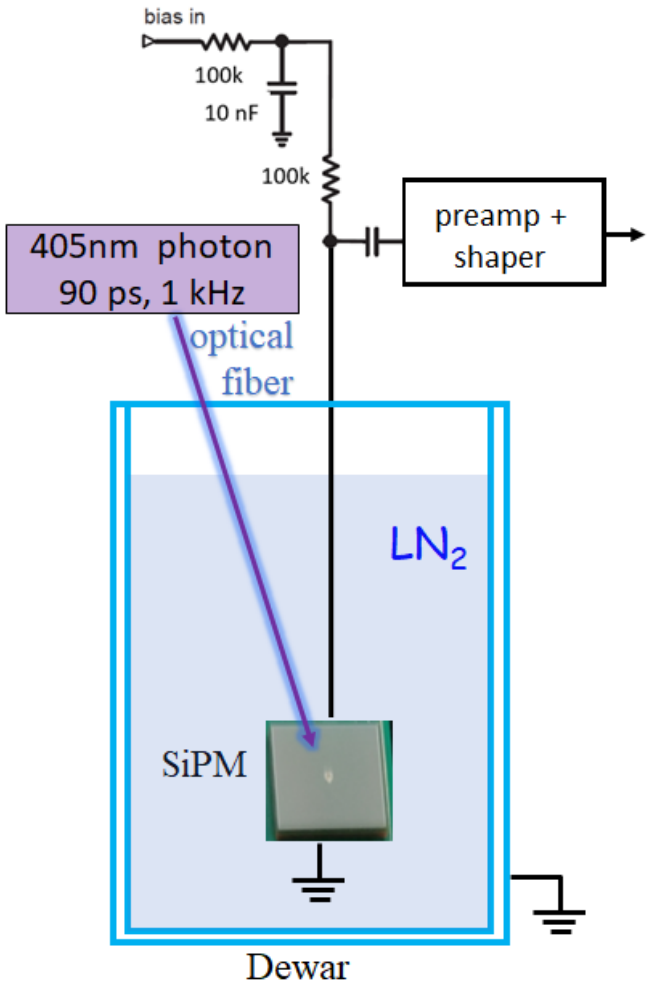
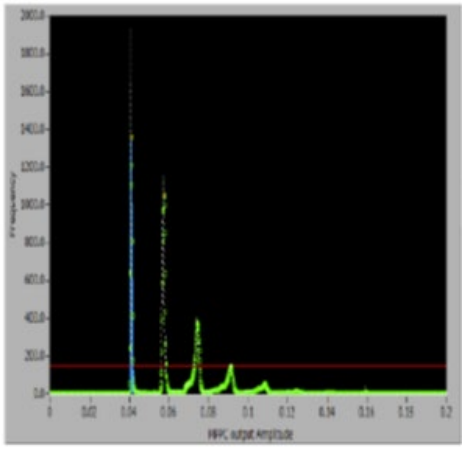
PDE is calculated by fitting a Poisson distribution to the photoelectron spectrum





$$\bullet P(n, x) = \frac{n^x e^{-n}}{x!}$$

n: average number of photons detected by MPPC
x: number of photons detected by MPPC

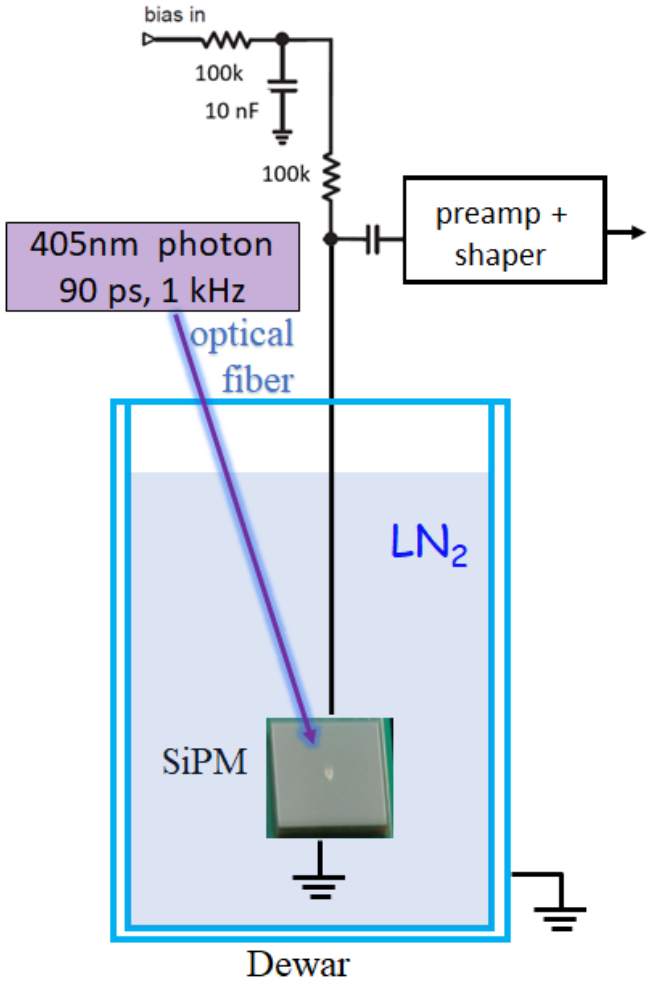
$$\bullet P(n, 0) = \frac{\left(\frac{N_{ped}}{N_{tot}}\right)}{\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)} \quad (\text{<- dark pulse correction})$$

