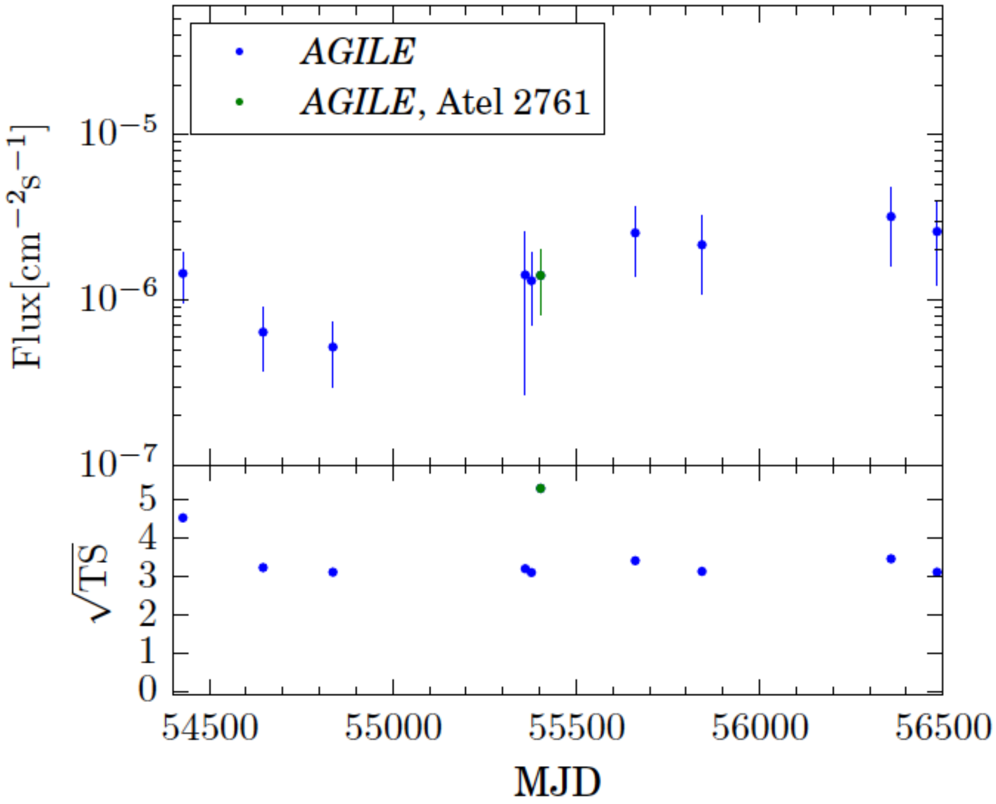
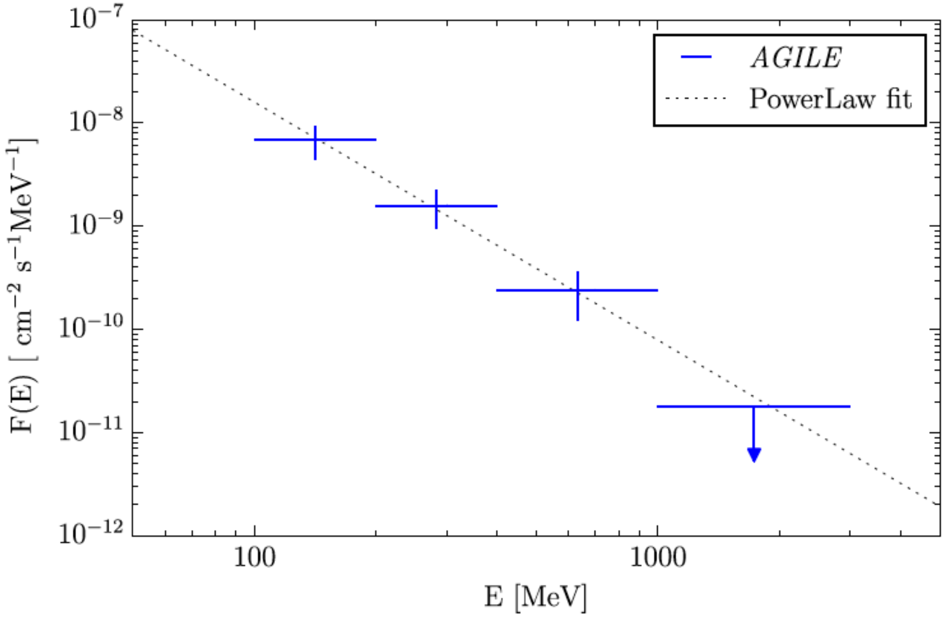


Results of ***AGILE*** from 2007 April until December 2013 (~7 yr):

- **Nine other transient events** compatible in position with AGL J2241+4454.
- **Hint of long-term GeV variability (Munar-Adrover et al. 2016)**.
- Stacking: 100 MeV to 1 GeV spectrum; fit with power law with $\Gamma = 2.3$.
- No source in ***Fermi*/LAT** data, but **less exposed** and significantly **off-axis**.





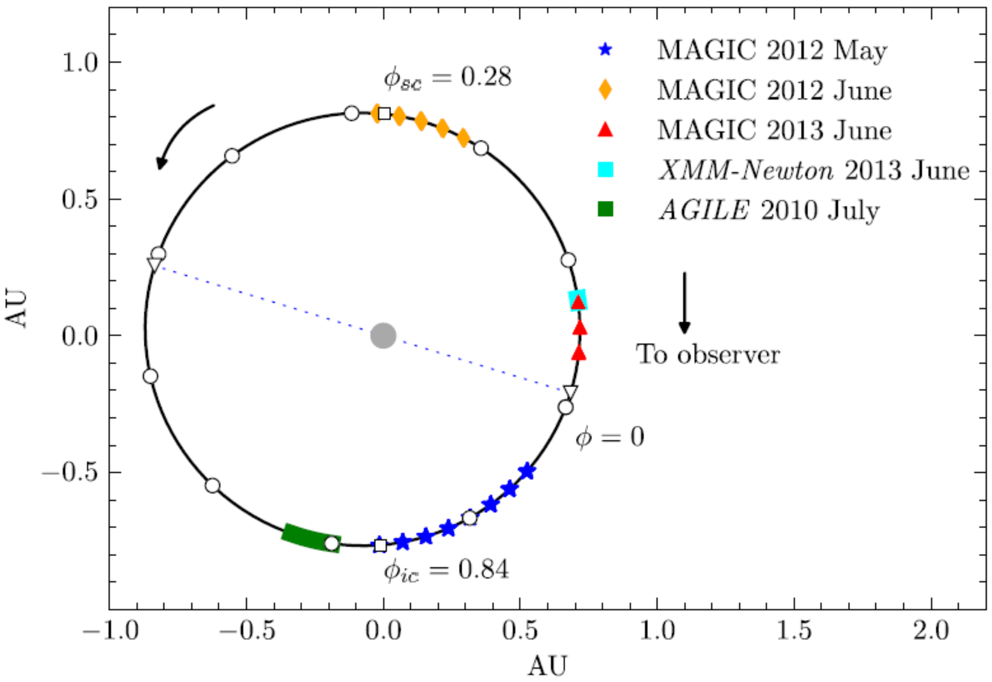
HE and VHE observations

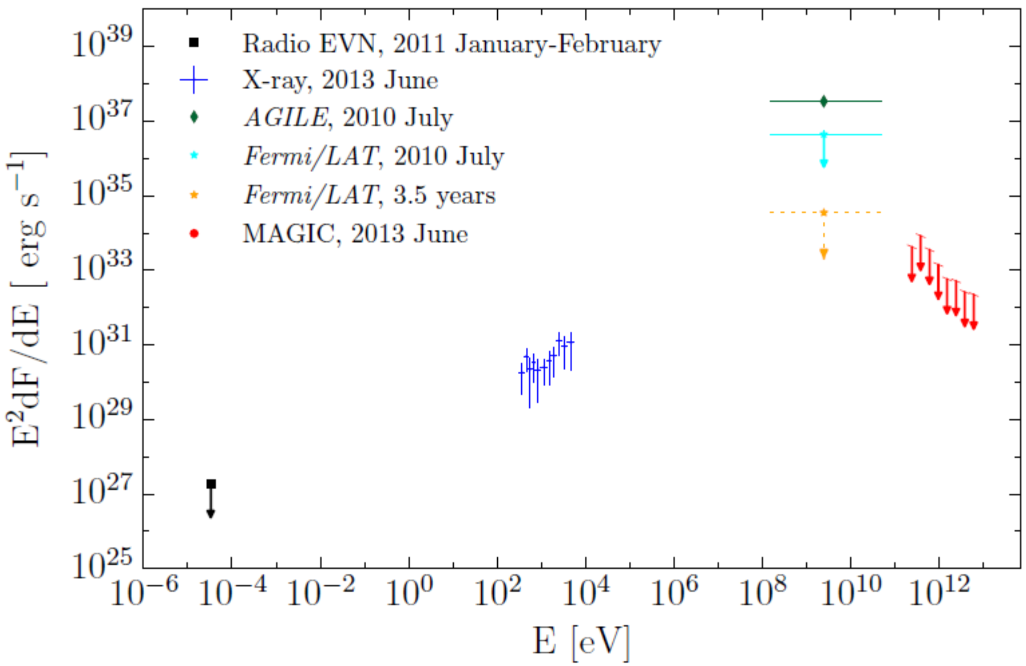
MWC 656 was observed at VHE gamma-rays for 23 hours with **MAGIC**:

- In 2012 using a single MAGIC telescope.
- In 2013 using both telescopes and simultaneous to the *XMM* observations.

