

# Electromagnetic signals of binaries: spectroscopy

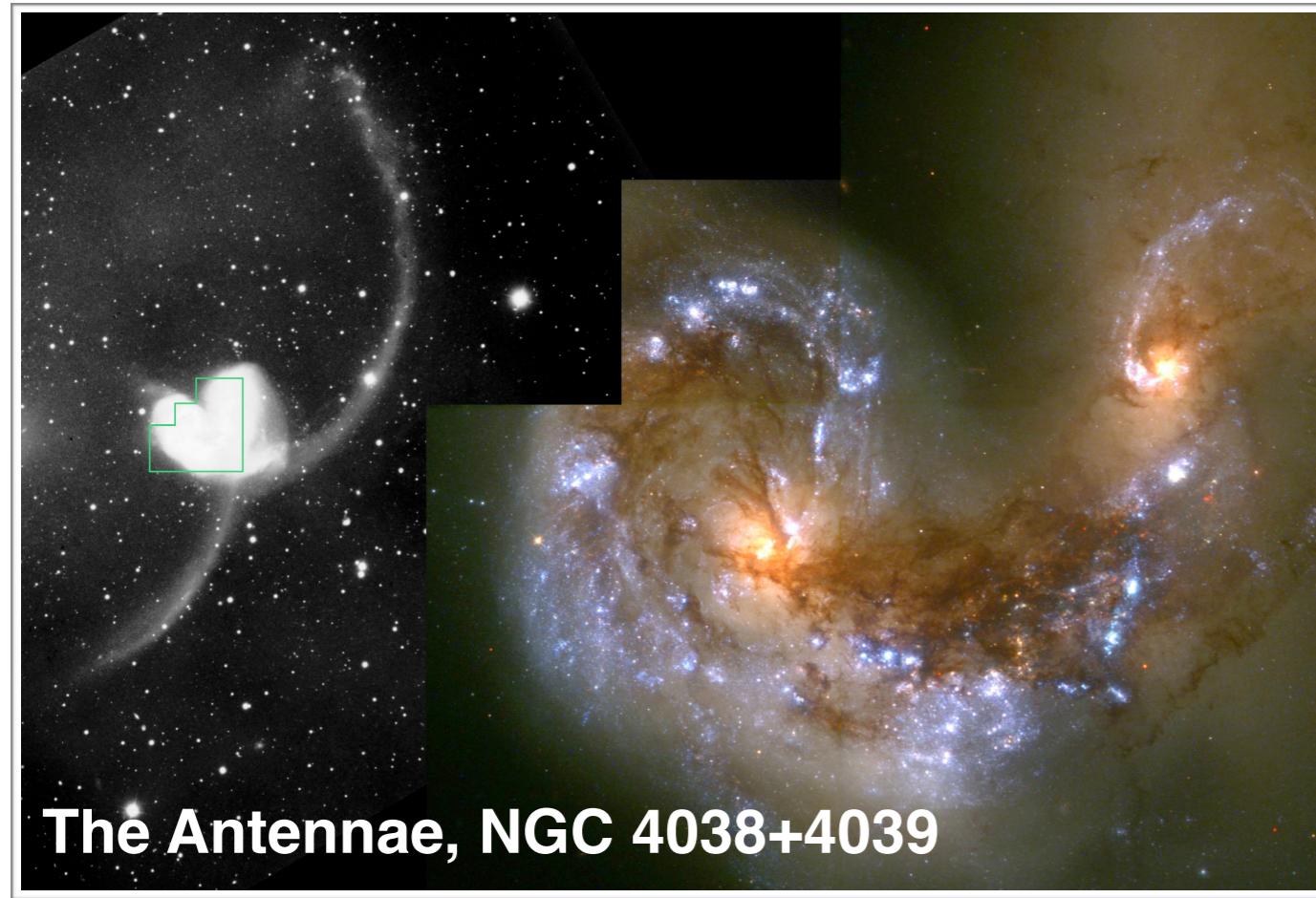
Jessie Runnoe  
Vanderbilt University  
Wednesday, July 20, 2022



VANDERBILT  
UNIVERSITY®

# {1} SMBH binaries: *Inevitable product of mergers?*

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# {1} SMBH binaries: *Basics of binary evolution*

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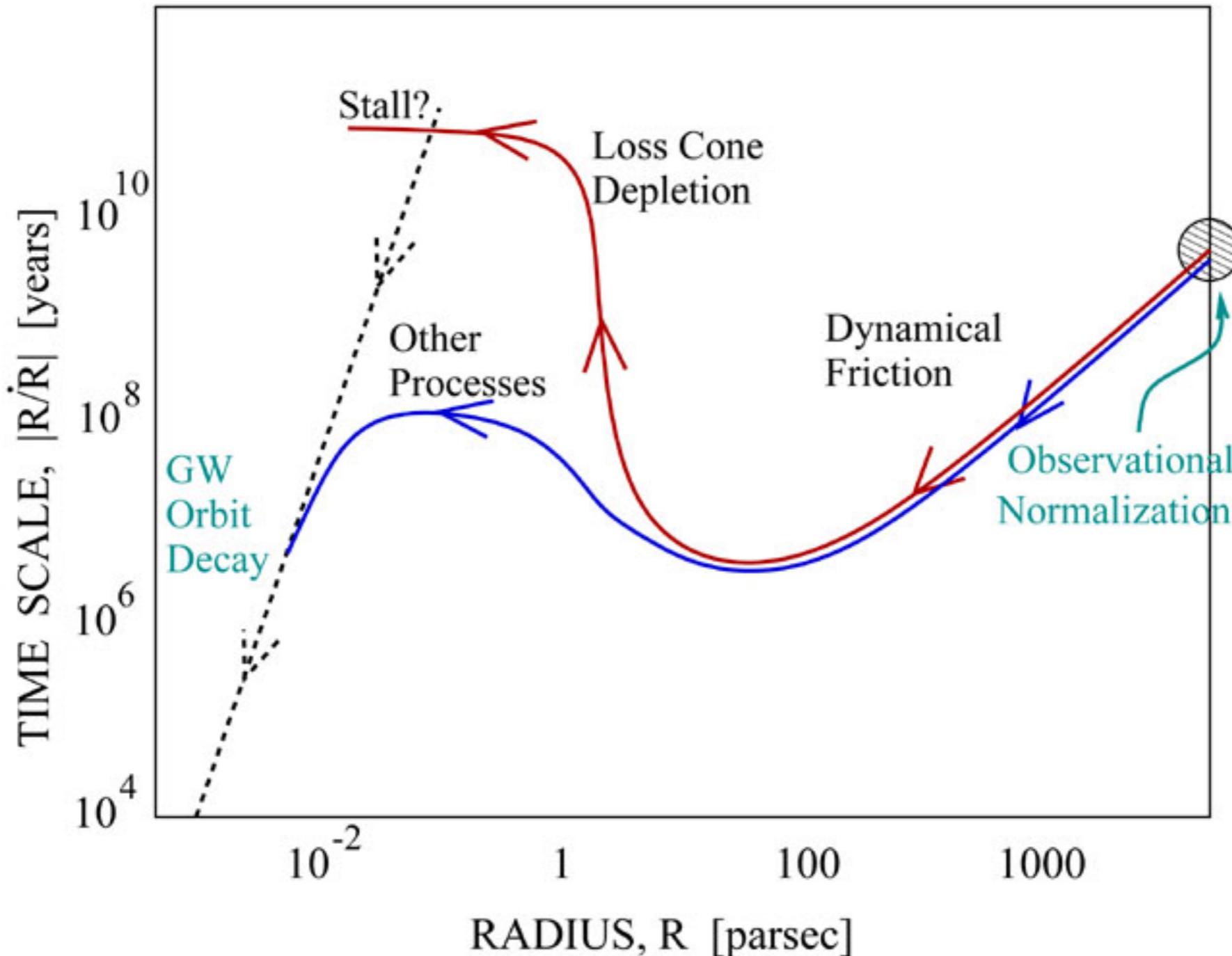


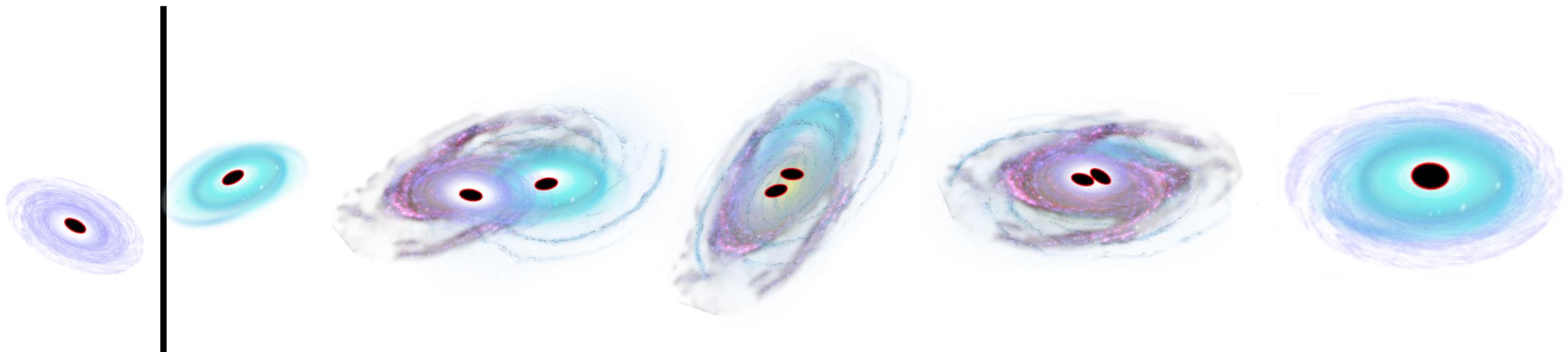
figure from Backer et al. (2003), based on  
the work of Begelman et al. (1980)

# {1} SMBH binaries: Methods for finding binaries

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Slide credit: Modified from N. Mohammed

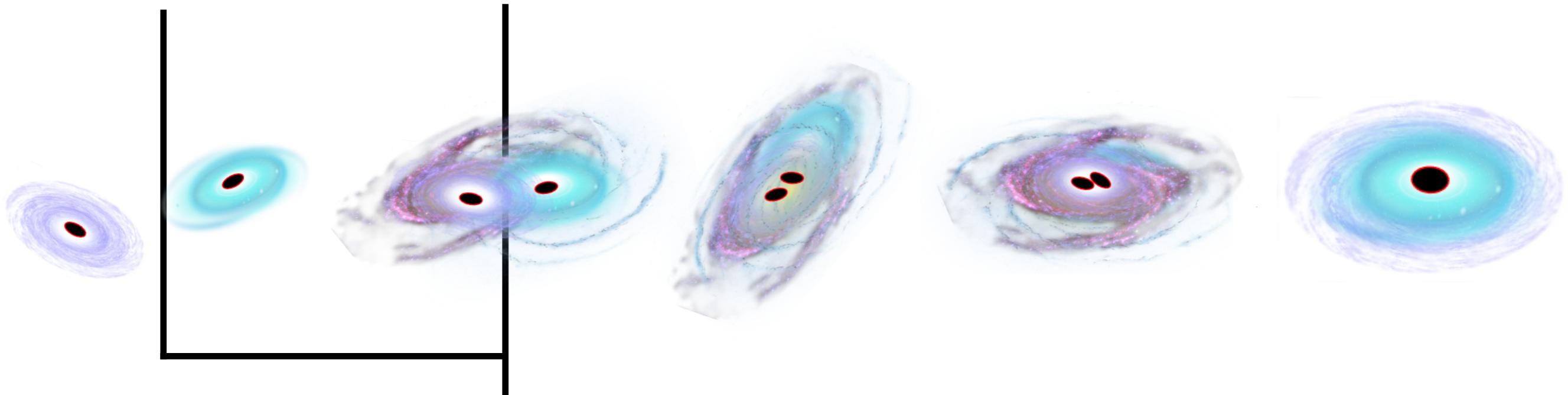
Galaxies approach  
each other



# {1} SMBH binaries: Methods for finding binaries

Slide credit: Modified from N. Mohammed

Galaxies approach  
each other      Dual AGN  
                        0.1-10 kpc



X-rays, “spectro-astrometry”

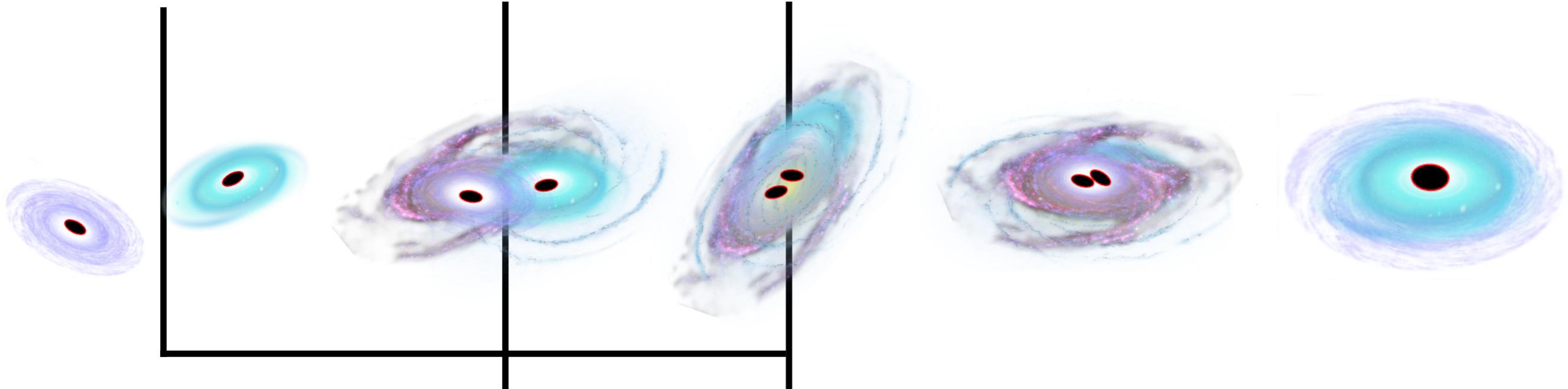
Comerford et al. (2015)

Foord et al. (2020)

# {1} SMBH binaries: Methods for finding binaries

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Galaxies approach  
each other      Dual AGN      Bound BH  
                        0.1-10 kpc      <10 pc



X-rays, “spectro-astrometry”

Comerford et al. (2015)

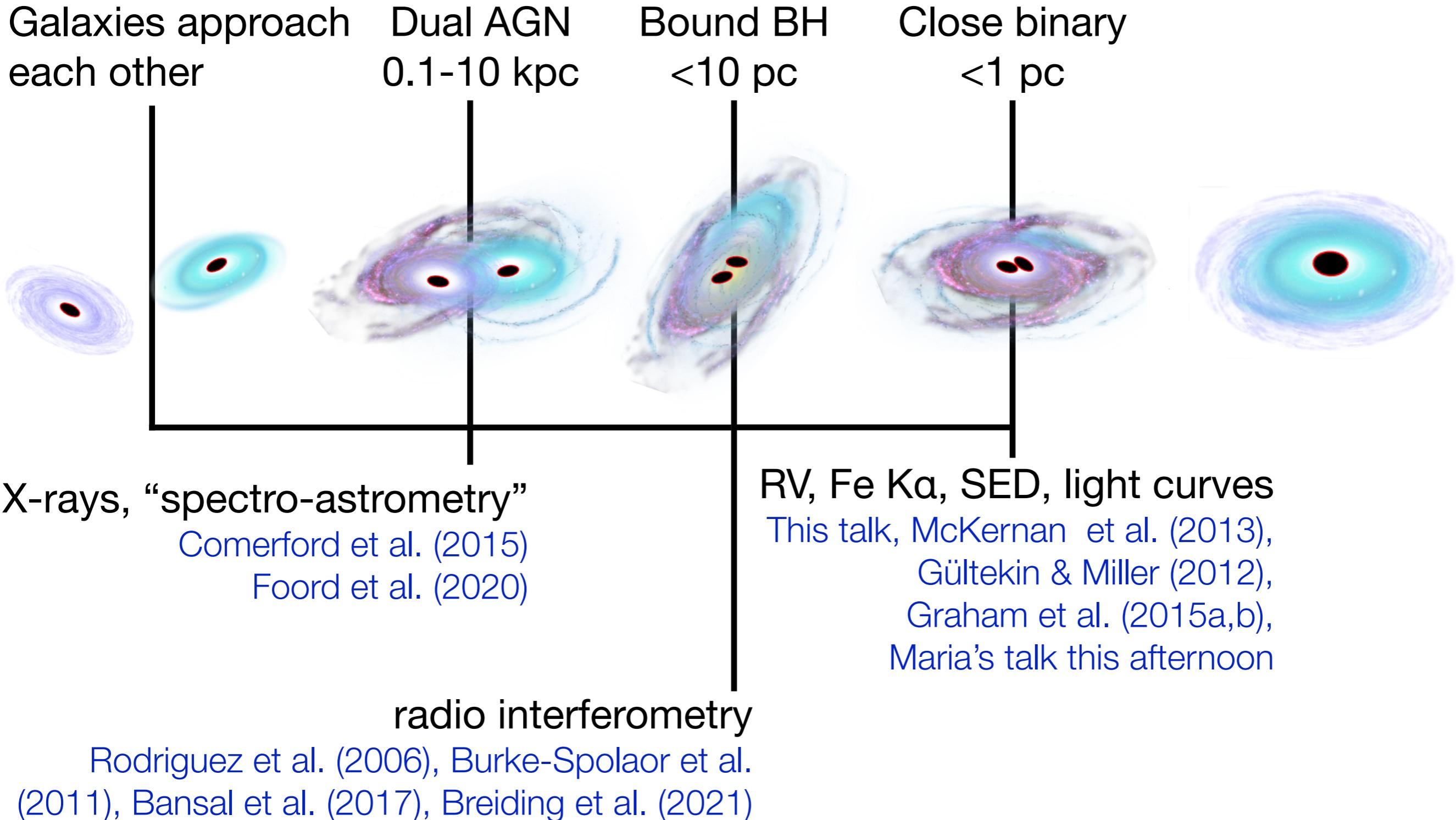
Foord et al. (2020)

radio interferometry

Rodriguez et al. (2006), Burke-Spolaor et al.  
(2011), Bansal et al. (2017), Breiding et al. (2021)

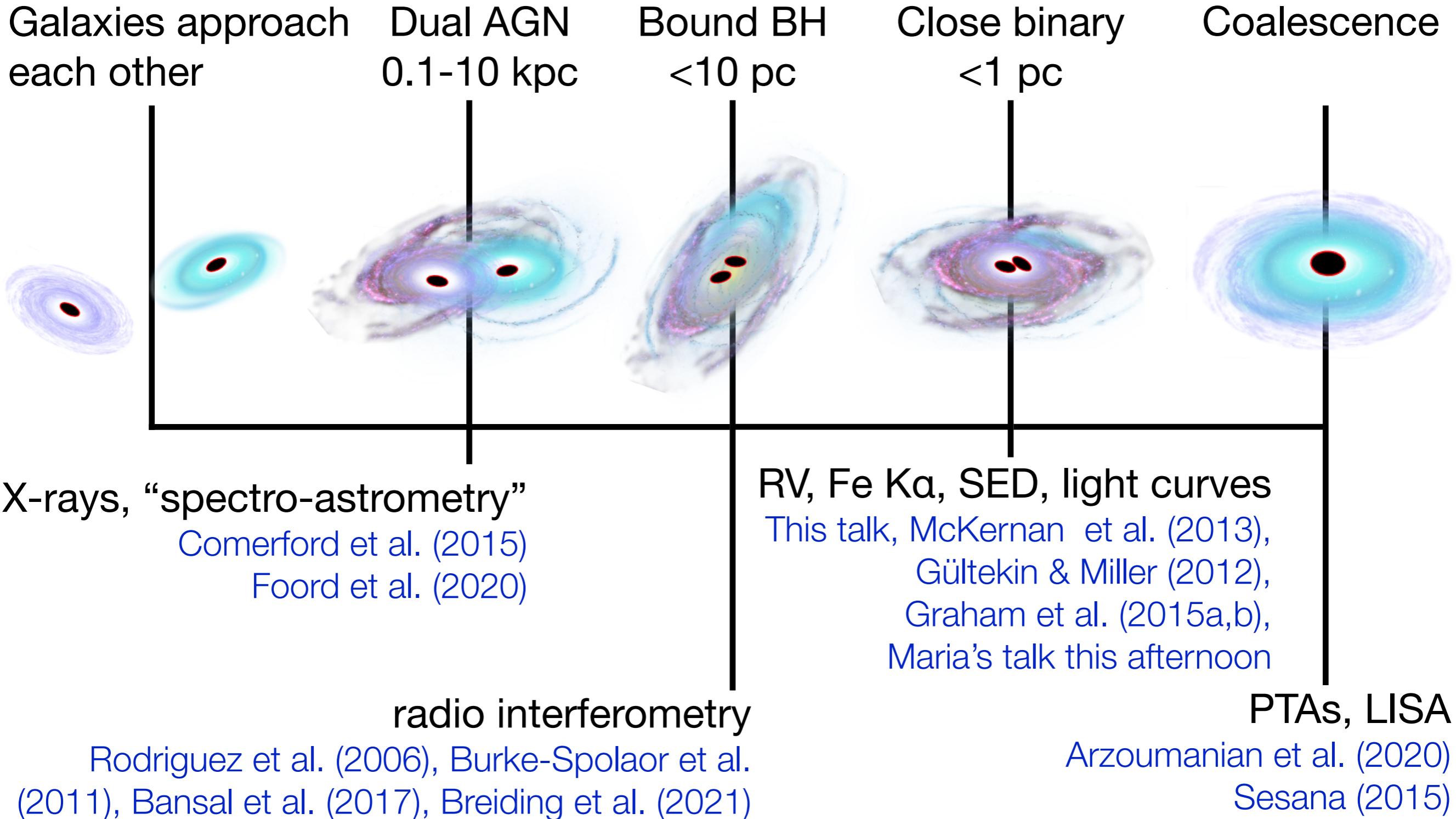
# {1} SMBH binaries: Methods for finding binaries

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# {1} SMBH binaries: Methods for finding binaries

Slide credit: Modified from N. Mohammed

## Indirect detection via radial velocity changes:

*Tsalmantza et al. (2011)*

*Eracleous et al. (2012), Runnoe et al. (2015, 2017)*

*Decarli et al. (2013)*

*Ju et al. (2013)*

*Shen et al. (2013)*

*Liu et al. (2014), Guo et al. (2019)*

Also: *Shen & Loeb (2010), Pflueger et al. (2018), Kelley et al. (2021)*

X-rays, “spectro-astrometry”

*Comerford et al. (2015)*

*Foord et al. (2020)*

radio interferometry

*Rodriguez et al. (2006), Burke-Spolaor et al. (2011), Bansal et al. (2017), Breiding et al. (2021)*

RV, Fe K $\alpha$ , SED, light curves

*This talk, McKernan et al. (2013),  
Gültekin & Miller (2012),  
Graham et al. (2015a,b),  
Maria’s talk this afternoon*

PTAs, LISA

*Arzoumanian et al. (2020)  
Sesana (2015)*

# {2} Quasars: *The cartoon picture*

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## Properties of the central engine