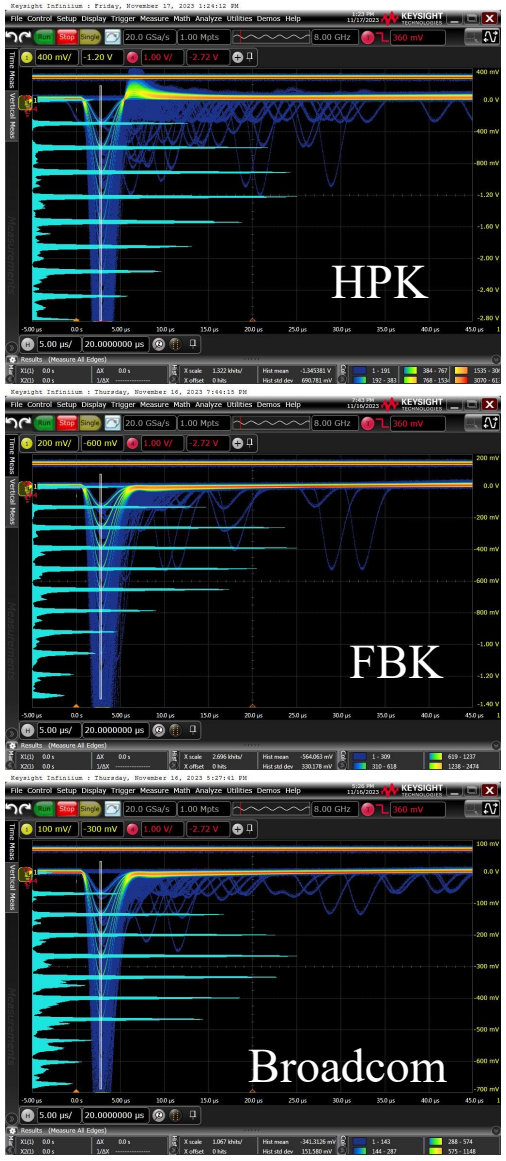
N_{ped} : number of events at 0 p.e. during pulsed light measurement
N_{tot} : number of all events during pulsed light measurement
N_{ped}^{dark} : number of events at 0 p.e. in dark state
N_{tot}^{dark} : number of all events in dark state

