- Astronomical telescopes -
Modern solutions for large telescopes

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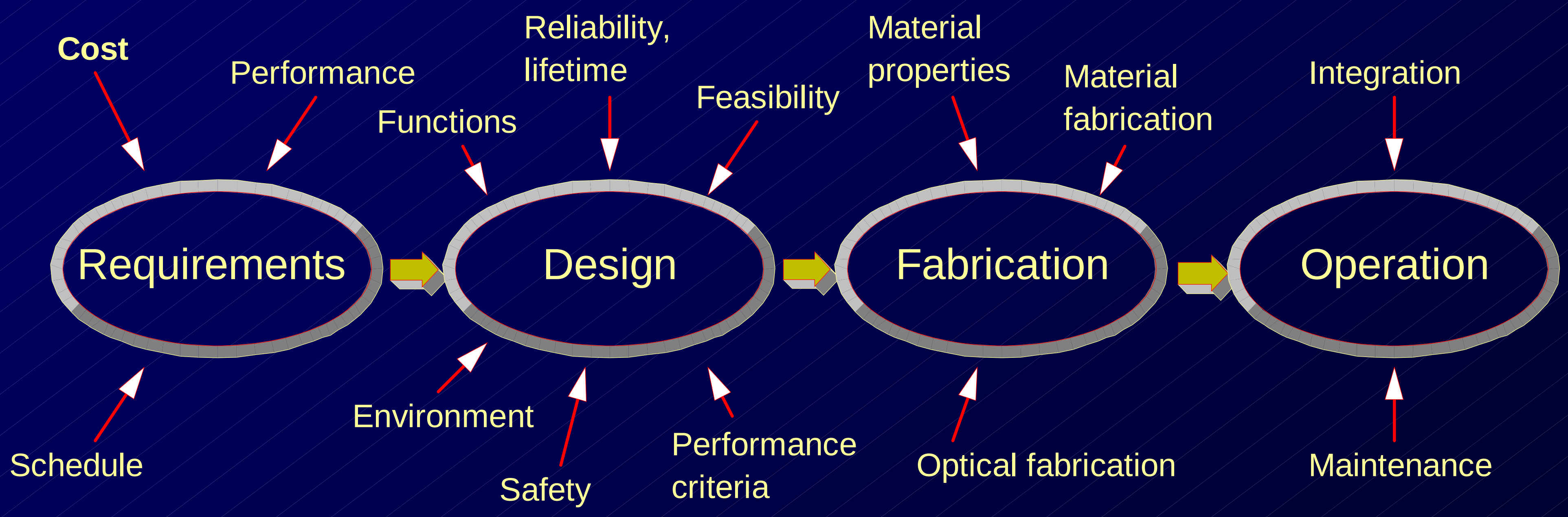
Big is beautiful

- Larger ⇨ higher S/N ratio & sensitivity, shorter exposure times
- Key issues – not only a matter of mirrors … !
  - Maximize throughput ⇨ large diameter
    ⇨ minimum number of surfaces
    ⇨ high reflectivity, low emissivity
  - Maximize resolution ⇨ optical quality (design, construction, operation)
    ⇨ site (atmospheric turbulence)
    ⇨ large diameter (with adaptive optics)
    ⇨ accurate guiding
  - Maximize efficiency ⇨ reliability, durability
    ⇨ operations scheme
  - Minimize cost ⇨ compact design (⇨ structure, enclosure, …)
    ⇨ affordable solutions
  - Minimize schedule ⇨ project management / risk management

Modern solutions

- Start with requirements, not with design !!!



- Engineers may do
  - A good job if you tell them <u>what</u> you want (keep checking them, though)
  - A good but potentially useless job if you let them do what <u>they</u> want
  - An awful job if you tell them <u>how</u> to do what you want

Setting down a few driving parameters

- Telescope diameter ?
- Specialized or multi-purpose ?
  - Specialized: high performance / cost ratio, but not flexible
    Examples: survey telescopes, dedicated to IR, spectroscopic telescopes
  - Multi-purpose: be prepared for compromises
- Fixed elevation or fully steerable ?
- Funding ?
- Timescale ?
  - Possible complementarity with other projects
  - Window of opportunity
  - Time for R&D ?
- Operations
  - your own telescope or service-oriented ?
  - Lifetime ?

