PAL
Photonics Architecture Laboratory

The 19th Korea-U.S. Forum on Nanotechnology

Neuromorphic Sensors for Anomaly Detection

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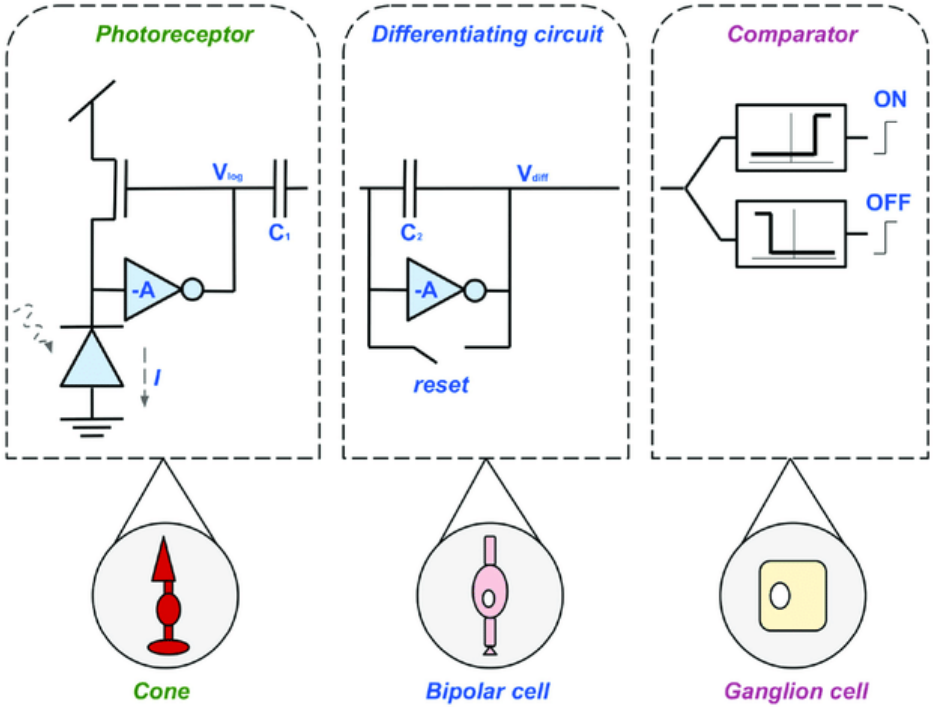
Neuromorphic Sensing



Fechner's law: *Perceived brightness ∝ log(Intensity)*

Log Companding of Speckle

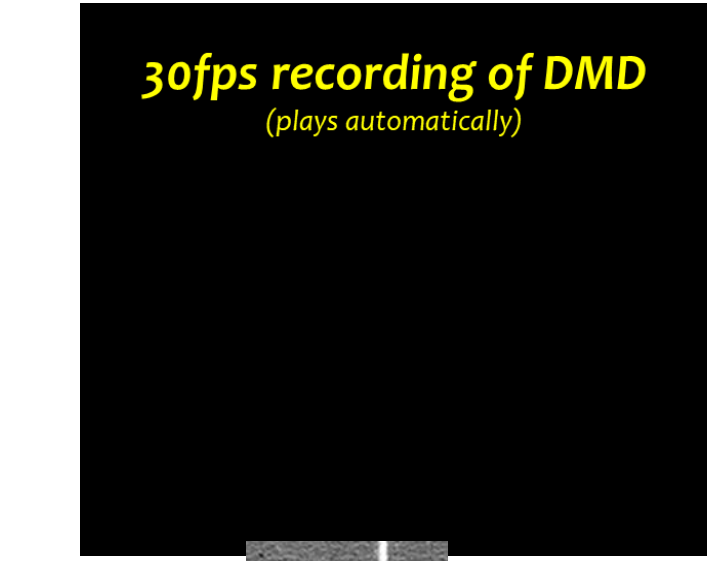
*Accumulate **change** in Perceived brightness*