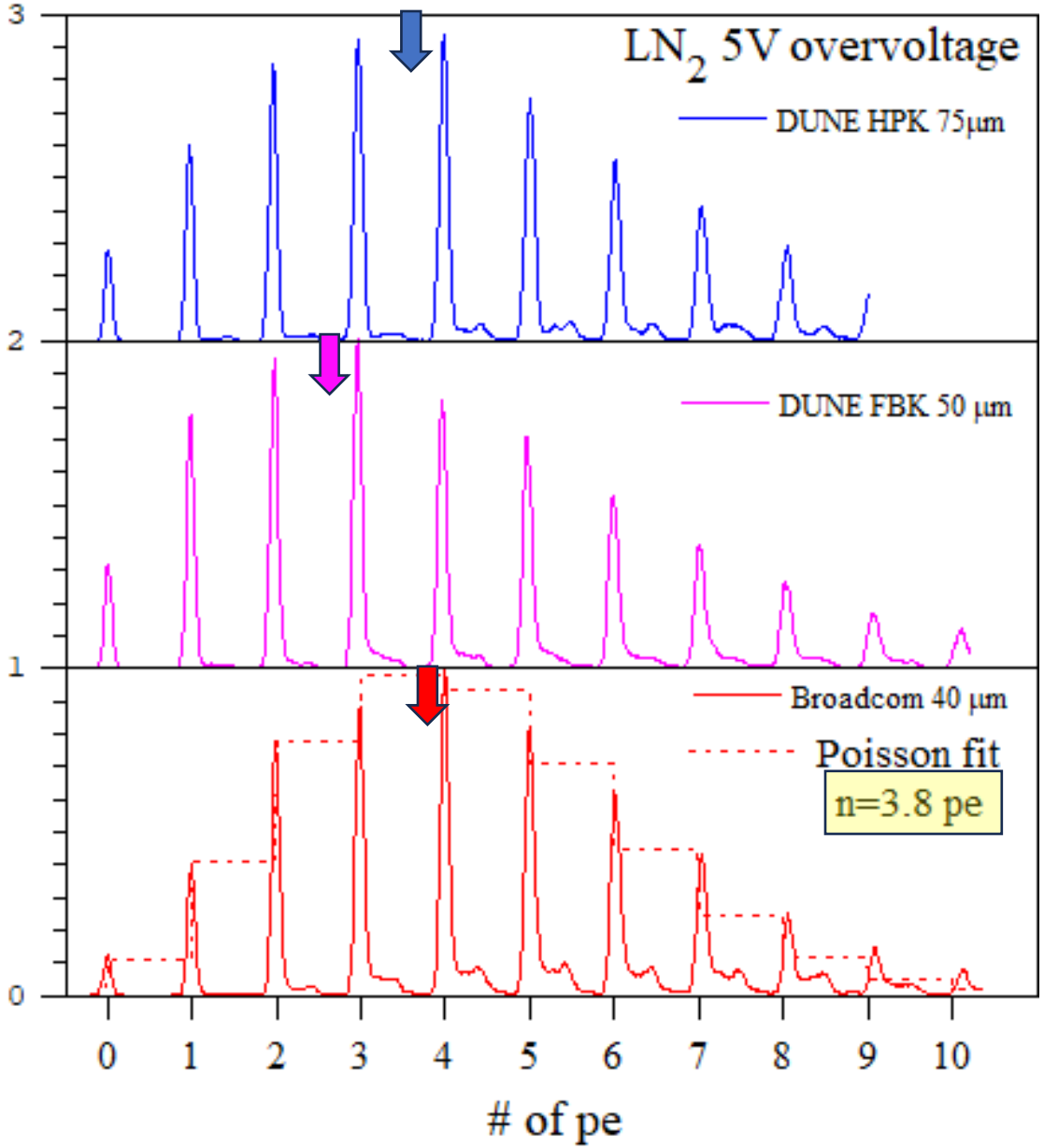
$$n = -\ln\left(\frac{\frac{N_{ped}}{N_{tot}}}{\frac{N_{ped}^{dark}}{N_{tot}^{dark}}}\right) = -\ln\left(\frac{N_{ped}}{N_{tot}}\right) + \ln\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)$$

n = Poisson fitted mean number of photoelectrons

relative PDE in LN_2 (Broadcom, DUNE FBK, DUNE HPK)







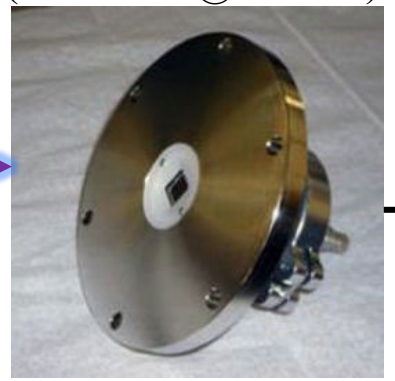
Number of incidence photons is determined from the measured photocurrent at the selected wavelength from a NIST calibrated photodiode

attenuate the intensity to a few photons/pulse

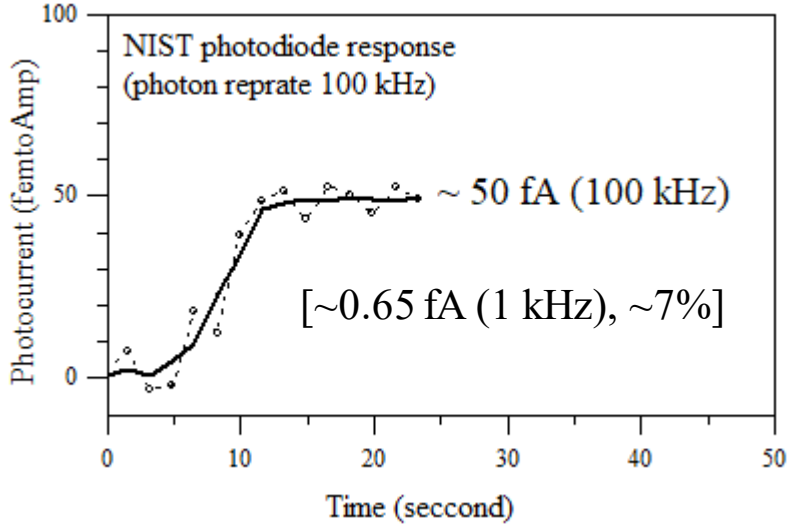
405nm photon
90 ps, 100 kHz

optical fibers

NIST calibrated pd
(0.19 A/W @ 405nm)



Electrometer
(average photocurrent)



$$\#\ of\ 405\ nm\ photons = \frac{0.65\ fA}{(1\ kHz)\left(0.19\frac{A}{W}\right)(1.6x10^{-19}J/eV)\ (3.06\ eV)}\ (0.86) =$$ 6.01 photons/pulse

