

**A comparison between possible  
post-VLT/VLTI instruments  
at horizon 2020**

**High-Angular-Resolution Prospective  
working group,  
Luc Arnold  
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## **HAR Prospective working group:**

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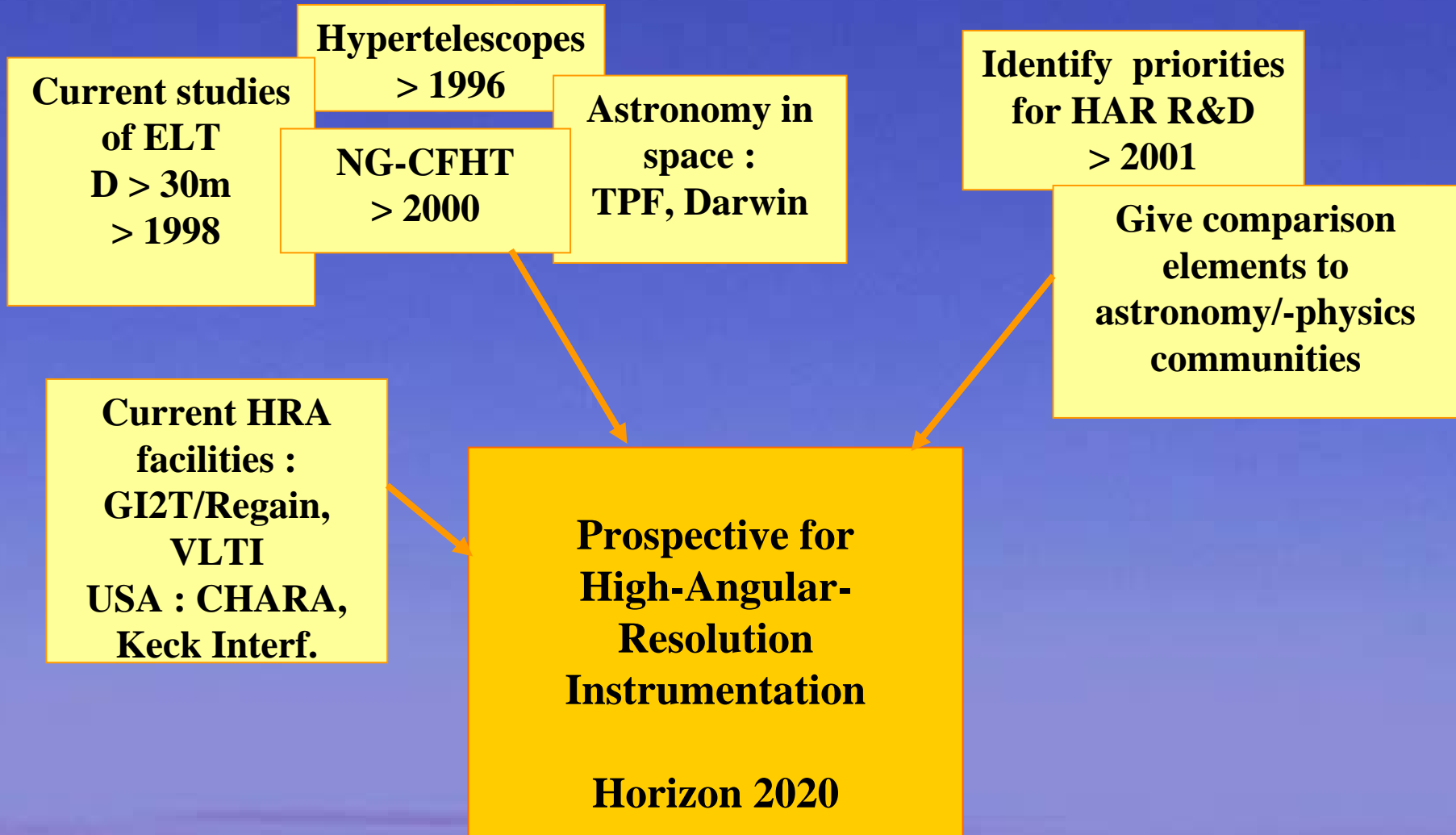
Rousset G., ONERA

Perrin G, Obs. Meudon

Ferrari M., LAM

Malbet F., LAOG





**Science**

**Astro**

**Instrumentation**

**NG-CFHT OWL  
FAST Carlina  
TPF Darwin  
OVLAAHT OHANA  
NG-VLTI network**

**Projects and studies  
survey**

**3 concepts :**

- **Single Pupil (ELT)**
- **Direct Imaging Interf. (HT)**
- **Indirect Imaging Interf. (AS)**

**Table 1 :  
Performances  
simulation**

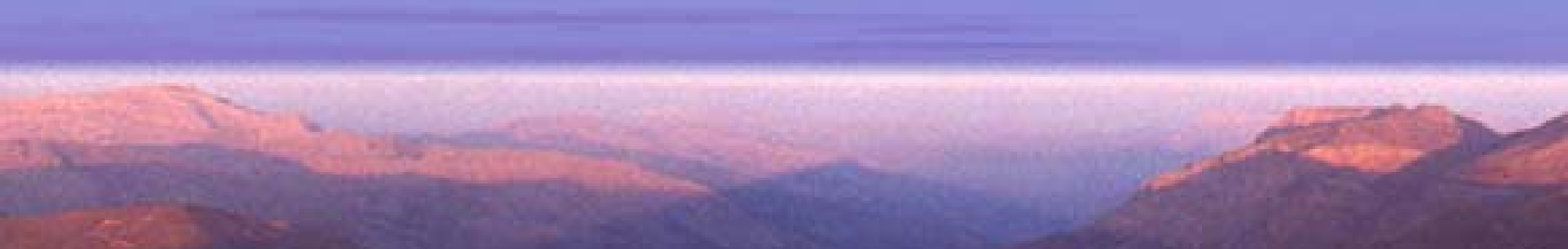
**Table 2 :  
Comparative  
system  
analysis**

**R&D  
priorities**

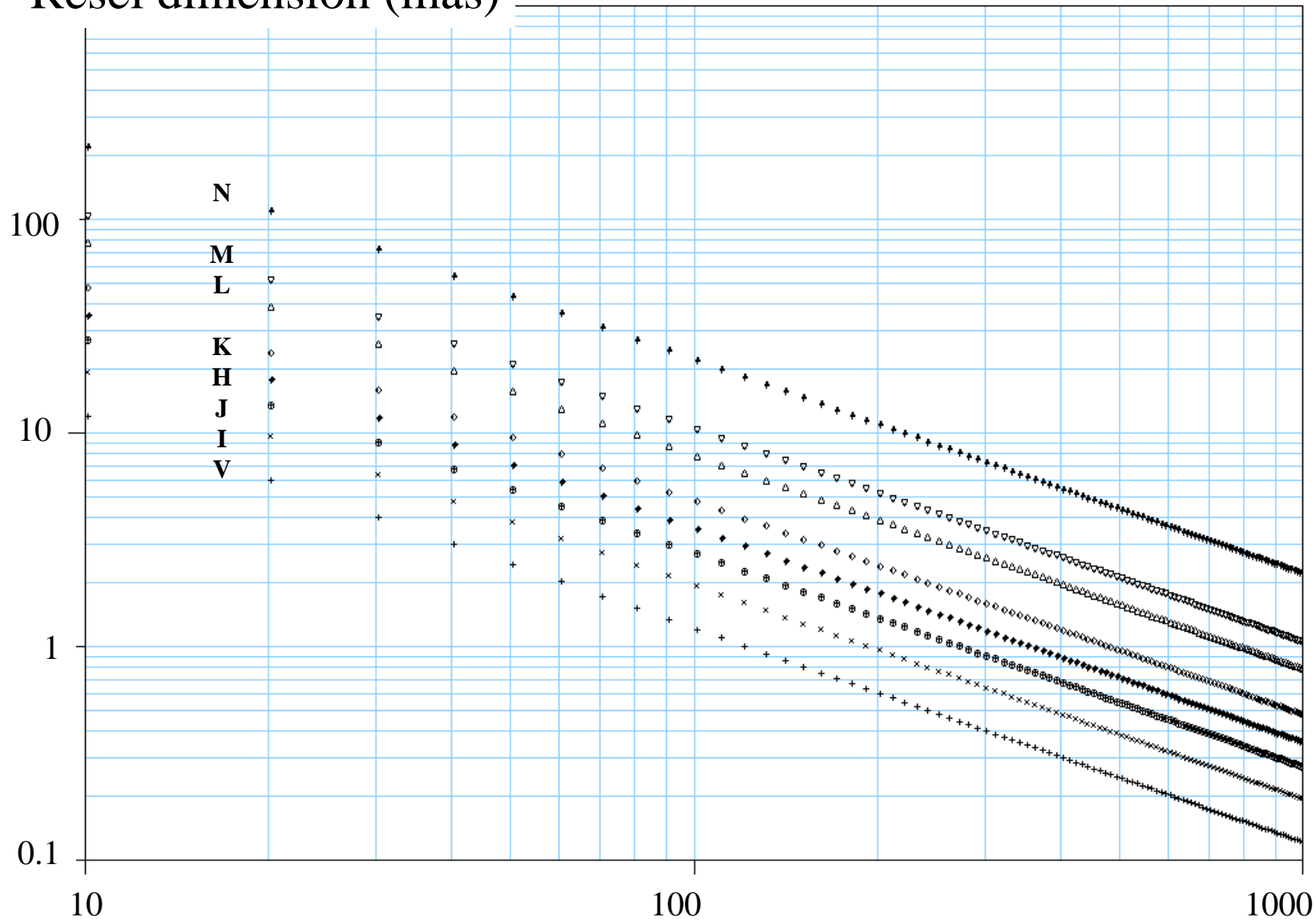
**Instrument  
/science**

## Scientific performance criteria (1/3)

- Spatial resolution  $\lambda/B$



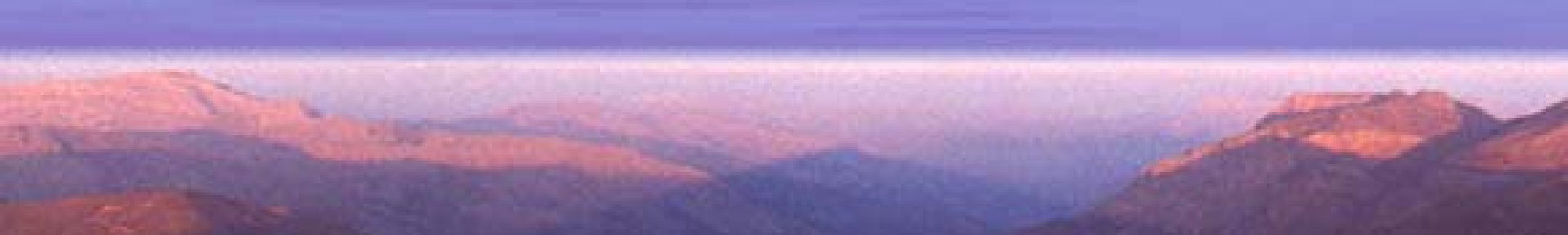
Resel dimension (mas)



Diameter or base length (m)

## Scientific performance criteria (2/3)

- Spatial resolution  $\lambda/B$
- Imaging capabilities
  - Direct imaging (snapshot)
  - Indirect imaging (aperture synthesis)
  - Number of resels in the final image
  - PSF profil
- **Field:** direct field, reconstructed field



## Scientific performance criteria (3/3)

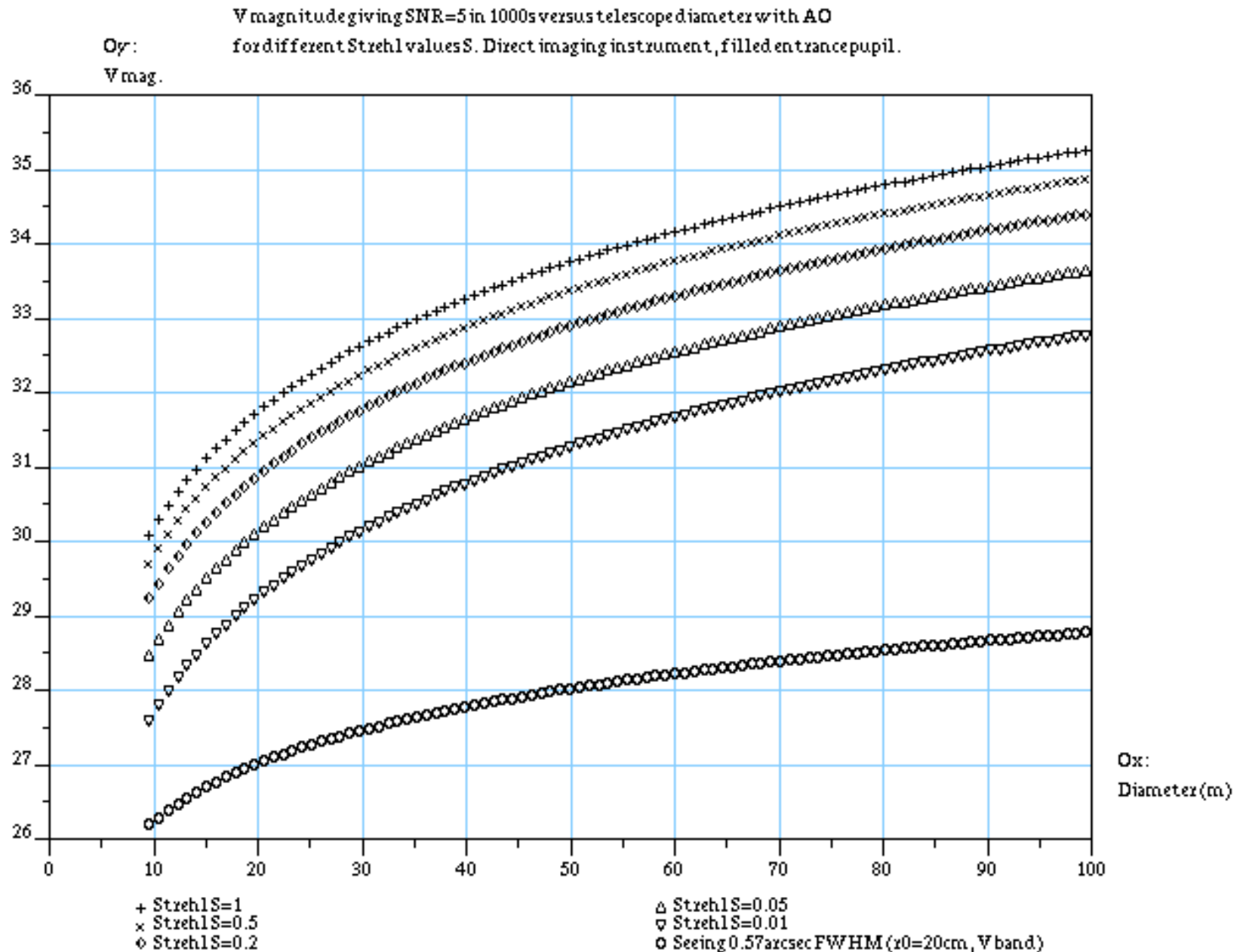
- **Sensitivity:** versus Strehl ratio,  $\Delta\lambda$ , etc
- **Photometric range:** High-dynamic imaging (PSF profil)
- **Spectral range:** V to N ( 0.5 to 10 microns), + UV+ IR in space
- **Focal instrumentation:**
  - Spectral and spatial resolution
  - Sensitivity
- **Instrument life:**
  - Pupil, base, collecting array *evolution or upgrade...*
  - Focal instrumentation upgrade
- **Instrument versatility:**
  - Different/multiple scientific programs must be satisfied

