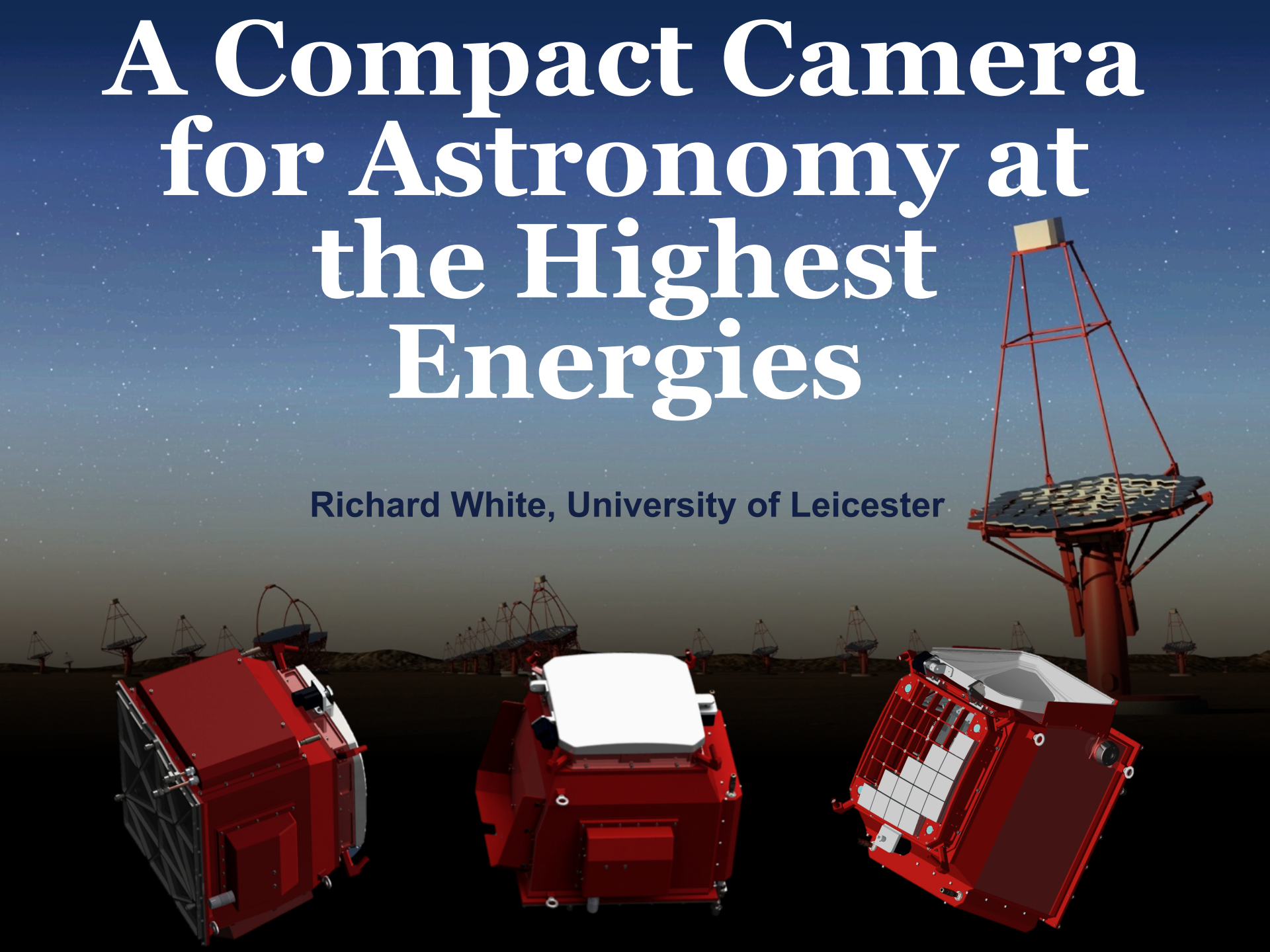
A Compact Camera for Astronomy at the Highest Energies

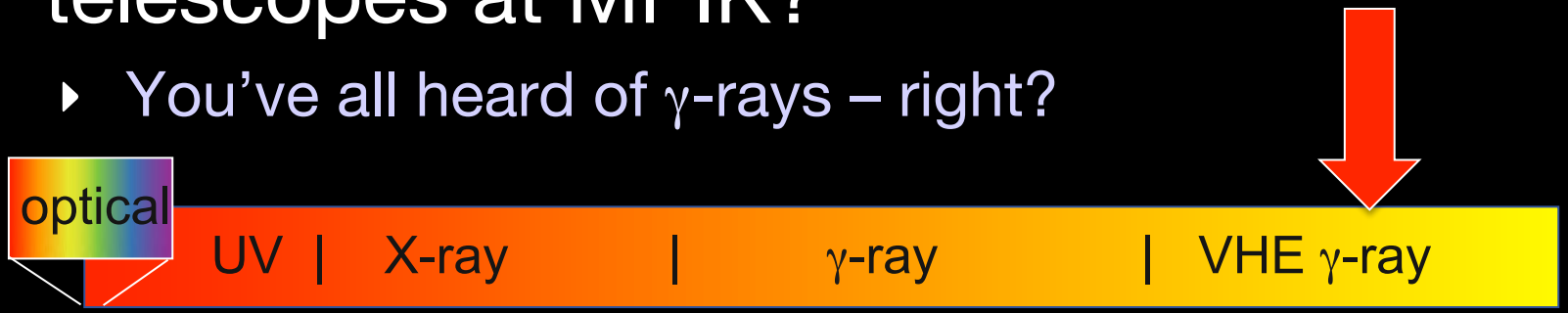
Richard White, University of Leicester



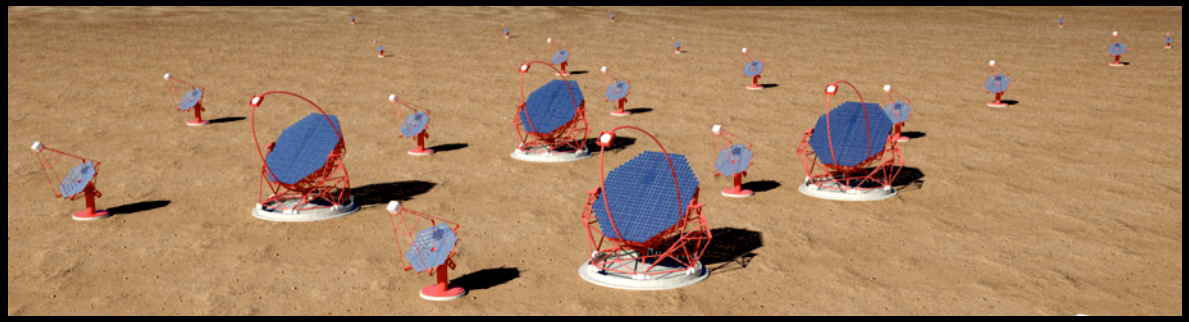
Where to start?

University of Leicester

- How to give a talk about Cherenkov telescopes at MPIK?
  - You've all heard of γ-rays – right?



  - You've heard of CTA – right?



- I will focus on my role in the project
  - The Compact High Energy Camera (CHEC)

The Plan!

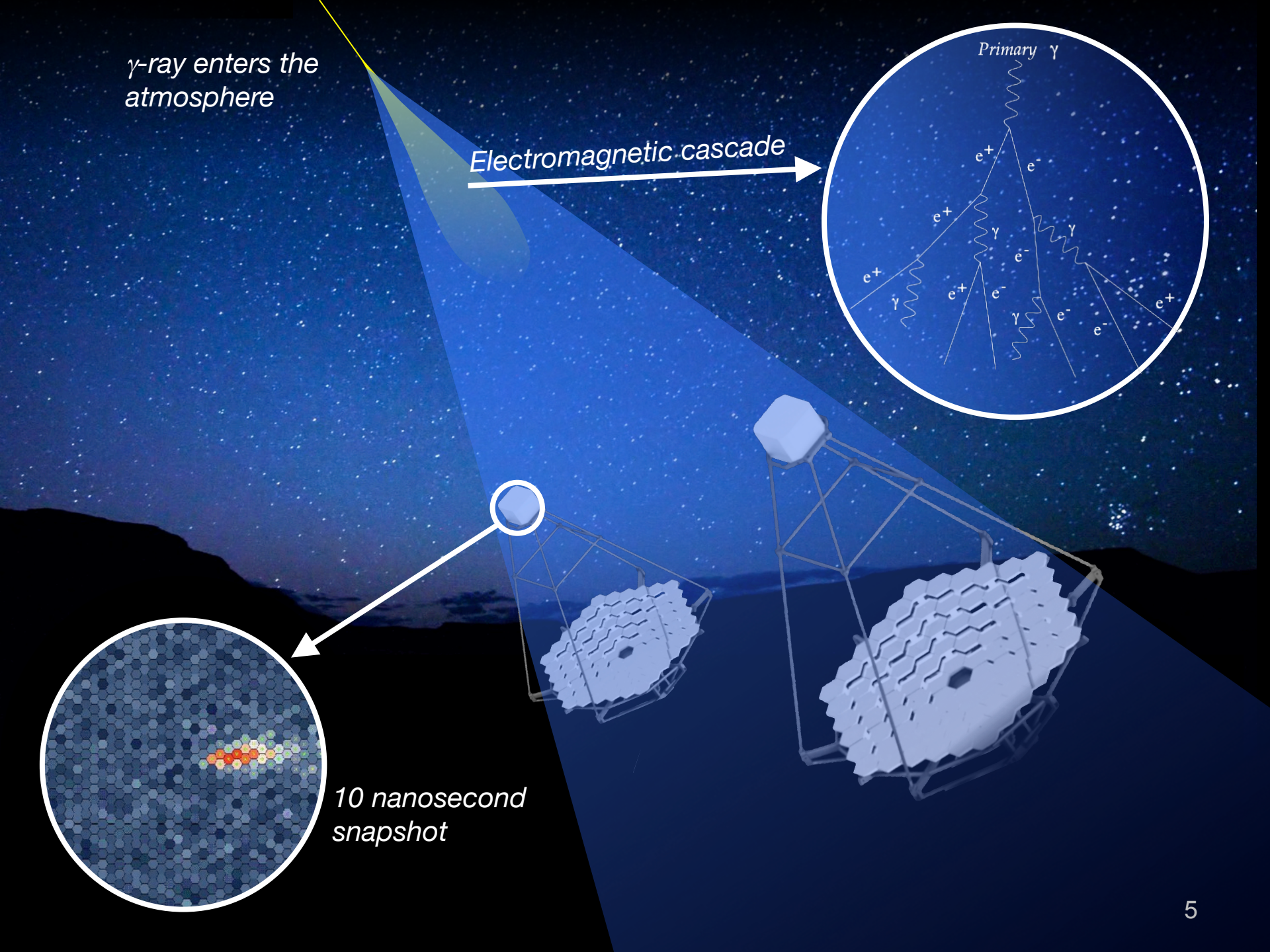
University of Leicester

- Context
  - The technique and current instruments
  - The technology
- The CTA Project
  - Brief overview
  - Focus on the high-energy component of CTA
- The Compact High Energy Camera (CHEC)
  - Design
  - Building and commissioning CHEC
- Beyond CHEC
  - The move from prototyping to ‘mass production’
  - Recent developments

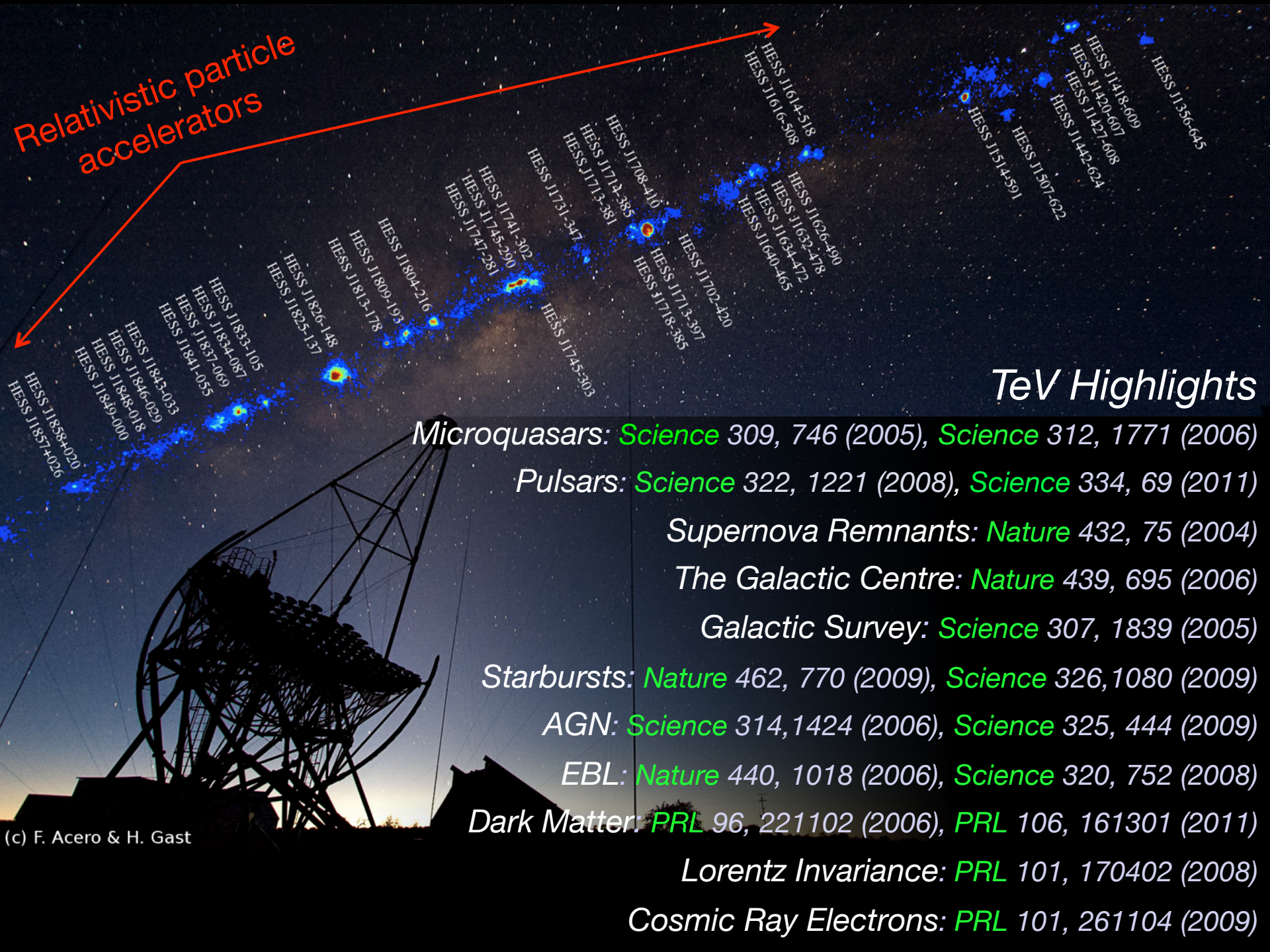
Context

University of Leicester

- How to detect these:


γ-ray enters the atmosphere
Electromagnetic cascade
Primary γ
e+
e-
γ
10 nanosecond snapshot

This technique has a proven track record



TeV Highlights

Microquasars: Science 309, 746 (2005), Science 312, 1771 (2006)

Pulsars: Science 322, 1221 (2008), Science 334, 69 (2011)

Supernova Remnants: Nature 432, 75 (2004)

The Galactic Centre: Nature 439, 695 (2006)

Galactic Survey: Science 307, 1839 (2005)

Starbursts: Nature 462, 770 (2009), Science 326,1080 (2009)

AGN: Science 314,1424 (2006), Science 325, 444 (2009)

EBL: Nature 440, 1018 (2006), Science 320, 752 (2008)

Dark Matter: PRL 96, 221102 (2006), PRL 106, 161301 (2011)

Lorentz Invariance: PRL 101, 170402 (2008)

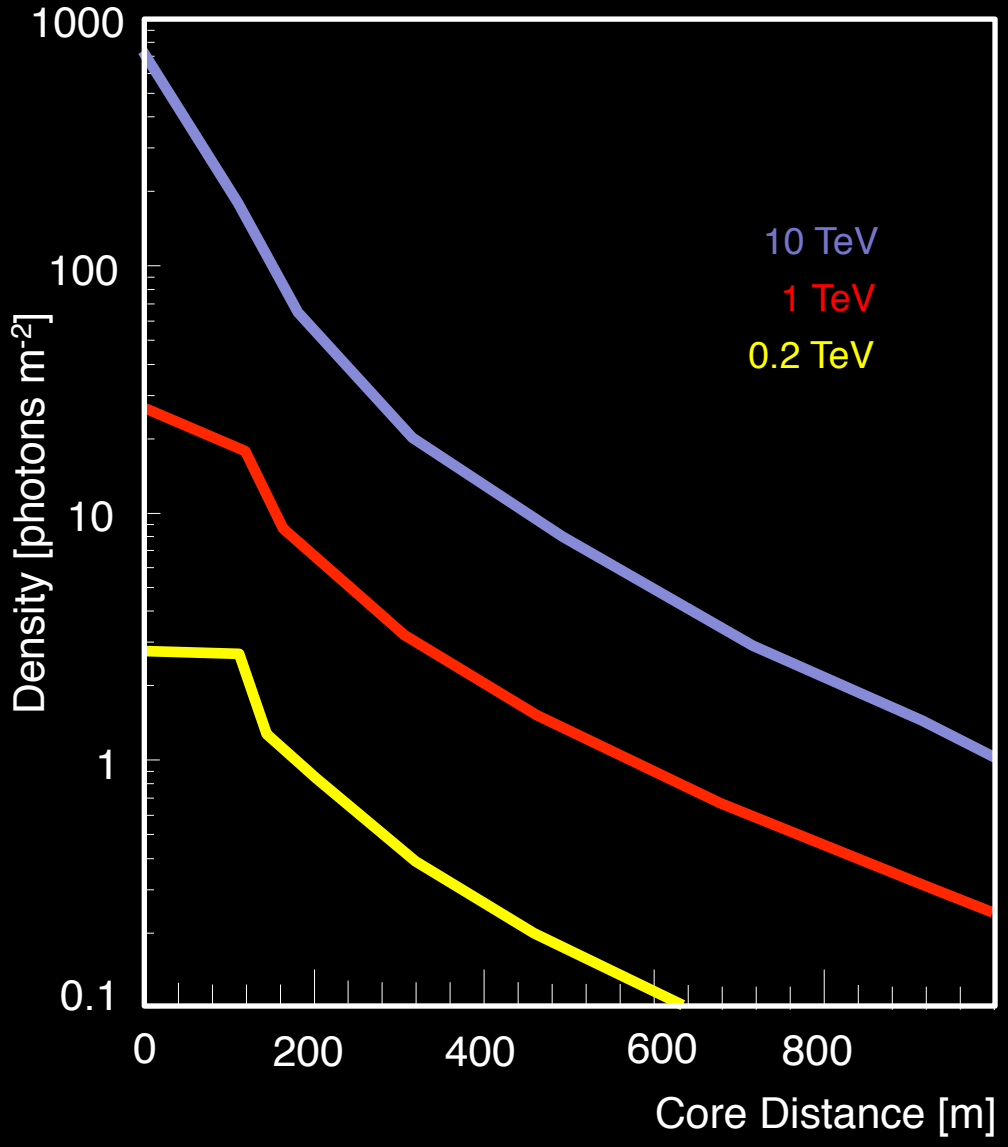
Cosmic Ray Electrons: PRL 101, 261104 (2009)

To do this amazing science requires some technology

Signal & Background

University of Leicester

- Cherenkov light:
  - Faint
    - 1 TeV gamma-ray → ~ 10 photons / m^2 @ 200 m from impact
    - → Big dishes
  - Fast
    - Lasts a few ns
    - → Fast photosensors and electronics
  - Blue
    - Peaks at 350 nm
    - → Blue sensitive photosensors

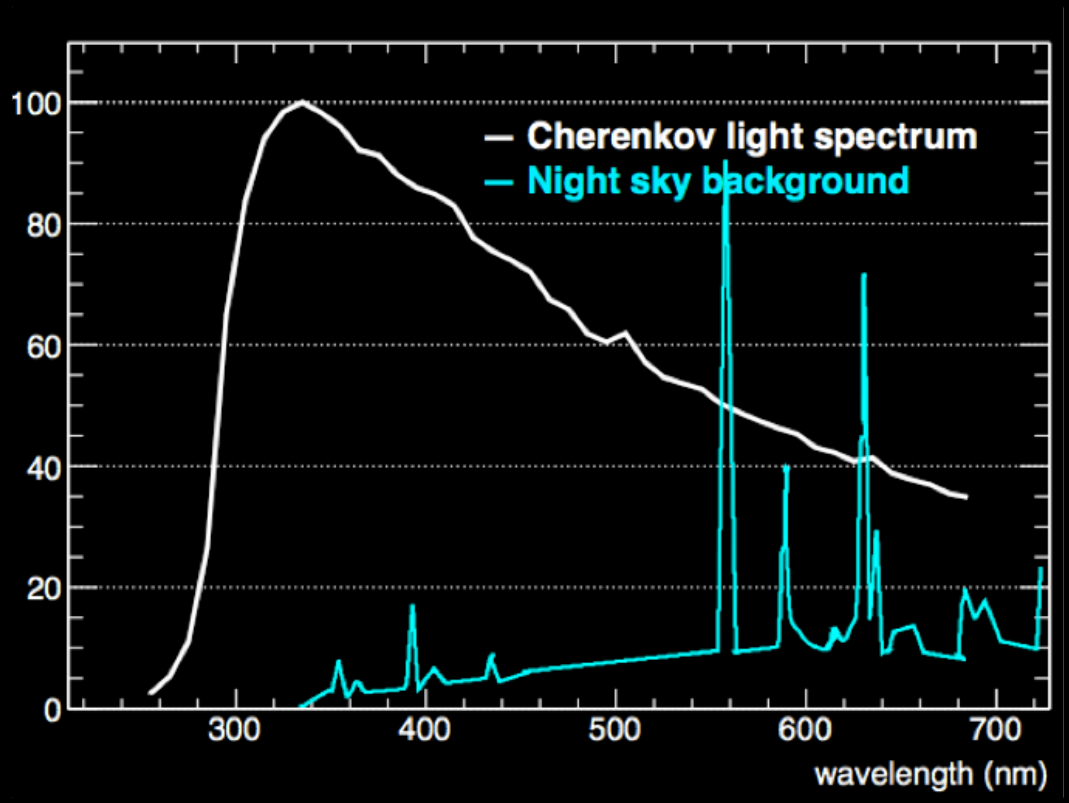


Cartoon version adapted from de La Calle Perez, Biller, 2006

Signal & Background

University of Leicester

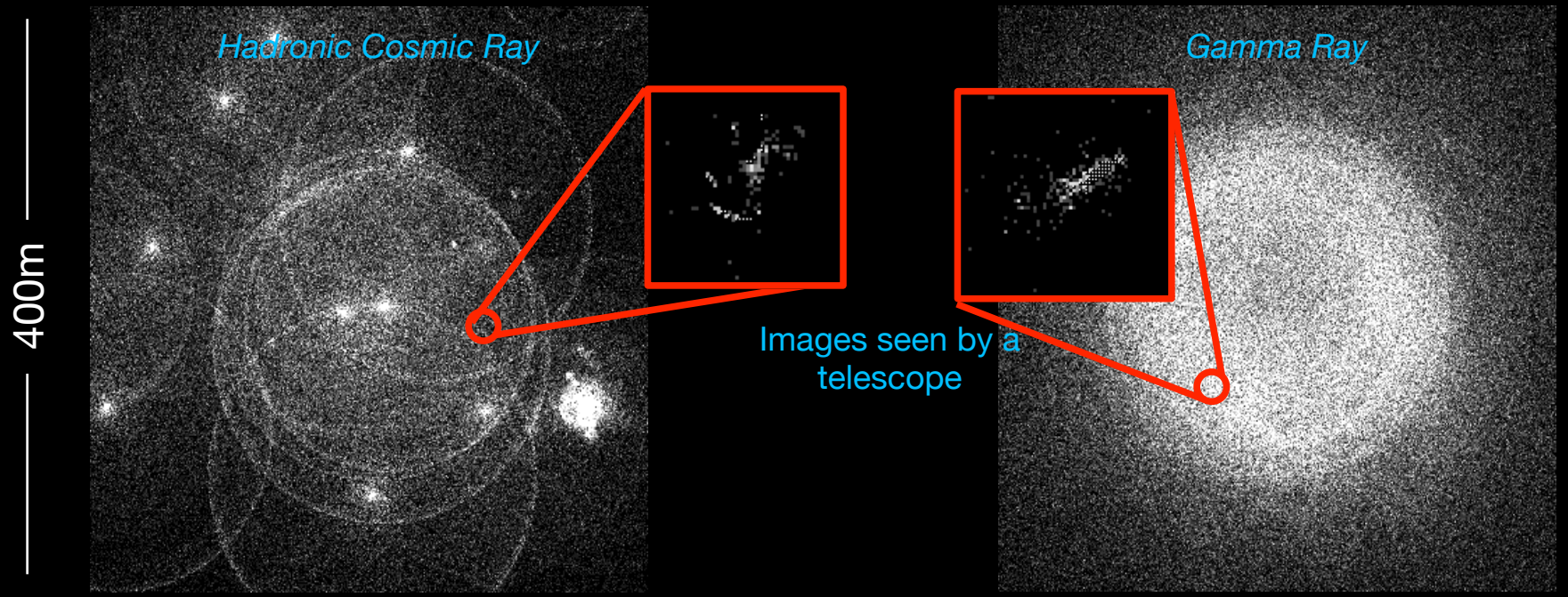
- Night Sky Background (NSB)
  - Stars, air-glow, Zodiacal light...
  - Extra-galactic rate ~100 MHz (for 100m^2 dish, 0.15^o pix)
  - → Can reduce using online triggering
  - → Red sensitive photosensors are bad



Signal & Background

University of Leicester

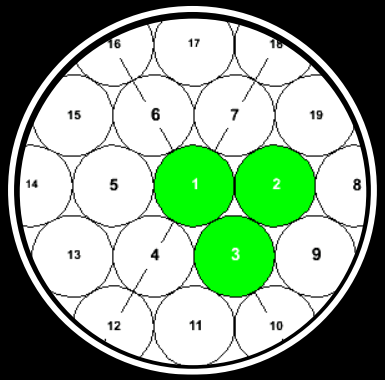
- Cosmic rays
  - Rate dominates gamma-ray rate, even after NSB is reduced
  - ~100 kHz for ~100 GeV threshold
  - → Offline image analysis



from Jamie Holder

The Camera
Key Technology

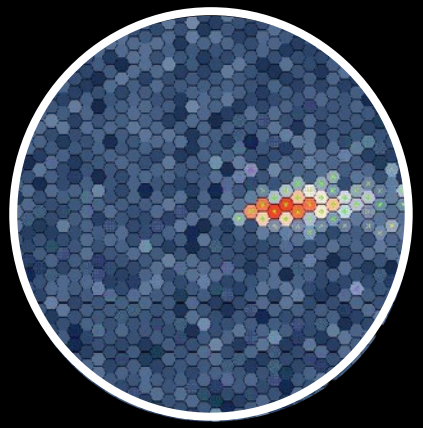
- Trigger
  - Flashes of Cherenkov light, random rate
  - Multi-level: threshold, multiple pixel, multiple cameras

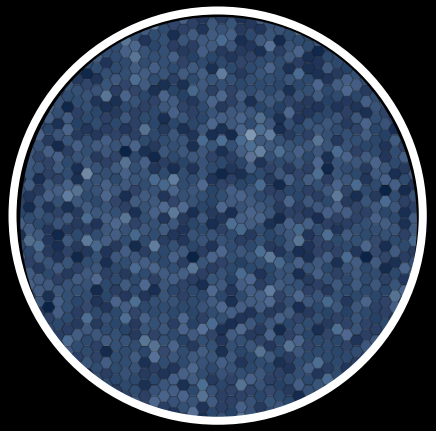


The Camera
Key Technology

University of Leicester

- Trigger
- Digitise
  - Window O(100ns) - digitised only 0.01% of the time
  - Integration window or waveform readout
  - Waveform sampling ASICs or FADCs

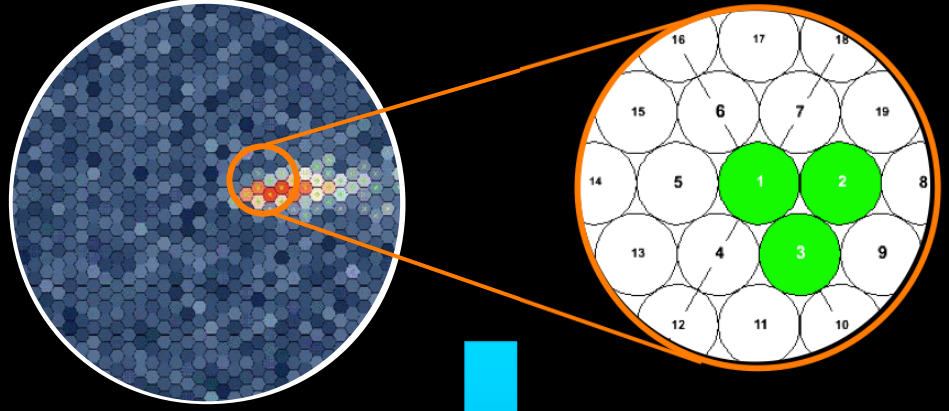


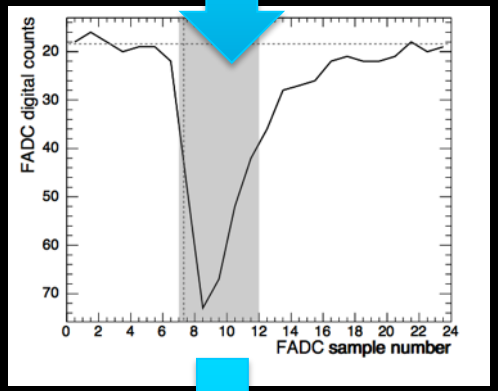


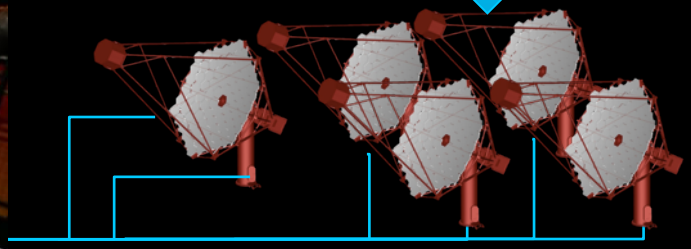
The Camera

Key Technology

- Trigger
- Digitise
- Readout
  - Transfer data
  - Array level trigger
  - Time synchronisation
  - Control and monitoring







The Camera

Key Technology: an example from HESS

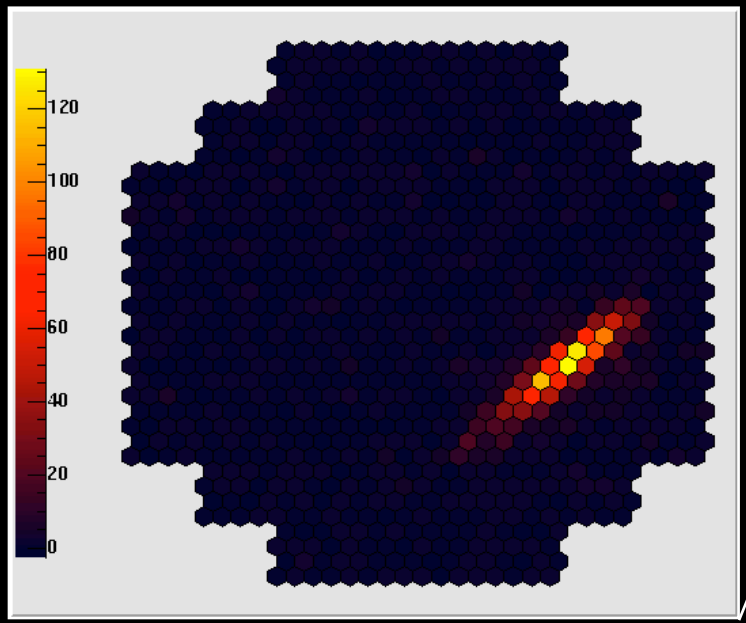
University of Leicester

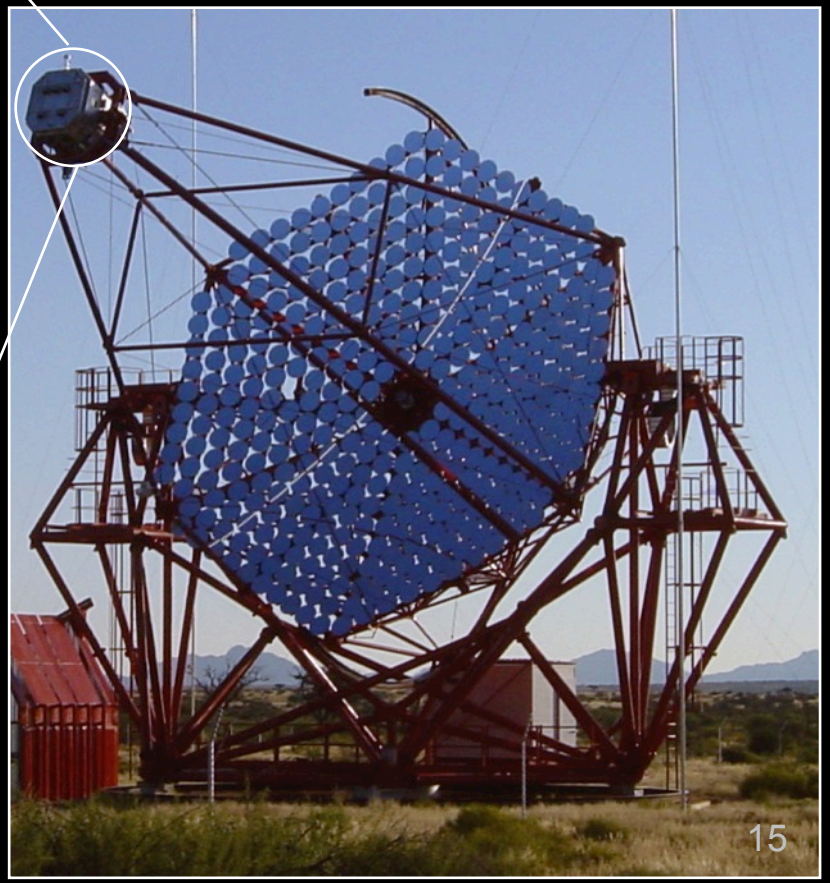
960 PMT pixels

Angular pixel size: 0.16°

Camera diameter: 5° FoV (1.4 m)