PDE in LN_2 (Broadcom, DUNE FBK, DUNE HPK)

$$\mathrm{PDE} = \frac{\#\,\mathrm{pe}}{\#\,h\nu} = F_{\mathrm{geometry}} \times QE_{e-p}(\lambda, T) \times \varepsilon_{\mathrm{avalanche}}(\Delta V, \lambda, T)$$

geometric — photon — photoelectron

$$PDE\,(Broadcom, 405\,nm, 5V, LN_2) = \frac{\#\,photoelectrons\,out}{\#\,photons\,in} = \frac{3.8}{6.01} = 0.63$$

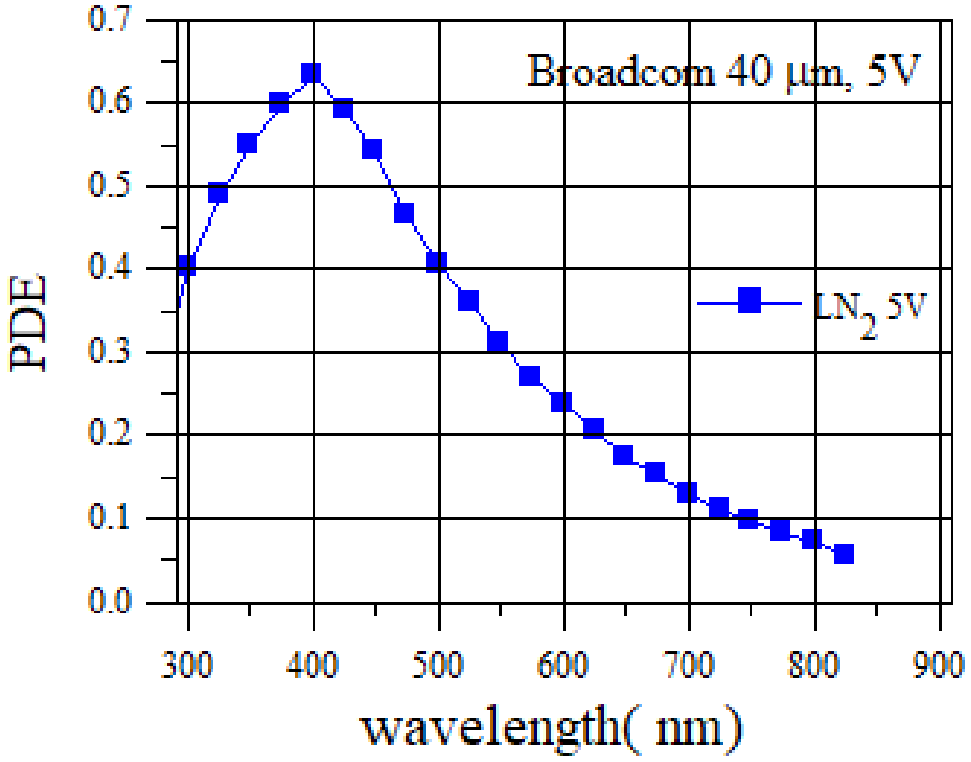
PDE @ 405 nm 5V OV in LN2	Poisson fitted n-pe	absolute PDE (±7%)	Spec. RT
DUNE HPK 75 µm	3.15	0.52	~0.47
DUNE FBK 50 µm	2.93	0.48	n/c
Broadcom 40 µm	3.8	0.63	~0.62

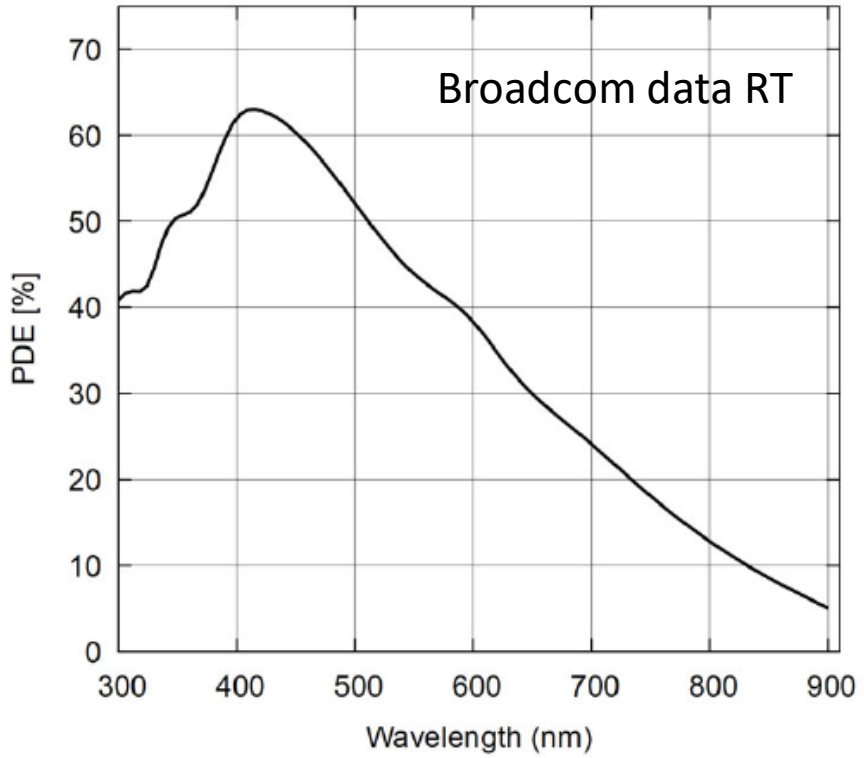
Broadcom: PDE spectral response – use white light source and calibrate against NIST photodiode

