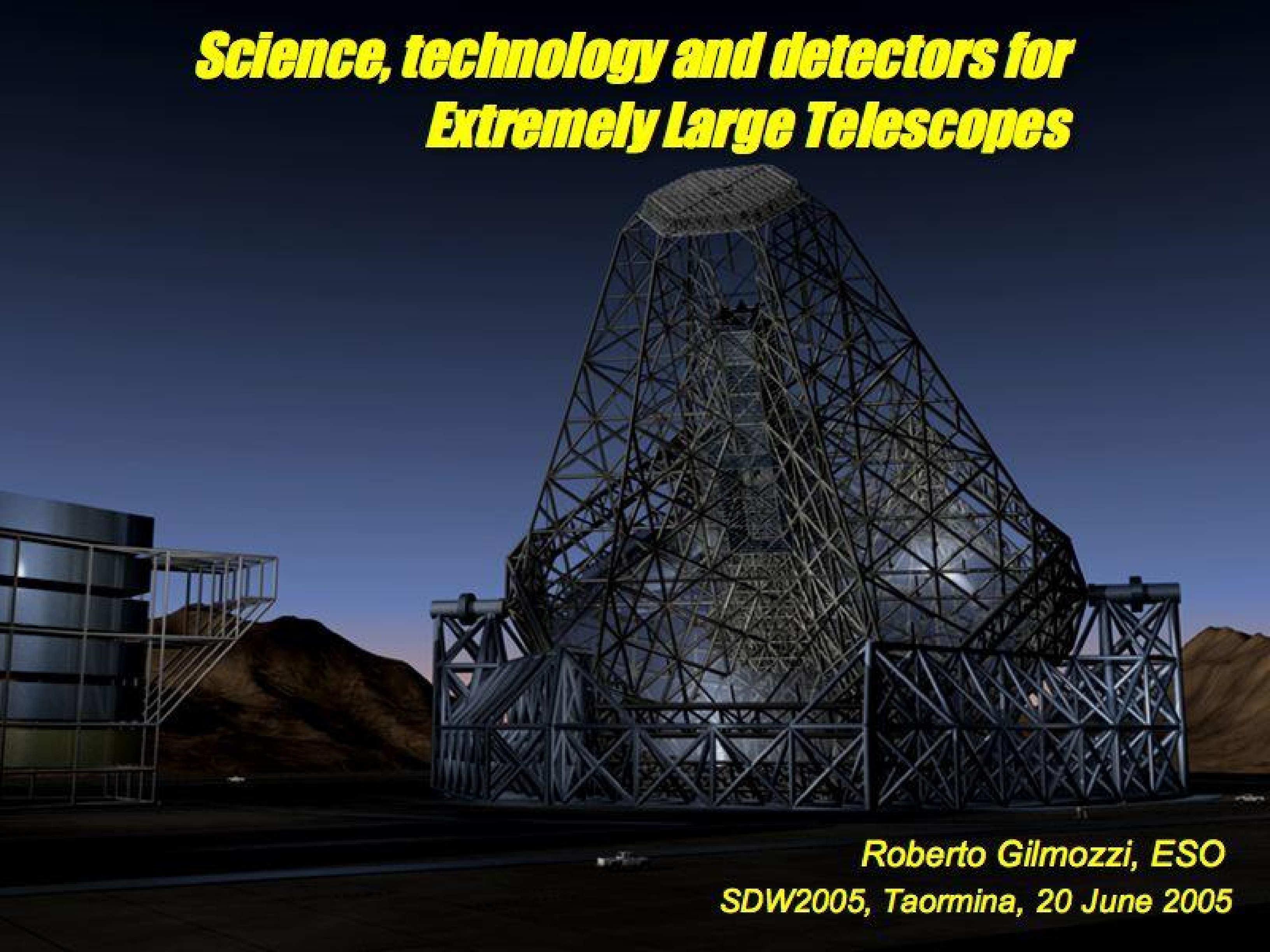
Science, technology and detectors for Extremely Large Telescopes



Roberto Gilmozzi, ESO

SDW2005, Taormina, 20 June 2005

Acronyms

- **ELT = extremely large telescope**

  © Tom Sebring
  - Appropriated as generic term
  - Sometime used as European LT
- **GOD = giant optical device**

  © Jerry Nelson

  (and they said "OWL" showed our *hubris*...)
- **FGT = future giant telescope**

➡ **Use ELTs as generic term**

- **ELD = extremely large detectors**

  are what we need for the future

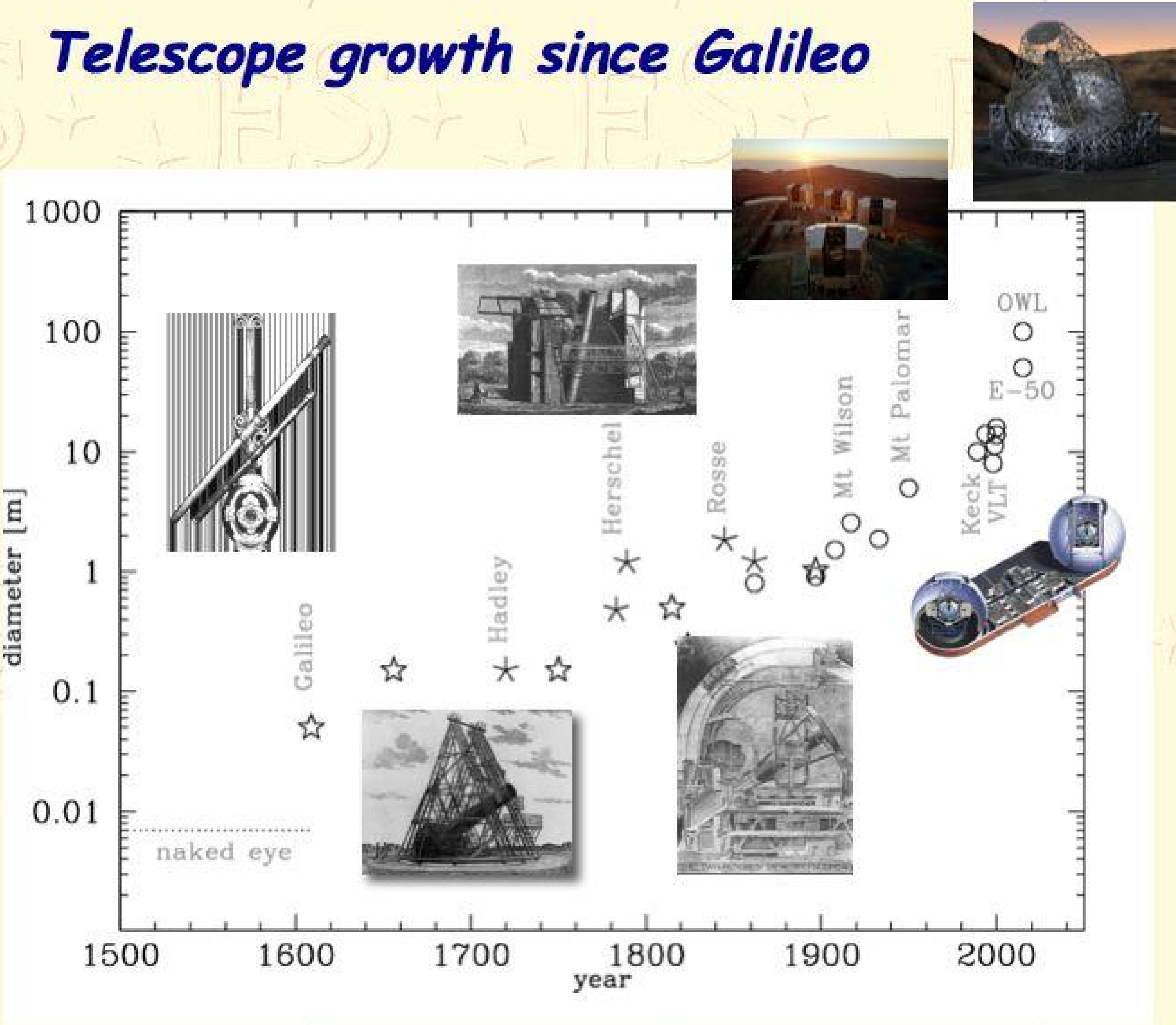
  Ah, they also need to be ***cheap*** ☺

  <u>and</u> have zero readout noise...

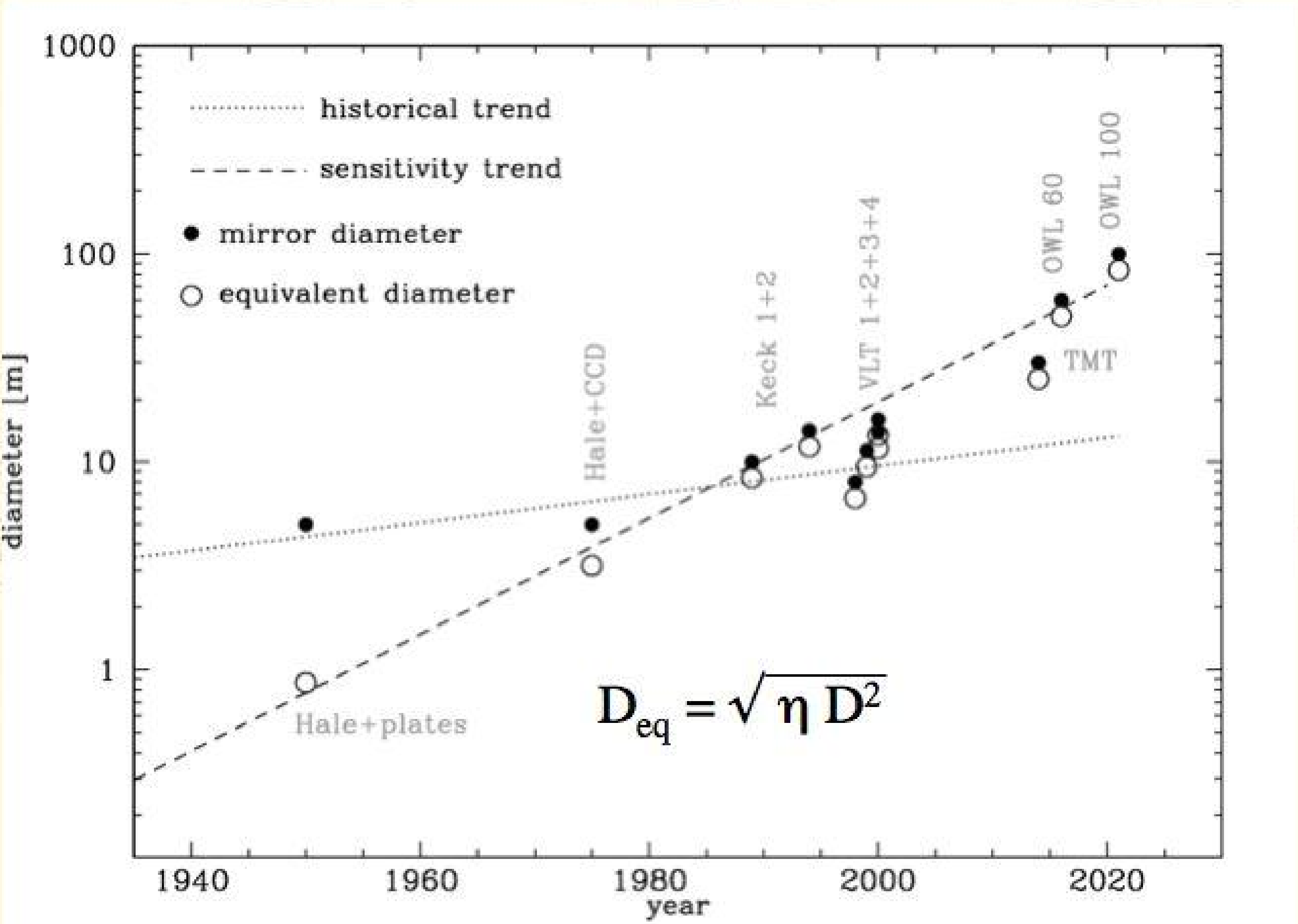
Context: II decade, III millennium AD

- "Maturity" of current generation
  - VLT, Keck, Gemini, Subaru, HET, LBT, GTC, SALT…
  - AO → λ/D performance, 2nd gen instruments
- Interferometry
  - "Faint object" regime (K~20), astrometry (μas)
- ALMA
  - mm, sub-mm "equivalent" of optical facilities
- New ground-based telescopes
  - 30 to 100m diameter, $\lambda/D \sim$ mas
  - OWL, CELT+GSMT=TMT, GMT, …
- New space telescopes
  - JWST, XEUS, TPF/Darwin precursors…

Telescope growth since Galileo



Detectors improved more than diameters



$$D_{eq} = \sqrt{\eta D^2}$$

Confusion about Confusion

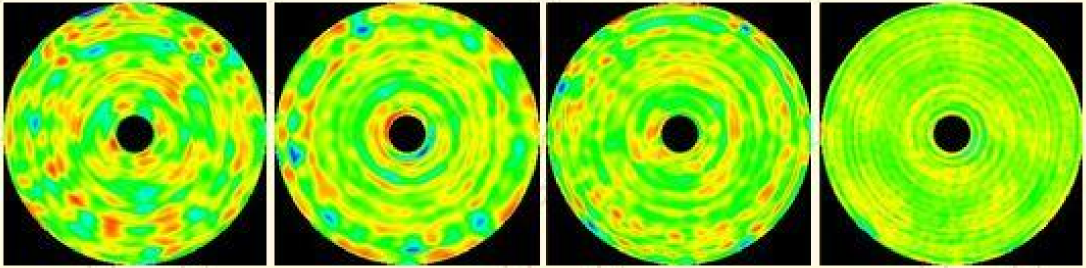
- Inheritance of the 1980s?
  - Poor spatial resolution
    - X-ray "background" (not there any longer…)
    - Overlapping faint galaxies (2" seeing!)
  - HDF's: mostly empty (5% covering factor)
  - DIFFRACTION LIMIT!
  - 3D information
  - Absence thereof: does it tell us something?
    - ~10^{11} galaxies in ~10^{11} square arcsec → typical size?
  - Olbers paradox
    - Can we deduce the "galaxy covering factor"?
- Not easy to predict how the universe looks at milliarcsecond resolution…

remember this

Not easy to predict how fast technology develops, either

- 1943
  - Thomas Watson, chairman of IBM:
    "I think there is a world for maybe five computers"
- 1981
  - Bill Gates, founder of Microsoft:
    "640K ought to be enough for anybody"

Example of progress



	SPEC	Mirror 1	Mirror 2	Mirror 3	Mirror 4
R. curvature (mm)	28800+-100	28762.9	28760.0	28762.6	28759.2
surface RMS (nm)	N/A	22	19.5	17.5	8.5
θ RMS (arc secs)	N/A	0.080	0.074	0.087	0.062
CIR @ r_0=500mm	**>0.82(*)**	**0.875**	**0.898**	**0.893**	**0.975**
CIR @ r_0=250mm	N/A	0.935	0.951	0.935	0.981
Strehl	**>0.25(*)**	**0.762**	**0.791**	**0.824**	**0.953**

- Very high spatial frequency errors ~3-7 nm RMS (wavefront)
- Microroughness < 20 Å
- Correction forces typically ~80 N (spec <120 N)
- Matching error measured by direct Hartmann test, negligible (below measurement accuracy)
- All radii of curvature within 3.7 mm
- *Provisionally accepted in 1996 (No 1 and 2), 1997, 1999.*

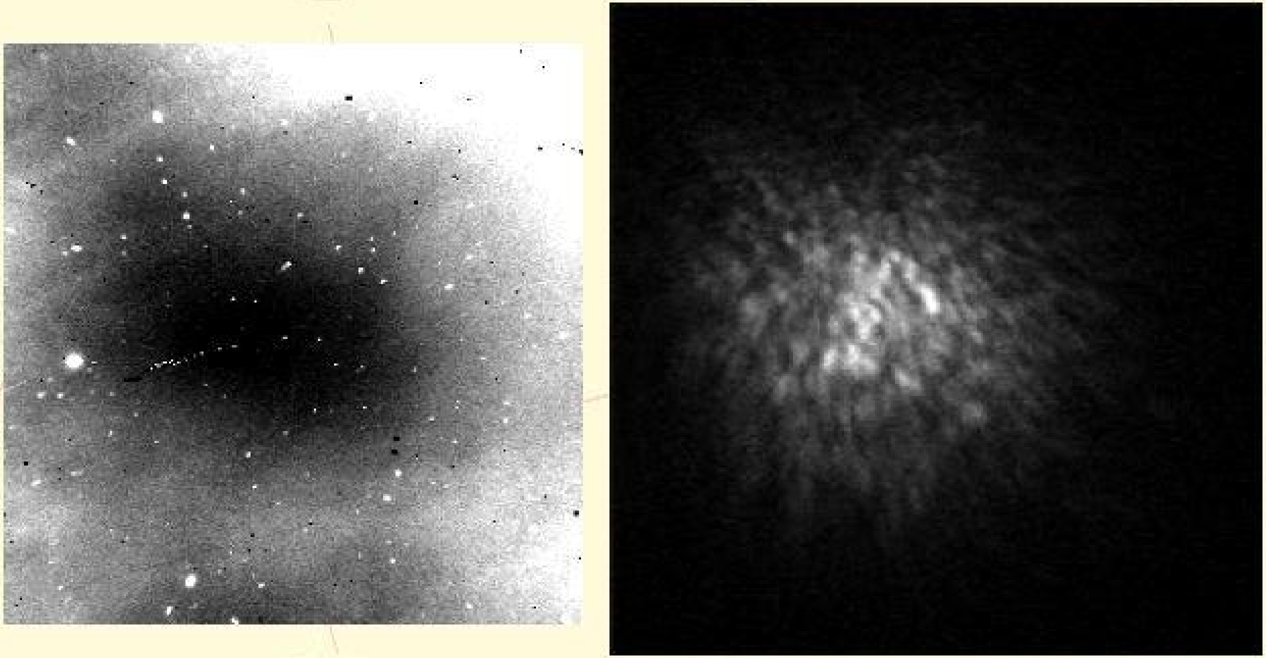
The challenges

- **Sensitivity**
  - If you want to get spectroscopy of the HDF galaxies you need at least a 30m telescope
  - If you want to get spectroscopy of the faintest galaxies discovered by JWST you need at least a 100m
  - If you want to get spectroscopy of candidate earth-like planets within 10pc you need at least an 80m

