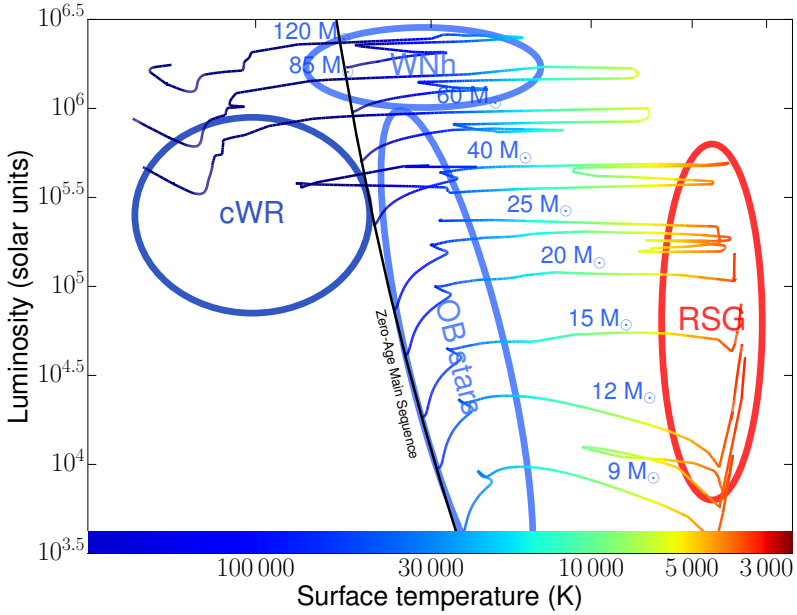
Massive Stars Outflows

in the Gravitational Wave context

http://www.ster.kuleuven.be/maestro



Leen Decin

Jon Sundqvist

Alex de Koter

Hugues Sana

MAESTRO

HOT ⟷ **COOL**

Interested?

2 PhD +1 Postdoc / Fall 2017

!!! Deadline July 15th !!!

2 PhDs / Fall 2018

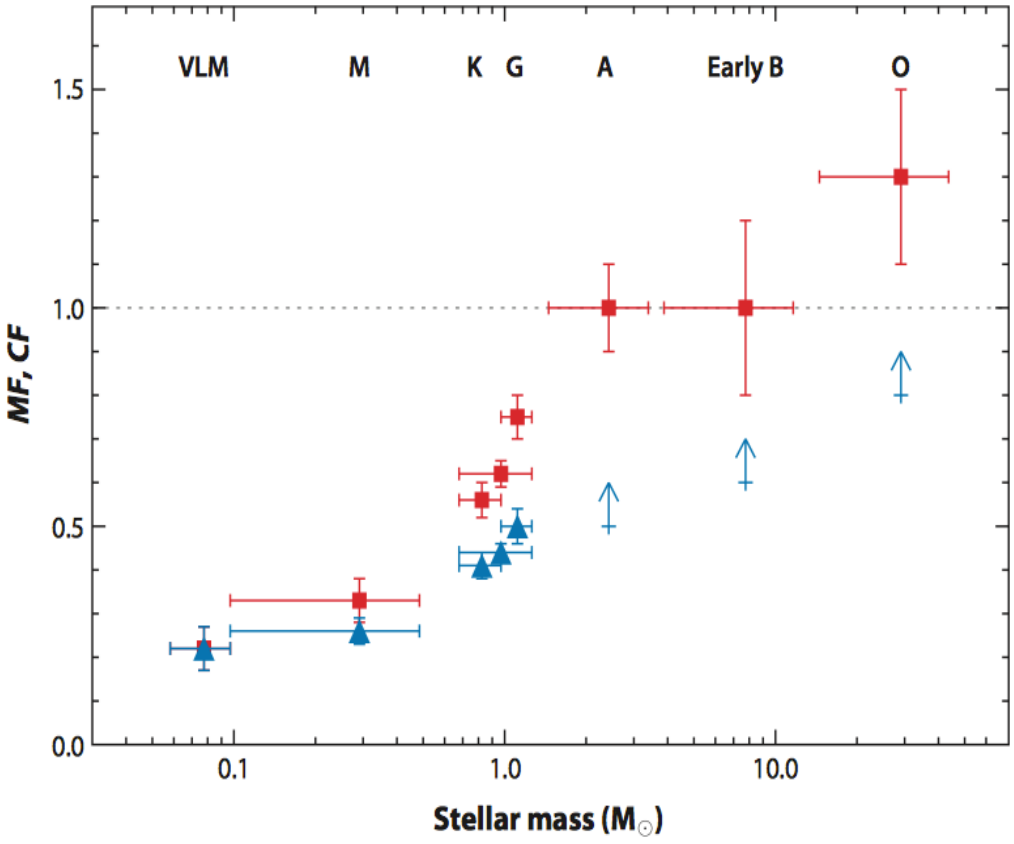
1 Postdoc / Fall 2020

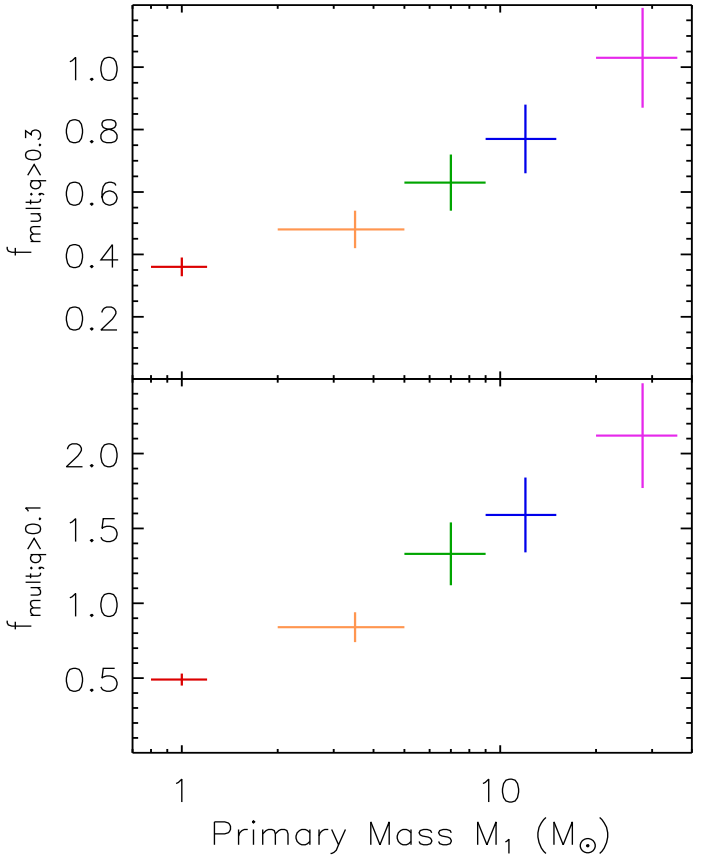
Goals: Mass-loss over the entire evolution and across a large metallicity range

KU LEUVEN

Multiplicity at high masses

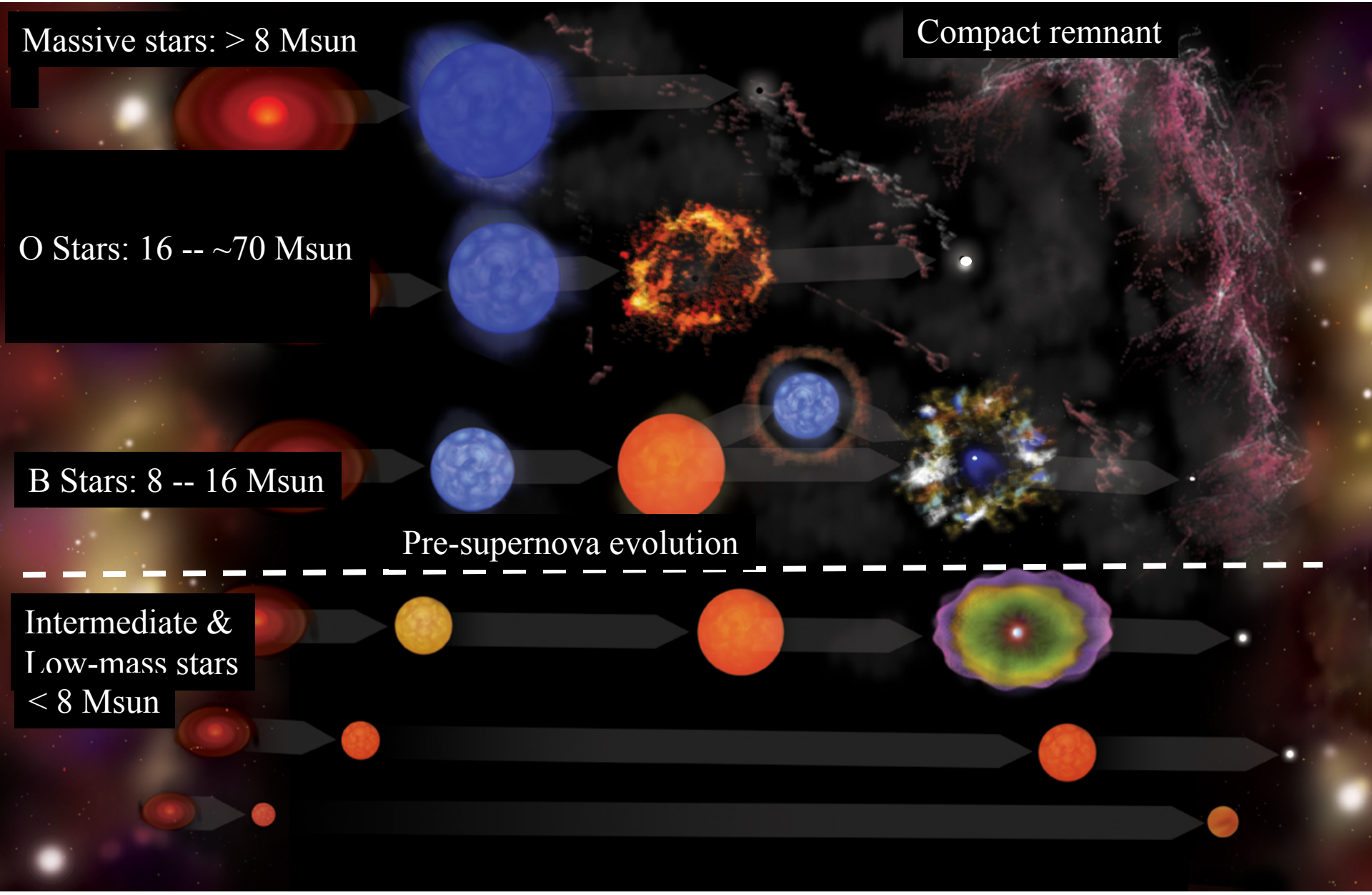
Hugues Sana



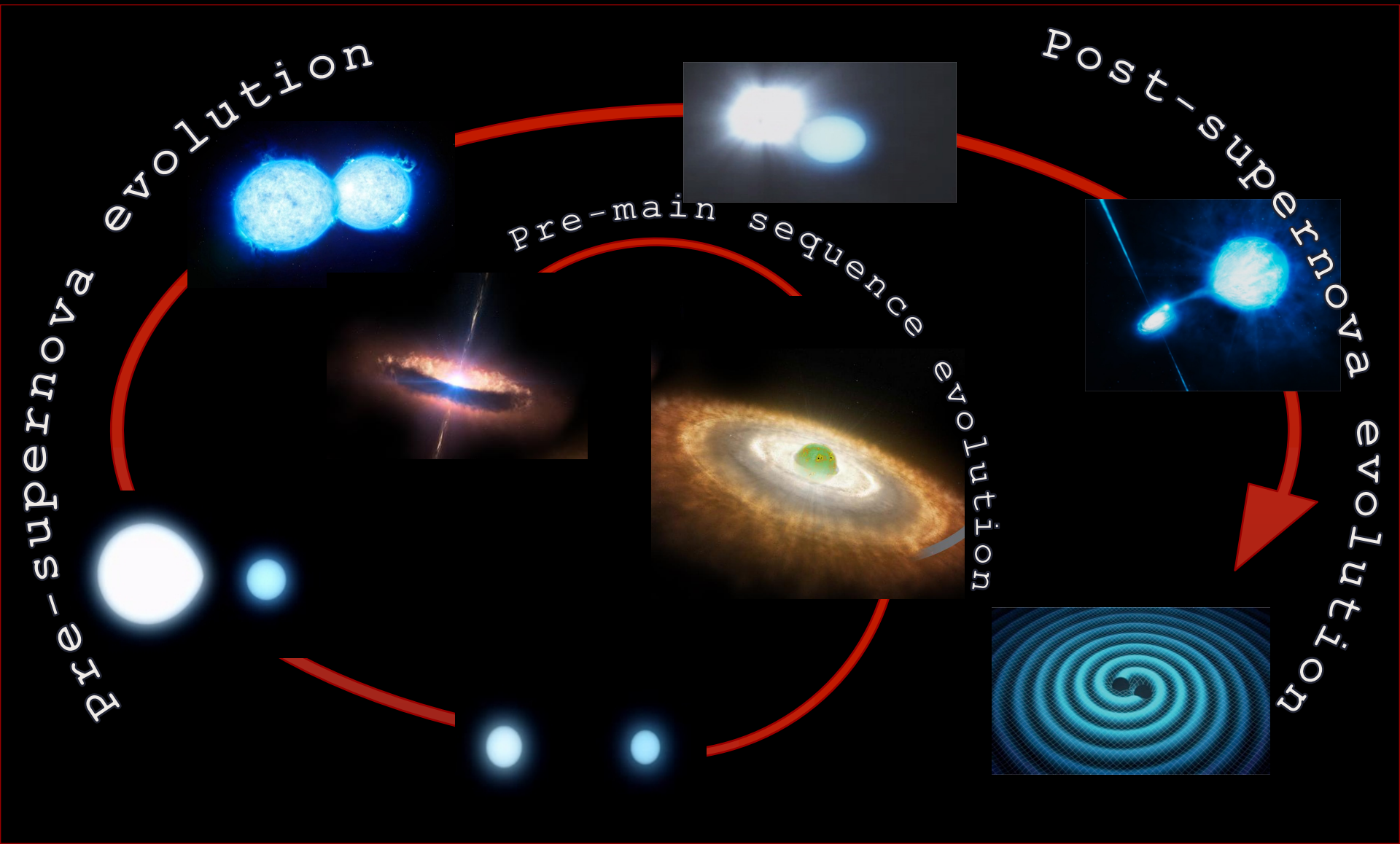


Duchene & Kraus'14

Moe+2017


Massive stars: > 8 Msun
Compact remnant
O Stars: 16 -- ~70 Msun
B Stars: 8 -- 16 Msun
Pre-supernova evolution
Intermediate &
Low-mass stars
< 8 Msun

The Life cycle of massive stars



The Life cycle of massive stars

Mission statement

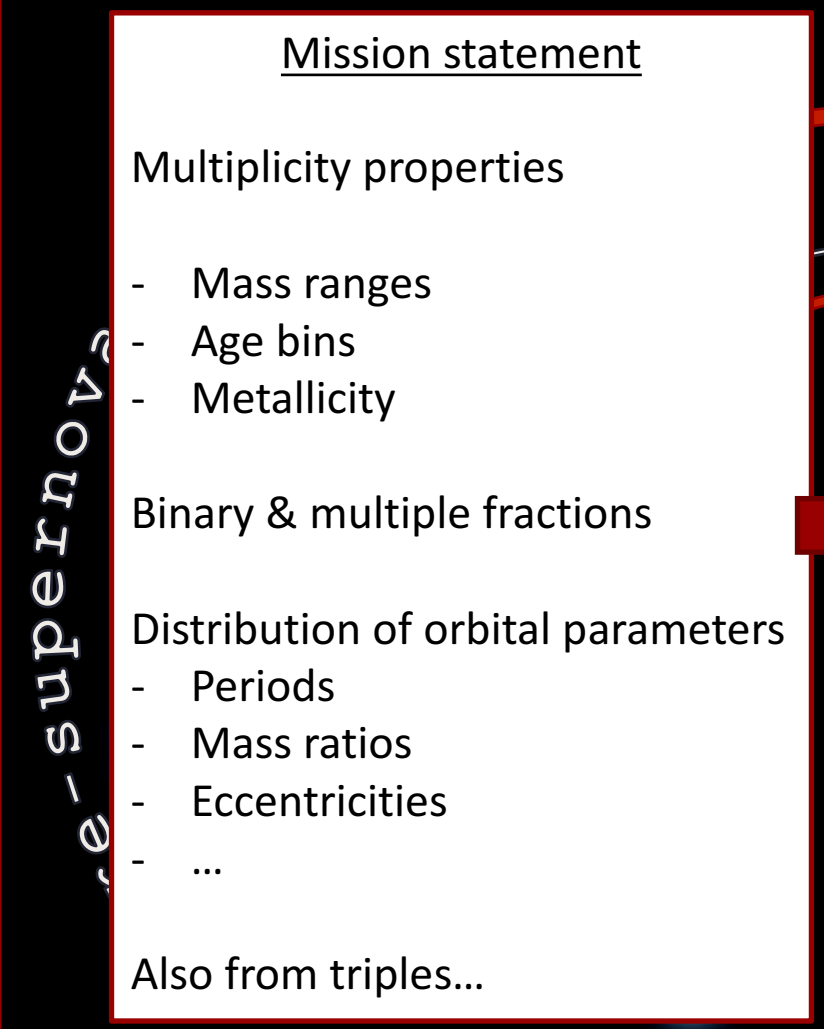
Multiplicity properties

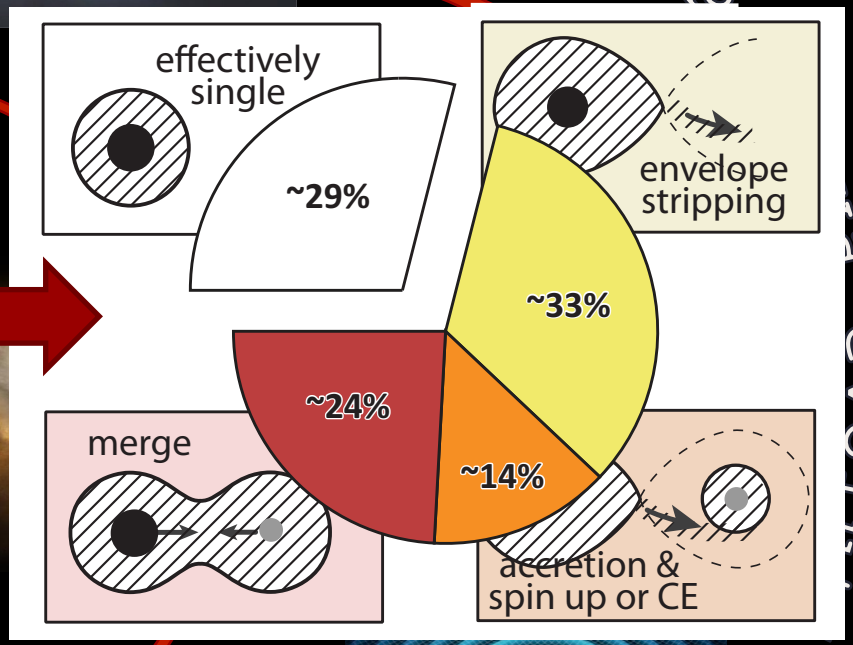
- Mass ranges
- Age bins
- Metallicity

Binary & multiple fractions

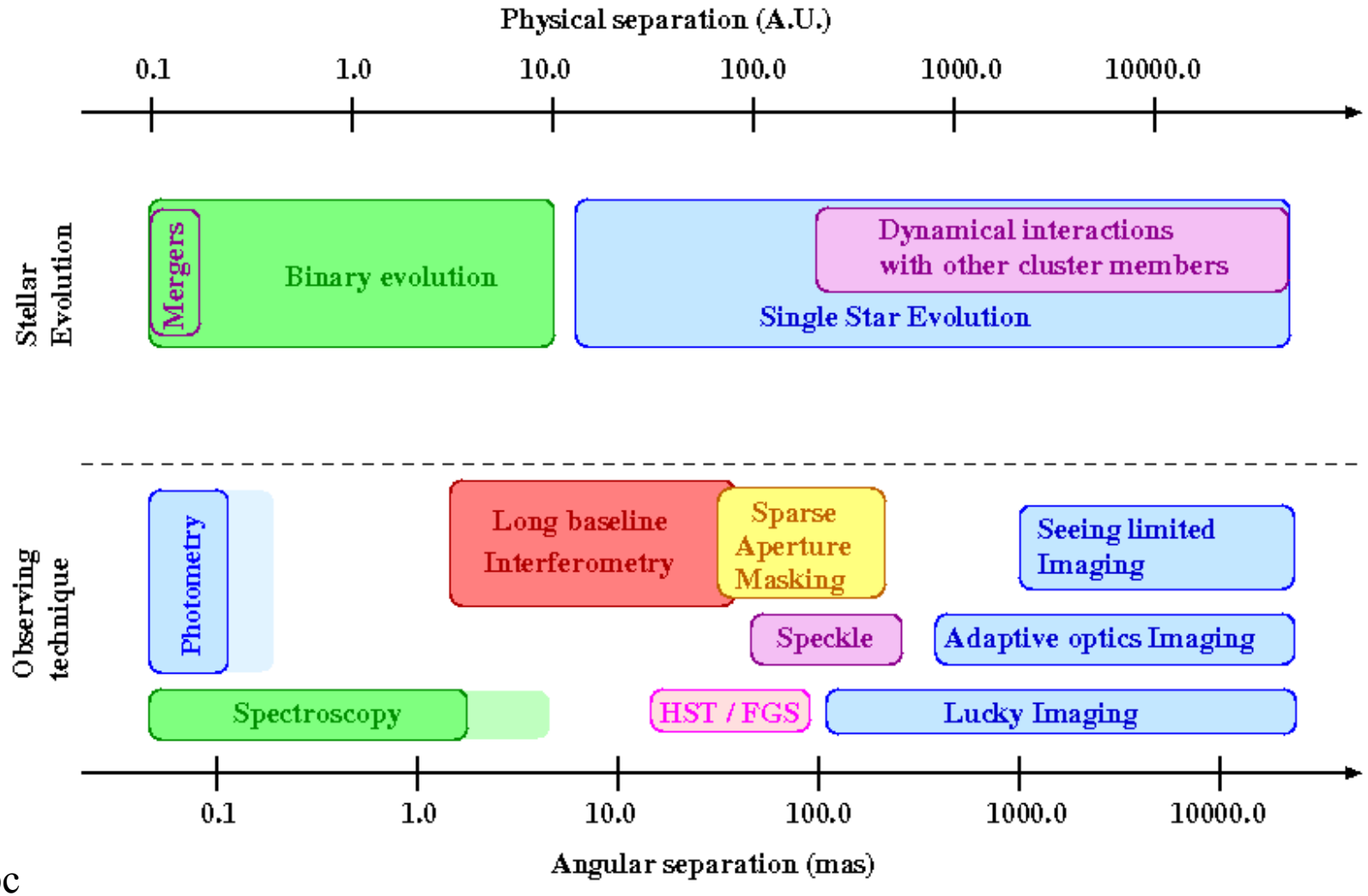
Distribution of orbital parameters
- Periods
- Mass ratios
- Eccentricities
- …

