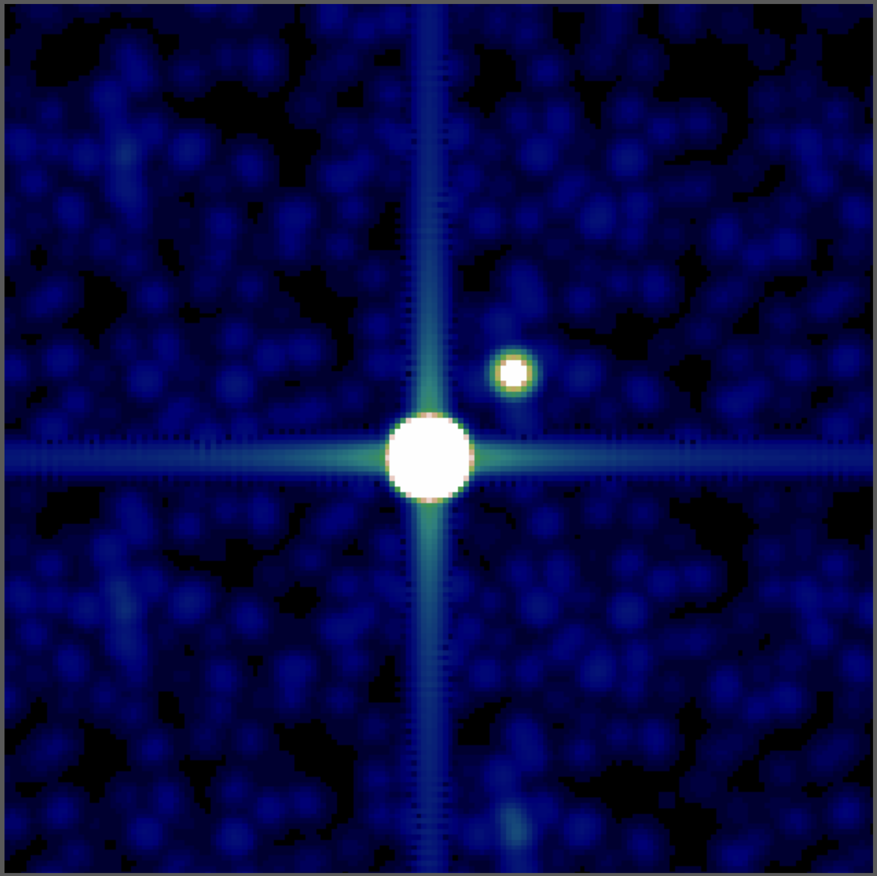
光ファイバー干渉計技術を用いたすばる用超高角分解能・高ダイナミックレンジ撮像装置について

Extremely High Angular-resolution, High-dynamic range Imaging Instrument with Single-mode fiber interferometric techniques



Takayuki Kotani (ISAS/JAXA)

Overview

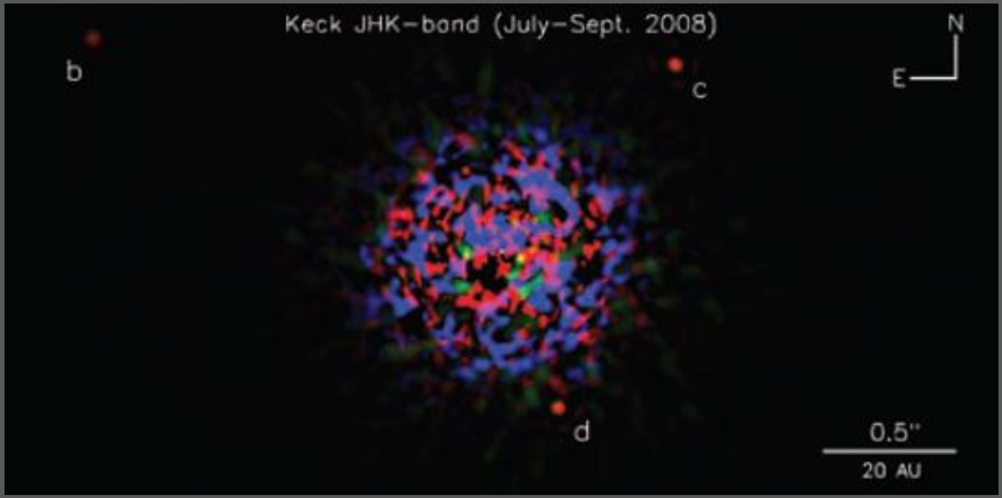
- Future instruments to realize very high-contrast, high-angular resolution imaging with/without AO for Subaru
- Pupil Remapping:
  - A new concept for diffraction-limited, high-contrast imaging in visible to NIR wavelengths
  - Aperture masking + single-mode fiber interferometer
- OHANA
  - Optical/Infrared Interferometer array on Mauna Kea
  - Extremely high angular resolution (< mas)
  - Combining large AO-equipped telescopes including Subaru with a single-mode fiber

High-Contrast, diffraction-limitted imaging from the ground

⇒ Adaptive Optics already realized diffraction limited imaging

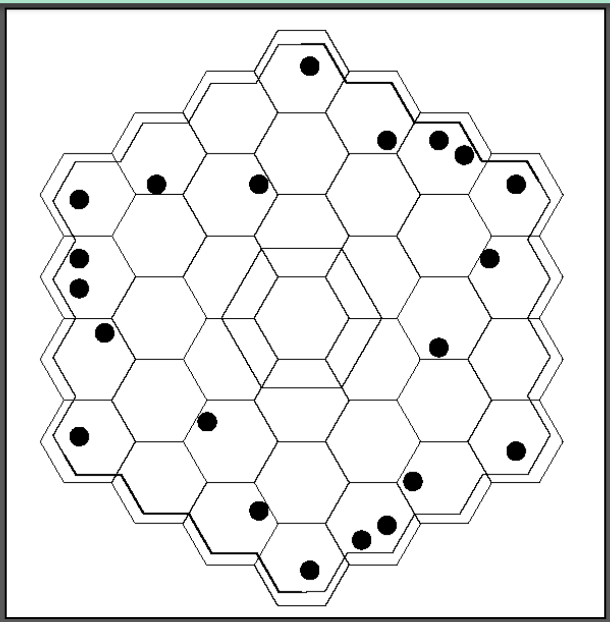
However,

- Relatively low dynamic range around ～λ/D due to residual Atmospheric turbulences
- AO performance is limited in the visible wavelengths



