EMCCD Operation

2021 Training #2

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Purpose

- In fulfillment of requirement, "Training in EMCCD camera operation: noise, gain, conventional and electron multiplication modes "
  - See "UCB Letter on additional tasks_09.28.21.pdf"
- This presentation should guide those using EMCCDs, especially for transient searches and measurements.

Camera Setting have *Consequences*

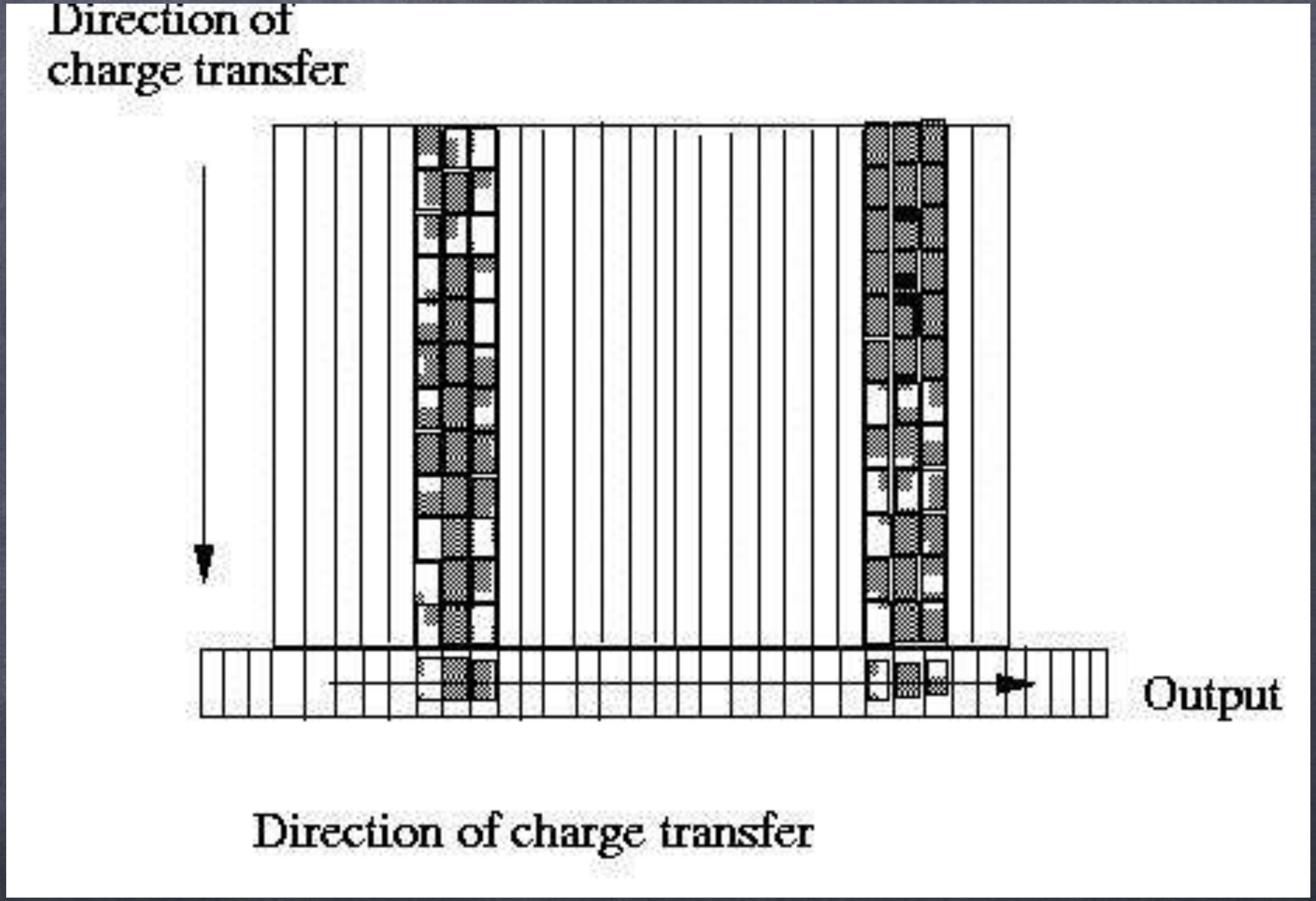
- *In the NuVu EMCCD, setting mode, vfreq, hfreq determines*
  - k-gain
  - read noise
  - well depth - which in turn affects dynamic range
  - minimum frame time
- EM Gain affects
  - dynamic range
  - noise
  - sensitivity

Documentation

- The best source of documentation is the "certificate of conformity" which comes with each of our NuVu cameras. They give measured values of e.g. read noise, so they are all similar, but *slightly* different. I have these two:
    - CertificateOfConformity_SN11502796.pdf
    - CertificateOfConformity_SN09293004.pdf
- Most of the information you need from these documents is in the tables, next slide.