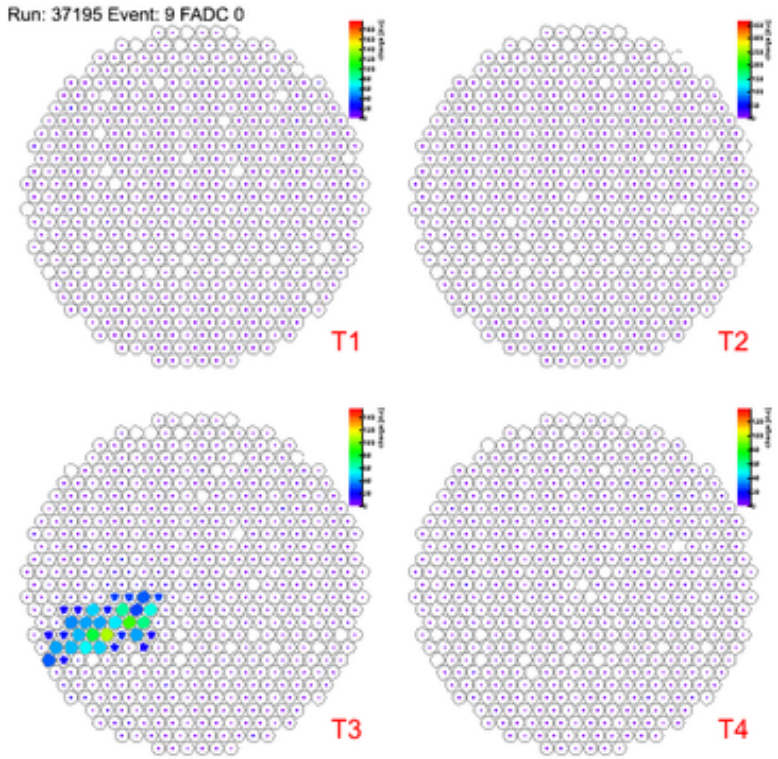
16 ns snapshots, 1000s times per second





The Camera

Key Technology: an example from Veritas

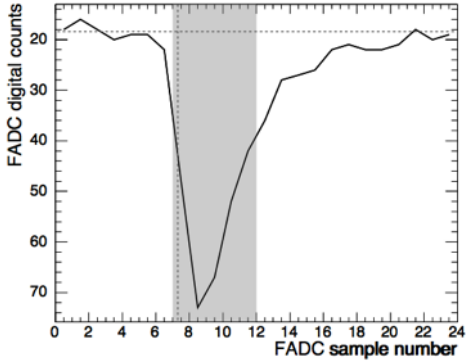


500 PMT pixels

Angular pixel size: 0.15°

Camera diameter: 3.5° FoV

24 ns movies, 1000s times per second



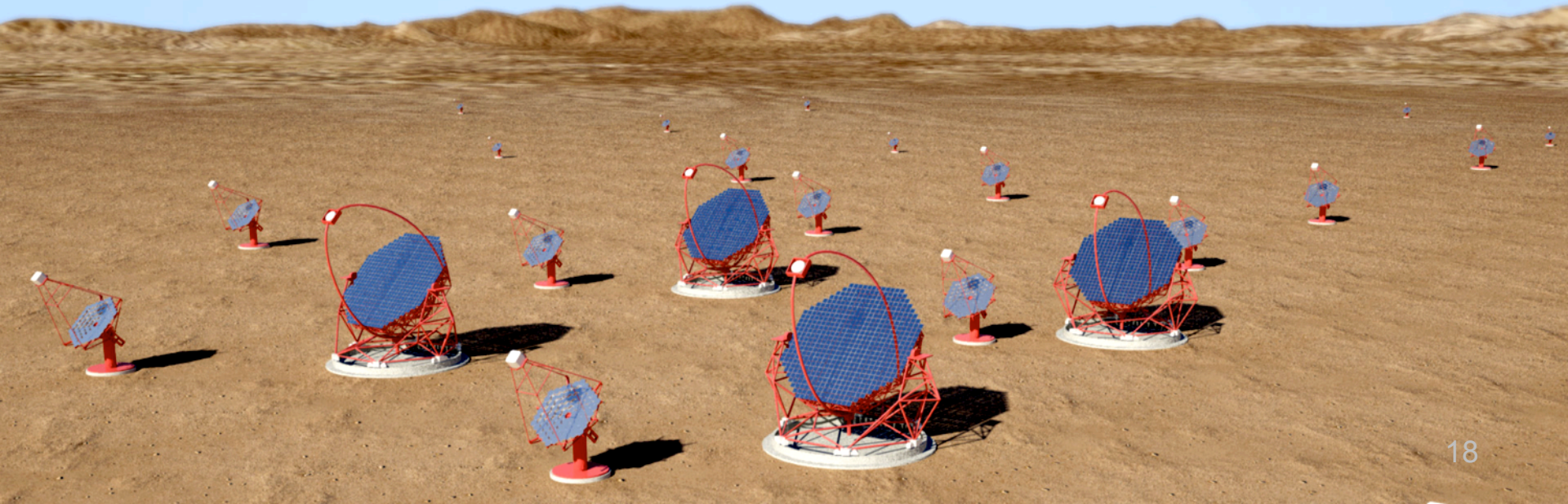
THE STATE OF THE ART:

HESS-2

HESS-1: 4 x 12m tels
HESS-2: +28m tel

The Cherenkov Telescope Array

- A huge improvement in all aspects of performance
- A user facility / proposal-driven observatory
  - With two sites and a total of >100 telescopes
- A global ~€200M project
  - Including everyone from HESS, MAGIC and VERITAS
  - >1000 scientists and engineers across 27 countries



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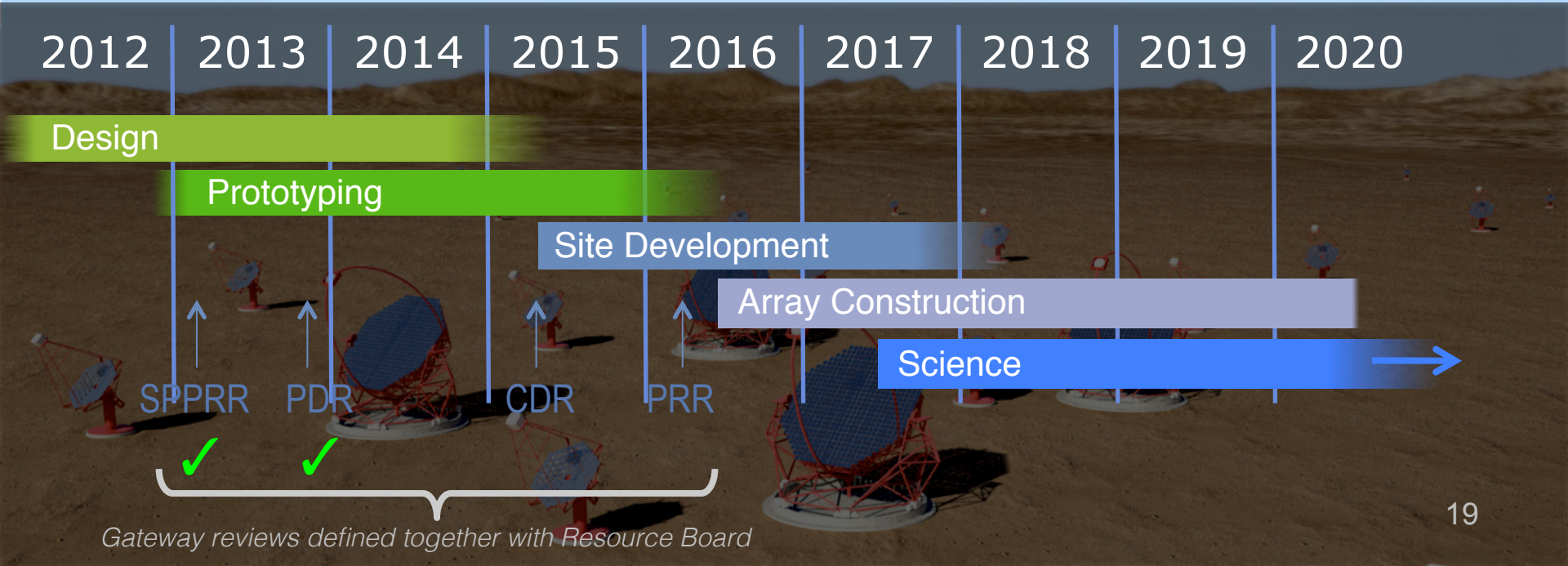
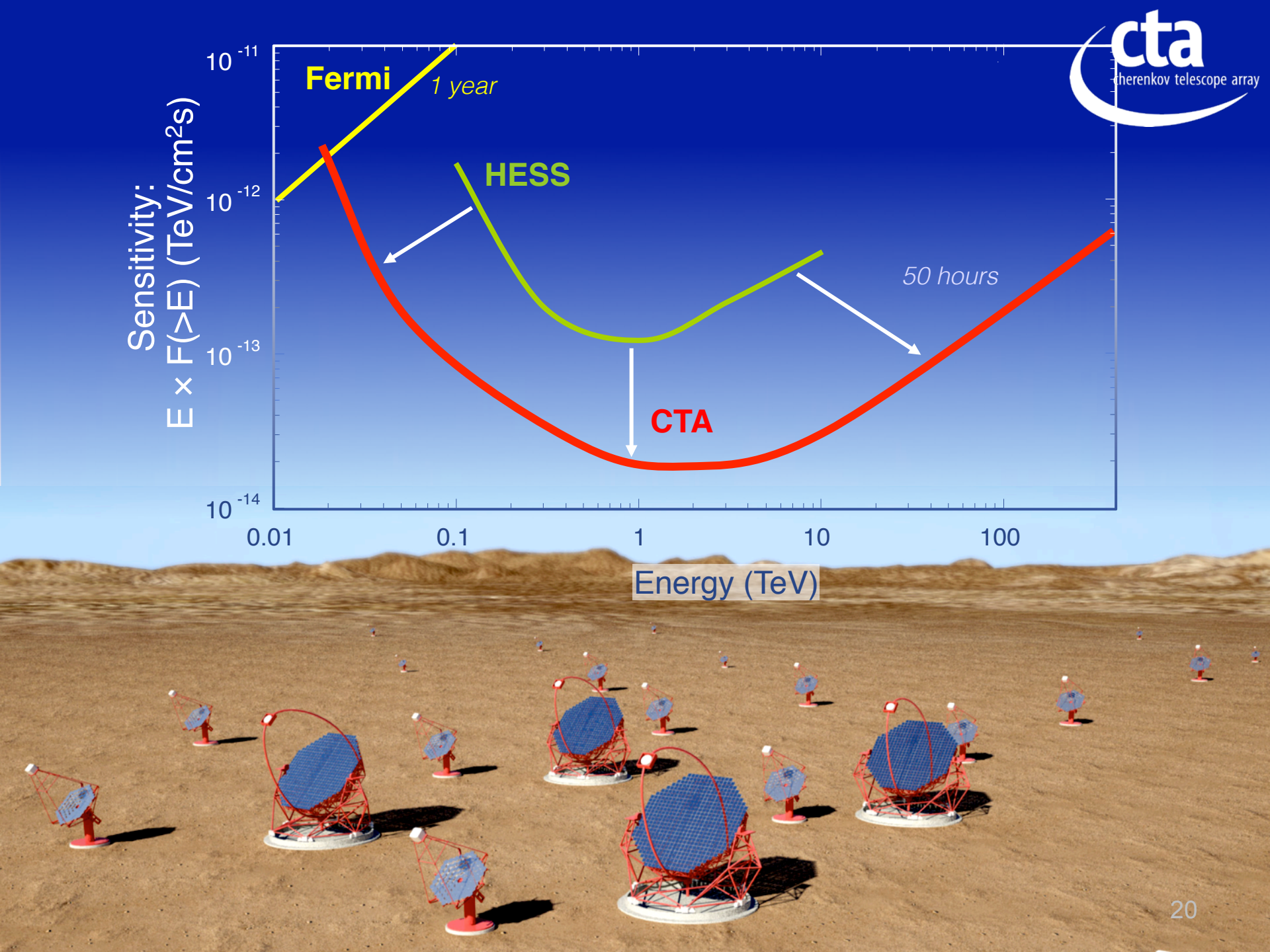
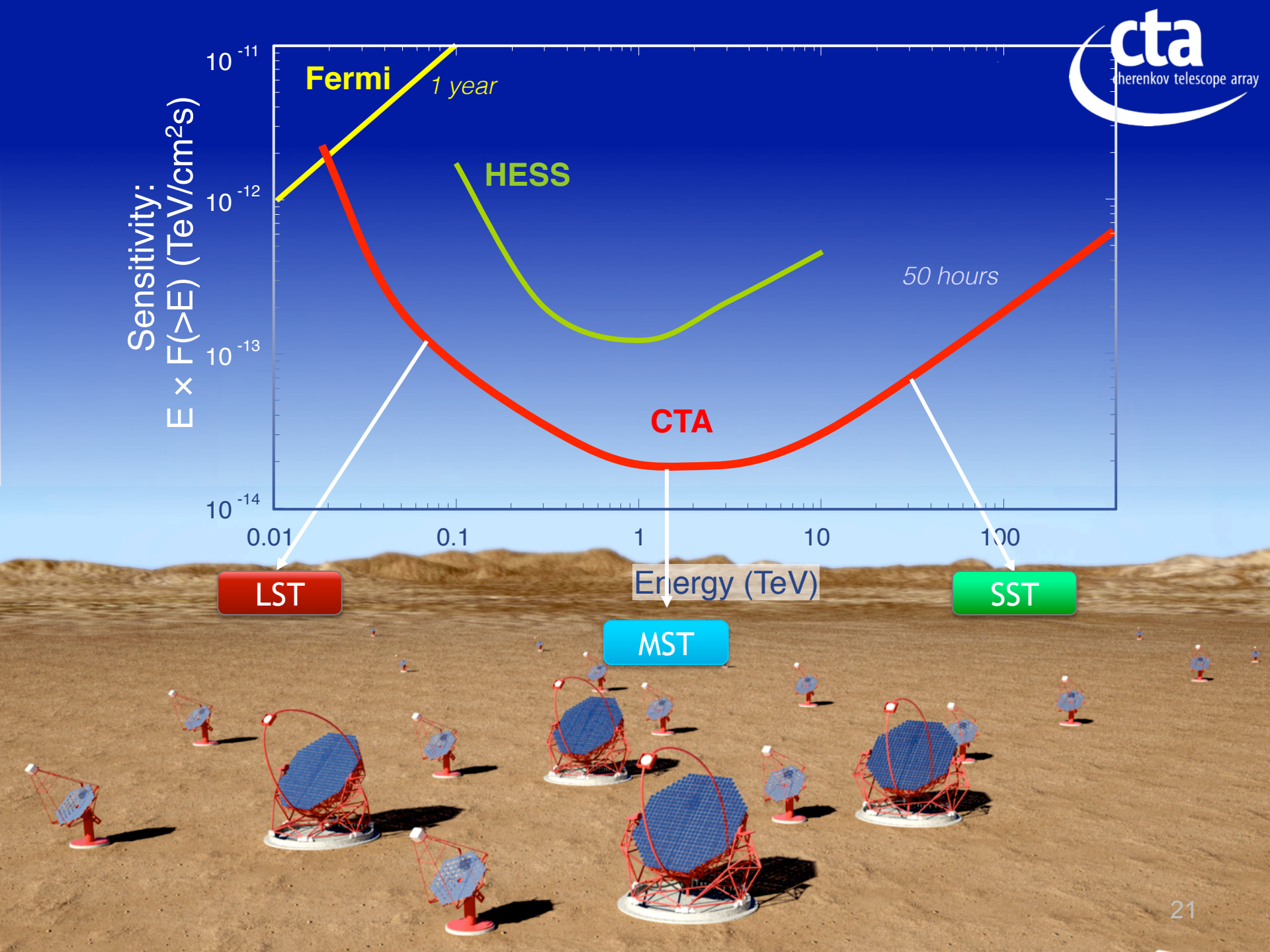



Fermi
1 year
HESS
50 hours
CTA
Sensitivity:
E x F(>E) (TeV/cm²s)
10 -11
10 -12
10 -13
10 -14
0.01
0.1
1
10
100
Energy (TeV)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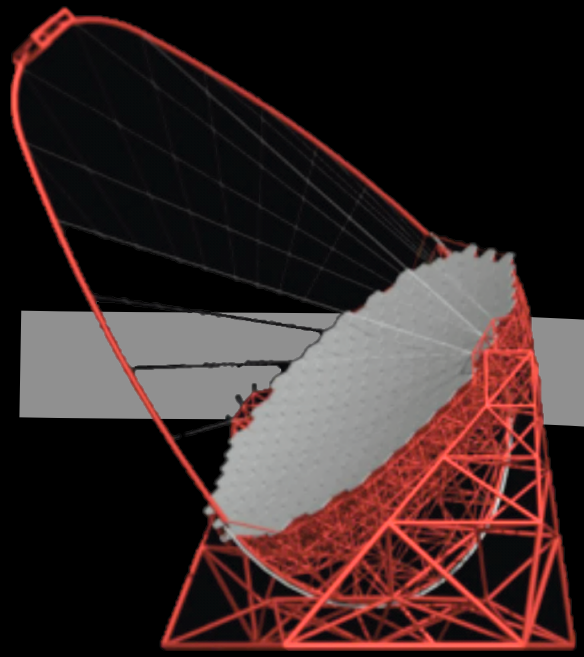
Energy (TeV)
LST
MST
SST

University of Leicester

LST



23 m
Carbon-Fibre
Evolution of
MAGIC design
Fast slewing

Similar Camera Requirements

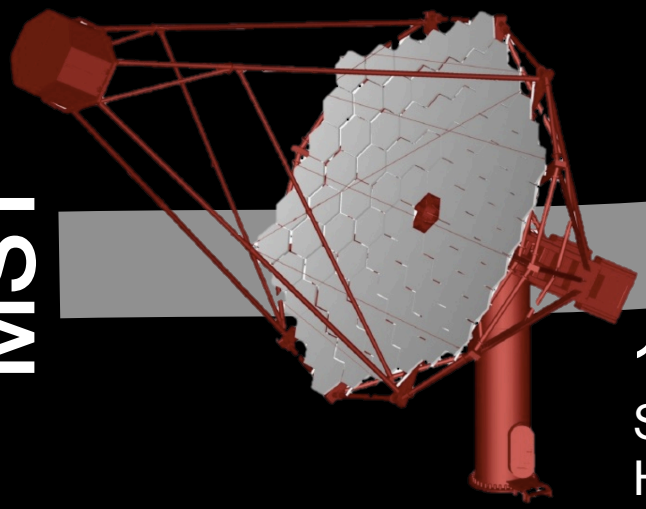
2m focal plane
~2000 pixel
~ns sampling

4.5° FoV
0.10° pix.

5 cm pixels

8° FoV
0.18° pix.

MST

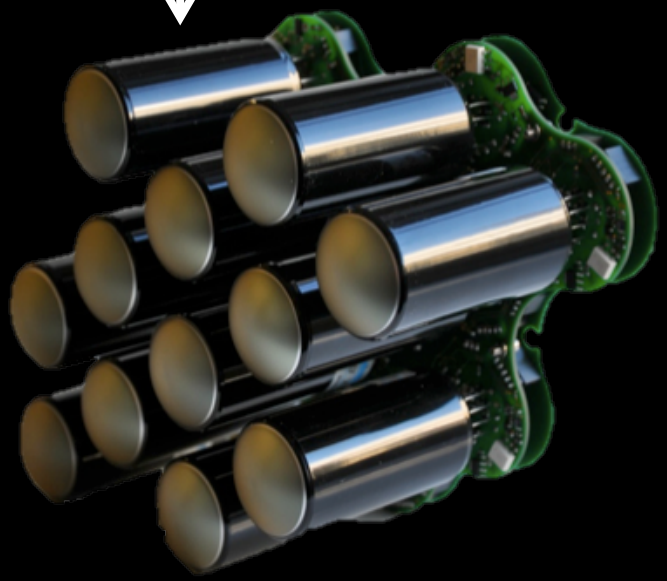


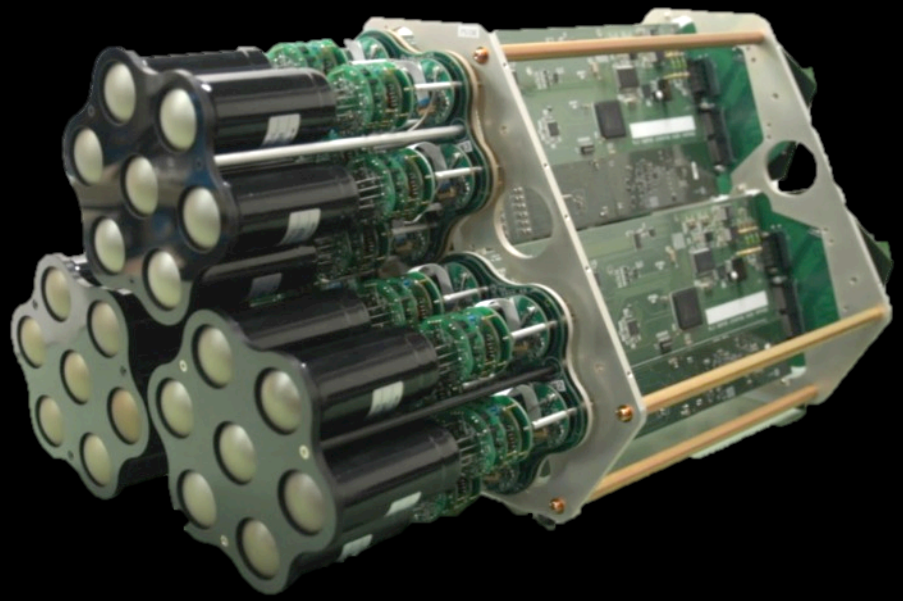
12 m
Steel
HESS/VERITAS
Influenced

Photomultiplier Cameras

University of Leicester

- Recording signal waveform for triggered images
- Options:
  - Capacitor pipeline + analog trigger + (identical) “drawers”
    - NectarCam
    - DragonCam
  - Flash-ADC + digital trigger + rack-based electronics
    - FlashCam

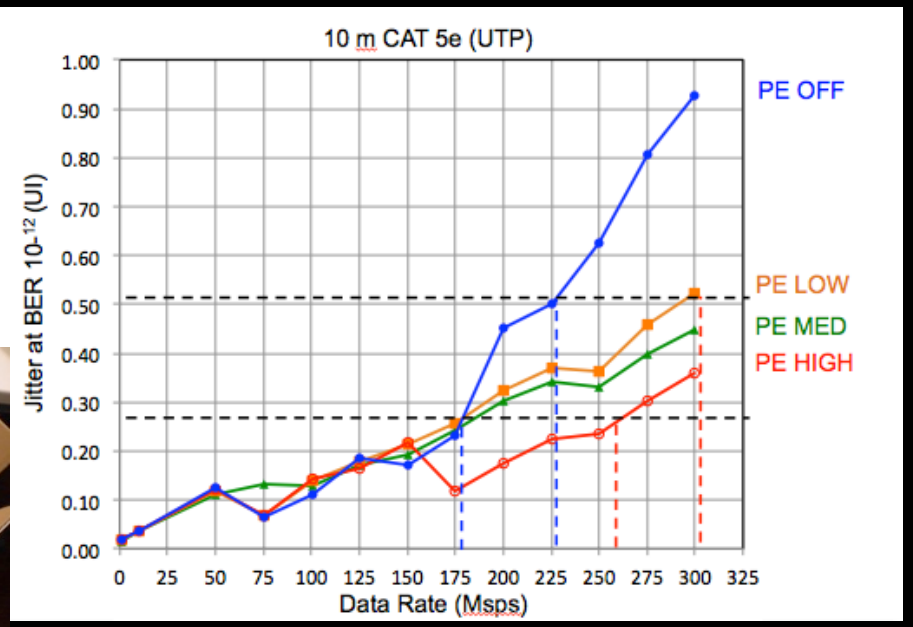


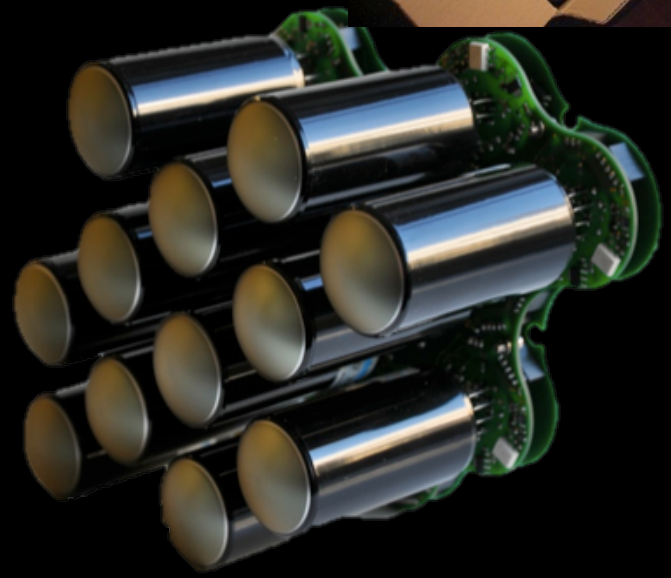


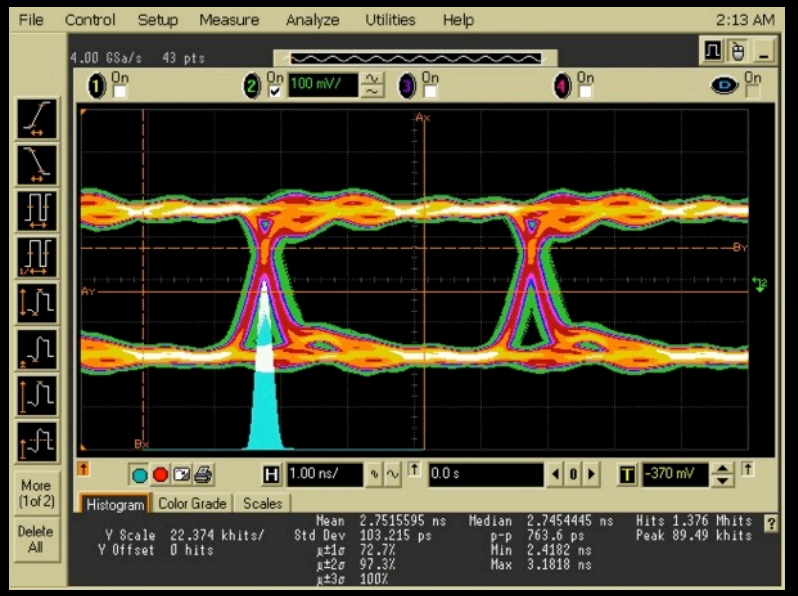
Photomultiplier Cameras

University of Leicester

- Some contribution to FlashCam in the ‘early days….
  - They really did everything properly!
  - Even choosing the cables





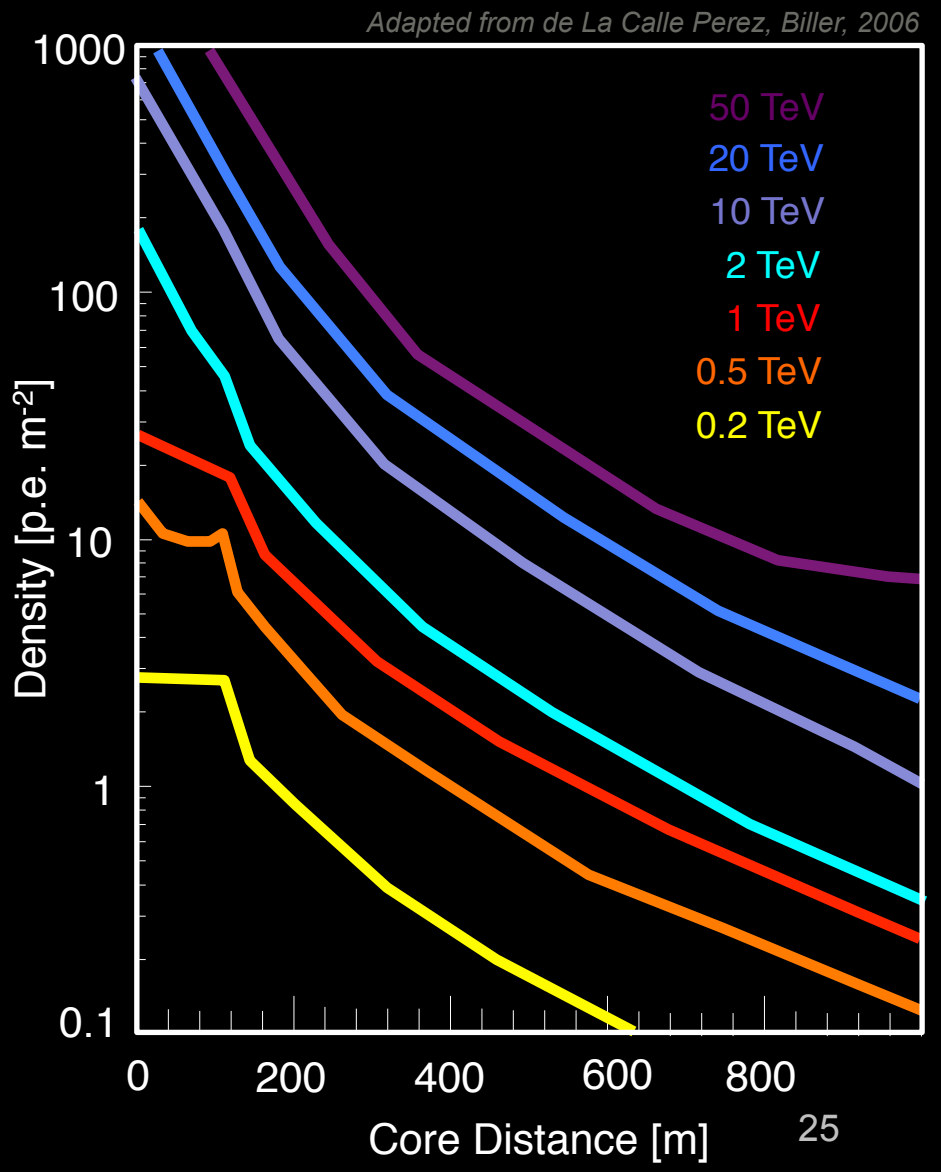


Small-Sized Telescopes

What to do at the 3 – 300 TeV?

University of Leicester

- Collection Area:
  - Require several km^2 to reach 10^{-13} erg cm^{-2} s^{-1} @ 10 TeV
- Telescope Size/Spacing:
  - Large reflectors?
    - Cherenkov light useful out to >600 m at few TeV
  - Small reflectors?
    - Separation >200m required for <100 telescopes
    - 100 pe images for 3 TeV shower @250m → 5m mirror



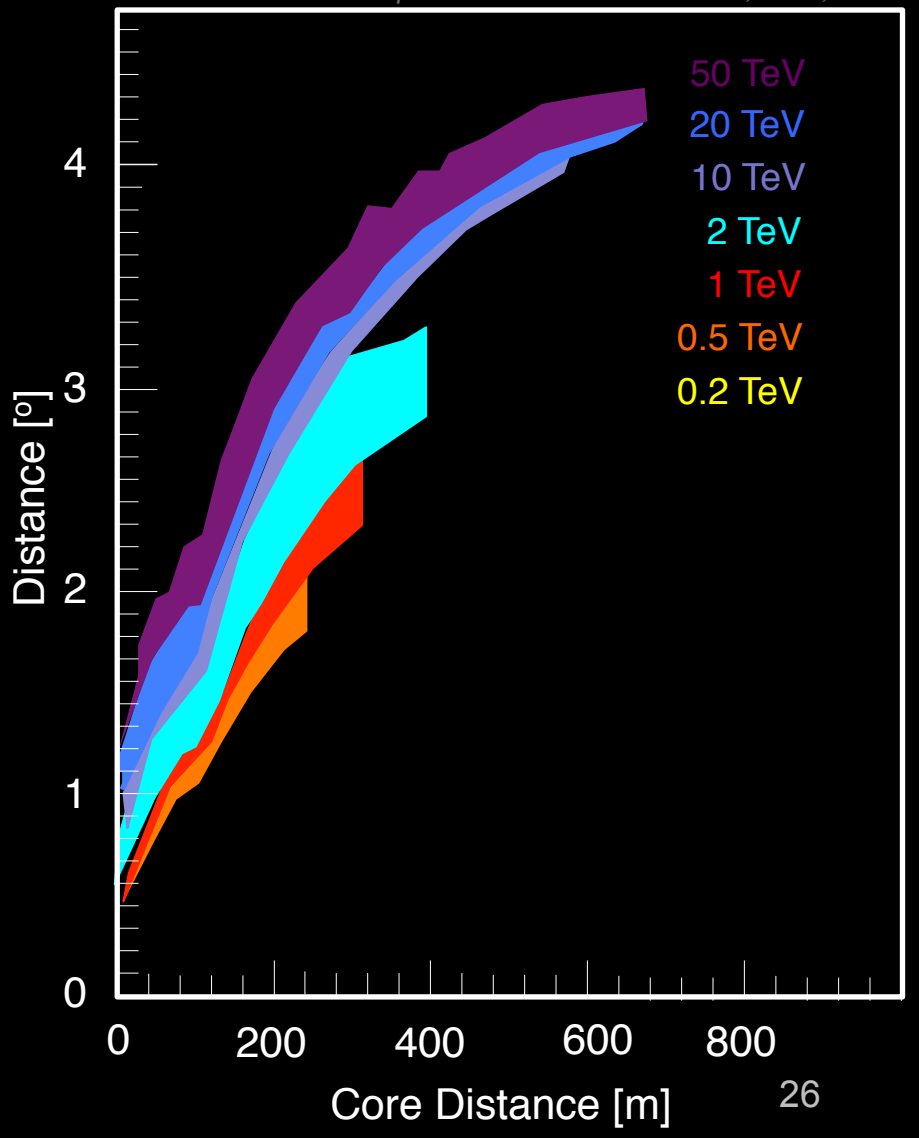
Small-Sized Telescopes

What to do at the 3 – 300 TeV?

