# Integrated Optics and Fiber Linked. Arrays

**Future Directions for Interferometry Workshop Tucson, November 14, 2006** 

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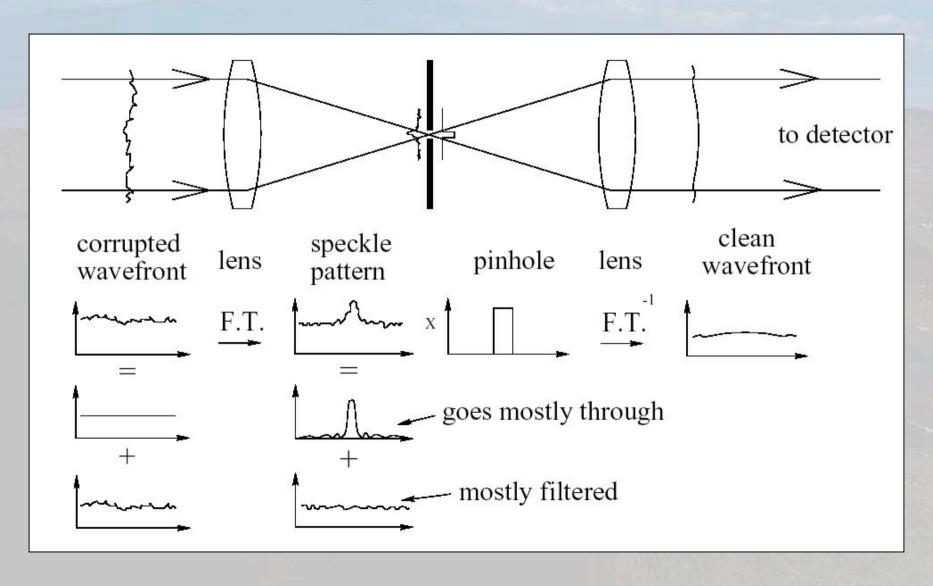
With contributions from J.-P. Berger, L. Labadie, J.D. Monnier

#### Outline

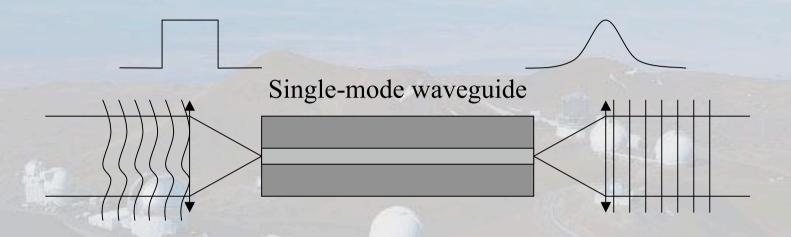
- Spatial filtering
- Field of view
- Beam combination
- Coherent beam transport
- Beam delay
- Fiber linking telescopes



#### Spatial filtering



#### Better way: modal filtering

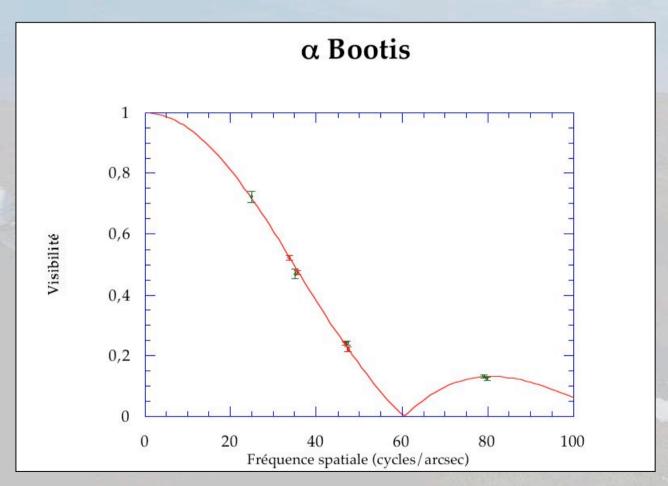


The spatial profile of the exit beam is the profile of the fiber fundamental mode (close to a gaussian).

The phase is flat in the waveguide. The spatial coherence is maximum.

The phase fluctuations of the input beam are traded against intensity fluctuations of the output. But these fluctuations can be measured.

