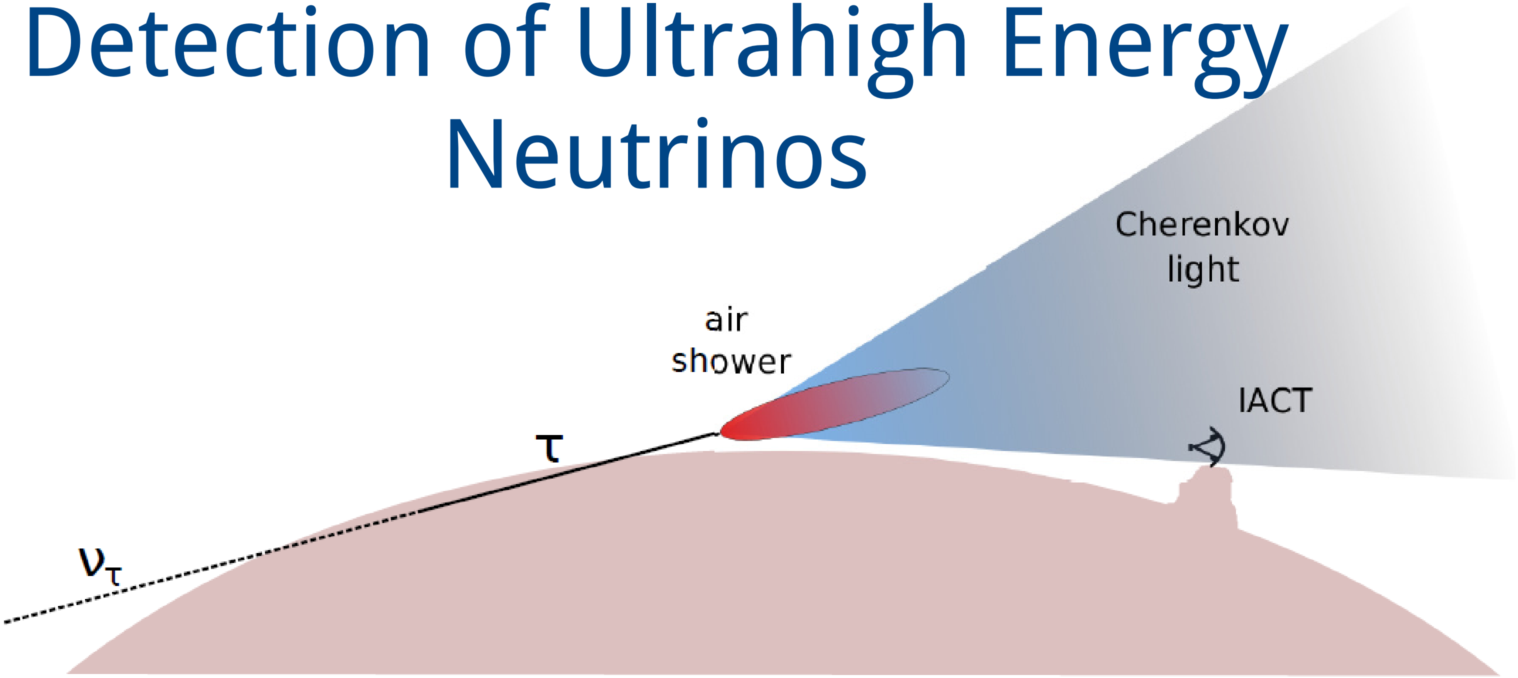
Evaluation and Integration of SiPMs in Air-Shower Imaging Telescopes for the Detection of Ultrahigh Energy Neutrinos



Nepomuk Otte

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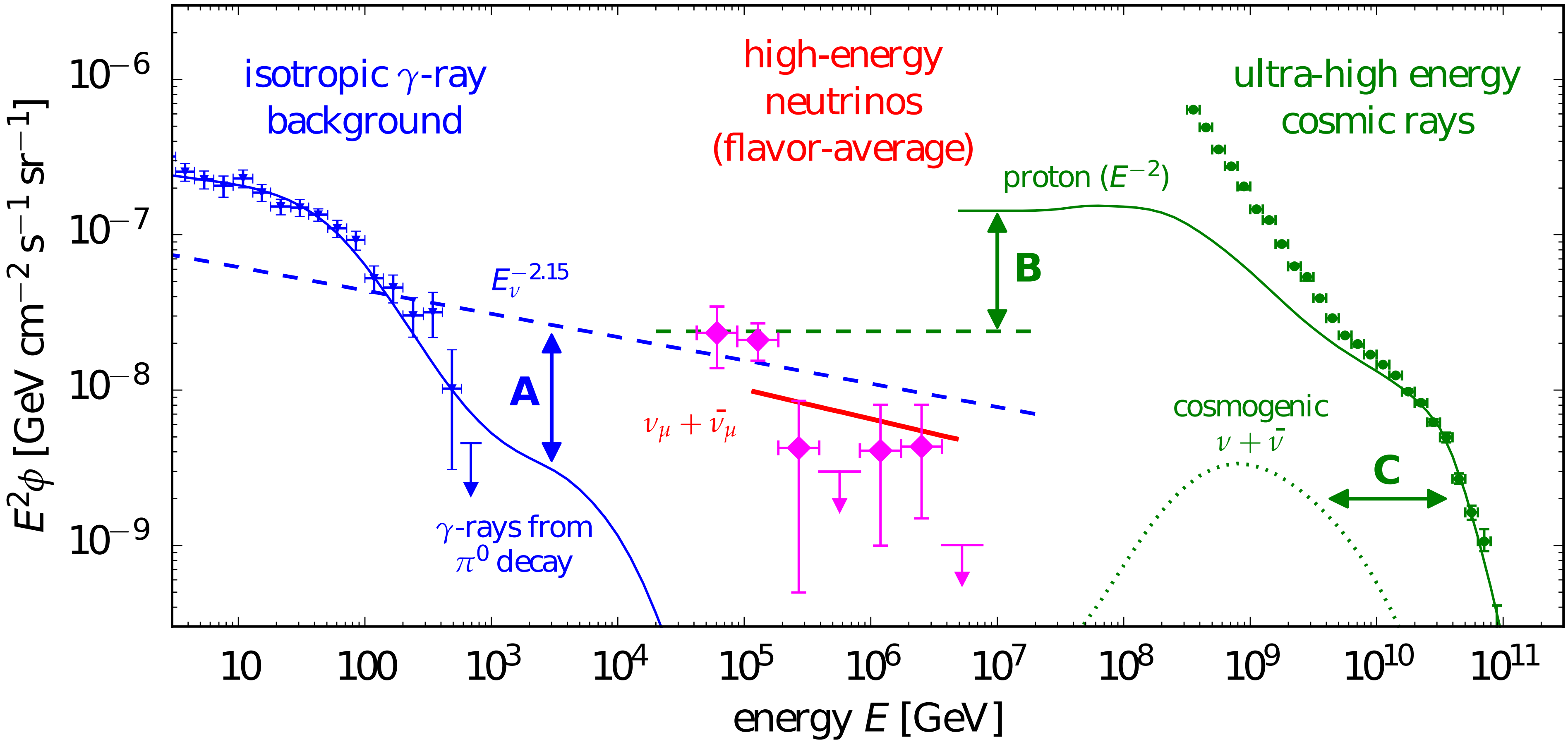
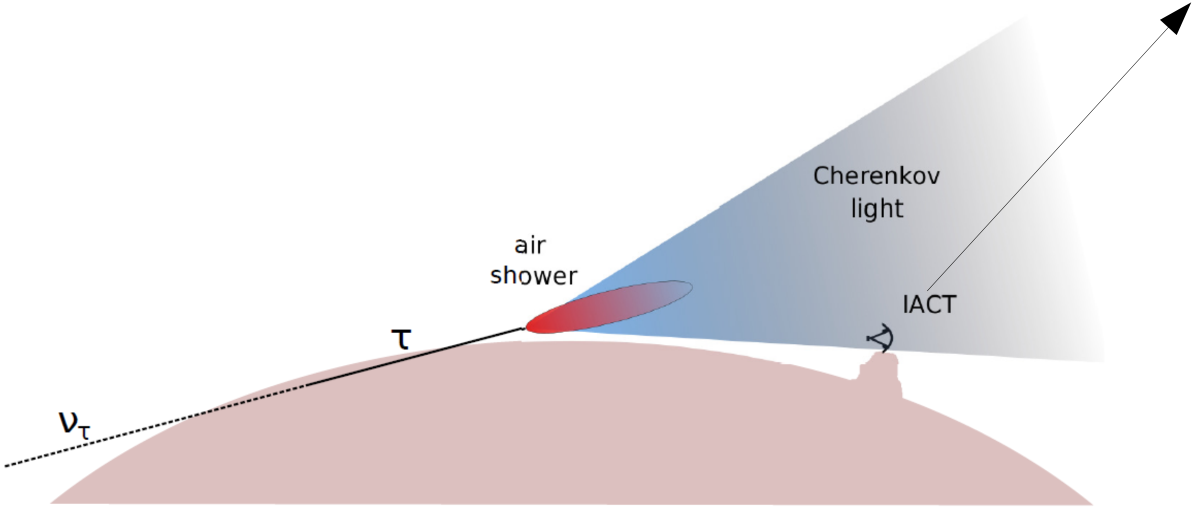
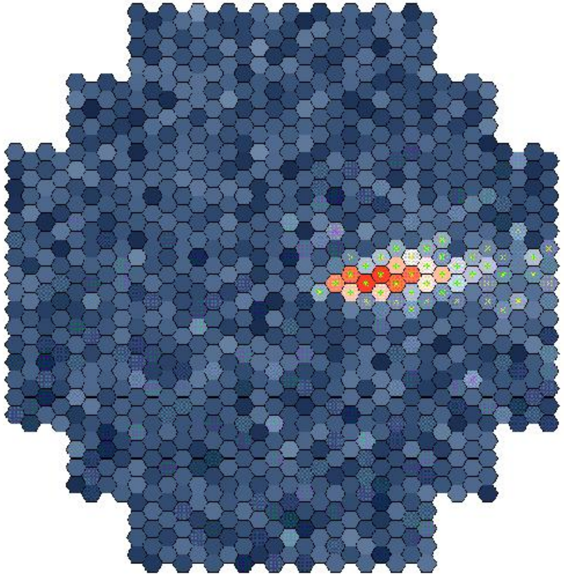
The Era of Multi-Messenger Astrophysics



Air-Shower Imaging



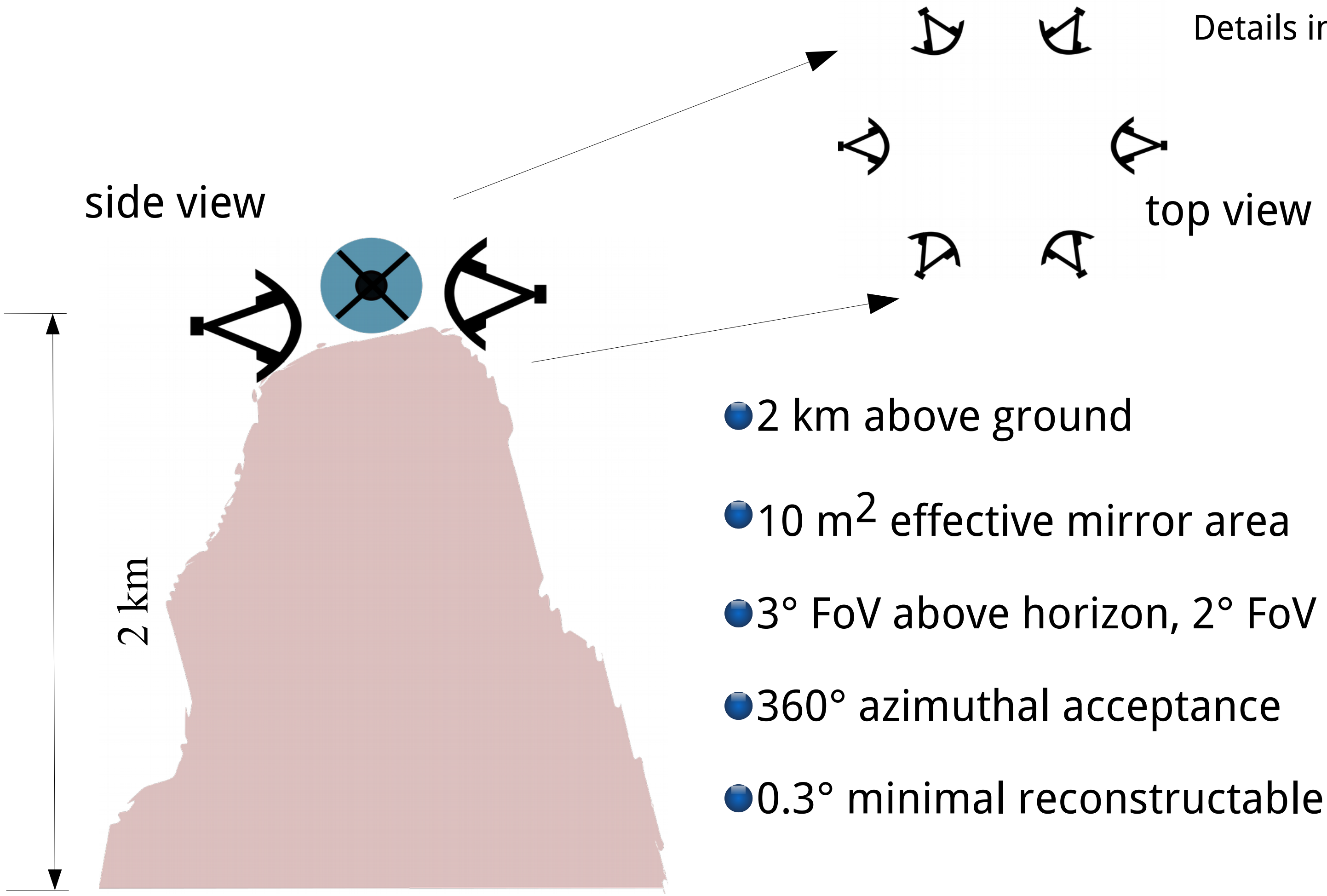


Proven Technique

- Angular resolution ~0.1°
- Energy resolution ~10%
- Excellent background suppression

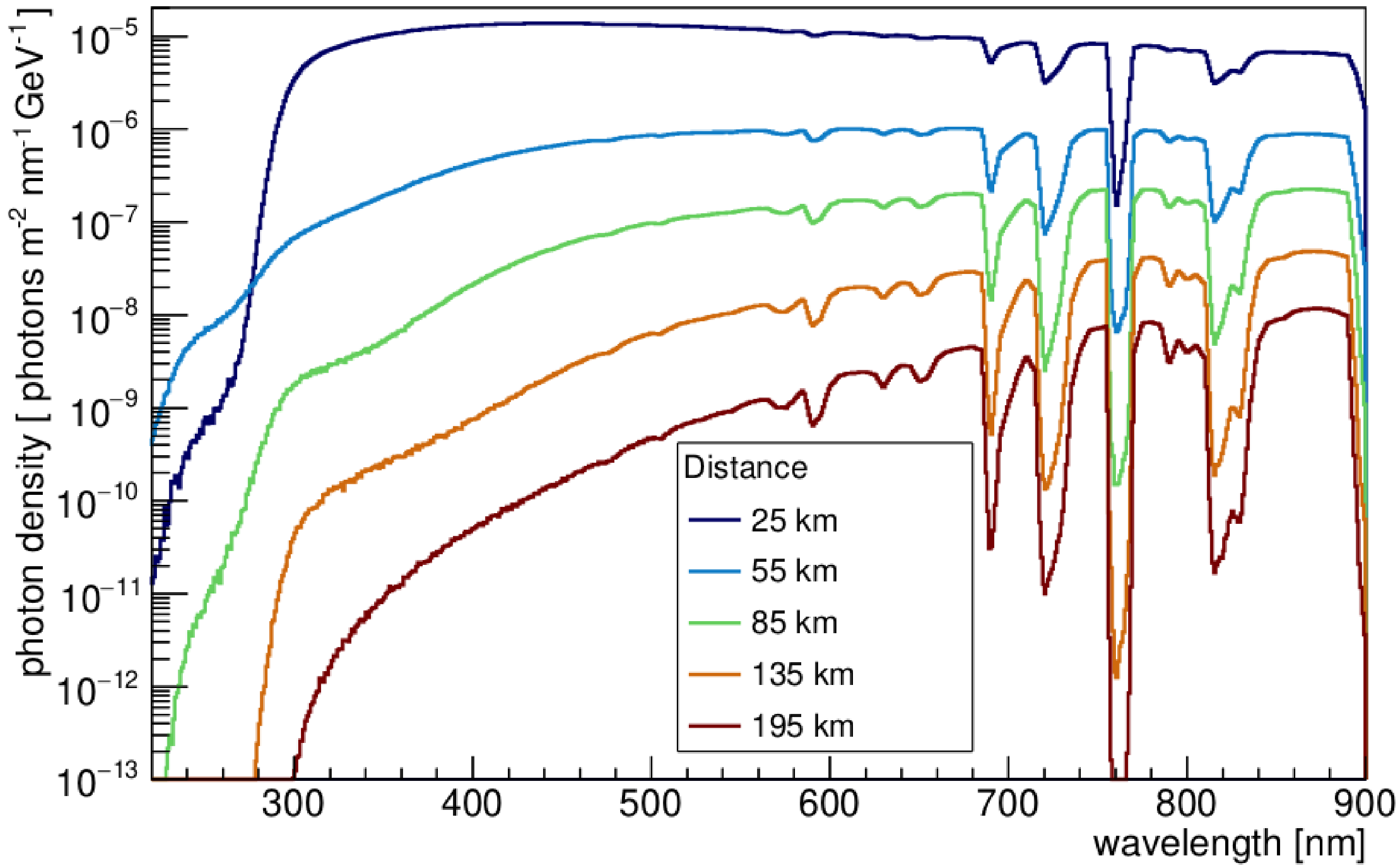
Trinity: Baseline Configuration

Details in Otte PRD (2019) arXiv 1811.09287

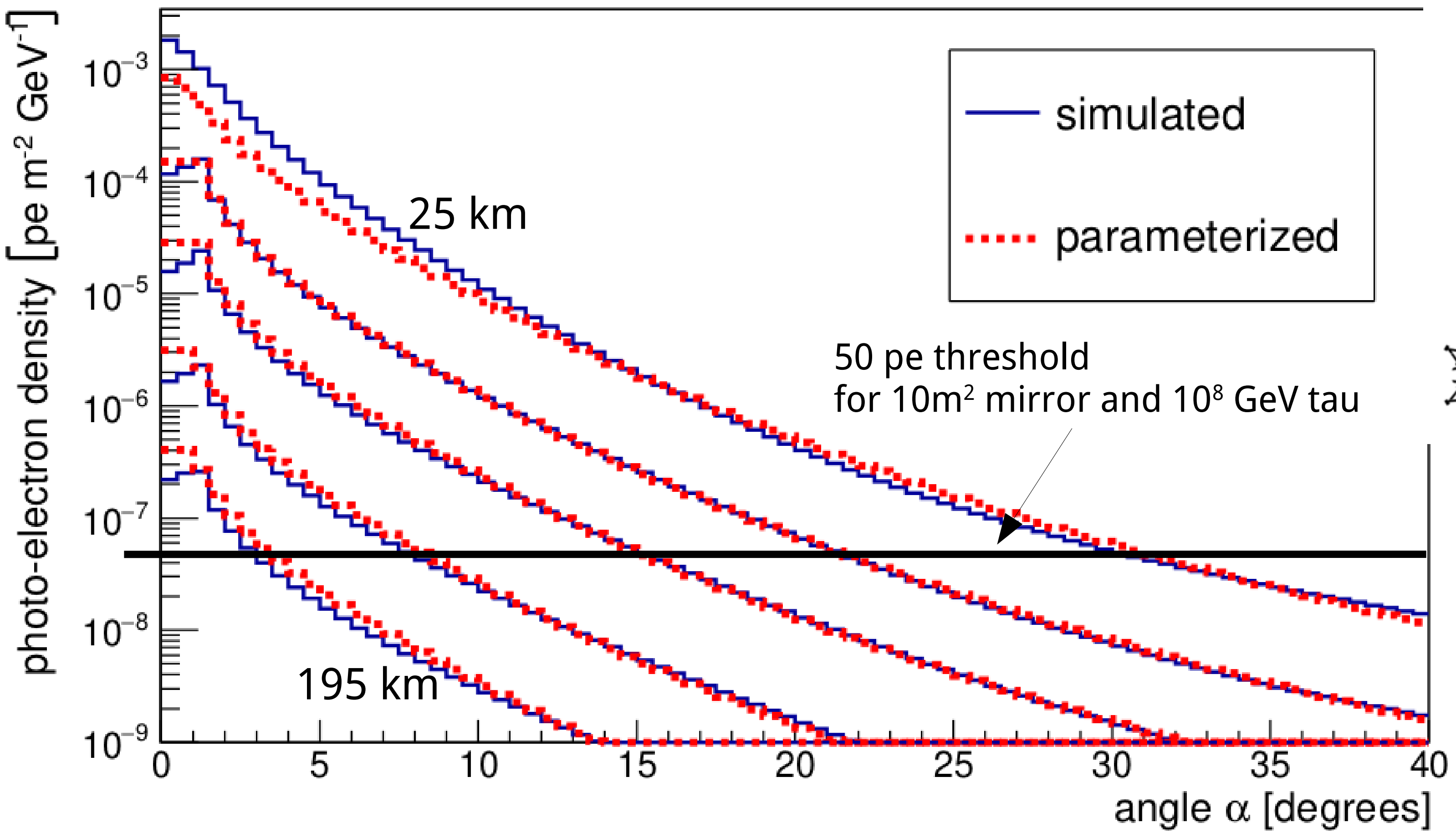


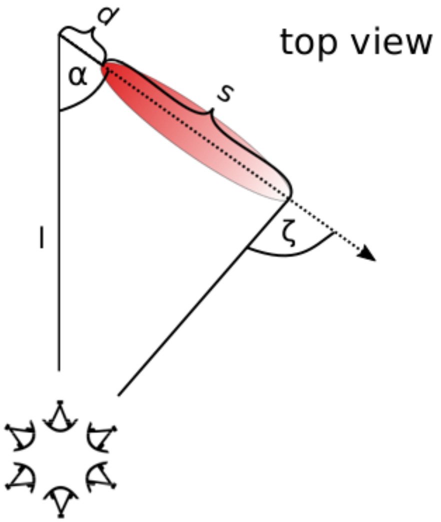
- 2 km above ground
- 10 m^2 effective mirror area
- 3° FoV above horizon, 2° FoV below horizon
- 360° azimuthal acceptance
- 0.3° minimal reconstructable image length

