Photonic Integrated Circuits (PICs): Enabling our future…

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2nd June 2021

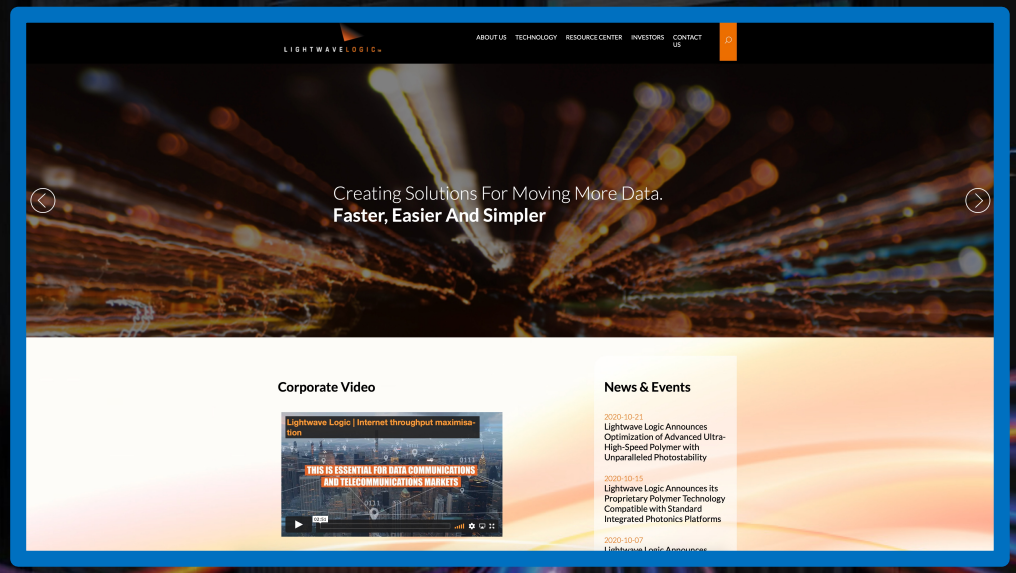
Photonic Integration Technology Center: Keynote

Safe Harbor

The information in this presentation may contain forward-looking statements within the meaning of the Private Securities Litigation Reform Act of 1995. You can identify these statements by use of the words "may," "will," "should," "plans," "explores," "expects," "anticipates," "continue," "estimate," "project," "intend," and similar expressions. Forward-looking statements involve risks and uncertainties that could cause actual results to differ materially from those projected or anticipated. These risks and uncertainties include, but are not limited to, general economic and business conditions, effects of continued geopolitical unrest and regional conflicts, competition, changes in technology and methods of marketing, delays in completing various engineering and manufacturing programs, changes in customer order patterns, changes in product mix, continued success in technological advances and delivering technological innovations, shortages in components, production delays due to performance quality issues with outsourced components, and various other factors beyond the Company's control.

This orange bar is the takeaway summary from each slide…

Slides will be posted at our website: www.lightwavelogic.com



Sit back…relax (no need to take notes!)

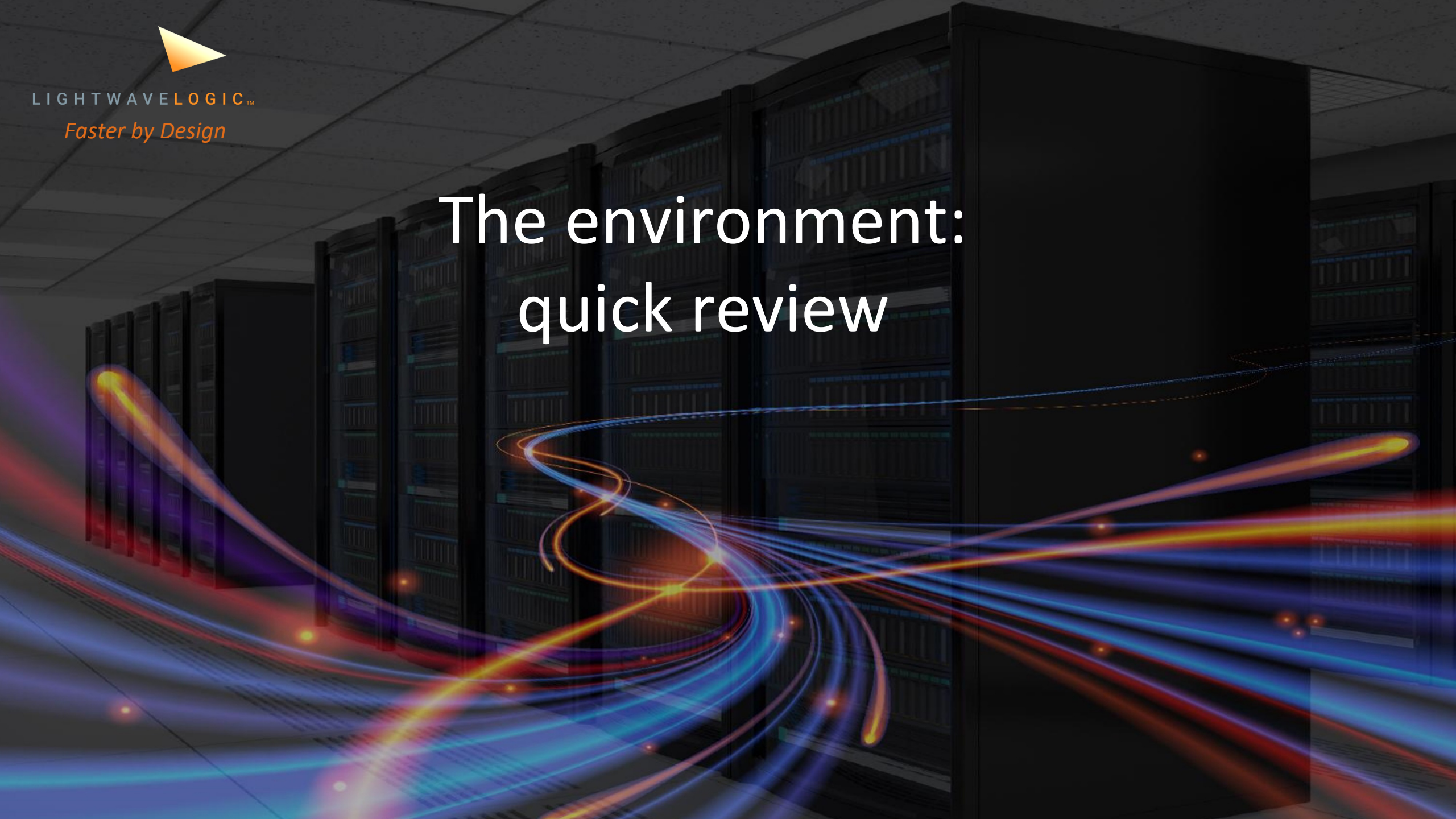
Agenda

- The environment
- Markets
- Technologies
  - Cost/performance, data rates & speed, packaging
- Roadmaps
- Summary

3 questions to remember today…

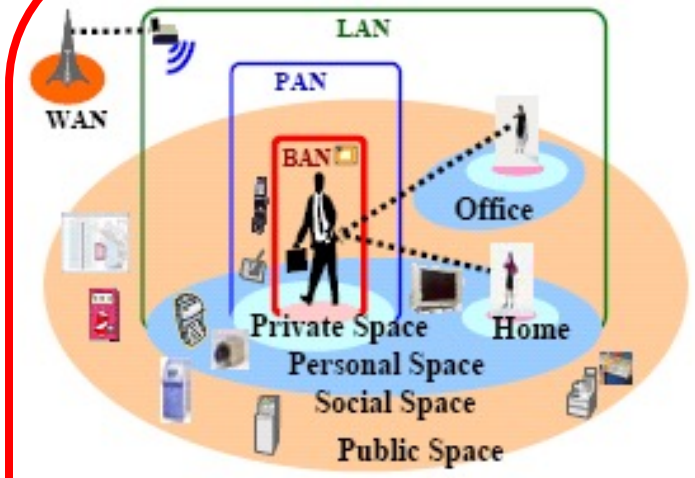
- **Will PIC photonics enable many things and will it be part of our lifestyle?**
- **Will photonics will be integrated – just like ICs 50 years ago and become the engine for new designs?**
- **Will integrated photonics (PICs) enable new products?**

What might be the impact of PICs over the next decade?



The environment: quick review

The internet as a catalyst for change in lifestyle…



- Before
- Computer centric
- Experts level
- Data exchange
- Exchange

- Today
- Network centric
- Trained level
- Archival access
- Datacenter

- Future
- User centric
- Pedestrian level
- Cloud access
- Hyper-scale datacenter

Use of heavy data…

Lifestyle evolves towards personal space…

Source: MIC Japan, Fujitsu, NTT; OIDA Research

What is affecting our lifestyle change?

- Virtual lifestyle – working from home
- Use of lots of data…
- Video
- New applications (AR/VR)…

Data-centric applications

Cloud services

aws Microsoft Azure

Industrial automation traffic

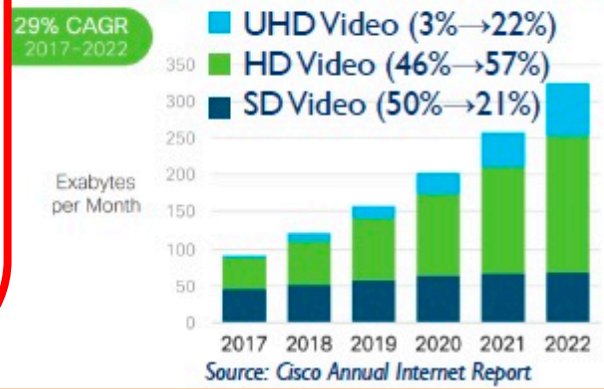
Video streaming at higher-definition (4k or 8k)