$$PDE_{\lambda} = [spectral\ reponse]_{\lambda} \times \frac{[PDE_{pulse}]_{405nm}}{[spectral\ reponse]_{405nm}}$$

noted: CT & AP – photoelectron effect, wavelength independent

PDE (QE) = photon effect, depends on wavelength





Broadcom: PDE spectral response – use white light source and calibrate against NIST photodiode

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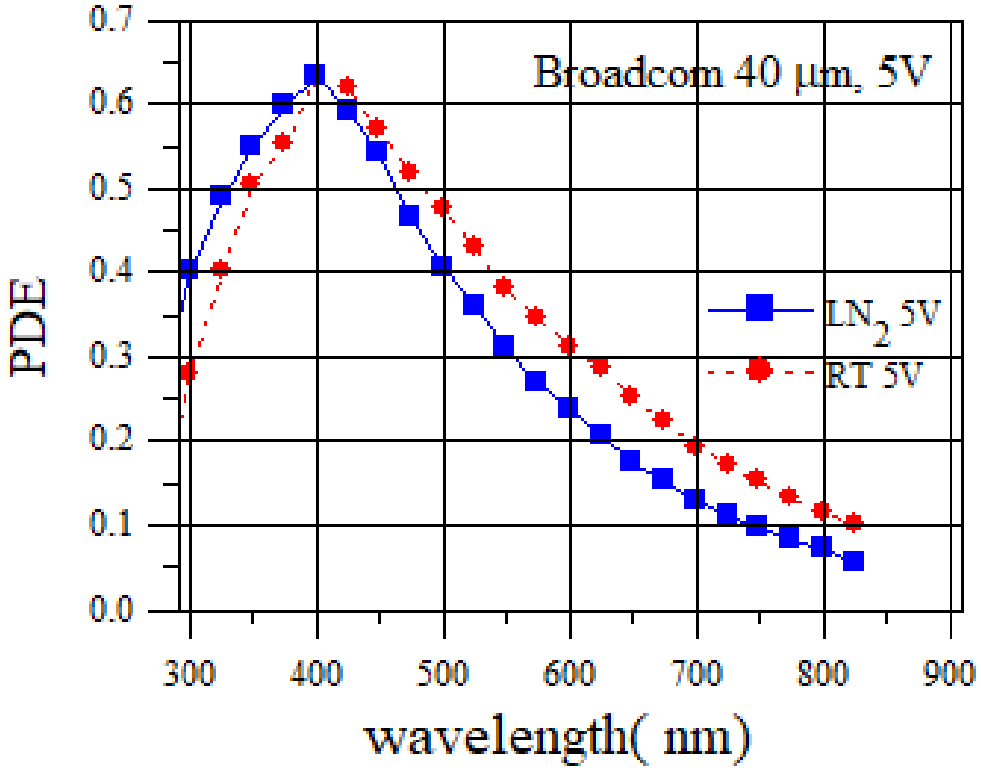
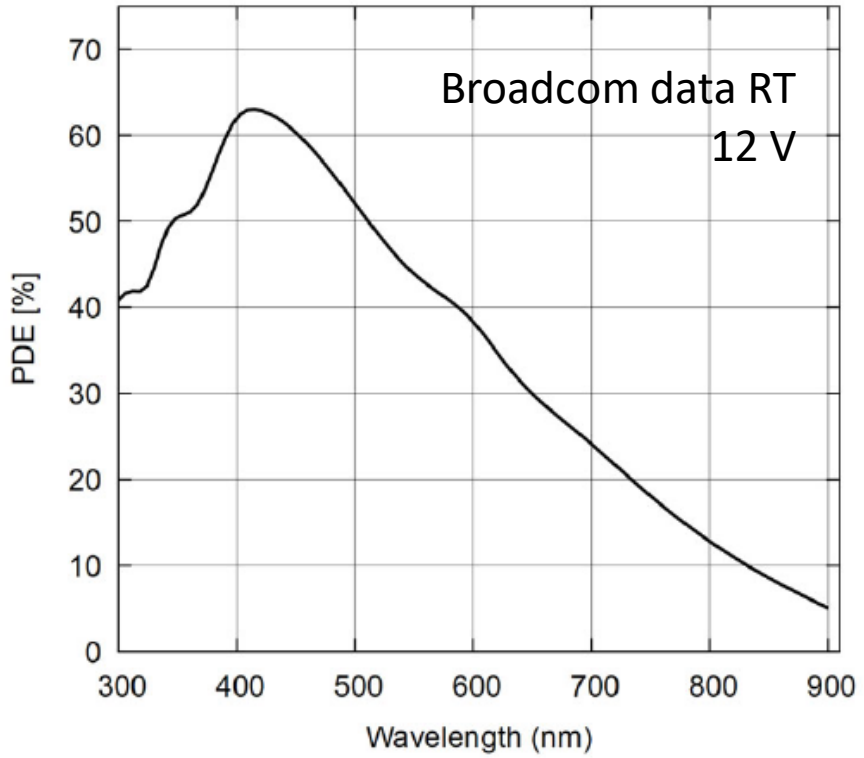
noted: CT & AP – photoelectron effect, wavelength independent