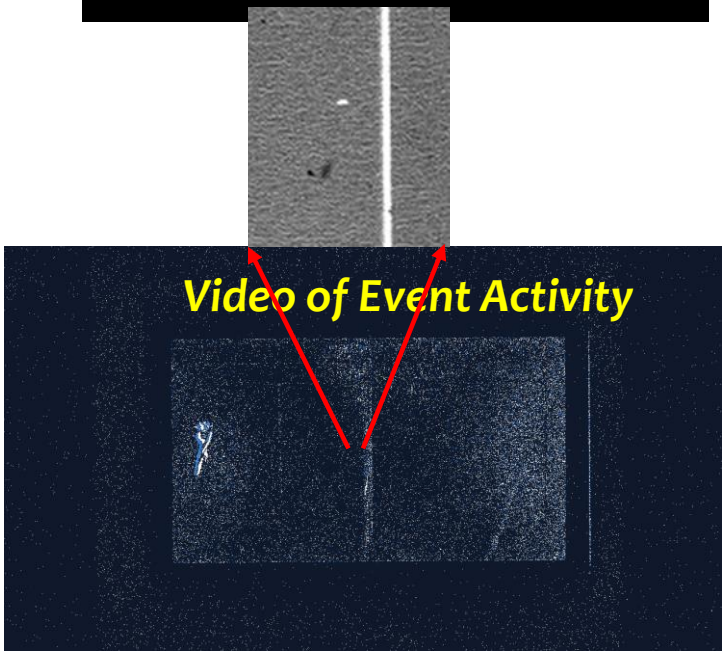
Derivative

Sparse Representation

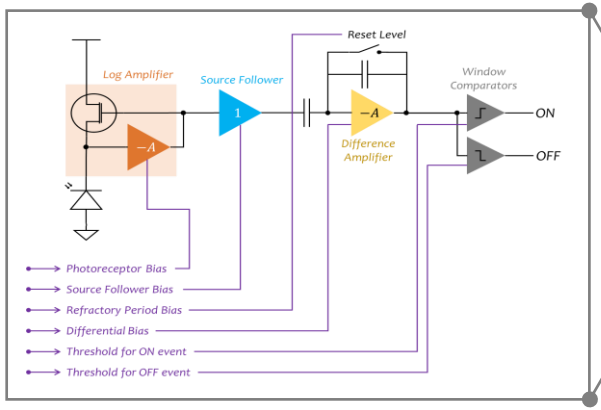
Ultra low power consumption

High bandwidth, low data rates





Event Sensor at a glance



Event Pixel

- Dynamic Range
- Analog Bandwidth
- Contrast Sensitivity
- Latency (Propagation delay)
- Jitter (noise/variability)

User-configurable parameters

Threshold/ Bias Generators

Configuration & Control Logic

Event Pixel

Event Sensor

Async Readout

Readout

- Timestamp Resolution
- Number of Pixels sharing timestamp
- Latency (Arbiter)
- Jitter (variability + arbitration)

