Optical II observations with the MAGIC and CTAO-N LSTs

T. Hassan
on behalf of the MAGIC-LST Interferometry Team

European Research Council
Established by the European Commission

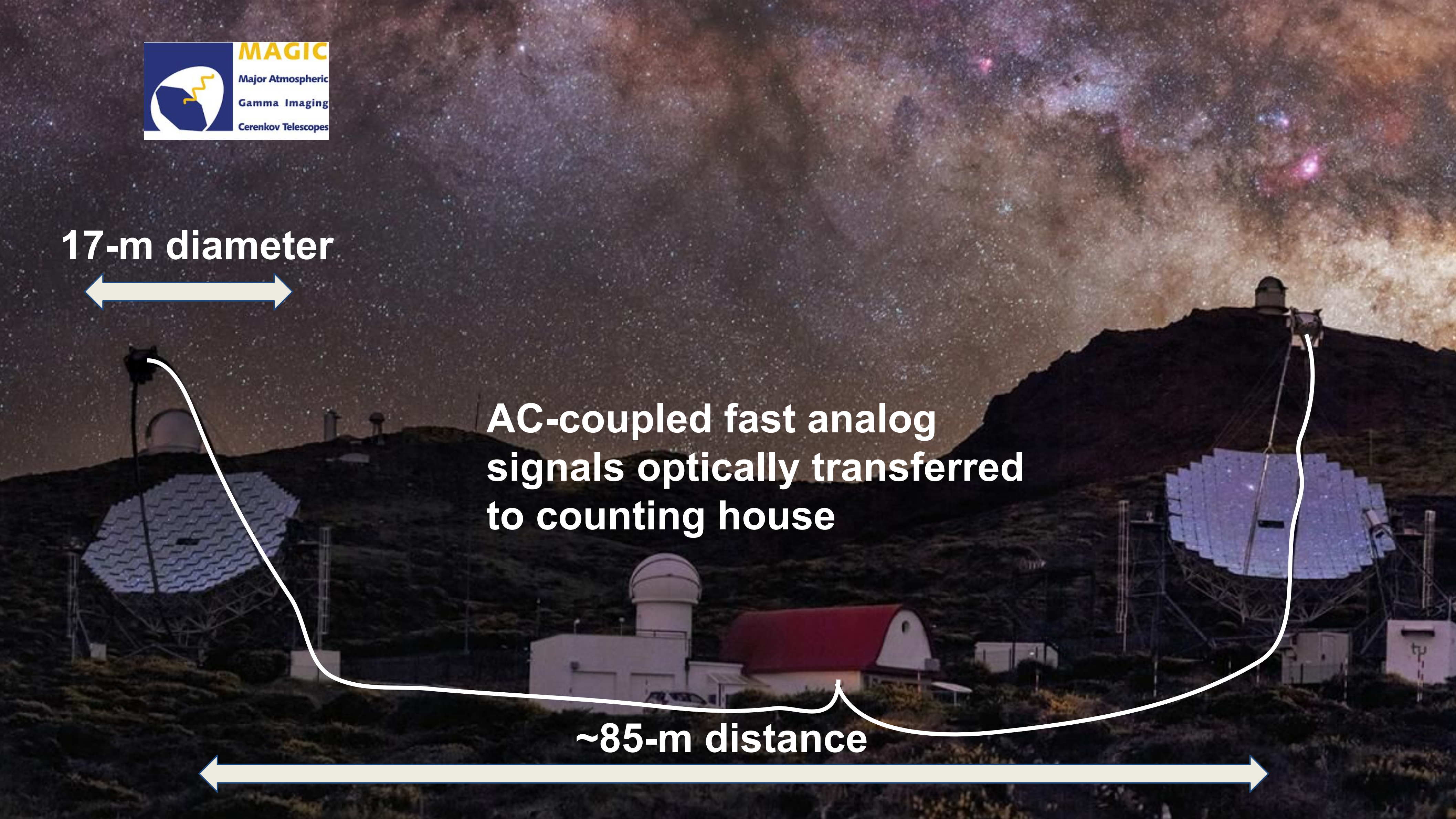
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

CTAO
LST COLLABORATION


MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes


MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes
17-m diameter
AC-coupled fast analog
signals optically transferred
to counting house
~85-m distance

MAGIC-SII: Outline

- Triggered by the interest raised within the **CTA SII group**, few MAGIC members started to realise exploring such a science case in MAGIC would be entirely possible

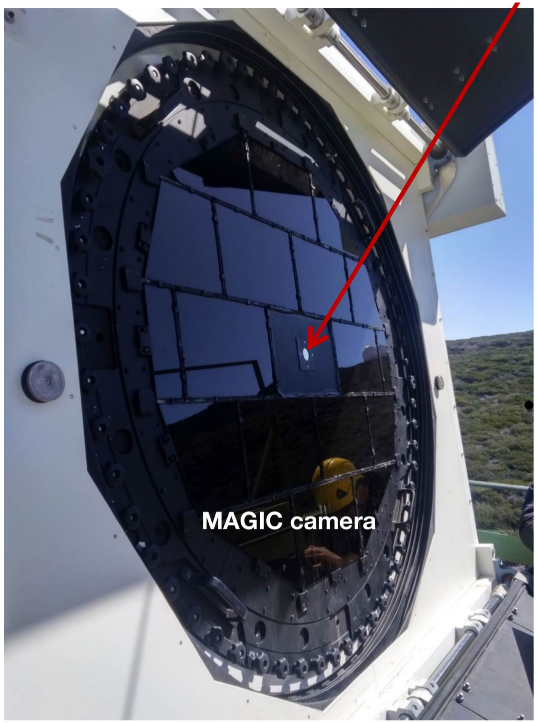
- A **first exploratory design** was tested to confirm MAGIC is able to perform SII observations (first correlation measurements published in 2020)

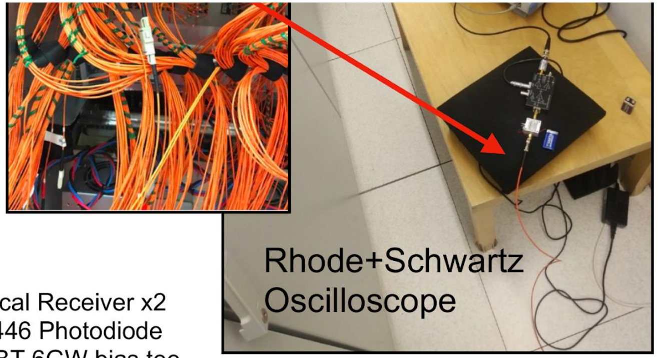
- Since then, **a more professional setup has been implemented**, allowing MAGIC to routinely perform SII measurements every Moon cycle

- Encouraging **future plans**: several large-scale funded projects involving intensity interferometry measurements with IACTs at ORM

MAGIC-SII setup: Exploratory implementation

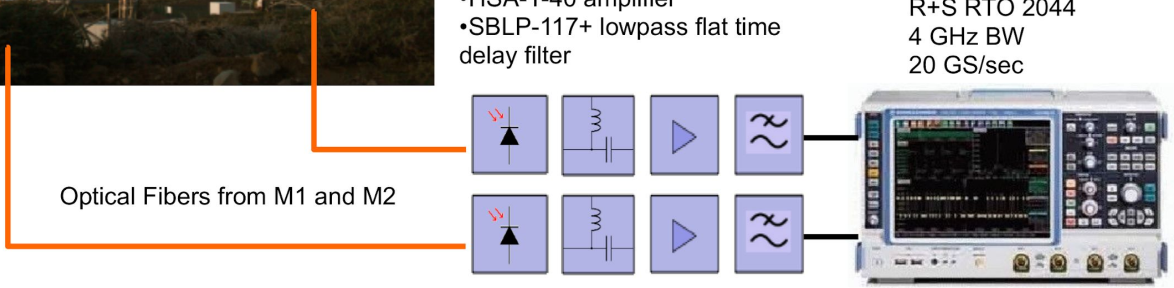
- Minor modifications to MAGIC → x10 the sensitivity of NSII!





Optical Receiver x2
•1a446 Photodiode
•ZFBT-6GW bias tee
•HSA-Y-40 amplifier
•SBLP-117+ lowpass flat time delay filter

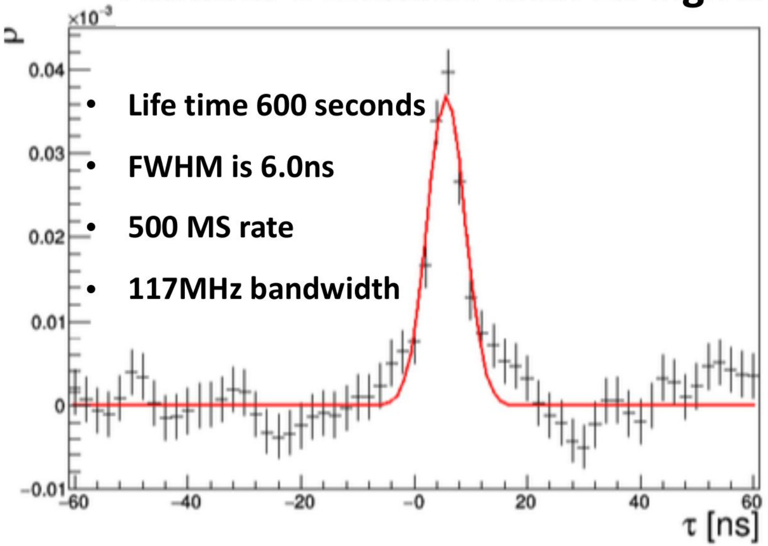
R+S RTO 2044
4 GHz BW
20 GS/sec



MAGIC-SII setup: Exploratory implementation

- Minor modifications to MAGIC → x10 the sensitivity of NSII!

Adhara: Detection with 15 sigma



Optical intensity interferometry observations using the MAGIC imaging atmospheric Cherenkov telescopes

V. A. Acciari[1], M. I. Bernardos[2], E. Colombo[1], J. L. Contreras[3] J. Cortina[2]★, C. Delgado[2], C. Díaz[2], D. Fink[4], M. Mariotti[5], S. Mangano[2]†, R. Mirzoyan[4], M. Polo[2], T. Schweizer[4]‡ M. Will[4].

[1] *Inst. de Astrofísica de Canarias, E-38200 La Laguna & Universidad de La Laguna, Dpto. Astrofísica, E-38206 La Laguna, Spain*
[2] *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain*
[3] *IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid E-28040 Madrid, Spain*
[4] *Max-Planck-Institut für Physik, D-80805, Munich, Germany*
[5] *Università di Padova and INFN, I-35131 Padova, Italy*

First correlation signals from IACTs! (in parallel with VERITAS)

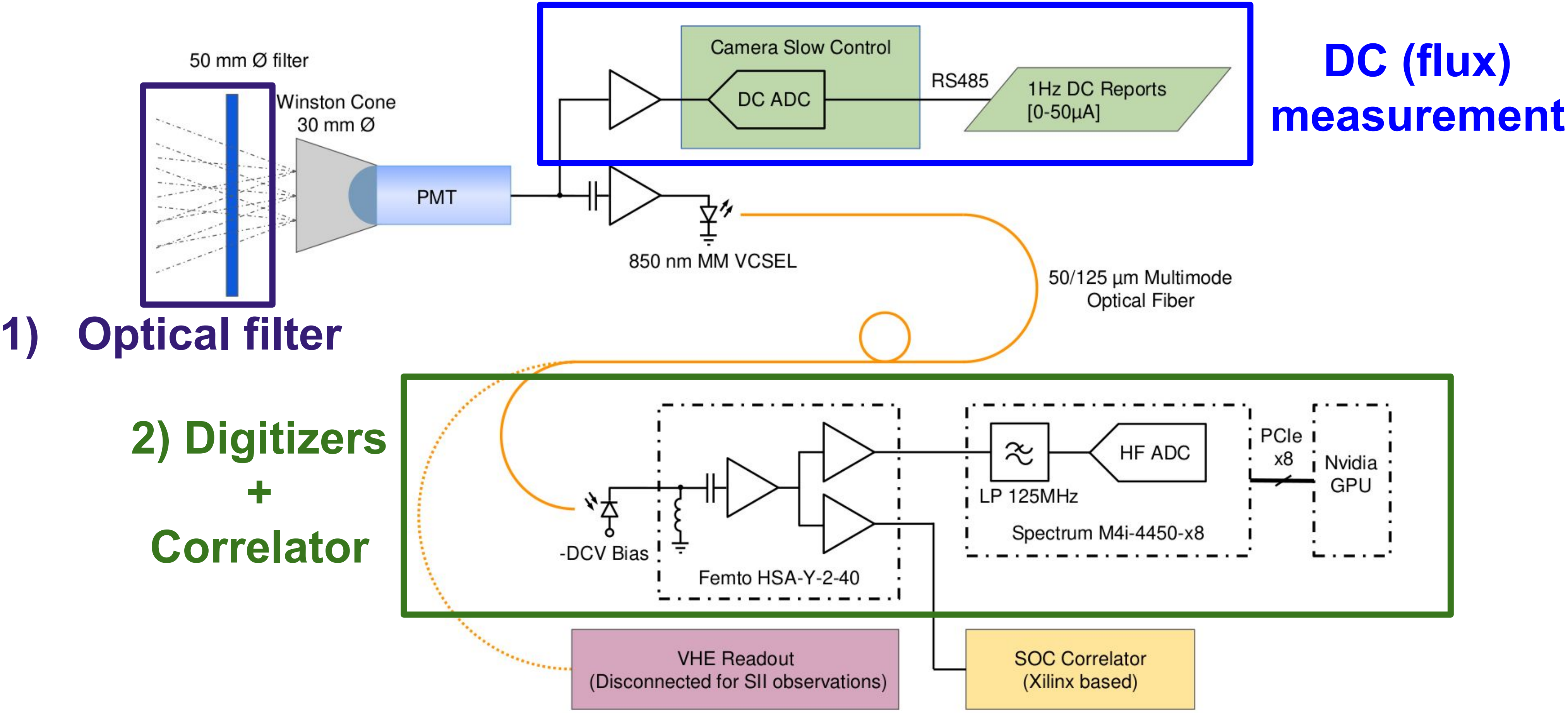
Acciari et al. 2020, MNRAS, 491, 1540

MAGIC-SII setup: Exploratory implementation

- The main conclusions from this experiment were:
  - Demonstrated MAGIC has the potential to become the most sensitive SII telescope (parabolic shape + large diameter → good S/N!)
  - A simple upgrade of certain parts of the telescopes would allow to routinely perform these measurements