Solution: Aperture Masking＋Single-mode fiber

Aperture Masking



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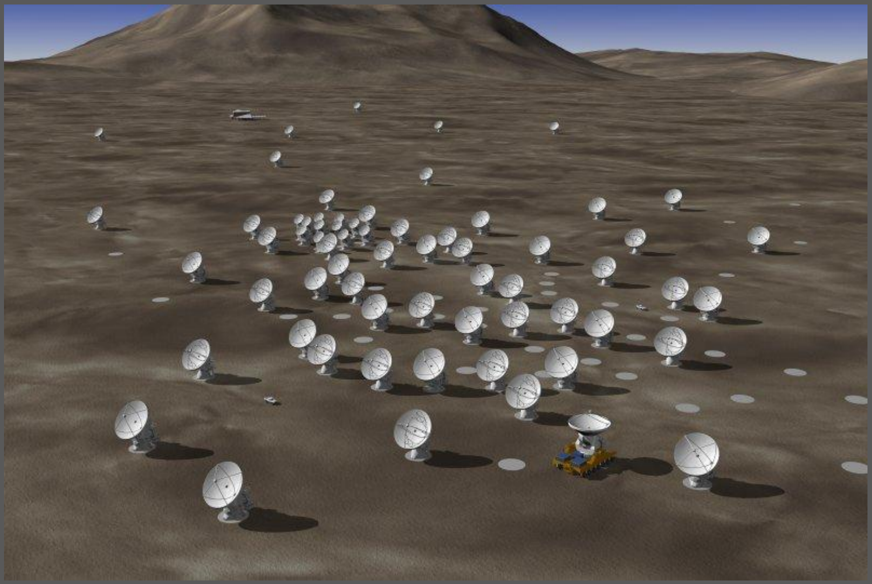
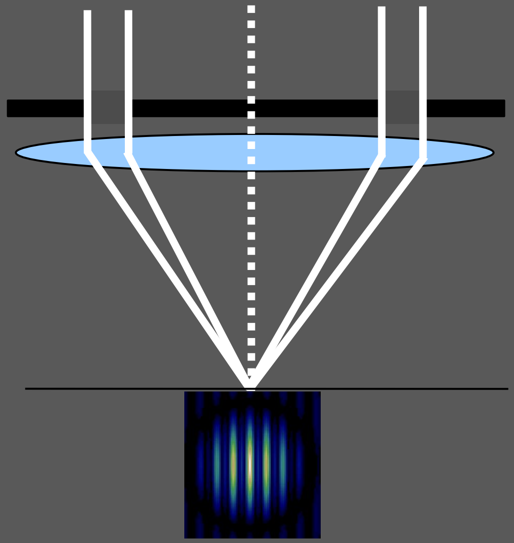
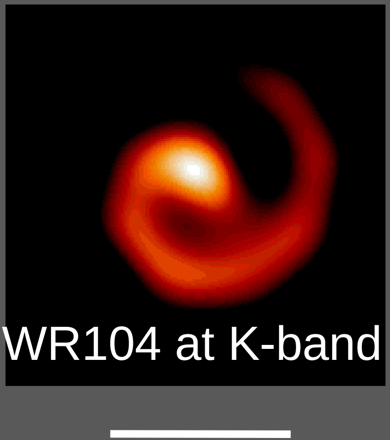


- Several sub-apertures can be used as the array of small telescopes
- Original image can be reconstructed with interferometric techniques



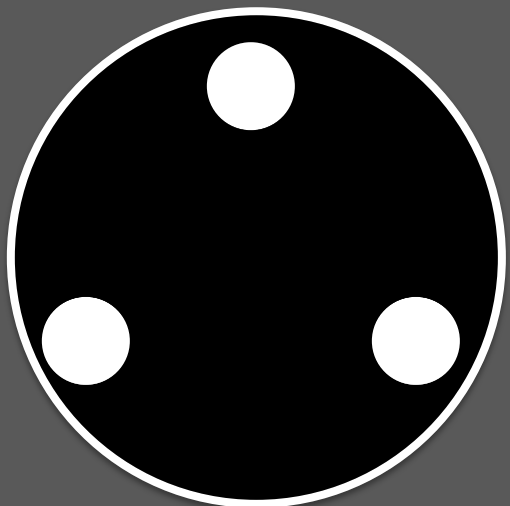


0.1 arcsec

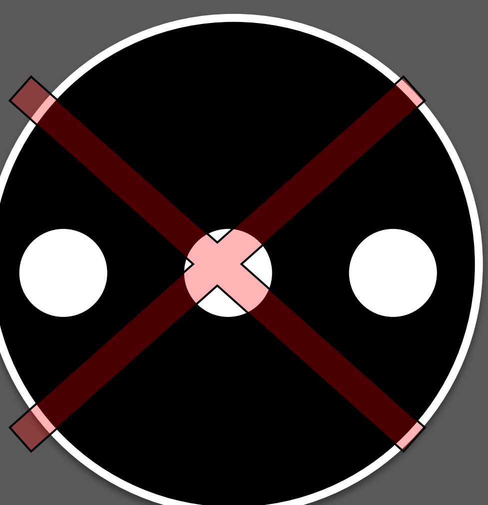
Tuthill, Monnier & Danchi, Nature 1999, 398, 487

Image reconstruction with Aperture Masking

Telescope (Mask)

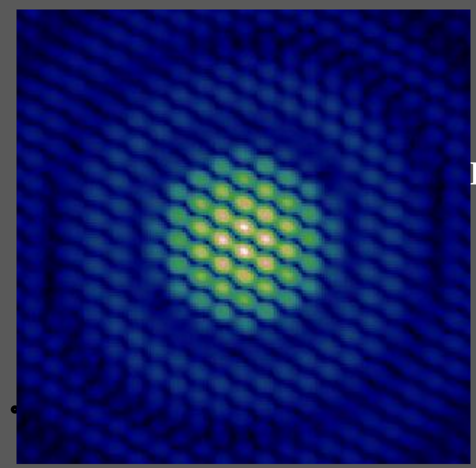


Non−Redundant



Redundant

Focal Plane



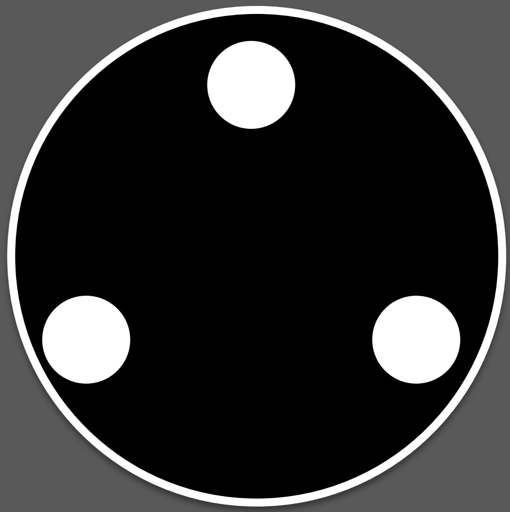
Complex visibility measurement

Image reconstruction

(Clean, Maximum Entropy, etc)