Air Showers for Lovers



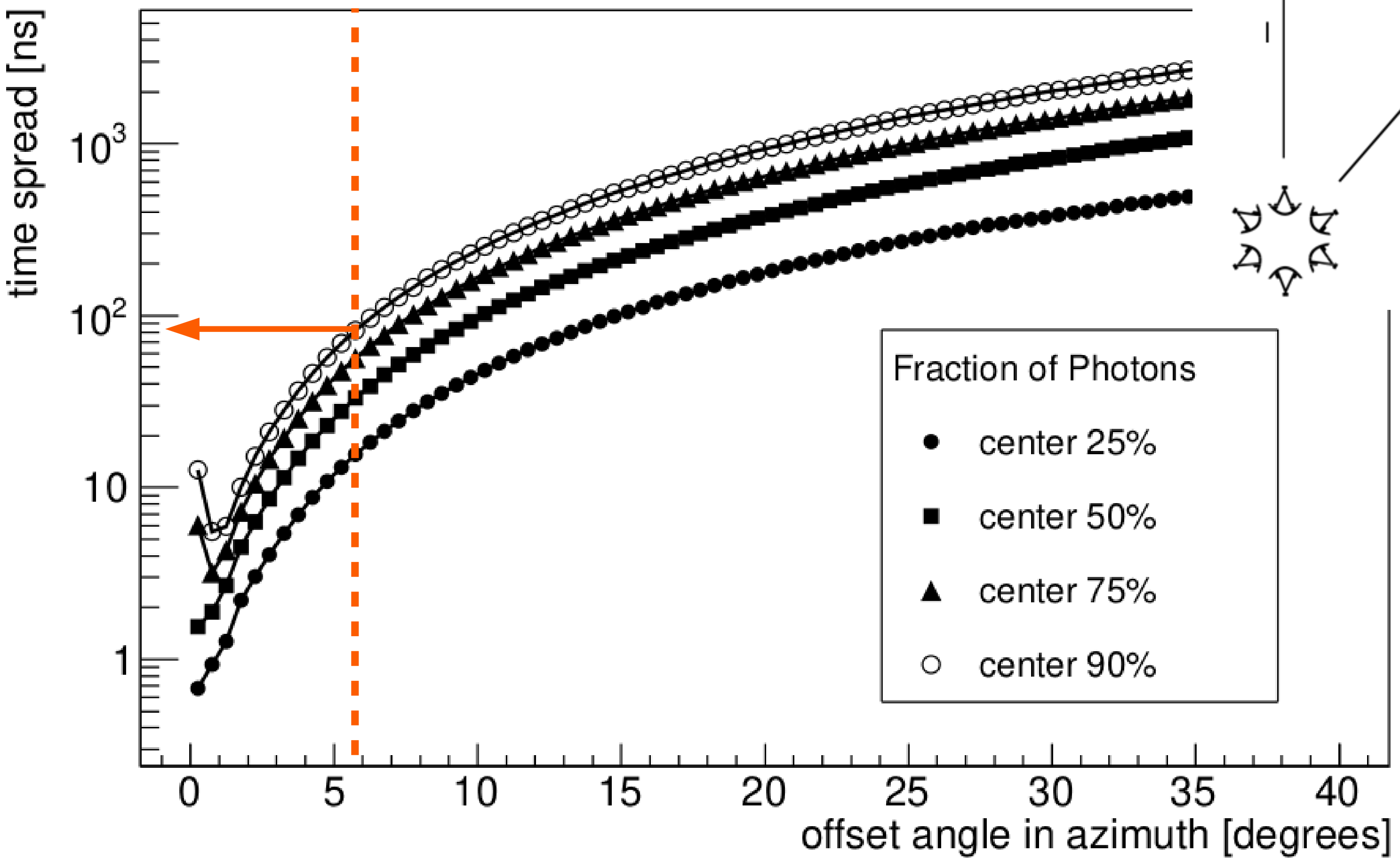
Detected Cherenkov Light

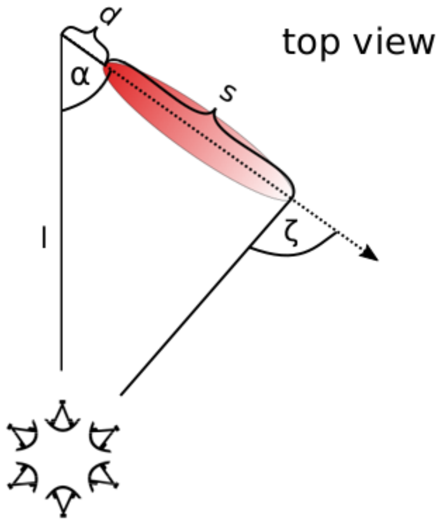




Calculated with PDE of Hamamatsu S14520

Spread of Photon Arrival Times



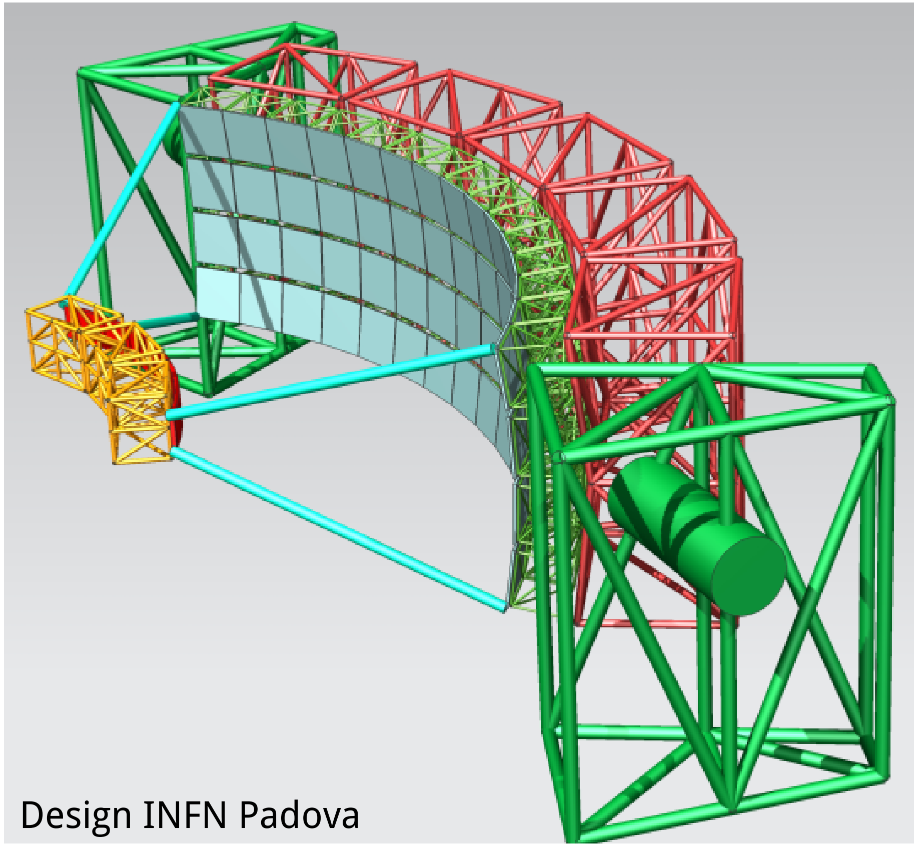



PREF
+031.69168° / -110.88498° 8436ft 13:15:52
MAIL
POSITION - ALTITUDE - TIME
MAP
LOG
1° veto region
HORIZON
+00.8°
ANGLE
4° signal region
ELEVATION
-01.9°
ANGLE
-05
00
+05
-05
00
AZIMUTH - BEARING
301° N59W 5351mils TRUE
ZERO
A-B
CAL
W
300
330
LENS
1.0X
S

Optics

Based on J. Cortina et al., Astrop. Physics 72 (2016) 46

- **FoV 5° X 60°.**
- 5.6 m focal length.
- 0.3° optical PSF.
- 20 mm Winston cones coupled to **9 mm SiPMs**.
- 3,300 pixel camera.
- 68 m^2 mirror area → **16 m^2** in any direction.
- Rotates in elevation.
- Thin-glass replica mirror technology ~\$2k/m^2.
- Implementation based on MAGIC structure.
- \$170k for one telescope (excl. camera).



Design INFN Padova

Photon Detector Requirements

- High sensitivity >600nm where Cherenkov emission peaks
- Single photoelectron signals < 100 ns
- Sensor diameter <1 cm
- A dark-count rate of several 100 kHz is below the background photon intensity

SiPMs are a good match

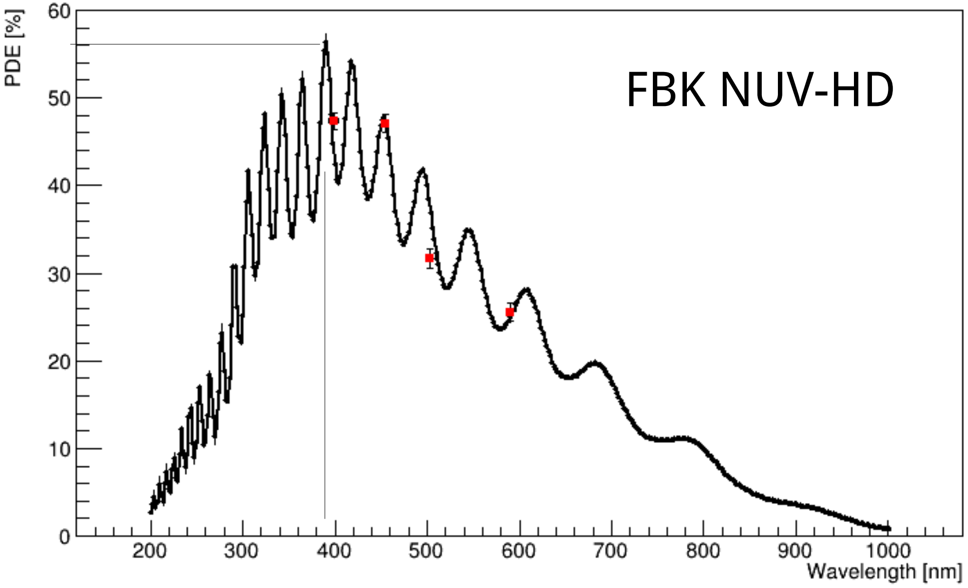
Evaluated SiPMs

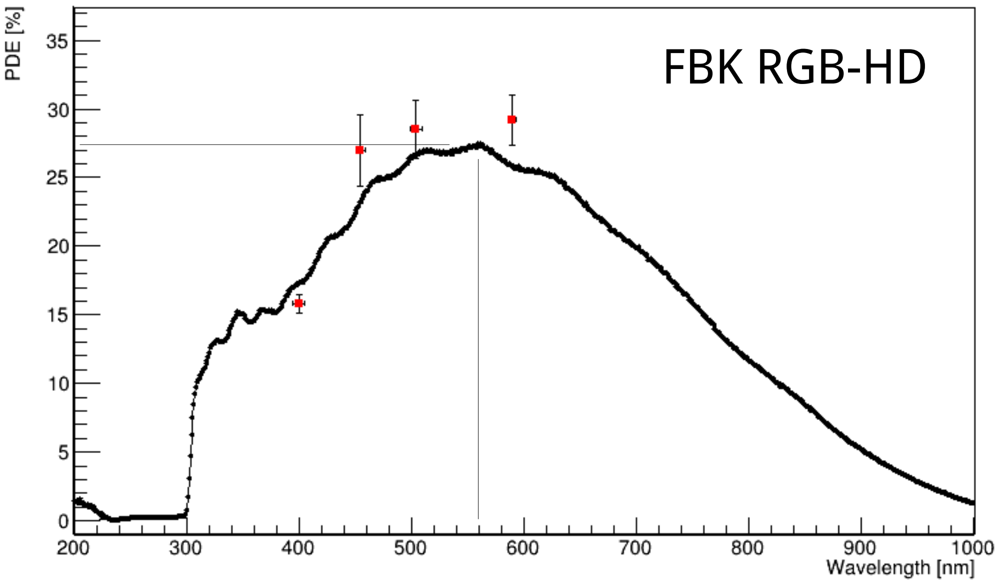
- FBK RGB-HD with 15um and 25 um pixels
- FBK NUV-HD (used in CTA-SCT camera upgrade)
- Hamamatsu S14520 50 um cells (Optimized for CTA, p-on-n)
- Hamamatsu S14420 50 um cells (Optimized in red, n-on-p)

Procedures described in NIMA Otte et al. (2016)

Photon Detection Efficiency

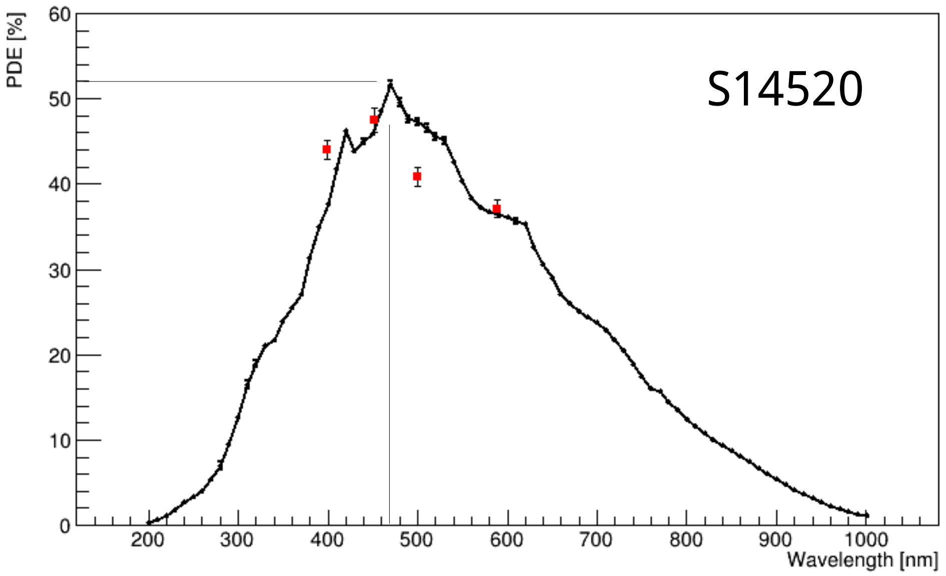
@ 90% breakdown probability





Photon Detection Efficiency

@ 90% breakdown probability



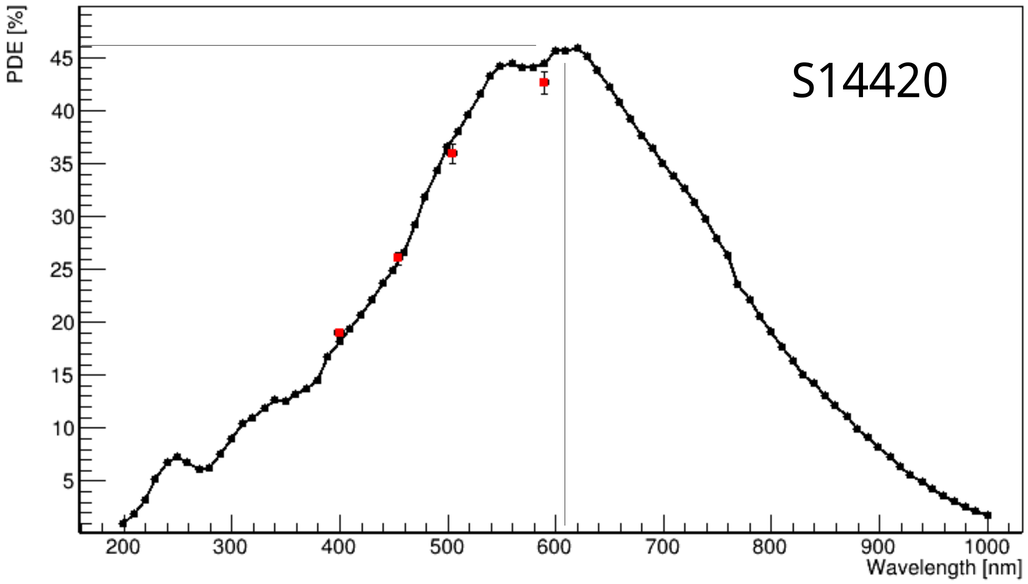
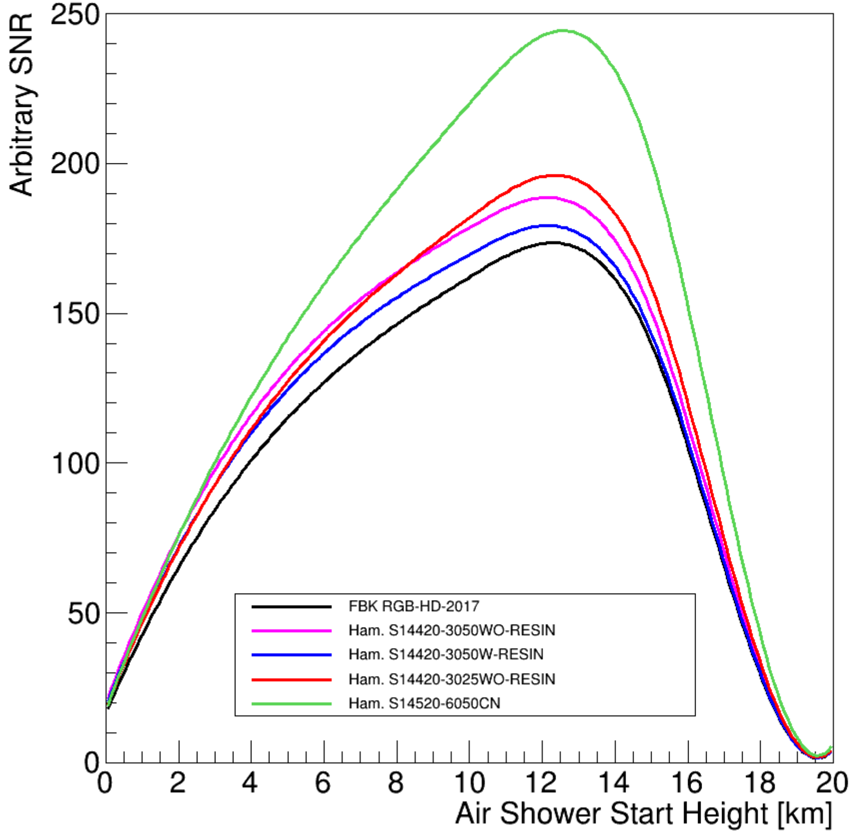
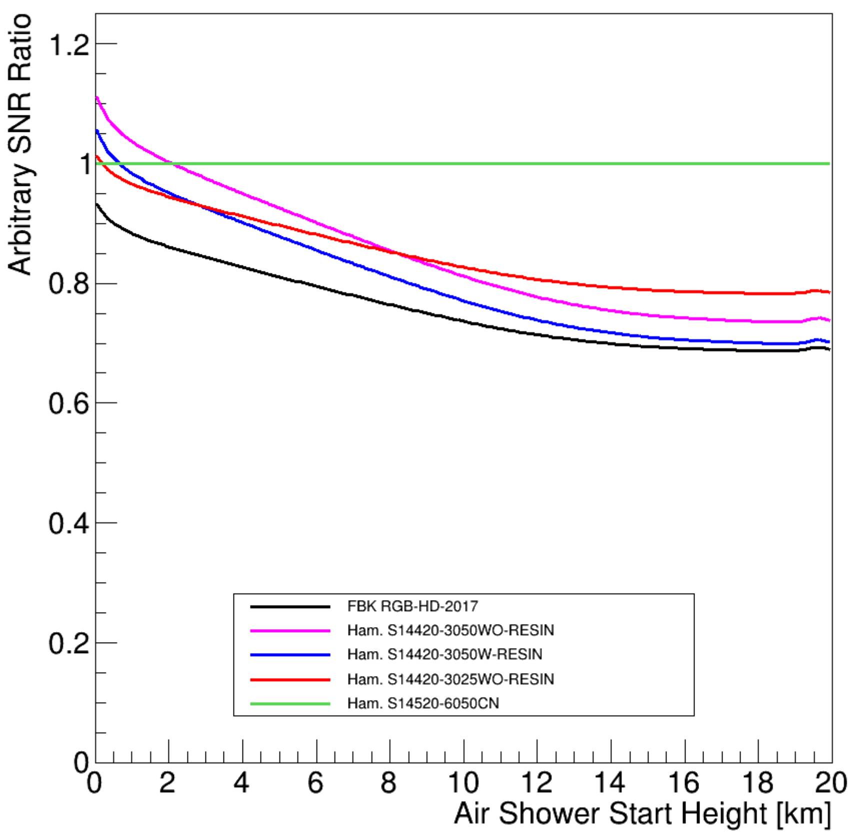


