

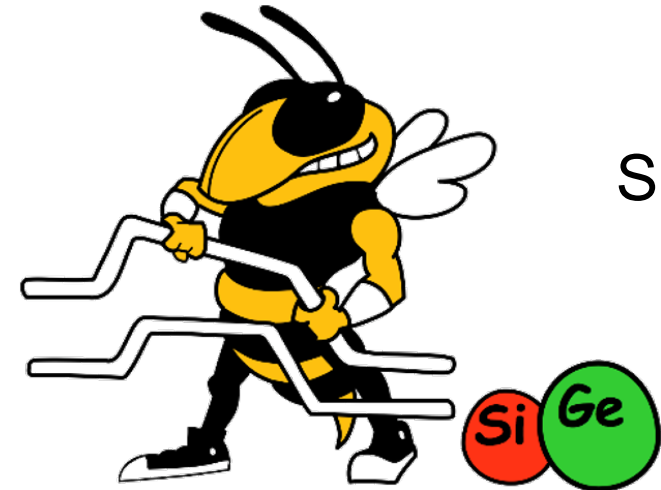
# Radiation Effects in Integrated Silicon Photonic Systems

George N. Tzintzarov and John D. Cressler

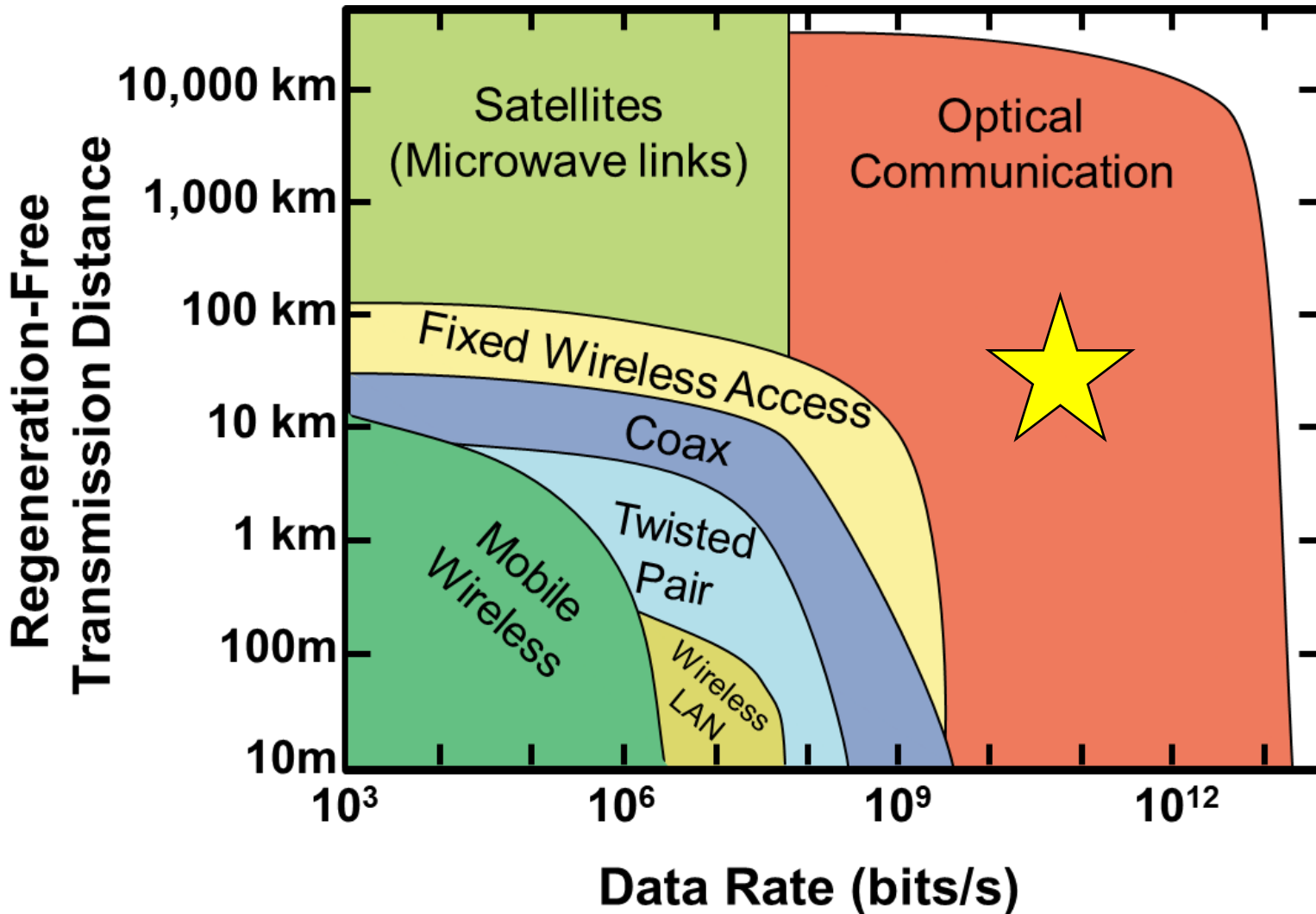
[george.tz@ece.gatech.edu](mailto:george.tz@ece.gatech.edu)  
[cressler@ece.gatech.edu](mailto:cressler@ece.gatech.edu)

School of Electrical and Computer Engineering  
Georgia Tech, Atlanta GA 30332-0250 USA

This work was supported by JPL, NSF, and NRL



# Why Optical Communications in Space?



## Optical Communications Systems


- + Increased Bandwidth
- + Can Operate Over Long Distances

- **Optical Communications Have Inherent Advantages Over RF**
  - size, power, bandwidth
- **Silicon Photonic Integration**
  - further reduce size and power (and cost)!

