The Future of Photonics

Eugene G. Arthurs
CEO, SPIE
October 24, 2017

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Personal Entanglements

- Steering Committee for the U.S. National Photonics Committee
- Board member Edmund Optics
- Advisory Board of Luminar Technologies
- Advisory Board to Scottish Universities Physics Alliance
- Advisory Board to Canada's National Institute of Optics
- Advisory Board to NY's Luminate ($10m Photonics Start up fund)
- Advisor Taichung City Economic Development Bureau
- Consulting Professor, University of Shanghai for Science and Technology

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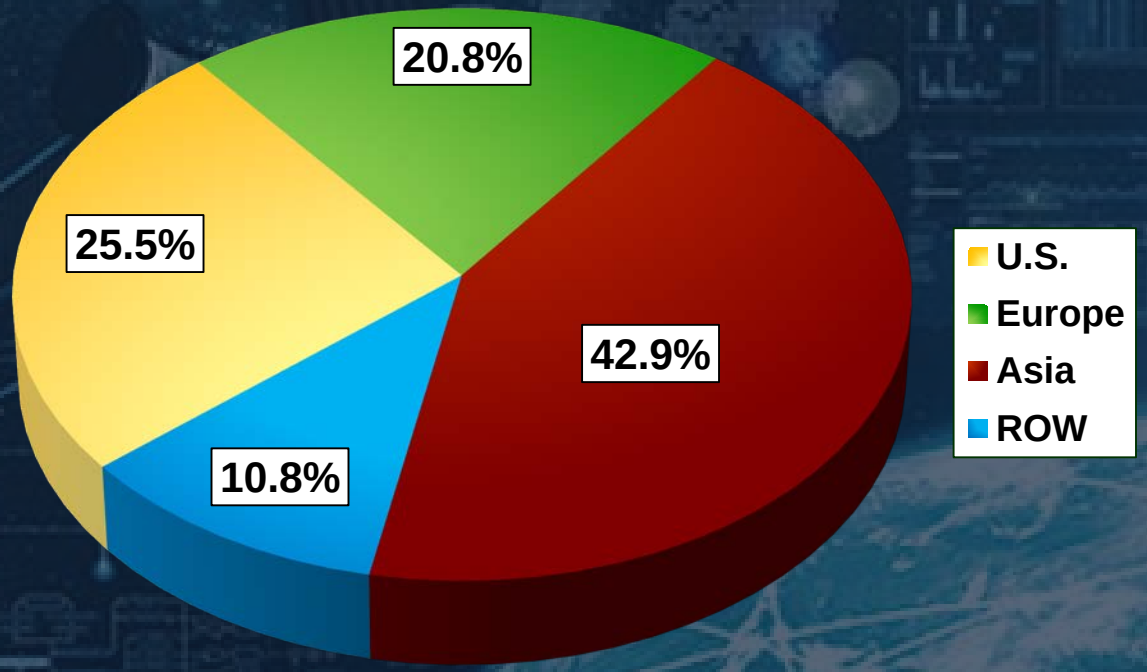
2017 Global R&D Forecast

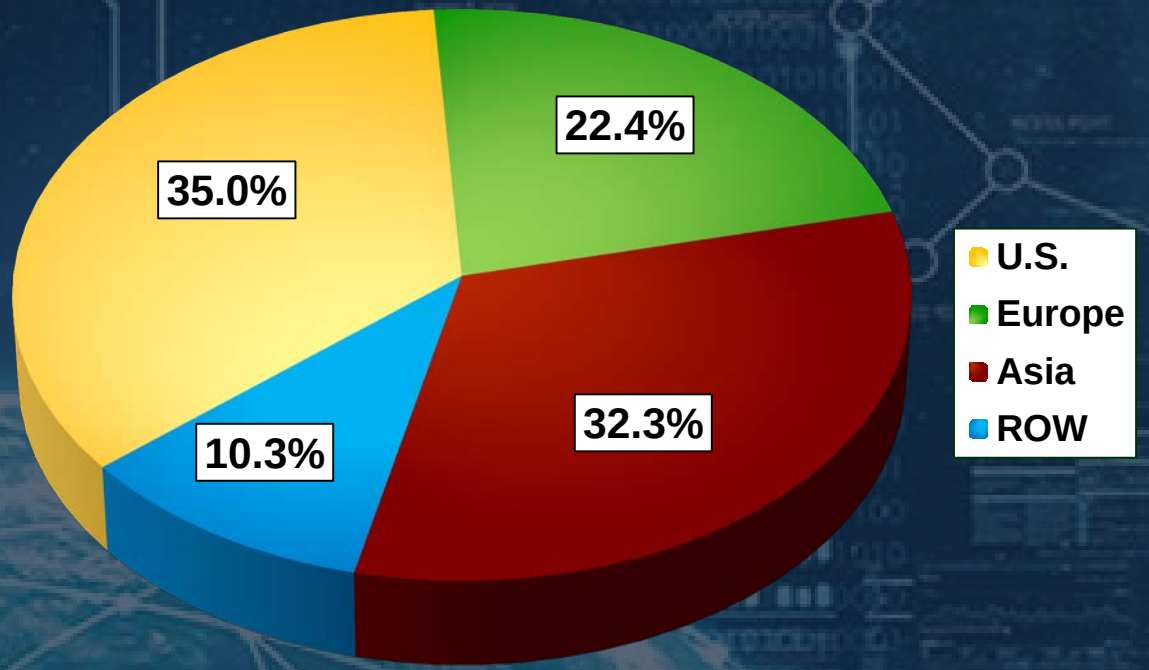
in PPP

Total ~ $US 2 trillion



in MEX

Total ~$US 1.5 trillion



US GDP ~$18.6 tr
Federal Budget ~$4.2 tr

sources: IRI & R&D Magazine 2017 Global R&D Funding Forecast & *The Economist's* World in 2017

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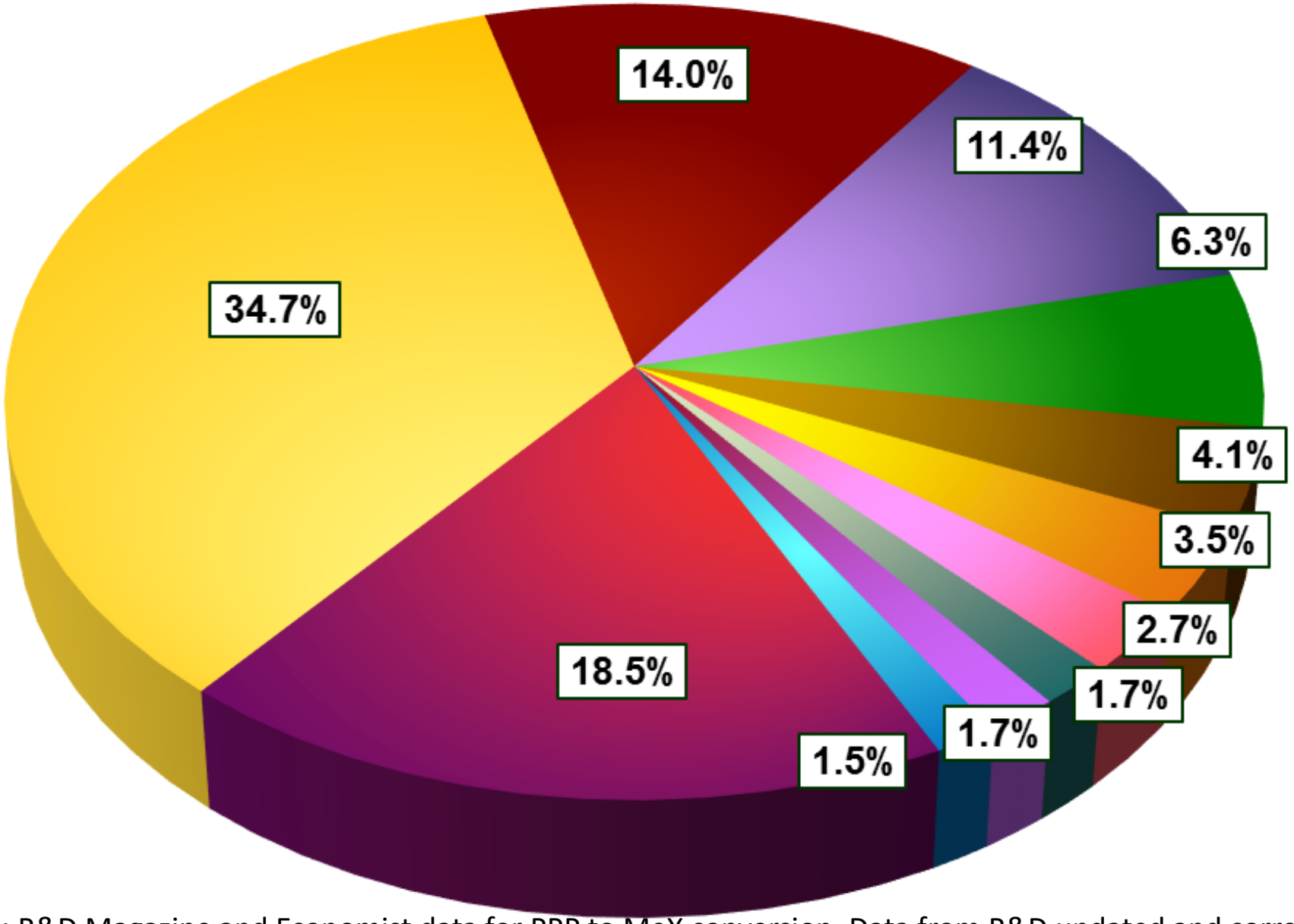
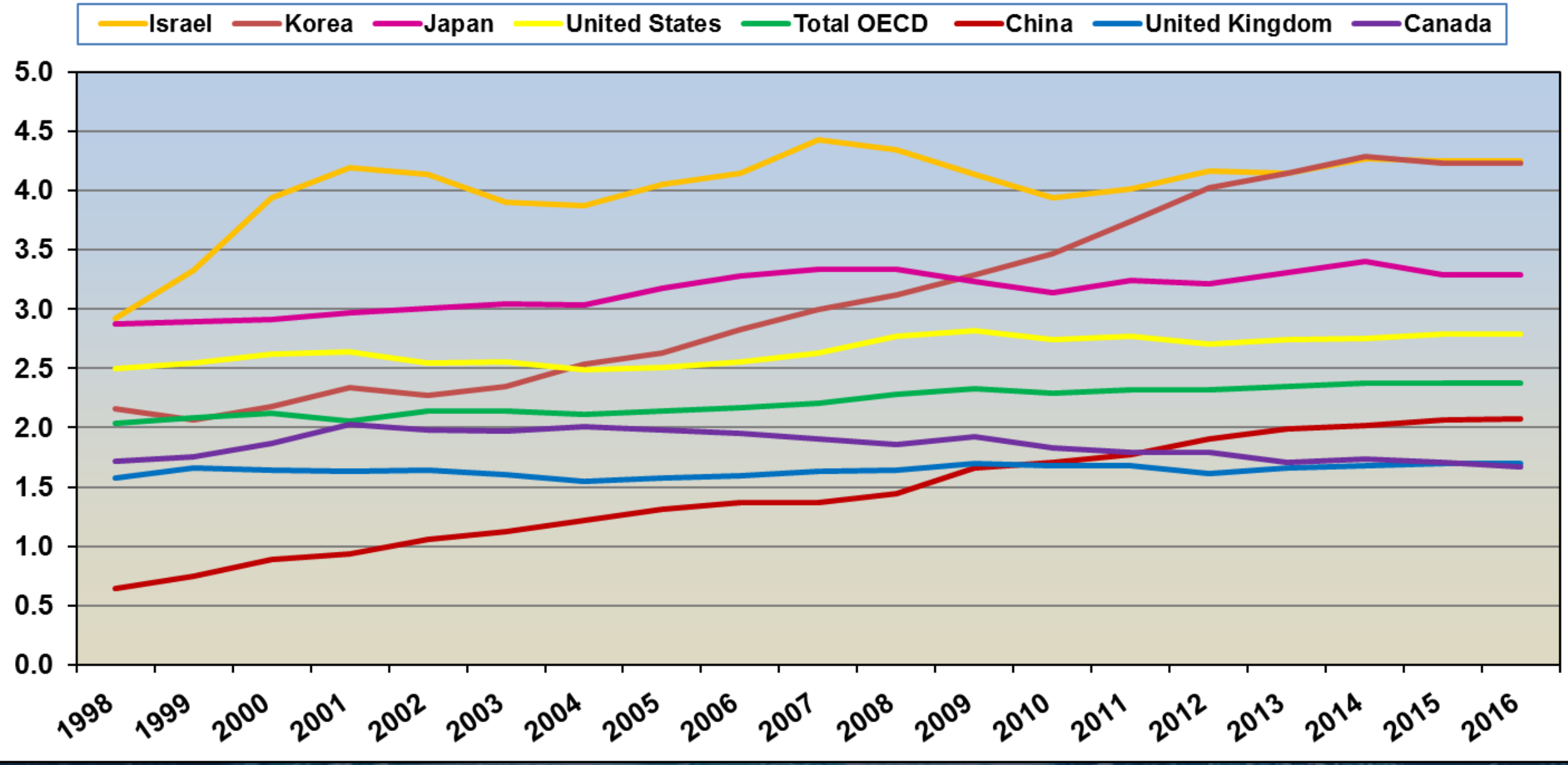
2017 R&D in MEX = $1.493 trillion



Source: R&D Magazine and Economist data for PPP to MeX conversion. Data from R&D updated and corrected by SPIE

GERD as a Percentage of GDP

(GERD = Gross Domestic Expenditure on Reseach & Development)



source: OECD Main Science and Technology Indicators database

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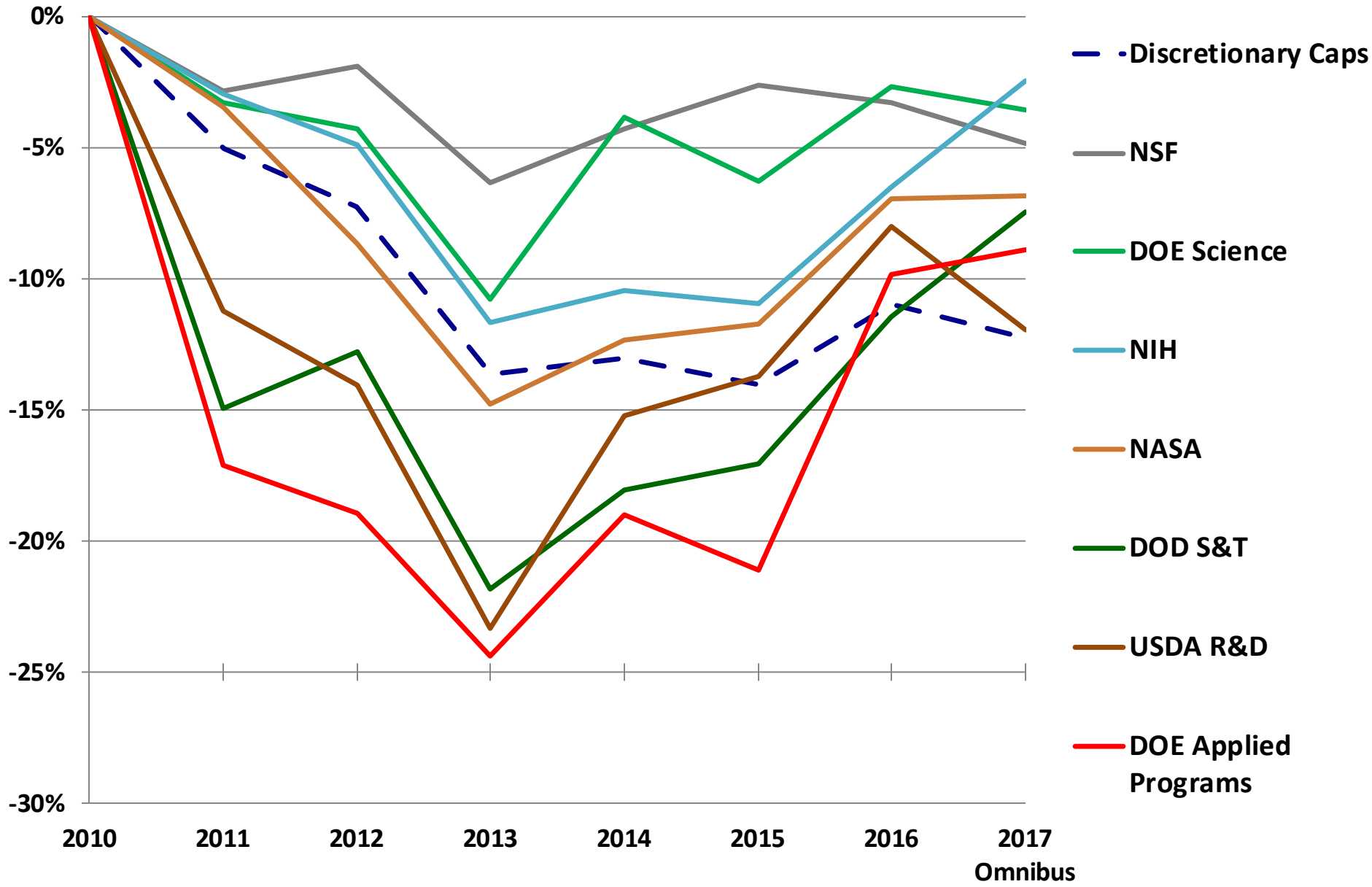
Federal S&T Spending Since FY 2010

Percent change from FY10 levels, constant dollars



Based on AAAS analyses of historical OMB , agency, and appropriations data. © 2017 AAAS

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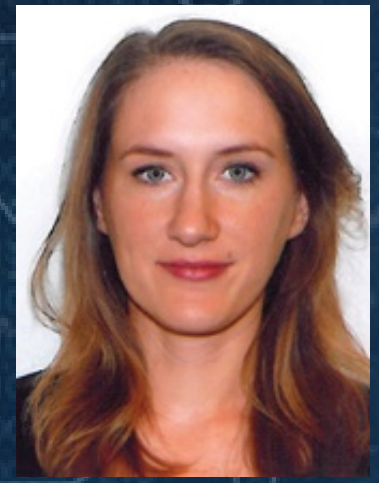
SPIE Policy Activities

- SPIE &OSA fund the NPI, paying the Podesta Group to act on behalf of the community
- NPI current priorities include the "Cancer Moonshot" (imaging aspects), a U.S. Quantum initiative, NIST support, federal funding, and the upcoming NAS report on high power lasers.
- Separately SPIE's Director Government Affairs, Jennifer Douris O'Bryan is working on ITAR issues, workforce visas, protecting the SBIR program, the R&D tax credit, and the university overhead allocation
- Industry's voice is crucial for policy impact



Jennifer Douris O'Bryan
SPIE Director
Government Affairs

jennifero@spie.org

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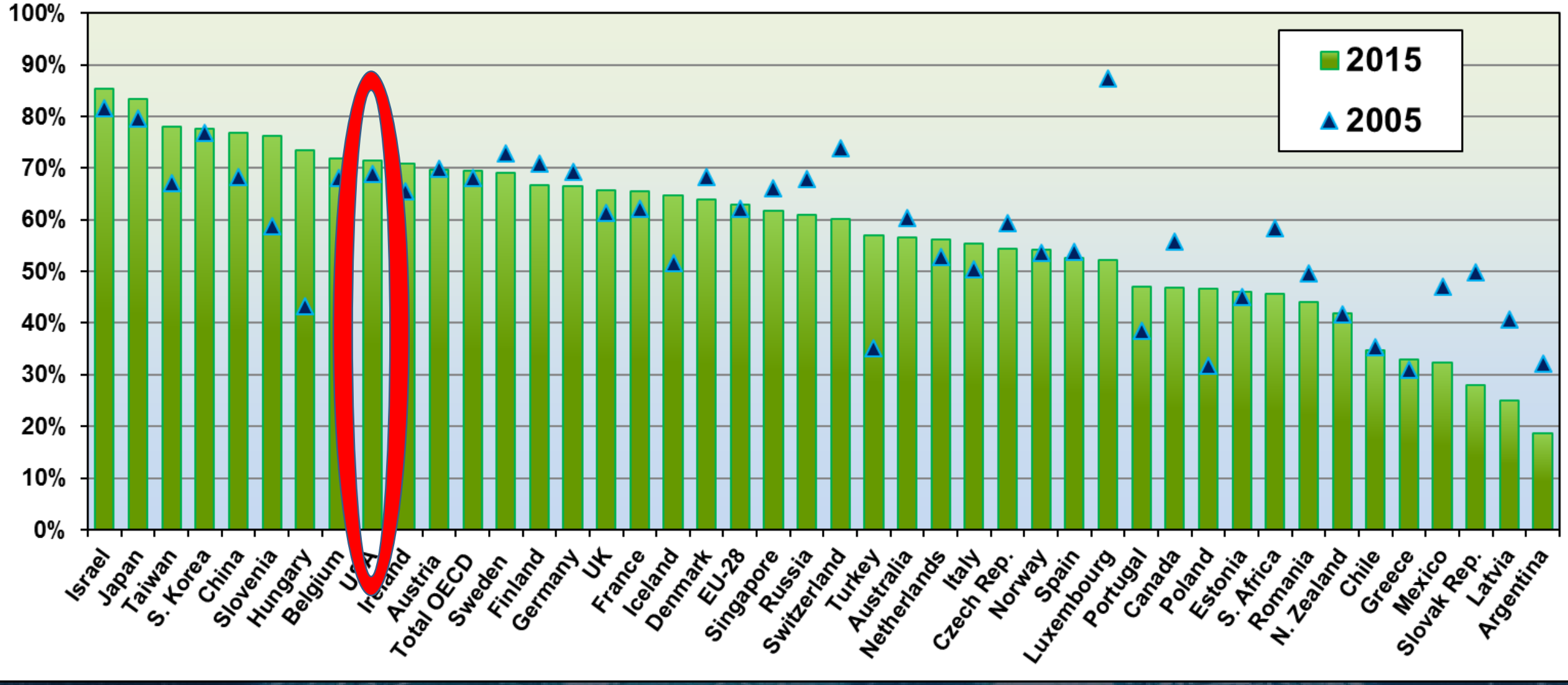
R&D Funded by Industry

2015 and 2005 or nearest available years



source: OECD Main Science and Technology Indicators database

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Global R&D

- Global R&D spending is creeping up, mainly due to intense transglobal corporate competition There are two ways of counting the spending; purchasing power parity (PPP), and market exchange (MEx) – the chart is MEx
- Global R&D spending in 2017 will be more than $2tr PPP, ~$1.5tr (MEx)
- R&D personnel costs are ~30% of total spending

Exhibit B: **The Top 20 R&D Spenders**

Although some rankings shifted, the 2016 list of the 20 biggest R&D spenders features many of the same names as the previous year's list (and in nine cases, as lists from the last decade). However, there were two notable entrants to the top 20: Bristol-Myers Squibb and Oracle.

Companies in RED have been among the top 20 R&D spenders every year since 2005.

RANK			R&D Spending				
2016	2015	Company	2016 US$ Billions	Change from 2015	% of Revenue	Headquarters	Industry
1	1	Volkswagen	$13.2	2.7%	5.6%	Europe	Auto
2	2	Samsung	$12.7	-3.0%	7.2%	South Korea	Computing and Electronics
3	7	Amazon	$12.5	35.2%	11.7%	North America	Software and Internet
4	6	Alphabet	$12.3	24.9%	16.4%	North America	Software and Internet
5	3	Intel	$12.1	5.1%	21.9%	North America	Computing and Electronics
6	4	Microsoft	$12.0	5.8%	12.9%	North America	Software and Internet
7	5	Roche Holding	$10.0	-3.2%	19.9%	Europe	Healthcare
8	9	Novartis	$9.5	-1.6%	19.2%	Europe	Healthcare
9	10	Johnson & Johnson	$9.0	6.5%	12.9%	North America	Healthcare
10	8	Toyota	$8.8	5.1%	3.7%	Japan	Auto
11	18	Apple	$8.1	33.5%	3.5%	North America	Computing and Electronics
12	11	Pfizer	$7.7	-8.4%	15.7%	North America	Healthcare
13	13	General Motors	$7.5	1.4%	4.9%	North America	Auto
14	14	Merck	$6.7	-6.6%	17.0%	North America	Healthcare
15	15	Ford	$6.7	0.0%	4.5%	North America	Auto
16	12	Daimler	$6.6	4.5%	4.0%	Europe	Auto
17	17	Cisco	$6.2	-1.4%	12.6%	North America	Computing and Electronics
18	20	AstraZeneca	$6.0	7.5%	24.3%	Europe	Healthcare
19	32	Bristol-Myers Squibb	$5.9	30.6%	35.7%	North America	Healthcare
20	22	Oracle	$5.8	4.8%	15.6%	North America	Software and Internet
		TOP 20 TOTAL	$179.4	6.3%	8.7%		

Source: Bloomberg data, Capital IQ data, Strategy& analysis

NSF's annual budget is ~$7bn

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"Lower Bound" of Worldwide Photonics Market

"Factory Gate" prices (internal estimate)

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Why do we forecast growth for Photonics?

- The technology is advancing at a rate and in ways that will continue to outpace the effects of price erosion in consumer devices, solar etc.

  - bigger, higher resolution, higher performance displays including laser displays

  - VR & especially AR, moving into consumer markets, and will have application in industry, transportation and medicine

  - higher penetration of cost effective photonics based medical devices

  -large increases in solar deployment across the world with diminishing panel cost reduction and & expected more economic storage development

  - increasing use of optics and hyperspectral imaging in defense and security

  -laser based countermeasures are here; laser weapons are now near term

  - higher value add in smart and human centric lighting as LED lighting penetrates

  - declining cost per watt from LEDs, fiber and “diode lasers” make applications such as sterilization, water purification, photonics in precision farming, horticulture, etc. viable

  Increasing adoption of lasers, optical metrology, machine vision for Industry 4.0, in transportation, especially automobiles etc.

