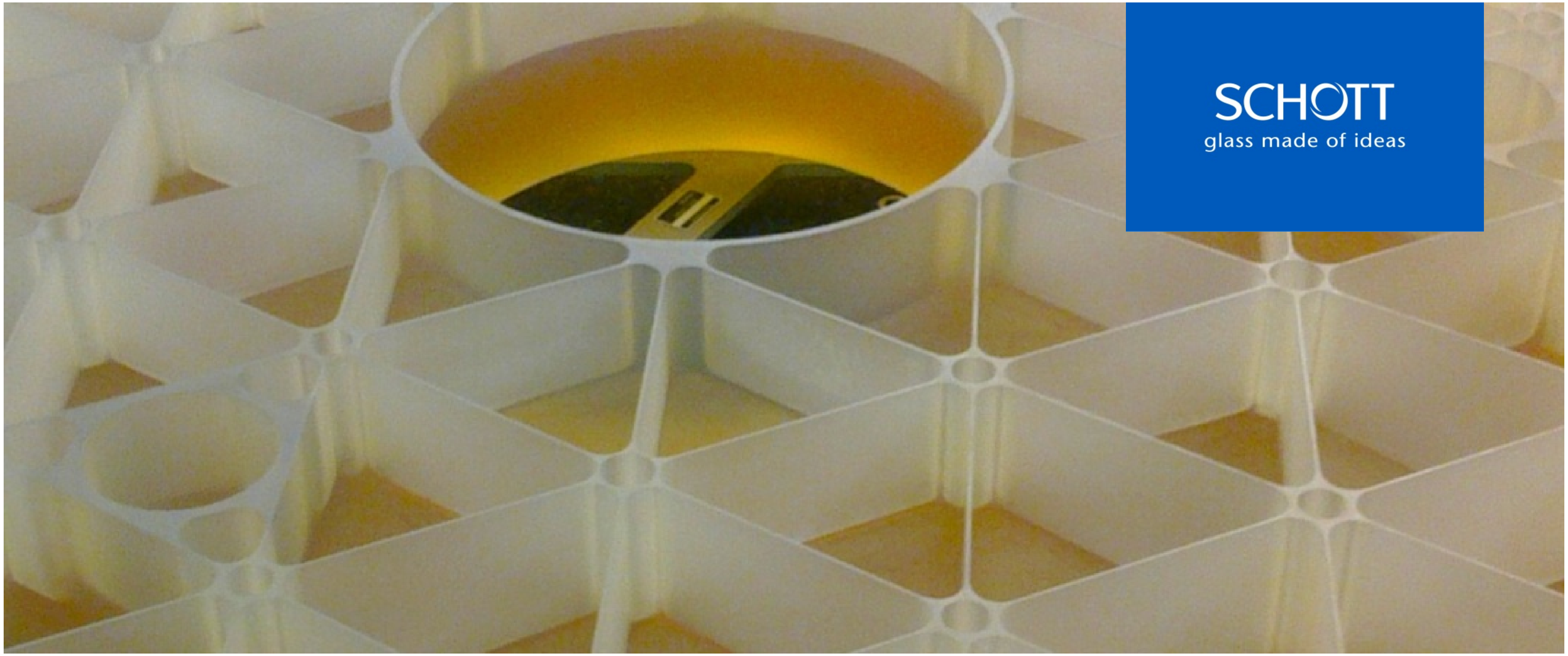


SCHOTT – Ultra low expansion glass ceramic ZERODUR®

Improvements in properties, understanding and production

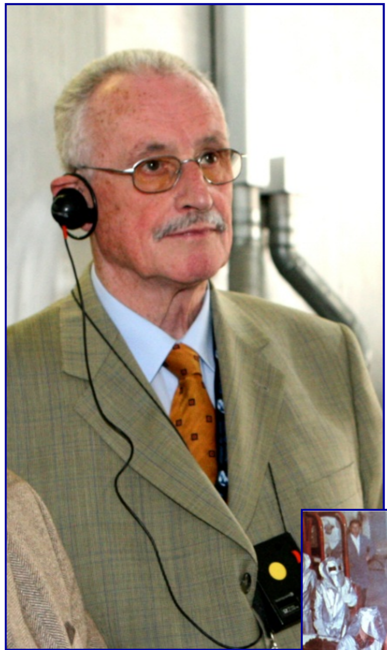
MPI für Astronomie, Heidelberg Astro Tech Talk 30.1.2015 Peter Hartmann SCHOTT AG

What is ZERODUR®?

1957 Glass Ceramic discovered by Donald S. Stookey (Corning)

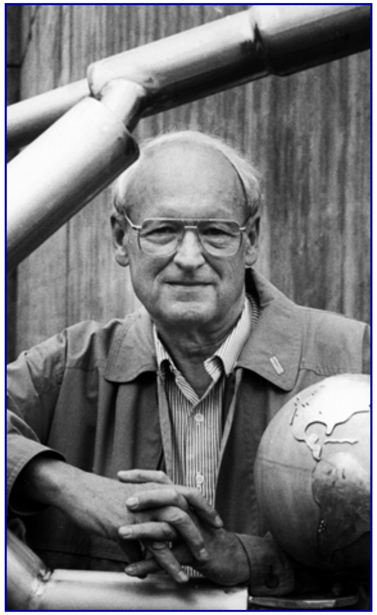
From mishap during development
of light sensitive glass
Furnace became much too hot.

ZERODUR®– Work of Two Pioneers
The first 4 m Zerodur Mirror

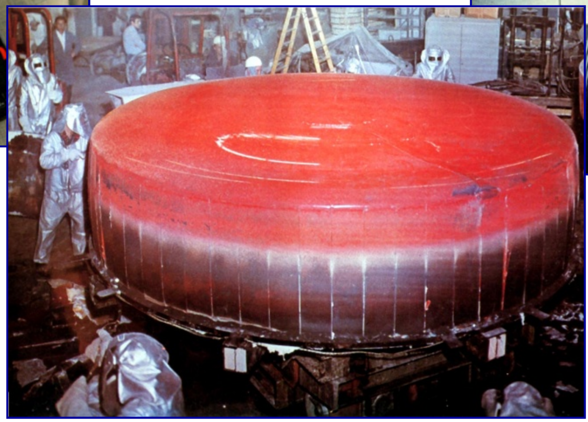


Jürgen Petzold
SCHOTT
Developer of glass ceramics

3,6 m Telescope Calar Alto

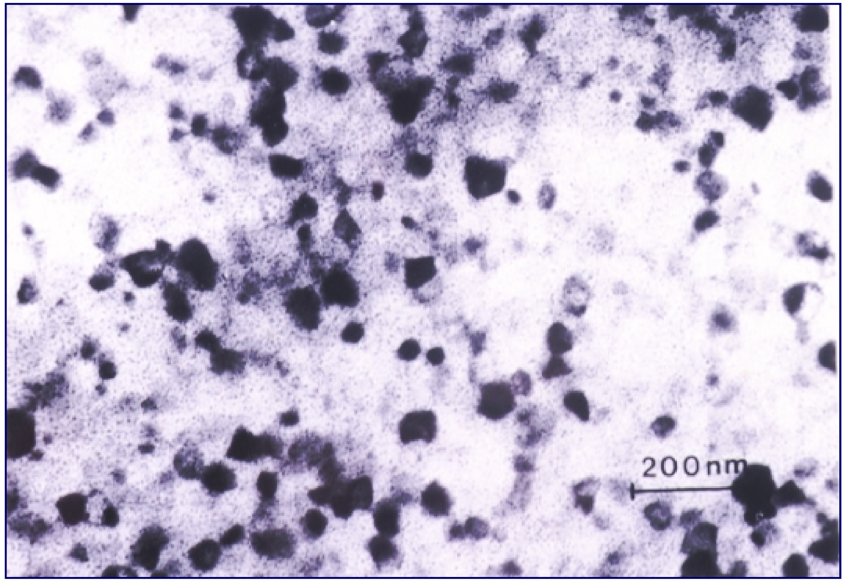


Hans Elsässer
MPI Astronomy
Initiator and Customer



1973 Cast of the first 4 m glass ceramic mirror blank for the Max-Planck-Insitute for Astronomy Heidelberg Germany

ZERODUR® - Zero Expansion Glass Ceramic



Zerodur is a Li-Al-Si glass ceramic
a composite of 70 – 78 vol-% microcrystallites
embedded in a glass phase

Size and number of the negative CTE microcrystallites are adjusted to achieve a net zero thermal expansion

Scanning microscope image of Zerodur microcrystallites

Size: 30 – 50 nm

ZERODUR® is molten like Optical Glass

Therefore it is

- Extremely homogeneous
- Isotropic
  down to sub microscopic scale
  → Free from rings, layers
  Seams, flaws, pores
- Highly polishable
- In transmission inspectable
  → no surprises
- Highly reproducible
  in all properties

1.5 m Blank with outstanding homogeneity and striae quality

Coefficient of thermal expansion CTE

Coefficient of Thermal Expansion (CTE)
Narrower tolerances have been added

CTE Absolute Values

Class	CTE [1/K]
2	$\pm 0.10 \cdot 10^{-6}$
1	$\pm 0.05 \cdot 10^{-6}$
0	$\pm 0.02 \cdot 10^{-6}$

New

Class	CTE [1/K]
0 Special	$\pm 0.010 \cdot 10^{-6}$
0 Extreme	$\pm 0.007 \cdot 10^{-6}$
Taylored	Adapted to specific temperature profile

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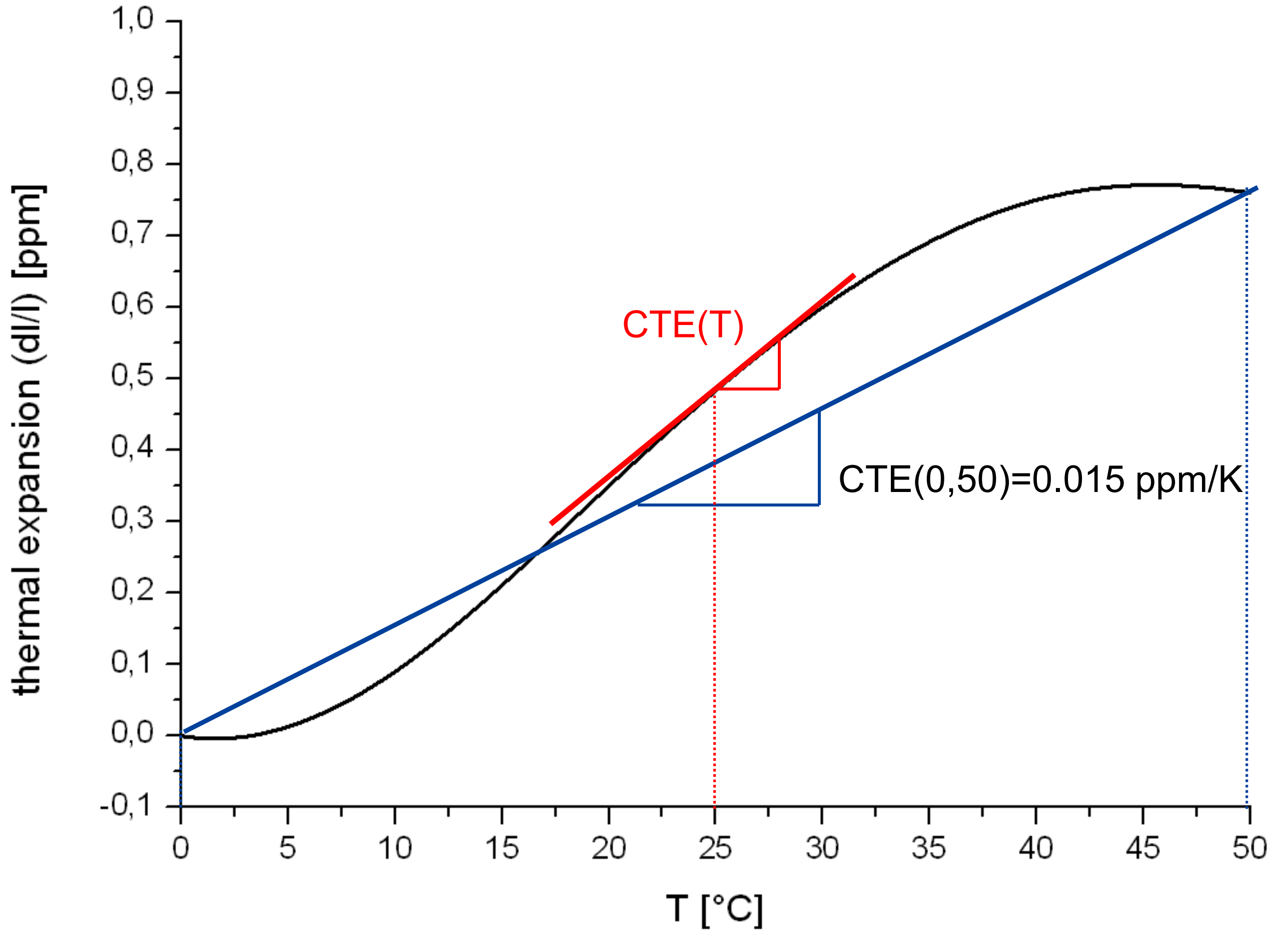
The CTE at a specific temperature T might differ from the mean value determined by the slope of the expansion between 0° and 50°C.



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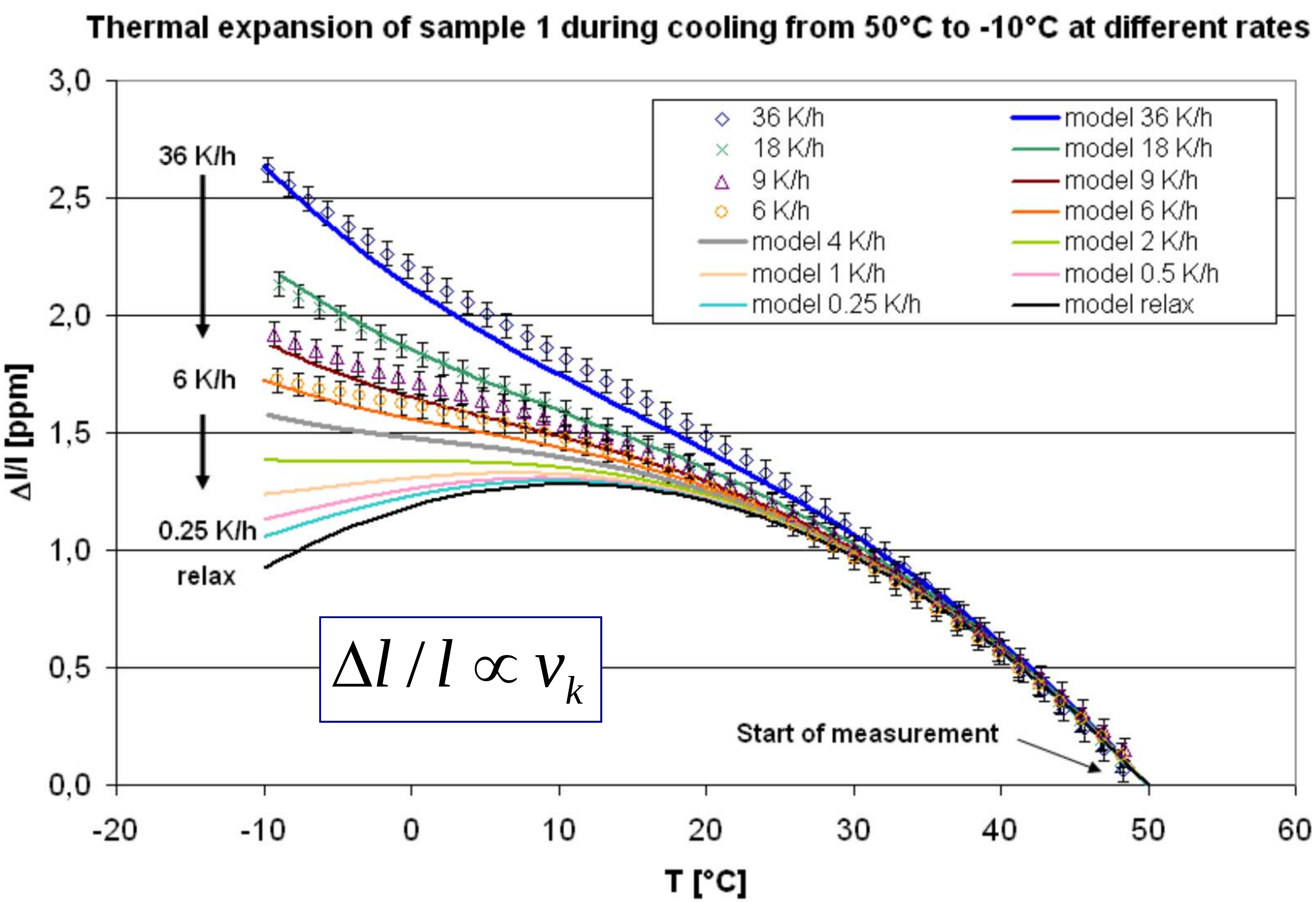
Structural relaxation can be calculated

Length change depends on temperature and temperature change rates.

Physical model capable to predict the thermal expansion at low temperature change rates.

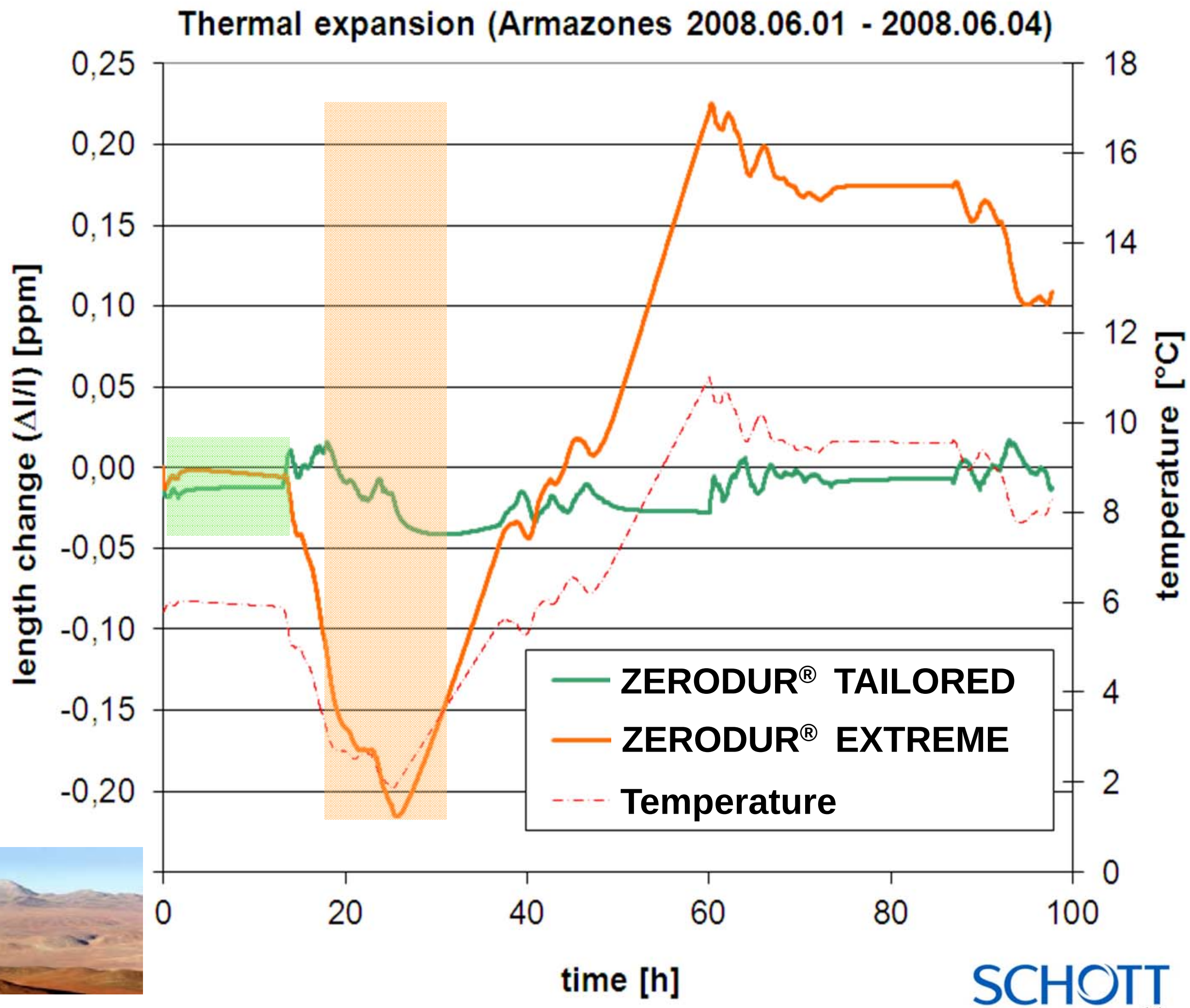


$$\Delta l / l \propto v_k$$

ZERODUR® TAYLORED allows adjustment of thermal expansion to given temperature profile

For extreme requirements small expansion lagging of ZERODUR may be compensated on the basis of a calculation model

Temperature Profile
→ Model
→ Provision of material with minimum thermal expansion



