Using Cameras for Measurements

2021 Training #2

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Purpose

- In fulfillment of requirement, "Training in observations planning, detector settings, and imaging performance "
  - See "UCB Letter on additional tasks_09.28.21.pdf"
- Viewing this material should prepare you for planning observations using the BSTI camera.

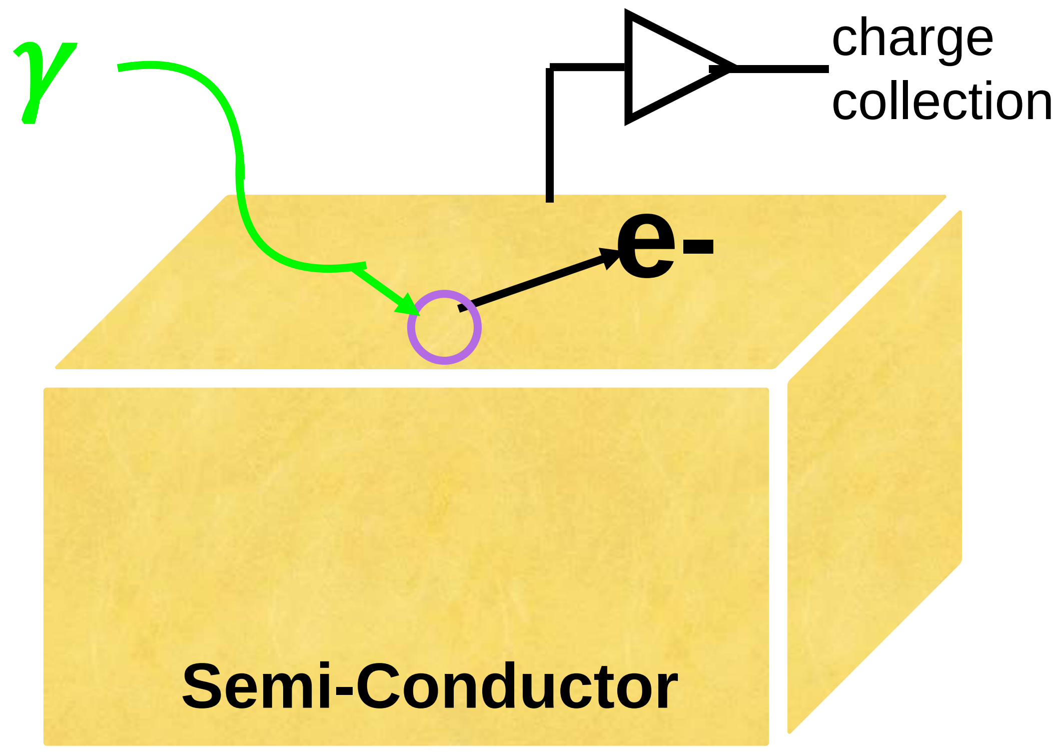
Sensors for Astronomy

- Charge-Coupled Device, or CCD.
  - CCDs can detect 1- a few HUNDRED THOUSAND photons

CCD Sensor

- **Physics**: a single photon interacts in semi-conductor to "free" an electron for collection
  - said to "pop" electron into conduction (energy) bands where they can move and be collected
  - Each pixels is a detector; electrons are pushed across the detector's rows and columns for counting.

Single CCD Pixel



- **Electronic Noise**: tiny bit from "reading" CCD
  - Noise ~ 5 e-, for constant targets, collect until lots of e-
  - But short exposures => few e- from target, 5e- noise
  - **short exposures NO GOOD - too many noise e-!**

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 ~ $t_{exp}^{1/2}$
- 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.

Basic Basics of Astronomcal Imaging

- Measurement aperture has some number of pixels Npix,ap.
  total readout noise = sqrt(Npix,ap)* single pix read out noise

- Signal in aperture has noise: Poisson(Ne-, signal)
  -> sqrt(Ne-, signal) is Ne- large (~>50)

- To set Texposure: NOT readout-dominated regime
  - don't saturate anything of interest!
  - make sqrt(Ne-, signal) > a few * total readout noise
    ==> Noise dominated by nature, not electronic artifact
  - if target signal small compared to background, calculate signal as background, "background-dominated" regime. Take many such frames ==> max dynamic range for standard stars, etc.