  - In data processing, and transmission, the photon will increasingly solve the problems of electronics which is facing immutable limits of fundamental physics

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Worldwide Semiconductor Revenue

Consumer Electronics Market ~US$1.97 tr in 2017

Source: gartner.com; as of July 11, 2017

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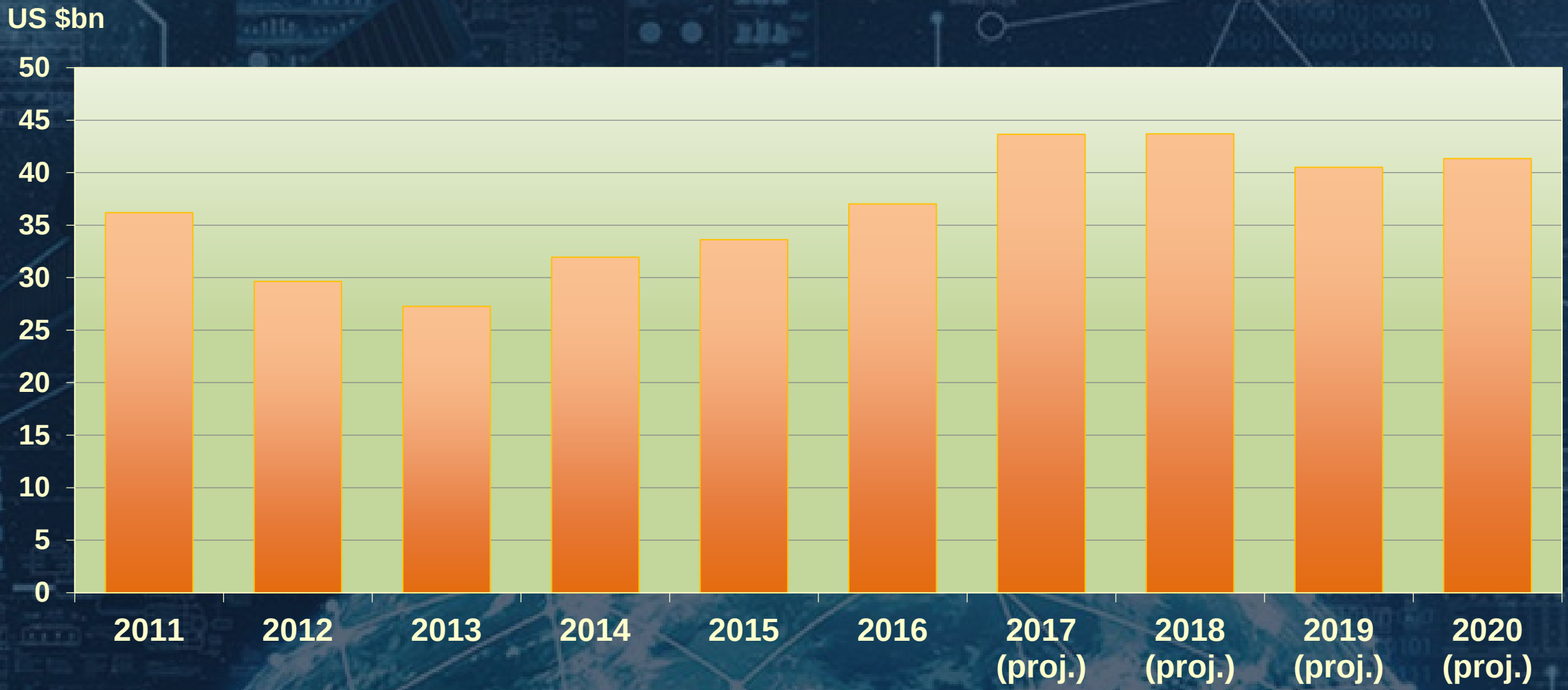
Worldwide Wafer Fab Equipment Spending



Source: gartner.com; as of August 2, 2017

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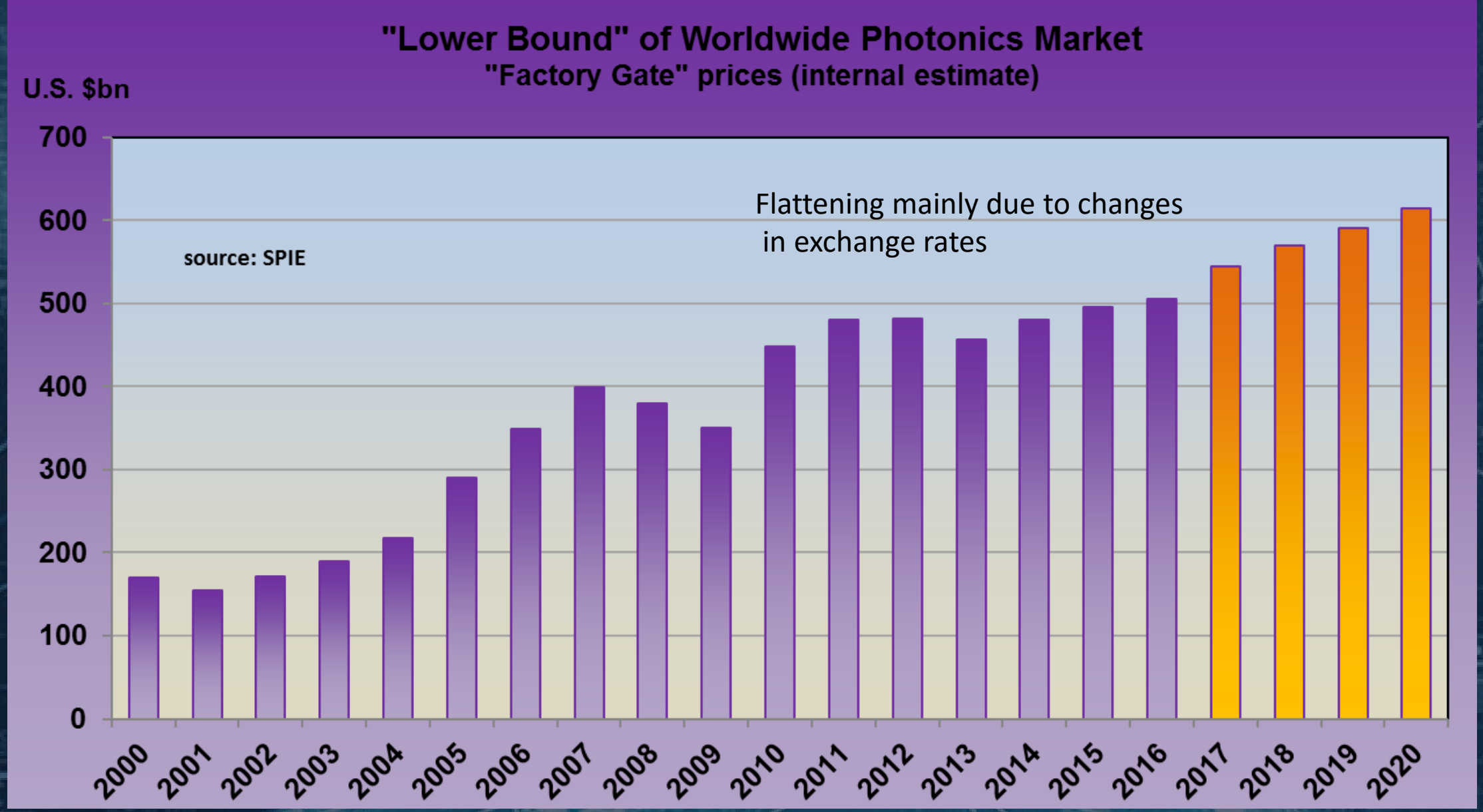

- Data from PIDA, SPIE, OECD. Projections based on 2017 economic forecasts by WB, OECD, IMF. (excludes US administration forecasts) Judgment of photonics growth forecasts relative to global growth, SPIE, Photonics21. (Includes price/volume considerations) Changes in exchange rates not included in projection

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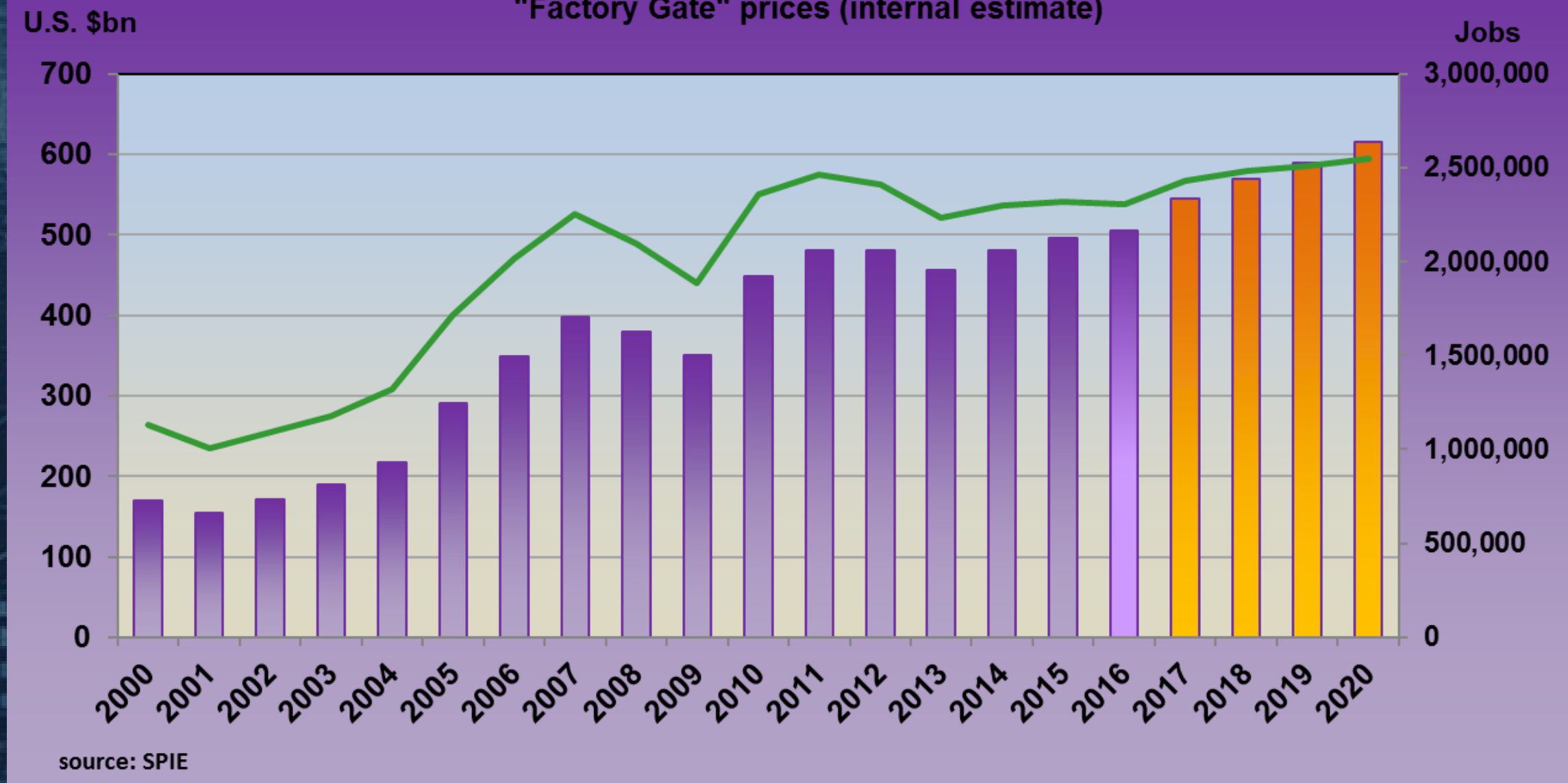
"Lower Bound" of Worldwide Photonics Market

"Factory Gate" prices (internal estimate)



source: SPIE

Job projections based on our industry data $210k revenue per job.
Benchmarks: U.S. 12.4 million manufacturing jobs, Canada 1,7 million in 2016
It is not yet clear how robotics will impact the employment or revenue per employee

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Revenue per Employee

- Revenue per employee average for “Photonics Companies” is ca. $210k, down somewhat from $225k

  For established companies this ranges from ca. $100k to beyond $1 m (Apple, Facebook Google

  Added value would be a better measure but is much more difficult to determine

  Some companies that fabricate optics from relatively low cost material are successful at lower revenues per employee
- If you are building a company then keeping a revenue per employee figure in mind can be very helpful
- SPIE itself has ~$220k per FTE employee

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SPIE's Market Estimate

- SPIE has extensive data for the overall market at factory gate pricing and separate data for photonics components
- Our product market data misses two important employment sectors for photonics
  - Retail sales, marketing, management, installation, maintenance. Think of the solar and telecommunications segments
  - "Knowledge generation" – optics and photonics in academia, and the many facilities that are funded for light related science, e.g. all the astronomical telescopes, the synchrotrons and large laser facilities. We estimate up to $60 bn spending a year worldwide on this segment

The global market "enabled by photonics" is at least US$10 tr. The EU estimated that "*20-30% of its economy (*the world's largest*) and 10% of the workforce depend on photonics*"

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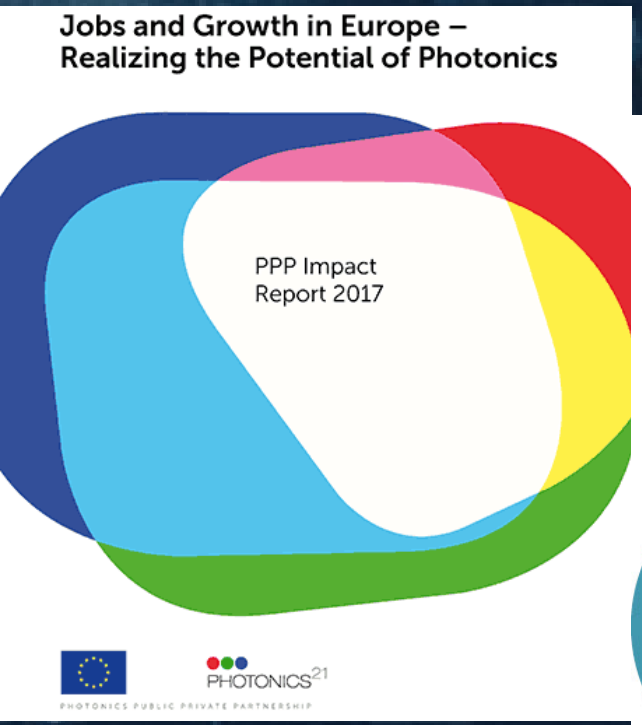
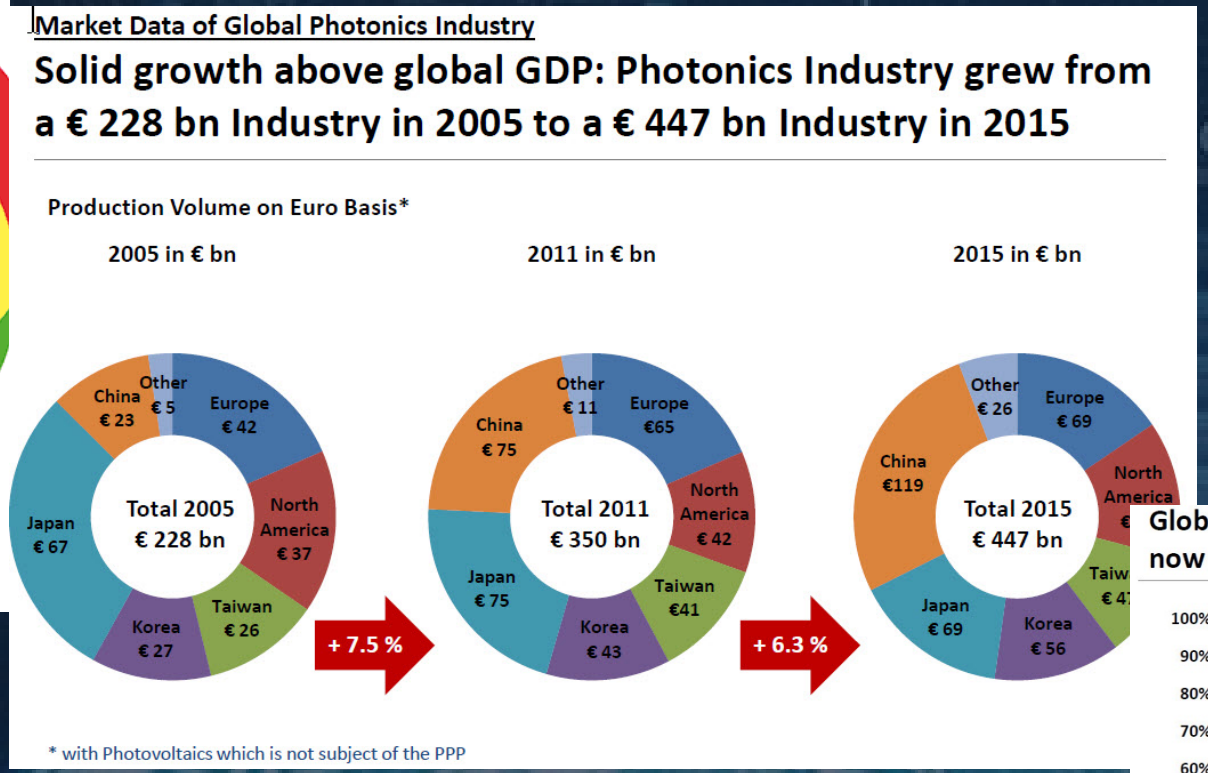
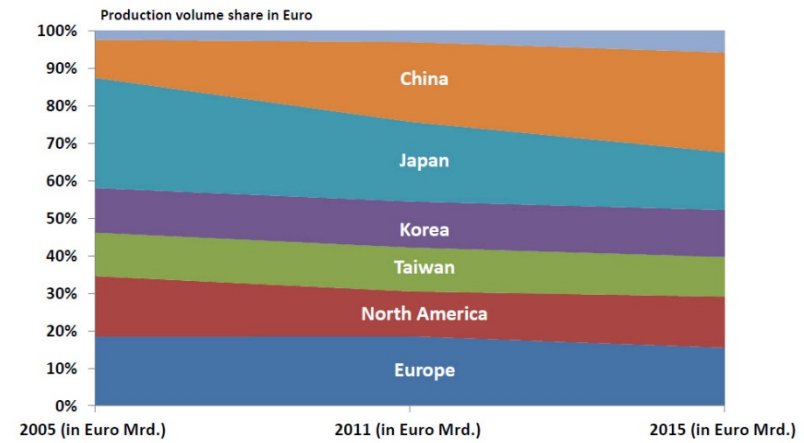
The EU's 2017 Photonics21 Impact Report





In 2015 there were over 300,000 jobs in photonics in the EU
Growth is projected at ~5.5% per year

Global Share Shift: China became the # 1 producer – Europe now on # 2 Position – former Champion Japan dropped to #3



* with Photovoltaics which is not subject of the PPP

Source: Optech Consulting Market Research Study 24.1.2017 and Branchenreport Photonik 2013

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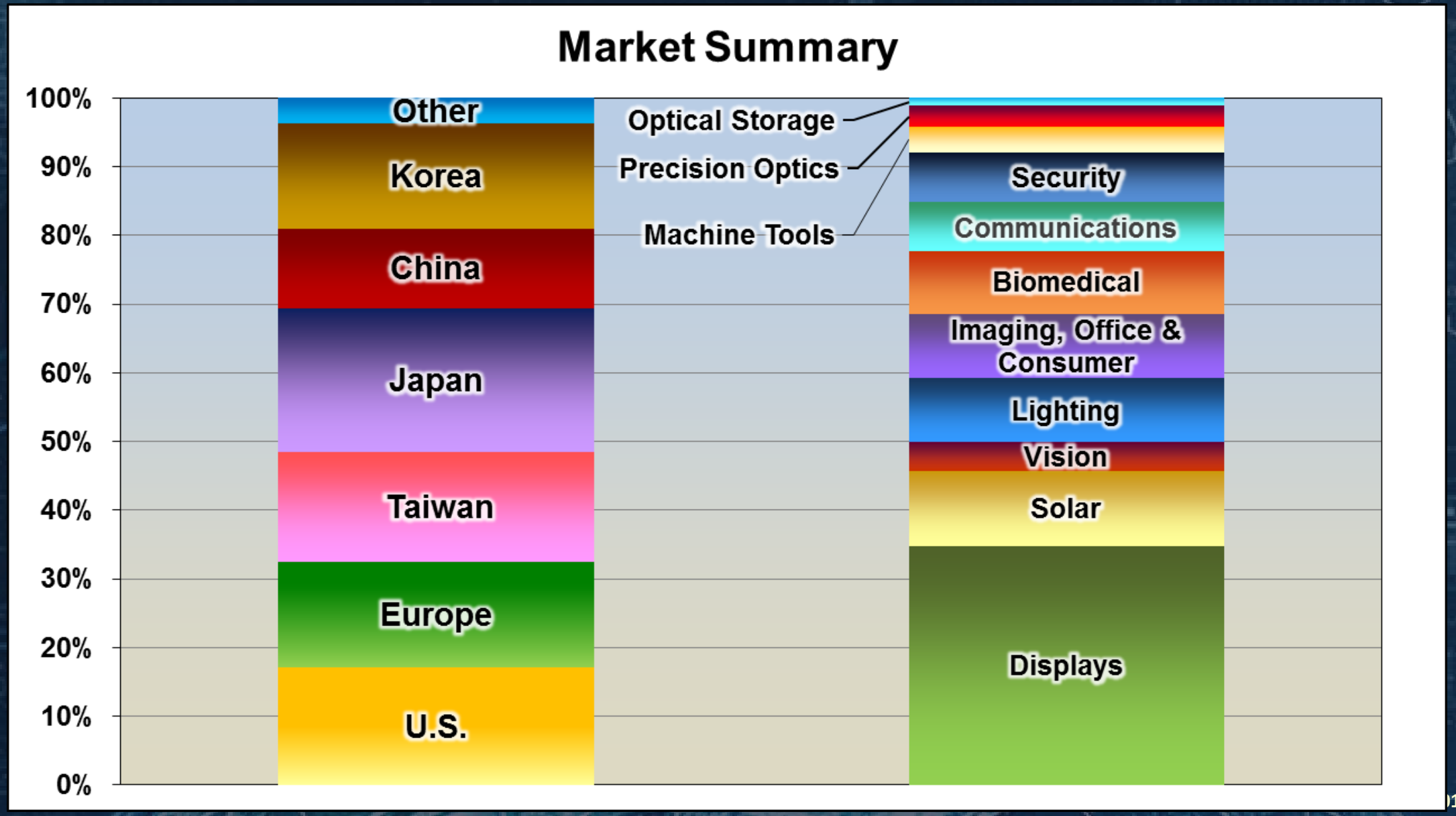
Market: Countries and Sectors; By Company HQ



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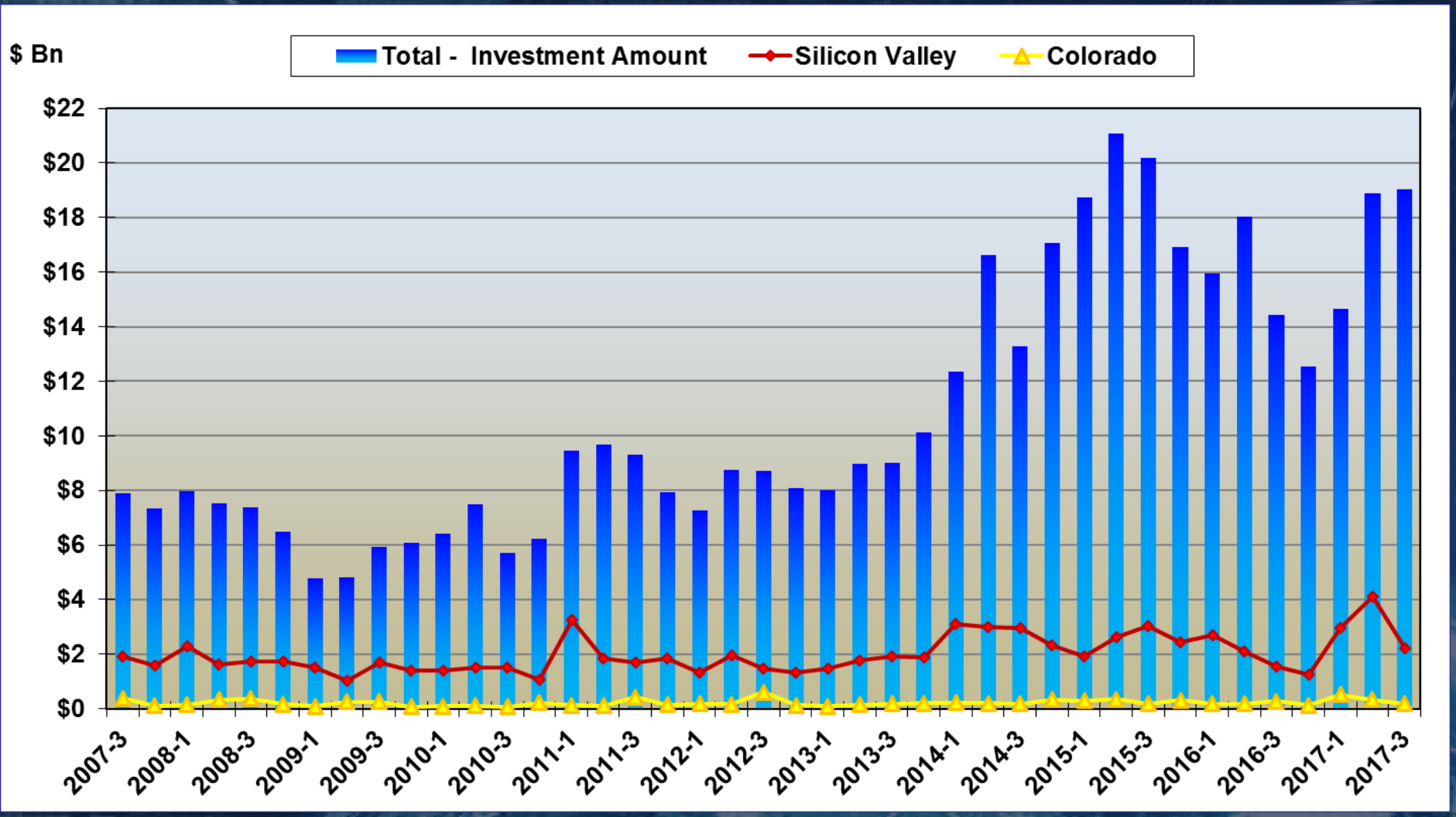
U.S. Quarterly VC Investment



US VC investment has moved away from small seed investment to later rounds, and prefers software products for consumer markets It is now fairly rare that VC money will go to a product idea without a prototype

SPIE. Colorado attracted $1.16 bn (1.78%) in the last 4 quarters

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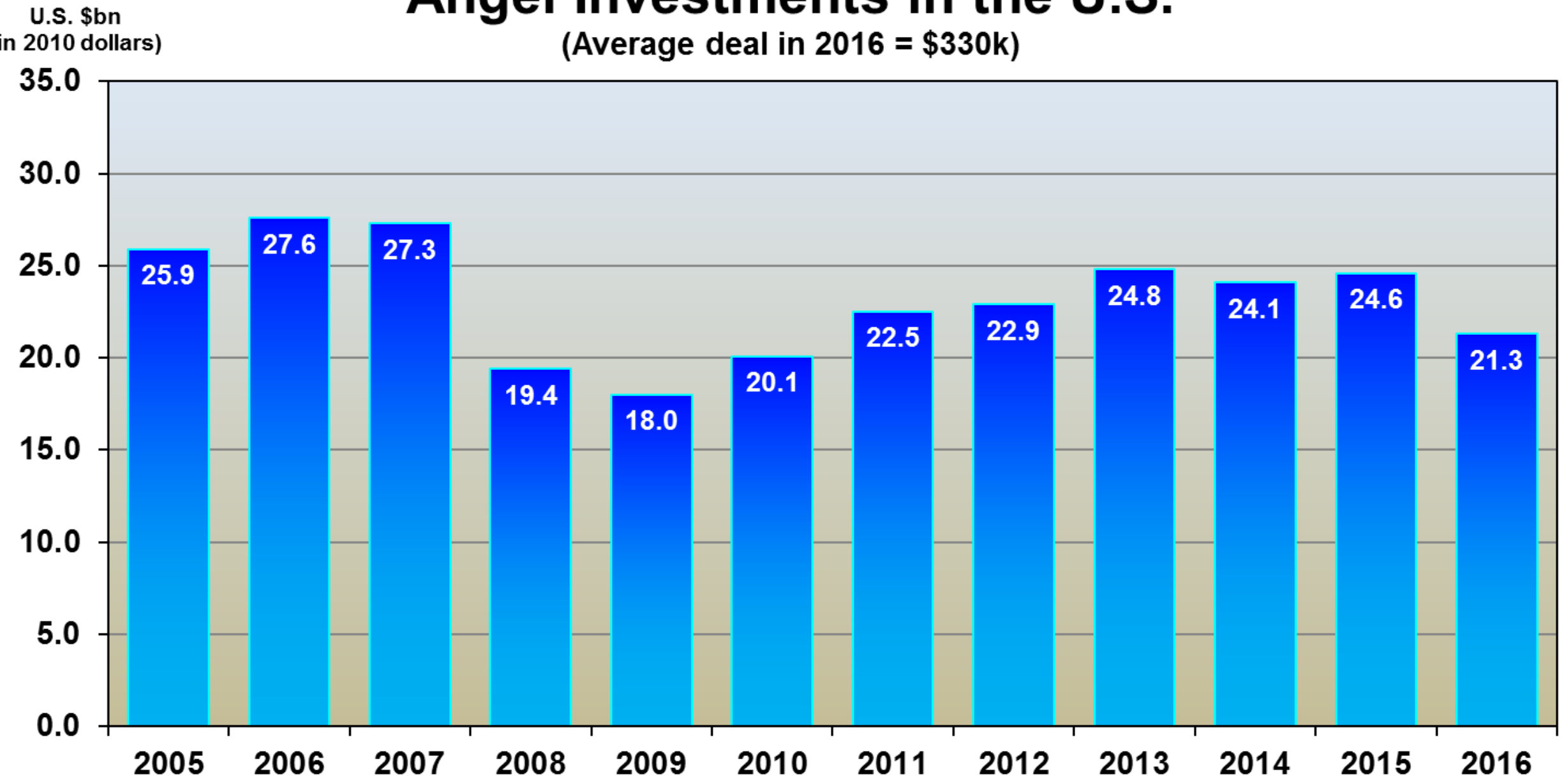
Angel Investments in the U.S.