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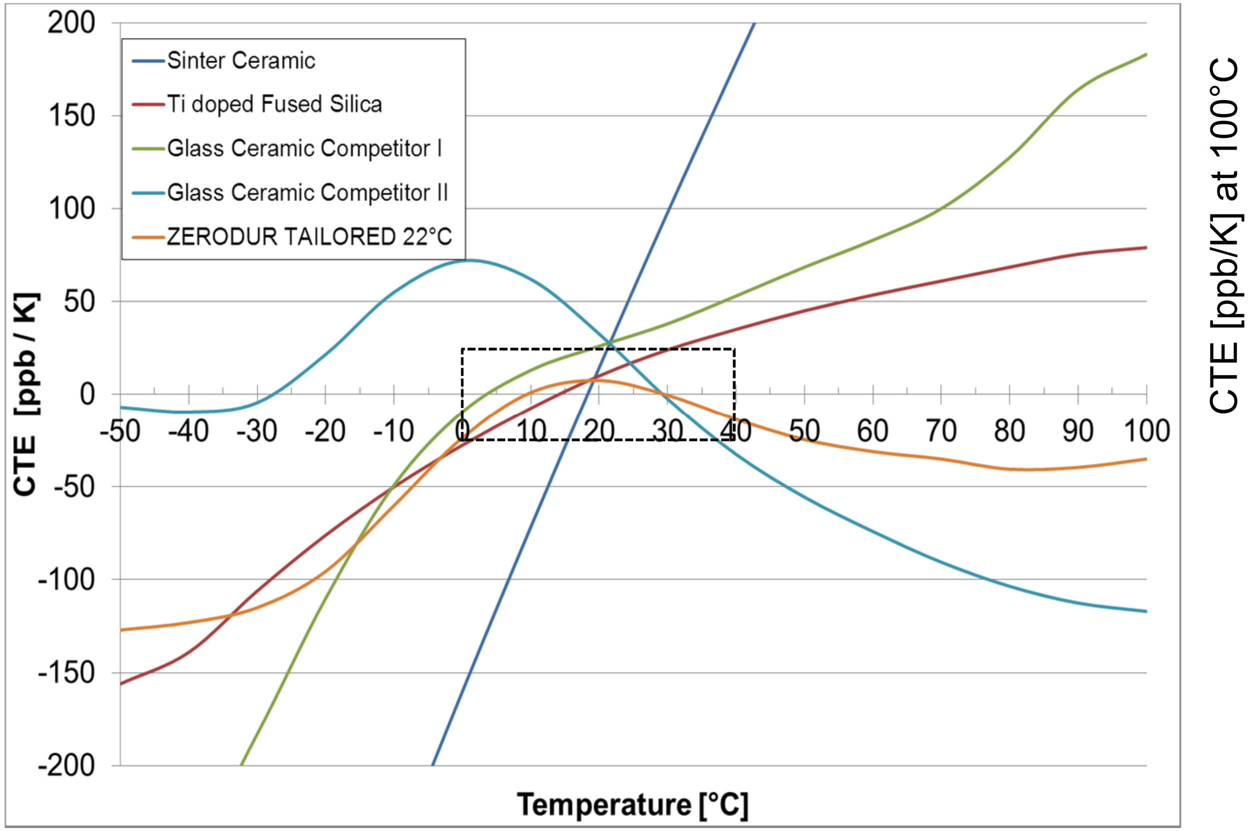
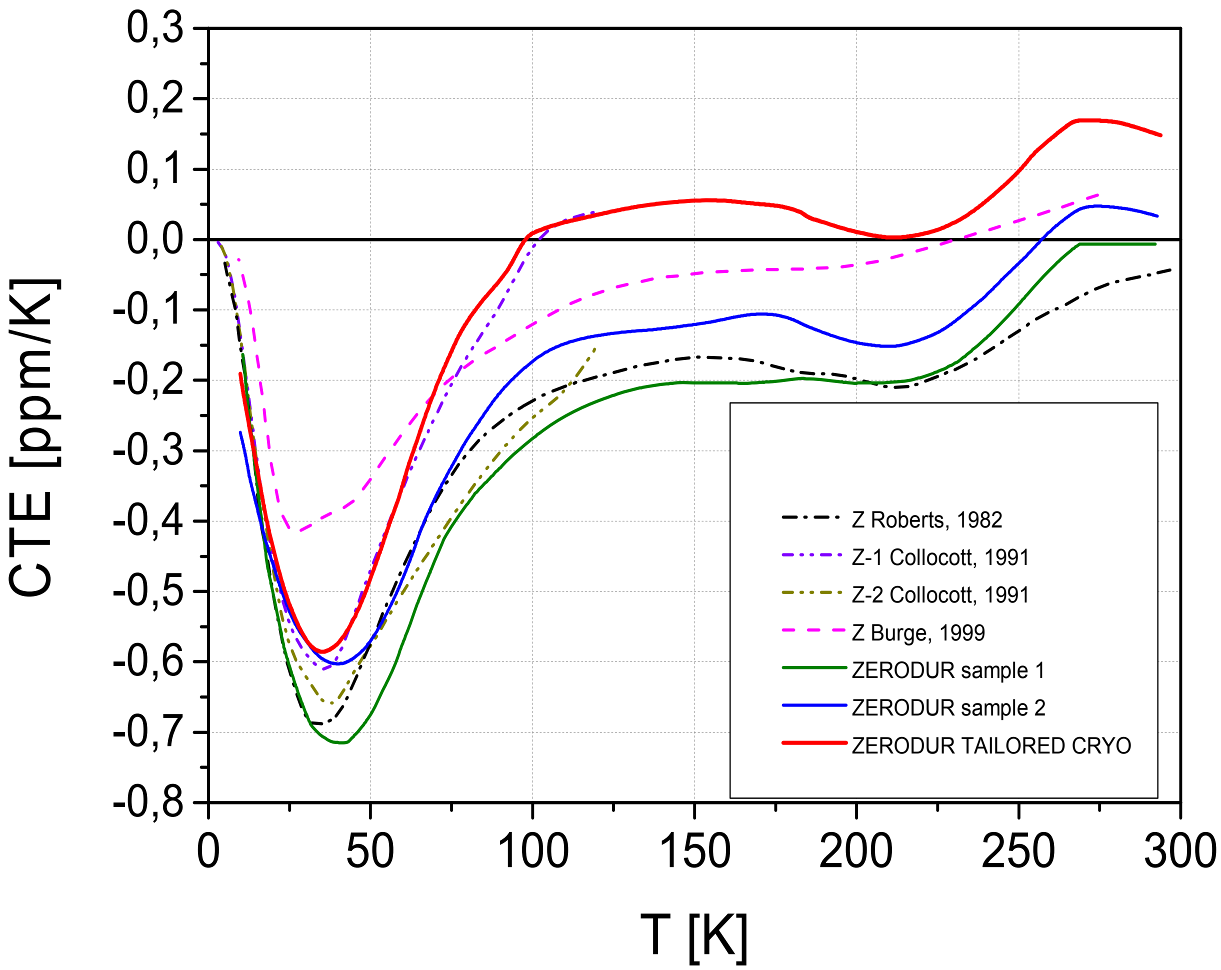
ZERODUR® TAILORED optimized for 22°C shows smallest CTE variation between -50°C and +100°C



CTE data generated at SCHOTT dilatometer during heating from -50°C to +100°C

ZERODUR® TAILORED CRYO: very low thermal expansion over a wide temperature range (250K to 70K).

- New ZERODUR® CTE(T) cryo data* in comparison with results published in earlier papers
- ZERODUR® **TAILORED CRYO**: is optimized for low temperature applications.



* ZERODUR® sample 1, sample 2 and TAILORED CRYO measured by the PTB (Physikalisch Technische Bundesanstalt, national standardization laboratory 2013/2014)

CTE Measurement

- Push rod dilatometer
- Interferometric measurement head
- Sample size 100 x 6 x 6 mm

CTE (0°-50°C)	Accuracy [ppb K^{-1}]	Repro (95%) [ppb K^{-1}]
Standard	± 10	± 5
Improved	± 6.2	± 1.2

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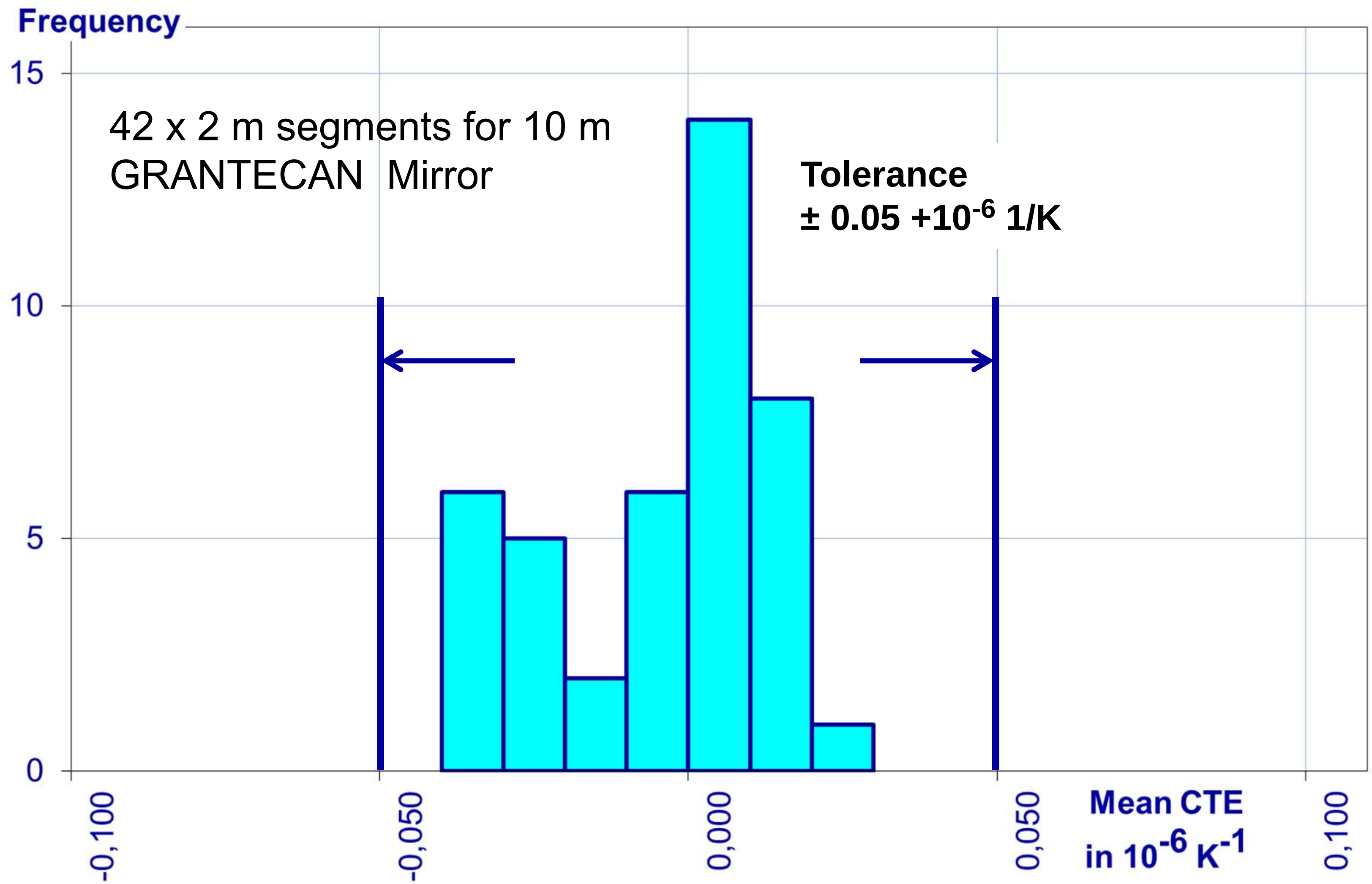
Absolute CTE values of 42 Segments lie fairly well in tolerance



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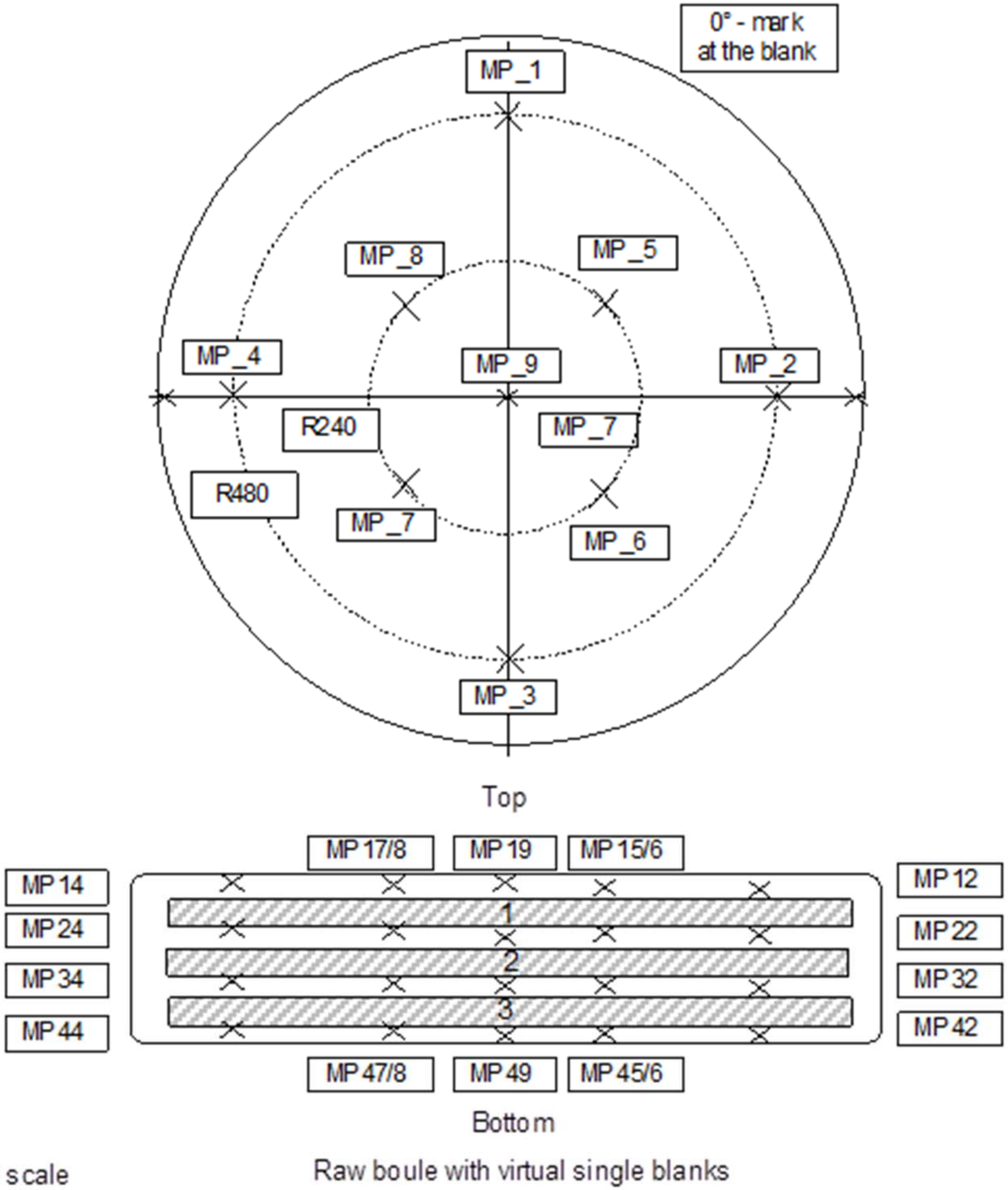
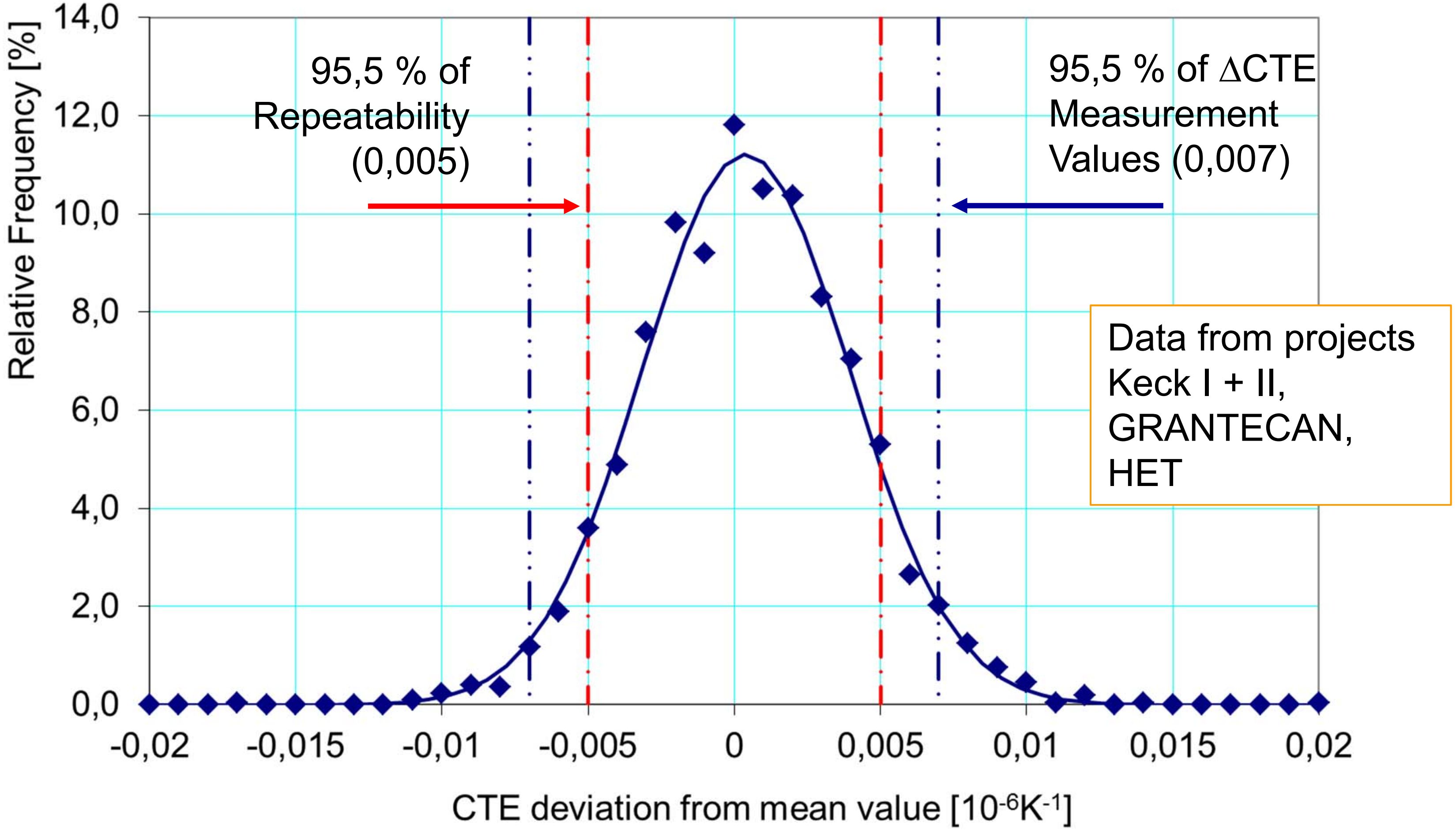
Coefficient of thermal expansion CTE Homogeneity

CTE Homogeneity is highly repeatable



not to scale

CTE Homogeneity is highly repeatable - as statistics of more than 200 mirror blanks in sizes 1 – 2 m show



Largest part of statistical variation comes from measurement repeatability variations

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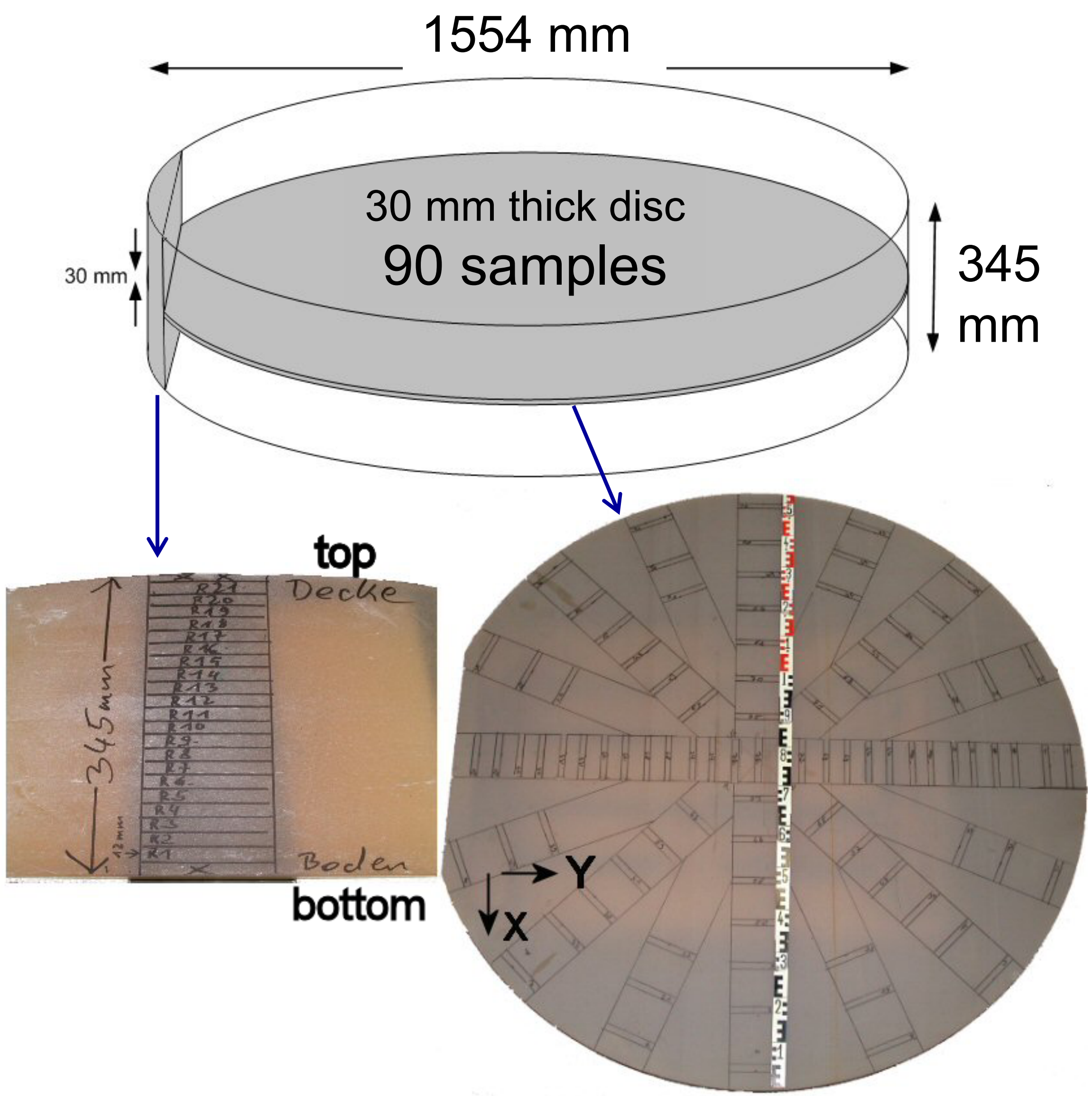
CTE-Homogeneity of two 1.5 m x 0.35 m disks

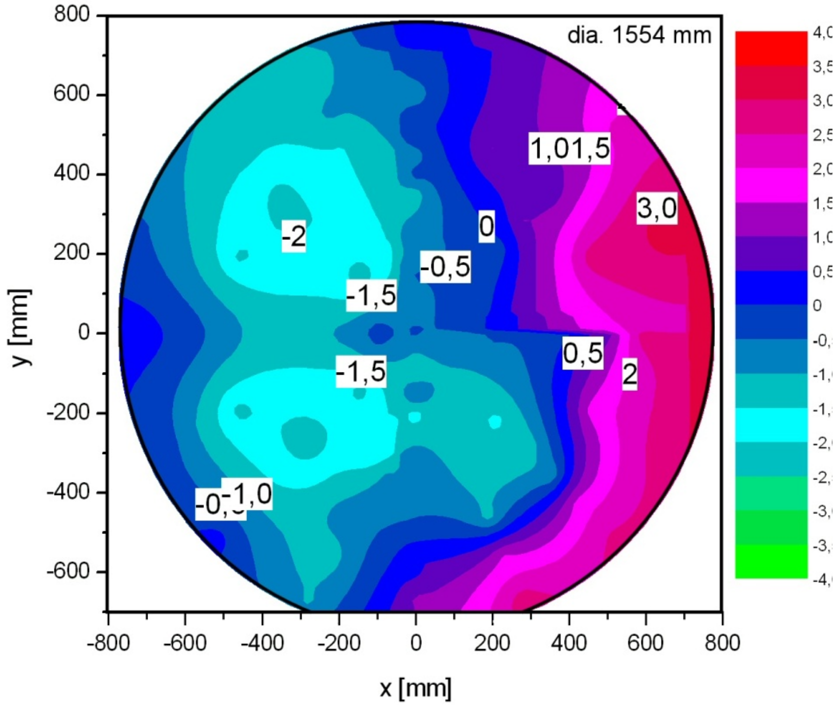
- Highly resolved
  with 90 + 21 samples
- Standard blank
  no special selection
- Measured with best
  reproduction accuracy

Vertical cut off:
21 samples

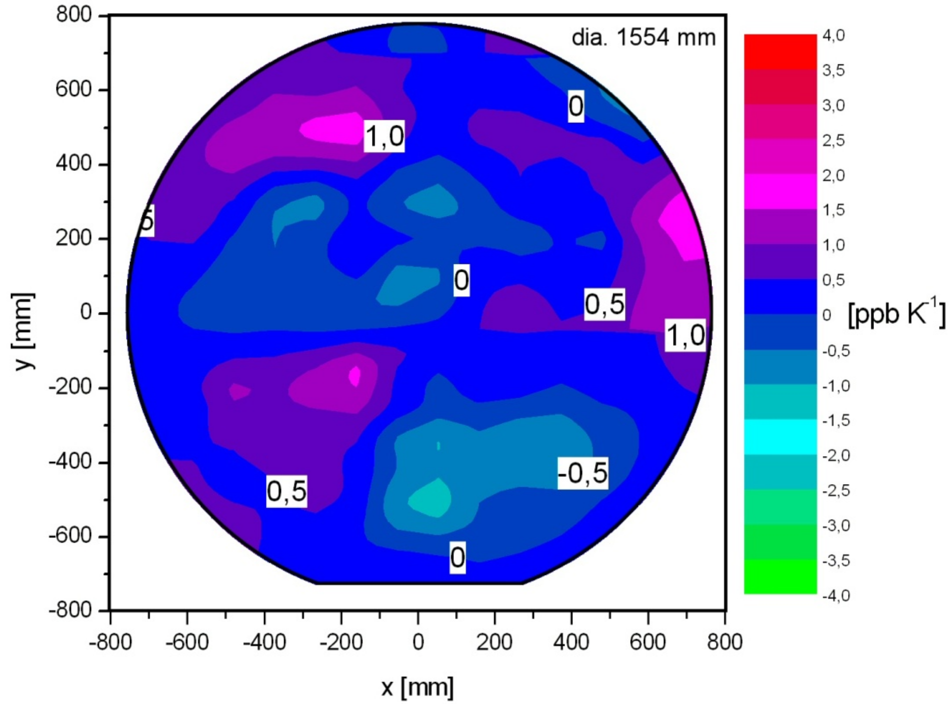


CTE Homogeneity of two 1.5 m ZERODUR® disks

Blank 1, 2006



Blank 2, 2008



		Blank 1	Blank 2
Mean CTE (0°C, 50°C)	[ppb K^{-1}]	42.4	39.9
Homogeneity (p-v)	[ppb K^{-1}]	6.4	3.8
Axial gradient (mean)	[ppb K^{-1} mm^{-1}]	< 0.02	< 0.01