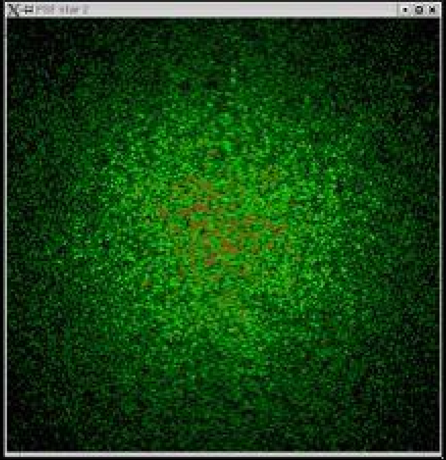
➡ **Maximize diameter**

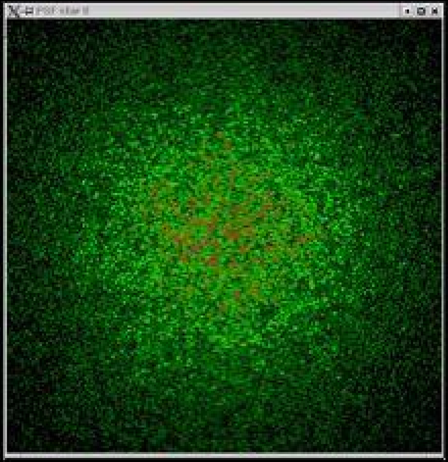
The challenges *cont'd*

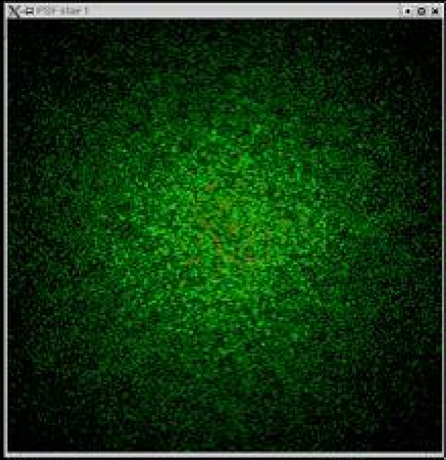
- The atmosphere

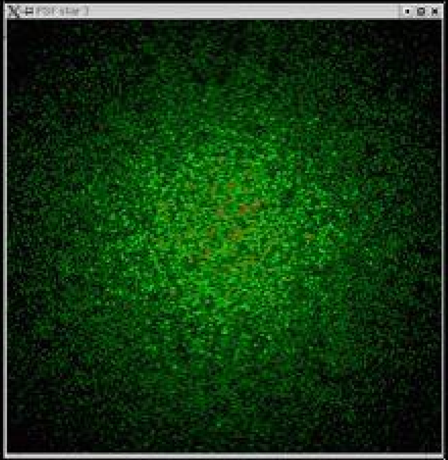


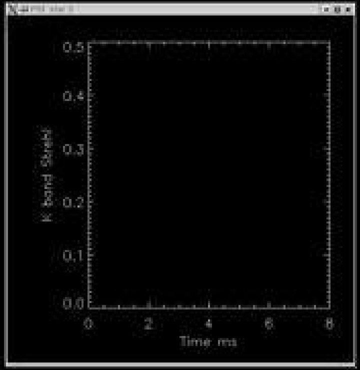
MCAO simulation

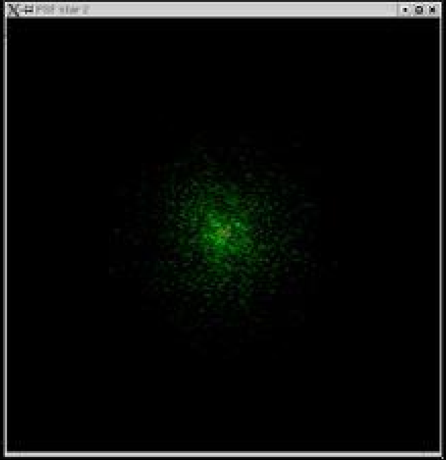


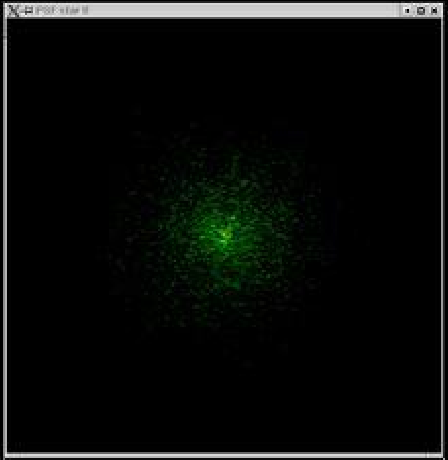


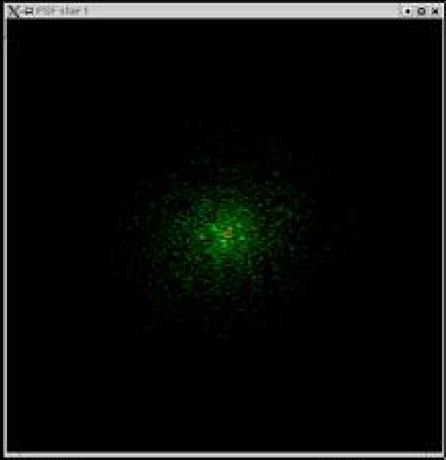


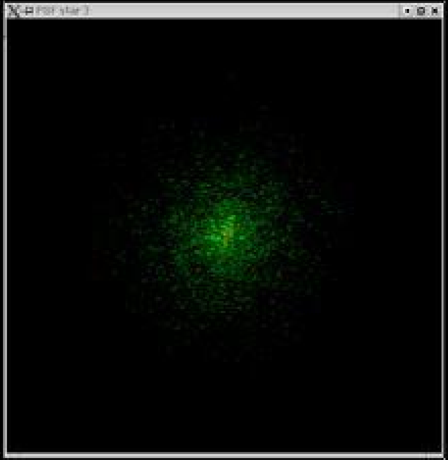


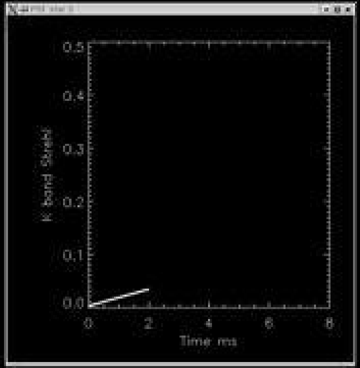



PSF star 2


PSF star 0


PSF star 1


PSF star 3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K band Strehl
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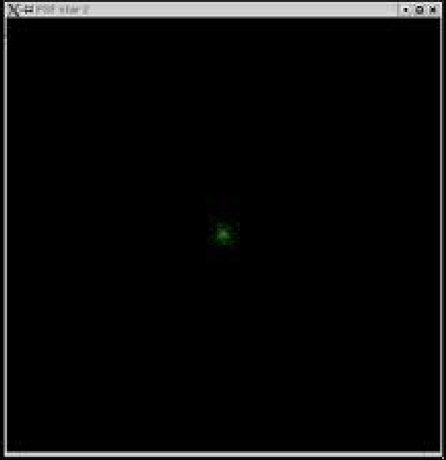
Time ms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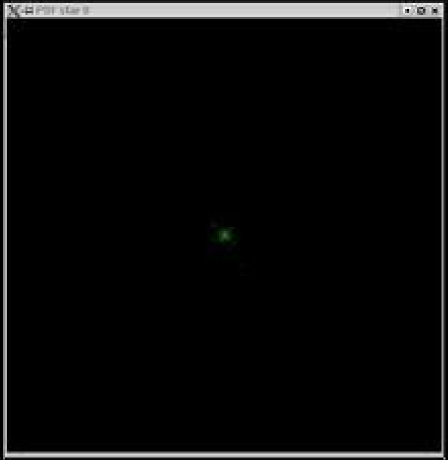
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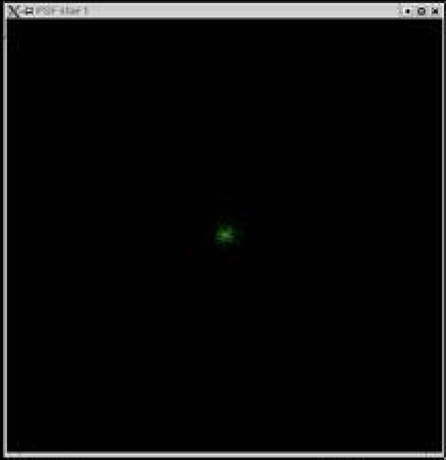
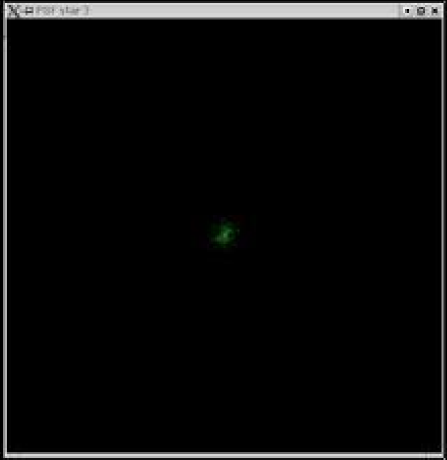
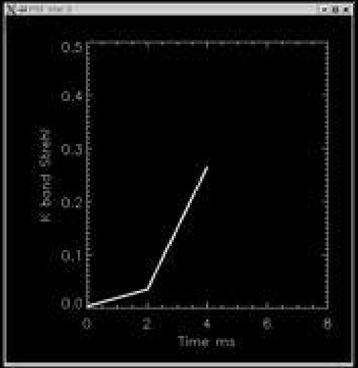

PSF star 1


PSF star 3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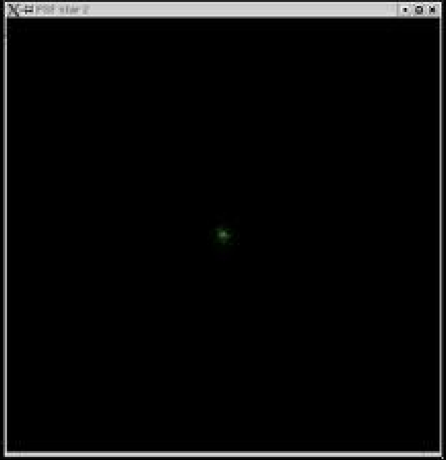
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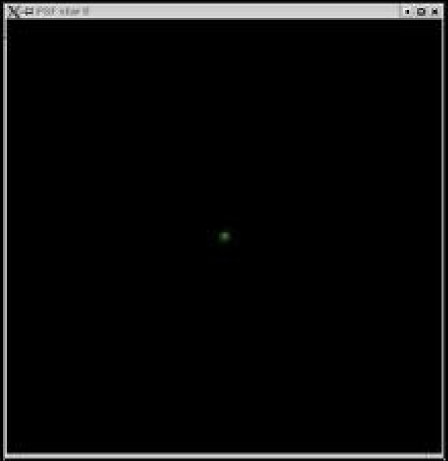
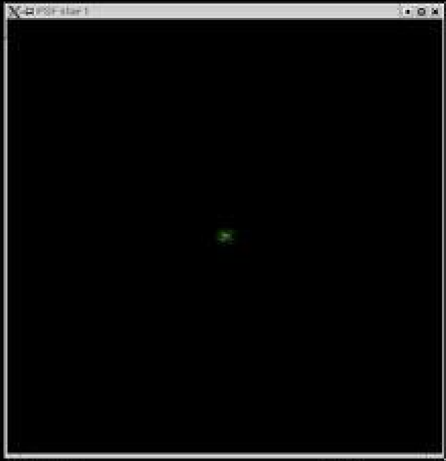
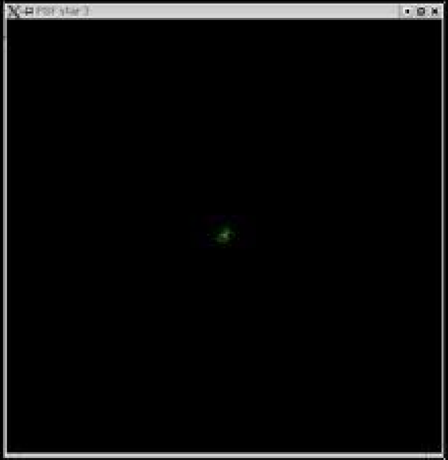
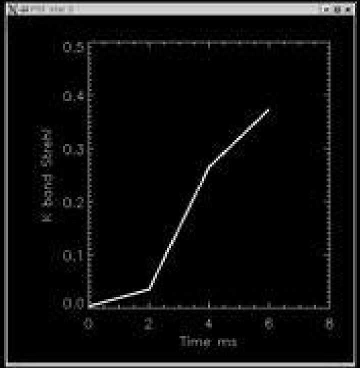
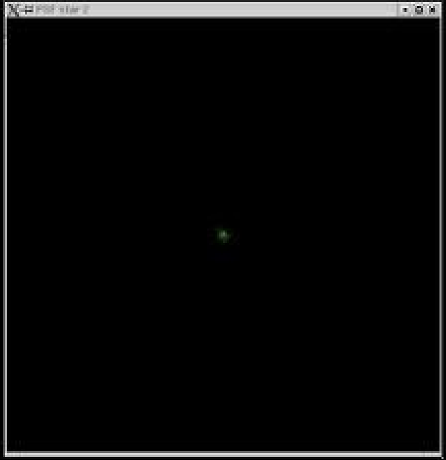

PSF star 0

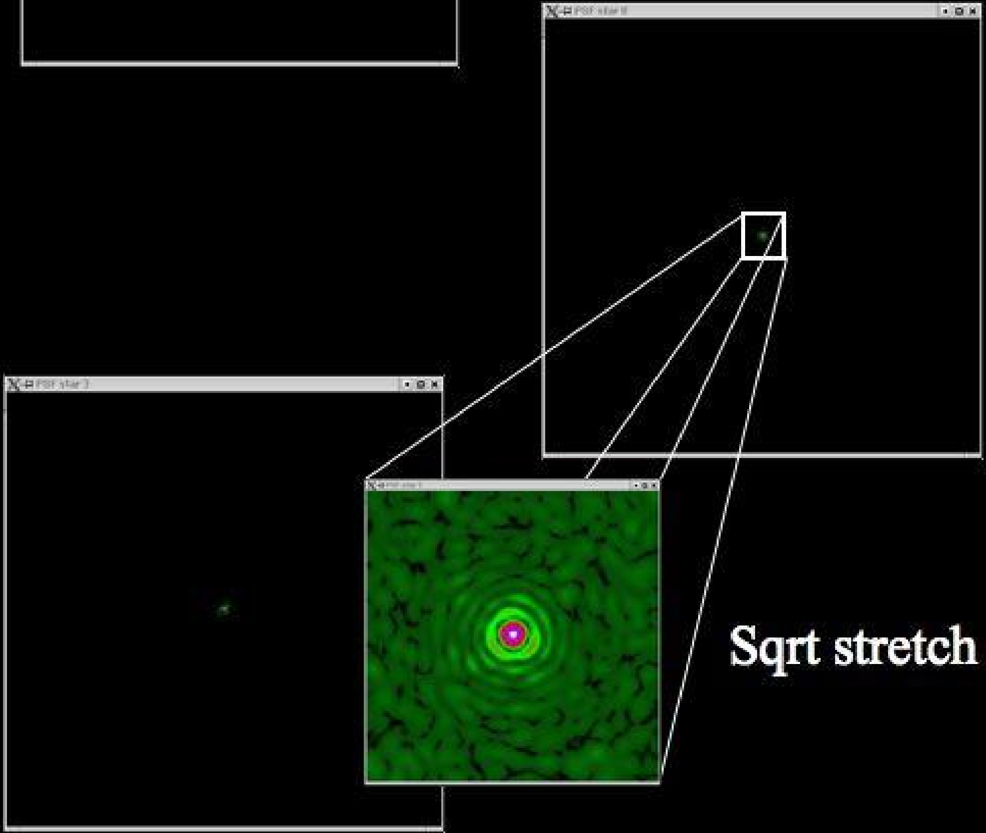

PSF star 1


PSF star 3

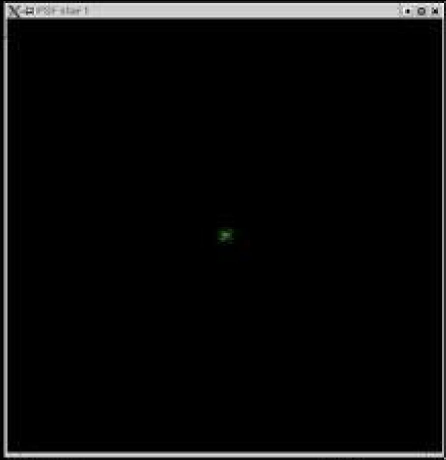

PSF star 0
0.5
0.4
0.3
0.2
0.1
0.0
K band Strehl
0
2
4
6
8
Time ms

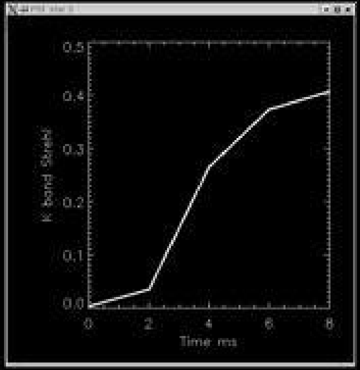
Total FOV: 2' (diameter)
100m telescope, K-Band
FWHM: ~5mas, Sr ~ 30-40%
2 DMs (8k - 9k actuators)
3 NGSs (100x100 Shack-Hartmann)





Sqrt stretch

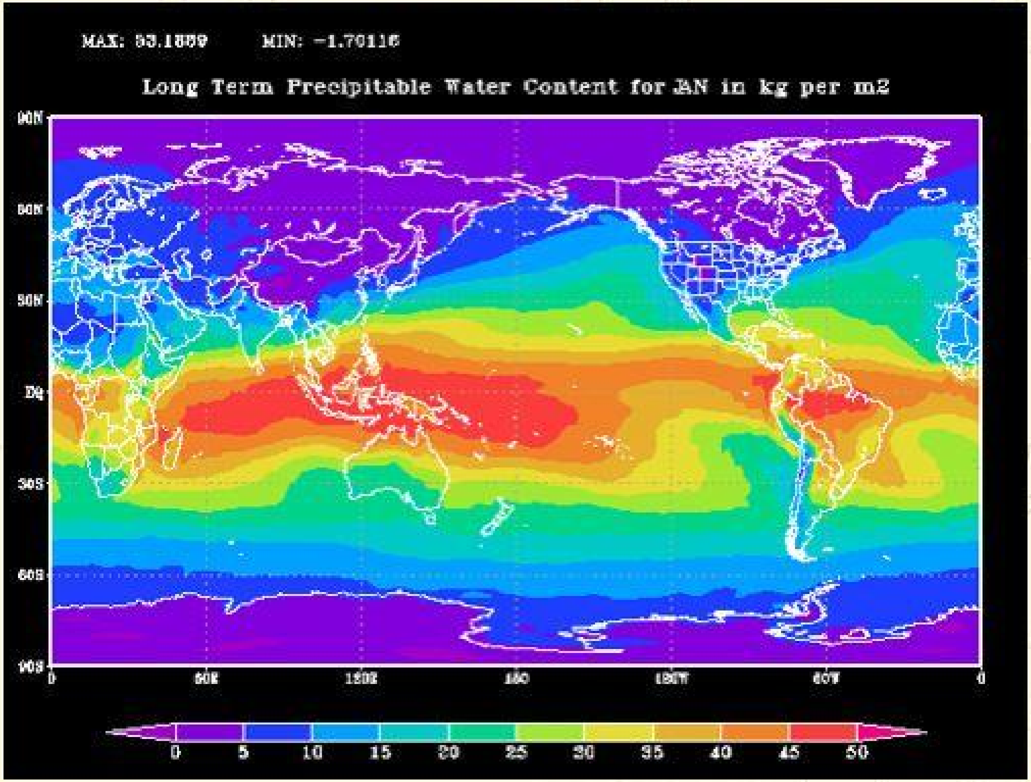




The challenges *cont'd*

- **Site selection**

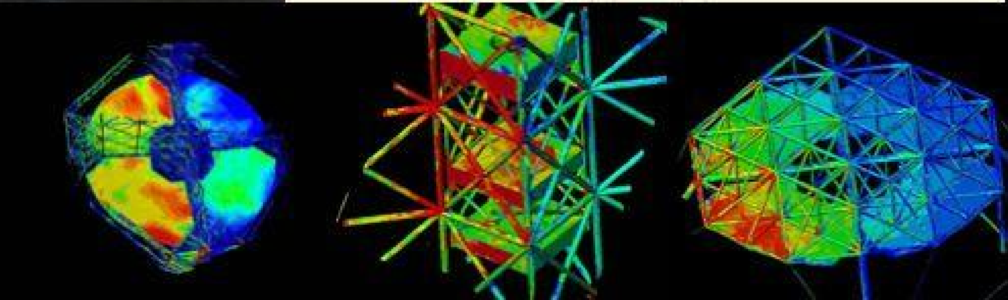
NCEP / NCAR PRECIPITABLE WATER CONTENT 1948-2001

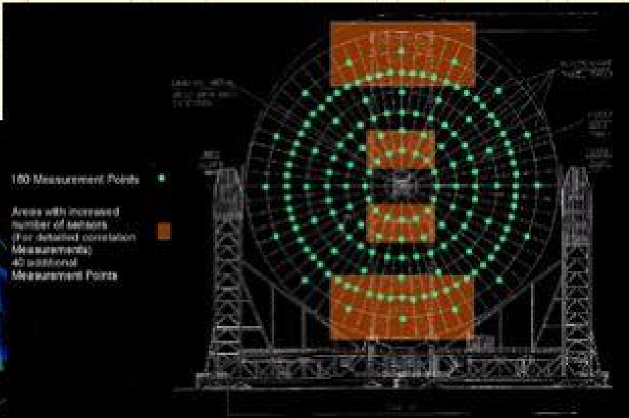


FRIOWL, University of Fribourg

The challenges *cont'd*

- **Wind**
  - Control system
  - Design
  - Brute force (enclosure, screens,…?)
  - A lot of work being done (CFD, wind tunnel, experiments, etc)

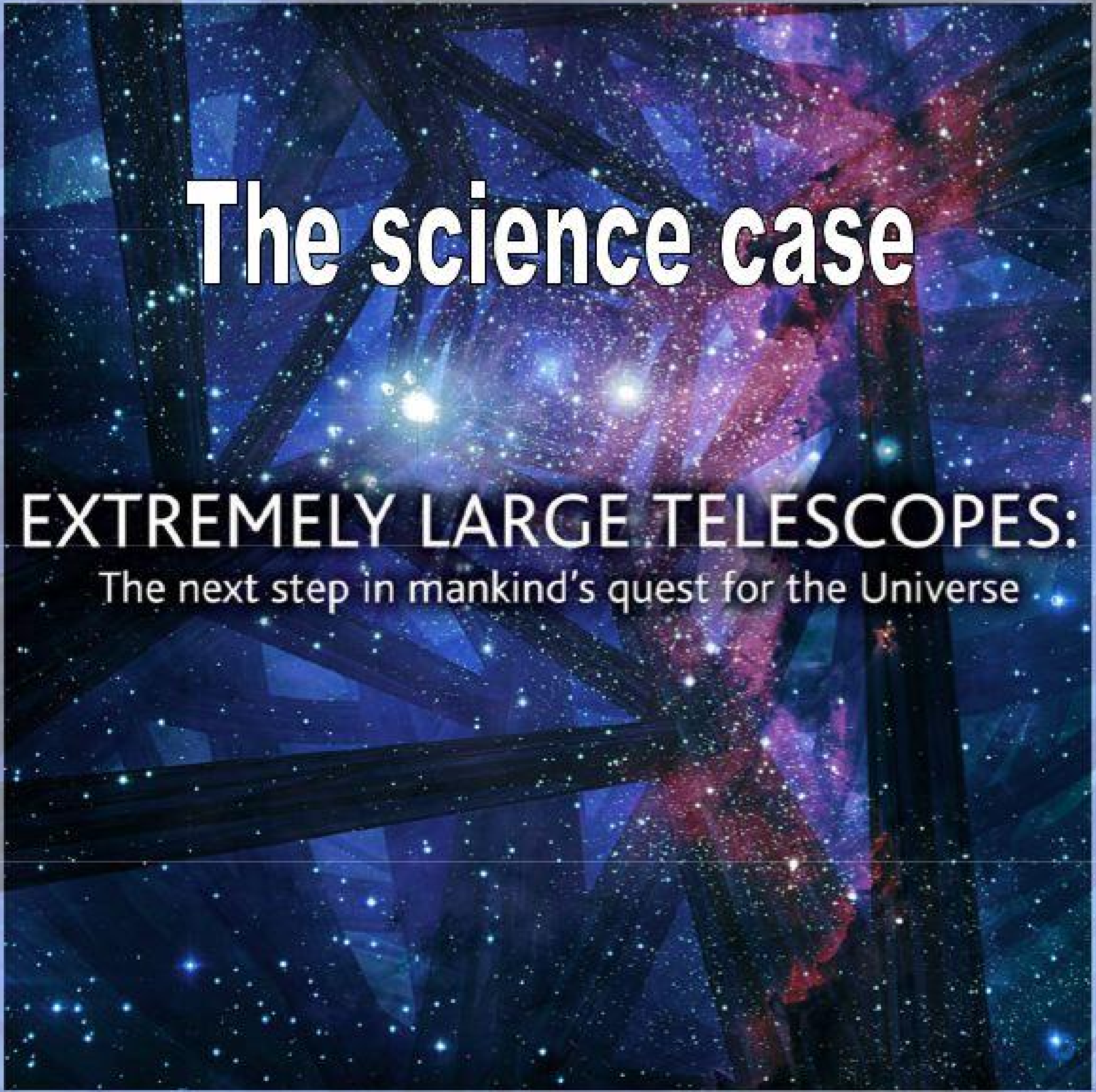




The challenges *cont'd*

- **The instruments**
  - A **LOT** of pixels
  - "easy" for single point sources
    - Beam size ~ D x slit ~ D x 1/D ~ const
  - Not easy at all for other applications
    - Though an F/30 camera is better than a F/0.5!
  - Large multiplex required
  - Large stability required
  - Physics experiment-like approach?
  - Active control?
- **Collaboration ESO-community**
  - Instrument designs from science cases (see talk by Sandro D'Odorico)

The science case



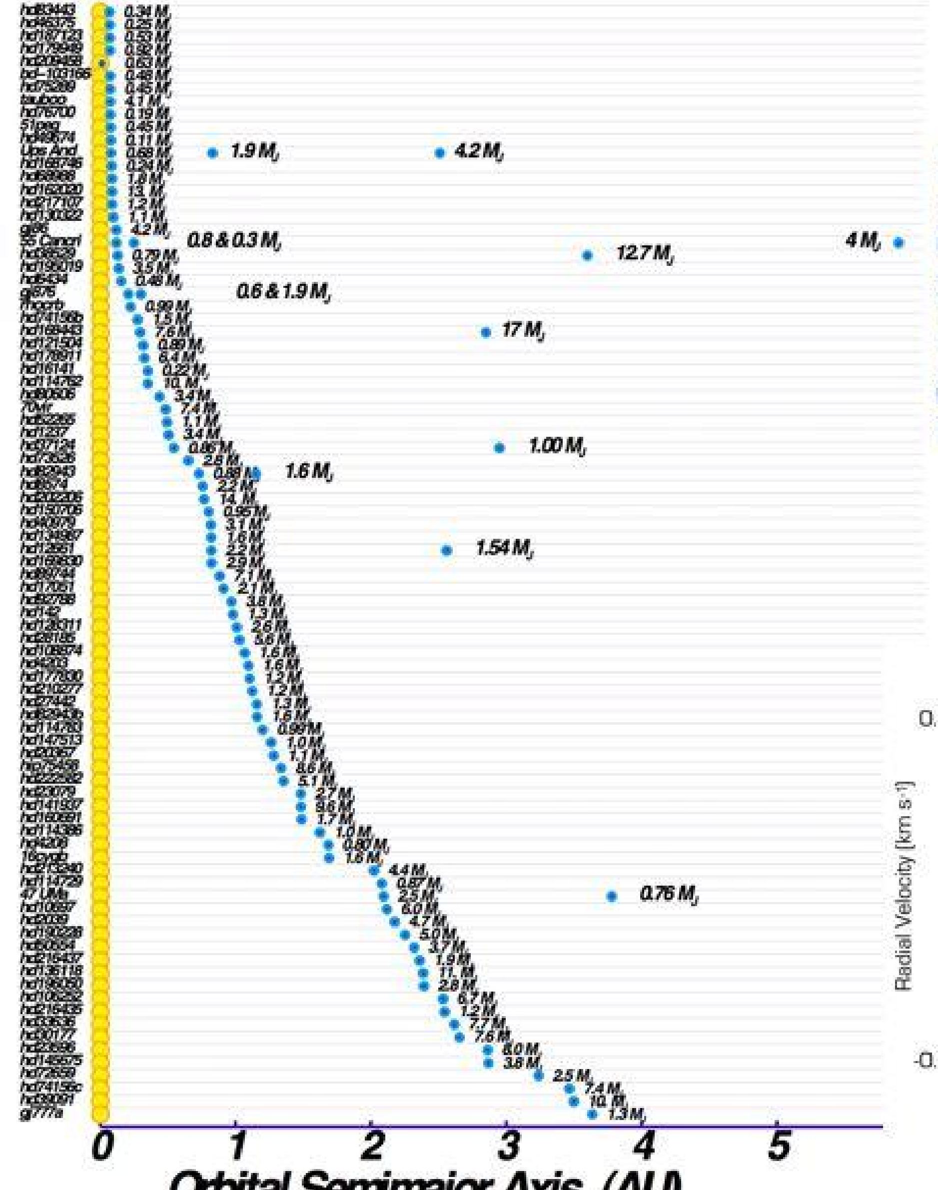
EXTREMELY LARGE TELESCOPES:

