CANARY on-sky

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Garching

CANARY 101

- MOAO technology demonstrator for EAGLE
  - The proposed E-ELT MOAO instrument
  - MOAO: Multi-Object AO
- On 4.2m William Herschel Telescope
  - Visitor instrument
  - First light 2010
  - Second light 2012
- 4 NGS (3 open-loop, 1 closed-loop truth senso
- 1 LGS
  - 3 more May 2013
- On-axis correction
  - 1 MOAO channel
  - Open-loop correction

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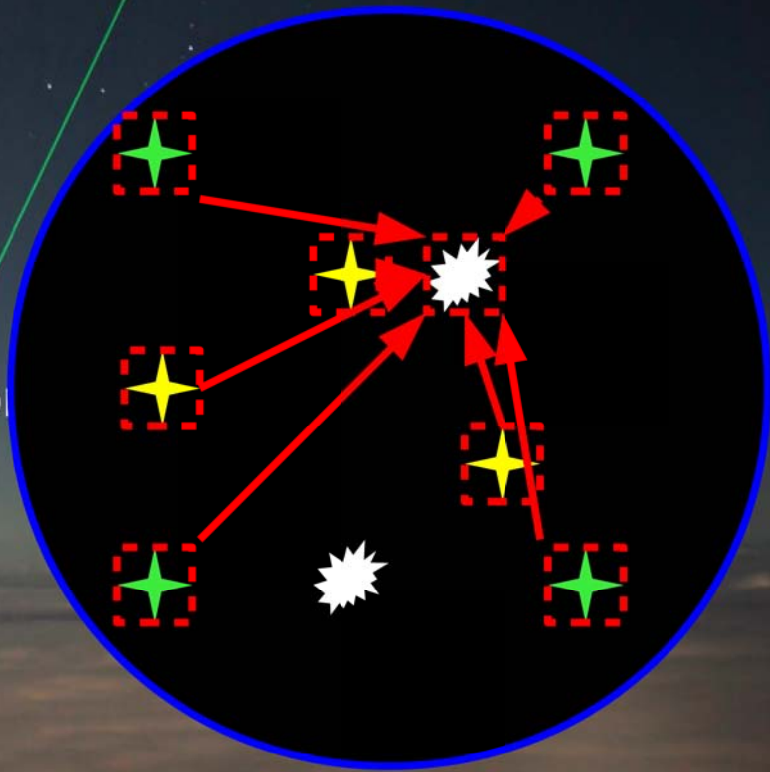
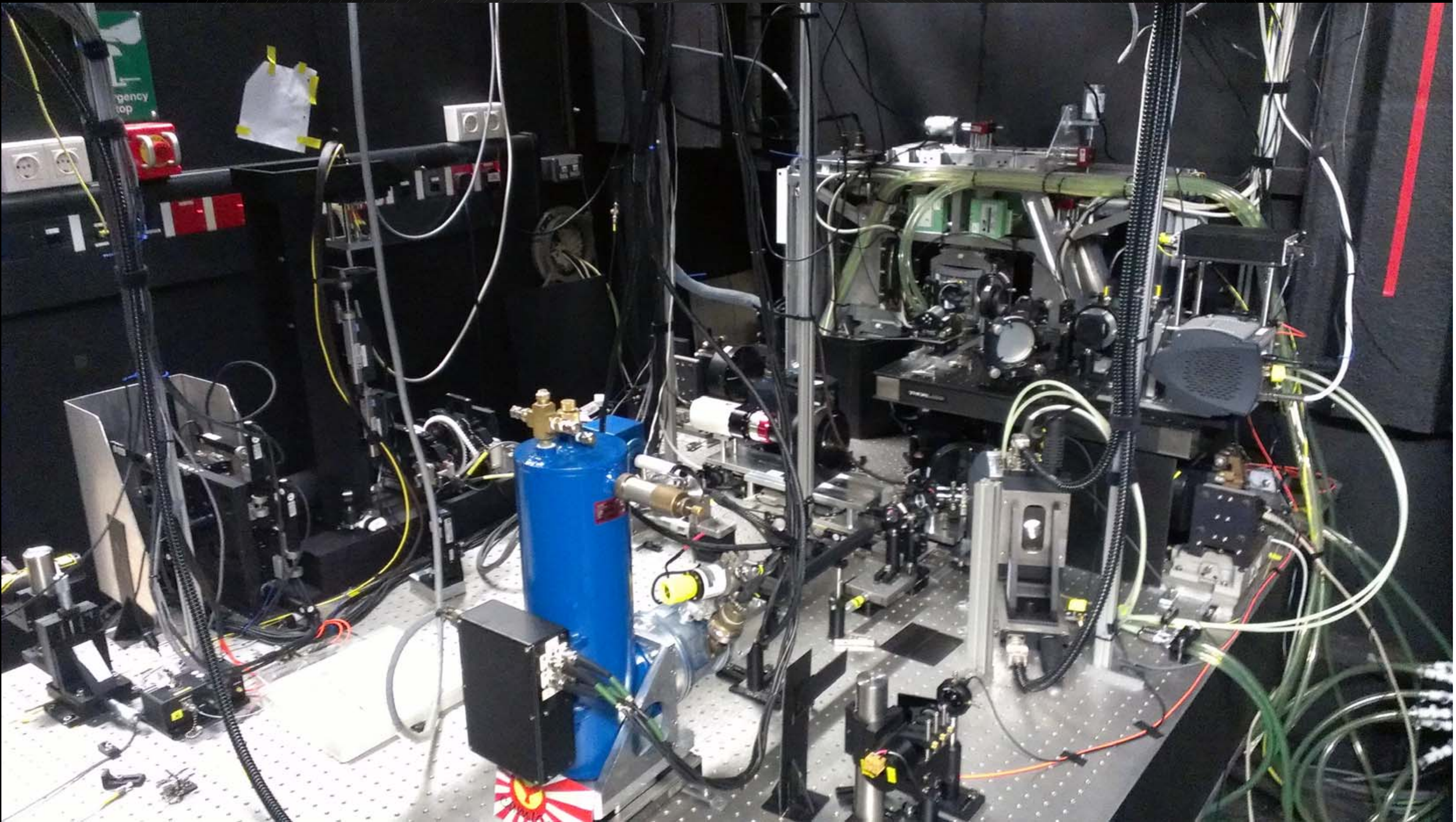


The CANARY bench



CANARY Real-time control

- Uses DARC
  - The Durham AO Real-time Controller
  - Downloadable from Sourceforge
  - Completely generic
    - CANARY is one usage example
- Principally a CPU based controller
  - Optional FPGA front-end
  - Optional GPU reconstruction
  - Modular design ideal for CANARY
    - Lots of algorithms to test and try

CANARY experiences

- A complex system
- Multiple wavefront sensors (of different types)
  - LGS and NGS
- Multiple offload loops
  - TT, LGS steering and alignment, LGS asterism rotation and tracking, telescope offloads (autoguider etc)
- Multiple trigger signals
  - Lasers at 10kHz, synchronised with LGS camera at 100-500Hz and range gate at 10kHz
  - NGS triggers

Synchronisation

- Using a custom programmable FPGA based trigger box
- Multiple BNC and fibre outputs
  - And inputs (unused)
- Provides the required flexibility

Algorithms

- Lots of algorithms tried and used
- Lots of practical experience garnered
  - Lets have a look at some of the more interesting things...

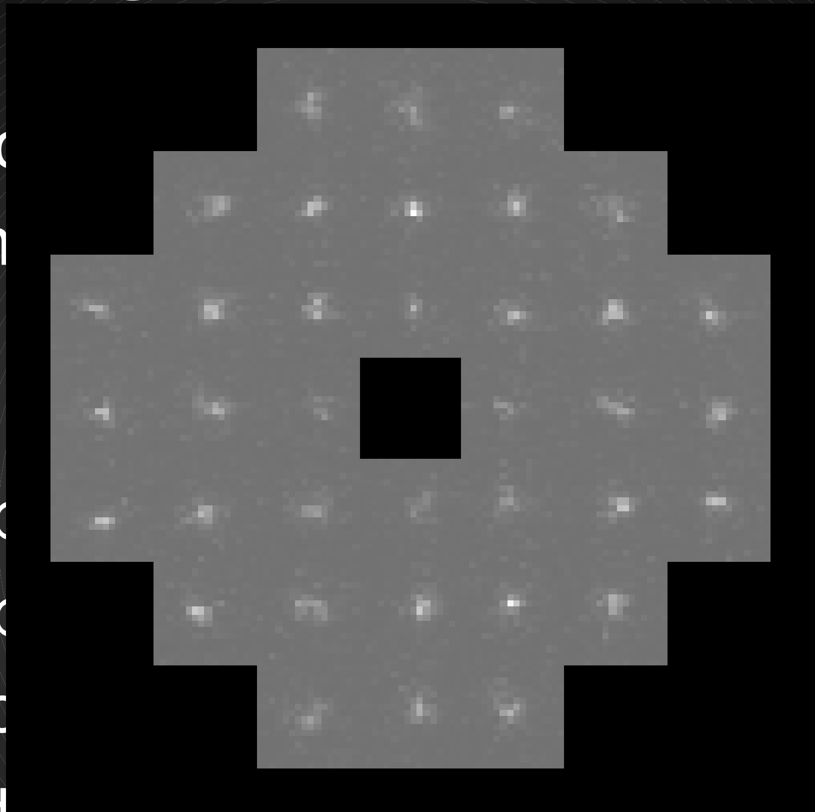
Image calibration

- If background subtraction is wrong:
  - Poor slope estimate → poor reconstruction
  - Critical performance loss for open-loop AO
- So, we use a “brightest pixel” selection algorithm to help
  - In each sub-aperture, the N (typically ~12-40) brightest pixels are selected
  - All others are set to zero
    - i.e. fall below the background