University of Leicester

- Field of view:
  - Greater spacing → larger FoV
  - 250 m spacing implies typical offset of image from source of ~3° – need an 8° camera
  - 600 m → 12° camera

Adapted from de La Calle Perez, Biller, 2006



Small-Sized Telescopes
What to do at the 3 – 300 TeV?

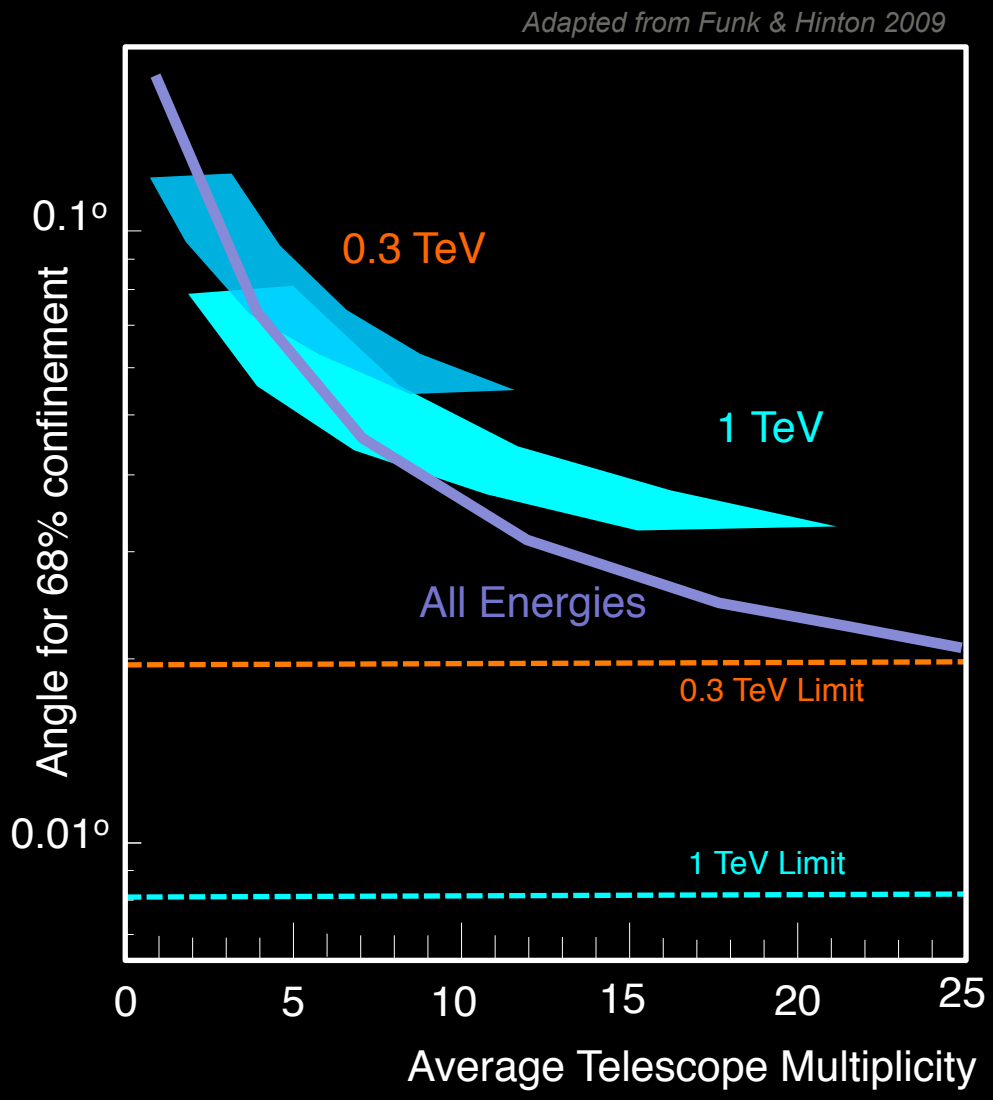
University of Leicester

- So, there are options:
  - Several large telescopes very far apart with very large FoV?
  - Many small telescopes closer together with reasonable FoV?

Small-Sized Telescopes
What to do at the 3 – 300 TeV?

University of Leicester

- So, there are options:
  - Several large telescopes very far apart with very large FoV?
  - Many small telescopes closer together with reasonable FoV
- Angular Resolution:
  - Big opportunity in this energy range: 1’ @10 TeV - shower fluctuations ↓ with energy…
  - Improves with multiplicity



The Telescopes

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LST

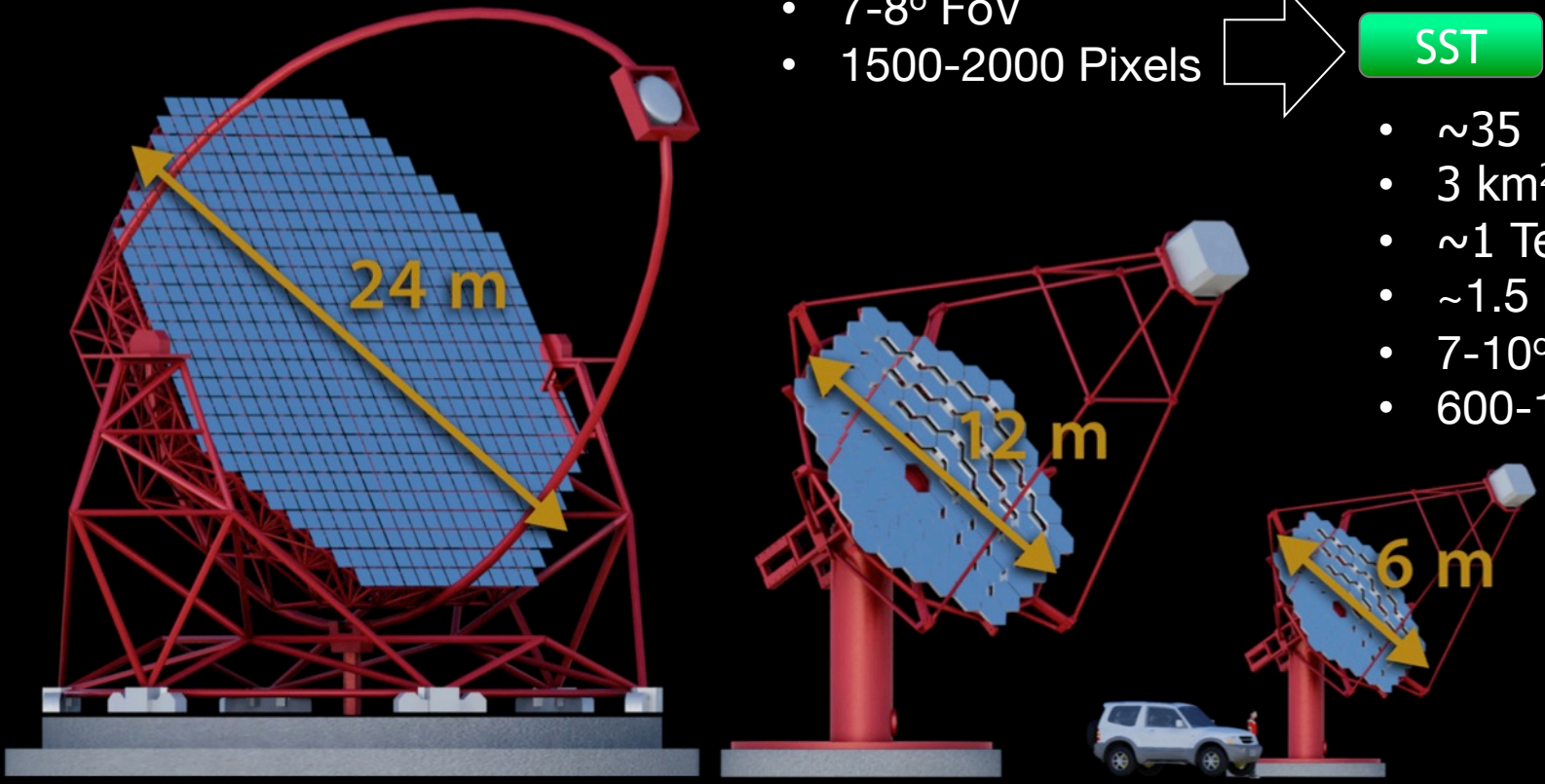
- ~4
- threshold ~30 GeV
- ~2.2 m Camera
- 4.5° FoV
- 1700 Pixels

MST

- ~25
- 200 GeV– 5 TeV
- ~2 m Camera
- 7-8° FoV
- 1500-2000 Pixels

SST

- ~35
- 3 km² area
- ~1 TeV - 300 TeV
- ~1.5 m Camera
- 7-10° FoV
- 600-1300 Pixels



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University of Leicester

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- 200 GeV– 5 TeV
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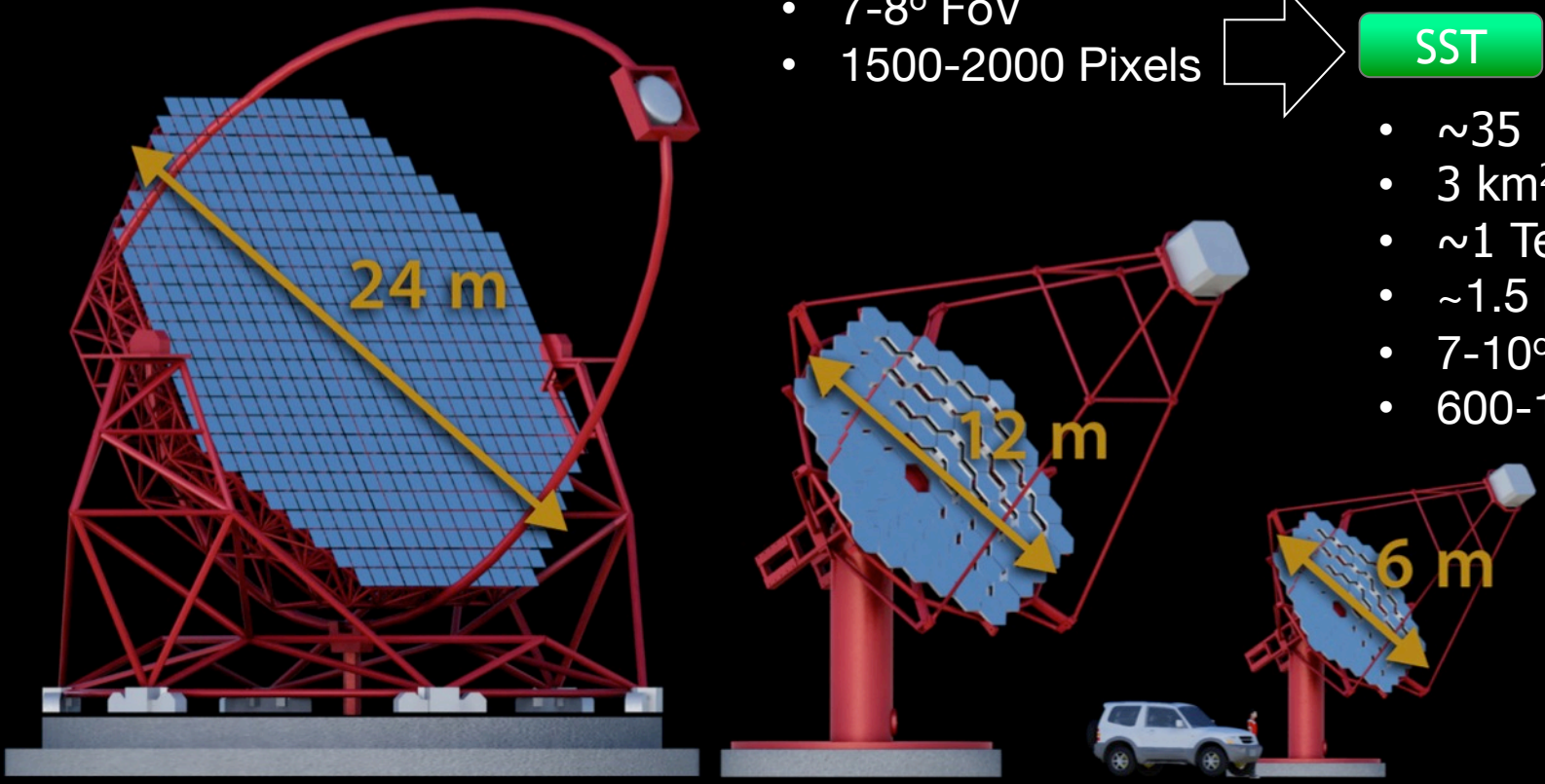
Cheap telescope

Problem:

Expensive Camera

SST

- ~35
- 3 km² area
- ~1 TeV - 300 TeV
- ~1.5 m Camera
- 7-10° FoV
- 600-1300 Pixels



SST Solution?
The dual mirror concept

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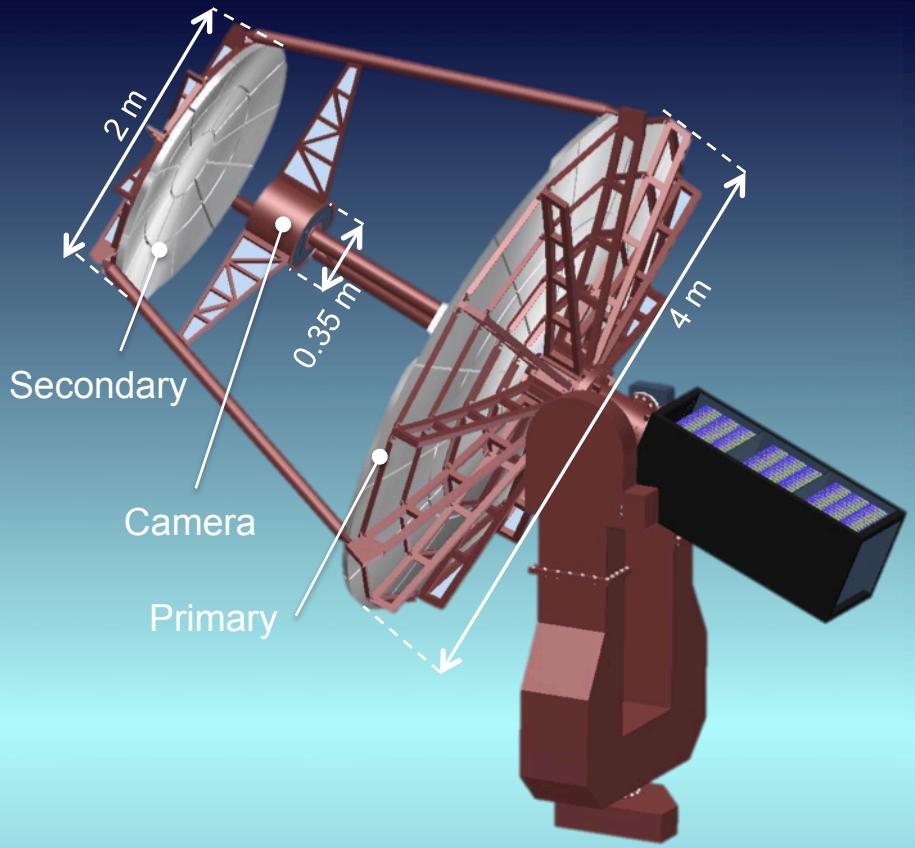
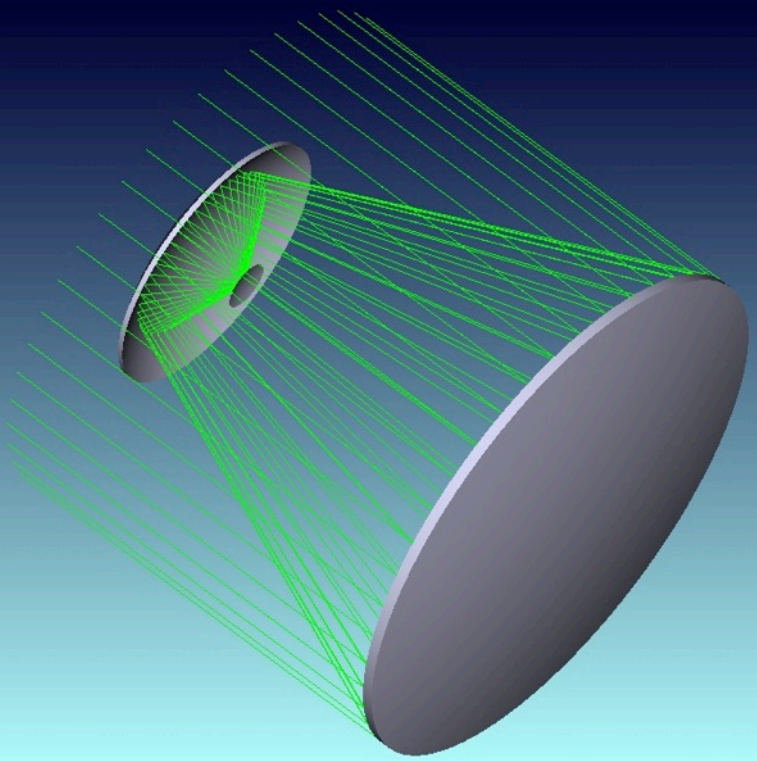
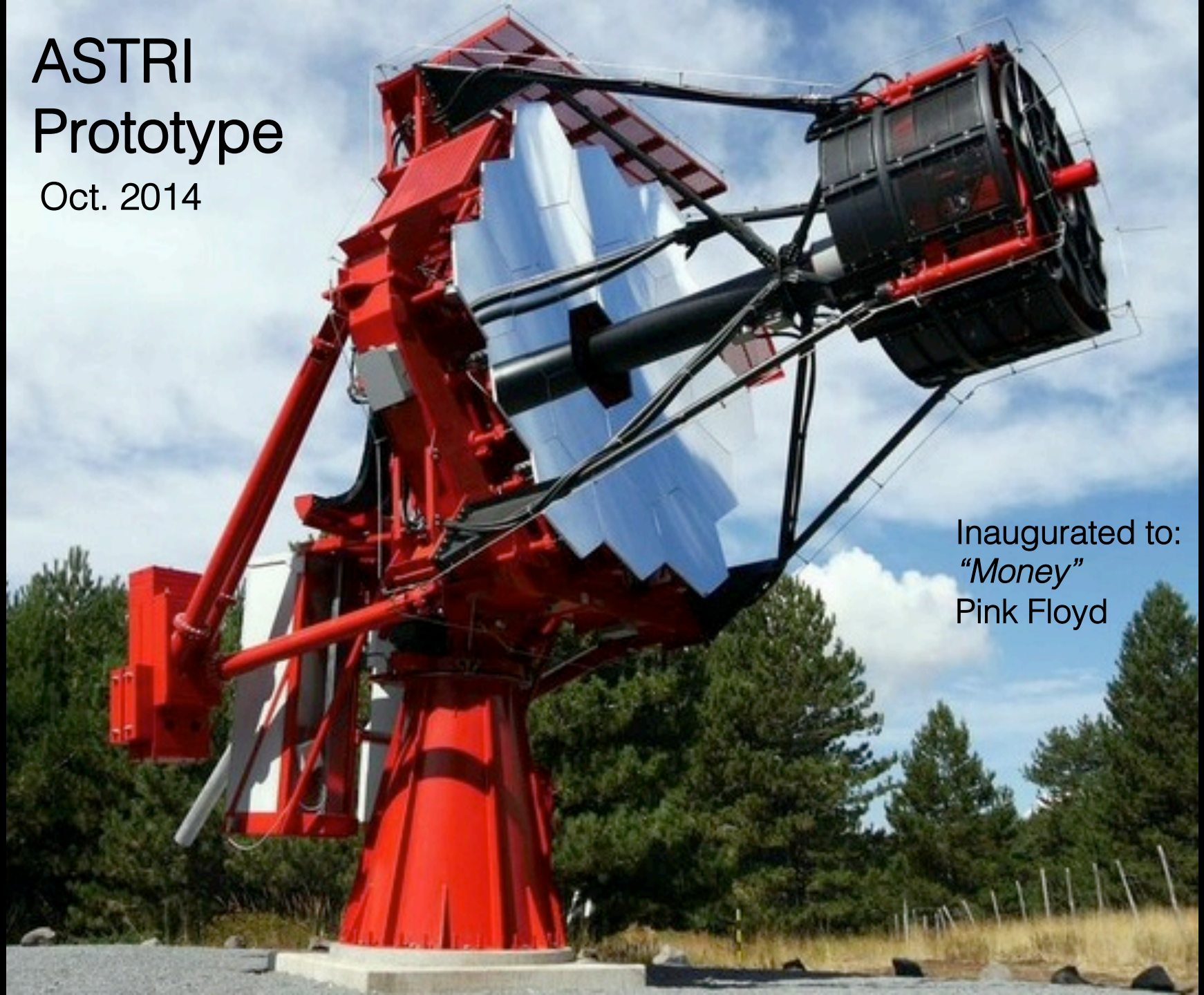
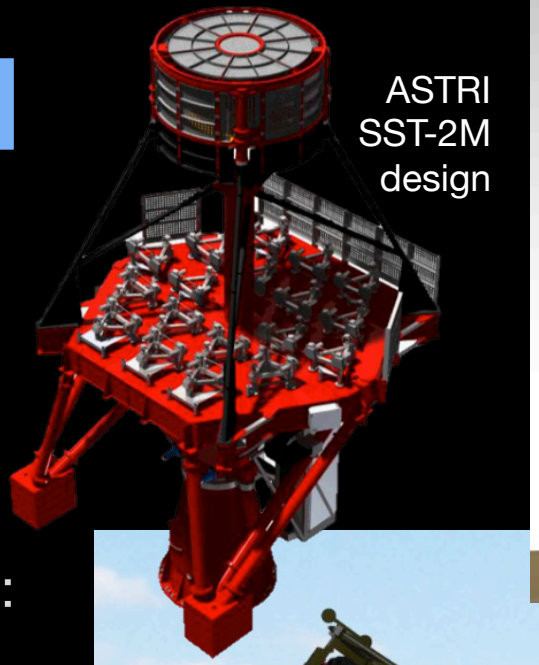




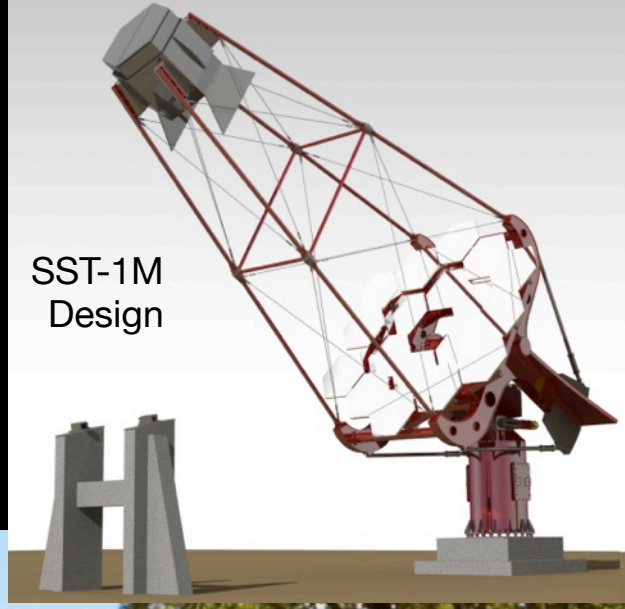
- Secondary optics reduces the plate scale:
  - Cheaper photosensors
  - The camera becomes 0.35 m across
  - ~70 SSTs become possible


ASTRI
Prototype
Oct. 2014
Inaugurated to:
"Money"
Pink Floyd

Small-Sized Telescopes



ASTRI SST-2M design



SST-1M Design

~8 m^2 dish area

Dual and single mirror options:
- SST-1M
- SST-2M

~9° field of view
0.17-0.24° pixels

70 SSTs on South site

Require low cost and high reliability

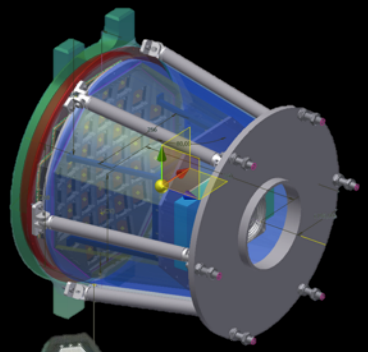
~4-7 km^2 collection area

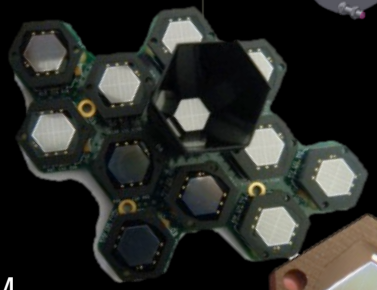
Meudon SST-GATE SST-2M prototype
Artists Impression!

Small-Sized Telescopes

Corresponding selection of cameras….

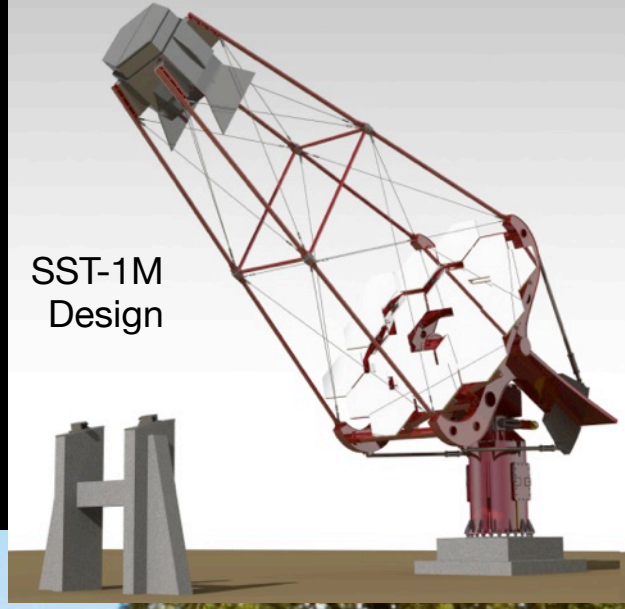
SST-2M:
6 mm x 6 mm pixel
~2k pixels per camera





SST-1M
~20 mm hexagonal pixel
~1.3k pixels per camera

ASTRI
SST-2M
design



SST-1M
Design

Meudon SST-GATE
SST-2M prototype
Artists Impression!

Small-Sized Telescopes

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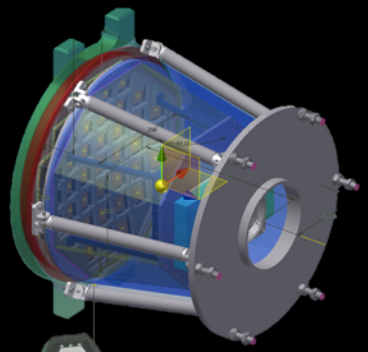
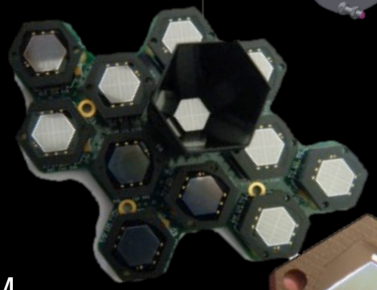
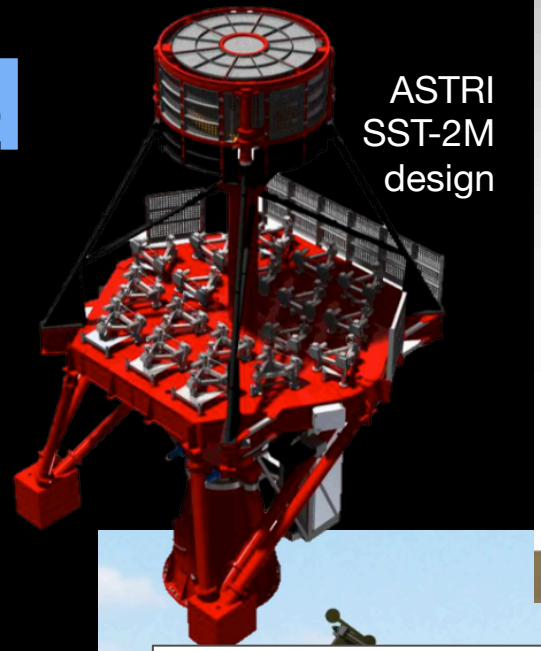
6 mm x 6 mm pixel
~2k pixels per camera

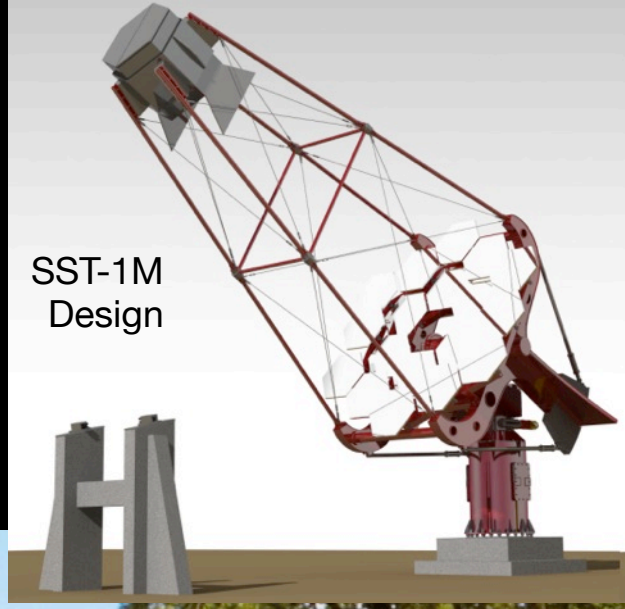




SST-1M
~20 mm hexagonal pixel
~1.3k pixels per camera



ASTRI
SST-2M
design



SST-1M
Design

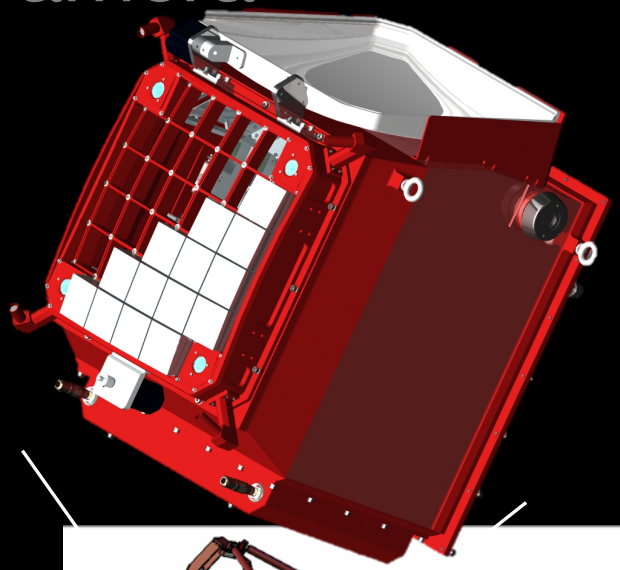
Could be seen as partially my fault as I was the SST Camera Coordinator from 2010 – 2012...

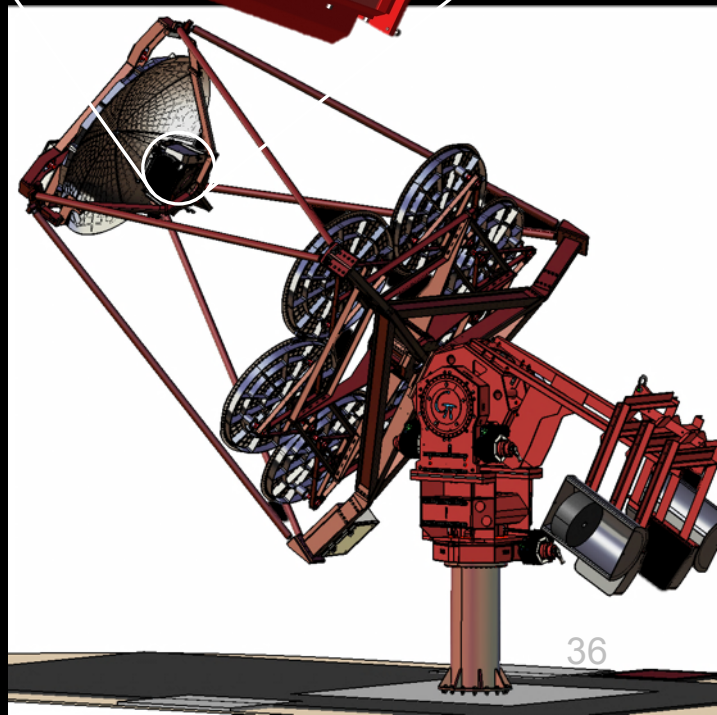
Meudon SST-GATE
SST-2M prototype
Artists Impression!