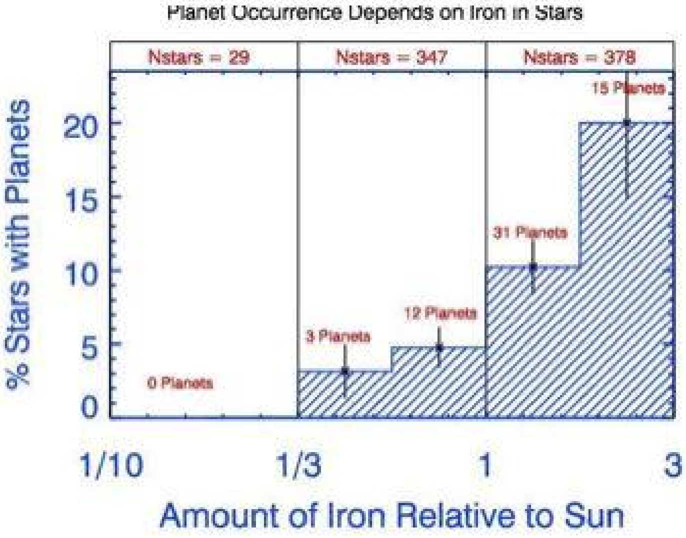
The next step in mankind's quest for the Universe

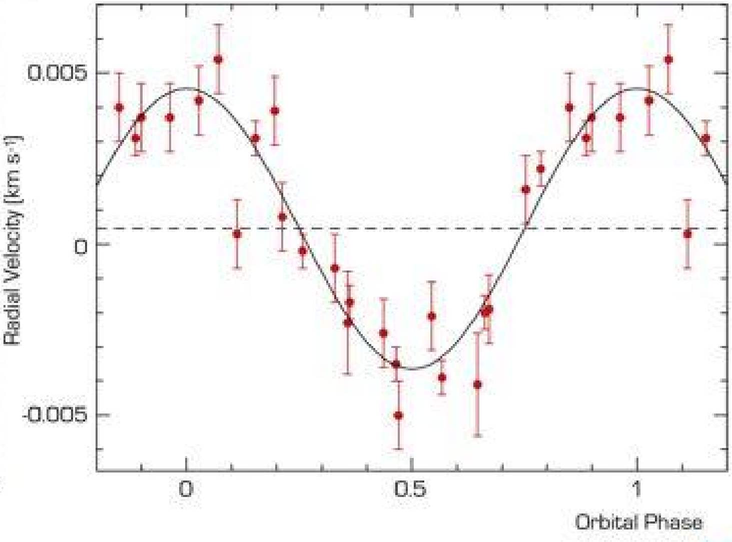
Science requirements*

- Choice of design driven by science
  - (new science)
  - Terrestrial planets in extra-solar systems
    - Imaging and spectroscopy (exo-biospheres)
  - Virgo or bust!
    - What is the stellar population of ellipticals?
  - Dark matter and dark energy
    - Map DM content (~80%), link to particle physics
  - Star formation history of the Universe
    - Evolution of the Cosmos from Big Bang to today
  - First objects and the re-ionization
    - Primordial stars and their role
  - Direct measurement of deceleration
    - No assumptions, no extrapolations, no models

(*) what we think today we will do with ELTs, which probably has little to do with what we actually will do







ESO PR Photo 05d/03 (22 January 2003)

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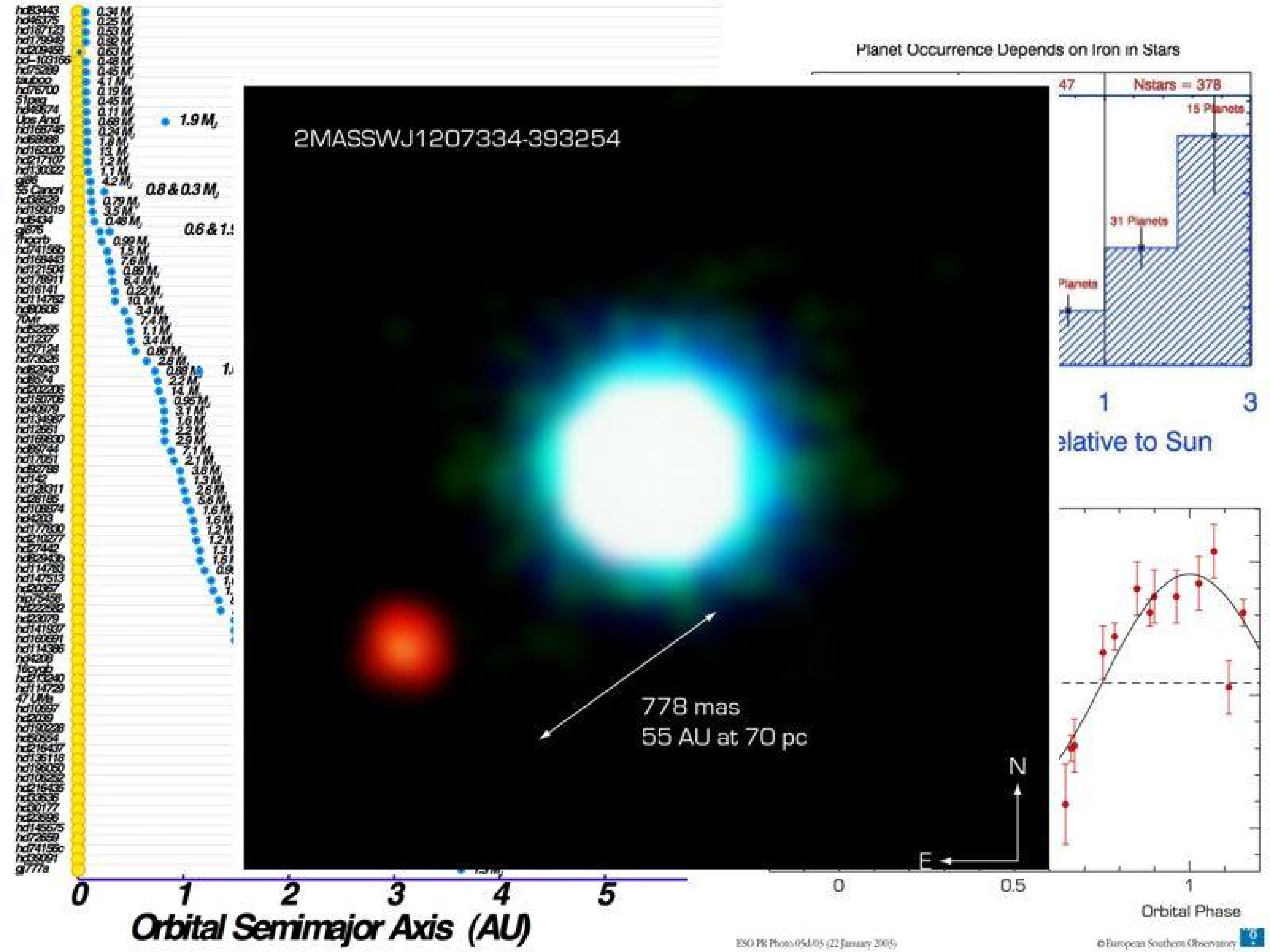

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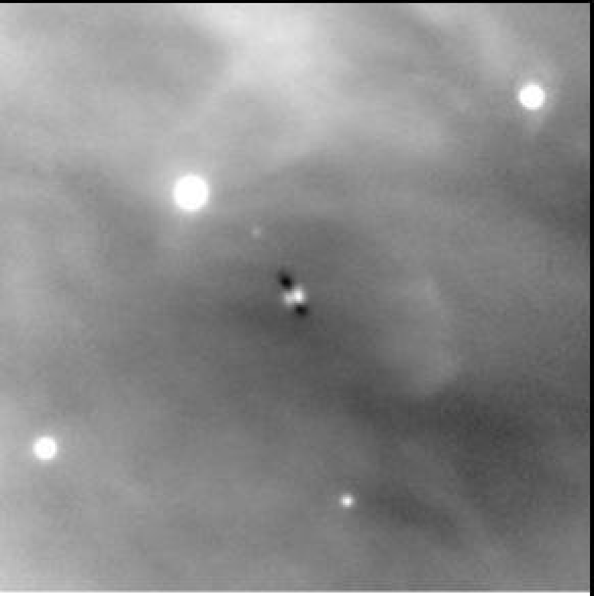
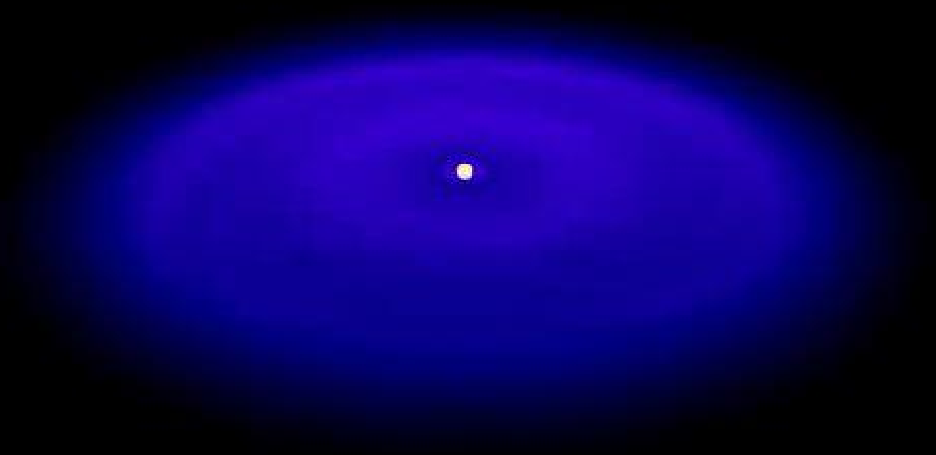
We think we know how they form

So we expect earth-like ones to exist…

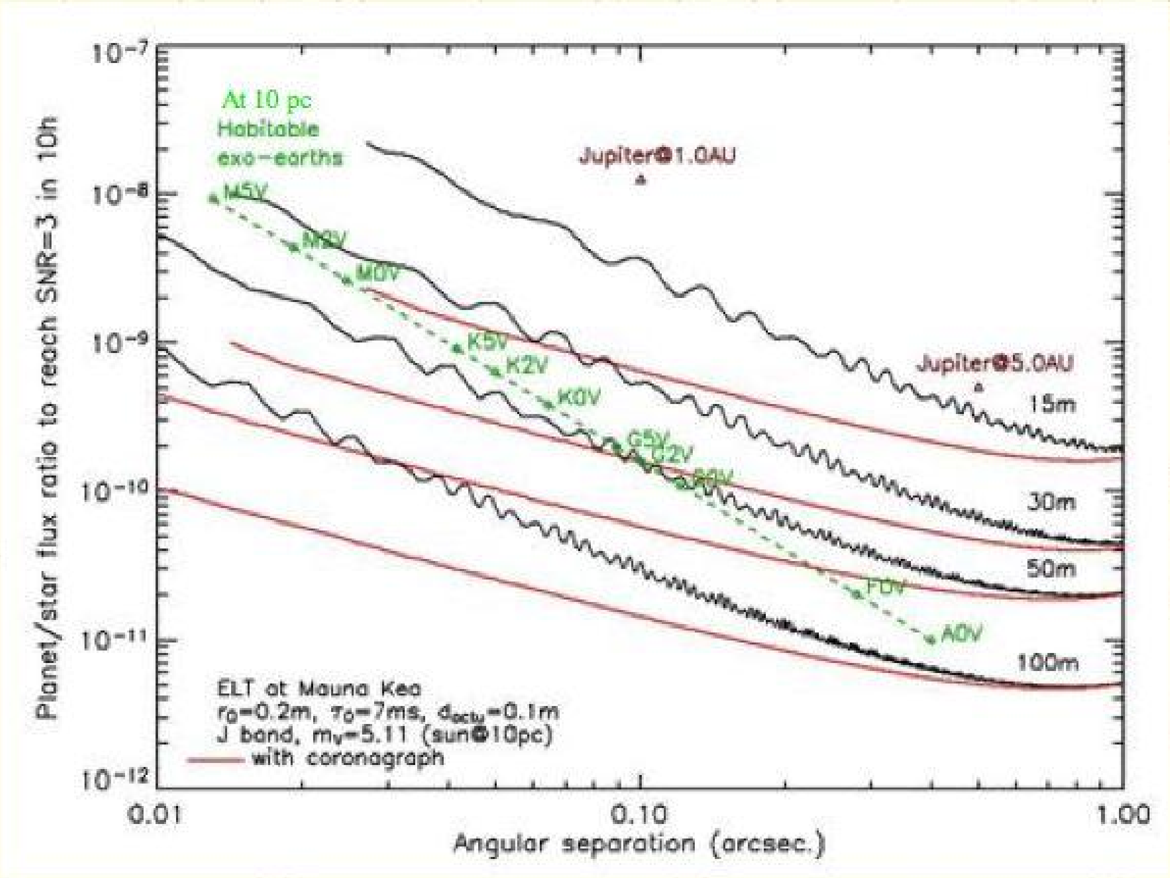


Silhouette Disk Orion 114-426 (J_s- band)



Density fluctuations
in protoplanetary disks

Detecting exo-earths



Lardiere et al 2003

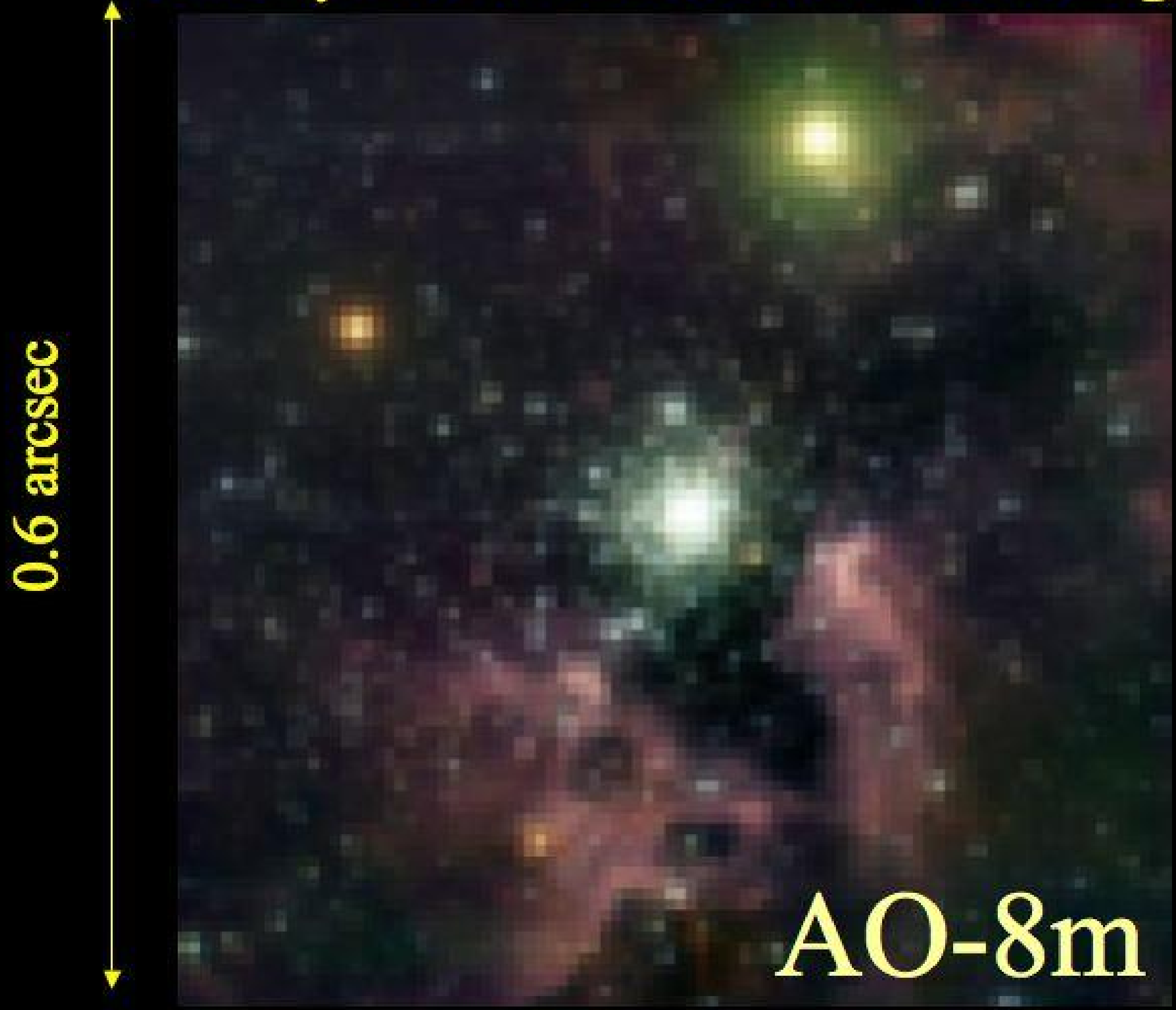
Quest for high-contrast imaging

- Coronagraphy
- Nulling interferometry
- Multi-Conjugated Adaptive Optics
- eXtreme Adaptive Optics
- Simultaneous Differential Imaging

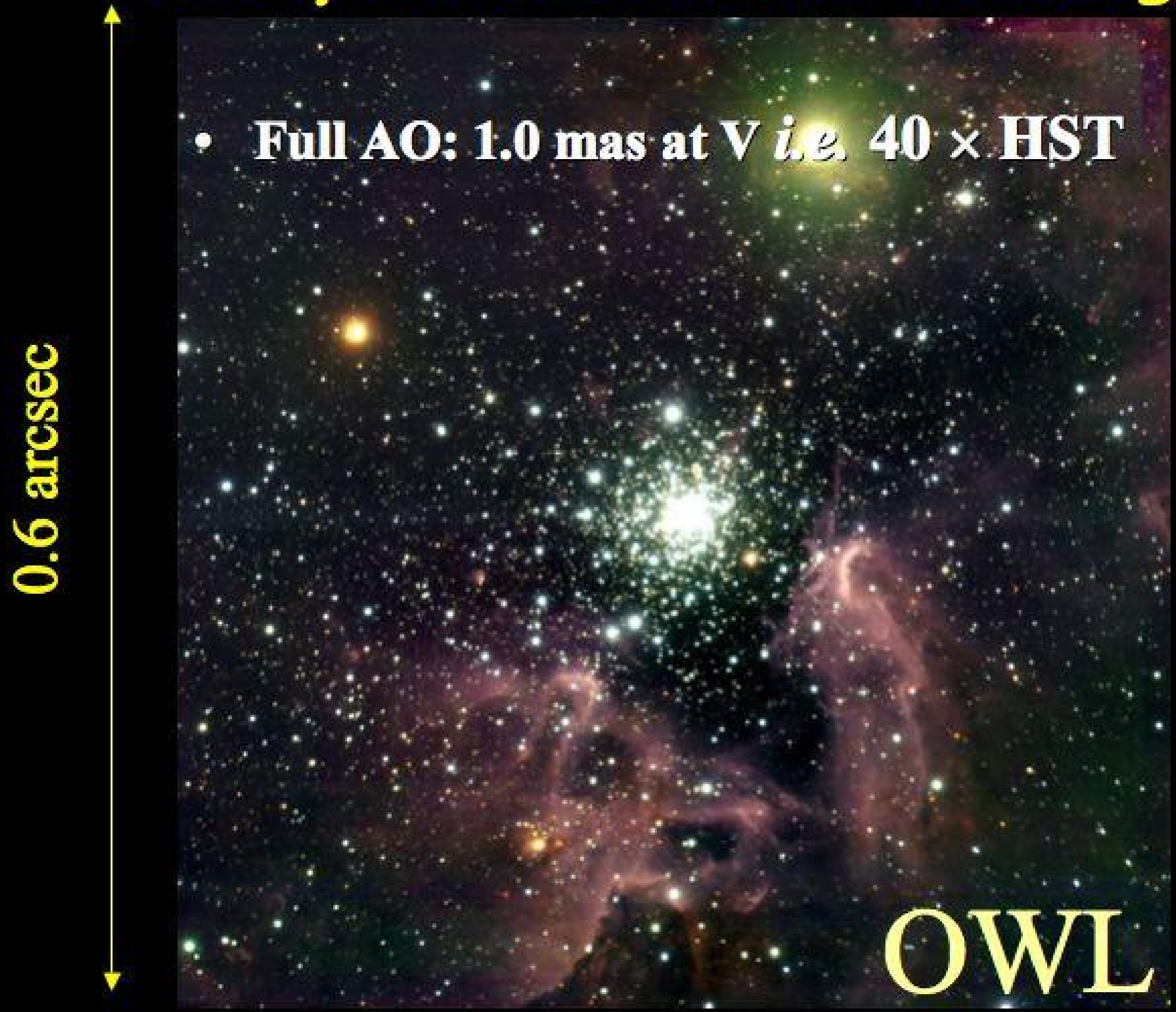
The spatial resolution challenge

The spatial resolution challenge

The spatial resolution challenge



The spatial resolution challenge



- **Full AO: 1.0 mas at V *i.e.* 40 × HST**

Limiting mag in 10^h: V=38

Sensitivity and Field-of-view

Simultaneous Differential Imaging

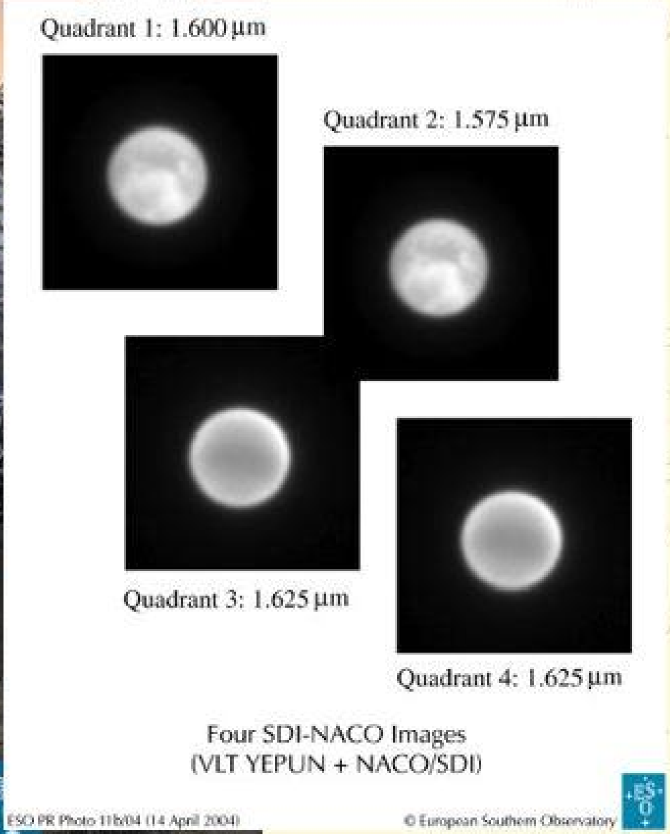
Adaptive Optics

- @ Specific wavelengths
- Cancel the speckles in real time

→Very high contrast (~50k)