Differential **upper limits** have been obtained in all cases, at the level of 5% of the Crab Nebula flux **(Aleksic et al. 2015)**.

Caution: the orbit is an old one!





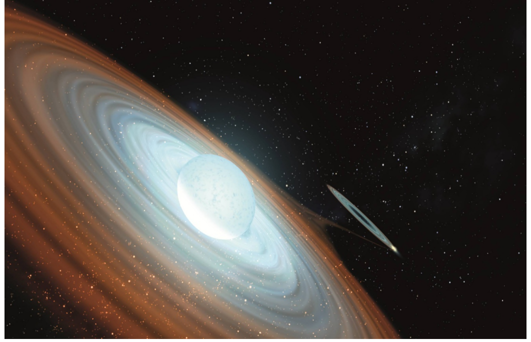
What is the origin of the HE gamma-ray flare seen by *AGILE* ?

We **have neither simultaneous nor contemporaneous data** at other wavelengths during the *AGILE* flare. Therefore, **we can speculate**.

The *AGILE* flare could be the result of accretion/ejection processes like a **sudden accretion event, magnetic reconnection in the jet, strong shock in the jet**, etc. However, these phenomena can also happen in BH LMXBs such as GRS 1915+105 or many others in outburst, **but no GeV emission has ever been detected from LMXBs**.
On the other hand, **similar transient GeV phenomena** seem to take place in the BH HMXB **Cygnus X-1** (as seen by *AGILE* but not by *Fermi*). A difference between LMXBs and HMXBs is the **powerful wind of the massive companion**, which could play a role in sudden accretion events, shocks in the jet and reconnection events, etc., in addition to a higher UV photon flux useful for IC scattering emission. However, **these ideas are just speculation**.

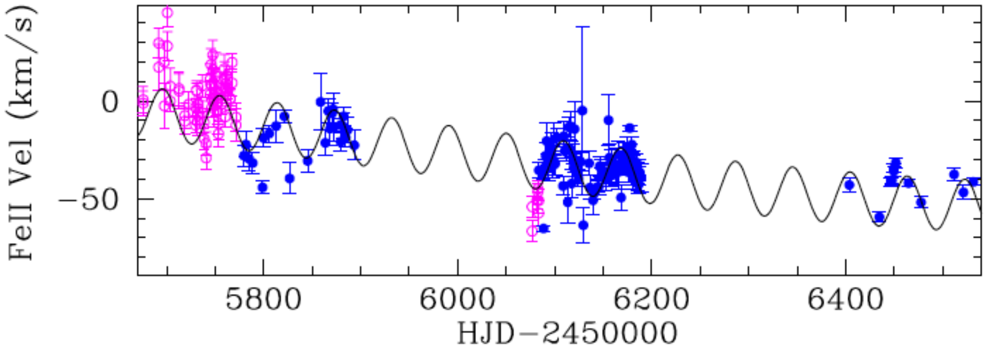
Another option: the *AGILE* GeV flare has nothing to do with MWC 656, but it is just a transient event of unknown nature in the field of MWC 656.

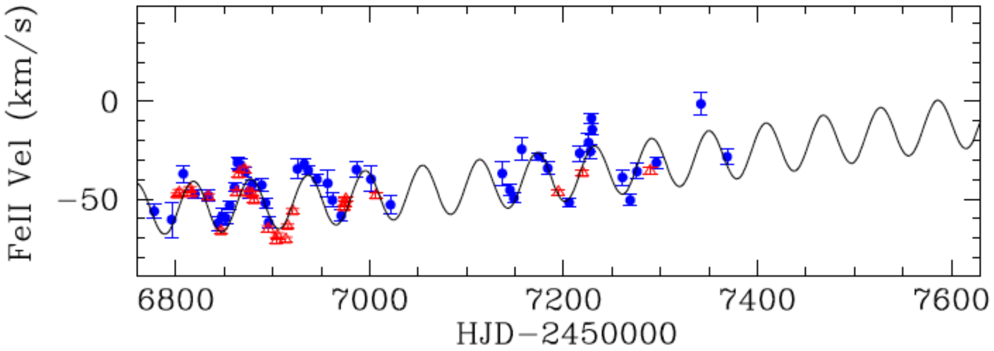
Work in progress



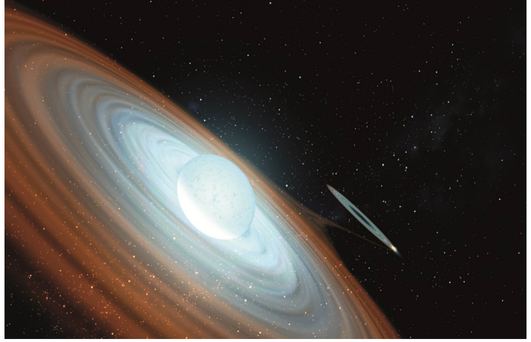
After 5 years of observations…

- The **FeII** emission lines from the decretion disk of the Be star show a **decreasing/increasing trend in the systemic velocity**, with a possible **long-term periodicity of ~7.6 years!** **(Casares et al., in prep.)**.





Work in progress



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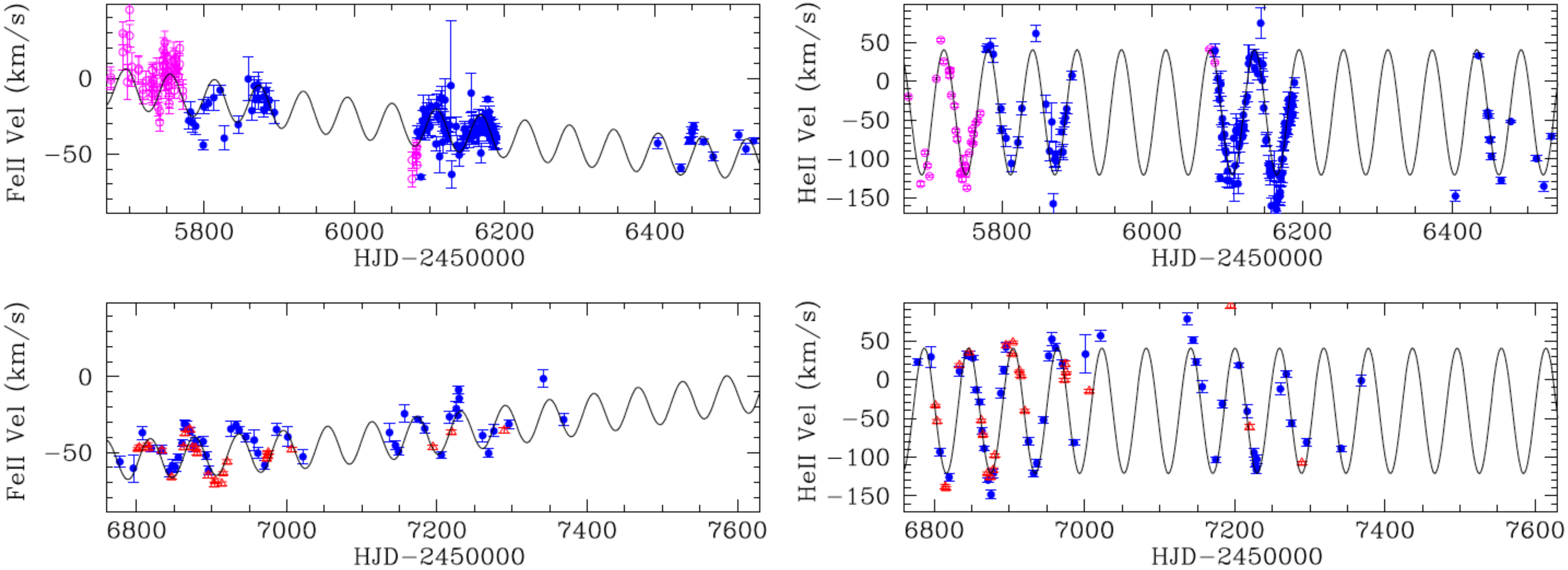


