Cherenkov cameras ... for Pedestrians

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HELMHOLTZ | ASSOCIATION

DESY

Cherenkov cameras and me

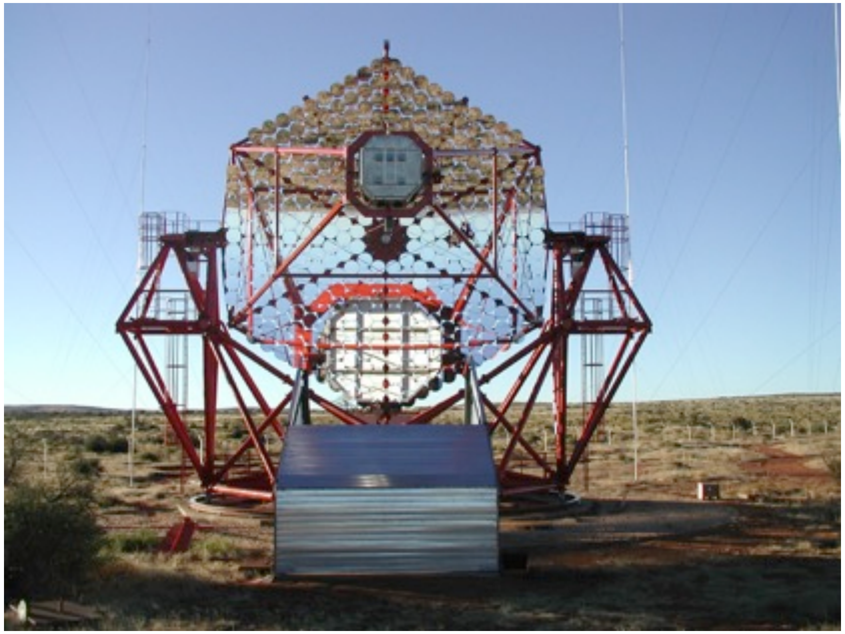
- 2005: Cherenkov Mirrors for HESS-II – **0 Cherenkov cameras**
- 2010-2012: MAGIC upgrade – **2 Cherenkov cameras**
- 2012-2017: HESS-I camera upgrade – **4 Cherenkov cameras**
- 2017- : CHEC cameras - **? > 20 Cherenkov cameras**

- **Cherenkov cameras operating now: 13**
- **Total Cherenkov cameras built so far => ~30**
- **Total sources discovered approaching 200.**

Which type of Cherenkov camera?

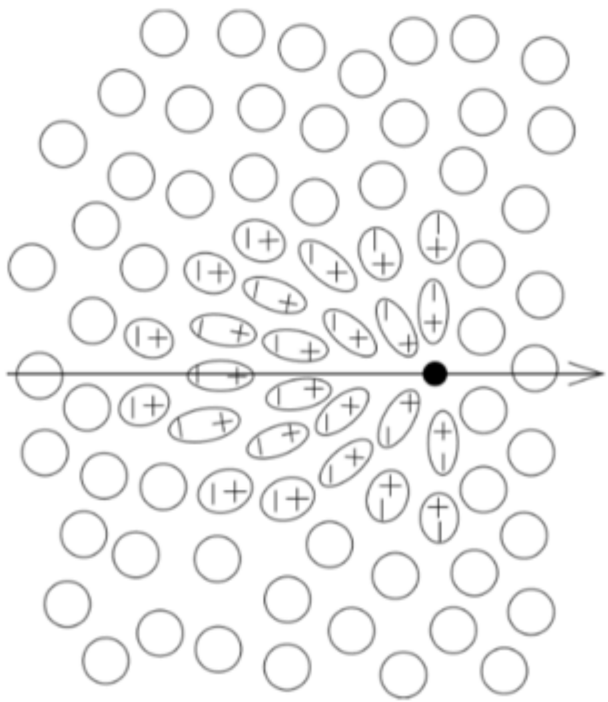
Many types Cherenkov Cameras!

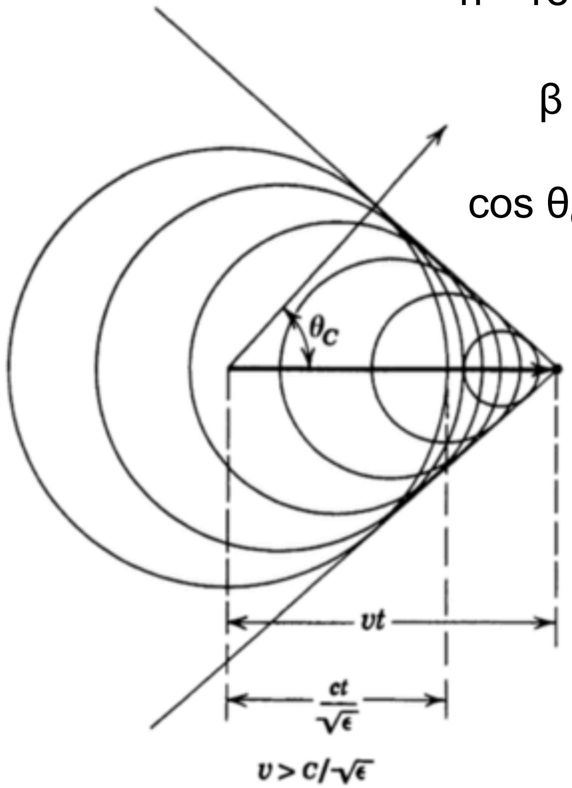
- Not particle detector (~~RICH~~)
- No neutrino detector (~~Super-K~~ or ~~IceCube~~)
- Not even Water-Cherenkov gamma-ray detector (~~Milagro~~, ~~HAWK~~)
- I only do Atmospheric Imaging Cherenkov Telescope Cameras



Cherenkov Effect

- Cherenkov 1934, Frank & Tamm 1937
- Super-luminal charged particle polarizes molecules that emit dipole radiation that adds up coherently.





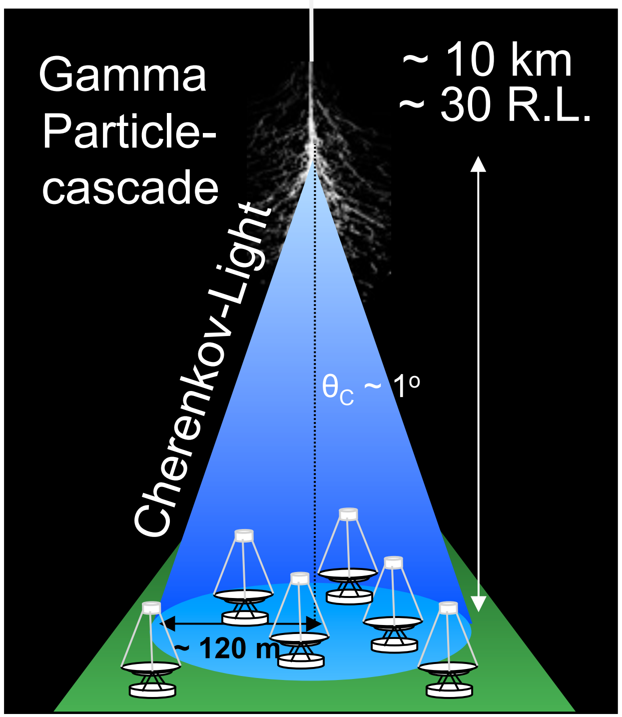
n = refraction index

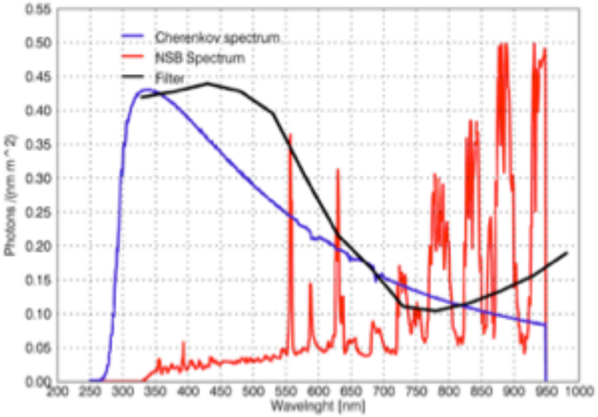
$\beta > 1 / n$

$\cos \theta_C = 1 / \beta n$

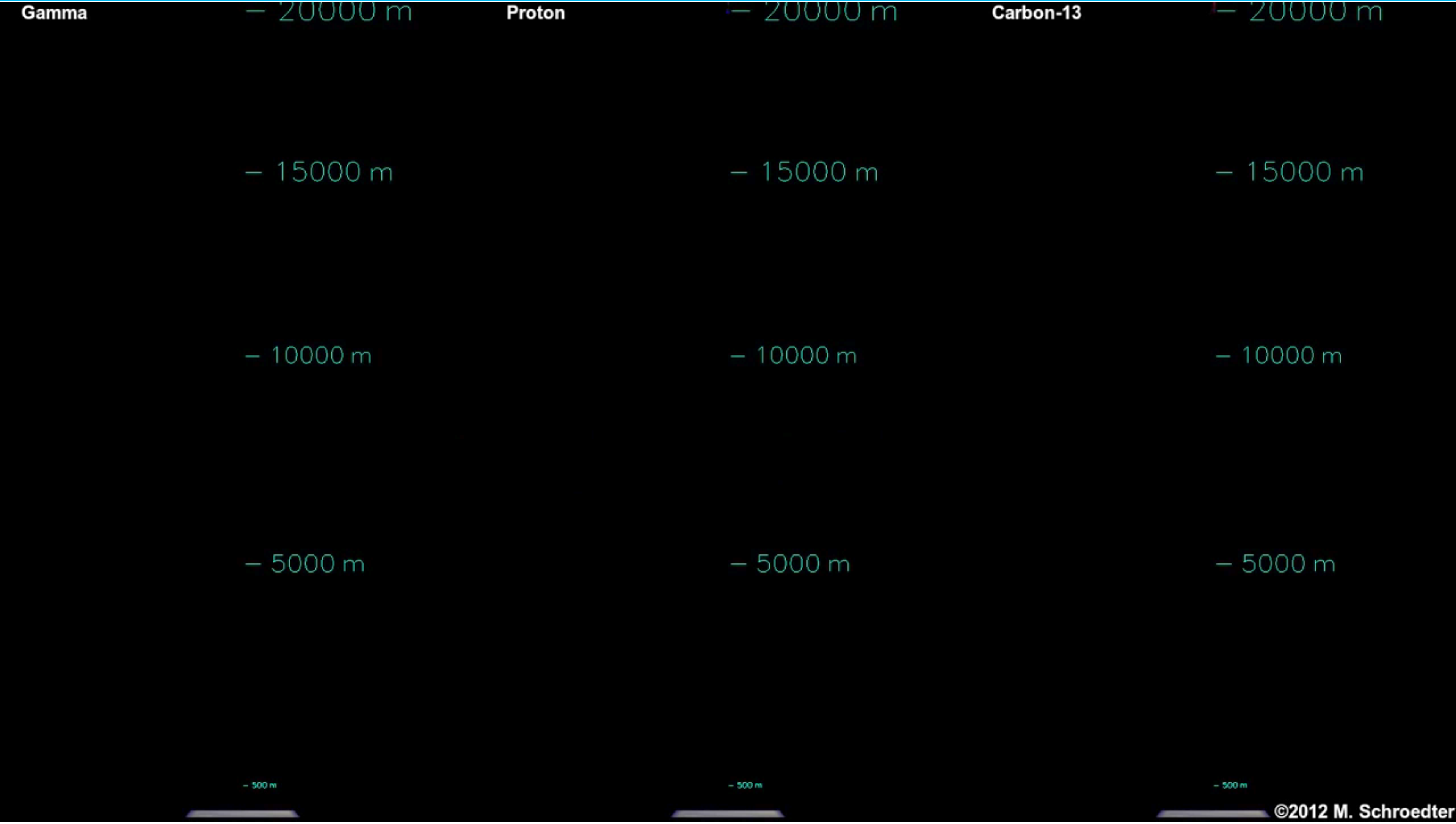
Cherenkov light from atmospheric showers

- Cherenkov angle:
  θ_C = 1.3º at sea level
  θ_C = 0.5º at 10 km
- Air yield =
  100 ph / m at sea leveL
  8 ph / m at 10 km
- Light pool lateral spread ~ 120 m
- Light temporal spread ~ 3 – 5 ns
- Photon density:
  3 m^{-2} at 100 GeV, 30 m^{-2} at 1 TeV
  proportional to E_γ
- Spectrum:
  ~ λ^{-2} above ~300 nm
- Image size ~1º , structures ~0.2º
- Night sky background photon flux
  10^{12} ph / m^2 / s / srad



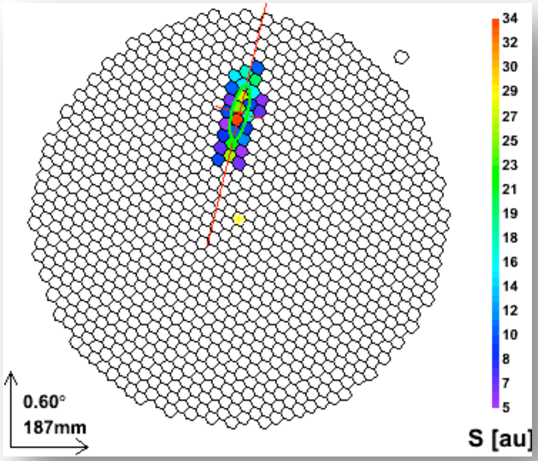


Anatomy of an air shower

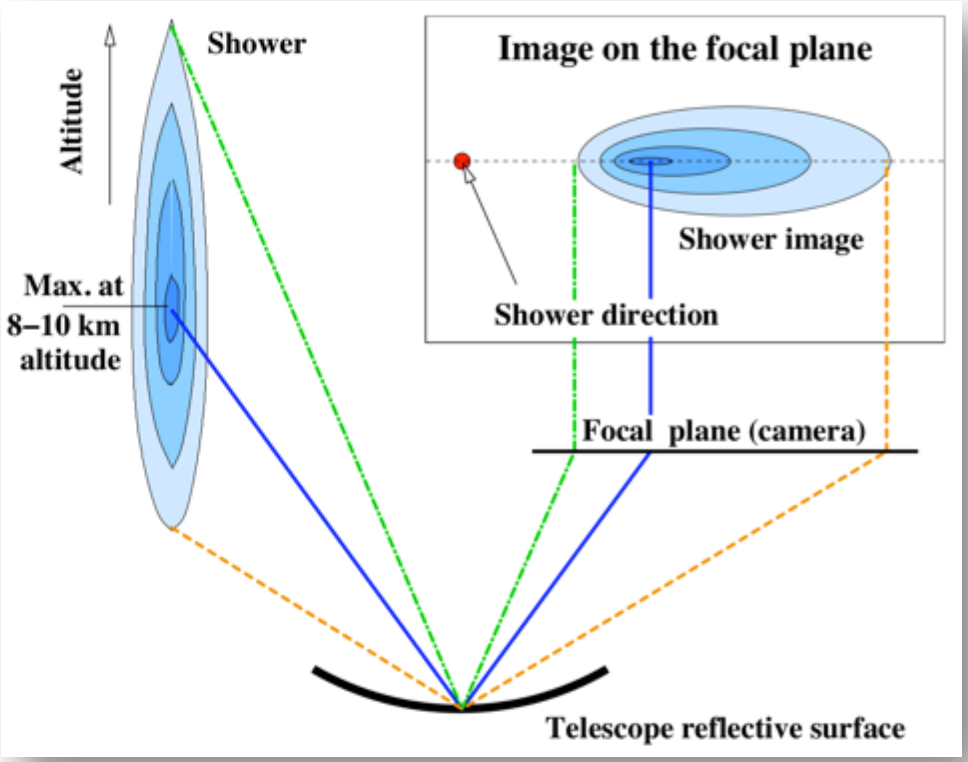


Imaging atmospheric showers

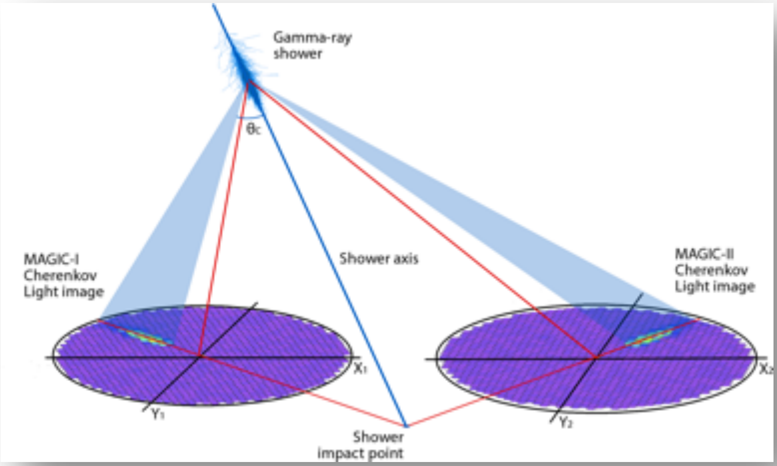
Image parametrization



Geometry of the shower image

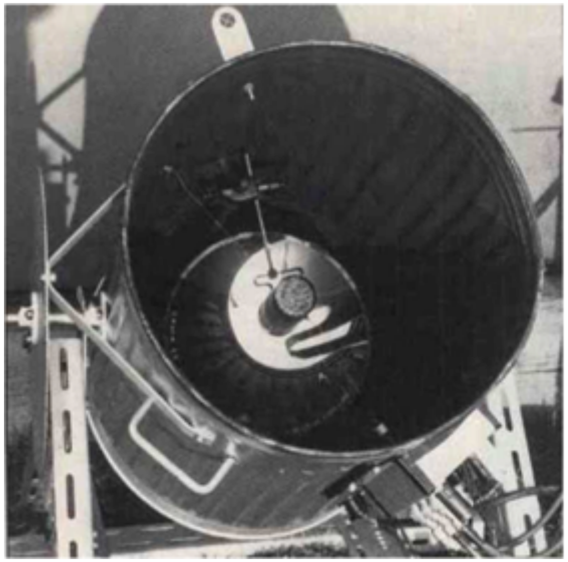


Stereoscopic reconstruction



Interesting past

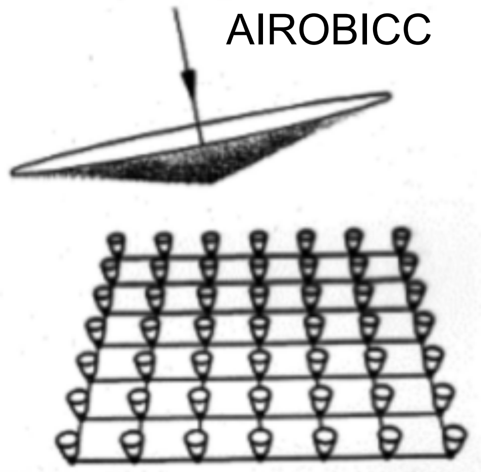
- "Pioneering" age of ground-based Cherenkov astronomy
  - Galbraith and Jelley (1954): First detection of Atmospheric Cherenkov light (with trashcan)
  - Crimea 1960: First array of Cherenkov detectors
  - Several others in the 60s, all cameras where single-pixel
- First source discovered only in 1989 by Whipple! With imaging!