#### Example of result



(Perrin et al. 1998)

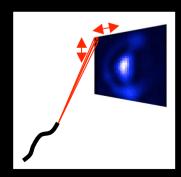


#### On-sky and on-AO source PSFs

#### Alternative:

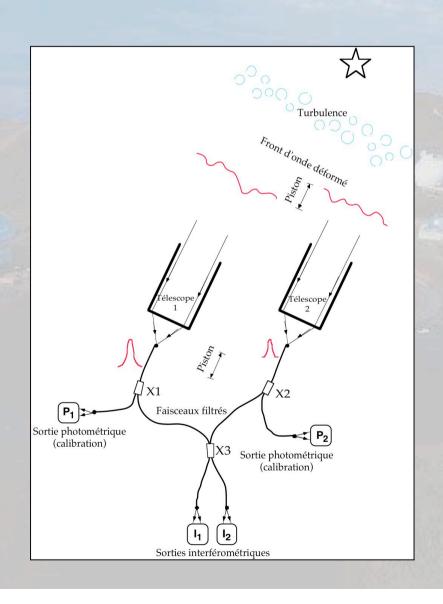
multiple fibers at the focus of the telescopes to carry individual fields

2D-mapping for wide field interferometry





#### Single-mode fiber beam combiner (FLUOR)

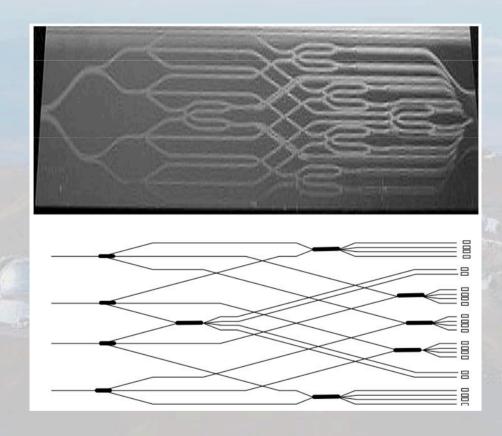


#### Integrated optics beam combiners

- Well known technology
- Telecommunication in NIR
- Application to astronomical interferometry: IONIC with 2 and 3T
- Different technologies:
  - Silica (up to K)
  - Lithium Niobate (for H, K, L)
- Very versatile for beam combiner design



#### 4T Beam Combiner



Example of design (bottom) and prototype (top) of a 4-telescope integrated optics beam combiner (Le Bouquin et al. 2005)

Four  $\lambda/4$  separated samples output (ABCD fringe sampling co-axial beam combiner)

#### 4T Beam Combiners study for VLTI 2<sup>nd</sup> generation

Le Bouquin et al. (2005)

Temporal All In One	Temporal Pair wise	Spatial All In One	Matricial Pair wise
4+4	12 + 0	28 + 4	24 + 0
12 (2pix/fringe)	6	1	1
<b>96</b> ~ 800	<b>72</b> ~ 800	<b>32</b> ~ 170	<b>24</b> 112
Atmospheric Affected sampling rate :  OPD ✓ Inapplicable first order estimator residual effect		Reduced contrast (jitter effect)	
		✓ SNR loss,	
✓ Fringe peak aliasing		✓ Required calibration	
Available, not tested	Operational (IOTA 3T beam combiner)	Better transmission due to less IO functions	2-T coupler to be tested
	All In One  4 + 4  12 (2pix/fringe)  96  ~ 800  Affected sam  ✓ Inapplicable first  ✓ Fringe peak aliasing  Available,	All In One Pair wise  4 + 4 12 + 0 12 (2pix/fringe) 6 72 ~ 800  Affected sampling rate: ✓ Inapplicable first order estimator  ✓ Fringe peak aliasing  Available, Operational	All In One  Pair wise  All In One  4 + 4  12 + 0  28 + 4  12 (2pix/fringe)  6  72  ~800  Affected sampling rate:  ✓ Inapplicable first order estimator  ✓ SNR loss, ✓ Required  Available, not tested  Operational (IOTA 3T beam combiner)  Better transmission due to less IO

#### Integrated optics

- Many functions are possible:
  - Electro-optics phase modulation with Lithium Niobate
  - opd multiplexing
  - metrology...
- Very compact beam combiners
- A single interferometer can have different modes with very specific IO chips for each mode
- According to experts, beam combination is ok up to ~10-12 beams
- Beyond that, fibers+free space optics may be the solution

## Wavelength range for single-mode guided optics spatial filtering and beam combination

Visible to M band: fiber couplers beam combination

Visible to L (M?) band: integrated optics beam combination

Mid-infrared: integrated optics spatial filtering

single-mode fibers

hollow metallic waveguides

Transmissions: guided optics = few dB/cm

fibers few 0.1 dB/km (near-IR) down to few dB/cm

(mid-IR)