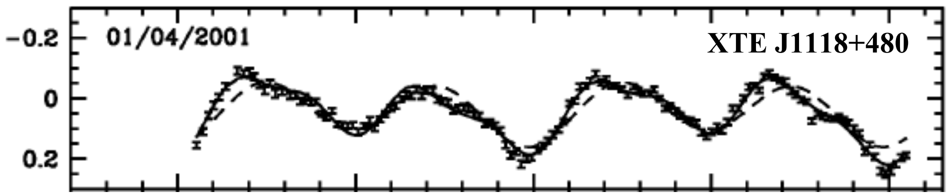
- ➢ The **HeII** emission lines from the accretion disk show a **similar trend with lower amplitude**.

Work in progress

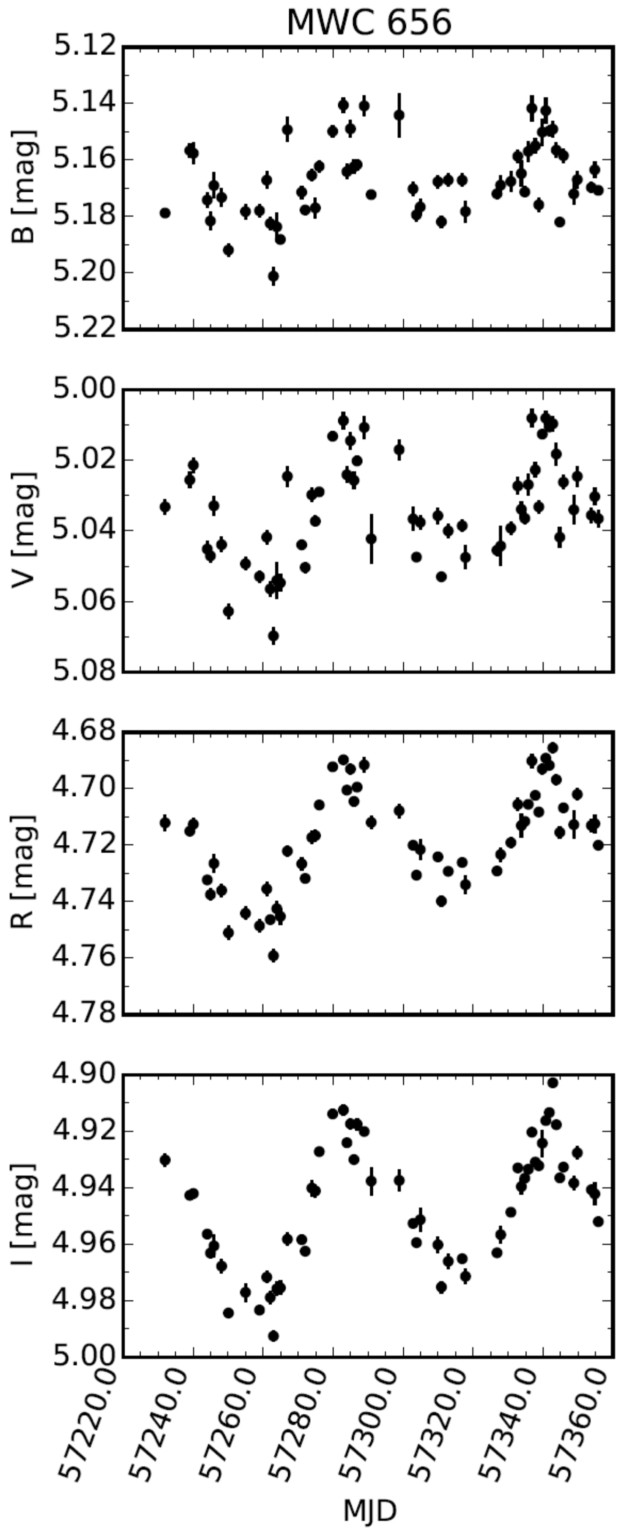
Long-term periodicity related to **Be decretion disk**: probably inhomogeneous warped precessing disk.

Produces a **photometric variability with a saw-tooth pattern**. More relevant in redder filters.

Widely observed in low-mass X-ray binaries: the low-mass star perturbs the accretion disk around the BH (e.g., **Zurita et al. 2002** for XTE J1118+480).



In MWC 656 the **BH perturbs the disk of the Be star**. This is the **first time this phenomenon is observed**.



Work in progress

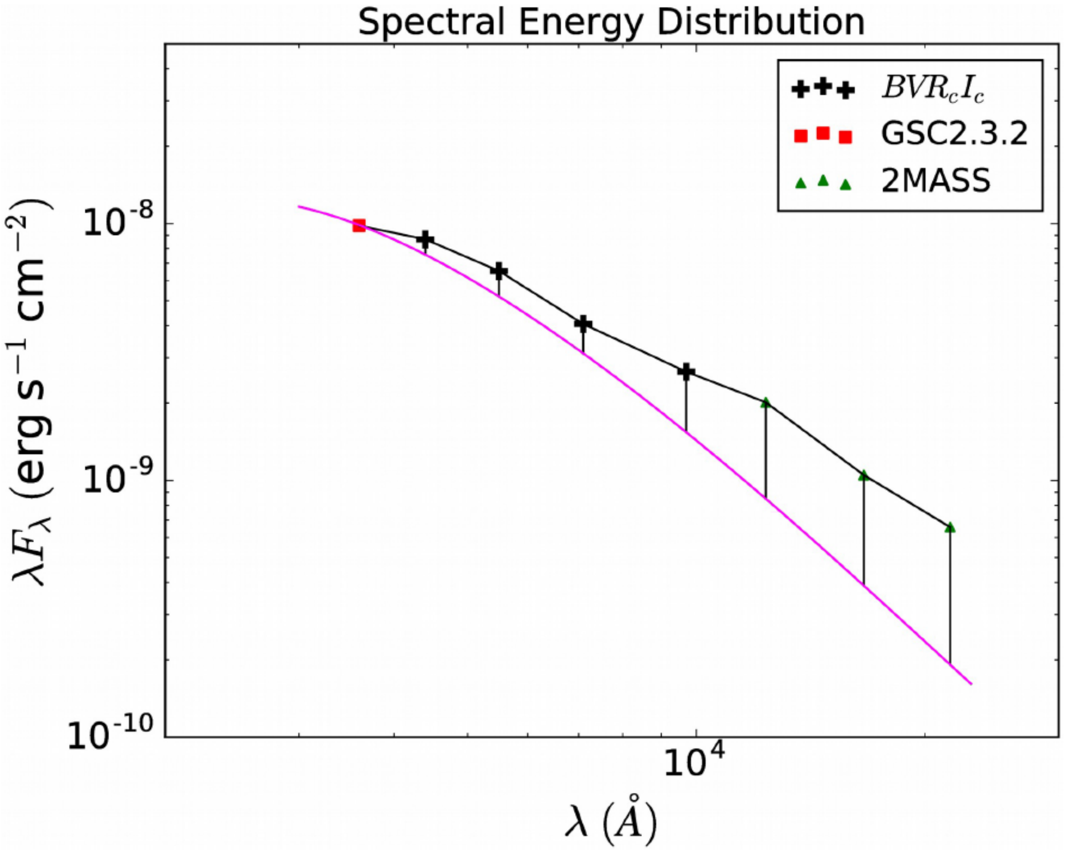
A factor of 3 **more variability in *I* than in *B***.

This could indicate that outer parts (redder) are more variable than inner ones (bluer).

But: **disk contribution varies as a function of λ**.

Therefore, the variability is always **around 3-4% of the disk flux**.

(Martí-Devesa 2017).



