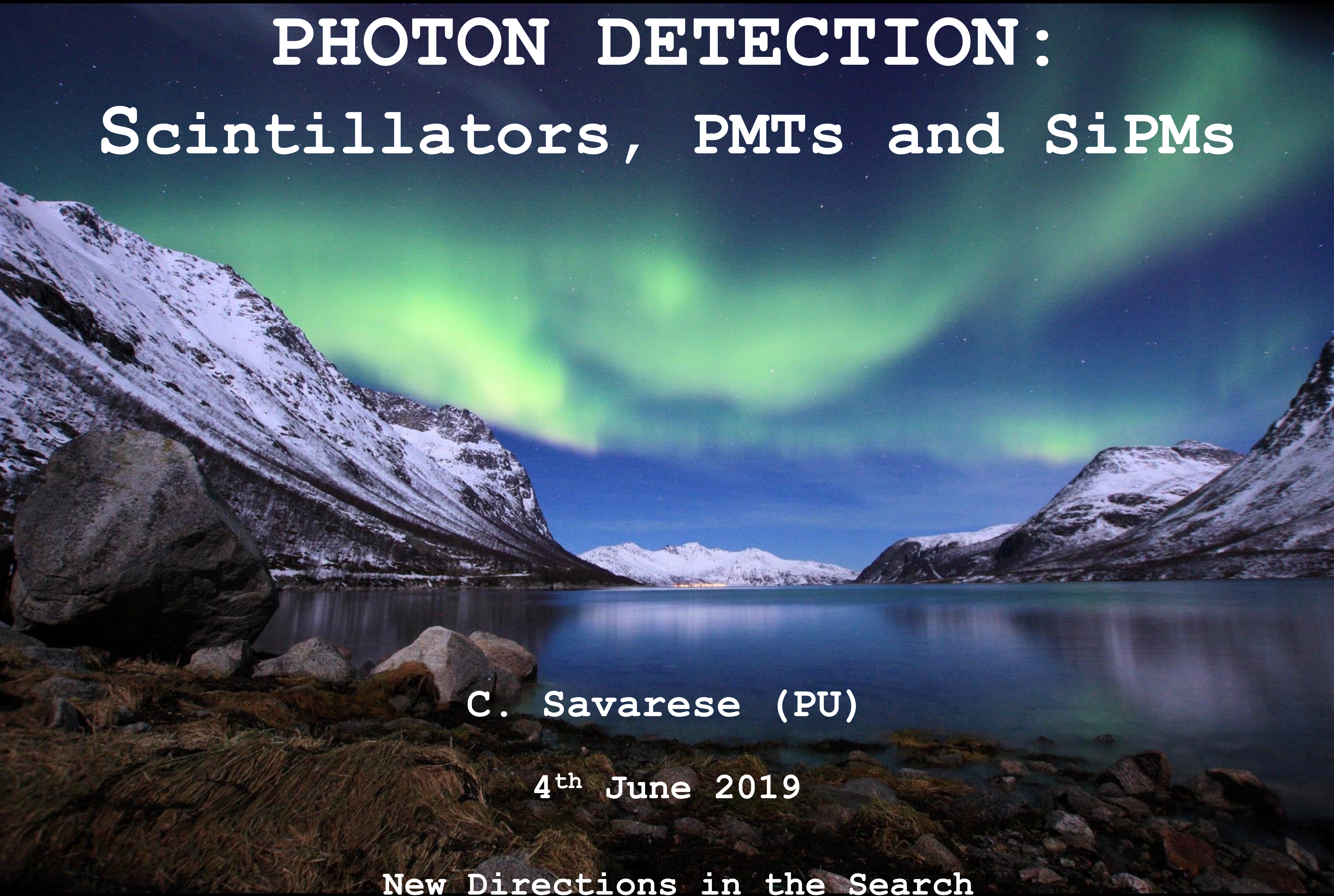


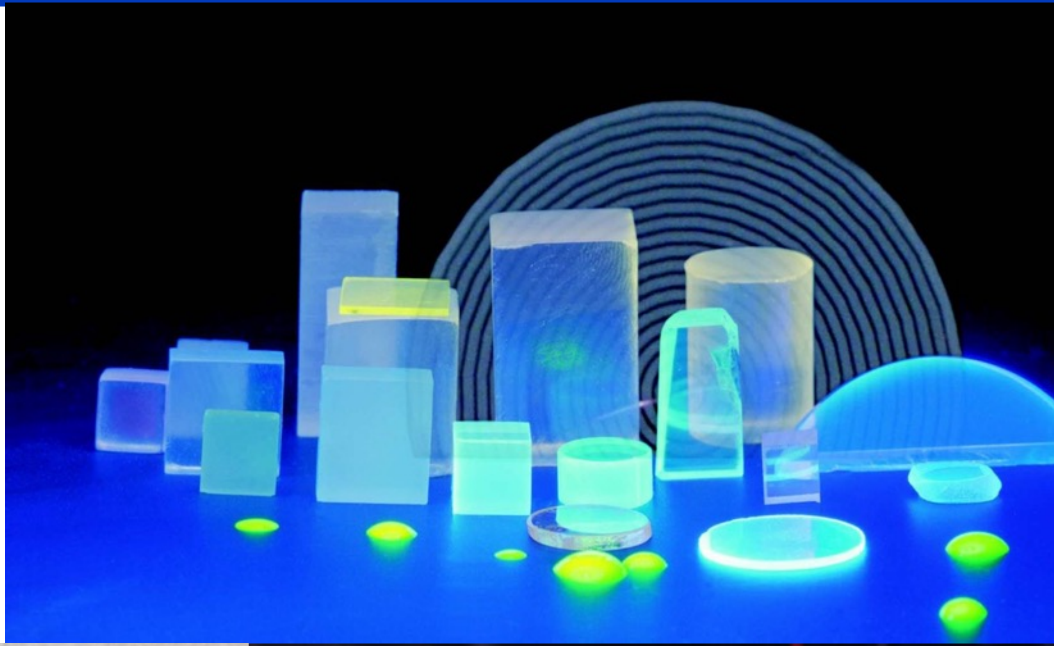
PHOTON DETECTION: Scintillators, PMTs and SiPMs

C. Savarese (PU)

4^{th} June 2019

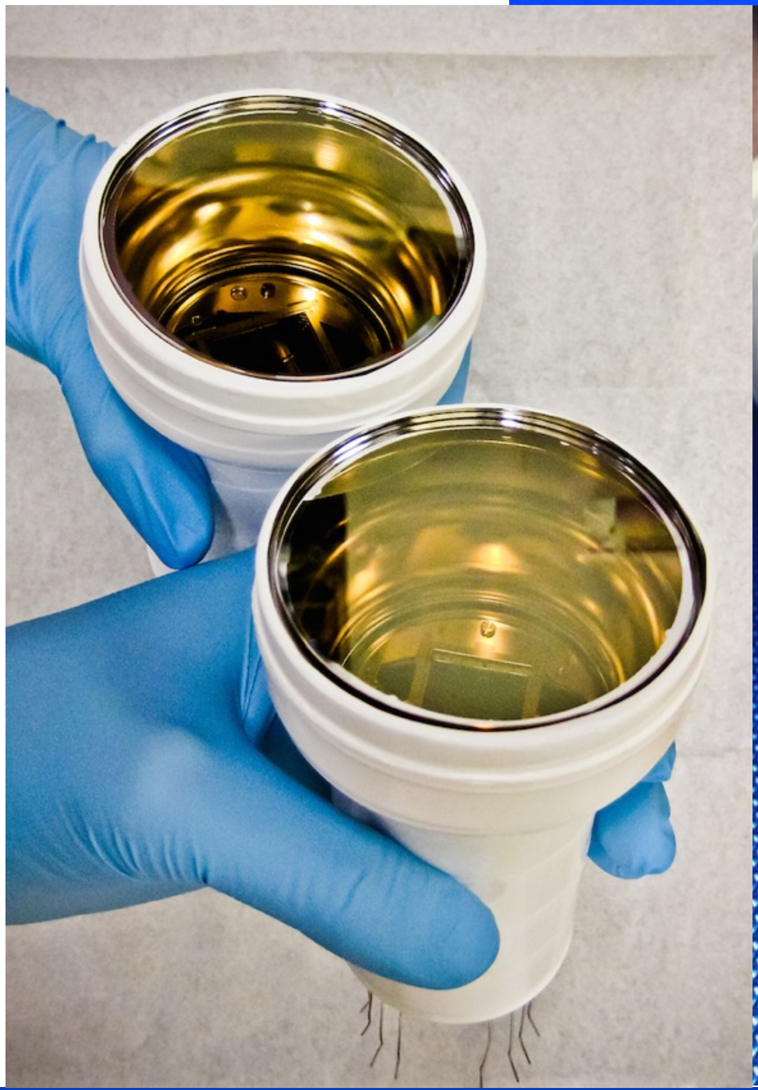
New Directions in the Search for Light Dark Matter Particles

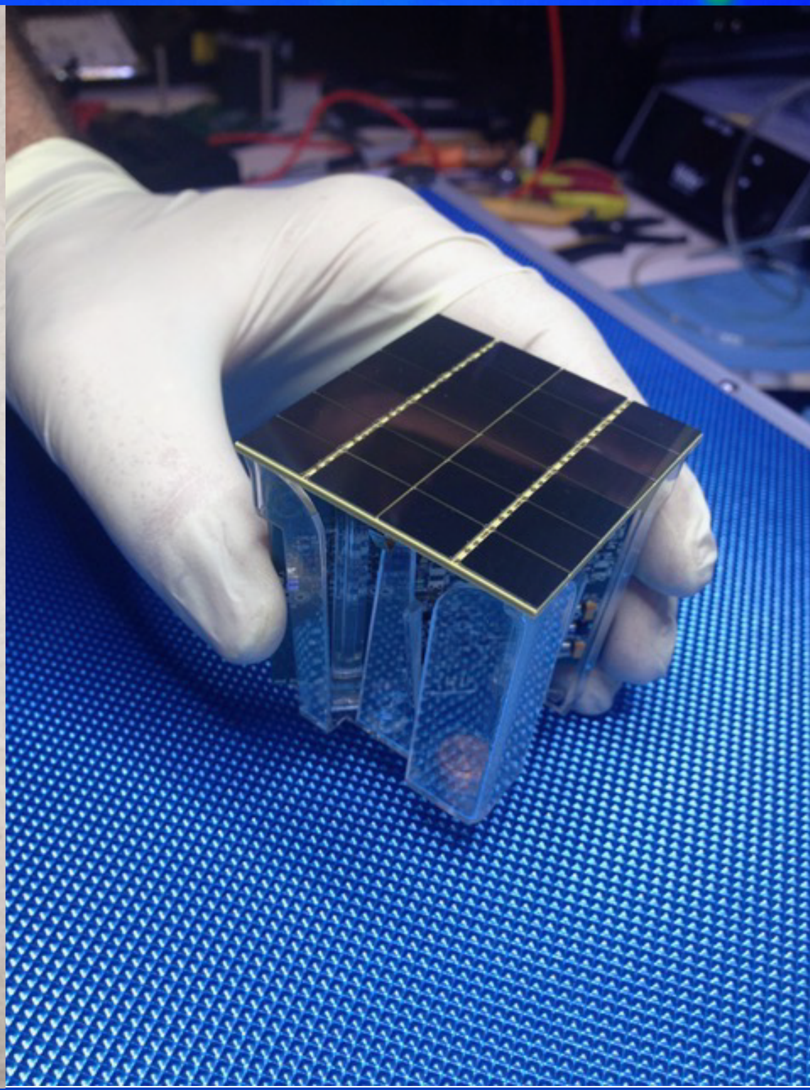
Overview



Scintillation in dark matter search

- Mechanisms
- Properties
- Wavelength shifters
- Ultra-pure scintillators



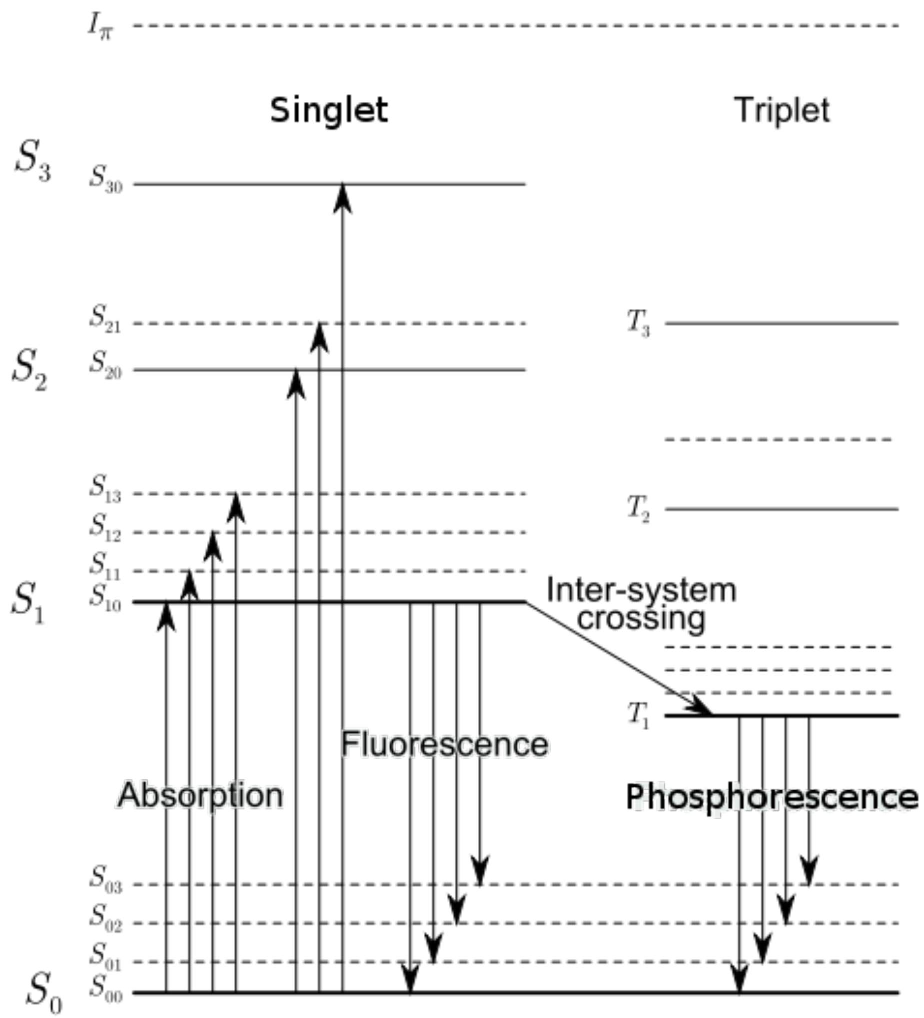


Single photon detectors

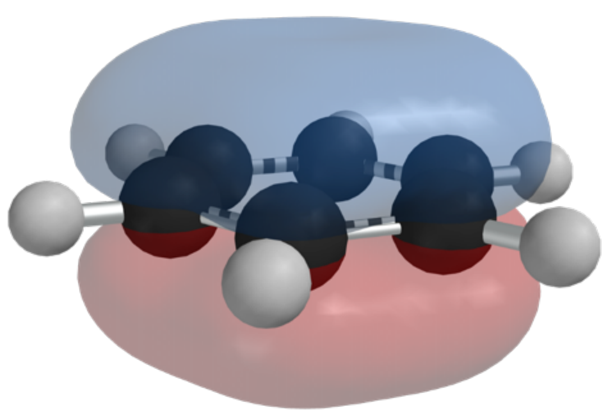
- Operation of PMTs and SiPMs
- Signal features
- Noises
- Operation in cryogenics
- Comparison
- SiPMs tiling and readout

Scintillation mechanisms

Organic scintillators

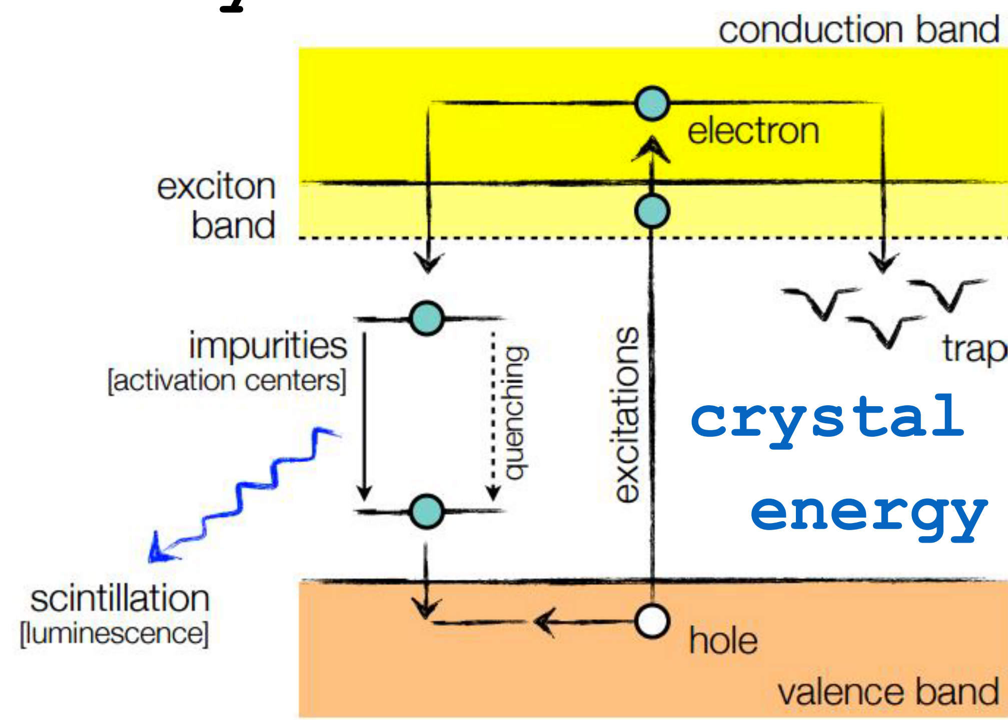


π-orbitals in molecules



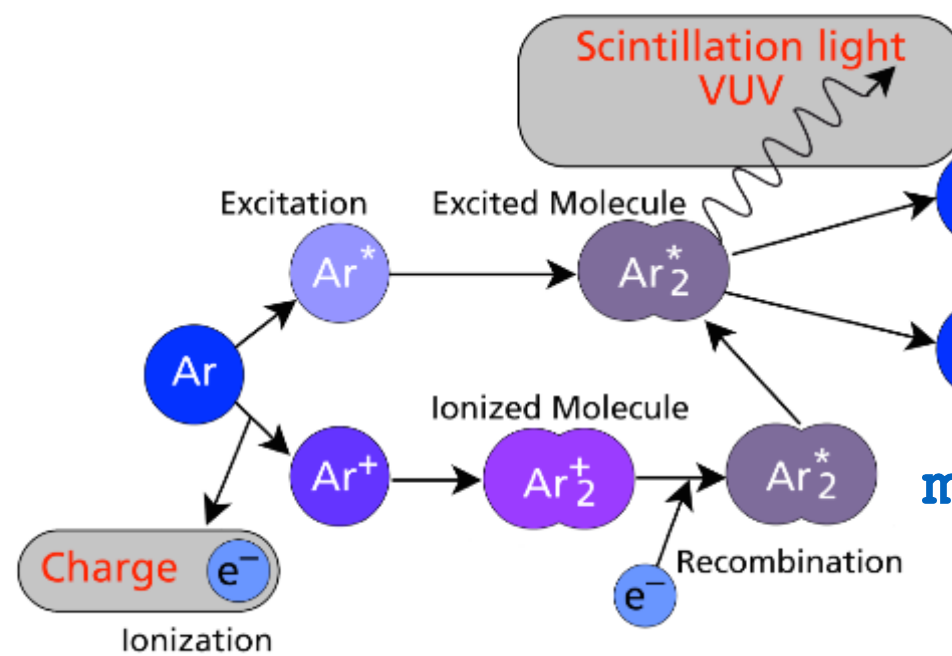
Inorganic scintillators

Crystals with Activators



crystal lattice energy bands

Noble liquids

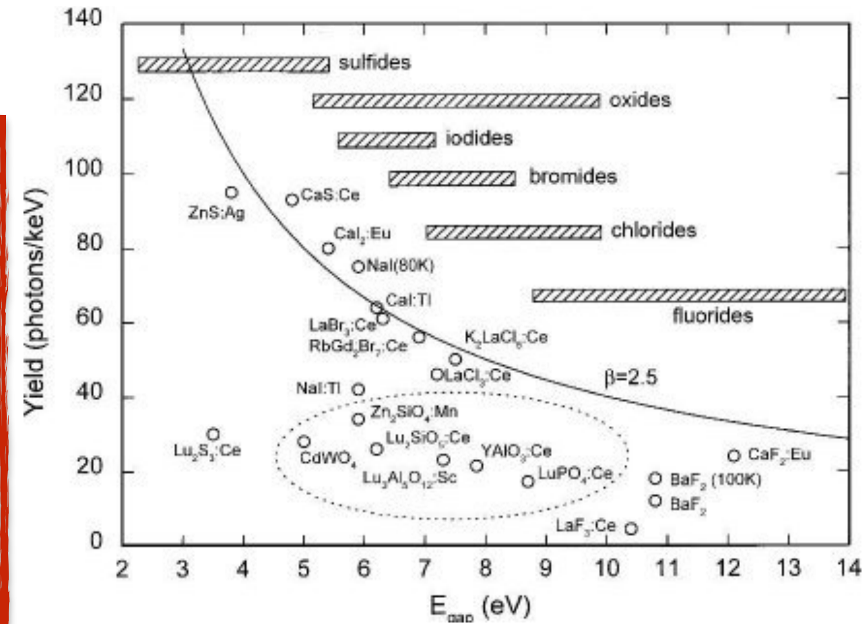


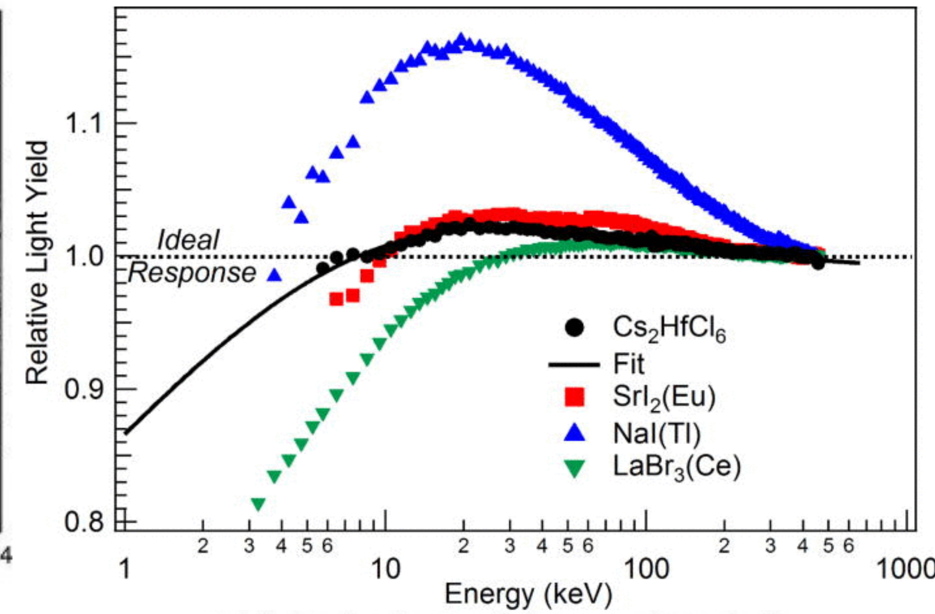
metastable dymers

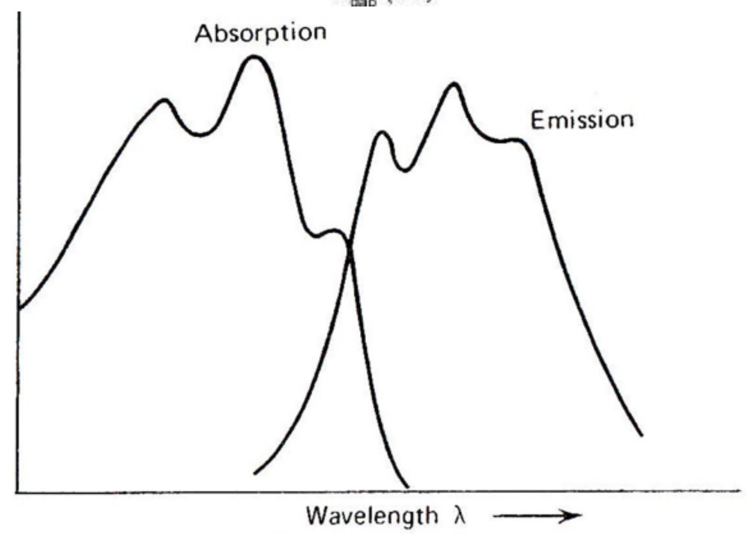
Properties

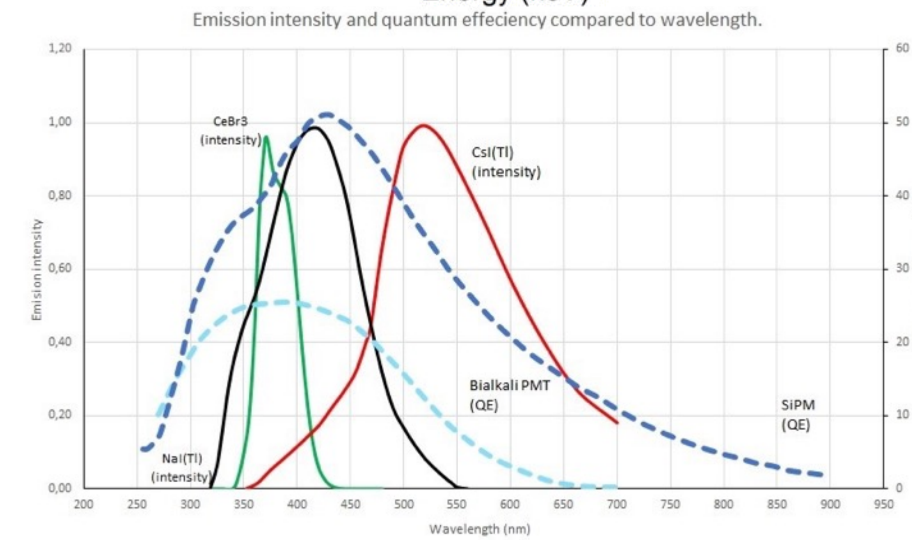
1. Light yield
2. Linearity
3. No self-absorption
4. Emission wavelength
5. Fast
6. Optical coupling to photo-sensors

