PIONIER and the massive stars

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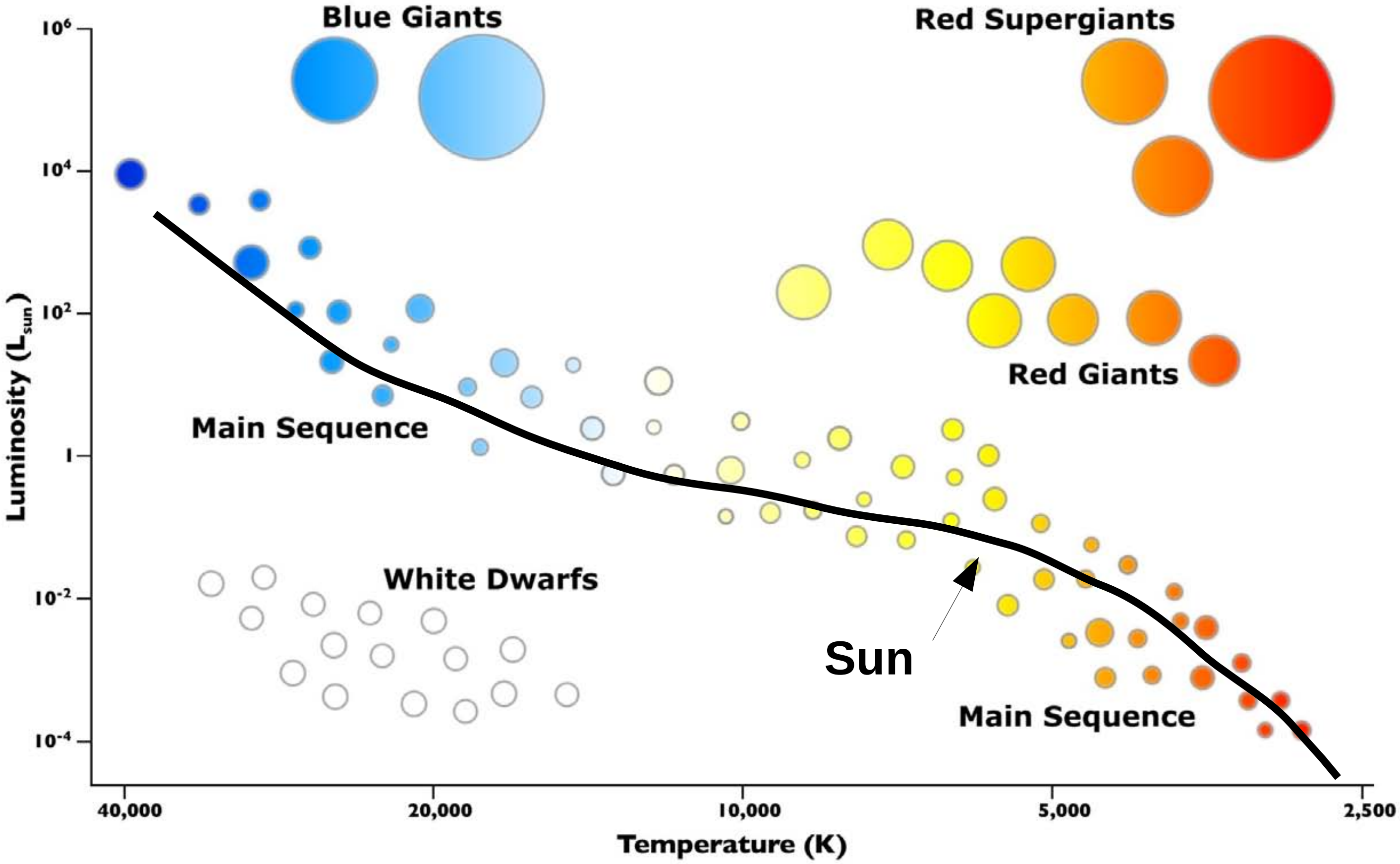
SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

In collaboration with: **J.-B. Le Bouquin**, **S. Lacour**, O. Absil, J.-P. Berger, M. De Becker, A. De Koter, K. Kratter, L. Gauchet, E. Gosset, B. Lazareff, L. Mahy, B. Norris, J. Olofsson, D. Pickel, O. Schnurr, H. Zinnecker, G. Zins

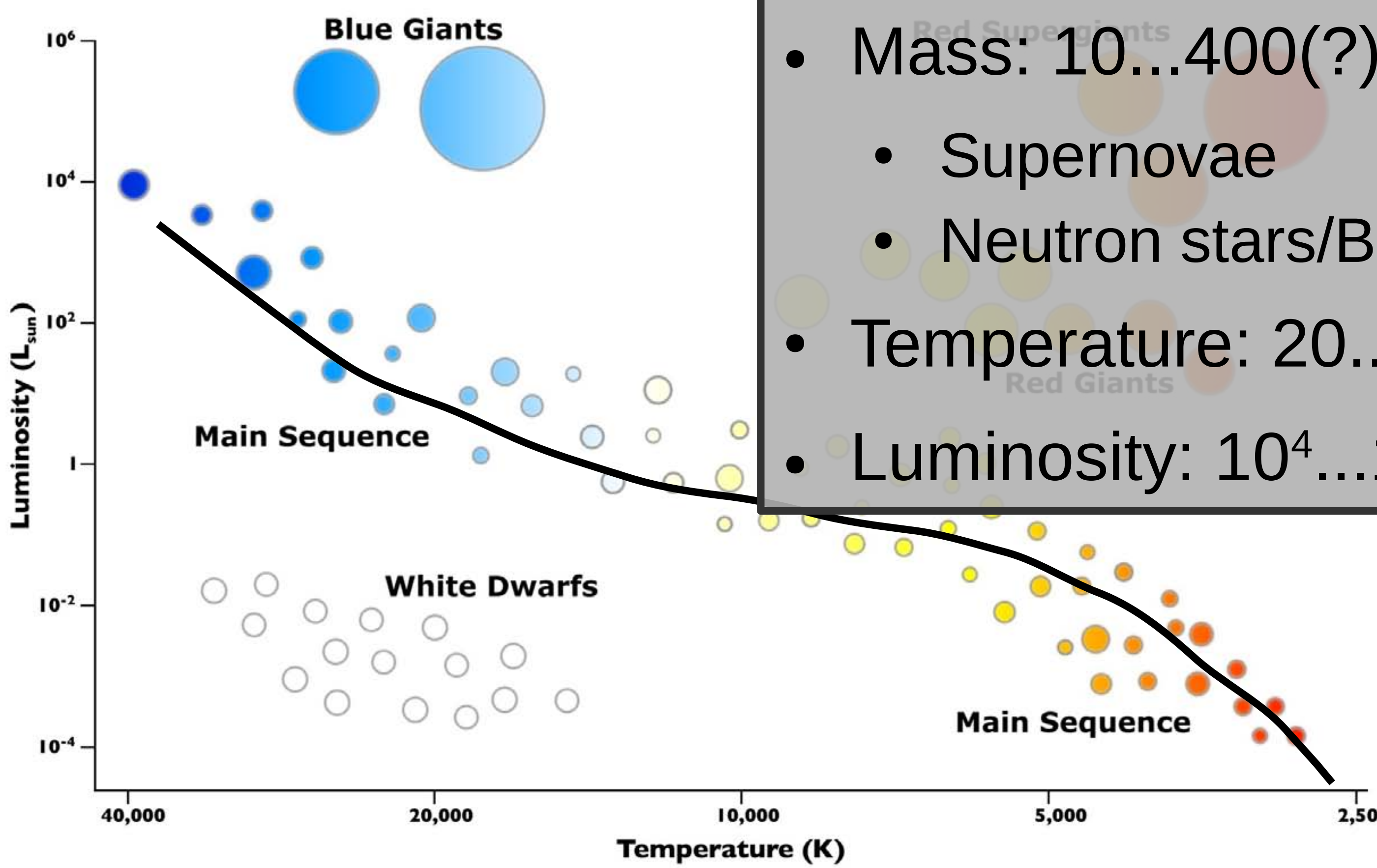
Storyboard

- Introduction to massive stars
  - Their role in the Universe & in astrophysics
  - Open questions
- Massive star formation
  - The SMaSH+ survey (a PIONIER large program)
- Massive star evolution
  - Towards accurate mass determination
  - Colliding wind binaries

Hertszsprung-Russell diagram

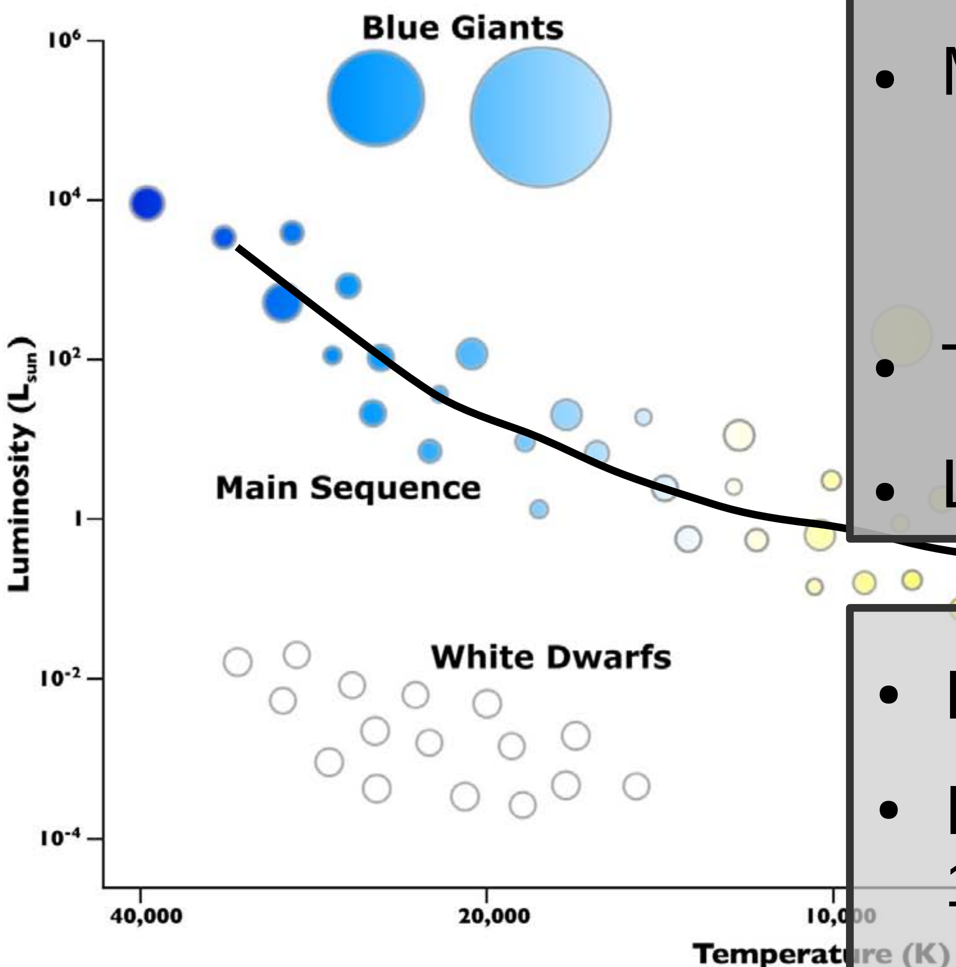


Hertszsprung-Russell diagram



- Mass: 10...400(?) M_{Sun}
  - Supernovae
  - Neutron stars/Black holes
- Temperature: 20...50kK
- Luminosity: 10^4...10^6 L_{Sun}

Hertzsprung-Russell diagram



- Mass: 10...400(?) M_{Sun}
  - Supernovae
  - Neutron stars/Black holes
- Temperature: 20...50kK
- Luminosity: $10^4...10^6$ L_{Sun}

- Lifetime: 2...20Myr
- Initial mass function: 1 x $100M_{Sun}$ >< 50,000 x $1M_{Sun}$

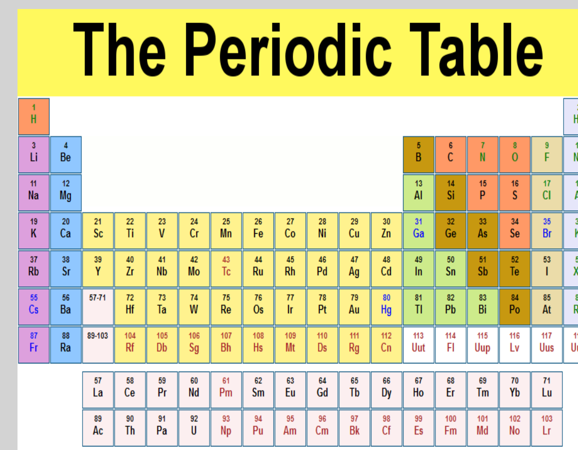
Massive stars matter in the Universe

- Strong ionizing flux
- Large radiation and momentum input
- Main source of heavy elements

First stars

Energy

Chemistry



... COSMIC ENGINES

Massive stars matter in the Universe

Star formation

Cosmol. medium

So bright that ...

- Populations of massive stars
- SN and GRBs

... can be seen throuhout the Universe

... COSMIC CANDLES

Massive stars matter in the Universe

Progenitors of
- Neutron stars
- Black holes
- Double compact objects
  NS+NS / NS+BH / BH+BH

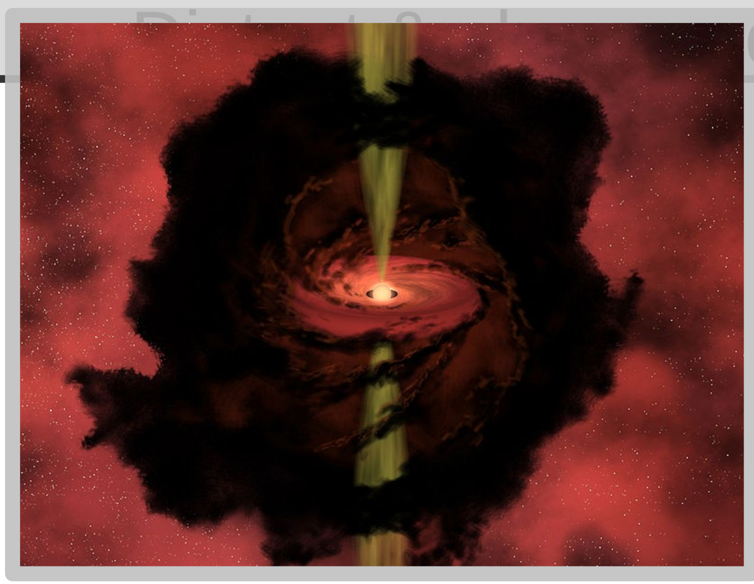
Potential source of
- Gravitational wave
- Several 10s to 1000s of events
  per year? (2016-2018)