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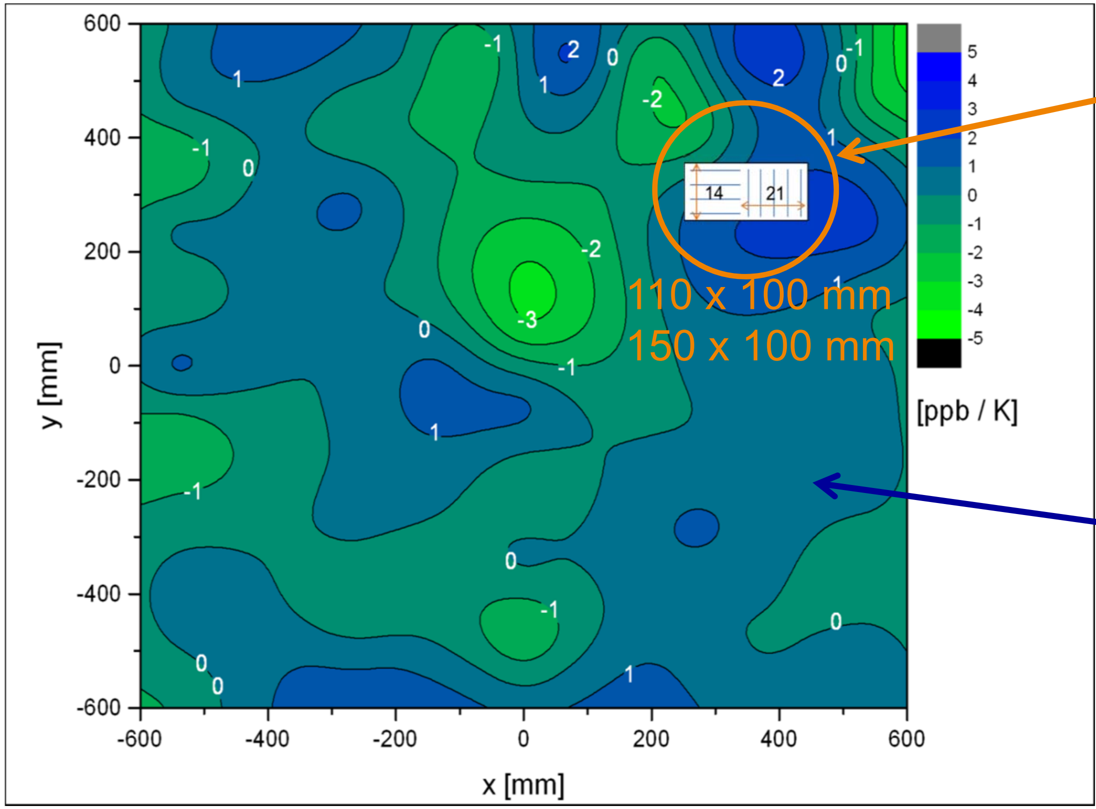
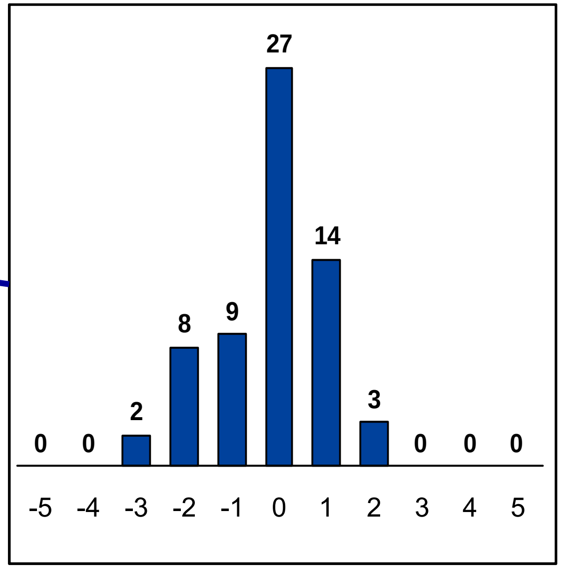
Excellent CTE homogeneity of a 1.2 m x 1.2 m rectangular 5 ppb/K p-v



Small scale homogeneity
21 (x) and 14 (y) samples
4 ppb/K   3 ppb/K



CTE differences in ppb/K of relative to mean CTE

64 samples

Reproducibility: ± 1.2 ppb/K (95% CB)

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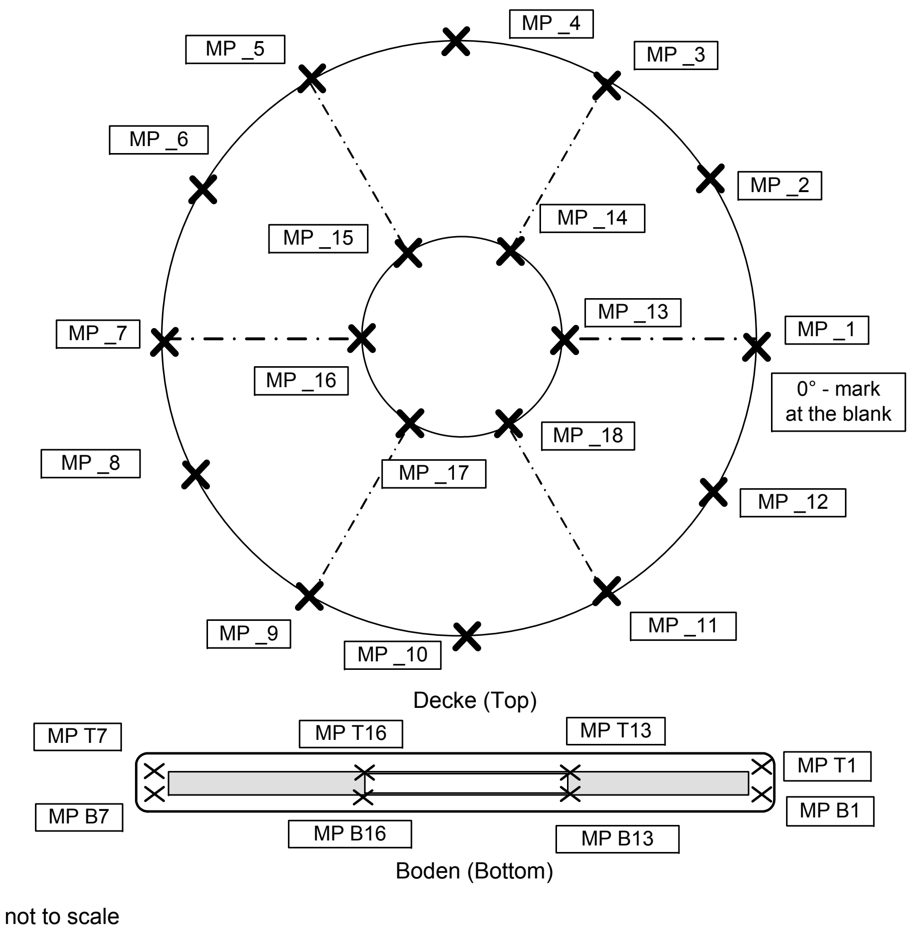
Outstanding CTE Homogeneity of a 4m Mirror Blank

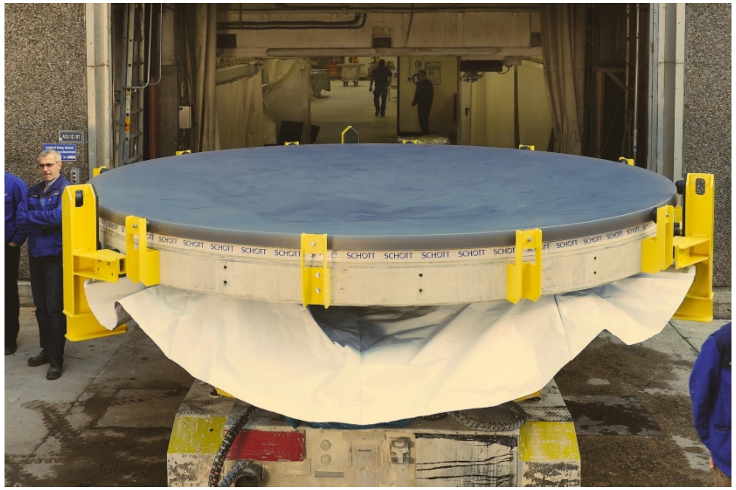
36 Samples



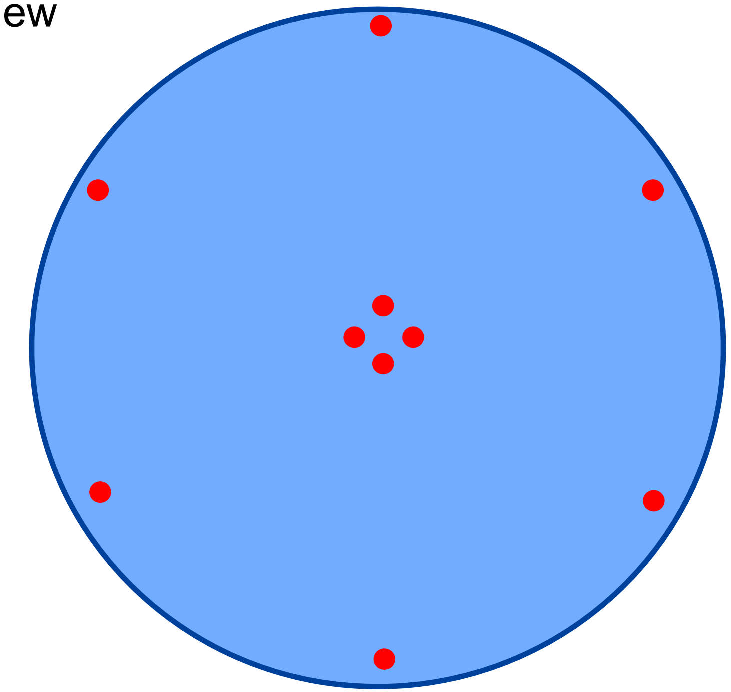
Raw boule with virtual single blank

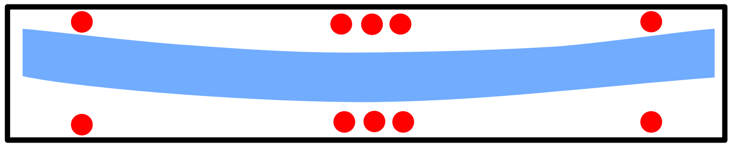
Mean value: 54 ppb/K
Homogeneity: 8 ppb/K (!)
Axial gradient: 2 ppb/K (!)

DKIST Daniel K. Inouye Solar Telescope (formerly ATST) CTE Mean value and Homogeneity are excellent



CTE	Temperature Interval	
	5°C / 35 °C	0°C / 50 °C
Mean	6 ppb/K	0 ppb/K
PV	6 ppb/K	3 ppb/K





The CTE values of the 6 most recently produced 4 m class ZERODUR® blanks show outstanding results in CTE homogeneity.

	Dimension	Sam-ple	CTE (0°; 50°) absolute value [ppb / K]		CTE (0°; 50°) homogeneity [ppb / K]	
Year	[mm]	#	Specification	Achieved	Specification	Achieved
2003	4100 x 171	18	+/- 50	66	20	18*
2005	3610 x 370	12	+/- 100	80	30	25*
2009	3700 x 163	36	+/- 150	54	40	9
2010	3400 x 180	12	+/- 100	42	30	5
2012	4250 x 350	16	+/- 30	60	40	5
2013	4250 x 350	16	+/- 30	0	40	3

* Measurement performed with older dilatometer

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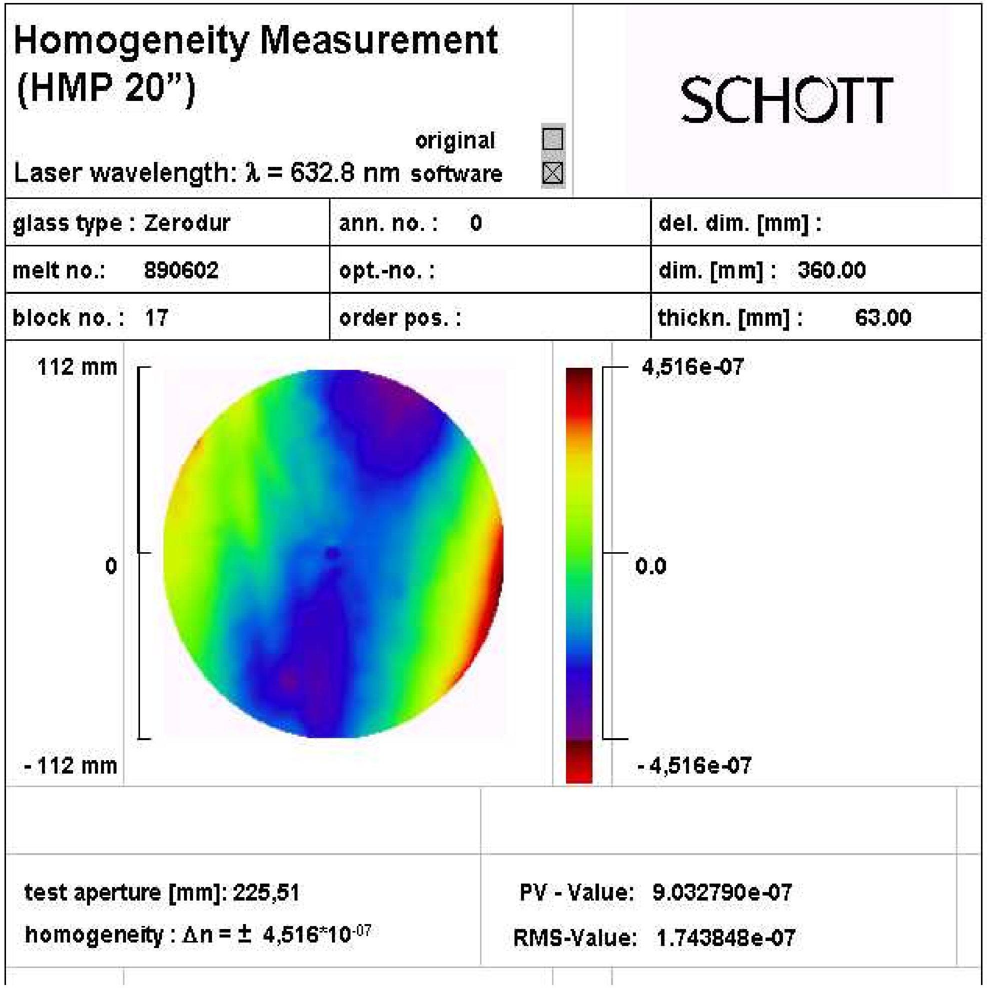
ZERODUR® Optical Homogeneity

Ø 360 (Ap.: 226) mm
x 63 mm

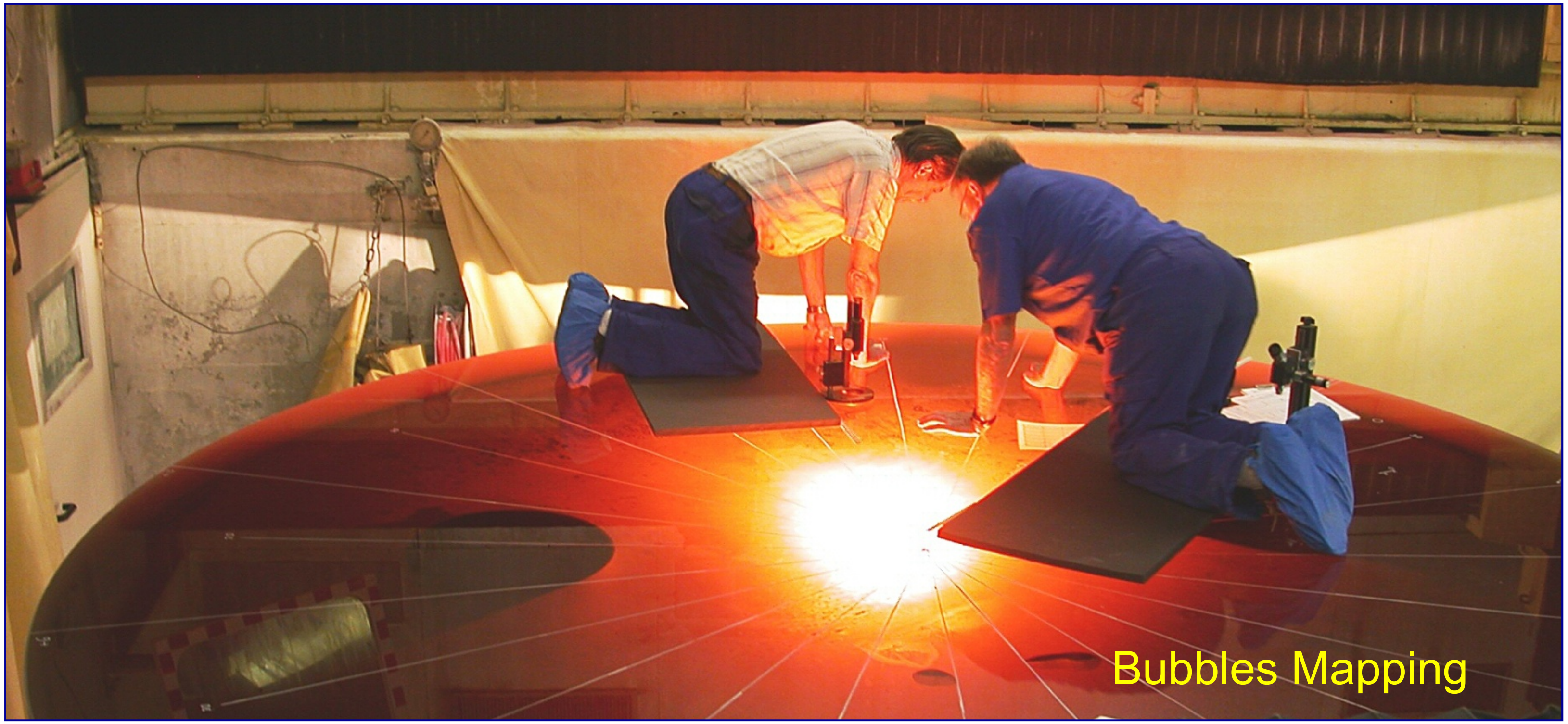
PV: 9 × 10^{-7}
RMS: 1,7 × 10^{-7}
Class H5



Exceptional homogeneity of selected disk

Material Homogeneity
Material Properties

Extremely low bubble content is typical for ZERODUR®



Example of a 4 m blank

Number of inclusions 0.1 - 0.5 mm	12
Number of inclusions 0.5 mm - 1.0 mm	8
Bubbles ≥ 1.0 mm	11
Max. diameter	2.7 mm

31 bubbles in the range of 0.1 – 2.7 mm in ca. 3000 kg!

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Very low striae is a heritage of optical glass production process

Striae are refractive index variations within short ranges ≈ 0.1 – 1 mm

SCHOTT has delivered several selected 2 m blanks with striae quality equivalent to best optical glass

1.5 m Blank with outstanding homogeneity and striae quality

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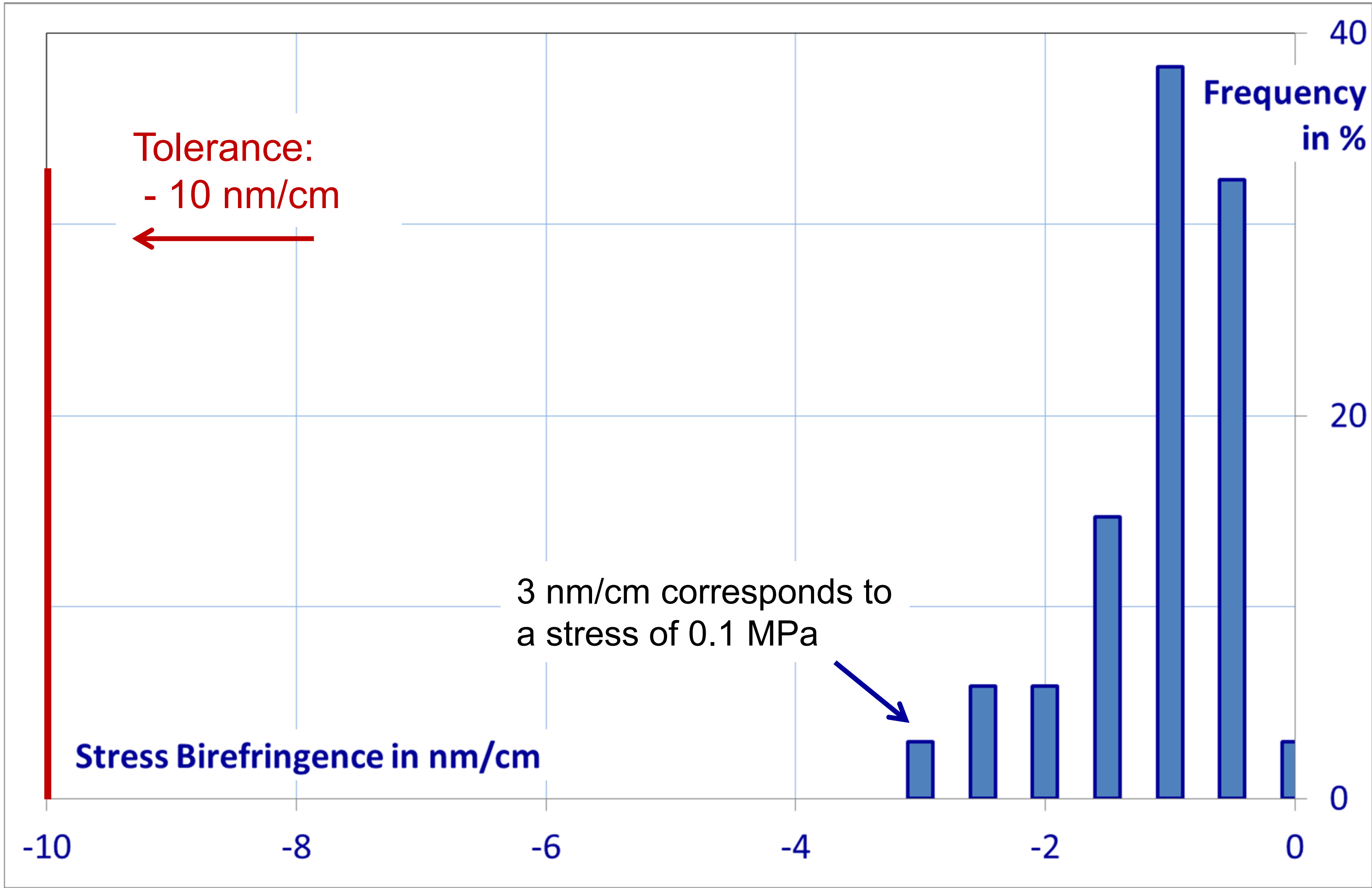
glass made of ideas

Stress birefringence statistics of 42 2 m diam. blanks for GRANTECAN 10 m mirror show stress below 0.1 MPa