Basic Basics 2

- How do I go from ADU to e-?
  K-gain! Conv. mode 100kHz hfreq -> K-gain = 3.473 e-/ADU.
  CAUTION: This is only CHANGE in ADUs with time....

- BIAS and ZERO POINT
  Texp~ 0s frames have ~ 1490 ADU in typical Conv. exposures.
  ------> Subtracting bias takes care of most of this.
  ------> IMPORTANT: LOOK at over-scan region, last line of CCD covered by metal, no light:
  See only offset+ dark current.

- ADU to e-
  - 15 s images:~ 1503 ADU in bgnd pix
  - bgnd signal= 1503 ADU - (overscan=1491) = 12 ADU / pix
  - 12 ADU * (k-gain = 3.473 e-/ADU) = 41.4 e-;   in 15 s==> bgnd rate = 2.76 e-/s

What is brightness of sky, typical source?

- Faint source ~17.75 mag -> 9e-/s peak pix; bgnd~ 2.8 e-/s

- How did I get this?
  - 201015a, 15 s images:~ 1503 ADU bgnd/pix
    BUT overscan line ~ 1491 ADU zero-point offset,
    MUCH BIGGER THAN SIGNAL!
  - 1503 ADU bgnd pix -1491ADU = 12 ADU bgnd signal;
    in 15 s, that's 12/15=0.8 ADU/s bgnd
    vfreq 8e5 hfreq 3.33e6 => k-gain 3.538e-/adu.
    Finally, 0.8 ADU/s * 3.538 e-/ADU = 2.83 e-/s
  - Faint source ~ 17.75 mag; peak is 1529ADU or
    38 ADU/15 s ==> (3.538 e-/ADU*38ADU)/15s
    ~ 9e-/s peak pix.

characteristic	r'
zero-point (ADU/pix)	1491 (1)
bgnd/pix e-/s	2.83 (1)
FWHM (pix)	3.5 (1)
bgnd/1 FWHM circ aperture (e-/s)	27.2 e-/s (1)

(1) technut.pro, grb201015a r' frames 4 and 13, conv mode, vfreq 8e5 hfreq 3.33e6, k-gain 3.538e-/adu.

Basic Basics 3

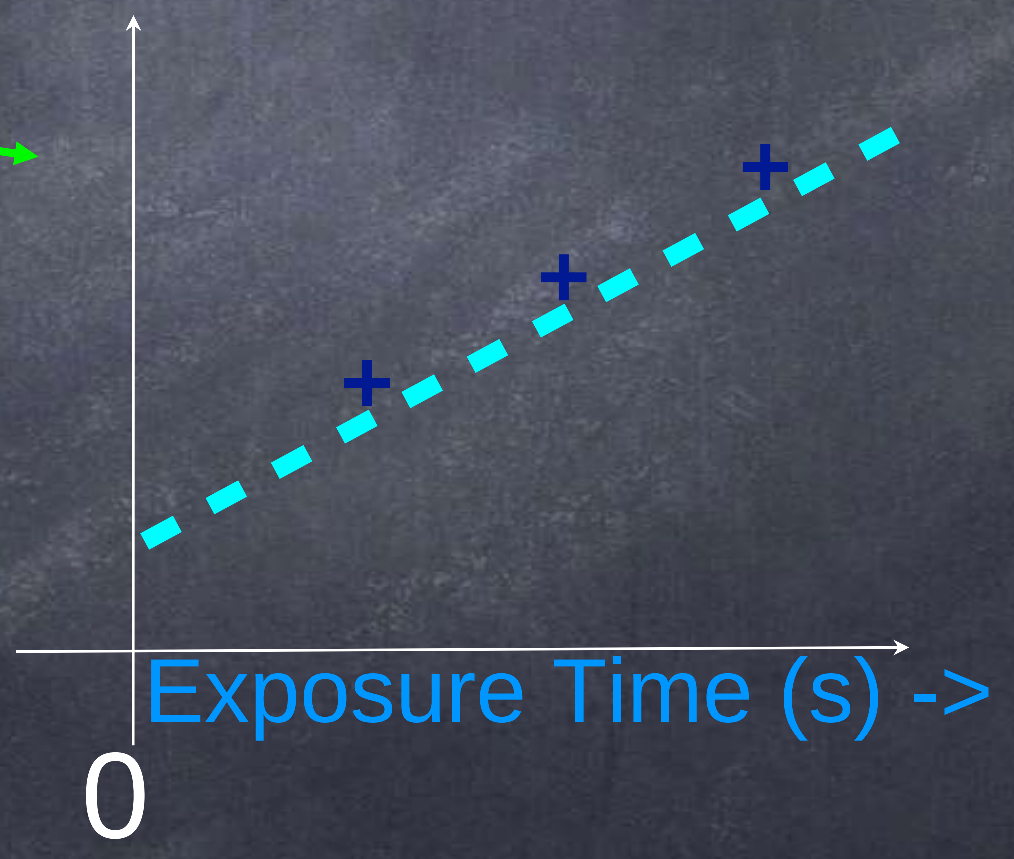
- **ALWAYS bias-subtract!!!!**
  - Large offsets just confuse you. As we say on last slide, offset often >> signals
- **Convert frames to e-/s using K-gain**
  Will help you understand Poisson noise
  bepsimr0009.fits=(imr0009.fits - median_bias.fits)/kgain;
  b for bias subtracted, eps for units of e- per secon.
- Someday soon: flat corrections!
  - b**f**epsimr0009.fits=(imr0009.fits - median_bias.fits)/kgain/medflatr.fits
    f for flat-corrected.

