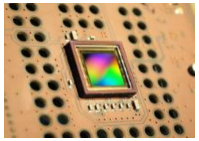
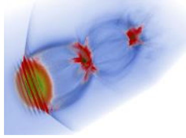
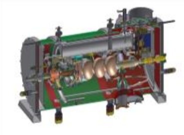
Matter and Technologies

# Silicon Photonics and Teratronics: Enabling Technologies for Next-Generation Detectors

Christian Koos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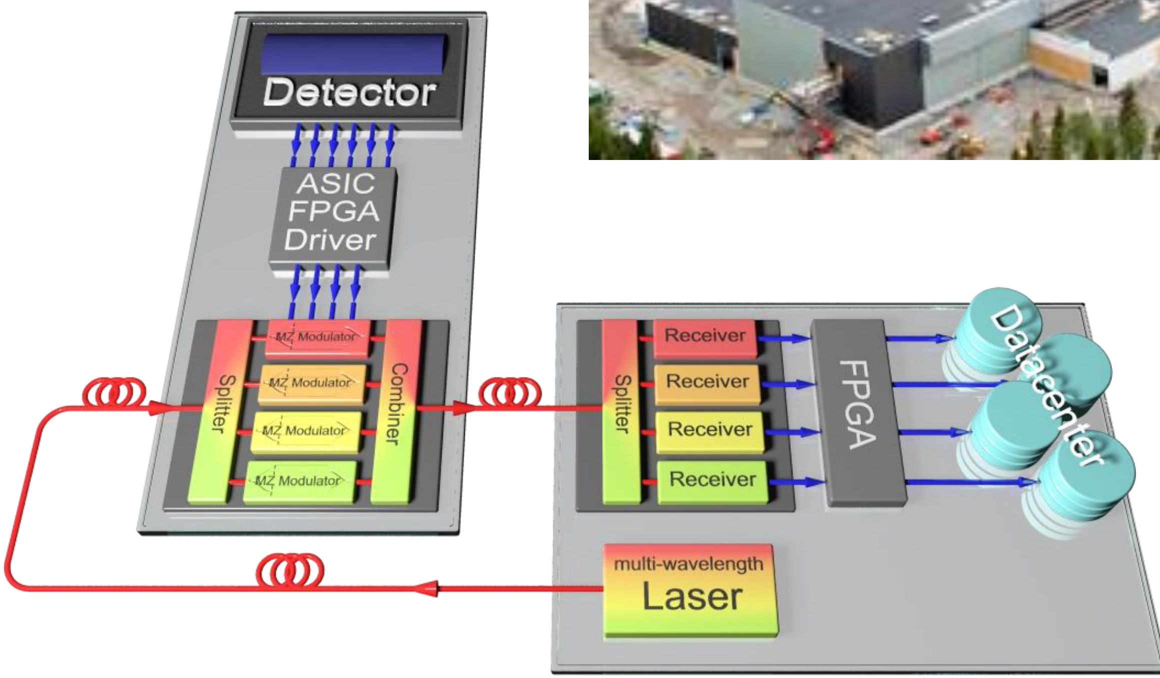
# Interconnect bottlenecks and optical communications

**Facebook's data center in Luleå, Sweden:**

- > 100 000 servers
- 40 Gbit/s per server
- 4 Pbit/s data traffic
- Power and space constraints…




**Large-scale particle detector**

- > 1000 staves (?)
- 500 Gbit/s per stave
- 0.5 Pbit/s data stream
- Power and space constraints…

