Direct imaging and characterisation of giant exoplanets

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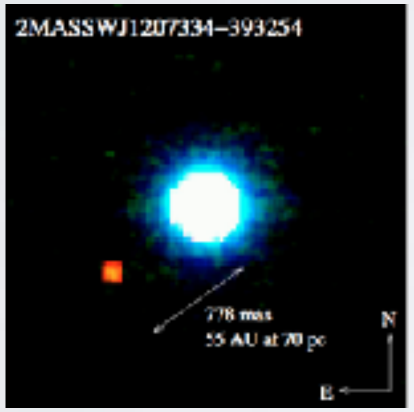
Deep imaging survey of nearby young A stars

Part of the International Deep Planet Search survey

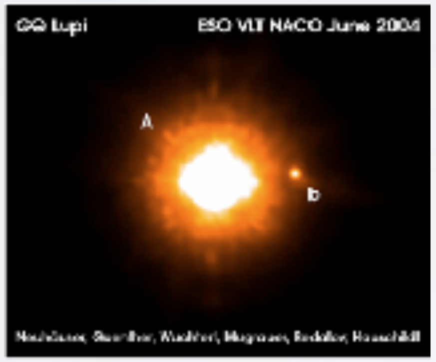
In collaboration with J. Patience, C. Marois, M. Bonavita, R. J. De Rosa, B. Macintosh, I. Song, R. Doyon,
B. Zuckerman, D. Lafrenière, T. Barman and R. Galicher

Motivations

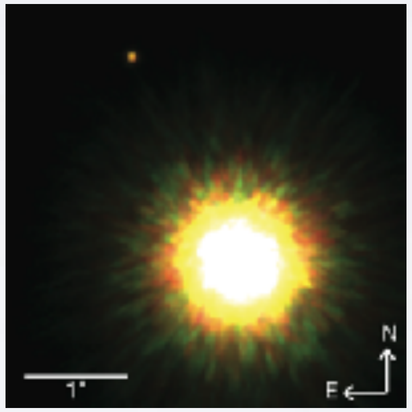
- Previous surveys focused on Solar-type stars
  (Masciadri et al. 2005; Lafrenière et al. 2007; Kasper et al. 2007; Leconte et al. 2010; Chauvin et al. 2007)
- Very few detections of sub-stellar companions
  → 2M 1207, AB Pic, 1RXS 1609, CT Cha, GQ Lup, ...



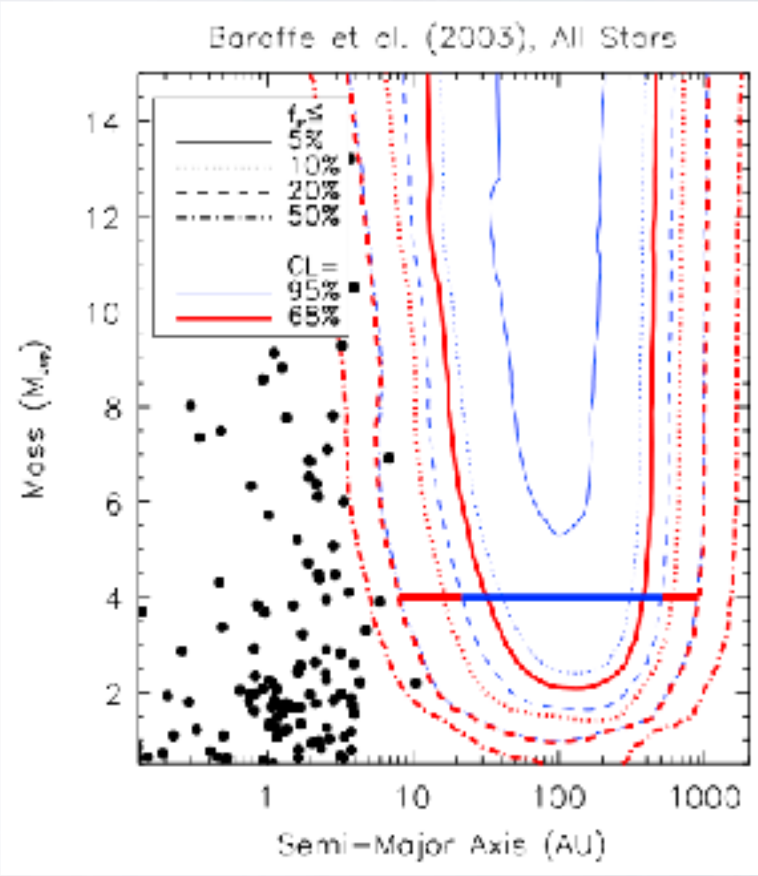
Chauvin et al. (2004)



Neuhauser et al. (2005)



Lafrenière et al. (2008)



Nielsen & Close (2010)

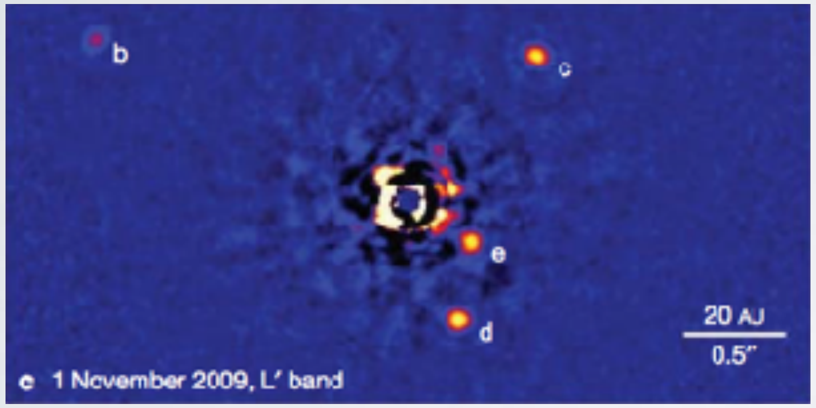
- Recent surveys focused very massive
  (Janson et al. 2011) or low-mass stars (Delorme et al. 2012)

Main conclusion: planets are rare around FGKM stars

Motivations

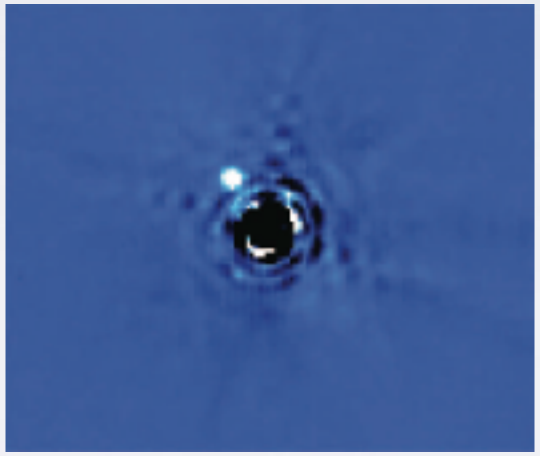
- Recent breakthrough discoveries around young A stars

HR 8799 - 30 Myr



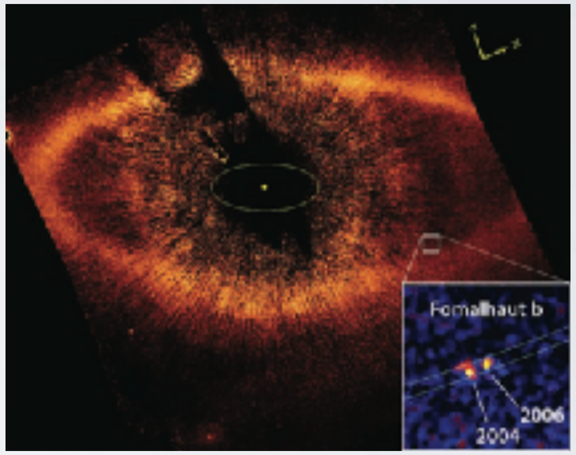
Marois et al. (2008, 2010)

ß Pictoris - 12 Myr



Lagrange et al. (2010)

Fomalhaut - 100-300 Myr

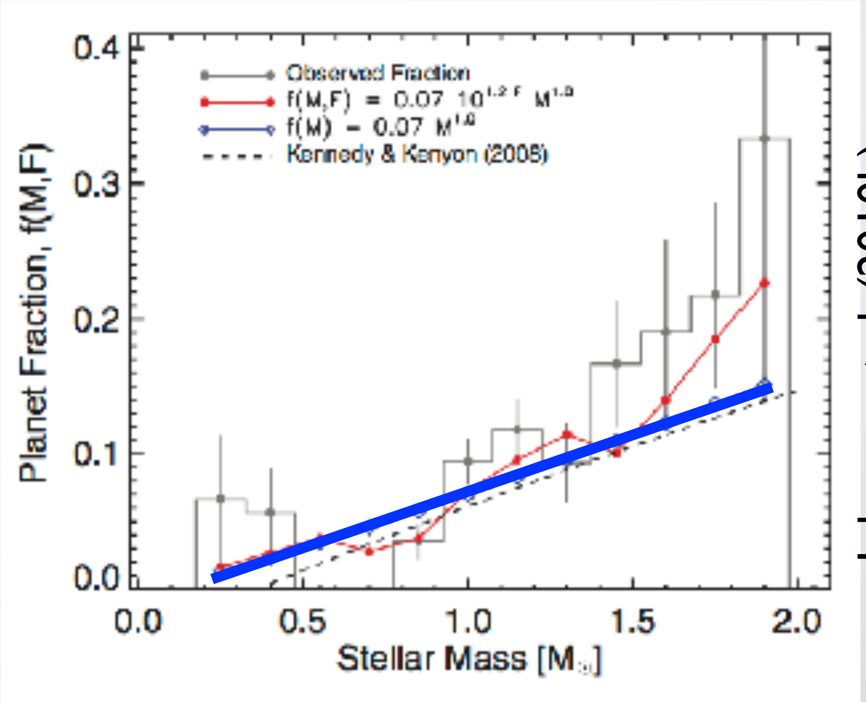


Kalas et al. (2008)...

... but see also Janson et al. (2012)

- Recent discoveries of RV planets around old A stars
  Lick and Keck subgiant surveys
  (Johnson et al. 2010, 2011; Bowler et al. 2010)

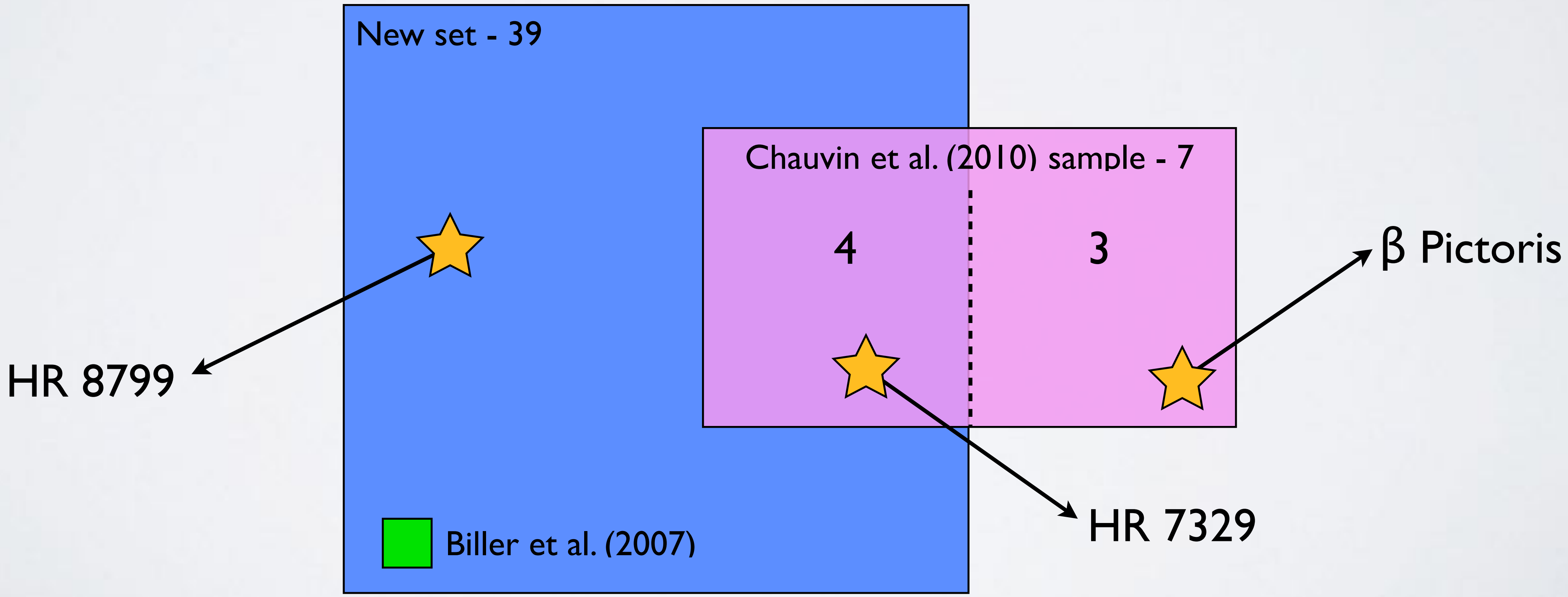
→ strong correlation between stellar mass and planet mass



Johnson et al. (2010b)

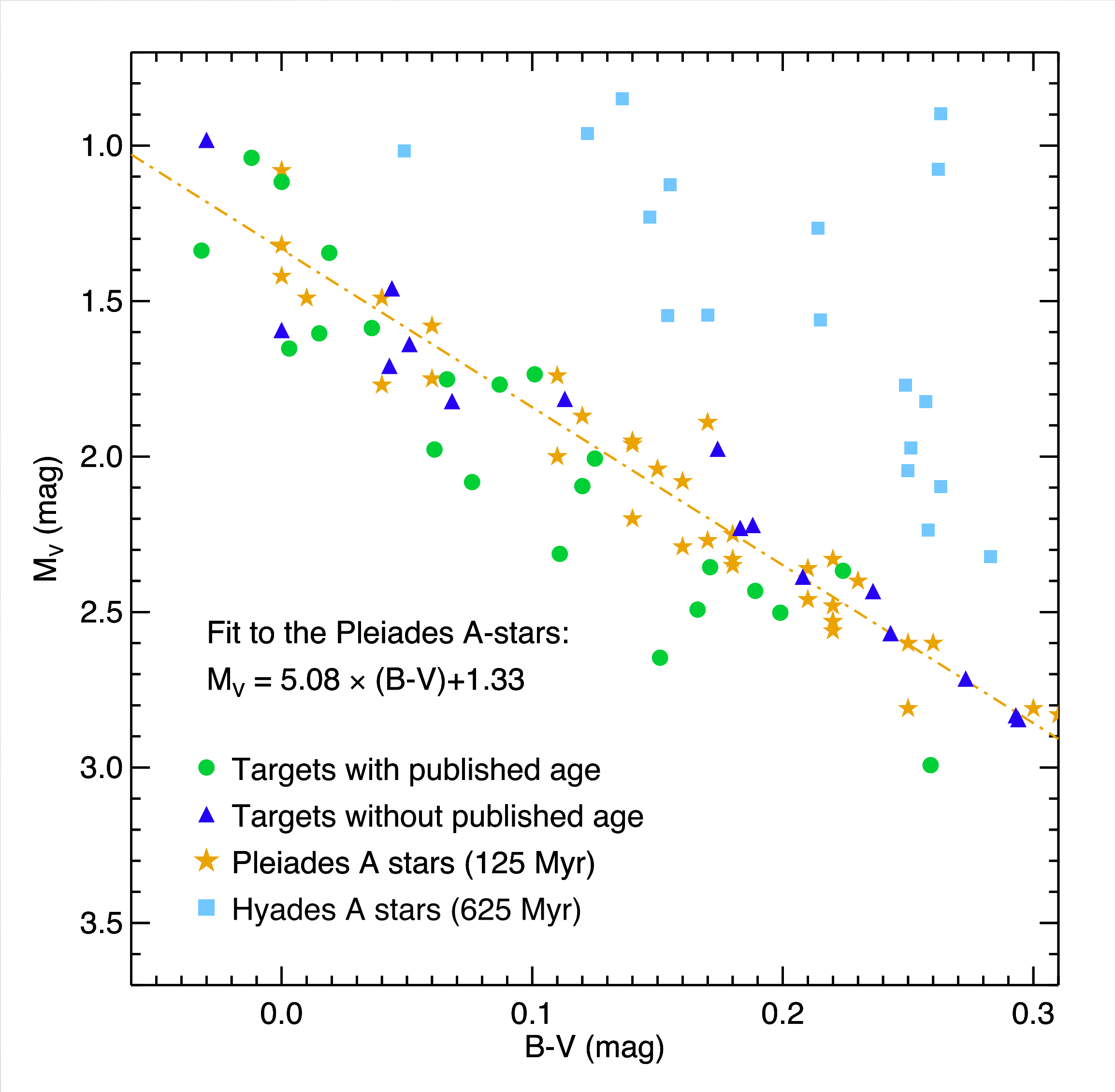
Sample selection

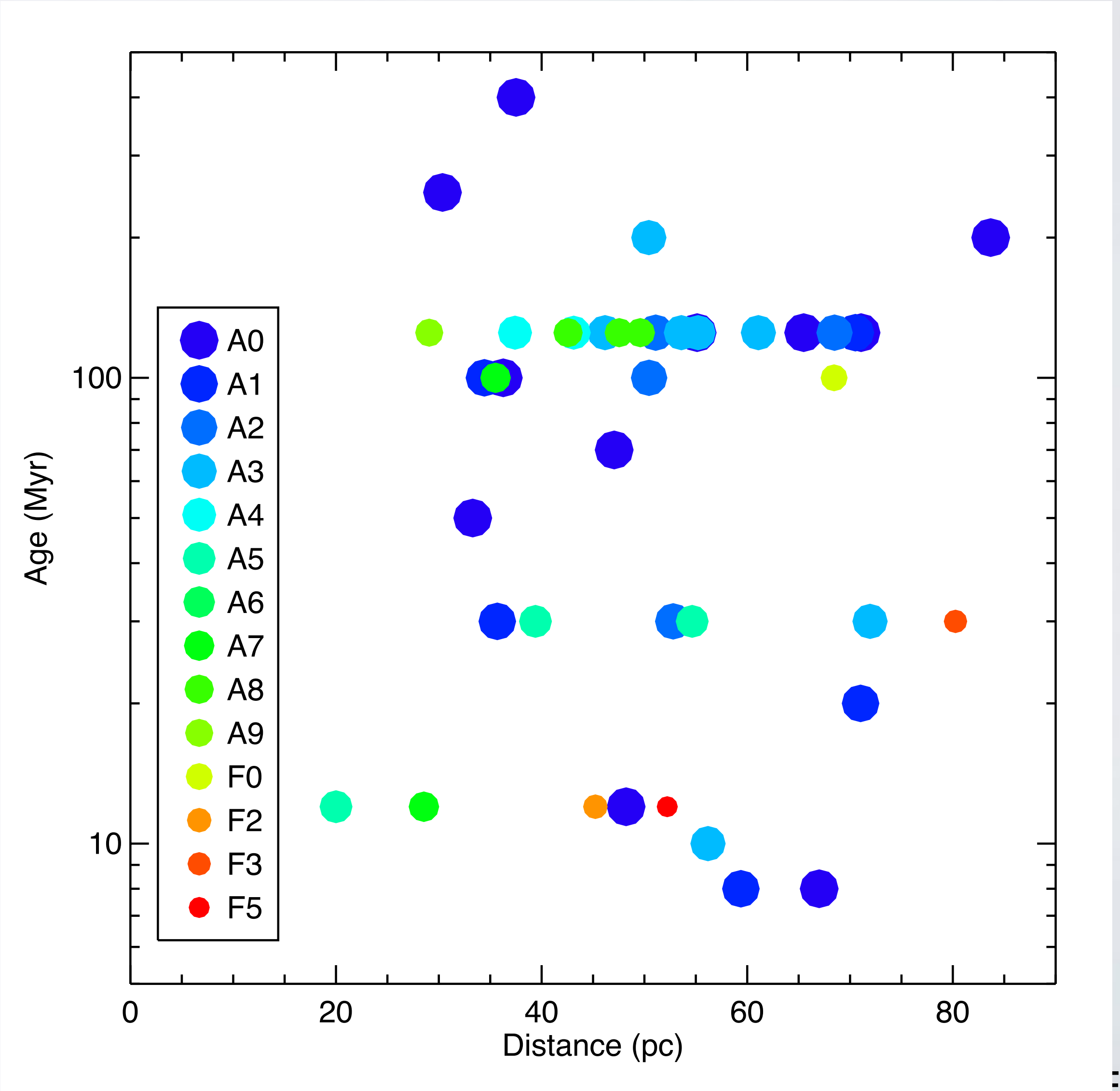
- Our sample includes a total of 42 stars:
  - a new set of young (median age 100 Myr), nearby (d ≲ 85 pc) A-stars (+4 early F)
  - A-stars previously observed in planet-search surveys



Sample selection

- Selection of the new set of targets:
  - initial fit to the Pleiades A-stars (125 Myr)
  - search for published ages in initial selection



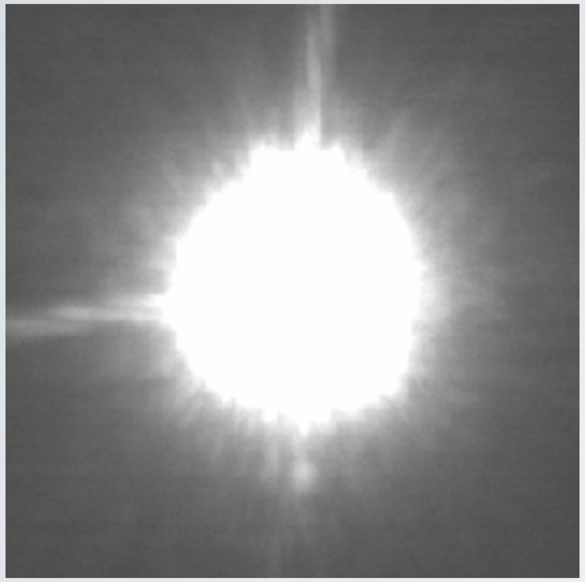


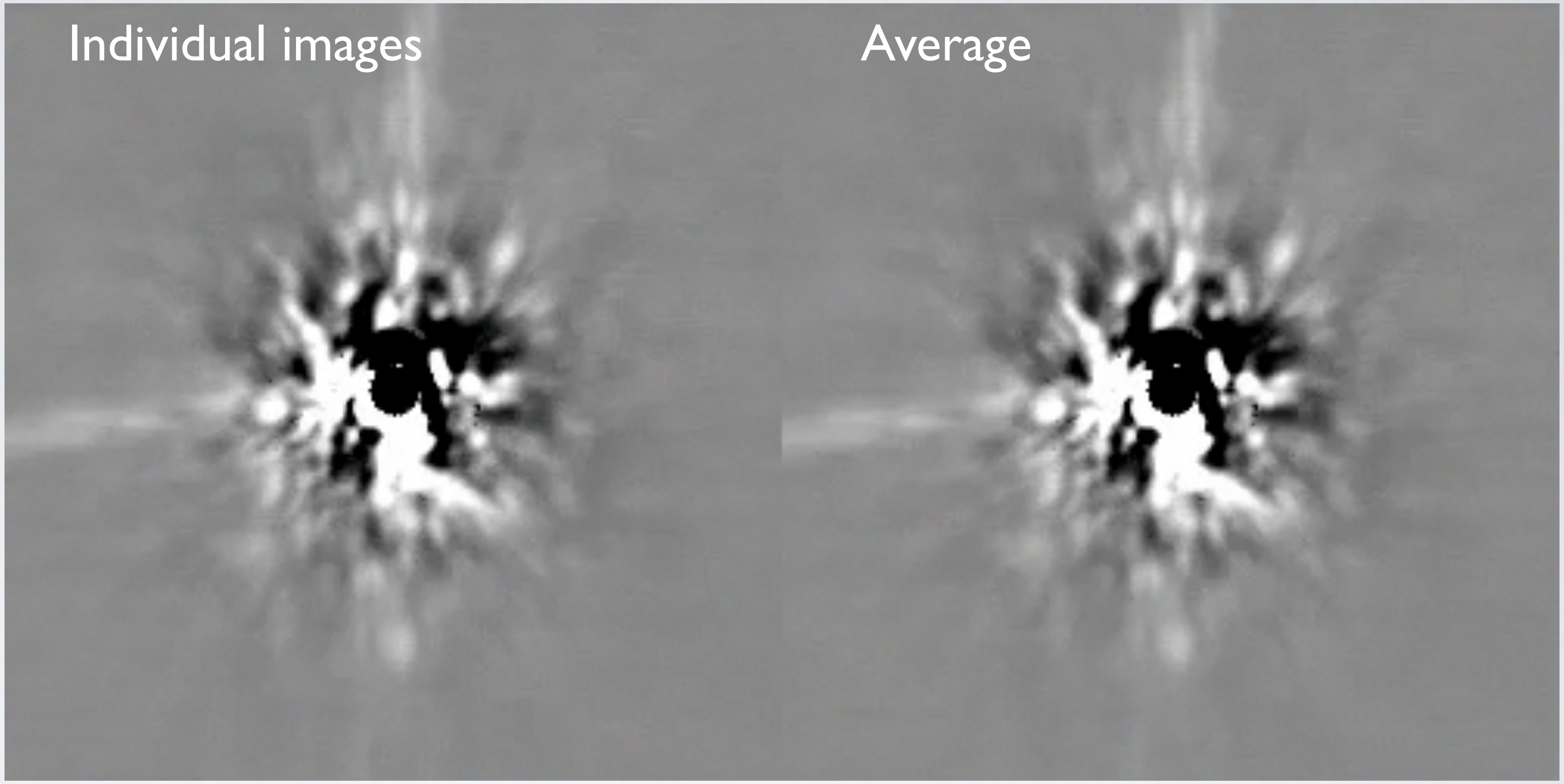
Observations

	VLT/NaCo	*Gemini/NIRI*
# of targets	19	20
Filters	Ks	K’ + CH4short
Periods	2009-2012	2007-2010
Pixel size	~13.20 mas	~21.4 mas
Field of view	~13.5”	~22”
Mode	saturated imaging angular differential imaging	