- ◆ Size:  
a few light-hours  
(10s - 100s of AU)
- ◆ Luminosity:  
up to  $10^{47}$  erg s<sup>-1</sup>  
( $10^{40}$  W or  $10^{14}$  L<sub>⊙</sub>)
- ◆ Mass:  
 $10^6$ – $10^9$  M<sub>⊙</sub>

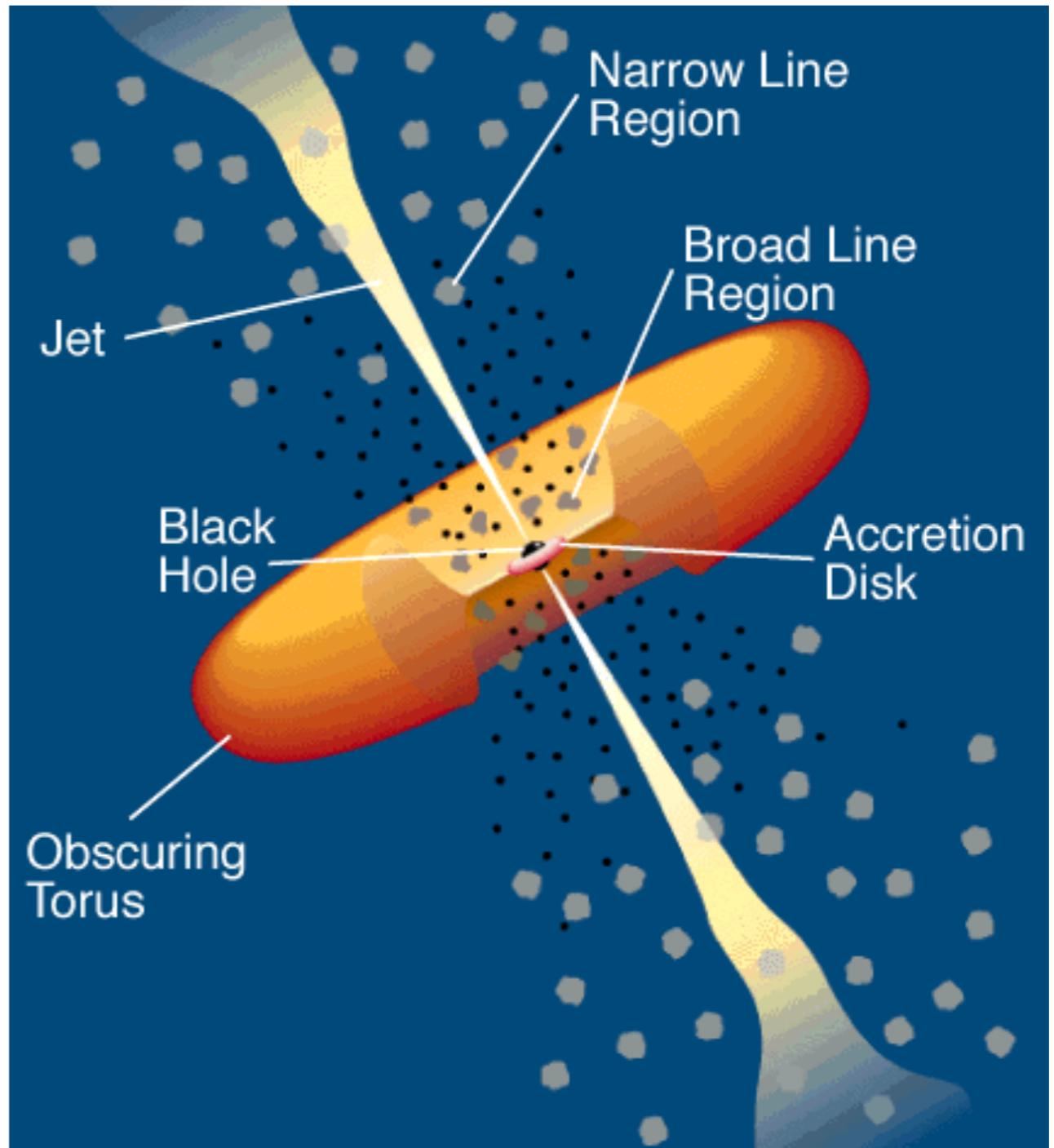
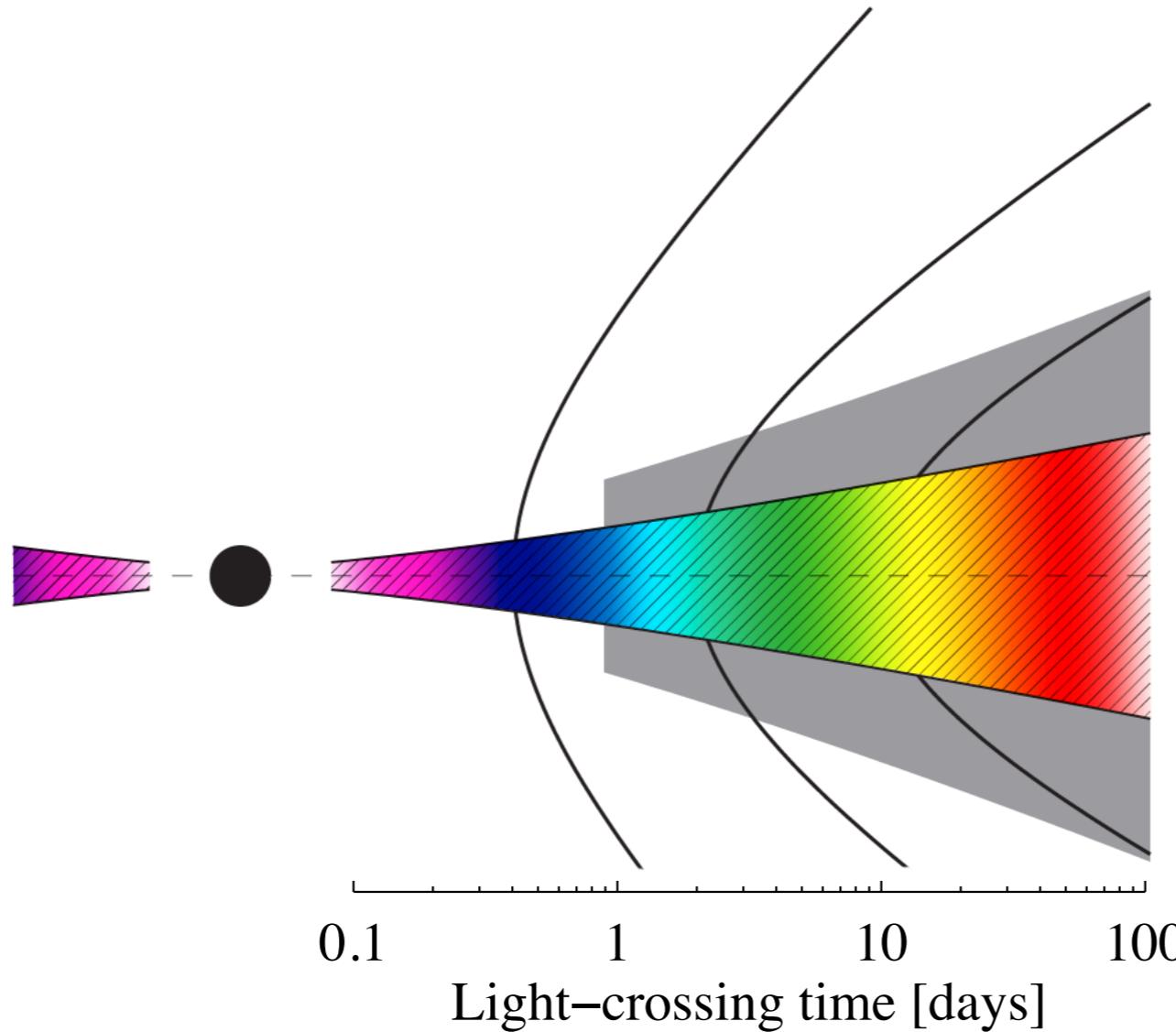


figure from Urry & Padovani (1995)

## {2} Quasars: *The modern broad-line region*

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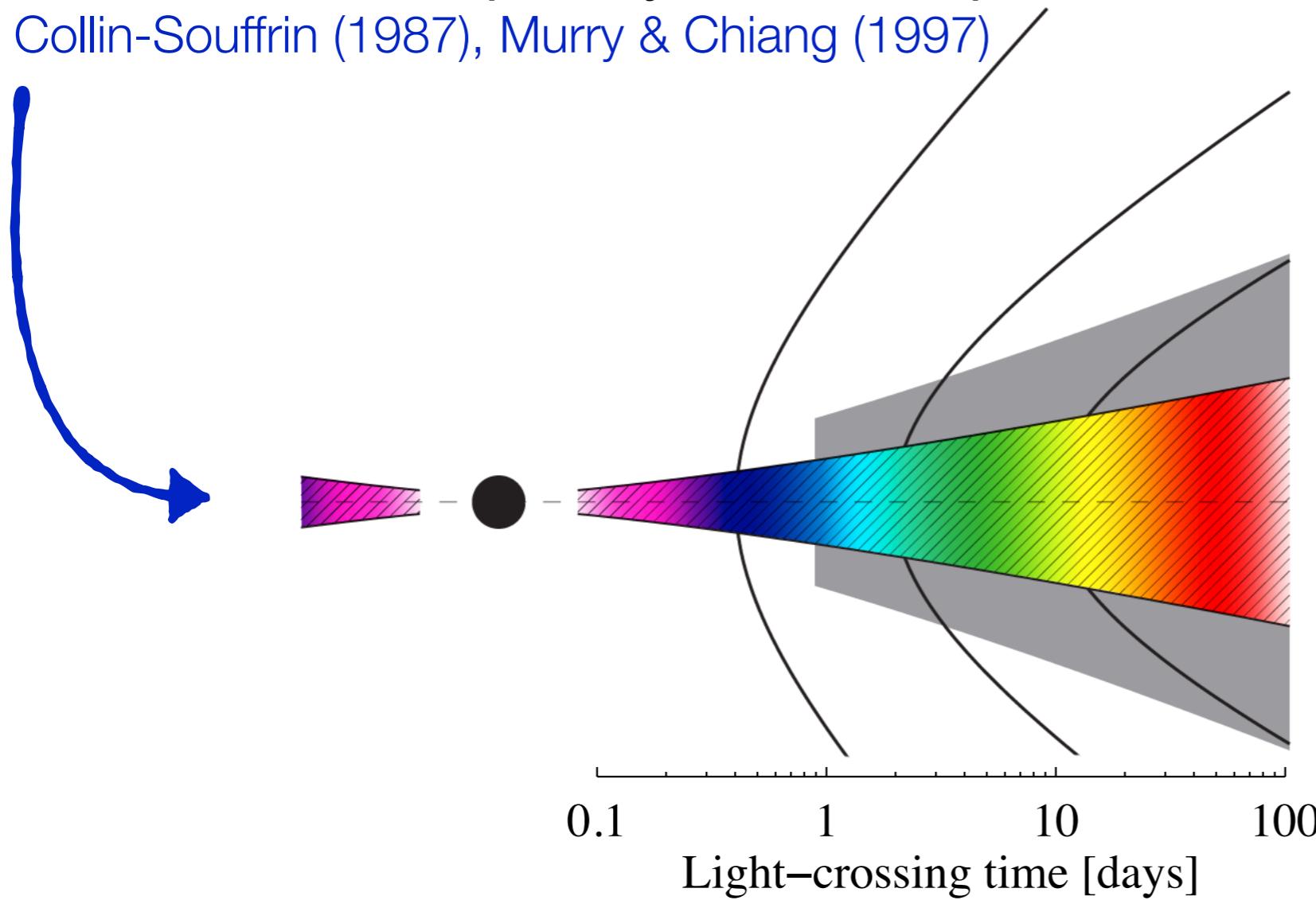
Modified from Murray & Chiang (1997)

## {2} Quasars: *The modern broad-line region*

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Dense disk with optically thin atmosphere

Collin-Souffrin (1987), Murray & Chiang (1997)



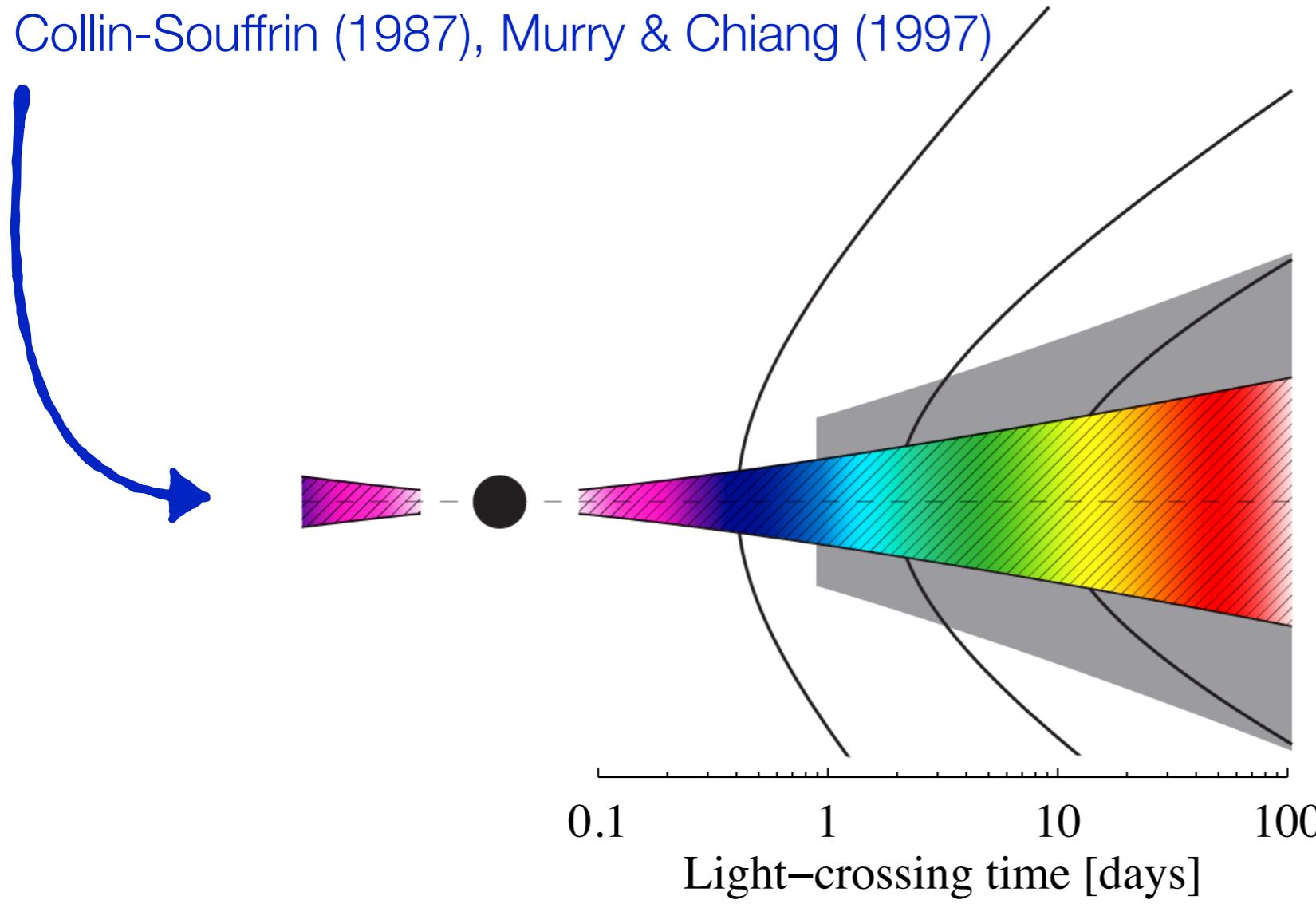
Modified from Murray & Chiang (1997)

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Dense disk with optically thin atmosphere

Collin-Souffrin (1987), Murry & Chiang (1997)



Keplerian motions

Koratkar & Gaskell (1991)

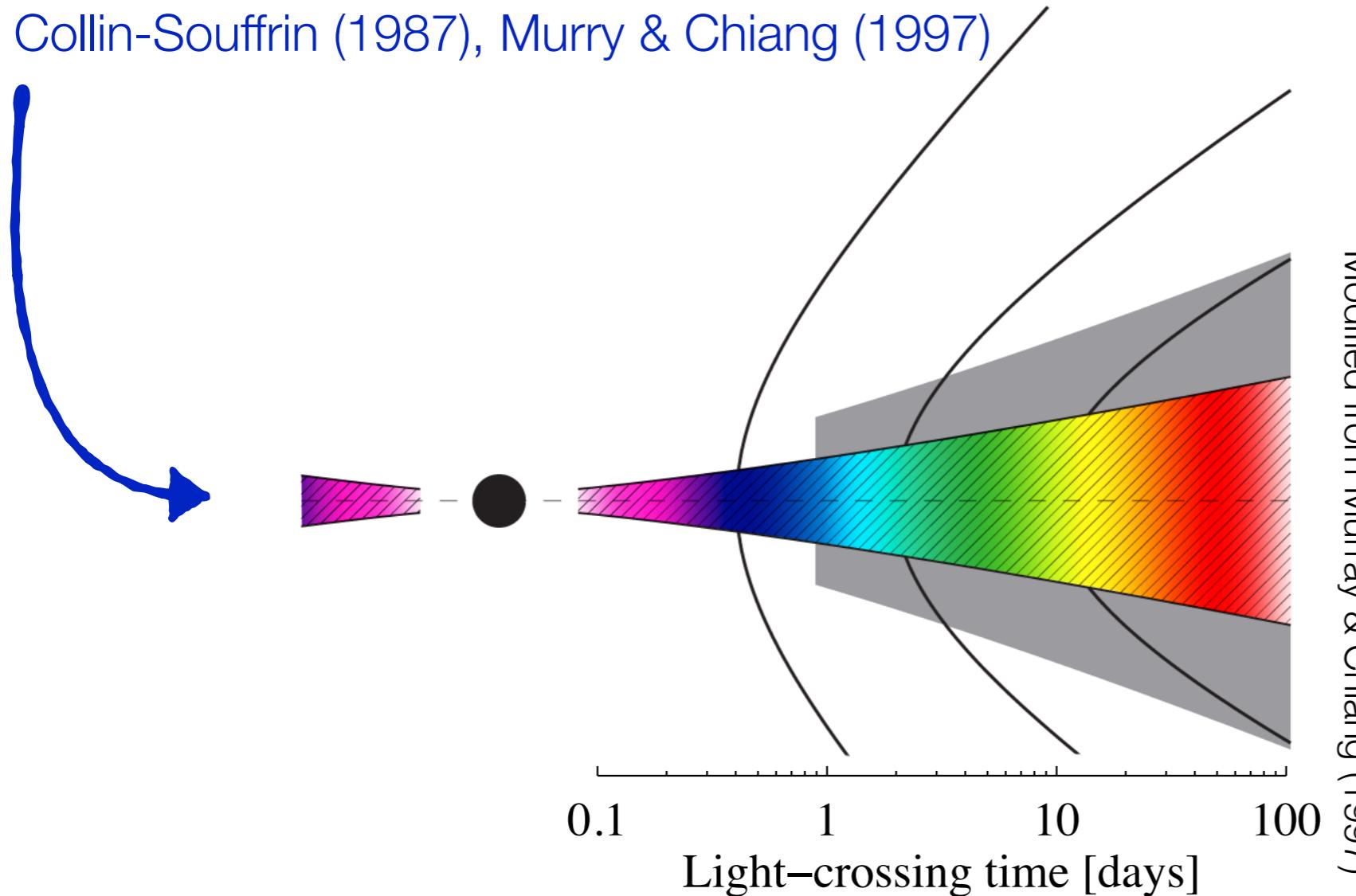
Peterson & Wandel (1999, 2000)

Pancoast et al. (2014)

## {2} Quasars: *The modern broad-line region*

Dense disk with optically thin atmosphere

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Keplerian motions

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Peterson & Wandel (1999, 2000)

Pancoast et al. (2014)

Disk-like orientation dependence

Wills & Browne (1986)

Jackson et al. (1991)

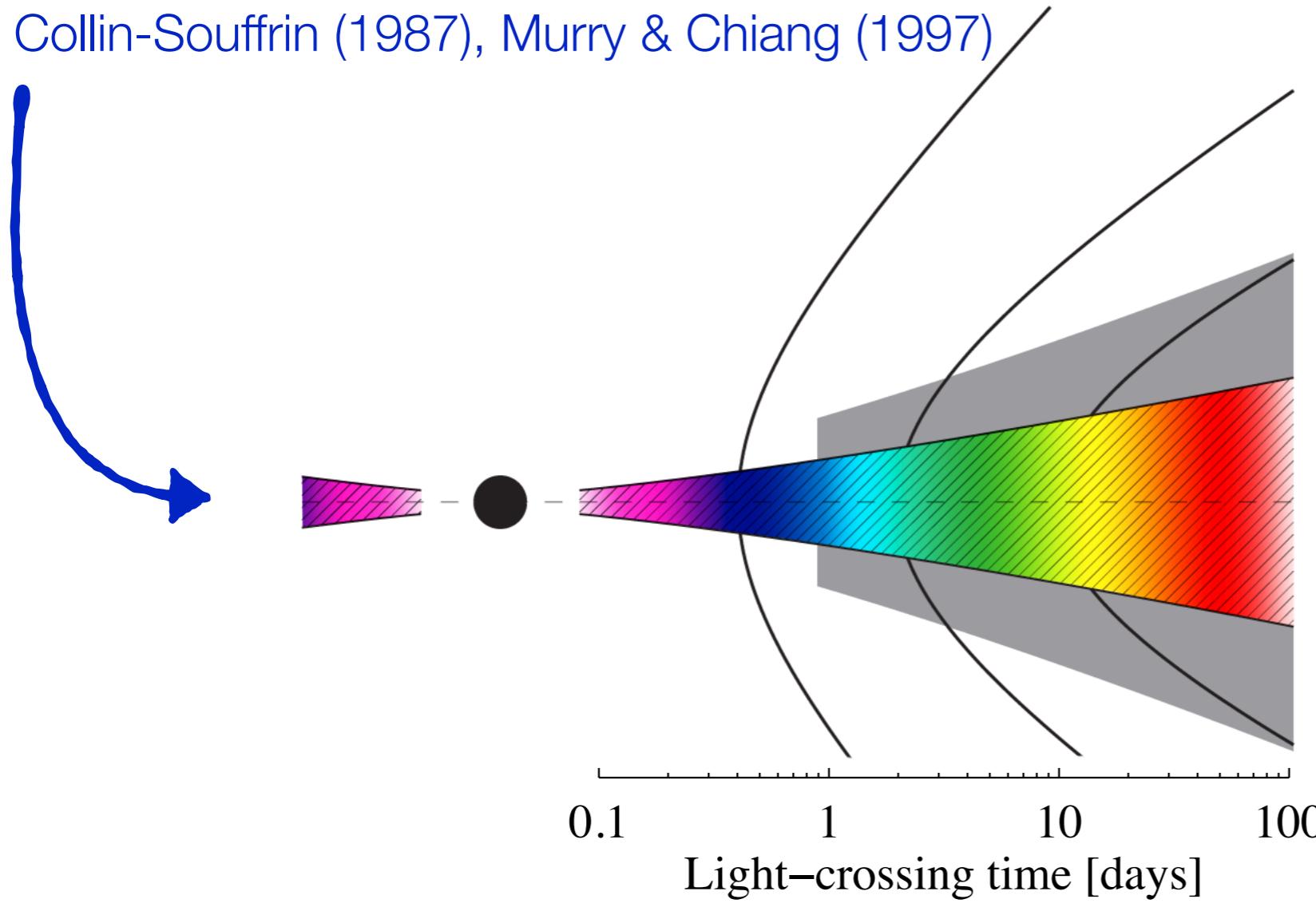
Brotherton (1996)