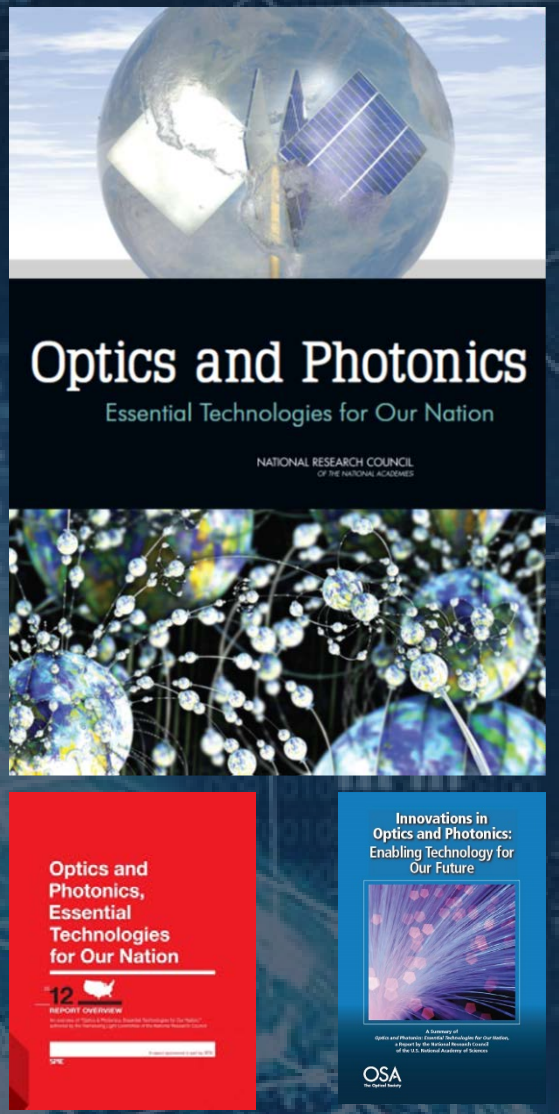
(Average deal in 2016 = $330k)



source: Center for Venture Research, University of New Hampshire

2012 U.S. National Academy Report Recommended a National Initiative

- This report was instigated largely by SPIE
- SPIE & OSA partially funded this National Academy update to the 1998 Harnessing Light report. NSF was the major funder
- The NA Committee included two economists
- It was published in 2012 with the title "*Optics and Photonics; Essential Technologies for our Nation*"



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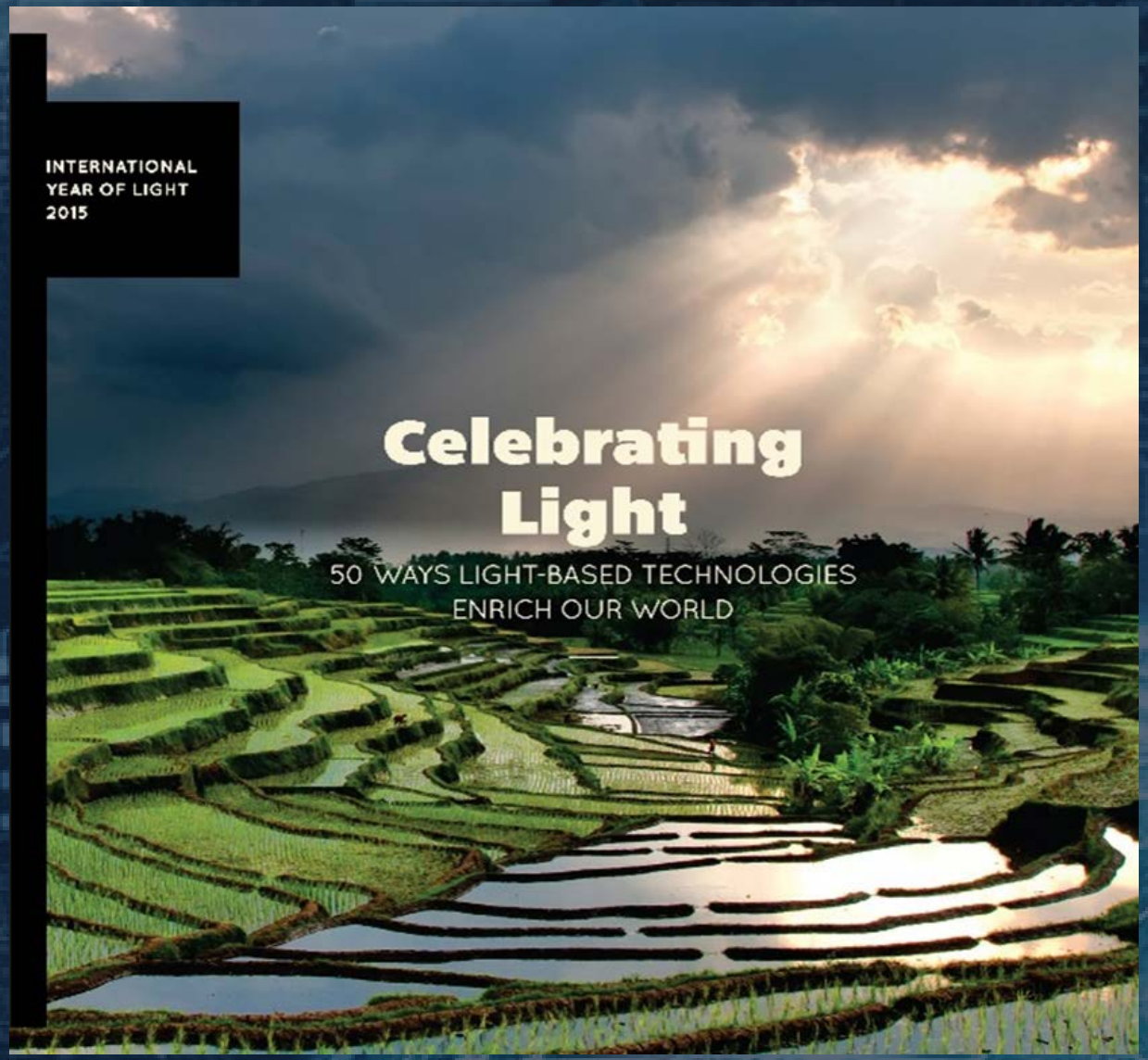
The Breadth of Optics & Photonics



The International Year of Light and Light-based Technologies (2015) helped people who work with light in some way, perhaps all their life in one area, realize the breadth of the field and that there are many opportunities

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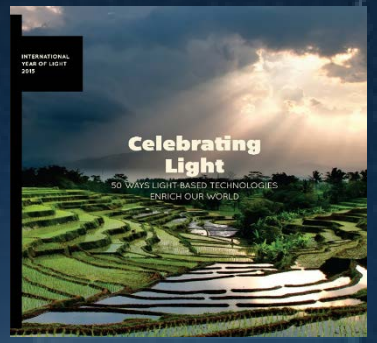
50 selected areas

3D Movies and Displays
3D Printing
Agriculture
Aircraft Safety
Airport Screening
Art Studies
Cancer Diagnosis and Therapy
Car Safety
Climatology
Computer Chip Manufacturing
Data Storage
Dentistry
Disease Understanding and Treatment
Displays
Drones
Drug Verification and Safety
Elementary Particle Detection
Food Screening for Safety
Forensics
Global Positioning
Holography
Infrared Imaging
The Internet
Laser Fusion
Lasers
Lasers in Medicine
Lighting
Manufacturing
Mapping Our Planet
Mapping Our Universe
Medical Imaging and Radiology
Microwave Technologies
Neurophotonics
Oceanography
Ophthalmology



Optical Tweezers
Photography
Photonic Integrated Circuits
Photosynthesis
Pollution Monitoring and Management
Quantum Encryption
Radio Communication
Scanners and Barcodes
Search for Extraterrestrial Life
Solar Cells
Structural Health Monitoring
Ultraviolet Technologies
Virtual and Augmented Reality
Wearable Technology
Weather Prediction

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Hot Pockets

- Quantum – communications, computer, quantum sensors
- Autonomous vehicles – vision systems, LIDAR
- 3D printing
- Industry 4.0. Laser applications in fabrication, in precision machining and metrology growing apace
- Lithography the transition to EUV. IOT driver
- Security. Imaging, optical biometrics, forensics
- Deep learning everywhere
- Energy
- Use of drones for imaging and hyperspectral imaging
- Biomedical explosion e.g. cell counters, genomics, telemedicine, personalized medicine
- High power lasers and the convergence with nuclear physics
- JWST, ELT, LIGO, LISA ELI because of near completion of facilities. Techniques like frequency combs for cosmic spectral analysis
- Exploiting the lower cost of photons from LEDs

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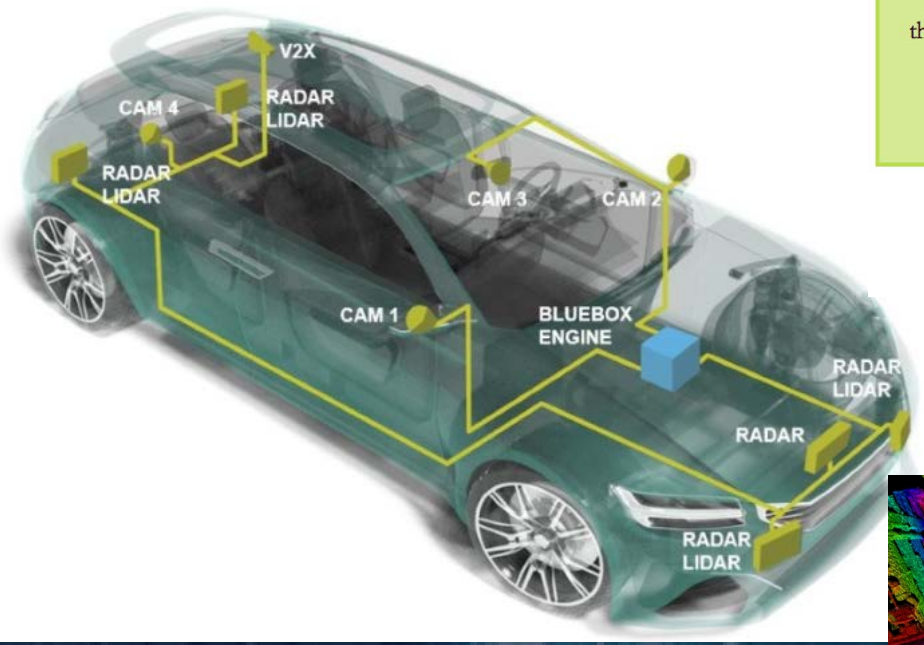
2017 Photonics New Frontiers & Disruptors

- Autonomous vehicles
- AR, VR, MR
- "Deep learning"
- The Brain



Intel paid ~$15bn for Mobileye and GM just bought a LIDAR company

30th Annual

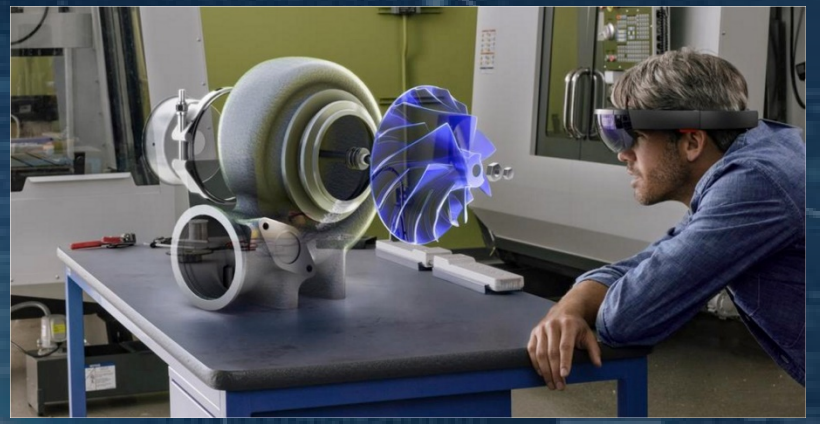
John Cameron Lecture

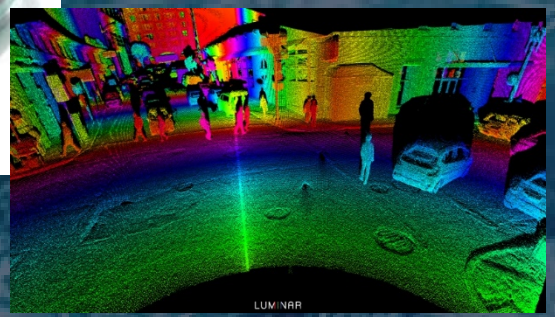
Monday, April 17, 2017 4:00 p.m.

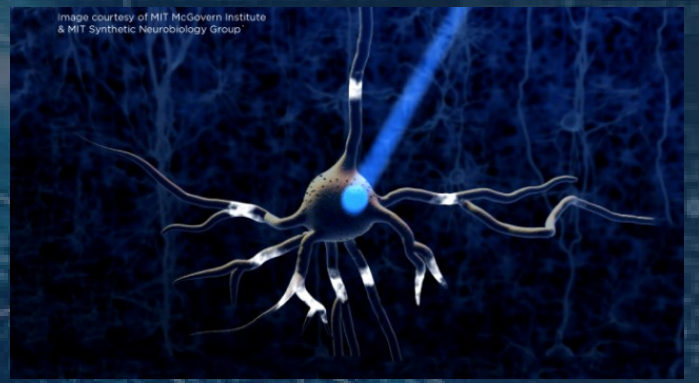
Maryellen Giger, Ph.D.

A.N. Pritzker Professor of Radiology,
the Committee on Medical Physics, and the College at the
University of Chicago;
Vice-Chair for Basic Science Research,
Department of Radiology

Radiomics and Deep Learning in Medical Imaging for Precision Medicine







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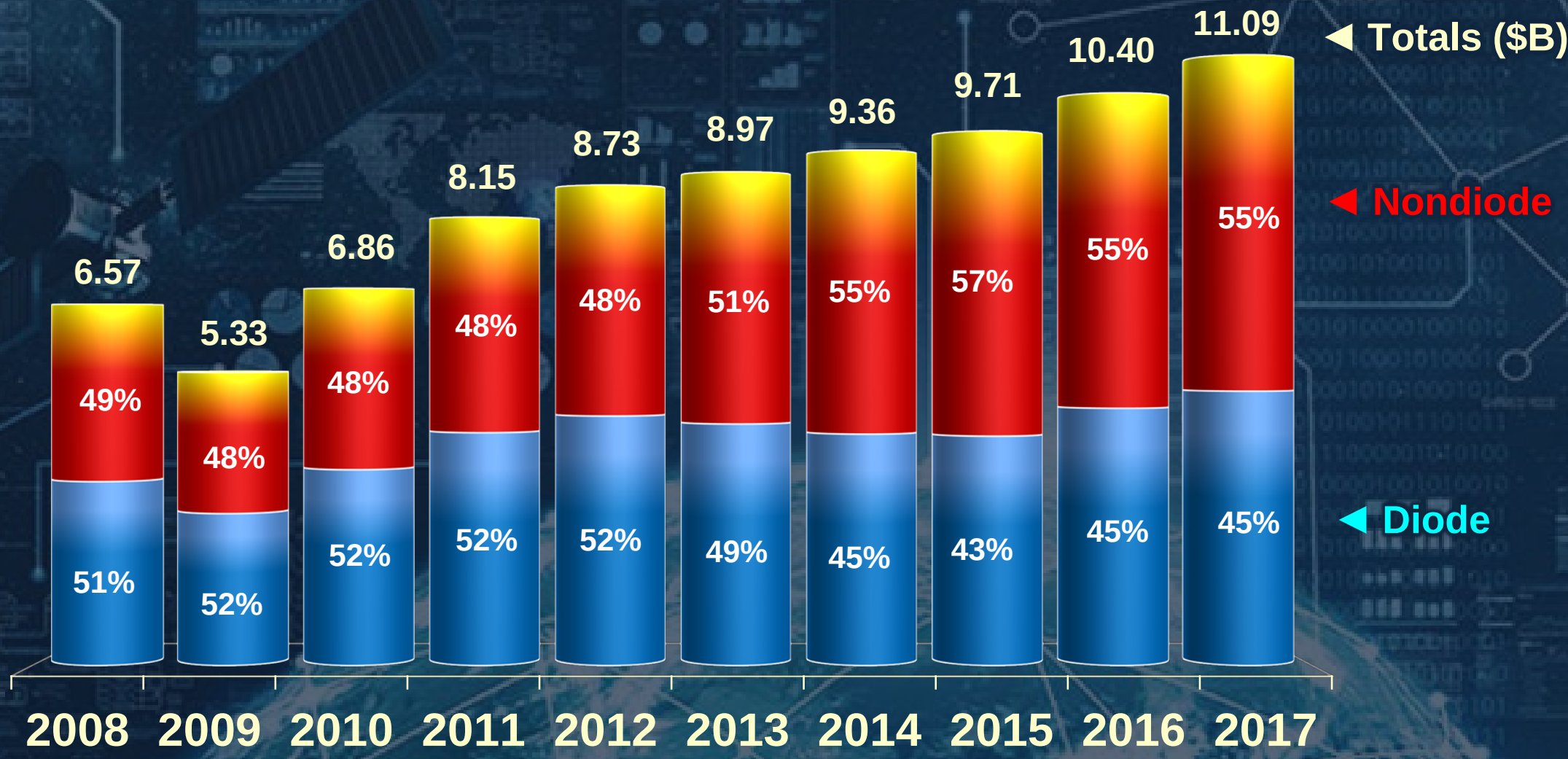
Worldwide Commercial Laser Revenue



source: Laser Focus World / Pennwell; 2017 = forecast

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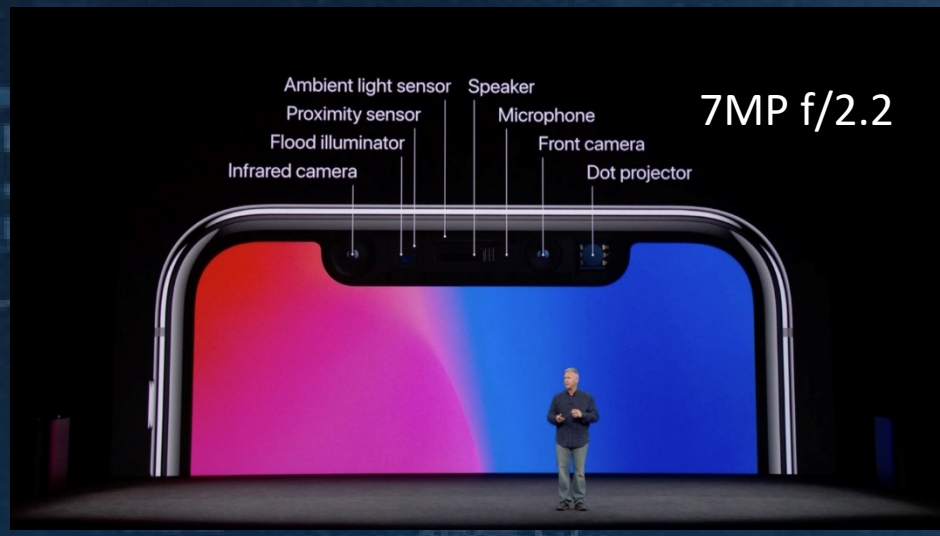
Photonic?

- Smartphones (etc) are not included in the SPIE photonics market data, yet:
  - information flows in and out via the photonics powered internet,
  - information out to the user is via the photonic display
  - purchasers are wooed by the screen, cameras, photo taking and processing capability –when did you least hear about audio quality?



12MP wide-angle, f/1.8, OIS |
12MP telephoto, f/2.4, OIS
Face recognition
Display 5.8-inch OLED
Display 2436×1125 (458ppi)

Galaxy S8 phone
5.8-inch Super AMOLED
2960×1440 (570ppi)
Rear camera12MP, f/1.7, OIS
Front Camera: 8MP, f/f.7

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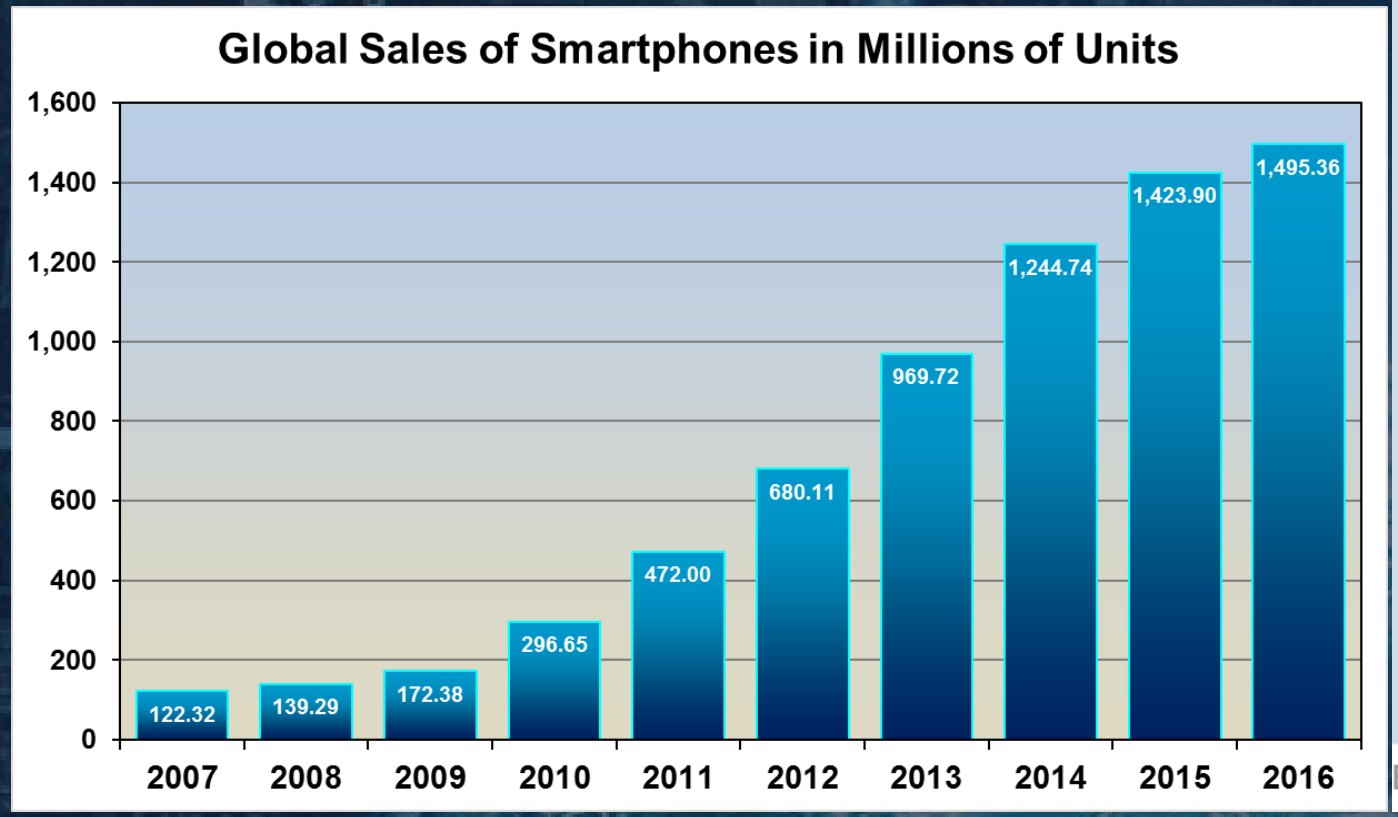
Smartphone?

How Smartphones Hijack Our Minds

Research suggests that as the brain grows dependent on phone technology, the intellect weakens

Wall St Journal October 7thooed

~1.5bn



Economist.com

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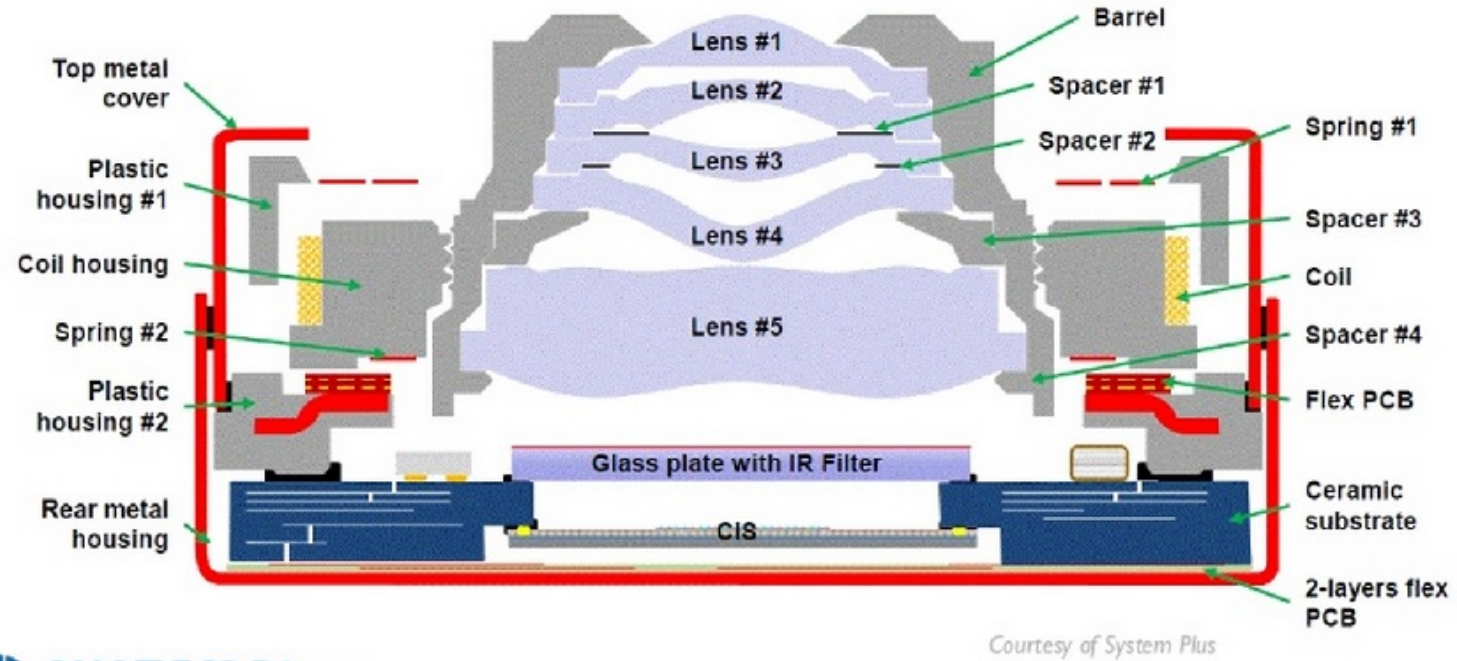
MOBILE TECHNOLOGY TREND