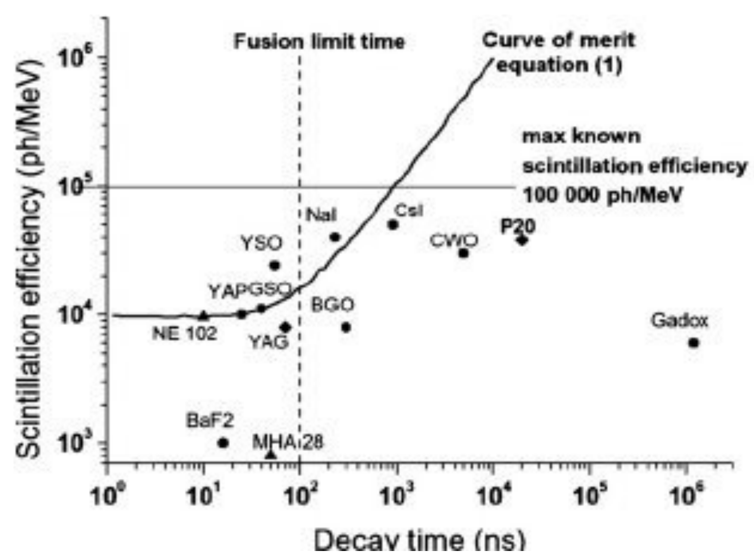
7. Scalable
8. Radio-pure!
9. Particle discrimination

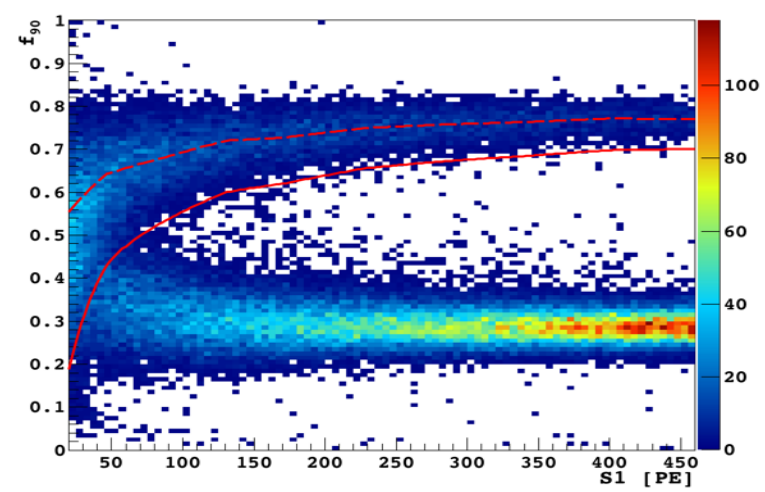








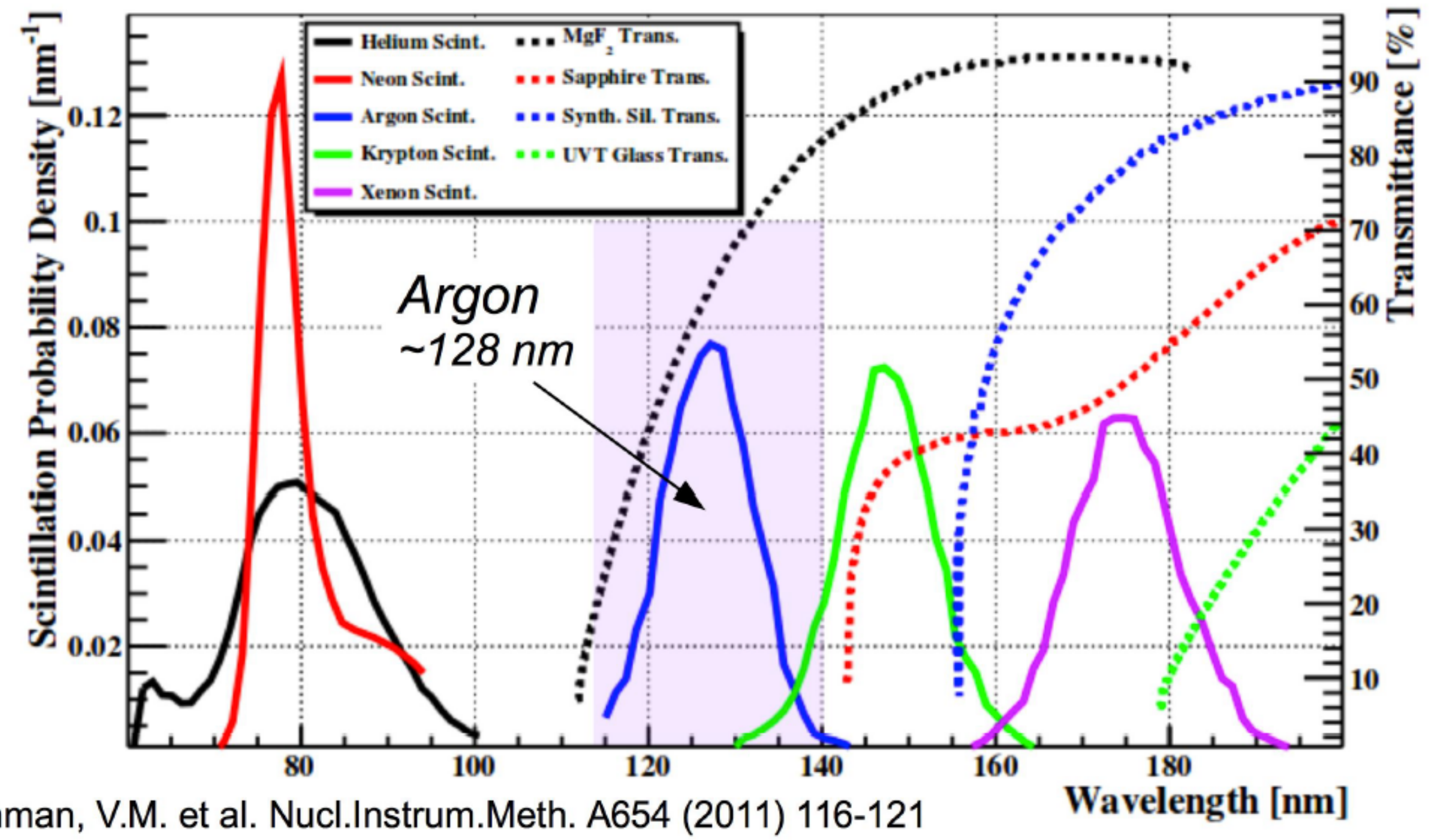




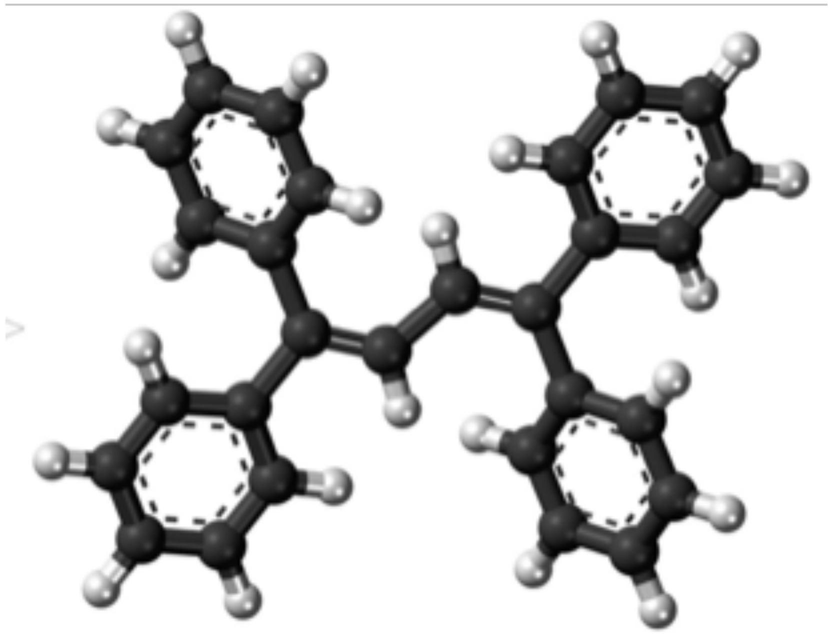
A compromise: wavelength shifters

Any scintillator able to absorb primary scintillation light and re-emit it to more suitable wavelengths

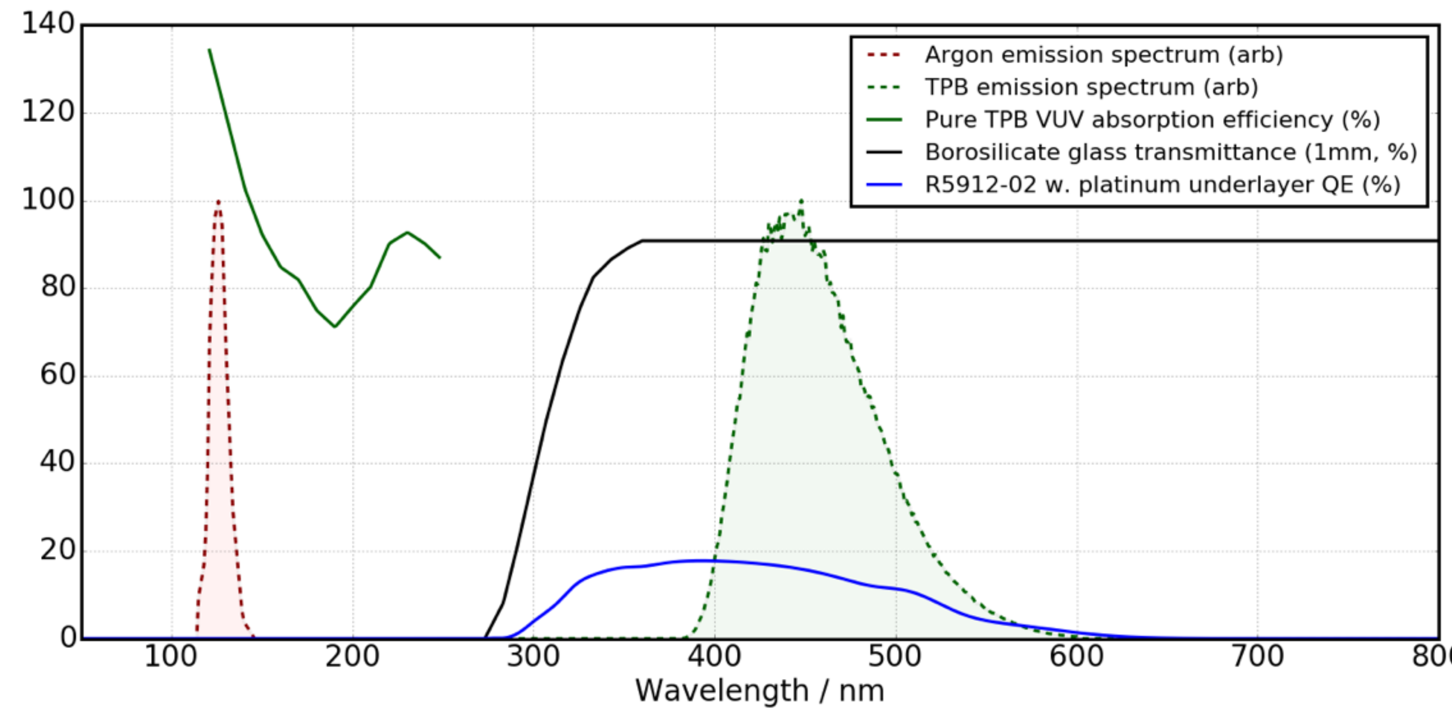
- High conversion efficiency
- Fast



Gehman, V.M. et al. Nucl.Instrum.Meth. A654 (2011) 116-121



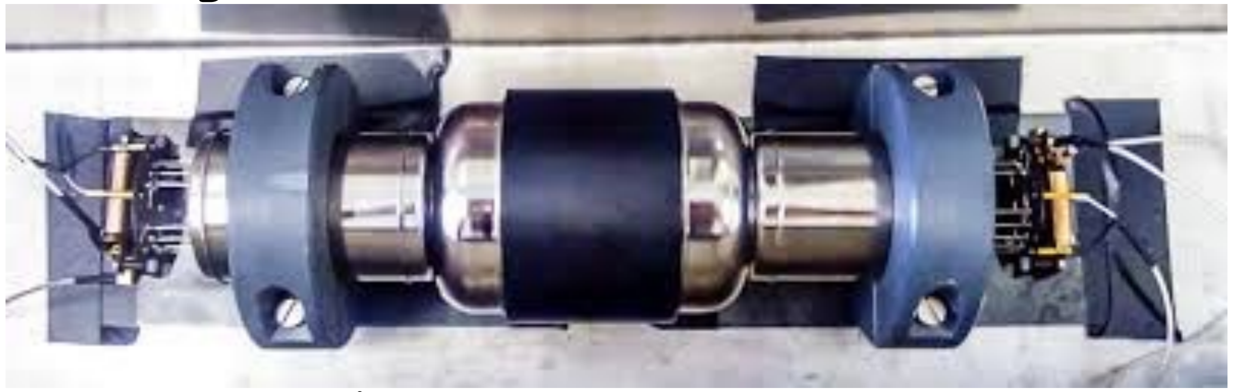
Tetraphenyl Butadiene (TPB)



Ultra-pure scintillators for DM searches

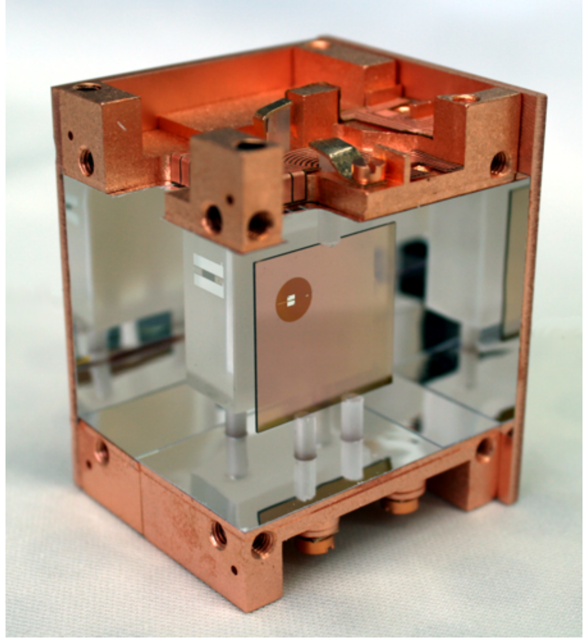
Crystals

Room temperature:
light measured with PMTs

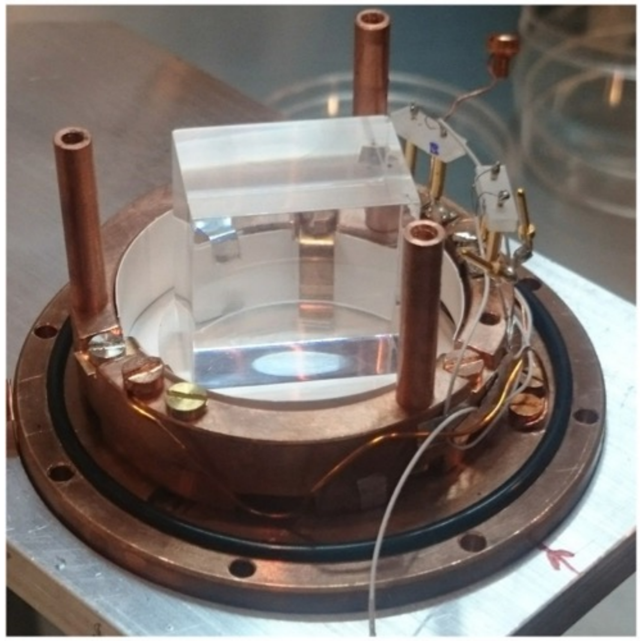


DAMA/LIBRA,ANAIS: NaI
KIMS: CsI

Cryogenic (<20mK):
light measured with calorimeters

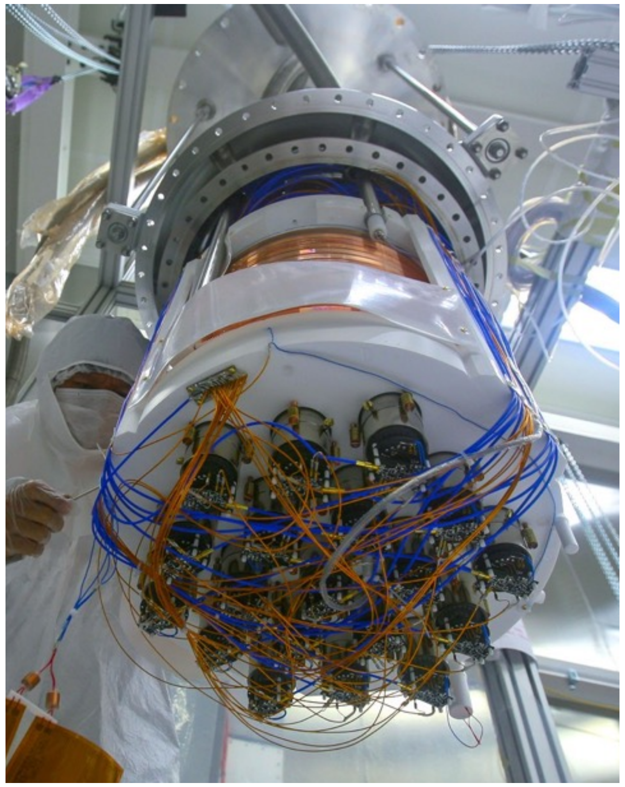


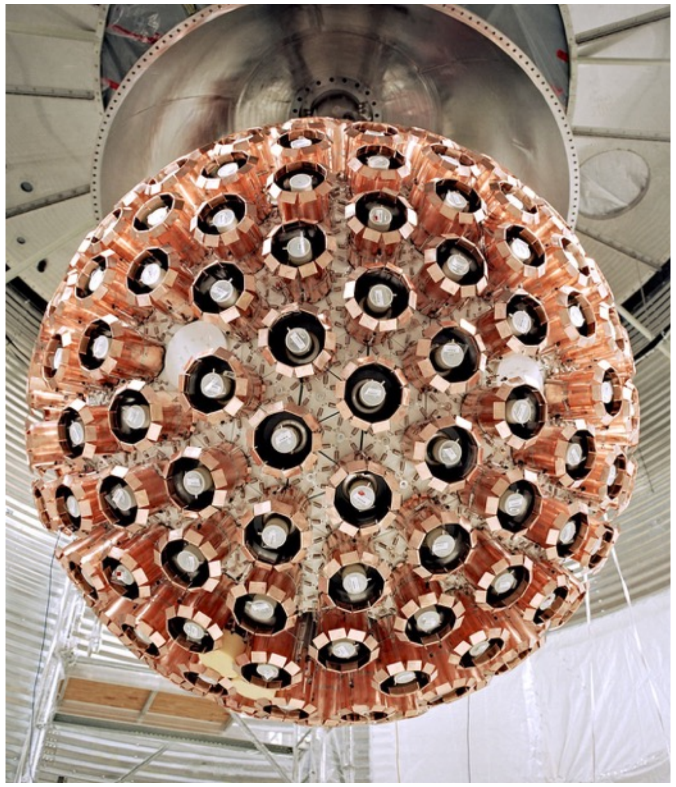
CRESST: $CaWO_4$



Cosinus: NaI

Noble liquids

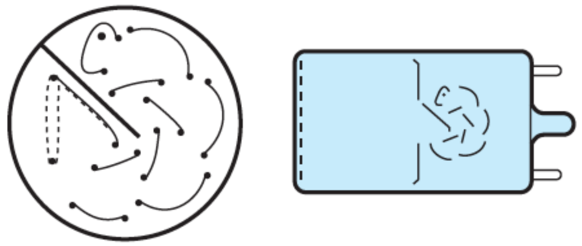




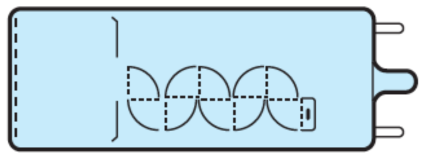
Xenon,LUX,PandaX: Xe
DarkSide,DEAP,ArDM: Ar