Figure of Merit Studies for SPB2





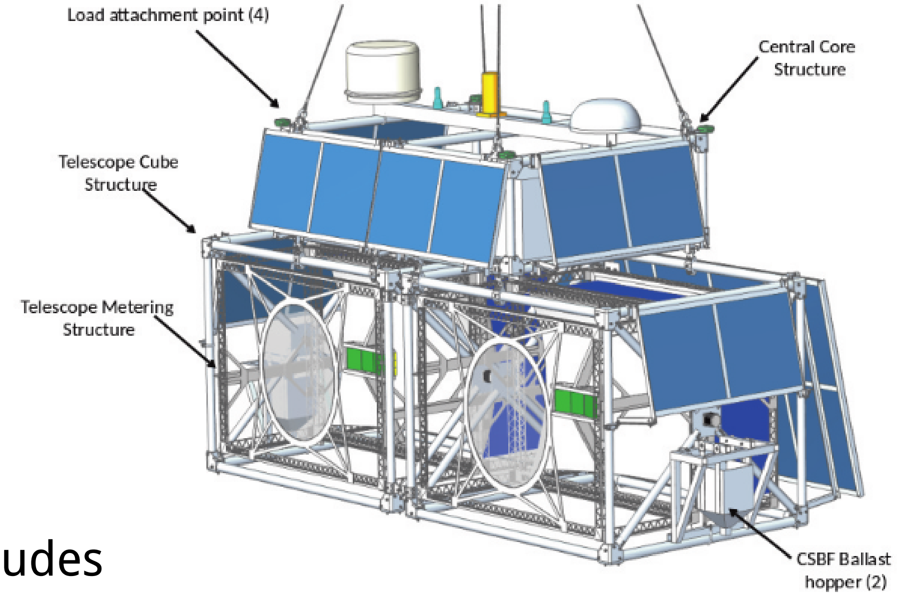
Evaluation Summary

Device	Peak PDE [%]	Peak Wave-length [nm]	Optical Cross-talk [%]	After-pulsing [%]	Delayed Optical Crosstalk [%]	Dark-count rate [kHz/mm^2] @ 20C	Operating Voltage [V]	Over-voltage [%]	Cell size [um]
RGB-HD	27	560	14	1.5	4	200	33	11	25
NUV-HD	56	390	15	1	<1	80	31	22	40
S14520	52	470	1	5	5	50	44	9	50
S14420	46	610	6	<1	0.5	200	50	20	50

See backup slides for details

SPB2

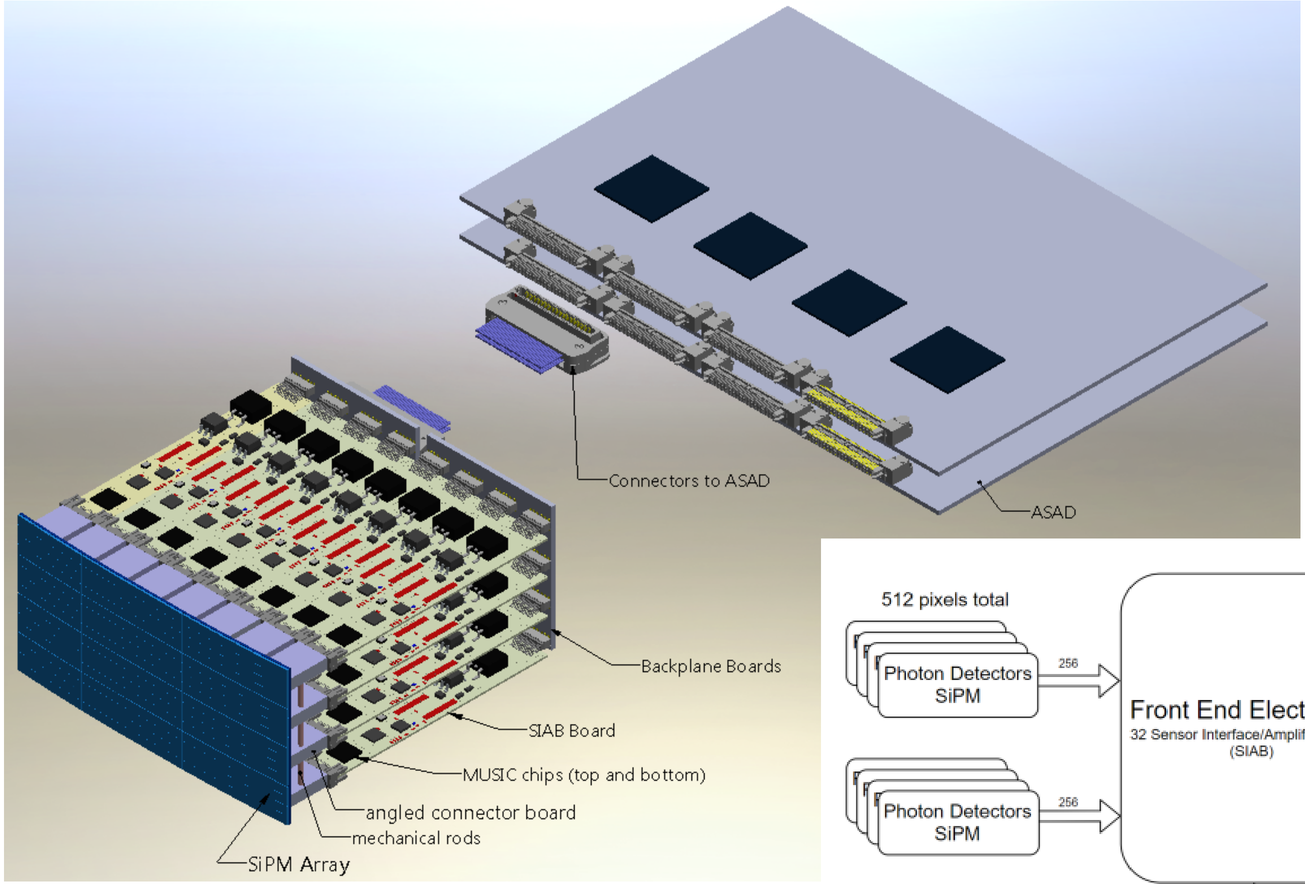
- Ultra-long duration flight from New Zealand in 2021
- One Cherenkov Telescope
- One Fluorescence Telescope

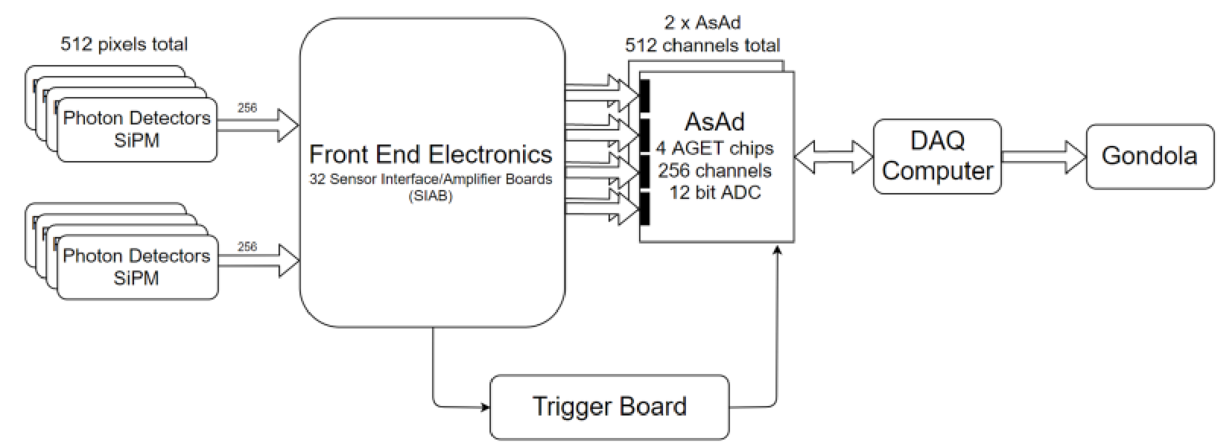


Objectives

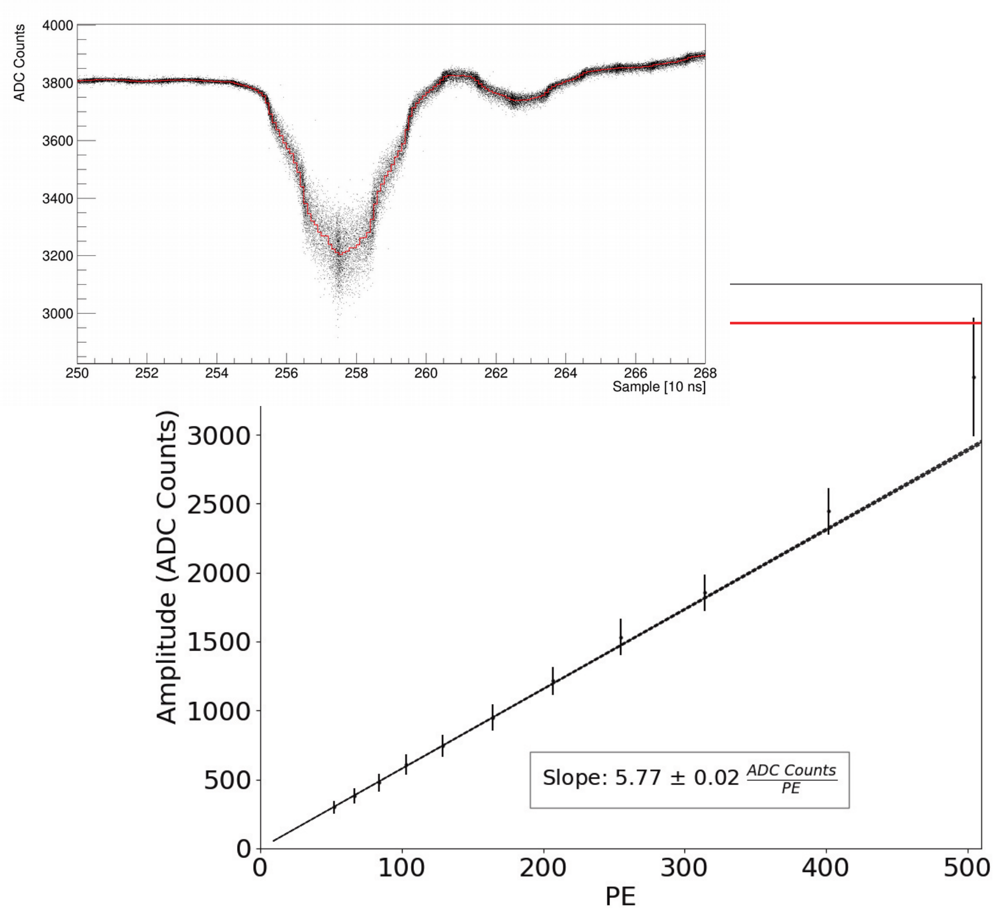
- Test imaging of air-showers from high altitudes
- Evaluate background sources

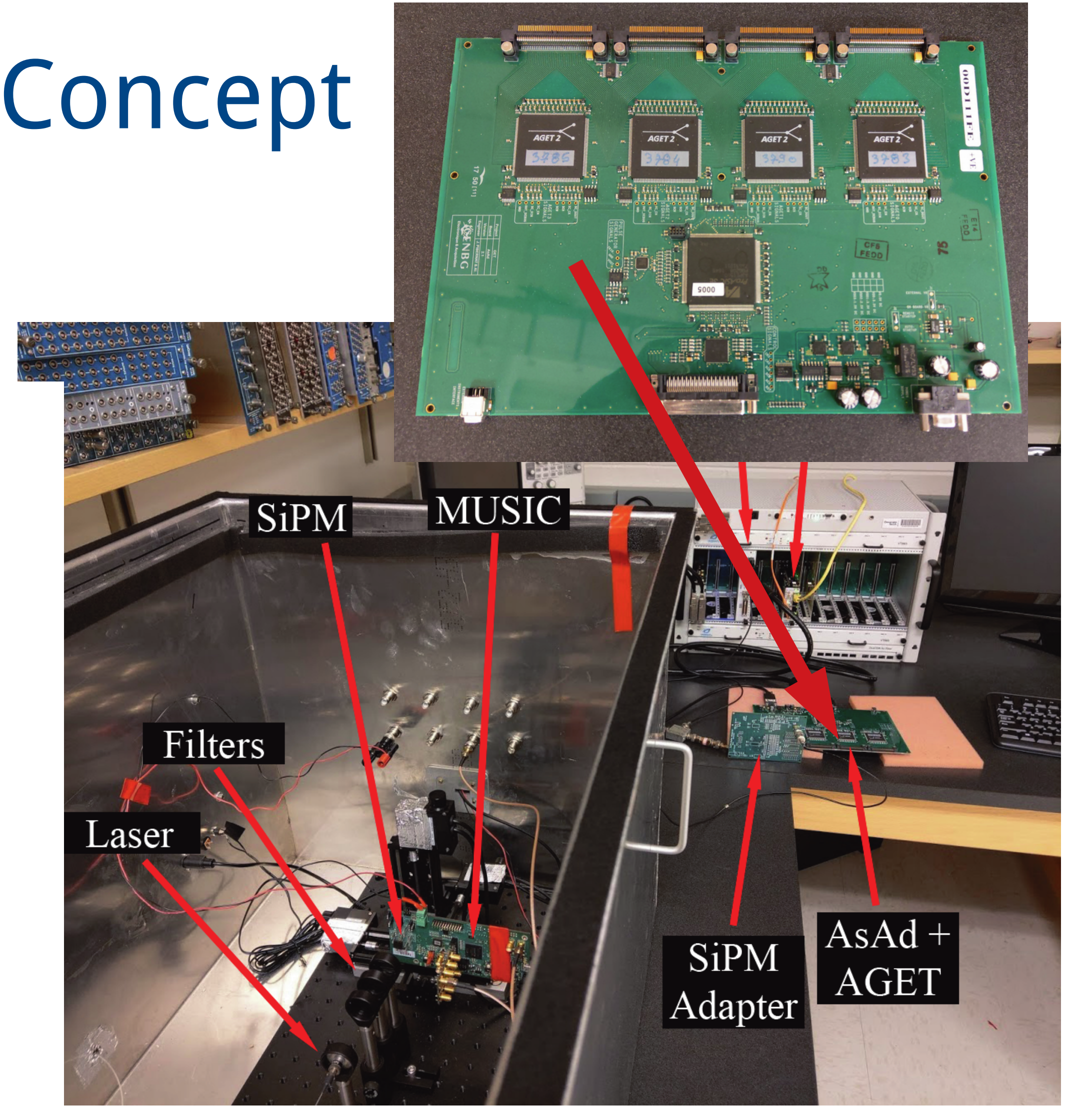
Electronics for SPB2 and Trinity





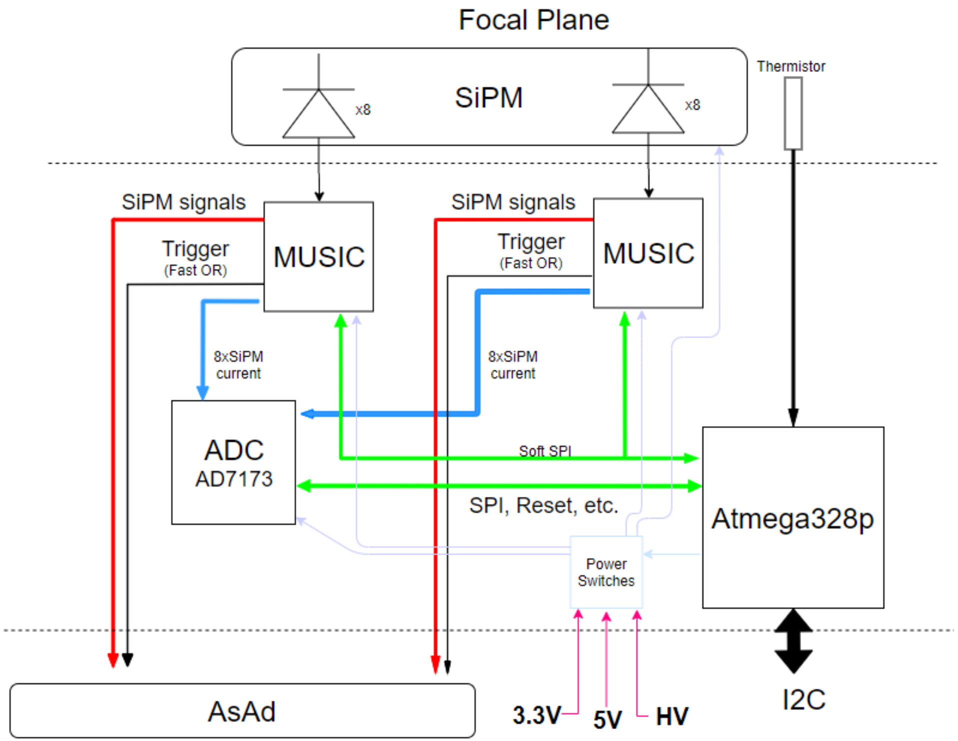
Signal Chain Proof of Concept



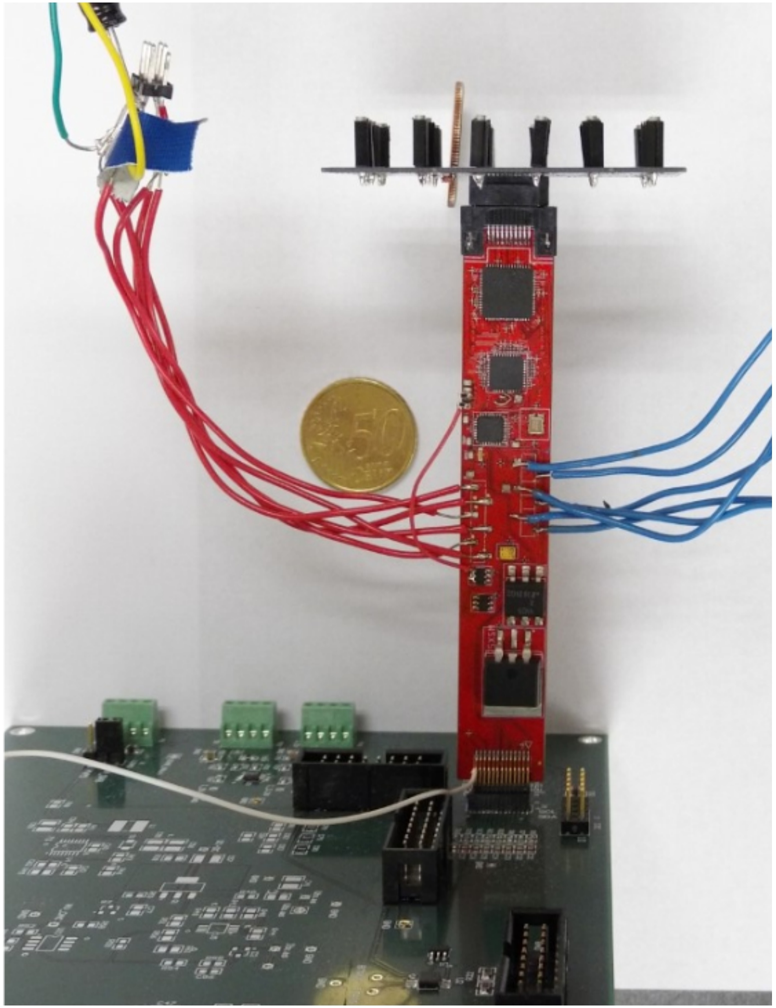


For details see arXiv:1907.08728

Front-End Electronics

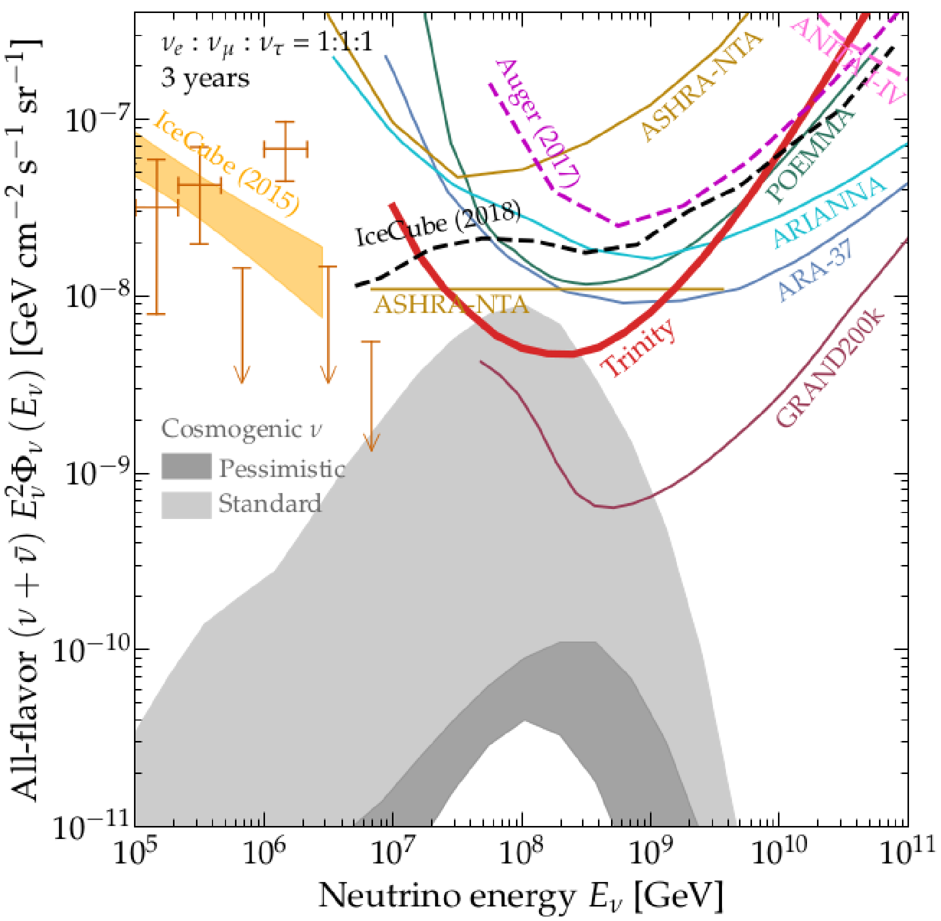


50 mW/channel



Conclusions

- Air-shower imaging is a viable technique to search for UHE neutrinos from ground and space.
- New experiments feasible because of SiPMs
- Different SiPMs show similar and acceptable performance
- More ASIC developments of front-end electronics for SiPMs would be great.