- conditions from poor to excellent
- typical field of view rotation = 30°

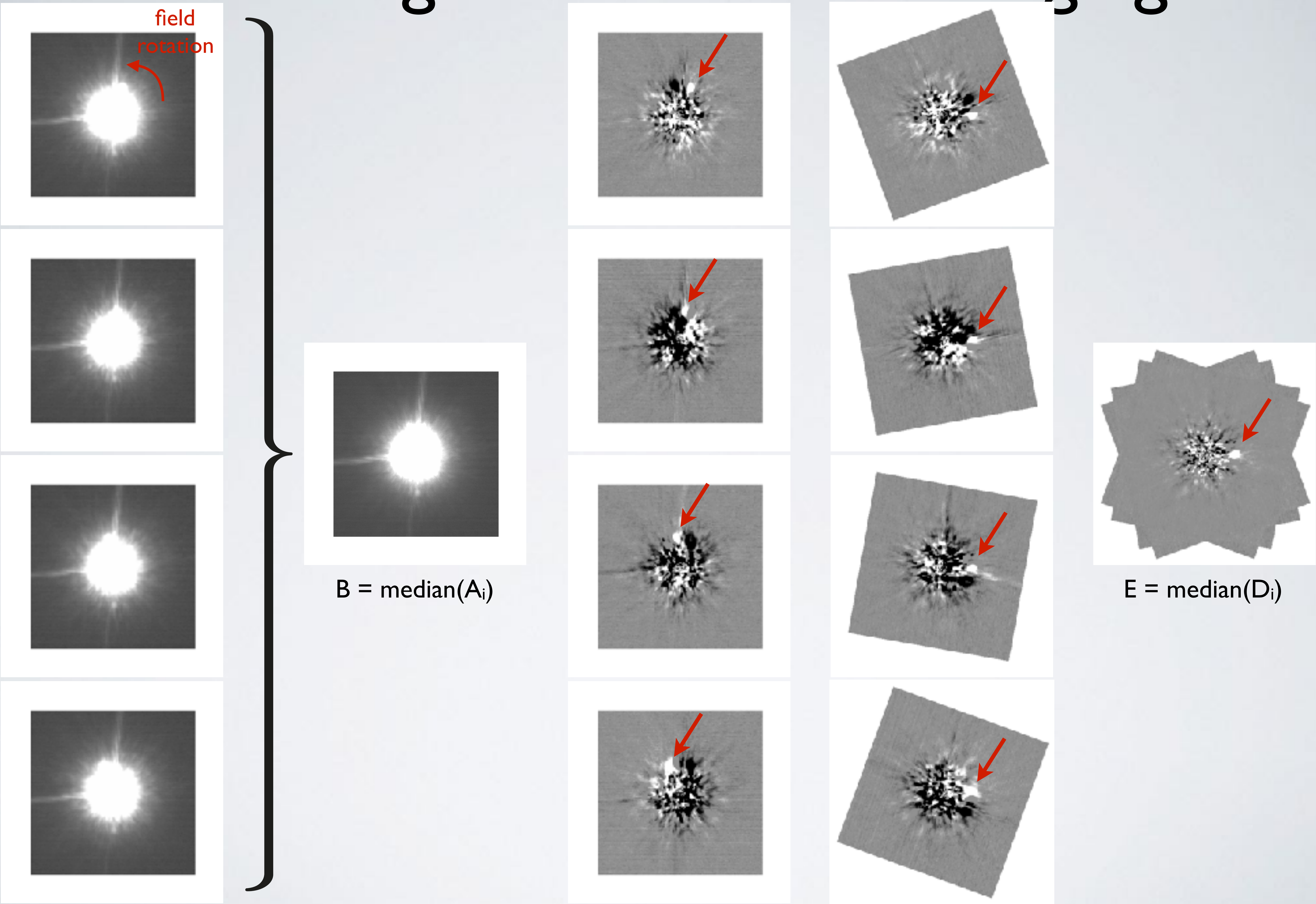
Speckle noise attenuation





- high-contrast data limited by "speckle noise"
- NOT static.... but definitely not random!
- need to subtract a reference PSF to faint companions

Angular differential imaging



A_i

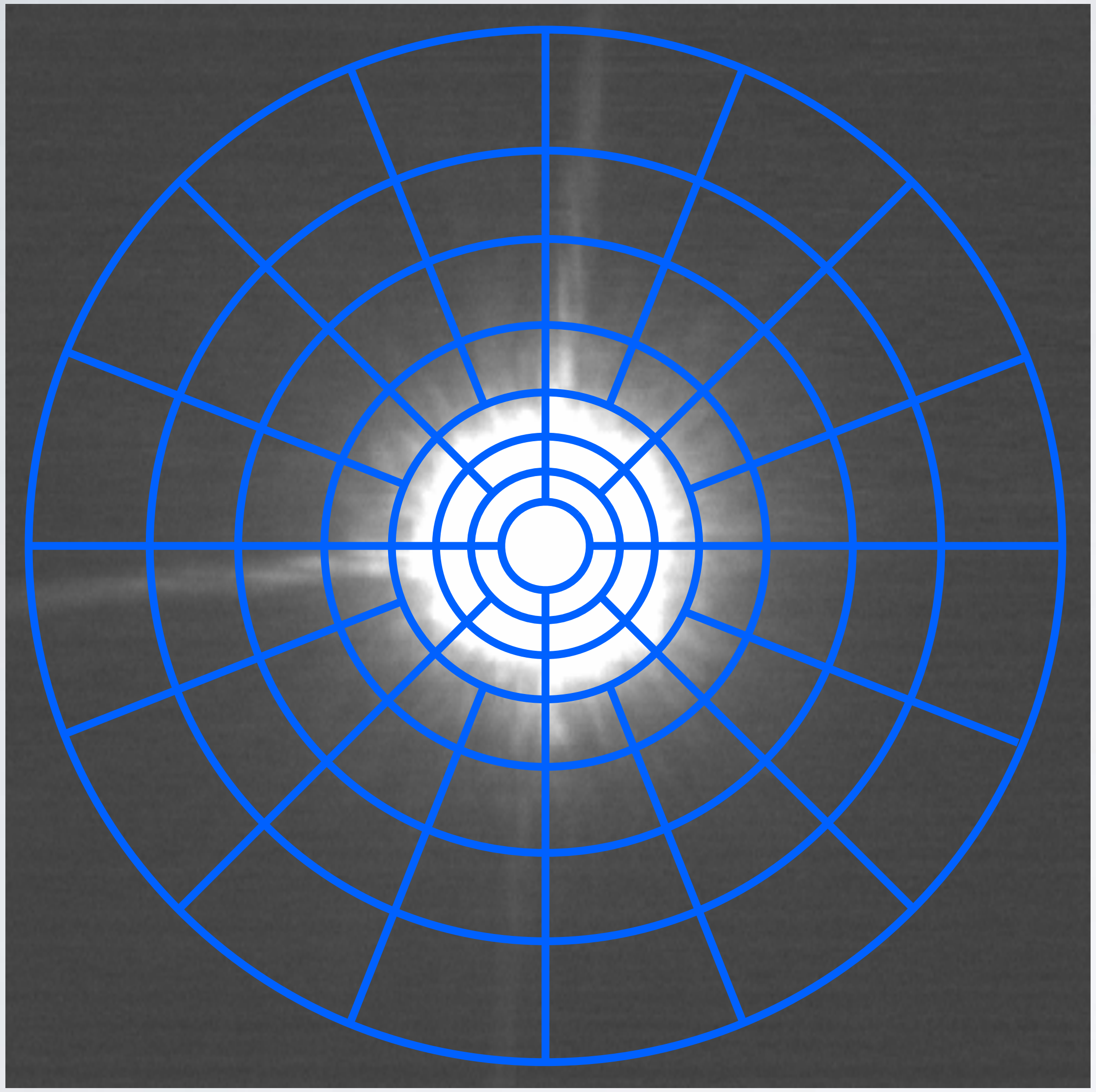
$B = \mathrm{median}(A_i)$

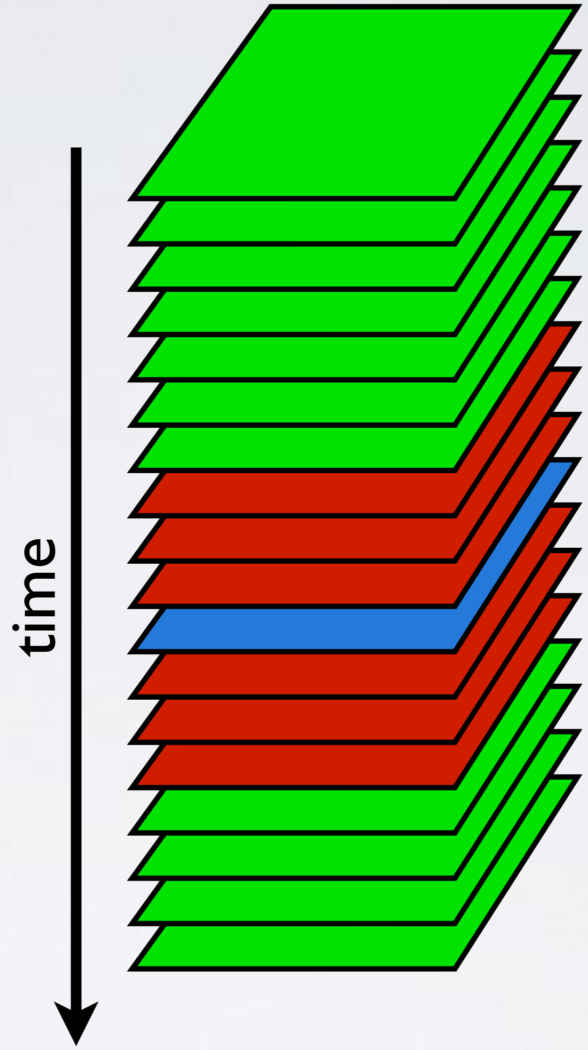
$C_i = A_i - B$

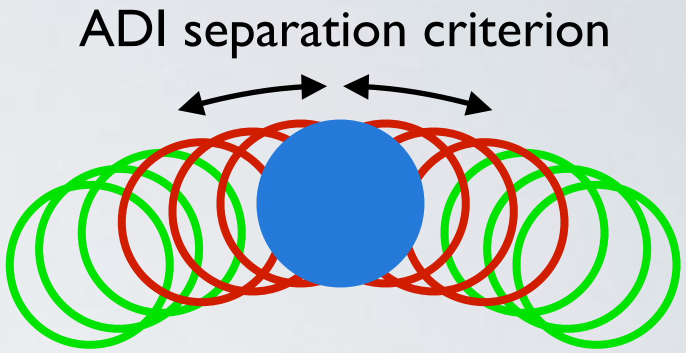
$D_i = \mathrm{derot}(C_i)$

$E = \mathrm{median}(D_i)$

Locally optimised ADI





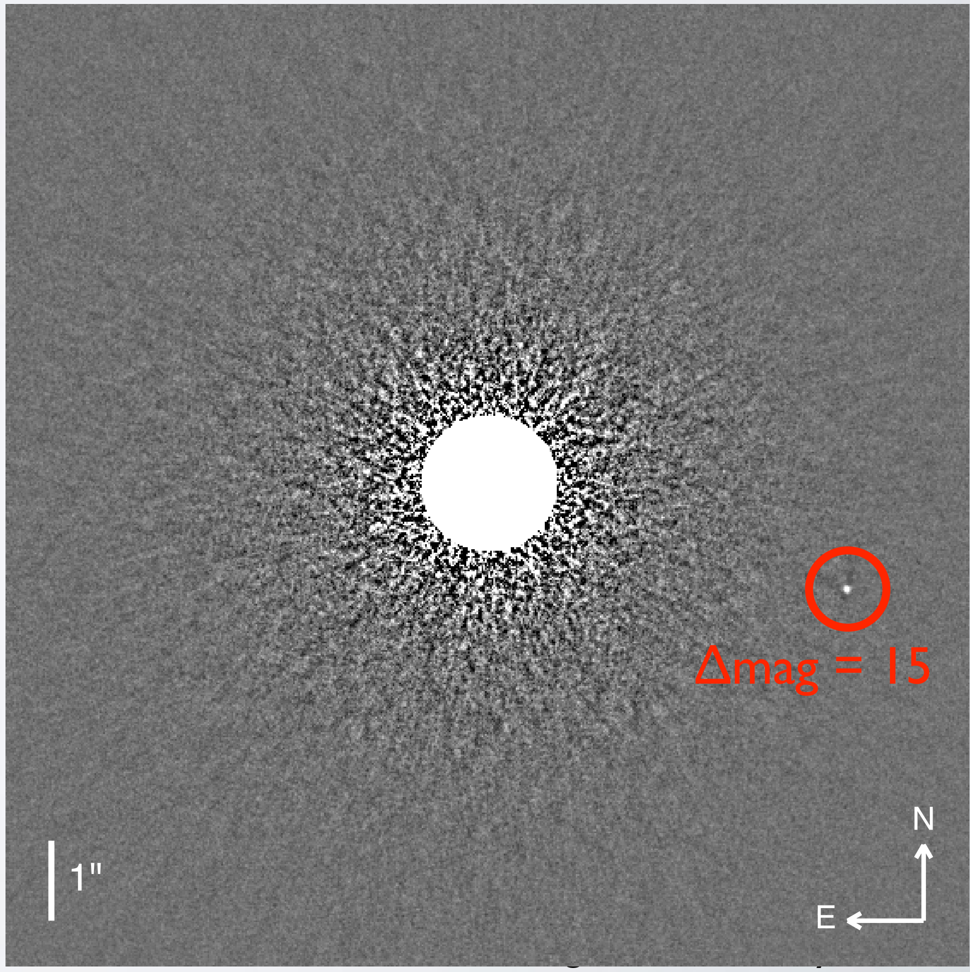


criterion defines the **minimal angular separation** between the planet position in two frames to avoid self-subtraction

- image divided in multiple segments (Lafrenière et al. 2007)
- PSF reference constructed and subtracted in each segment
- reference is a linear combination of all usable frames

Data reduction and analysis

- standard data reduction
- frame registration using Moffat profile fitting
- frame selection based on encircled energy and maximal flux
- unsaturated PSF used for normalization
- analysis of the data sets with LOCI:
  - N_δ = 0.75 FWHM
  - N_A = 300-500 PSF footprints

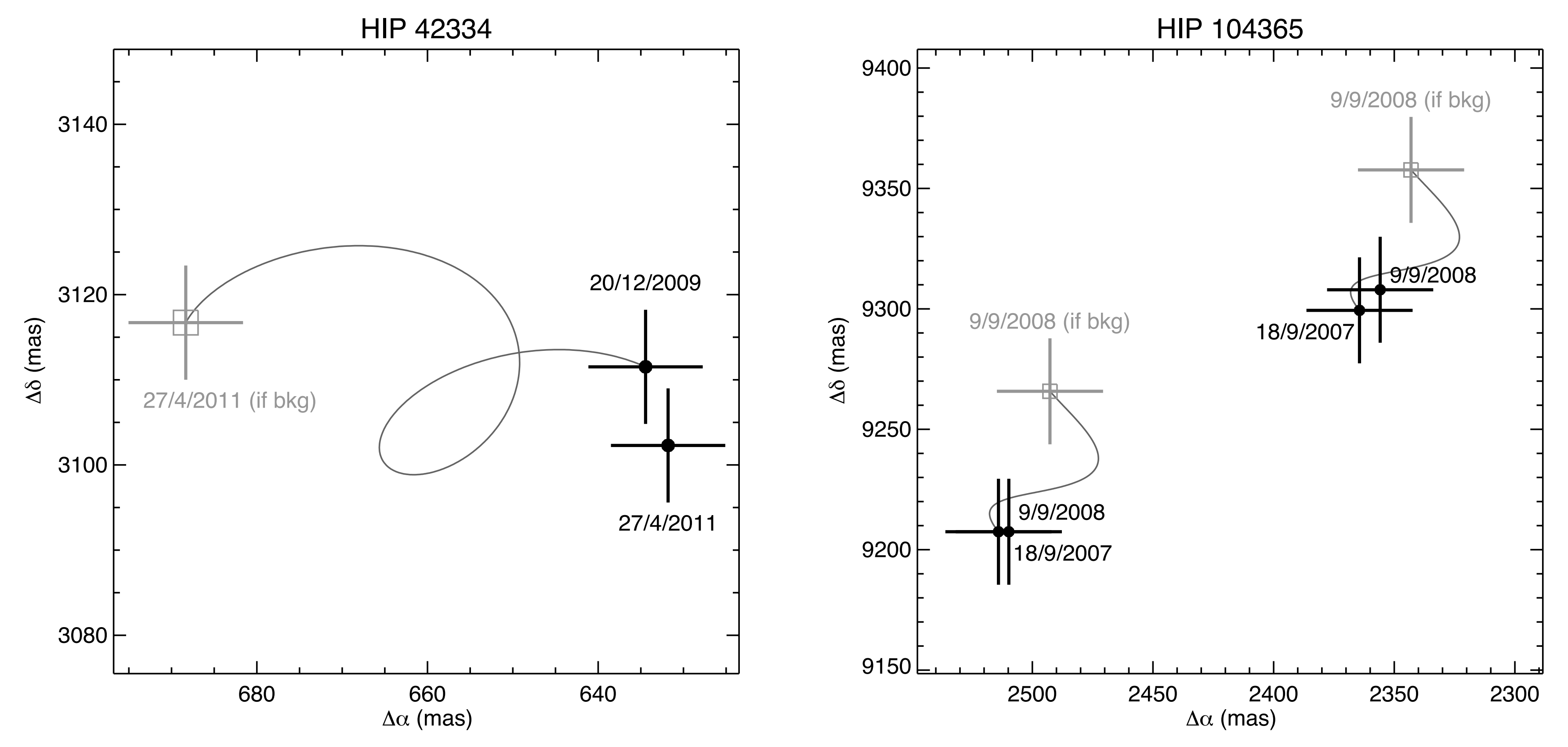


Companion candidates

- candidates identified by eye on images and SNR maps
- ~50 candidates ≥5σ around 22 of the targets
- second epoch for candidates with separation ≤ 320 AU
- no new substellar companions

HIP 42334
- A0V
- 125 Myr
- 71 pc

M6/M8 companion

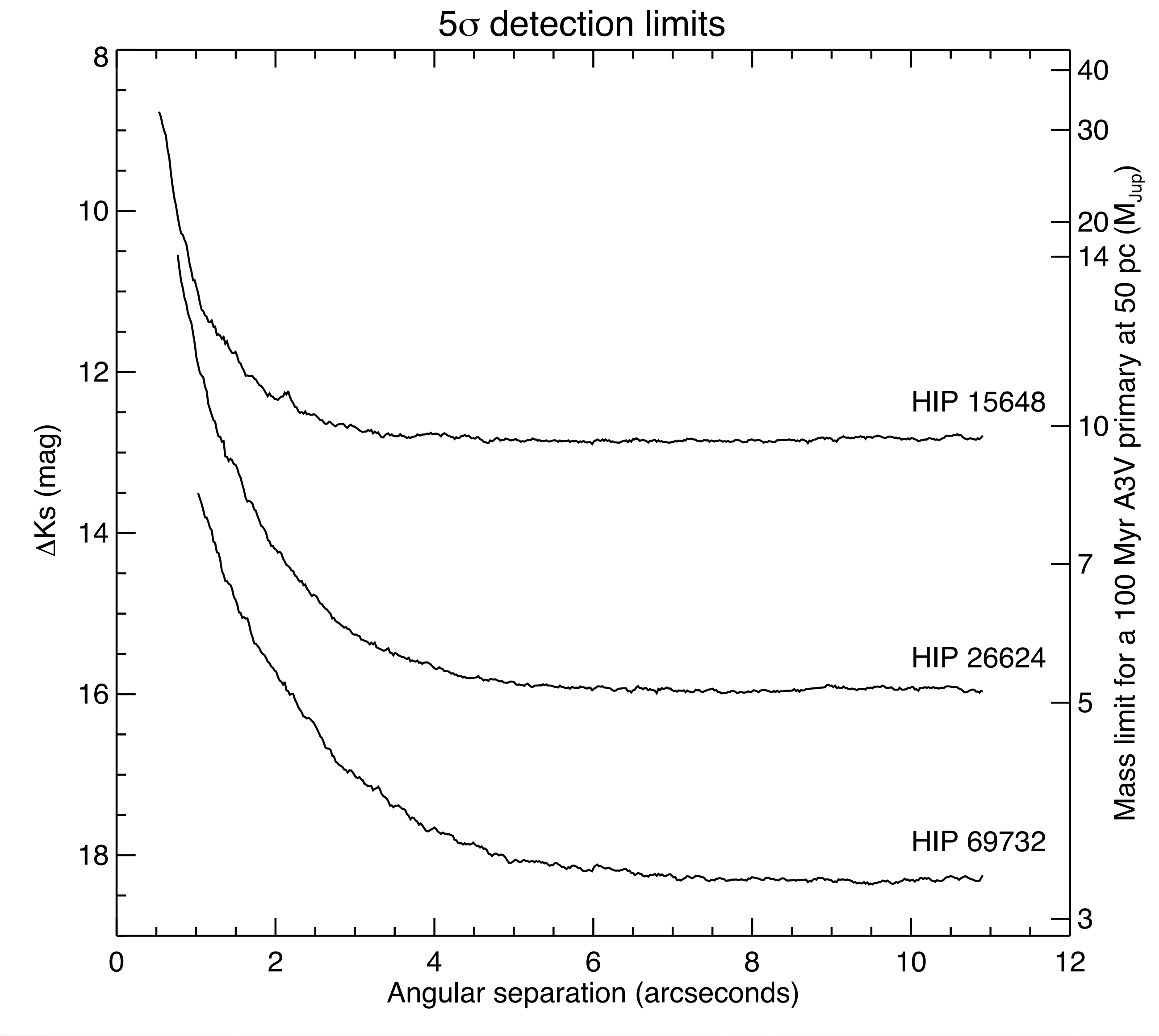


HIP 104365
- A0V
- 125 Myr
- 55 pc

M5/M7 companions

Detection limits

- noise in annuli of increasing radius ➙ 5σ detection limits
- normalisation by unsaturated PSF obtained with neutral density (NaCo) or narrow-band filters (NIRI)



Median target of the sample

- A3V
- 100 Myr
- 50 pc

➙ reach 3-10 M_{Jup}

Statistical analysis

- What statistical properties can be inferred from the data?
- Previous surveys have used non-detections to:
  - set upper limits on the fraction of stars with planets
  - set constraints on the population of planets at wide separation
- Now that there are detections... what can we say?