Packaging : CCM have become marvels of micro technology

Apple 6 Plus Rear (Main) camera module



Courtesy of System Plus

SYSTEMPlus CONSULTING

YOLE Développement

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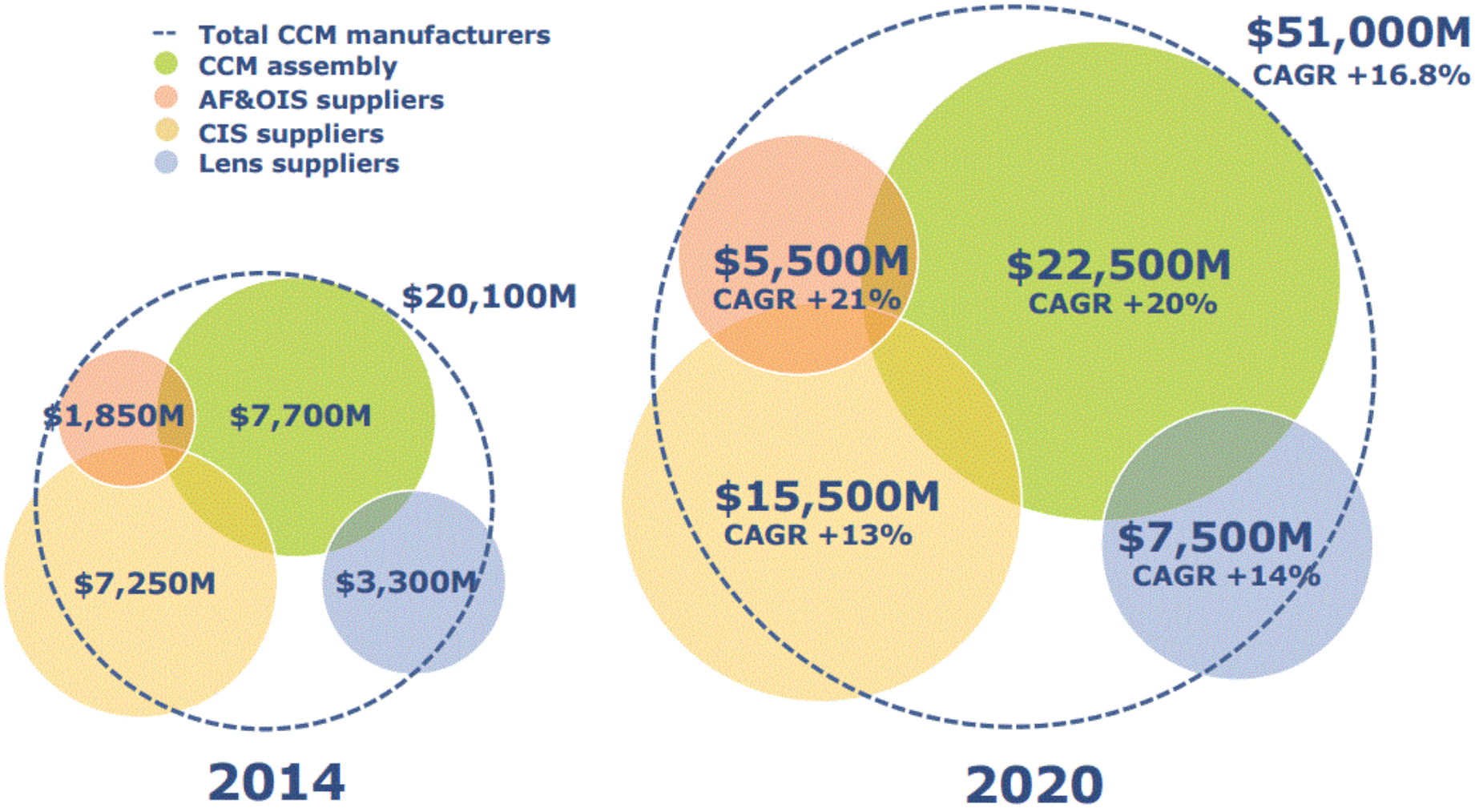
2014-2020 camera module industry



(All lasers: $9,200M in 2014, ≈$13,000M in 2020, LFW)
Courtesy Chris Dainty

(Yole Développement, August 2015)

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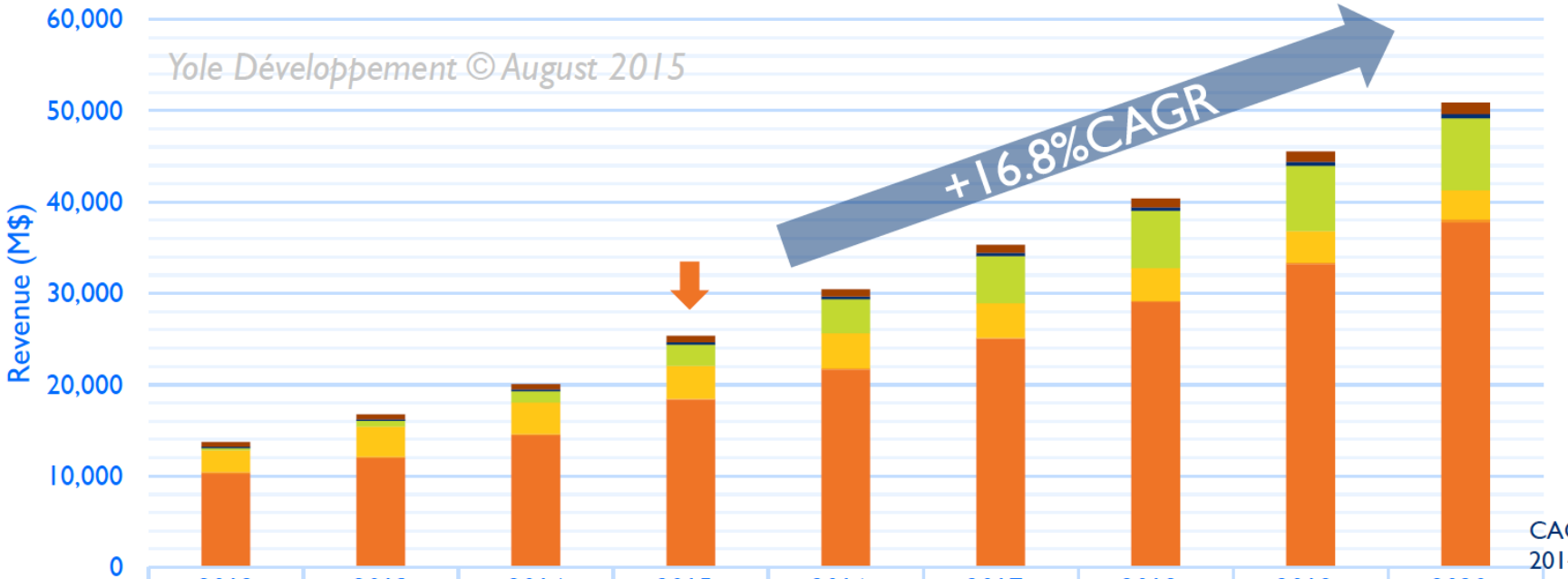
2012–2020 CCM Revenue Forecast (in $M) by Market



	2012	2013	2014	2015e	2016e	2017e	2018e	2019e	2020e	CAGR 2014–2015
Industrial	534	559	604	687	774	876	980	1,113	1,266	13%
Security	128	160	200	243	285	328	367	401	431	14%
Medical	3	4	5	7	8	10	11	12	13	15%
Automotive	280	621	1,228	2,348	3,750	5,196	6,248	7,166	7,887	36%
Computing	2,343	3,310	3,482	3,590	3,873	3,795	3,627	3,442	3,196	-1%
Consumer	213	161	136	100	92	97	129	201	319	15%
Mobile	10,233	11,934	14,436	18,356	21,665	25,025	29,023	33,174	37,778	17%
TOTAL	13,735	16,750	20,091	25,331	30,446	35,328	40,386	45,509	50,889	16.8%
YoY Growth	22%	22%	20%	26%	20%	16%	14%	13%	12%	

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Lasers Key to Smartphone Manufacturing

SOME OF THE LASER APPLICATIONS FOR SMART PHONES

DISPLAY MODULE
LTPS Annealing
Laser lift-off
Glass cutting
ITO touch screen patterning
Polarizer film cutting

DISPLAY LIGHT GUIDE/ BACK PLANE
Patterning of light guide panel
Dicing LEDS
Laser Lithography

CAMERA MODULES
CMOS Sensor lithography
CMOS Sensor Anneal
Sapphire lens and cover cutting
LED Flash cutting

BATTERY
Welding
Laser marking/coding
Structuring

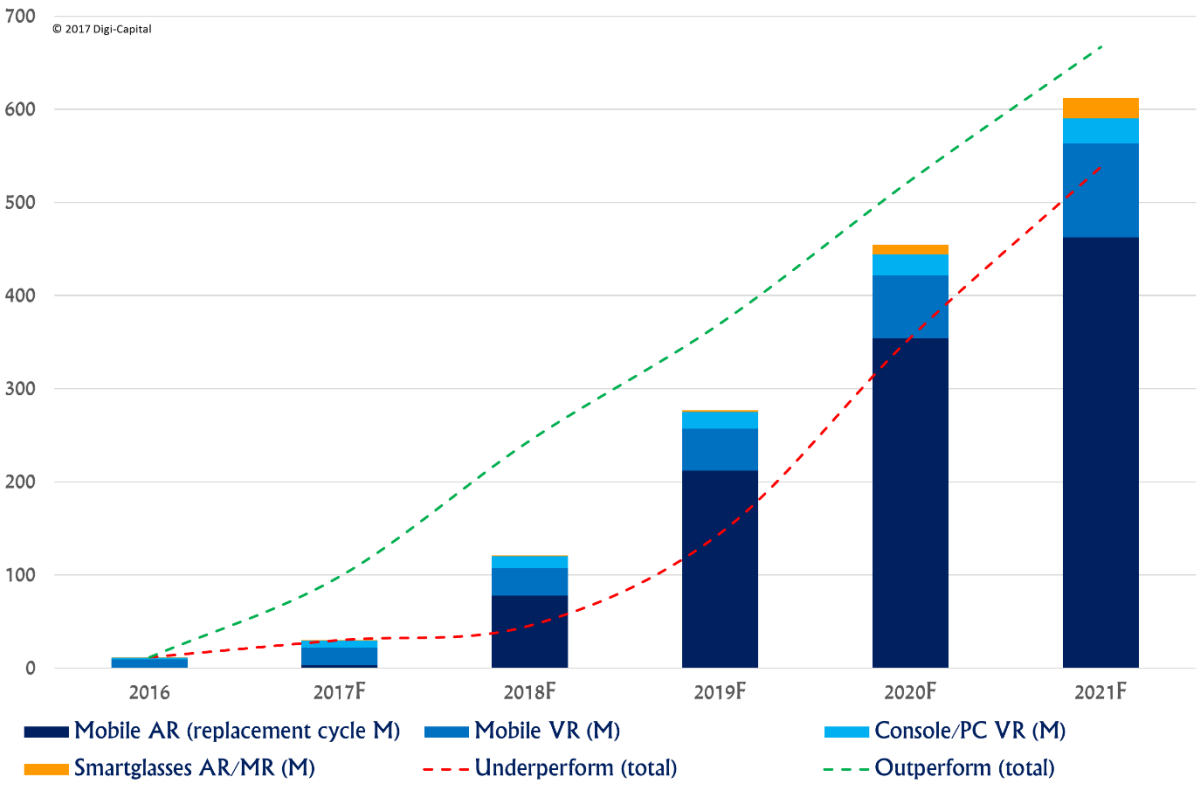
MAIN PCB
Micro via drilling
Laser direct imaging
Laser singularization/depaneling
Marking/coding

IC LOGIC/MEMORY/ MODEM COMPONENTS
DUV Lithography and metrology
Bare and patterned wire inspection
Reticle inspection
Wafer dicing/low k scribe
VIA drilling and patterning
LC Substrates
SP package machining

CASE
Cutting/engraving
Laser marking/coding
3D molded interconnects
Cutting glass

FINGERPRINT SENSORS
Sapphire cutting
Flex circuit cut/drill

AR & VR or MR



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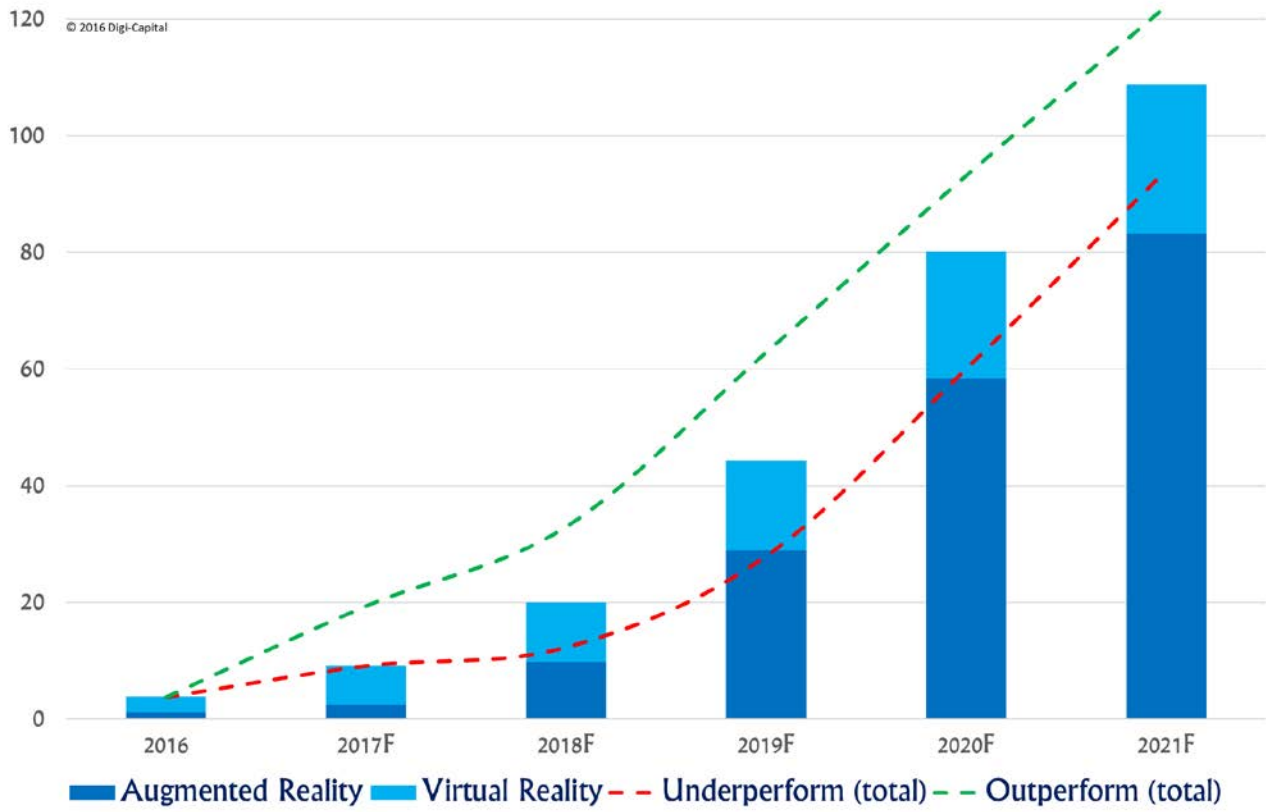

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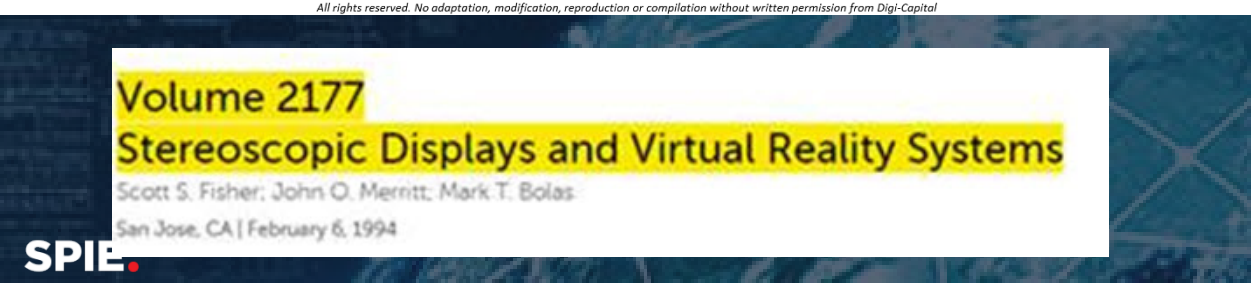
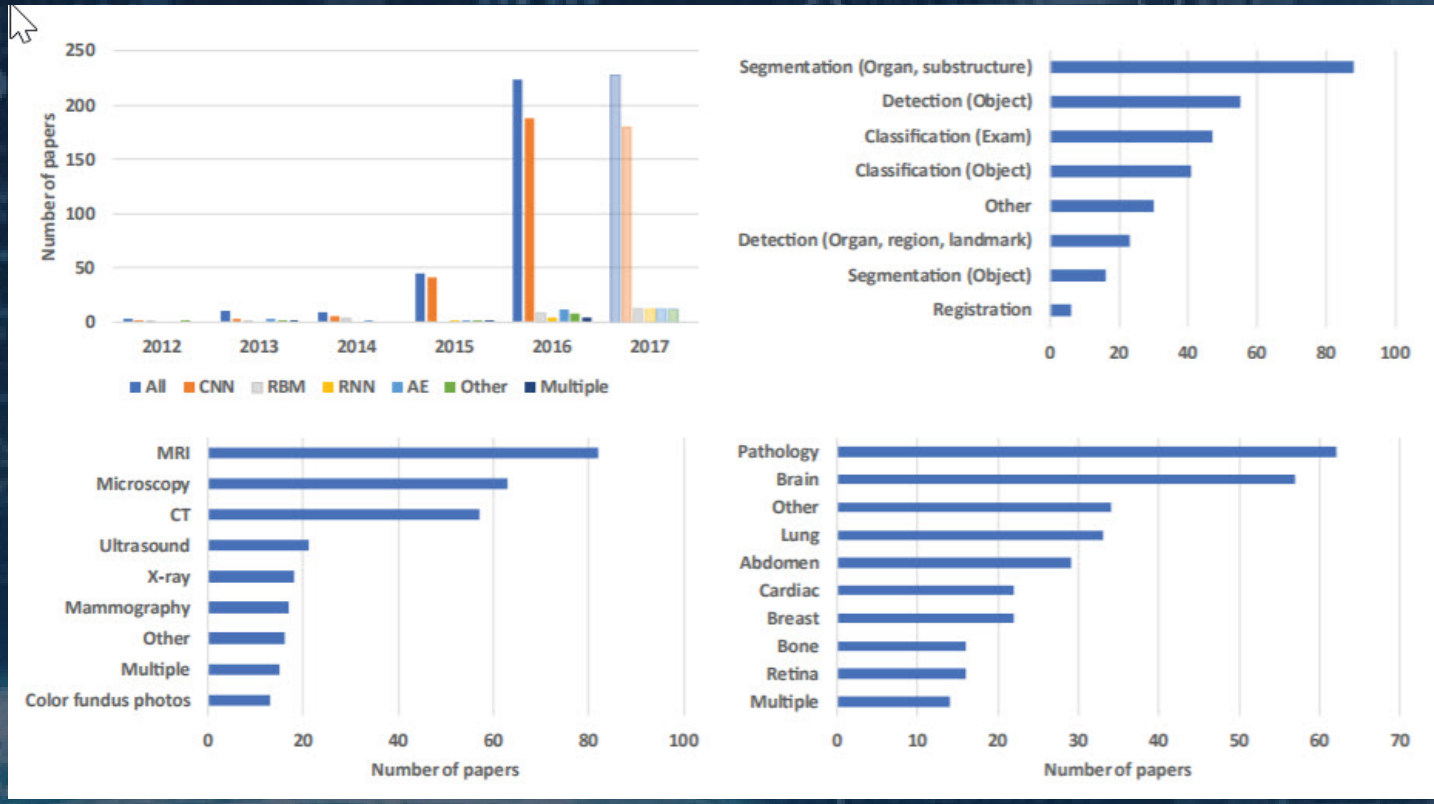


Deep Learning in Medical Imaging

- Deep learning, AI (artificial intelligence), machine learning, neural networks
- "Challenges" becoming more common – competitions for the best image analysis algorithms for specific tasks; e.g. SPIE/NIH Lung X Challenge 2016, SPIE prostate X Challenge 2017,
- CNN - convolutional neural networks
- RNN - recurrent neural networks.



"it is evident that deep learning has pervaded every aspect of medical image analysis. This has happened extremely quickly: the vast majority of contributions, 242 papers, were published in 2016 or the first month of 2017" A Survey on Deep Learning in Medical Image Analysis Litjens et al

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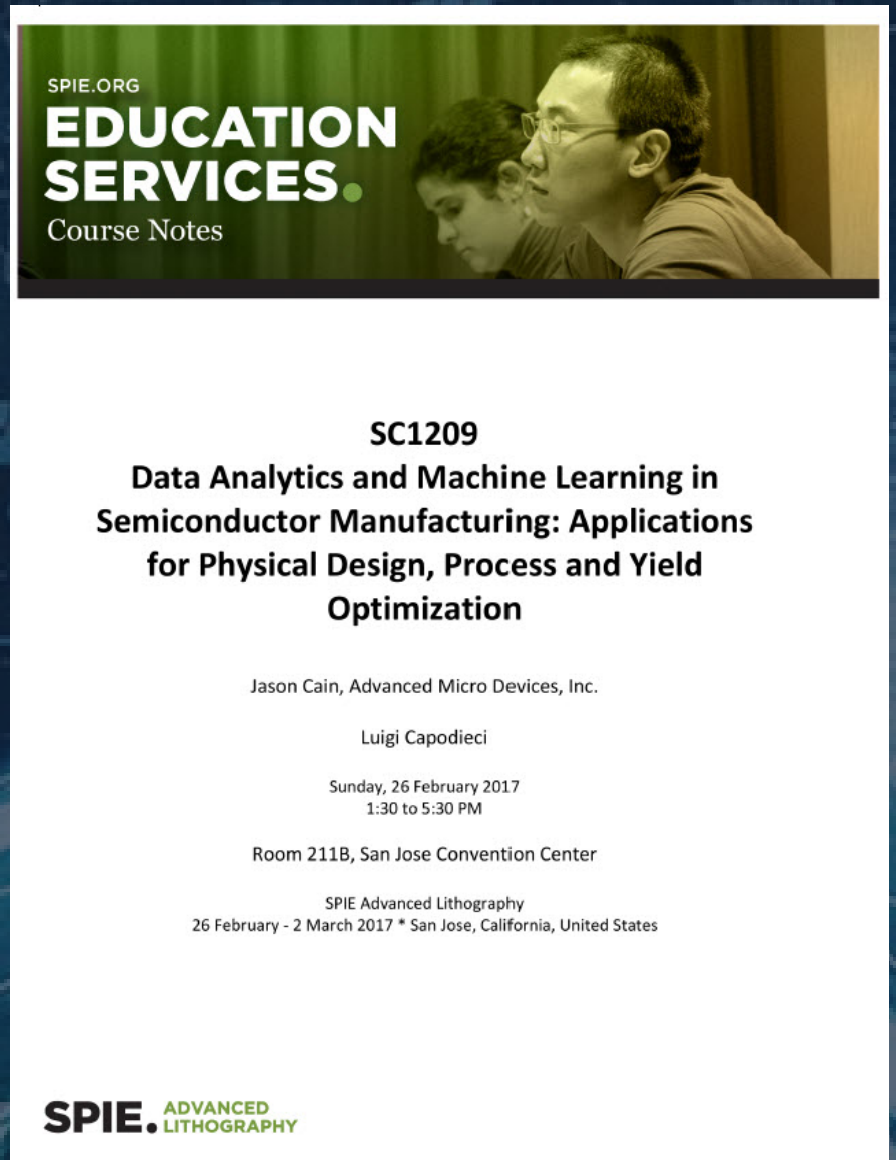
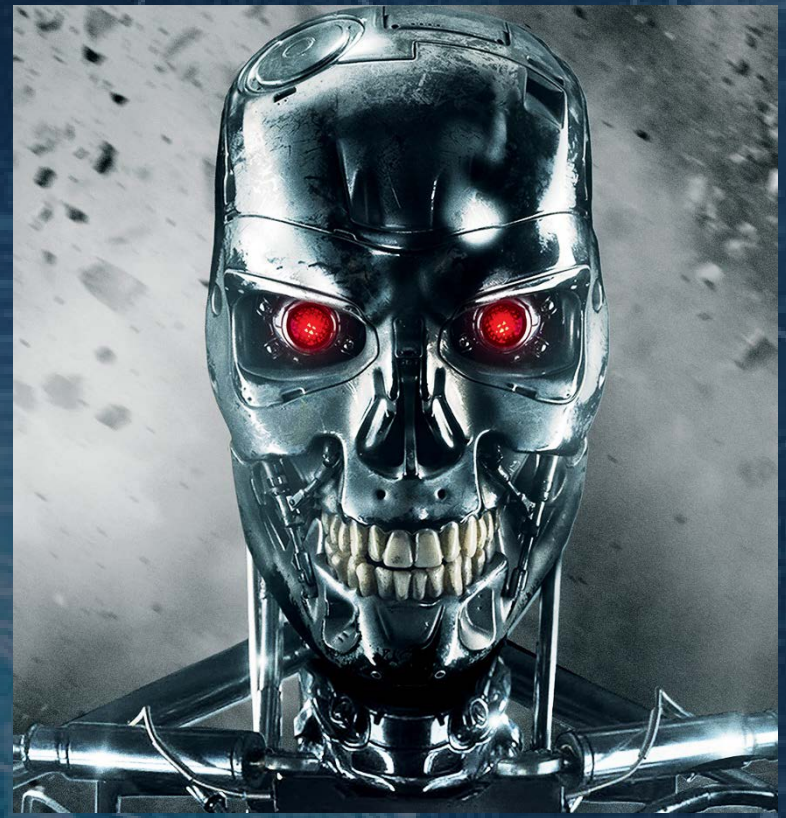
The Most Popular Short Course at SPIE's Advanced Lithography Meeting 2017

Machine learning for the machines that make the world's chips

On the path to Skynet?





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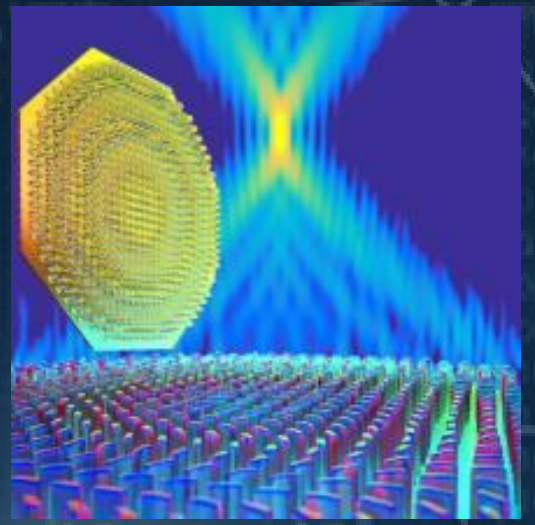
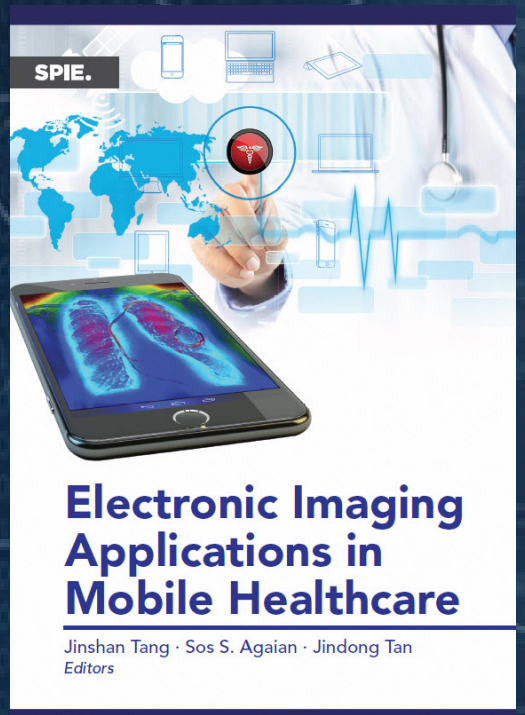
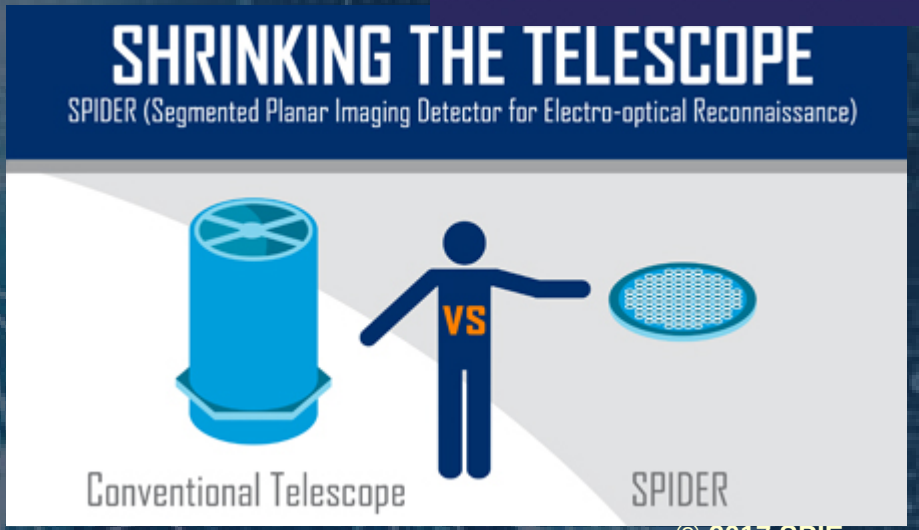
New World: Computational Optics and Metamaterials

- Will computational power make precision imaging optics obsolete?
- Will smart mobile devices disrupt the optics instrument market?
- This ultra-thin planar lens developed at Capasso at Harvard was named a runner-up for Science's Breakthrough of the Year 2016
- DARPA's SPIDER project aims to reduce the size and weight of optical surveillance systems







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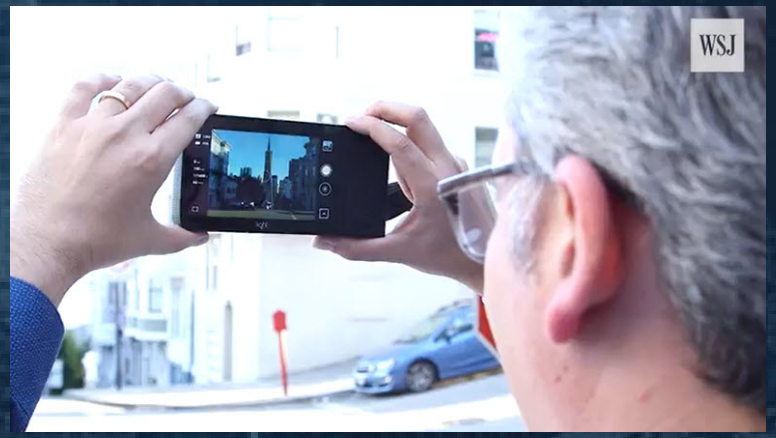
More Disruption Ahead?