Runnoe et al. (2013a)

## {2} Quasars: *The modern broad-line region*

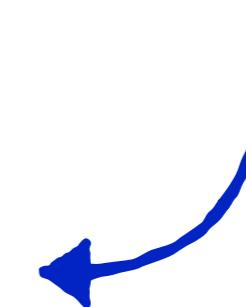
Dense disk with optically thin atmosphere

Collin-Souffrin (1987), Murry & Chiang (1997)



Continuous medium

Arav et al. (1997, 1998)  
Dietrich et al. (1999)  
Laor et al. (2006)

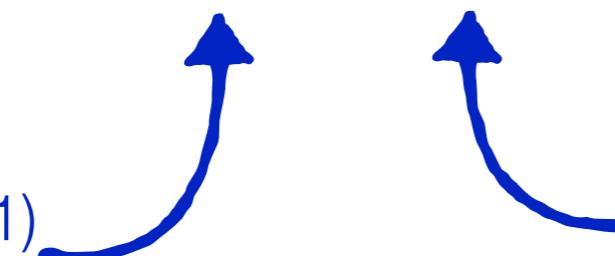


Keplerian motions

Koratkar & Gaskell (1991)

Peterson & Wandel (1999, 2000)

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Disk-like orientation dependence

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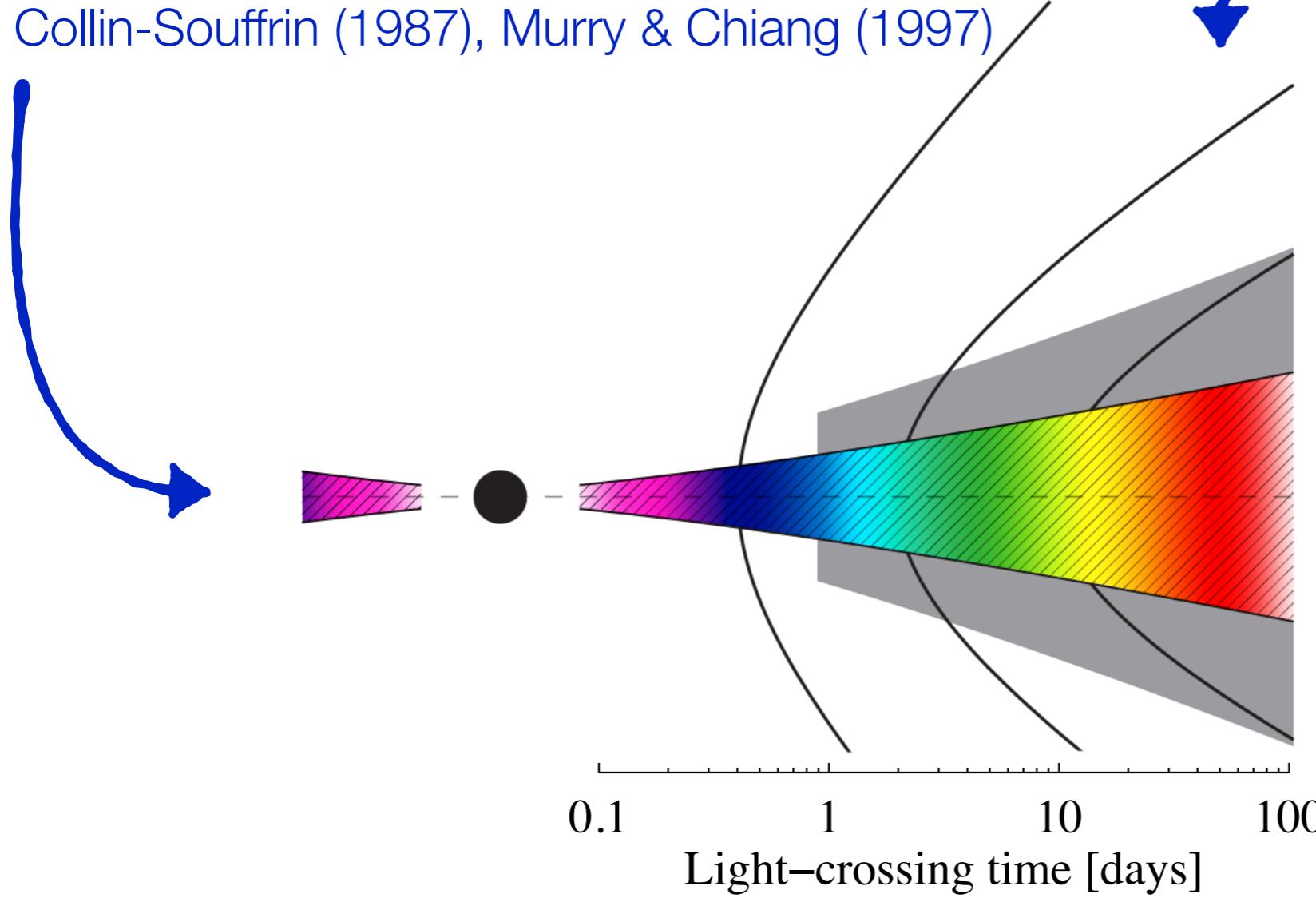
Brotherton (1996)

Runnoe et al. (2013a)

## {2} Quasars: *The modern broad-line region*

Dense disk with optically thin atmosphere

Collin-Souffrin (1987), Murry & Chiang (1997)



Disk signature in spectra

Eracleous et al. (2009)

Continuous medium

Arav et al. (1997, 1998)  
Dietrich et al. (1999)  
Laor et al. (2006)

Keplerian motions

Koratkar & Gaskell (1991)

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Disk-like orientation dependence

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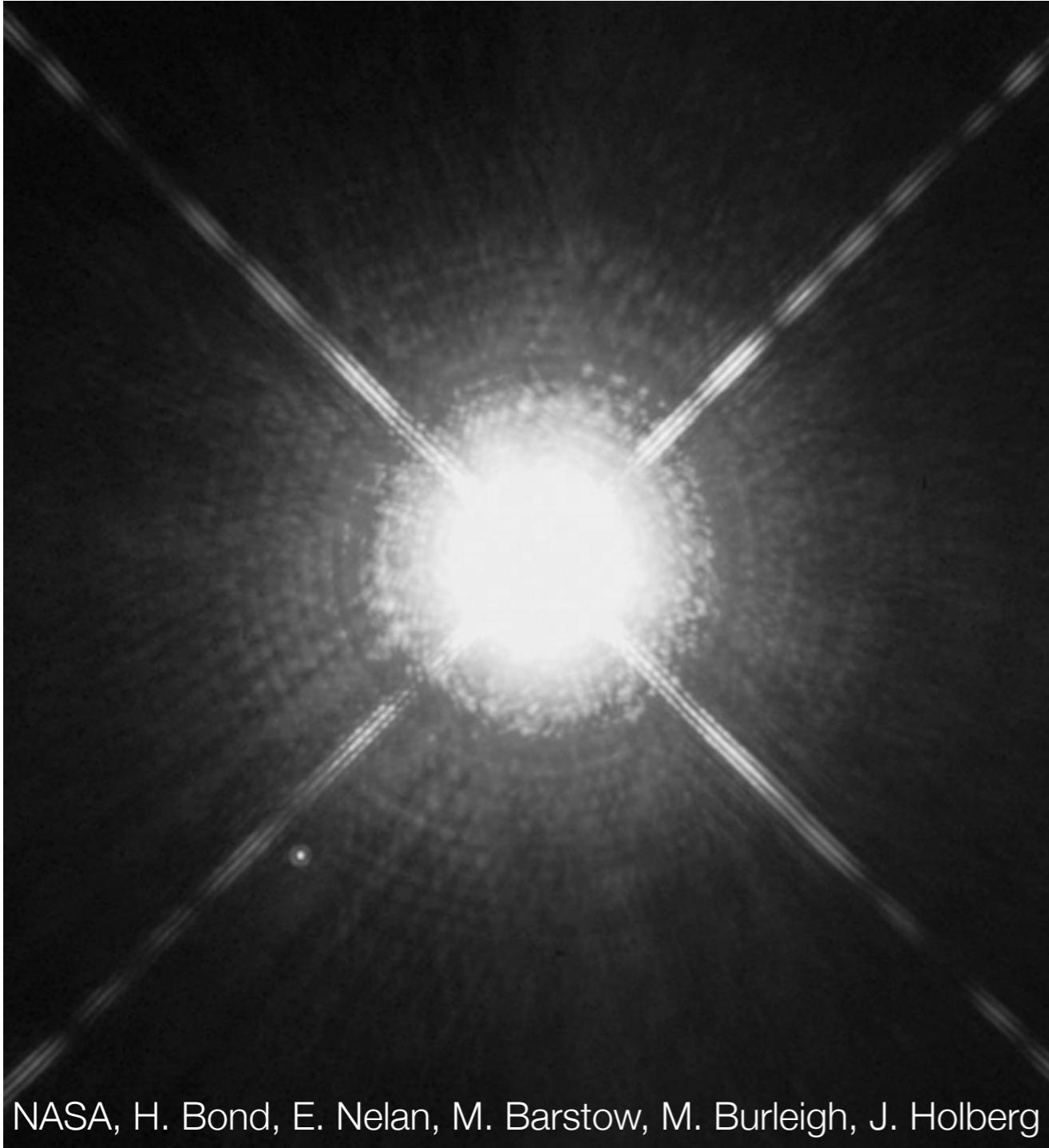
Brotherton (1996)

Runnoe et al. (2013a)

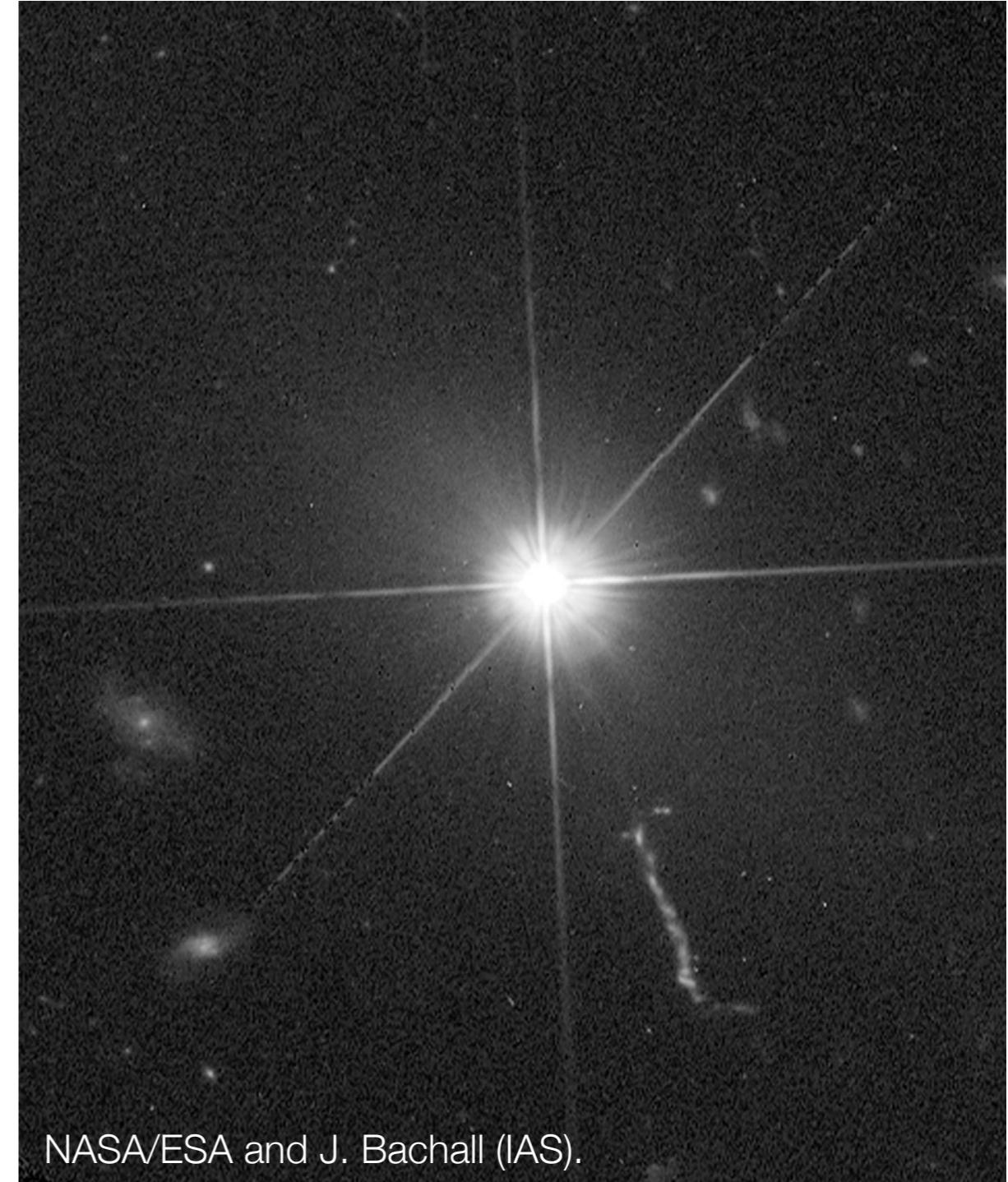
# {2} Quasars: What's in a name?

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The word **quasar** comes from **quasi-stellar radio source**.



Star

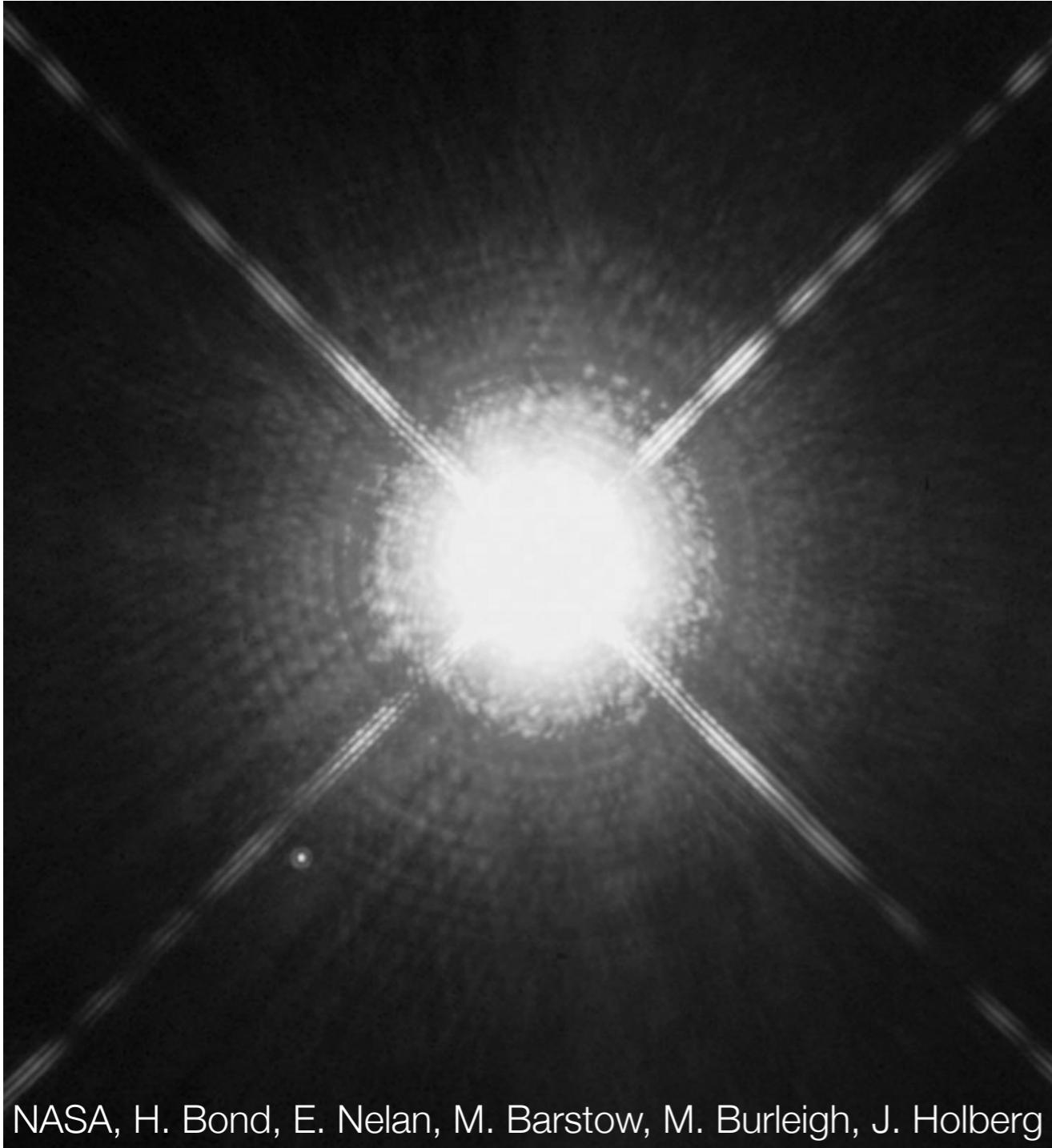


Quasar

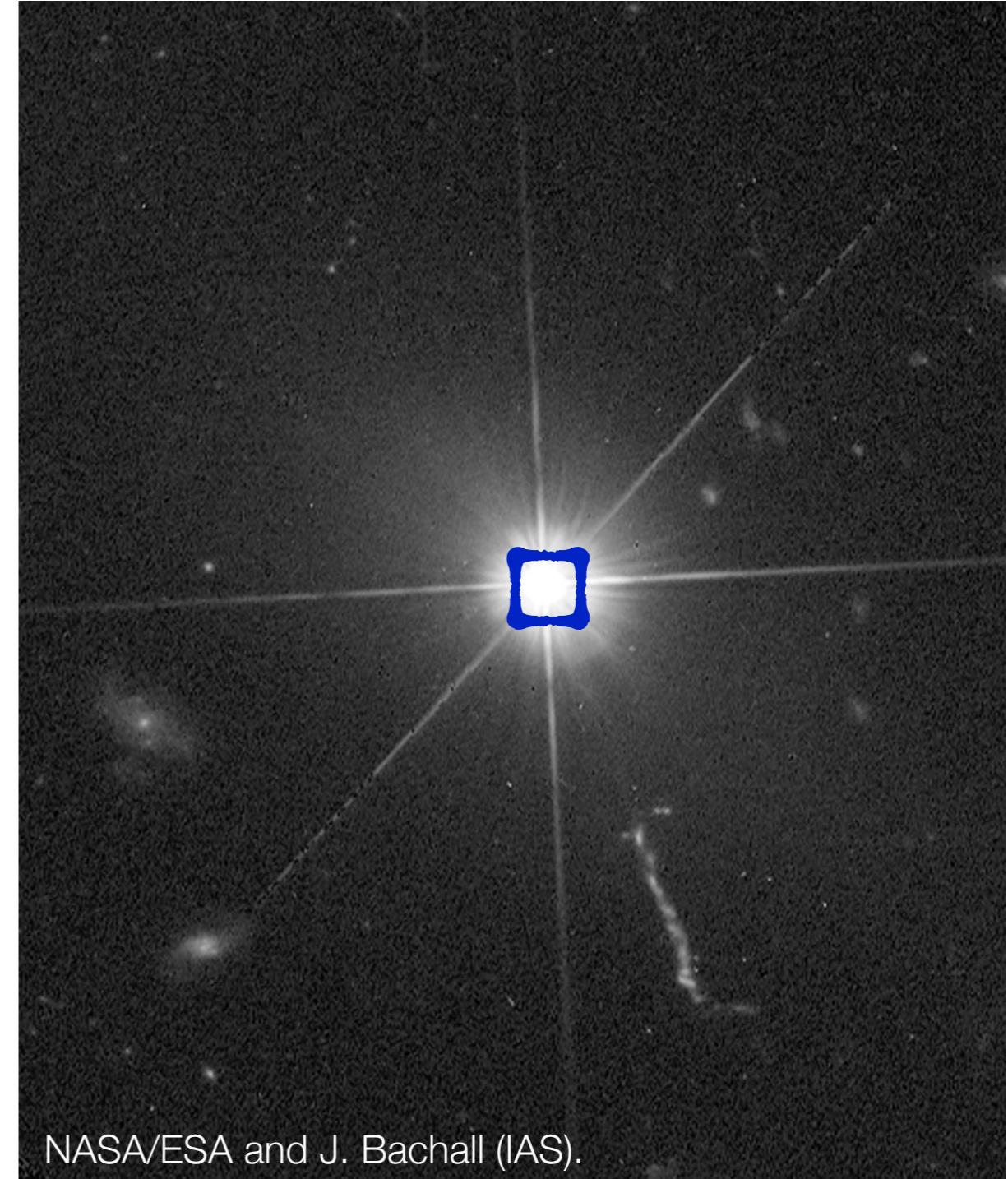
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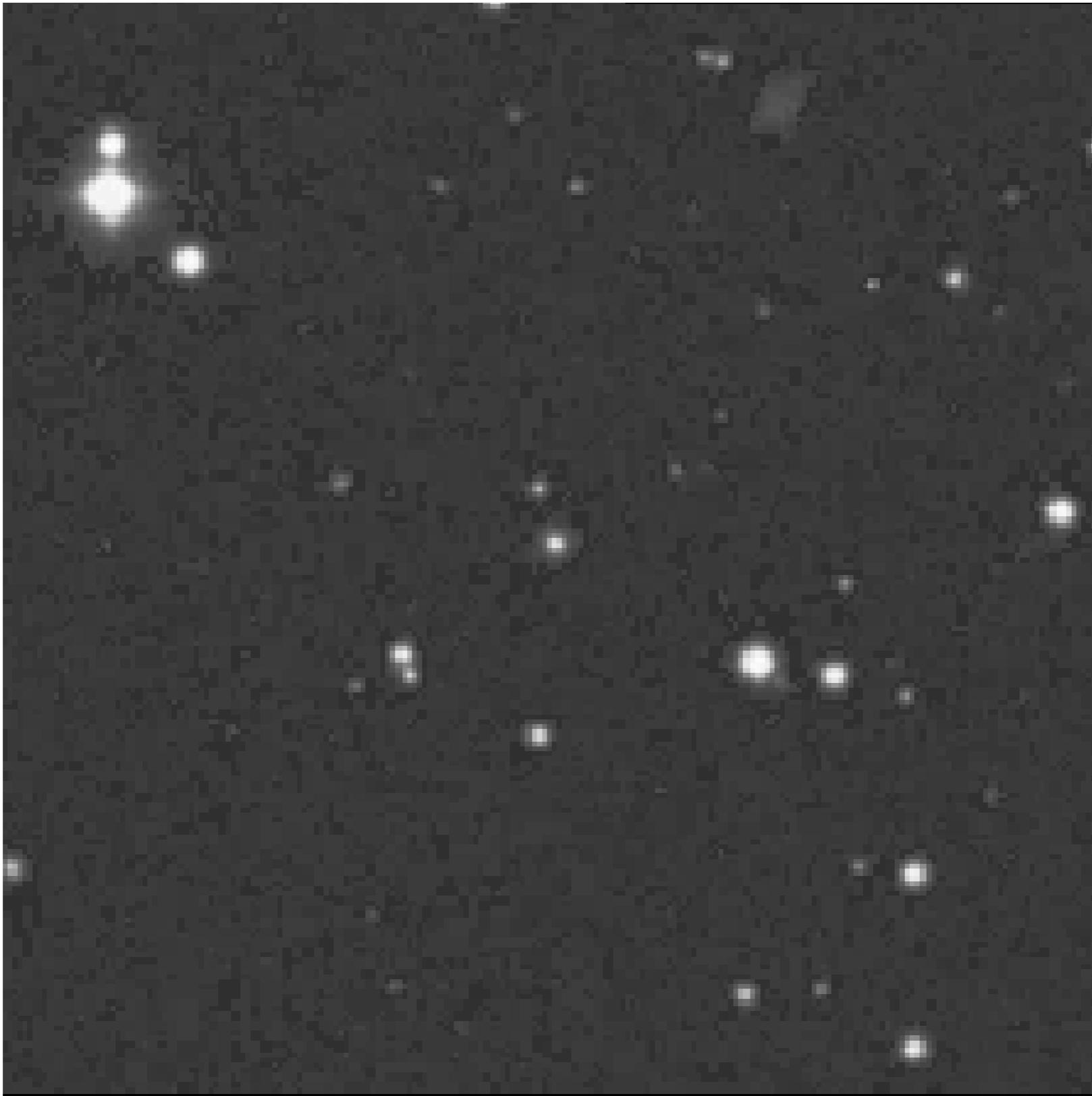
Quasar

NASA, H. Bond, E. Nelan, M. Barstow, M. Burleigh, J. Holberg

NASA/ESA and J. Bachall (IAS).