Raw Event Activity

$E(x, t, p)$

Processed Event Activity

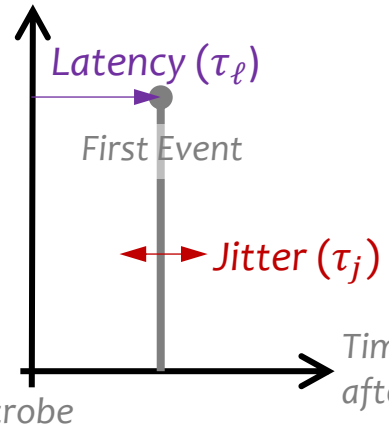
$f(E(x, t, p), \phi)$

Irradiance

$L(x, t)$

Sensor

Event Camera



Expectation vs. Reality

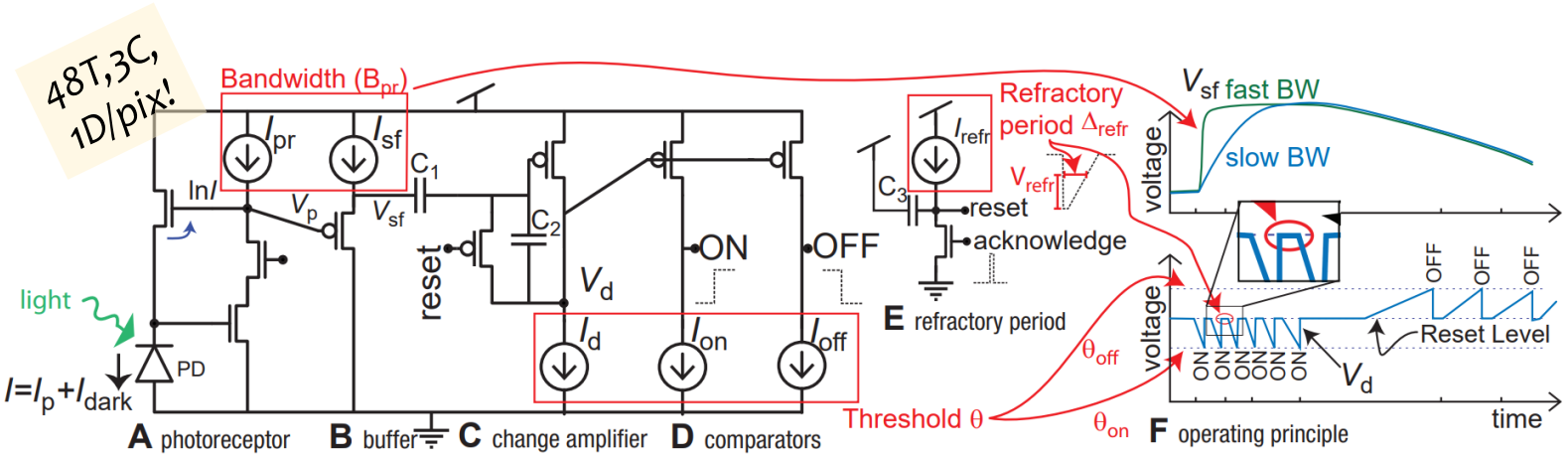
Idealized Event Pixel / Sensor

- Symmetric response to change in luminosity (ON/OFF)
- Low latency at all light levels (track fast moving objects), $O(\mu s)$
- High Temporal Bandwidth (laser pulse detection, vibration sensing), $O(MHz)$
- Excellent Contrast Sensitivity ($< 2\%$)
- Zero false events due to electronics
- No threshold mismatch
- Event Sensors don't respond to static retinal input

Real Event Pixel / Sensor

- Asymmetric response to change in luminosity (ON/OFF)
  ON/OFF events: slower, faster
- Increased latency at lower luminosity
- Reduced temporal Bandwidth at lower luminosity, $O(Hz - kHz)$
- Reduced Contrast Sensitivity ($> 15\%$) at lower luminosity
- False events due to electronics (Leakage, Thermal noise, f^{-1} noise)
- Increased non-uniformity in pixel response at lower thresholds (device mismatch)
- Secondary events due to optical shot noise (stochastic nature of photon arrival)

