The Technology of the NUTTelA, Technical Details

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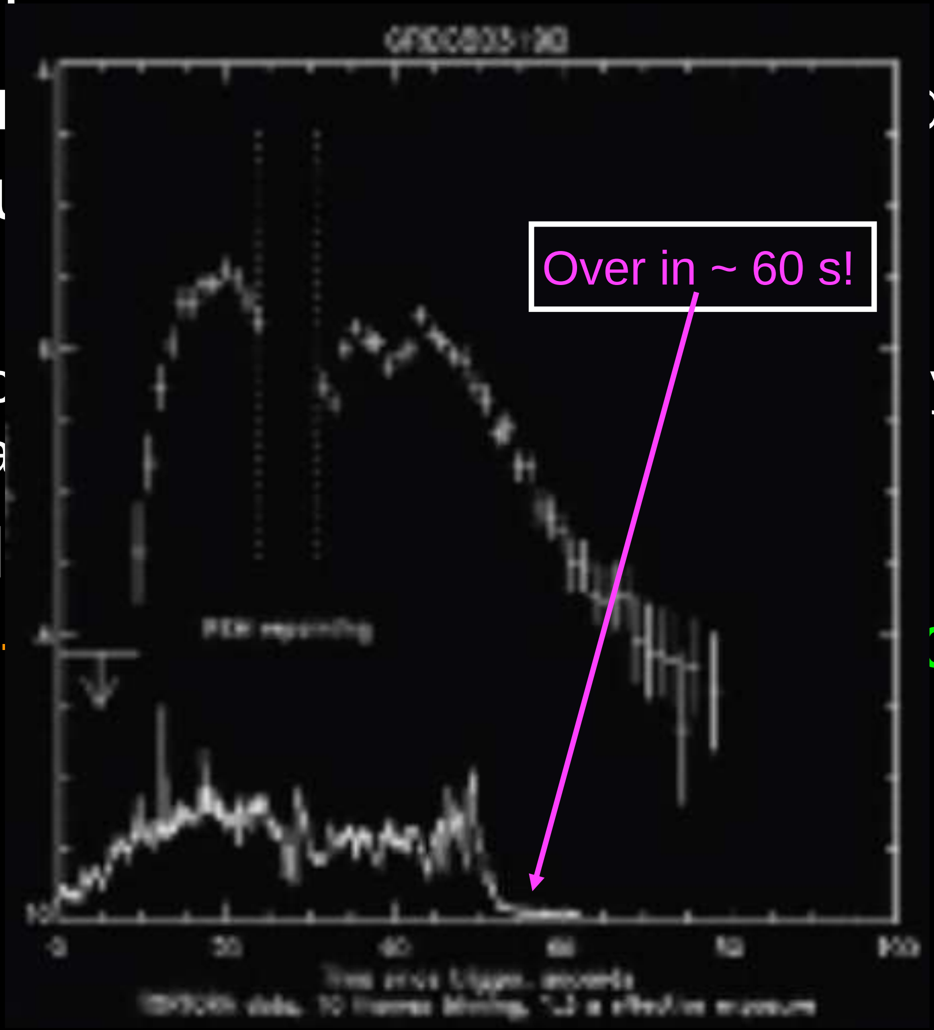
Tech Challenges: A Need for Speed

- Need for speed: Science all about fast measurements
- Automatio d start, autonomou
  - Need tec y to implement with small tea
- Camera/M
  Need high dynamic range