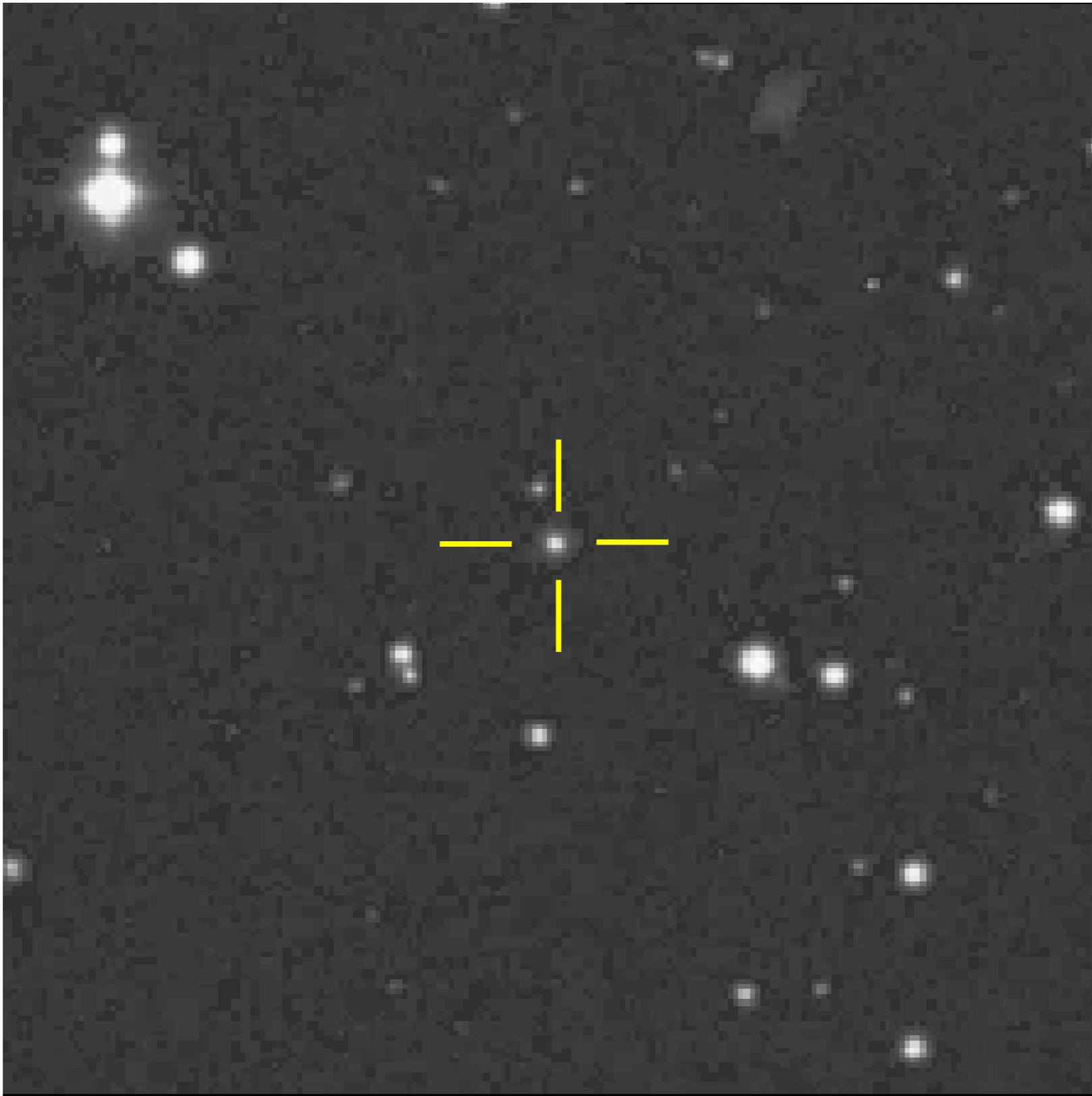
## {2} Quasars: *They are spatially unresolved*

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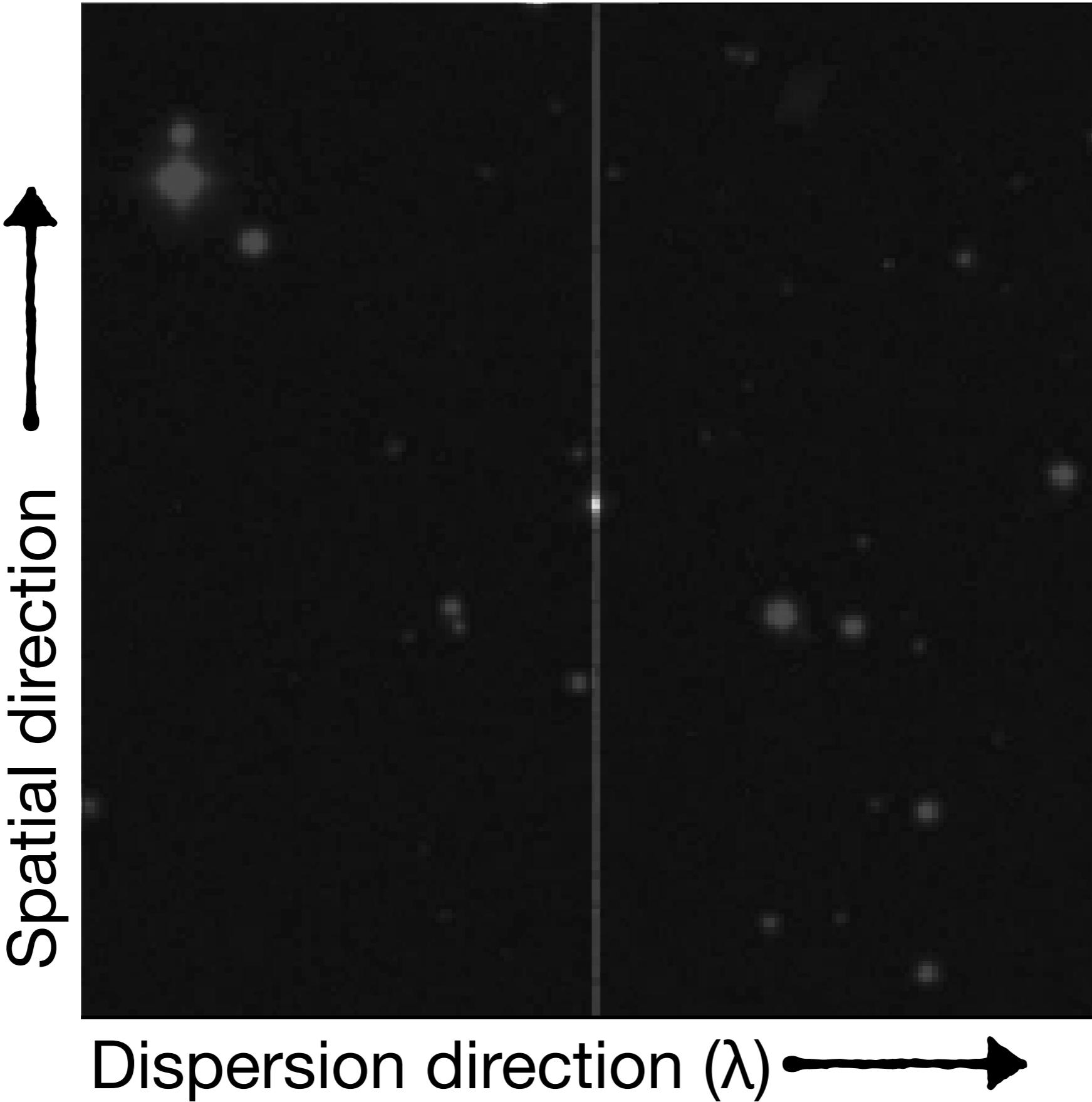
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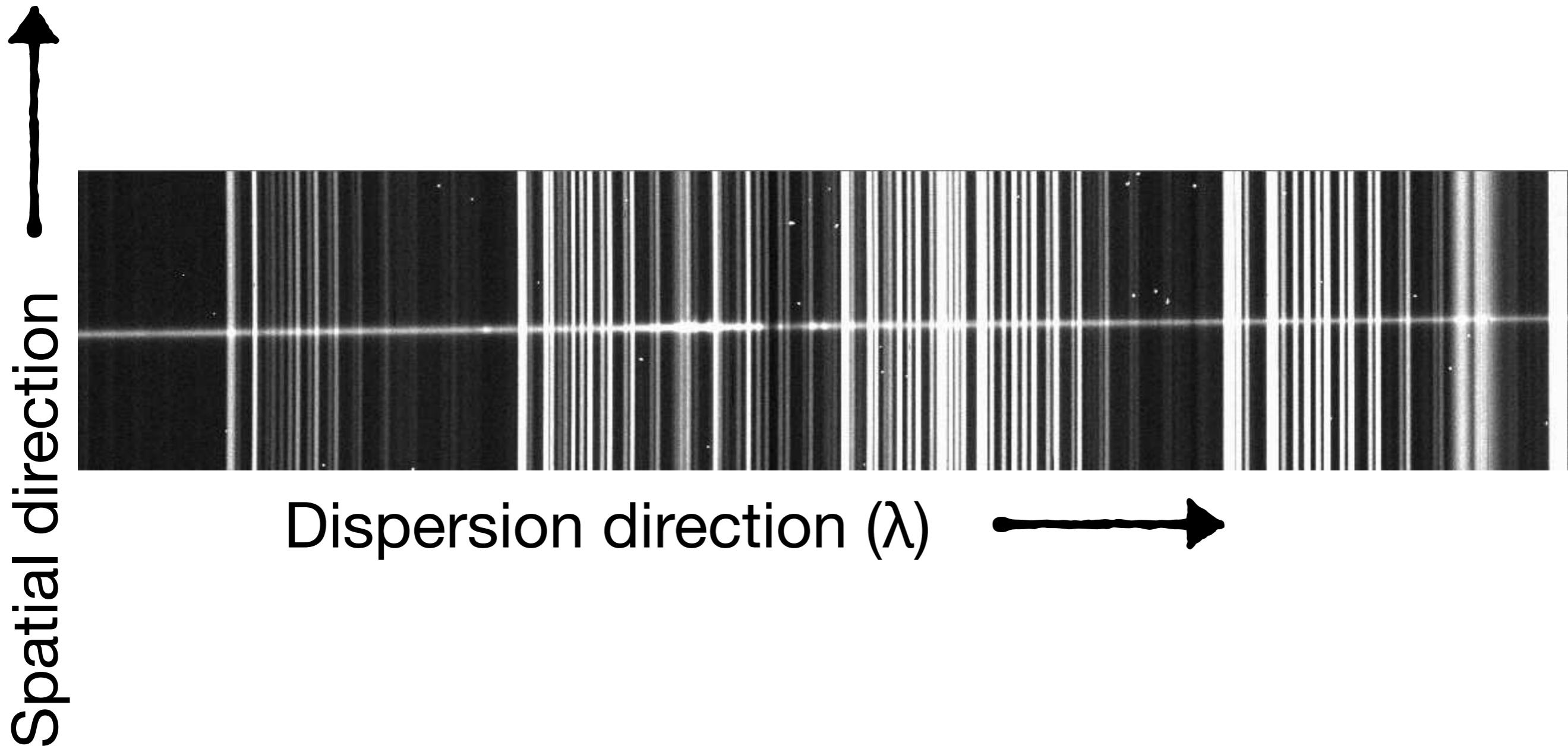
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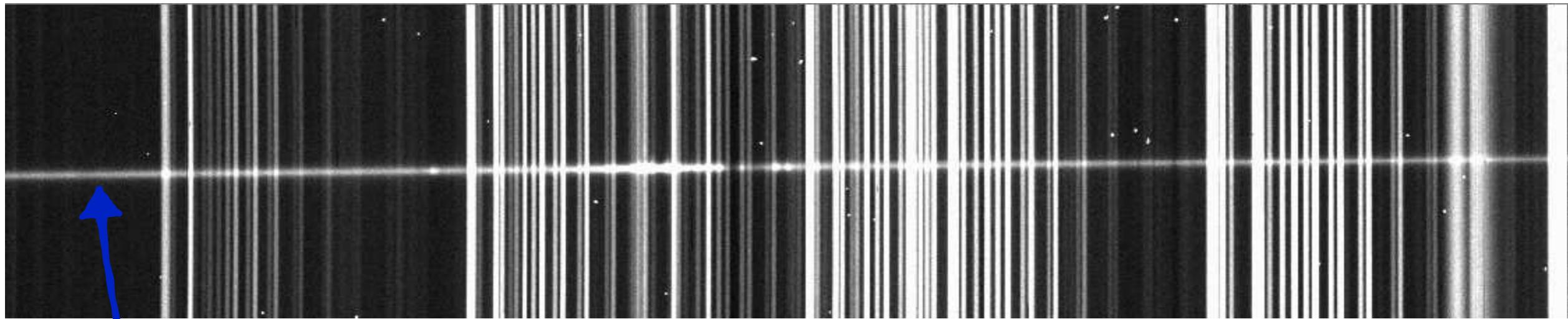
## {2} Quasars: *The raw spectrum*

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## {2} Quasars: *The raw spectrum*

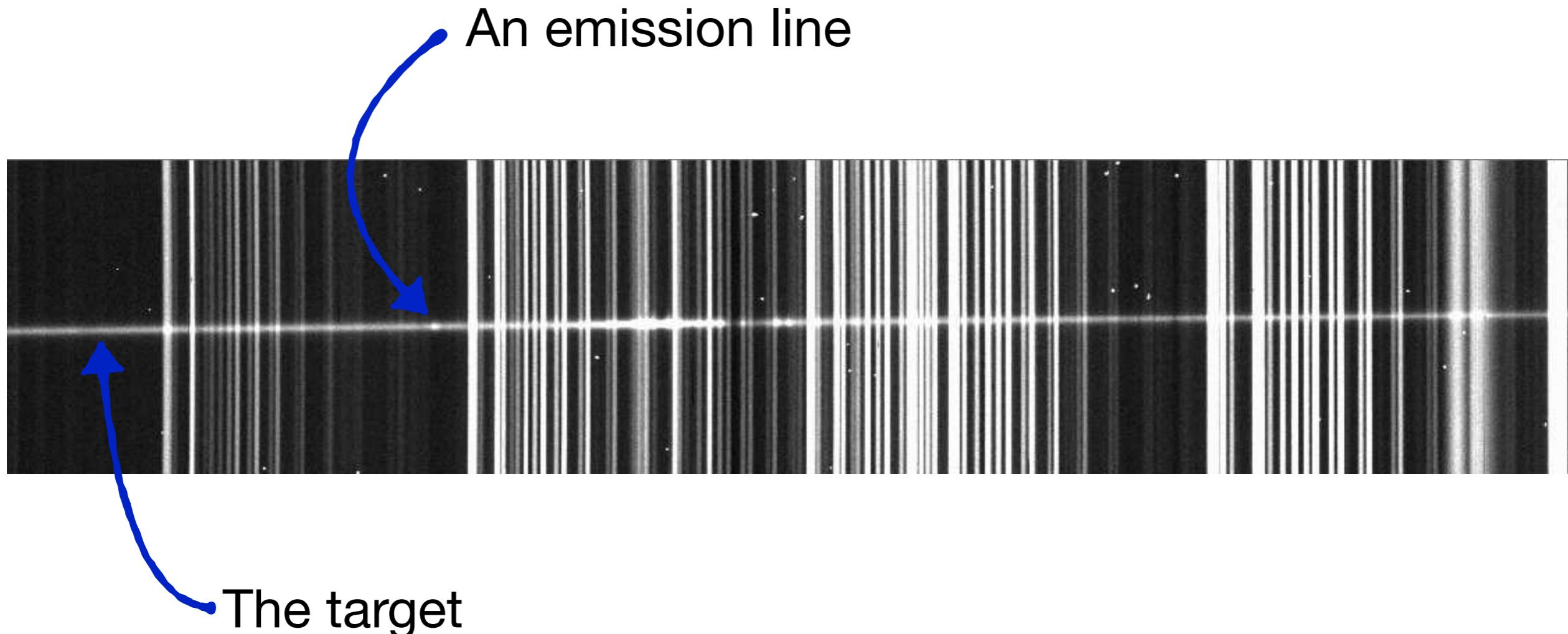
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The target

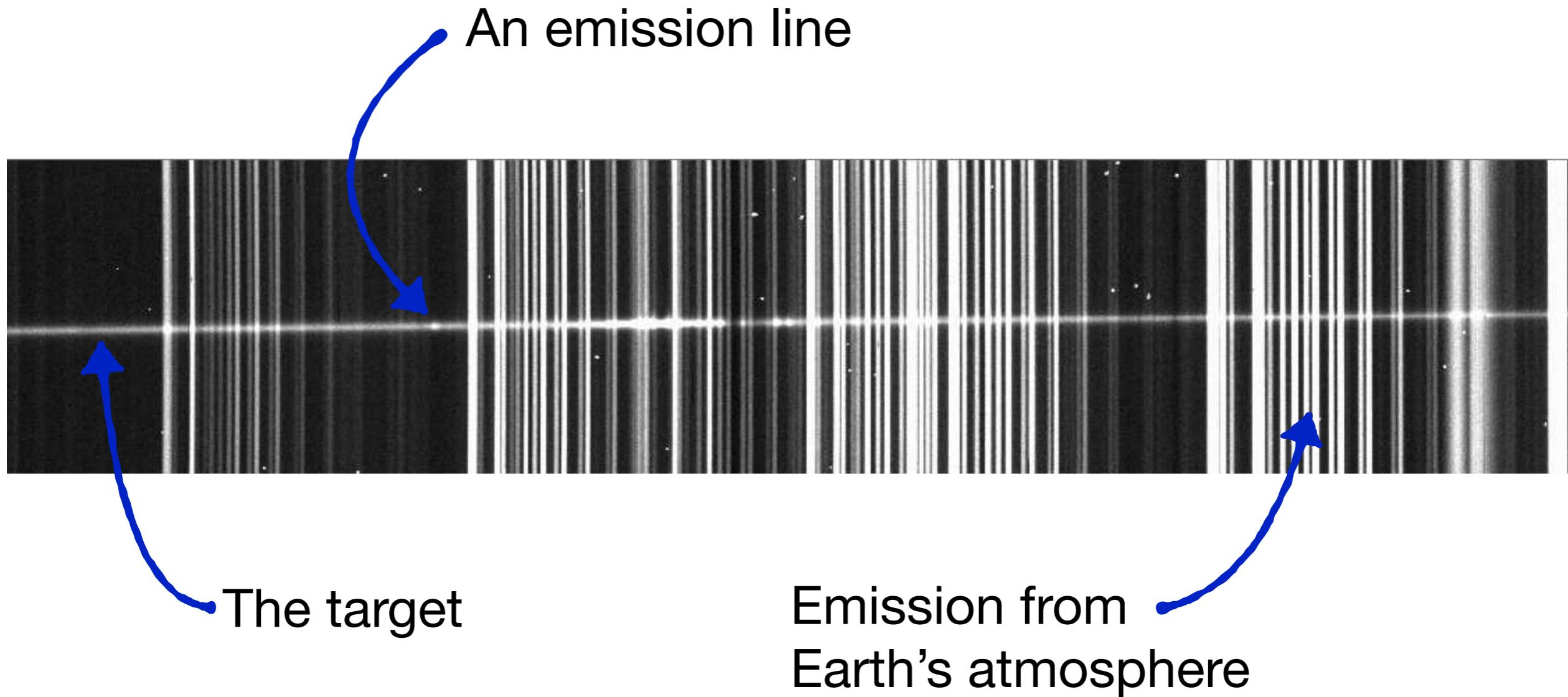
## {2} Quasars: *The raw spectrum*

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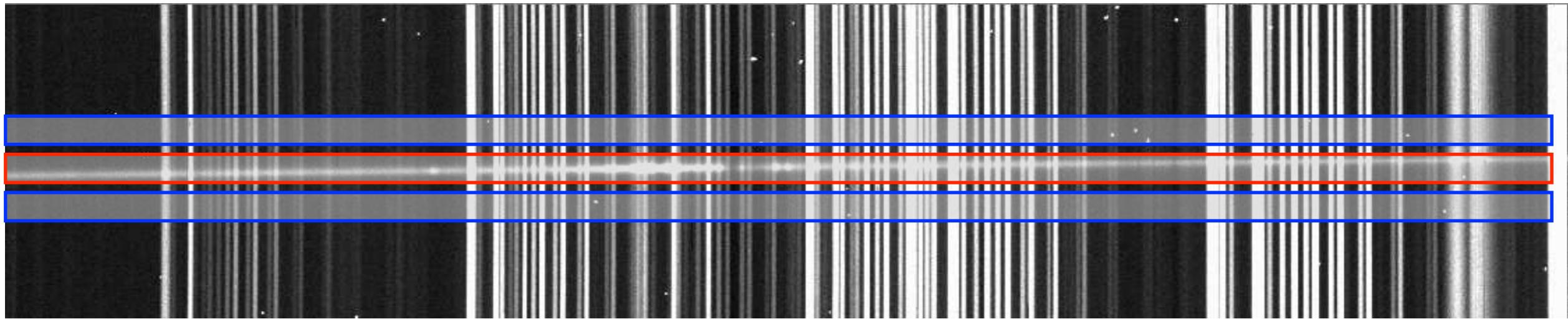
## {2} Quasars: *The raw spectrum*

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## {2} Quasars: *The raw spectrum*