Figures Measurement Results

Comparison
FBK RGB-HD and
Hamamatsu S14520-6050CN

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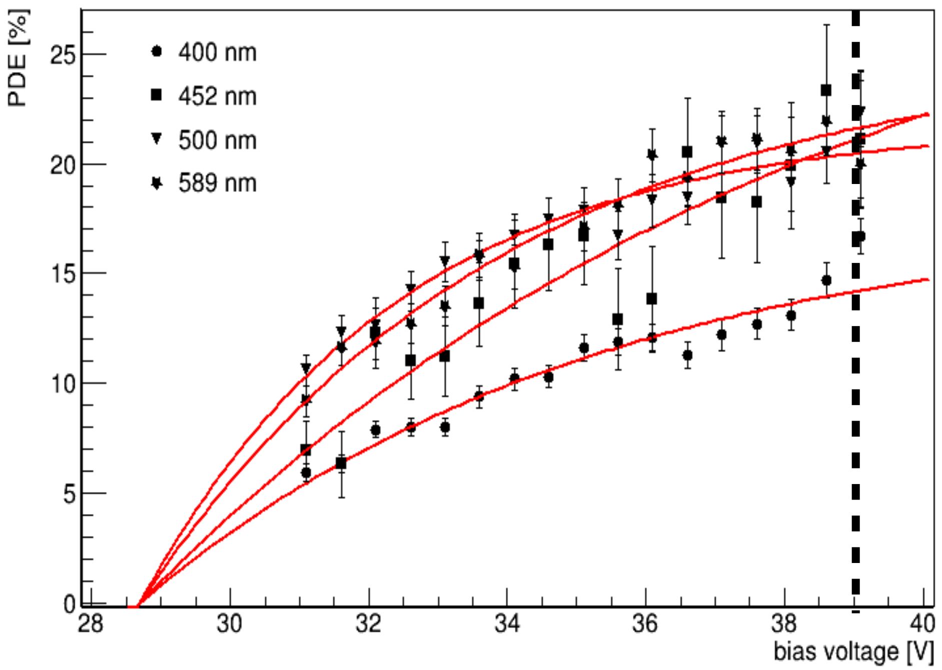
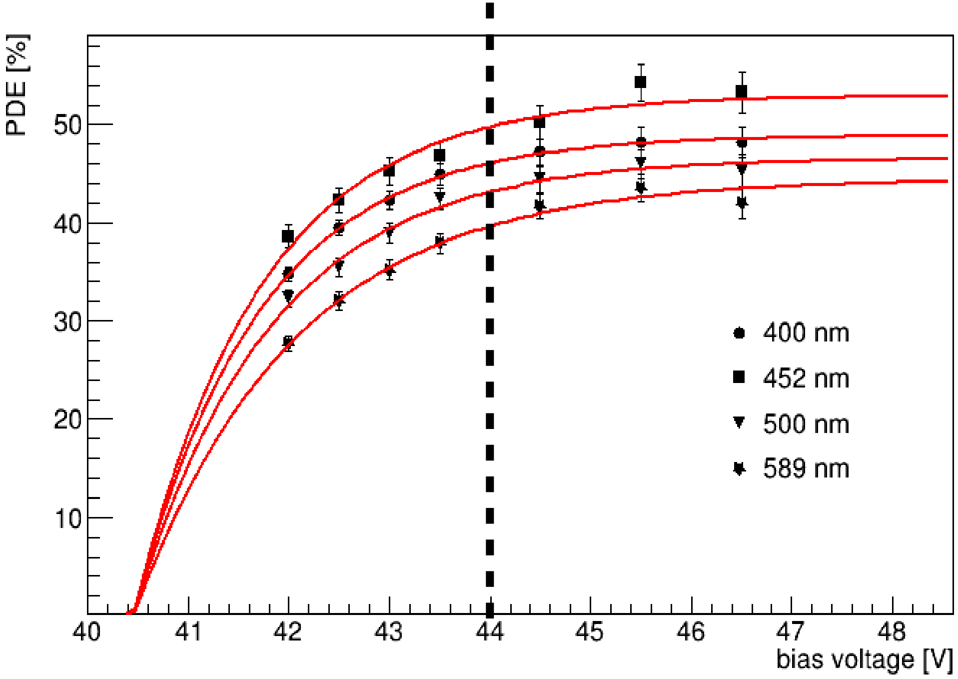
36% overvoltage

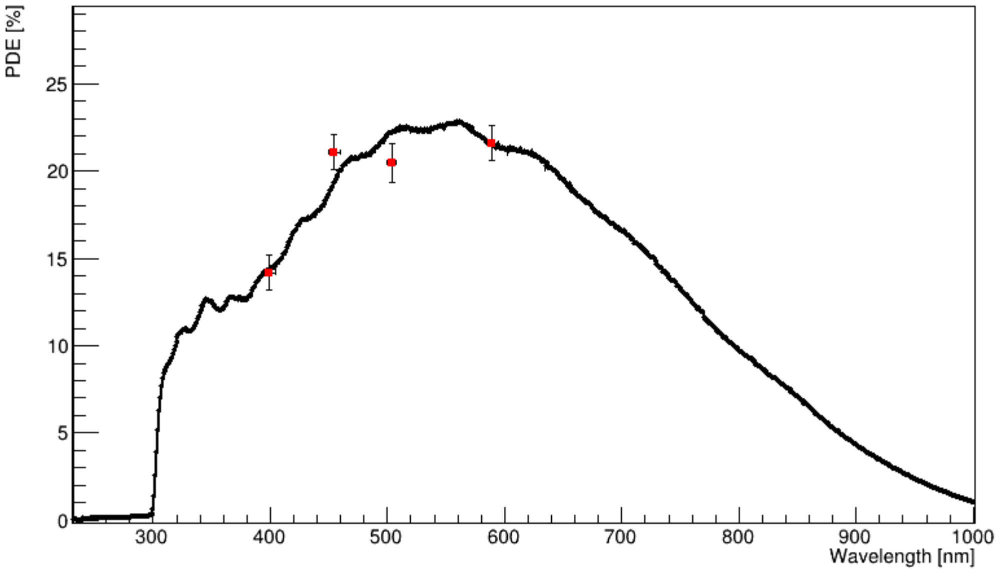


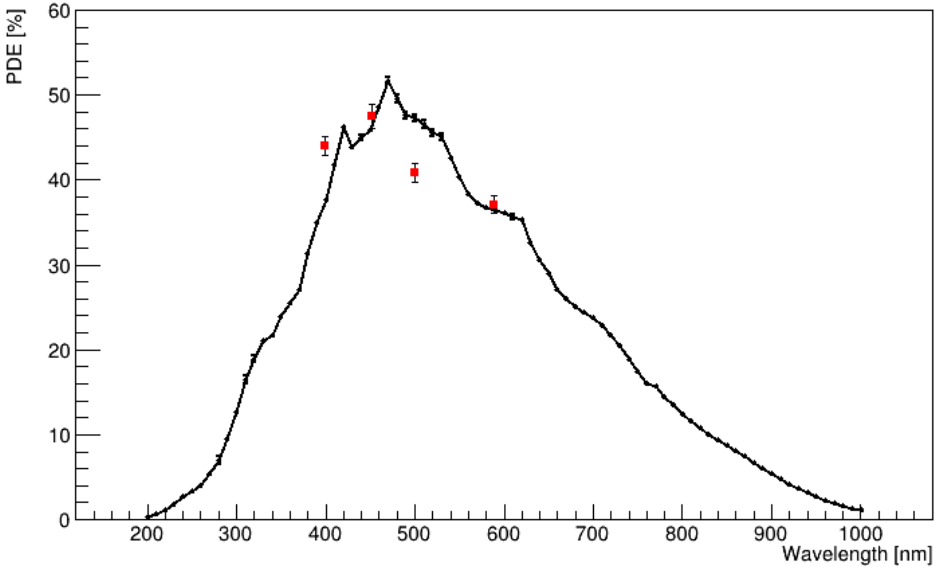
FBK

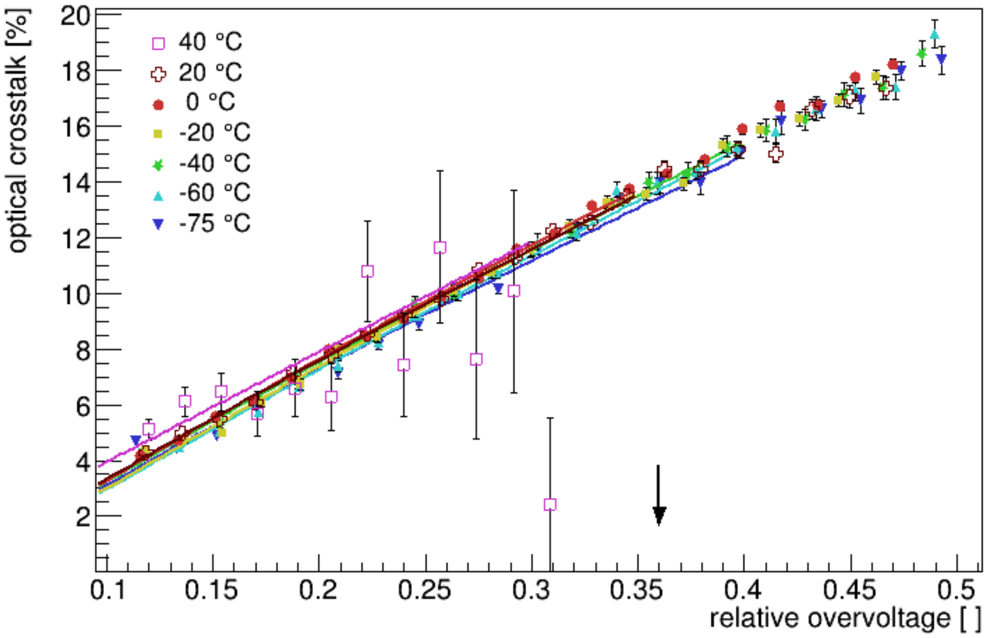
9% overvoltage

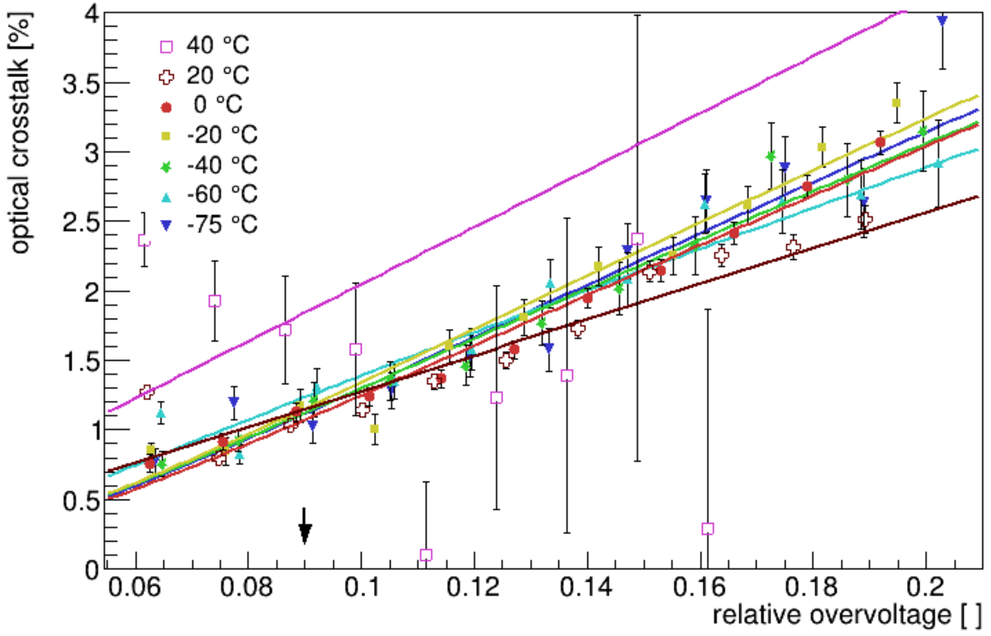


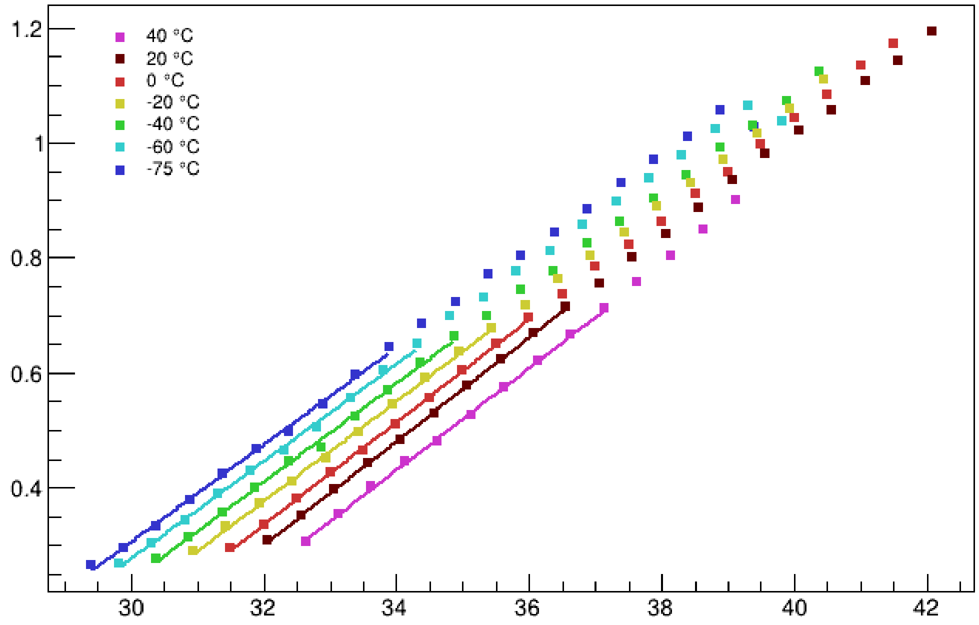
Hamamatsu

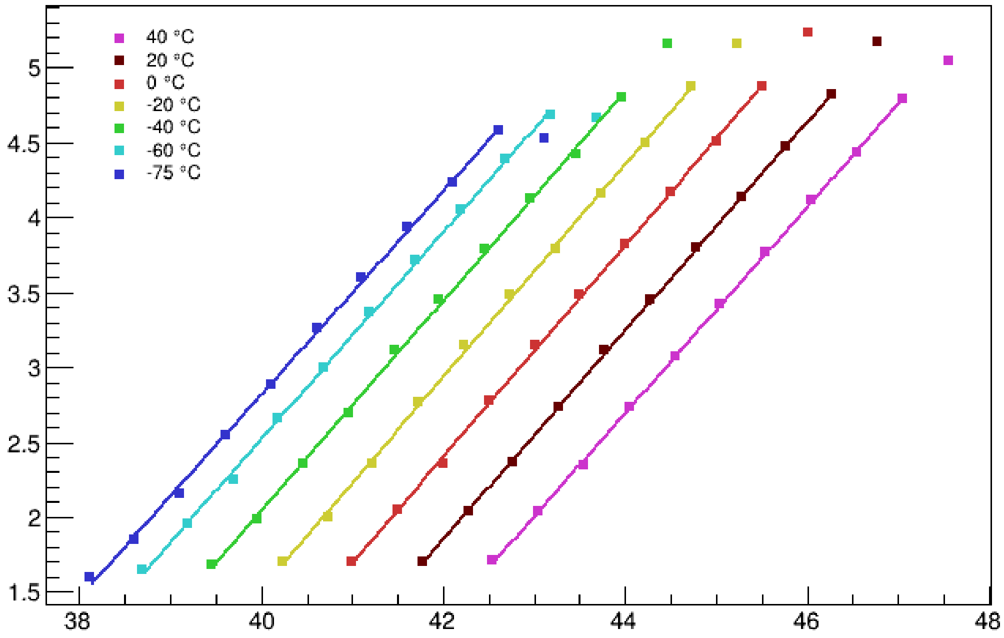

PDE [%]
25
20
15
10
5
0
300
400
500
600
700
800
900
1000
Wavelength [nm]

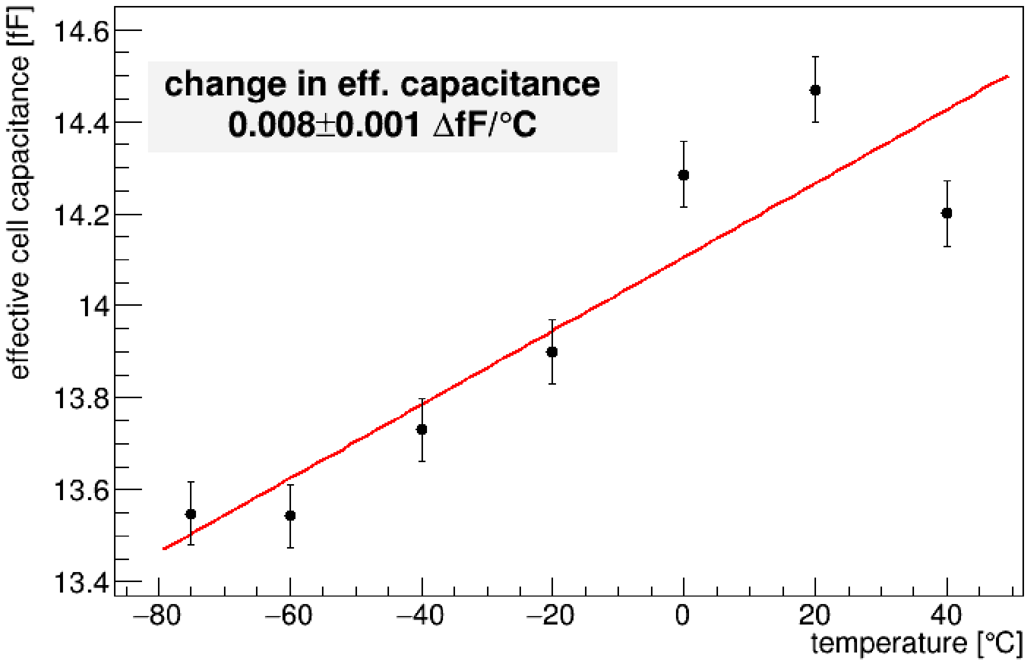

PDE [%]
60
50
40
30
20
10
0
200
300
400
500
600
700
800
900
1000
Wavelength [nm]

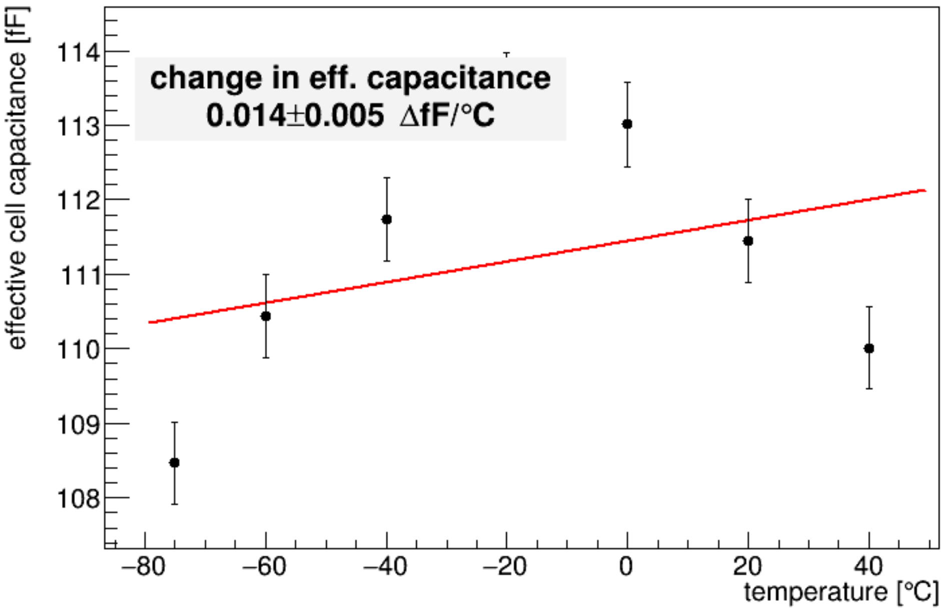

optical crosstalk [%]
relative overvoltage [ ]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C