- Light's new camera ($1950) uses multiple lenses for an effective 52 MP image
- Will be followed by many more consumer products that will further change the traditional imaging market.

Pictures from Wall St Journal article, Sep 2017

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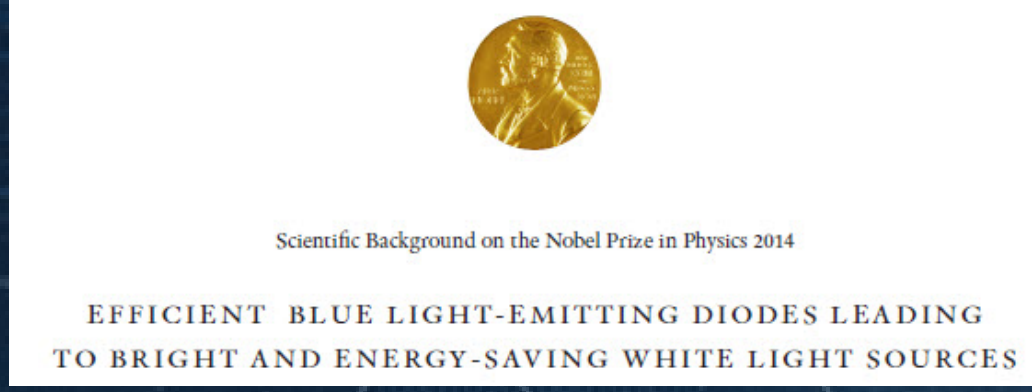
Energy: LED Revolution

- The high efficiency, long life, robustness of LEDs opens up new applications and brings the cost of photons down
- Lighting takes ~20% of electricity, mostly produced by fossil fuels: in the U.S. alone, by 2027, widespread use of LEDs could save about 348 TWh of energy
- LEDs allow human centric and smart lighting
- LEDs are rapidly penetrating the automotive lighting market
- LEDs are well suited to remote areas and as part of “picosolar units”, provide light for study



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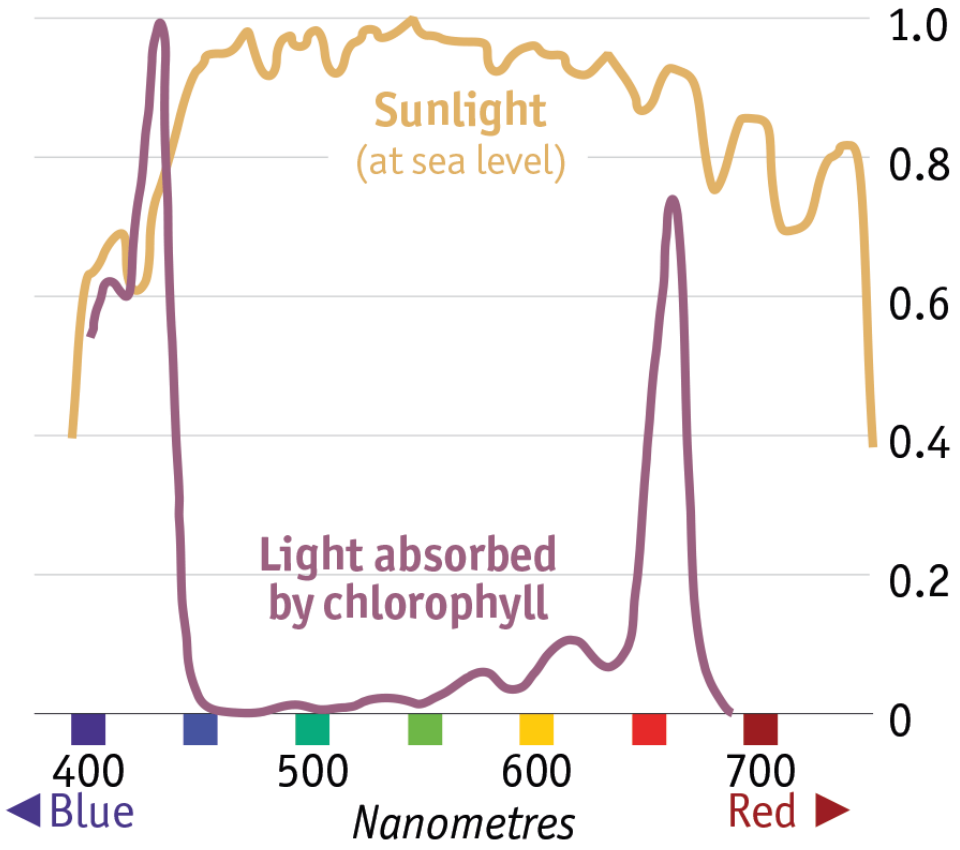
Wasted illumination

Emission/absorption by wavelength

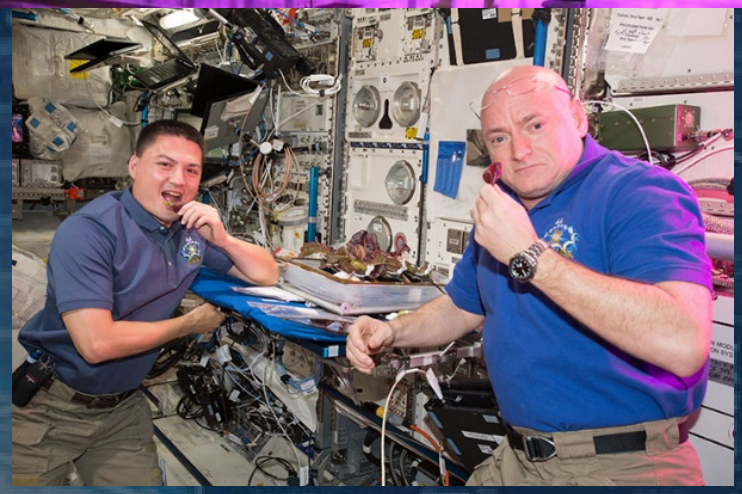


Chlorophyll absorbs blue and red light. Modern LEDs can be tuned to provide only these, so that all of their output is used for photosynthesis.

Sources: University of Queensland;
The Economist

LEDs make "urban farming" more practical

Growing interest in using LEDs to grow marijuana!



Eating plants grown using LEDs on the ISS

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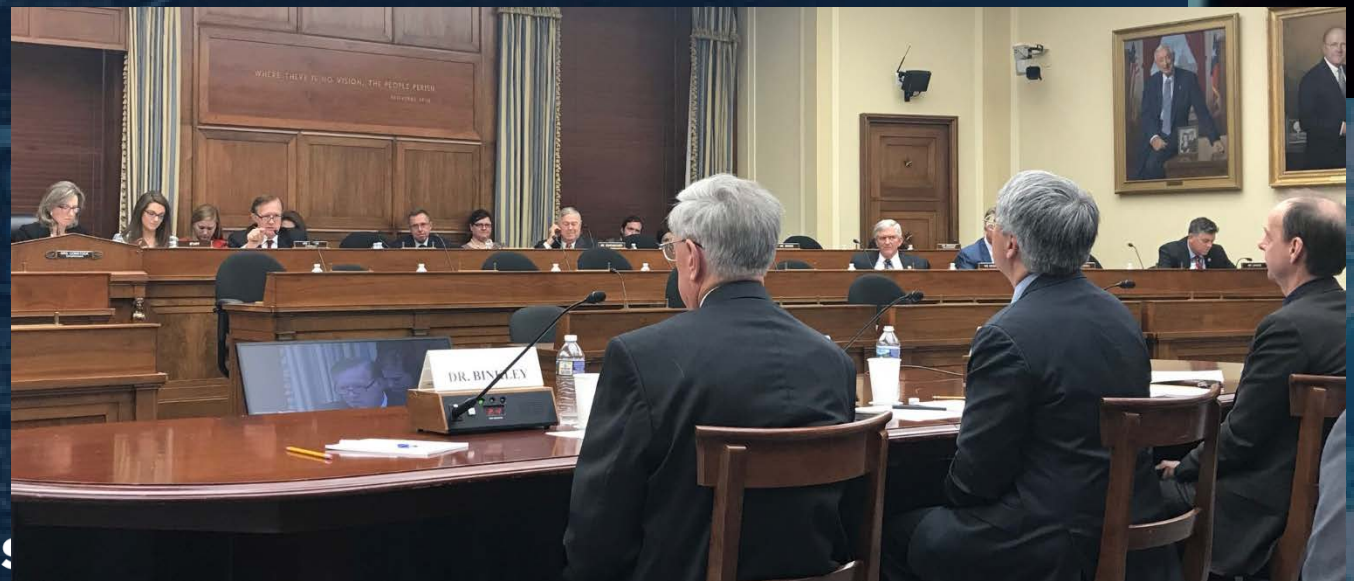
The Graduate, Updated

"I just want to say one word to you, one word. Are you listening? Quantum. There is a great future in quantum. Think about it."



Subcommittee on Research & Technology and Subcommittee on Energy Hearing - American Leadership in Quantum Technology October 24th 2017

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Quantum

- Investment in quantum science and technology is booming and funding is expected to grow for the next decade
- The UK investment of £270 million is well underway
- Products are promised within five years!
- European Commission is launching a €1 billion quantum technologies flagship
- Quantum communications
- Quantum computing
- Quantum simulation
- Quantum sensors
- China's secure quantum communication with a satellite has caught attention
- Alibaba is to invest $15 million in international labs

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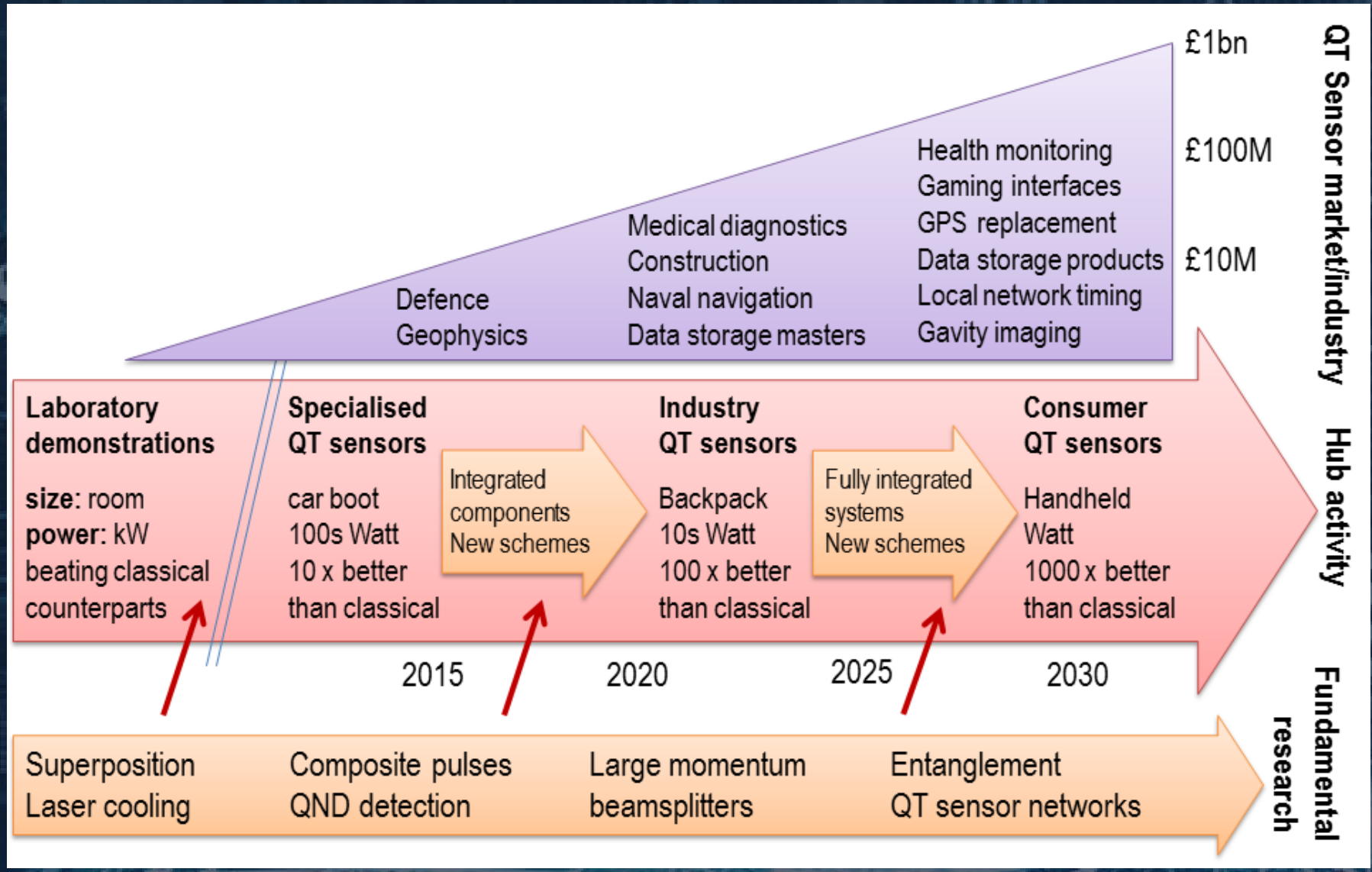
U.K. Quantum Sensor Roadmap



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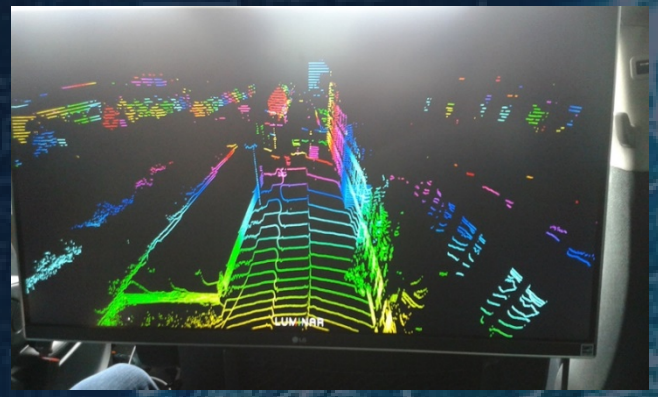
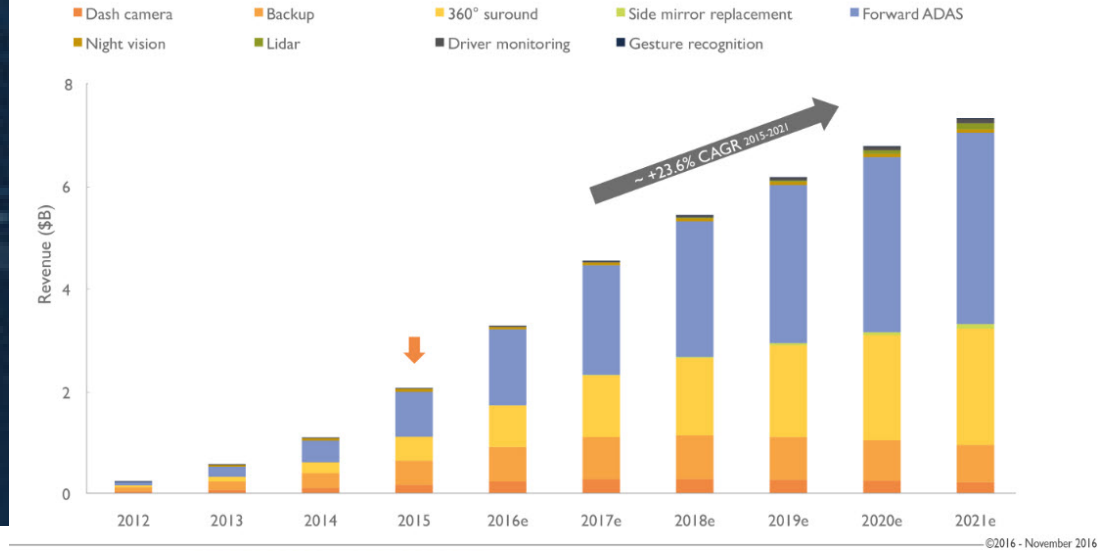
Surge in the Automotive Sector

- Here today – , headlights, cameras, to assist the driver
- Smart lights and highways
- Longer term - autonomous vehicles





Activity

- March 2016: GM acquires (start-up) Cruise Automation for “more than $1bn”
- August 2016: Innoviz Technologies announced a $9 million Series A round to fund the development of a high-performance, low-cost, solid-state light detection and ranging (lidar)
  - Quanergy raises $90M to fund autonomous life-saving lidar technology
  - Ford and Baidu make $150 million investment in Velodyne
- October 2016: Infineon acquires Innoluce
- December 2016: Analog Devices acquires solid-state laser beam steering technology from Vescent Photonics
- March 2017: Intel acquires Mobileye for $15.3bn
- August 2017: Oryx Vision attract $50 m for automotive lidar
- October 2017: GM acquires Strobe (a spin off of OEWaves)

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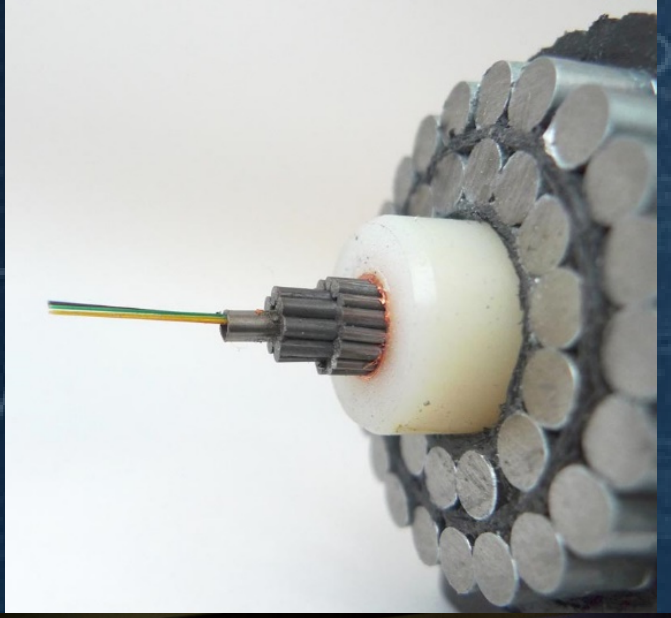
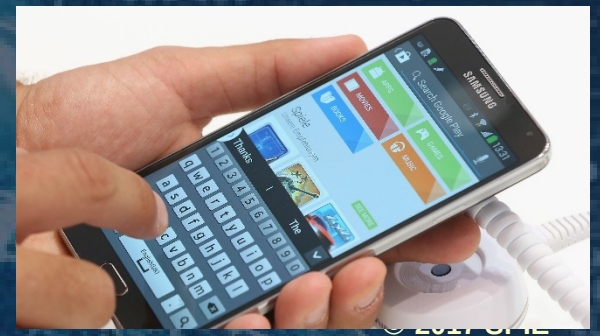
Global Communication is Photonics Driven

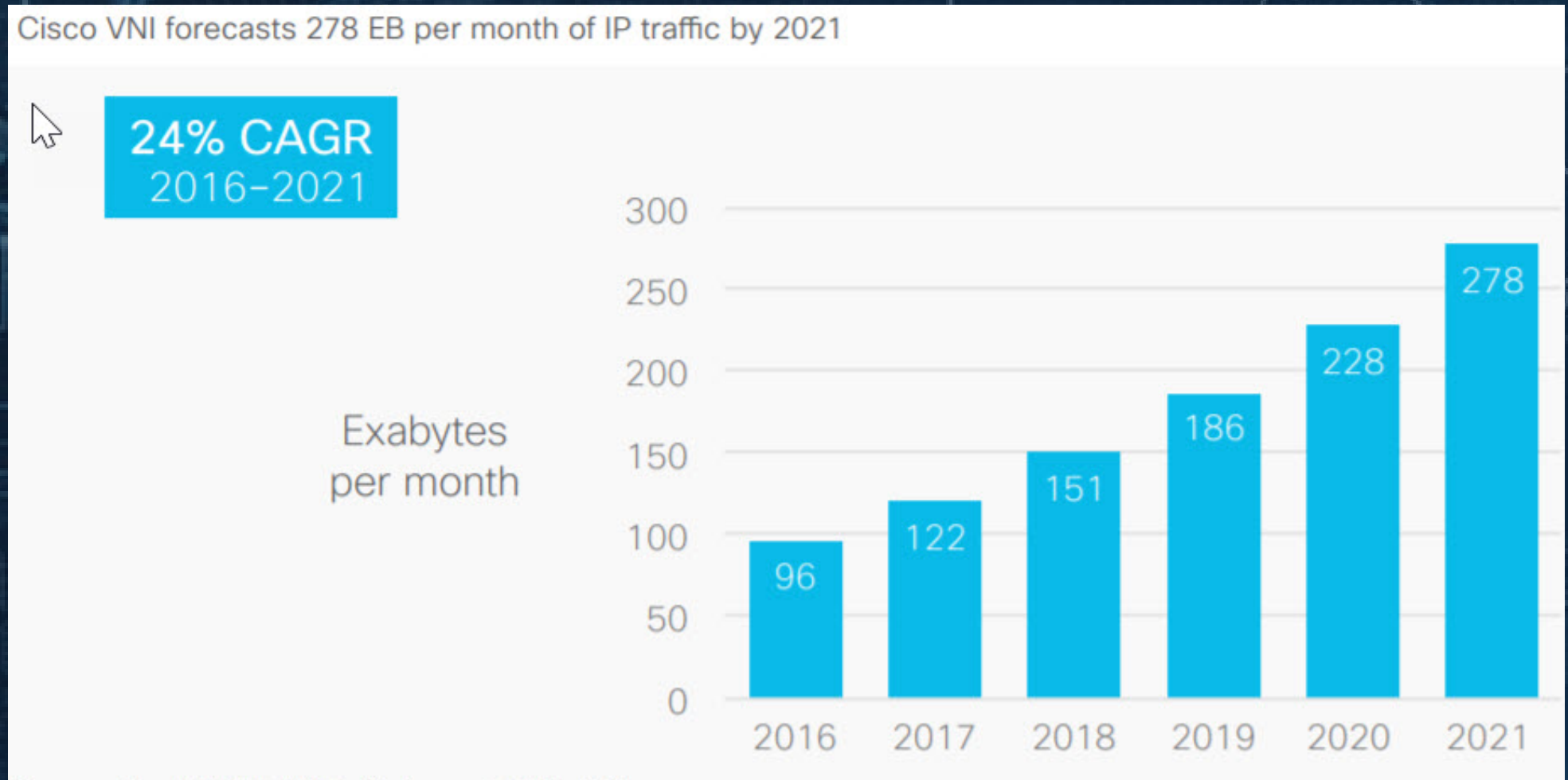
- The broadband internet relies on transmission of light through fiber optic cables
- Improvements will also rely on innovations in generating and detecting photons and in novel fiber transmitting structures and materials
- Today's information transmission relies on increasingly sophisticated screens (photonic devices)
- The processors in our lives and those to come in the "*internet of things*" can only be fabricated using advanced lasers
- The miniaturization of devices is only possible with precision laser techniques and metrology





Major Driver

CISCO Projections – will take a lot of optically manufactured chips and information transmission and storage capacity



Cisco June 2017

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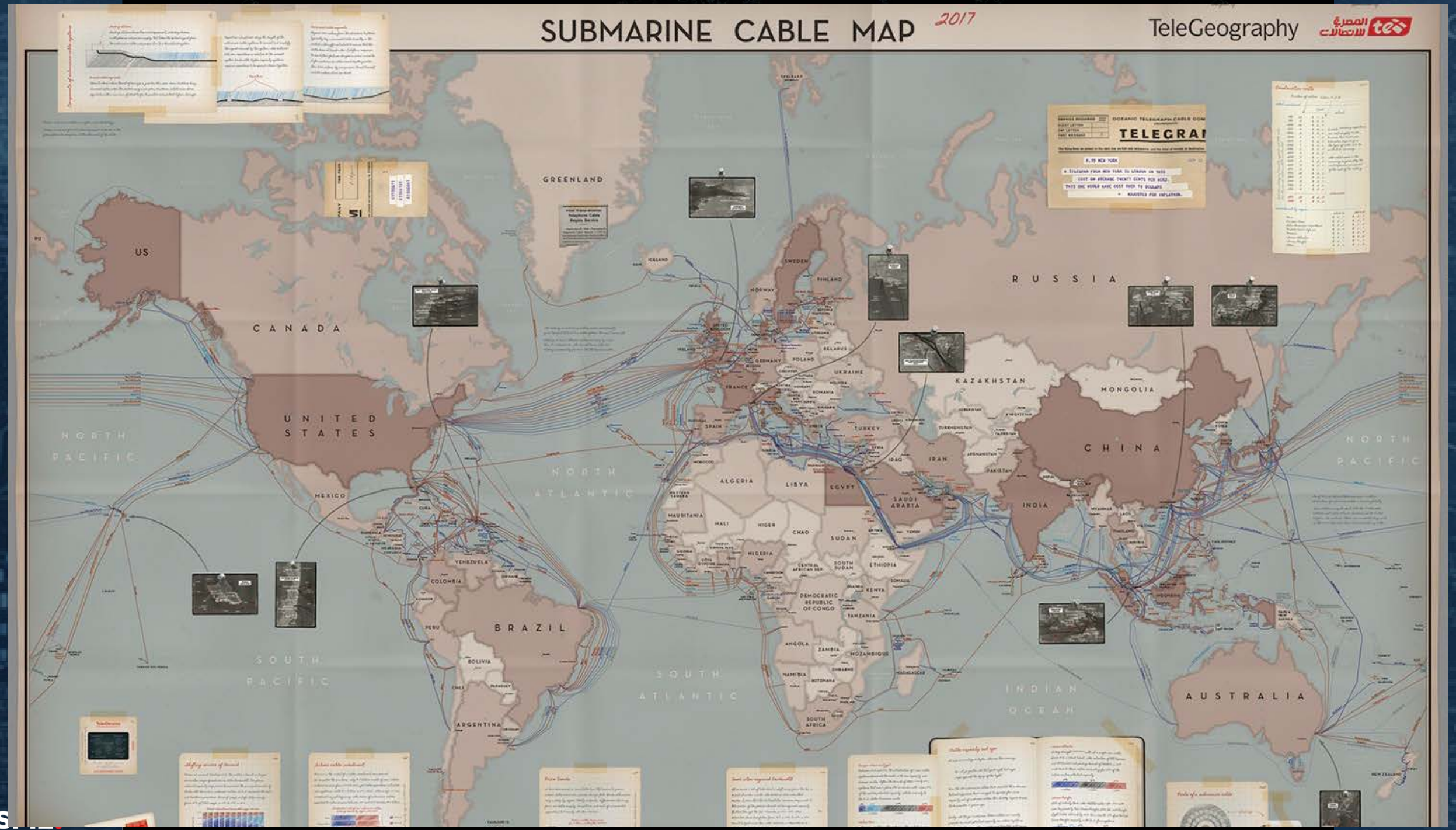
SUBMARINE CABLE MAP
2017
TeleGeography
المصرية للاتصالات
GREENLAND
ICELAND
US
CANADA
UNITED STATES
MEXICO
CUBA
VENEZUELA
COLOMBIA
PERU
BRAZIL
BOLIVIA
CHILE
ARGENTINA
PARAGUAY
URUGUAY
NORTH PACIFIC
SOUTH PACIFIC
NORTH ATLANTIC
SOUTH ATLANTIC
INDIAN OCEAN
SWEDEN
FINLAND
NORWAY
RUSSIA
BELARUS
UKRAINE
POLAND
GERMANY
FRANCE
SPAIN
PORTUGAL
IRELAND
ROMANIA
TURKEY
KAZAKHSTAN
MONGOLIA
CHINA
IRAN
IRAQ
AFGHANISTAN
PAKISTAN
INDIA
SAUDI ARABIA
EGYPT
LIBYA
ALGERIA
MOROCCO
MAURITANIA
MALI
NIGER
CHAD
SUDAN
NIGERIA
ETHIOPIA
KENYA
SOMALIA
TANZANIA
DEMOCRATIC REPUBLIC OF CONGO
ANGOLA
ZAMBIA
MOZAMBIQUE
NAMIBIA
BOTSWANA
SOUTH AFRICA
AUSTRALIA
NEW ZEALAND
TELEGRAM

Not the Usual Suspects

- Sept 2015: Microsoft partner with Hibernia Express and AEConnect for new Tbps low latency trans Atlantic fiber cables
- June 2016: Google “Faster cable” Japan to US 60 Tbps
- Sep 2017: Microsoft & Facebook Marea subsea cable complete., Has a transmission capacity of 160 Tbps
- Google and Facebook planned cable, Hong Kong to Los Angeles 120 Tbps
- Google Indigo cable to connect Singapore Perth and Sydney will be 18Tbps
- Submarine internet cable business is more than $1bn p.a. and growing at 5%

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Data Centers Full of Photonics

- Apple has datacenters in Oregon, North Carolina, California, and Nevada. Now to spend $1.3 bn on two data centers in Iowa. Apple is building a $1 bn data center in Ireland, and a second in Denmark
- Facebook U.S. data centers are in Oregon, North Carolina and Iowa. Centers in Fort Worth, Texas and Los Lunas, New Mexico are currently under construction, and Facebook announced plans for sites in Papillon, and Ohio. Facebook also has data centers in Ireland and Sweden
- Microsoft with data centers all over the globe is to spend ~$2bn on third center in Iowa. Chicago, Virginia, Washington Ireland, Netherlands, India Africa…..
- Amazon has nine datacenters in Oregon, a major center in Virginia, Ohio, Sao Paulo, Ireland Singapore, Beijing, Sydney, London, Frankfurt, Seoul…..