## More Science!

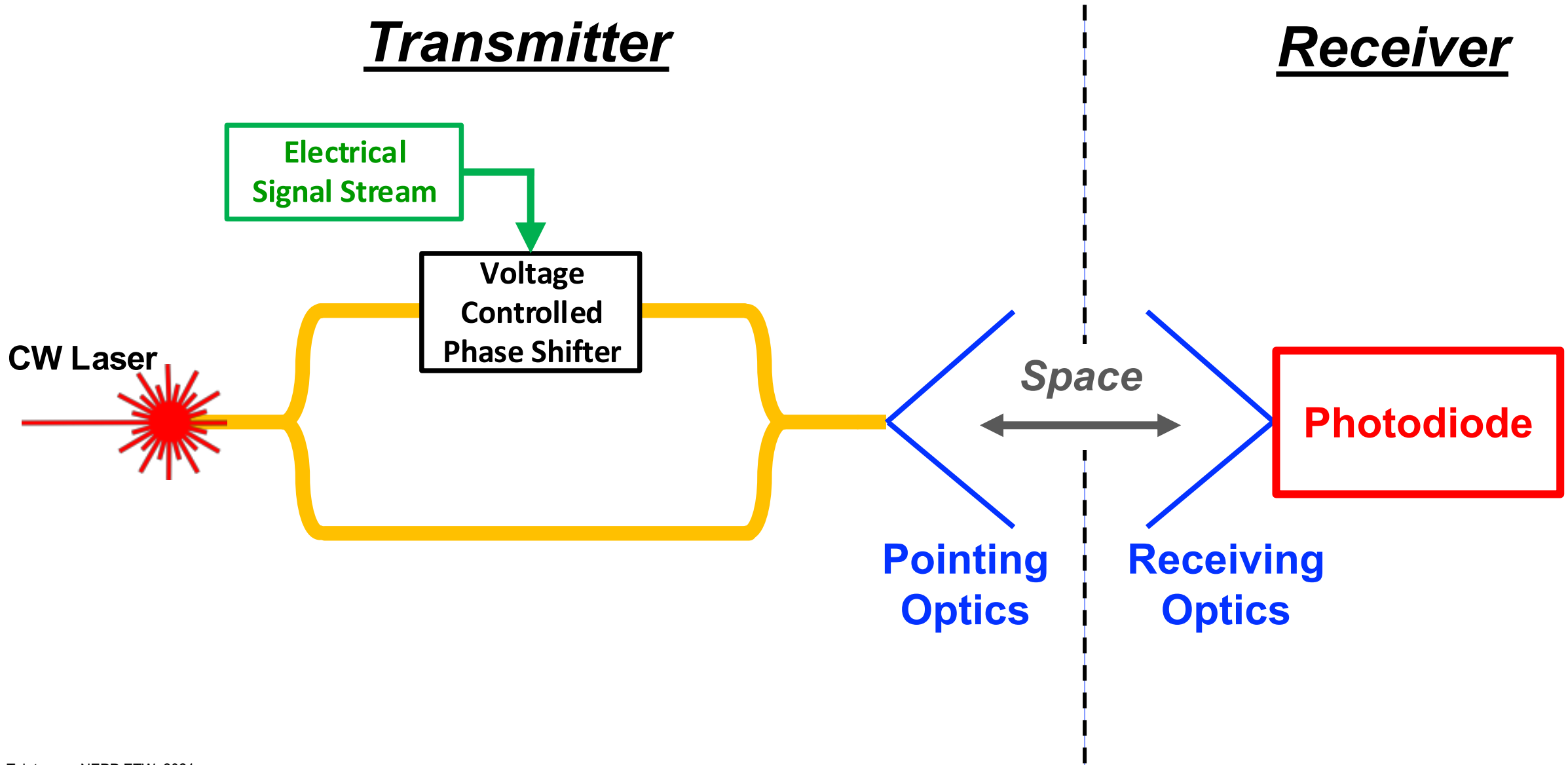


**Legacy:**  
**Discrete,**  
**Bulky**

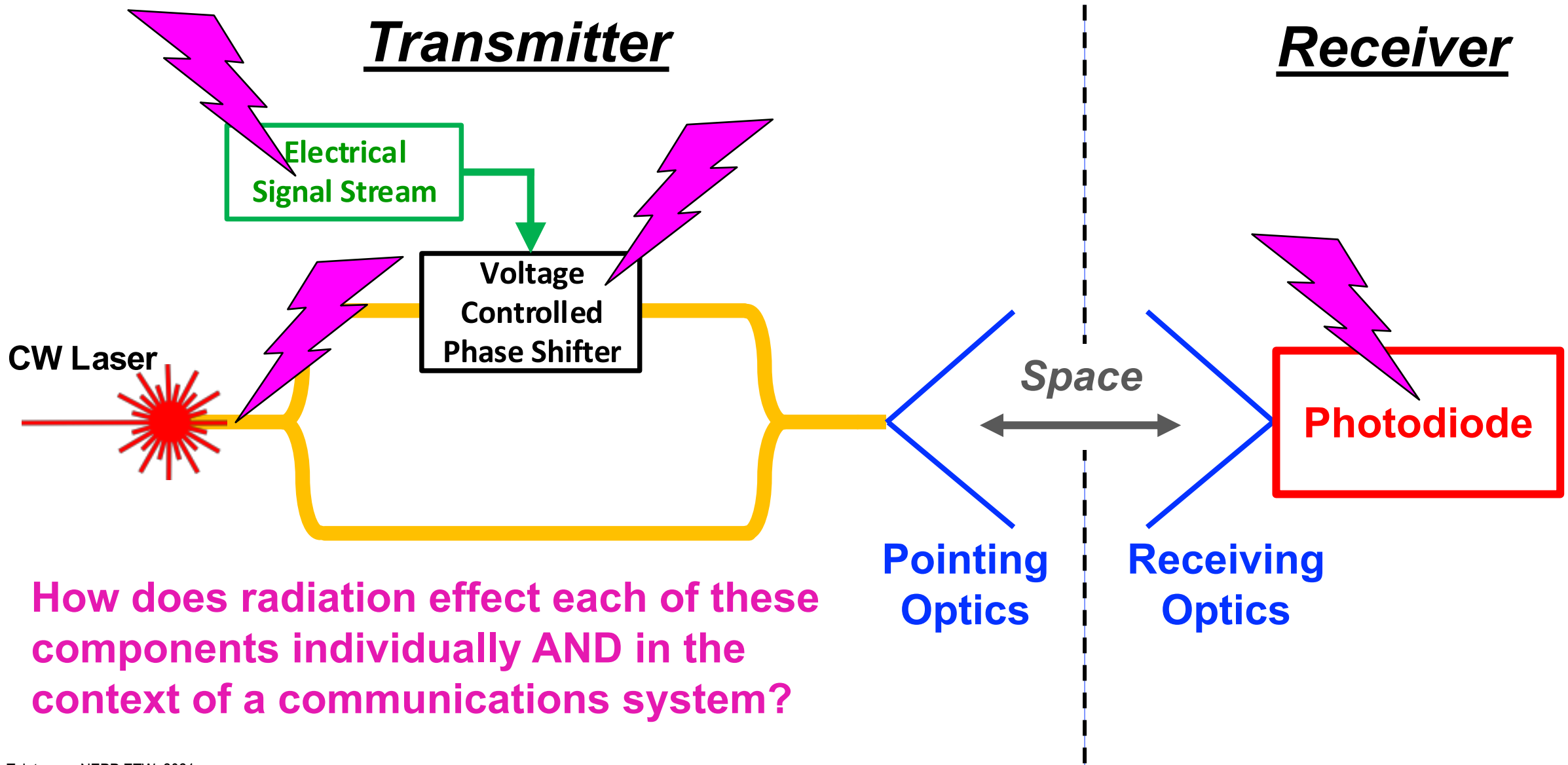


**Silicon Photonics:**  
**Integrated,**  
**Compact**

# Typical Integrated Si Photonic Transceiver



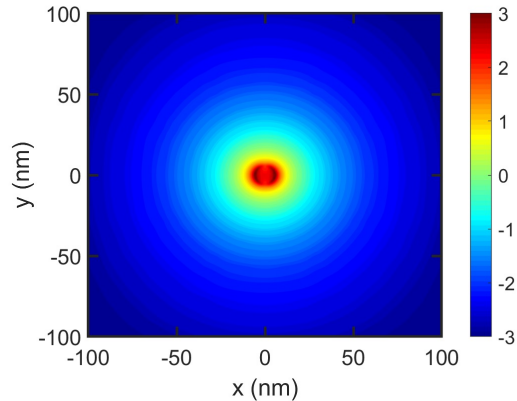
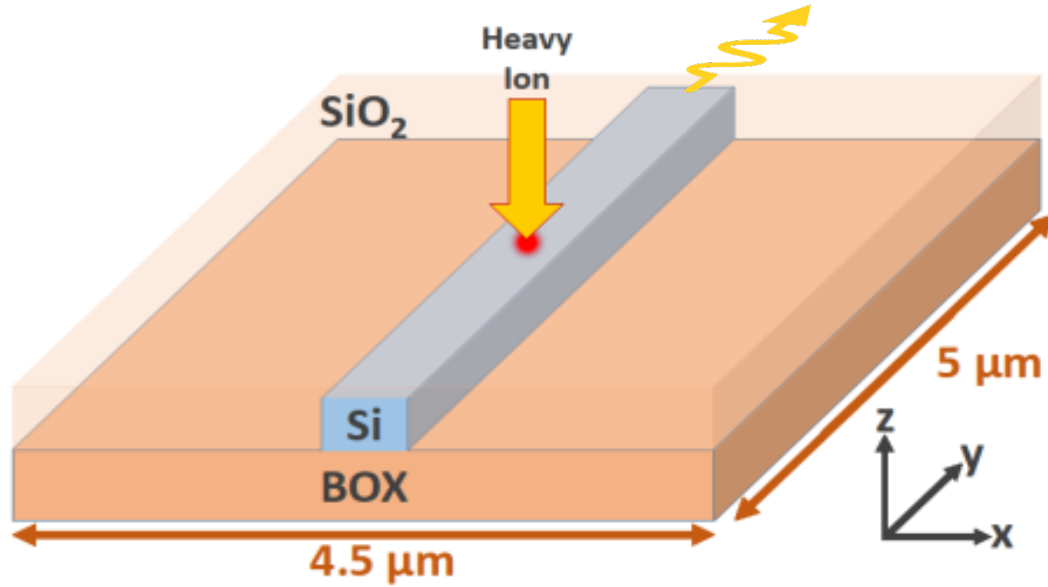
# Typical Integrated Si Photonic Transceiver



How does radiation effect each of these components individually AND in the context of a communications system?

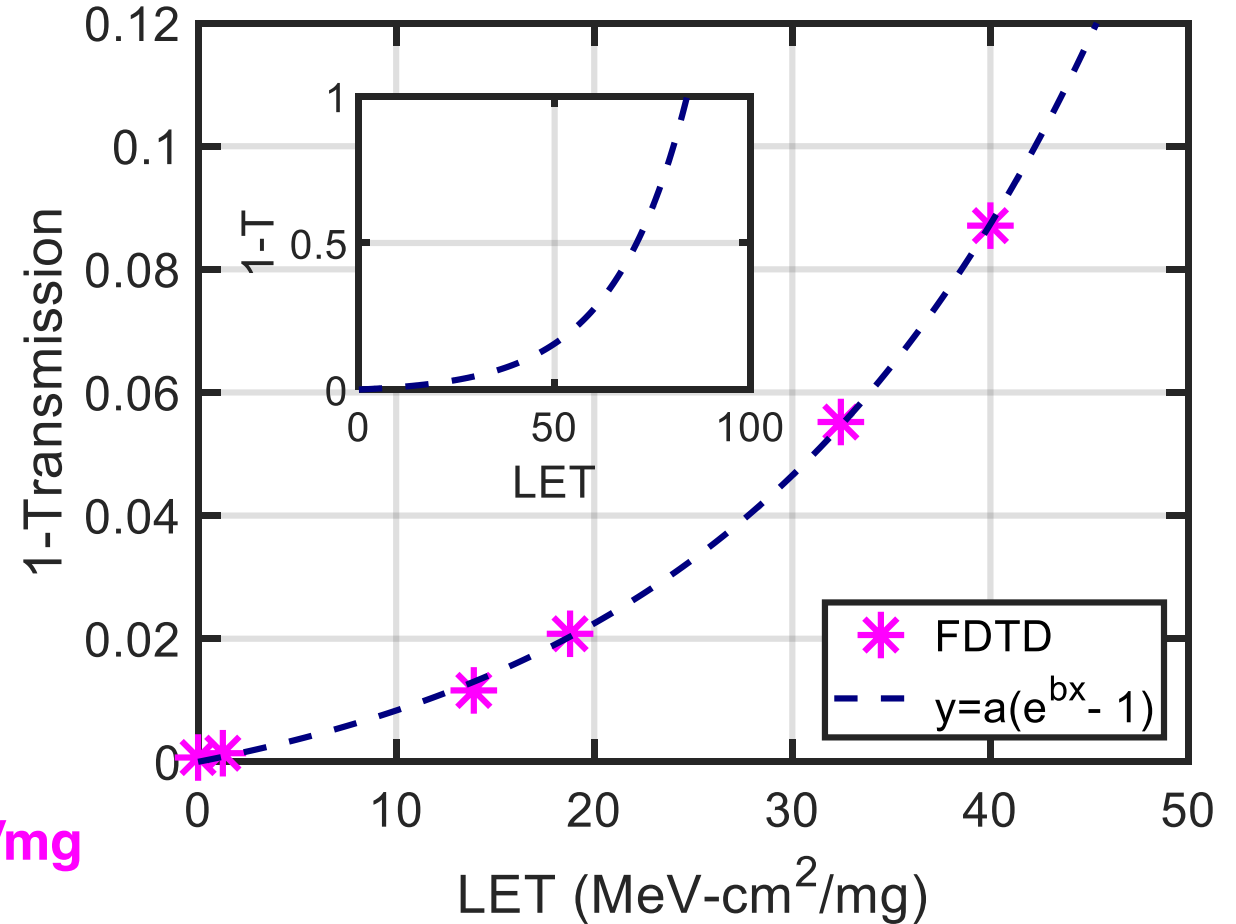
# Optical Single-Event Transients

# Heavy Ion Strikes in Photonic Waveguides



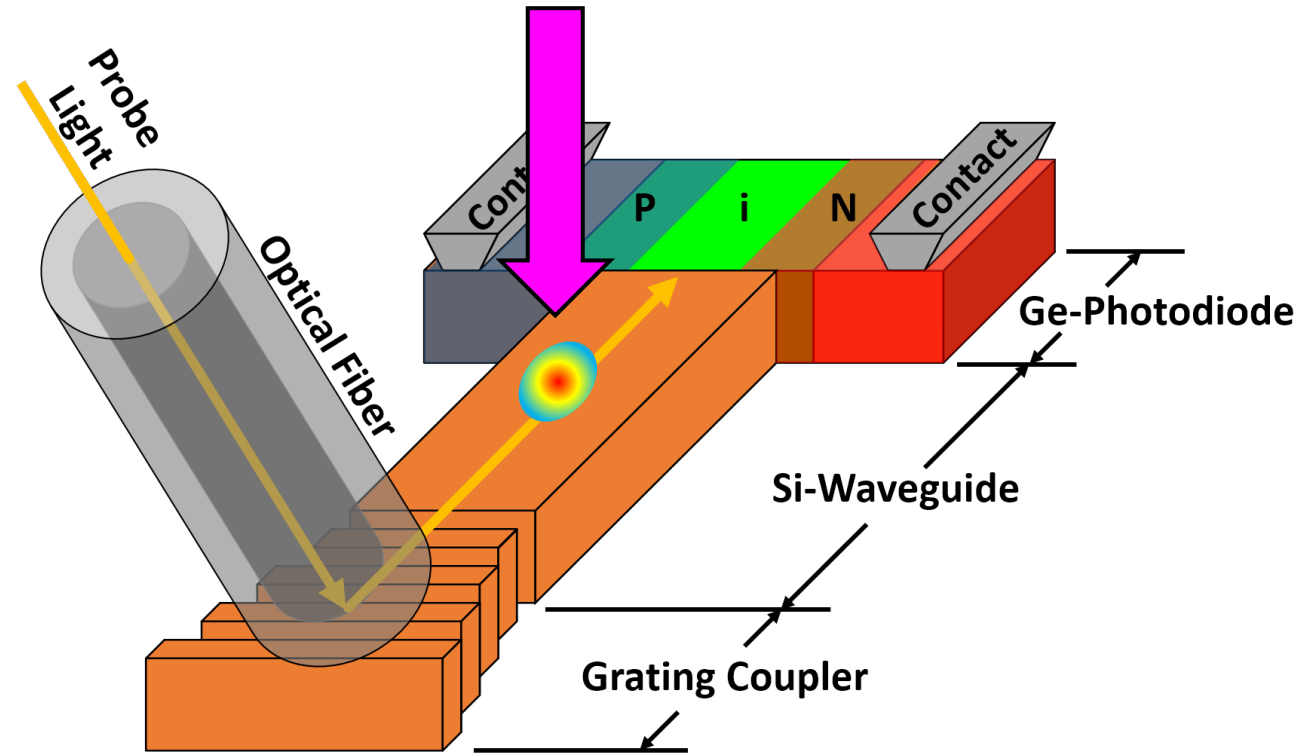
LET 13.9 MeV-cm<sup>2</sup>/mg

## Simulations



**Waveguides Can Be Sensitive to Heavy Ion Strikes!**

## Pulsed-Laser Strike



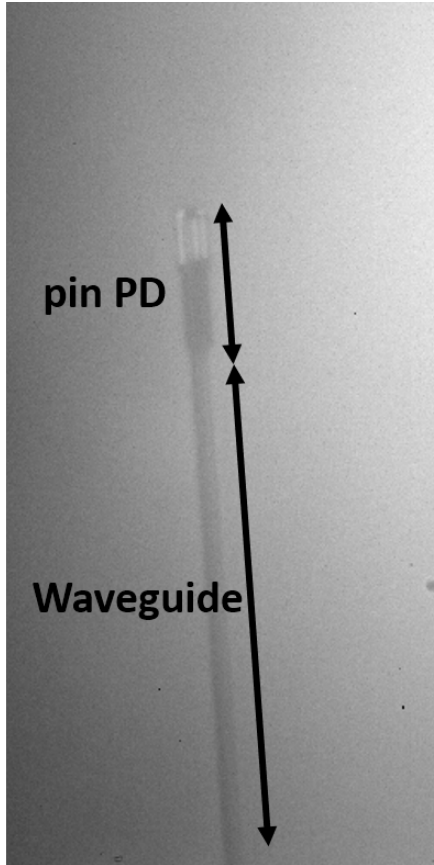
- **OSETs Fundamentally Different Than Electrical SETs**
  - SETs in electronics generate carriers that get collected by electrical terminals
  - OSETs in waveguides generate carriers that perturb the laser light going through the waveguide...  
**no charge collection!**
- **OSETs Cannot Be Measured Directly... Must Be Inferred Through Photodiode**