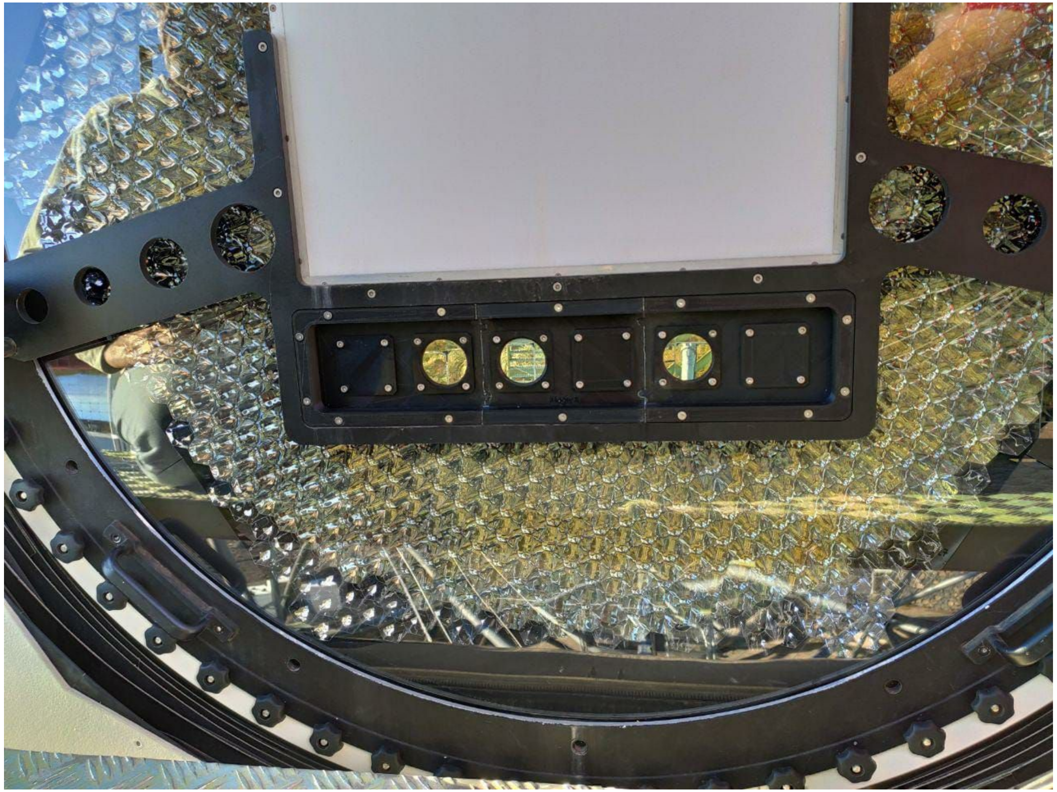
- Main objectives of the upgrade:
  - **Remove the need of filter manual installation**
  - **Reach ~100% duty cycle**

MAGIC-SII setup: 2020 upgrade summary



MAGIC-SII setup: 2020 upgrade summary

1) narrow-band optical filters on white target



- Shifters are able to place optical filters by clicking a button from central control
- No manual intervention needed to perform SII observations
- Allows to perform observations on (ultra-bright) optical transients, if we are ever lucky

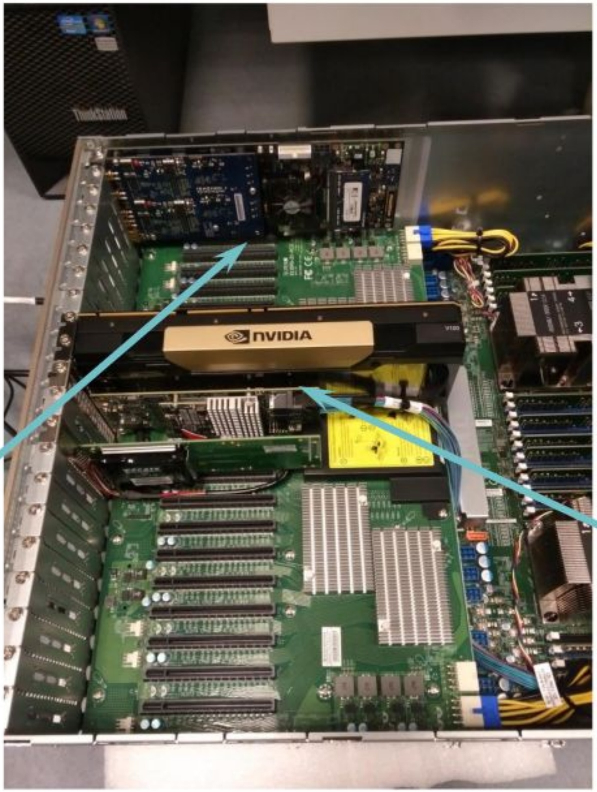
C. Díaz et al

MAGIC-SII setup: 2020 upgrade summary

2) Signal transmitted to a GPU-based correlator

Current SII Setup

- SUPERMICRO GPU SuperServer SYS- 6049GP-TRT
- NVIDIA® Tesla V100-32GB – PCIe GPU
- 2 Spectrum M4i.4450-x8 Digitizers
- 4 channels of 14 bit resolution @500MS/sec



- Signals from 4 pixels sent to digitizers (labeled A, B, C and D)
- Raw data is never stored: directly sent to GPU and correlated
- Able to produce on-line correlation measurements
- Currently 6 Corr + 4 Autocorr

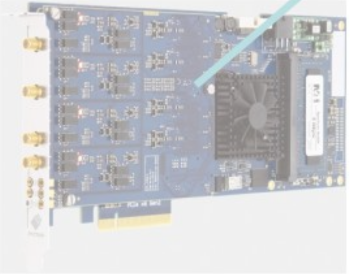
D. Fink
C. Delgado,
J. J. Rodriguez et al

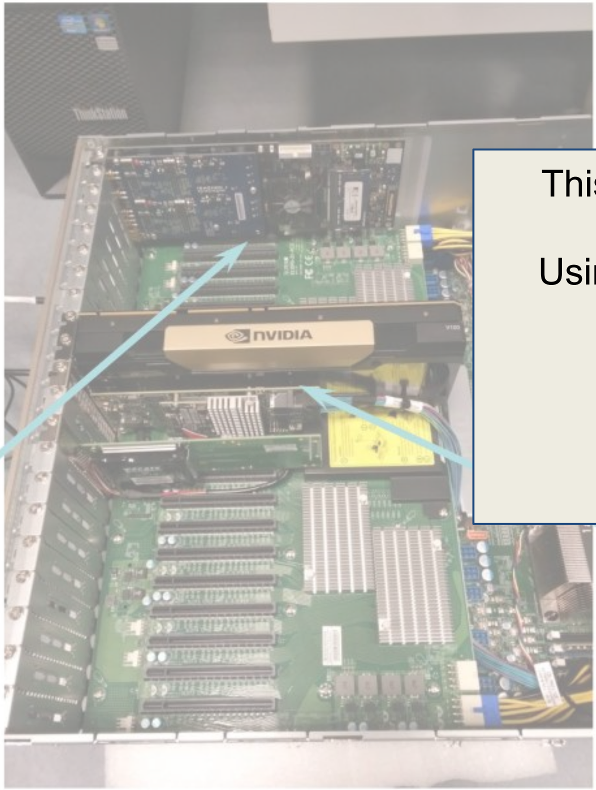
MAGIC-SII setup: 2020 upgrade summary

2) Signal transmitted to a GPU-based correlator

Current SII Setup

- SUPERMICRO GPU SuperServer SYS- 6049GP-TRT
- NVIDIA® Tesla V100-32GB – PCIe GPU
- <u>2</u> Spectrum M4i.4450-x8 Digitizers
- <u>4</u> channels of 14 bit resolution @500MS/sec





- Signals from 4 pixels sent to digitizers (labeled A, B, C and D)

This GPU-based correlator philosophy scales well!

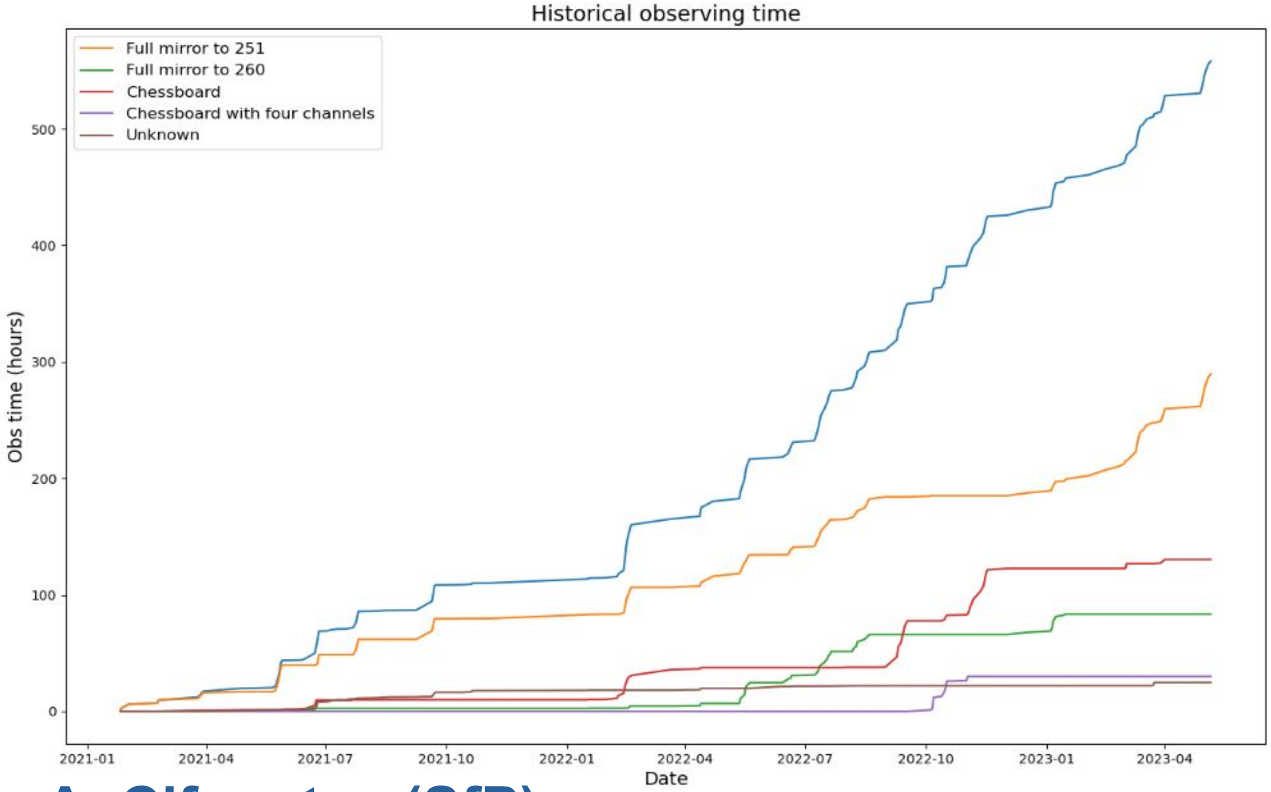
Using high-speed GPU-GPU memory transmission allows online measurement of correlation at GHz frequencies for many channels

Available funding to build a ~12 channel proof-of-concept correlator

D. Fink
C. Delgado,
J. J. Rodriguez et al

MAGIC-SII: Datataking status

- By April 2023, more than 500h of observation have been performed



A. Cifuentes (SfP)

- MAGIC observing shifts have been extended to partially cover Moon nights

- Given the “independence” of SII data taking, it has been very successful for not wasting MAGIC time due to VHE-related technical issues

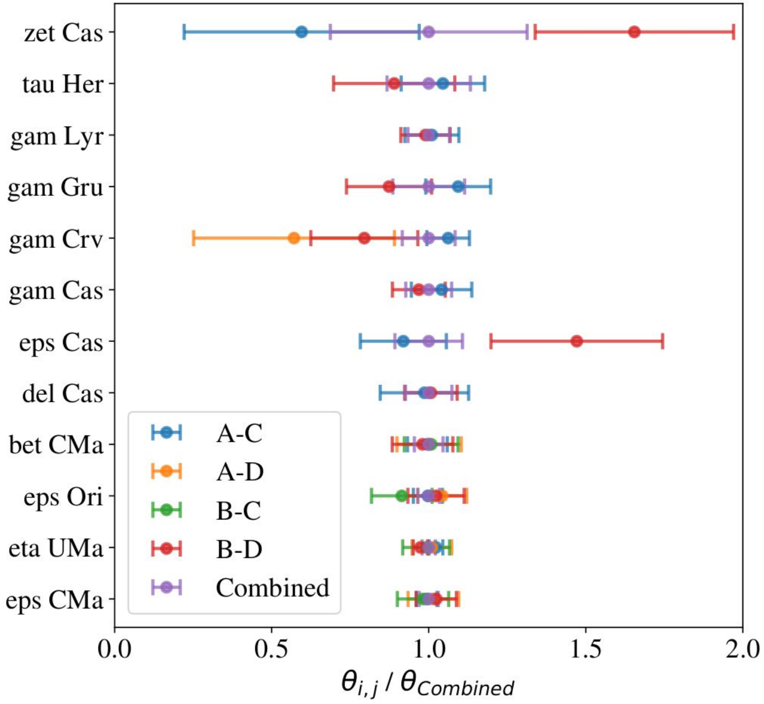
MAGIC SII – Performance paper

- Big effort to validate the analysis (lots of material in the backup!):
    - All results were extracted from at least 2 independent analyzers with 100% independent code (except DAQ of course)
    - Angular diameters extracted from 4 independent analysis chains
- Also lots of work devoted to evaluate the associated **systematics**
- Measured angular diameters were released to show how they match the expectations, as well as “sell” the capabilities of MAGIC-SII

MAGIC SII – Performance paper – Results

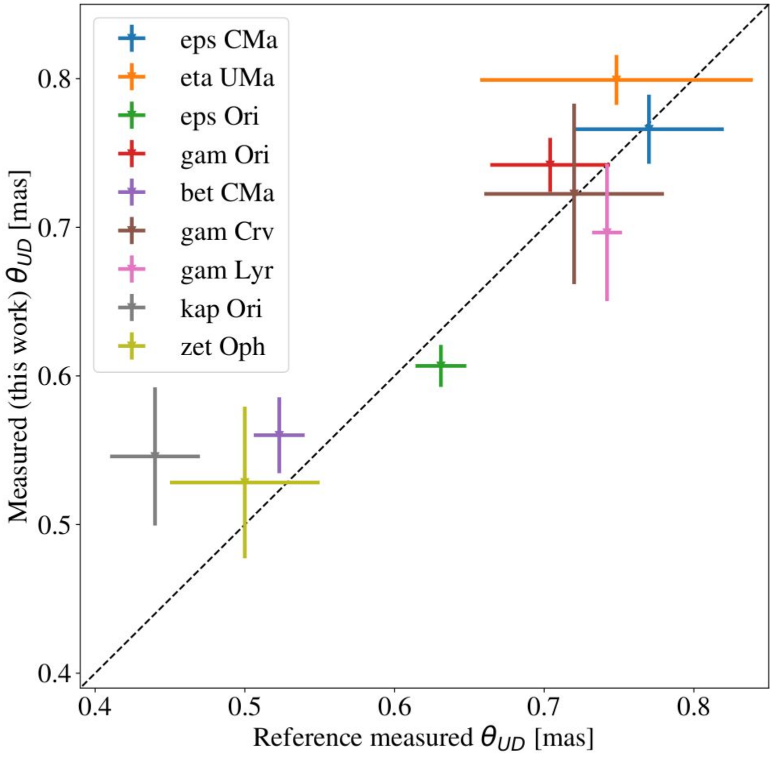
- Active mirror control flexibility allows to use different pixels. Excellent check for systematics (see backup for details)

Different channels provide consistent results, with (almost) 100% independent observations