Compact objects

... EXTREME PHYSICS

How massive stars form is a mystery

- Complex problem
- Time/space scales
- Observational challenges

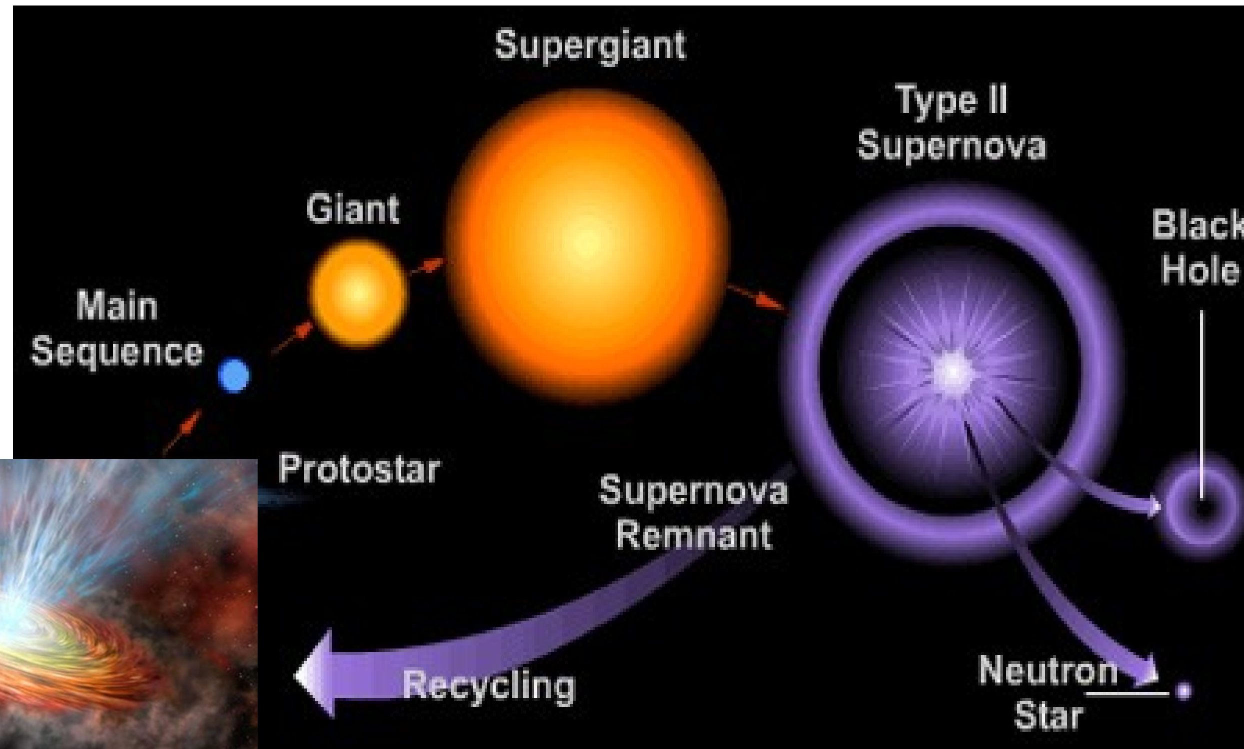


- Theoretical challenges
  - Accretion rate
  - Luminosity barrier
  - Angular momentum

Massive star evolution

Traditional view

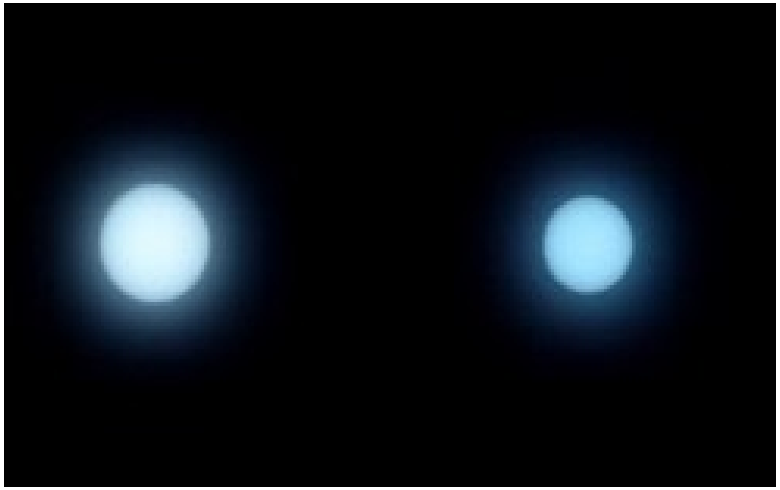
as single star



<u>Key parameters</u>

- Mass & mass-loss
- Metallicity
- Rotation rate

A high fraction of close binaries

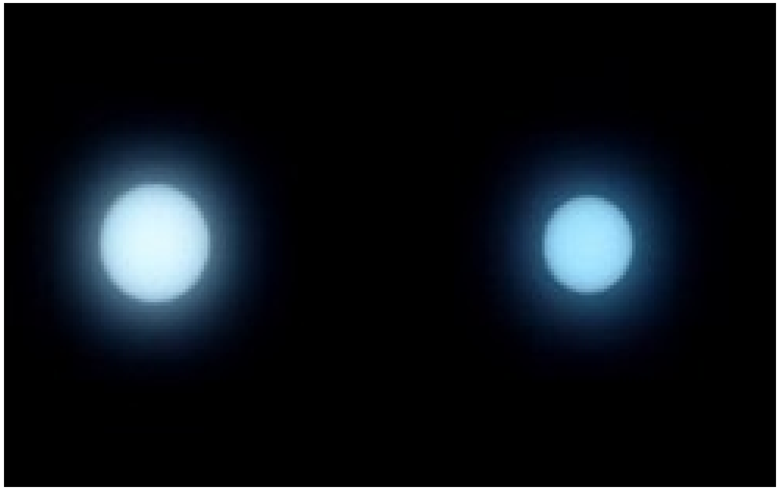


Most massive stars are born as part of a close binary system

→ Fundamental aspect of formation

- Sana+ 2012

A high fraction of close binaries



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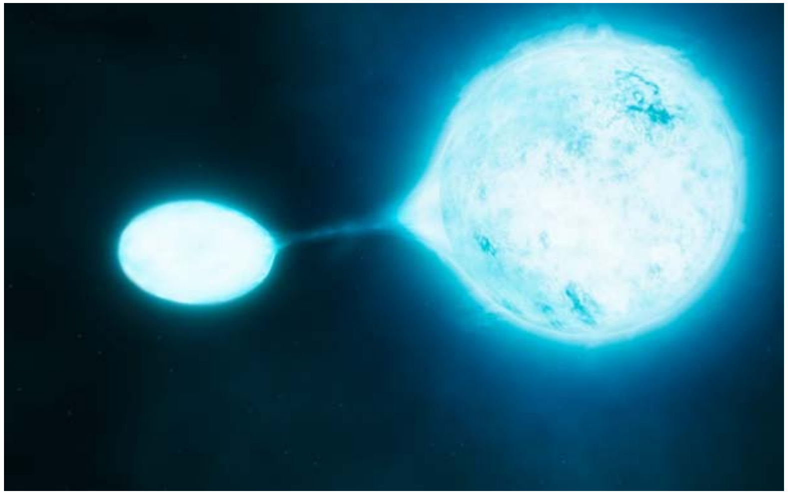


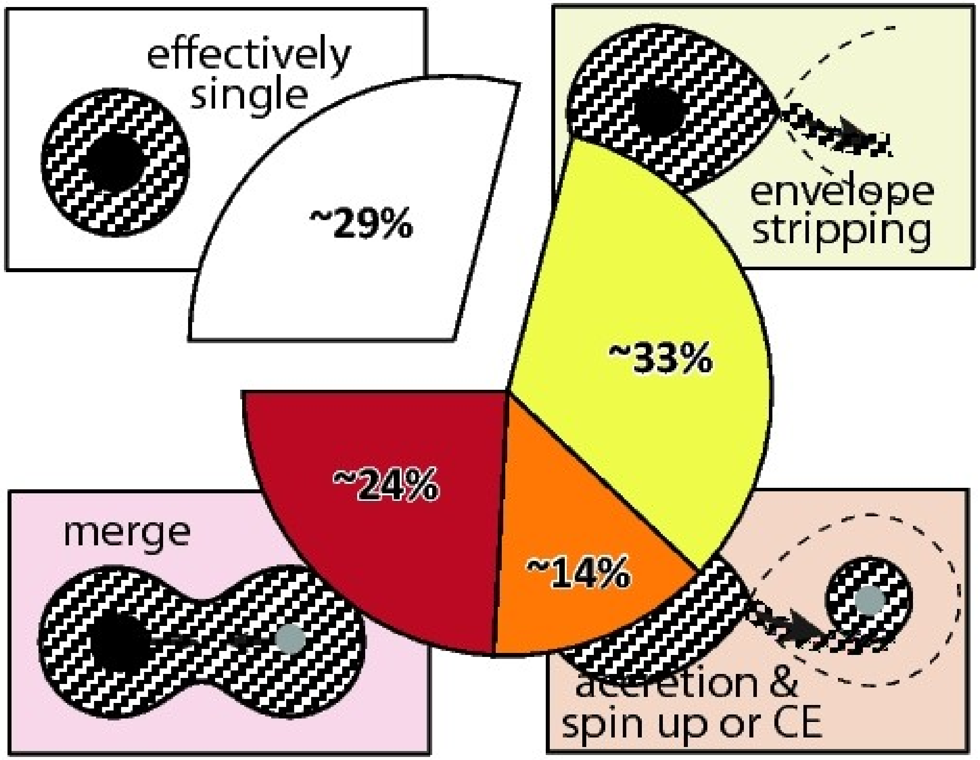
Almost all massive stars interact with a companion

→ Fundamental aspect of evolution

- Sana+ 2012

Binary interaction

Binary interaction dominates the evolution of massive stars



Sana+ 2012, Science

Binary interaction

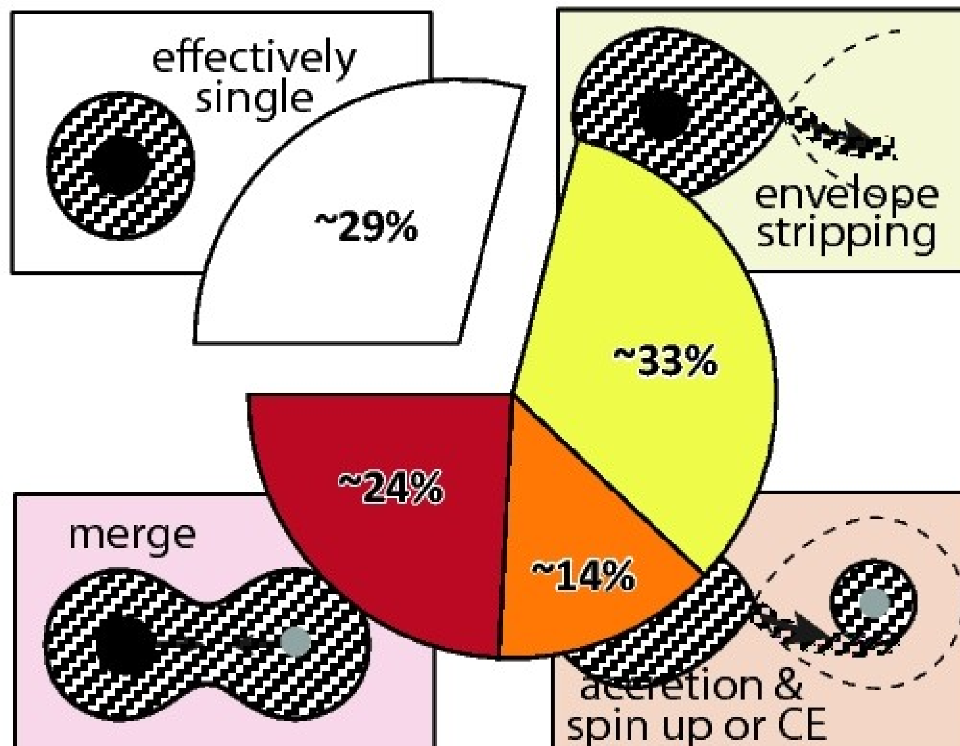
Binary interaction dominates the evolution of massive stars

Final fate

- Lifetime
- Evolutionary path
- Final explosions

Population properties

- Age
- Colour & ionizing flux
- Mass function
- Rotation rates



Sana+ 2012, Science

Open questions

Massive star formation

Massive star evolution

Final stages

Open questions

Massive star formation

Main sequence

Wolf-Rayet

Massive star evolution

Overshooting

Clumping

Final stages

LBVs

Magnetic fields

Absolute masses

Wind acceleration

Rotation

Mass-loss rates

Metallicity

RSGs

Binary interaction

Line blanketing

More/new observational constraints

Detailed studies of normal objects

→

Accurate parameters

Rare and/or spectacular objects

→

Extreme physics / Rapid evolutionary phase

Entire populations

→

Statistical properties

Galactic O-type binaries

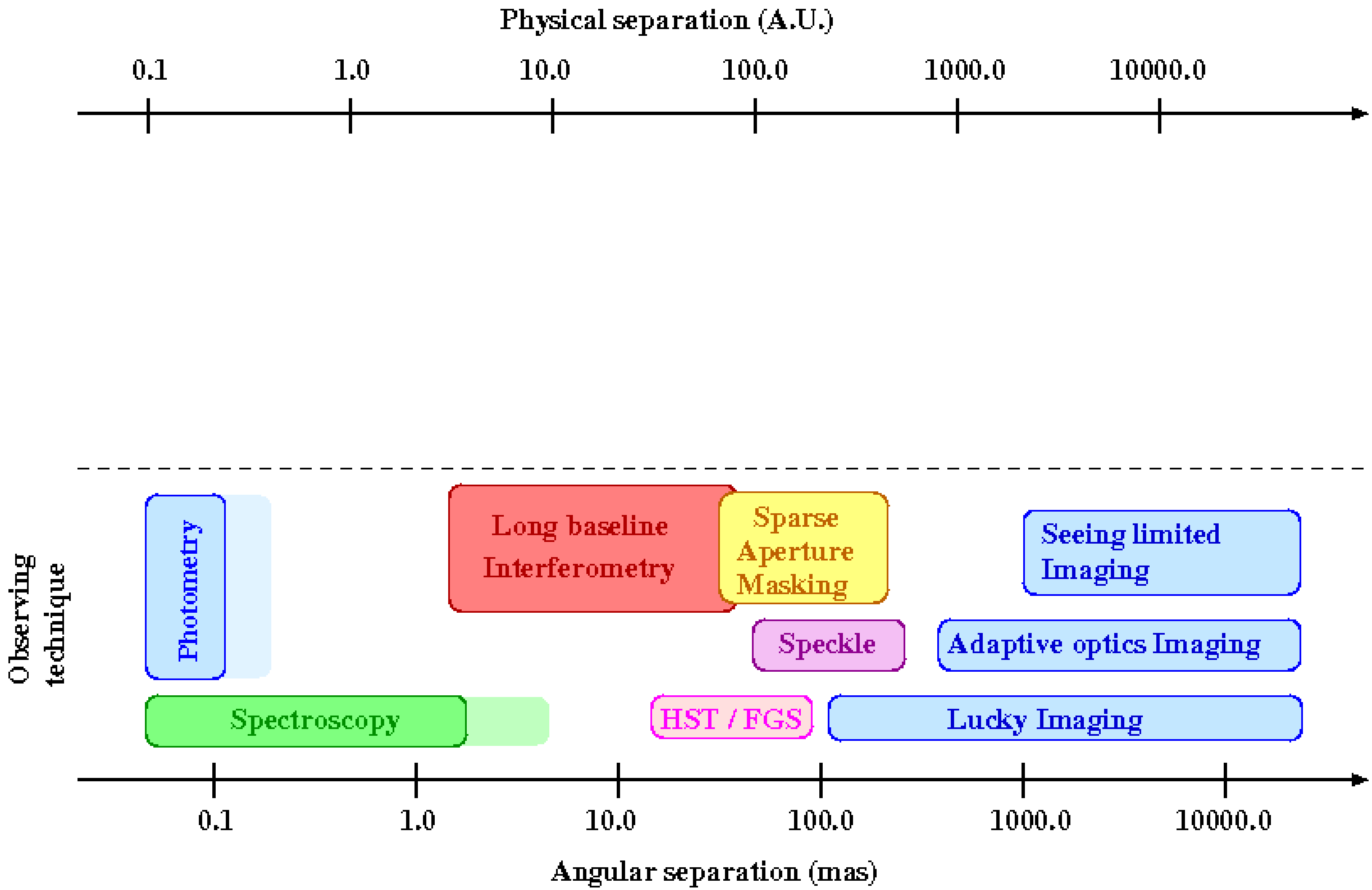
- Mason et al. 2009 (~400 O stars)
  - 55% SB; 43% VB --> 75% have SB or VB companion

- Sana et al. 2012: 56% SB --> 69% (bias corrected)
- Chini et al. 2012: 79% SB (before bias correction)