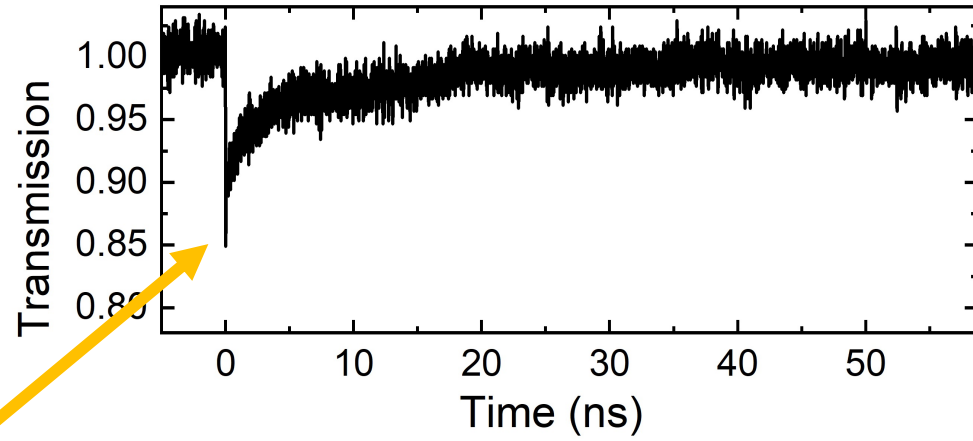
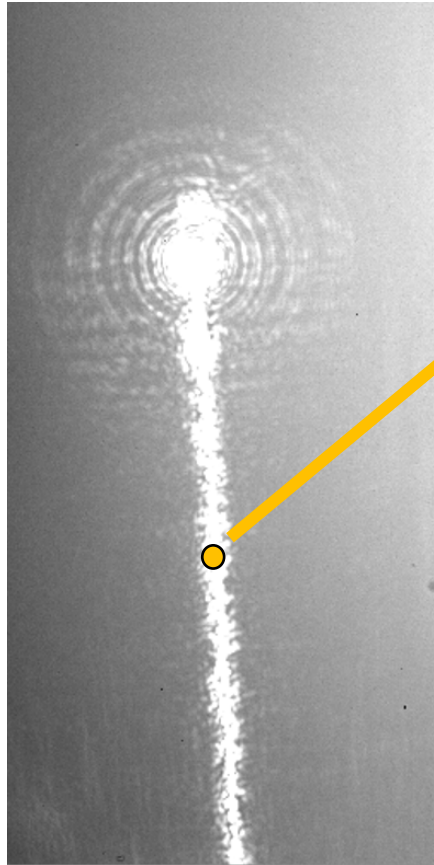
# Recent OSET Results

## Waveguide and PD

No Light



With Light



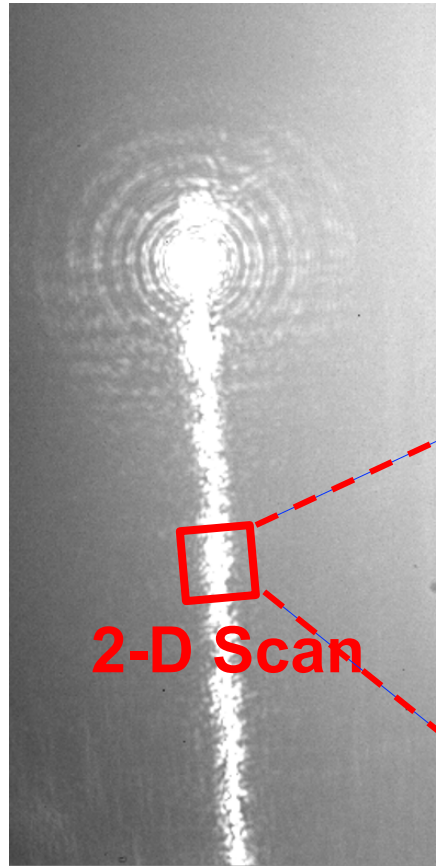
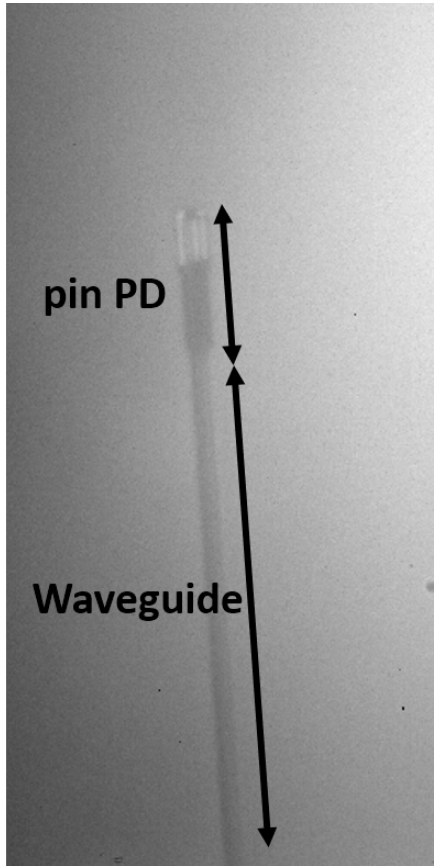
Example Transient

# Recent OSET Results

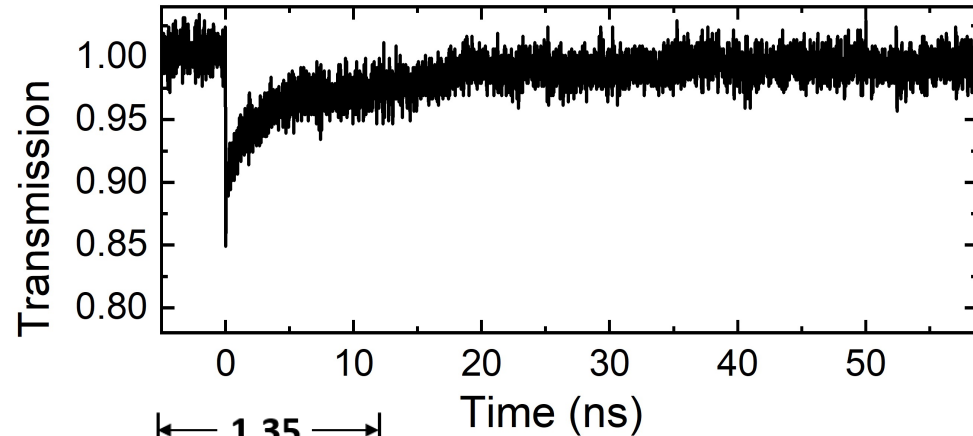
## Waveguide and PD

No Light

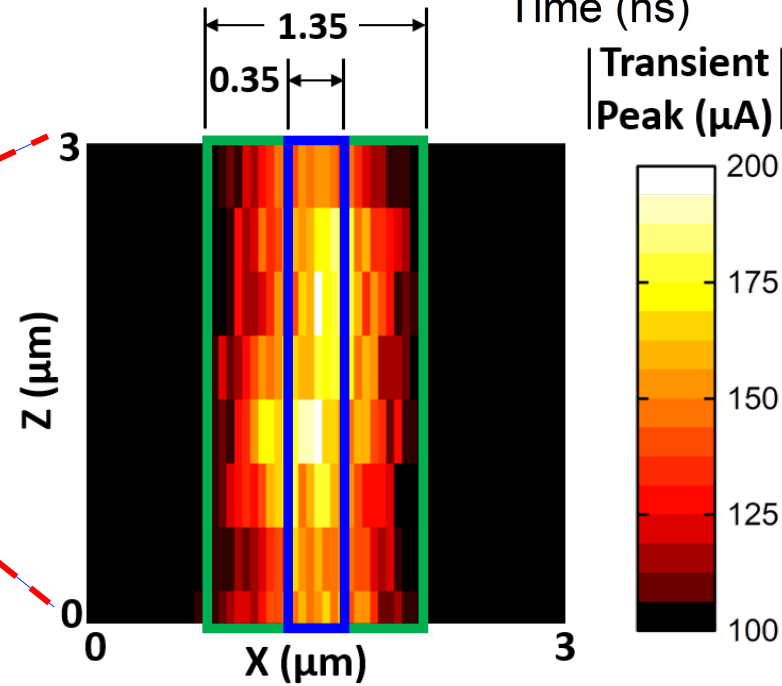
With Light



2-D Scan



Example Transient



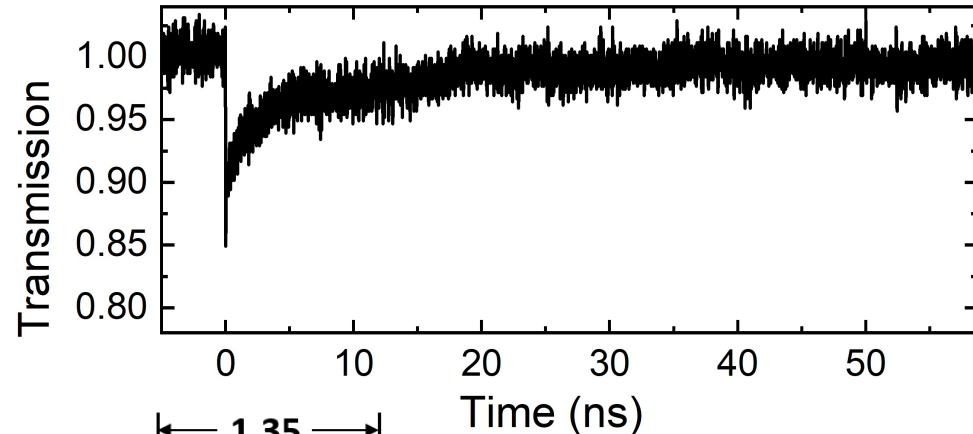
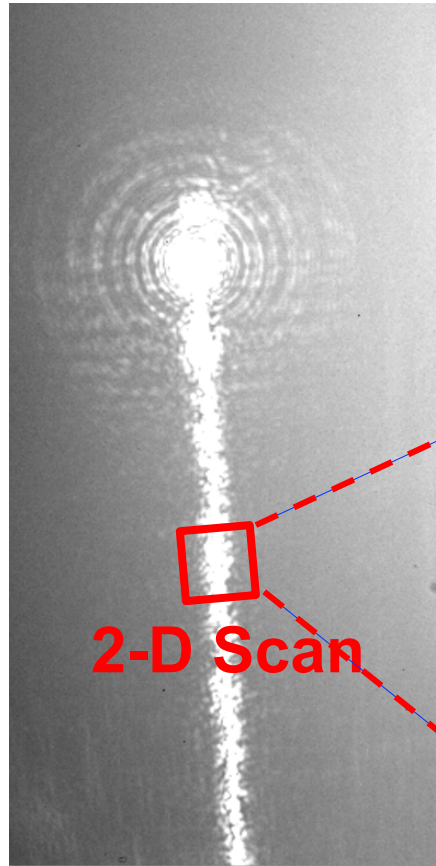
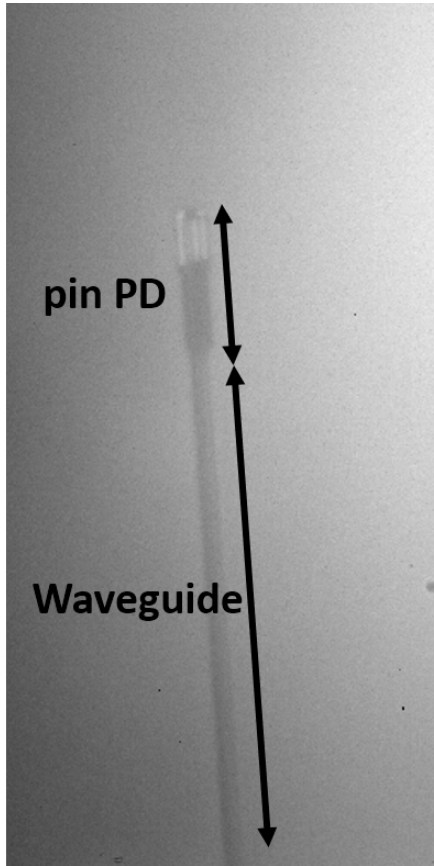
- Waveguide Width **0.35  $\mu\text{m}$**
- Scanning Spot Size **1  $\mu\text{m}$**
- Detected Transients **1.35  $\mu\text{m}$**