NETFLIX tv+ Disney+ prime video HBOmax hulu

Emerging applications

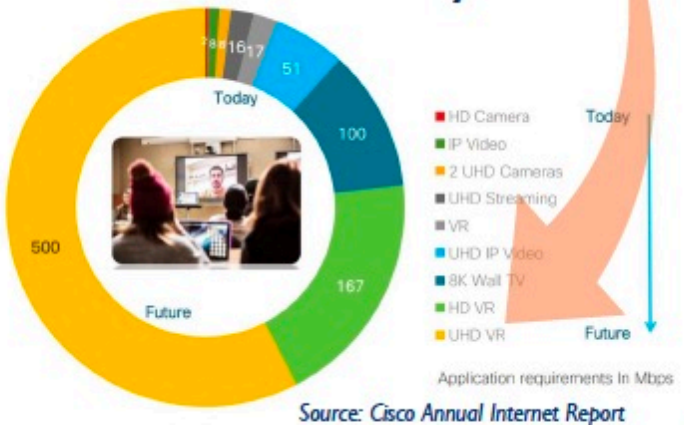
AR/VR

Global internet video traffic



Source: Cisco Annual Internet Report

Video data rates of today and the future

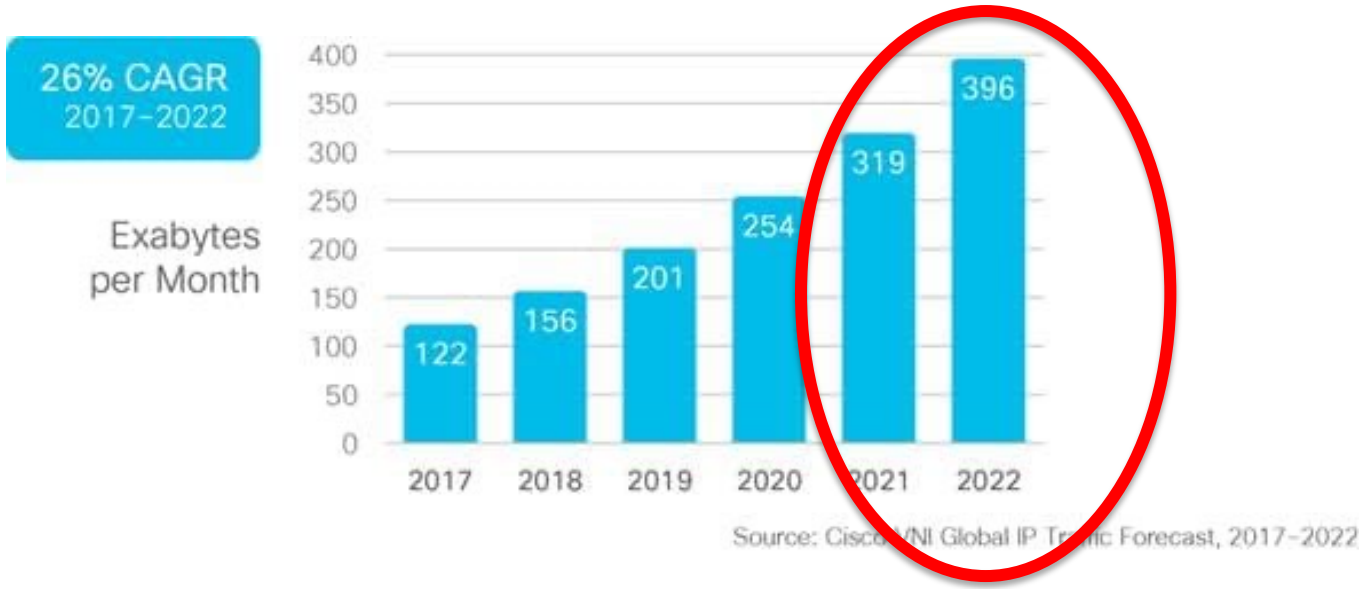


Source: Cisco Annual Internet Report

Video – use of heavy data…

Sources: Cisco, Yole, EPIC

Video driving internet traffic…



~400 Exabytes per month
or
~4 Yottabytes per year today

	International Metric
Old phone Kbps →	Kilo = 10^3
Home Mbps →	Mega = 10^6
Business Gbps →	Giga = 10^9
Datacenter Tbps →	Tera = 10^{12}
Hyperscale DC →	Peta = 10^{15}
Traffic last few yrs →	Exa = 10^{18}
Traffic today →	Zetta = 10^{21}
Traffic tomorrow →	Yotta = 10^{24}

NB: SI prefixes stop at Yotta…

Virtual lifestyle is now the 'new normal'

Sources: Cisco VNI

New trends → Automotive

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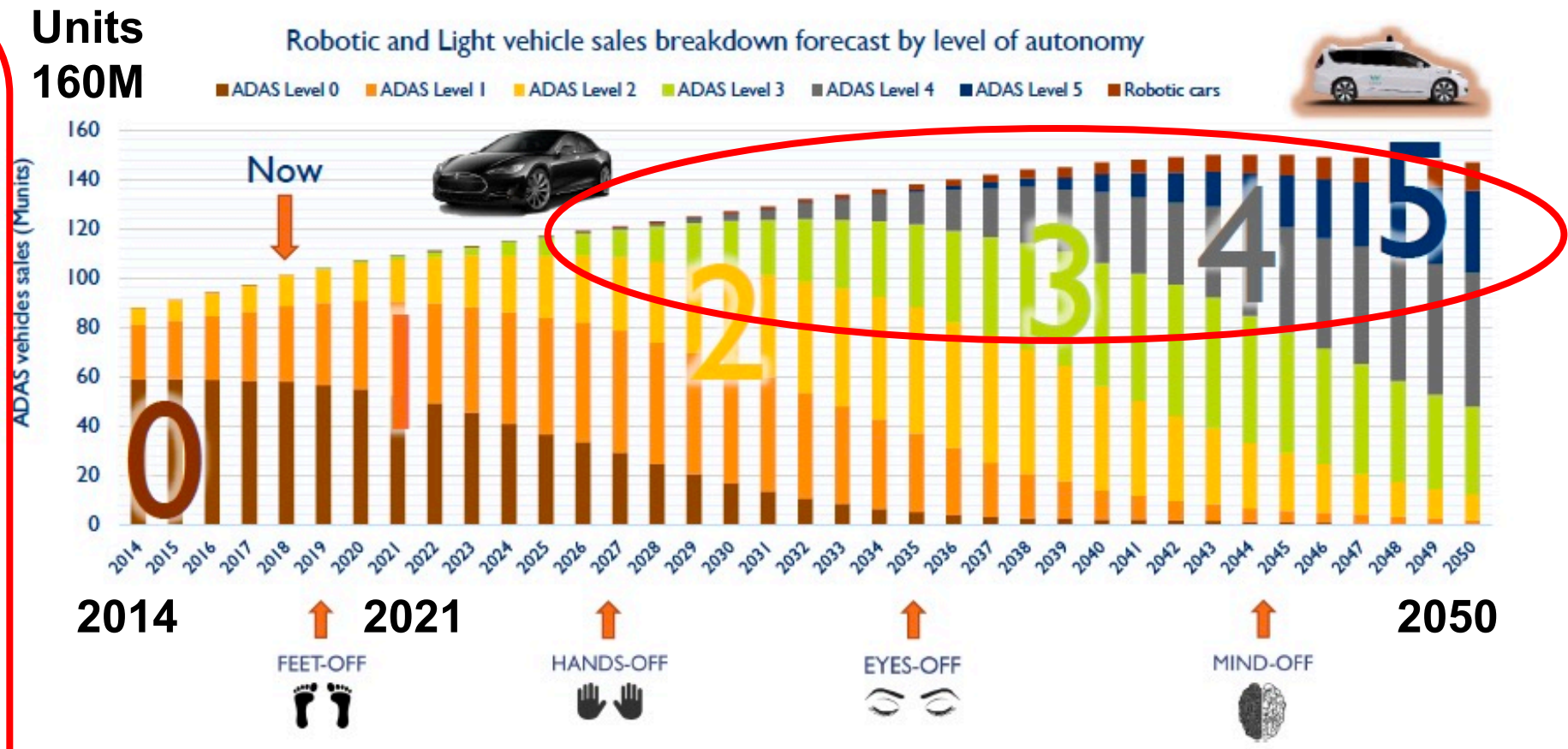
- Networking, LIDAR, sensing, cameras…
- Integrated systems will need PICs
- Level 4&5 need more data → fuels datacenters and traffic



PICs will benefit from the 'heavy data' use…

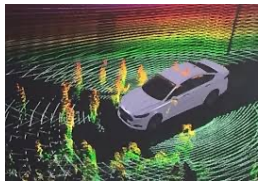
Sources: Yole, EPIC, Waymo, Jaguar

New market opportunities are growing

- 5G systems
- RF over fiber
- Automotive (LIDAR)
- Optical sensing
- Bio-photonic sensing
- Medical
- Instrumentation
- Fiber comms
- HPC
- DCI

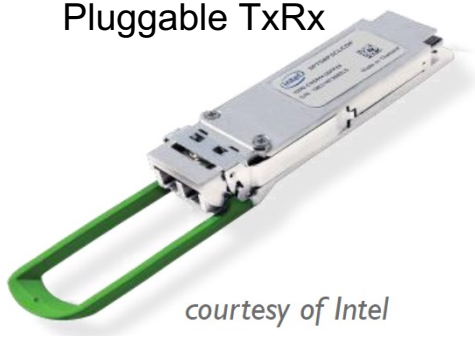
5G

RF over fiber



Automotive

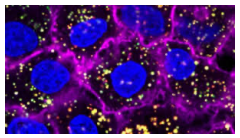
Pluggable TxRx



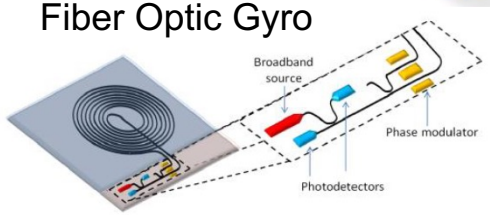
courtesy of Intel

Medical

Bio sensing



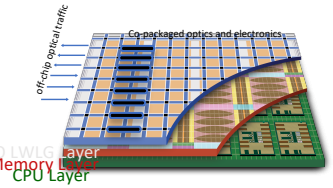
Fiber Optic Gyro



courtesy of Optics Express

Submarine FO

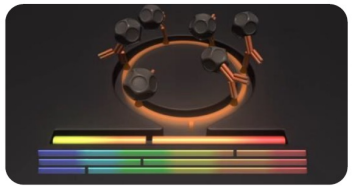
HPC



Datacenter

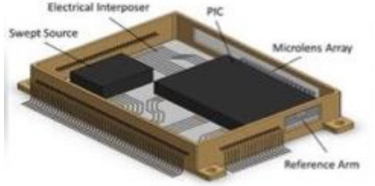
Source: Mitsubishi Electric, Luxtera, IBM, Google

Immunoassays



courtesy of Genalyte

OCT



courtesy of OCTCHIP

LiDAR

courtesy of SiLC

Broad applications for PIC platforms…that send/receive optical data…

Sources: Yole, LWLG, OCTCHIP, SiLC, Intel, Genalyte, Optics Express, IBM, Cisco, Google, Mitsubishi

 (OTCQB: LWLG)

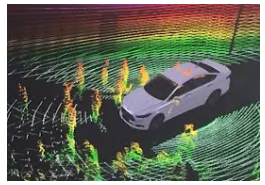
Photonics expected to grow significantly

	2030 photonics (rough forecasts*)
• 5G systems	~$4-10B
• RF over fiber	~$2-5B
• Automotive (LIDAR)	~$20-30B
• Optical sensing	~$2-5B
• Bio-photonic sensing	~$2-5B
• Medical	~$5-10B
• Instrumentation	~$1-3B
• Fiber comms	~$40-60B
• HPC	~$10-20B
• DCI	~$20-30B

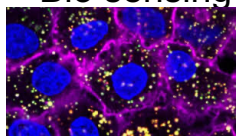
*Many market forecasts predict huge photonics opportunities

Automotive

RF over fiber

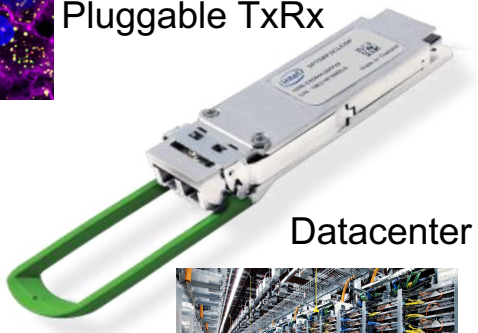


Bio sensing



5G

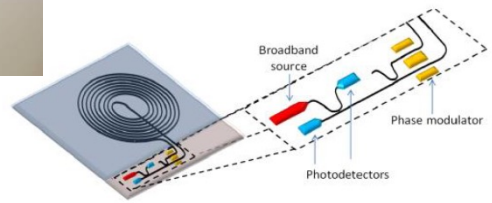
Pluggable TxRx



Datacenter

Medical

Fiber Optic Gyro



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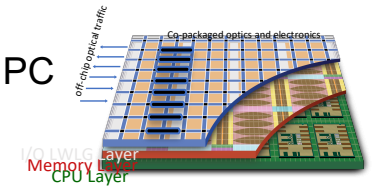
Submarine FO

HPC



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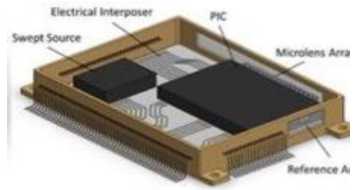
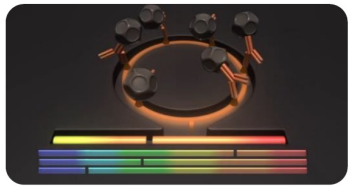


courtesy of OCTCHIP

LiDAR

courtesy of SiLC

Immunoassays



courtesy of Genalyte

Markets for photonics are huge…

Sources: Oculi llc, Yole, LWLG, OCTCHIP, SiLC, Intel, Genalyte, Optics Express, IBM, Cisco, Google, Mitsubishi