		BB at 15300 K	
Filter	A/S_T (%)	S_D/S_T (%)	A/S_D (%)
B	0.43 ± 0.07	12.8 ± 0.2	3.4 ± 0.6
V	0.62 ± 0.05	20.5 ± 0.2	3.0 ± 0.3
R_c	0.89 ± 0.06	23.1 ± 0.1	3.9 ± 0.3
I_c	1.26 ± 0.06	41.9 ± 0.1	3.0 ± 0.2

Work in progress

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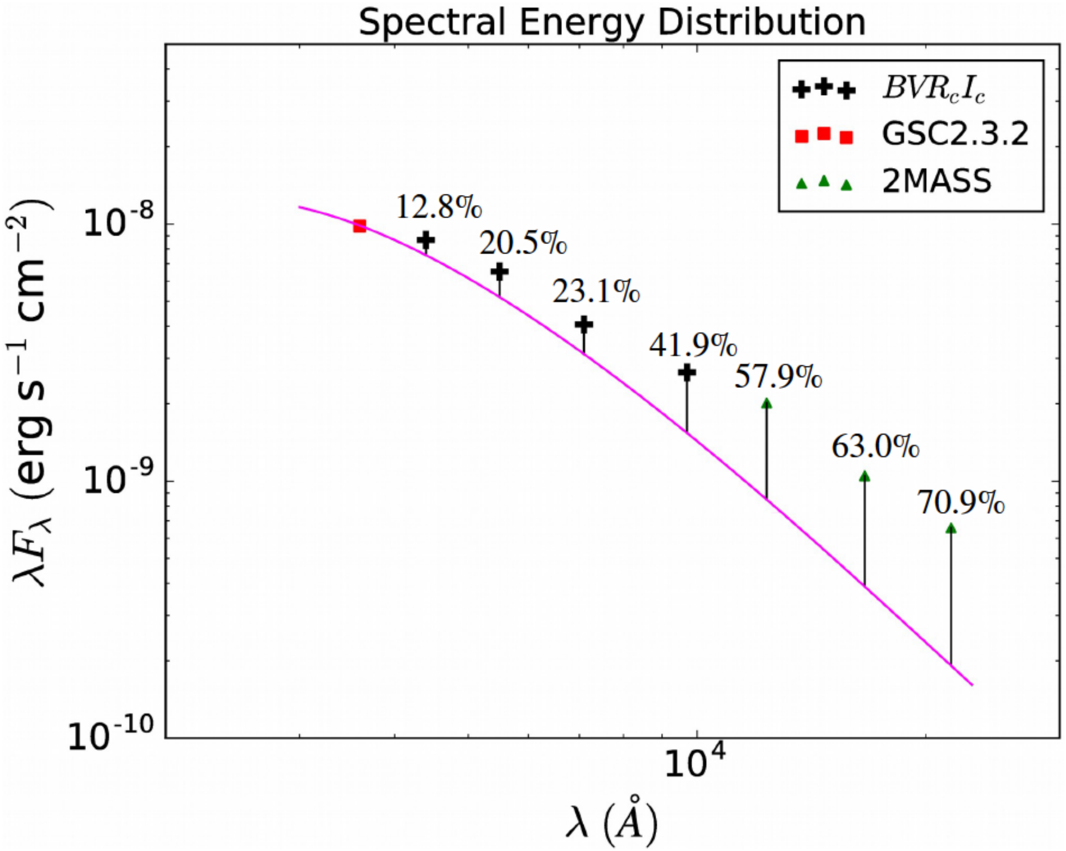

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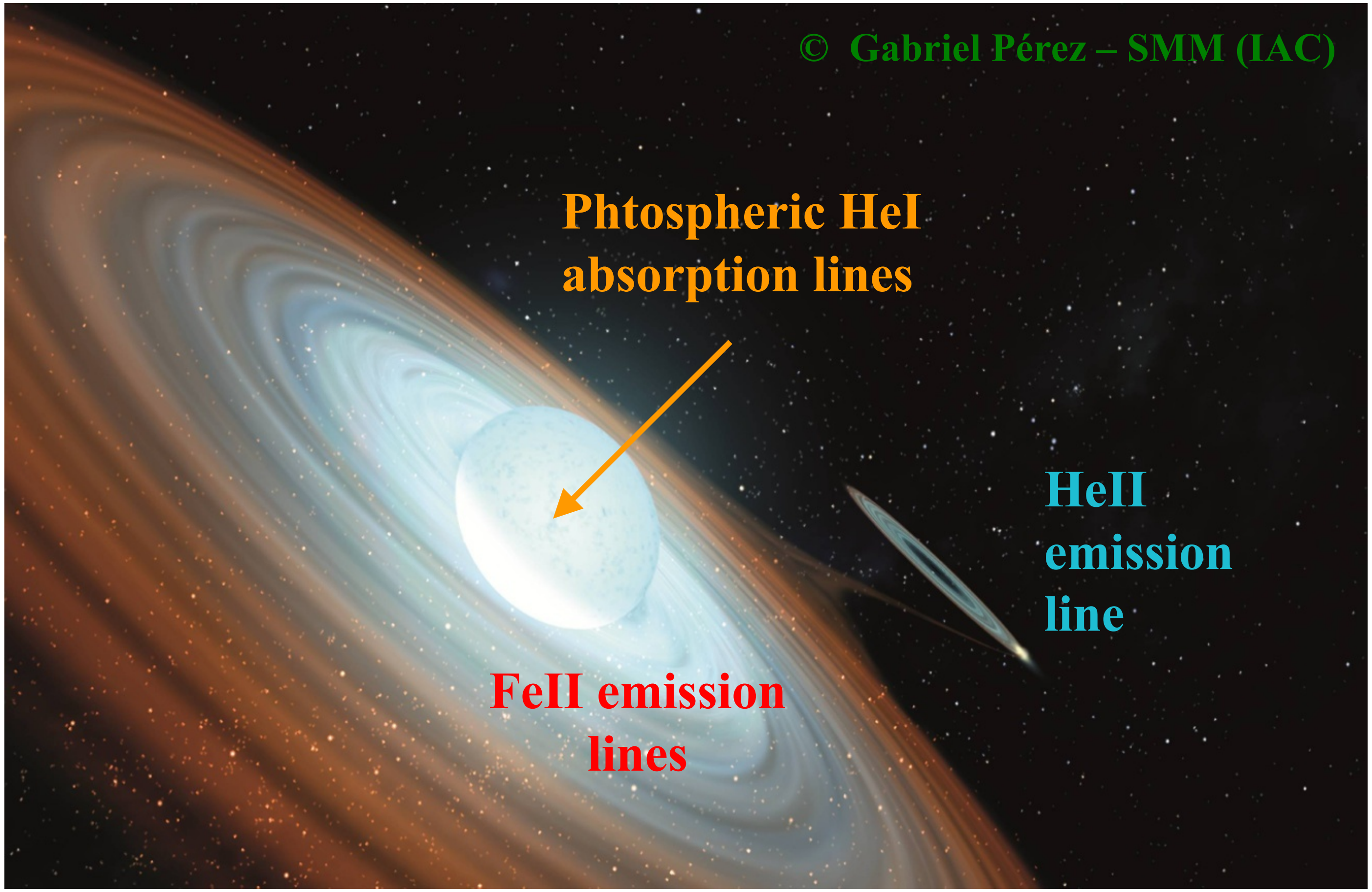
V	0.62 ± 0.05	20.5 ± 0.2	3.0 ± 0.3
$R_{\rm c}$	0.89 ± 0.06	23.1 ± 0.1	3.9 ± 0.3
$I_{\rm c}$	1.26 ± 0.06	41.9 ± 0.1	3.0 ± 0.2

Work in progress

Radial velocities from different lines:

- **Photospheric HeI** absorption lines
- **Accretion disk HeII** emission line
- **Decretion disk FeII** emission lines