# Recent OSET Results

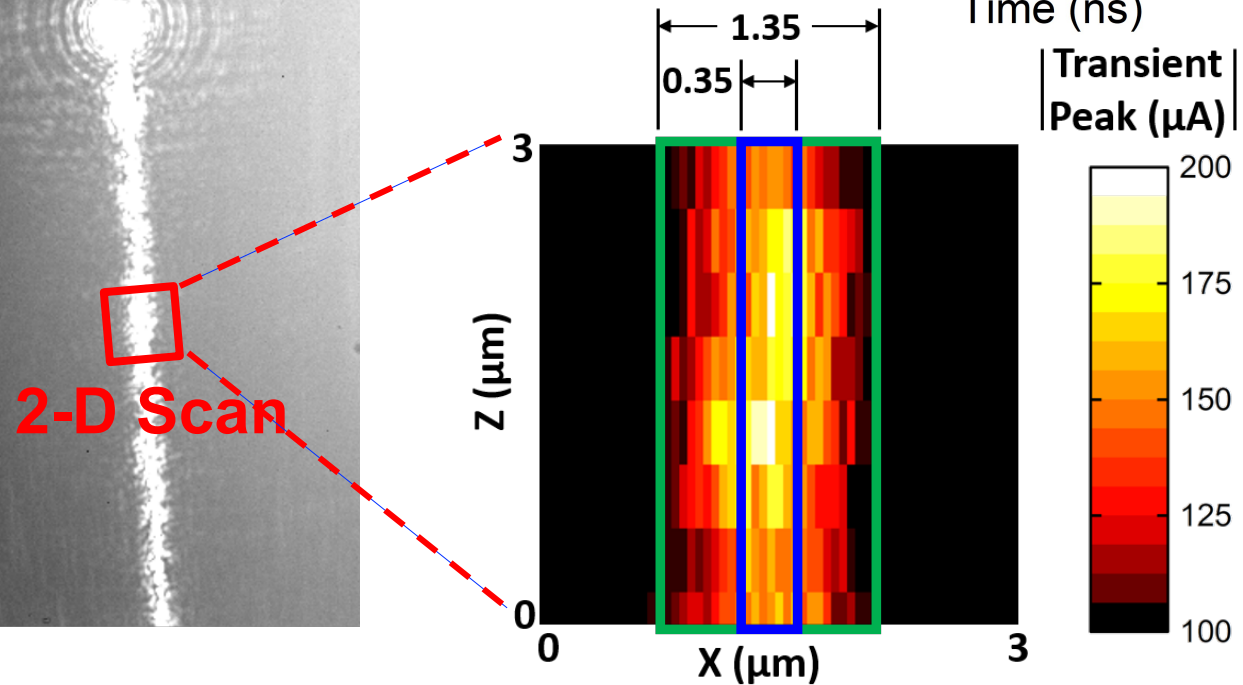
## Waveguide and PD

No Light

With Light



Example Transient



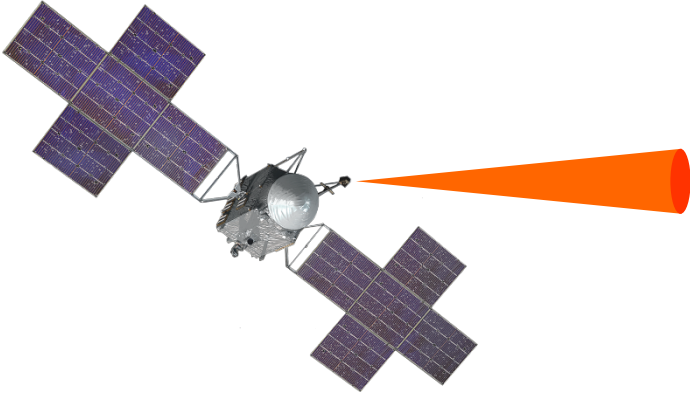
- Waveguide Width **0.35  $\mu\text{m}$**
- Scanning Spot Size **1  $\mu\text{m}$**
- Detected Transients **1.35  $\mu\text{m}$**

➡ Confirmed OSETs Can Perturb Optical Signal

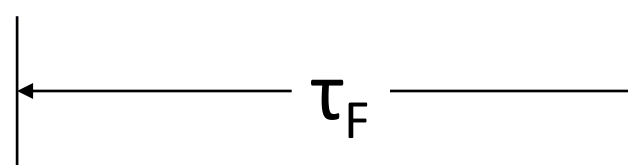
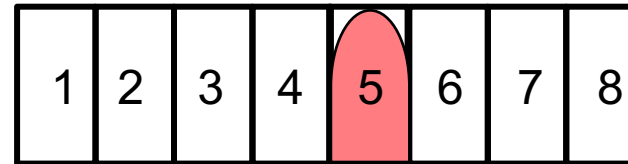
# Optical Single-Event Transients Within Communications System

# Pulse-Position Modulation

- Pulse-Position Modulation (PPM)
- Proposed Modulation Scheme for Space



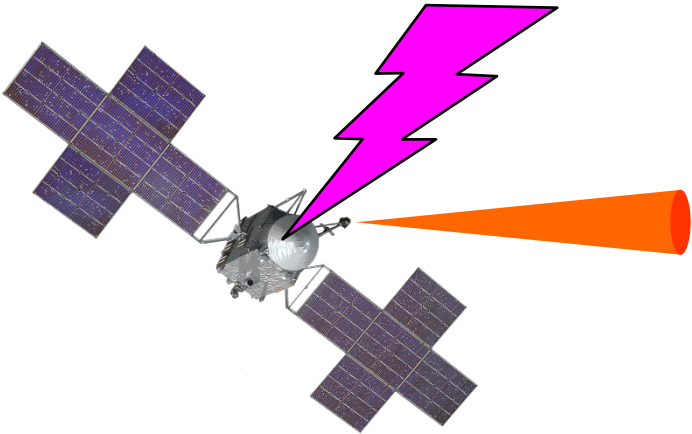
Example – 8<sup>th</sup> Order PPM



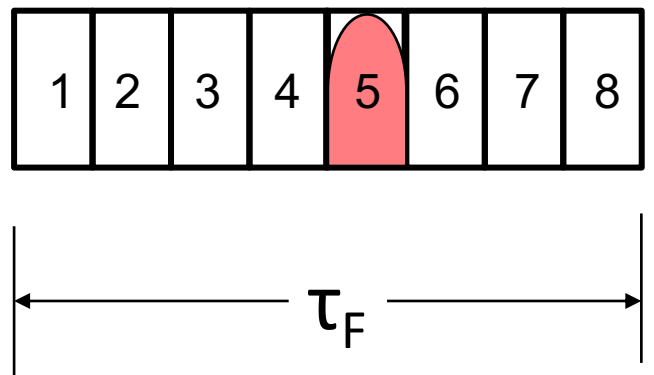
<u>Bit Slot</u>	<u>Bit Pattern</u>
1	000
2	001
3	010
4	011
5	100
6	101
7	110
8	111

# Pulse-Position Modulation

- Pulse-Position Modulation (PPM)
- Proposed Modulation Scheme for Space



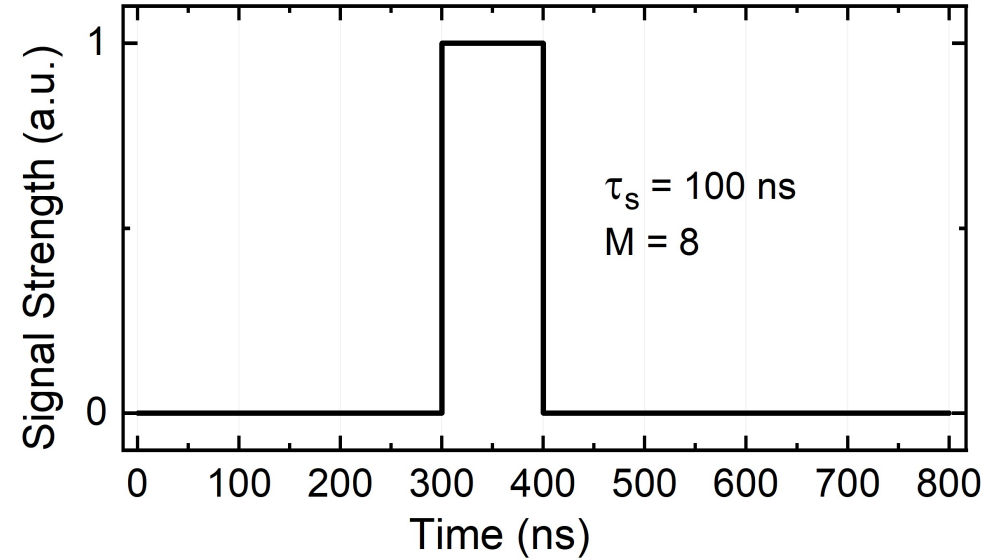
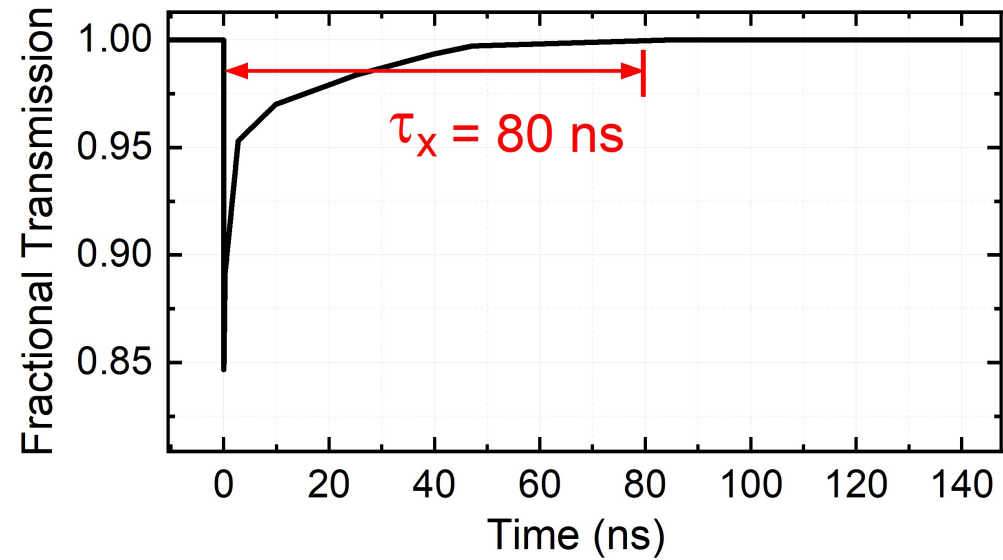
Example – 8<sup>th</sup> Order PPM



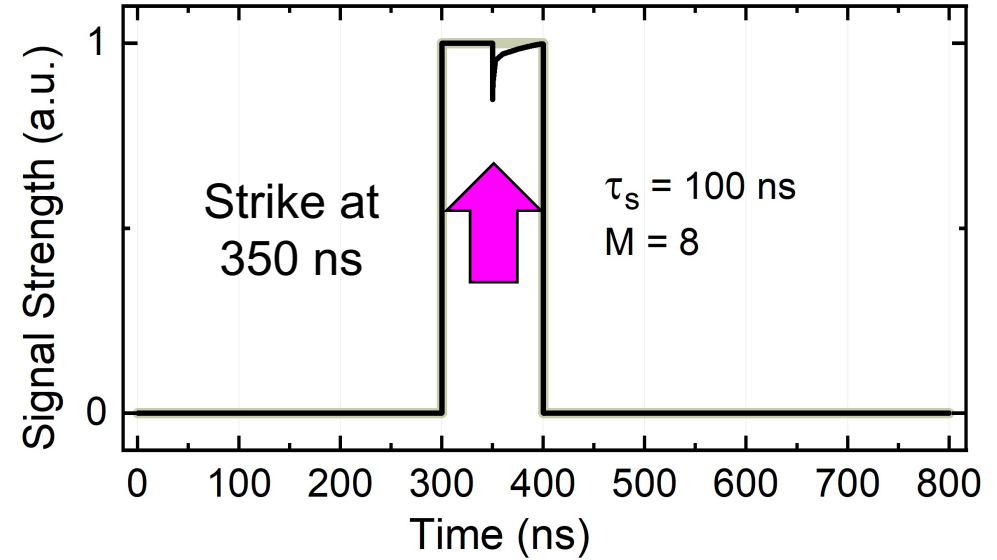
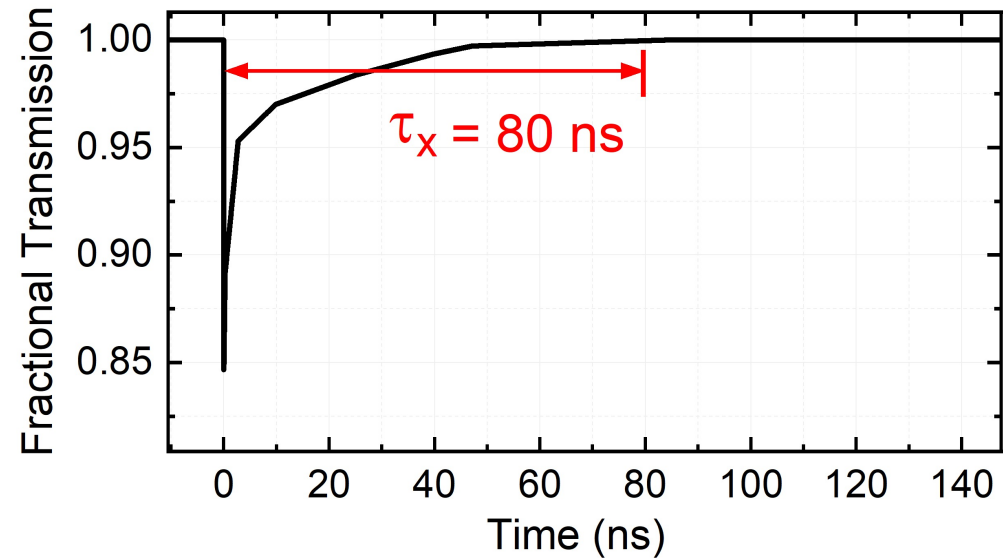
<u>Bit Slot</u>	<u>Bit Pattern</u>
1	000
2	001
3	010
4	011
5	100
6	101
7	110
8	111