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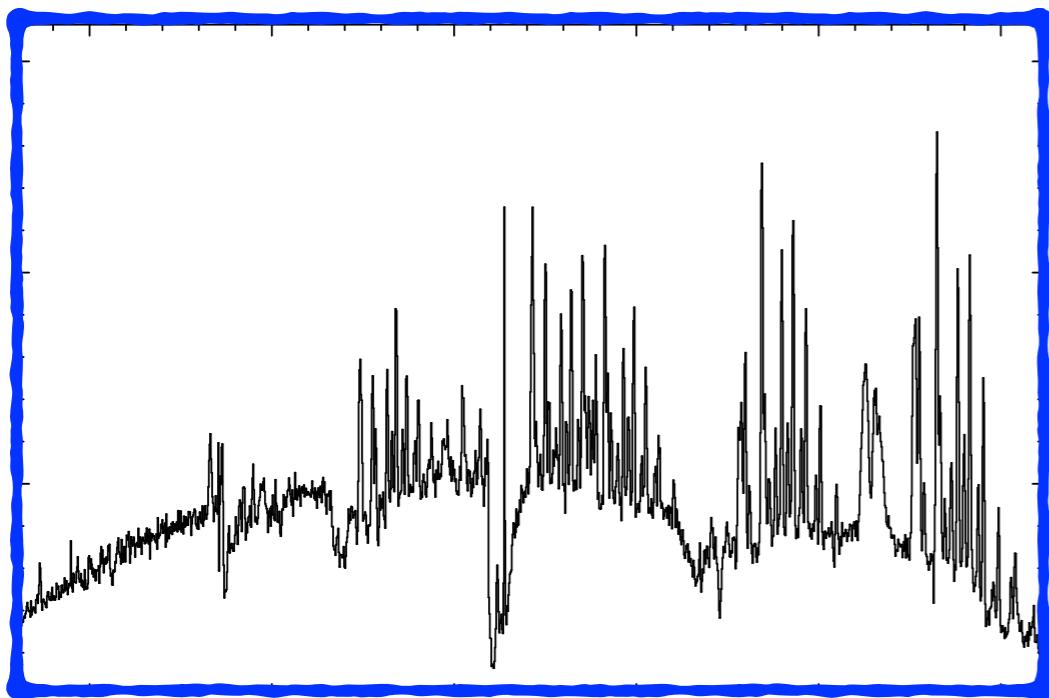
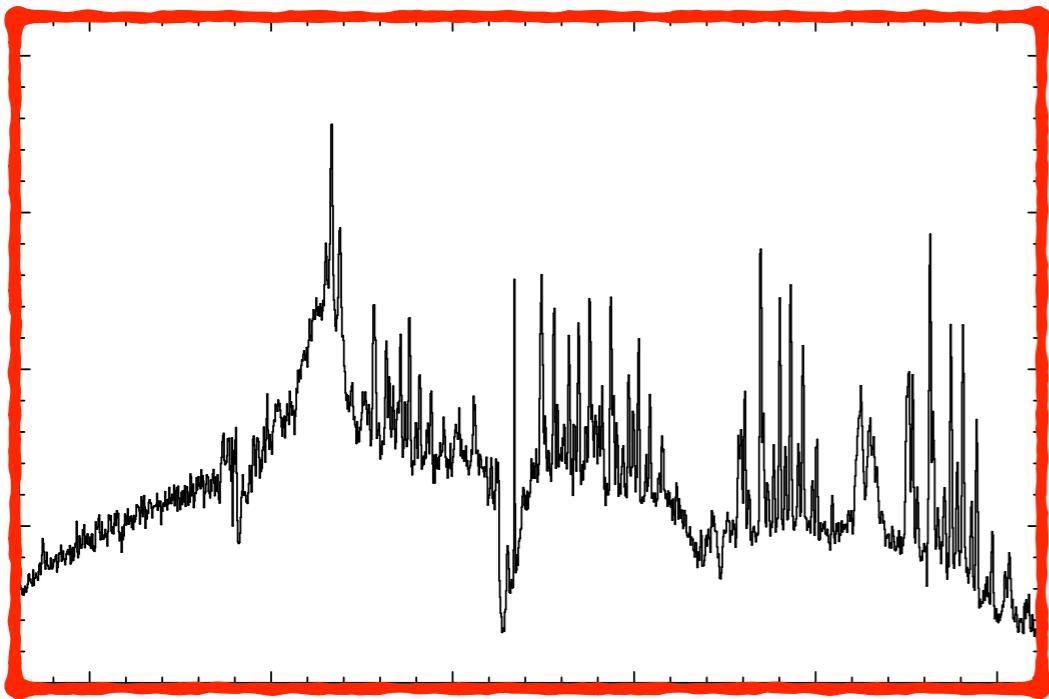


The target + sky

The sky

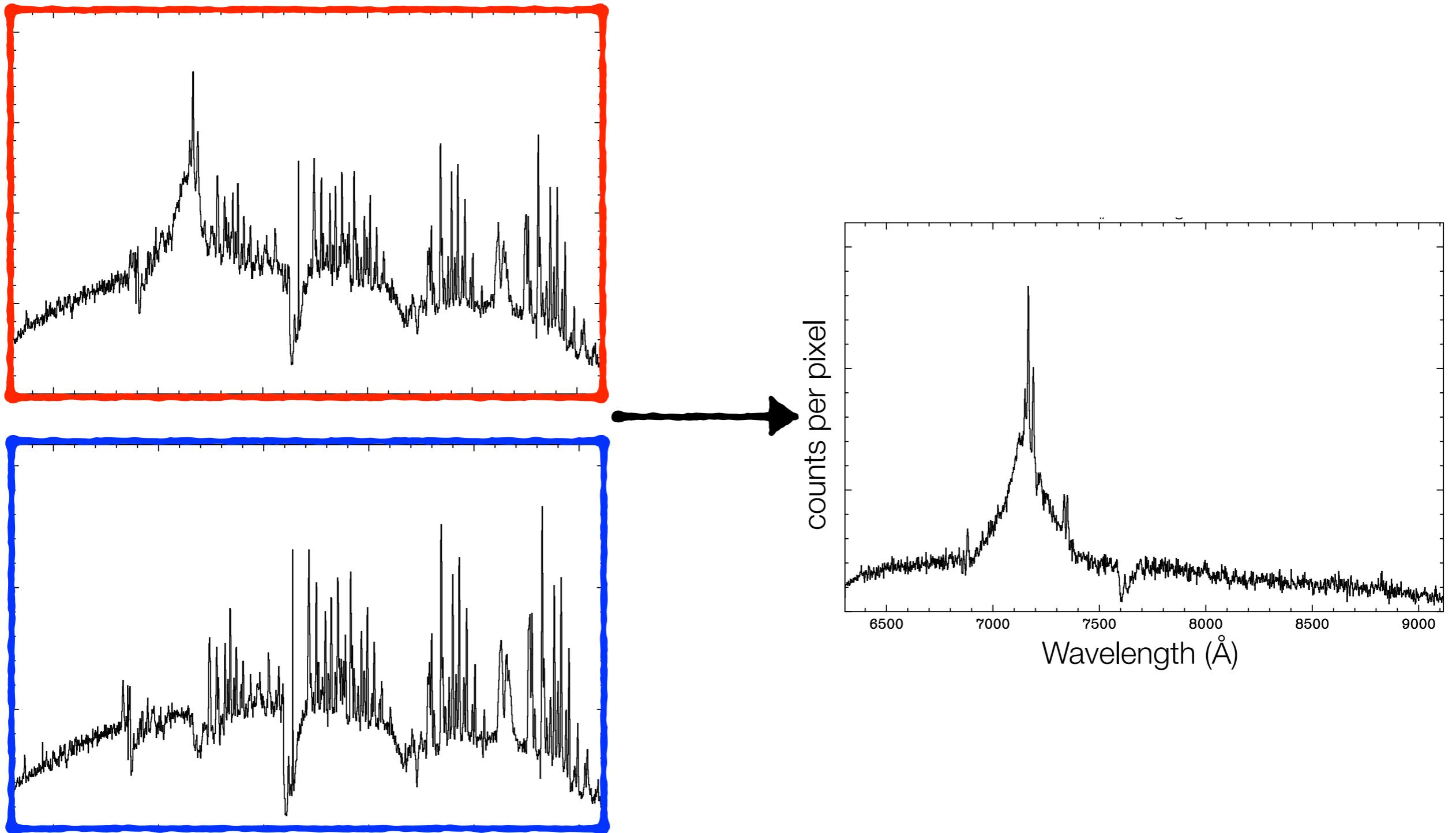
## {2} Quasars: *The spectrum of the target*

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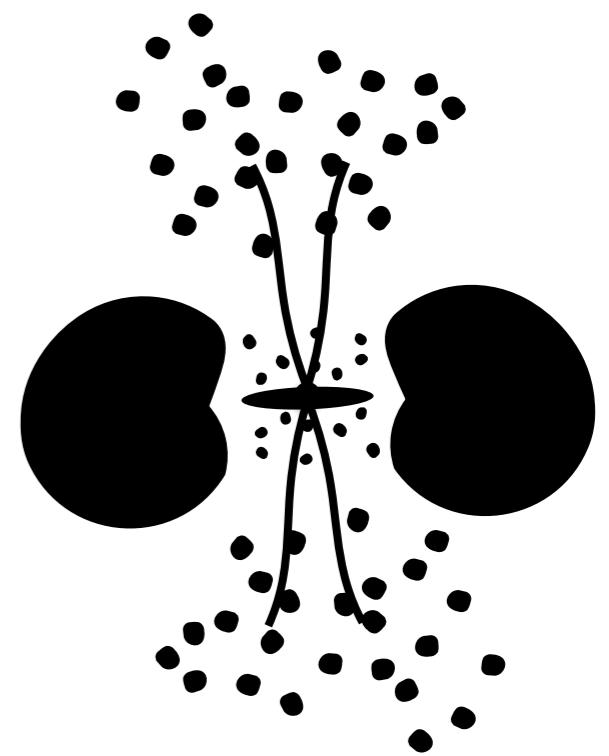
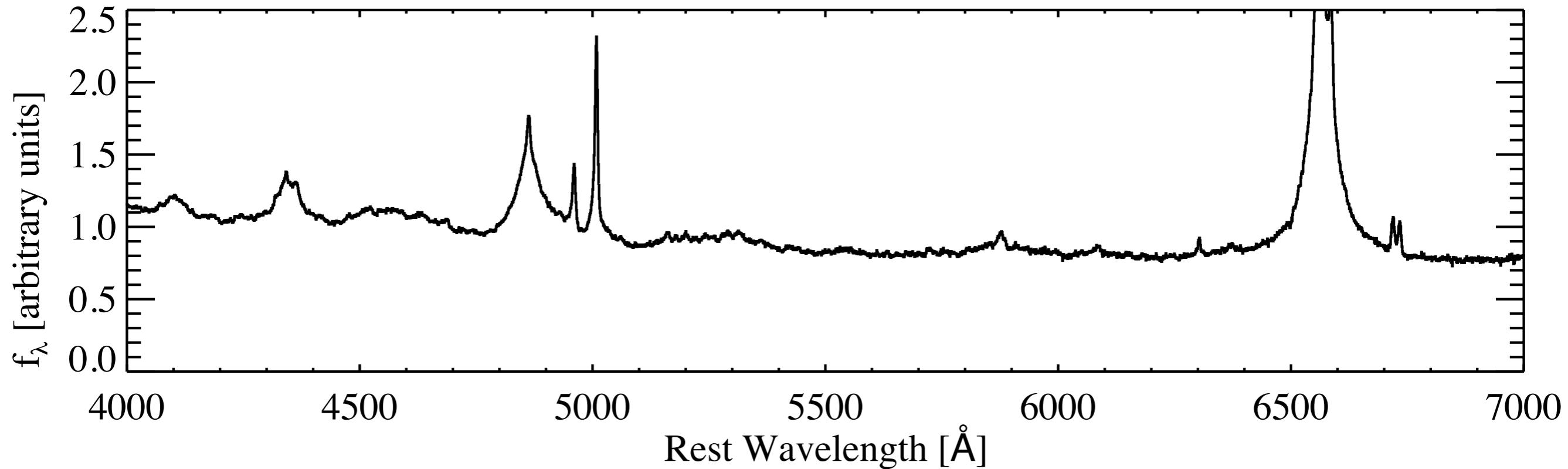
## {2} Quasars: *The spectrum of the target*

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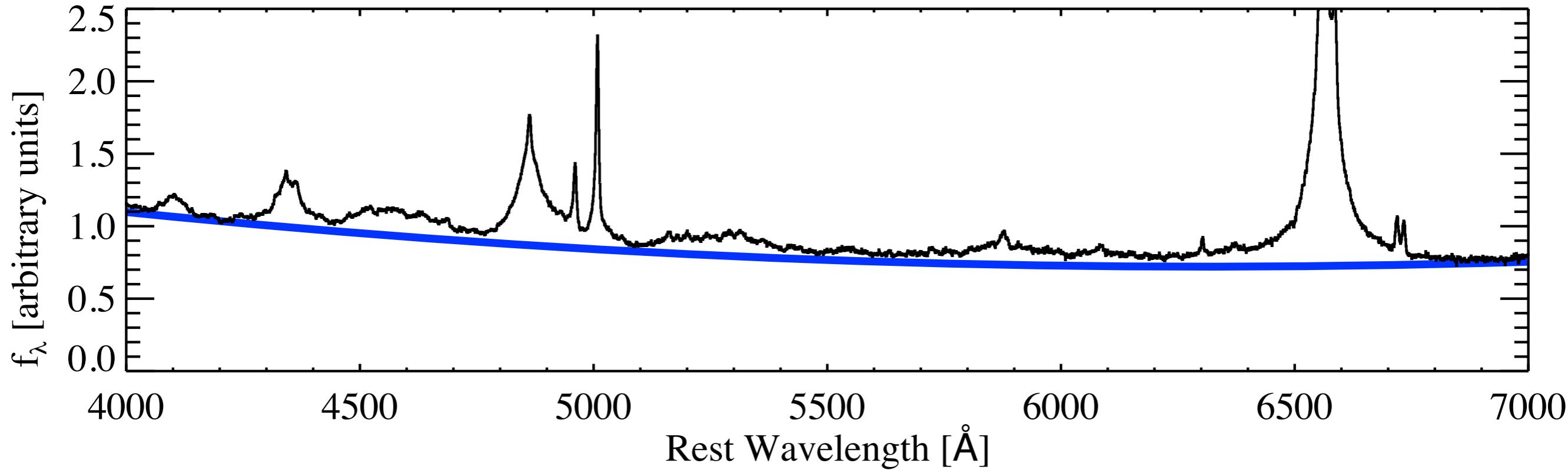
## {2} Quasars: Anatomy of a spectrum

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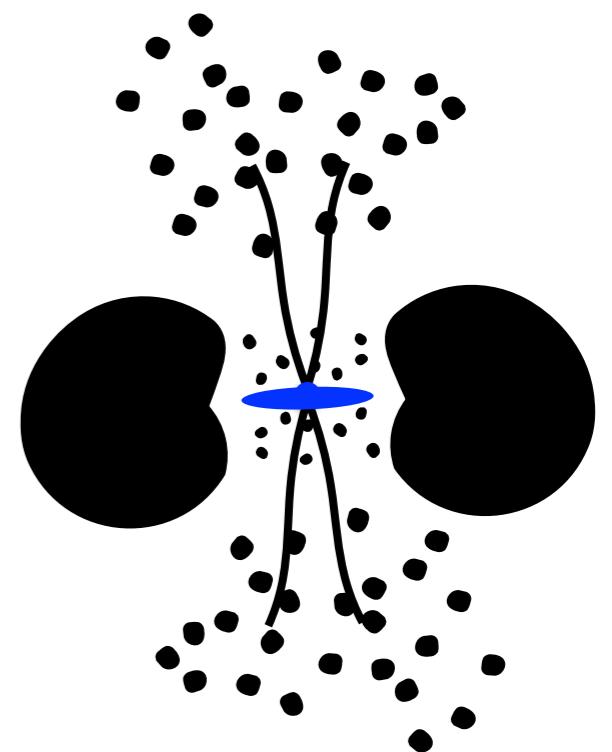


## {2} Quasars: Anatomy of a spectrum

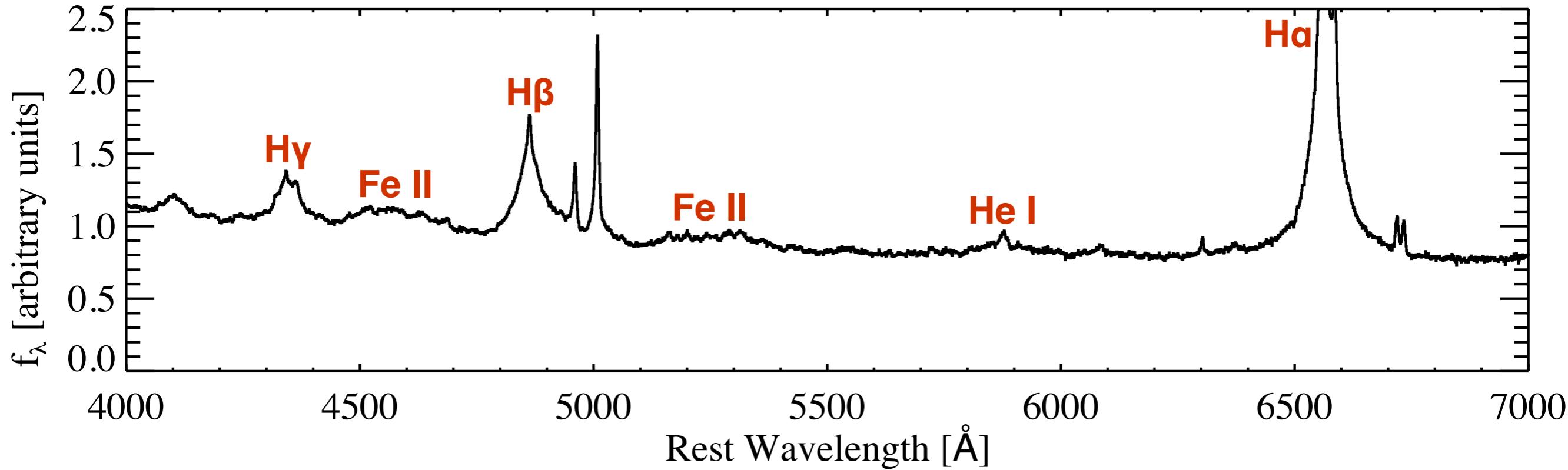
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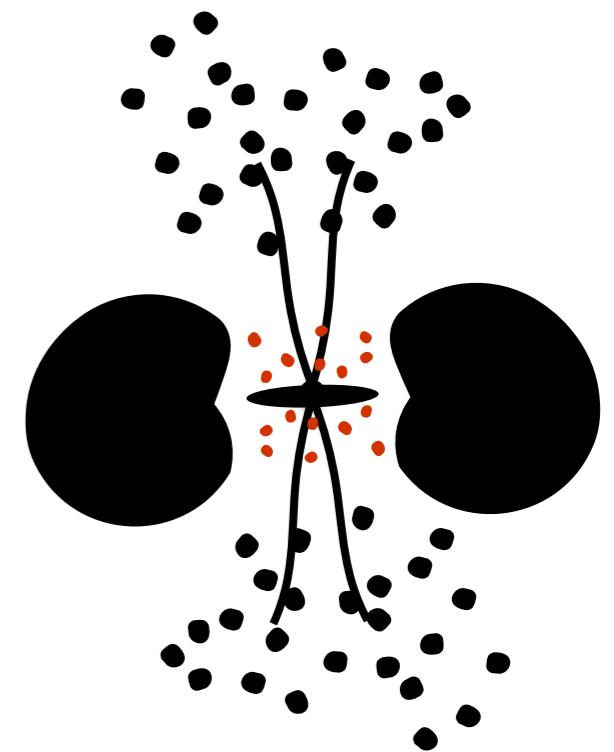
The **continuum** emission comes from the **accretion disk** around the SMBH.



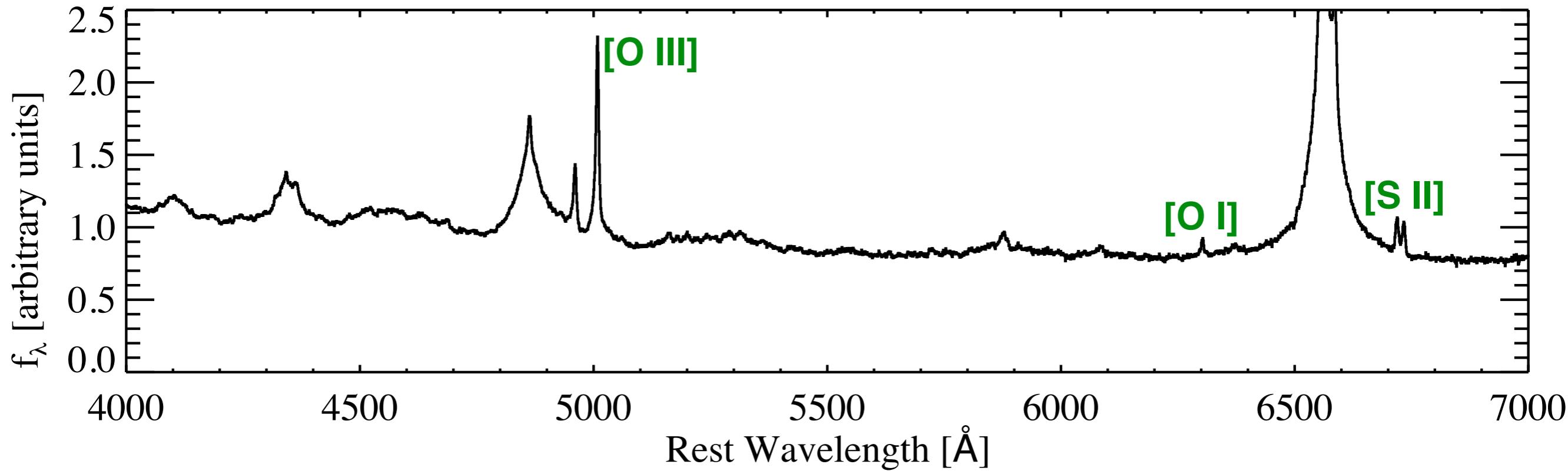
## {2} Quasars: Anatomy of a spectrum



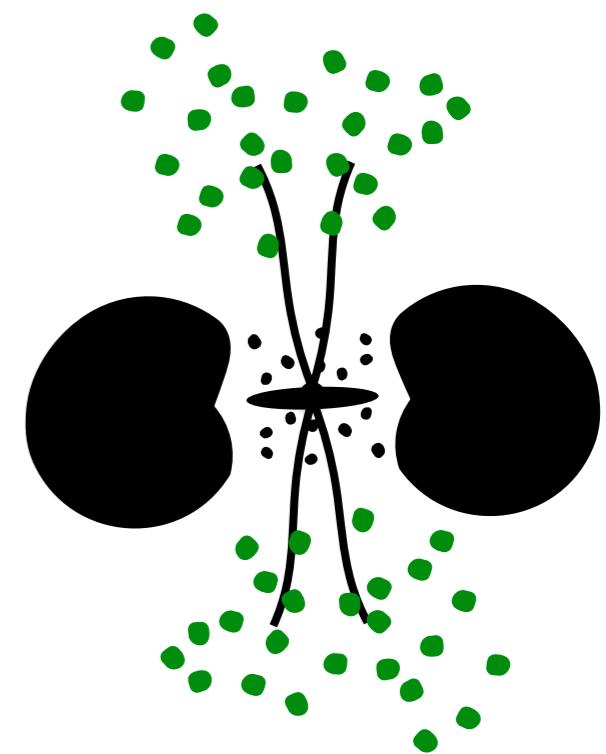
The **broad emission lines** come from the **broad-line region** which includes high-velocity gas near the SMBH.