Also from triples…



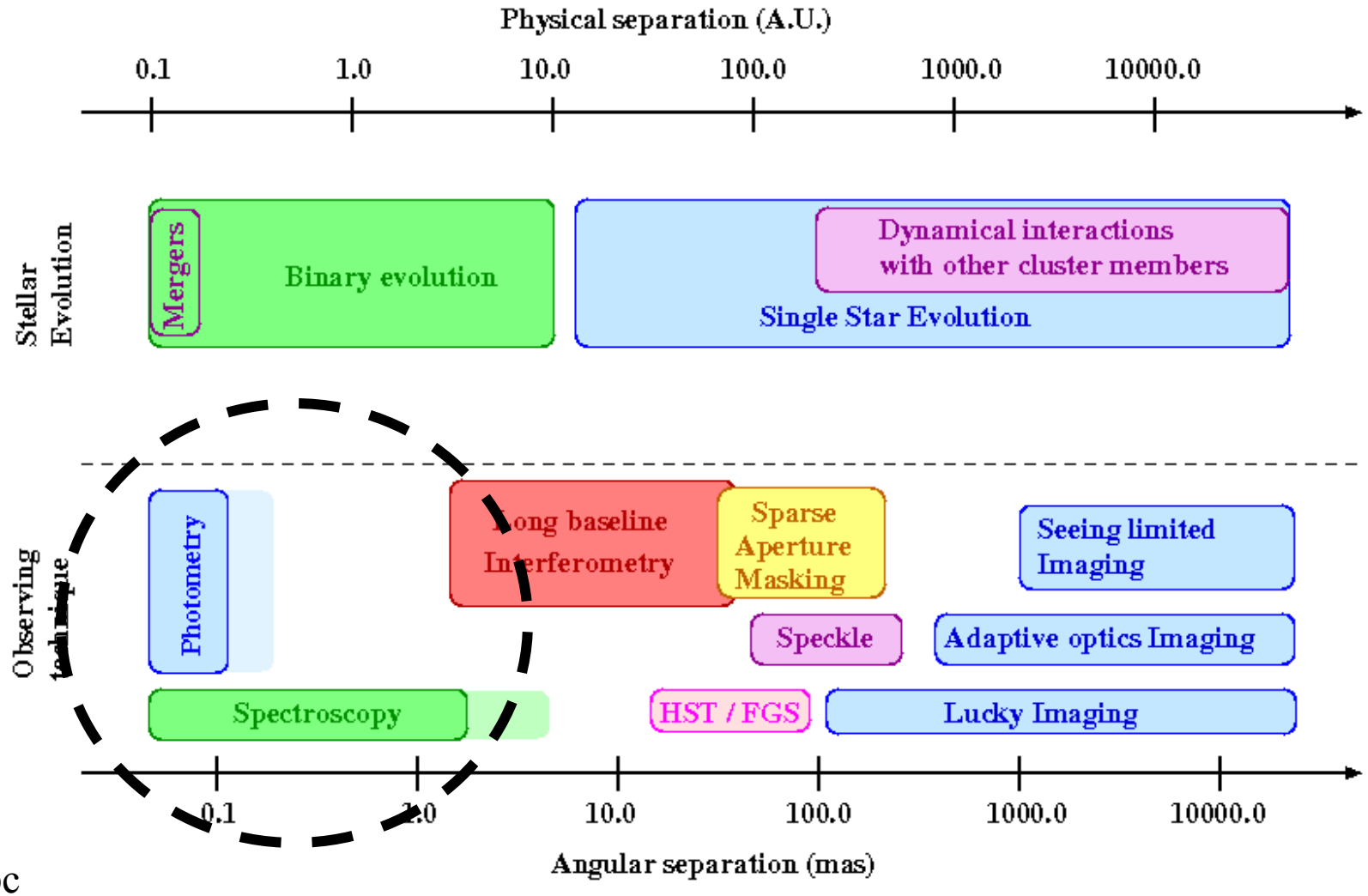


Parameter space



D=2kpc

Parameter space



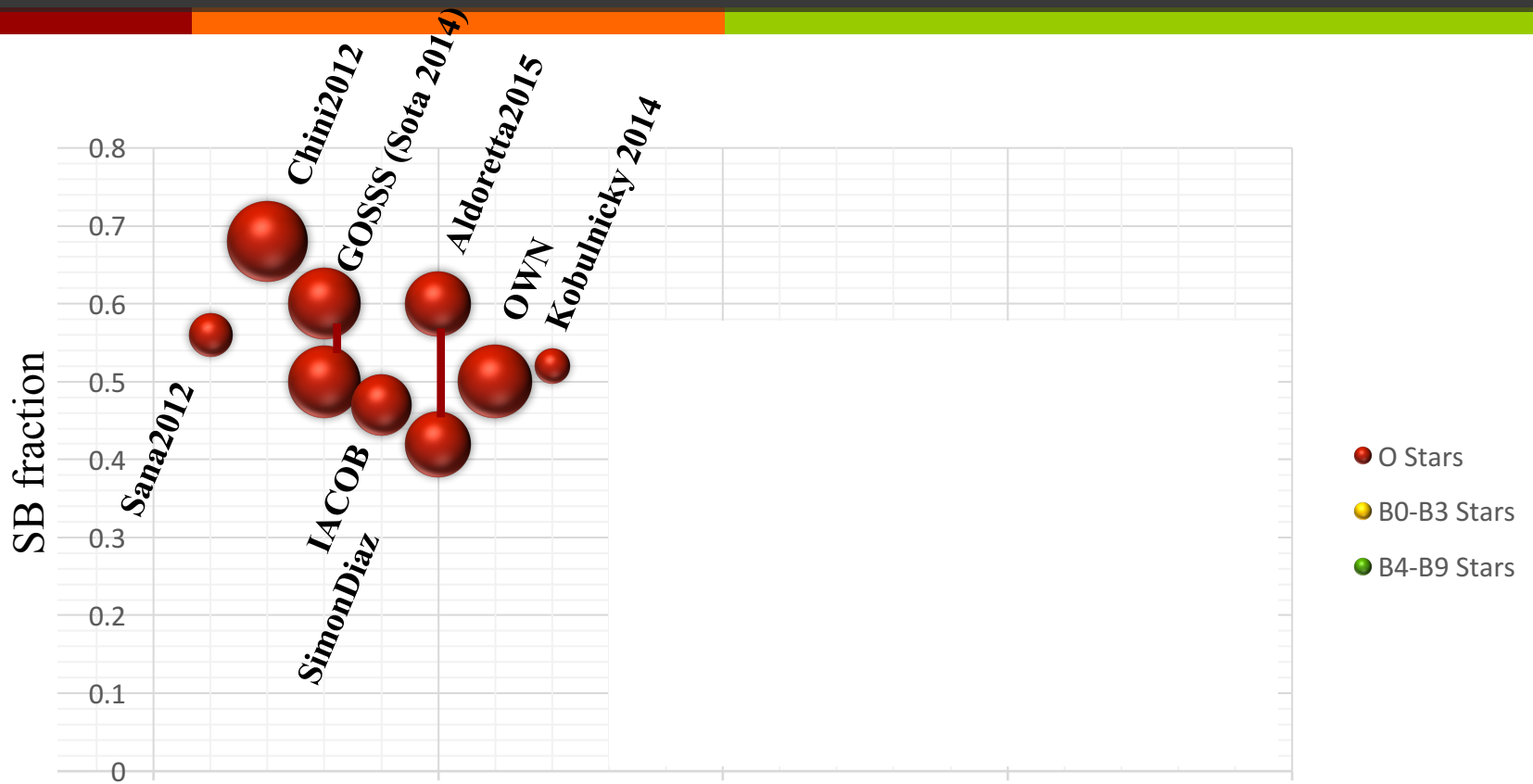
D=2kpc

Spectroscopic Binary Fraction

Multiplicity surveys

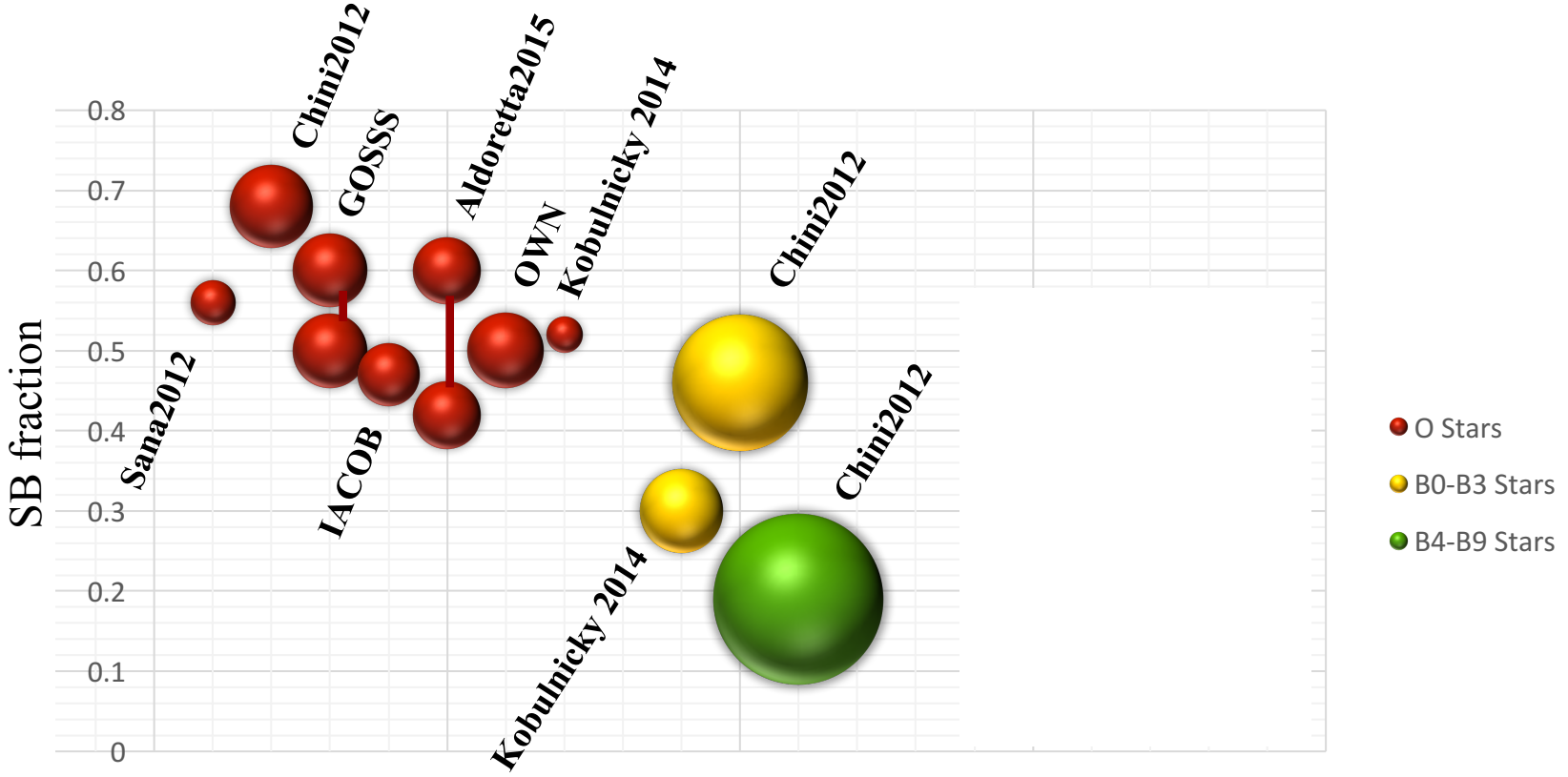
Region/Survey	SpT	N	N_{SB}	N_{SBO}	f_{SB}^{obs}	$f_{SB}^{corrected}$	Reference
Milky Way: O-type stars[a]							
BESO Survey	O	243					Chini et al. (2012)
Young Clusters	O	71					Sana et al. (2012)
GOSSS	O	194					Sota et al. (2014)
	O						
IACOB[b]	O	141					Simón-Díaz (these proceedings)
Clusters/Assoc	O	161					Aldoretta et al. (2015)
	O						
OWN	O	205					Barbá (these proceedings)
Cyg OB2	O	45					Kobulnicky et al. (2014)
	OB	*128*					
Milky Way: B-type stars							
Cyg OB2	B0-2	83					Kobulnicky et al. (2014)
BESO Survey	B0-3	226					Chini et al. (2012)
	B4-9	353					
Large Magellanic Cloud							
30Dor/VFTS	O	360					Sana et al. (2013)
30Dor/TMBM	O						Almeida et al. (2017)
30Dor/VFTS	B0-3	408					Dunstall et al. (2015)

Observed Spectroscopic Binary Fractions



$f_{SB}(obs) \sim 0.5\text{-}0.7 < f_{SB}(P < \sim 10yrs)$

Observed Spectroscopic Binary Fractions

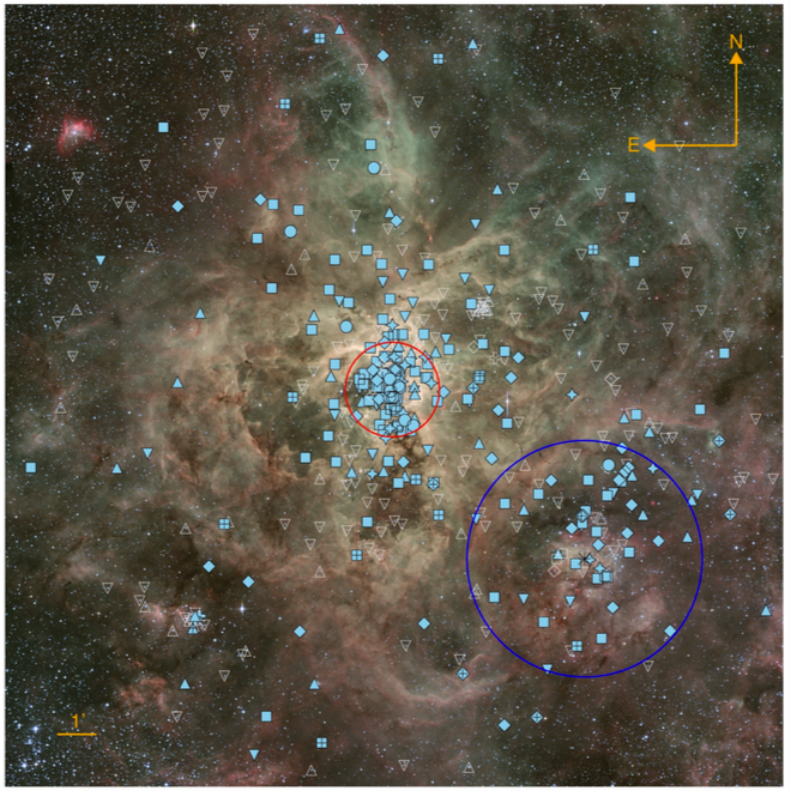


$f_{SB}(obs) \sim 0.5\text{-}0.7 < f_{SB}(P < \sim 10yrs)$

$f_{SB}(obs) \sim 0.3\text{-}0.5 < f_{SB}(P < \sim 10yrs)$

The VLT-Flames Tarantula Survey

Multi-epoch spectroscopy
of 800 massive stars



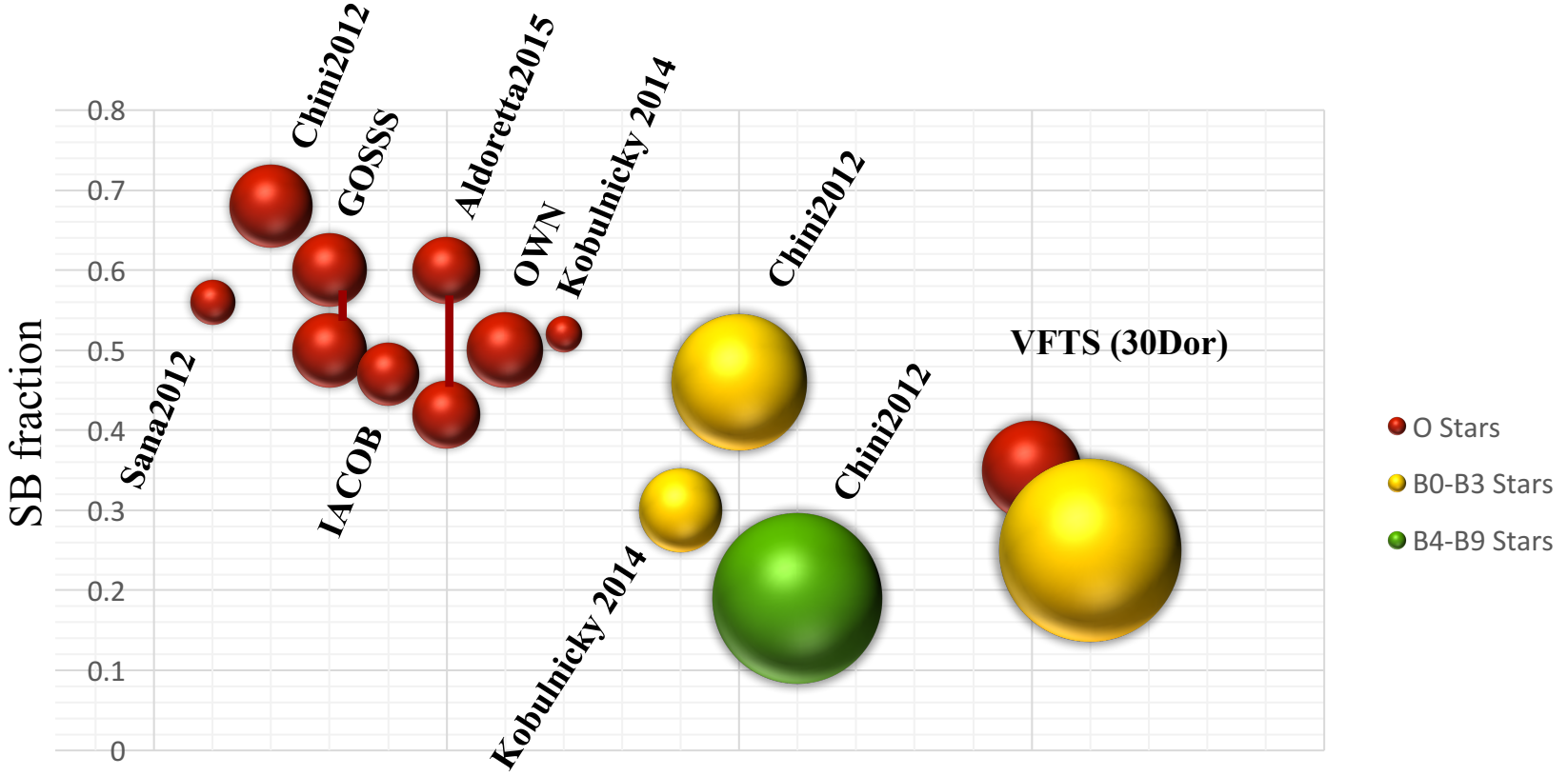
Stellar & cluster evolution:

- Stellar rotation, mass loss, multiplicity
- Census of the nearest young starburst
- Dynamics of the Tarantula region
- …

- 30 Doradus provides:
  - Statistics, rare objects, unique environment

Evans+2011

Observed Spectroscopic Binary Fractions



$f_{SB}(obs) \sim 0.5\text{-}0.7 < f_{SB}(P < \sim 10yrs)$

$f_{SB}(obs) \sim 0.3\text{-}0.5 < f_{SB}(P < \sim 10yrs)$

Multiplicity surveys

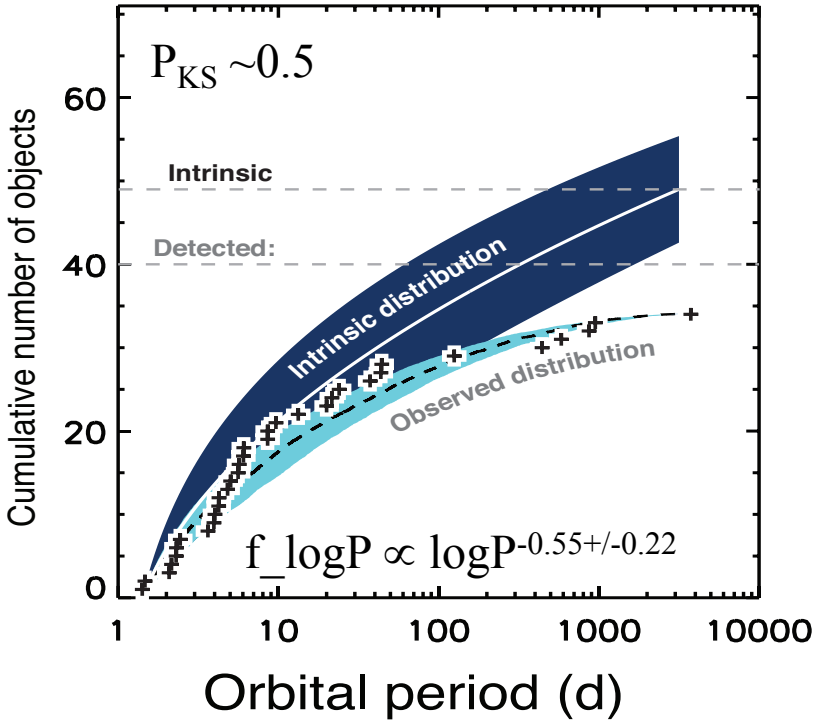
Region/Survey	SpT	N	N_{SB}	N_{SBO}	f_{SB}^{obs}	$f_{SB}^{corrected}$	Reference
Milky Way: O-type stars[a]							
BESO Survey	O	243	166	–			Chini et al. (2012)
Young Clusters	O	71	40	34		( )	Sana et al. (2012)
GOSSS	O	194	97 (low)	–			Sota et al. (2014)
	O		117 (high)	–	0.5		
IACOB[b]	O	141	66	–			Simón-Díaz (these proceedings)
Clusters/Assoc	O	161	68 (low)	68	...		Aldoretta et al. (2015)
	O		96 (high)	68	0.7		
OWN	O	205	102	85			Barbá (these proceedings)
Cyg OB2	O	45	23	23			Kobulnicky et al. (2014)
	OB	*128*	*48*	*48*			
Milky Way: B-type stars							
Cyg OB2	B0-2	83	25	25	0.3 ...	–[c]	Kobulnicky et al. (2014)
BESO Survey	B0-3	226	105	–		–	Chini et al. (2012)
	B4-9	353	67	–	0.5	–	
Large Magellanic Cloud							
30Dor/VFTS	O	360	124	–	0.35 ...		Sana et al. (2013)
30Dor/TMBM	O			79			Almeida et al. (2017)
30Dor/VFTS	B0-3	408	102	–	0.25		Dunstall et al. (2015)

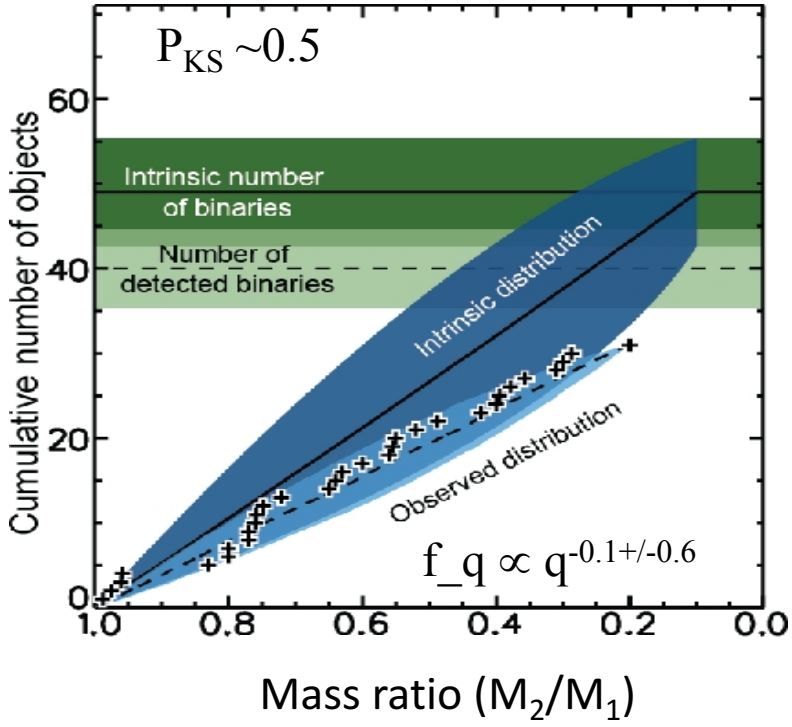
Multiplicity surveys

Region/Survey	SpT	N	$N_{\rm SB}$	$N_{\rm SBO}$	$f_{\rm SB}^{\rm obs}$	$f_{\rm SB}^{\rm corrected}$	Reference
Milky Way: O-type stars[a]							
BESO Survey	O	243	166	–		–	Chini et al. (2012)
Young Clusters	O	71	40	34		0.69 ± 0.09	Sana et al. (2012)
GOSSS	O	194	97 (low)	–		–	Sota et al. (2014)
	O		117 (high)	–	0.5	–	
IACOB[b]	O	141	66	–		–	Simón-Díaz (these proceedings)
Clusters/Assoc	O	161	68 (low)	68	...	–	Aldoretta et al. (2015)
	O		96 (high)	68	0.7	–	
OWN	O	205	102	85		–	Barbá (these proceedings)
Cyg OB2	O	45	23	23		–[c]	Kobulnicky et al. (2014)
	OB	*128*	*48*	*48*		*0.55*[c]	
Milky Way: B-type stars							
Cyg OB2	B0-2	83	25	25	0.3 ...	–[c]	Kobulnicky et al. (2014)
BESO Survey	B0-3	226	105	–		–	Chini et al. (2012)
	B4-9	353	67	–	0.5	–	
Large Magellanic Cloud							
30Dor/VFTS	O	360	124	–	0.35 ...	0.51 ± 0.03	Sana et al. (2013)
30Dor/TMBM	O			79		≈ 0.58	Almeida et al. (2017)
30Dor/VFTS	B0-3	408	102	–	0.25	0.58 ± 0.11	Dunstall et al. (2015)

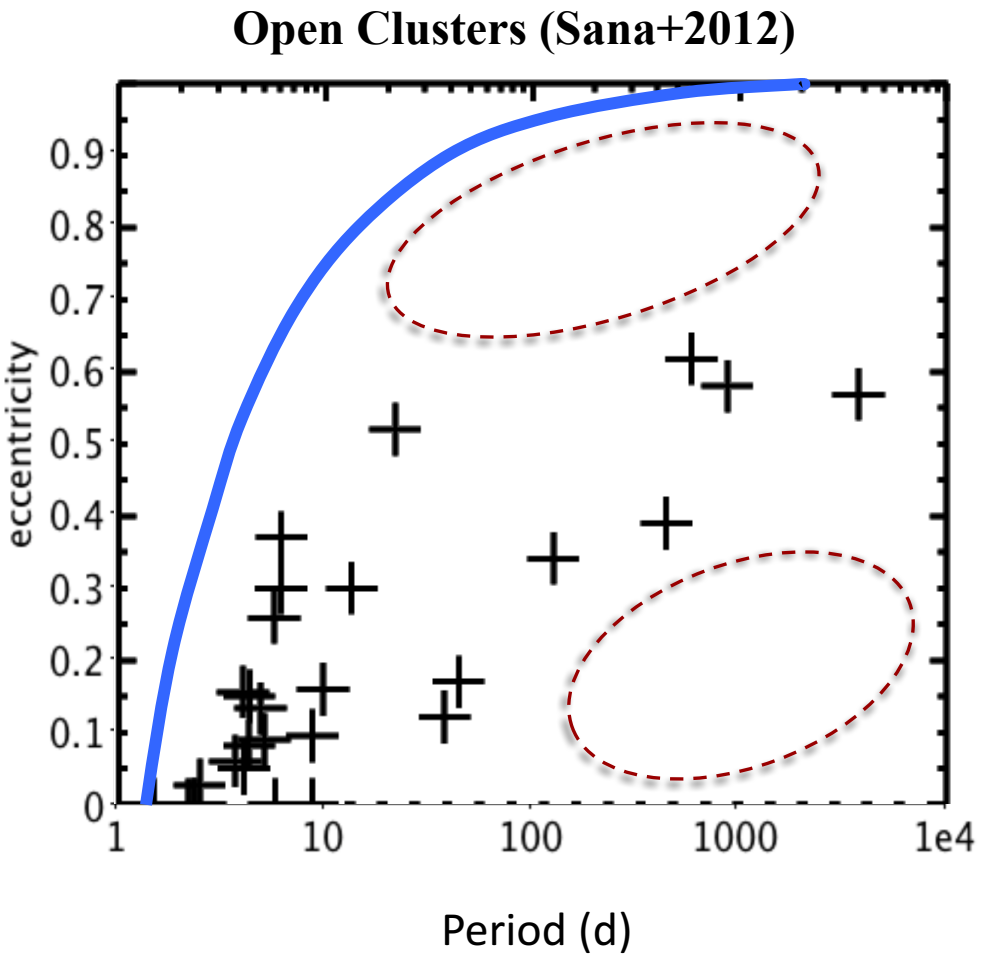
Orbital distributions

O stars in Milky Way young open clusters





Strengths and Limitations



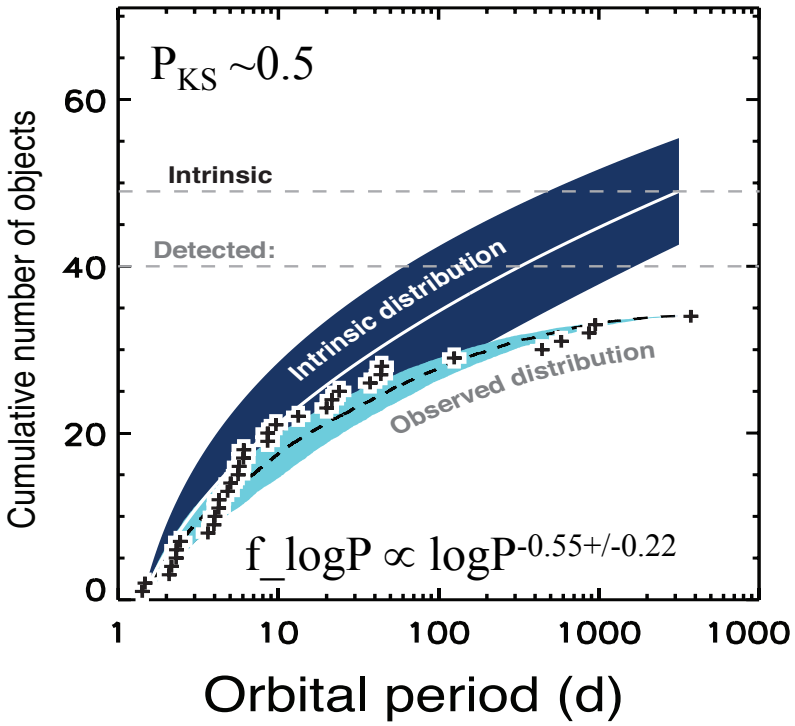
Strengths:
- Young sample
- Volume complete > 90%
- 85% have orbits
- Self-consistent bias correction in 4D