- Today on NaCo, VLT UT4

  Hartung, Close, Lenzen et al, A&A July 2004



Four SDI-NACO Images
(VLT YEPUN + NACO/SDI)

ESO PR Photo 11b/04 (14 April 2004)

© European Southern Observatory

Simultaneous Views of Titan's Surface and Atmosphere
(VLT YEPUN + NACO/SDI)

ESO PR Photo 11c/04 (14 April 2004)

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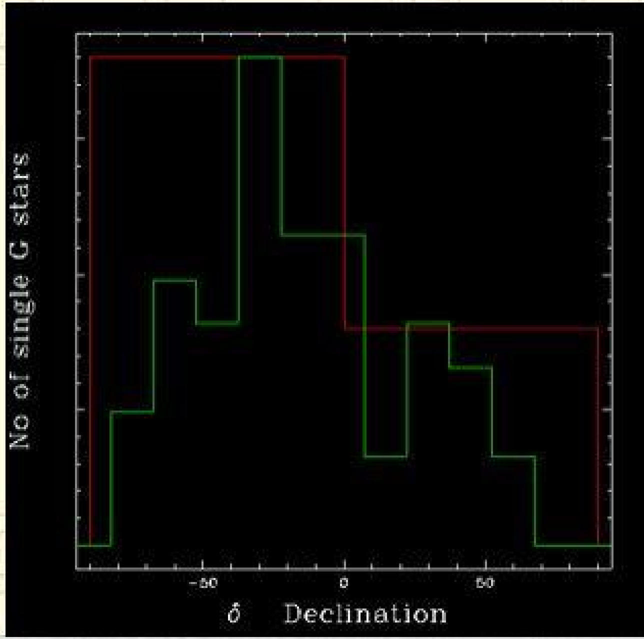
Exo-earths: strong dependence on D

- **Accessible volume ∝ D^3**

  30m: 20 G stars (*)

  60m: 165 G stars

  100m: 750 G stars



- **Sensitivity**

  Science case ∝ D^4

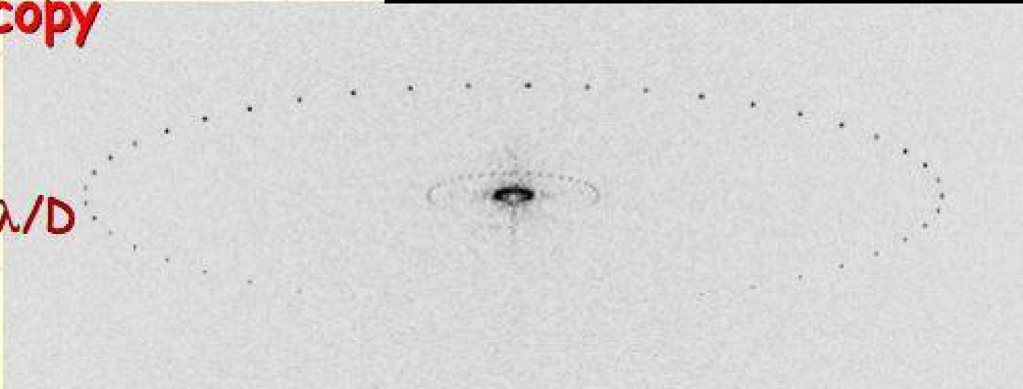
  → to reach same S/N:

  $t_{30m} = 123 \times t_{100m}$

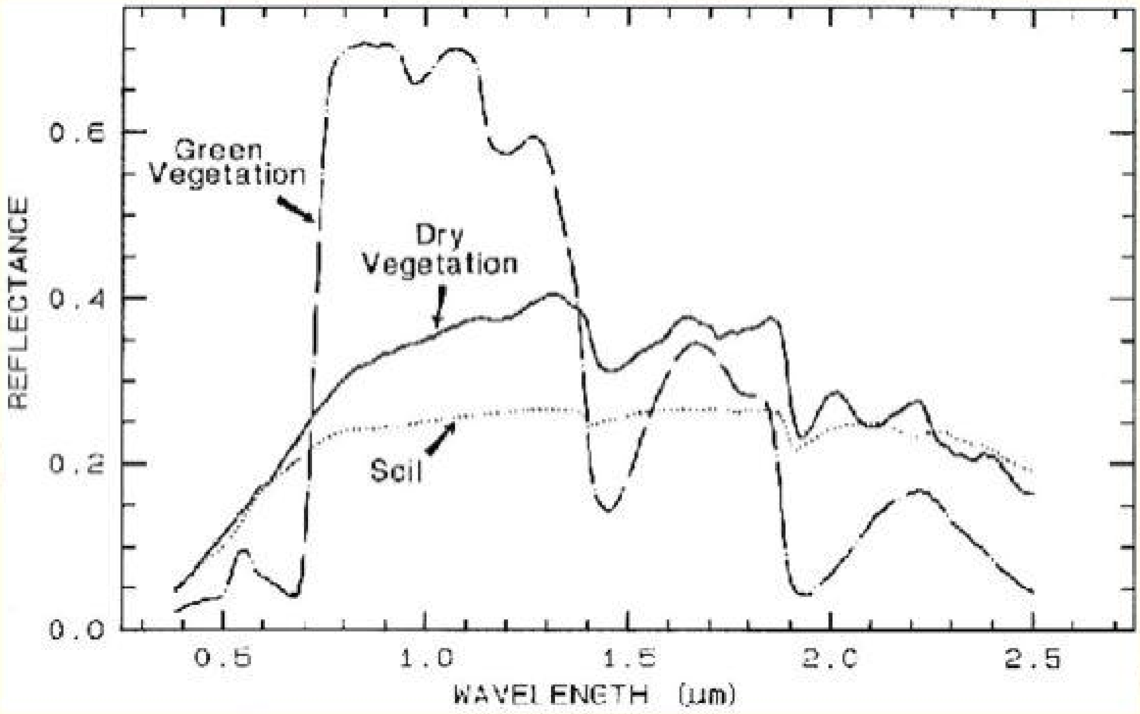
- **Spectroscopy**

  D ≳ 80m

(*) ∀ $d_{min} = 5\,\lambda/D$



Detecting vegetation



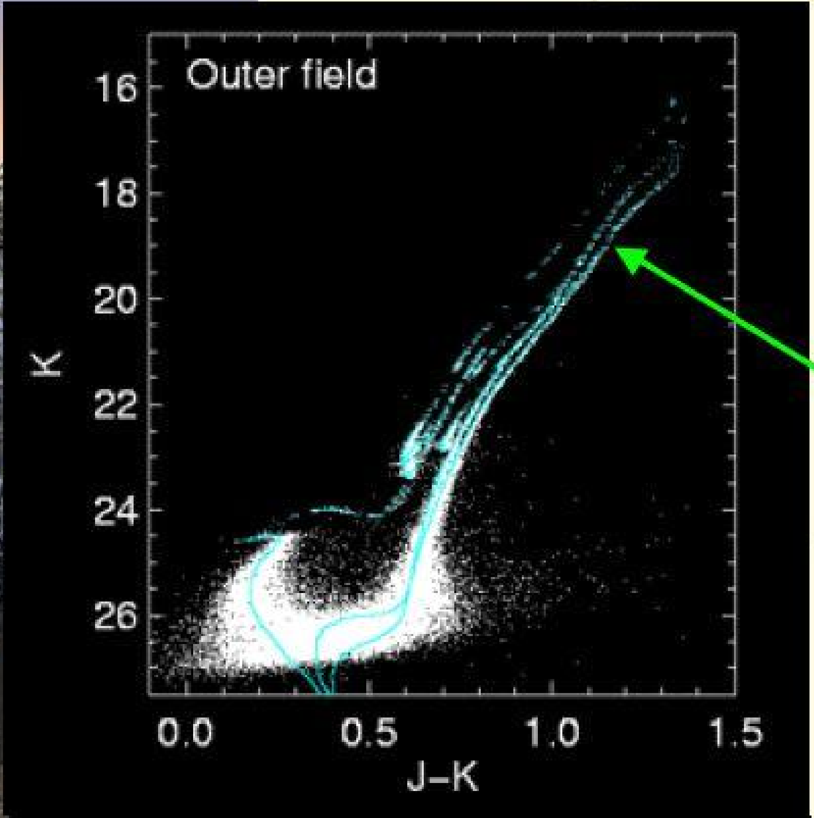
Arnold et al 2002

Exo-earths: detection comparison

(Angel, 2003)

telescope		wave (μm)	mode	S/N	(earth@10pc, t=24h)
space interf	4x2m	11	nulling	8.4	Darwin, TPF
space filled	7m	0.8	coronagr	5.5-34	JWST or HST successor
Antarctic	21m	11	nulling	0.52	GMT
		0.8	coronagr	5.9	
ground	30m	11	nulling	0.34	Celt, GSMT
		0.8	coronagr	4.1	
ground	100m	11	coronagr	4.0	OWL
		0.8	coronagr	46	
Antarctic	100m	11	coronagr	17	BOWL=better OWL
		0.8	coronagr	90	

Resolved Stellar populations and Galaxy Formation



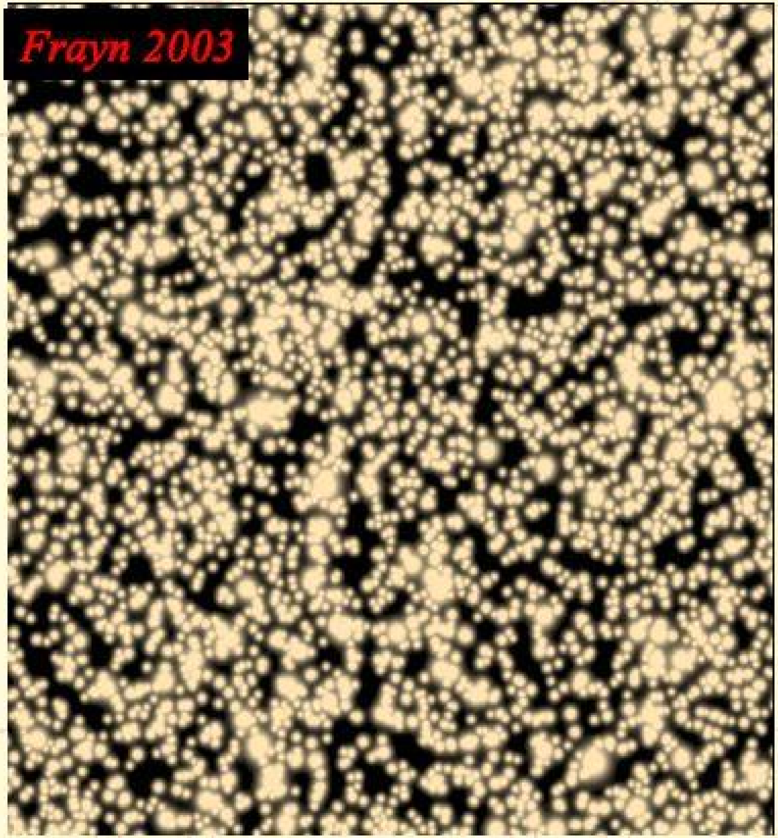
Simulated M32 CM Diagram Observed with 30-m Telescope *from GSMT study*

- We can learn a lot about the formation and evolution of our nearby neighbours with a 30-m telescope

E.g. Colour-mag diagram reveals multiple stellar pops

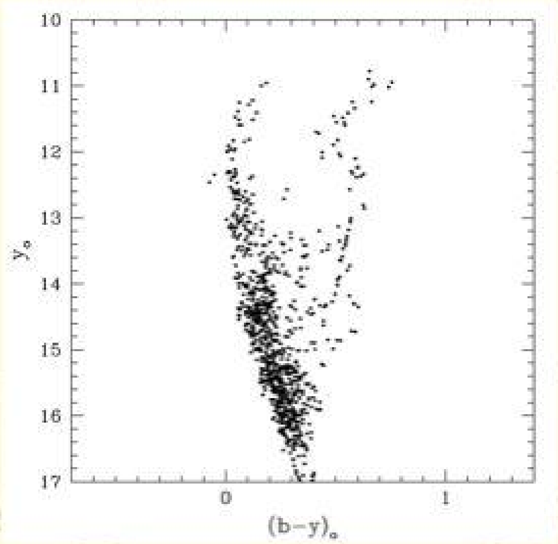
- What about a more representative slice of the Universe?

Simulated M87 field observed with 100-m telescope



Frayn 2003

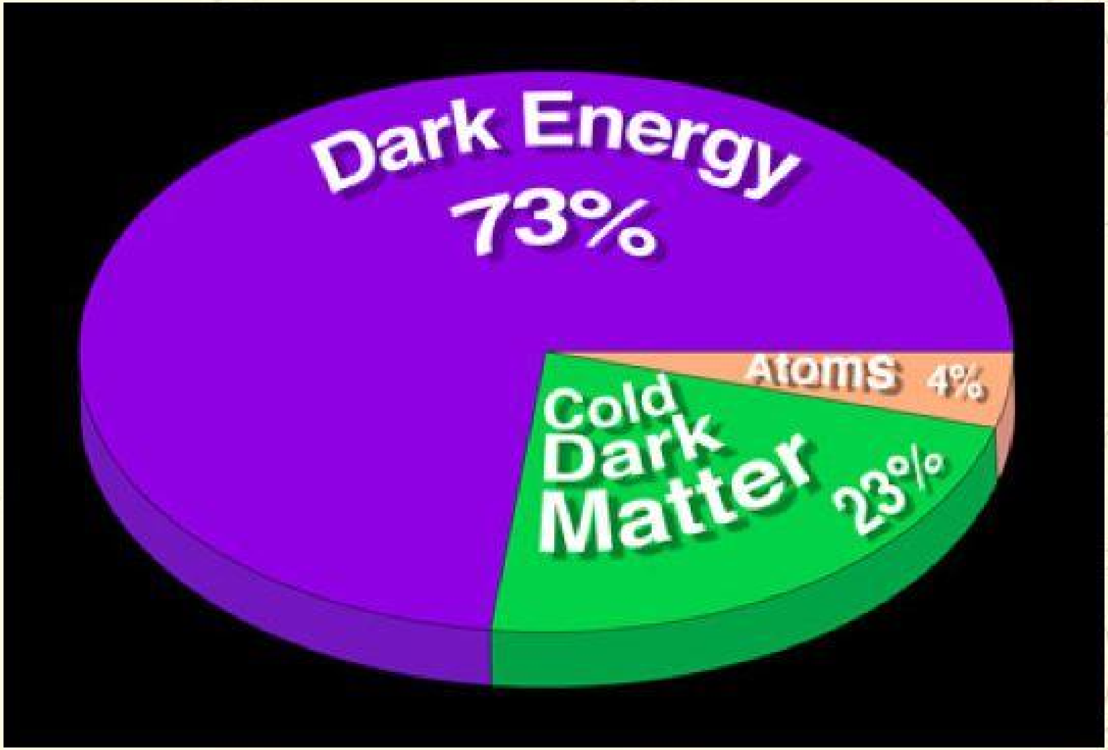
- 3 hour exposure
- Diffraction-limited observation
- Outer field ($\mu I = 28$)
- Realistic IMF plus population synthesis to two magnitudes below MSTO



Simulated observations with a 50m *by Peter Linde*

Need ~100m to reach Virgo
Need AO-corrected imaging over 10 arcsec - preferably in optical

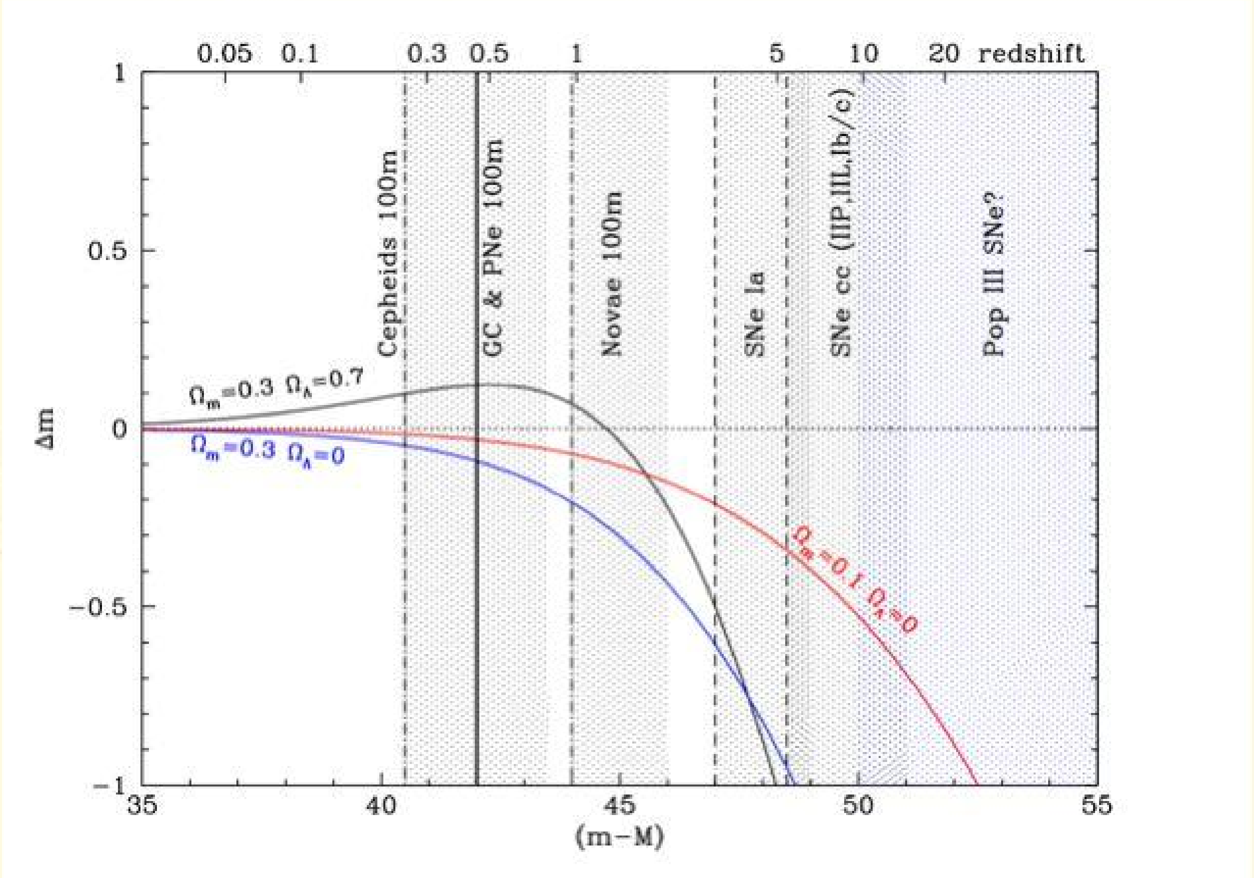
Cosmology:
96% of Universe unaccounted for



It is indeed embarrassing that 95% of the universe is unaccounted for: even the dark matter is of quite uncertain nature, and the dark energy is a complete mystery

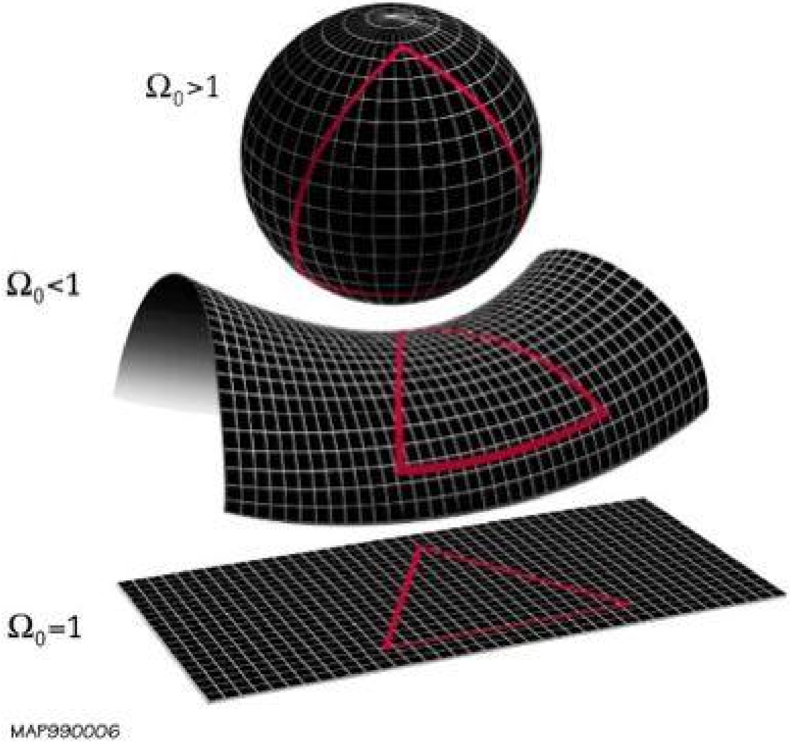
Sir Martin Rees, Astronomer Royal

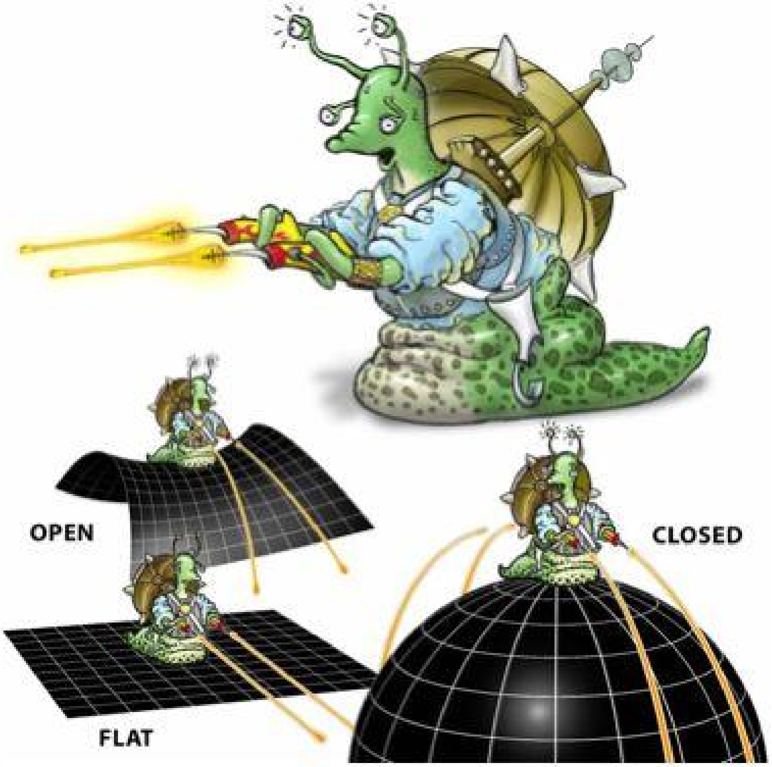
Measure of cosmic parameters with primary distance indicators