# Concept #1: Single pupil instruments (1/6)

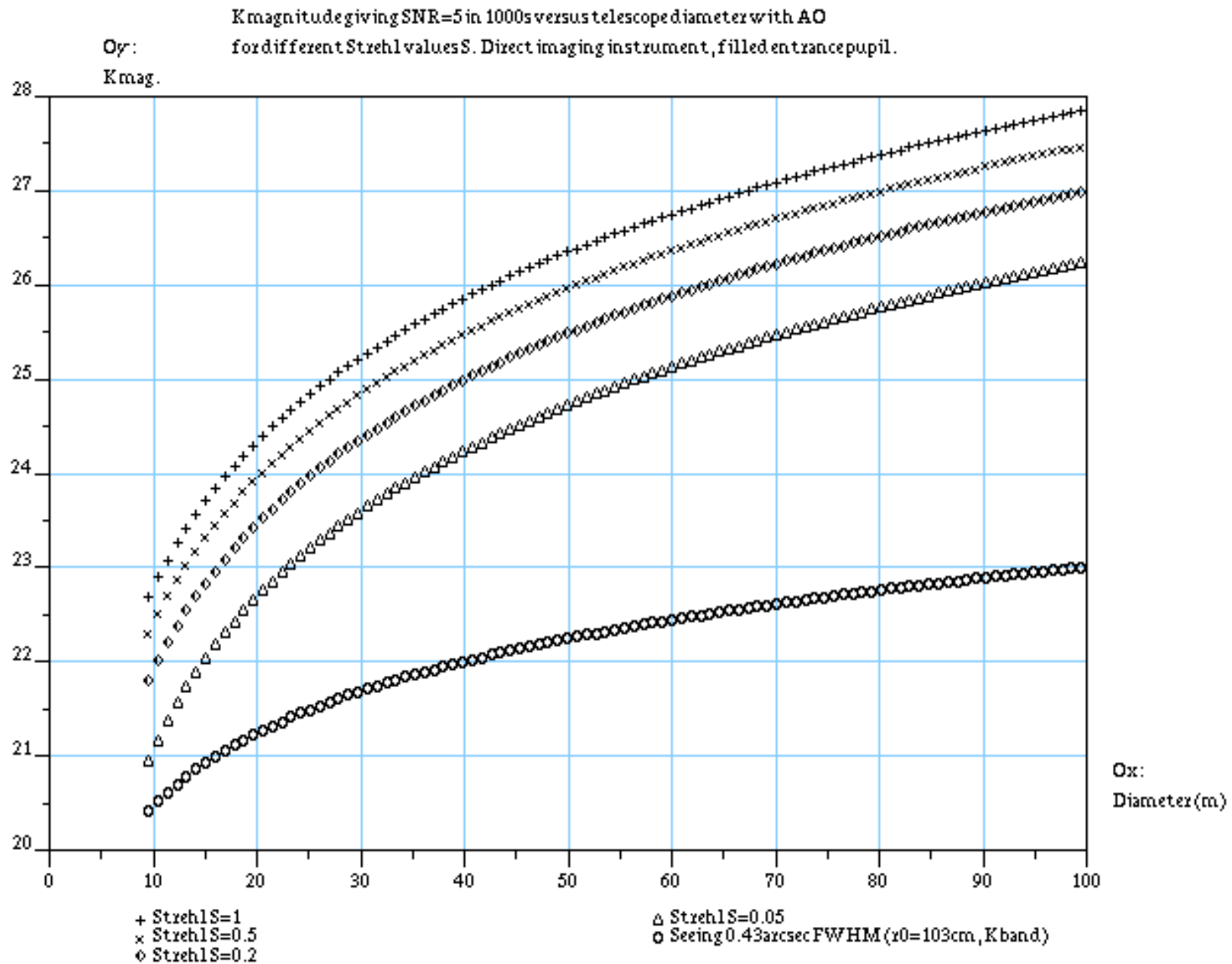
- Filled or quasi-filled entrance pupil (pupil filling factor  $c=0.5$  to 1)
- Diameter: 30 to 100m
- Segmented primary: segment size 1 to 8m
- Case of a quasi-filled pupil:
  - Fizeau design: homothetic transport of the pupil (entrance pupil pattern = exit pupil pattern)
  - Field of view: limited by aberrations or vignetting, typically 1 arc-minute
  - Snapshot imaging
  - PSF: ~close to PSF given by a filled aperture
- Good for coronagraphy, i.e. high-dynamic imaging
- Large collecting array, high sensitivity:  $D=100\text{m}$ ,  $V=35$ , 1000s,  $S/N=5$



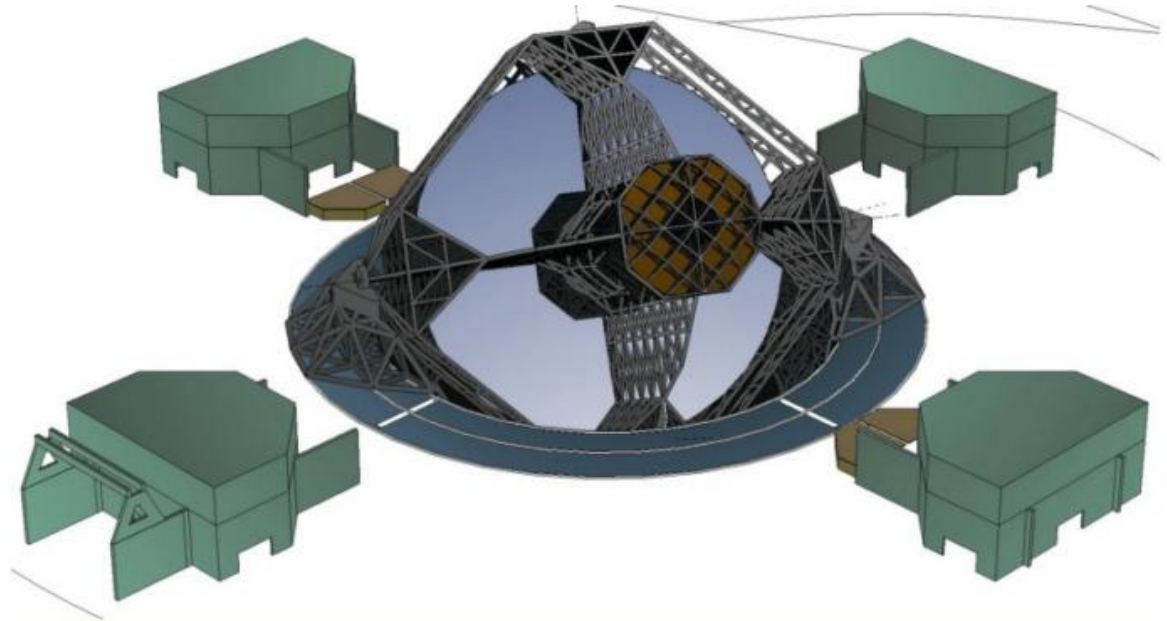
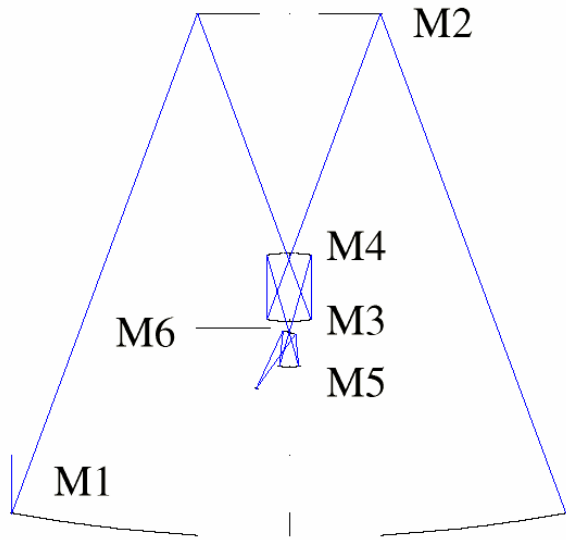
# Concept #1: Single pupil instruments (2/6)



# Concept #1: Single pupil instruments (3/6)

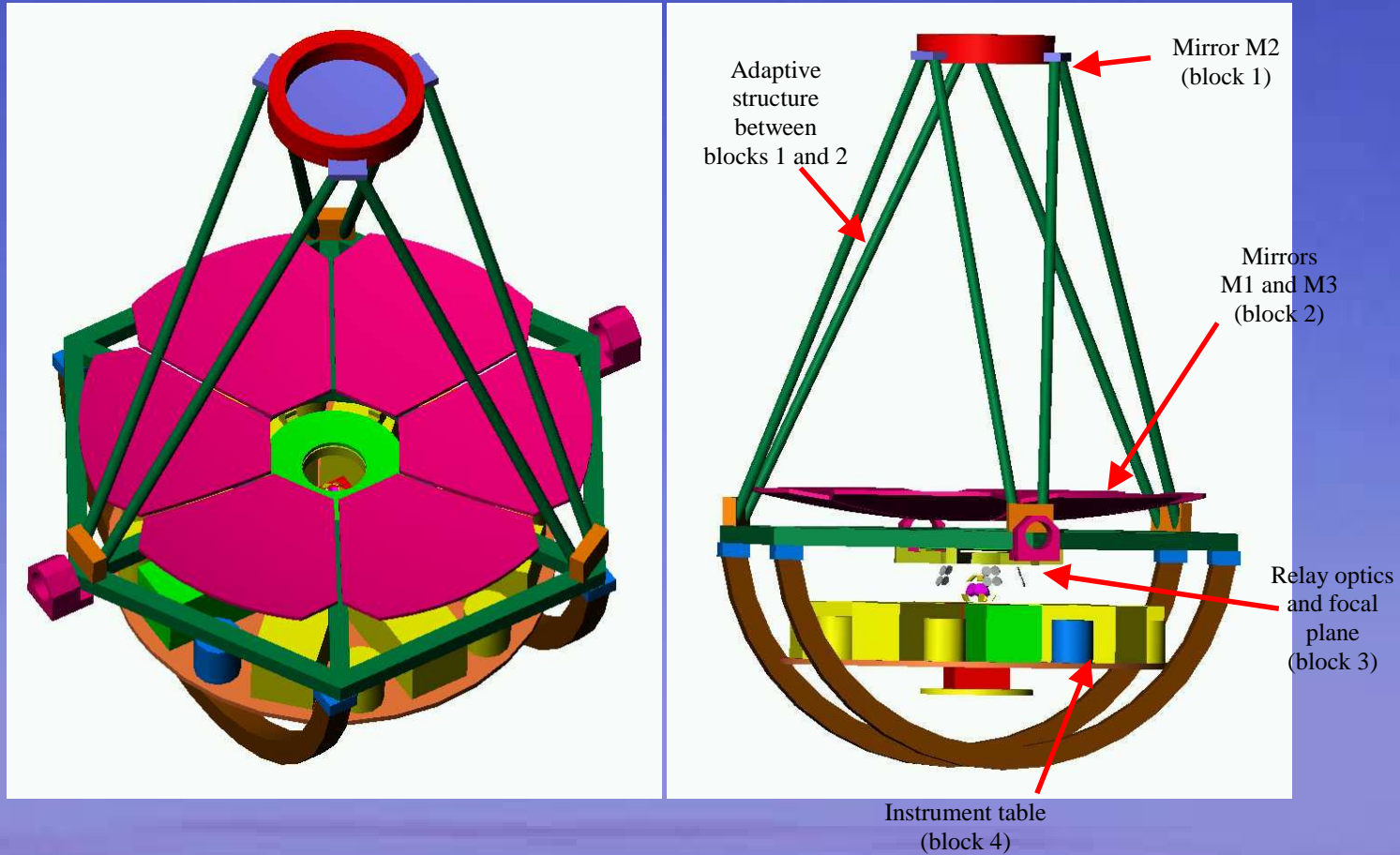


# Concept #1: Single pupil instruments (4/6) Examples



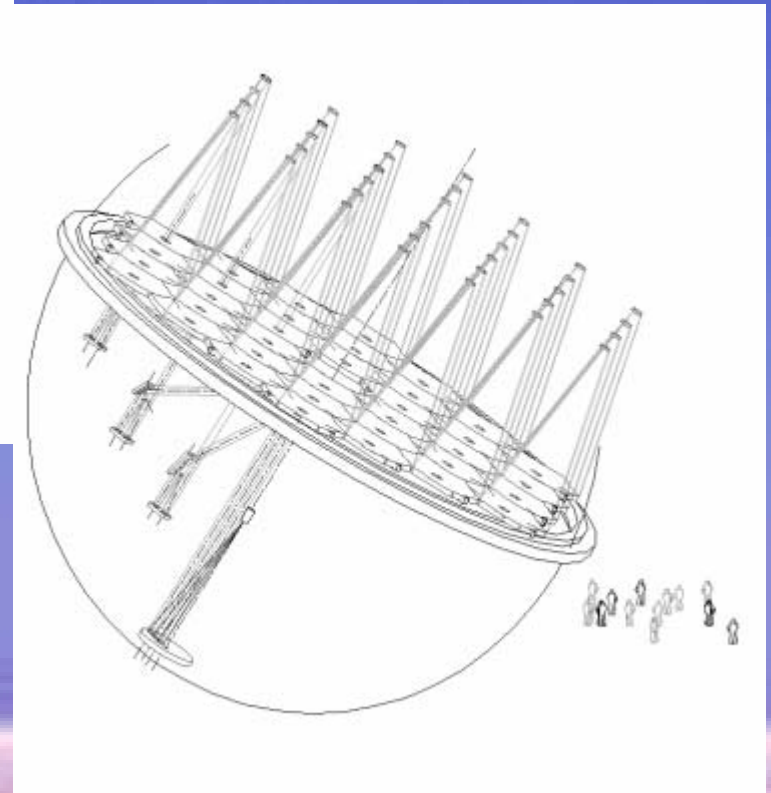
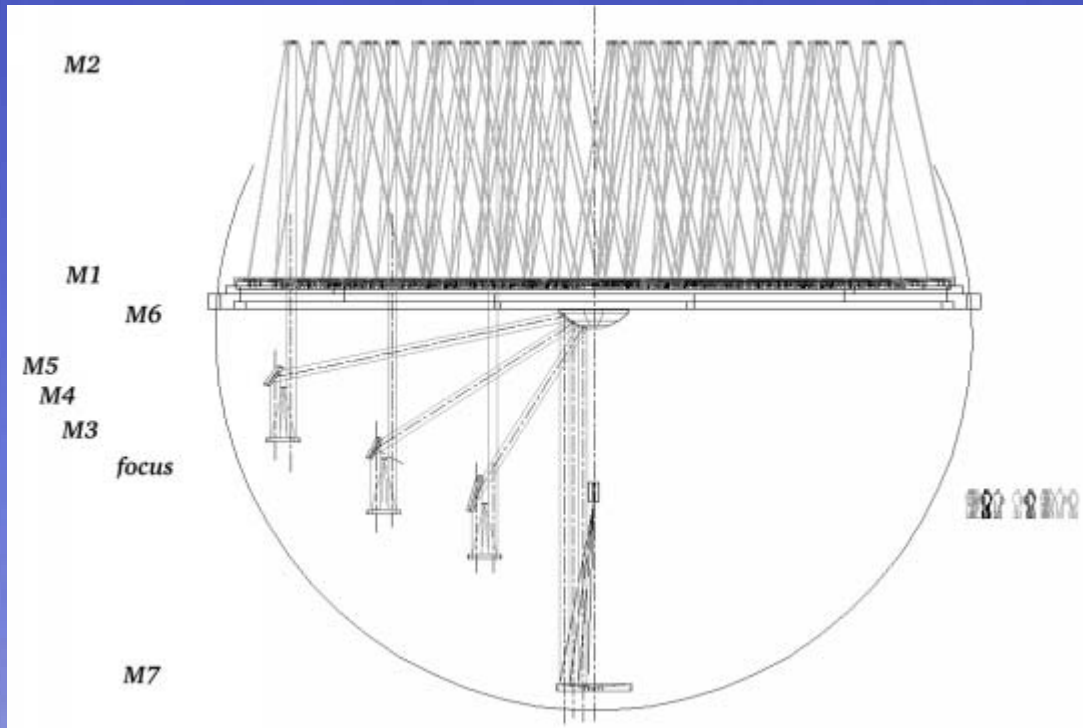
OWL  
(Gilmozzi et al. 2000)

