A noninteracting low-mass black hole–giant star binary system

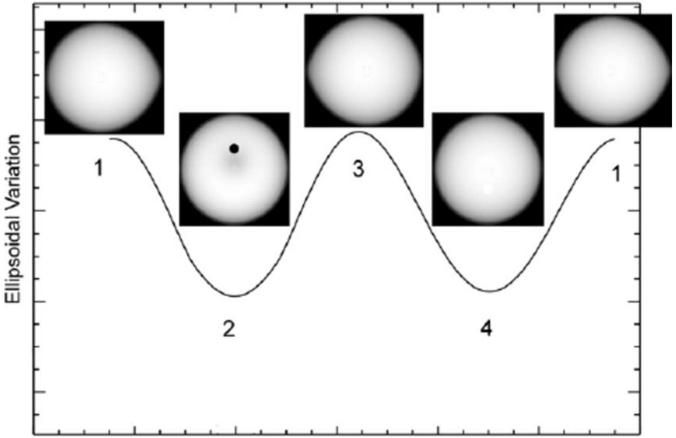
Todd A. Thompson, Christopher S. Kochanek, Krzysztof Z. Stanek, Carles Badenes et al. 2019, Science, 366, 637-640

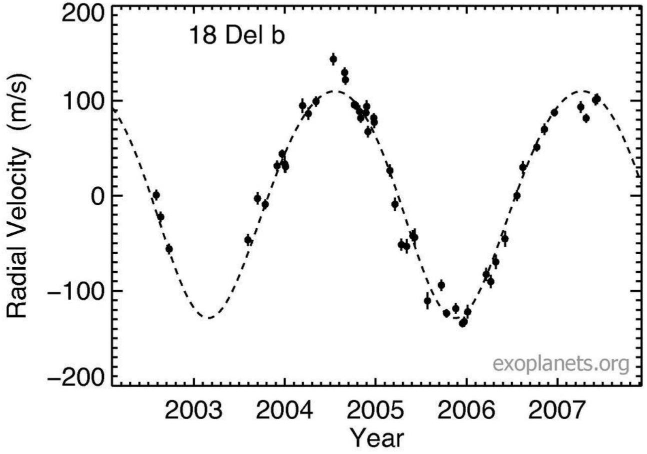
How to find a stellar mass BH?

- Interacting
  - X-rays : HMXBs, LMXBs, Accretion of ISM
  - Mergers - LIGO

- Non-interacting :
  - Microlensing
  - Spectroscopy of binaries
  - Light curve modulations followed by spectroscopy

Light curve modulation + RV

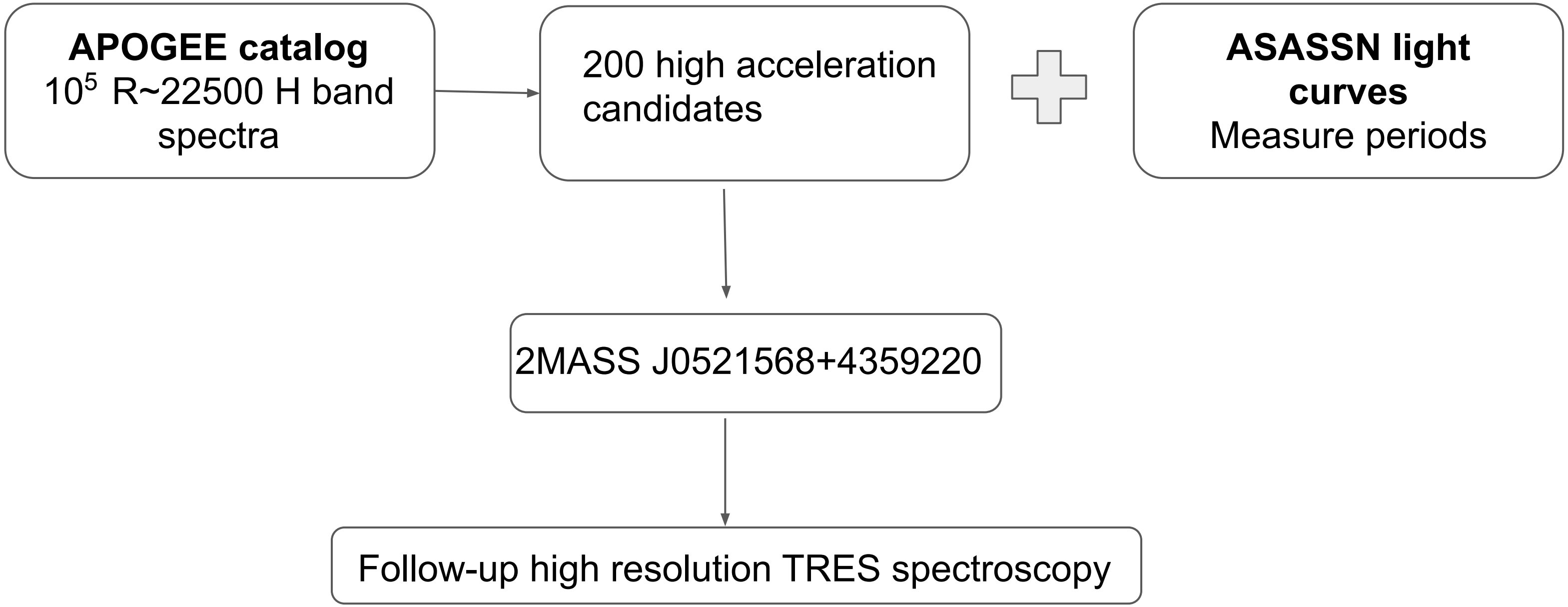




- Ellipsoidal modulation
  - P, q =(M2/M1), R, i
- Star spots
  - P

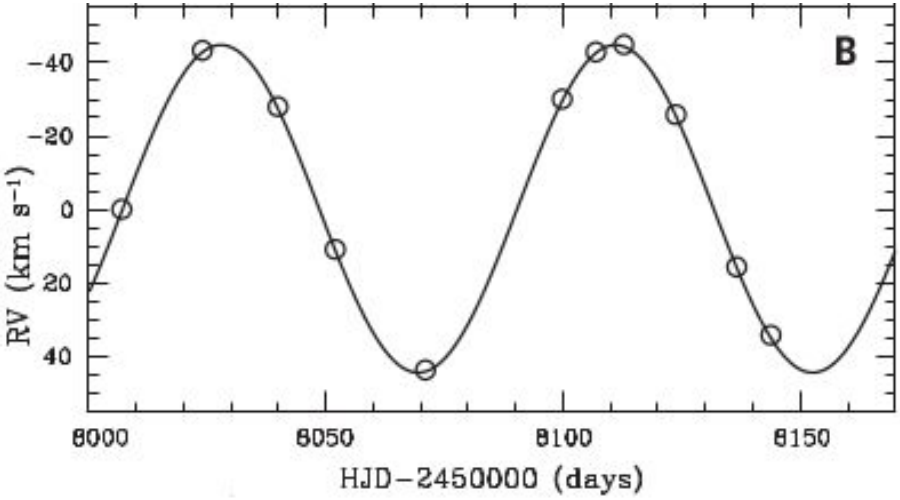
- K = v_{max} sin(i)
- P : orbital period
- e: eccentricity

