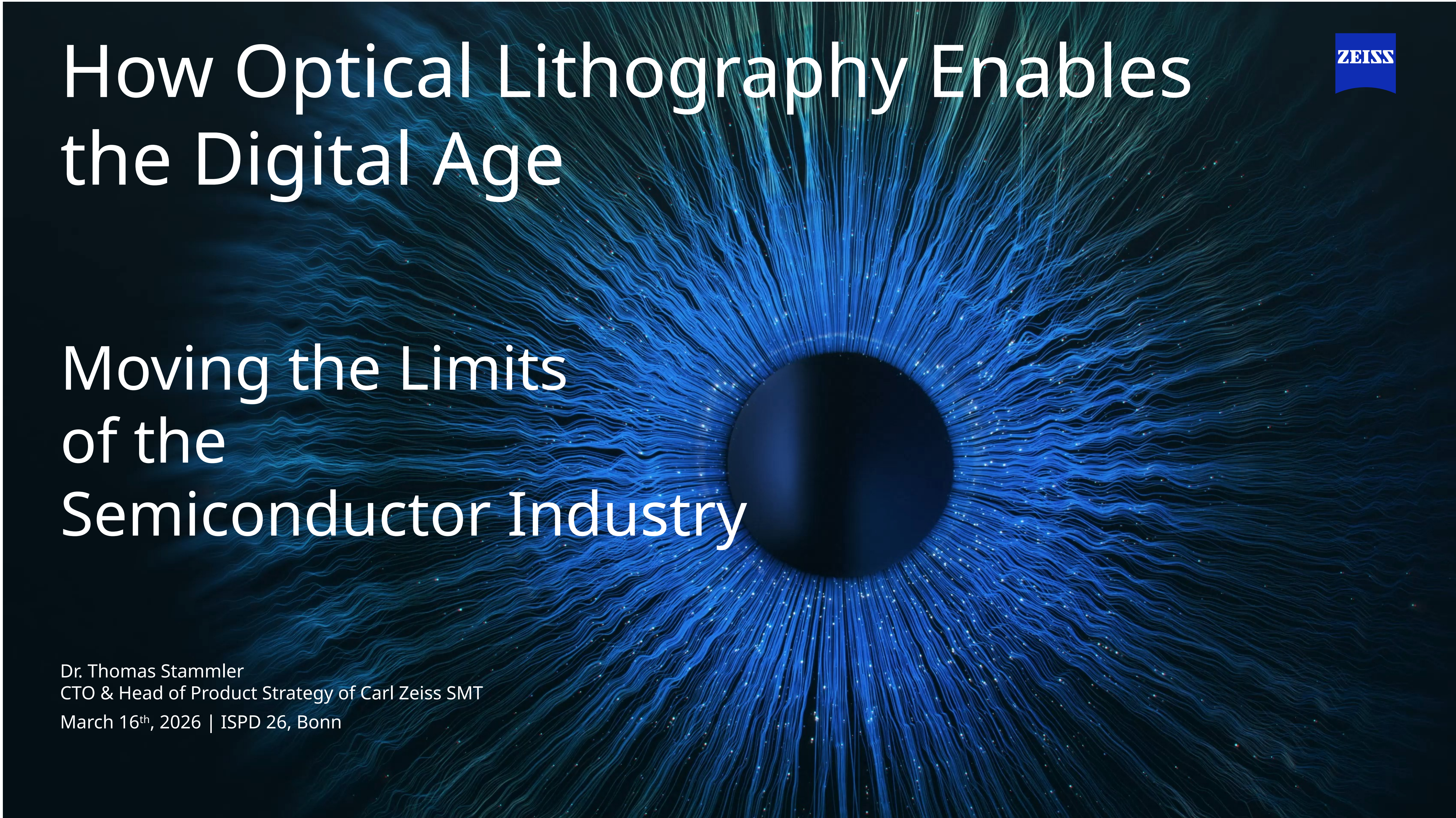
How Optical Lithography Enables the Digital Age

Moving the Limits of the Semiconductor Industry

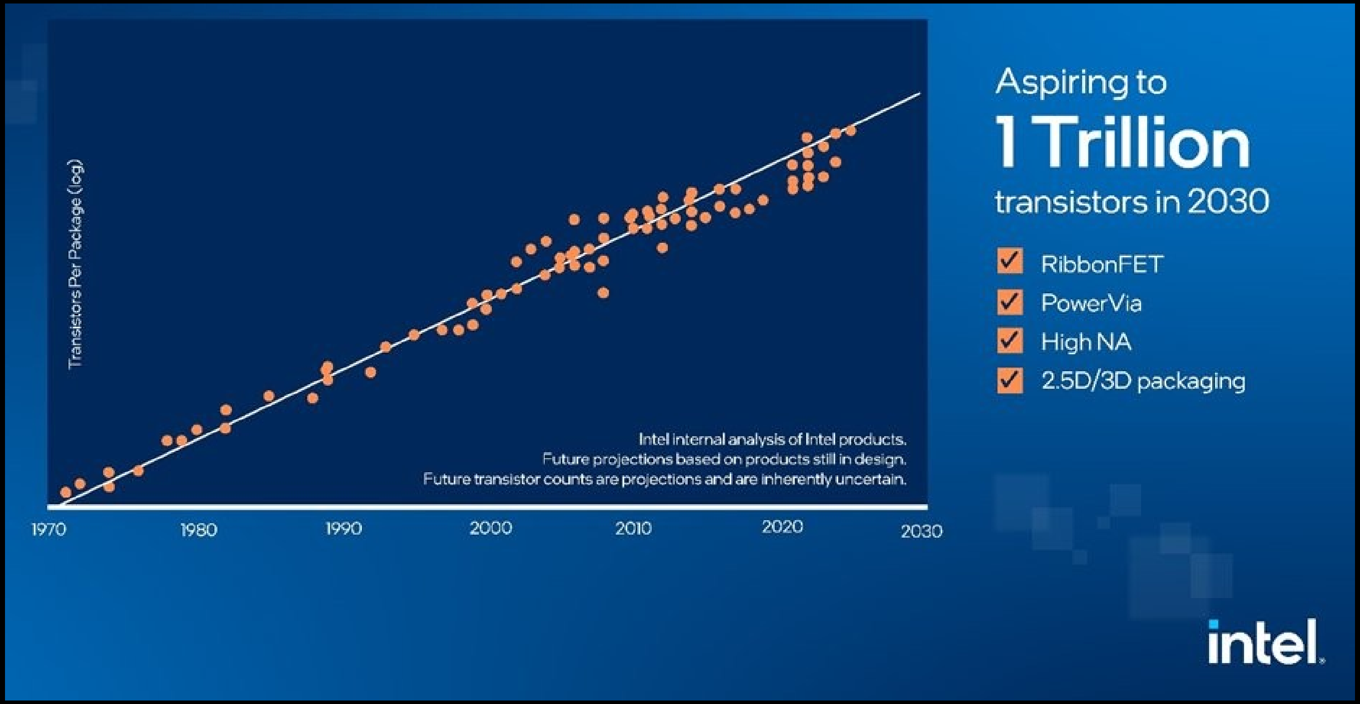


Dr. Thomas Stammler
CTO & Head of Product Strategy of Carl Zeiss SMT
March 16th, 2026 | ISPD 26, Bonn

The power of innovation

Picture car: https://www.classic-trader.com/de/automobile/inserat/porsche/908/908/1968/207475
Picture rocket: Dr. Thomas Stammler

Moore’s law – Driving the industry for more than 5 decades



Intel internal analysis of Intel products.
Future projections based on products still in design.
Future transistor counts are projections and are inherently uncertain.

Aspiring to
1 Trillion
transistors in 2030

- ☑ RibbonFET
- ☑ PowerVia
- ☑ High NA
- ☑ 2.5D/3D packaging

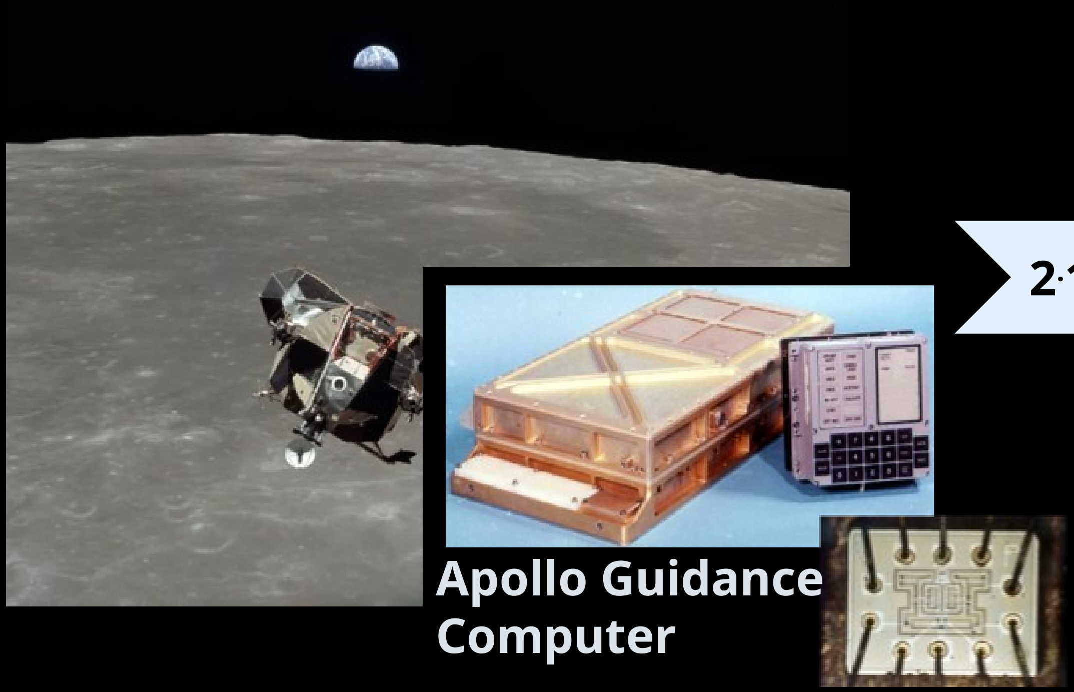
intel.

2x every 2 years over 50 years → 225 = 3x107

Source: Intel

The incredible evolution of semiconductor technology…

From the moon landing in 1969…



Apollo Guidance Computer

2$\cdot$10^{7}x

… to AI datacenters powered by GPUs

NVIDIA Blackwell

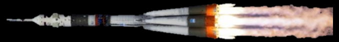
10k Transistors

200bn Transistors

Source: https://en.wikipedia.org/wiki/Apollo_Guidance_Computer

What if Automotive would have shown the same progress…

Sojus



30M HP

Porsche 908 (1970)

400 HP

Factor:
$\sim 2 * 10^7$

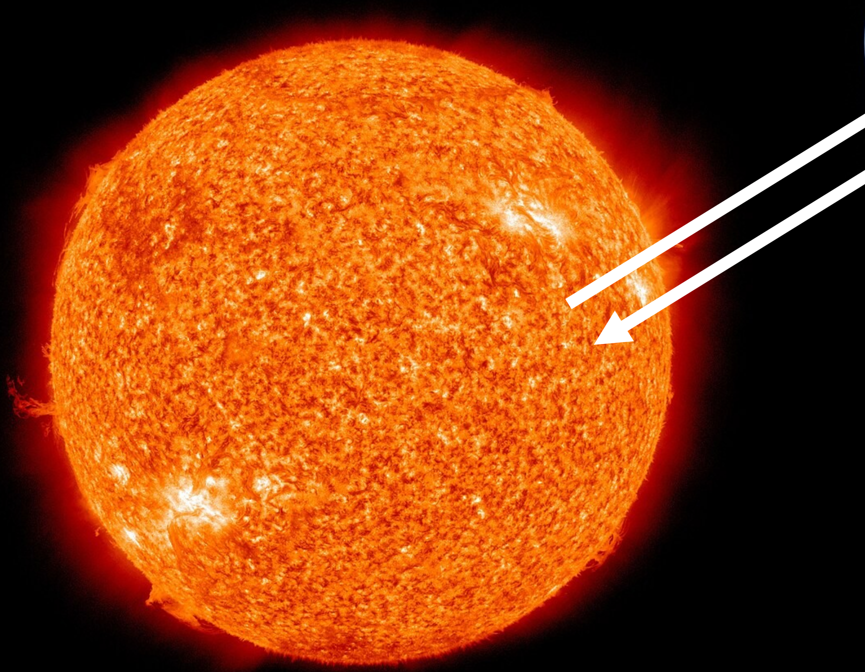
Powered by equivalent of ~ 250 rocket engines

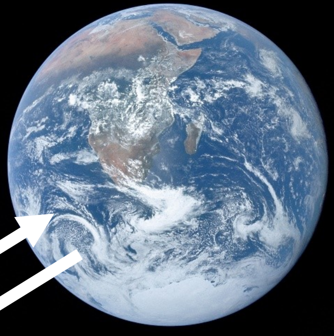
Picture car: https://www.classic-trader.com/de/automobile/inserat/porsche/908/908/1968/207475
Picture rockets: Dr. Thomas Stammler

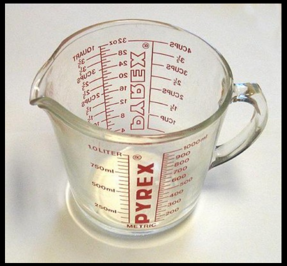
As for power consumption … we would travel to the sun and back on 1l of fuel

~25 l/100km

Picture car: https://www.classic-trader.com/de/automobile/inserat/porsche/908/908/1968/207475





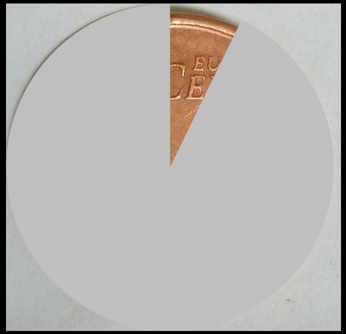


1 l

But wasn‘t Moore‘s Law about economics?

DM
20.000,-

›



~0.1
cent

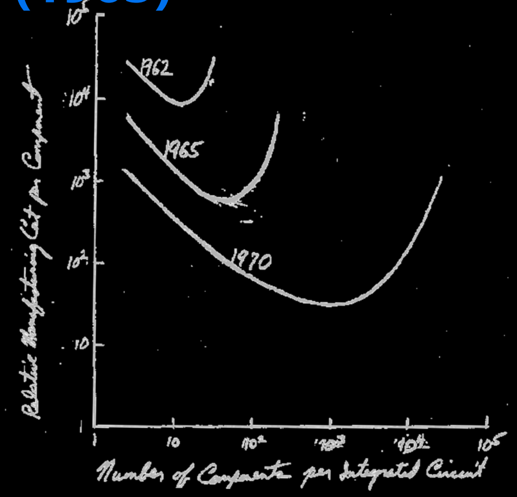
Picture: https://commons.wikimedia.org/wiki/File:1970_Mercedes-Benz_280_SE

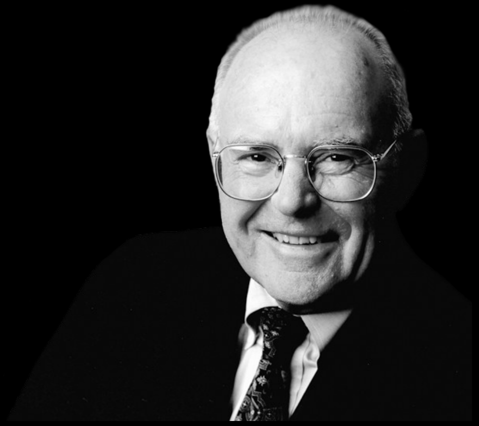
?

How did we get there?