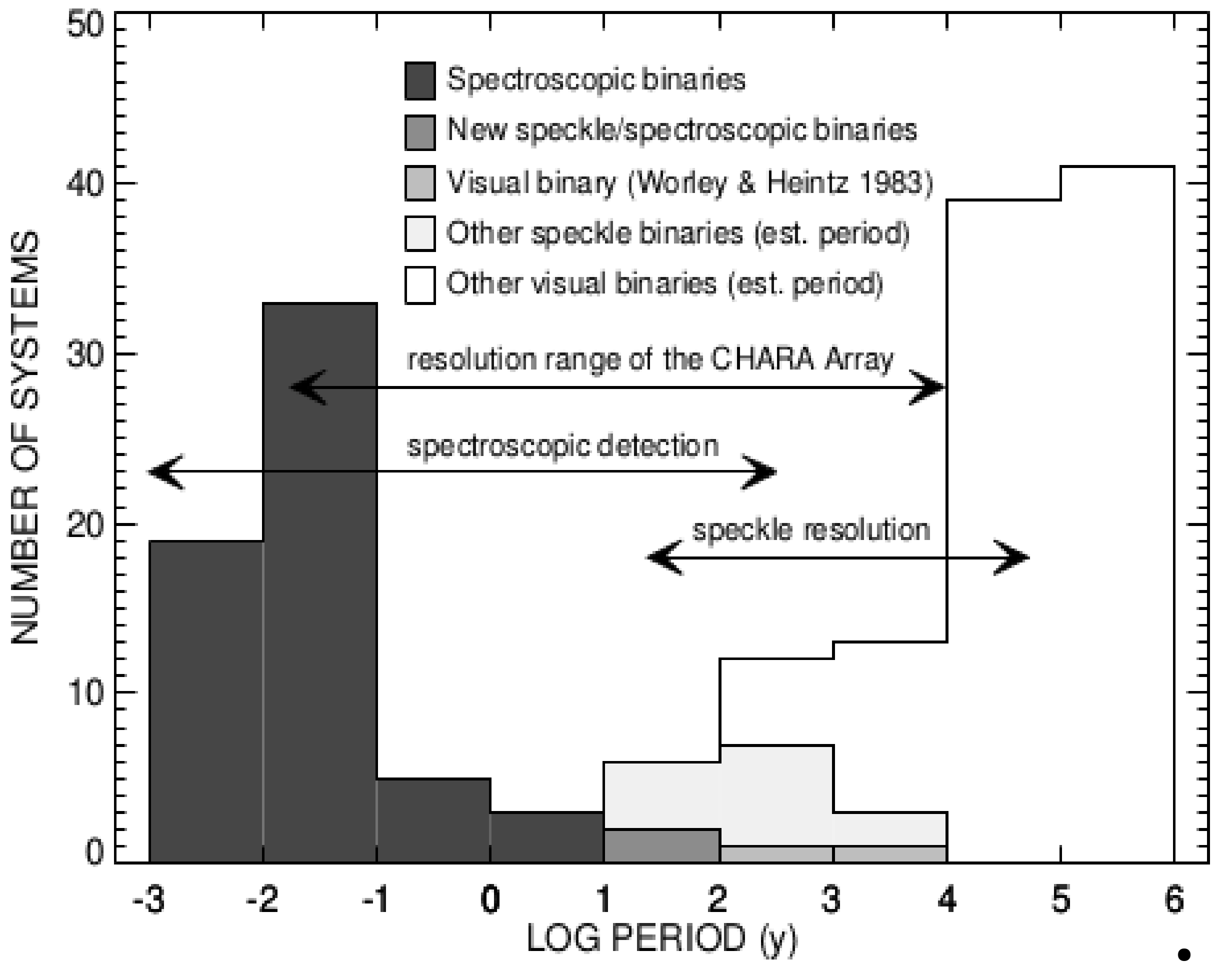
- *The end product of massive star formation is a multiple system*

  ==> Massive star formation theories can be tested by the multiplicty properties of their end products

Observational techniques



Previous high angular resolution survey



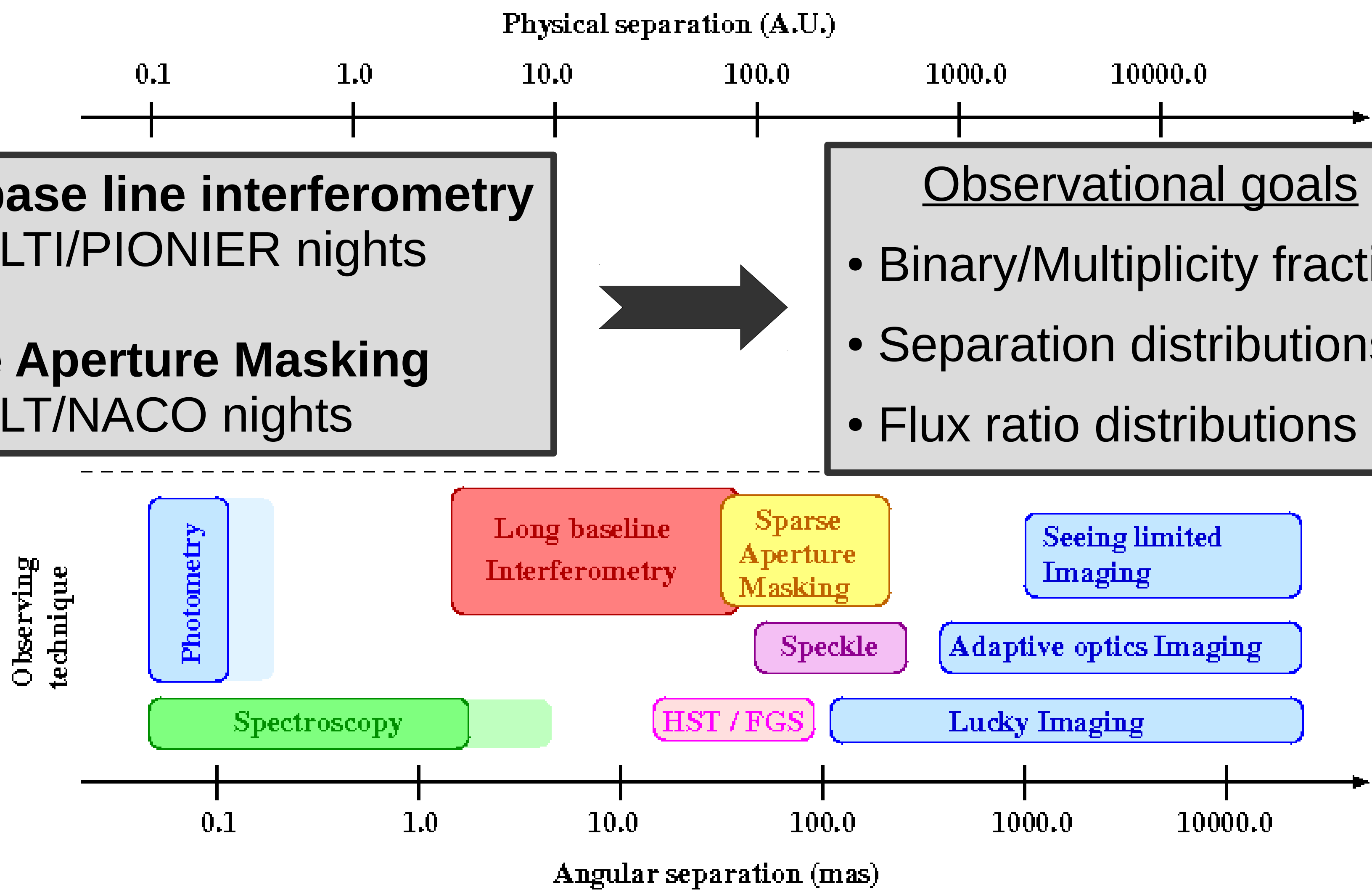
- **Mason+ 1998**

The SMaSH+ Survey (189.C-0644): Southern Massive Stars at High angular resolution

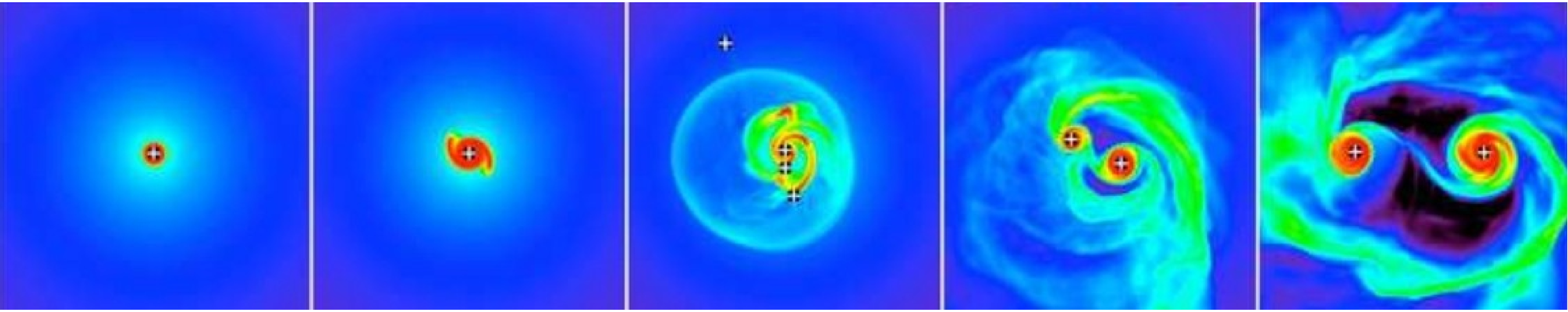
Long-base line interferometry
- 20 VLTI/PIONIER nights

Sparse Aperture Masking
- 13 VLT/NACO nights

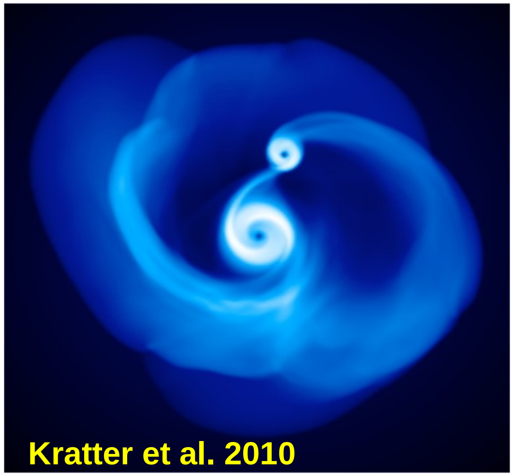
<ins>Observational goals</ins>
- Binary/Multiplicity fraction
- Separation distributions
- Flux ratio distributions



High angular resolution survey



Krumholz+2009



Unexplored region of parameter space

- Probes separation ranges expected by **disk fragmentation theories**
- First quantitative **test of massive star formation**

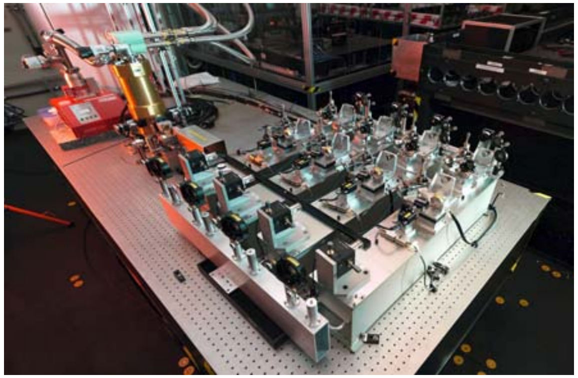
The SMaSH+ survey

Sample selection
- Galactic O star catalogue
- $\delta < 0^o$
- H < 7.5
- Not Orion

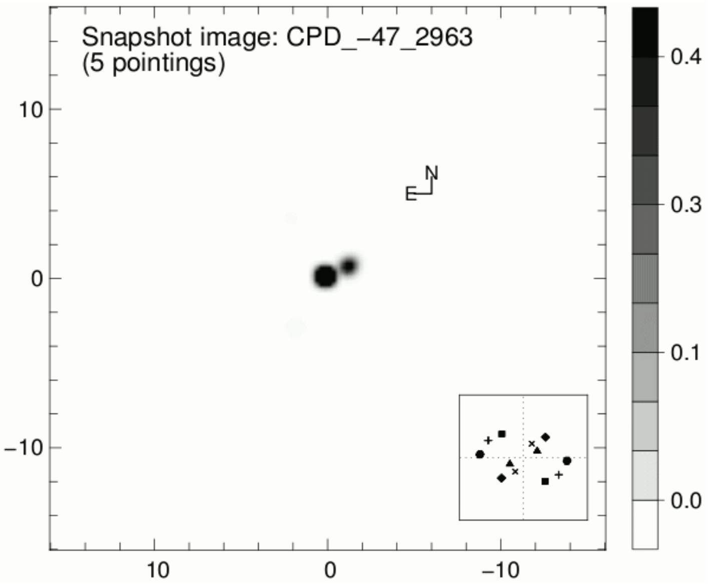
Long-base line interferometry
- 107 O stars

Sparse Aperture Masking
- 165 O stars

VLTI / PIONIER



- **$1 < \rho < 50$ mas**
- **Δ H < 3.7**



NACO

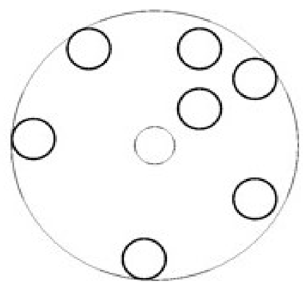
The SMaSH+ survey

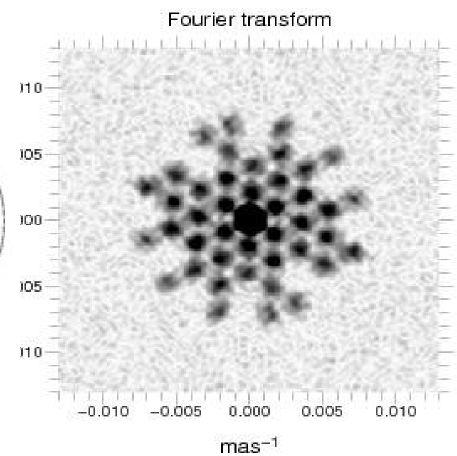
Sample selection
- Galactic O star catalogue
- DEC < 0^{o}
- H < 7.5
- Not Orion

Long-base line interferometry
- 107 O stars

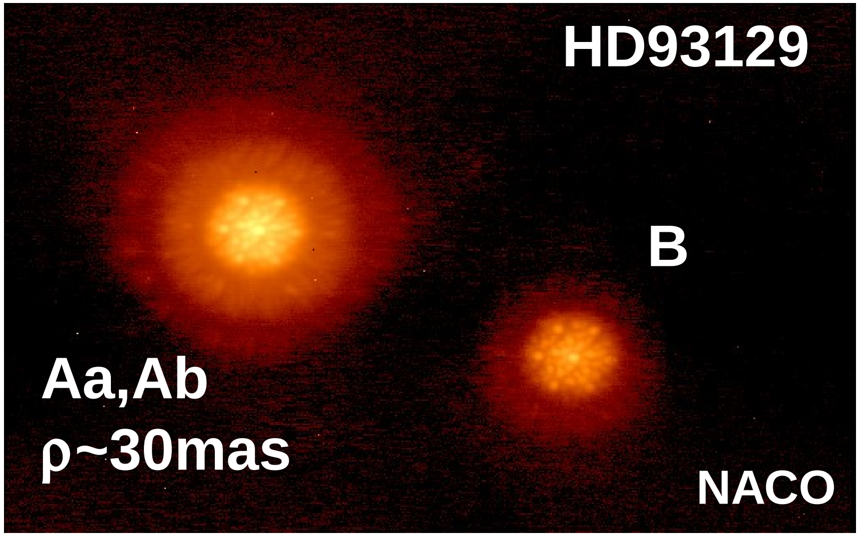
Sparse Aperture Masking
- 165 O stars

Sparse Aperture Masking (NACO/SAM)