Candidate selection



Binary system parameters

RV :



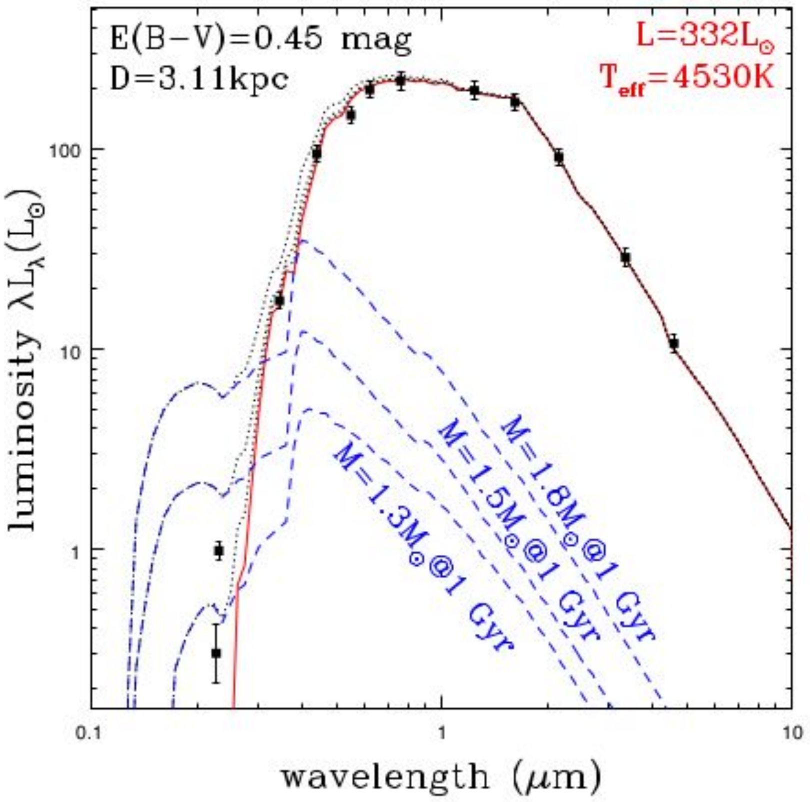
P = 83.2+/- 0.06 days, K = 44.6 +/- 0.1 km/s, e = 0.0048 +/- 0.0026

$$f(M) \equiv \frac{M_{\rm CO}^3 \sin^3 i_{\rm orb}}{(M_{\rm giant} + M_{\rm CO})^2} = \frac{K^3 P_{\rm orb}}{2\pi G}(1-e^2)^{3/2} \simeq 0.766 \pm 0.006\, M_\odot$$

Binary Parameters

- $f(M) \sim 0.76$
- $M_{giant} > 1\ M_{\odot}$ suggests $M_{CO} > 1.8\ M_{\odot}$

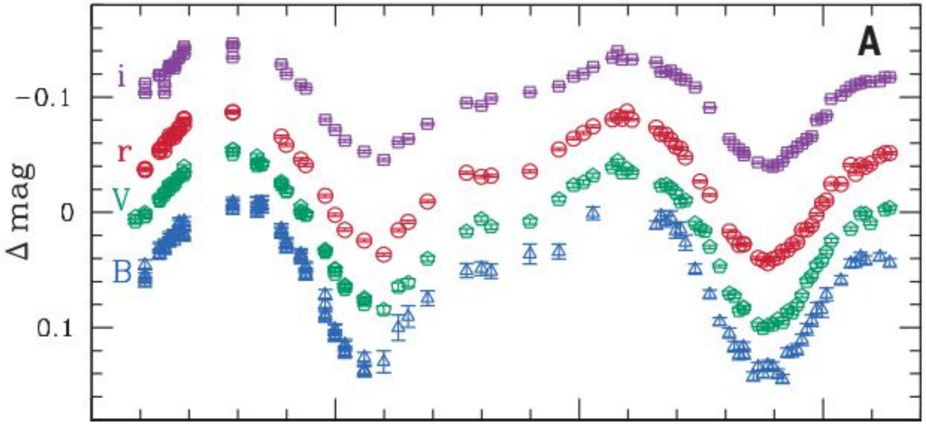
- SED modeling rules out a stellar companion

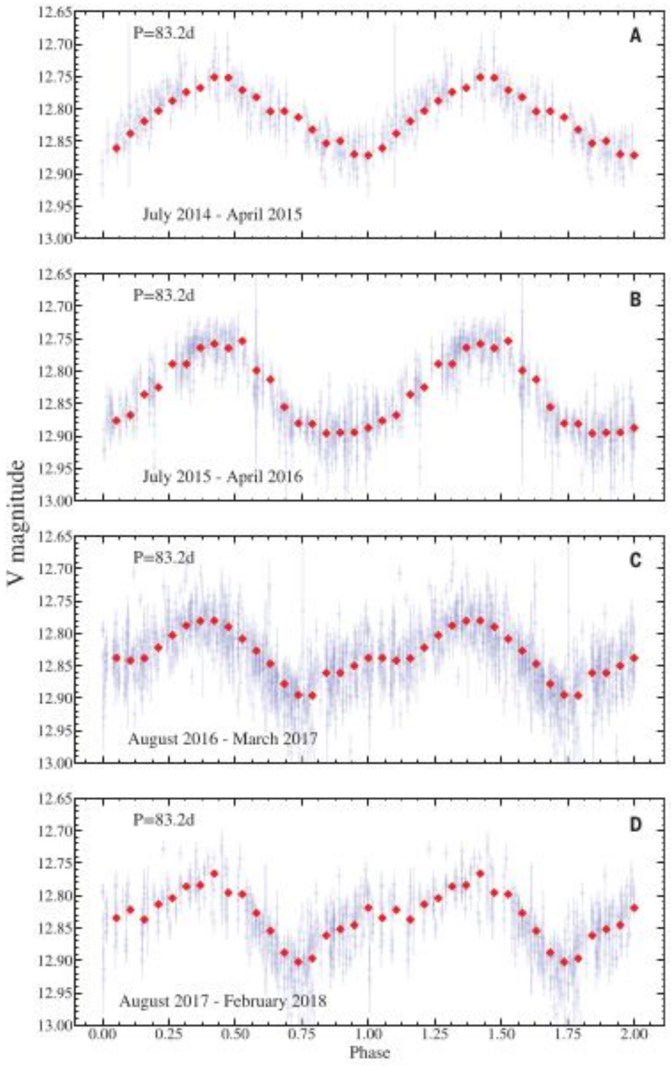


Giant mass, inclination

Lightcurve?

