FIRST, a Pupil-Remapping Fiber Interferometer at the Subaru Telescope

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Context: High contrast imaging at high angular resolution

➢ **Scientific goals**: detection and characterization of faint companions such as exoplanets around their host star + characterization of Giant star surfaces

➢ **Requirements**:
→ High angular resolution
→ High contrast

➢ **Challenge**: Turbulent atmosphere spoils telescope performance

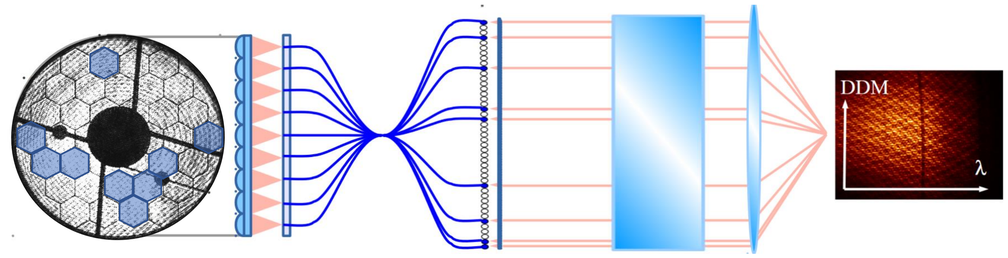
➢ **Solutions:**
→ Adaptive Optics (AO): allows to reach diffraction limit BUT residual speckle noise limits contrast
→ Speckle interferometry: allows to reach diffraction limit BUT contrast limited to ~100
→ Aperture masking: retrieve highest spatial frequency information of the pupil with contrast ~10^{-3}
BUT sacrifice of a large percentage of the full pupil + speckle noise over each sub-pupil

→ New solution proposed: Pupil remapping combined with the use of single-mode fibers

Pupil remapping with single-mode fibers

➢ **Principles:**

- **Pupil remapping** is applying the aperture masking technique on the whole pupil thanks to single-mode fibers (***A***)
- The use of **single-mode fibers** allows to remove speckle noise over each sub-pupil (***B***)
- The fiber outputs are rearranged in a **non-redundant configuration**. Each pair of sub-pupils have an independent phase and contrast (***C***)
- **Interferometric fringes** are **spectrally dispersed** and deliver measurements below the telescope diffraction limit (***D***)

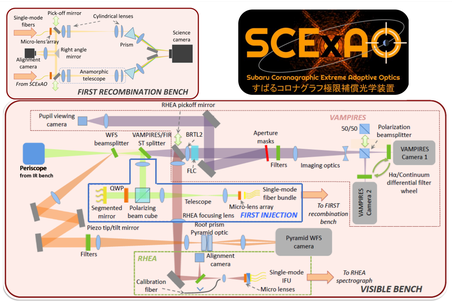


(***A***) (***B***) (***C***) (***D***)

→ Fibered Imager foR a Single Telescope (FIRST) is a module of the Subaru Coronographic Extreme Adaptive Optics (**SCExAO**)

FIRST @ SUBARU/SCExAO

Setup and performance



FIRST is located on SCExAO Visible bench. Recombination is performed on a separate bench

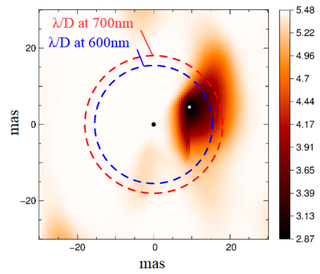
➢ Spectral bandwidth: **650-800nm**
➢ Field of view: **~136mas at 700nm**
➢ Spectral resolution: **300@700nm**
➢ ExAO system allows FIRST to acquire stable fringes with **long exposure times** (>10 sec)
→ current **magnitude limit = 6.6**

Data reduction

Fringes
↓
Complexe coherence terms estimation *V2PM method*
↓
Closure phase measurements
↓
Closure phase modeling
↓
Model parameters: **angular separation spectral flux ratio**

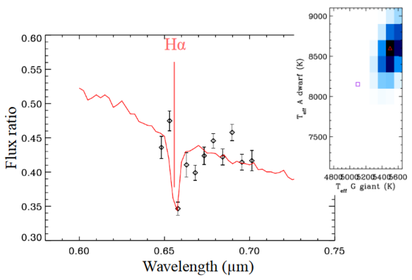
On-sky results

Super-resolution with FIRST at Subaru : Alpha Equ



Reduced X^2 map resulting from the binary fit for one data set (1000 frames, 100s total integration).

Huby et al. (in prep.)