- **30 < ρ < 250 mas**
- **Δ H < 5**



The SMaSH+ survey

Sample selection
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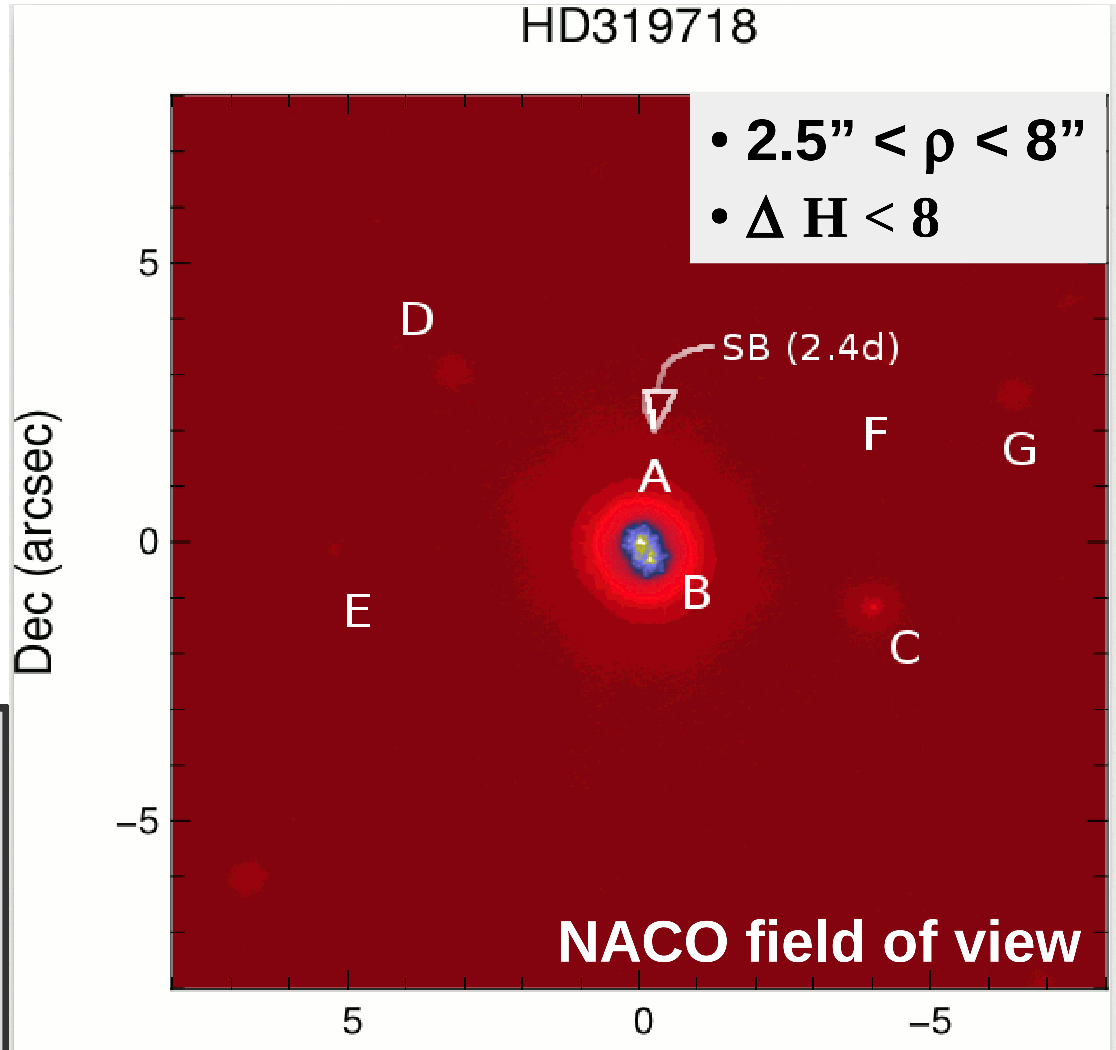
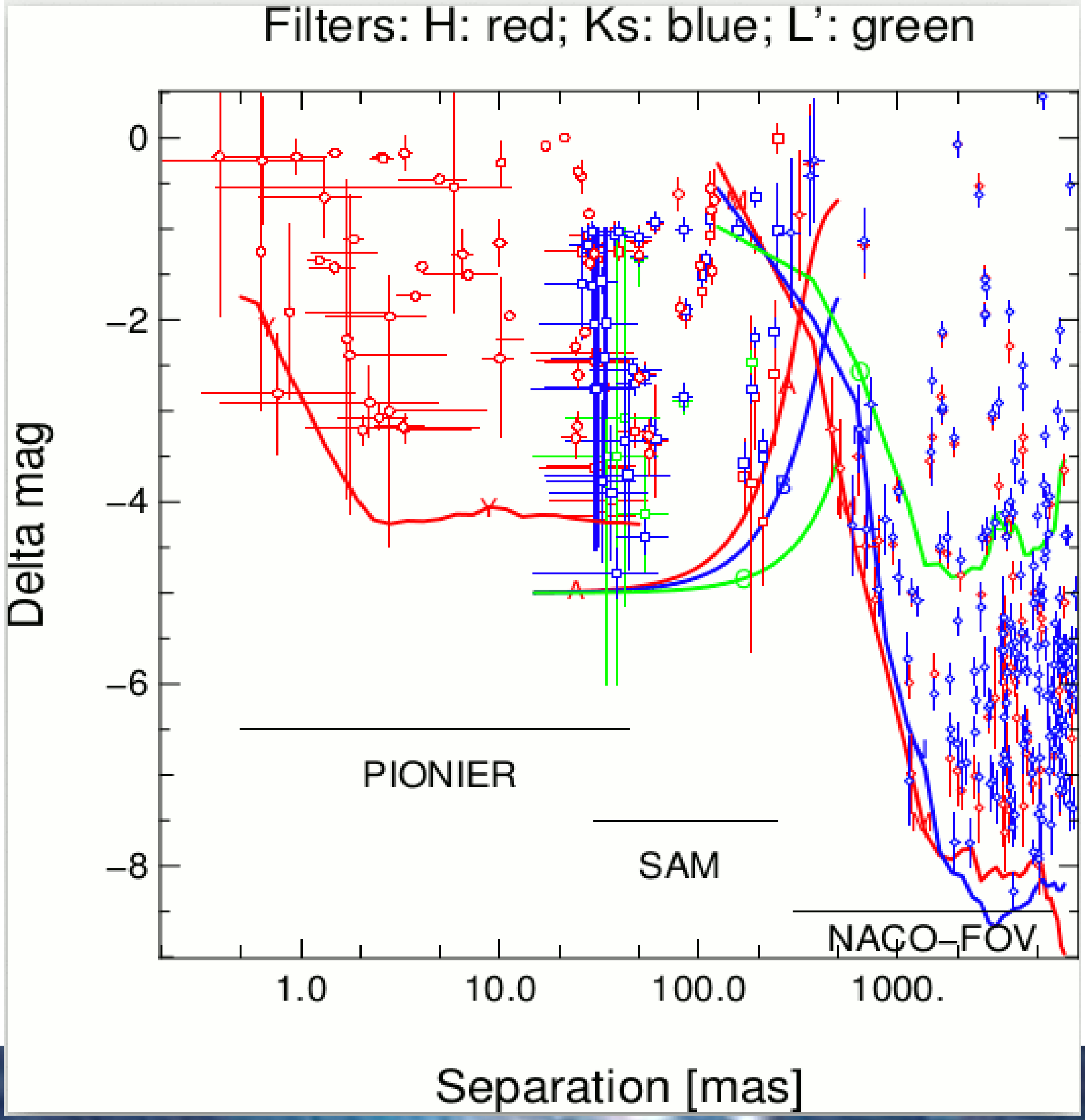
Long-base line interferometry
- 107 O stars

Sparse Aperture Masking
- 165 O stars



SMaSH+ : early results

246 companions detected



SMaSH+ early results

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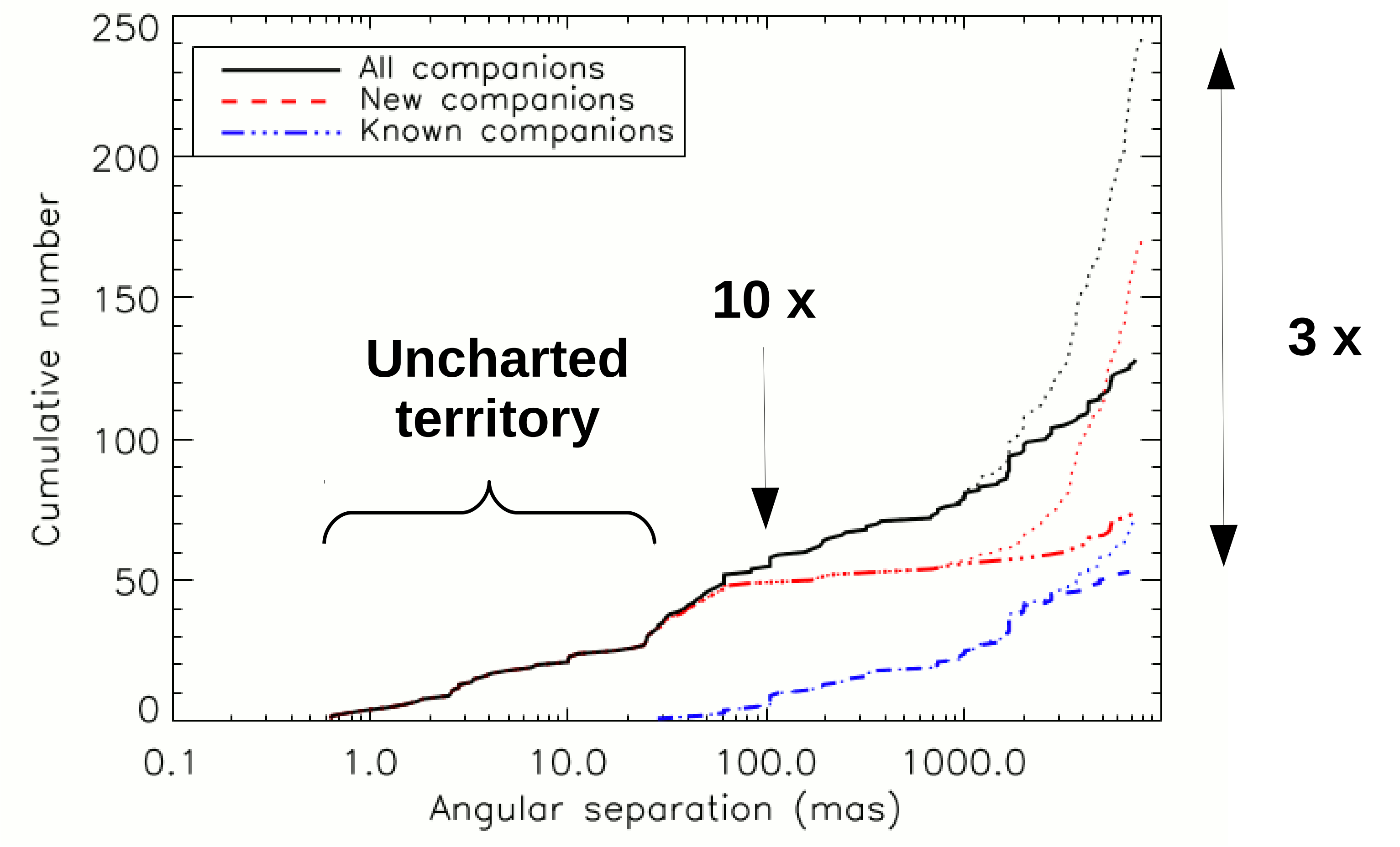
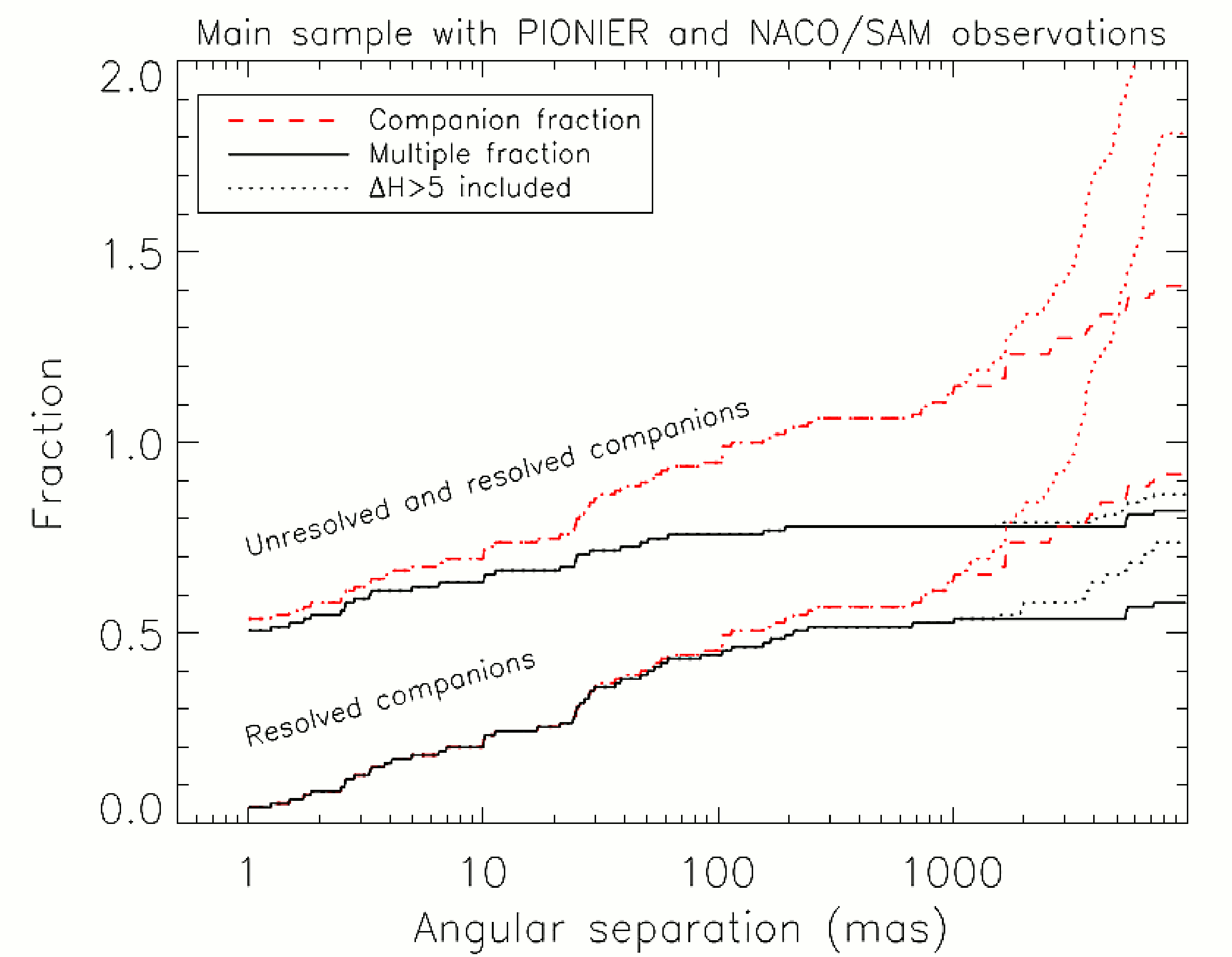


