Optical Technologies

Rob van der Meer

ILO-net webinar, 18 May 2021

Nikhef

Main Mirrors

- Current detectors (& ET high frequency)
  - Fused silica with extremely low absorption (ppm level) at 1064nm
  - Radii of curvature several km, deviation a few meters
  - Deviation from perfect sphere < 2nm
  - Super polishing <0.2nm RMS

- Challenge for ET: silicon mirrors
  - ca. 45cm diameter, 55cm thickness
  - High purity, >10kΩcm, for ppm-scale optical absorption
  - Similar polishing requirements
- 4 per detector, i.e. 12 for ET, plus spares
- Upgrades roughly every 5 years
- Smaller scale *now* for ETpathfinder

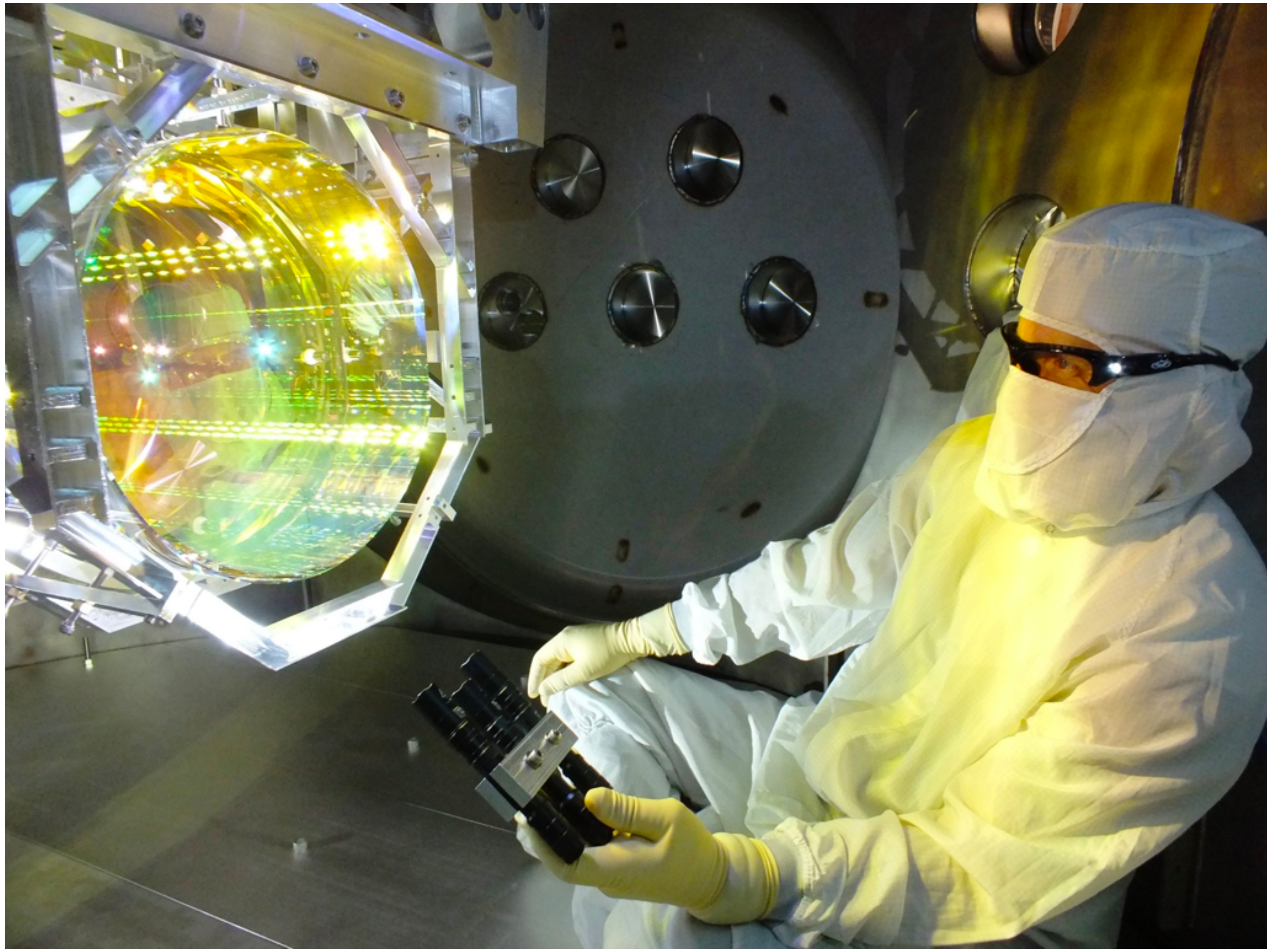
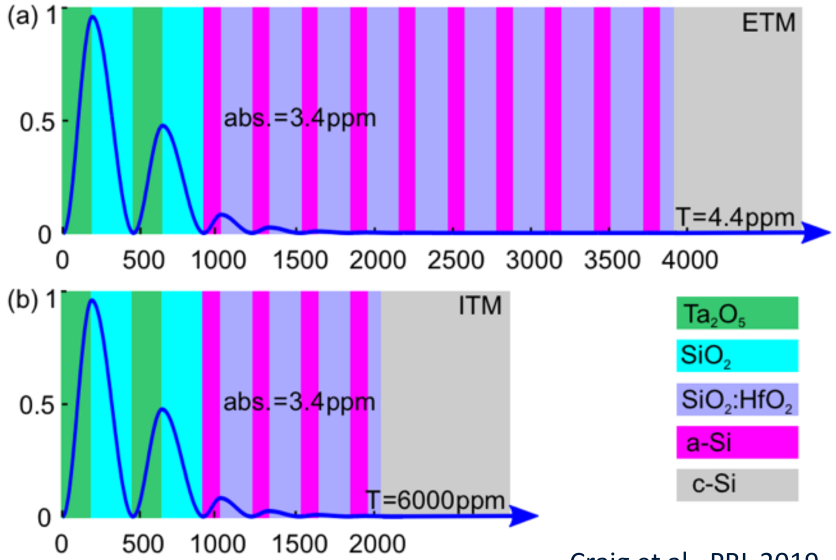


Photo: LIGO lab

Optical Coatings

- Current status
  - Silica/Tantala dichroic coatings
  - Optimized for very low absorption & scattering (ppm level)
  - Optimized for low mechanical loss (becomes high at low temperatures)
  - Two optics coated at once, for minimal spread in reflectivity

- Challenge for ET:
  - Low-loss (optical & mechanical) coatings for cryogenic silicon test-masses
  - Virtually free from scattering/absorbing points
  - Large diameter (45cm), homogeneous
  - Able to handle larger masses and diameters