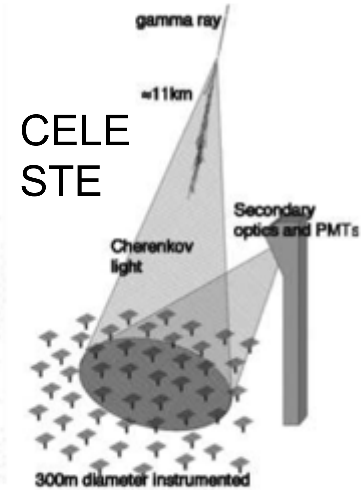


Original Whipple Camera

Interesting past 2

- Wave-front detectors using solar concentrators in the 90's

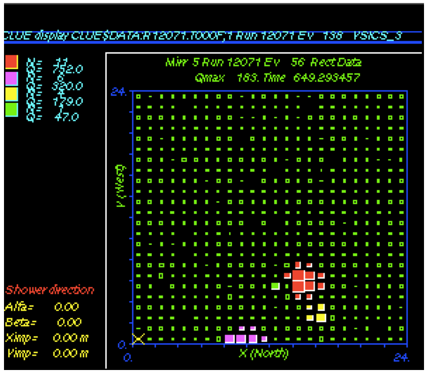


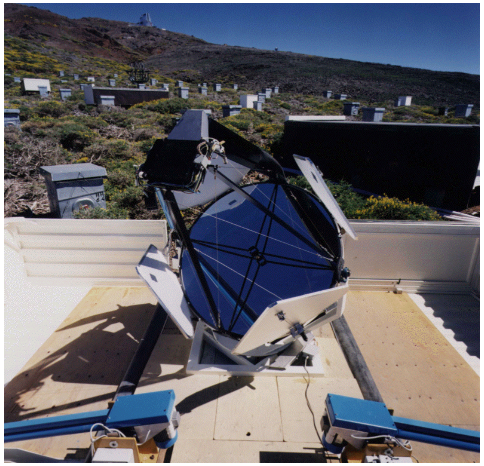


- Unconventional approaches, CLUE:
  UV telescope with a MWPC as camera!

TMAE, $C_4H_{11}NO$ +
Ethane:Isobutane (3:1)

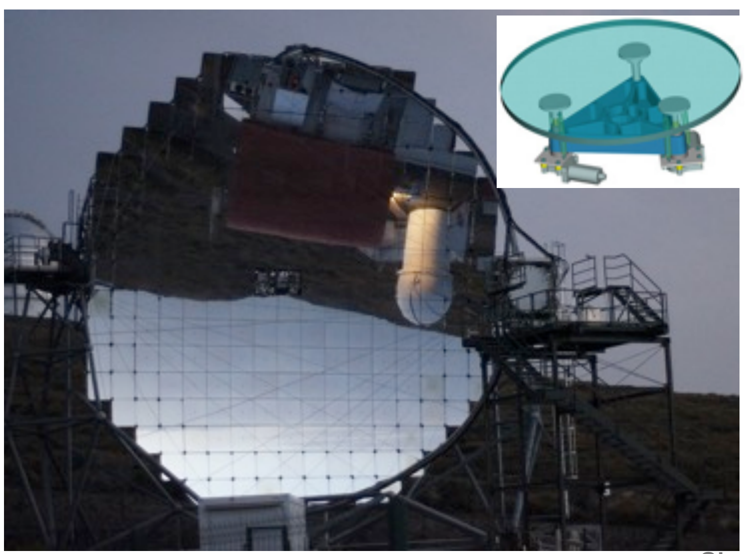
Sensitive to 180-240 nm
But UV absorption was too big!





Building blocks of a contemporary Imaging Atmospheric Cherenkov Telescope

Structure

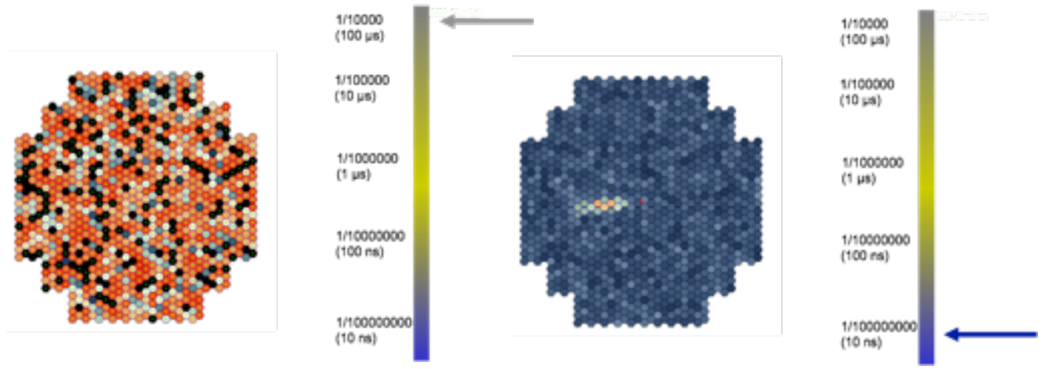


Mirrors

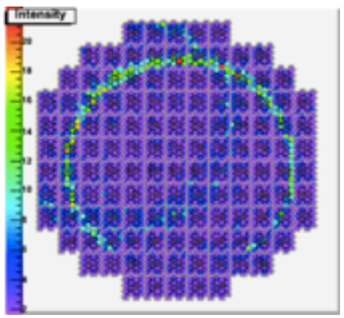
Camera

The backgrounds of a Cherenkov Camera

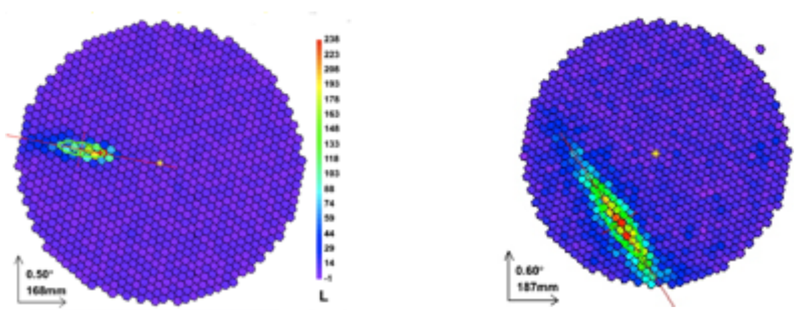
- Night sky background photons
  - Fight them with timing



- Muons
  - Fight them with stereoscopy



- Hadronic showers
  - Fight them with imaging



Camera must be...

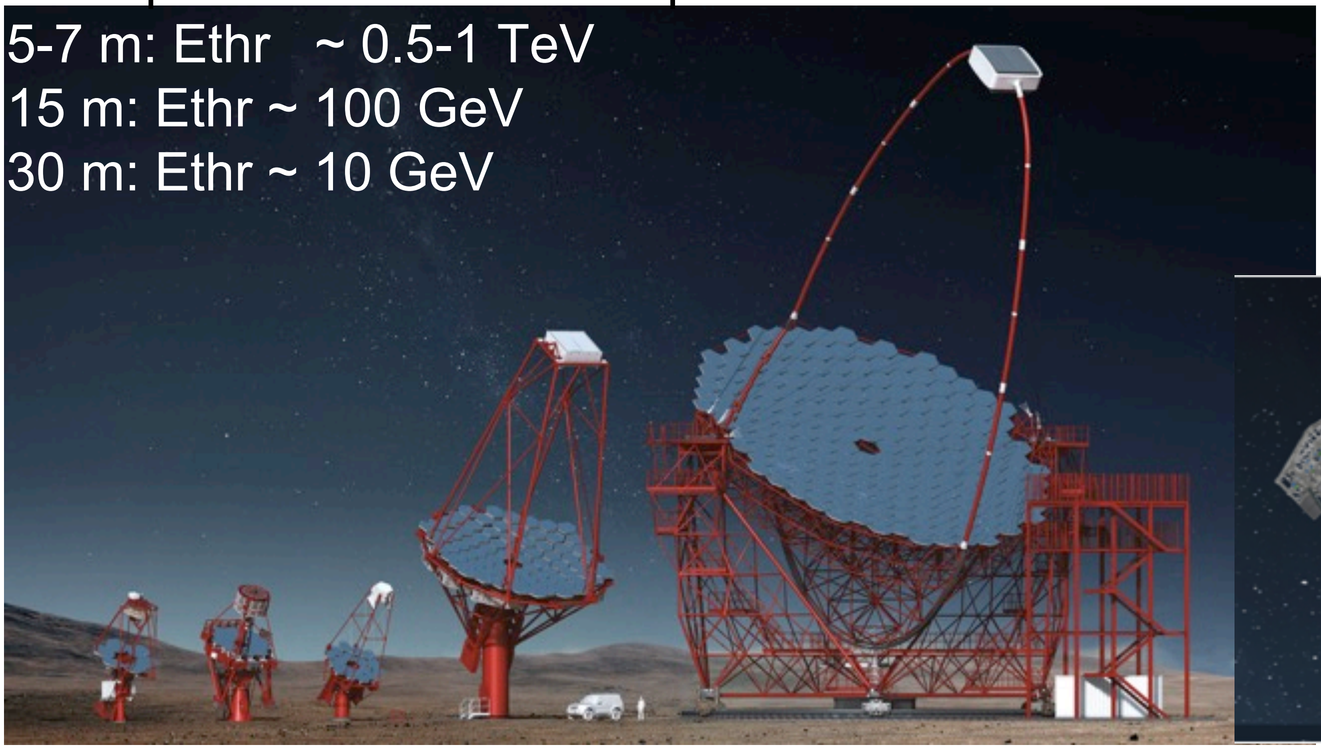
FAST O(10ns)

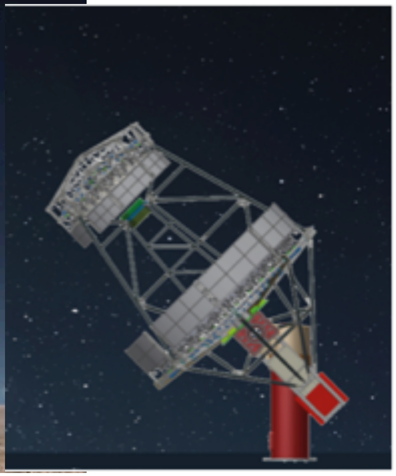
CHEAP O(1-10M€)

PIXELISED O(0.1º)

Cherenkov Telescopes: Size Matters!

> Example of different telescopes: size matters!



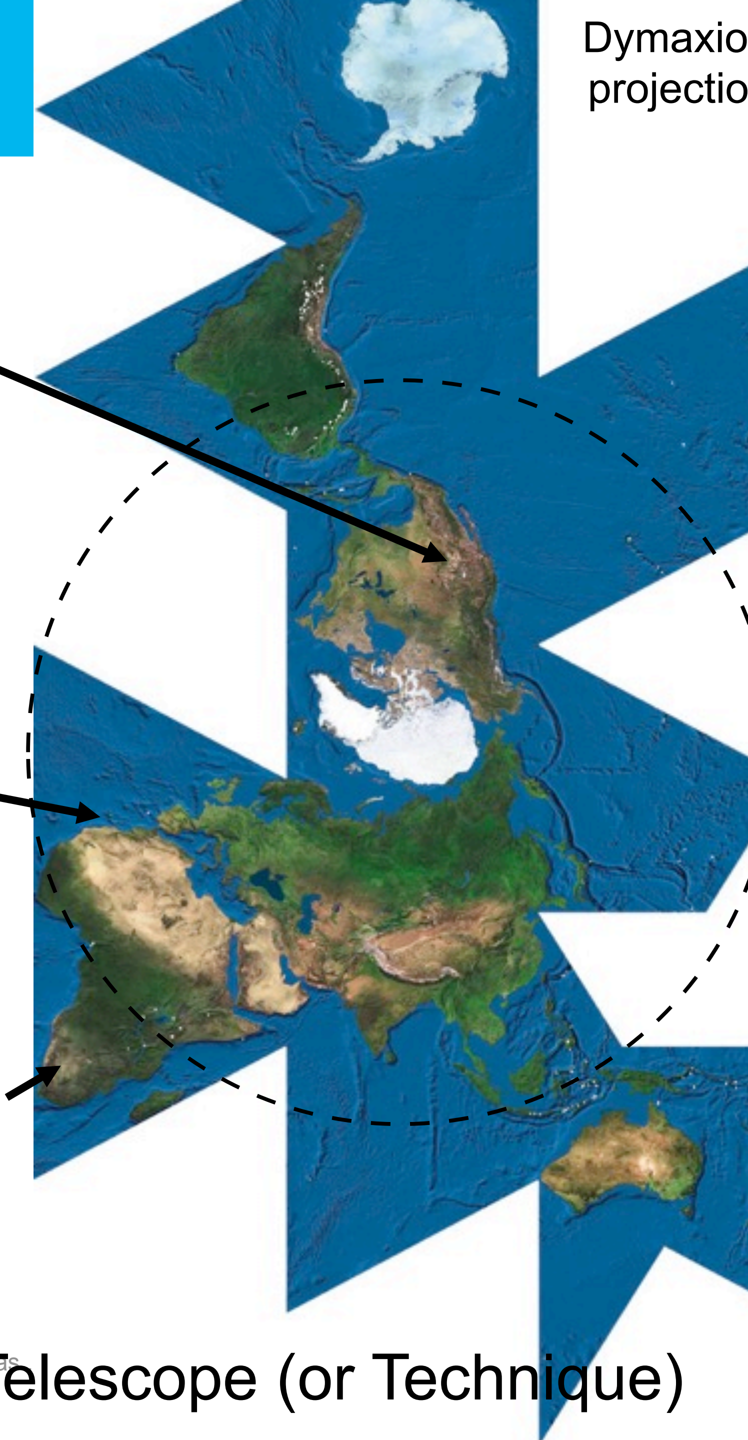


> Pixel size ~0.1º: large telescope -> large pixels

> The bigger the telescope and FoV, the bigger the camera.

> Double-mirror Schwarzschild-Couder telescopes "solve" this size issue

Current IACTs arrays



IACT: Imaging Atmospheric Cherenkov Telescope (or Technique)

General working principles of a Cherenkov camera

- Photons collected by fast detectors
- Converted into electrical signals which are digitised and forwarded to back-end

} **Front-end**

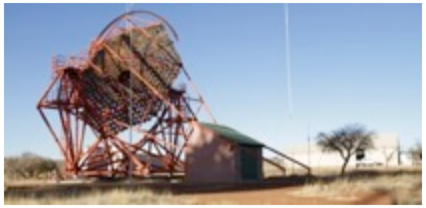
- Camera trigger generation
- If trigger is present, an event is built, its data is stored.
- Power, network distribution

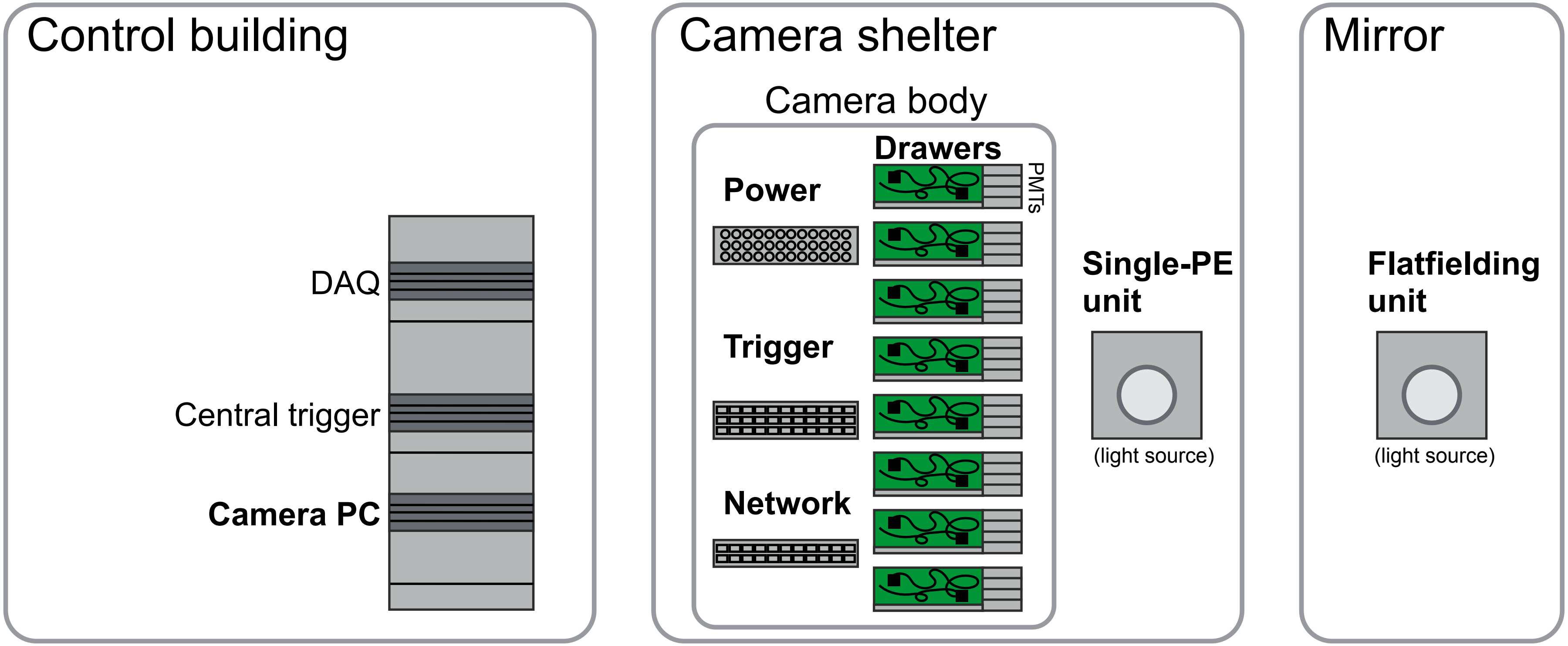
} **Back-end**

- Reference calibration light pulsers
- Cooling system
- Safety systems

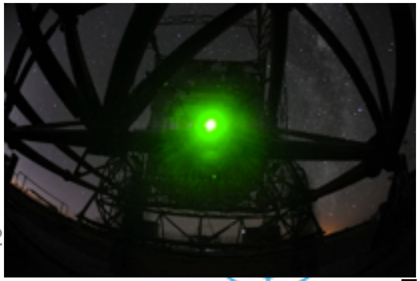
} **Auxiliary**

Example of a Camera: HESS-I upgraded camera

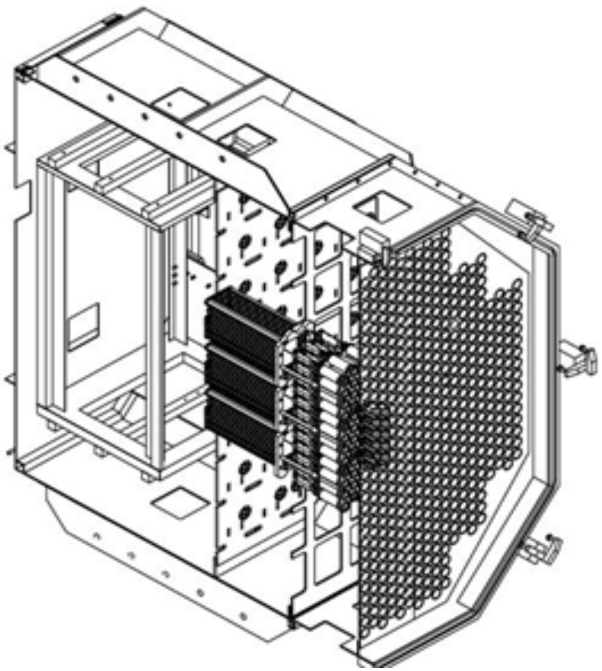





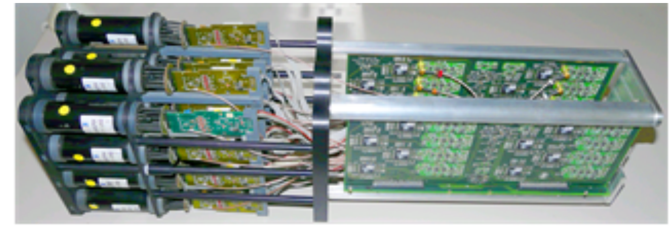


Example: HESS-I Front-end

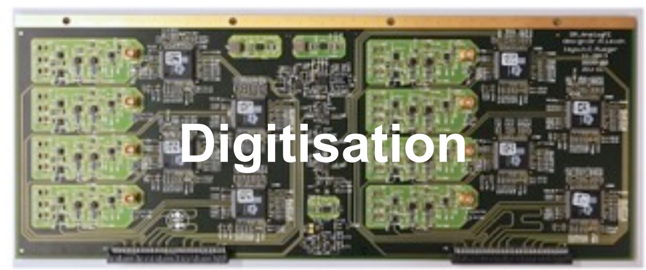
- Light detection, sampling and readout.