- Spotted K-type giant star





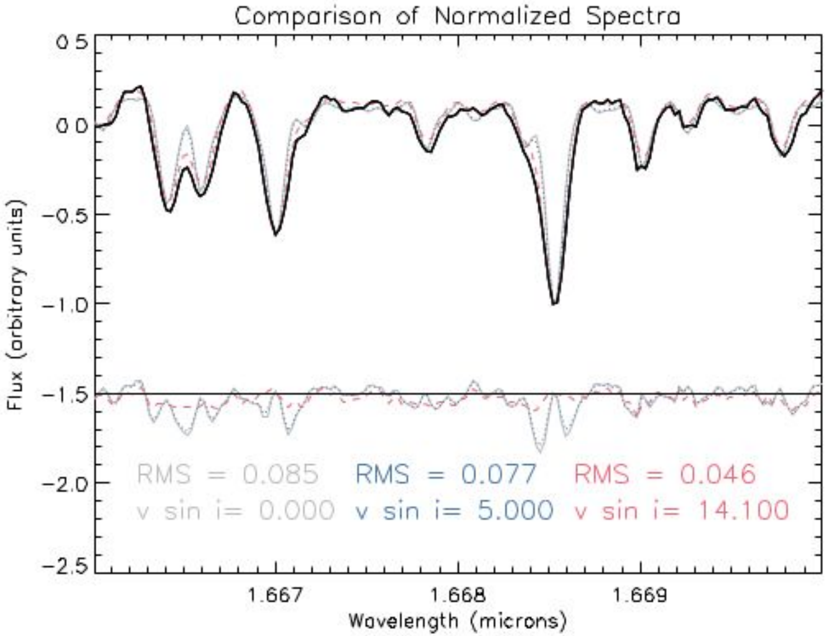
Giant mass, inclination

- Assume the system is tidally locked : $P_{rot} = P_{orb} = P$, $i_{rot} = i_{orb} = i$
- $v_{rot} = (2\pi/P) * R * \sin(i)$
- Measure $v_{rot} \sin(i_{rot})$ from high res. spectrum (= 14.1 km/s)

- $R \sim 14.1 * P/\sin(i)$
- $g \sim GM_{giant}/R^2$
- Measured log(g) = 2.35 +/- 0.14

$$R \simeq 23 \pm 1\, R_\odot / \sin i$$

$$M_{\rm giant}^{\log g} = 4.4^{+2.2}_{-1.5}\, M_\odot / \sin^2 i,$$



Giant Mass, inclination

Observed flux + GAIA distance

- Corrected GAIA parallax ~ 0.372 mas, D ~ 3.11 kpc

$$L \simeq 331^{+231}_{-127}\, L_{\odot} \text{ and } R \simeq 30^{+9}_{-6}\, R_{\odot}$$

- Comparing the two radii gives

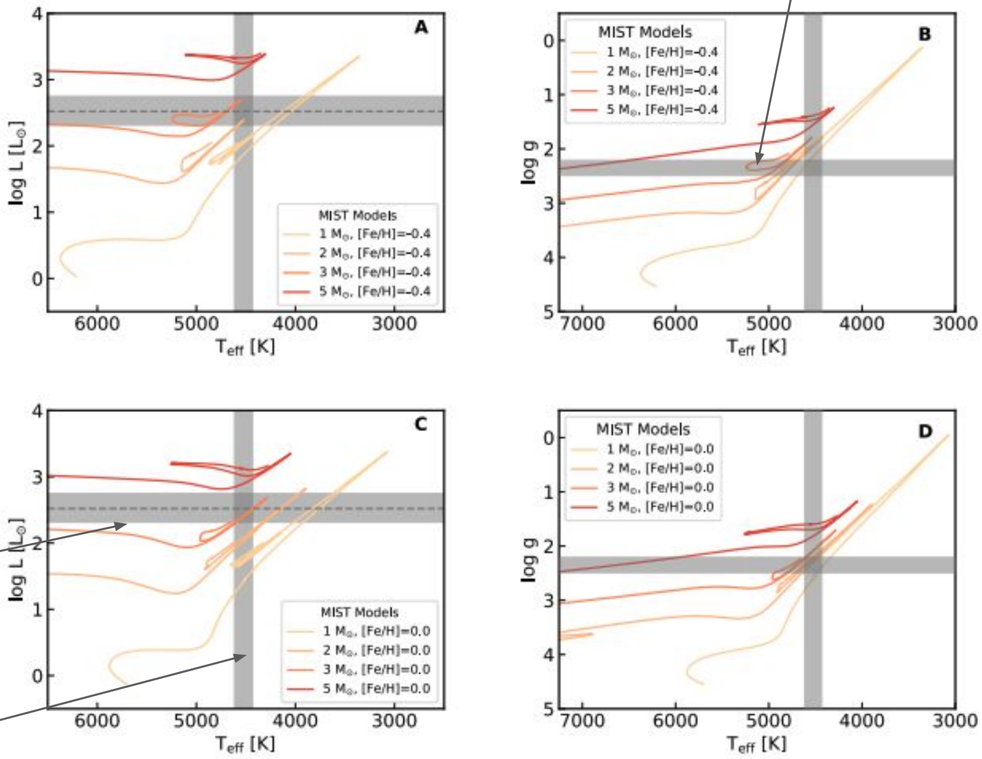
$$\sin i \simeq 0.8 \pm 0.2 \qquad M^{\log g}_{\rm giant} \gtrsim 3.2^{+1.2}_{-0.9}\, M_{\odot} \qquad M_{\rm CO} \gtrsim 2.5\, M_{\odot}$$

- A better estimate of M_{giant} will constrain i and M_{CO}

Comparison to Stellar Evolutionary Tracks

log(g) from
spectra

- log(g) and Teff of the giant determined from spectra
- L (determined from flux, distance) and R given by parallax method
- Use solar metallicity models to determine best-fit mass of giant