Photonics market forecast: fiber optic communications

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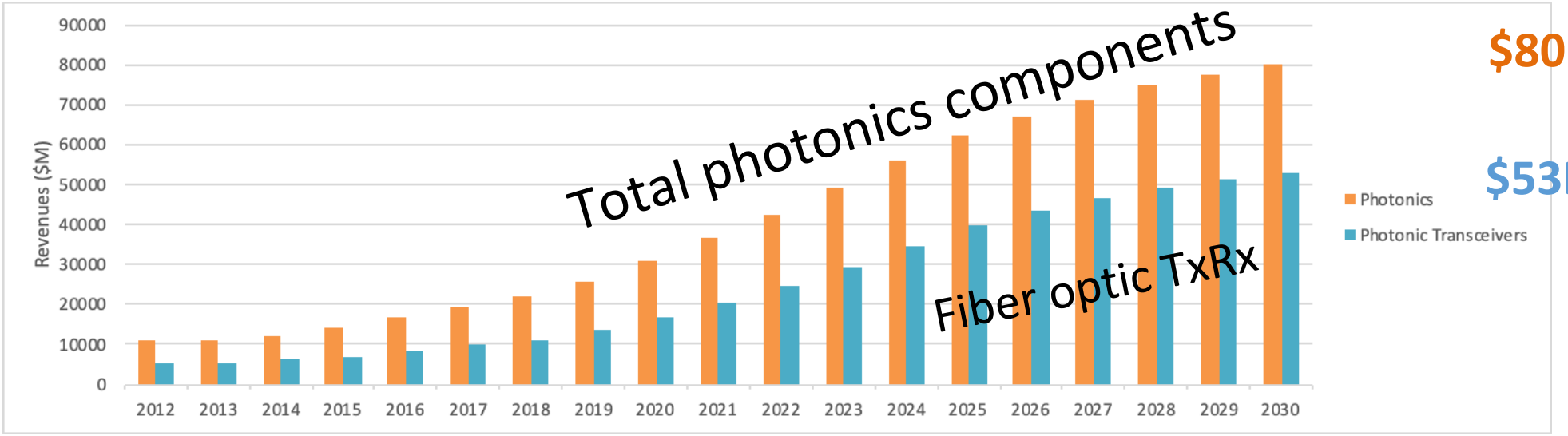
Fiber Optic transceivers are the perfect vehicle for PICs



$80B; 2030

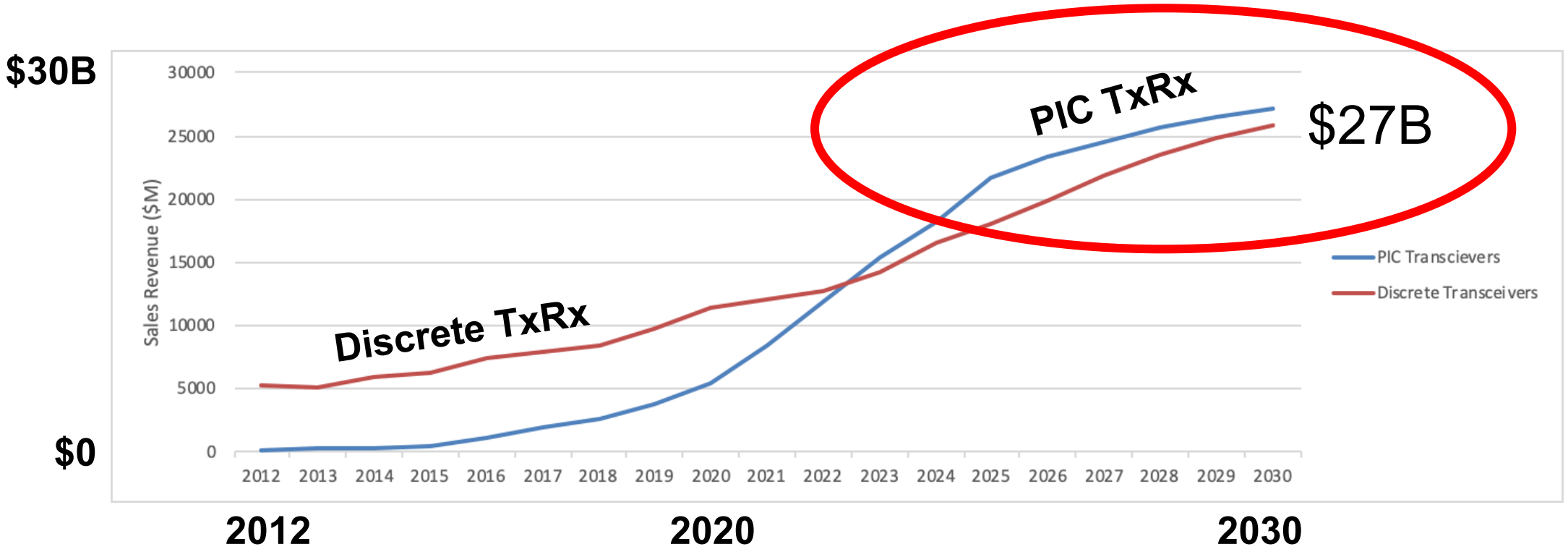
$53B, 66%

Fiber optic transceiver explodes over the next decade…

Sources: Oculi llc

Important PIC metrics…

- PIC based transceivers lead the segment by 2030

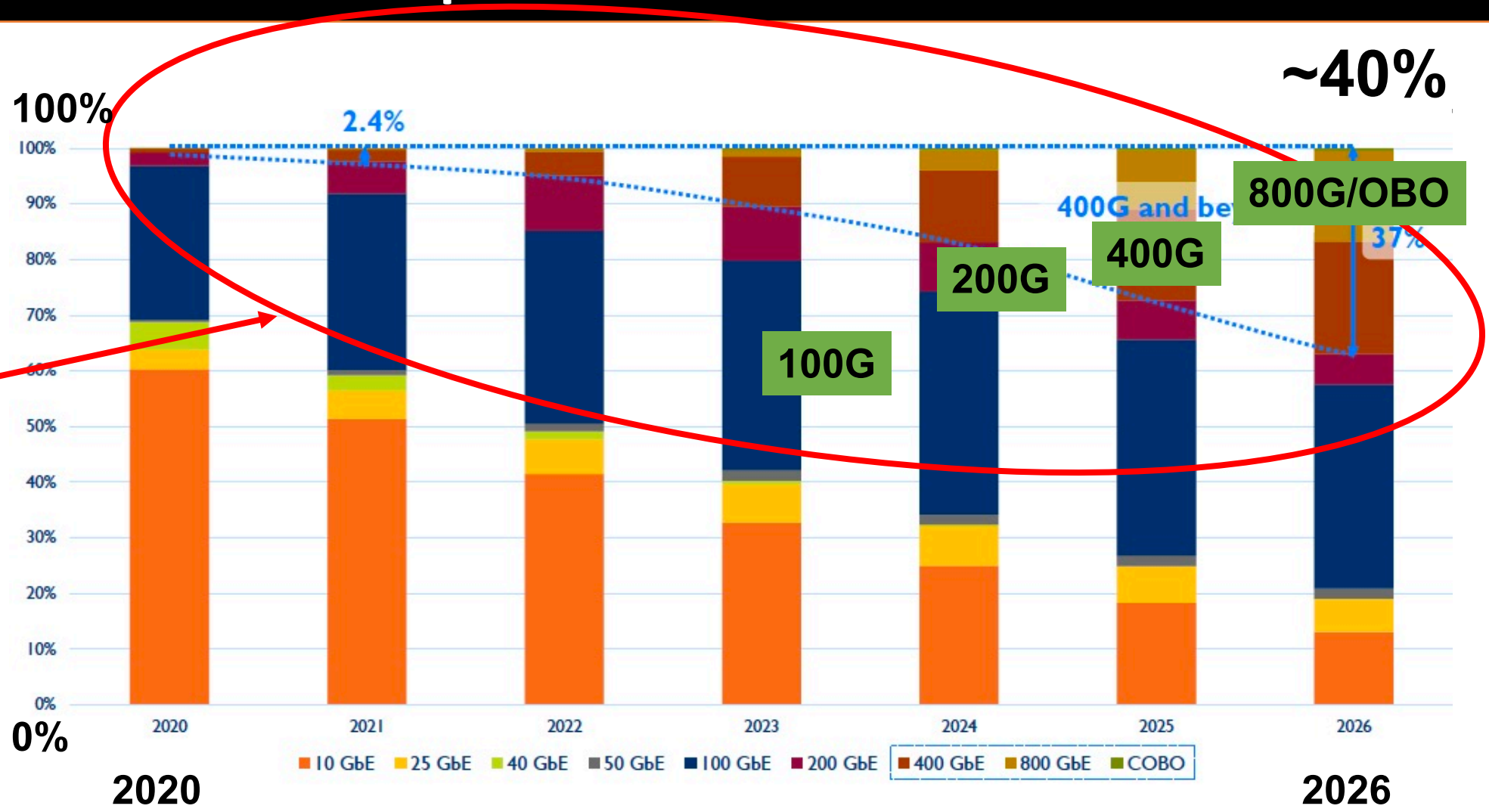


PICs are expected to accelerate in their adoption over the decade…

Sources: Oculi llc

Datacenter optical TxRx module penetration

- Strong growth of 400G, 800G and OBO (onboard optics)
- This represents a huge opportunity for PICs



PICs will be the engine for growth with 400, 800Gbps data rates…

Sources: Yole, LWLG

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Technologies

Key PIC technology platforms

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- Historic incumbent:
  - InP (Indium Phosphide)
  - GaAs (Gallium Arsenide)
- New incumbent:
  - SiP (Silicon photonics)
- ***New platforms and hybrid accelerators for PICs***
  - *Polymer, dielectrics, glass, lithium niobate thin film, plasmonic, barium titanate, silica, glass, germanium etc.*