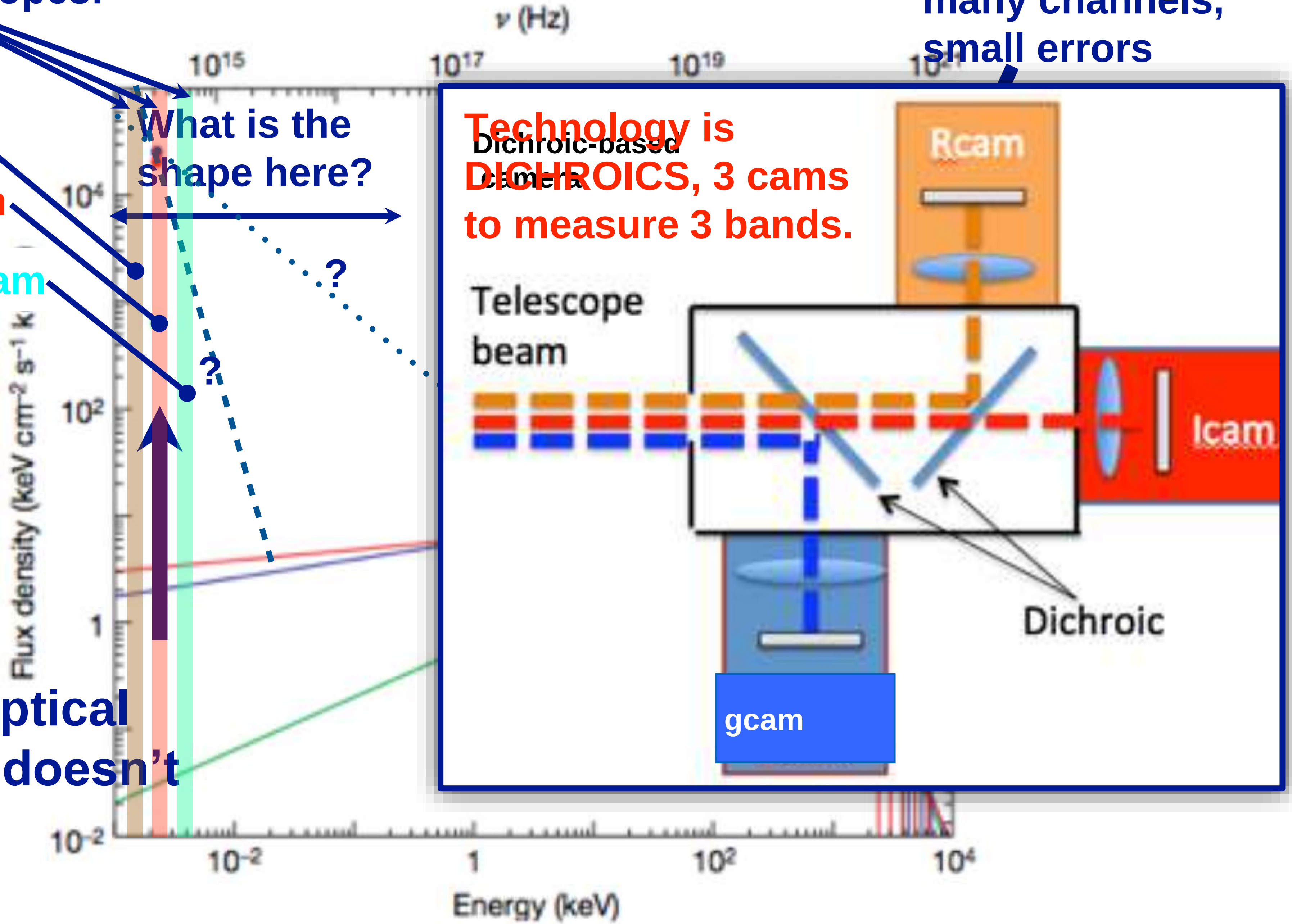
Spectral shape key to science

Get shape in optical with 3 bands / 2 slopes!

Rich data here; many channels, small errors

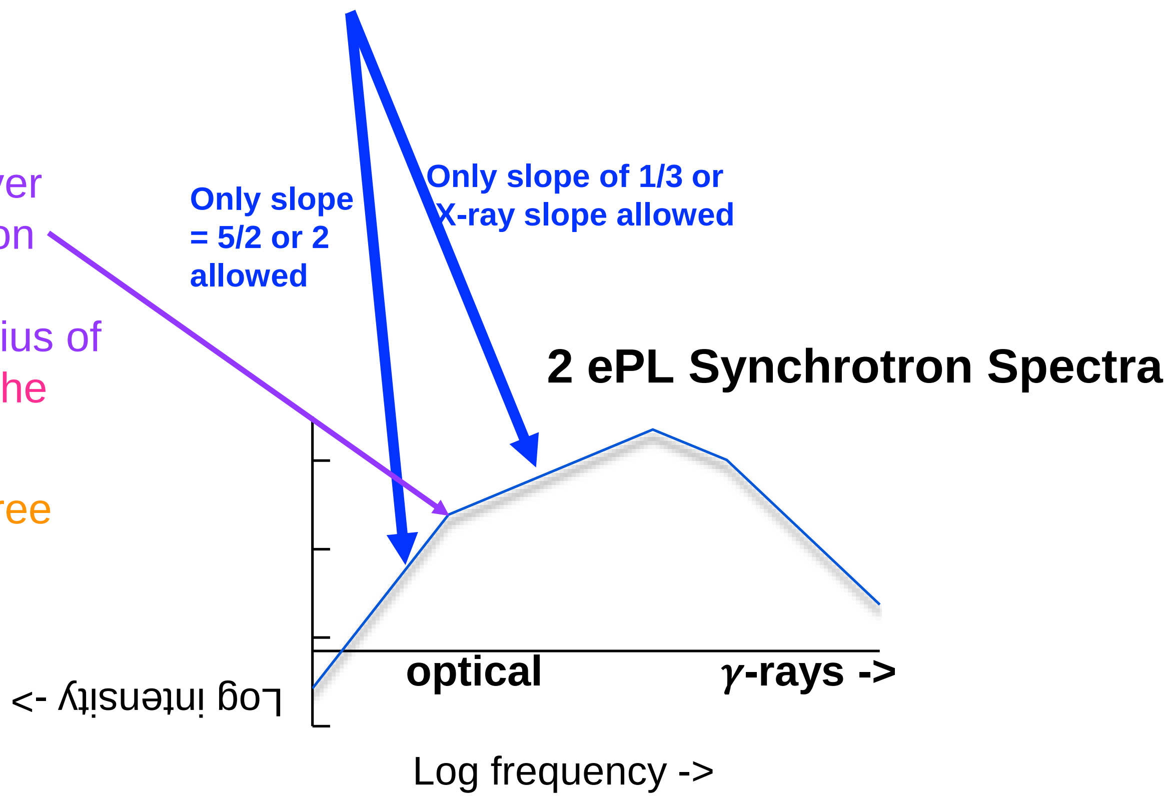
Technology is DICHROICS, 3 cams to measure 3 bands.

Just one optical point, and doesn't fit!!!



Spectral Shape is the key

- Prediction: “2ePL synchrotron”-shape in optical verifies theory
  - shape in γ-rays does not uniquely identify; various scenarios can make it. optical slopes are critical parameter



- Frequency of crossover feature (self-absorption frequency) carries information about radius of emission - i.e. maps the emission!
- Therefore, at least three frequencies required.