# Concept #1: Single pupil instruments (5/6)



NG-CFHT: Burgarella et al. 2000

# Concept #1: Single pupil instruments (6/6)



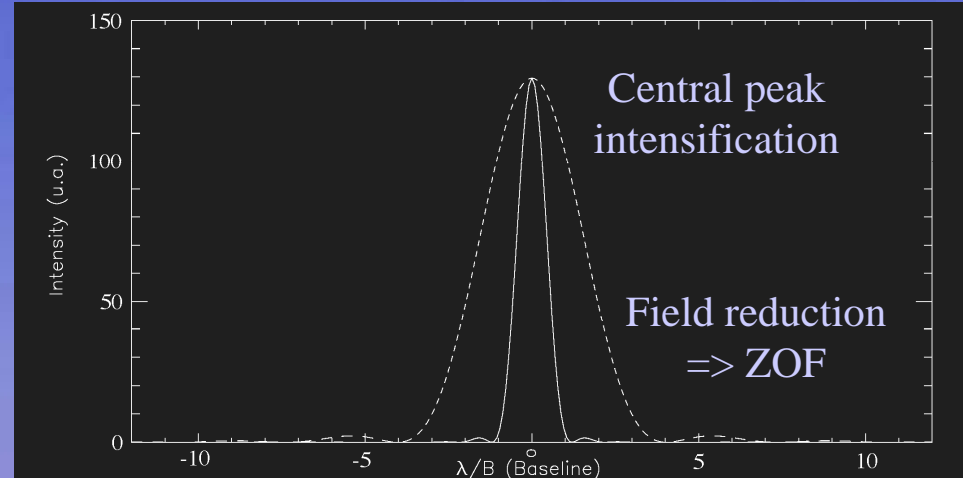
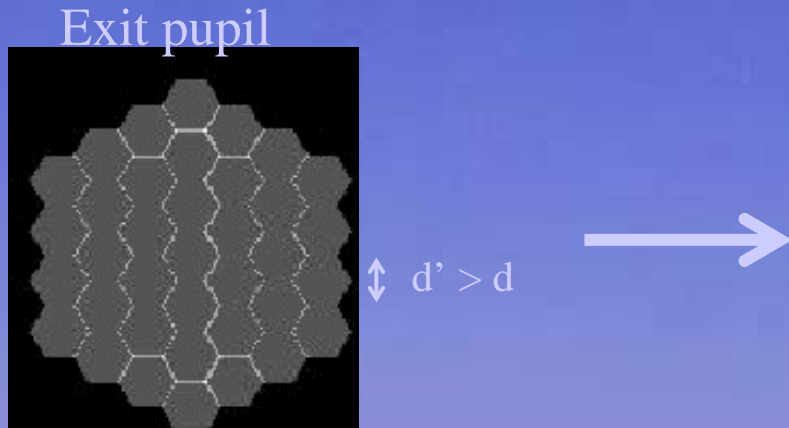
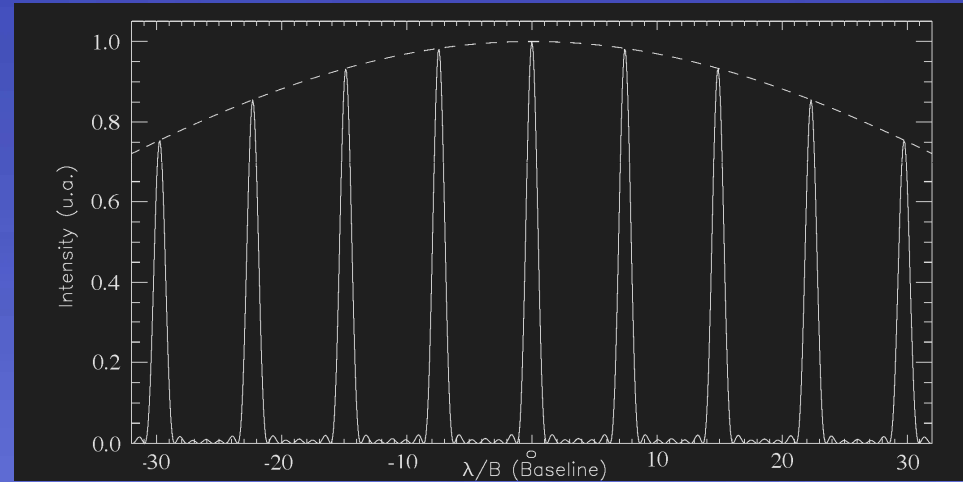
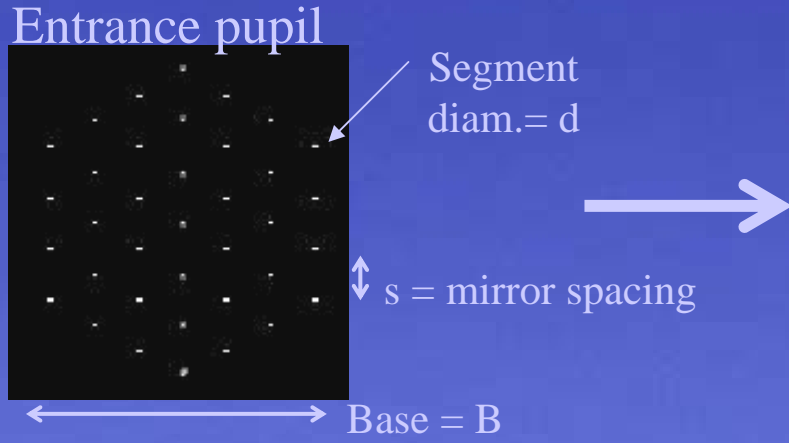
FAST: Arnold 1999  
( see also Beckers 1999)

## Concept #2: Direct imaging interferometers

- Diluted entrance pupil:
  - Pupil filling factor  $c = N * d^2 / B^2$
  - $c = 10^{-1}$  to  $10^{-4}$
  - Baseline  $B = 100$  to  $1000\text{m}$  ( $>1000\text{m}$  in space)  $\Rightarrow \lambda/B > 0.1$  mas in  $V$
- Direct imaging:  $\Rightarrow$  new kind of Michelson interferometry
  - These instruments are called *densified pupil* instruments or *hypertelescopes* (Labeyrie 1996)
  - Pupils transport: 2 different homotheties to *densify the pupil*
- What means *pupil densification* ? *why* ? And *how* ?

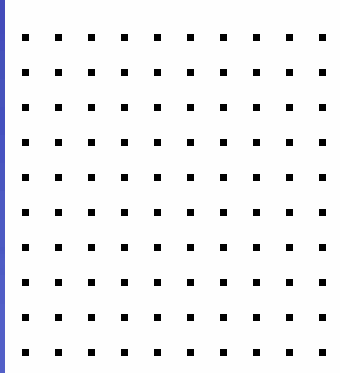


# Monochromatic PSF

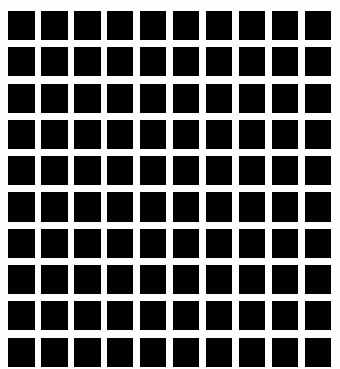
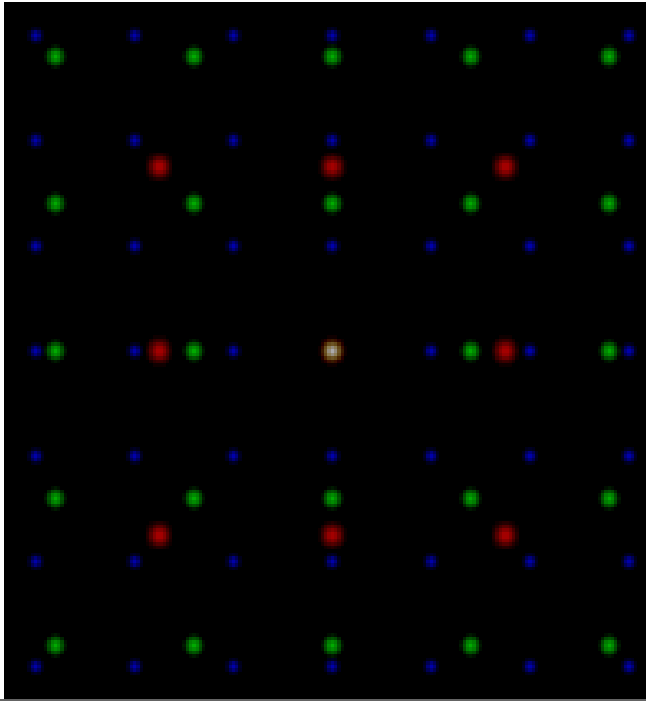


Why should we densify ?

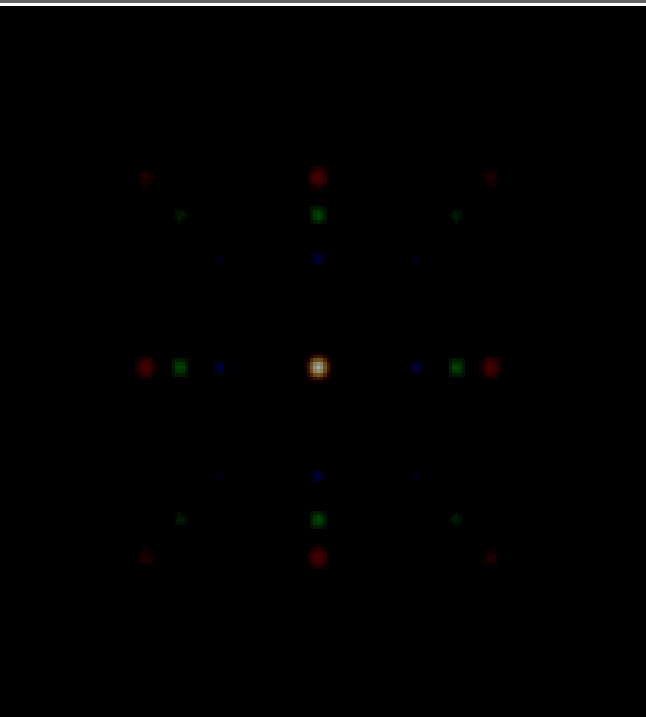
- Because image is intensified with respect to Fizeau array by a factor  $(s/d)^2$
- Because direct imaging becomes possible