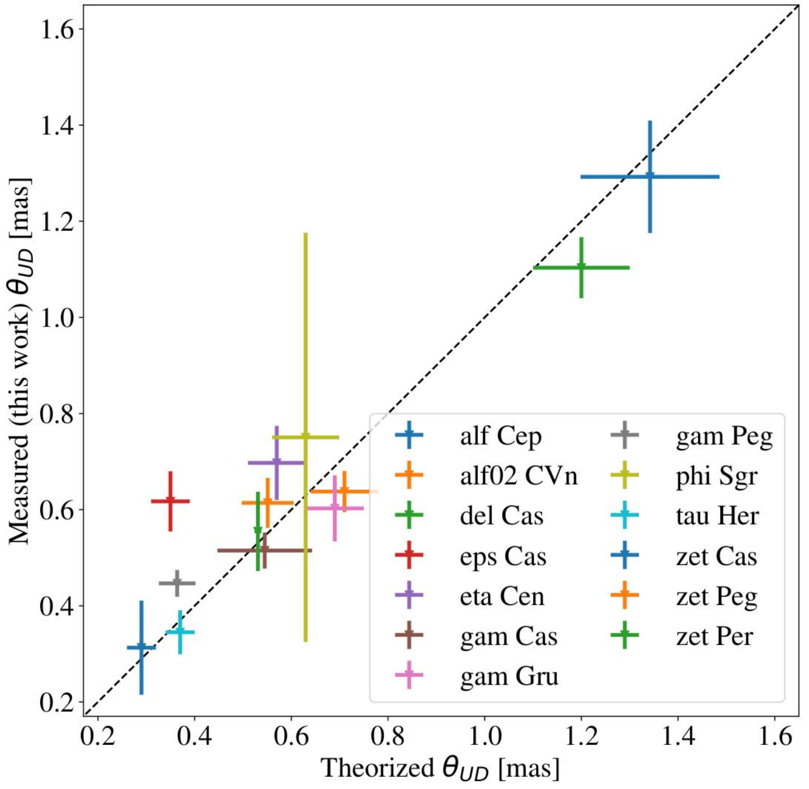
MAGIC SII – Performance paper – Results

- Measurements match reference values (from NSII, VERITAS or CHARA)



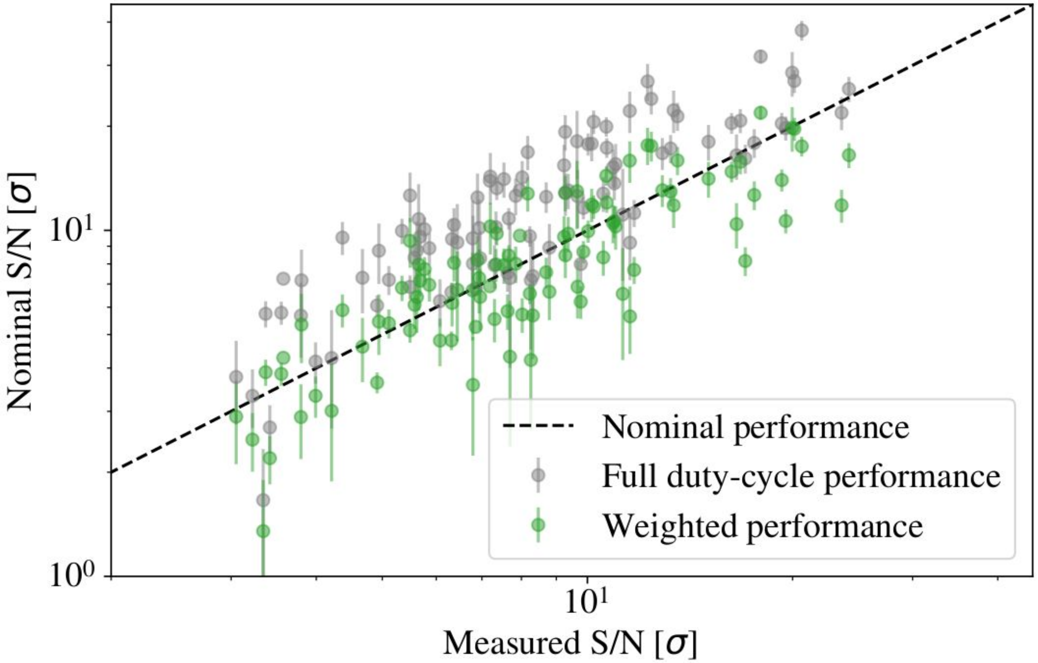
MAGIC SII – Performance paper – Results

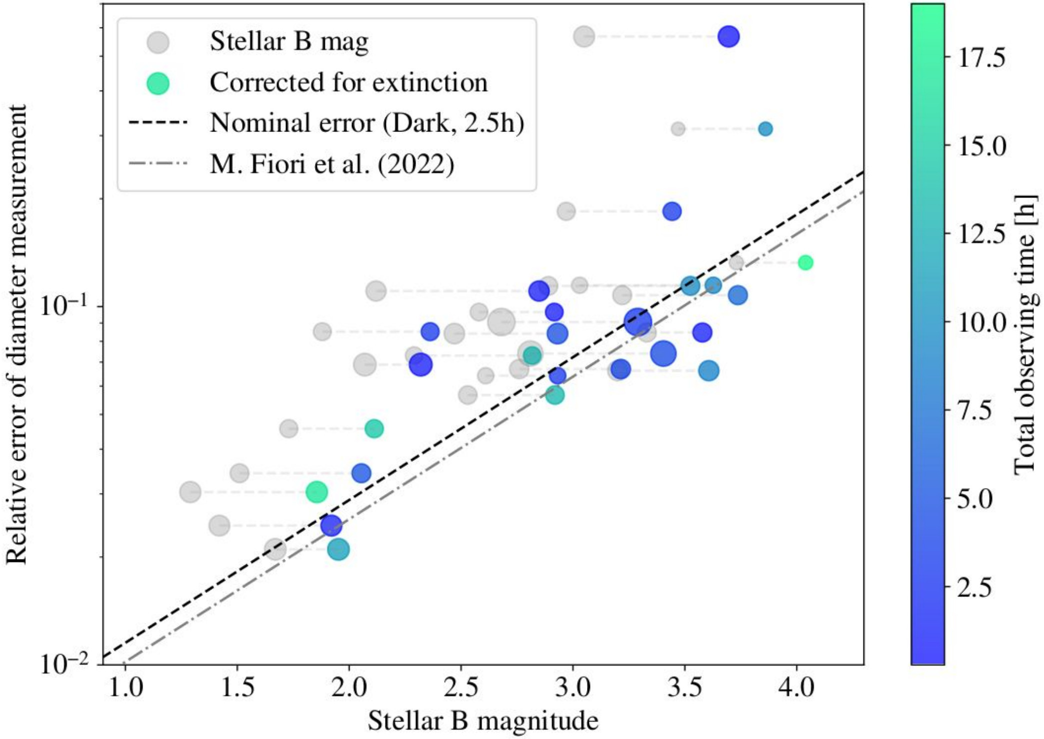
- New measurements also match expectations:



MAGIC SII – Performance paper – Results

- Signal to noise matches expectations:





MAGIC SII – Performance paper – Results

- Systematics associated with the “AC-coupled method” do not dominate:

Systematic effect	Uncertainty
Electronic bandwidth	0.5%
Optical bandwidth	$< 1\%$
Gain evolution of DC ADC branch	
- Seasonal temperature	Negligible
- Gain drift after DC jump	1%
- Long-term degradation	0.8%
- Deviations from linearity	Negligible
Residual electronic noise	Negligible
I_i(NSB) substraction	1.5/3% ($B_{mag} > 3.5$)

- Properly evaluating the background flux is currently the limiting systematic we identified
- This table does not include source-related systematics (multiple sources in FoV, etc…)
- These systematics may prevent detections in the $V^2 < 0.1$ range. **They are important!!**

CTAO - The next-generation VHE Observatory

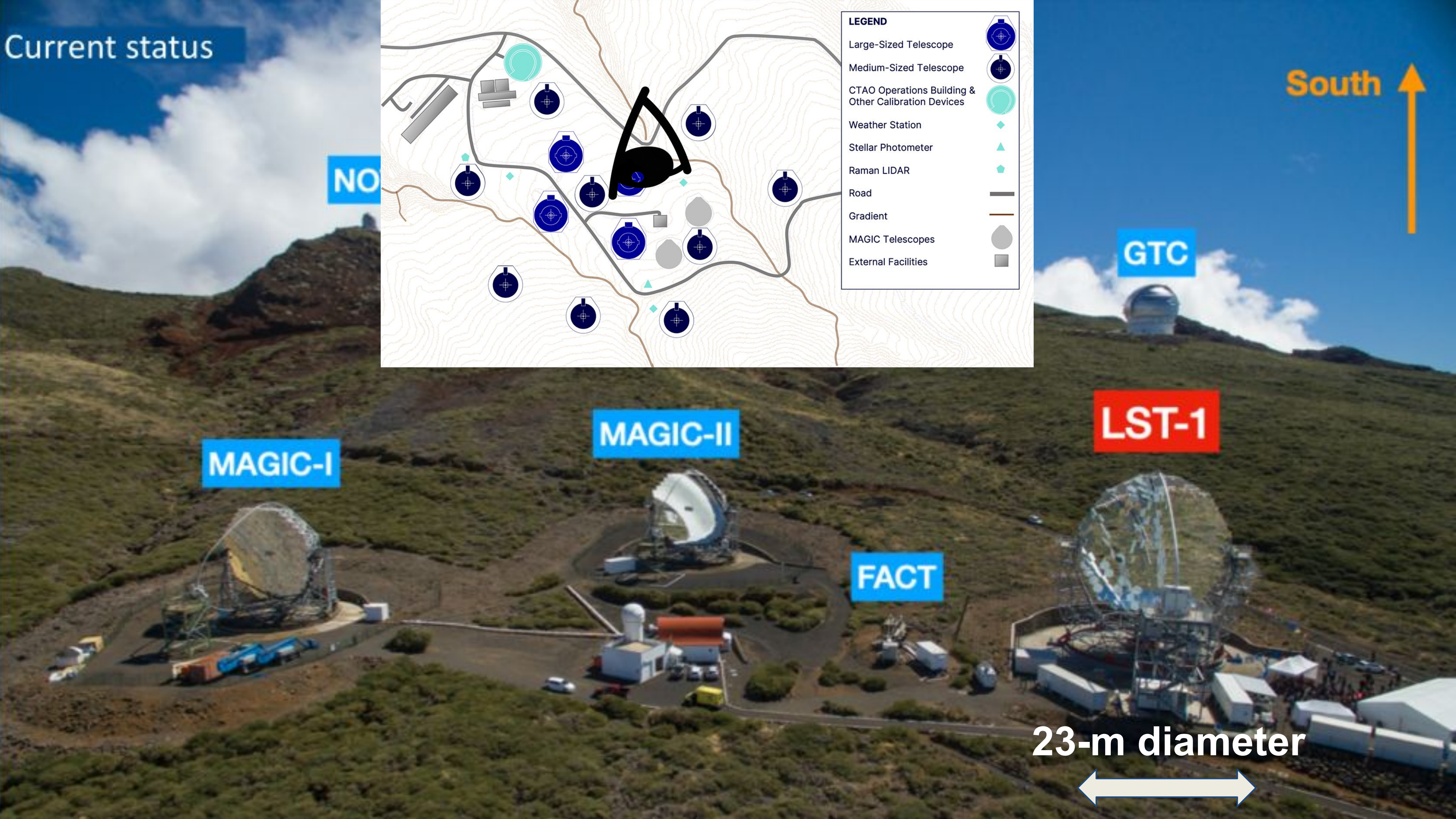
- MAGIC telescopes are not the only IACTs operating in the Canary Islands anymore

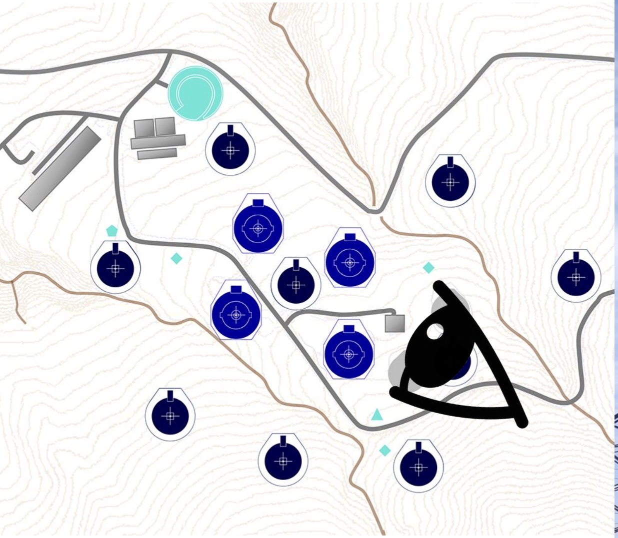
- They have big (noisy) neighbours! (remember J. Biteau slides!)

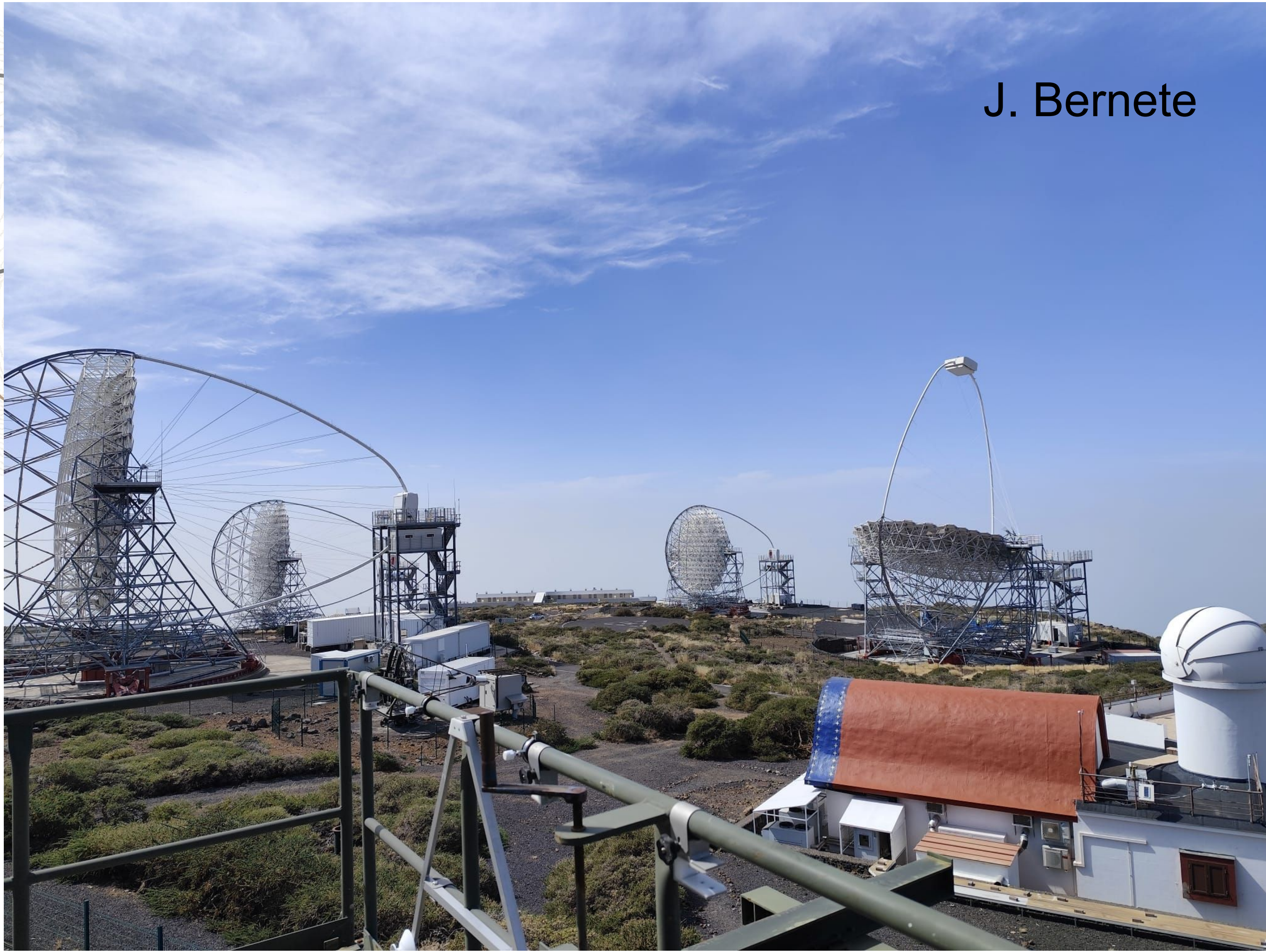
- Let’s zoom out a bit!