Work in progress

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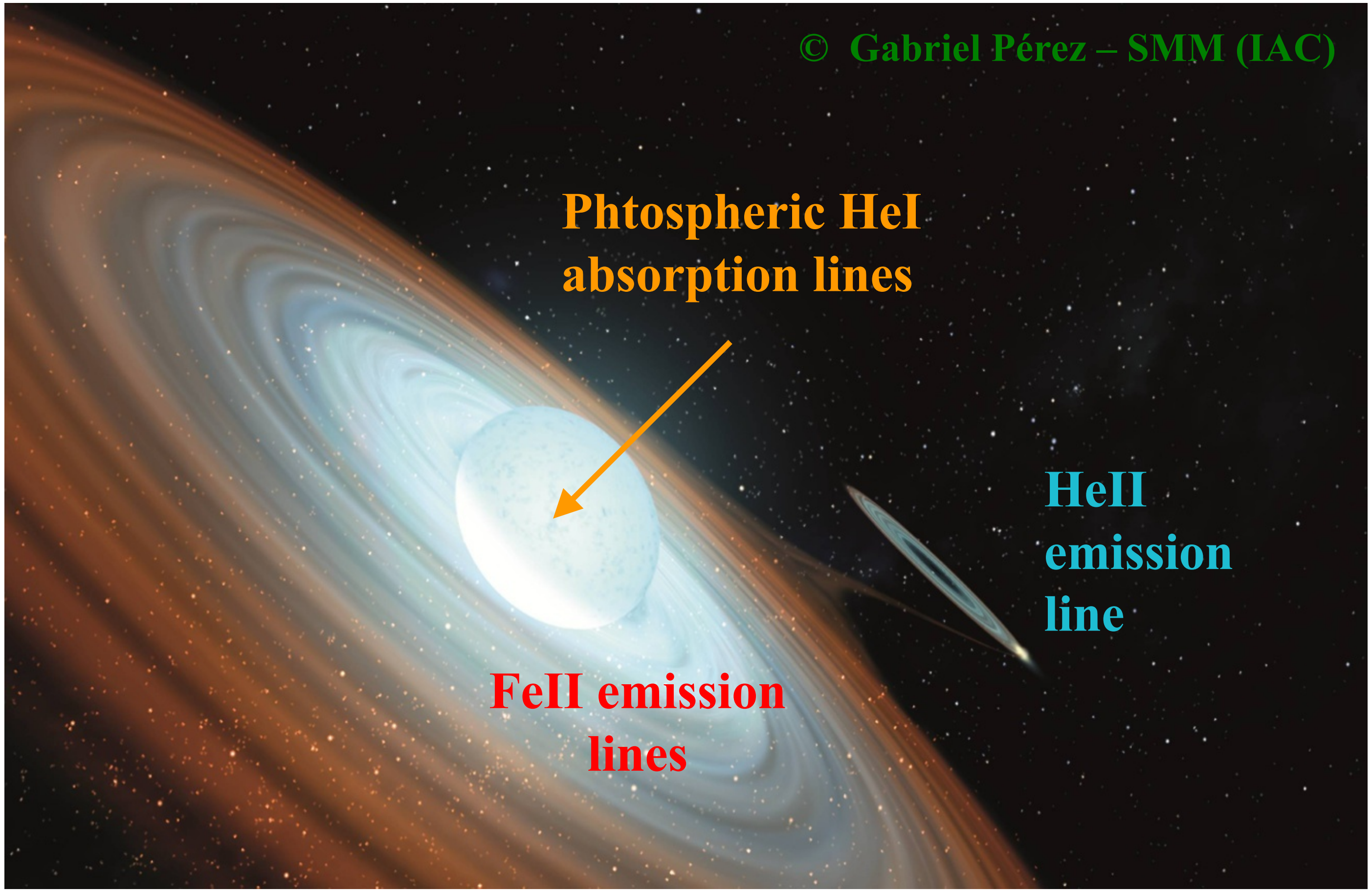

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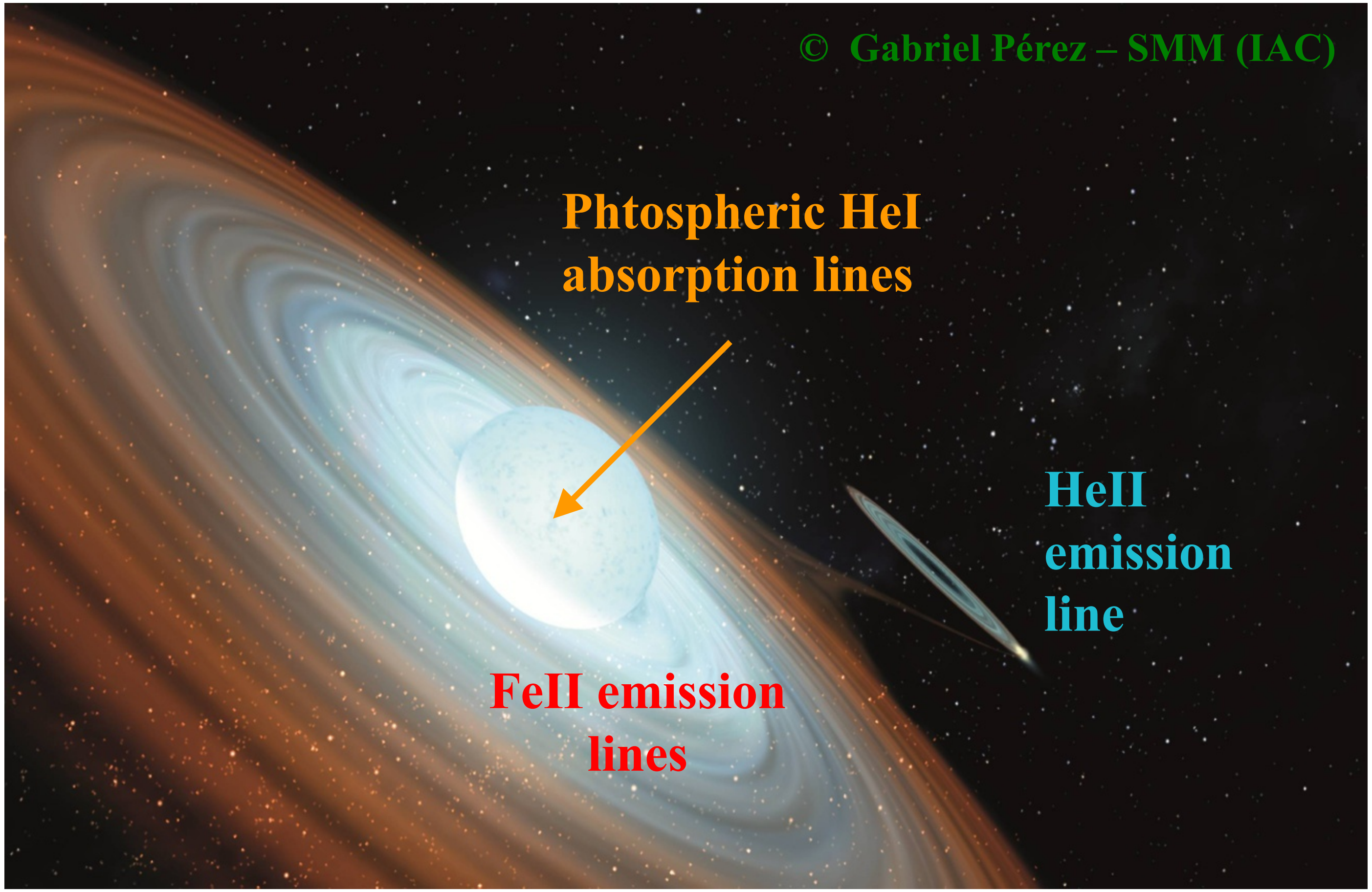