L from
parallax

Teff from
spectra

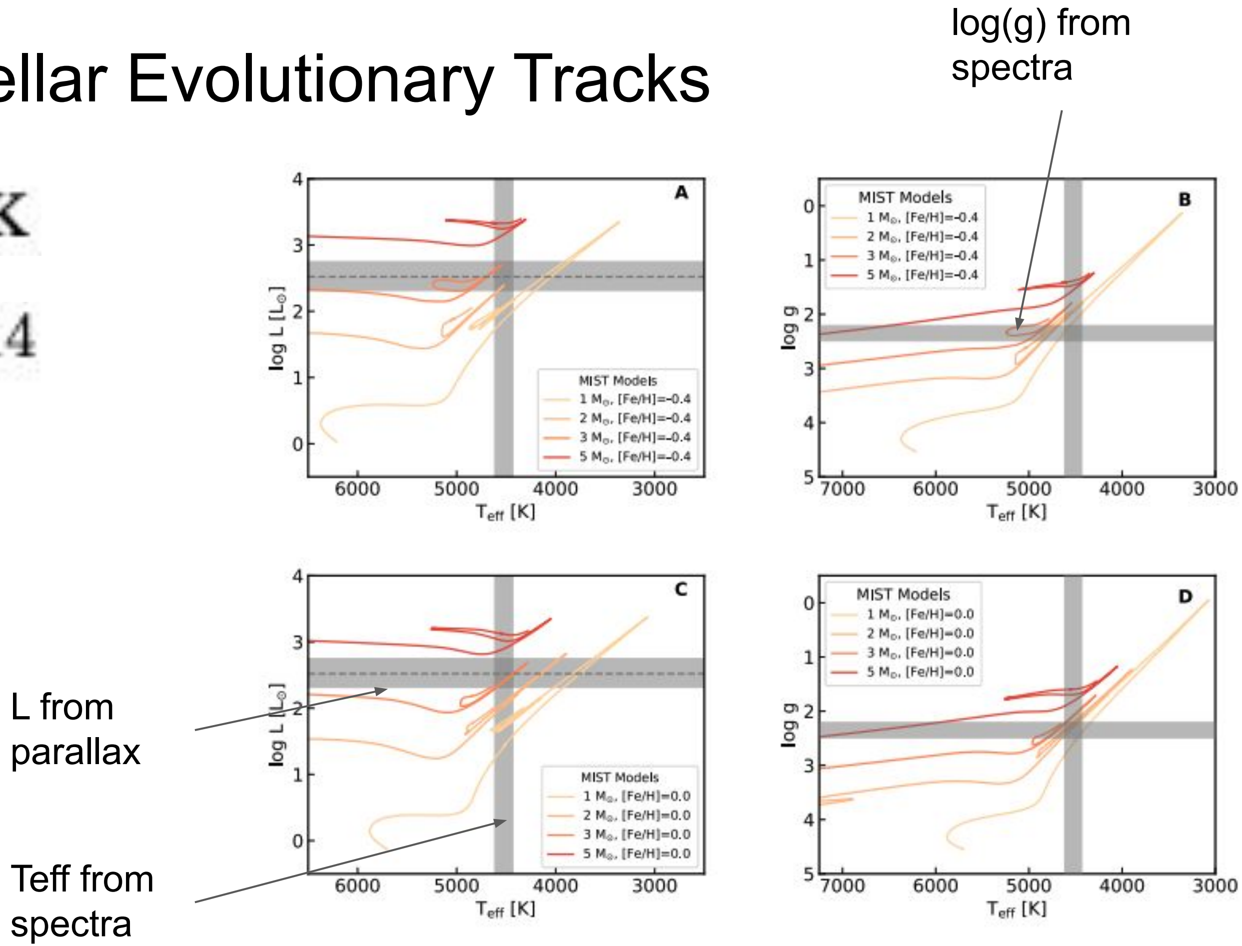
Comparison to Stellar Evolutionary Tracks

$$T_{\rm eff} = 4525 \pm 90\,\mathrm{K}$$

$$\log g = 2.35 \pm 0.14$$

$$L \simeq 331^{+231}_{-127}\, L_\odot$$

- Low Teff favors ~1 Msun giant
- Bolometric luminosity favors 2-3 Msun giant



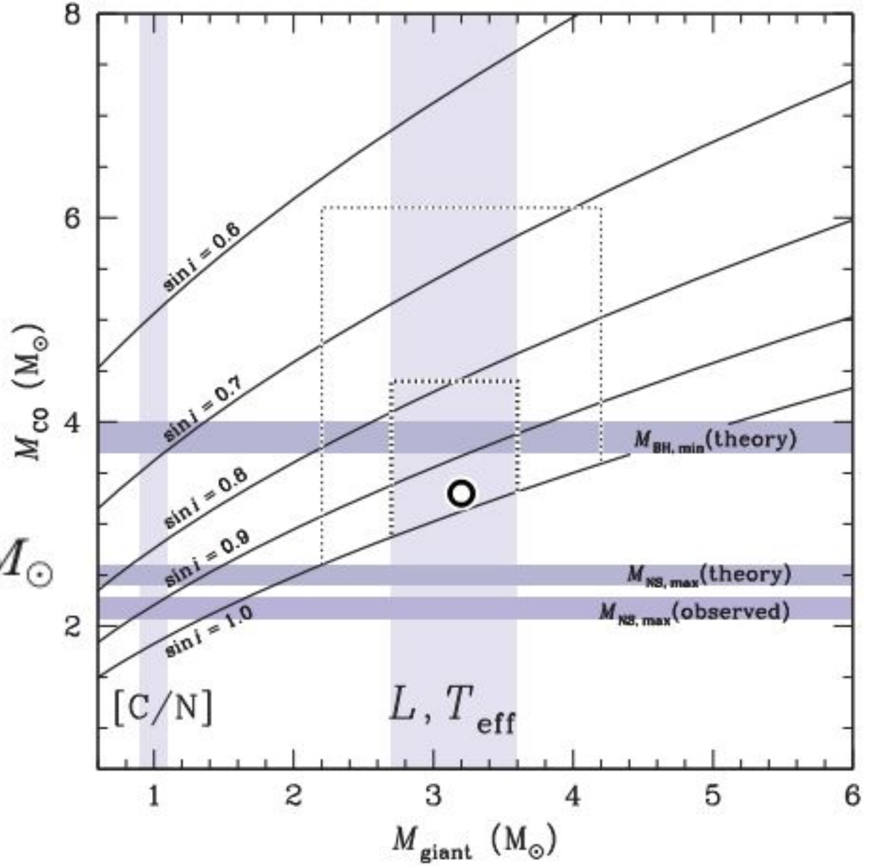
Compact Object Mass Constraints

- Given APOGEE v*sin(i) measurement along with v from Mgiant, R, and log(g) gives sin(i)

$$M_{\rm giant} \simeq 3.2^{+1.0}_{-1.0}\,{\rm M}_\odot \quad \sin i \simeq 0.97^{+0.03}_{-0.12}$$