Brightest pixels

- But this can introduce bias
  - So, improvements made:
    - The N+1th brightest pixel value can be used as the threshold
    - This is subtracted from all brighter pixels
    - Reduces bias
  - Further improvements:
    - N+1 → N+M pixels can be averaged to be used as the threshold
    - Reduces the randomness (due to read noise) in the threshold
- Used with great effect on CANARY
  - Slope variance and WFE reduced

Brightest pixels



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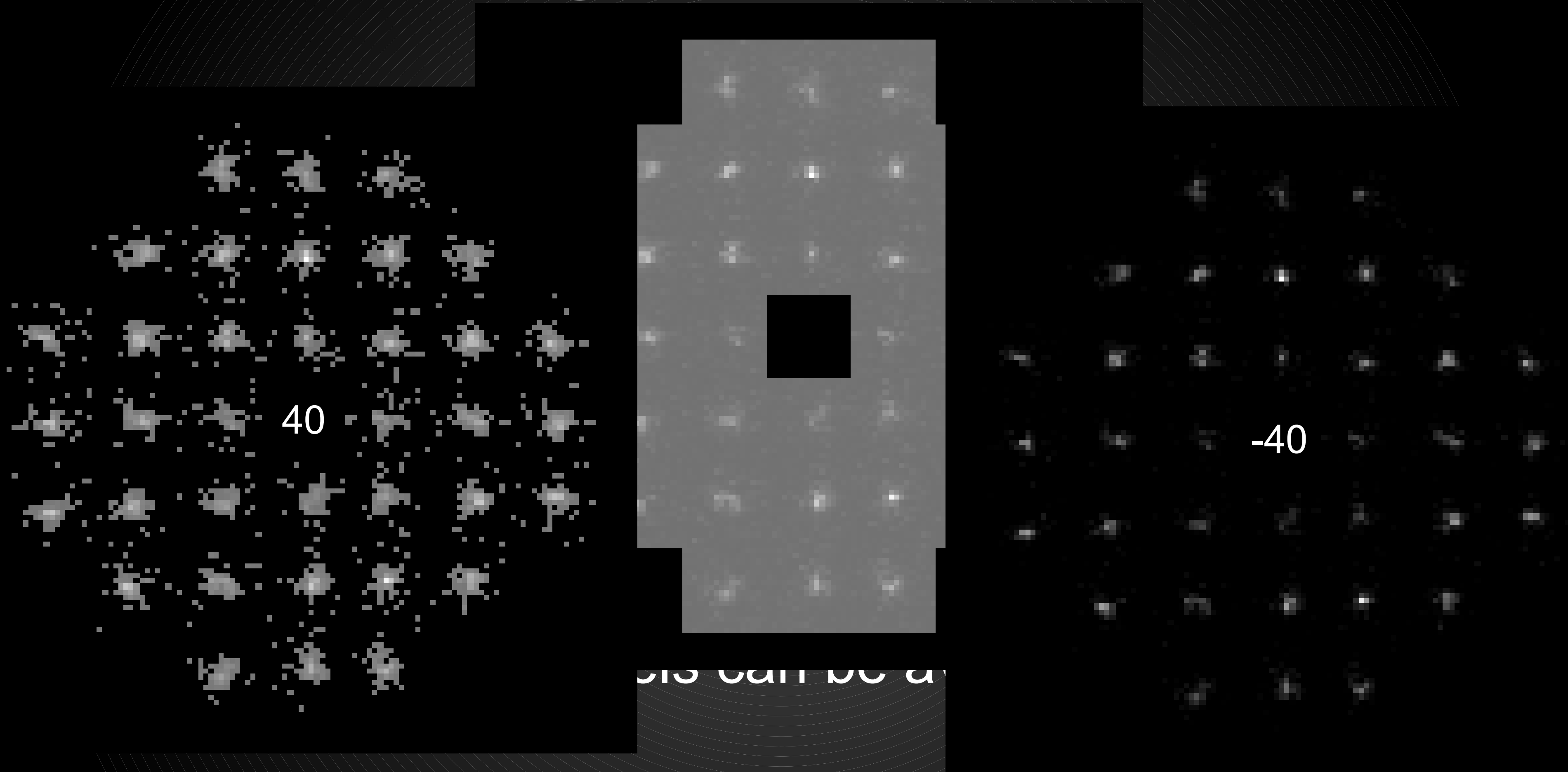

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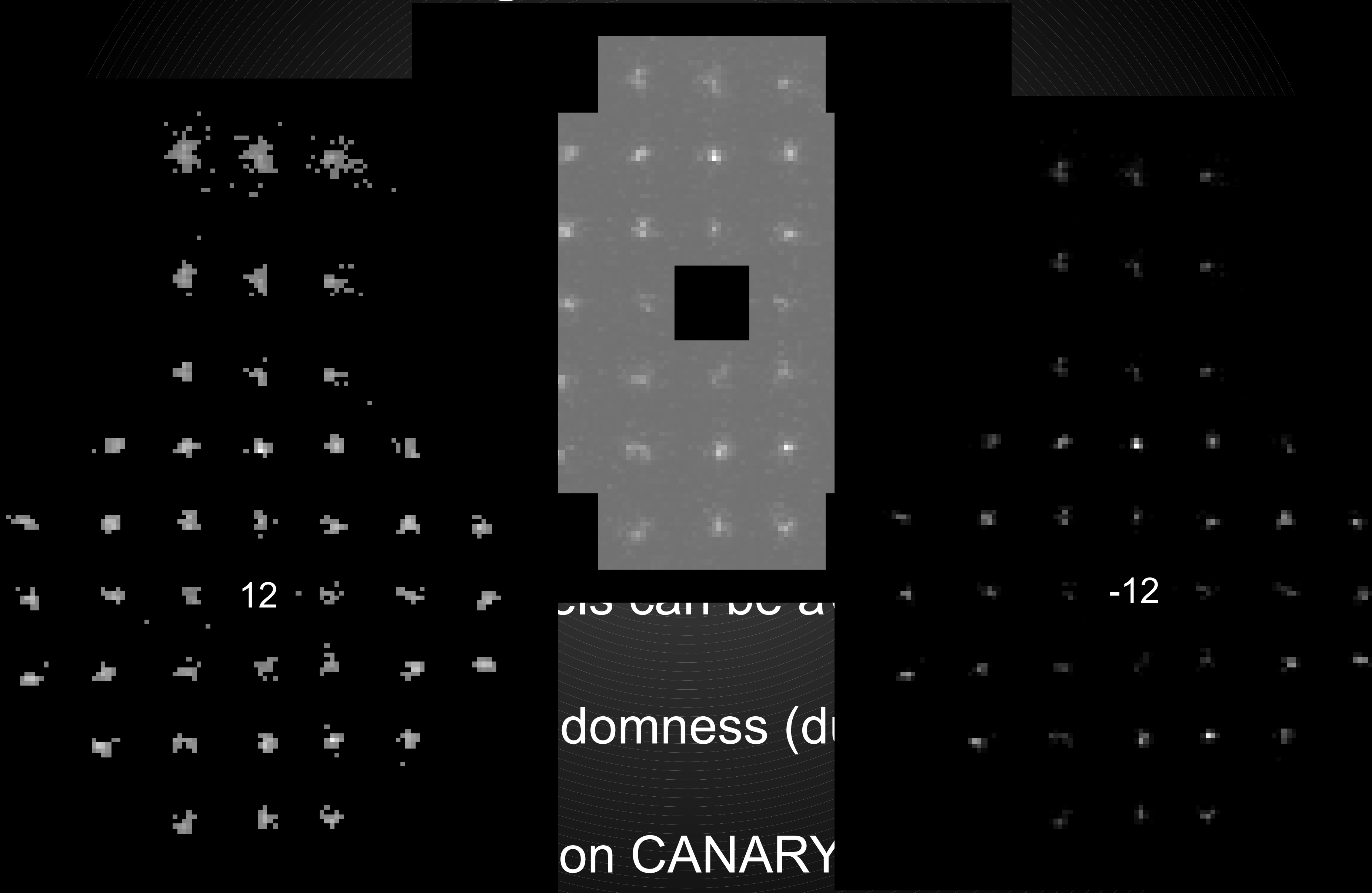