Exhaustive Open Loop Benchmarking is infeasible



Problem: *Behavior of event pixel is nonlinear, tunable, and redout dependent*

- *Complete sweep of bias parameter space is computationally intractable*

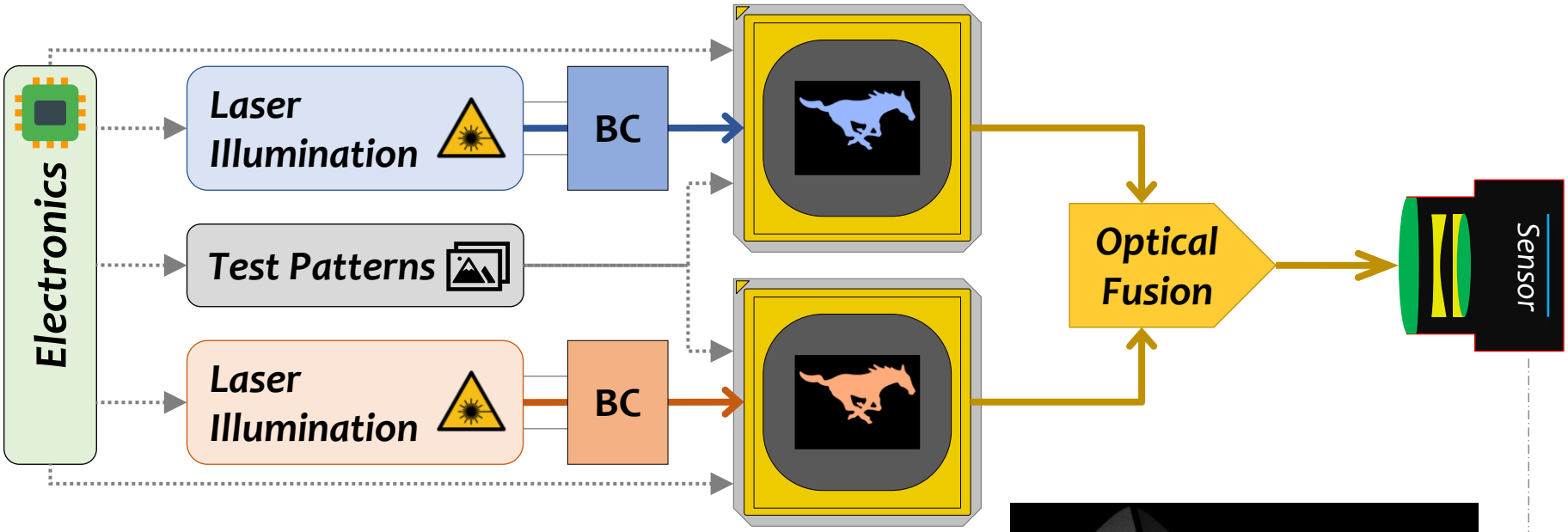
$$\tau \frac{\text{sec}}{\text{measurement}} \times \left(2^n \frac{\text{options}}{\text{parameter}}\right)^{m \text{ parameters/config}} = \tau \times 2^{nm} \frac{\text{sec}}{\text{sweep}}$$

- *For a **single** 1kHz stimulus on a DAVIS sensor would take **at least:***

$$1 \frac{\text{ms}}{\text{measurement}} \times \left(2^{16} \frac{\text{options}}{\text{parameter}}\right)^{6 \text{ parameters/config}} \approx 2.5 \times 10^{18} \frac{\text{yrs}}{\text{sweep}}$$

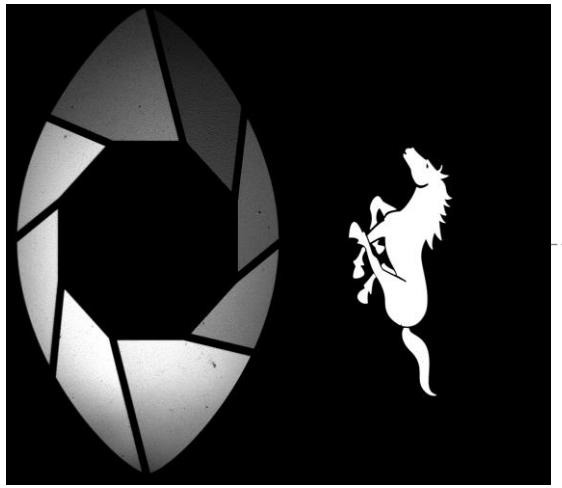
What's needed? *Efficient method to search performance space* ⇒ ***Metric, Closed-loop optimization***