Current status

Current status







Current CTAO-N status:

4 LSTs being built in parallel

Expected to be ready for on-sky observations in 2026-2027

MAGIC+LSTs-SII: Not-so-future integration plans

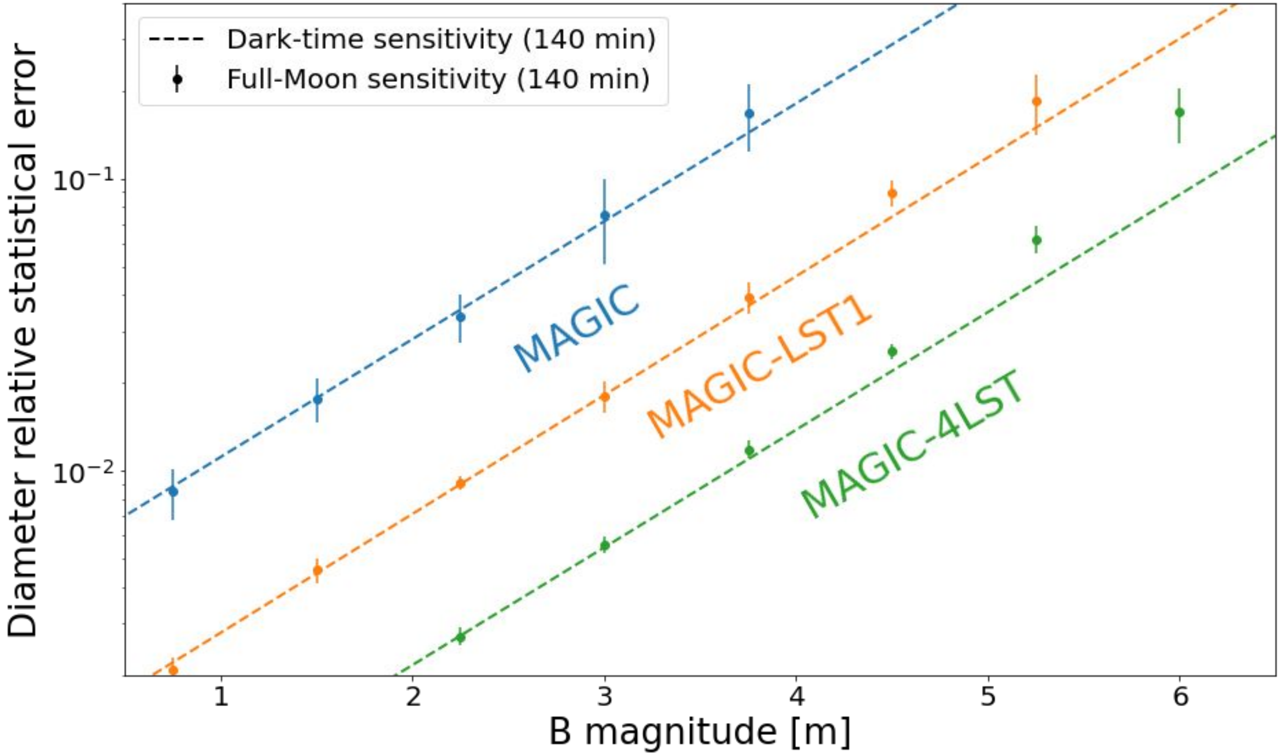
European Research Council

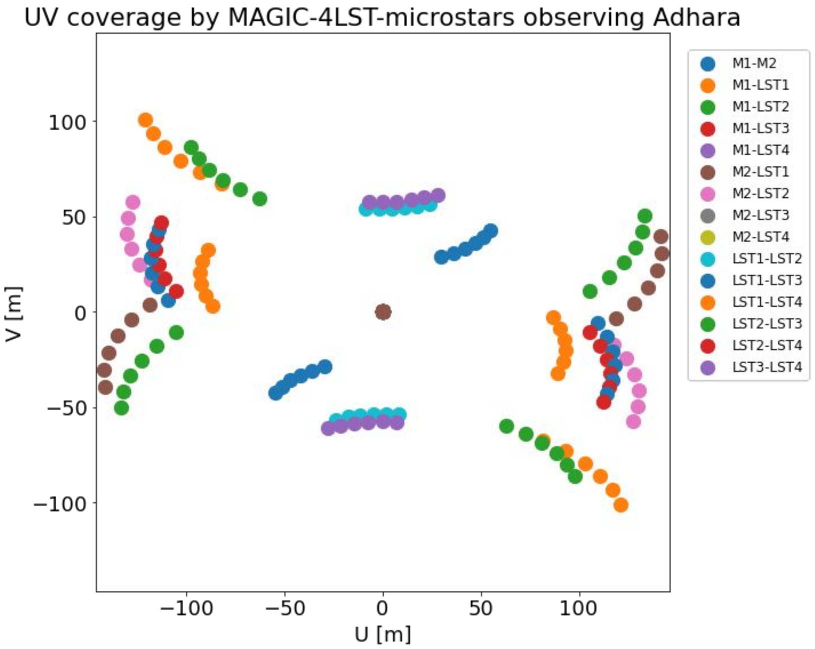
Established by the European Commission

- ERC StG was fully funded (2.5M€) to integrate LSTs into the interferometer
    - Demonstrate the feasibility of CTAO-SII
        - Scalable correlator capable of handling full CTAO-North
        - Telescope modifications needed to perform observations
    - Explore the use of this same setup for fast optical astronomy (millisecond-scale optical transients)

MAGIC+LSTs-SII: Impact on sensitivity

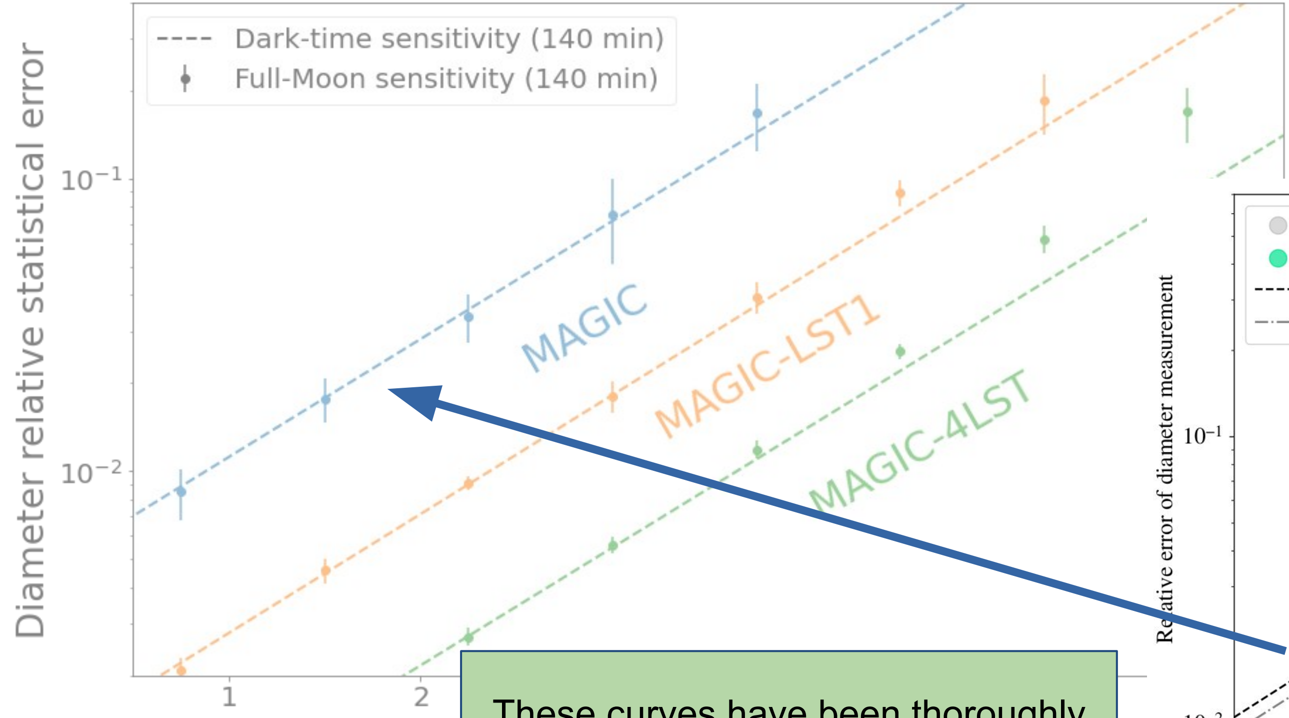
- If we were able to add LSTs into the array, we would gain **a lot**:

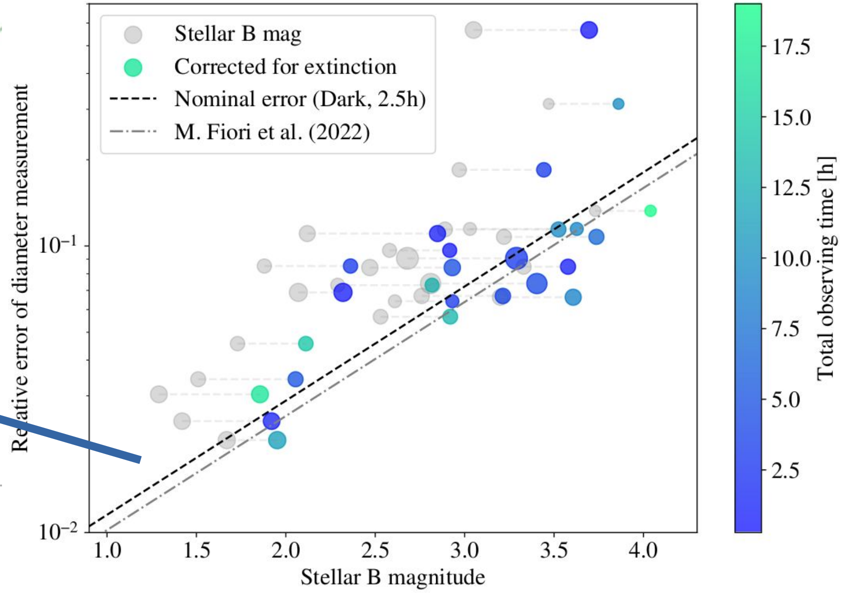




MAGIC+LSTs-SII: Impact on sensitivity

- If we were able to add LSTs into the array, we would gain **a lot**:

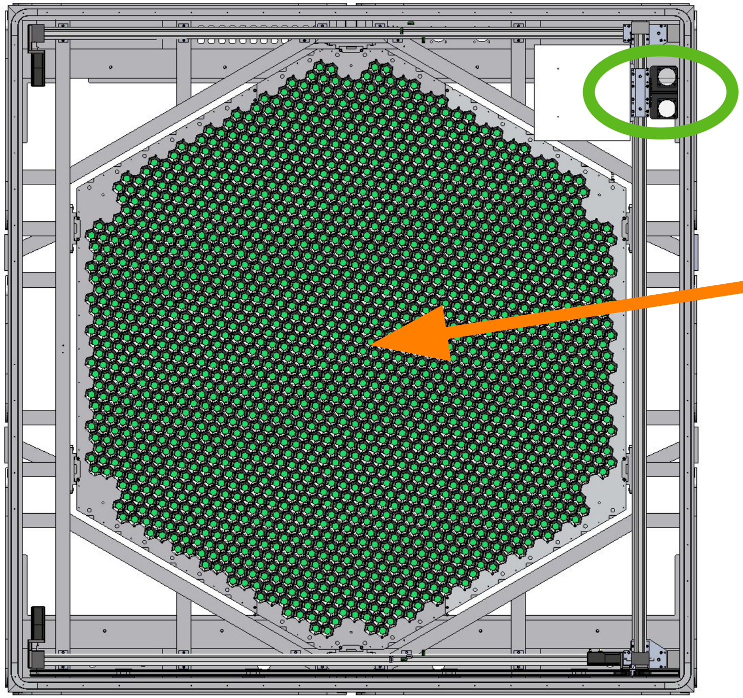


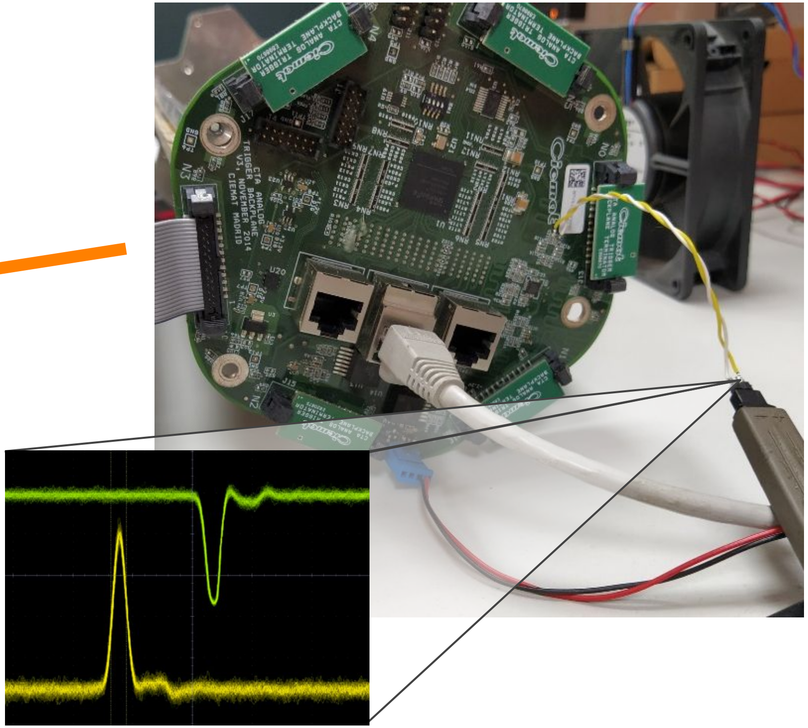


These curves have been thoroughly tested **with observations**!