- Interference between each sub-apertures
- Sub-aperture size < fried length r_0
- Exposure time (1 frame) < Coherence time t_0
- Non-Redundant aperture configuration

Limirations of Aperture Masking



- Sub-aperture size < fried length r_0

 1) Wavefront erros inside a sub-aperture cannot be zero

- Non-Redundant mask

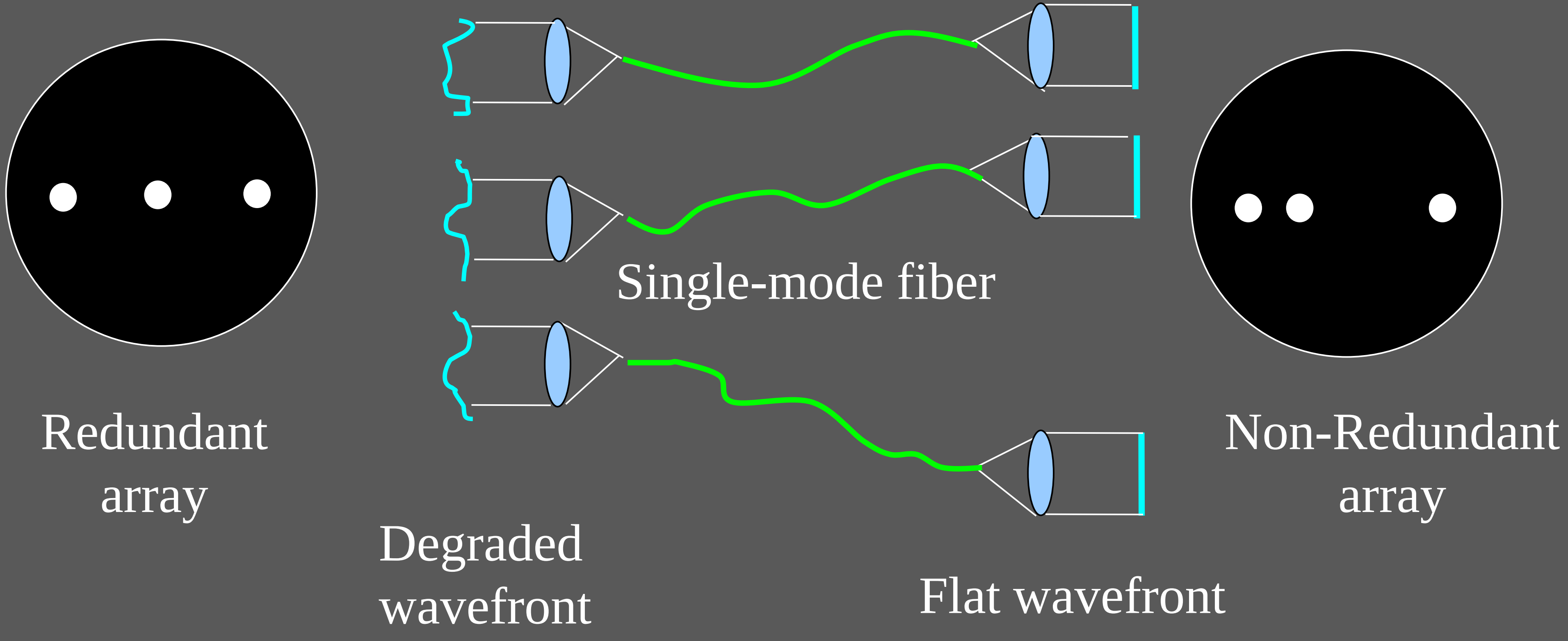
 2) Only small part of a telescope aperture can be used

 3) Limited number of baselines

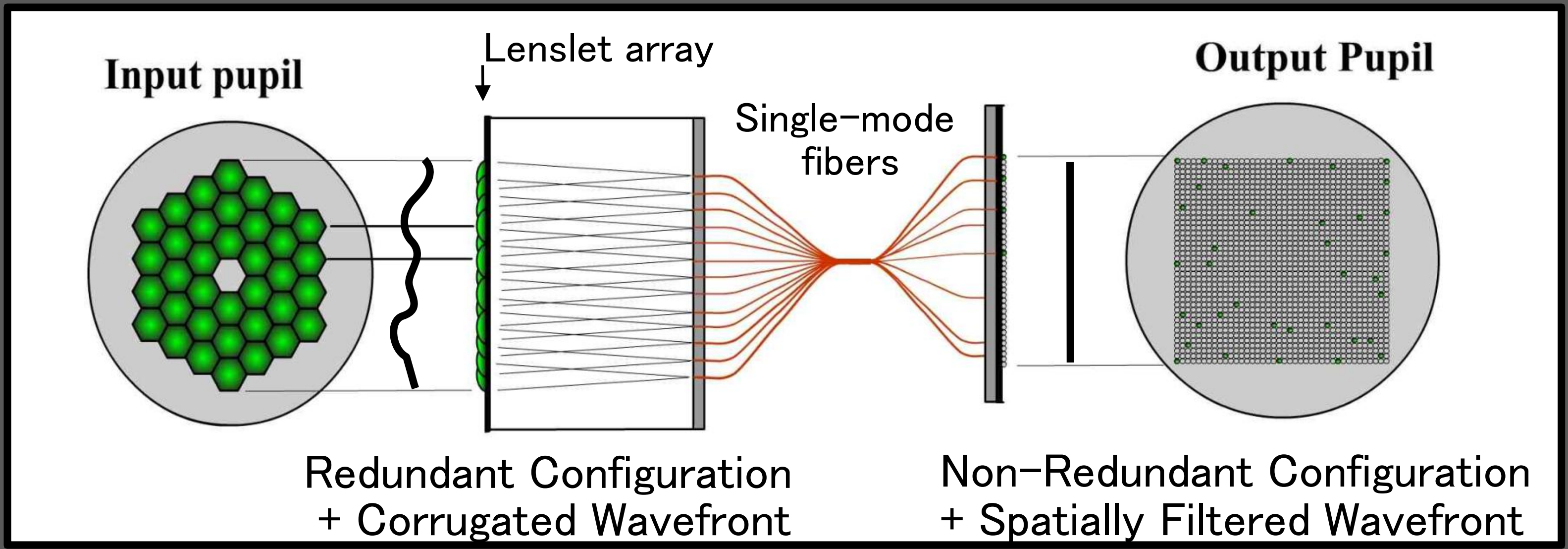
Dynamic range is limited to <1000

Aperture Masking + Single-mode fiber

- Single-mode fiber can filter out atmospheric turbulences
- Re-arrangement of Sub-aperture positions



FIRST (Fibered Imager foR Single Telescope)