Technology For Transient Imaging:

- *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.
- – These are the conditions for NUTTelA transients from Swift: We can never know the brightness before hand, so we need to understand what our EMCCD settings mean in all potential cases.

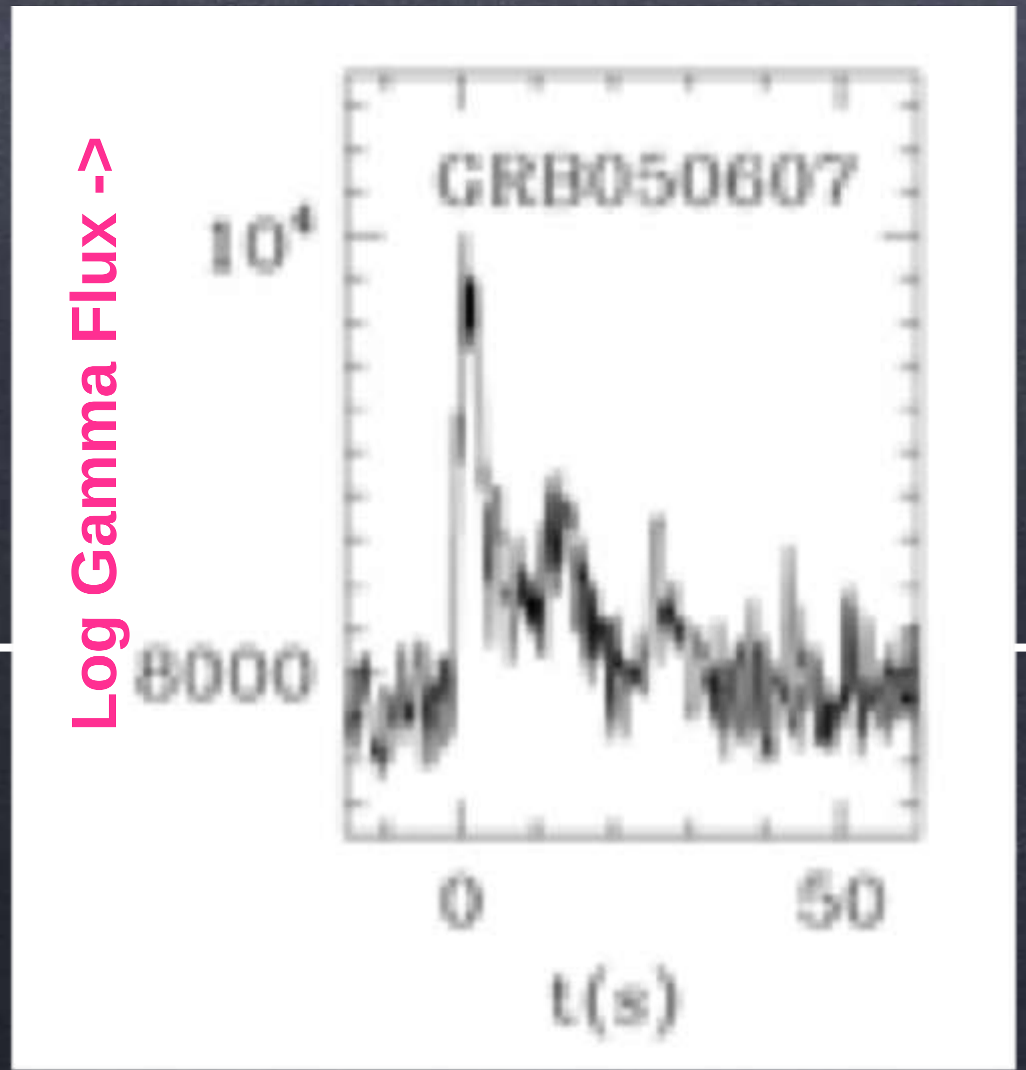
Imaging Measurements

