Lessons learned with GUFI: using L3-CCDs to unlock the full potential of smaller telescopes

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Small Autonomous Scopes, UCD, Dublin August 2008

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(The superiority of L3-CCDs in the high-flux and wide dynamic range regimes)

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Outline

- Why do we need fast optical cameras (high cadence imaging)?
  - The 3 scenarios
  - Duty Cycle, Dynamic Range, Scintillation
- L3-CCDs
  - Design, specs, operation modes
  - Comparison to regular CCDs: Single & Cumulative Signal-to-Noise Ratio (SNR)
  - Observing strategies
- Galway Ultra Fast Imager (GUFI)
  - Design, specs
  - Differential Photometry Method
  - Data reduction/analysis pipeline
  - Results, Performance & Side-effects

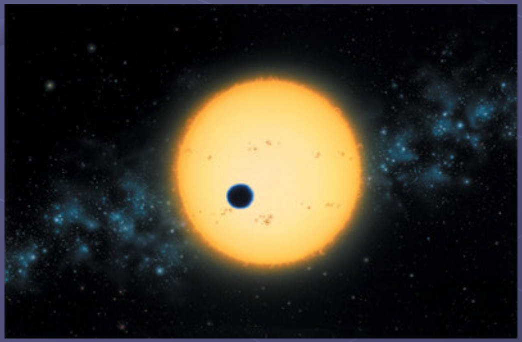
Why do we need fast optical cameras (high cadence imaging)?

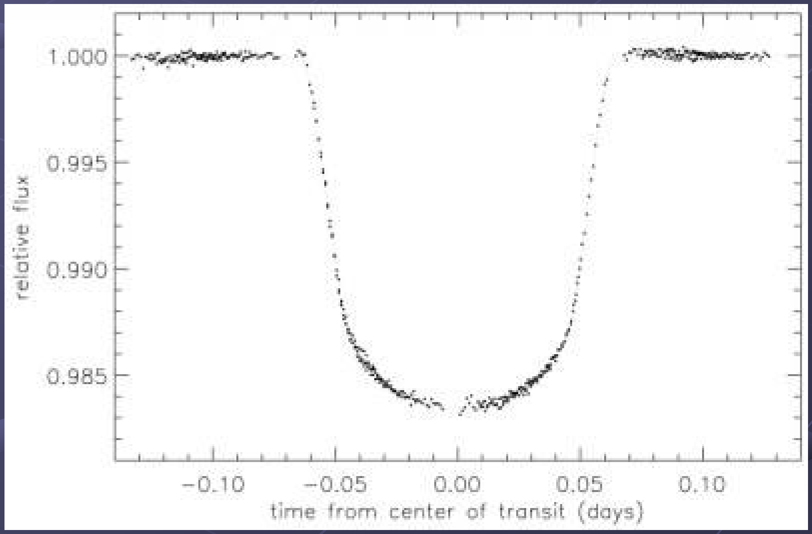
1. For Astrophysical reasons:

"Normal"/faint sources with rapid variability

- CVs, XRBs, GRBs, pulsars, asteroseismology, eclipsing binaries, transits, occultations

- e.g. GUFI, Ultracam, Optima, POETS, SOFI, Berkeley VIT, TRIFFID, ...





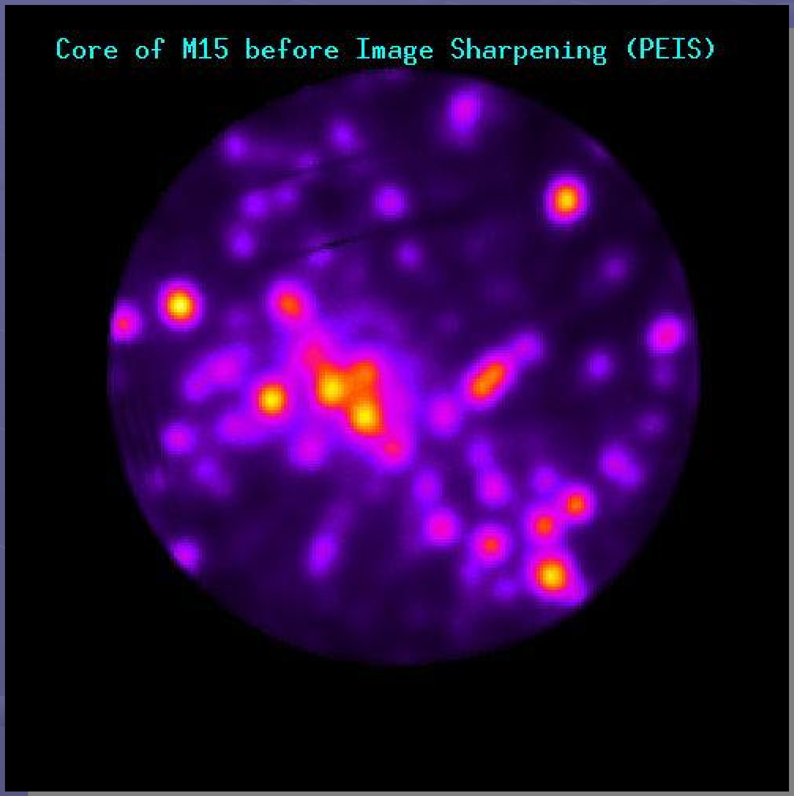
Why do we need fast optical cameras (high cadence imaging)?

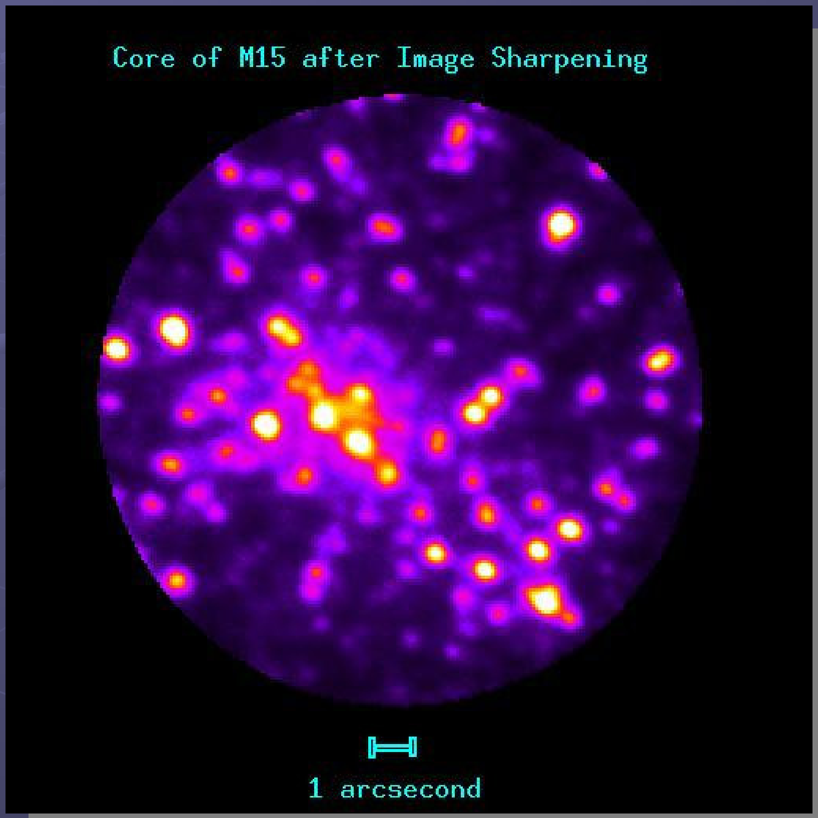
2. For Atmospheric reasons:

Adaptive Optics - Wavefront sensing (Shack-Hartmann, Pyramid WFS)

Post-exposure image sharpening (PEIS) and “lucky imaging” (frame selection)
- e.g. TRIFFID, LuckyCam, GUFI

PEIS



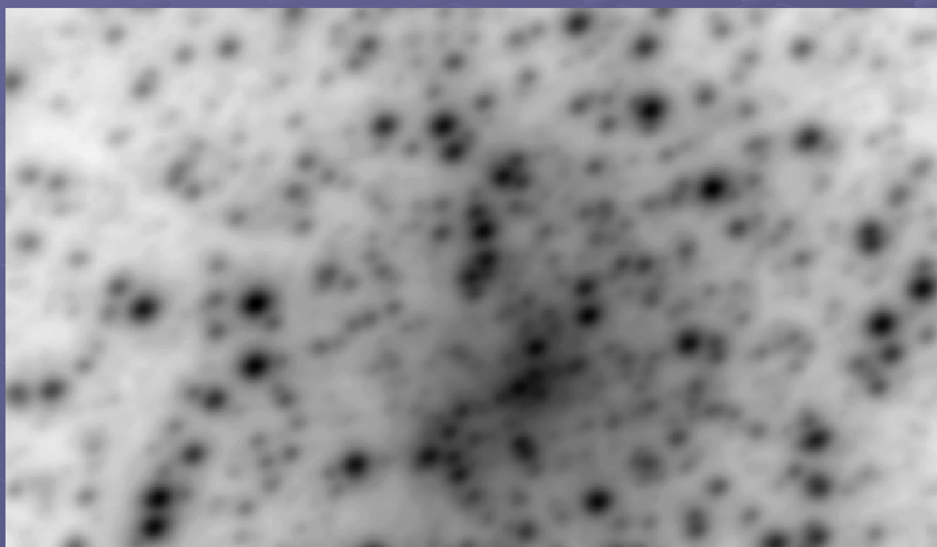


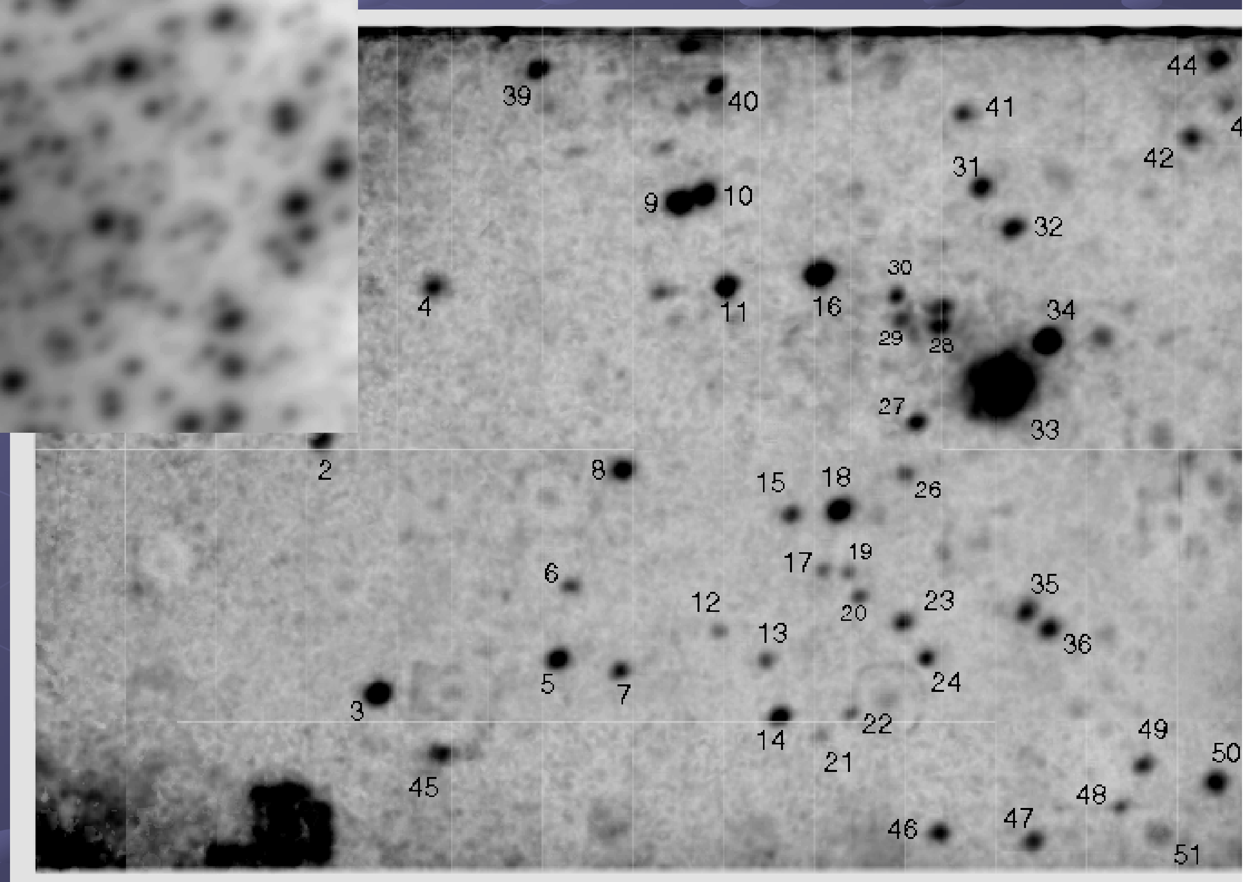
Core of the globular cluster M15 - PEIS by TRIFFID/MAMA camera on 4.2m WHT

Butler et al., 1998, MNRAS

PEIS *& Variability* in Crowded Fields

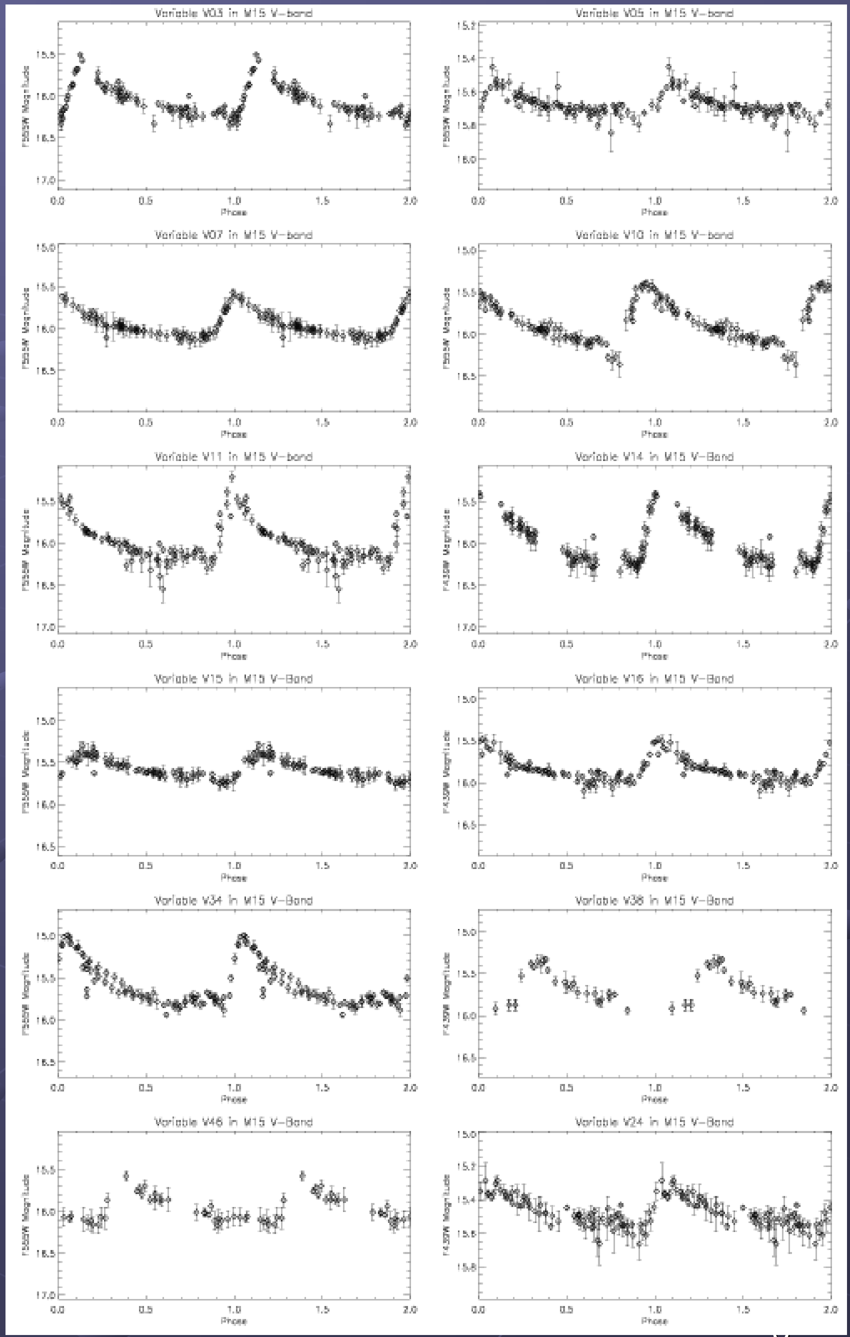
- TRIFFID/MAMA data; PSF-matching + image-subtraction technique





Average of ~30 matched & subtracted images of M15 - variable stars numbered

PEIS *& Variability* in Crowded Fields



- Light-curves of 12 of our new variable stars in M15

Ó Tuairisg et al., 2003, MNRAS

Why do we need fast optical cameras (high cadence imaging)?

3. For Practical Observational reasons:

Observing in the high-flux regime
- bright objects (whether variable or not)

Observing in the wide dynamic range regime
- faint targets embedded in a field of bright objects

Beating down the effects of atmospheric scintillation
- time-series observations

Very Bright Sources

Photometry/astrometry of very bright stars (esp. on larger telescopes)...

- Best astrometric standards are bright: Hipparcos ~ mag 6, Tycho ~ mag 10
- Ditto for best photometric standards

- Exoplanet transits/candidates – bright selection bias (RV surveys, widefield surveys)
  - mag ~8-9 not uncommon

- High S/N, high cadence lightcurves – for fine temporal structures

Saturation sets limit – imposes short exposures

Duty Cycle

$$\text{Duty Cycle} = \frac{\text{Exptime}}{\text{Cycle time}} * 100\% \quad = \quad \frac{\text{Exptime}}{\text{Exptime} + \text{dead time}} * 100\%$$

Avoiding CCD saturation → poor duty cycle for high cadence & high S/N imaging

Solutions?

- Increase well depth...delay onset of saturation
- Reduce readout time...but penalty in increased readout noise (~2 e^- → ~10-100 e^-)
- Window down for fewer pixels...not always feasible
- Defocus...introduces new problems

Duty Cycle

$$\text{Duty Cycle} = \frac{\text{Exptime}}{\text{Cycle time}} * 100\% \quad = \quad \frac{\text{Exptime}}{\text{Exptime} + \text{dead time}} * 100\%$$

Avoiding CCD saturation → poor duty cycle for high cadence & high S/N imaging

Solutions?

- Increase well depth...delay onset of saturation
- Reduce readout time...but penalty in increased readout noise (~2 → ~10-100)
- Window down and/or bin pixels...not always feasible
- Defocus...introduces new problems

→ all telescopes have ≈same ceiling of flux/runtime for given CCD

Dynamic Range

Ratio between brightest & faintest object which can be discriminated at any one time

CCD: Brightest object → Well depth   Faintest object → Readout noise

Conventional CCD

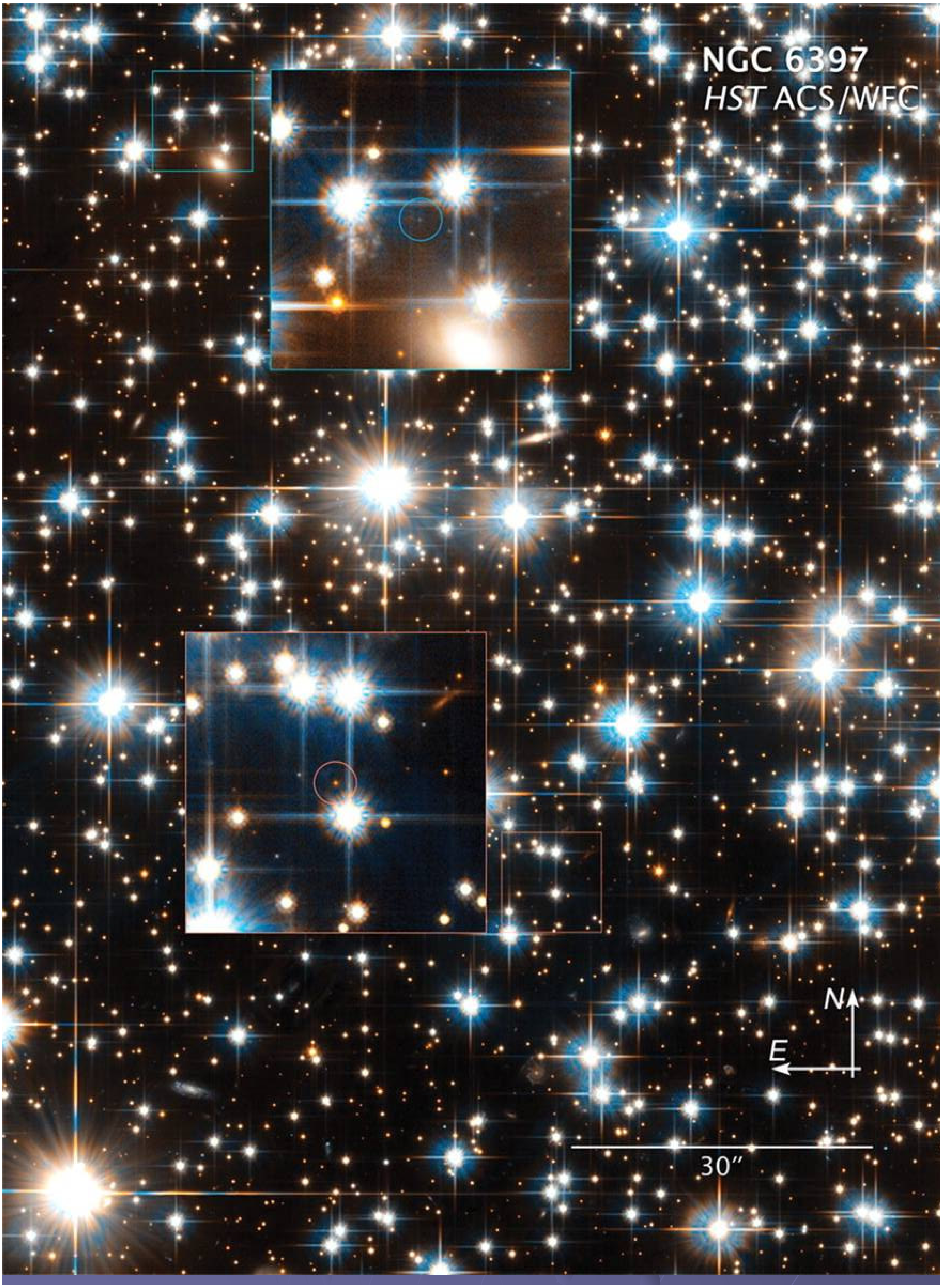
$$DR = \frac{\text{Well Depth}}{\text{Readout noise}}$$

Bigger telescope aperture, for given exposure time:

- pushes mag limit deeper
- loses mags at the bright end

$\rightarrow$ "moving window" of dynamic range

Stacking frames widens the range...