Statistical formalism

- Formalism of Carson et al. (2006) and Lafrenière et al. (2007)
- Likelihood of the data given *f*:

fraction of stars with at least 1 planet in $[m_{min},m_{max}]\cap[a_{min},a_{max}]$

$$L(\{d_j\}|f) = \prod_{j=1}^{N} (1 - f p_j)^{1-d_j} \cdot (f p_j)^{d_j}$$

probability of detecting a planet around star *j*

- Probability of *f* given our data (Bayes' theorem):

$$p(f|\{d_j\}) = \frac{L(\{d_j\}|f) \cdot p(f)}{\int_0^1 L(\{d_j\}|f) \cdot p(f)\,df},$$

posterior distribution

prior

Choice of the prior:
➙ linear-flat, *p(f)* = 1
"maximum ignorance"

Statistical formalism

- posterior distribution used to determine f_{min} / f_{max} with a confidence level α:

$$\alpha = \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} p(f|\{d_j\})df,$$

- Since we have detections, an equal-tail confidence interval is calculated:

$$\frac{1-\alpha}{2} = \int_{f_{\mathrm{max}}}^{1} p(f|\{d_j\})df$$

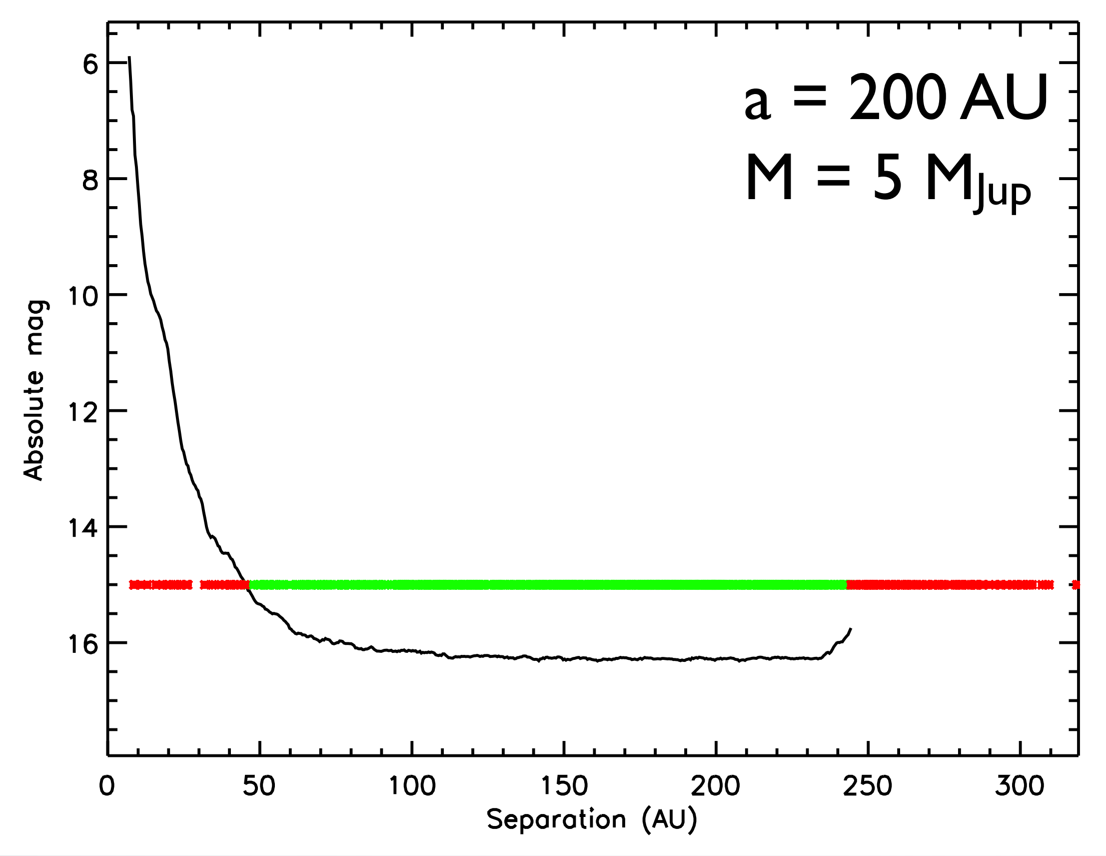
$$\frac{1-\alpha}{2} = \int_{0}^{f_{\mathrm{min}}} p(f|\{d_j\})df$$

Numerical integration to obtain f_{min} and f_{max}

Monte-Carlo simulations

- MC simulations are used to estimate p_j
- MESS tool (Bonavita et al. 2012) was used
- generation of 10^4 planets at each point of a grid in mass/SMA
- other orbital parameters are randomly chosen

$$L(\{d_j\}|f) = \prod_{j=1}^{N} (1 - f p_j)^{1-d_j} \cdot (f p_j)^{d_j}$$



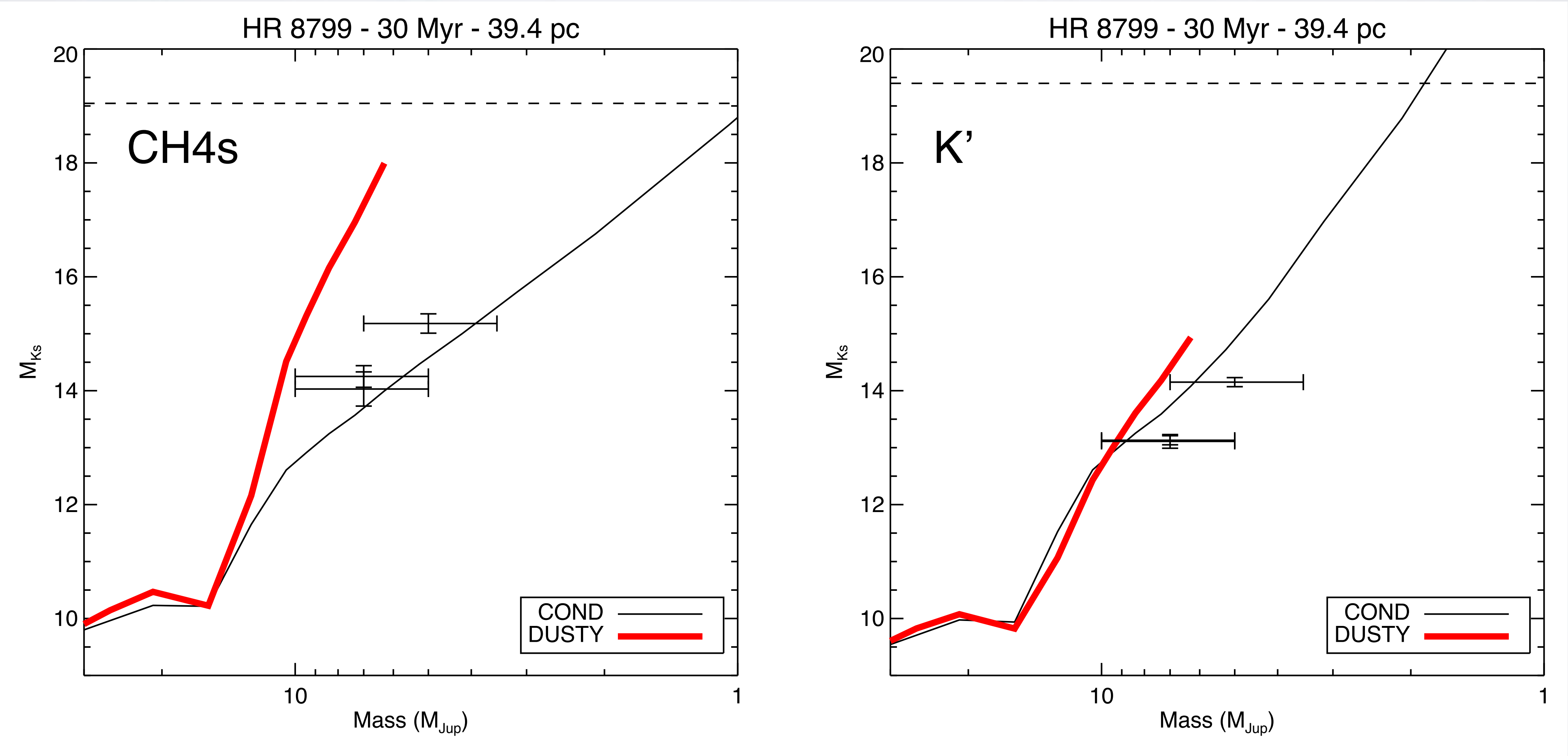
mass to mag

→ COND models (Baraffe et al. 2003)

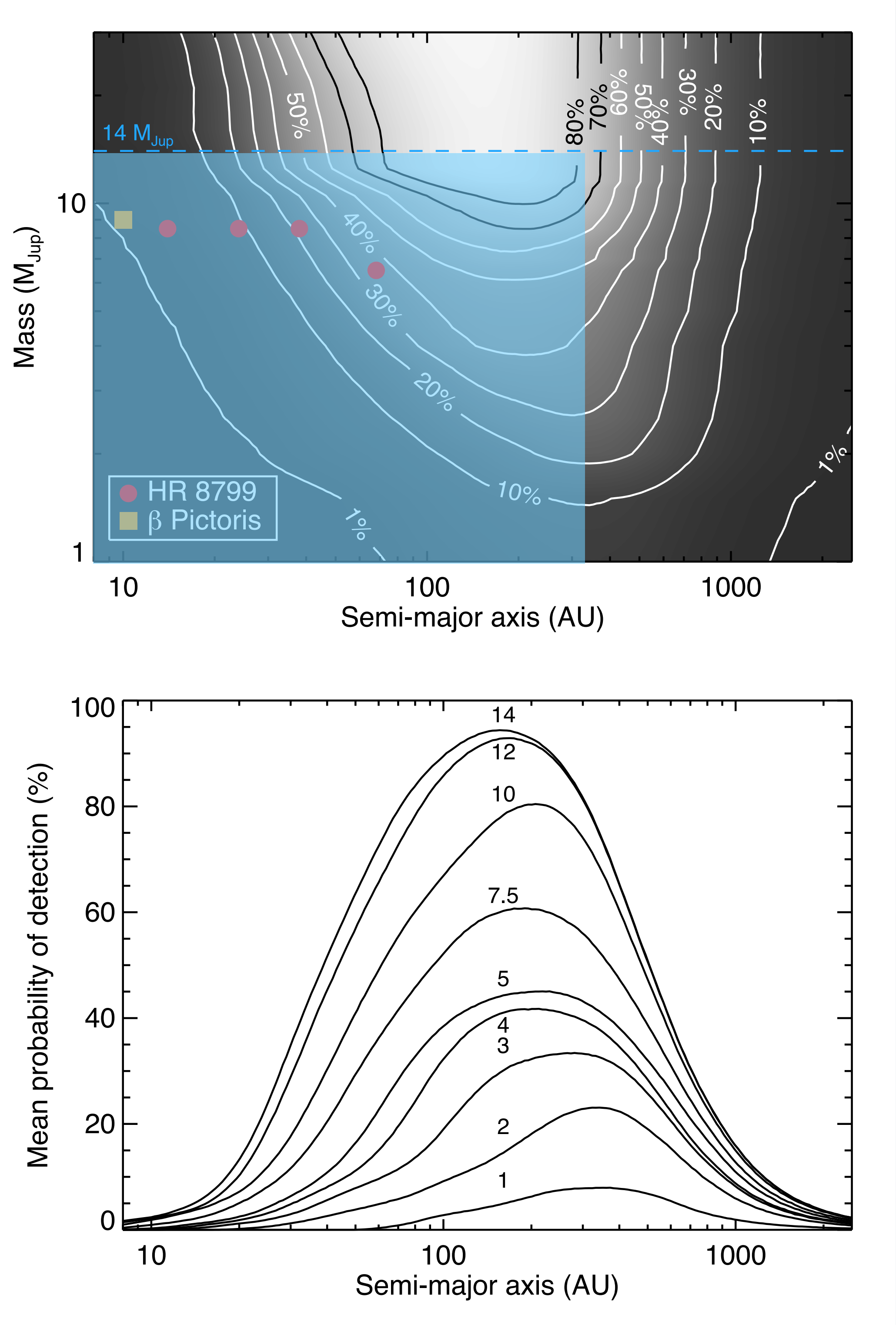
p_j = fraction of detected planets

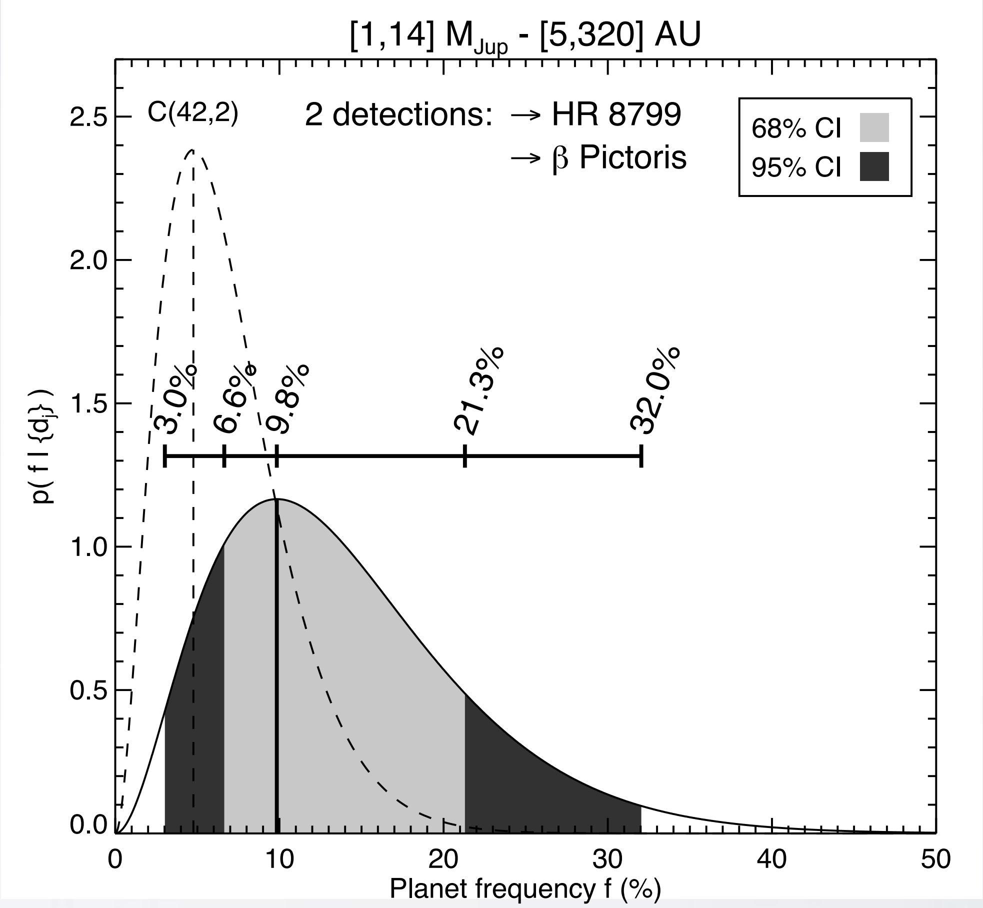
Choice of evolutionary models

- current estimation of the masses in agreement with AMES-COND models... but very large error bars
- only COND models go deep enough
- distinct features identified in the spectra ➙ need for updated grid of models



Wide-orbit planets frequency





Vigan et al., submitted

f ∈ [6.6%,21.3%] at 68% confidence

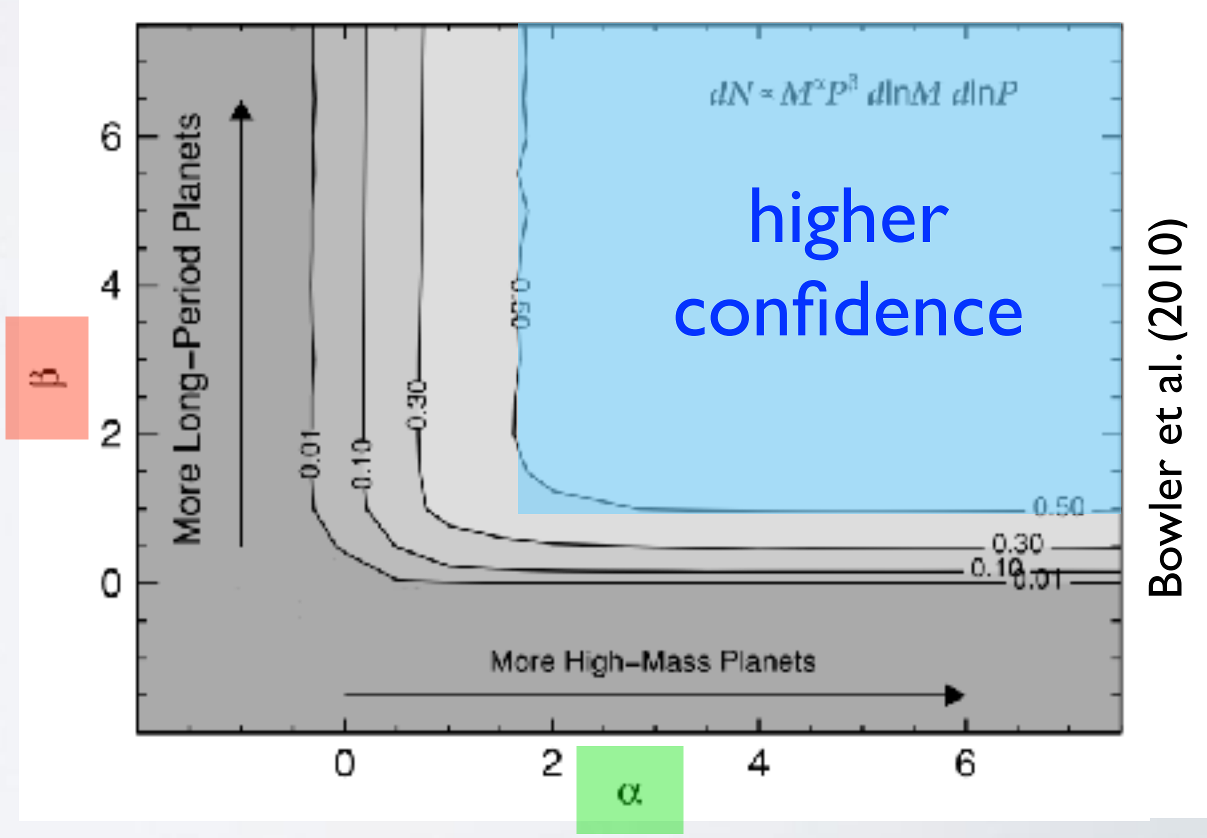
- 1 $M_{Jup} \leq$ mass $\leq$ 14 M_{Jup}
- 5 AU ≤ a ≤ 320 AU

Constraints on wide-orbit planets population

- Extrapolation of RV survey results
- Solar-type stars → Cumming et al. (2008) measure
  f = 10.5%
  for 0.3-10 M_{Jup} planets with *P* < 1826 days

$$dN \propto M^{-1.31} dM$$
$$dN \propto a^{-0.61} da$$

- Early-type stars (old stars)
  - → Johnson et al. (2010)
    measure *f* = 11 ± 2%
    for 0.5-14 M_{Jup} in 0.1-3.0 AU
  - → Bowler et al. (2010) bring
    some constraints on α and β



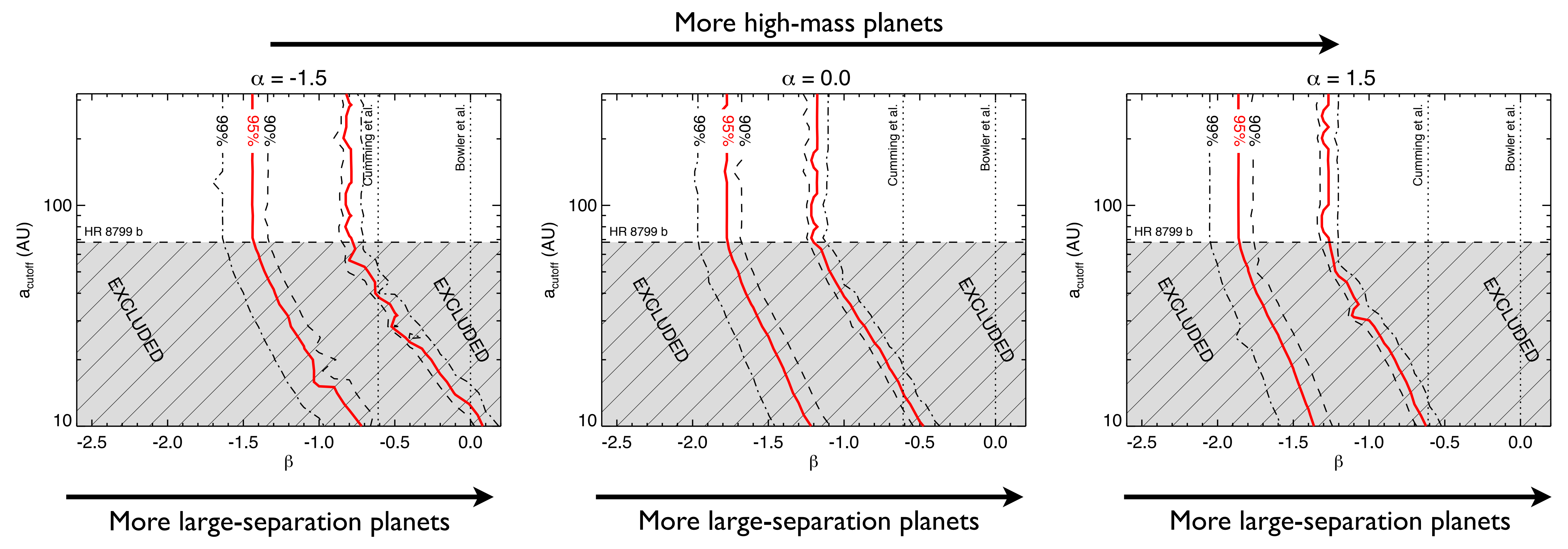
Bowler et al. (2010)

Constraints on wide-orbit planets population

- simulations with populations drawn from powerlaws
- cutoff on semimajor axis distribution (a_{cutoff})
  - ➙ α from -1.5 to 1.5 by steps of 0.1
  - ➙ β from -2.5 to 0.5 by steps of 0.1
  - ➙ a_{cutoff} from 10 to 320 AU by steps of 10 AU
- assumed frequency $f = 11 \pm 2\%$ (Johnson et al. 2010) for 0.5-14 M_{Jup} planets in 0.1-3.0 AU
- ∑ fraction of detected planet × normalised frequency = number of expected detections

➙ inside [3.5,12] M_{Jup} and [8,68] AU

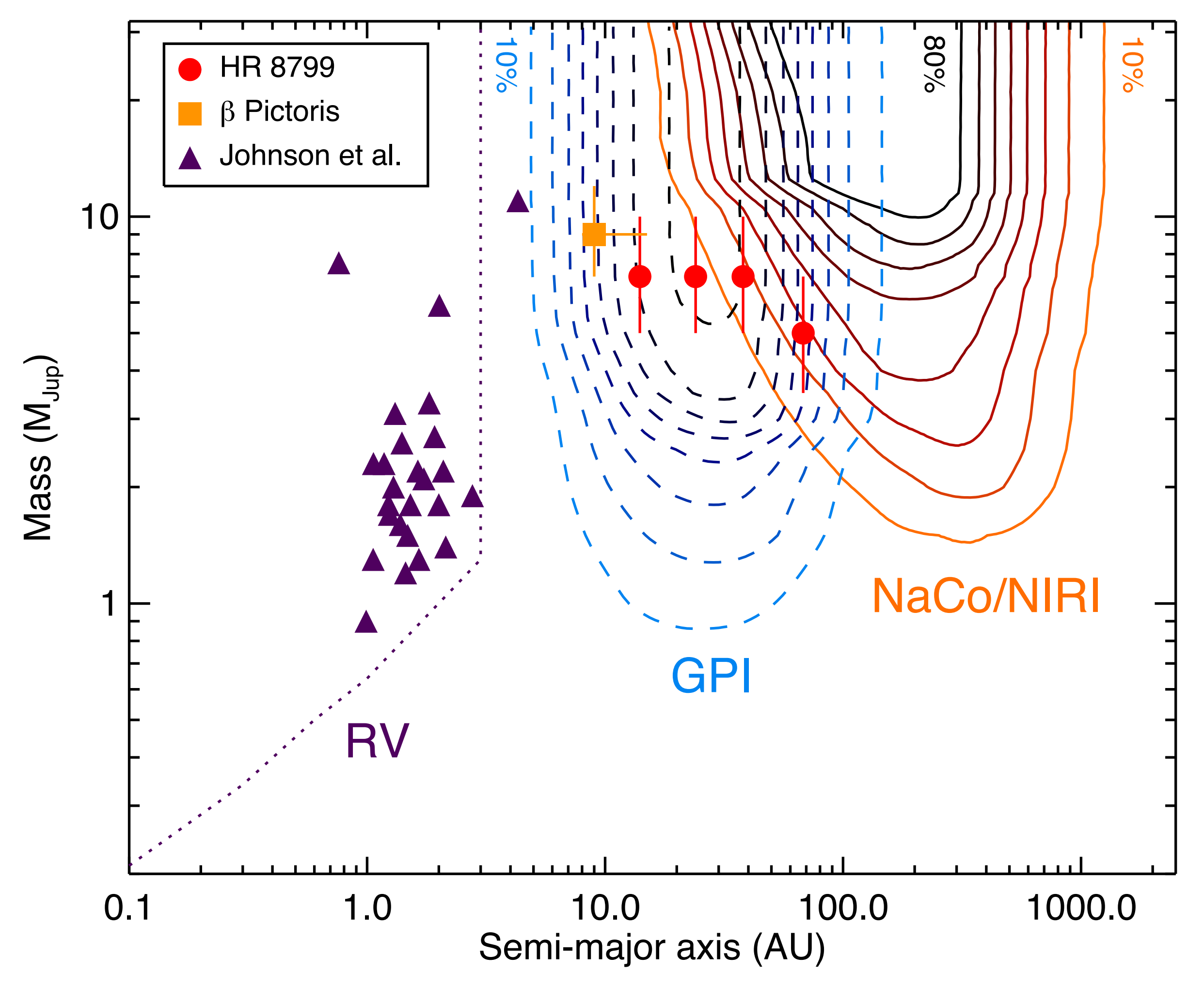
Constraints on wide-orbit planets population



- values not in agreement with RV constraints from Bowler et al.
  - ➝ different planet population at wide orbit?
  - ➝ population cannot be described by a single powerlaw?