Quite likely …

Assumption: you want it

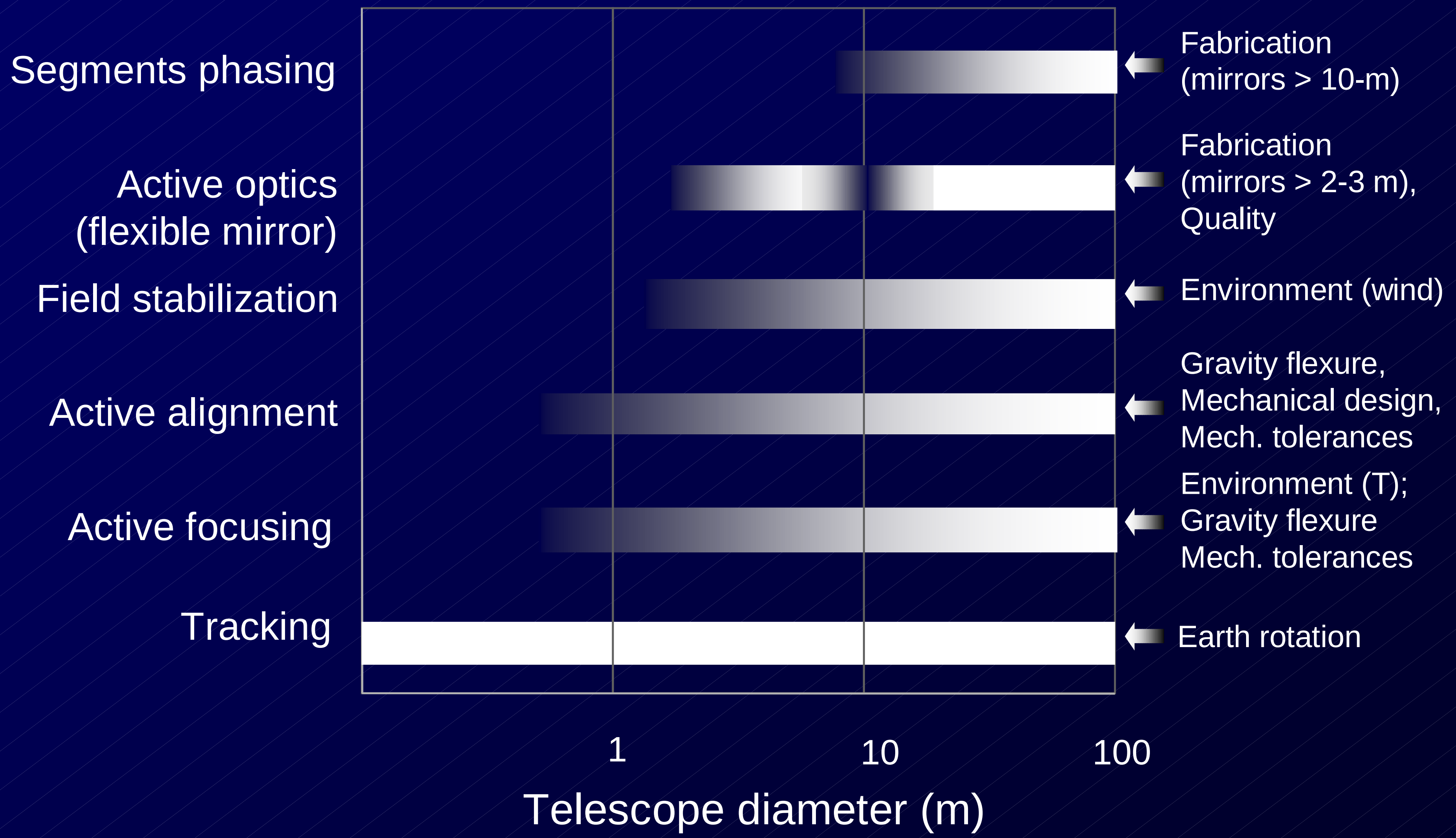
- Big (> 4-m)
- Multi-purpose
  (with possible optimization, e.g. infrared)
- Fully steerable
- Funding not hopeless
- Fast enough to compete
- For yourself only, but for some money you'd allow strangers to touch it
- To last until you retire

A common design for modern telescopes

Assumption: size not much larger than 10-m

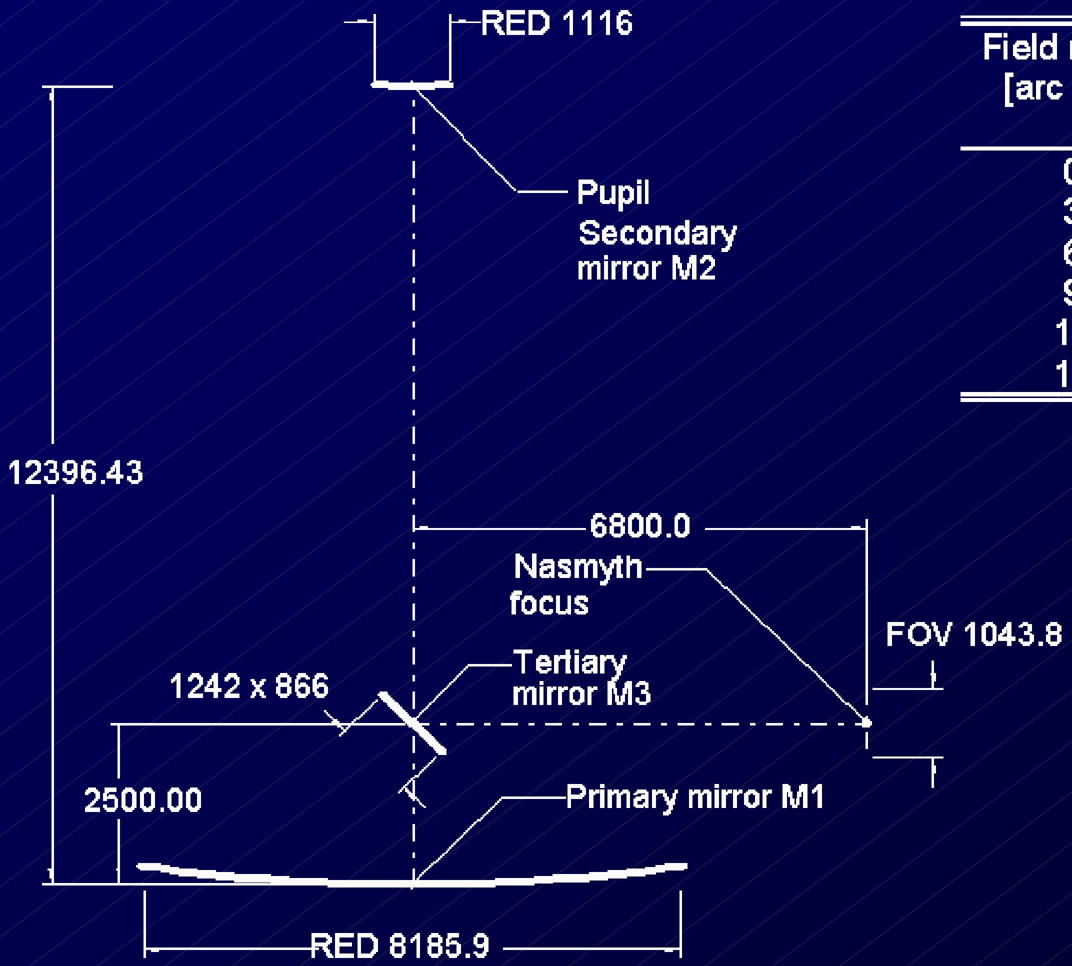
Design solution	Comments (incomplete)
Ritchey-Chrétien	Best image quality (FOV) with 2 mirrors, high throughput
~ F/1.5 primary mirror	Compact design (structure, enclosure)
~ F/8-F/15 telescope	Obscuration, M2 max. size, plate scale, instrumentation
Nasmyth & Cassegrain foci	Several foci; NB: better without Cassegrain (higher fork)
Backfocal distance	Design volume for sensors, instruments
Primary mirror (M1)	
Glass / Glass-ceramics	Proven technology
Segmented or active	Segmented if D > 9-m, otherwise monolithic, active
Fixed secondary mirror unit	Alternative: exchangeable units; prime focus
Active focusing & alignment	thermal & gravity loads
Fast steering (~10-50 Hz) / chopping	vibrations, wind load / Infrared
Lightweight	fast steering; lower mass / inertia
Telescope pupil	Infrared
Alt-az telescope mount	Compact structure, small enclosure, low air volume
Co-rotating enclosure	Alternative: open air (sliding shelter, inflatable dome)
Air conditioned	Keep temperature to night one
Openings	for wind flushing