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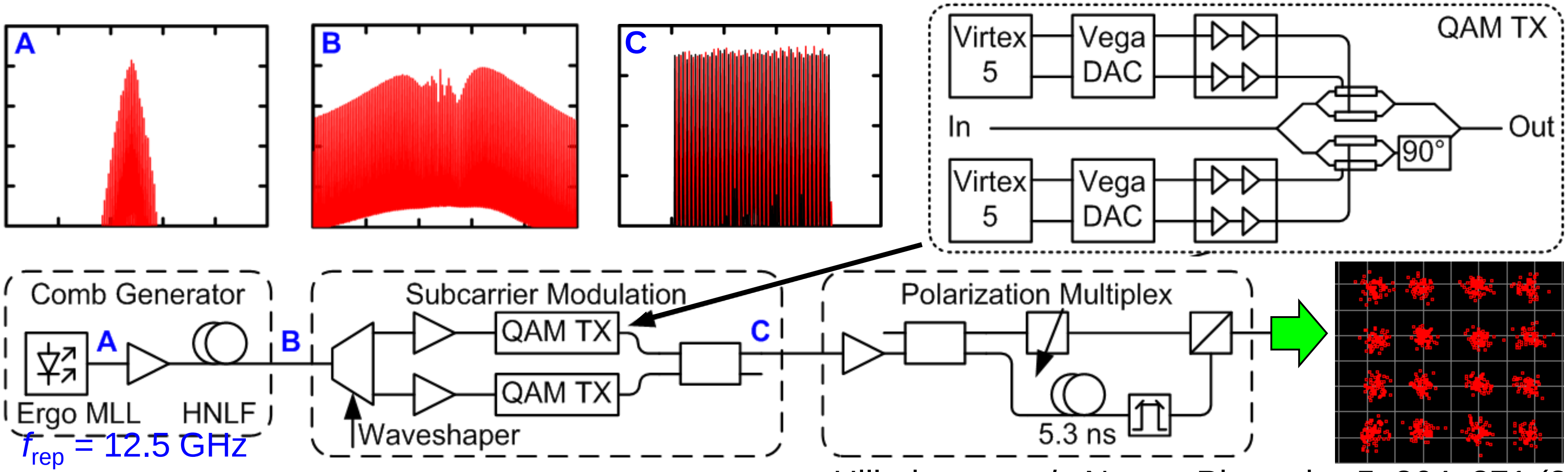
# Terabit communications: Proof-of-principle

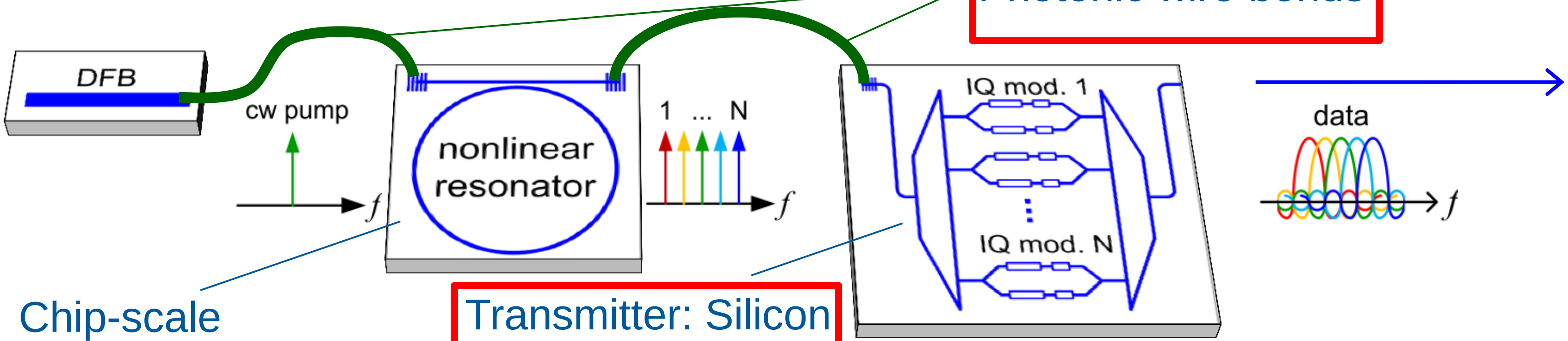
Frequency comb source: 325 channels, 12.5 GBd, 16 QAM, PolMUX => **32.5 Tbit/s**




Hillerkuss *et al.*, Nature Photonics 5, 364–371 (2011)