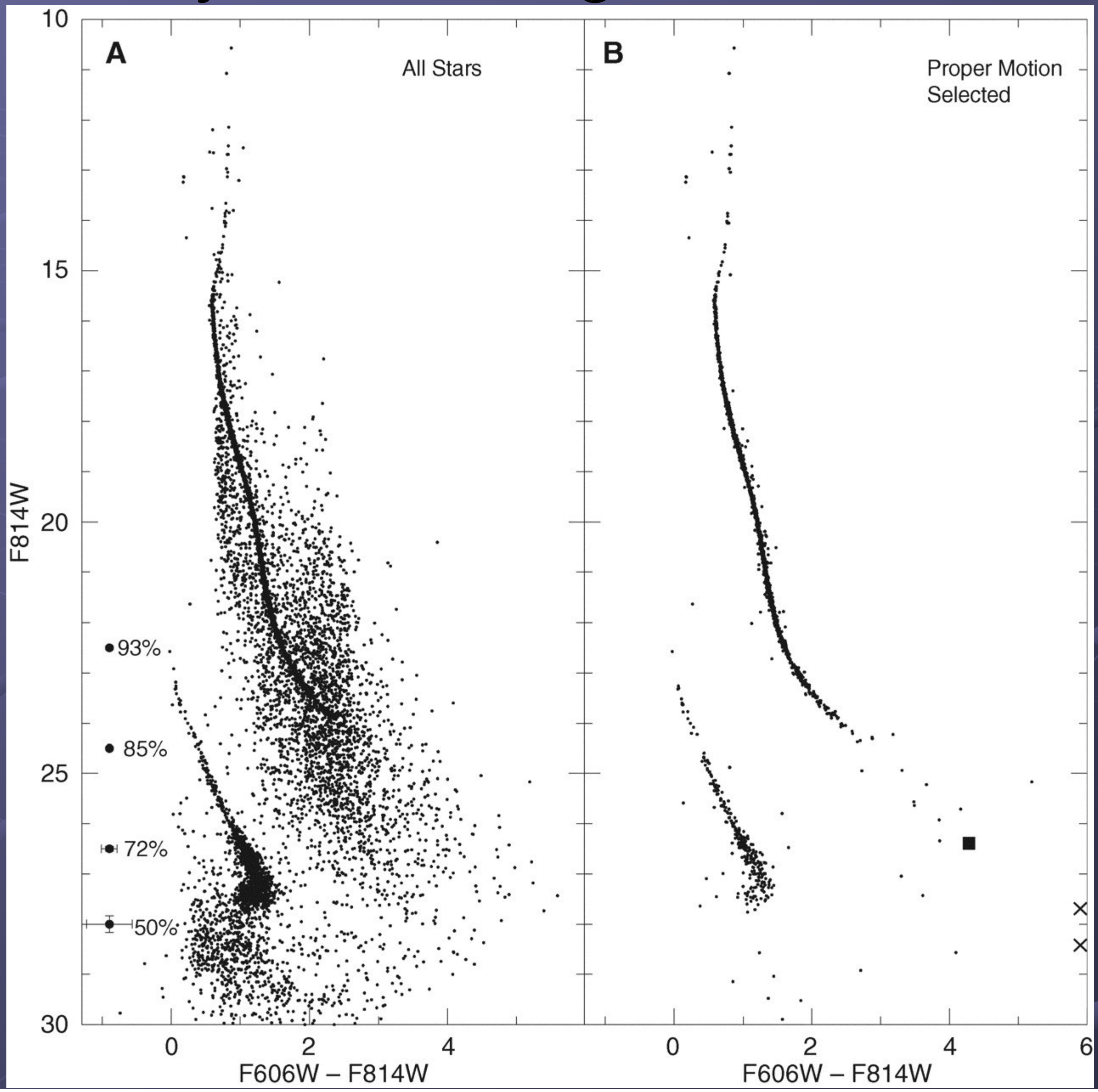

NGC 6397
HST ACS/WFC
N
E
30″

Wide Dynamic Range

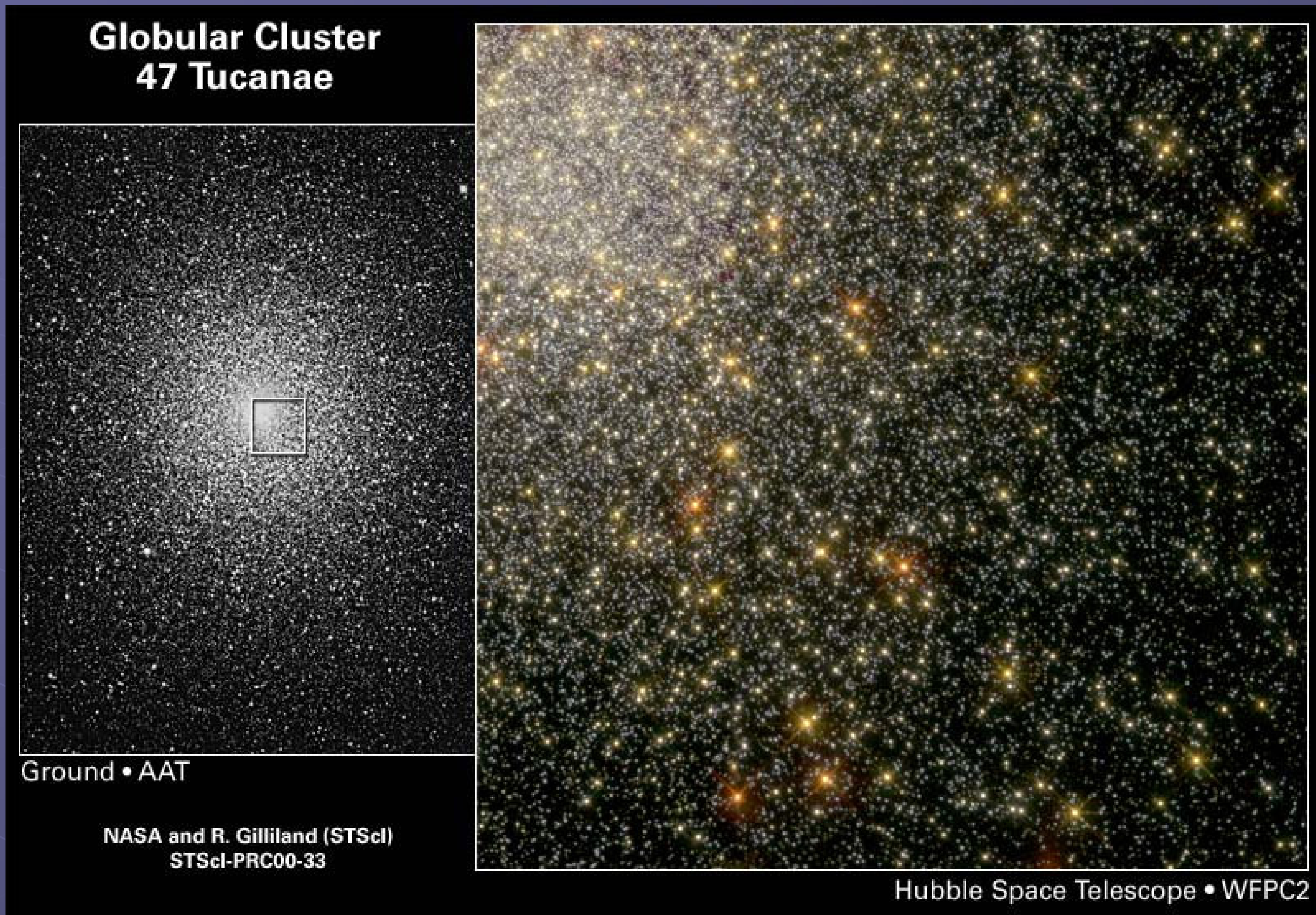
Globular Cluster M4: White Dwarf population

20 magnitudes range!
= 10^8 x flux range

…but could be done much faster with a better duty cycle



Wide Dynamic Range & *Variability*



...and what if the frames are a timeseries? Then, Duty Cycle limits SNR & DR.

e.g. 47 Tuc was searched for exoplanet transits of upper MS stars (HST; Gilliland et al. 2000)

Scintillation Noise

- Scintillation is a random variation in the illumination of the telescope pupil.

  When exptime T is small, scintillation imposes significant photometric noise - scintillation noise α, scales as:

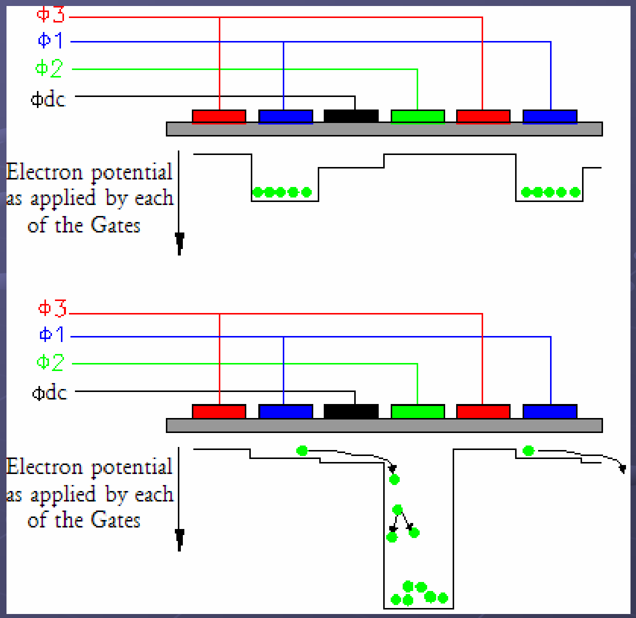
$$\alpha \propto \frac{1}{\sqrt{2T}}$$

- Percentage/fractional effect...not dependent on source brightness
- Becomes the dominant error source when flux is high...sets ultimate limit on photometric precision
- High duty cycle increases cumulative T over a run, thus reducing α.

  100% duty cycle makes α as low as theoretically possible for a given telescope aperture

Low Light Level (L3)CCD Technology

- Designed to alleviate the problem of read noise at MHz readout rates
- On-chip gain (Electron Multiplication or EM gain) increases the average signal above the noise floor of the amplifier
- Clocking stage $\Phi2 \rightarrow$ 40-45 volts, thereby allowing impact ionization to occur



Total Gain $= (1 + \alpha)^N$

Gain per stage (probability of producing one extra electron), $\alpha \approx 0.01$

Total number of gain stages, $N = 536$

<u>Total Gain ~ 2900</u>

Available since 2001 (E2V Technologies).

L3-CCD: Andor iXon DV-887-BV

Dual Readout Modes

- Conventional ~ 10 fps
- EMCCD ~ 30 fps

Frame Transfer

Dead time ~2ms

Variable readout rates

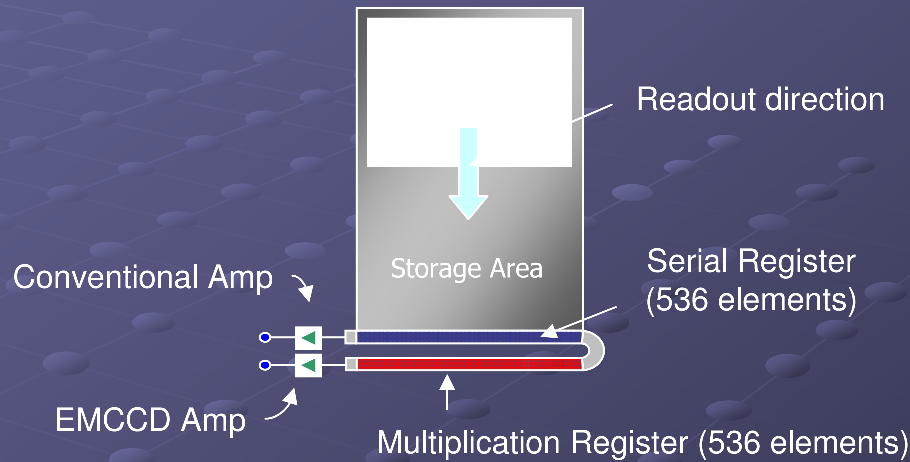
1, 3, 5, 10 MHz

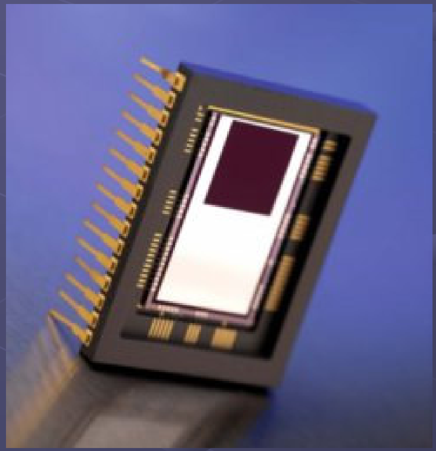
Variable EMCCD gain

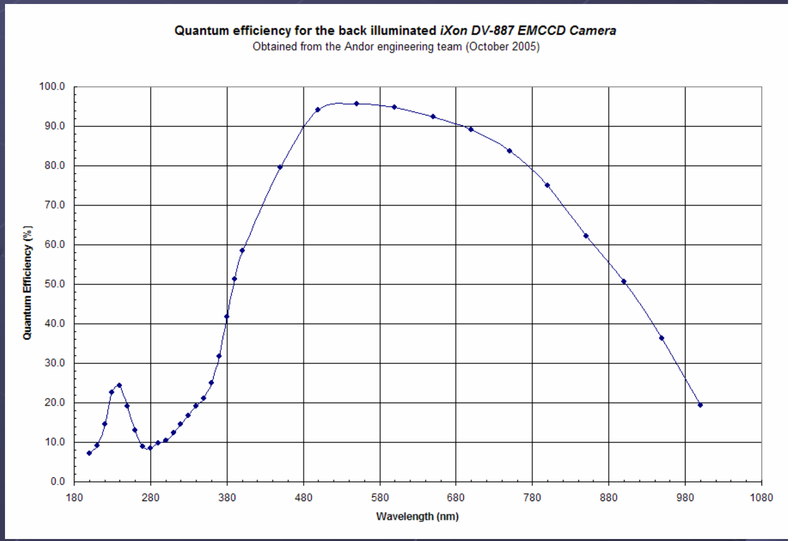
0 – 1000x

Variable Pre-amp gain

1x, 2.4x, 4.6x







Thinned, Back-illuminated, ARC, -87C water cooling, 512 x 512 (16 μm) pixels, 8.2 x 8.2mm

L3-CCD: Andor iXon DV-887-BV

Active Pixels	:	512×512
Pixel size	:	16×16 μm (W $\times$ H)
Active Area Well depth	:	200,000 e^-
Gain Register Well depth	:	400,000 e^-
Frame Rates	:	$31 \rightarrow 400$ fps
Readout pixel Rates	:	1, 3, 5, 10 MHz
Vertical clock speeds	:	0.4, 0.6, 1.0, 1.8, 3.4, 6.0 (μs)
Binning modes	:	1×1, 2×2, 4×4
Peak QE (@ 575nm)	:	92.5%
Dark Current (@ -90°C)	:	0.0035 e^-/pixel/sec
Readout amplifiers	:	Conventional & EMCCD

Using Low Light Level (L3)-CCDs

3 scenarios/modes of operation (Mackay et al. 2001):

1. Conventional (no EM gain): like a regular CCD, but RON = 6 - 16 e^- rms
2. Low EM gain: reduces RON to ≤ 1 e^- rms, but ENF effectively halves QE
3. High EM gain: RON << 1 e^- rms, enables Photon Counting, ~full QE, but very low fluxes mandatory (very high frame rates) to avoid coincidence losses.

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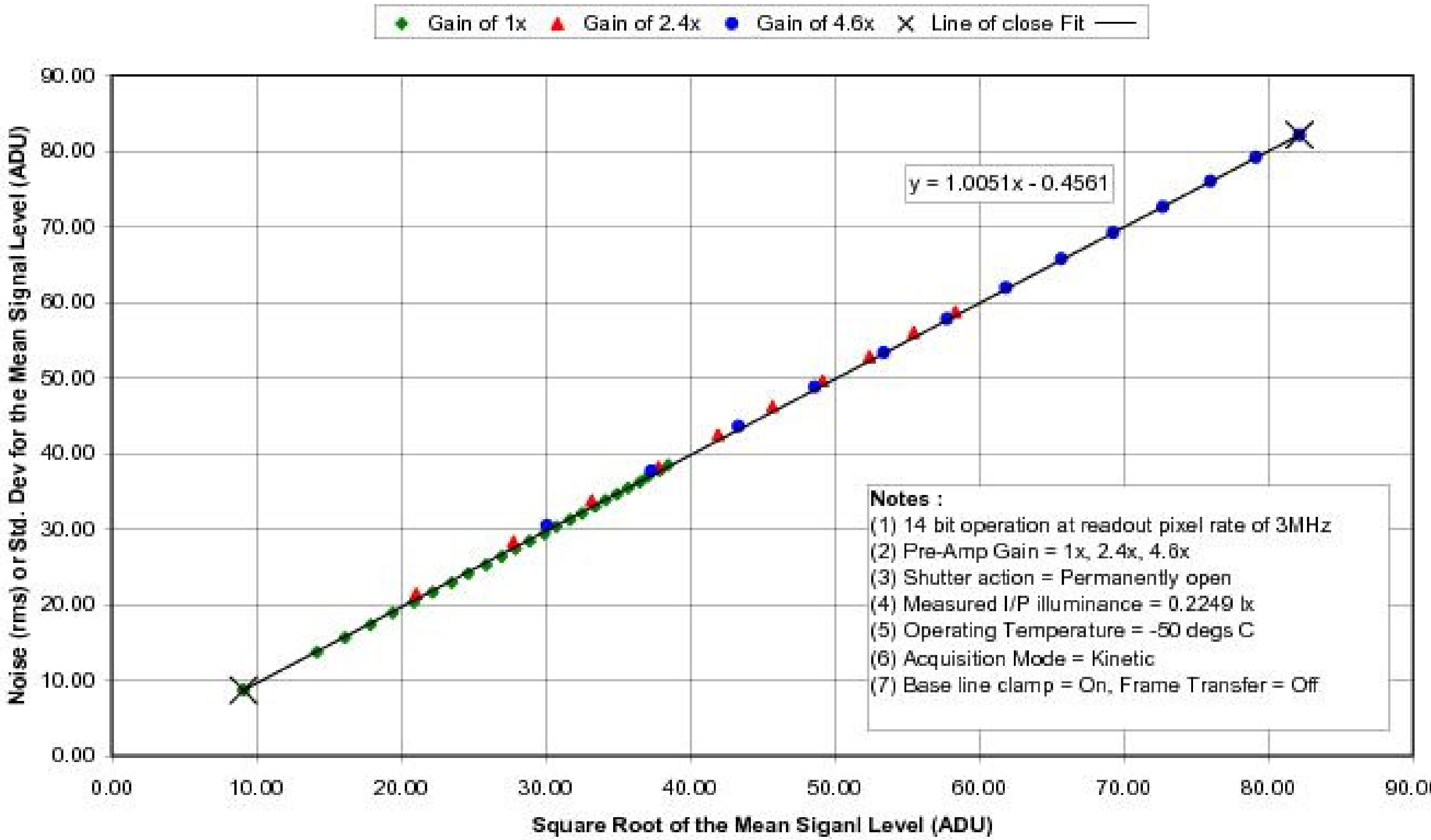
Conventional (Frame Transfer) mode

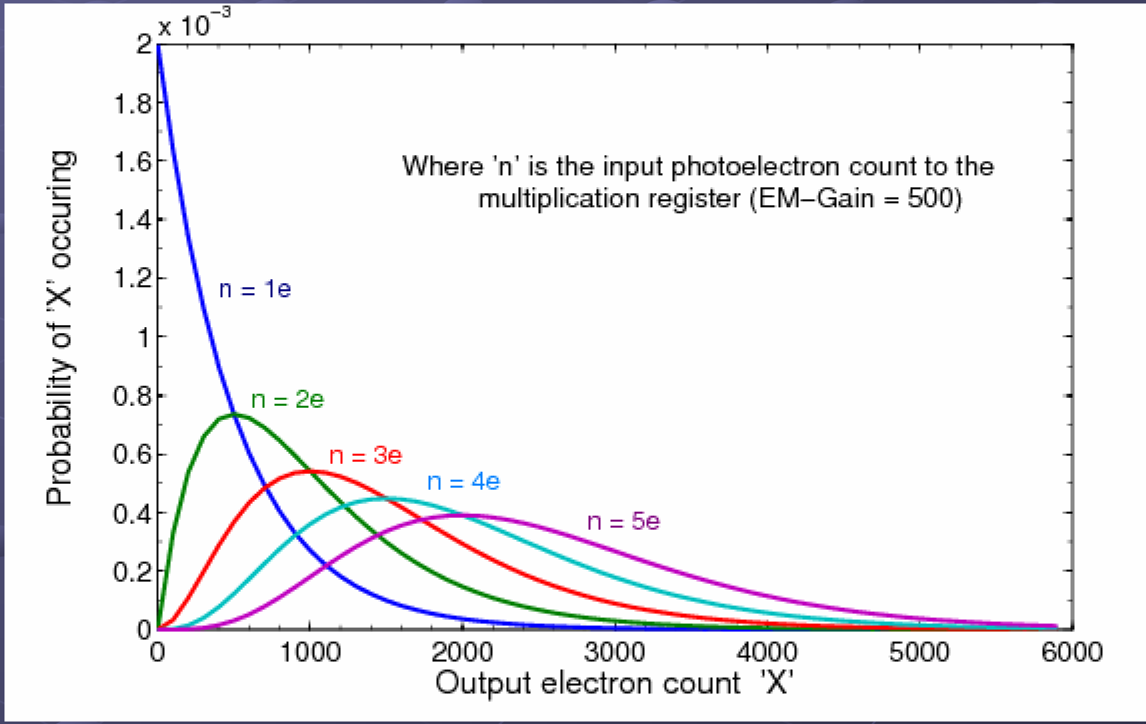
- Poisson-limited, as expected



Excess Noise Factor (ENF)

- Electron Multiplication is a stochastic process at each stage in EM register
  $\rightarrow$ output EM gain is not exactly predictable
  $\rightarrow$ a given input count will be amplified to a distribution of output counts:

$$p(x) = \frac{x^{(n-1)} exp(\frac{-x}{g})}{g^n (n-1)!}$$



- For 100s of input electrons, a Gaussian description is more appropriate

Excess Noise Factor (ENF)

- Coupled with the Poisson uncertainty of the input count, the extra photometric uncertainty due to the output EM distribution is called the Excess Noise Factor (ENF) aka Multiplication Noise

- ENF (*F*) given by: $$F^2 = \frac{\sigma_{out}^2}{M^2 \sigma_{in}^2}$$

  - where *M* = EM gain, σ^2 = input and output signal variances for EM register

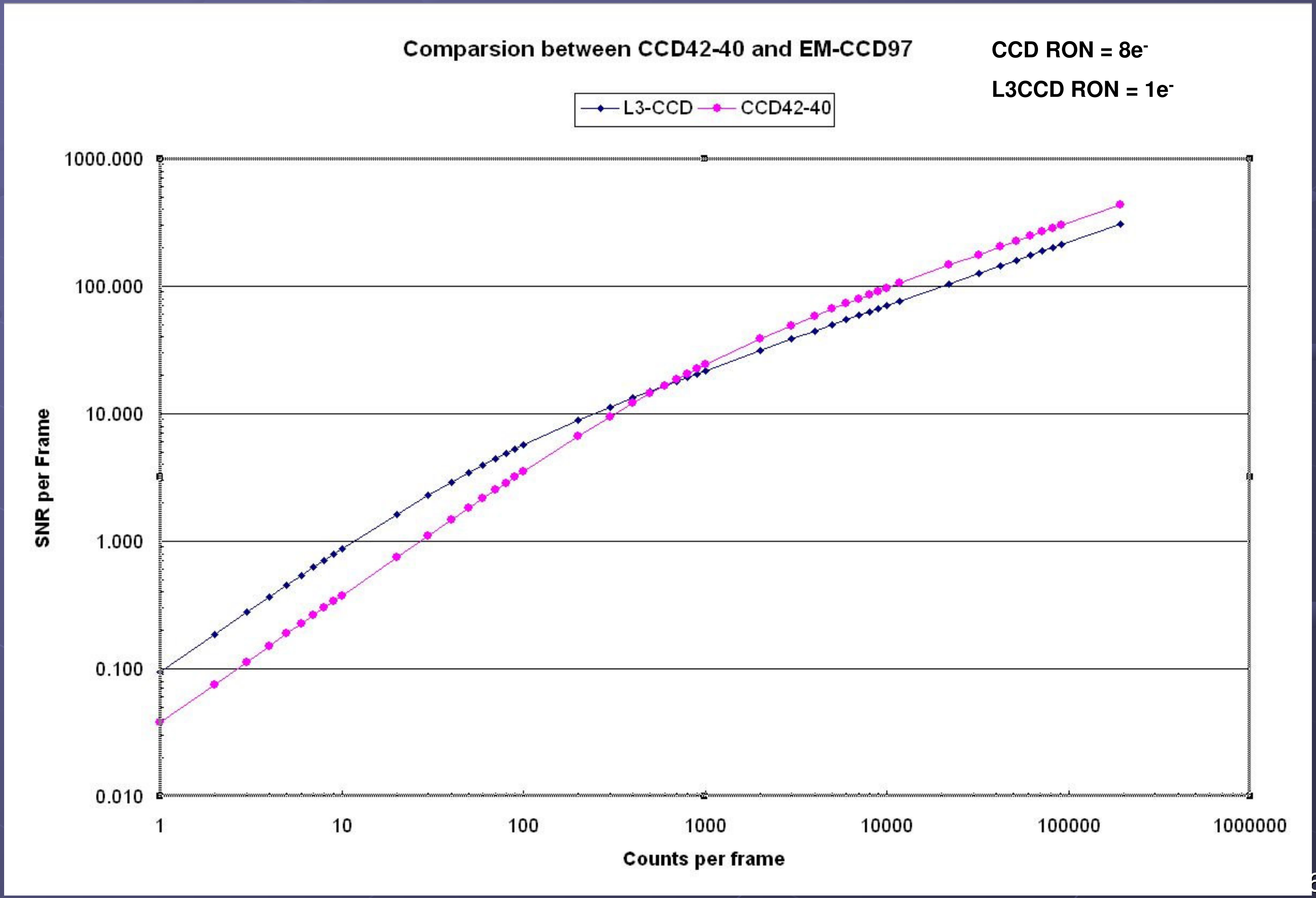
- For large *M*, $$F^2 \approx \frac{2}{\alpha + 1}$$ and with $\alpha \approx 0.01$, *F* tends to $\sqrt{2}$

- Thus ENF is equivalent to halving the Quantum Efficiency

- At high input counts (>100's of photo-electrons), CCDs regain the SNR advantage per frame

Signal to Noise calculations: CCD versus L3-CCD

Single frame with EM gain; shows ENF penalty at high counts



Duty Cycle Case Study: CCD versus L3-CCD

2.5m telescope; I-band mag = 12; 15 sec exposure (just unsaturated)

- Conventional CCD:
  - 1024 x 1024 pixel, Readout rate = 20kHz, No Frame Transfer
  - Readout (dead) time = 29 seconds; Cycle time = 15 + 29 = 44 seconds