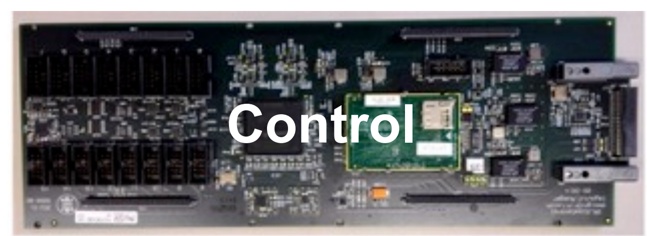
Half section of camera body showing the front-end modules.



Drawer with 16 PMTs, 2 Analog Boards, Slow Control (SC) Board



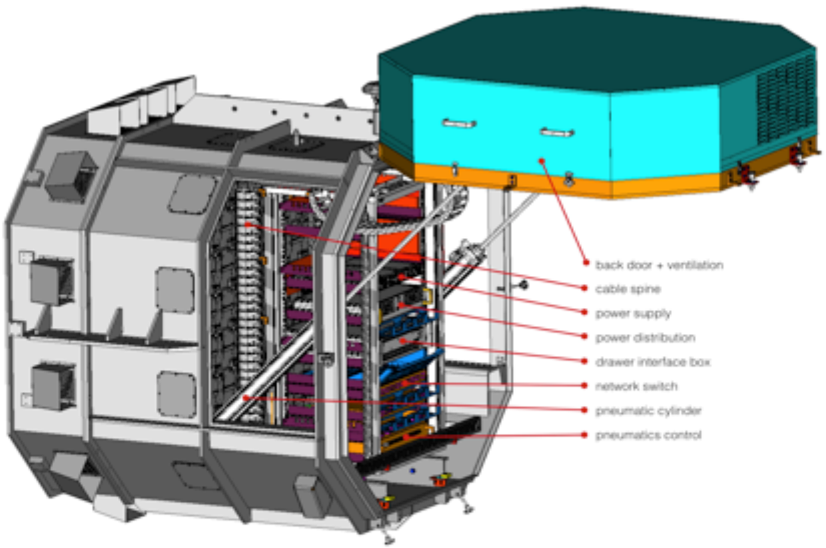
Analog board with NECTAr chips



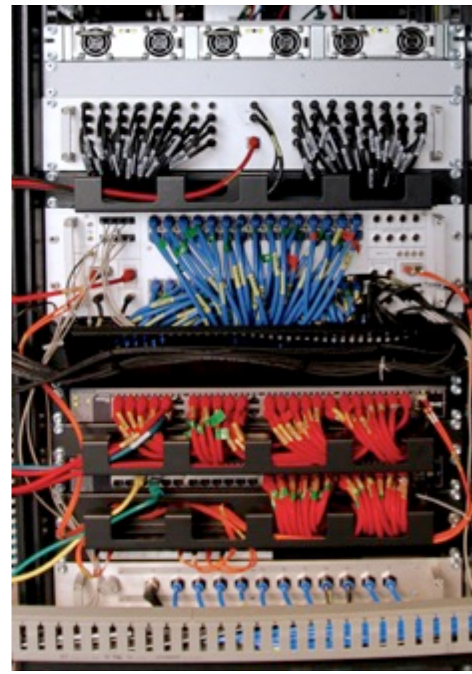
SC board with FPGA + ARM

Example: Back end

- Trigger, power, cooling, network and cabling



- Back-end rack



24 V Power supply

Power distribution

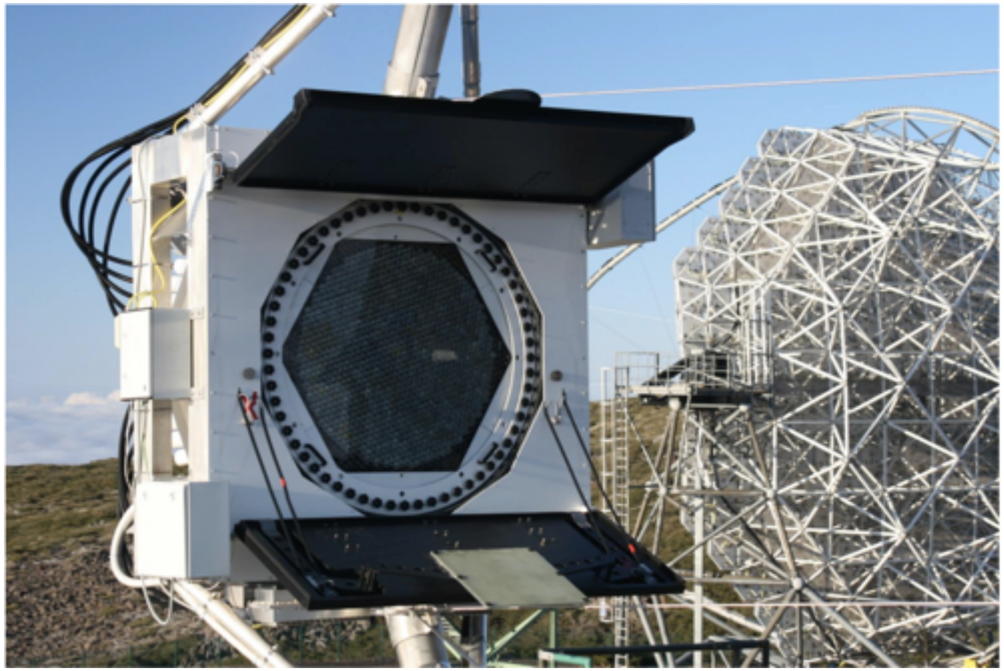
Drawer interface

Data network switch

Pneumatics control

Fully open camera showing the back-end rack. The ventilation unit is inside the back door.

Distincion can be blurry: case of MAGIC



"Thin" camera: only photodetectors

"Thick" back-end: everything else

Analog signal over light fibre

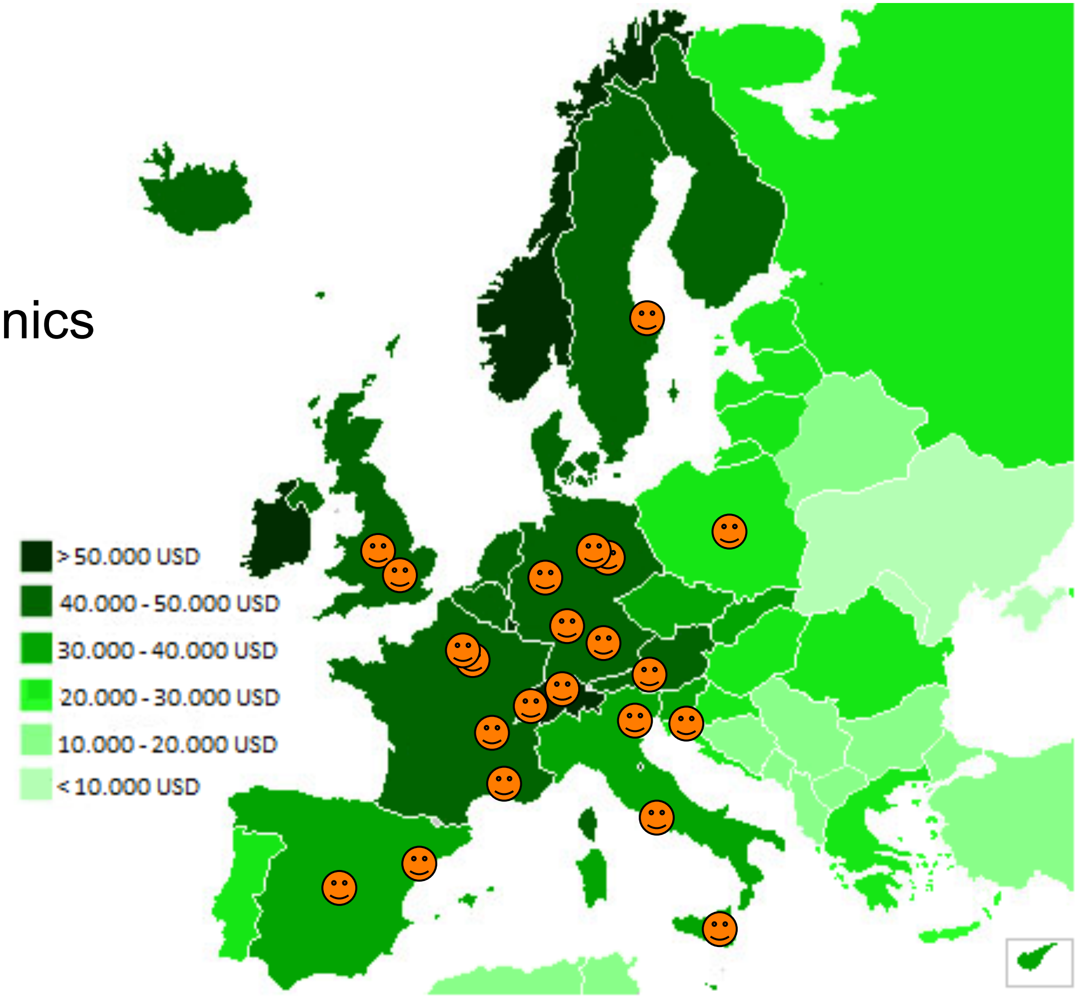
Build-your-own Cherenkov Camera: everybody's doing it

Follow the path of the signal:

- Light concentrators
- Photodetectors
- Low-noise Amplifying electronics
- Readout
- Trigger

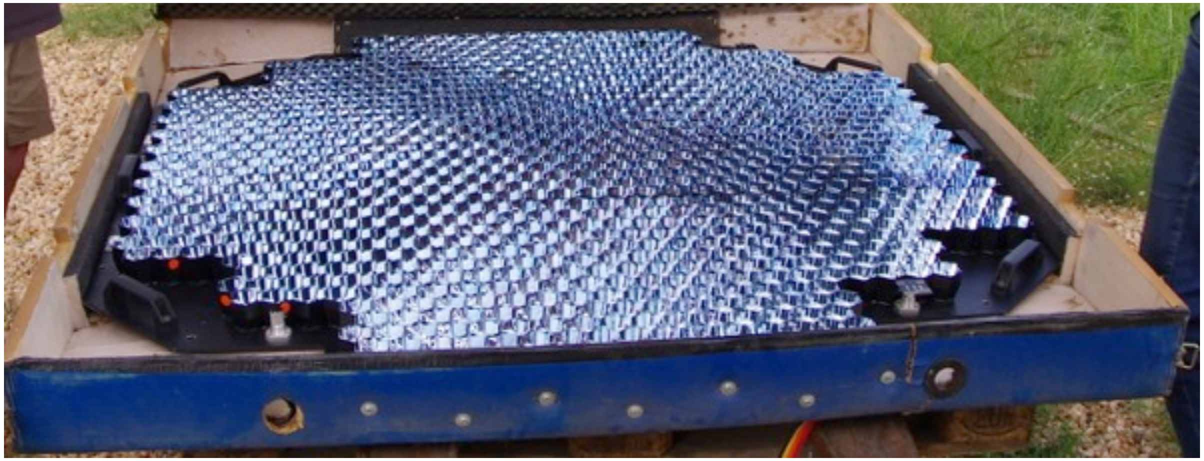
Other important parts

- Enclosure & Cooling
- Calibration devices
- Timestamping

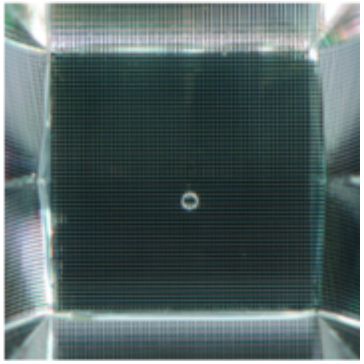


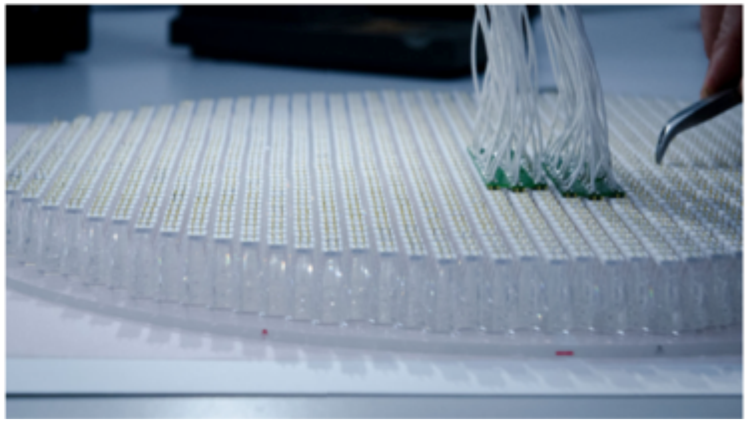
Light concentrator (if any)

- Hollow: "Winston cone" (HESS, MAGIC, many CTA ...)



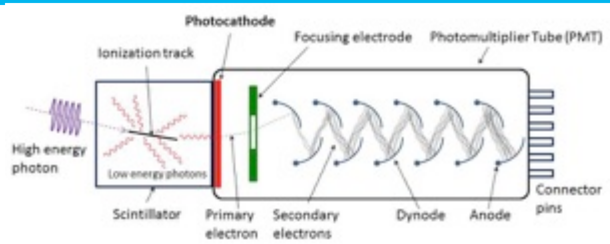
- Filled (FACT)

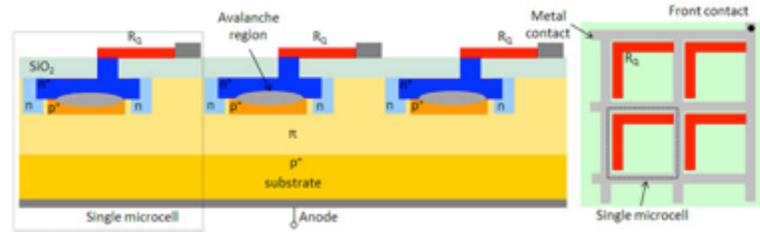




- Similar transmittance, 80-90%

Photodetectors: PM Tubes vs. Si-PM



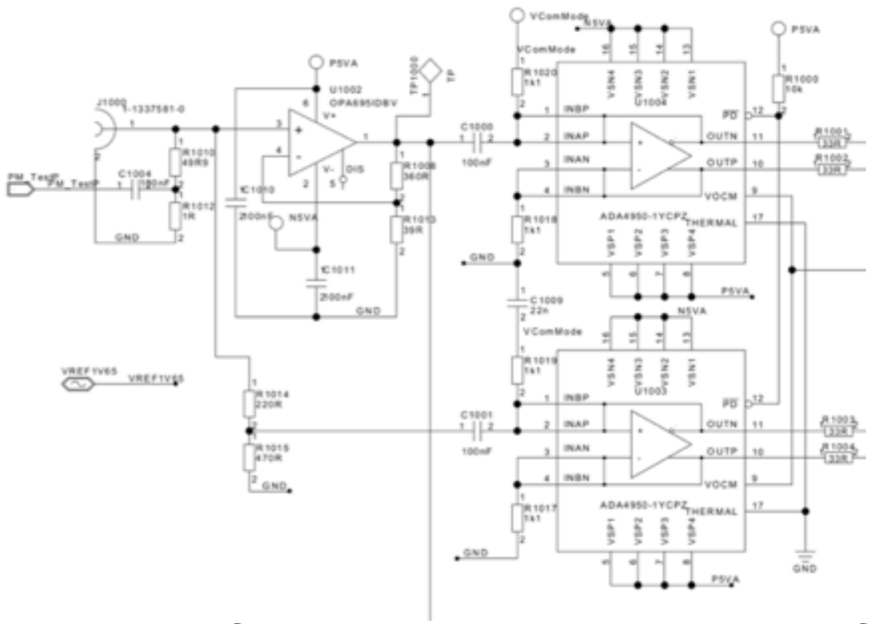


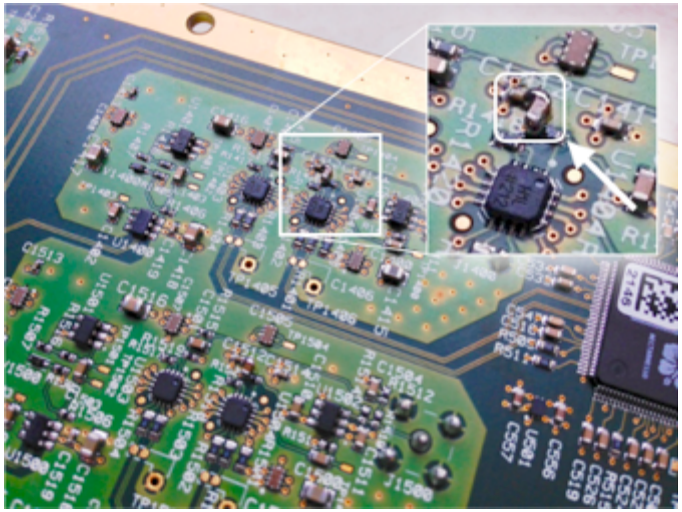
	PMTs	G-APDs
Devel. Status	Well understood	New
Shock resistance	Fragile	Resistent
Ambient light	Fragile	Resistent
Voltage required	>1000 V	< 120 V
Photo-detection e	35-40% @ 350nm	45-60% @450nm
Temperature dep.	None	Gain and noise
Size	**few mm – few cm**	**~ few mm**
Rise time	fast ~1.5 ns	faster ~ 100 ps
Dark count rate	low (~10/s)	high ~1000/s
Optical cross-talk	none	can be relevant

Here's 1 hour video about this: https://www.youtube.com/watch?v=d6y-6YjoRCU

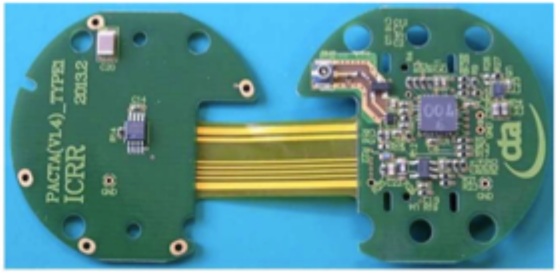
Low-noise amplifying electronics

- Single-photon signals from photodetector need to be amplified and sometimes shaped to adapt to readout.