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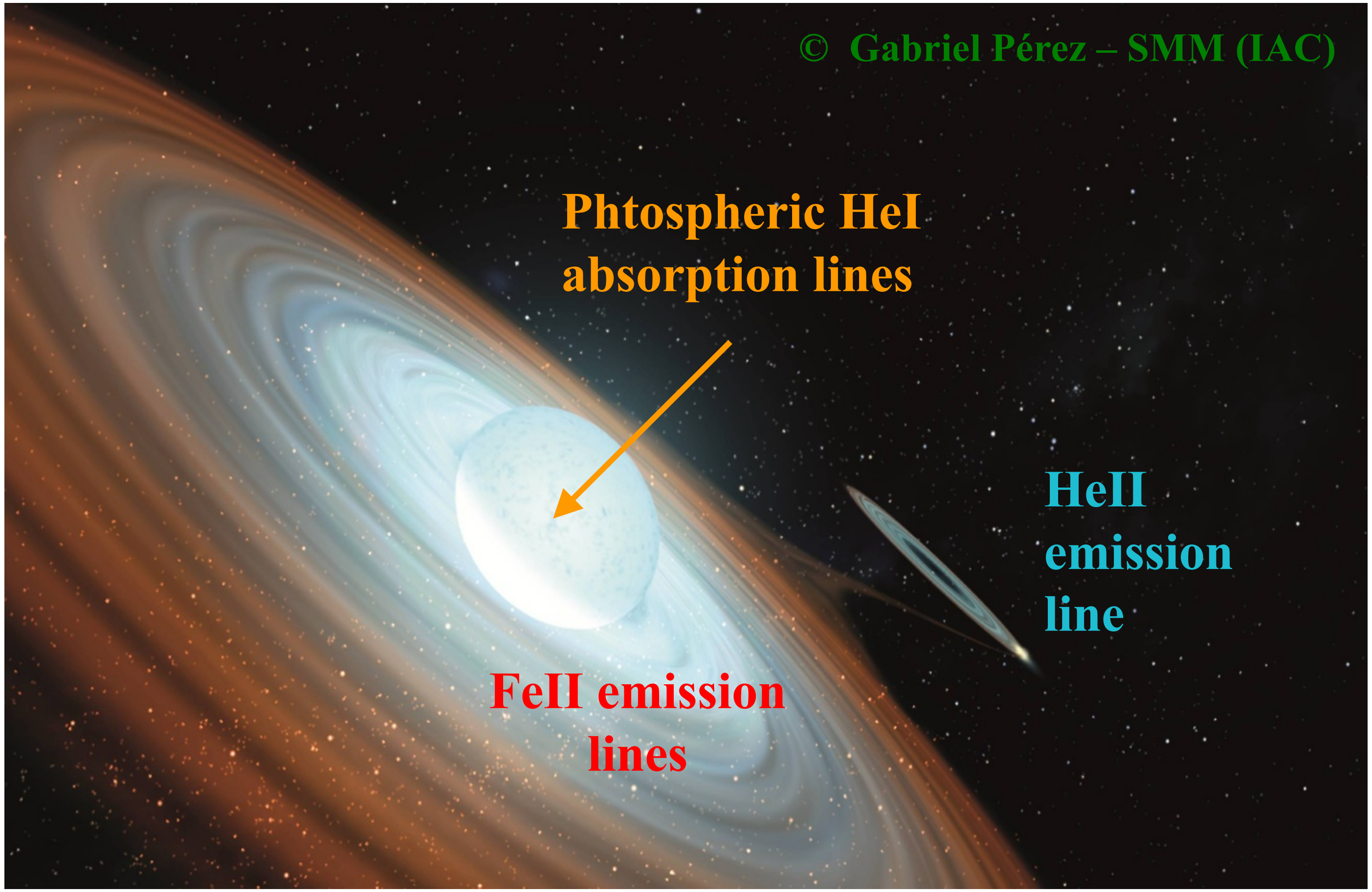
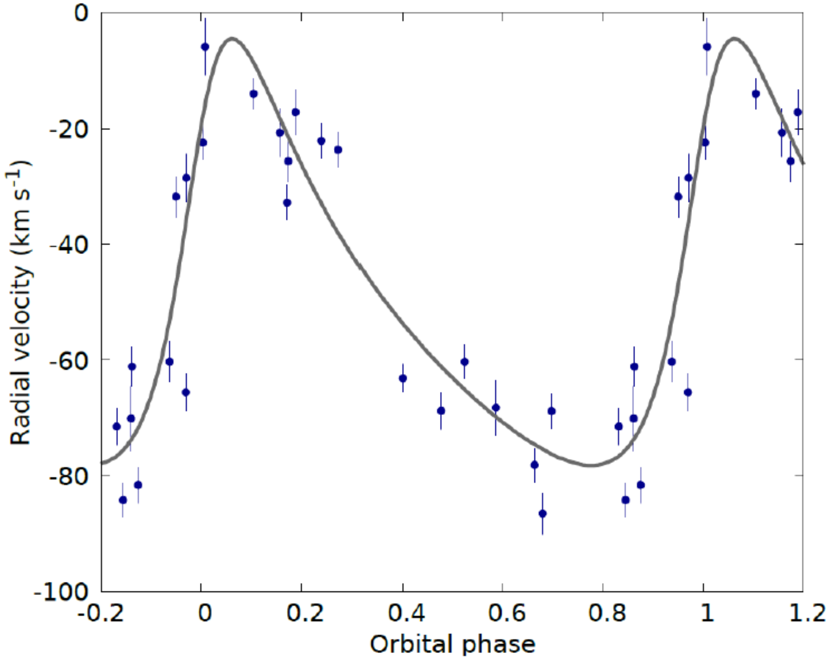


Work in progress

Radial velocities from a **photospheric HeI absorption line** data obtained with a few months of Nordic Optical Telescope high-resolution spectroscopy.

The **orbit is clearly eccentric**! $e \sim 0.4$, $w = 306 \pm 17°$, $\gamma = -50 \pm 2$ km/s.

Photospheric HeI absorption lines



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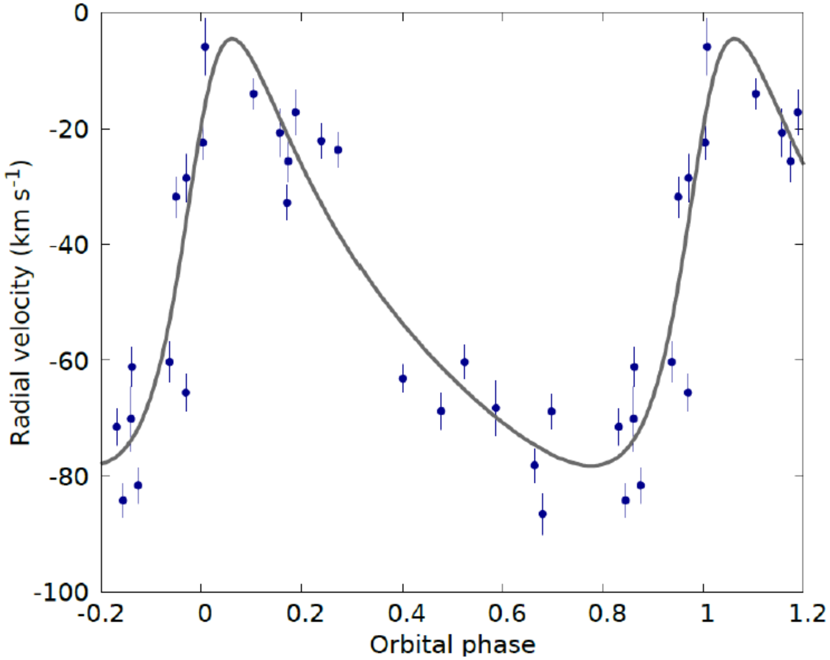
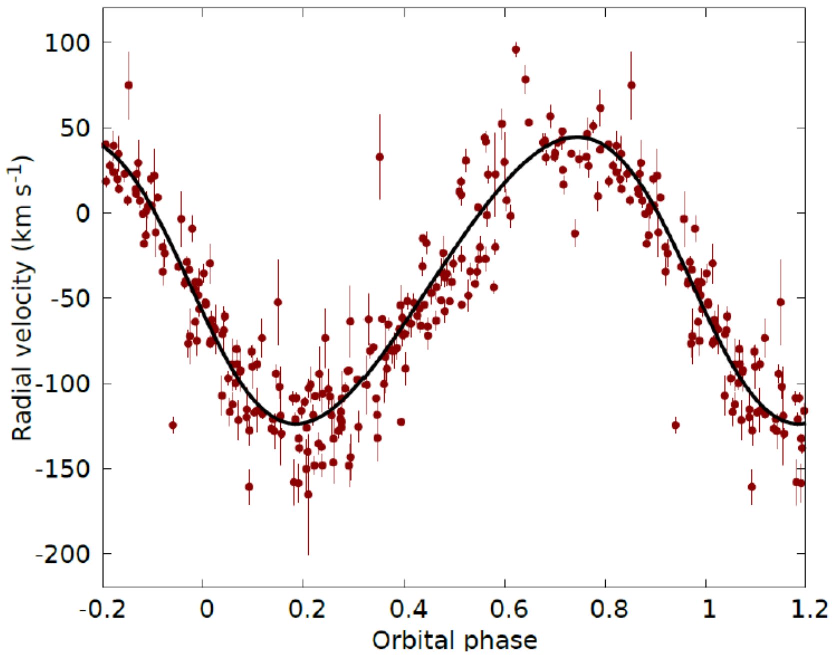