Note: NOT H_NOT ☺

Geometry

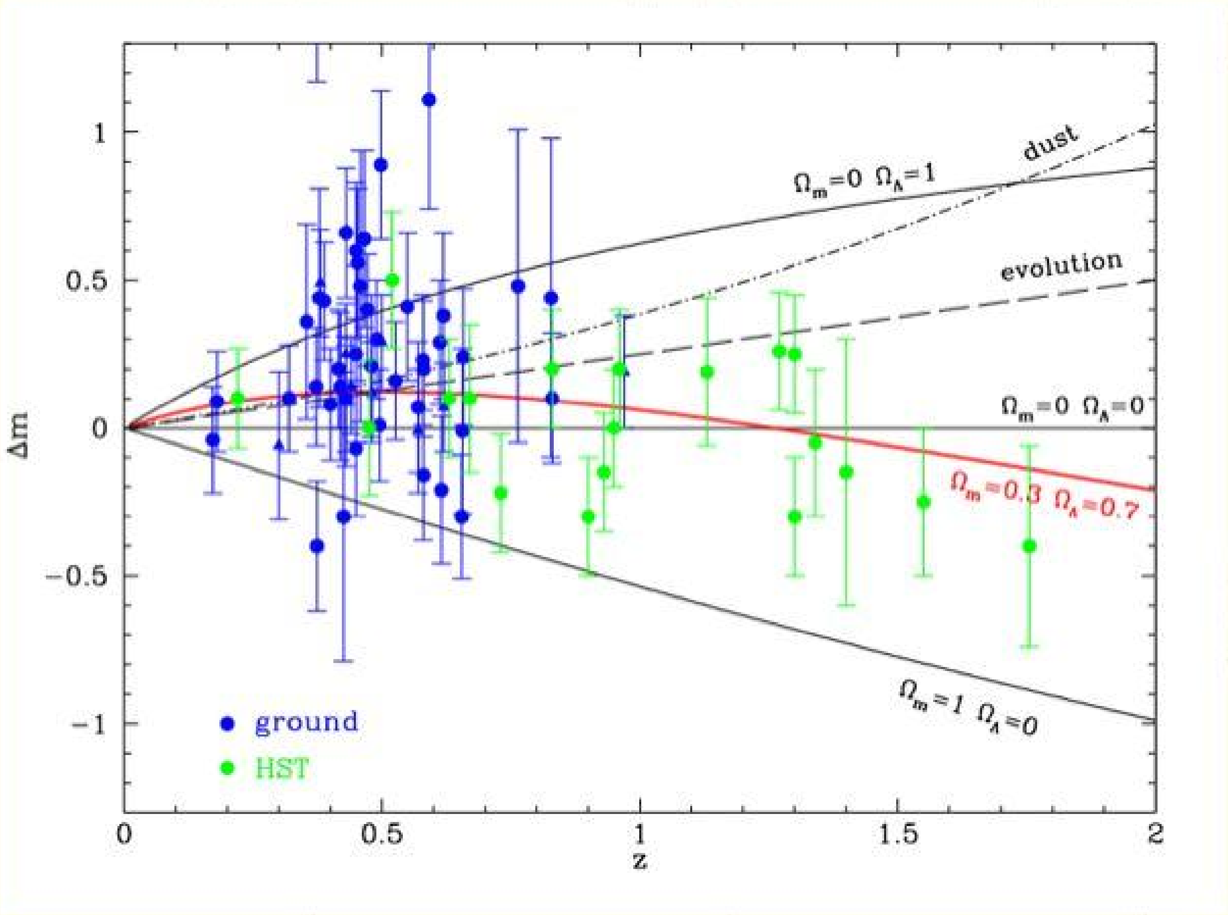




WMAP has shown that the Universe is flat

Science with OWL: a practical case

- The cosmic SN rate up to z ~ 10
  - Simulations of OWL observations yield:
    - Jx3+Hx3+Kx7: ≥ 200 SNe (extrapolating Miralda & Riess 1997) or ≥ 400 SNe (MDP 1998)
      - Light curves, photometric redshifts (galaxy & SN)
    - Spectroscopy $\Re\sim50$: ~ 50-100 SNe at z < 4.5
  - Spectral classification:
    - **SNe Ia visible up to z ~ 5**
      - Blind below 2400A, K last useful band
    - **SNe II visible up to z ~ 10**
      - Strong UV emitters (time-dilated UV flash)
    - **Pop III SNe (?)**
      - Possibly much brighter and visible to z ~ 20


Δm
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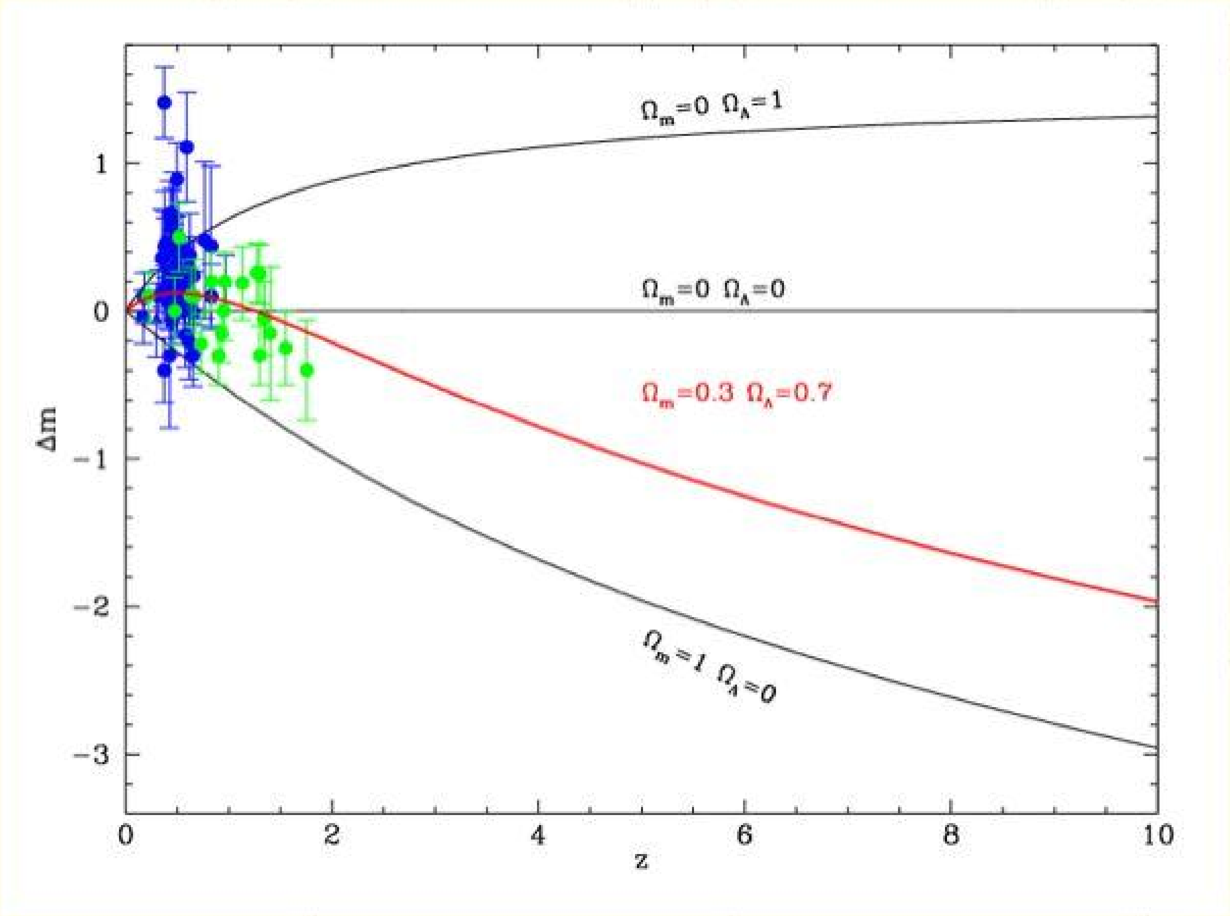
0
−0.5
−1
0
0.5
1
1.5
2
z
dust
$\Omega_m=0\ \Omega_\Lambda=1$
evolution
$\Omega_m=0\ \Omega_\Lambda=0$
$\Omega_m=0.3\ \Omega_\Lambda=0.7$
$\Omega_m=1\ \Omega_\Lambda=0$
● ground
● HST



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Ω_m=0 Ω_Λ=0
Ω_m=0.3 Ω_Λ=0.7
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Δm
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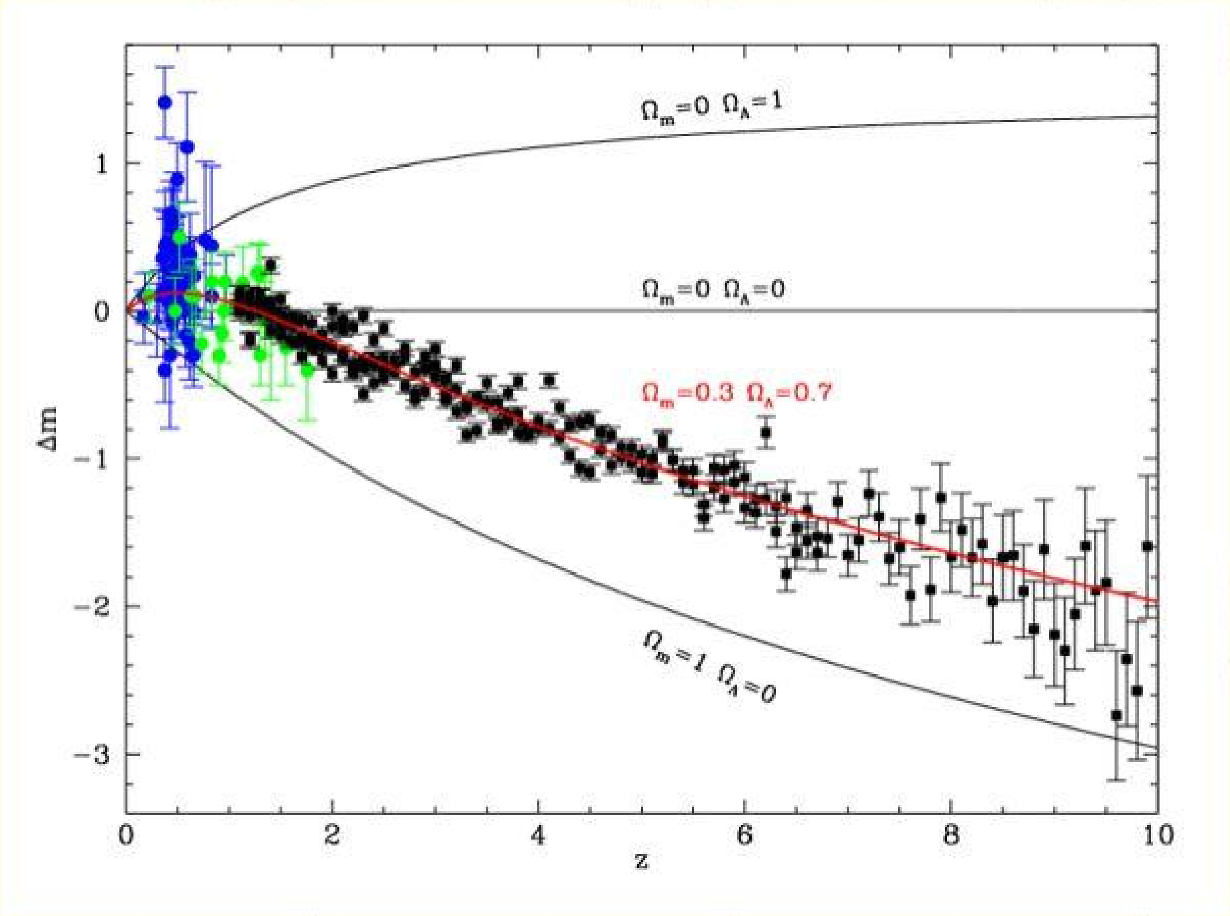
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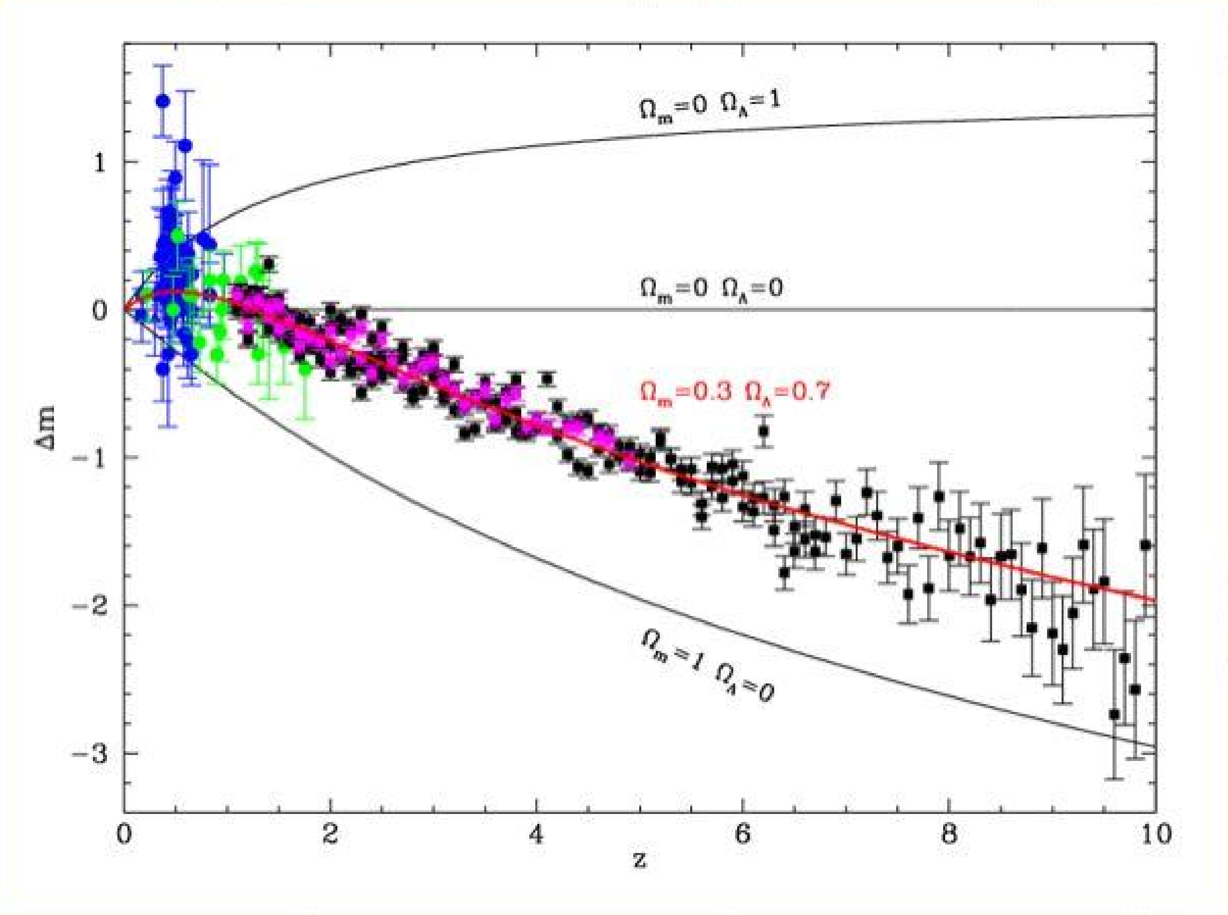
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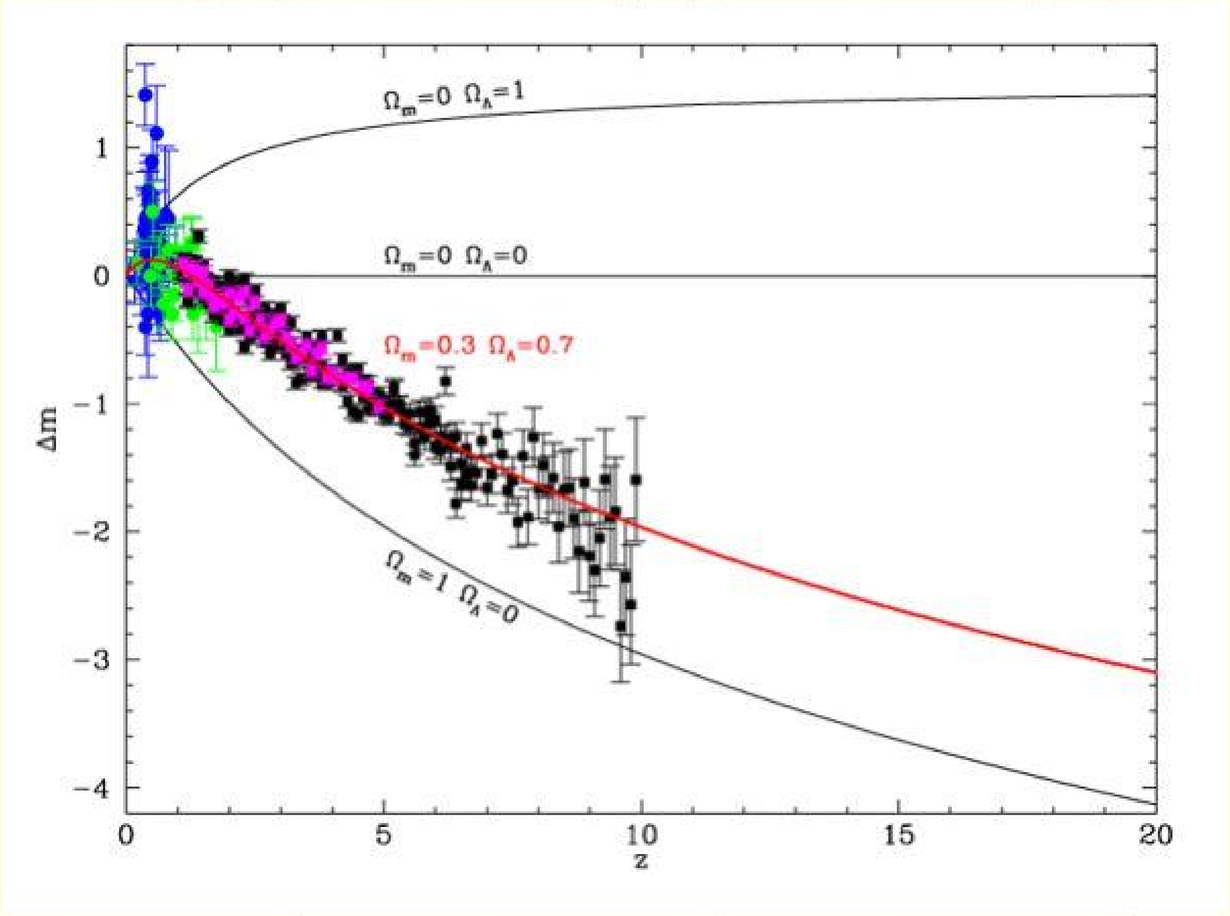
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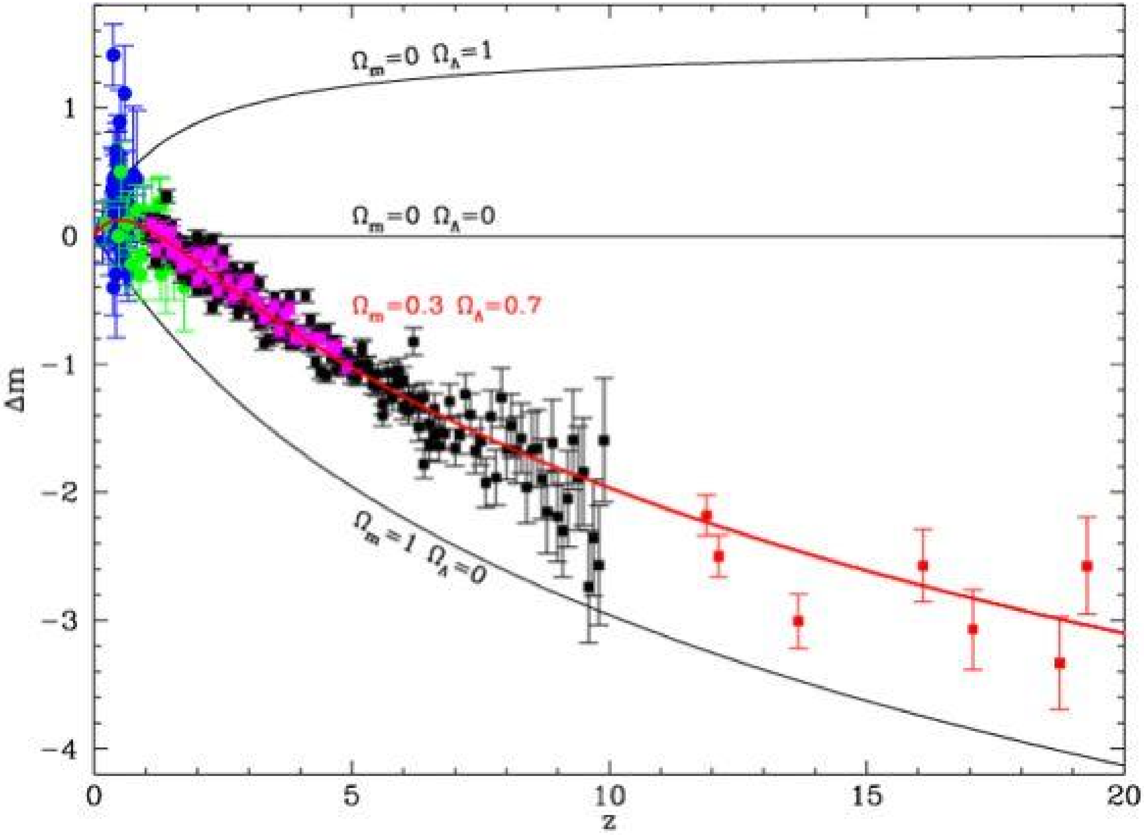