PDE (QE) = photon effect, depends on wavelength



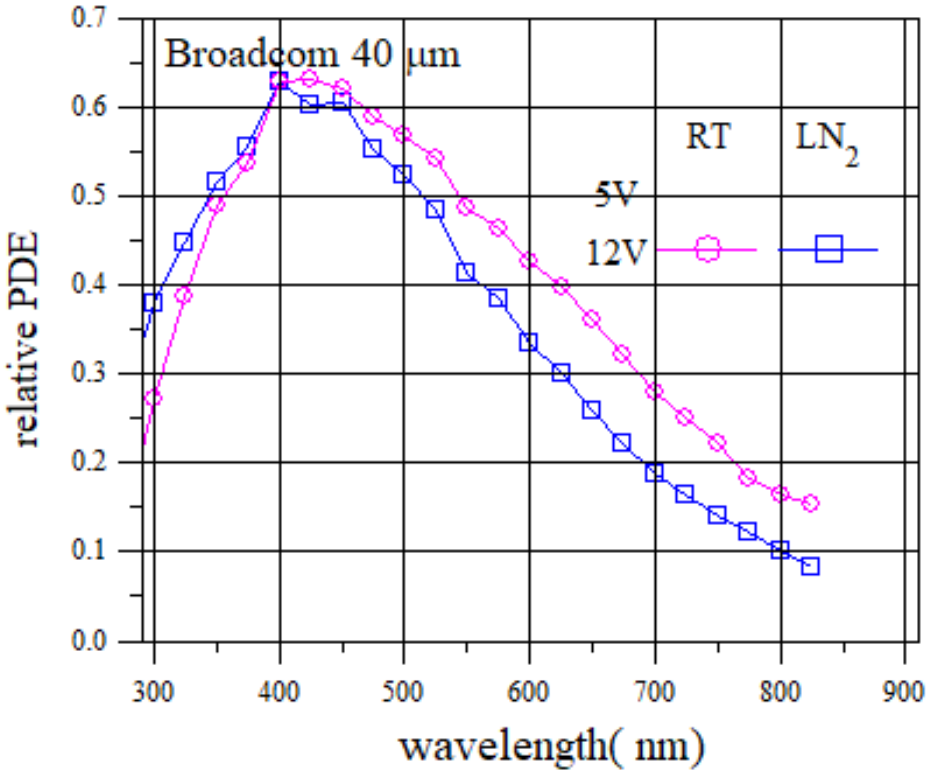


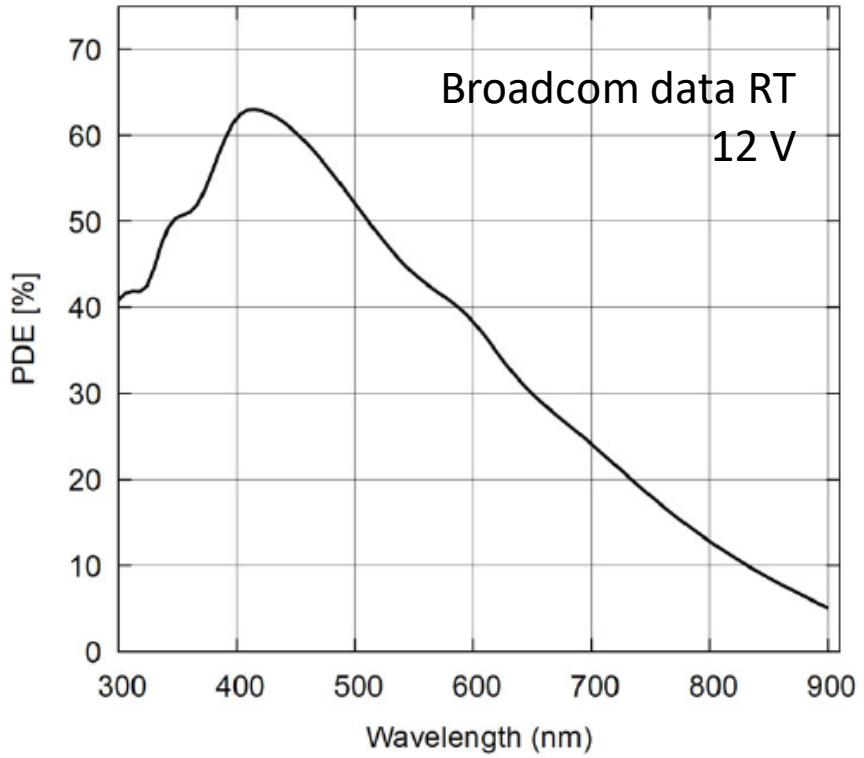
Broadcom: PDE spectral response – use white light source and calibrate against NIST photodiode