**How Might a Heavy Ion Strike Affect PPM Communications Systems?**

# OSET Impact on Optical Pulses

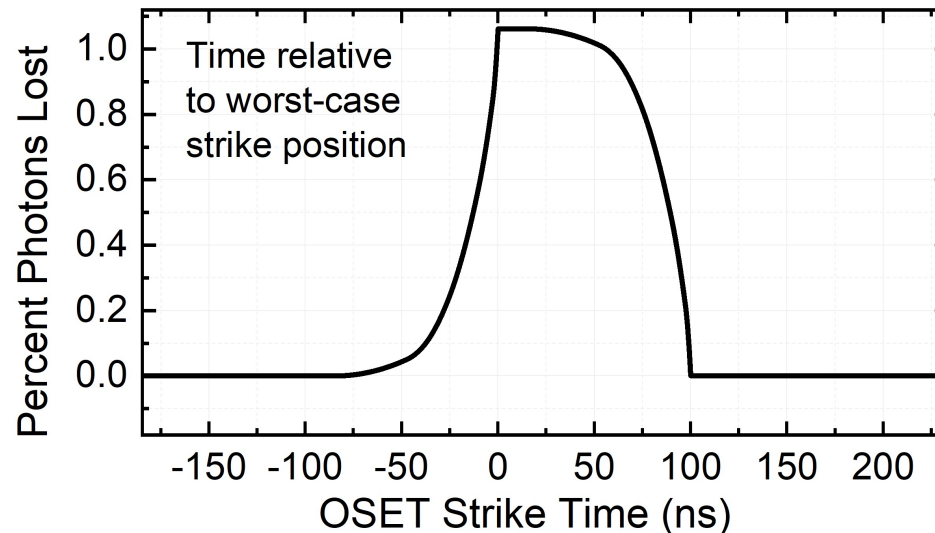
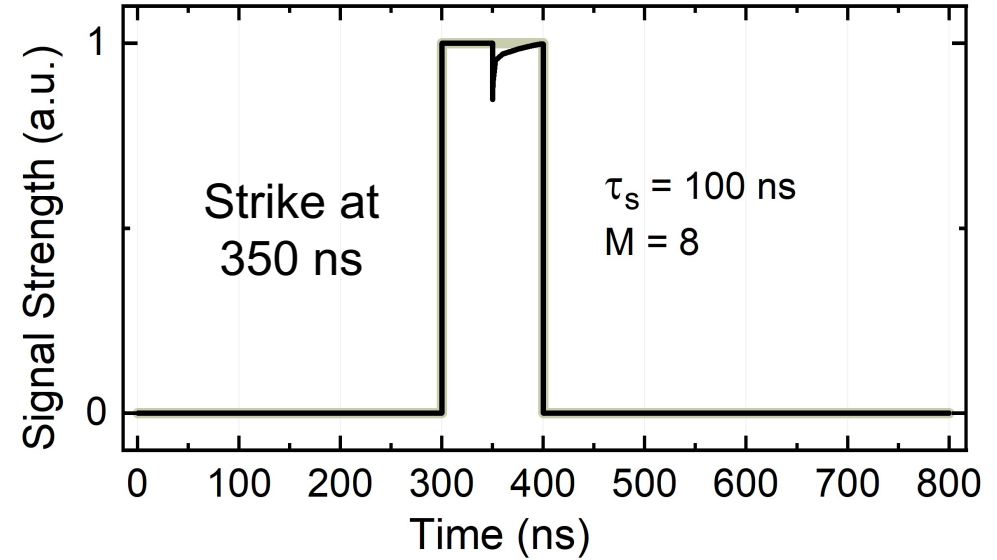
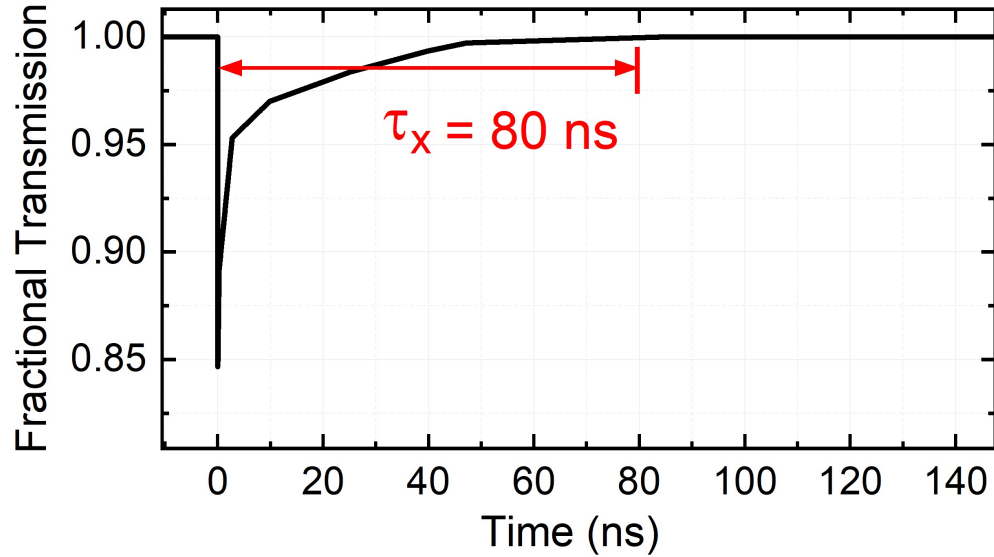


# OSET Impact on Optical Pulses



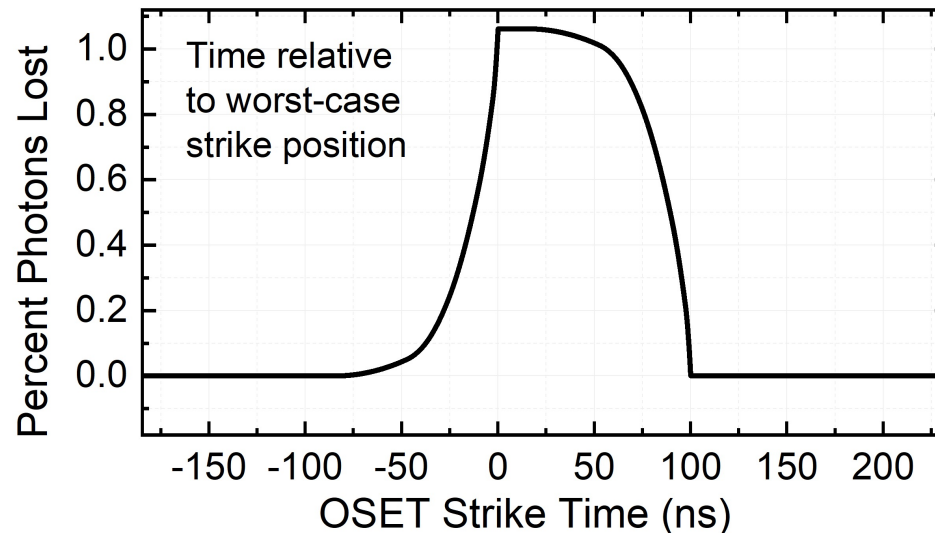
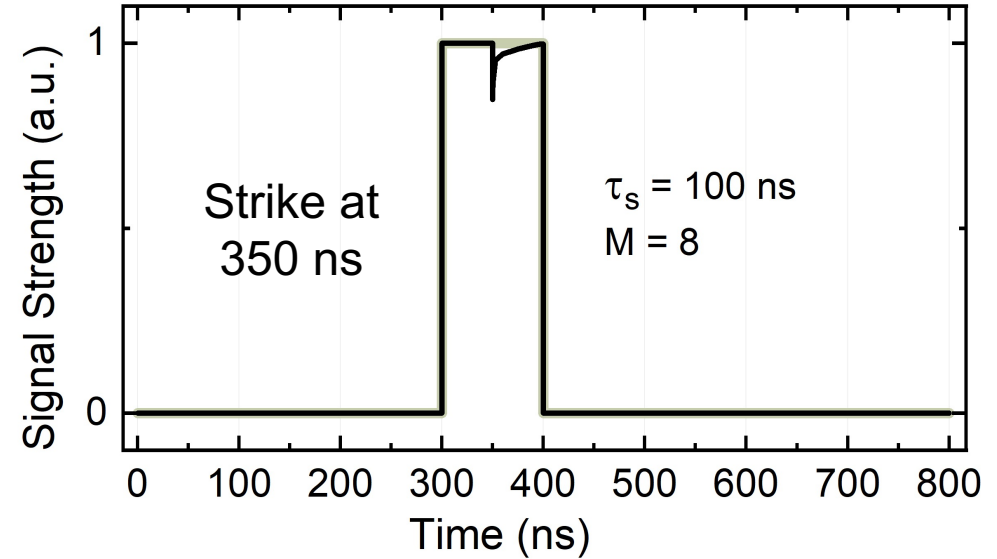
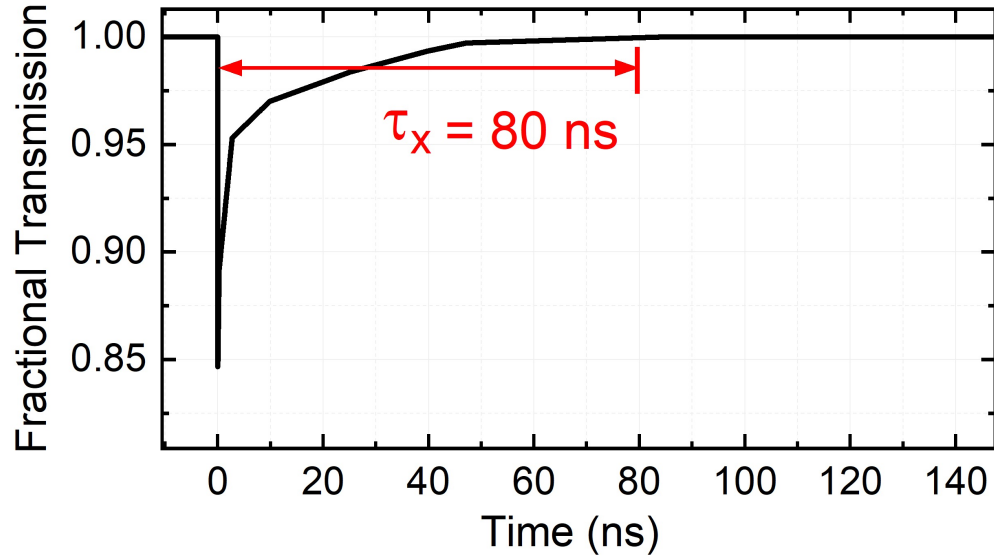