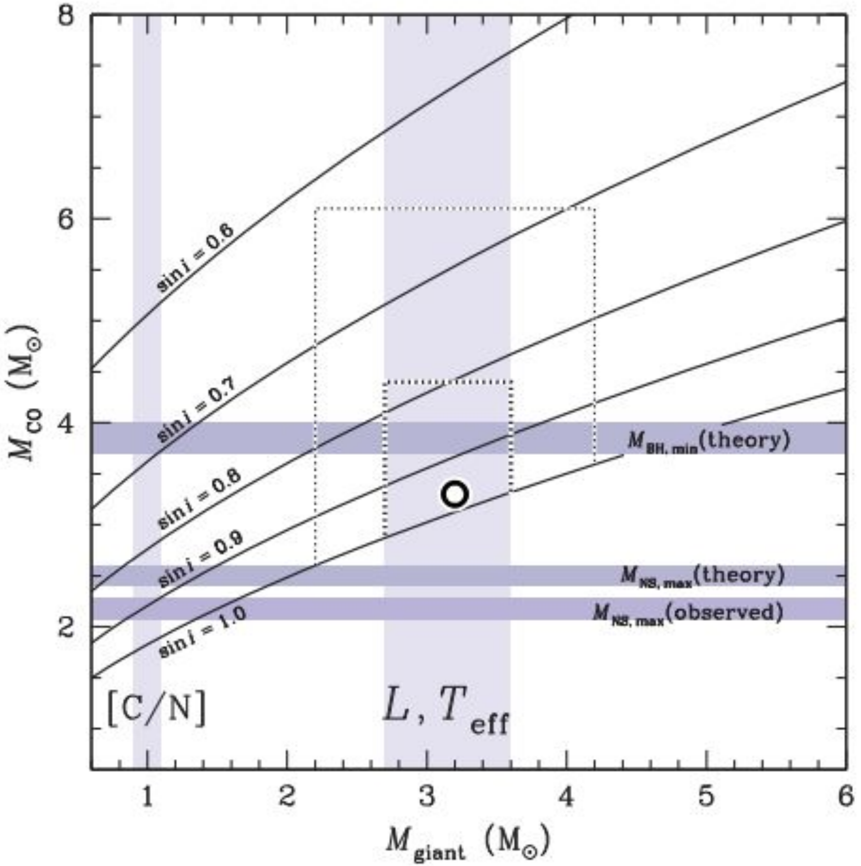
$$f(M) \equiv \frac{M_{\rm CO}^3 \sin^3 i_{\rm orb}}{(M_{\rm giant} + M_{\rm CO})^2} \simeq 0.766 \pm 0.006\, M_\odot$$

$$\boxed{M_{\rm CO} \simeq 3.3^{+2.8}_{-0.7}\, M_\odot}$$



Compact Object Mass Constraints

- Variation in log(g) and sin(i) gives MCO ~ 2.9-4.0 Msun
- Empirical relation b/w [C/N] and Mgiant implies low mass giant (Mgiant~1 Msun), but unlikely:
  - Inconsistent with previous mass derivation
  - Anomalies in APOGEE sample



X-ray limits: evidence for non-interaction

- Swift XRT limits from 0.3-10 keV:
  - **Fx = 4.4x10^(-14) erg cm^(-2) s^(-1)**
  - 10^(-2) Lsun at 3.1 kpc
  - 10^(-7) Ledd for 3Msun BH
- For efficient wind-powered accretion, 0.35 Lsun needed
- X-ray limits imply radiatively inefficient accretion
- Gas may be expelled from system without accreting

$$\dot{M}_{\rm acc} \sim \frac{\dot{M}_{\rm wind}}{(4\pi s^2)}\pi\left(\frac{GM_{\rm CO}}{V_{\rm wind}^2}\right)^2 \sim 2\times10^{-13}\,{\rm M_\odot\ yr^{-1}}\ \frac{\dot{M}_{\rm wind,\,-10}\,M_{\rm CO,\,3}^2\sin^2 i}{V_{\rm wind,\,200}^4}$$

Thompson et al. rebuttal to van den Heuvel & Tauris

The argument: J05215658 is actually a triple system: 1 M_solar giant with two 0.9 M_solar stars

Is there validity to this argument?

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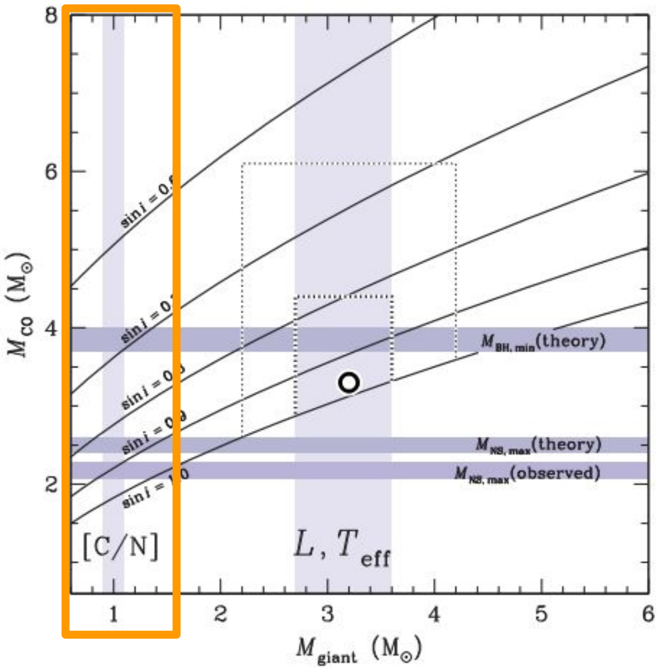

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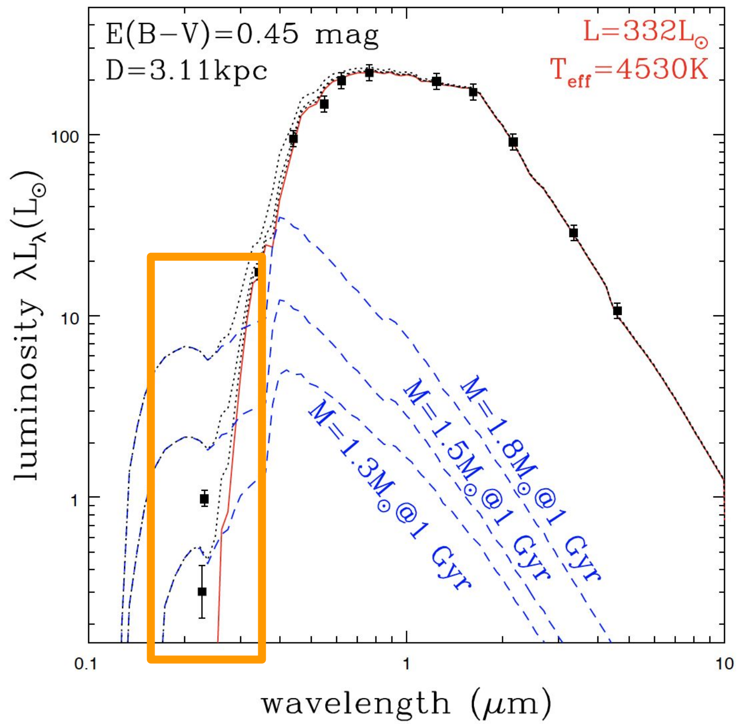