# Coherent beam transport' With single-mode fbers

#### Two types of materials

#### Two technologies available:

- silica fibers

 $(0.8 \ \mu\text{m} \le \lambda \le 1.8 \ \mu\text{m})$ 

A=1-2 dB/km

- fluoride glass fibers

 $(1.9 \ \mu \text{m} \le \lambda \le 4 ? \mu \text{m})$ 

A=3 dB/km

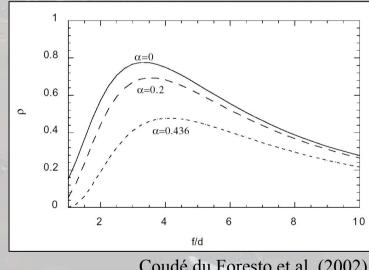
#### Fibers main characteristics:

- small fiber cores

- optimum coupling f-ratios

 $4-6.5 \mu m$ 

~ 3-4



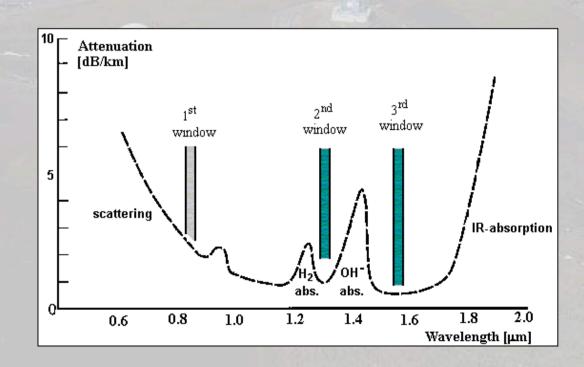
Coudé du Foresto et al. (2002)

*Minimum transmission for 1 km*  $\geq$  50% Therefore potentially as good as 10% with turbulence and a few mirrors To be compared to current interferometers (coherent) transmissions ~ 1%

#### Sources of absorption

- Scattering
- Micro-cracks, inhomogeneities
- Bends
- Material transmission

Silica fibers ->



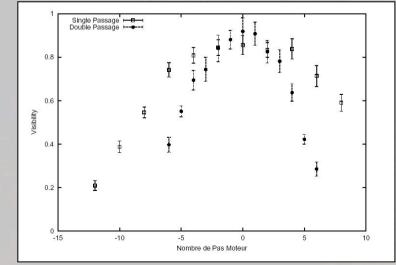
#### Polarization issues and solutions

#### Silica fibers are naturally birefringent:

- force extra birefrigence (asymmetric structure) to isolate polarisation axes
- -> polarization maintaining fibers
- polarizations need to be separated (or synchronized but difficult in practice)

#### Fluoride glass fibers:

- very small birefringence (beat length measured to be larger than 1 km)
- force to get PM fibers
- or rotate polarizations by twisting fibers to optimize fringe contrast:

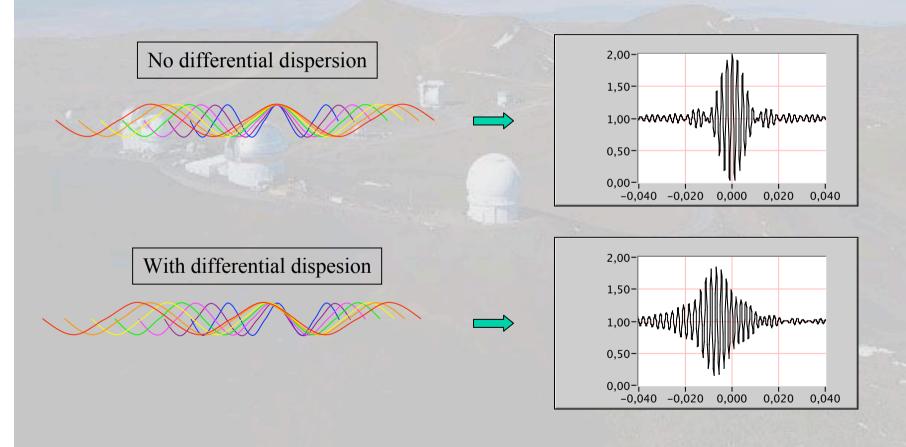


Result with fiber twister ->

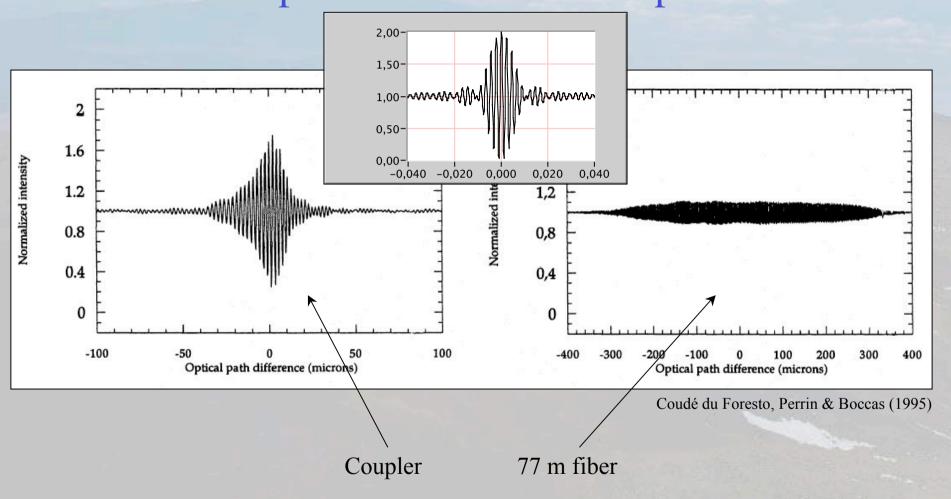


#### Differential chromatic dispersion

The zero optical path difference is wavelength dependent:  $\delta(\lambda) = n_1(\lambda)L_1 - n_2(\lambda)L_2$ 

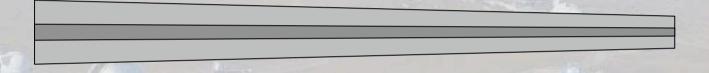


#### Examples of differential dispersion



#### Practical dispersion issues

- Differential dispersion should be 0 with identical fibers and equalized lengths
- In practice, fibers are not homogeneous
  - Conical shape



Sausage shape

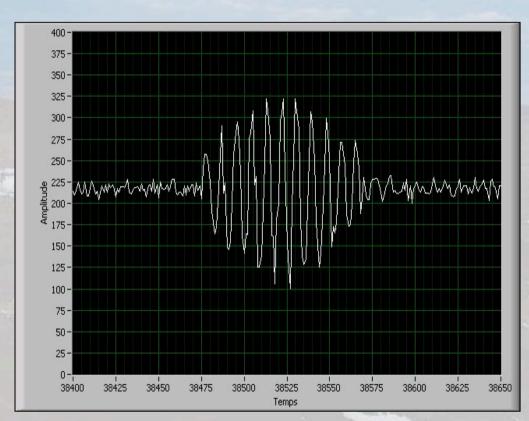


• Dispersion can be balanced by matching pairs of fiber sections (losses at connections)

#### Example: 'OHANA fibers



2x300 m K band fiber cables with 6 sections (0.1 dB loss per connection)



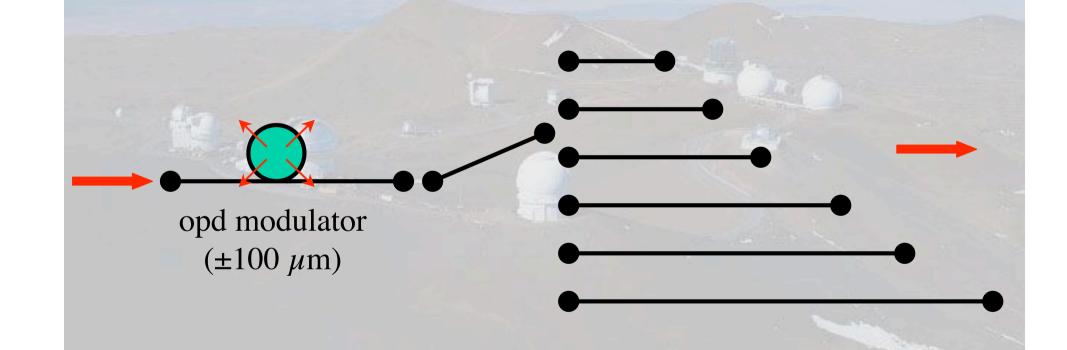
- S. Vergnole, et, al., 2005, Optics Communications, 251, 115 (J band fibers)
- T. Kotani, et al., 2005, Applied Optics (K band fibers)

#### Conclusion on fibers for beam transport

- Differential dispersion is not really an issue but requires fiber sections to be matched
- Demonstrated over 600 m
- Wavelength coverage:
  - $-0.8 \mu m$  up to 2.4  $\mu m$  (L band may be possible over long distances)
  - Need for 1 fiber per band with classical fibers
  - Potentially 1 fiber for a wide wavelength range with Photonic Cristal Fibers
- Transmissions of 'OHANA links (300 m): 90% for J&H, 50% for K
- Dispersion-Transmission -> kilometric with a limit to 10 km arrays can be contemplated
- Polarization issues can be handled: polarization maintaining fibers or fibers with negligible birefringence.