Moore’s Law …and how it relates to optics

Moore’s Law (1965)





Abbe Equation (1873)

$$CD = k_1 \frac{\lambda}{NA}$$

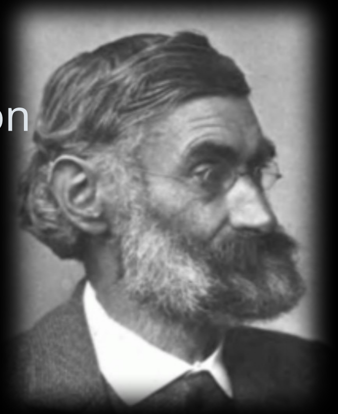
CD……Resolution / Critical Dimension

k_1…….Process Factor

λ …….Wavelength

NA……Numerical Aperture

$$d=\frac{\lambda}{2n\sin\alpha}$$

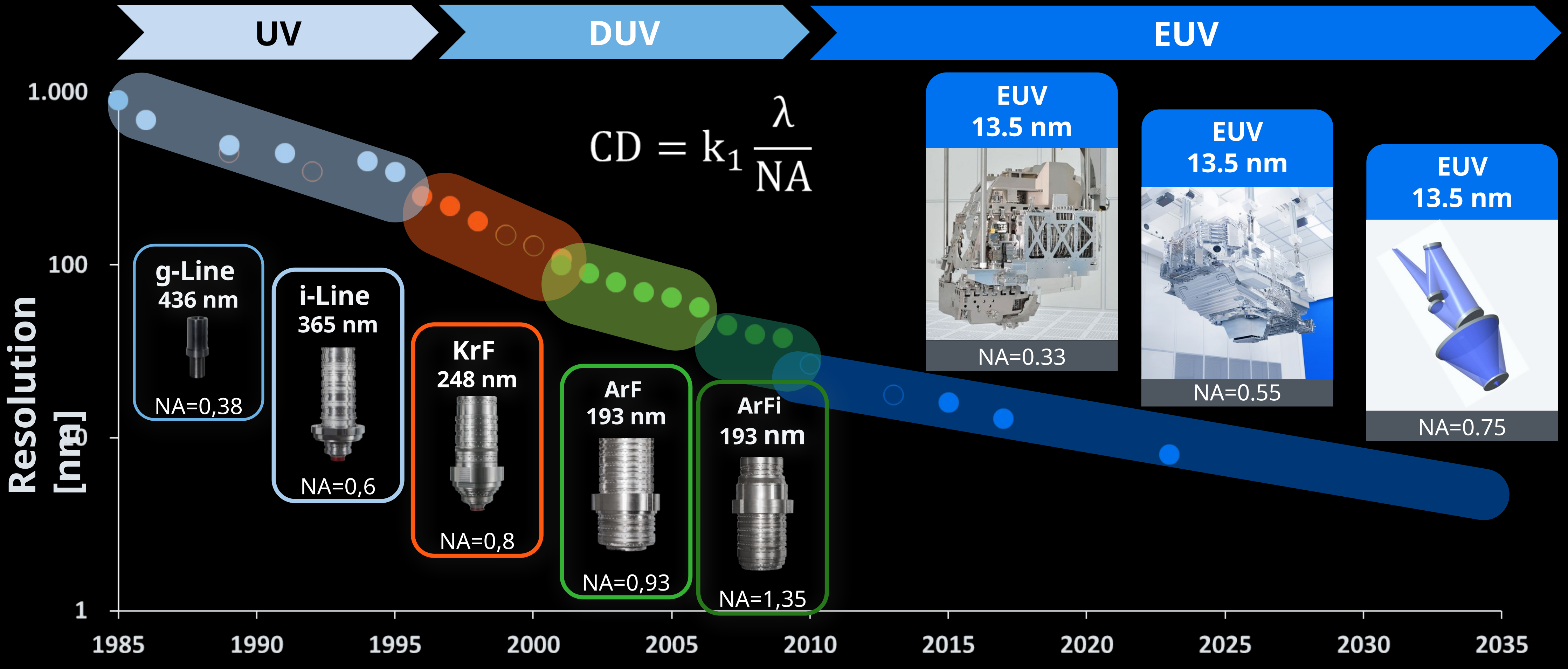


“Transistor density doubles
every 24 months”

“Optics resolution improves ~30% with each new generation”

Picture Gordon Moore: University of California, San Diego, Department of Computer Science and Engineering CSE 140, WS 2016
Graph: Cramming more components onto integrated circuits, Gordon Moore, Electronics, Volume 38, #8, 1965

Litho-Roadmap enabled by Wavelength reduction and increase of NA

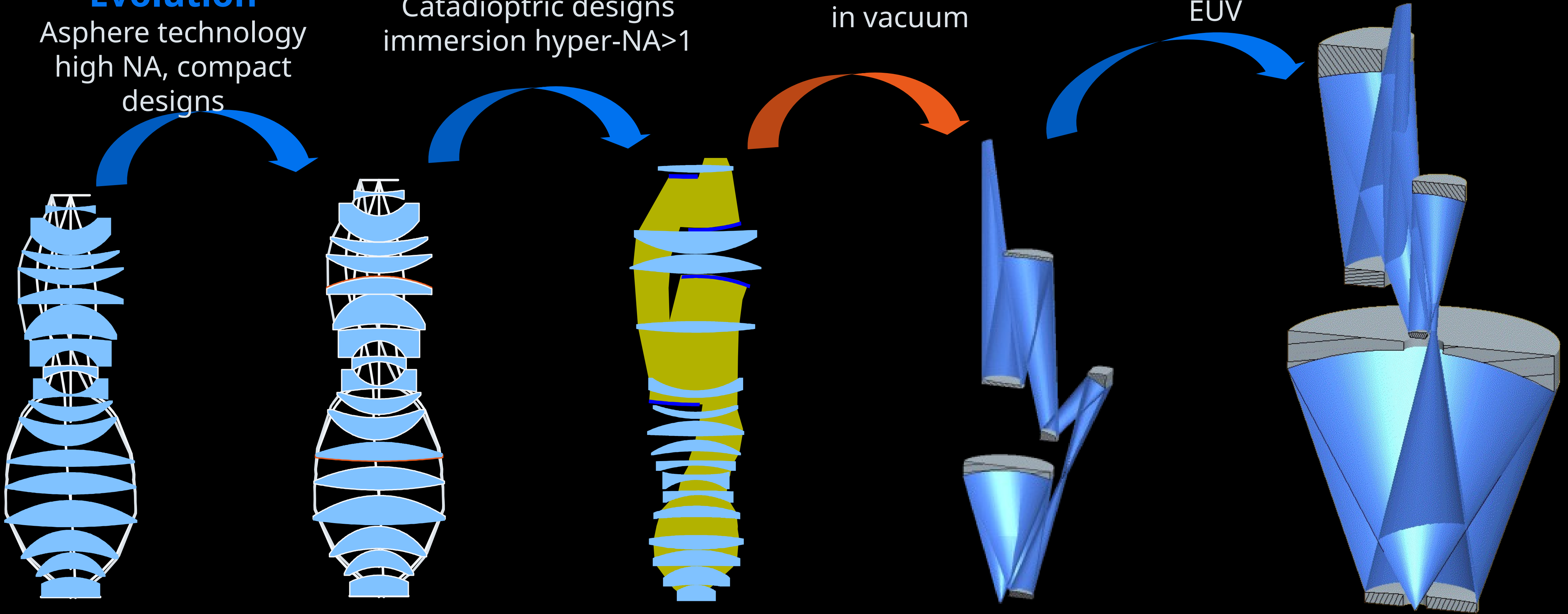


$$CD = k_1 \frac{\lambda}{NA}$$

● Production systems

○ Development systems

How Optical Innovations have enabled the continuation of Moore‘s Law



Evolution
Asphere technology high NA, compact designs

Evolution
Catadioptric designs immersion hyper-NA>1

Revolution
Mirror-only EUV optics in vacuum

Evolution
Extreme aspheres for EUV

KrF: 248nm

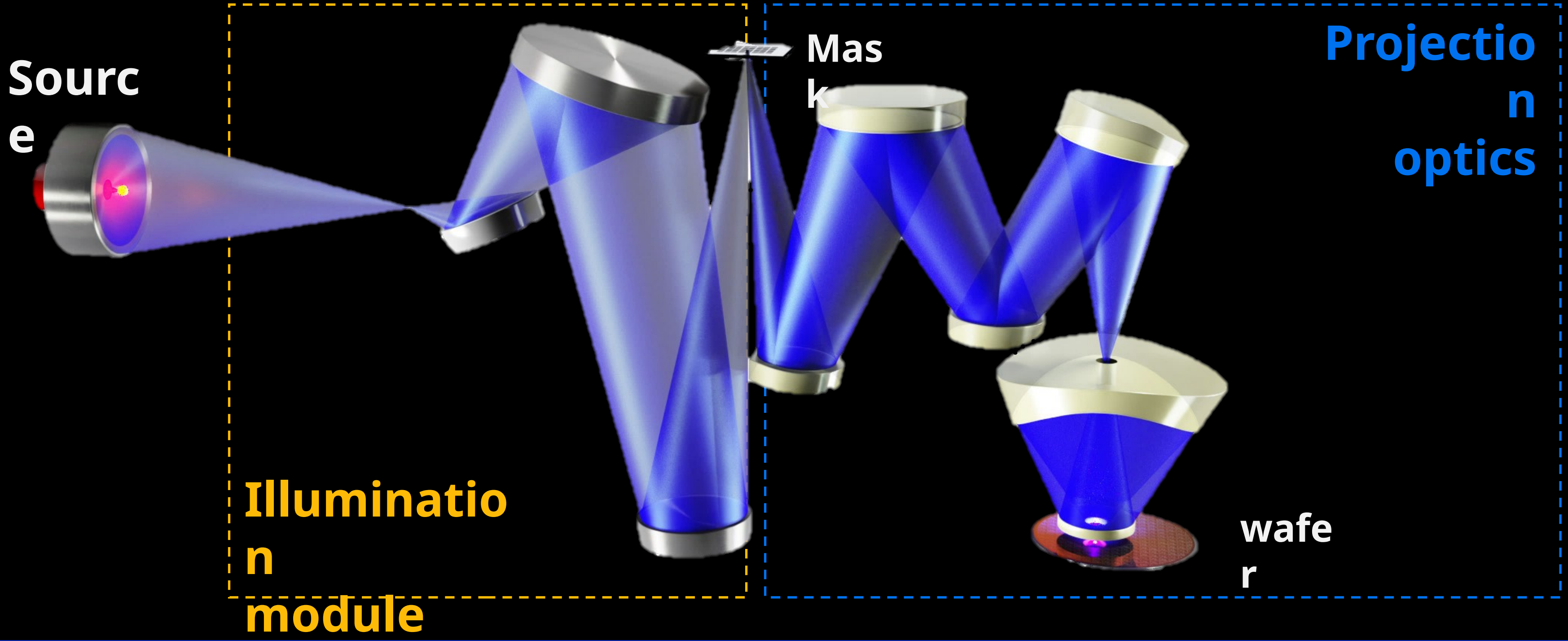
ArF dry: 193nm

ArFi:193nm Immersion

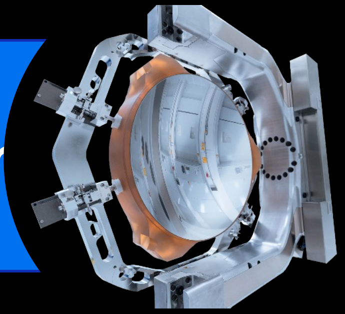
EUV: 13.5nm

EUV: 13.5nm, High-NA

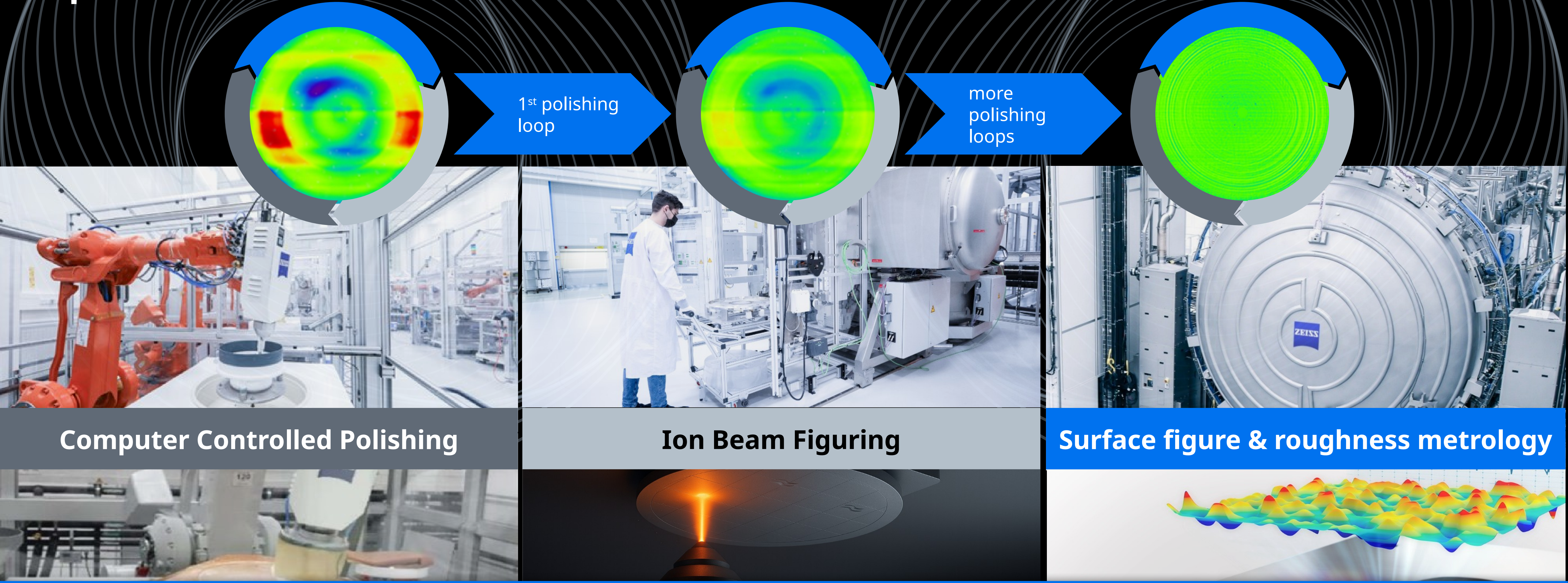
State of the art: High-NA EUV



Need for ultra precise mirrors – but how to manufacture them



How to manufacture a mirror to high precision...