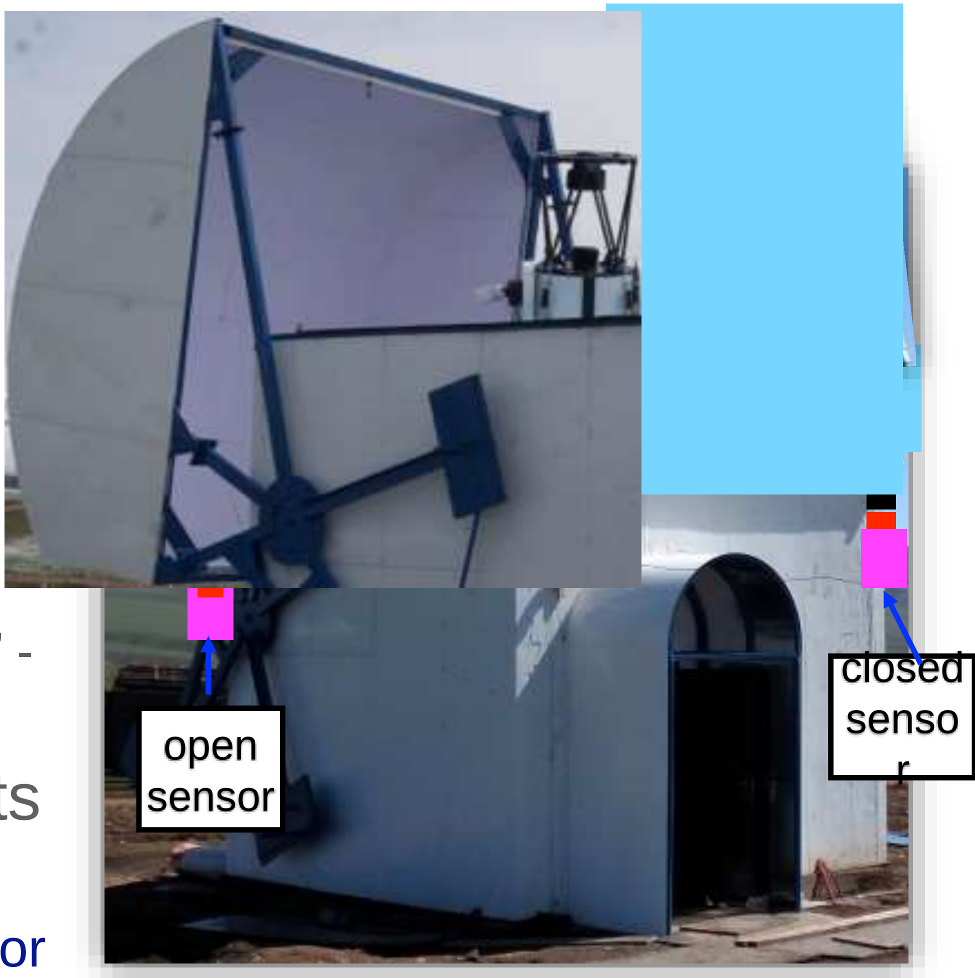
Automation For Scientists

- *Need to have computers control devices*
  open/close roof, mirror covers, communicate with weather sensors, control cameras & telescope
- *Finite time and difficulty to automate system*
  We're not coders, not industry, want to spend time on science.
- *Has to be reliable* **-** No time for human intervention
- *Can't be too expensive*
  NASA automation good, but cost is millions of USD / device!
  - **Why?** Computers, motor, sensors everywhere, and cheap!
  - **Every part is there; so why is automation hard?**

Why is automating *simplest* actions complicated?

Part 1: No true two-state mechanical system

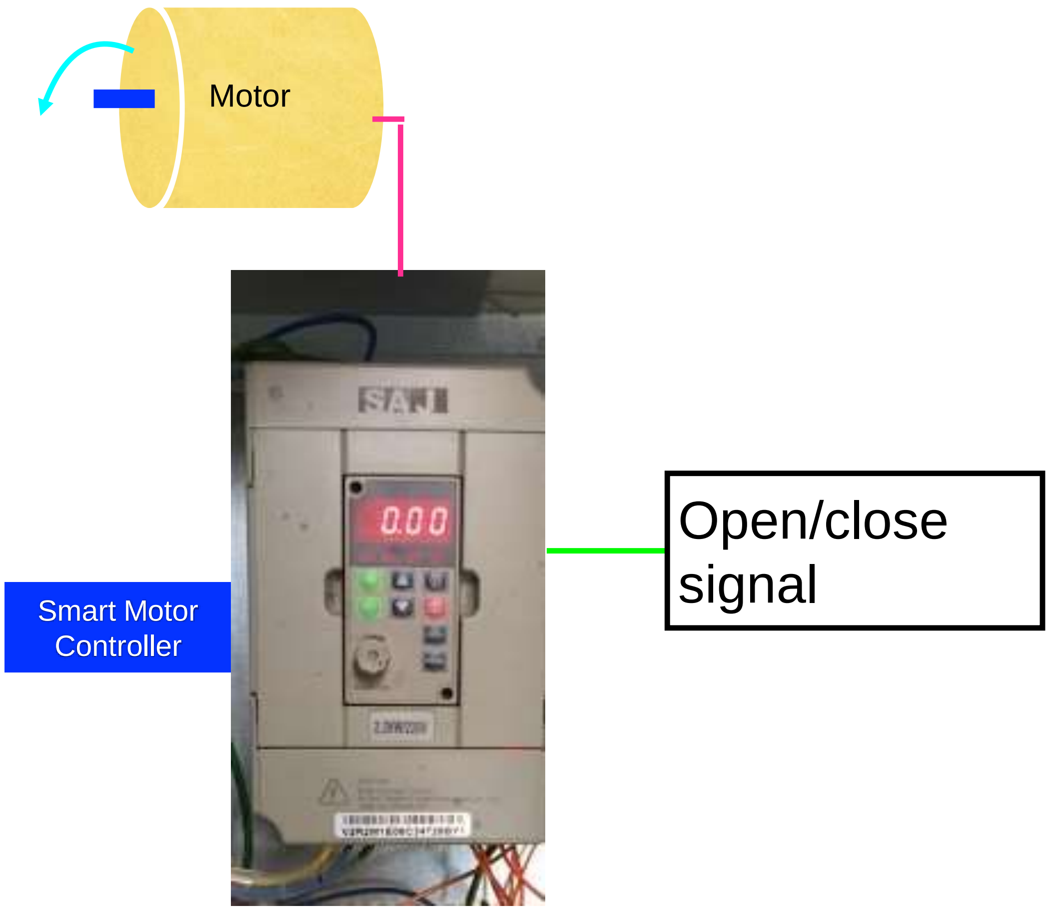
- Example: 1980's: Open a cover
  - sensor at open, closed positions- open action until open, close action until closed.
  - doesn't work! Intermediate state problem. Door bounces, neither open or closed. Sensor goes off too late, motor burns out. Sensor too early, door doesn't open/close all the way.
  - More sensors? “hard limit, soft limit sensors” - same problems, but at all limits!



- Complications =>Many failed projects
  - Proposals to “automate” telescopes *everywhere* by 1990's. Either failures, or $50,000 1 year proposed required 5 years, cost > $1M to engineer every intermediate state, other problems...

Fix Part 1: Smart Devices

- Devices/sensors with internal microprocessor ~ 2000's
  - complex (continuous position, velocity) data now technically easy.
  - Issue only simple command
  - Each widget fully engineered, but two-state (on/off, open/closed) from outside.



Why Complicated? Part 2: Communication

- 1980’s-90’s: comm over RS232, GPIB, CAN
  - complicated code, drivers to start widget, read data, etc.
  - *Always* problems sychronizing all components
    loading drivers, starting software, powering card & firmwear...