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Google Data Centers

Google's South Carolina Data Center- with cooling water issues

- Google data centers for cloud services planned in California, Canada, The Netherlands, Northern Virginia, São Paulo, London, Finland, Frankfurt, Mumbai, Singapore, and Sydney.

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Photonics in Data centers

- Data centers have energy and bandwidth problems
- Optical fibers and transceivers help both
- Photonics will move onto the boards, linking chips, then onto the chips. (Some see optical computers eventually)
- Silicon photonics, indium phosphide-based technology (InP) and VCSEL-based technology all in the competition
- Microsoft has said publicly that it is test-driving Intel's silicon photonics in its cloud infrastructure
- The DoD put $100 million into the AIM photonics integrated circuits project (NY) and NY state put in $500 million
- There is a need for a US owned and based volume packaging capability

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Lithography: Lasers Changing Our World

- The semiconductor revolution has changed lifestyles and brought about huge social consequences
- Progress in this field is due to multidisciplinary science and engineering teams
- Light plays several key roles in semiconductor fabrication, but it is innovation in lithography, the printing of the chips with light, that has made possible what we have today
- The use of laser light sources allowed the industry to stay on Moore's "law" – without the laser we would not have the computing power or memory of today
- Think that a typical smart phone has 1 million times the memory and operates at ~30,000 times the rate of the main computer on Apollo 11

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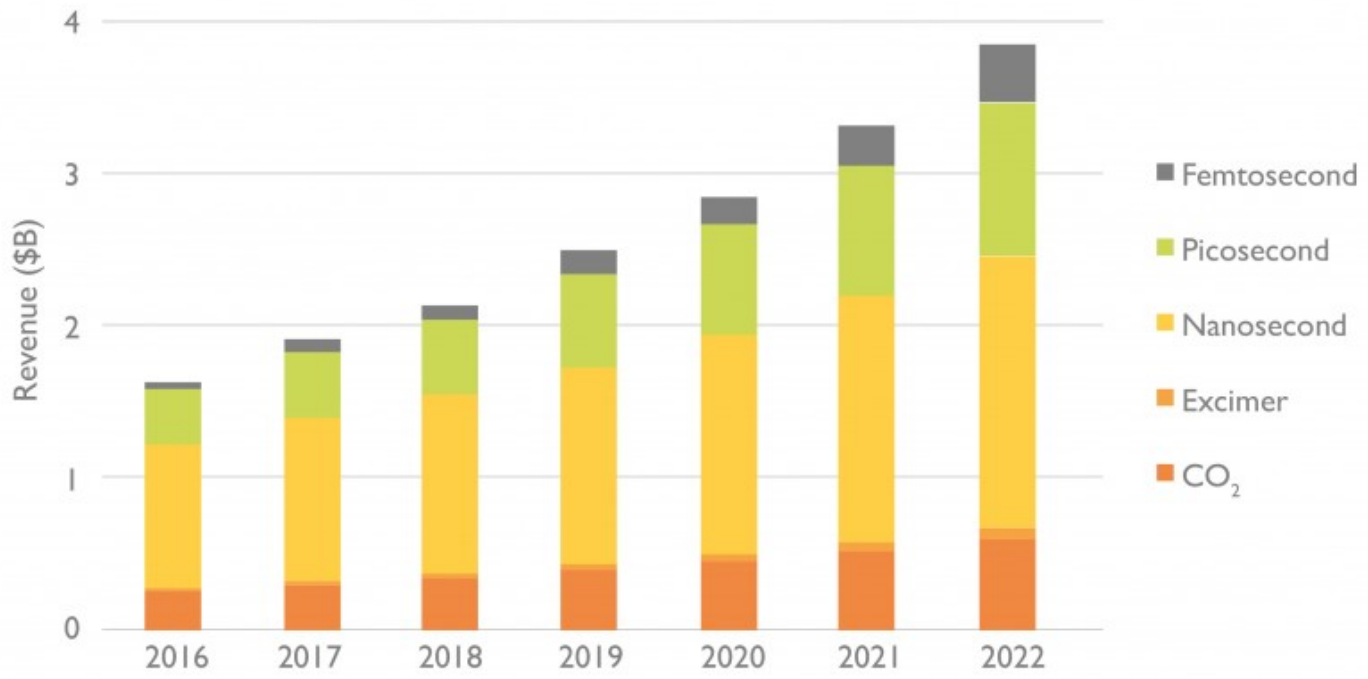
Lasers for Semiconductor Manufacturing

YOLE Développement

Laser market revenue ($B) split by laser type

(Source: Laser Technologies for Semiconductor Manufacturing Trends 2017 report, Yole Développement, October 2017)



Yole Développement is part of Yole Group of Companies

©2017 - www.yole.fr – www.i-micronews.com

Most of the familiar laser and precision motion companies record significant revenues from the semiconductor industry

And most are thriving in the current semiconductor boom

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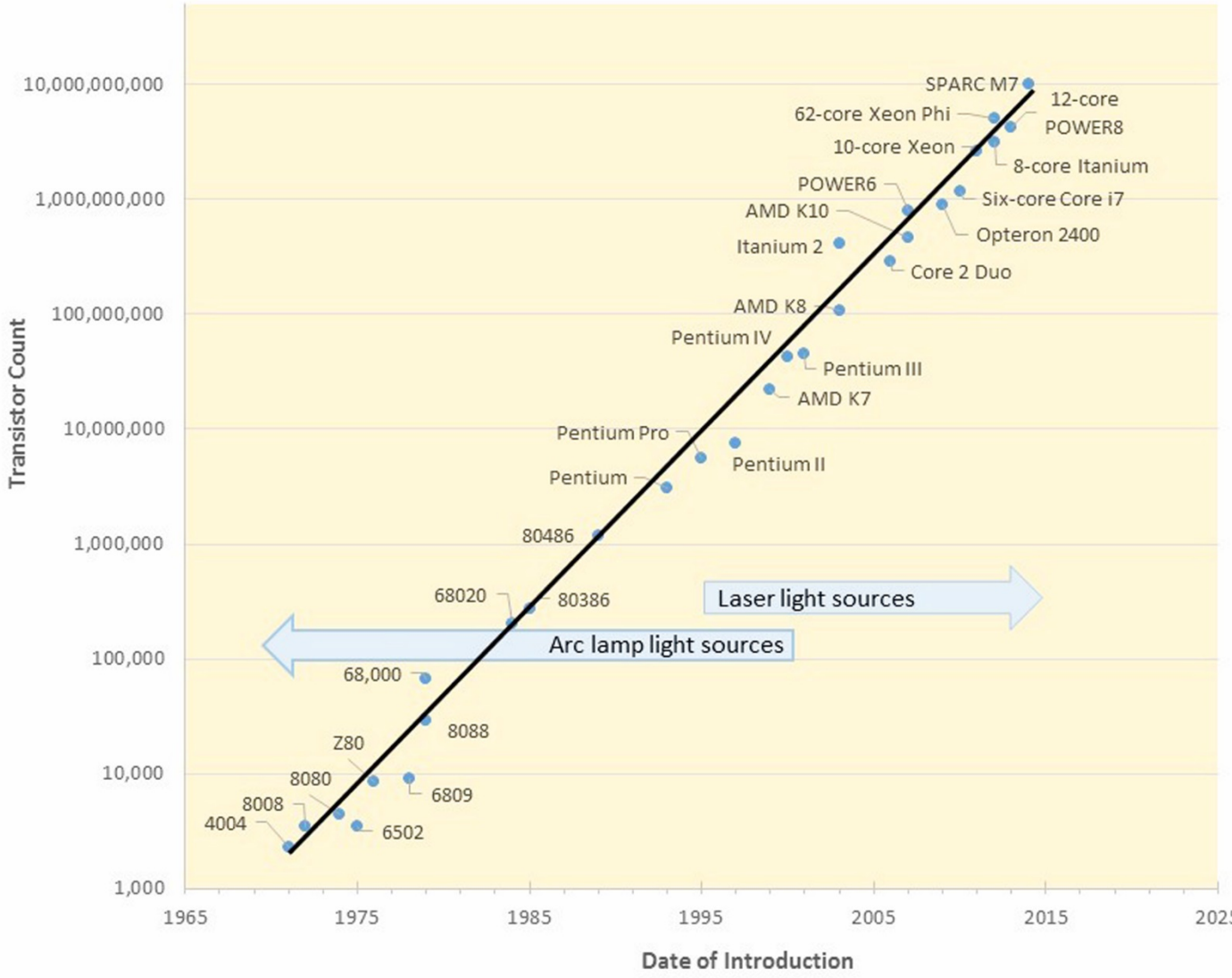
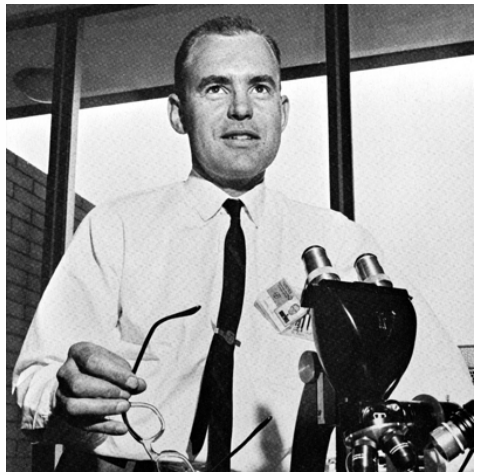
Microprocessor Transistor Counts 1972–2015 & Moore's Law





In 1965 Gordon Moore proposed Moore's "Law"

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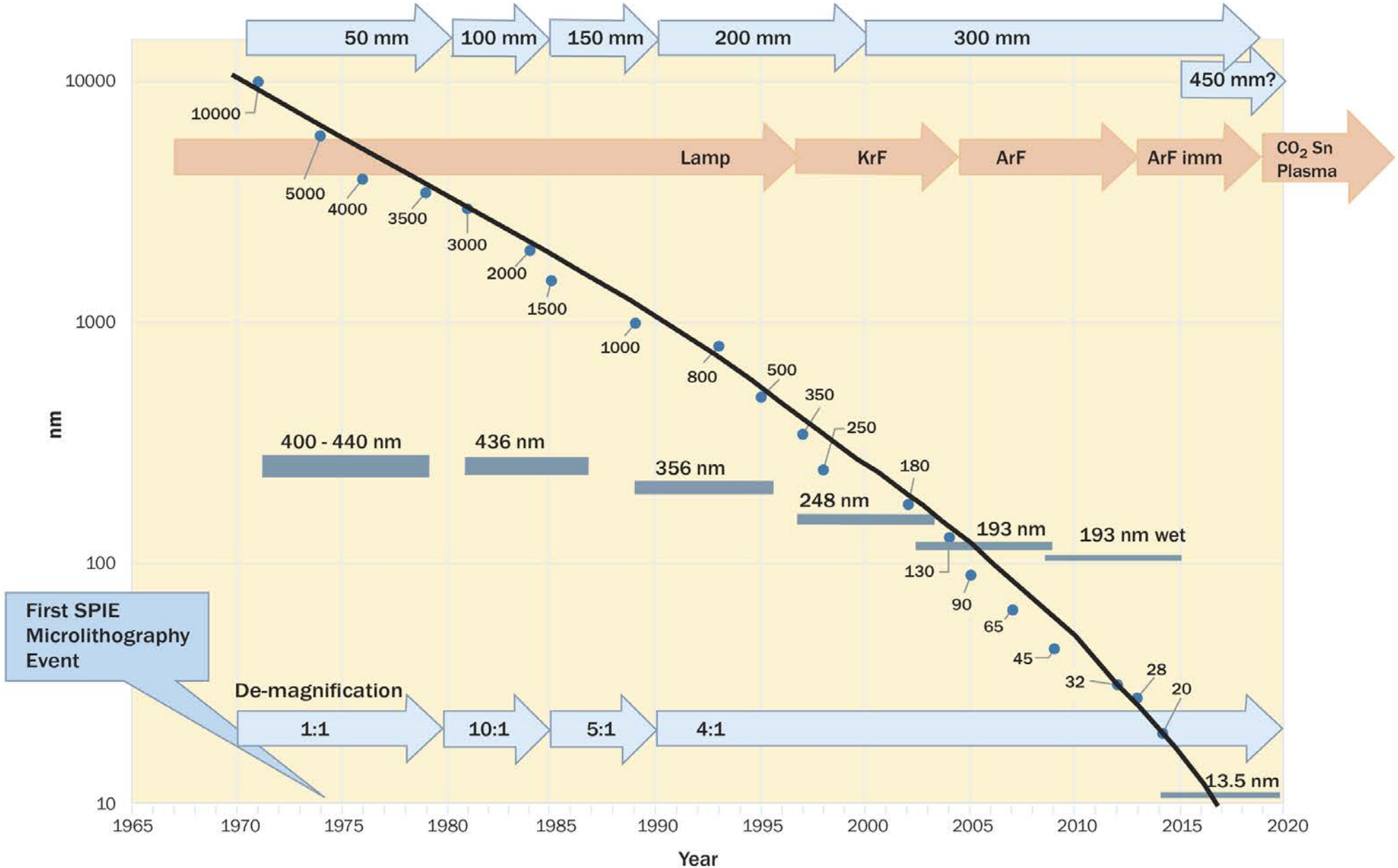
Lithography Scaling Evolution



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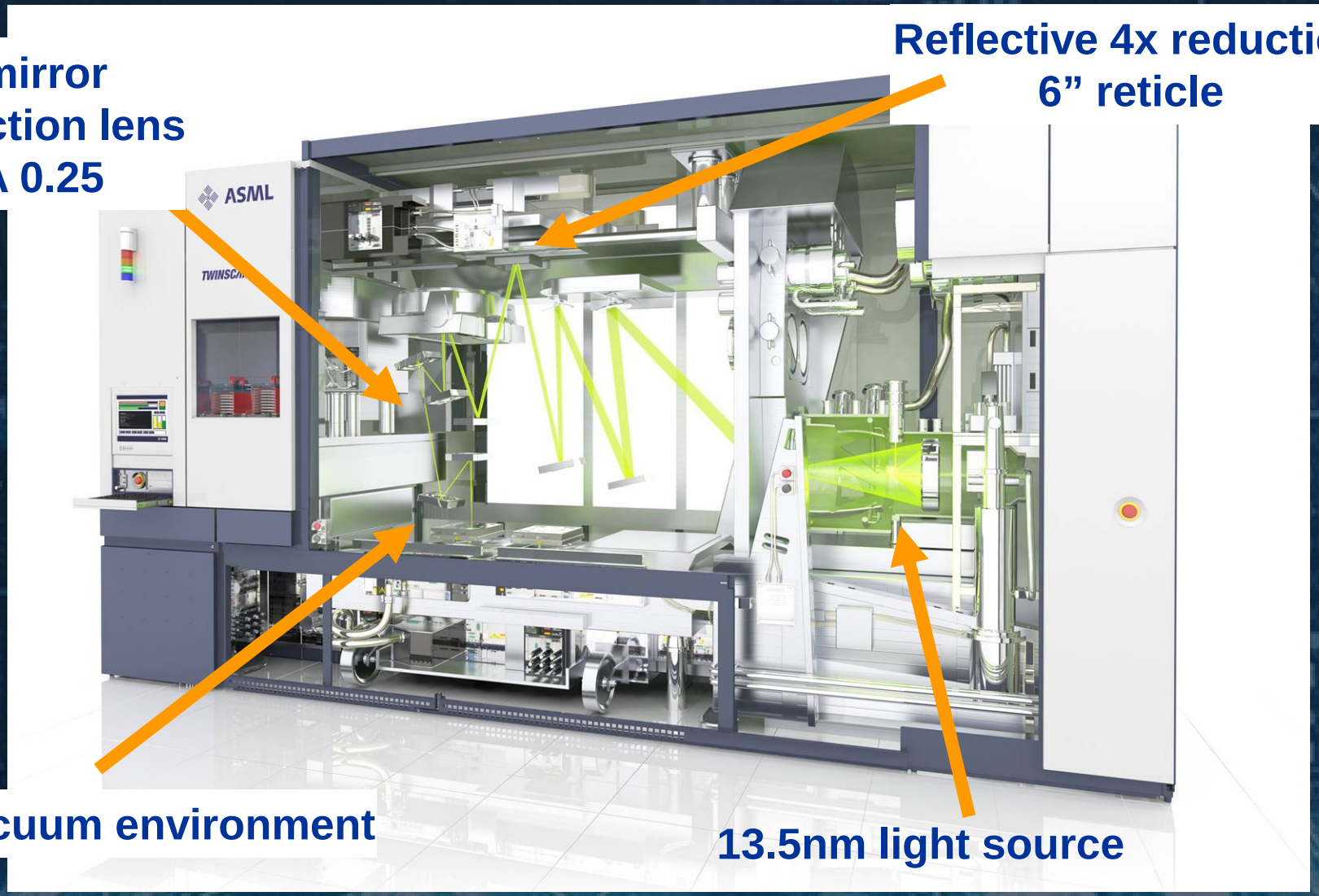
EUV Scanner Layout



The first EUV production units shipped in 2016

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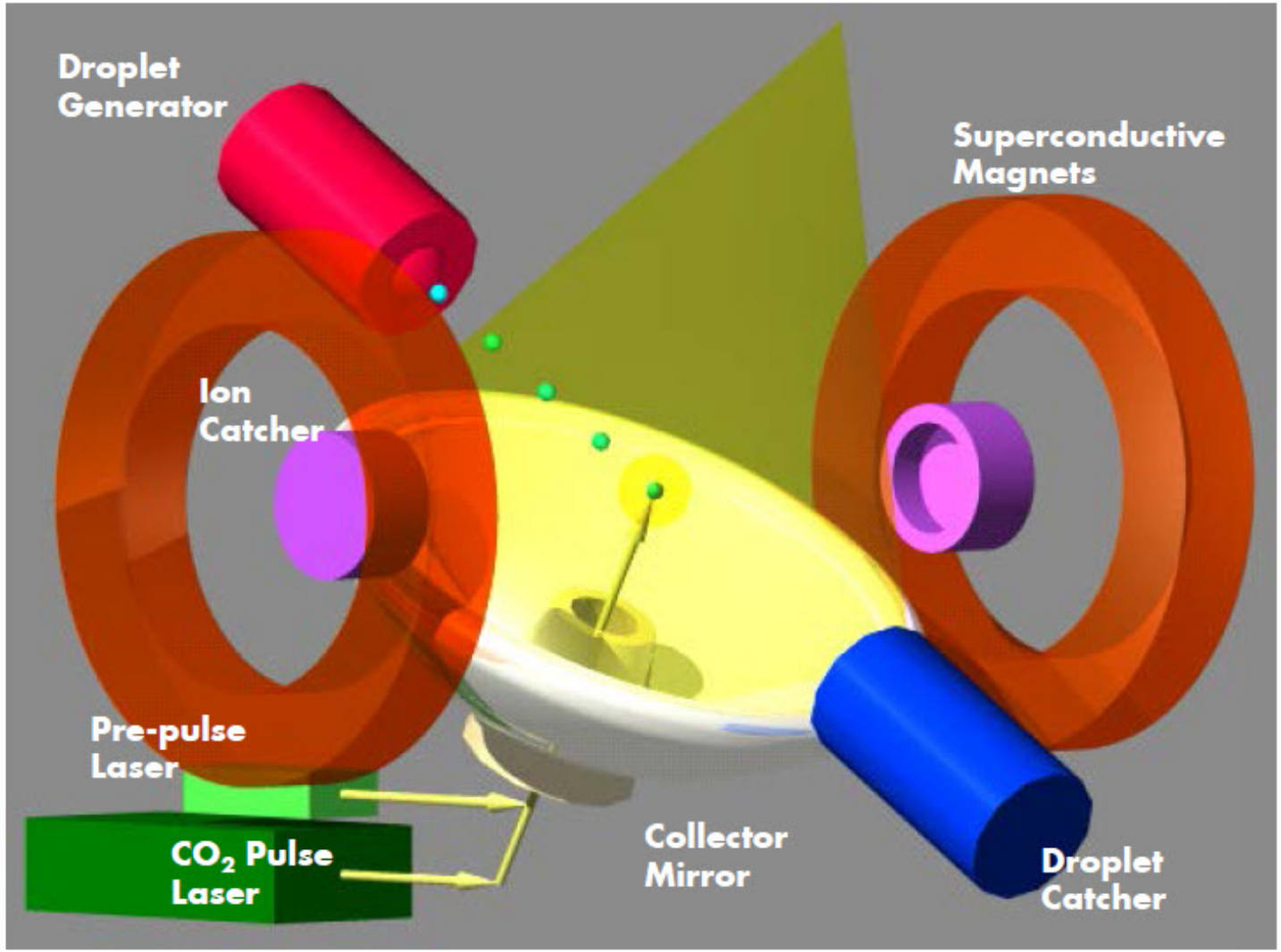
Gigaphoton's LPP Light Source Concept

- High ionization rate and CE EUV tin (Sn) plasma generated by CO_2 and pre-pulse solid laser dual wavelength shooting
- Hybrid CO_2 laser system with short pulse high repetition rate oscillator and commercial cw-amplifiers
- Accurate shooting control with droplet and laser beam control
- Tin (Sn) debris mitigation with a super conductive magnetic field
- High efficient out of band light reduction with grating structured C1 mirror



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Pilot and Proto Systems Configuration

Target System Specification

Operational Specification		Pilot #1	Proto #1	Proto #2
Target Performance	EUV Power	250 W	25 W	> 100 W
	CE	4%	3%	3.5%
	Pulse rate	100 kHz	100 kHz	100 kHz
	Output angle	62°upper (matched to NXE)	Horizontal	62°upper (matched to NXE)
	Availability	> 75%	1 week operation	1 week operation
Technology	Droplet generator	< 20 µm	20 – 25 µm	20 µm
	CO_2 laser	**27 kW**	5 kW	**20 kW**
	Pre-pulse laser	picosecond	picosecond	picosecond
	Debris mitigation	> 3 month	validation of magnetic mitigation in system	10 days

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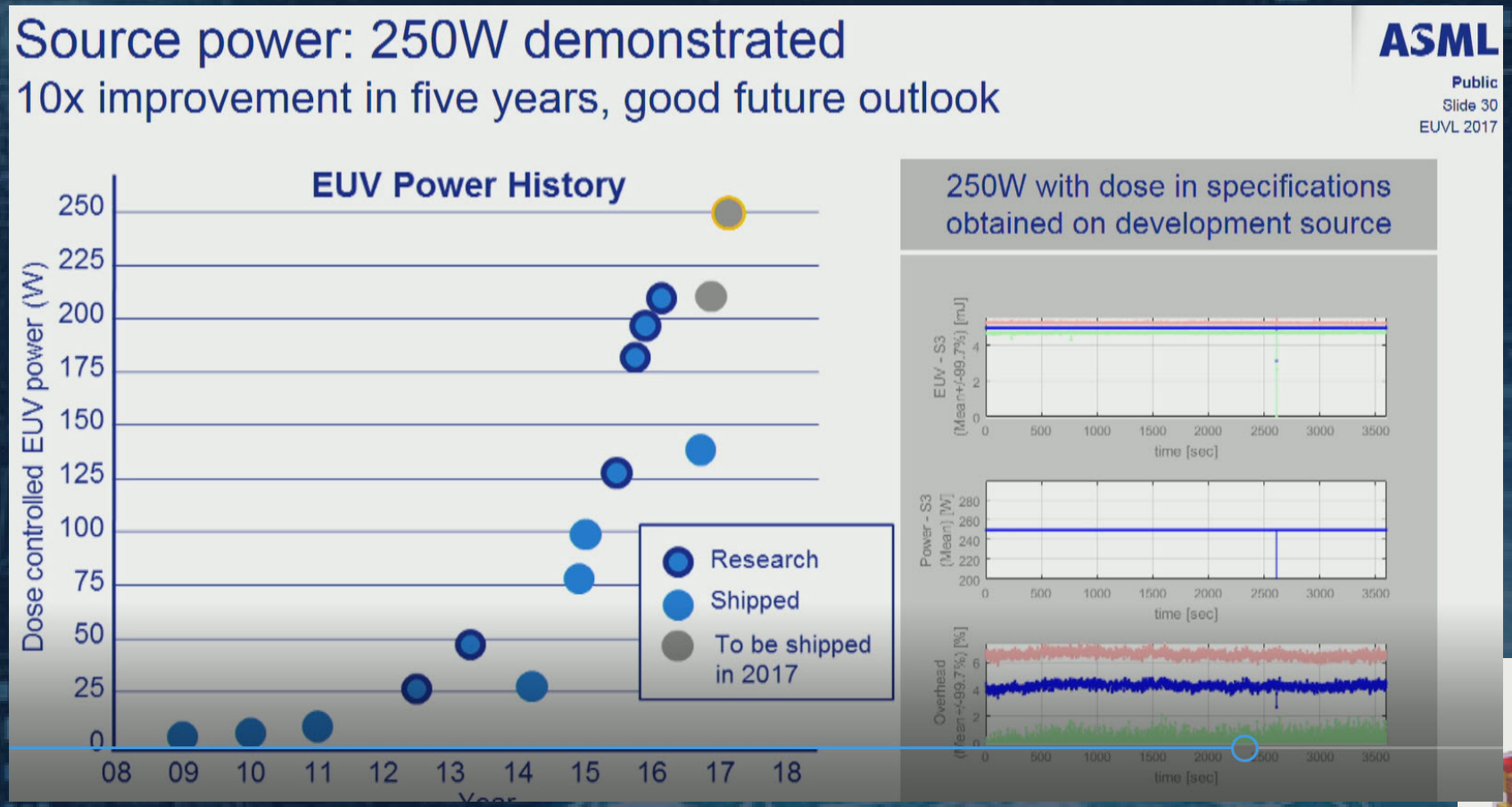
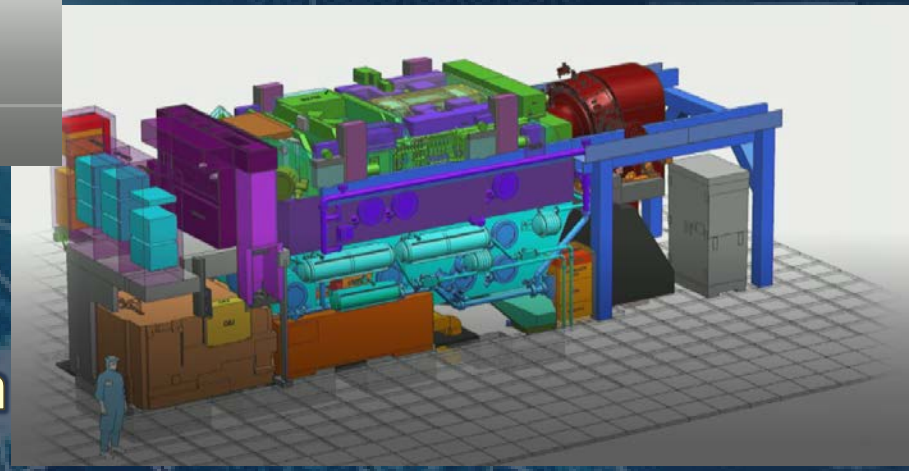
Confidence in EUV Growing