Silicon photonics is the new kid on the block; new platforms → hybrid PICs

Sources: LWLG

Sample global players and their PIC platforms

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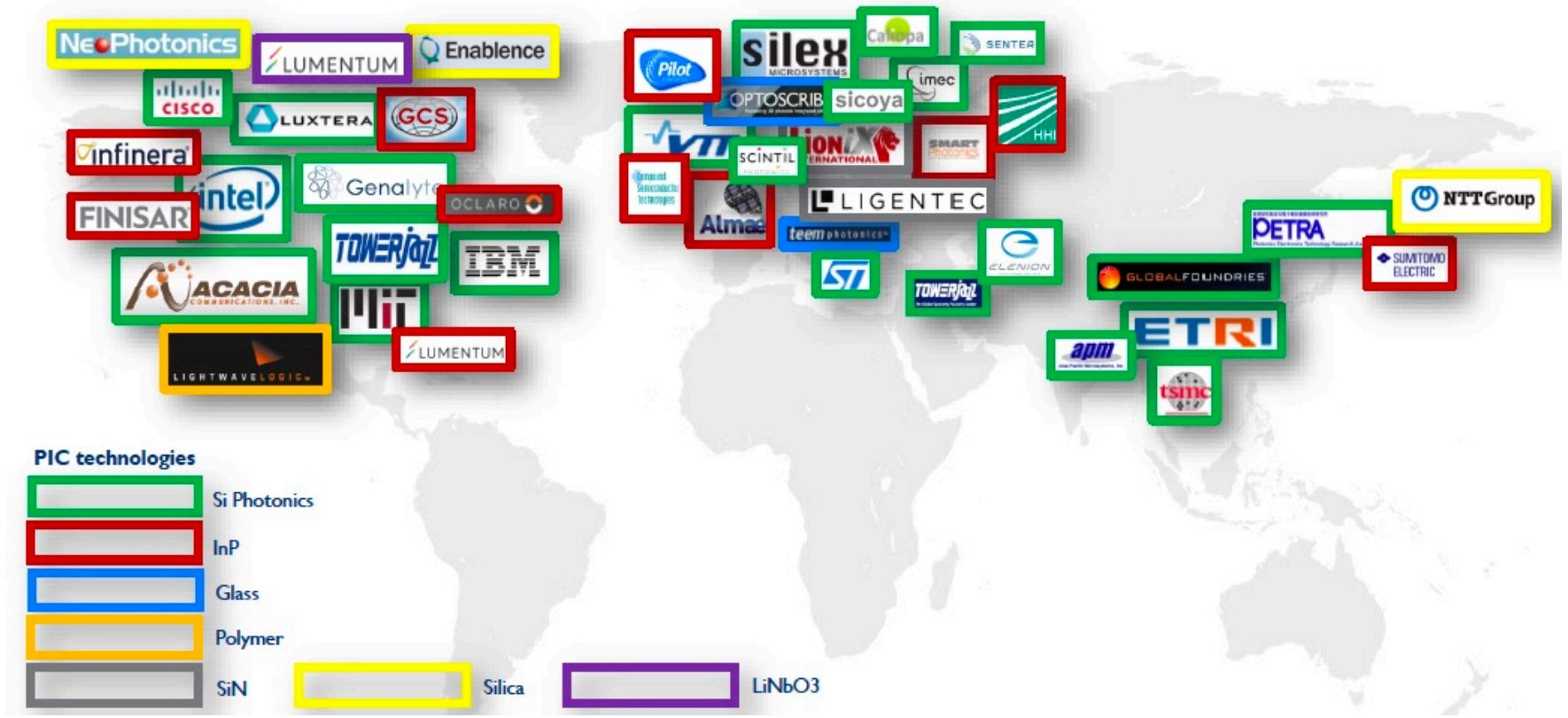
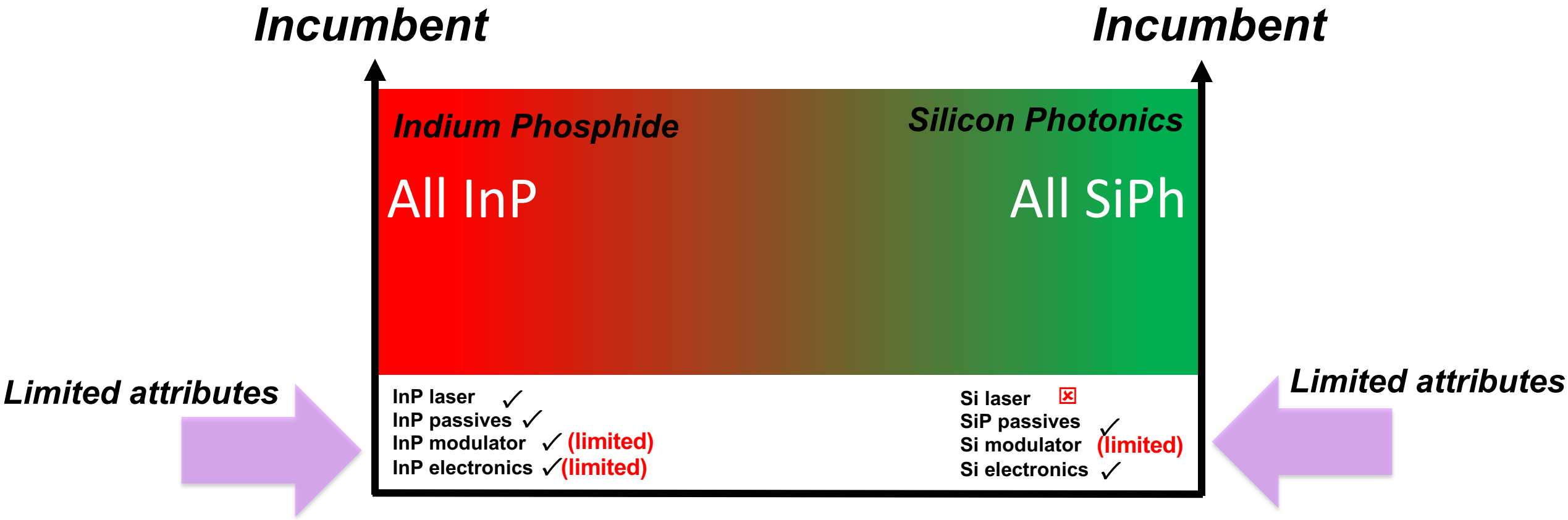
- Growth of Silicon photonics
- Trend towards hybrid platforms for PICs
- What combinations of technology make sense for hybrid PICs?



Challenge is to further PIC performance with other materials → hybrid PICs

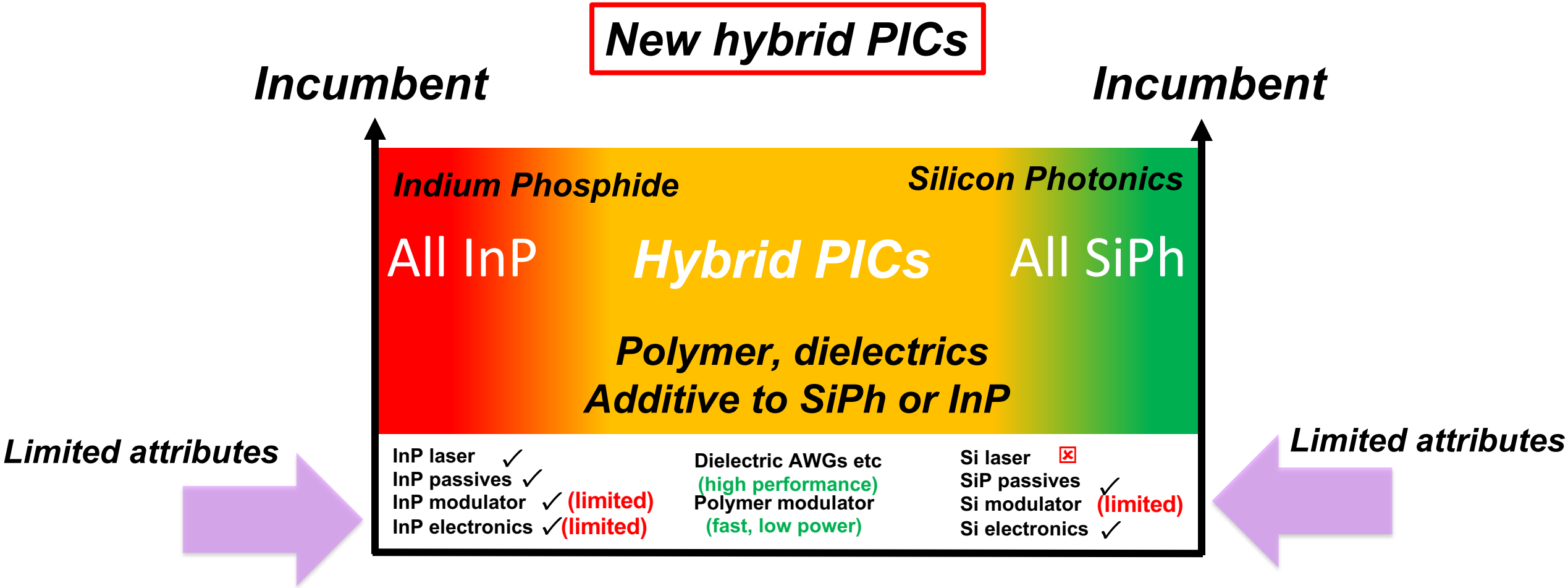
Sources: Yole

Industry has 2 incumbent PICs…



Incumbent technologies can't do everything…need help from hybrid PIC technologies…

Hybrid PICs increase performance…



Hybrid PICs can boost performance of PICs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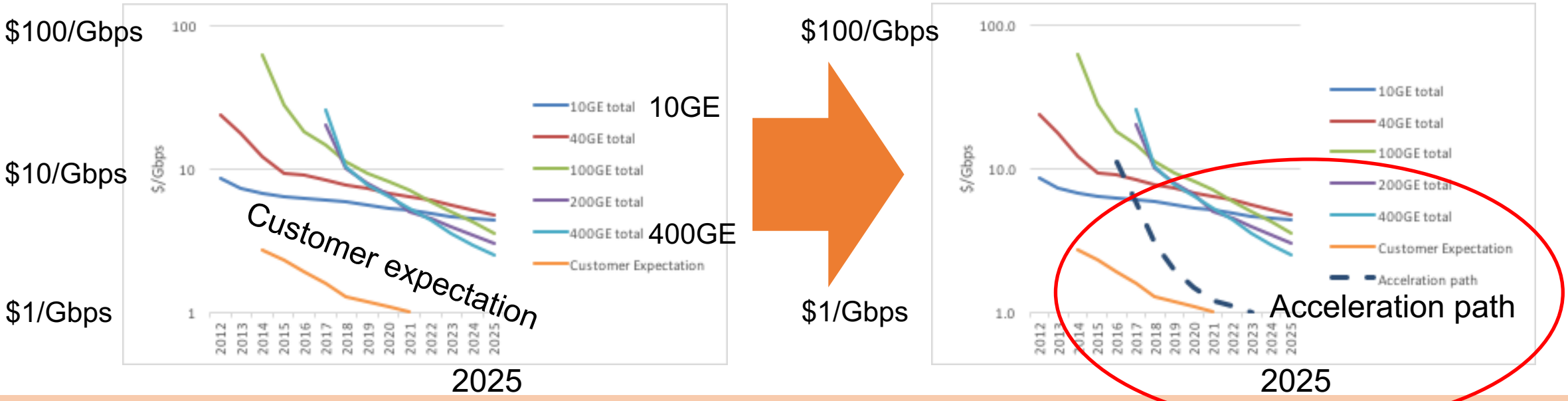
Cost performance:
Achieving <$1/Gbps will open
new markets for PICS…

Motivators for PICs in fiber optics

- Industry is expected to lag the wishes of customers at datacenters
  - Challenge: $0.5/Gbps for 800G link is $400 (or $200 each end)



PICs can close this gap…

Sources: Oculi llc

Increasing die size trends for PICs

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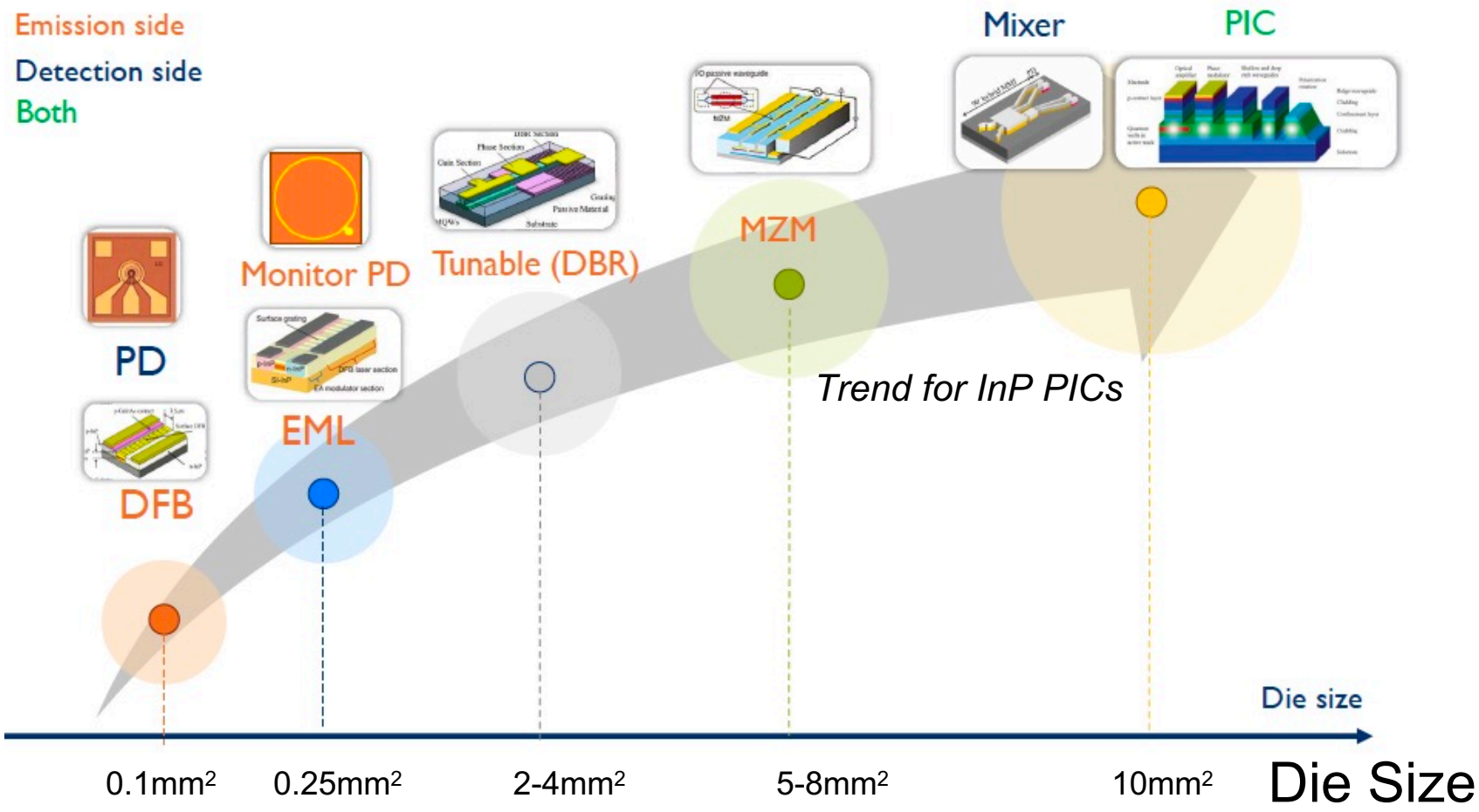
- Complexity → bigger PIC chips
- Pressure to increase wafer size for economics of scale
- Hybrid PICs will allow both InP and SiPh to create competitive PICs in the next decade…



Industry can achieve cost/speed metrics through PIC platforms

Sources: Yole, EPIC

Silicon foundries are hungry for 'opto' business

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- CMOS fabrication plants want silicon photonics…new upside
- PDKs will drive the hybrid integration of PIC platforms

*PDK = Process Development Kit

Drive to 200/300mm allows competitive PIC cost/volume


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PIC speed:
Can we make PIC devices faster?