Voltmeters, still available today (front at left, back at right).

fat serial cable

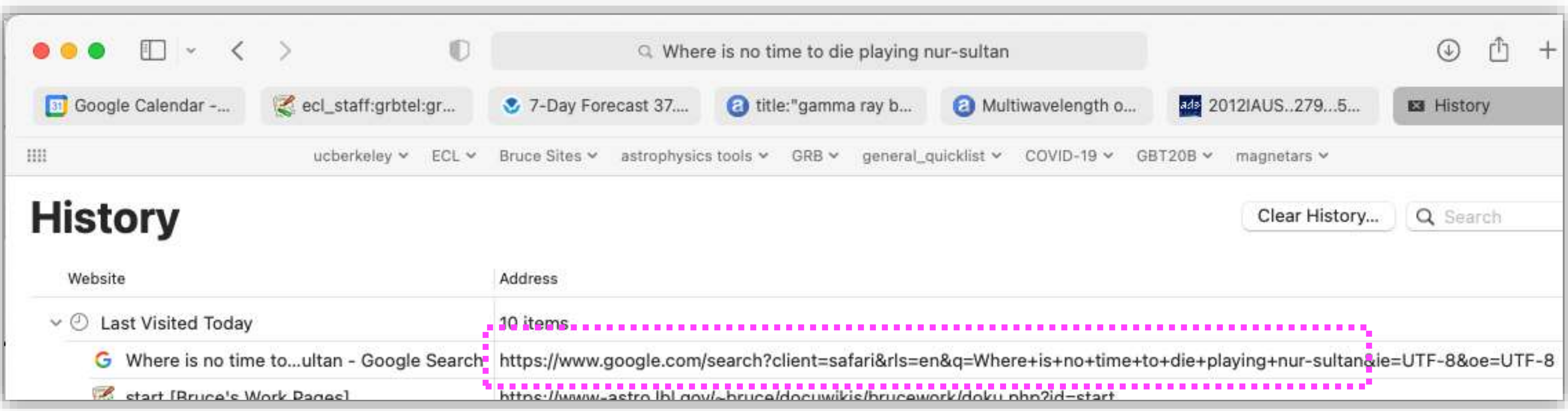
Special software

Driver system software

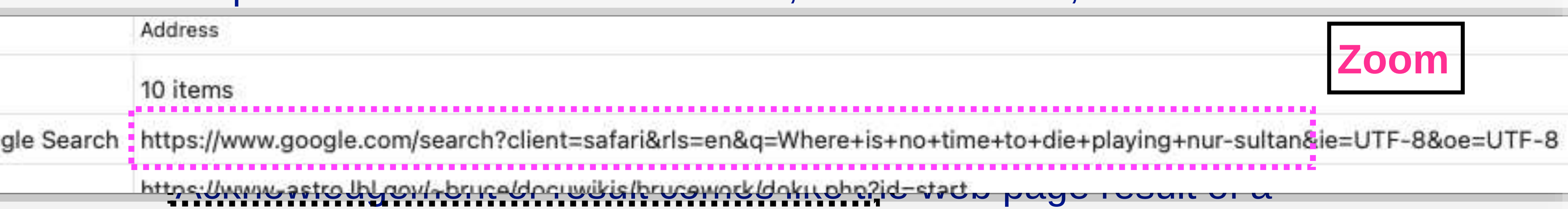
Hardware Card

NOTE: You can ask me about synch-ronous communications, and time, in the question period or some time after the talk.

Fix Part 2: Communication: Net Commands!



– To point NUTTela to coordinates ra, dec = 11 22 33, 88 54 32:

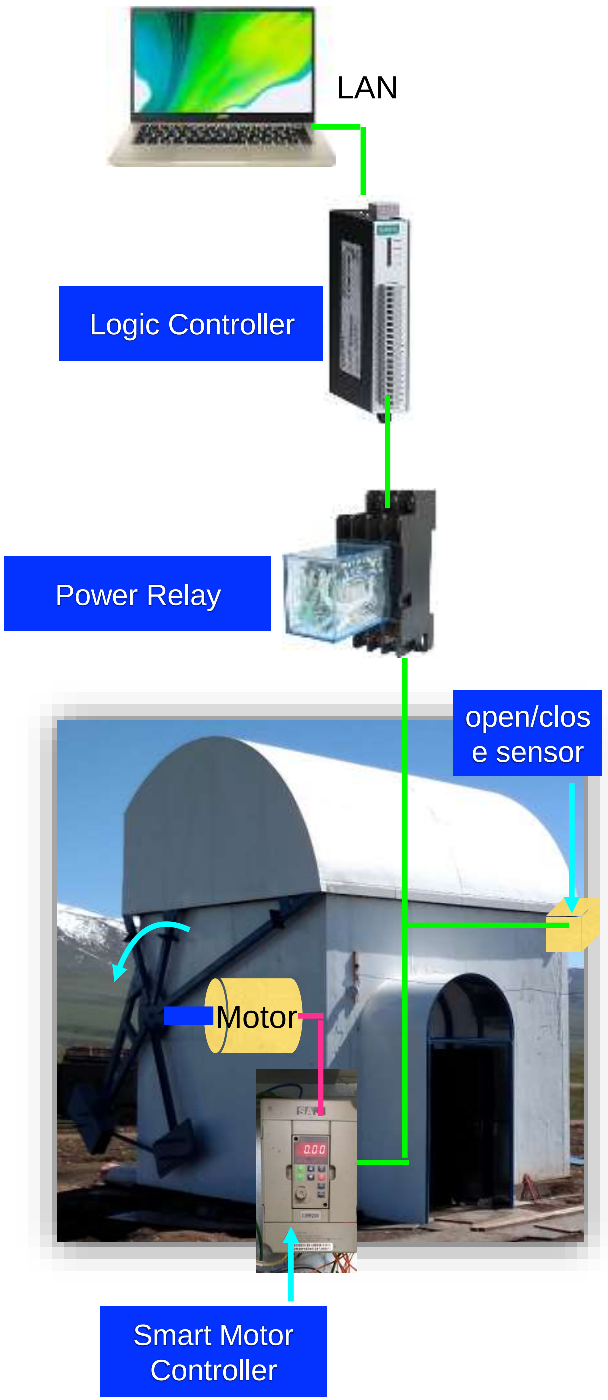


URL

- Full Commands:
  - From a linux program (python, IDL, etc. etc.):
    system(curl -L [the URL above], result) where result gives you BACK information !