SMaSH+: Early results

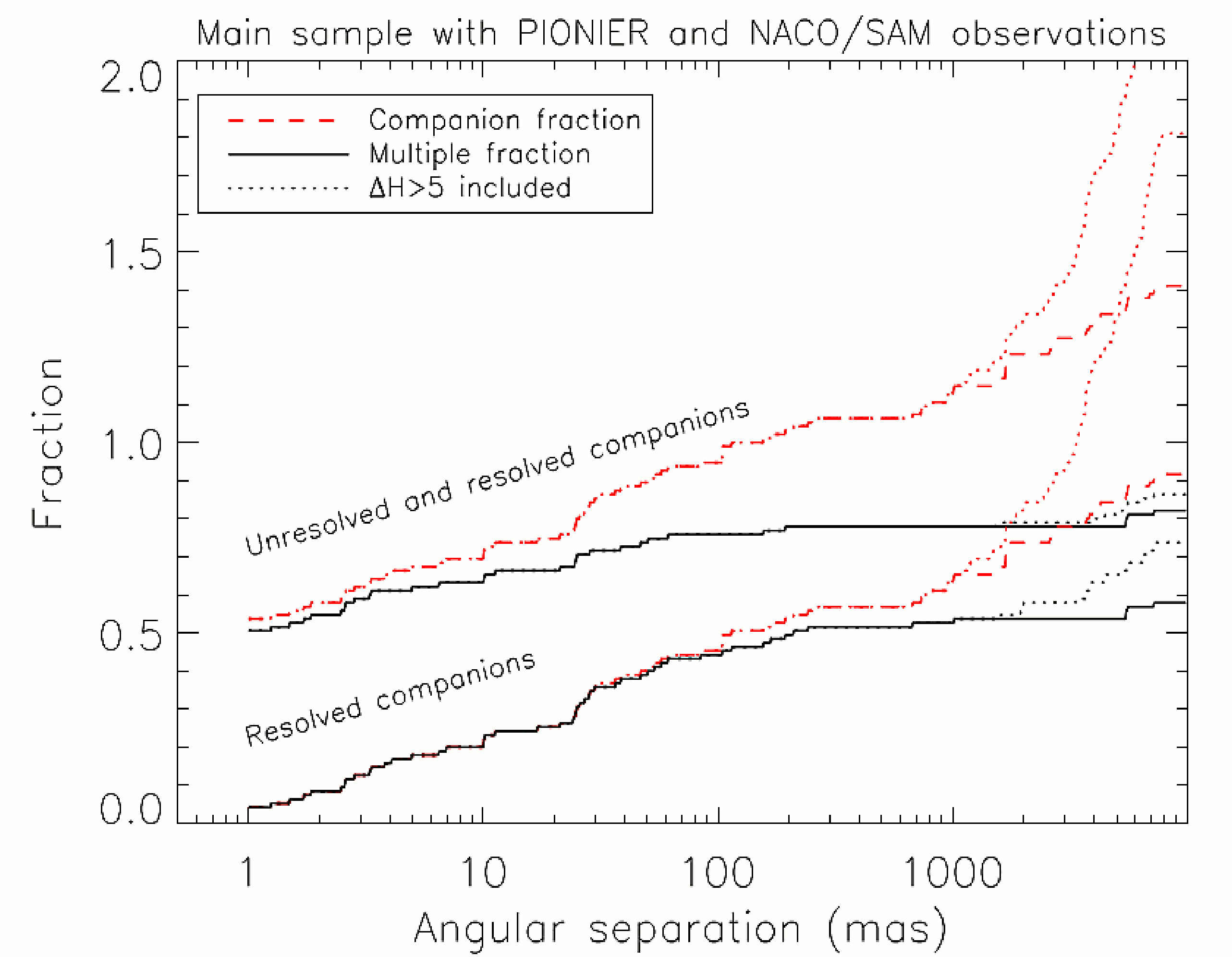


Main sample of V-I O-type stars

82%

54%

SMaSH+: Early results



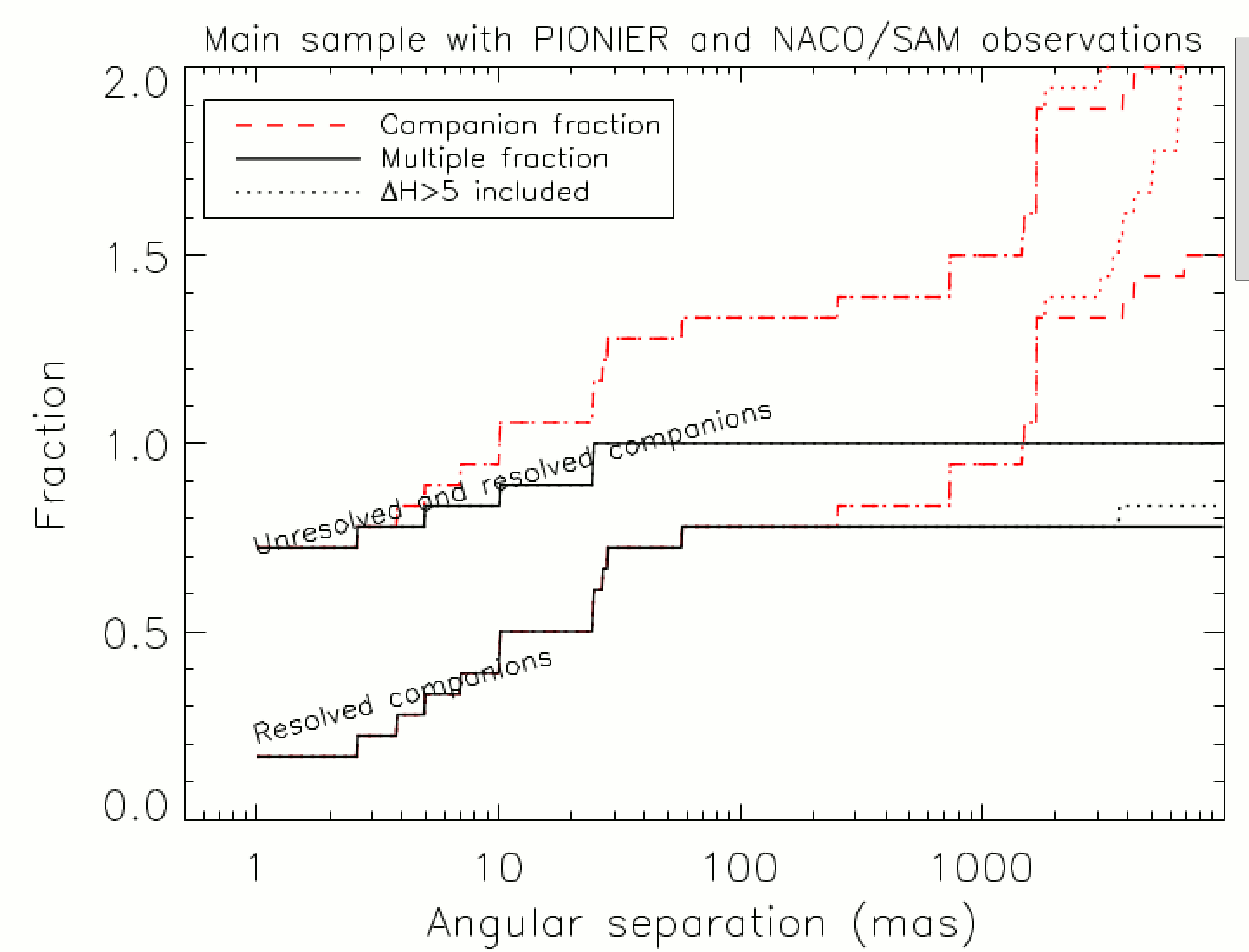
82%

54%

Main sample of V-I O-type stars

Contamination ~20% on average, i.e. ~0.2 mag

SMaSH+: Early results

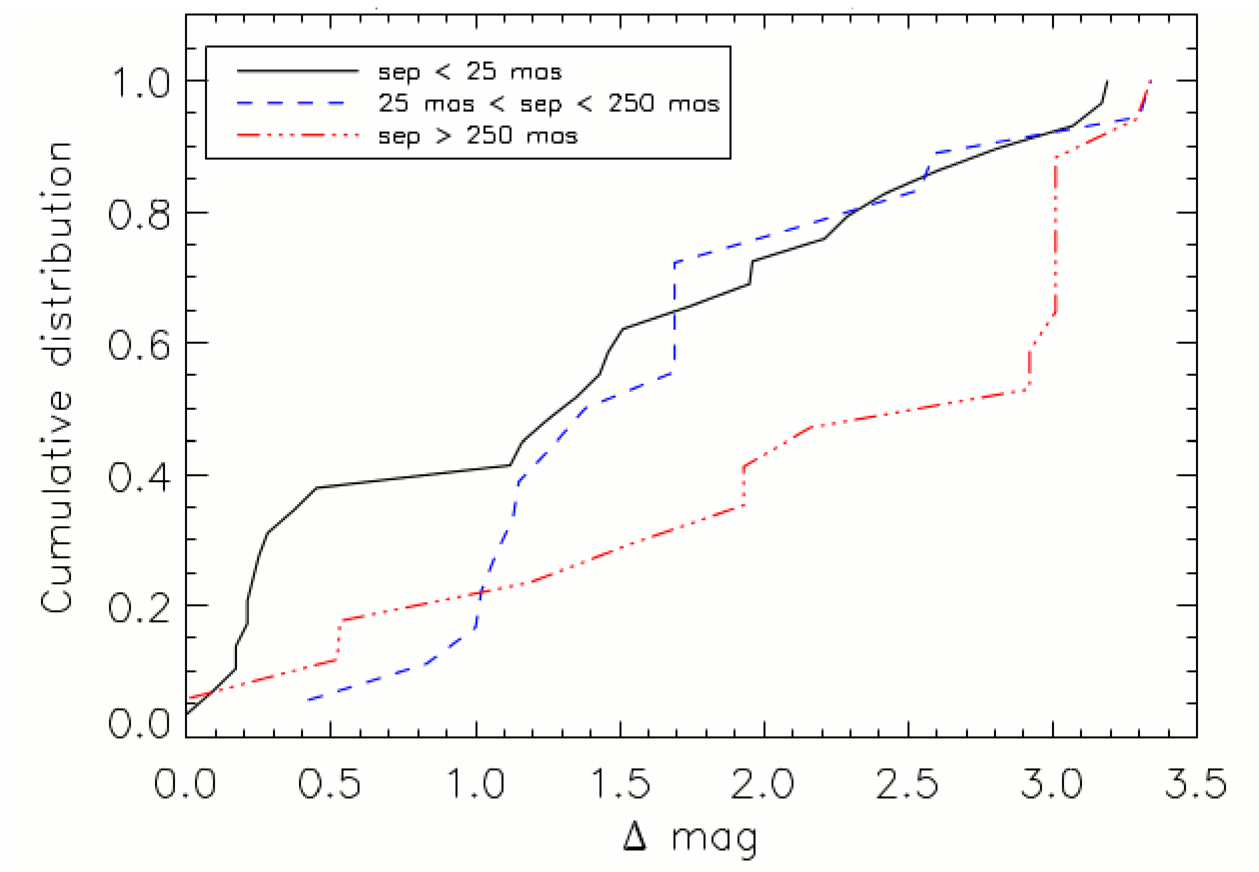


Sample of dwarfs O-type stars

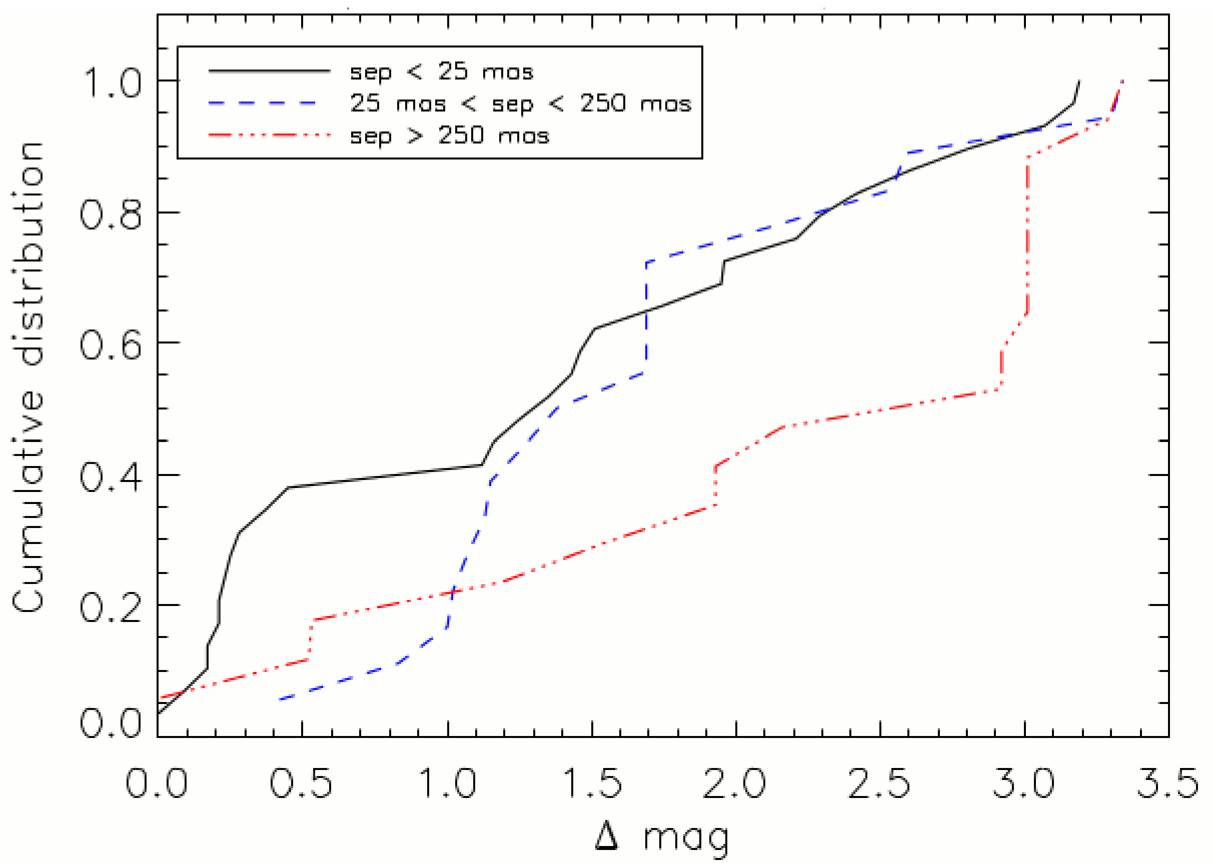
100%

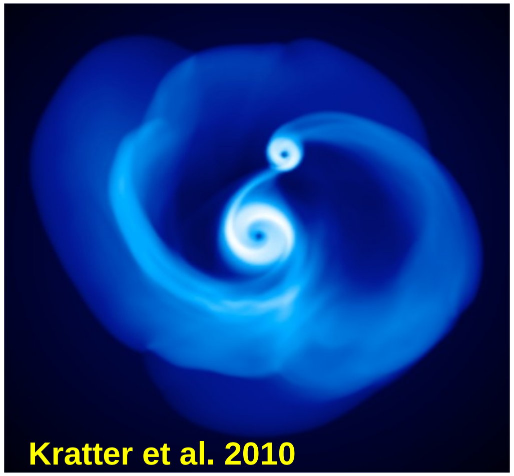
79%

SMaSH+: early results



SMaSH+: early results

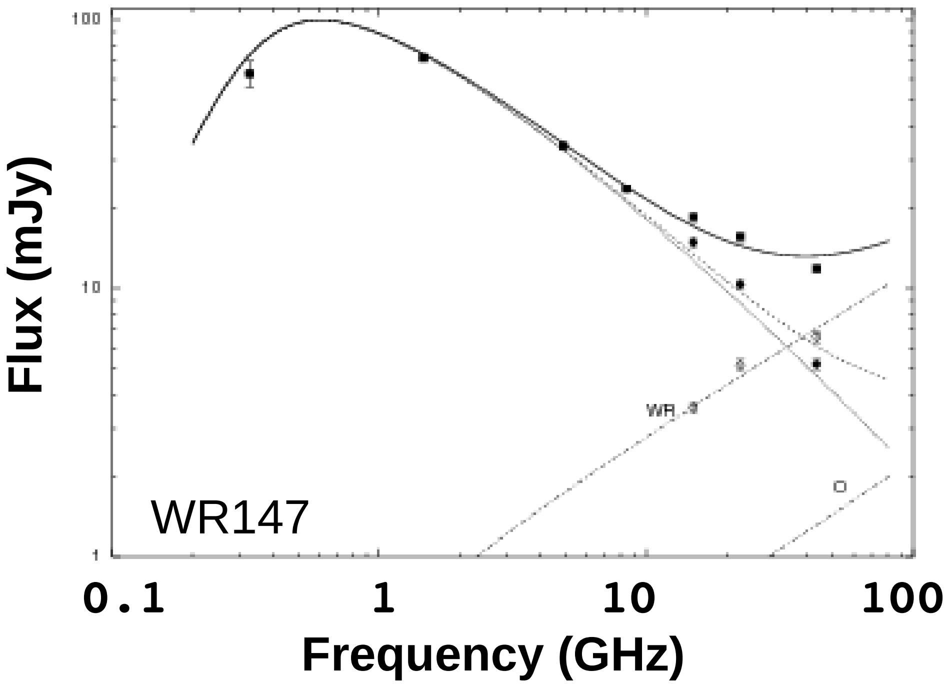


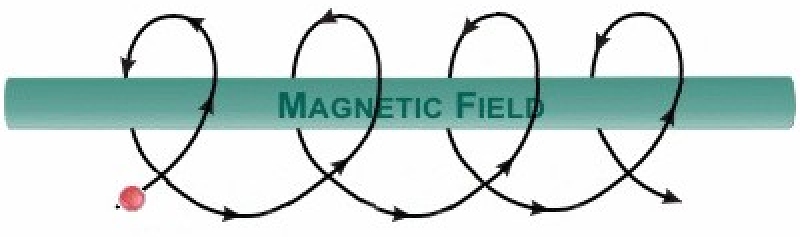


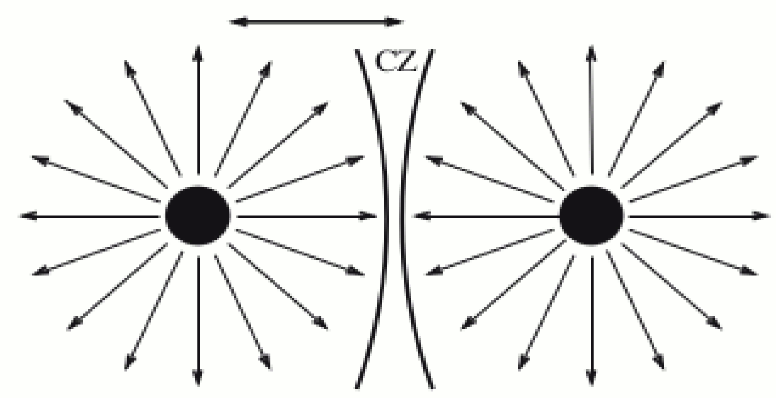
Early trends compatible with disk fragmentation through gravitational instabilities

BUT ...