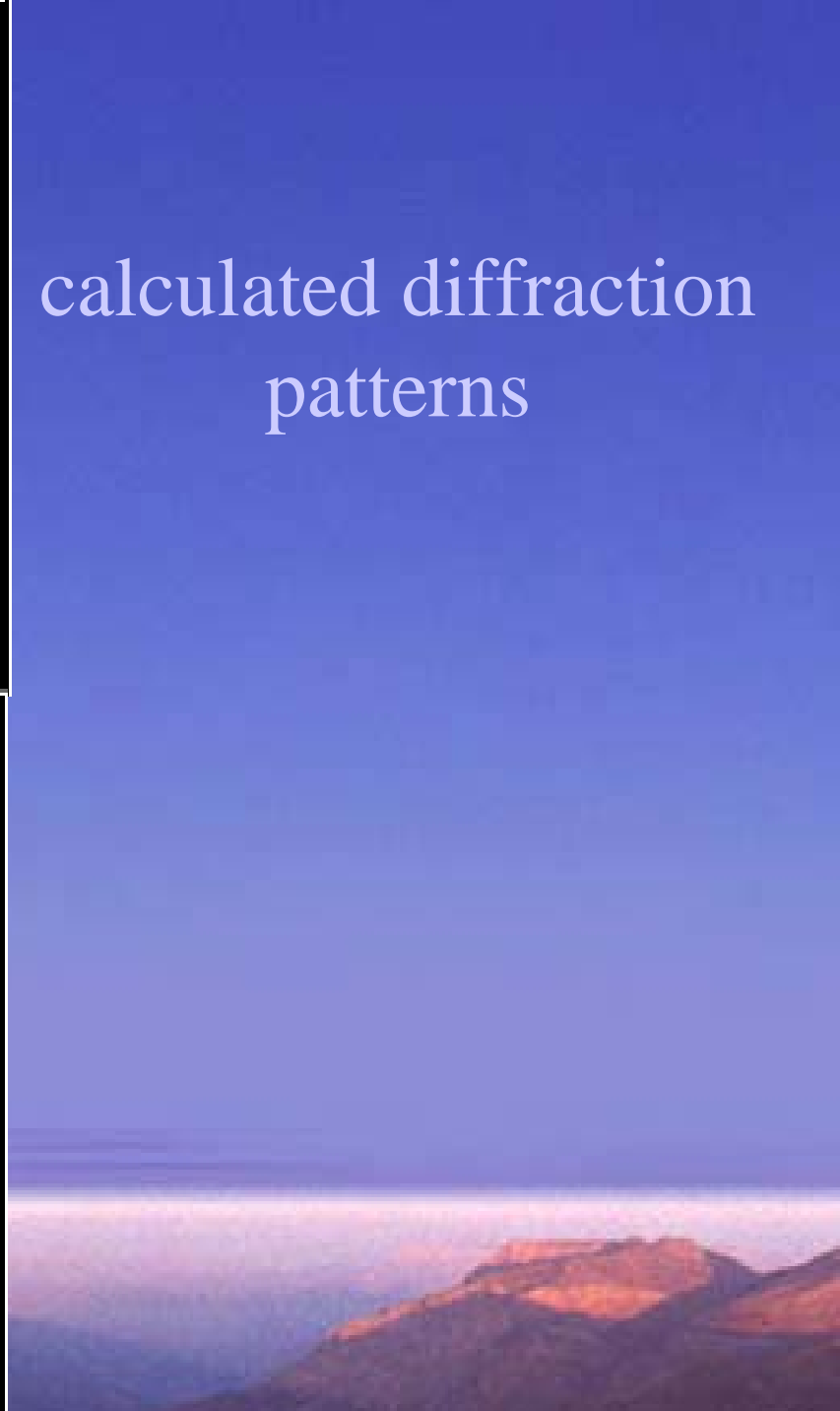
10x10  
diluted



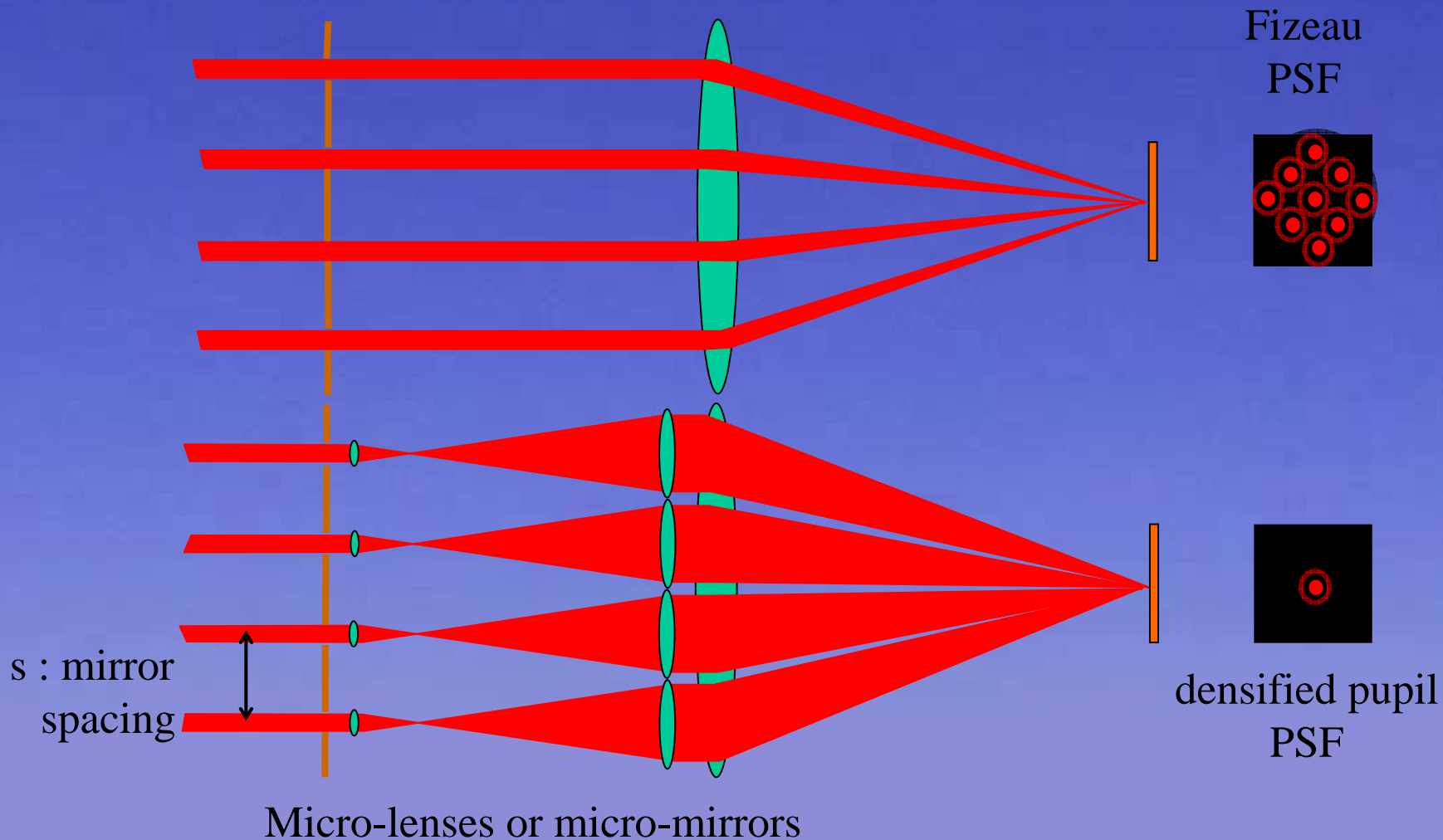
10x10  
dense



calculated diffraction  
patterns

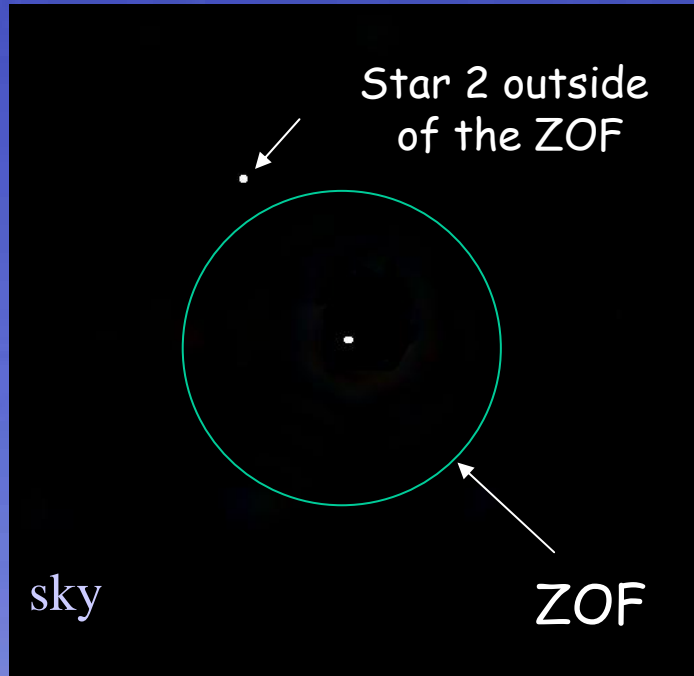


# How is obtained the densification?



(From Labeyrie 2000)

# Field of view: Imaging beyond the Zero-Order Field



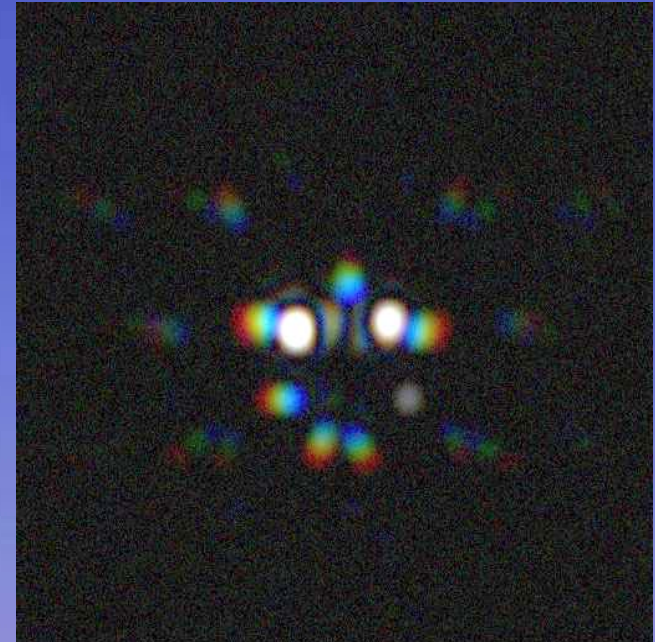
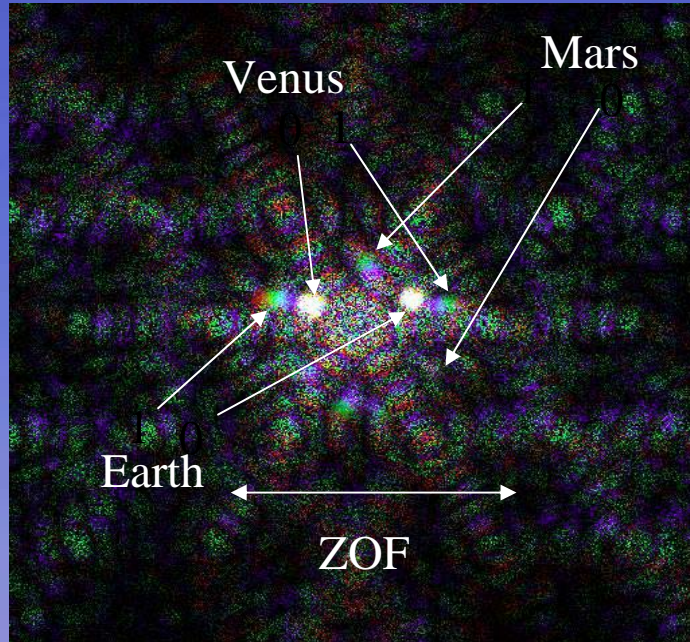
(From Labeyrie 2000)

- Objects in the ZOF window =  $\lambda / s = \lambda/d'$ , give a white image
- Objects outside ZOF (Star#2) have a dispersed image in the ZOF (high order image from the grating function)
- Extended image can be reconstructed if :
  - fewer than  $\pi N$  to  $N^2$  active pixels in object (OK for exo-planets)
  - multi- $\lambda$  camera (ex : STJ,... Courtès optics)

# Hypertelescope image simulation

Earth, Venus, Mars image simulation (Sun nulled), as viewed at 20 pc by a 100m base TPF with 36 0.6m sub-apertures.

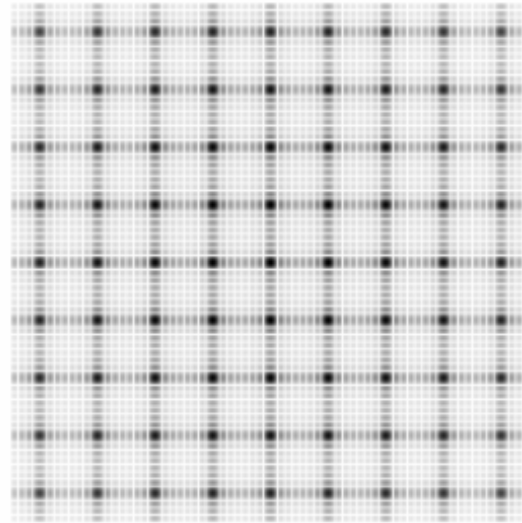
(Boccaletti et al, 2000)



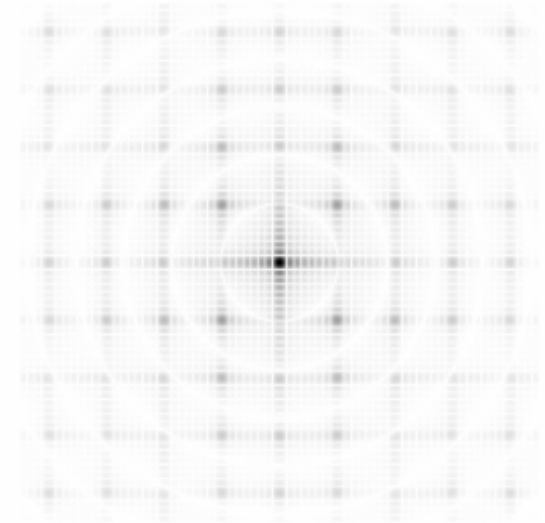
Theoretical **contrast advantage of hypertelescopes** with respect to beam-splitter nulling interf.: **large sensitivity gain** (up to 100x) (Labeyrie 2001, Roddier & Guyon 2000)

# First hypertelescope image *on the sky*

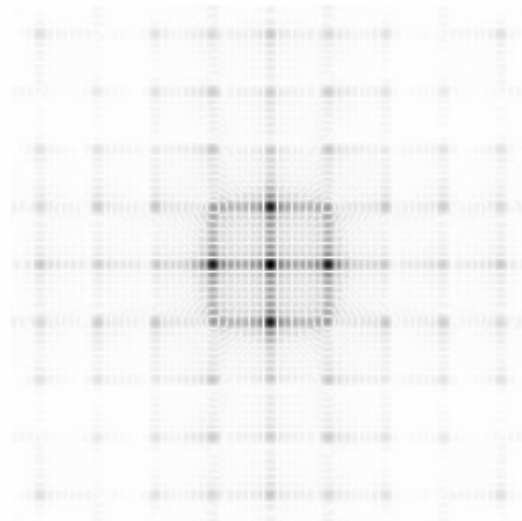
Pedretti et al, 2001



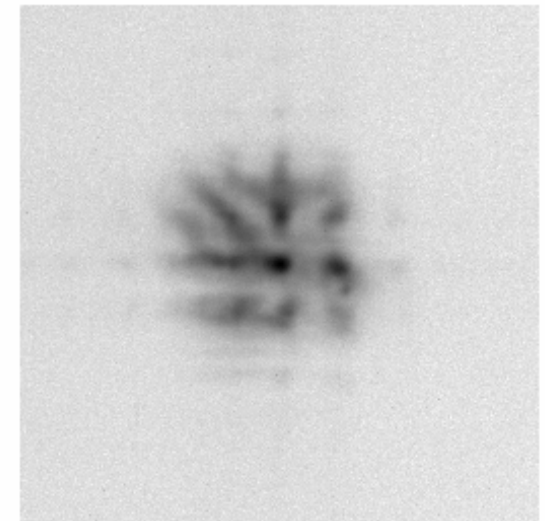
$l_{\max}=1$



$l_{\max}=68$



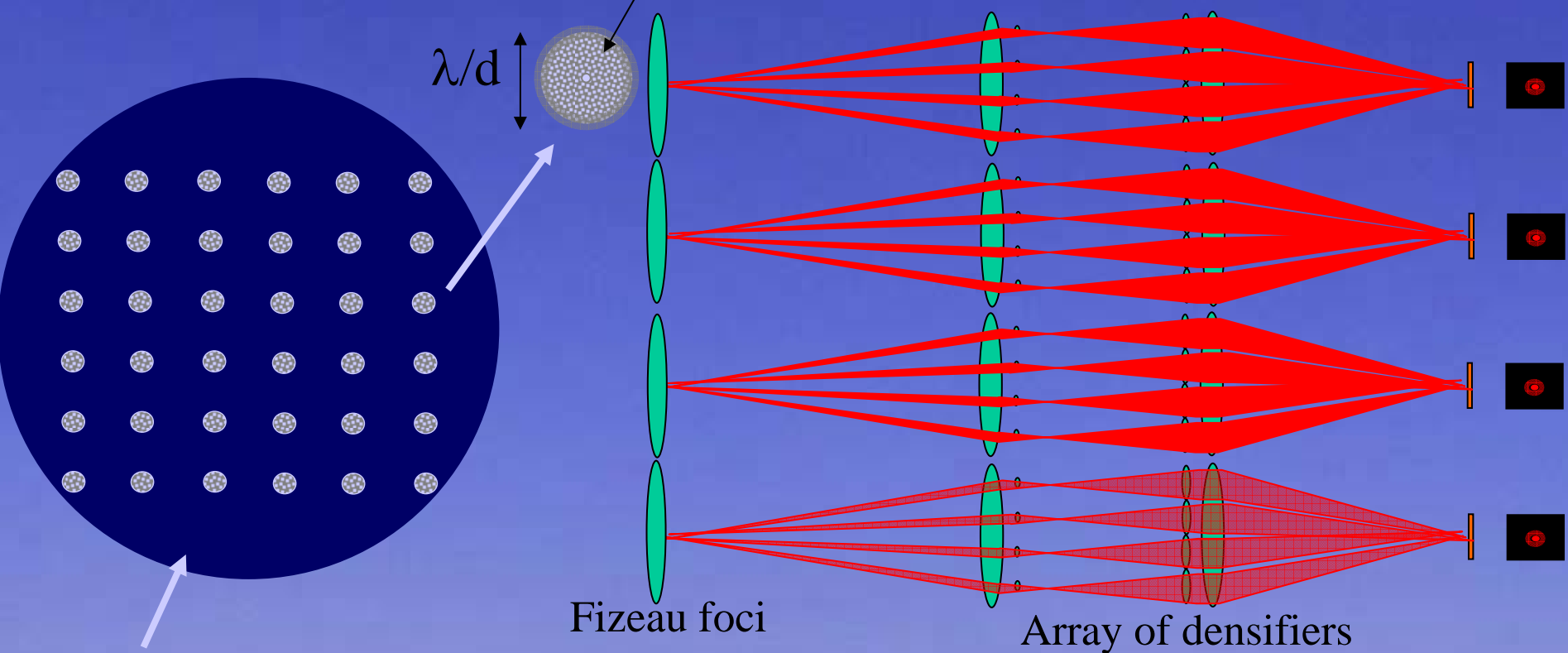
$l_{\max}=20$



$l_{\max}=15 \pm 5$

Sub-aperture's Airy radius,  
Fizeau PSF (multi peaks...)