- ASML reporting at SPIE Photomask and EUVL in September
- *"customers are now focusing on full adoption of EUV starting in 2019 and accelerating into 2020, helped in particular by DRAM spending"....analyst*





ASML concept for next gen EUV tool with higher NA
Gradual improvements in mirror reflectivity at 13.5nm

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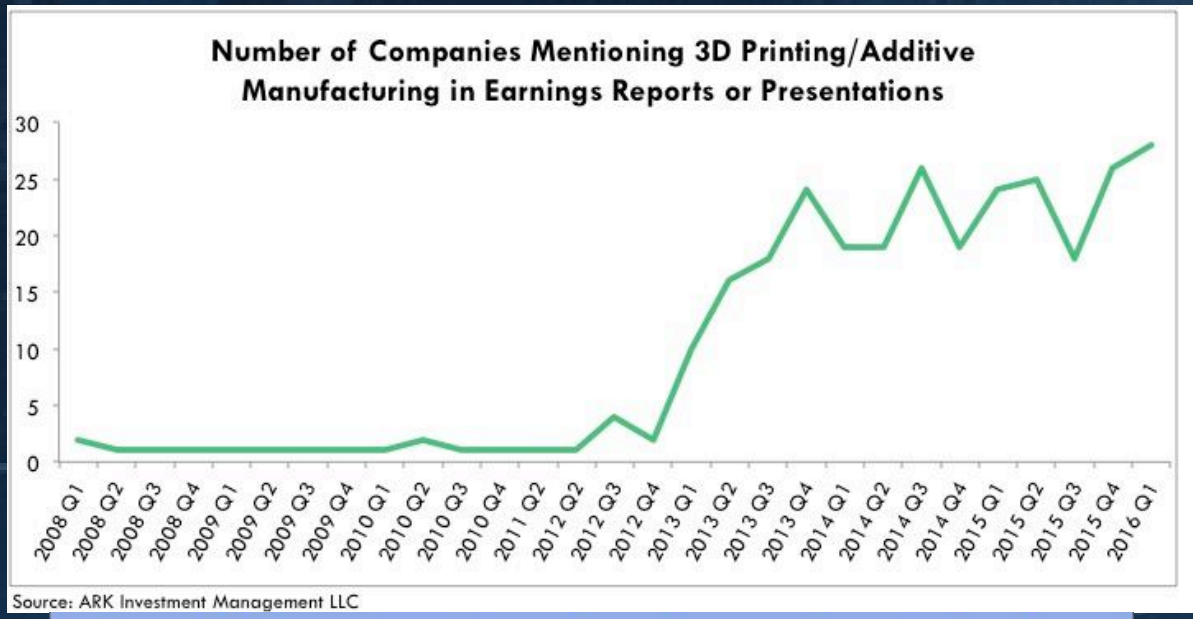
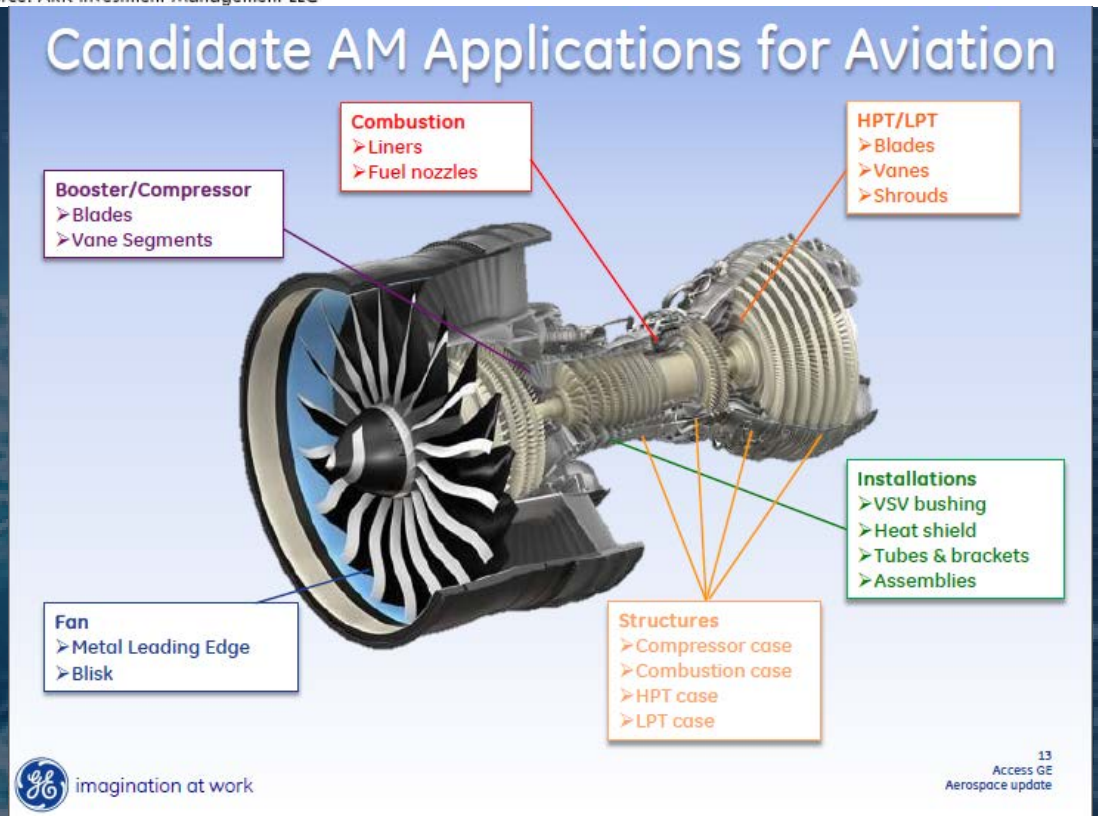
3D Printing on the Rise

- Industrial 3D printing is growing ““*The Time for 3D Printing is Now*” GE
- (Consumer 3D is still plagued with hype)
- *"You're not going to be able to do a whole jet engine (with 3D printing). But you're going to be able to do enough content that you can probably shrink your developer time by maybe 50% and you're going to be able to take 25% of the cost out of an engine*“…Jeff Immelt, former CEO GE,





Industry 4.0
GE's 3D Center, Pittsburgh

GE acquired 2 US additive manufacturing companies in 2012, and two European 3D companies for $1.4 bn in September 2016. It has separately invested more than $1.5bn in the technology, and expects to reduce manufacturing costs by $3-5bn using the technology

Siemens new metal printing facility in Sweden

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3D Printing of Organs & Implants

- Printed organs from 3D imaging systems can be very valuable for surgeons preparing to operate
- Johnson and Johnson working with GE printed the heart shown from GE CT scans
- Customized cranial titanium implants using laser additive manufacturing have already been used
- 3D bioprinting is being explored for organs

"*There are possibilities in medicine*".. Ted Maiman 1964

- Lasers continue to be key to advancing our understanding of our biology
  - It is not economically viable to make the processors, memory, or imagers that are key to today's medical imaging and the coming AI revolution in medicine without lasers
  - Sensitive laser techniques are key to in vivo imaging, with and increasingly without markers
  - Lasers underpin the growing suite of techniques and acronyms for super resolution microscopy (2014 Chemistry Nobel) and time resolved techniques

Lasers are ubiquitous in clinical medical instrumentation, e.g genome readers, flow cytometers. "Real time" cytology and biopsy results are closer

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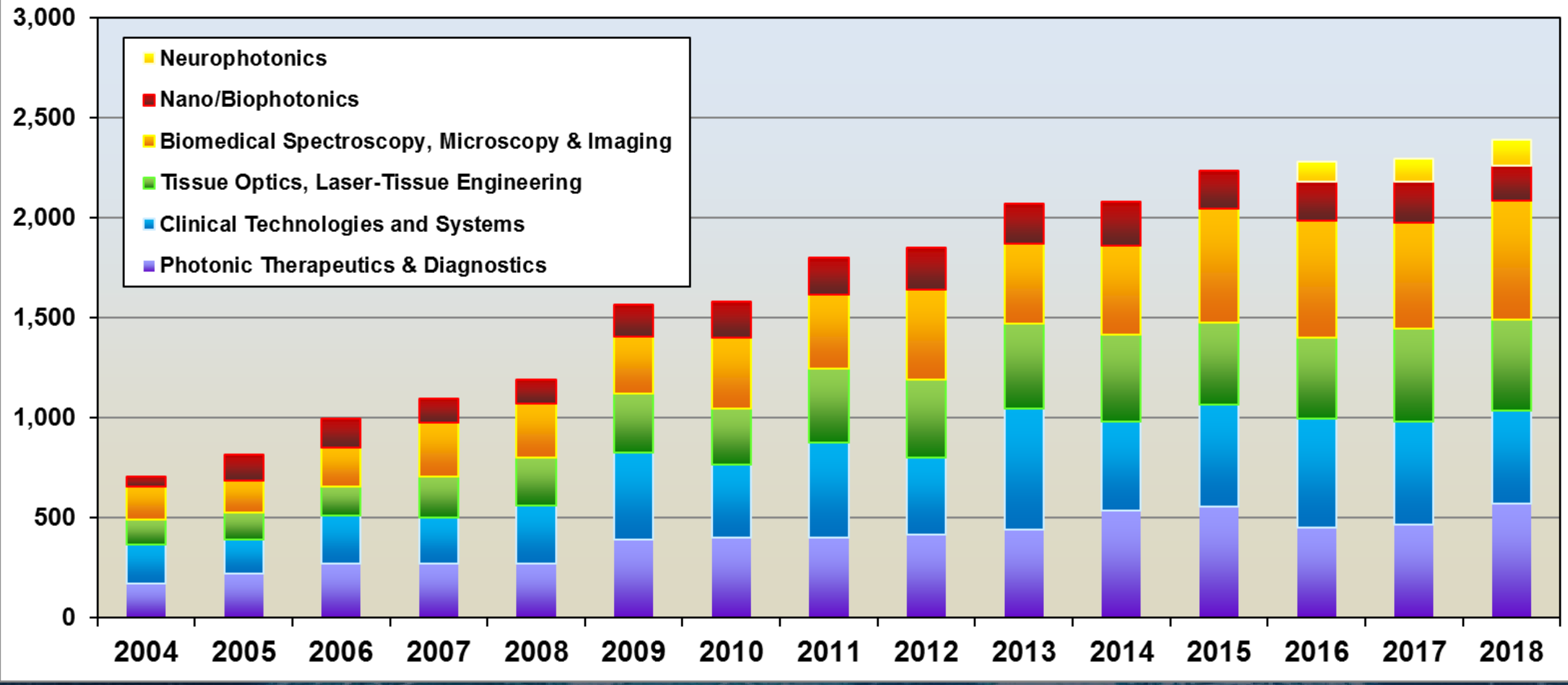
SPIE Biomedical Optics Conference (BiOS) Papers



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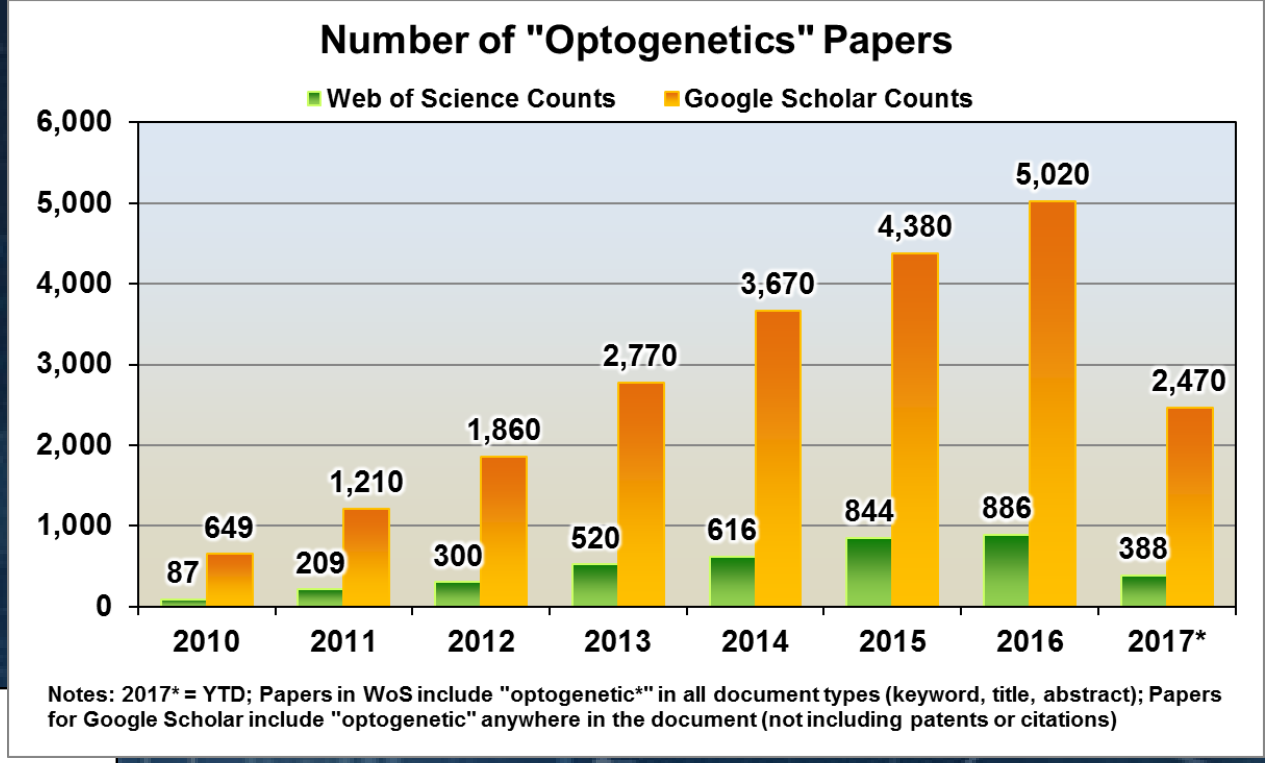
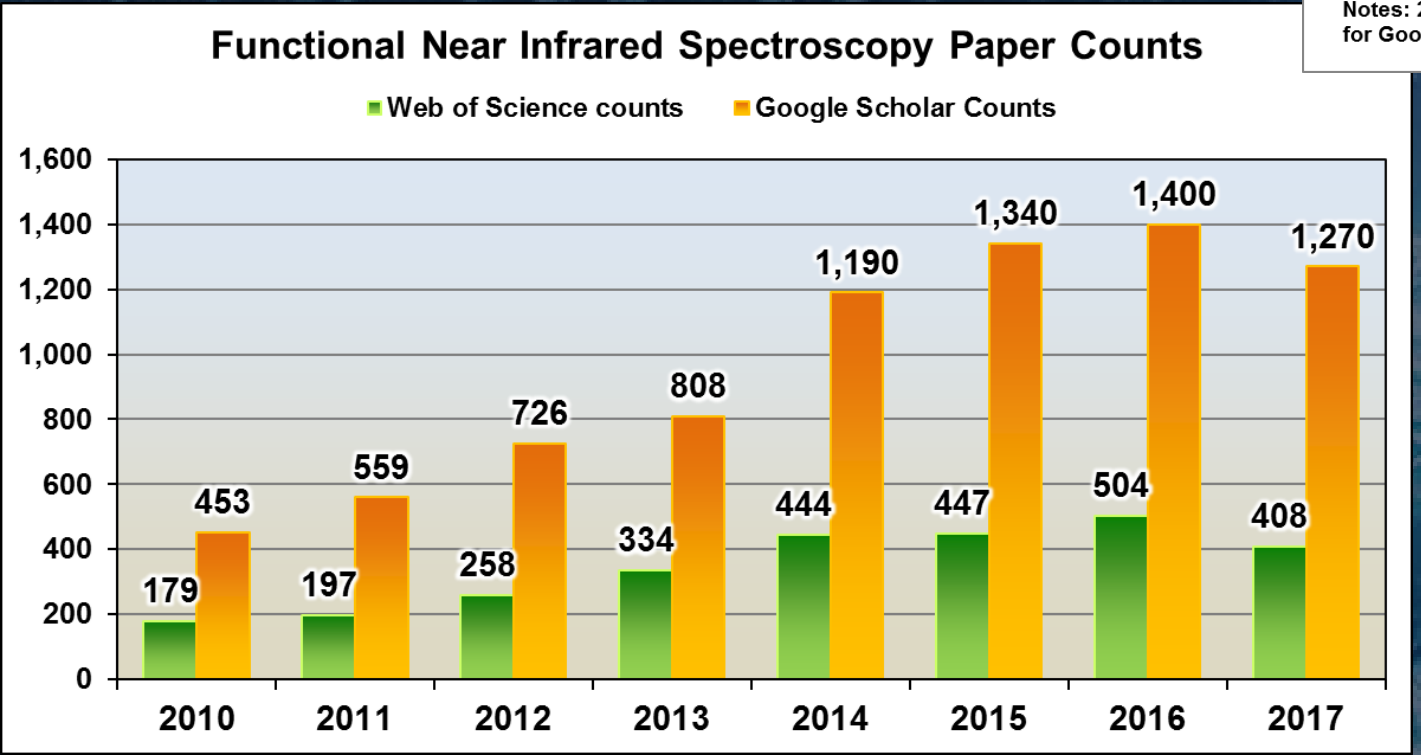
Optogenetics –the possibility of therapy





fNIRS –the promise of wearable MRI like information

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LED Photons for Health

- Low cost (<$100) LED Bililights phototherapy equipment for neo natal jaundice in infants from Rebecca Richards-Kortum of Rice University: Currently being used in Malawi and Guatemala
- ~405nm Indigo-Clean lighting reduces harmful bacteria including MRSA

Strathclyde University testing 405 nm on pathogens in 2012

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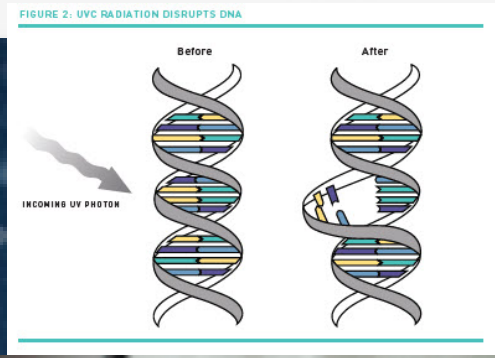
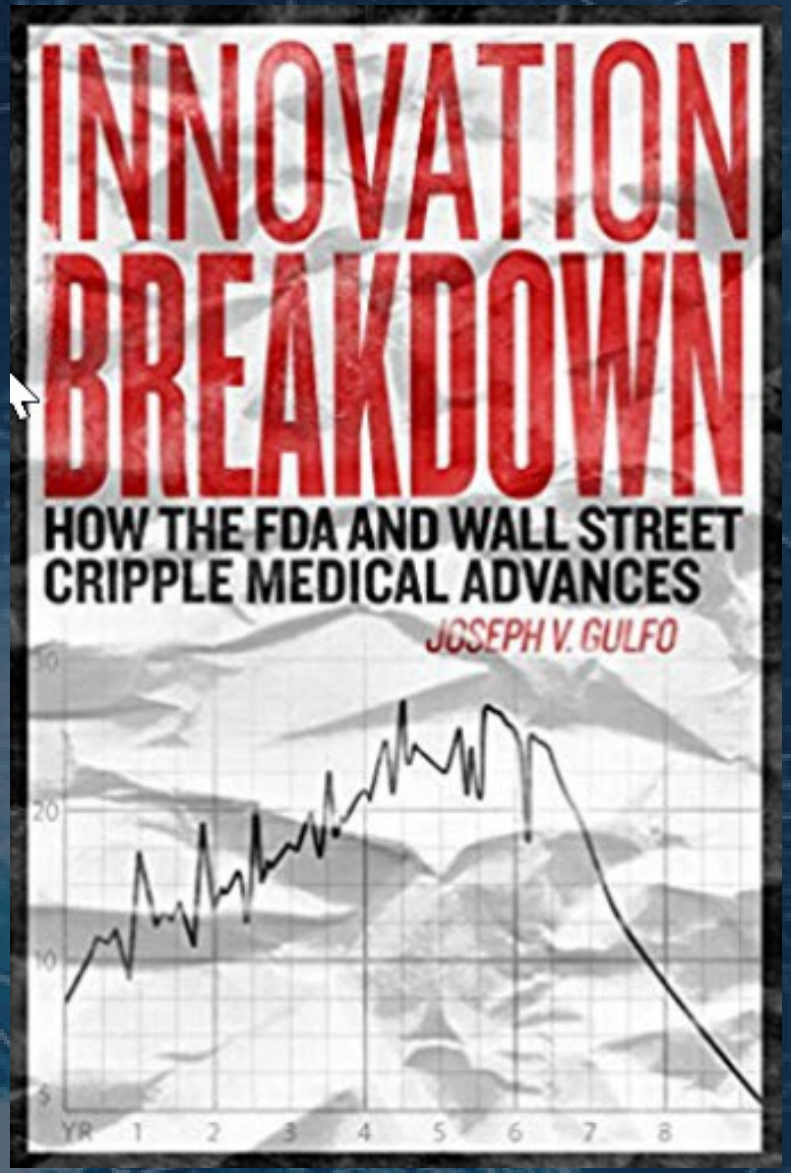
LEDs are increasingly used for water purification, sterilization in medical facilities, phototherapy, and photocuring of industrial inks and coatings, replacing mercury lamps and keeping mercury out of our environment



The use of LED light for cosmetic applications, (skin and hair) is growing, and investigations in brain therapy continue though the mechanisms of low light level therapy may be unclear

One of Many Broken Dreams

- Hundreds of millions of VC and other investment dollars have gone into promising medical spectroscopic technologies to no avail
- In many cases the technology worked, but the economics didn't, or investor patience ran out
- Mela Sciences, with a product intended to identify melanoma struggles on as Strata Skin Sciences. It was crippled in dealing with the FDA
- Gulfo was considered by Trump to head the FDA



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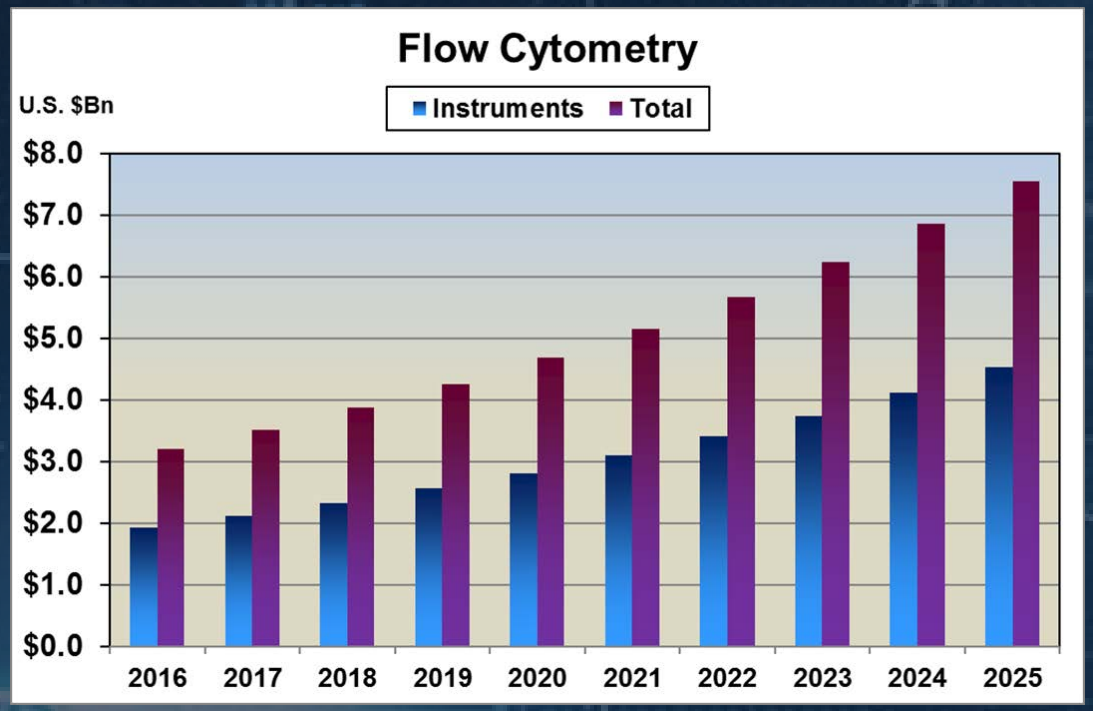
Flow Cytometry

- Played a major role in recent pandemic threats
- Market growing ca 5% p.a.
- Flow cytometers, now using multiple lasers are expected to grow in clinical usage and can be expected to move closer to the patient
- Cytogenetics may expand their usage



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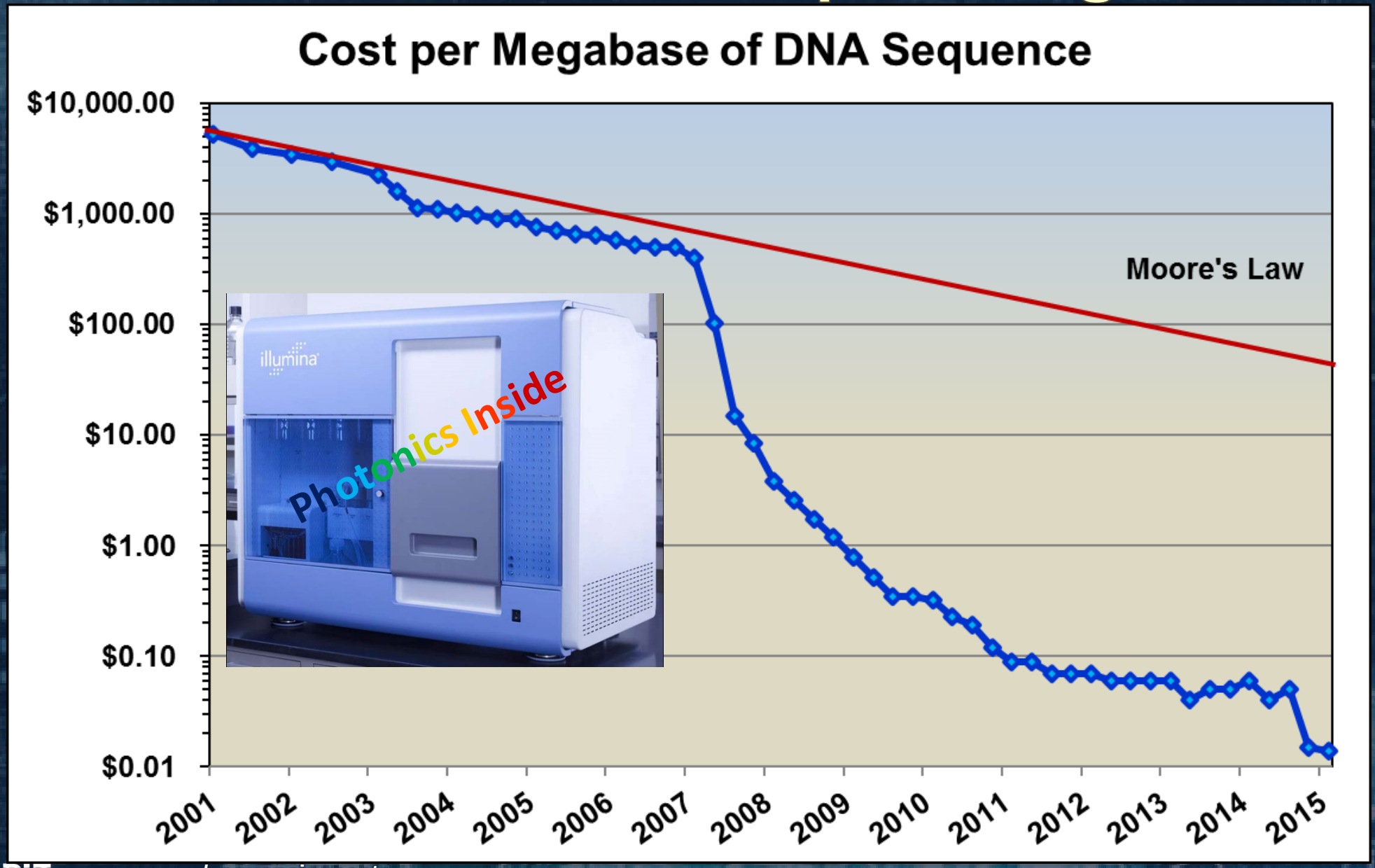
Genome Sequencing Costs



The genomics market is projected to reach $US20 bn by 2020

About US$160 billion is spent every year on biomedical research"
Lancet Editorial

Source: genome.gov/sequencingcosts

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Next, $100?