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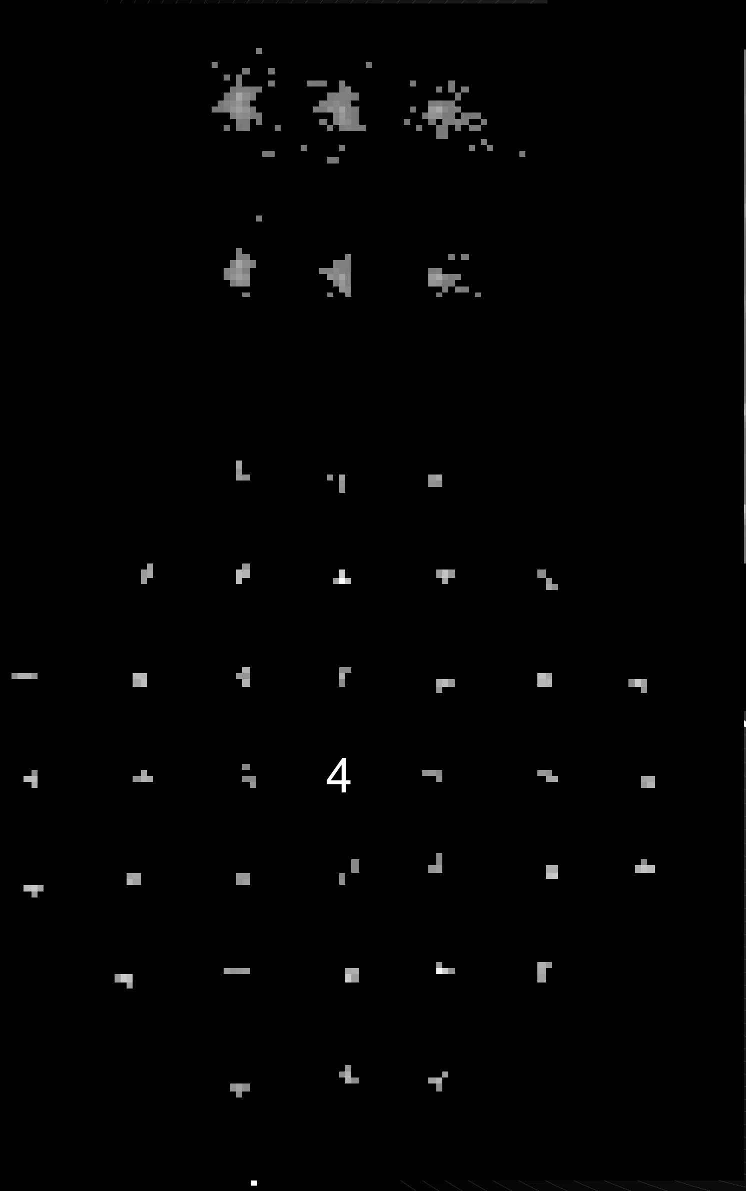