Future prospects: adding Large Sized Telescopes

- A simple solution to include LST-1 into the MAGIC correlator (1/2):



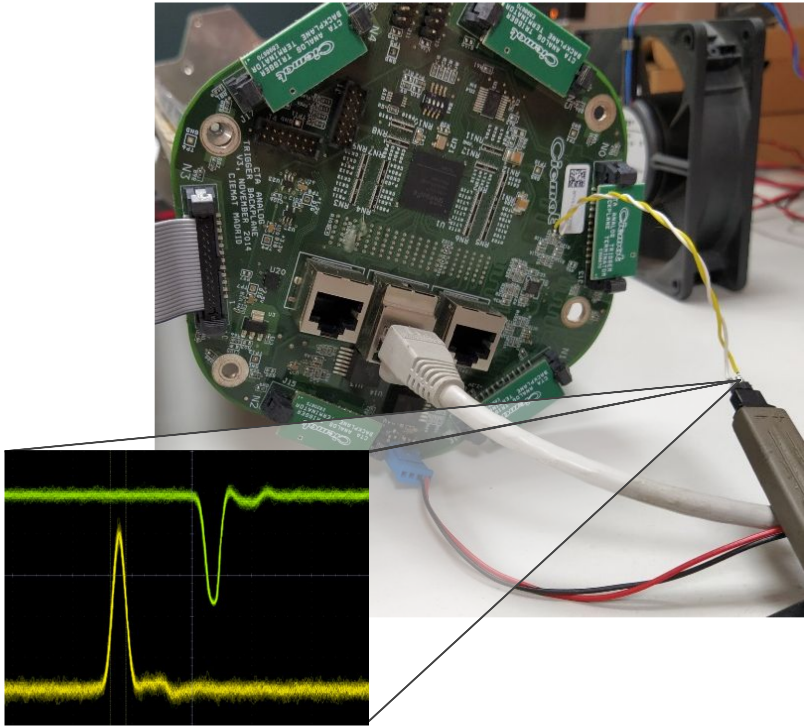


Carlos Díaz, Miguel Polo, Miguel Lobo (CIEMAT)

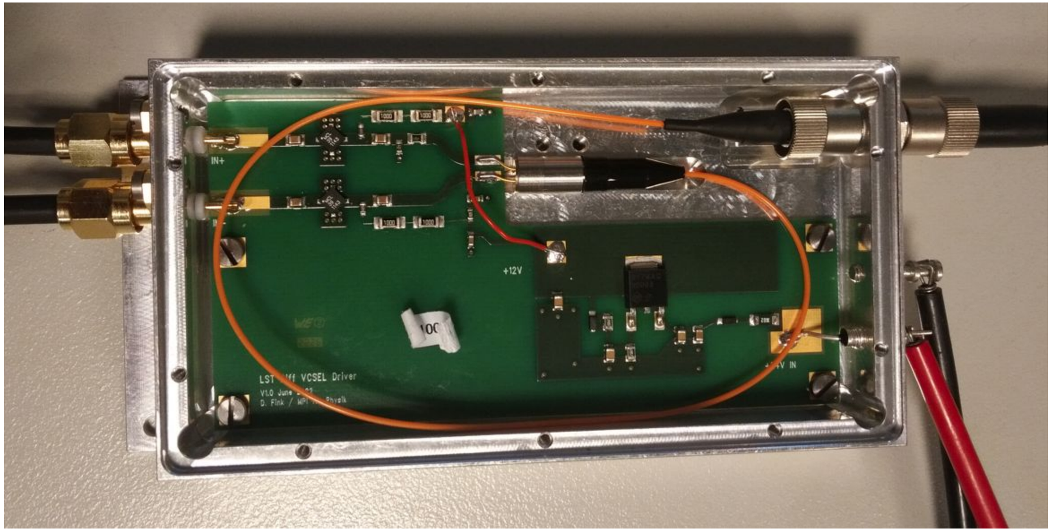
Gustavo Martínez (CIEMAT)

Future prospects: adding Large Sized Telescopes

- A simple solution to include LST-1 into the MAGIC correlator (2/2):



Gustavo Martínez (CIEMAT)

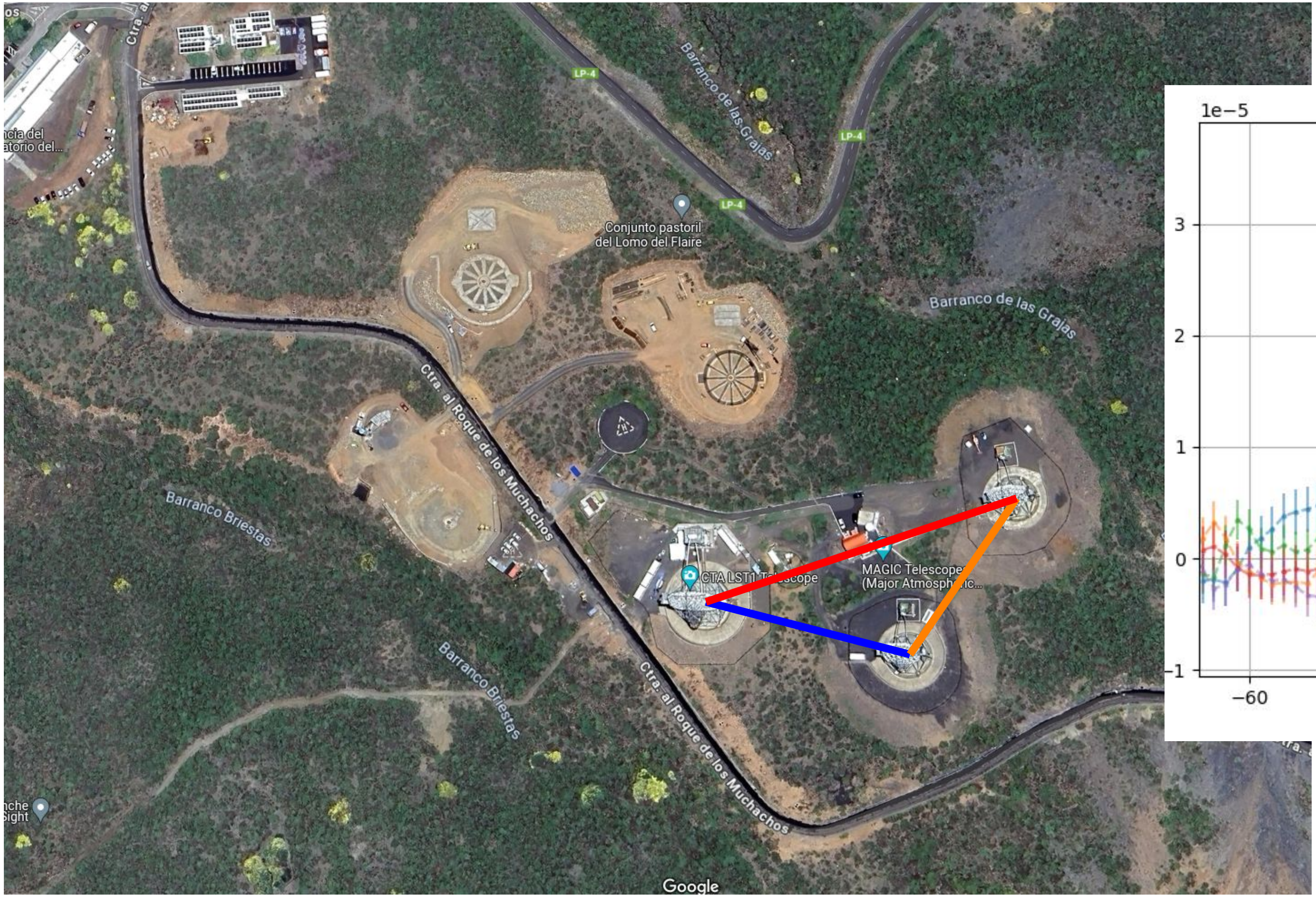


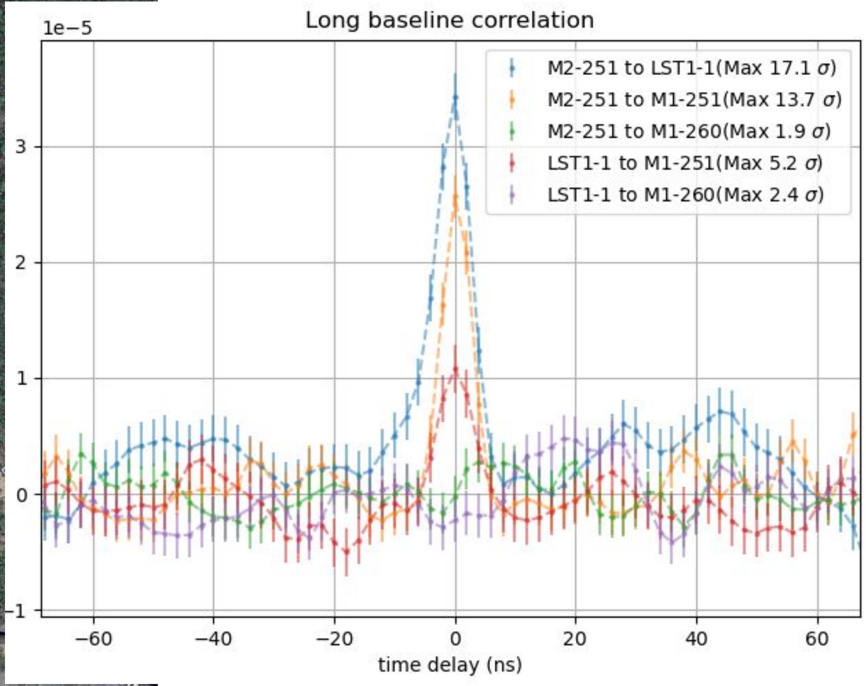
David Fink (MPI Phys)

Future prospects: adding Large Sized Telescopes

- By the end of 2023 we had:
    - Installed the modified backplane. Confirmed VHE observations were not harmed at all
    - Installed optical transmission (backplane -> counting house)
    - Optimal position of optical-filter white target identified
- January 2024 -> all that was needed was for all the experts sitting together and control software to allow our complex measurements