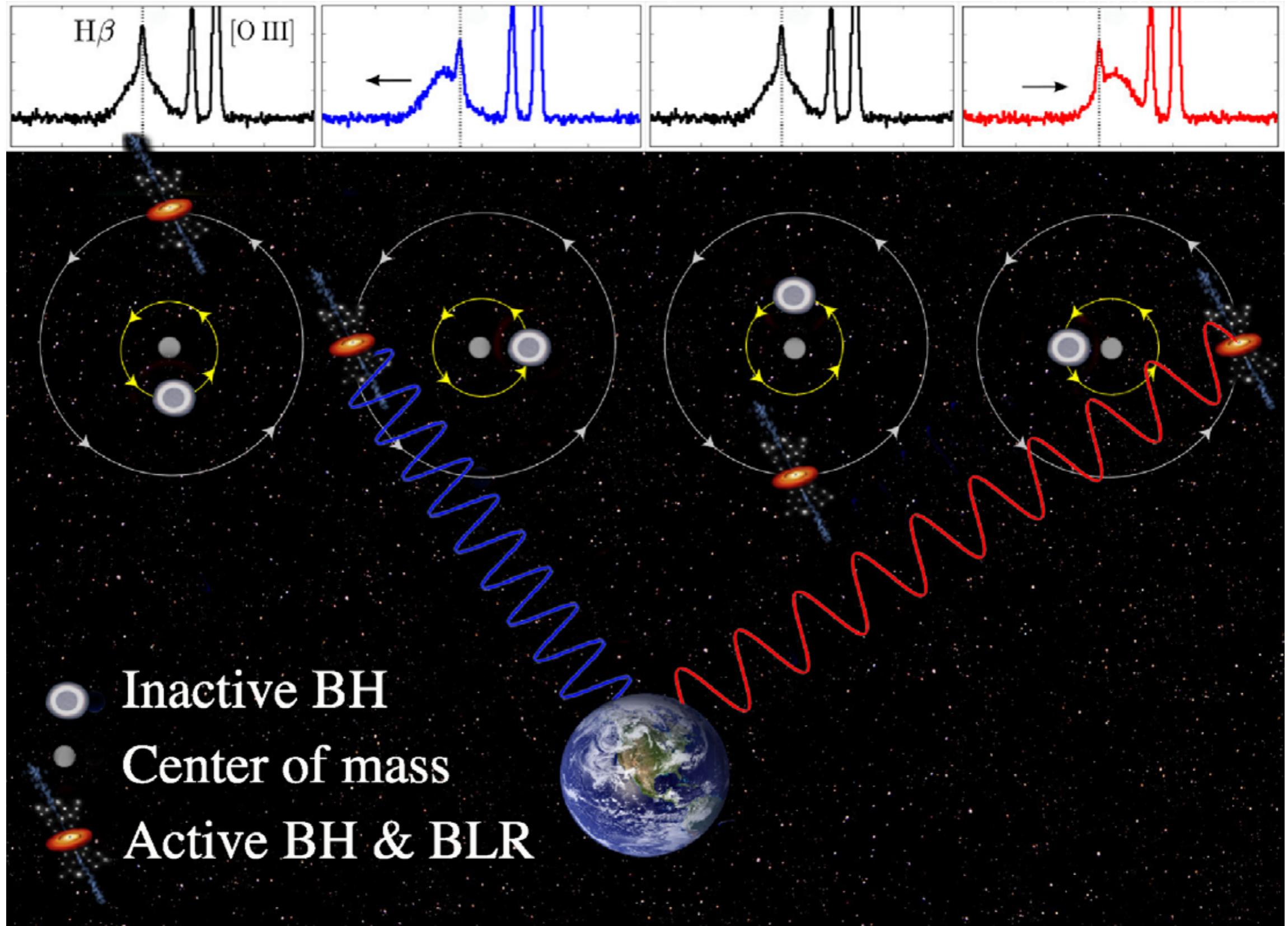
## {2} Quasars: Anatomy of a quasar spectrum



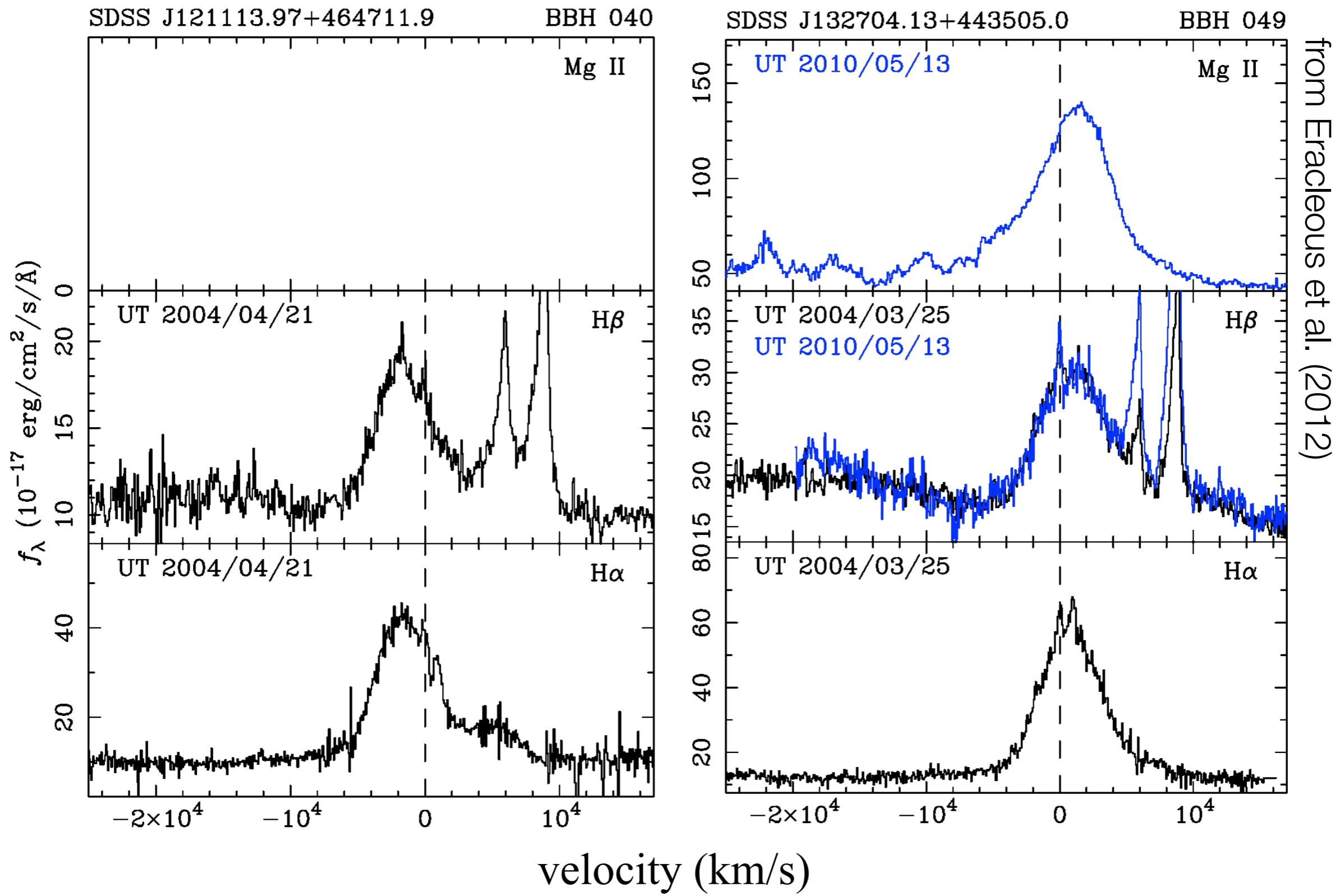
The **narrow emission lines** come from the **narrow-line region** which is farther from the SMBH and lower velocity gas.



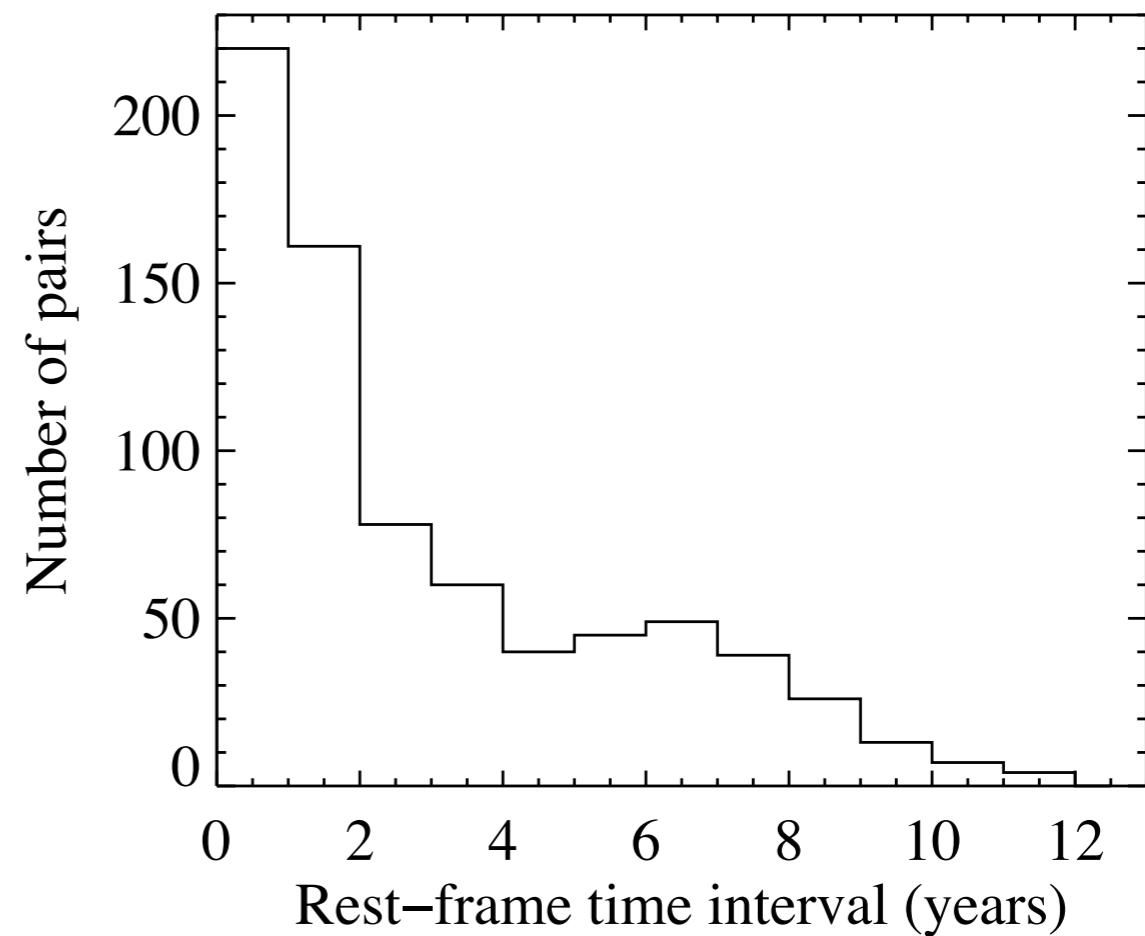
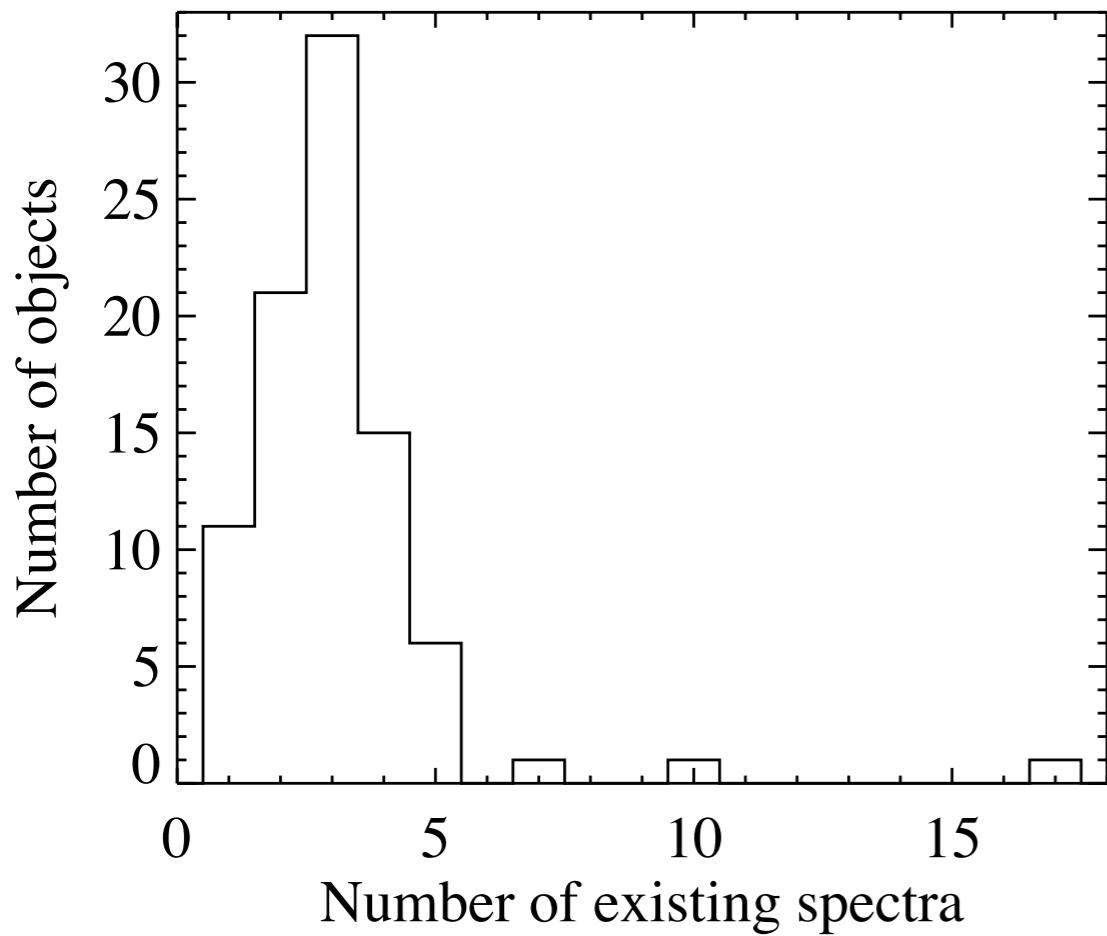
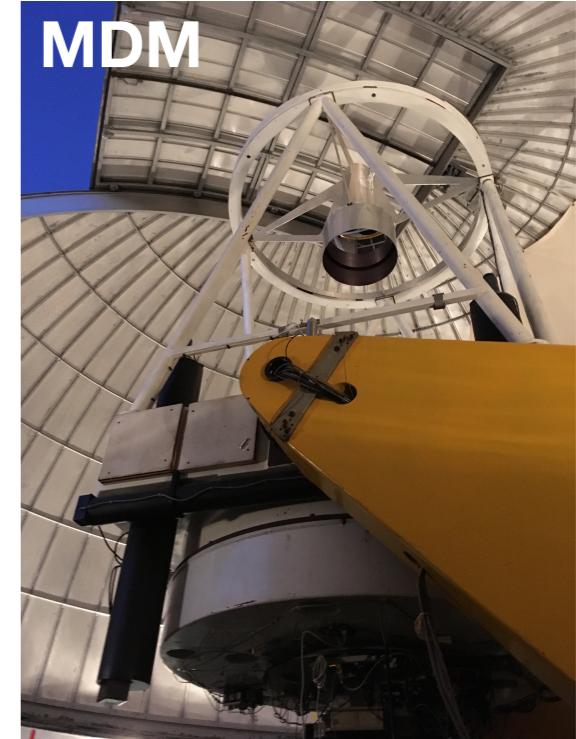
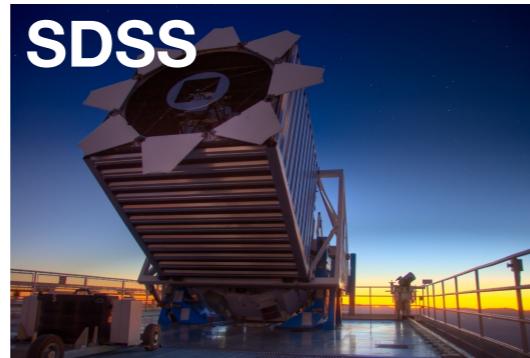
# {3} RV method: How it works



# {3} RV method: *Binary candidates*

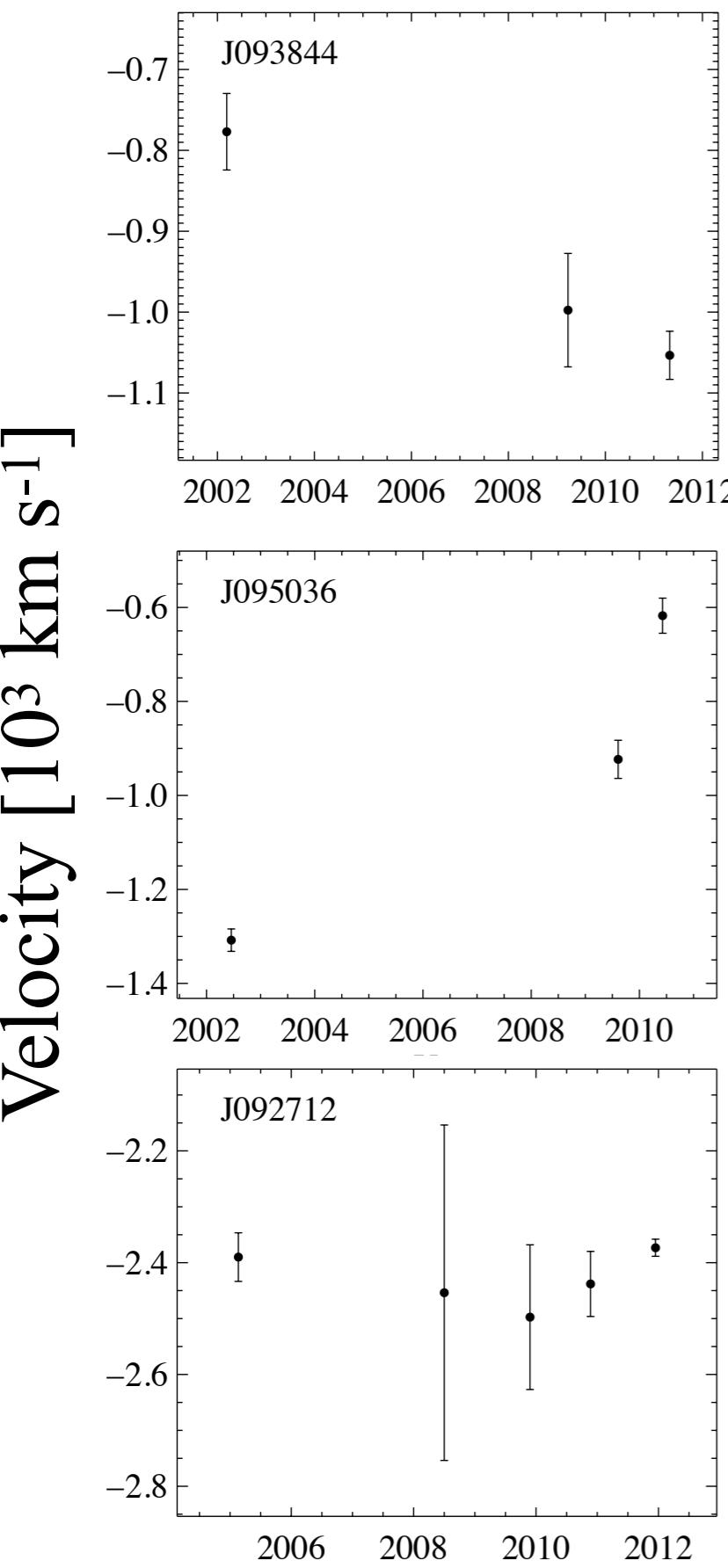


# {3} RV method: Spectroscopic monitoring

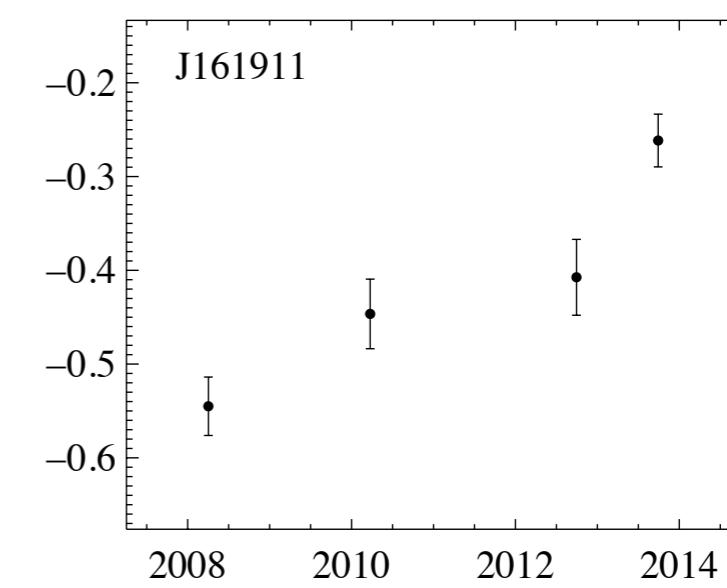
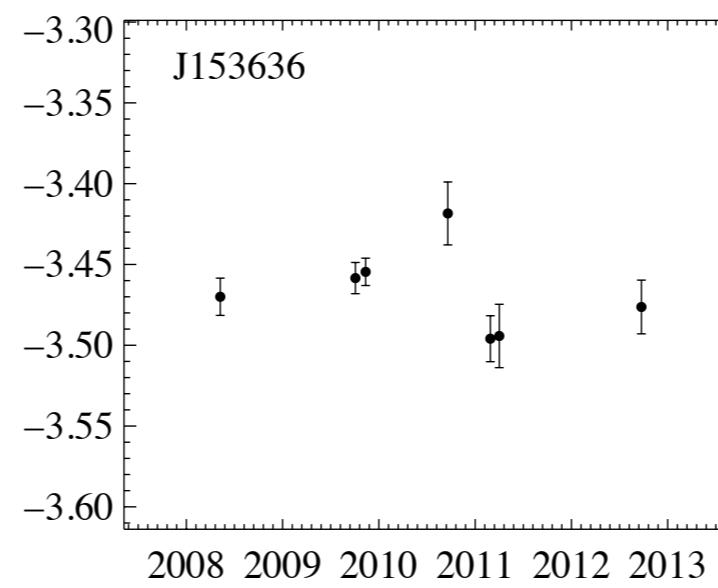
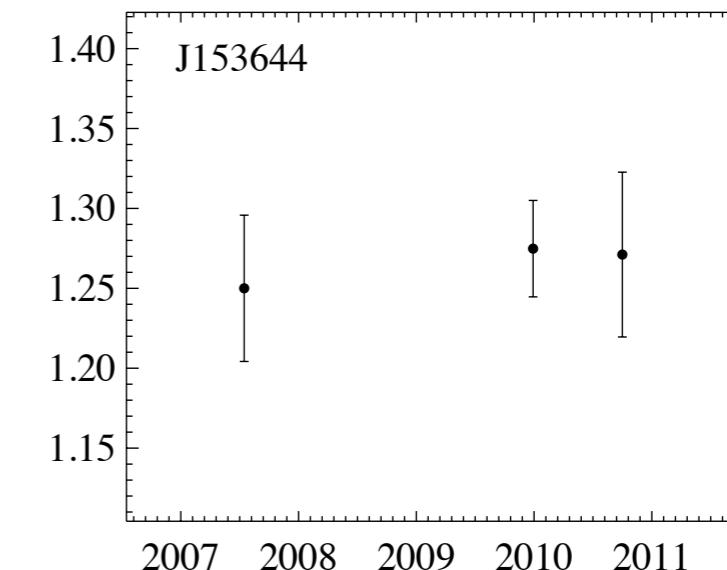
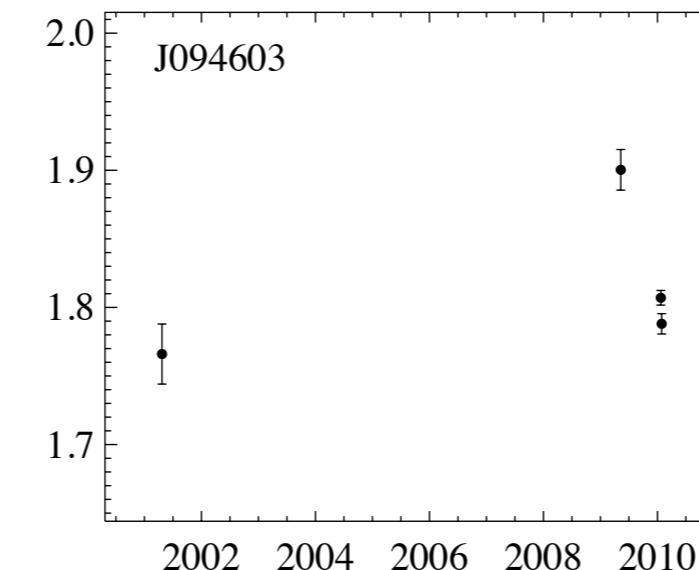