Conclusions - part I

- survey of 42 A and early-F stars
- Monte Carlo simulations for the statistical analysis
- planet frequency f ∈ [6.6%,21.3%] @ 68% confidence
  - for 1 MJup ≤ mass ≤ 14 MJup
  - for 10 AU ≤ a ≤ 320 AU
- constraints on the population show differences with RV studies

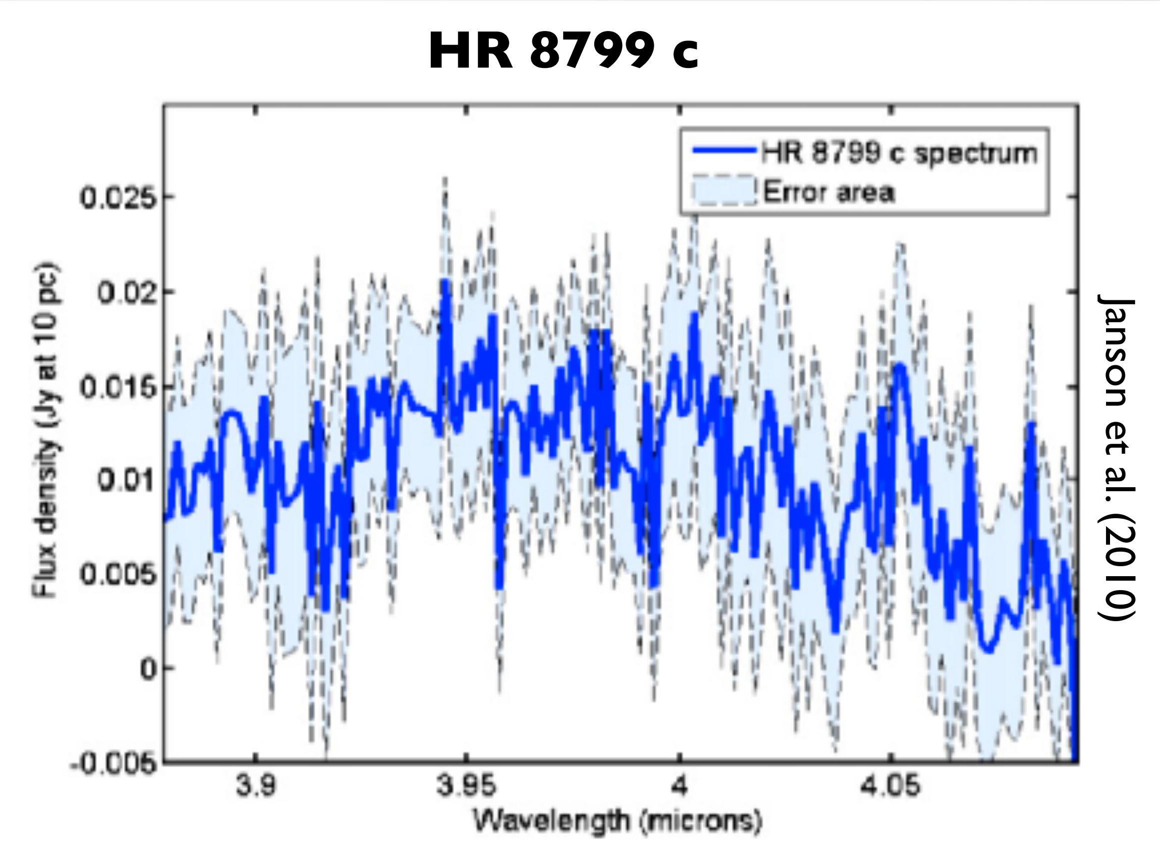


High-contrast long slit spectroscopy for exoplanet characterisation

With contributions since 2006 from Claire Moutou (LAM), Maud Langlois (CRAL), Kjetil Dohlen (LAM), Mickaël Bonnefoy (MPIA), Gaël Chauvin (IPAG), Mamadou N'Diaye (LAM), Anthony Boccaletti (LESIA), Marcel Carbillet (Laboratoire Fizeau), Guillaume Montagnier (ESO)

Motivations

- Photometry is degenerate
- High-quality spectra are essential to study physical properties
- Cool atmospheres of young objects are not fully understood
- Few low-mass objects with accurate spectra:
  - high-contrast
  - small angular separation
  - ... very few imaged planets!

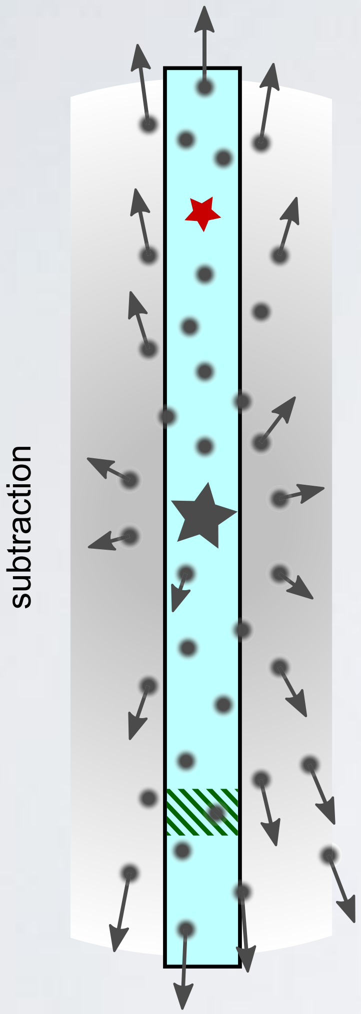


Janson et al. (2010)

Previous techniques

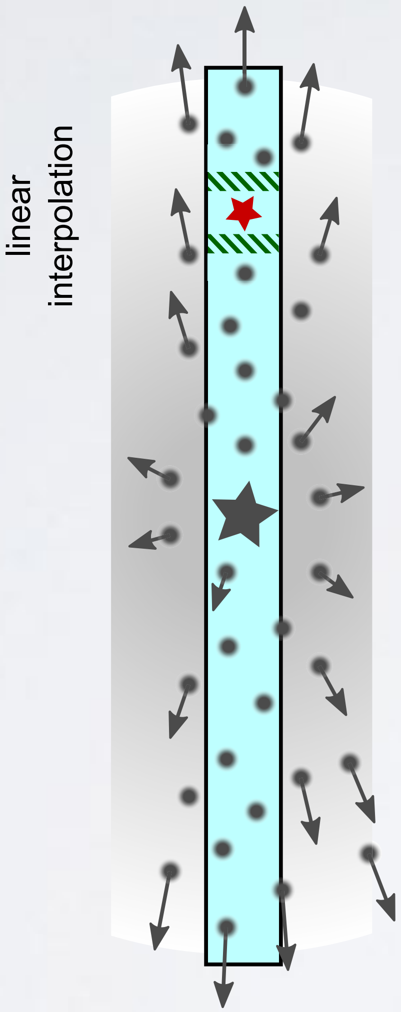
- Methods previously used to extract a spectrum:

Close et al. (2005)



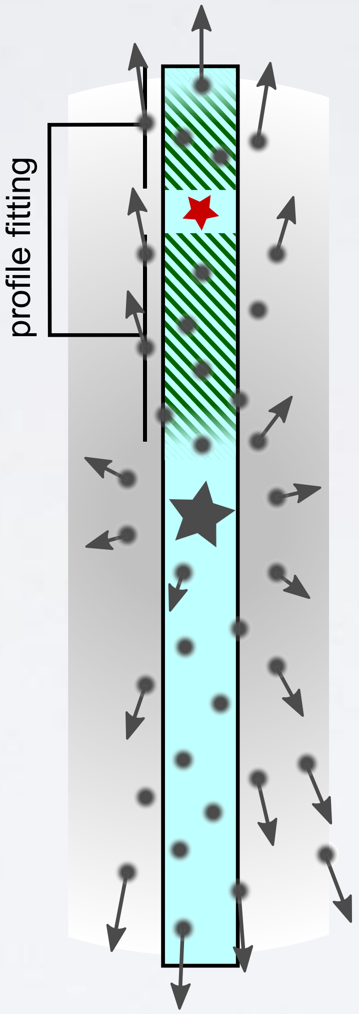
Symmetry of stellar profile

Kasper et al. (2007)
Lafrenière et al. (2008)

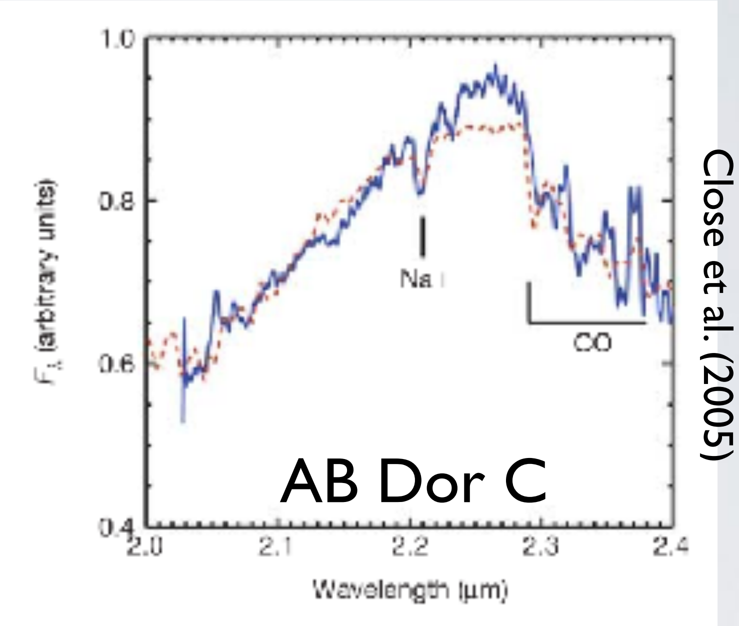


Linear interpolation of stellar profile

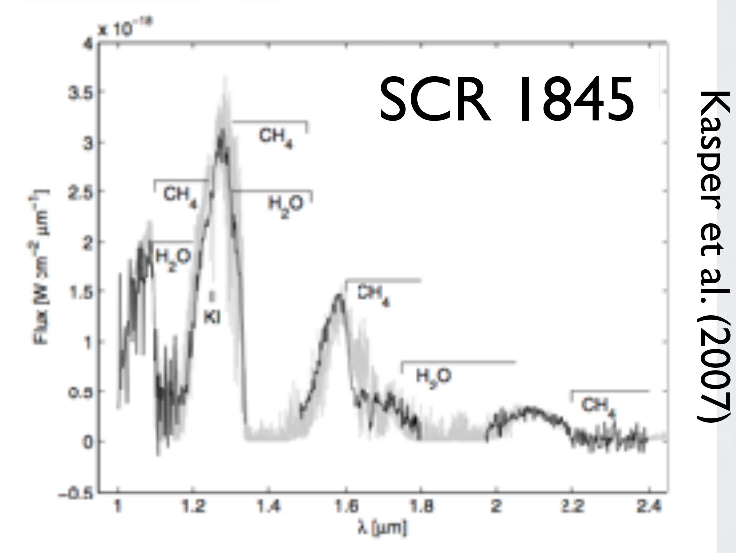
Mohanty et al. (2007)



Moffat or Gaussian fitting of stellar profile



Close et al. (2005)

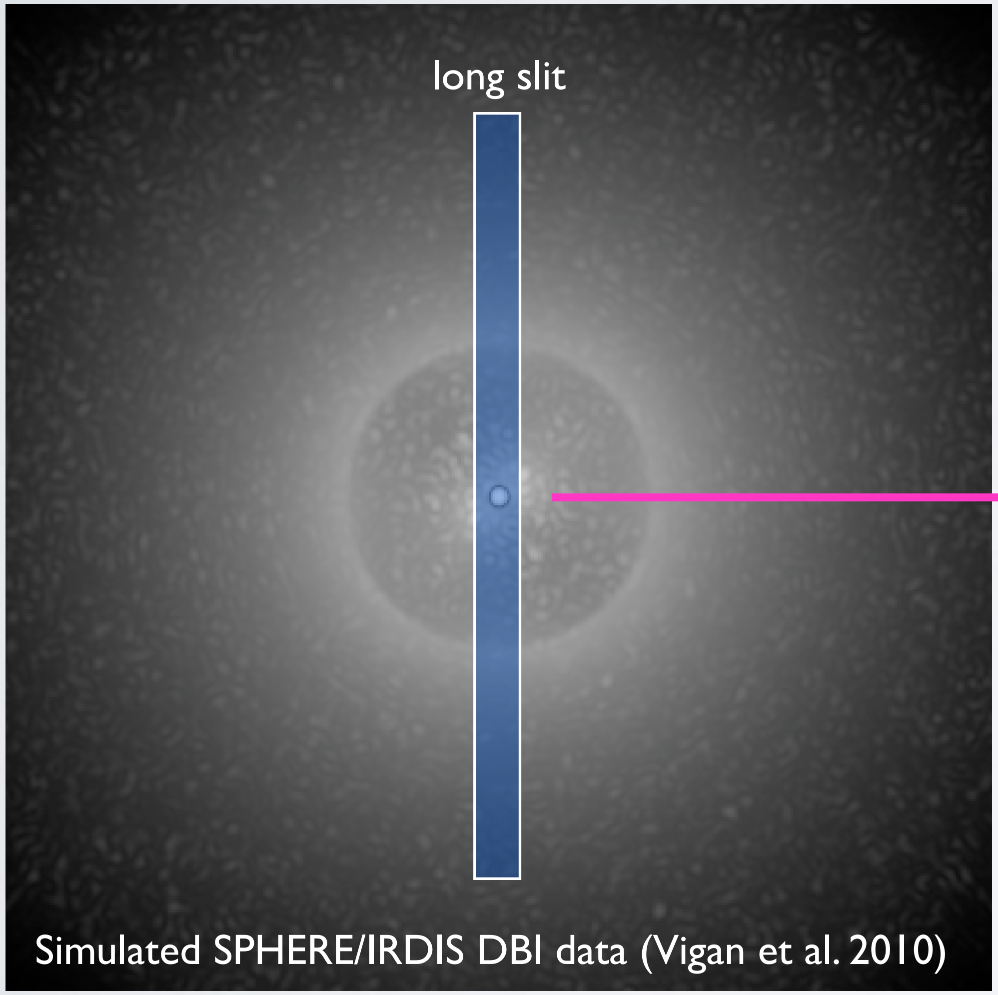


Kasper et al. (2007)

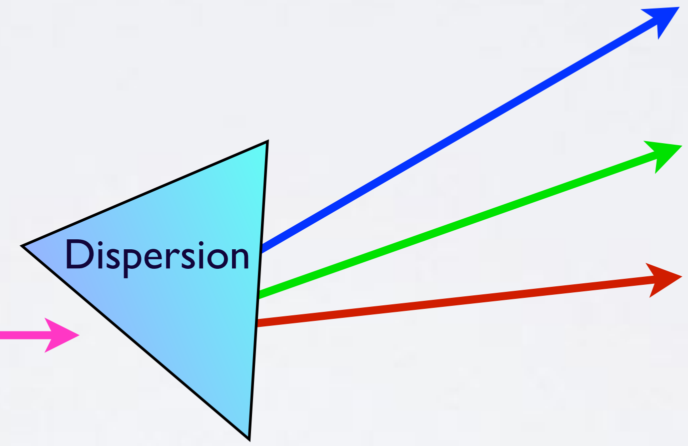
➙ Decent results with current instrumentation

Speckle-dominated data

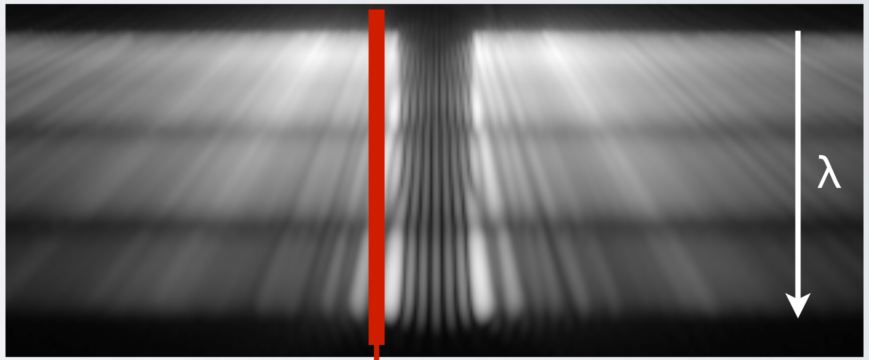
- quasi-static speckles strongly dominate over halo
- we are looking at objects below the speckle noise

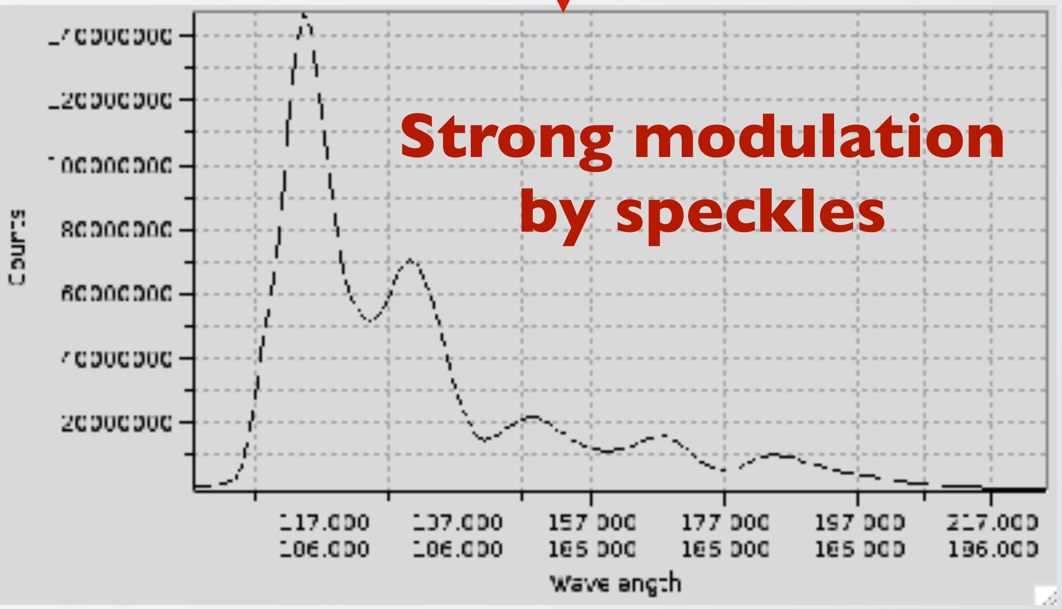


Simulated SPHERE/IRDIS DBI data (Vigan et al. 2010)



Simulated SPHERE/IRDIS LSS data (Vigan et al. 2008)



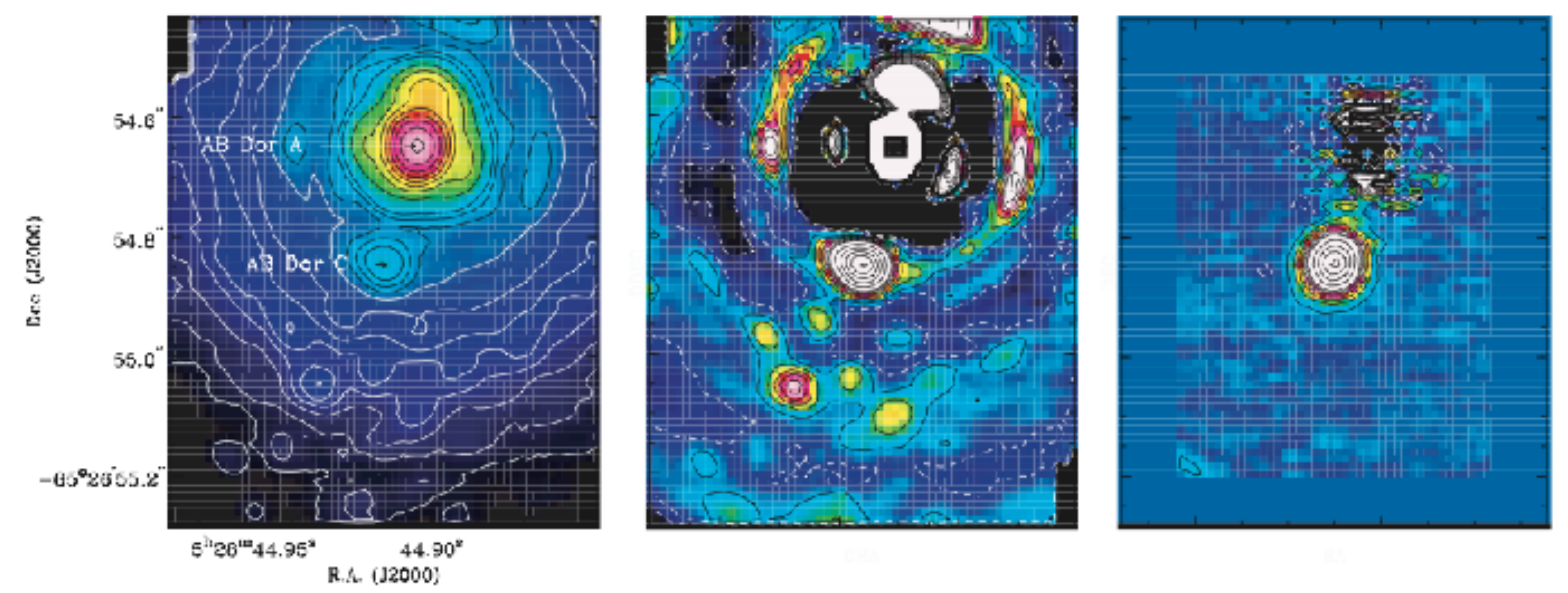


Strong modulation by speckles

How to get a clean planet spectrum?