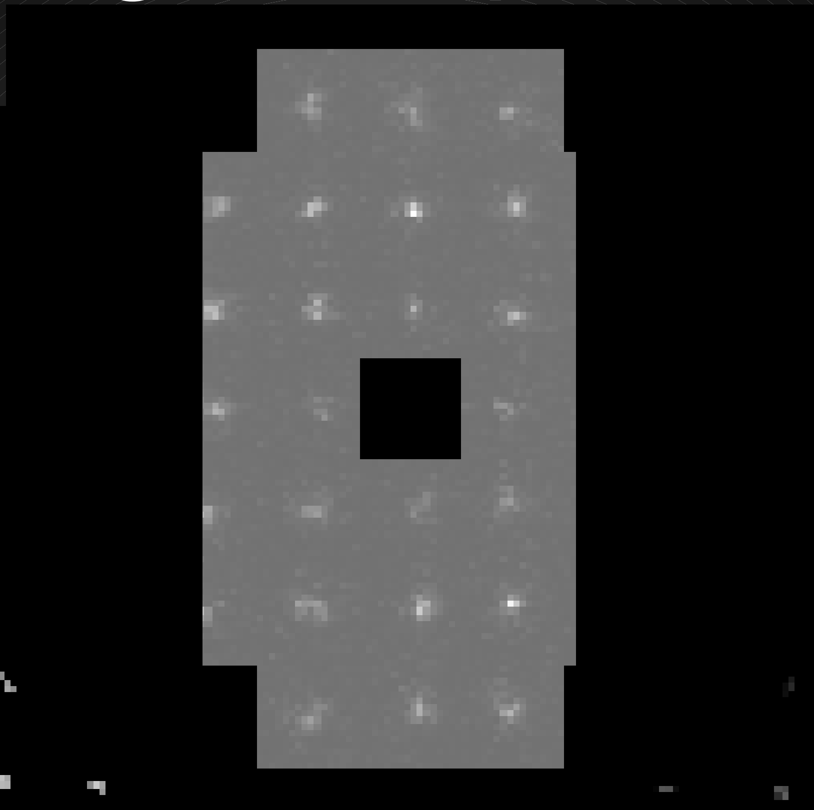

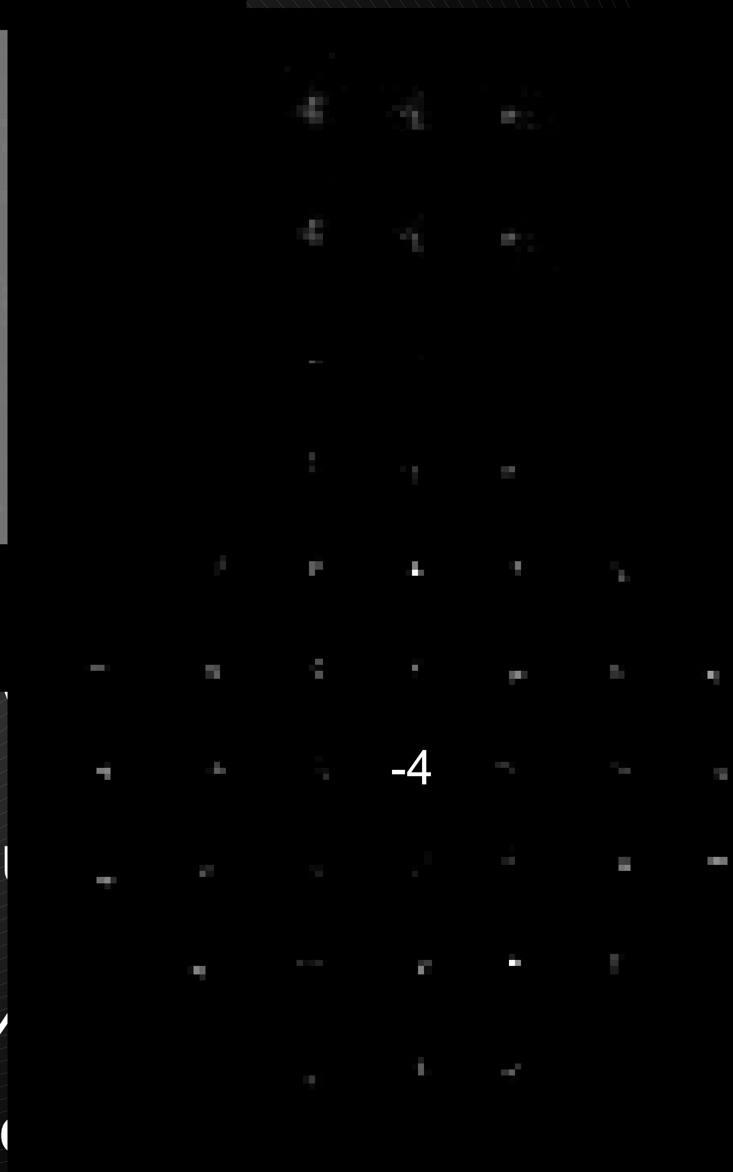

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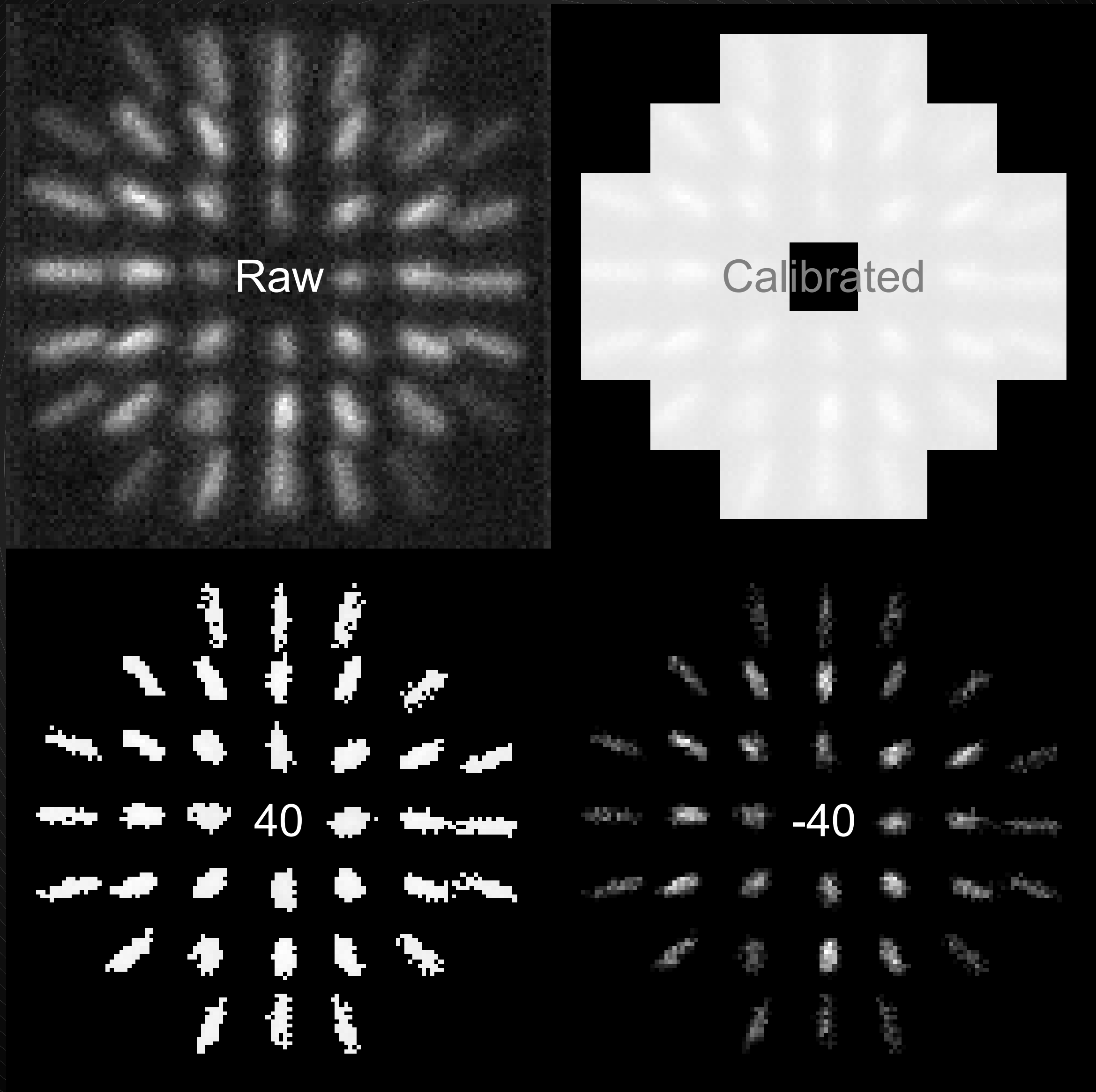
on CANARY

WFE reduc

And LGS example



Adaptive windowing

- CANARY off-axis WFS are open-loop
  - Large spot motions → large sub-apertures
- Spot tracking
  - Per sub-aperture or as groups (for TT)
  - Sub-apertures are shrunk
  - Adaptive windowing switched on
    - Sub-aperture location defined by open-loop integrator based on current spot location
      - User defined gain
  - Typically we reduce sub-aperture area by x4

Adaptive problems

- Noise or short bursts of bad turbulence can mean spots get lost
- Sub-apertures then wander
  - Until they fix on a spot (which may be from a neighbouring sub-aperture)
- So: Limit the range of motion
- But: Can still get stuck at the edge of allowed motion (e.g. vignetted sub-apertures or when TT offload is wrong)
  - This is noticeable for CANARY
  - But with 80x80 sub-apertures and >6 WFS not
  - So, automatic unsticking logic added
    - If sub-aperture is at the edge of allowed motion for some user defined time, resets to the centre
    - Worked well even under very poor seeing conditions

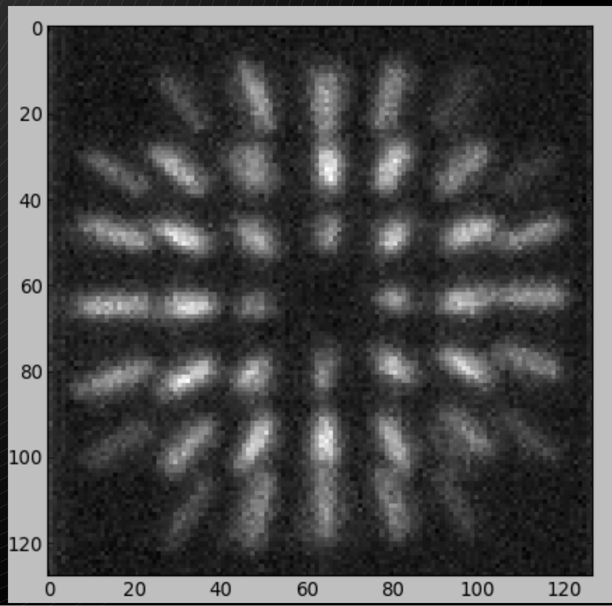
Sub-aperture resizing

- User controlled (or scripted)
- Nothing clever in the real-time core
  - Though something could easily be added...!

Adaptive windowing

Correlation WFSing

- CANARY uses Rayleigh lasers
- Spot elongation can be controlled by adjusting the laser range gate
  - Allowing studies of different spot elongations
  - Well suited for testing correlation based wavefront sensing
    - Linear, ideal for open-loop WFS



Solar correlation primer

- Reference image taken from a single sub-aperture from a single frame
  - Used for all sub-apertures
  - Typically updated every 30s
  - Insensitive to Tip/Tilt between successive reference images

    - Jump in science image position
    - But this doesn't matter since science integration time is ~few seconds

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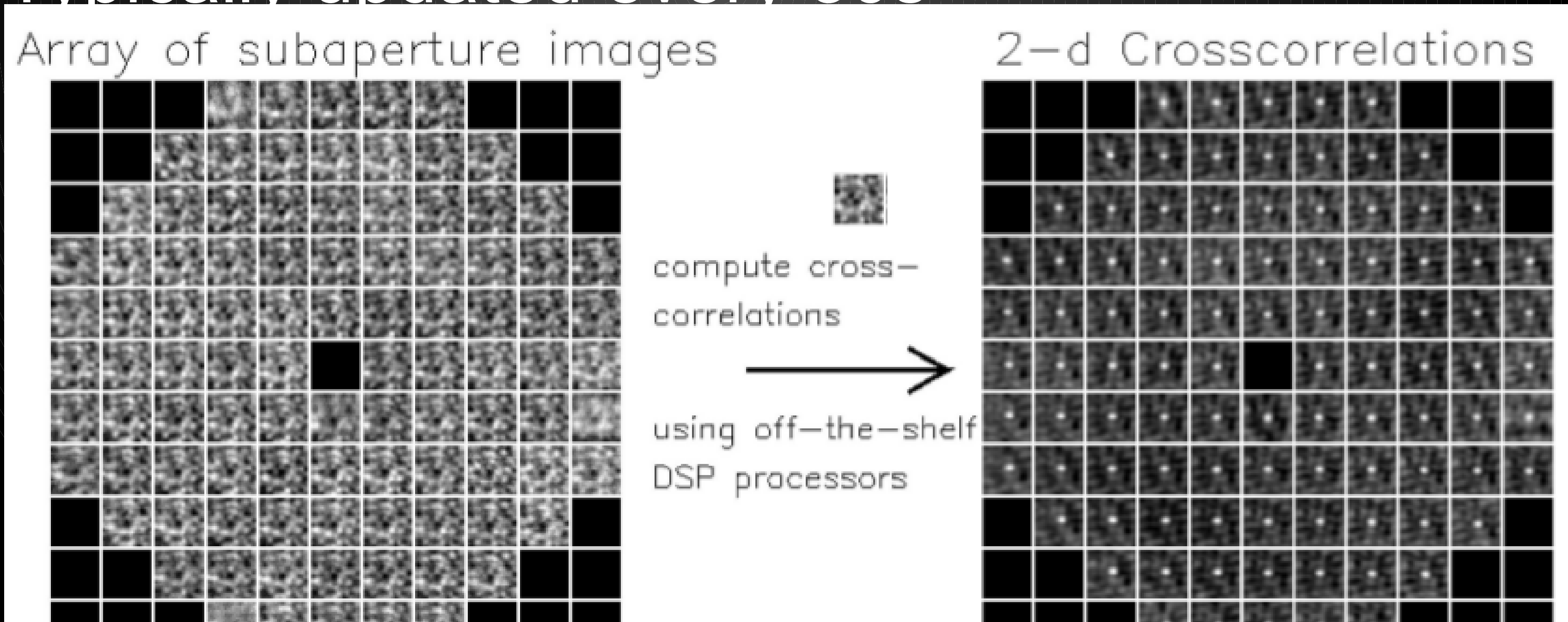