NUTTelA Control

- **Computer** makes complicated calculations, decisions
- **Separate** computers and hardware!
- Smart (but simple) devices -**No Drivers!**
  - computer -> logic controller: request device *n* open/close
    - » controller gives binary e.g. open command to relay
    - » relay sends power to device
    - » smart device takes care of details



Fix Part 3: Easy Programming Language

- Use an easy programming language
  - We use IDL (gdl)- better interactive de-bug tools; python similar, more popular, tools not as good
  - c poor, c++ extremely difficult, requires specialized programmers

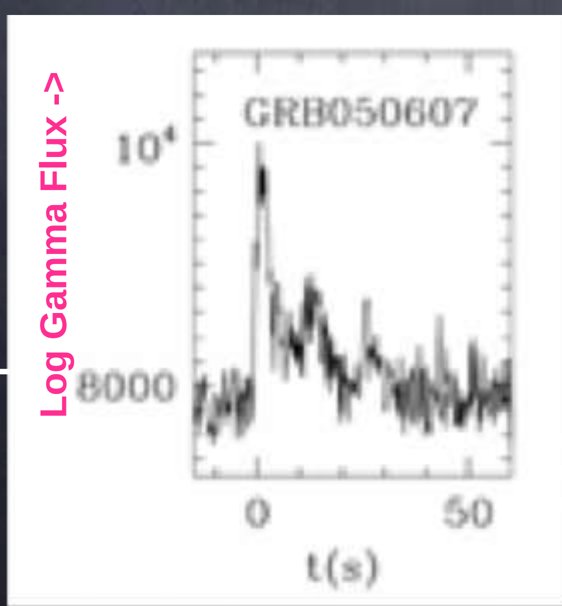
- Problems ~ language_complexity$^{\alpha}$; $\alpha \gg 1$
  - Telescope problems ~ 7 days; (well-documented URL Commands)
    Logik Controller ~ 14 days (more complex, still URL comm.s)
    Camera problems ~ 70 days! (must use c programs)

Technology For Imaging: Pushing the Limits

- *Need* sensitivity ***and*** time resolution ***and*** dynamic range
  - Fast transients means need time resolution
  - Fainter transients still need sensitivty
  - Random alerts means we cannot know which are super-bright, good for high time resolution studies, which are faint, need longer exposures.

What is high-time resolution for?

- Can't cross-correlate with just a few points!
- Need time resolution
  - Important if spectrum changes during burst
  - Timescale of each pulse important in some theories
  - Reverse shock emission component does not have fast variability
  - Cross-correlation of gamma and optical signal measures what fraction of optical from same process as gamma.



Log Time ->

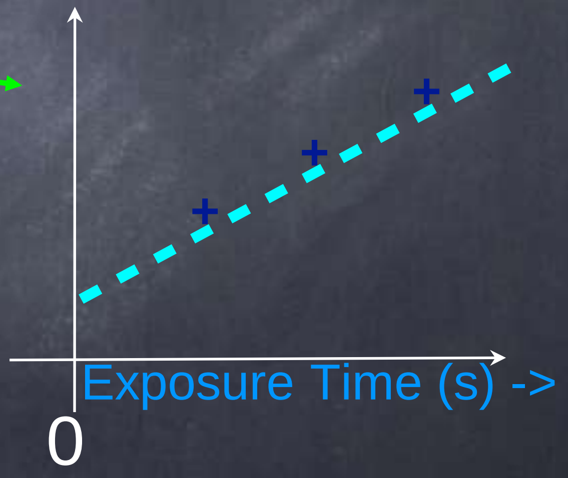
Imaging Measurements

- Standard CCDs- pix detectors that convert photons -> electrons (e-) -> ADU

- Add up numbers in aperture, subtract background, gives flux, desired measurement.

- The longer you expose an image, the more ADU (e-s) you get.

- A CCD is only read at the end of the exposure => sampling time = exposure time, which gives time resolution of measurements.



- Since pixels are numbers, can add images sky-pixel to sky-pixel, called "co-adding", for more signal and sensitivity.

Noise in Measurements

- Noise adds in "quadrature"= $(\sigma^2_{read} + \sigma^2_{Poisson} + \sigma^2_{other} + \ldots)^{1/2}$
  - where σ^2_{read} is the electronic noise from reading CCD.
  - $\sigma_{Poisson}$ -> $N_{e-}^{1/2}$ for N large (otherwise you integrate Poisson distribution).
- Longer exposures always more sensitive:

  Signal ~ t_{exp} ; Noise ~ sqrt(t_{exp}) so

  $S/N \sim t_{exp}^{1/2}$
- Noise= $(\sigma^2_{read} + \sigma^2_{Poiss} + \ldots)^{1/2}$ so expose until $\sigma^2_{Poiss} >> \sigma^2_{read}$.
  - » This gives minimum t_{exp} and limits time resolution.

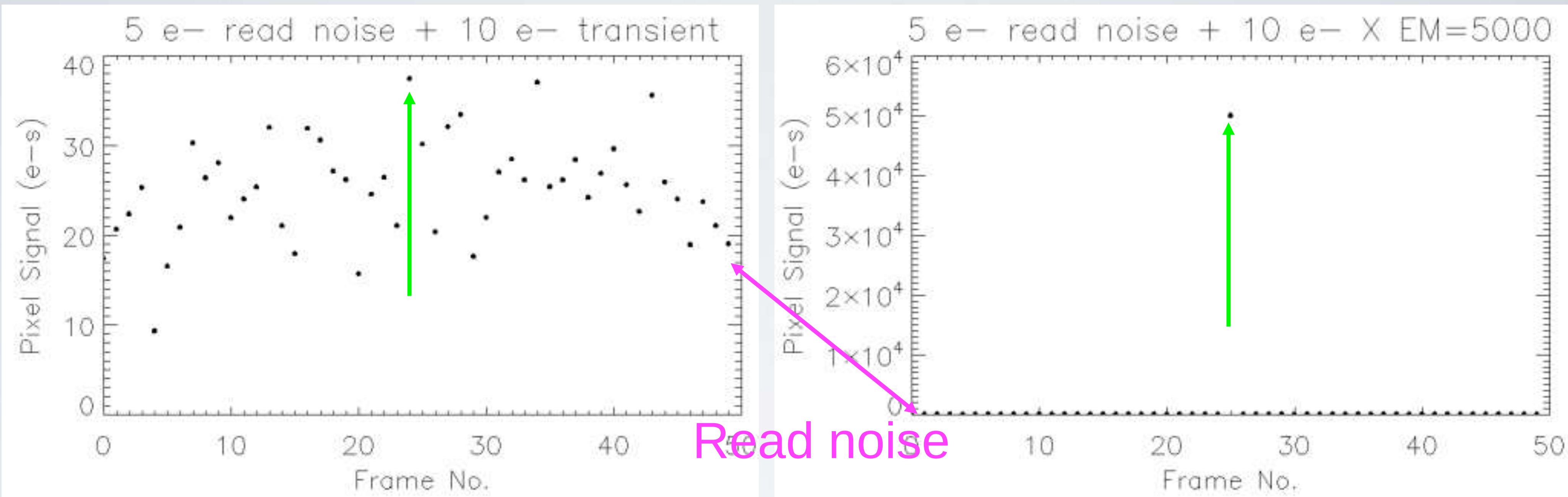
Co-adding: time resolution or noise?