$\lambda/d$



Corrected Fizeau  
Field (size F on sky)

Fizeau foci

Array of densifiers

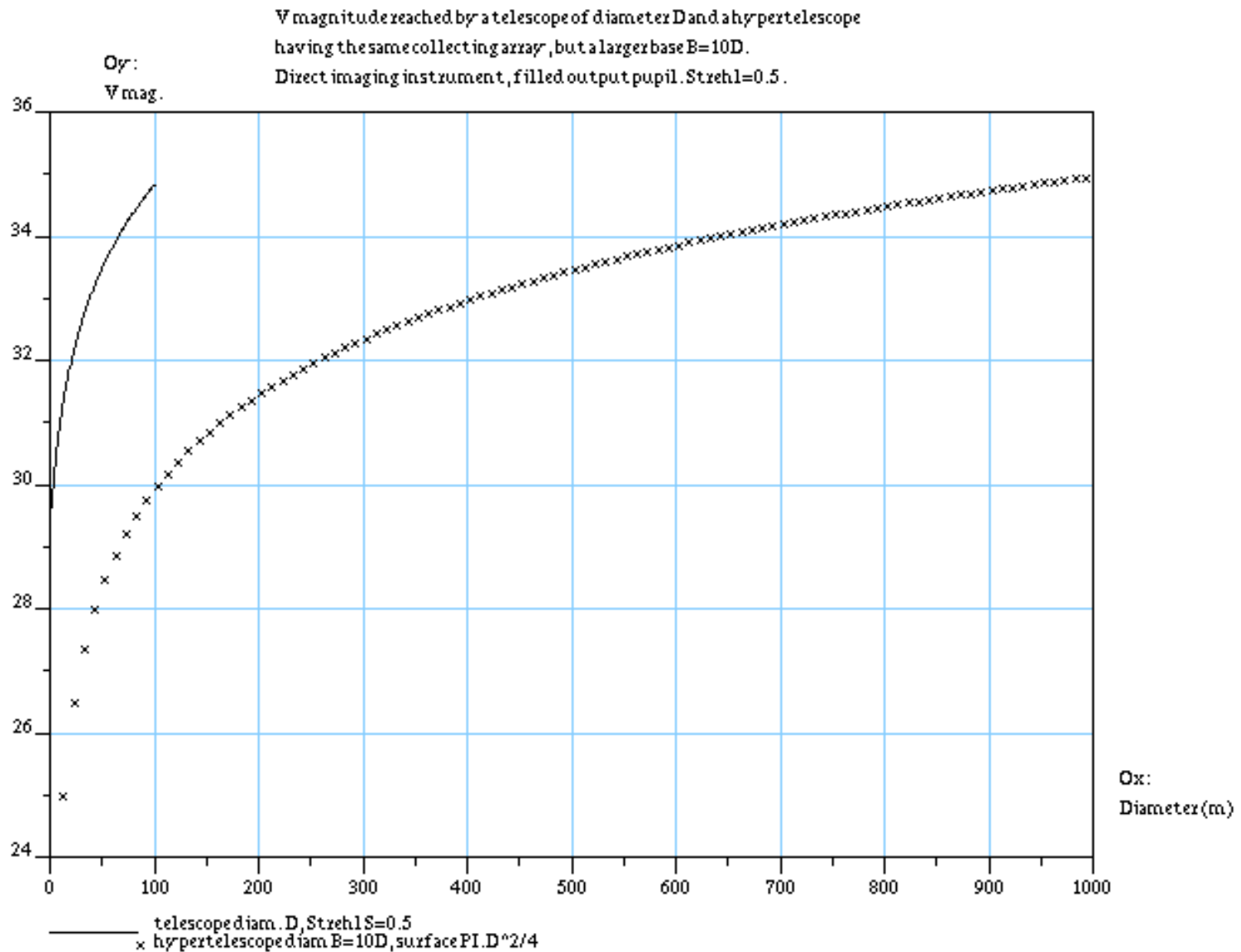
- Number of simultaneous imaged ZOFs =  $(F d / \lambda)^2$
- Relative coverage of sky area =  $N (d / B)^2$   
(1% for an 'exploded' OWL over a 1-km base)

# Hypertelescopes at a glance (1/6)

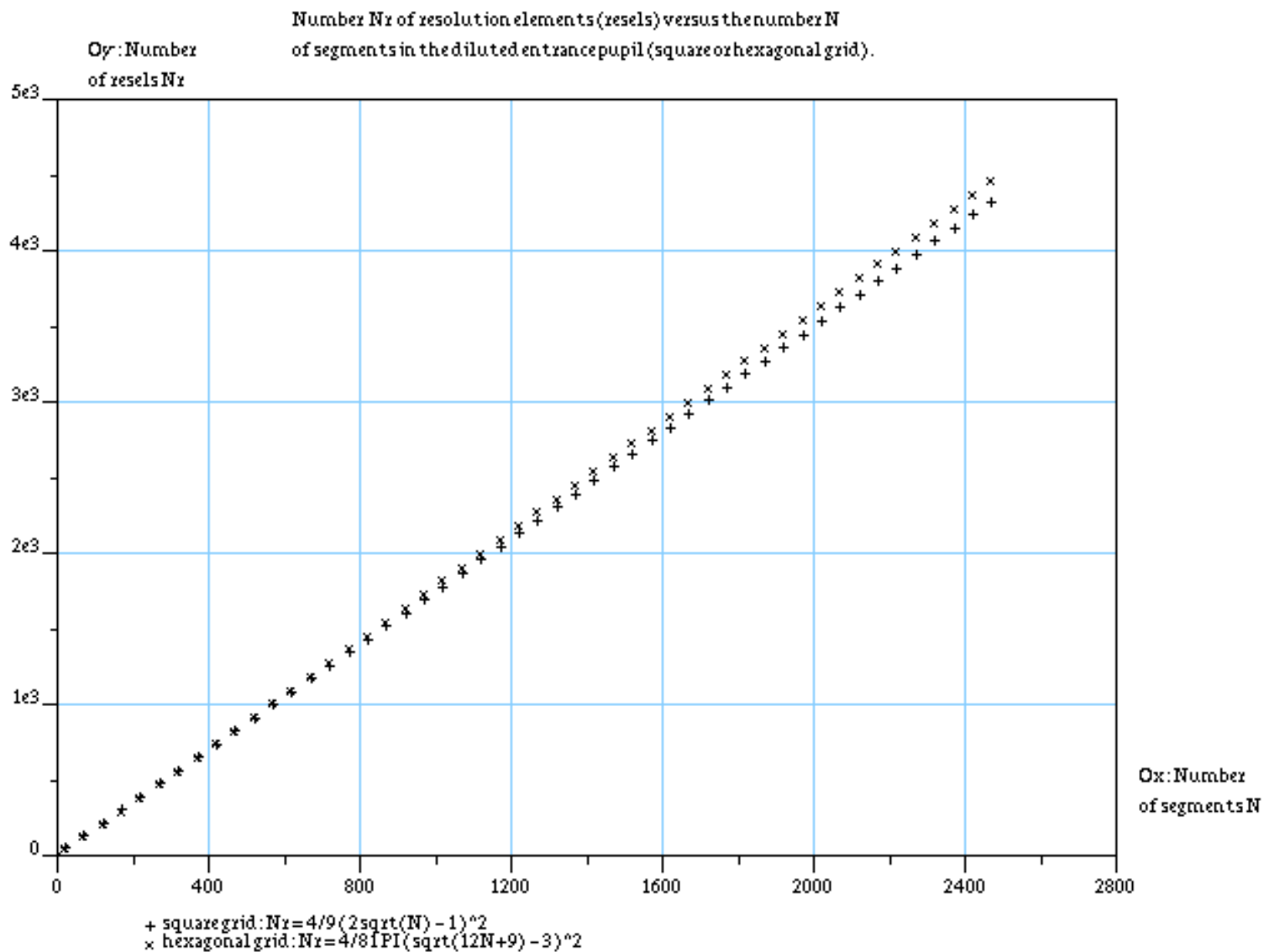
- $ZOF = \lambda/s$
- $HOF = \lambda/d$ , is typically the reconstructed field (by ZOF unfolding)
- Possibility of multiple ZOFs simultaneous observation
- Sky coverage  $\sim 1\%$  (*wrt* Fizeau field)
- $\sim N$  to  $\sim N^2$  resels in the final image formed from one observed ZOF, depending on the pupil redundancy
- Up to 100x sensitivity gain in planet detection *wrt* beam-splitter nulling interferometer (Labeyrie 2001, Roddier & Guyon 2000)
- Good for coronagraphy, to.
- For a given collecting array, a hypertelescope and a classical telescope have the same sensitivity. *See figure...*



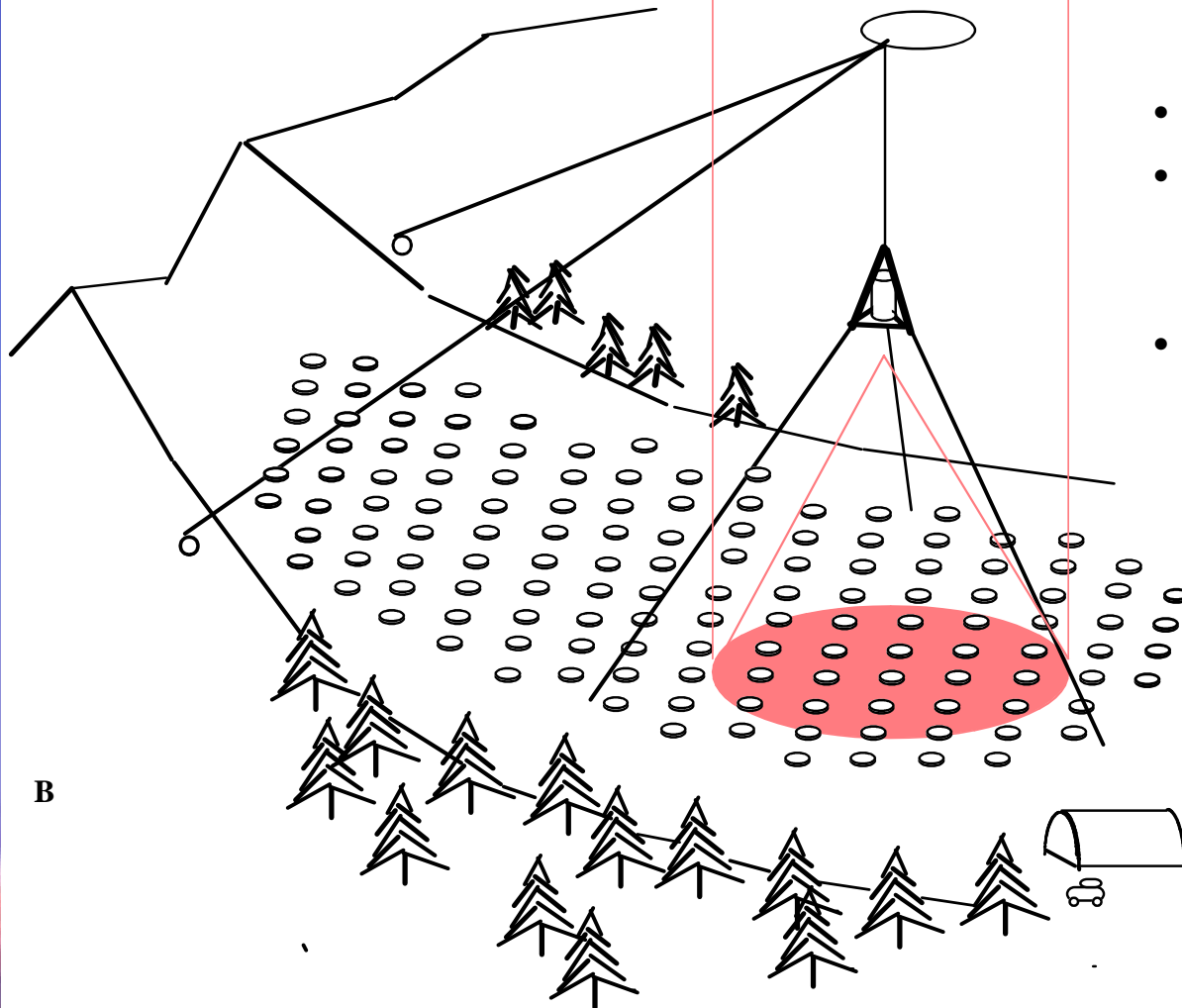
# Hypertelescopes at a glance (2/6)



# Hypertelescopes at a glance (3/6)



# CARLINA: 200-m hyper-telescope



- sparse spherical primary
- correction of spherical aberration and coma in focal cage
- several cages can be used

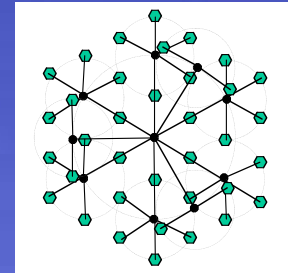
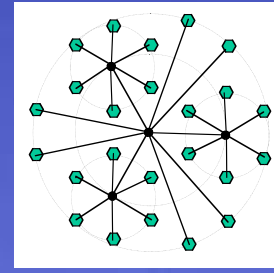
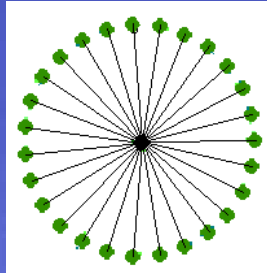
B

Labeyrie 2000

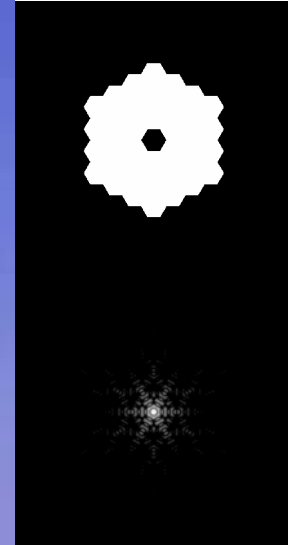
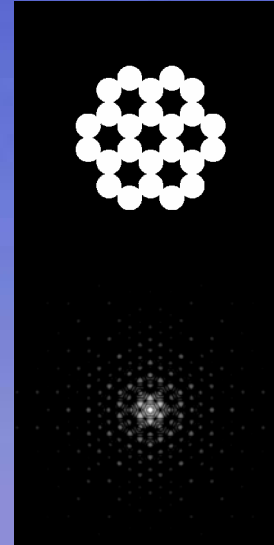
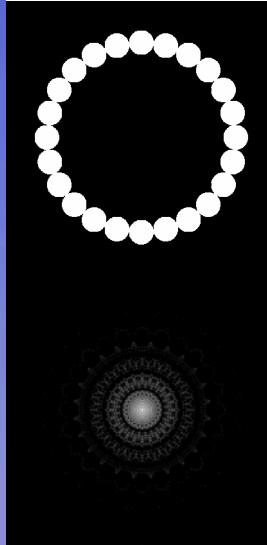
# Hypertelescopes at a glance (5/6)

- OVLAHT (Lardière 2000)

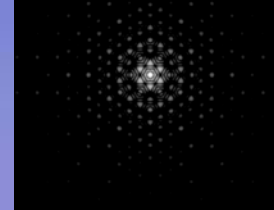
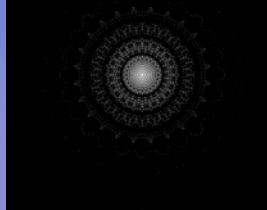
Entrance pupil



Densified pupil  
(exit pupil)