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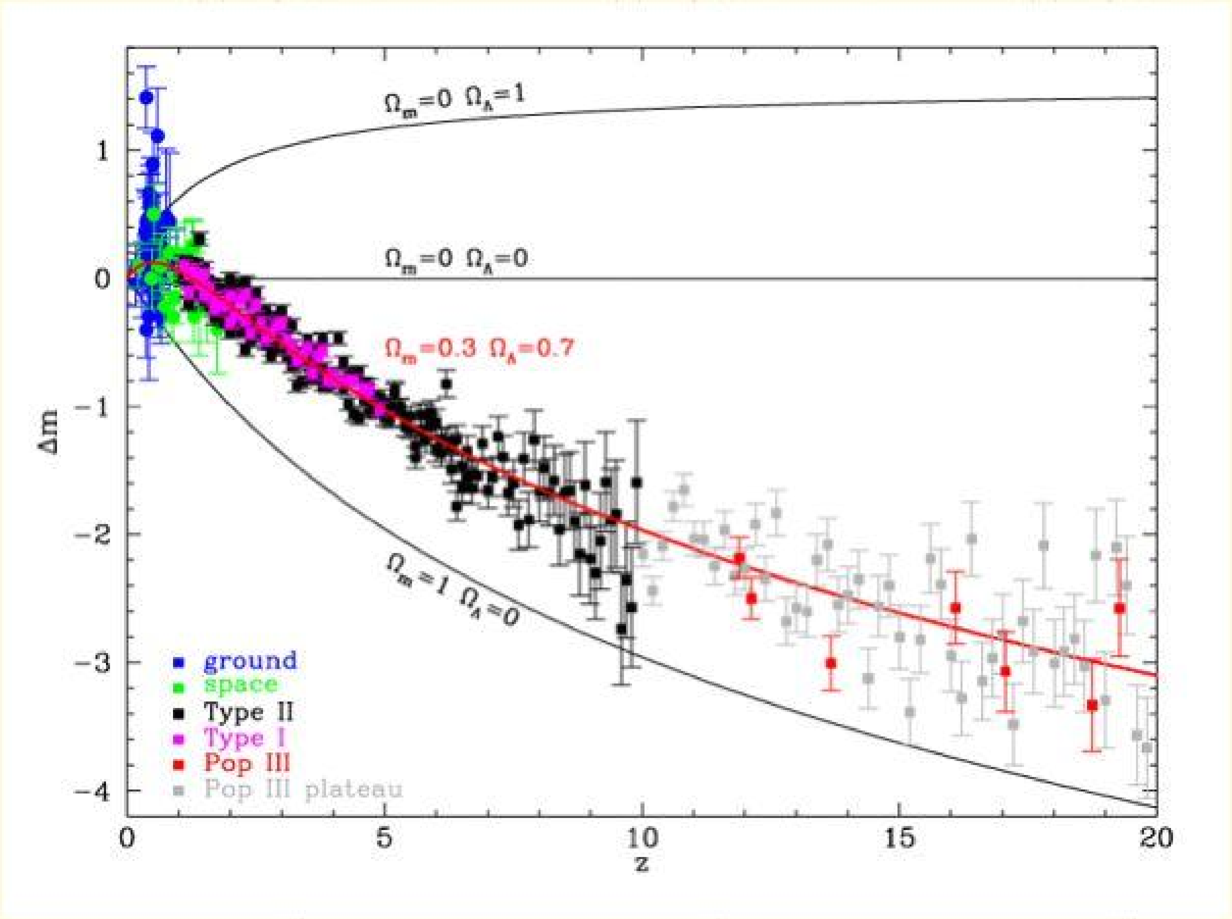

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$\Omega_m=1$ $\Omega_\Lambda=0$
Δm
1
0
−1
−2
−3
−4
0
5
10
15
20
z
■ ground
■ space
■ Type II
■ Type I
■ Pop III
■ Pop III plateau

Requirements from this case

- **Field of view**
  - 2x2 arcminutes
- **Resolution**
  - Diffraction limited at J
- **Pixel size: 0.5 λ/D ~ 1.6 mas**

➼ 75,000 x 75,000 > 5 G pix

(that's **>1m^2** for 15 μm pixels)

(at present cost of 10¢/pix this would be ~ **$500 million**)

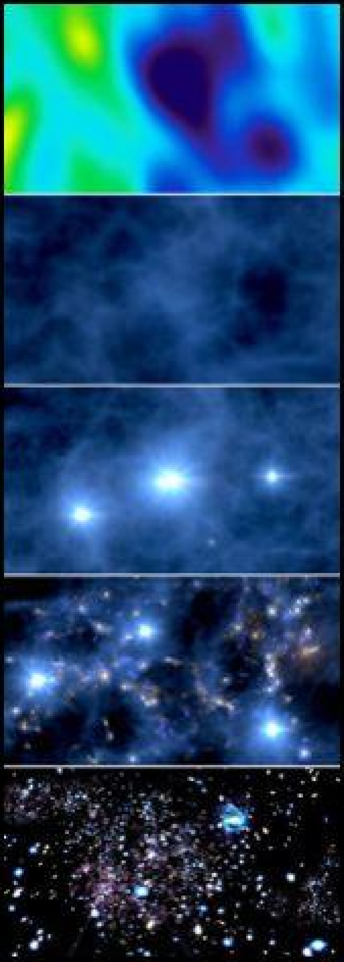
(hopefully controllers will be manageable by then)

What can be done?

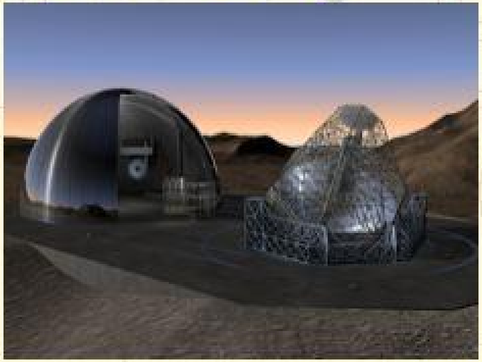
- Resize science case
  - Factors of a few are possible
- Smart focal plane coverage
  - Observe only where is needed
- This may reduce 10x-20x
- Need for a break-through
  - eg: mass production of astronomy-grade detectors should decrease cost
    - Volume up by > 100x

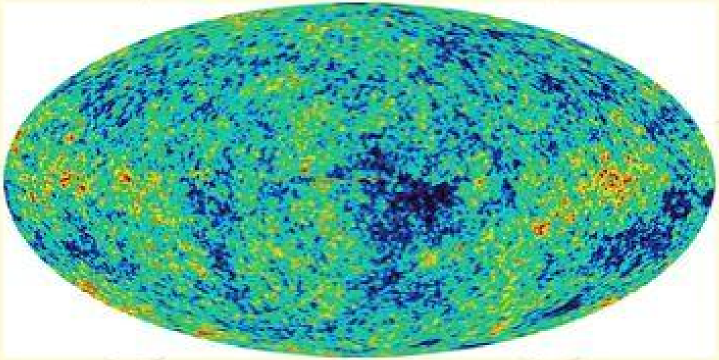
Back to dark matter…

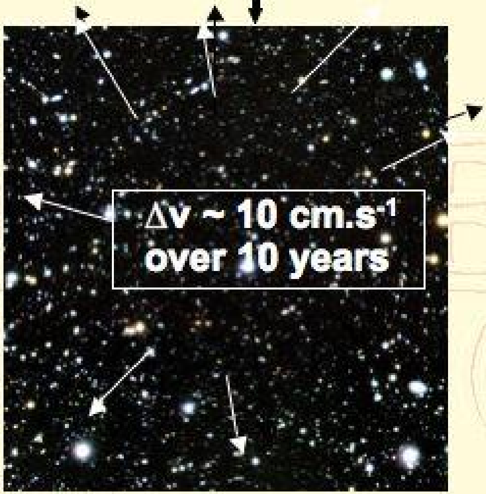
Gravitational Lens in Galaxy Cluster Abell 1689 HUBBLESITE.org z=49.000



Direct Measurement of q







$\Delta v \sim 10$ cm.s^{-1}
over 10 years

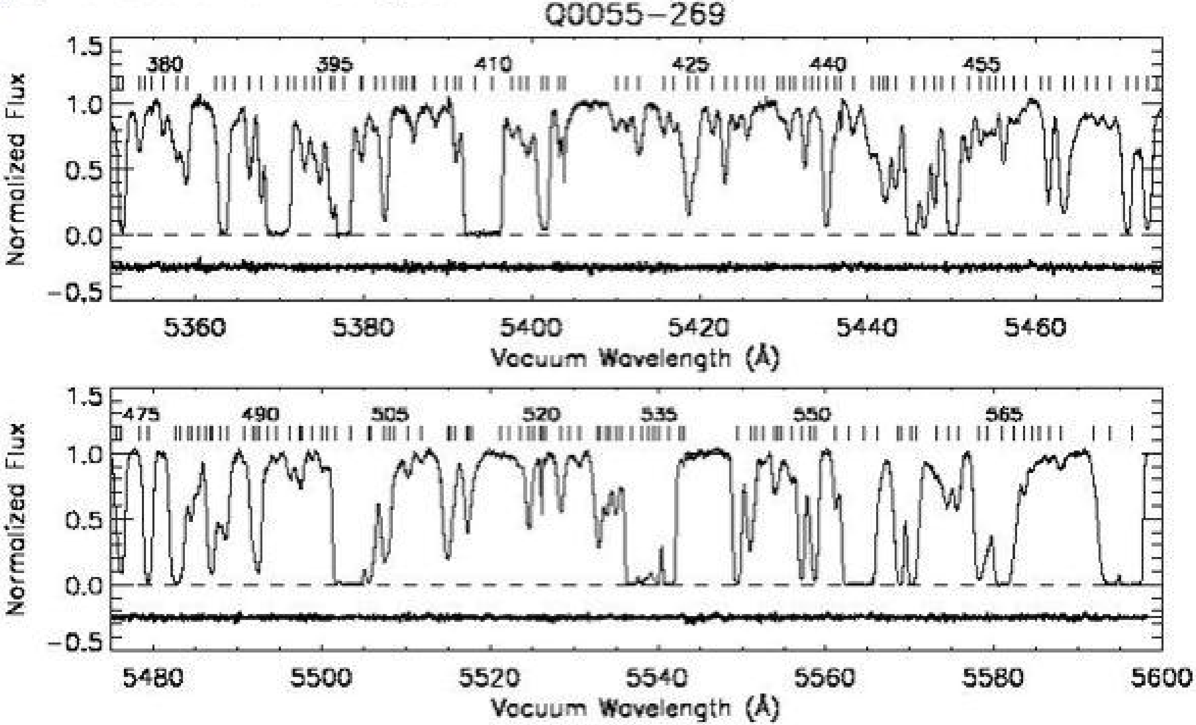
As for WMAP, this experiment with OWL would provide a direct cosmological measurement , albeit a different one: the Universe acceleration around z ~ 5

Direct Measurement of q

- direct measurement of cosmic deceleration
  - from 10 cm/s accuracy Lyα forest R.V. over 10 years (Loeb 1998; Cristiani et al. 2002)
- scientific feasibility ensured from:
  - $M_V < 17.5$ QSO samples done (HIRES/KECK – UVES/VLT)
  - high R.V. accuracy reached for exo-planets (e.g. HARPS)
  - high collecting power

Direct Measurement of q

Ly α forest of a z >3 QSO.

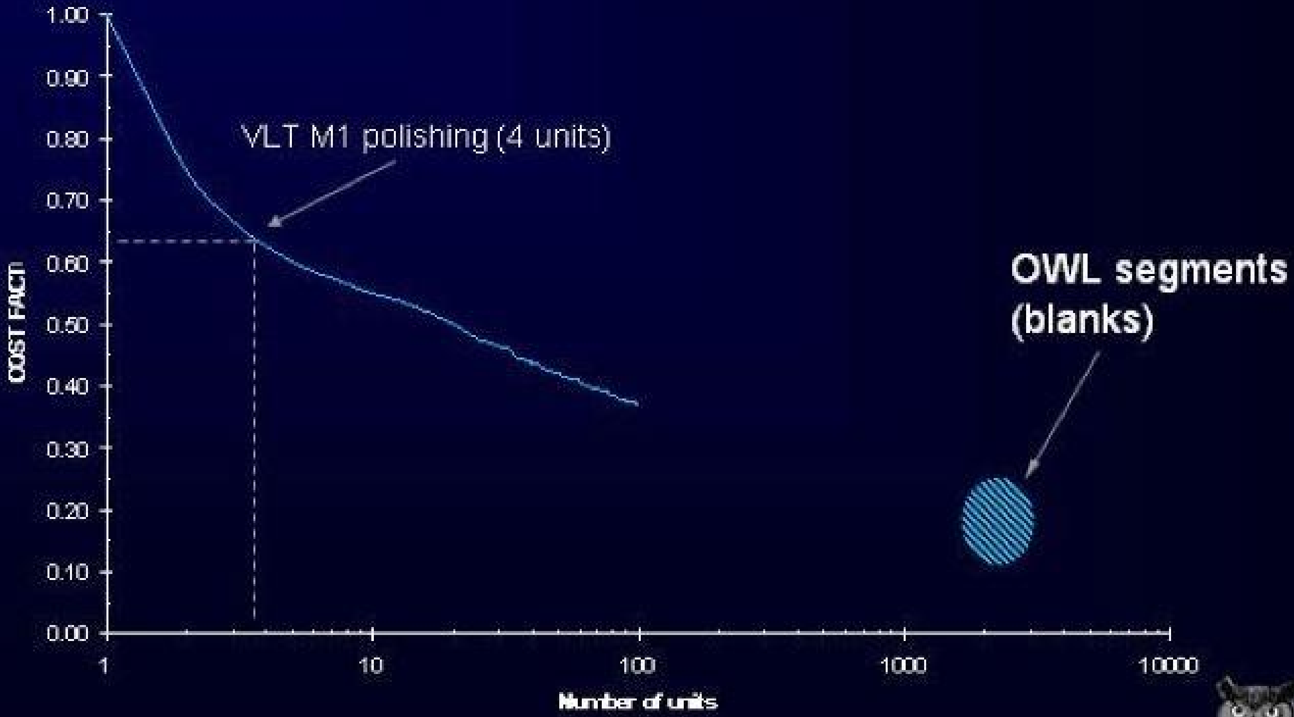


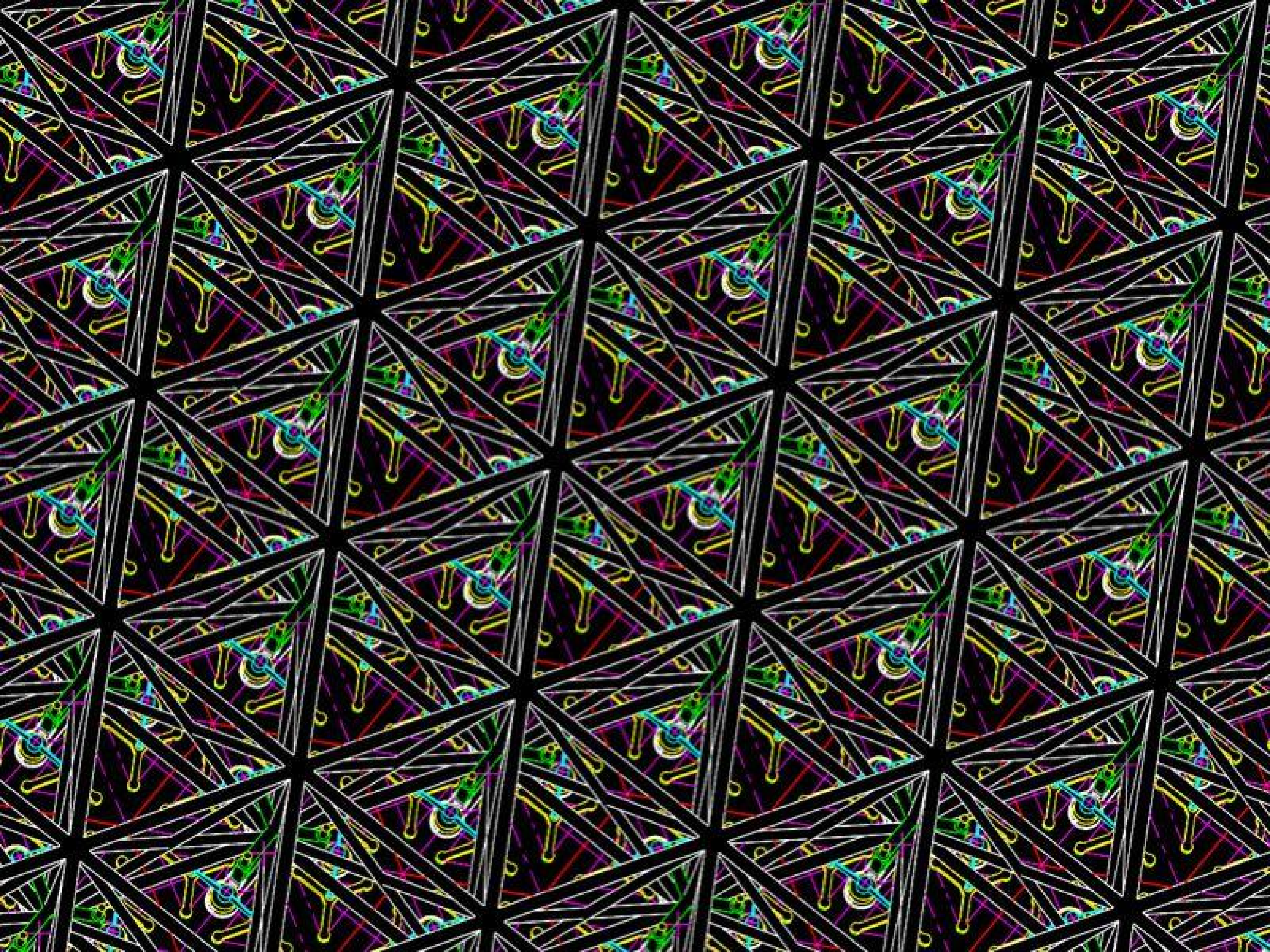
More challenges: cost

- **Break the historical $D^{2.6}$ cost law**
  - Innovative designs
  - Industrial involvement
    - To determine early in the process what is feasible
  - "New" concepts (e.g. serialized production)
    - New to the art of telescope making, that is
  - "Built-in" maintenance concepts
    - Running a facility with a goal of ~3% of capital per year
- **Constrain budget to a "reasonable" total**
  - e.g. $\text{cost}_{\text{OWL,100m}} < \text{cost}_{\text{JWST,6m}} < \text{cost}_{\text{HST,2.4m}}$
- **Make design scalable where possible**

Cost vs quantity

Industrial data
Applies to conceptually simple items
(e.g. segments, structural nodes)





Feasibility – progress of technology

Glass-making

- Slowly evolving technology
- Extrapolation from 5-m required active optics !
- Not easily scalable

Segmentation

Optical figuring

- Metrology-dependent
- Rapid evolution
- Scalable (somewhat)

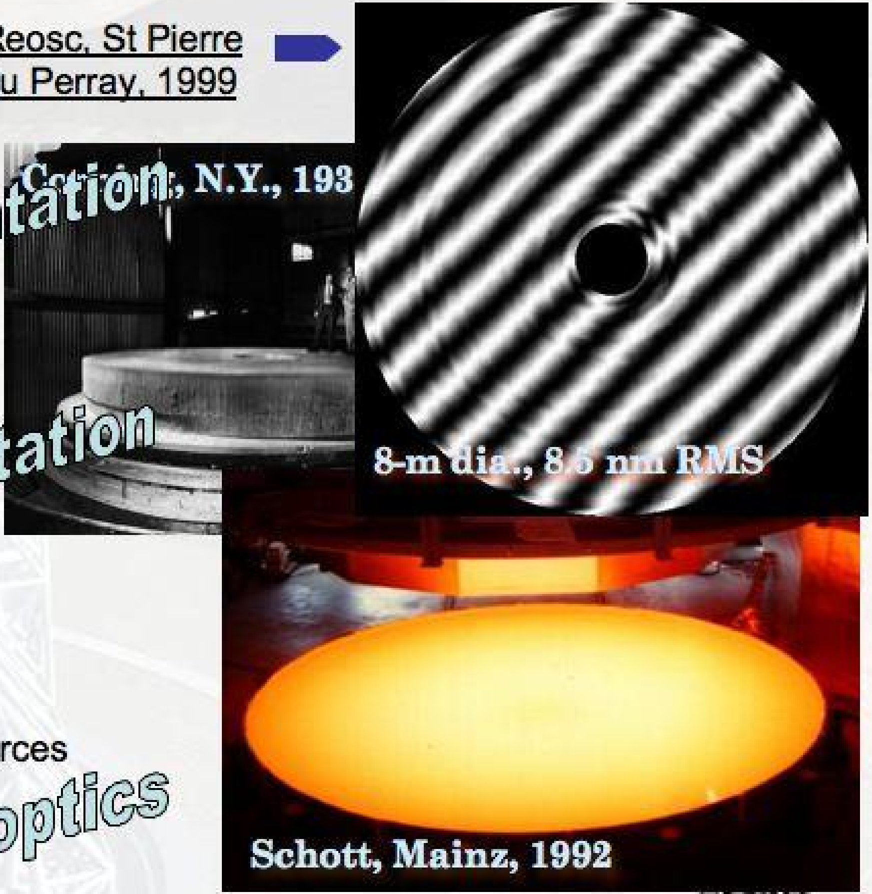
Segmentation

Wavefront control

- In-situ control of performance
- Dealing with inevitable error sources
- Tolerances relaxation
- Scalable