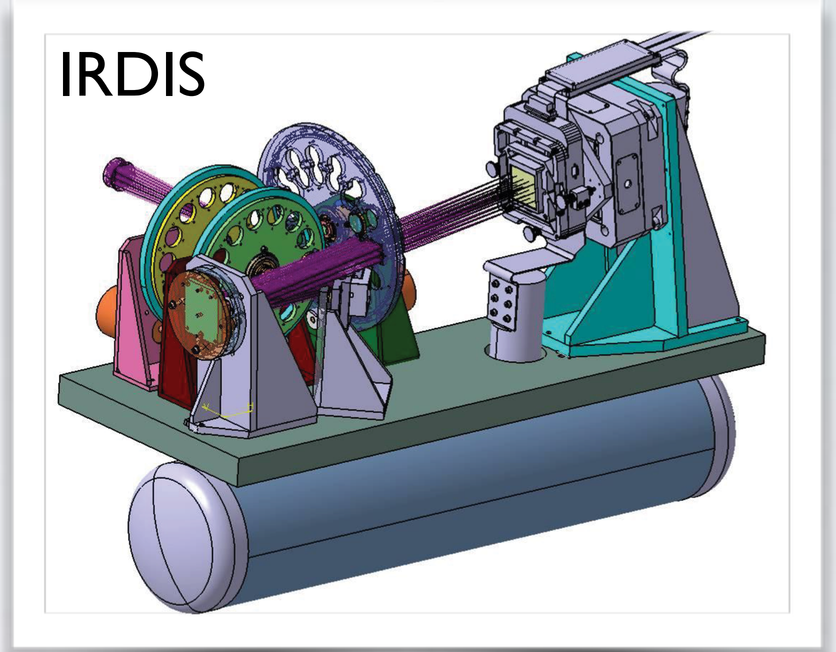
Removing the speckles

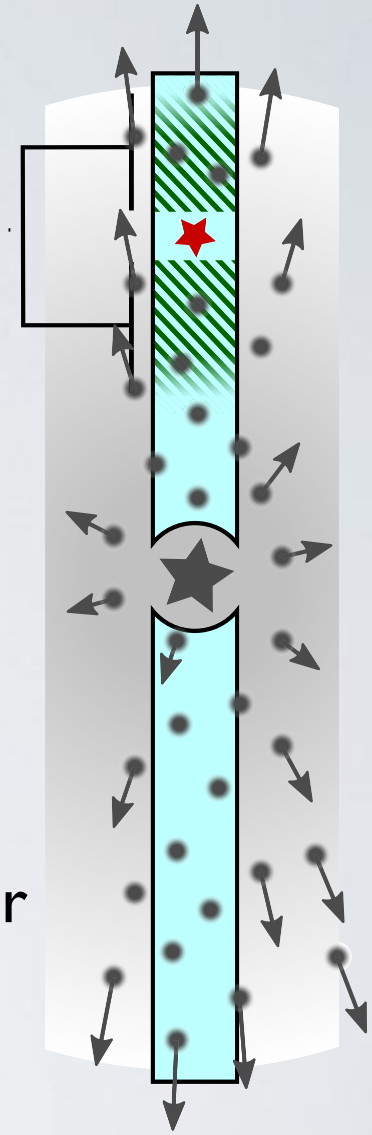
- IFS data ➙ spectral diversity (SDI) + angular diversity (ADI)
- “Spectral deconvolution” (Sparks & Ford 2002) (no ADI)
  - uses the chromaticity of the PSF and speckles
  - polynomial fit to the speckles
- SD demonstrated with SINFONI on AB Dor C (Thatte et al. 2007)

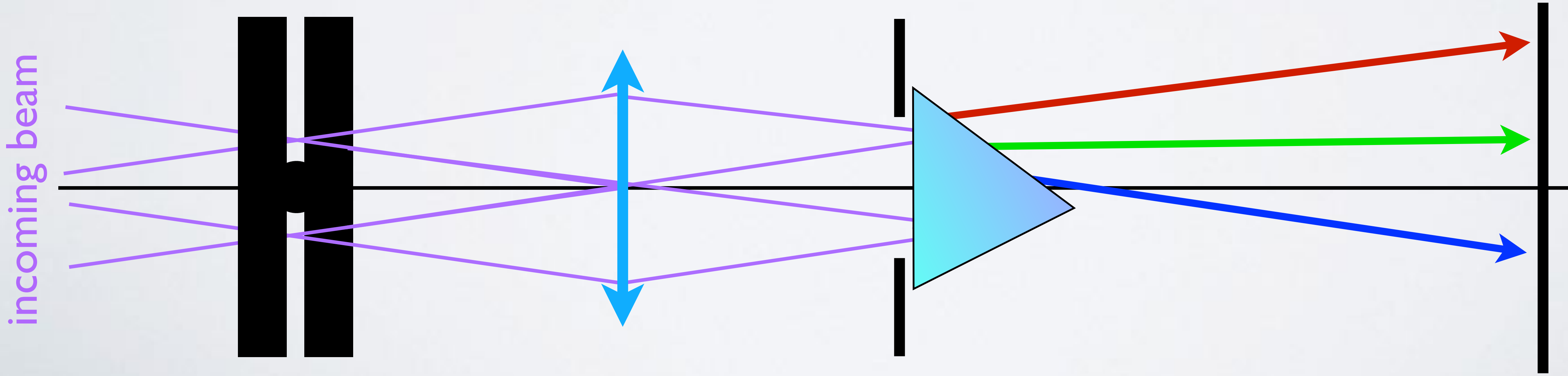


High-contrast LSS in SPHERE/IRDIS

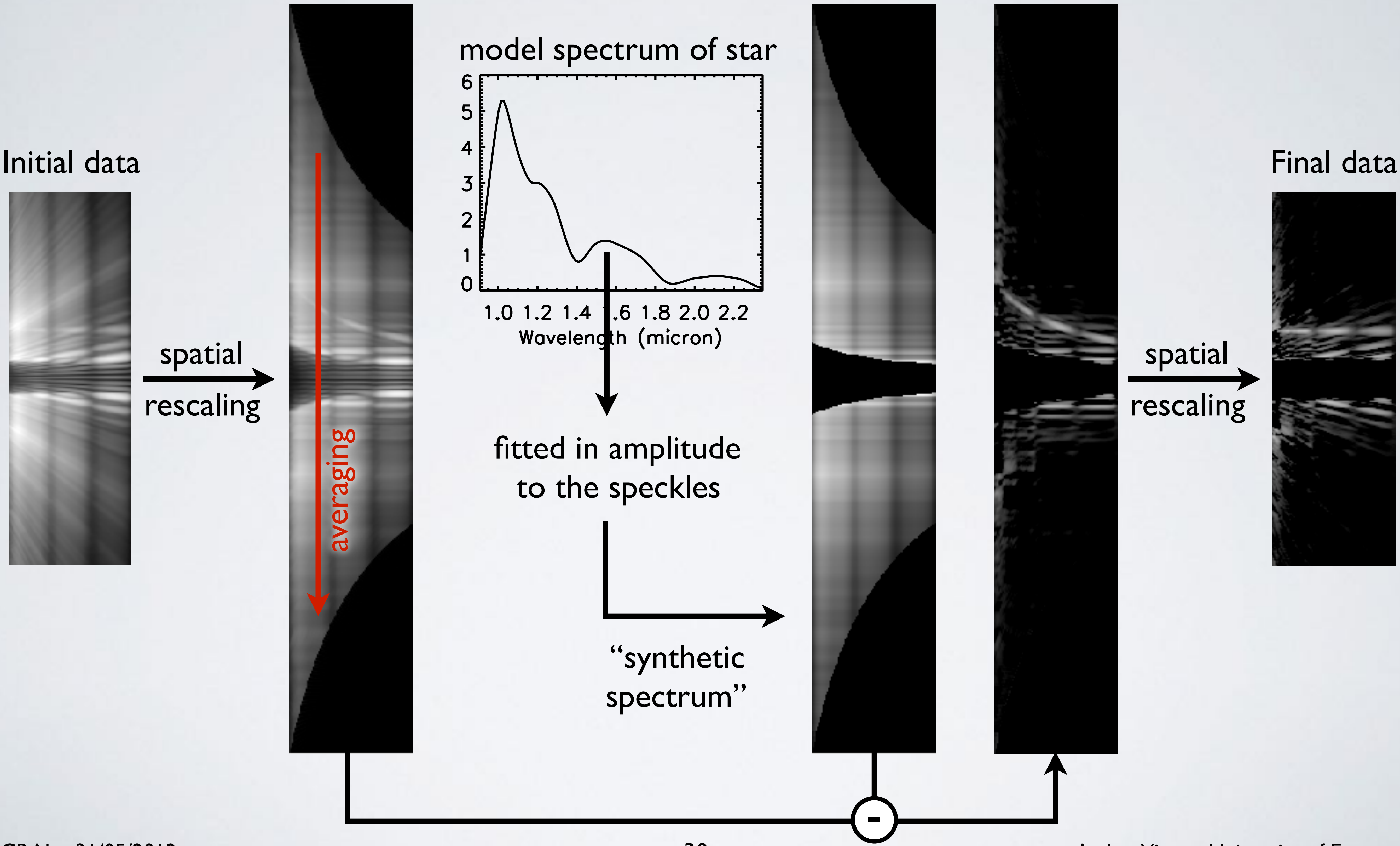
- IRDIS ➙ differential spectro-imager
- LSS + Lyot coronagraph ➙ LSC
- low (R~50) and medium (R~400) resolution
- non-optimal setup of the Lyot stop







Spectral deconvolution on LSS data



Initial data

spatial rescaling

averaging

model spectrum of star

fitted in amplitude to the speckles

"synthetic spectrum"

-

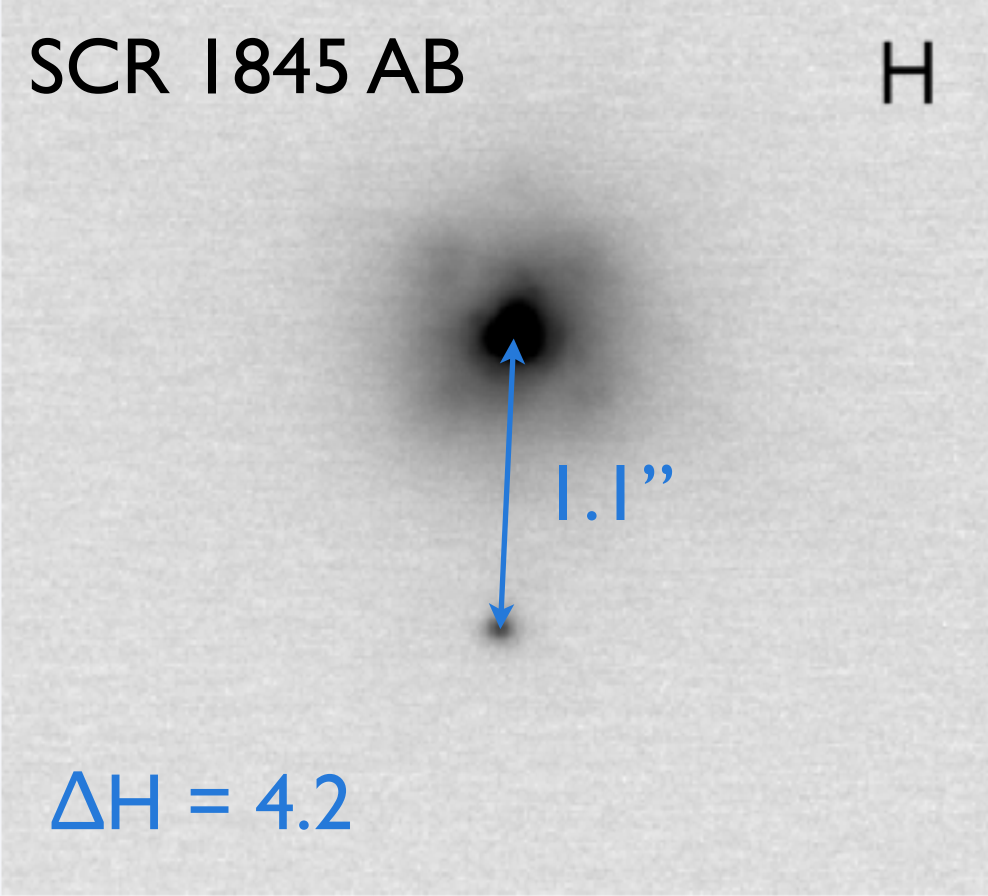
spatial rescaling

Final data

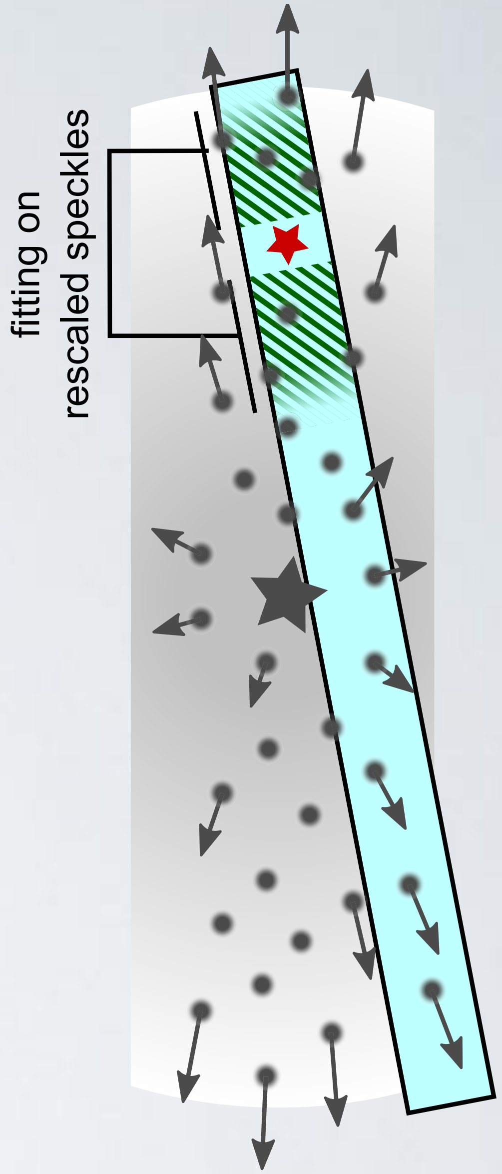
On-sky demonstration

- No instrument with AO, LSS and coronagraphy
- Closest match → VLT/NaCo... in a special config.

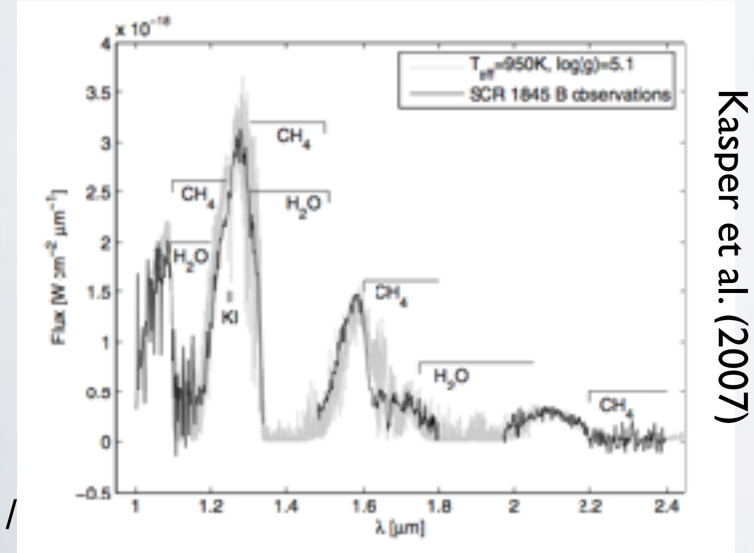
- Best target?
  - moderate contrast
  - separation of ~1"
  - published spectrum



Kasper et al. (2007)



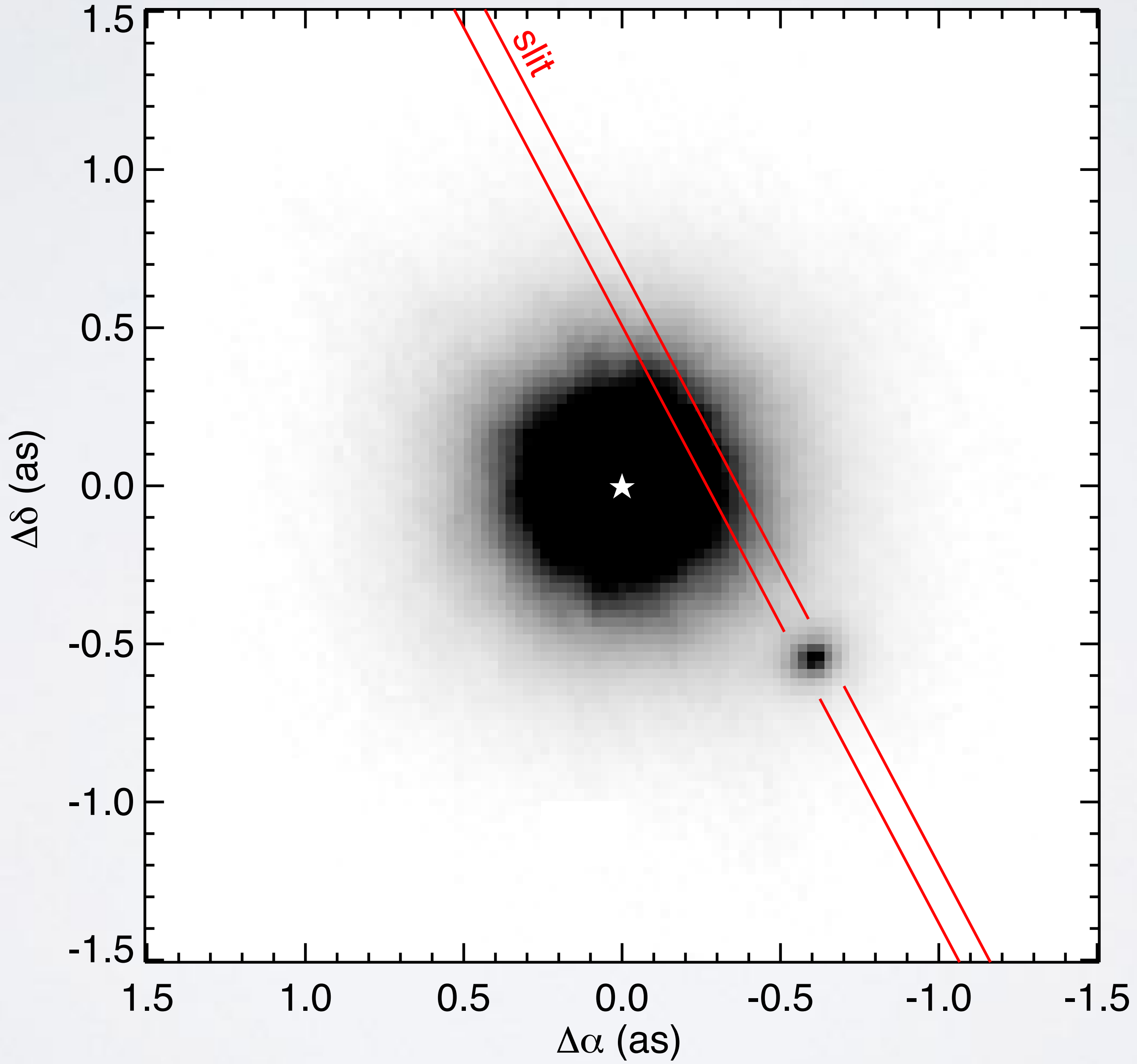
Tilted slit+
spatial rescaling+
speckle fitting



Kasper et al. (2007)