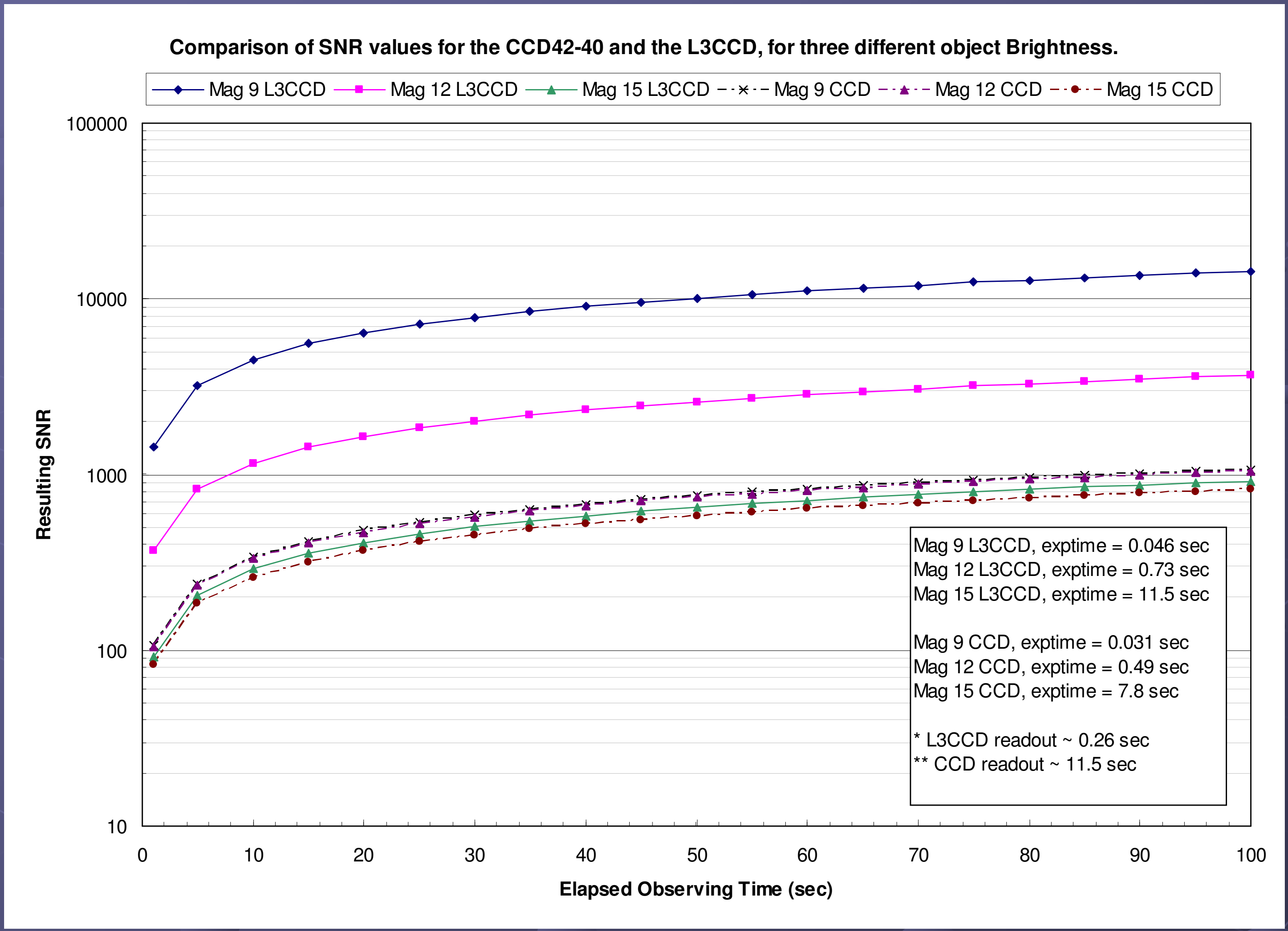
→ **34.09%**

- L3-CCD:
  - 512x512 pixels, Readout rate = 1 MHz, Frame Transfer (EM unnecessary)
  - Readout time from storage area = 262 ms
  - Cycle time = 262 ms + frame transfer time = 2ms → 264 ms
  - *BUT* if exposure time > cycle time, dead time = 2 ms

→ **99.98%**

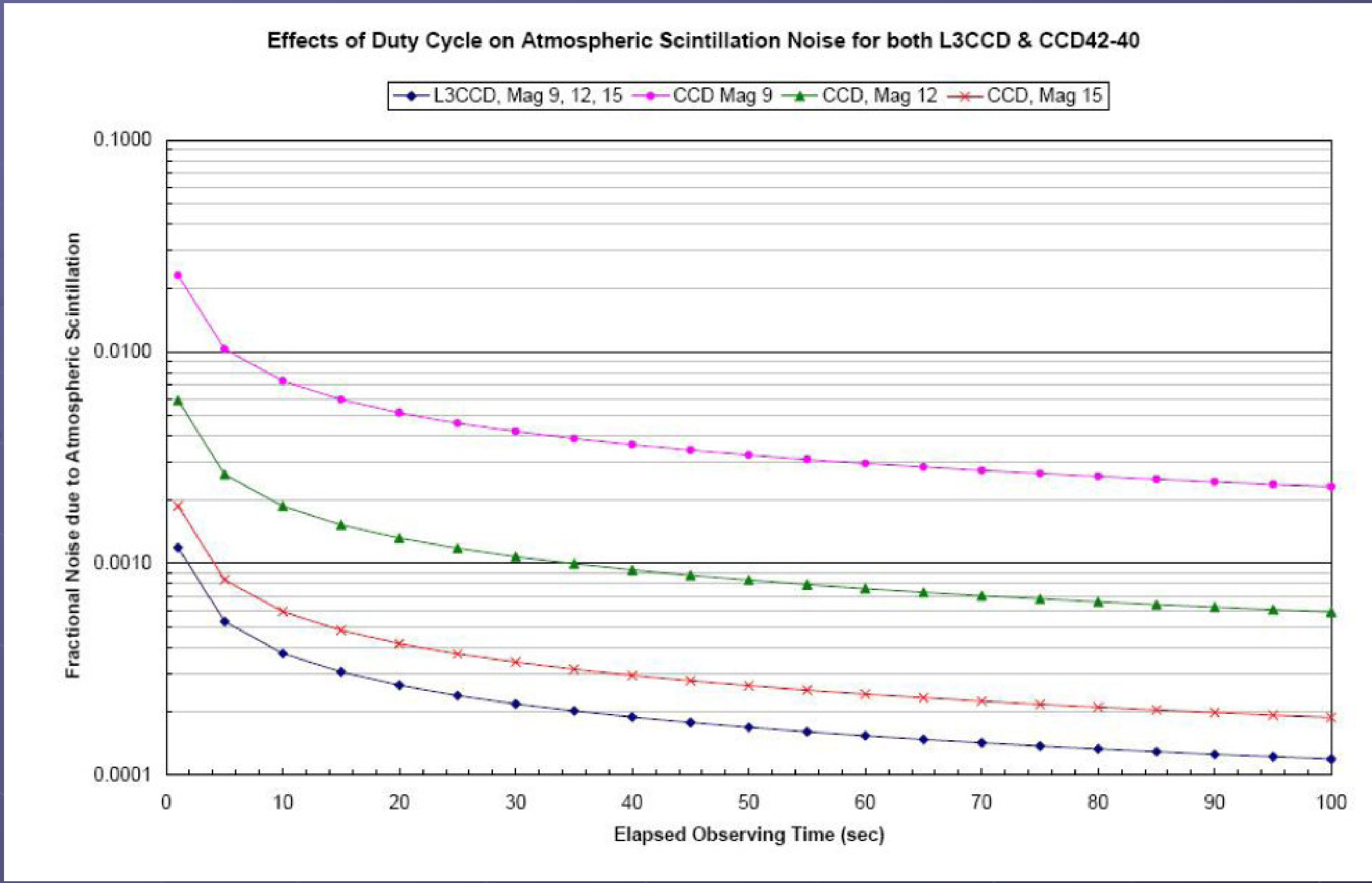
- Frame transfer alone is all you need in most situations

Duty cycle effects: CCD versus L3-CCD



- Cumulative Signal to Noise calculations (2.5m, V band)
- L3-CCD vastly superior for brighter objects
- Performance for CCD and L3-CCD converges for dimmer objects.

Scintillation Noise: CCD versus L3-CCD



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Dynamic Range

CCD versus L3-CCD

Conventional CCD

$$DR = \frac{\text{Well Depth [of Pixel]}}{\text{Readout noise}}$$

L3-CCD

$$DR = \frac{\textit{Effective}\ \text{Well Capacity}}{\textit{Effective}\ \text{Readout Noise}}$$

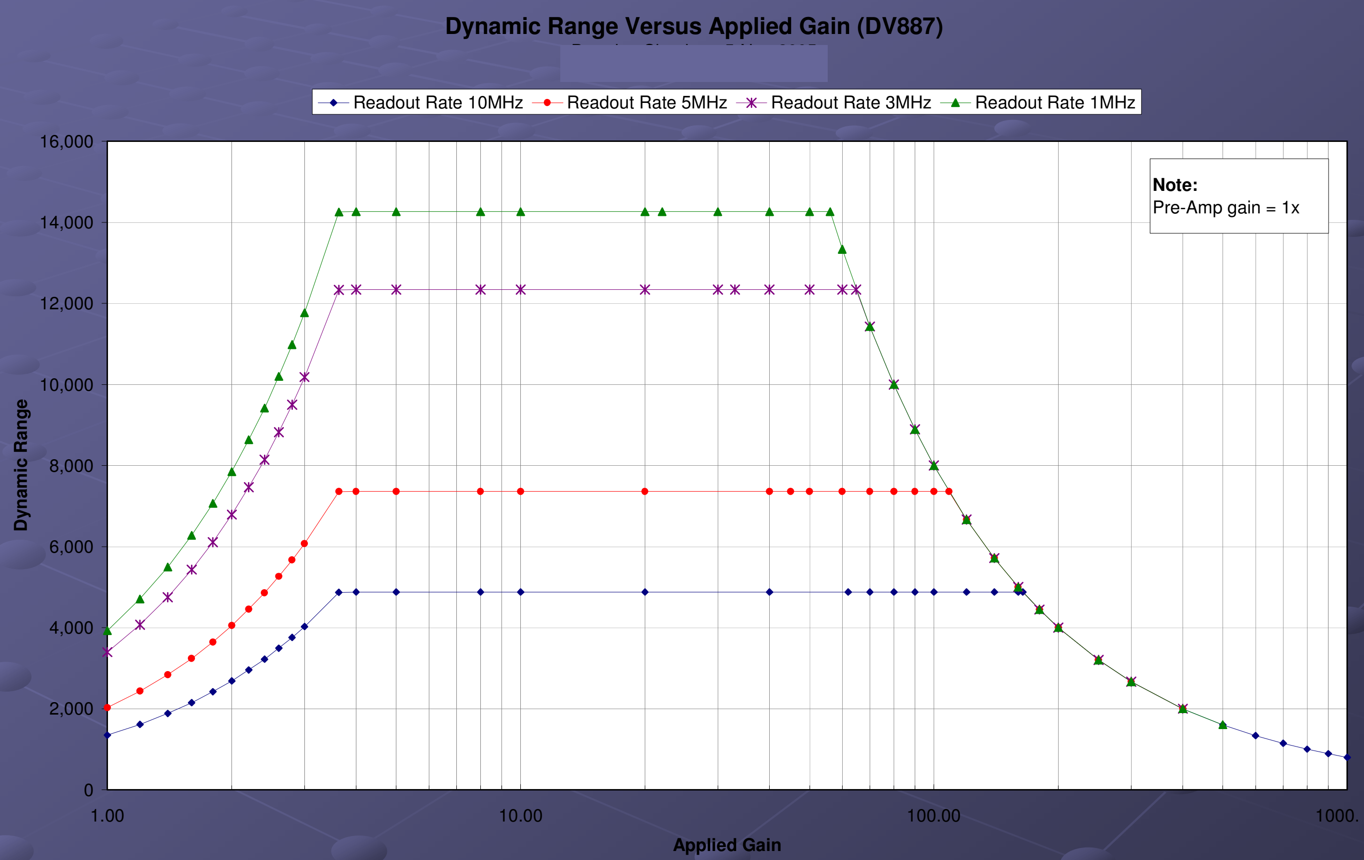
$$\text{Effective Well Capacity} = \frac{\text{Well depth of Gain Register}}{\text{EM Gain}}$$

$$\text{Effective Readout Noise} = \frac{\text{Readout Noise}}{\text{EM Gain}}$$

L3-CCD

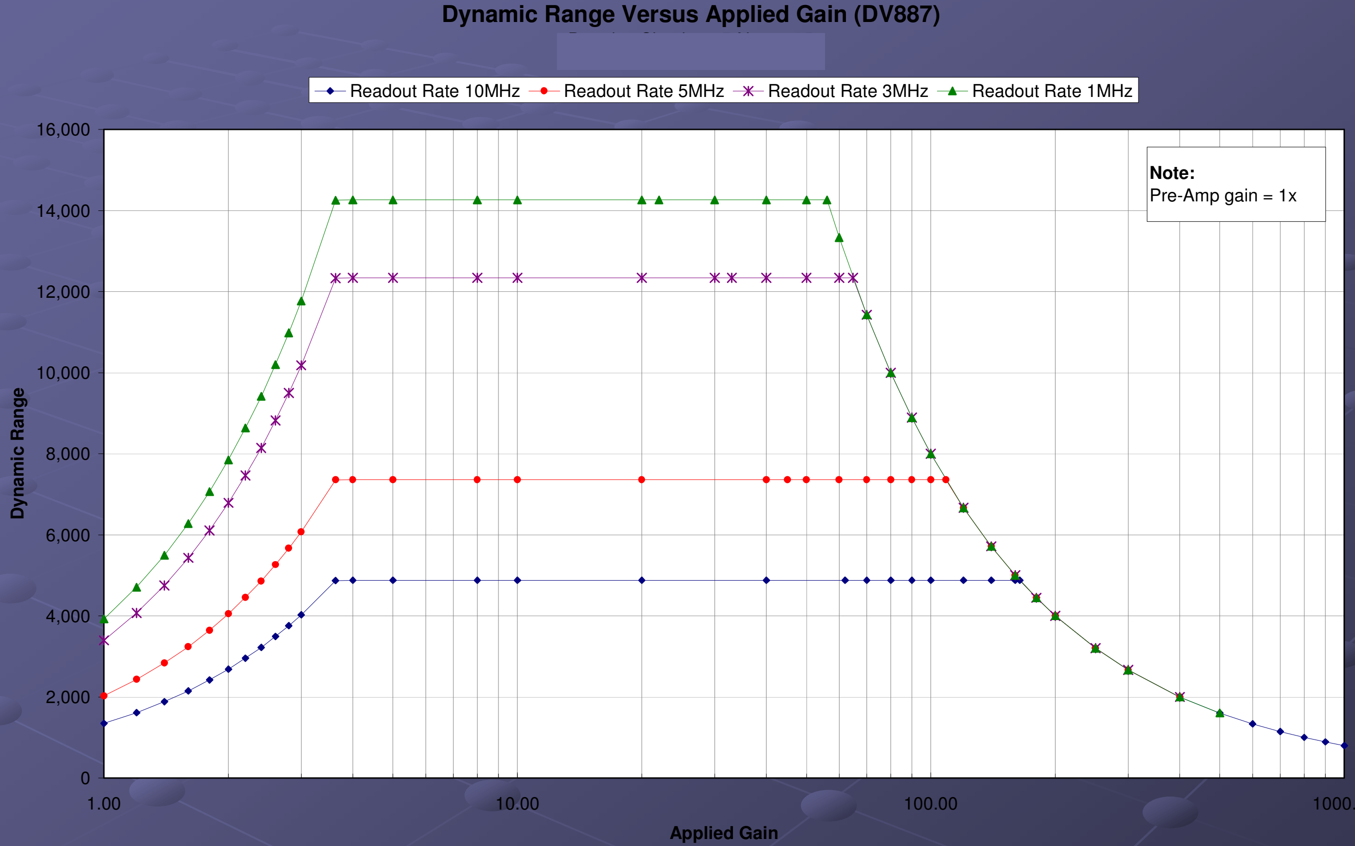
$$DR = \frac{\text{Well Depth of Gain Register}}{\text{Readout Noise}}$$

Dynamic Range & EM-Gain



1. DR will rise as EM decreases effective readout noise
2. DR constant as reduction in eff. readout noise balanced by decrease in eff. well depth.
3. When minimum readout noise reached (1 e-), DR falls due to further reduction in effective well depth.

Dynamic Range vs. Signal to Noise



- Best dynamic range obtained <u>with</u> EM gain
- But at high flux, best S/N obtained <u>without</u> EM gain

  - RON reduction (few e^-) doesn't compensate for ENF/effective QE 2x reduction (Poisson noise dominates over RON)
- ⇒ Dynamic range is not coupled to S/N ! You have to choose…

When to use EM gain, on bright sources?

1. For maximum dynamic range (rather than maximum S/N)

2. For very brightest sources, which would saturate even at the maximum 3MHz (~10 fps) Frame Transfer rate
   - Can use EM mode (with low EM gain) – at 10MHz (~33 fps)

3. When the cadence is more important than the S/N
   - PEIS & Lucky Imaging
   - Very fast astrophysical phenomena where time smearing is unacceptable

Basic Observing strategy

Use L3 with read noise minimised

Optimum DR or cadence

Exposure time (with no saturation)

Due to higher readout rates, will acquire more images (more signal) per unit observing time

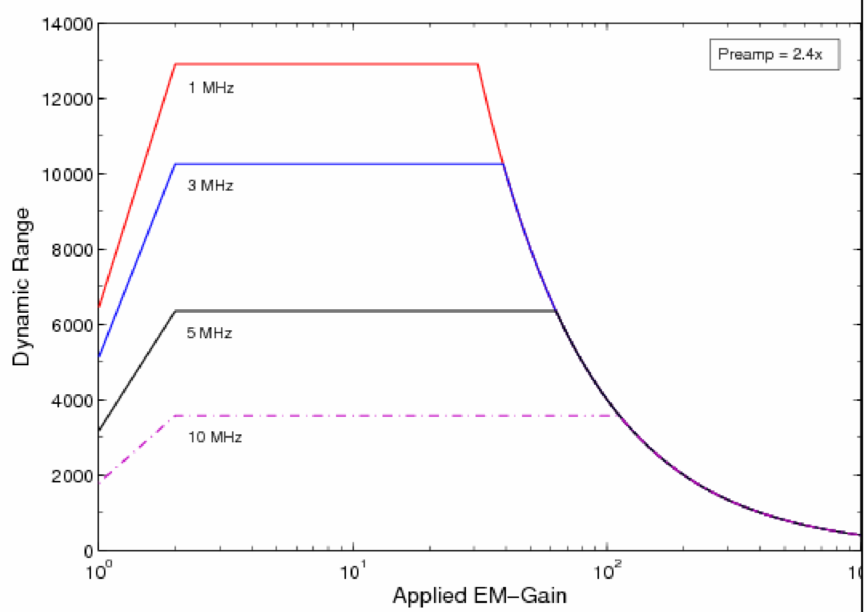
Coadding the N images will improve the SNR $\sqrt{N}$ times

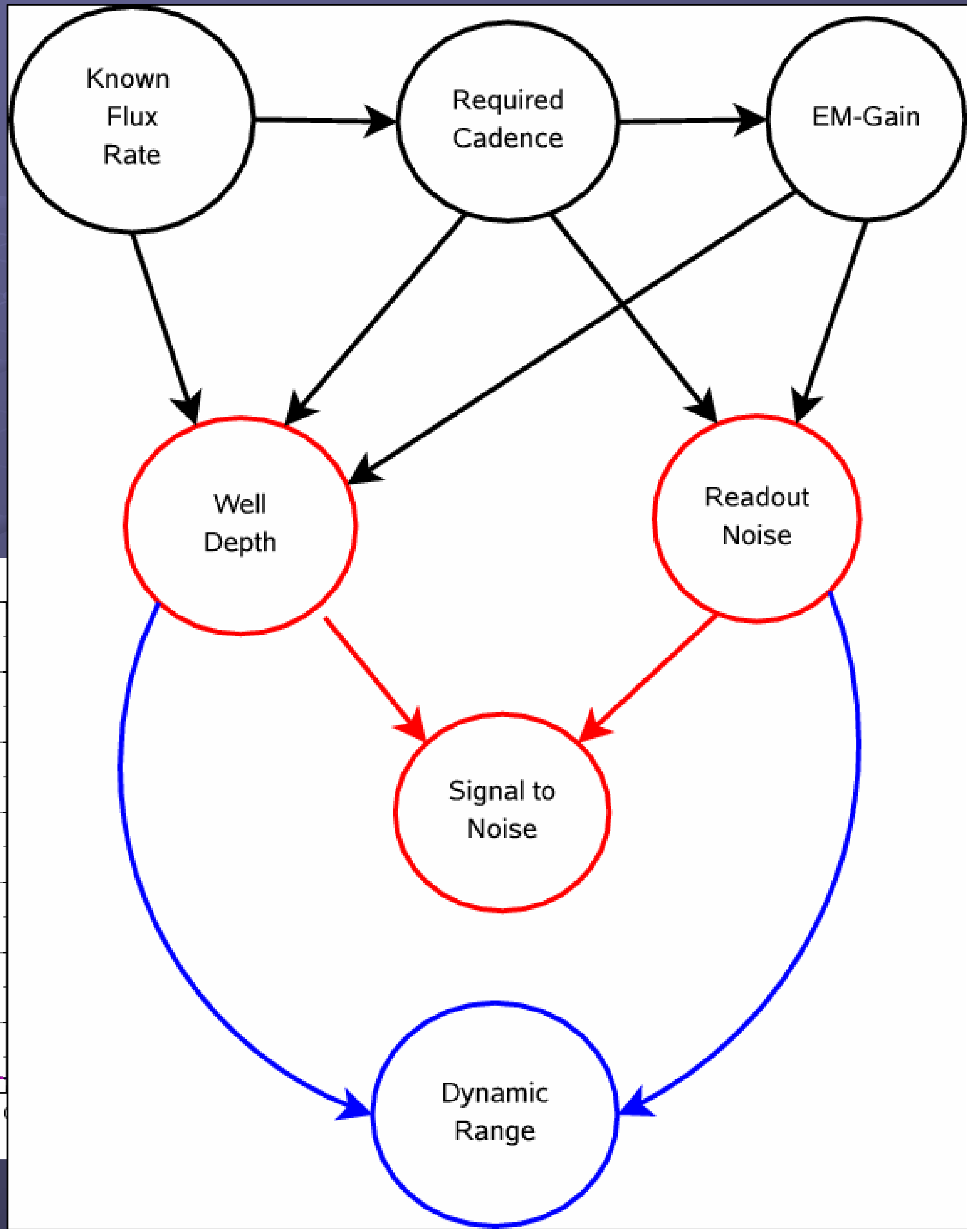
Light curves (time series data) have more points per run, improving their quality, statistical fit, etc.

Operation model

Multi-parameter matrix of all possible operation modes…

Need a systematic way to find the "best" operation mode for a given observing scenario.