1st polishing loop

more polishing loops

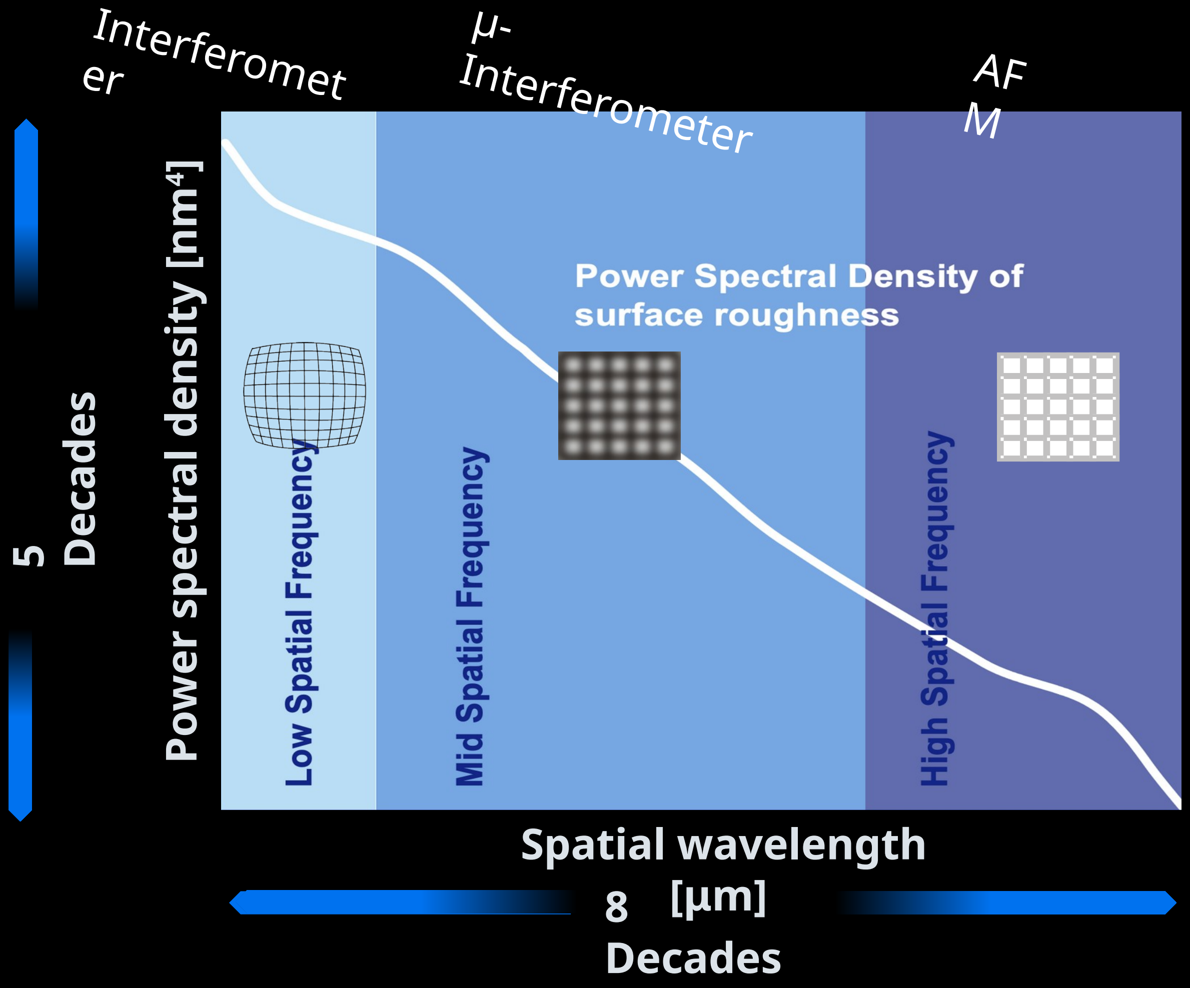
Computer Controlled Polishing

Ion Beam Figuring

Surface figure & roughness metrology

Ok, so what's the problem...?

Mirror Figure and Mirror Roughness have to be controlled at the same time!



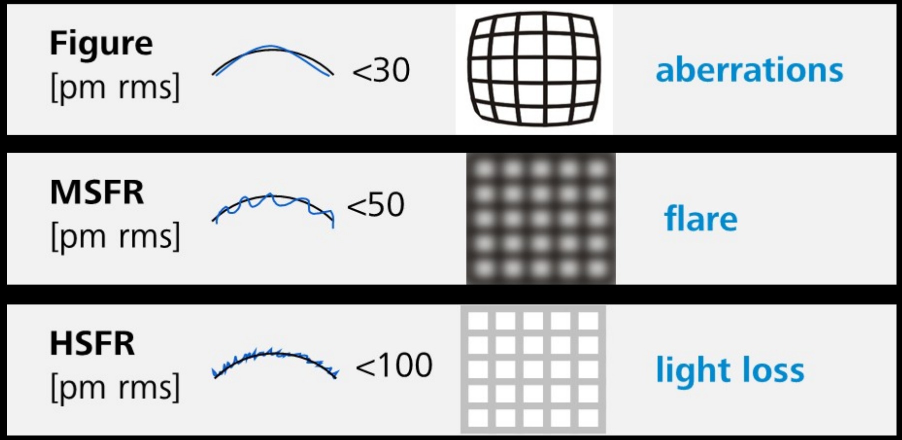
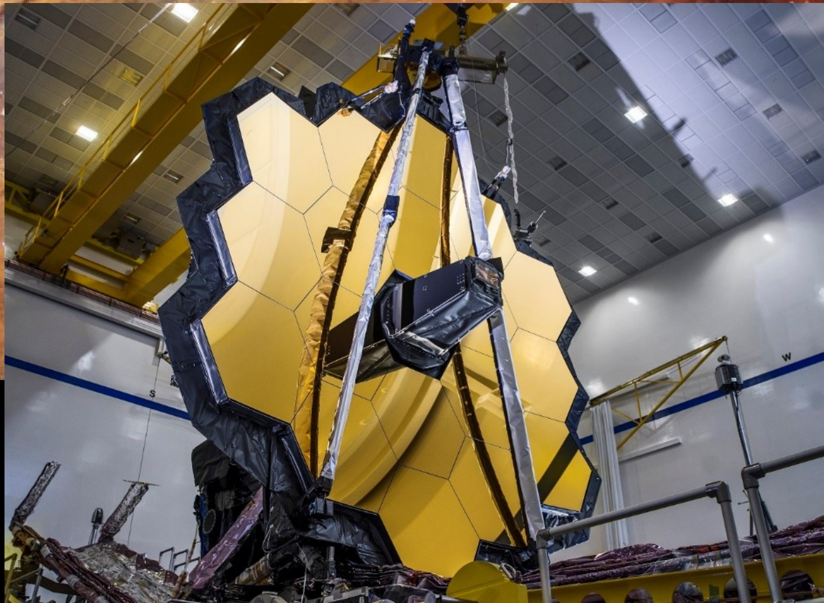


Figure [pm rms]	<30		aberrations
MSFR [pm rms]	<50		flare
HSFR [pm rms]	<100		light loss

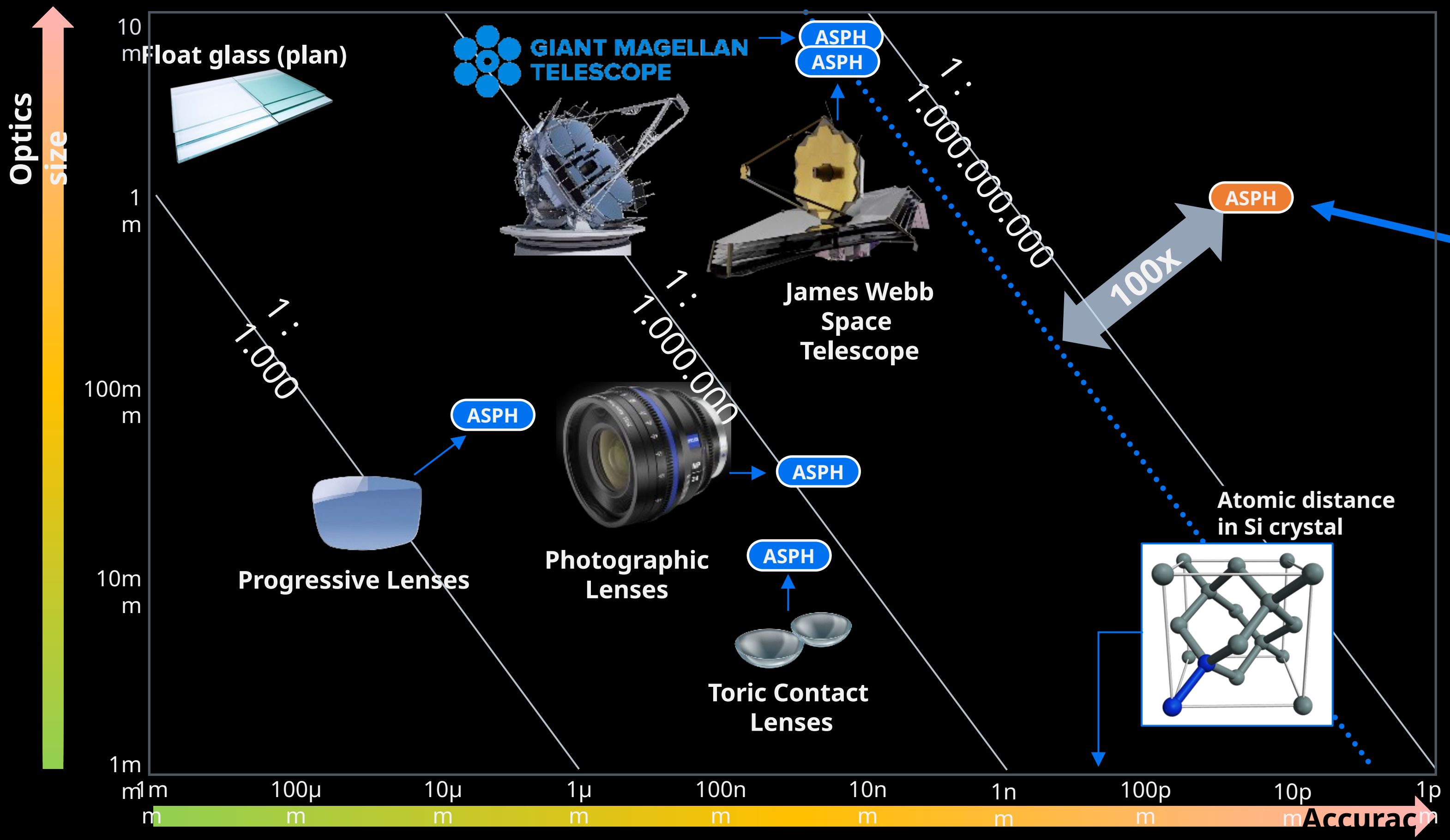
The Power of Innovation

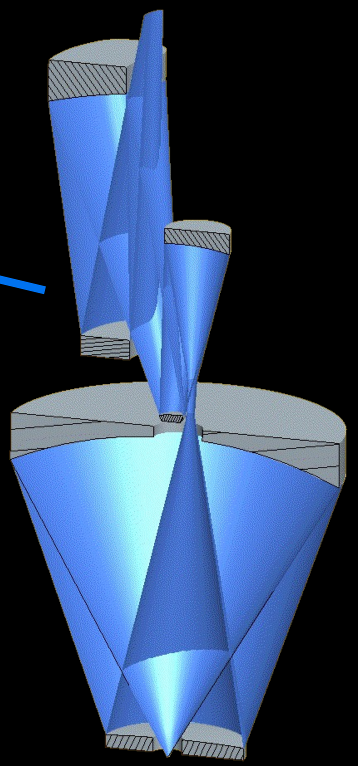
Star forming area NGC 3324 in Carina Nebula NGC 3372

NIRCam JWT, credits ESA



HighNA requires high accuracy mirrors on large optical surfaces



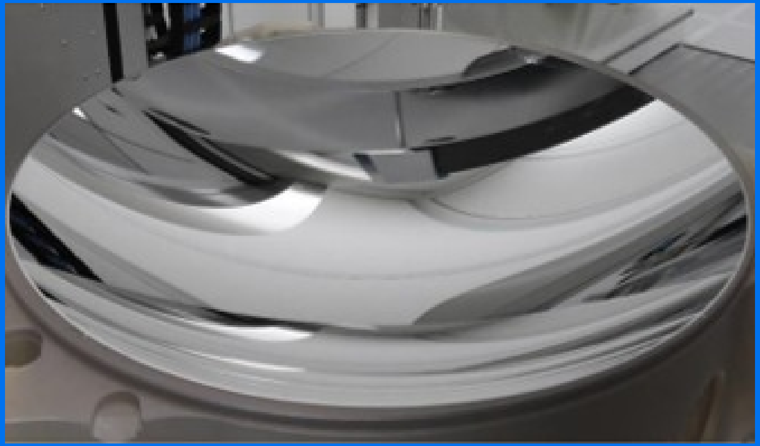


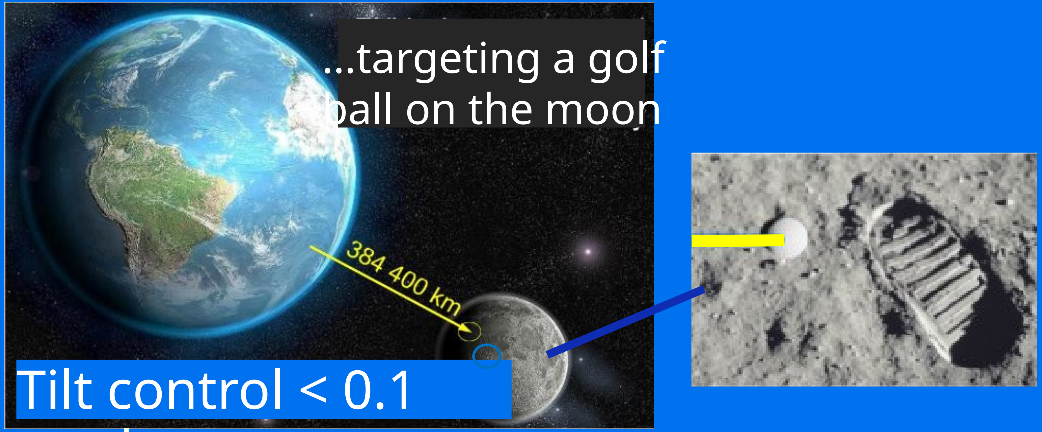
Lithography mirrors are 100x more demanding than any other optical instrument!

EUV manufacturing challenges: precision surface and positioning control

Mirror surface of >1m in diameter with figure control of 20 pm.

If mirror were the size of Bonn the mean deviation of the target figure should be smaller than 200 nm.





…targeting a golf ball on the moon

Tilt control < 0.1 nrad

Key driver for mirror production.

Key driver for mirror and frame integration.

What needs to be taken care of...

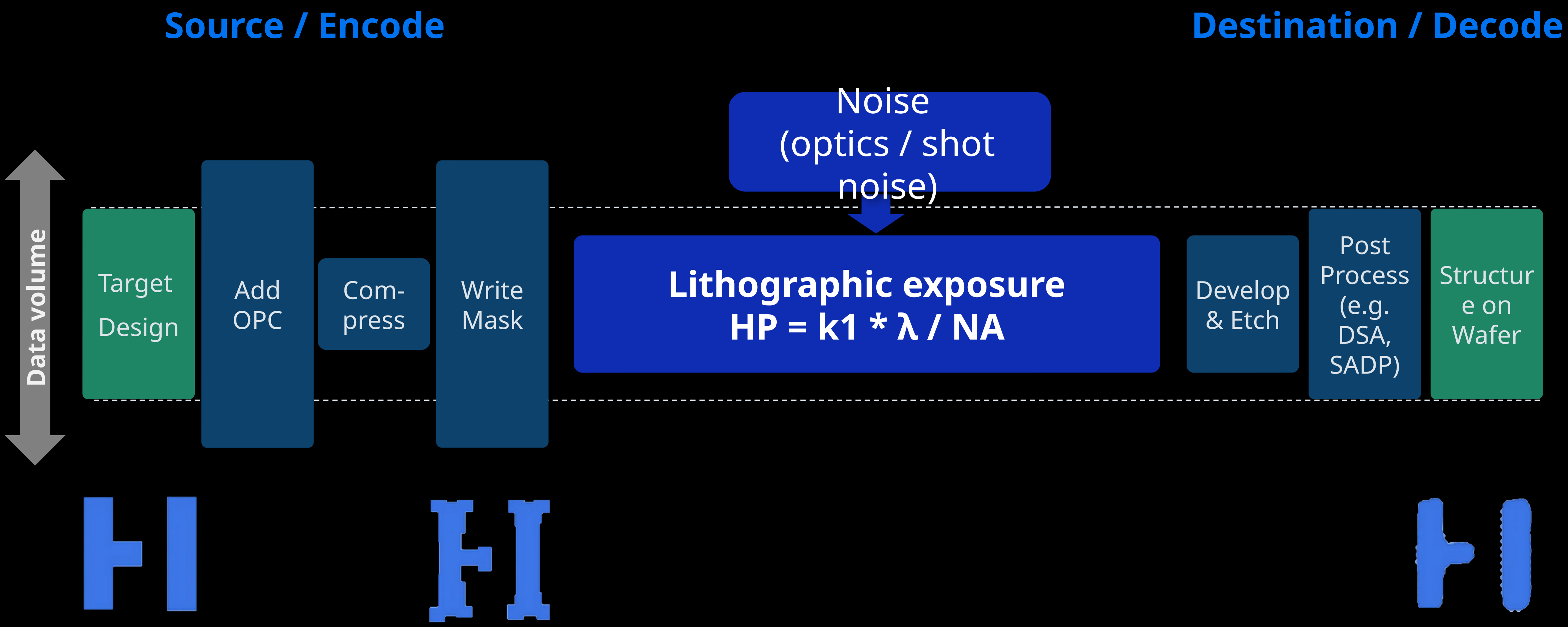
Heat of electric components
Electrical drift effects
Position deviations
Camera noise
Straylight
Optical design of the interferometer
Quality of the optical components
Polarization effects
Mechanical Drift
Air turbulence
Temperature effects
acoustic influences
Radiation
Vibrations
Handling effects
Insufficient calibration
Varying environment conditions
Sample handling
Shot-Noise
Heat of electric components
Electrical drift effects
Position deviations
Camera noise
Straylight
Optical design of the interferometer

?