What are horizontal and vertical frequencies?

- Convention given at right
- Vfreq moves all charge on chip
-
- Hfreq moves charge across register and to reading. (typically faster)



Frame Transfer Devices

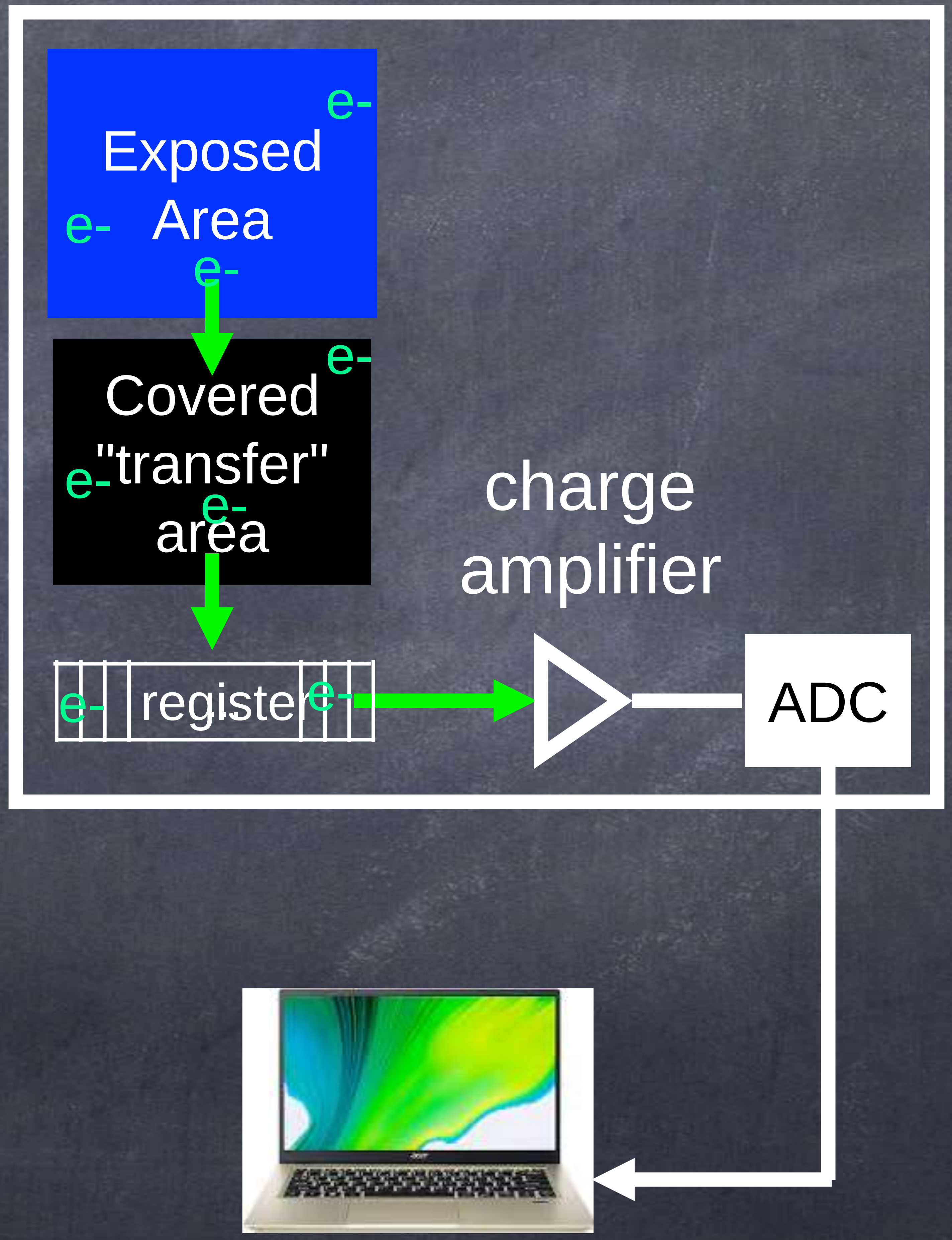
- Note NuVu EMCCDs are frame transfer devices

- transfer area -second covered area on chip, blocked from light

  - stores frame during exposure

    > reading is done while next frame exposing.