Operation Mode Selection – Details

1. Firstly, the input signal must be related to the number of detected photons as a function of exposure time, i.e. Signal = flux rate × exposure time.
2. The calculated signal represents the total number of counts from the supposed target. To check if saturation will occur in the imaging pixels, it would be desirable to know the peak count. By assuming a Gaussian PSF as the star's profile,, an approximate value for the peak count may be evaluated as follows:

$$\text{Peak count} = \frac{\text{Signal}}{2\pi\xi^2} \tag{2.28}$$

   where ξ is defined as,

$$\xi = \frac{\text{FWHM}}{2.354} \tag{2.29}$$

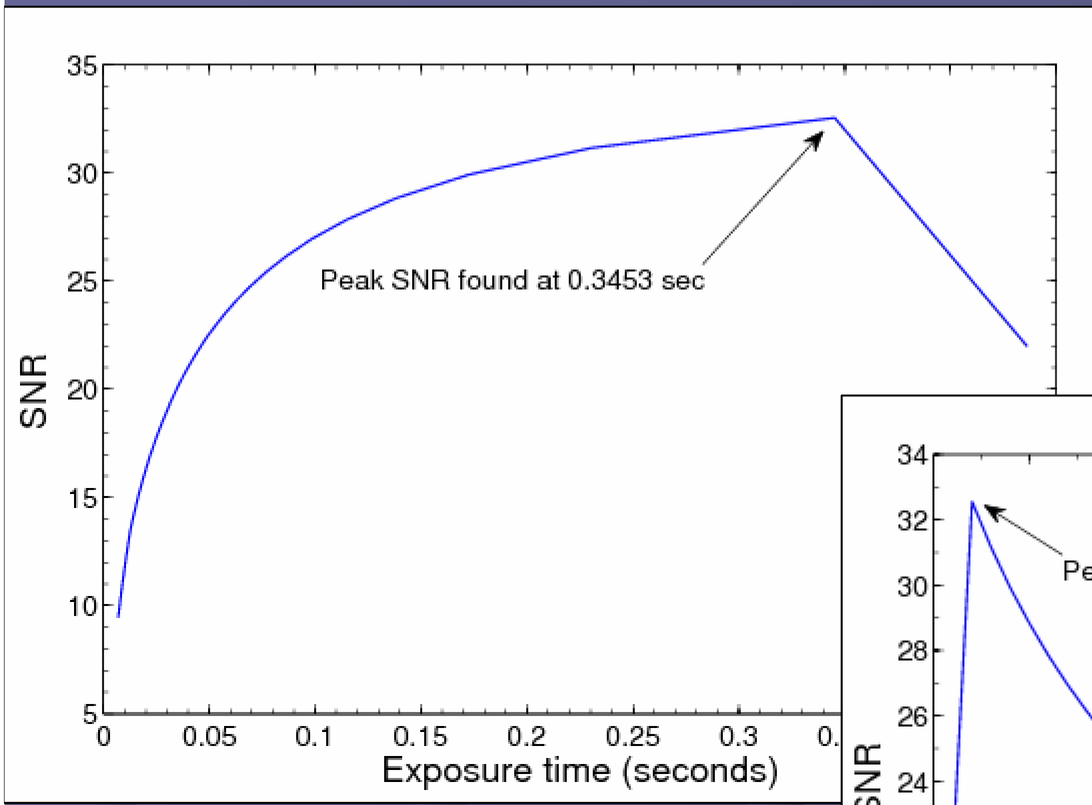
   and FWHM is the full width at half maximum of the star profile in units of pixels.
3. To avoid the effects of saturation, it is ensured that the peak count does not exceed the well depth of the imaging pixels.
4. Equating the peak count to the effective well depth allows the level of EM-gain to be computed so that saturation will not occur in the EM-register during the amplification process.

$$\text{Peak count} = \frac{\text{well depth}}{\text{EM-gain}} \tag{2.30}$$

   Or

$$\frac{[\text{flux rate} \times \text{exposure}]}{2\pi\xi^2} = \frac{\text{well depth}}{\text{EM-gain}} \tag{2.31}$$

Operation Mode Selection – Example

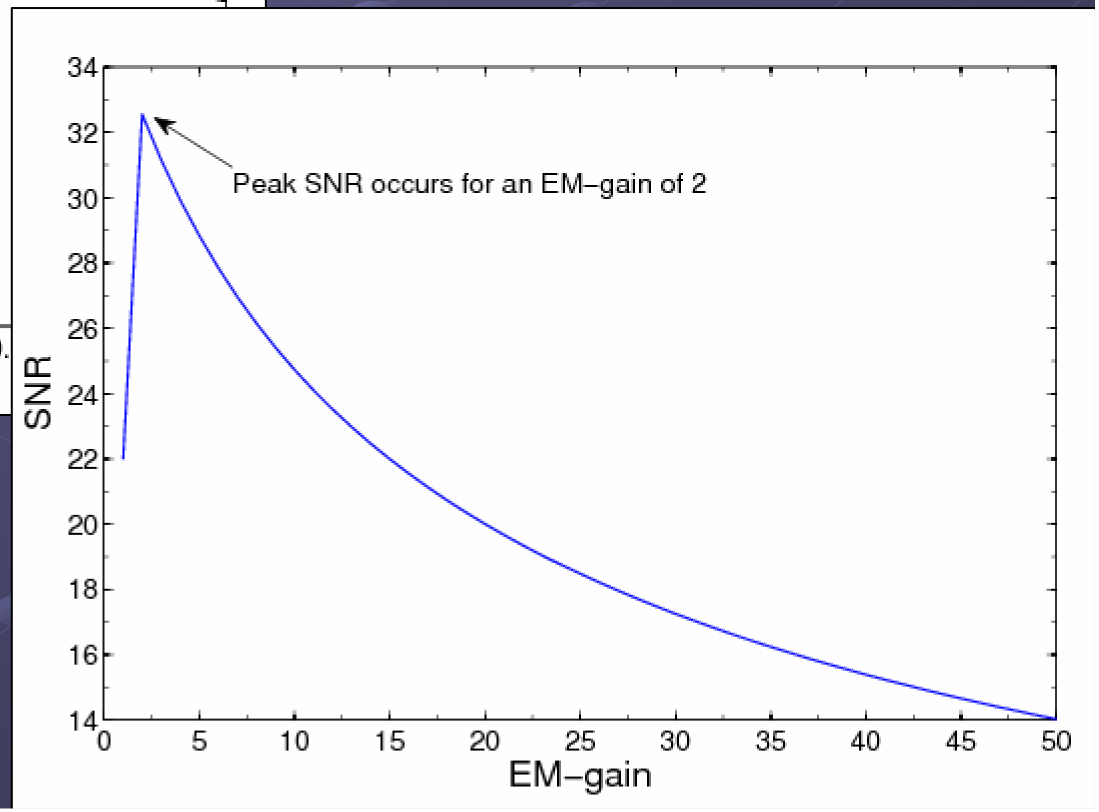


- The task: Find optimal Exposure time & EM-gain for D=2.5m, I = 12.9 mag, 1” seeing

GUFI pixel scale assumed

Pixel Well Depth = 200,000 e^-

EM Register Depth = 400,000 e^-



Galway Ultra Fast Imager: GUFI

- The goal in 2004:

  Build an imager/photometer to yield the benefits of

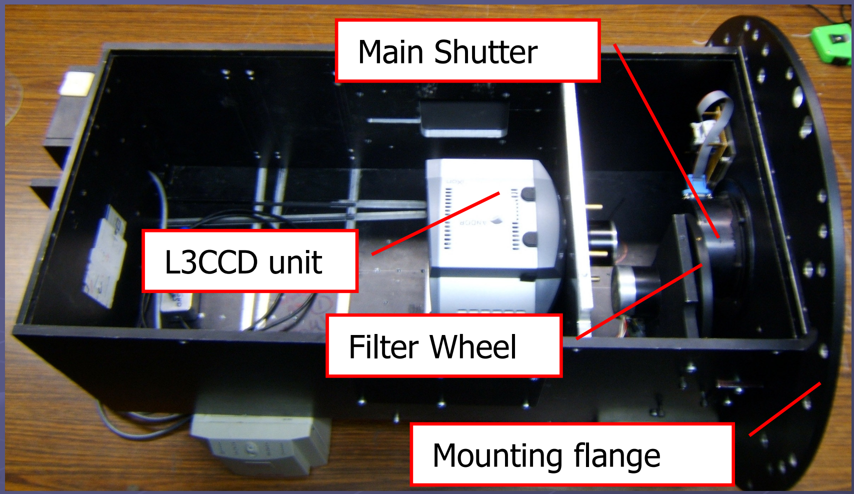
  - 100% duty cycle, and

  - "as-fast-as-you-want-it" sampling,

  for variability studies, PEIS, and high S/N studies of bright sources.

GUFI Instrument

- Optional 0.62x flat-field focal reducer
- Filter wheel: 5 x 48mm filters
- Water cooler for L3-camera unit (-87°C minimum)

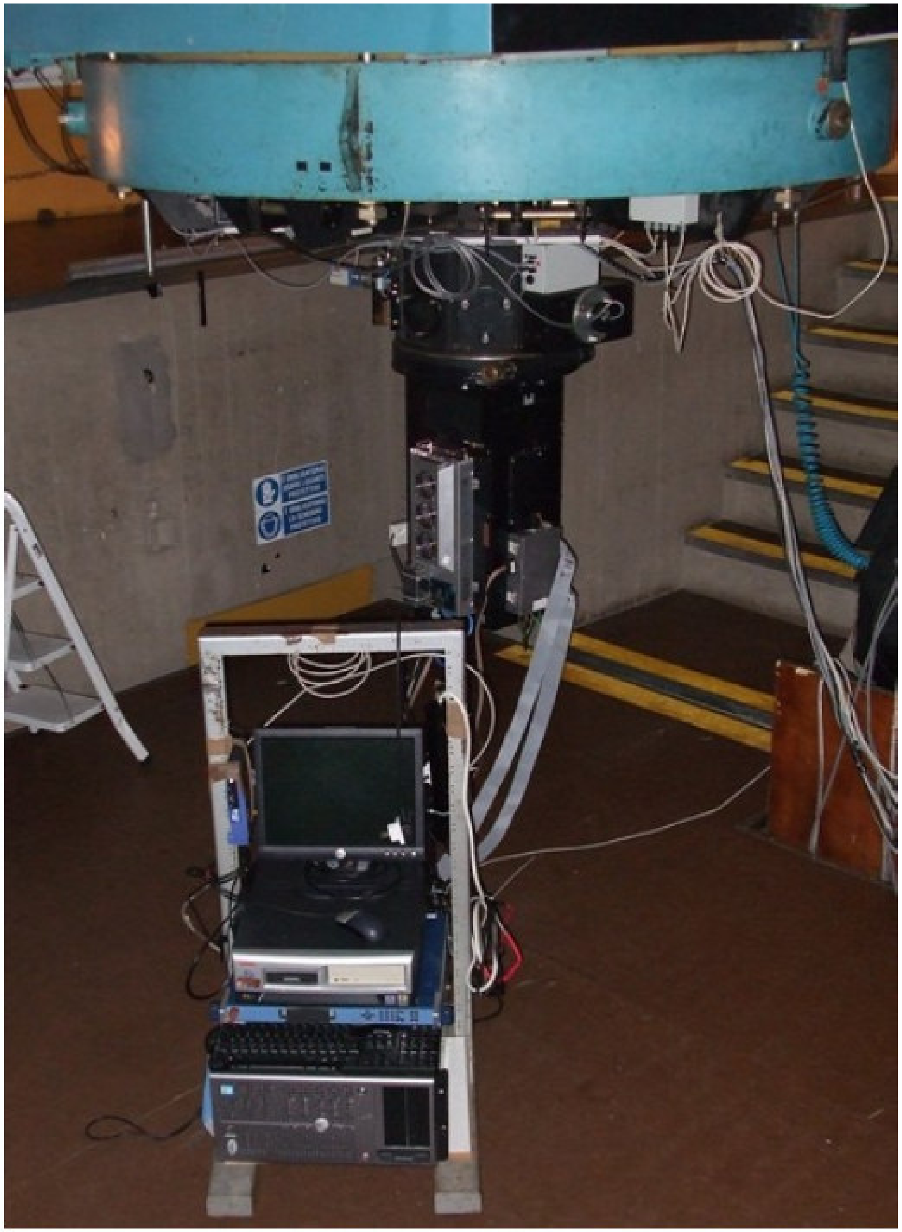


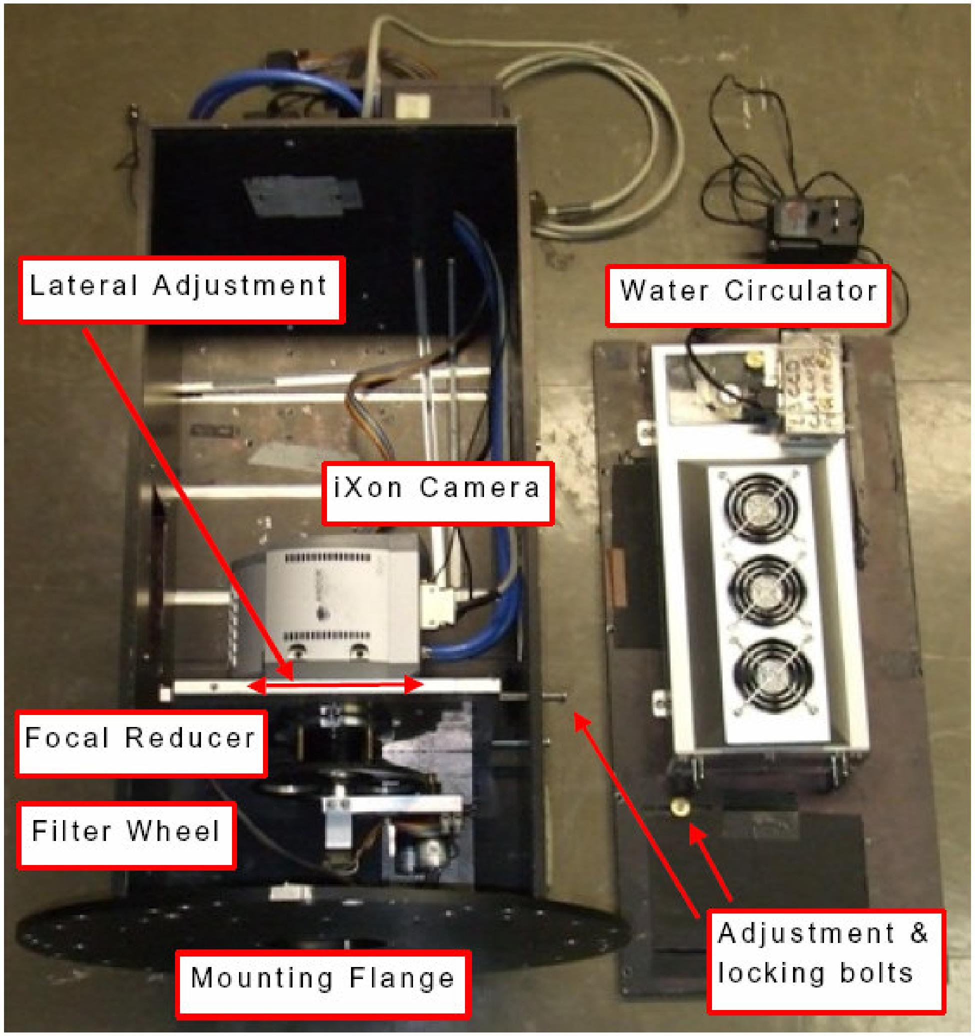
Data Rates:

- FITS format, 0.5 – 1 MB file size
- At 30 fps, ~ 50 GB per hour

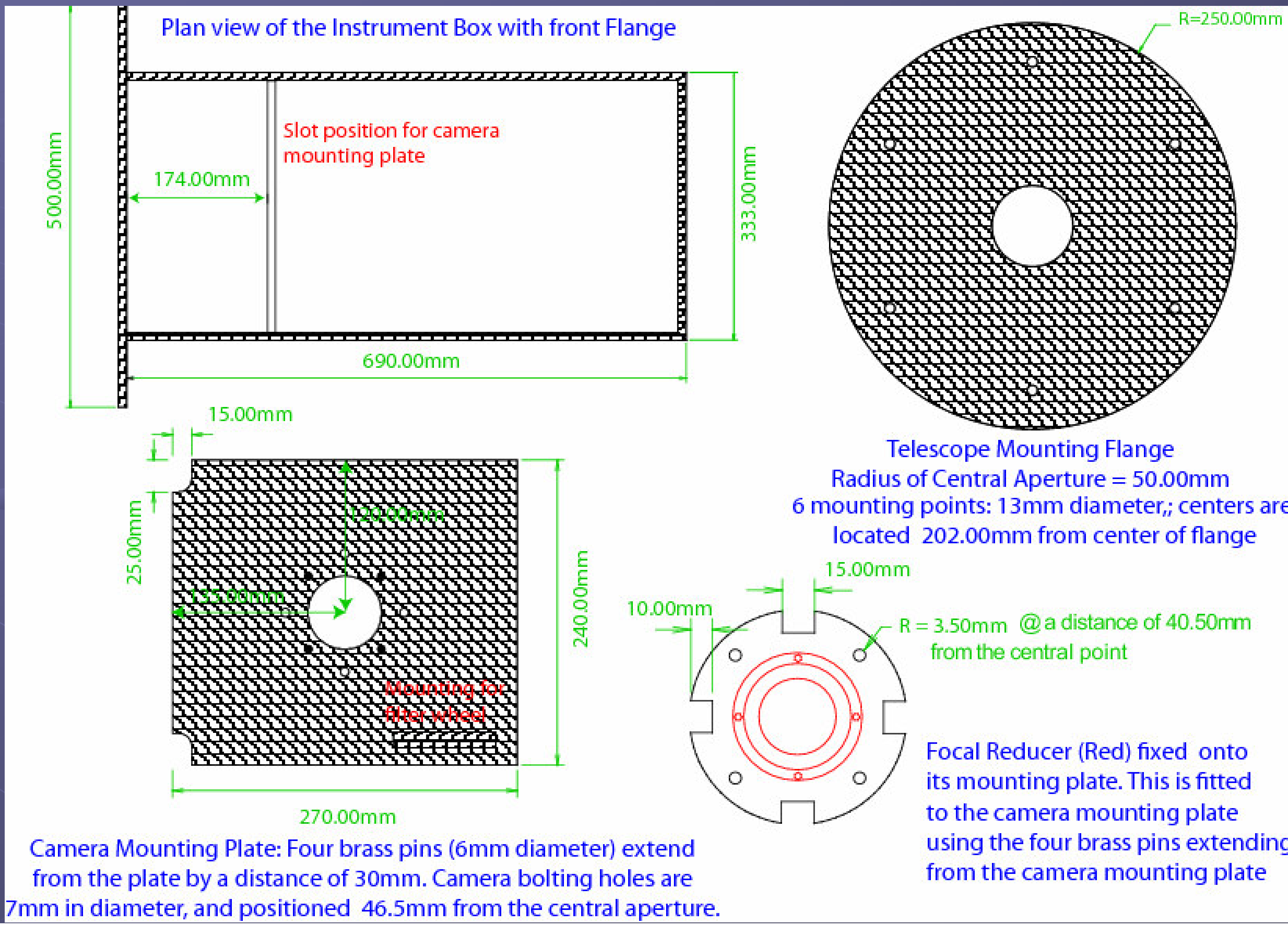
  → 1 TB storage
- Lossless compression (RICE)