Active optics

Reosc, St Pierre du Perray, 1999

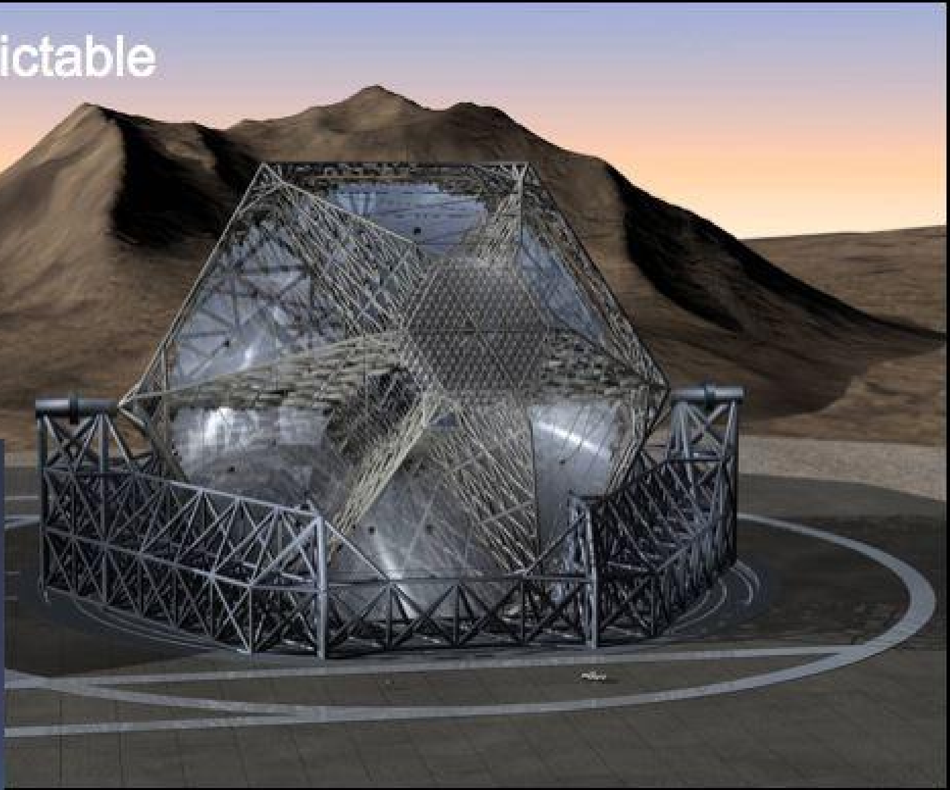


Co[illegible], N.Y., 193

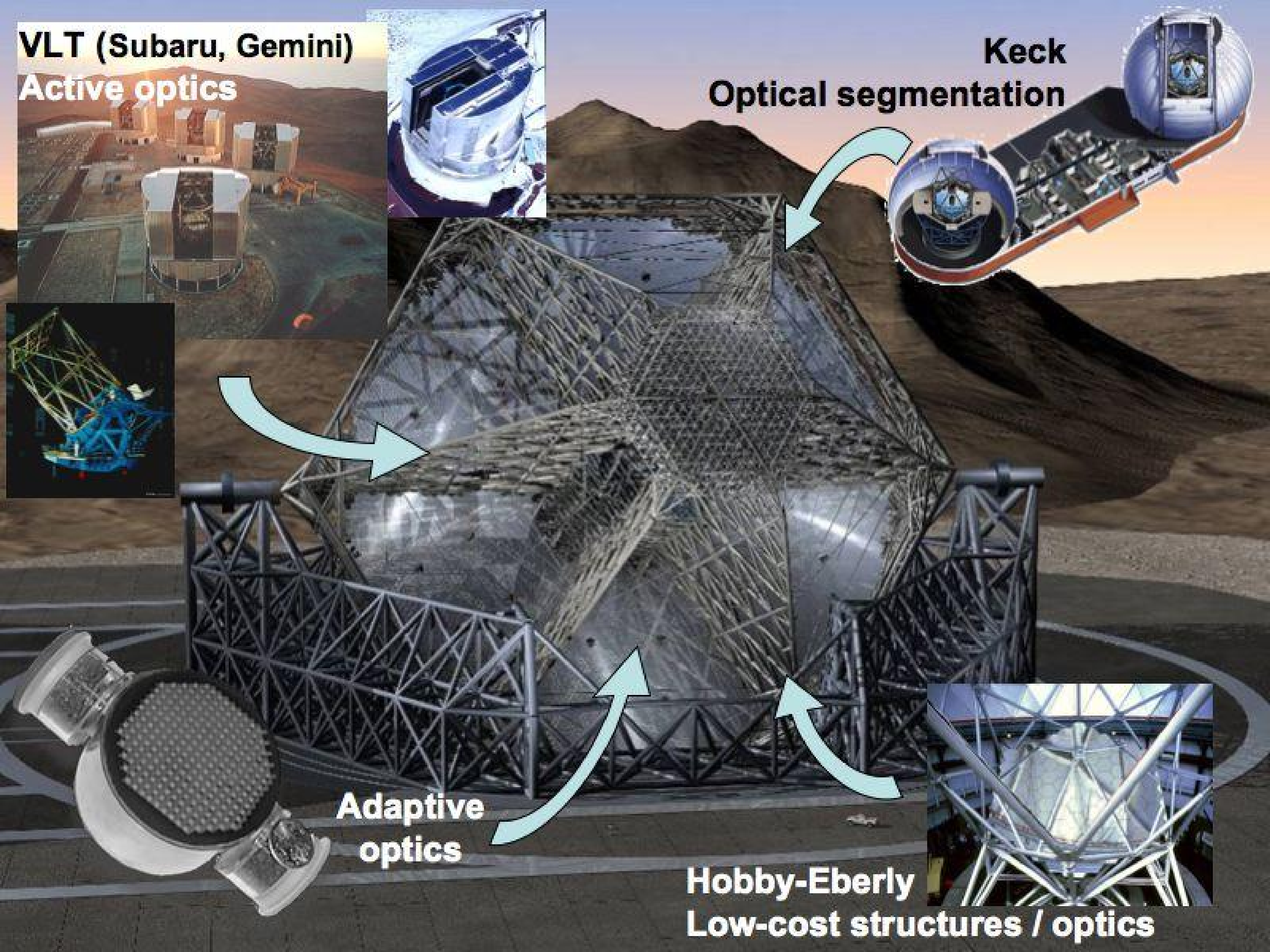
8-m dia., 8.5 nm RMS

Schott, Mainz, 1992

Large structures are predictable



Green Bank
100-m, 7,300 tons
8 years construction
75 Mio. USD

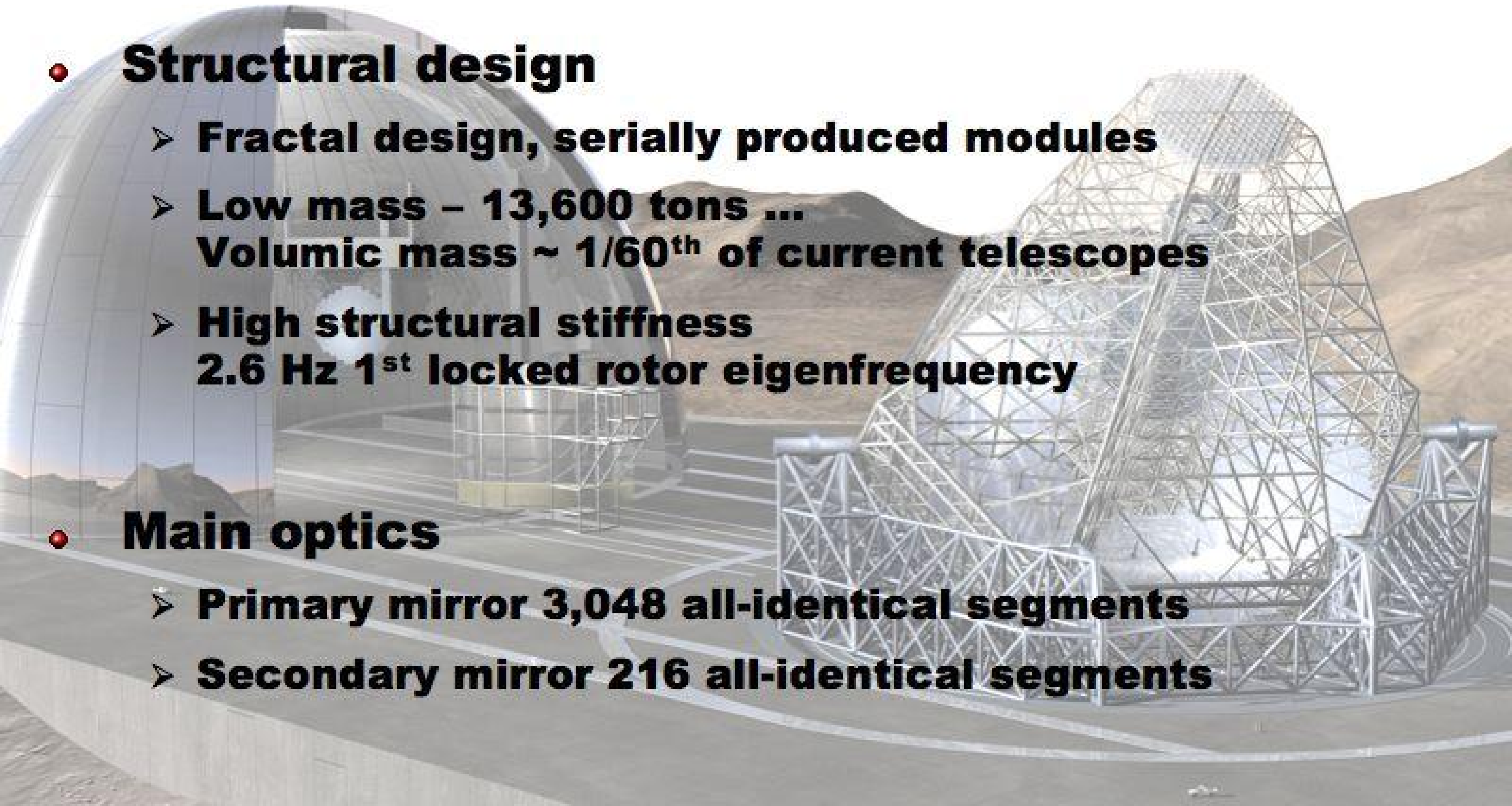


VLT (Subaru, Gemini)
Active optics

Keck
Optical segmentation

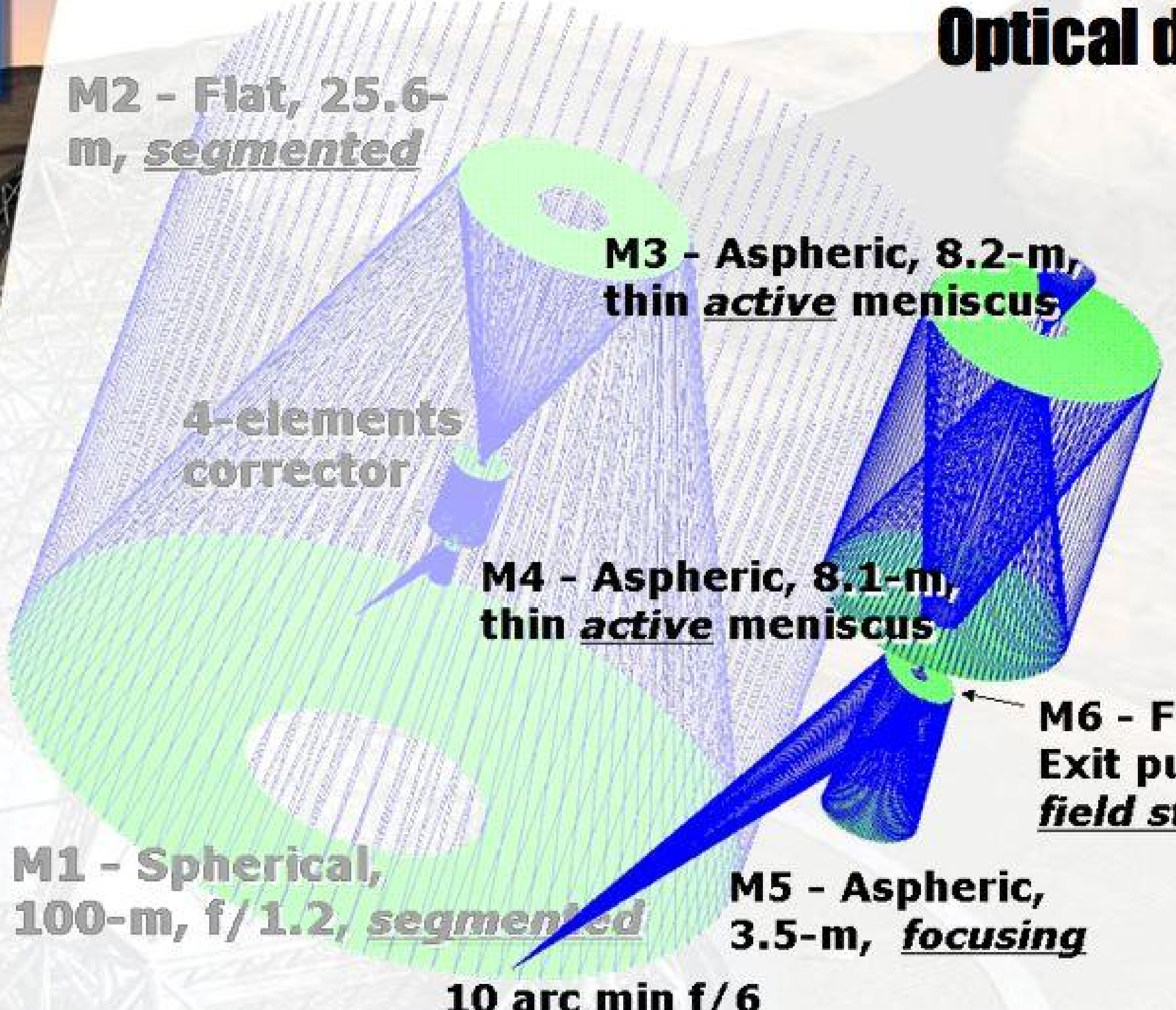
Adaptive
optics

Hobby-Eberly
Low-cost structures / optics



- **6,700 m^2 collecting area**
  Angular resolution 0.001 arc seconds (visible)
- **Structural design**
  - **Fractal design, serially produced modules**
  - **Low mass – 13,600 tons …**
    Volumic mass ~ 1/60th of current telescopes
  - **High structural stiffness**
    2.6 Hz 1st locked rotor eigenfrequency
- **Main optics**
  - **Primary mirror 3,048 all-identical segments**
  - **Secondary mirror 216 all-identical segments**

Optical design



M2 - Flat, 25.6-m, *segmented*

M3 - Aspheric, 8.2-m, thin *active* meniscus

4-elements corrector

M4 - Aspheric, 8.1-m, thin *active* meniscus

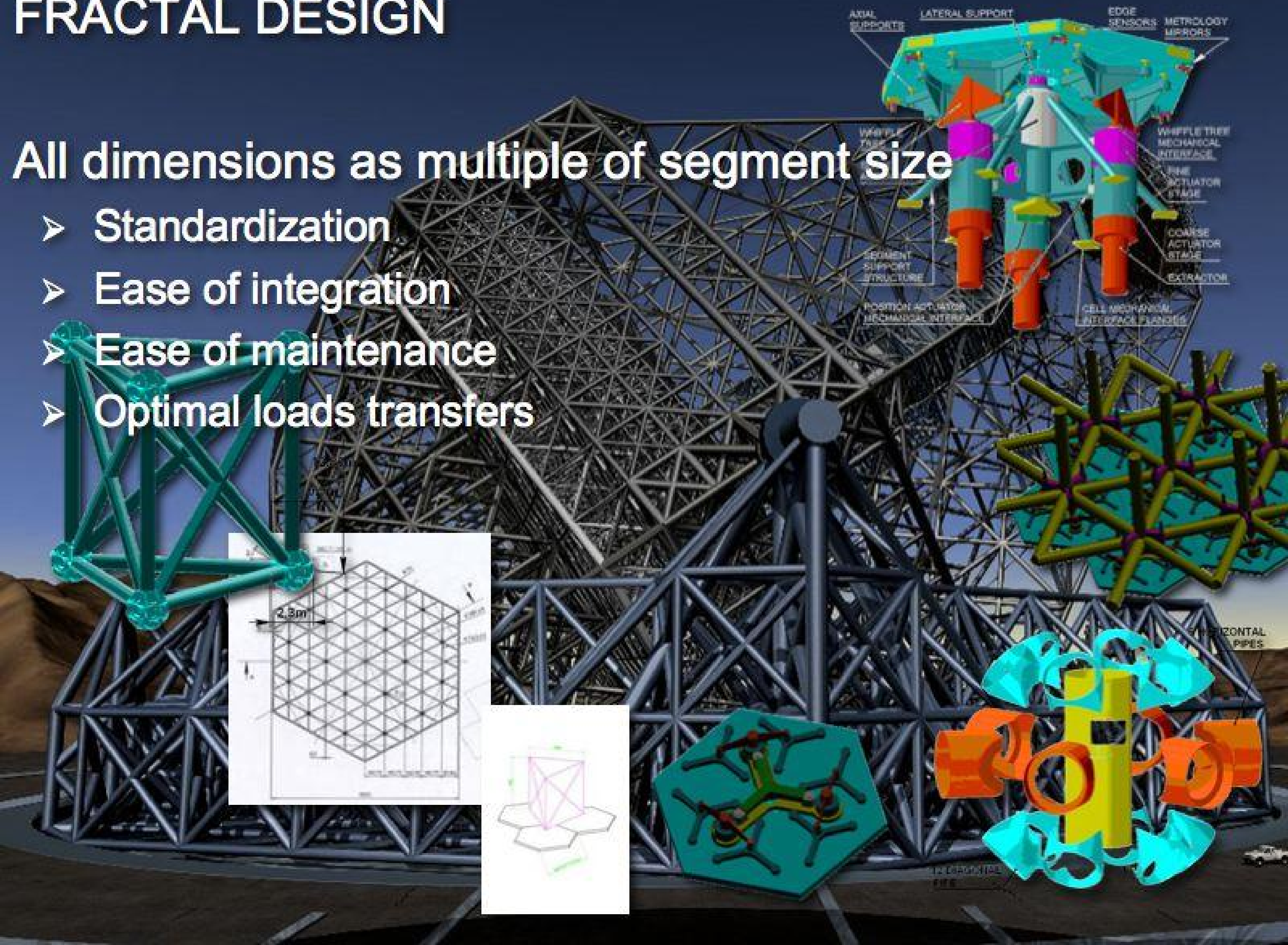
M6 - Flat, 2.2-m, Exit pupil, *field stabilization*

M1 - Spherical, 100-m, f/1.2, *segmented*

M5 - Aspheric, 3.5-m, *focusing*

10 arc min f/6 Field of view

FRACTAL DESIGN



All dimensions as multiple of segment size

- Standardization
- Ease of integration
- Ease of maintenance
- Optimal loads transfers

Controlled optical system

Pre-setting ⇨ *bring optical system into linear regime*
Metrology: internal, tolerances ~ 1-2 mm, ~5 arc secs
Correction: re-position Corrector, M3 / M4 / M5

Phasing ⇨ *keep M1 and M2 phased within tolerances*
Metrology: Edge sensors, Phasing WFS
Correction: Segments actuators

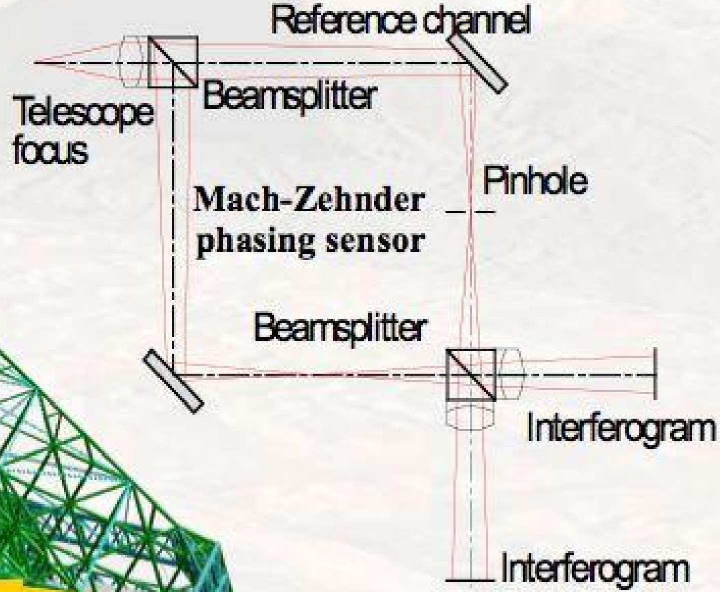
Field Stabilization ⇨ *cancel "fast" image motion*
Metrology: Guide probe
Correction: M6 tip-tilt (flat, exit pupil, 2.35-m)

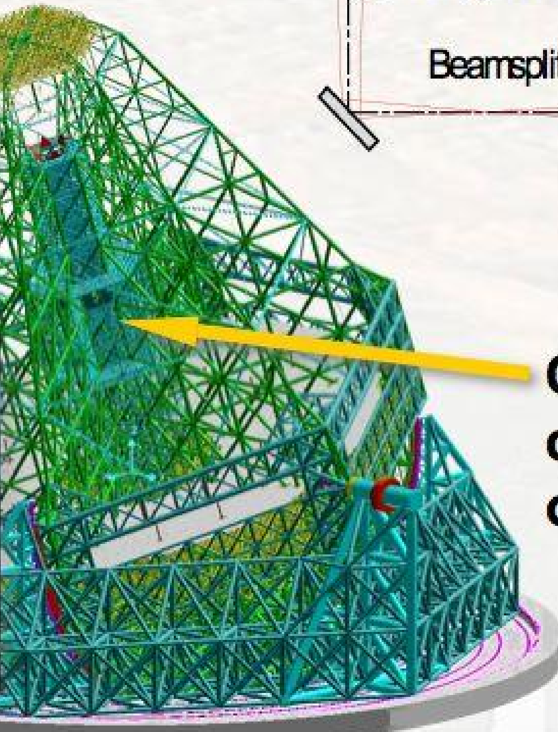
Active optics ⇨ *finish off alignment / collimation*
⇨ *relax tolerances, control performance & prescription*
Metrology: Wavefront sensor(s)
Correction: Rotation & piston M5; M3 & M4 active deformations

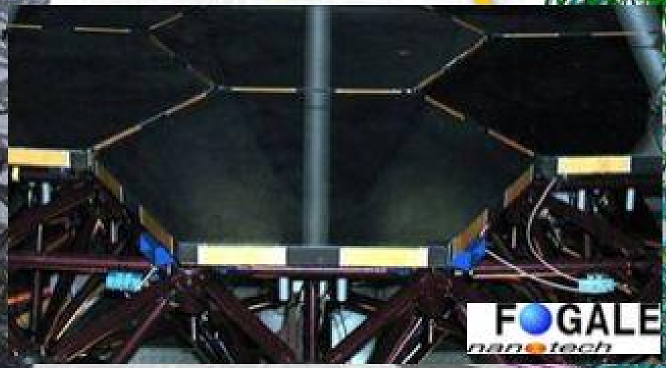
Adaptive optics ⇨ atmospheric turbulence, residuals
Metrology: Wavefront sensor(s)
Correction: M5, M6, …

Controlled opto-mechanical system
IV – Phasing

Two segmented mirrors
Bandwidth ~5 Hz TBC
Edge sensors (capacitive, Inductive or optical)

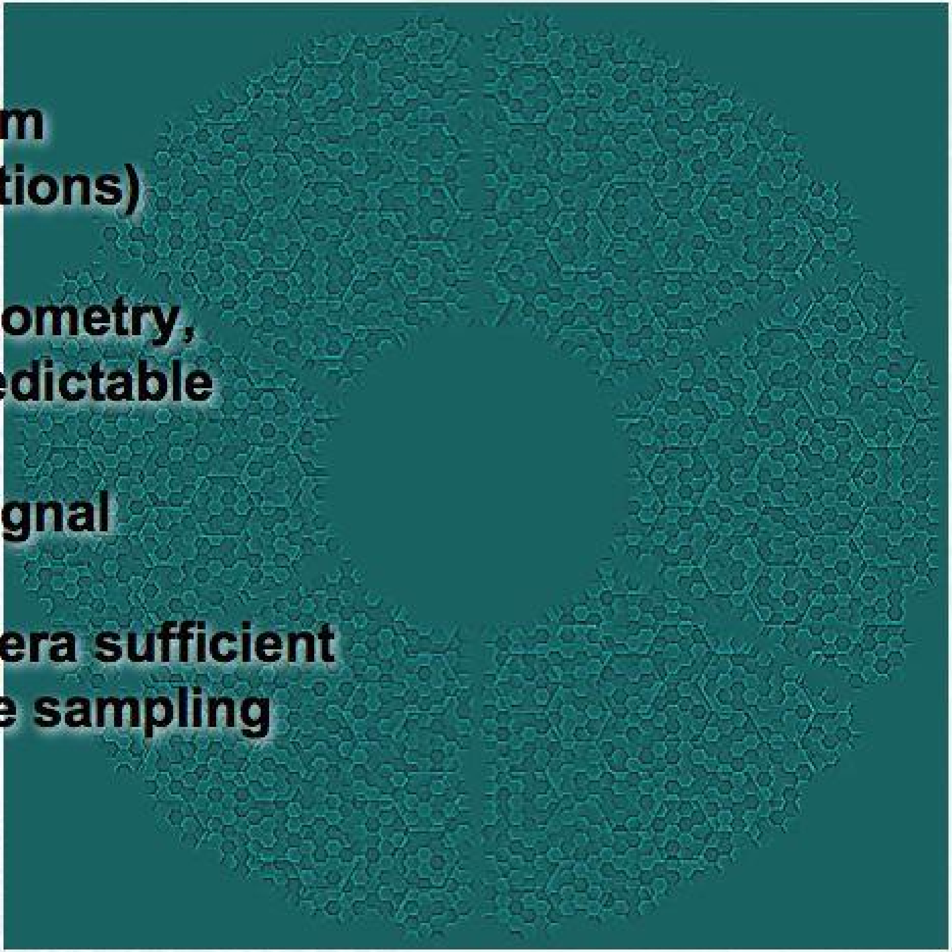






On-sky calibration off-axis

Mach-Zehnder calibration sensor



Interferogram
(ideal conditions)