Traffic capacity: road analogy

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Good roads: Faster cars: more traffic capacity

More lanes: more traffic capacity

We have already finished the easy things → like paving the road, adding more lanes…

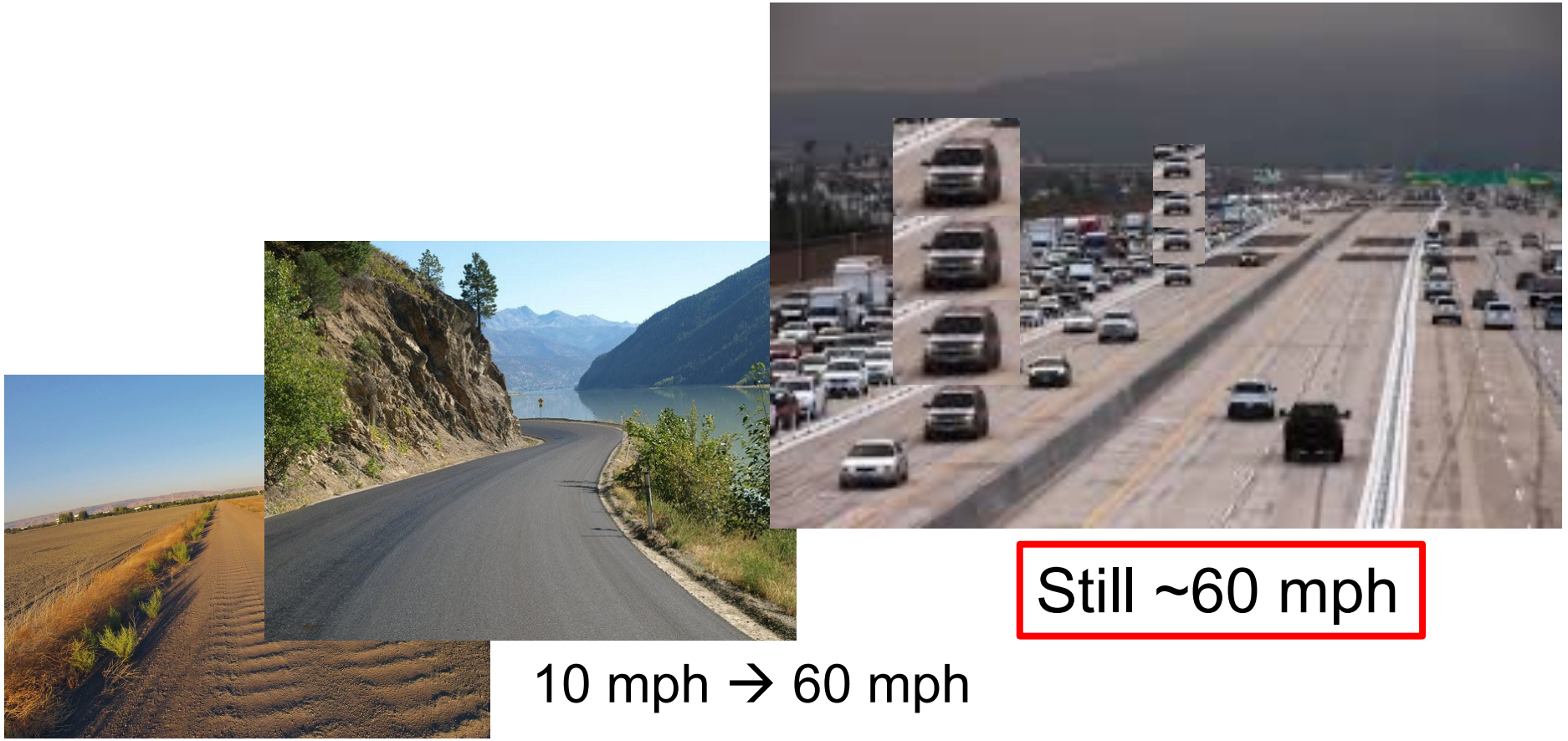
Sources: LWLG

Sending more data down the same lane (channel)…

Industry has already done the harder stuff like ‘higher order modulation’ [PAM4, QAM, etc.]

Sources: LWLG

What about speed?



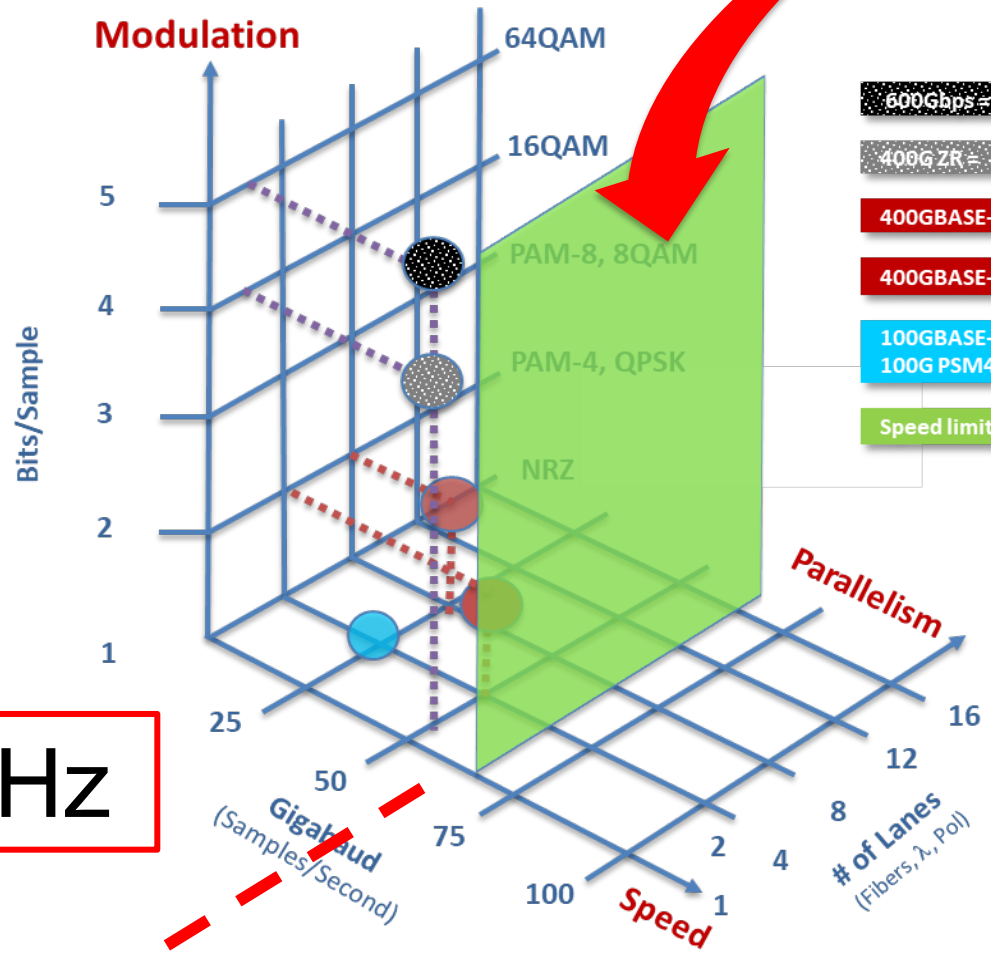
10 mph → 60 mph

Still ~60 mph

Speed has hit a plateau…

Sources: LWLG

Speed limited by conventional photonics



600Gbps = 64 Gbaud, 64QAM, 2 polarizations

400G ZR = 50Gbaud, 16QAM, 2 polarizations

400GBASE-DR4/ 400G FR4= 50 Gbaud, PAM4, 4 wavelengths

400GBASE-LR8= 25 Gbaud, PAM4, 8 wavelengths

100GBASE-LR4/100G CWDM4 = 25 Gbaud, NRZ, 4wavelengths
100G PSM4 = 25 Gbaud, NRZ, 4 fibers

Speed limitation of optical devices

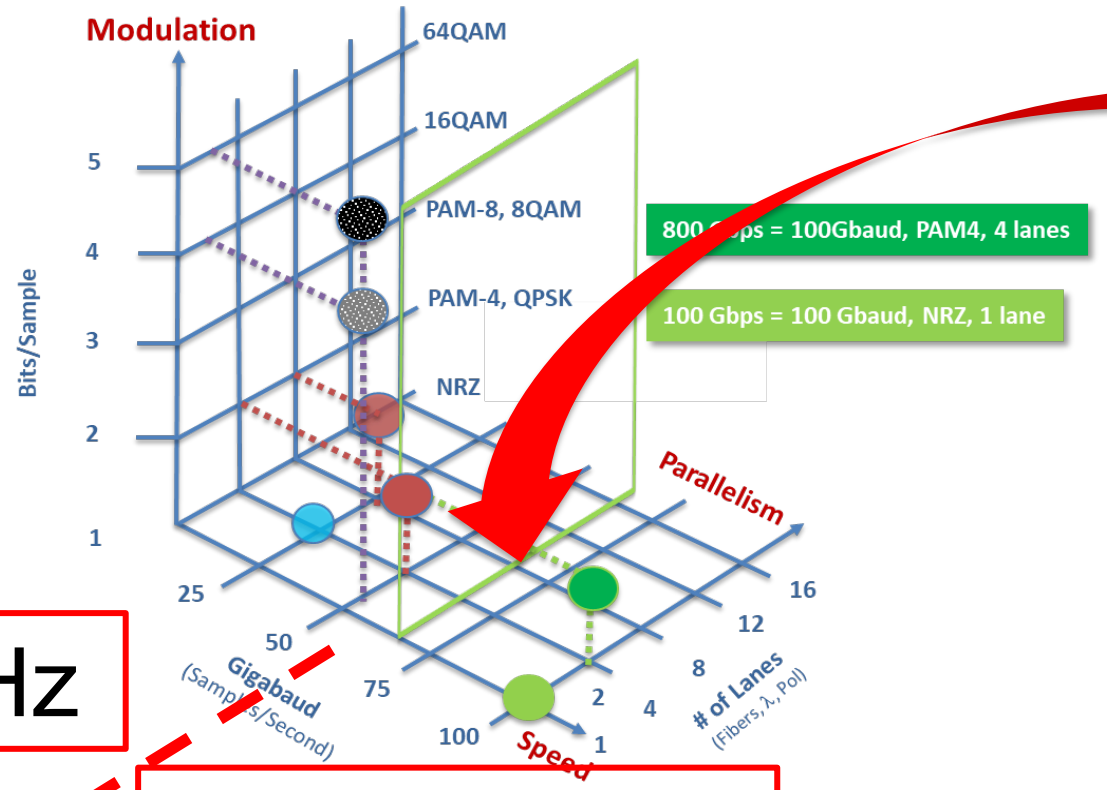
30-40GHz

3dB bandwidth; >35GHz is ~50Gbps NRZ or ~100GBaud PAM4

Speeds of optical devices limited to around 30-40GHz

Sources: LWLG

One way to get to 800 and 1600Gbps: faster PICs (modulator helps)



30-40GHz

~70GHz
→faster PICs

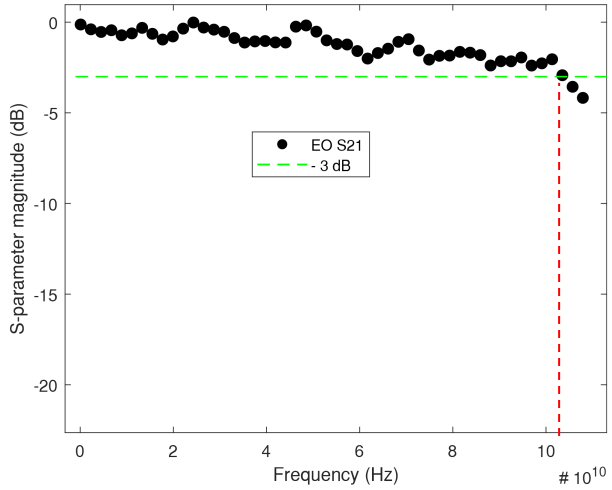
3dB bandwidth;
~70GHz is
~100Gbps NRZ or
~200GBaud PAM4
Double the speed

Can we make faster optical devices → PICs?