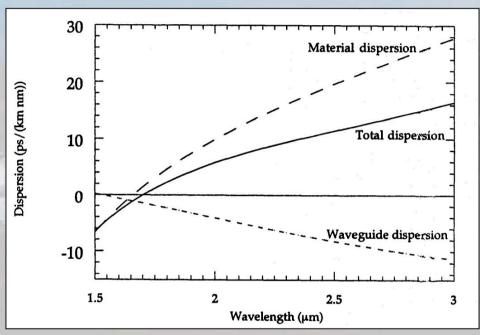
# Intrinsic dispersion and beam delay

# Simple fibered delay line concept if intrinsic dipersion nulled



#### Sources of intrinsic dispersion

#### Fluoride glass fiber



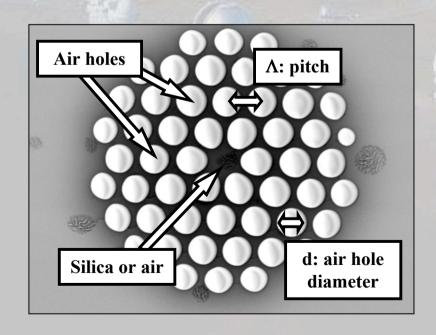
Coudé du Foresto, Perrin, Boccas (1995)

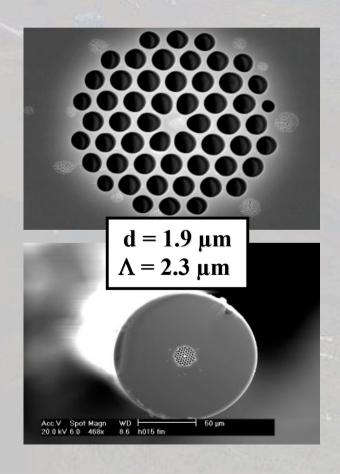
- Intrinsic dispersion could be nulled in this case
- Requires to adjust fiber parameters to a few nanometers during fiber pull
- Simply not possible in practice with current technology

# (Hollow) Photonic Cristal Fibers Hope?

#### Characteristics

Special optical fibre made with only pure silica First PCF in 1996 by Knight et al.

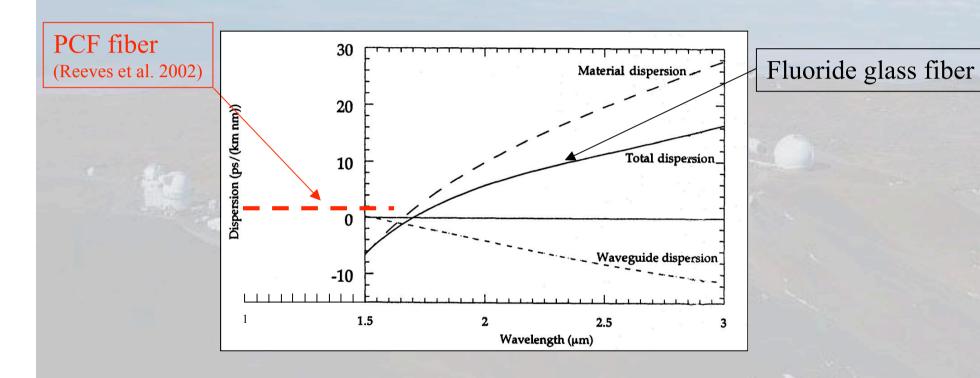




#### Why are (H)PCF fibers potentially interesting?

- In theory monomode on wide ranges of wavelengths: cut-off wavelength = wavelength!
- Large number of degrees of freedom to adjust dispersion
- Holes filled with air, low dispersive medium
- However:
  - Severe constraints on guide structure accuracy
  - Low dispersive fibers turn out to be single-mode over narrow wavelength ranges
  - Low dispersion achieved so far but not really zero
- But, this is clearly to be investigated

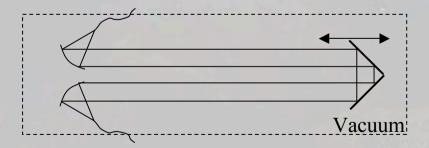
### Level of intrinsic dispersion achieved so far in a wide band (1 to 1.6 $\mu$ m)