Rimelle et al, 2011

Astronomical correlation

- Integration times much longer than correlation reference update time
- Elongated LGS spots differ between sub-apertures (radial pattern)
  - Cannot use the solar approach
- SHS images much fainter
- So:
  - Correlation reference obtained by averaging O(10) WFS frames → depending on SNR
    - A different reference image for each sub-aperture
  - Update of reference slopes also required
    - Correlate new reference image with current reference image (for each sub-aperture)
    - Compute CoG of this correlation (for each sub-aperture)
    - Add these values to the current reference slopes
  - Successful update of reference image and slopes while loop closed

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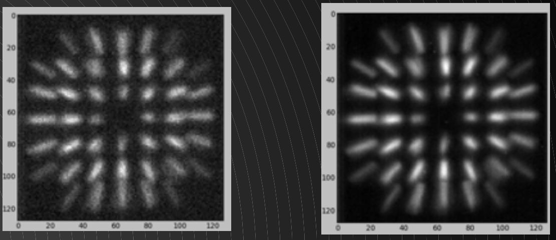

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Canary correlation details

- We use FFT-based correlation
  - Zero-padding necessary for extreme elongation
    - i.e. at the edge of pupil
    - Otherwise correlated image is biased
  - But this introduces extra computation
    - And is unnecessary when spot size is small
  - So we allow zero padding extent to be defined on a per-sub-aperture basis
  - Fast enough for Solar AO systems (20x20 subaps, 2kHz)
- WFS mode defined on a per-sub-aperture basis
  - Allows different techniques for NGS and LGS

Correlation: With no padding

4 pixel padding

8 pixel padding

Wavefront control

- MVM is the standard reconstructor for CANARY
  - SCAO → conventional least squares using SVD
  - GLAO (open-loop) → simple averaging off-axis WFS
  - MOAO → Learn and Apply algorithm
  - A GPU option is available and used on-sky
    - But not necessary for CANARY

Additional wavefront control

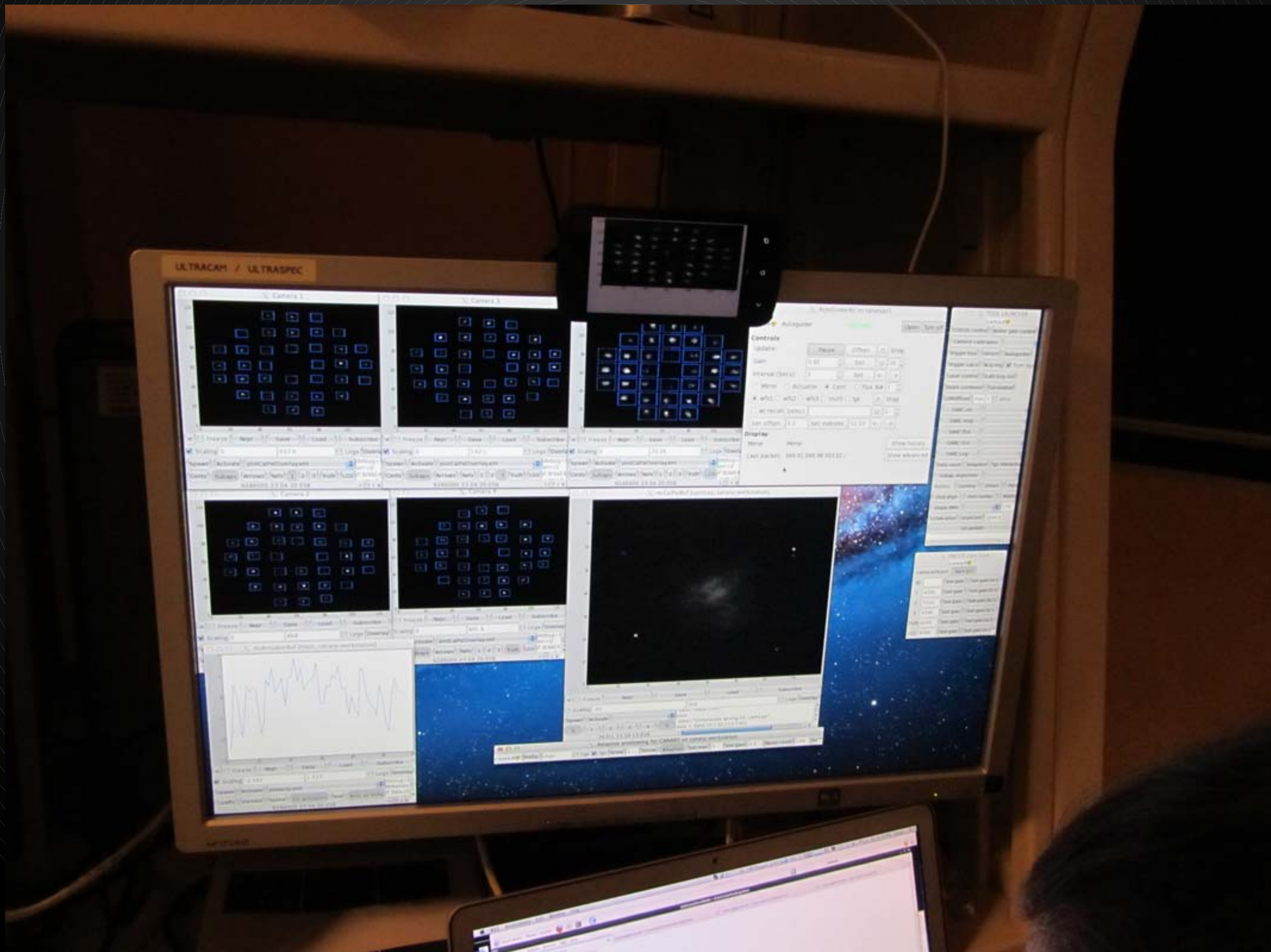
- Dynamically loadable modules allows rapid change between algorithms
  - And development while on-sky
- LQG: optimal control
  - Used in SCAO and MOAO modes
    - With and without LGS
  - Significant performance improvement seen when compared with L&A
  - State vector of size 238 for SCAO, ~800 for MOAO

CuRe and DiCuRe

- Also tested for SCAO
- Results in a later talk

Mobile DARC

- First instance of AO on a phone?



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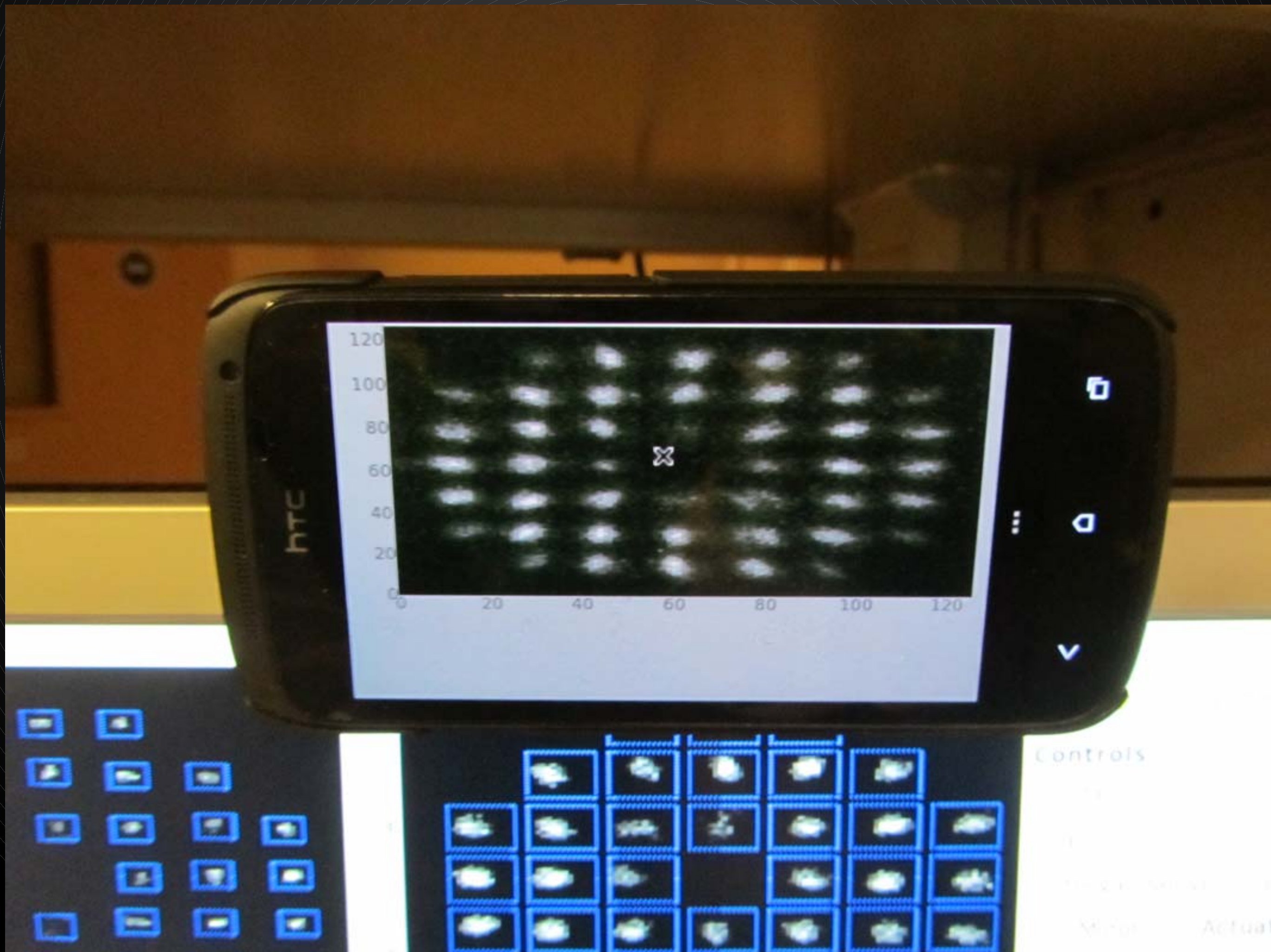