- Take short, e.g. 0.1 s frames:
  - » good time resolution!, but faint sources not detected
  - » Fix: if faint, co-add frames for enough signal to detect
    -right?
    -How does this affect noise?

- Noise= $(\sigma^2_{read} + \sigma^2_{Poiss} + \ldots)^{1/2}$ so for co-add:
  Noise(N_{frames}) = $(N_{frames} X \sigma^2_{read} + N_{frames} X \sigma^2_{Poiss} + \ldots)^{1/2}$
  - » Co-adds just keep adding σ^2_{read}, huge noise!
  - » Co-add conundrum:
    Short exposures– good time resolution, but **add read noise**
    Single long exposure –lower noise, but NO time resolution!

- **Beat this with EMCCD!**

EM GAIN BEATS READ NOISE



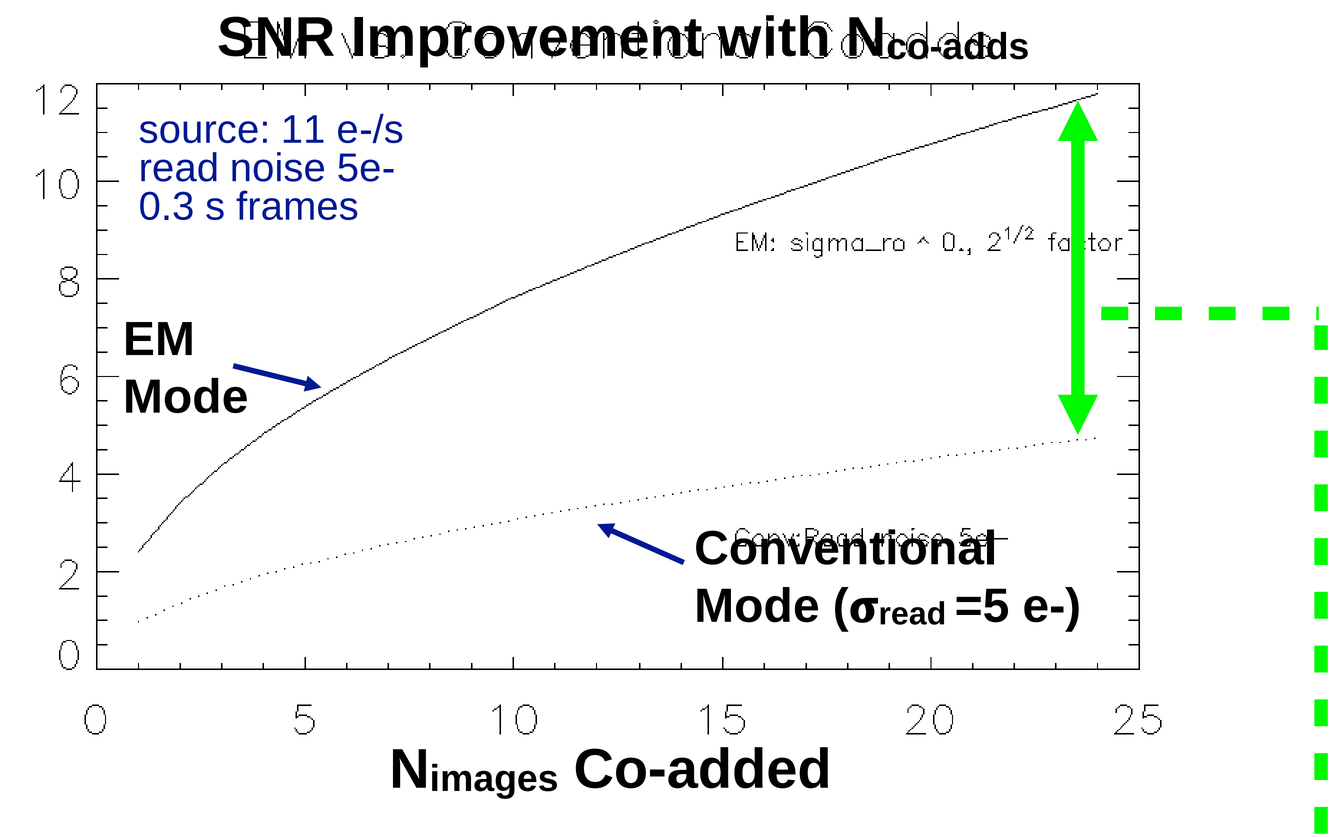
– 10 e- signal is impossible to find in 5e- noise

- Each pixel's signal is multiplied **before** read by up to 5000X
- Many frames may be co-added with negligible read noise

NOTE: There is Noise penalty for EM: Poisson noise increased by factor $2^{1/2}$, a lot.