Negative values: Compressive stress

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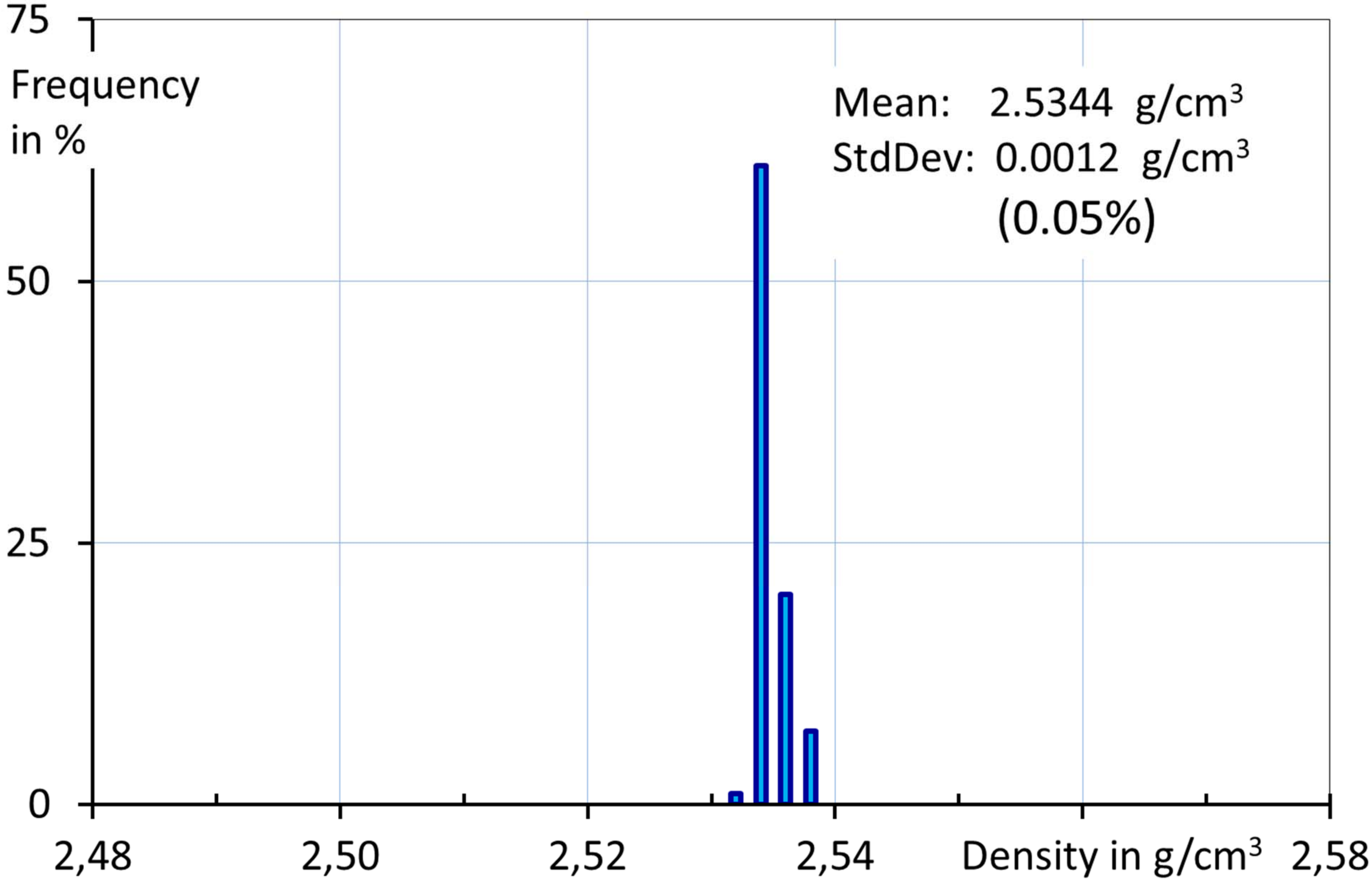
Variation in Density reflects measurement uncertainty



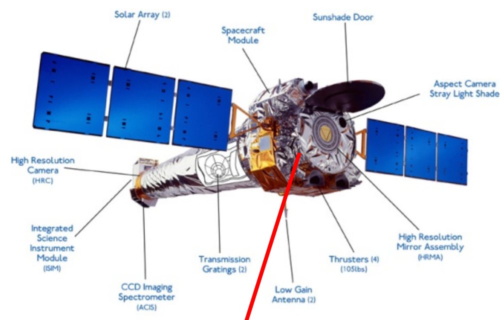
Data based on > 80 measurement within 5 years

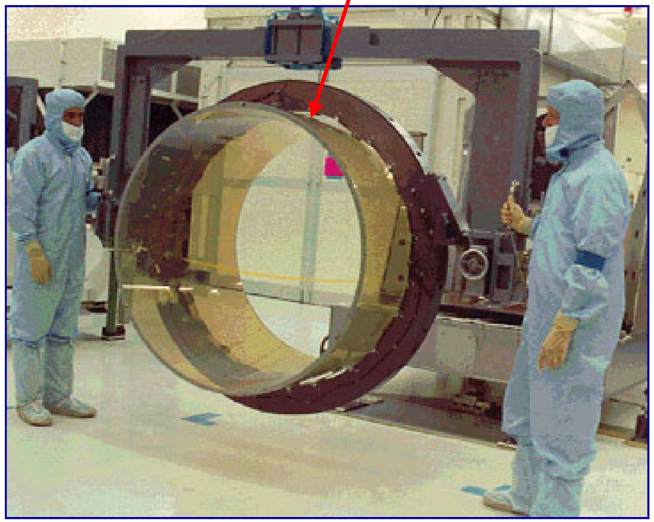
ZERODUR®: Polishability

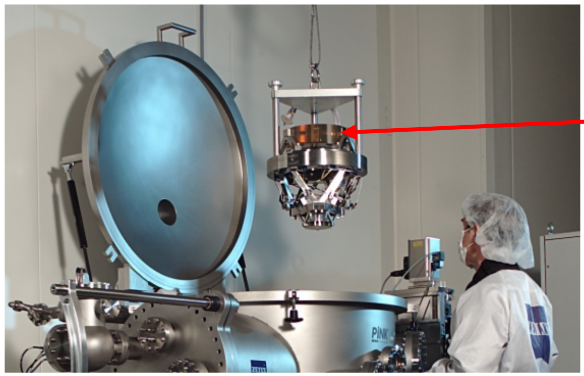
Zerodur can be polished
to a very low residual roughness.

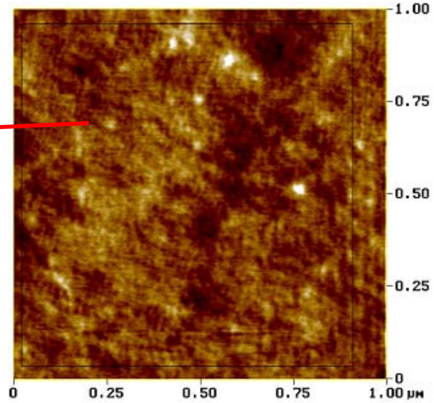
X-Ray satellite optics:
CHANDRA: 0.2 nm rms

Extreme UV Microlithography
EUVL: 0.15 nm rms



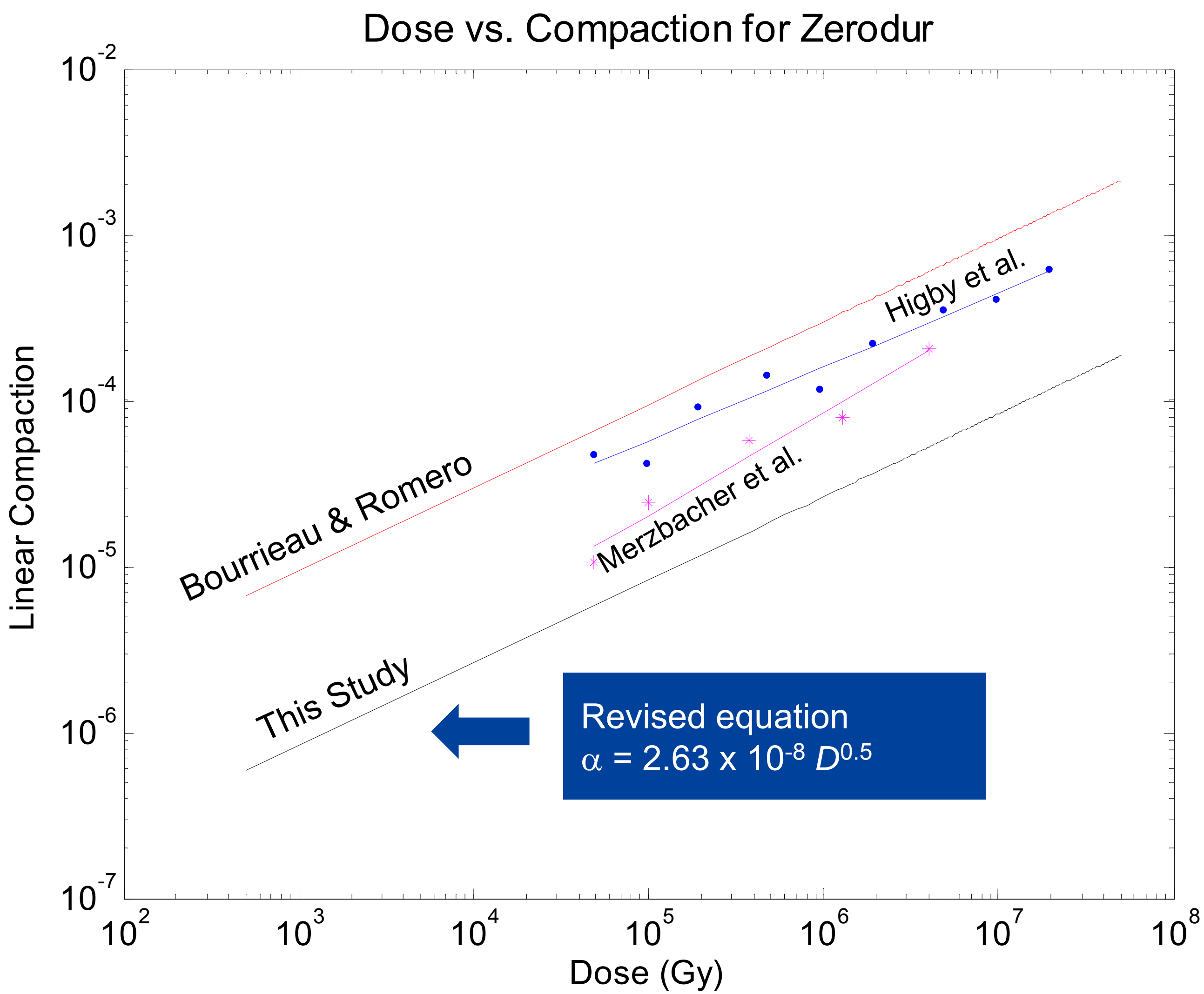






after polishing
under production
conditions
by Carl Zeiss

ZERODUR®: Resistance against ionizing radiation is high

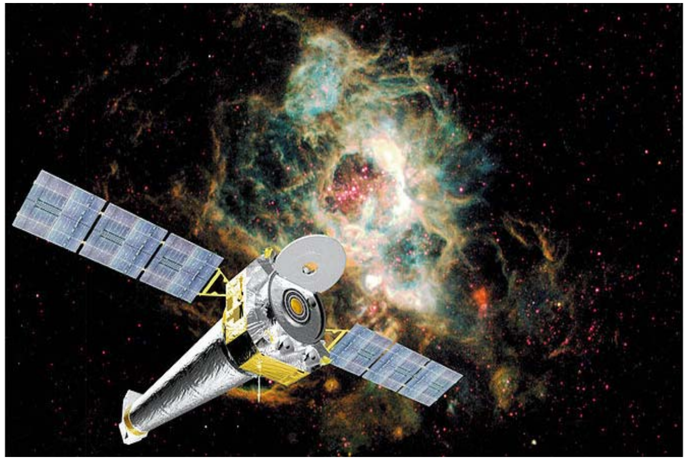


First analyses overestimated effect by factor > 10

Hubble and Chandra show excellent performance up to now this holds for many more space borne telescopes …

Hubble Space Telescope

Orbit:	LEO
Deployment:	April 1990
Lifetime:	> 20 years
Secondary Mirror Material:	ZERODUR®
M2 Diameter:	300 mm



Chandra X Ray Telescope

Orbit:	MEO
Deployment:	July 1999
Lifetime:	> 14 years
Wolter Mirror Material:	ZERODUR®
Mirror Diameter / Length:	800 mm / 600 to 1200 mm

⇒ Determine cumulated dose considering geometry and shielding

⇒ Real life proof of ZERODUR®'s performance

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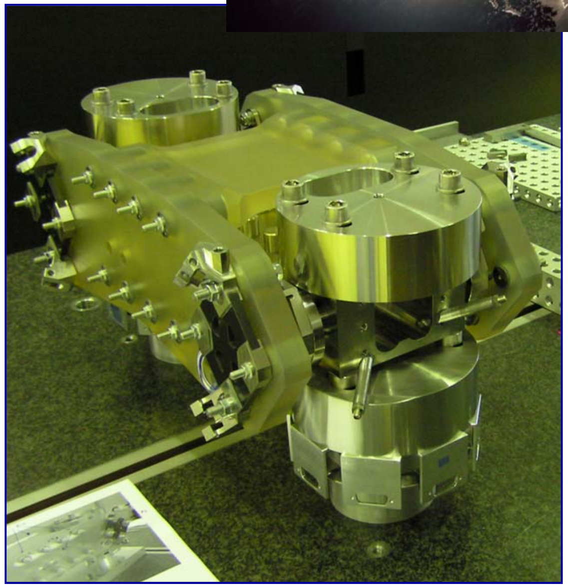
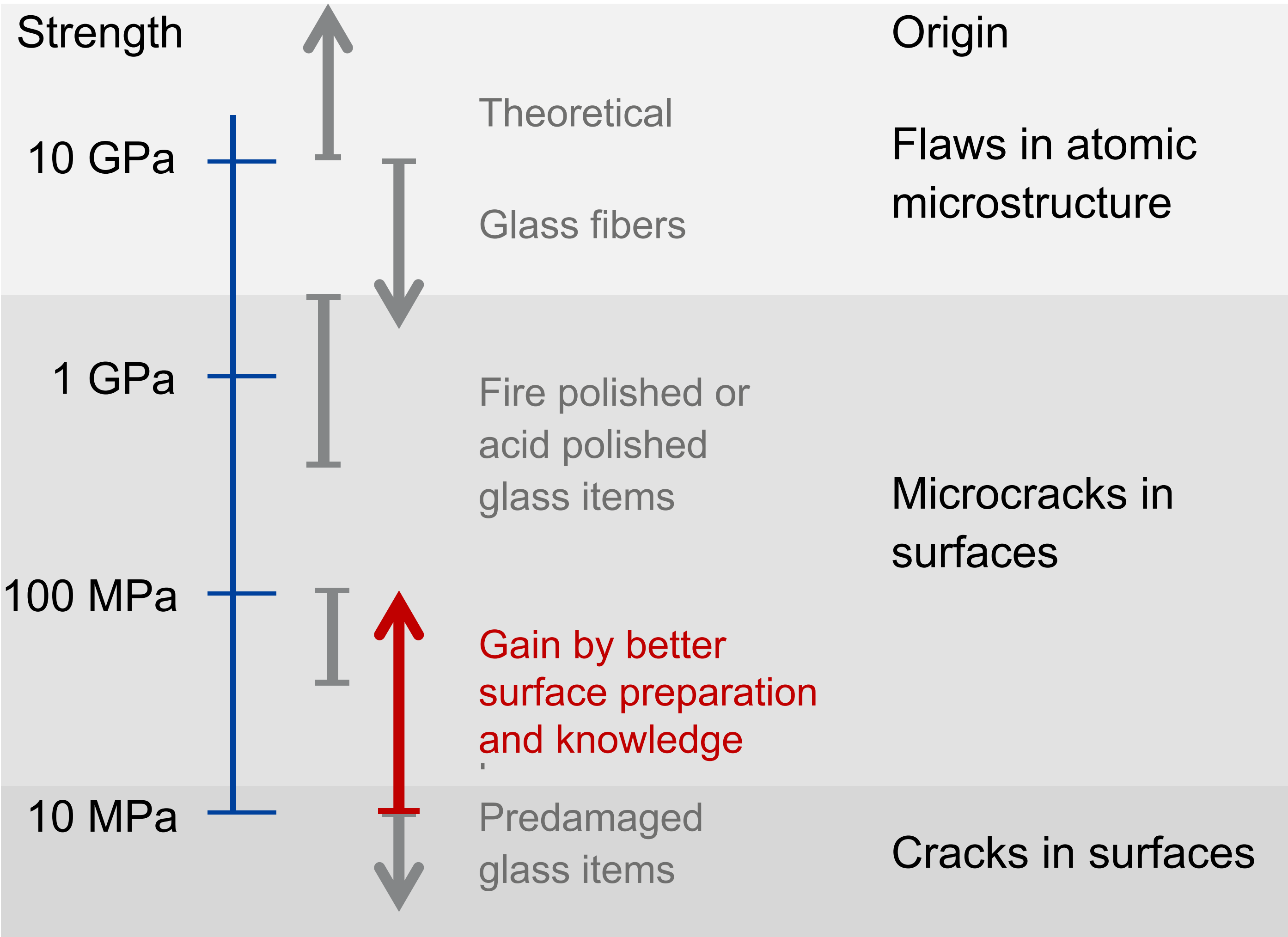
Bending strength

ZERODUR® Bending strength – New approach proves capability to endure high mechanical loads

- Generally ZERODUR®
  is stronger than glasses
- Strength is mainly determined
  by depth of micro cracks in its surface
- Much larger data sets are available now
- Ground surfaces lie higher than 40 MPa
  Etched surfaces higher than 100 MPa
- High mechanical load applications
  should be analyzed in detail