Other Canary systems

- Dual quad-core AMD server (2008 vintage)
  - Main RTCS system
  - SFPDP for WFS input (4 NGS, 1/4 LGS)
  - DM output by socket to a DMC PC
    - Also running DARC for a figure sensor
    - Mirror control using a COTS 96 channel DAC card
- 2 PCs for non-real-time tasks (GUIs, data processing, statistics, storage etc)
- DARC also used for:
  - Science camera
  - LGS acquisition camera
  - LGS beam steering camera
  - Separate operation of LGS WFS
    - Allowing simultaneous NGS MOAO operation and LGS tweaking/optimisation
  - Consistent interface for all cameras

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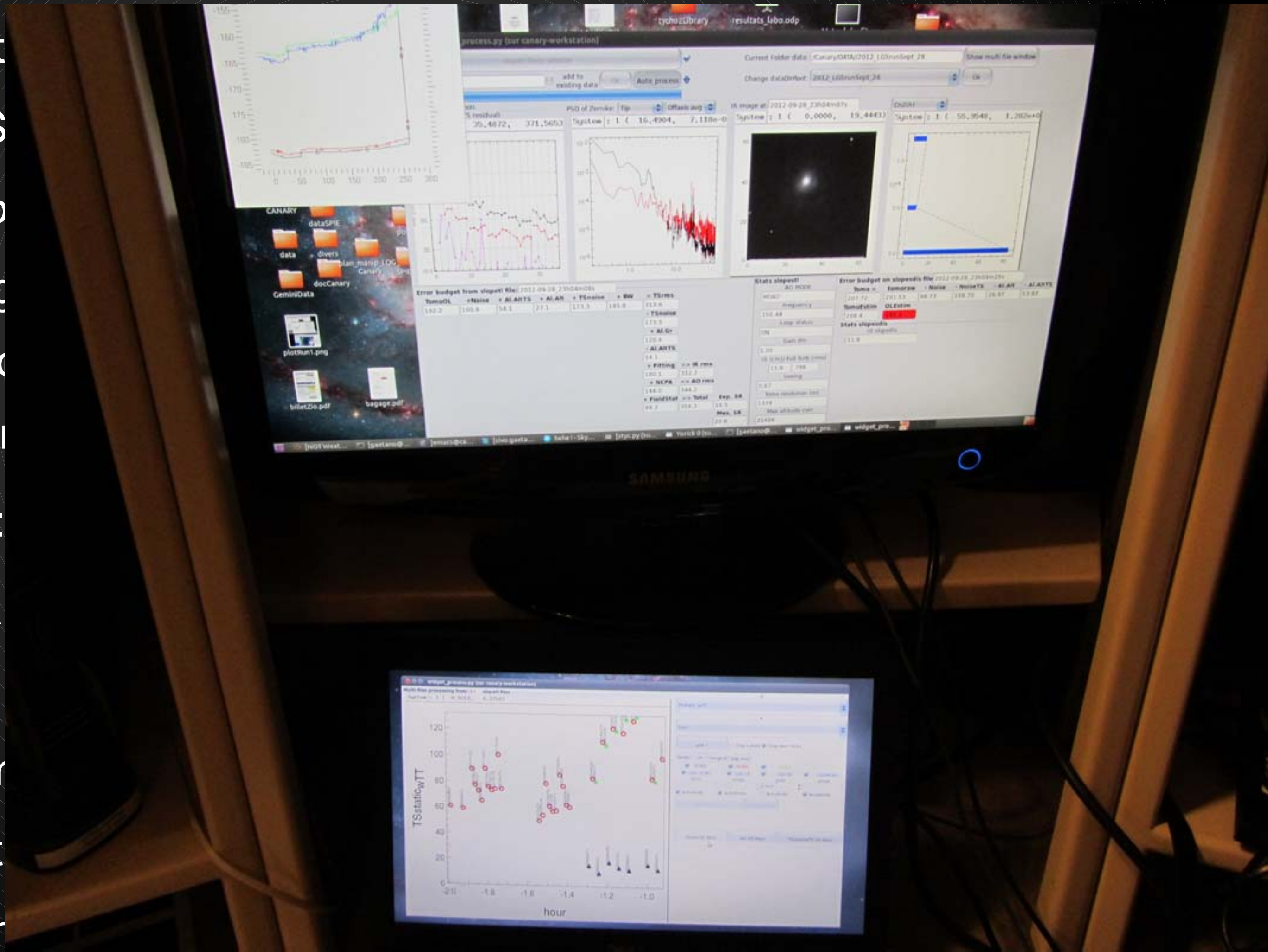

Offload loops

- Telescope autoguider
  - Offload based on:
    - mean WFS slope from one/all NGS WFS
    - WFS Flux
    - Tip/tilt of wavefront
    - Tip/tilt mirror demands
  - Truth sensor slopes no good when loop closed
    - Automagically swaps to mirror demands
  - Sensibly handles situations where no data arrives
  - And when flux is too low
  - And when the telescope is no longer autoguiding!
- Laser steering mirror
  - Using LGS slope measurements
  - Taking not of flux
- Laser beam combination
  - Itself a close loop AO system on M2
- Laser asterism rotation
  - Using 4-LGS slope measurements

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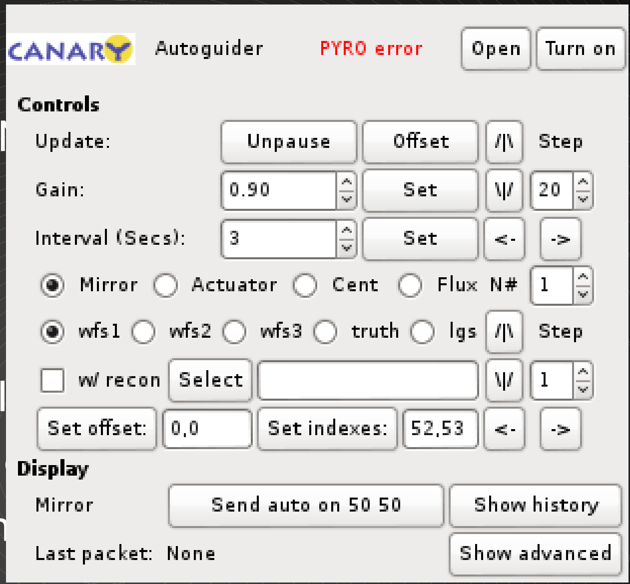