Sources: LWLG

Polymers break the speed limit…over 100GHz

3dB Bandwidth >100GHz



Faster PICs → alleviates circuit complexity in networking systems

Sources: LWLG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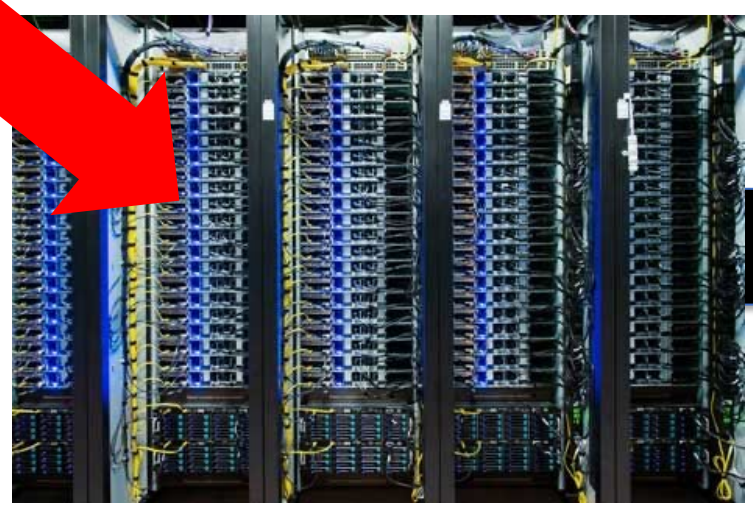
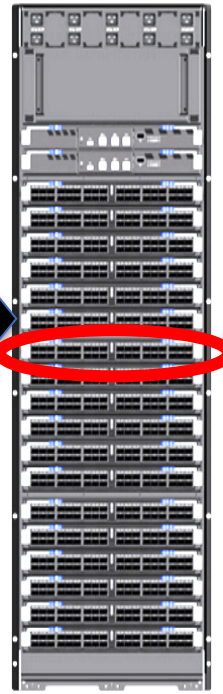
Packaging:
Can we package PICs just
like IC electronics?

Inside a datacenter there are racks…

Faceplate





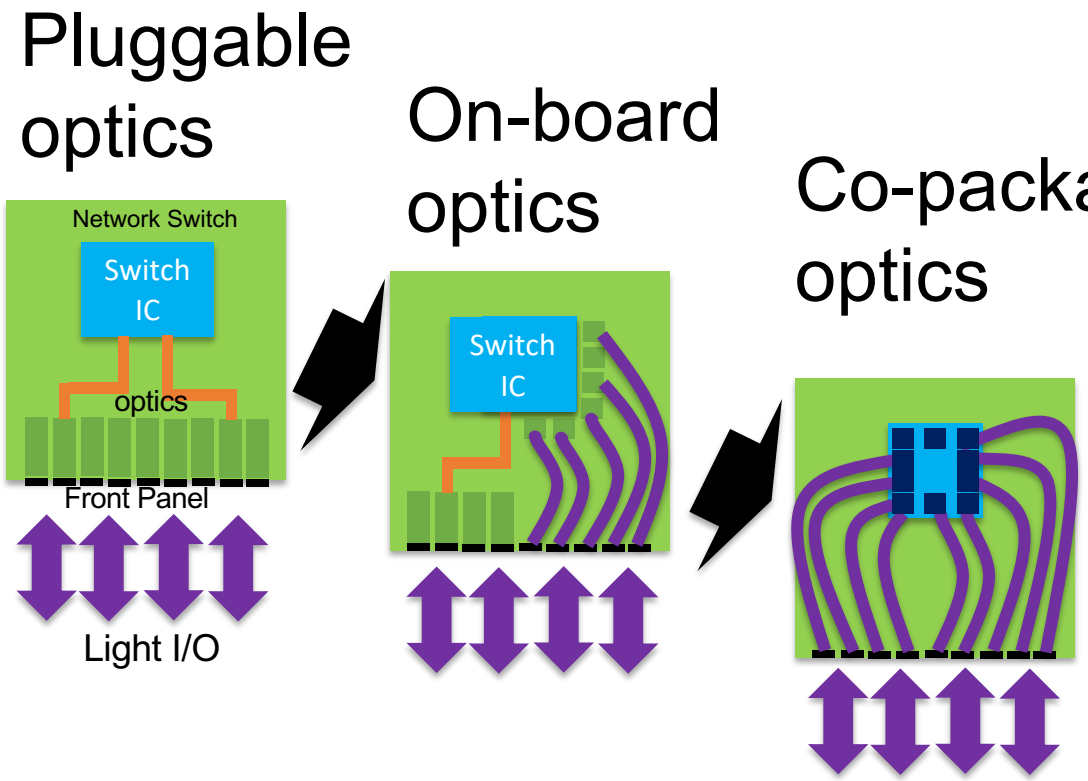
Equipment capacity is limited by how many transceivers can fit on the faceplate

Faceplates limit the flow of data → just like a blocked artery…

Sources: Facebook, Google

Re-think how to unblock the artery…

Pluggable transceivers are not scaling with data flow…



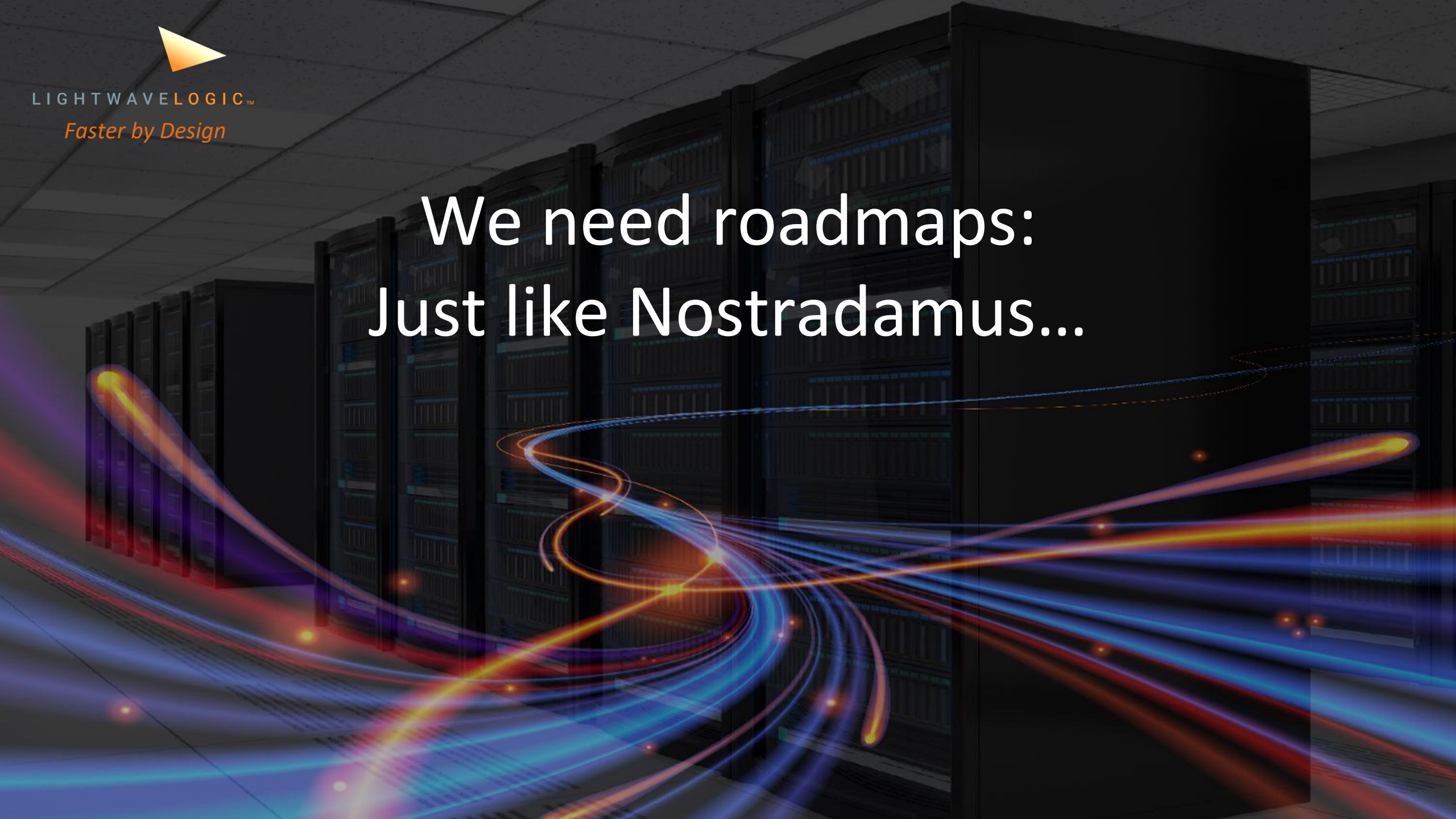
Co-packaging gets the optics right to the IC switch chip…

Photonics integration → electronics and photonics

Top View

Co-packaging (and chip scale packaging) are now considered *inevitable*

Sources: LWLG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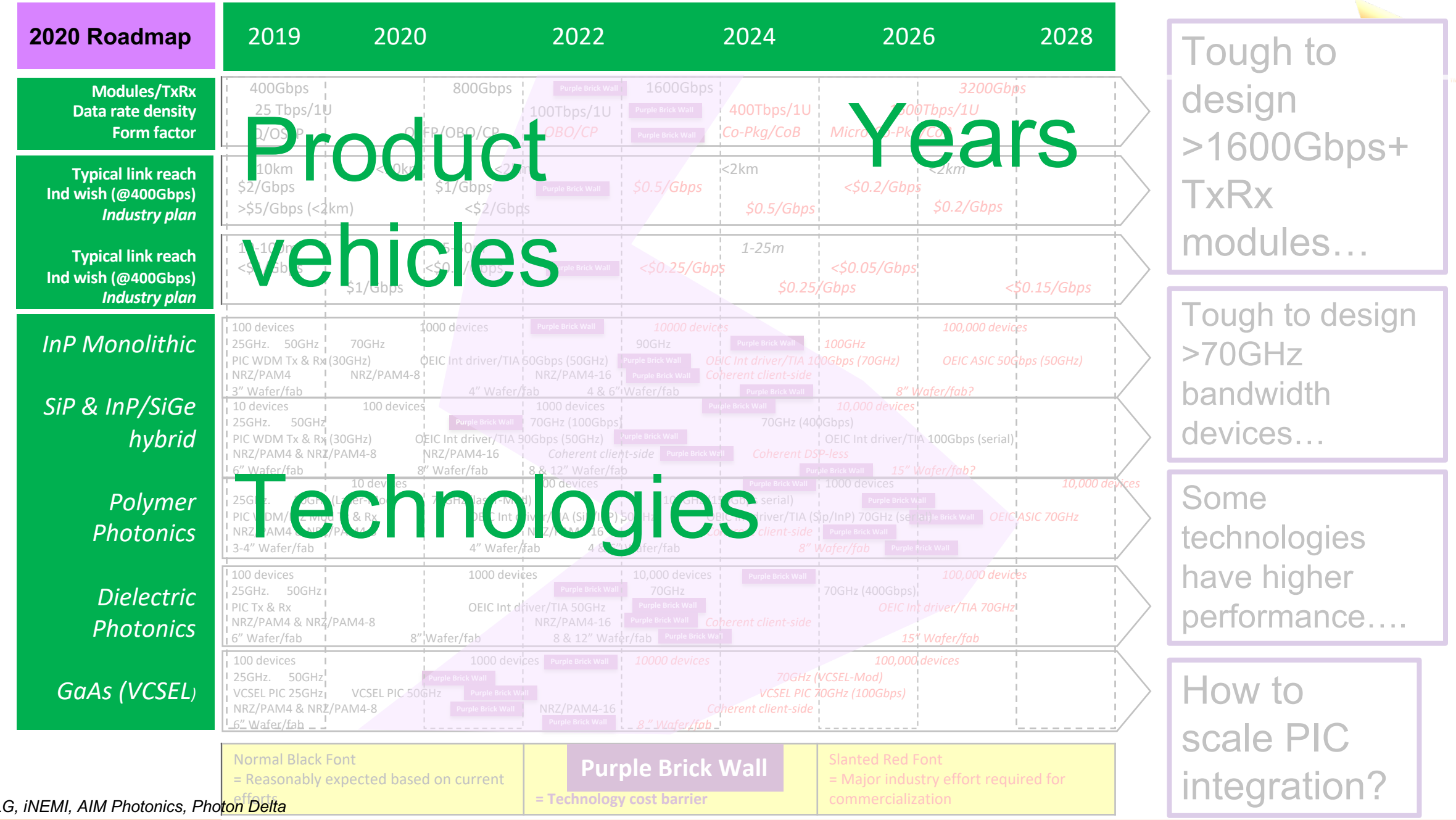
We need roadmaps:
Just like Nostradamus…