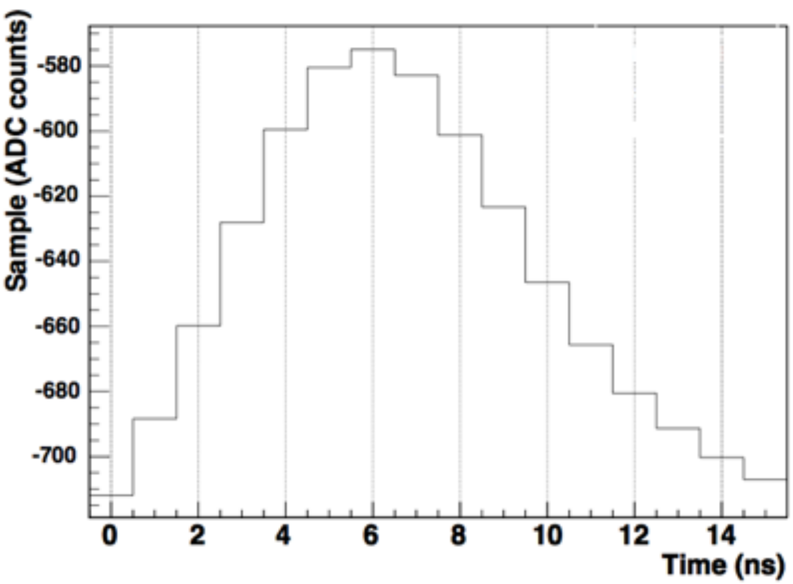
- Transition from discrete analog amplifying circutry to integrated ASICs



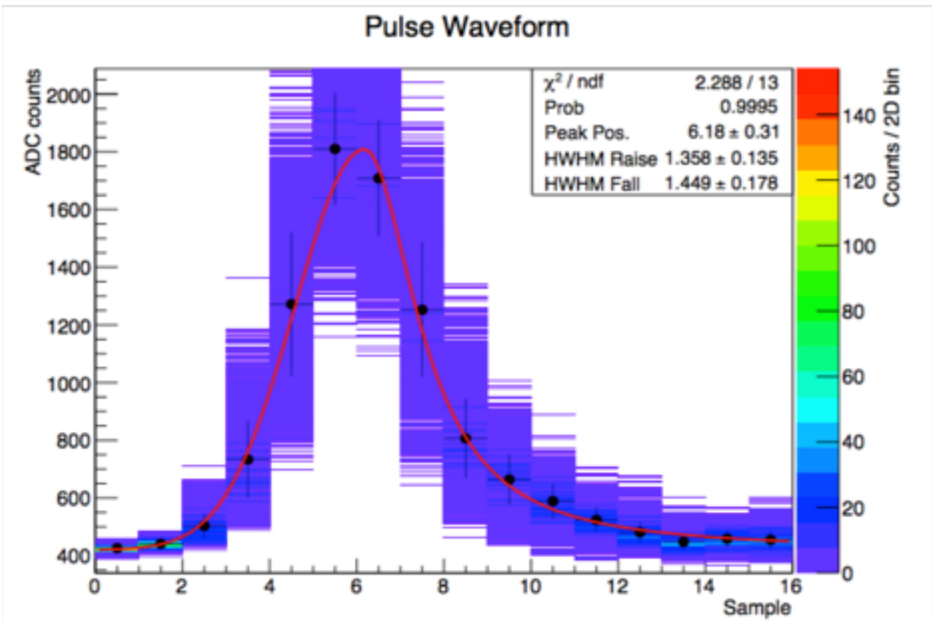
Bandwidth of amplifiers

- High bandwidth is almost always beneficial
- Can reduce time constant for signal integration -> less noise from NSB
- Makes design more sensitive to electronic noise
- Nyquist theorem: BW*2 ~ Sampling rate

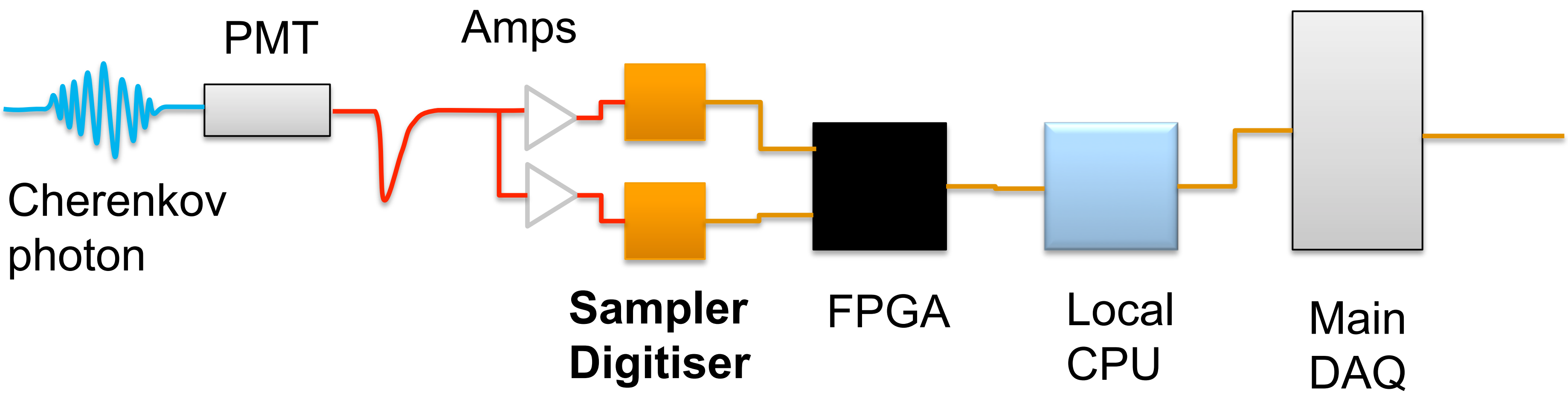
80 MHz



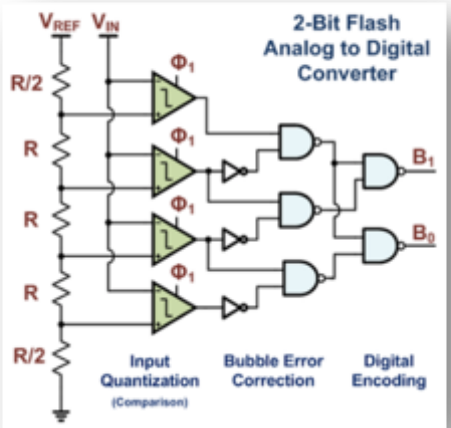
330 MHz



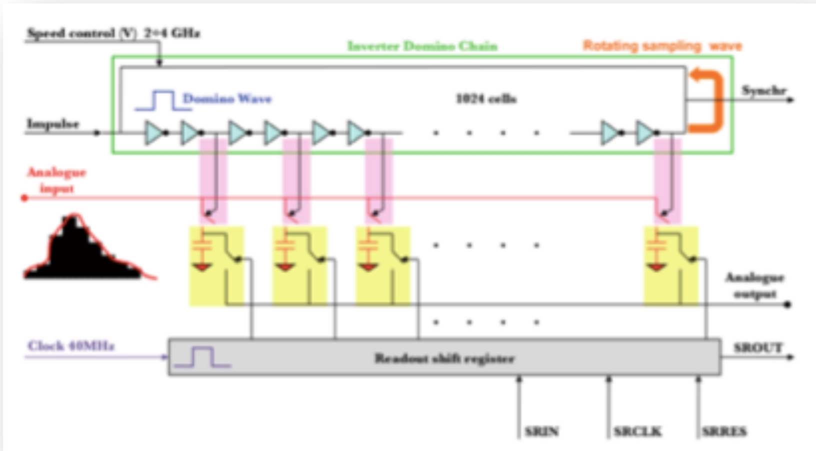
Readout scheme



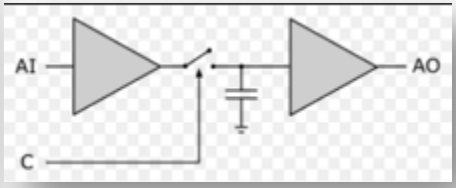
Traditional Flash ADC



Switched capacitor array (analog ring sampler)



Sample-and-hold

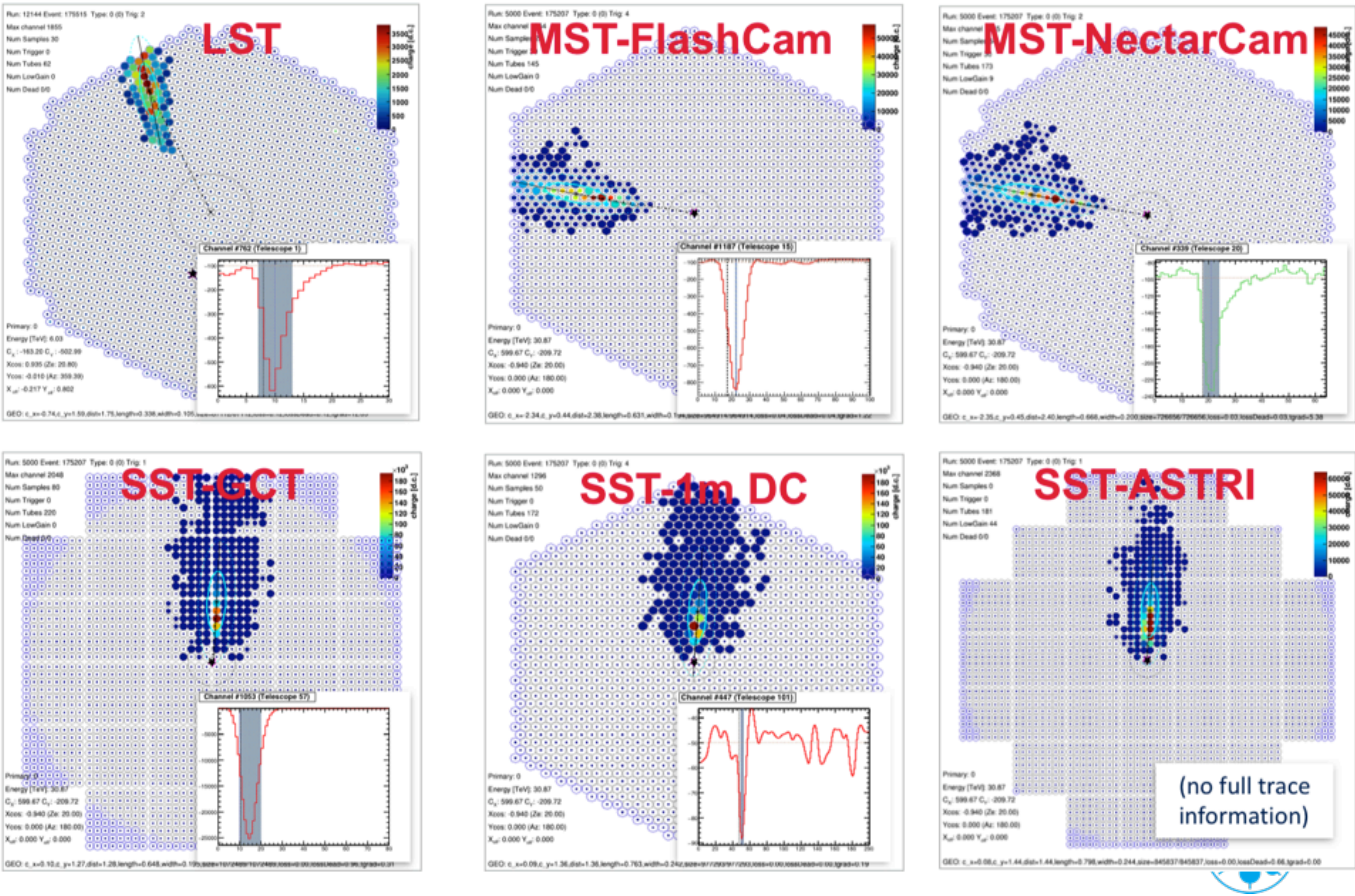


Readout types comparison

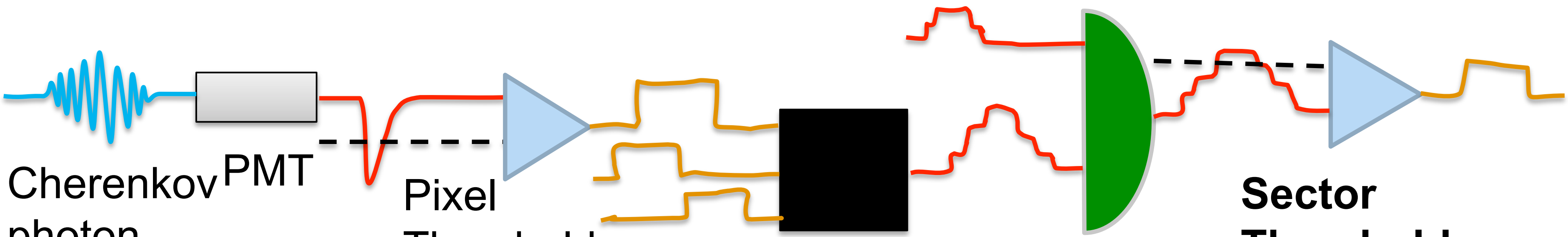
	Flash ADC	Analog Ring Samplers	Sample-and-hold
Cost	Expensive	Cheap	Cheap
Power req.	>100 mV/ch.	~10 mW/ch.	<10 mW/ch.
Dead-time	None or low	~10 µs	~ 100 µs
Dynamic range	0.1-2000 pe logarithmic	0.1-2000 pe 2ch. linear	1-2000 pe
Bandwidth	150-300 MHz	~400 MHz	?
Sample rate	0.25-2 GS/s	1-2 GS/s	n.a.
Usage	Easy	Tricky	Tricky
Max Rate	>50 kHz	>10 kHz	?

Tricks for F-ADC cost reduction:
use multiplexer, lower sampling rate, or use non-linear response

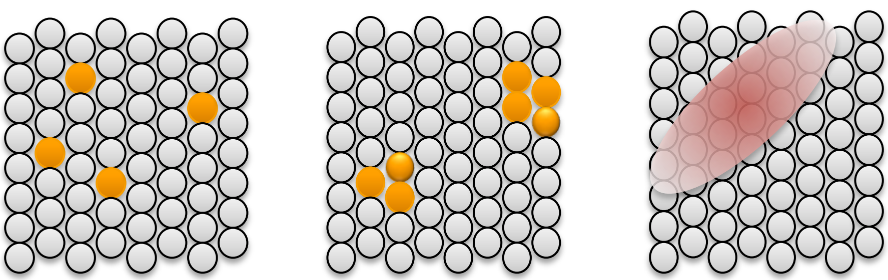
CTA readout simulations, courtesy of Gernot



Camera Trigger types



Trigger: pattern seen in few (<6 ns)

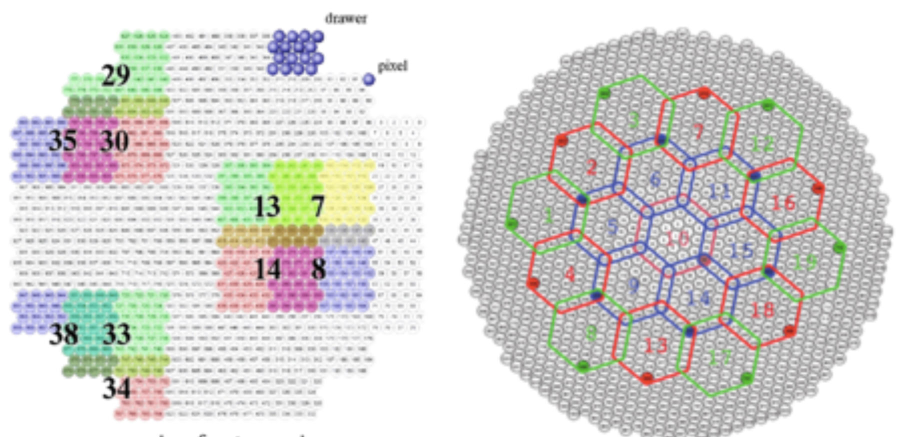


Majority (digital)

Neighbour (digital)

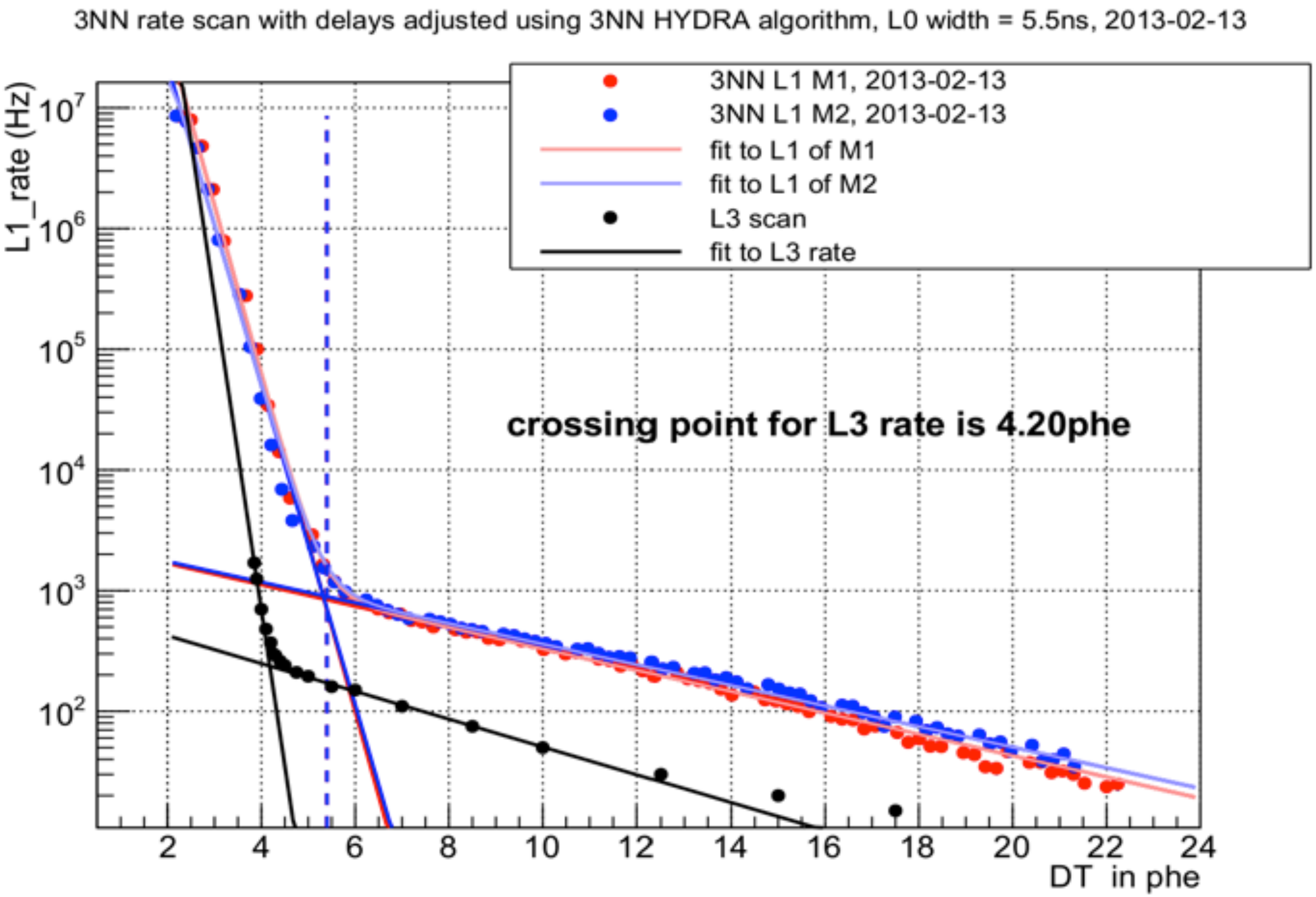
Sum (digi or analog)

Sector, or Macrocells in camera



Array-level trigger: time coincidence, gate ~80 ns, dependent on FoV.
can be even implemented in software, if camera can buffer latencies of ~1s

Trigger rate scan – a way to evaluate



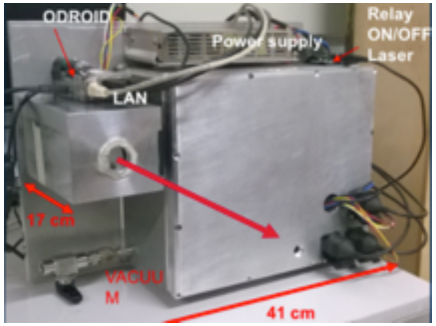
Enclosure and Cooling

- Enclosure and Cooling:
  Water-tight + Water Cooling or Shelter + Air Cooling

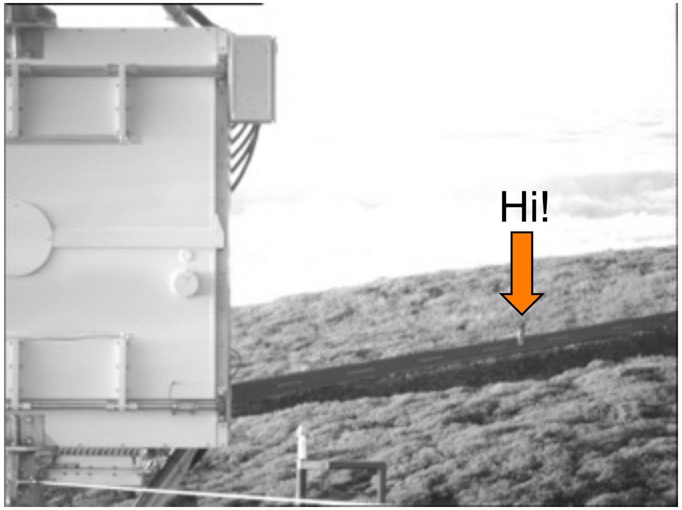
- Usual problems: if water can't get in it can't get out either.