System Architecture



Highlights

- *Modular design supporting upgrades*
- *Laser based Scene Projector (VIS-MWIR)*
- *High Bit Depth using pulsed amplitude modulation*
- *All reflective optical train*
- *Re-window DMD for operation in VIS-MWIR*
- *Double the pixel count of DMD without sacrificing speed (e.g: 1920 × [2160], 17.5 kHz Binary/Gray)*
- *Operable in two modes: WFOV mode, Hi-Res mode*



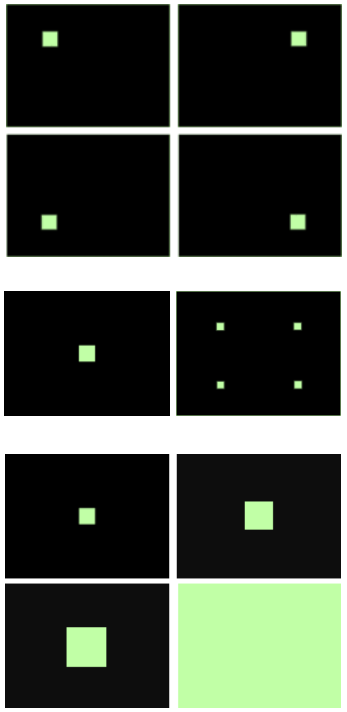
- ***Wide Field of View Mode:*** *2 × Field of Regard*
- ***High Resolution Mode:*** *2 × Pixel Density*

Event Sensor Open Loop Performance

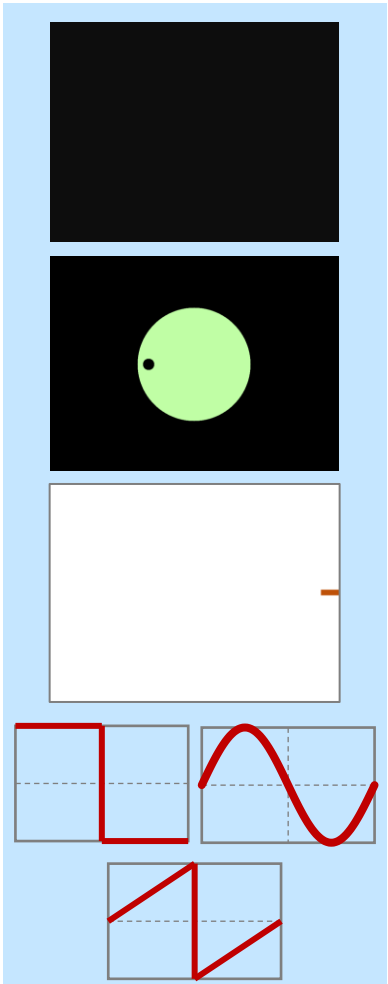
Dual DMD: *4MP*

DLP9500
1080p, 10.8 µm

Spatial Dependence



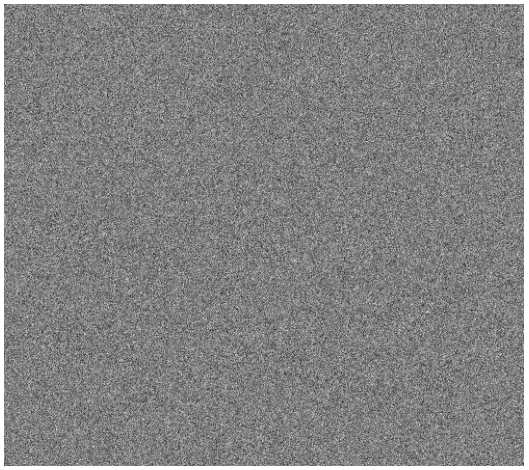
Temporal Dependence



Latency, Jitter, Pixel Bandwidth, Event Rate, Dynamic Range, SNR

20 kHz

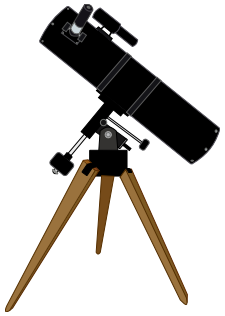
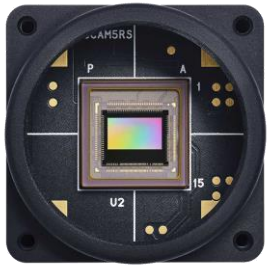
Stimulus loaded on DMD
1920 × 2160, *inspired by Random Dot Stereogram*