Tough to design >1600Gbps+ TxRx modules…

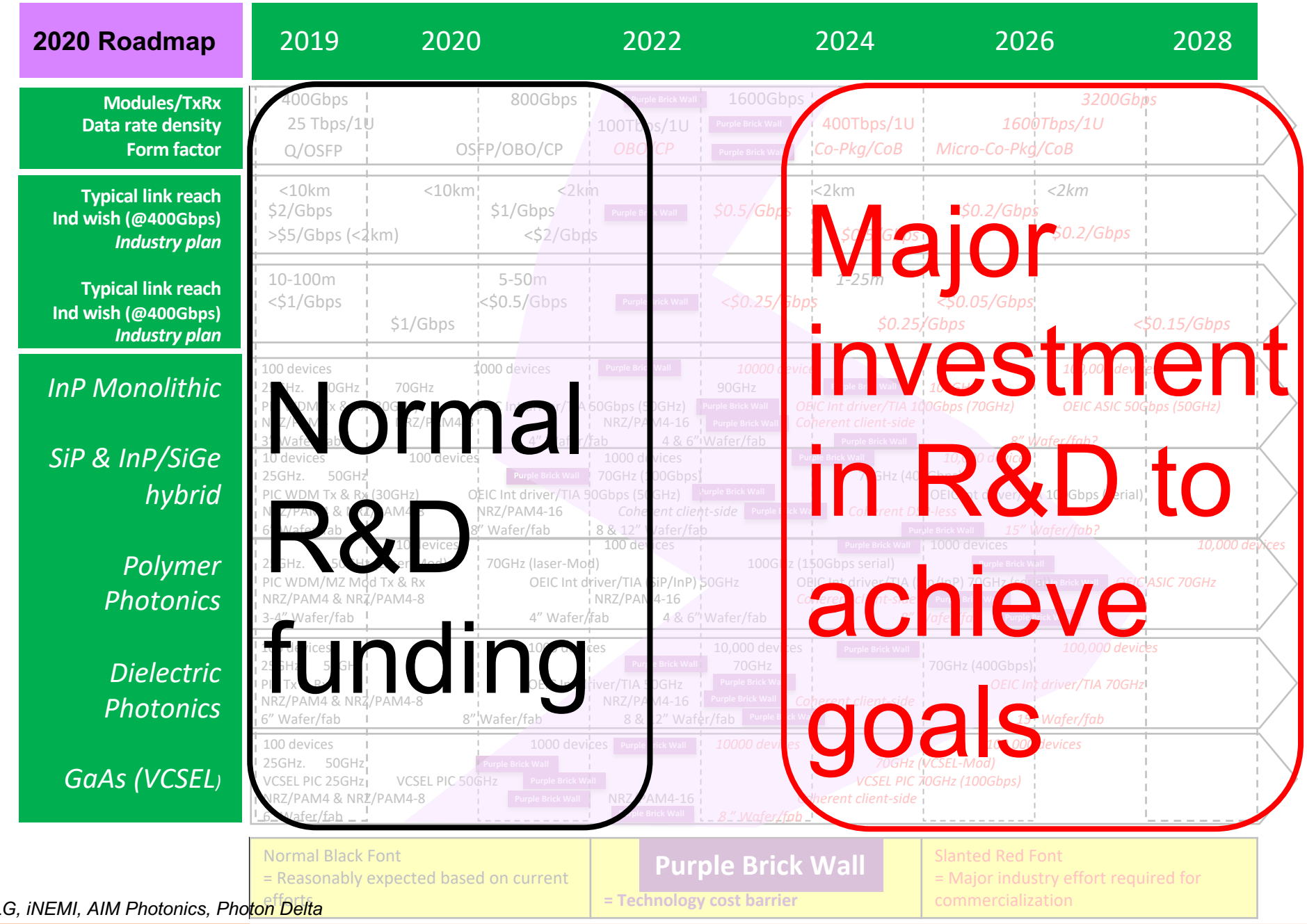
Tough to design >70GHz bandwidth devices…

Some technologies have higher performance….

How to scale PIC integration?

Sources: LWLG, iNEMI, AIM Photonics, Photon Delta

Simple metrics



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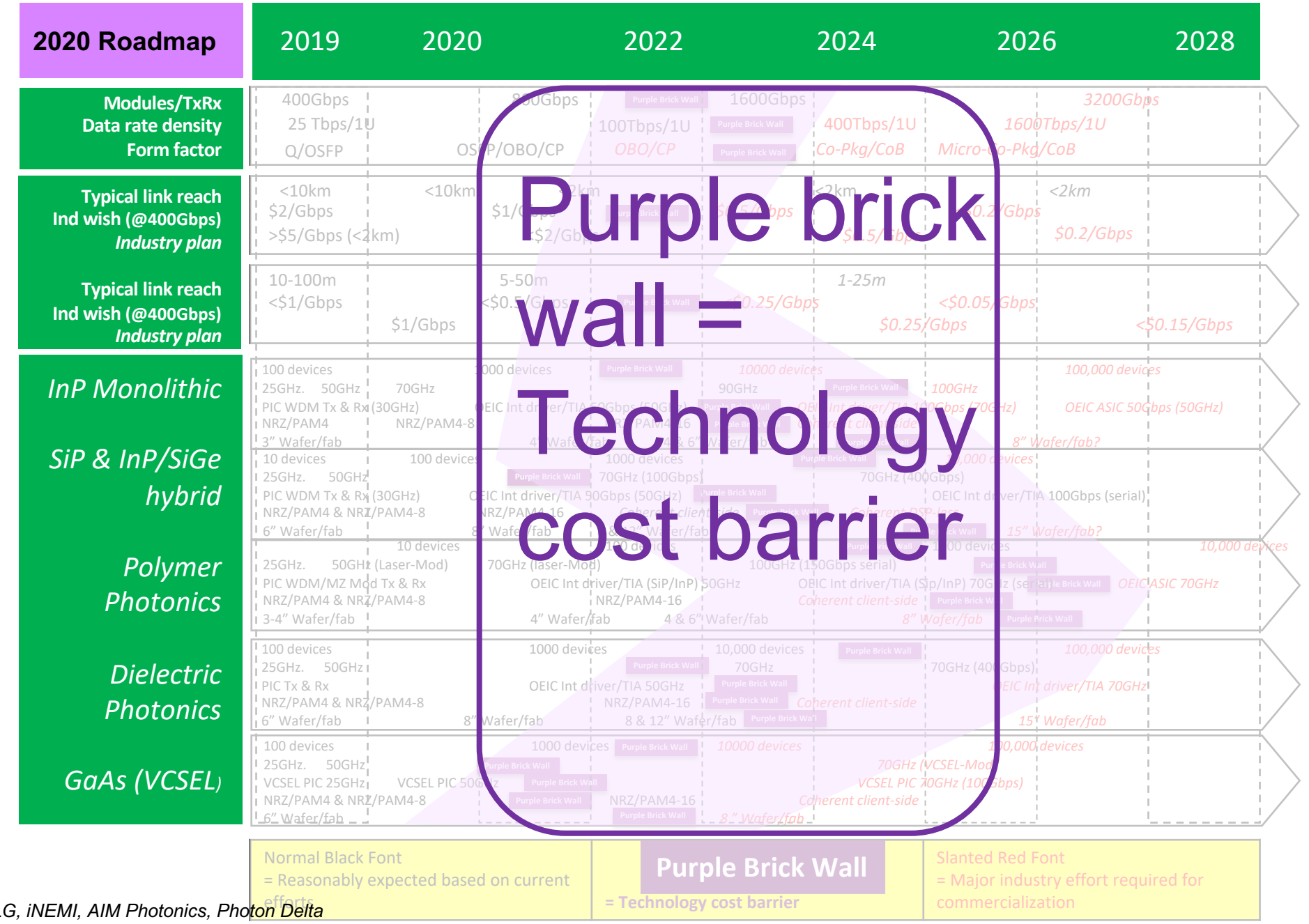
Sources: LWLG, iNEMI, AIM Photonics, Photon Delta

Red means major industry efforts needed for commercialization



Tough to design >1600Gbps+ TxRx modules…

Tough to design >70GHz bandwidth devices…

Some technologies have higher performance….

How to scale PIC integration?

Sources: LWLG, iNEMI, AIM Photonics, Photon Delta

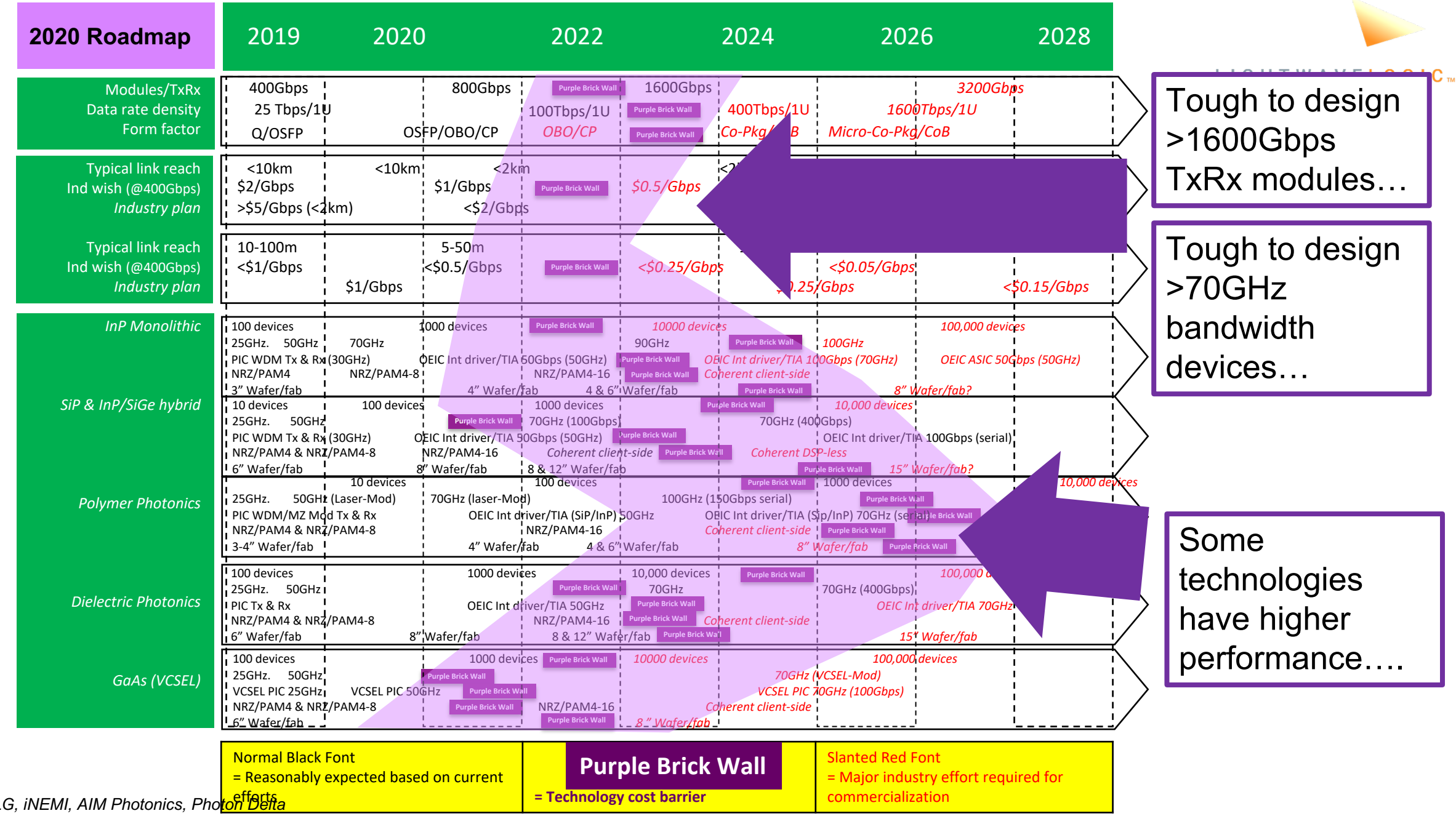
We may have photonics technology → but not at a cost for commercialization…

Advice on a 1-page roadmap…

- Huge amount of data and small font…1-page…
- Details can be better viewed better *online*

Roadmaps provide a vehicle for all stakeholders: Gvt, industry, academia, bankers and investors…

Sources: LWLG, iNEMI, AIM Photonics, Photon Delta



Sources: LWLG, iNEMI, AIM Photonics, Photon Delta

Where we penetrate the 'Purple Brick Wall'?