# OSET Impact on Optical Pulses



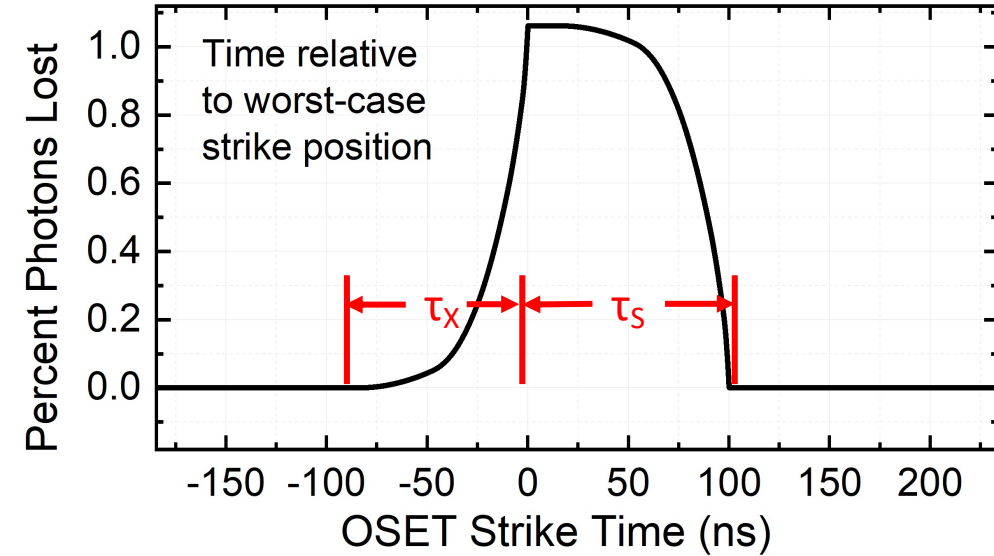
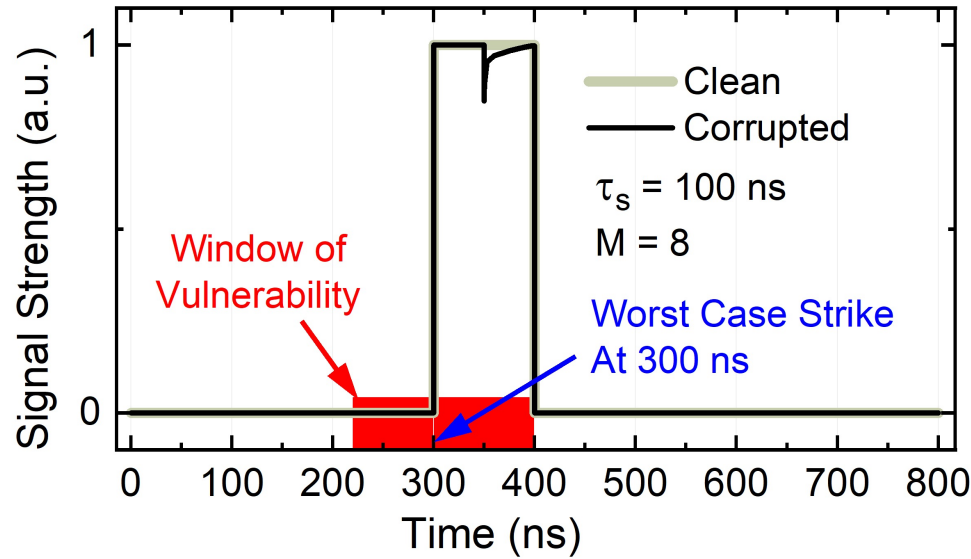
Monte Carlo Simulation  
With 1000 Strike  
Locations

# OSET Impact on Optical Pulses



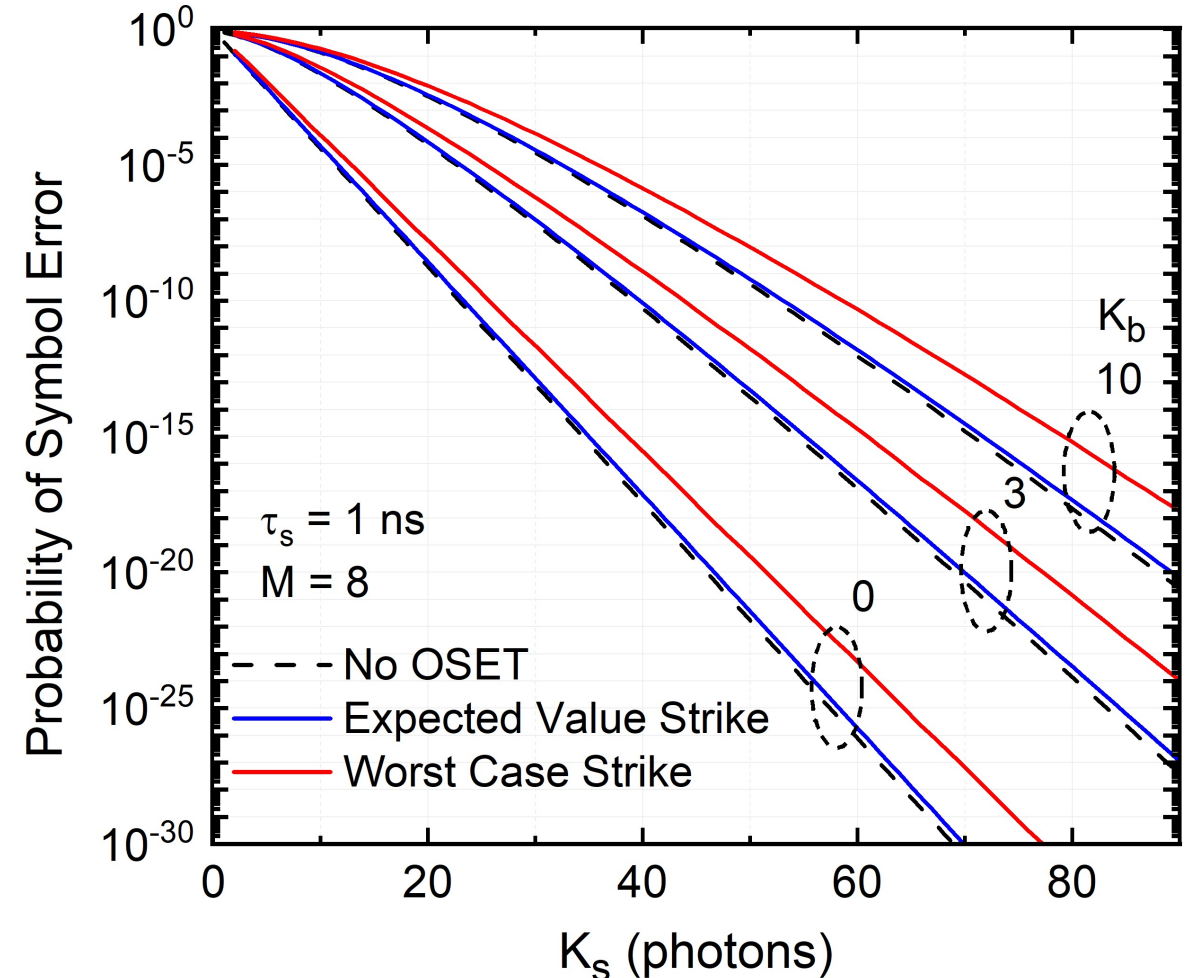
Identical Result with Cross-Correlation between OSET and PPM Signal

Monte Carlo Simulation With 1000 Strike Locations

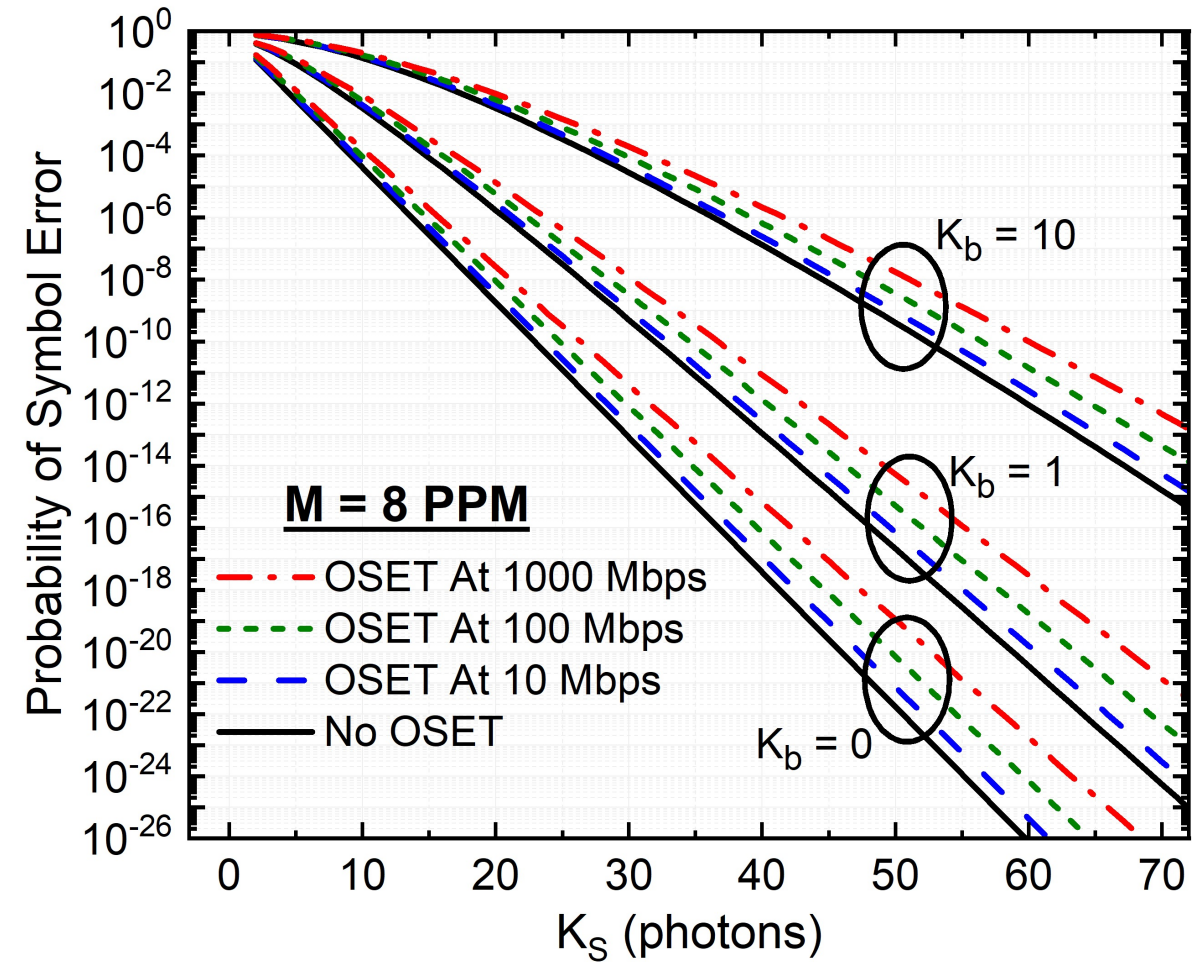


- **Worst-Case Strike Occurs at Start of Pulse**
- **Window of Vulnerability is Time Where Signal Can Be Corrupted**
  - transient duration + signal duration ( $\tau_x + \tau_s$ )
- **Result Applies to Any Arbitrary PPM System**

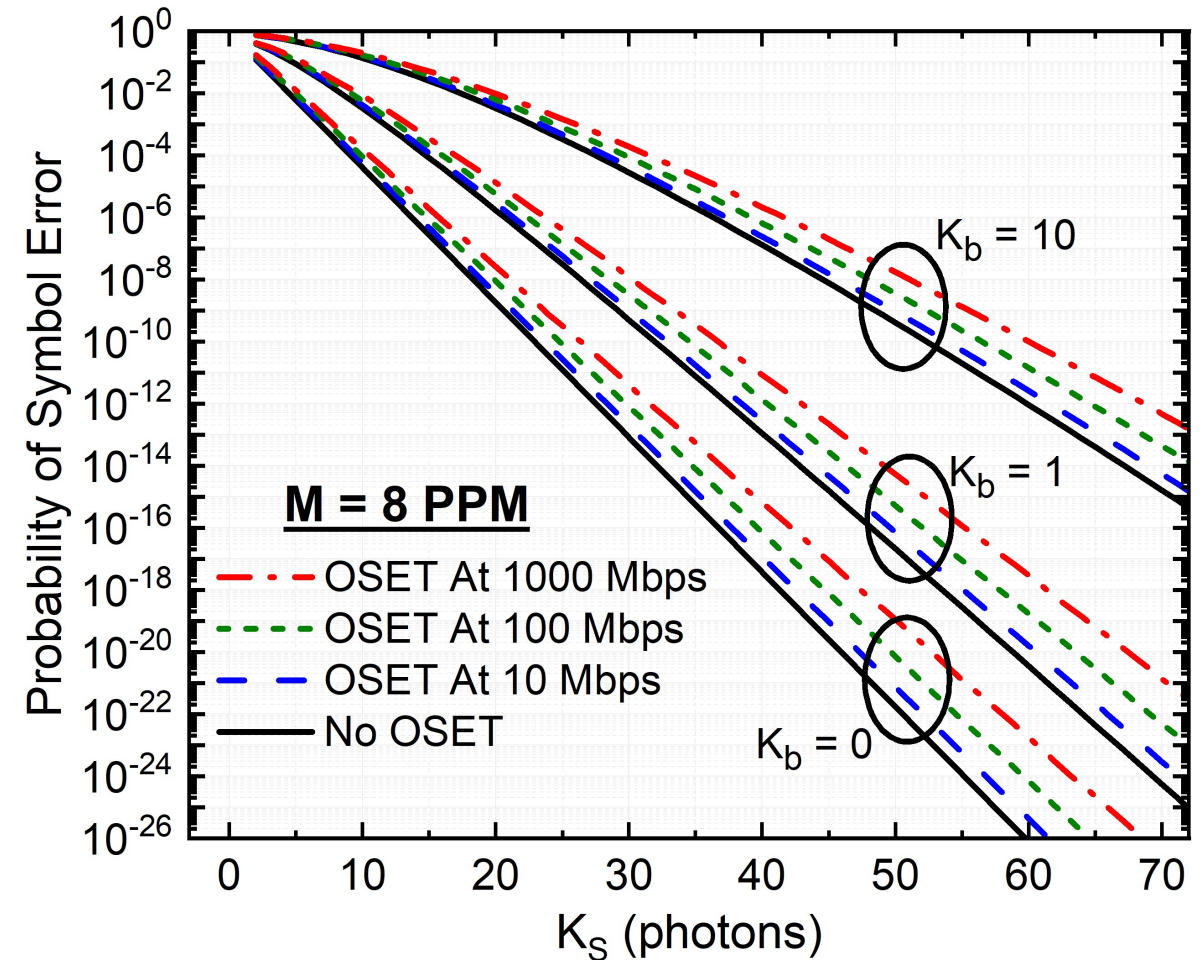
- **PPM Channel Modeled by Poisson Distribution**
  - expected signal photons ( $K_s$ )
- **Background Light Increases Probability of Symbol Error**
  - number of background photons is  $K_b$
  - $K_b = 0$  is quantum limited case
- **OSETs Can Significantly Increase Probability of Symbol Error**