    > Almost 100% duty cycle.



NuVu EMCCD Settings Tables

- *These are from the wiki nuvu cameras page: https://www-astro.lbl.gov/~bruce/docuwikis/eclex/doku.php?id=ecl_staff:grbtel:nuvuemccdcams*

Reciprocal gain and read-out noise

Output	Frequency	k-gain [ē/ADU]	Read-out noise [ē]
EM	1MHz	15.863	33.40
EM	5MHz	16.316	63.97
EM	10MHz	17.703	85.81
EM	20MHz	19.928	201.70
Conv	100kHz	3.473	4.08
Conv	1MHz	3.650	10.73
Conv	3MHz	3.667	12.61

This is absolutely phenomenal - in CONV MODE!

Calcuated values table

- *These are from the wiki nuvu cameras page: https://www-astro.lbl.gov/~bruce/docuwikis/eclex/doku.php?id=ecl_staff:grbtel:nuvuemccdcams*
- *effective noise means you multiply the photo-e- signal, but NOT the read noise.*
- *Note that Hfreq determines ro noise*

Effective read-out noise in ē as a function of the EM gain

	EM gain					
Horiz. Freq	**1**	**2**	**10**	**100**	**1000**	**5000**
1MHz	33.396	17.053	3.510	.387	.041	.011
5MHz	63.970	33.431	6.860	.751	.082	.017
10MHz	85.809	49.483	10.602	1.209	.132	.027
20MHz	201.701	111.552	23.279	2.483	.287	.061

Dark Current, CIC

- *Dark Current is pretty small, even for 1000 s exposures.*
- *Remember, CIC gets multiplied by EM; insignificant in conv mode, can kill you in EM mode.*

Dark current

Temperature [°C]	**Dark current** [ē/pix/s]
-65	.0042009
-75	.0011630
-85	.0003654
-90	.0000939

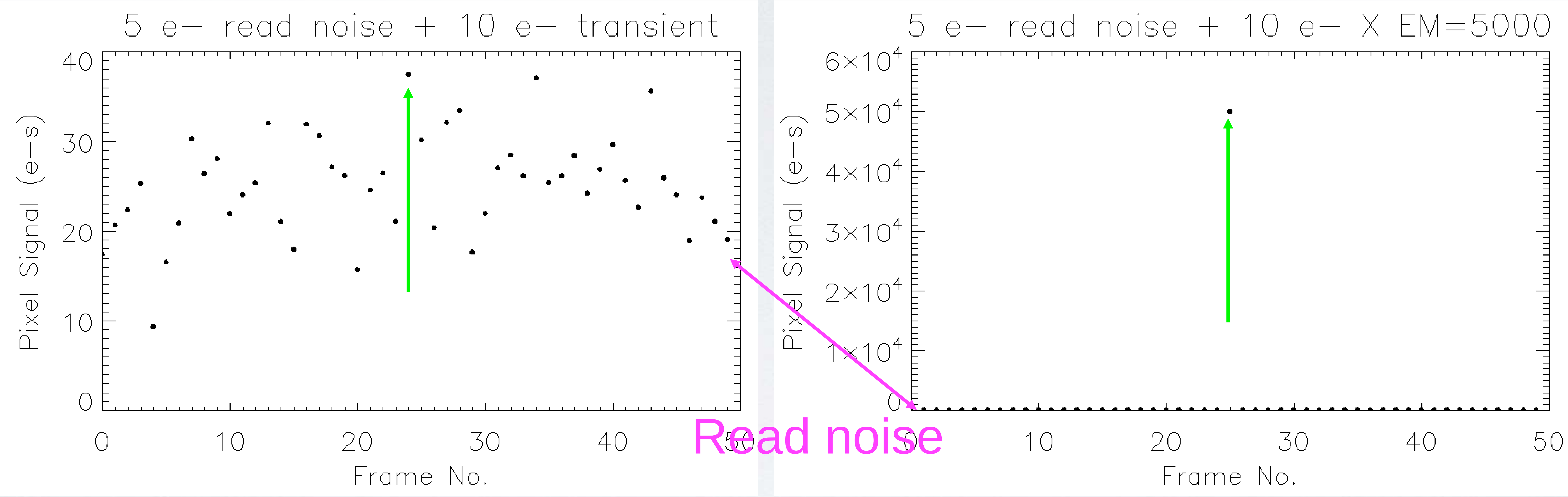
Clock induced charges

Horiz. freq.	**Vert. freq.**	**CIC** [ē/pix/im]
10MHz	1MHz	.0011437
10MHz	800kHz	.0013023
10MHz	200kHz	.0019455
5MHz	1MHz	.0024391
1MHz	1MHz	.0136865