Functions


Segments phasing
Active optics
(flexible mirror)
Field stabilization
Active alignment
Active focusing
Tracking
Fabrication
(mirrors > 10-m)
Fabrication
(mirrors > 2-3 m),
Quality
Environment (wind)
Gravity flexure,
Mechanical design,
Mech. tolerances
Environment (T);
Gravity flexure
Mech. tolerances
Earth rotation
1
10
100
Telescope diameter (m)

VLT optical design

Surface	Conic constant	Radius of curvature	Axial distance to next surface	Diameter [mm]	
M_1	-1.004690	28800	12396.429	RED	8185.9
M_2	-1.669260	4553.571	0	RAD	1116
Exit pupil	-	-	9896.429	EXP	1113.1
M_3	-	flat 45°	6800	RED	$\geq 866 \times 1242$
IMG	-	2089.6	-	RFD	1048.0

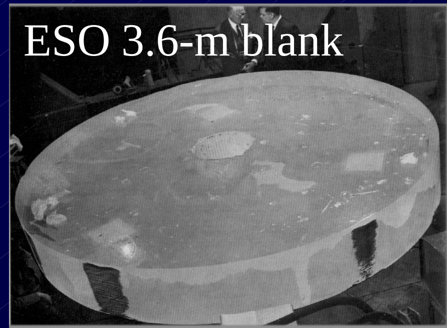


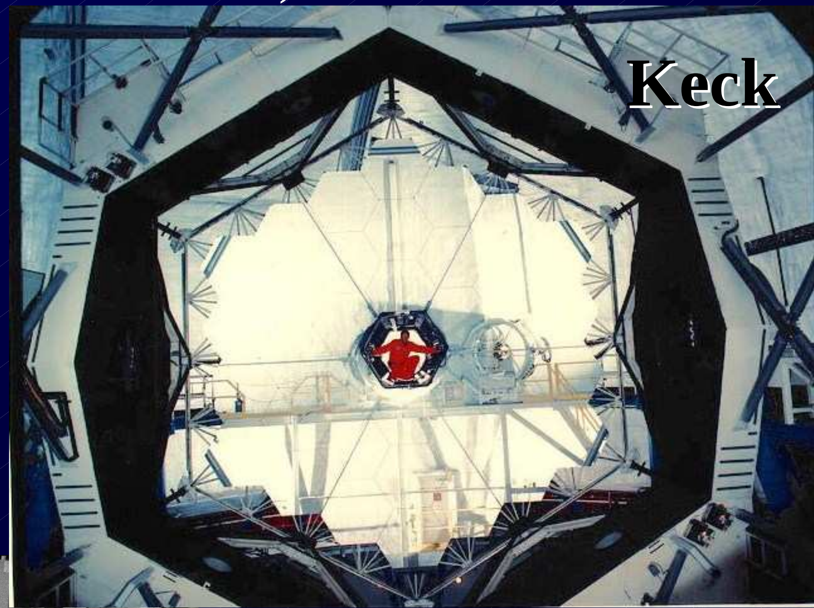
Field radius [arc min]	Astigmatism coef. [nm]	Wavefront RMS [nm]	RMS radius geom. image [arcsec]
0	0	0	0
3	173	71	0.013
6	691	285	0.050
9	1555	642	0.113
12	2769	1143	0.201
15	4333	1777	0.314

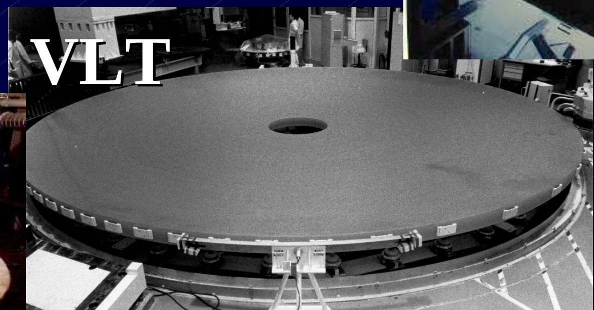
- Ritchey-Chrétien
- 8.2-m active f/1.8 primary mirror
- Secondary mirror
  - Pupil
  - Focusing
  - Tip-tilt (field stabilisation, chopping)
  - Centring (rotation about centre of curvature)
  - Ultra-lightweight (Beryllium)

Primary mirror technologies

- Classical approach (pre-1980):
  - Thick mirror blank, aspect ratio ~1/8, high mass
  - Passive support system (whiffle-tree or astatic levers)
  - Low expansion glass, but huge thermal inertia
  - Casting a serious issue (inhomogeneities, residual stresses)
- Modern options
  - Segmentation (Keck, HET) for D>9-m
  - Thin active meniscus for D < 8.4-m (NTT, VLT, Gemini, Subaru)
  - Semi-rigid, active structured mirror (Boro-silicate; also requires thermal control)







Primary mirror characteristics

4-m < D < ~8.4-m
Active mirrors

PRO

- Relaxation of fabrication specs
- Very high quality for the money
- Will do more than correct its own shape
- Very fast focal ratio achievable (~f/1)

CON

- Investment in production facilities
- Fragile; handling, & transport more cumbersome
- Requires large coating tank
- Unrealistic beyond ~8.4-m