Craig et al., PRL 2019

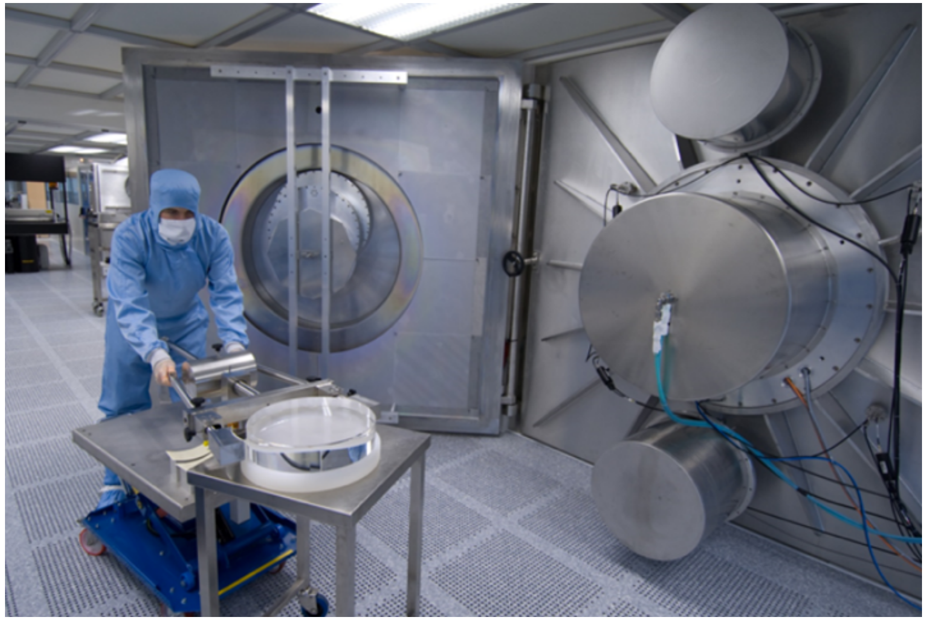


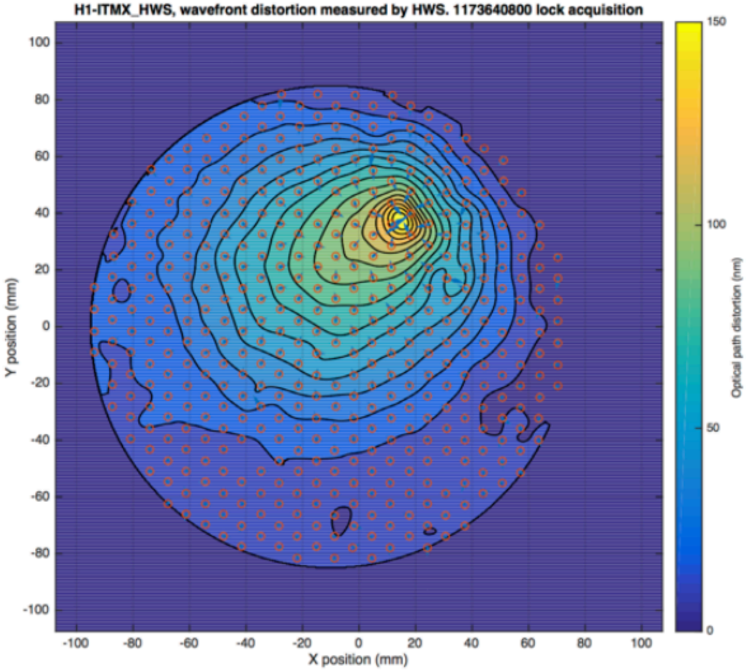
Photo: LMA

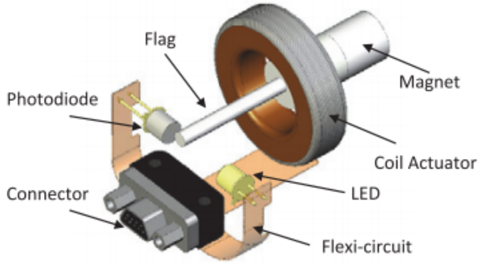
Optical Sensing and Metrology

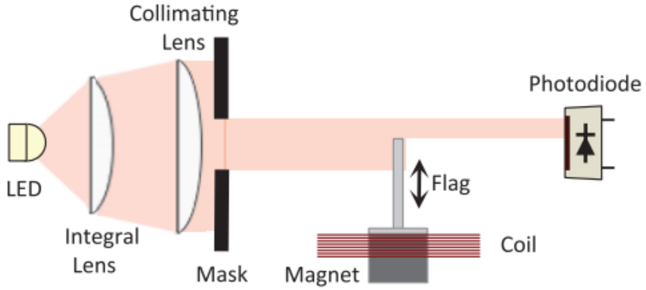
- Several types of optical sensors and metrology used during production and during operation

- Measuring reflected and transmitted waveform during polishing and coating, as well as surface roughness
- Beam profile monitoring and analysis
- In-situ monitoring of mirror curvature (wavefront sensors)
- Position alignment of test-masses with wide-range optical sensors

Photo: ZYGO/LIGO lab

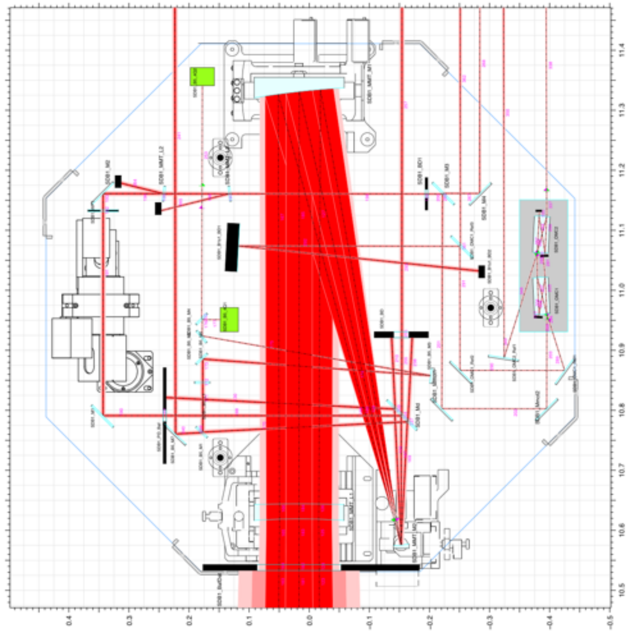






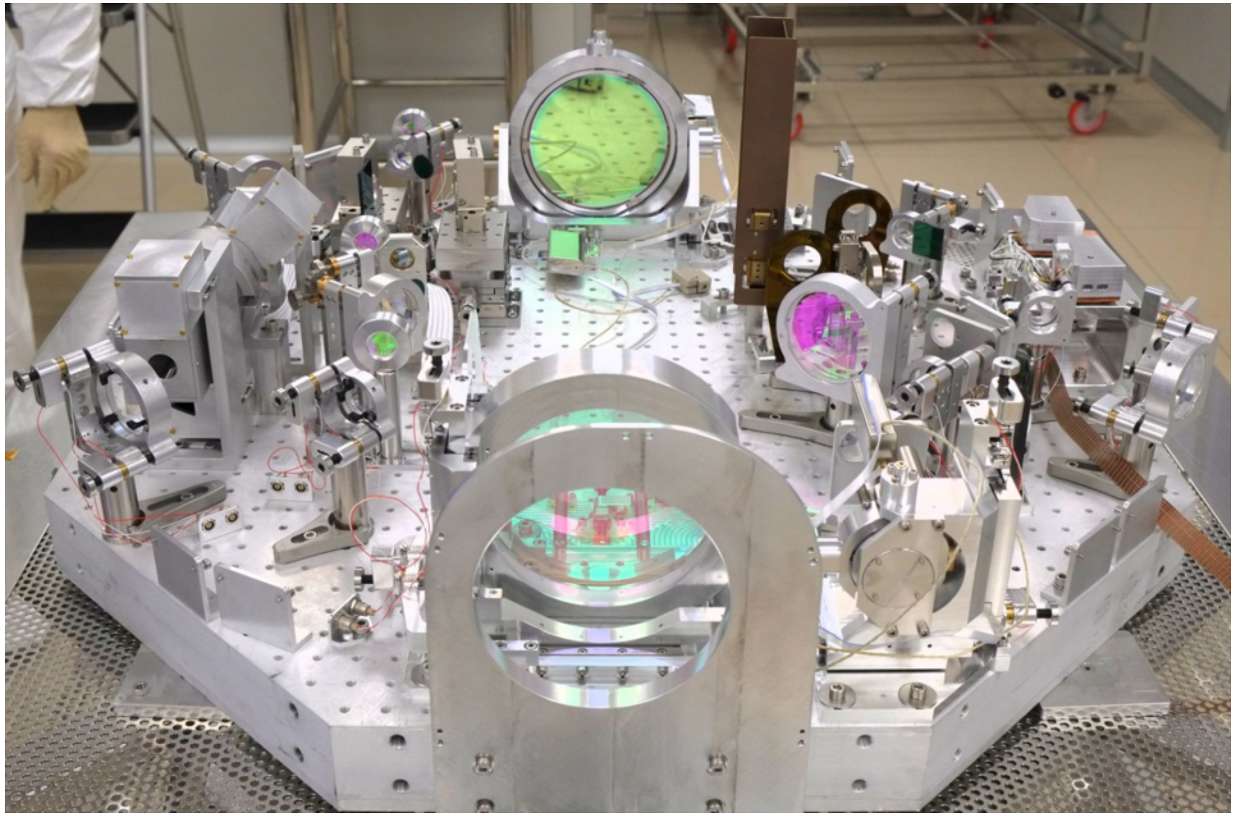
Auxiliary Optics

- In addition to main test-masses, each interferometer has
  - Around 10 large (20cm scale) optics with very high optical specifications
  - Some telescope optics with off-axis spherical/parabolic mirrors
  - Several hundred small optics, most of them super-polished



- Scope for e.g. free-form optics, adaptive optics, etc.
- In-vacuum and in-air optomechanics