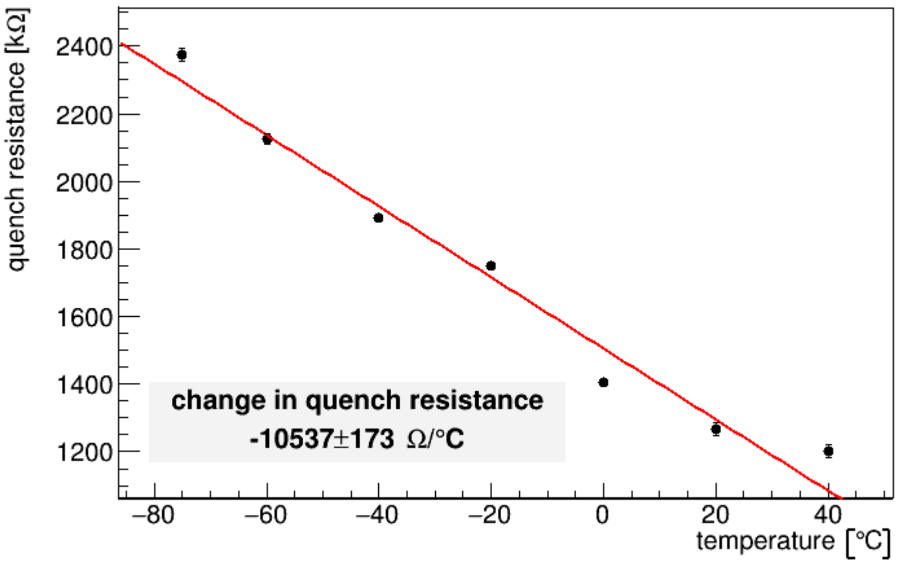

optical crosstalk [%]
relative overvoltage [ ]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C

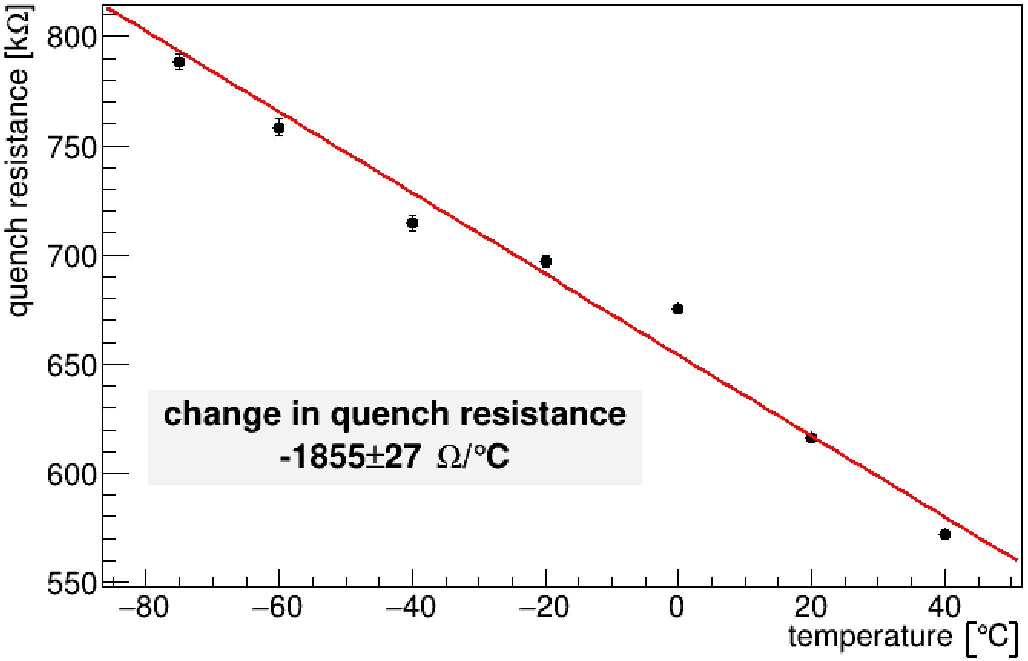

40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
1.2
1
0.8
0.6
0.4
30
32
34
36
38
40
42

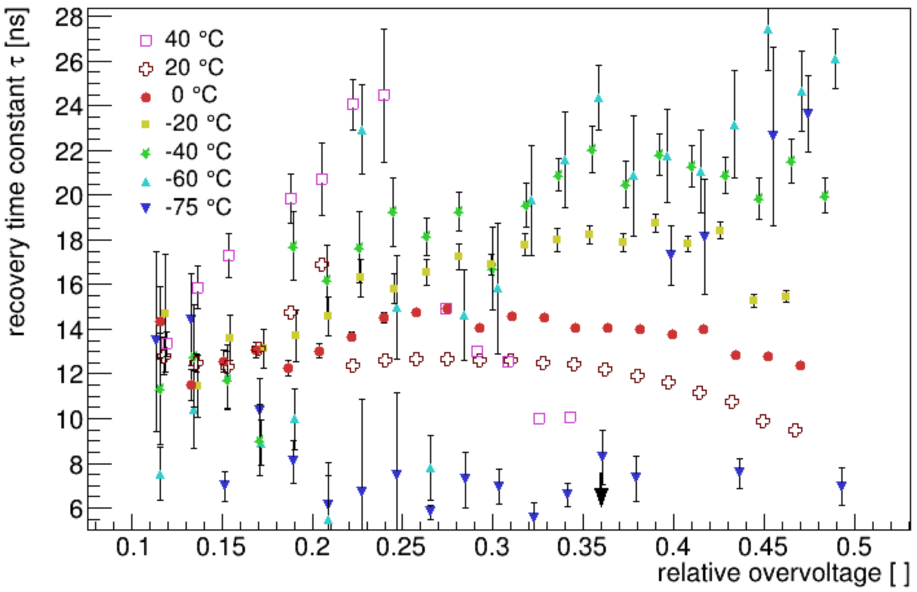

40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
5
4.5
4
3.5
3
2.5
2
1.5
38
40
42
44
46
48

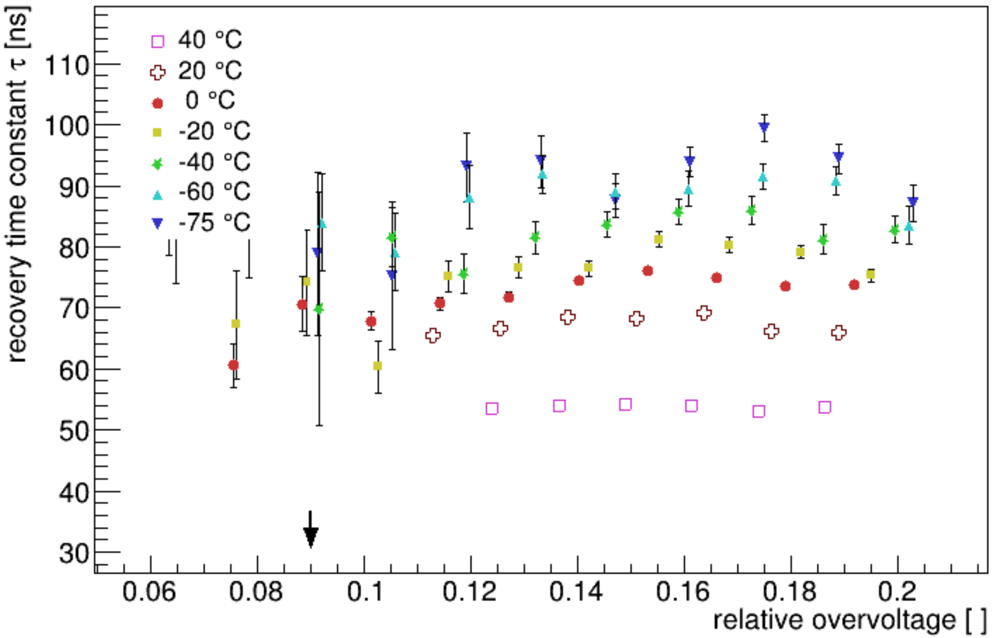

change in eff. capacitance
0.008±0.001 ΔfF/°C
effective cell capacitance [fF]
temperature [°C]

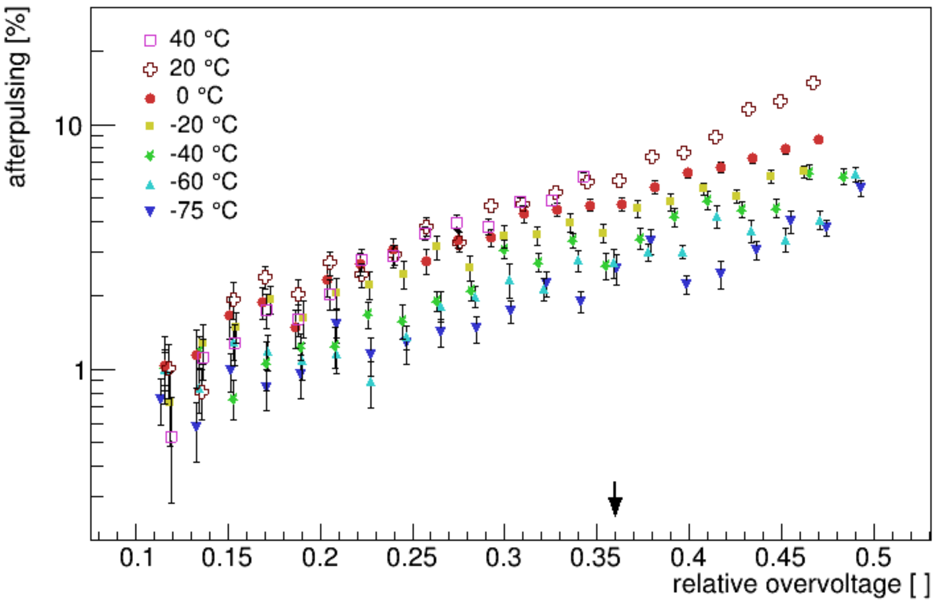

change in eff. capacitance
0.014±0.005 ΔfF/°C
effective cell capacitance [fF]
temperature [°C]

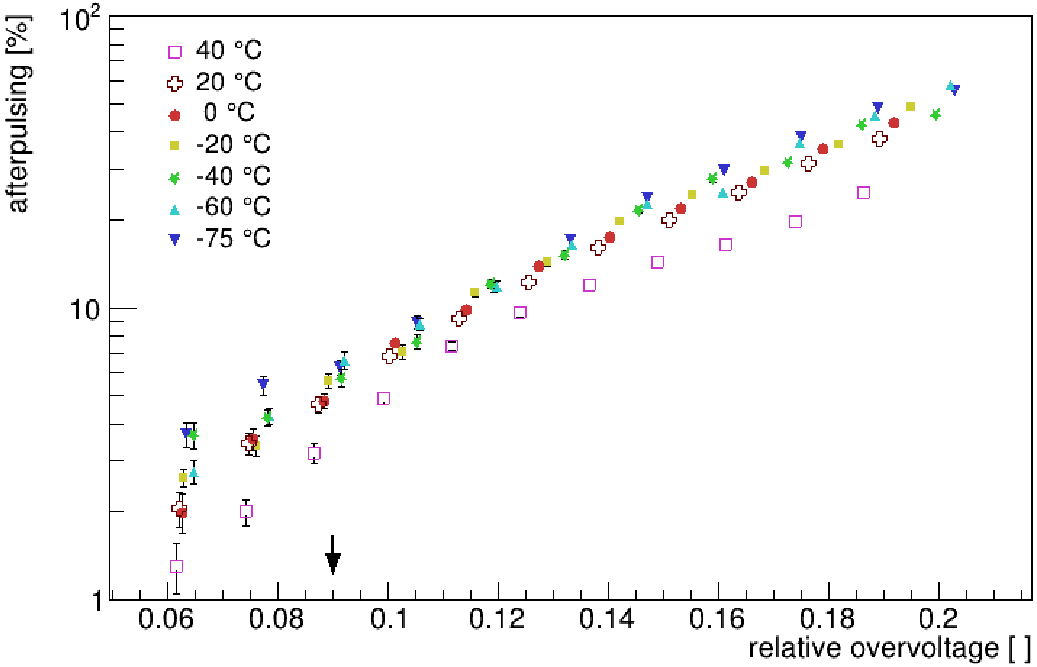

quench resistance [kΩ]
2400
2200
2000
1800
1600
1400
1200
change in quench resistance
-10537±173 Ω/°C
−80
−60
−40
−20
0
20
40
temperature [°C]

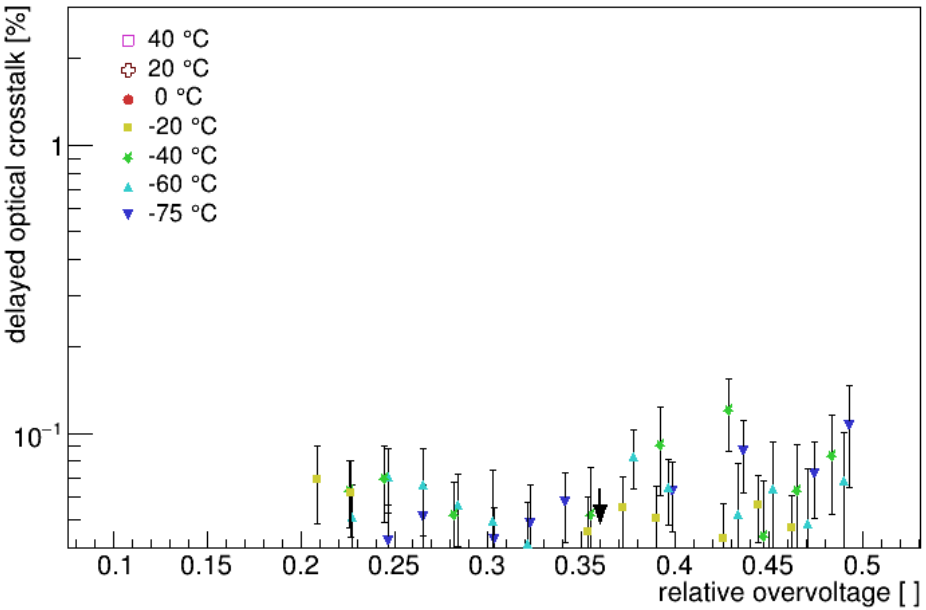

quench resistance [kΩ]
800
750
700
650
600
550
change in quench resistance
-1855±27 Ω/°C
−80
−60
−40
−20
0
20
40
temperature [°C]


recovery time constant τ [ns]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
relative overvoltage [ ]

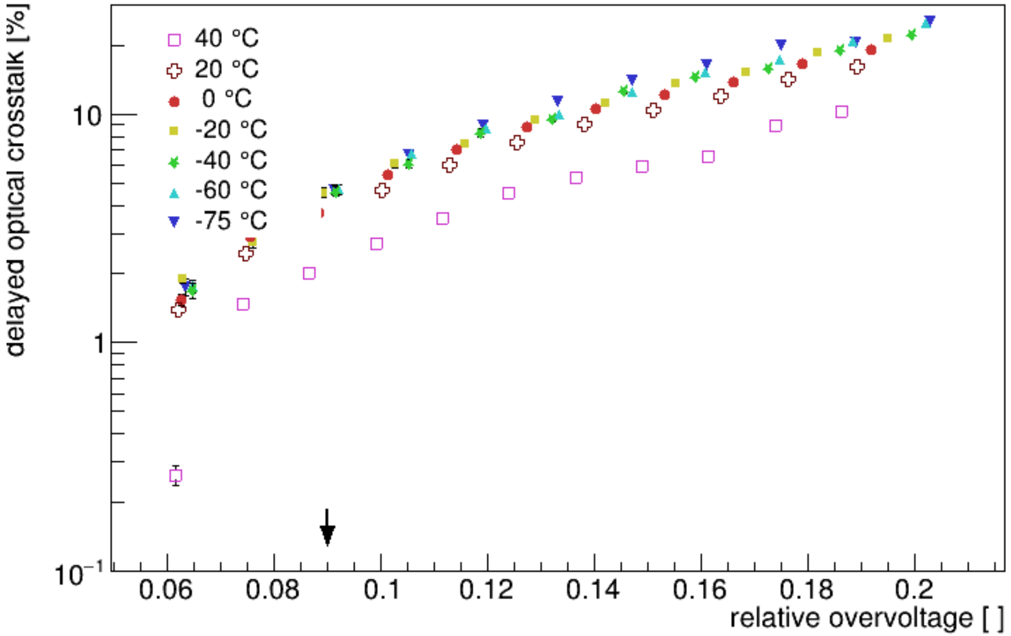

recovery time constant τ [ns]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
relative overvoltage [ ]


afterpulsing [%]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
10
1
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
relative overvoltage [ ]

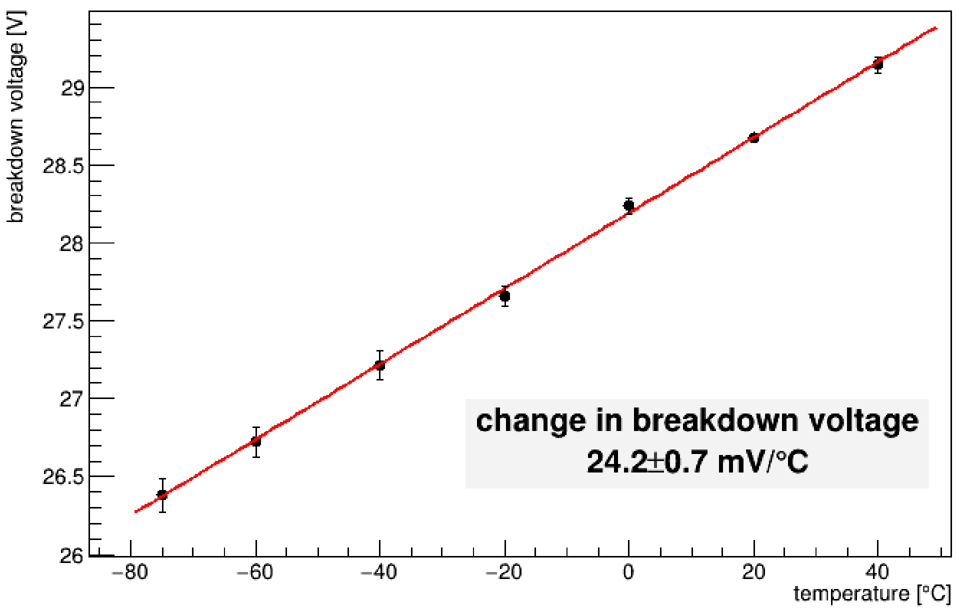

afterpulsing [%]
10^2
10
1
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
relative overvoltage [ ]



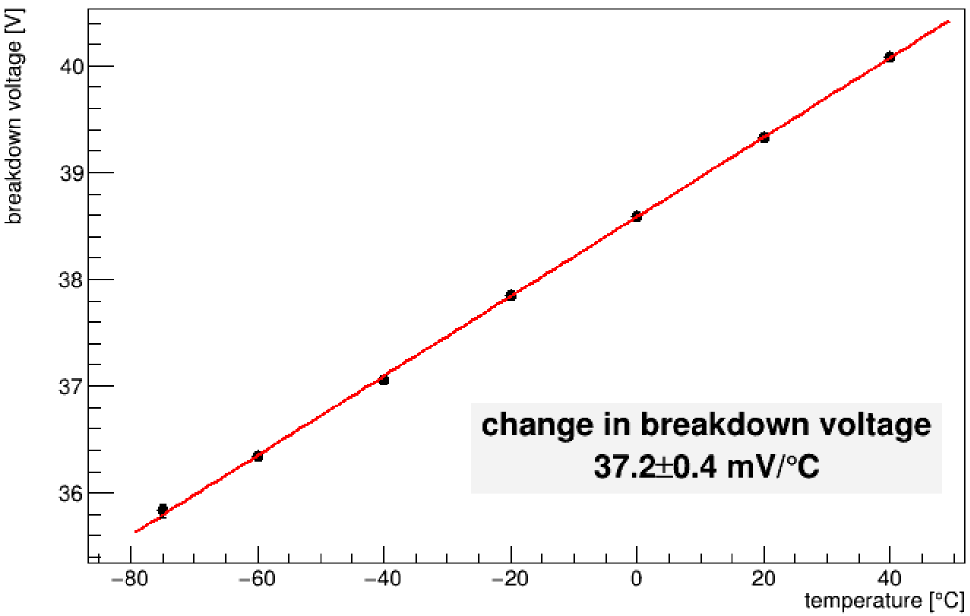
delayed optical crosstalk [%]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
1
10^{-1}
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
relative overvoltage [ ]



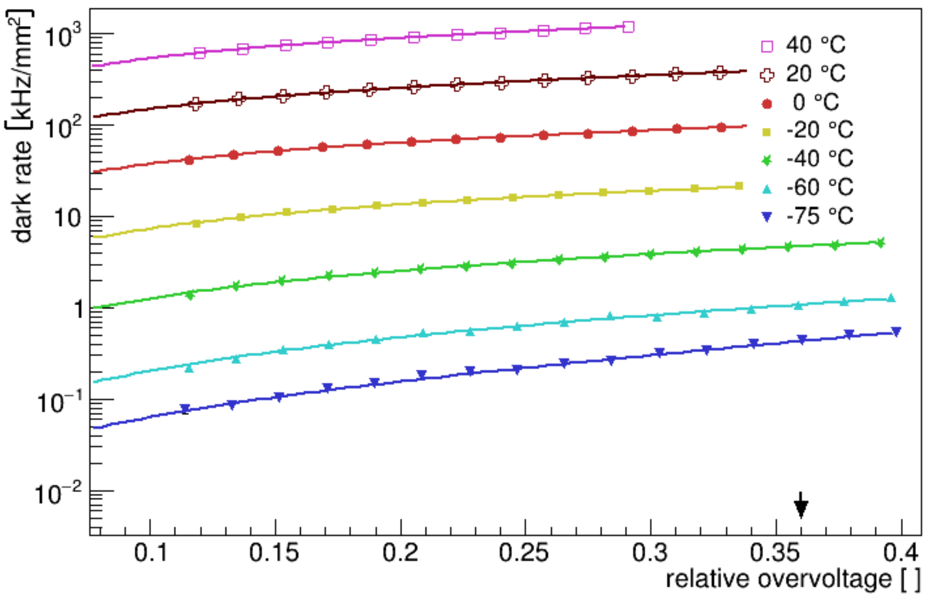
delayed optical crosstalk [%]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
10
1
10^{-1}
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
relative overvoltage [ ]