GUFI Instrument

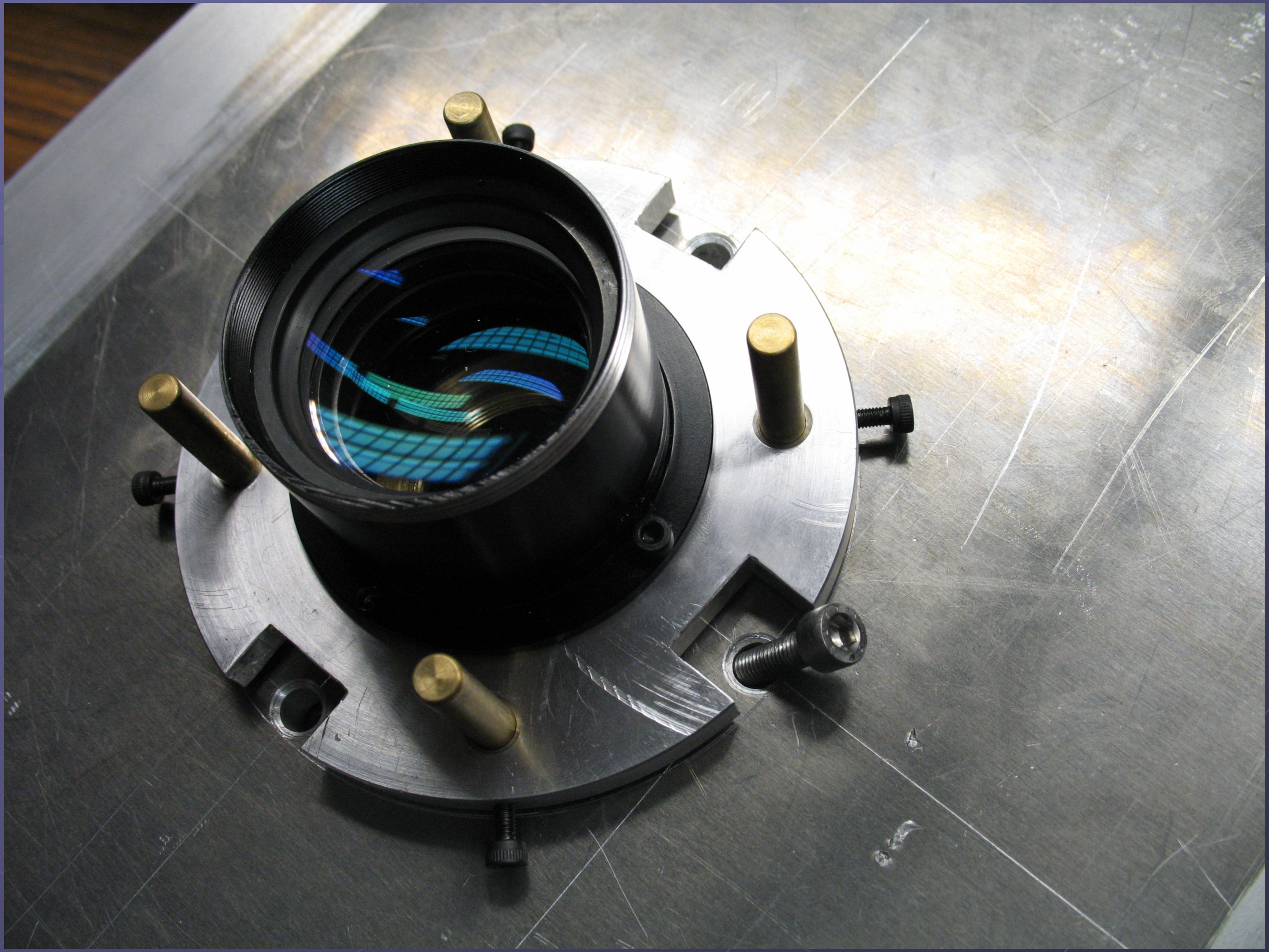




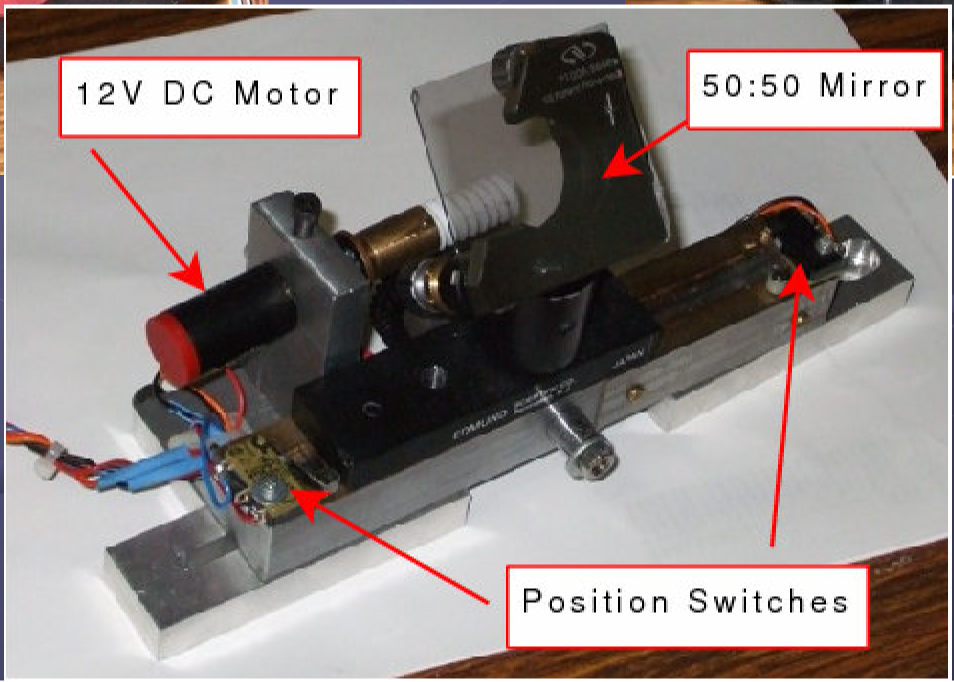
Mechanical specs



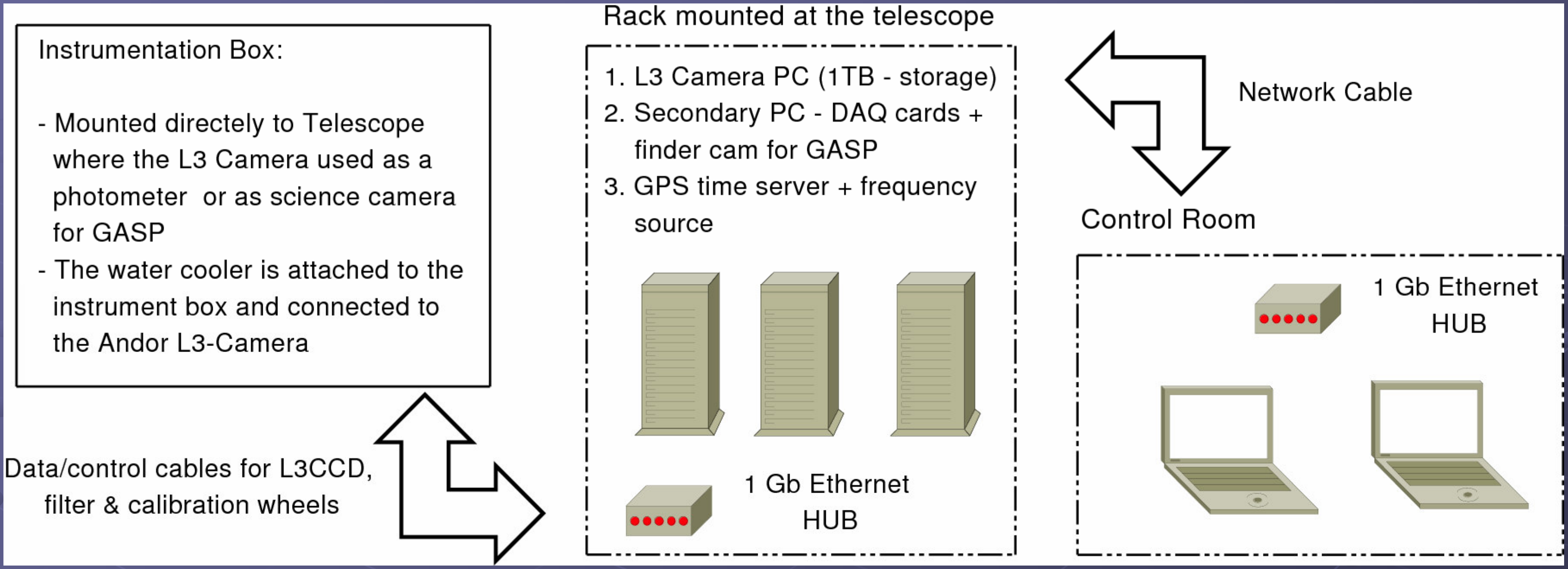
Focal Reducer



Filter Wheel



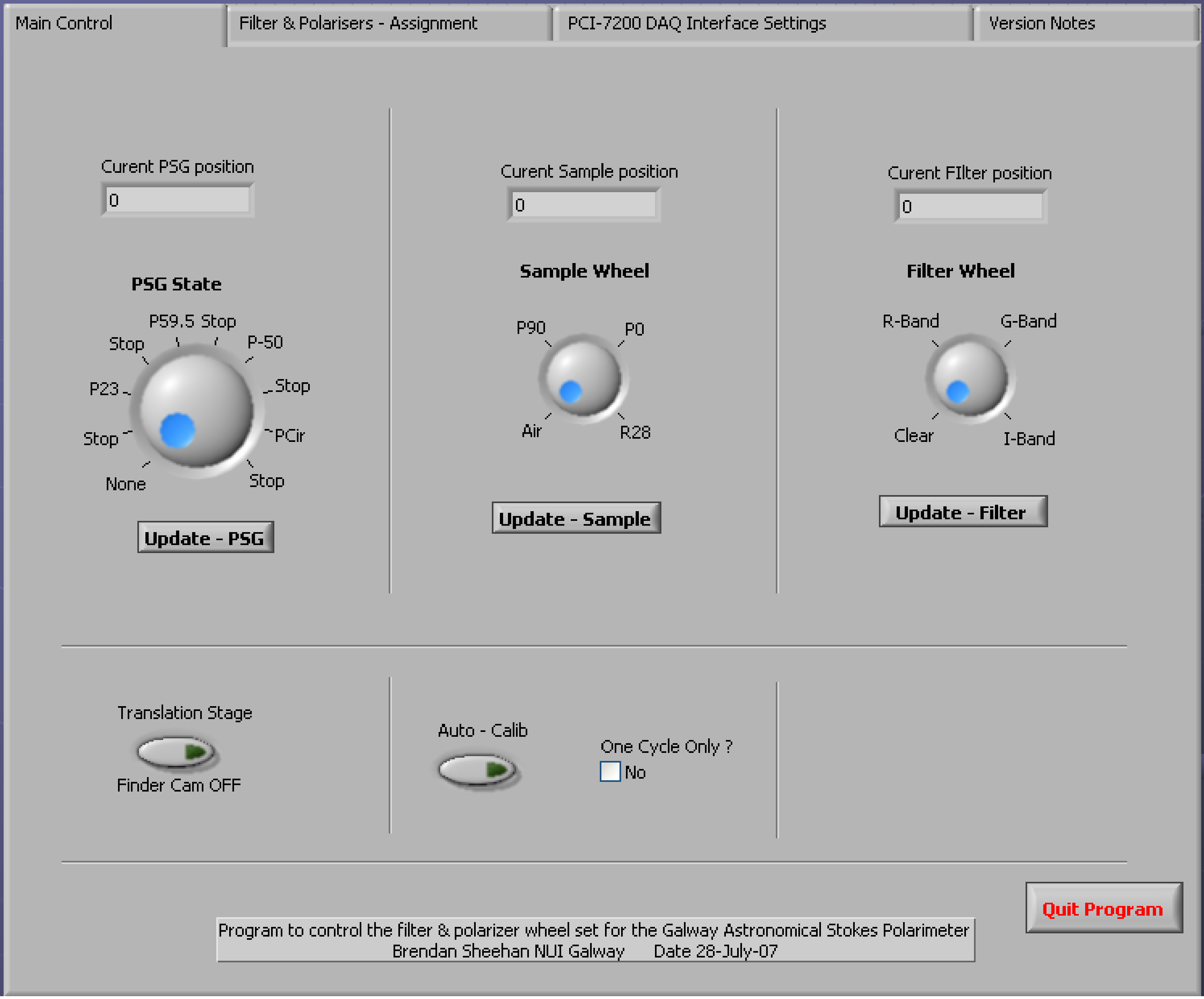
GUFI System Layout



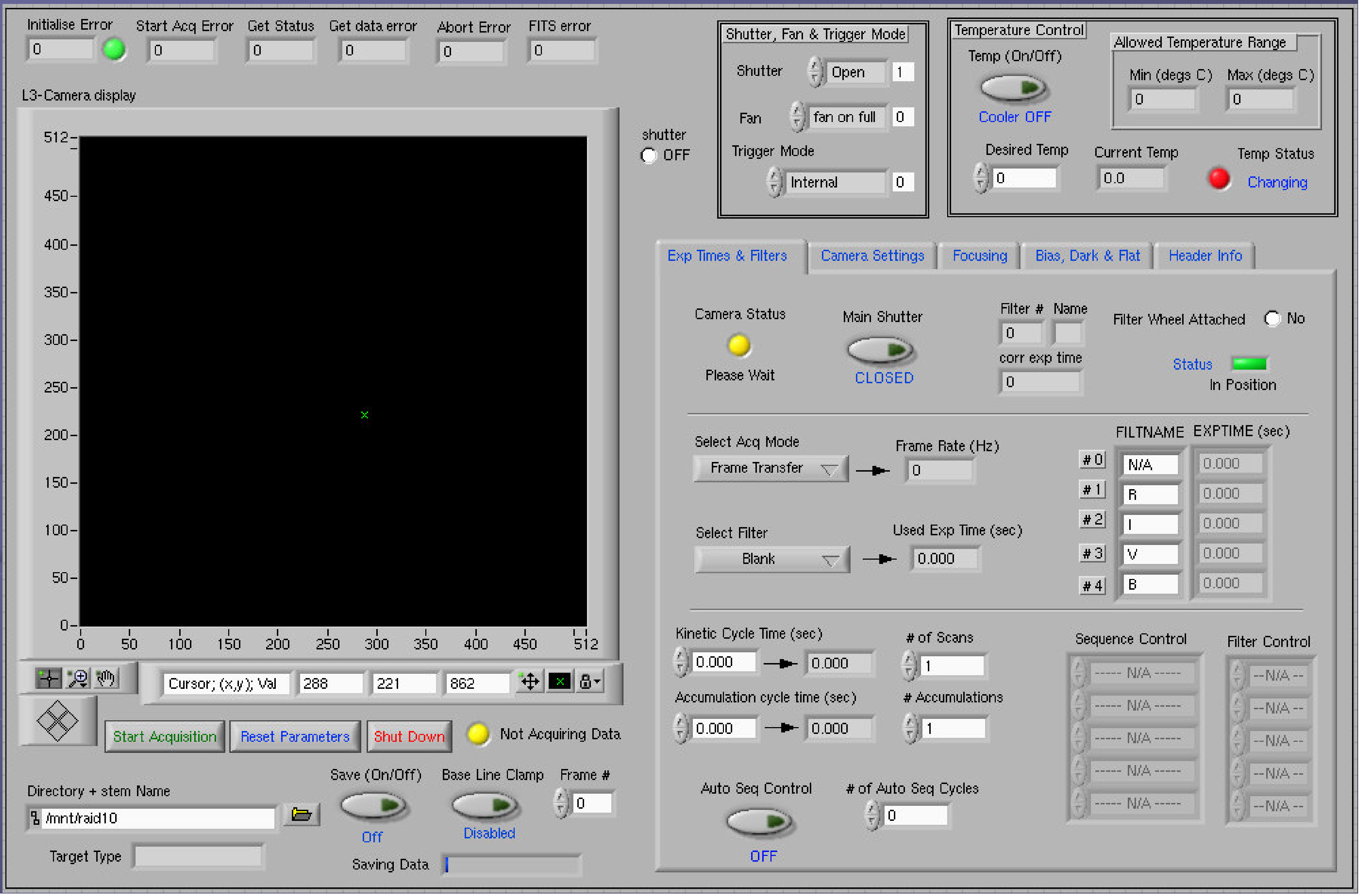
System Features:

- Real Time display - Video & data acquisition
- Spool to disk (4x 250GB, striped RAID0) for large data loads
- User-set windowing & binning
- Windows & Linux interfaces
  - GUI or custom C programs

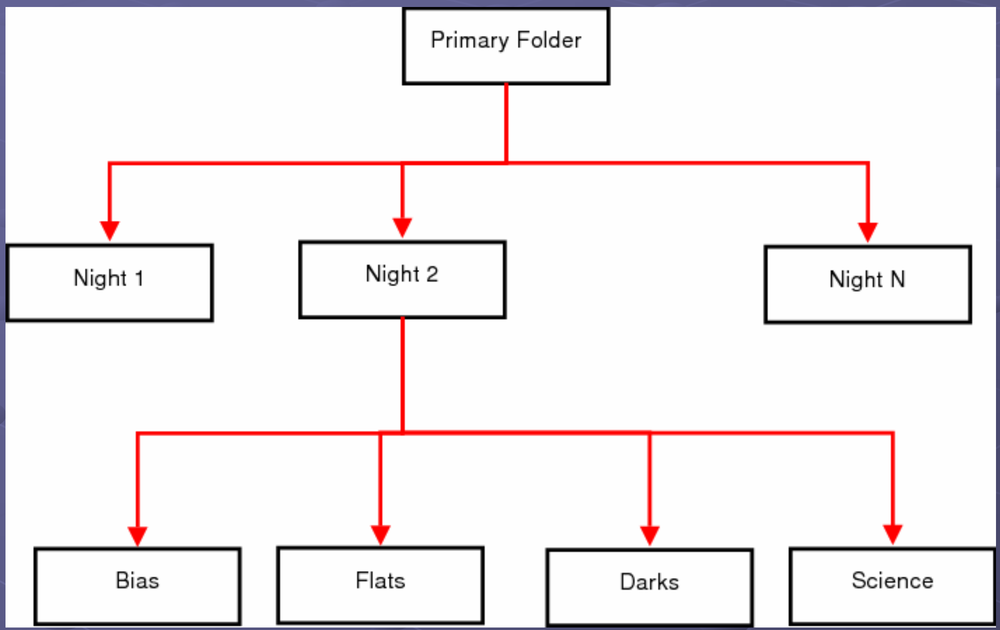
GUFI/GASP Control Interface (Labview)

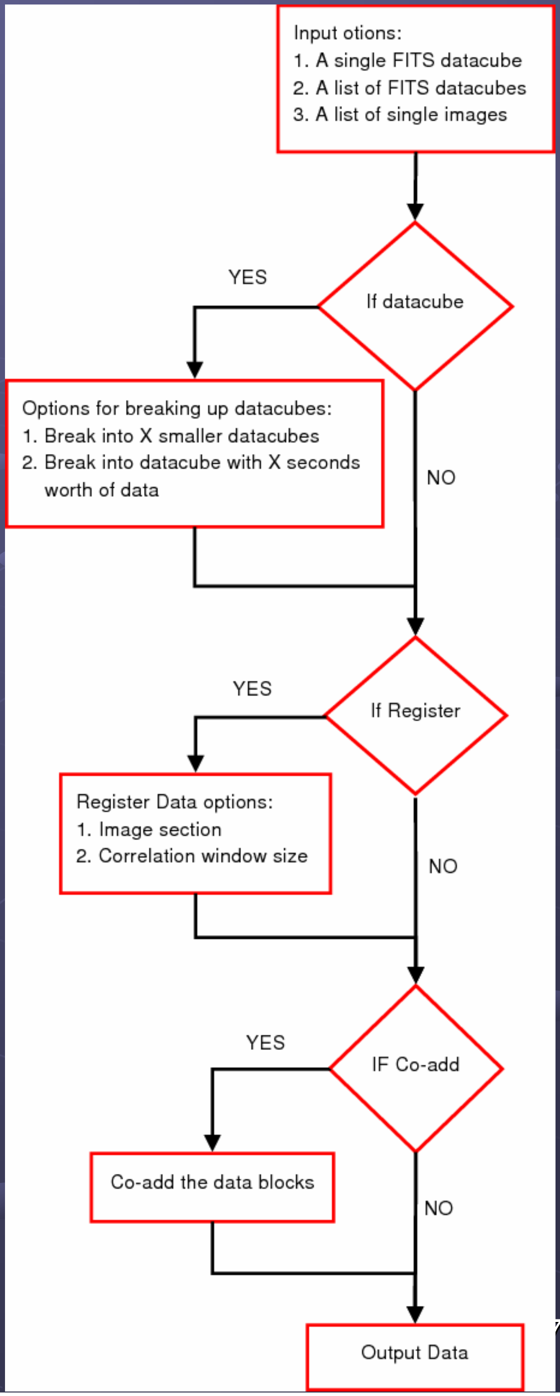


GUFI/GASP Control Interface (Labview)



GUFI Data Reduction/Analysis Pipeline





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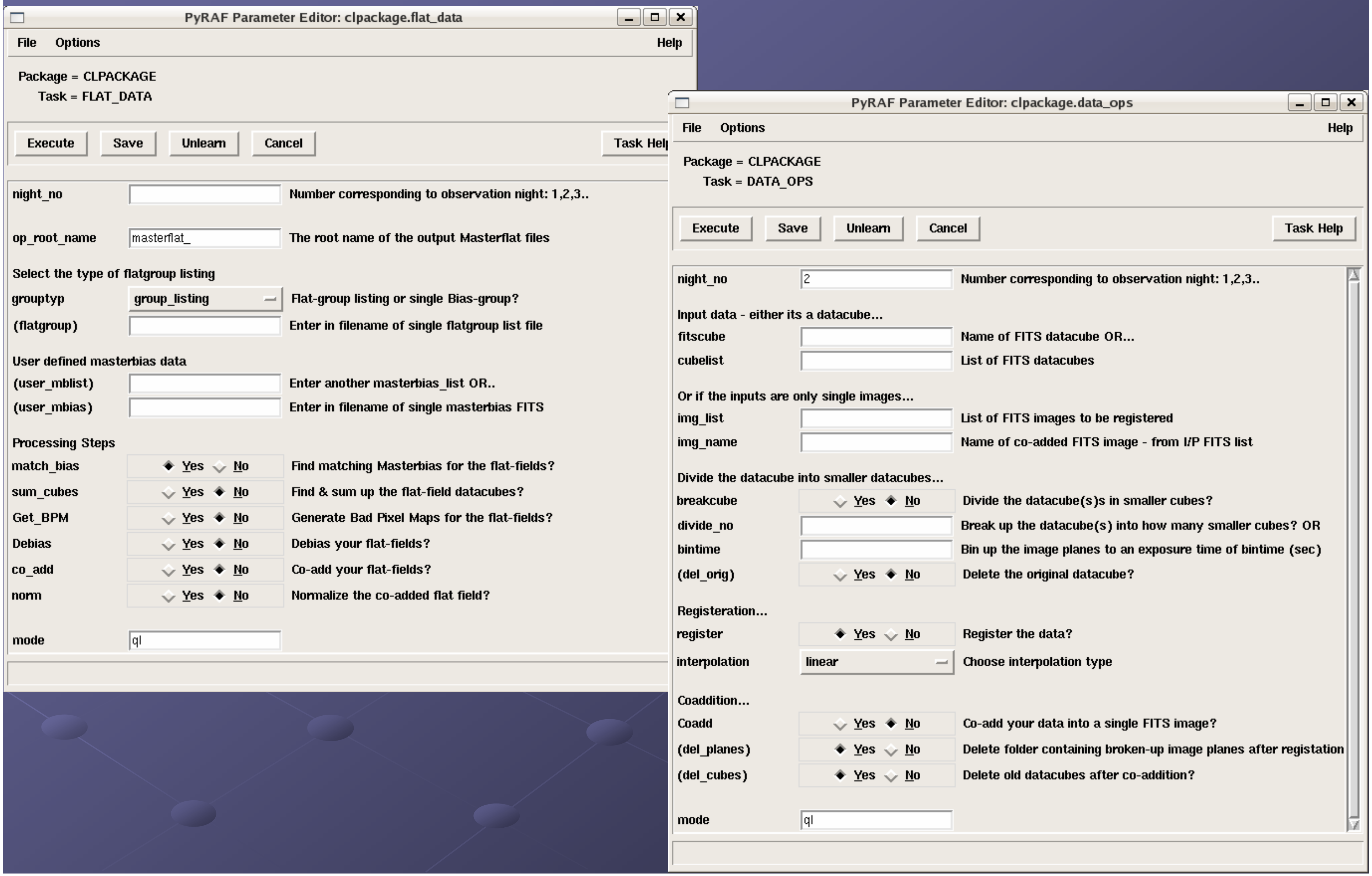


Some comments on L3-CCD Calibration

1. Bias:

   L3-CCD Bias subtraction must be very accurate, since Bias is often a much larger proportion of the total counts…

   ACCUM-mode bias collection is trivially easy! (1000x in a few sec)

2. Flatfields:

   Twilight Sky-flat collection is a joy!

   Reaches much greater depth/pixel/filter [duty cycle]; no saturation; can be done in much brighter twilight

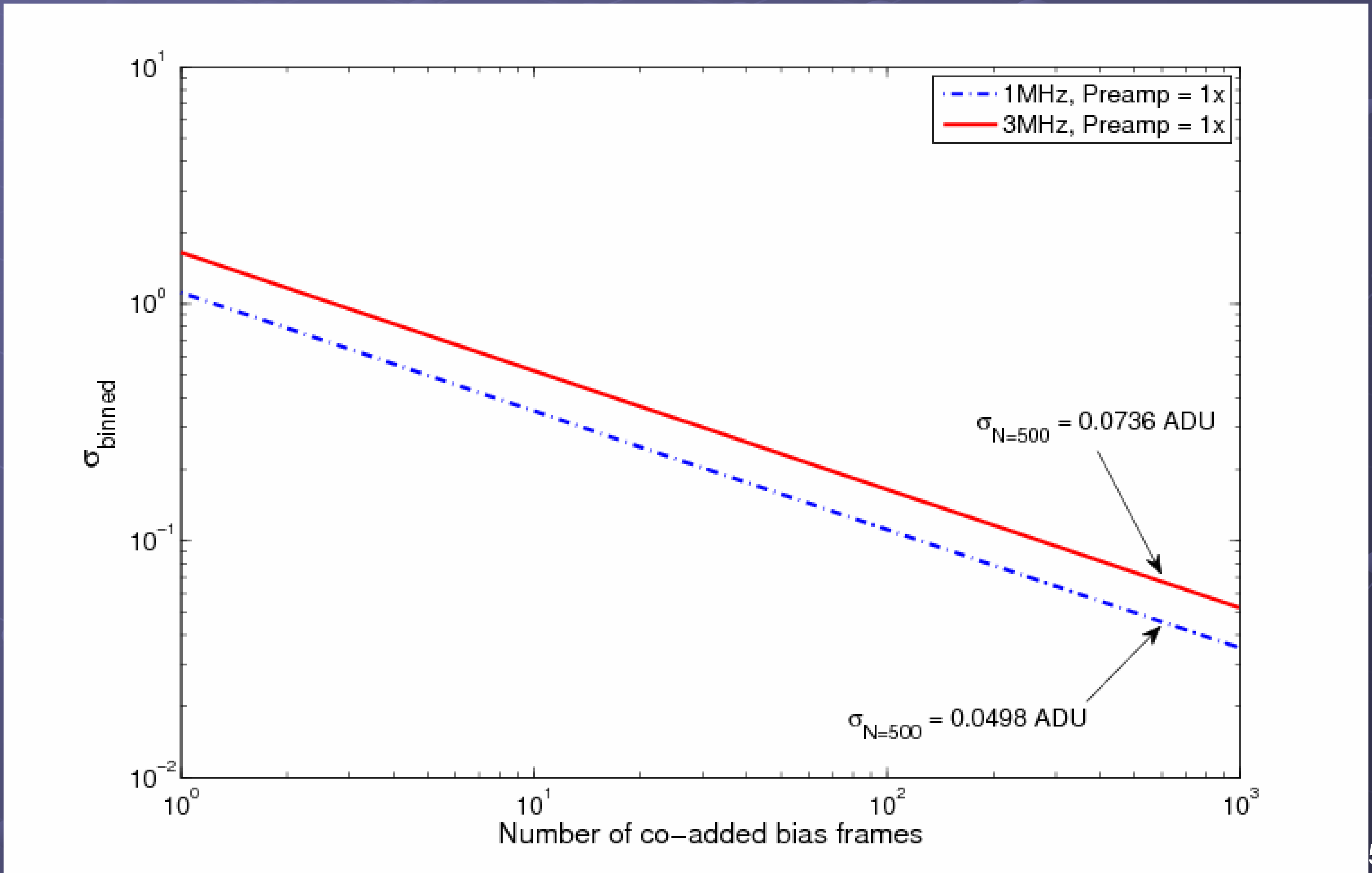
   Applying excellent flat-fields $\rightarrow$ eliminate FPN

3. Darks:

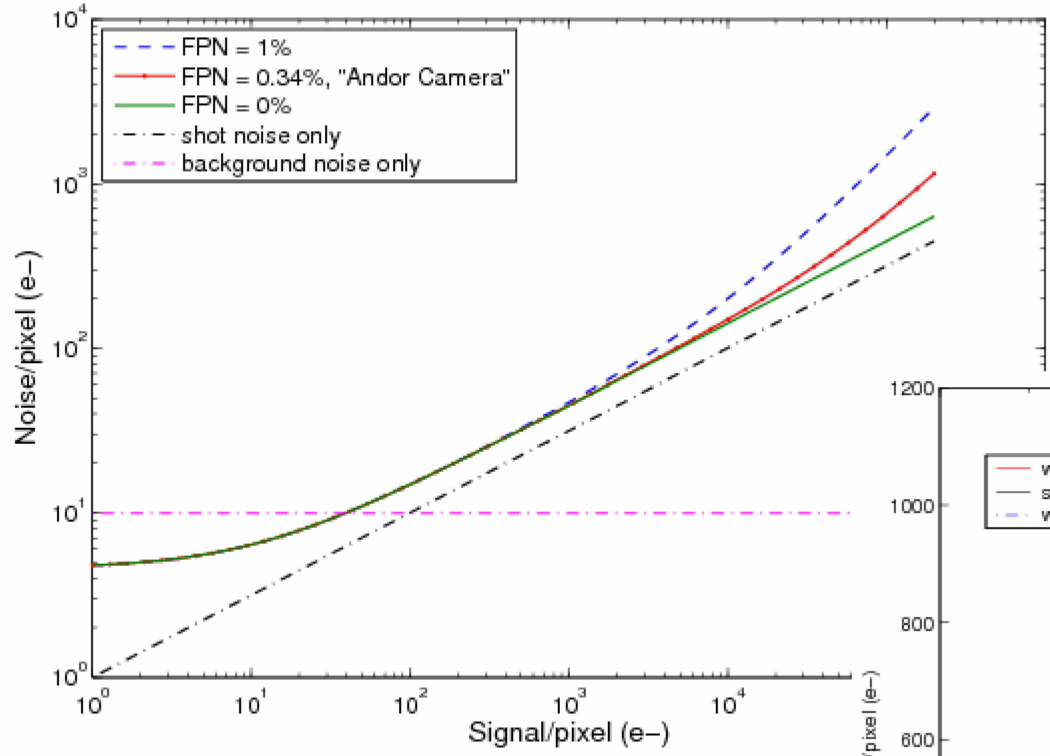
   Not needed at -80ºC

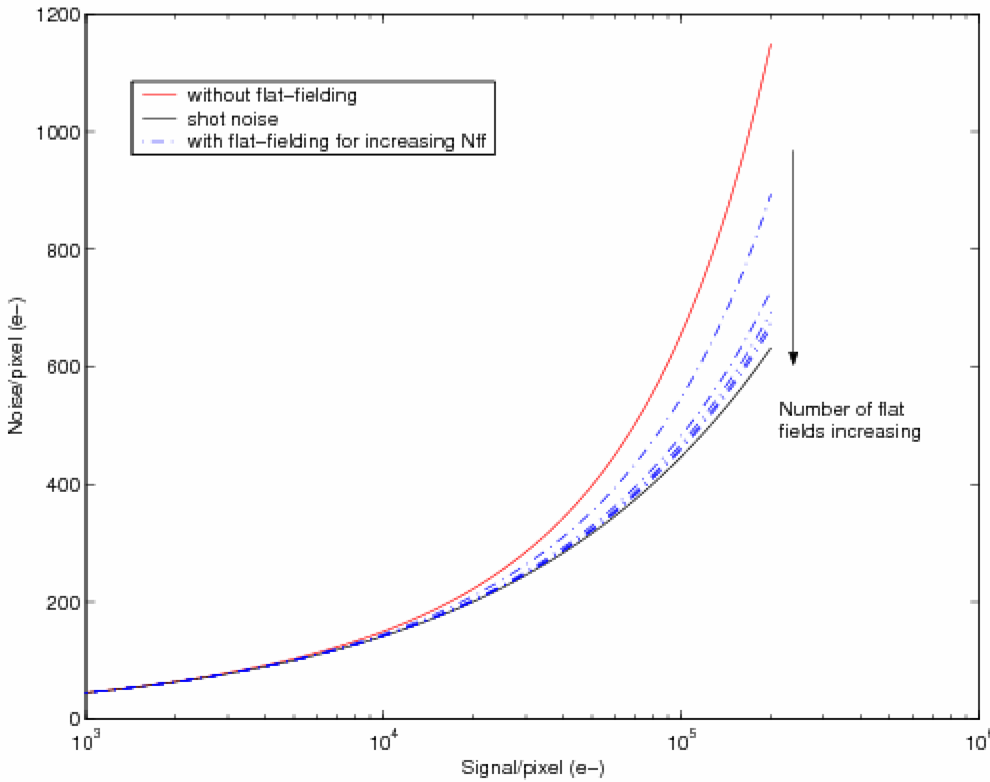
CCD Calibration: RON in averaged Bias

- Easy to achieve negligible residual RON in master-bias frames



CCD Calibration: Fixed Pattern Noise (FPN)





A-to-D Gain and Readnoise calibrations

- A-to-D Gain measurements (using an Integrating Sphere for flatfields)

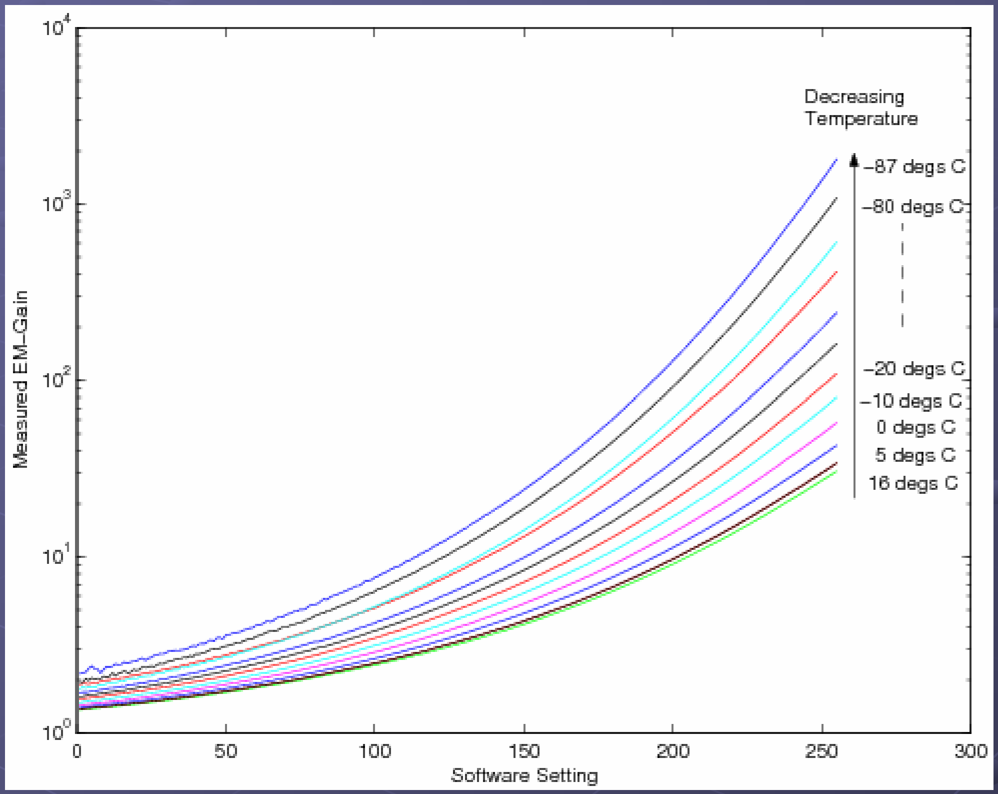
Software setting	Preamp 1x	Preamp 2.4x	Preamp 4.6x
Conventional Amp	10.08 ± 0.04	4.07 ± 0.01	2.111 ± 0.003
EMCCD Amp	57.45 ± 0.47	24.20 ± 0.10	12.64 ± 0.04

- taken @ 3MHz – independent of readout speed.
- note confusing Andor terminology! E.g "Preamp 4.6x" actually DIVIDES the gain by ~4.6 !