Calibration and timestamping devices

- **Flat-fielding / SPE calibration:**
  - Light pulser (LED or Laser)
  - Diffuser (Holographic or Ulbricht sphere)
  - Attenuator (Filter wheel / Electronic)

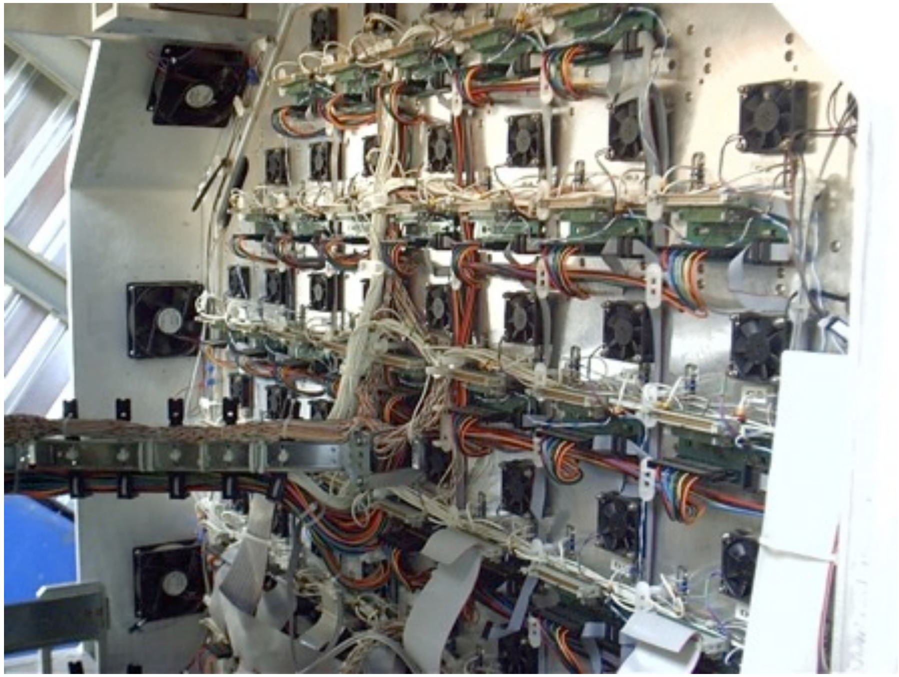
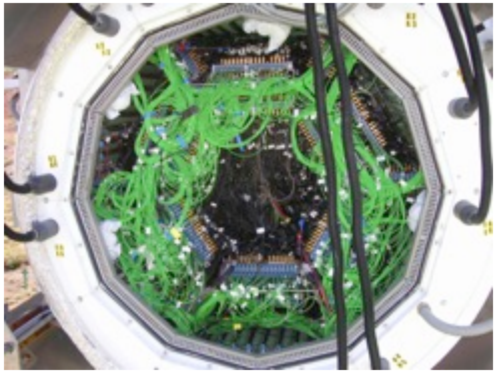


- **CCD cameras / Sky Cameras:**
  - Control and correct the tracking
  - Check the mirror alignment
  - Make bending and pointing models

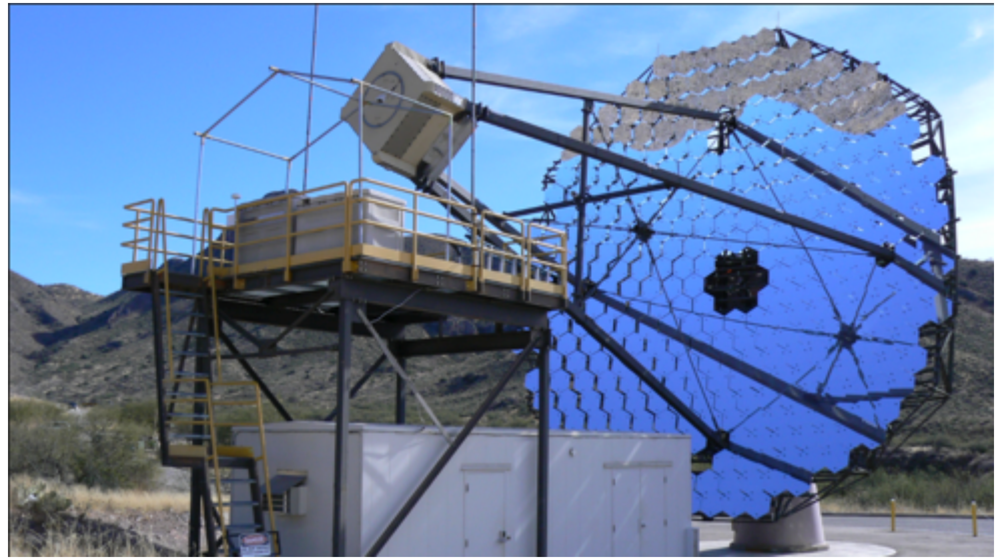


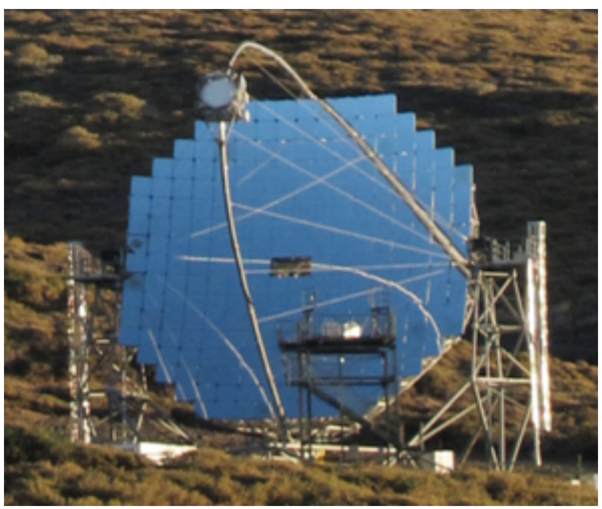
- **Timestamping devices**
  - Camera-internal timestamping: es. Rubidium clock + GPS
  - Distributed time-stamping: White Rabbit ps-level
    advantage: all cameras have same running time -> array-wide timing analysis

Things to look out for: cables and connectors

Things to look out for: working at heights

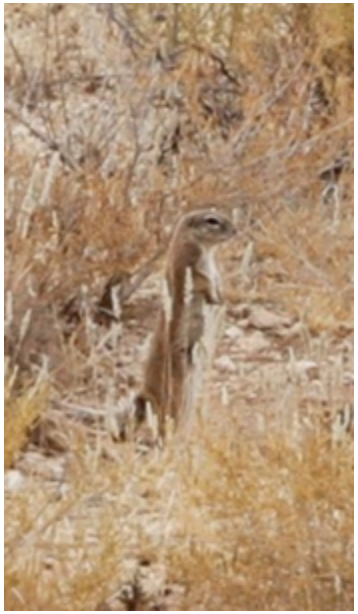




Things to look out for: local fauna





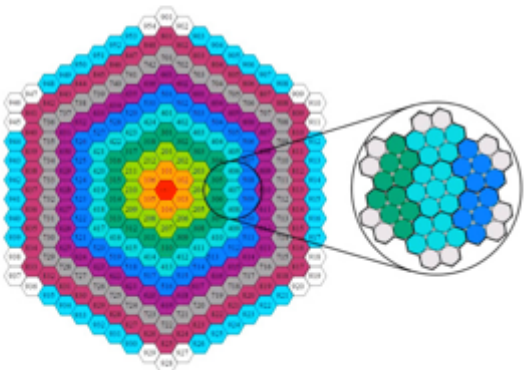



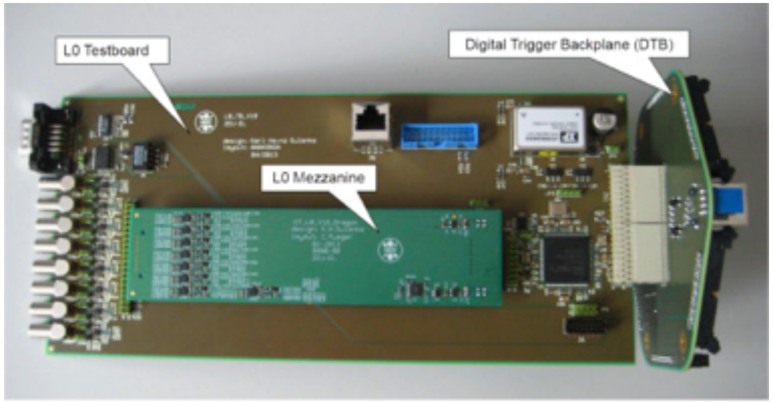

DESY and Cherenkov cameras

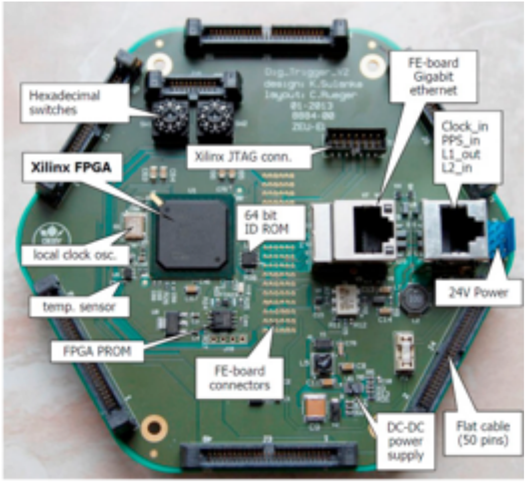
- 4 HESS-I upgrade Cherenkov cameras 2012-2017

DESY and Cherenkov cameras

- Digital trigger for CTA cameras (LST, NectarCam)



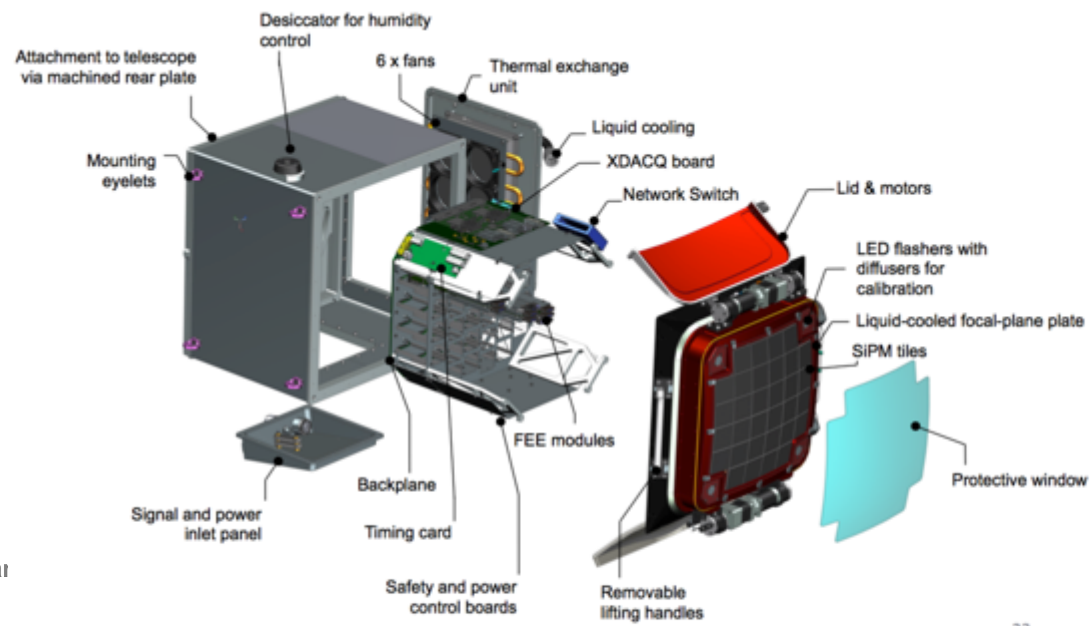




DESY and Cherenkov Cameras: CHEC

- Compact High-Energy Camera for CTA
- Destination: SST telescopes, Chile
- 2 Prototypes ready
- Bid to produce > 20

- Project Scientist: D. Berge



Thank you!

Upgrades of MAGIC and H.E.S.S.

Same motivations:
be better, faster, more reliable

MAGIC upgrade motivations

- Goals:
  - Less noise in readout
  - Easier maintenance
  - Deadtime 10 → 1%

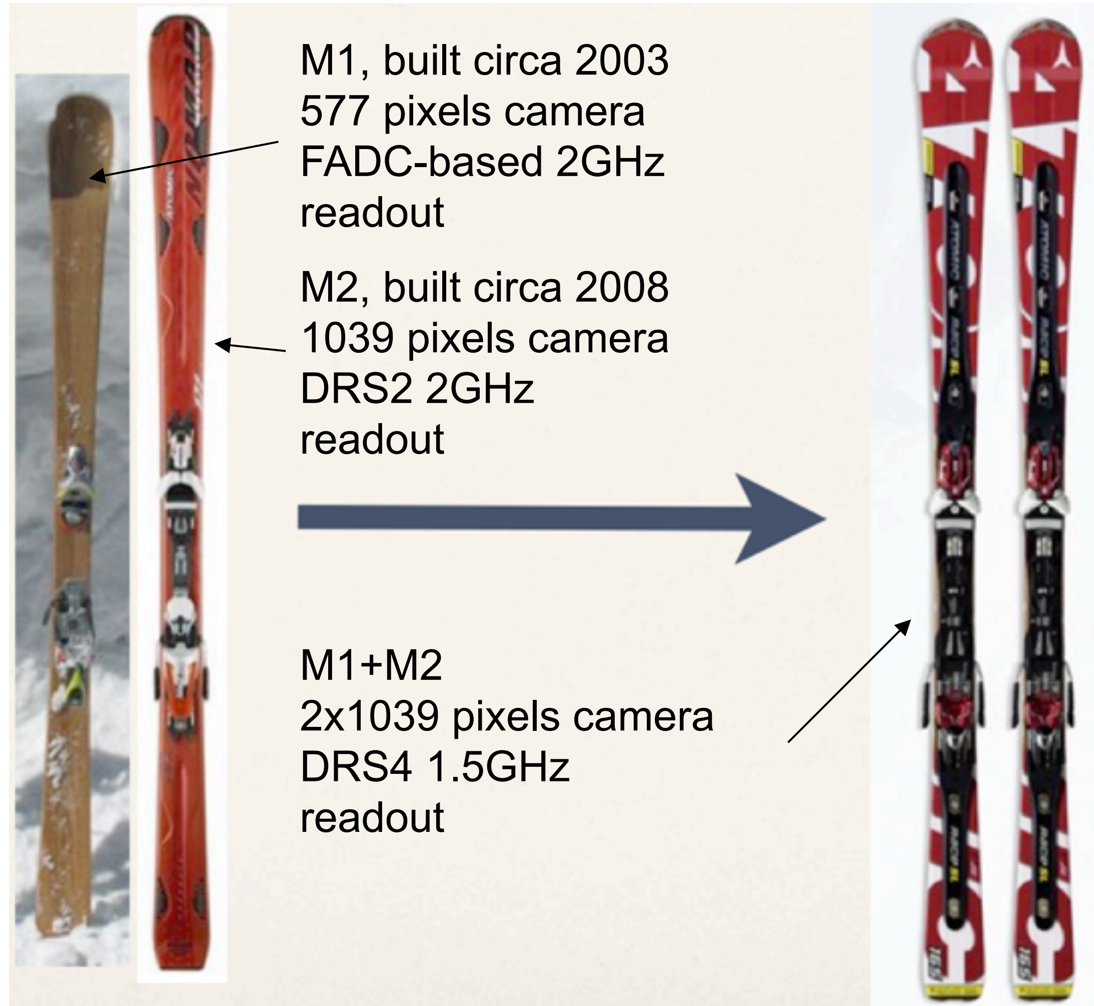
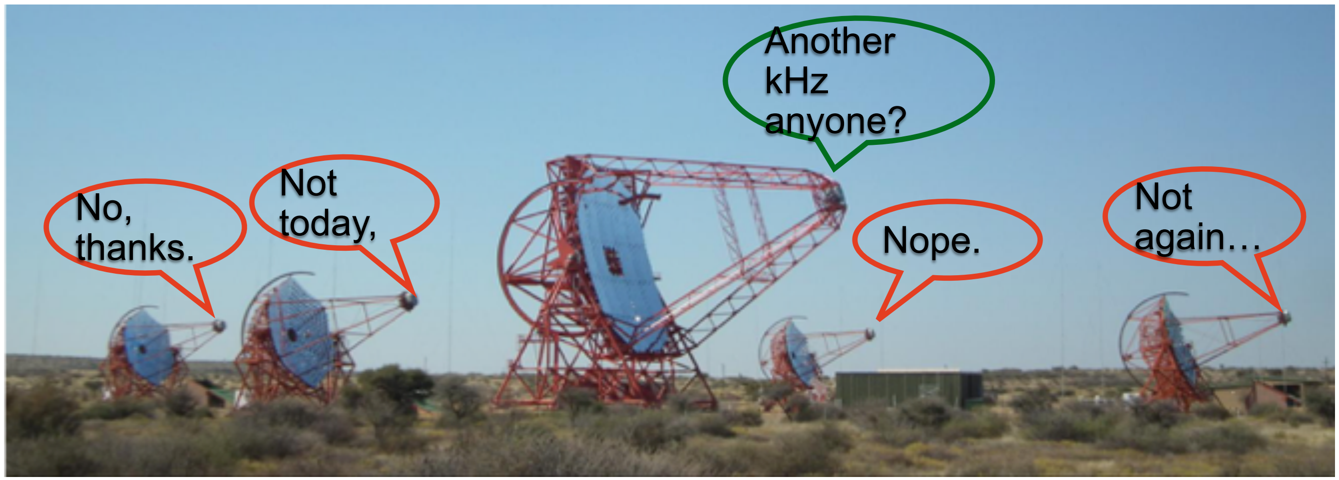