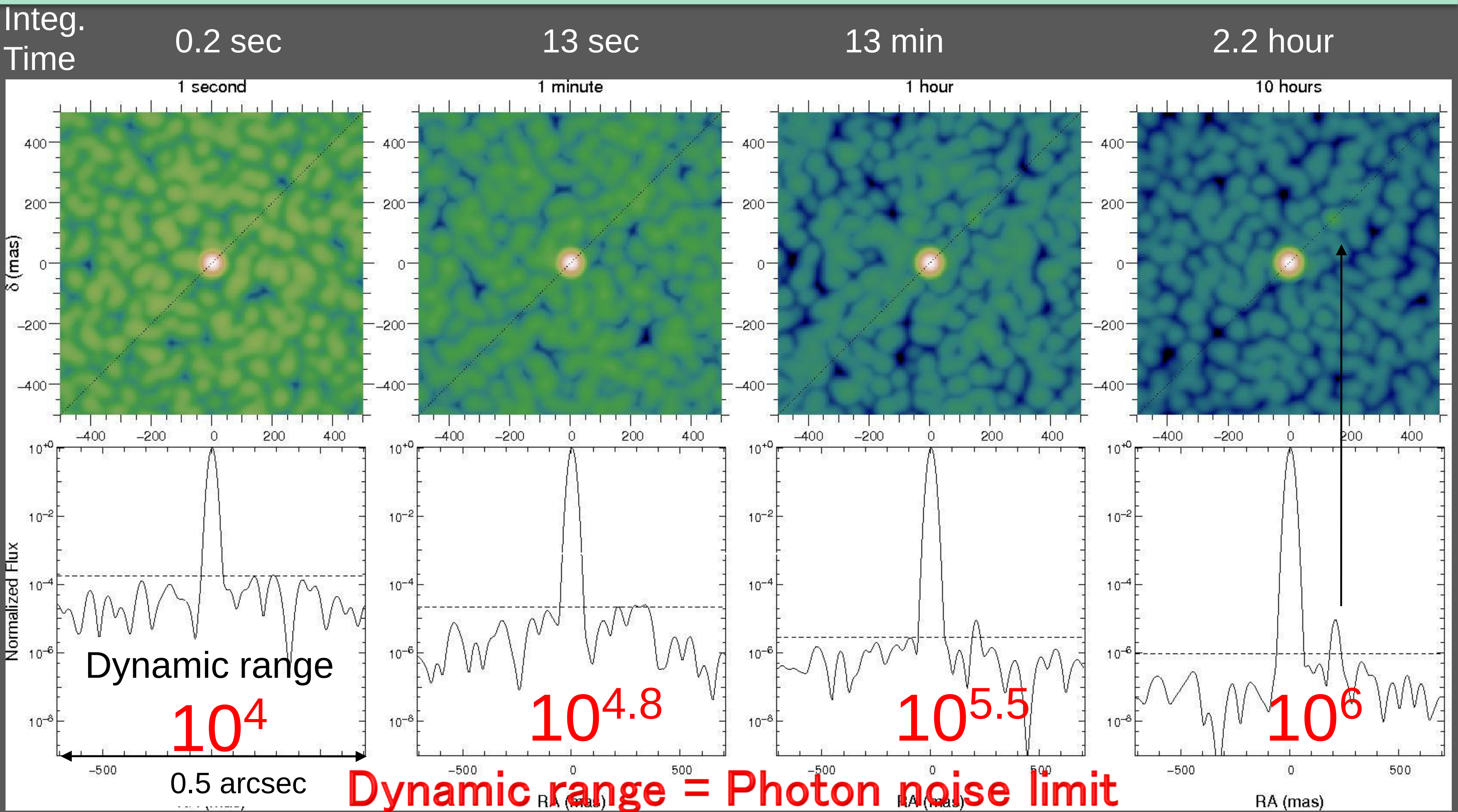


Perrin et al. 2006; Lacour et al. 2006

1. SM fibers remove wavefront errors within each sub-apertures
2. Re-arrangement of sub-apertures non-redundantly leads to a full usage of a telescope aperture
3. Post-data processing can remove piston errors between fibers

Extremely high-contrast, sensitive imaging possible

Simulation (8m telescope)

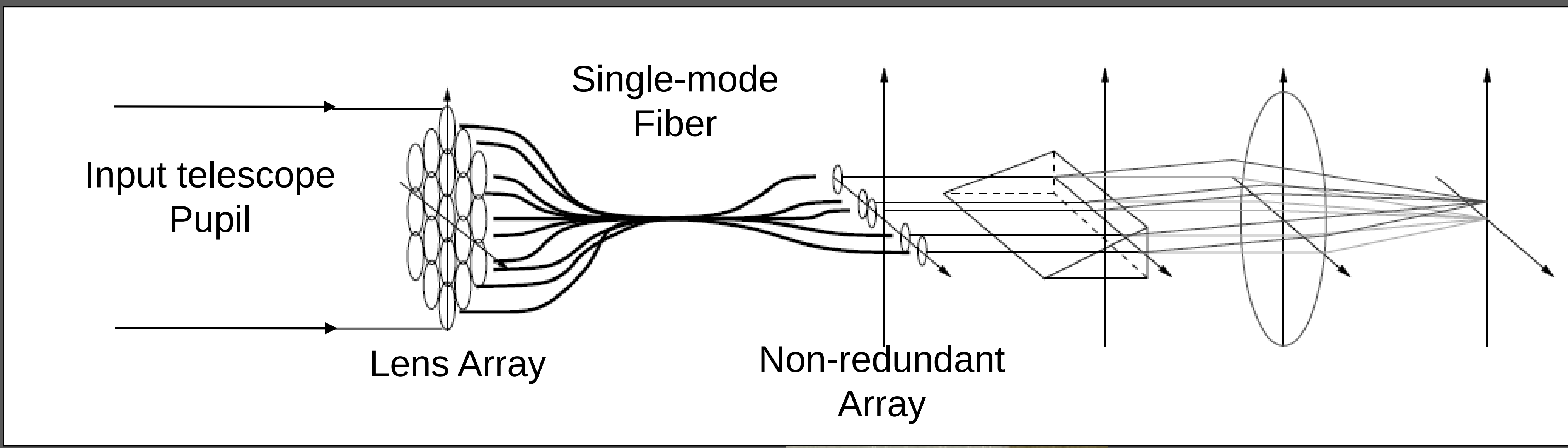


- **Hot-Jupiters** can be directly detected from the ground!
- Only this technique can achieve extremely high-contrast imaging in the visible wavelengths