Limitations:
- Moderate size sample:
  - 71 objects
  - 40 SB / 34 orbits

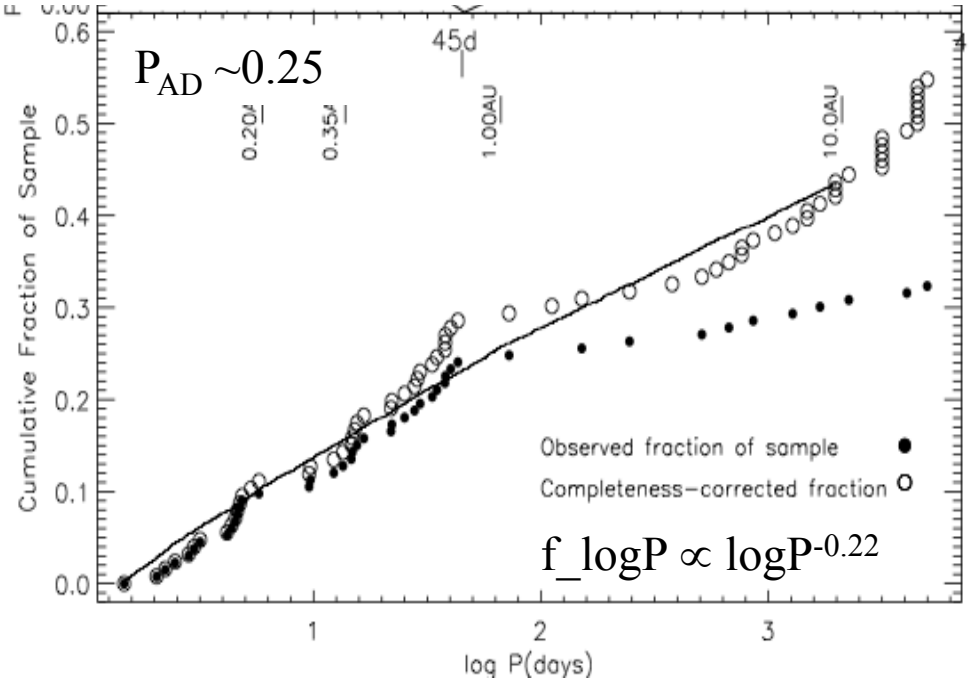
- Uneven coverage of the period-eccentricity diagram

Orbital period distributions

- Galactic young open clusters



- Cyg OB2 region

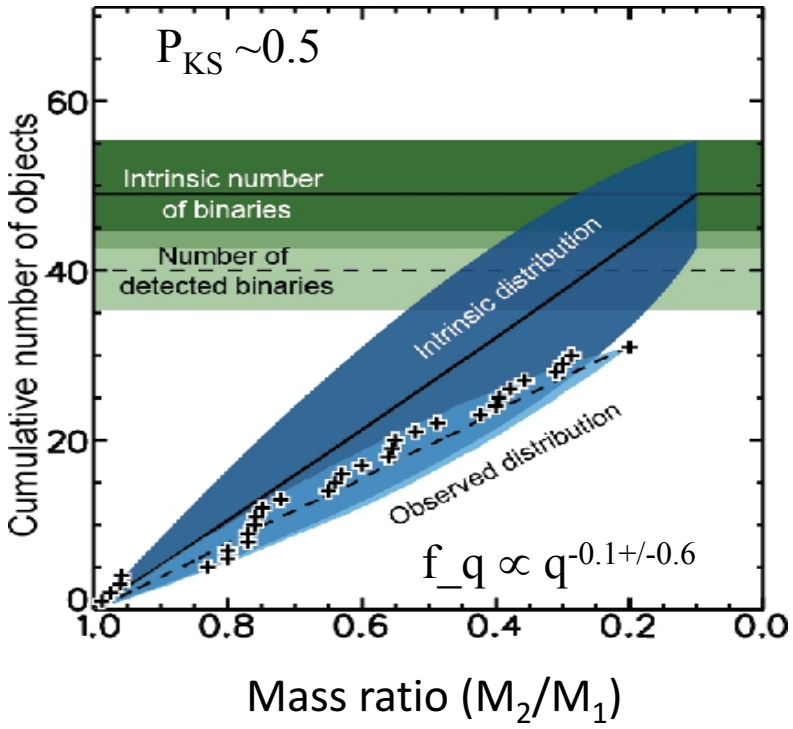


- VLT-Flames Tarantula survey O stars f_logP ∝ logP$^{-0.45+/-0.30}$

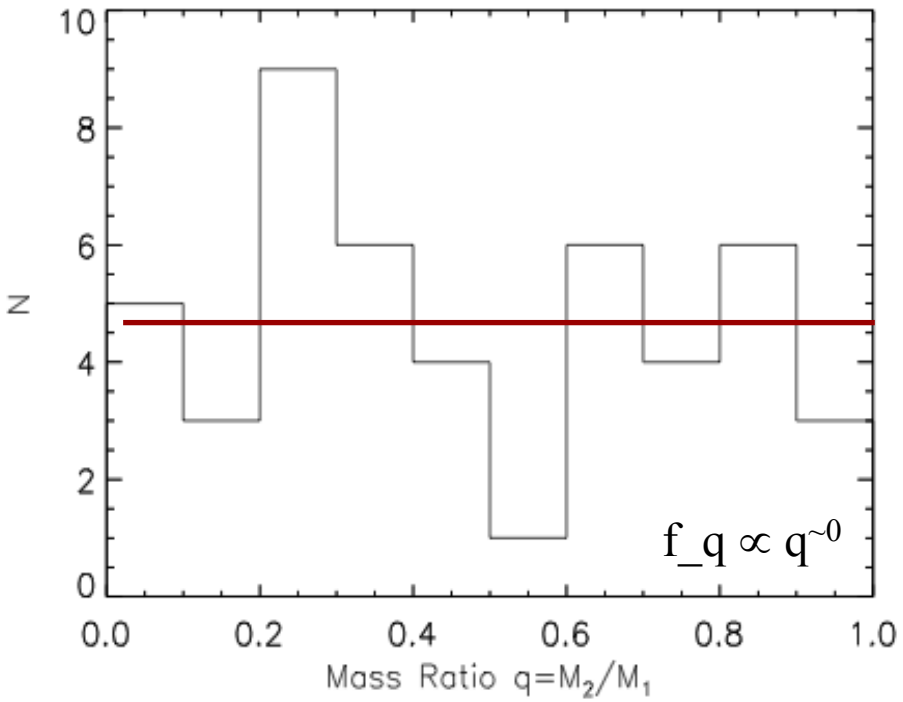
Sana+2012, 2013, Kobulnicky+2014, Dunstall+ 2015