	LXe	LAr
T(K)	165	87
WL(nm)	178	128
Shifter	No	TPB
Sensor	PMT	PMT,SiPM

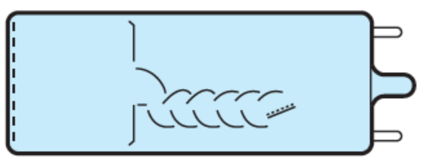
They come in all flavours and sizes



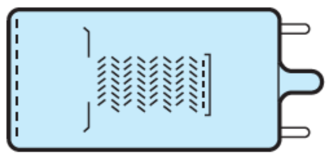
(1) Circular-cage type



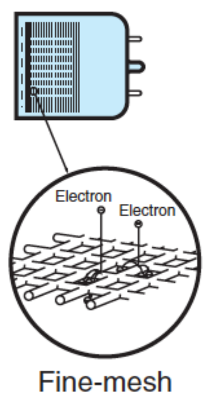
(2) Box-and-grid type



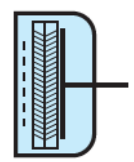
(3) Linear-focused type



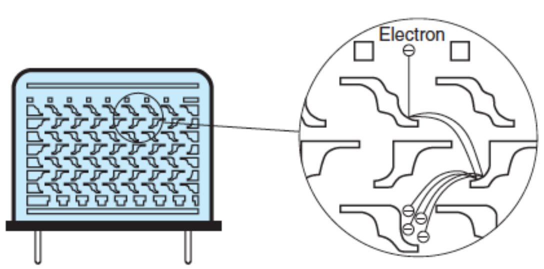
(4) Venetian blind type



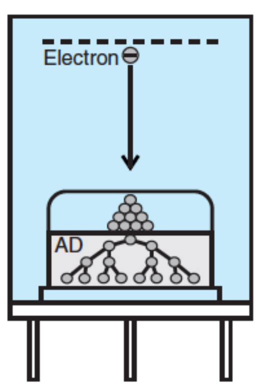
(5) Mesh type



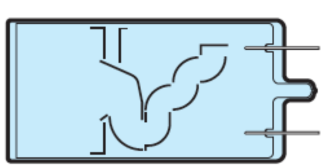
(6) MCP (Microchannel plate) type



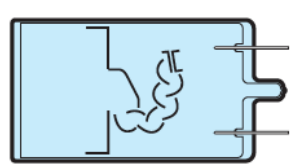
(7) Metal channel type



(8) Eelectron bombadment type

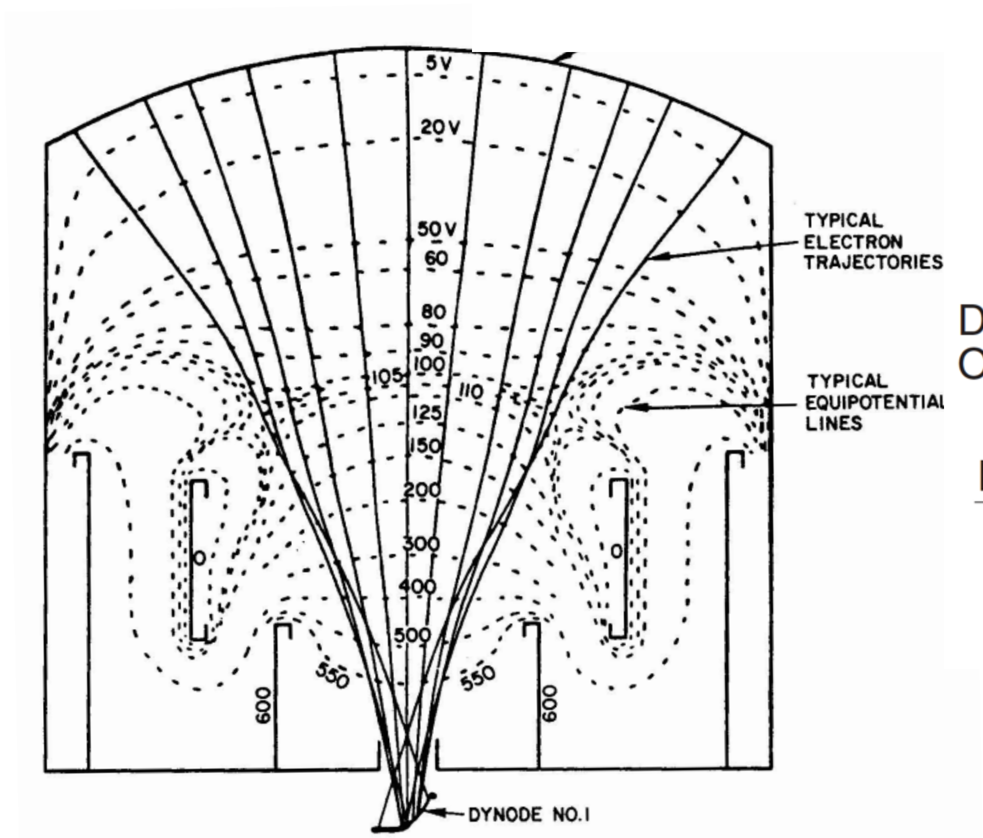


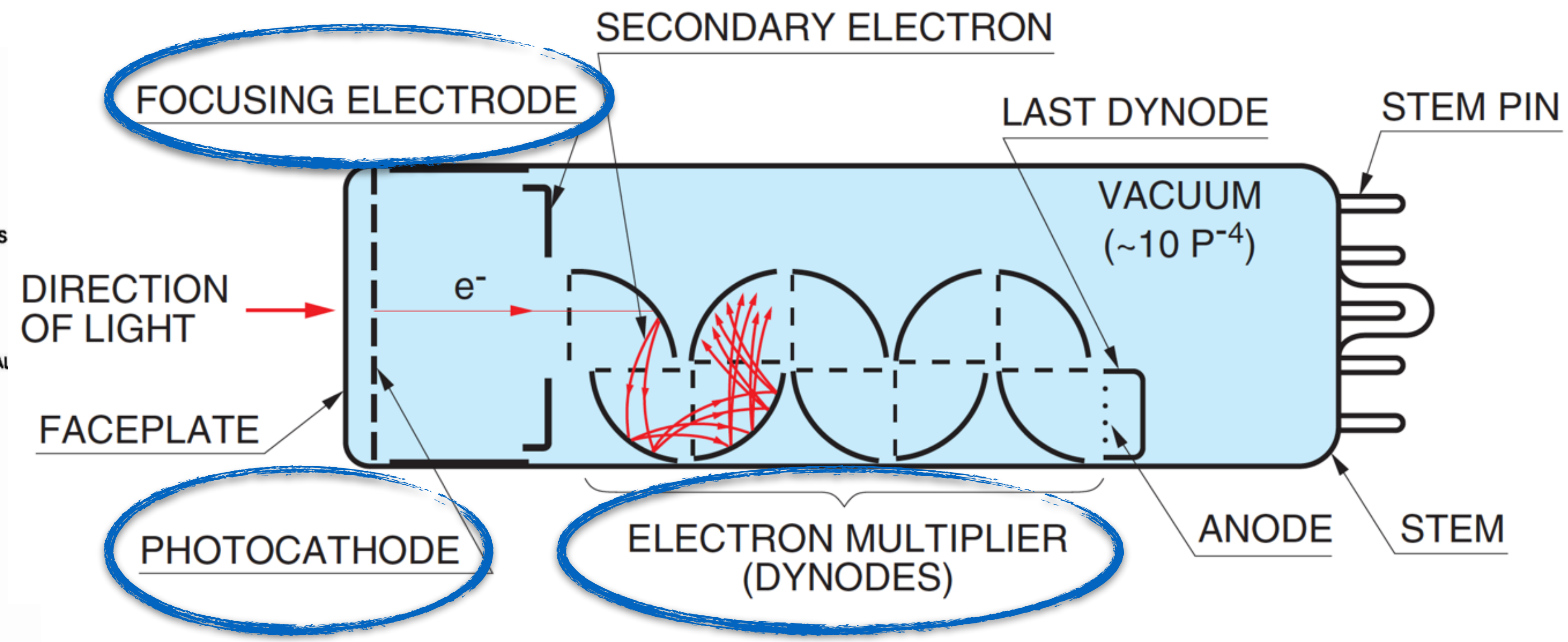
(9) Box-and-line type