CHEC
The Compact High Energy Camera

University of Leicester

- A prototype camera for the SST-2M
  - UK, US, Germany, Japan, Netherlands, Australia
  - Funding in place for:
    - 2 prototype cameras
      - UK funding from STFC and U. Leicester
    - Pre-production cameras
  - Compatible with ASTRI and SST-GATE



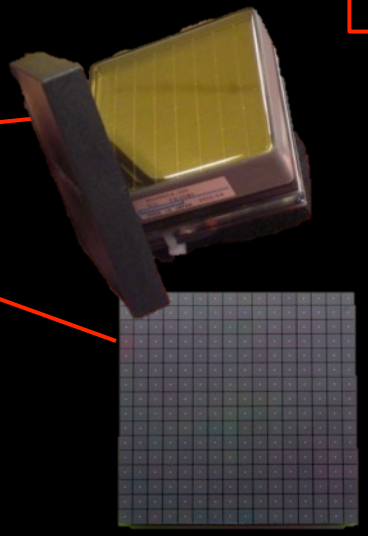


CHEC
Design Philosophy

University of Leicester

- Basic design criterion: low cost but high data quality
  - Relatively fine pixellation
  - Full waveform readout on all channels
    - Timing information, recovery beyond saturation ++
- Photosensors?
  - CHEC-M: based on MAPMs
  - CHEC-S: based on SiPMs
  - Prototype **both** to minimise risk
- Front-end electronics?
  - TARGET
    - Mature technological development
    - Very low cost per channel
    - 16 channel, 12 bits, 1 GSa/s, includes trigger

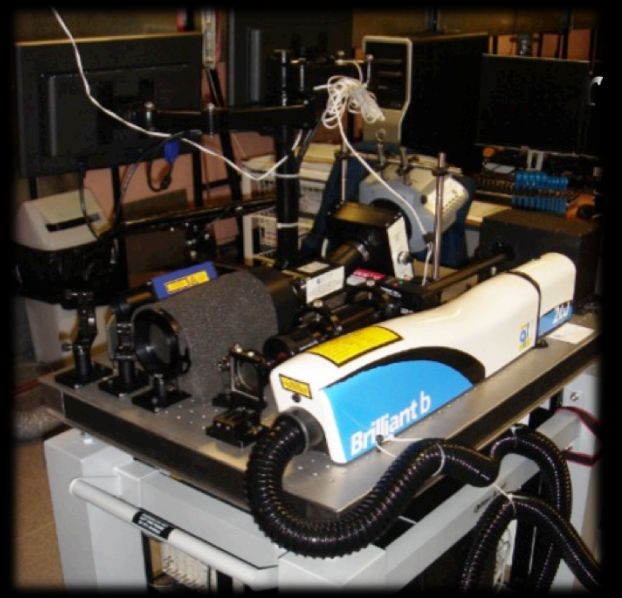
<75 euro/pixel
CF
>400 euro/pixel
For conventional tel



CHEC: Origins

- Rich: lasers on jeeps to detect liquid explosives
- Rich: fellowship, SST Cam. Coordinator
- Jim: convinced others in the UK to join CTA and had a good idea
- Jim: Postdoc → Prof.
  - Group established in Leicester
  - Great engineering support
- Successful funding bids:
  - STFC and University of Leicester → ~£1M (Researcher Co-I)
- CHEC is now a global effort
  - Rich: coordinator

2009



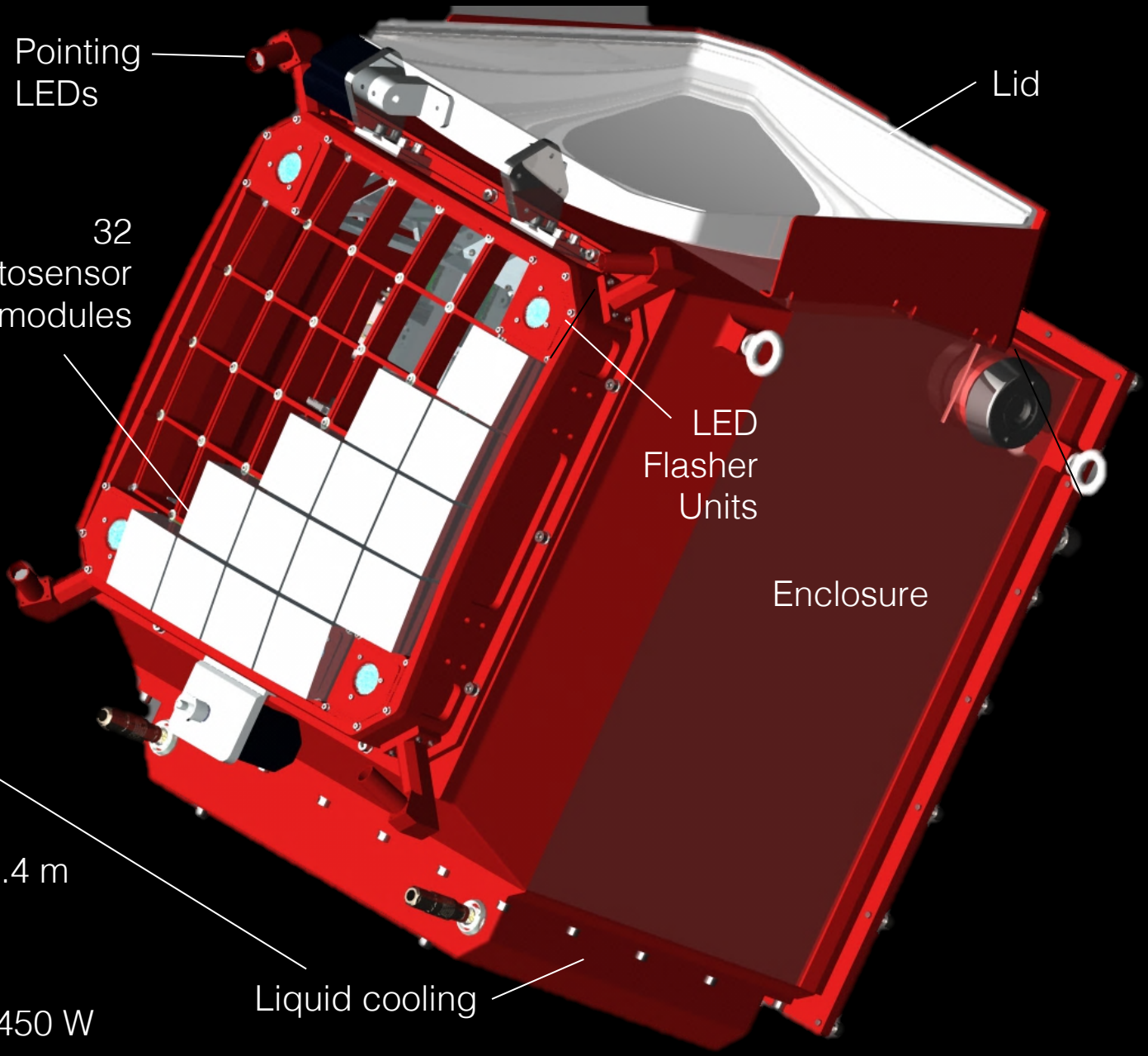
~2010

2012

2014

Overview

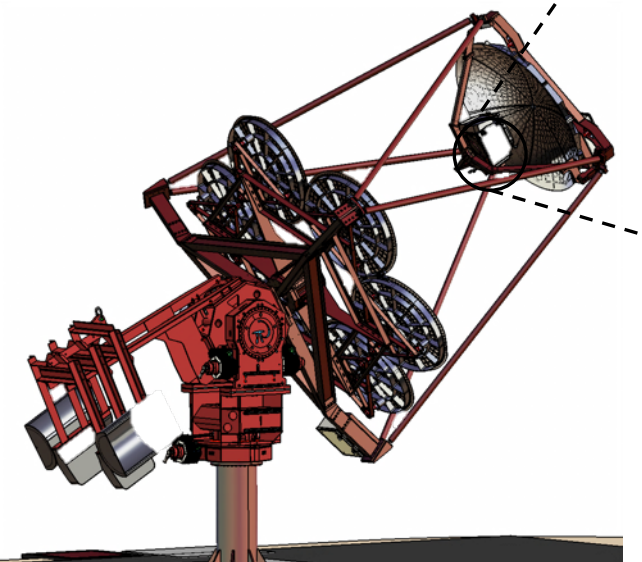
University of Leicester

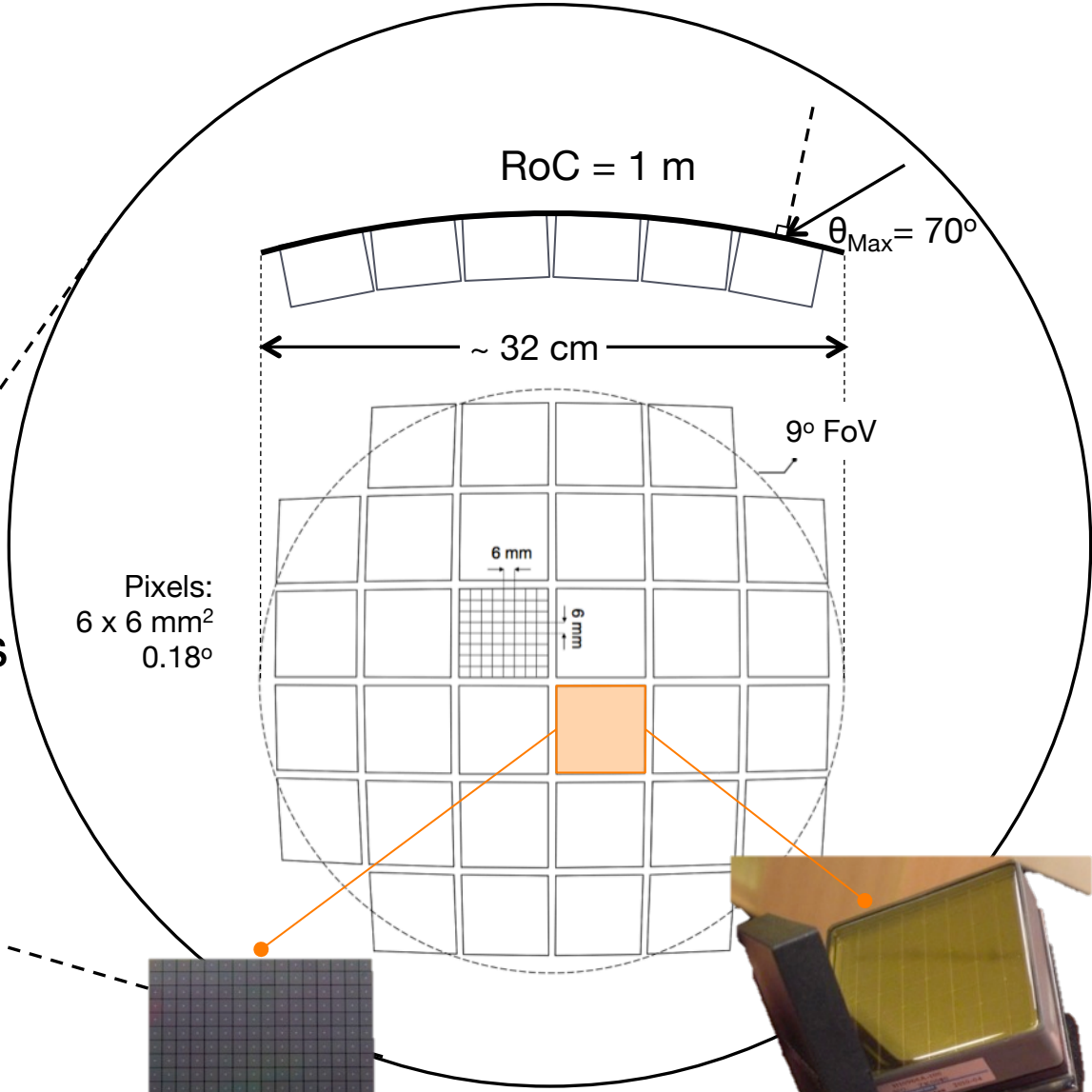


~45 kg ~450 W

Overview

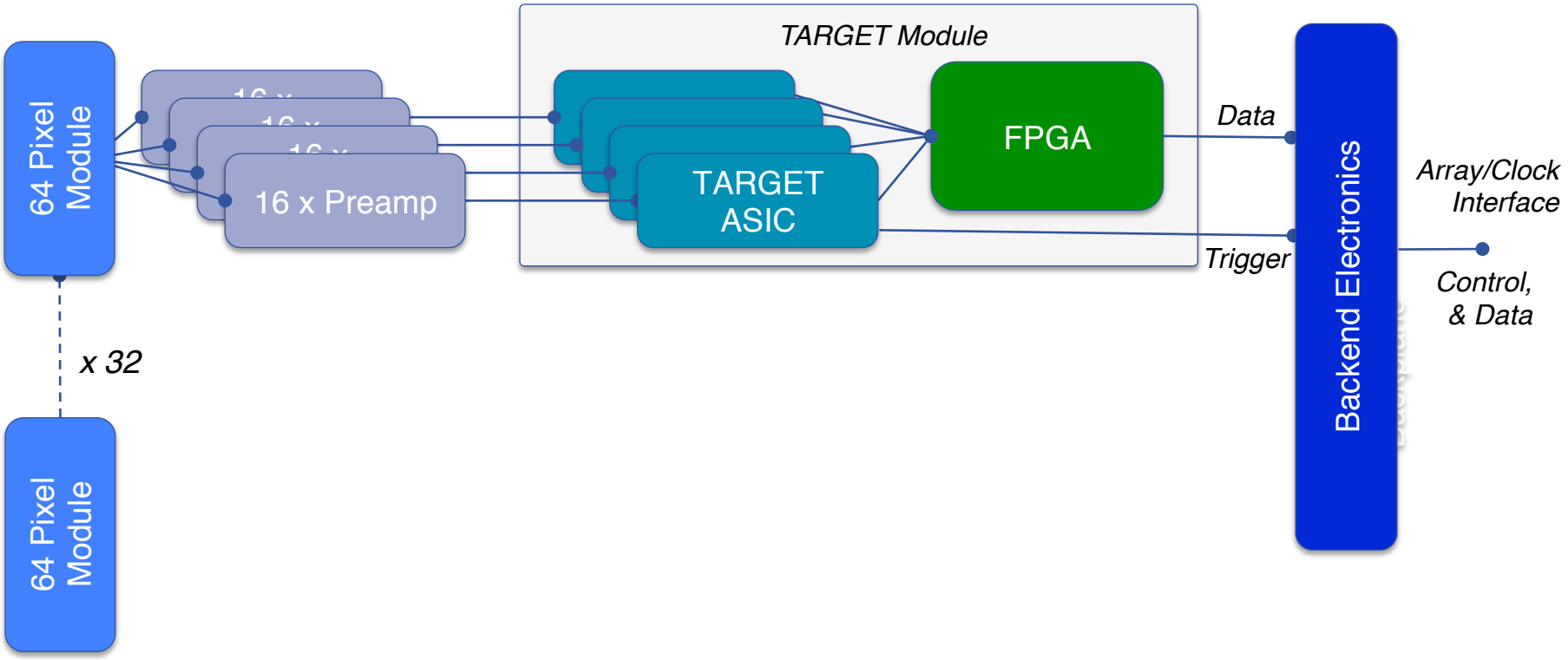
- Focal Plane:
  - 9º FoV, 0.18º pixels
  - 32 cm diameter
- Challenges:
  - Curved focal plane
  - Incident light from large angles
  - Compact electronics



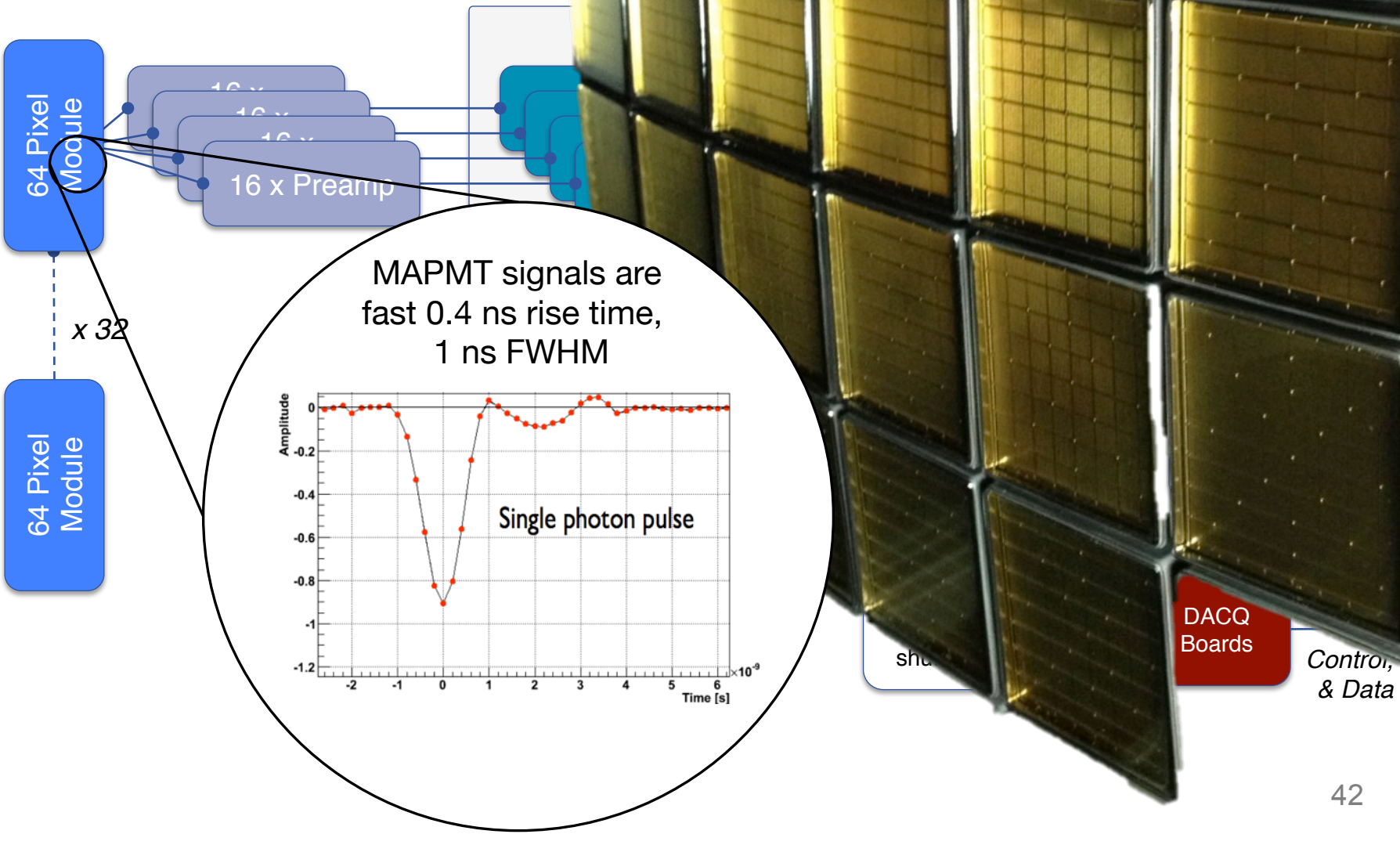


Electronics and Readout

University of Leicester



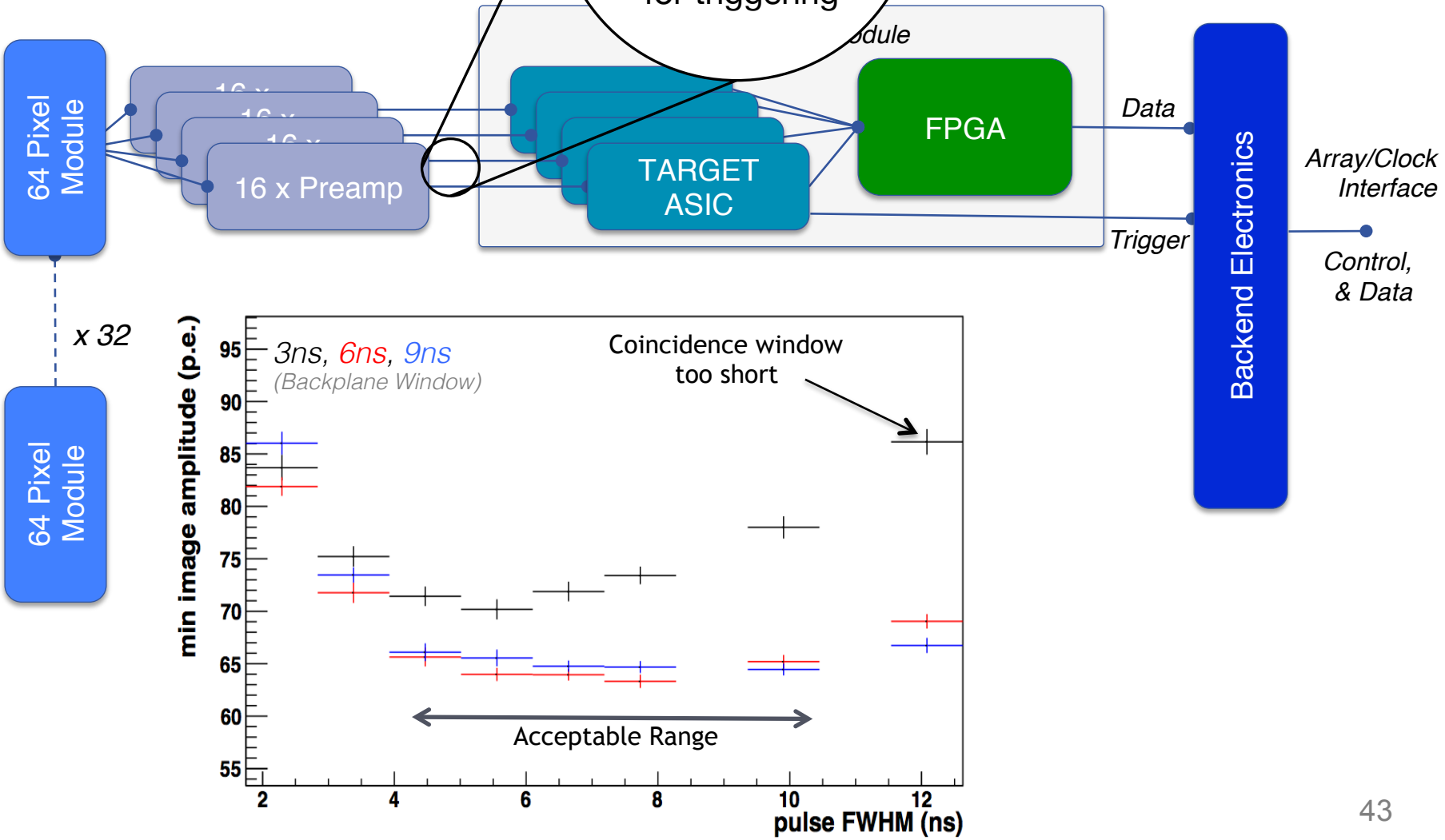
Electronics an



Electronics and Readout

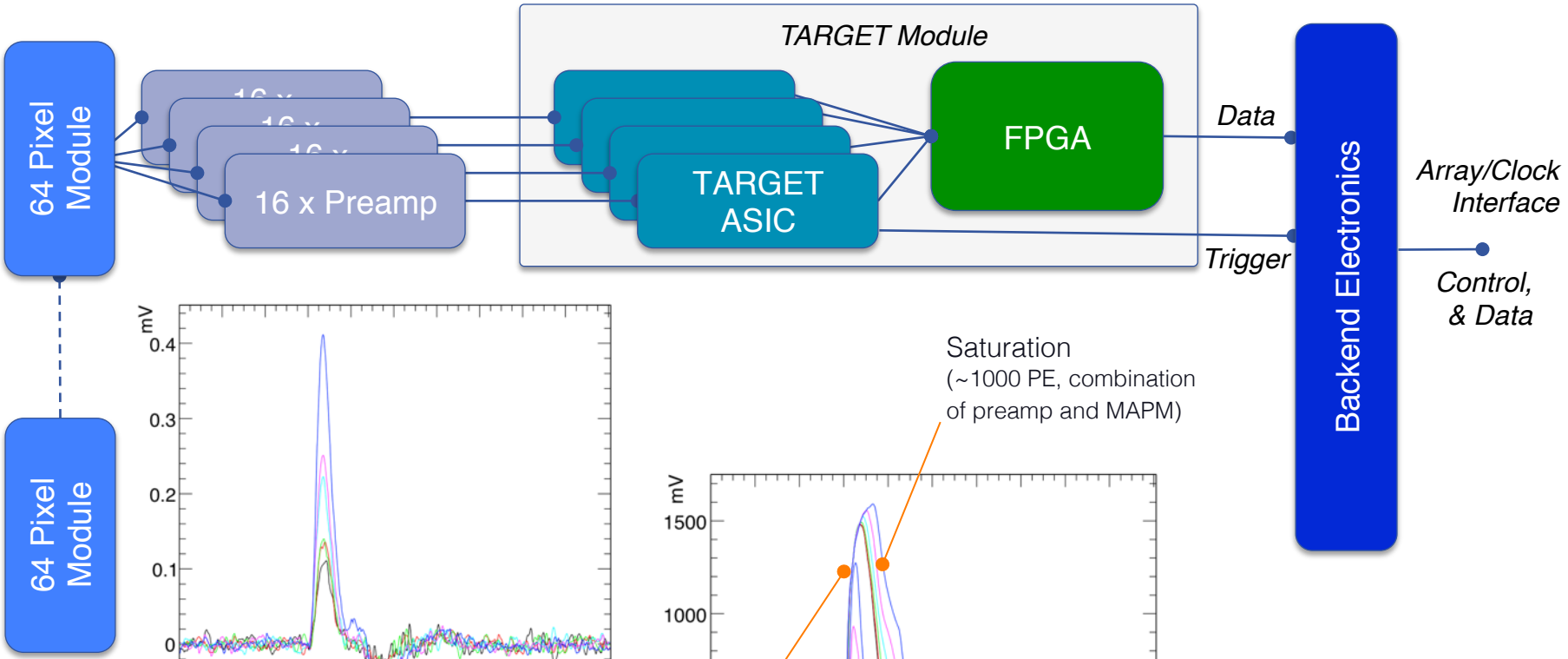
University of Leicester

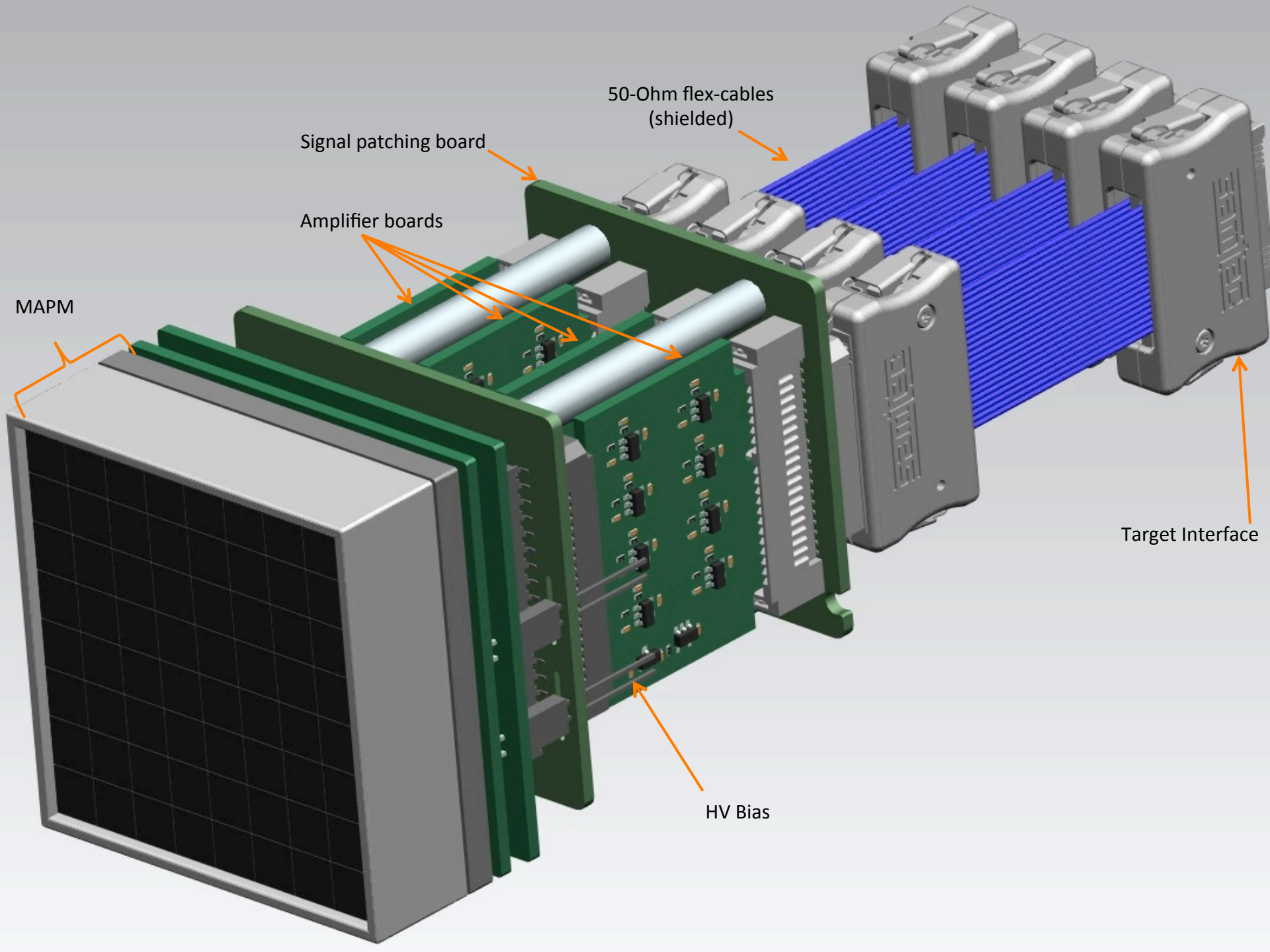
Simulations show that for >TeV energies ~ 6 ns FWHM is optimal for triggering



Electronics and Readout

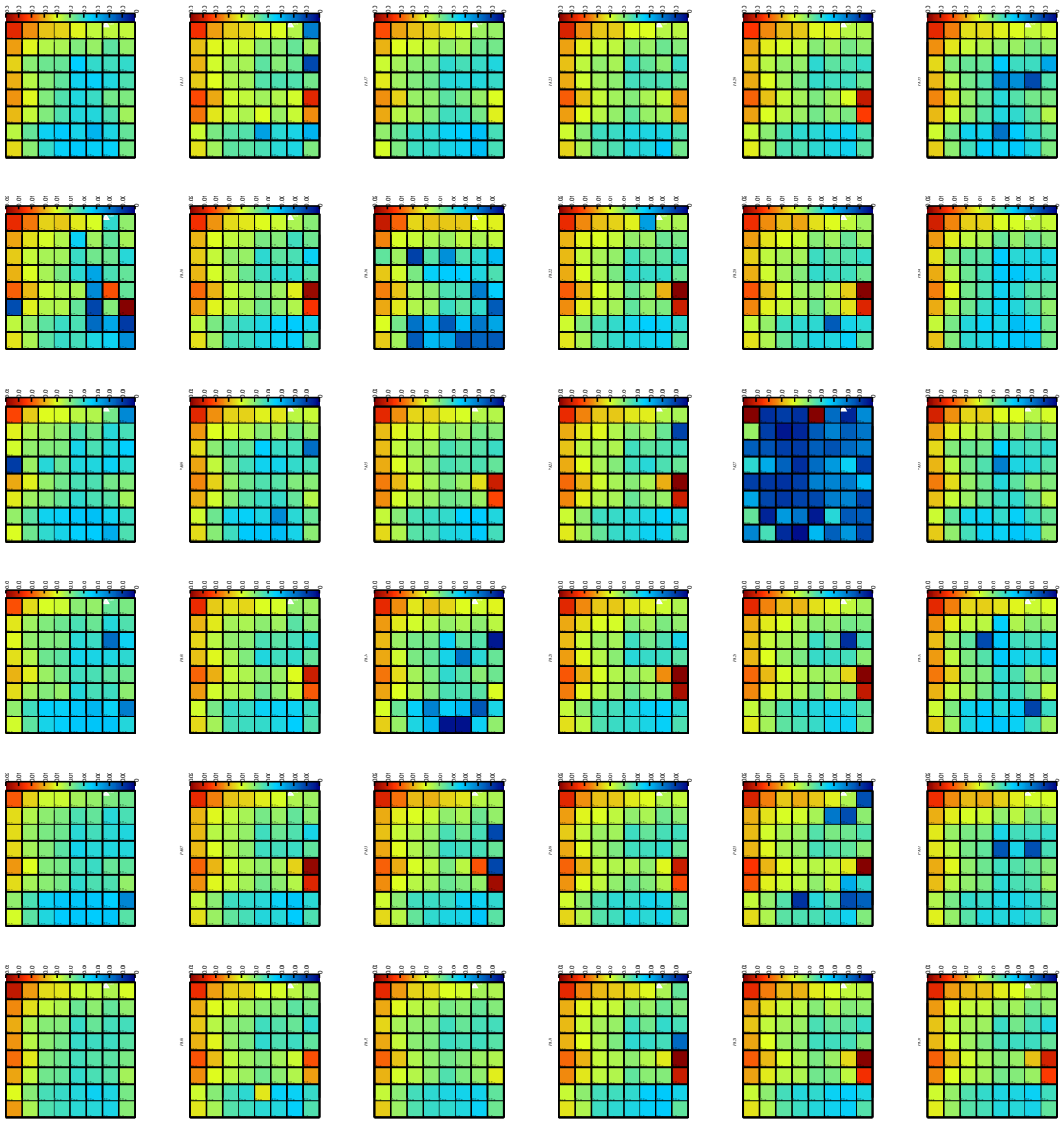
University of Leicester



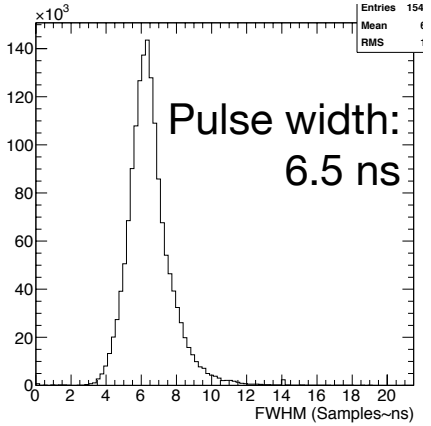

50-Ohm flex-cables
(shielded)
Signal patching board
Amplifier boards
MAPM
Target Interface
HV Bias