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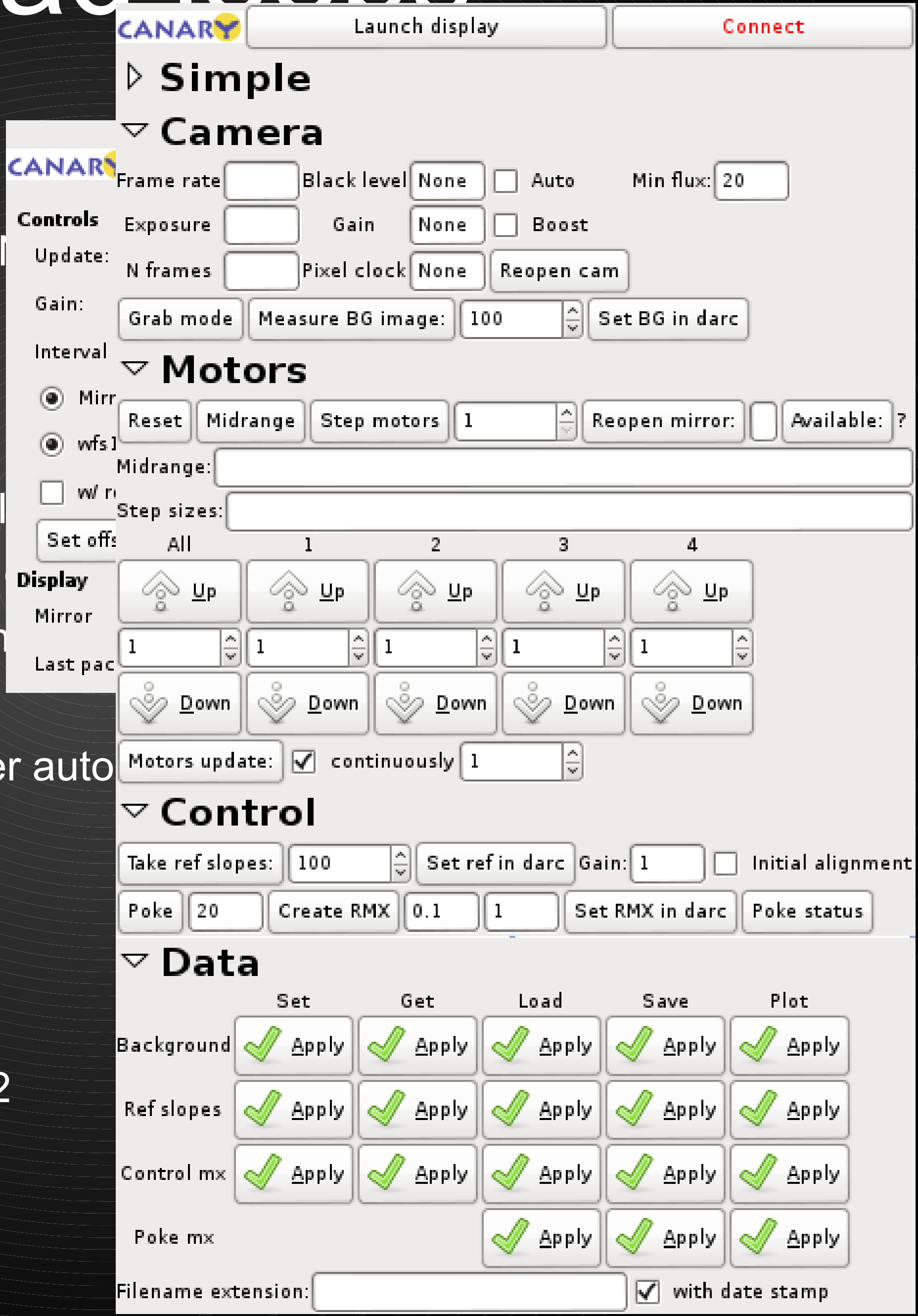

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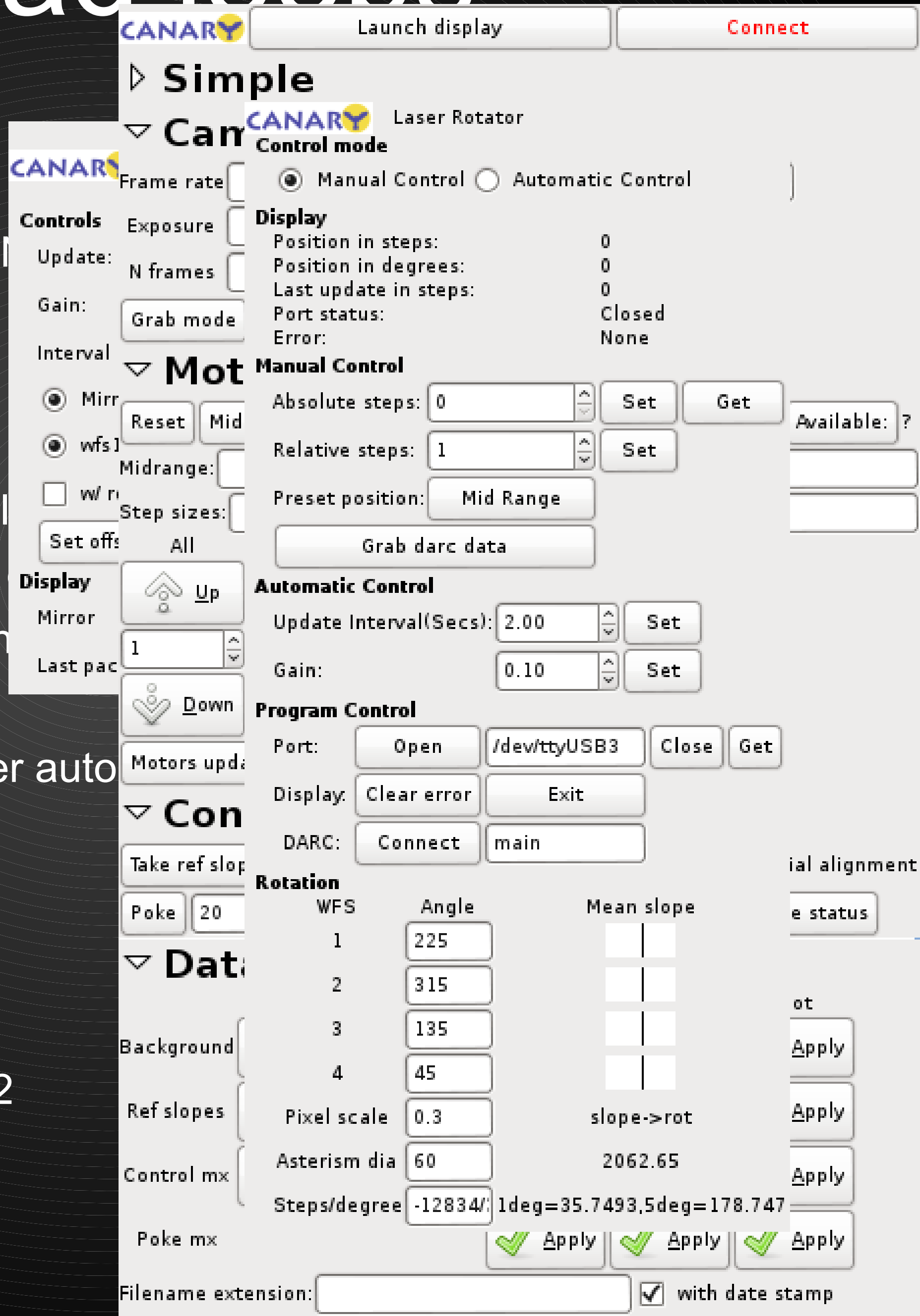
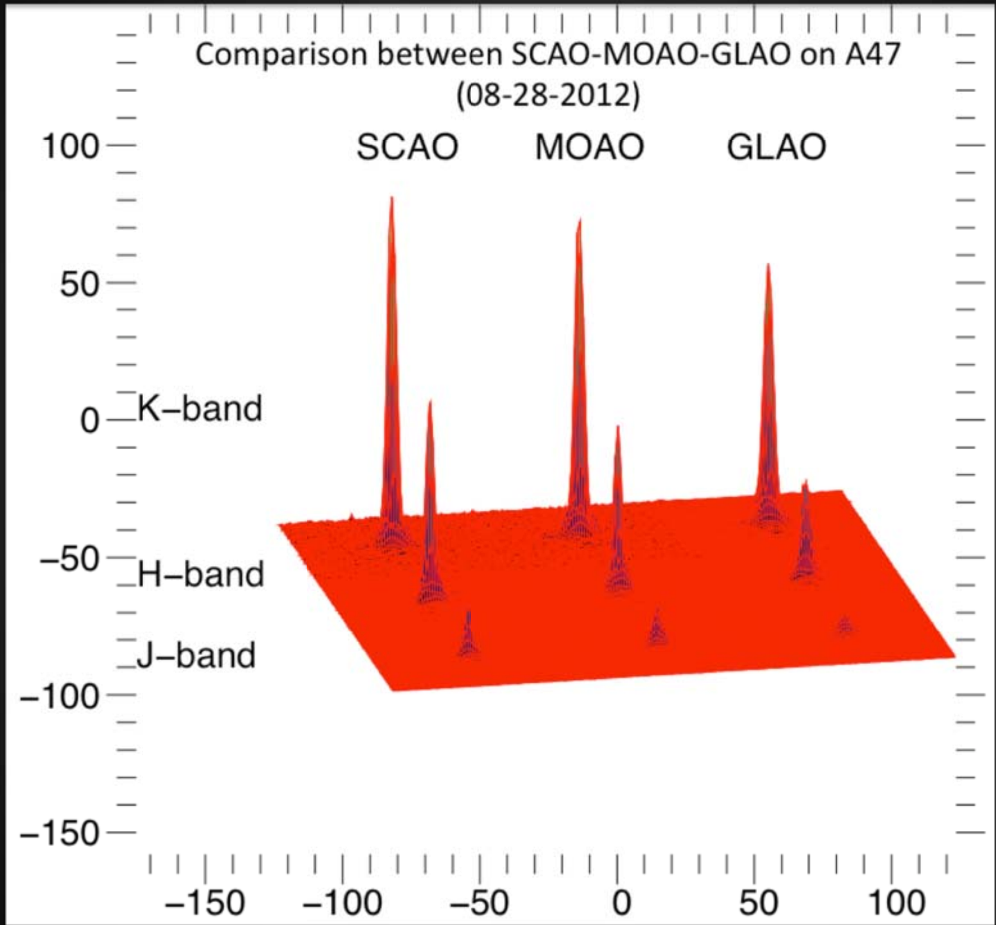