D > 9-m
Segmented mirrors

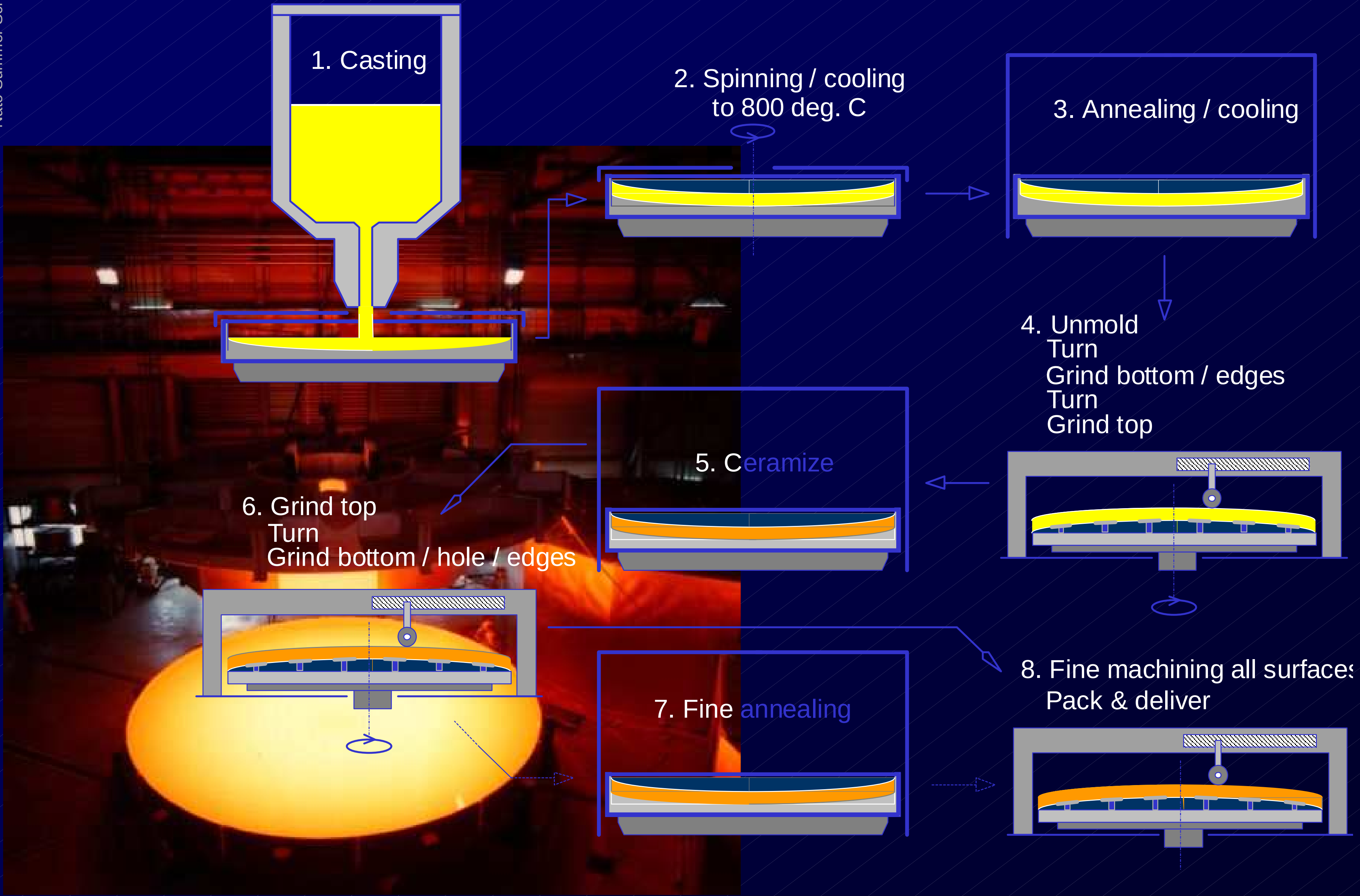
PRO

- Blanks fabrication (up to ~2-m segment)
- Light, cost effective (thin blanks)
- Easy handling & transport
- Accident not catastrophic
- Scalable !!!