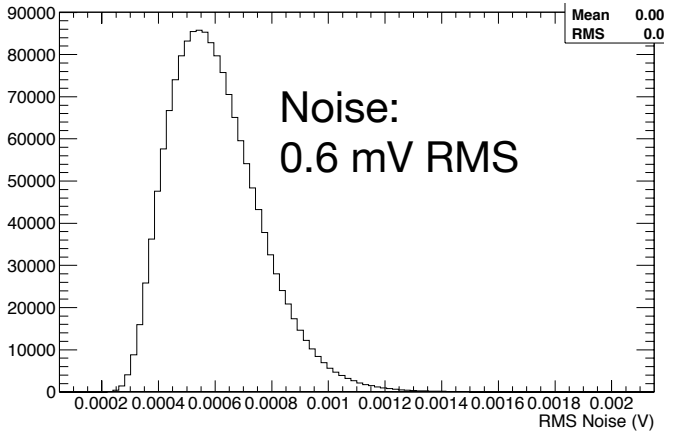
Preamplifiers

Batch testing with a reference TARGET module



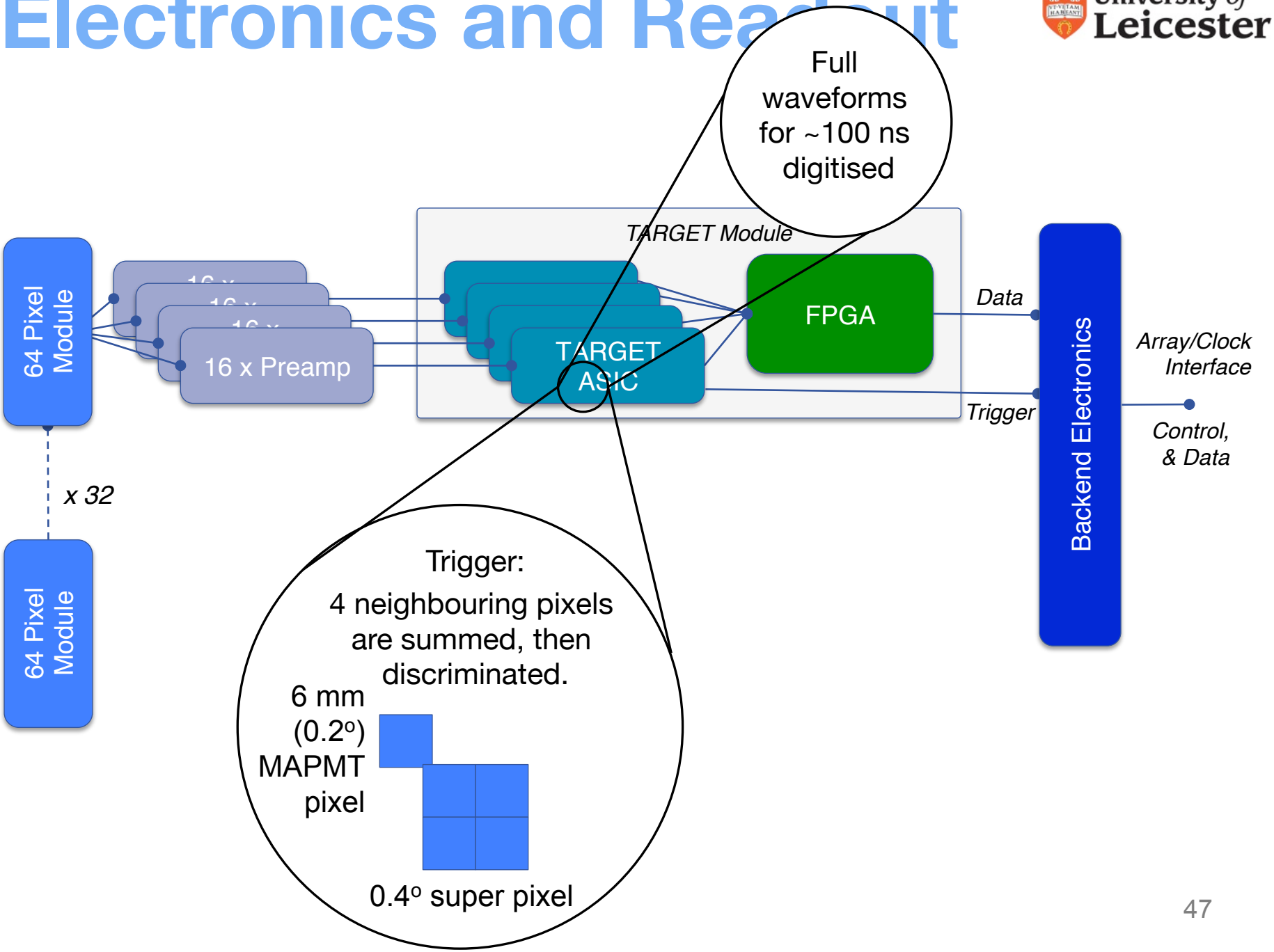
Including MAPM & TARGET response



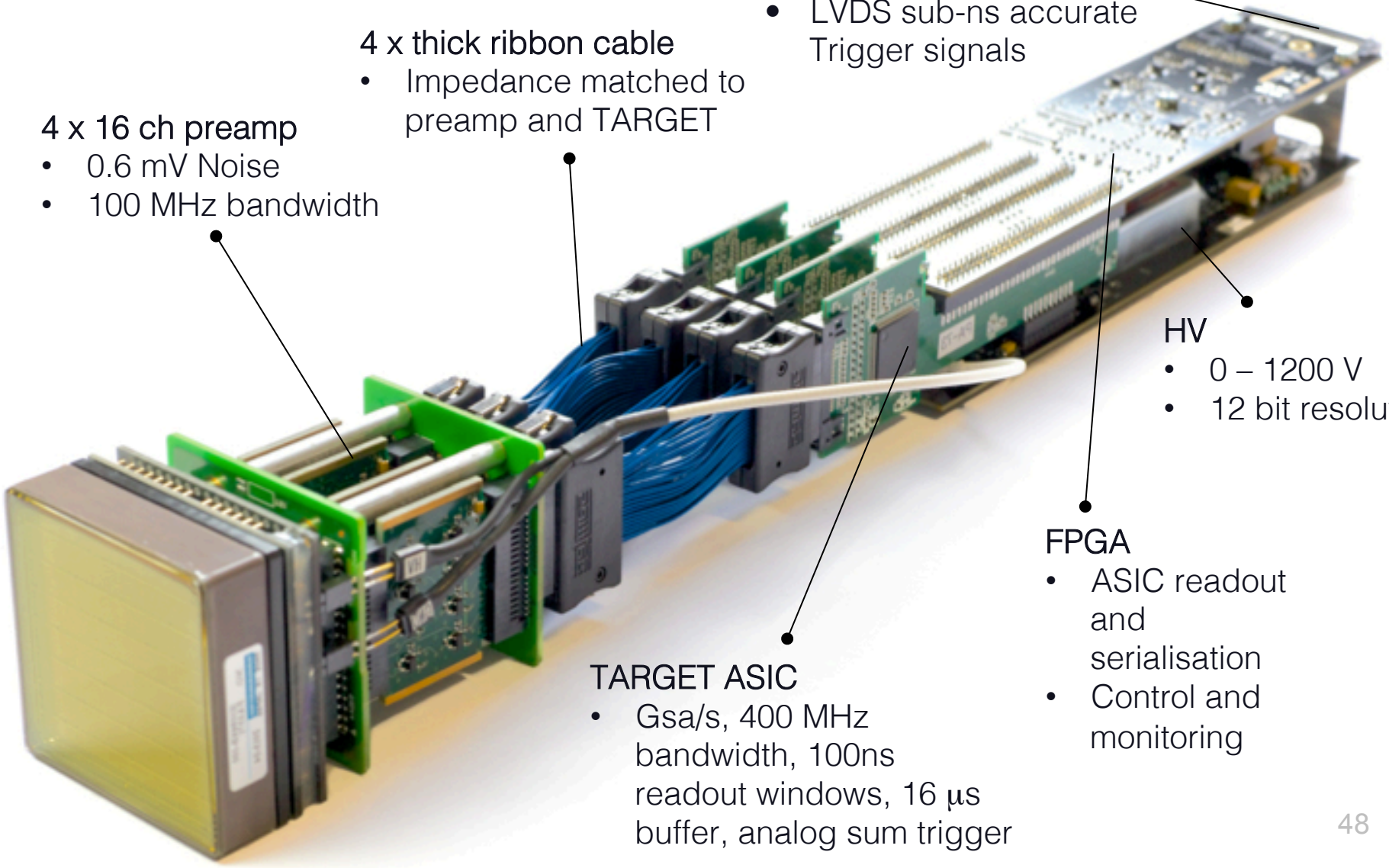


Electronics and Readout

University of Leicester



CHEC-M Camera Module



Connection to backplane
- Gbit/s UDP
- LVDS sub-ns accurate Trigger signals

4 x thick ribbon cable
- Impedance matched to preamp and TARGET

4 x 16 ch preamp
- 0.6 mV Noise
- 100 MHz bandwidth

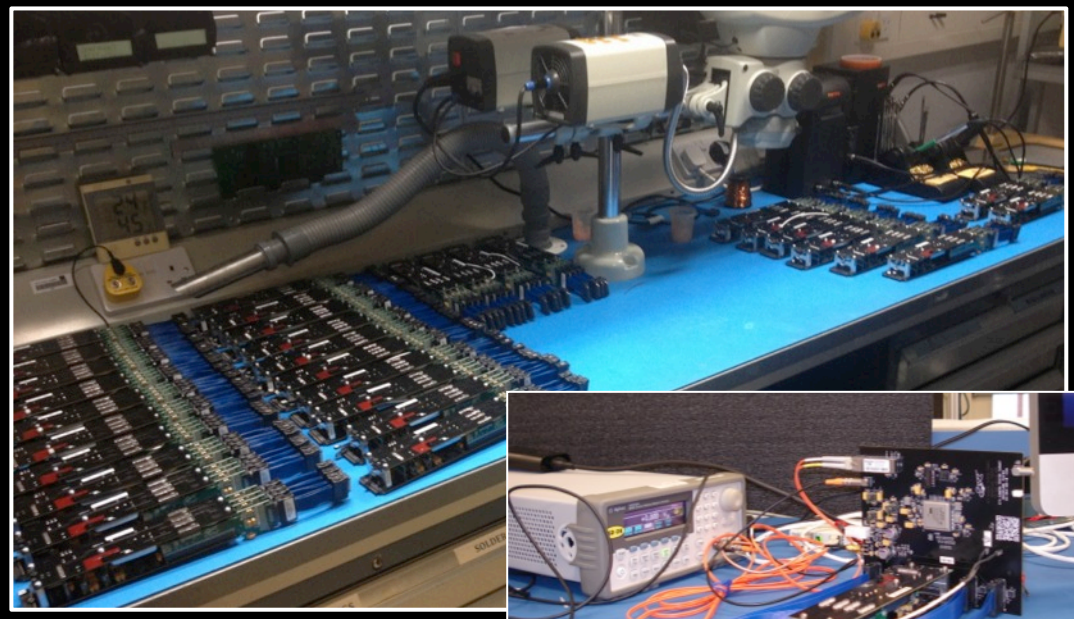
HV
- 0 – 1200 V
- 12 bit resolution

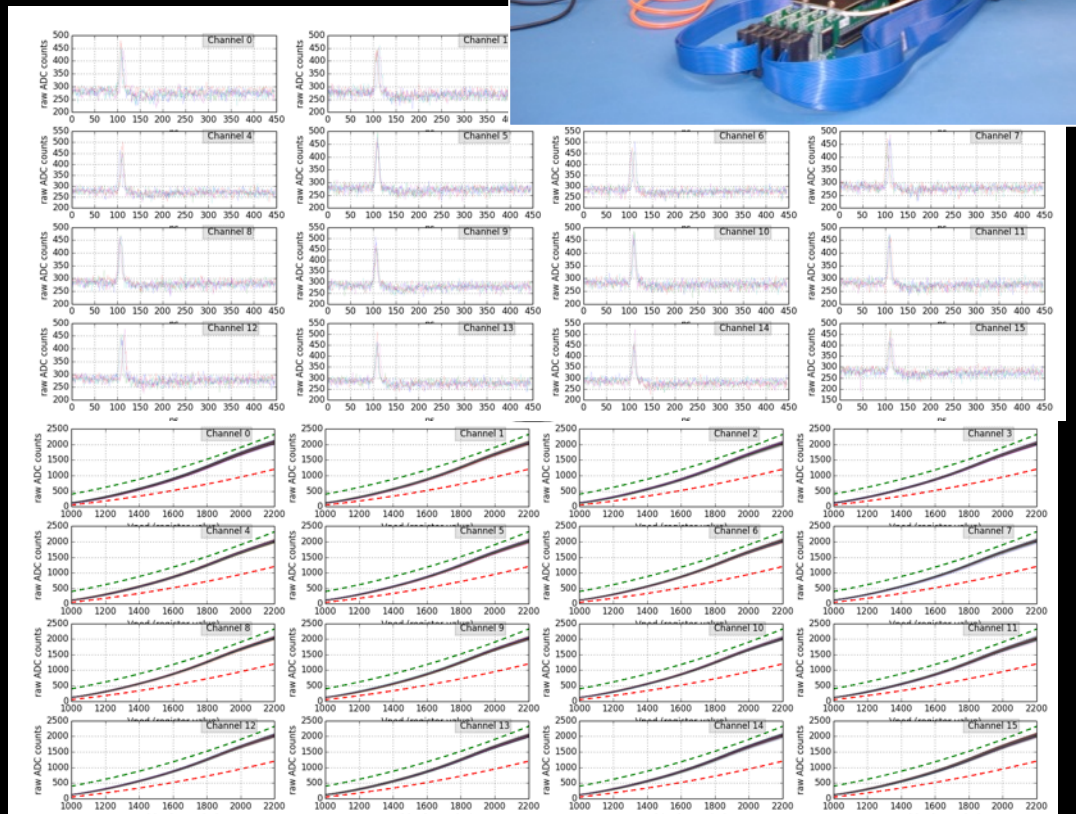
FPGA
- ASIC readout and serialisation
- Control and monitoring

TARGET ASIC
- Gsa/s, 400 MHz bandwidth, 100ns readout windows, 16 μs buffer, analog sum trigger

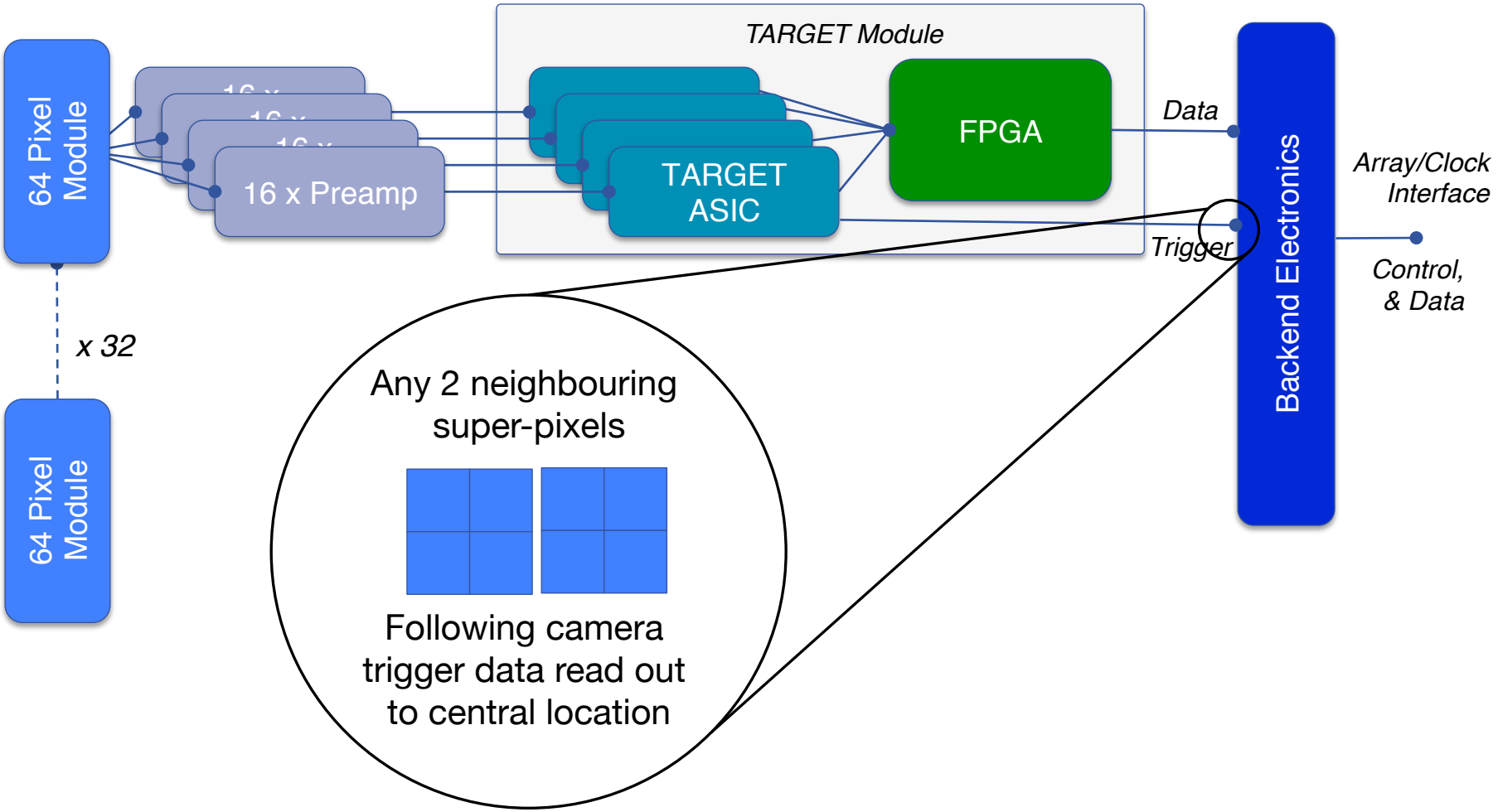
CHEC-M TARGET Modules

- Dec. 2013: ASIC boards fabricated in Nagoya
- Feb. 2014: 41 modules produced at SLAC
- Mar. 2014: Basic functionality tests at SLAC
- April 2014: 35 modules powered up for verification testing in Leicester