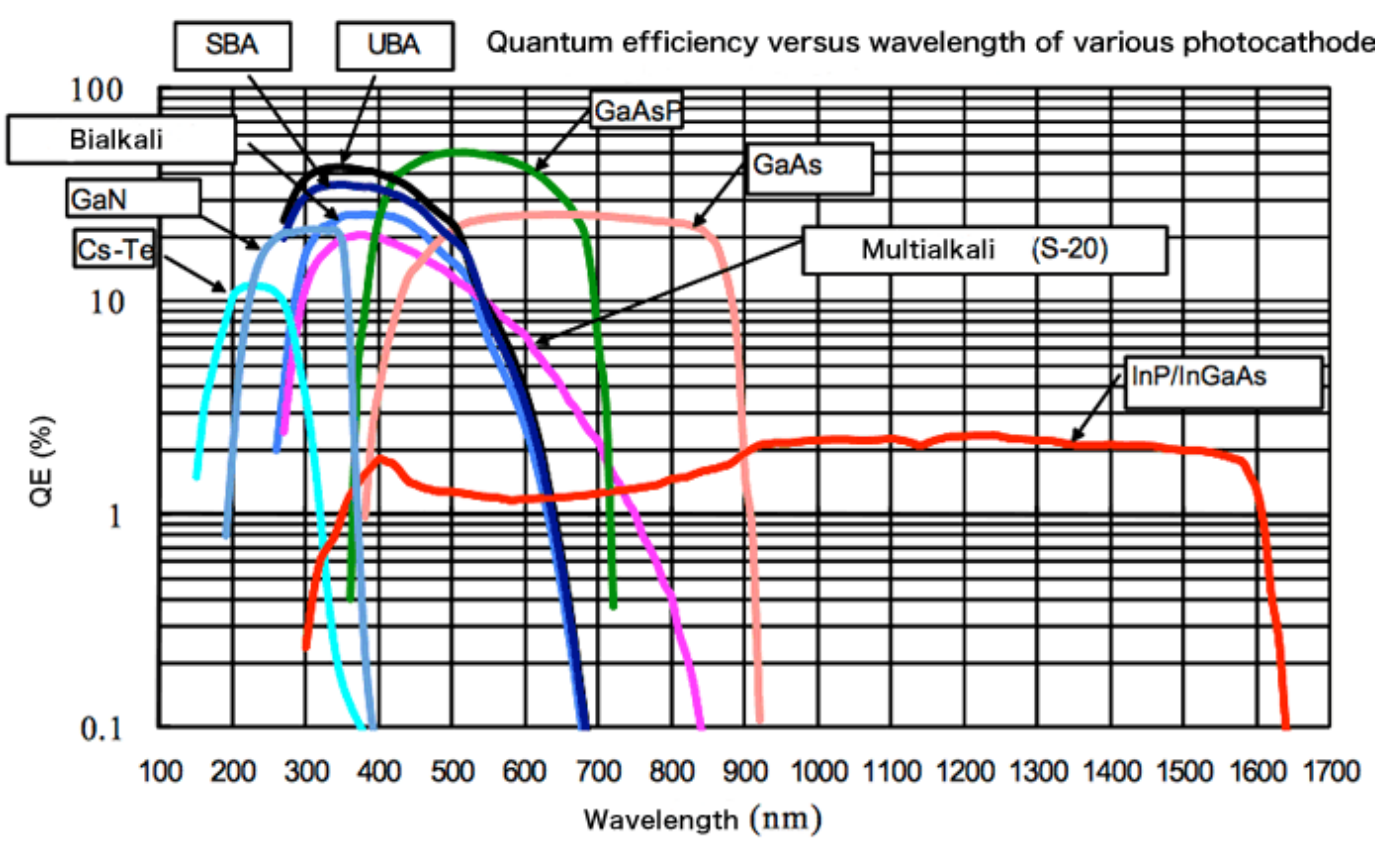


(10) Circural and linear-focused type

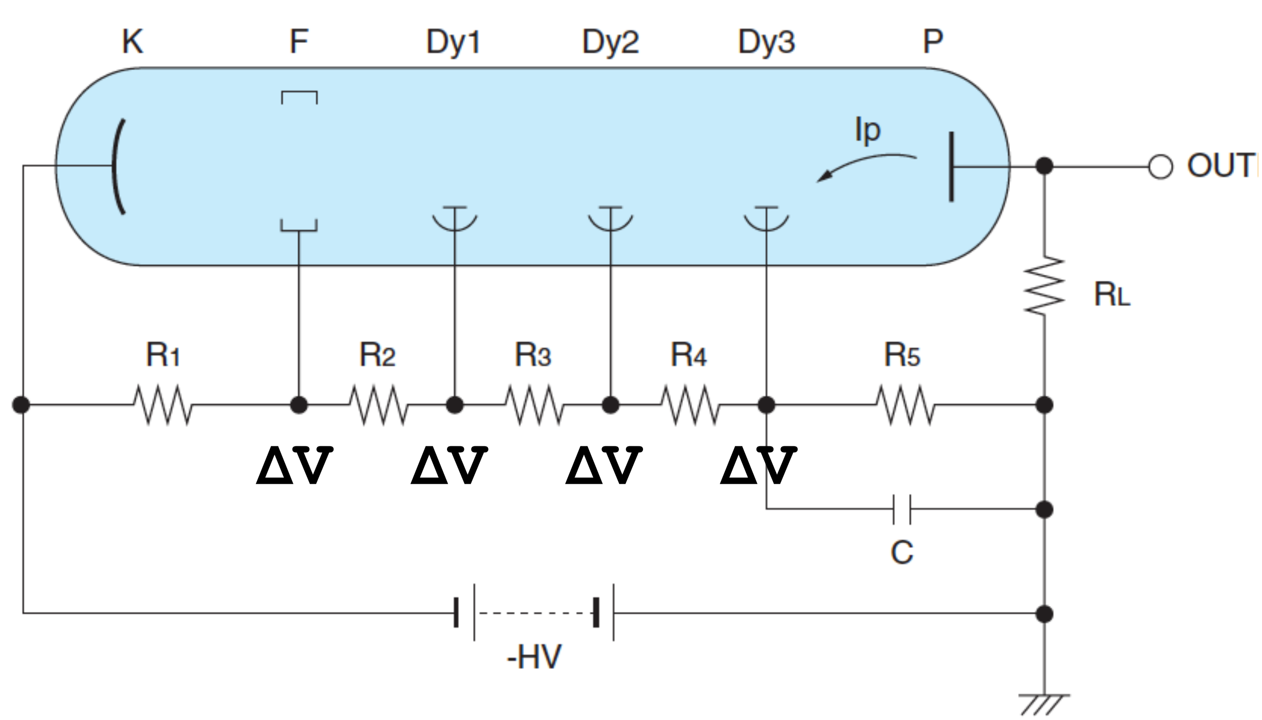
PMT structure





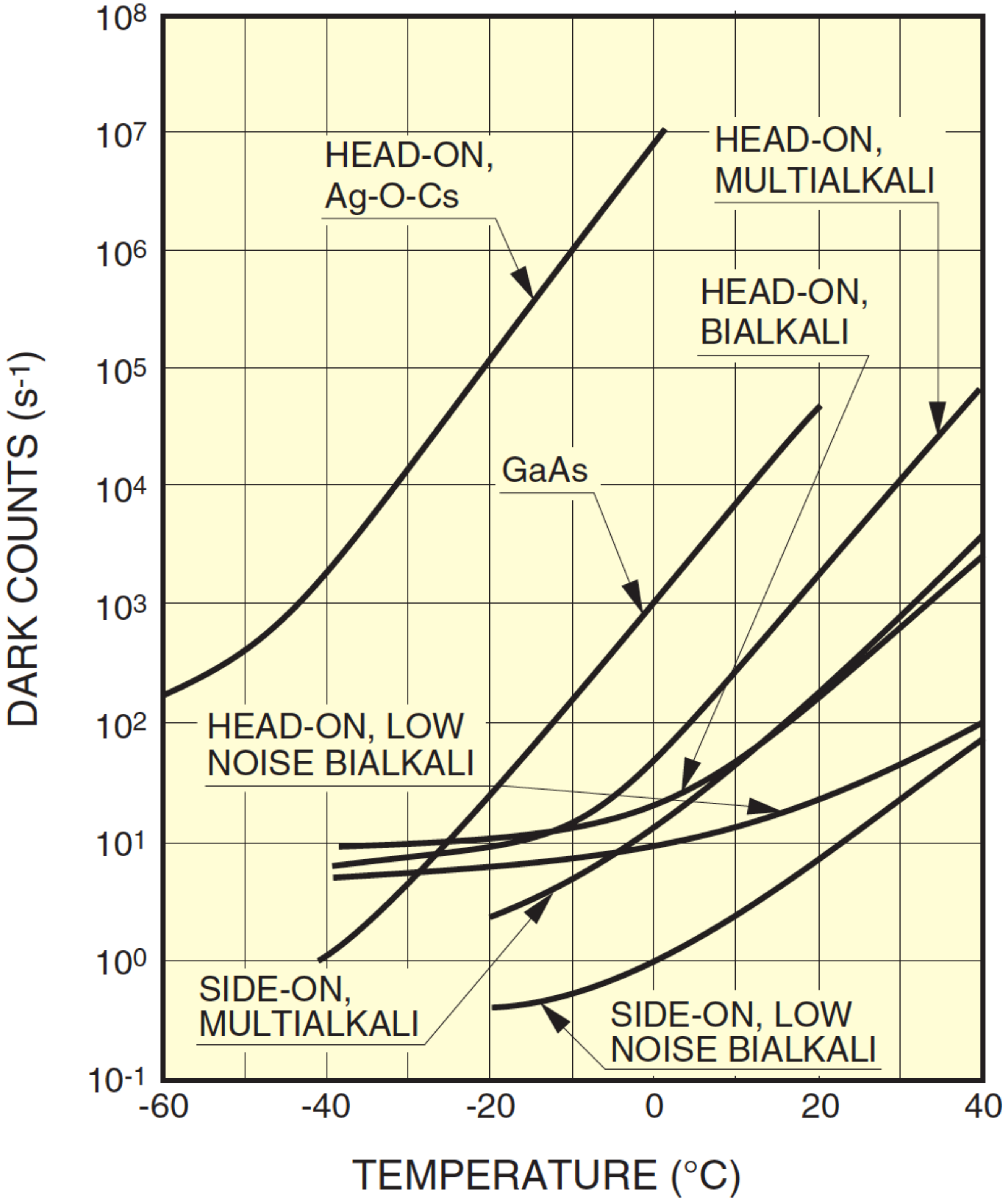


Dynodes ΔV accelerates e⁻

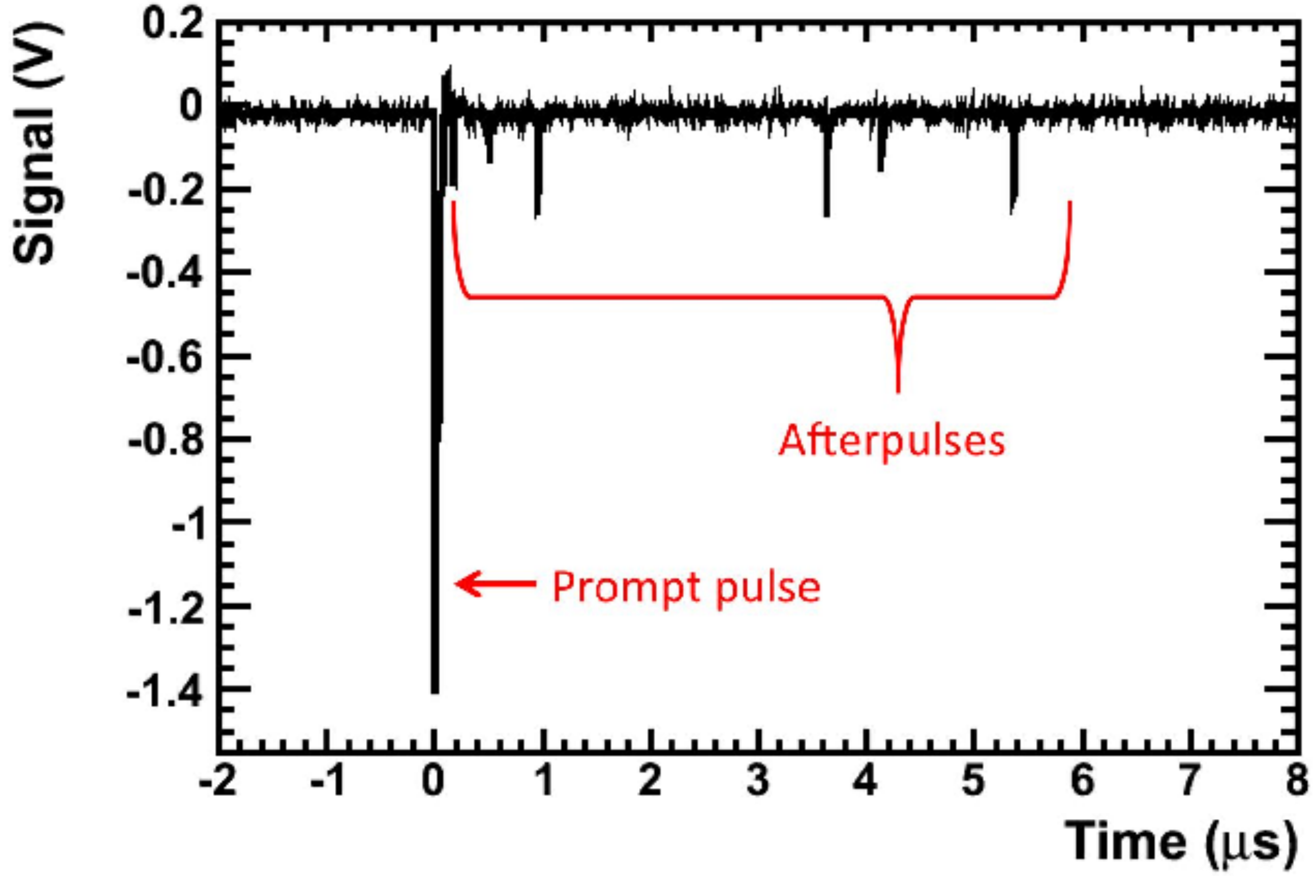


PMT Noises

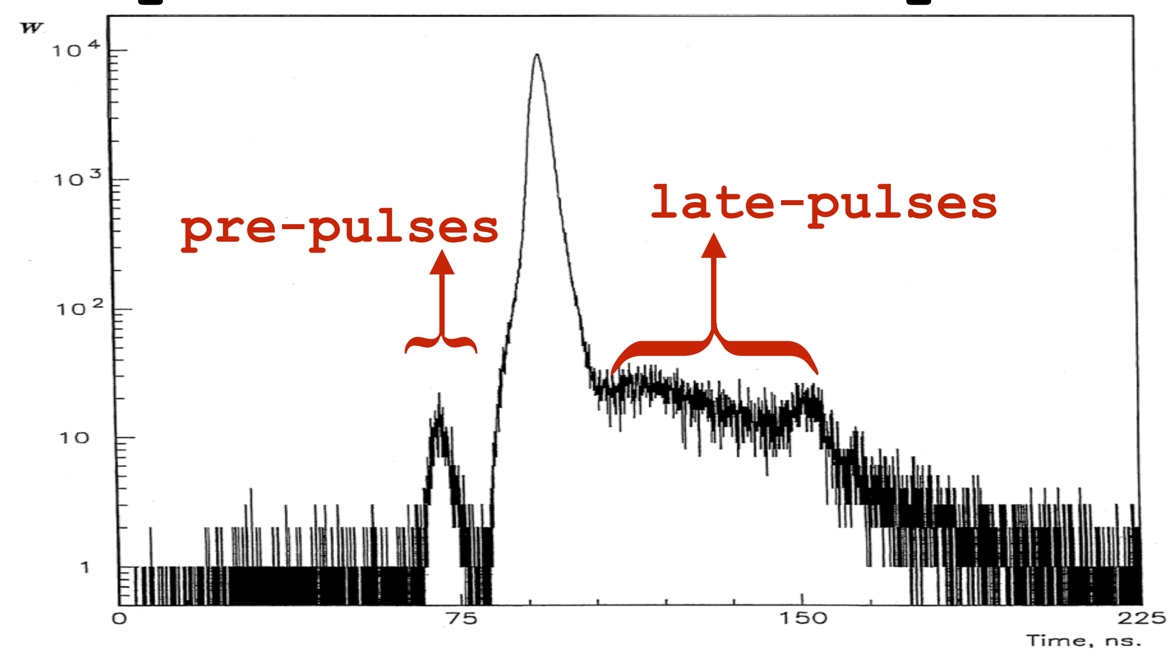
Dark Count Rate



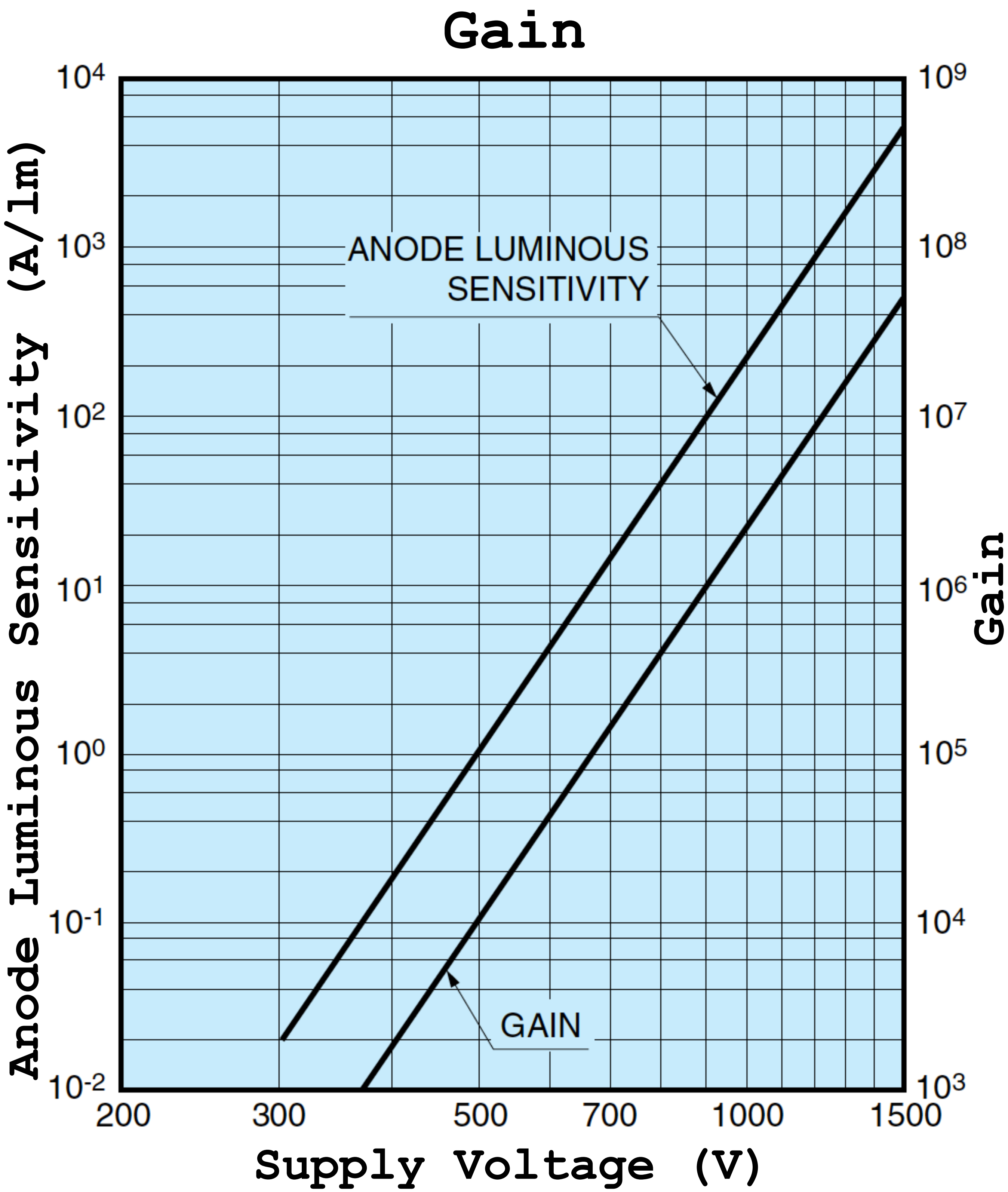
After pulses

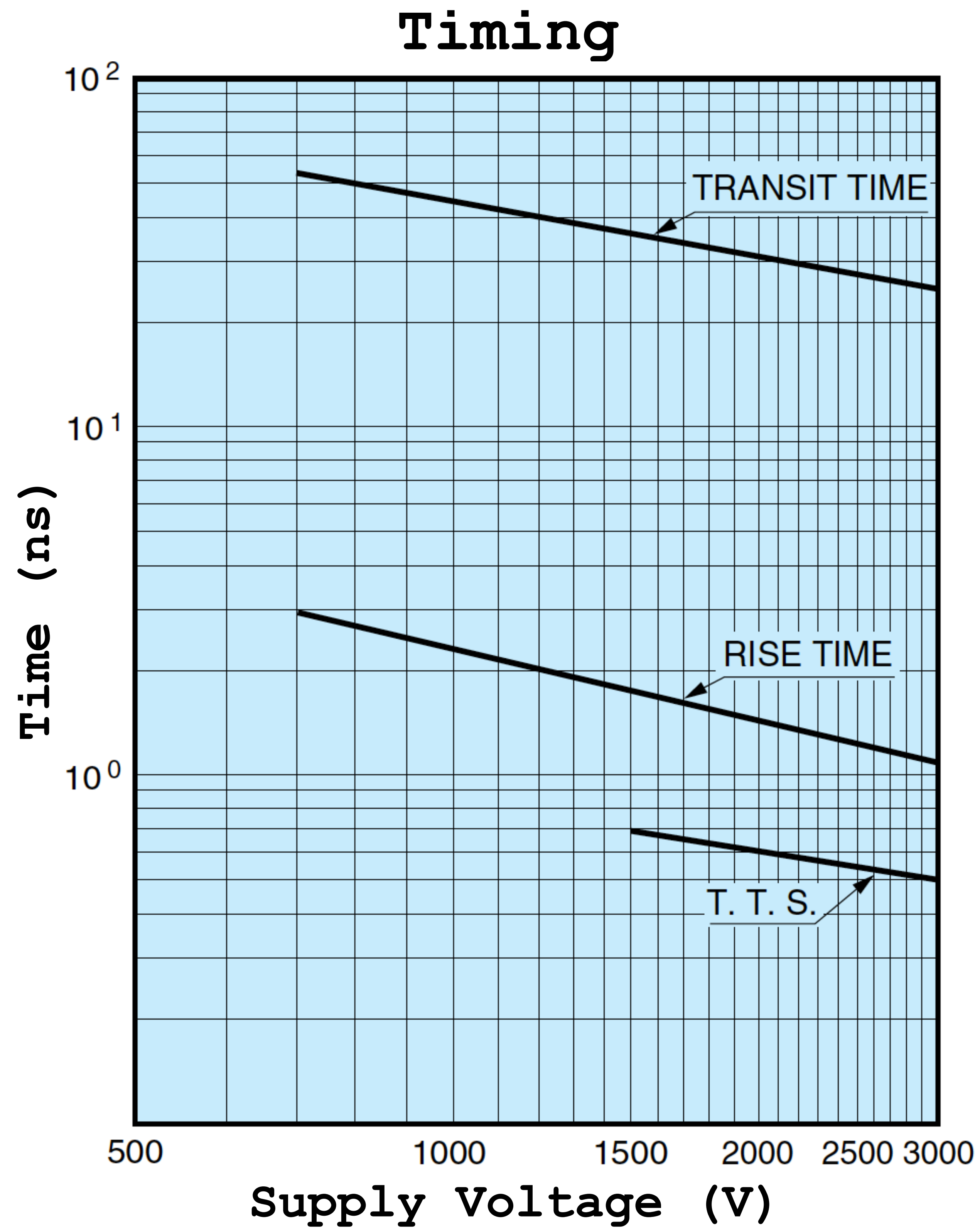


Prepulses and late-pulses



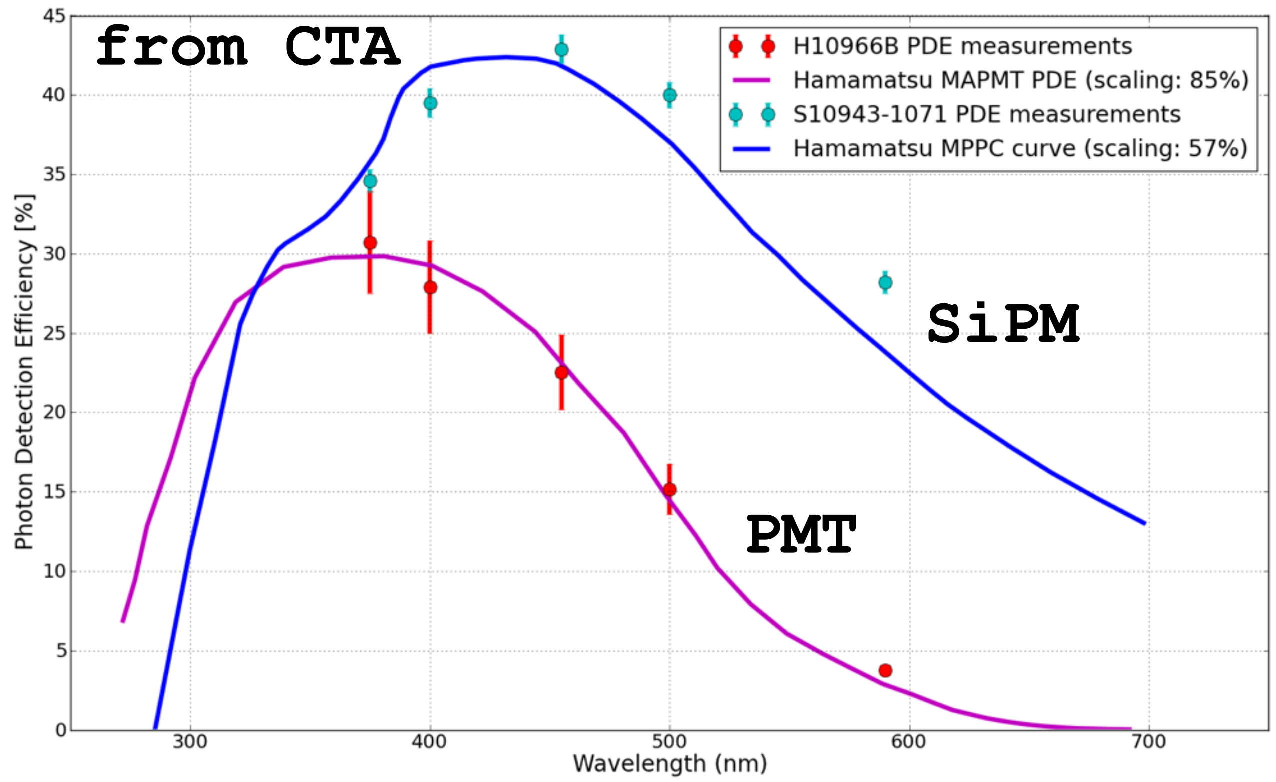
PMT common features

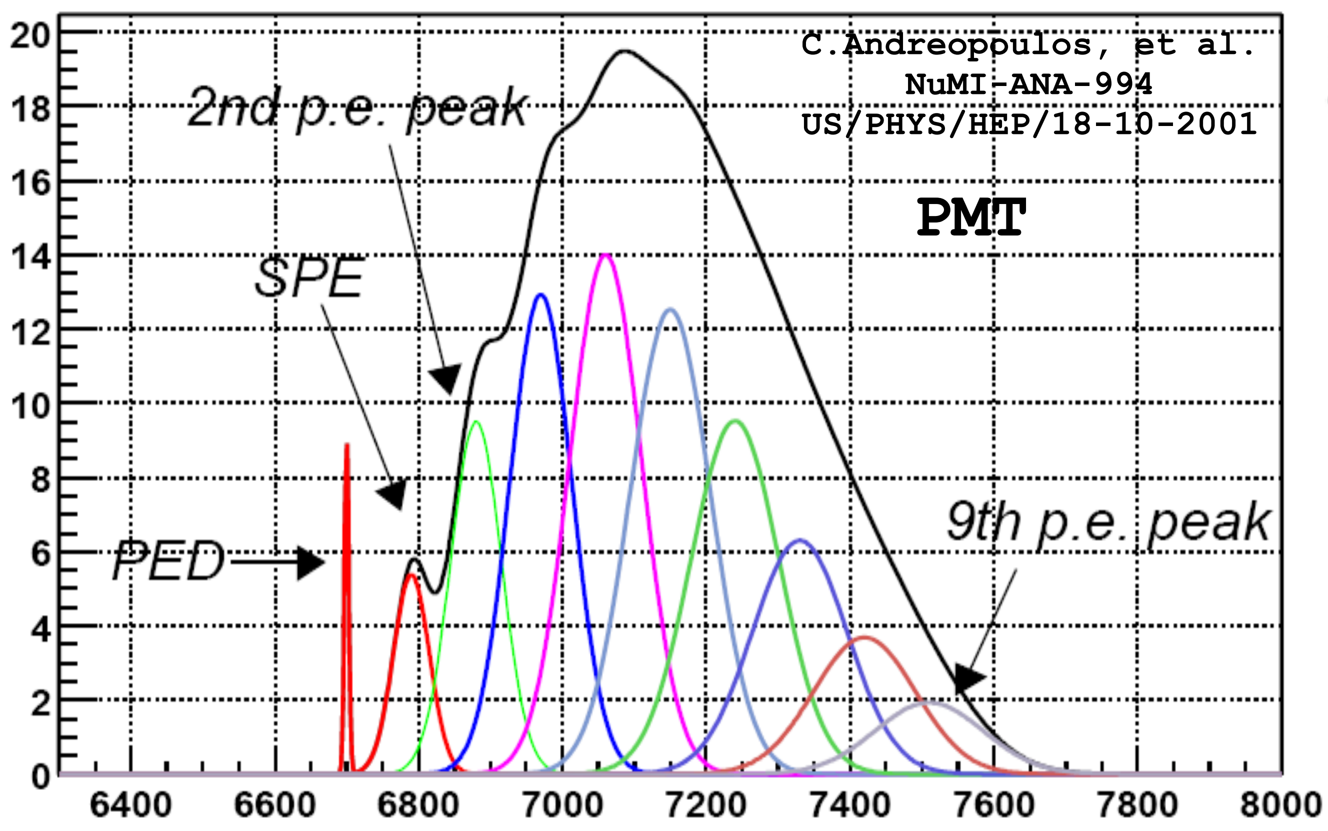


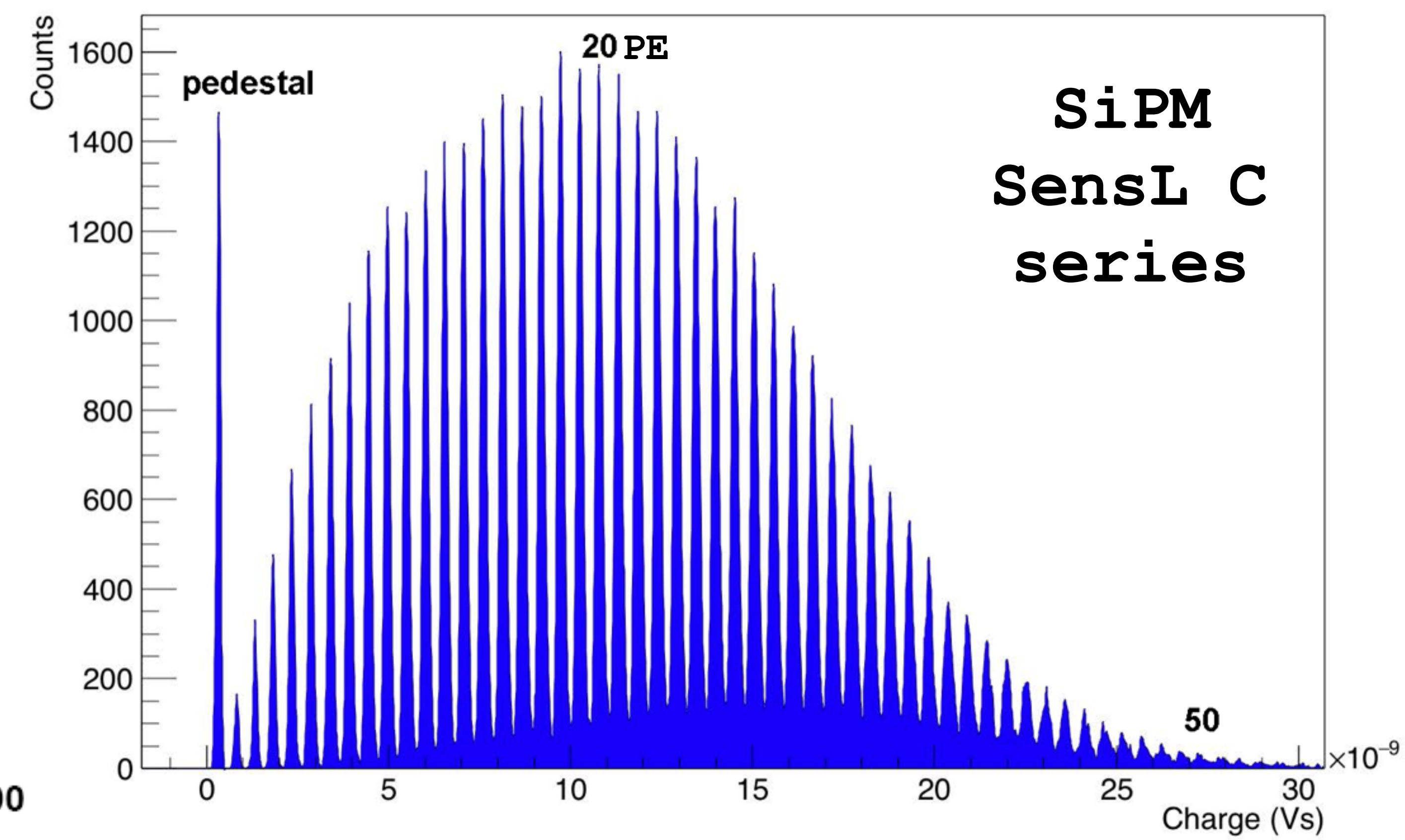


SiPMs: why bet on them?

1. Radio-purity
2. Resolution
3. PDE
4. Versatility







SiPMs

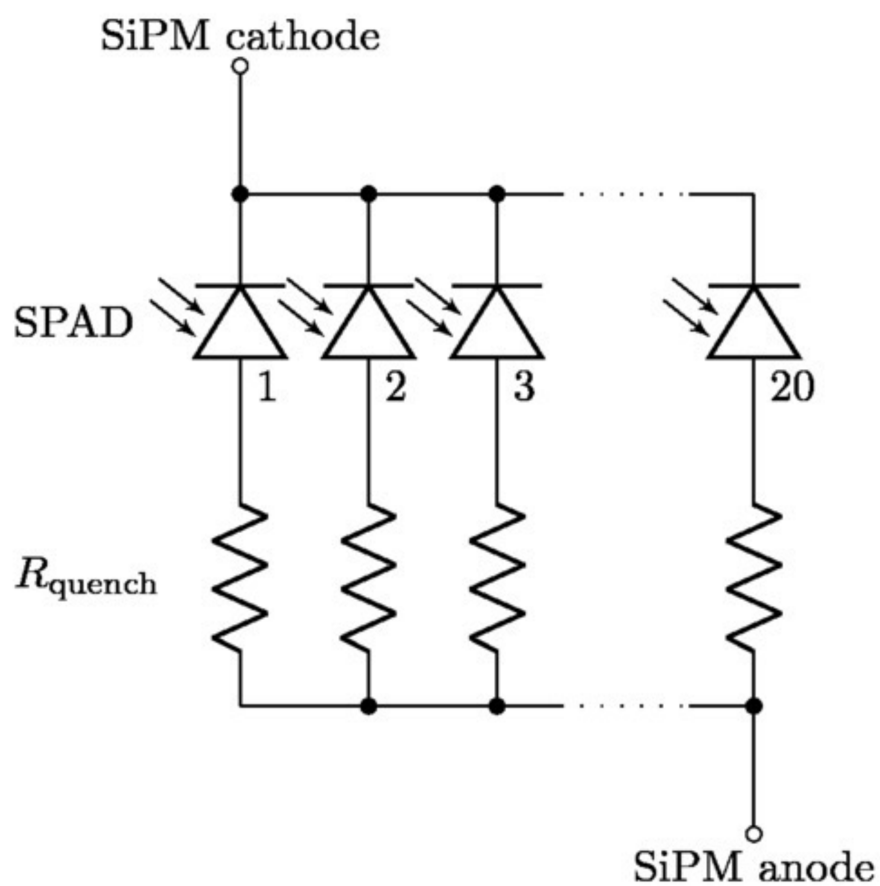
SiPM: matrix of SPADs mounted in parallel