$$PDE_{\lambda} = [spectral\ reponse]_{\lambda} \times \frac{[PDE_{pulse}]_{405nm}}{[spectral\ reponse]_{405nm}}$$

noted: CT & AP – photoelectron effect, wavelength independent

PDE (QE) = photon effect, depends on wavelength





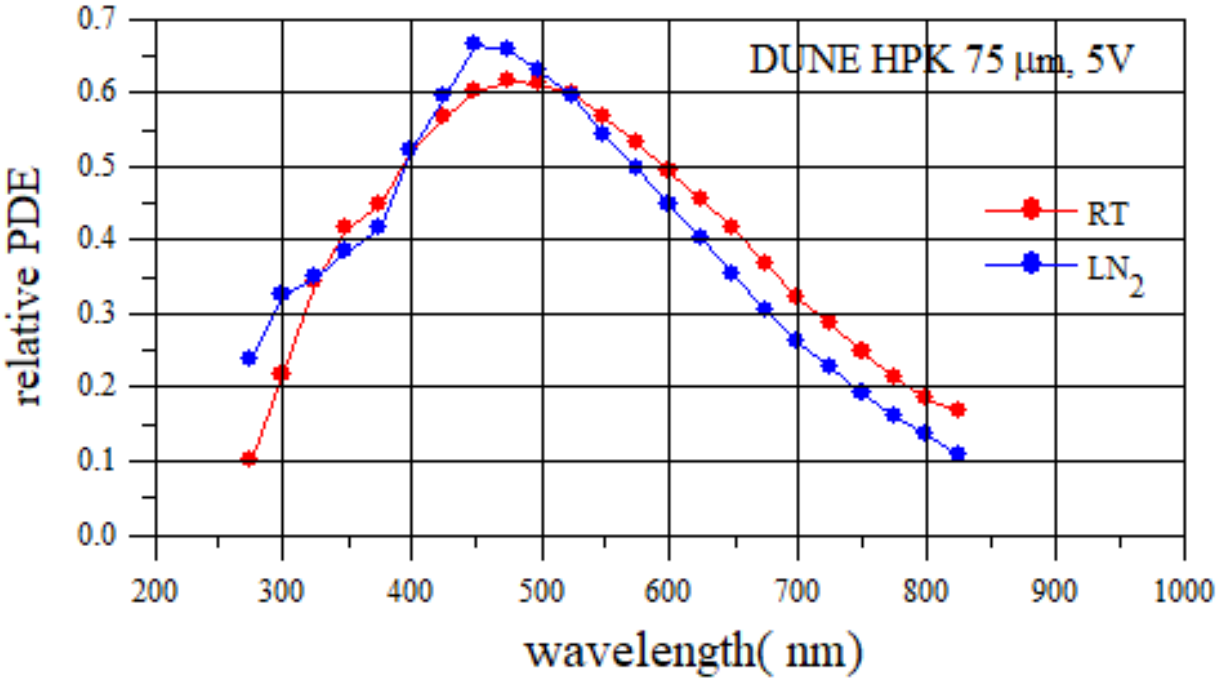
Spectral PDE response generally agrees with Broadcom (peak at ~410 nm) – but has a slight blue shift behavior in LN_2