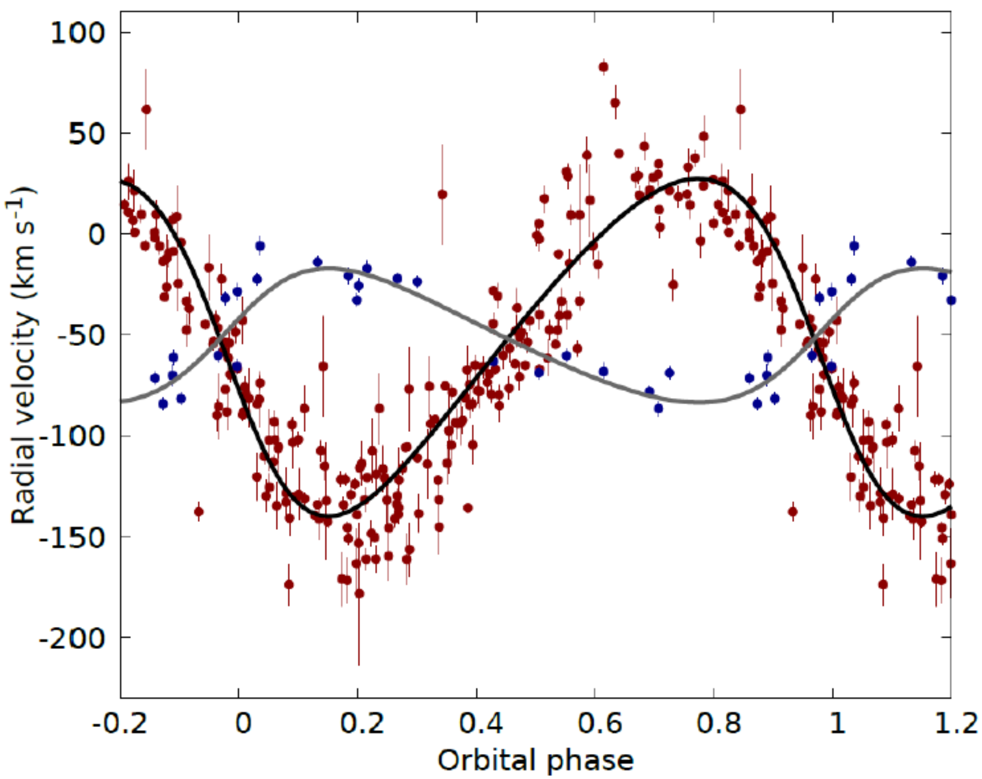
Accretion disk HeII emission line

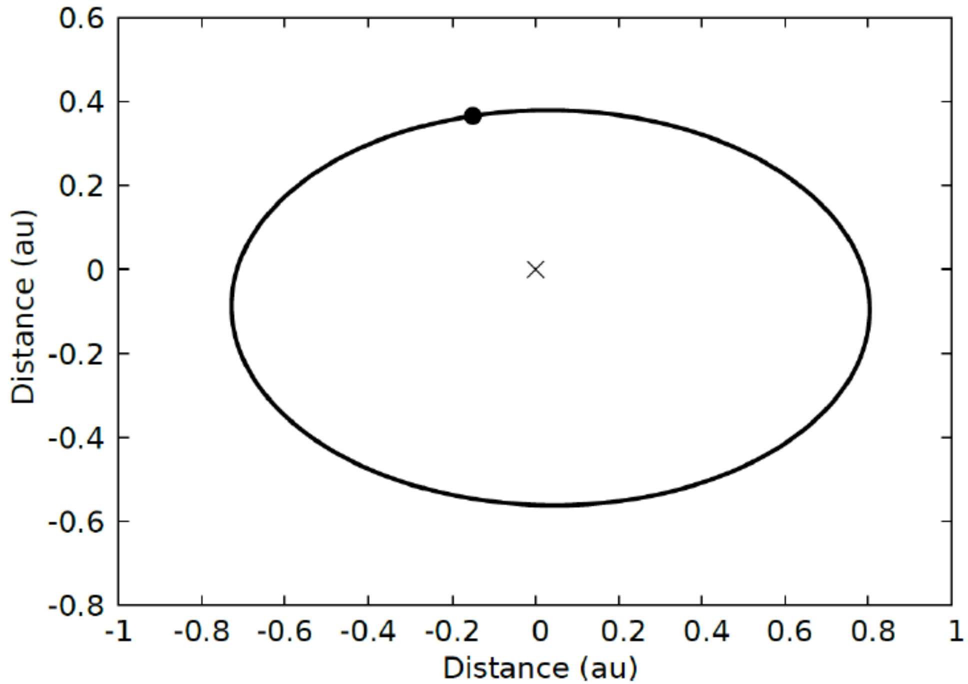


Radial velocities from the HeII emission line from the accretion disk obtained with different telescopes.
The orbit is **slightly eccentric only**. $e \sim 0.1$, $w = 103 \pm 21^{o}$, $\gamma = -38 \pm 2$ km/s.

Work in progress

- Double-line fit fixing the orbital period and imposing an eccentricity of 0.2.
- The mass ratio is 0.40±14, and the **BH mass is 3.0–7.4 solar masses**.
- The **inclination** is found to be **53º**.
- These values should improve with more high-resolution observations.