What makes Optical Lithography so attractive?

A change of perspective…

Data requirements in the lithography process chain



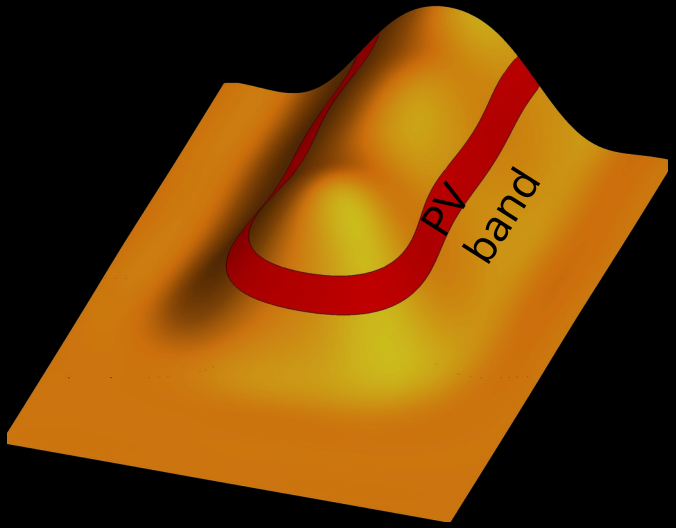
Source / Encode

Destination / Decode

Noise (optics / shot noise)

Lithographic exposure
HP = k1 * λ / NA

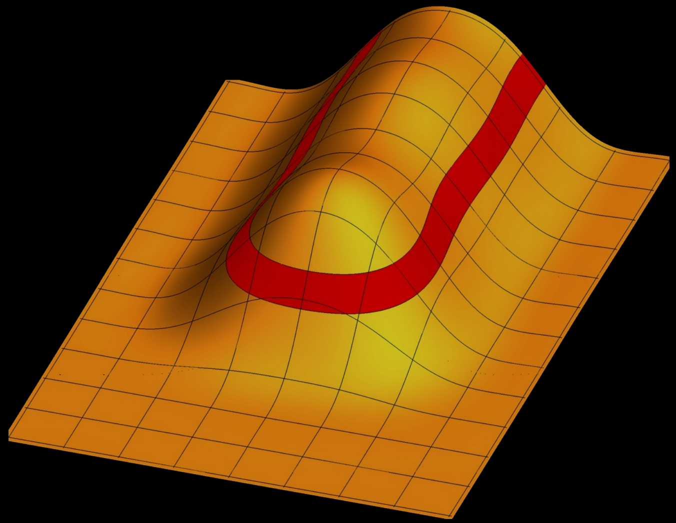
Data rates in lithography: channel capacity is optical bandwidth x Bits/px



Aerial image

Frequency cutoff at

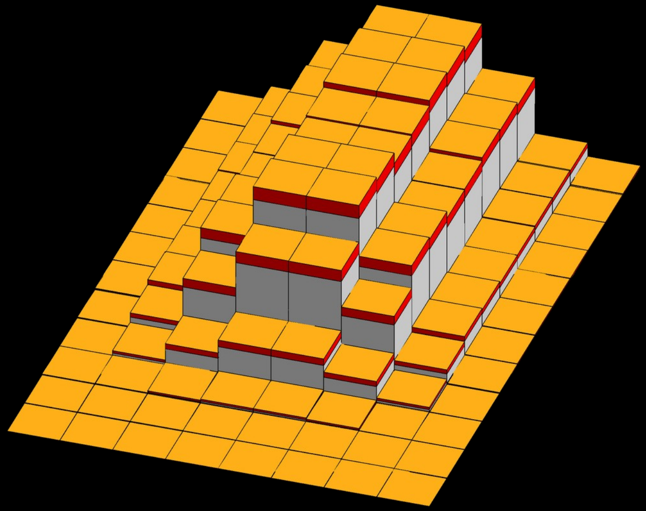
$$f_{max} = \frac{2*NA}{\lambda}$$



Nyquist sampling

Pixel grid

$$\Delta x = 0.25\,\frac{\lambda}{NA}$$



Signal to noise

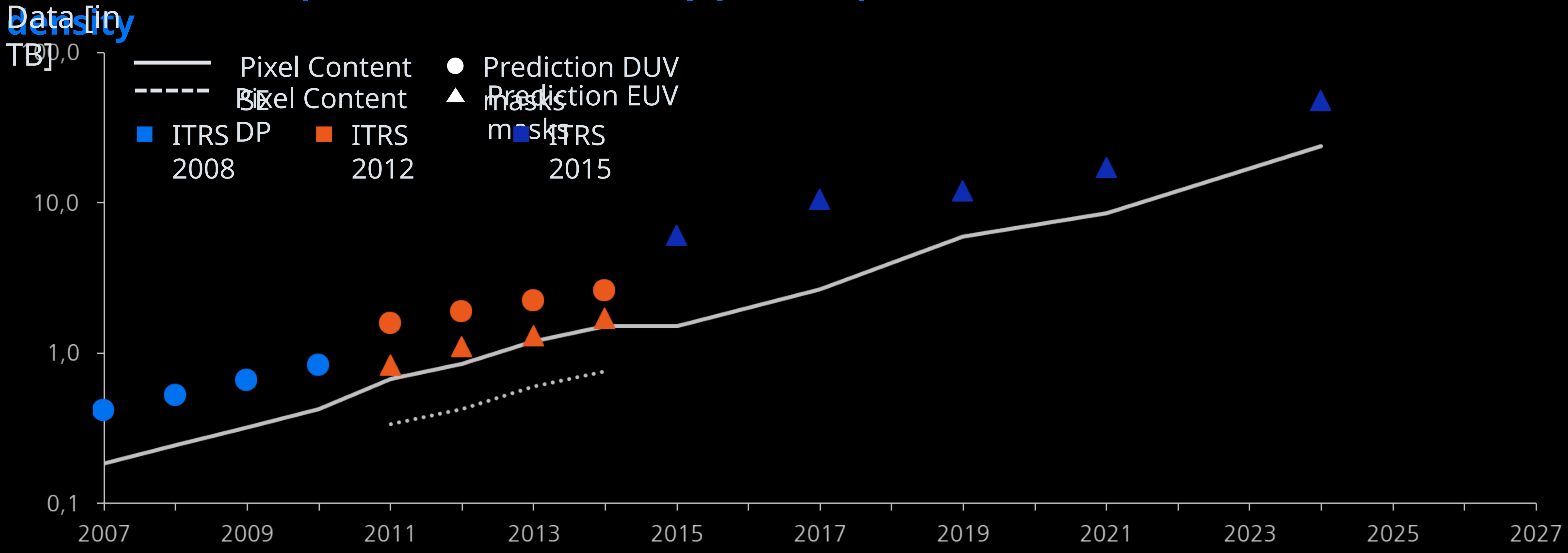
determines data content per pixel

$$\frac{bits}{pixel} = \log_2\left(1 + \frac{s}{n}\right)$$

Ref: Michael Rieger, "Communication theory in optical lithography," JMMM 2012

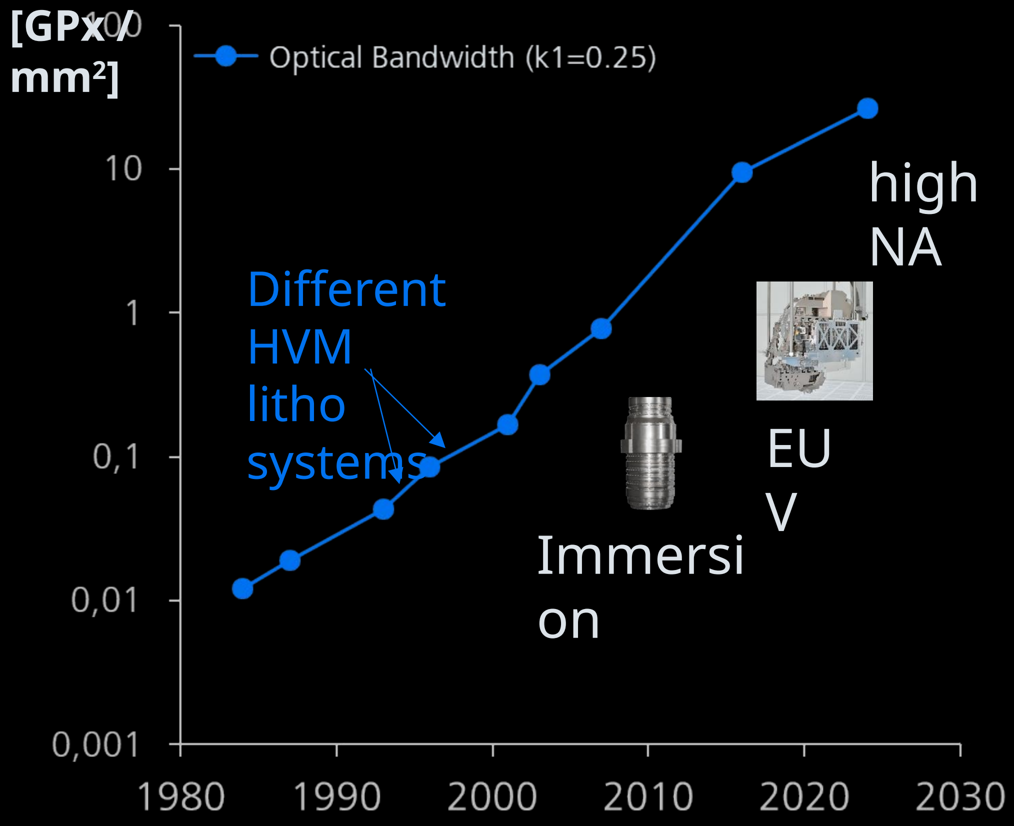
Growing pixel content drives multiple patterning or broader optics bandwidth

Predicted uncompressed Data vs. Binary pattern pixel density



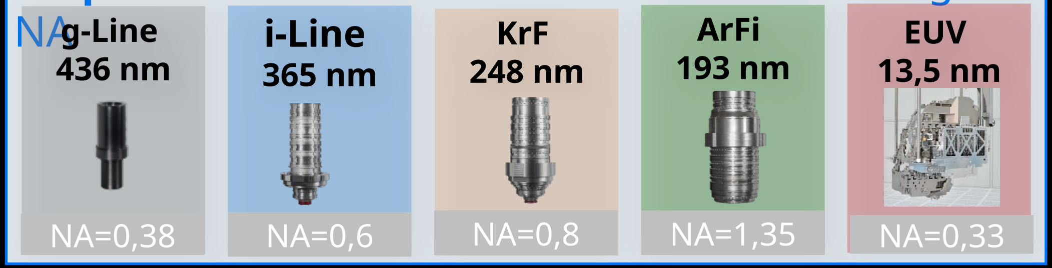
Optical Lithography is High-Bandwidth Data Transfer

Bandwidth

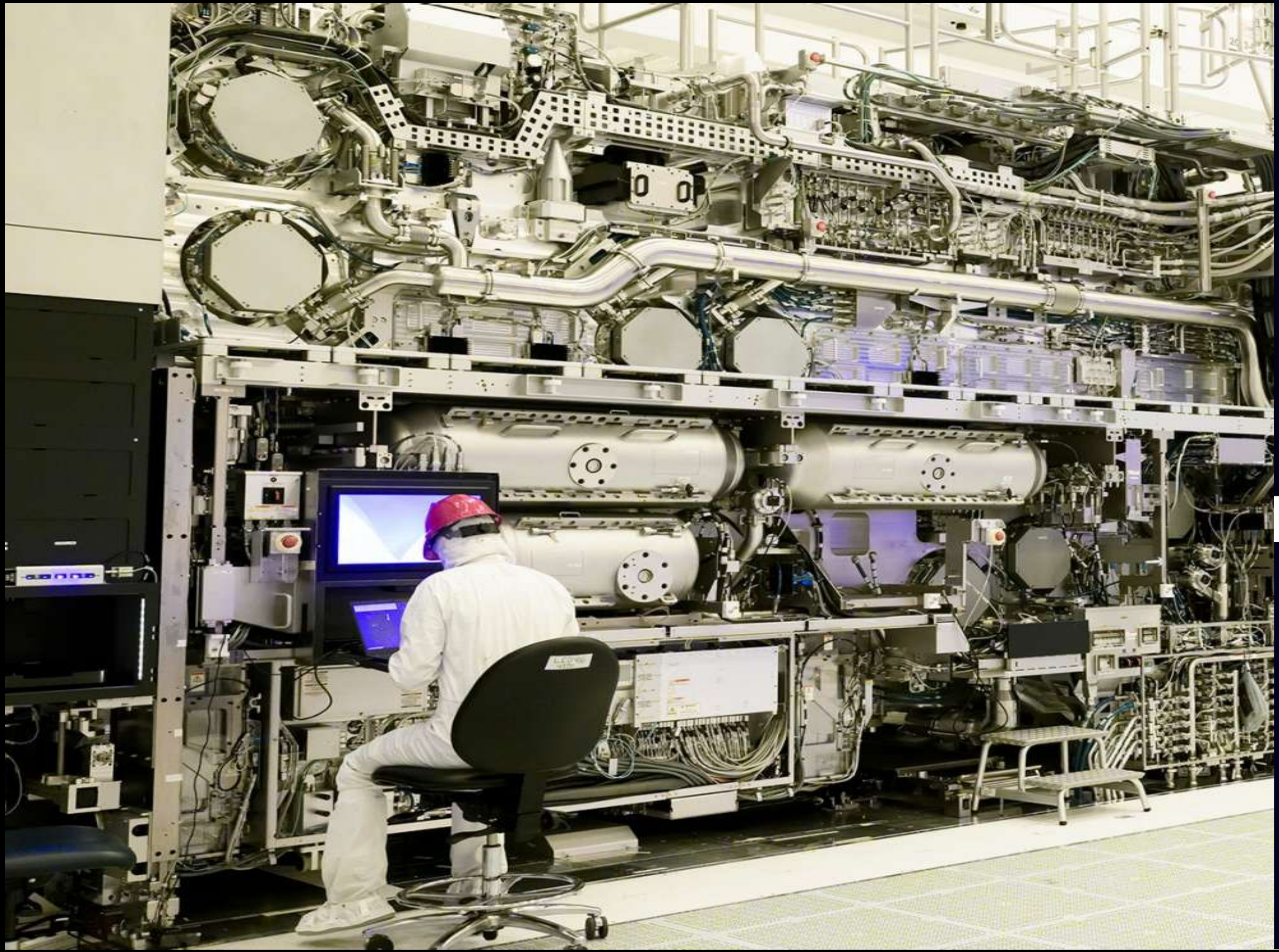


Levers for data rate

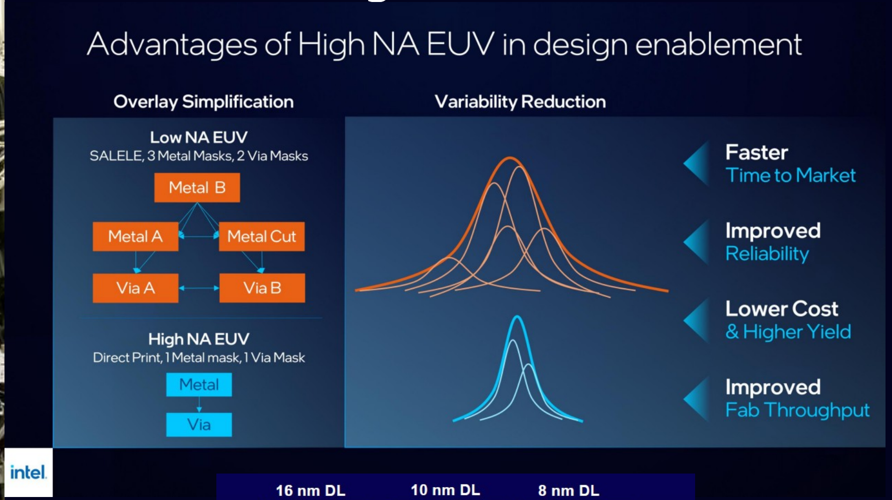
1.Optical Bandwidth increase: Smaller λ & higher NA



High NA systems installed at major fabs



First High NA Installations



Advantages of High NA EUV in design enablement

Overlay Simplification

Variability Reduction

Low NA EUV
SALELE, 3 Metal Masks, 2 Via Masks

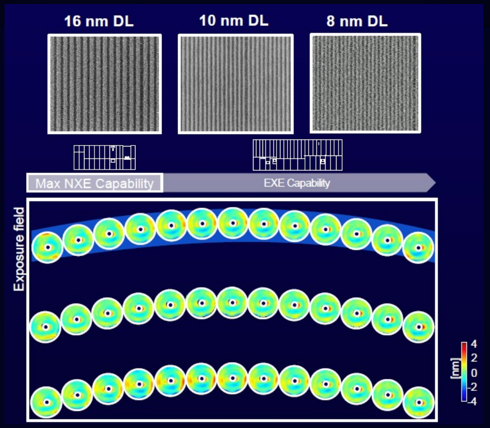
Metal B
Metal A
Metal Cut
Via A
Via B

High NA EUV
Direct Print, 1 Metal mask, 1 Via Mask

Metal
Via

- **Faster** Time to Market
- **Improved** Reliability
- **Lower Cost** & Higher Yield
- **Improved** Fab Throughput

intel.