Photo: EGO/Virgo



Sensors & Optics

for Gravitational Wave Detectors

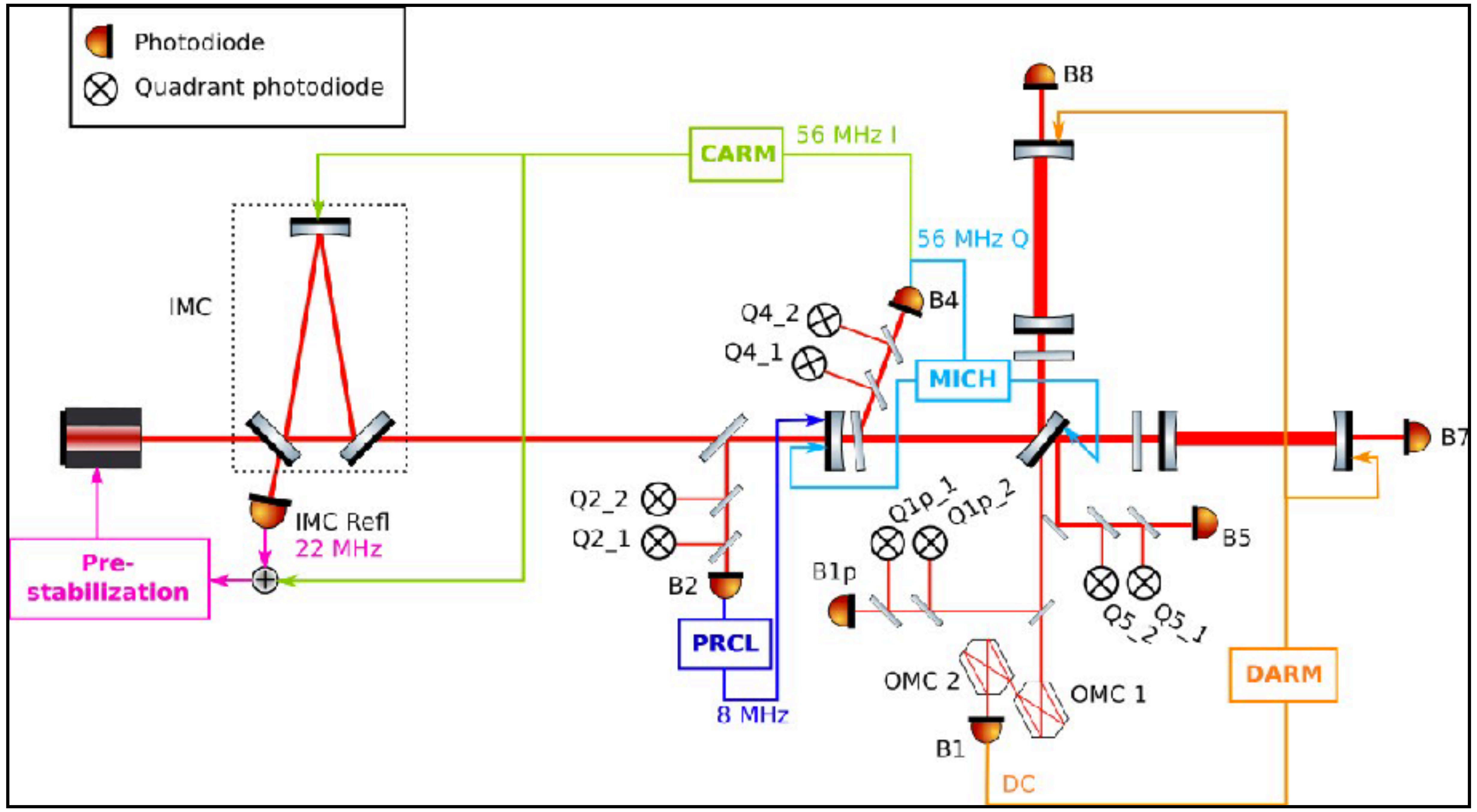
Rob van der Meer

Nikhef

ETpathfinder

Einstein Telescope

Sensors - Optical



- Photo diodes (PD, HQE-PD & QPD)
  - *Light power & beam centering*
  - *Longitudinal & angular alignment*
- Phase cameras
  - *To correct for mirror distortions*
- Beam cameras for (pre) alignment of the interferometer and monitoring:
  - *InGaAs pixel detectors, phosphor coated CCD or CMOS*
  - *For 1550 nm and 2000 nm?*

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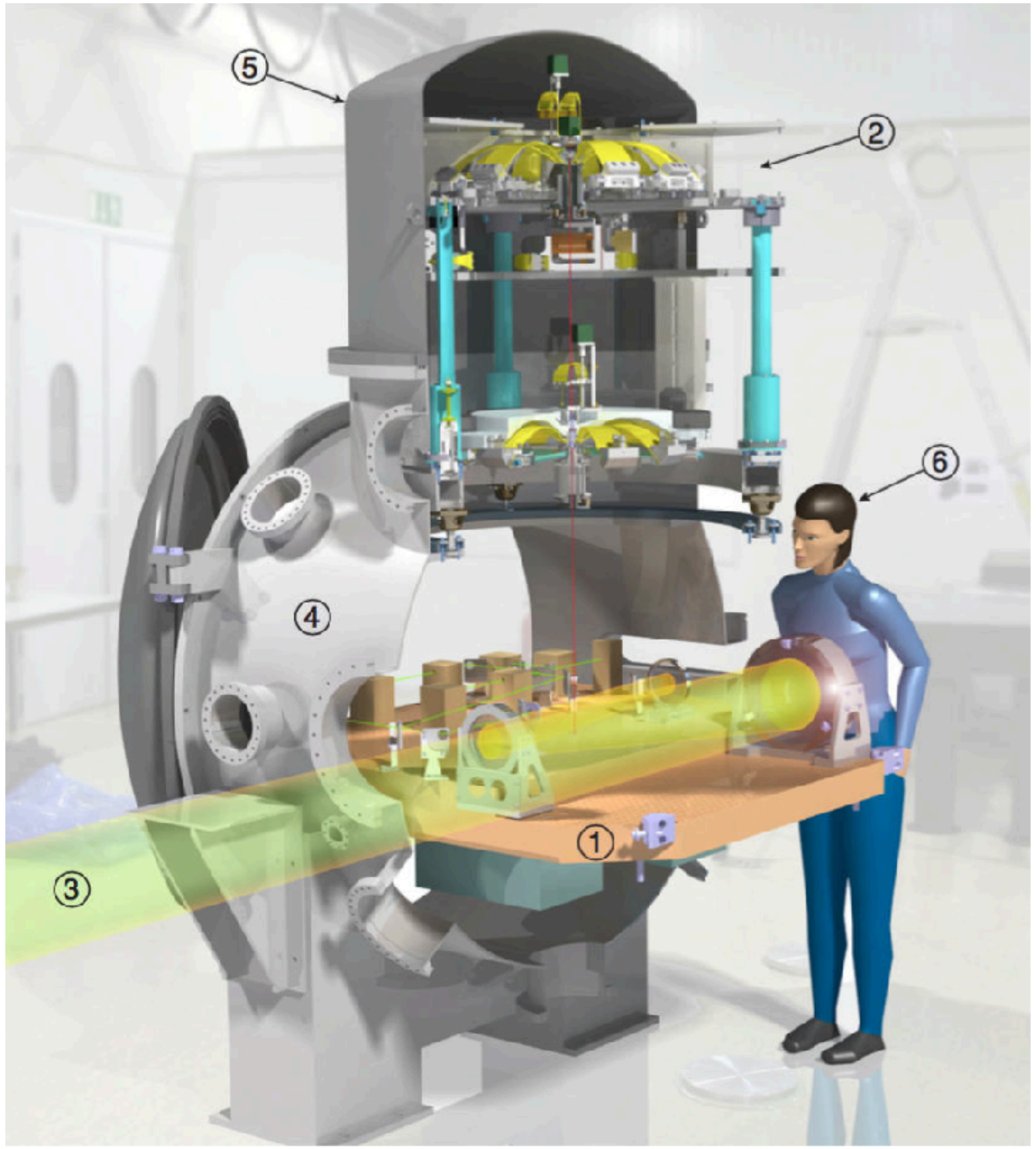
Sensors - Displacement, tilt, ...



- Accelerometers
- Displacement sensors (LVDT)
- Inertial rotation sensors (BRMS type)
- Optical levers for mirror tilt
- Inertial motion measurement (Triaxial Nanometrics TC–120 seismometers)

- Many environmental sensors: temperature, pressure, microphones, magnetometers…. (see Controls)

- Voice–coil actuators
- Piezo-electric stack actuators (PZT)
- Actuators and shadow sensors in a single unit (BOSEM)
- Laser for thermal compensation