Video of Event Activity

Event Driven SDA: The Good, The Bad & The Ugly



The Good

- *Optical signature of RSO's change relatively slowly* (*fastest change* $O(0.1s)$)

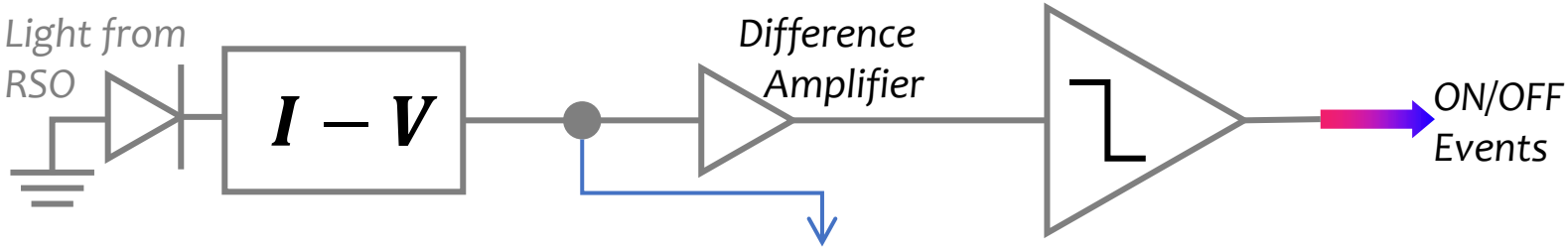
The Bad

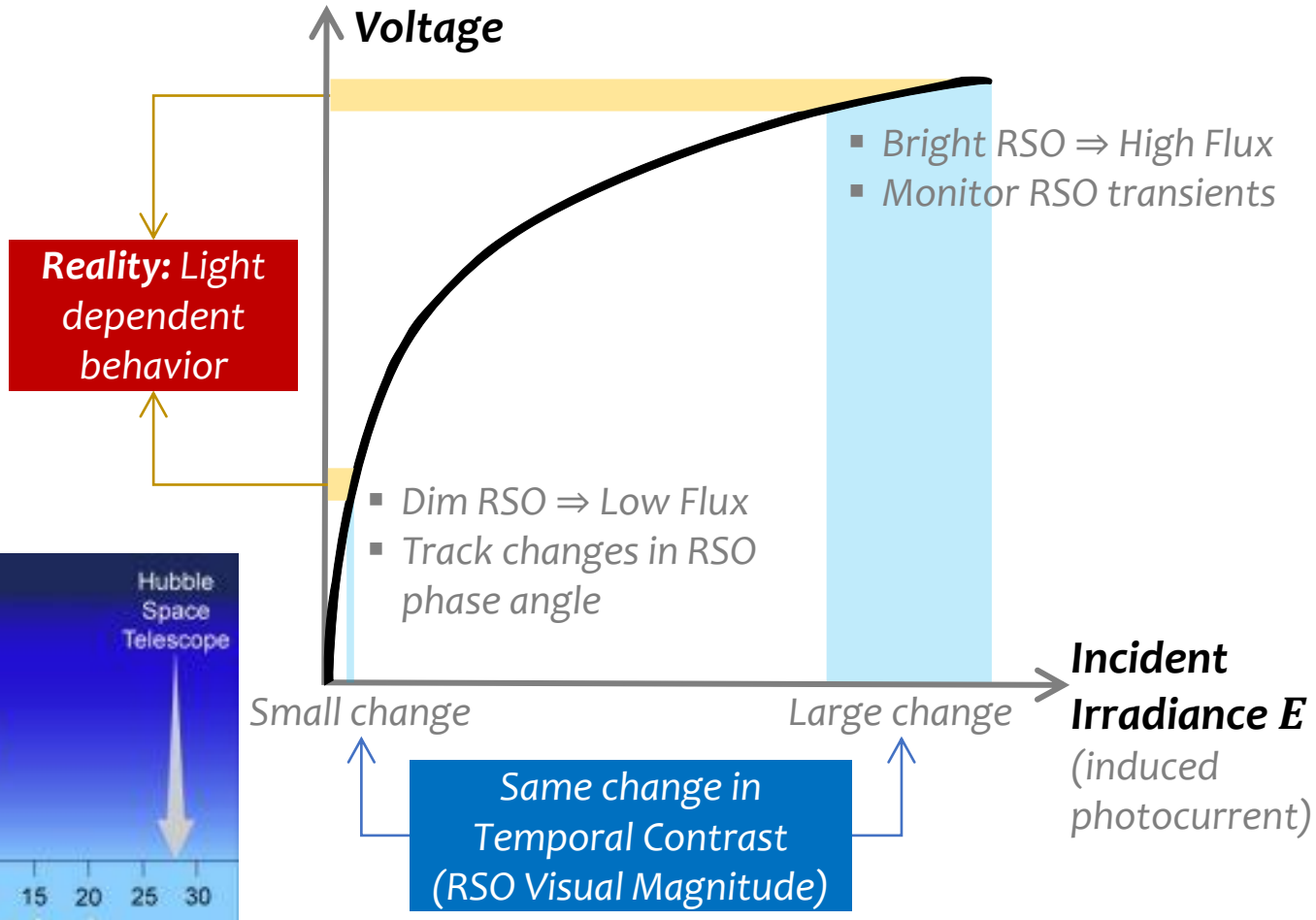
- *Wide variability in object luminosity* (*RSO size, albedo, solar phase angle, photocurrents in the* $fA - pA$ *range*)
- *Objects in GEO don't move as much* (*spiking activity due to changing luminosity*)
- *Objects outside of GEO can move rapidly or slowly* (*need low latency*)
- *Looking for dim & unresolved objects* (*low-light operation*)