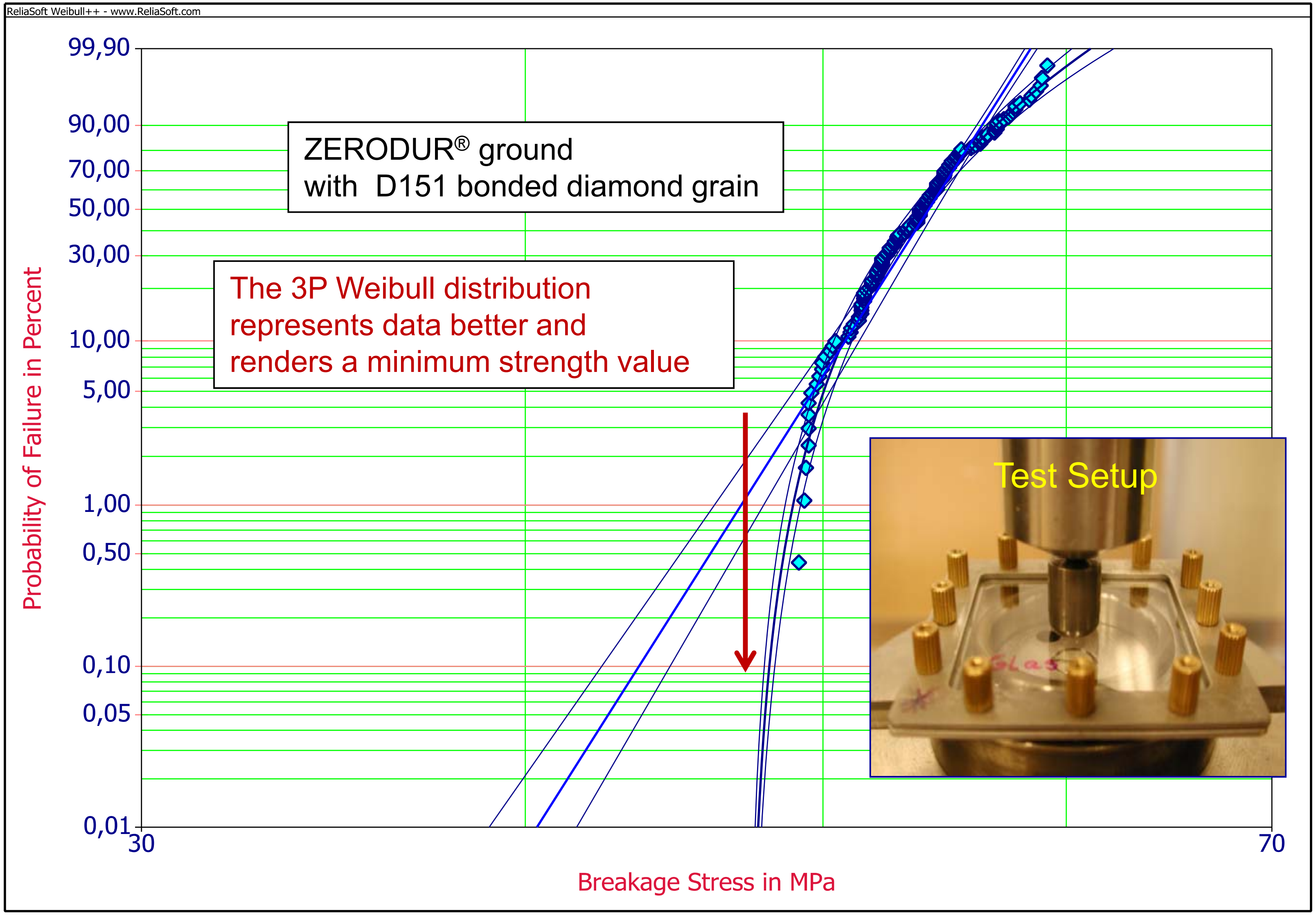


Bending Strength of Glass – Varies over Orders of Magnitude



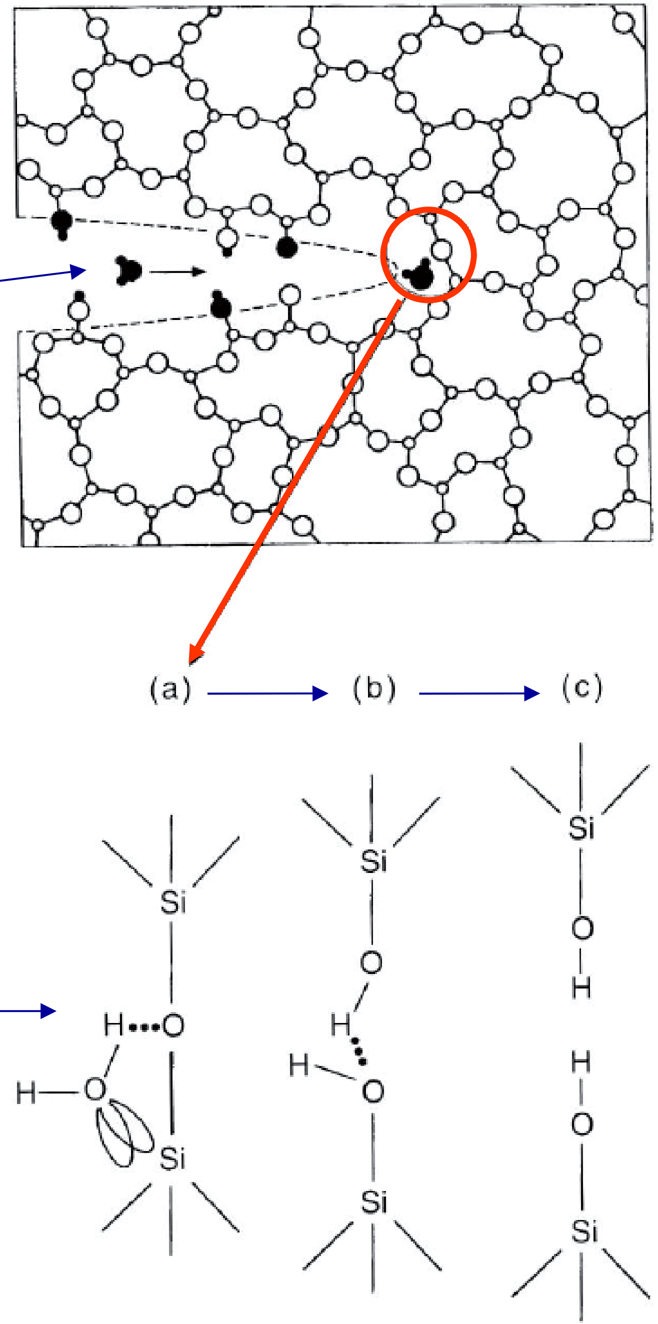
After: Scholze Glas 1988

Breakage stress of ground ZERODUR follows a 3P Weibull distribution



Strength Fatigue due to Stress Corrosion is enhanced by Humidity

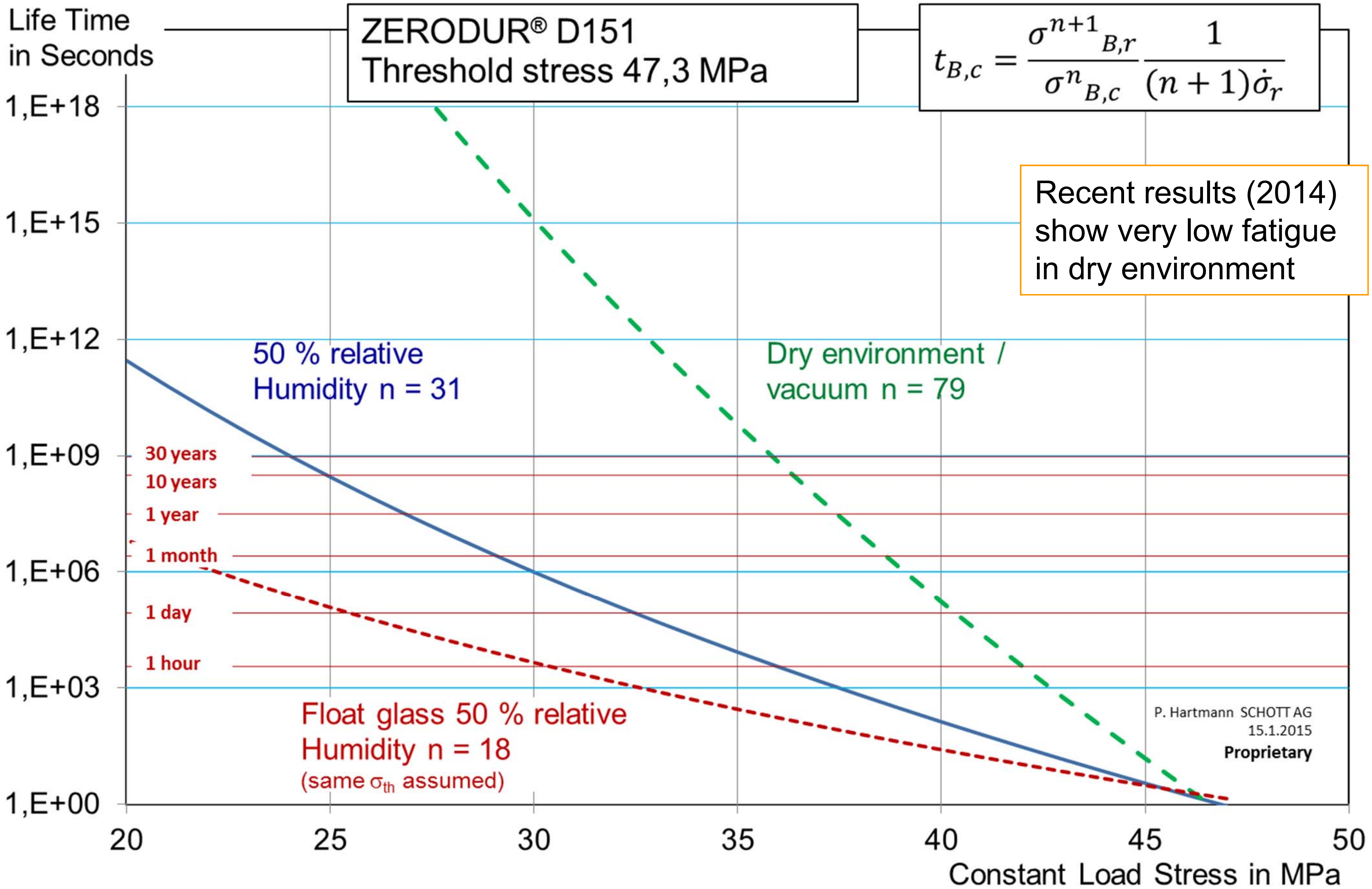
Water molecules diffusing into crack under tensile stress



Si – O – Si Bonding
Opened by water molecule

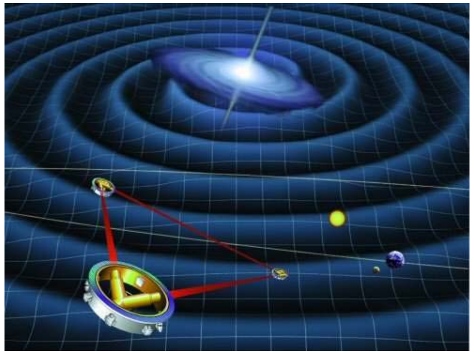
Acc. Michalske et al

Deterministic Lifetime Calculation



Feedback from application supports findings
LISA Pathfinder – LISA Technology Package

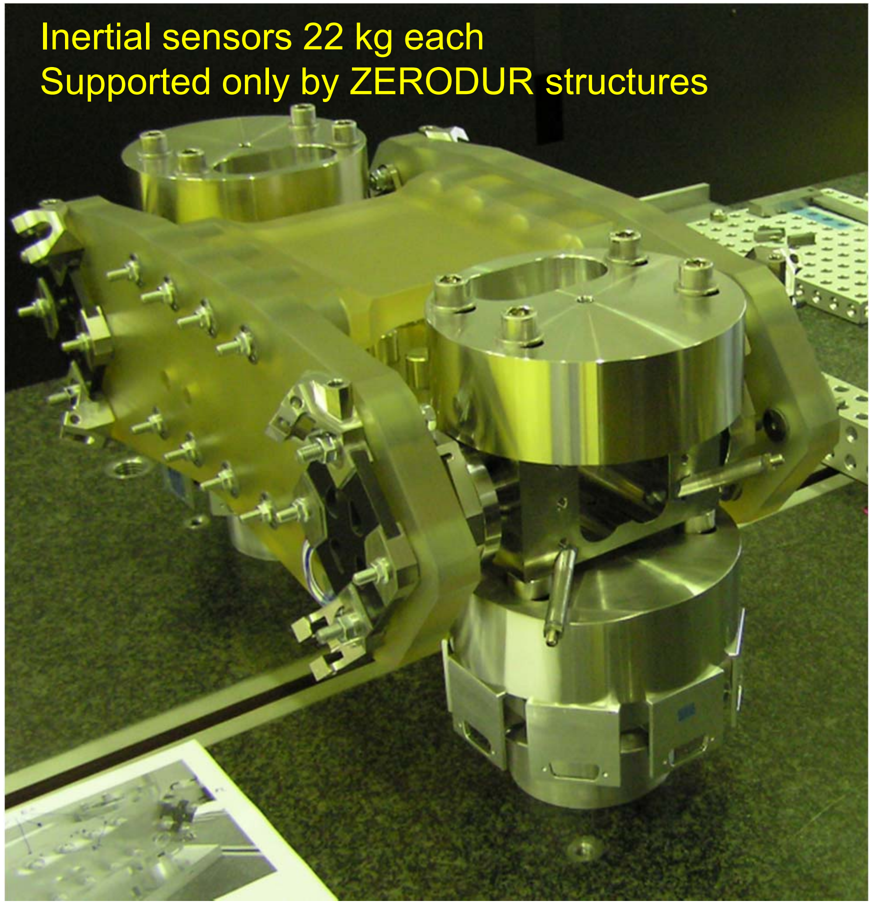
LISA – The Laser Interferometer Space Antenna Project of NASA / ESA



Assembled system of inertial sensors held by ZERODUR® structures

Successfully tested with 15 g sine and 18 g random vibrations

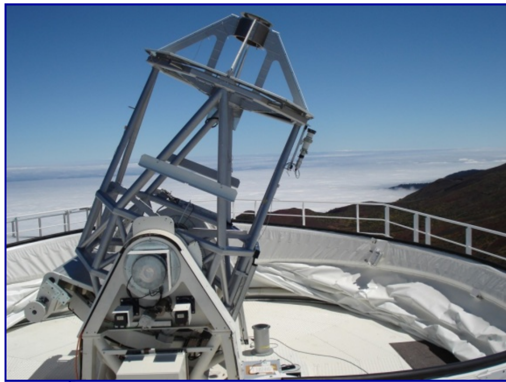
→ Major step forward in the LISA Pathfinder mission

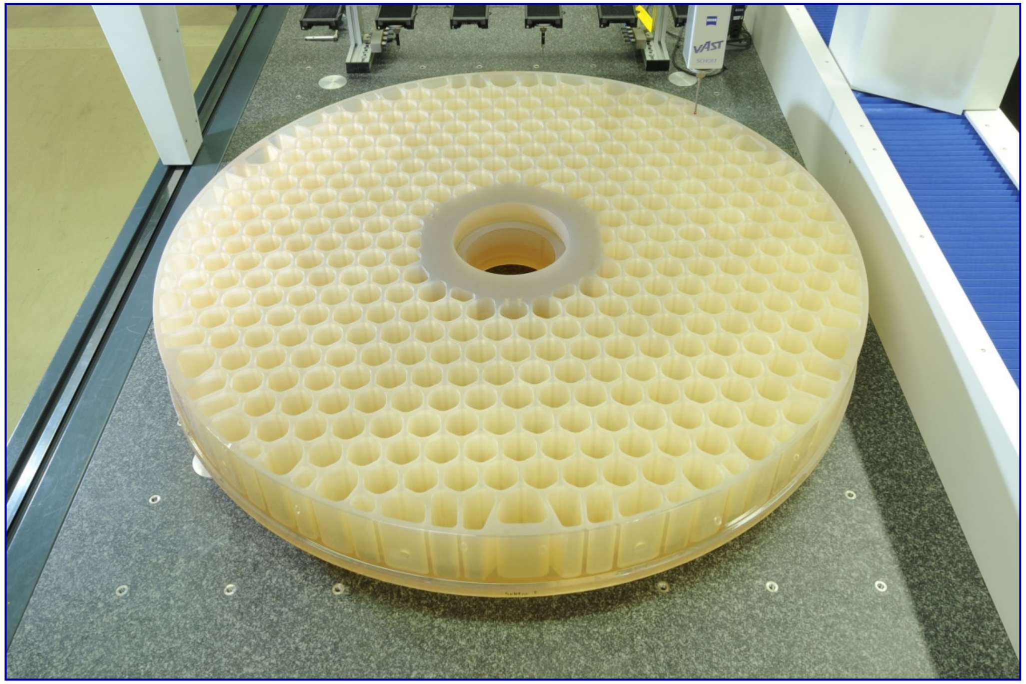


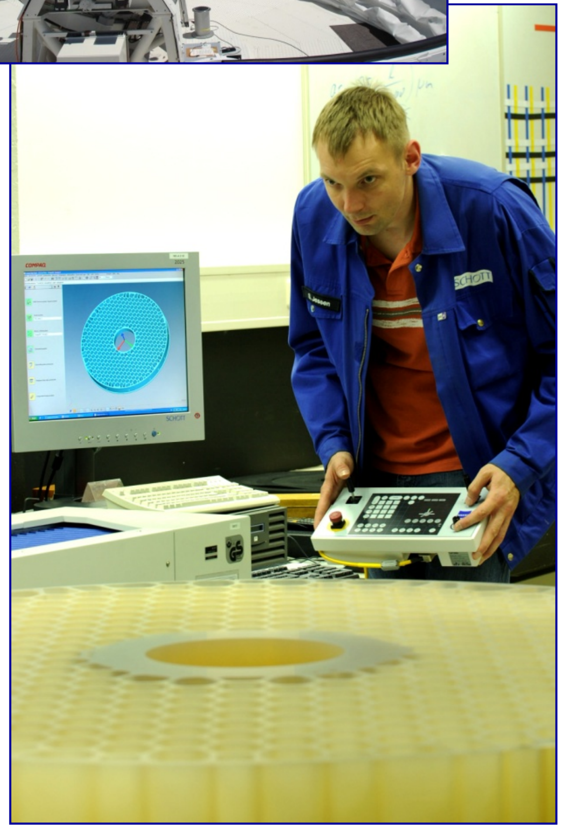
Lightweight substrates

Milled lightweighted mirror - GREGOR

1,54 m x 160 mm Mirror Blank 73 %
with curved constant thickness faceplate
Lightweighted by grinding delivered 08 / 2009







For Solar Telescope GREGOR, Tenerife

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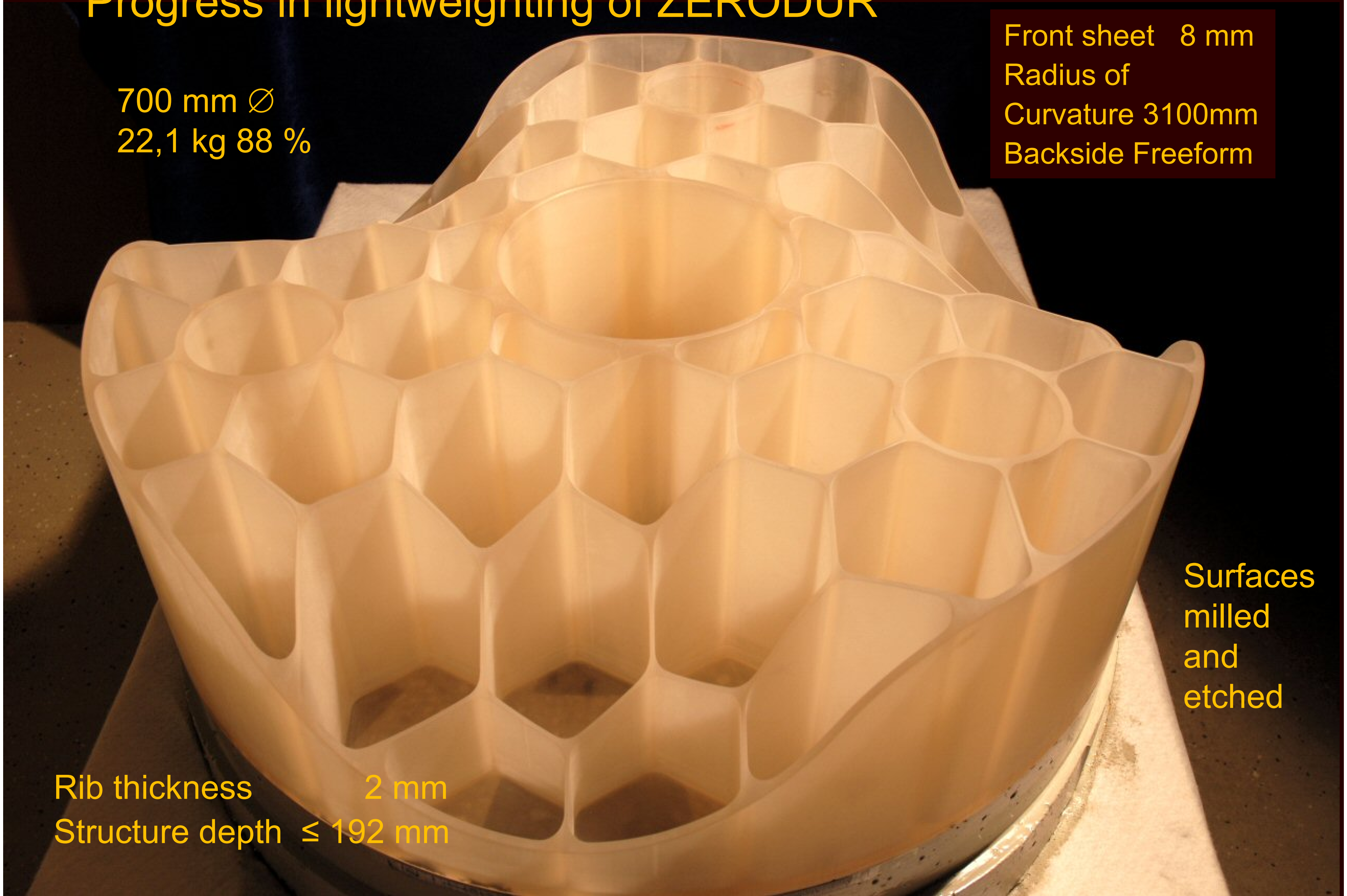
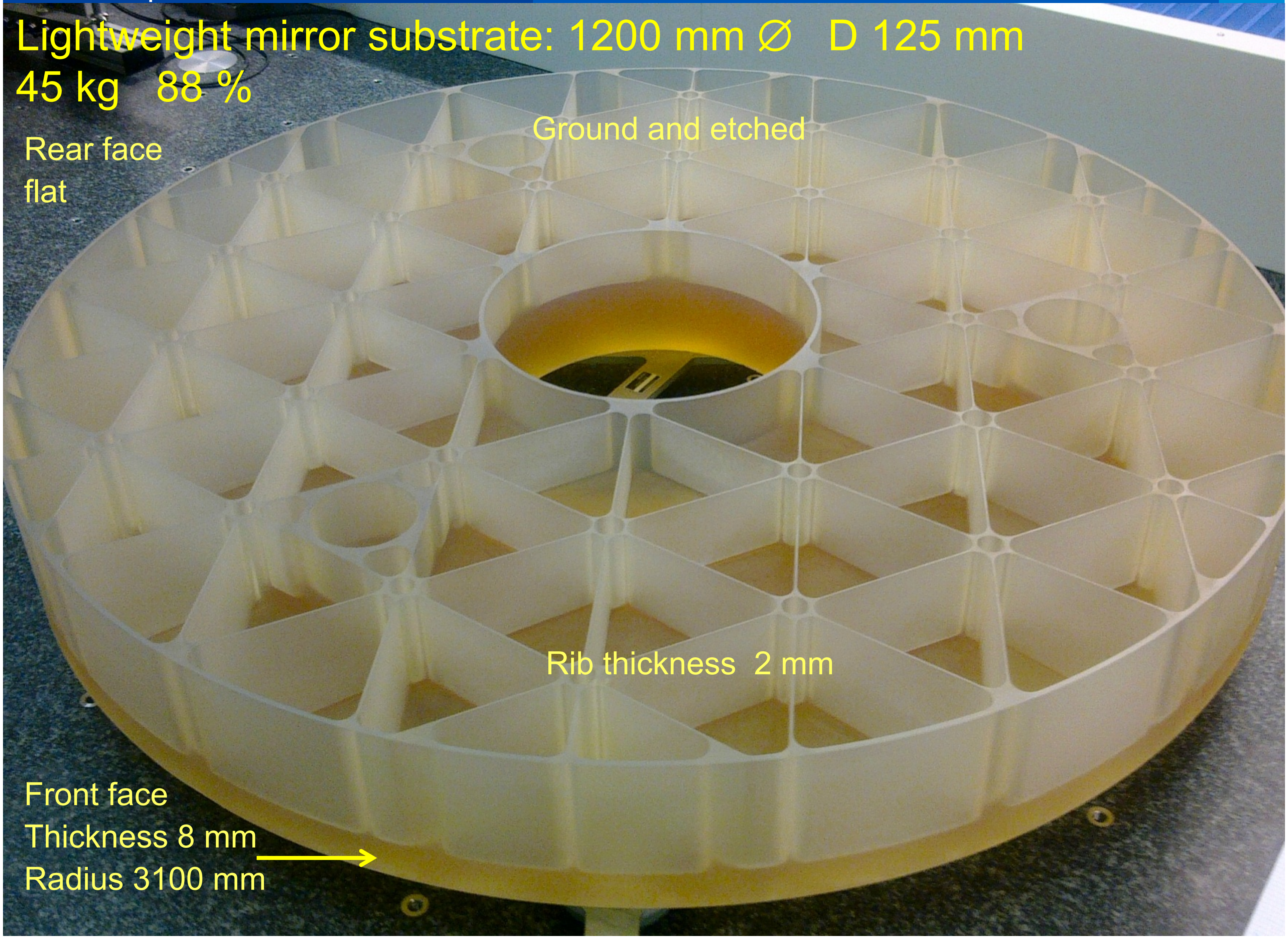
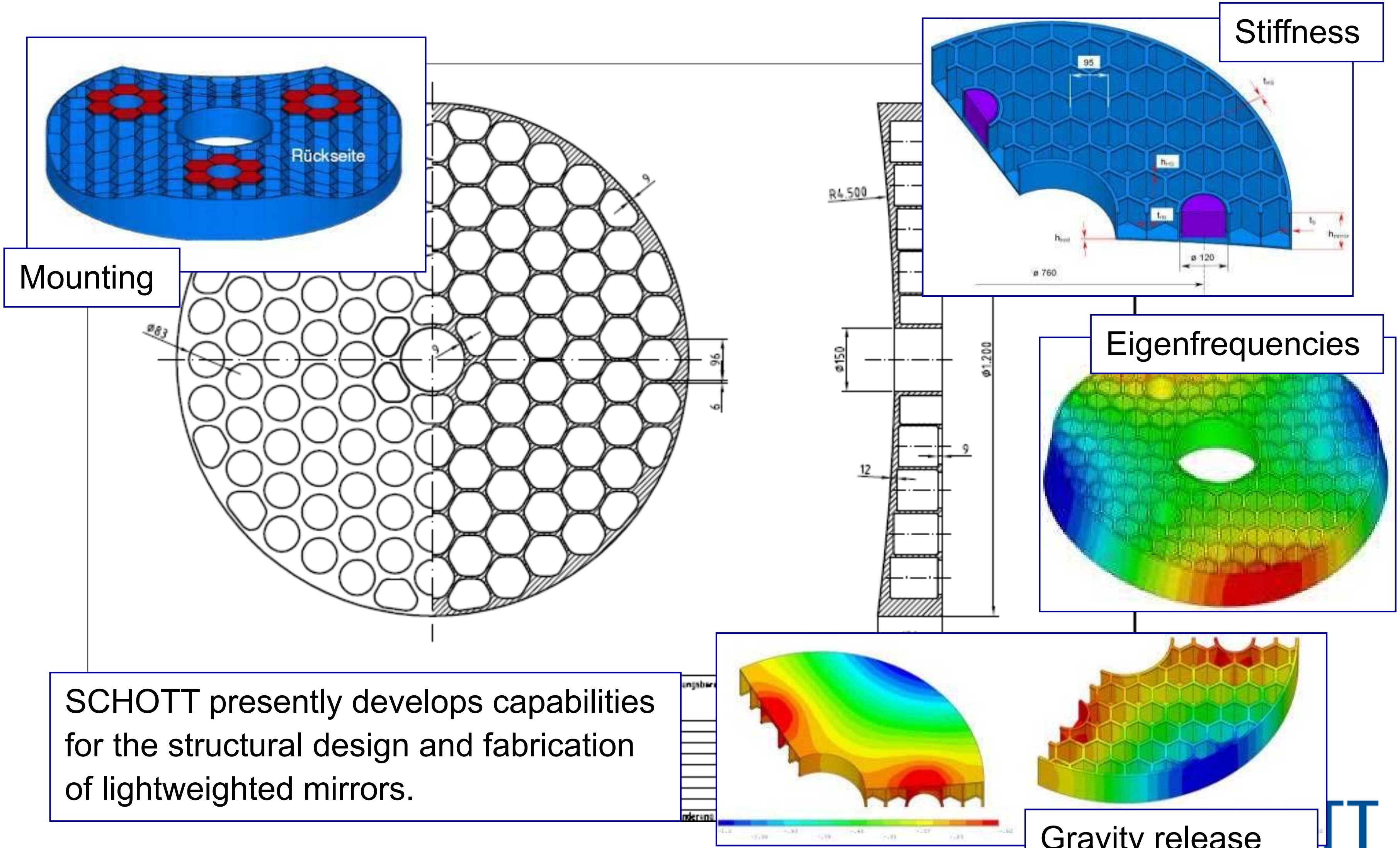
Progress in lightweighting of ZERODUR




Lightweight mirror substrate: 1200 mm ∅ D 125 mm
45 kg 88 %
Rear face
flat
Ground and etched
Rib thickness 2 mm
Front face
Thickness 8 mm
Radius 3100 mm

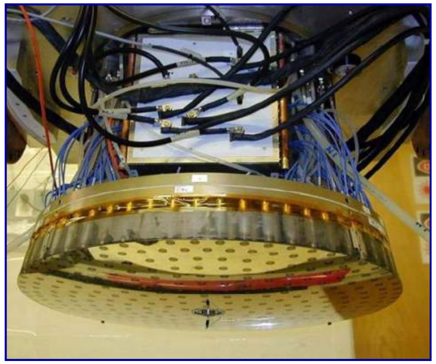
Light Weighted Mirror Design by SCHOTT



SCHOTT presently develops capabilities for the structural design and fabrication of lightweighted mirrors.