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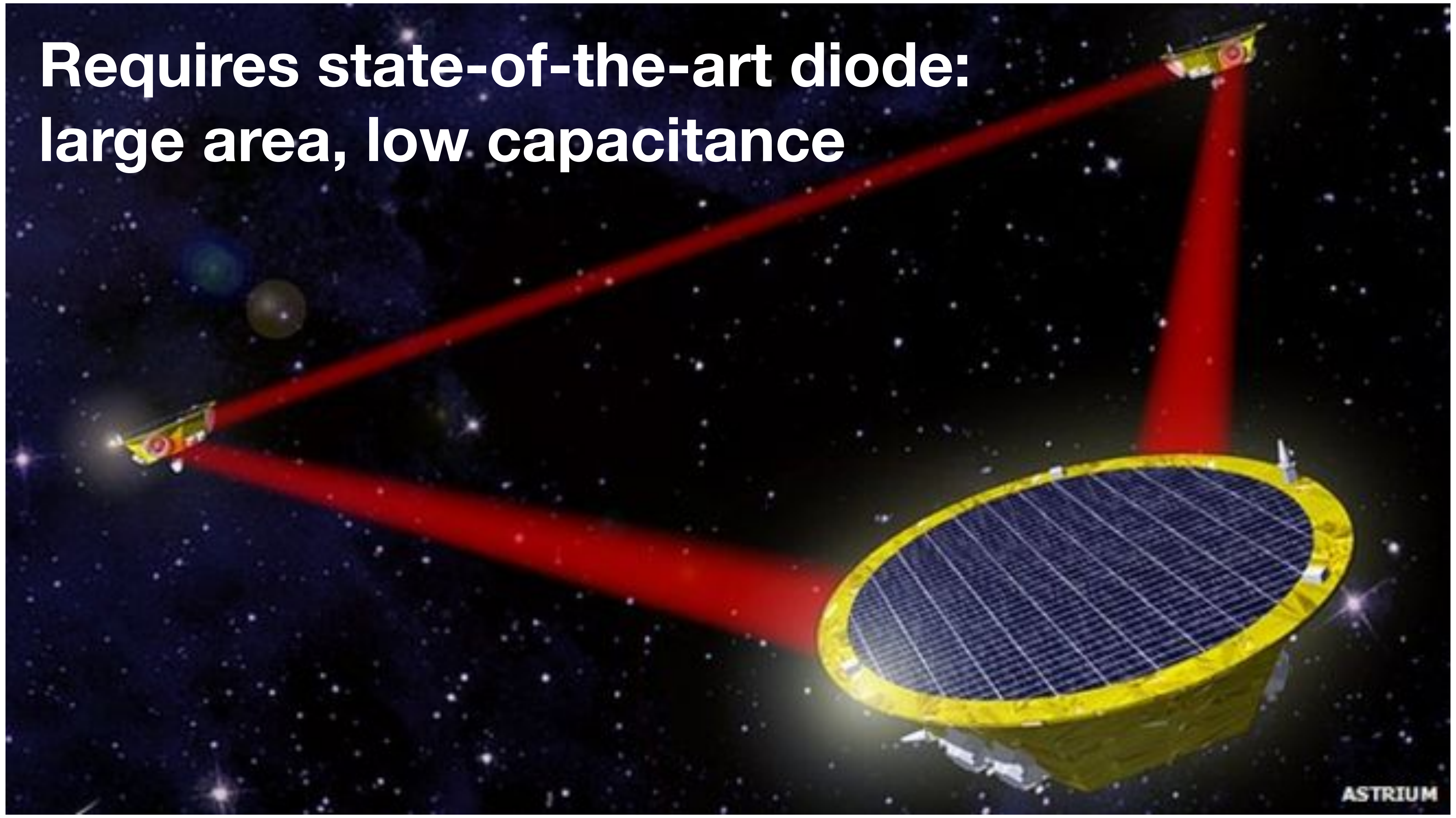
R&D examples

- Accelerometer
  - ***MEMS sensor*** *with integrated readout*
- Photodiodes for LISA
  - ***InGaAs QPD*** *with amplifier*

- Voice coil mirror driver
  - ***3D printing*** *in Aluminum*
- Readout electronics for photo-diodes
  - *Discrete and integrated (ASIC) electronics*

InGaAs Photodiode

- Quadrant diode with
  - ➡ 2 mm diameter, small gaps (10 - 20 µm)
- Input-referred current noise
  - ➡ < 2 pA/√Hz (per segment)
  - ➡ Hence, low capacitance
- Responsivity
  - ➡ > 0.7 A/W at 1064 nm ⟹ InGaAs
- Bandwidth
  - ➡ 2..25 (30) MHz
- Low power dissipation (QPD & TIA)
- Radiation hardness, mechanical & thermal stability …….



LISA QPD development

- Bright Photonics
  - ✓ *Design house for Photonic Integrated Circuits*
  - ✓ *Experience with InP & InGaAs materials*

BRIGHT Integrated PHOTONICS

- Smart Photonics
  - ✓ *Device processing of Indium Phosphide based components*

SMART PHOTONICS

Fotonica: een nieuwe chipindustrie ziet het licht

Technologie Een strategische lening van 20 miljoen euro bestempelt Smart Photonics tot spil van een nieuwe, veelbelovende Nederlandse chipindustrie.

Marc Hijink · 30 juni 2020 · Leestijd 2 minuten

https://www.nrc.nl/nieuws/2020/06/30/nieuwe-chipindustrie-ziet-het-licht-a4004596

Diodes for ETp & ET

- Diodes for 1550 nm and 2000 nm laser light
  - ➡ *Shot-noise limited*
  - ➡ *InGaAs for 1550 nm (commercial)?*
  - ➡ *Extended InGaAs or HgCdTe (MCT) photodiodes for 2000 nm?*
- In air-filled enclosure in vacuum
  - ➡ *Requires low power electronics*

ET Pathfinder

Description	Quantity
PD 1550 nm	6
HQE PD 1550 nm	2
QPD 1550 nm	12
PD 2000 nm	6
HQE PD 2000 nm	2
QPD 2000 nm	12

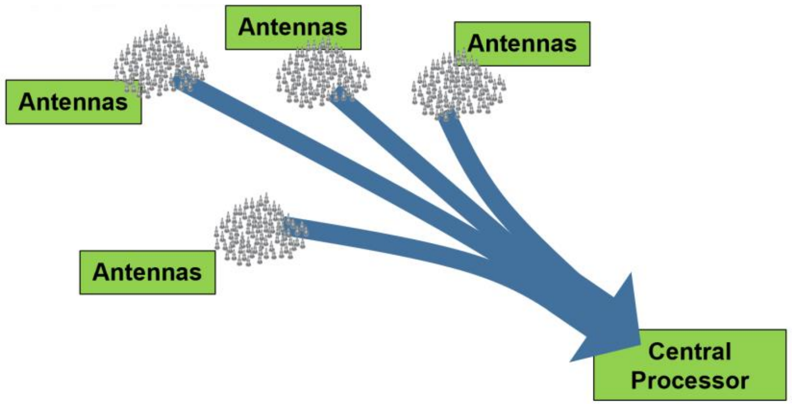
ET Table?

Sensors: what we need

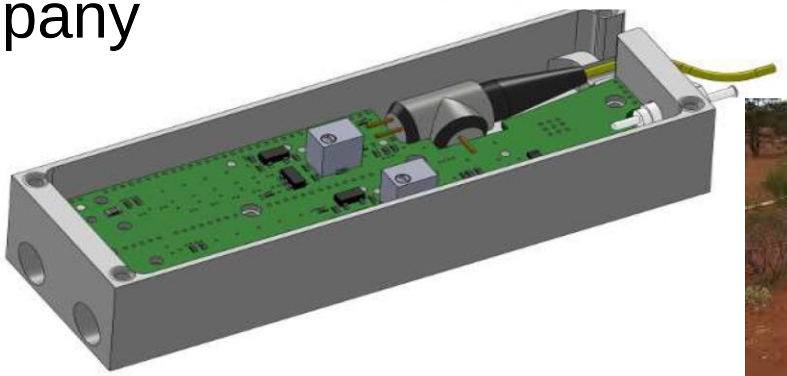
- What we have
  - Big Science pushing the boundaries
  - Exploring novel sensors & techniques (R&D)
- Challenges
  - Develop instrumentation because not commercially available: low noise, low power, high dynamic range, bandwidth, vacuum, radiation ……
- What we need
  - Collaboration with industry and research institutes on photonics, MEMS fabrication, wafer level packaging, integrated electronics, new materials ….

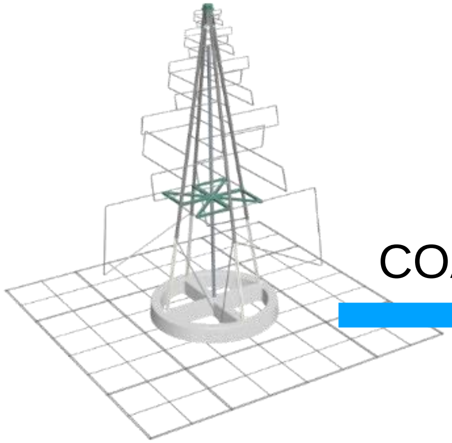
Ronald Broeke (Bright Photonics): "*The development of the diodes for LISA provides us with new knowledge that we will use in other applications in the future. Through collaboration with the NWO institutes Nikhef and SRON, we have explored new grounds in photonics regarding materials, simulation and application development for space*"

Power and Signal Distribution



- Provide Radio Frequency over Fibre (RFoF) technology
  - Focus on transmitter module development, inc. supply chain
  - 130,000 x 2 RFoF links to Central Processor
- Design not quite complete, some further development required
- Now production contract for EMS company





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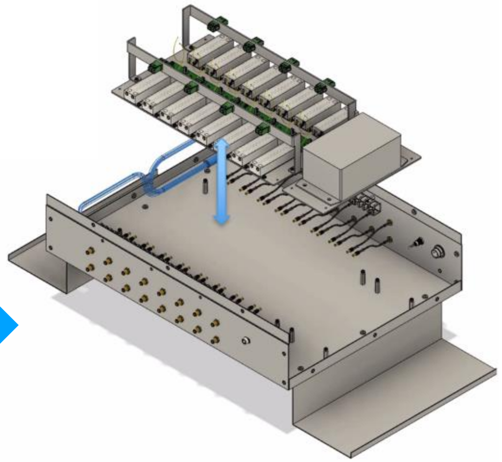