First LST1 correlation signals: Mirzam

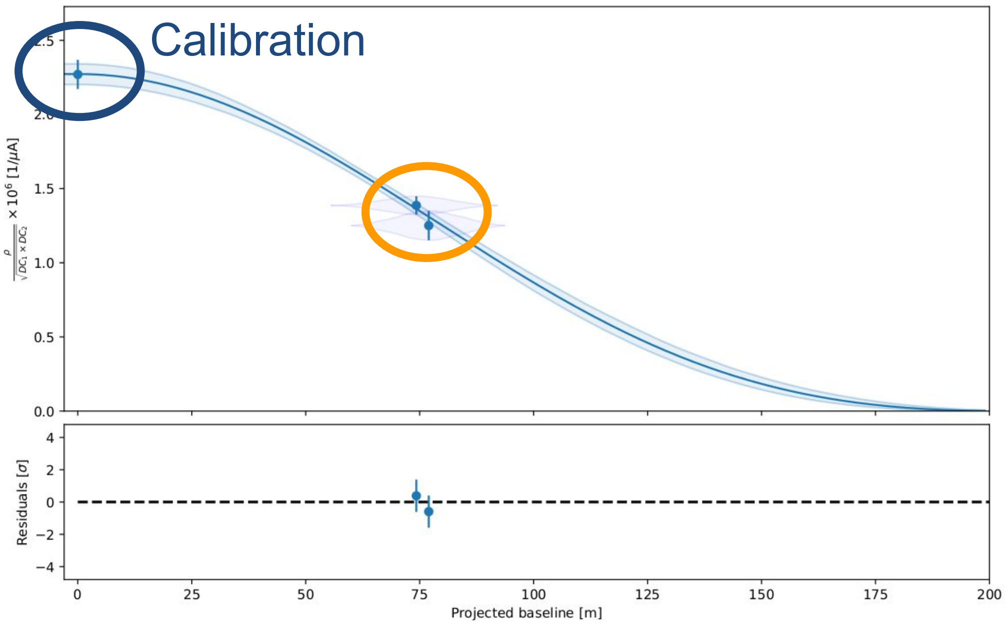




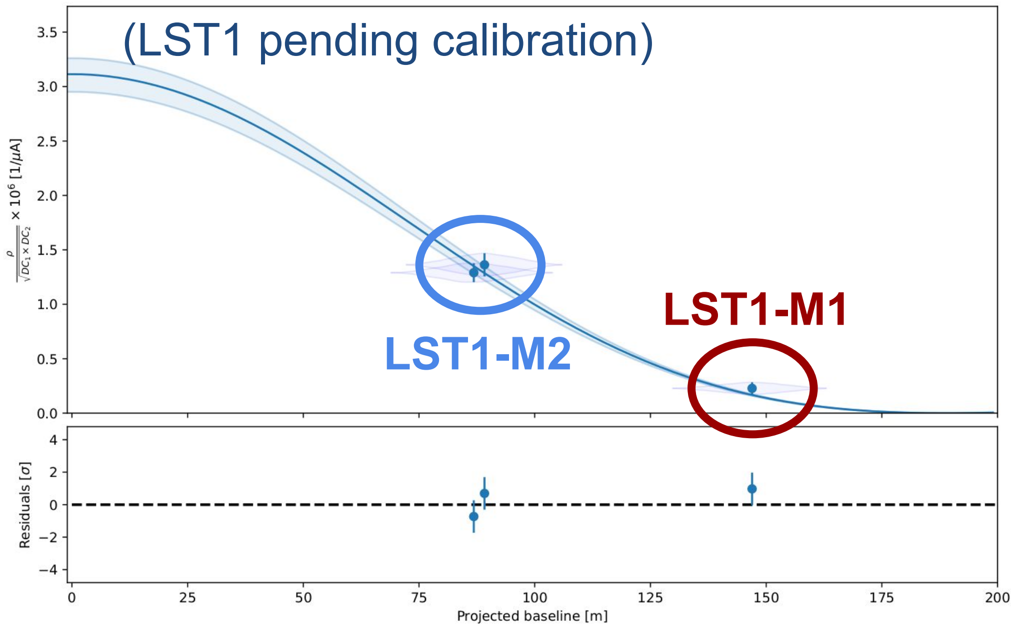
MAGIC-LST1 analysis: calibration ready

- Calibrating a system is much easier when performing cross-calibration

MAGIC-only measurement

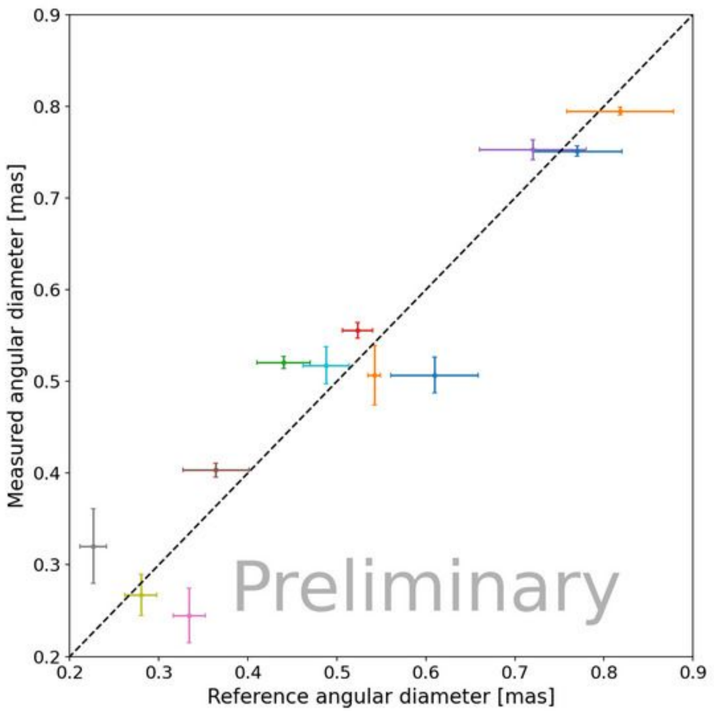


MAGIC-LST1 measurements



MAGIC-LST1 analysis: calibration ready

- Calibrating a system is much easier when performing cross-calibration



A. Cifuentes (SfP)

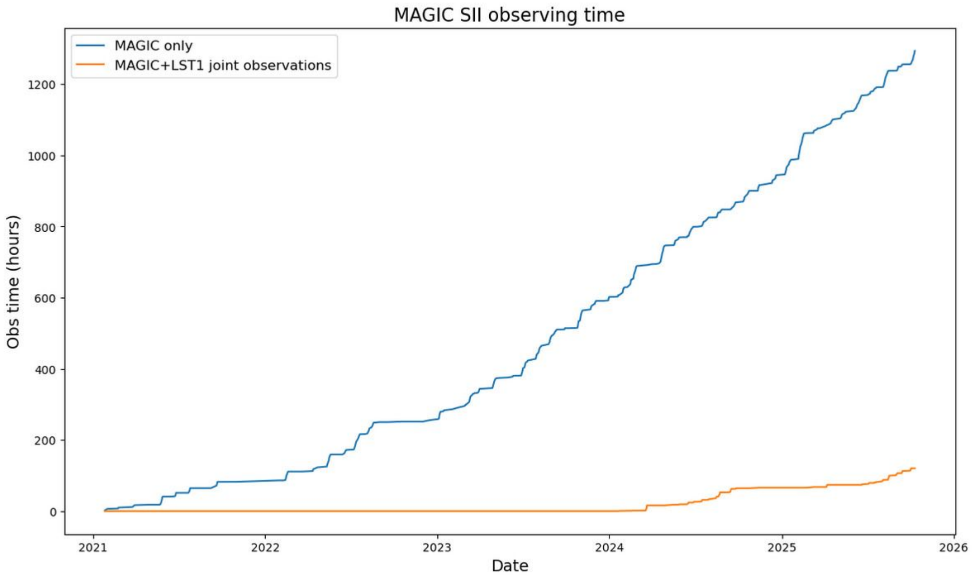
Implications

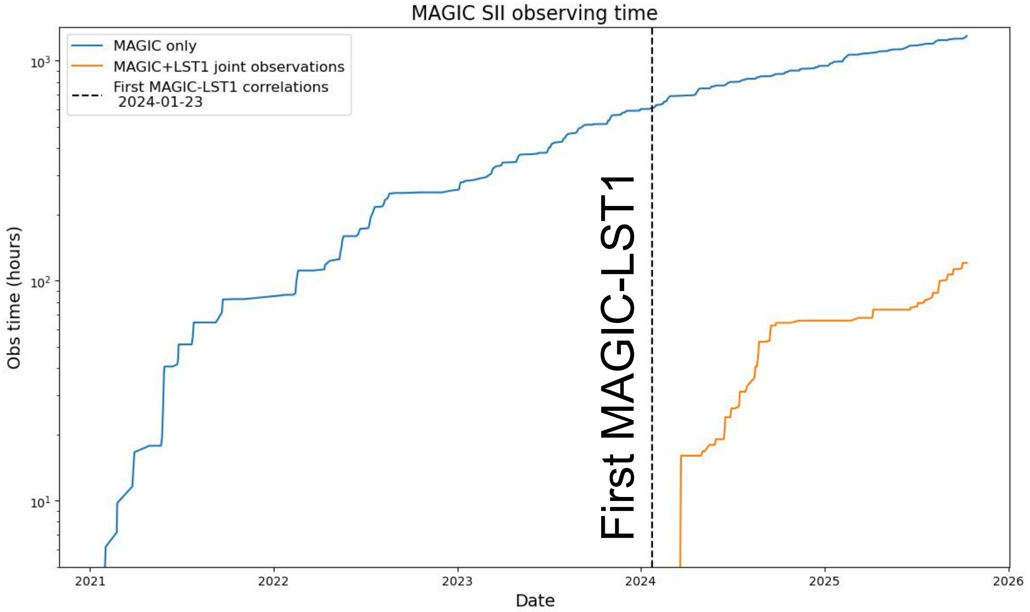
- These measurements have a good amount of implications for MAGIC:
  - LST1 provides a dramatic boost in sensitivity
- More implications for CTAO:
  - The concept proposed and implemented for LSTs work (plus clear plans + funding for all LSTs)
  - Identical concept being implemented for MSTs (see J. Biteau's presentation)
  - Correlator funded (no reason for it not to work as expected)
  - Adding more telescopes to the grid has proven not to be too problematic!

Implications

- Slowly going from MAGIC to MAGIC+LST1:

A. Cifuentes (SfP)





- MAGIC collaboration invested in SII observations (400h/year!)
- Hoping MAGIC+LST1 follows the same trend

MAGIC-LST1 SII: Correlator news

- **Next week** cooling will be connected to the new SII rack: work will start to validate a 12-channel SII correlator

MAGIC-LST1 SII: Correlator news

European Research Council
Established by the European Commission

Signal from LST-1

Signal from LST-2

Signal from LST-3

Signal from LST-4

Signal from MAGIC

Optical fibers

MAGIC CH

12-channel correlator

Rack with one server per digitizer

Higher-bandwidth digitizers

High-bandwidth GPU-GPU transfer

GPU → GPU → Correlation
GPU → GPU → Correlation
GPU → GPU → Correlation
GPU → GPU → Correlation

FFTs

x15 telescope-pairs!

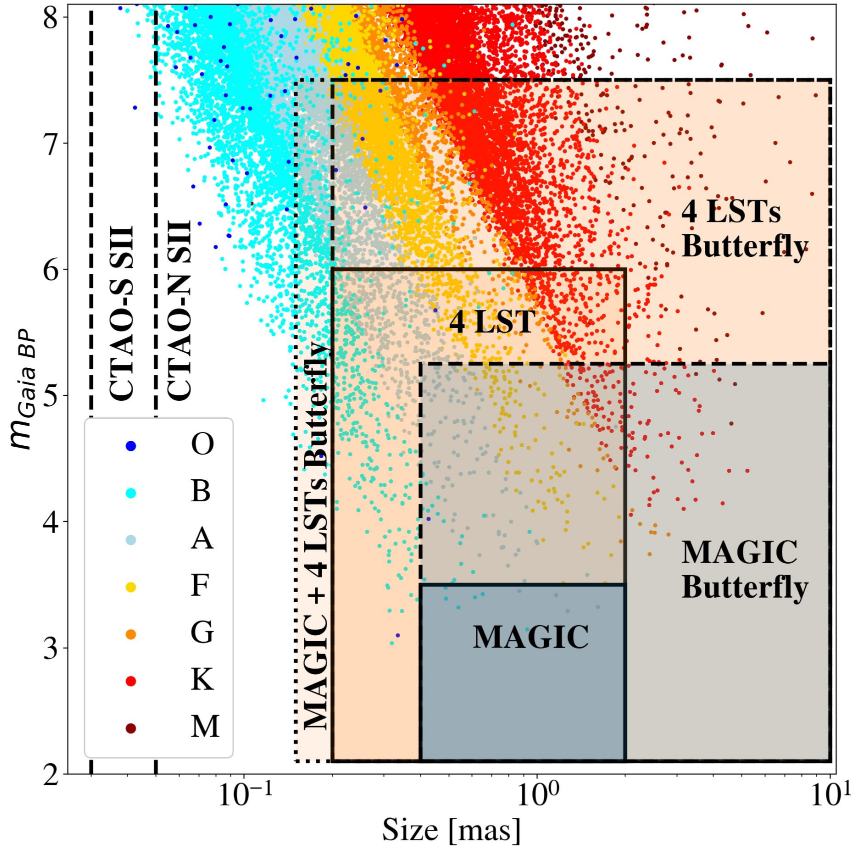
LST-LST correlations dramatically improve sensitivity

- Hardware profiting from the “AI fever”
- Same philosophy as used in MAGIC will be extended to 12 input channels

MAGIC-LST1 SII: New camera proposal

European Research Council
Established by the European Commission

Prospects for an advanced SII camera design



Stellar parameters taken from [Gaia DR3 Apsis (M. Fouesneau+, 2023)]

A Butterfly's Eye Camera for Intensity Interferometry with Cherenkov Telescopes
(J. Cortina et al, submitted)

First IACT on-sky ~20-ps TTS observations coming soon…

See next presentation by F. Frías!

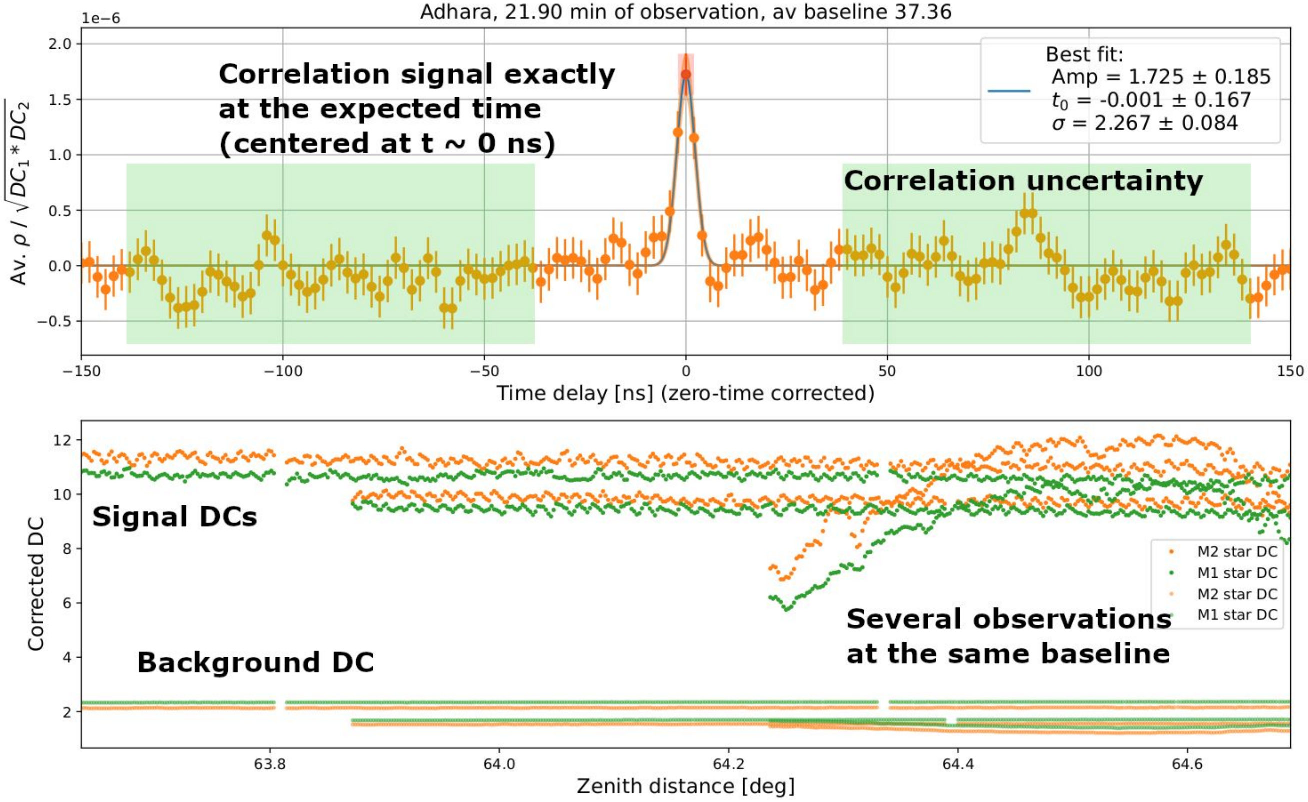
Next steps and conclusions

- CIEMAT will lead the integration of future LSTs (coming in 2026-2027) and next-generation SII GPU-based correlator
  - This demonstrator should be capable of correlating all telescopes from CTAO Northern array
- MAGIC and LST1 recently integrated their scientific exploitation (joint TAC between both collaborations)
- A total of 5 proposals graded in A-B focus on optical observations:
  - Raising interest from the collaborations to perform these measurements
  - Proposal submission is **open to externals**… Let us know if you want to exploit MAGIC+LST-SII observations!


BACKUP

MAGIC-SII Analysis – Our measurement

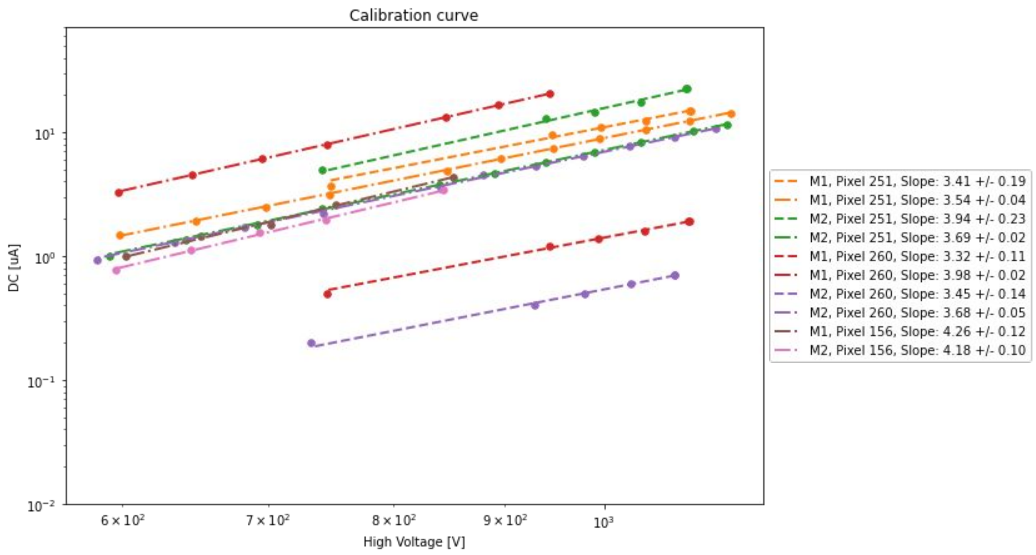
- For a given observation:

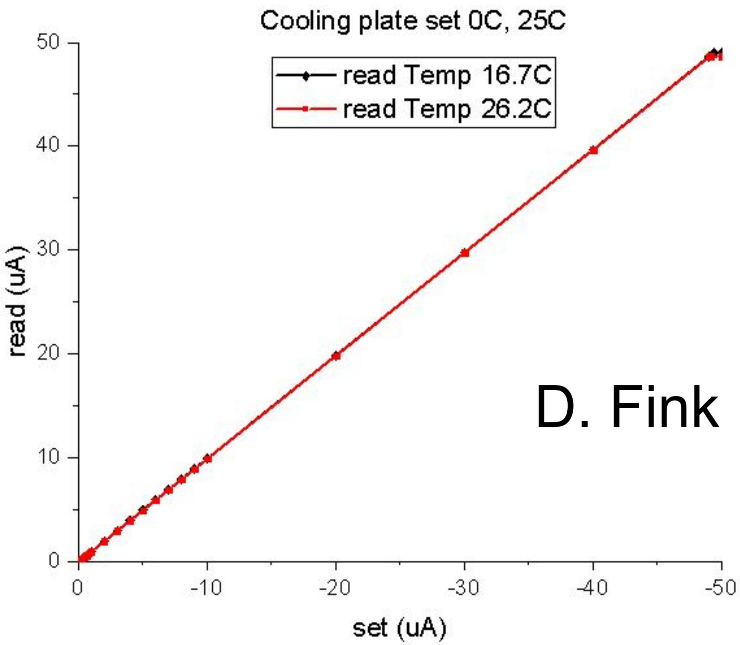


We weight observations with a higher DC (using the standard deviation seen in the background region)

MAGIC-SII Analysis – Our measurement

- Background-pixel DC measurements are calibrated to the used HV and converted to the equivalent signal-pixel DC:



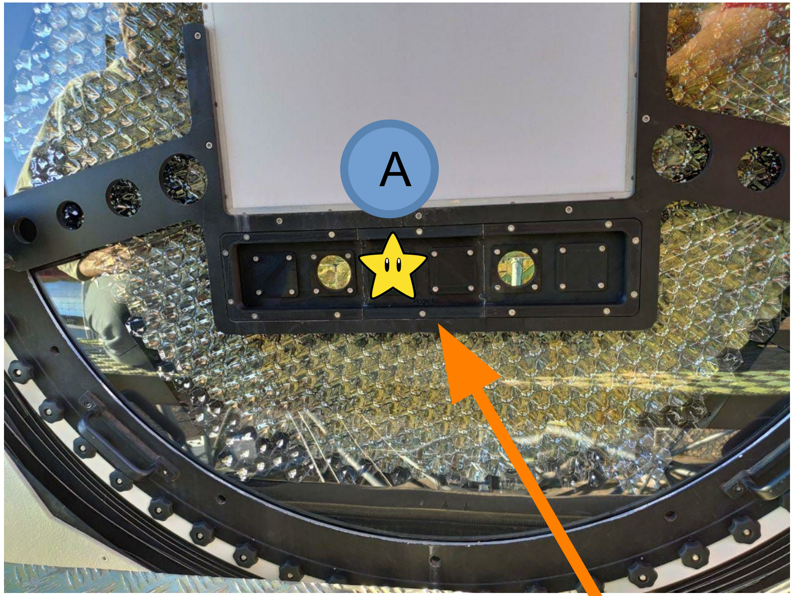


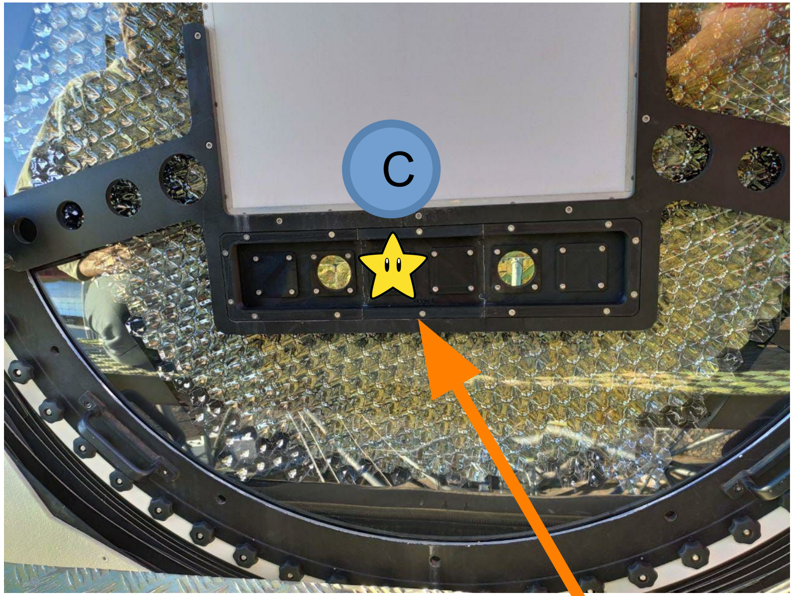
D. Fink

Measured DC is perfectly proportional to the input signal (seen in the lab!)