Canary results



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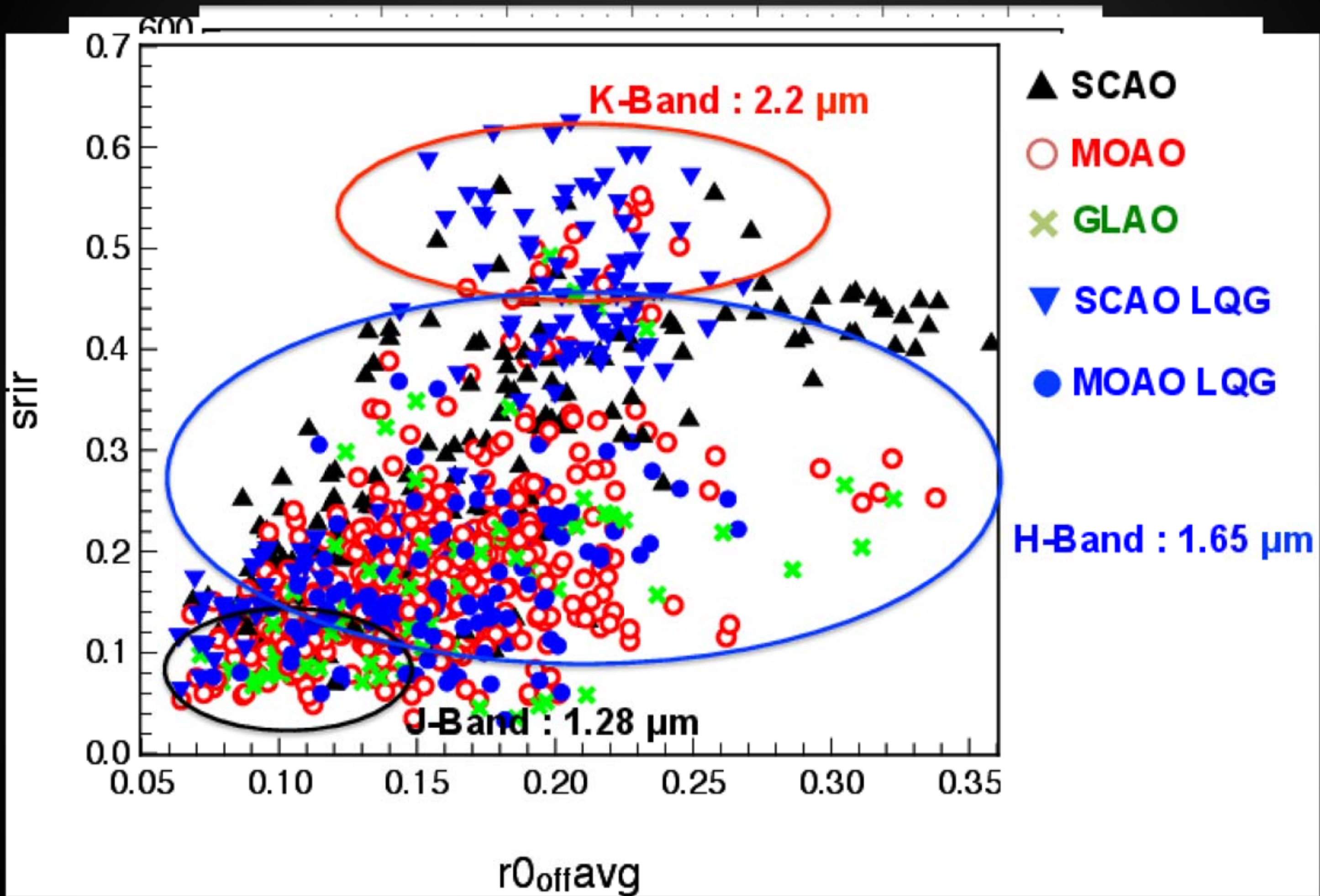

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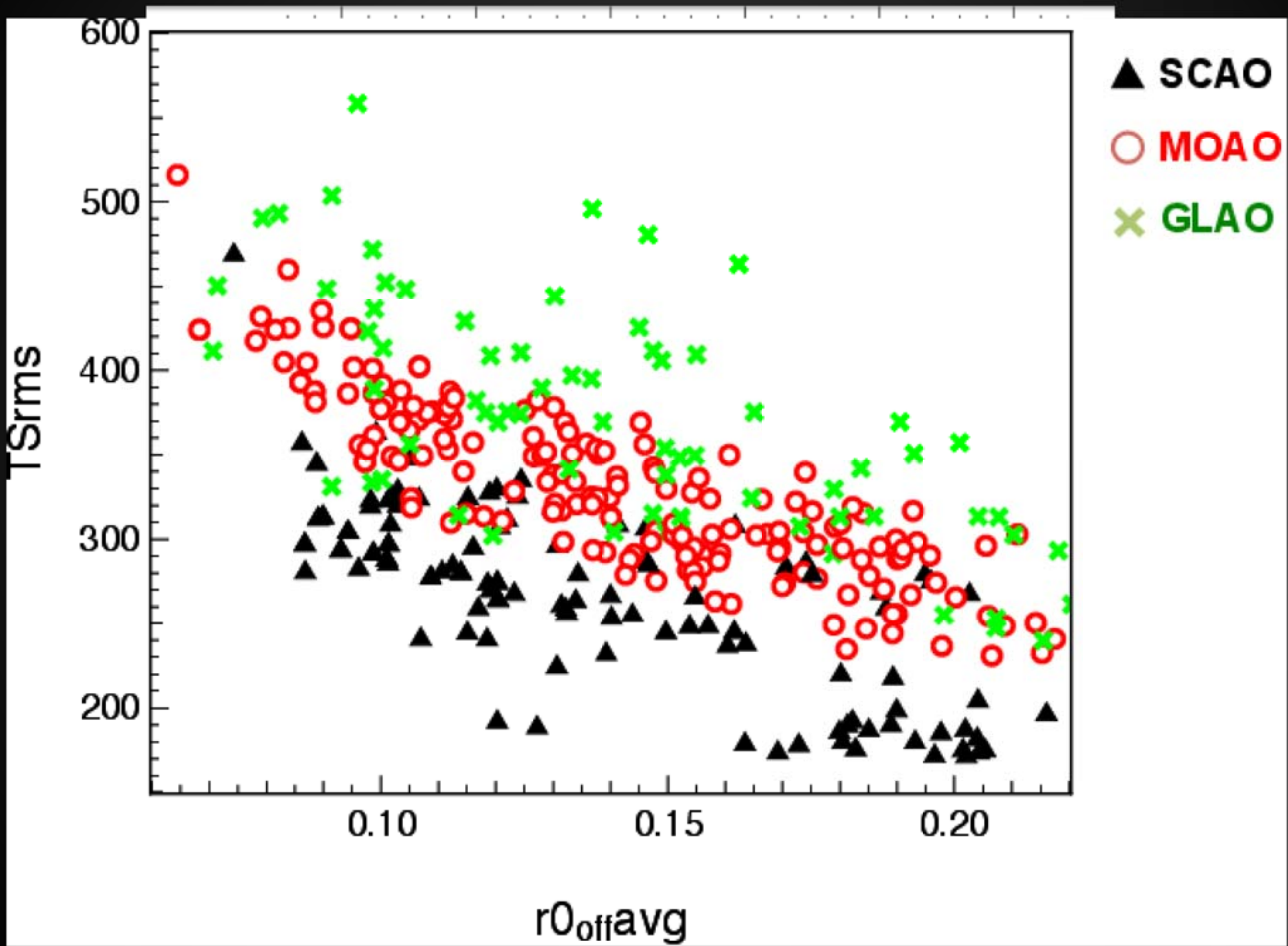

Notes

- Lots of fancy algorithms used in CANARY
- All helped to improve performance
- Can such complexity scale to the E-ELT?
  - We know we can scale basic AO for most E-ELT instruments
    - Including MAORY, EAGLE
    - Calibration (DN,BG,FF), WCoG, MVM
    - Using a small number of PCs/GPUs
  - But haven't yet studied performance with these extra algorithms

Ongoing work

- Implementation of robustness algorithms
  - Single button AO
- Other reconstructors for CANARY
  - Shop open for tests...!
- Implementation of full DARC pipeline in GPU
  - While maintaining the full feature set

Conclusions

- A number of complex algorithms all helped improve CANARY performance