Complex geometry,
But fully predictable

Localized signal

2k x 2k camera sufficient
for adequate sampling

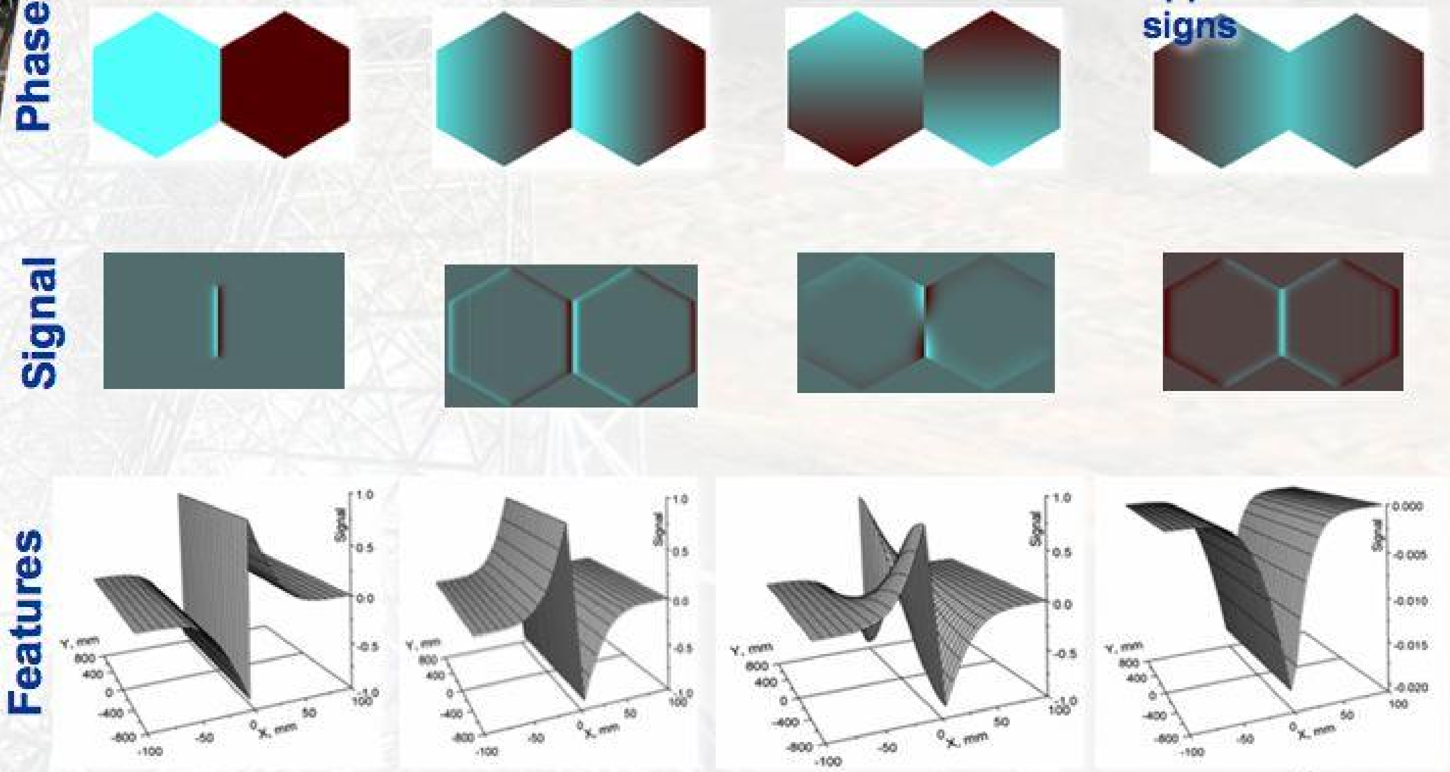
Piston, Tip, and Tilt: Examples

Piston only

X – tilts same signs

Y – tilts opposite signs

X – tilts opposite signs



Antisymmetry axis Y

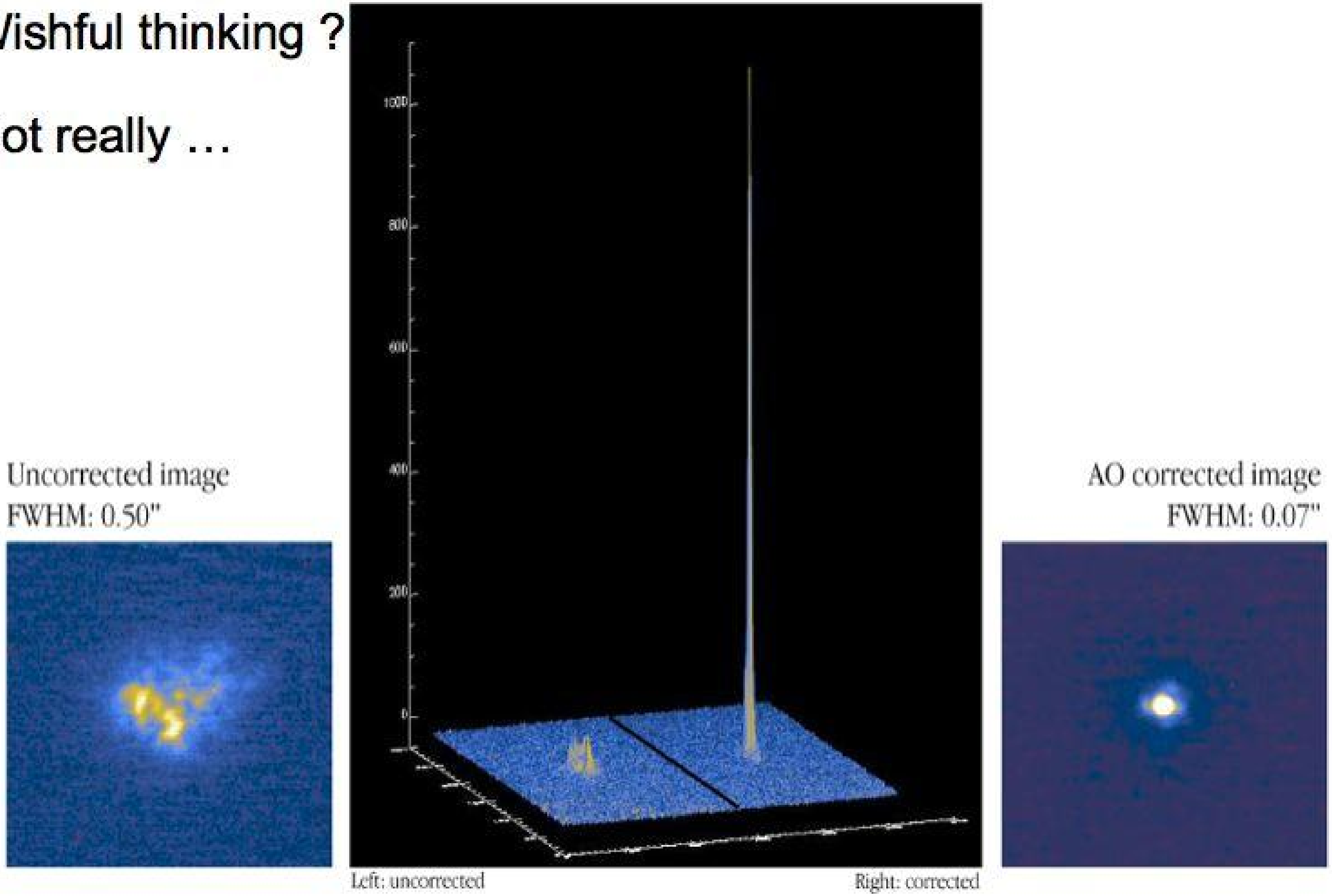
Antisymmetry axis Y

Antisymmetry axis X

Symmetry axis Y

Wishful thinking ?

Not really …



"First Light" for NAOS-CONICA at VLT YEPUN
(November 25, 2001)

ESO PR Photo 33a/01 (3 December 2001)

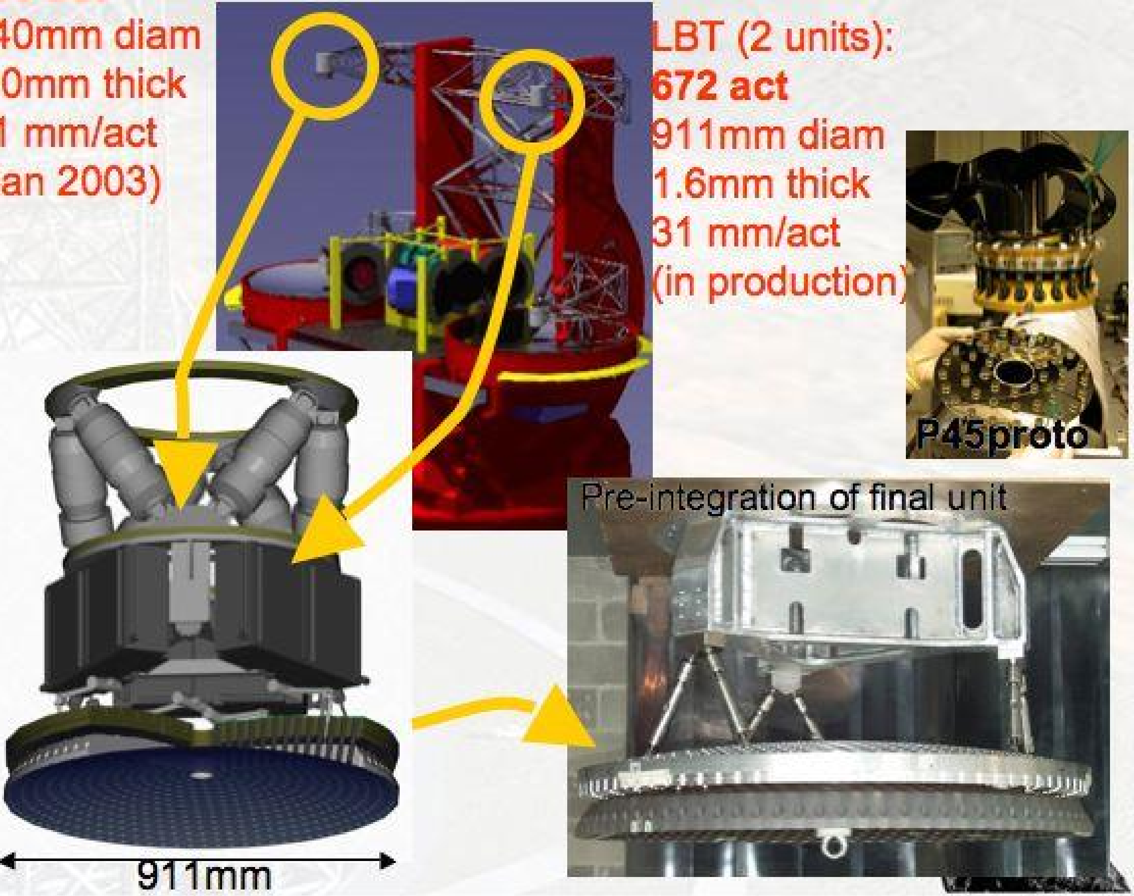
Adaptive Optics

	Today	2008	2015	2019
IR Deformable Mirrors	LBT (JWST)	Prototype	OWL 1st Gen.	2nd Gen.
Diameter	**1-m (2-m)**	**0.3-m**	**2-m**	**4-m**
Actuator spacing	**30 mm**	**15 mm**	**20-25 mm**	**10 mm**
XAO corrector				Moems/Pzt
Detector	256x256 ?		512x512	1kx1k
AO real time control			*Almost OK*	
Reference stars	NGS (LGS)		NGS	NGS / LGS

- High sky coverage in the near-IR (better filling of metapupil)
- LGS needed ~2018; lower number of LGS,
- Cone effect requires novel approaches e.g. PIGS (Ragazzoni et al)

Existing Large Adaptive Mirror Technology

MMT:
336 act
640mm diam
2.0mm thick
31 mm/act
(Jan 2003)



LBT (2 units):
672 act
911mm diam
1.6mm thick
31 mm/act
(in production)

Cost estimate (capital investment, 2002 M€)

SUMMARY	MEuros	
OPTICS	**406**	
Primary & secondary mirror units		355.2
M3 unit		14.4
M4 unit		21.4
M5 temporary unit		5.3
M6 temporary unit		10.1
ADAPTIVE OPTICS	**110**	
M5/M6 design & prototypes		10
M6 AO unit		25
M5 AO unit		35
XAO units		20
LGS		20
MECHANICS	**185**	
Azimuth		53.8
Elevation		34.9
Cable wraps		5.0
Azimuth bogies (incl. motors)		14.7
Altitude Bogies & bearings		5.7
Mirror shields		15.0
Adapters		6.0
Erection		50.0
CONTROL SYSTEMS (*)	**17**	
Telescope Control System		5.0
M1 Control System		8.0
M2 Control System		2.0
Active optics Control System		2.0
CIVIL WORKS	**170**	
Enclosure		40.4
Technical facilities		35.0
Site infrastructure		25.0
Concrete		70.0
INSTRUMENTATION	**50**	
INSTRUMENTATION		50
Total without contingency	**939**	*938.9*

(*) High level cs only; local cs included in subsystems

Diffraction-limited instrumentation

(acceptable étendue !)

Assumes "friendly site"

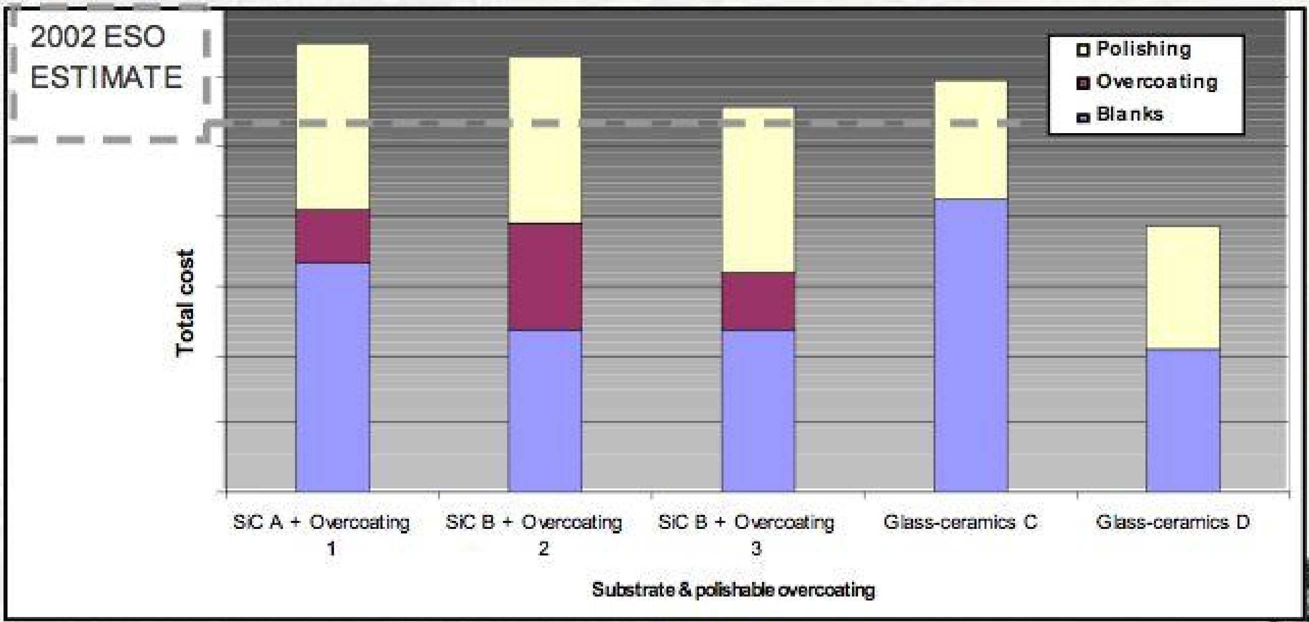
- Average seismicity (0.2g)
- Moderate altitude
- Average wind speed
- Moderate investment in infrastructures

Cost estimates (industrial studies)

Primary & secondary mirror segments; 1.8-m; polished, prices ex works.

Blanks: SiC (2 suppliers A and B) with overocatings (3 suppliers 1, 2, 3)
Glass-Ceramics (2 suppliers C and D)

Polishing: 2 suppliers, only one shown (both agree within 10%)



Schedule estimate

1st light 2016, start of science 2017, completion 2021

1. Faster path to science start
   - Order 8-m blanks in 2008
   - Order (competitive) final designs of enclosure & structure in 2008
   - Order competitive Preliminary designs of M6 in 2008
   - ⇨ **1st light 2014, 50-m science 2015, completion 2019 (TBC)**;

   Requires advanced commitment of M€ ~55 in phase B (2006-2010)

2. Faster path to completion
   - Advanced order of segments raw material (~50% of blanks cost)
   - Moderate increase segments storage capacity on-site
   - Moderate increase of maintenance capacity (or better coatings…)
   - Count on faster progress of AO technology / concepts
   - ⇨ Cost TBD (probably low), **completion in 2018 ?**

NB: alternatives mostly a cash flow problem

Near future

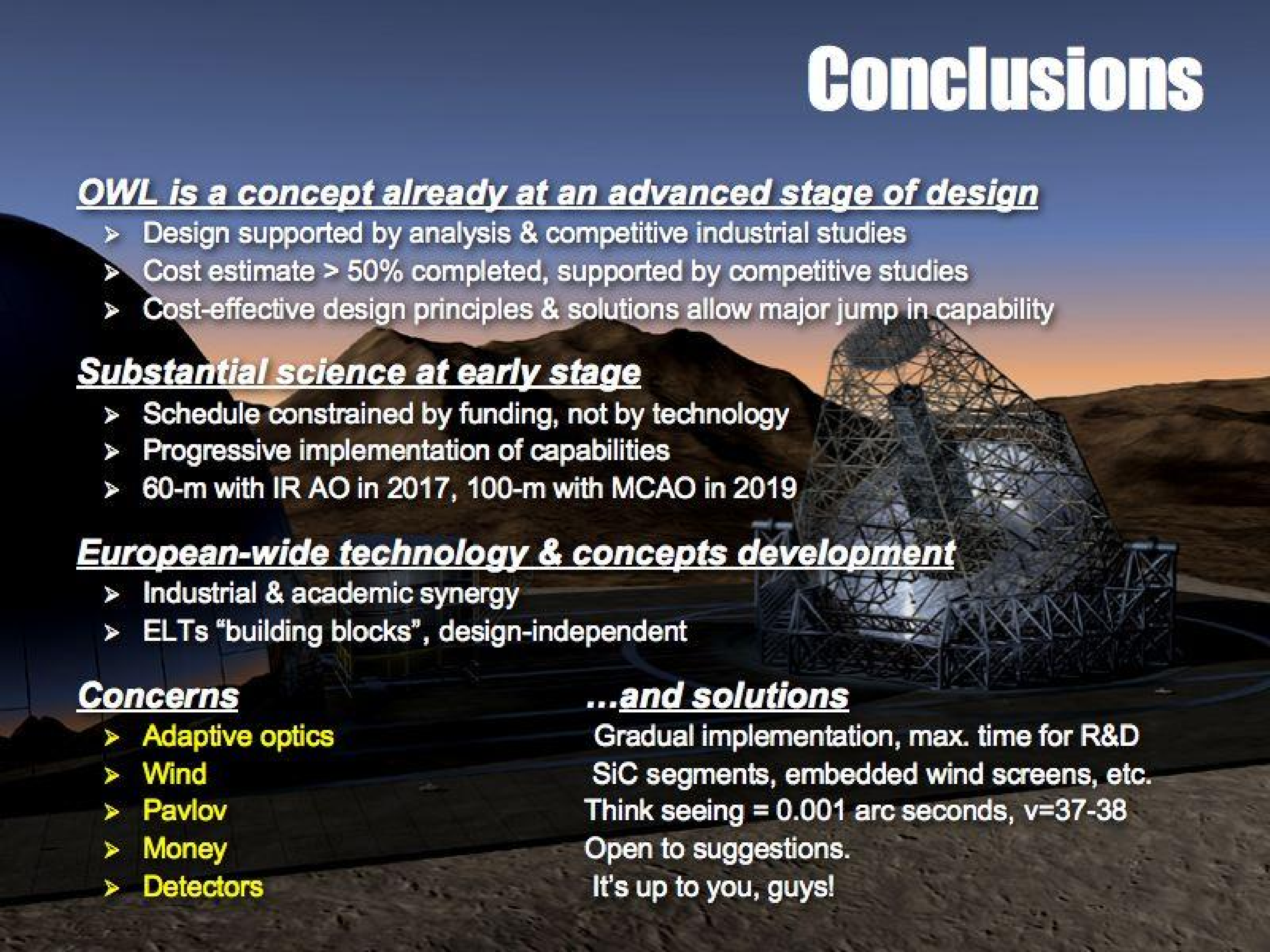

OWL Concept Design Report

Concept design review

- Phase A report end-2005
- ELT Design Study
  - FP6 EC-funded technology development programme
  - 31.5 M€, <u>approved</u>, <u>running</u>
  - 30 partners under ESO's lead
- 2006-2010 OWL Phase B
  - Estimated cost 43 M€
  - Major design contracts (subsystems)
  - Prototyping, breadboards
  - Site selection (2008)

See also www.eso.org

Conclusions



OWL is a concept already at an advanced stage of design

- Design supported by analysis & competitive industrial studies
- Cost estimate > 50% completed, supported by competitive studies
- Cost-effective design principles & solutions allow major jump in capability

Substantial science at early stage

- Schedule constrained by funding, not by technology
- Progressive implementation of capabilities
- 60-m with IR AO in 2017, 100-m with MCAO in 2019

European-wide technology & concepts development

- Industrial & academic synergy
- ELTs “building blocks”, design-independent

Concerns	…and solutions
Adaptive optics	Gradual implementation, max. time for R&D
Wind	SiC segments, embedded wind screens, etc.
Pavlov	Think seeing = 0.001 arc seconds, v=37-38
Money	Open to suggestions.
Detectors	It’s up to you, guys!

Cast of characters

E. Brunetto
Optomechanics

M. Dimmler
Control Systems

R. Gilmozzi
Prime
Investigator (PI)

N. Hubin
Adaptive Optics

M. le Louarn
Adaptive Optics

P. Dierickx
Project
Management /
Engineering

E. Fedrigo
Adaptive Optics

F. Gonte
Wavefront
Control

F. Koch
System Analysis /
Engineering

E. Marchetti
Adaptive Optics -
MAD(*) manager

(*) Multi-conjugate
Adaptive optics
Demonstrator

G. Monnet
Co-PI,
Instrumentation

M. Quattri
Enclosure /
Infrastructure

M. Sarazin
Site Selection

I. Surdej
Wavefront
Control

N. Yaitskova
Wavefront
Control

L. Noethe
Wavefront
Control

T. Sadibekova
Site Selection

J. Spyromilio
Science &
Observatory
Operations

C. Verinaud
Adaptive Optics