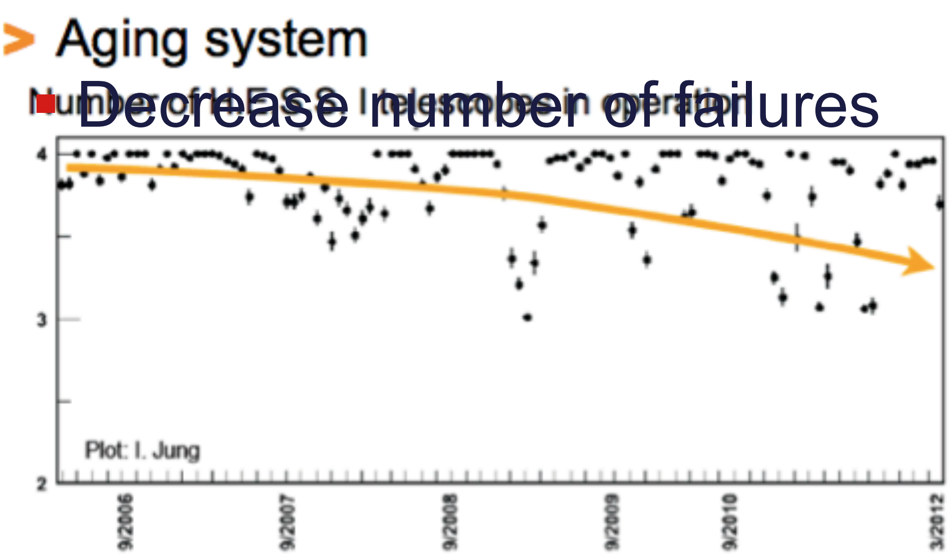
Image courtesy: D. Mazin

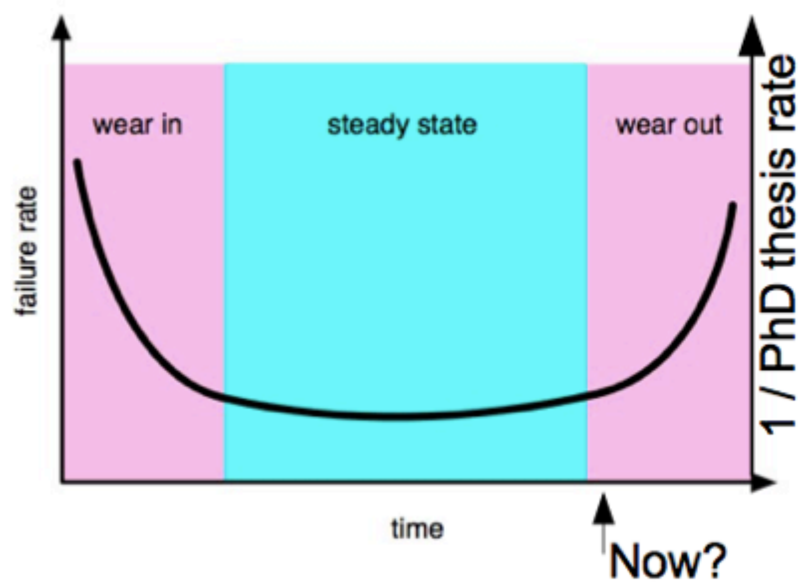
H.E.S.S.-I upgrade motivation

- Decrease dead-time



- Decrease number of failures





Same scope: full camera, camera trigger and readout

MAGIC upgrade scope

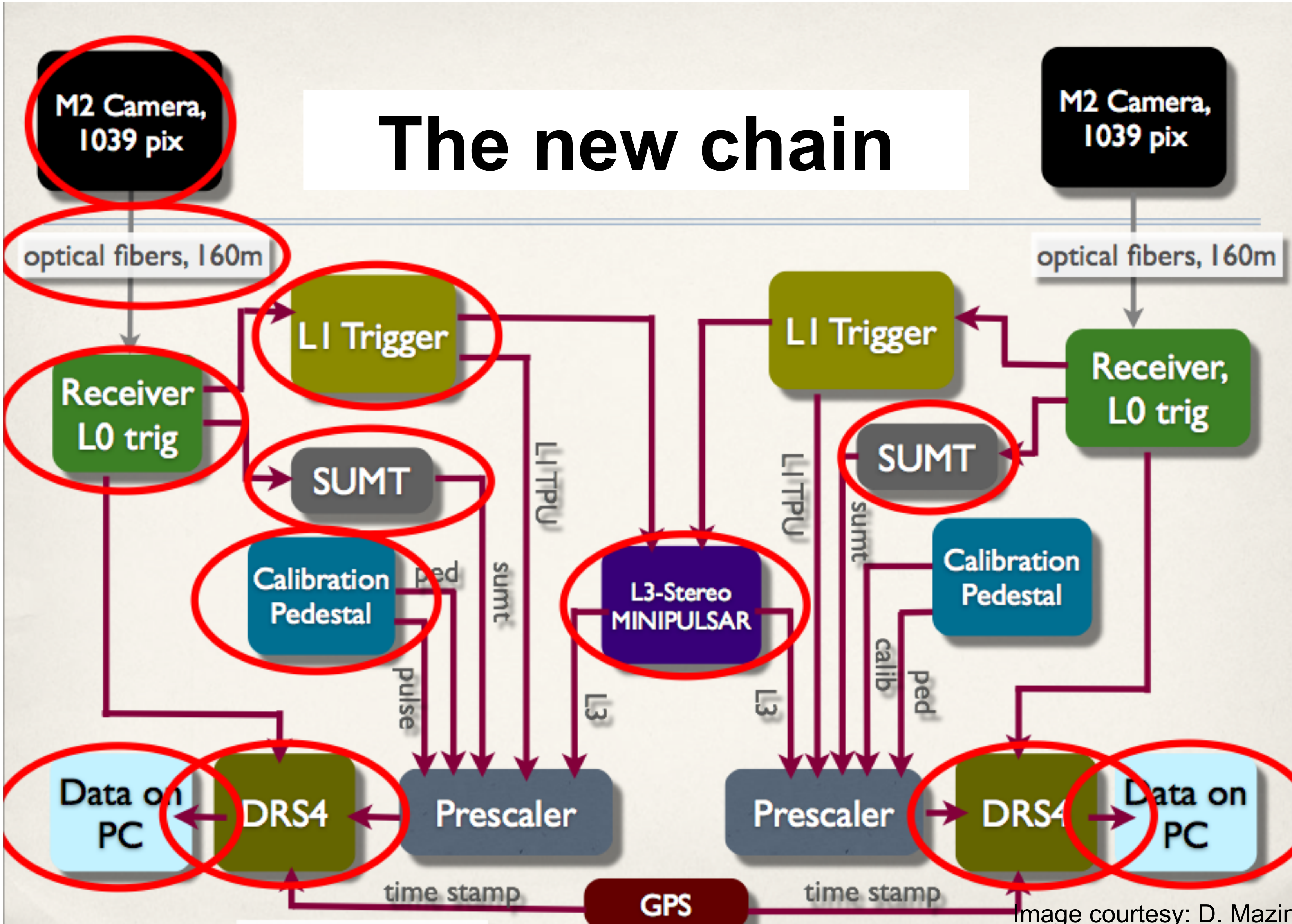
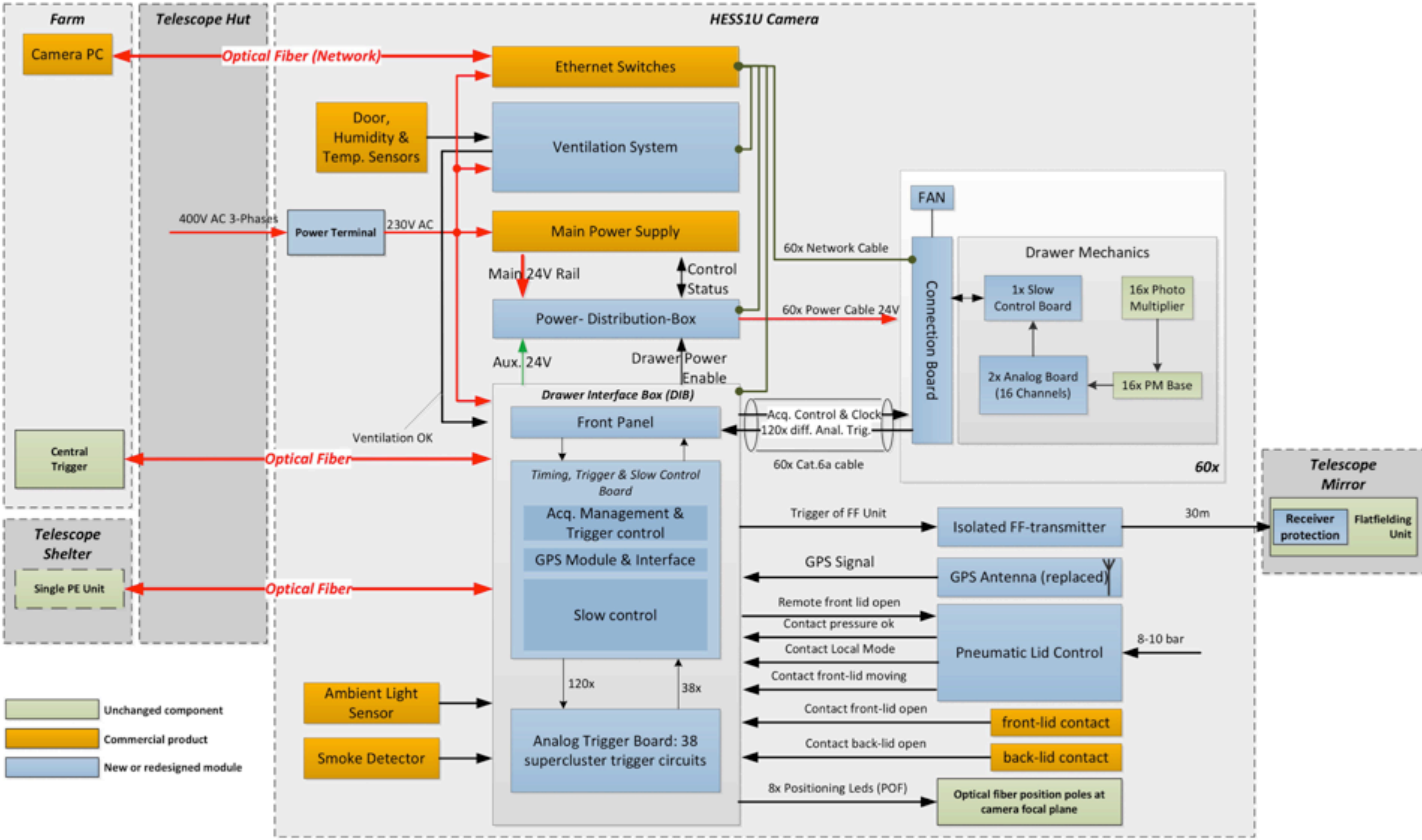