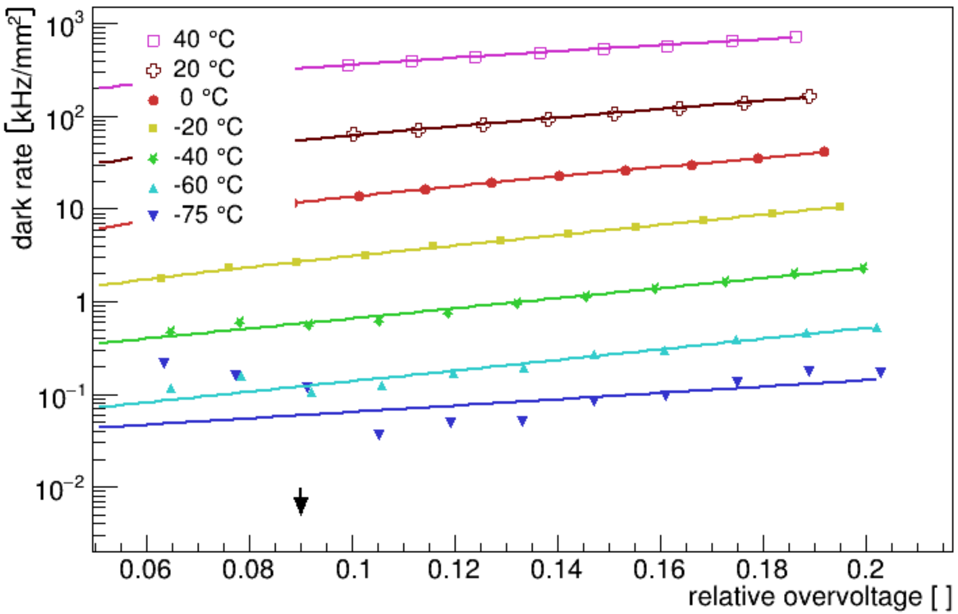


breakdown voltage [V]
temperature [°C]
change in breakdown voltage
24.2±0.7 mV/°C



breakdown voltage [V]
temperature [°C]
change in breakdown voltage
37.2±0.4 mV/°C


dark rate [kHz/mm²]
relative overvoltage [ ]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C


dark rate [kHz/mm²]
relative overvoltage [ ]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C

Hamamatsu S14420-3050WO-RESIN

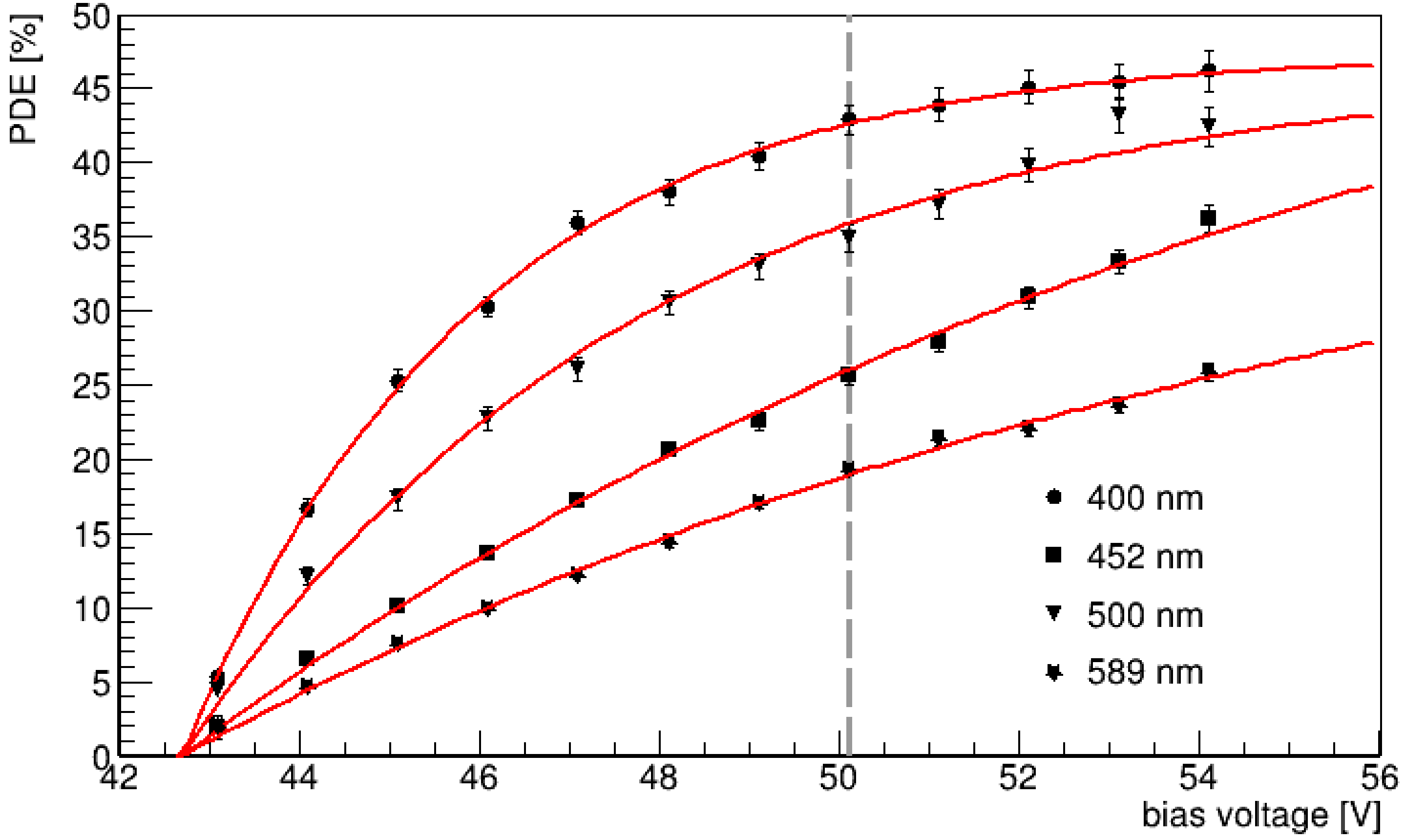
Nepomuk Otte

School of Physics
&
Center for Relativistic Astrophysics

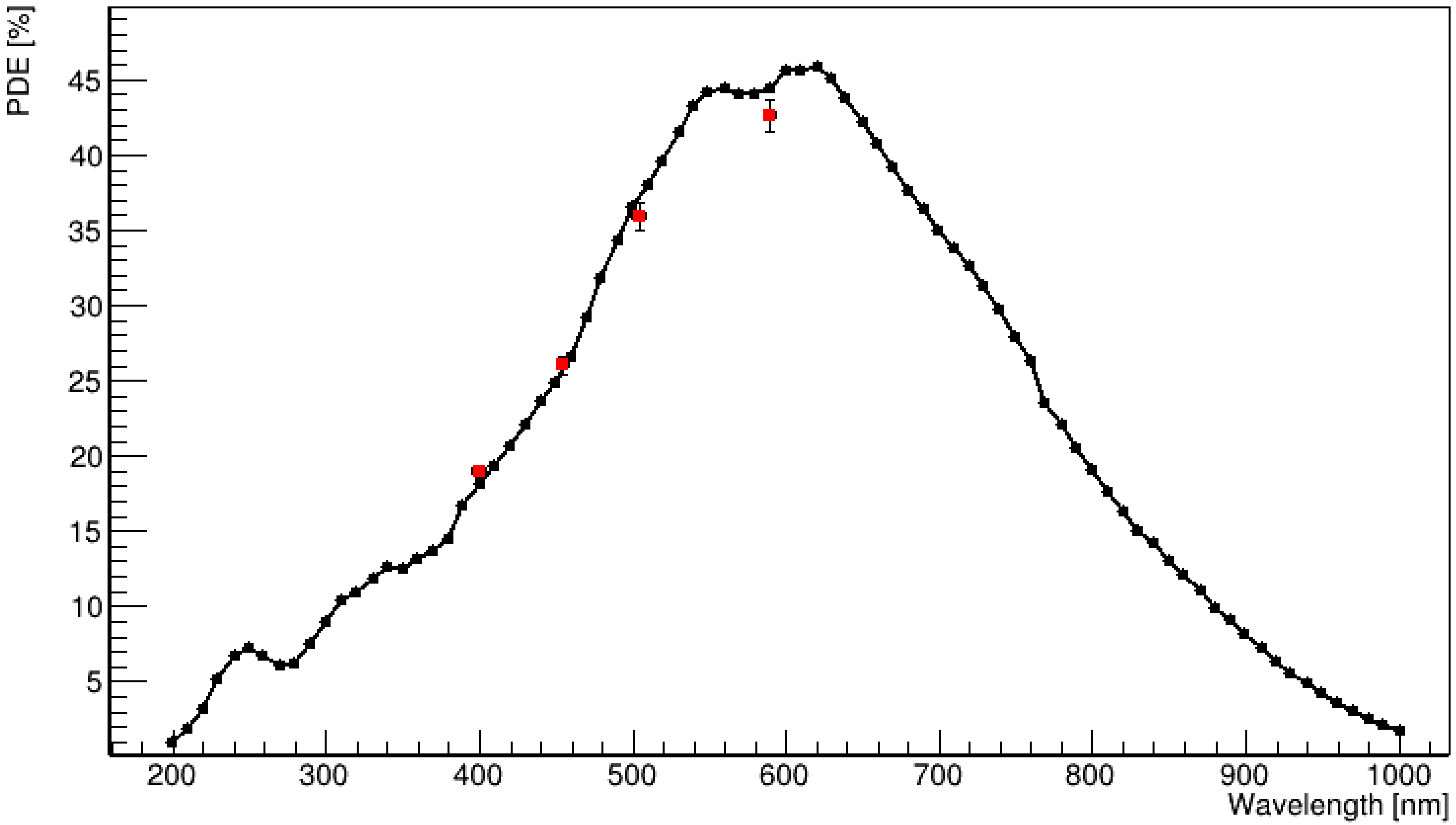
Georgia Tech Physics College of Sciences

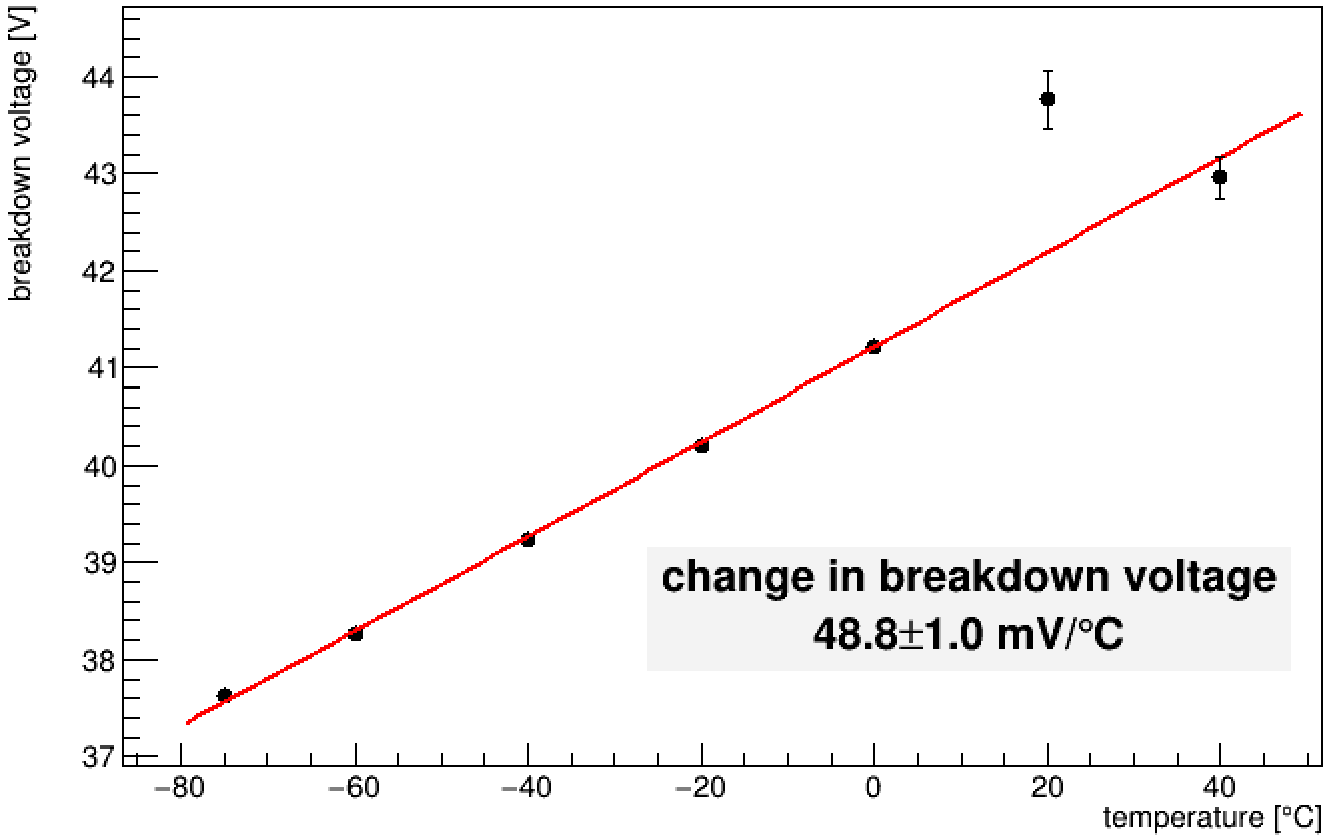
Specs

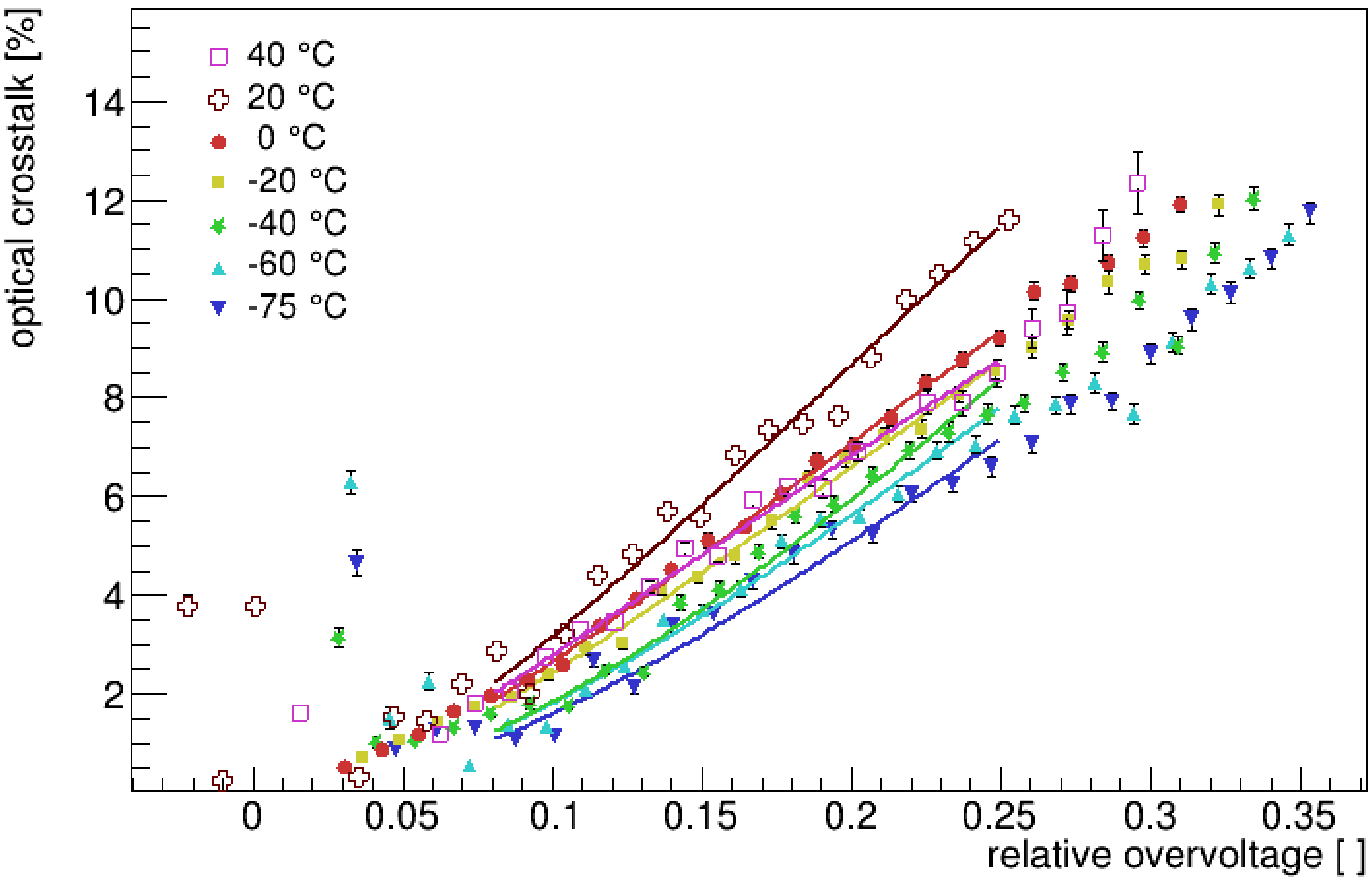
- Round device 3mm diameter
- 50um cells
- Estimated number of cells 2827
- Operating point 20% above breakdown
- 40ns boundary between delayed OC and AP



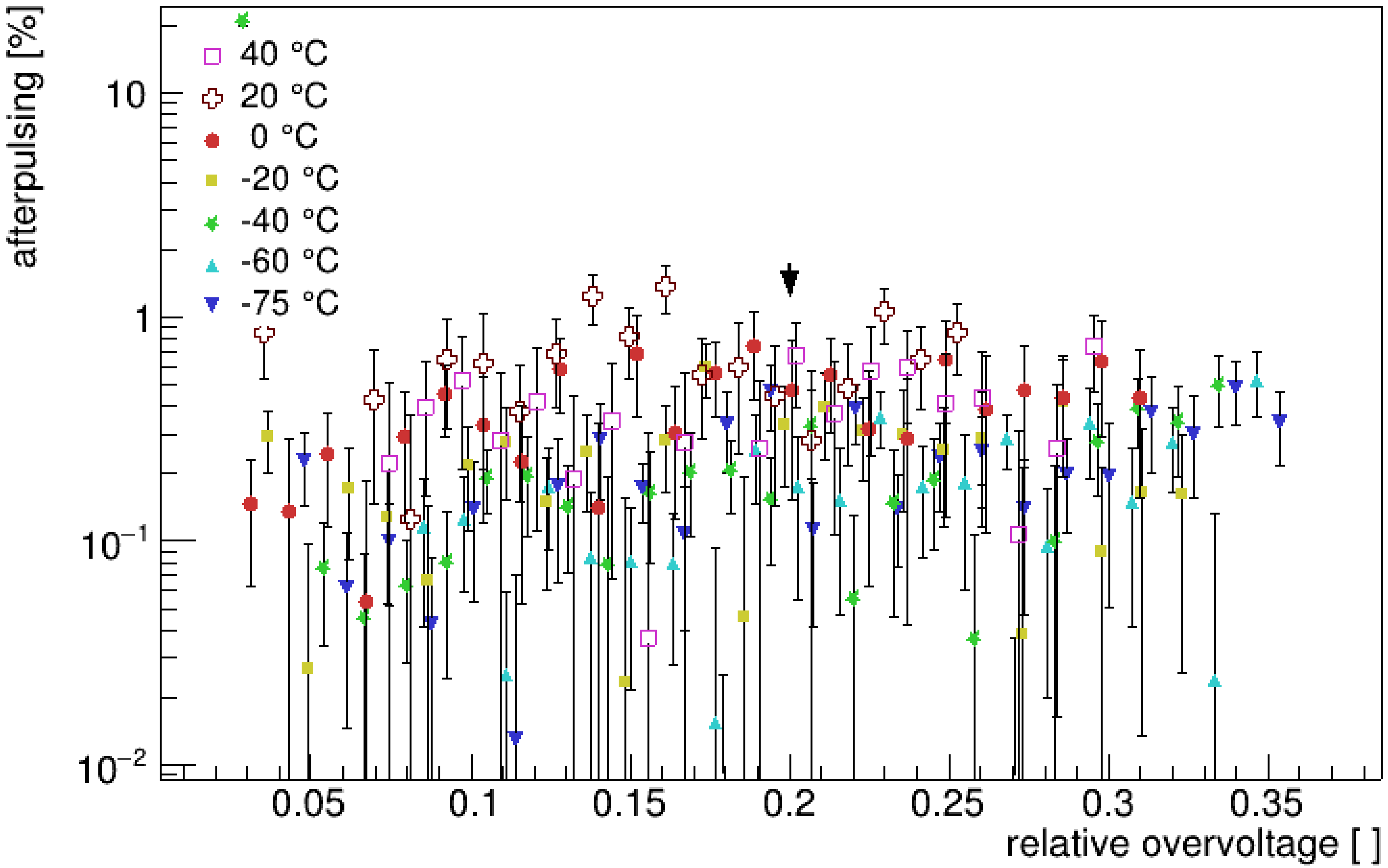
PDE [%]
0
5
10
15
20
25
30
35
40
45
50
42
44
46
48
50
52
54
56
bias voltage [V]
400 nm
452 nm
500 nm
589 nm