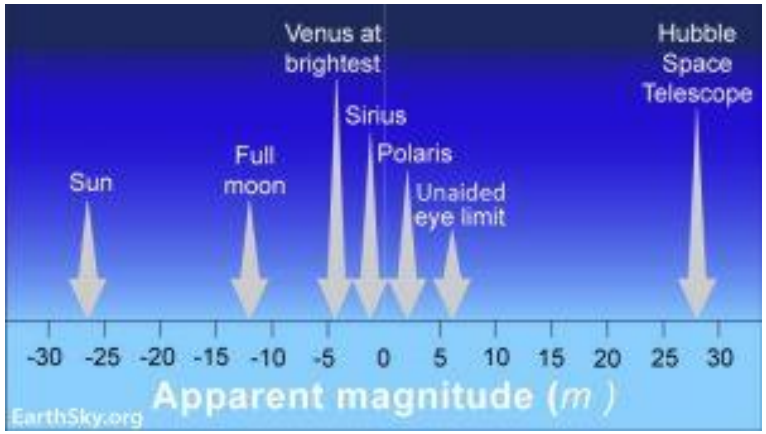
The Ugly

- *Observable is Spiking Activity, with asymmetry in ON & OFF response*
- *Inverse problem of recovering object luminosity from spiking activity is ill-posed*

Why Event Sensor for SDA?







Summary

- Potential benefits of neuromorphic sensing
  - Greatly reduced data rates for very high pixel count sensors
  - Very high dynamic range – large bit depth
  - Multiband sensing
- Neuromorphic sensors provide event sensing tuned to specific applications
  - Tracking stars in full sunlight
  - Autonomous driving
  - Tracking very high-speed objects
  - Tracking small objects in a cluttered environment
  - …..
- Acknowledgements
  - DARPA Phase II SBIR
  - AFRL Phase II SBIR
  - Space Force Phase I SBIR

Thanks!