The vision: Chip-scale multi-Terabit/s transceivers

Photonic wire bonds



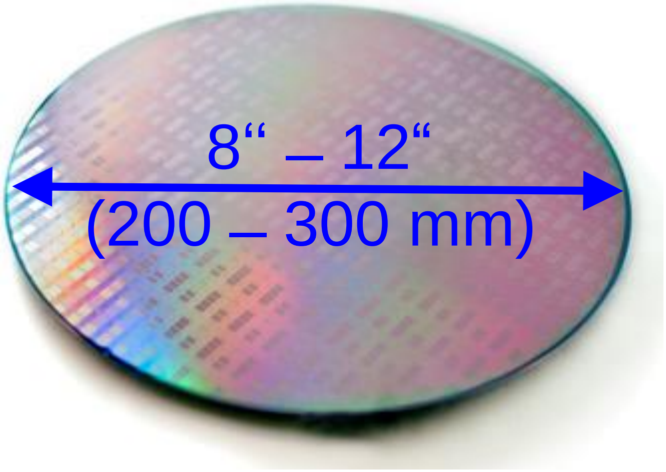

Chip-scale frequency comb sources

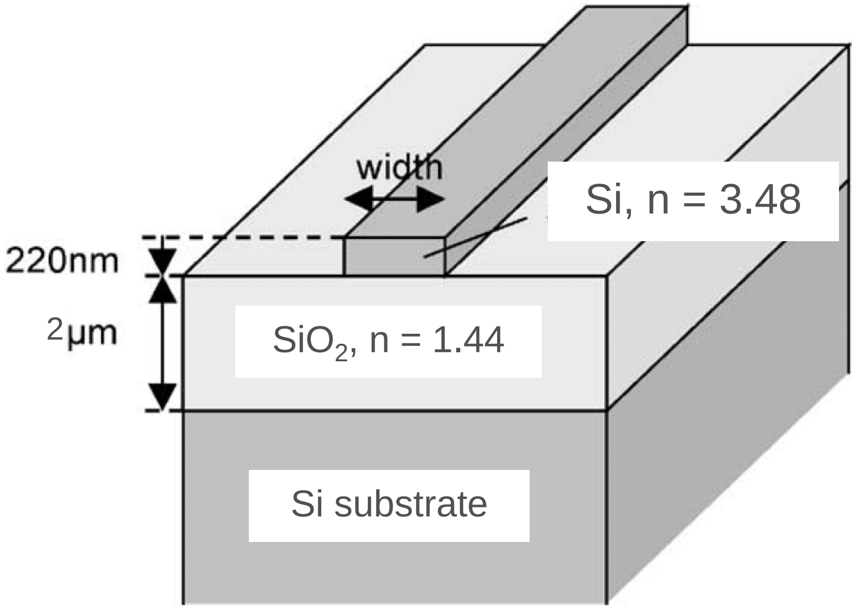
Transmitter: Silicon photonics and hybrid integration

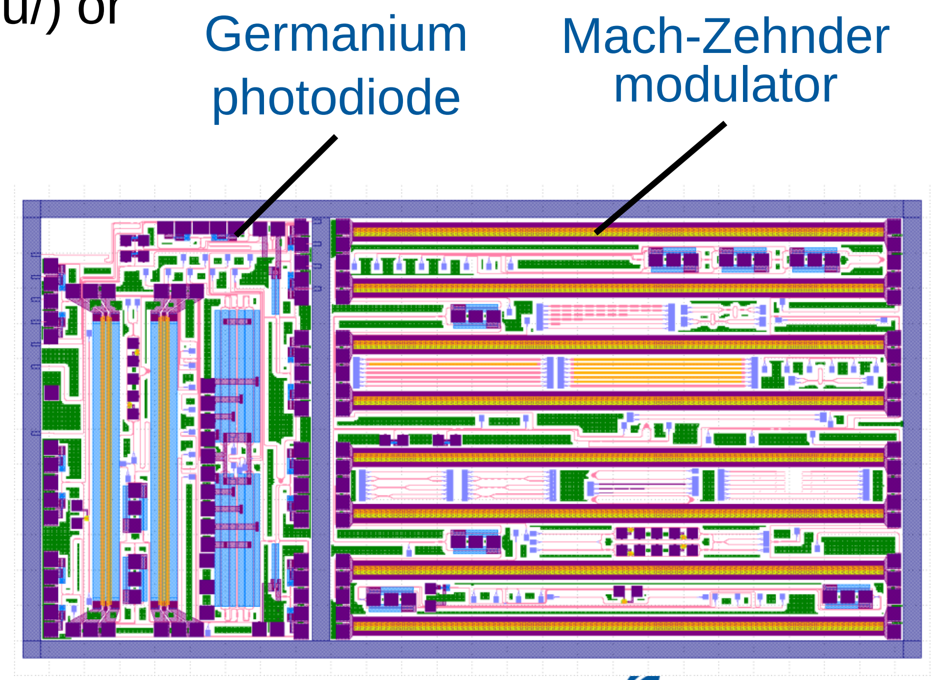
# Silicon photonics

- High-density integration by using high-index-contrast silicon-on-insulator (SOI) waveguides
- Use of CMOS foundries for photonic devices

⇒ Multi-project-wafer (MPW) shuttle runs, e.g., ePIXfab (http://www.epixfab.eu/) or OpSIS (http://opsisfoundry.org/)