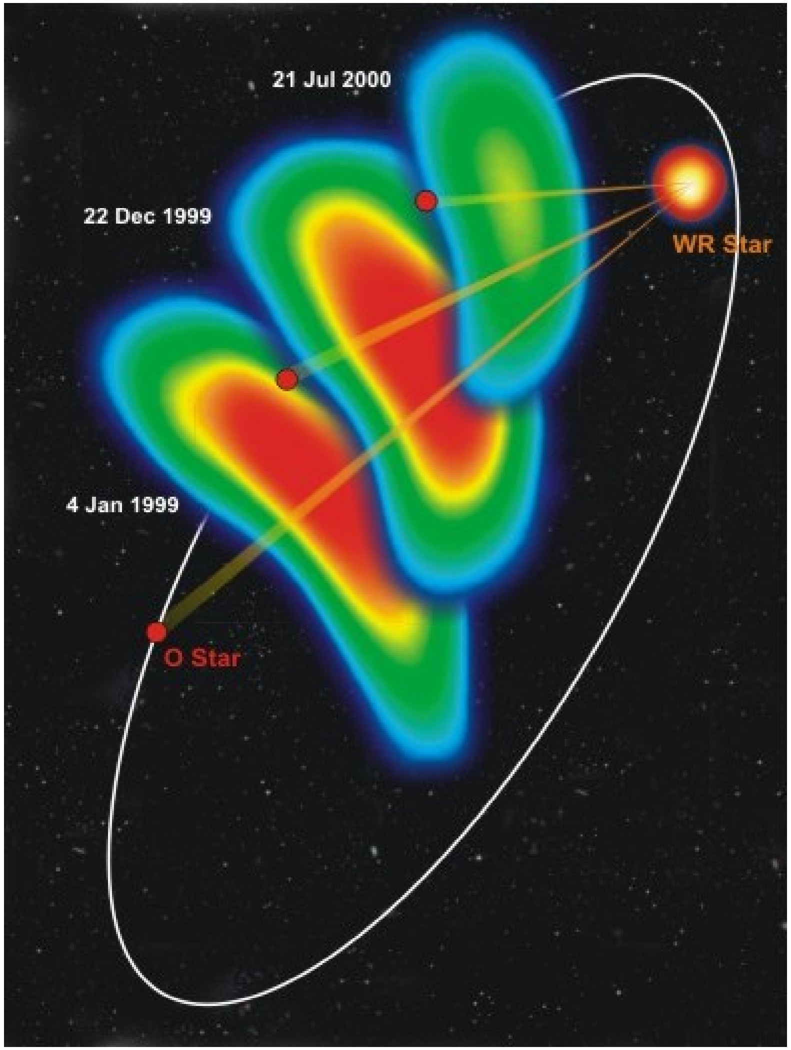
Non thermal radio emission

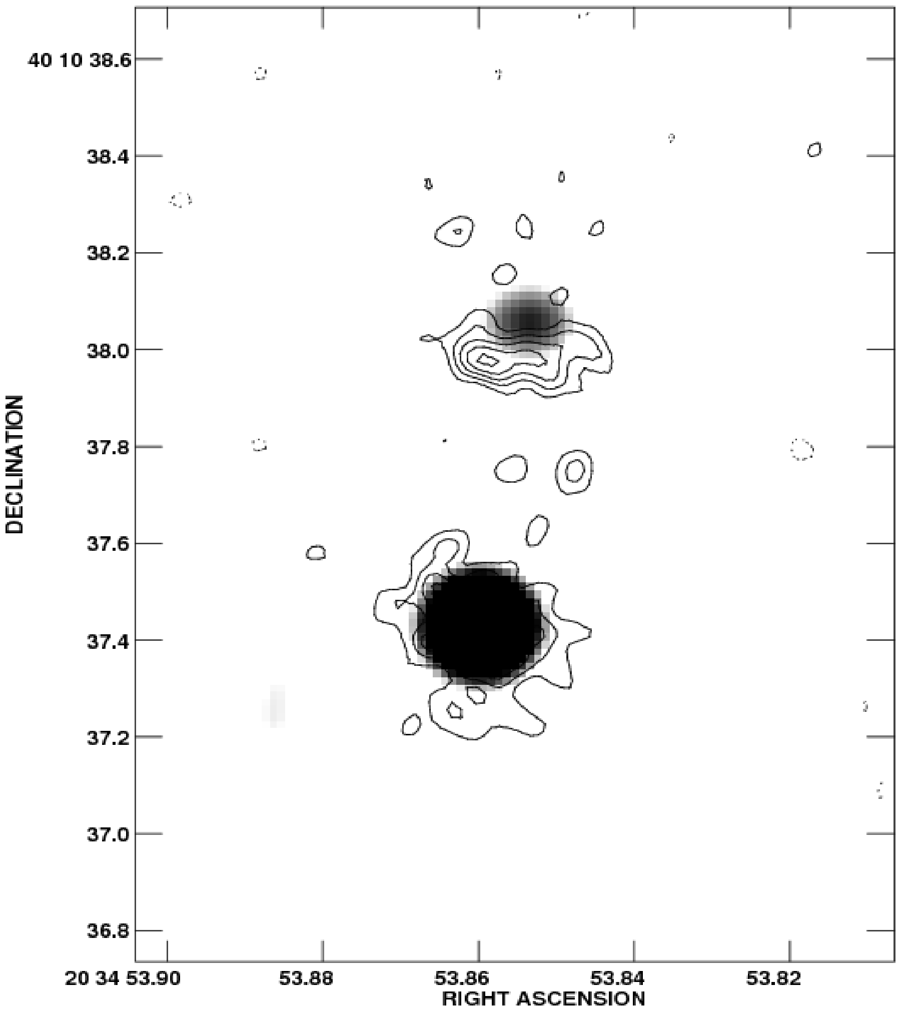






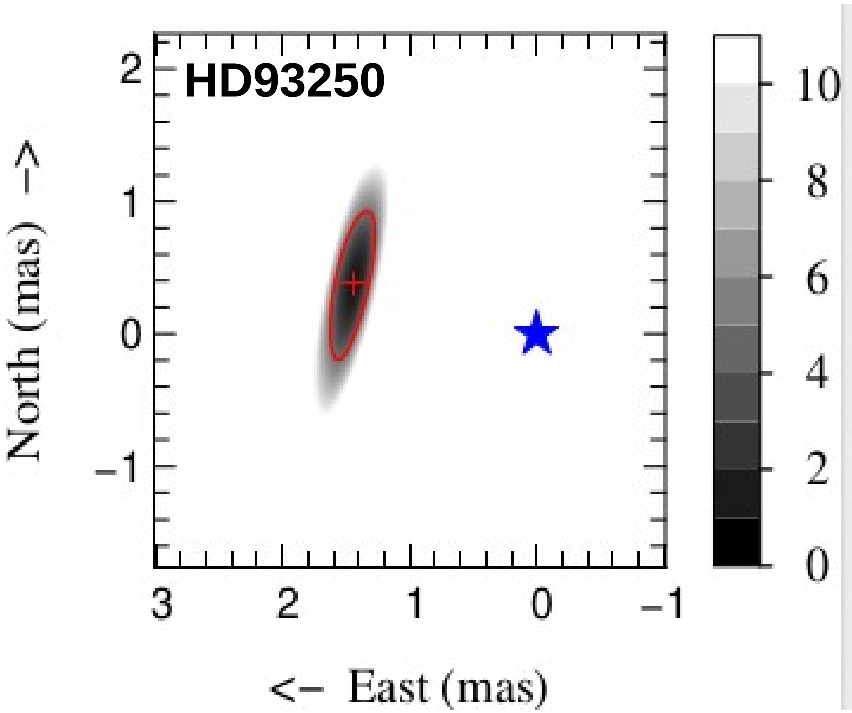
Non thermal radio emission



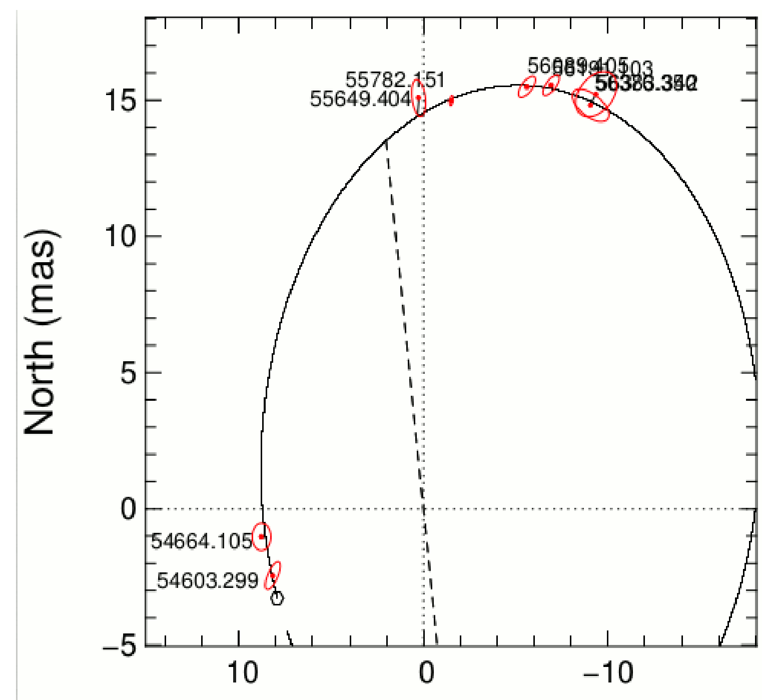


Non thermal radio emission

- 16 O-type NT radio emitters known (9 with $\delta < 0^o$)
- 1/3 have no indication of binarity despite intensive SB search
  - De Becker 2007