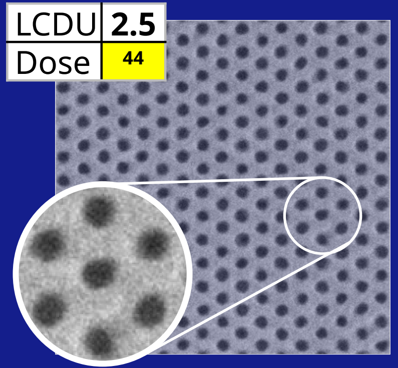


Source: Intel

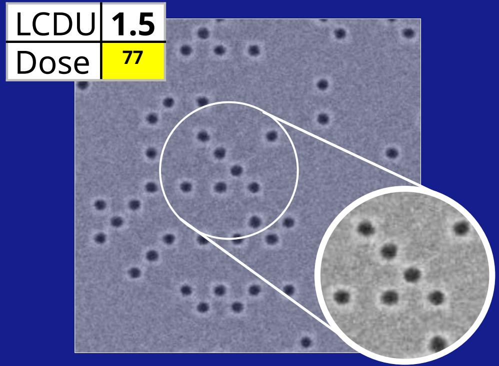
Excellent first results for High-NA

NA 0.55

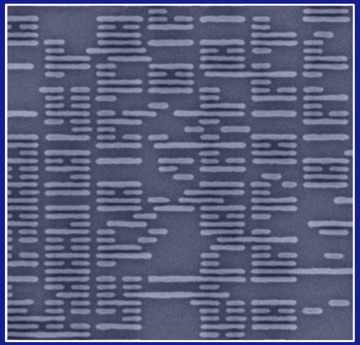
Contact holes
(15 nm)



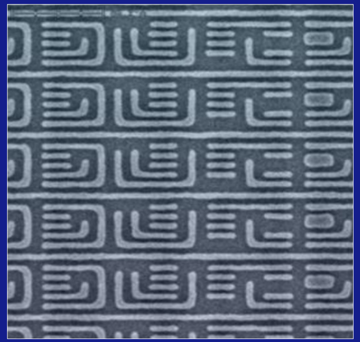
Random vias
(36 nm)



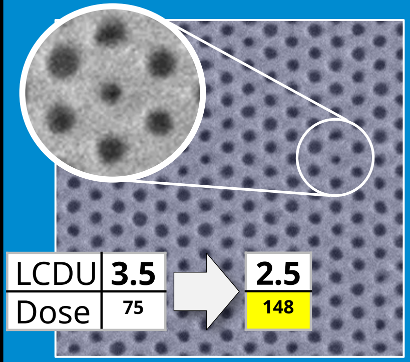
Logic Metal
(P19, tip2tip ~15nm)



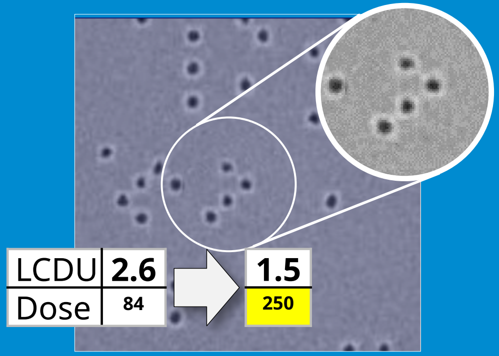
2D interconnects
(P22 H, P28 V)



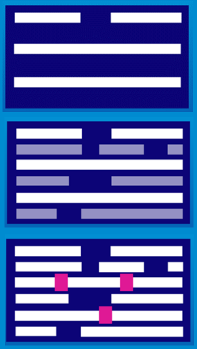
NA 0.33



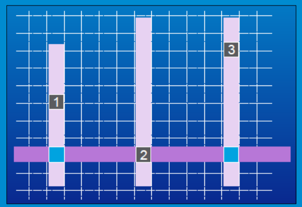
or 2x NA 0.33 + 1x DUV



or 2x NA 0.33



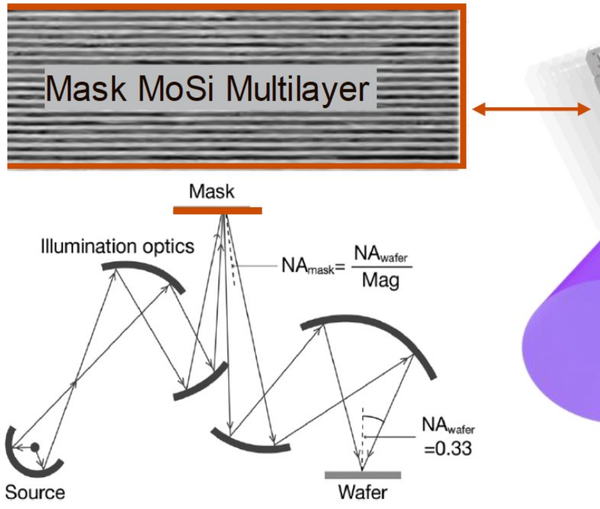
NA 0.33 litho etch
+
NA 0.33 litho etch
+
NA 0.33 cut

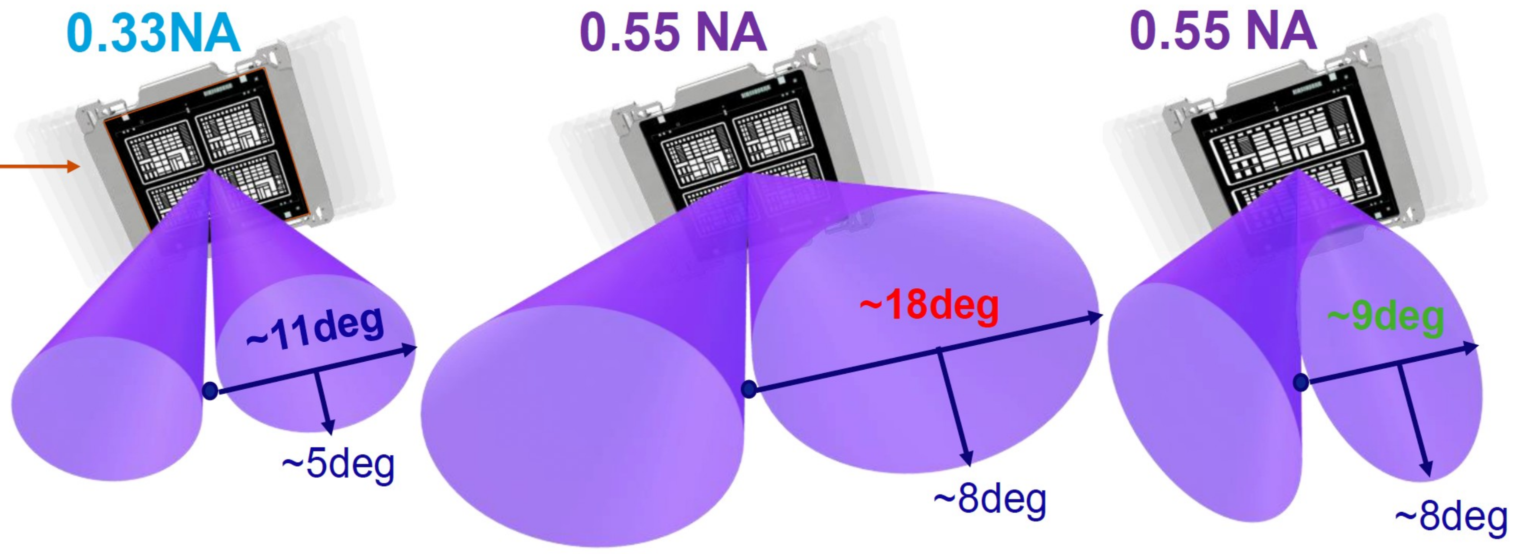


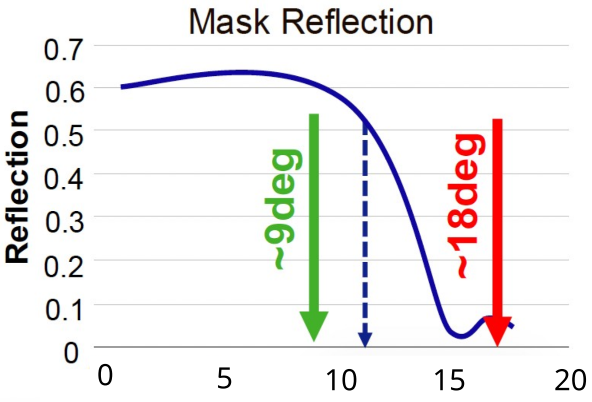
☐ **NA 0.33 metal 1**
☐ **NA 0.33 metal 1 V**
☐ **NA 0.33 via H**

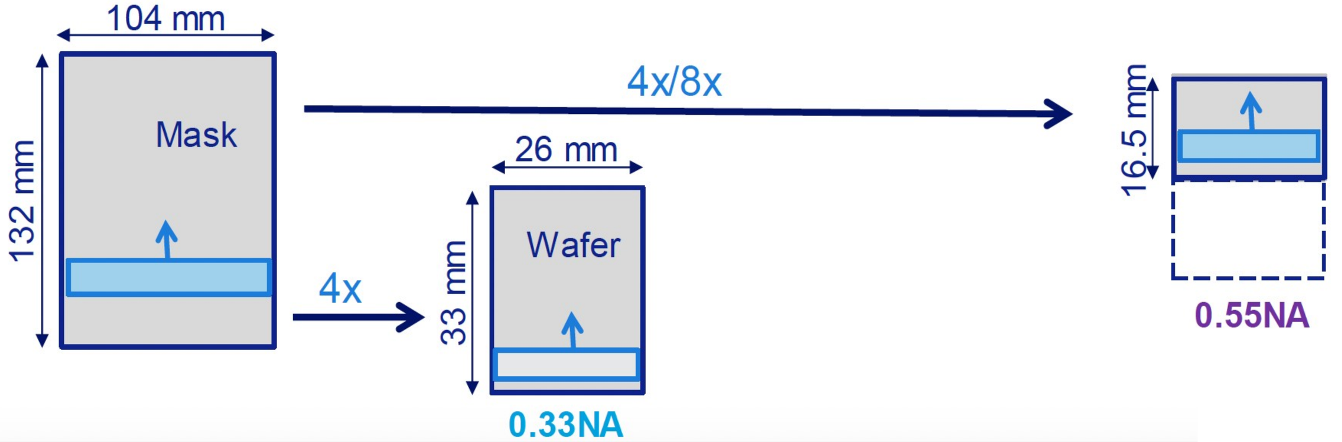
cf. Jan van Schoot – “Beams & More”, Stuttgart, Germany

High-NA EUV (NA=0.55) and half-field exposure



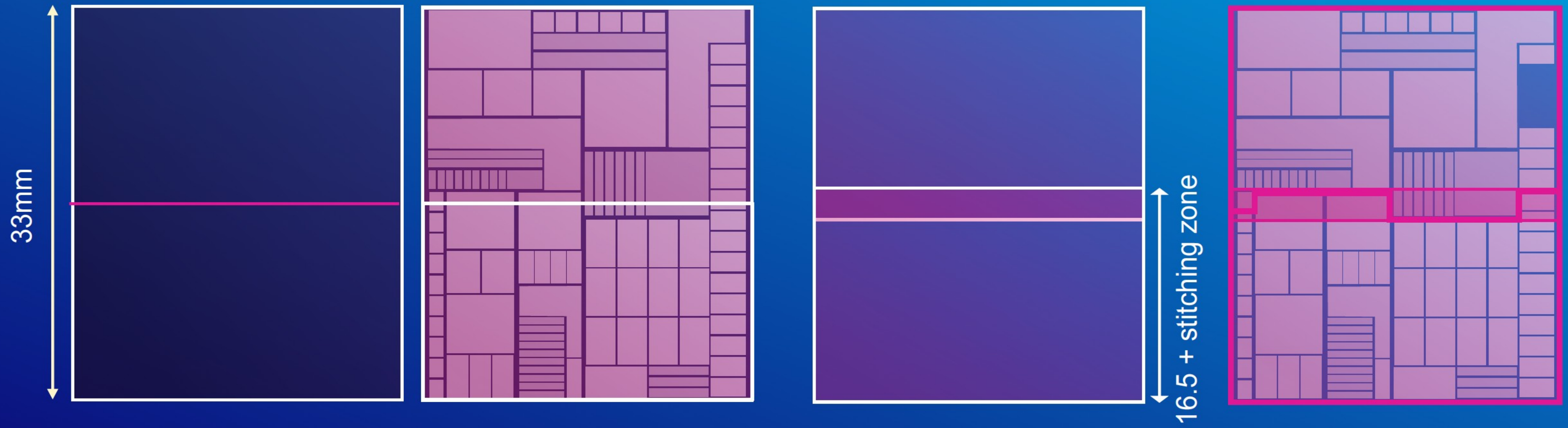






Block & route die-stitching solutions

to address HighNA half-field challenge



EXE Half field exposure

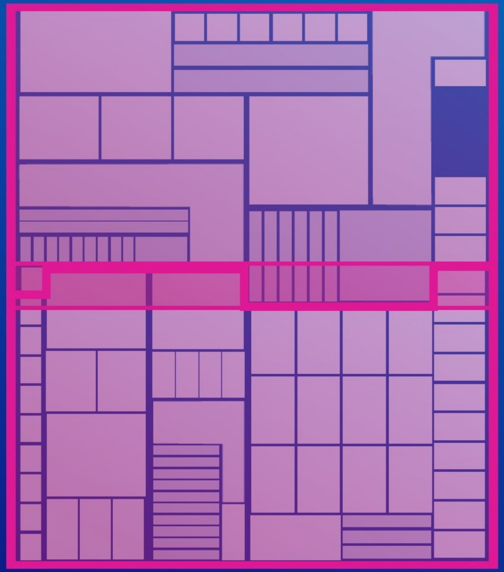
Floorplan
with IP Blocks

Scanner enables
exposure of
stitching zone on
top of 16.5 mm
half field

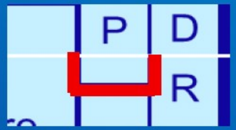
This enables
stitching for full field
chips

ASML/Chris de Ruiter, SPIE AL 2026

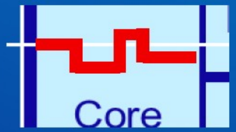
Block & route die-stitching solutions
to address HighNA half-field challenge



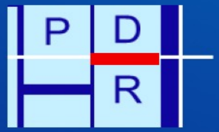
Solution options

1. 