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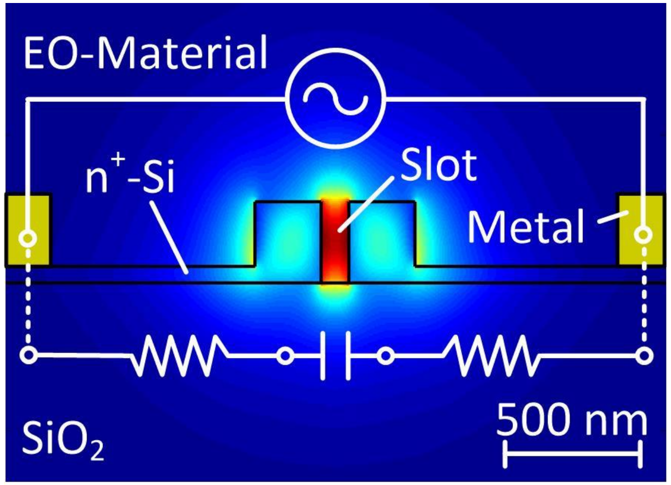
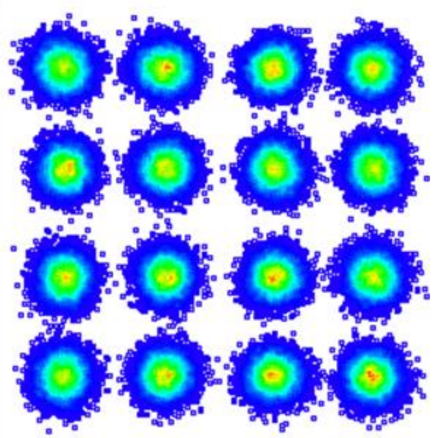
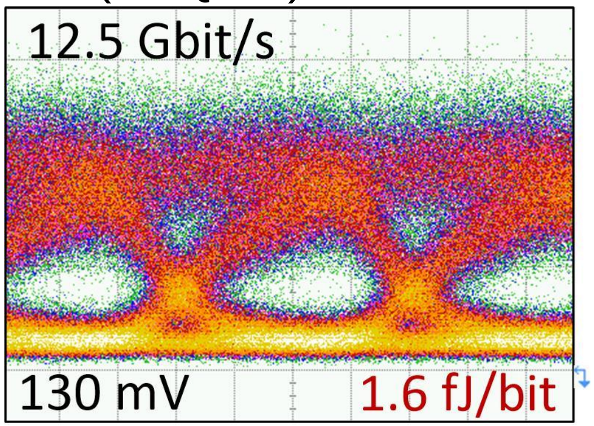
# Silicon-organic hybrid (SOH) integration

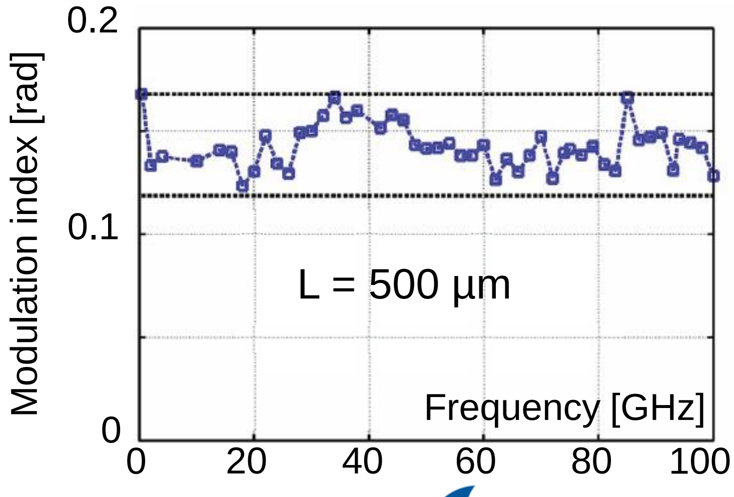
Idea: Combine nanophotonic silicon waveguides with electro-optic organic cladding materials

- High-speed modulation: 3 dB bandwidth > 100 GHz (All-silicon devices: 30 GHz)
- Highly efficient: $U_{\pi}L$ < 1 Vmm (All-silicon devices: $U_{\pi}L$ = 10 … 40 V mm)
- Lowest energy consumption of a Mach-Zehnder modulator (MZM) in any material system: < 2 fJ/bit (All-silicon MZM devices: 200 fJ/bit)
- No amplitude-phase coupling: Enables higher-order modulation formats (16 QAM)






Palmer *et al.*; ECOC 2013, paper We.3.B.3 – Best student paper award
Alloatti *et al.*, Opt. Express 19 (12), 11841-11851 (2011)
Palmer *et al.*, IEEE Photonics Journal 5, 6600907 – 6600907 (2013)
Korn *et al.*, Opt. Express 21; 13219–13227 (2013)