Mass-ratio distributions

- Galactic young open clusters



- Cyg OB2 region



Sana+2012, Kobulnicky+2014

The Tarantula Massive Binary Monitoring

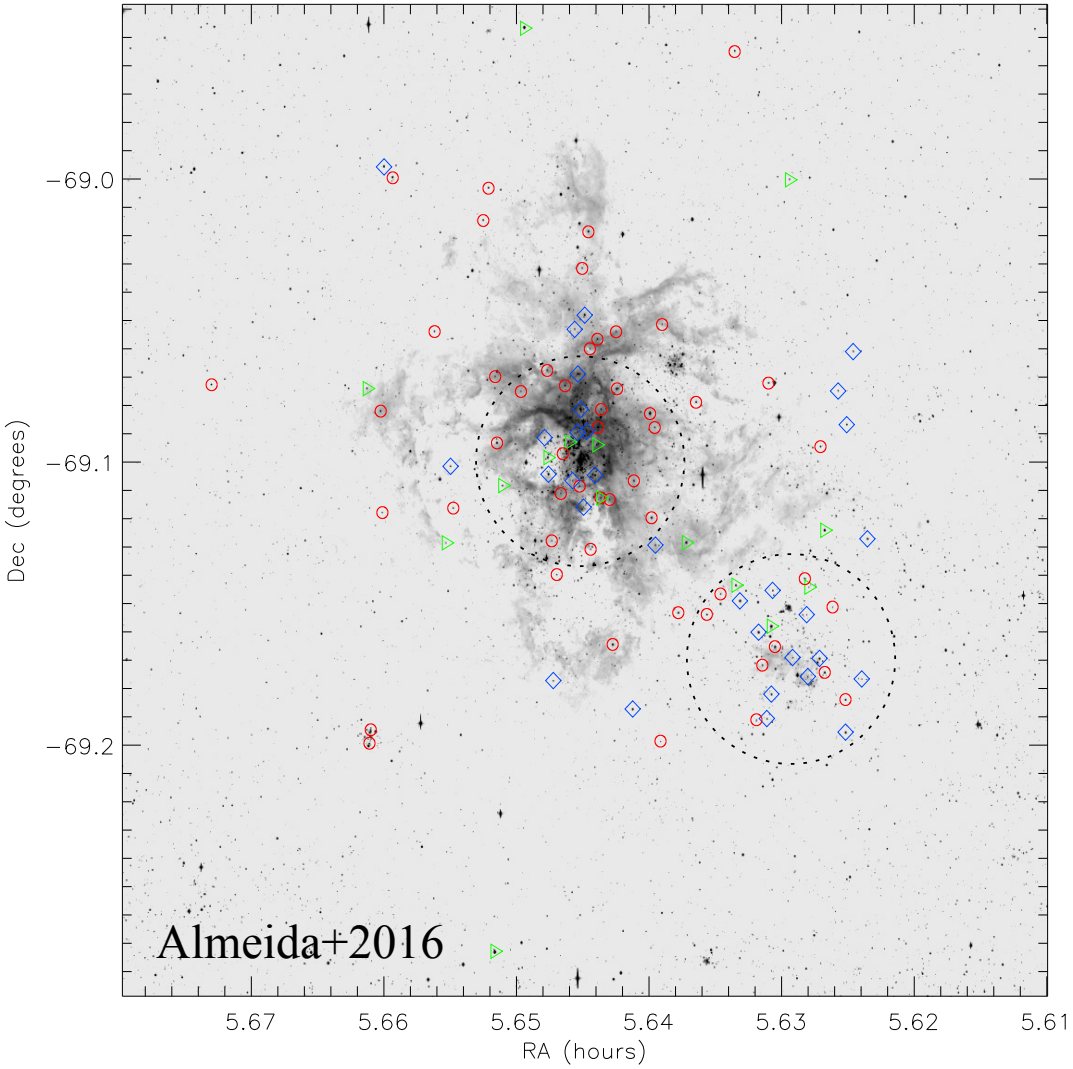
TMBM

102 massive RV variables
93 O stars

↓

79 O-type orbits

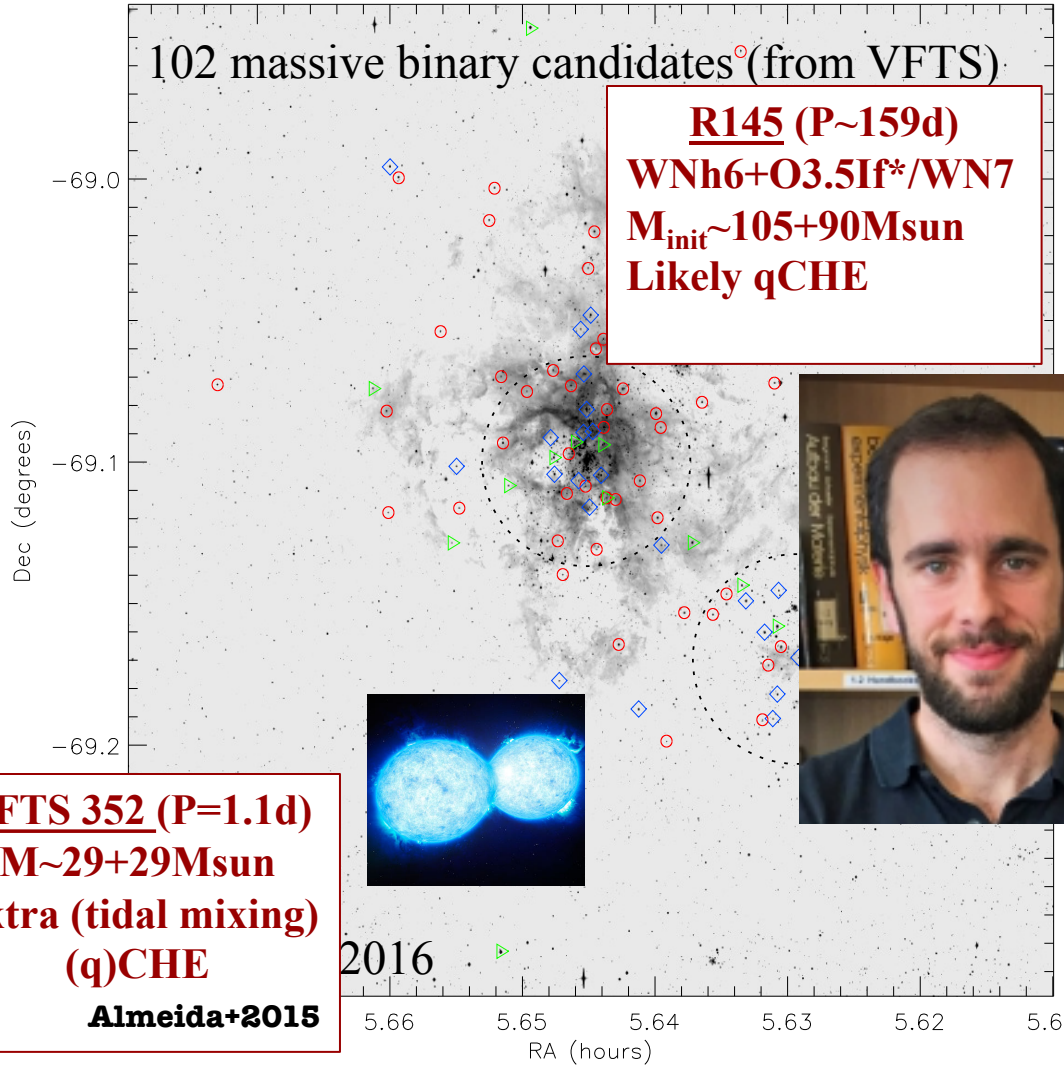
Leonardo Almeida



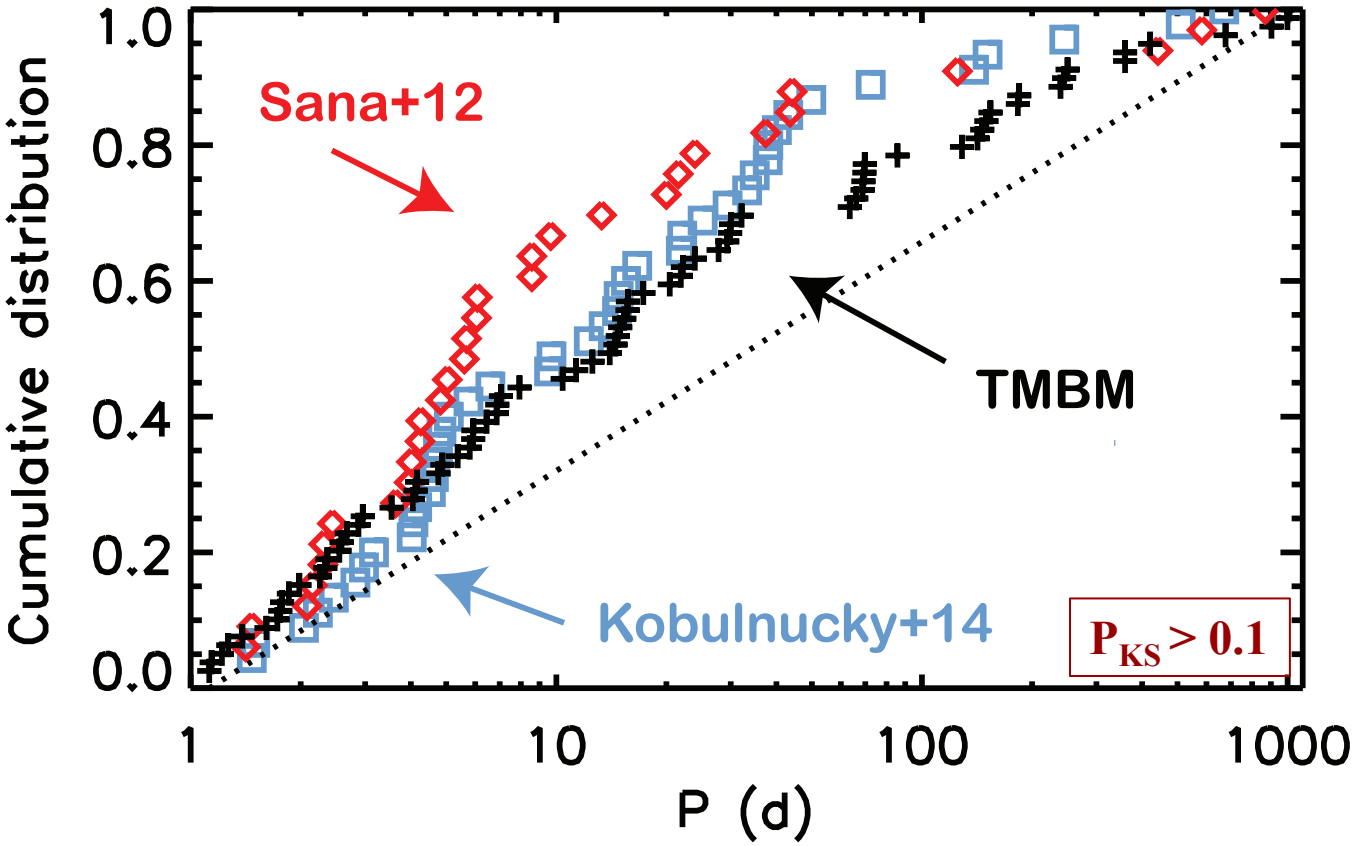
The Tarantula Massive Binary Monitoring

Michael ABDUL-MASIH

Leonardo Almeida



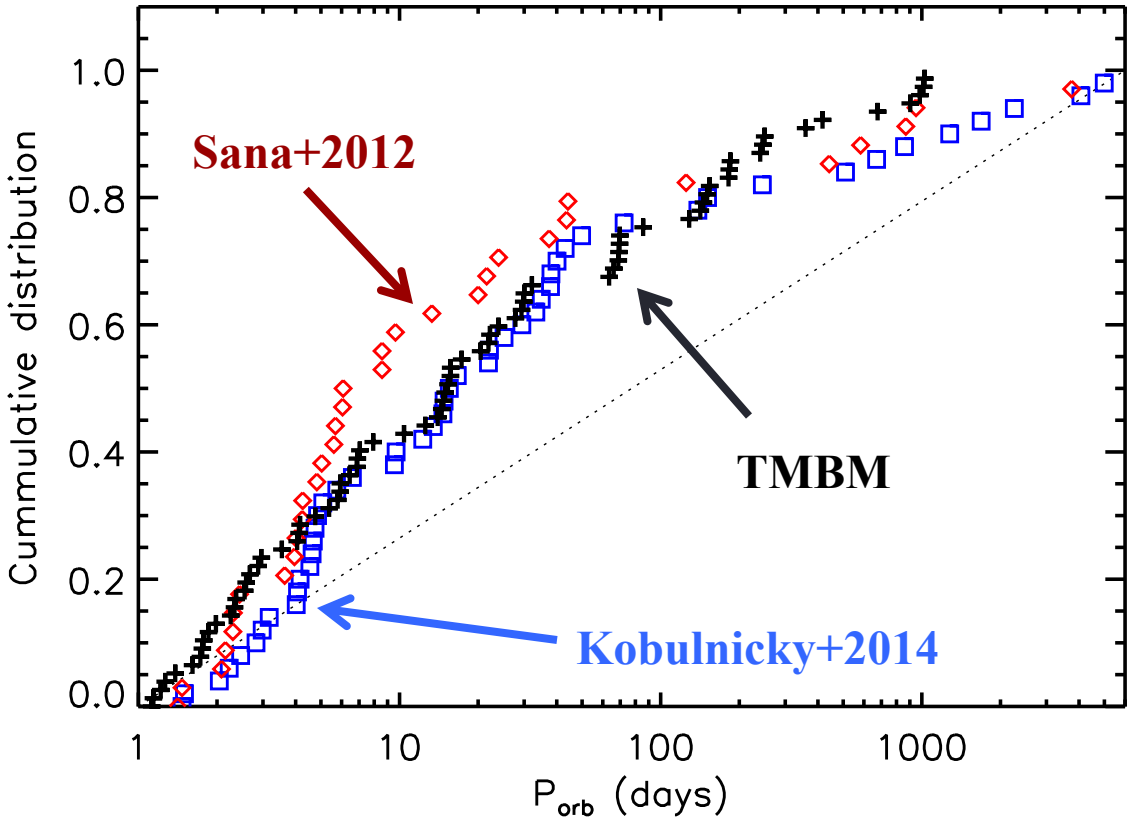
Observed period distributions



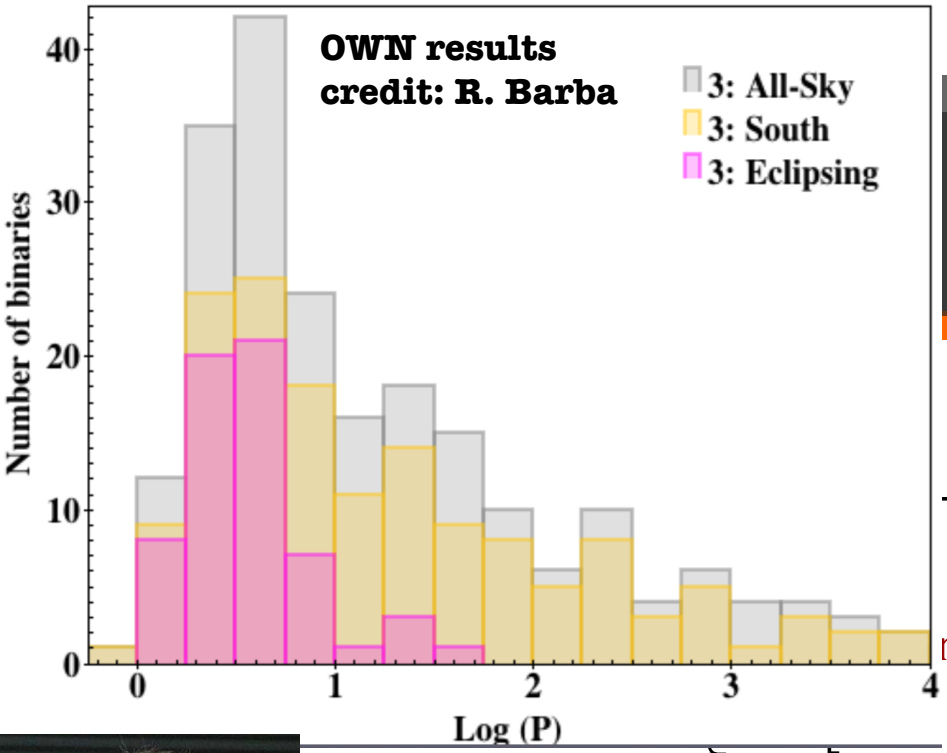
Leonardo Almeida

Almeida+2016

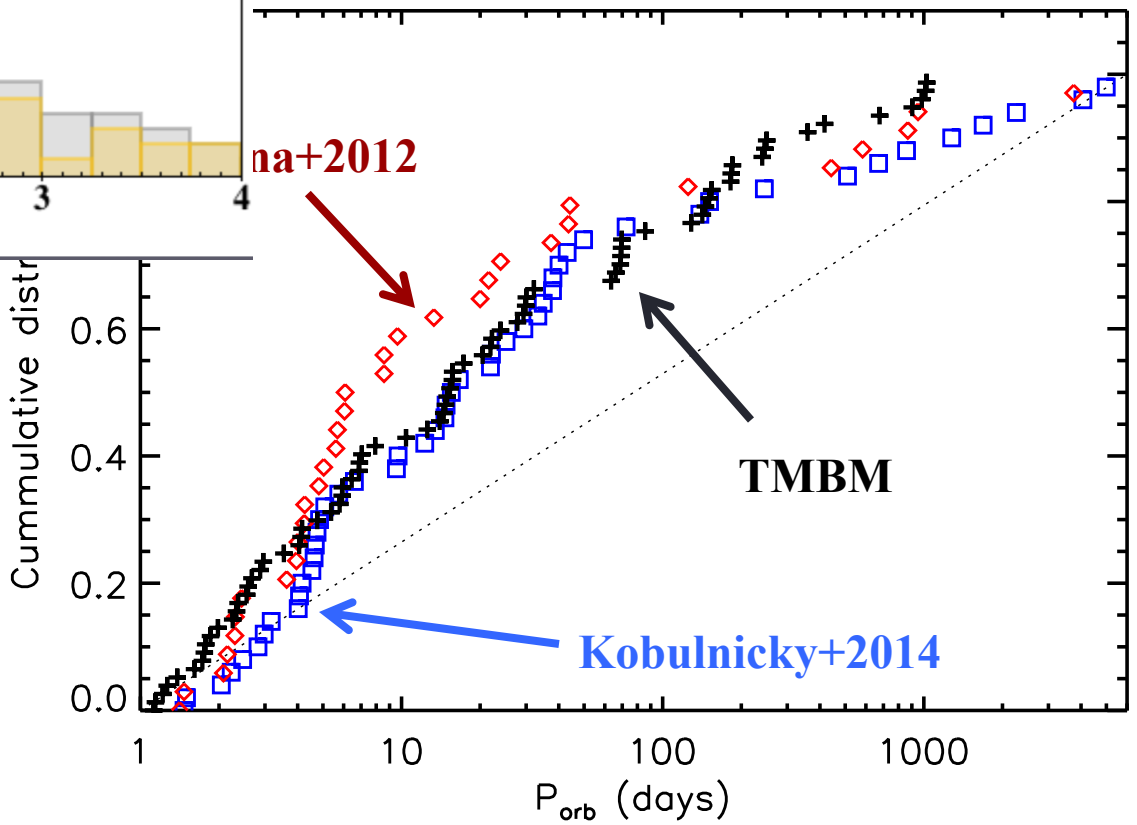
Observed period distributions



OWN Survey

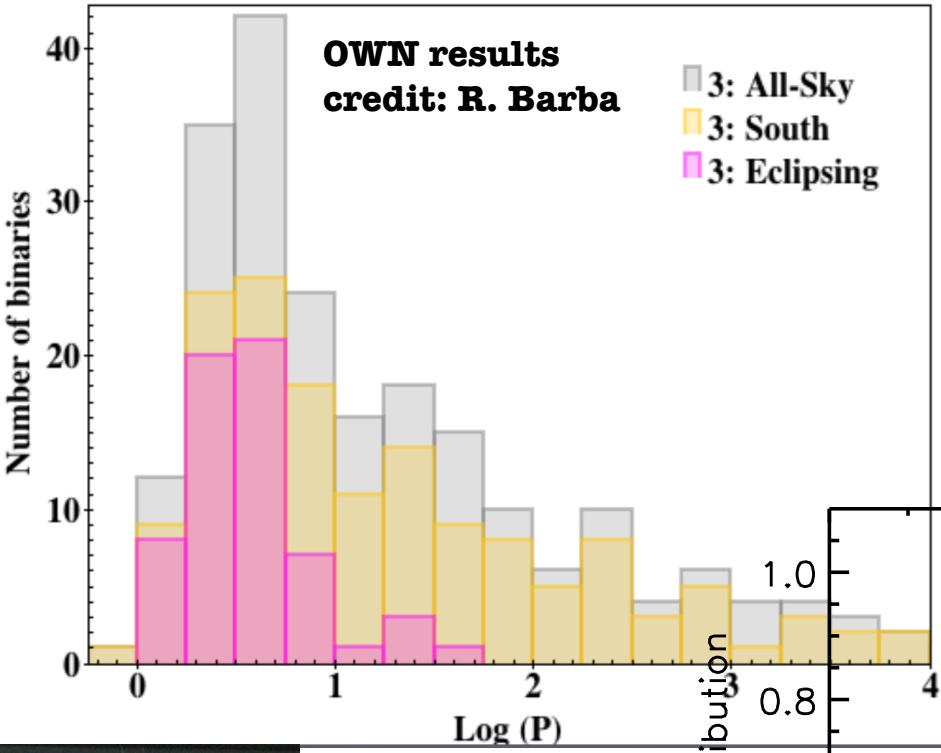


Rodolfo Barba

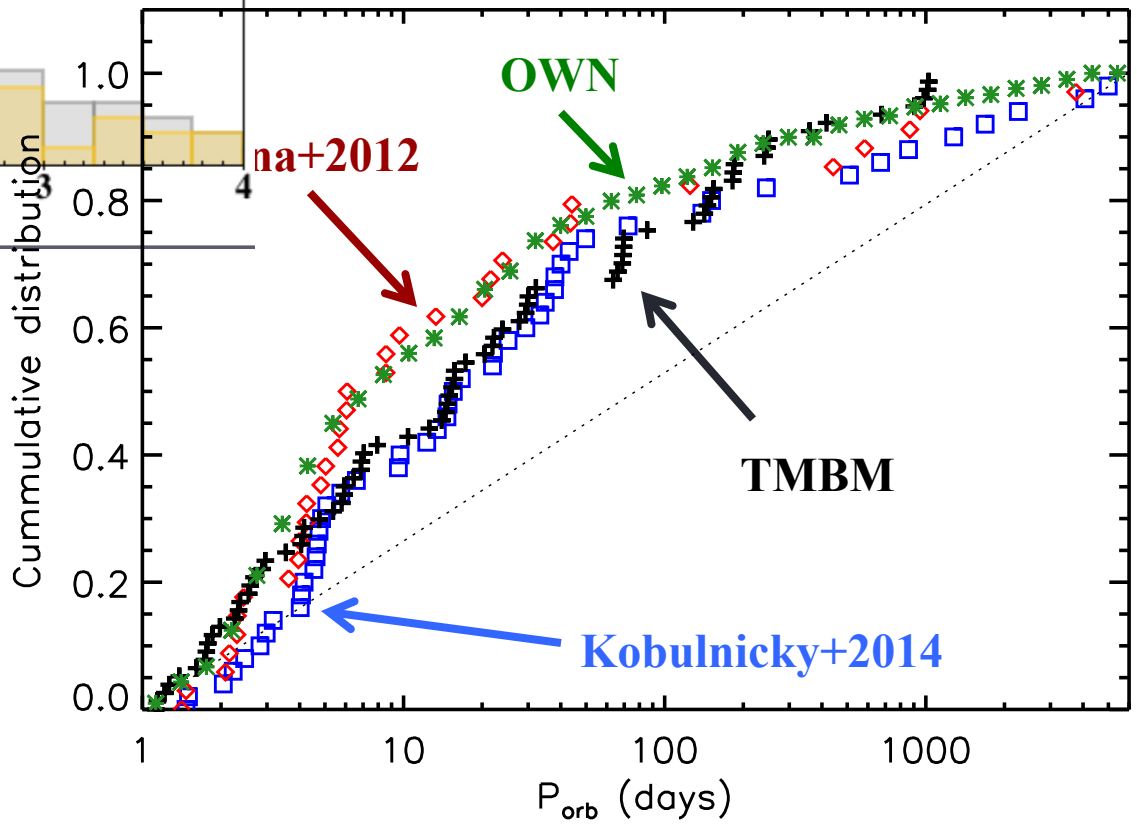


Barba+2017

OWN Survey



Rodolfo Barba

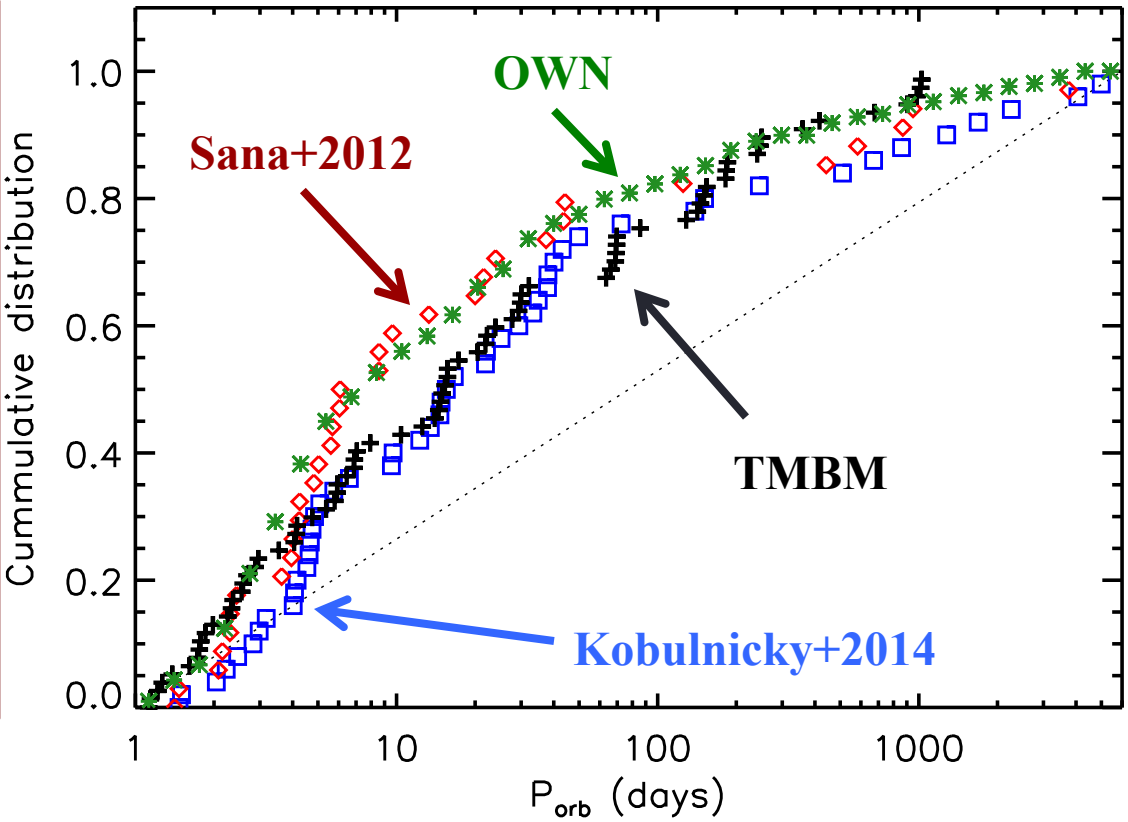


Observed period distributions

Little variations for
- **Different environments**
- **Different Z [1…0.4 $Z_\odot$]**

Similar results for q & e

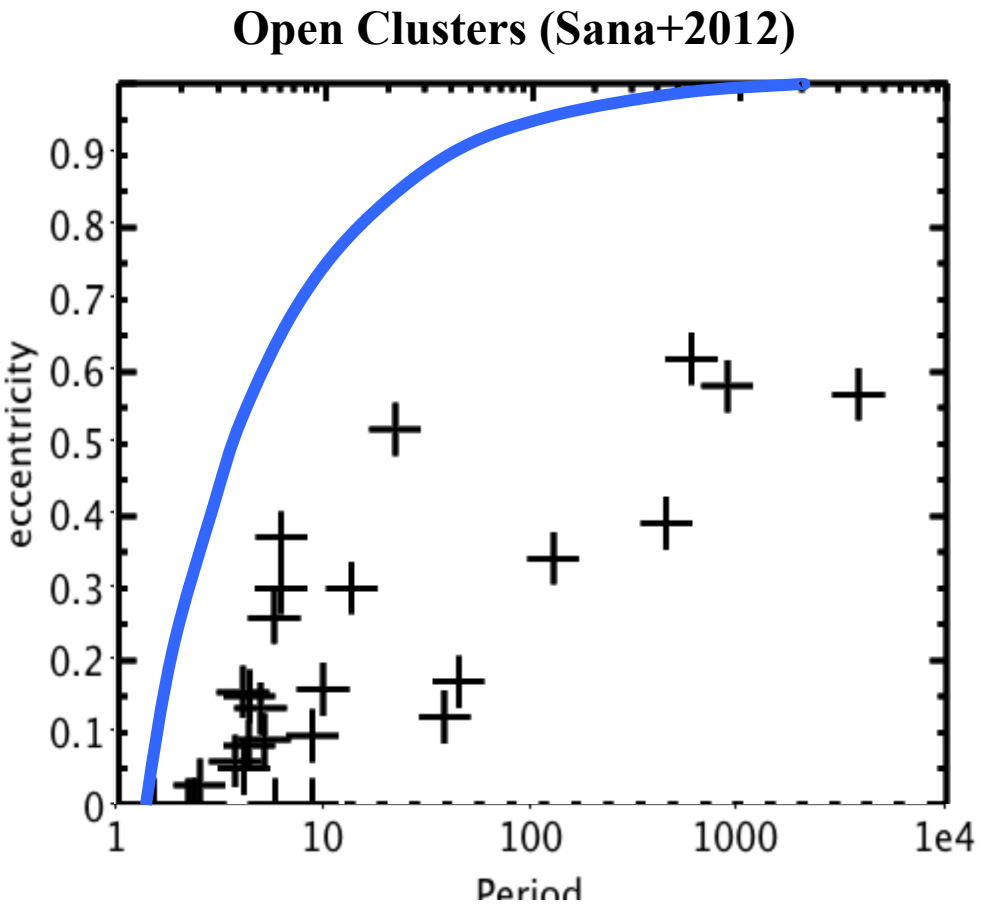
Relative universality results from physics of the formation process ?



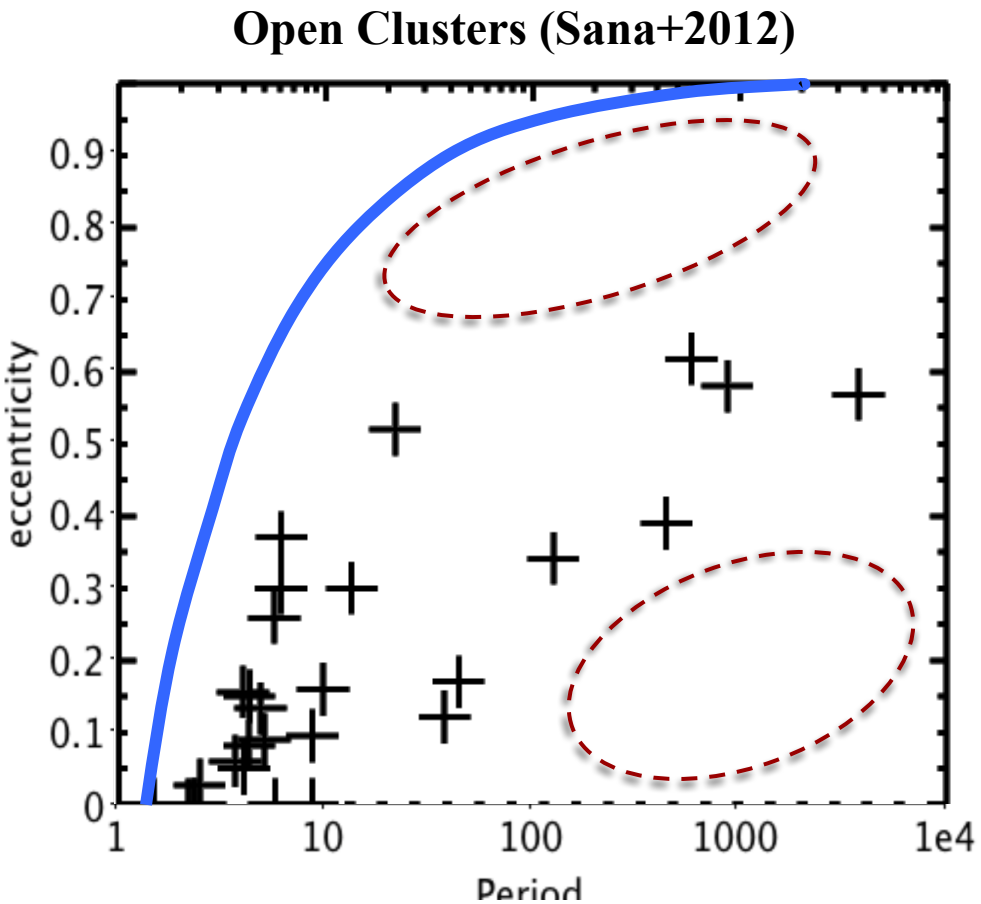
New results for B stars are coming → Poster #69 Ramirez-Agudelo et al.

Almeida+2016

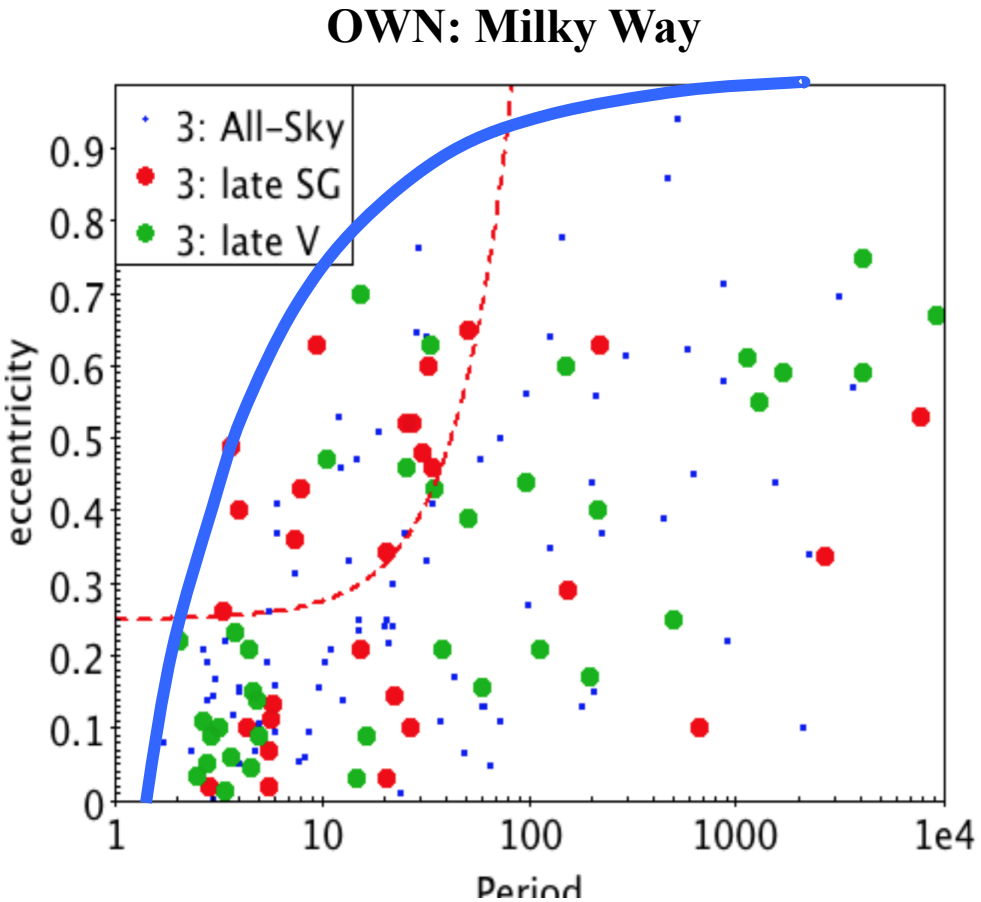
Period-eccentricity



Period-eccentricity

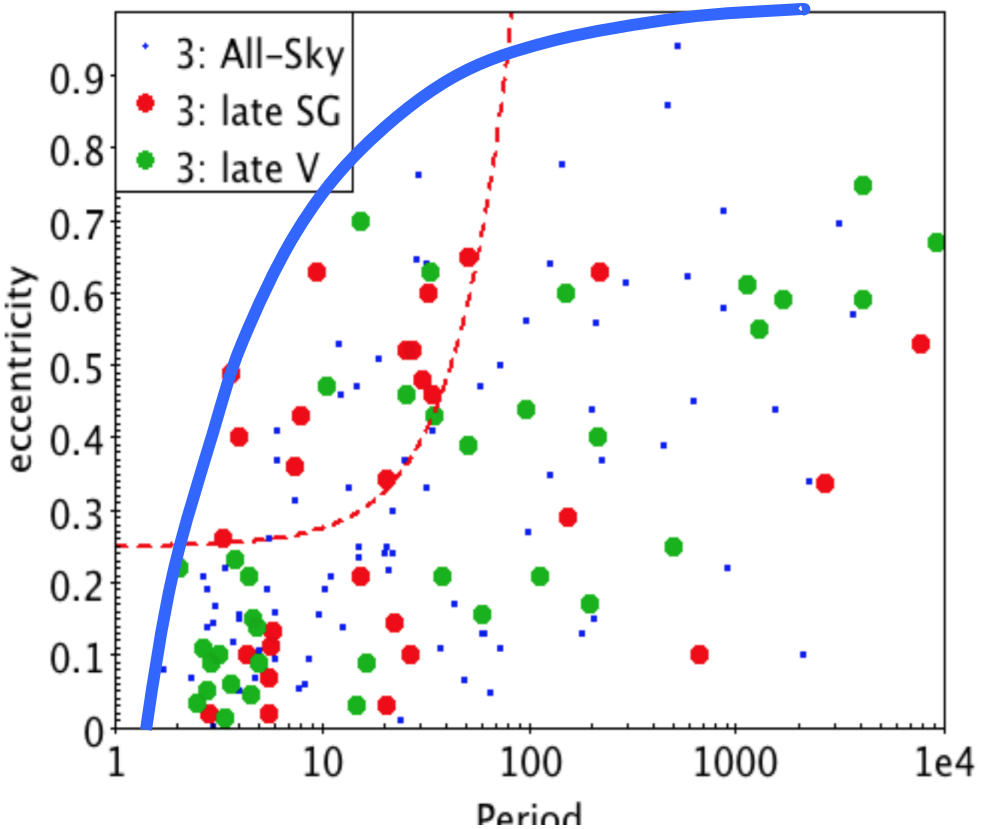


Period-eccentricity

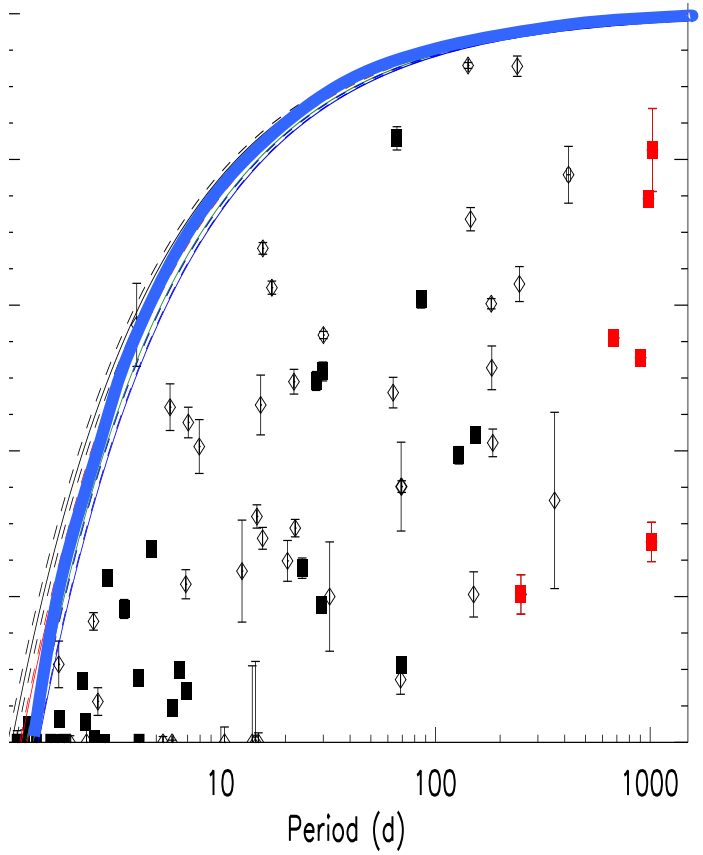


Period-eccentricity

OWN: Milky Way



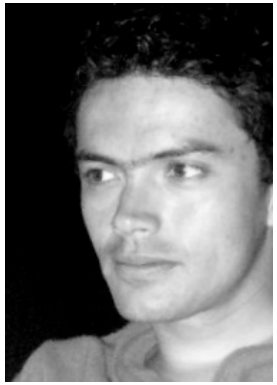
TMBM: 30 Doradus (LMC)



Rotation rates

Rotation rates

Rotation distribution of single O stars in 30 Dor



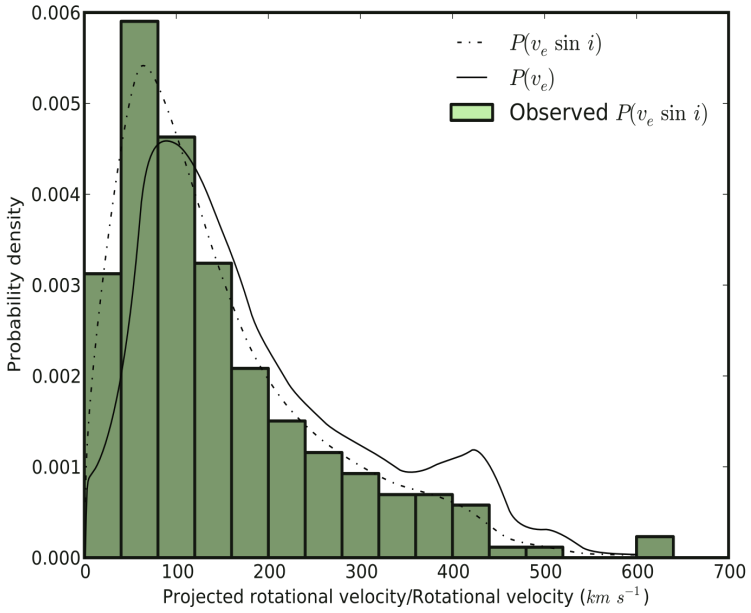
Ramirez-Agudelo+ 2013

… and in the Milky Way

Simon-Diaz+ 2014

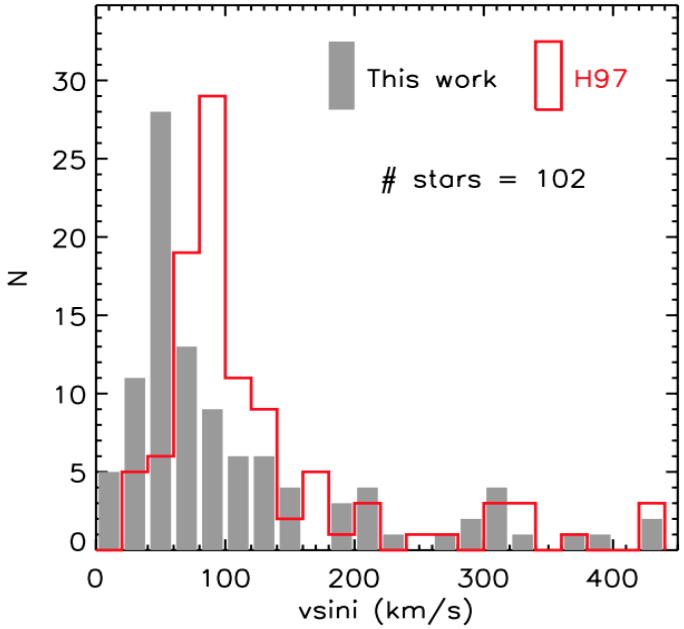
Rotation rates

Spin distribution of single O stars in 30 Dor



Ramirez-Agudelo+ 2013

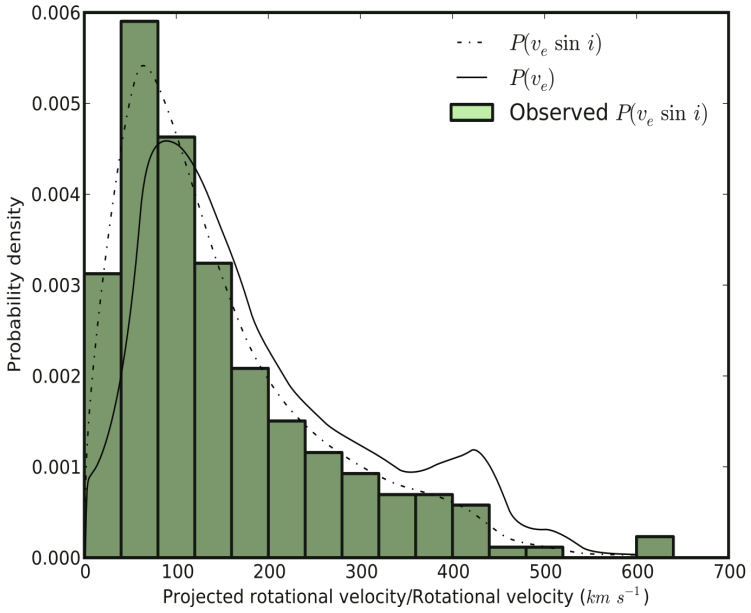
… and in the Milky Way



Simon-Diaz+ 2014

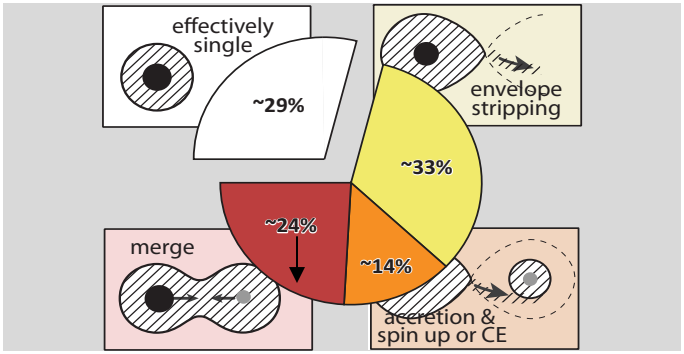
Rotation rates

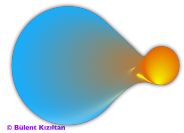
Spin distribution of single O stars in 30 Dor