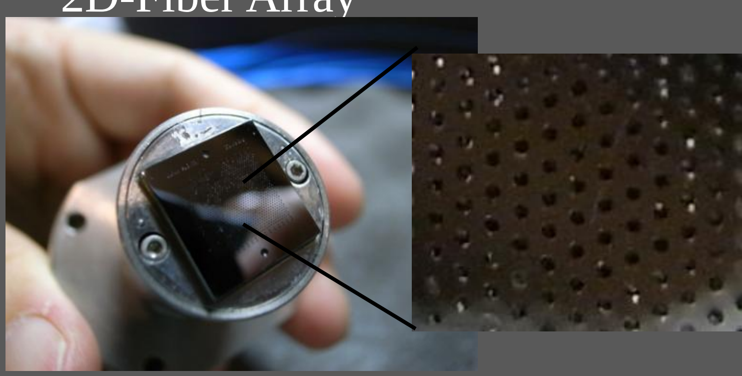
- Seeing: r_0 = 8cm @ 550nm, t_o =
- Integration time per frame: 1 ms
- 8m telescope
- λ = 550 nm, Δ λ = 90 nm
- Star magnitude = 5

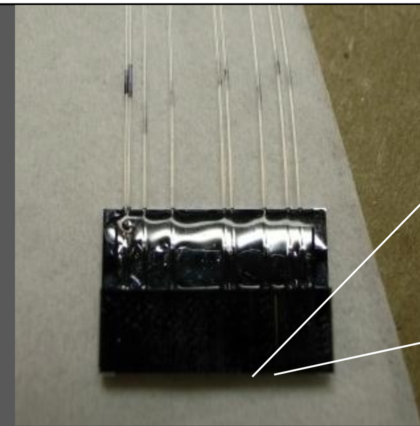
FIRST: Development of a 9-fiber prototype system

- 9-fiber, single-mode fiber Pupil Remapping System
- Operating at the visible wavelength (600-800nm)
- Spectroscopy (R ~ 100)
- Observations at the Lick Shane Telescope(3m)