EM co-adds allow choice: time resolution v. SNR

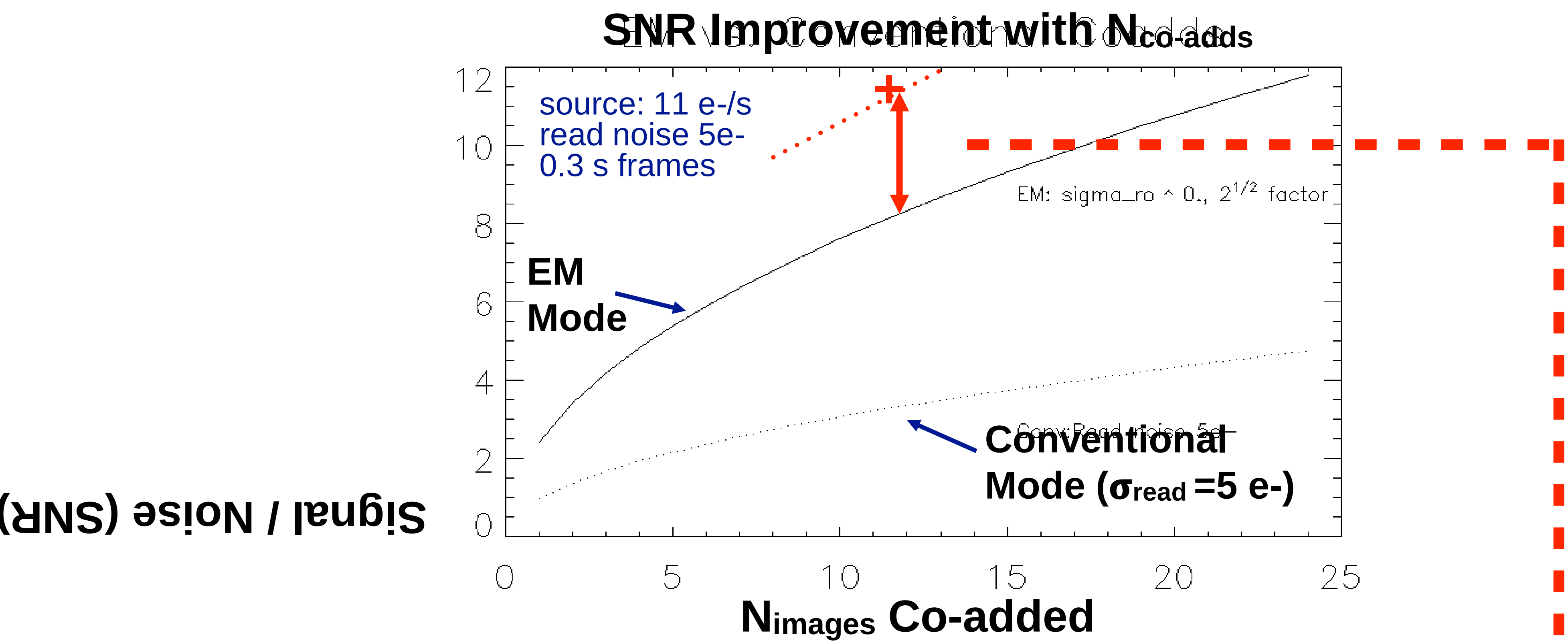
- SNR co-adding short frames of faint source.
- EM mode SNR grows faster vs Conventional mode



NUTTelA uses EM mode cameras - high time resolution (when target is bright enough)
Cross-correlation with γ-rays allows us to ID components that do (not) radiate both in optical, γ.

- **RESULT: FLEXIBILITY --> BOTH sensitivity AND time resolution:**
  - Bright sources - don't co-add, use max. time resolution.
  - Faint sources - co-add as needed for detections.

But what about **factor $2^{1/2}$ advantage** of No EM?



- SINGLE conventional long exposure still better by factor **$2^{1/2}$**
  -BUT NO TIME INFORMATION!

- **Is there a way to beat $2^{1/2}$ factor, but still have time resolution?**

Next Tech: **Co-add Binary Images**

- Noise of counting multiplied e-s $2^{1/2}$ X $\sigma_{Poisson}$, 40% penalty!

Trick: *Don't Count multiplied e-s.* Threshold, each pix 1 or 0 only; with

EXAMPLE NUMBERS

tar

Disadvantages:

- Dynamic range limited to factor N_{frames} (1e-/pix/frame max)
- ultimate limit above Poisson is another amplified noise, (CIC), not too bad.

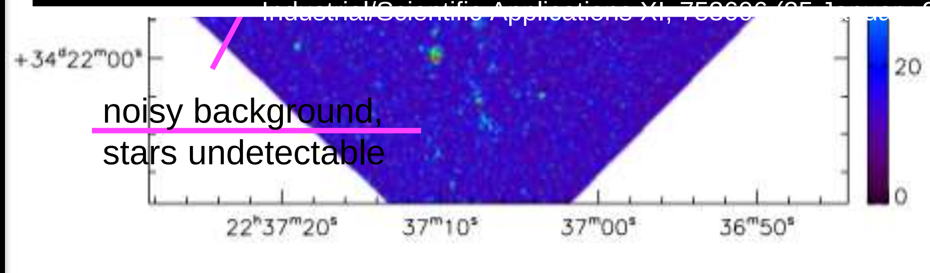
(usually <1)

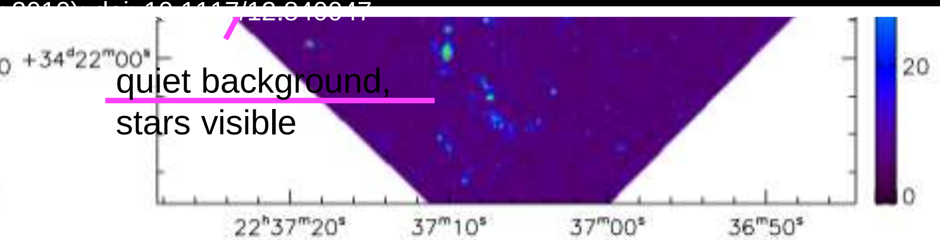
40 frames co-added yield same 40 e-

Result: SNR = 6.3 good!