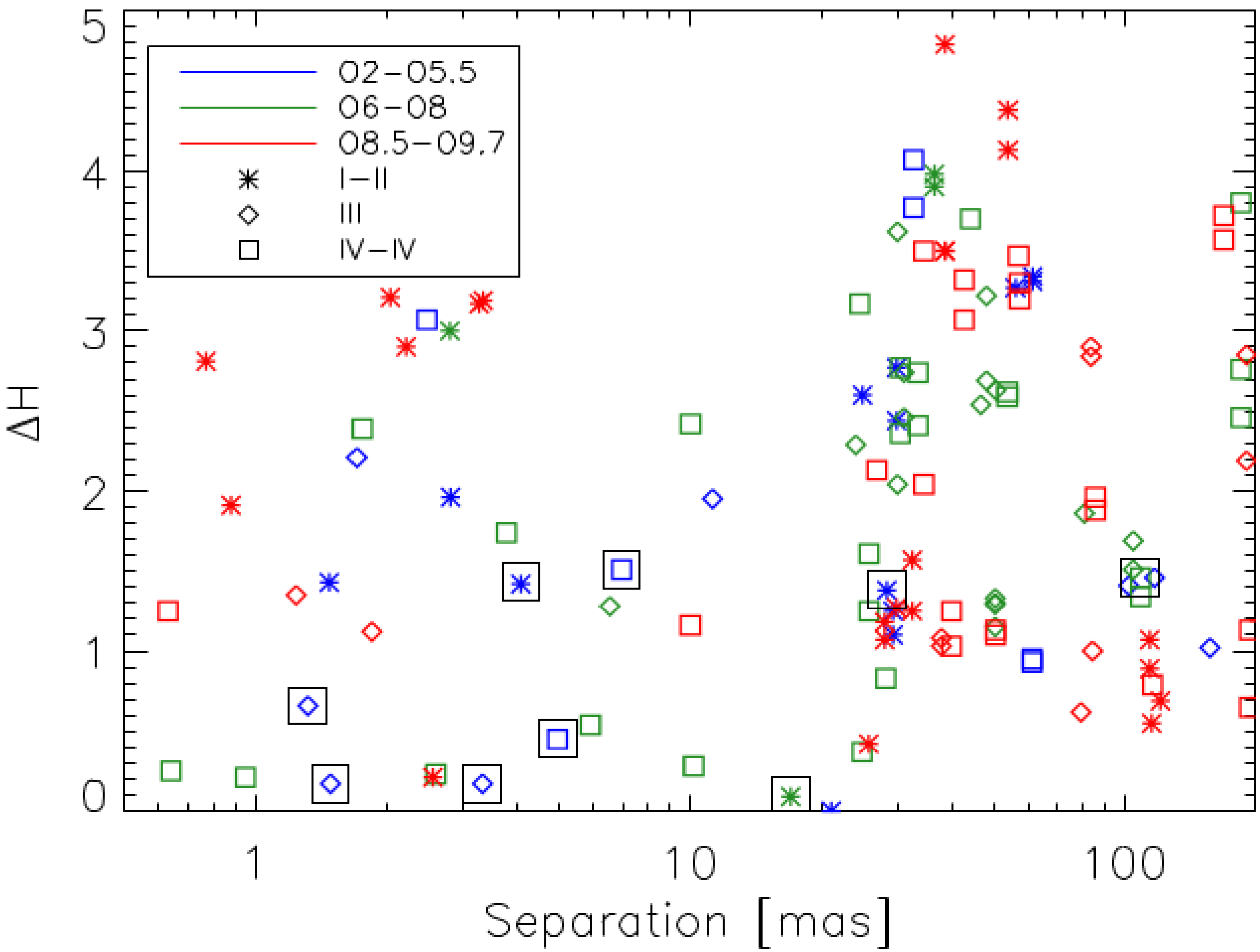


- Sana, Le Bouquin+2012



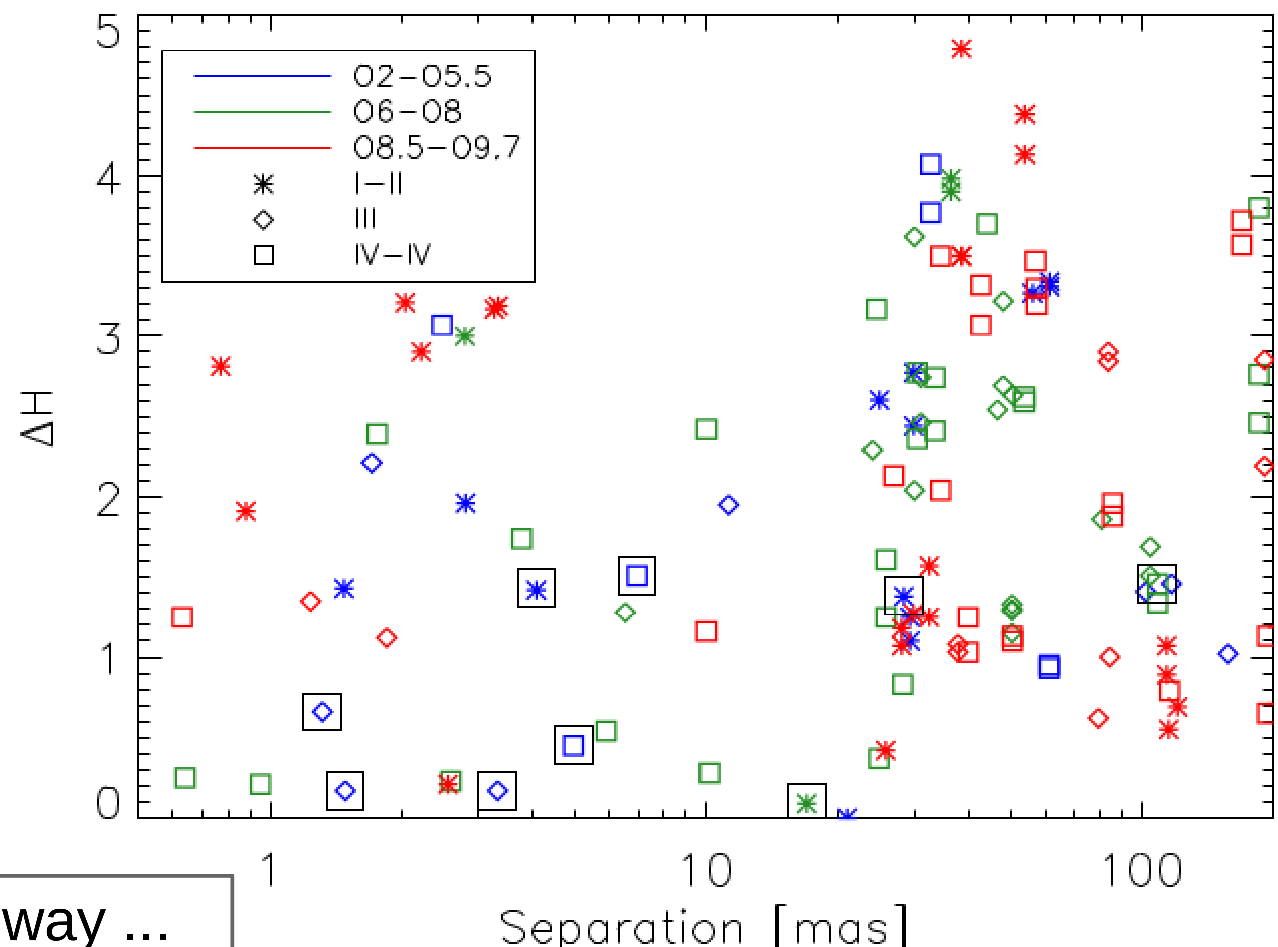
- De Becker+2012

• 16 O-type NT radio emitters known (9 with d < 0º)



• 16 O-type NT radio emitters known (9 with d < 0º)

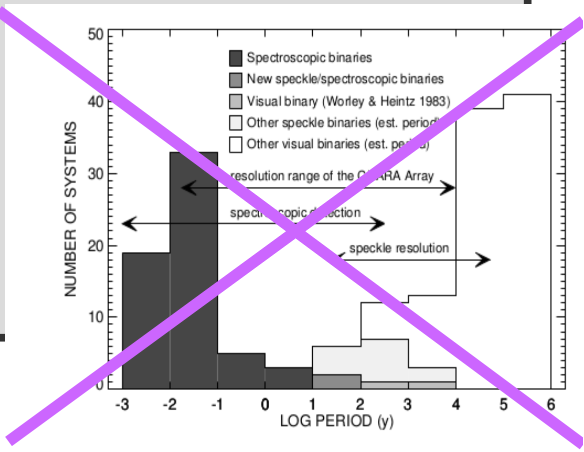
Wind-wind collision in wide binaries as the **universal** explanation of the origin of non thermal radio emission



Quantitative work on the way ...

SMaSH+ early results

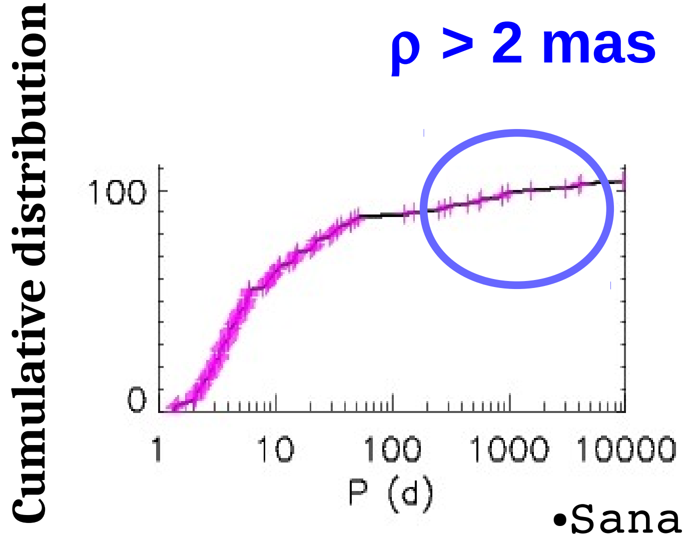
- > 100 O-type stars observed: 246 companions
- 35% have a companion < 200 mas
- # of companions 10x @ ρ < 100 ; 3x @ ρ < 8”
- Multiplicity fraction of O V : F_{mult}=100% < 100 mas
- F_{mult} decreases for O III and O I (bias ?)
- Hints for different Δmag - ρ
- All SB with P > 150d are resolved
- All non-thermal radio emitters are resolved



Binaries as laboratories

- Eclipsing binaries provide direct measurements of masses, radii & distance
  - 25 masses with accuracy < 5% (Gies. 2011)

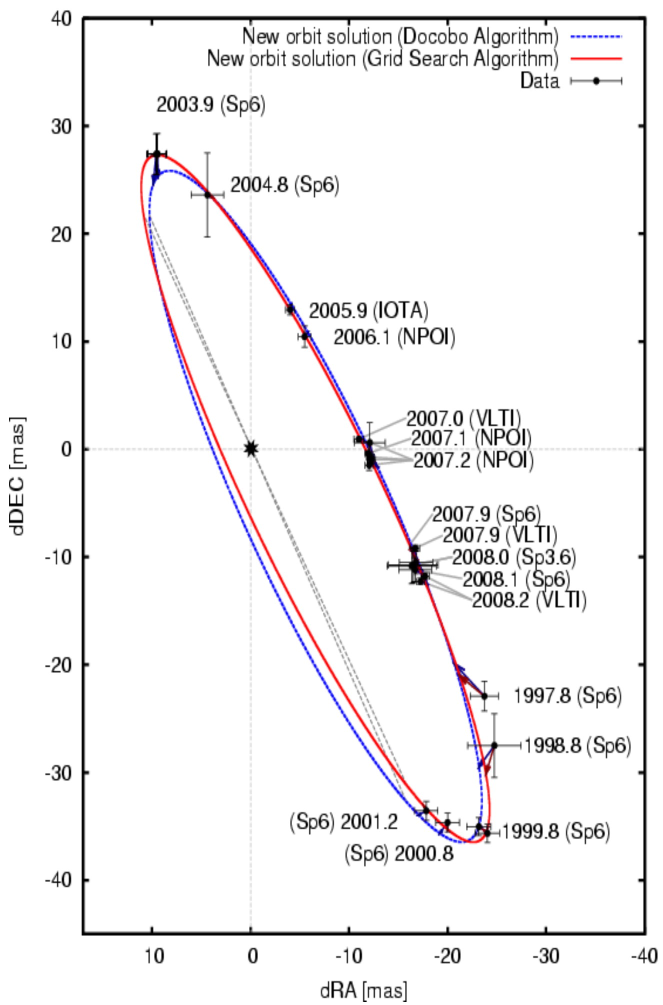
SB period distribution



- 6 candidates with P > 130 d identified
- Proof of concept with AMBER + UTs

•Sana & Evans 2011

Binaries as laboratories



Combining interferometry and spectroscopy can help !

Need of D > 1.5 kpc to find candidates

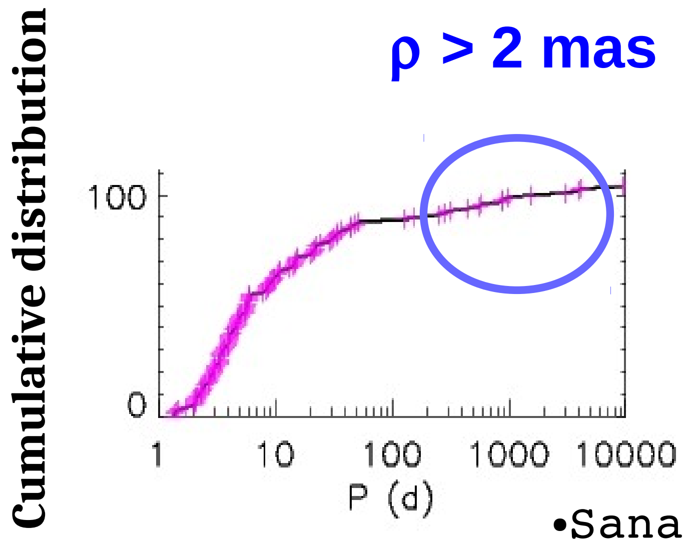
- θ^1Ori C (P~11yr))
- Kraus+ 2009

Binaries as laboratories

Combining interferometry and spectroscopy can help !