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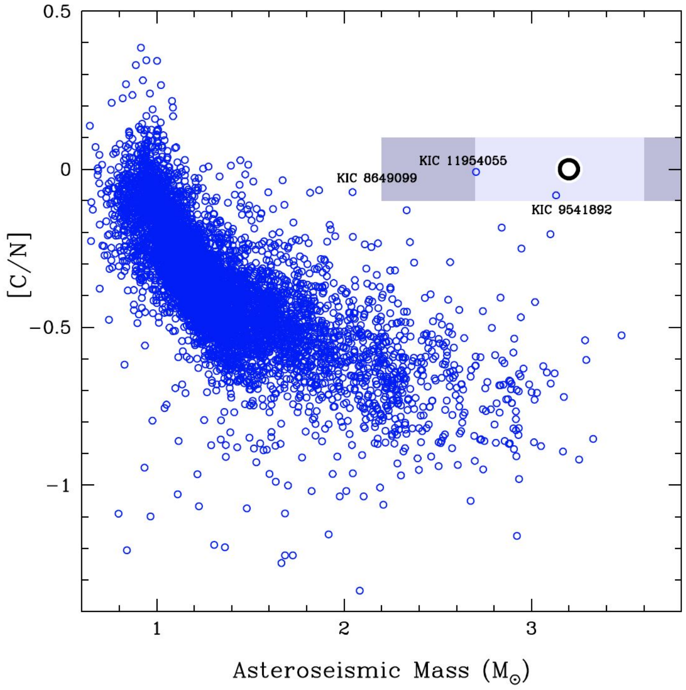
-Relation between mass and [C/N] ratio



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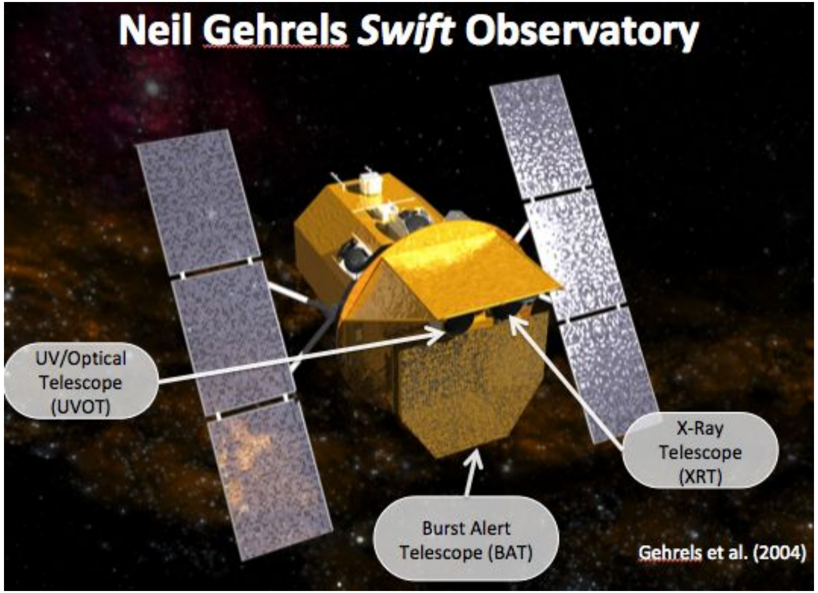
-low x-ray luminosity implies low accretion

Rate



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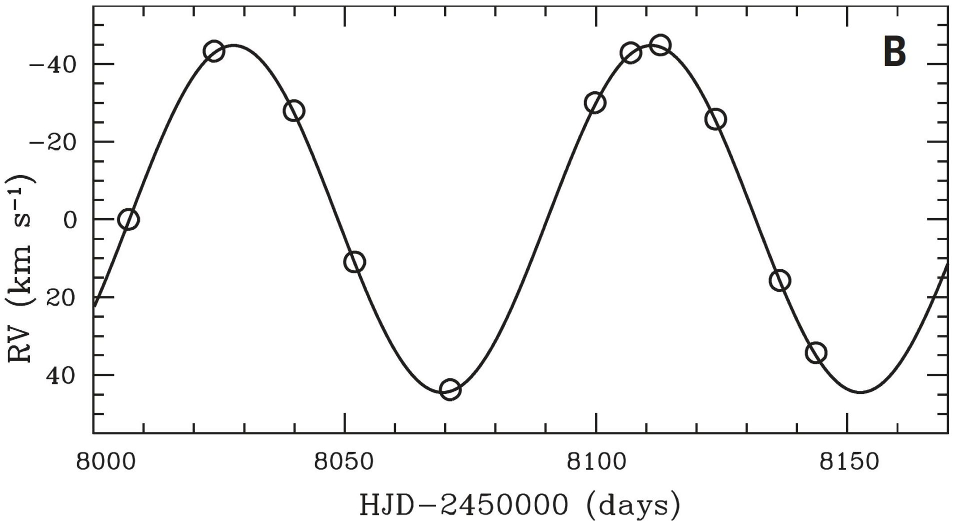
Rate

-Spectroscopic atmospheric model-derived

masses can be very large



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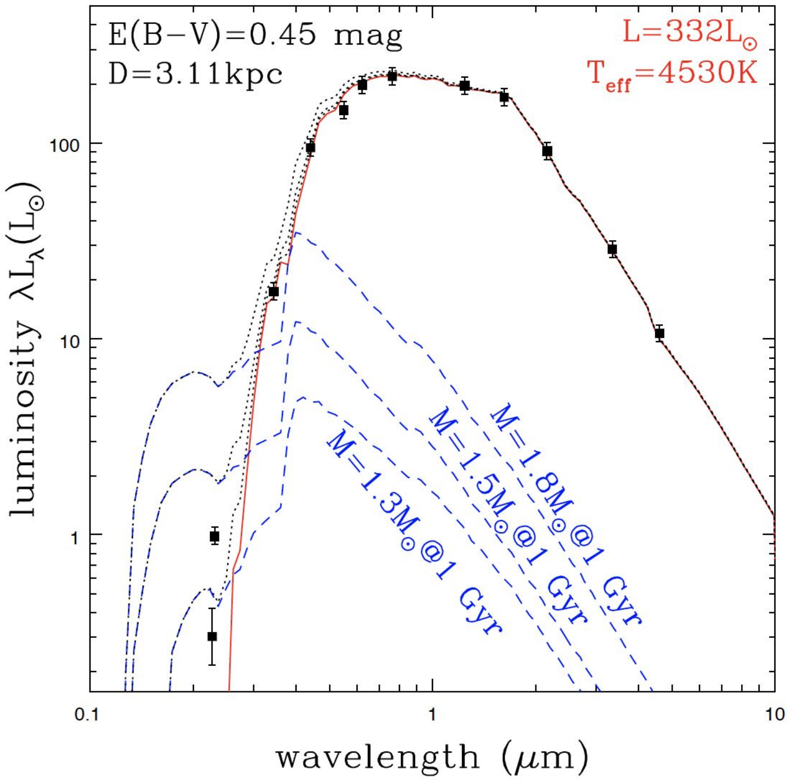
Counter arguments