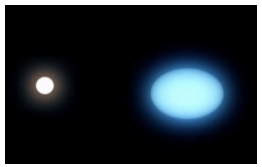
Ramirez-Agudelo+ 2013

Pop. Synthesis of the impact of binarity on massive star rotation rate





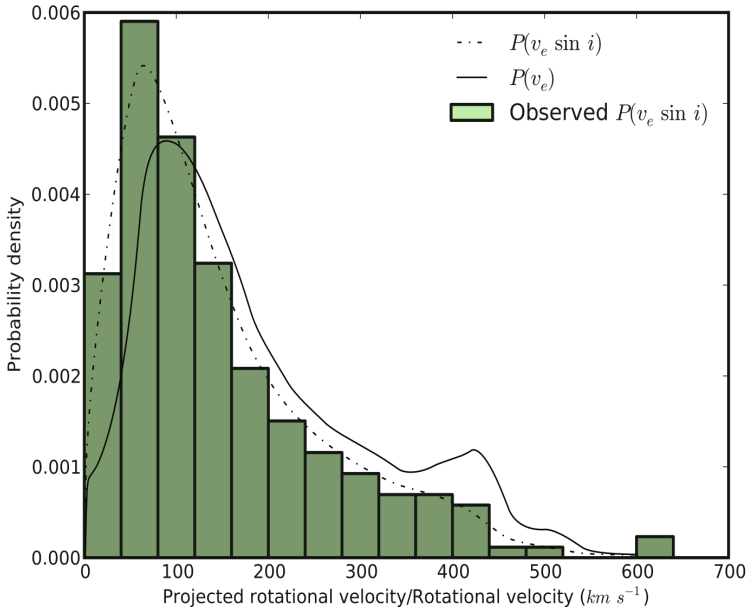
Coallescence



Spun up mass gainer

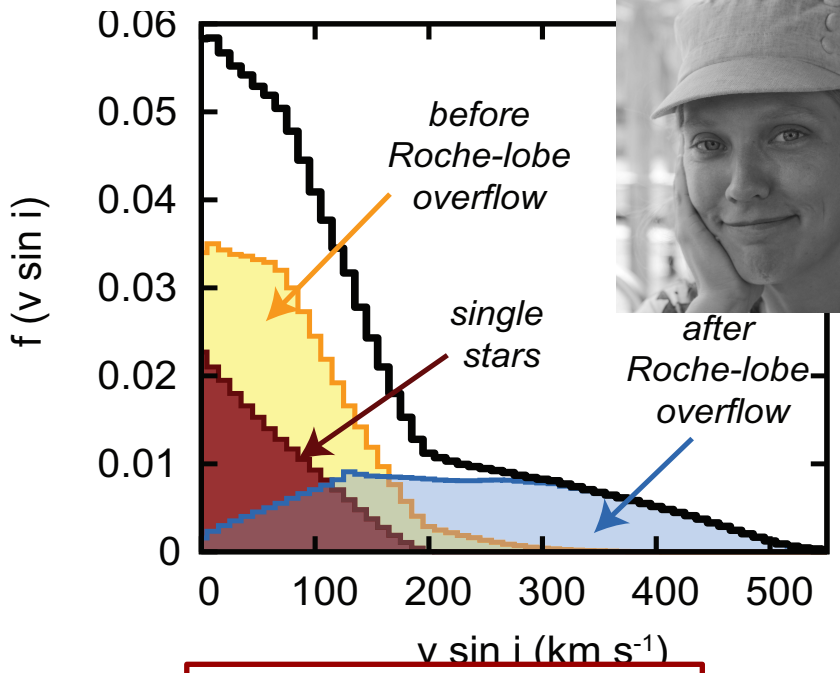
Rotation rates

Spin distribution of single O stars in 30 Dor



Ramirez-Agudelo+ 2013

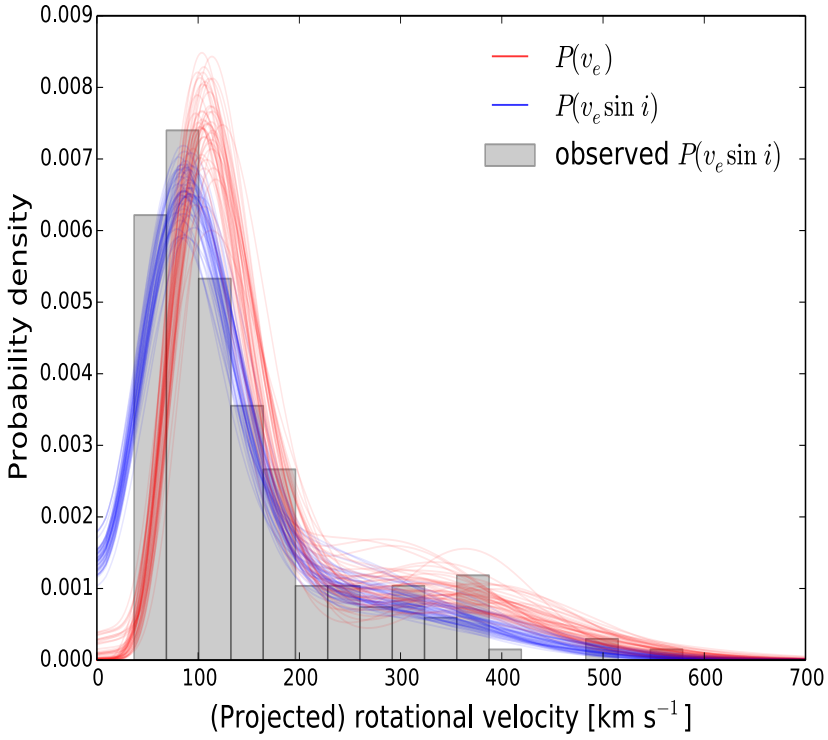
Pop. Synthesis of the impact of binarity on massive star rotation rate