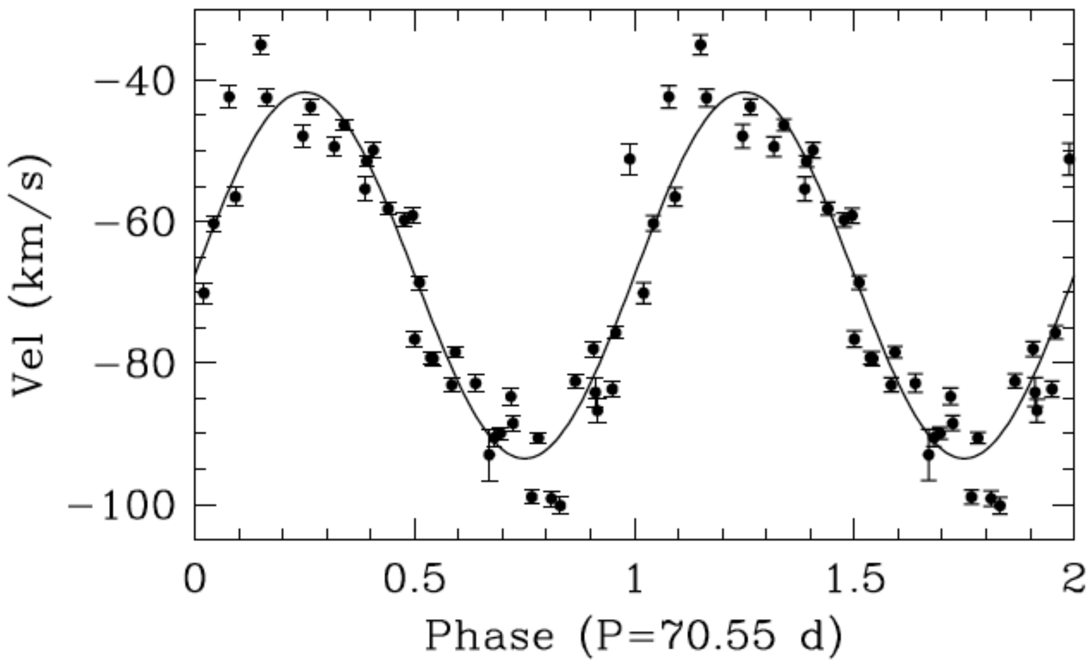


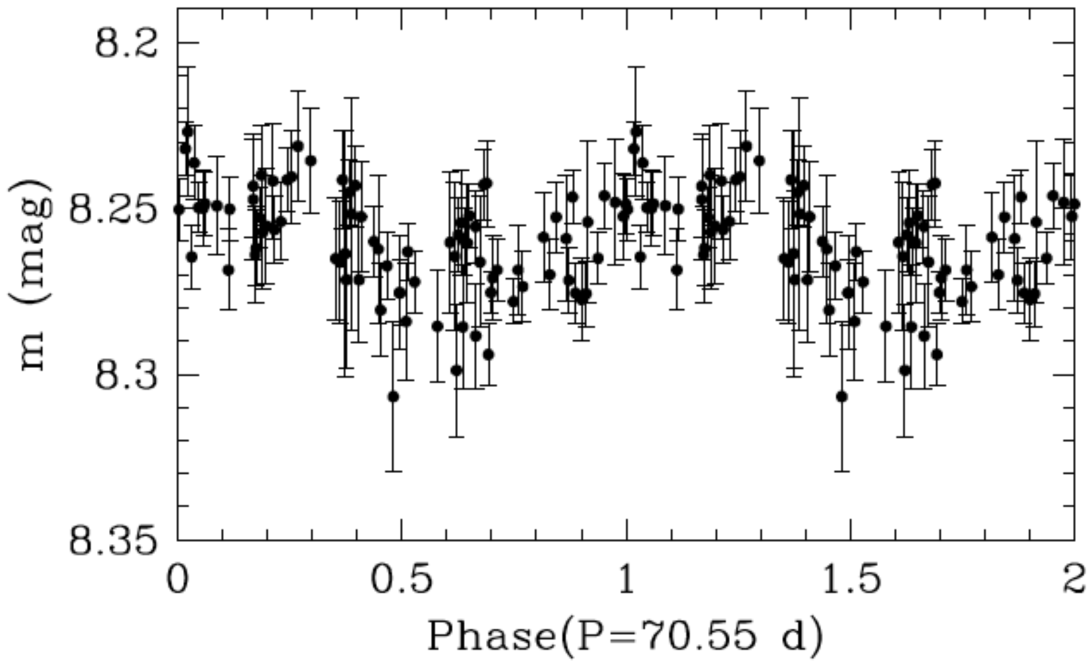


Work in progress

To **search for new Be/BH** binary systems we have searched for the signature of the **HeII 4686 A emission line** in a catalogue of 600 classic Be stars (http://basebe.obspm.fr/basebe).

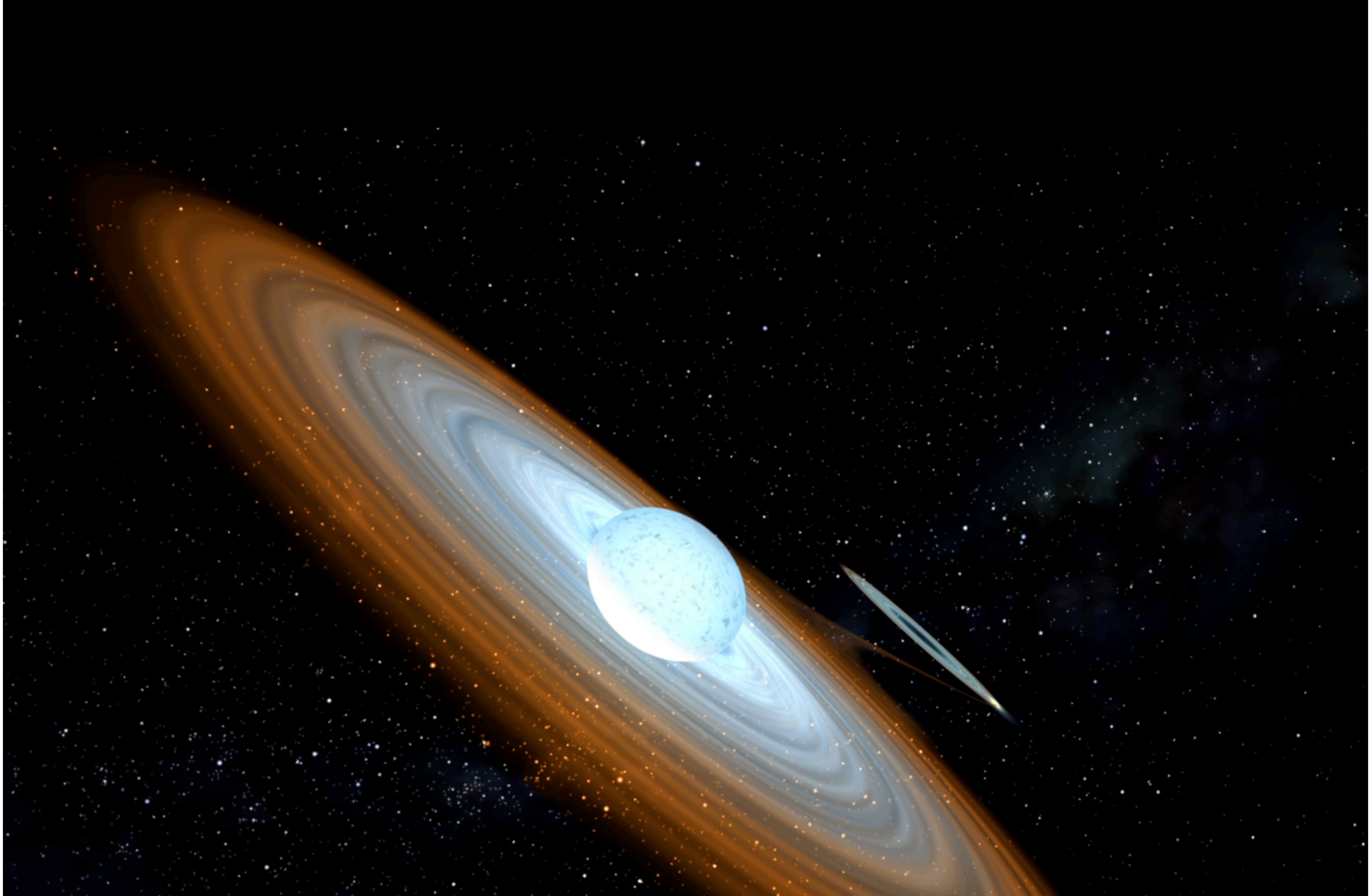
We are now studying the variability of this emission line, and **found at least a very good candidate** with a period of ~70 d in both radial velocities and optical photometry.





Conclusions

- We have **discovered the first Be/BH binary system** after an *AGILE* alert.
- **Be/BH binaries may be more abundant than predicted by Binary Population Synthesis models**.
- **Be/BH binaries** may evolve into close **BH/NS binaries** that would emit **GWs** during coalescence detectable by LIGO/Virgo in nearby galaxies.
- *Fermi*/LAT has only provided upper limits. *AGILE* data show other possible periods of activity and **hints of long-term GeV variability**.
- There is a **clear long-term variability in radial velocities** and optical photometry. We have discovered **superhump variability** in this system.
- New orbital ephemerides indicate $e \sim 0.4$ (will be published soon).
- More systems to be discovered. Is there a population of **hidden black holes?**



Formation and evolution of MWC 656

Details on the future evolutionary channels **(Grudzinska et al., 2015)**:

Table 2. Future evolution of MWC 656-like binaries[a]

Channel	$f_{\rm form}$	Evolutionary history[b]	Mergers[c] CE/RLOF	Fate[d] (BH–NS): Close	Wide	Disrupted
BeBH:1a	15.4%	CE1(4-1) SN1 MT2(14-2) MT2(14-9) ECSN2	0%	0%	15.4%	0%
BeBH:1b	23.1%	CE1(4-1) SN1 MT2(14-2) SN2	0%	0%	0.5%	22.6%
BeBH:2a	7.7%	CE1(4-1) SN1 CE2(14-4) MT2(14-7) SN2	0%	5.6%	0.7%	1.4%
BeBH:2b	53.8%	CE1(4-1) SN1 CE2(14-2) MT2(14-7) SN2	38.4%	10.7%	1.3%	3.4%

[a] We list only formation channels of MWC 656-like systems which are defined by Eq. 4.
[b] Sequences of different evolutionary stages: CE1 and CE2: common envelope with a primary and secondary as a donor, respectively; MT2: non–conservative mass transfer with a secondary as a donor; SN1 and SN2: type Ib/c supernova of the primary (black hole formation) and secondary (neutron star formation), respectively; ECSN2: electron capture supernova of secondary (neutron star formation).
Numbers in parenthesis denote evolutionary stage of primary–secondary: 1 - main sequence, 2 - Hertzsprung gap, 4 - core helium burning, 7 - helium main sequence, 9 - helium giant branch, 13 - neutron star, 14 - black hole.
[c] This is probability that two binary components merge in RLOF or CE events that are encountered between the two SNe events.
[d] Outcome of future evolution of MWC 656-like systems; close (delay time from ZAMS to BH and NS merger shorter than 10 Gyr) or wide BH–NS systems or disrupted BH and NS objects may form.