- Note: most pix are 0 e- (~ 200 ADU baseline); max pixels, in only about 10 of these frames, are1e- (~1600 ADU)

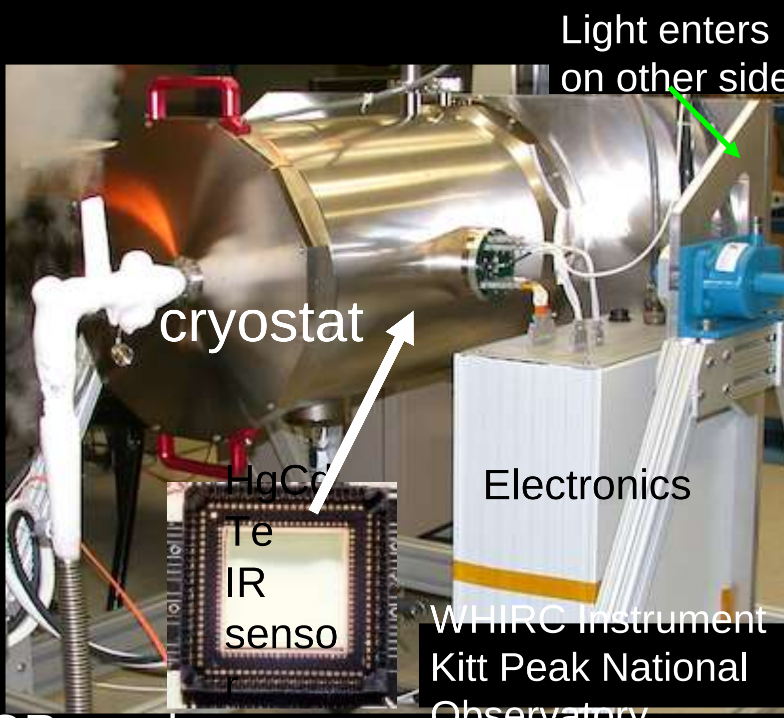
- Olivier Daigle, Sébastien Blais-Ouellette, "Photon counting with an EMCCD," Proc. SPIE 7536, Sensors, Cameras, and Systems for Industrial/Scientific Applications XI, 753606 (25 January 2010); doi:10.1117/12.840847

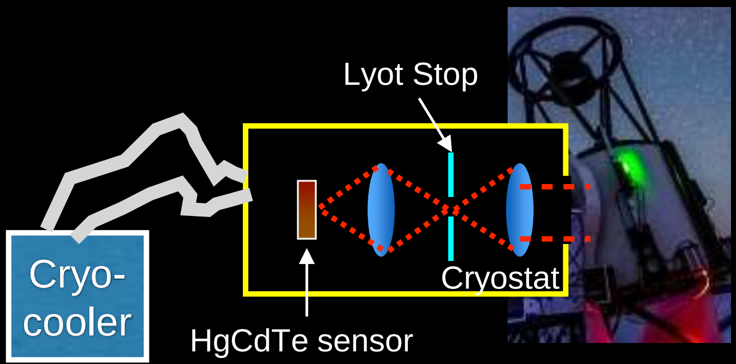




What's Next For NUTTela Tech? IR?

- IR CAMERA?
  - » Going to ~ 1600 nm increases spectral window factor of >5
  - » Means error in slope smaller by > 5 !
- – Lots of Tech Required
  - – Need HgCdTe chip, w/high dark noise, means:
    - » Big cryostat; too heavy for NUTTelA
    - » Needs expendable liquid LN, not automatable, OR needs (Cryo-mech) cryo-cooler - big, heavy hoses
  - – IR is like taking a picture inside a glowing light fixture
    - » Need to block environmental IR emission by imaging pupil of telescope on "Lyot Stop", all optics in cryostat.





Summary

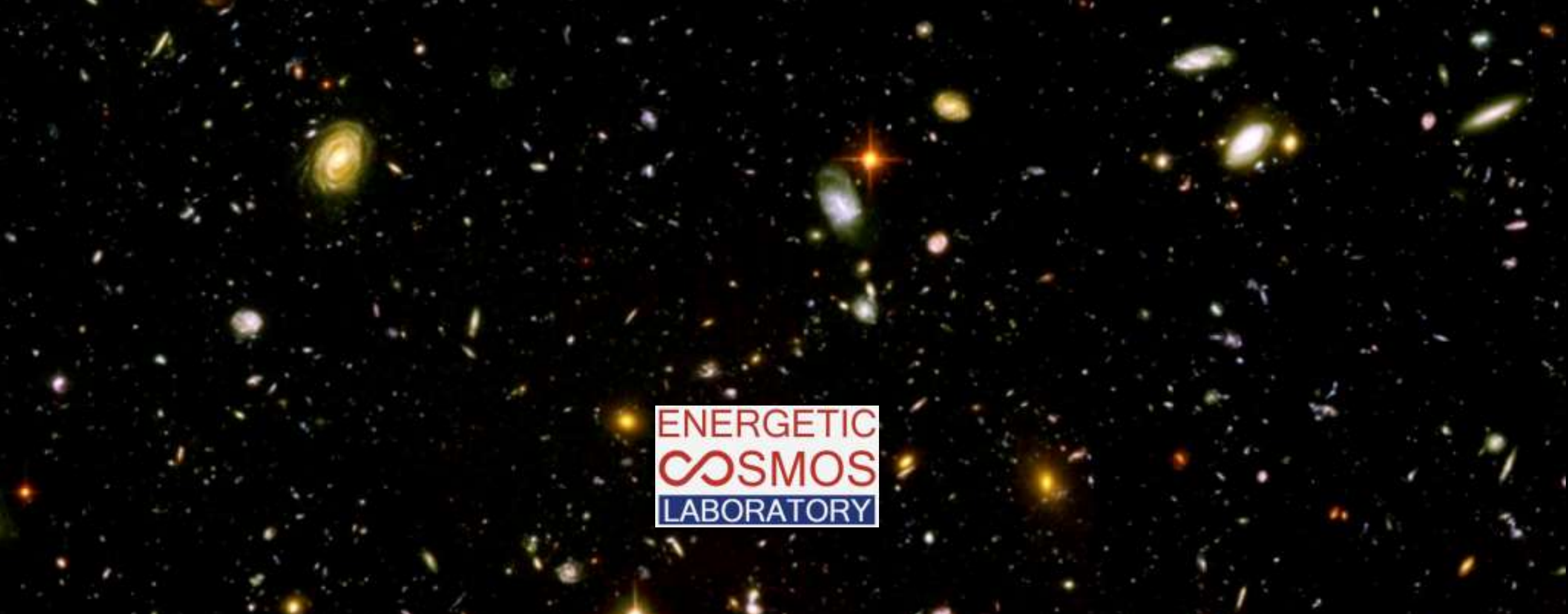
- NUTTelA driven by experimental needs: fast response, 3 channels, high-time resolution

- Automation by non-expert scientists: You can too!
  - use LAN communication and easy URL commands
  - use easy language

- Fancy electronic tricks can help a lot - keep up on developments for your instruments
  - explore and *test* how to use these tricks!

- New tech hard (IR Cam), but exciting possibilities!

Thank you for your attention!



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