PSF

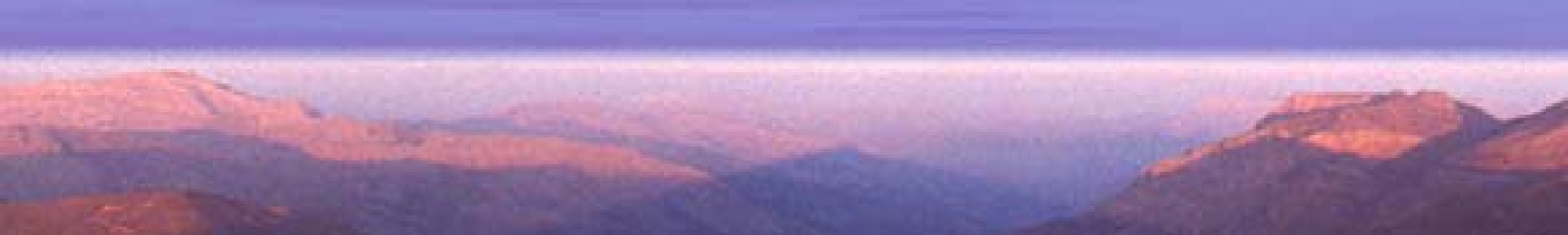


Energy in the  
central peak

16%

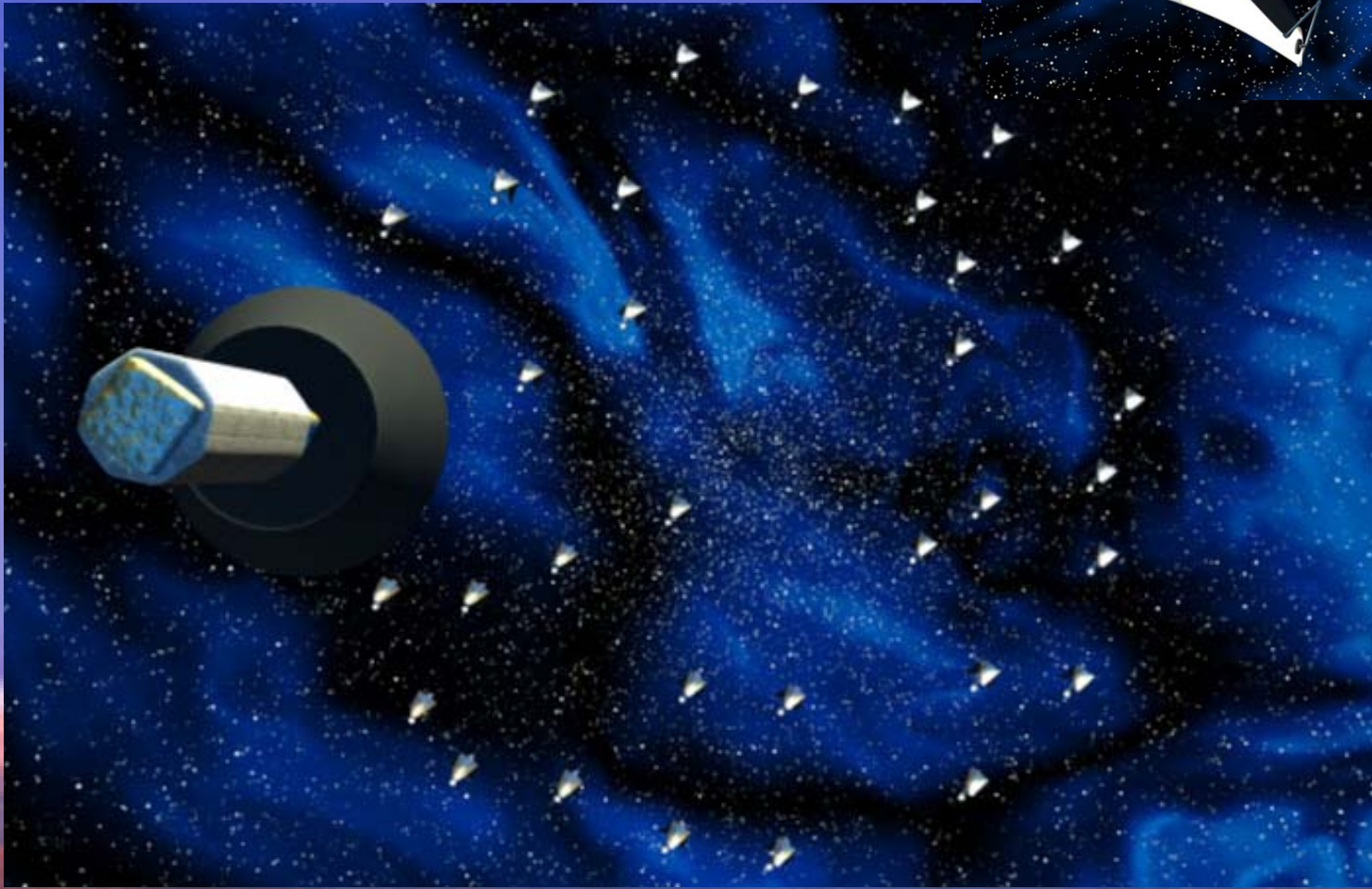
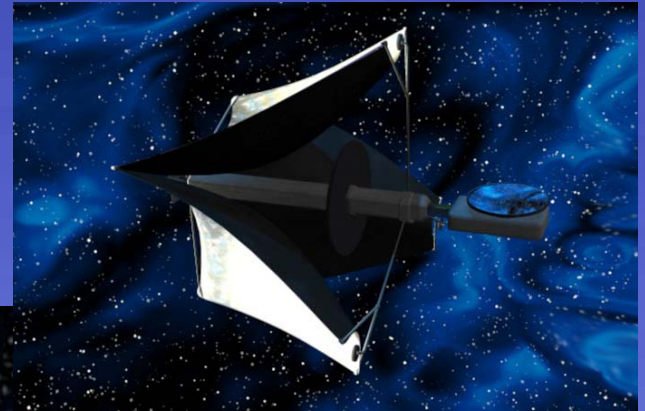
56%

79%



# Hypertelescopes at a glance (6/6)

- NASA TPF: hypertelescope solutions under study  
(NASA-sponsored Boeing/SVS proposal)



## Concept #3: Indirect Imaging Interferometer (1/1)

- No direct image at instrument focus
- Visibility measurement
- Reconstructed image with  $\sim N$  to  $\sim N^2$  resels depending on pupil redundancy
- Base 100 to 1000m
- $c = 10^{-1}$  to  $10^{-4}$

### Examples: (current VLTI)

- Network of 8 or 10m telescopes (VLIA, Mountain 1996) ?
- IRVLA: 4m telescopes for Mauna Kea (Ridgway & Roddier 2000)
- Super VLTI,  $N > 6$  to 150 UT (= collecting array of OWL) ?



# Scientific Performances Comparison

Instrument Concept =>	Concept #1		Concept #2		Concept #3	
	Single pupil telescope		Direct Imaging Interferometer		Indirect Imaging Interferometer (AS)	
Diameter (or base) of M1 $B$	$B = 30$ m	$B = 100$ m	$B = 100$ m	$B = 1000$ m	$B = 100$ m	$B = 1000$ m
Spatial Res. in V (with AO) ( $\lambda/B$ )	3 mas	1 mas	1 mas	0.1 mas	1 mas	0.1 mas
In space: Base and spat. resolution in UV	$B < \text{or} = 100$ m (Angel et al. 1999) Resel $> 0.1$ mas in UV ( at $\lambda = 100$ nm)		Resel $< 0.1$ mas in UV for $B > 100$ m at $\lambda = 100$ nm			

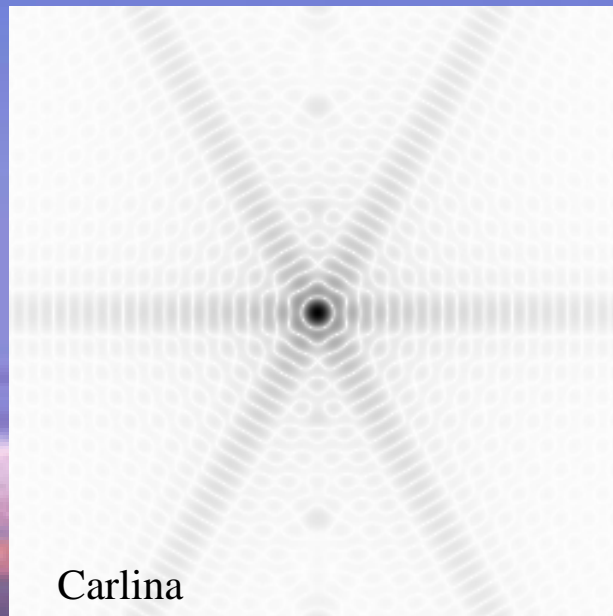
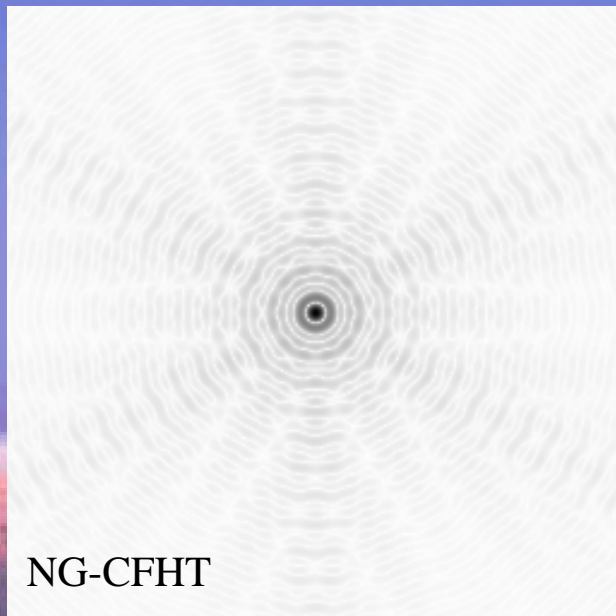
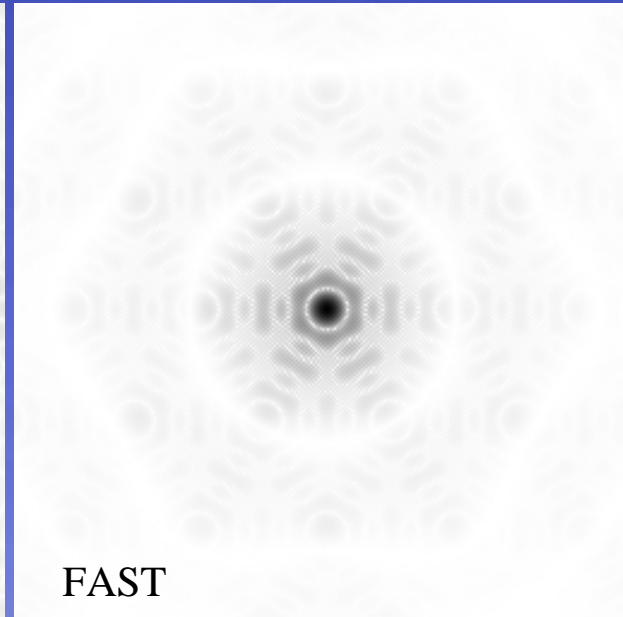
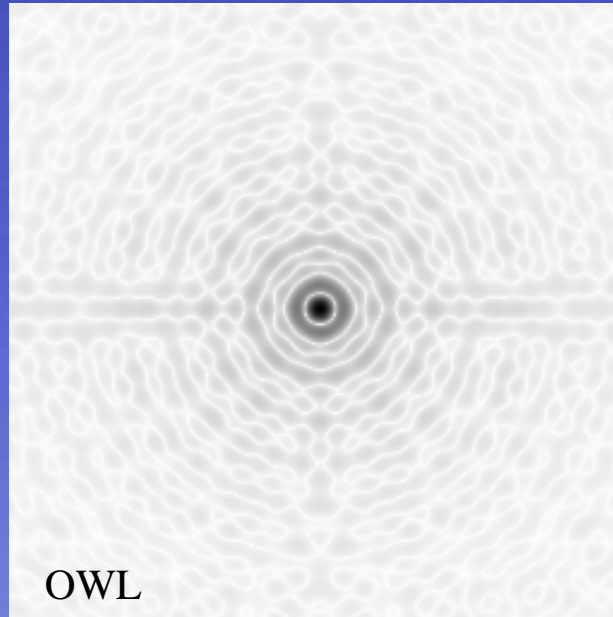
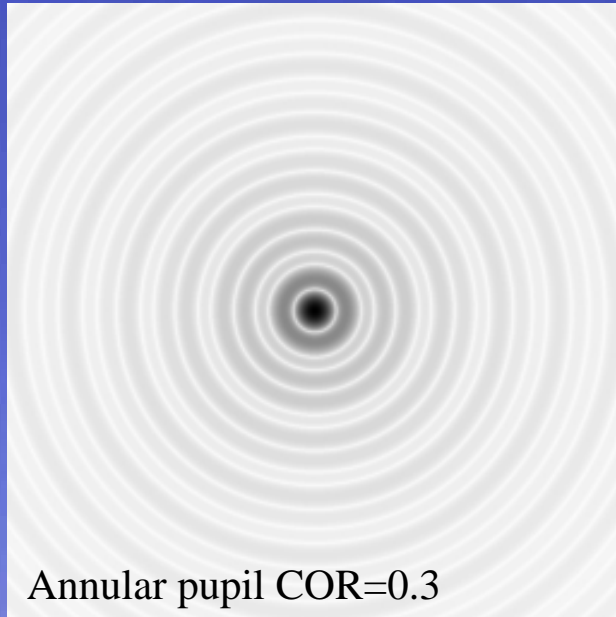


Instrument Concept	Concept #1 Single pupil telescope		Concept #2 Direct Imaging Interferometer		Concept #3 Indirect Imaging Interferometer (AS)	
	30m	100m	100m	1000m	100m	1000m
<b>Instrument geometry:</b> Pupil filling fac $c$ Collecting array $SC$ , Segment diam $d$ , Number of segments $N$ in M1	$c = 0.5$ to $1$ $SC = 353$ to $707 \text{ m}^2$ $d = 2$ to $8 \text{ m}$ $N = 7$ to $225$  For the record VLT-UT: $SC = 50 \text{ m}^2$	$c = 0.5$ to $1$ $SC = 3922$ to $7856 \text{ m}^2$ $d = 2$ to $8 \text{ m}$ $N = 78$ to $2500$	$c = 2.9 \times 10^{-2}$ to $9 \times 10^{-2}$ $d = 0.6$ to $1 \text{ m}$  $d = 0.6 \text{ m}$ : $N = 800$ to $2500$ $SC = 226$ to $707 \text{ m}^2$  $d = 1 \text{ m}$ : $N = 450$ to $900$ $SC = 353$ to $707 \text{ m}^2$	$c = 4.5 \times 10^{-4}$ to $10^{-2}$ $d = 0.6$ to $2 \text{ m}$  $d = 0.6 \text{ m}$ : $N = 1250$ à $27800$ $d = 1 \text{ m}$ : $N = 450$ to $10000$ $d = 2 \text{ m}$ : $N = 113$ to $2500$  $SC = 353$ to $7856 \text{ m}^2$	$c = 3.8 \times 10^{-2}$ to $0.23$ $N = 6$ to $36$ $d = 8 \text{ m}$ $SC = 301$ to $1810 \text{ m}^2$	$c = 3.8 \times 10^{-4}$ to $10^{-2}$ $N = 6$ to $156$ $d = 8 \text{ m}$ $SC = 301$ to $7841 \text{ m}^2$
<b>Instrument geometry in space</b>	$B < \text{or} = 100 \text{ m}$ (Angel et al. 1999)		$N < \text{or} = 36$ (TPF) $d < \text{or} = 2 \text{ m}$ $SC < \text{or} = 113 \text{ m}^2$ <i>free-flyers</i> , $B = 100 \text{ m}$ ( $> 1000 \text{ m} ?$ ) for thermal IR  $N < \text{or} = 36$ (TPF) $d < \text{or} = 1 \text{ m} ?$ $SC < \text{or} = 30 \text{ m}^2 ?$ Structure $B > 10 \text{ m}$ $B < 50 \text{ m} ?$			

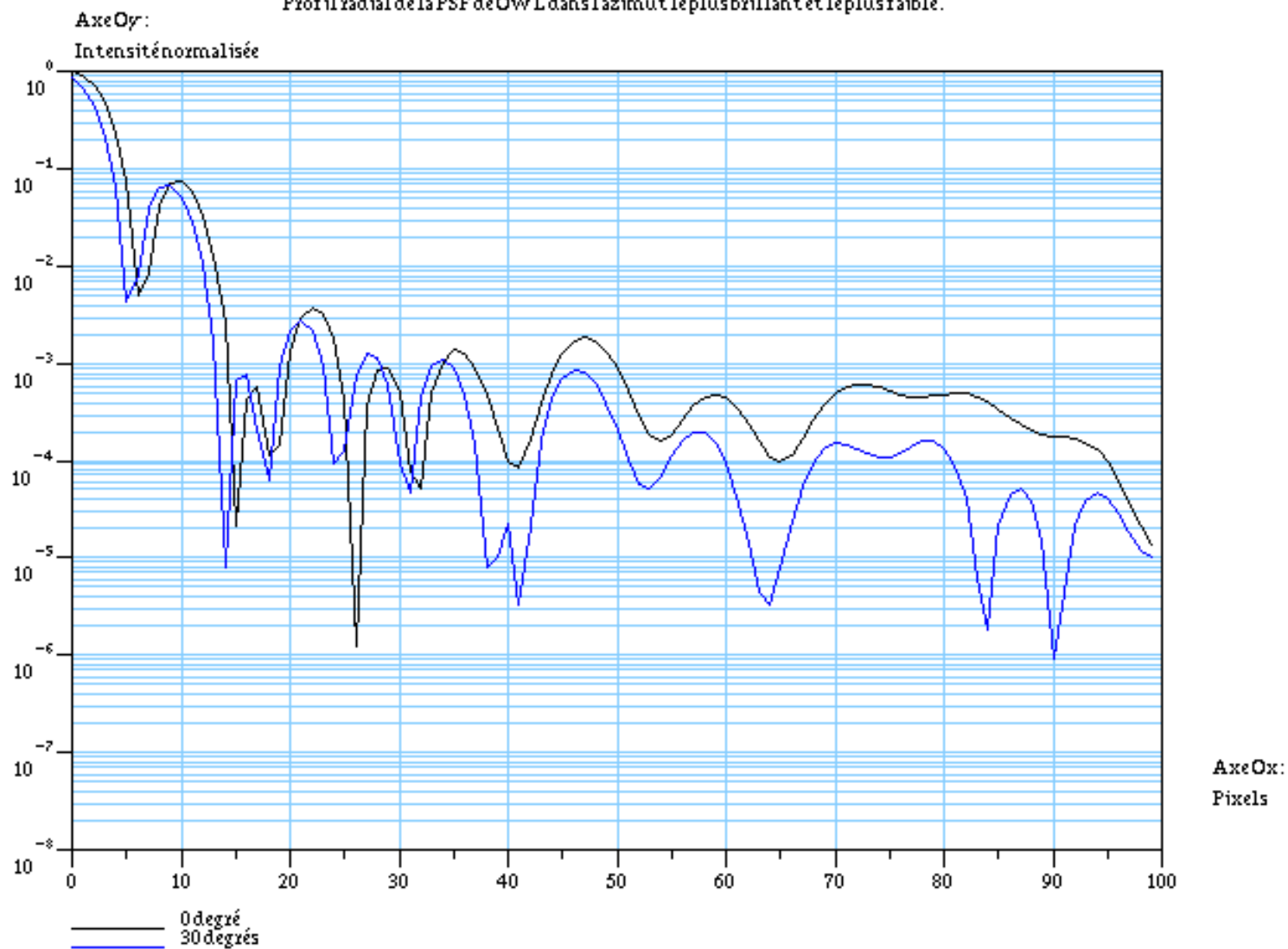
Instrument Concept	Concept #1 Single pupil telescope		Concept #2 Direct Imaging Interferometer		Concept #3 Indirect Imaging Interferometer (AS)	
	30m	100m	100m	1000m	100m	1000m
BP	V to N					
BP in space	UV(>100nm) IR					
Imaging capabilities,	direct	direct	direct	direct	AS imaging with $\leq N(N-1)/2$ inputs	AS imaging with $\leq N(N-1)/2$ inputs
Temporal resolution	'snapshot'	'snapshot'	'snapshot'	'snapshot'	Hours to days, versus N	Hours to days, versus N
PSF intensity	Linear obscur. $\sim 0.34$ à $\sim 0.15$		Linear obscuration $\sim 0$		-	-
1 <sup>er</sup> ring	8.e-2 to 2.e-2		2.e-2			
2 <sup>nd</sup> ring	2.e-3 to 7.e-4		1.e-3			
3 <sup>ième</sup> ring	3.e-3 to 4.e-4		$\sim 1.e-5$			



# PSF, Log scale (computed by P. Riaud)



Profil radial de la PSF de OWL dans l'azimut le plus brillant et le plus faible.