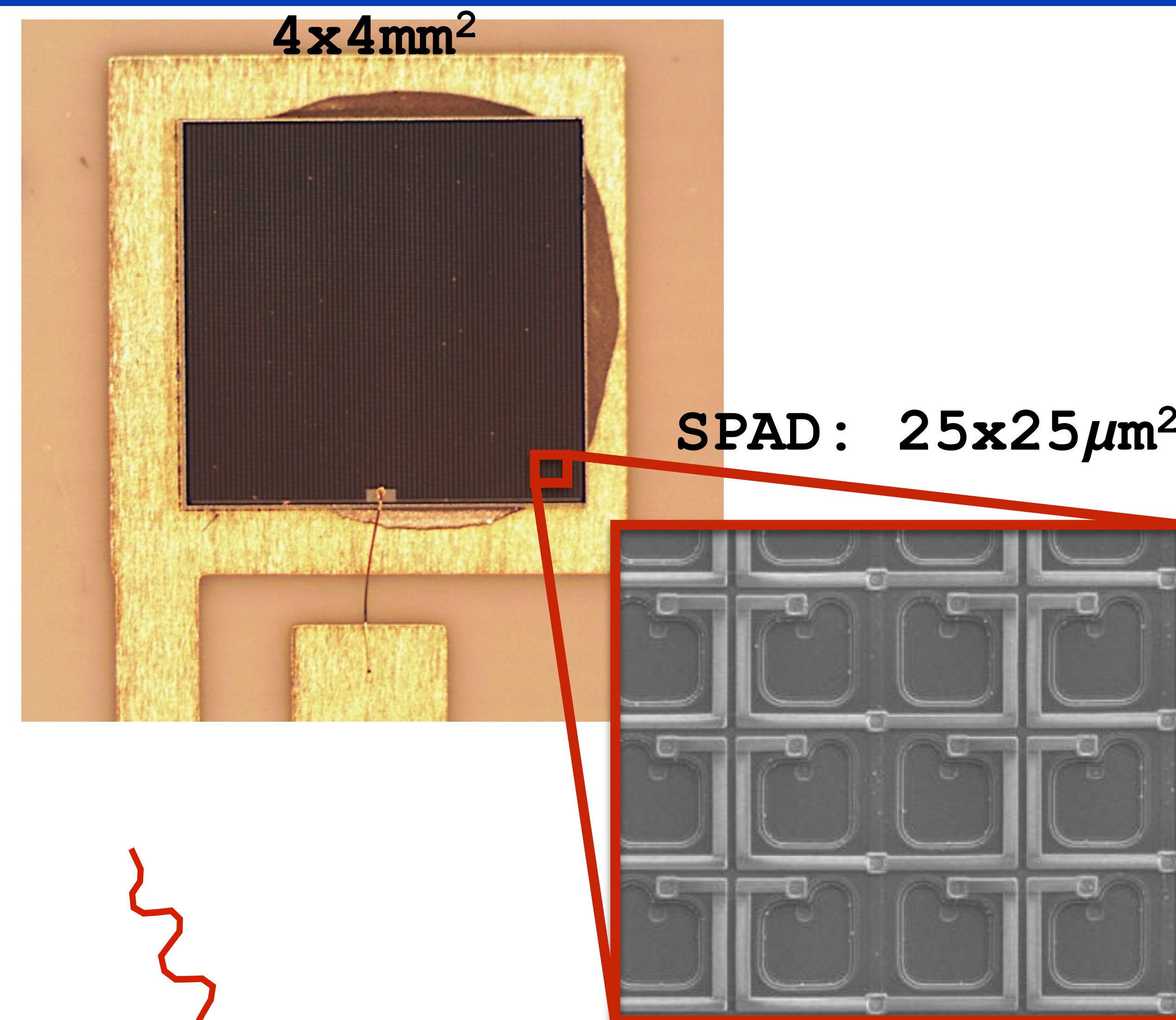
↓

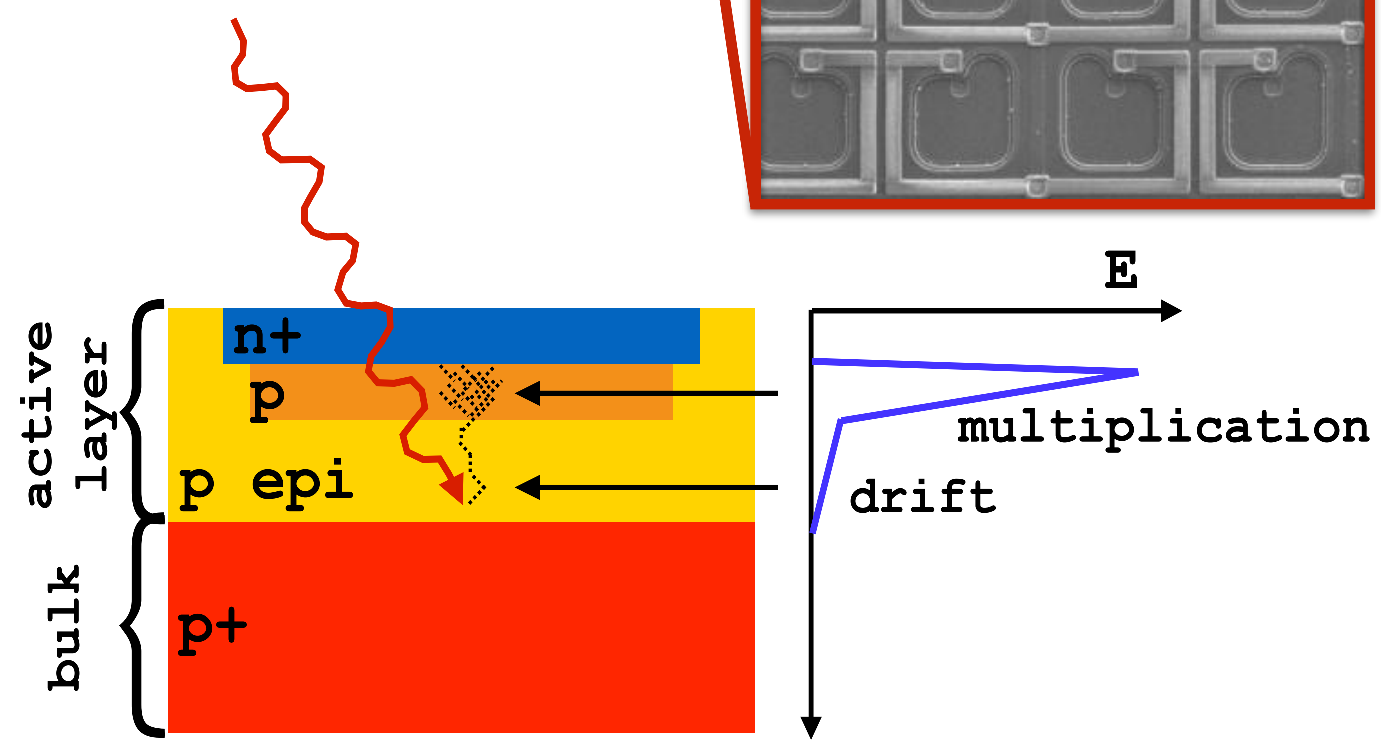
SPAD: Avalanche PhotoDiode operated in geiger mode

↓

Passive avalanche quenching through R_q~MΩ resistor

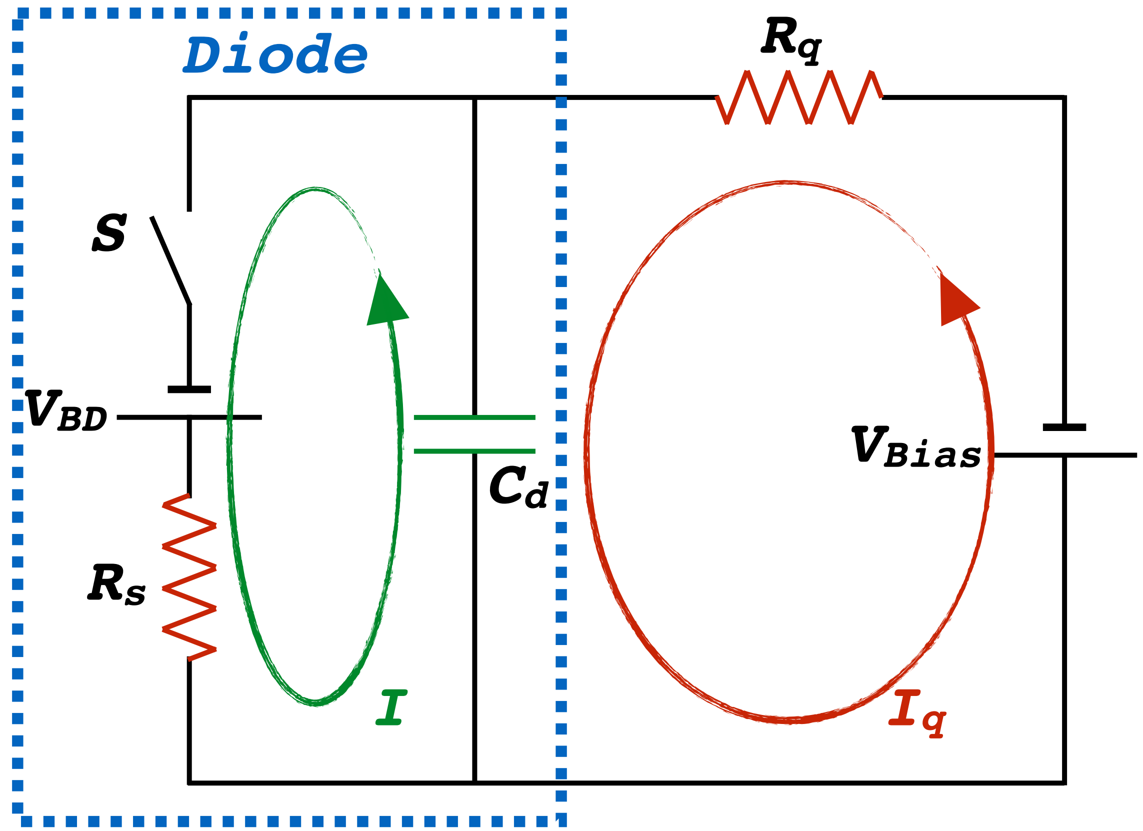


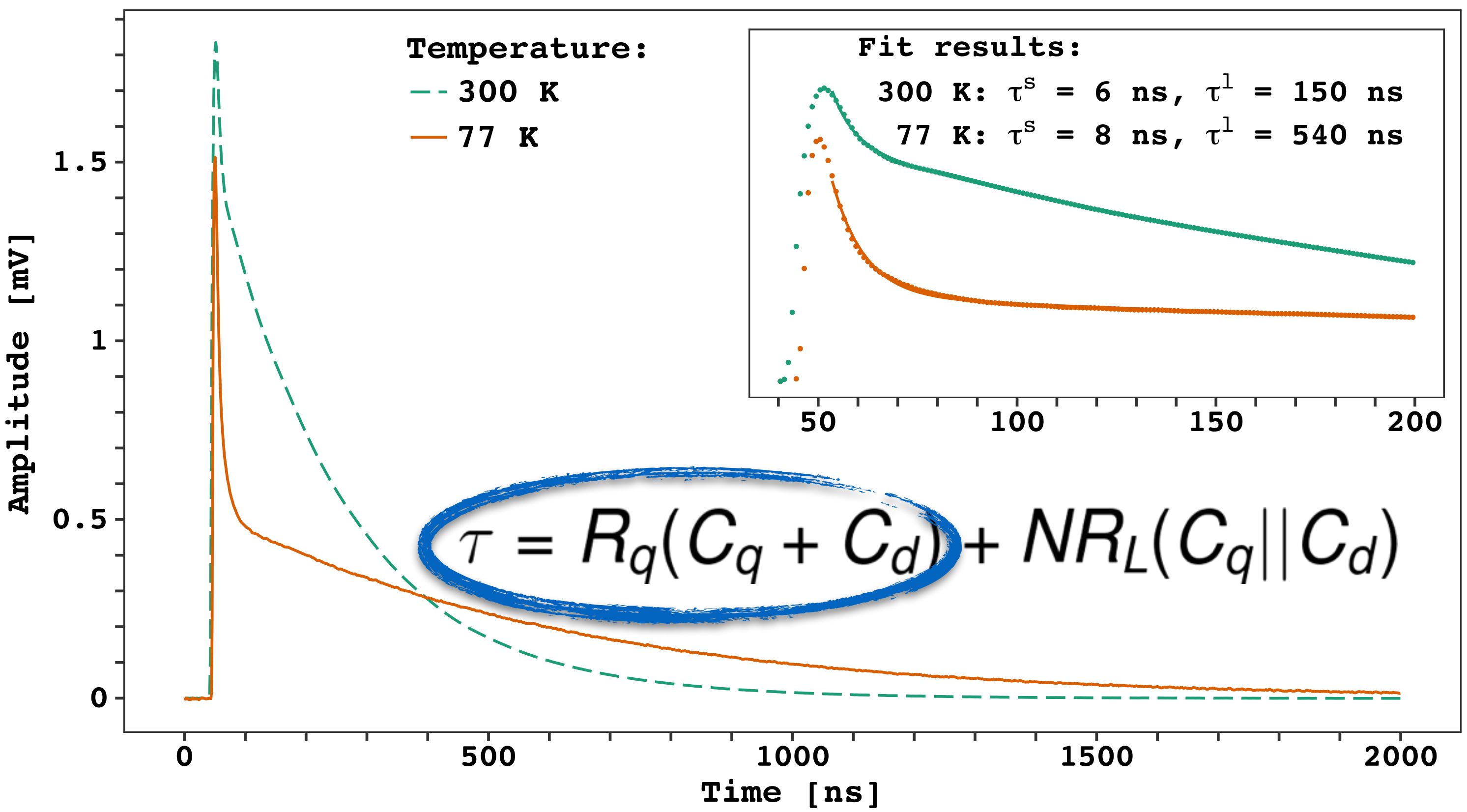




Signal formation in SiPMs

- SPAD equivalent to 2 RC meshes
- Important parameters: diode capacitance (C_d) and resistance (R_s), and quenching resistor (R_q)

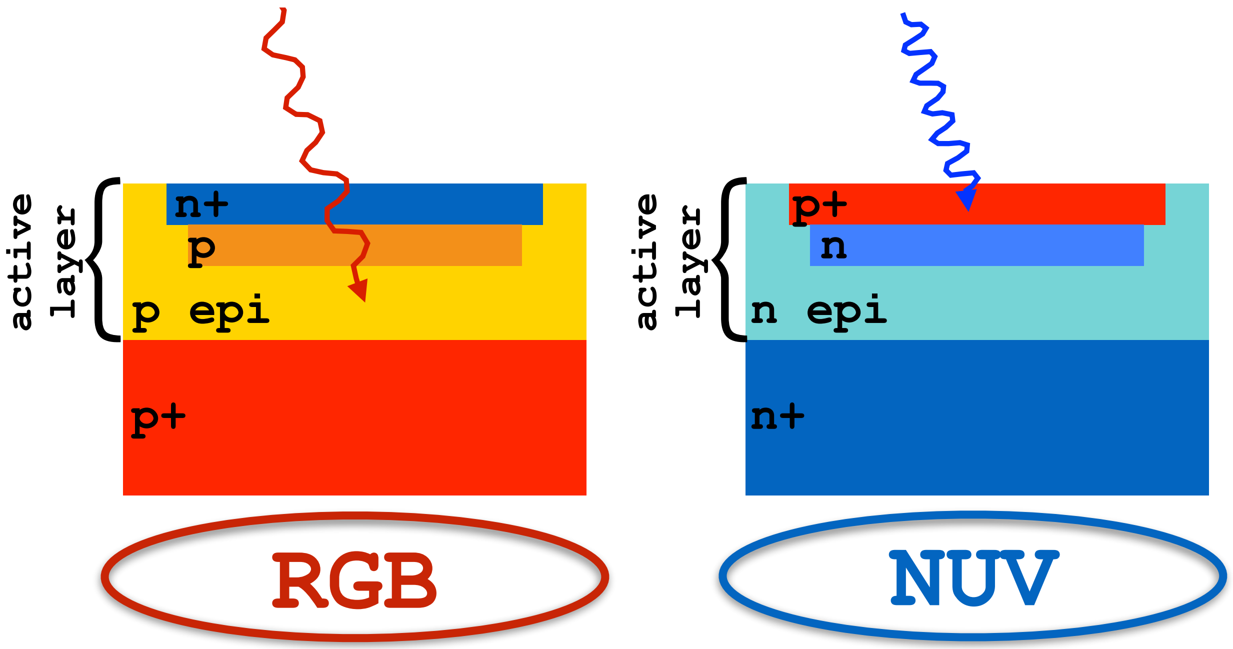


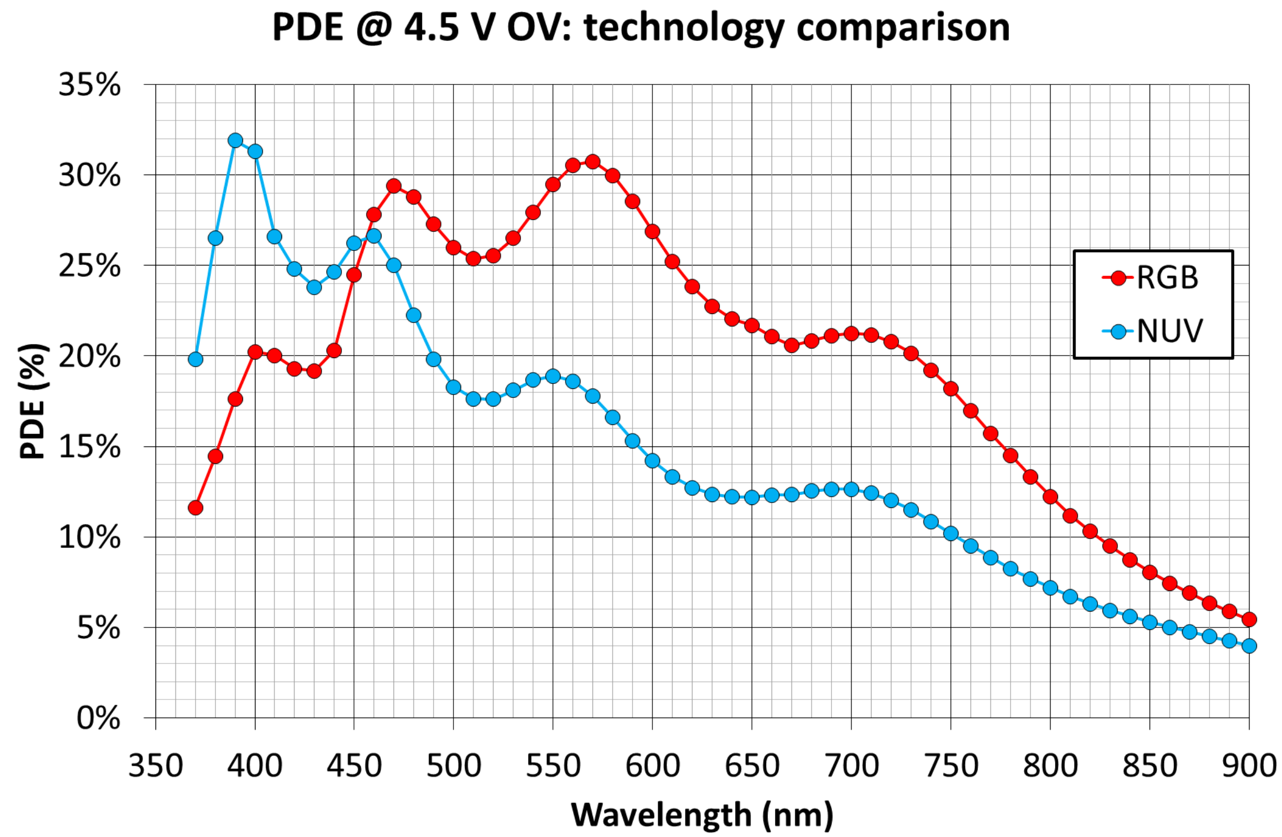


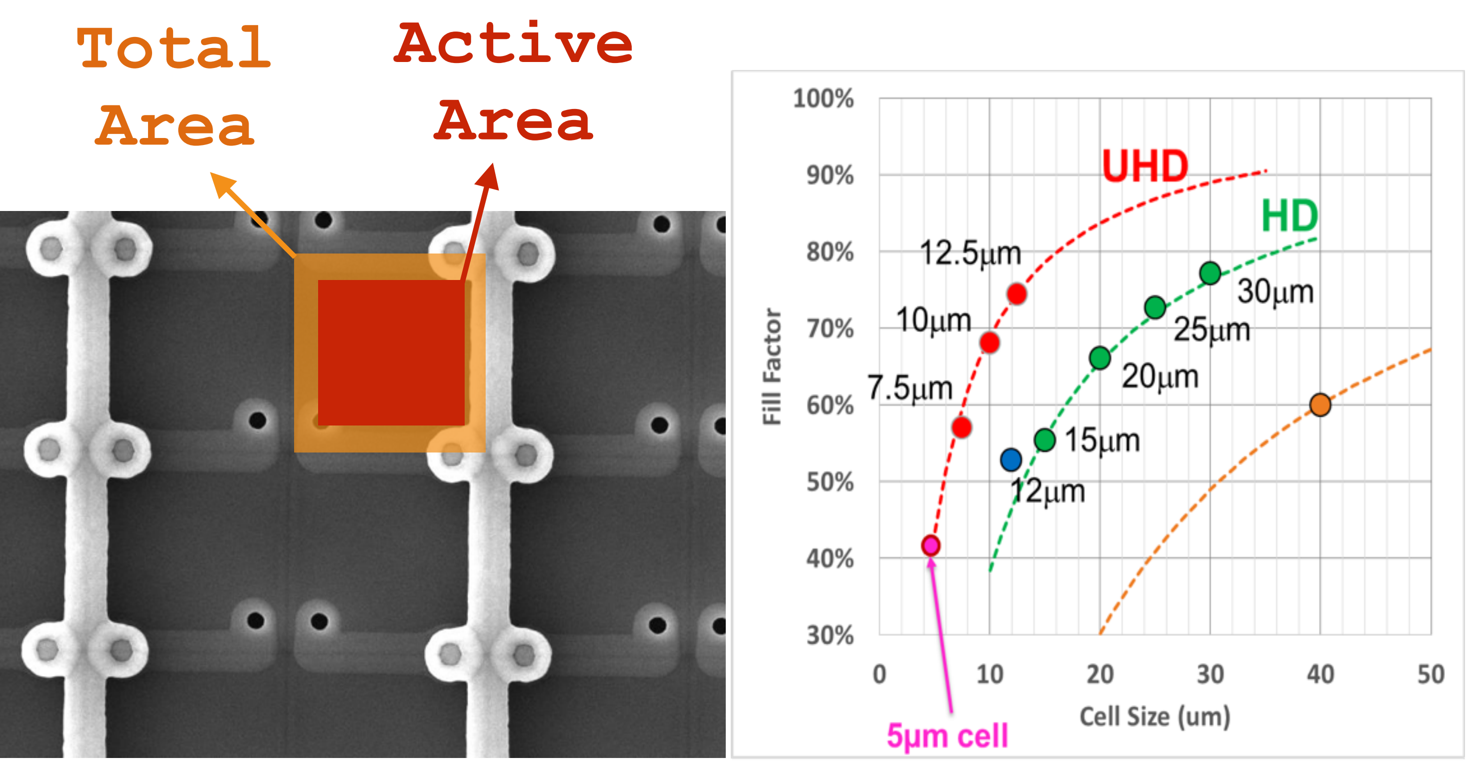
1. Fast peak: C_d discharge through R_s
2. Slow exponential tail: C_d recharge through R_q