MAGIC-SII setup: The power of AMC

- This functionality adds enormous versatility to MAGIC: **full-mirror**

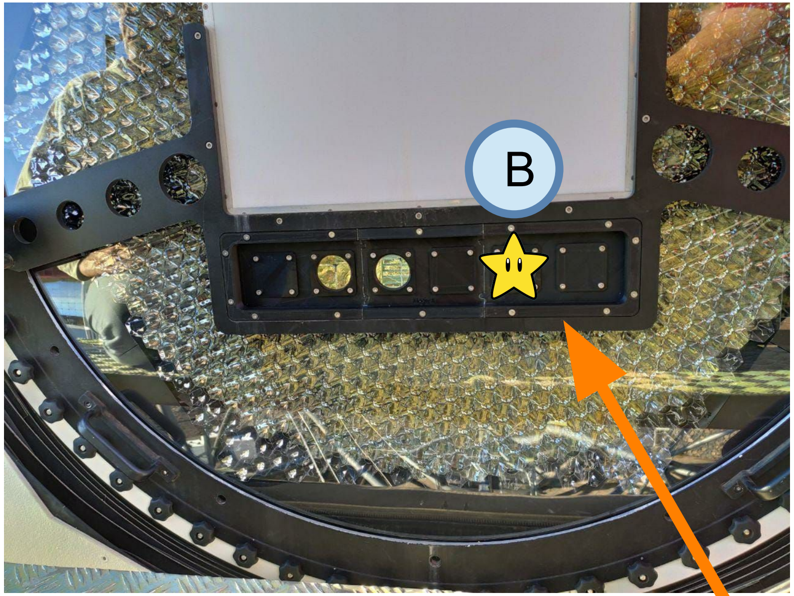


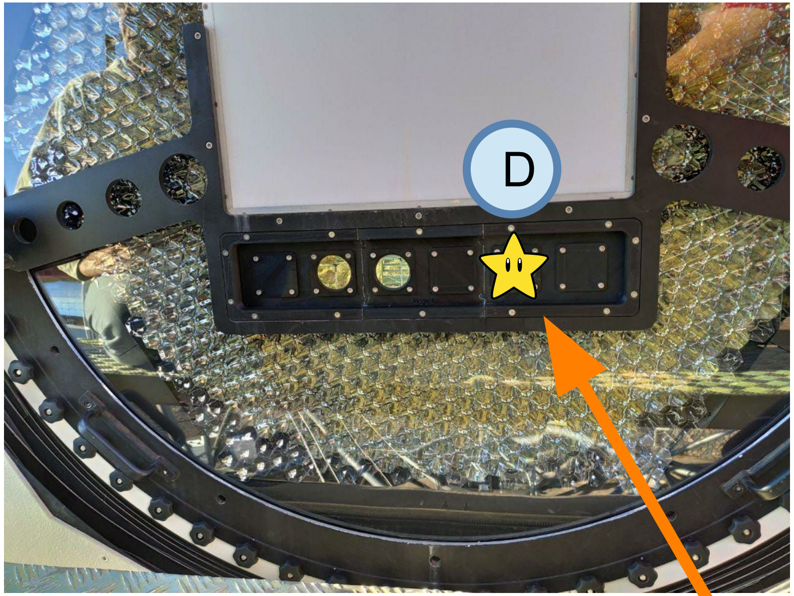


AMC allows to focus all starlight in the pixel you want

MAGIC-SII setup: The power of AMC

- This functionality adds enormous versatility to MAGIC: **full-mirror**

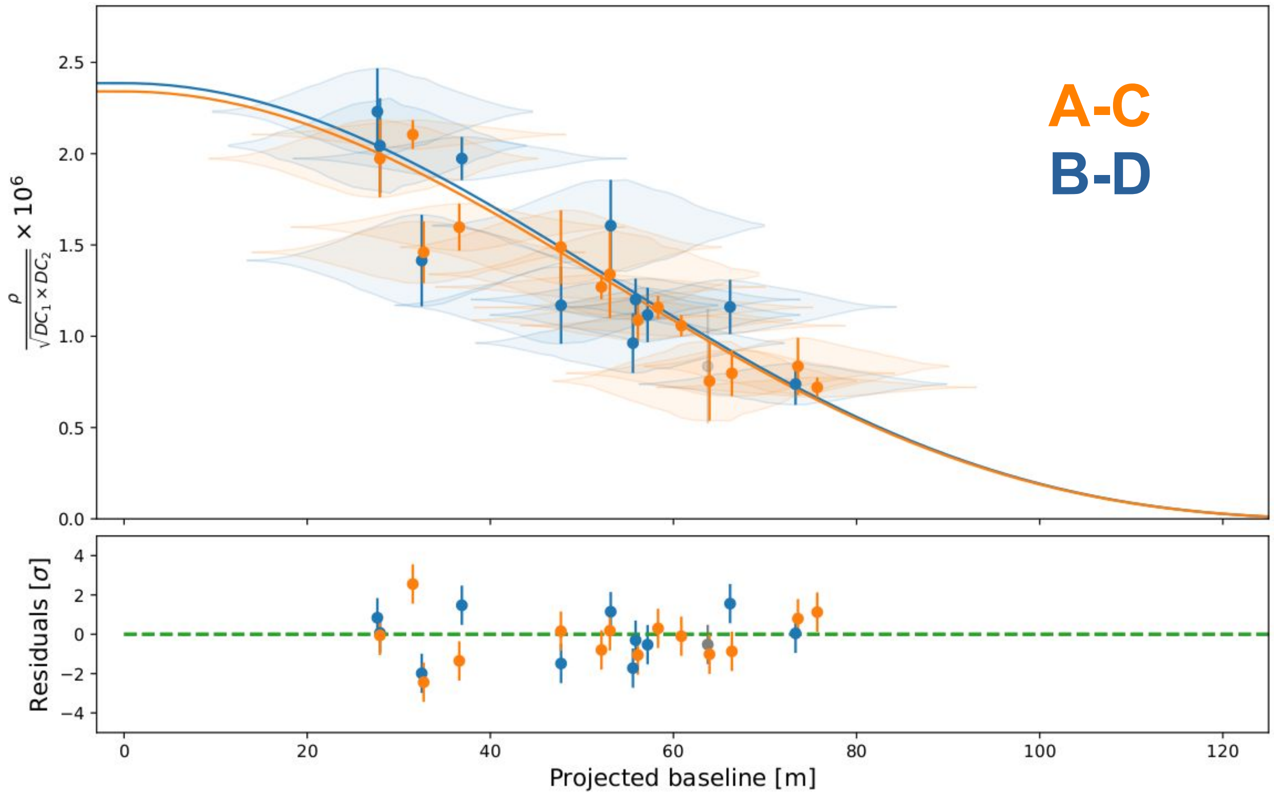




AMC allows to focus all starlight in the pixel you want

MAGIC-SII Analysis – Our measurement

- Only have two telescopes: Adhara provides best brightness + UV coverage



- Adhara dominates the determination of our ZBC
- How consistent is the analysis of A-C vs B-D?
- Allows to test the dependence on pixel gains, transmission, etc...

ZBC: The constant of our system

- From HB&T, we know that the expected correlation:

$$\overline{c(d)} = \langle \Delta i_1(t) \Delta i_2(t) \rangle = e^2 A^2 \alpha^2 n^2 |\gamma_d(0)|^2 \Delta\nu \Delta f \qquad (4.28)$$

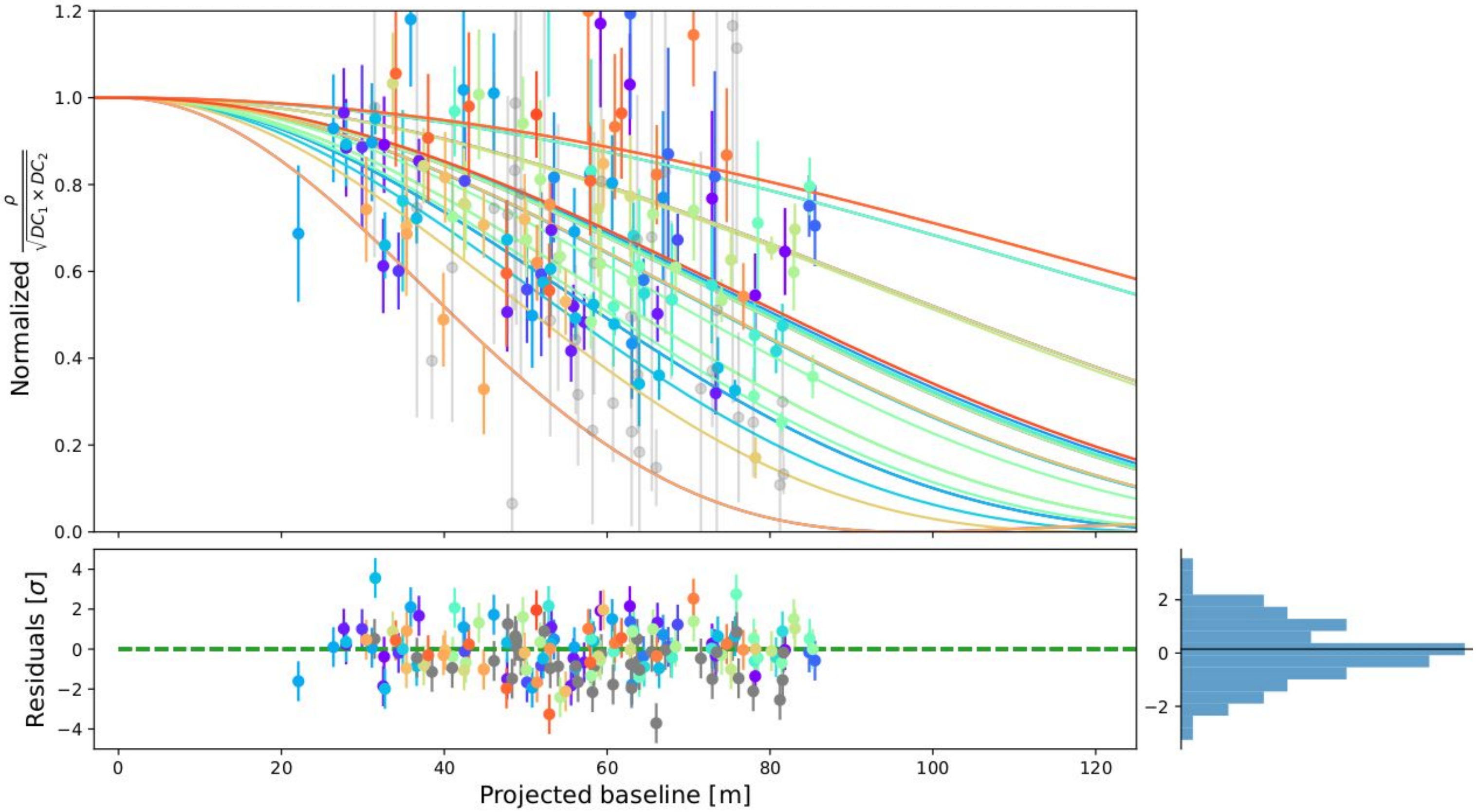
- After dividing by the flux, the remaining correlation should be:

- But as with our setup, our “flux” is the DCs (different gain than the correlation):