Around IP blocks

2. 

Through “non-critical space” in IP blocks

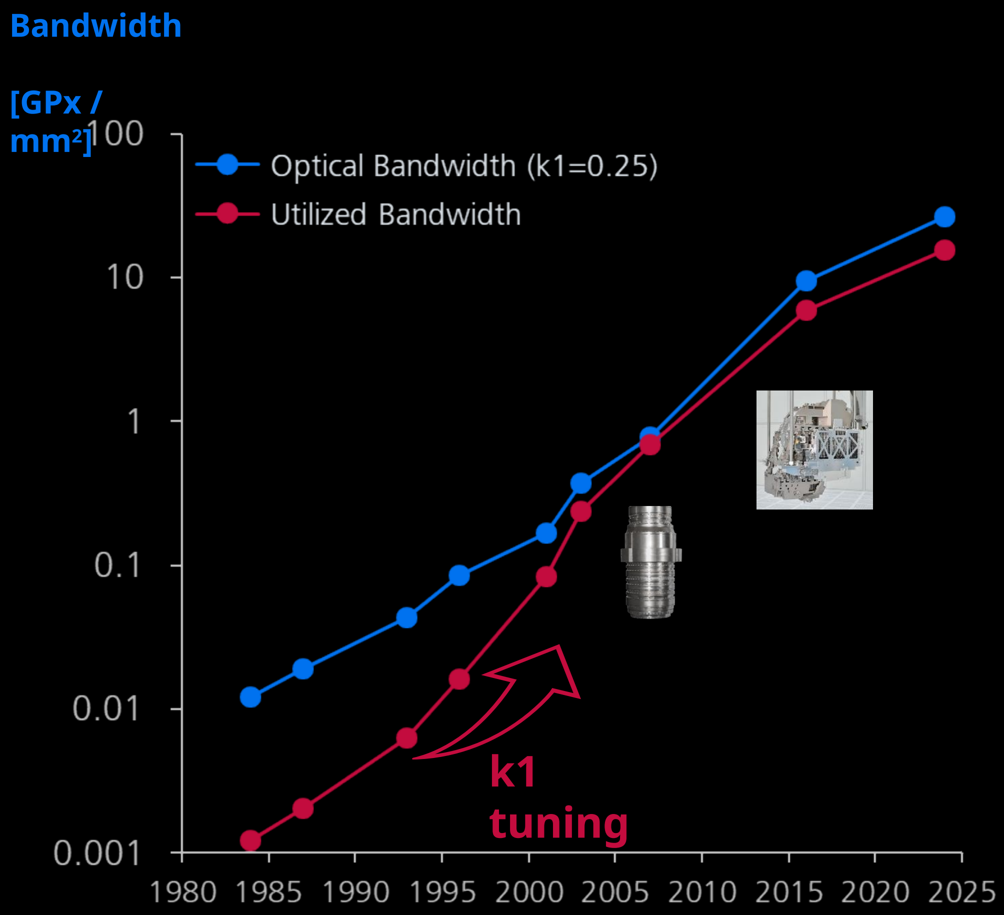
3. 

Utilizing collateral cell through IP

This enables stitching for full field chips

ASML/Chris de Ruiter, SPIE AL 2026

Optical Lithography is High-Bandwidth Data Transfer

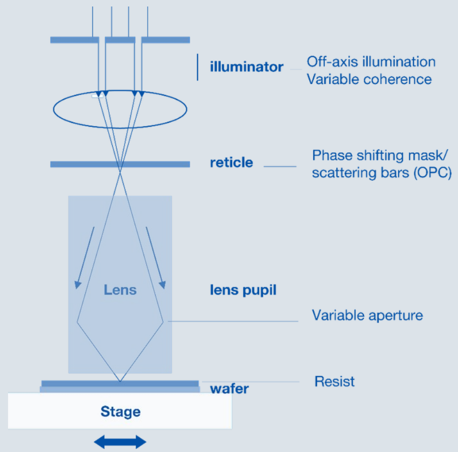


Levers for data rate

1. Optical Bandwidth increase: Smaller λ & higher NA

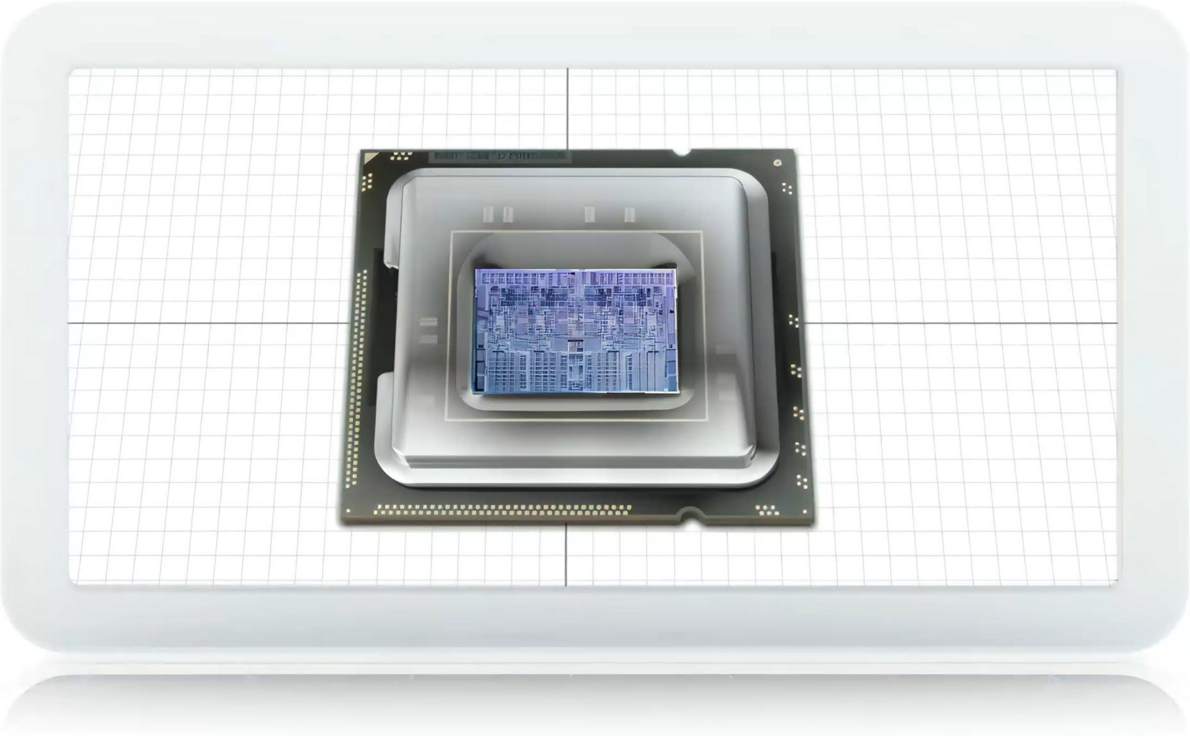
×

2. k1 tuning



🟦 Illumination
🟥 Mask
🟩 Mask OPC
⬜ Tool
🟪 Process

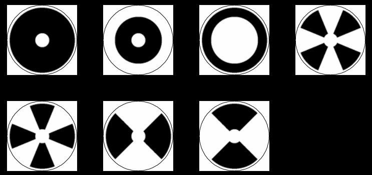
Low k1: what you see (on mask) is not what you get (on wafer)



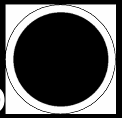
Source: ASML

The EUV illumination optics journey

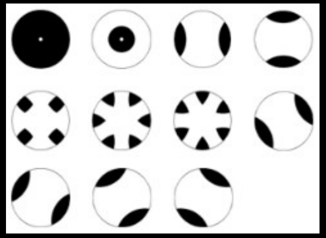
2012
PFR
40%



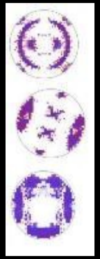
2009
conventio
annular
settings



2016
PFR
20%

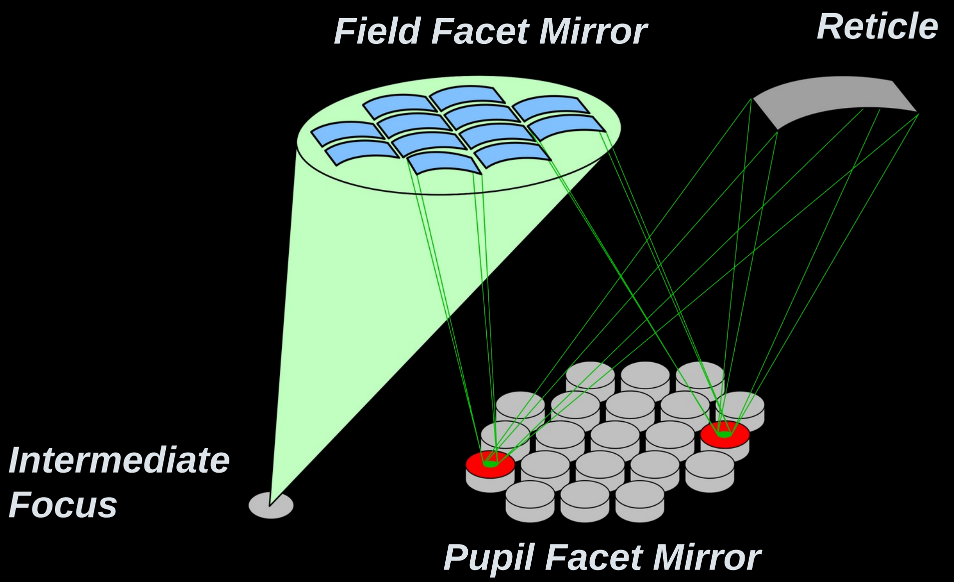


Standard settings

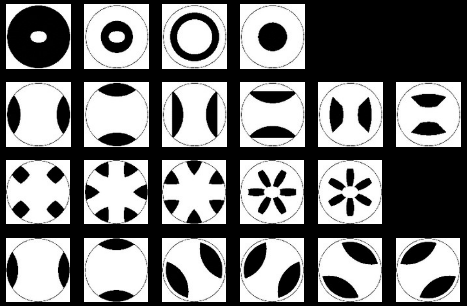


SMO (examples)

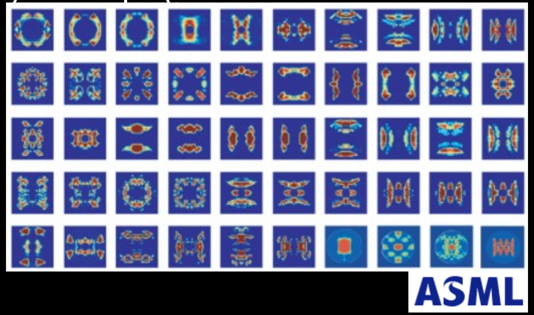
Illumination concept



2024
PFR
20%

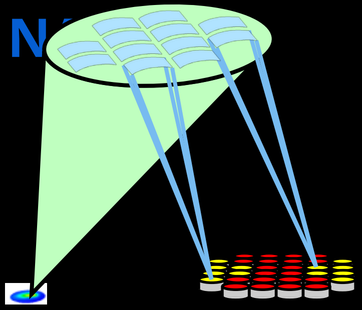


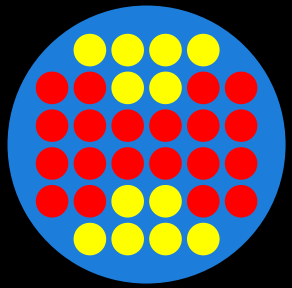
SMO



New High-Transmission / High-Flexibility Illumination for EUV

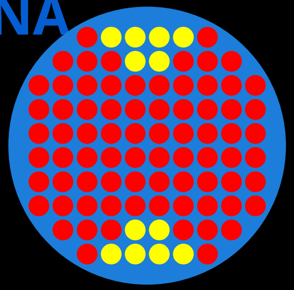
Current 0.55 N





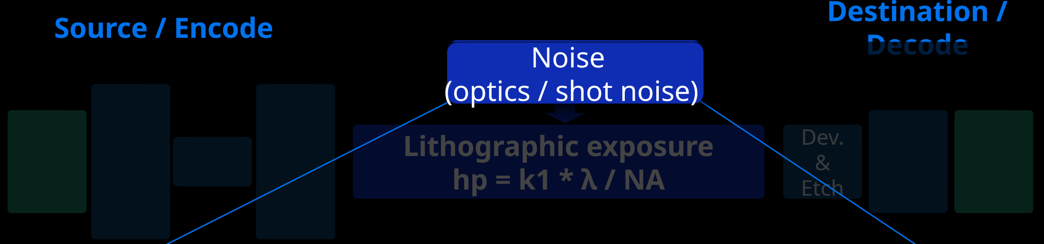
Pupil Fill Ratio 20%

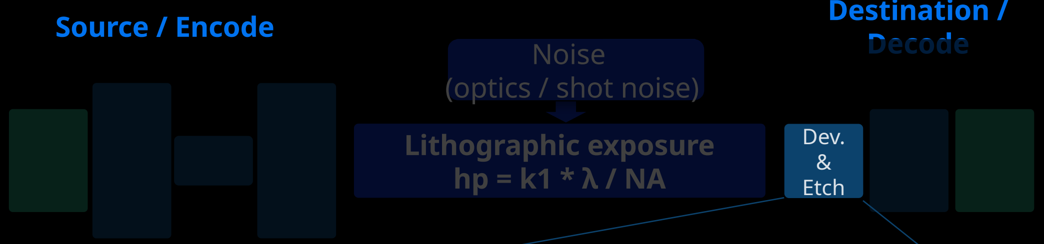
New Concept 0.55 NA



Pupil Fill Ratio ~10%, High transmission

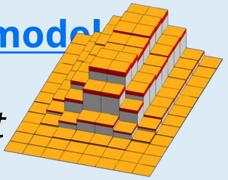
Limit noise: Shot noise & Stochastics

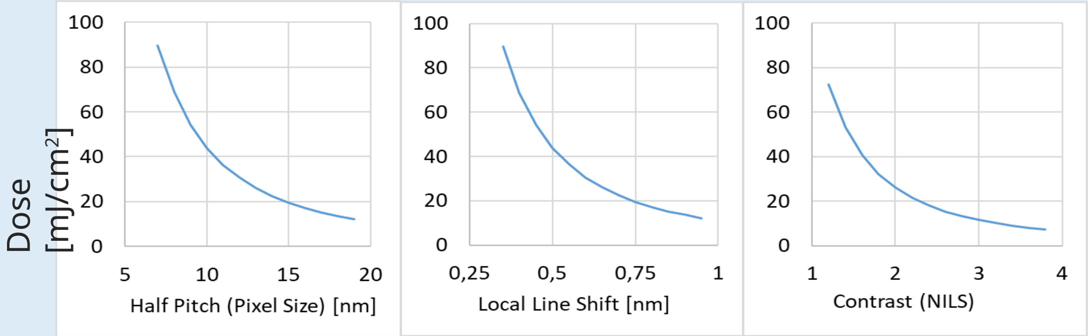




Noise received per pixel - simple shot noise model

Dose for shot noise ***scales quadratically***
in resolution, in line shift (roughness) and contrast