-[C/N] ratio implies a lower mass

 -> counter argument: strong independent

Constraints on mass from SED



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Counter arguments

-[C/N] ratio implies a lower mass

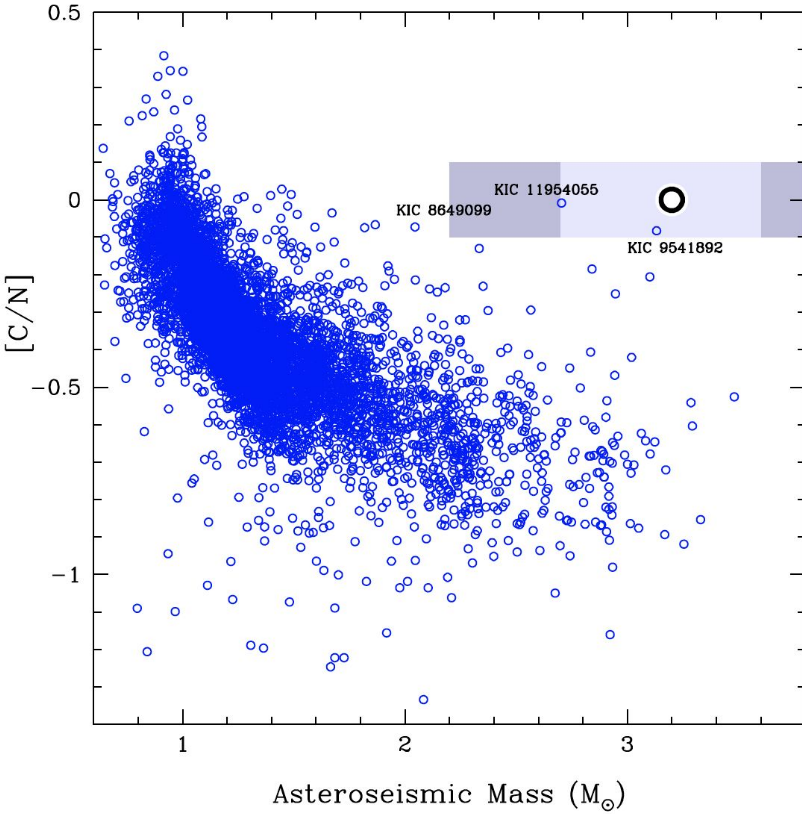
-> counter argument: strong independent

Constraints on mass from SED

-> counter argument: 6% of > 3 M_solar stars

Have high [C/N]

-> systematics in APOGEE [C/N] measurements



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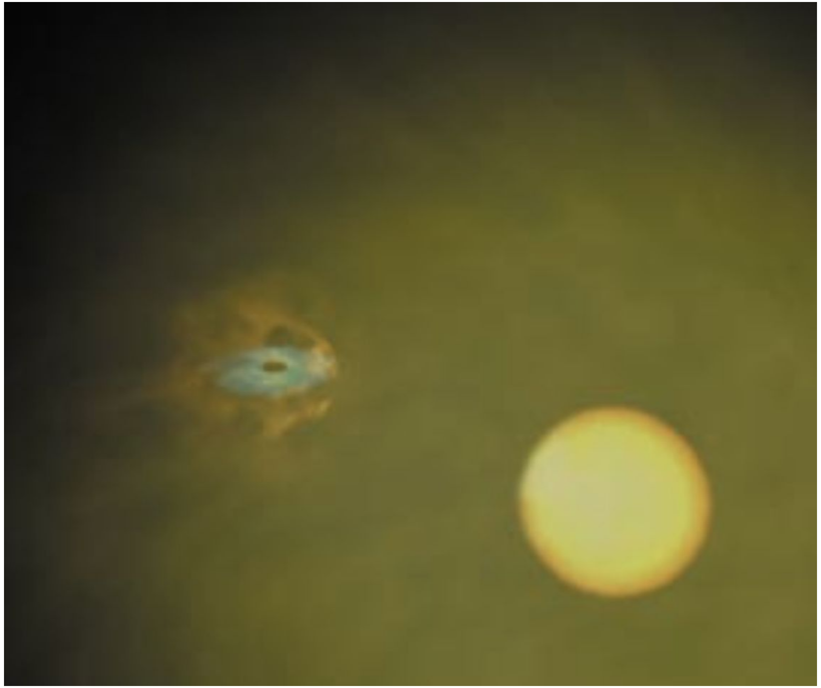
-low x-ray luminosity implies low accretion

Rate

-> counter argument: Mass accretion rate from stellar wind is in the radiatively inefficient regime given the ~3 M_solar mass of the black hole



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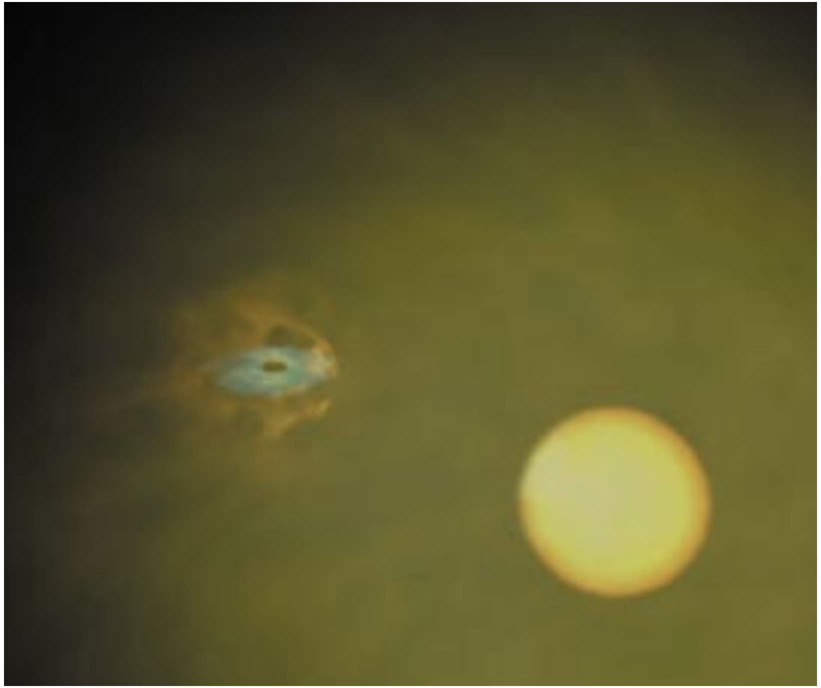
Rate