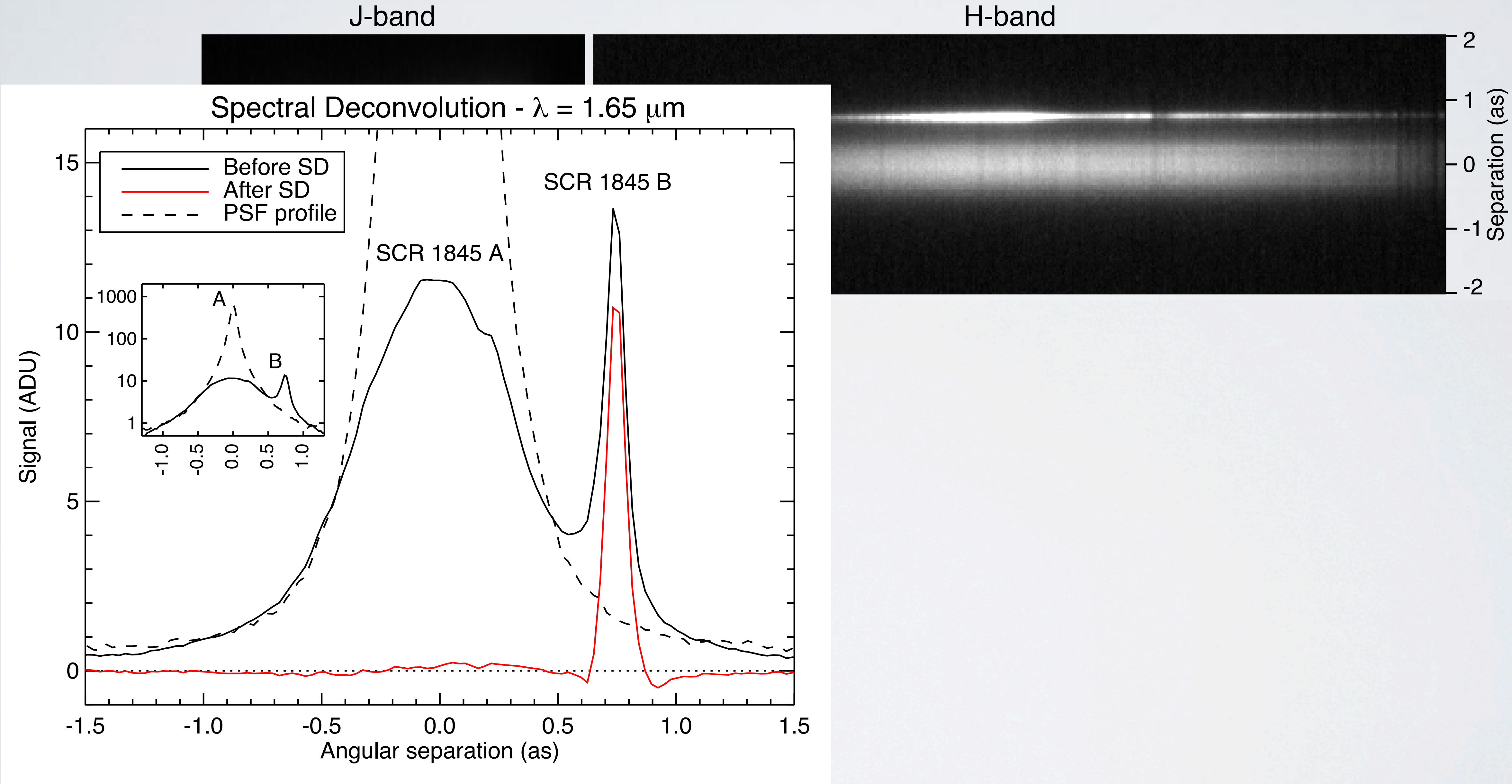
Spectral deconvolution on SCR 1845

- calibration proposal accepted in P86 ➙ J and H-band spectro

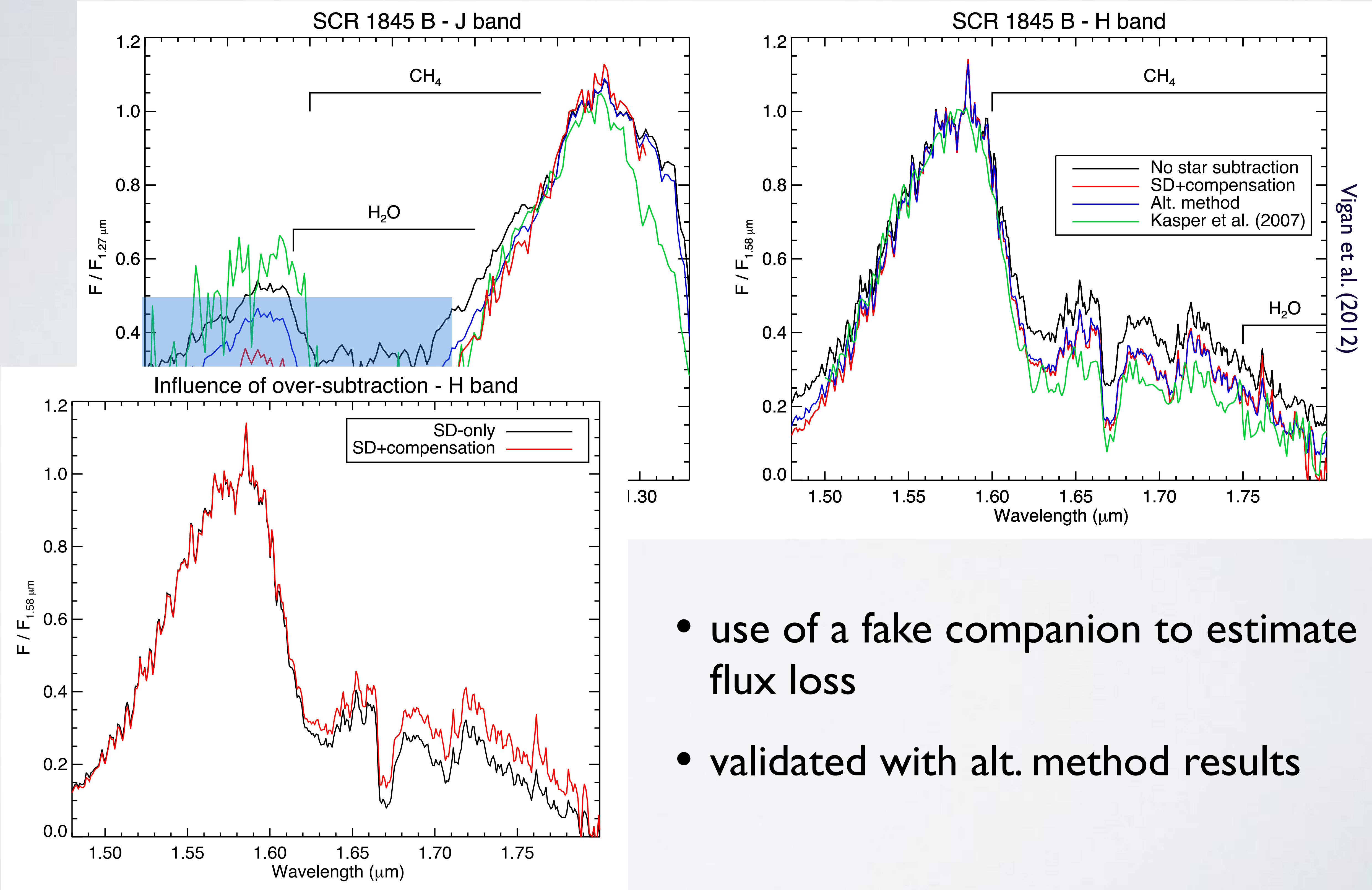


Spectral deconvolution on SCR 1845

- calibration proposal accepted in P86 ➙ J and H-band spectro



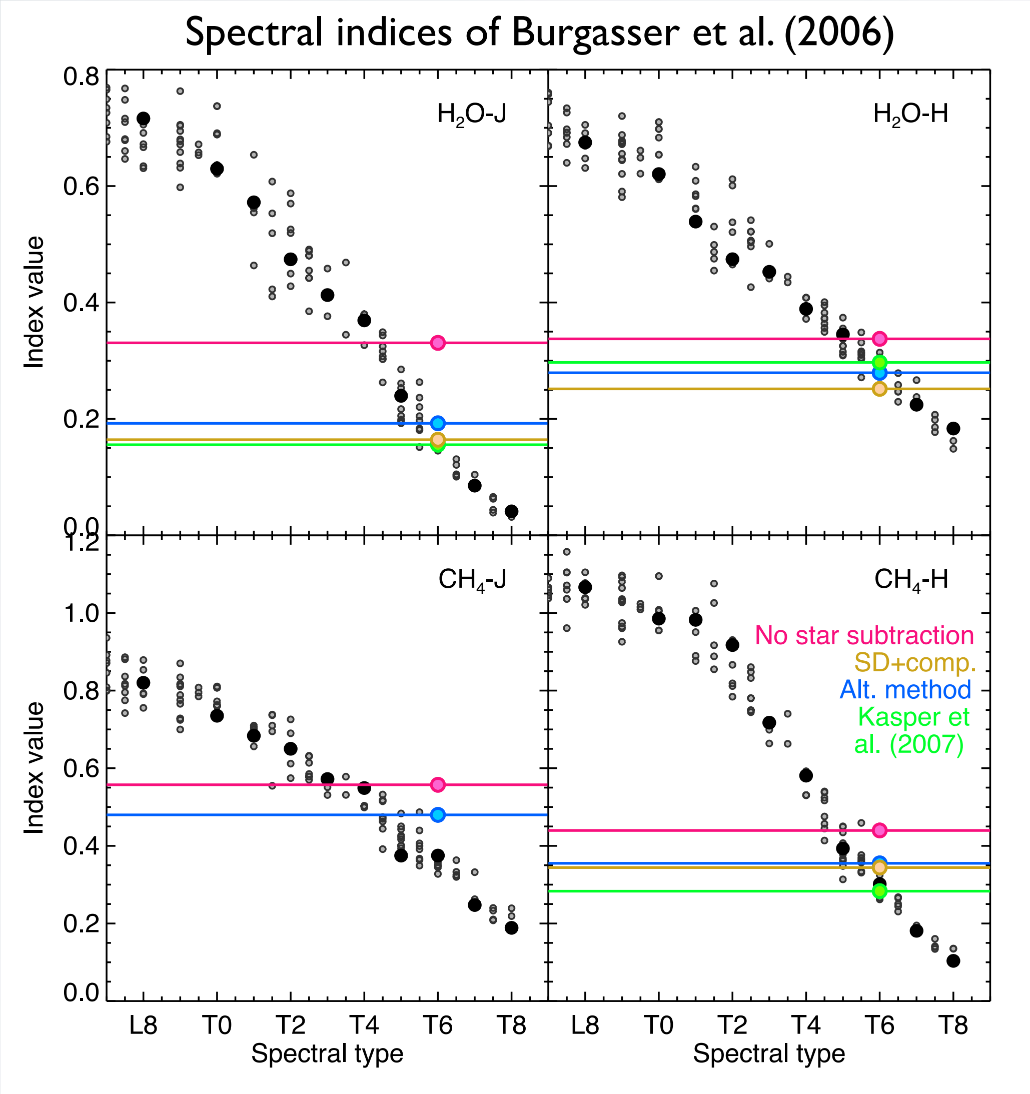
Extracted spectrum

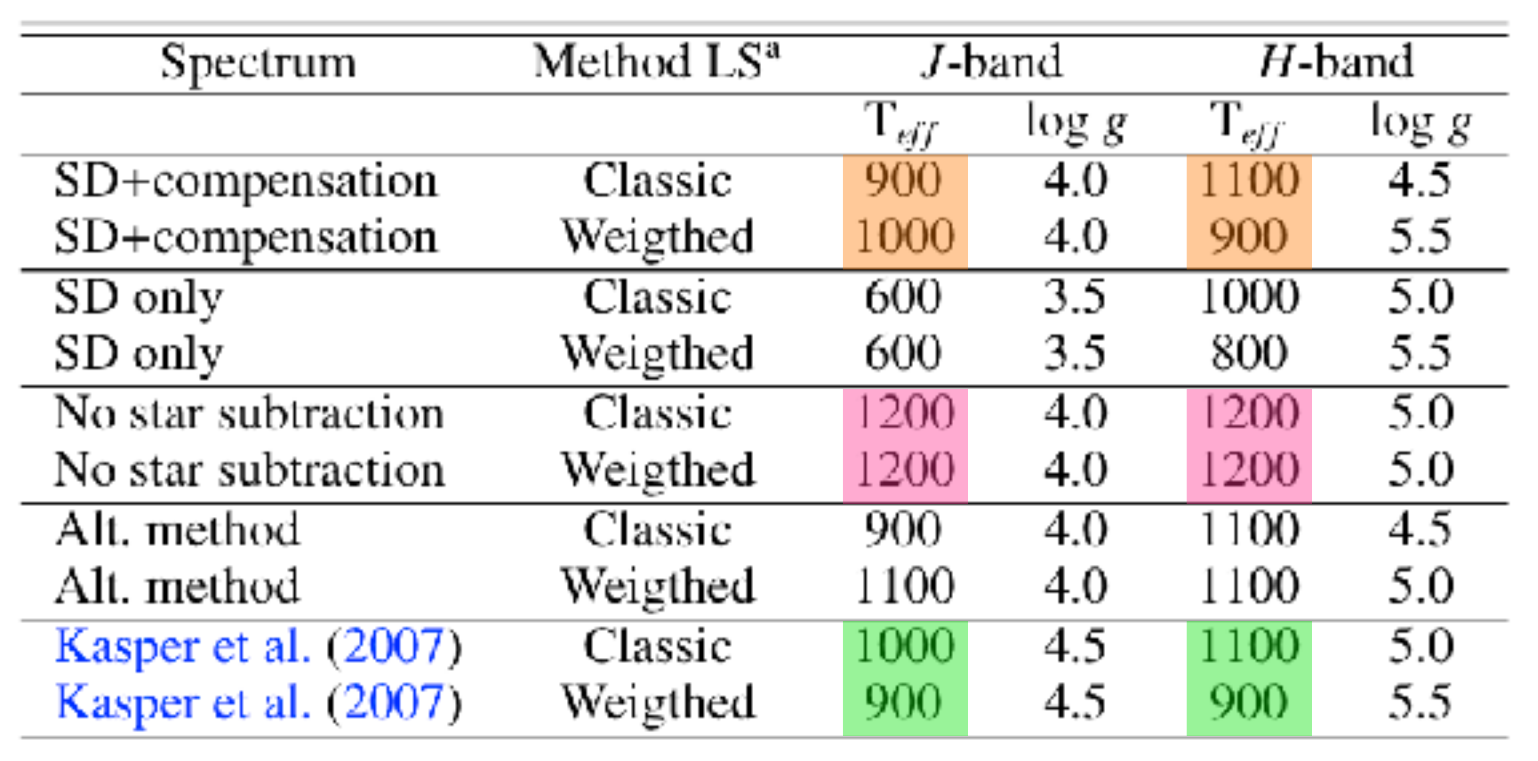


Vigan et al. (2012)

- use of a fake companion to estimate flux loss
- validated with alt. method results

Necessity to remove star contribution


Spectral indices of Burgasser et al. (2006)

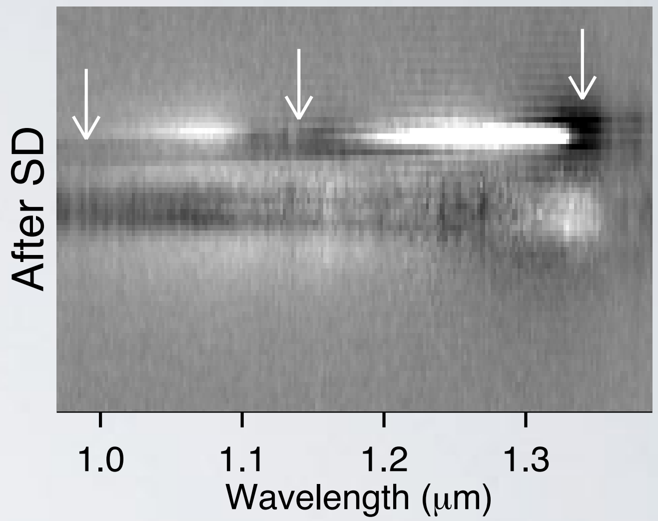


Spectrum	Method LS[a]	*J*-band		*H*-band	
		T_{eff}	log *g*	T_{eff}	log *g*
SD+compensation	Classic	900	4.0	1100	4.5
SD+compensation	Weigthed	1000	4.0	900	5.5
SD only	Classic	600	3.5	1000	5.0
SD only	Weigthed	600	3.5	800	5.5
No star subtraction	Classic	1200	4.0	1200	5.0
No star subtraction	Weigthed	1200	4.0	1200	5.0
Alt. method	Classic	900	4.0	1100	4.5
Alt. method	Weigthed	1100	4.0	1100	5.0
Kasper et al. (2007)	Classic	1000	4.5	1100	5.0
Kasper et al. (2007)	Weigthed	900	4.5	900	5.5

- serious bias on T_{eff} and *log(g)* when star is not subtracted
- bias increases at higher contrast ➙ SPHERE, GPI, ...

Limitations

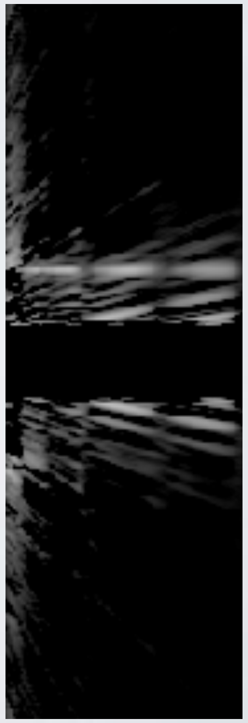
- NaCo data:
  - problem of sampling in J-band
  - over-subtraction of the companion
  - not applicable at very small separation



- IRDIS data:
  - non-optimal setup of the coronagraph
  - strong diffraction residuals

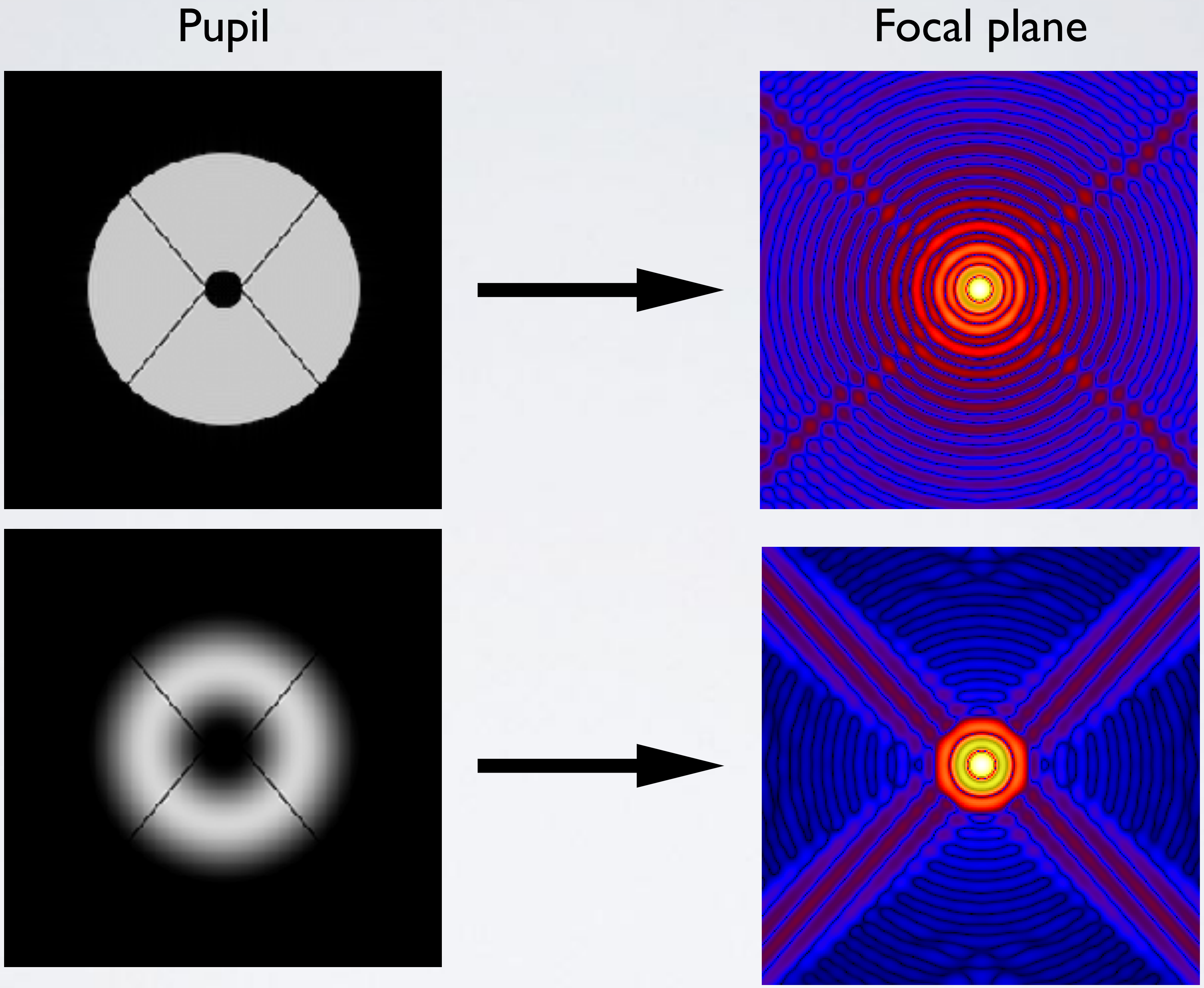
Initial data

Final data



Need for diffraction suppression!

What is apodization?



- smooth the pupil to attenuate the diffraction

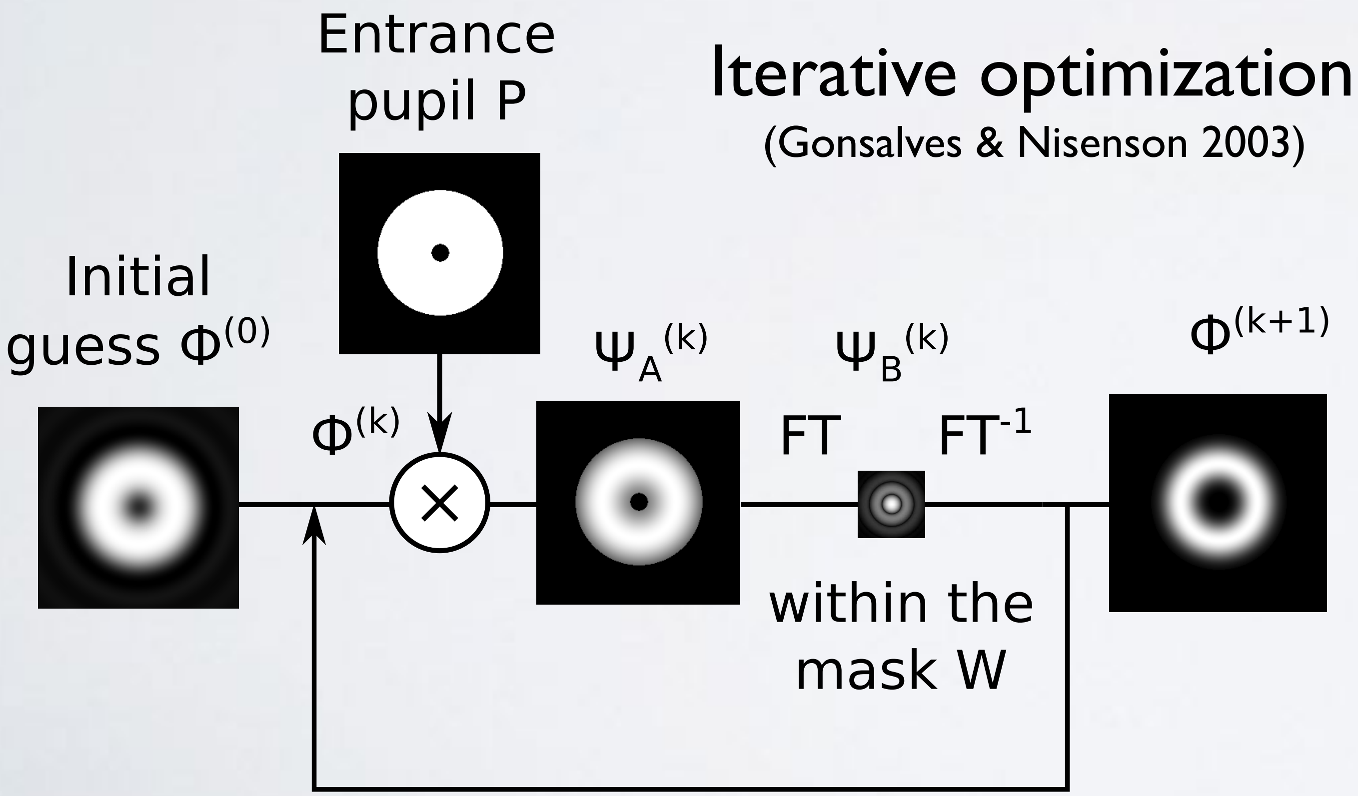
Stop-less Lyot coronagraph

- main constraint ➙ no optimized Lyot stop (IRDIS) or no stop position at all (GTC/Frida)
- grey apodization optimized to concentrate all the energy inside PSF core

N'Diaye et al. (2007)

Iterative optimization

(Gonsalves & Nisenson 2003)