Lessons of Settings

- Hfreq determines read noise
- vfrequency well depth
- both determine CIC

EM GAIN BEATS READ NOISE for VERY SMALL signals



– 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.

Example - conv mode

- Choose vfreq=100kHz for astounding 4 e- read noise
  sheet gives full well 200kHz=81ke-, but doesn't give 100kHz; typo?
  k-gain (e-/adu) =3.473

- Assume background = 2e-/s/pix, aperture has 9 pix

  - read noise = sqrt(9) * 4 e- = 12e-
  - 1 s gives backround of 18e-, Poiss noise *roughly* ~ 5-6 e- ==>killed by read noise!
    ==> Conv terrible for short exposures
  - 30 s gives 540 e-, Poiss noise is 23 e-; adding ro noise gives 26e-
    ==> background noise dominated!
    ==>Very sensitive, because limit is nature, Poisson noise, not electronic artifact.

Example - EM mode

- Choose hfreq=1MHz for 33.4 e- ro noise;
  Can I choose 200 kHz vfreq for largest well?
  Check frame time: Horiz read takes ~ 1 ms; each vertical move takes 1/2e5= 5µs, so dominated by horiz read, 1024*1 ms = 1.024 s, so this limits your min exposure time.

- 800 KHz vfreq: can do ~250 ms frames, 51ke- well depth, and 1 MHz hfreq ==> 33.4 e- ro noise. EM=100 ==> ~ .33e- effective RO noise; very low.
  - 1 photo-e- ==> 100 e- / (k-gain=15.9 e-/ADU) ===> 6.3 ADU.
  - NOTE: 51ke- ==> 3207 ADU, Waaay under saturation, so no loss in dynamic range for EM=1000; EM=1000 ==> 1e- ==>63 ADU. The well depth limited dynamic range, not ADC saturation.