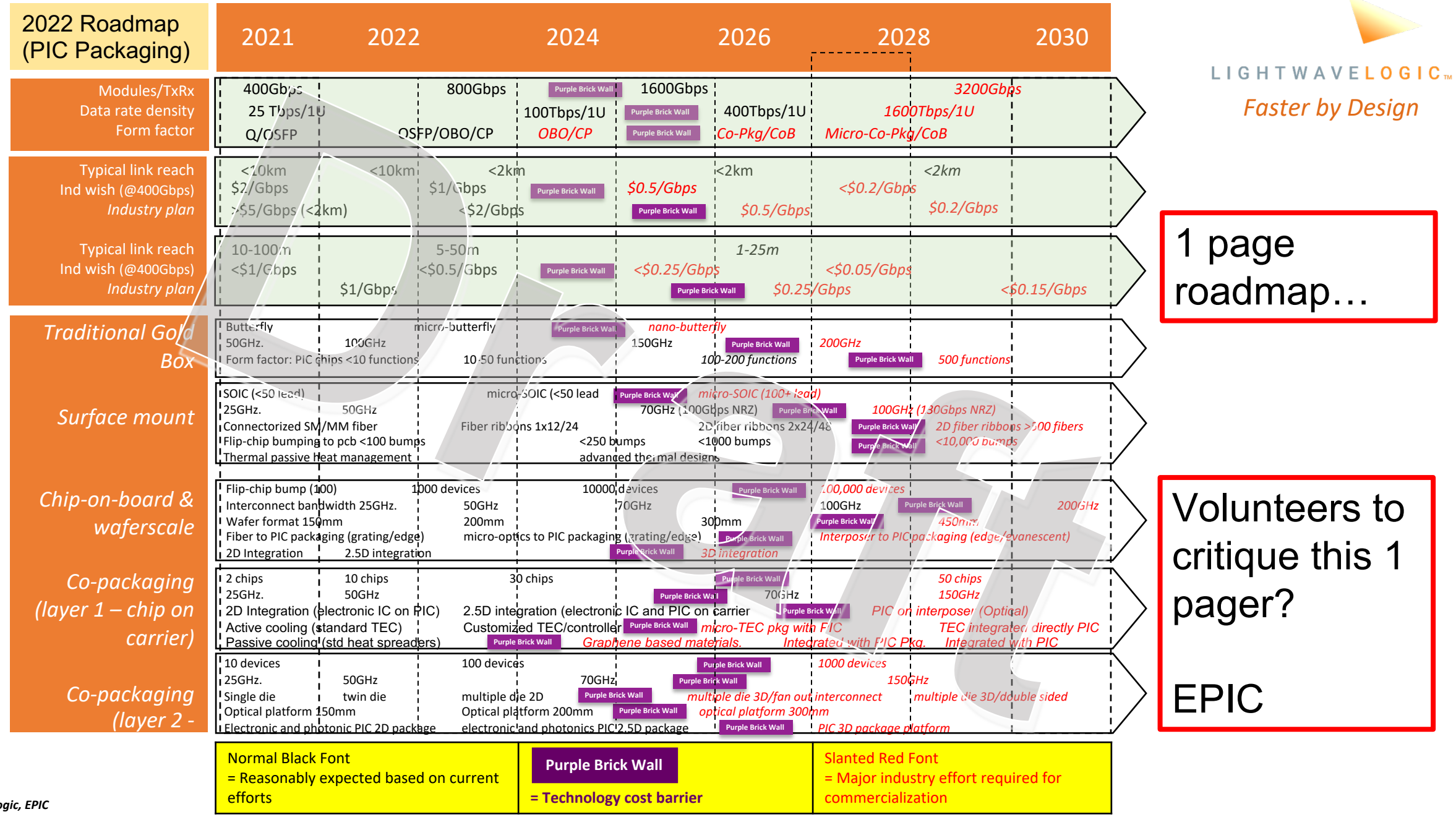
How about a new 1-page roadmap?

LIGHTWAVELOGIC™

- A *1-page PIC packaging roadmap*…
- Details can be better viewed better *online*

Simple 1 slide roadmaps – have impact

Sources: LWLG, iNEMI, AIM Photonics, Photon Delta



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1 page roadmap…

Volunteers to critique this 1 pager?

EPIC

Source: Lightwave Logic, EPIC

A PIC Packaging roadmap…

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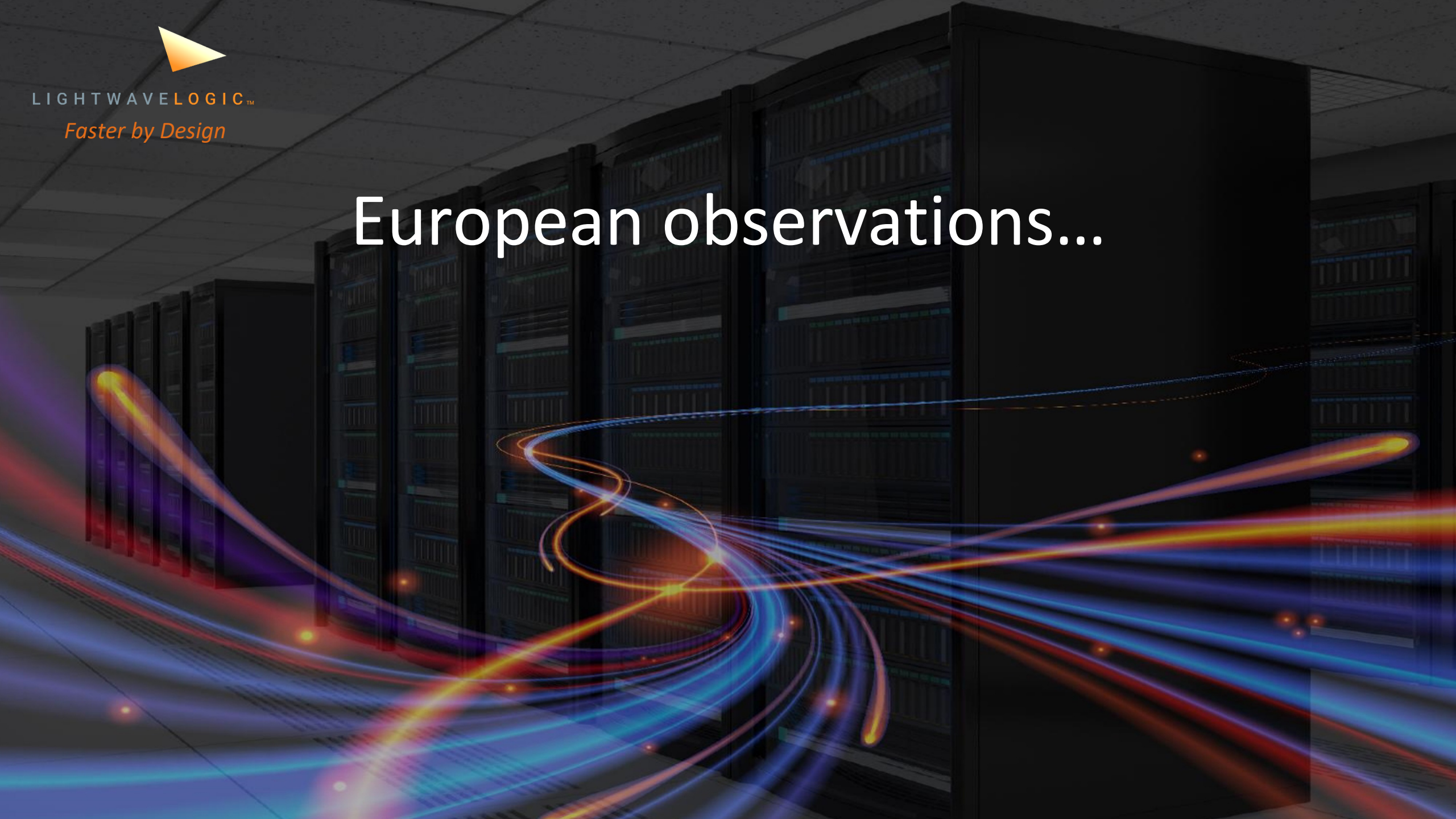
European observations…



Positioning for PICs…

- USA
  - Large silicon foundry platform with government funds
  - Suitable for defense contractors, and large corporations
  - InP PICs with Infinera, Lumentum, II-VI
- Japan and Asia
  - Huge silicon foundries hungry for silicon photonics (TSMC, Hisilicon, Samsung etc.)
  - Suitable for large companies with SiPh platforms
  - InP PICs with Fujitsu, NTT, Sumitomo
- Europe…
  - Has a mix of large and small foundries all hungry for PIC leadership…
  - EU has deep experience with PICs…

SME = Small and medium size enterprise

How does Europe win with PICs?

Sources: LWLG

Nurture and grow PIC platforms…

- EU has made broad investment into PIC photonics R&D last 30years
  - There has been early focus on PIC InP/SiPh/hybrid core competency
- Today → EU has PIC pilot lines in Europe
  - Small focused PIC photonic teams → *that can scale to manufacturing, and self-sustainability*

PI-SCALE

PIXAPP Photonic Packaging Pilot Line

PIX4life

MIRPHAB ENABLING CHEMICAL SENSING

MedPhab Photonic Medical Devices

Phabulous

JePPIX

Foster these types of projects to commercialization…hub-spoke architecture…

Pilot lines for PIC: PIXAPP, PIX4LIFE, PI-SCALE, MIRPHAB, PHABULOUS, MEDPHAB, INPULSE

Creating leadership…

- How to win?
  - *Provide easier access for SMEs…they drive innovation…*
  - Create a sharper focus on *hybrid PIC performance/foundry* & packaging (co-packaging, chip-scale), PIC design infrastructure, EU PIC manufacturing.
  - Create more PIC pilot line scale projects…that impact growing markets (Auto, medical, sensing, display etc.)

Build into a global center of excellence…

Pilot lines for PIC: PIXAPP, PIX4LIFE, PI-SCALE, MIRPHAB, PHABULOUS, MEDPHAB, INPULSE

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Summary

3 takeaways to remember today…

- Will PIC photonics enable many things and will it be part of our lifestyle?
  - **YES!…from 'heavy data' today for virtual working to enabling new market opportunities: consumer, health, bio, defense, display, lighting, automotive…**
- Will photonics be integrated – just like ICs 50years ago and become the engine for new designs?
  - **Absolutely…it will be the next generation IC…the PIC**
- Will integrated photonics (PICs) enable new products?
  - **Of course!…and the applications are broad and exciting**

Why drive a horse buggy when the motor car is available?