Fibre-optic link to CL

ASTRON
Netherlands Institute for Radio Astronomy

Fast timing developments
Timepix 4

Jan Visser

- *Industrial Liaison Officer for CERN & ET*

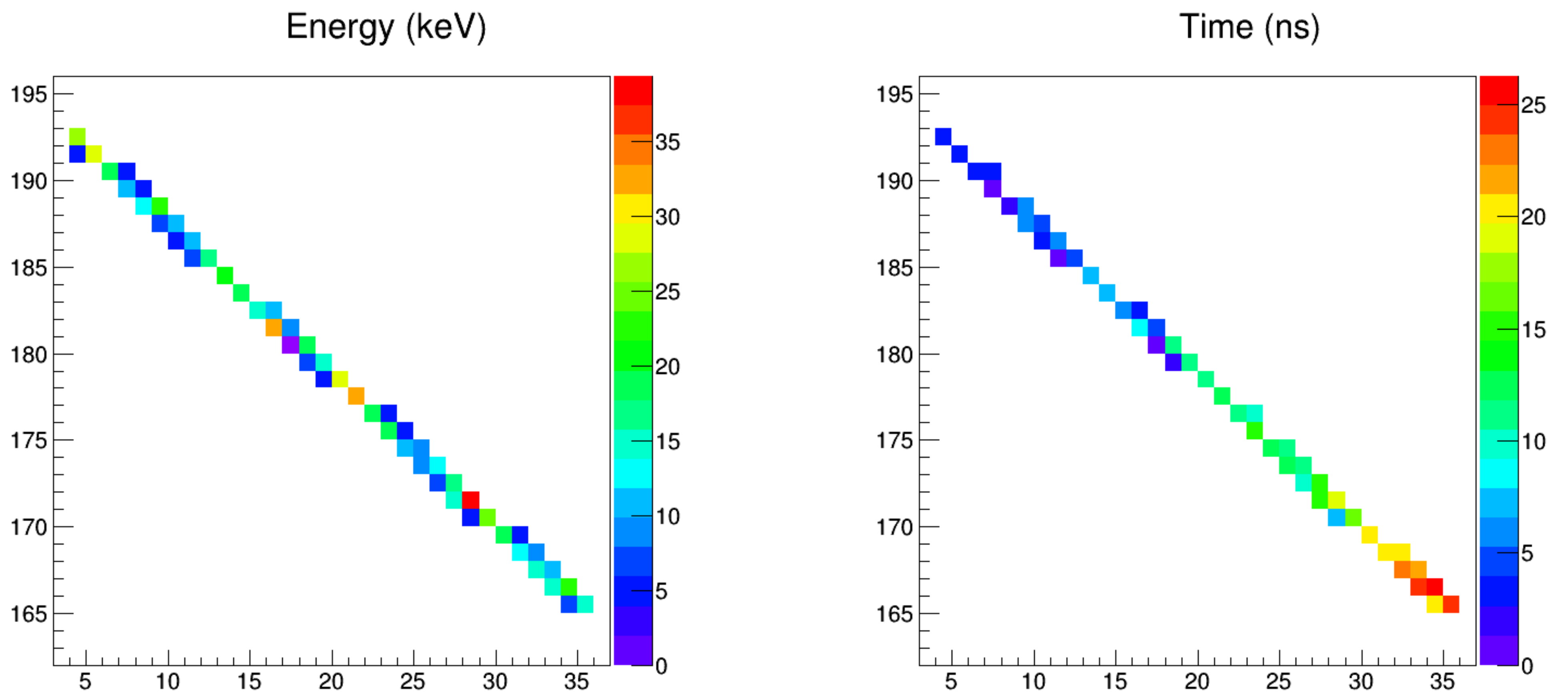
Timepix4 applications

- Data-Driven applications:
  - HEP:
    - Very high rate pixel telescope
    - Sensor studies (high speed)
  - Time-of-flight mass spectrometry
  - Neutron time-of-flight imaging
  - Radiation monitors
  - Electron microscopy
  - X-ray and powder diffraction
  - Compton camera for medical diagnostics
  - Sub-pixel resolution imaging
  - Gamma and neutron imaging for nuclear industry and Homeland Security

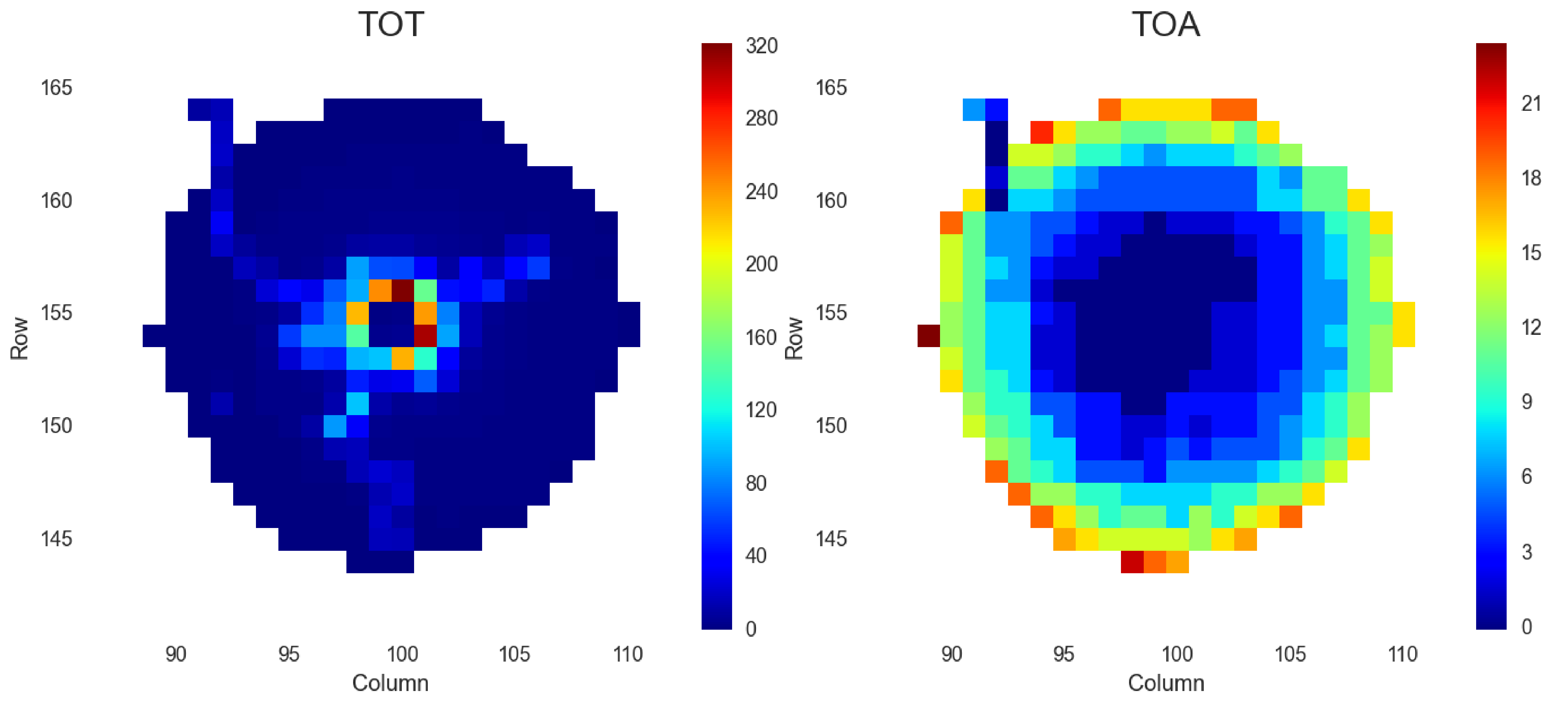
- Frame-based imaging applications:
  - X-ray imaging in synchrotrons with extreme high rates > 10^9 particles/mm^2/s

Particle detection using Timepix3

Cosmic ray



Ar 150 GeV/c
[p-on-n 500 μm sensor]



Precise arrival time information (1.56ns steps) provides depth of interaction within the sensor layer