- The practicality of genome reading stems in large part from improvements in the cost performance of computing power and storage, and advances in lasers, (optics) and detectors applied to PCR
- Major players include Illumina, Inc. (U.S.), Affymetrix, Inc. (U.S.), Agilent Technologies, Inc. (U.S.), BGI (China), Thermo Fisher Scientific, Inc. (U.S.), Bio Rad Laboratories, Inc. (U.S.), Cepheid, Inc. (U.S.), GE Healthcare (U.K.), QIAGEN N.V. (Netherlands), and Roche Diagnostics (Switzerland)
- The Illumina HiSeq 10 costs ca $10m, the 5, $6m. Output per run is 1.8Tb. More than 400 of these have been sold
- Illumina's new NovaSeq 6000 with "improved optics" is expected to reduce the cost of decoding the human genome from the current $1000 to $100 by 2018

NovaSeq 6000

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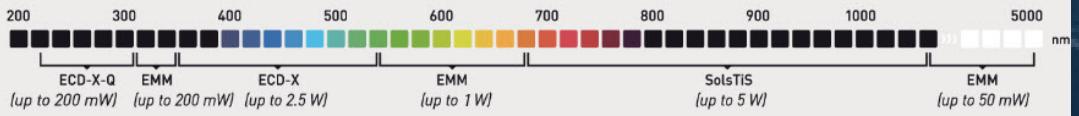
Number 79 of the UK's Top 100 Fastest Growing Tech Companies: The Sunday Times Sept 10th 2017

- M Squared Lasers
- Founded 2006
- Sales £13.9m
- Employees 92

M Squared is a leading developer of photonic and quantum technologies, harnessing the power of light to drive society changing innovation

SOLSTIS PLATFORM



SPRITE PLATFORM

Pulsed Tunable NIR

SPRITE XT

An ultrafast laser source combining flexibility with stability, reliability and productivity - available as femtosecond, picosecond and fixed wavelength or tunable versions.

CW Tunable NIR

SOLSTIS

The award-winning SolsTiS is a step-change in continuous-wave Ti:Sapphire laser technology - compact, ultra-narrow linewidth, fully automated and widely tunable.

CW Tunable UV

SOLSTIS ECD-X

A compact frequency conversion module that extends the range of SolsTiS output wavelengths via frequency doubling in a resonant cavity with optimised conversion efficiency.

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Number 56 of the UK's Top 100 Fastest Growing Tech Companies: The Sunday Times Sept 10th 2017

- iPulse – pulsed light for hair removal
- Backed by BGF
- 2016 sales £17.5 m
- 32 employees

- The technology was developed at CyDen by Prof. Clement, originally a laser plasma researcher and now with a web of medical device companies
- "*IPL is closer to natural light, similar to that generated by a camera flash. Laser light is a very specific (man-made) type of light. For the purposes of hair removal, both laser light and IPL light work by exactly the same mechanism*"
- Ironically another lucrative market is low light level therapy for hair growth

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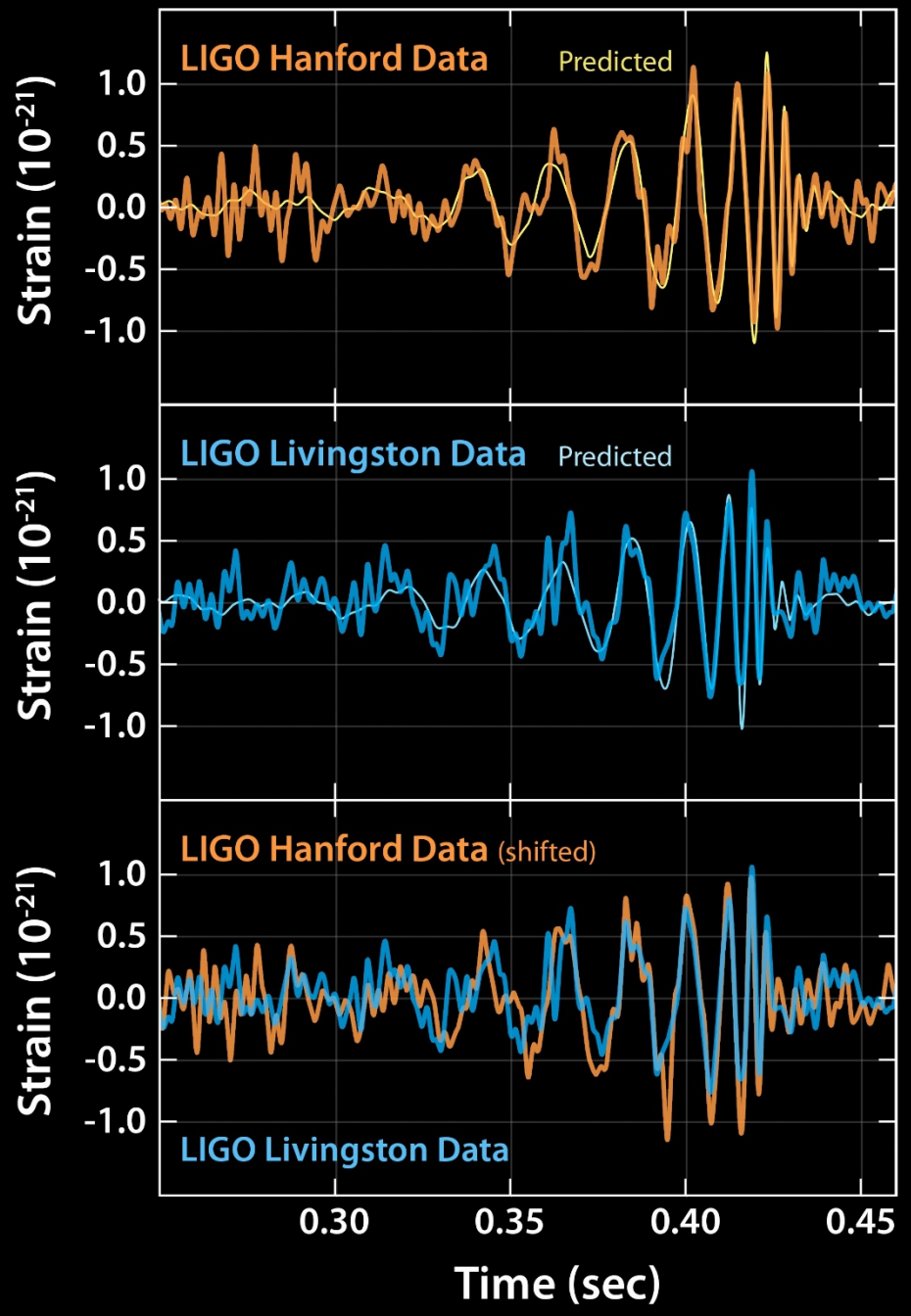
A New Astronomy

Made possible by lasers, optics and patient funding

- On 14th September 2015 LIGO detected gravitational waves from the merger of two black holes coalescing 1.3 billion light years away
- 26th December 2015, a second smaller event was detected
- January 4th a third event, another merger of black holes was recorded
- August 14th a fourth event - detection of a neutron star event just announced brought "conventional astronomy" and gravitational wave detection together



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More LIGOs

- The two LIGOs were substantially upgraded and it was during the initial testing of the upgrade that the first momentous discovery occurred. Now there are four discoveries, the last also having been recorded by VIRGO in Italy
- October 3rd, Rainer Weiss, Kip Thorne, and Barry Barish were awarded the 2017 physics Nobel "*for decisive contributions to the LIGO detector and the observation of gravitational waves*".

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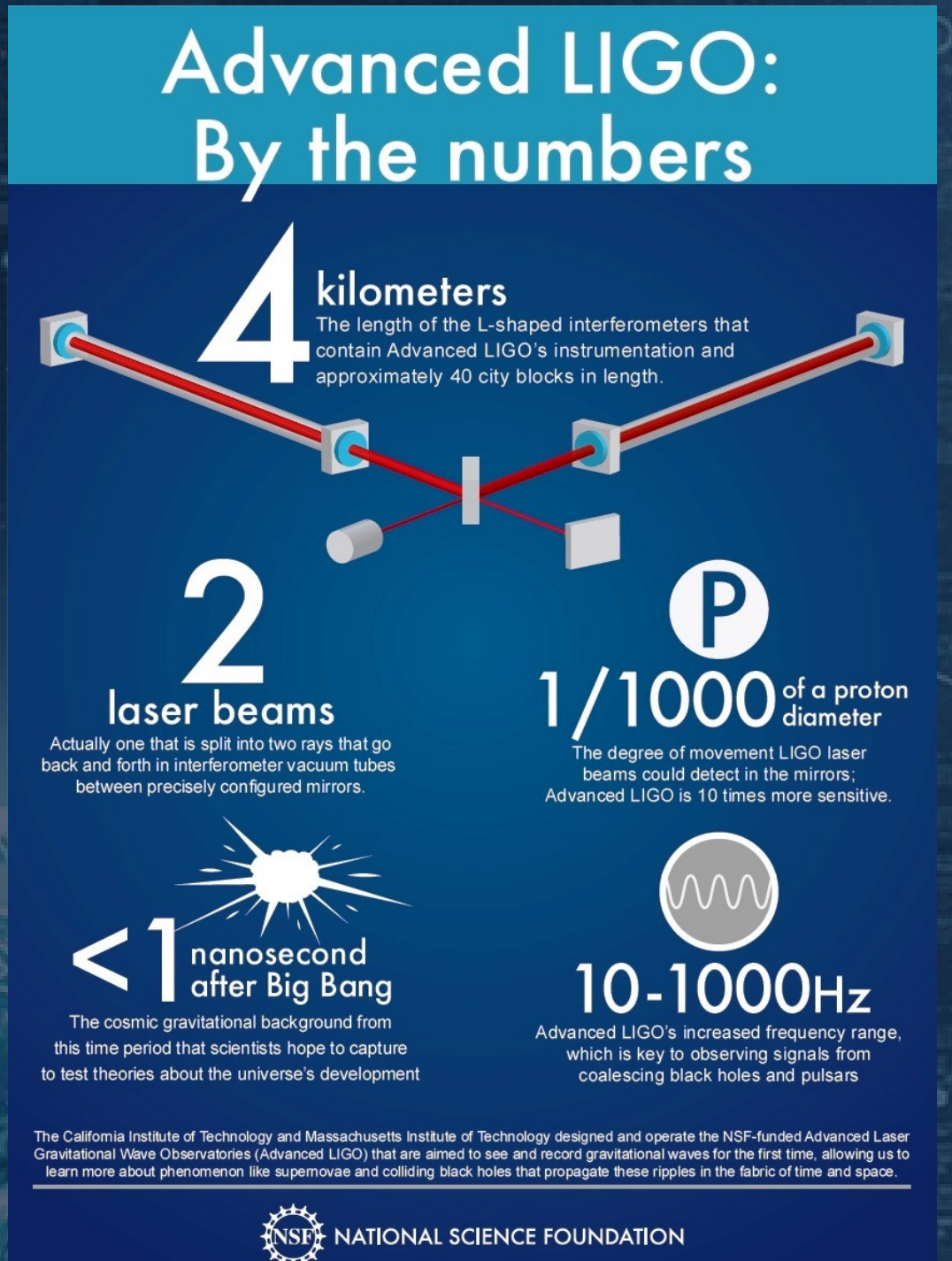
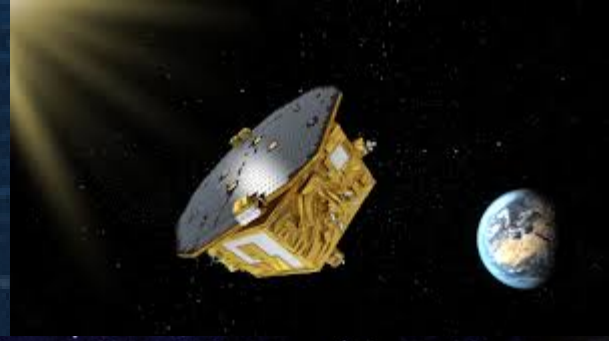
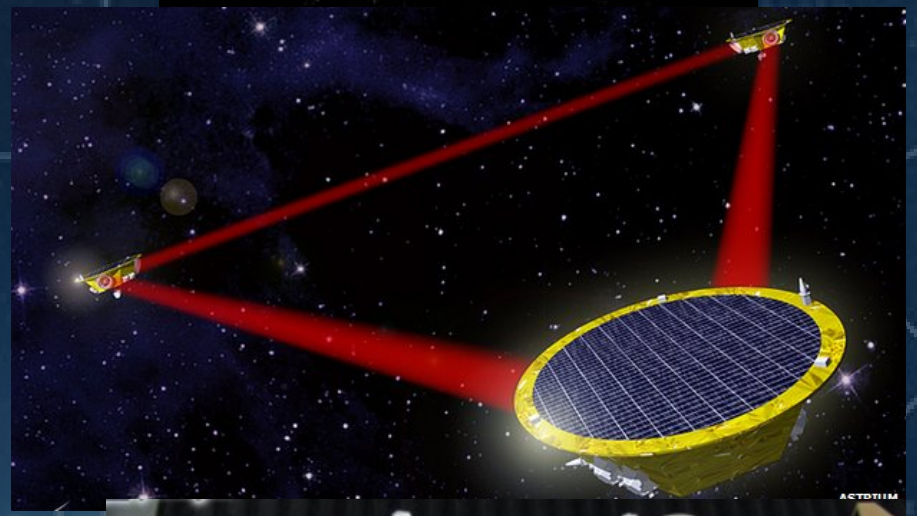
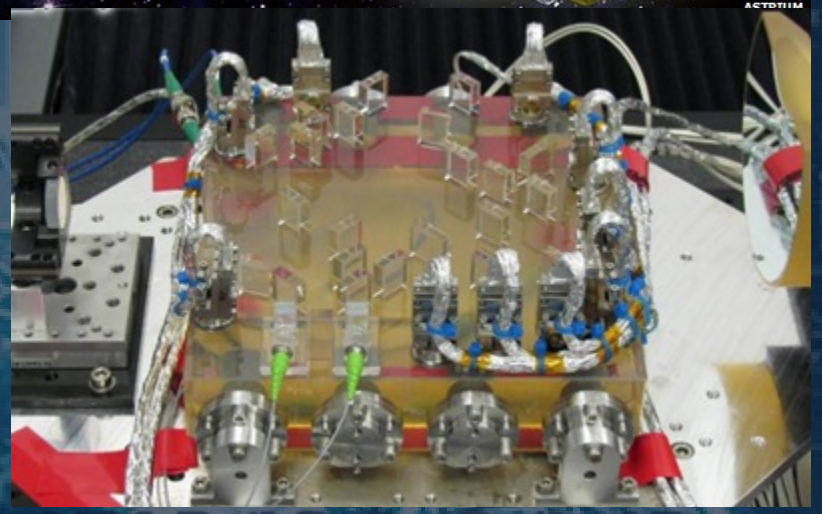


LISA

- The next big leap forward will be LISA, a multisatellite based detector system with 5 million km optical paths
- A test satellite for LISA, LISA Pathfinder, was successfully launched December 15th 2015. ESA said that the tests of the optical system were successful. The mission ended in June
- LISA is expected to launch in the 2030s







LISA Pathfinder Optical Bench
University of Glasgow

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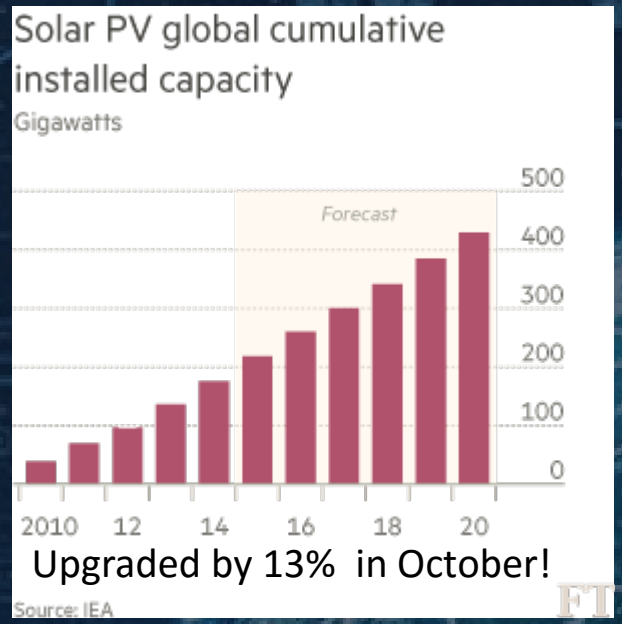
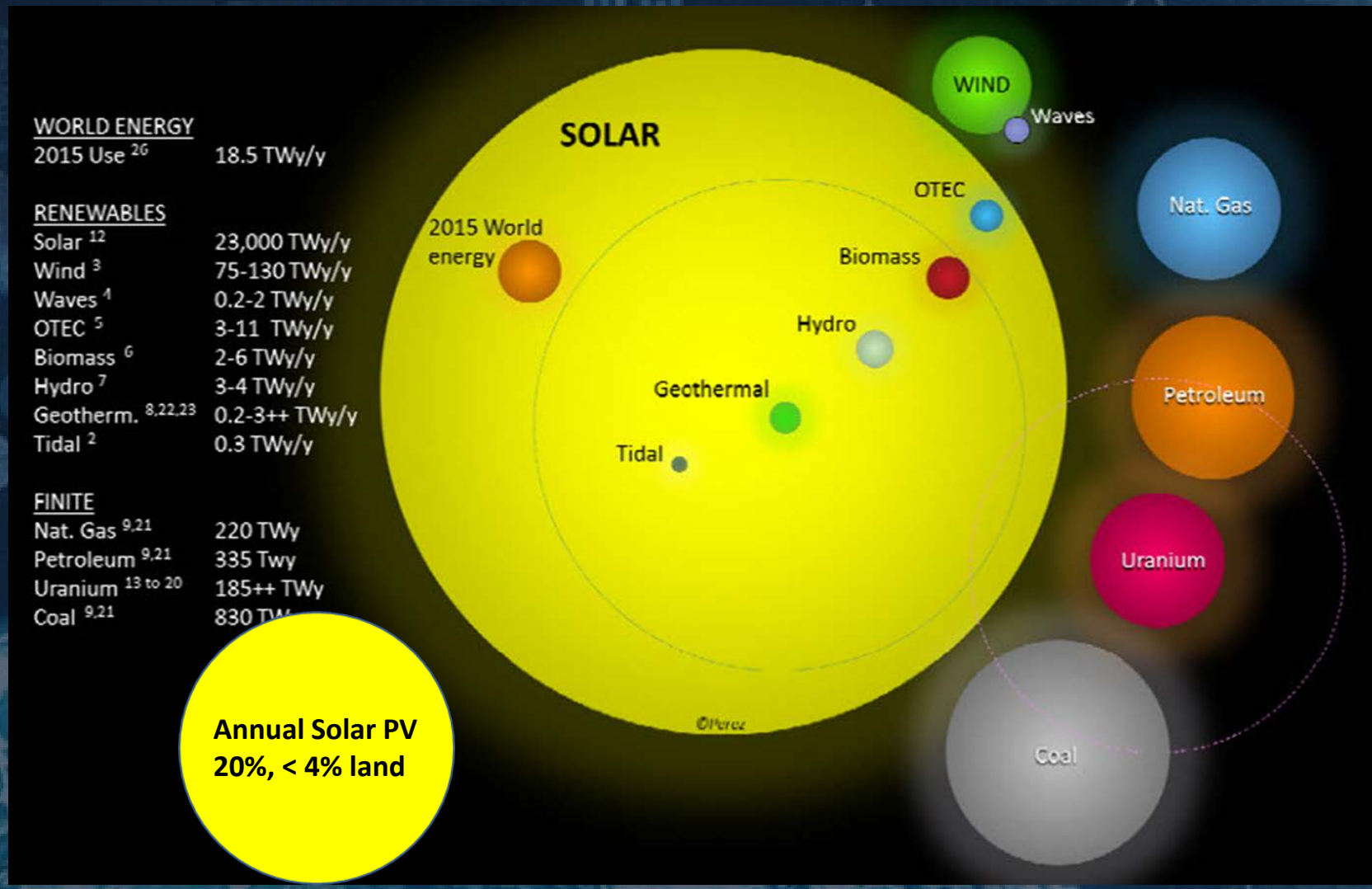
Energy

- "Proven" total energy reserves vs. potential of annual renewables
- At present consumption rates – and ignoring the non sustainable climate impact of these, there are less than 100 years of the 2 billion years of stored solar photons left



Upgraded by 13% in October!

WORLD ENERGY	
2015 Use [26]	18.5 TWy/y
RENEWABLES	
Solar [12]	23,000 TWy/y
Wind [3]	75-130 TWy/y
Waves [4]	0.2-2 TWy/y
OTEC [5]	3-11 TWy/y
Biomass [6]	2-6 TWy/y
Hydro [7]	3-4 TWy/y
Geotherm. [8,22,23]	0.2-3++ TWy/y
Tidal [2]	0.3 TWy/y
FINITE	
Nat. Gas [9,21]	220 TWy
Petroleum [9,21]	335 Twy
Uranium [13 to 20]	185++ TWy
Coal [9,21]	830 TW



Annual Solar PV 20%, < 4% land

Adapted from Perez & Perez

IEA-SHCP-Newsletter Vol. 62, Nov. 2015

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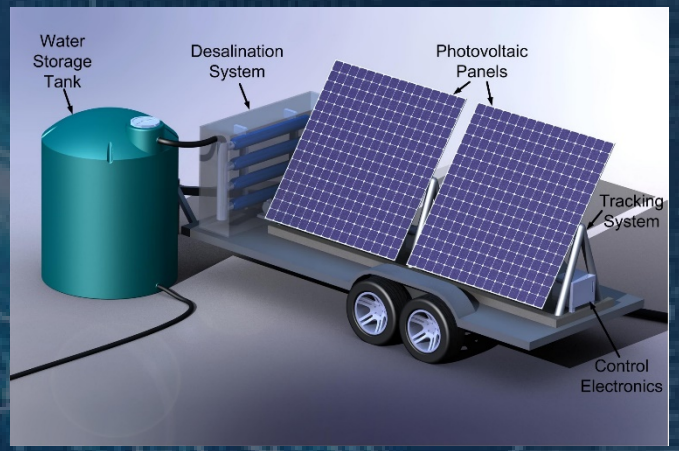
Photons to Water

- Solar powered water desalination and water treatment is sustainable and more and more affordable
- Avoids the storage problem
- Large-Scale Solar Powered Desalination Plants- e.g. Al Khafji (Saudi Arabia), Ras Al Khaimah (UAE), etc.
- Local agricultural water clean up, e.g. Firebaugh, CA. (USA)
- Mobile desalination (MIT, USA)



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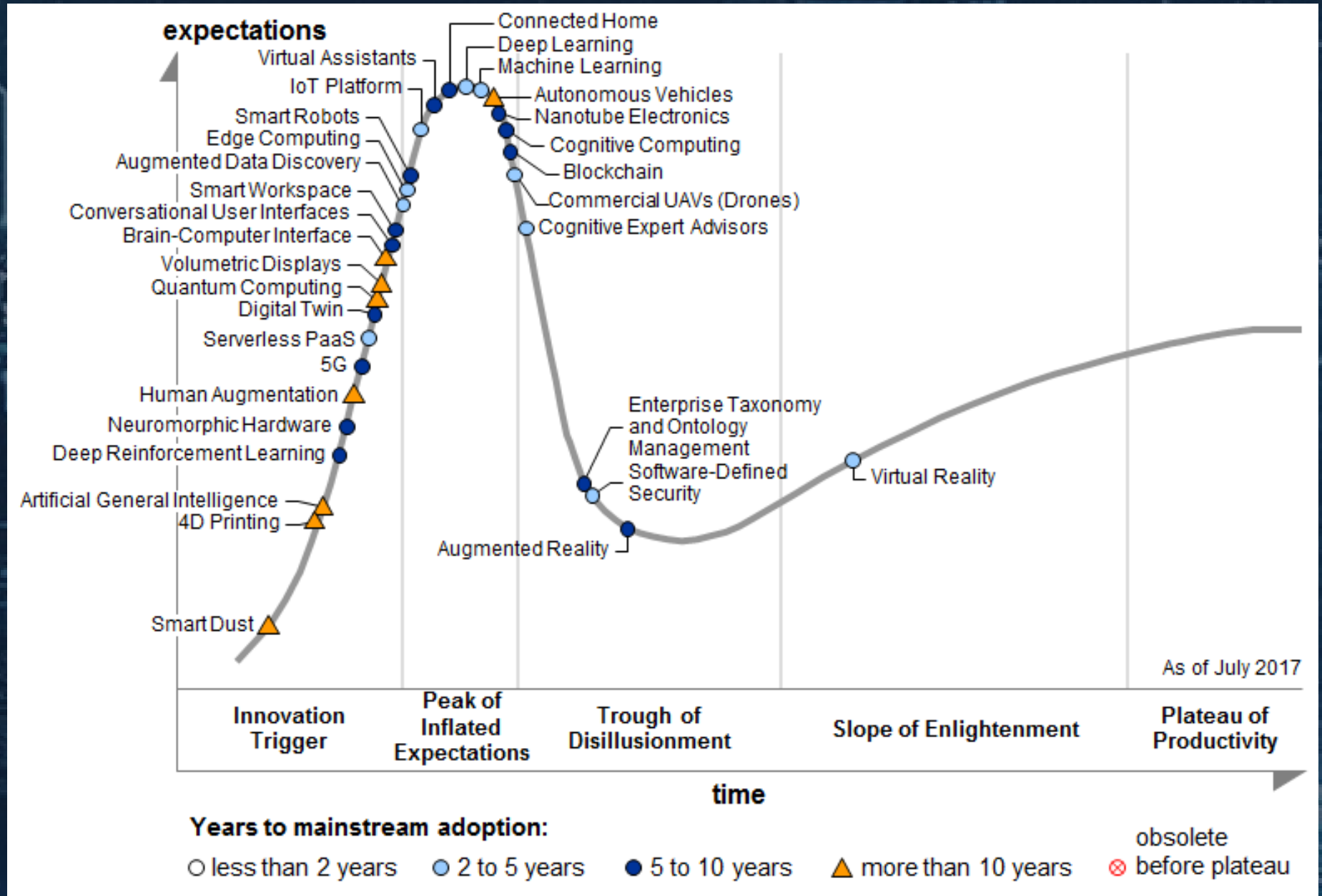
2017 Gartner Hype Curve



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The Future

- I hope I gave you a sense that photonics has an unbounded future
- You will find all of today's financially exciting photonic activity in SPIE's meetings and proceedings of the past, some decades ago

"*The future depends on what you do today*"

Mahatma Gandhi

Thank You

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