Entrance pupil P

Initial guess $\Phi^{(0)}$

$\Phi^{(k)}$

$\Psi_A^{(k)}$

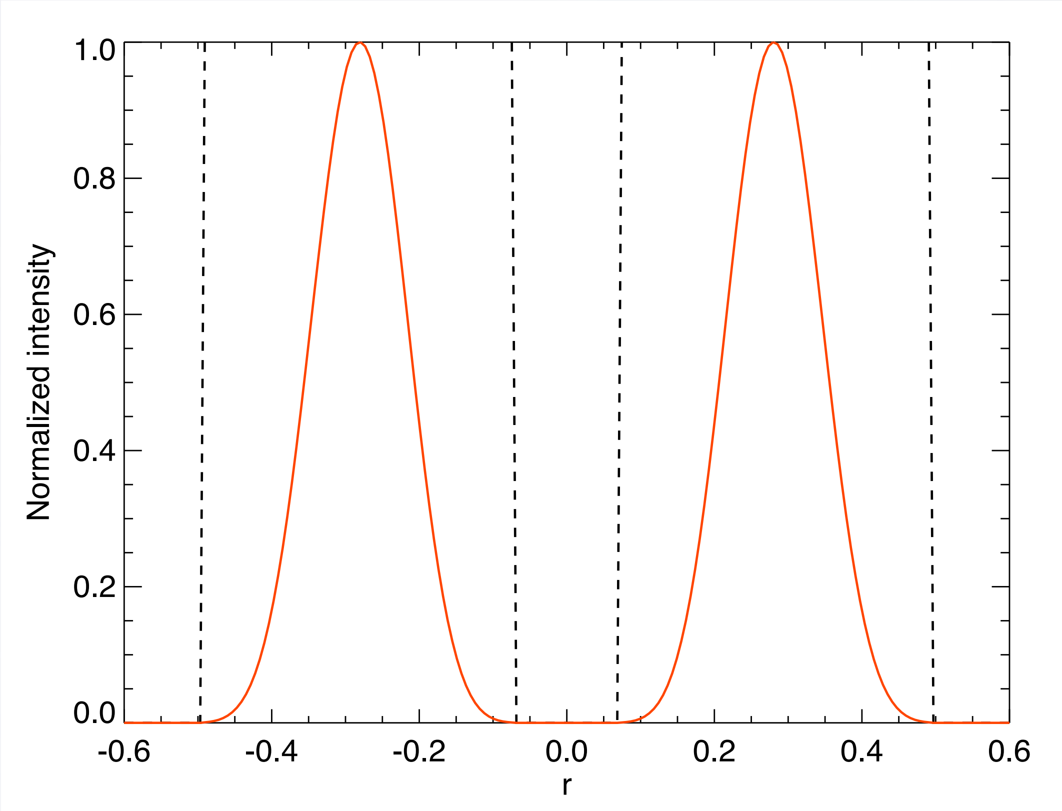
$\Psi_B^{(k)}$

FT

FT^{-1}

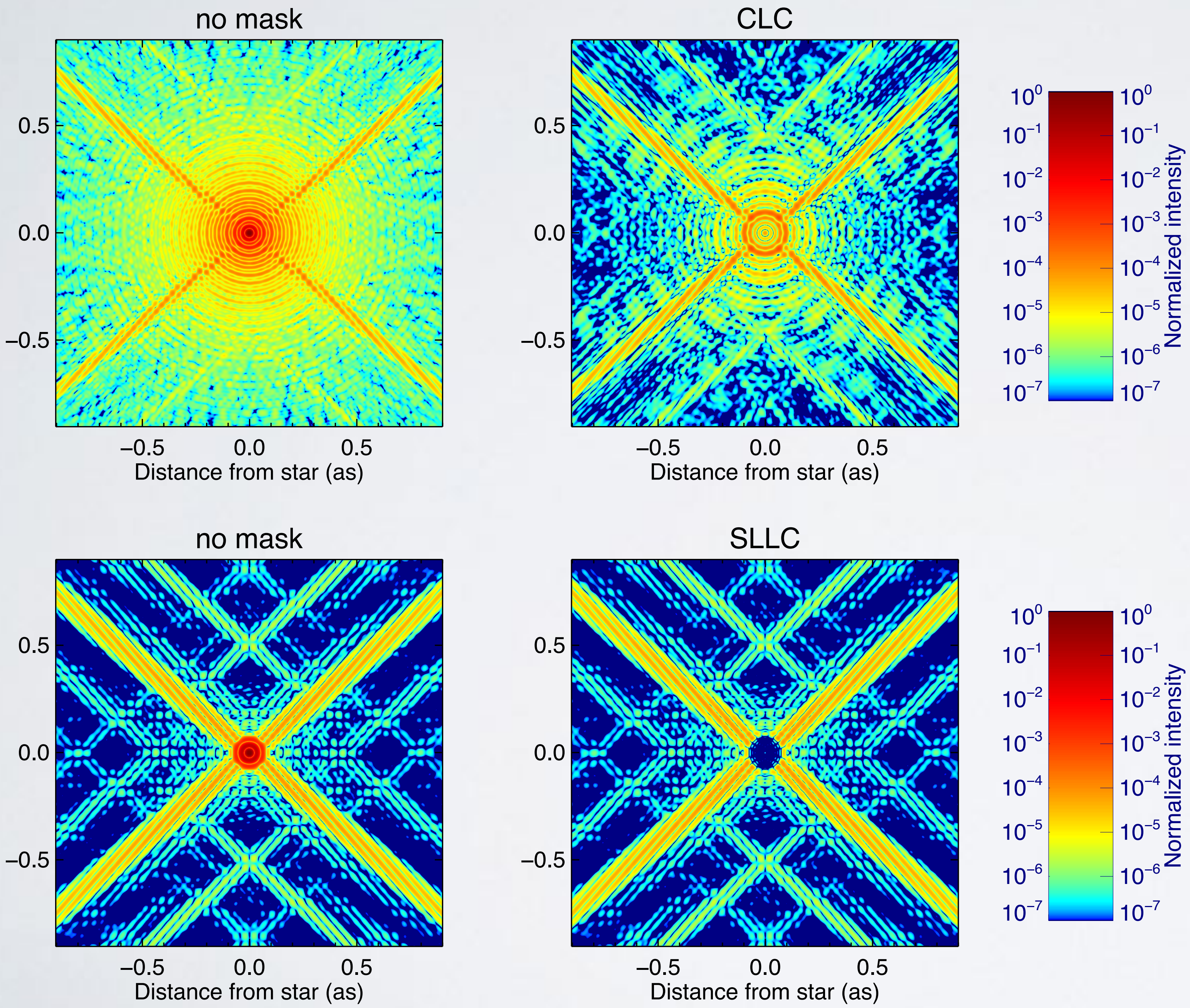
$\Phi^{(k+1)}$

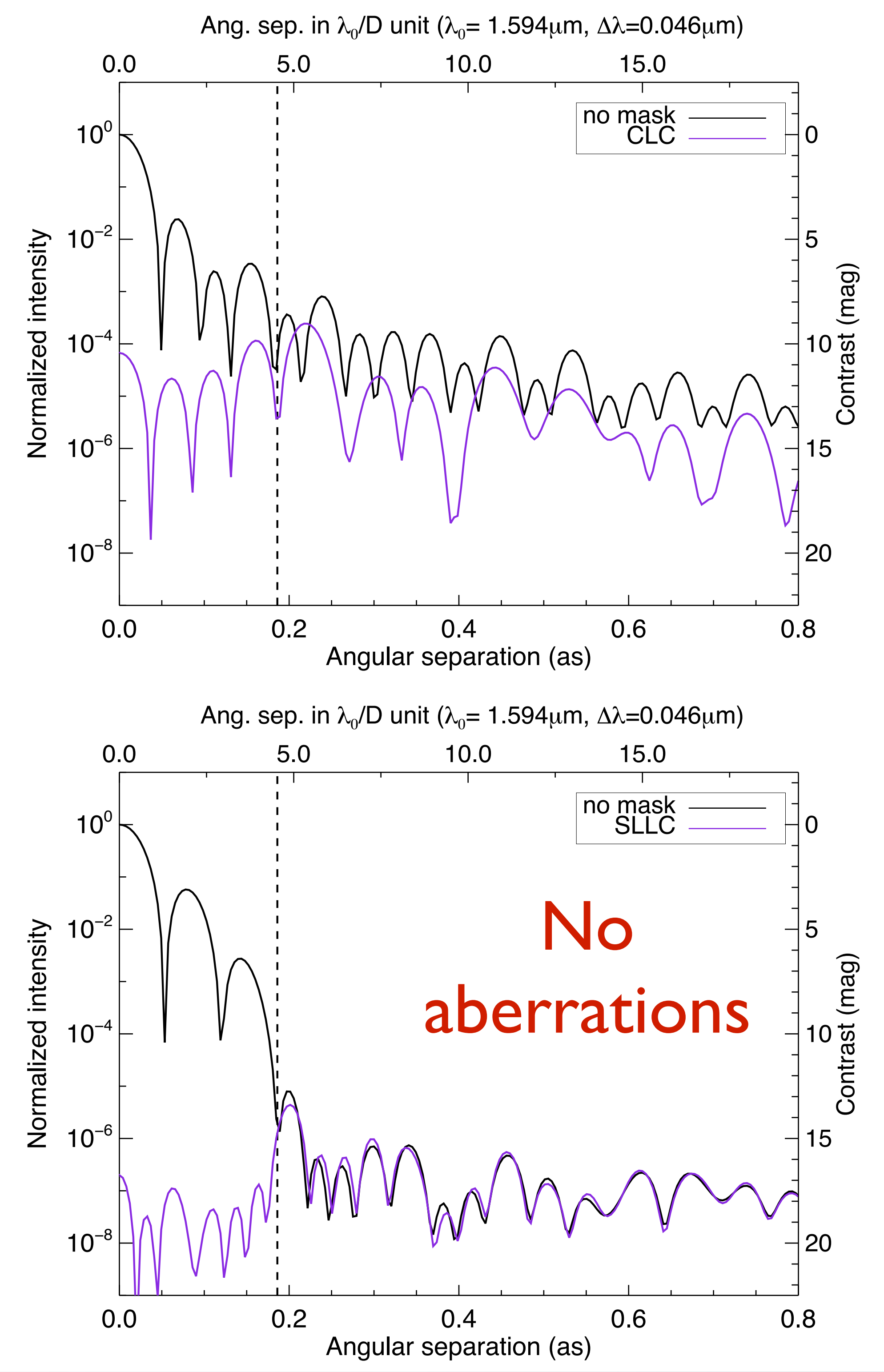
within the mask W



CLC vs. SLLC

Optimization for 0.18” mask and λ = 1.6 µm



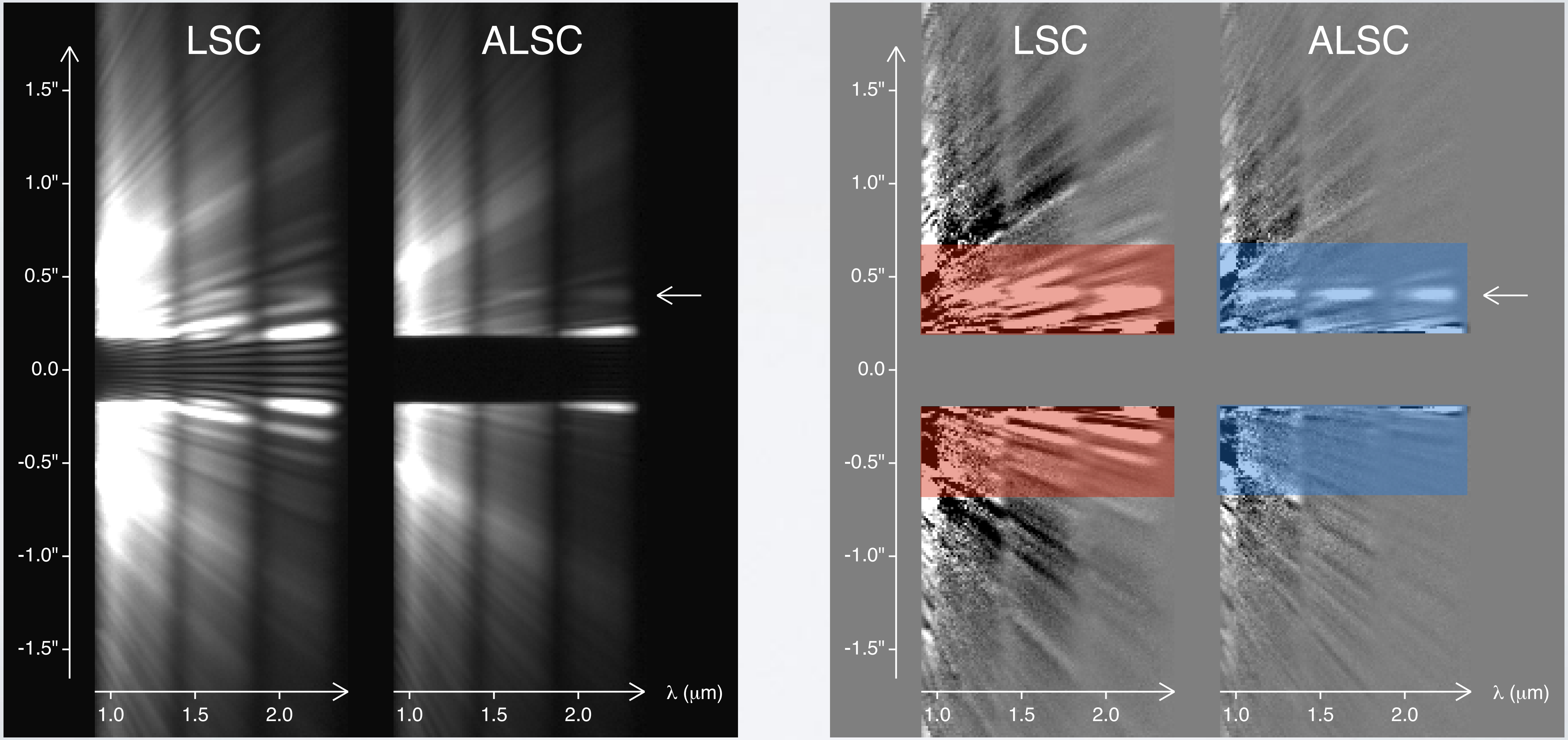


No aberrations

Vigan, N’Diaye & Dohlen, submitted

LSC vs. ALSC

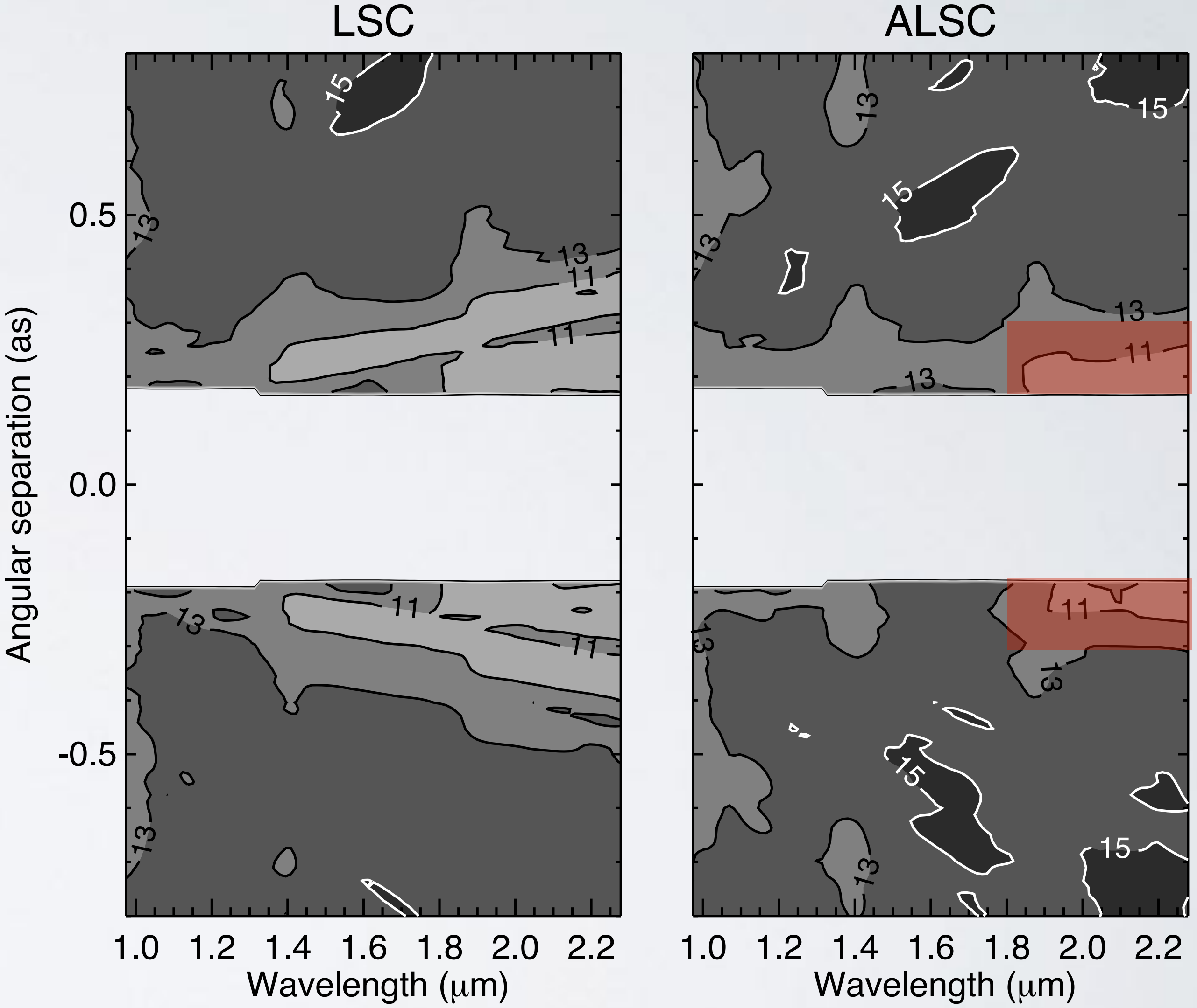
- 5 simulations for both concepts with different instrumental aberrations ➞ SPHERE/IRDIS overall design

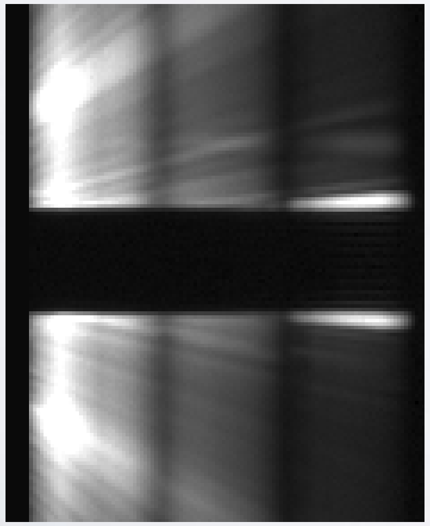


Vigan, N'Diaye & Dohlen, submitted

Speckle noise attenuation

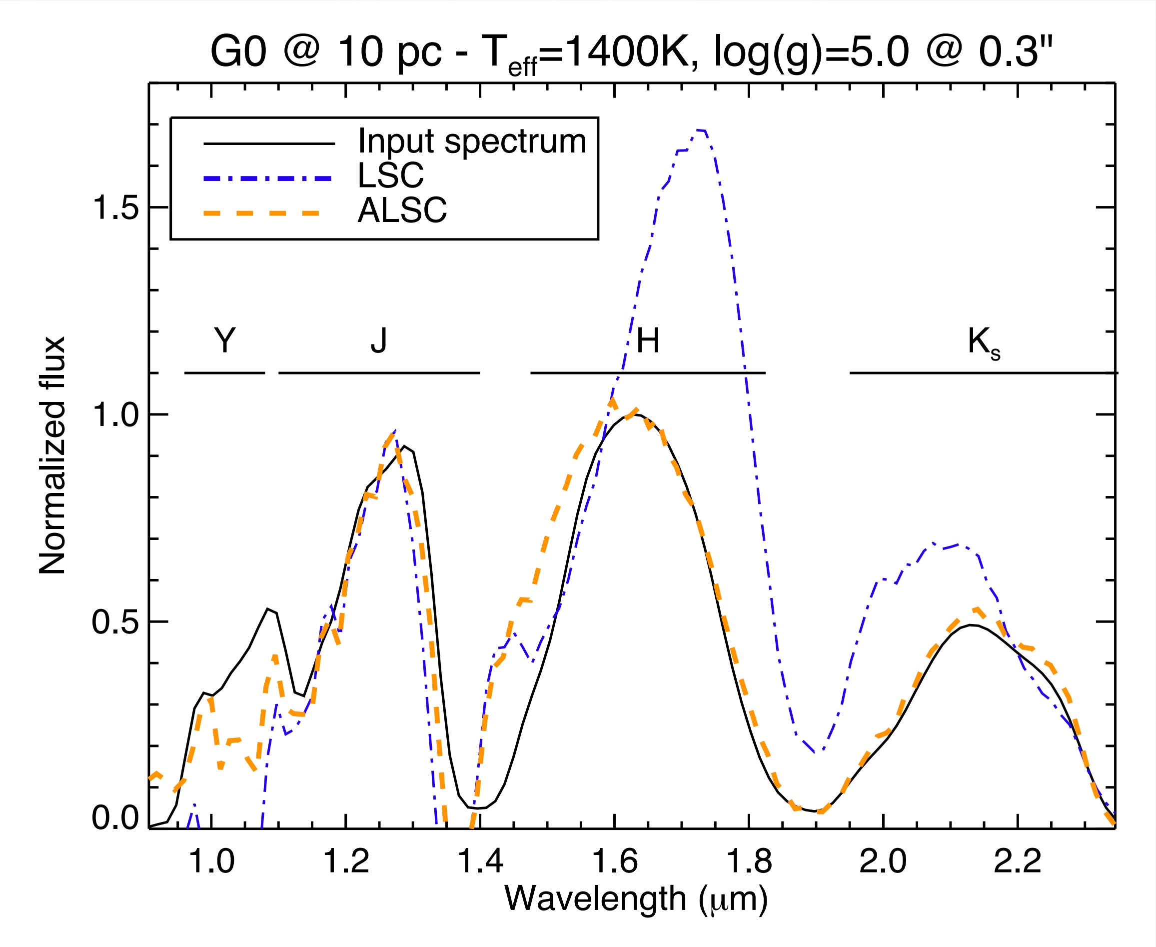
- Simulations without detection noise ➙ limited by speckles
- diffraction residuals are no longer visible
- 2 mag gain at 0.3”
- *K*-band still limited
  ➙ chromaticity of the PSF





Spectral extraction

- Real performance estimation → spectral extraction
- 2 methods:
  - comparison of input/output spectrum
  - comparison of extracted spectrum to libraries of models

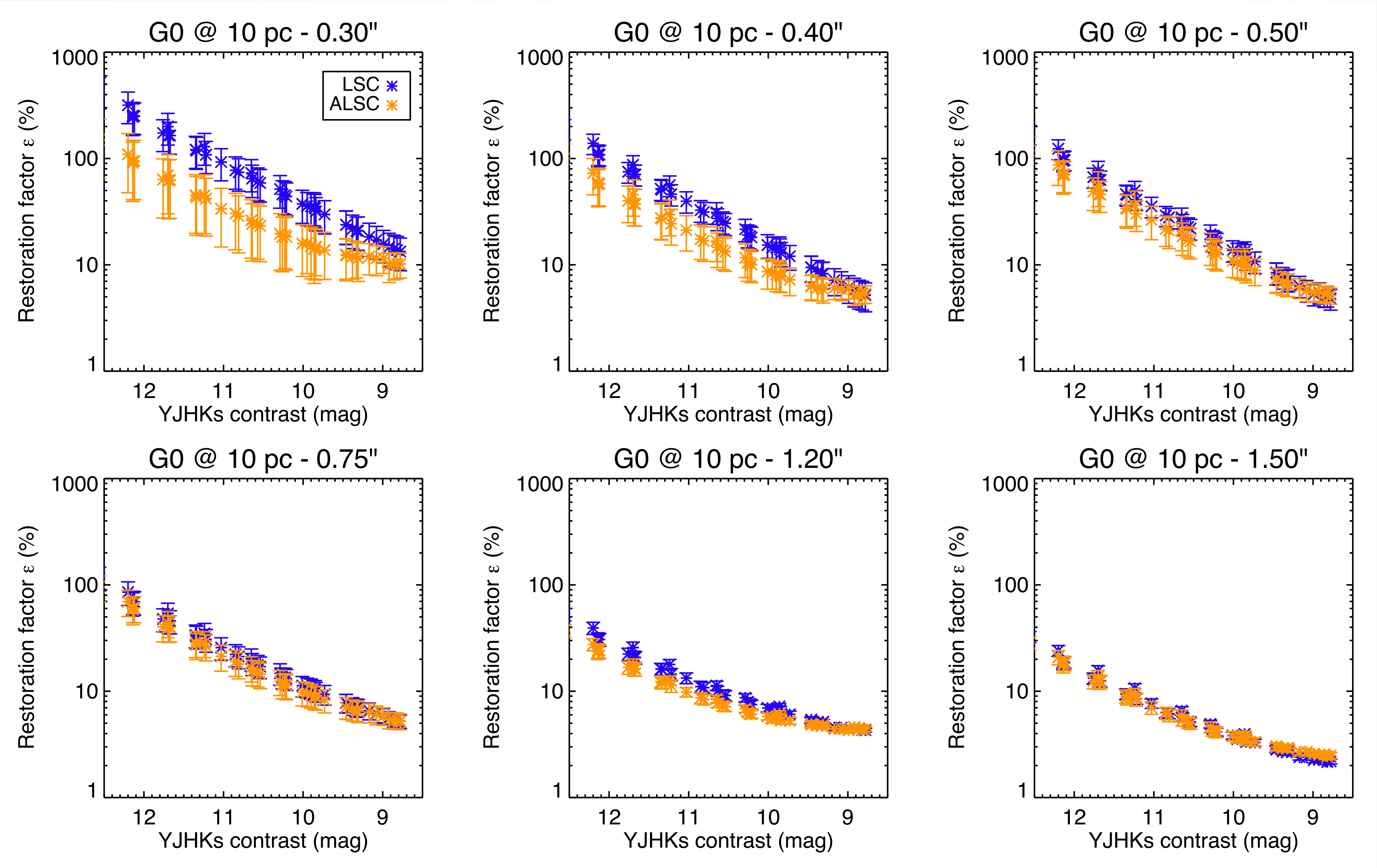


Results on spectral extraction

- restoration factor:

$$\epsilon = \sqrt{N_\lambda \sum_{p=1}^{N_\lambda} \left(\frac{I_p}{\sum_{k=1}^{N_\lambda} s_k^{\mathrm{atm}} I_k^{\mathrm{ref}}} - \frac{I_p^{\mathrm{ref}}}{\sum_{k=1}^{N_\lambda} s_k^{\mathrm{atm}} I_k^{\mathrm{ref}}} \right)^2}$$