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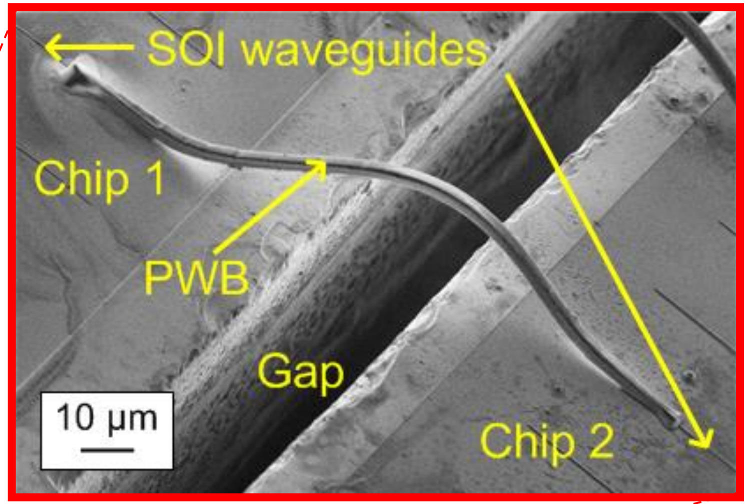
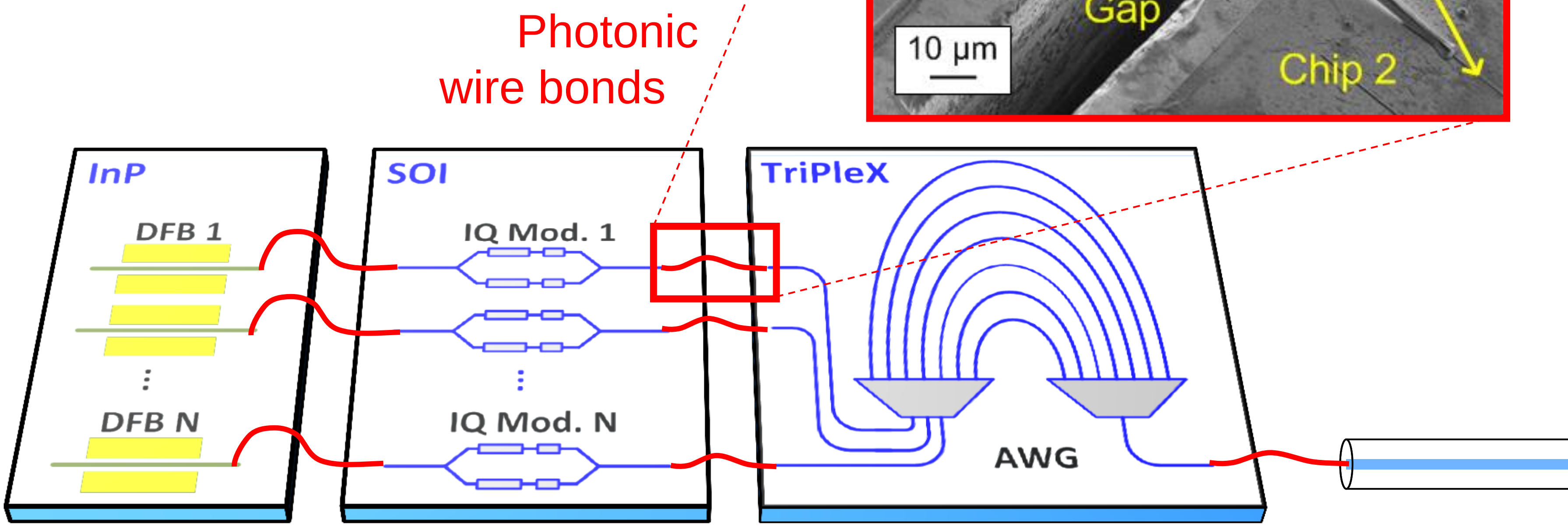
# Photonic multi-chip integration

Various different integration platforms, each with specific strengths: InP, SOI, TriPleX
⇒ Combine advantages by heterogeneous multi-chip integration




Example: Chip-scale WDM transmitter:




- Use best available platform for each subsystem.
- Optimize individual fabrication processes for performance, not for compatibility!
- Assemble complex systems from “known-good” components.

Lindenmann *et al.*, Opt. Express 20, 17667-17677 (2012)

# The Vision: Terabit/s communications in particle detectors

- Intimate co-integration of photonics and electronics for terabit communications
- Fast readout of full detector: Get raw data out for "offline processing" in data center
- Less electronics and more detectors in detector volume
- Less mass in detector for higher accuracy