2D-Fiber Array

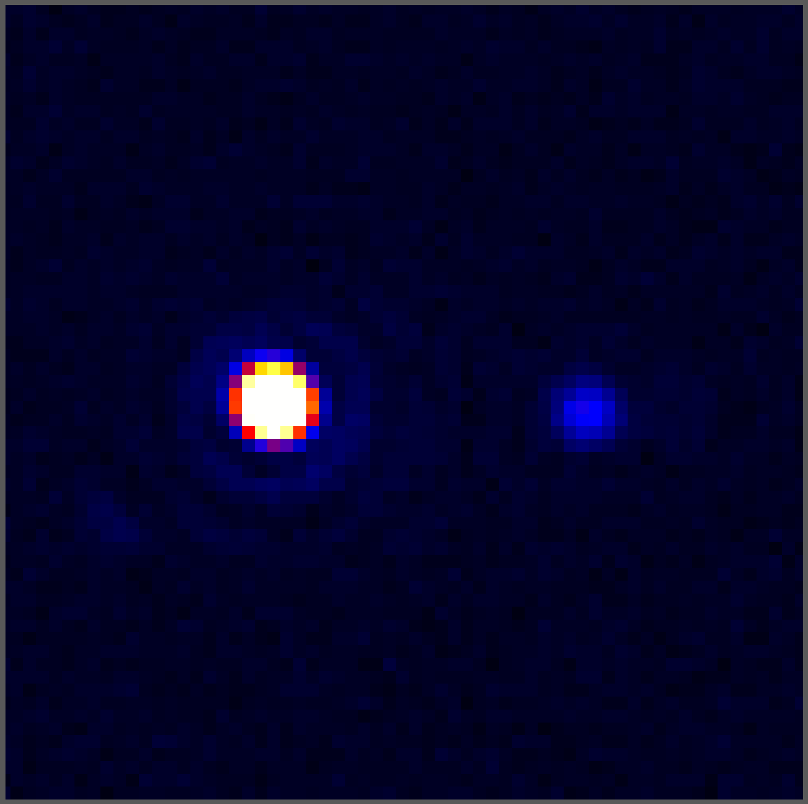




Silicon V-groove chip

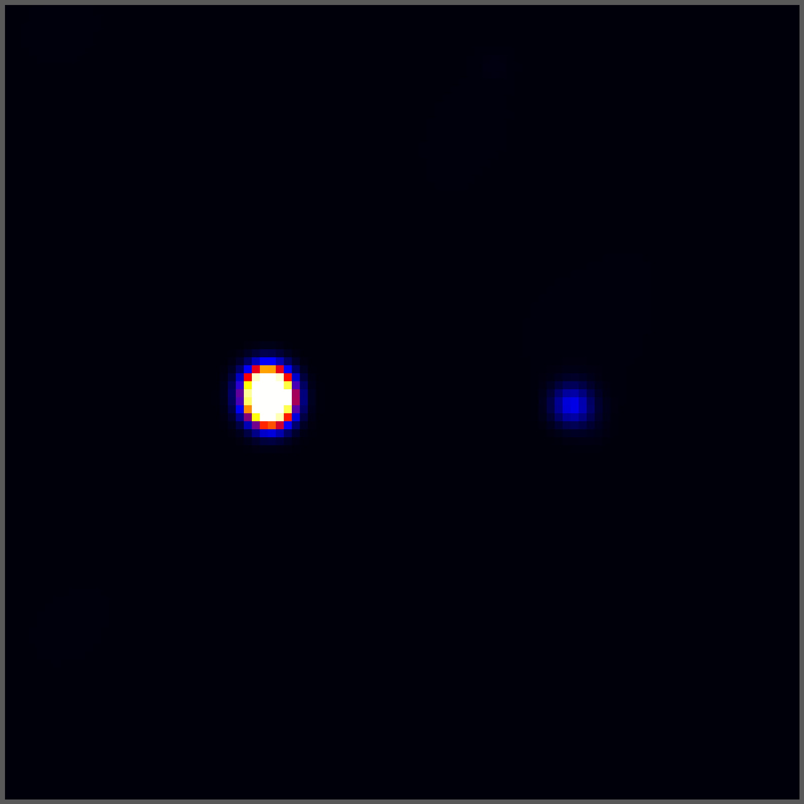
Image reconstruction in the laboratory

Kotani et al., 2009, Optics Express, 17, 1925



CCD Image

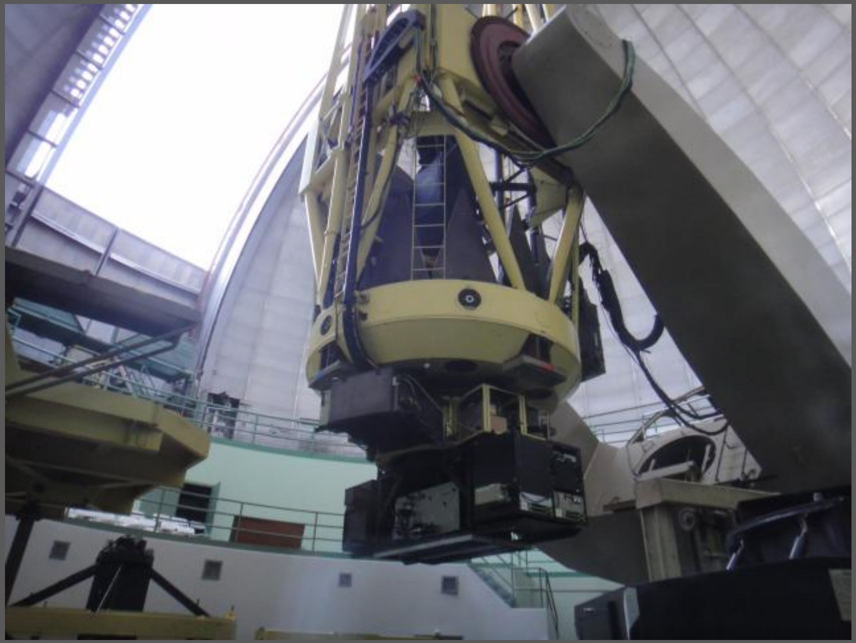
(2 x He-Ne Laser)



Reconstructed image from visibility measurements

On-sky demonstration successfully completed!