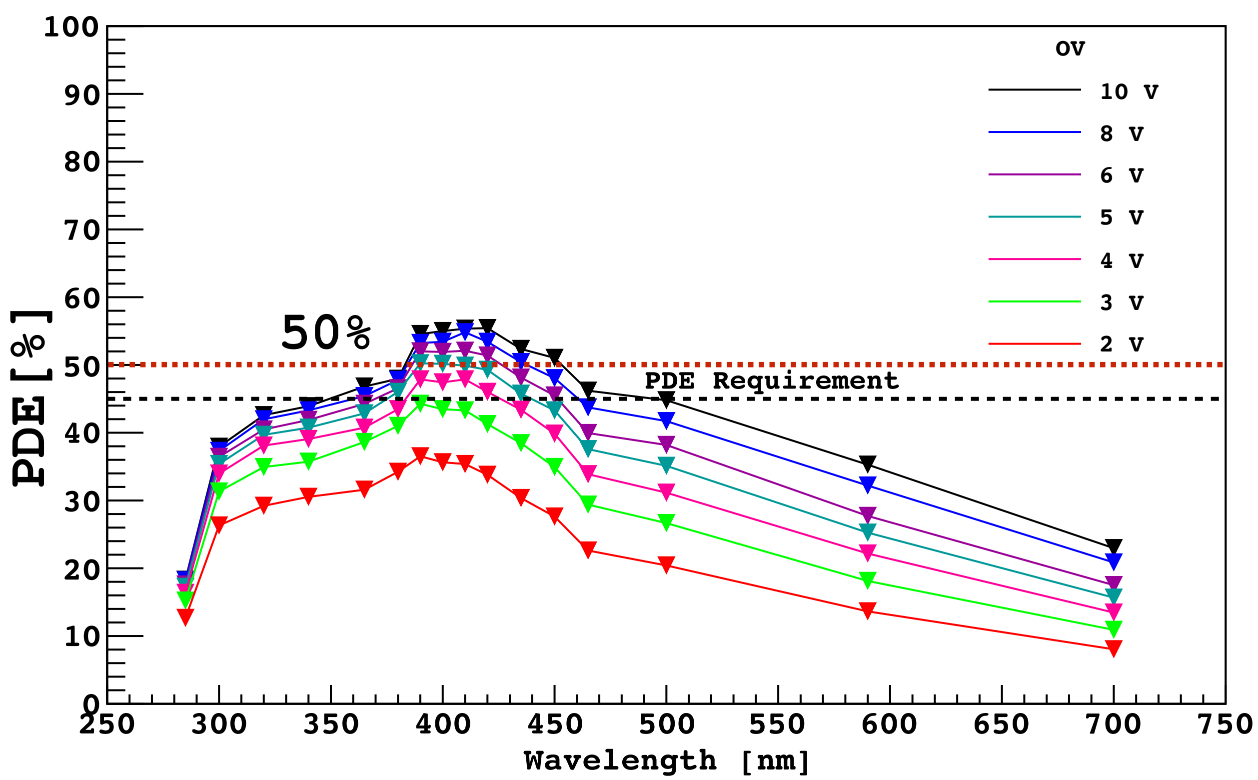
PDE

$$PDE = QE \cdot P_{01} \cdot FF$$

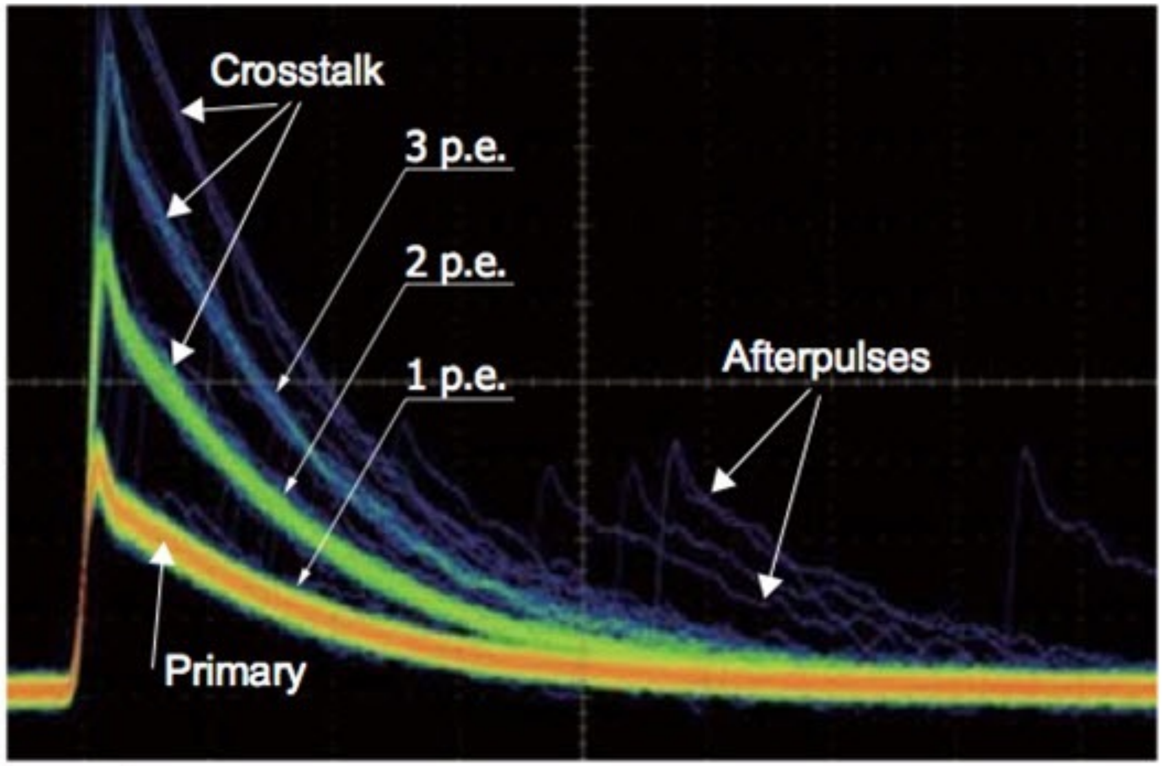


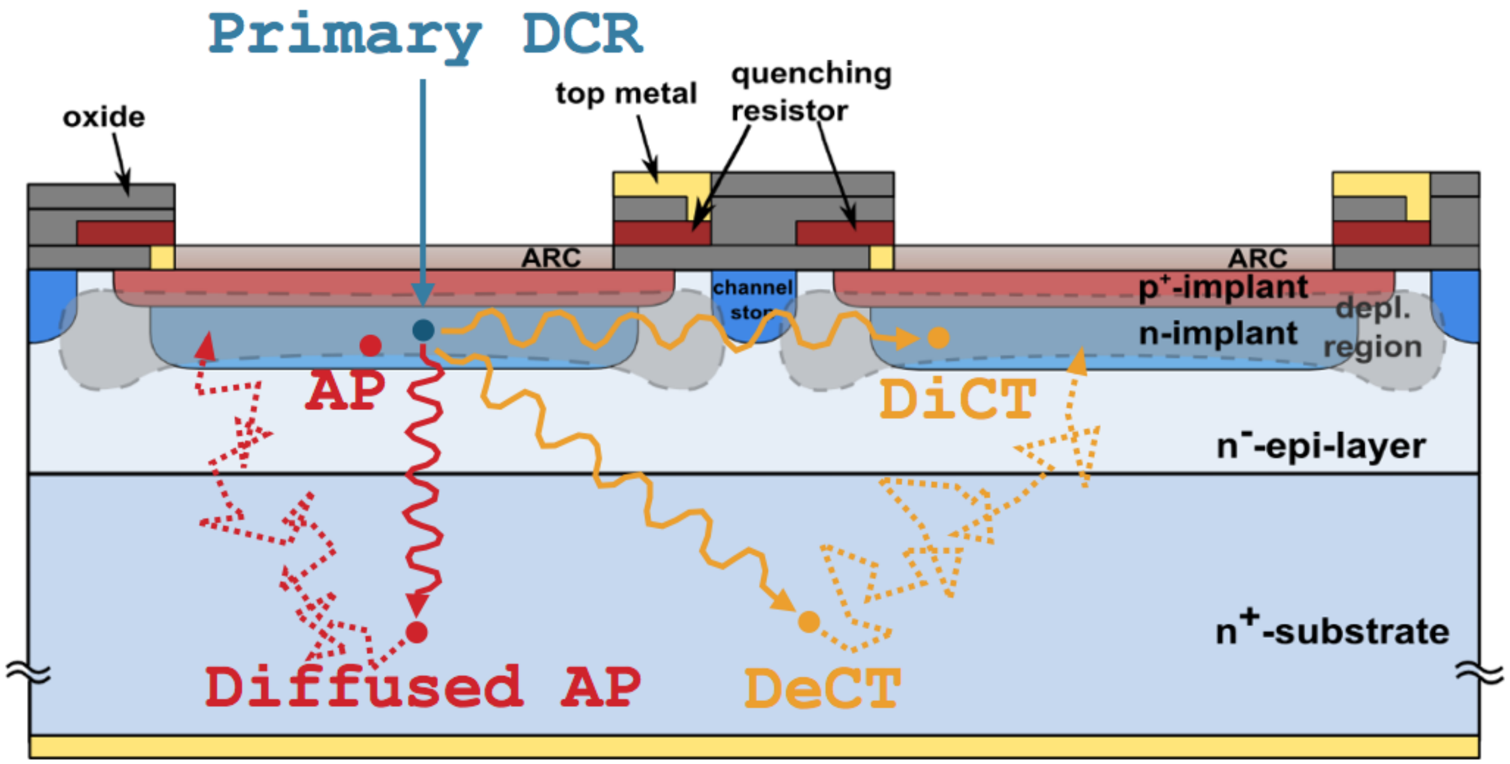






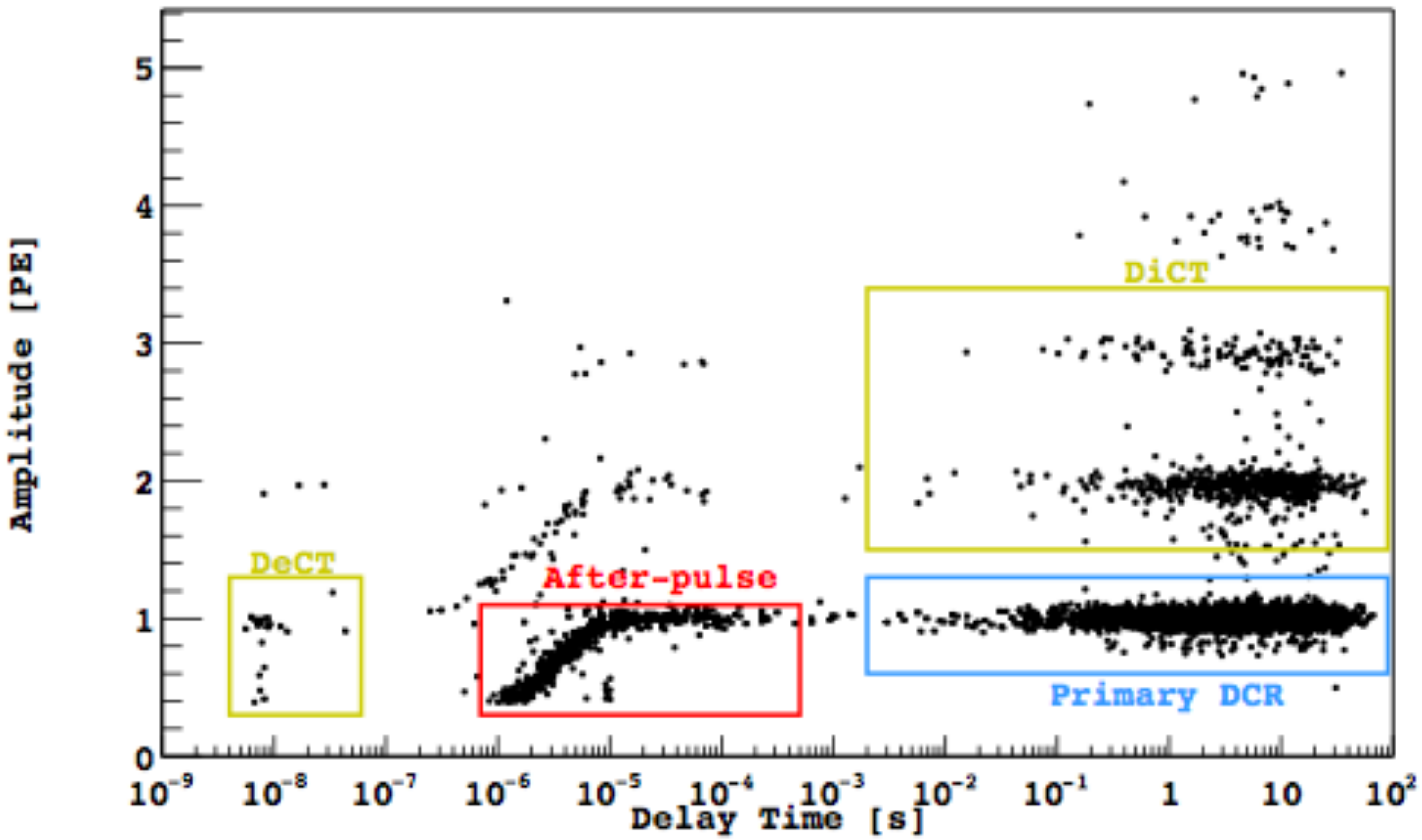
SiPM technology: noises





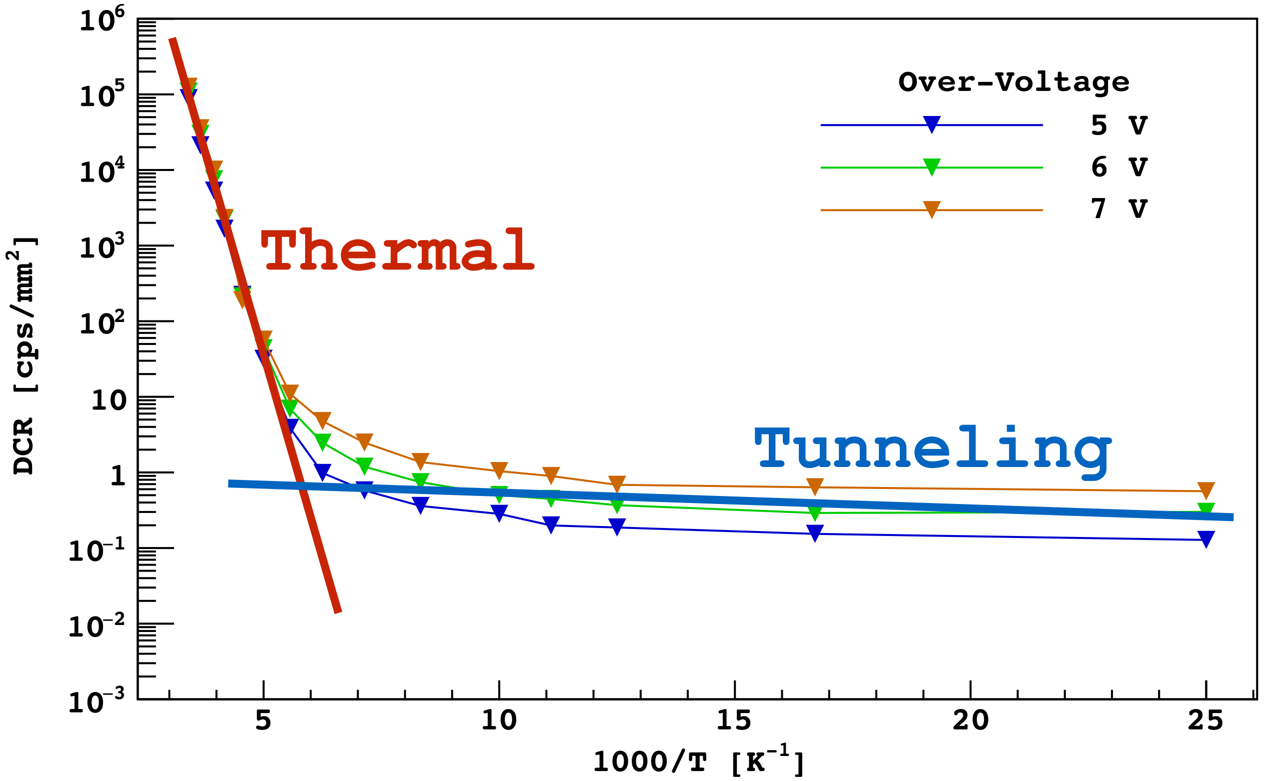
- Primary: DCR
- Correlated: DiCT, DeCT, AP

- An effective way to distinguish the several components of CN is a Amplitude vs Δt scatter plot.