Adaptive Secondary Mirrors enable high resolution with ground based telescopes

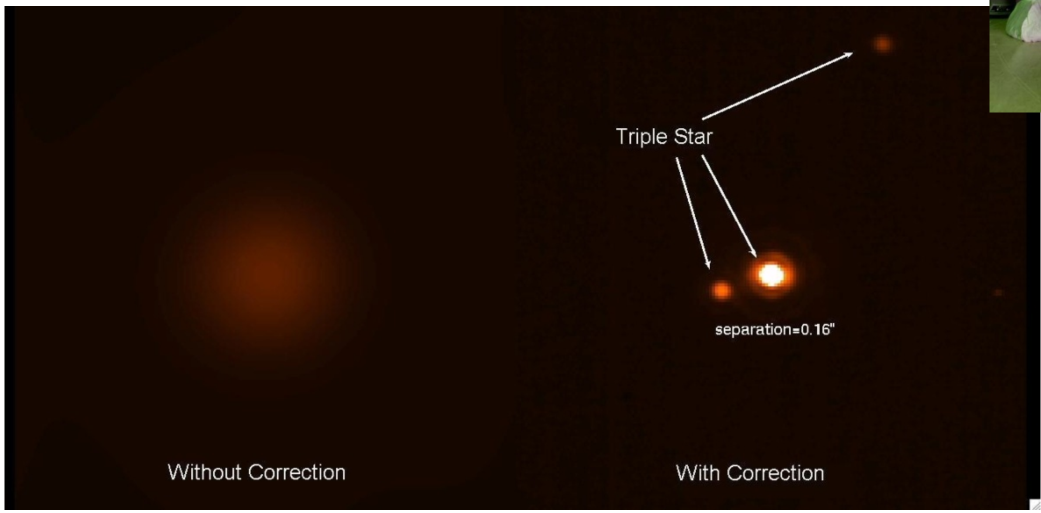
MMT Telescope



M2 0,64 m
Thin Membrane (1,9 mm)
+ Support plate (50 mm)

Large Binocular Telescope

M2 0,9 m similar to above



Pictures:
Large
Binocular
Telescope

Zerodur Variant: ZERODUR K20® Keatite

Zerodur K20 Keatite is a thoroughly ceramized variant of Zerodur.
It can withstand significantly higher temperatures (850°C) than Zerodur itself while maintaining still low CTE.

CTE (0°C, 50°C)	1.5 ppm / K
CTE (20°C, 700°C)	2.0 ppm / K

To be used as Mandrels for slumping of thin sheet glass mirror elements for X-Ray Telescopes

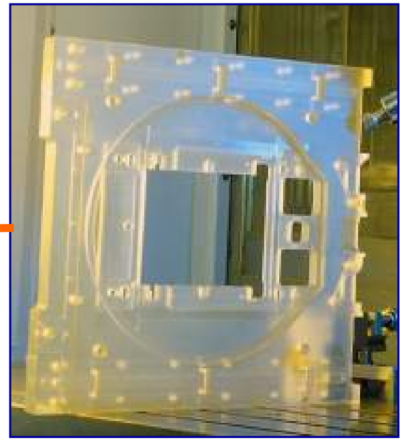
ZERODUR® Applications in Industry

Transmissive Microlithography from i-Line to 157 nm

ASML

UV - Wafer-Stepper
for Chip-Production

Reticle-
Stage



Wafer-Stage

Position
reference
mirrors

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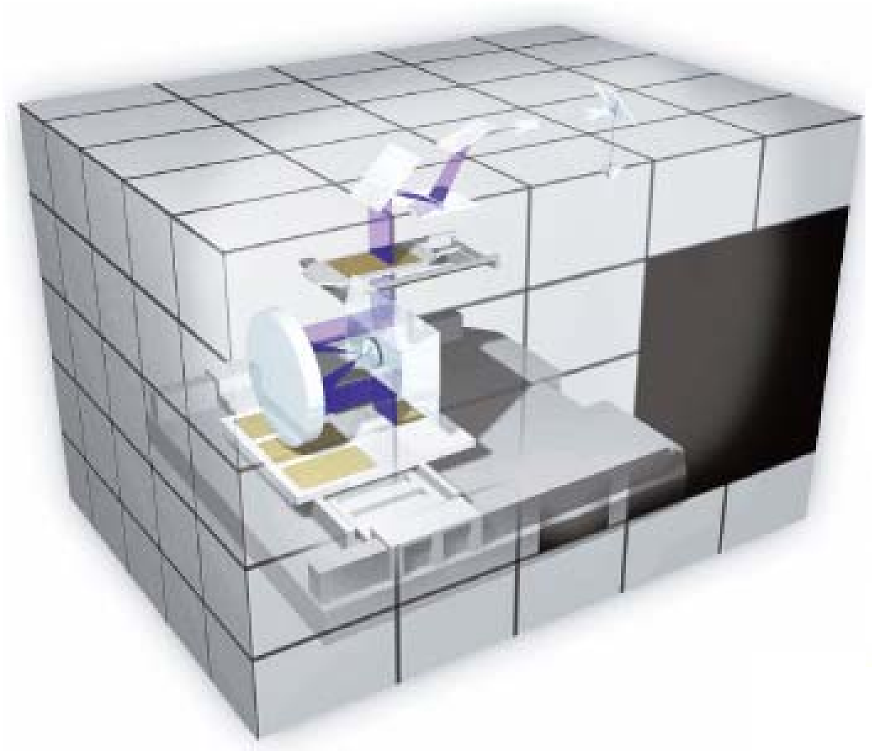
ZERODUR® in Lithography Machines for Flat-Panel-TV-Screens



8th-generation glass substrate sizes, making possible the single exposure production of widescreen TVs up to 57 inches in size

Pics: Canon, Panasonic, Apple

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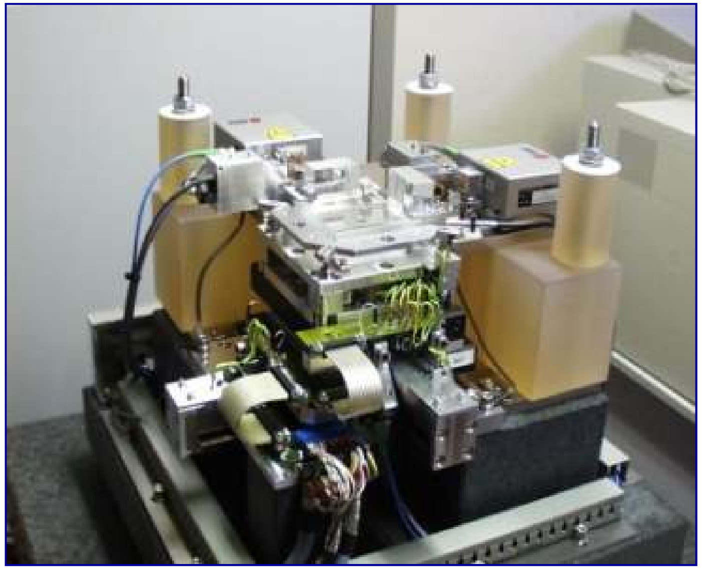
Extremely Sensitive Measurement Devices



L-Frame for an
Atomic Force Microscope

Gyroscopes for
earth rotation
measurements

Astronomical Applications

ESO-VLT 8 m-Telescopes

4 Zerodur-Mirrors
8 m Ø x 0,18 m

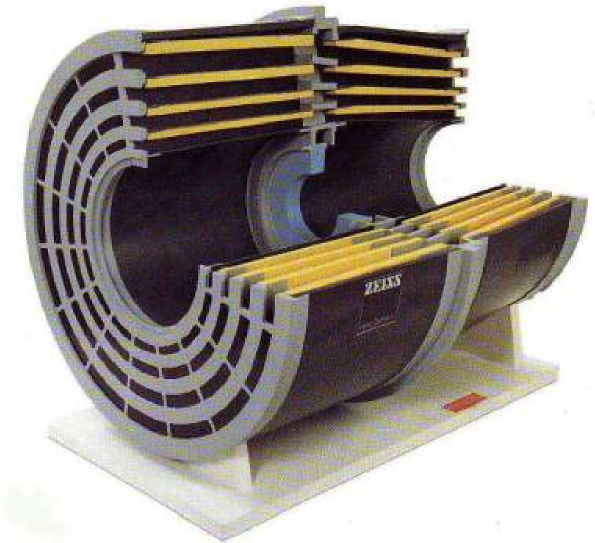
Pictures: ESO

ROSAT – German X - Ray Satellite

ZERODUR-Mirrors

4 x 2 Mirror Elements
0.85 m wide max x 0.5 m long

Super polish: 0.2 nm



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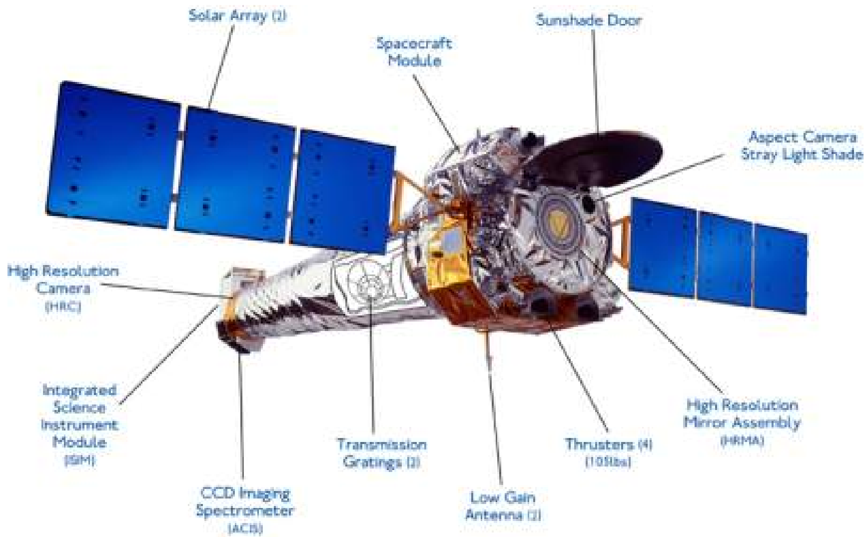
X-Ray Satellite CHANDRA (formerly AXAF)

X-Ray telescope
with best image resolution

Hollow conical cylinders
made from ZERODUR



ZERODUR-Mirrors

4 x 2 Mirror Elements
1.2 m wide max x 1 m long

Super polish: 0.2 nm

Pic: NASA

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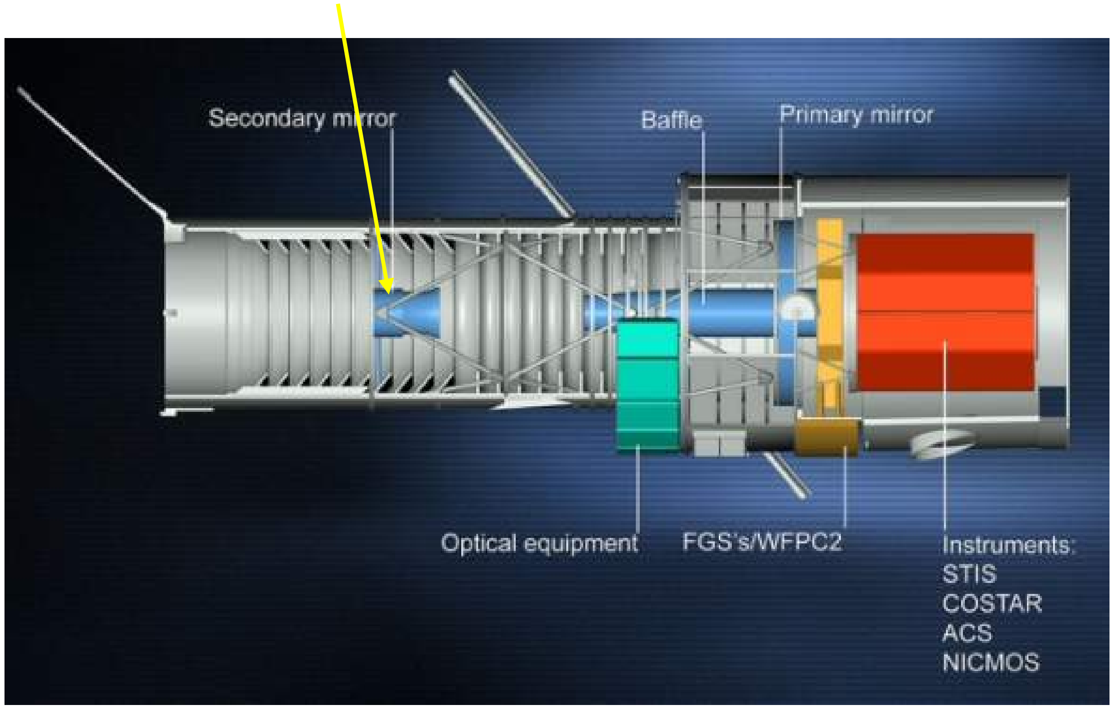
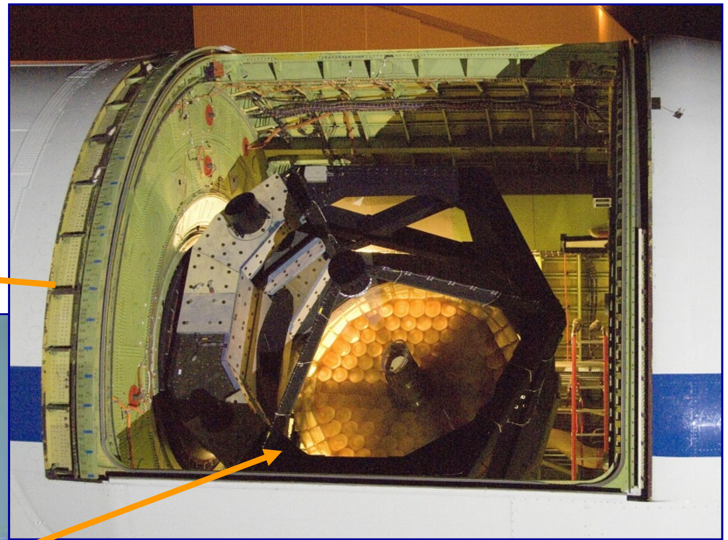
Hubble Space Telescope

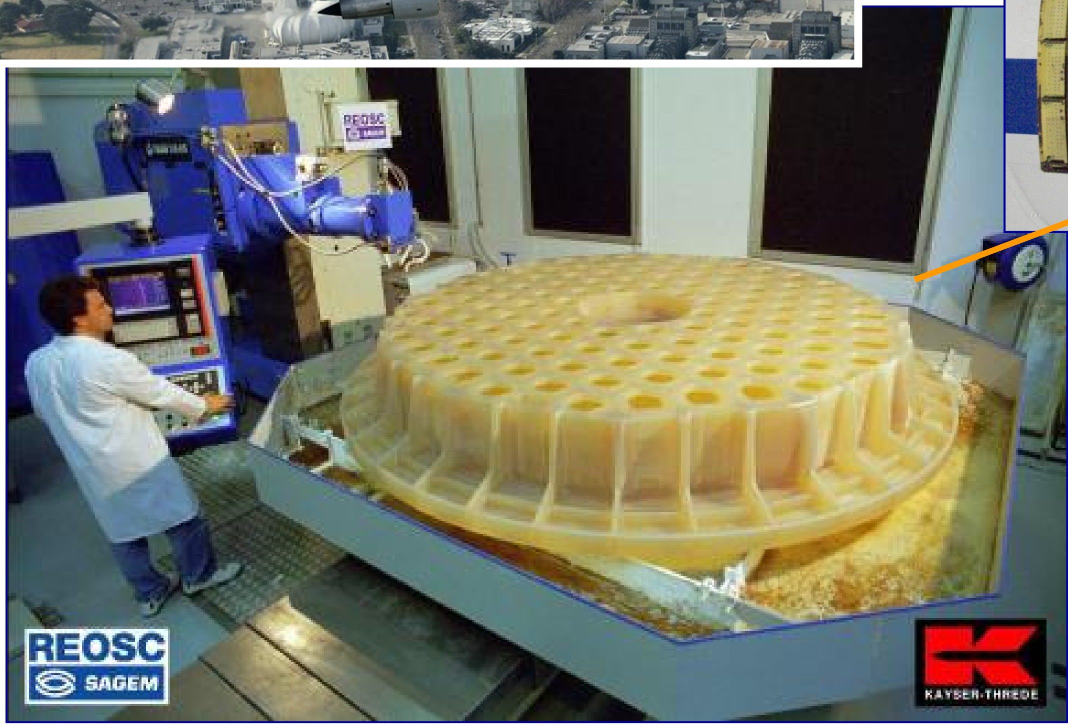
The secondary mirror
is a 308 mm x 65 mm ZERODUR Mirror 12.3 kg
convex hyperboloid 1.36 m radius



Pics: NASA

SOFIA: Largest lightweight mirror made from ZERODUR®





SOFIA-M1 Infrared Telescope
(Dia. 2.7m) in Jumbo Jet

ZERODUR 4 m Mirrors

Since 1975 SCHOTT delivered
9 blanks in the 4 m range

e.g.

VISTA

TNG Padua

ESO NTT

Calar Alto

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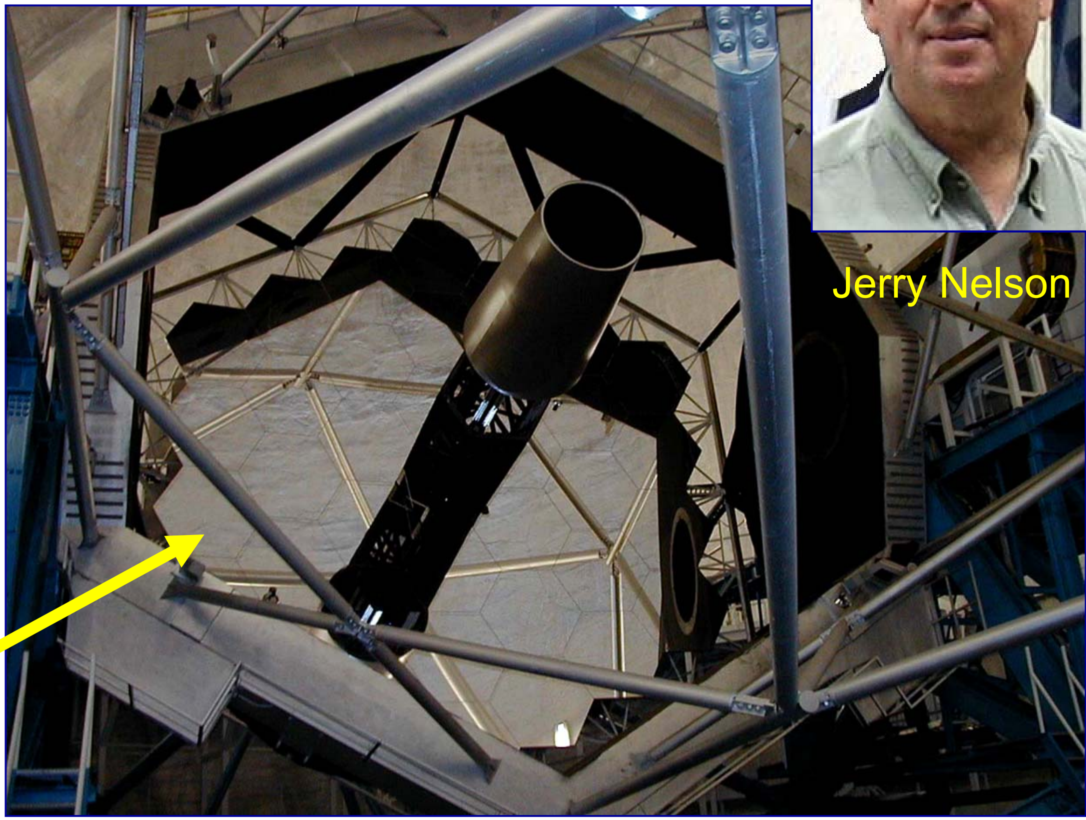
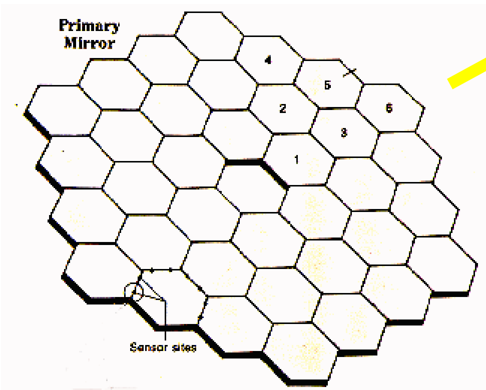
Astronomical Future Applications

Role model: 10 m Keck telescopes with segmented primary mirrors



Jerry Nelson

36 2 m Zerodur Hexagons



Pics: Keck Obs.