- Readnoise (RON) measurements (using bias frames)

Readout Rate	Preamp 1x	Preamp 2.4x	Preamp 4.6x
1 MHz, Conventional	10.88	7.07	6.21
3 MHz, Conventional	16.03	10.74	9.45
1 MHz, EM-Mode	56.08	31.48	24.38
3 MHz, EM-Mode	64.84	40.42	32.98
5 MHz, EM-Mode	112.86	63.40	N/A
10 MHz, EM-Mode	185.24	112.72	N/A

EM gain must also be calibrated



Pipeline: Differential Photometry Method

Optimal method (Bailer-Jones & Mundt)

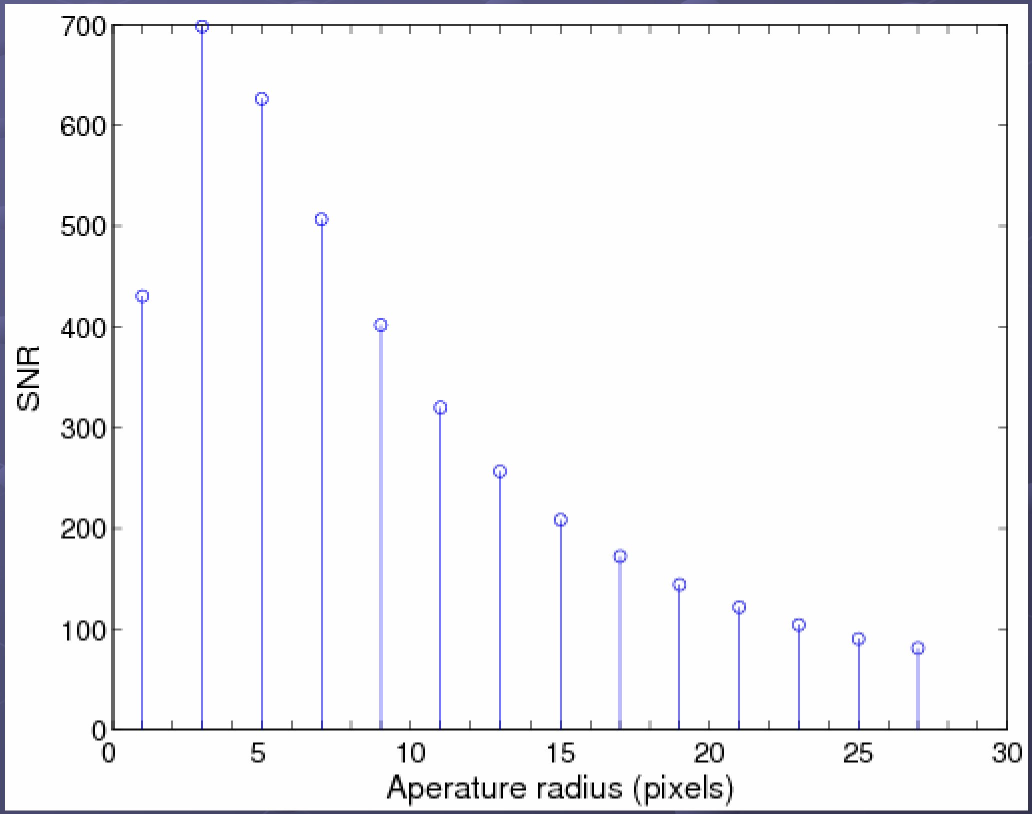
(1) Rules to select reference/comparison stars:

1. A star with a near-circular profile or PSF.
2. An isolated star which is not near the edge of the image and which does not have bright neighboring stars.
3. A star which is no more than 1.5 magnitudes brighter, nor 0.5 magnitude fainter, than the target star.
4. A star which is not near the saturation limit of the detector; as this would otherwise introduce non-linearity.

Pipeline: Differential Photometry Method

Optimal method (Bailer-Jones & Mundt):

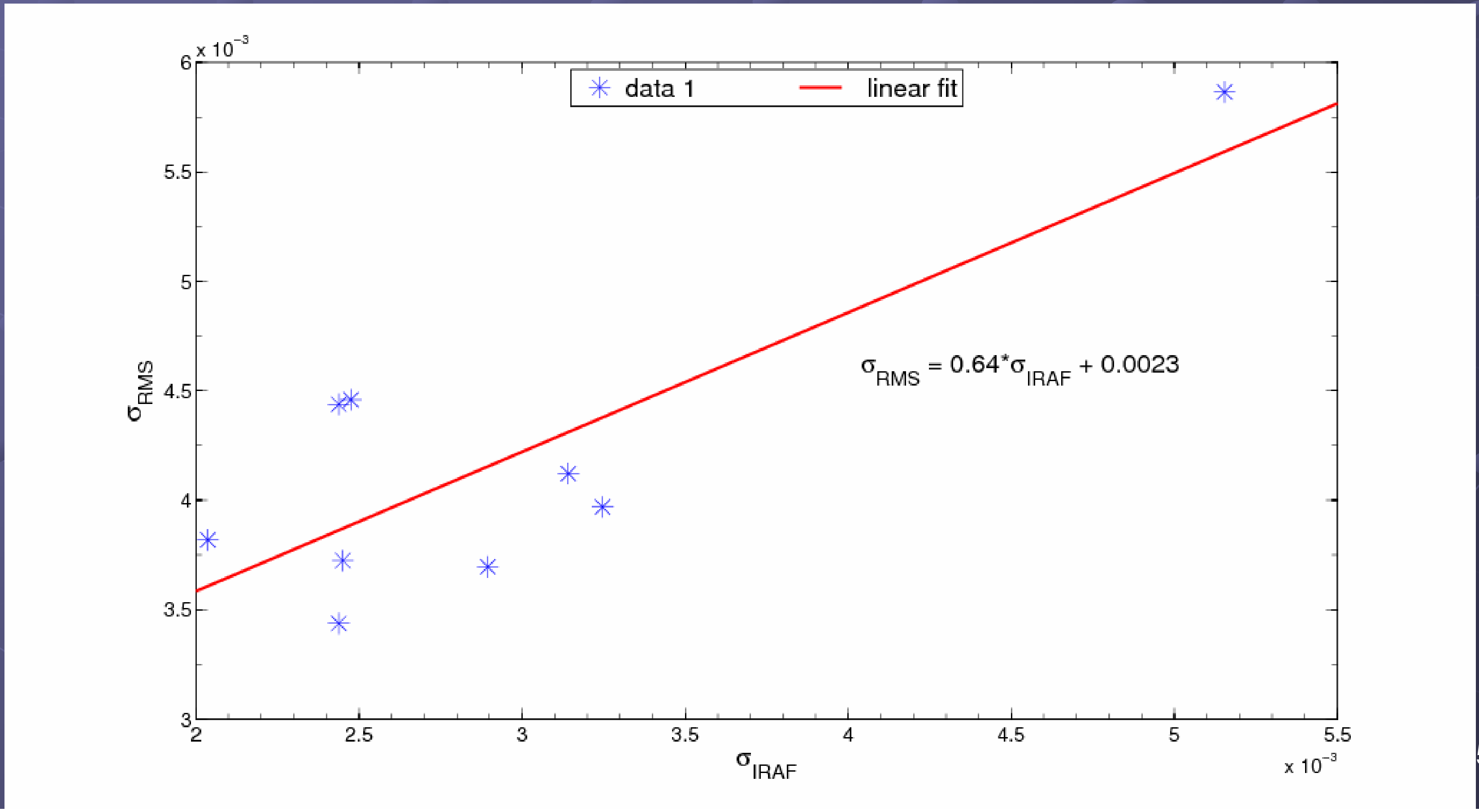
(2) Find optimal aperture for photometry by testing a representative frame with a range of apertures over target star:



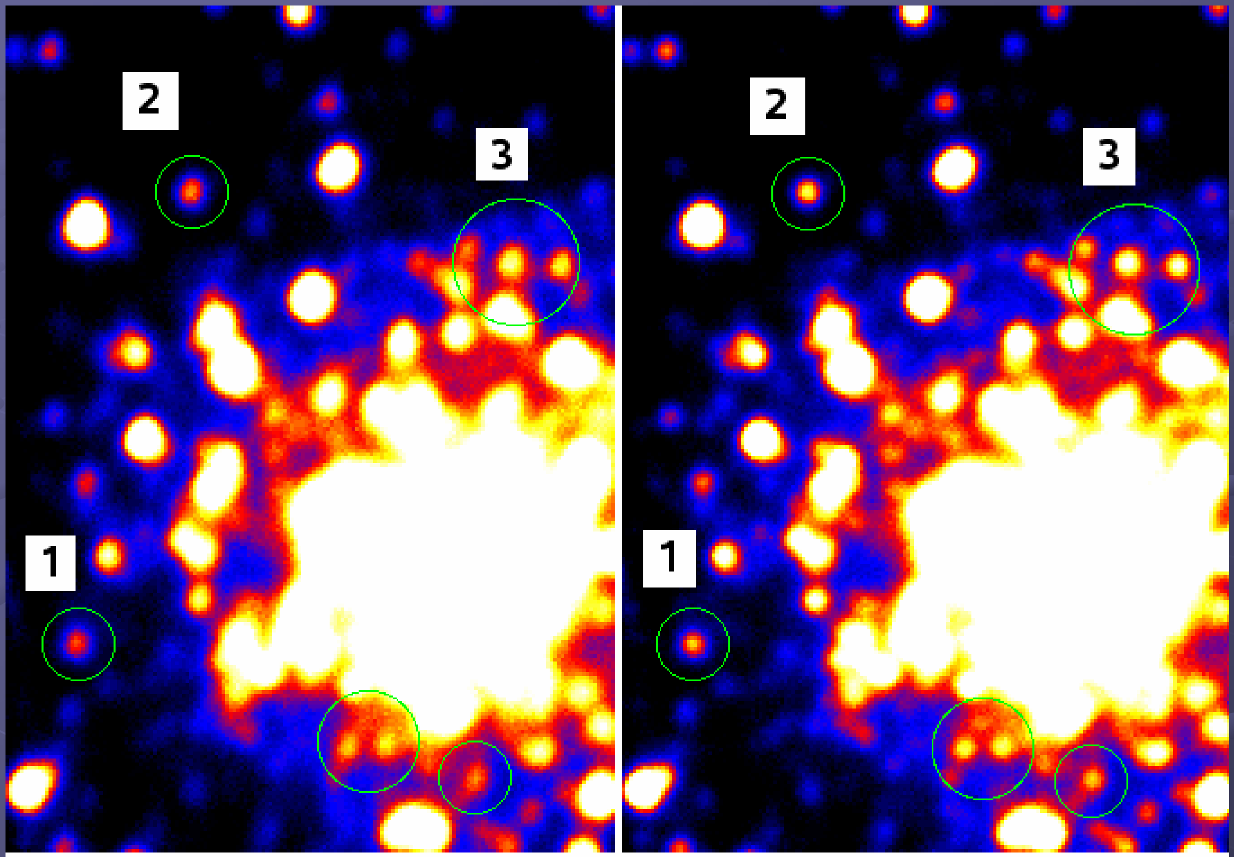
Pipeline: Differential Photometry Method

Optimal method (Bailer-Jones & Mundt):

(3) Determine true photometric errors by fitting actual lightcurve scatter (of non-variable field stars) against their "formal" (IRAF/phot) predicted errors.



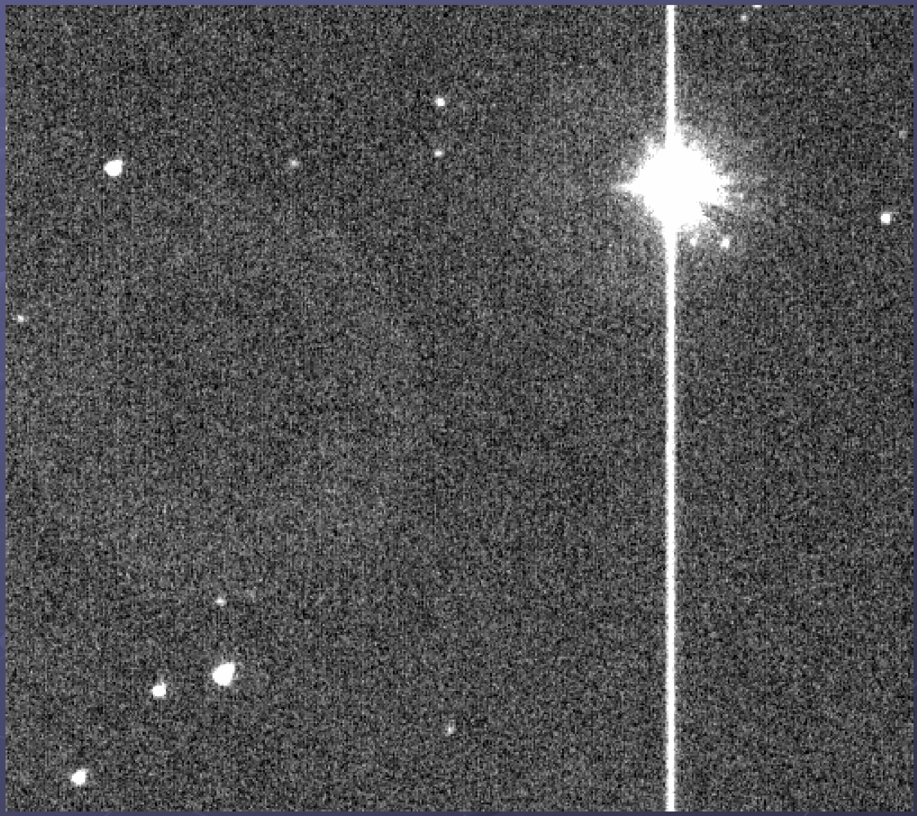
Results: PEIS on Globular Cluster M15



(a) (b)

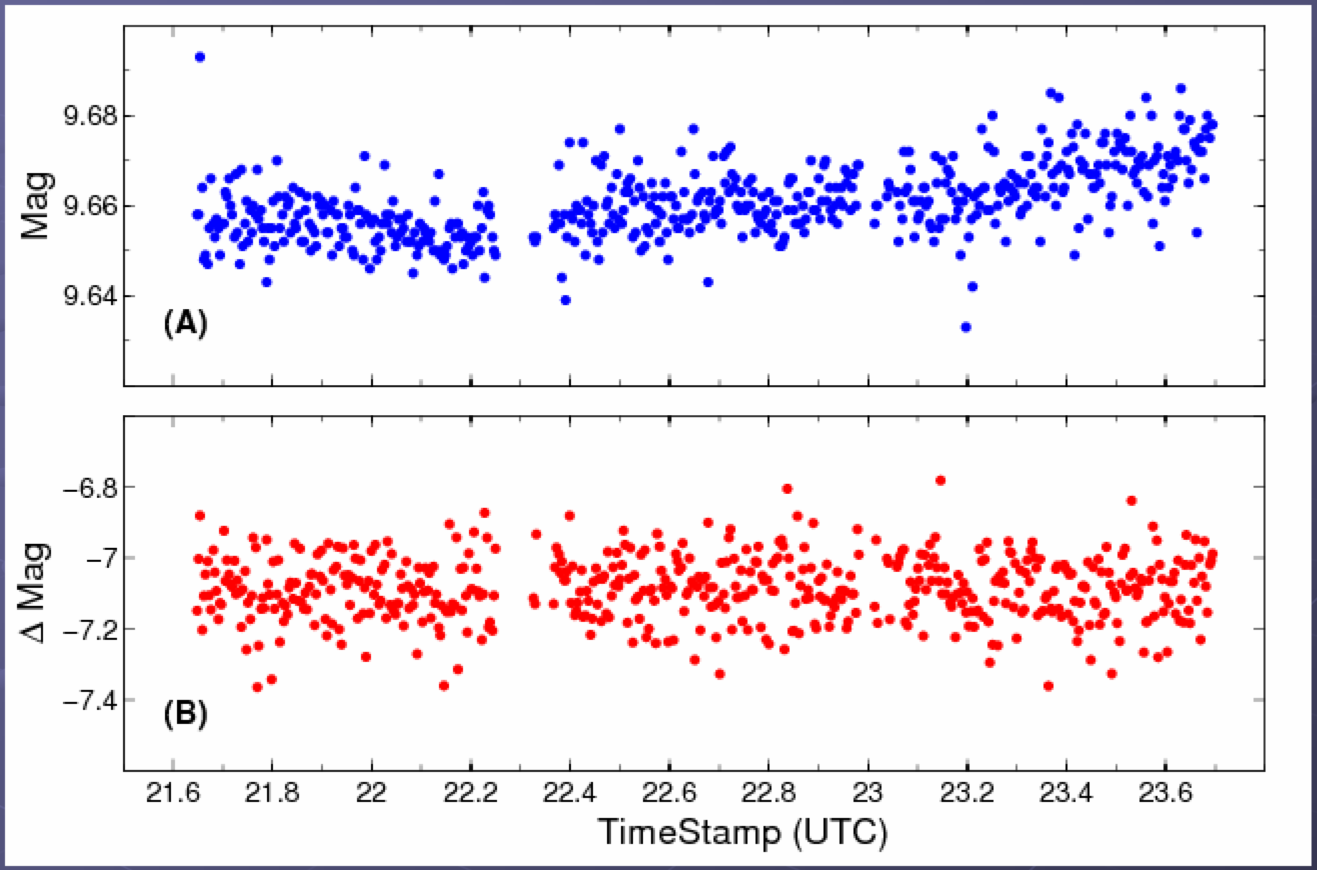
- July 2006: Loiano 1.5m, I-band, poor seeing: still a 12% FWHM improvement - in line with expectations from D/r_0 ~ 20 [should be ~ 4]

Results: roAp star, 10 Aql



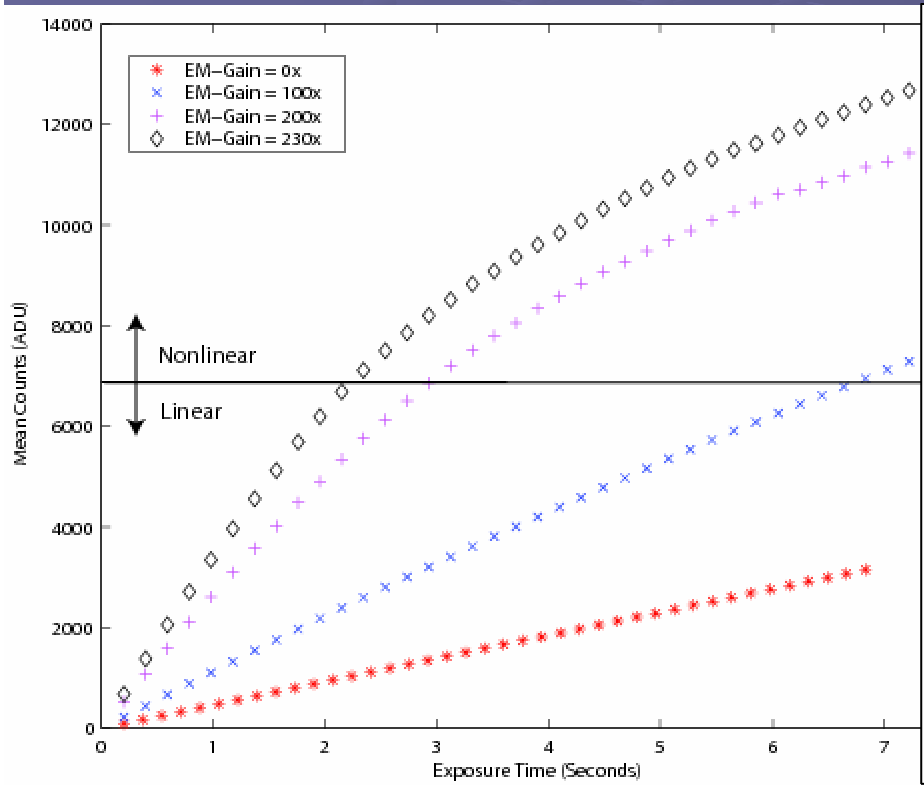
- Pulsating stars with very low (mmag) amplitude, P ~ 10 min
- Amplitude greatest in IR (~5 mmag); decreases bluewards
- Loiano 1.5m, B-band, July 2006
- No reference stars of similar magnitude!

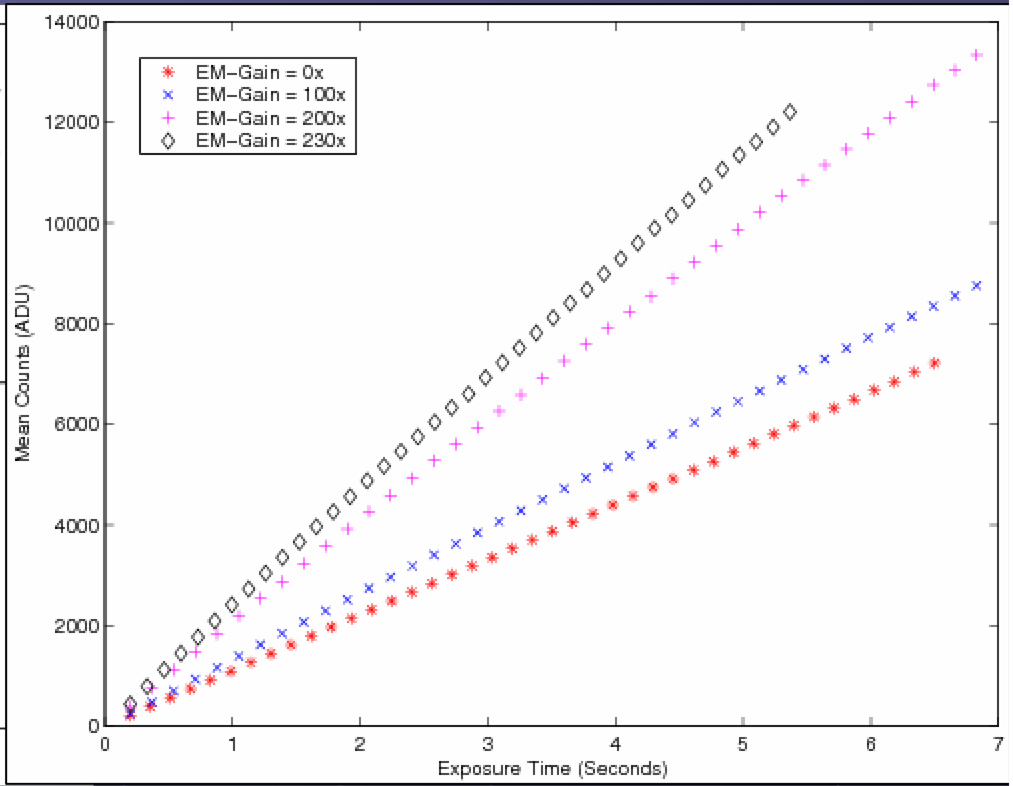
Results: roAp star, 10 Aql



- Differential lightcurve – using faint reference stars – has worse scatter than the original 10 Aql lightcurve!
- Eyeball hints at lightcurve structure; Periodogram shows nothing

RTFM! Linearity issues in the small print…





- 10 Aql data seemed fine – well under saturation – but unaware that the EM register's "extended" dynamic range is non-linear.
- Problem at "1x" gain (left); no problem at "2.4x" gain (right).