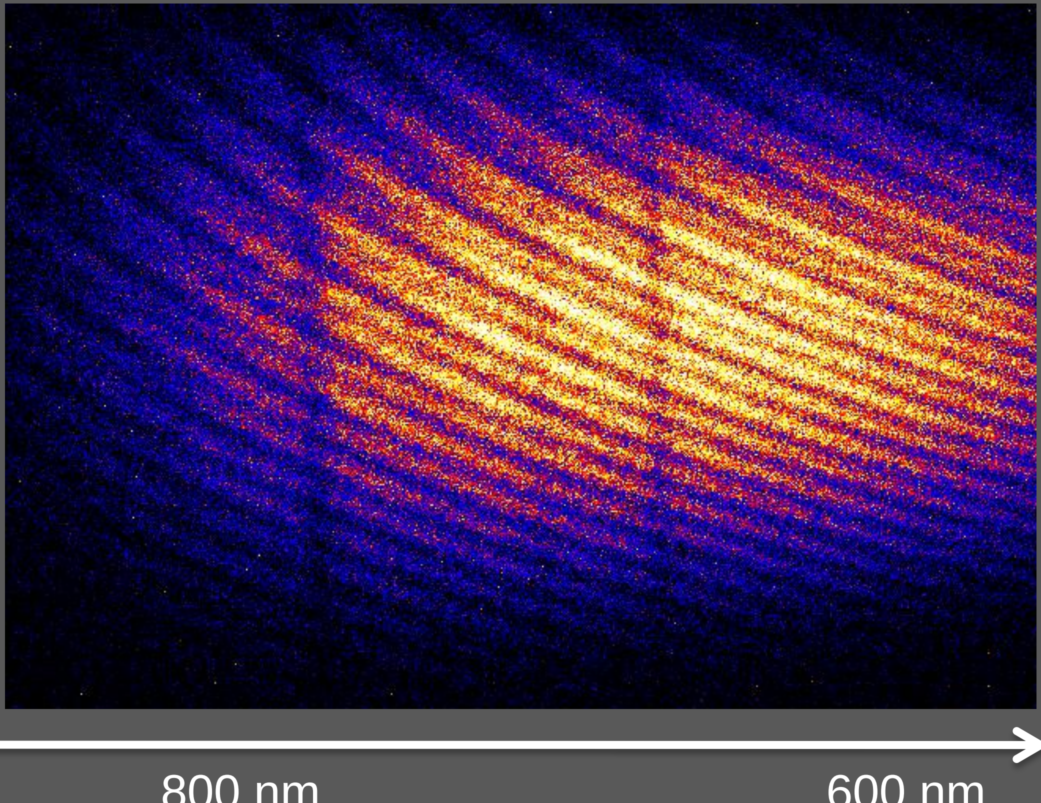
July, 29, 2010



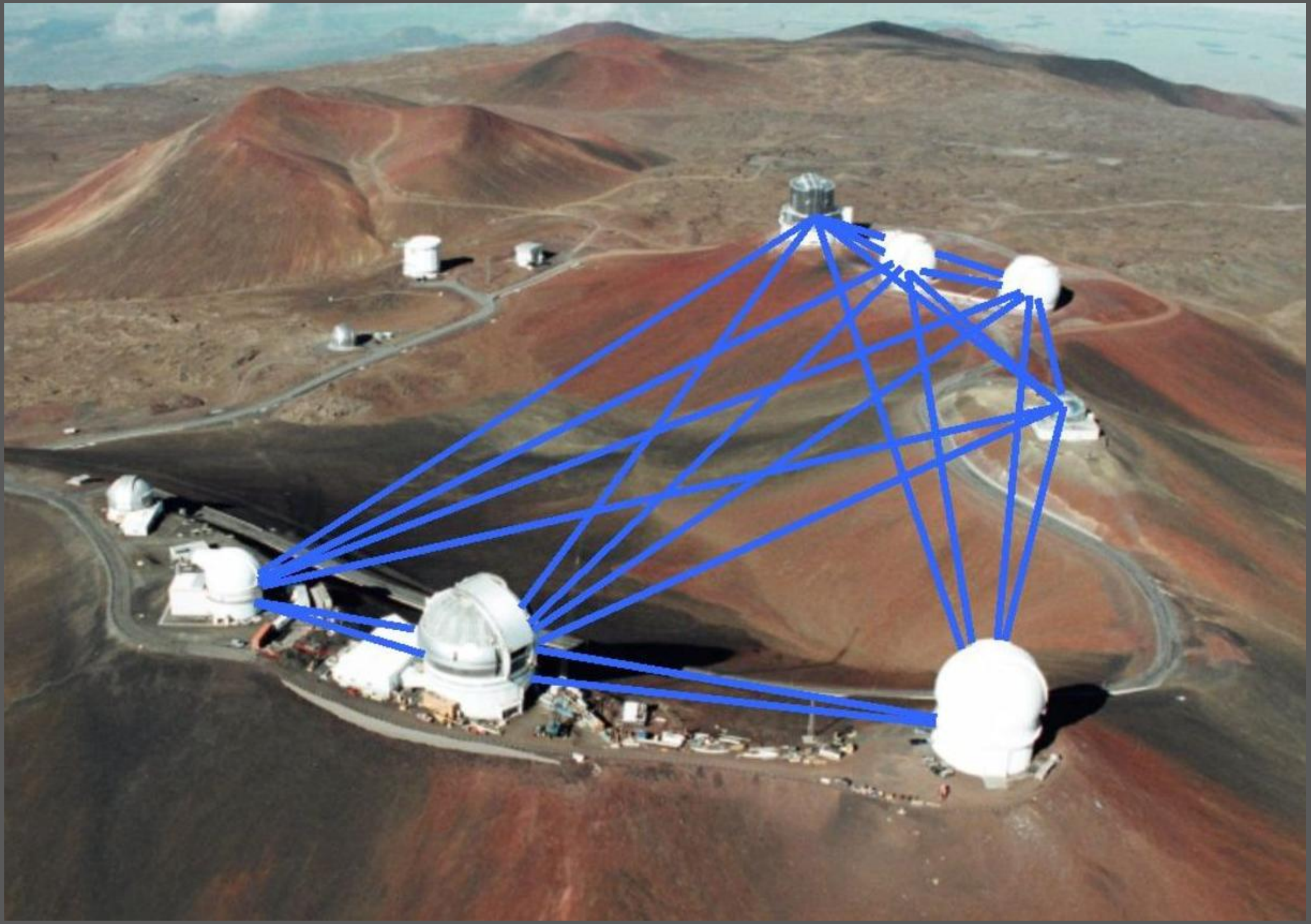
Lick 3m telescope

- 9-fiber system
- Spectro-interferometry
- 600-800nm
- Ready to go for a larger telescope (Subaru…)

Interferogram of Vega



OHANA: Optical Interferometer on Mauna Kea



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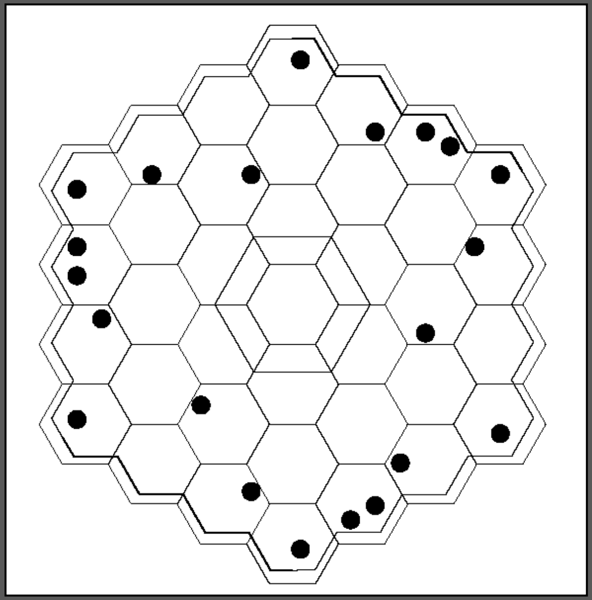

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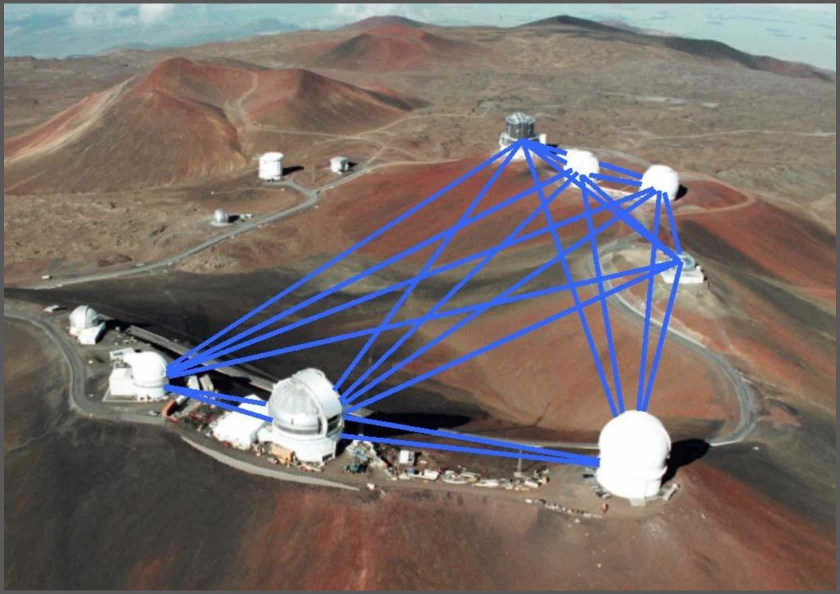


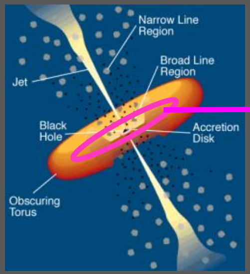
OHANA (Optical Hawaiian Array for Nanoradian Astronomy)

- Optical/Infrared Interferometer array on Mauna Kea
- Combining AO-equipped large telescopes **including Subaru** with a single-mode fiber
- Extremely high angular resolution (sub mas)
- Project started in 2000 (the international team led by Paris observatory)
- 2006: First on-sky fringes at Keck-I and Keck-II in the K-band

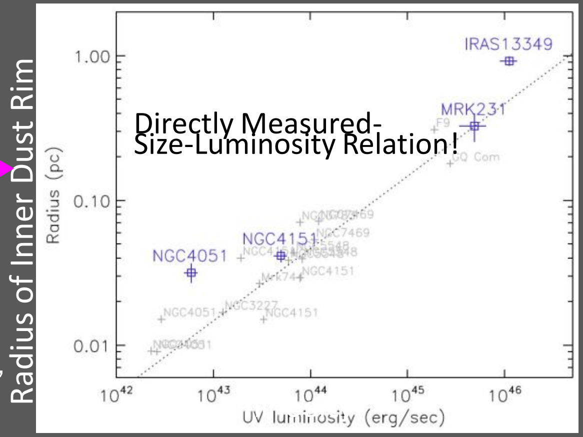
What can we do with OHANA?