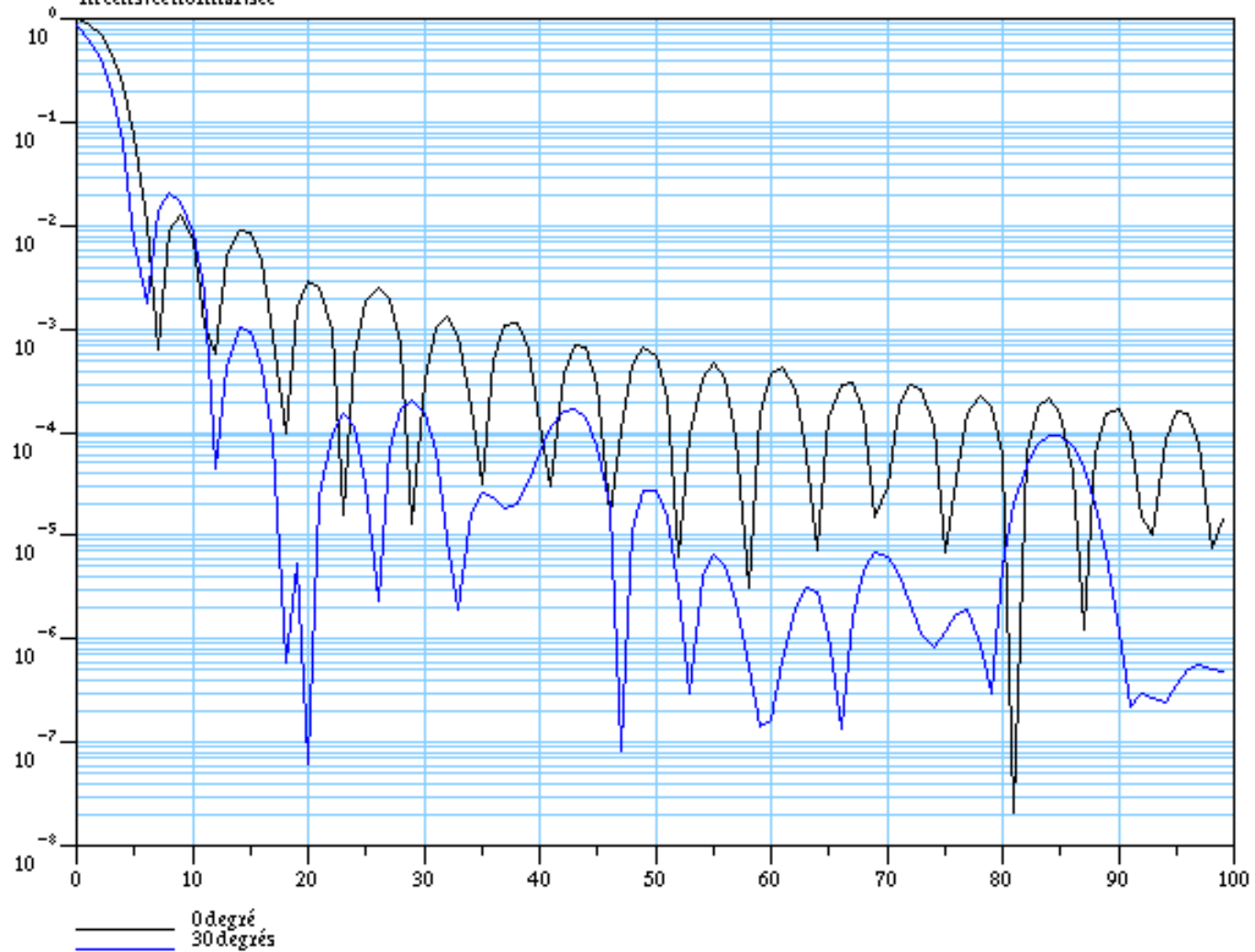


Profil radial de la PSF de Carlina dans l'azimut le plus brillant et le plus faible.

Axe Oy:

Carlina avec 2500 segments dans la pupille.

Intensité normalisée



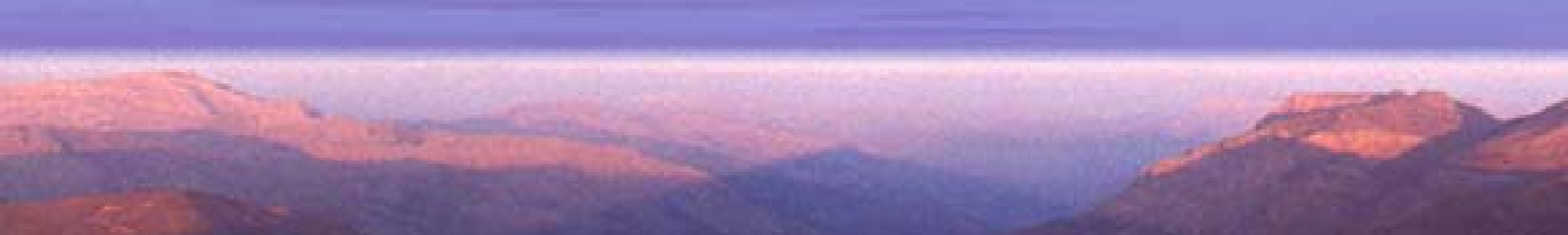
Instrument Concept	Concept #1 Single pupil telescope		Concept #2 Direct Imaging Interferometer		Concept #3 Indirect Imaging Interferometer (AS)	
	30m	100m	100m	1000m	100m	1000m
<b>Photometric Range (high dyn. Imaging)</b>  <b>With coronagraphy</b>	K band, S=0.8: $\Delta m=8$ mag COR=0.25  $3*\lambda/D +$ coro 4Q (Rouan et al. 2000)  And for OWL ?	K band, S=0.8: $\Delta m=8$ mag COR=0.25  $3*\lambda/D +$ coro 4Q (Rouan et al. 2000)  And for OWL ?	K band, S=0.8: $\Delta m=10$ mag COR=0.  $3*\lambda/D +$ coro 4Q (Rouan et al. 2000)	K band, S=0.8: $\Delta m=10$ mag COR=0.  $3*\lambda/D +$ coro 4Q (Rouan et al. 2000)	$\Delta m < 5.7$ mag sur FLUOR $\Delta m < 5$ mag sur IOTA K band	



Instrument Concept	Concept #1 Single pupil telescope		Concept #2 Direct Imaging Interferometer		Concept #3 Indirect Imaging Interferometer (AS)	
	30m	100m	100m	1000m	100m	1000m
ZOF diam. or reconstructed field	3 to 60 arc-min,	3 arc-min,	28 to 67 mas in V HOF = 0.2''	1.4 to 22 mas in V HOF = 0.2''	2.5 to 6 mas + supersynth.	0.25 to 1.2 mas + supersynth.
Resels in MCAO field in V (30''), or in ZOF or in reconstructable field	$N_r = 100 \times 10^6$	$N_r = 900 \times 10^6$	$N_r \sim 1.8 N$ $N_r = 810$ to 4500	$N_r \sim 1.8 N$ $N_r = 200$ to 50000	$N_r \leq N(N-1)/2$ $N_r \leq 15$ to 630	$N_r \leq N(N-1)/2$ $N_r \leq 15$ to 12090
Resels without AO or MCAO	(FHWM=0.7'' over 1°x1°) $N_r = 30 \times 10^6$					
Zenital distance	>1 to 60°	>1 to 60°	0 à 45°(up to 60° ?)	0 à 45°(up to 60°?)	>1 à 45°(up to 60°?)	>1 à 45°(up to 60°?)



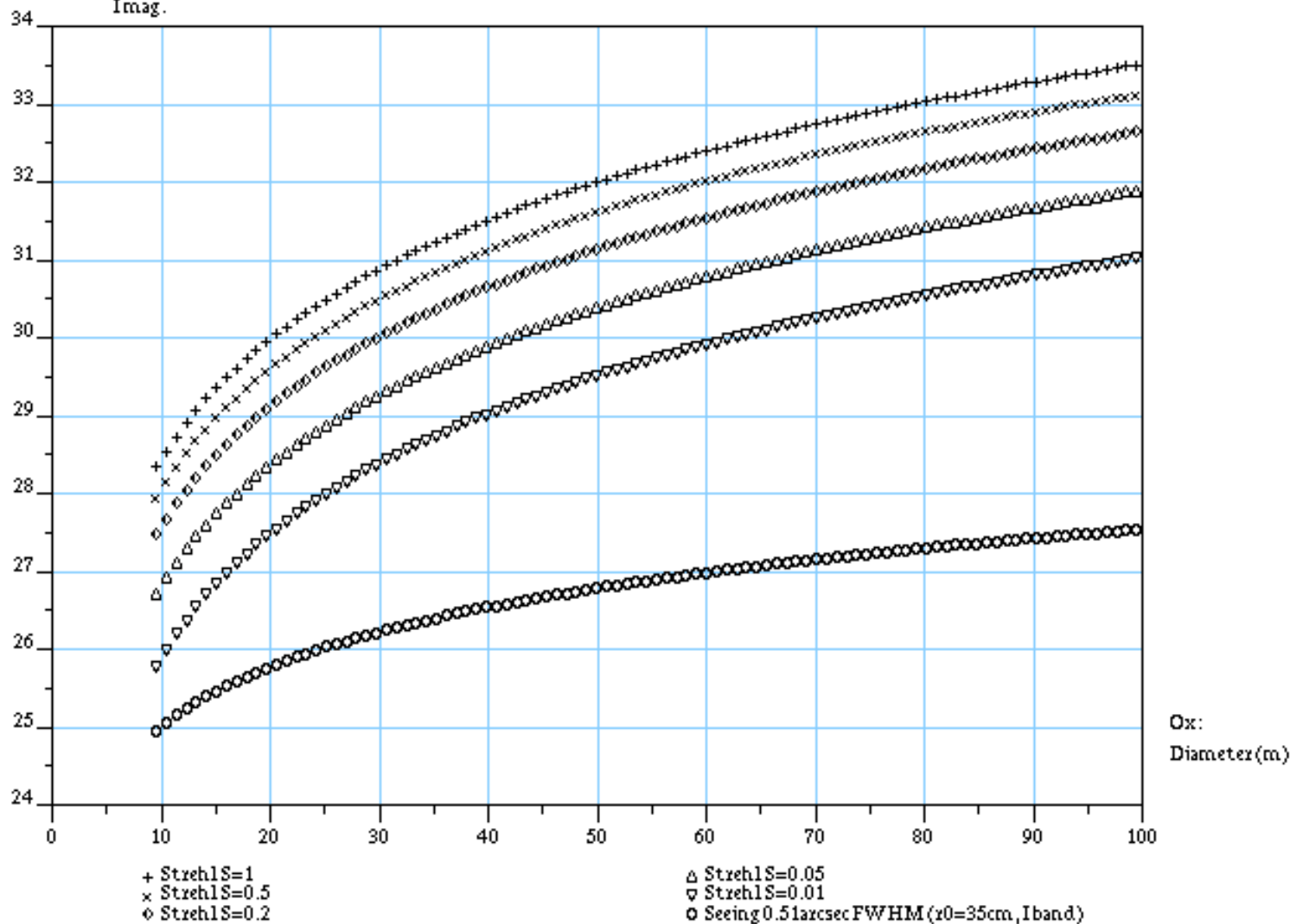
Instrument Concept	Concept #1 Single pupil telescope		Concept #2 Direct Imaging Interferometer		Concept #3 Indirect Imaging Interferometer (AS)	
	30m	100m	100m	1000m	100m	1000m
<b>Sky coverage</b> <b>(cs en %)</b>  <b>with MCAO +</b> <b>NGSs</b>	In I : S=0.1, cs=30% J : S=0.4, cs=30% H : S=0.6, cs=30% K : S=0.8, cs=30% L : S=0.9, cs=30% M : S=0.97, cs=40% N : S=0.98, cs=95%  CELT 30m (Dekany et al. 2000)	In V: S=0.2, cs=20 à 100% (versus galactic latitude) In V: S=0.4, cs=10 to 70% In J : S=0.4, cs=0.1 to 100% En K : S>0.8, cs=10 to 100%  OWL 100m (Le Louarn et al .2000)	Idem CELT or OWL TBC	Idem CELT or OWL TBC	TBD	TBD