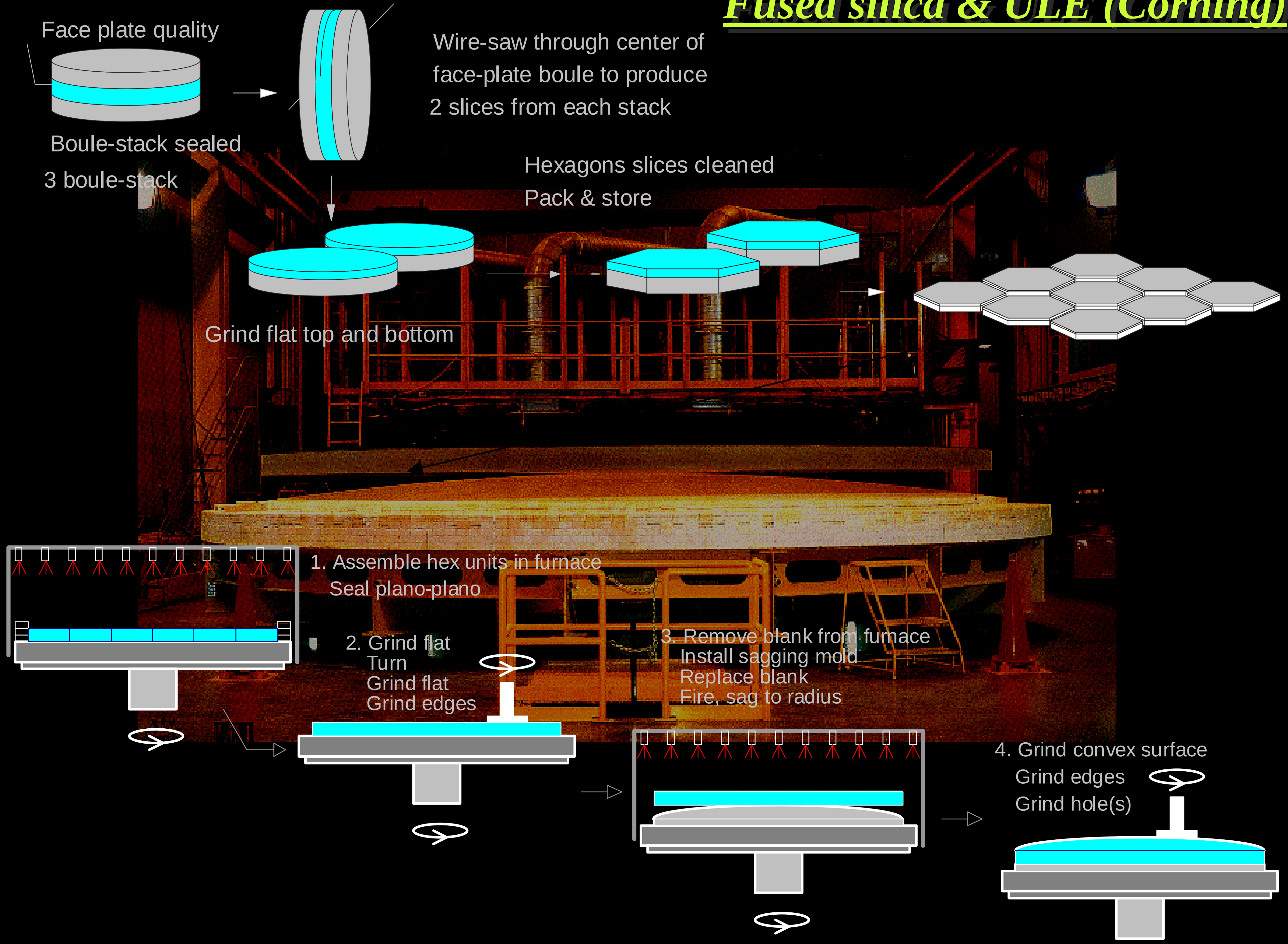
CON

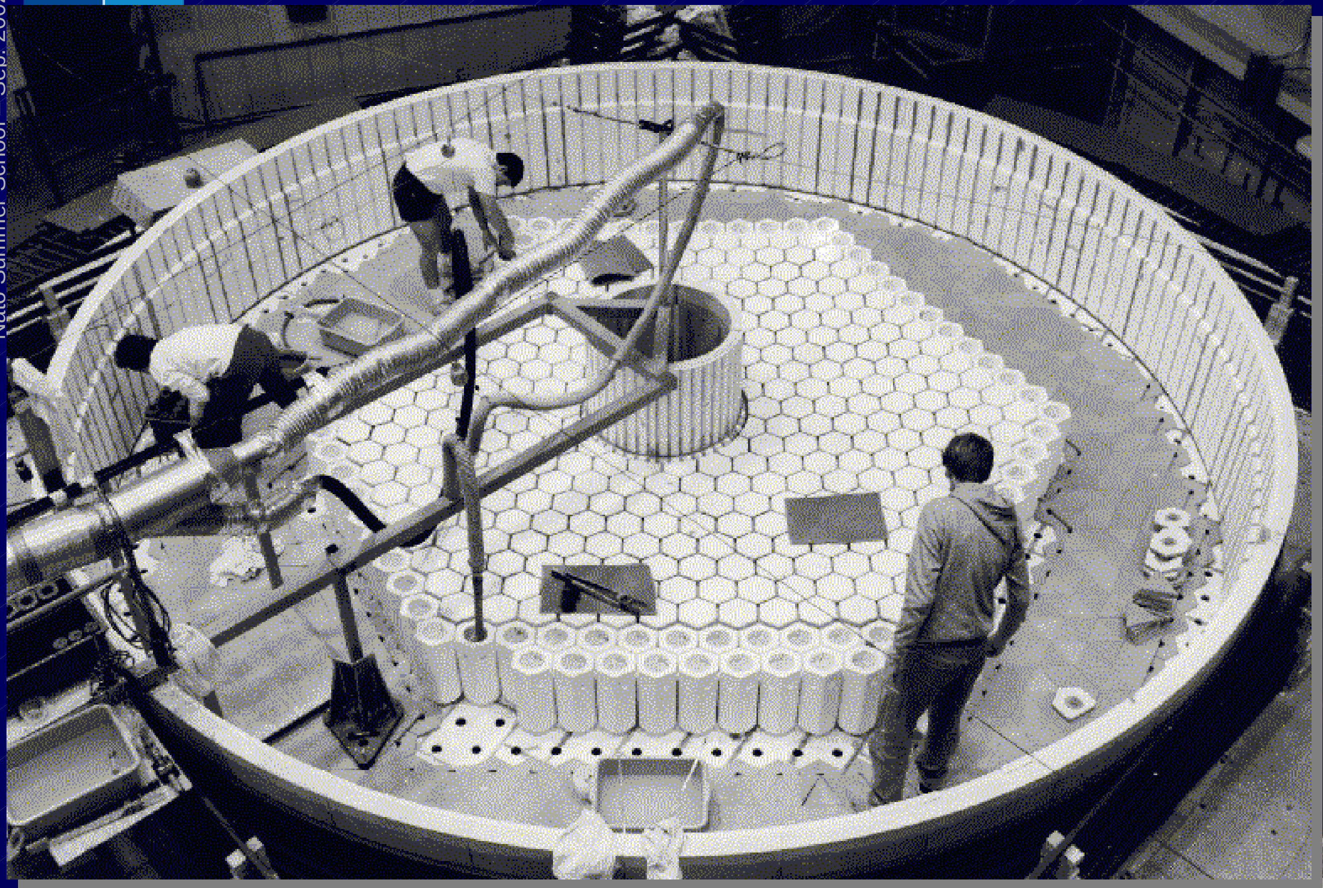
- Discontinuous aperture (uncritical if properly phased)
- Frequent handling
- Polishing & testing more difficult (off-axis aspheric segments, curvature)
- Longer focal ratio