OHANA has a potential of:

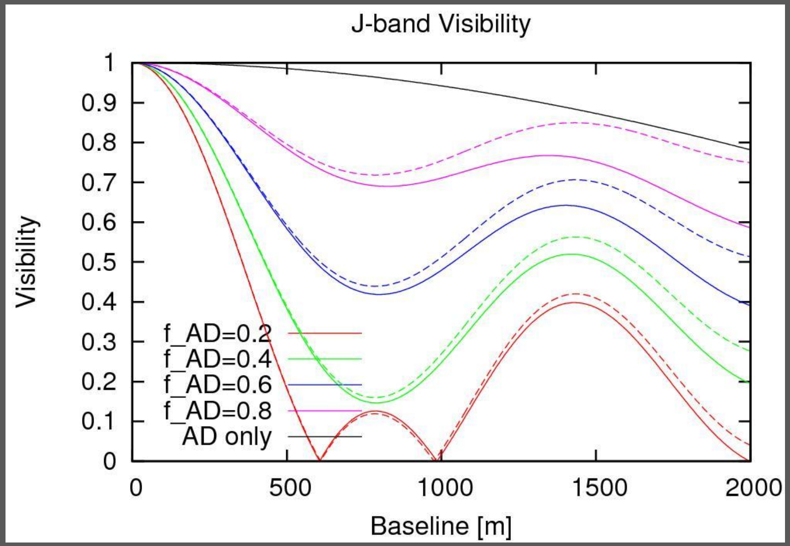
- Resolving inner most regions of AGN torus
- Directly measuring an accretion disk size



Kishimoto et al. 2009, A&A, 507, L57



Measured AGN torus size with Keck-interferometer



Futur plan

- 2011: CFHT – Gemini recombination
- 201?: Subaru – Keck
- Design of a fiber injection module for Subaru is ongoing at NAOJ

Summary

Pupil Remapping:

- High-dynamic range, high-angular resolution imaging can be realized with the single-mode fiber pupil remapping technique in the visible to NIR wavelengths
- On-sky demonstration successfully completed at the Lick 3m telescope
- Pupil remapping at Subaru: up to 10^6 dynamic range, 12 mas angular resolution imaging possible
- Direct detection of extra-solar planets (Hot-Jupiters) in the visible is possible with Subaru

OHANA:

- Extremely high-angular resolution optical interferometer
- Resolving inner-most regions of AGN dust torus
- R&D is ongoing to realize Subaru-Keck interferometer

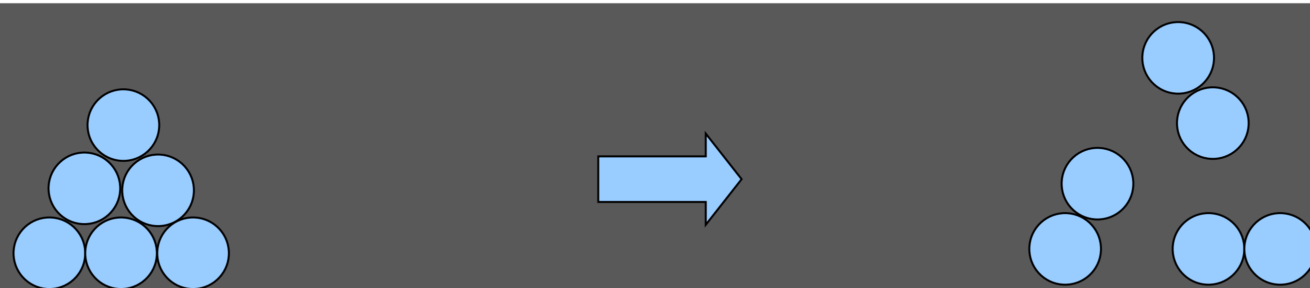
Thanks for your attention!
Takayuki Kotani

ピストン（位相差）は解くことができる！

$$\mu_{i,j} = V_k G_i G_j^{\star} ,$$

V_k: Object Visibility
G_i: 複素透過率 (位相と入射効率)

実際に観測できる量は天体のVisibilityではなく、μ (Mutual coherence factor)



Input (Redundant)

14個の未知数
(5個の複素透過率G＋9個の複素数Visibility)

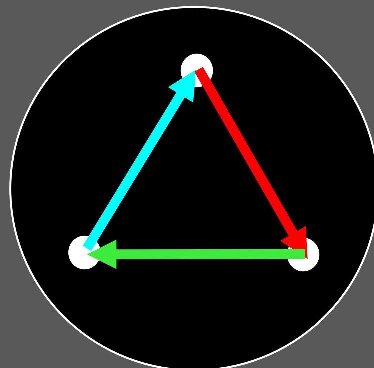
Output (Non-redundant)

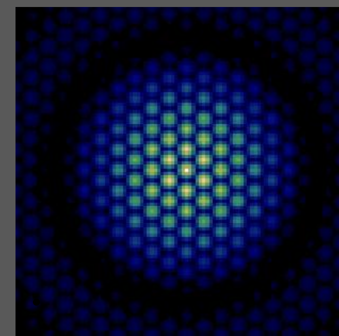
15個の観測可能な量 > 14個の未知数

Post data processingにより、位相差・入射効率の影響を取り除き、完全にフラットな波面を再構築できる！

Non-redundant VS Redundant

Non-redundant
mask





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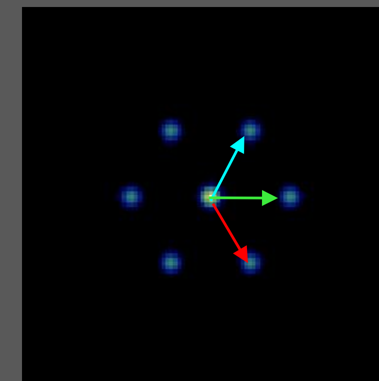
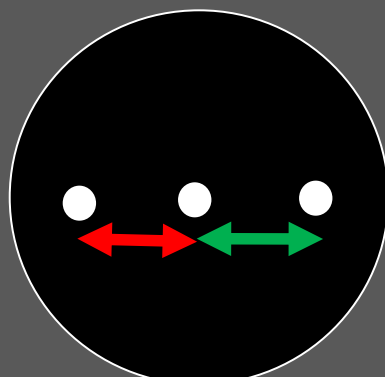
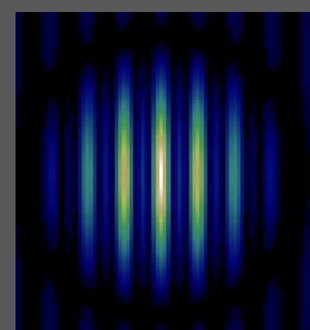


Redundant
mask





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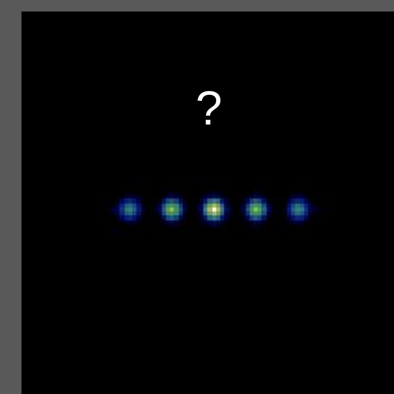

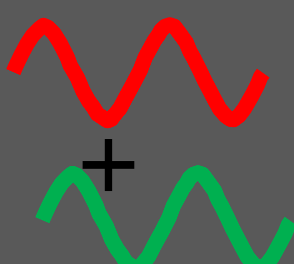

縞の間隔が等しい2つの干渉縞の重なり
位相・振幅は互いに独立に時間変化する

2つの干渉縞を分離できないので、
Visibilityを正確に測定できない

＝低S/N, 低ダイナミックレンジ