- $M^{\text{th}}$ -Order PPM Symbol Contains  $\log_2(M)$  Bits
- Bitrate is Dependent on Order and Pulse Width ( $\tau_s$ )
- Probability of Symbol Error is Dependent on Target Bitrate

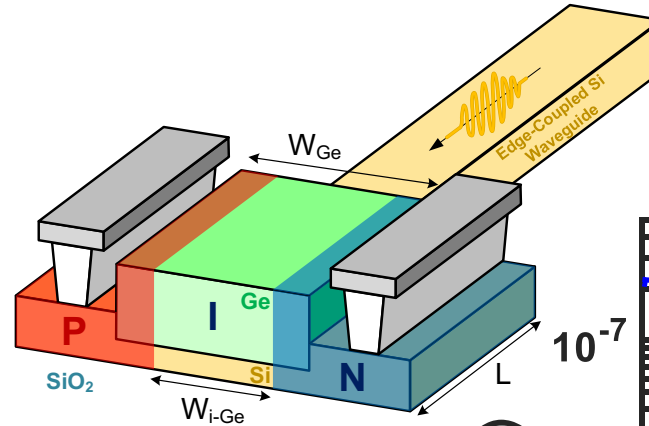
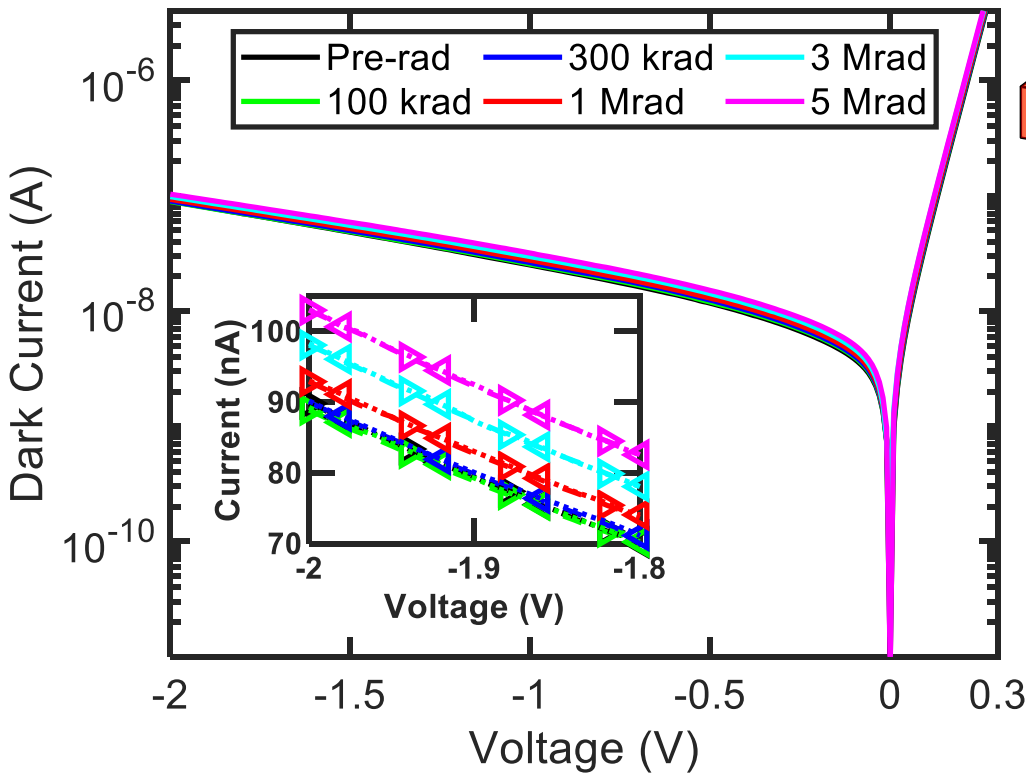


- **M<sup>th</sup> -Order PPM Symbol Contains  $\log_2(M)$  Bits**
- **Bitrate is Dependent on Order and Pulse Width ( $\tau_s$ )**
- **Probability of Symbol Error is Dependent on Target Bitrate**
- **Space System Designers Can Optimize Communications Systems for SEE Hardness**

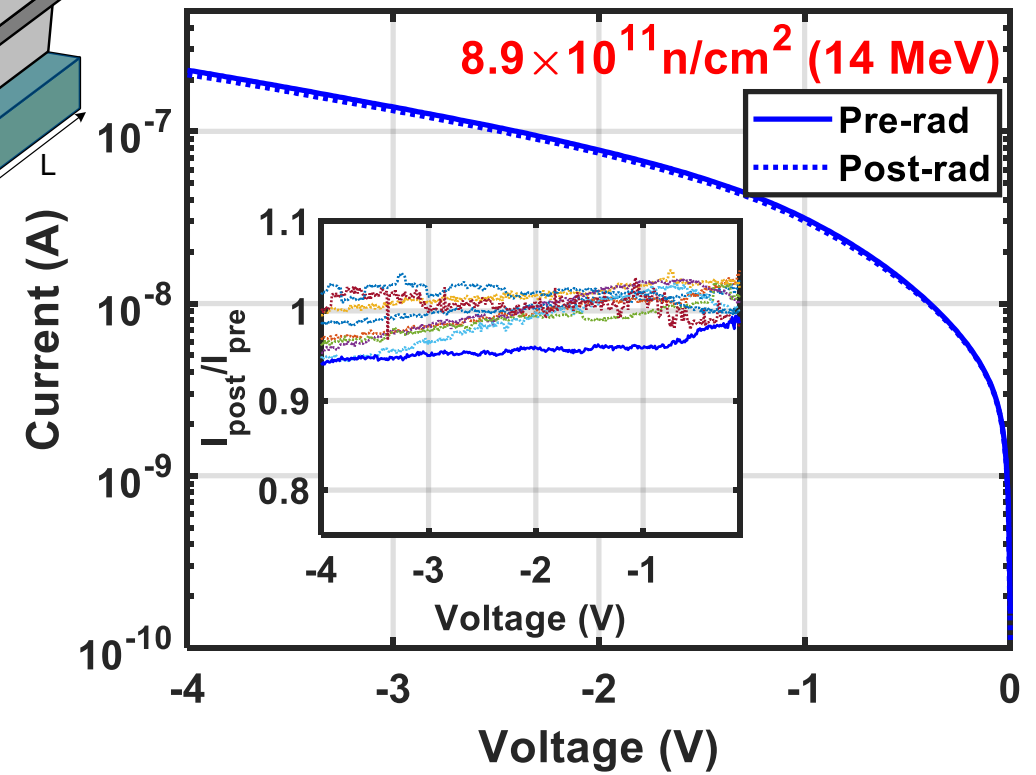


# Other Radiation Effects Efforts

## TID (X-ray)



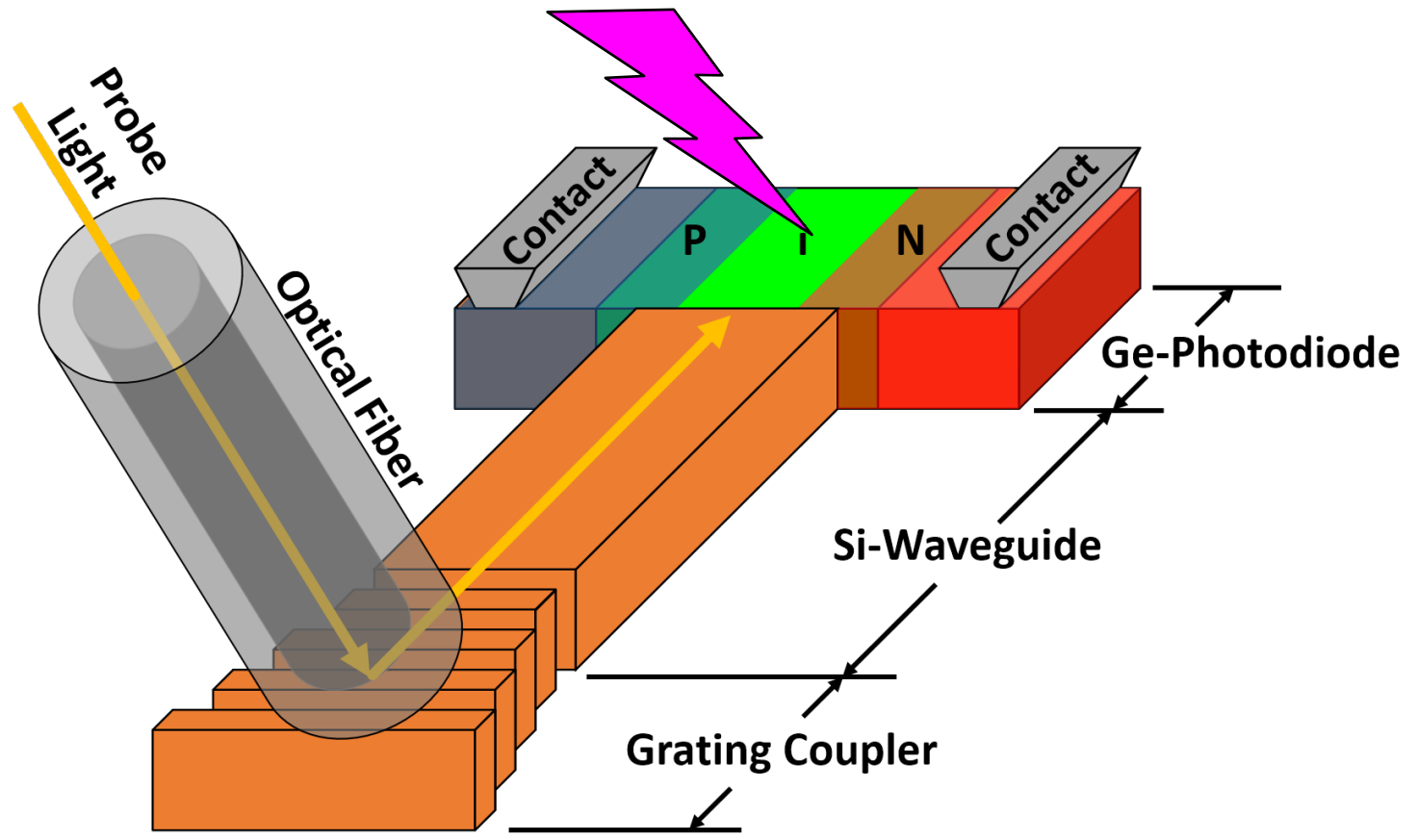
## DD (neutron)