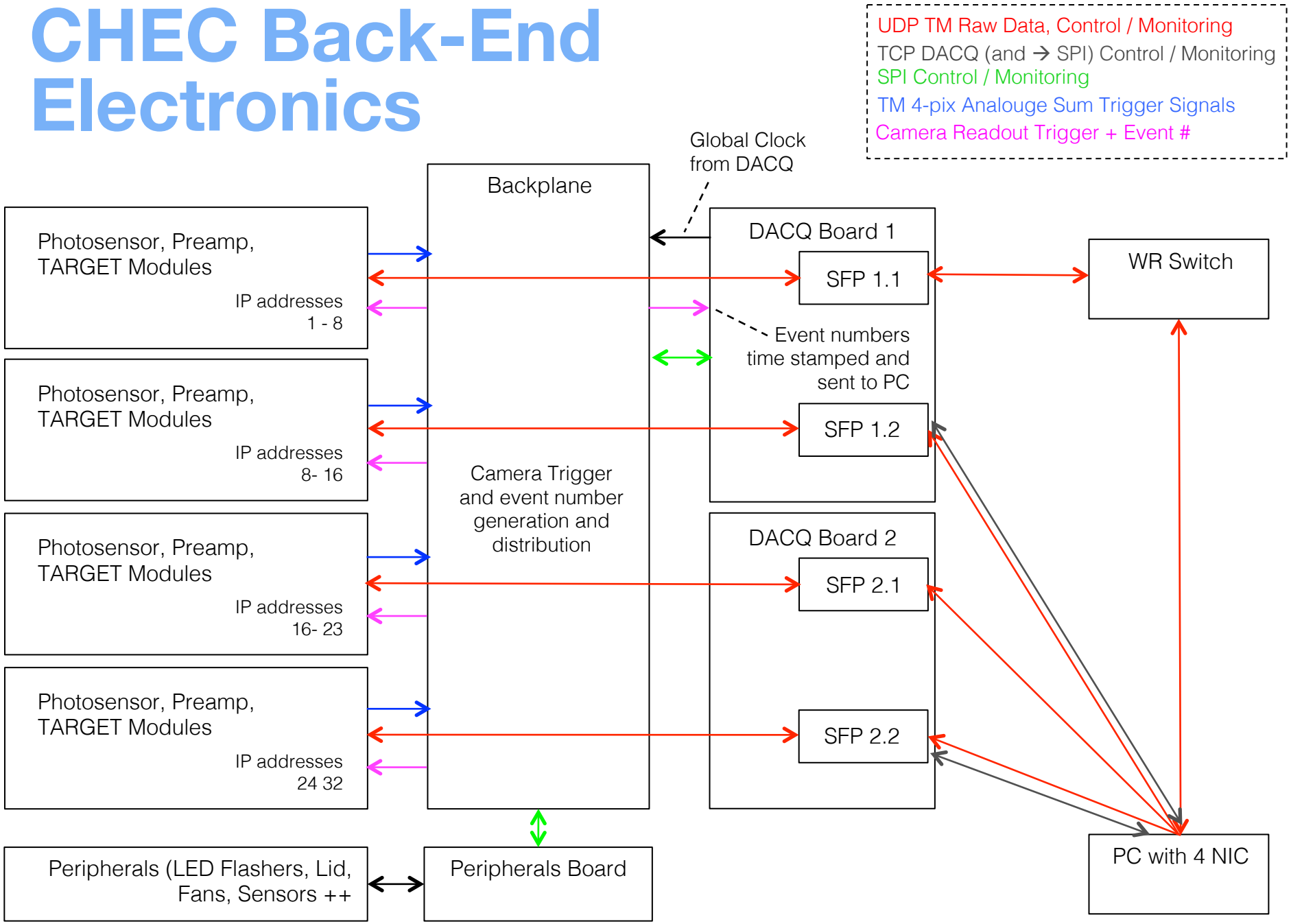




Electronics and Readout

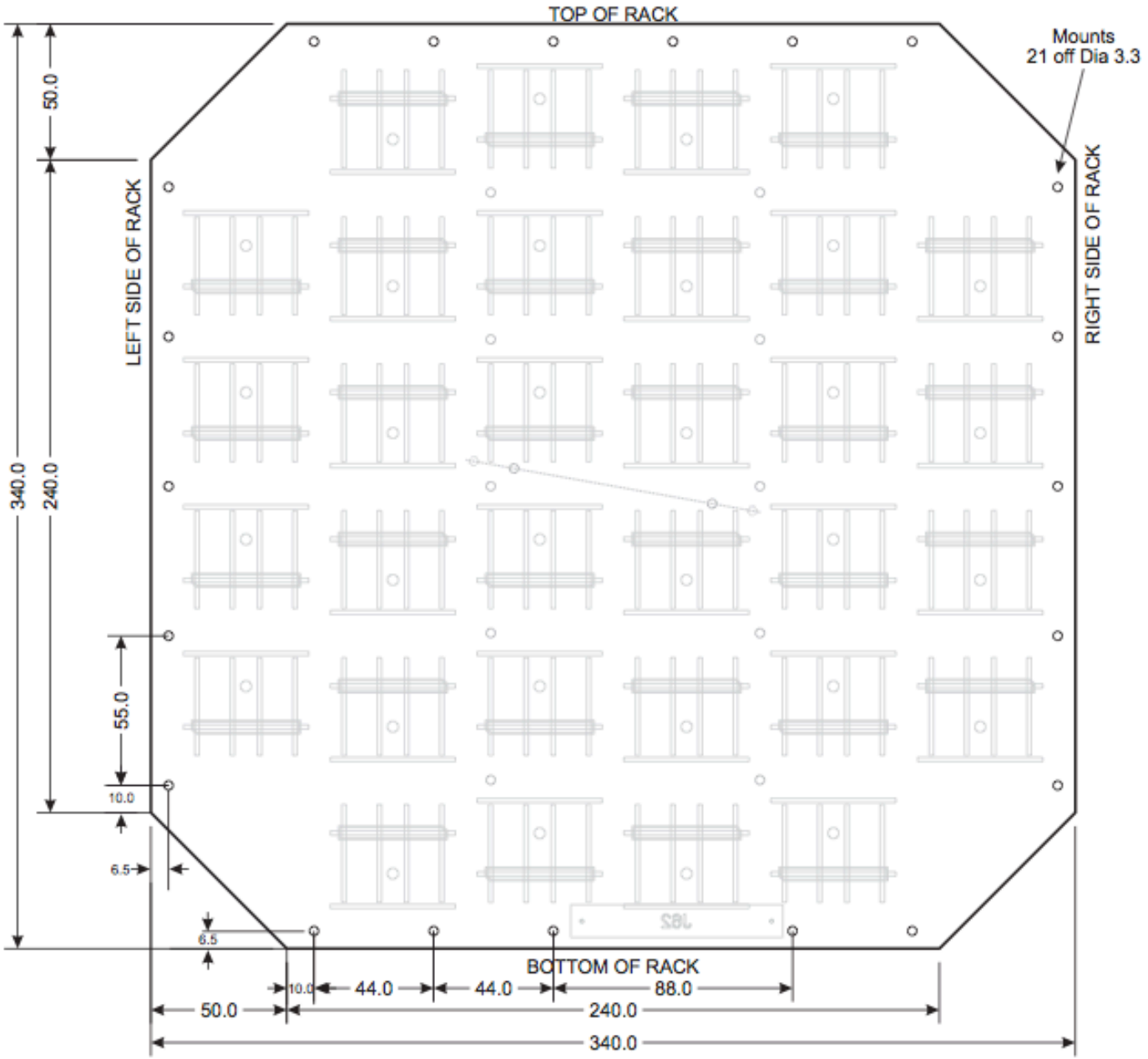


CHEC Back-End Electronics



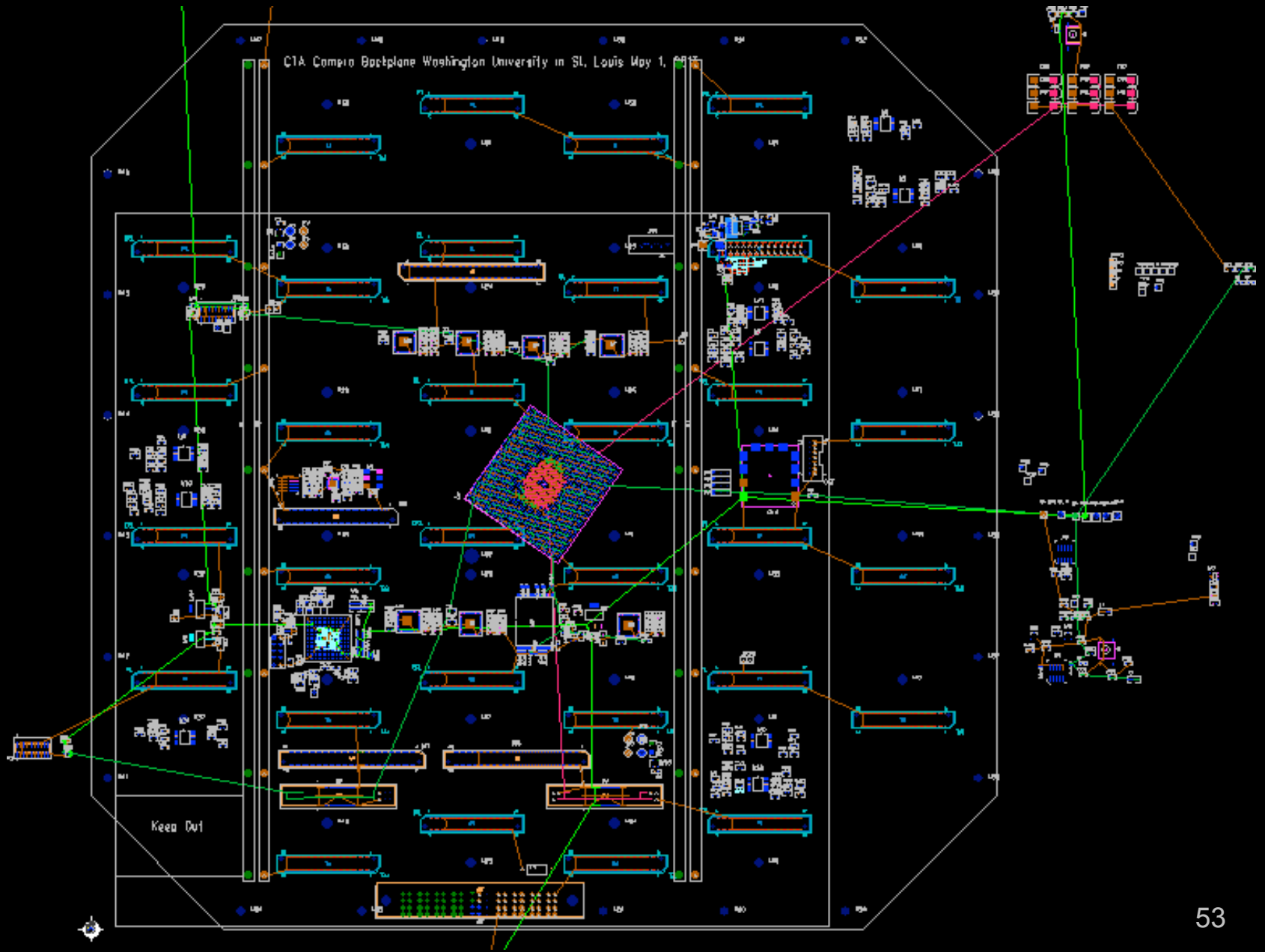
CHEC Backplane

University of Leicester



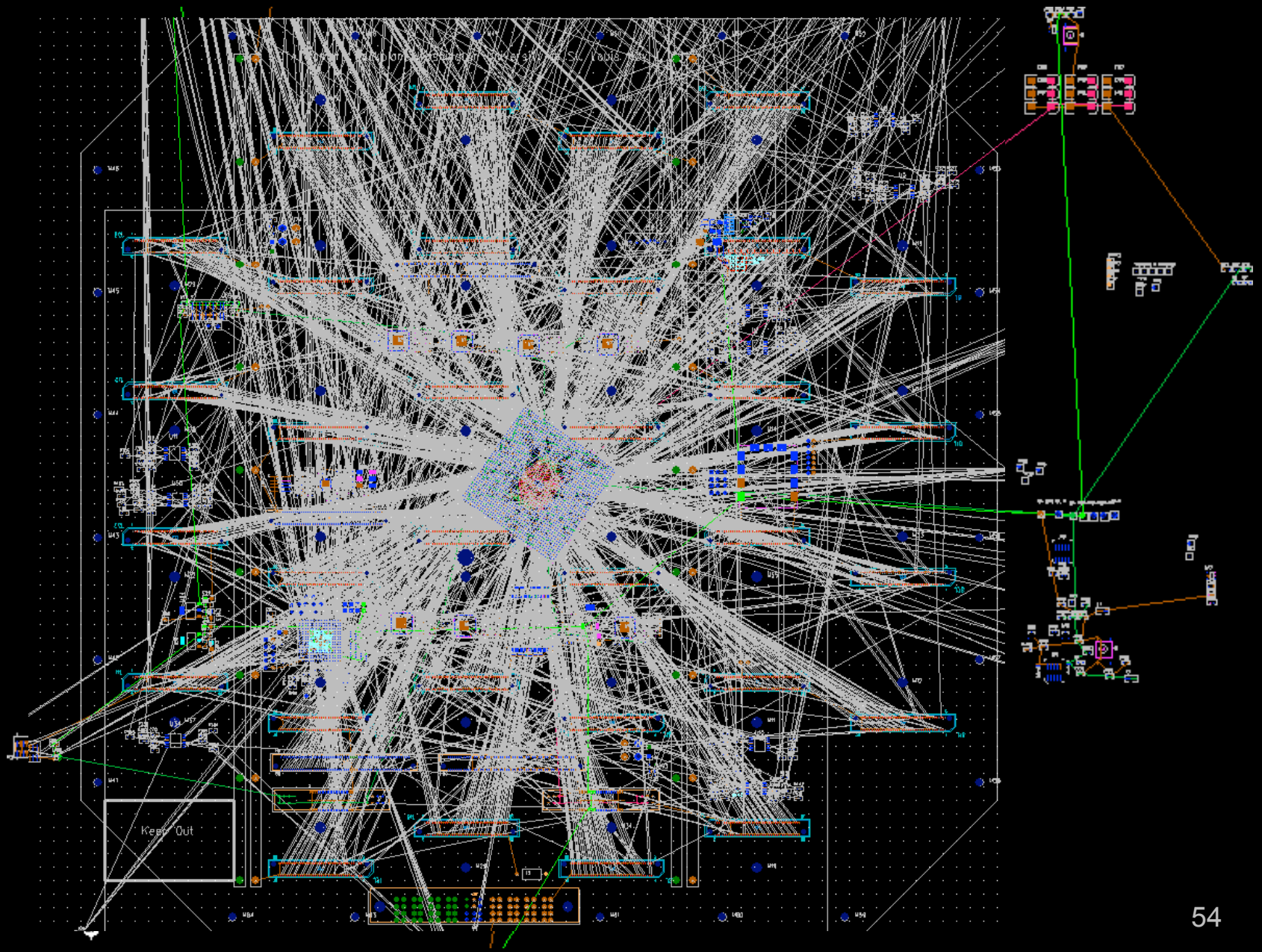
CHEC Backplane

University of Leicester



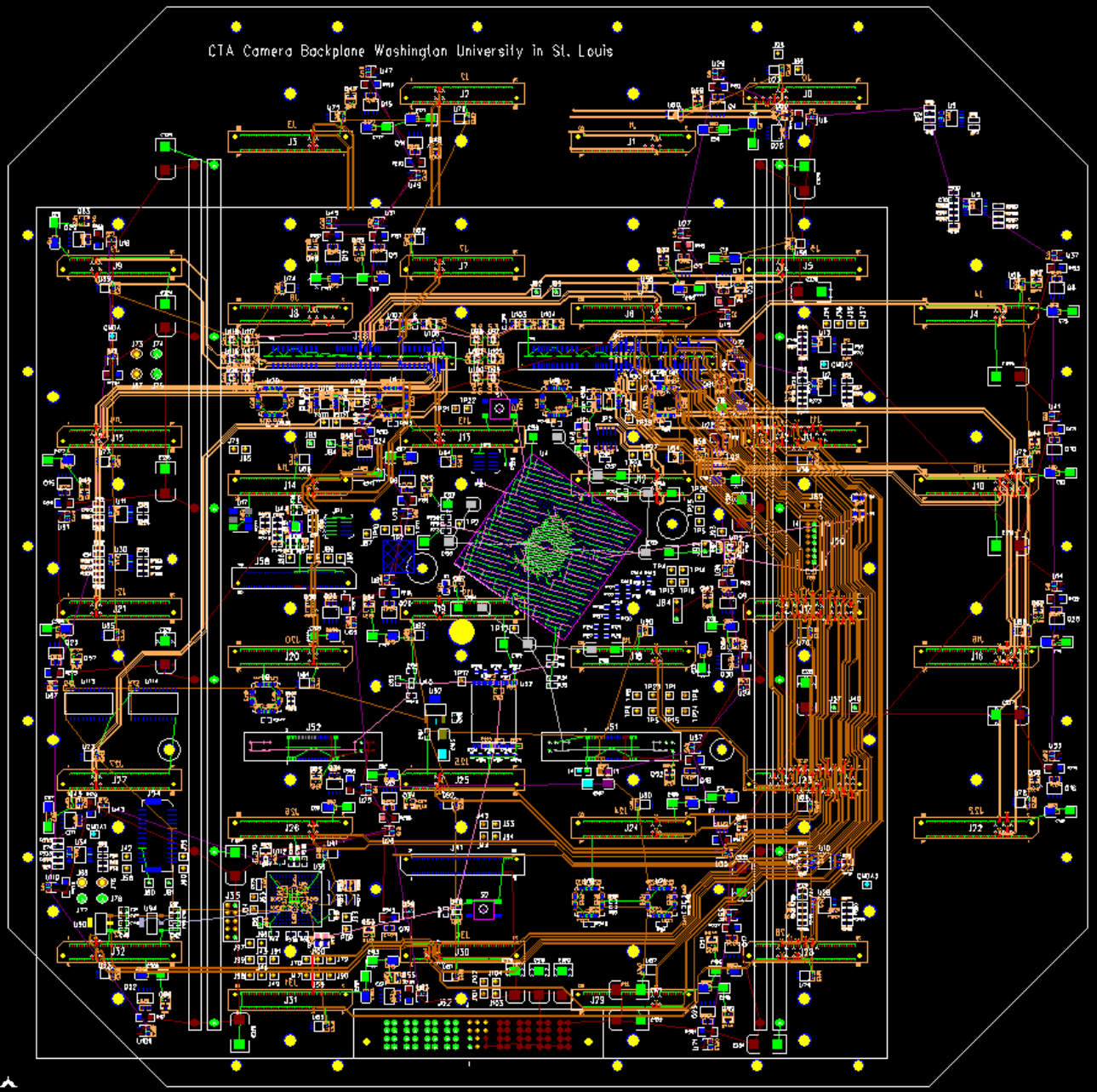
CHEC Backplane

University of Leicester



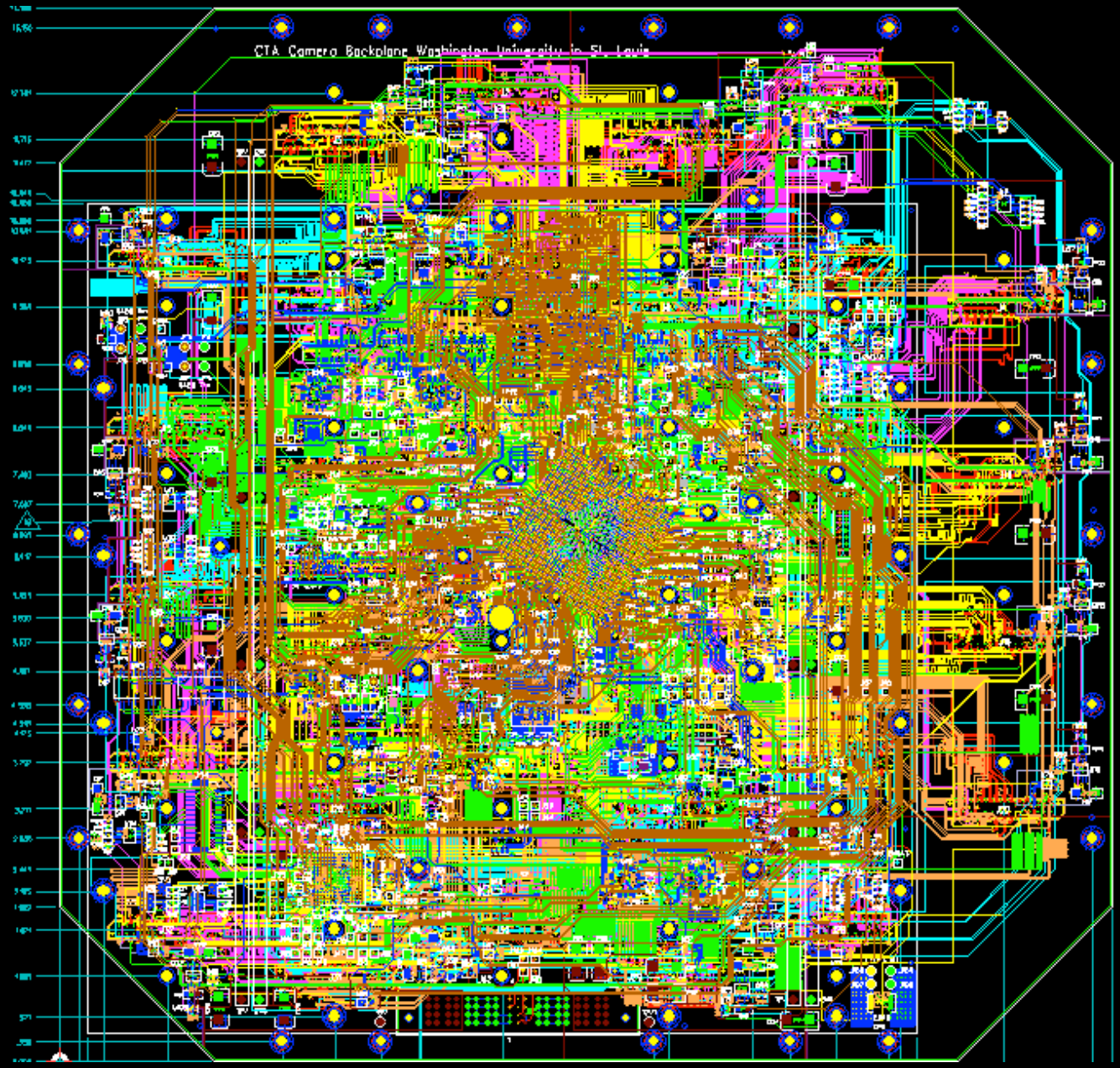
CHEC Backplane

University of Leicester



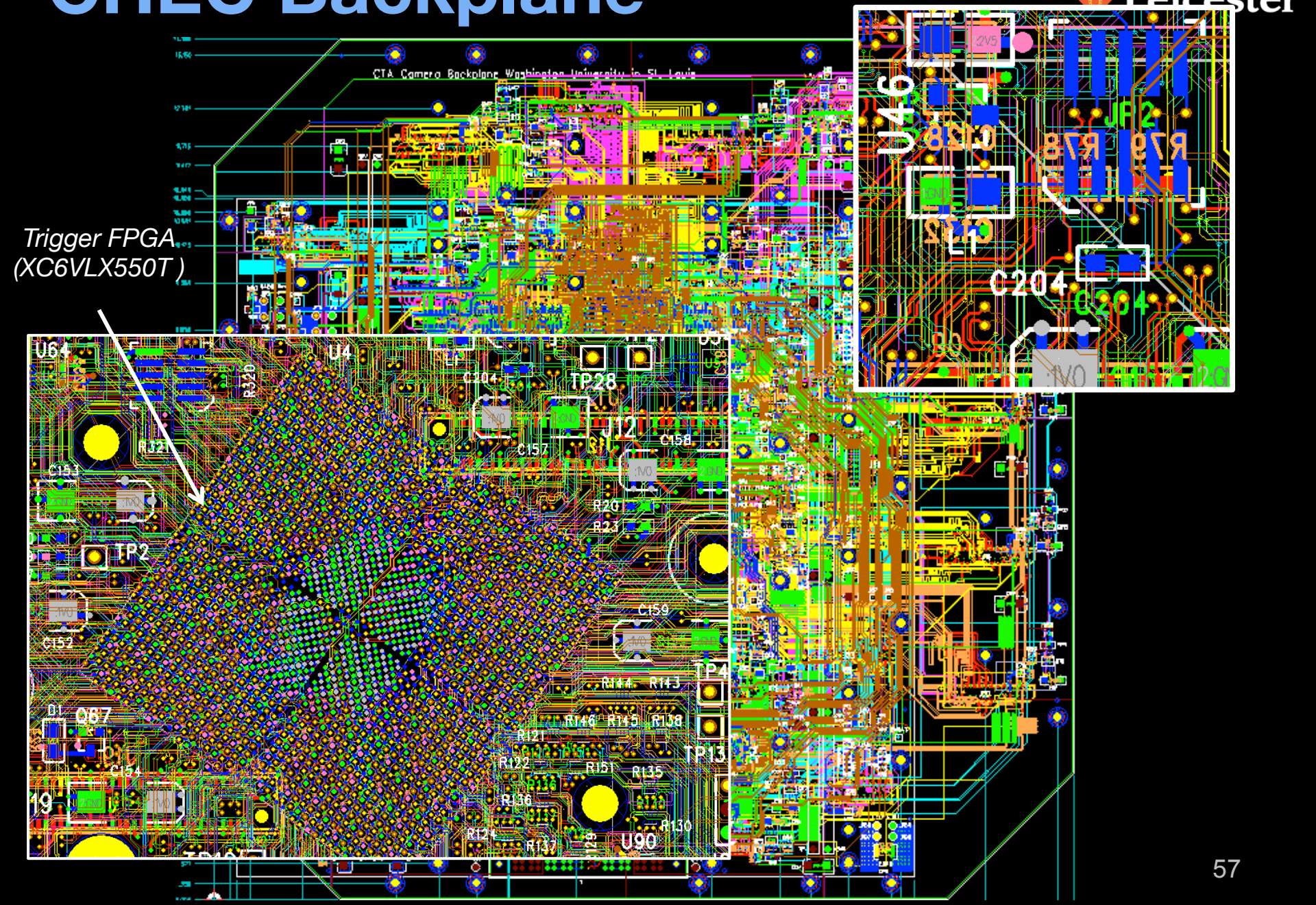
CHEC Backplane

University of Leicester



CHEC Backplane

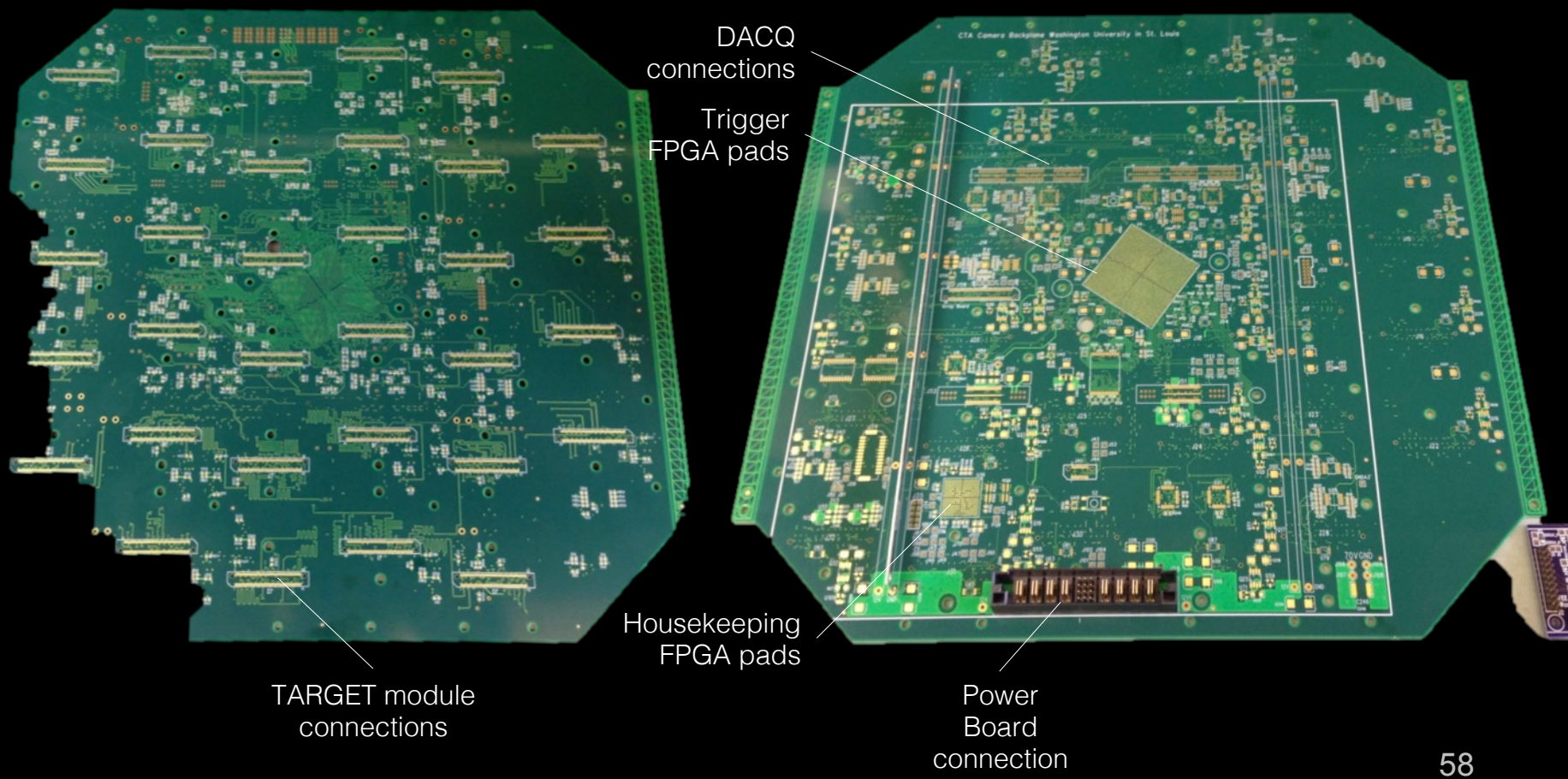
University of Leicester



CHEC Backplane

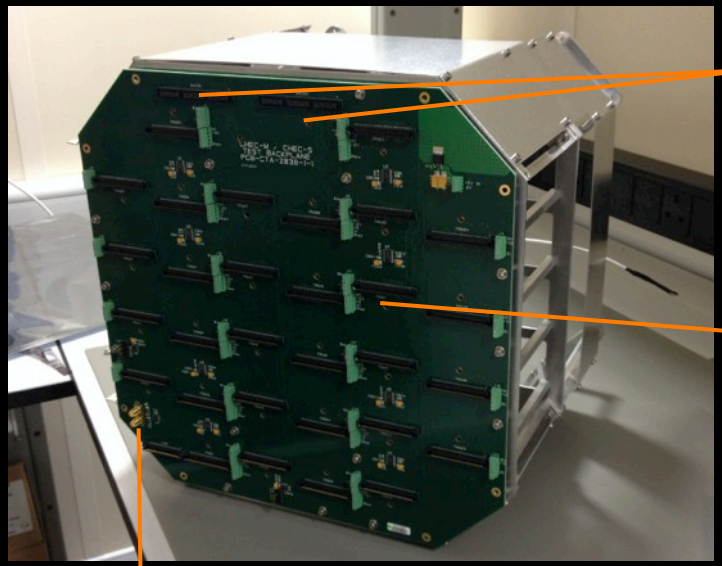
University of Leicester

- Delayed, but:
  - Layout complete, PCB manufactured, population underway



CHEC Backplane

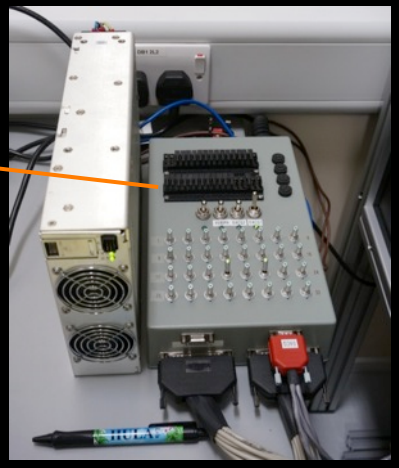
University of Leicester



Connection to DACQs

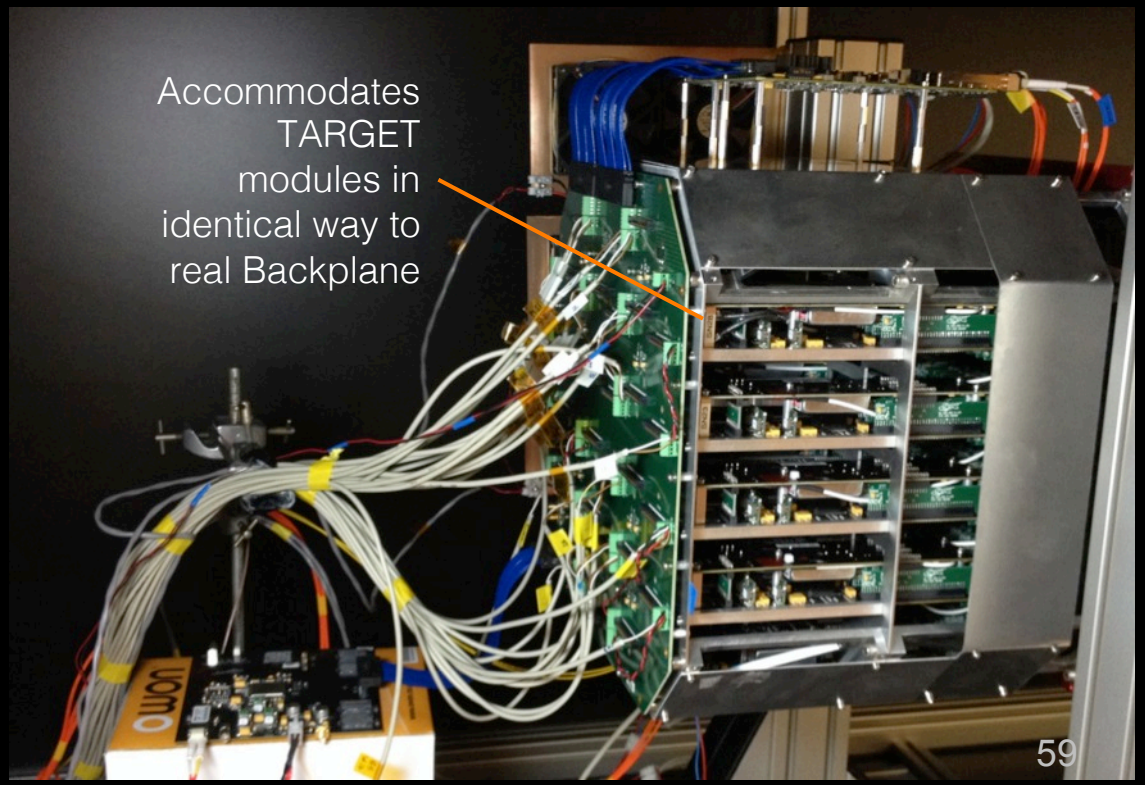
Power to TARGET modules

Trigger and CLK input & fan-out



PSU and switch box

- Proceeding with a proto-Backplane
- All tests apart from triggering possible

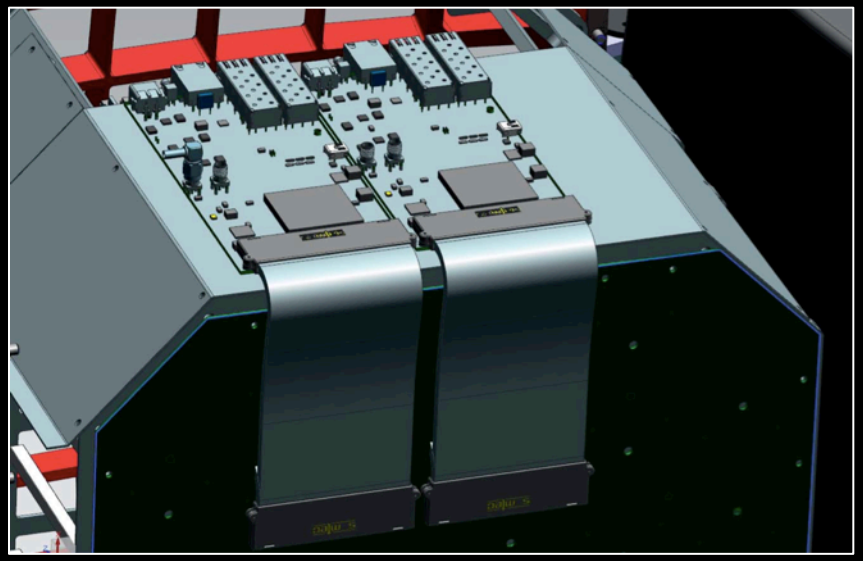


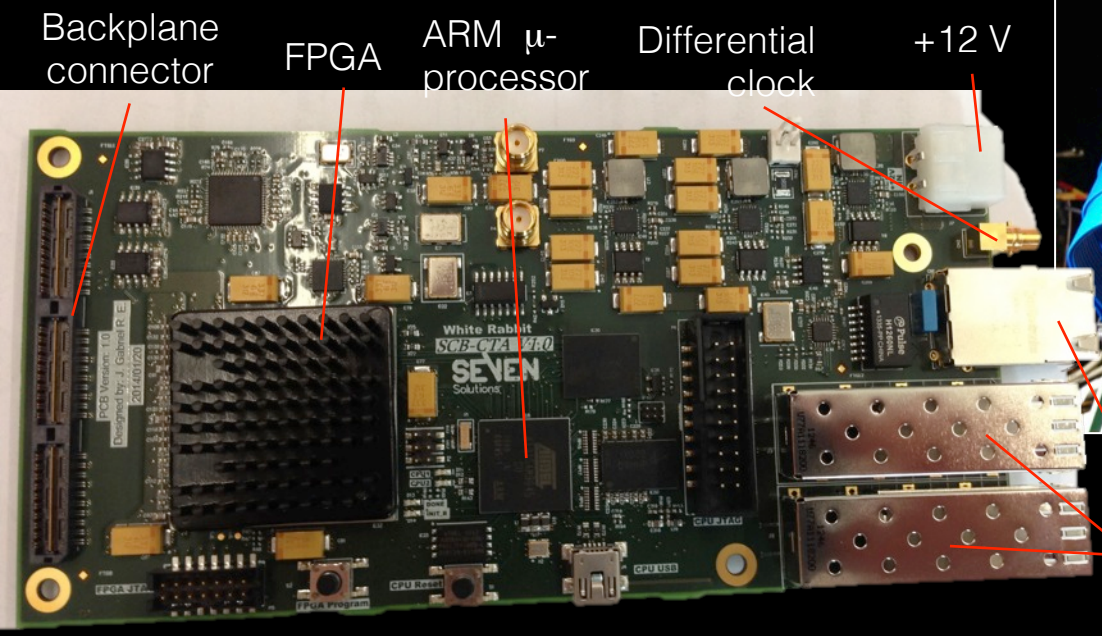
Accommodates TARGET modules in identical way to real Backplane

CHEC-M DACQ Boards

University of Leicester

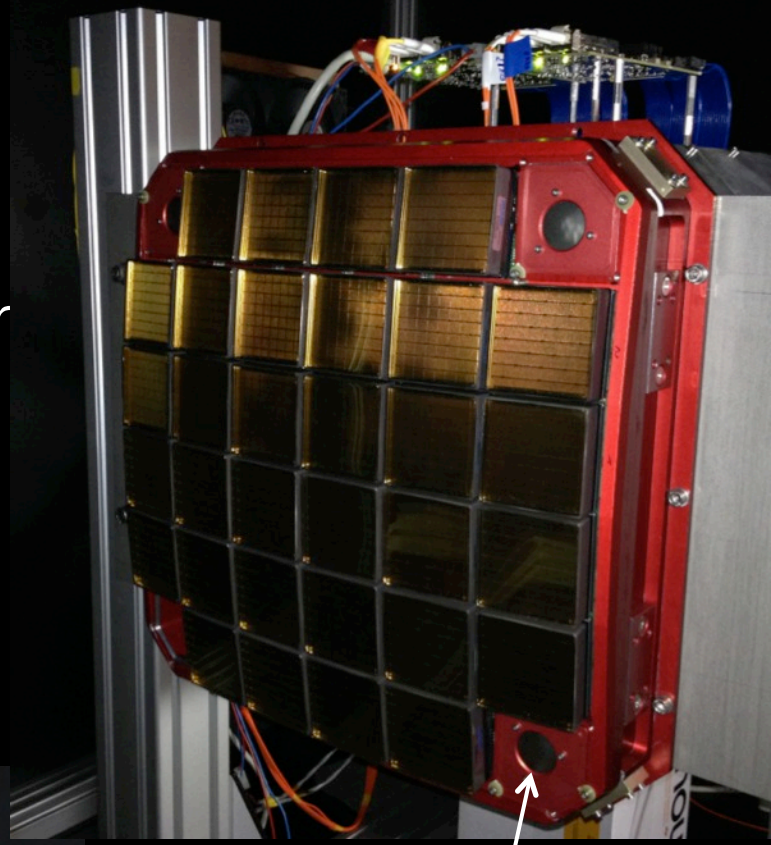
- University of Amsterdam & Seven Solutions:
  - 2 boards for CHEC-M manufactured
- 2 boards provide:
  - 36 port switch
  - 4 x 1 Gb/s uplinks
  - Absolute time synchronisation (using White Rabbit)

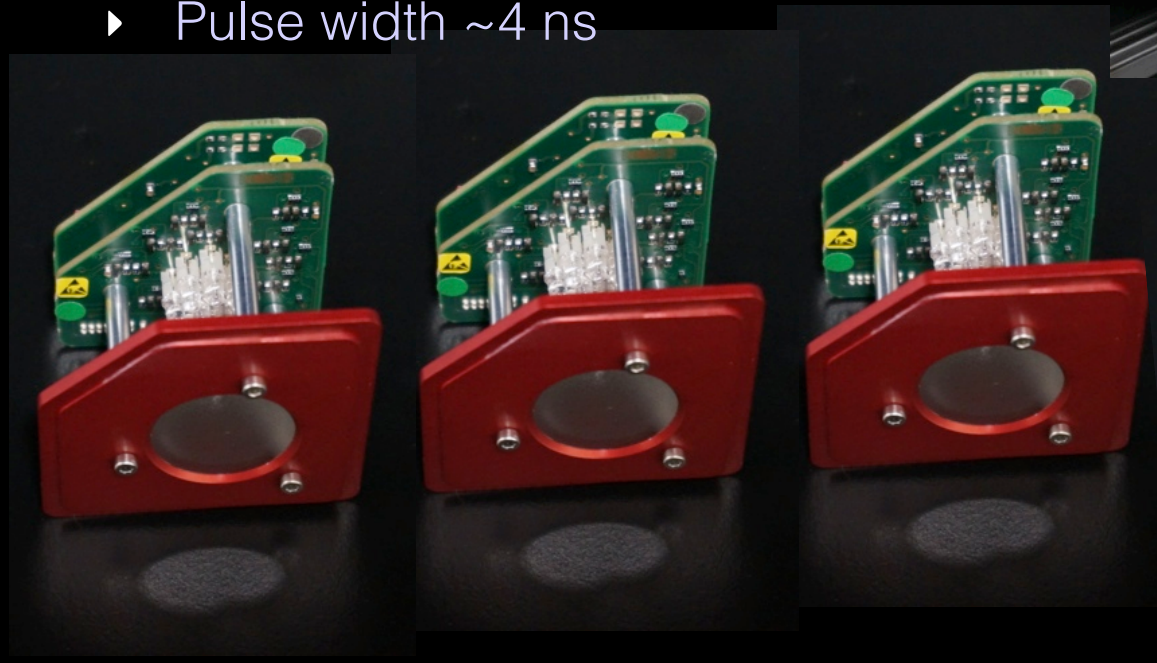


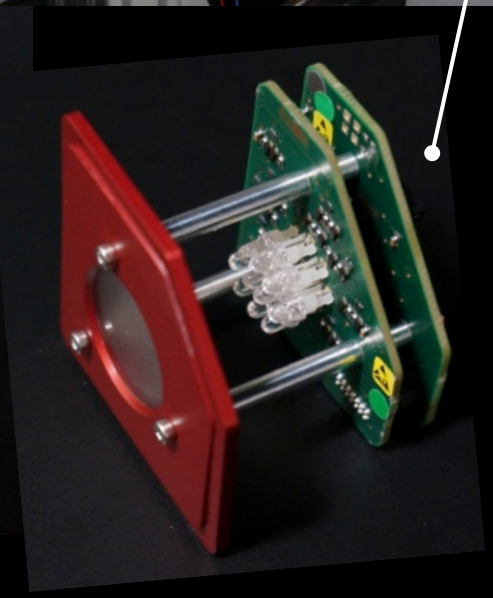


Calibration Units

- Illumination of the focal plane via reflection from the secondary mirror
- Installed in each corner of the camera
- Performance:
  - Multi-LED provides ~1 - 1000 pe
  - Pulse width ~4 ns



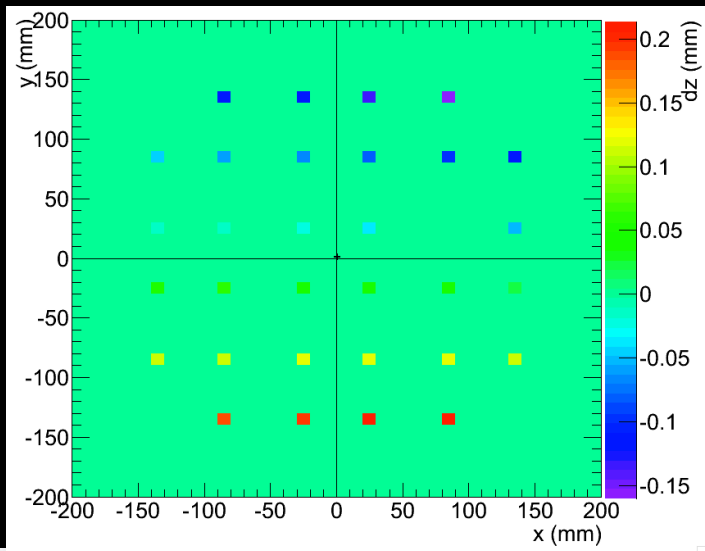


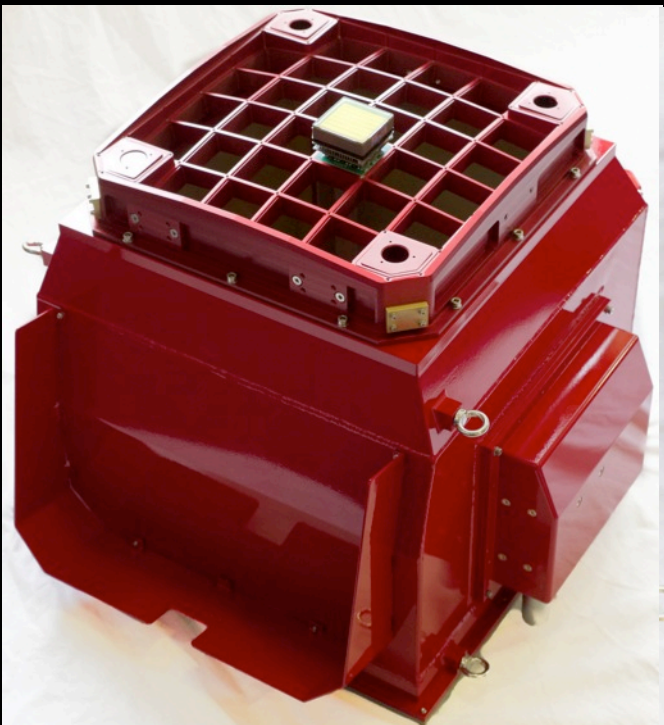


CHEC-M Mechanics

University of Leicester

- Machined and bent Aluminum
- Defocus of 1 mm → PSF degradation of 10% (on axis)
  - Achieve ~0.35 mm spread between MAPM centres with no adjustment
  - Can be reduced to 0.035 mm



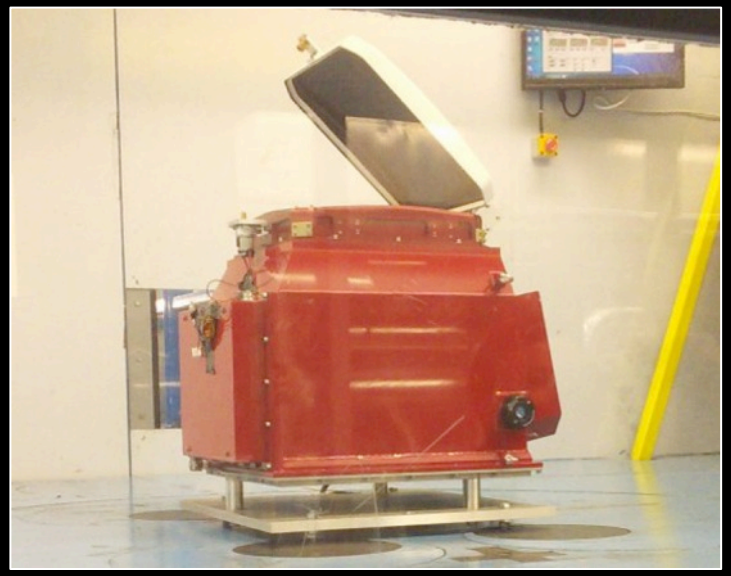


Environmental Tests

University of Leicester

UV

Wind



Rain

Environmental Tests

University of Leicester

Rain

Results:

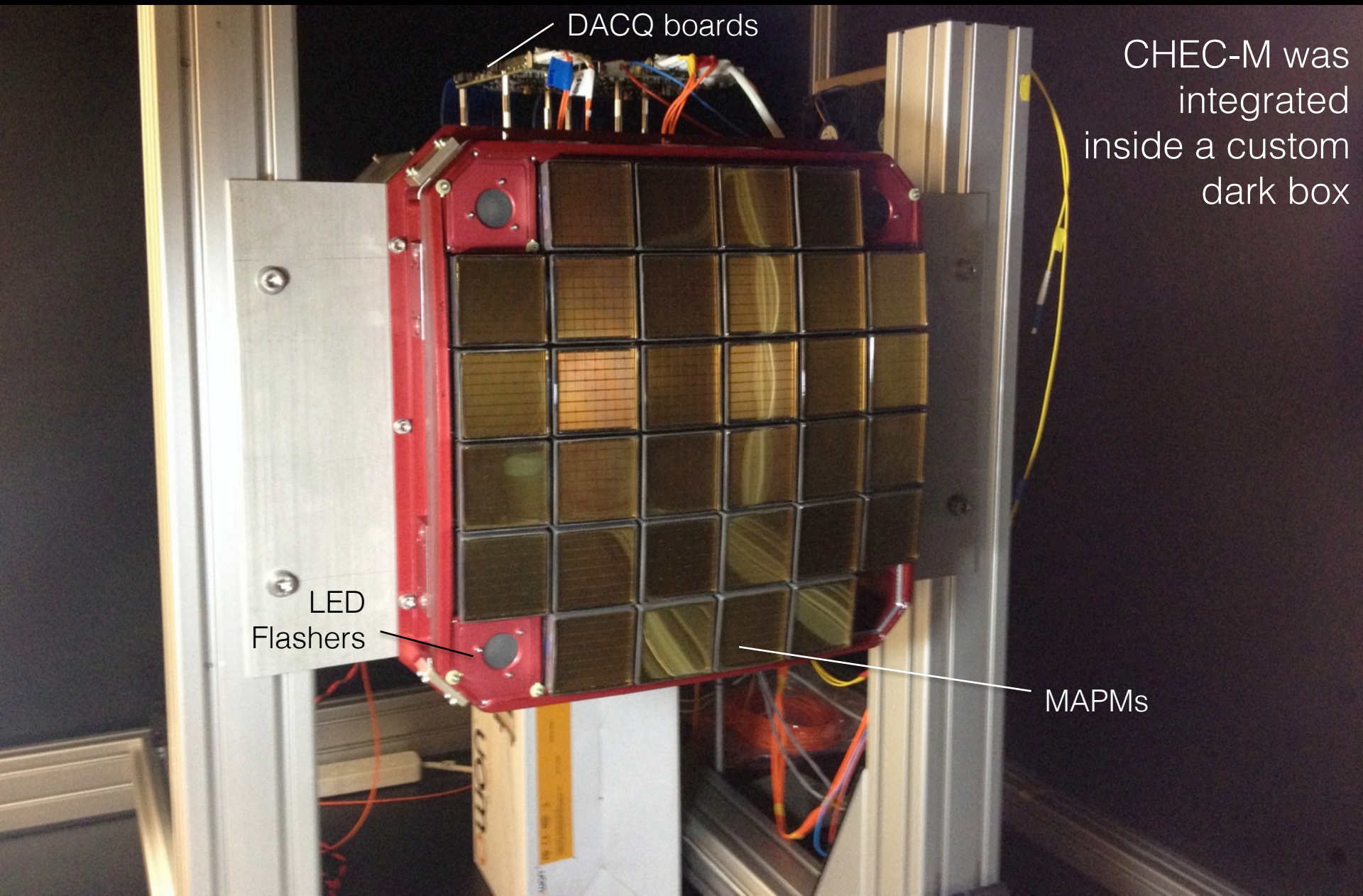
…it leaked

→ lid redesign in progress

UV

CHEC-M Commissioning

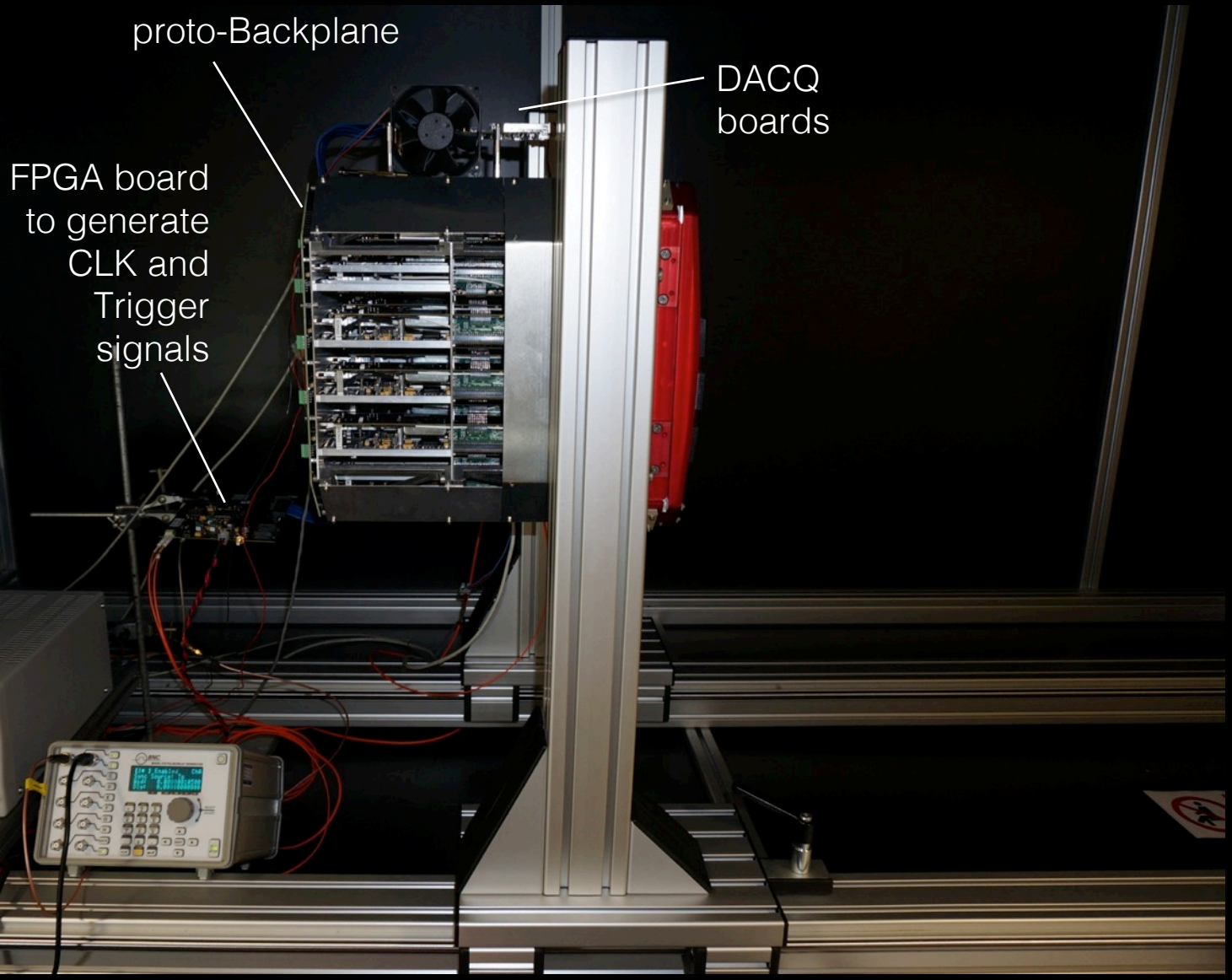
University of Leicester



CHEC-M was integrated inside a custom dark box

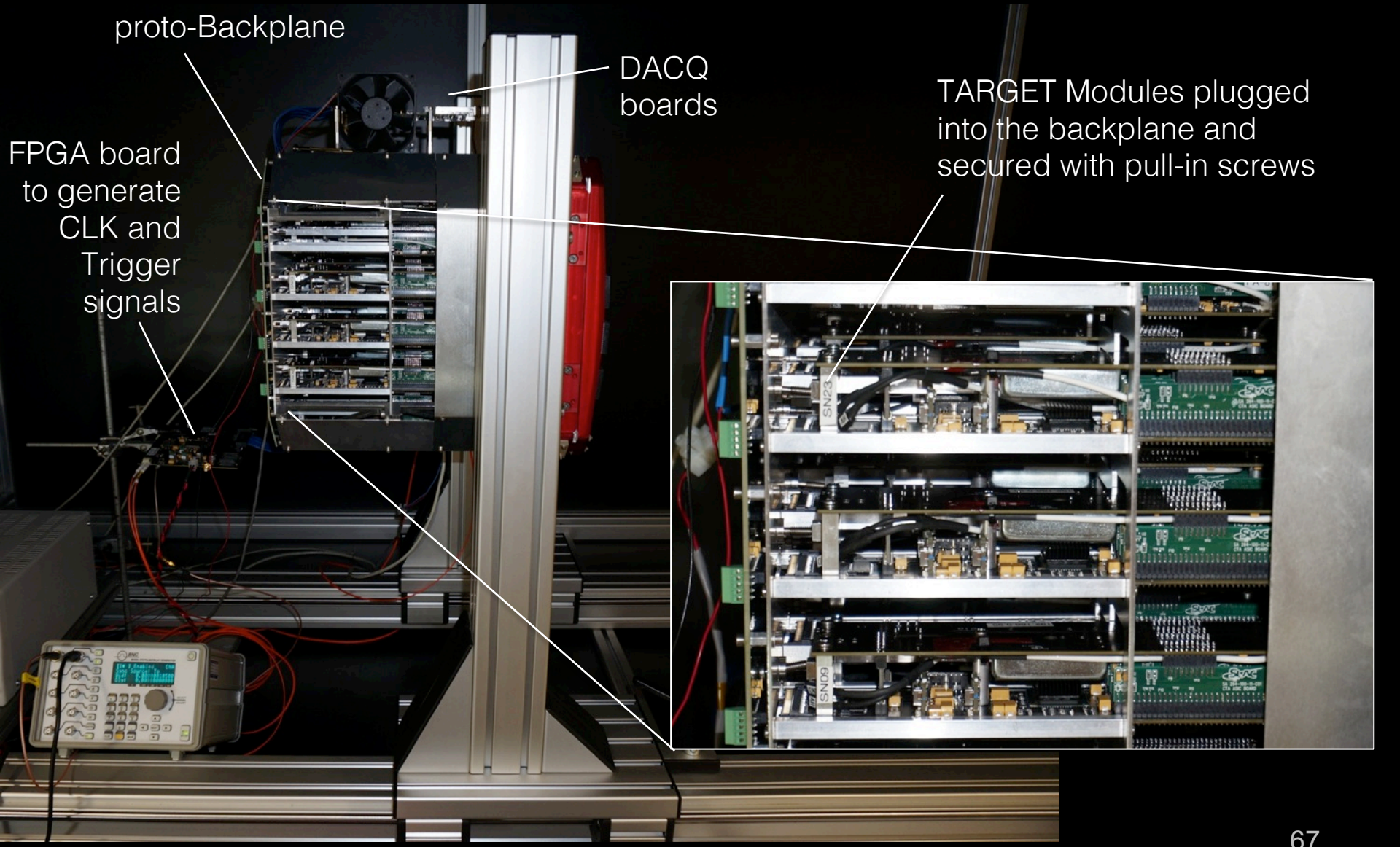
CHEC-M Commissioning

University of Leicester



CHEC-M Commissioning

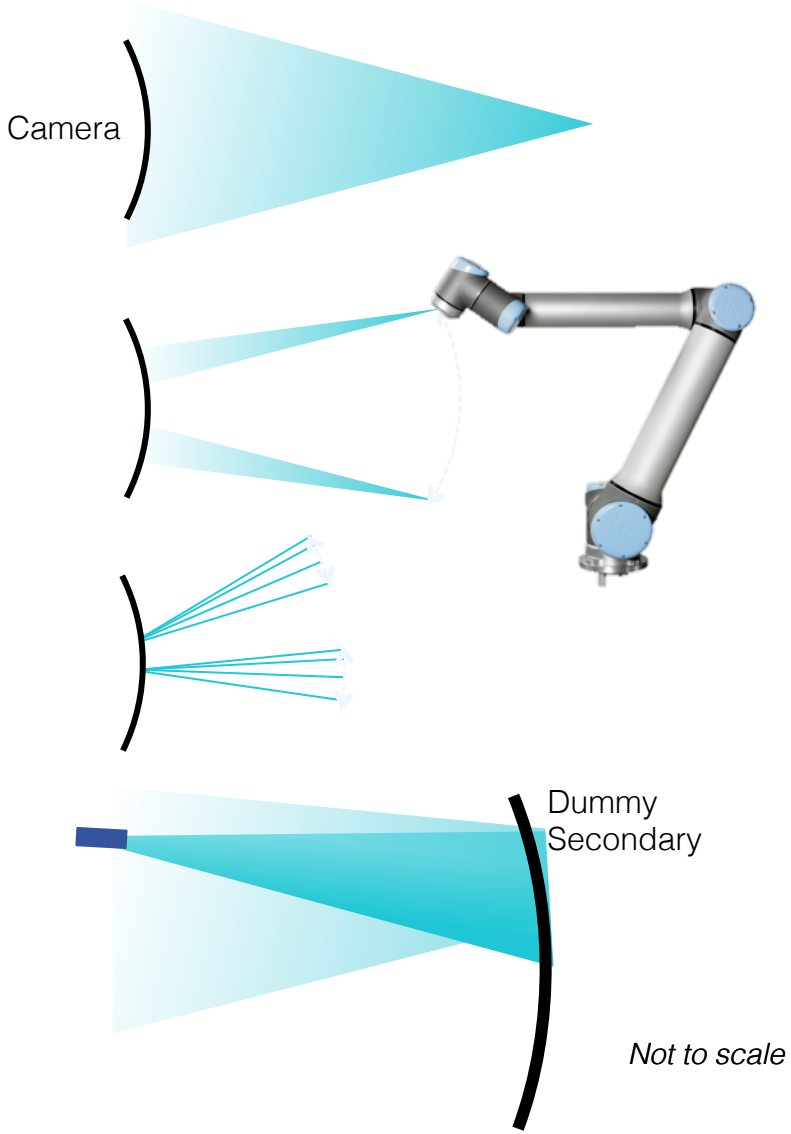
University of Leicester



CHEC-M Commissioning

University of Leicester

CHEC-M Commissioning

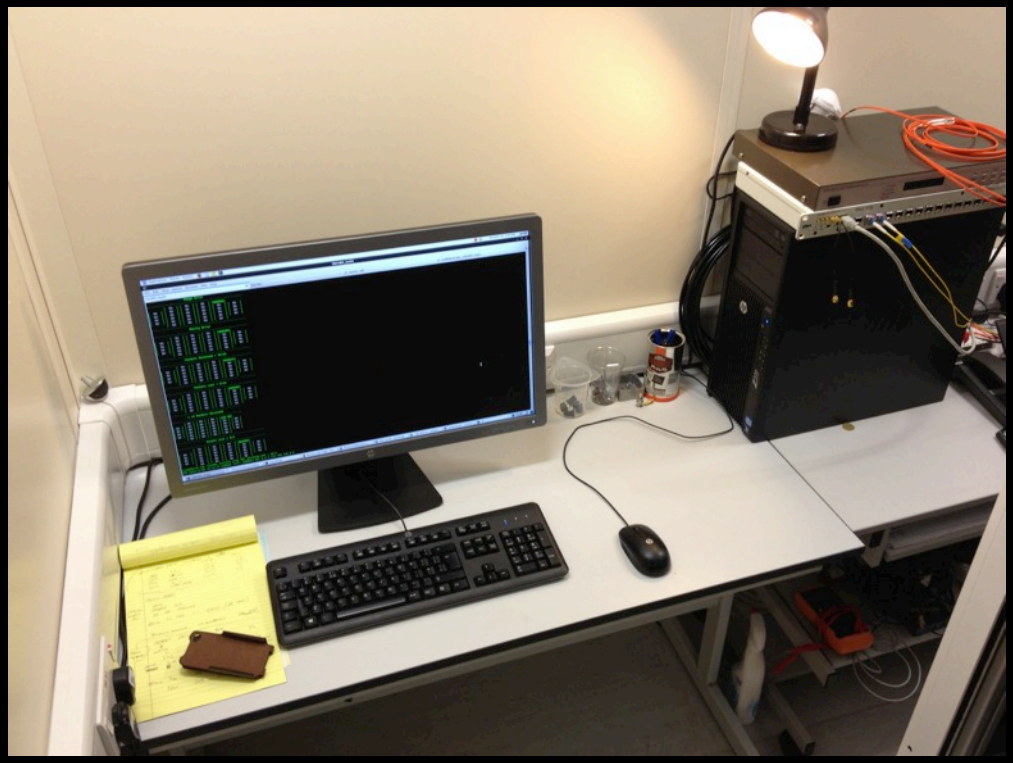


- Several desirable test setups
  - Uniform illumination
  - Trigger patch illumination and scan
  - Sub-pixel illumination, scan and rotate
  - Illumination of camera with inbuilt flashers via ‘dummy’ secondary mirror

CHEC-M Commissioning

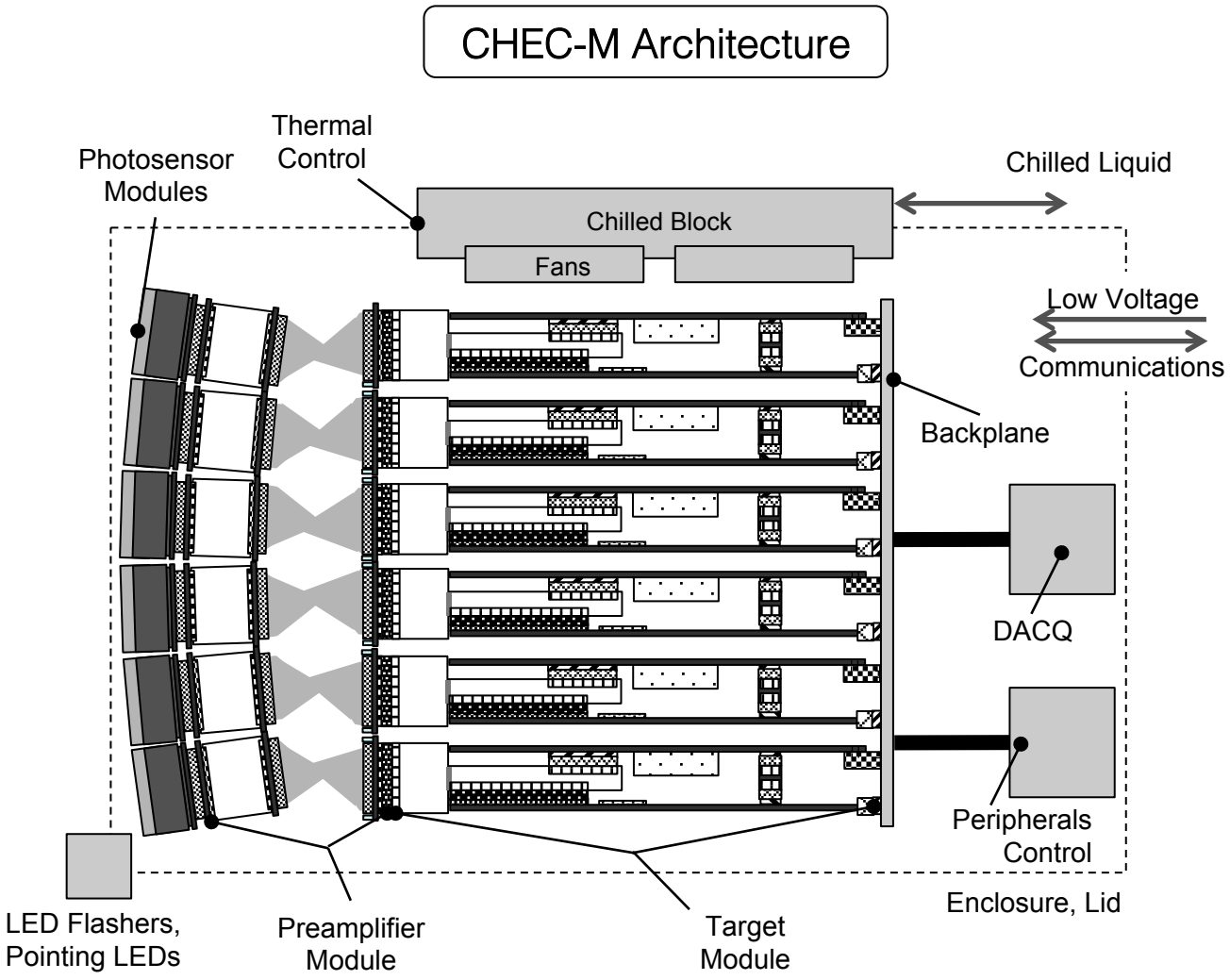
University of Leicester

- Status
  - All physical (electrical and mechanical interfaces a success) - ICDs
  - Debugging has focused on communication problems so far
  - 32 camera modules with MAPMs now integrated
  - Multiple TARGET module communication established
  - First light very soon



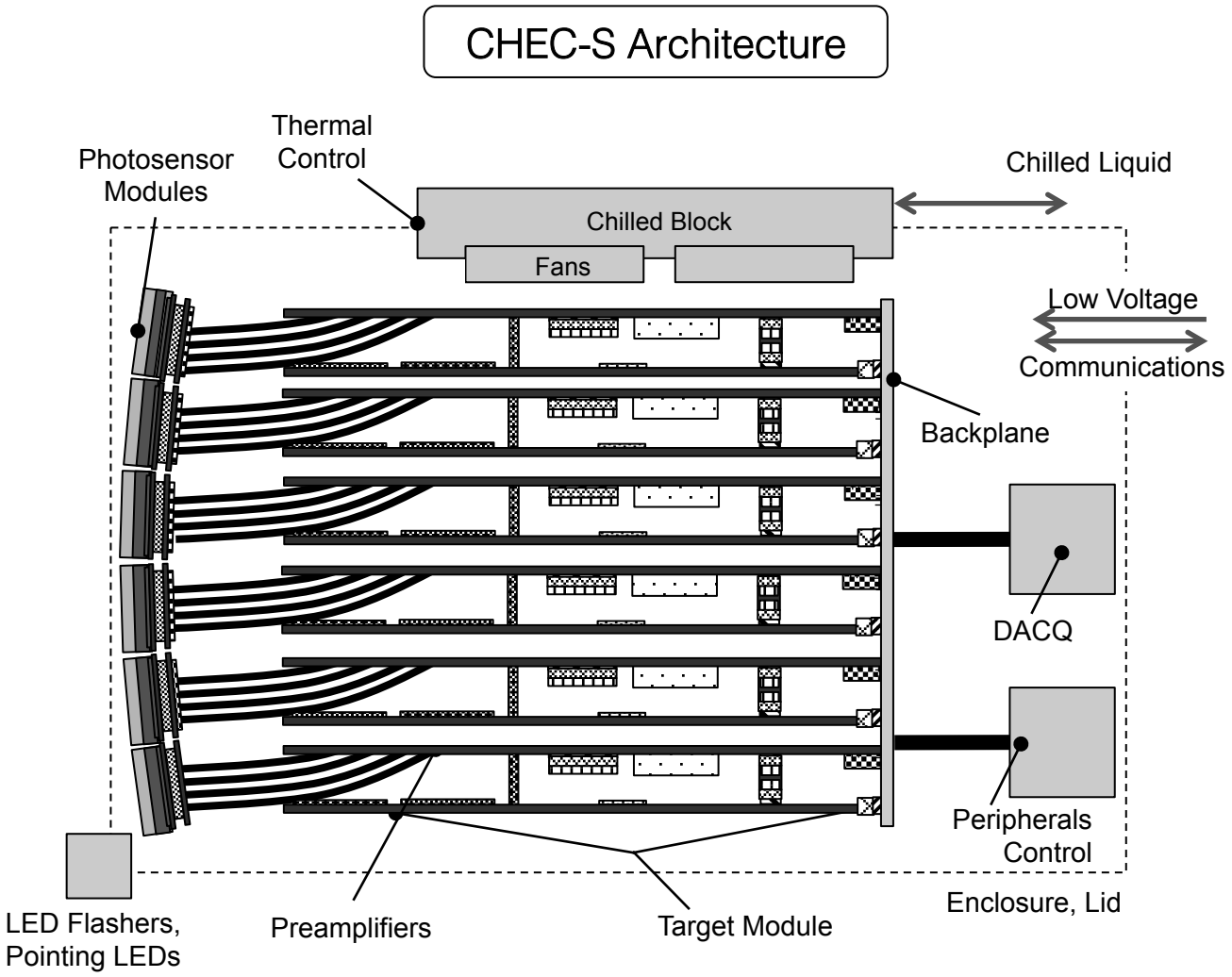
Towards CHEC-S

University of Leicester



Towards CHEC-S

University of Leicester



CHEC-S

University of Leicester

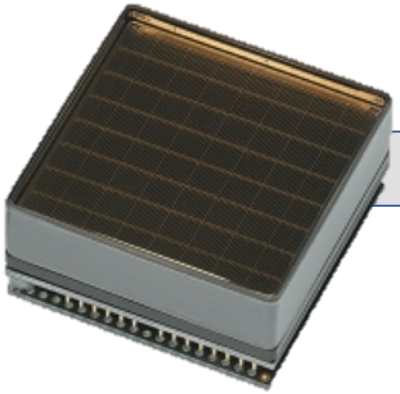
Requires modification

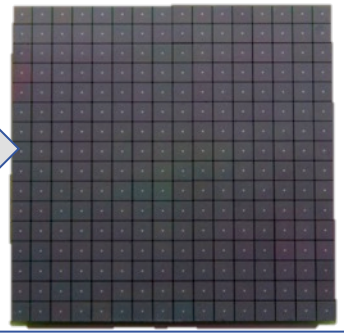
Can be the same

CHEC-M	CHEC-S
Photosensors → MAPMs	→ SiPMs

32 x 64 pixel modules
2048 pixels
0.17º
~3 mm gaps, 9º FoV

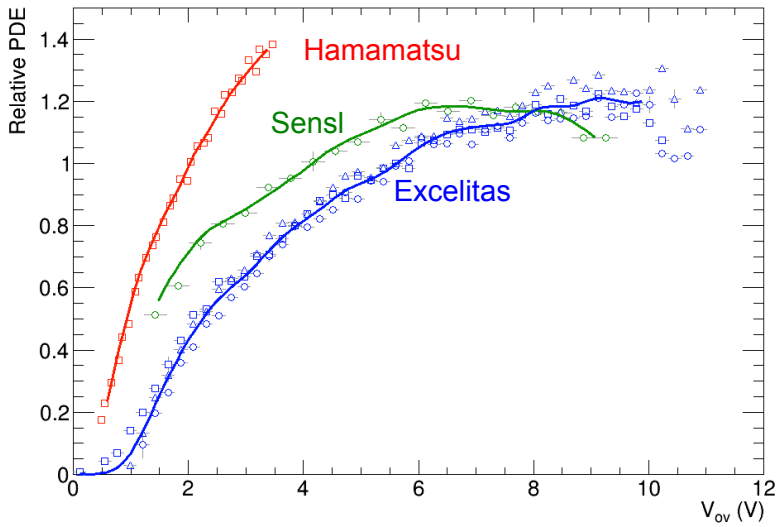
<1 mm gaps, 8.6º FoV



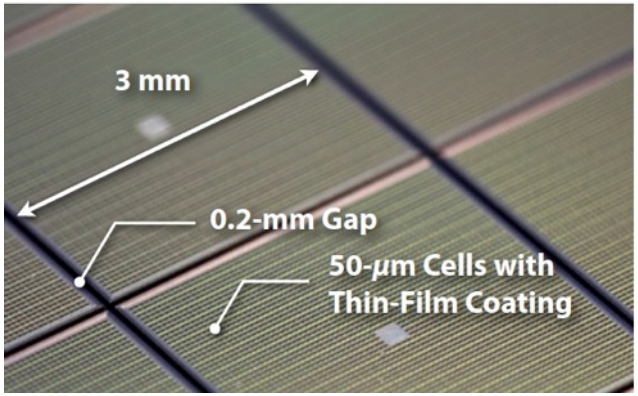


Hamamatsu

35 ordered
27 delivered
to date



Geometric fill factor: 87%
Size: 51.4 mm x 51.4 mm



CHEC-S

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Requires modification

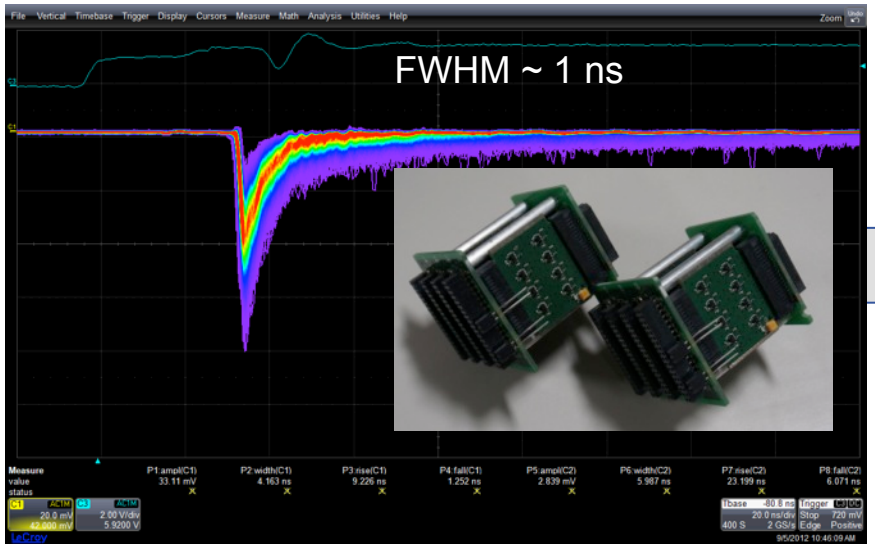
Can be the same

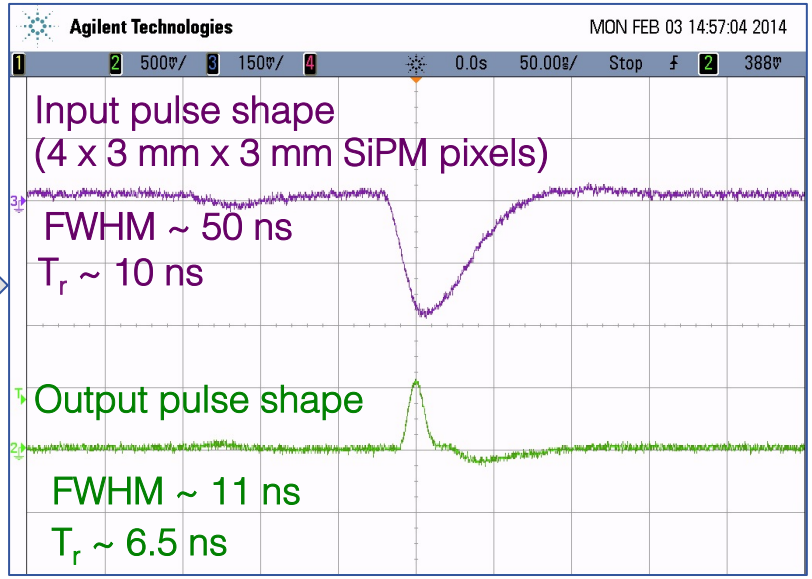
	CHEC-M	CHEC-S
Photosensors	MAPMs	SiPMs
Preamp Modules	MAPM Specific	SiPM Specific
		Addition of slow-signal monitoring

Need to lengthen the fast signals

Need to shorten the slow signals

Allows telescope pointing to be monitored





Discussions on going with D, Gascon about a PACTA variant to implement SiPM preamp on an ASIC

CHEC-S

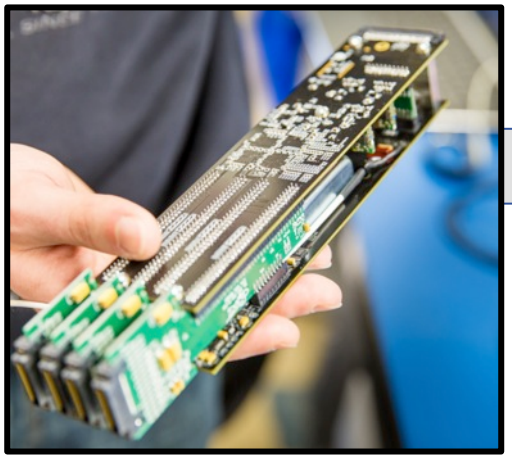
University of Leicester

Requires modification

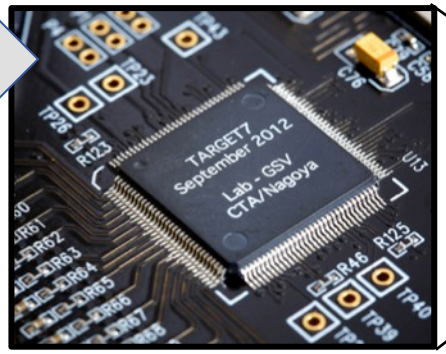
Can be the same

	CHEC-M	CHEC-S
Photosensors	MAPMs	SiPMs
Preamp Modules	MAPM Specific	SiPM Specific
		Addition of slow-signal monitoring
TARGET Modules	TARGET 5	TARGET 7

First full modules now assembled at SLAC



Also used in SCT



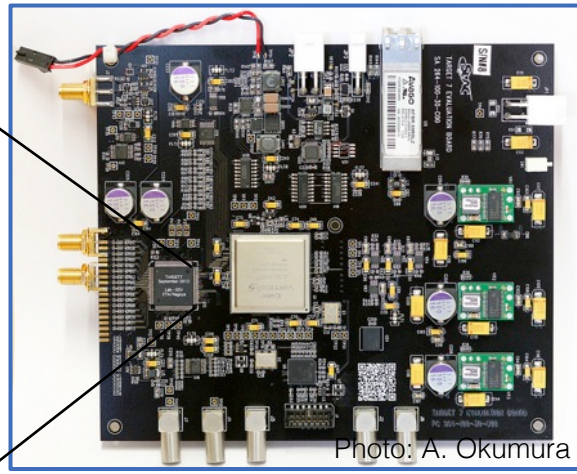


Photo: A. Okumura

Demo board

TARGET Transfer Functions

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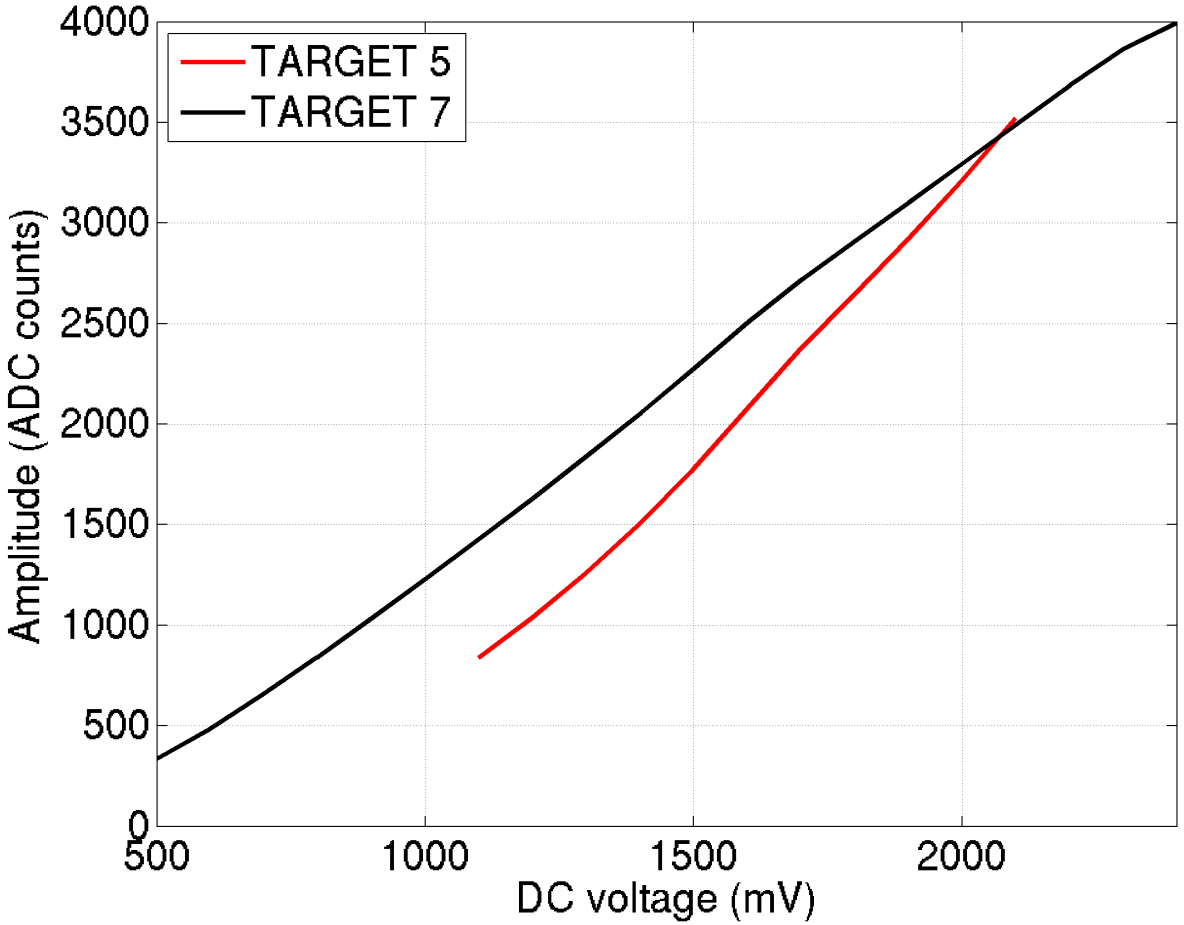