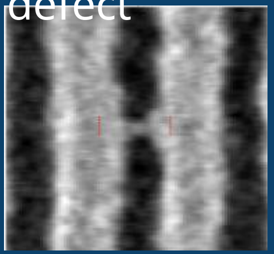
HP (Pixel size)	**variable**	HP (Pixel size)	13nm	**HP (Pixel size)**	**13nm**
3σ line shift*	5% of px	3σ line shift	**variable**	3σ line shift	5% of px
NILS	2	NILS	2	NILS	**variable**
Absorption	30%	Absorption	30%	**Absorption**	**30%**

*Local Line Shift: edge variation at pixel

More stochastics at the receiver

Local defects with high frequency and 3d content

Bridge defect

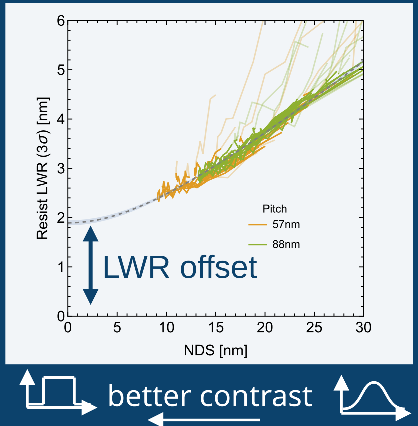


De Bisschop, Hendrickx
SPIE AL 2018

CH blockage

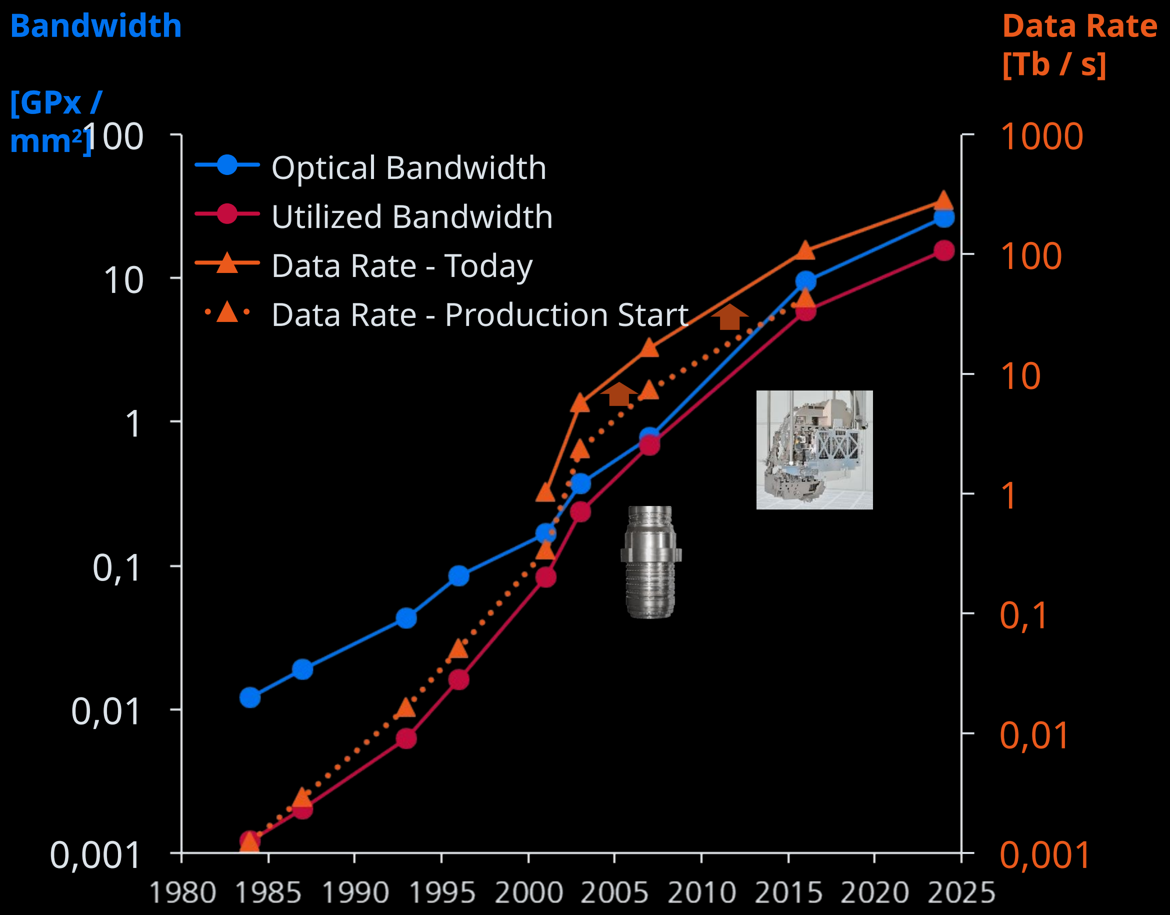
Yen, Hansen,
EUVL workshop (2018)

Dose independent randomness



van Bree et. al.,
SPIE AL 2025

Data Rates in Optical Lithography



Levers for data rate improvements:

1. Optical Bandwidth increase: Smaller λ & higher NA

×

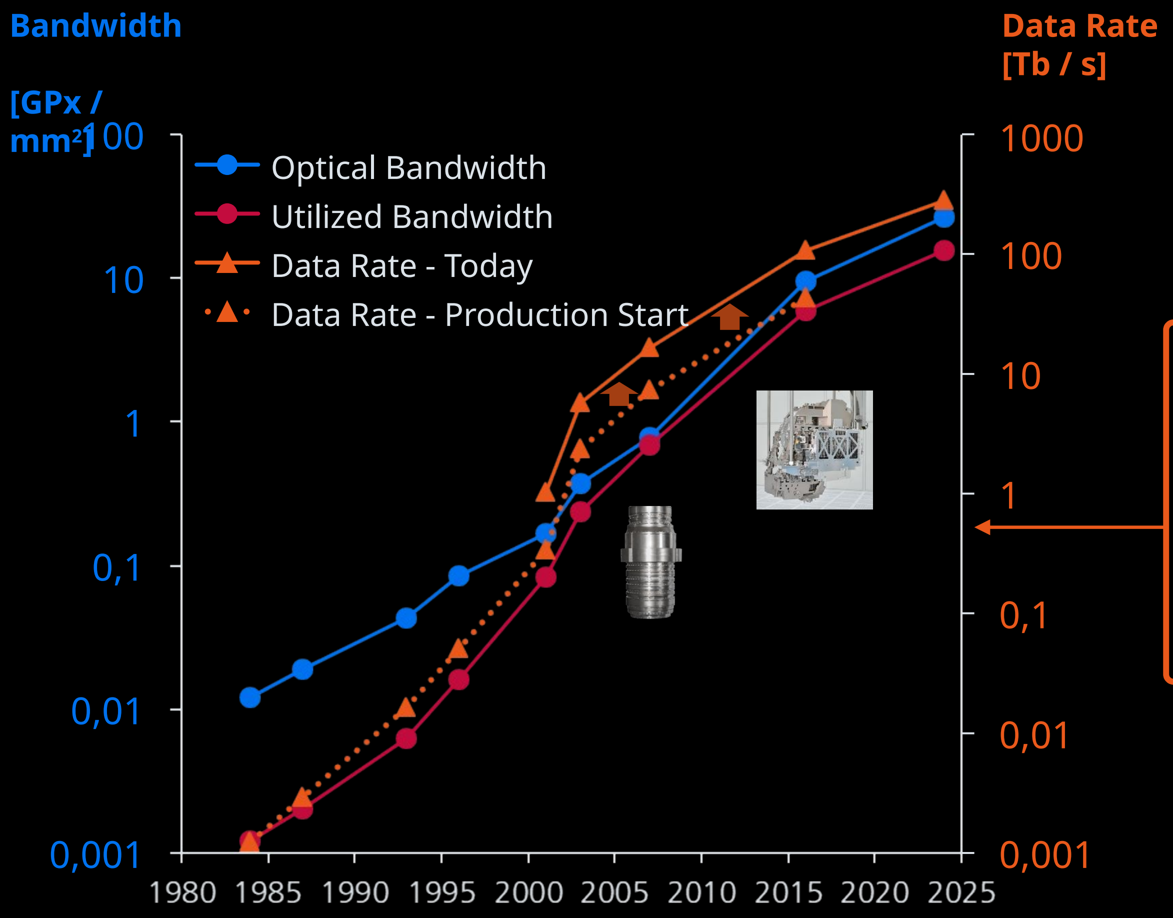
2. k1 tuning

🟦 Illumination 🟥 Mask 🟩 Mask OPC 🟪 Process ⬜ Other (Tool)

×

3. Processed area increase: increasing throughput

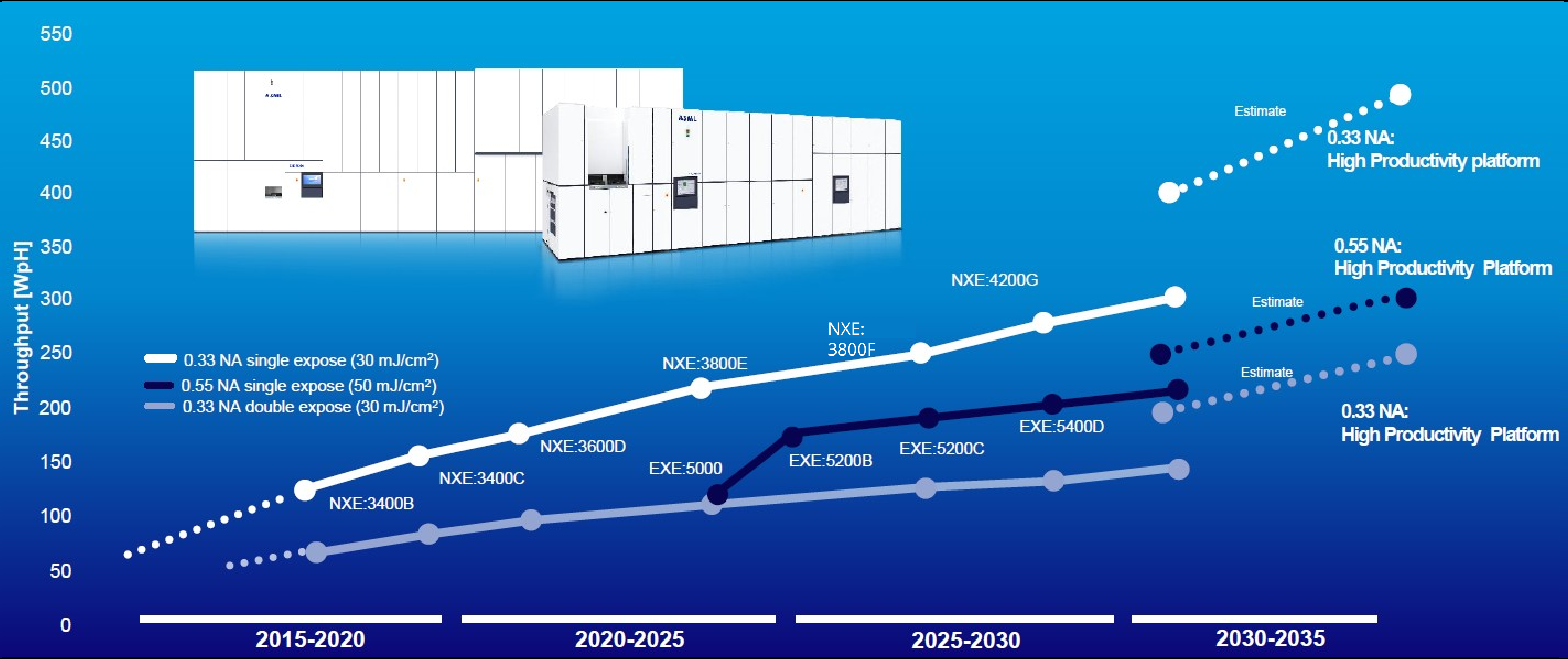
Data Rates in Optical Lithography



Compare to e-Beam writing:

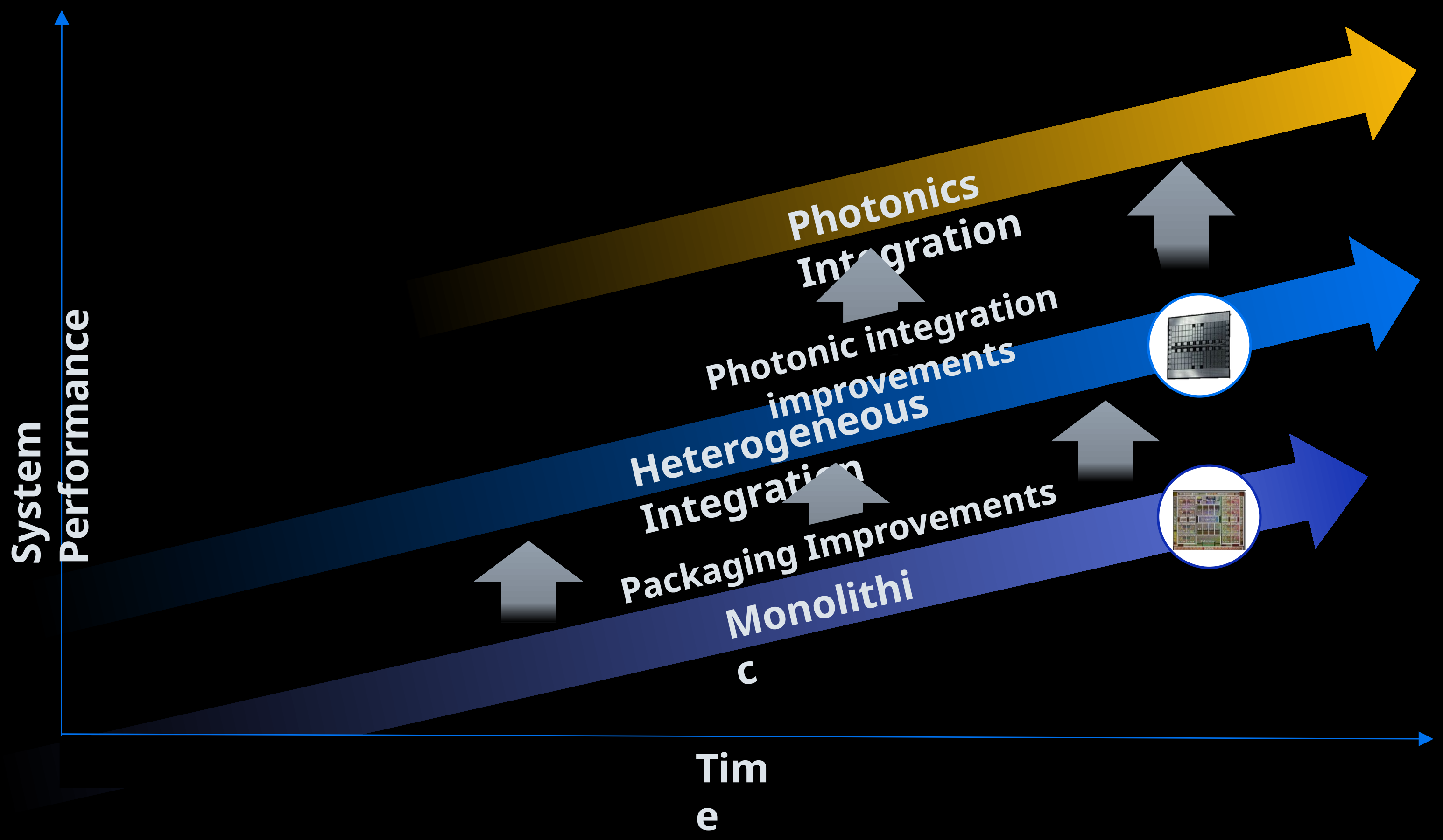
State of the Art Multi Beam Mask Writer
675 Gb/s data rate