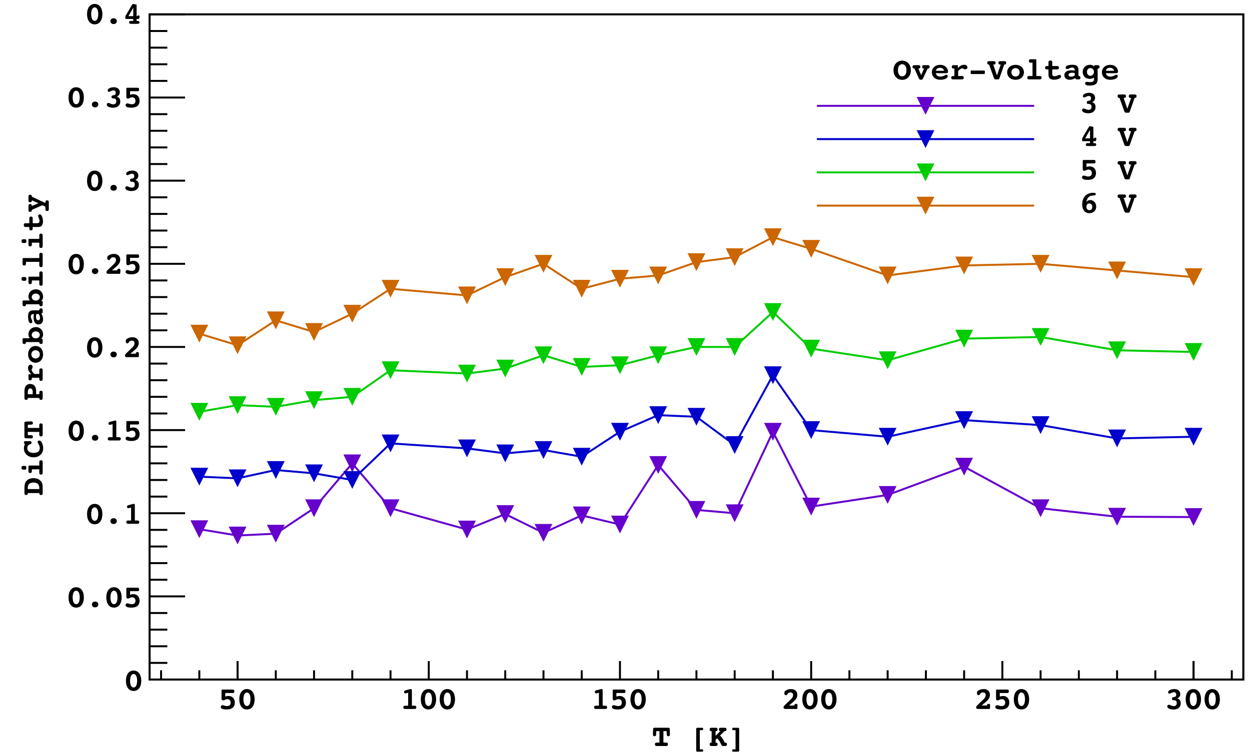


Noises vs Temperature

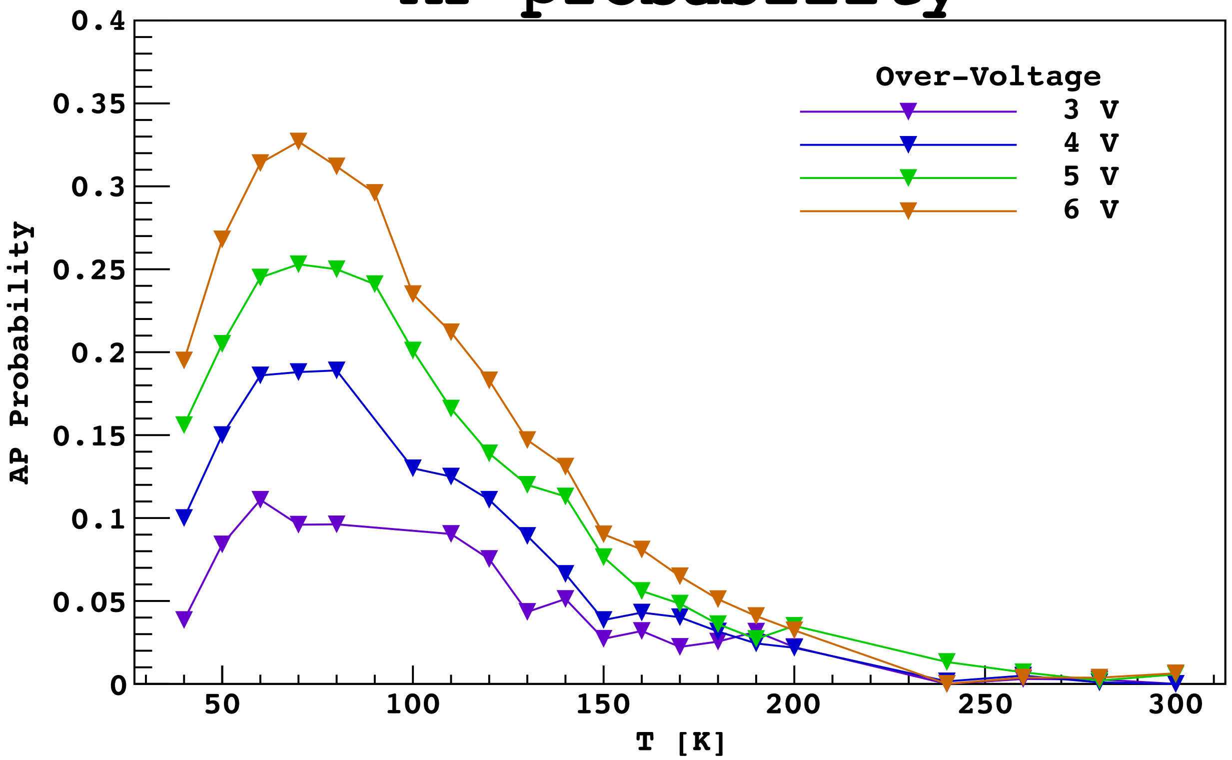
DCR



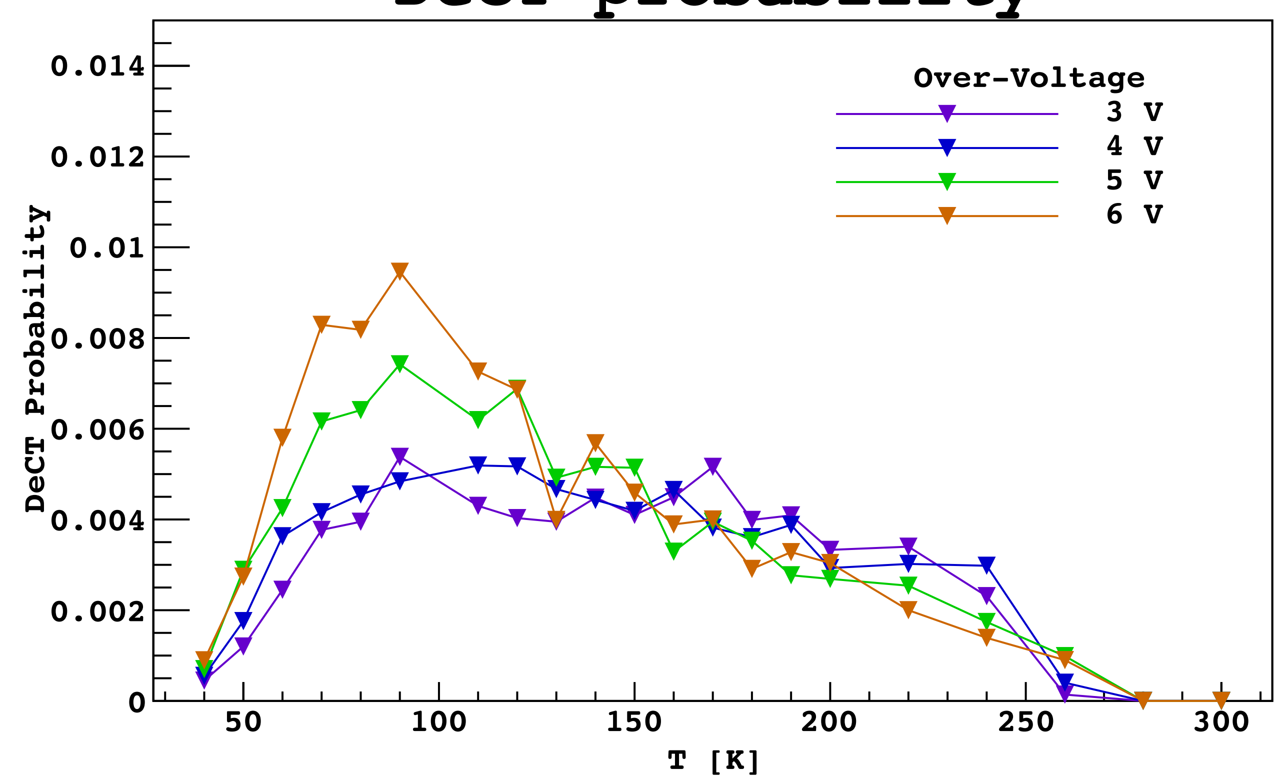
DiCT probability



AP probability



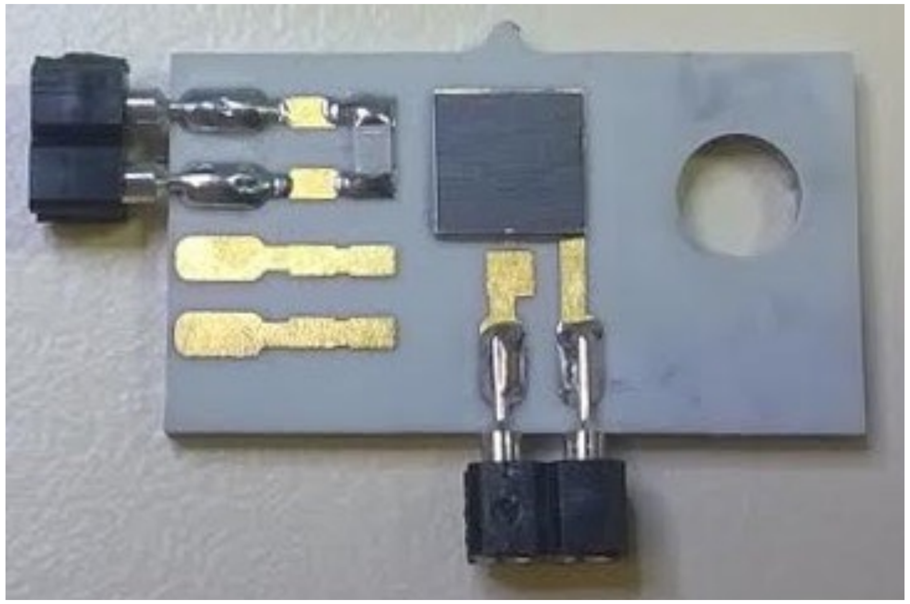
DeCT probability



PMT Vs SiPM

3″ diameter

4x4mm^2

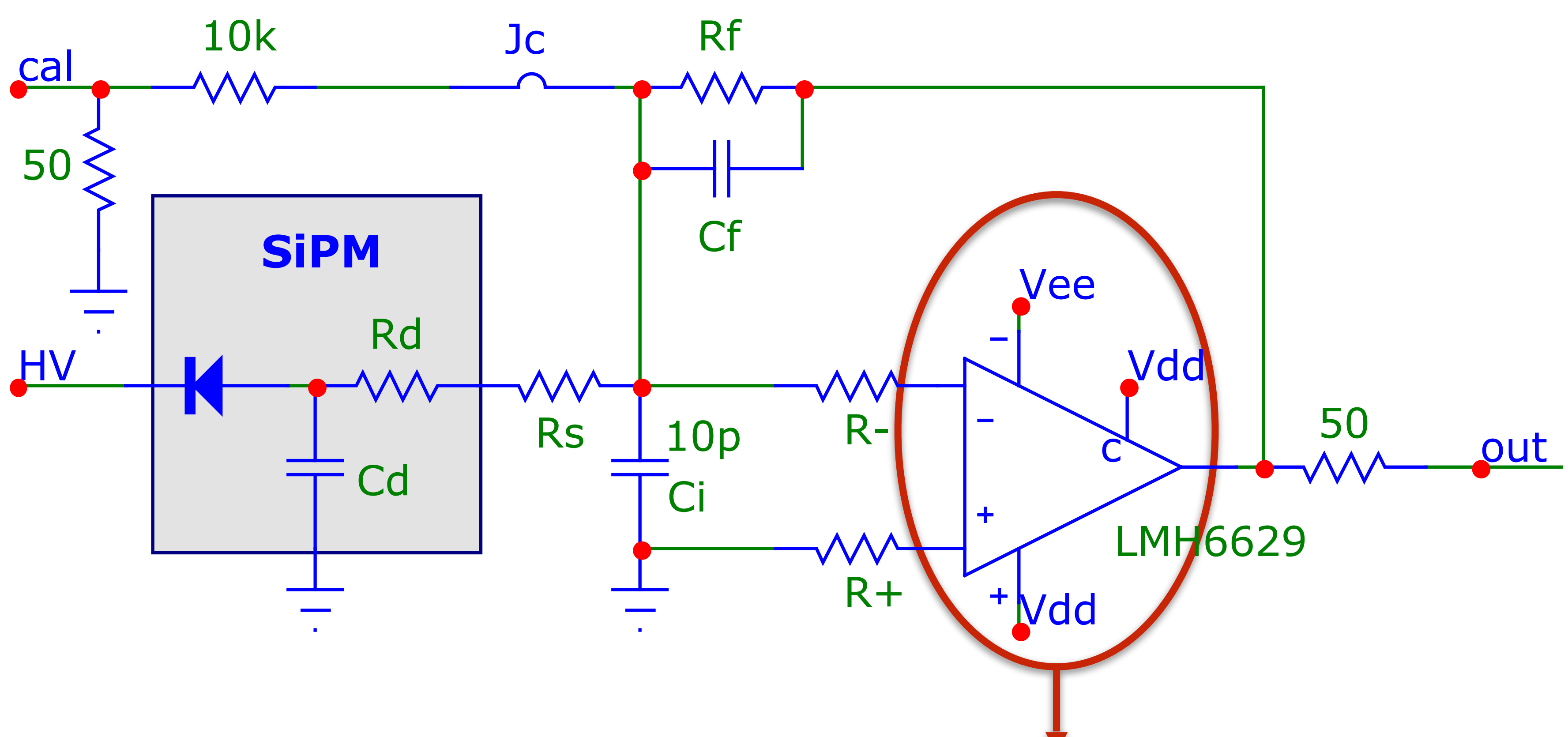


Comparison among commercial devices at CRYOGENIC temperature (87K)

	PMT	SiPM
Bias Voltage	~(1000-2000)V	~(30-40)V
Sensitivity to B fields	Yes	No
QE/PDE@420nm@300K	34%	(20-50)%
Packing efficiency	60%	(80-90)%
SPE resolution	20%	~(1-5)%
Dynamic range	>> 10^3	O(10^3)
Gain	10^6-10^7 nominal	O(10^6)
DCR	O(1cps/PMT)	(10-100)cps/mm^2

Electronics: a fast cryogenic pre-amp

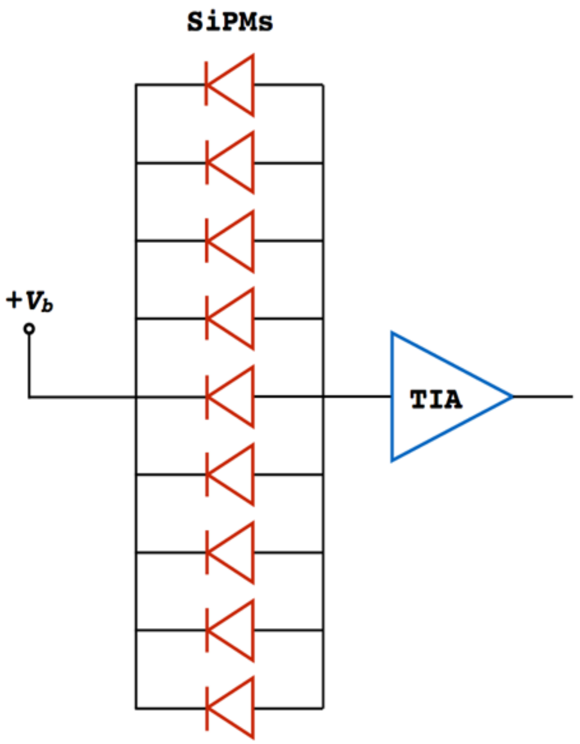
- Pre-amplification is needed near the photo-sensor.
- SiPMs are current generators and present a huge output capacitance (~50pF/mm^2).
- A Transimpedance amplifier (TIA) is the most suitable choice: **High Bandwidth** and **Low Noise** at cryogenic temperatures.

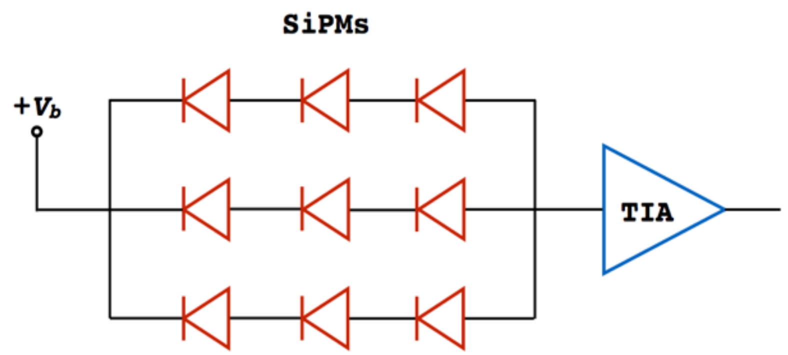


But a high BW, Low-Noise Op.Amp. is needed!
(and should be stable at 87K)

SiPM Tiling

Not a trivial task:
- **Signal from 1 SiPM, noise read-out from all SiPMs.**
- **Huge input capacitance reduces the BW of the system.**



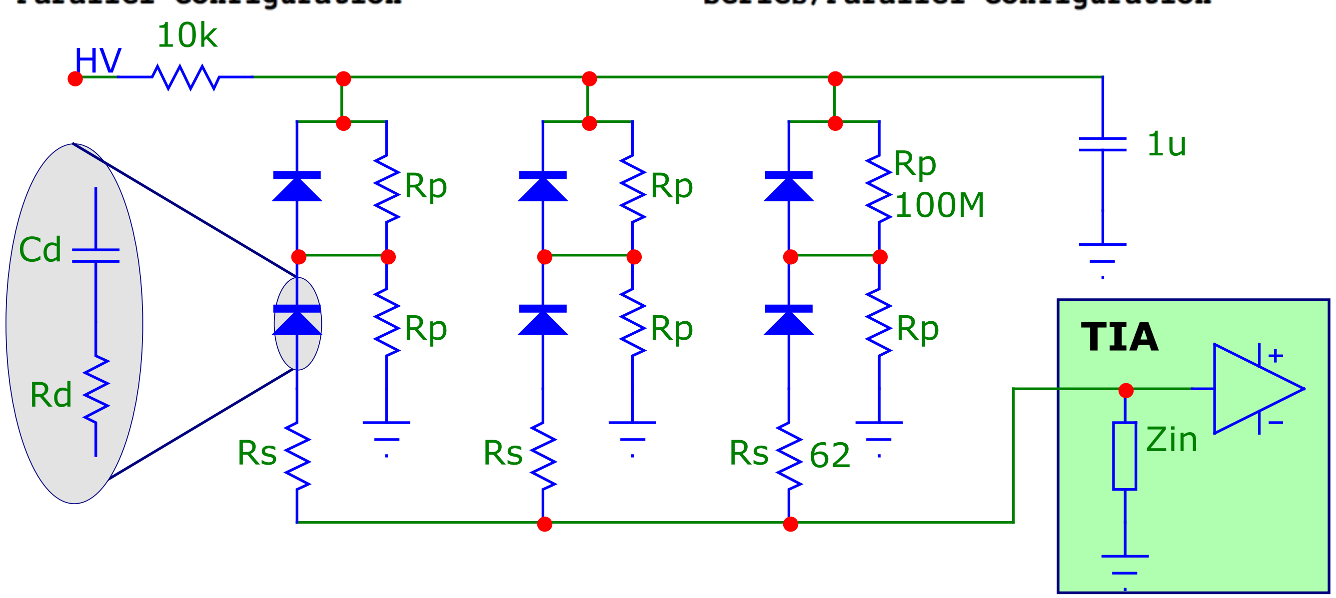


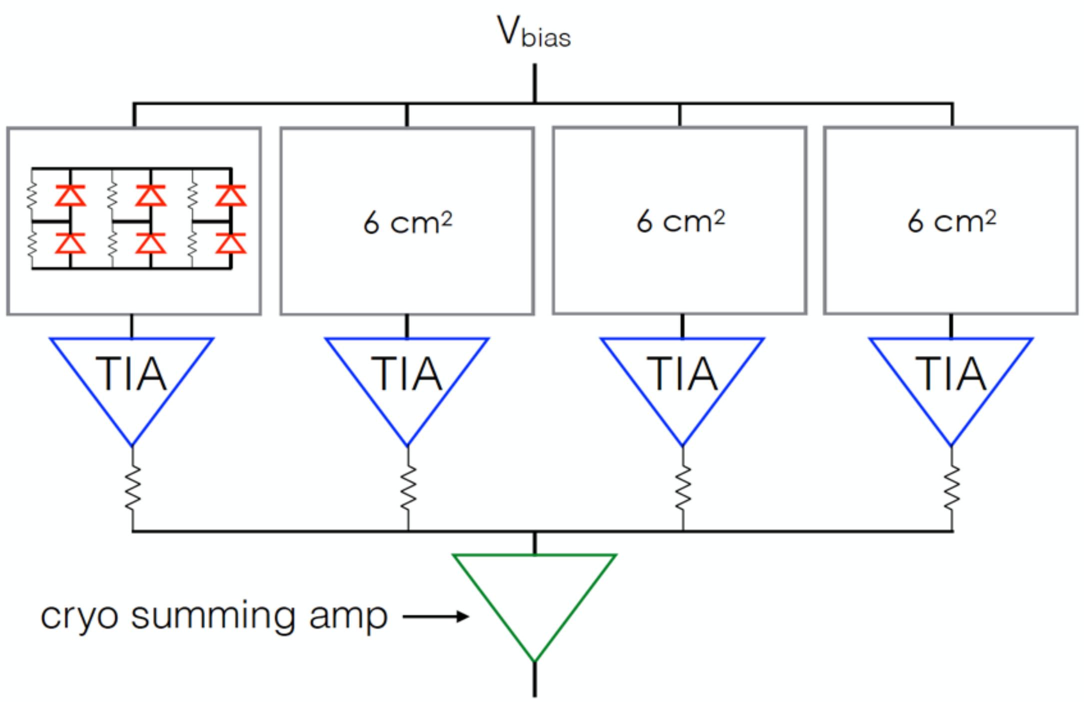
$$SNR_{9p} = \frac{S_1}{3N_1} = \frac{1}{3}SNR_1$$

$$SNR_{3s3p} = \frac{S_1/3}{N_1} = \frac{1}{3}SNR_1$$

- **Total Noise ∝ $\sqrt{C_{in}}$**
- **Signal divided n_{series}**
- **Same BW of 1 SiPM**

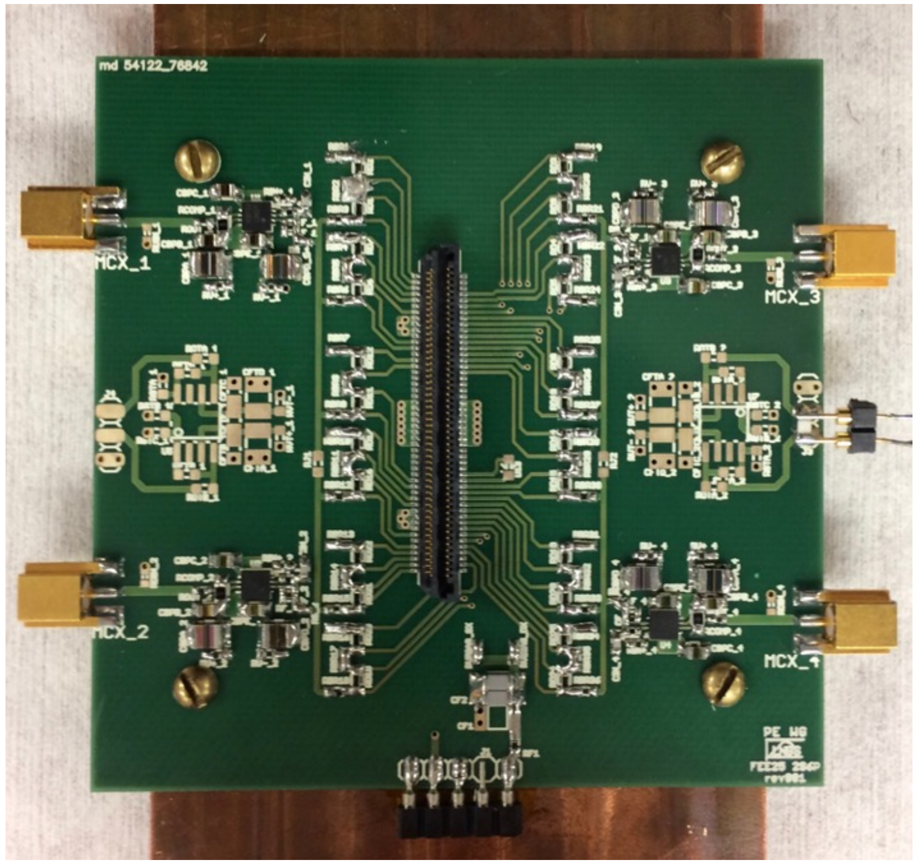
Parallel Configuration **Series/Parallel Configuration**

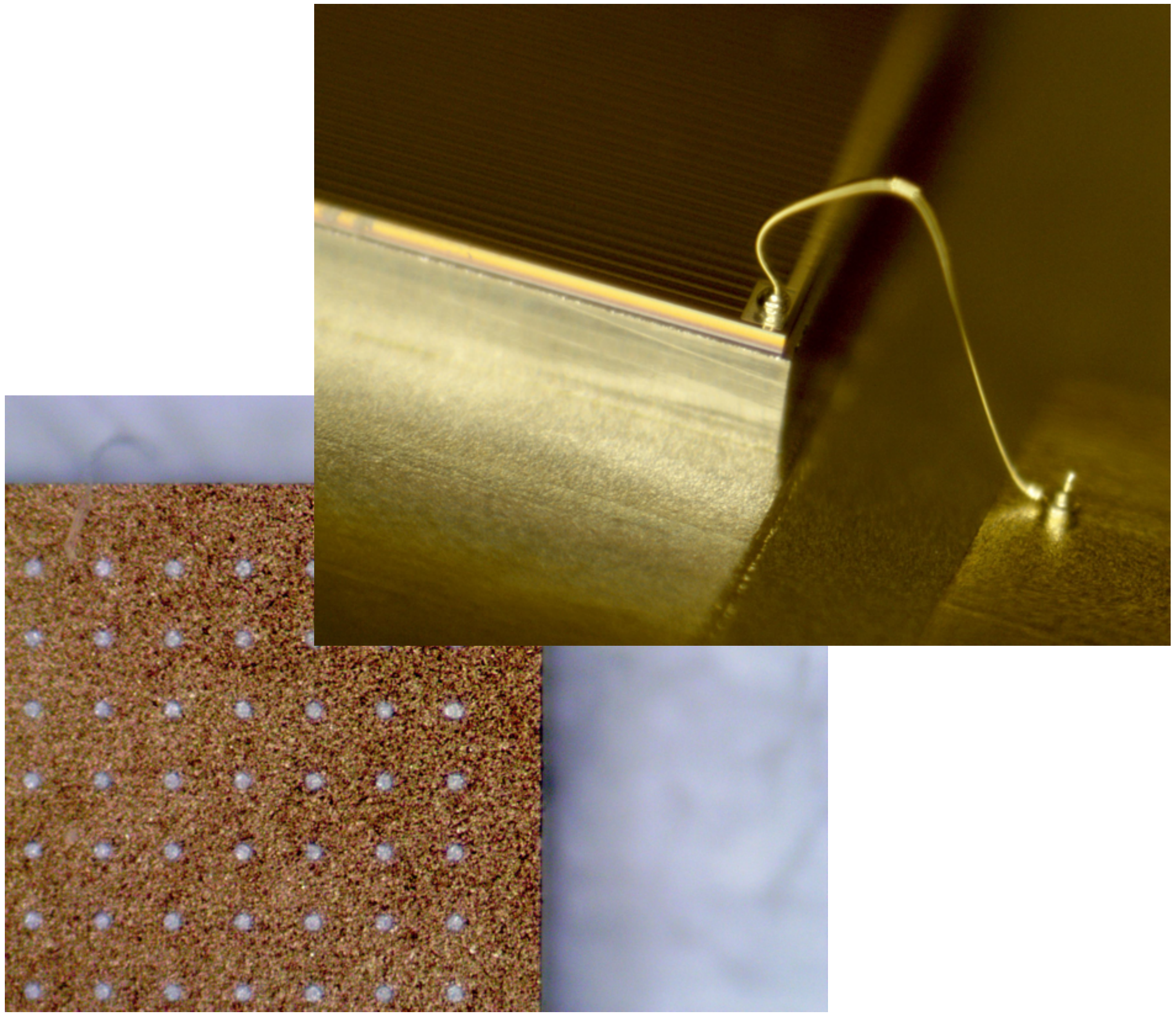


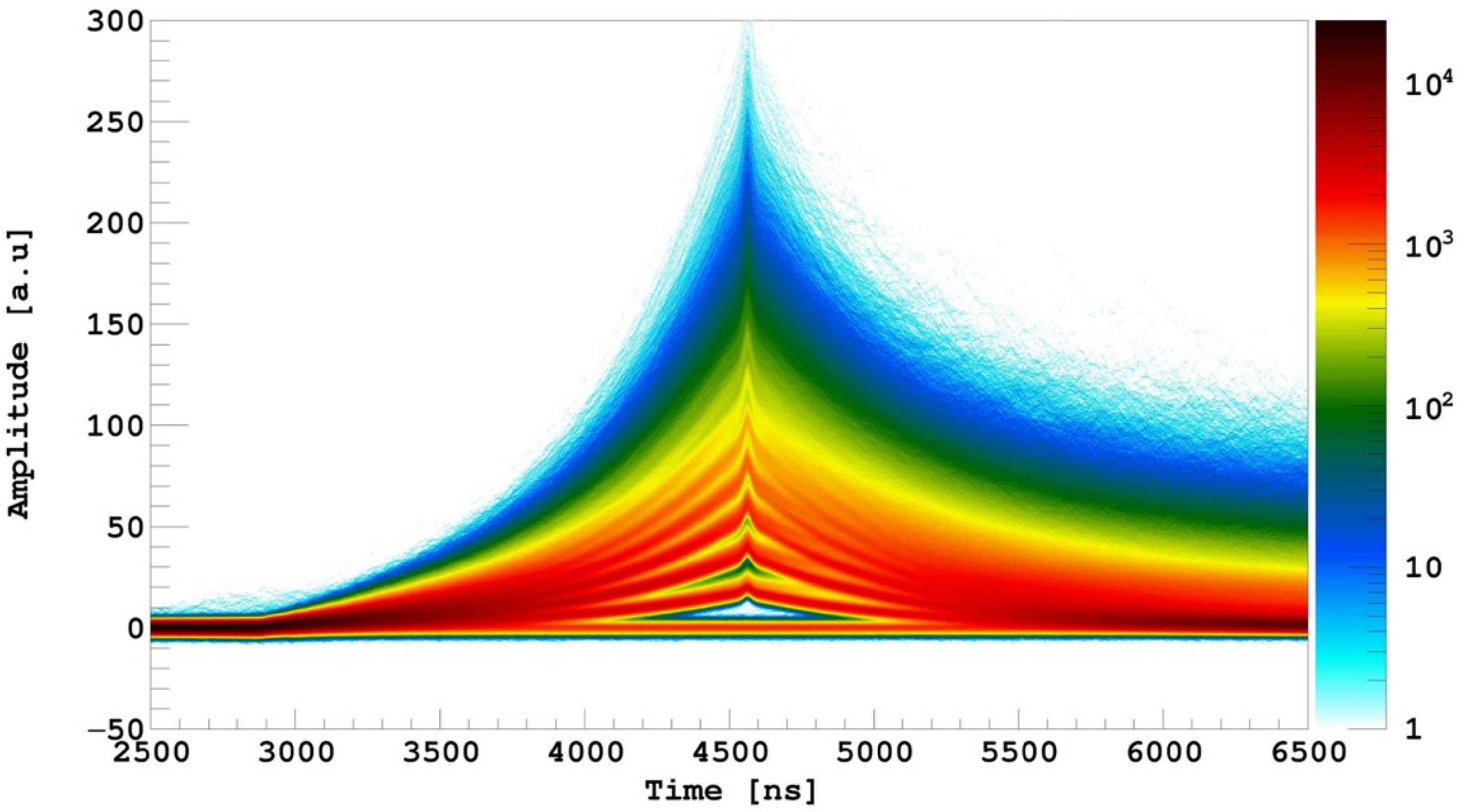


There's no such thing as free lunch

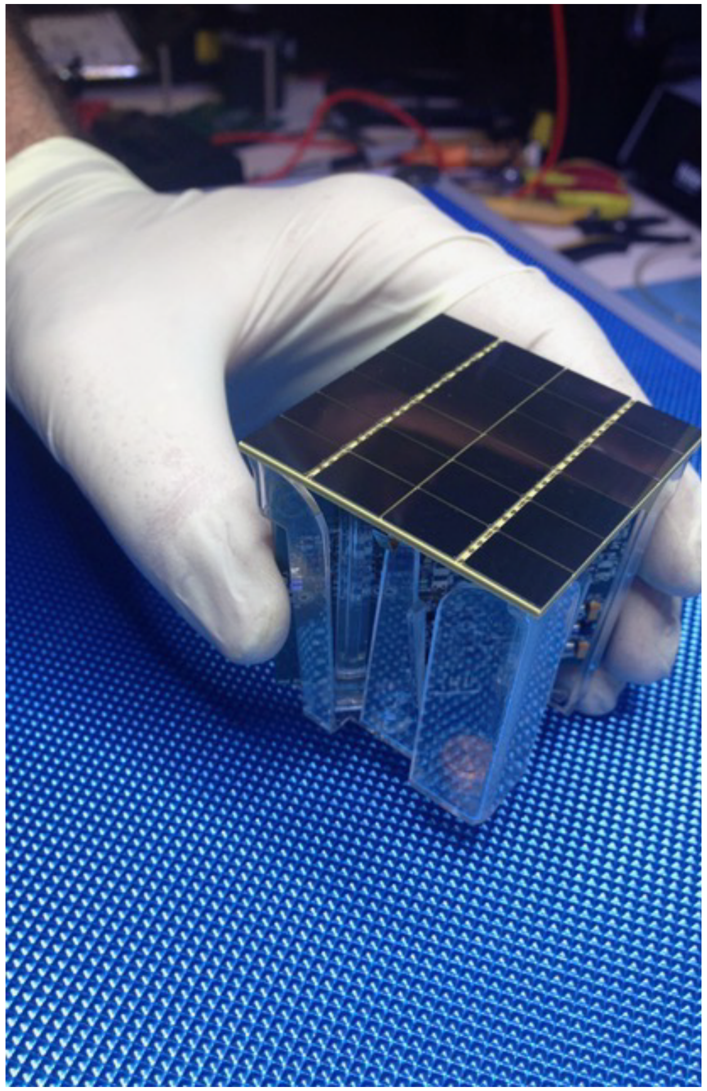
1. Discrete electronics radiopurity
2. Packaging
3. Signal filtering