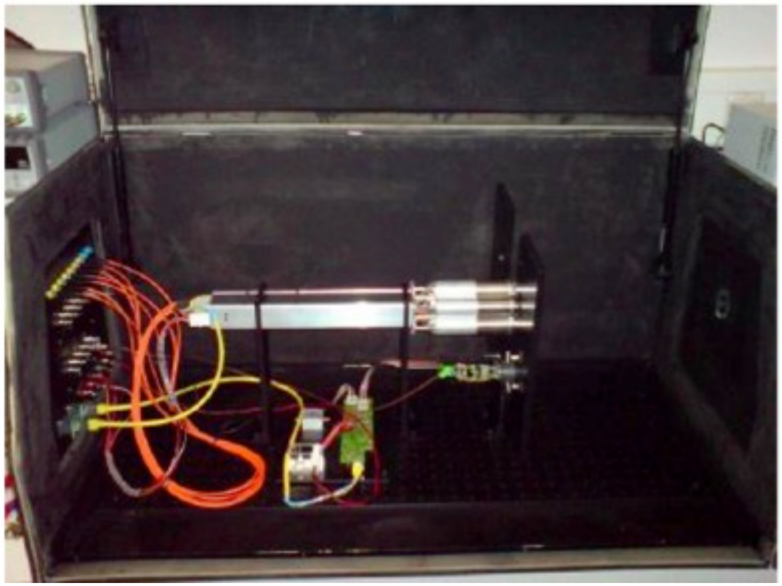
Image courtesy: D. Mazin

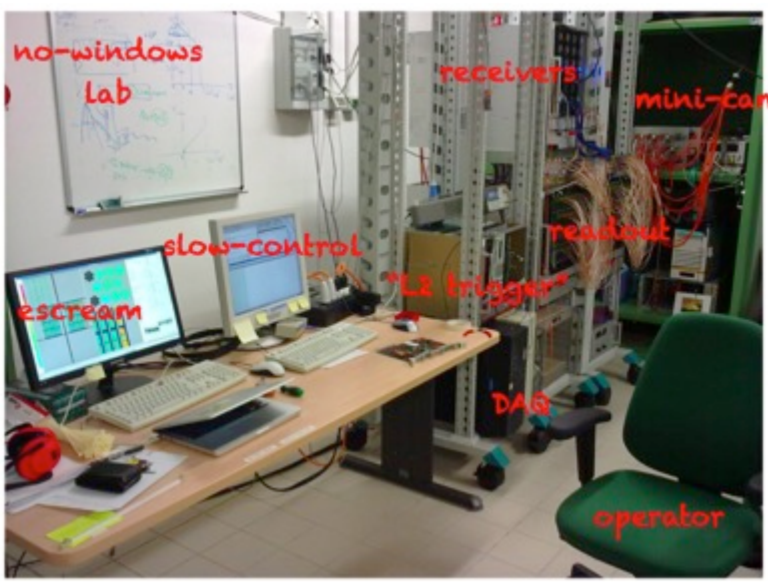
H.E.S.S. upgrade scope



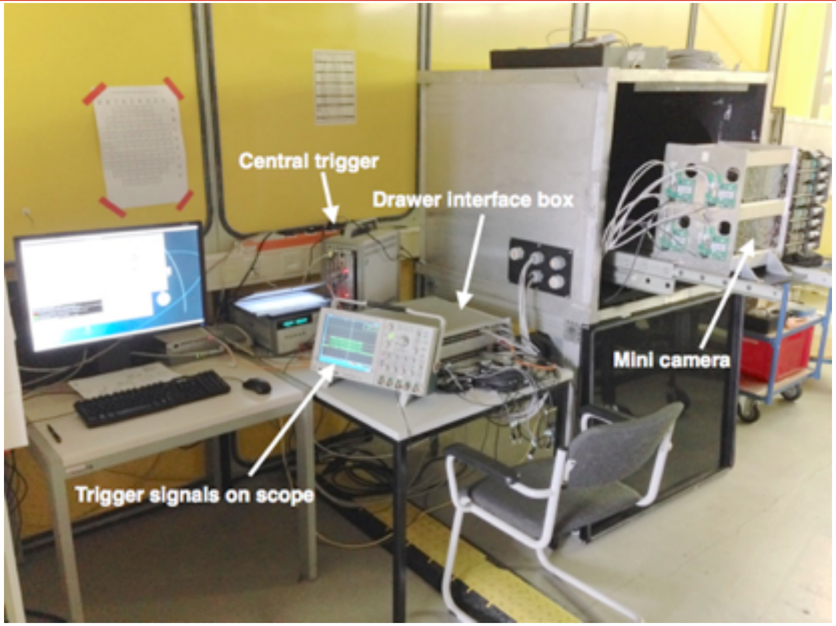
Testing

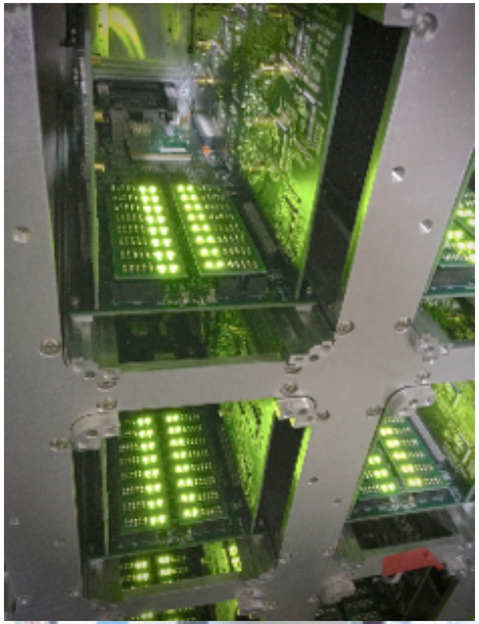
MAGIC upgrade testing

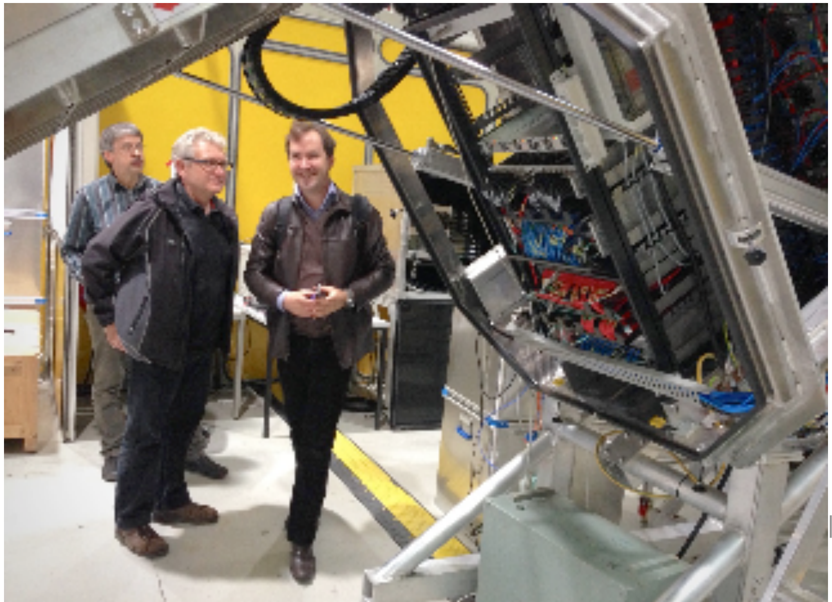


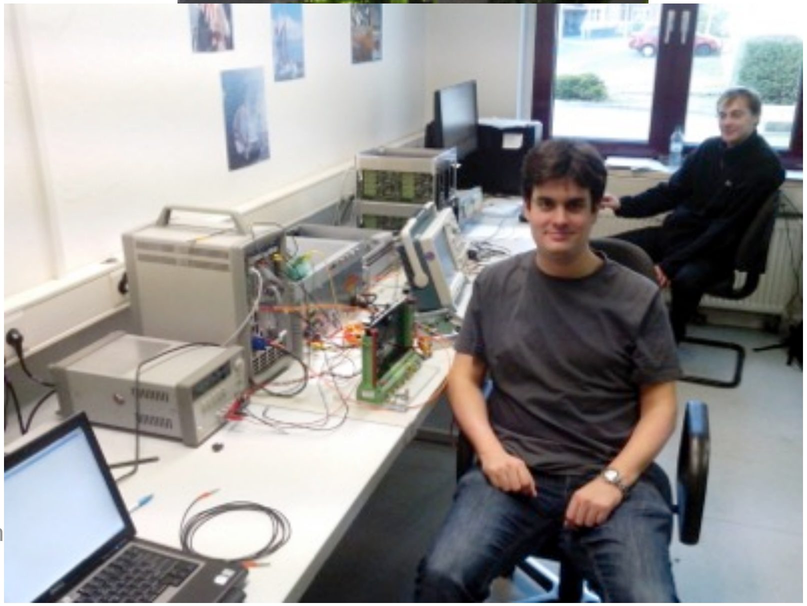


H.E.S.S. upgrade testing



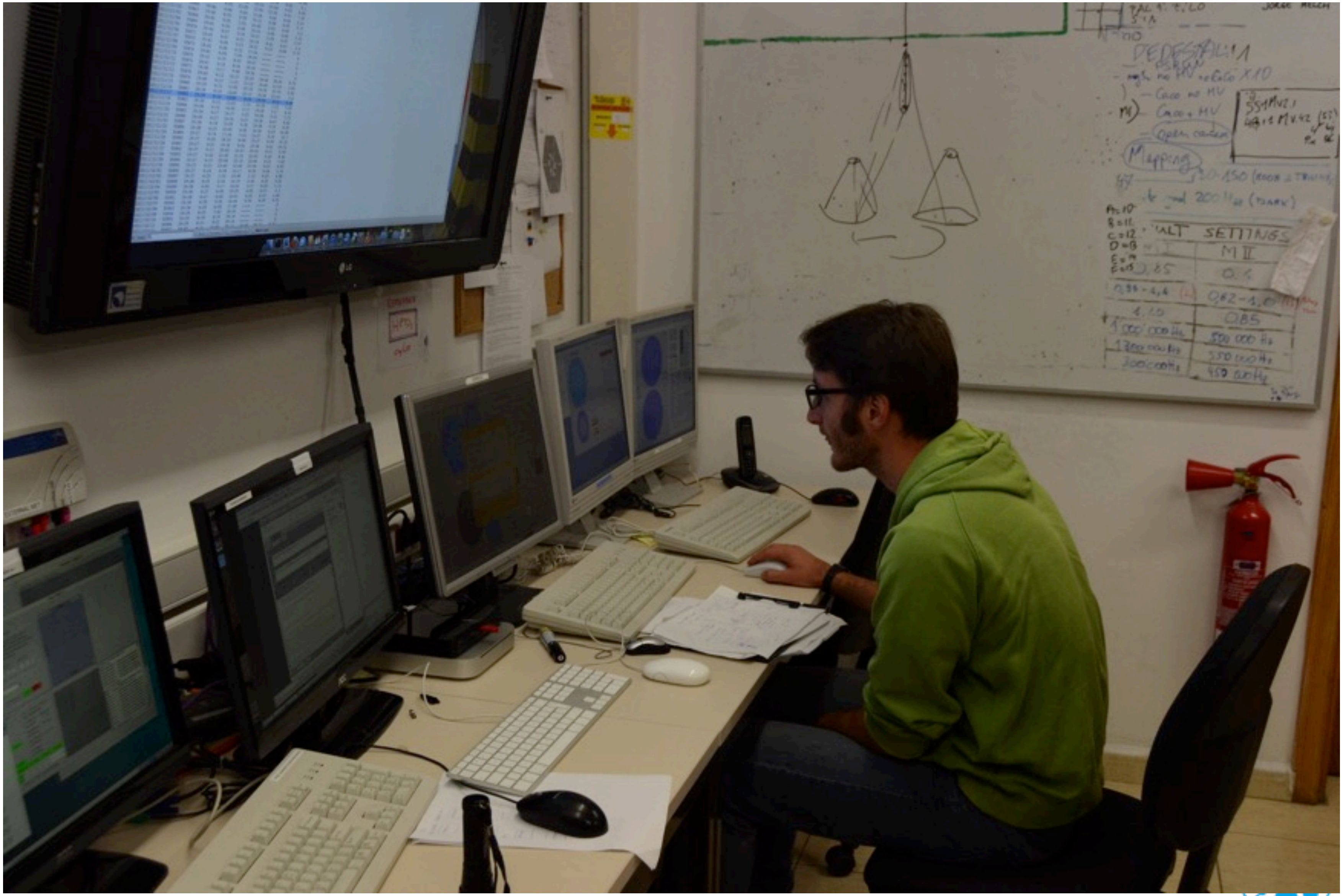






Commissioning

MAGIC commissioning

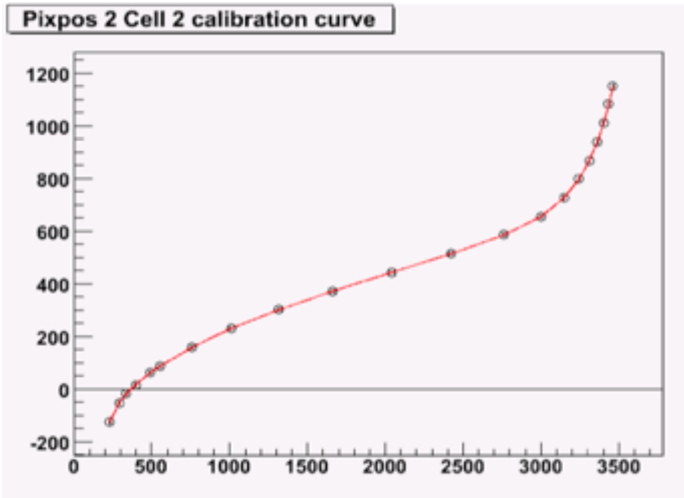


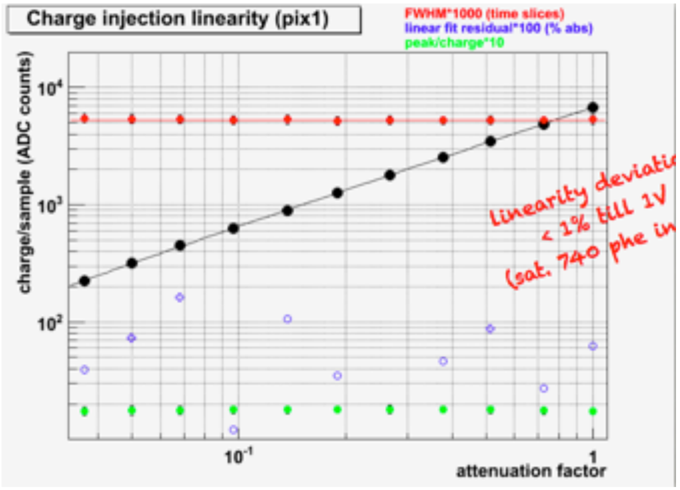
H.E.S.S. commissioning

DESY

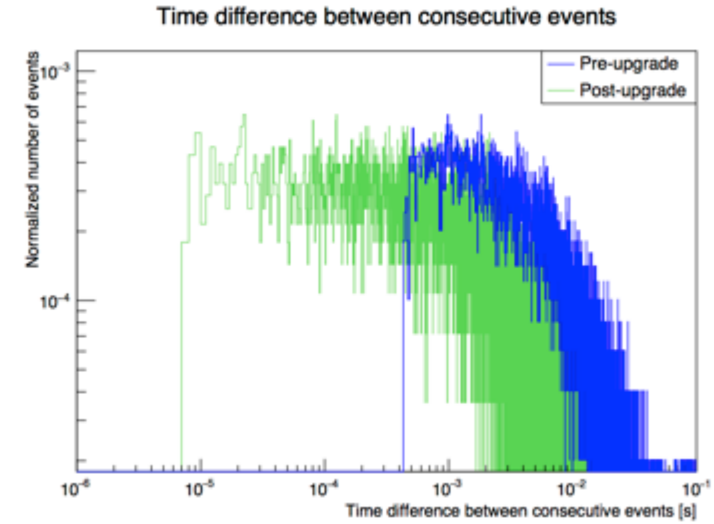
Before and after pictures

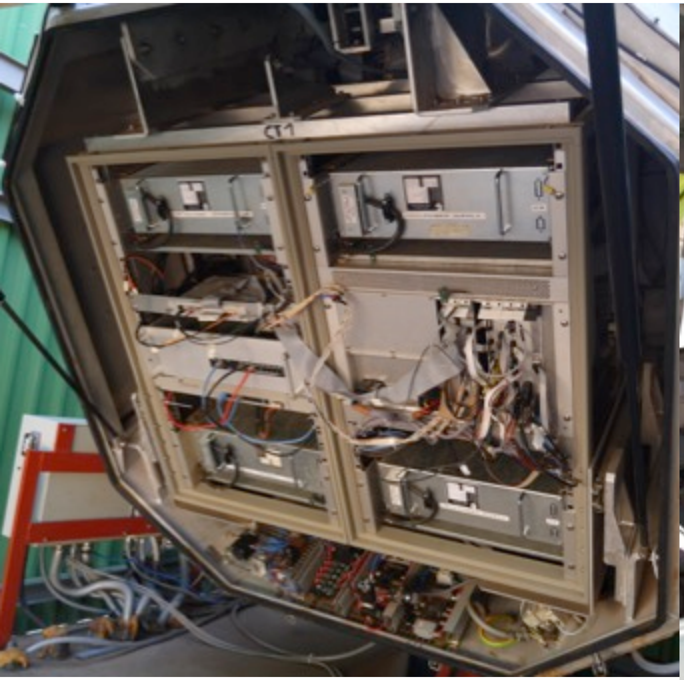
MAGIC before and after upgrade

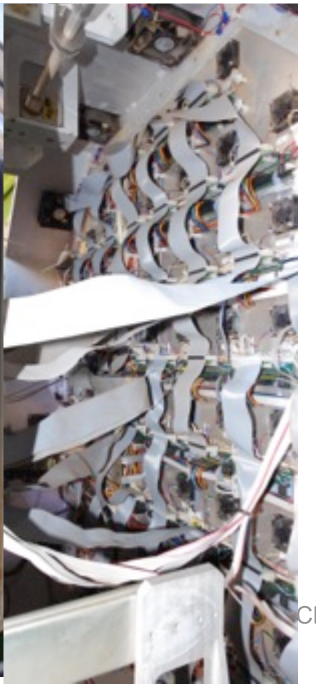


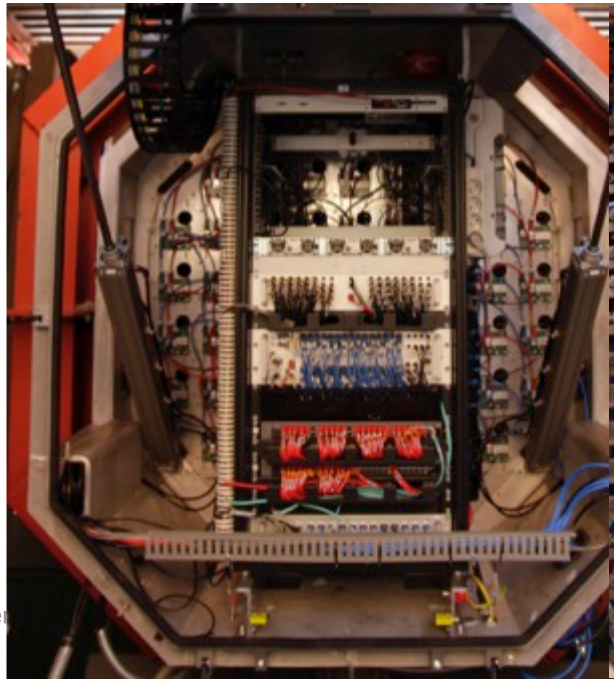


H.E.S.S. before and after upgrade



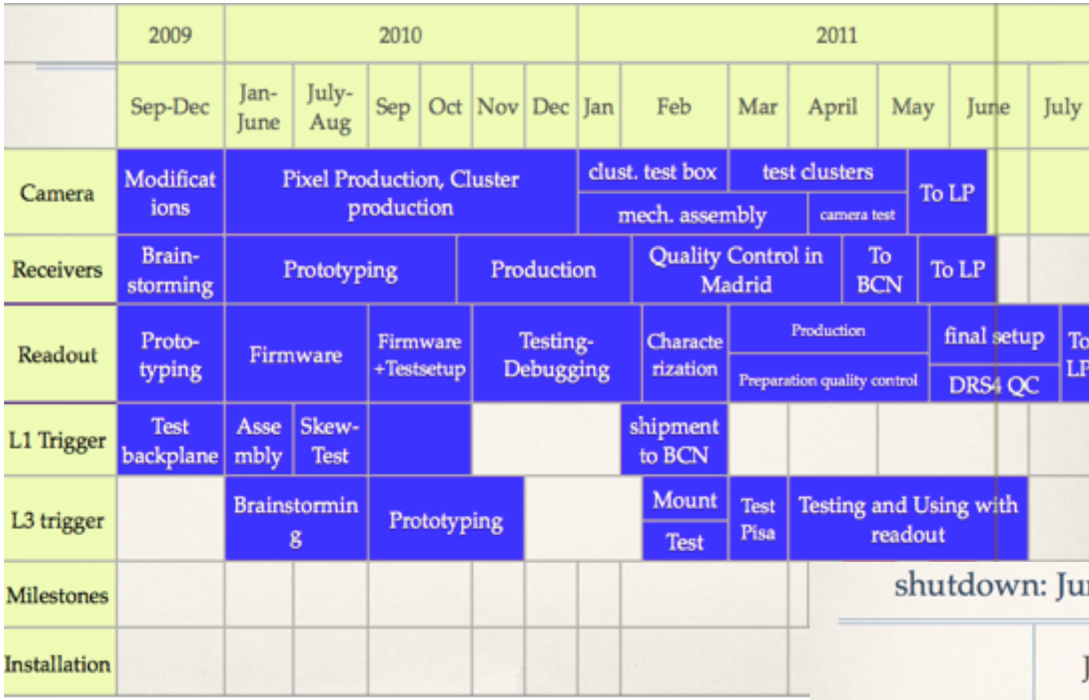




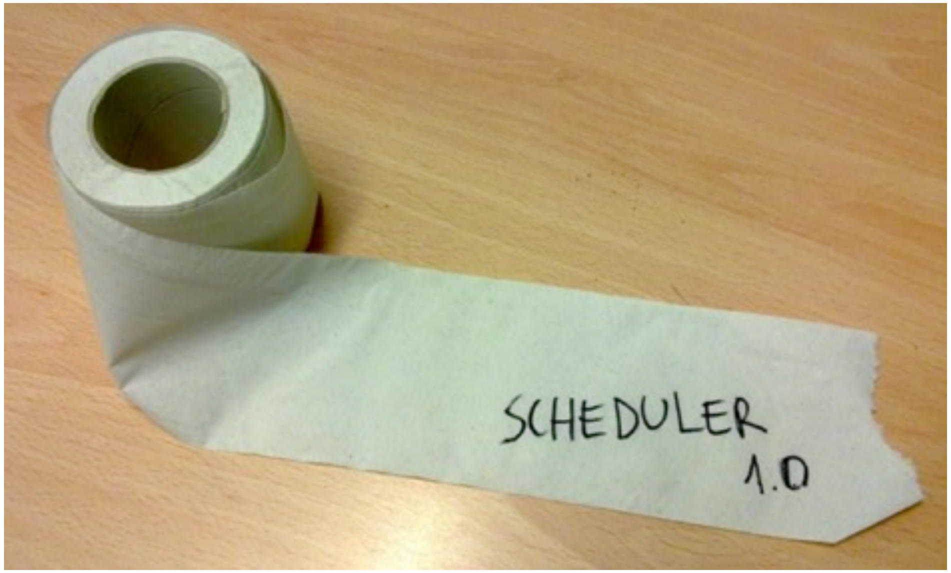


Timeline and scheduling

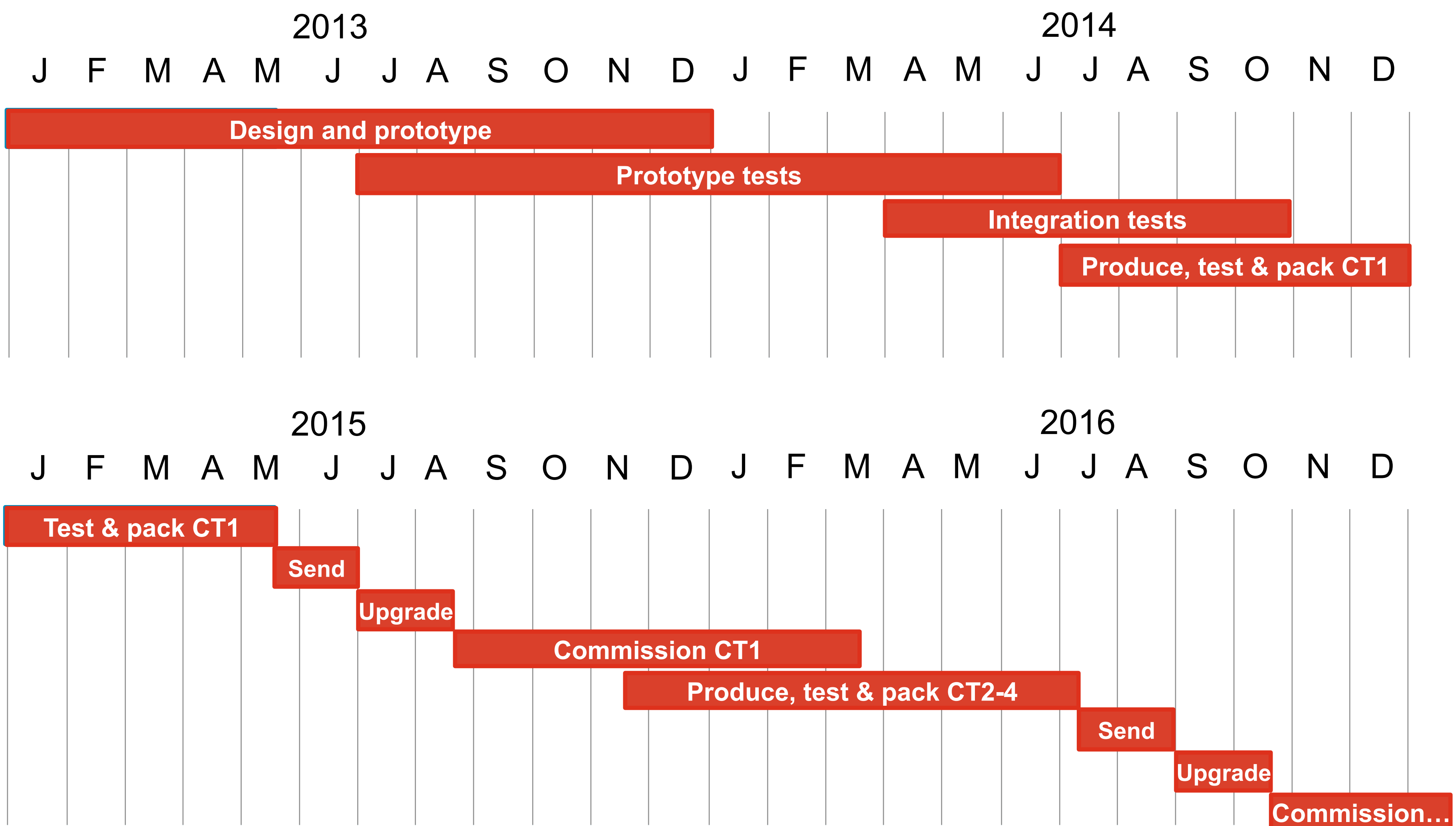
MAGIC Schedule



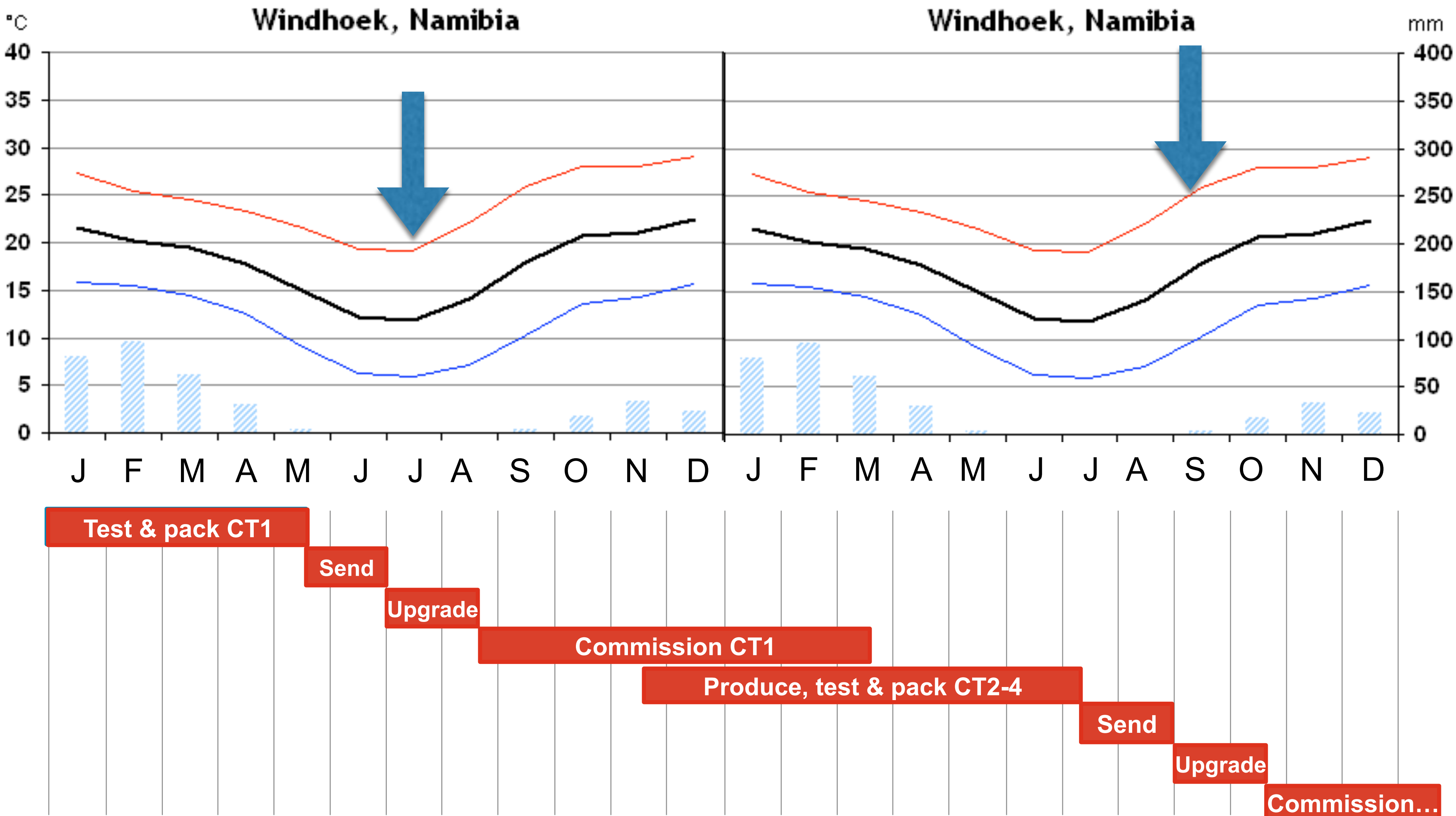
MAGIC Schedule



H.E.S.S. Schedule