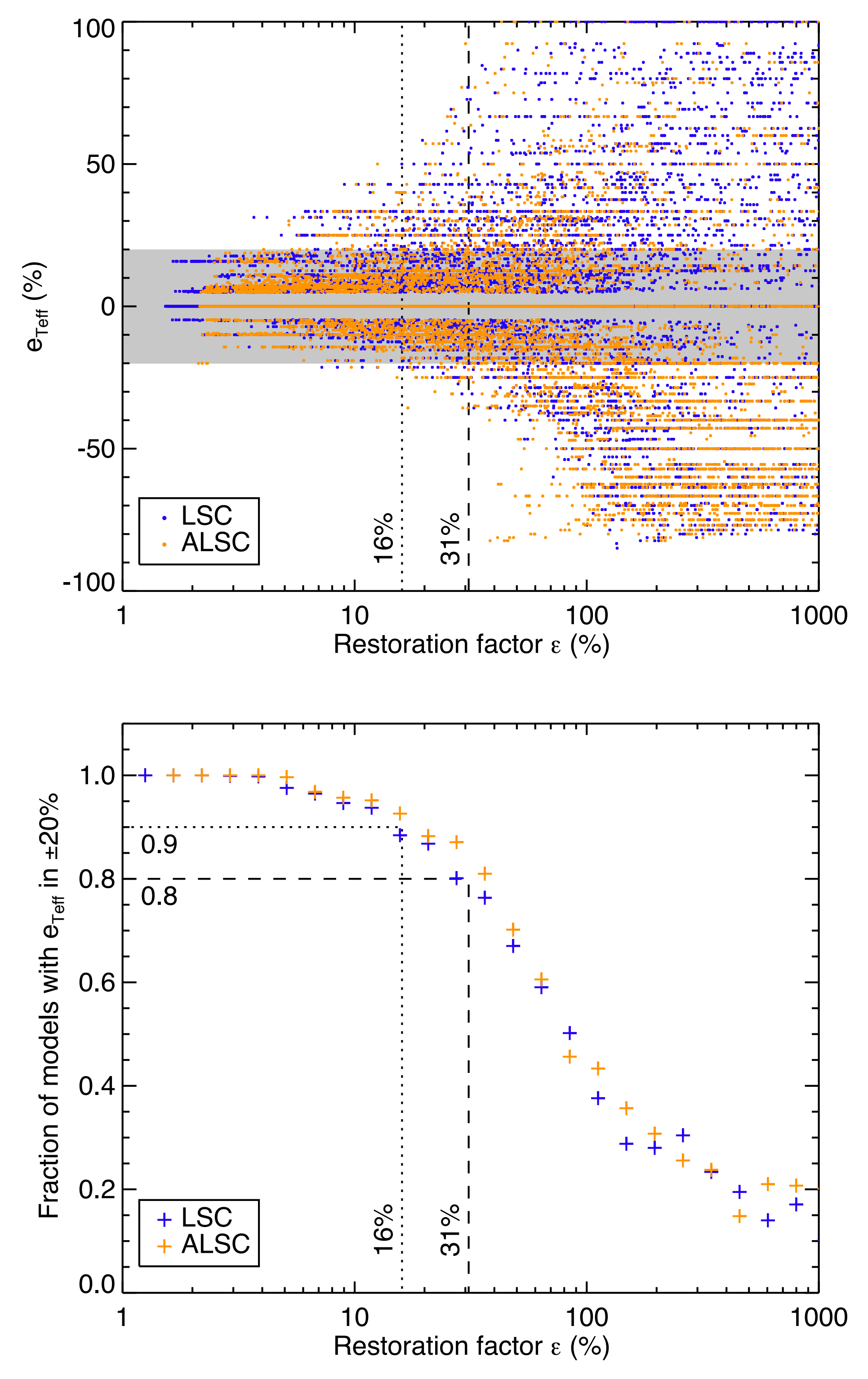
Pueyo et al. (2012)

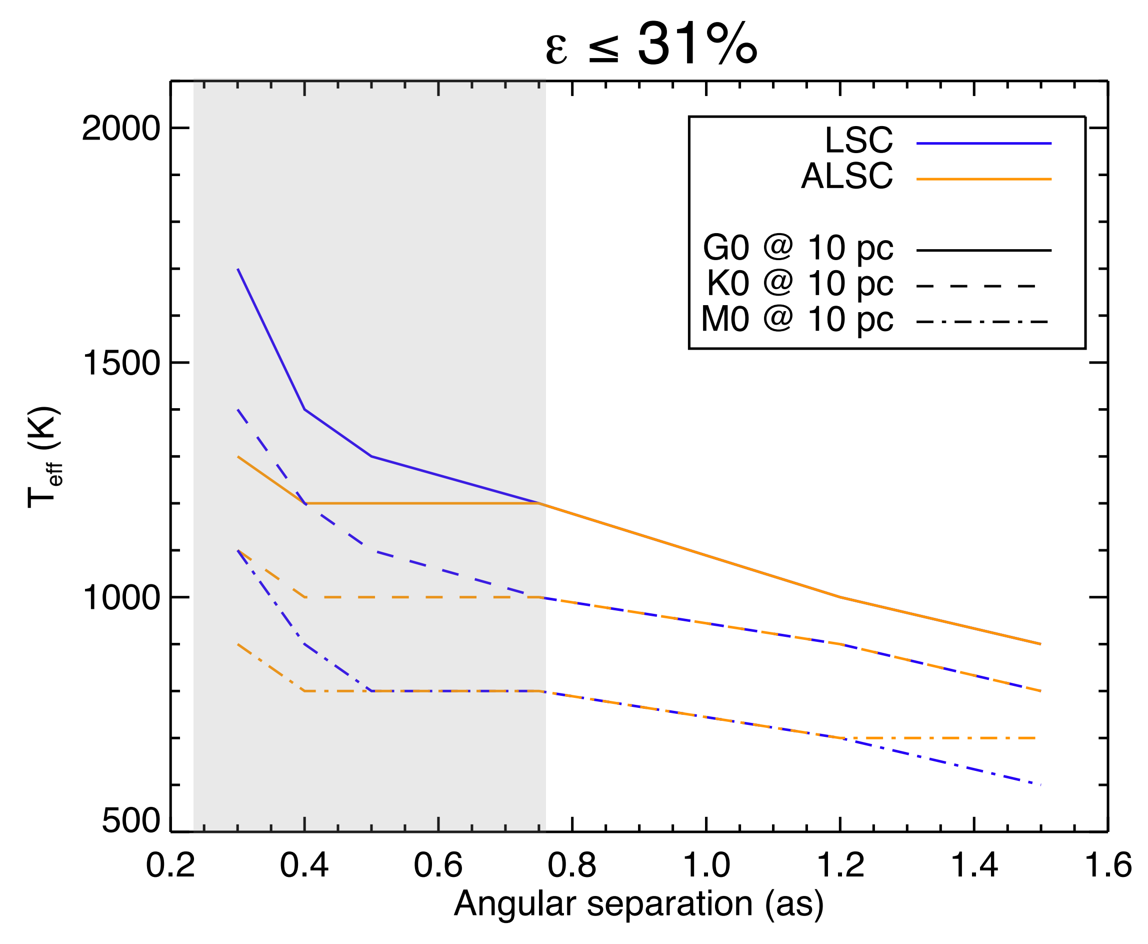


ALSC systematically better below 0.5”

Limits on T_{eff}

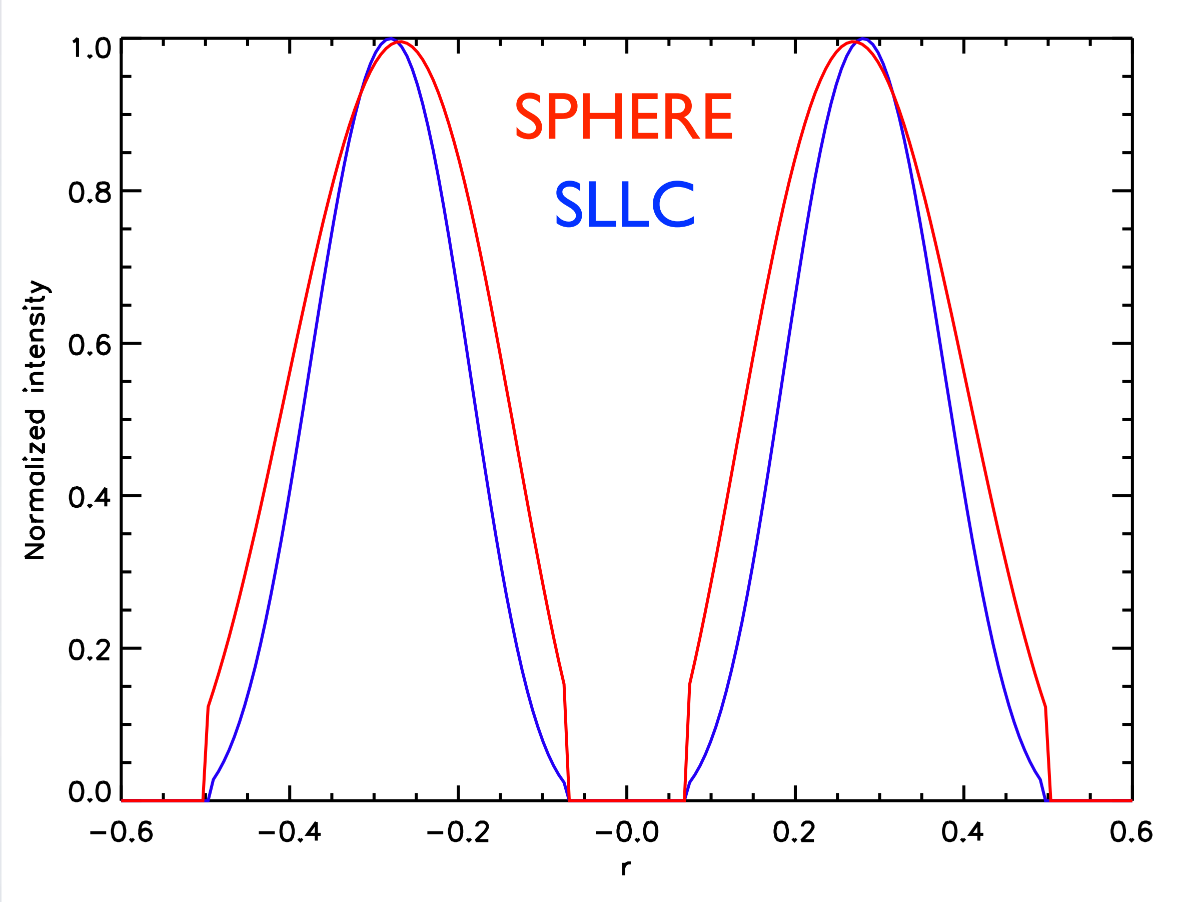
- comparison of output to libraries of models with χ^2 minimization
- comparison of best fit T_{eff} to the input T_{eff}

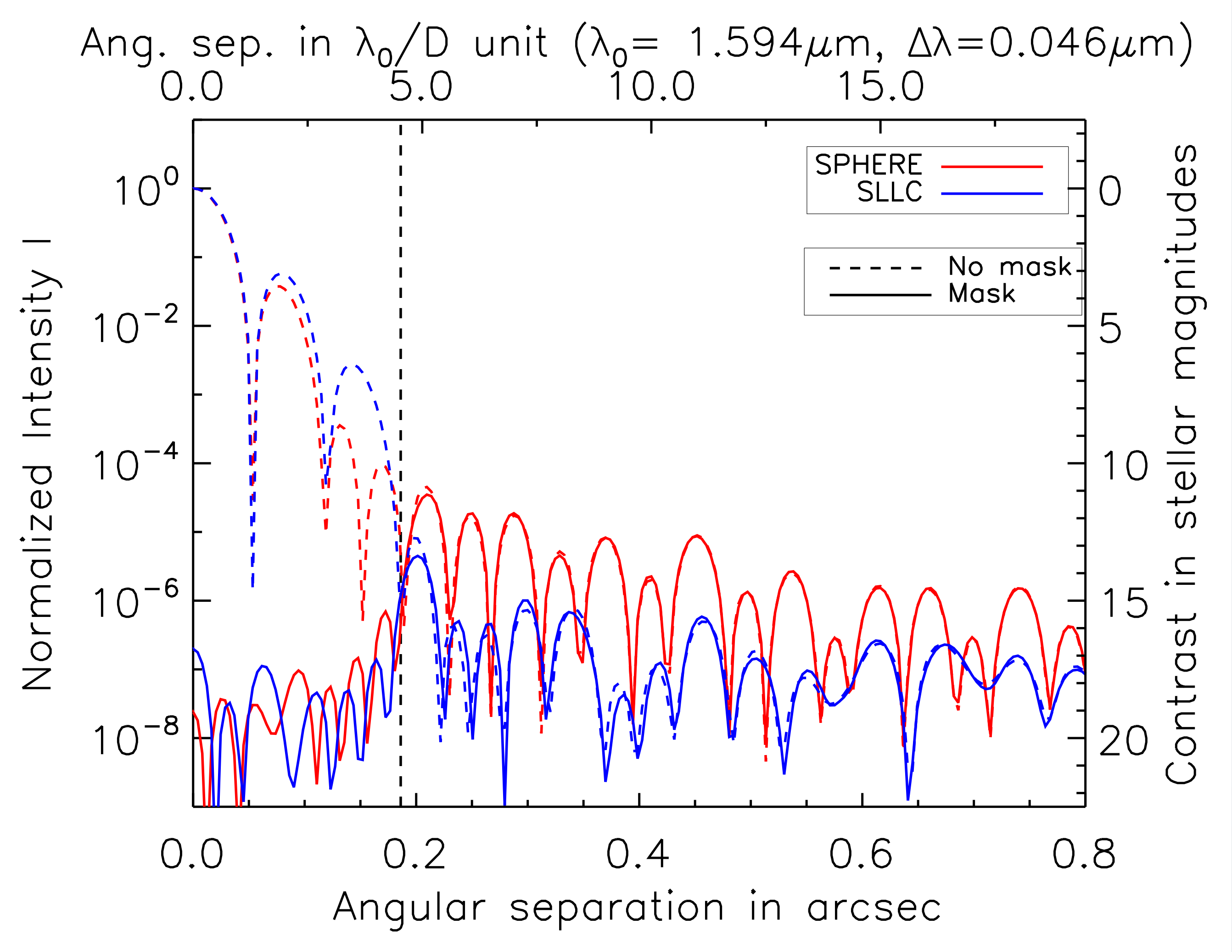




Implementation in SPHERE?

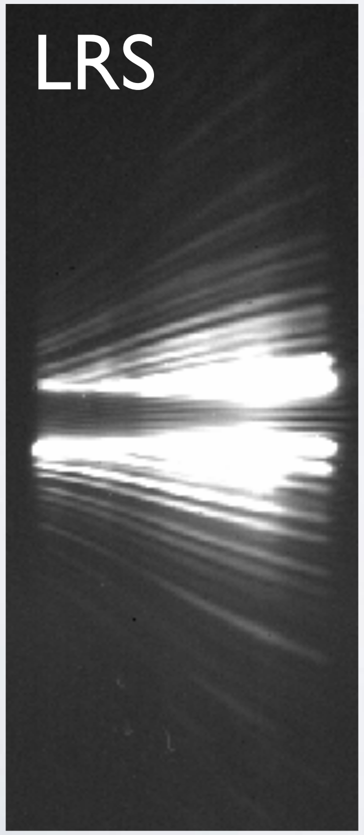
- under discussion with SPHERE system engineer
- 2 apodizers already in SPHERE... one very similar to SLLC

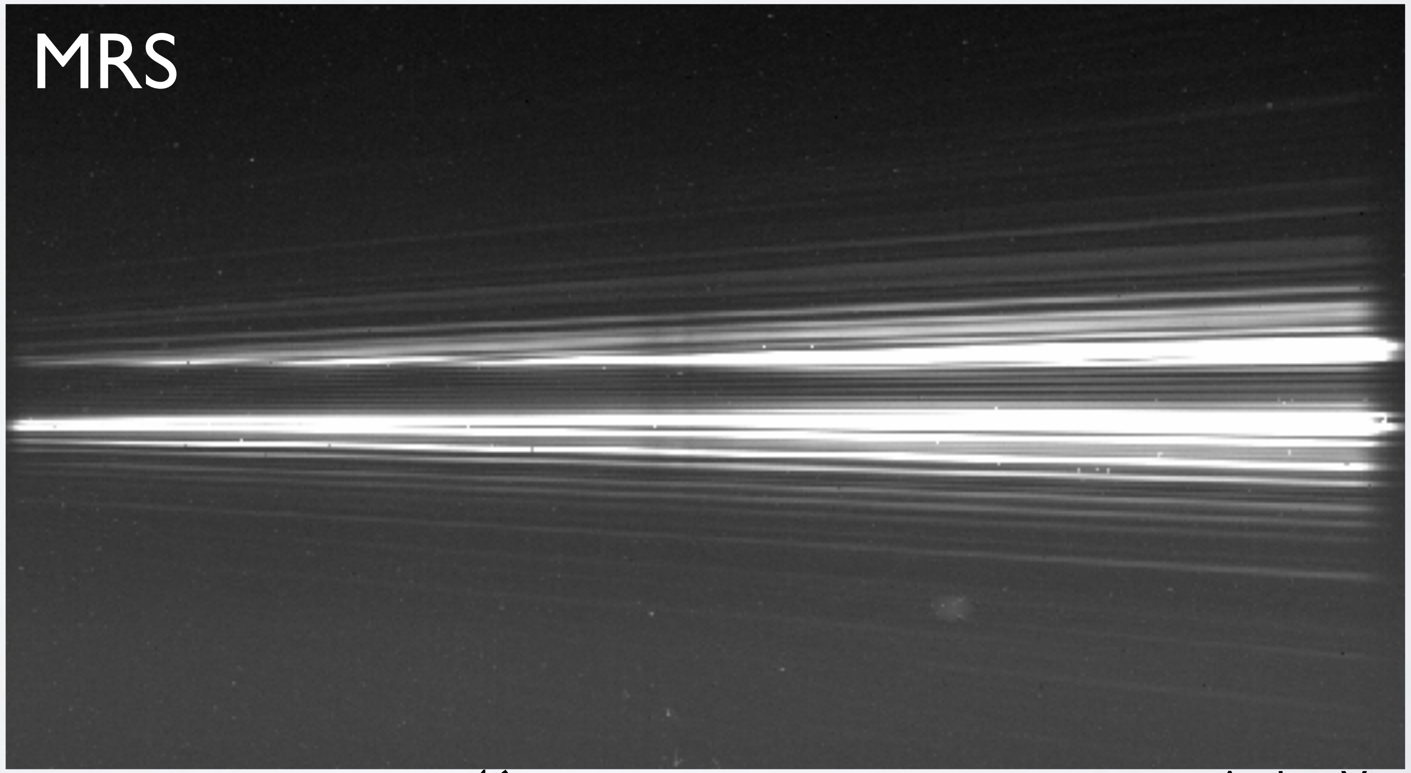




Conclusions - part II

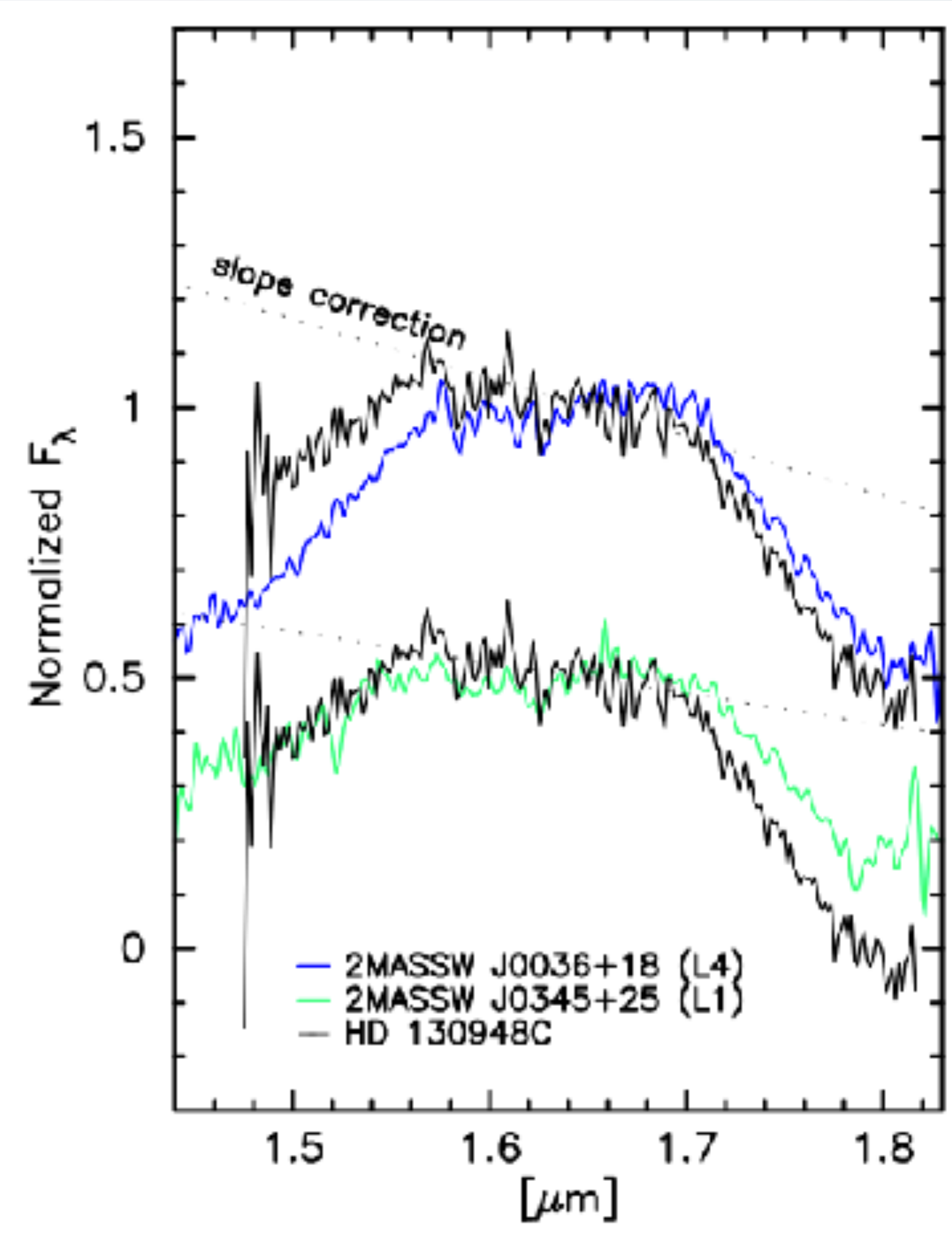
- SD is essential for high-contrast spectro data
- validated on-sky with VLT/NaCo data
- extraction of spectra highly biased by the speckles
- significant improvement when diffraction is suppressed by the use of an apodizer





Spectral slope variations in AO spectroscopy

- slit losses because of varying AO performance with wavelength
- differential flux losses between science target and spectroscopic standard
- SPHERE → IFS and IRDIS
  - measure slope in YJ with IFS
  - correct slope in IRDIS LSS data



Goto et al. (2003)

β Pic as a test case for IRDIS?

- Best fit of M. Bonnefoy with models BT-SETTL10:
  - T_{eff} = 1700 K
  - *log(g)* = ~4.0