**Ge Photodetector Both TID and DD Radiation Tolerant!**

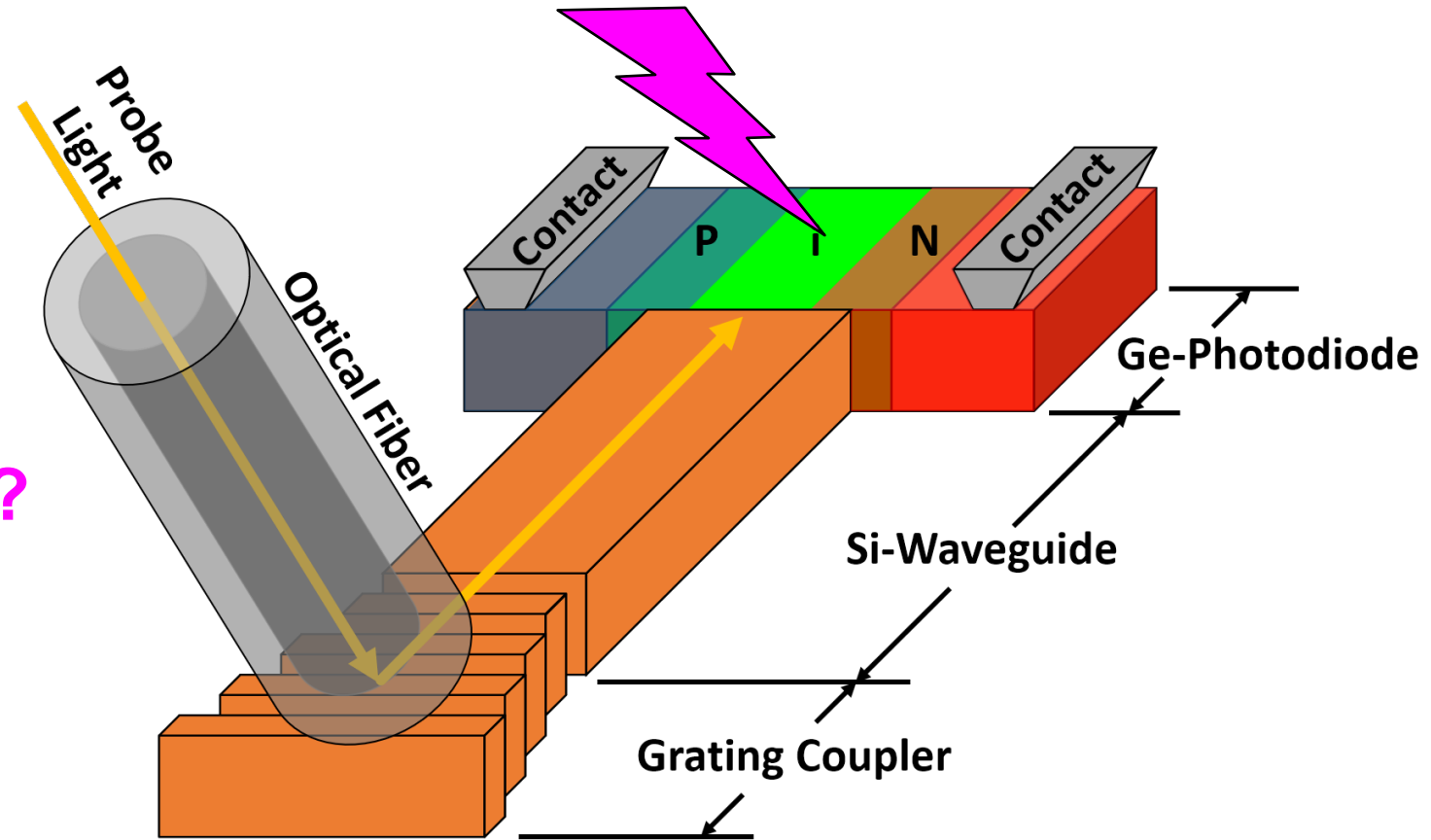


- **Experimental Method**
  - similar to OSET
  - use heavy-ions
  - laser testing is too complex



- **Experimental Method**
  - similar to OSET
  - use heavy-ions
  - laser testing is too complex

Do SETs within the photodiode corrupt the conversion operation? How?

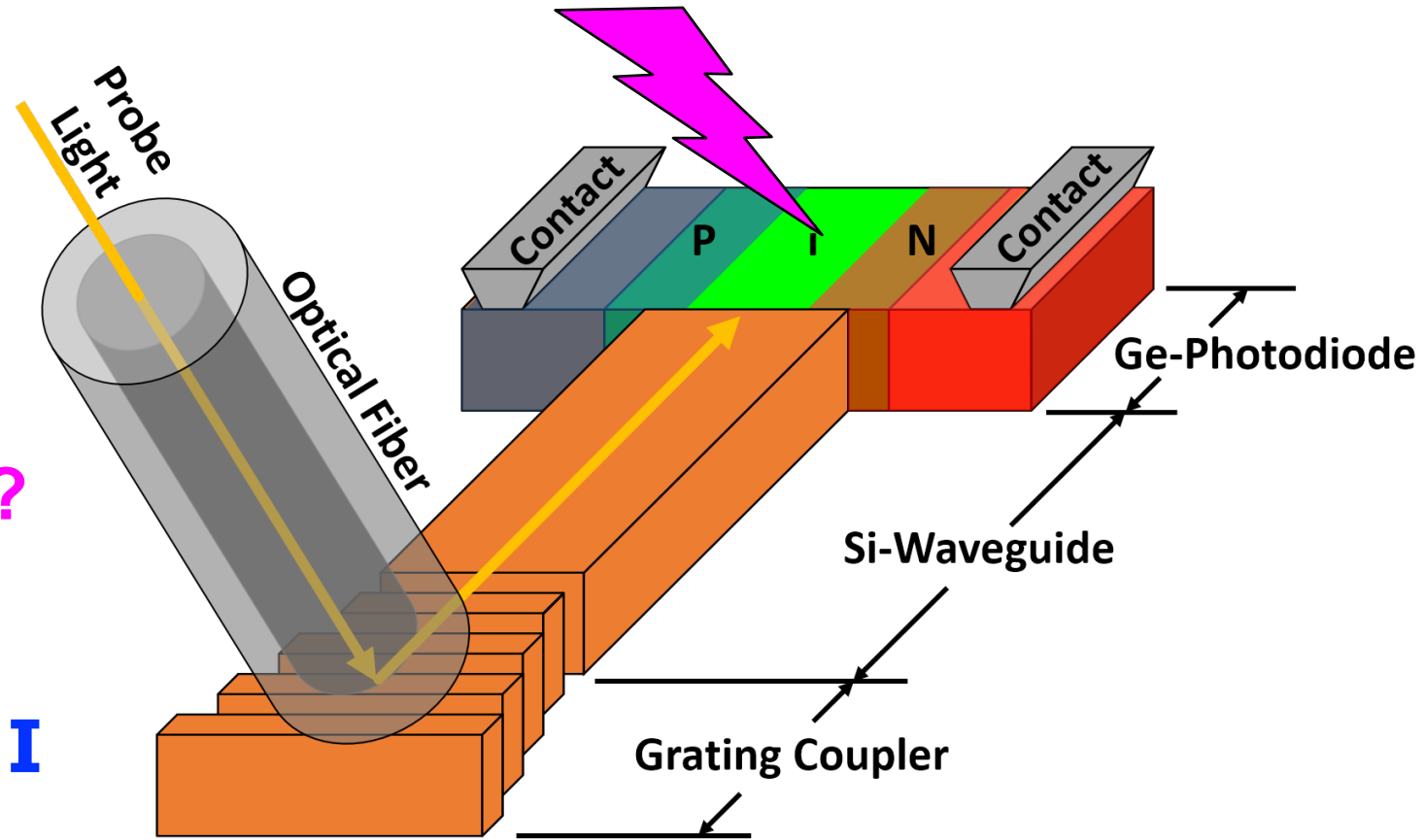


# Photodiode SET Response

- **Experimental Method**
  - similar to OSET
  - use heavy-ions
  - laser testing is too complex

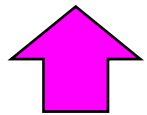
Do SETs within the photodiode corrupt the conversion operation? How?

Come See Me at NSREC  
Next Month, Poster Session I  
*(late news)*

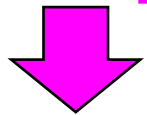


# Laser/Ion Comparison of Induced OSETs

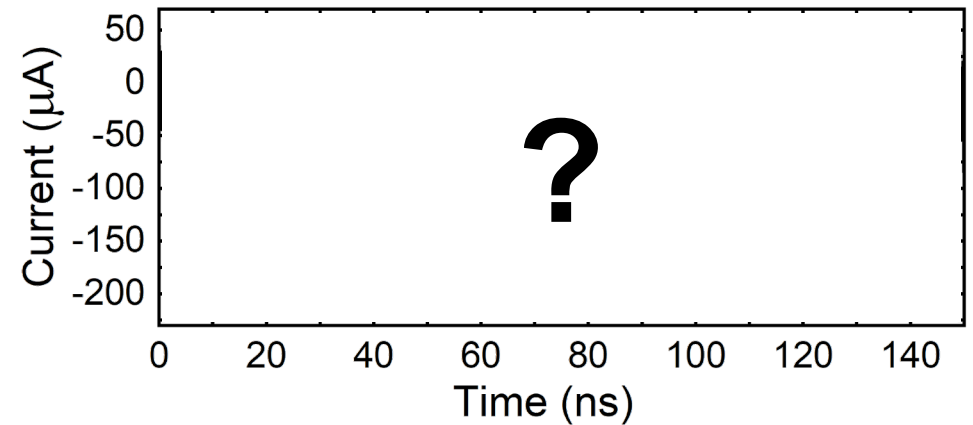
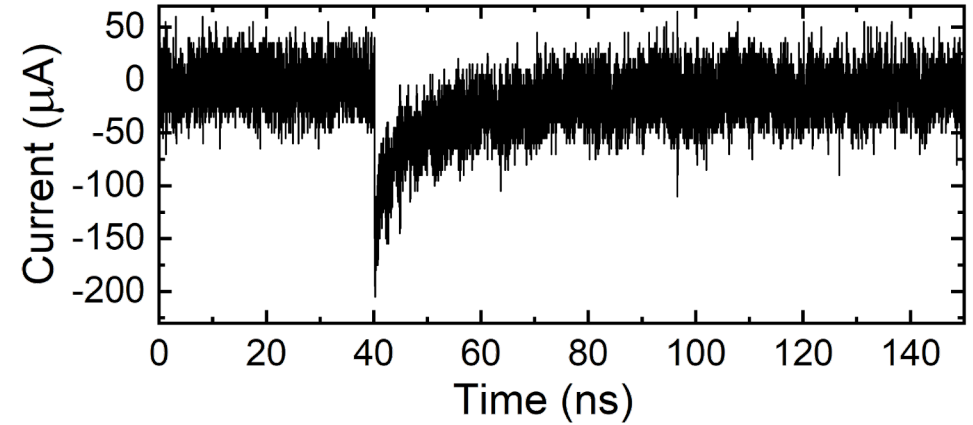
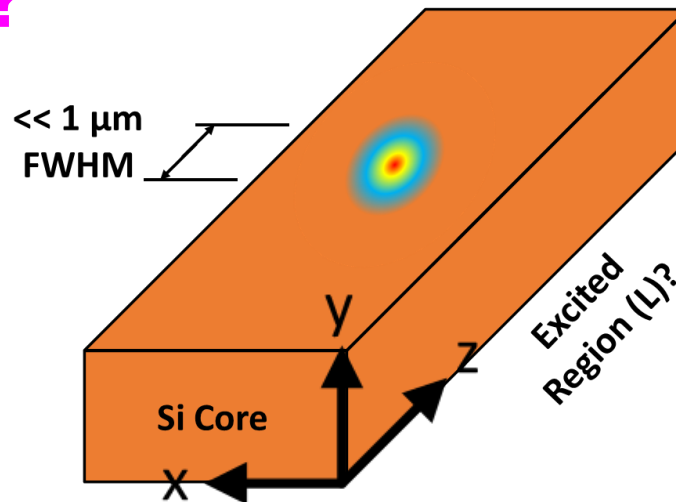
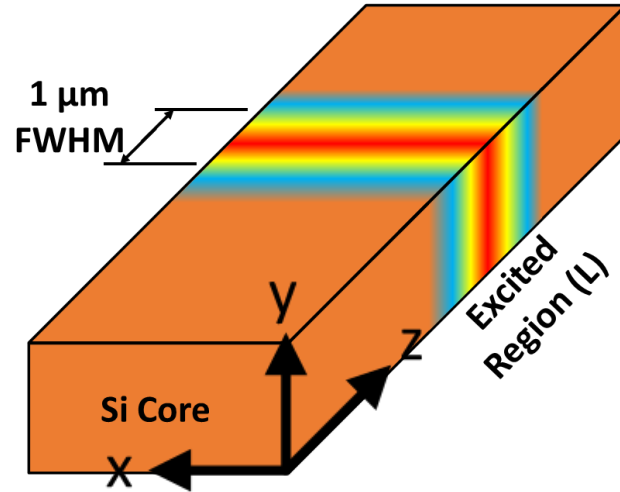
Laser-Induced OSETs



How do these two compare?



Ion-Induced OSETs





## Integrated Si-Based Photonics is Exciting for Space Systems

**BUT ...**

### Much Remains to be Done to Understand Radiation Effects

- OSETs in nm-scale waveguides have been predicted and observed, and are a potential concern for space communications systems (specifically PPM-based)
- Ge photodetectors are TID and DD Hard, as built, BUT, *potentially* sensitive to SETs (NSREC 2021)
- Experiments in collaboration with JPL are on-going to identify difference between laser- and ion-induced OSETs

**Exciting Stuff, But Much to Be Done!**