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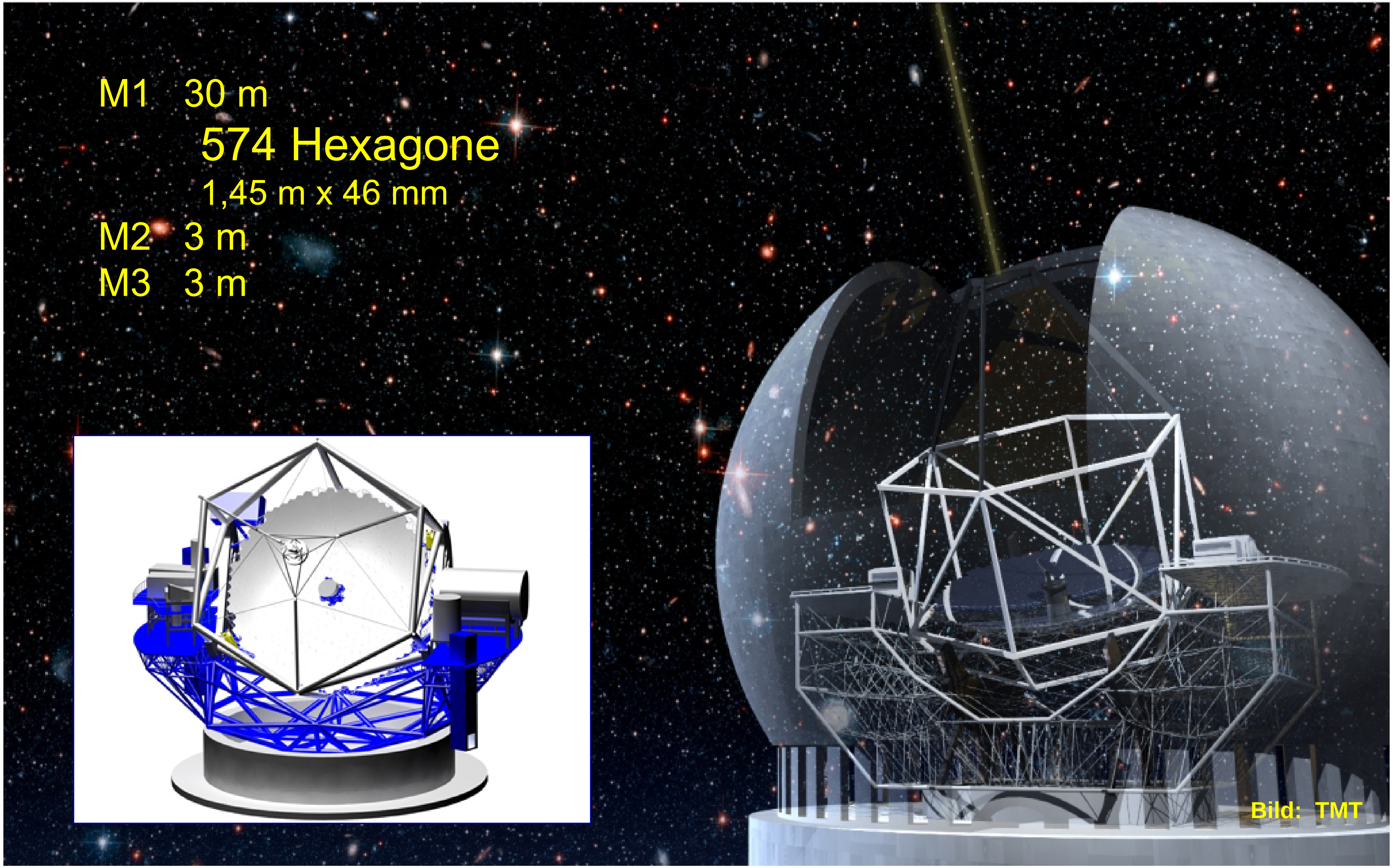
TMT –Thirty Meter Telescope

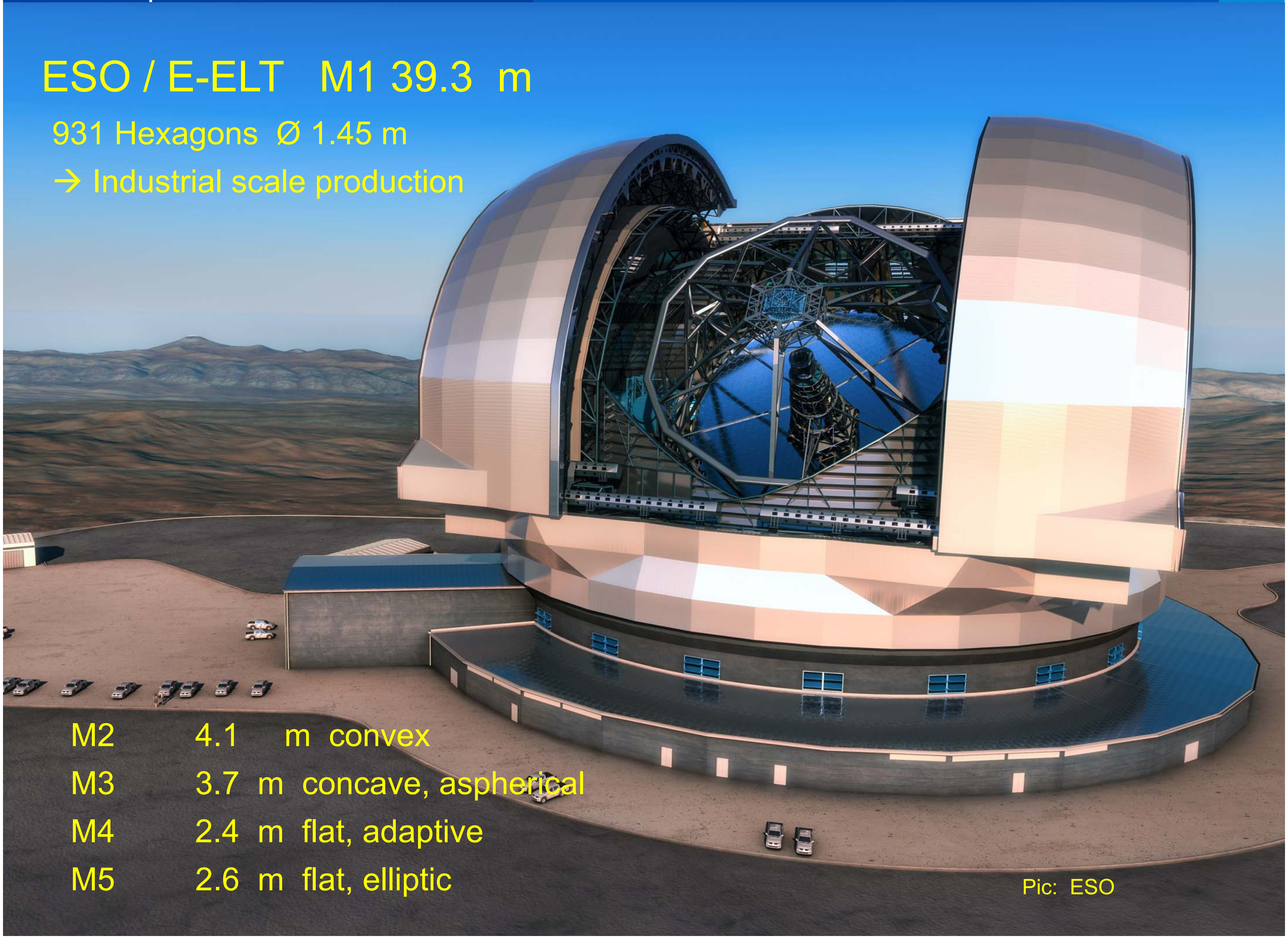
CALTECH, Uni California
AURA, ACURA, ...



ESO / E-ELT   M1 39.3 m

931 Hexagons Ø 1.45 m

→ Industrial scale production



M2	4.1	m	convex
M3	3.7	m	concave, aspherical
M4	2.4	m	flat, adaptive
M5	2.6	m	flat, elliptic

Pic: ESO

Reproducibility of High Quality

The polishing process for a huge number of mirrors needs to be highly automated.

This requires mirror blanks with reproducible quality.

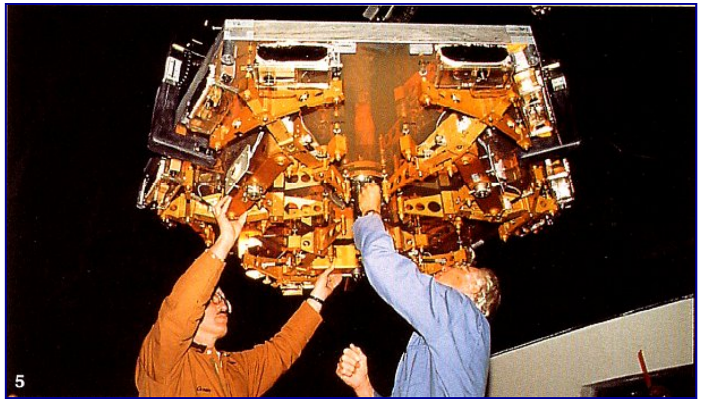
In-line adjustments of the polishing process due to blank quality variations will

- → Burst time schedule
- → Burst cost budget
- → May endanger the whole telescope project

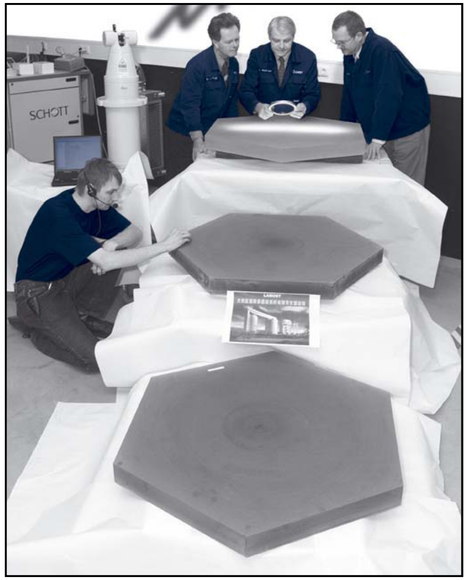
More than 250 Large Zerodur Mirror Blanks were Delivered for Segmented Telescopes

▪ Keck I + II	85 disks	1900 mm x 76 mm
▪ HET	96 hex.	1180 mm x 56 mm
▪ GRANTECAN	42 hex.	1870 mm x 83 mm
▪ LAMOST	40 hex.	1100 mm x 82 mm

HET



KECK I + II



LAMOST

GRANTECAN

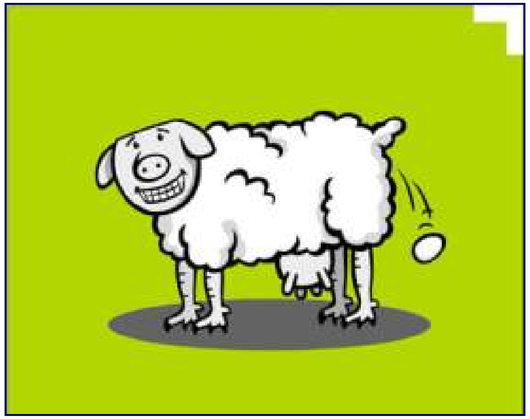
The Ideal Mirror Material

- Zero thermal expansion (CTE)
- High homogeneity of all properties
  (CTE, Young‘s Modulus, Refractive Index)
- Isotropic, monolithic, free from:
  seams, flaws, layers, rings, pores, bubbles, inclusions, stress, striae, hard micro-crystals
- Stable properties
  - with temperature changes (hysteresis),
  - with time (long-term contraction),
  - with humidity
  - at very low (cryo-) temperatures,
  - in space
- Can be produced in large sizes
  without quality degradation
- High polishability
  Roughness < 0.2 nm rms

Pic.: ESO VISTA Primary mirror

The Ideal Mirror Material cont.

- High thermal conductivity,
  low heat capacity, low density
- High stiffness, strength, fracture toughness
- Ideally elastic: instant full reaction
  on applied forces (no creep)
- high damping to suppress vibrations
- Good economic cutting, grinding, lightweighting, polishing (conventional, ion beam) and coating (directly on bulk material)
- High chemical resistance for cleaning processes
- In any size, shape and amount deliverable
  in short time over long times
- Easy to measure in all properties,
- Non-toxic
- Economic in purchase and subsequent processes
- All that proven in many applications since long times

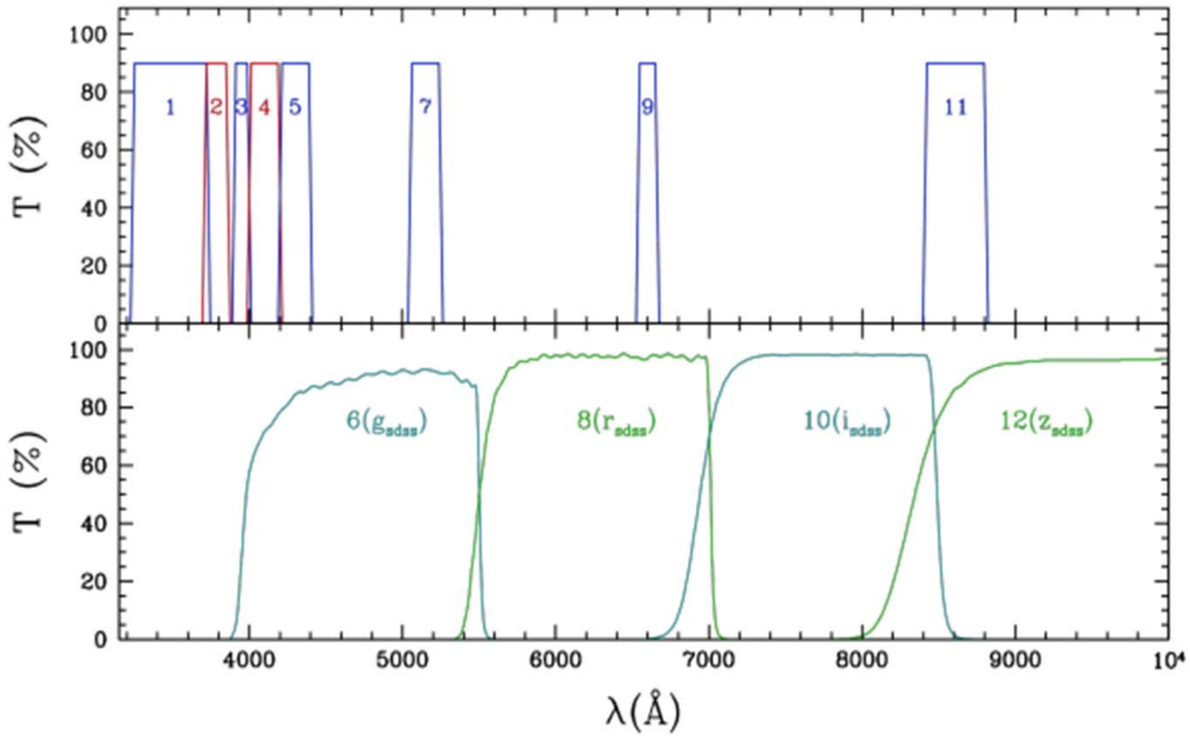


„Eierlegende Wollmilchsau“
German breed
Egg laying, wool and milk giving pig

... Wow!

JAST/T80 telescope (Obs. Astrofísico Javalambre Teruel Spain) SCHOTT supplies very tightly specified filters

JAST/T80 Telescope



See:

Reichel et al: „Narrow bandpass steep edge optical filter for telescope instrumentation", Paper 8860-22, SPIE Proceedings Volume 8860, Oct. 2013

Reichel et al: „Additional narrow bandpass steep edge optical filters for the JAST/T80 telescope instrumentation ", Paper 9151-205, SPIE Proceedings Volume 9151, Aug. 2014

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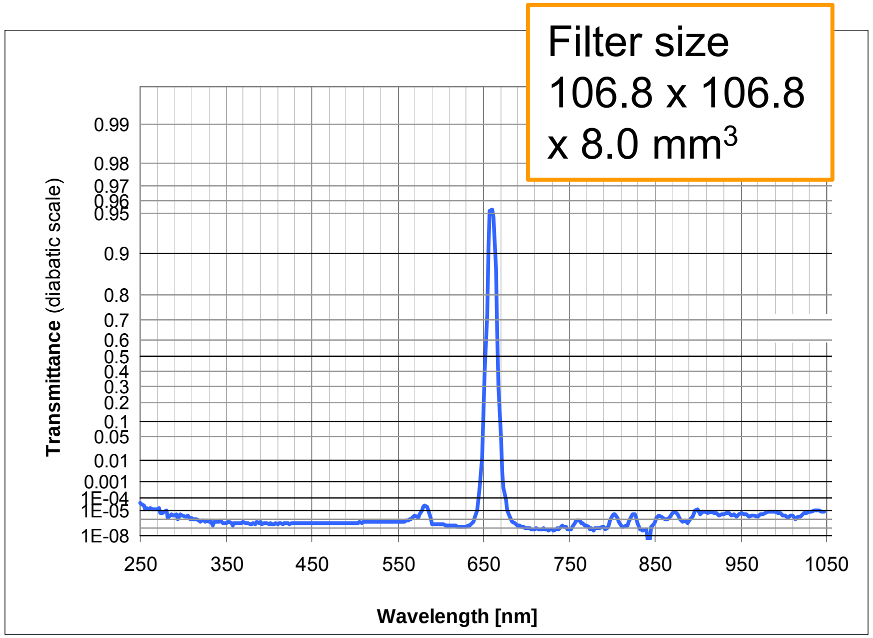
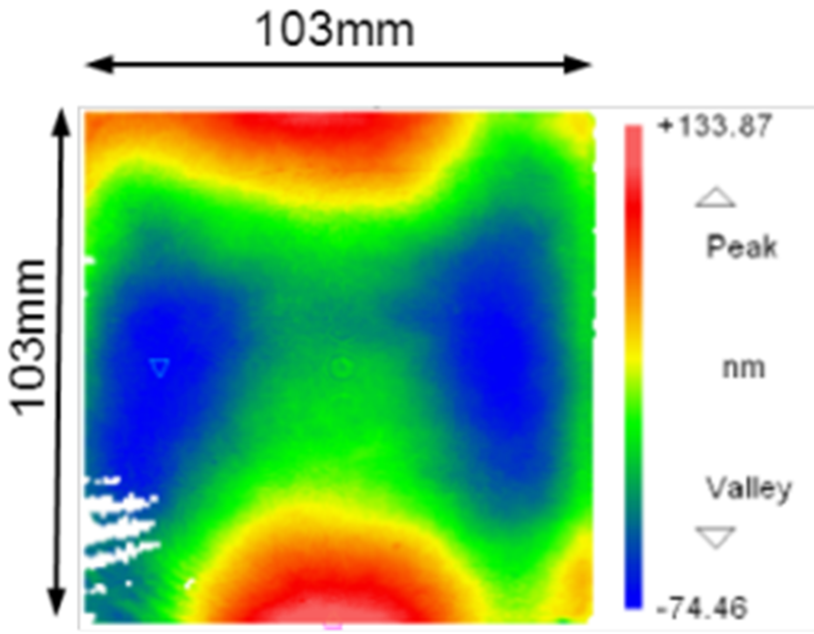
Spectral properties of the steep edge narrow bandpass filter as well as transmitted wavefront error exceed specifications





	Specification	Measurement
CWL [nm]	660.00 +/- 1.32	659.97
FWHM [nm]	14.50 +/- 1.00	14.38
T_{max} [%]	> 85	96.6
Blocking (on average)	$T < 10^{-5}$	$T < 10^{-5}$
TWE	$\lambda/2$ @ 633 nm	$< \lambda/14$

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Next Step: Frequency comb achieved by combining > 60 overlapping narrow bandpass filters

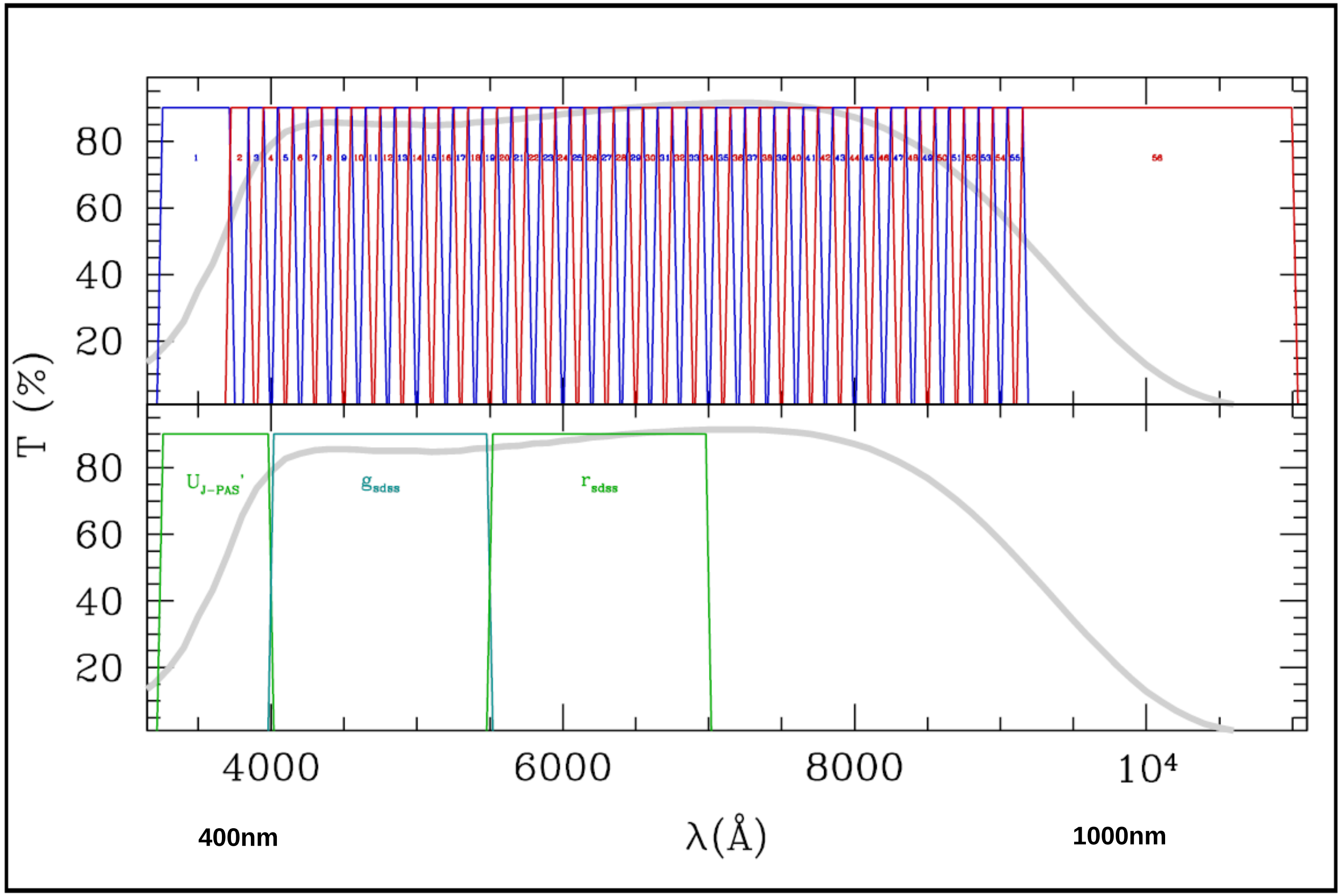

Figure 6: J-PAS set of filters. J-PAS filters are shown in red and blue (upper panel) while the $u_{J\text{-}PAS}$ and Sloan filters are shown in green (lower panel).