Timepix4 main specifications

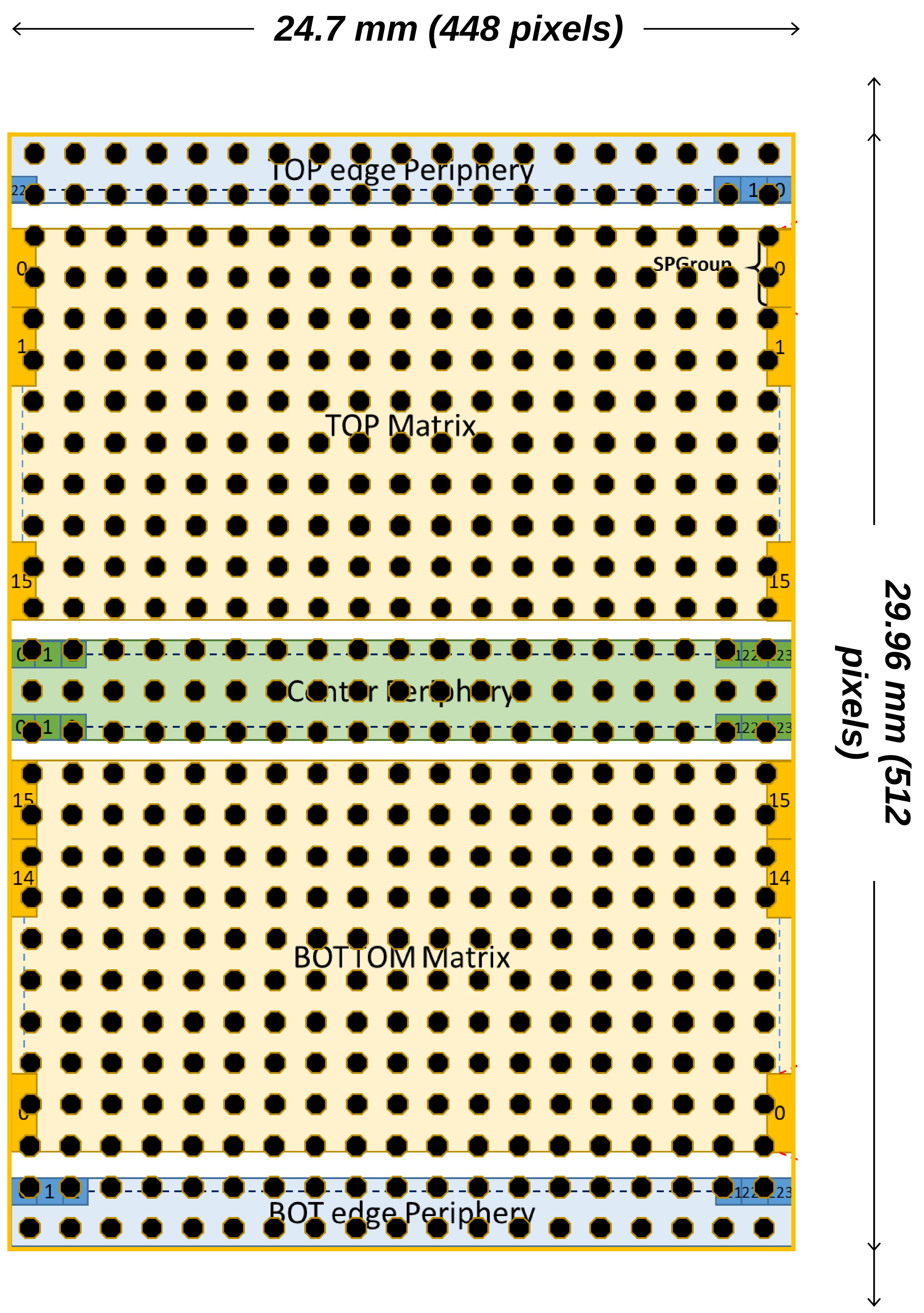
- Use of a commercial 65nm CMOS process
- Build a 4-side buttable pixel array
- Particle identification and tracking
  - Data-driven and zero suppressed
  - Sub-ns time binning
  - Improve the energy resolution
- Imaging
  - Increase particle count rate
- Design team from CERN, Nikhef and IFAE

Timepix3 → Timepix4

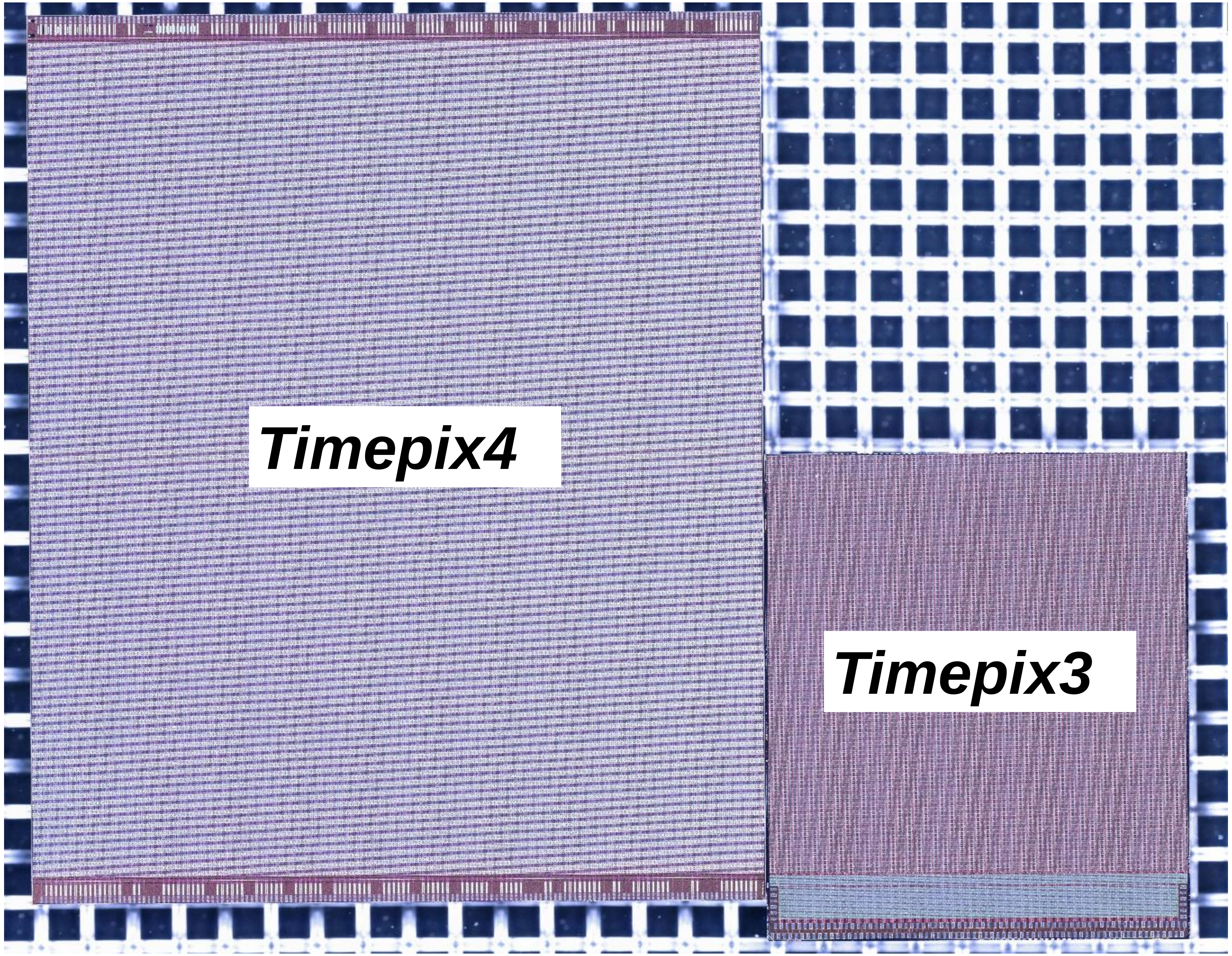
			Timepix3 (2013)	Timepix4 (2019)	
Technology			130nm – 8 metal	65nm – 10 metal	
Pixel Size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	3.5x
Sensitive area			1.98 cm^2	**6.94 cm^2**	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA		
		Event Packet	48-bit	64-bit	33%
		Max rate	$0.43x10^6$ hits/mm^2/s	**$3.58x10^6$ hits/mm^2/s**	8x
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s	5x
TOT energy resolution			< 2KeV	**< 1Kev**	2x
TOA binning resolution			1.56ns	**195ps**	8x
TOA dynamic range			409.6 µs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz)	4x
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps (16x @10.24 Gbps)**	32x
Target global minimum threshold			<500 e^-	<500 e^-	

Timepix4 floorplan arrangement

- 512 x 448 of 55 x 55 µm pixels
- 3 peripheries with TSV (Through-Silicon-Vias):
  - TOP Edge: Data Readout & Slow Control
  - BOTTOM Edge: Data Readout & Slow Control:
  - CENTER: Slow Control and Analog Blocks
- On-chip bump to pixel redistribution layer (RDL)
- Chip size:
  - With WB (wirebonds extenders): 29.96 mm x 24.7 mm
    - **>93.7%** active area (28.16mm x 24.64mm)
  - Without WB (TSV Only) : 28.22 mm x 24.7 mm
    - **>99.5%** active area (28.16mm x 24.64mm)
- Control architecture allows to operated Timepix4 from any of the 3 peripheries:
  - i2C protocol
  - Custom Slow Control protocol
  - Interface to DAQ