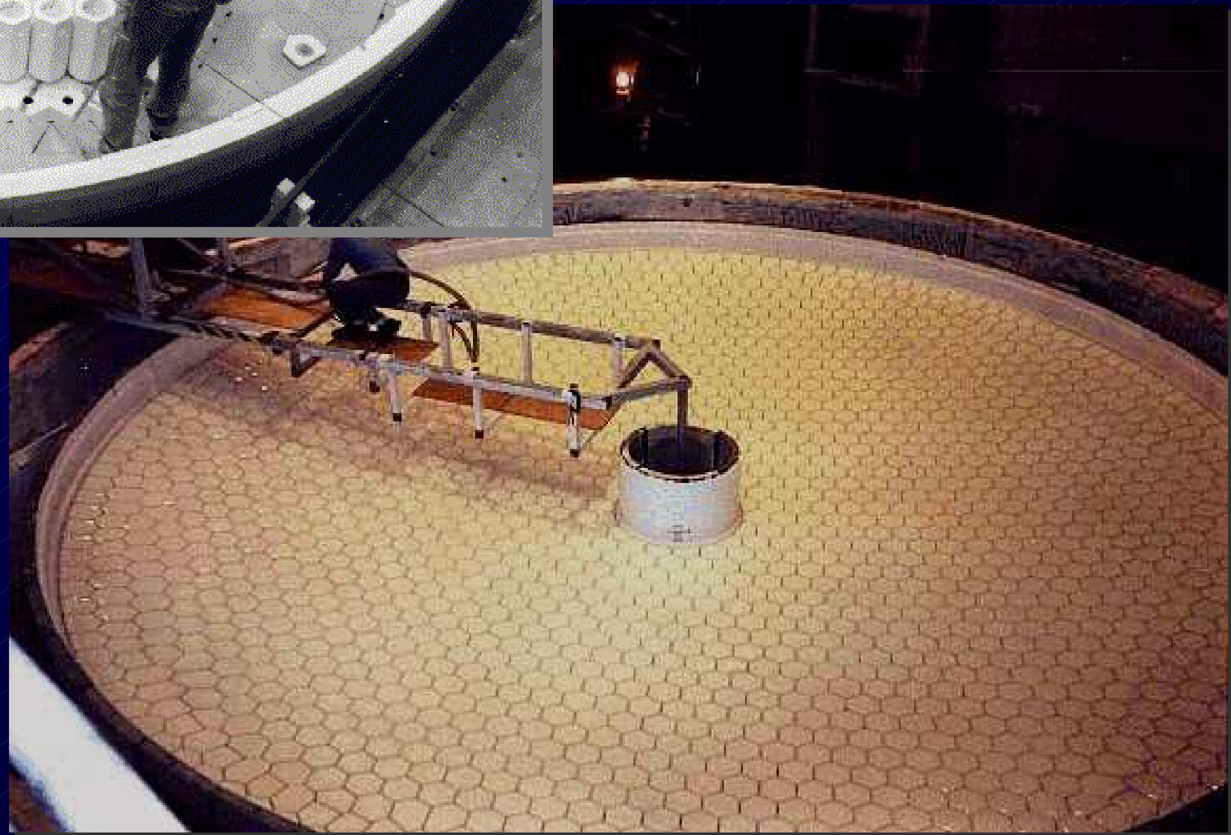
SCHOTT Zerodur (spin-casting)



Fused silica & ULE (Corning)