RTFM! Linearity issues in the small print…

Preamp	Well depth (e^-)	e^-/ADU	Saturation level Unity EM-Gain (ADU)	Saturation level EM-Gain = 2 (ADU)
‘1x’	200,000	57.45	3,481	6,962
‘2.4x’	200,000	24.20	8,264	16,384
‘4.6x’	200,000	12.64	15,822	16,384

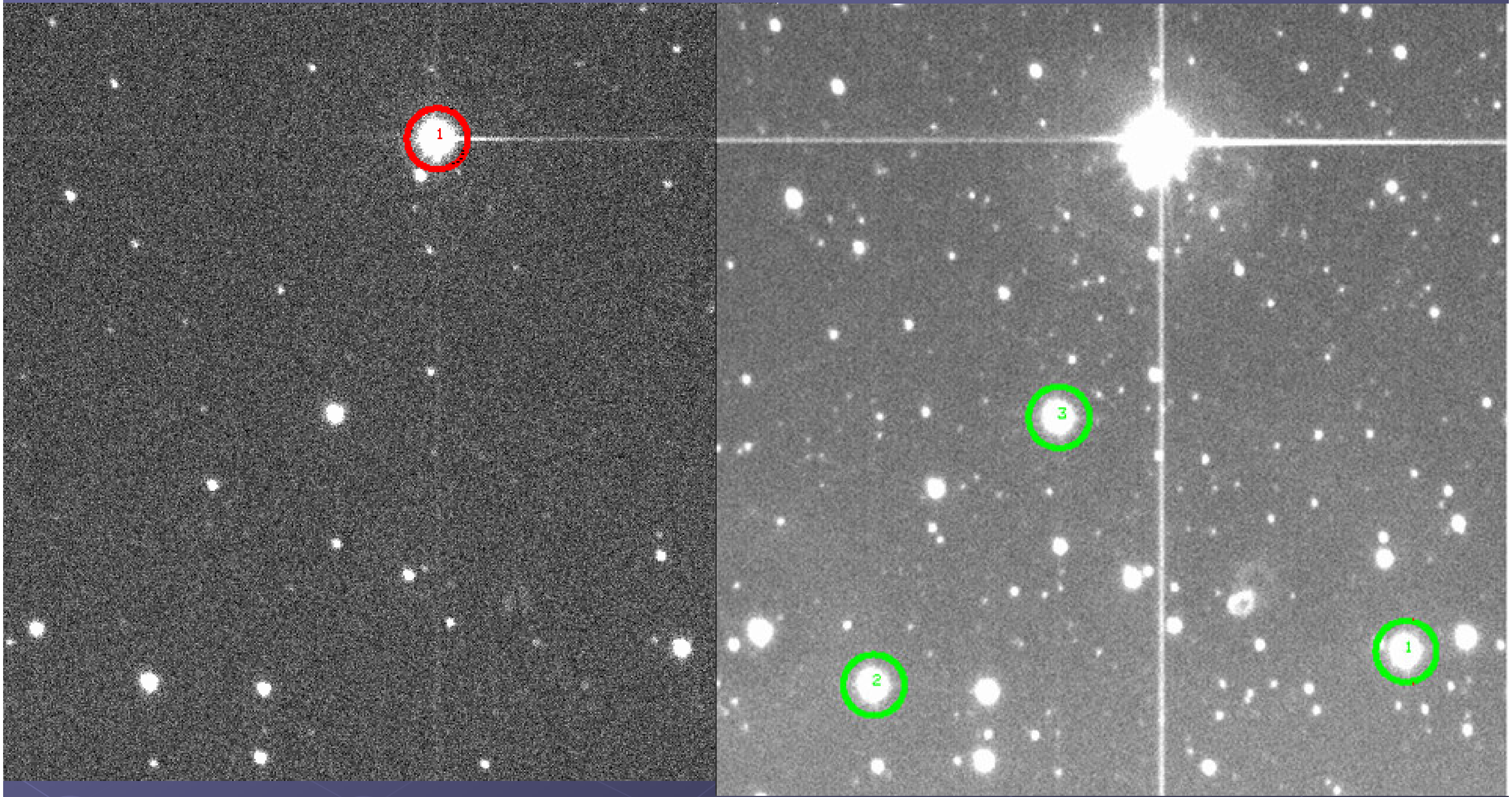
Table 3.4: ADU saturation values for different preamp settings (EM readout mode).

Preamp	Well depth (e^-)	e^-/ADU	Saturation level Unity EM-Gain (ADU)	Saturation level (e^-)
‘1x’	200,000	10.08	16,384	165,150
‘2.4x’	200,000	4.07	16,384	66,682
‘4.6x’	200,000	2.11	16,384	34,406

Table 3.5: ADU saturation values for different preamp settings (conventional readout mode).

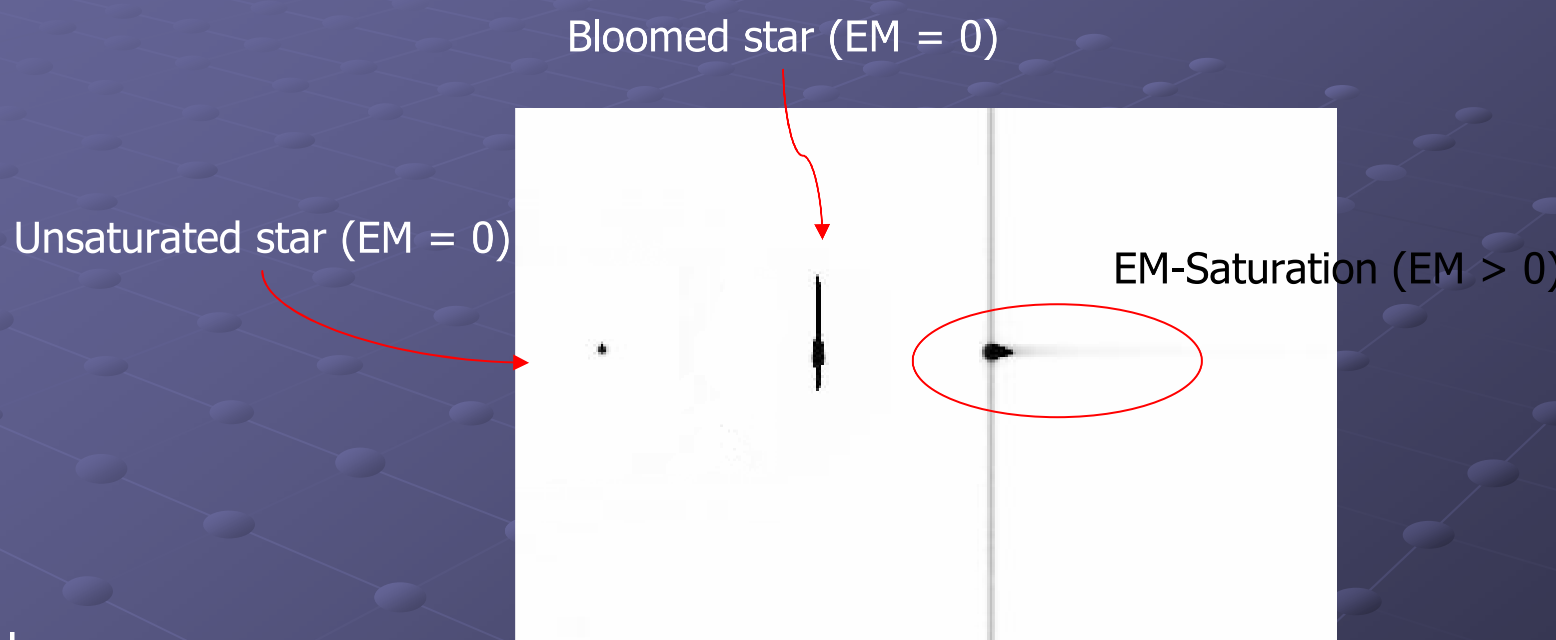
- Need to keep a close eye on saturation levels, since 14-bit A-to-D.
- Different levels and reasons: conventional mode → A-to-D saturation; EM mode → EM-register saturation

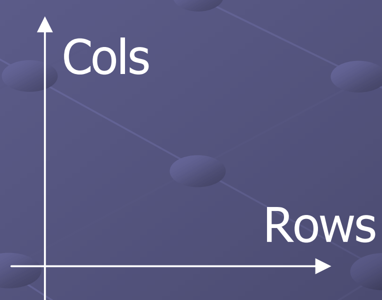
Results: Transiting exoplanet, HD189733



- Loiano 1.5m, V and I band, July 2006
- Reference stars ~OK; but saturation issue…

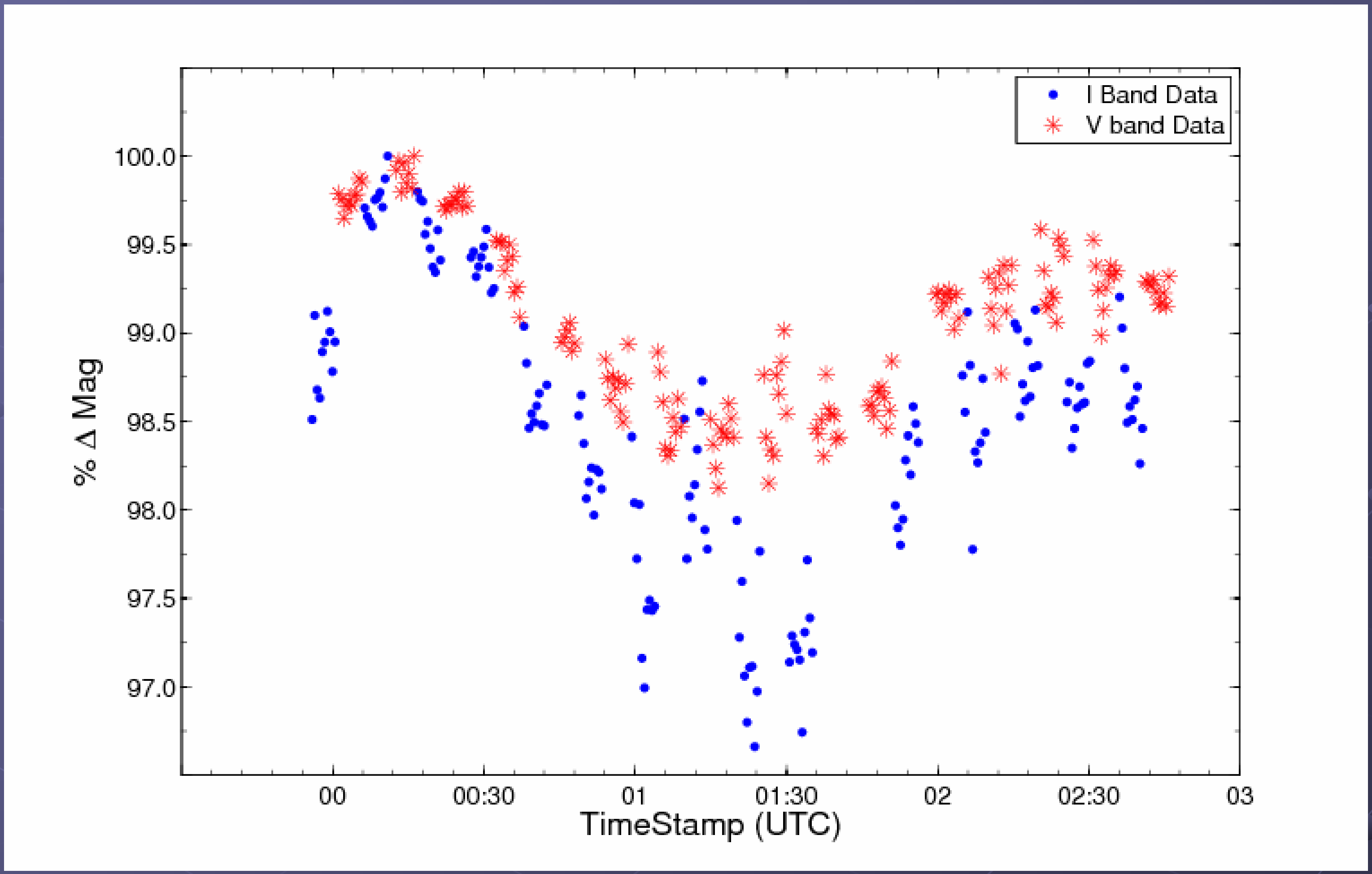
Side effects of EM-gain!





1. Bloomed → conventional over-exposure, along <u>columns</u>
2. Separate effect due to EM-Gain is seen along the <u>rows</u>
3. EM-saturation also shows a full column with counts of 50 ADU above back ground

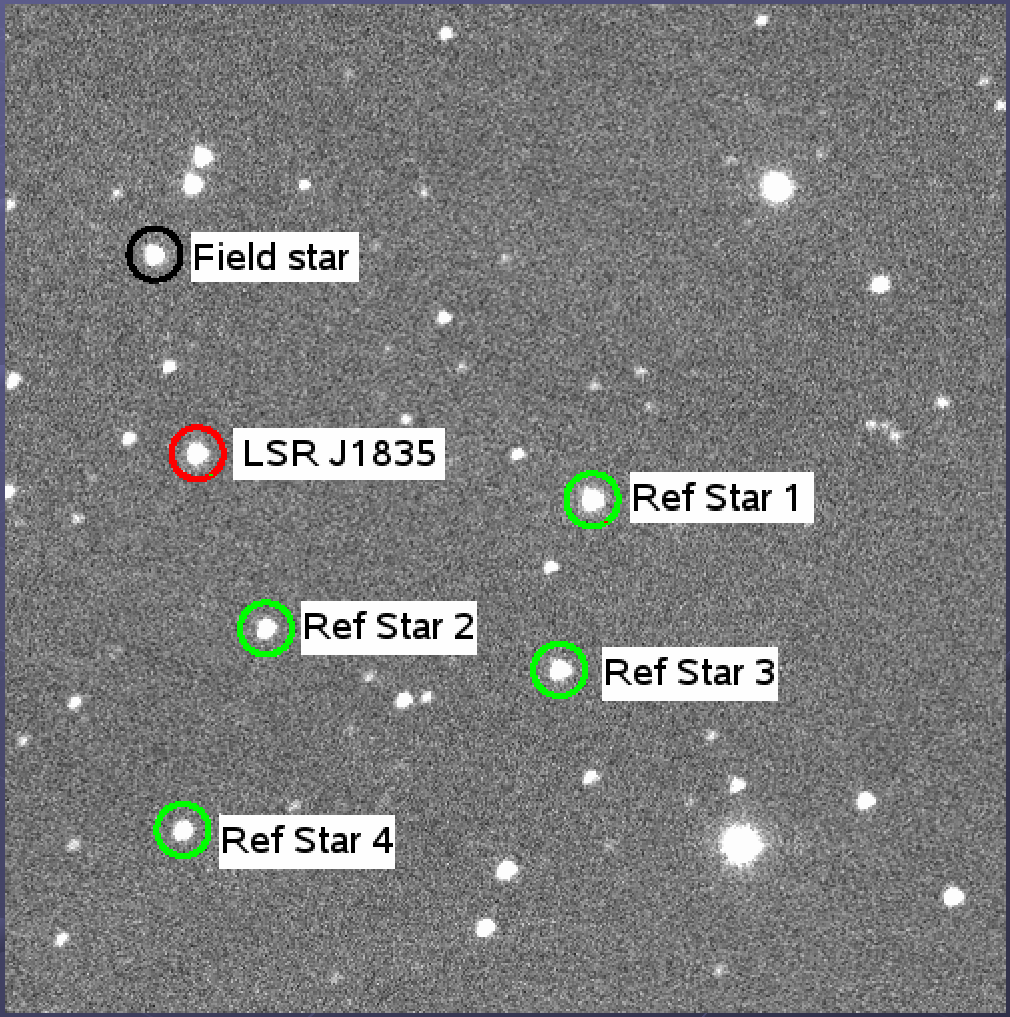
Results: Transiting exoplanet, HD189733



- Light-curve structure mainly due to saturation level changing as seeing changes