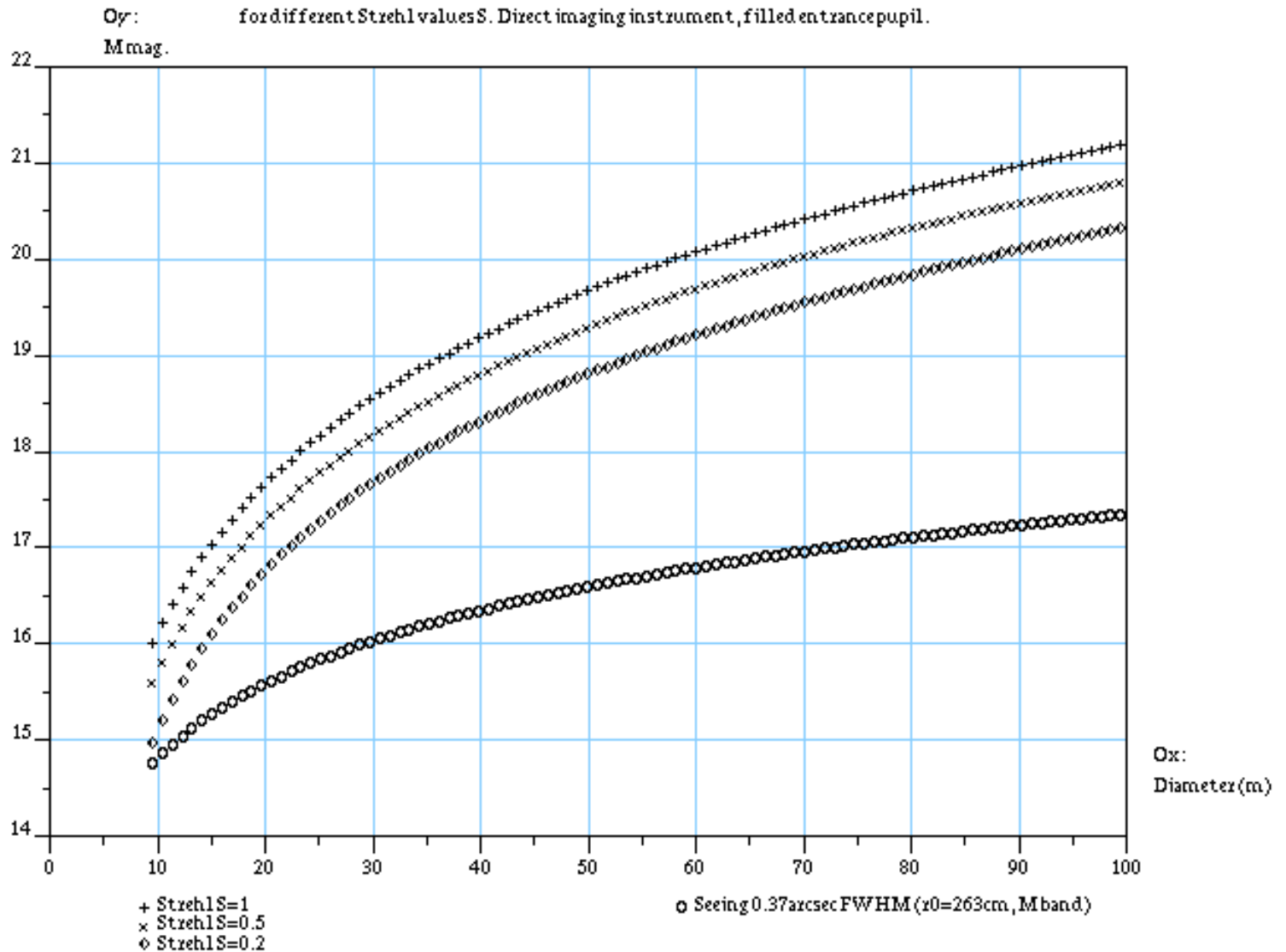
Instrument Concept	Concept #1 Single pupil telescope		Concept #2 Direct Imaging Interferometer		Concept #3 Indirect Imaging Interferometer (AS)	
	30m	100m	100m	1000m	100m	1000m
<b>Sensitivity with AO: mag. per resel</b>  <b>Strehl = 0.5 from V to H</b> <b>Strehl = 1 from K to N</b>	<b>V = 32.2</b> <b>I = 30.5</b> <b>J = 28.1</b> <b>H = 26.7</b> <b>K = 25.2</b> <b>L = 20.1</b> <b>M = 18.5</b> <b>N = 15.4</b>	<b>V = 34.8</b> <b>I = 33.0</b> <b>J = 30.8</b> <b>H = 29.3</b> <b>K = 27.8</b> <b>L = 22.7</b> <b>M = 21.1</b> <b>N = 18.0</b>	<b>V = 32.2</b> <b>I = 30.5</b> <b>J = 28.1</b> <b>H = 26.7</b> <b>K = 25.2</b> <b>L = 20.1</b> <b>M = 18.5</b> <b>N = 15.5</b>	<b>V = 34.8</b> <b>I = 33.0</b> <b>J = 30.8</b> <b>H = 29.3</b> <b>K = 27.8</b> <b>L = 22.7</b> <b>M = 21.1</b> <b>N = 18.0</b>	<b>V = 26.3</b> <b>I = 25.3</b> <b>J = 23.7</b> <b>H = 22.3</b> <b>K = 20.8</b> <b>L = 15.7</b> <b>M = 14.2</b> <b>N = 11.0</b>	<b>Mag lim for two 8m UT</b>  <b>Transmission 0.35%</b>
<b>Tr = 22.5% (60% for the focal inst.)</b>						

Imagnitude giving SNR=5 in 1000s versus telescope diameter with AO

for different Strehl values S. Direct imaging instrument, filled entrance pupil.



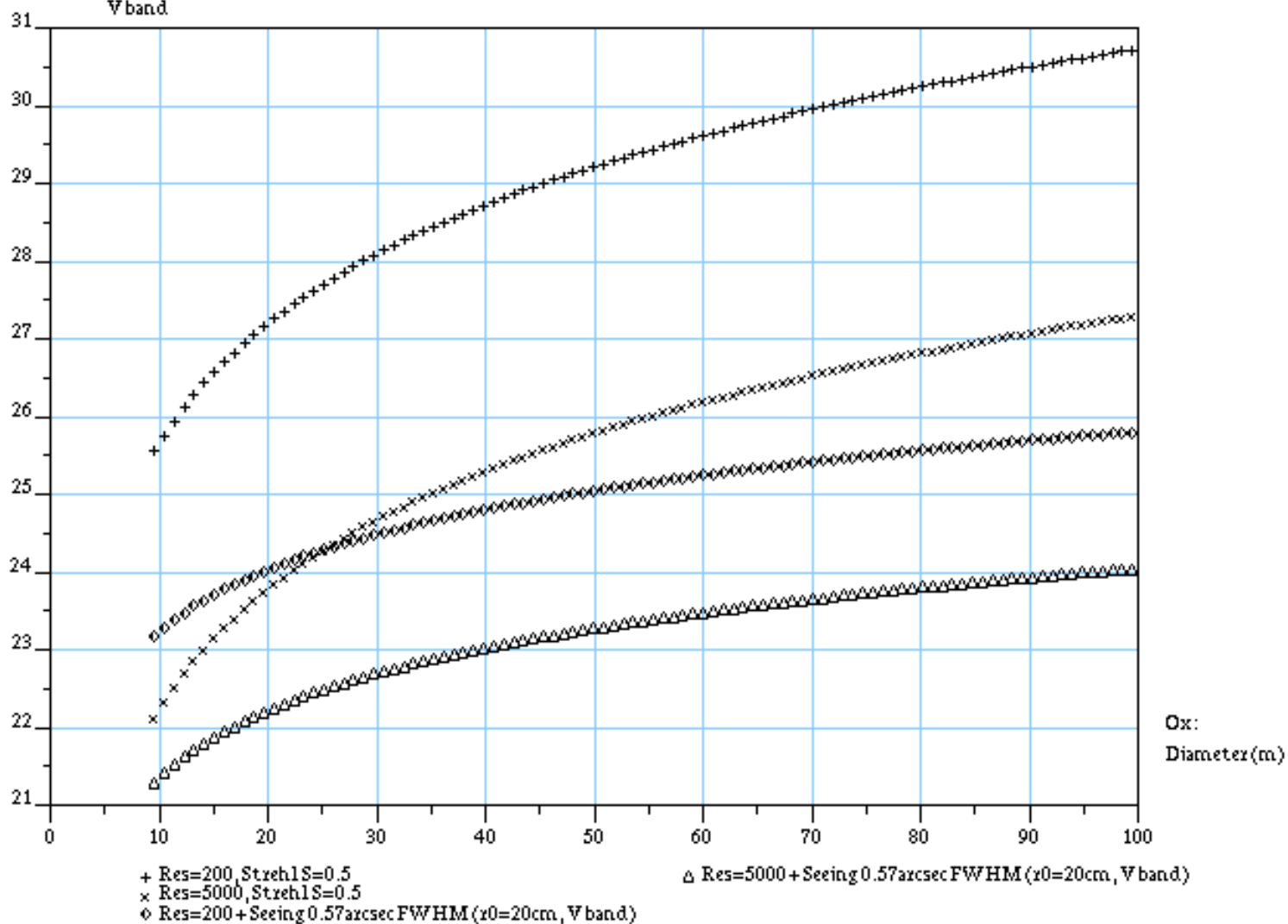
M magnitude giving SNR=5 in 1000s versus telescope diameter with AO  
for different Strehl values S. Direct imaging instrument, filled entrance pupil.



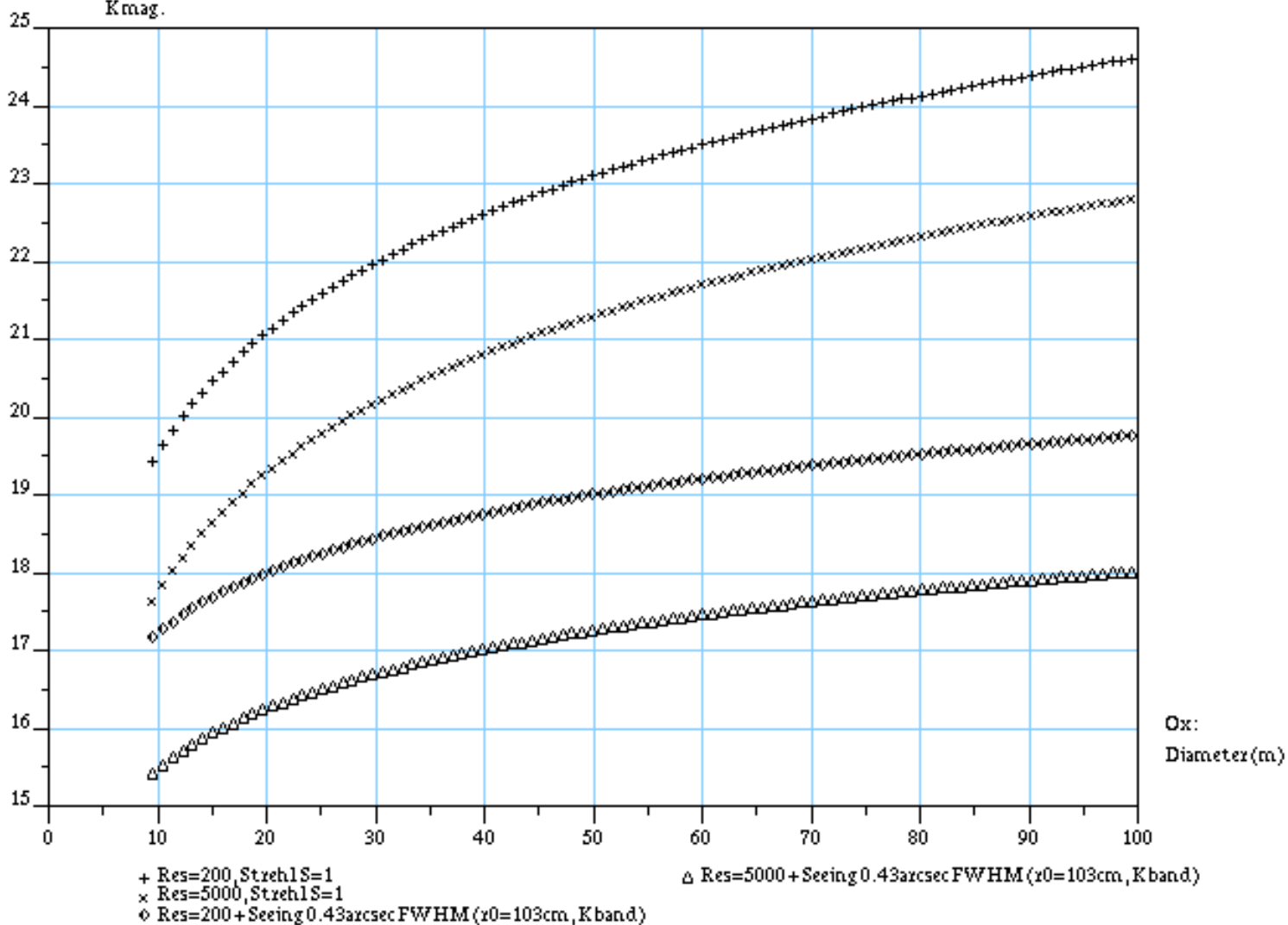
Instrument Concept	Concept #1 Single pupil telescope		Concept #2 Direct Imaging Interferometer		Concept #3 Indirect Imaging Interferometer (AS)	
	30m	100m	100m	1000m	100m	1000m
	Res=200	Res=200	Res=200	Res=200	Res=200	Res=200
Focal instrumentation:	V = 28.0, S=0.5	V = 30.6, S=0.5	V = 28.0, S=0.5	V = 30.6, S=0.5	V = 21.8, S=0.5	V = 21.8, S=0.5
Sensitivity for low resolution spectroscopy (Res=200) (pose 1h, S/N=20)	I = 27.2, S=0.5	I = 29.8, S=0.5	I = 27.2, S=0.5	I = 29.8, S=0.5	I = 21.4, S=0.5	I = 21.4, S=0.5
	J = 24.8, S=0.5	J = 27.4, S=0.5	J = 24.8, S=0.5	J = 27.4, S=0.5	J = 19.8, S=0.5	J = 19.8, S=0.5
	H = 23.5, S=0.5	H = 26.1, S=0.5	H = 23.5, S=0.5	H = 26.1, S=0.5	H = 19.0, S=0.5	H = 19.0, S=0.5
	K = 21.9, S=1	K = 24.5, S=1	K = 21.9, S=1	K = 24.5, S=1	K = 17.7, S=1	K = 17.7, S=1
	L = 16.7, S=1	L = 19.3, S=1	L = 16.7, S=1	L = 19.3, S=1	L = 12.6, S=1	L = 12.6, S=1
	M = 15.5, S=1	M = 18.1, S=1	M = 15.5, S=1	M = 18.1, S=1	M = 11.4, S=1	M = 11.4, S=1
	N = 11.9, S=1	N = 14.5, S=1	N = 11.9, S=1	N = 14.5, S=1	N = 7.8, S=1	N = 7.8, S=1
<b>For Res=5000,</b> <b>V - 3.5</b> <b>N - 1.8</b>	Res=200, <i>seeing limited</i>	Res=200, <i>seeing limited</i>	Res=200, <i>seeing limited</i>	Res=200, <i>seeing limited</i>	Res=200, <i>seeing limited</i>	Res=200, <i>seeing limited</i>
	V = 24.4	V = 25.7	V = 24.4	V = 25.7	V = 24.4	V = 25.7
	I = 23.3	I = 24.6	I = 23.3	I = 24.6	I = 23.3	I = 24.6
	J = 21.0	J = 22.3	J = 21.0	J = 22.3	J = 21.0	J = 22.3
	H = 19.9	H = 21.2	H = 19.9	H = 21.2	H = 19.9	H = 21.2
	K = 18.3	K = 19.6	K = 18.3	K = 19.6	K = 18.3	K = 19.6
	L = 13.8	L = 15.1	L = 13.8	L = 15.1	L = 13.8	L = 15.1
	M = 13.0	M = 14.3	M = 13.0	M = 14.3	M = 13.0	M = 14.3
	N = 10.3	N = 11.7	N = 10.3	N = 11.7	N = 10.3	N = 11.7



V magnitude giving SNR=20 in 1h versus telescope diameter with or without AO  
for different spectral resolutions. Direct imaging instrument, filled entrance pupil.



K magnitude giving SNR=20 in 1h versus telescope diameter with or without AO  
for different spectral resolutions. Direct imaging instrument, filled entrance pupil.



# Conclusion (1/3)

## Science issues

- **Single pupil telescope:** large field, high sensitivity
- **Direct imaging interferometer:** higher spatial resolution, same sensitivity, high contrast, much narrower field and resels number, same sky coverage
- **Indirect imaging interferometer:** high spatial resolution, much lower sensitivity, narrower field and resels number



## Conclusion (2/3)

### Technological issues

- **Single pupil telescope:** mount, instrument height, aspheric optics, AO/MCAO
- **Direct imaging interferometer:** recombiner optics, balloon-borne recombiner, AO (discontinued wave-front, but smaller sub-apertures, piston control for large number of segments N)
- **Indirect imaging interferometer:** long and fast delay lines, but AO simpler ? Sub-aperture  $< \text{ or } = 8\text{m}$ , technology *available*, piston control



## Conclusion (3/3)

- All concepts are very complex
- Each concept has its own specificity
- Each concept has different performances
- Futur instruments should probably be slightly ‘specialized’ (as today the VLT compared to VLTI: different performances, but scientific complementarity)
- *To be discussed*: AO available in 2020 on ELTs only, but earlier on interferometers ?



More...

- Be quantitative: specify field, sensitivity, PSF stability, Strehl ratio, etc, for all scientific topics you will report on this week !
- Prospective document available online at URL <http://grasse.obs-azur.fr/fresnel/ashra/>  
(sorry, it's in french)
- Related A&A paper in preparation (Arnold et al, 2001)