PDE [%]
45
40
35
30
25
20
15
10
5
200
300
400
500
600
700
800
900
1000
Wavelength [nm]

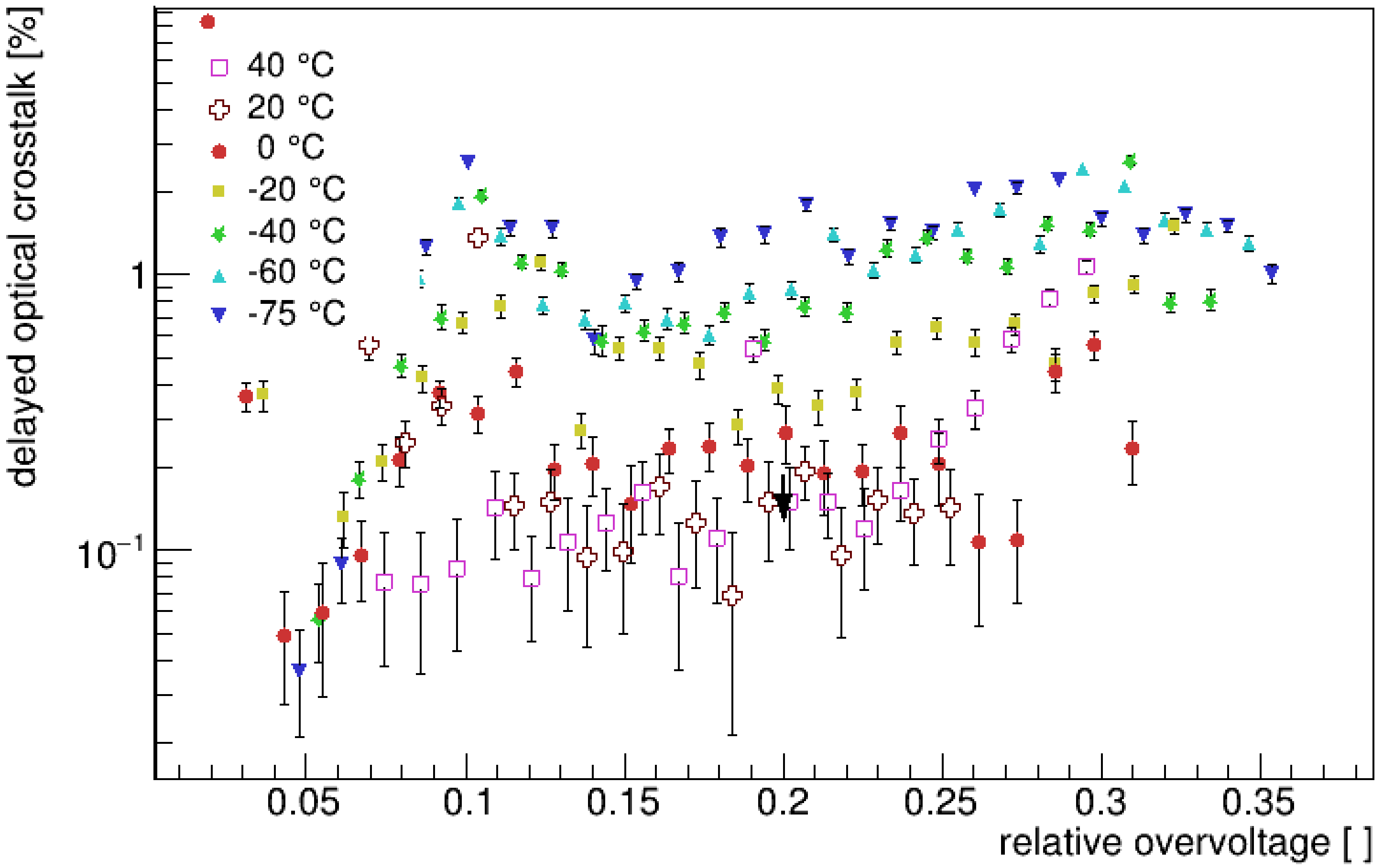

breakdown voltage [V]
44
43
42
41
40
39
38
37
−80
−60
−40
−20
0
20
40
temperature [°C]
change in breakdown voltage
48.8±1.0 mV/°C



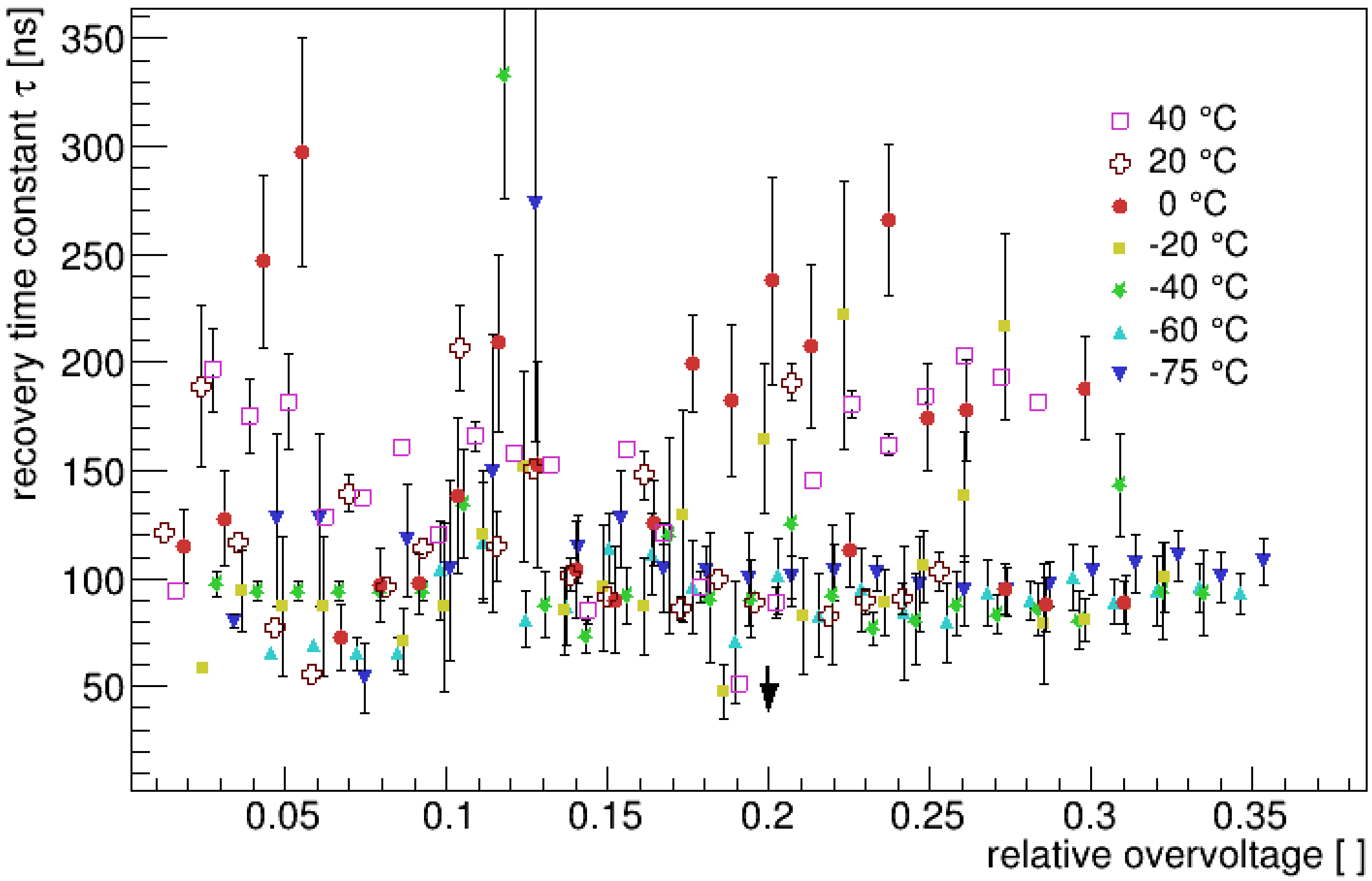
optical crosstalk [%]
relative overvoltage [ ]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
14
12
10
8
6
4
2
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35



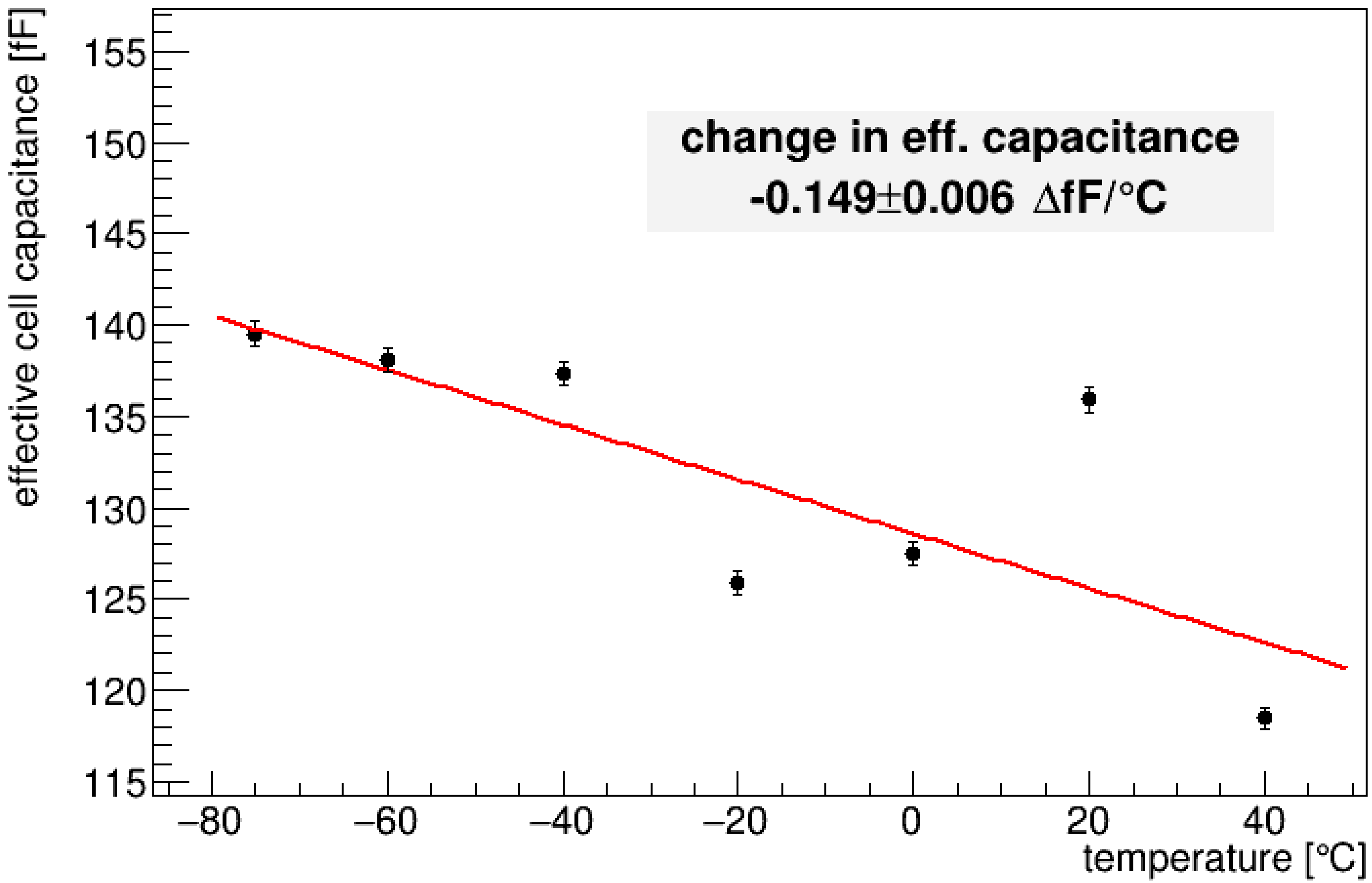
afterpulsing [%]
10
1
10^{-1}
10^{-2}
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
0.05
0.1
0.15
0.2
0.25
0.3
0.35
relative overvoltage [ ]



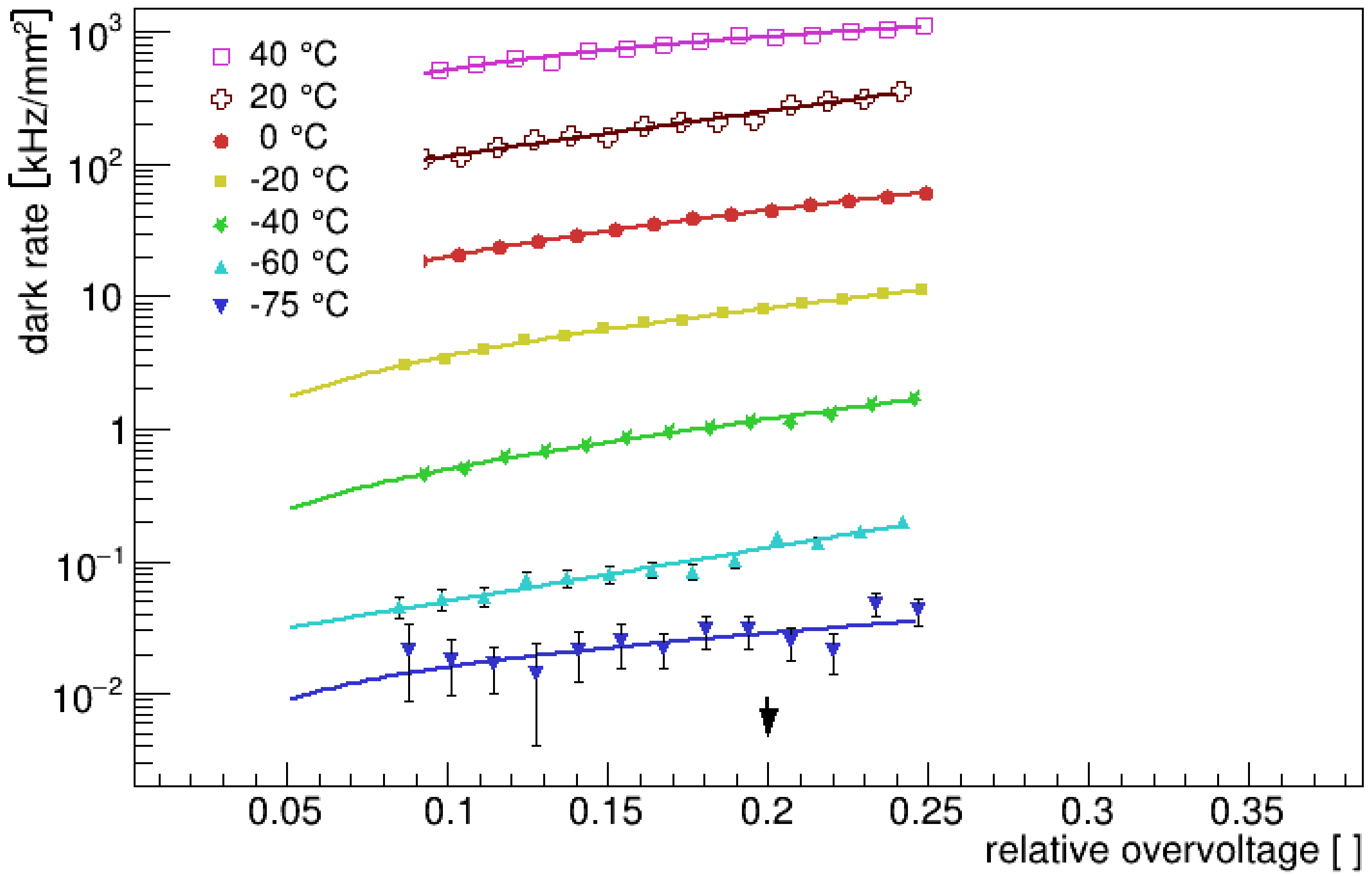
delayed optical crosstalk [%]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
1
10^{-1}
0.05
0.1
0.15
0.2
0.25
0.3
0.35
relative overvoltage [ ]



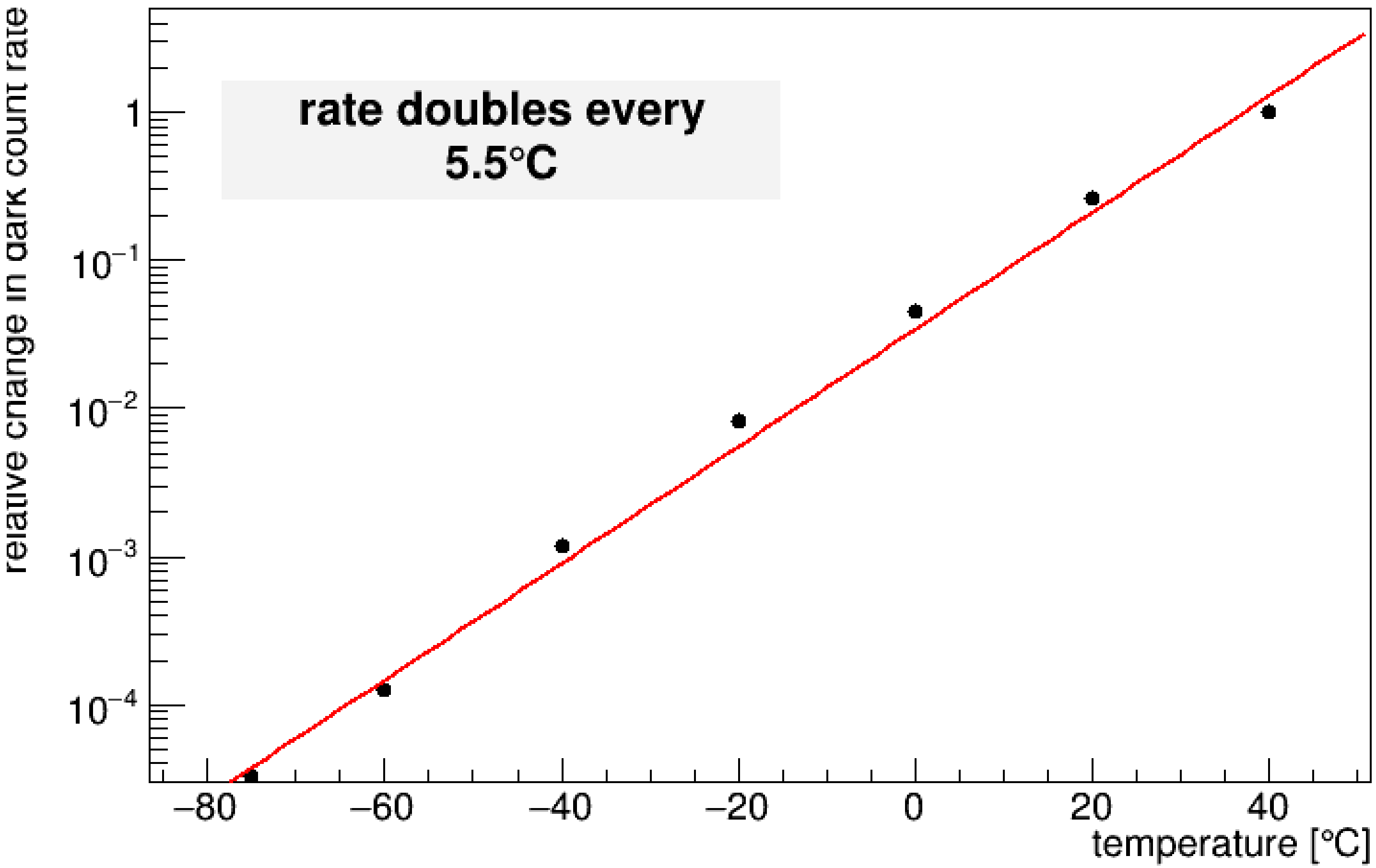
recovery time constant τ [ns]
350
300
250
200
150
100
50
0.05
0.1
0.15
0.2
0.25
0.3
0.35
relative overvoltage [ ]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C



change in eff. capacitance
-0.149±0.006 ΔfF/°C
effective cell capacitance [fF]
155
150
145
140
135
130
125
120
115
−80
−60
−40
−20
0
20
40
temperature [°C]



40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
dark rate [kHz/mm²]
relative overvoltage [ ]



rate doubles every
5.5°C
relative change in dark count rate
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
−80
−60
−40
−20
0
20
40
temperature [°C]