Any time evolution in the DC gain will be a **systematic**

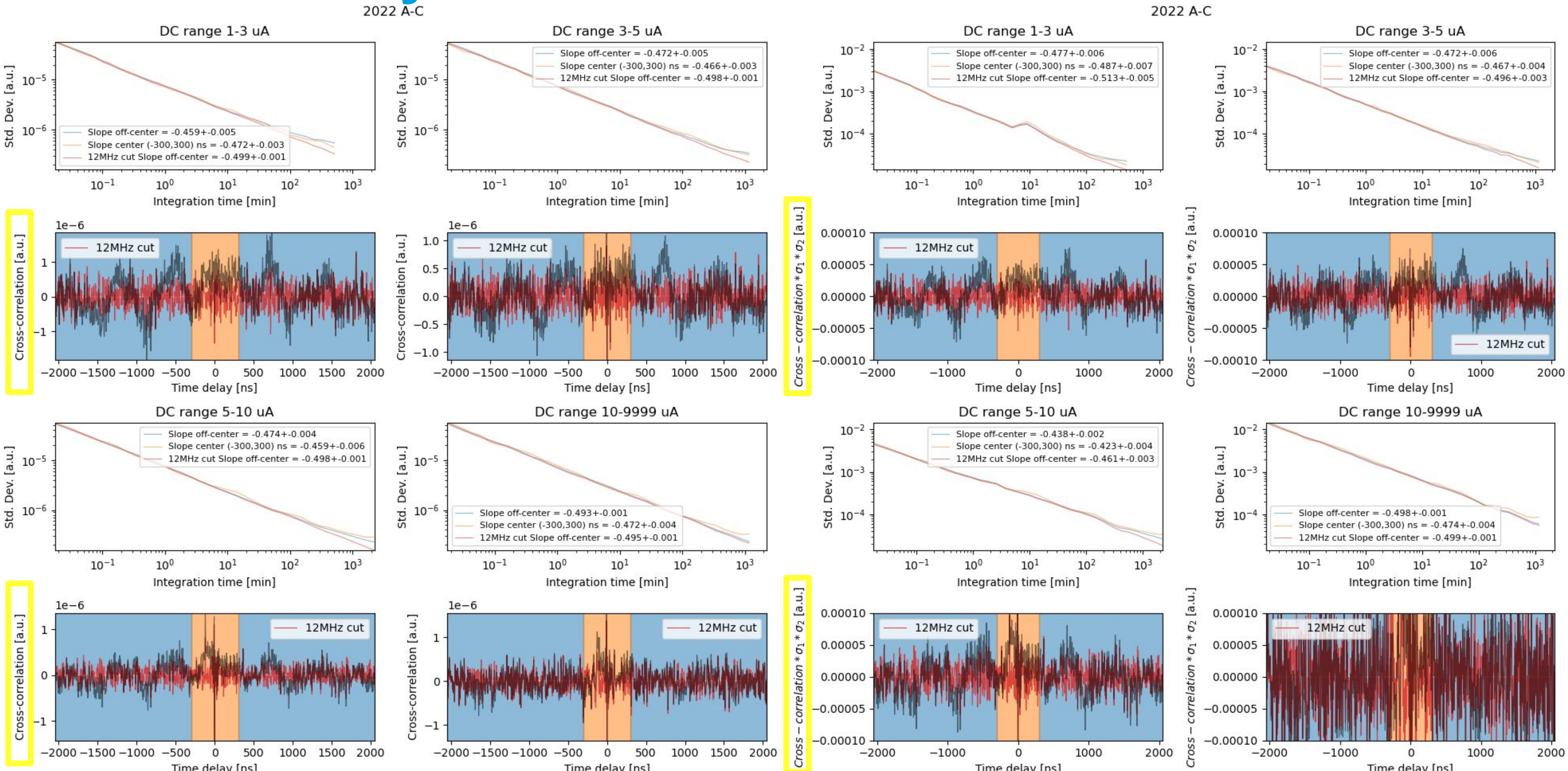
MAGIC-SII: Results

- Combined analysis of all sources: statistical residuals



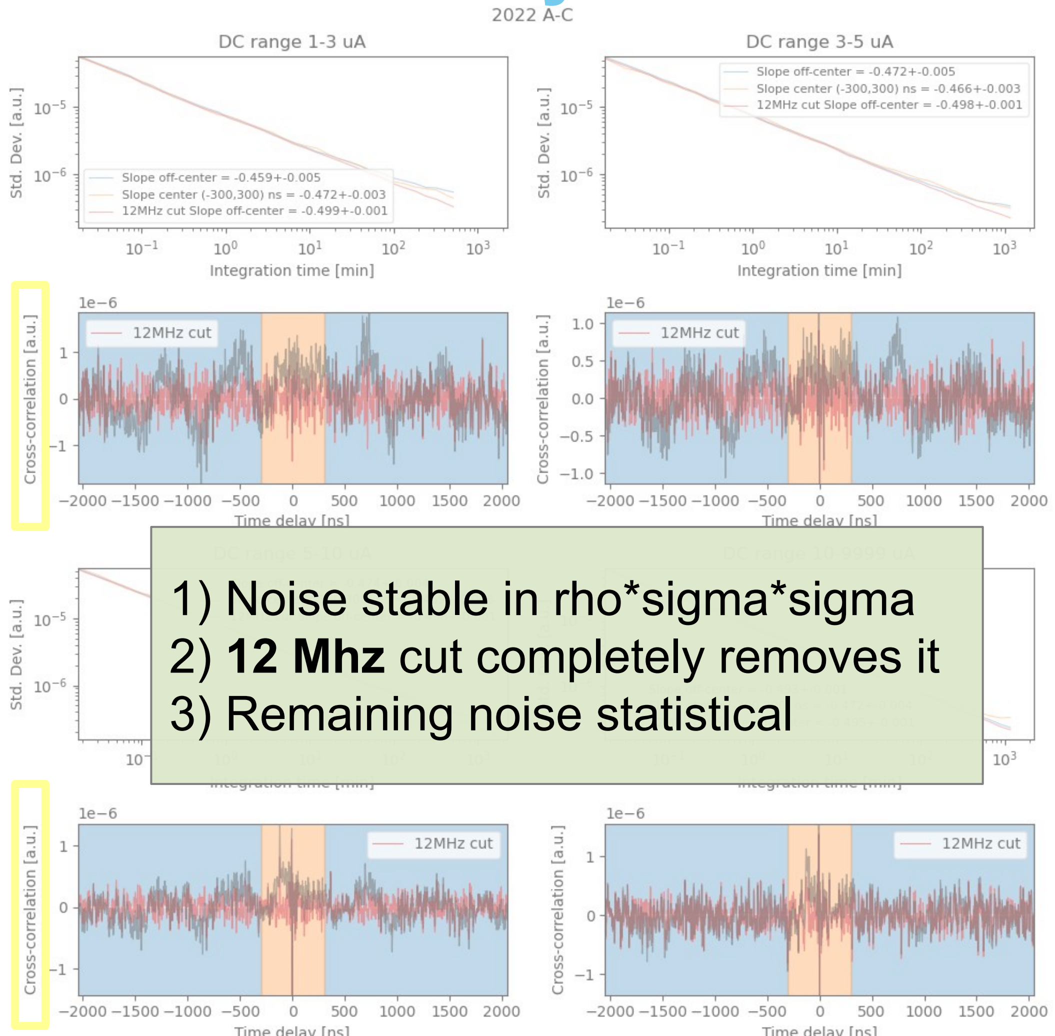
MAGIC SII Systematics: Residual noise

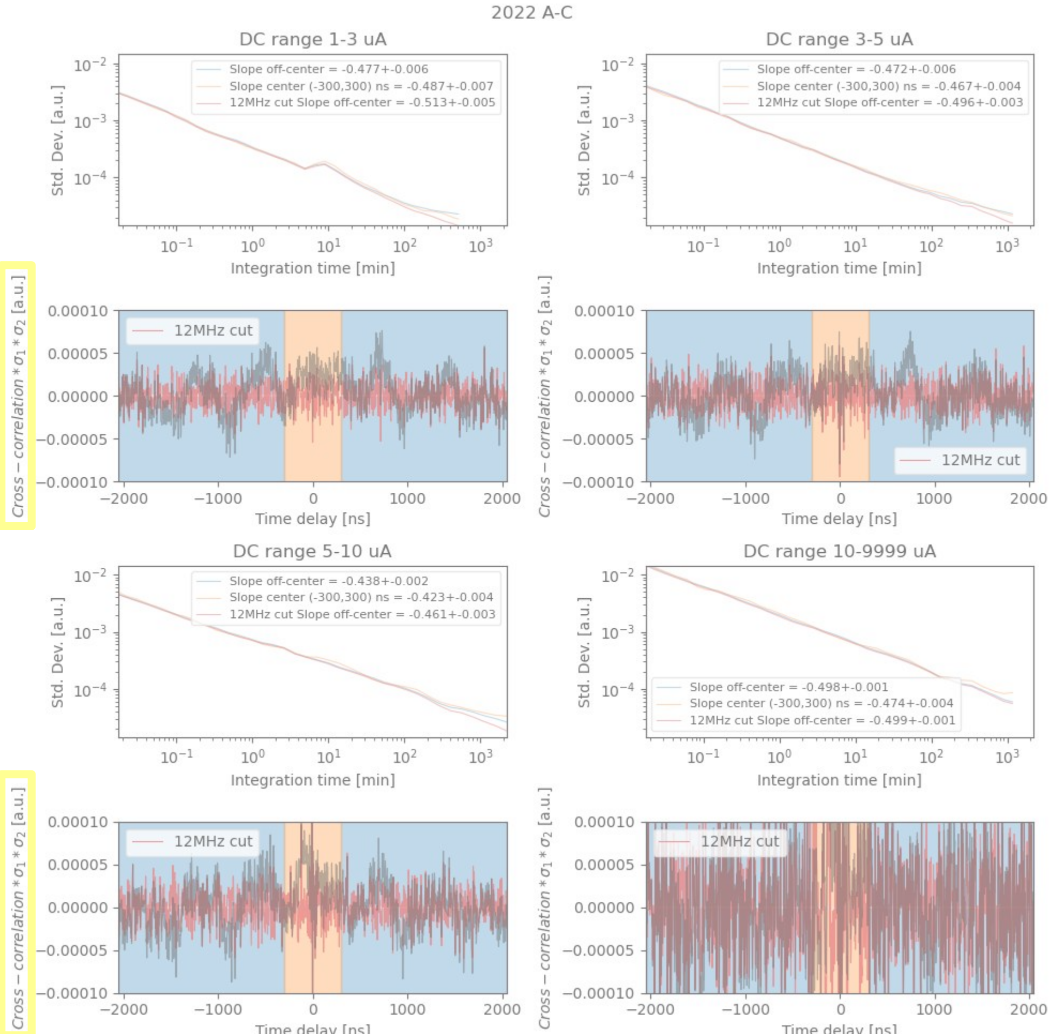
I. Jimenez



MAGIC SII Systematics: Residual noise

I. Jimenez

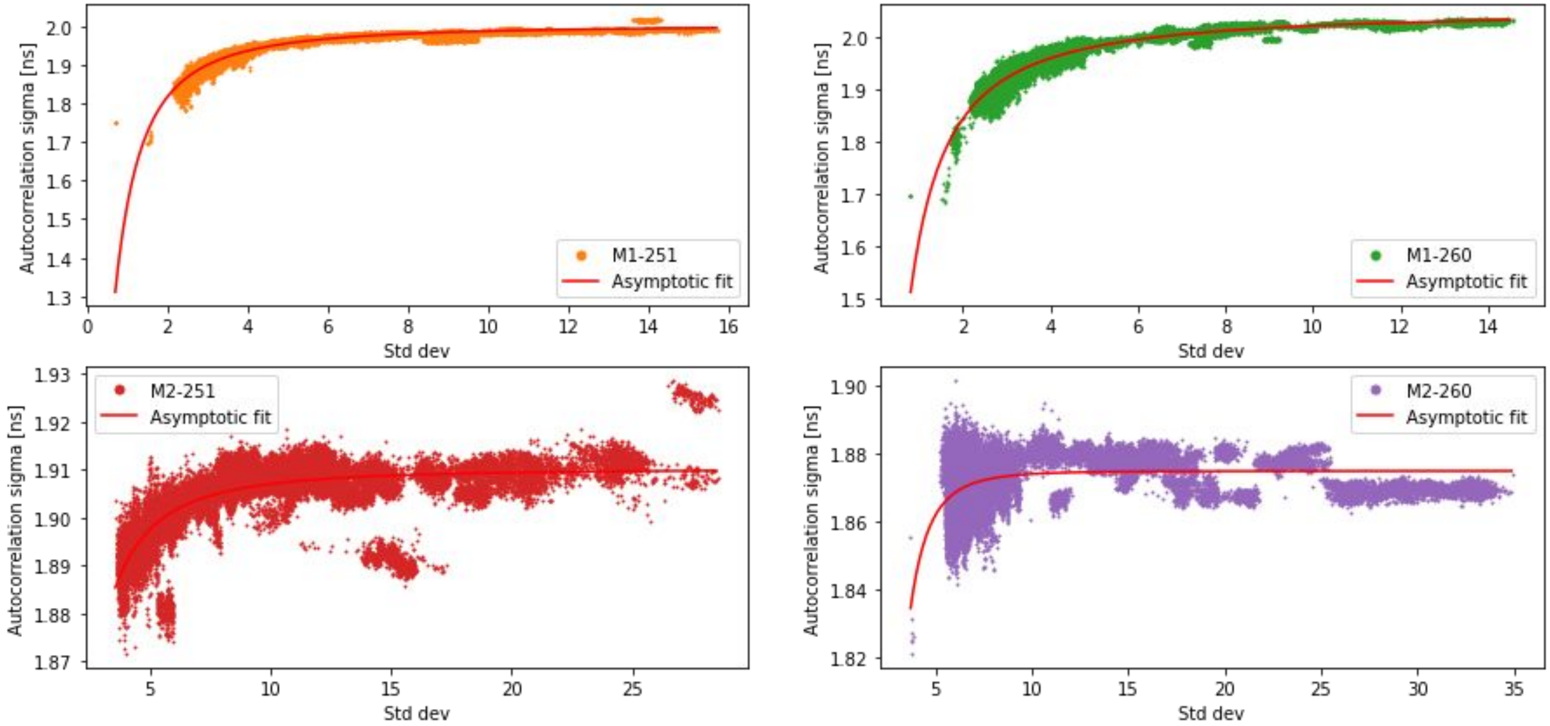




1) Noise stable in rho*sigma*sigma
2) **12 Mhz** cut completely removes it
3) Remaining noise statistical

MAGIC SII Systematics: Signal bandwidth

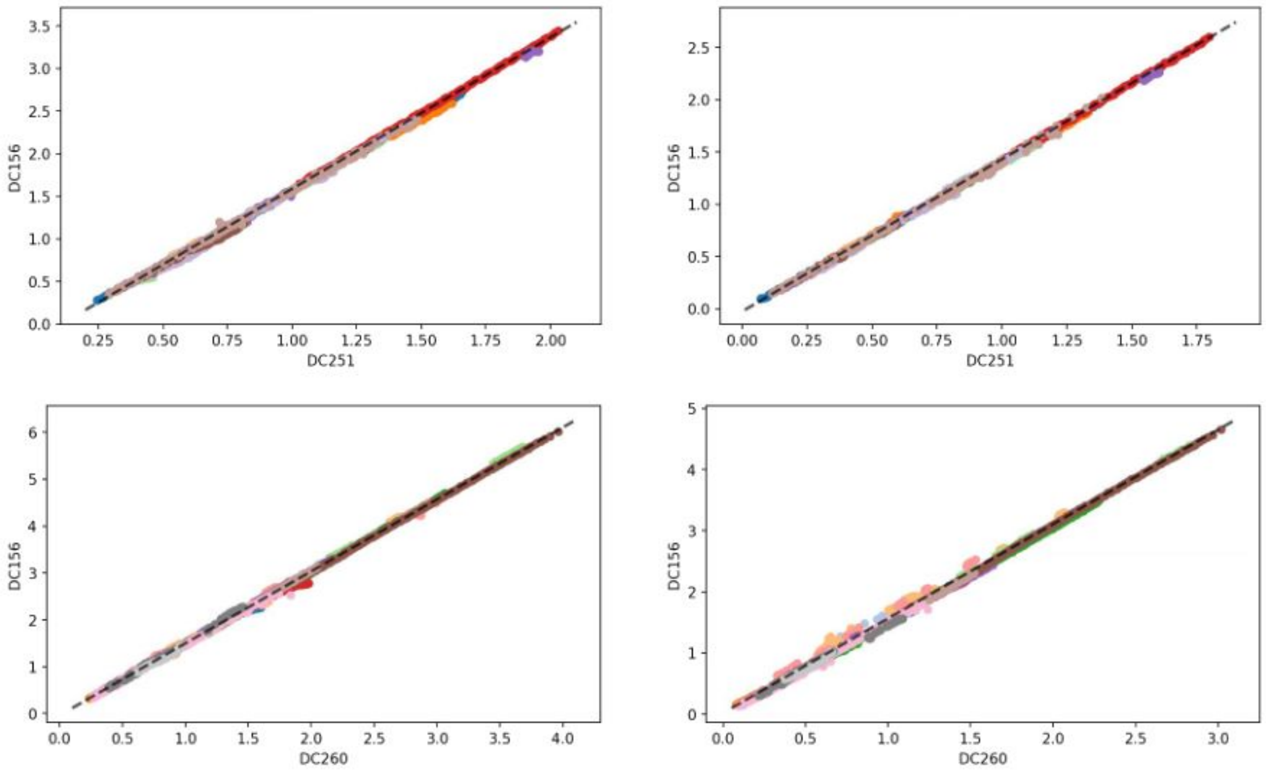
- Computing autocorrelation allows to test the stability of the signal bandwidth



Autocorrelation depends on DC level (few photons -> elec. noise dominates)

MAGIC SII Systematics: Background evaluation

- Full-mirror observations → Simultaneously measures NSB with two pixels



M. Fiori