- 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.



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.



Co-adding: time resolution or noise?

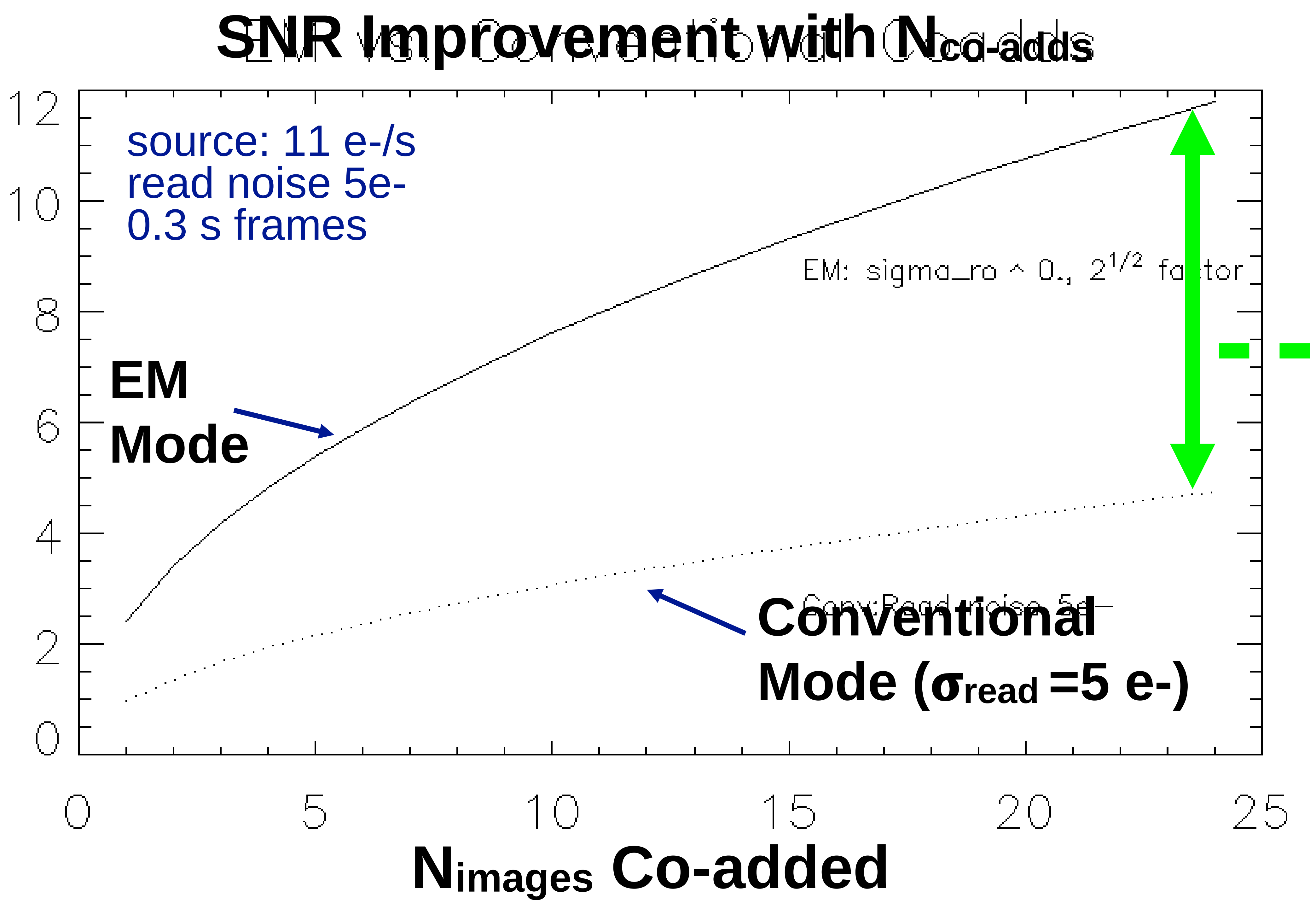
- Take short, e.g. 0.1 s frames:
  - » good time resolution!, but faint sources not detected
  - » Fix: if faint, co-add frames for enough signal to detect
    -right?
    -How does this affect noise?