Big step forward

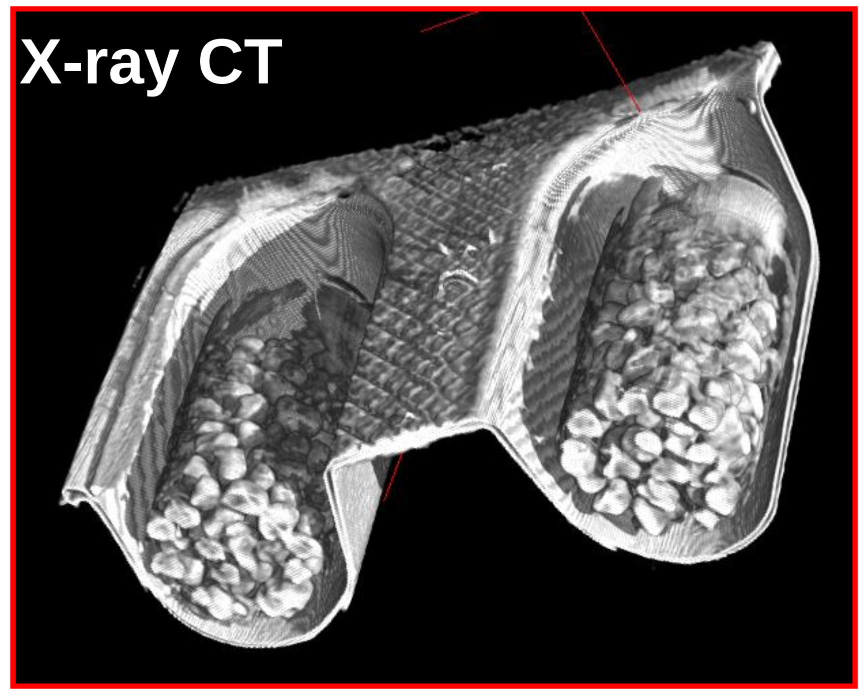


HEP to 'Medipix' applications

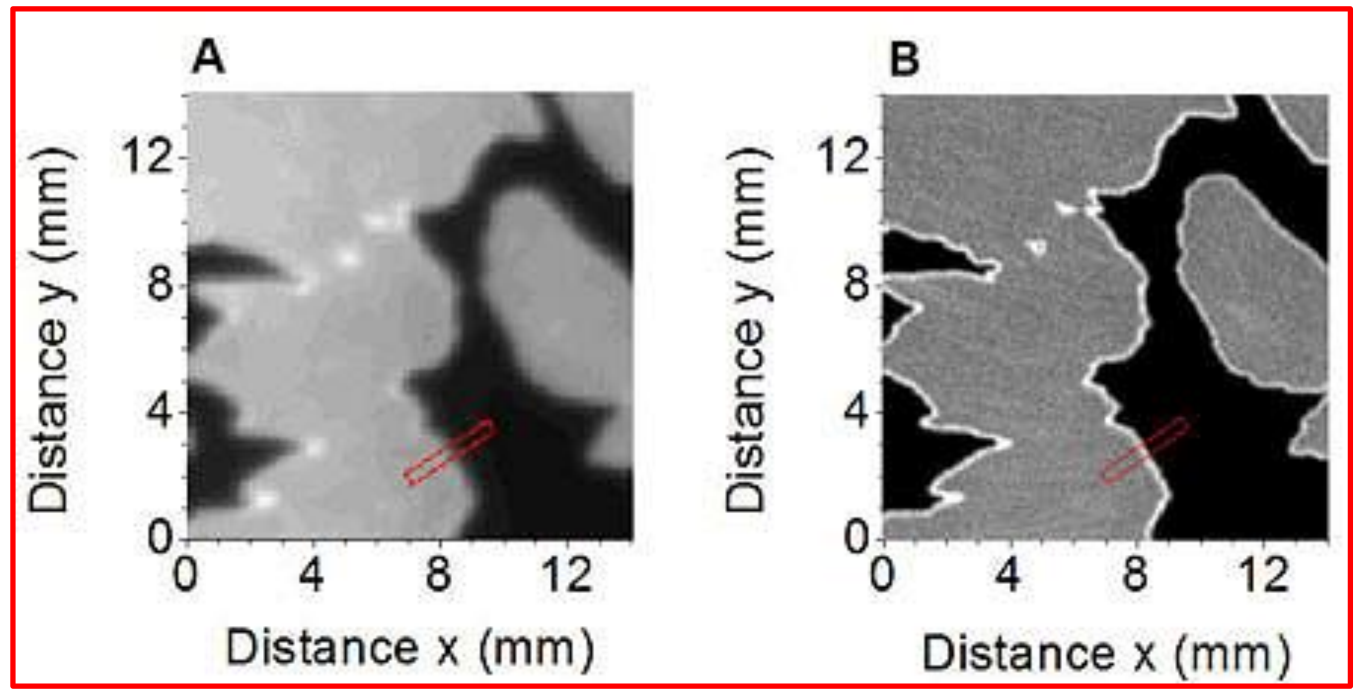
Imaging

- X-ray diffraction
- Electron Microscopy
- Neutron imaging
- Space dosimetry
- Many more

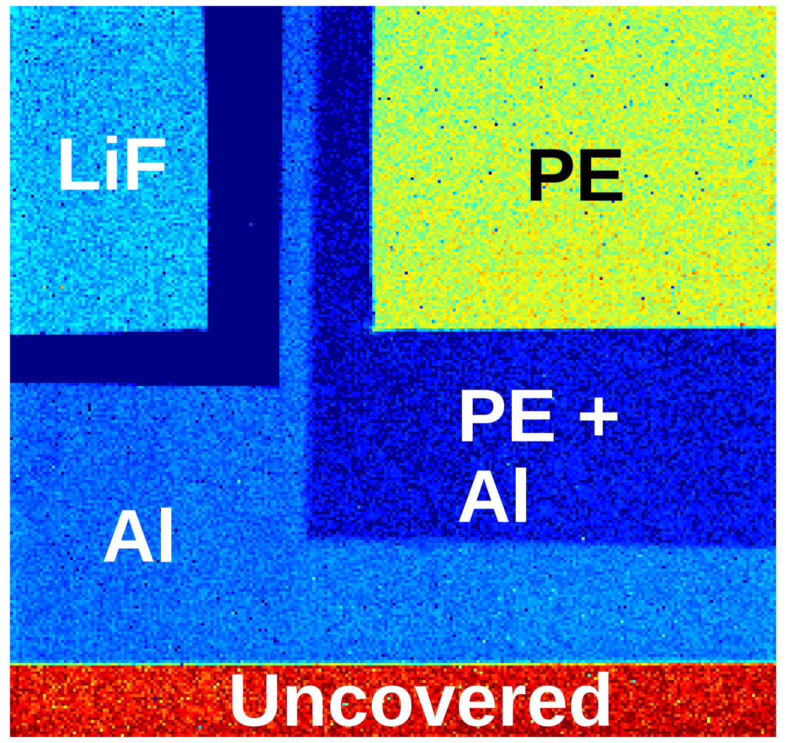
Courtesy of many!