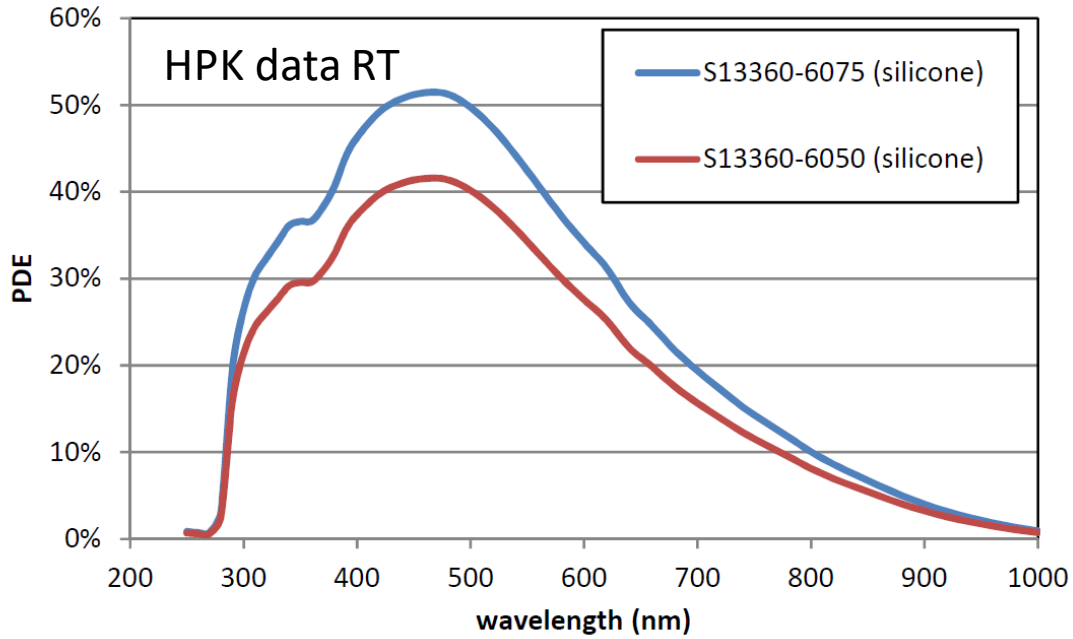
DUNE HPK: PDE spectral response – use white light source and calibrate against NIST photodiode

$$PDE_{\lambda} = [spectral\ reponse]_{\lambda} \times \frac{[PDE_{pulse}]_{405nm}}{[spectral\ reponse]_{405nm}}$$

noted: CT & AP – photoelectron effect, wavelength independent

PDE (QE) = photon effect, depends on wavelength





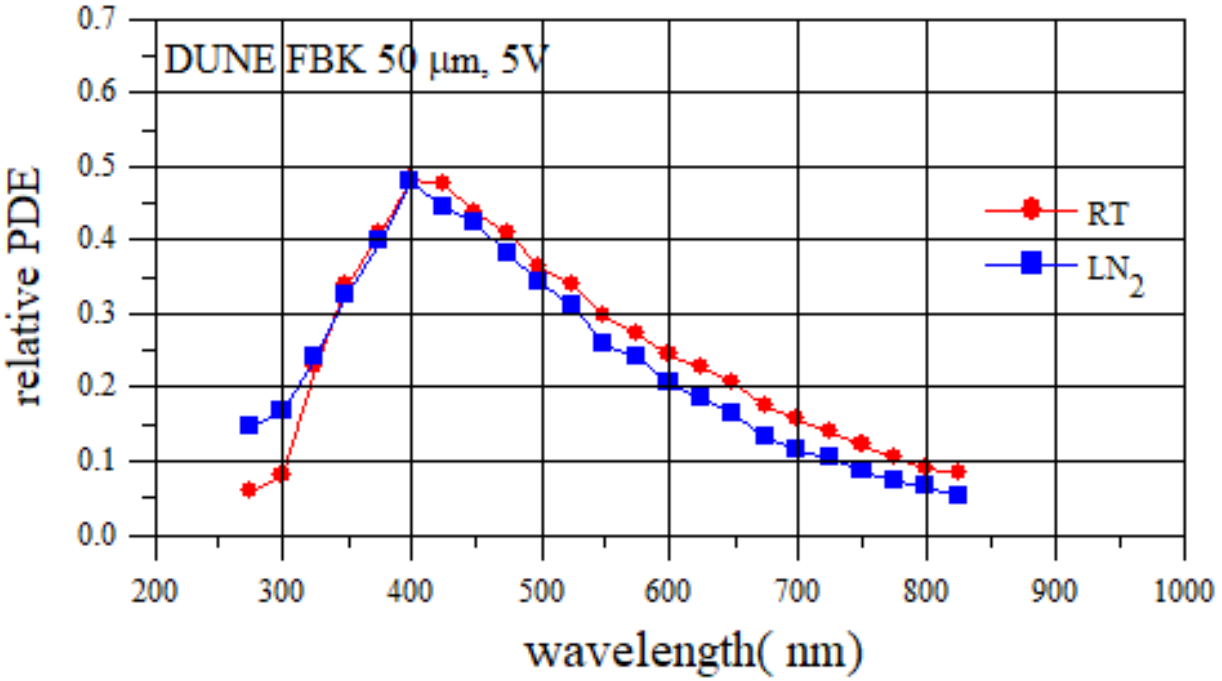
Spectral PDE response generally agrees with HPK (peak at ~460 nm) – also has a slight blue shift behavior in LN_2

DUNE FBK: PDE spectral response – use white light source and calibrate against NIST photodiode

$$PDE_{\lambda} = [spectral\ reponse]_{\lambda} \times \frac{[PDE_{pulse}]_{405nm}}{[spectral\ reponse]_{405nm}}$$

noted: CT & AP – photoelectron effect, wavelength independent

PDE (QE) = photon effect, depends on wavelength



FPK data RT

N/C

Can't compare to FBK data (peak at ~400 nm) – may have a very slight blue shift behavior in LN_2