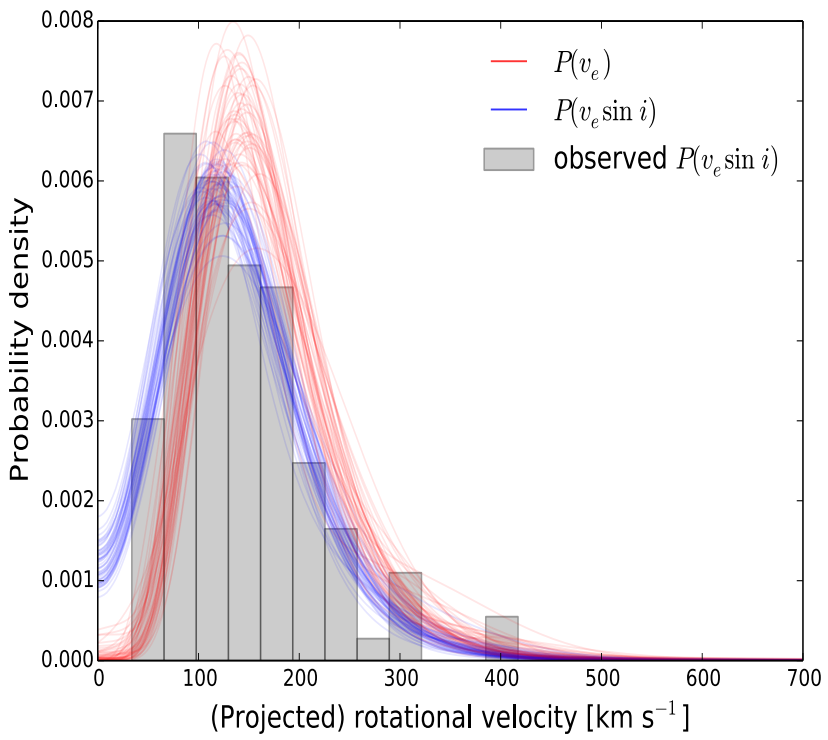
De Mink+ 2013

Single vs. binaries

Single O stars in 30 Dor



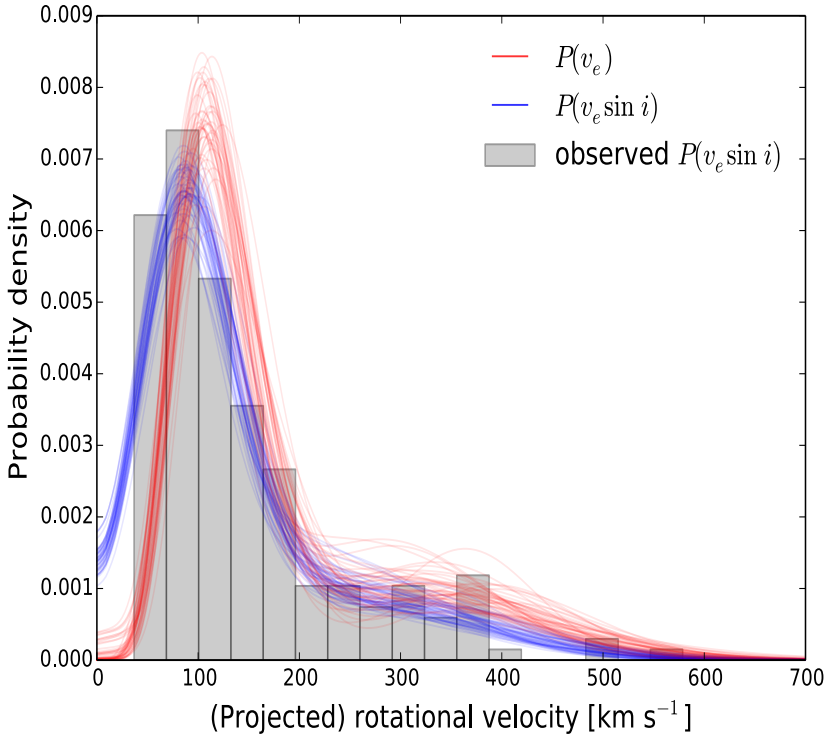
Primary O stars in SB1/SB2



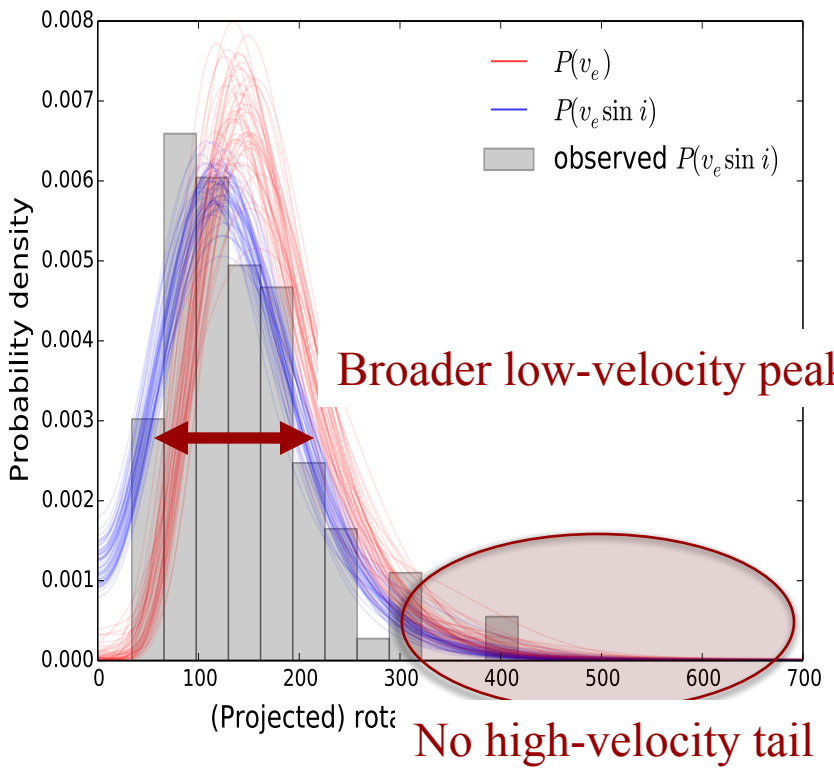
Ramirez-Agudelo+ 2015

Single vs. binaries

Single O stars in 30 Dor



Primary O stars in SB1/SB2



Ramirez-Agudelo+ 2015

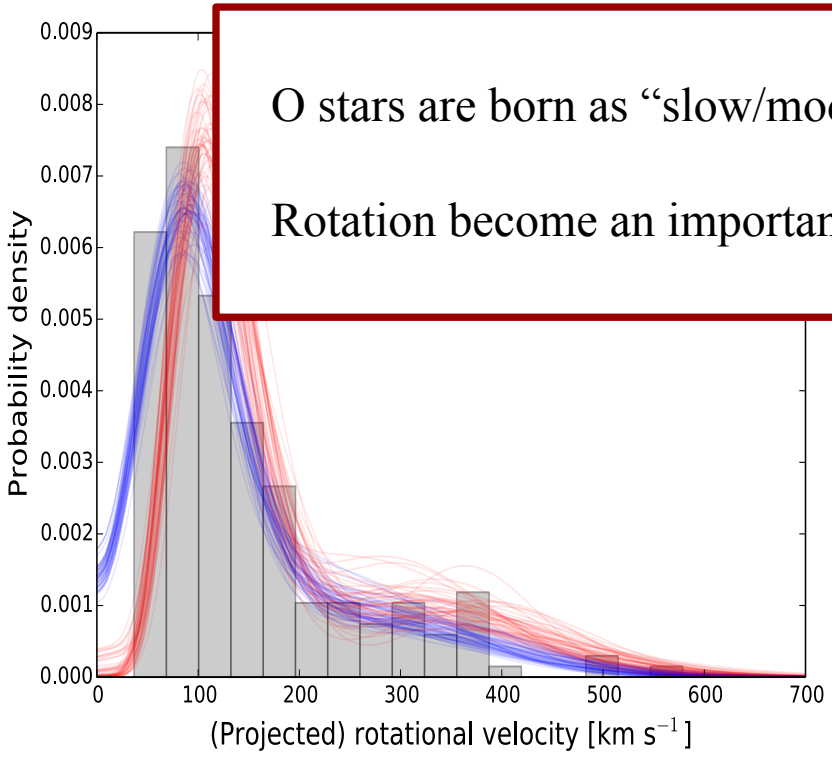
Single vs. binaries

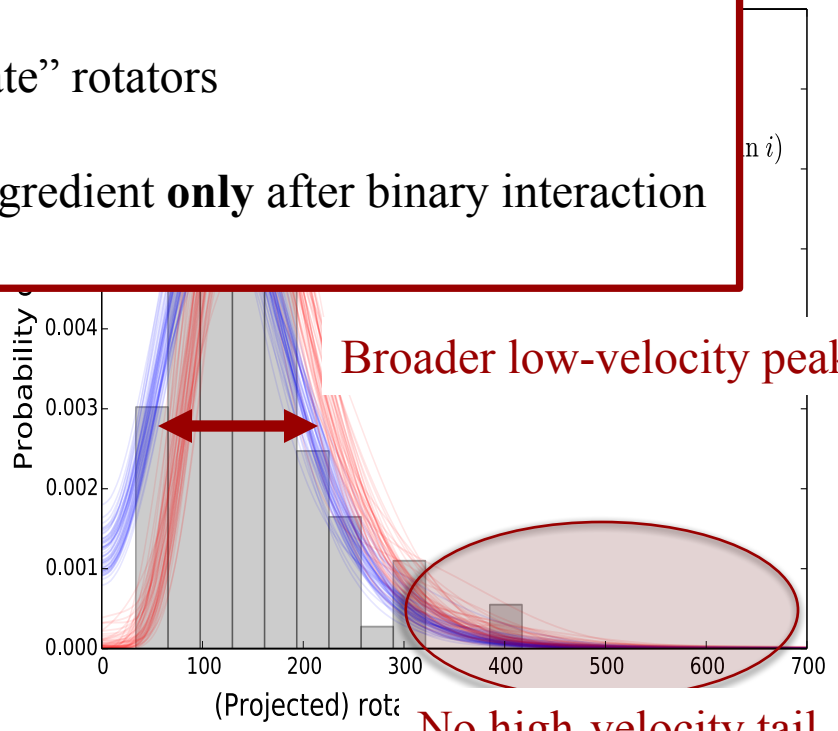
Single O stars in 30 Dor

Primary O stars in SB1/SB2

O stars are born as "slow/moderate" rotators

Rotation become an important ingredient **only** after binary interaction





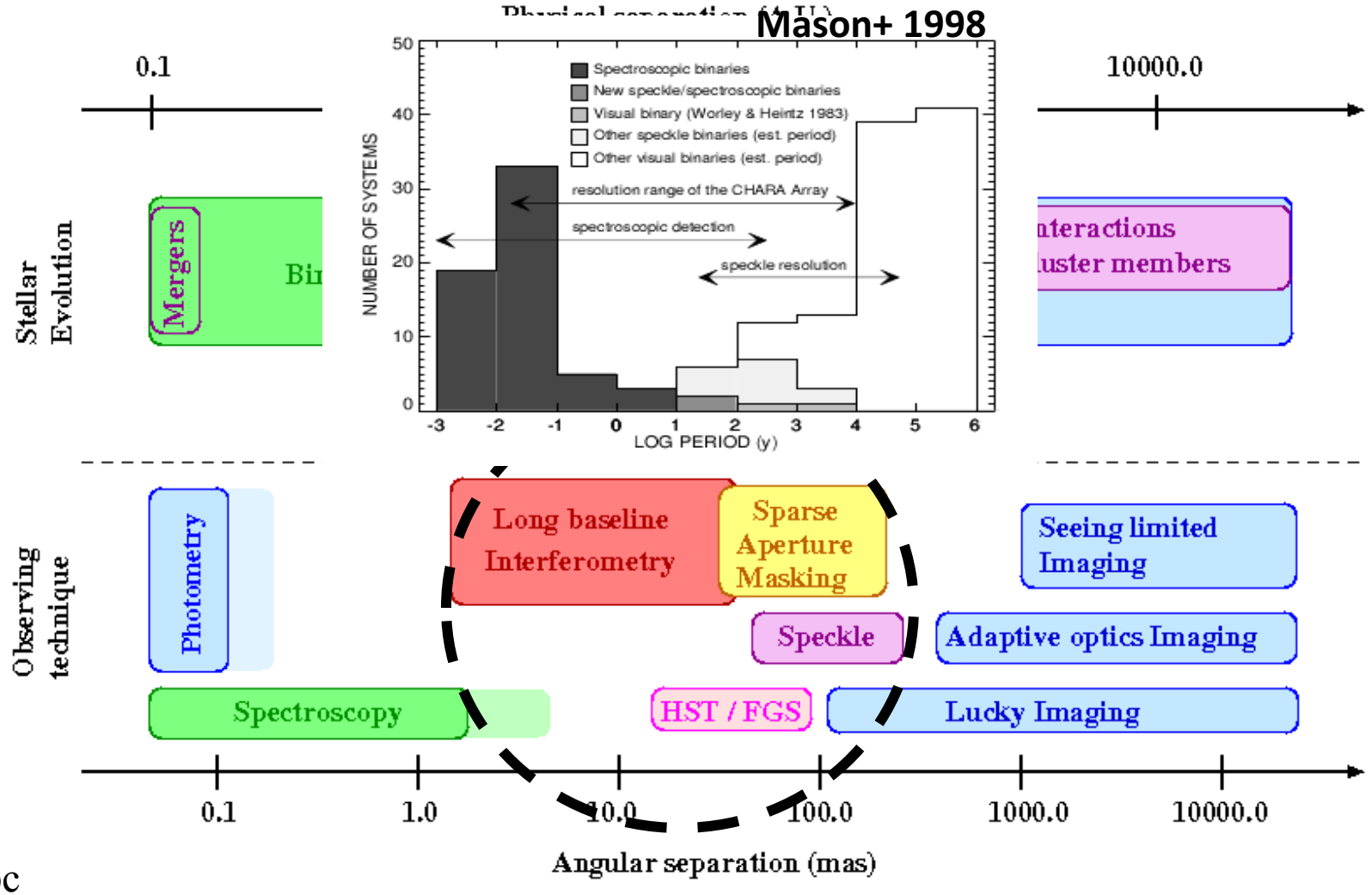
Broader low-velocity peak

No high-velocity tail

Ramirez-Agudelo+ 2015

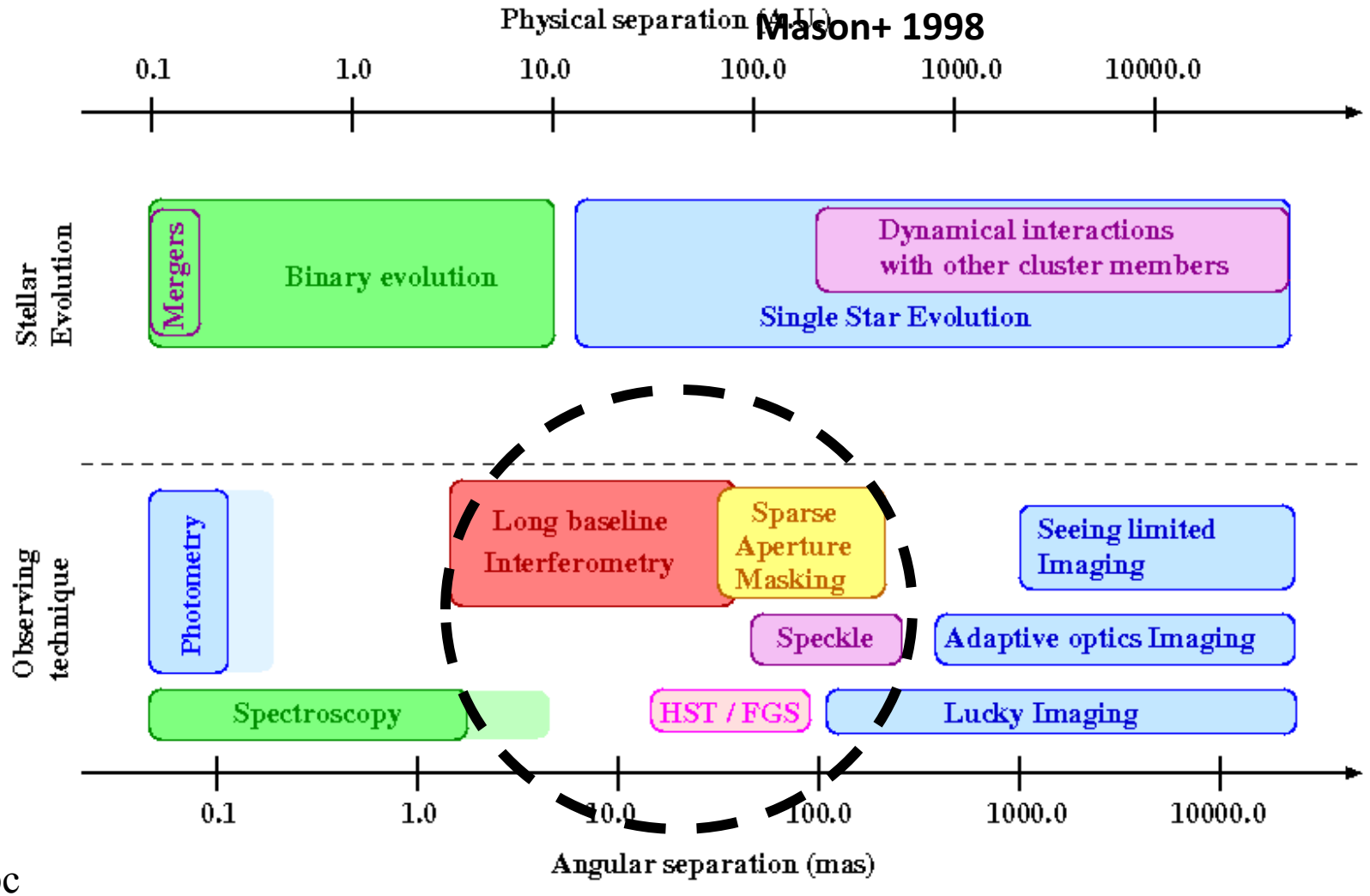
High-angular resolution techniques

Parameter space



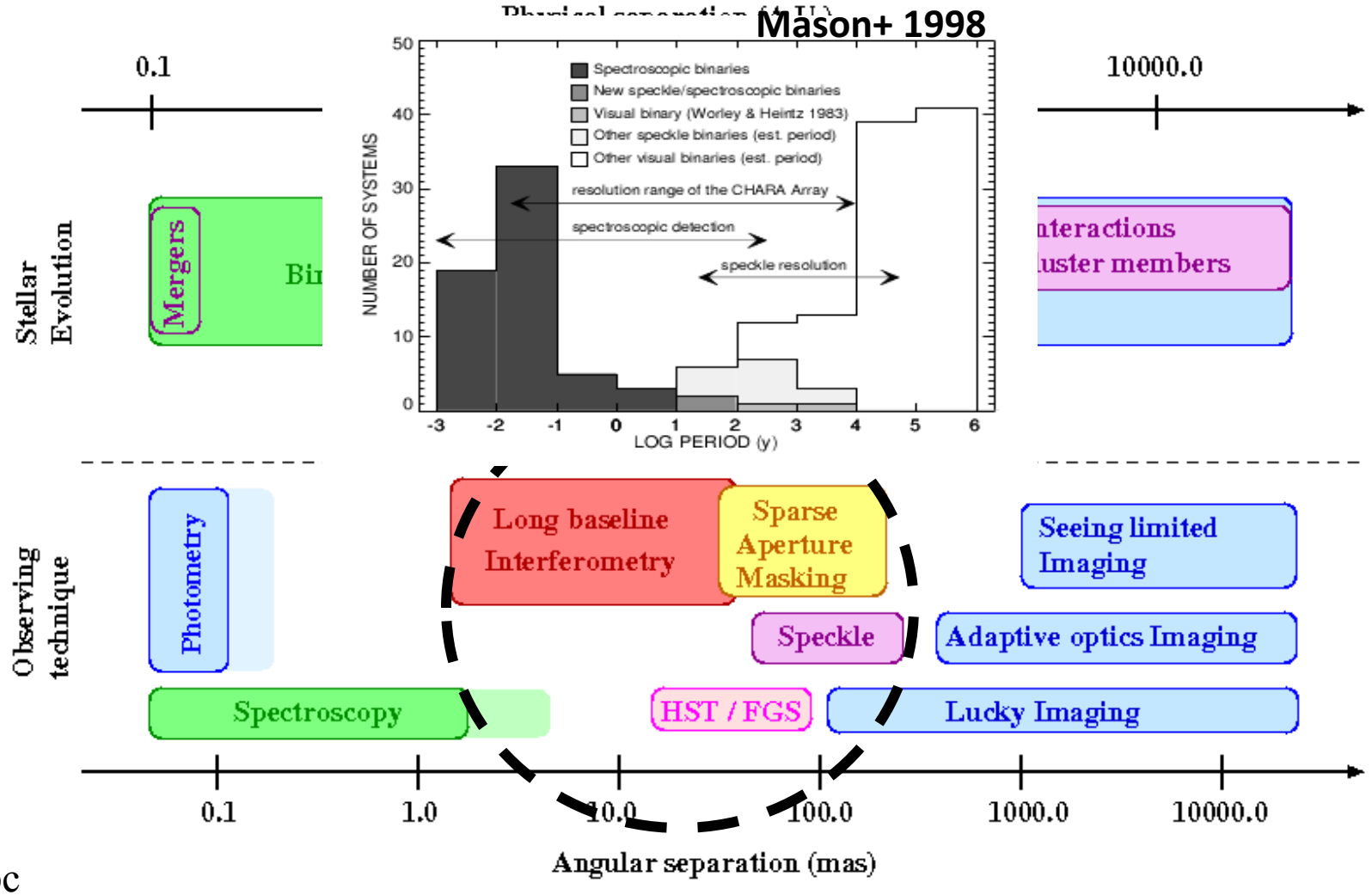
D=2kpc

Parameter space



D=2kpc

Parameter space



D=2kpc

The SMASH Survey

SMASH+

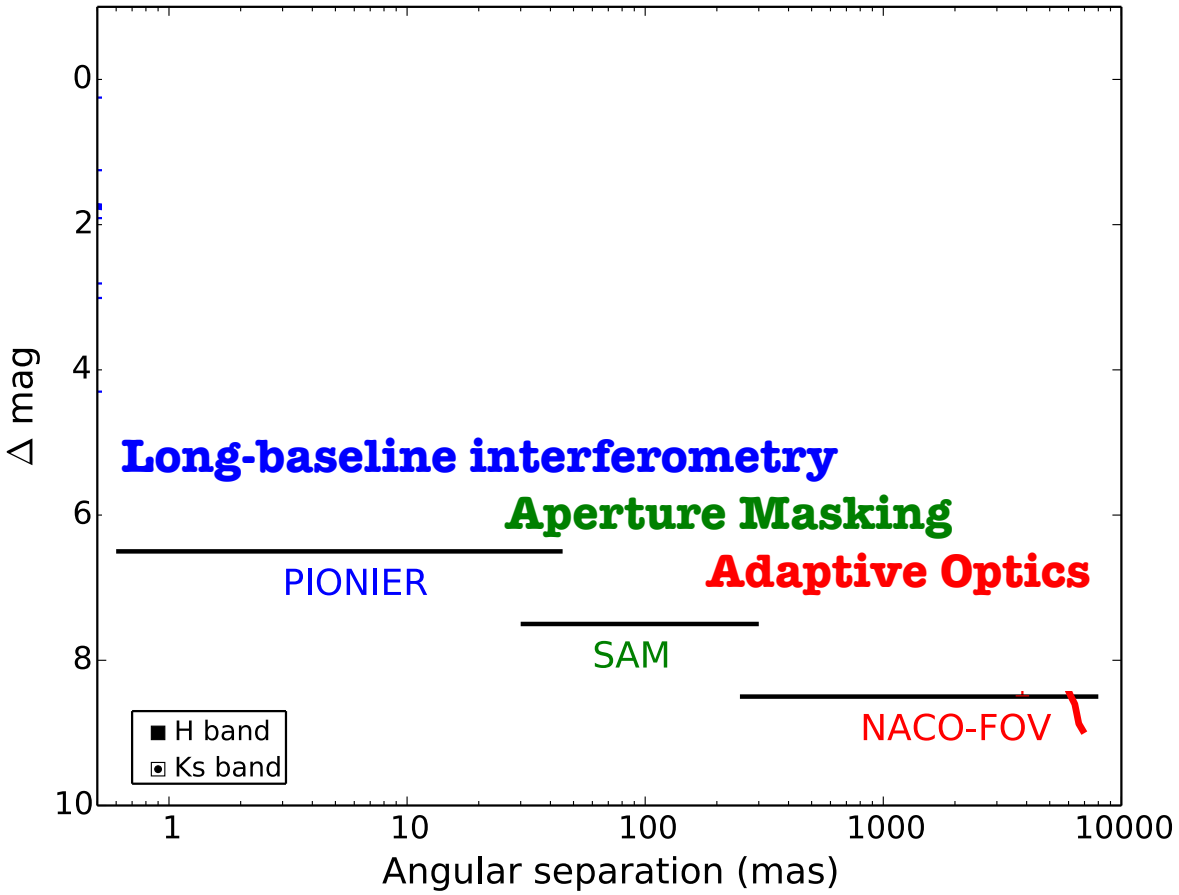
Sana+2014

Sample selection:
DEC< 0° , H < 7.5mag

174 targets
196 new companions

HST/FGS

Aldoretta+2014



SMASH & HST/FGS

SMASH+

Sana+2014

Sample selection:
DEC< 0° , H < 7.5mag