Need of D > 1.5 kpc to find candidates

SB period distribution



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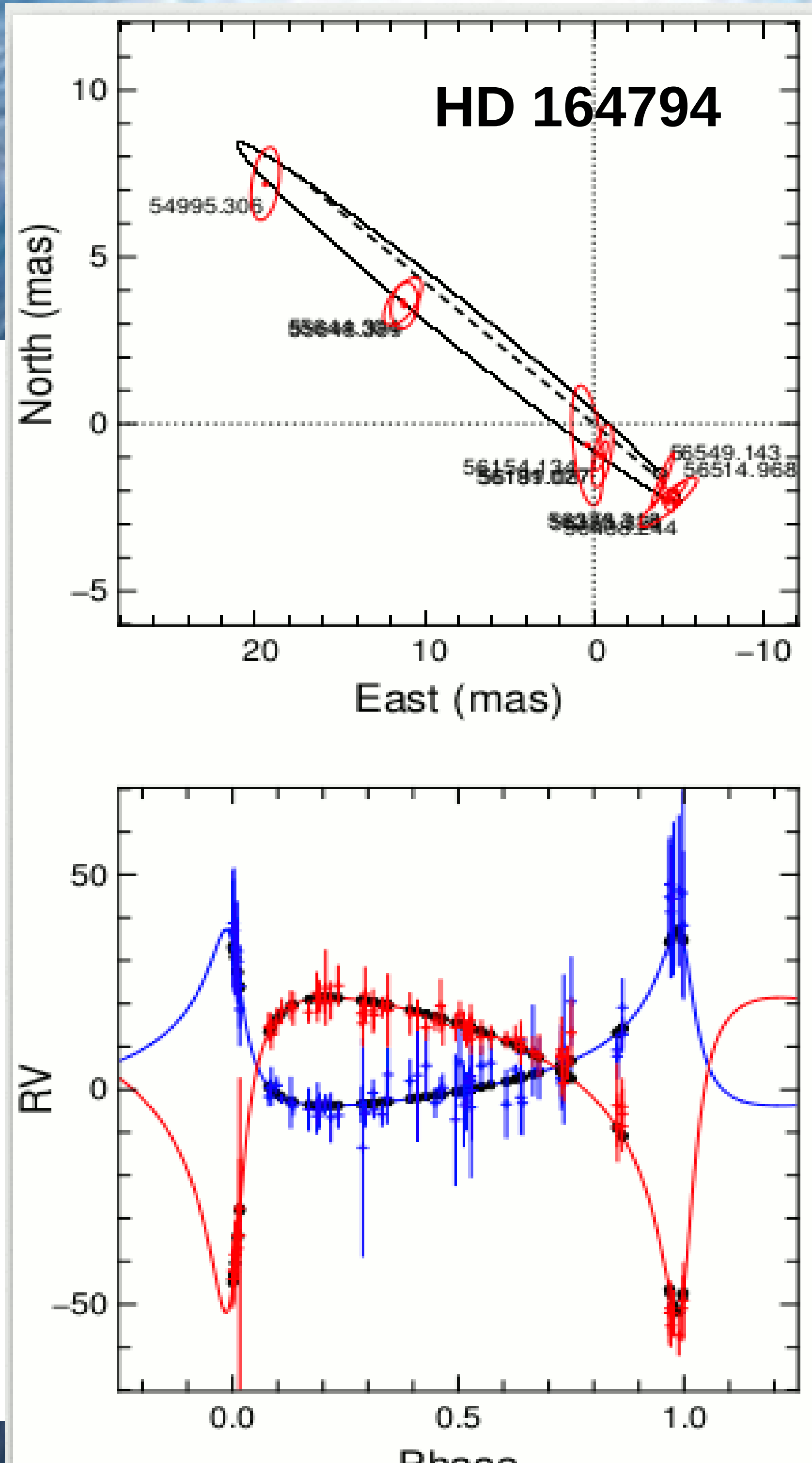
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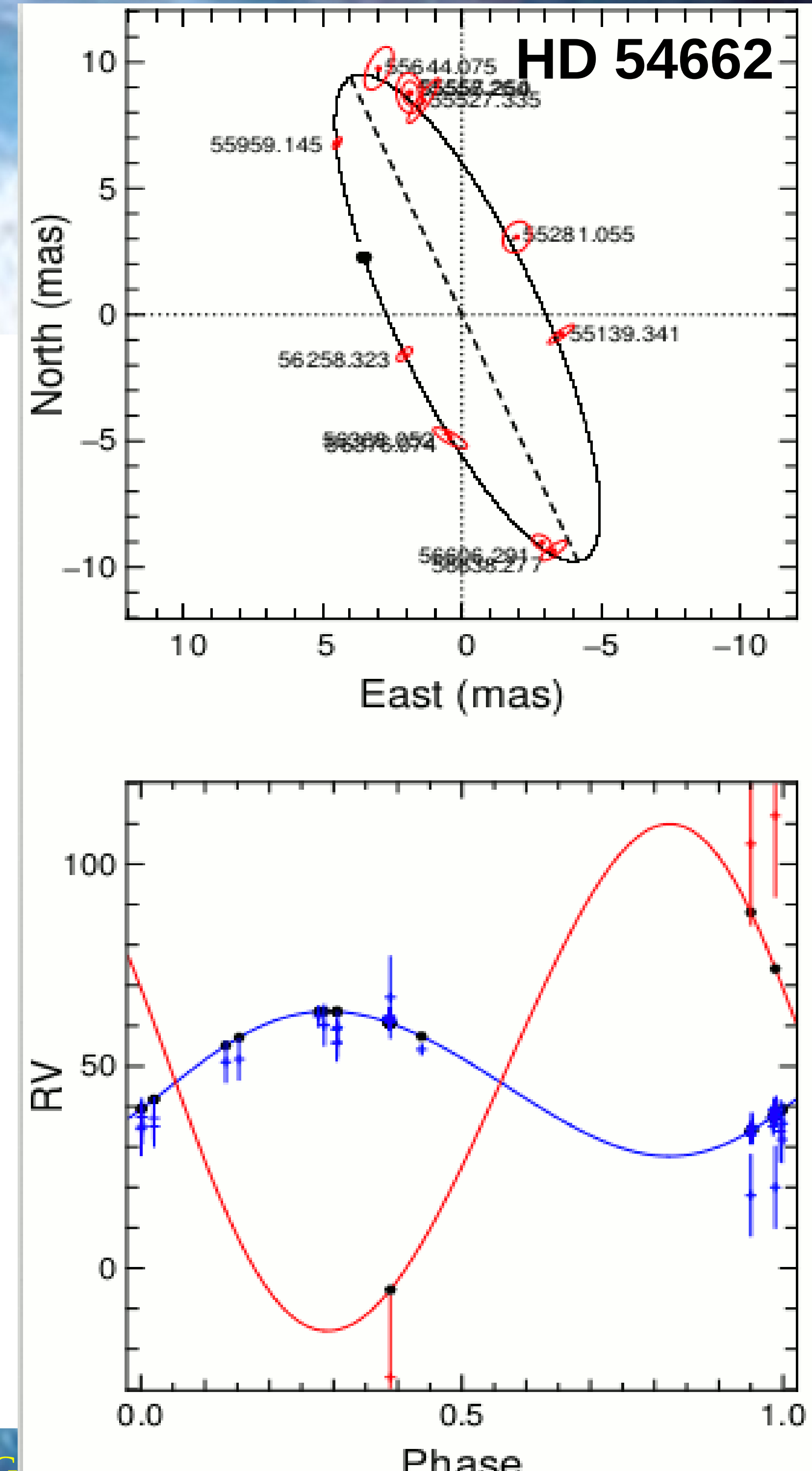
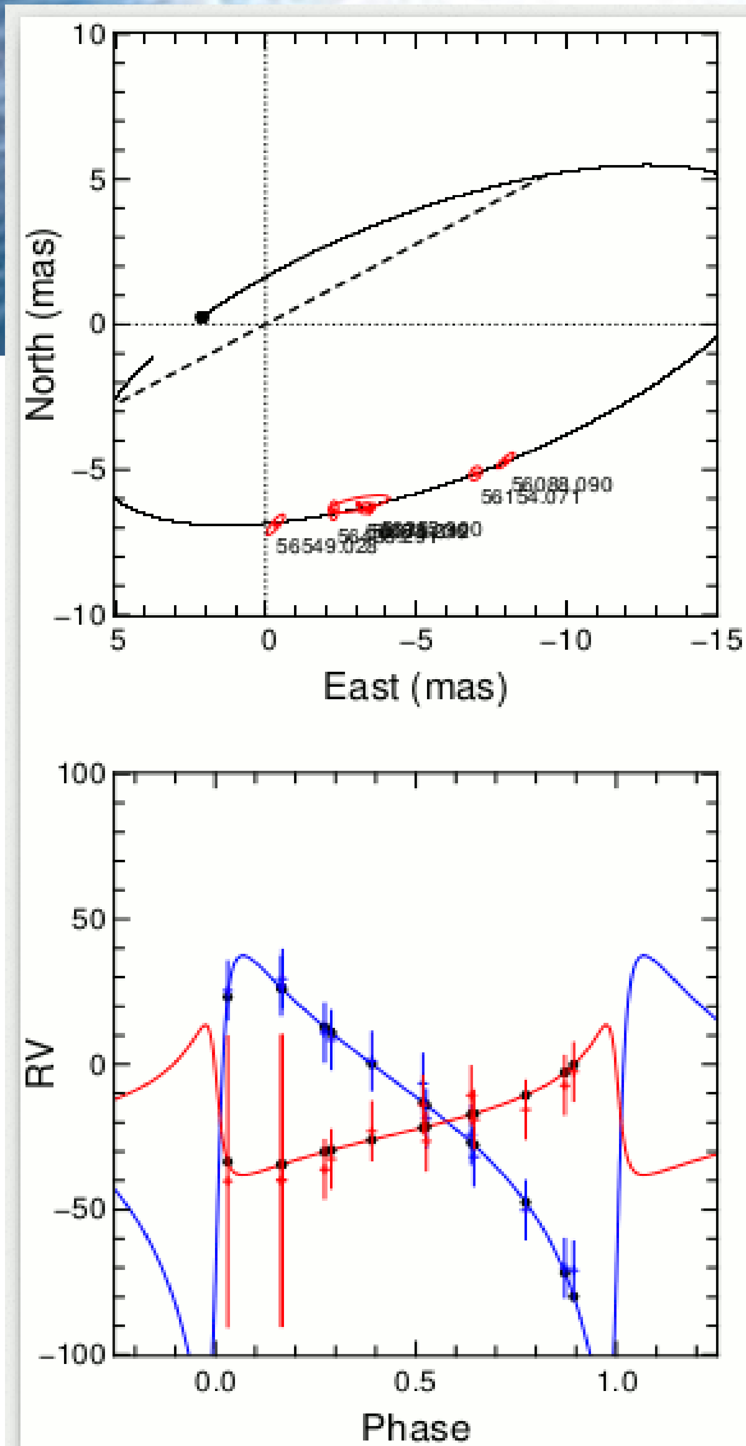
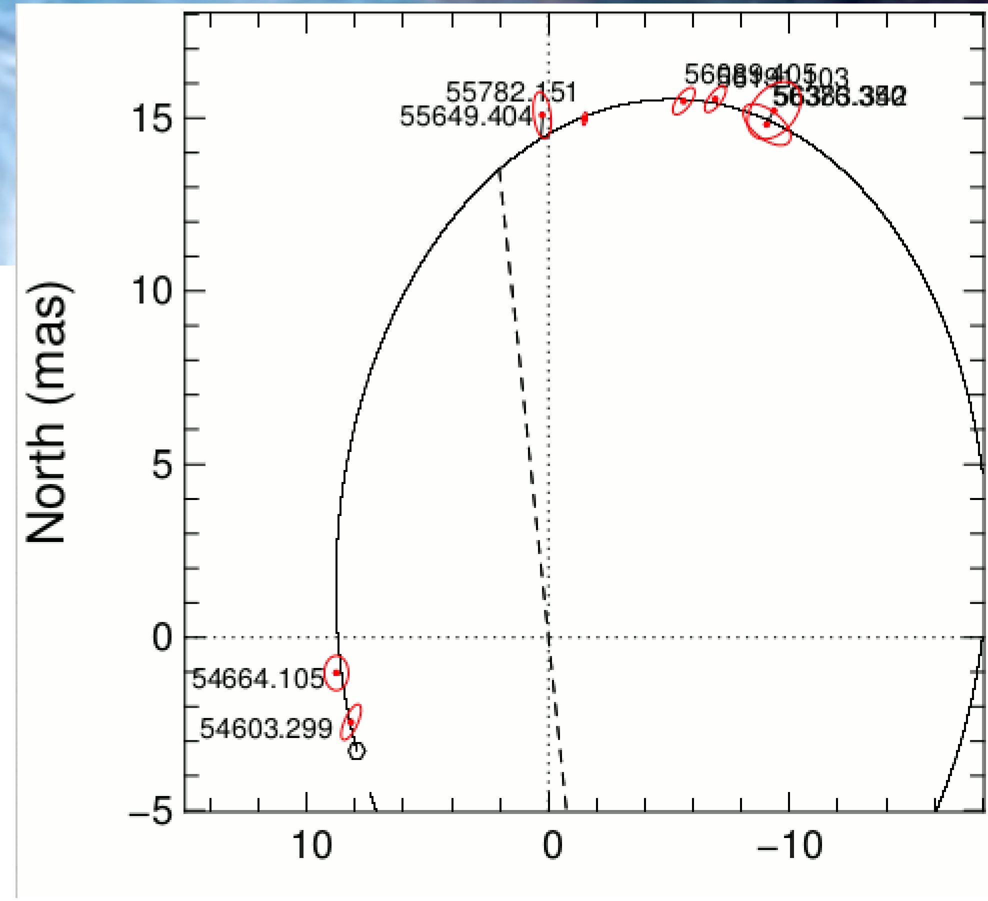
North (mas)
East (mas)
54995.306
55644.384
56549.143
56514.968
RV
Phase


HD 54662
North (mas)
East (mas)
55644.075
55527.335
55959.145
55281.055
55139.341
56258.323
56606.291
56638.277
RV
Phase





- De Becker, Sana, Le Bouquin+2013

VLTI + spectral disentangling
(+ time)
→
accurate mass and distances

- Sana, Le Bouquin+2013

PIONIER offers a new window of investigations for massive stars

- Fundamental parameters
- Wind physics
- SMaSH+: Statistical multiplicity properties in an uncharted range of separations

Thanks to the PIONIER team

for a wonderful instrument

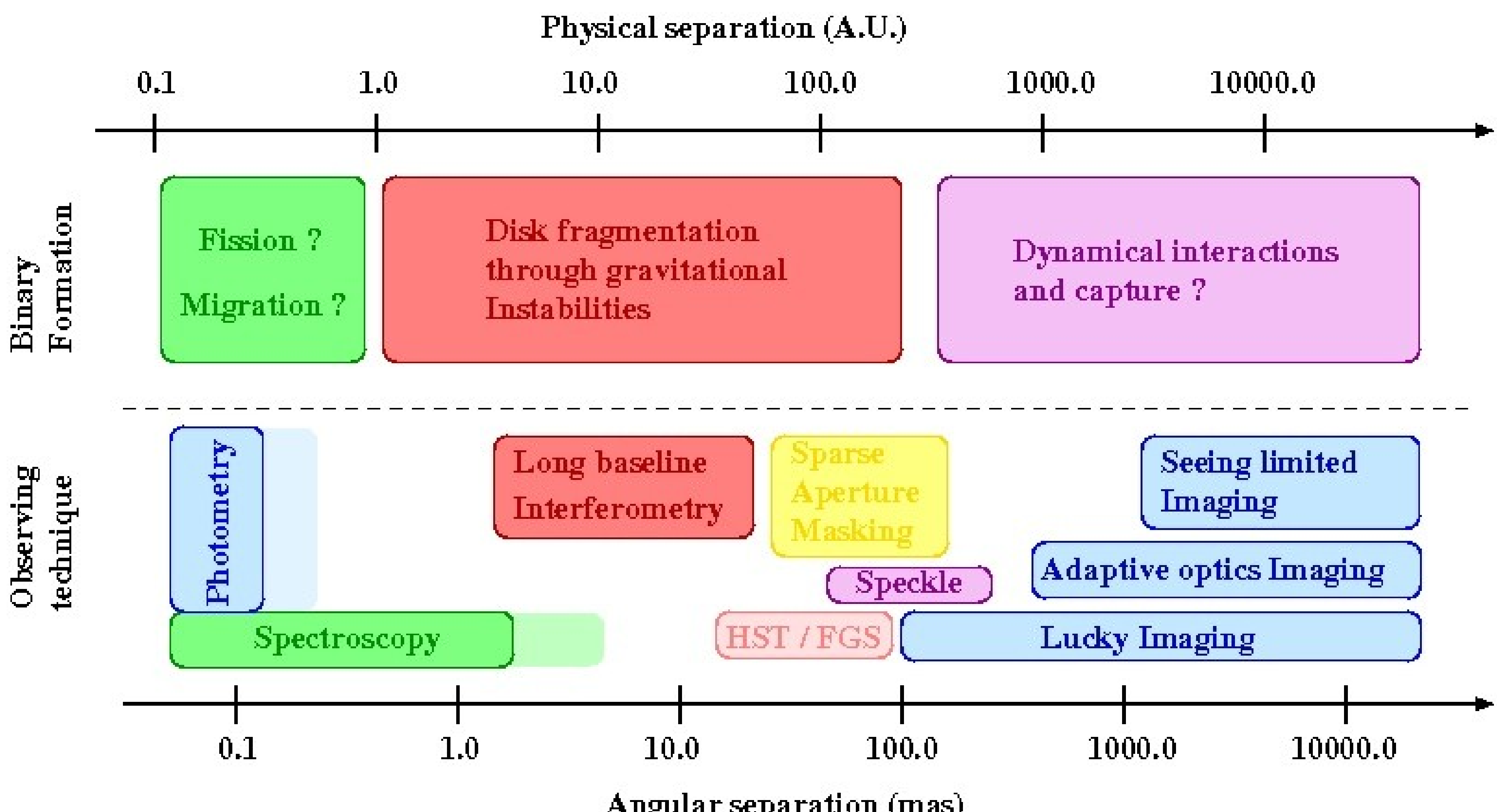
Thanks to the VLTI team for great support

Backup slides

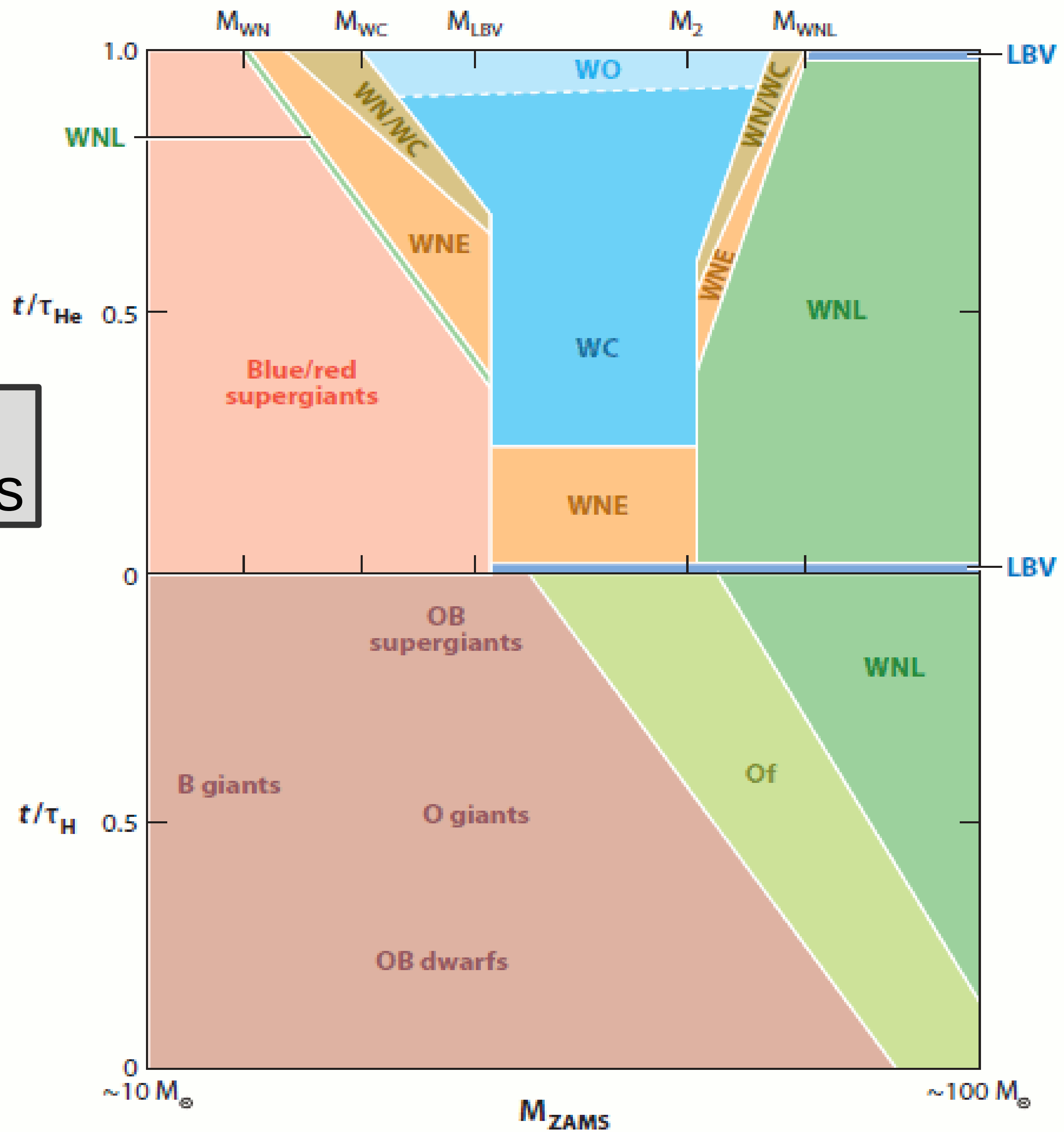
for

nasty questions

Preliminary results at half-course



Variety of pre-SN evolutionary products



Langer 2012

- Mass & mass-loss
- Metallicity
- Rotation rate

SMaSH+ sample