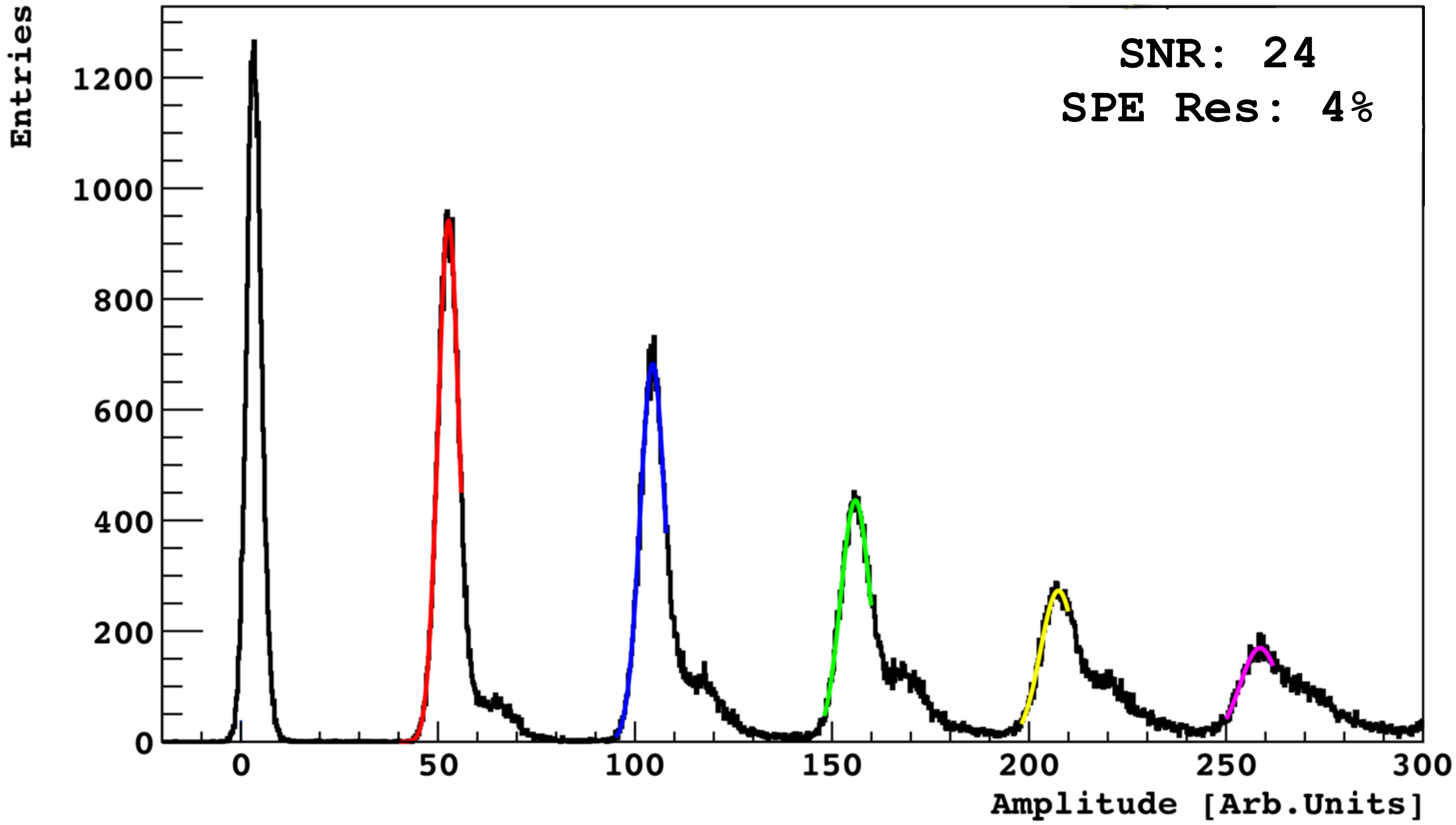


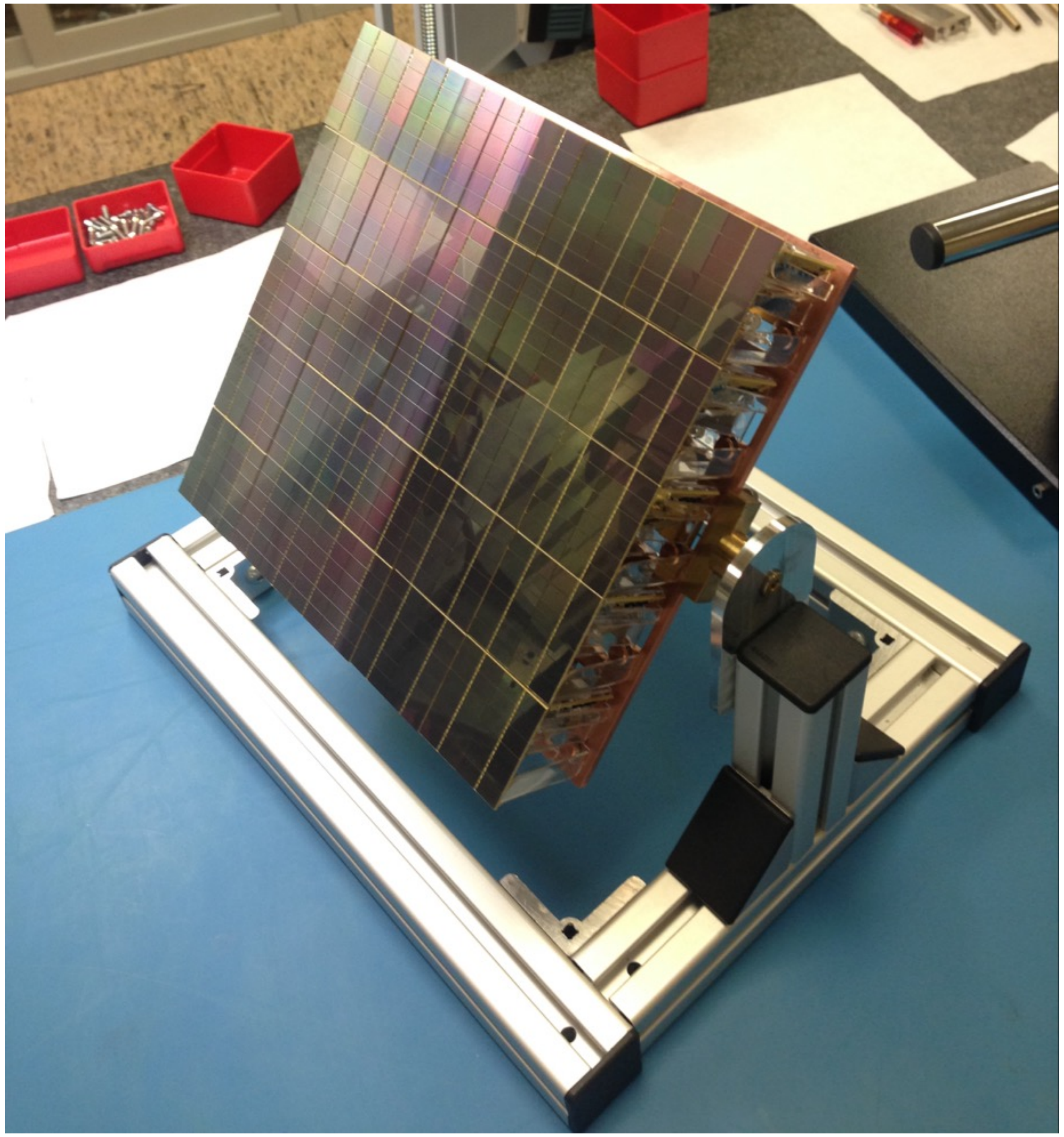




Prototype Tile performances

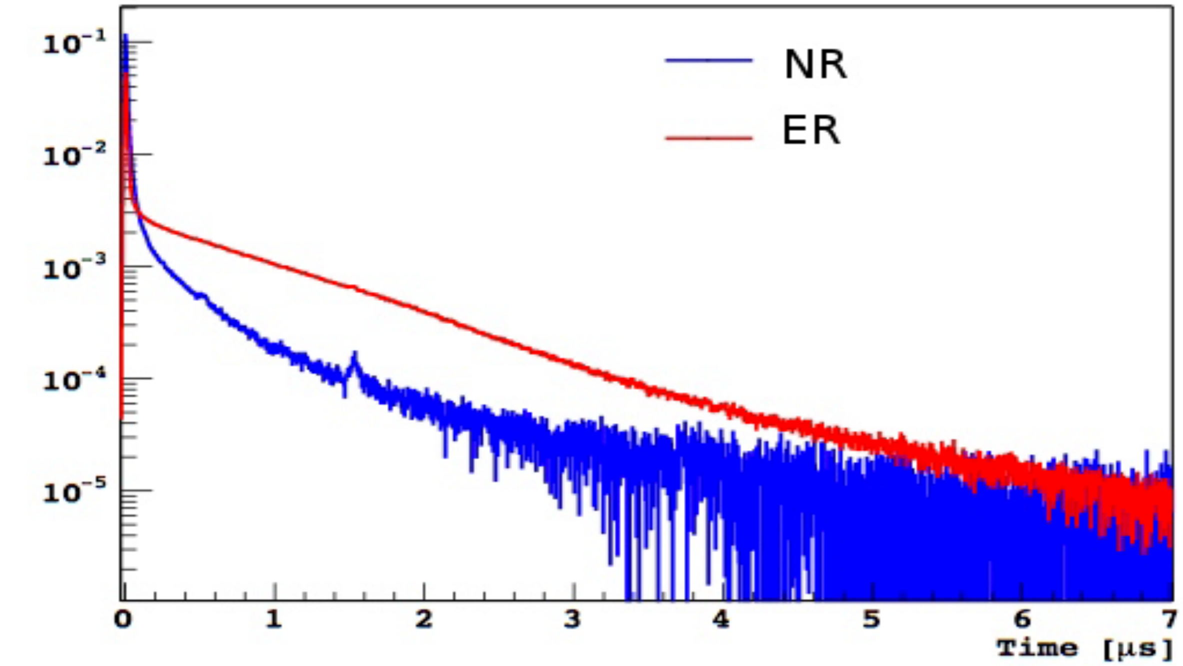






Thank you for the attention!

ER/NR identification via PSD

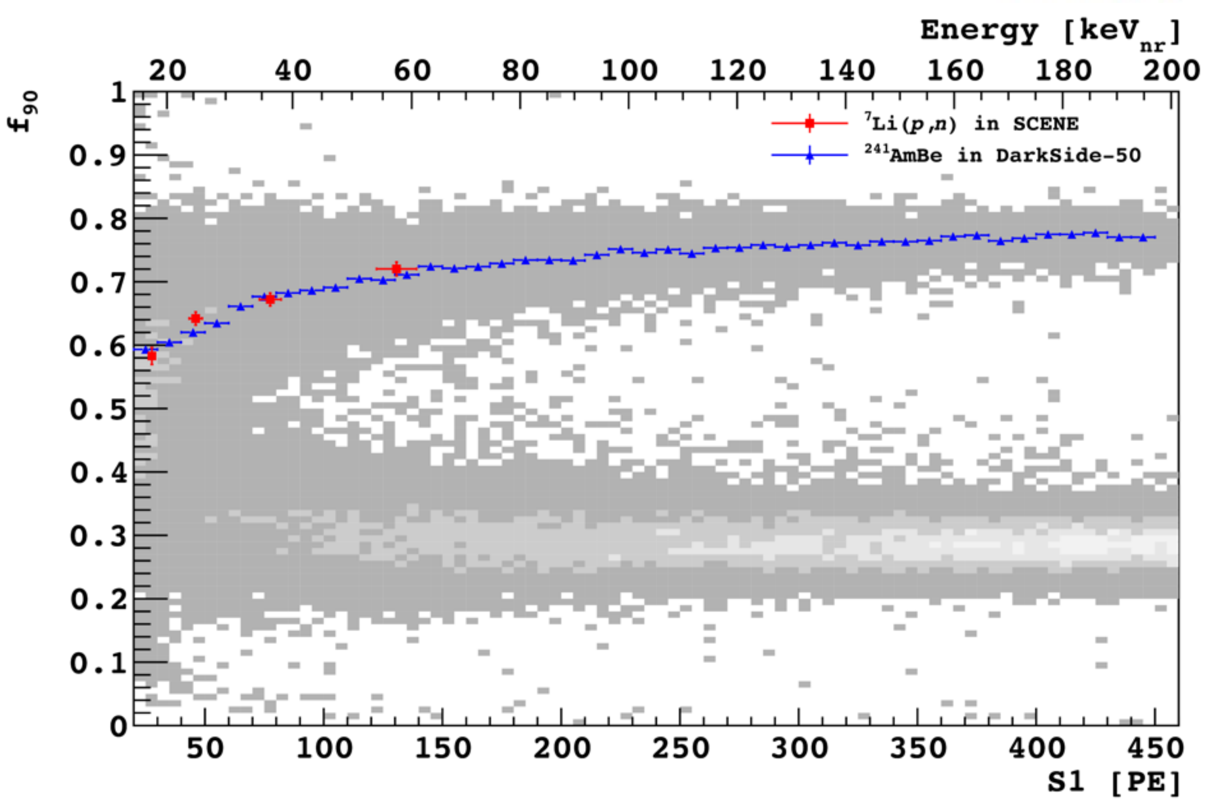


LAr scintillation light has 2 decay times: τ_{fast}=7ns, τ_{slow}=1600ns

Discriminating variable:

$$f_{prompt} = \frac{\#\ \text{prompt photons}}{\#\ \text{total photons}}$$

In DS-50 90ns is the optimal time window to optimize PSD.



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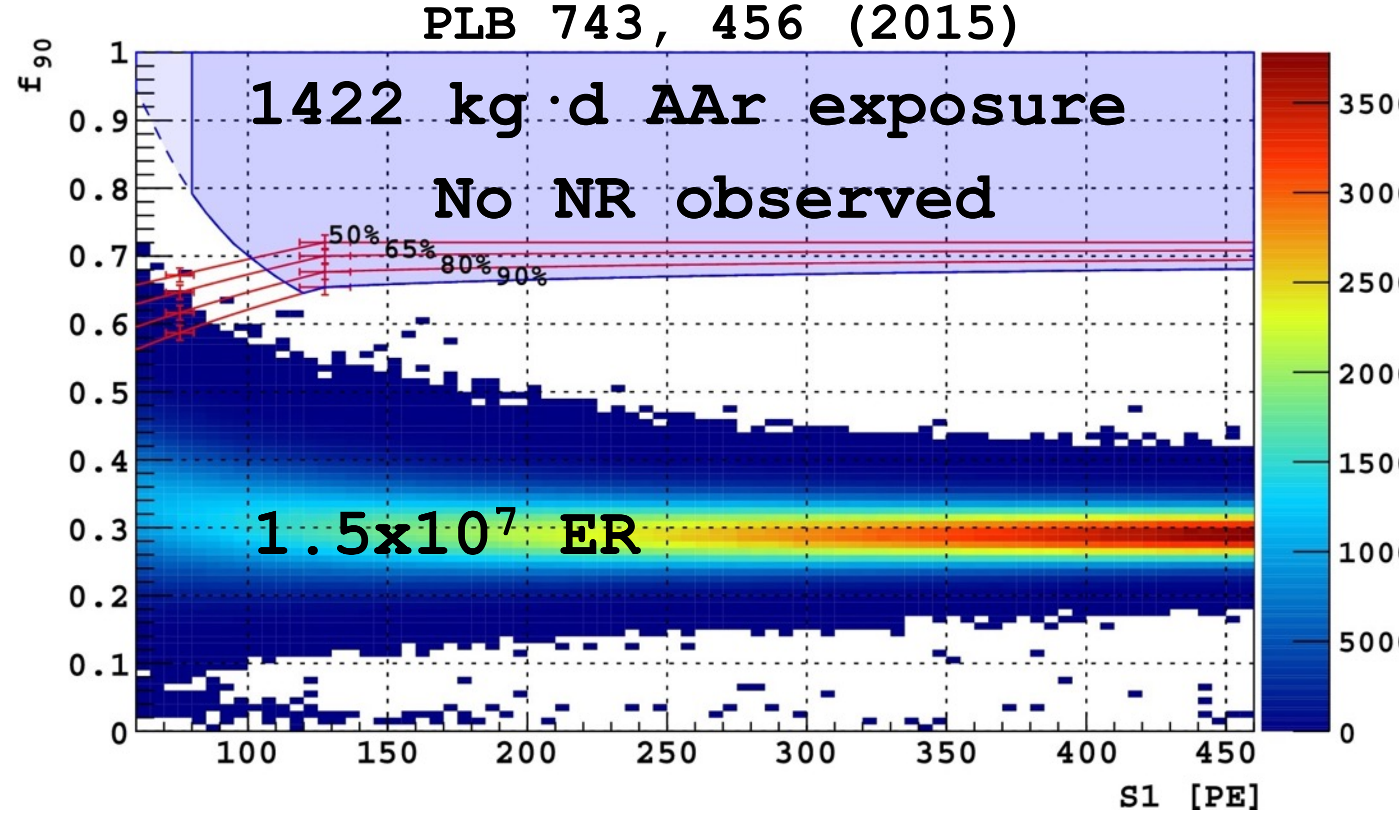
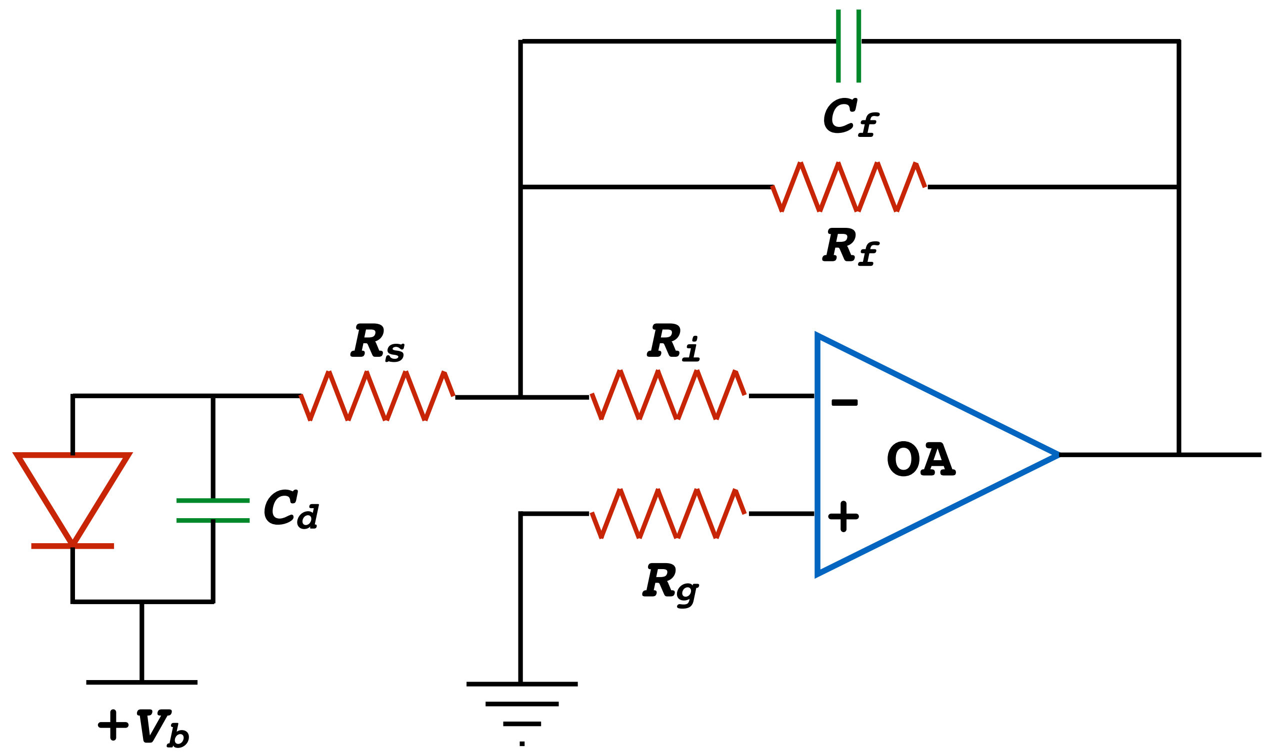


ER and NR produce light with different τ_{fast}/τ_{slow} fractions.

Discrimination Power > 1.5 x 10^7
Background-free UAr exposure: 5.5ton·yr

TIA working principle

- A TIA transforms current pulses in voltage pulses.
- Amplification is achieved “shaping” the open loop gain of the OA through a feedback on the inverting pin.
- Noise at the output of the system has 3 sources:



Noise Gain ↑   Transfer function ↑

$$V_n^2(f) = e_n^2|NG(f)|^2 + \left(i_n^2 + \frac{4k_bT}{R_f}\right)|T_z(f)|^2$$

Voltage input noise density

Current input noise density

Johnson-Nyquist noise