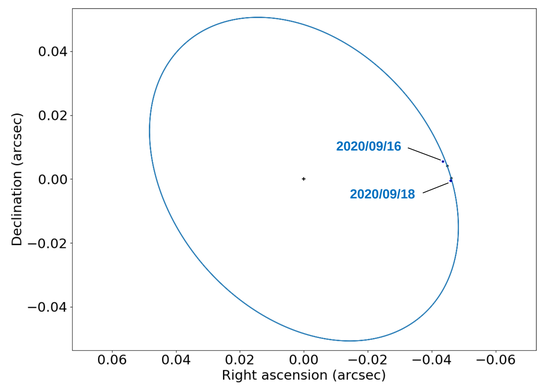
Estimated flux ratio spectrum (black points). Spectral channels have been binned (res. ~100) to maximize SNR. A preliminary spectral modeling result is shown in red, with the corresponding effective temperatures (on the right).

➢ **α Equ** is a spectroscopic binary – R_{mag}=3.5 $^{+}/_{-}$ ~0.8mag

➢ Measured separation: **10.1 $^{+}/_{-}$ 0.1 mas** (exp. 11mas) → **0.6 λ/D**

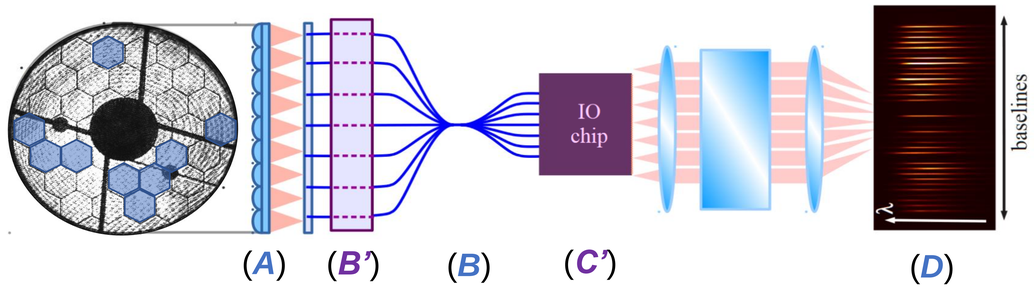
➢ Preliminary spectrum modeling also leads to consistent estimation of the effective temperature (analysis lead by G. Duchêne)

Capella detection with FIRST at Subaru



➢ Capella binary system observed over 2 days with the Subaru telescope
➢ Both position estimation **match with the orbit and predicted position** (from *Torres et al, 2015*)

FIRSTv2 : UPGRADES TO INCREASE SENSITIVITY

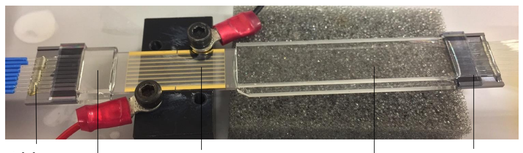


(***A***) (***B'***) (***B***) (***C'***) (***D***)

(***B'***) - **Fiber path length matching** with delay lines

(***C'***) - **Active Integrated optics (IO) chip** (***C'***) with new recombination scheme and fast phase modulation (MHz)

→ New science goal : **protoplanet detection and characterization**



FIRST : WAVEFRONT SENSING CAPABILITIES (under development)

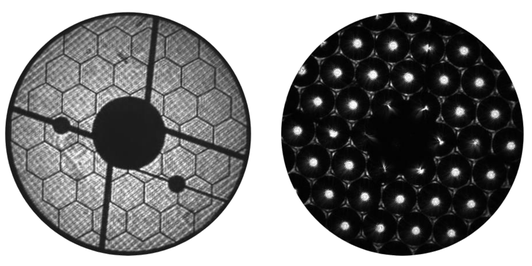
➢ Single telescope interferometers sample the pupil and allow relative measurements between the sub-pupils

➢ Coupled with a spectrometer, possibility to have these measurements as a function of the wavelength

➢ Critical for fragmented (or segmented) pupils
→ Tackle down **the Island Effect** caused by the spiders
→ **Co-phasing** of segmented telescopes

➢ On FIRST, use the baseline complex coherence (currently not used to compute the Closure phase) to retrieve the sub-aperture differential piston

➢ Unique instrument with **science and wavefront sensing capabilities**



Sampling of the Subaru pupil
Injection into single-mode fibers using a micro-lens array

Fringes
↓
Complexe coherence terms estimation *V2PM method*
↓
Sub-aperture differential piston

Conclusion + Perspectives

➢ FIRST at Subaru : pupil remapping for **detection and characterization of faint companions**
➢ On-sky results **: detection of companions even well below the telescope diffraction limit**
➢ Many upgrades to come for **phase stabilization** and enable new science cases
➢ Investigations to use FIRST as a **wavefront sensor**.

Relevant references

G. Perrin et al., High dynamic range imaging by pupil single-mode filtering and remapping, *MNRA, 2006*
S. Lacour et al., High dynamic range imaging with a single-mode pupil remapping system: a self-calibration algorithm for redundant interferometric arrays, *MNRA, 2007*
E. Huby et al., FIRST, a fibered aperture masking instrument. I. First on-sky results, *A&A, 2012*
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S. Vievard et al., FIRST, a Pupil-Remapping Fiber Interferometer at the Subaru Telescope: on-sky results, *arXiv:2012.12416 (2020)*