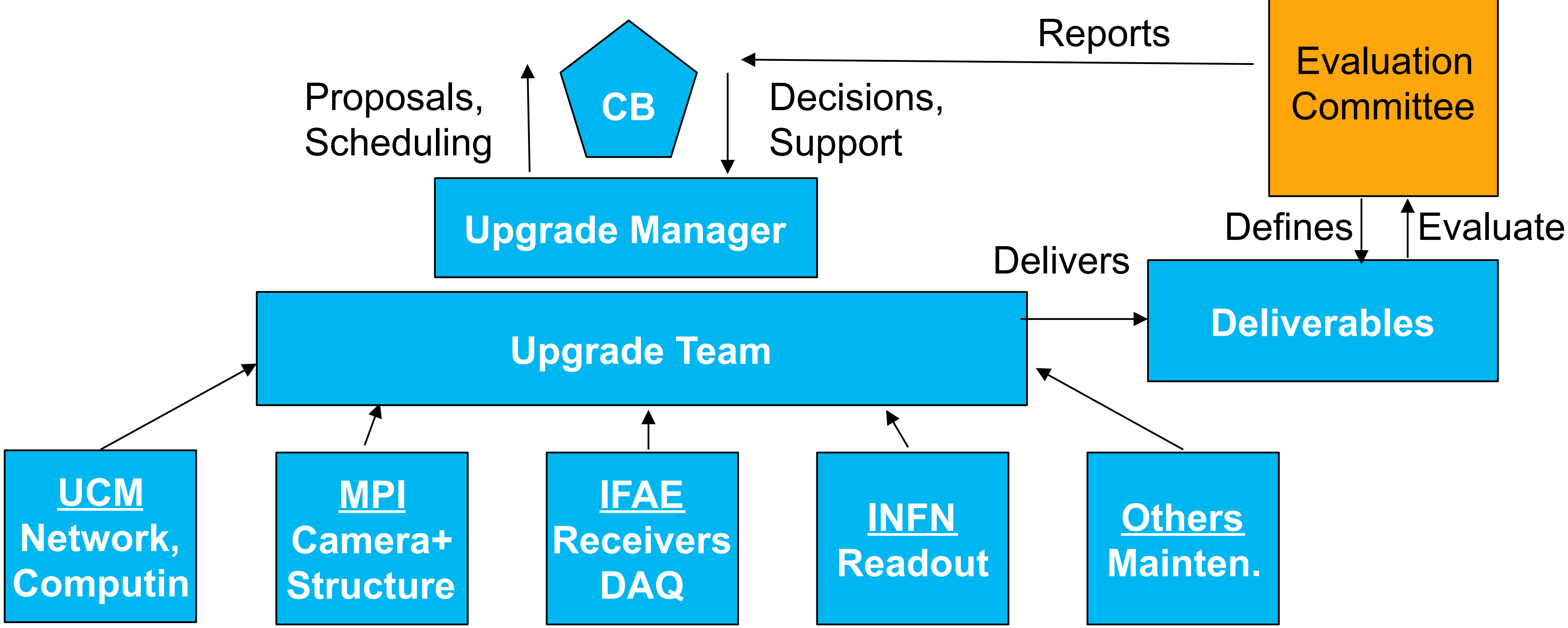
H.E.S.S. Schedule

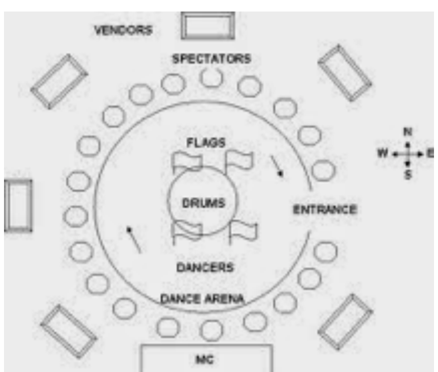


Organization

MAGIC upgrade organization

- ~50 people, 10 core, 5 institutes – equal contributions

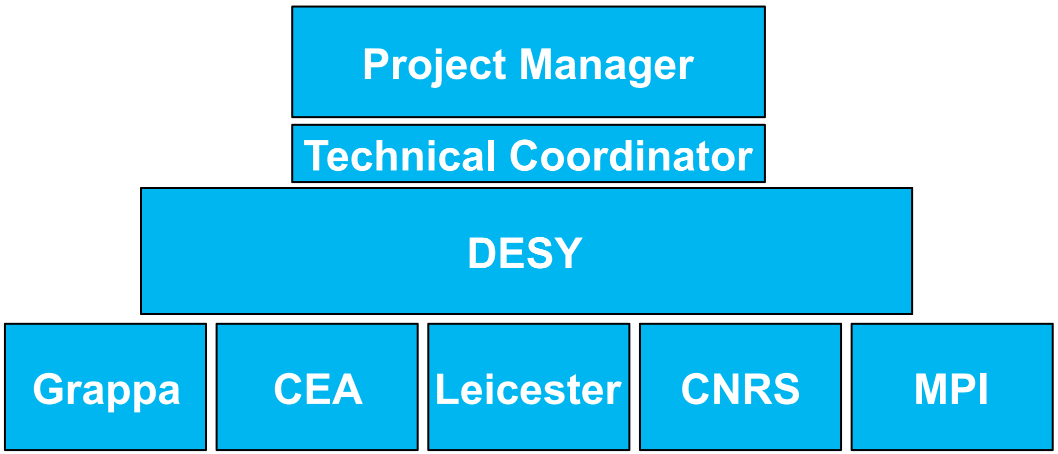


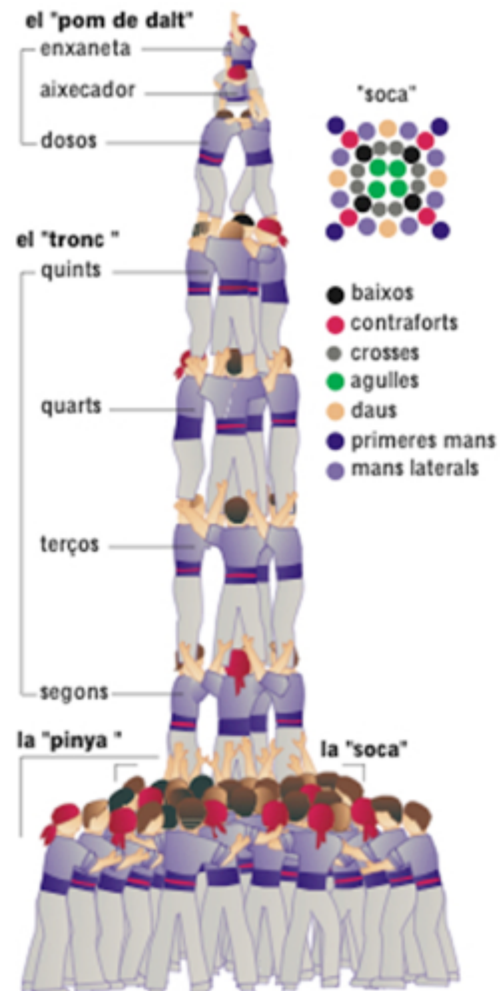


Complex politics

H.E.S.S. upgrade organization

- ~ 25 people, 5 core, one lead institute + 5 support
- Mostly people from DESY - bulk in-house





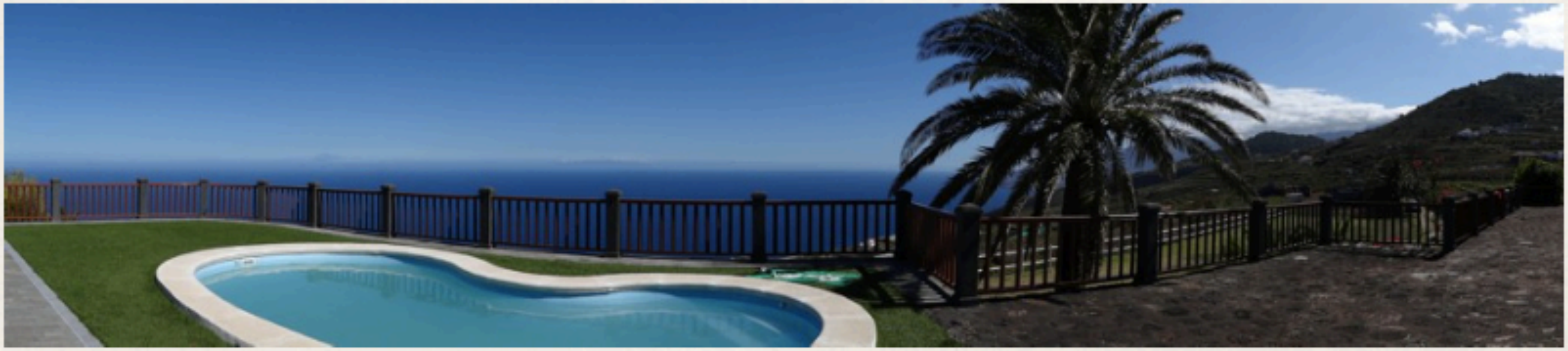
Much tighter knit

Upgrade life and accomodation

MAGIC upgrade life

H.E.S.S. upgrade life

MAGIC upgrade accomodation



H.E.S.S. upgrade accomodation

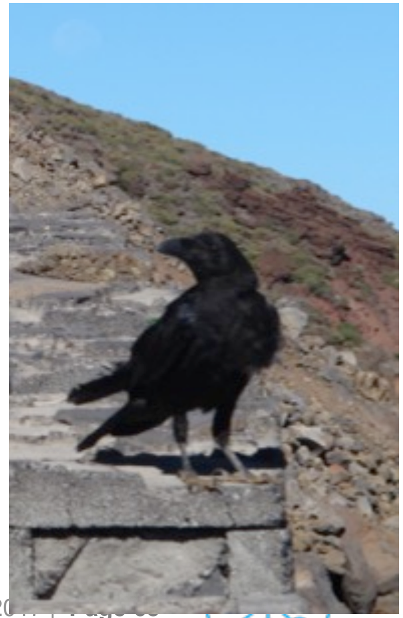
… fo

Local Fauna

MAGIC local fauna



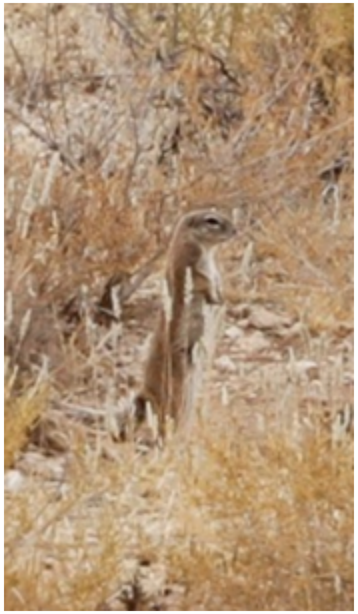


H.E.S.S. local fauna



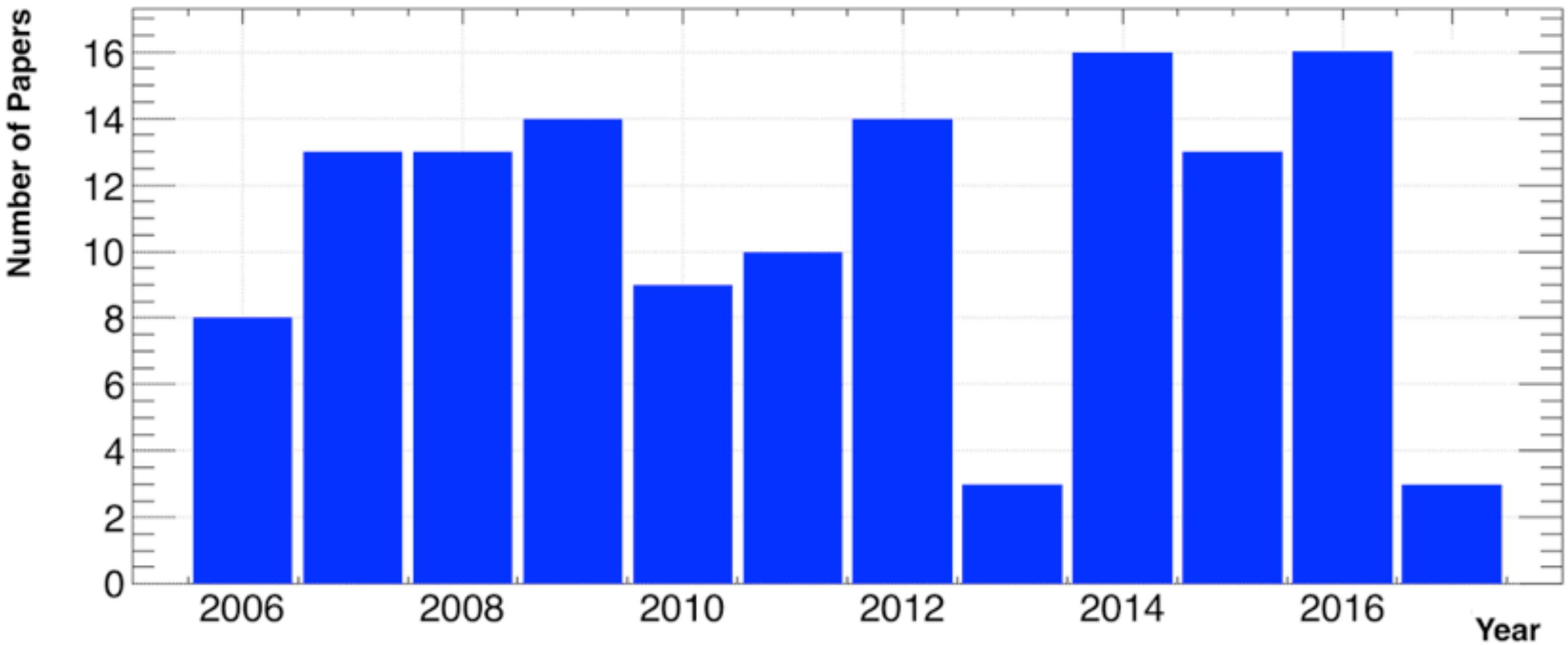



Outcome

MAGIC upgrade outcome

- Great success!
- System works very well, reliably (to the point of boring) since 4 years



H.E.S.S. upgrade outcome

- Great success!
- System works very well, reliably (but never boring) since 4 months