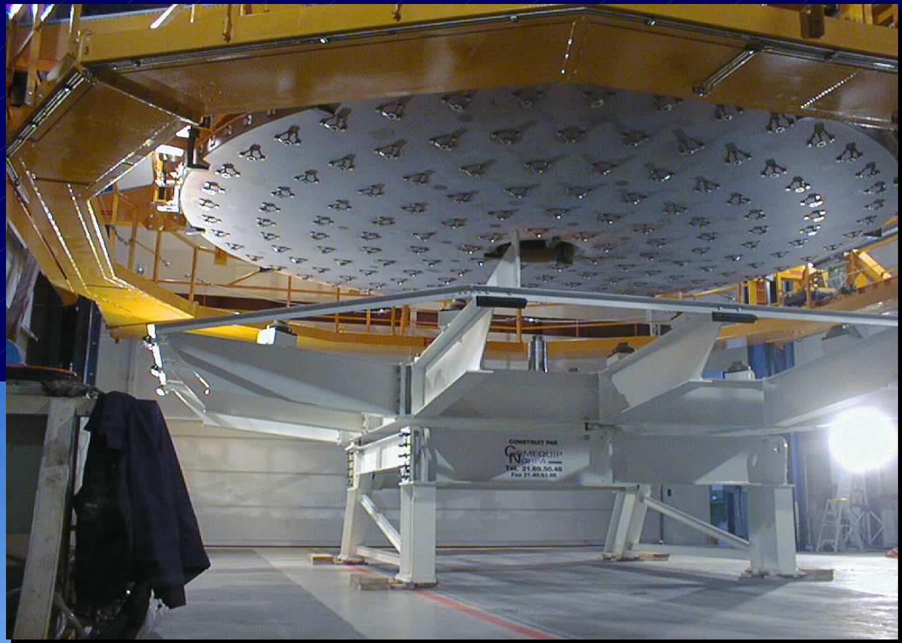




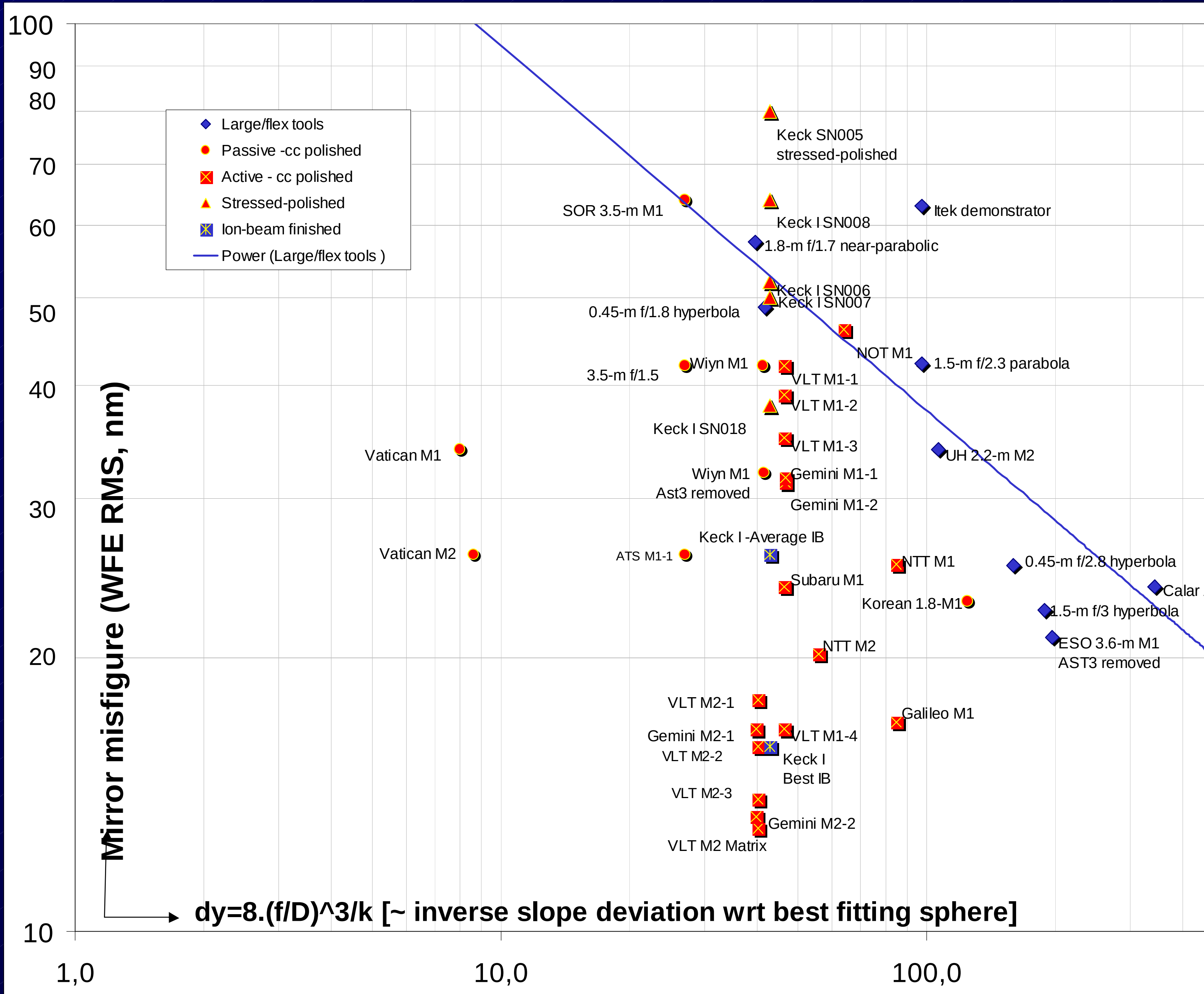


Borosilicate Spin-casting, structured (Mirror Lab, UZ)