### {3} RV method: *RV curves*

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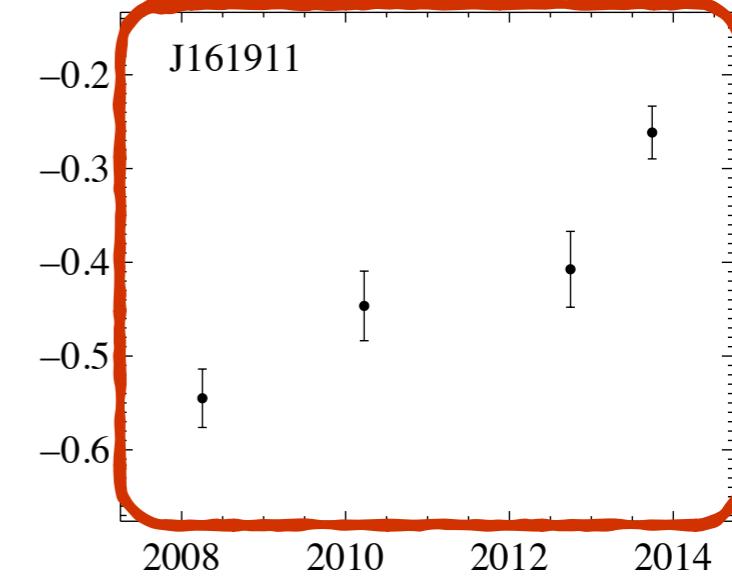
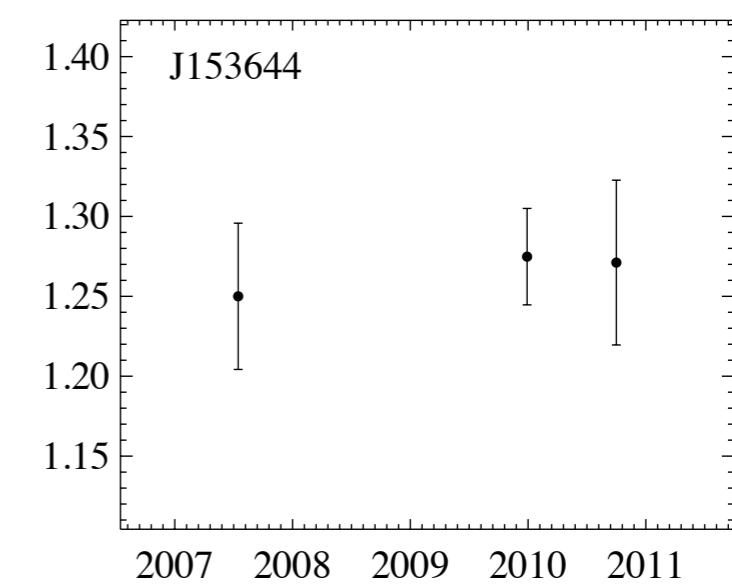
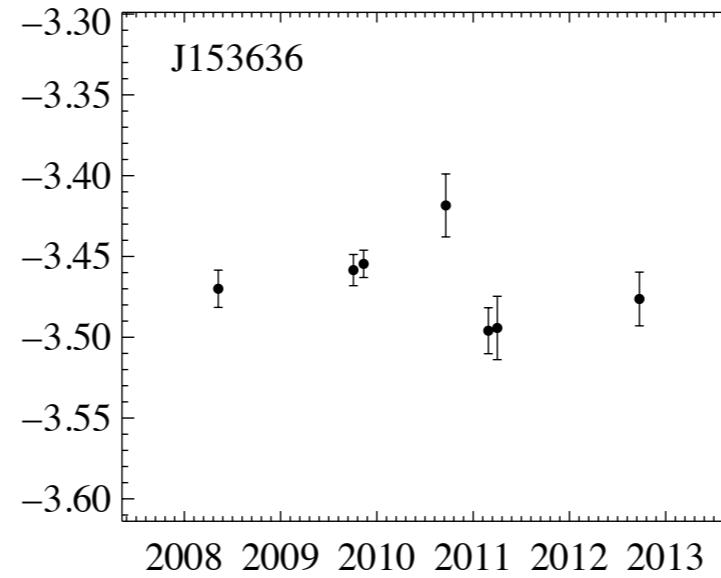
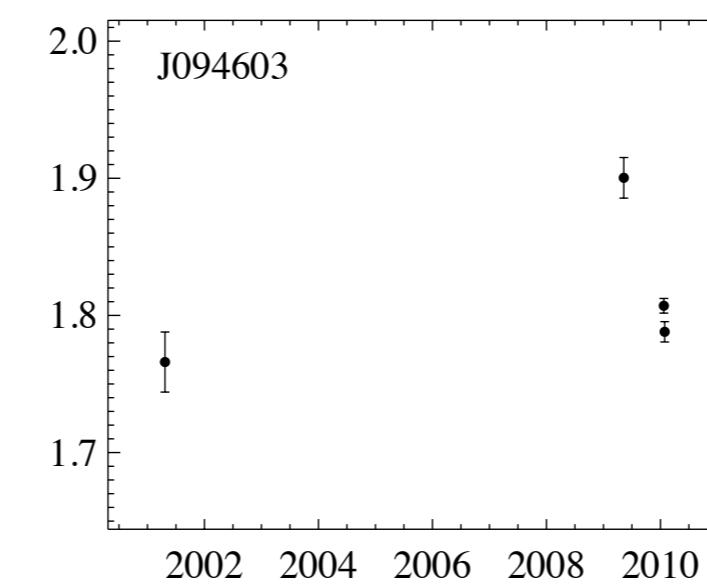
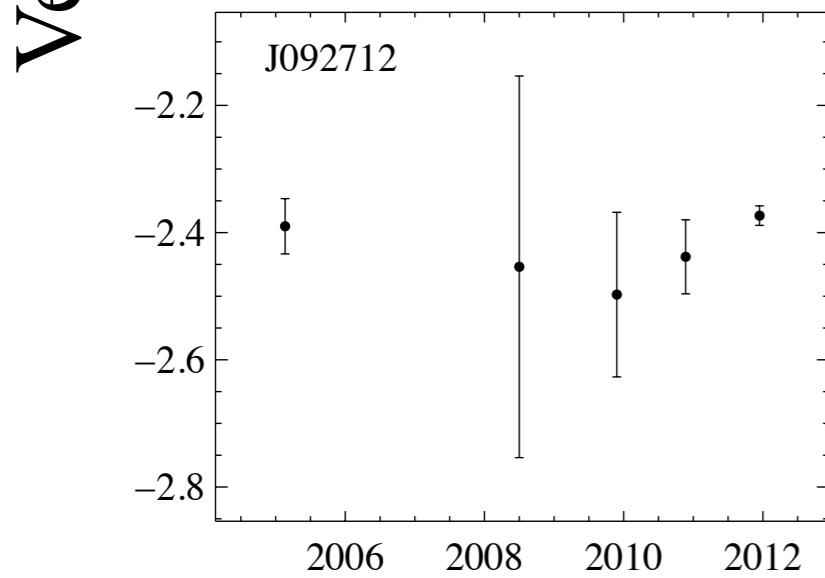
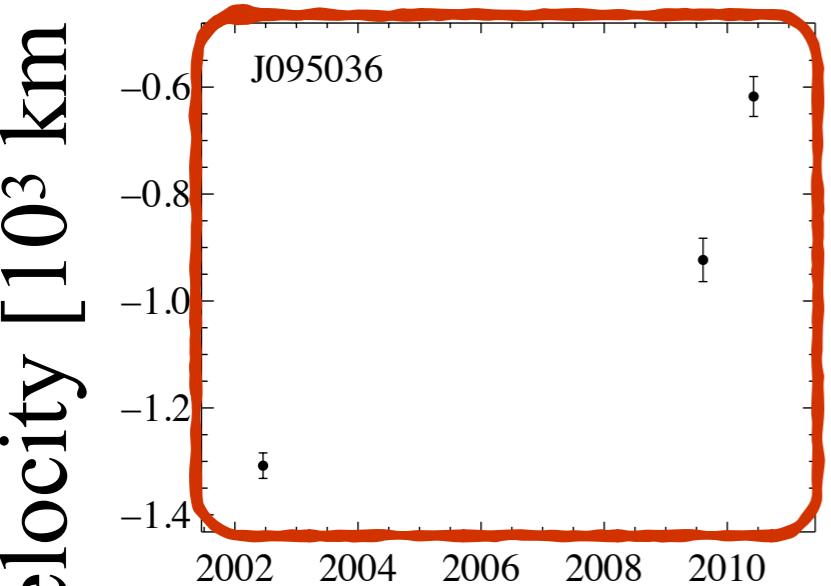
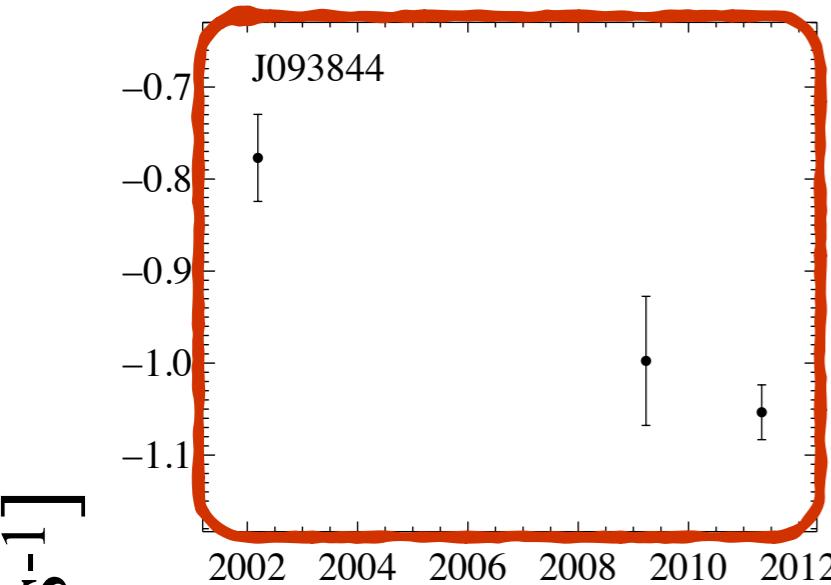
Runnoe et al. (2017)



Year

### {3} RV method: *RV curves*

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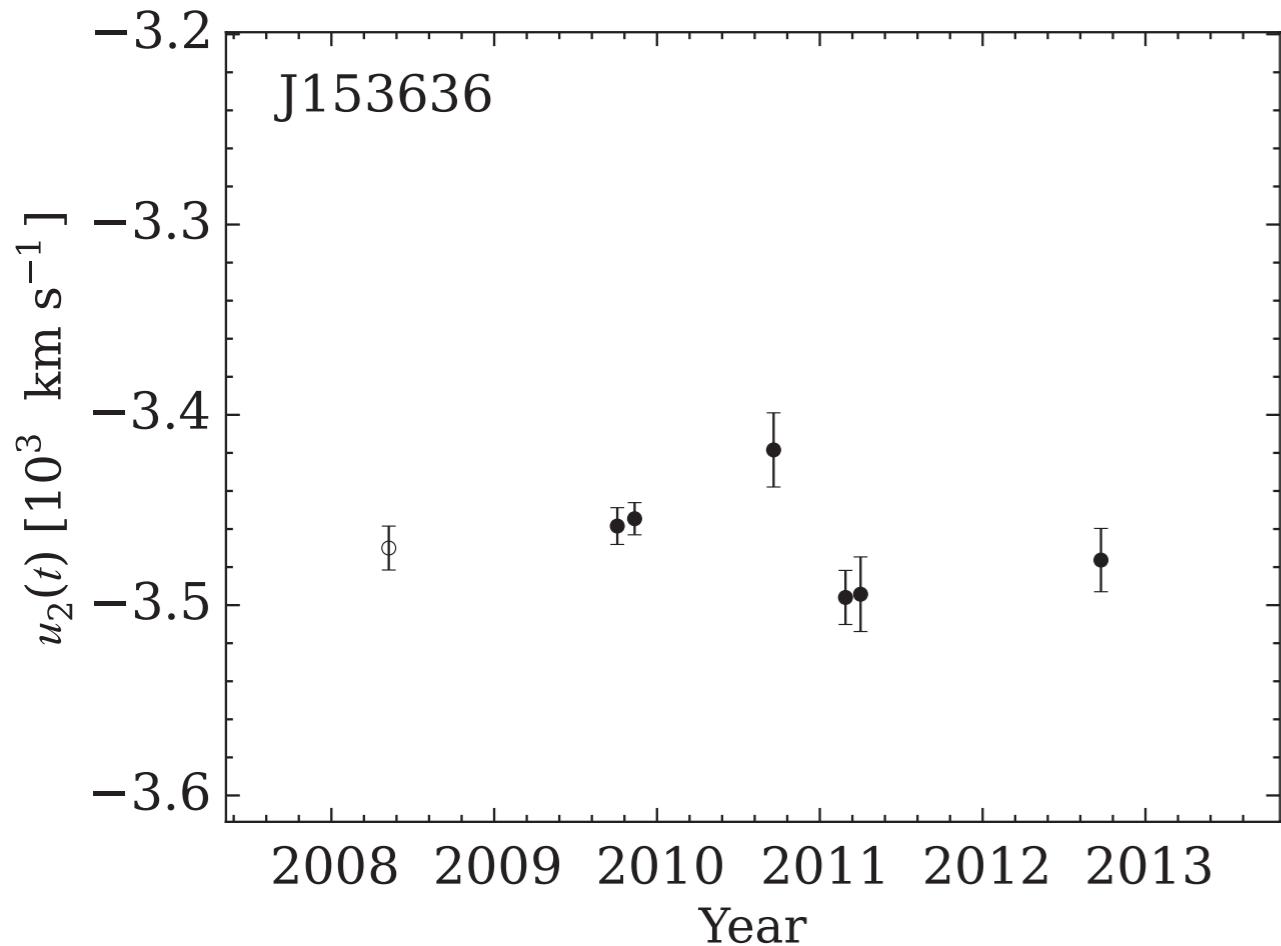
Year

Runnoe et al. (2017)

# {3} RV method: *Limits on the SBHB properties*

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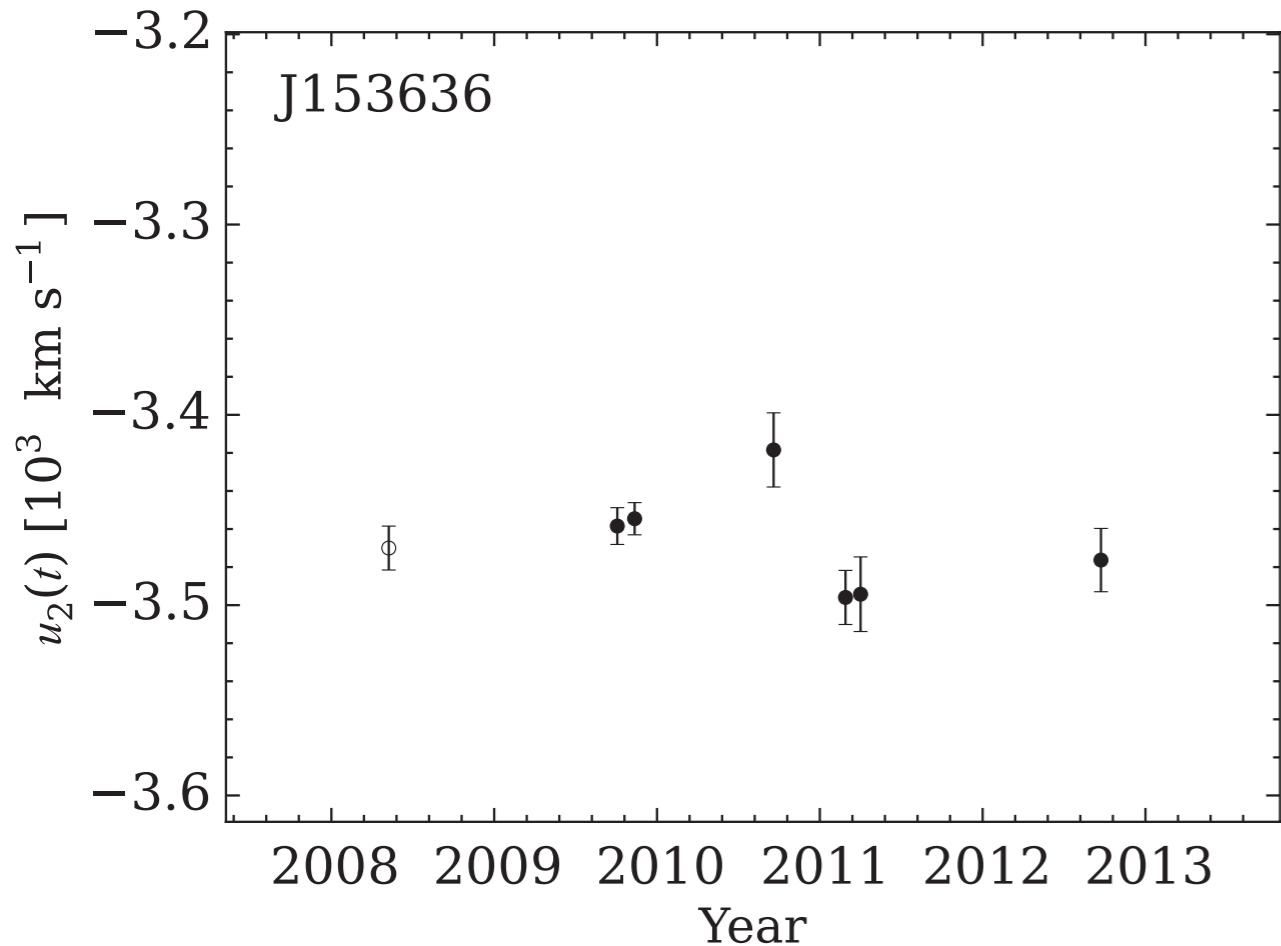
Runnoe et al. (2017)



# {3} RV method: *Limits on the SBHB properties*

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Runnoe et al. (2017)