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

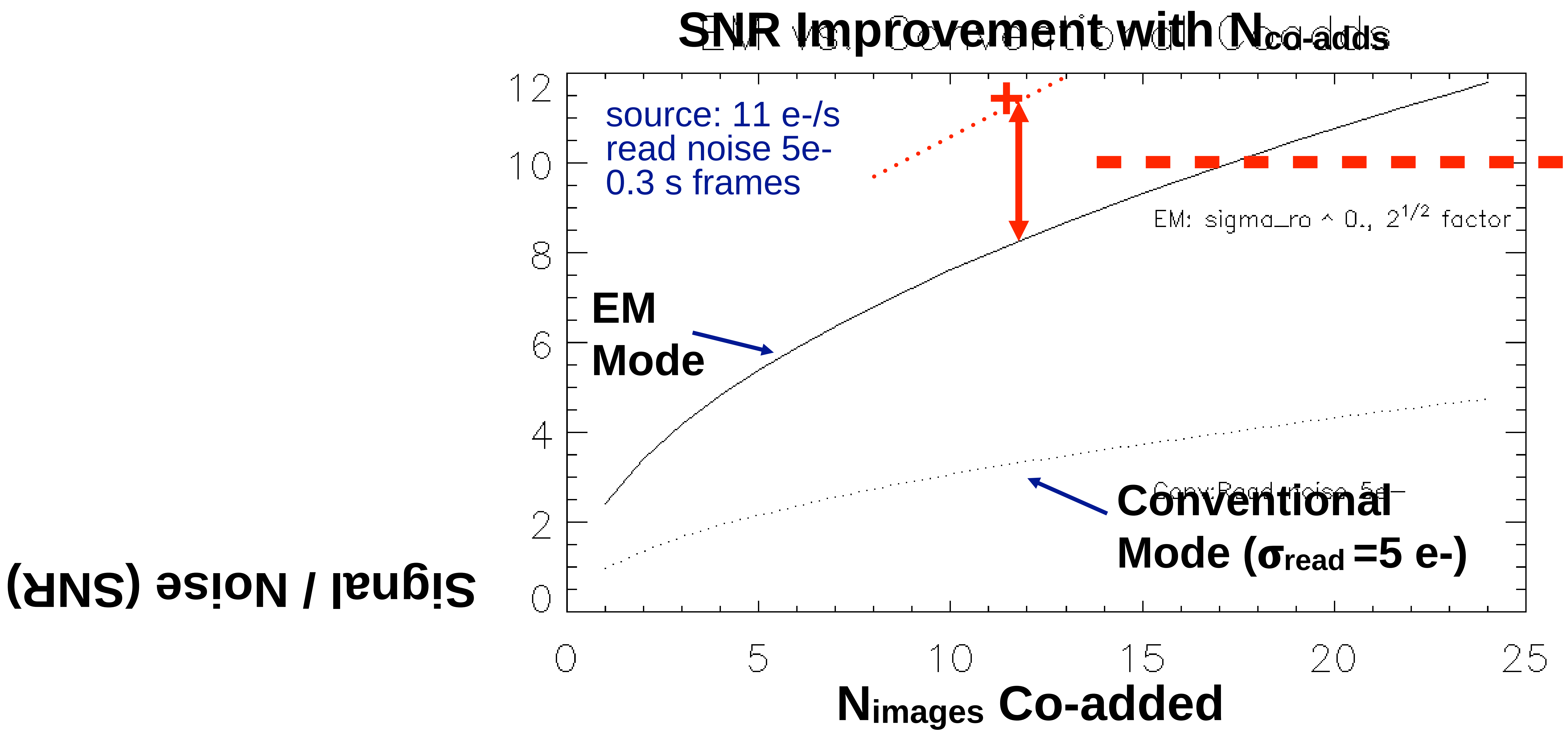
- SNR co-adding short frames of faint source.
- EM mode SNR grows faster vs Conventional mode



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?**