Transport & handling



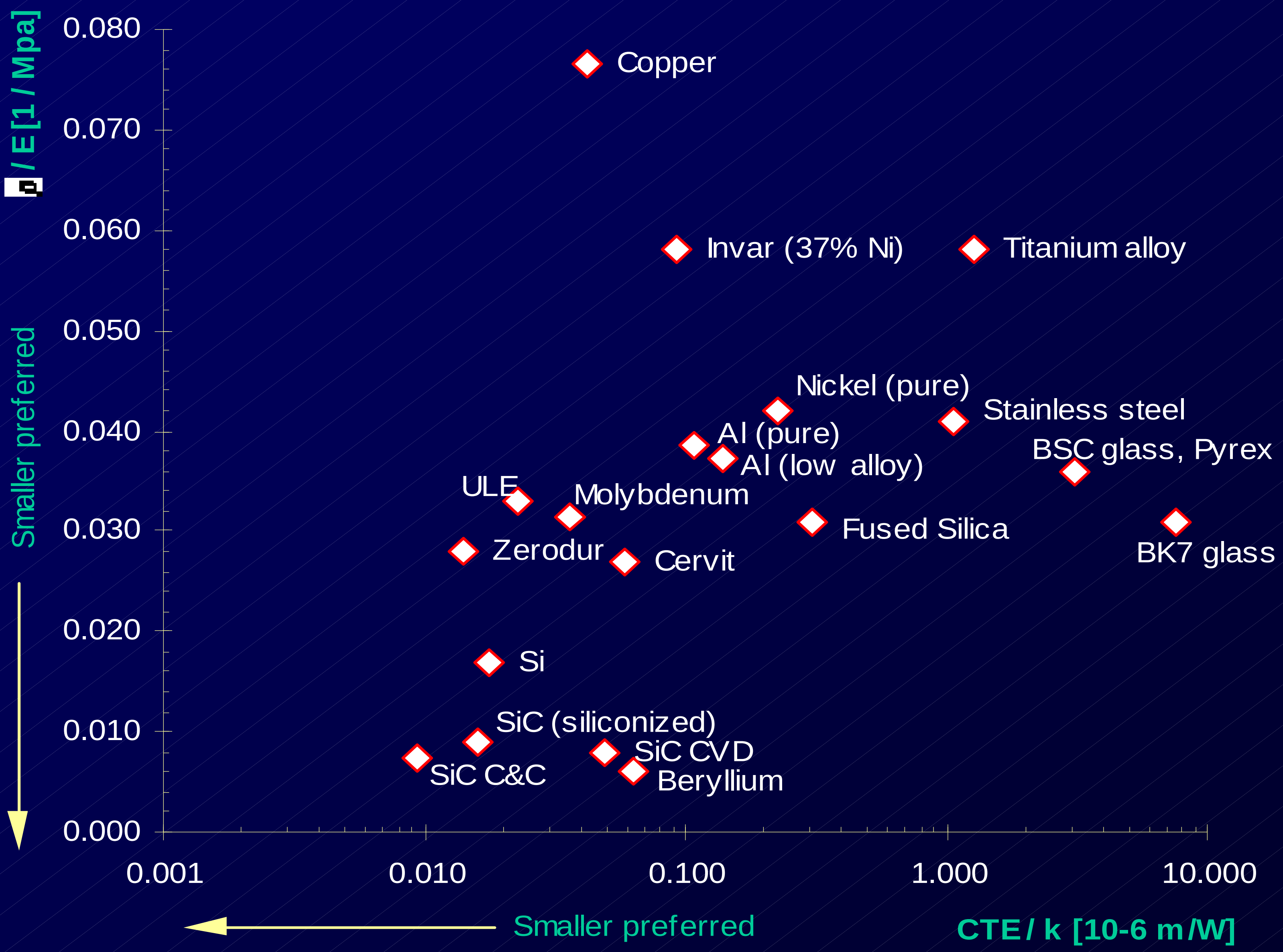
Focal ratio


100
90
80
70
60
50
40
30
20
10
1,0
10,0
100,0
Mirror misfigure (WFE RMS, nm)
dy=8.(f/D)^3/k [~ inverse slope deviation wrt best fitting sphere]
Large/flex tools
Passive -cc polished
Active - cc polished
Stressed-polished
Ion-beam finished
Power (Large/flex tools)
Keck SN005
stressed-polished
SOR 3.5-m M1
Keck I SN008
Itek demonstrator
1.8-m f/1.7 near-parabolic
Keck I SN006
Keck I SN007
0.45-m f/1.8 hyperbola
NOT M1
3.5-m f/1.5
Wiyn M1
1.5-m f/2.3 parabola
VLT M1-1
VLT M1-2
Keck I SN018
VLT M1-3
Vatican M1
UH 2.2-m M2
Wiyn M1
Ast3 removed
Gemini M1-1
Gemini M1-2
Keck I -Average IB
Vatican M2
ATS M1-1
NTT M1
0.45-m f/2.8 hyperbola
Subaru M1
Calar
Korean 1.8-M1
1.5-m f/3 hyperbola
ESO 3.6-m M1
AST3 removed
NTT M2
VLT M2-1
Galileo M1
Gemini M2-1
VLT M1-4
VLT M2-2
Keck I
Best IB
VLT M2-3
Gemini M2-2
VLT M2 Matrix

Want some R&D ? Mirror Materials

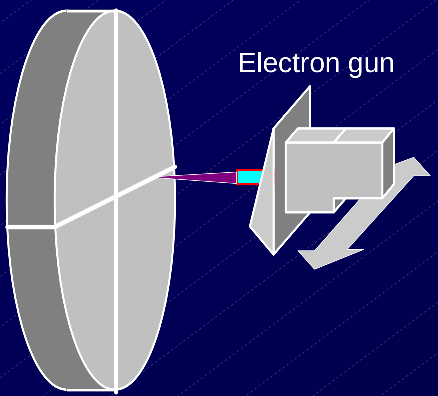
- Category I - thermally stable. Astro-Sitall, Zerodur, Silica, ULE, (aluminium)
  - Thin active meniscus up to ~8-m, 12-14-m probably feasible.
  - Lightweight machined/structured up to ~2-4 -m
- Category II - BSC glass.
  - Spin-cast structured up to ~8.5-m, moderately active, needs thermal control
  - Lower aerial density, higher stiffness
- Category III - "Super-materials", Be, SiC
  - Very high specific stiffness, ultra-lightweight mirrors.
  - Max size ~1-m, ~2.5-m probably feasible.

Thermal & mechanical figure of merit

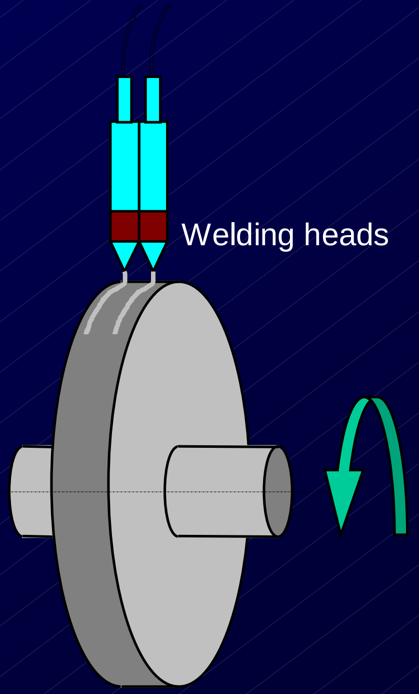


Aluminium

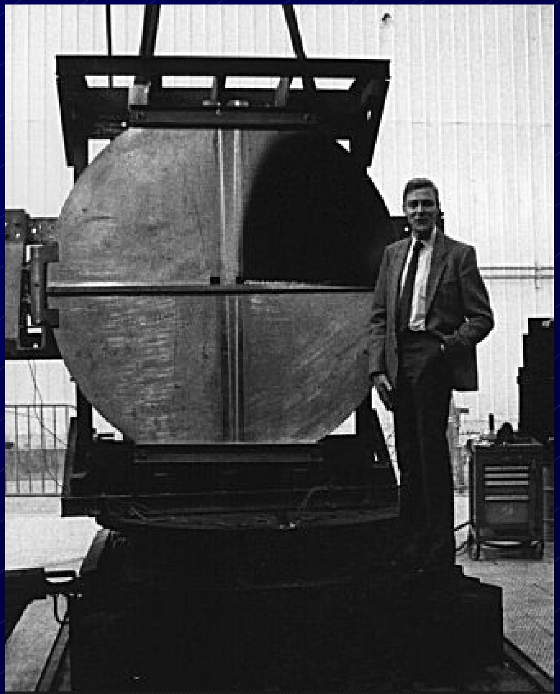
- 1.8-m mirrors, 2 technologies (backup VLT M1):
  - Electron-beam welding
  - Build-up welding
- Thermally cycled, found stable within ~1 fringe, suitable for active mirrors
- Ni overcoating a source of risk
- Room for improvement: residual stresses, canigen coating.
- A cost-effective alternative above 1-2m
- CTE homogeneity still needs to be demonstrated.



Electron-beam weldi



Build-up welding



Ultra-lightweight optics

- Aerial density ~ 40 Kg / m^2
- Glass-ceramics (Gemini), Beryllium (VLT)
  - 1-m class demonstrated to diffraction-limited quality
  - very high cost (risk, process complexity)
- Silicon Carbide
  - history of “problems” -above all commercial!
  - Not all technologies suitable -CVD unsuccessful
  - Potentially the most attractive: best material, fully elastic, fast processes
  - Ultra-lightweight ~20-30 Kg/m^2 OK up to ~ 1-m.
  - ~50 Kg/m2 cost effective within 3-5 years?