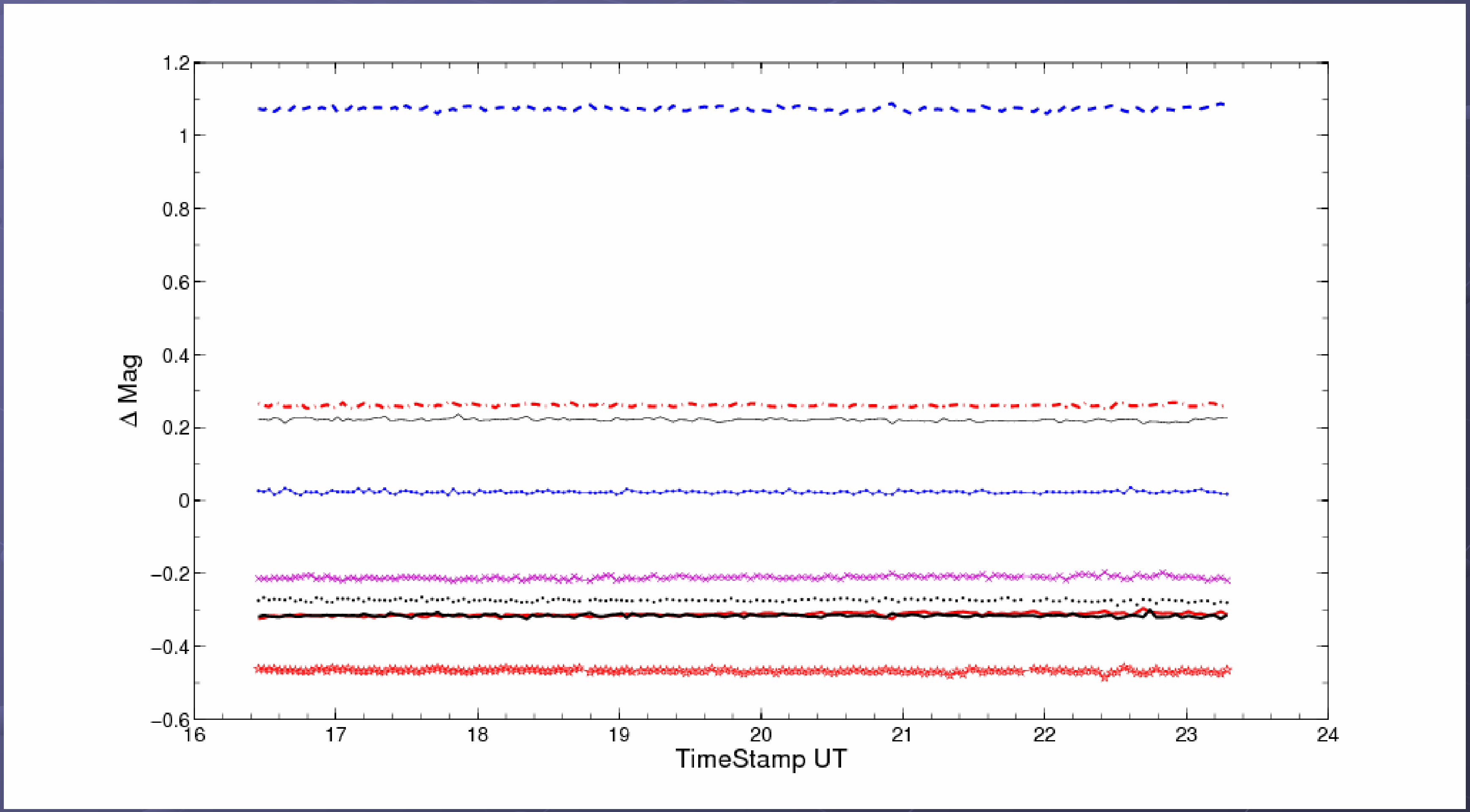
Results: Ultracool Dwarf, LSR J1835

- Loiano 1.5m, I-band, July 2006
- FOV = ~ 4 x 4 arc minutes



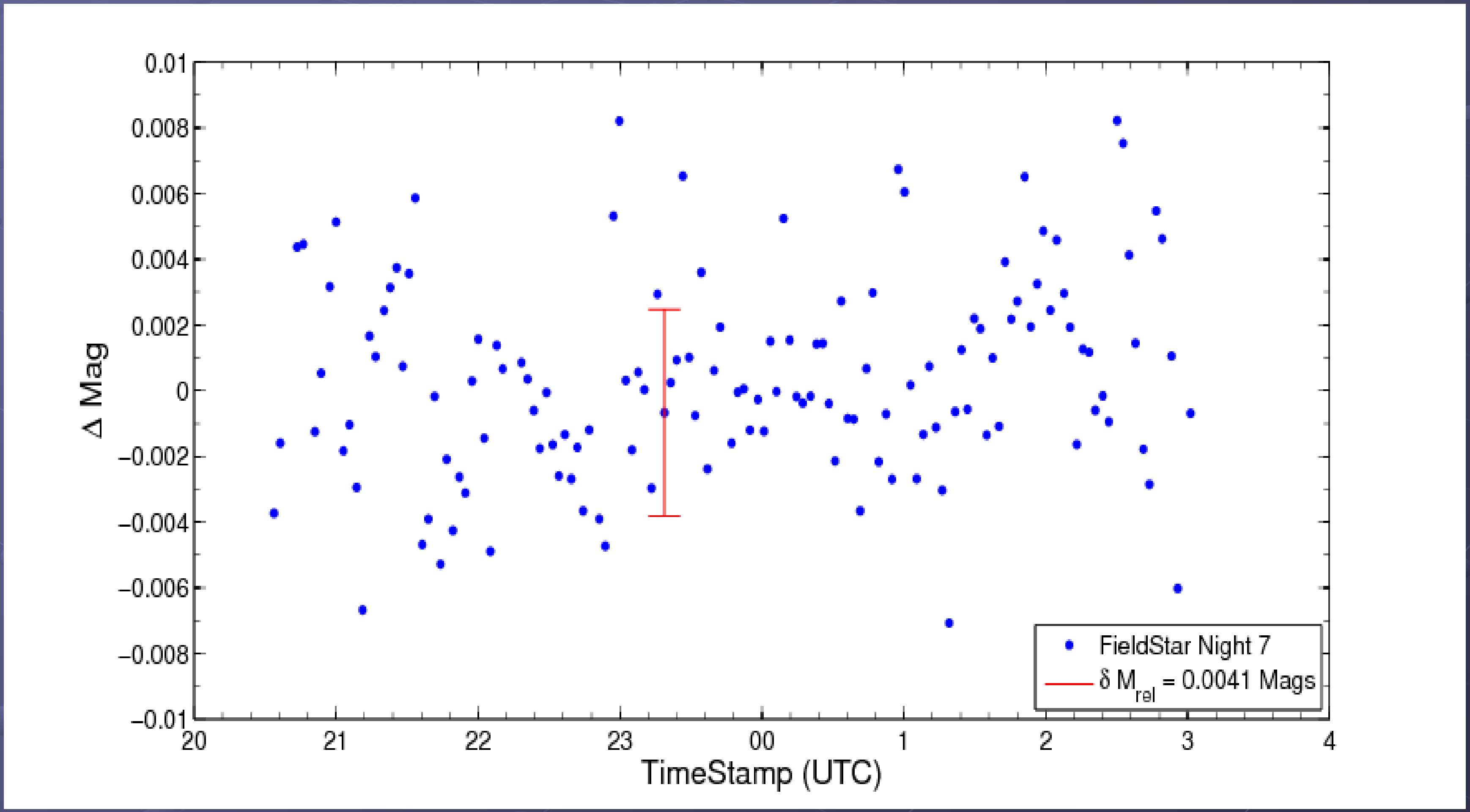
Results: Ultracool Dwarf, LSR J1835

- Differential Light-curves of Field/Reference stars

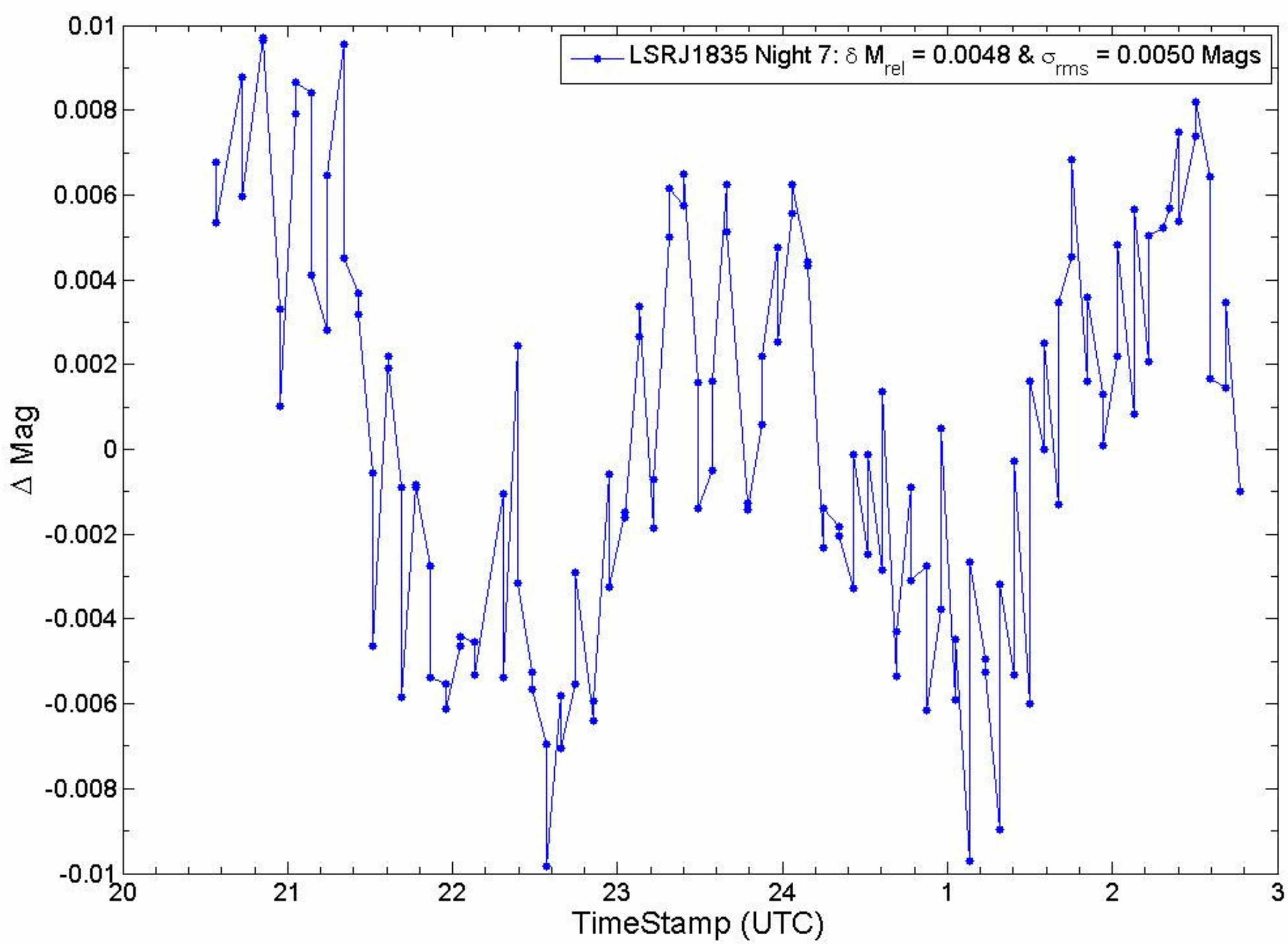


Results: Ultracool Dwarf, LSR J1835

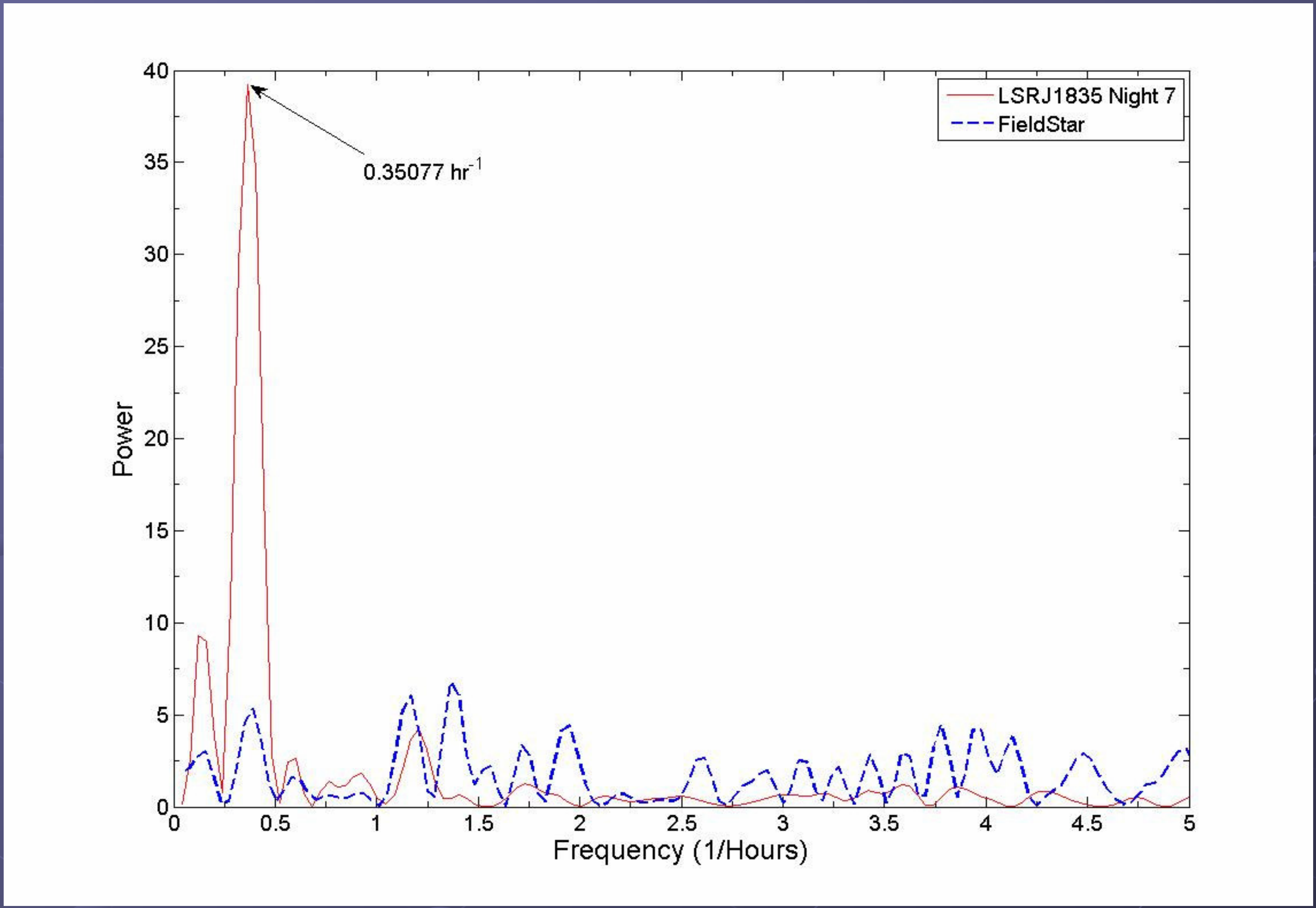
- Differential Light-curve of Field star



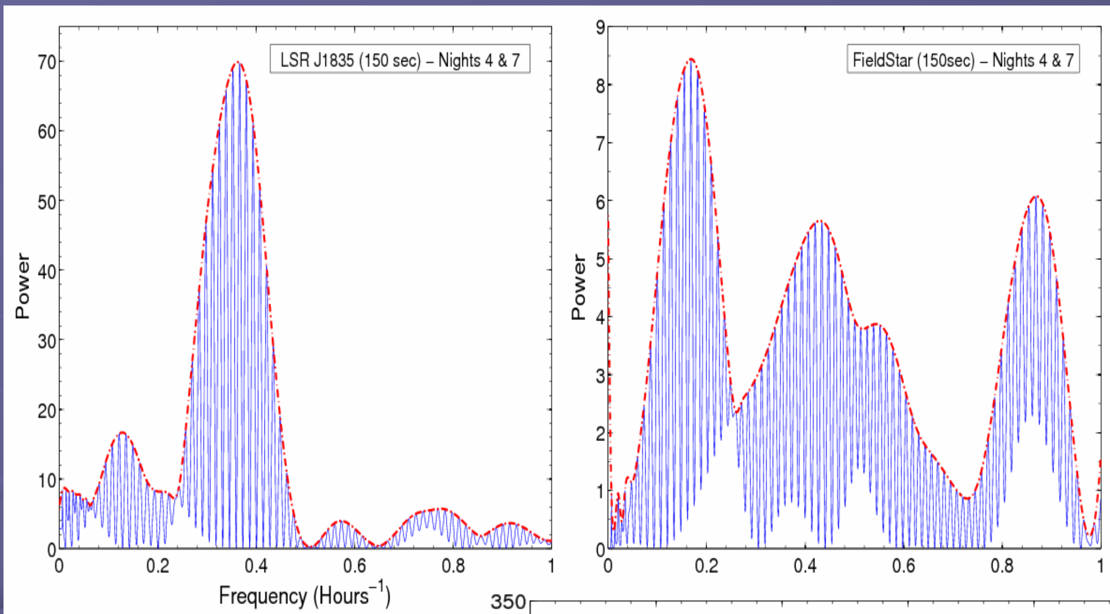
Results: Ultracool Dwarf, LSR J1835



Results: Ultracool Dwarf, LSR J1835

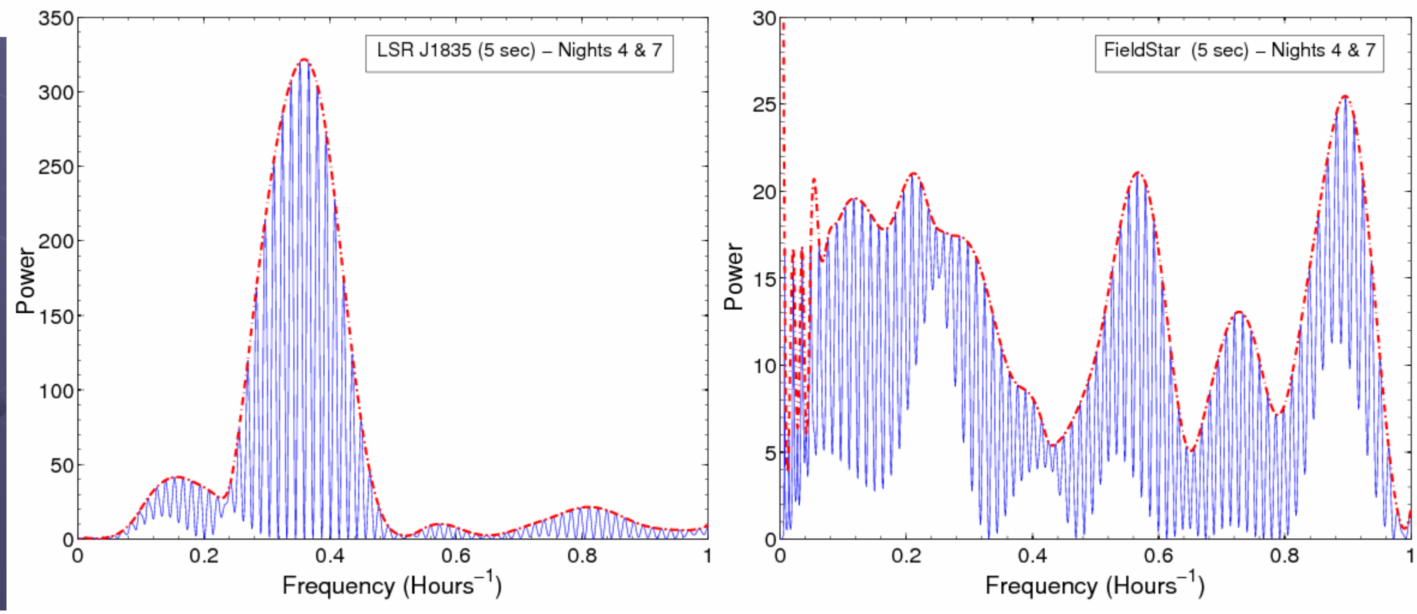


Results: Ultracool Dwarf, LSR J1835
Pump up the Cadence!



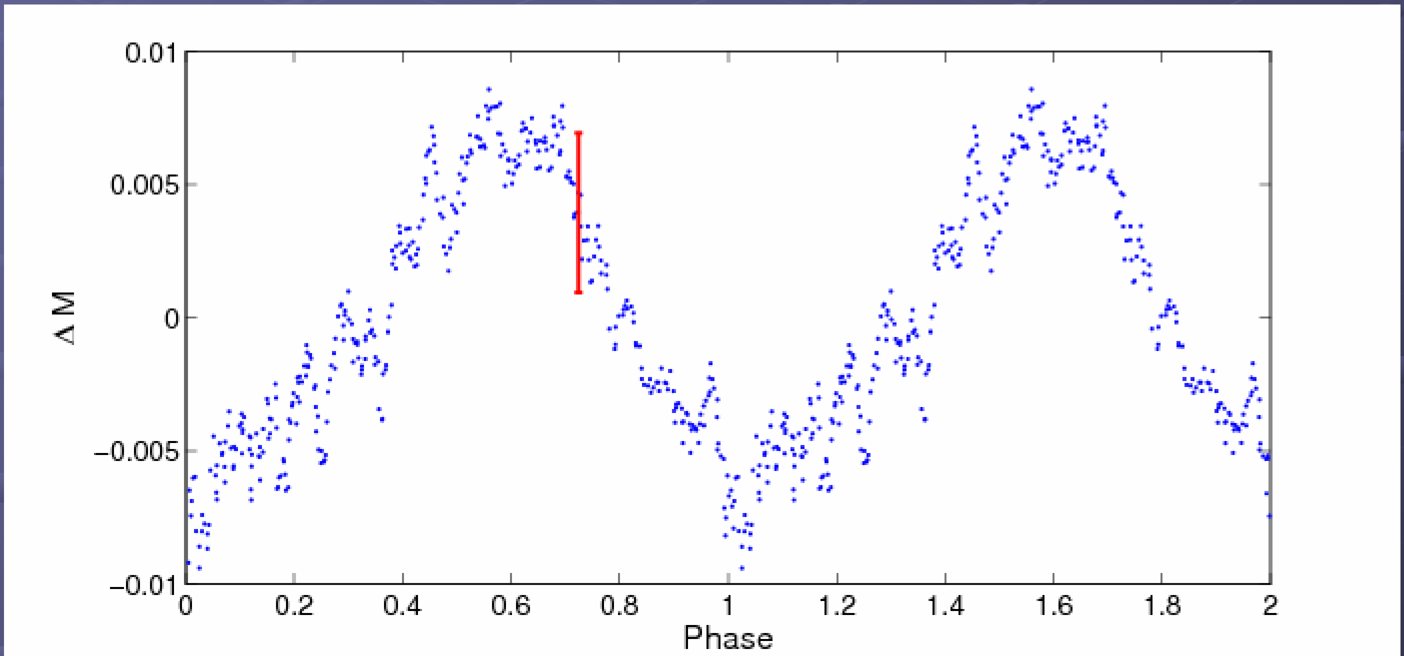
Cadence can be re-binned at will...

Higher cadence gives higher P significance with Lomb-Scargle



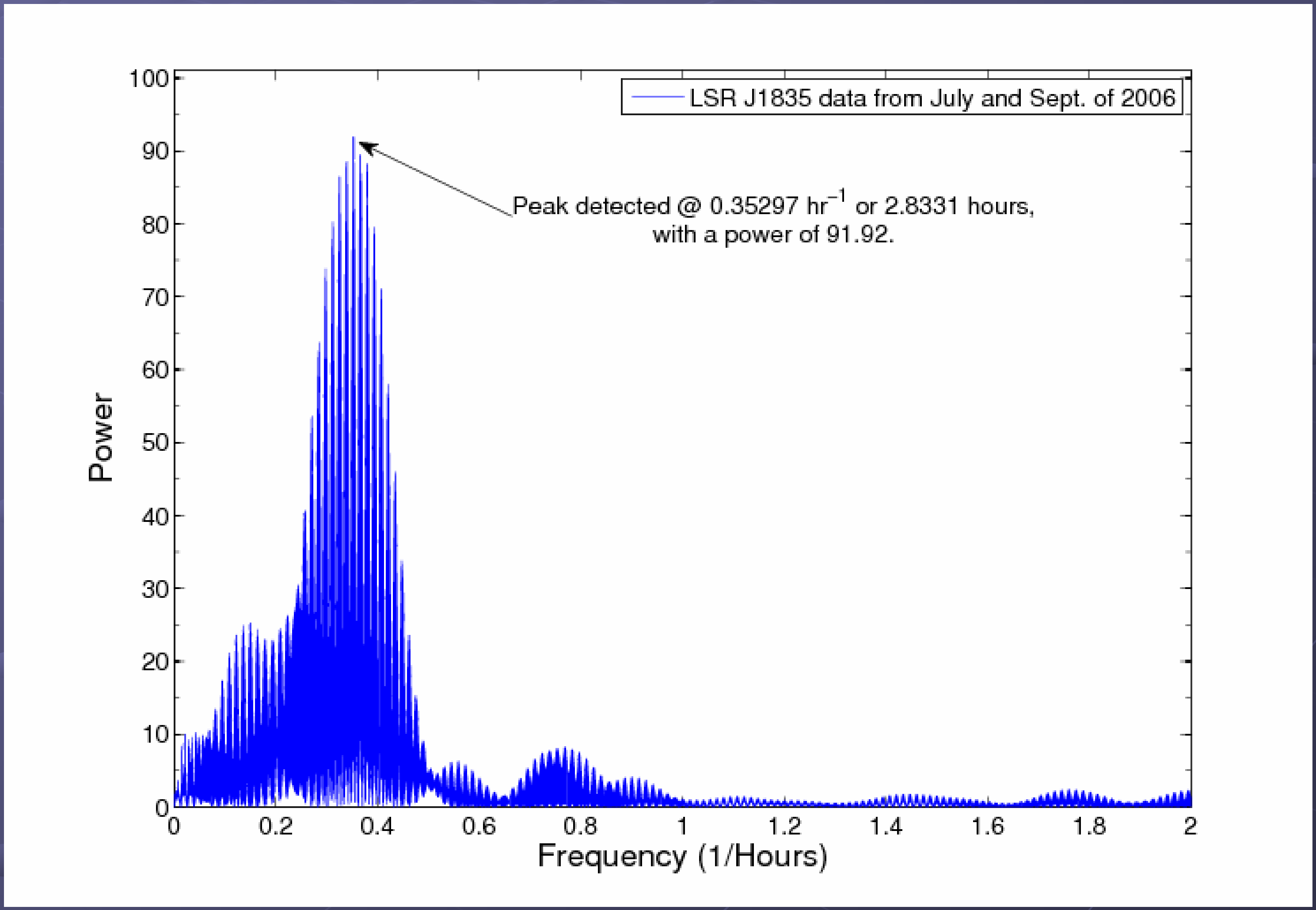
Results: Ultracool Dwarf, LSR J1835

- Nights 4 + 7, phase-folded, smoothed by 10-point moving average
- Error bar = 0.003 mag

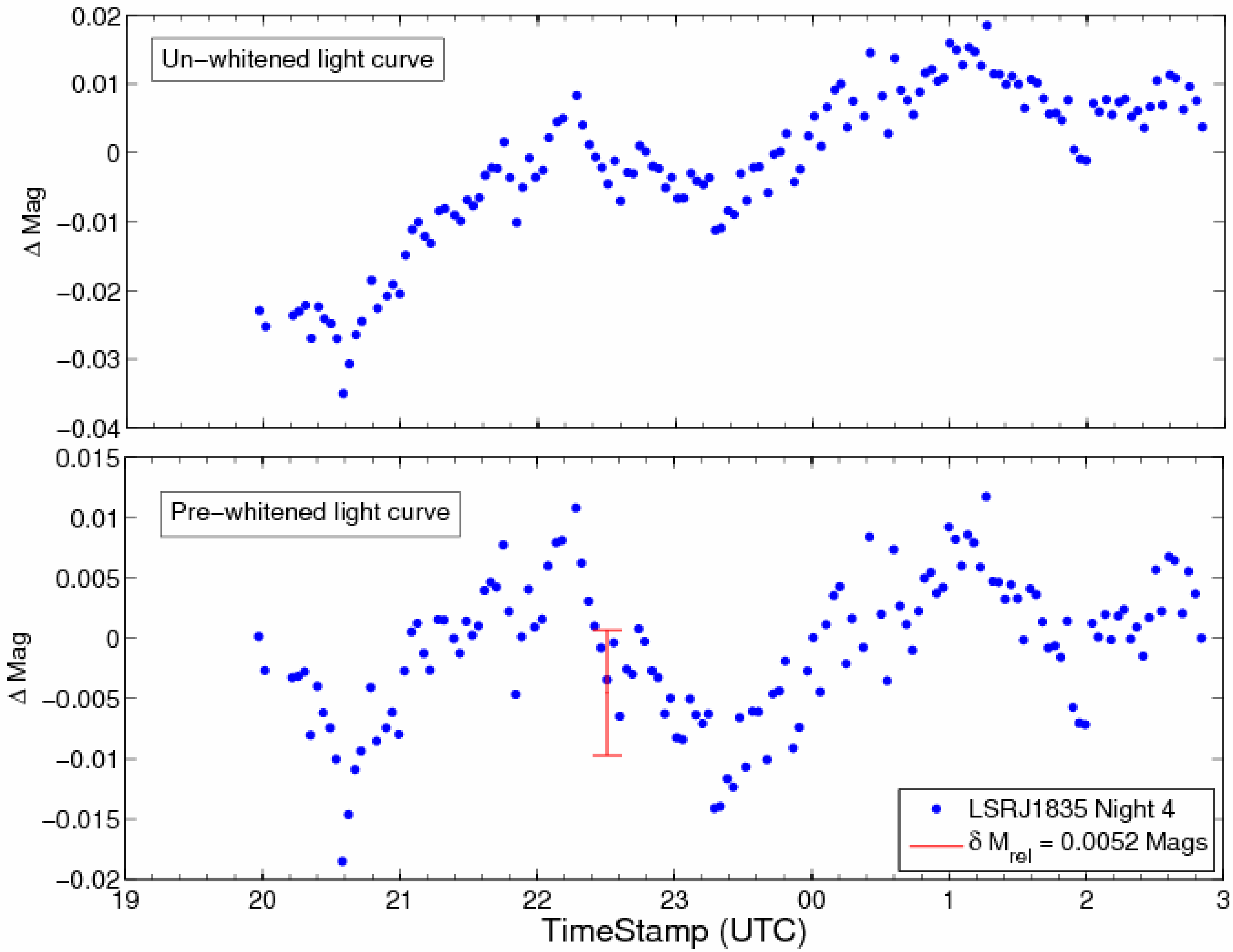


Results: Ultracool Dwarf, LSR J1835

- Combined with USNO run 2 months later (conventional CCD) – allows us to test long-term period stability of the modulation



LSR J1835 - why is pre-whitening needed?



LSR J1835 - why is pre-whitening needed?

I think that the trend could be caused by one of –

1. If the PSF varies with position in the field (SV-PSF)

2. If the spectral types of the reference stars are very different to LSR
   - in a broad wavelength range like I-band, you could get 2nd-order extinction effects (affecting different spectral types to different extents), which change as a function of airmass

3. If (2) were true AND if any haze/cloud present was not a "grey absorber"

Tests - why is pre-whitening needed?

- Either the seeing or the airmass will correlate with the trend in the data.

- The SV-PSF possibility can also be investigated by:
  - Repeating the automated lightcurve extraction, but this time using larger and smaller radii.
  - Measuring for the PSF of different stars around the frame…repeat for a few frames…are the same stars systematically different?
  - The SV-PSF effect could be simulated

- The 2nd-order extinction effects can also be investigated by:
  - Mining the colour indices or spectral types for the field/reference stars
  - Calculating the difference in extinction for either end of the I-bandpass, for the range of airmasses in our data. To what extent is

    $$d(E) = E(730) - E(1030) = f(\text{airmass})?$$

  - Convolving model spectra through transmission curves of filter and detector and an extinction function: our ETC with full $T(\lambda)$ propagation.

Conclusions re. L3-CCDs

- L3-CCDs give higher SNR due to better duty cycle (in <u>all</u> modes)
- Very high SNR photometry of bright objects (incl. variable objects)
- L3-CCDs can deliver the widest dynamic range
- L3-CCDs make full use of telescope apertures – small and large
- High duty cycle maximizes cumulative exposure time over a run, thus reducing scintillation noise to theoretical minimum.

<u>Practical observing recommendations for high fluxes:</u>

Frame transfer alone is all you need in most situations.

Use EM gain only:

1. For maximum dynamic range (rather than maximum S/N)
2. For very brightest sources, which would saturate at max Frame Transfer rate
3. When the cadence is more important than the S/N

Conclusions re. GUFI

- The goal in 2004:

  Build an imager/photometer to yield the benefits of 100% duty cycle, and as-fast-as-you-want-it sampling, for variability studies, PEIS, and high S/N studies of bright sources.

- The outcome in 2007-8:

  It has taken time, but –

  (1) We now know how to configure the complex matrix of L3-CCD settings for any given observing scenario;

  (2) It is now a 'plug and play' system at the analysis end too;

  (3) Some of the July 2006 data was not taken at the best settings, but –

  (4) That will not happen again, now that we have characterised the S/N, linearity and dynamic range at each permutation.