-> counter argument: Mass accretion rate from stellar wind is in the radiatively inefficient regime given the ~3 M_solar mass of the black hole

-> counter argument: black holes have intrinsically lower x-ray luminosities in x-ray binaries



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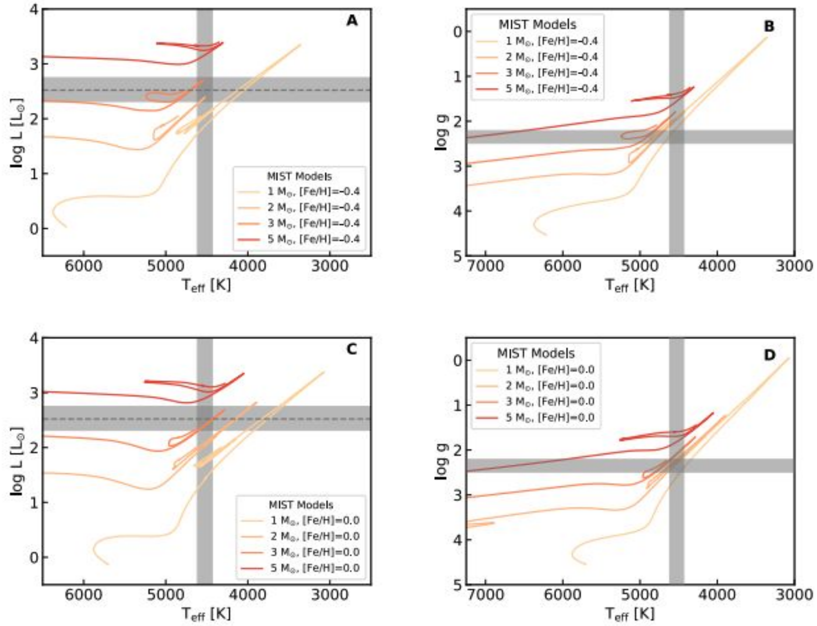
Counter arguments

-Spectroscopic atmospheric model-derived

masses can be very large

-> counter argument: independent mass estimates using L, T_eff and log g to evolutionary models



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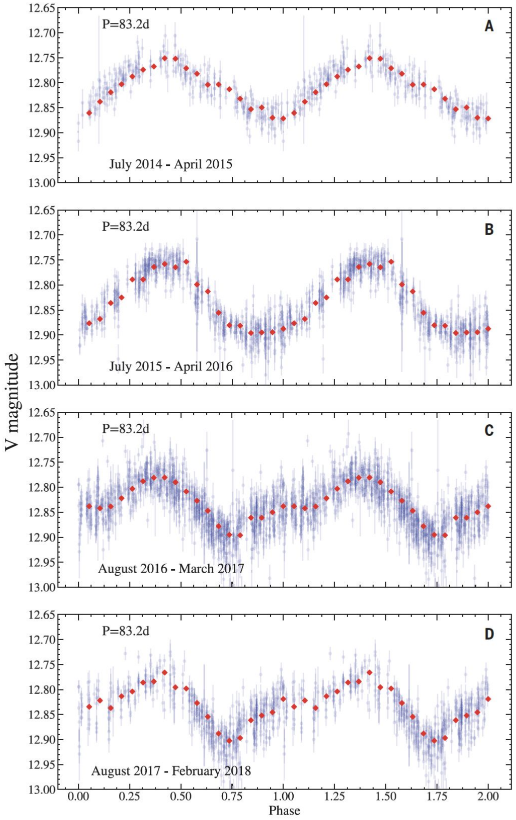
Counter arguments

-System is a triple, secondary and tertiary are 0.9 M_solar each

-> a triple system would require semi-major axis of secondary and tertiary to be much smaller

-> lack of ellipsoidal variations detected in lightcurve

-> inconsistent with distance measurement from parallax measurement from Gaia



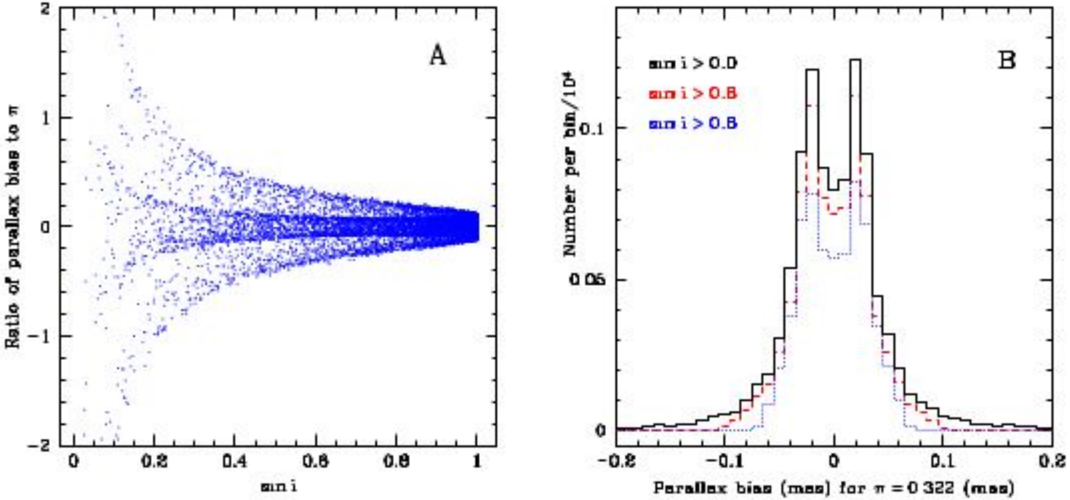
Backup Slides

Parallax measurement

Measured : $\pi = 0.322\,\text{mas} \pm 0.049\,\text{mas (random)} \pm 0.043\,\text{mas (systematic)}$

Binary motion can induce biases as large as ~ s/1AU ~ 0.11/sin(i) mas

Perform a simulation to quantify these biases



Parallax measurement

Corrected $\pi \simeq 0.322^{+0.086}_{-0.074}$

Very high biases ruled out by RUWE