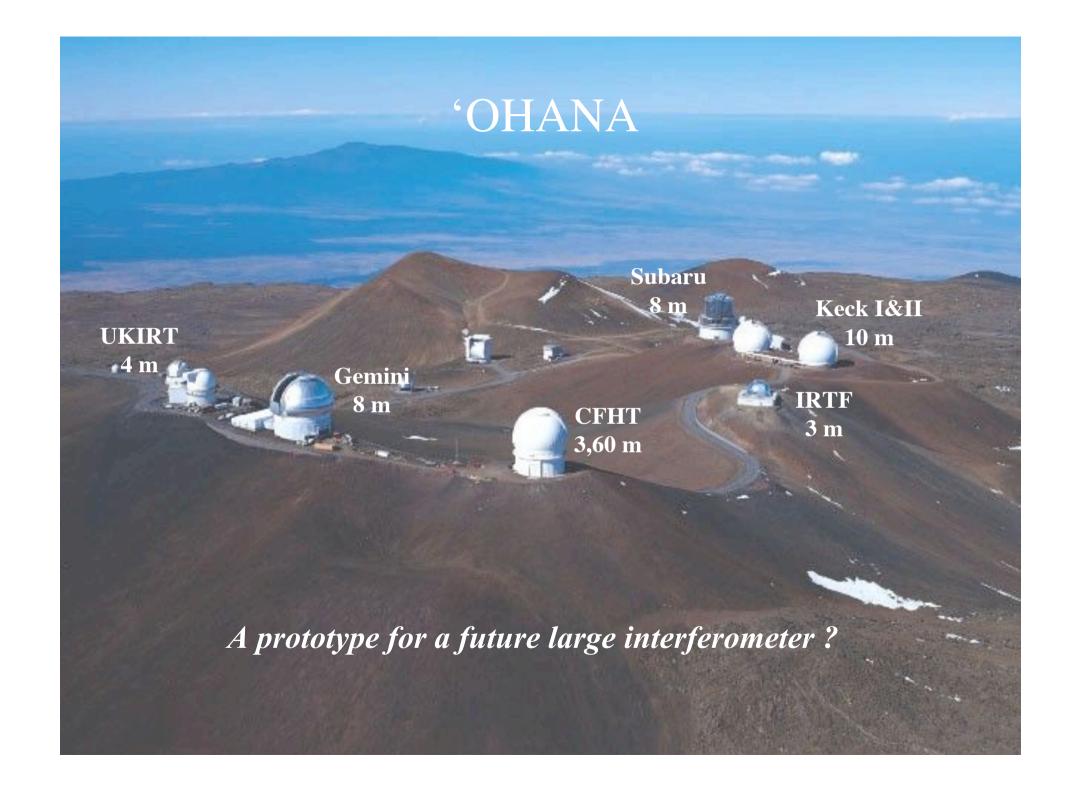
- Gain of a factor of 10
- Factors of 10<sup>4</sup> to 10<sup>5</sup> are required

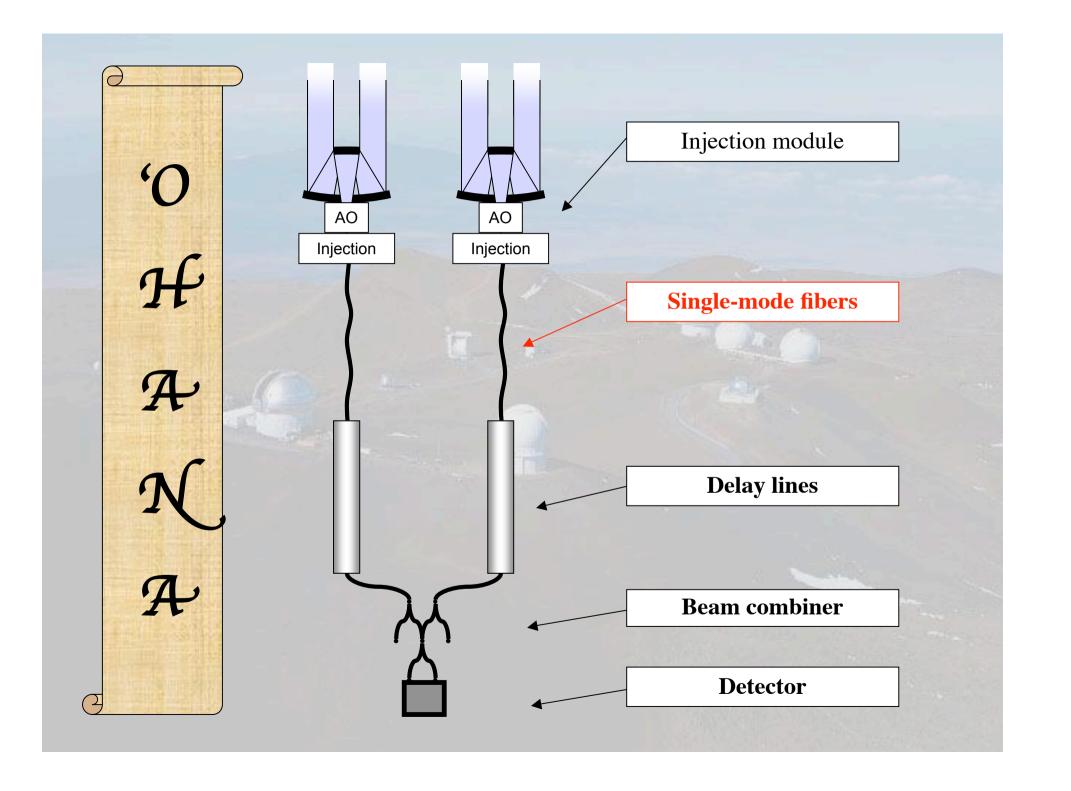
### Is the dispersion issue a killer for fiber-linked arrays?