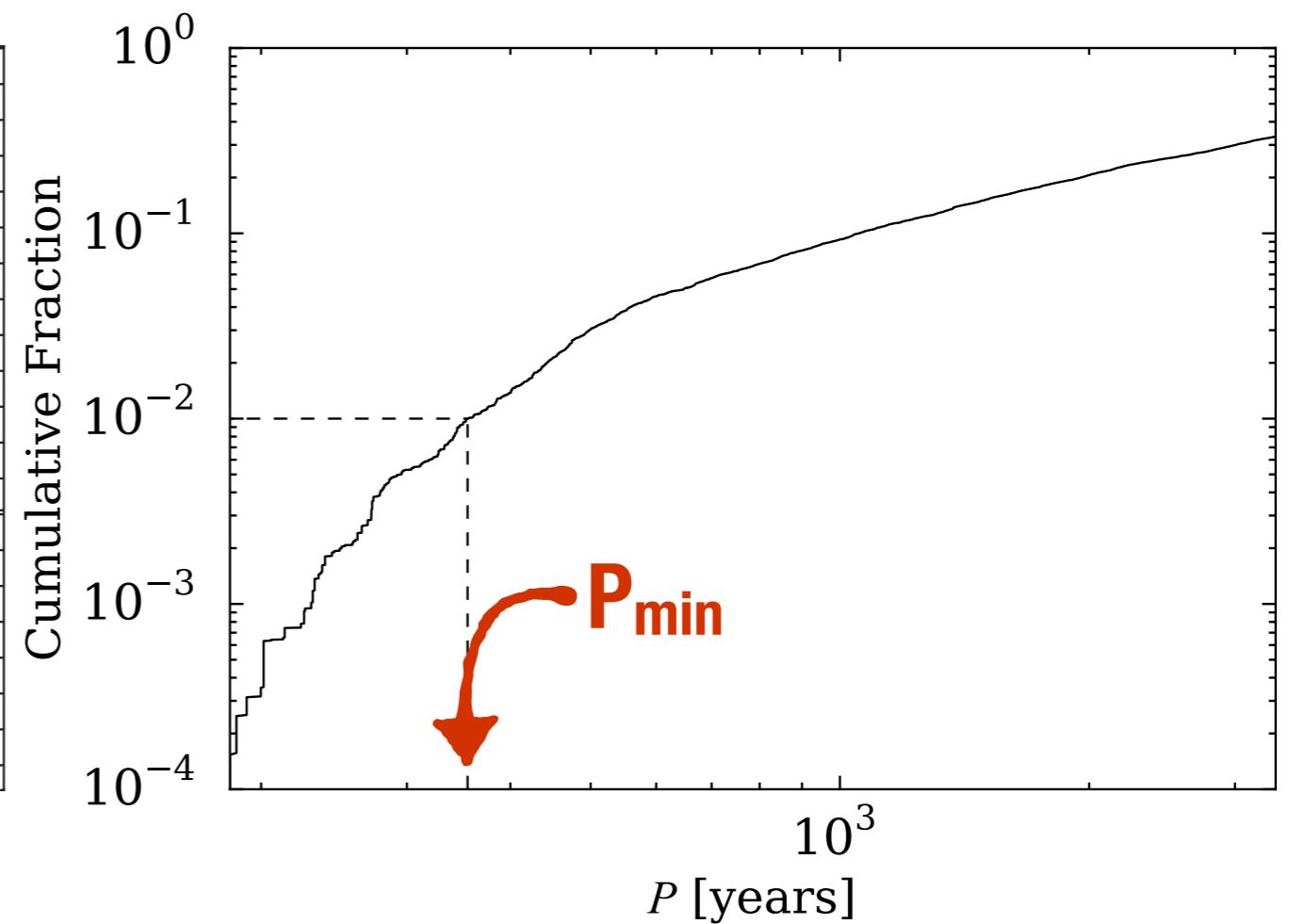
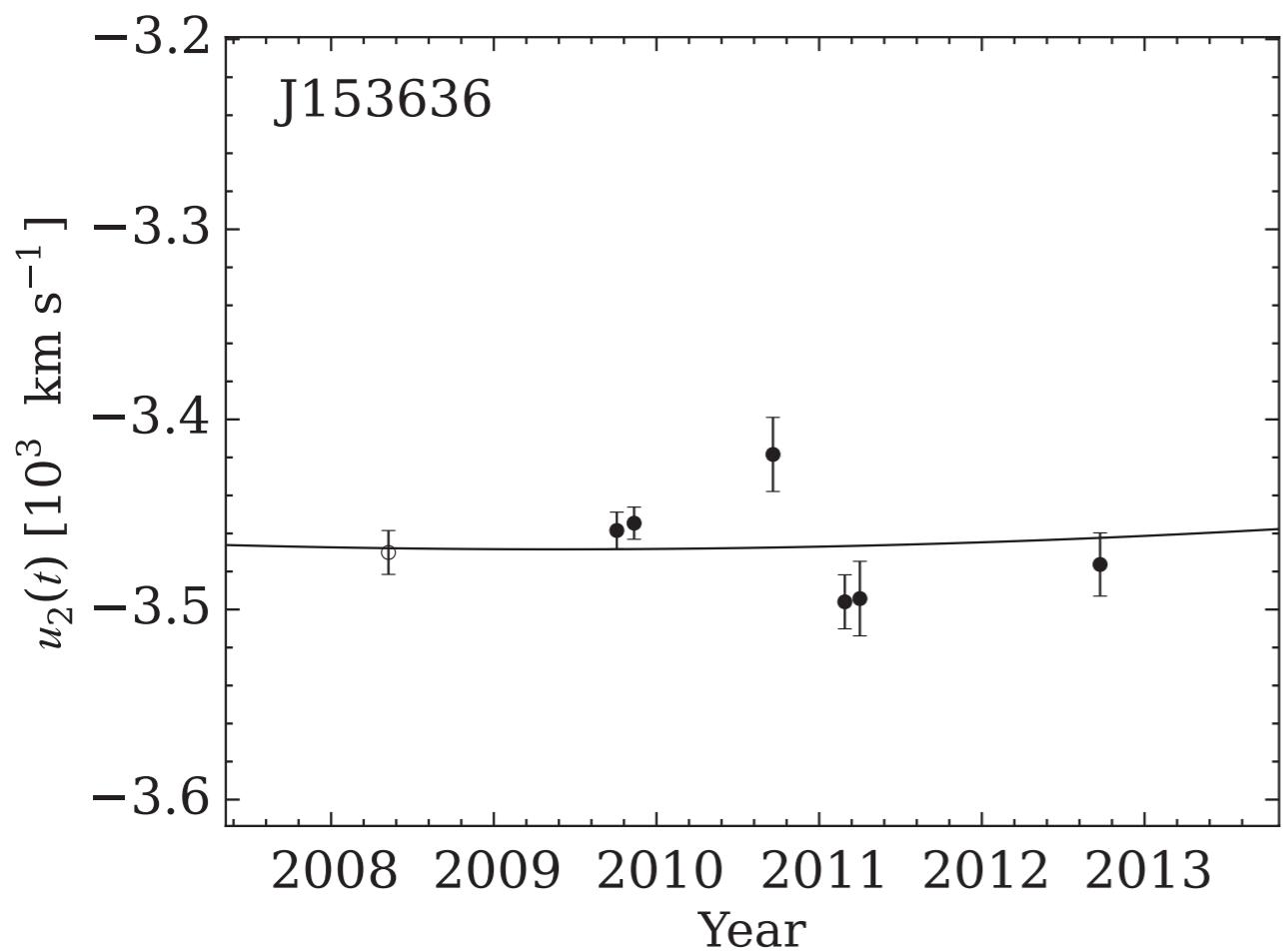


$$u_{2,3}(t) = v \sin i \sin \left[ \frac{2\pi}{P} (t - t_0) \right]$$

# {3} RV method: *Limits on the SBHB properties*

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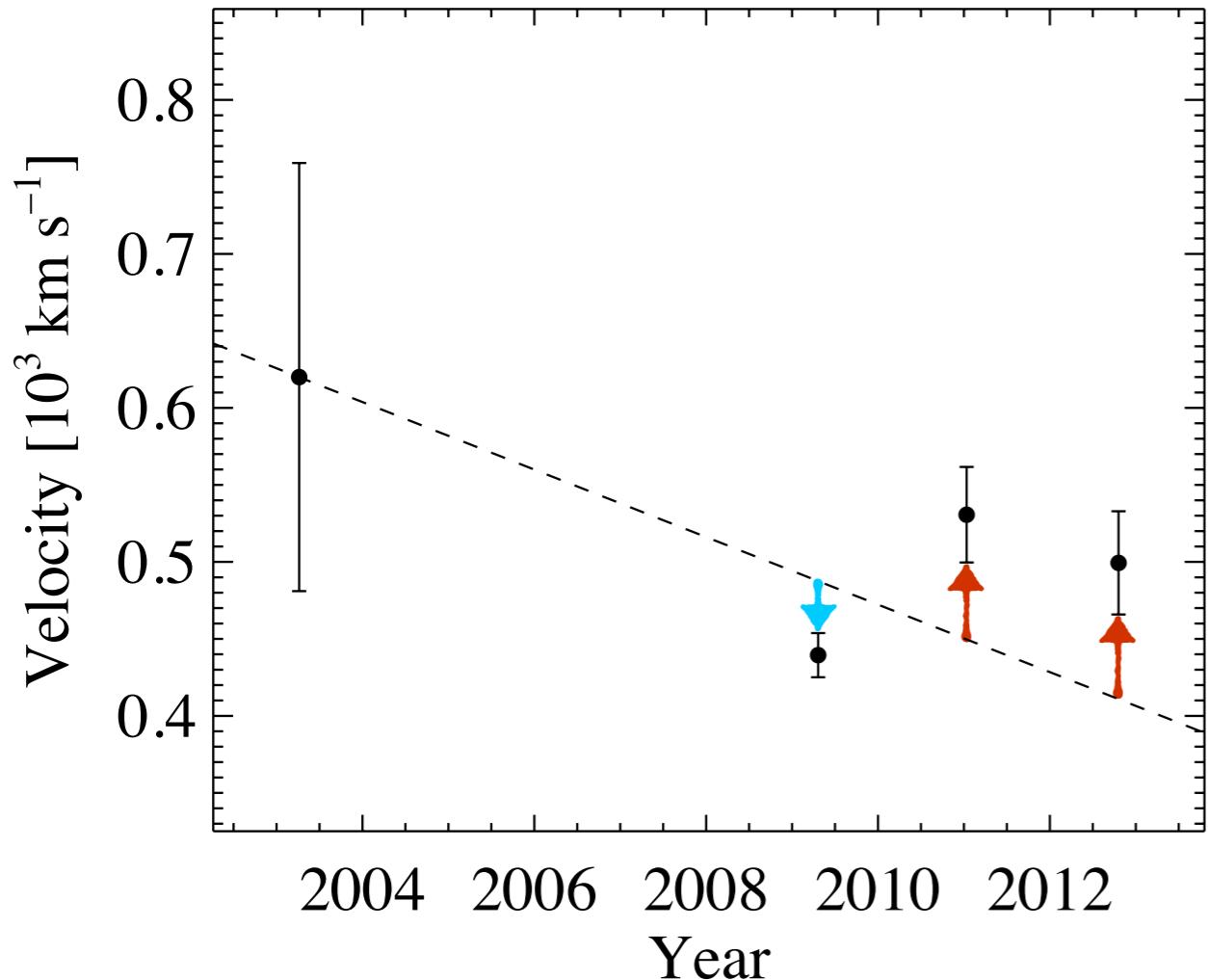
Runnoe et al. (2017)



$$\begin{aligned}P_{\min} &= 260 \text{ years} \\M_{\min} &= 4.1 \times 10^8 M_{\odot}\end{aligned}$$

## {4} Future: Radial velocity “jitter”

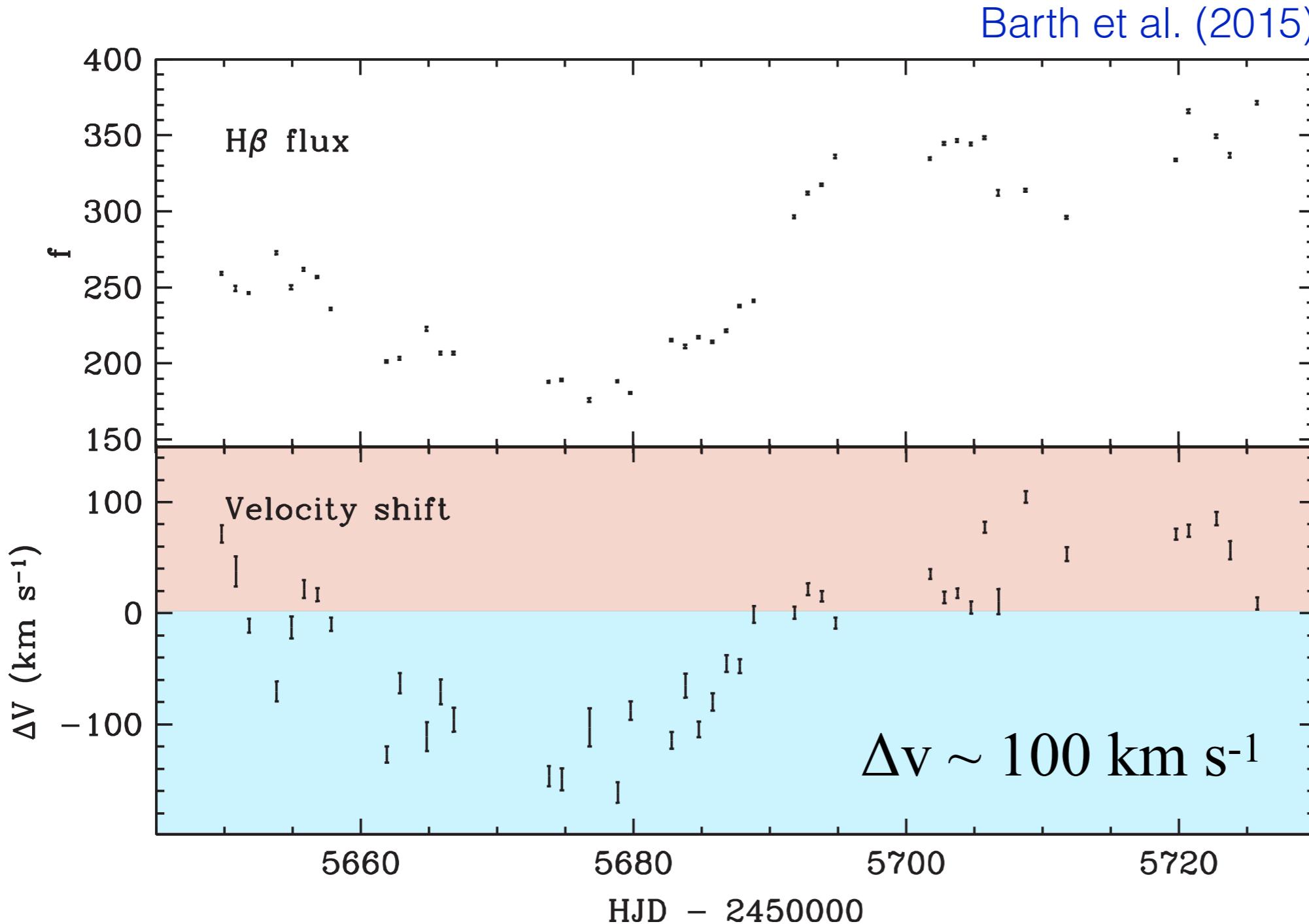
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### What is jitter?

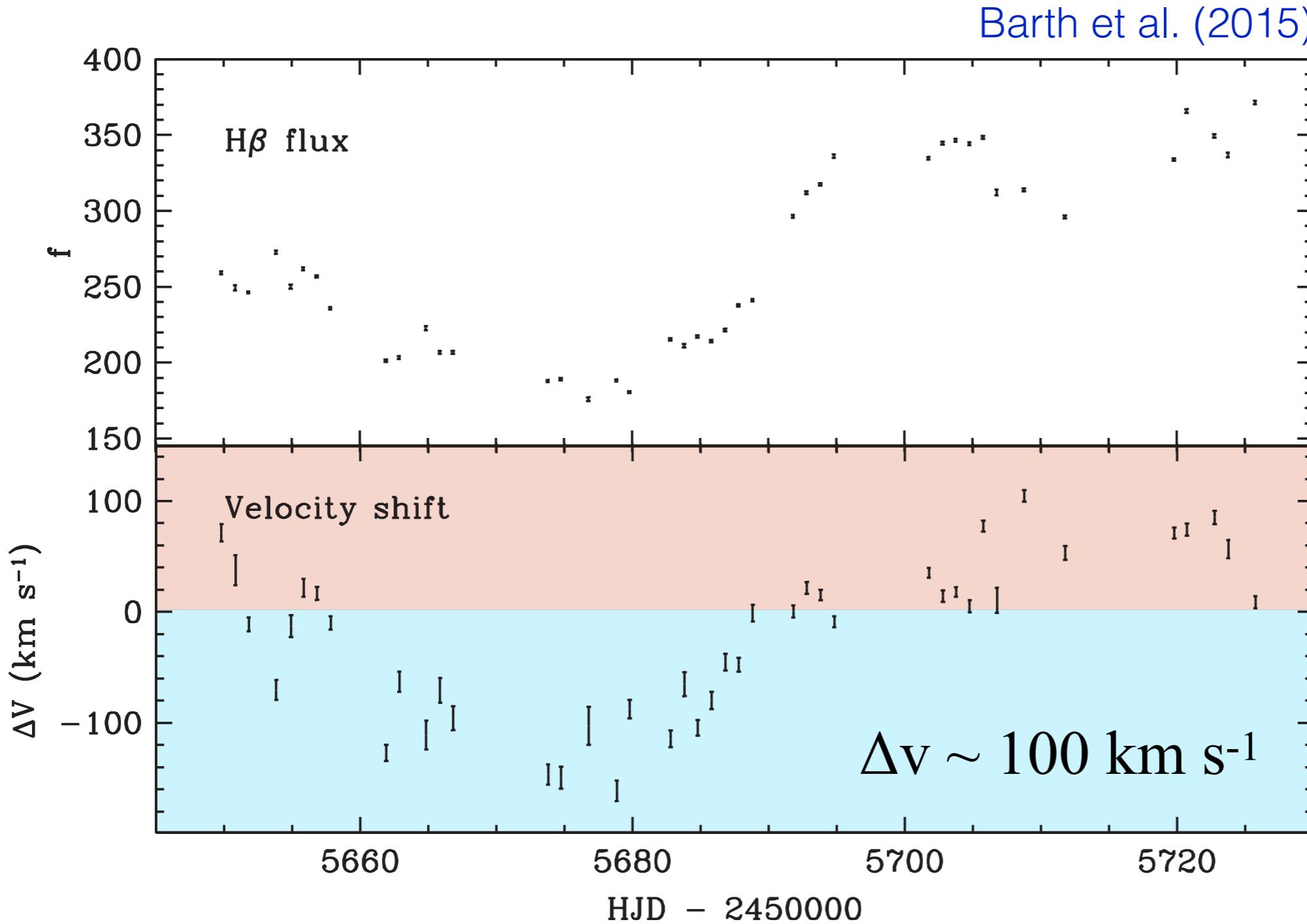
- ◆ Stochastic fluctuations in the radial velocity of a broad emission line from a variety of processes.
- ◆ Similar to noise in a photometric light curve.

## {4} Future: Radial velocity jitter



Asymmetric reverberation can cause jitter on short timescales (<months).

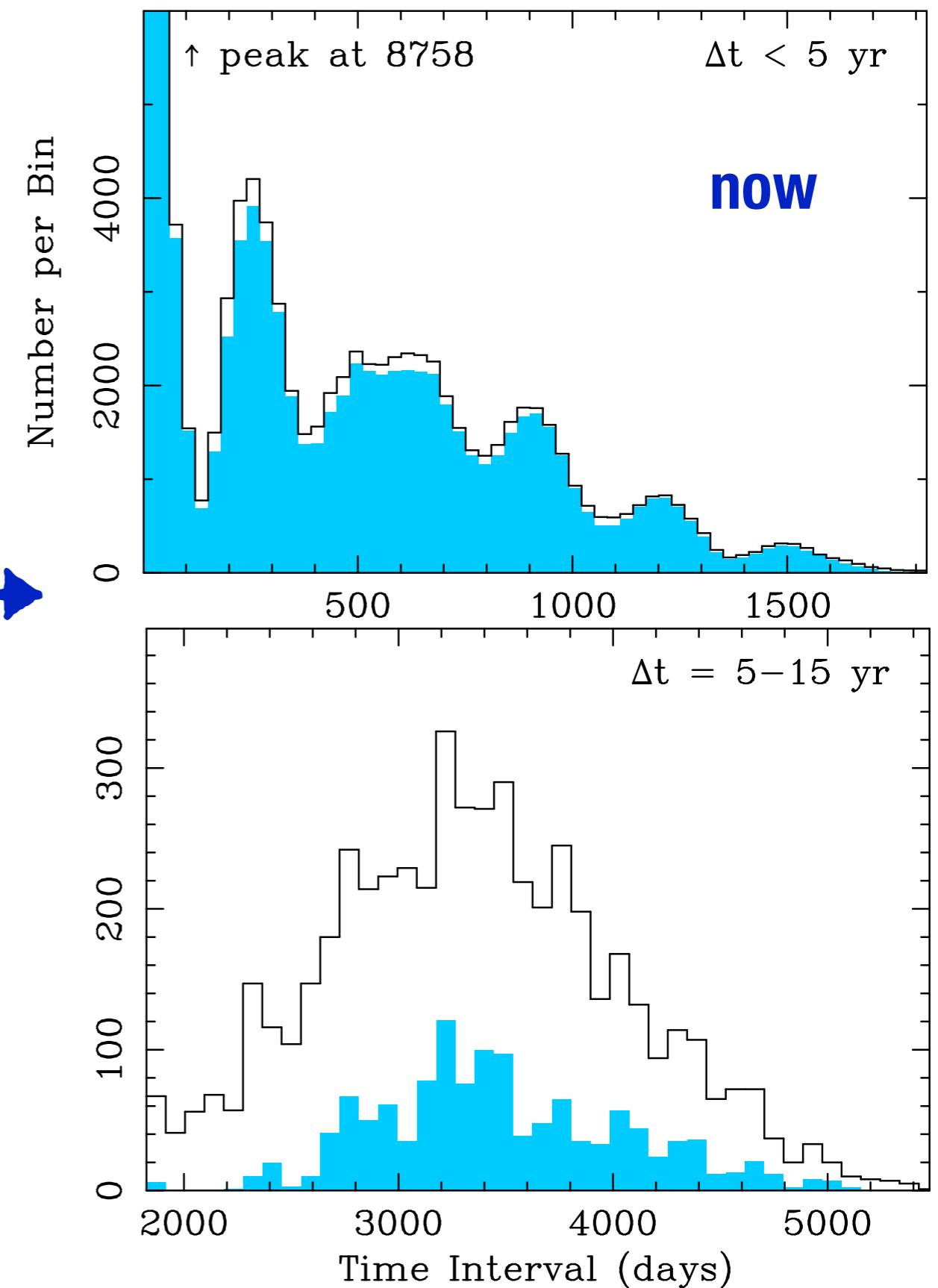
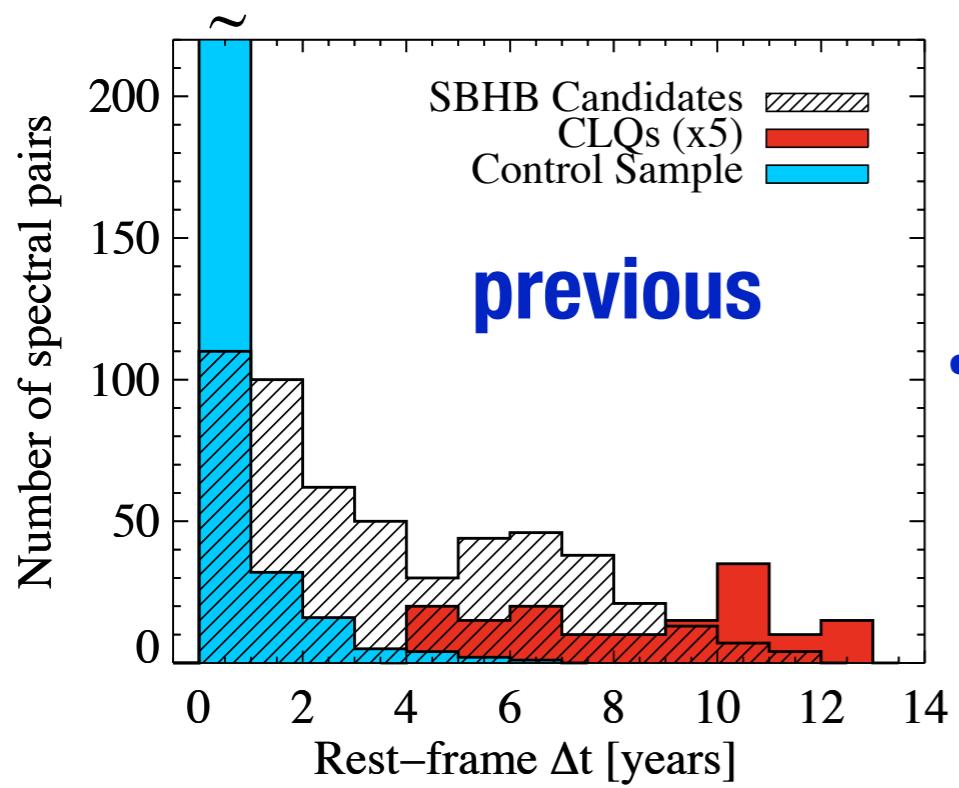
# {4} Future: Radial velocity jitter



But very few measurements on **long timescales**

Sergeev et al. (2007), Runnoe et al. (2017), Doan et al. (2019), Guo et al. (2019)

# {4} Future: Time-domain spectroscopy



# **Summary: Reasons to be optimistic**

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## **The radial velocity technique**

Spectroscopy has been a reliable method to select and test binary supermassive candidates, but [we need a longer time baseline and control sample.](#)

## **Where do we go from here?**

A new door is opening on quasar variability with enormous investments in the time domain. With new surveys like the SDSS V, we will really be able to observe [processes around many SMBHs.](#)