TARGET 5
Operating range: 1.1 V
Integral nonlinearity: 338 counts

TARGET 7
Operating range: 1.9 V
Integral nonlinearity: 77 counts

CHEC-S

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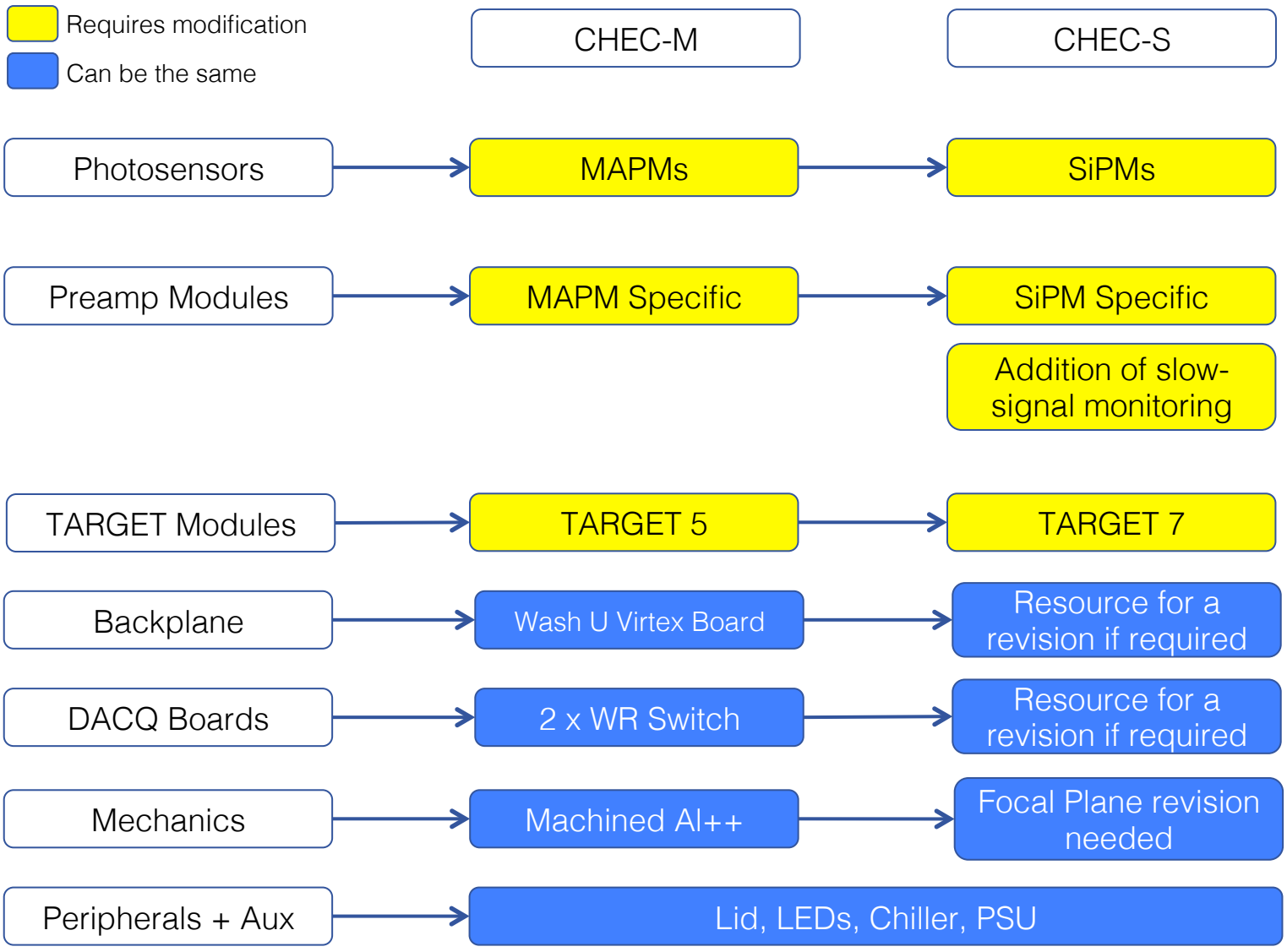

CHEC-S

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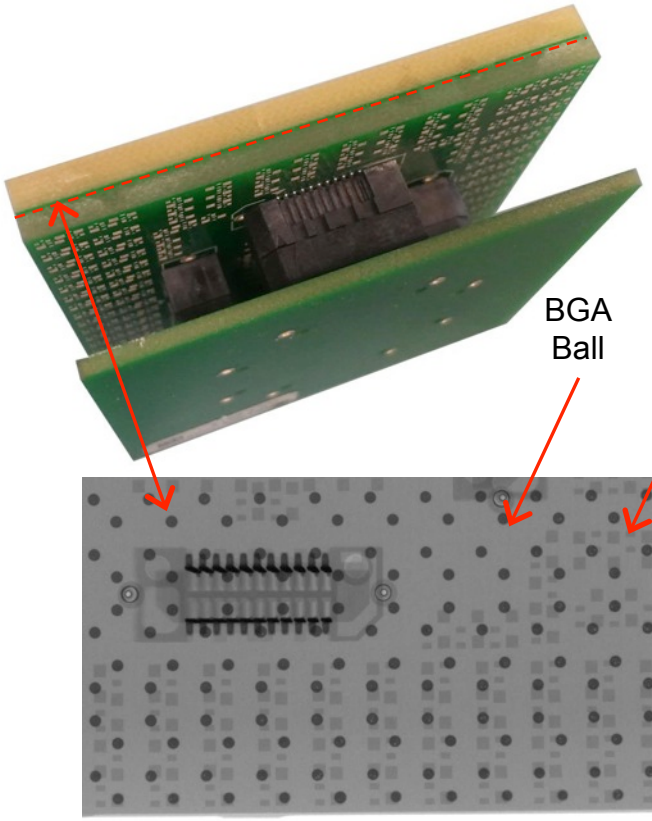
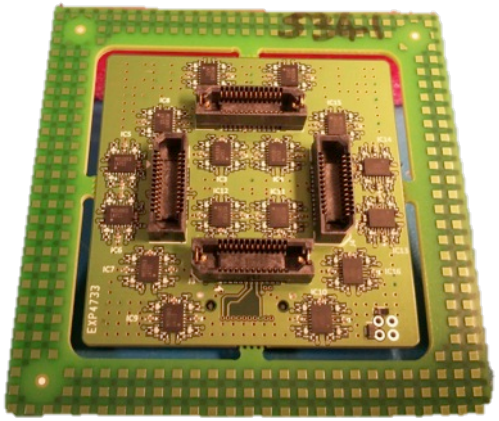
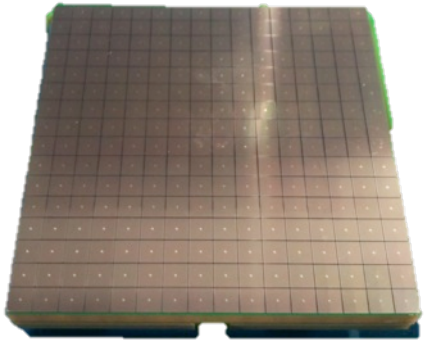
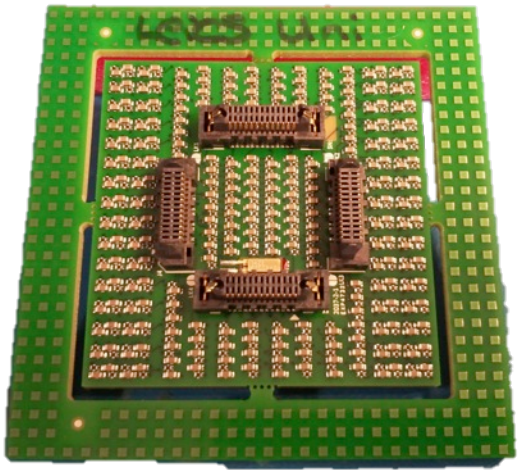
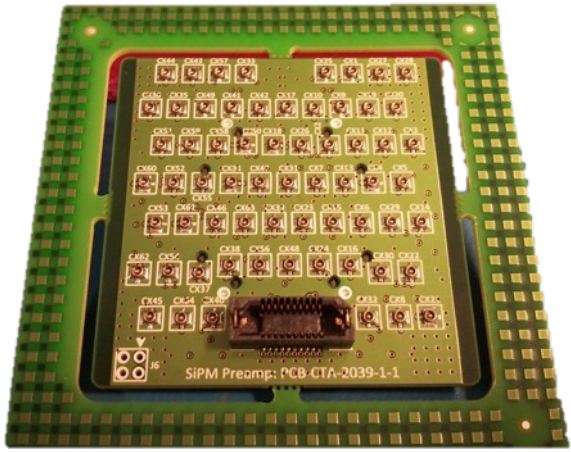


- SiPM Module:
  - SiPM tile
  - Base PCB
  - Preamp buffer
- Assembly checks successful
- First real version produced this week









CHEC-S Mechanics

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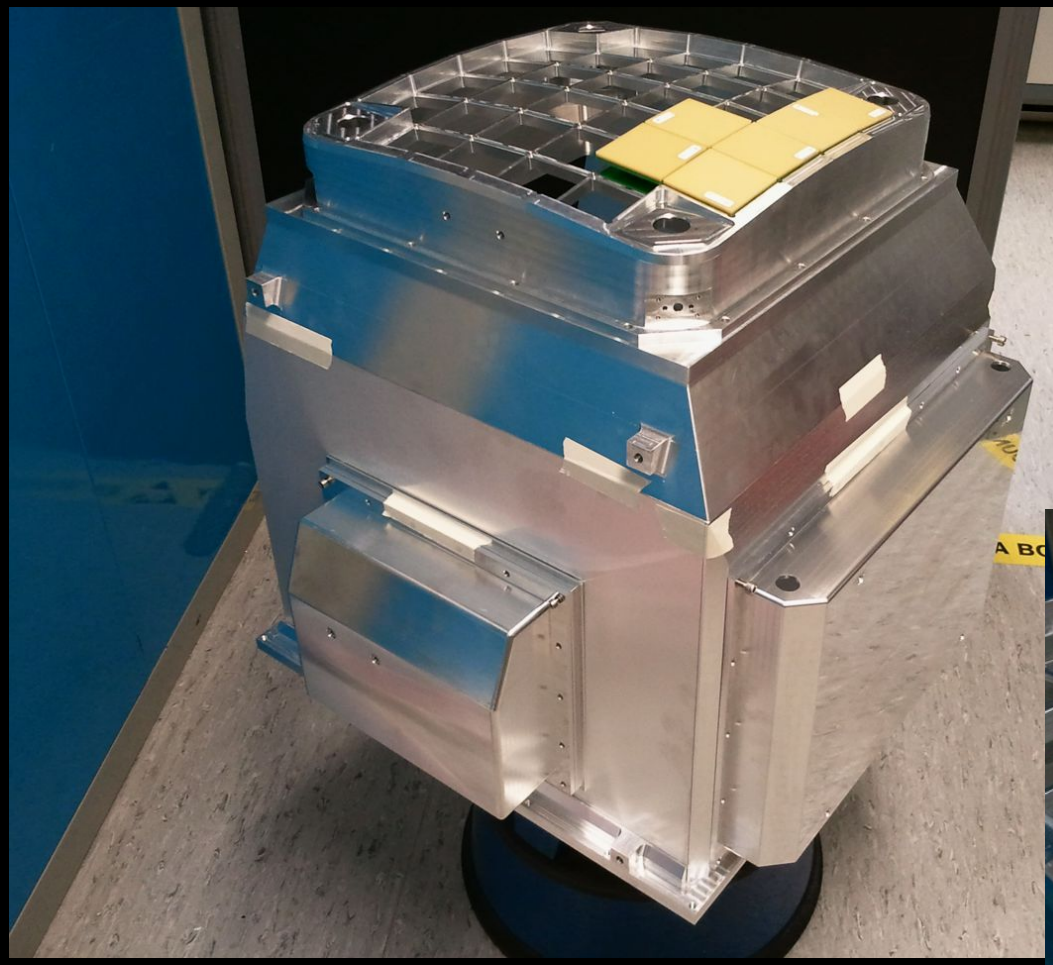

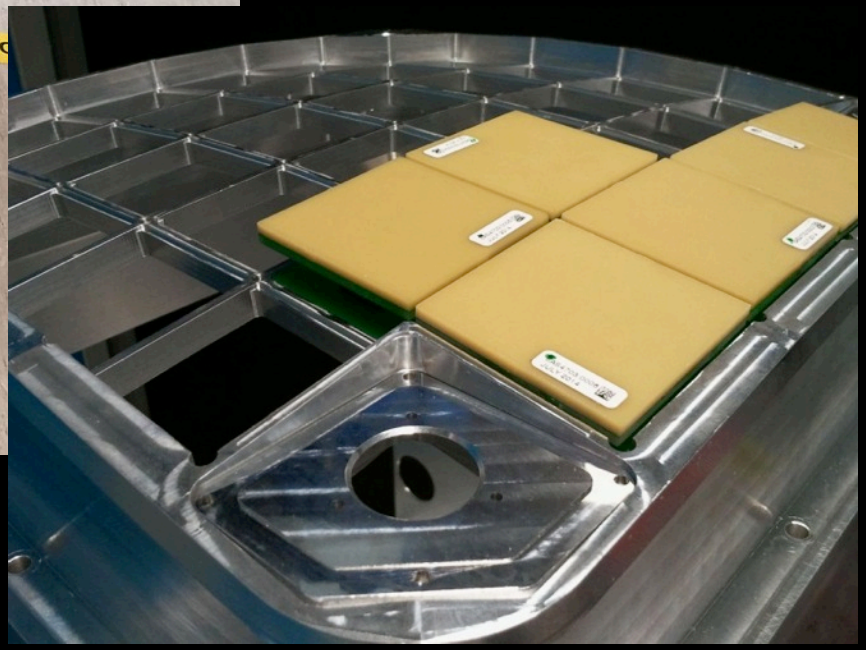

On-Telescope Tests

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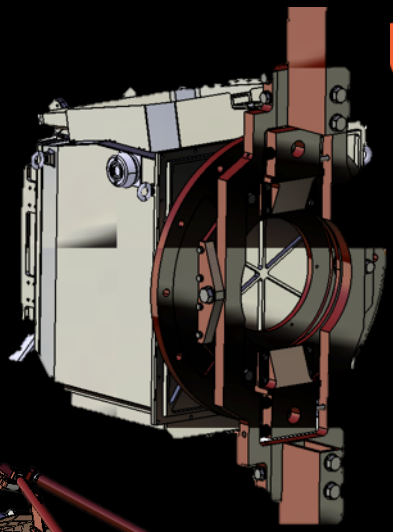
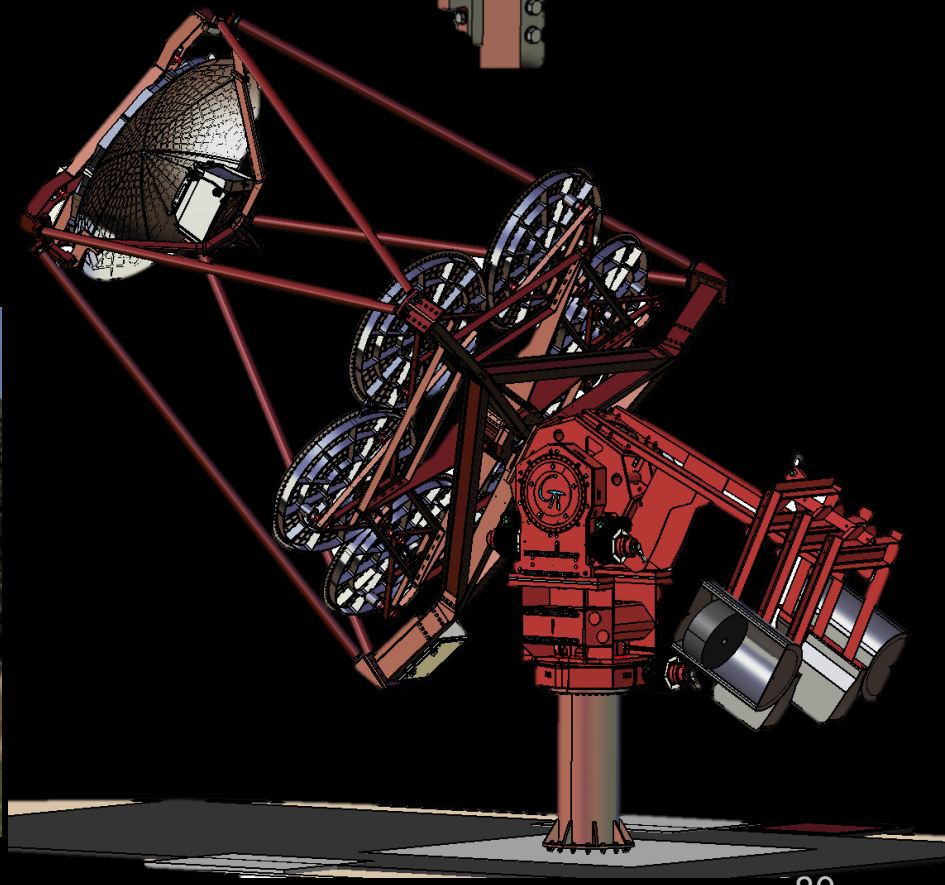
- CHEC-M will be deployed on SST-GATE
  - Paris
  - Latest date: June 2015
- Test plan underway



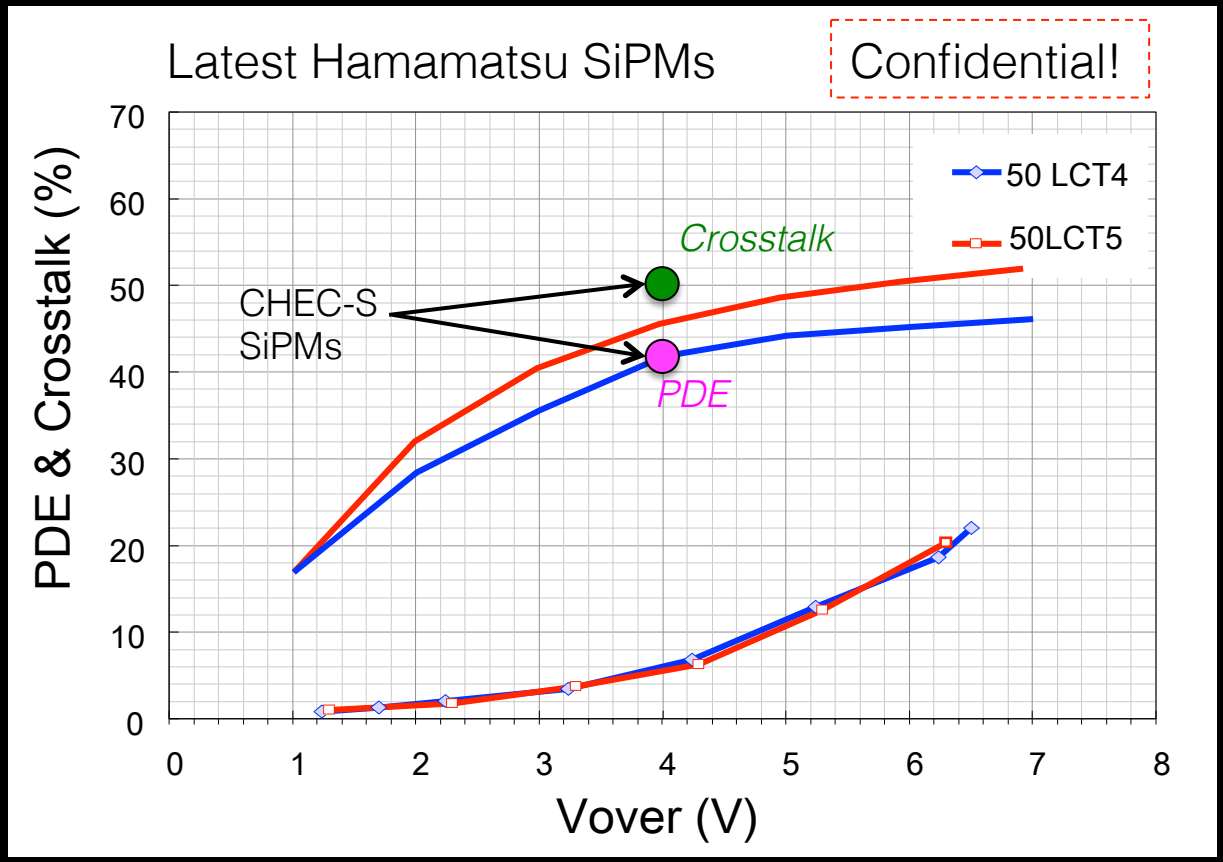


Beyond CHEC-M/S

The final camera

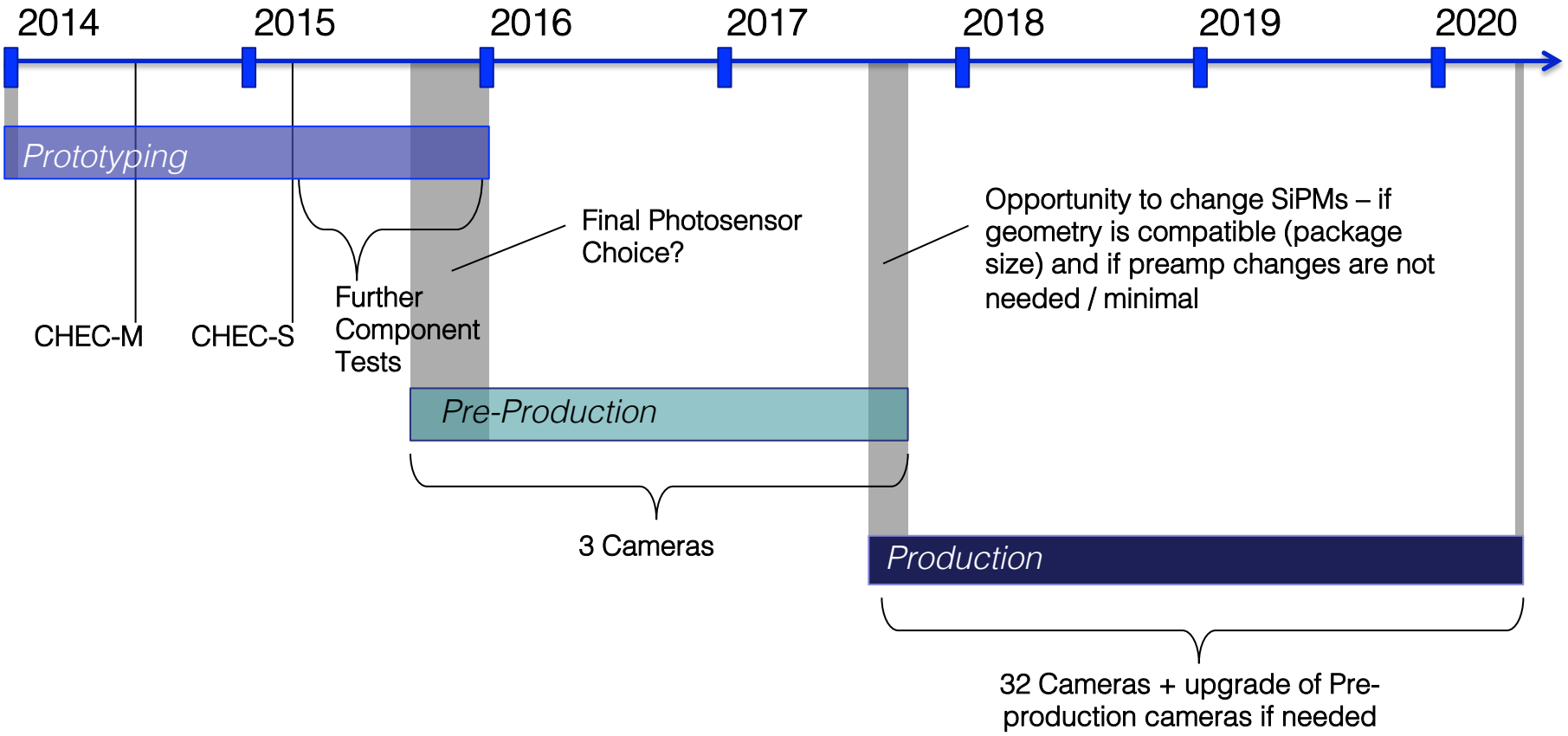
University of Leicester

- At some point you have to stop prototyping!
- But when?
- Some components will undergo further development:
  - SiPMs:
    - 6 mm x 6 mm
    - Low Cross Talk (LCT)
  - TARGET:
    - Split trigger and sampling ASICs



Beyond CHEC-M/S

The final camera



Recent Developments

The GATE-CHEC Telescope (GCT)

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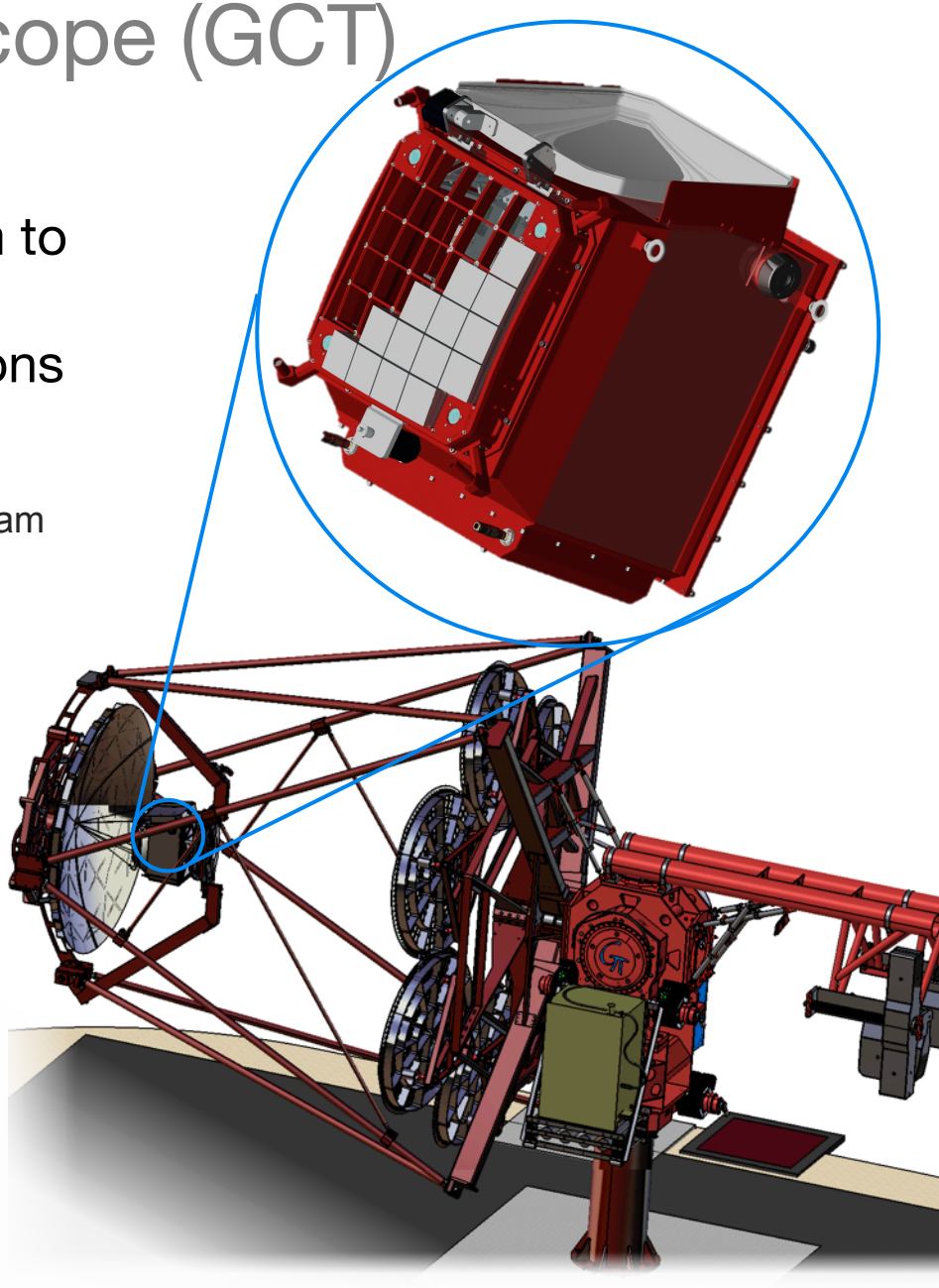
- GATE and CHEC merge
  - Formed a single sub-consortium to provide complete SST-2M telescopes as in-kind contributions to CTA
    - Observatoire de Paris
    - CNRS
    - University Paris
    - Leicester
    - Liverpool
    - Durham
    - Oxford
    - Amsterdam
    - ECAP
    - Nagoya
    - Adelaide
    - MPIK
    - Open to others
  - Declaration of Intent and management structure under consideration



Recent Developments
MPIK

University of Leicester

- Jim's appointment
- There will be CHEC work done at MPIK
  - I would like to be apart of it!

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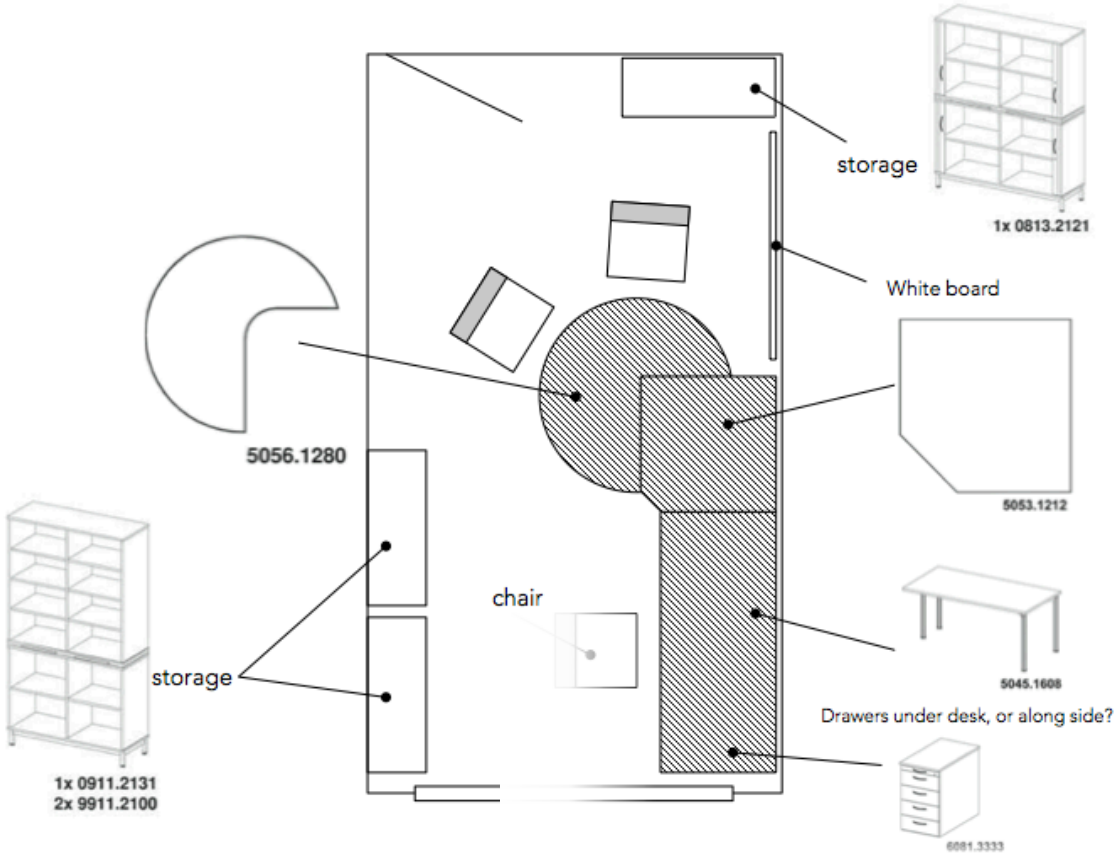

Conclusion

- **CTA is on track**
  - Operating as an open observatory by the end of the decade
- **CHEC is on track**
  - A high-performance low-cost solution for the SST cameras
  - First full prototype being commissioned
- **This is an exciting time to be in CTA, especially at MPIK!**