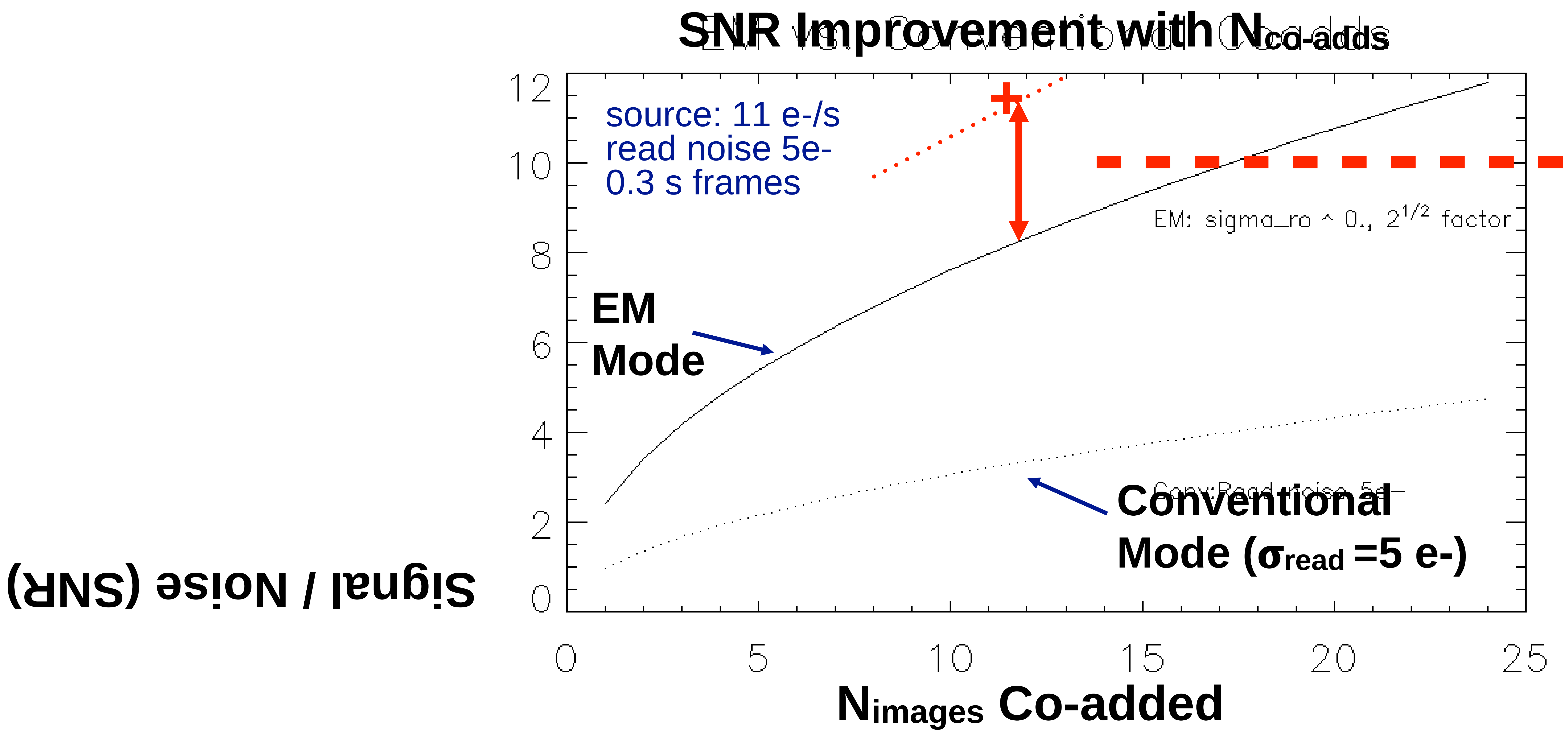
Compare EM to Conv modes

- EM causes Excess noise factor of sqrt(2)!!!
- From previous: Conv:1 s ->18e-, Poiss noise ~ 5.5 e-; ro noise 4e-, tot=6.8e-
- EM: 1s: measure noise ~ 5.5*sqrt(2) = 7.8e- ---> close, SNR worse by 14%.
  BUT ***IF*** bright transient occurred in short (e.g. 333 ms) exposure, you would get 3X better time resolution!
  So, you added 3 frames, to get the result above, with ro noise ~ 0.
  =======> THIS is the advantage of EM!
- What about dynamic range? In some sense, you get a factor of 3 for 3 exposures, you lost a factor of 50/80 in well depth; big win! (factor 5/8*3=1.9)

Additional Techniques

- *We don't do this at this time, but in the future, maybe...*

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:

Disadvantages:

– Dynamic range limited to factor N_{frames} (1e-/pix/frame max)

– ultimate limit above Poisson is another amplified noise, (CIC), not too bad.

lly

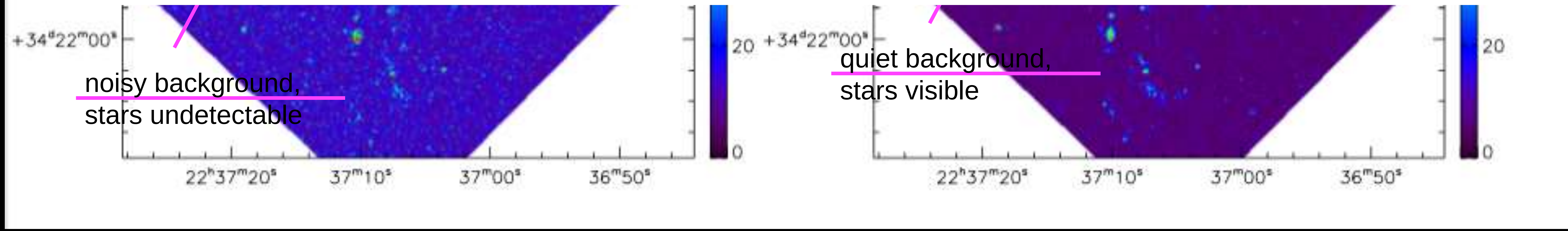
<1)

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: 10.1117/12.840047



Why not for us?

- *We don't know anything about our source brightness during the alert at the time we set up the camera*
- *In order for this to be useful, we would have to have a maximum of 1 e-/pix*
- *We have several e-/pix in 300 ms exposures in most stars on the field. I believe the fastest rate we could expose would be 100 ms; so bright sources definitely saturate.*