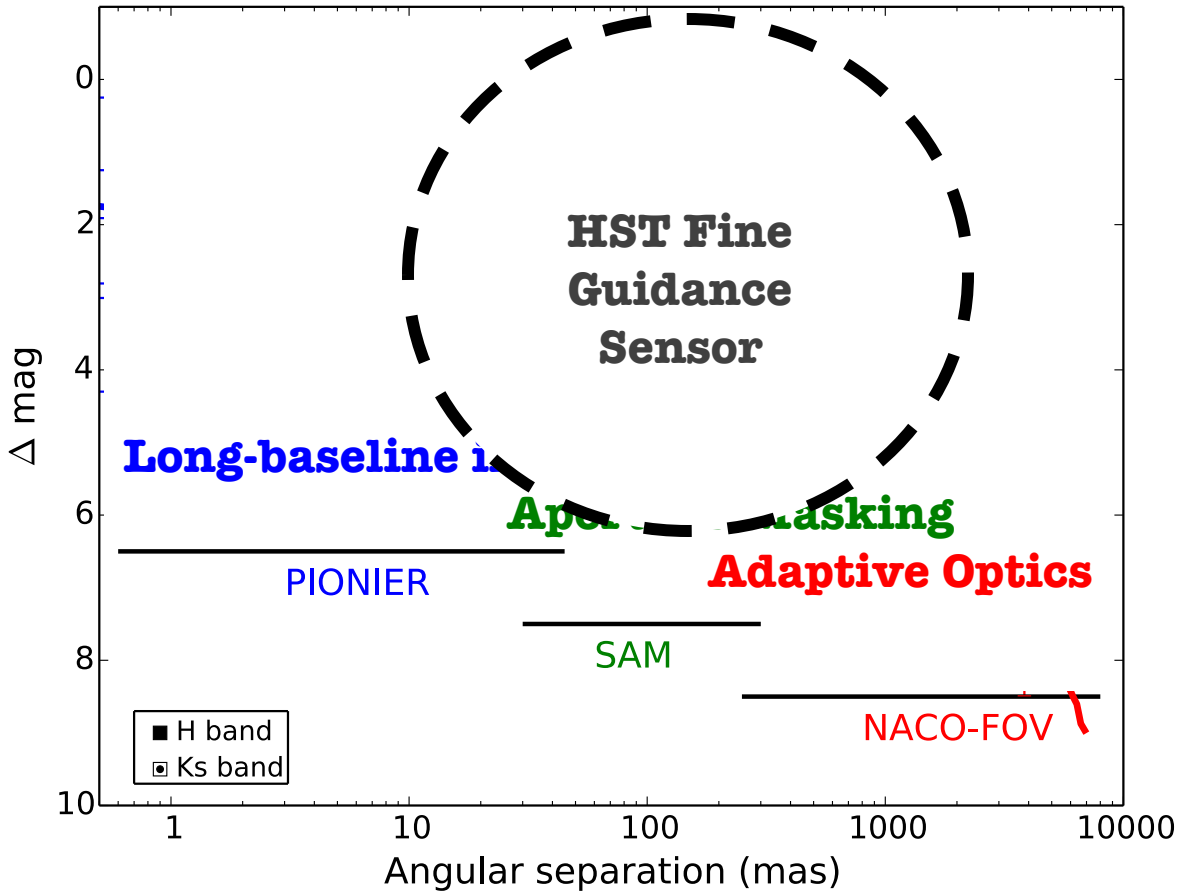
174 targets
196 new companions

HST/FGS

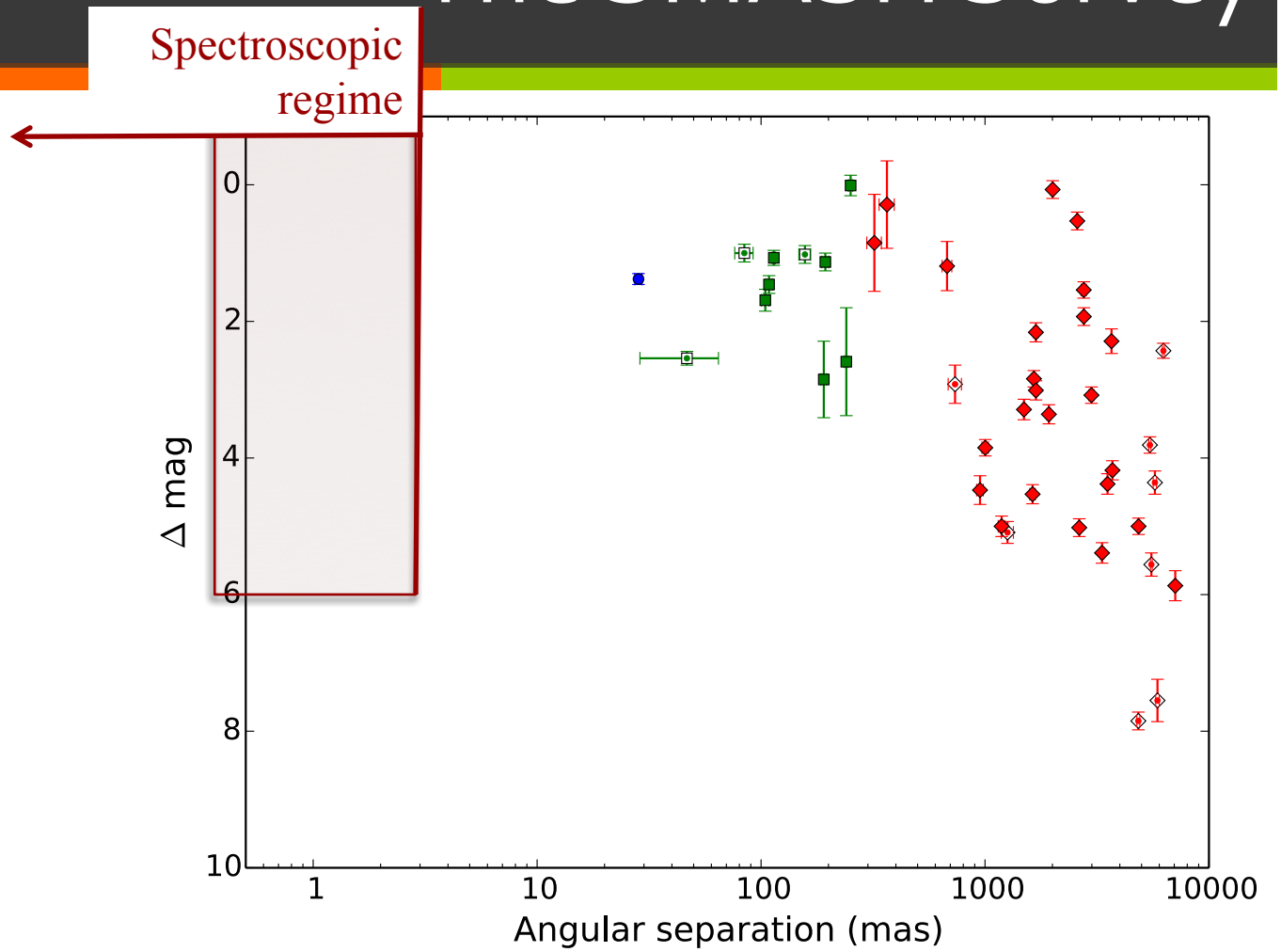
Aldoretta+2014

Sample selection:
DEC< 0° , H < 7.5mag

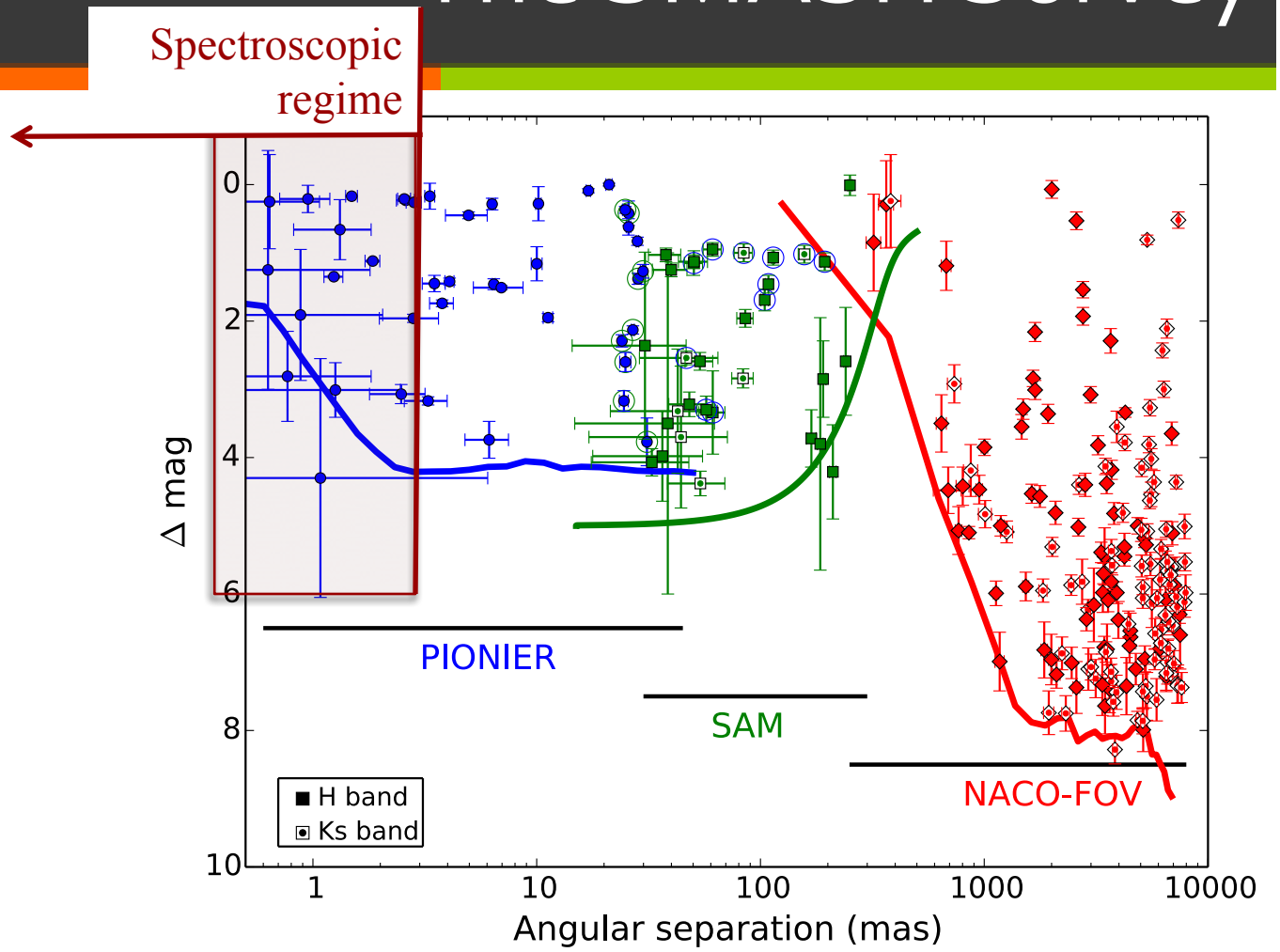
224 targets
43 new companions



The SMASH Survey



The SMASH Survey



SMASH & HST/FGS

With SB

F_mult > 0.90

@ ρ < 700au

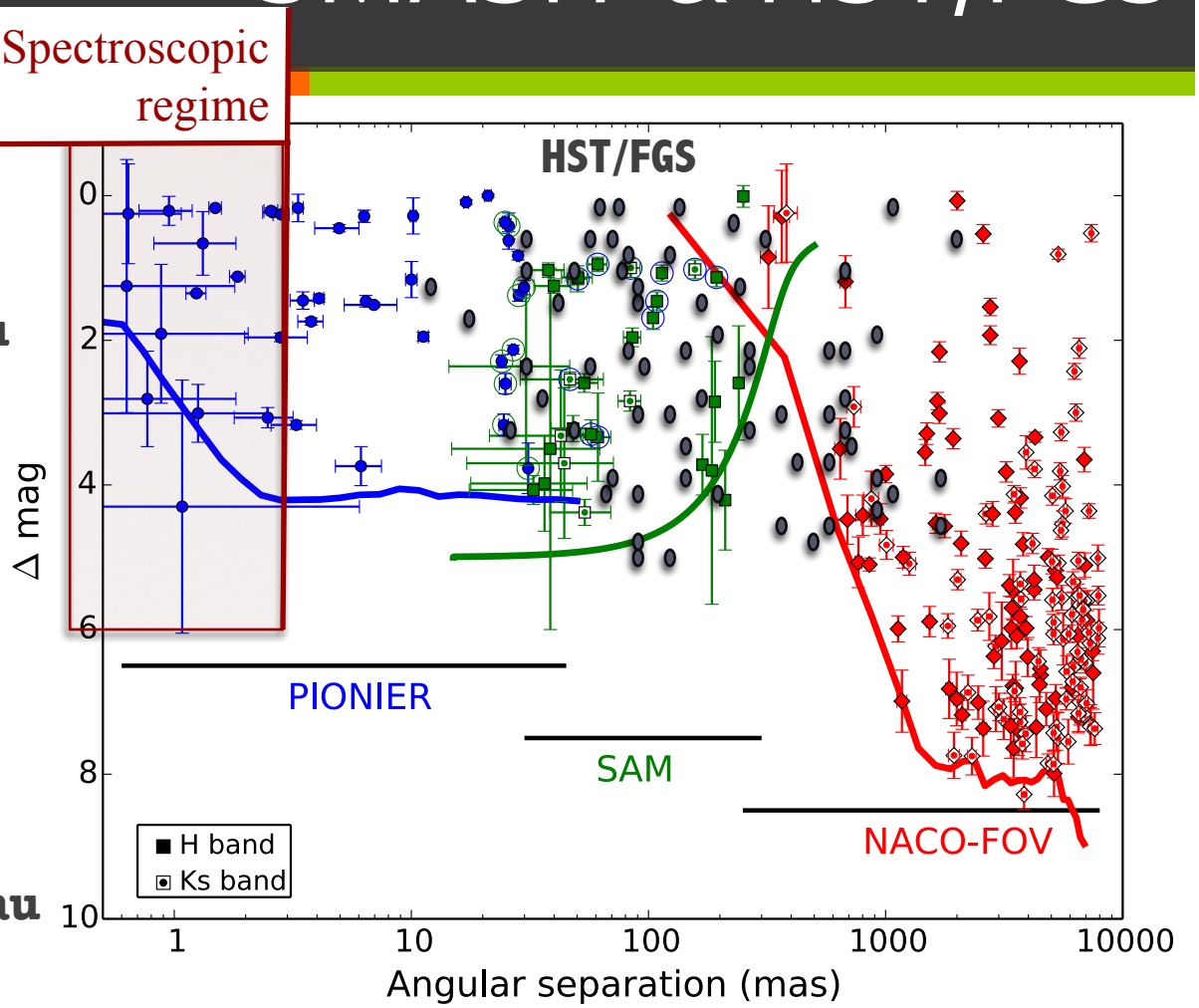
< N_companion> ~ 2.1

For dwarfs

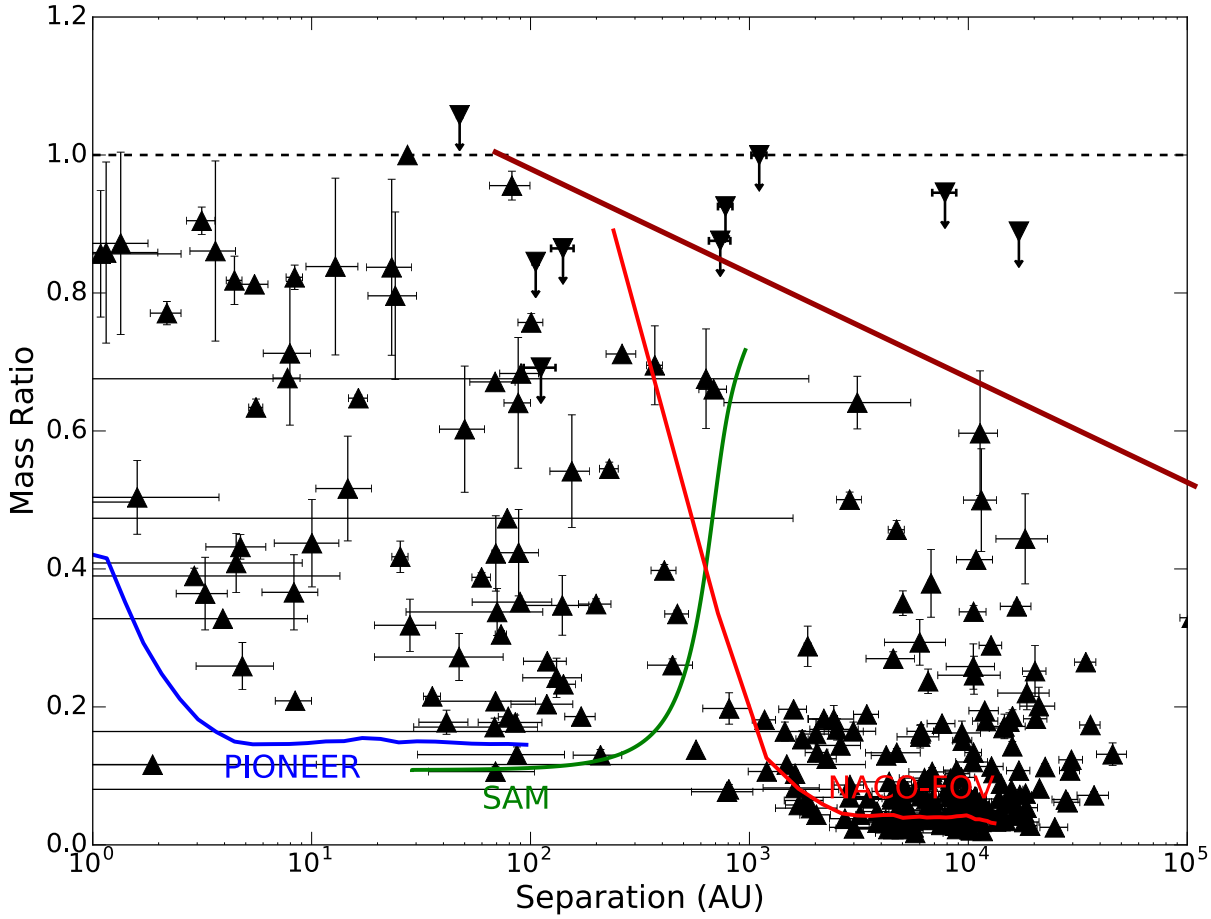
F_mult = 1.00

@ ρ < 100au

< N_companion> ~ 2.2

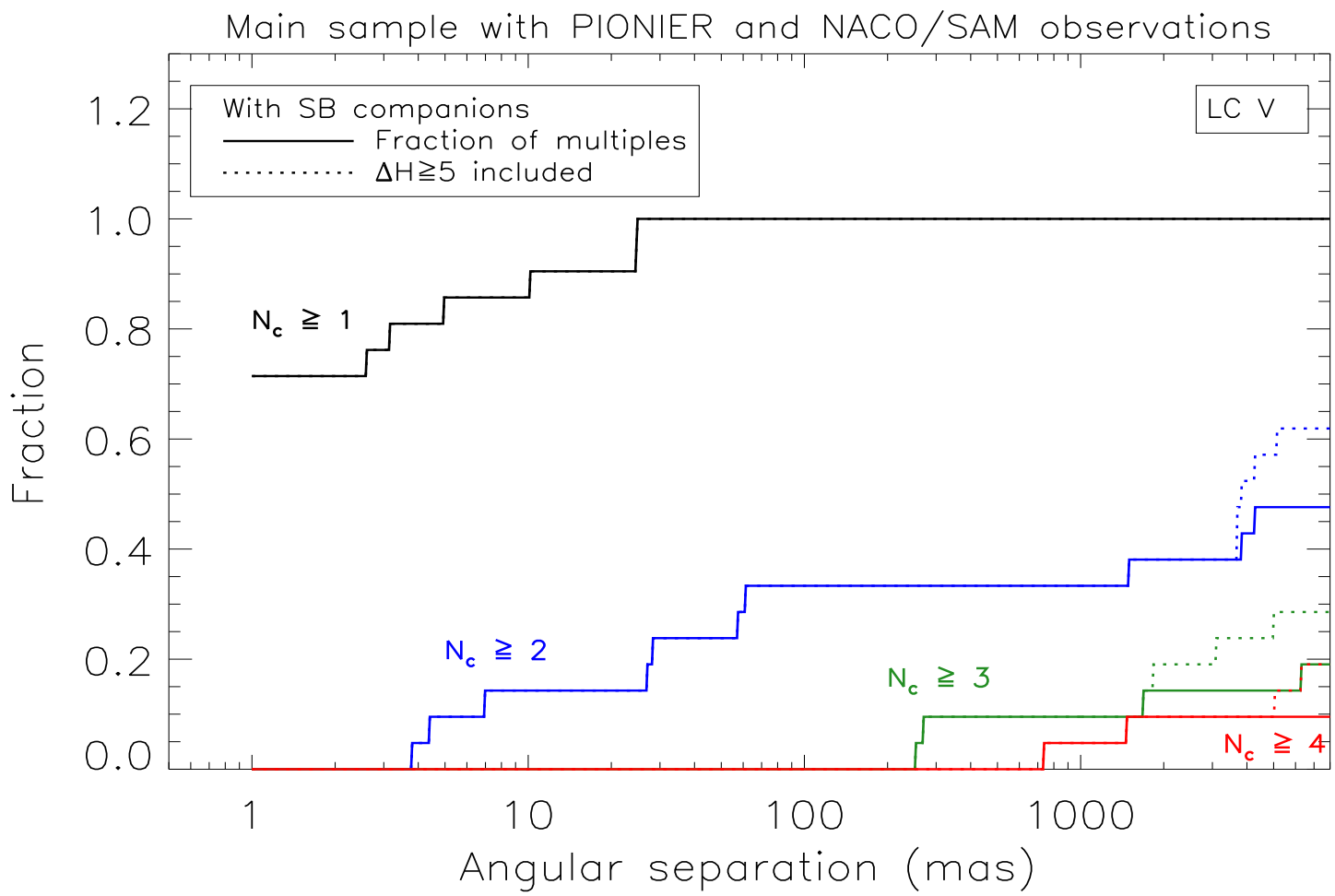


Physical quantities

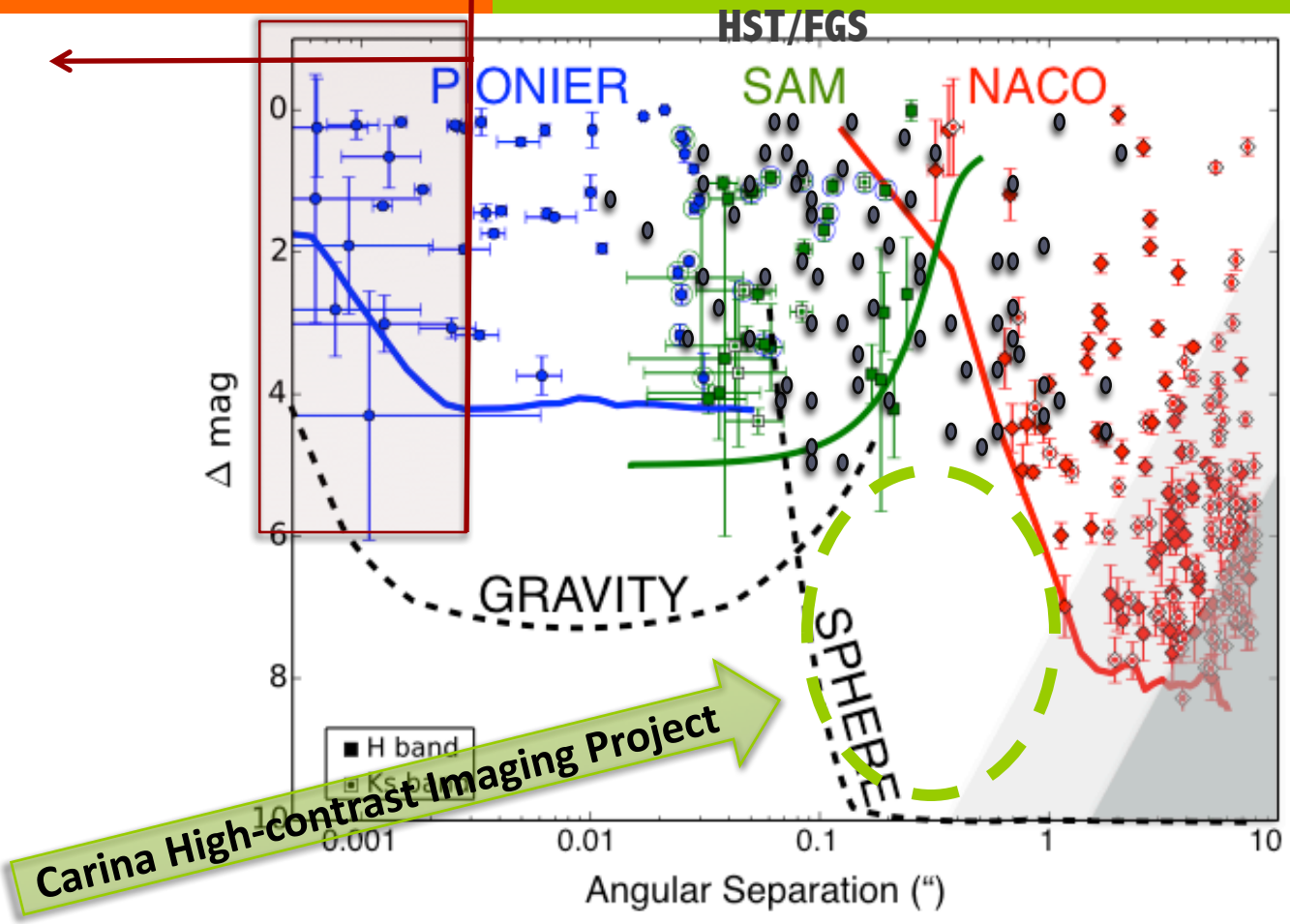


Tramper et al. , in prep

25-35% of triples in SMASH

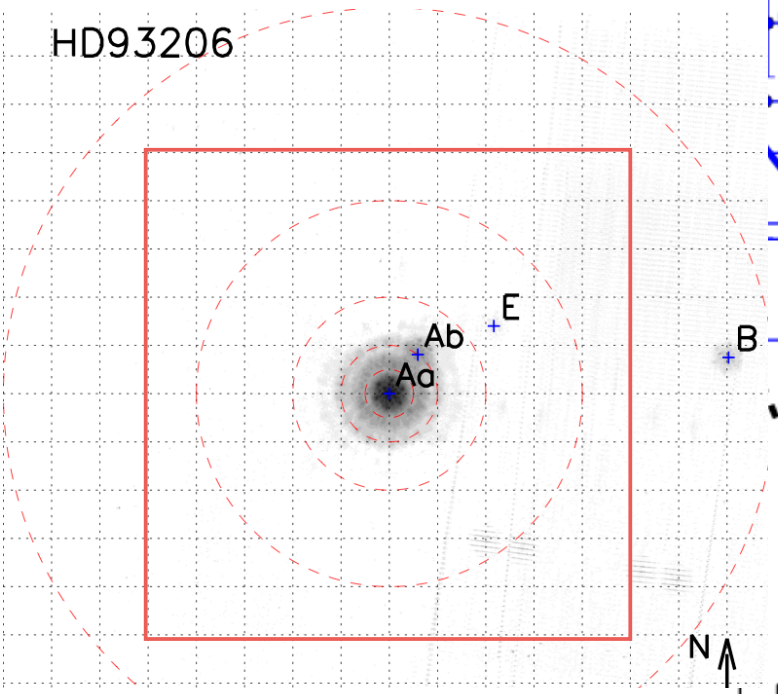


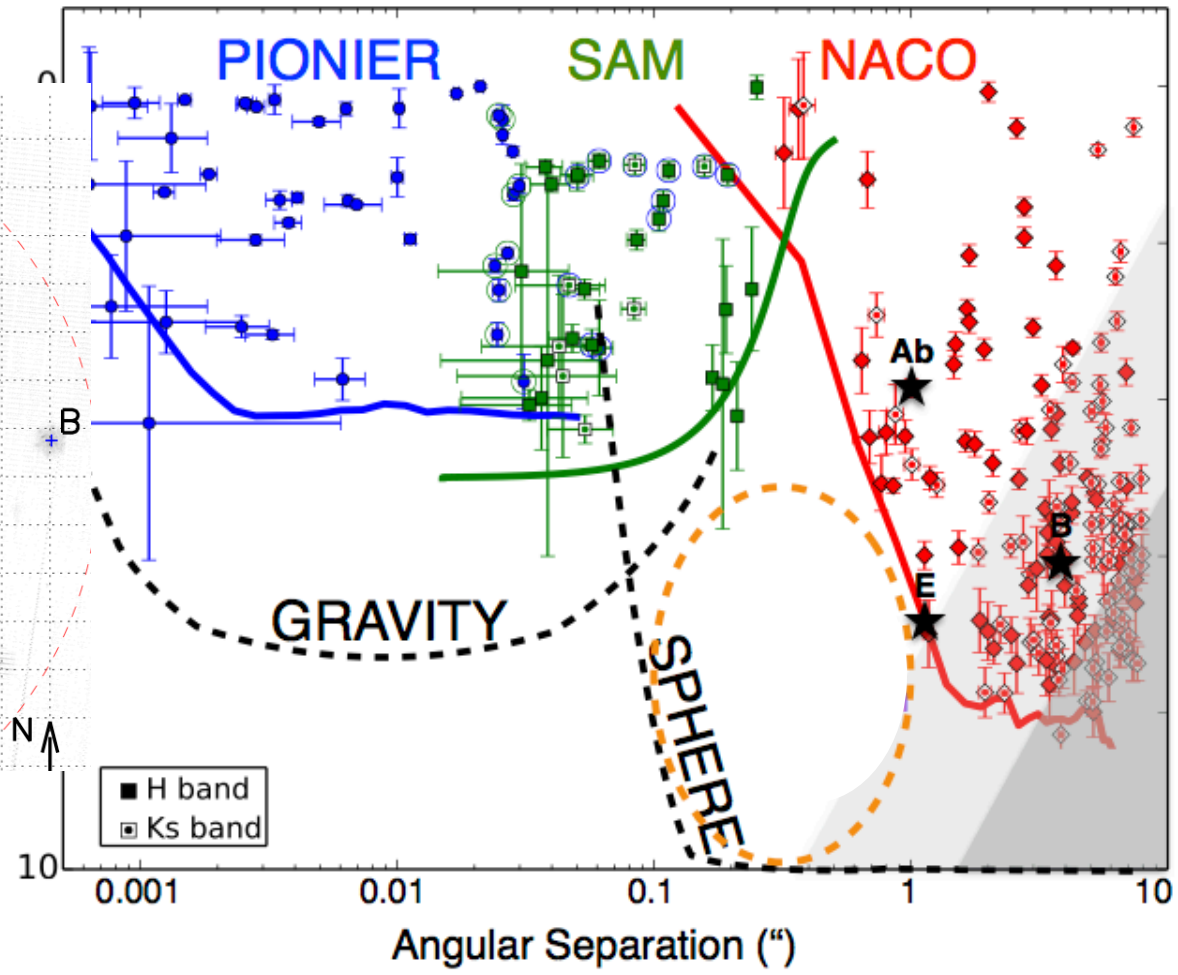
Beyond SMASH & HST/FGS



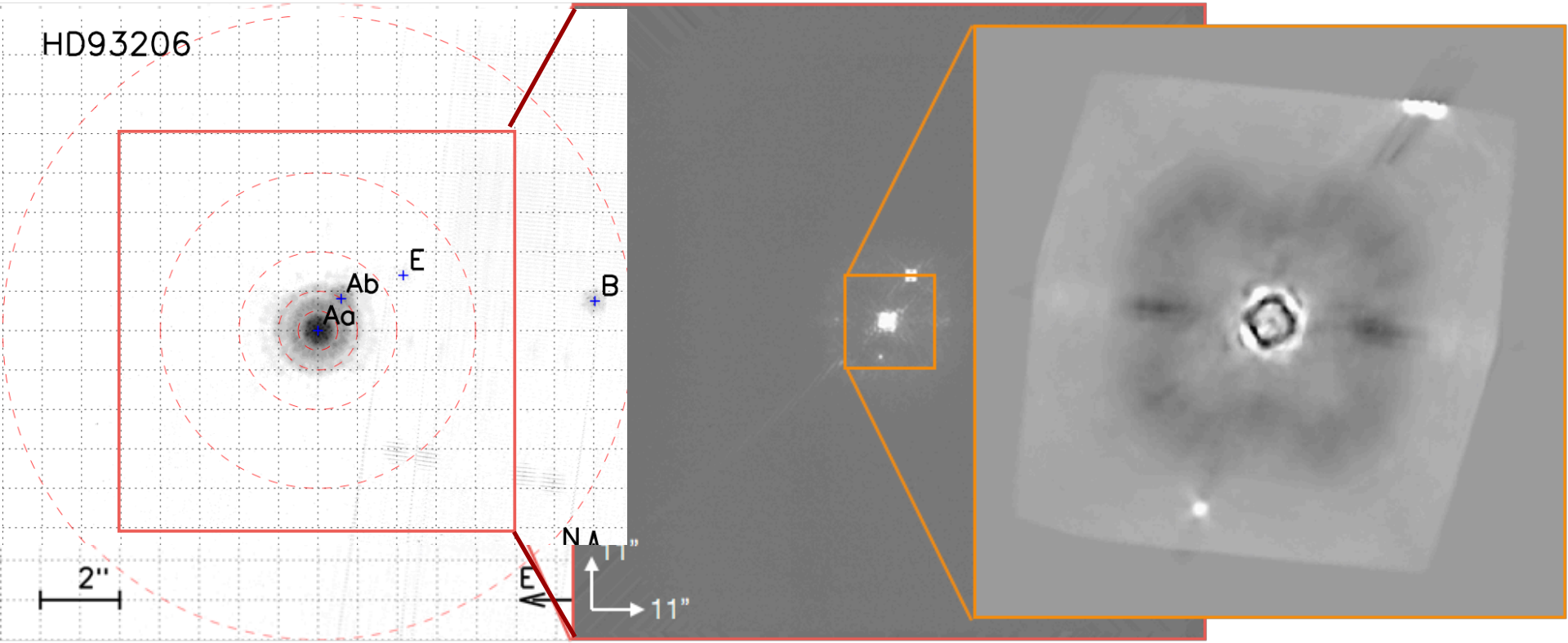
Alan RAINOT

QZ Car (HD93206)





QZ Car (HD93206)



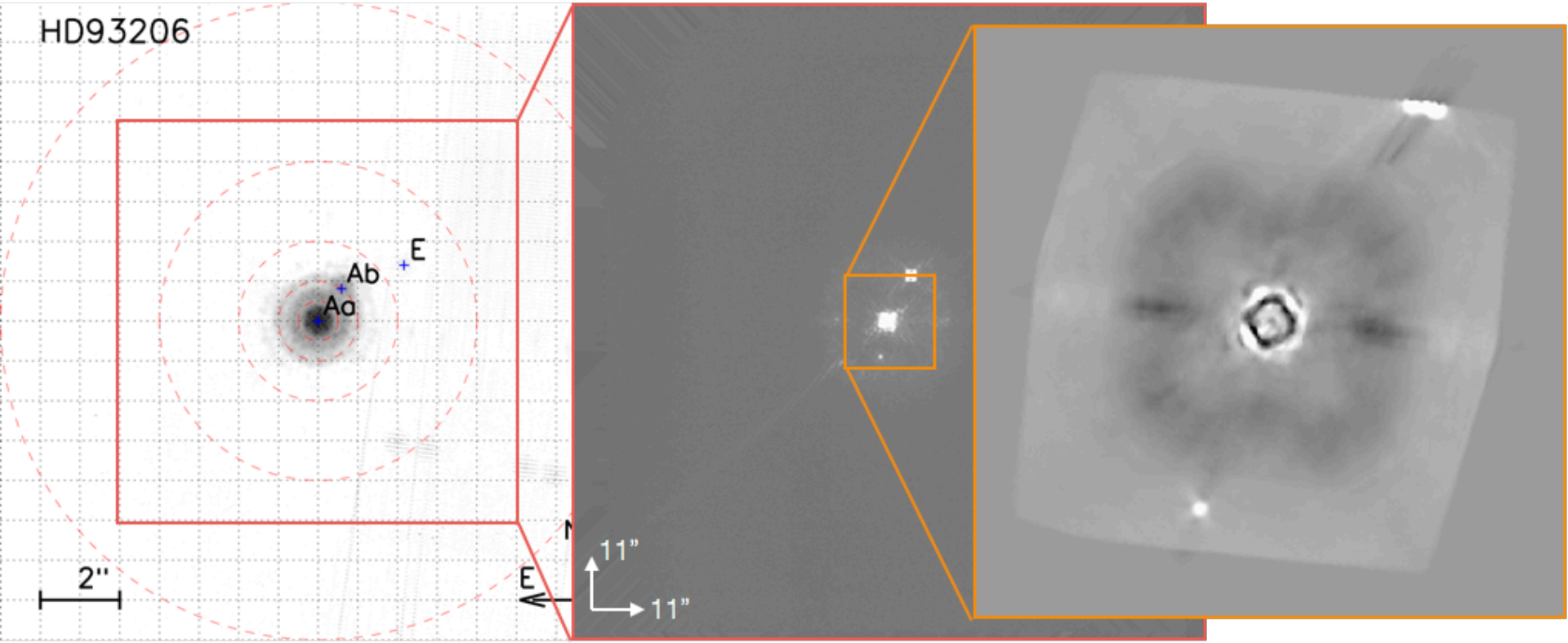
SMaSH+ Image
Sana et al, 2014

IRDIS

IFS

Rainot+, in prep

QZ Car (HD93206)



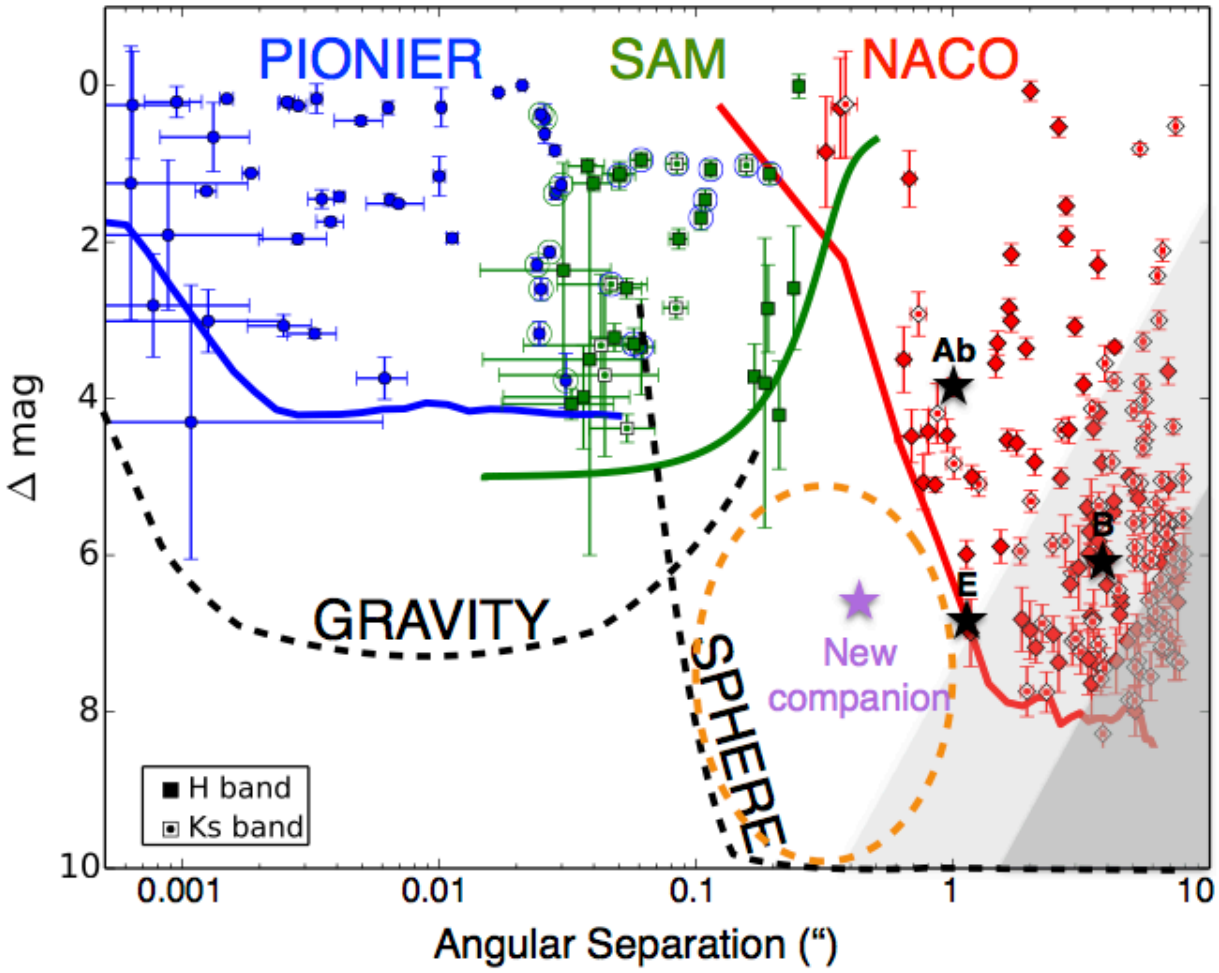
SMaSH+ Image
Sana et al, 2014

IRDIS

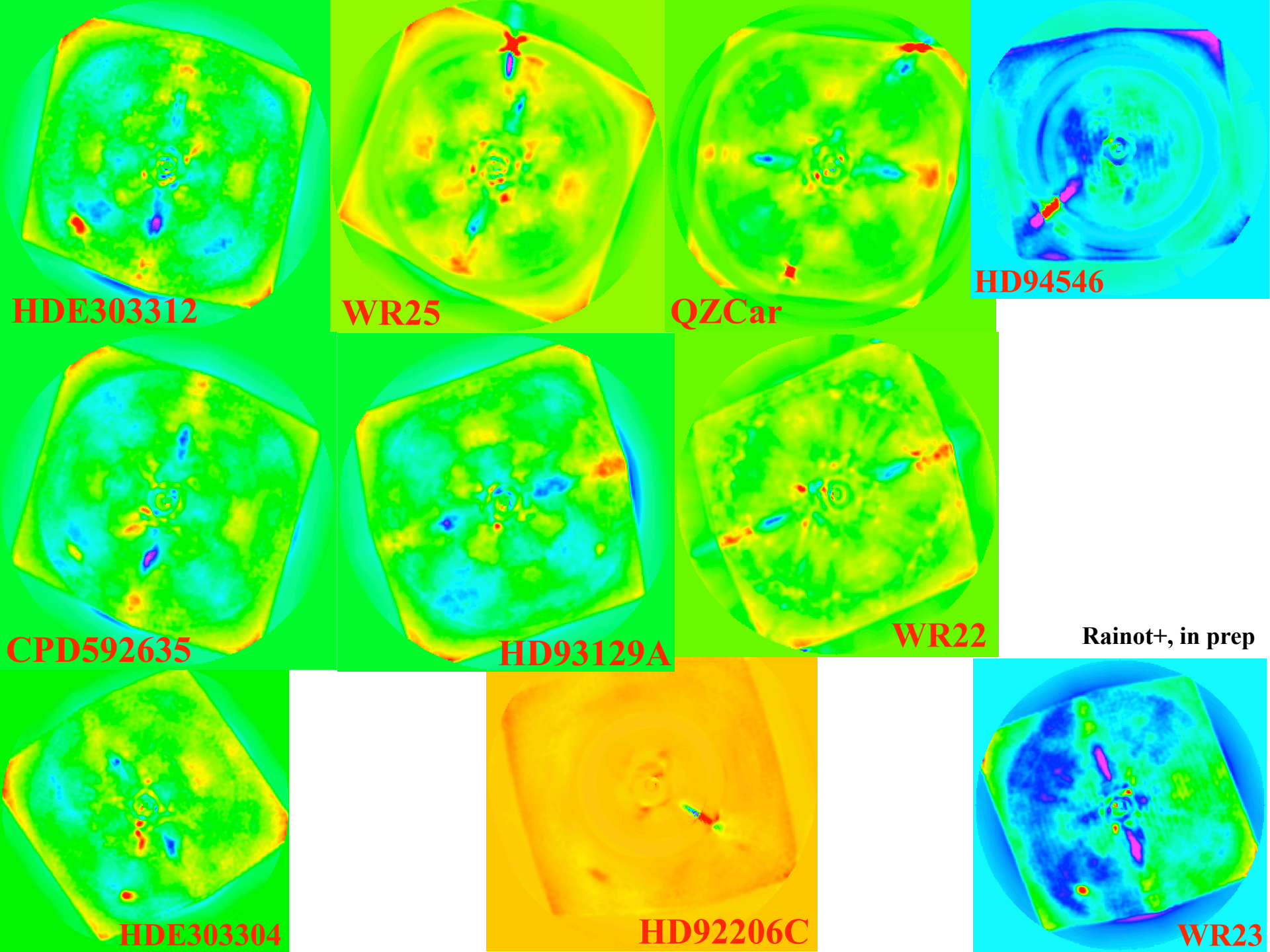
IFS

Rainot+, in prep

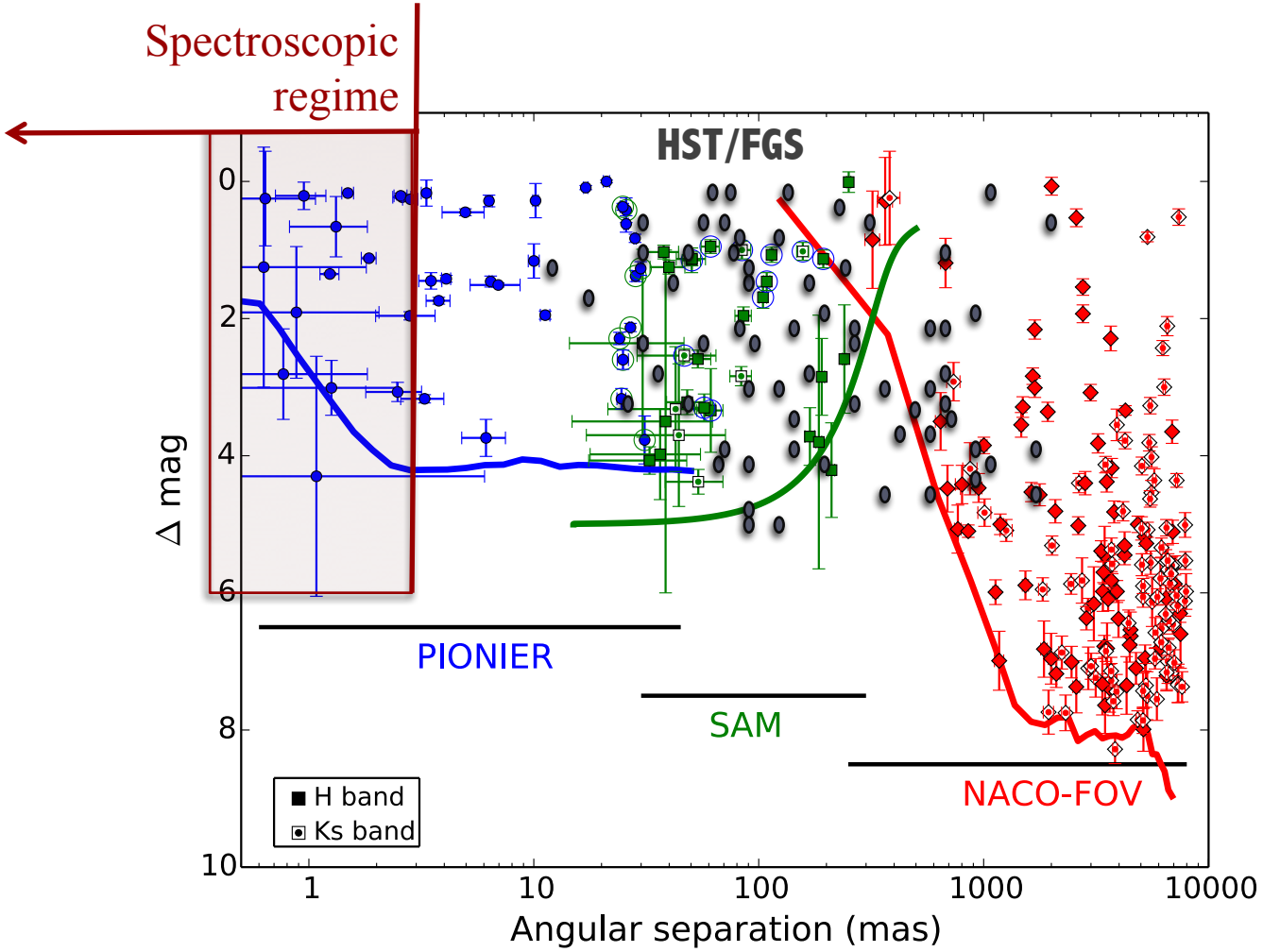
QZ Car (HD93206)