- Fibers could be used to transport light to an evacuated long delay line
- Beam at fiber output are very close to a gaussian beam: very favorable for beam propagation, transmission can be made close to 100%
- Delay line system could be made very simple (4 reflections) with an actively pointing carriage

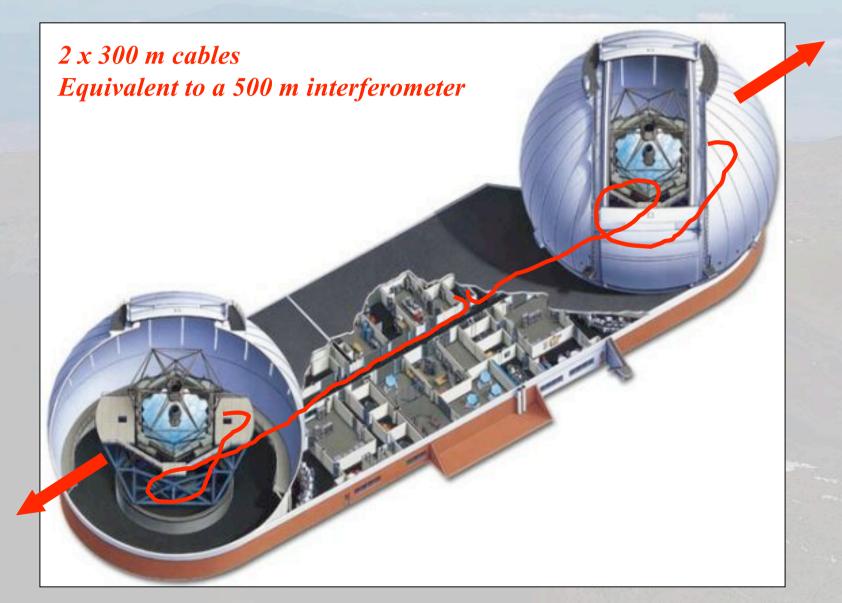


# Fiber linking telescopes/arrays



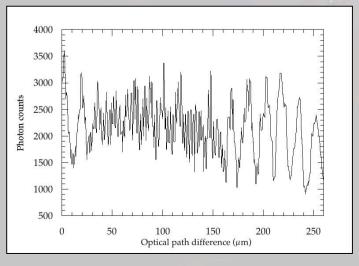