Throughput: The Bandwidth multiplier – EUV productivity roadmaps ASML/ZEISS



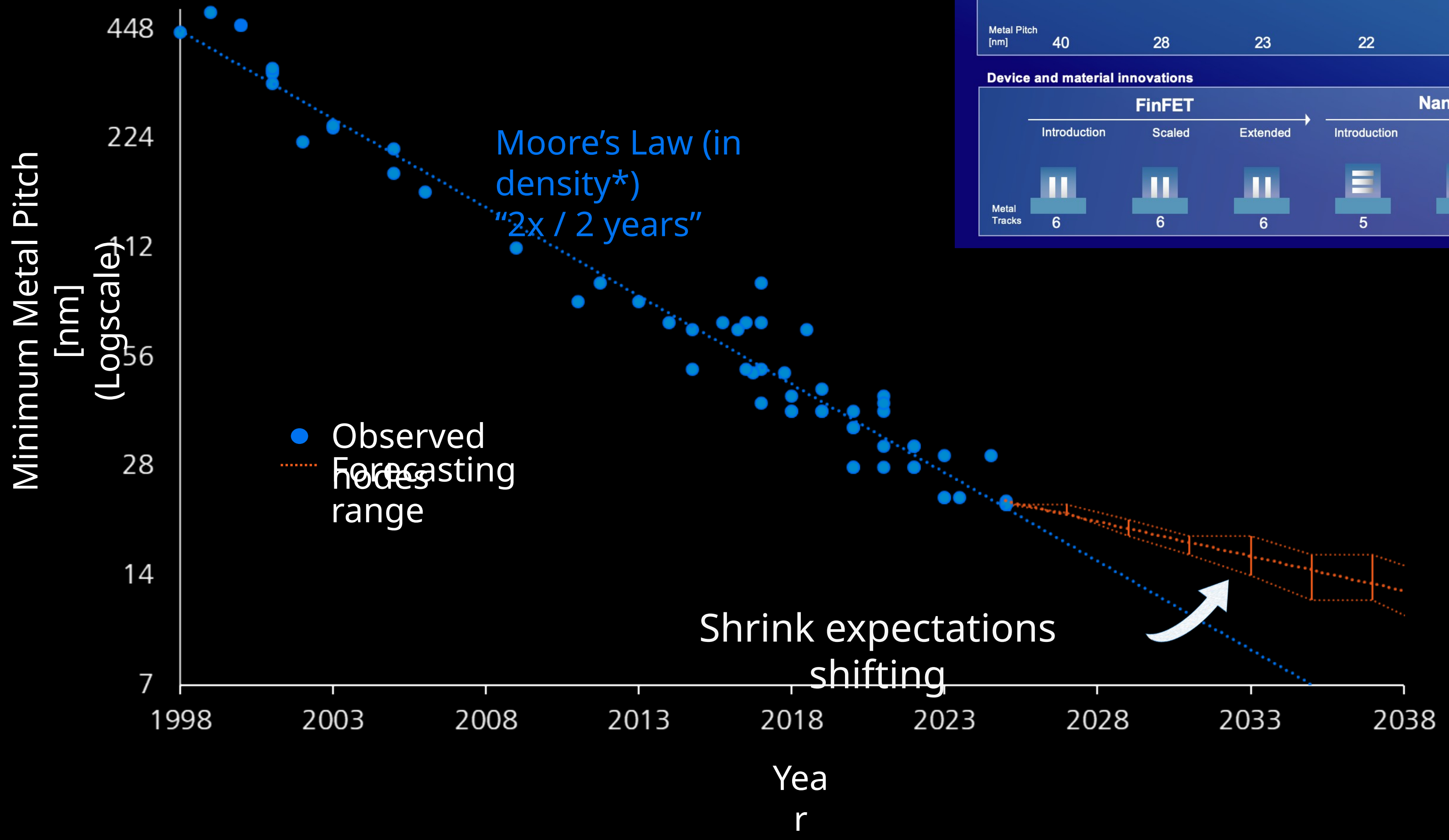
Source: Christophe Fouquet, Scaling EUV and holistic lithography, SPIE AL 2025

Moore’s law & new scaling approaches to complement litho



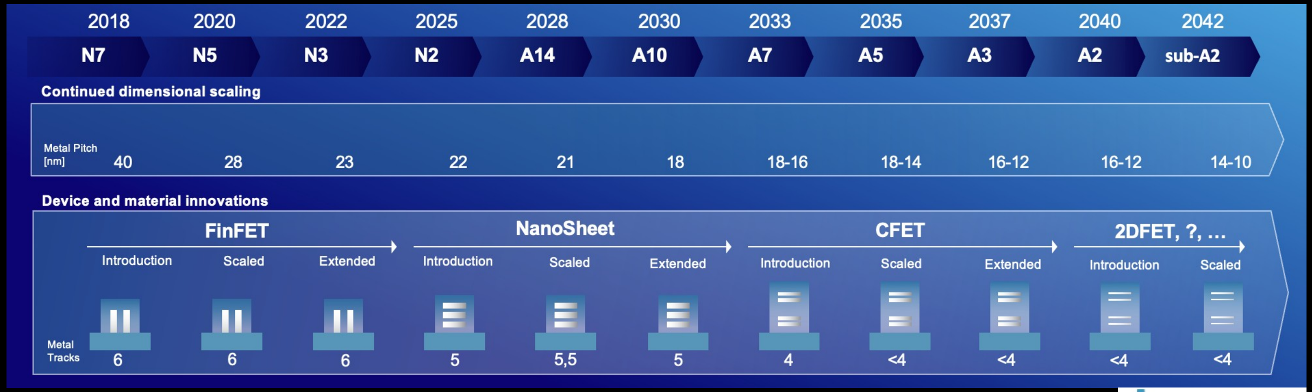
- AI computing demand can **only** be met on a **system level** by leveraging Shrink, **Advanced Packaging & Photonic integration**
- Advanced Packaging is already **in HVM state** at major players
- **Photonic integration** gaining traction - fast

Shrink is continuing at a slower pace – optical bandwidth keeps increasing



Moore's Law (in density*) "2x / 2 years"

Shrink expectations shifting

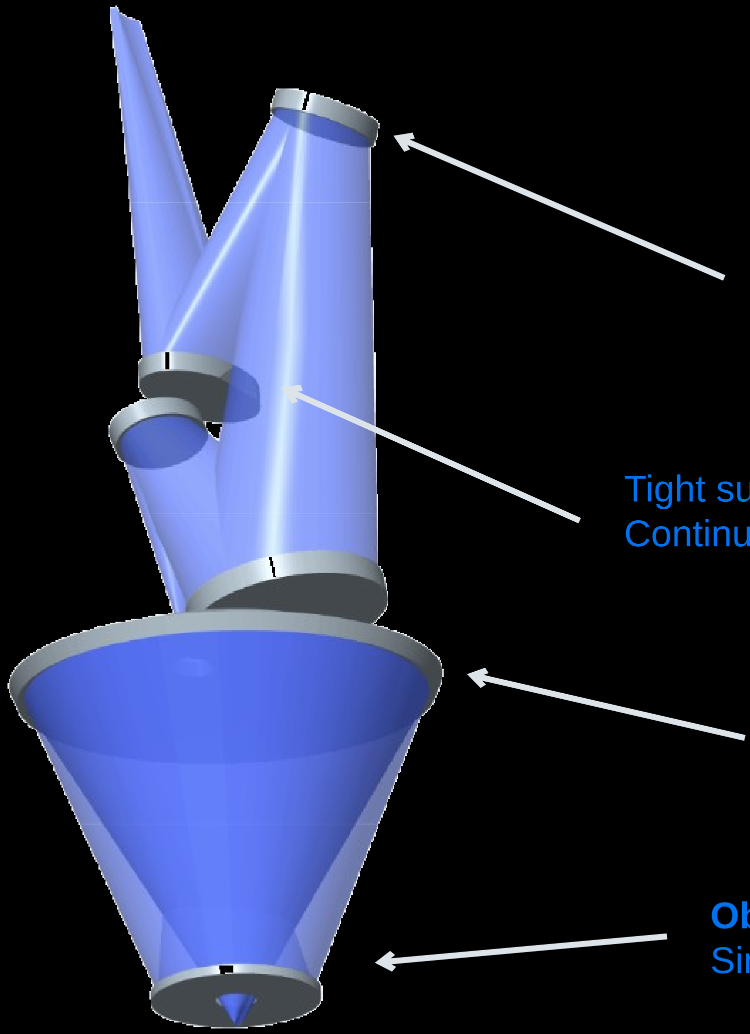


	2018	2020	2022	2025	2028	2030	2033	2035	2037	2040	2042
	N7	N5	N3	N2	A14	A10	A7	A5	A3	A2	sub-A2
Continued dimensional scaling											
Metal Pitch [nm]	40	28	23	22	21	18	18-16	18-14	16-12	16-12	14-10
Device and material innovations											
	FinFET			NanoSheet			CFET			2DFET, ?, …	
	Introduction	Scaled	Extended	Introduction	Scaled	Extended	Introduction	Scaled	Extended	Introduction	Scaled
Metal Tracks	6	6	6	5	5,5	5	4	<4	<4	<4	<4

imec

Hyper NA will be based on continuous improvements from 0.55NA

Expected footprint for hyper NA very similar to HighNA!



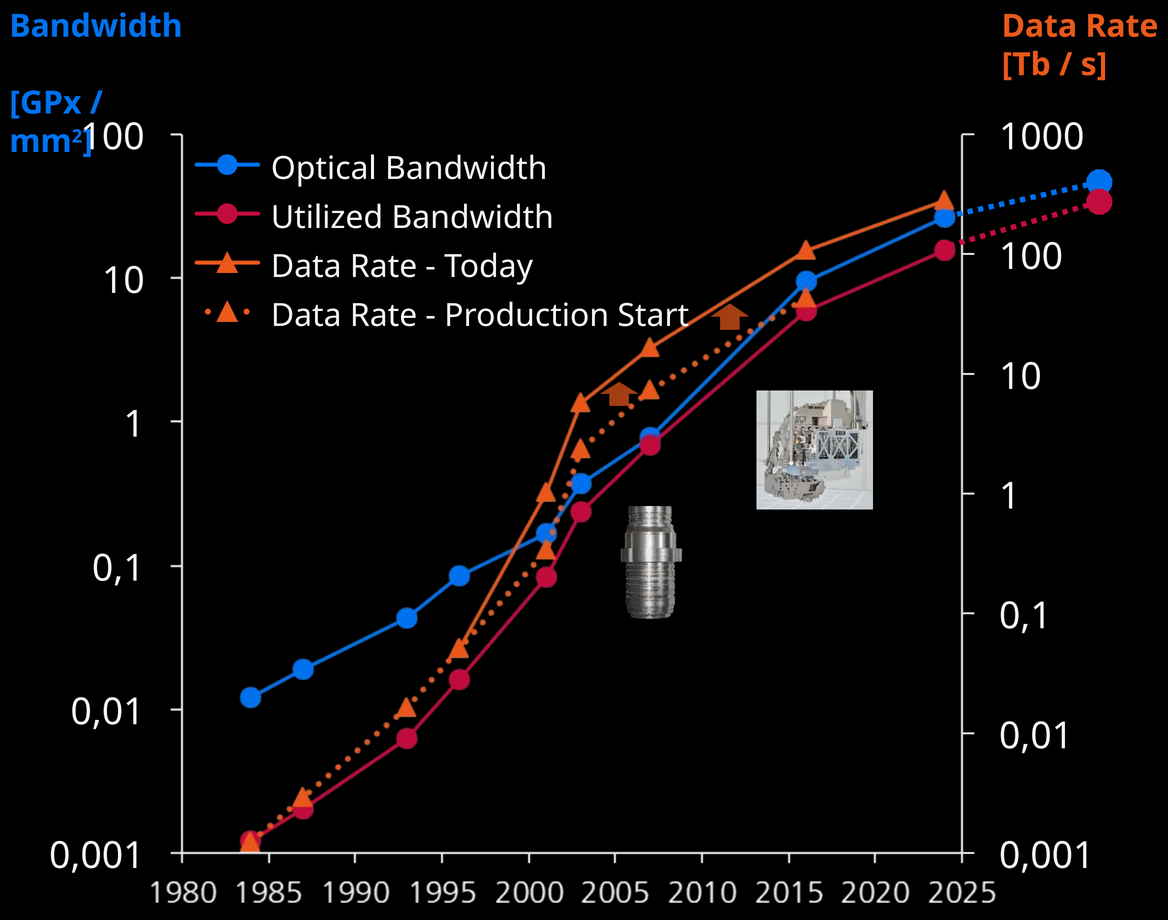
Extreme aspheres
Extending technology from NA 0.55

Tight surface specifications
Continue Improvement

Big last mirror
Will become larger as NA increases

Obscuration
Similar concept as NA 0.55

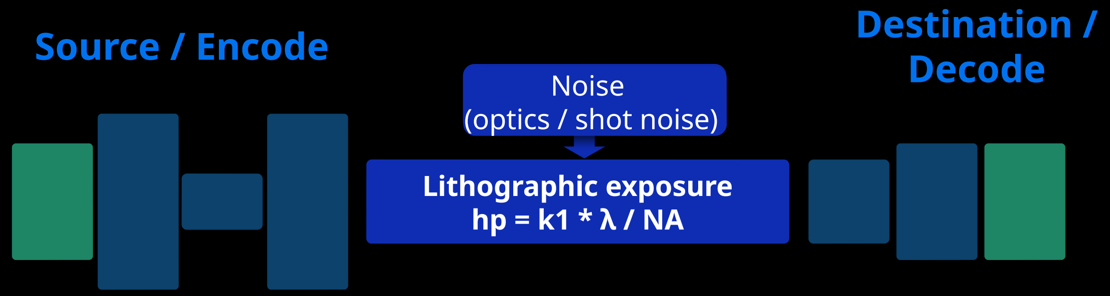
Data Rates in Optical Lithography: The journey continues



Hyper NA will improve **optical bandwidth by another ~2x**

Summary

Optical Lithography is high-bandwidth data transfer...



Source / Encode

Noise
(optics / shot noise)

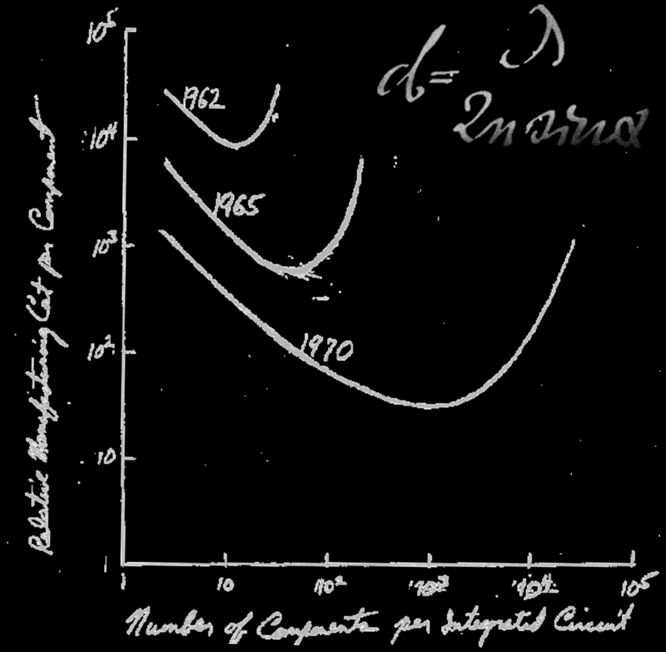
Lithographic exposure
hp = k1 * λ / NA

Destination / Decode

Data rates increased by **5 ½ orders of magnitude** via

- Optical Bandwidth
- Productivity (m^2/h)
- **Reduction of noise factors**
  Send: Mask technology & OPC
  Transmit: Illumination & Optics quality
  Receive: Resist & Process

... enabling Moore’s law for more than 5 decades – and into the future!



...by providing ever higher optical resolution enabling printing smaller feature sizes

Successful cooperation with partners from industry and science, supported by the European Union and the Federal Republic of Germany

ChipsJU

IPCEI Microelectronics and Communication Technologies

Bundesministerium für Wirtschaft und Energie

Bundesministerium für Bildung und Forschung

Baden-Württemberg
MINISTRY OF ECONOMIC AFFAIRS, LABOUR AND TOURISM

Freistaat Thüringen

Thuringian Ministry for Economic Affairs, Science and Digital Society

ZEISS

Seeing beyond