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Large optical
glass disks
Glass Type
N-FK5

Diam. 1020 mm x 199 mm
0.40 tons

High Quality

Present estimation of maximum feasible volume of optical glass item

Ø1500 mm x 500 mm
N-BK7: 2.2 tons

Interferometric measurement of N-BK7 Ø 1 m blanks

500 mm Oil-on plates at upper rim zone

Latest production of large N-BK7 blanks

10 blanks 600 – 950 mm with excellent quality

SCHOTT Infrared Materials

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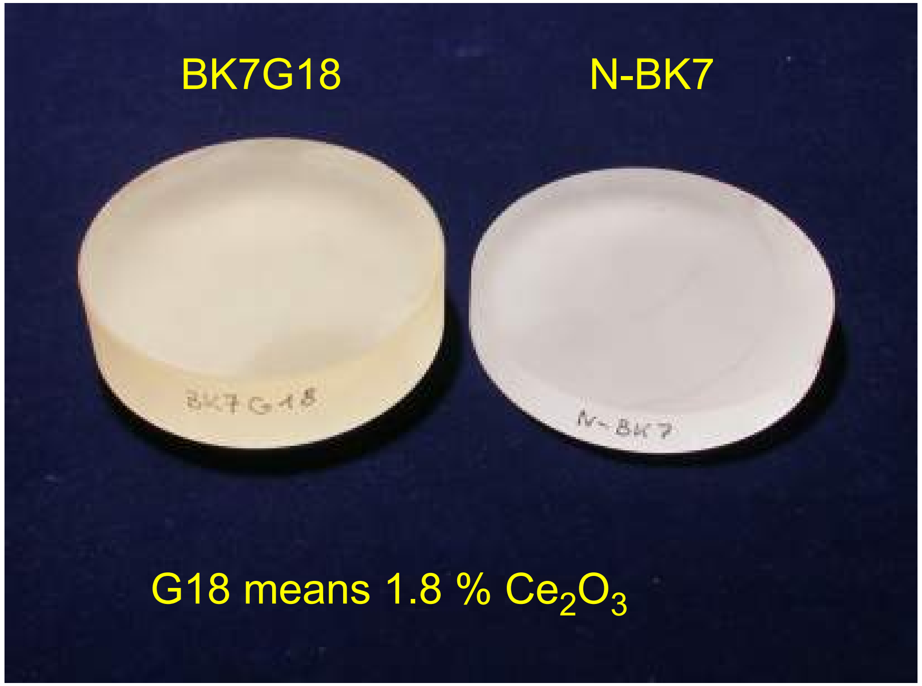
Radiation Resistant Optical Glasses



Laser glass and finished components

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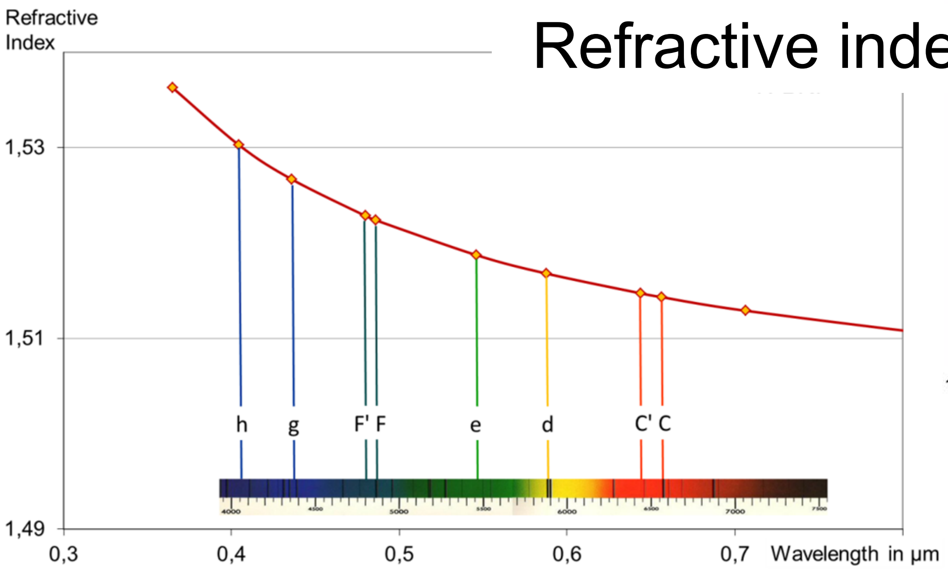
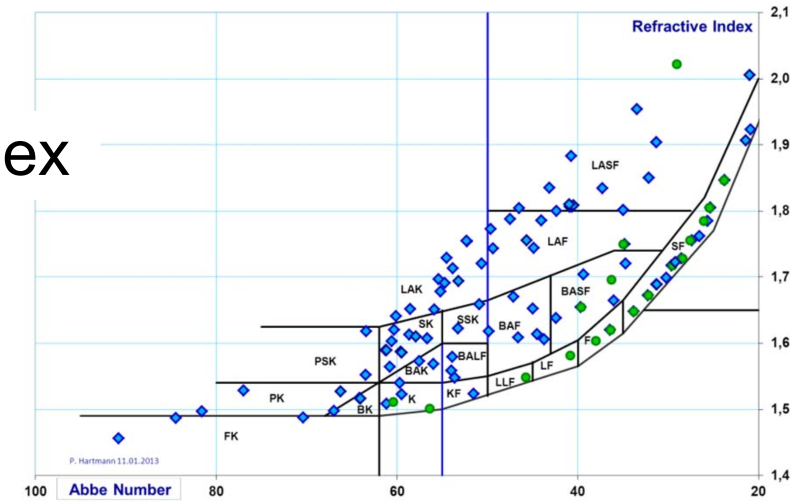
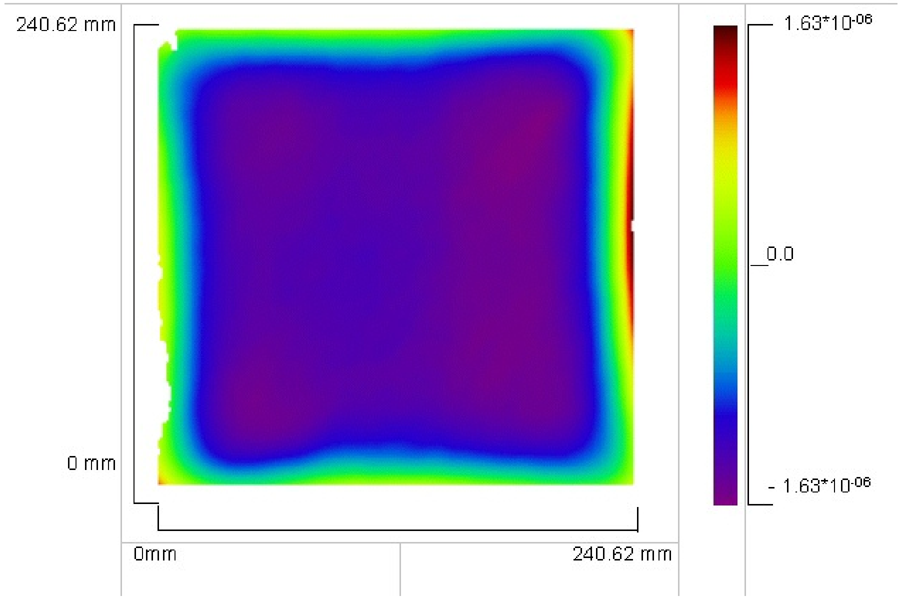
Optical Glass Properties

Refractive index

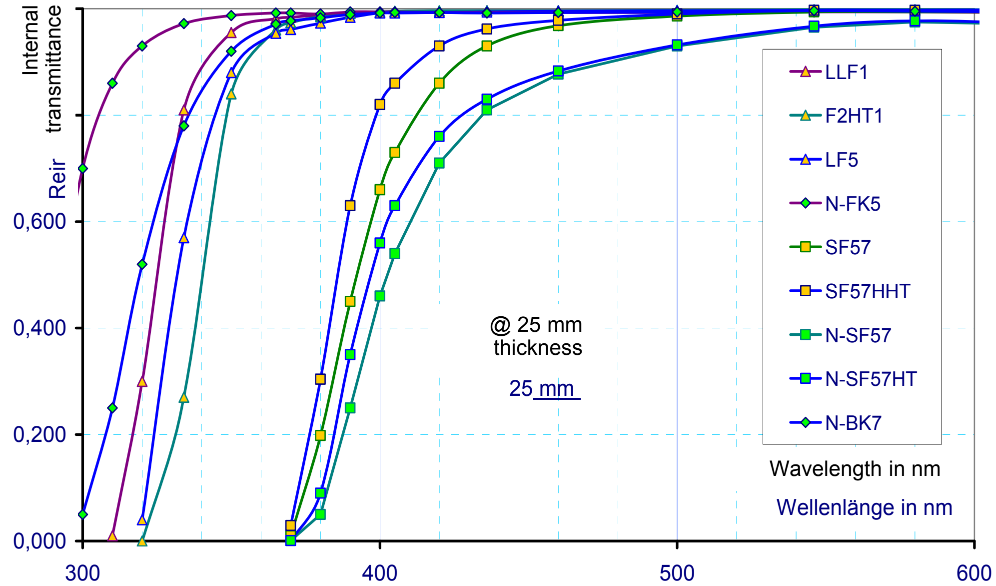




Refractive index homogeneity



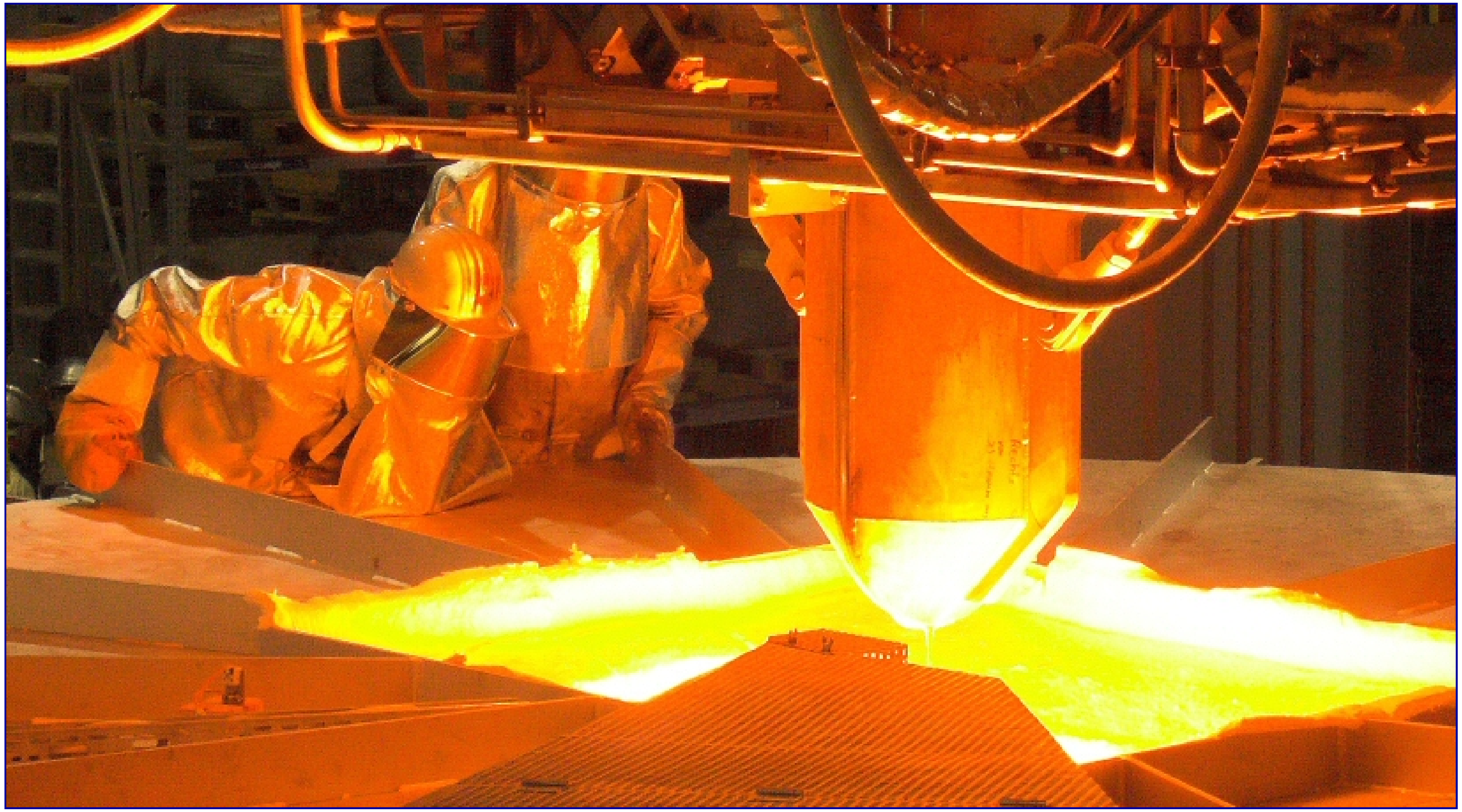
Transmission



Stress birefringence

4 m Mirrors

Casting of a 4 m ZERODUR® Mirror Blank



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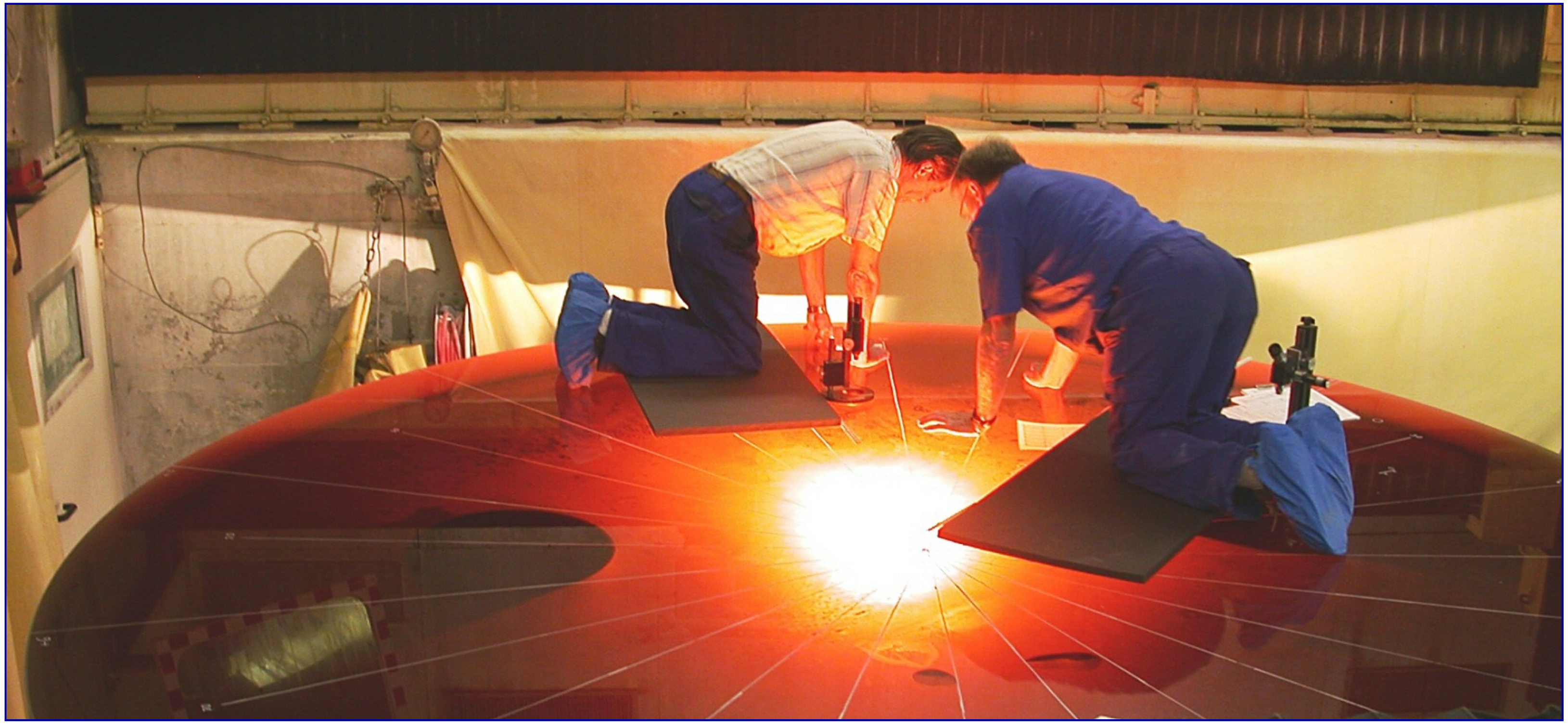
Rapid Temperature
Ramp down

4 m Blank in glassy state – still clear transparent

4 m Blank - Bubble and inclusion inspection



4 m Blank – Ceramization
Just in furnace but for along time

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4 m Blank – Ceramized and waiting for project

Grinding of the ESO NTT blank

Lifting and turning devices for VISTA

VISTA – Concave Surface Form Measurement

Final acceptance with customer VISTA

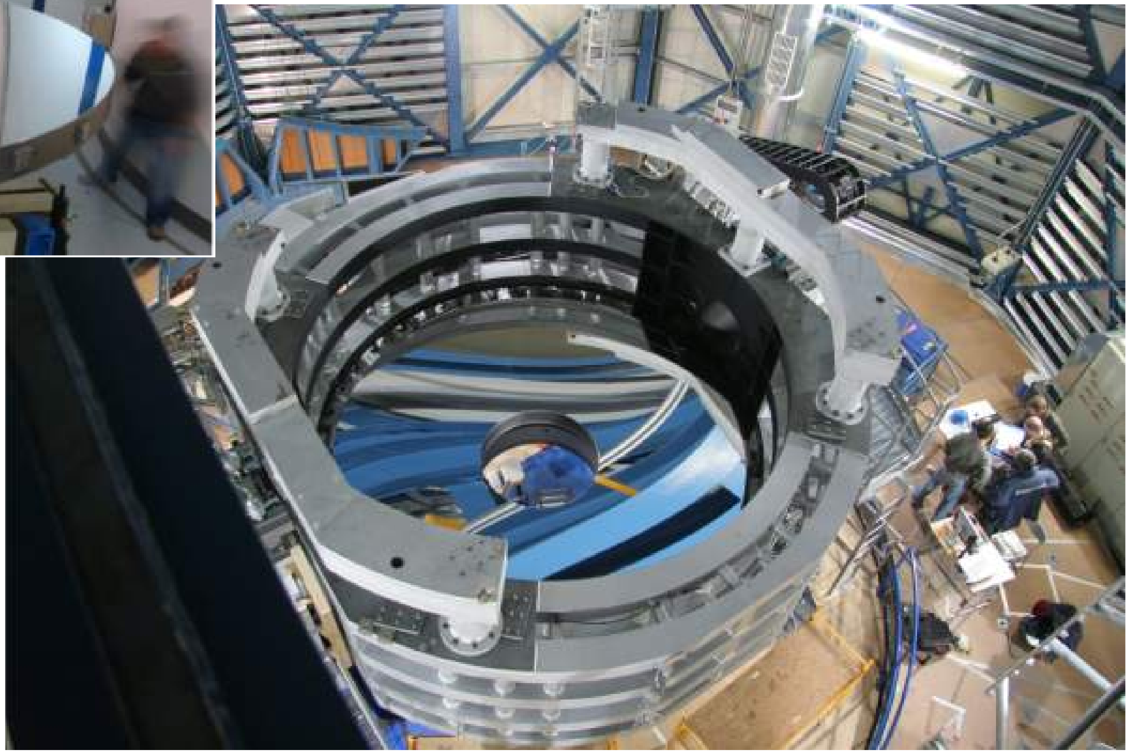
VISTA – Primary mirror arrived in Chile in 4/2008

Pics.: ESO

VISTA – Mirror Lifting Into Observatory

Pics.: ESO

VISTA – Mirror Mounting Into Support Structure



Pics.: ESO

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VISTA – First Light Dec 2009

Pics.: ESO

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SCHOTT – Publications on ZERODUR® 2010 – 2014 (1)

Tony Hull, Thomas Westerhoff	**Lightweight ZERODUR mirror blanks: recent advances supporting faster, cheaper, and better spaceborne optical telescope assemblies**	Proc. SPIE 9241	92411L	**SPIE**	2014
Ralf Jedamzik, Thomas Werner, Thomas Westerhoff	**Production of the 4.26 m ZERODUR® mirror blank for the Advanced Technology Solar Telescope (ATST)**	Proc. SPIE 9151	915131	**SPIE**	2014
Peter Hartmann, Antoine Leys, Antoine Carré, Franca Kerz, Thomas Westerhoff	**ZERODUR® - Bending strength data for etched surfaces**	Proc. SPIE 9151	91512Q	**SPIE**	2014
Ralf Jedamzik, Clemens Kunisch, Johannes Nieder, Thomas Westerhoff	**Glass ceramic ZERODUR® enabling nanometer precision**	Proc. SPIE 9052	90522I	**SPIE**	2014
Tony Hull, T. Westerhoff	**Lightweight ZERODUR®: A Cost-Effective Thermally-Stable Approach to both Large and Small Spaceborne Telescopes**	Proc. SPIE 9070	90702D	**SPIE**	2014
R. Jedamzik, T. Westerhoff	**ZERODUR® TAILORED for Cryogenic Application**	Proc. SPIE 9151	91512P	**SPIE**	2014
Ralf Jedamzik, Antoine Leys, Volker Seibert, Thomas Westerhoff	**ZERODUR® iso-grid design of a 3 m class light weighted mirror blank for the E-ELT M5**	Proc. SPIE 9151	91510H	**SPIE**	2014
T. Westerhoff, M. Davis, P. Hartmann, T. Hull, R. Jedamzik	**Lightweighted ZERODUR® for telescopes**	Proc. SPIE 9151 Invited Paper	91510R	**SPIE**	2014
Ralf Jedamzik, Clemens Kunisch, Thomas Westerhoff	**ZERODUR®: Progress in CTE characterization**	Proc. SPI'E 8860	88600P	**SPIE**	2013
Thomas Westerhoff, Ralf Jedamzik, Peter Hartmann	**Zero expansion glass ceramic ZERODUR® roadmap for advanced lithography**	Proc. SPIE 8683	86832H	**SPIE**	2013
Peter Hartmann	**ZERODUR® - Deterministic Approach for Strength Design**	Opt. Eng. 51(12)	124002	**SPIE**	2012

SCHOTT – Publications on ZERODUR® 2010 – 2014 (2)

Peter Hartmann, Ralf Jedamzik, Thomas Westerhoff	**Zero-expansion glass ceramic ZERODUR® - Recent developments reveal high potential**	Proc. SPIE 8450	845022	**SPIE**	2012
Tony Hull, Thomas Westerhoff et al.	**Game-changing approaches to affordable advanced lightweight mirrors II: new cases analyzed for extreme ZERODUR lightweighting and relief from the classical polishing parameter constraint**	Proc. SPIE 8450	845050	**SPIE**	2012
Ralf Jedamzik, Clemens Kunisch, Thomas Westerhoff, Ulrich Müller, Jay Daniel	**ZERODUR for stressed mirror polishing II: improved modeling of the material behavior**	Proc. SPIE 8450	84504P	**SPIE**	2012
Thomas Westerhoff, Peter Hartmann, Ralf Jedamzik, Alexander Werz	**Performance of industrial scale production of Zerodur mirrors with diameter of 1.5 m proves readiness for the ELT M1 segments**	Proc. SPIE 8444	844437	**SPIE**	2012
Tanja Bizjak, Peter Hartmann, Thomas Westerhoff	**ZERODUR: bending strength data for tensile stress loaded support structures**	Proc. SPIE 8326	83261Q	**SPIE**	2012
Ralf Jedamzik, Volker Seibert, Armin Thomas, Thomas Westerhoff, Michael Müller and Marc Cayrel	**Design and fabrication of a 3m class light weighted mirror blank for the E-ELT M5**	Proc. SPIE 8126	812607	**SPIE**	2011
Peter Hartmann	**ZERODUR: new results on bending strength and stress corrosion**	SPIE 8146	81460P	**SPIE**	2011
Tony Hull, Andrew Clarkson, et al	**Game-changing approaches to affordable advanced lightweight mirrors: Extreme Zerodur lightweighting and relief from the classical polishing parameter constraint**	Proc. SPIE 8125	81250U	**SPIE**	2011
Ralf Jedamzik, Clemens Kunisch et al	**ZERODUR for stress mirror polishing**	Proc. SPIE 8126	812606	**SPIE**	2011
Thomas Westerhoff, et al.	**Progress in 4m class ZERODUR mirror production**	Proc. SPIE 8126	81260A	**SPIE**	2011
Tony Hull, Peter Hartmann, Andrew R. Clarkson, John M. Barentine, Ralf Jedamzik, Thomas Westerhoff	**Lightweight high-performance 1-4 meter class spaceborne mirrors: emerging technology for demanding spaceborne requirements**	Proc. SPIE 7739	77390C-1	**SPIE**	2010
Peter Hartmann, et al.	**ZERODUR 8m mirror for space telescope**	Proc. SPIE 7731	77313Y	**SPIE**	2010
Thomas Westerhoff et al. Alexander Werz	**Manufacturing of the ZERODUR® 1.5 m primary mirror for the solar telescope GREGOR as preparation of light weighting of blanks up to 4 m diameter**	Proc. SPIE Vol. 7739	77390M-1	**SPIE**	2010
Ralf Jedamzik, Thoralf Johansson, Thomas Westerhoff	**Modeling of the thermal expansion behavior of ZERODUR® at arbitrary temperature profiles**	Proc. SPIE 7739	77390I-1	**SPIE**	2010

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SCHOTT – Publications on Optical Glass 2010 – 2014

Peter Hartmann.	**Optical Glass (Textbook)**	SPIE Press		**SPIE**	2014
S. Reichel, U. Brauneck, S. Bourquin, A. Marín-Franch	**Additional narrow bandpass steep edge optical filters for the JAST/T80 telescope instrumentation**	Proc. SPIE 9151	91515D	**SPIE**	2014
Hartmann, P.	**EU regulations threaten availability of raw materials for optics**	SPIE Professional		**SPIE**	2014
S. Reichel, R. Biertümpfel	**Precise dispersion equations of absorbing filter glasses**	Proc. SPIE 9138	91380O	**SPIE**	2014
Englert, M., Hartmann, P., Reichel, S.	**Optical glass - refractive index change with wavelength and temperature**	Proc. SPIE 9131	91310H	**SPIE**	2014
Jedamzik, J., Reichel, S., Hartmann, P.,	**Optical Glass with tightest refractive index and dispersion tolerances for high-end optical designs**	Proc. SPIE 8982	89821F	**SPIE**	2014
Ralf Jedamzik, Frank Elsmann	**Recent Results on Bulk Laser Damage Threshold of Optical Glasses**	Proc. SPIE 8603	860305	**SPIE**	2013
Hartmann, P.	**110 years BK7 – Optical glass type with long tradition and ongoing progress**	Proc. SPIE 8550	85500U-1	**SPIE**	2012
Hartmann, P.	**Optical glass: past and future of a key enabling material**	Adv. Opt. Techn. 1	5 - 10	**Thoss**	2012
Hartmann, P., Hamm, U.	**Optical glass and the EU directive RoHS**	Proc. SPIE 8065	806511-1	**SPIE**	2011
Hartmann, P.	**Optical Glass – Dispersion in the Near Infrared**	Proc. SPIE 8167	816702-1	**SPIE**	2011
Peter Hartmann, Ralf Jedamzik, Steffen Reichel, Bianca Schreder	**Optical glass and glass ceramic historical aspects and recent developments: a Schott view**	Applied Optics, Vol. 49, No. 16	D157 - D176	**OSA**	2010

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