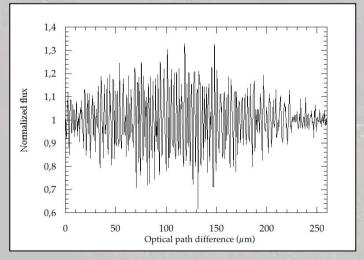
#### Tests with Keck I - Keck II

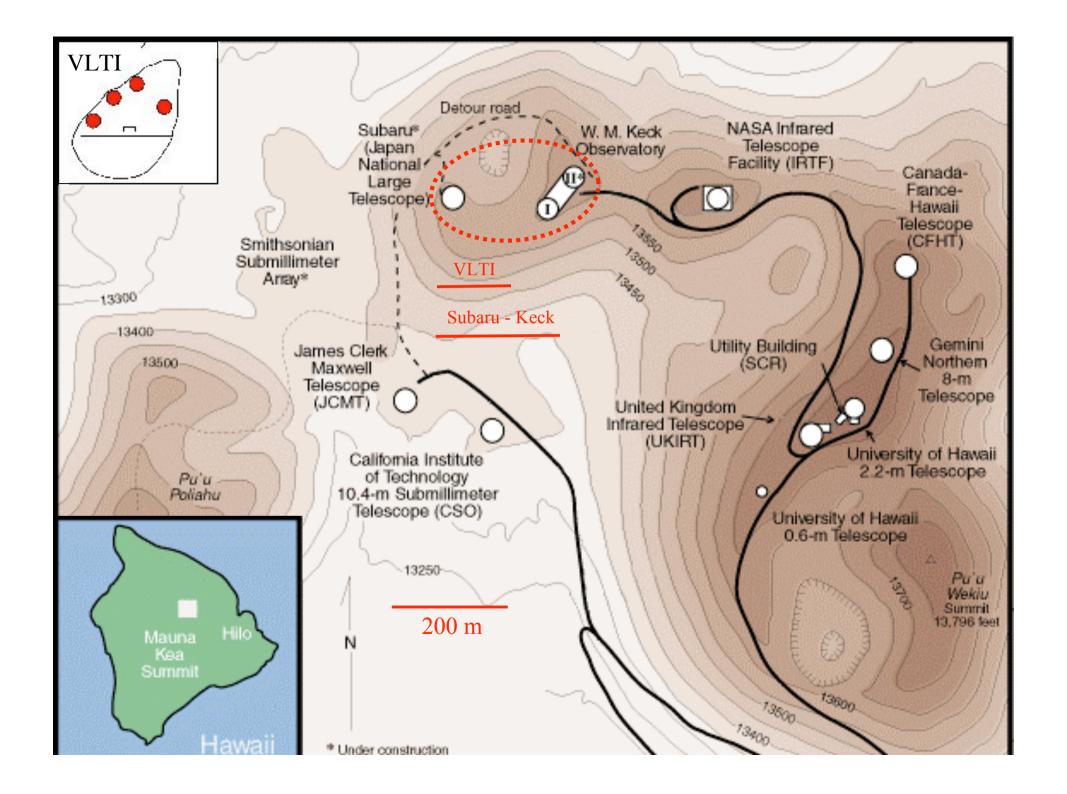


#### First fringes on 107 Herculis (June 2005)

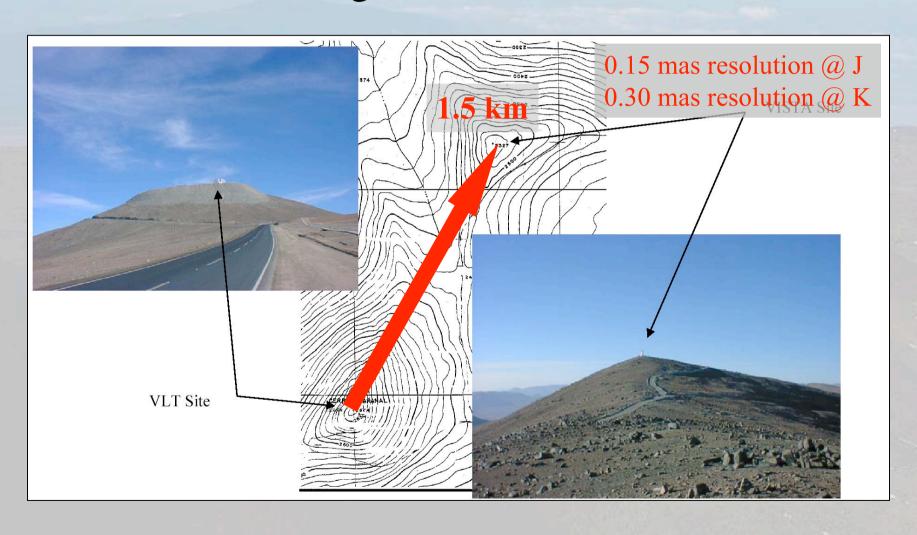






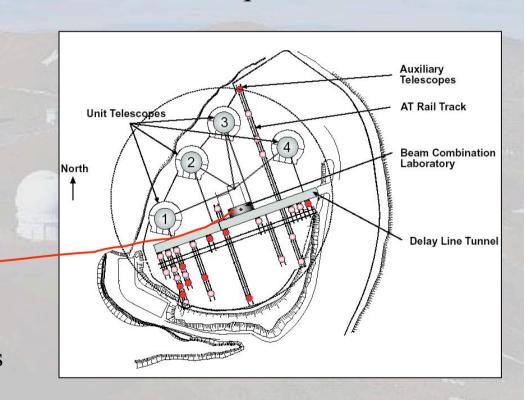


#### Linking VLTI and VISTA



# Alternative/complementary proposal by T. Henning

Put another AT outside the current VLT perimeter





Few hundred meters