Rainot+, in prep

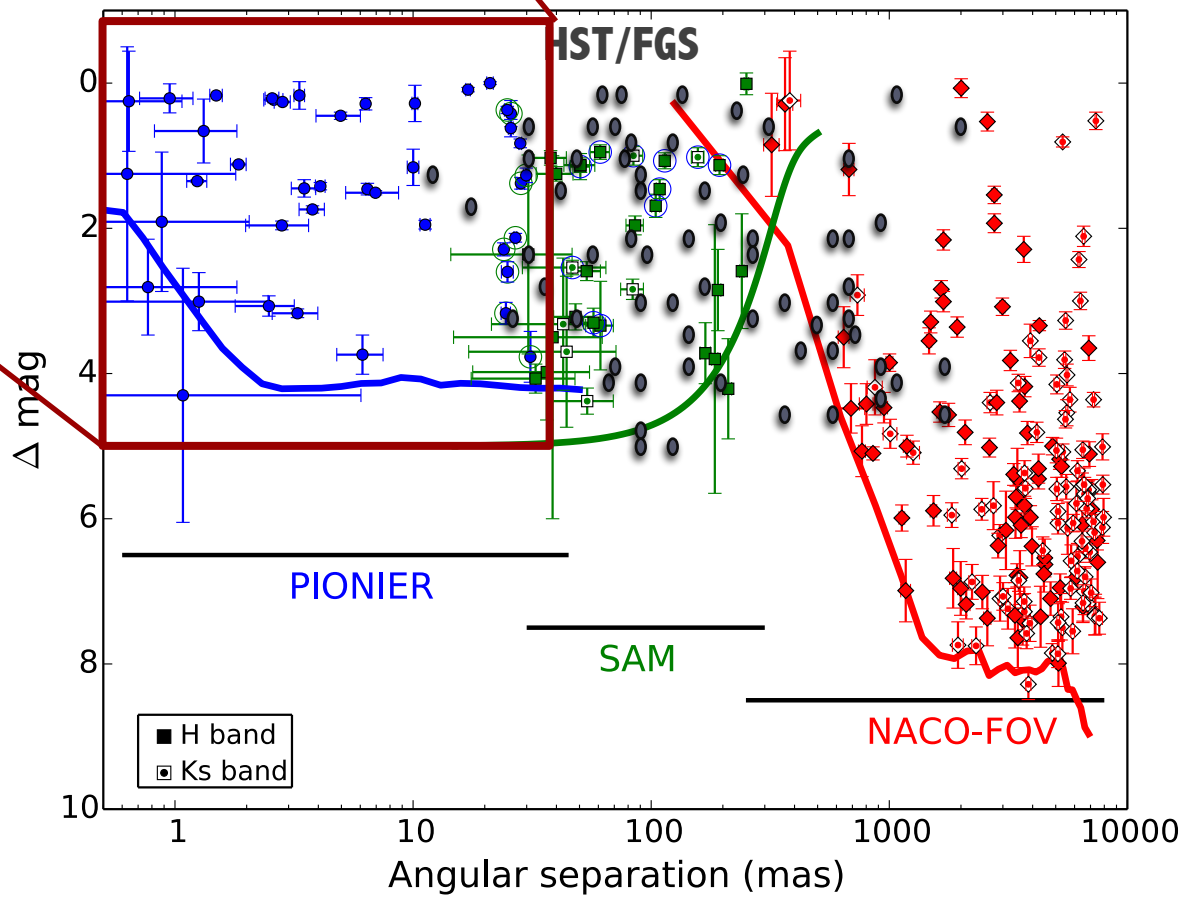

HDE303312
WR25
QZCar
HD94546
CPD592635
HD93129A
WR22
Rainot+, in prep
HDE303304
HD92206C
WR23

Beyond the SB regime



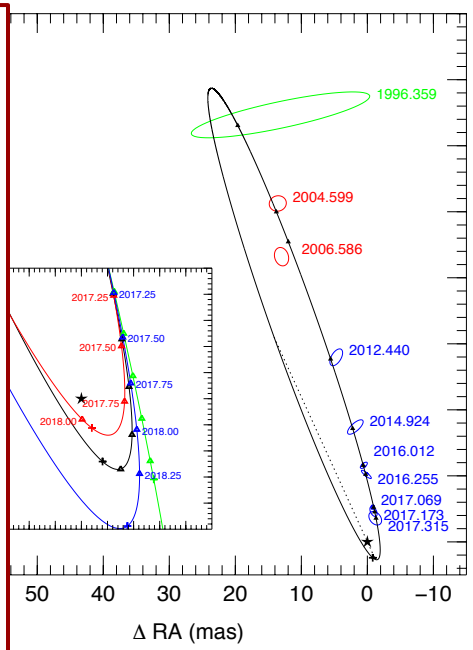
Long-term VLTI follow up (monitoring programs)

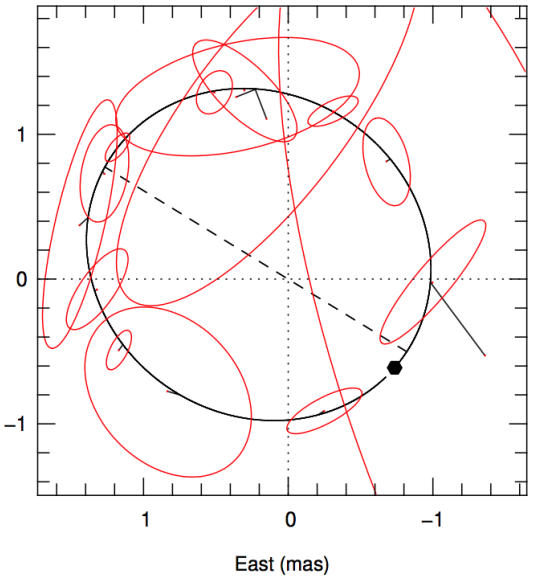
Beyond the SB regime

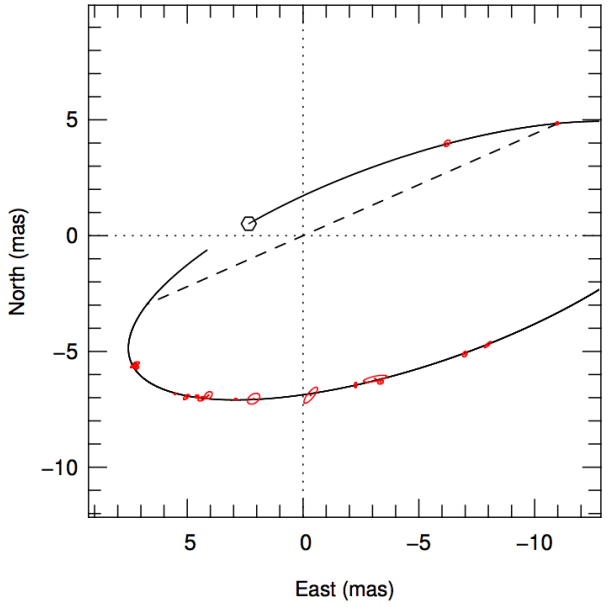


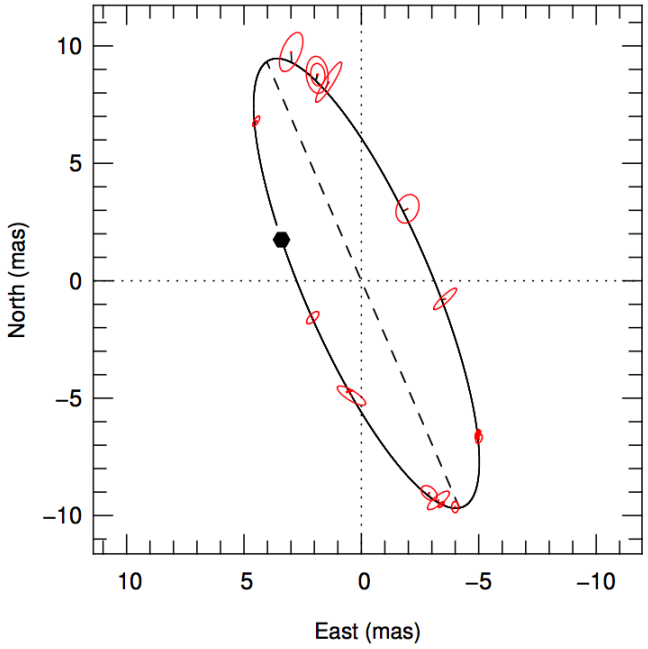
Long-term VLTI follow up (monitoring program)

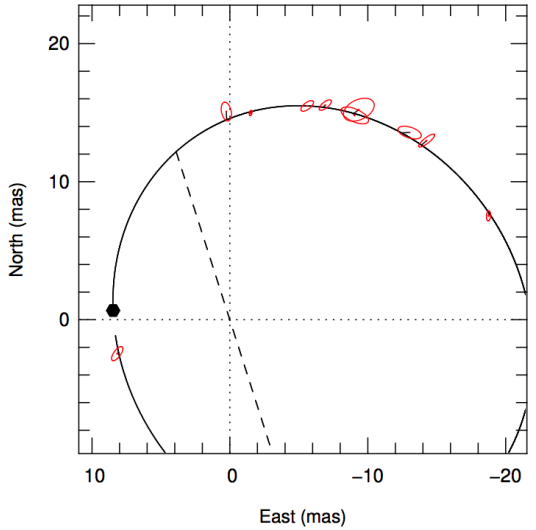
- 11 orbits so far (P~4mo to 150 yr)
- Another ~30 objects followed
- Unprecedented P, e accuracy
- 3D orbits → absolute masses
- orbital inclinations (also of triples !!!)







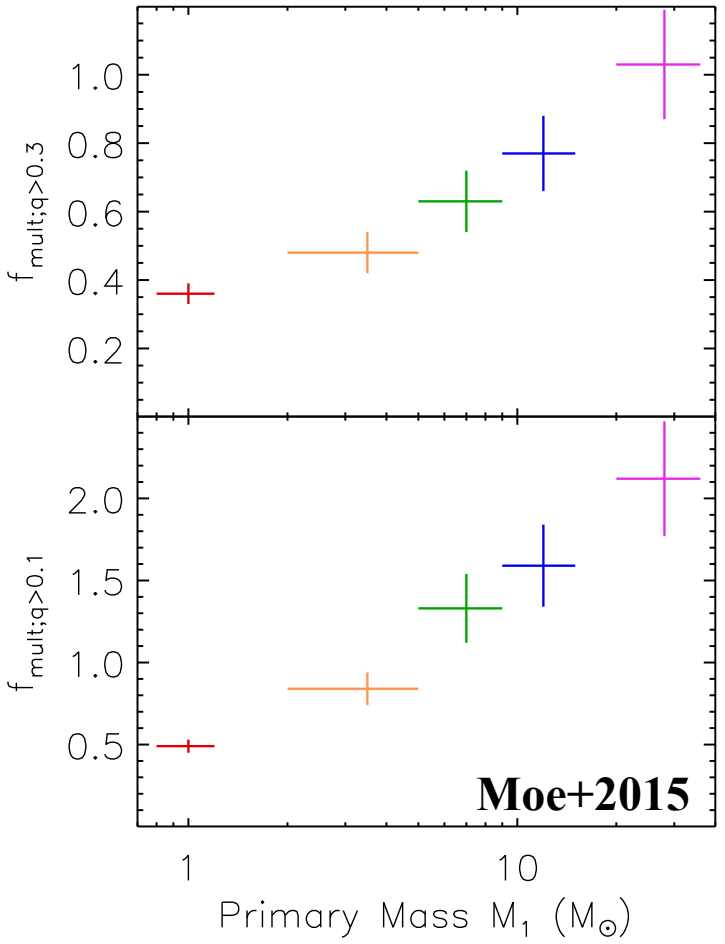




Le Bouquin+2017
Maiz Apellaniz+2017

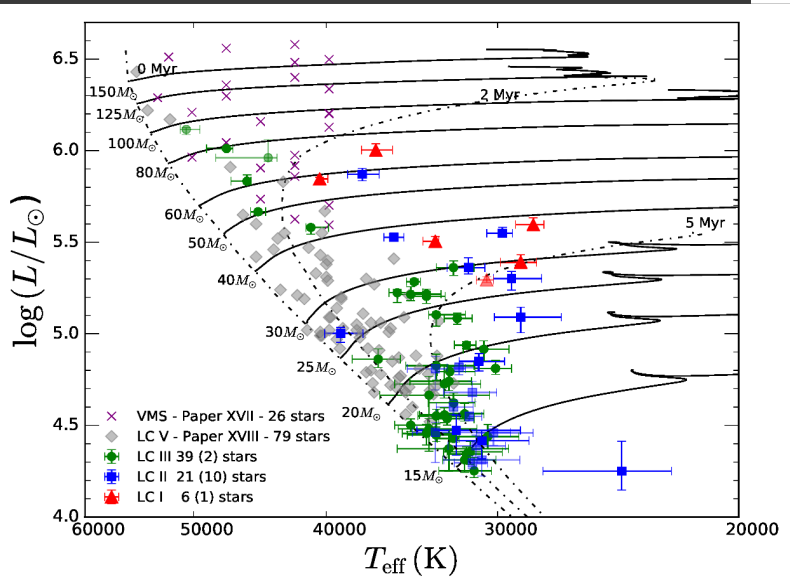
Progresses in the last 5 years

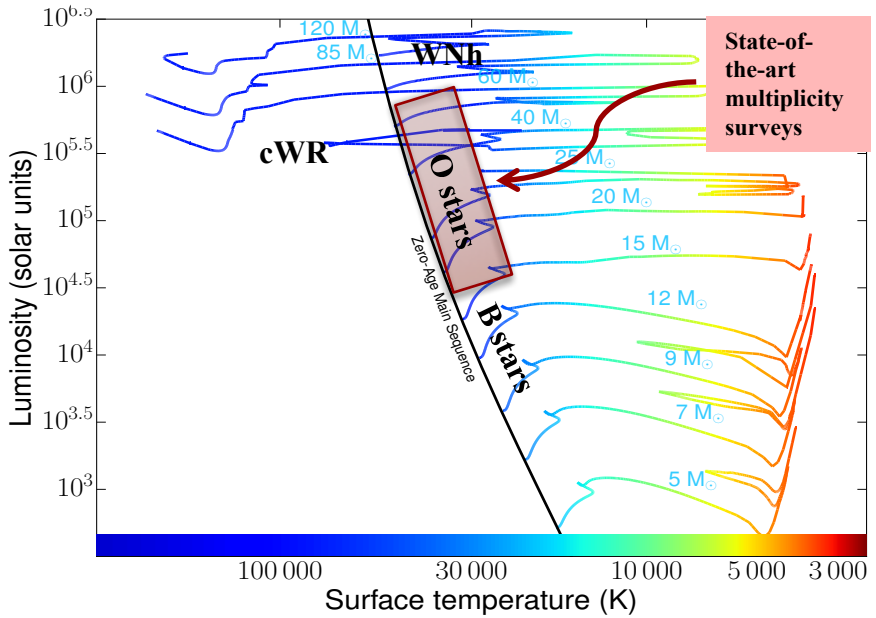
- **Impressive number of large surveys**
  - **MW spectro: OWN, GOSSS, IACOB…**
  - **MW high-res: SMASH, HST/FGS…**
  - **LMC: VFTS, TMBM, OGLE…**
- **Interferometric gap has been bridged**
- **Multiplicity pumped up even higher**
- **Record number of companions**
- **Striking similarities in orbital distributions**
  - **Start to explore Z**
  - **Start to explore age**
- **Gravitational Waves exist**



Future multiplicity work

- **HRD with 100+ Binary Components**
- **Extreme brightness ratios**
- **B0-B3 (8-15Msun) dominates CC-Sne**
  - **→ same multiplicity as the O stars ?**
- **Multiplicity @ highest masses ?!?**
- **Multiplicity post-main sequence (WR, RSG, LBV, …)**
- **Identification & Characterisation of Binary Interaction Products**

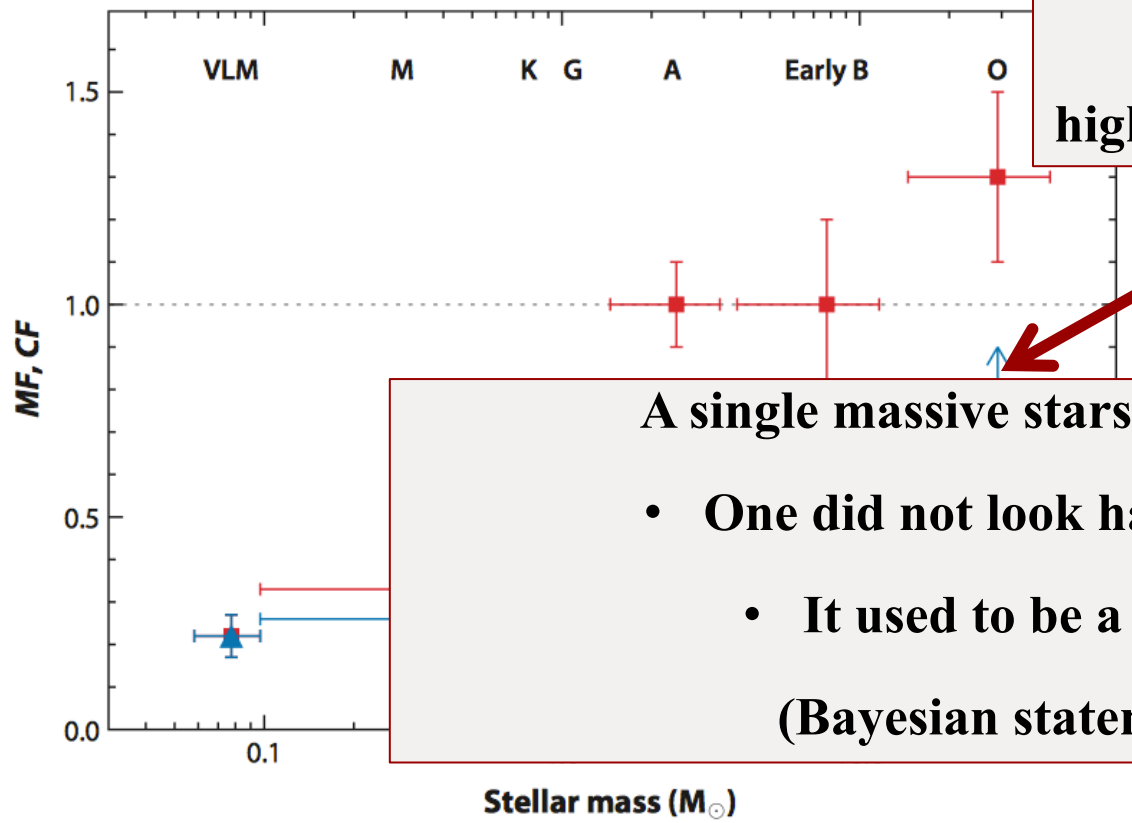




KU LEUVEN

The multiplicity of massive stars 2016

Hugues Sana



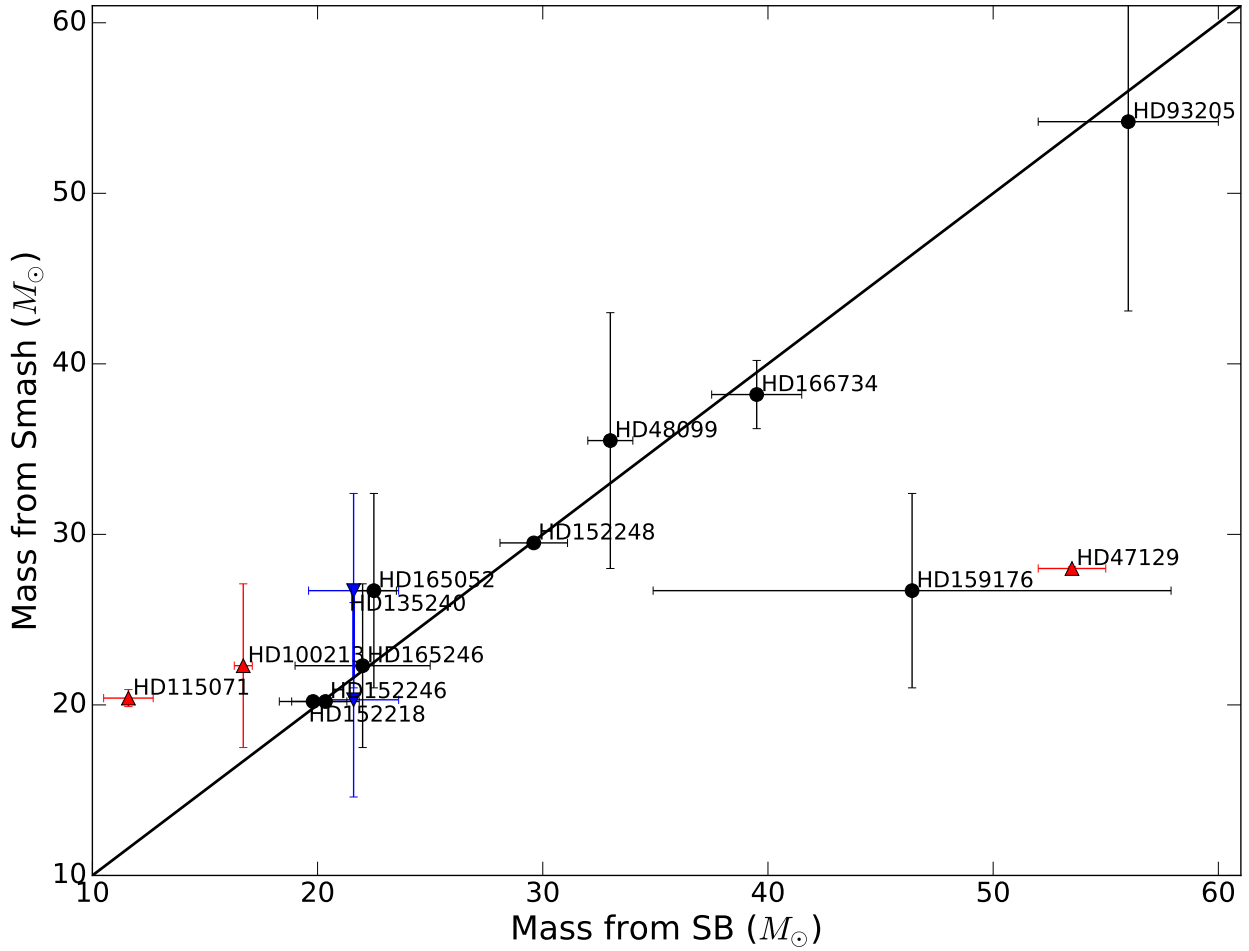
Most massive stars belong to a binary or higher multiplicity system

A single massive stars observed ?

- **One did not look hard enough**
- **It used to be a binary**

(Bayesian statement)

Duchene & Kraus'14


Mass from Smash ($M_\odot$)
Mass from SB ($M_\odot$)
10
20
30
40
50
60
HD93205
HD166734
HD48099
HD152248
HD47129
HD159176
HD165052
HD135240
HD100213
HD165246
HD115071
HD152246
HD152218