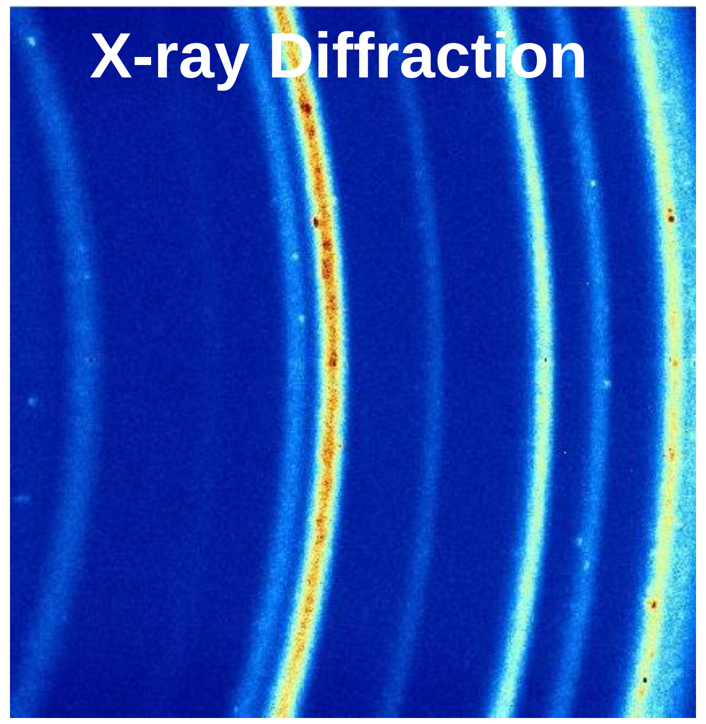


Electron microscopy



X-ray image of conversion layers





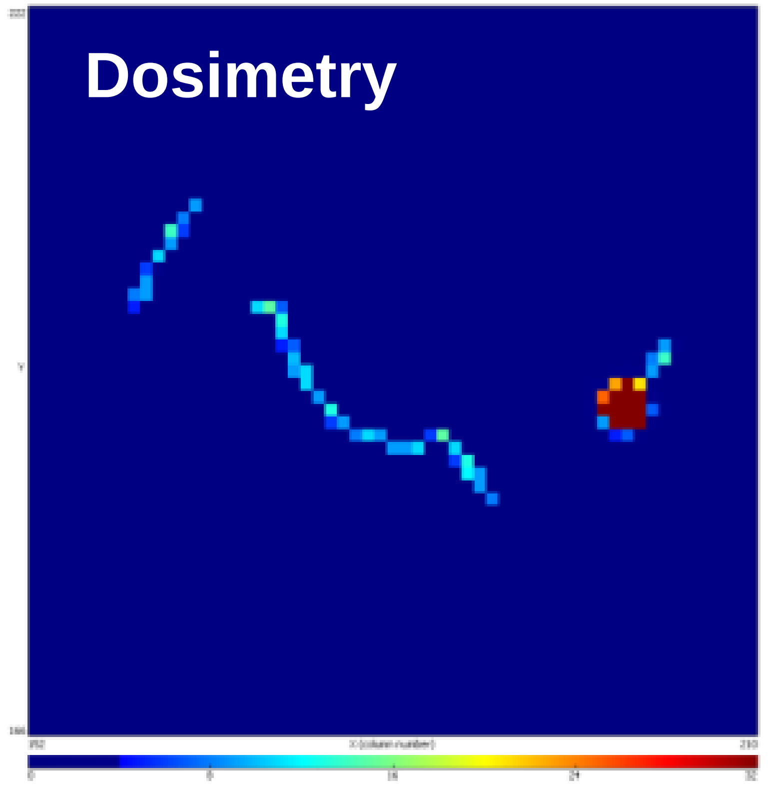
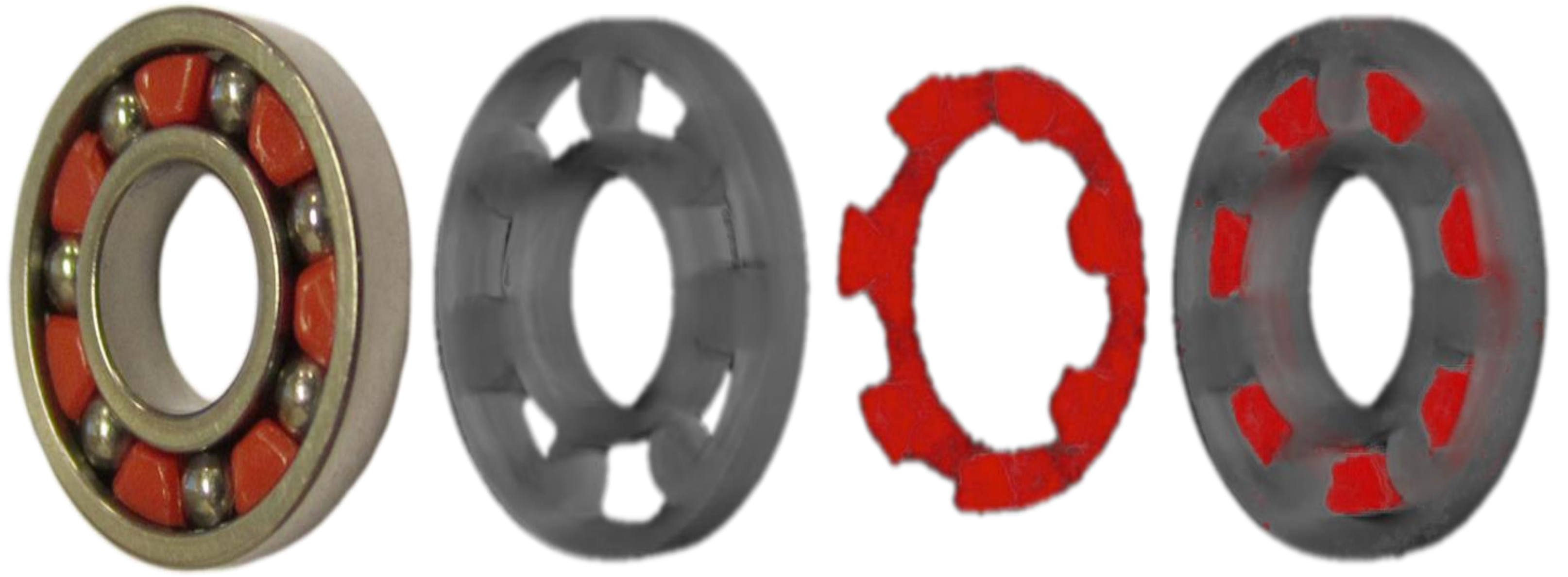
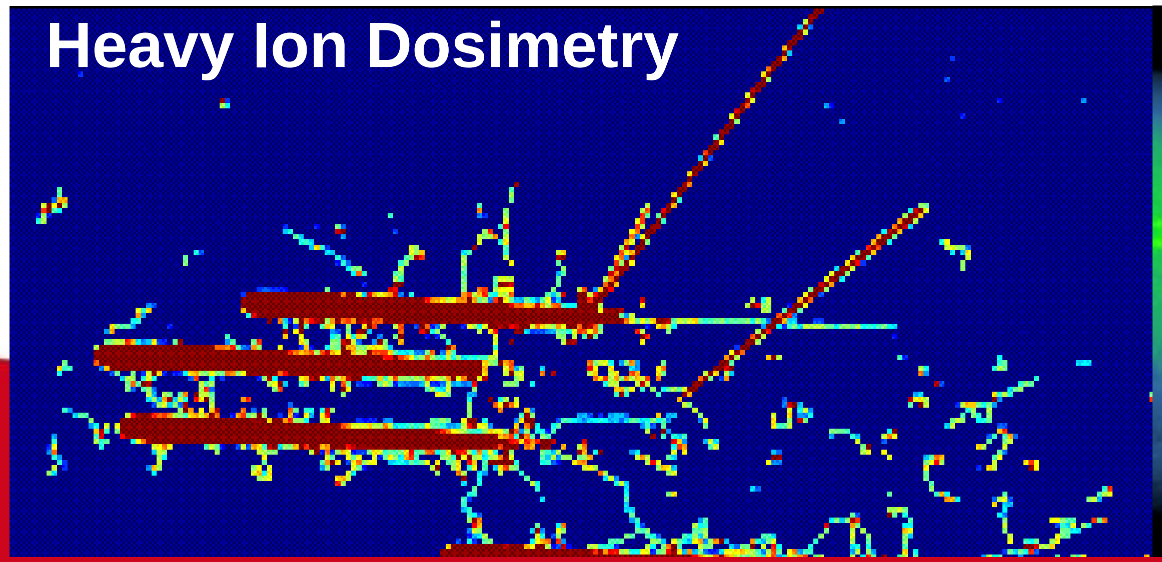
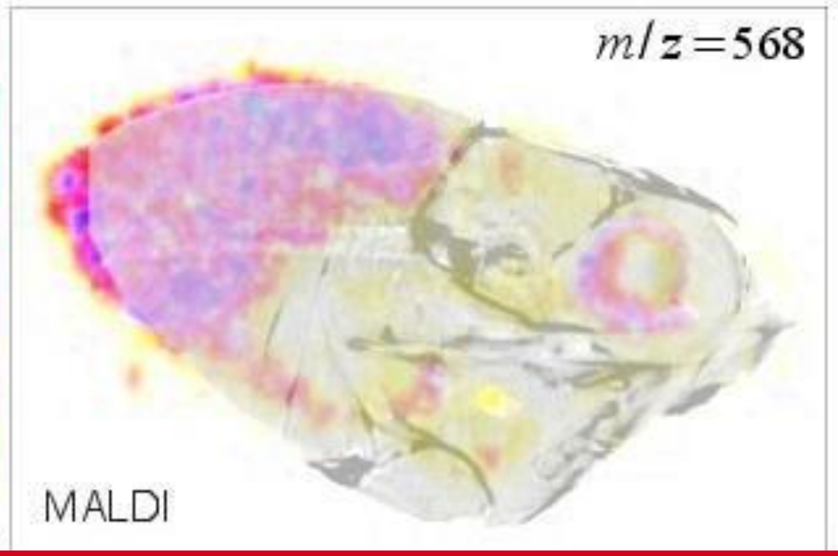
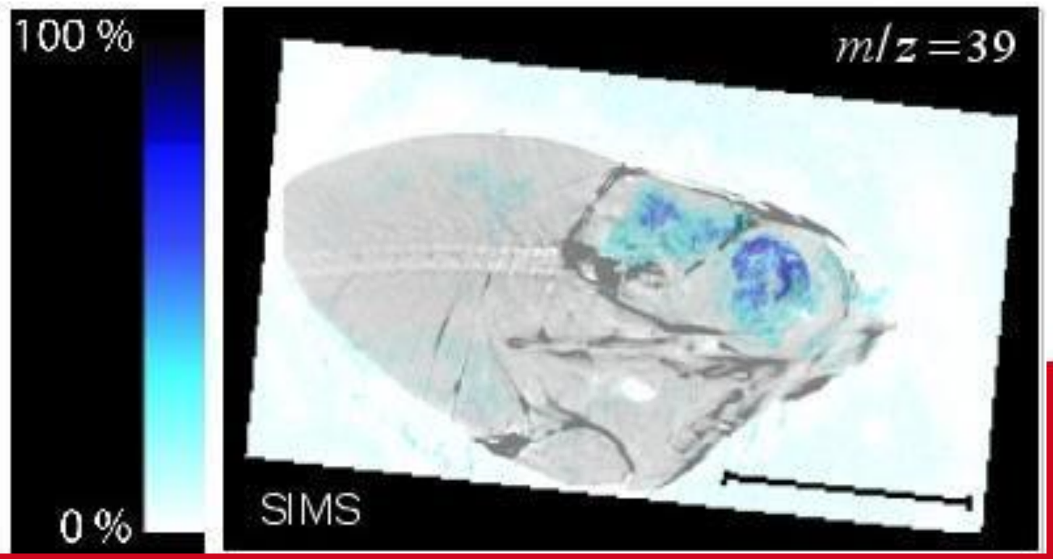


Photo X-ray CT Neutron CT Combined CT









Mass Spectrometry + X-ray CT slice