Measurements: FBK NUV-HD3-4

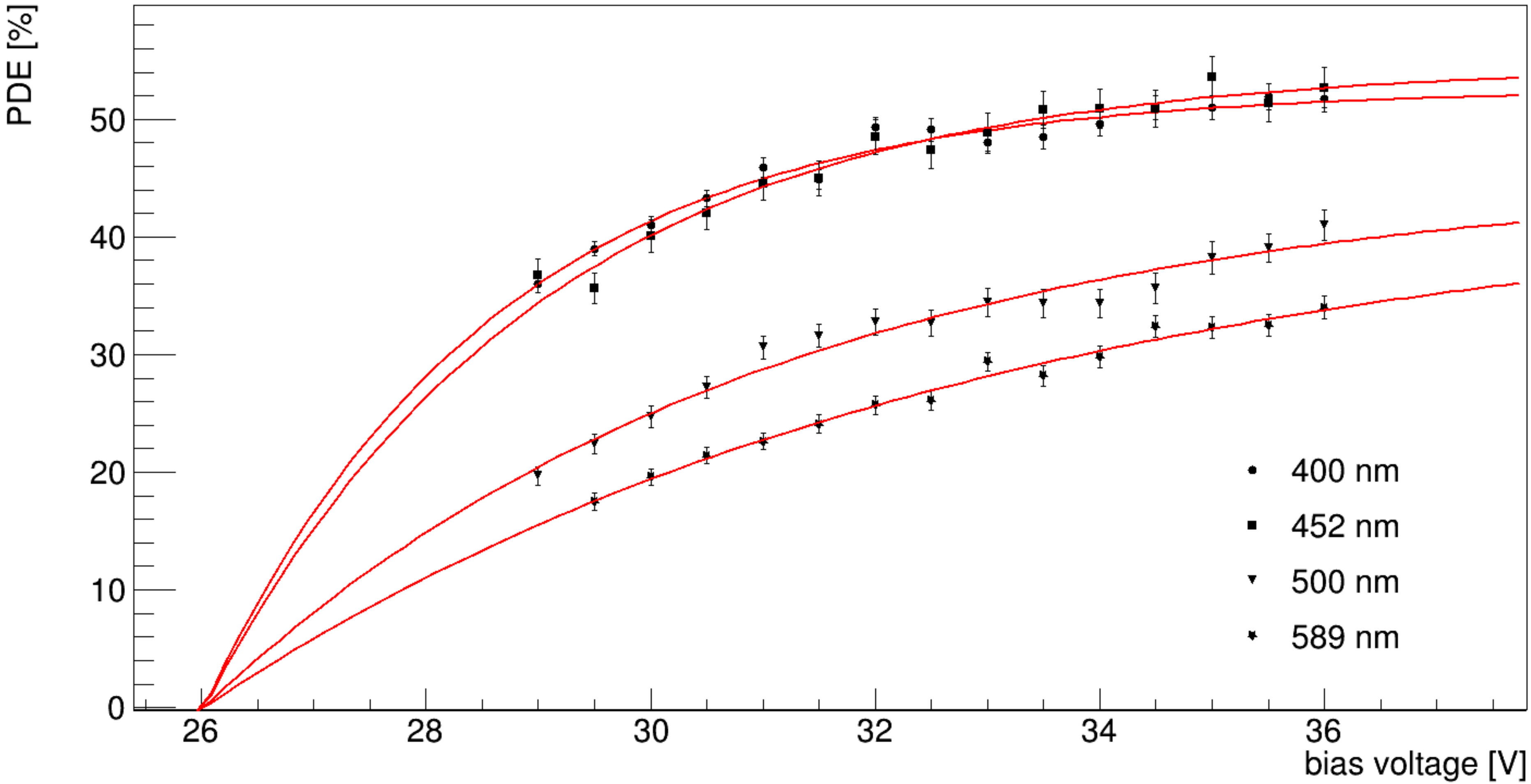
Katherine Powell
Nepomuk Otte

School of Physics
&
Center for Relativistic Astrophysics

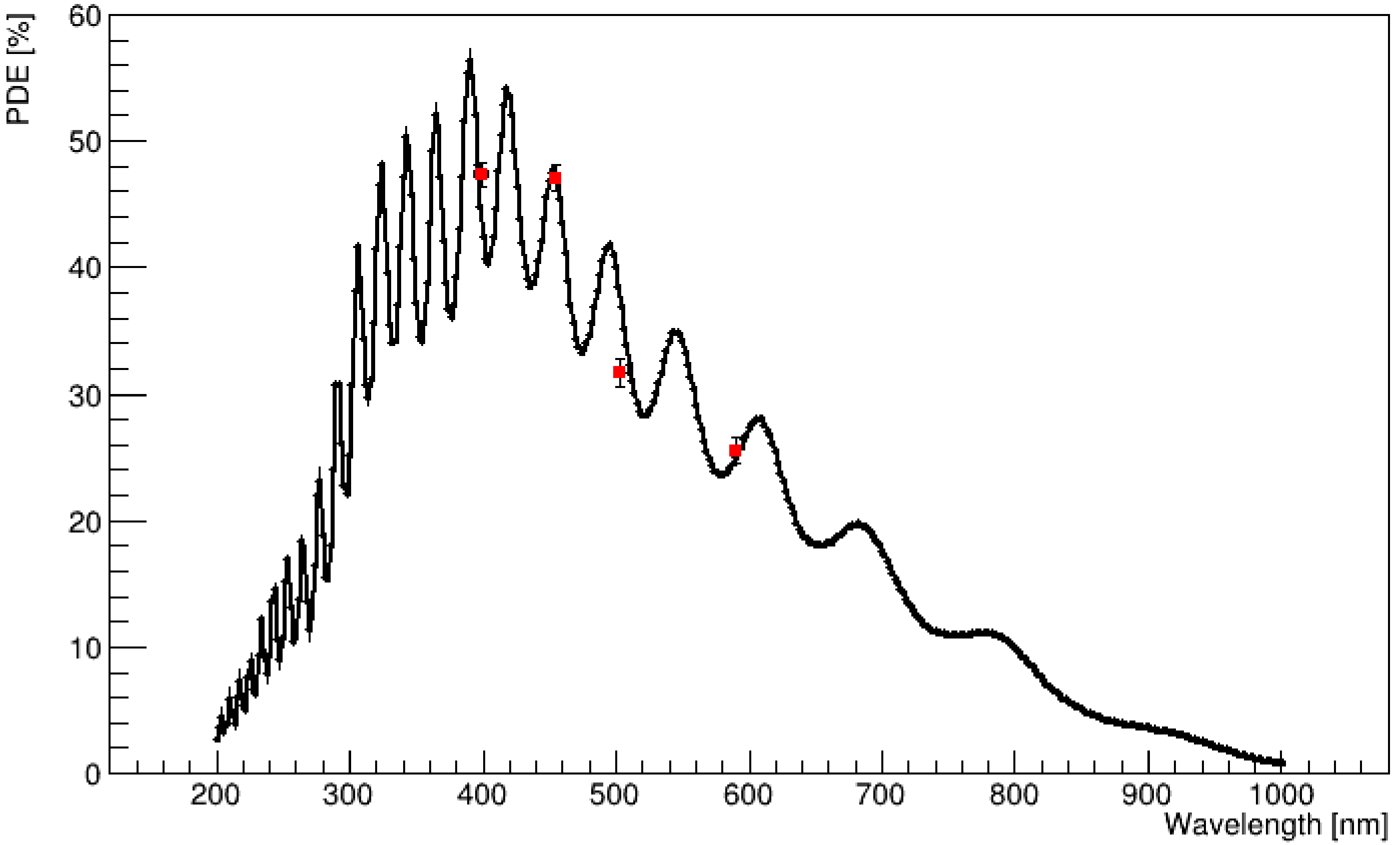
Georgia Tech Physics College of Sciences

Specs

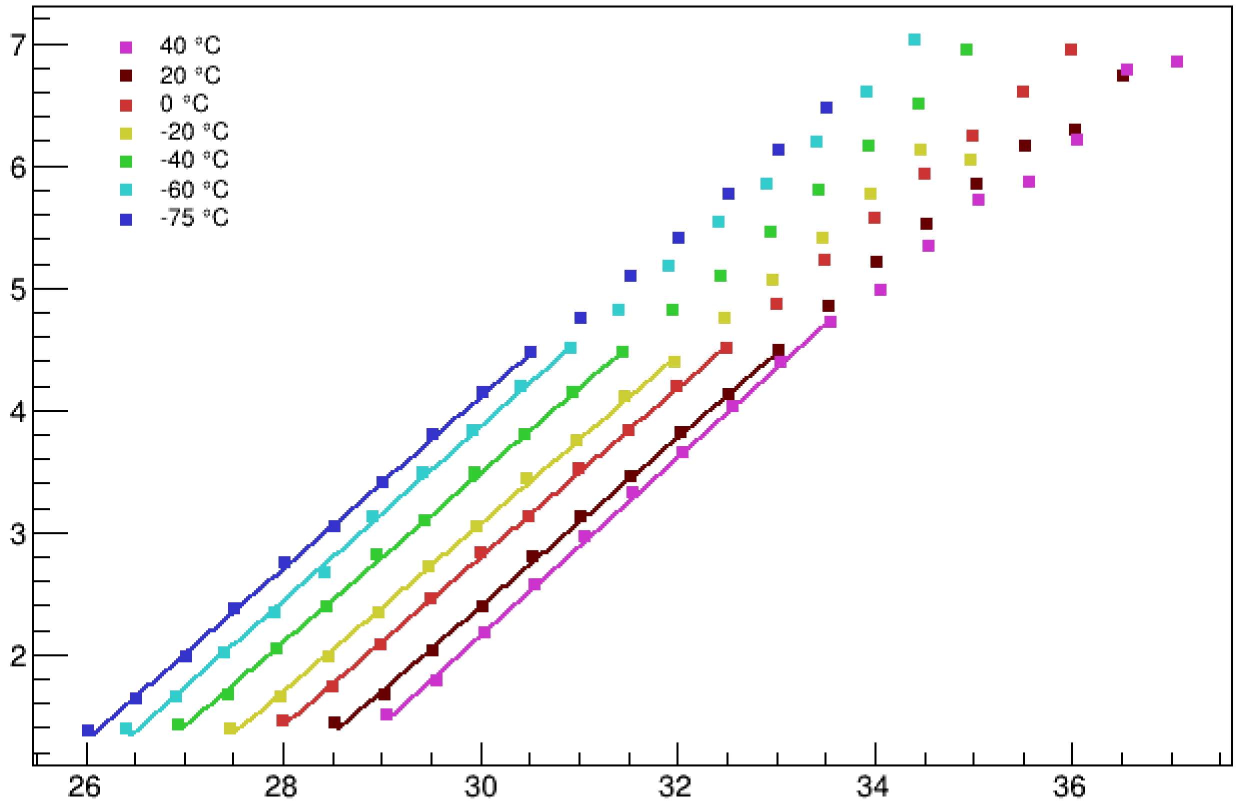
- Uncoated
- 6.3mm x 6.3mm
- 40 um cells

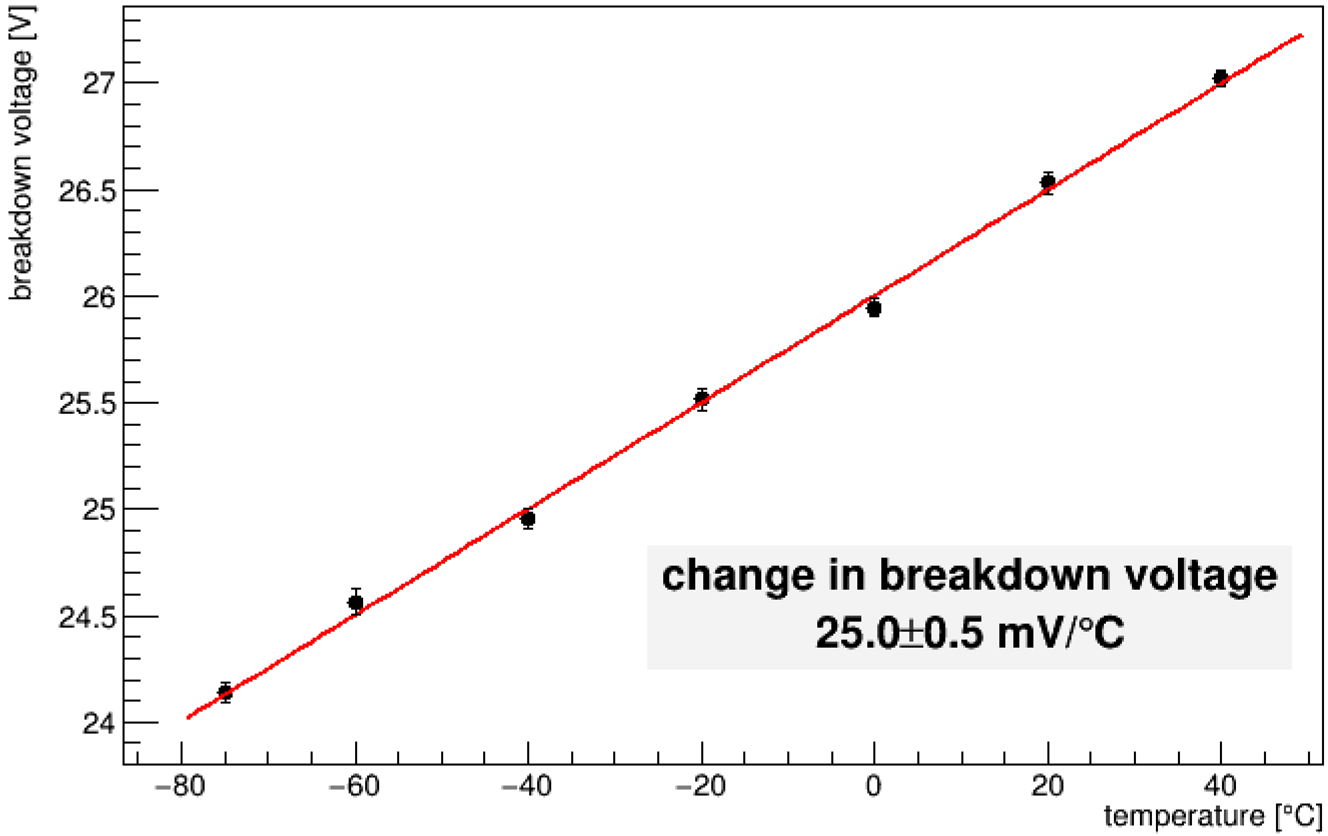


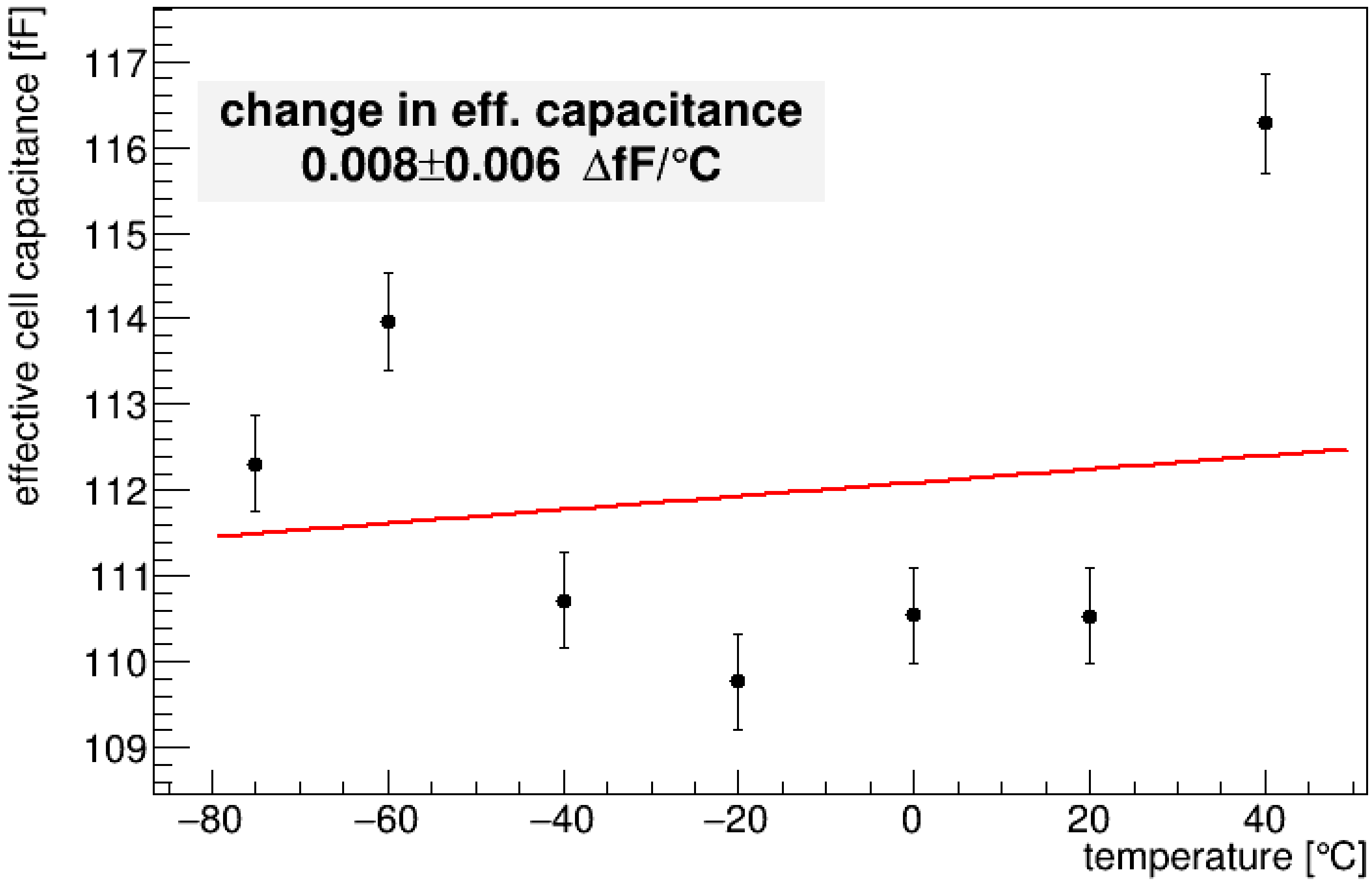
PDE [%]
50
40
30
20
10
0
26
28
30
32
34
36
bias voltage [V]
400 nm
452 nm
500 nm
589 nm

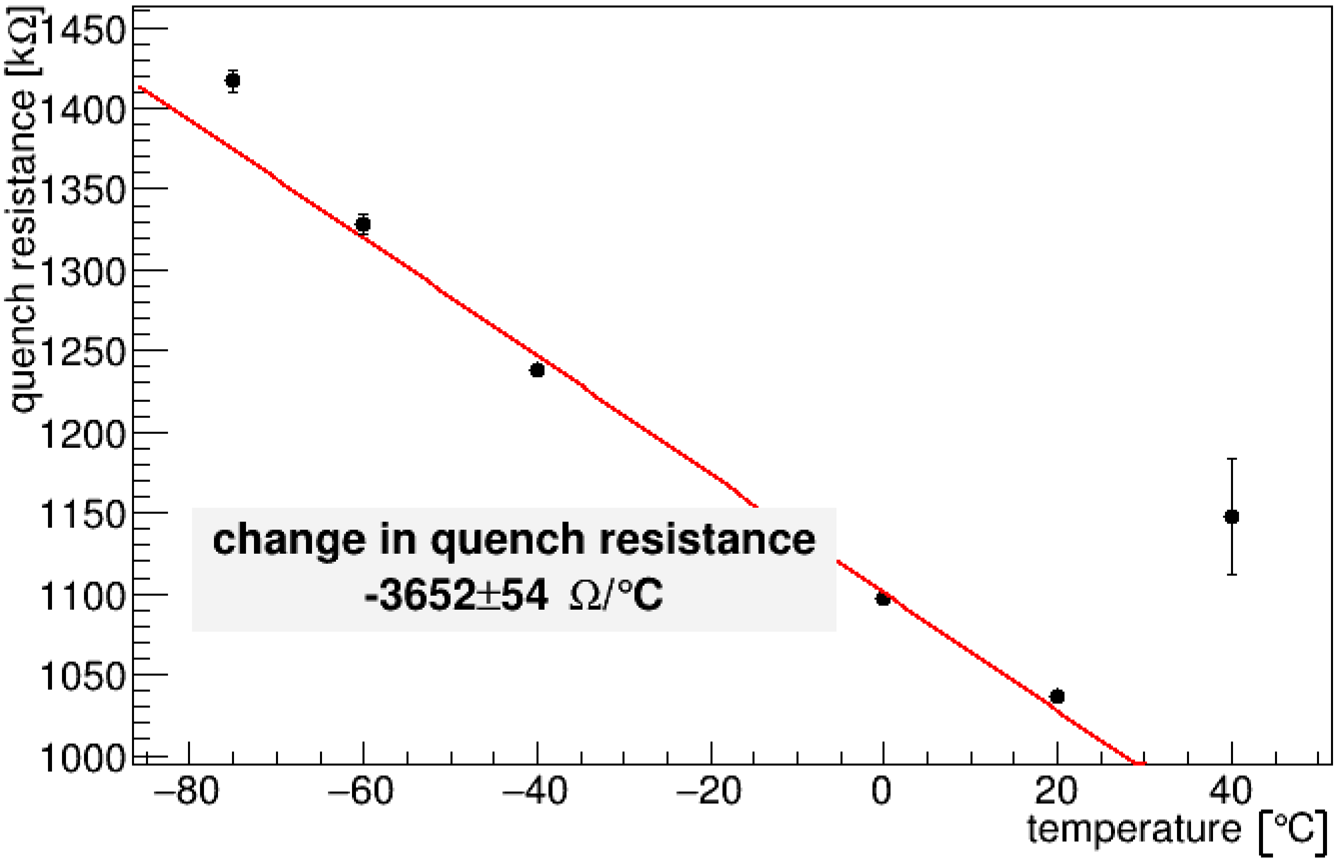


PDE [%]
60
50
40
30
20
10
0
200
300
400
500
600
700
800
900
1000
Wavelength [nm]

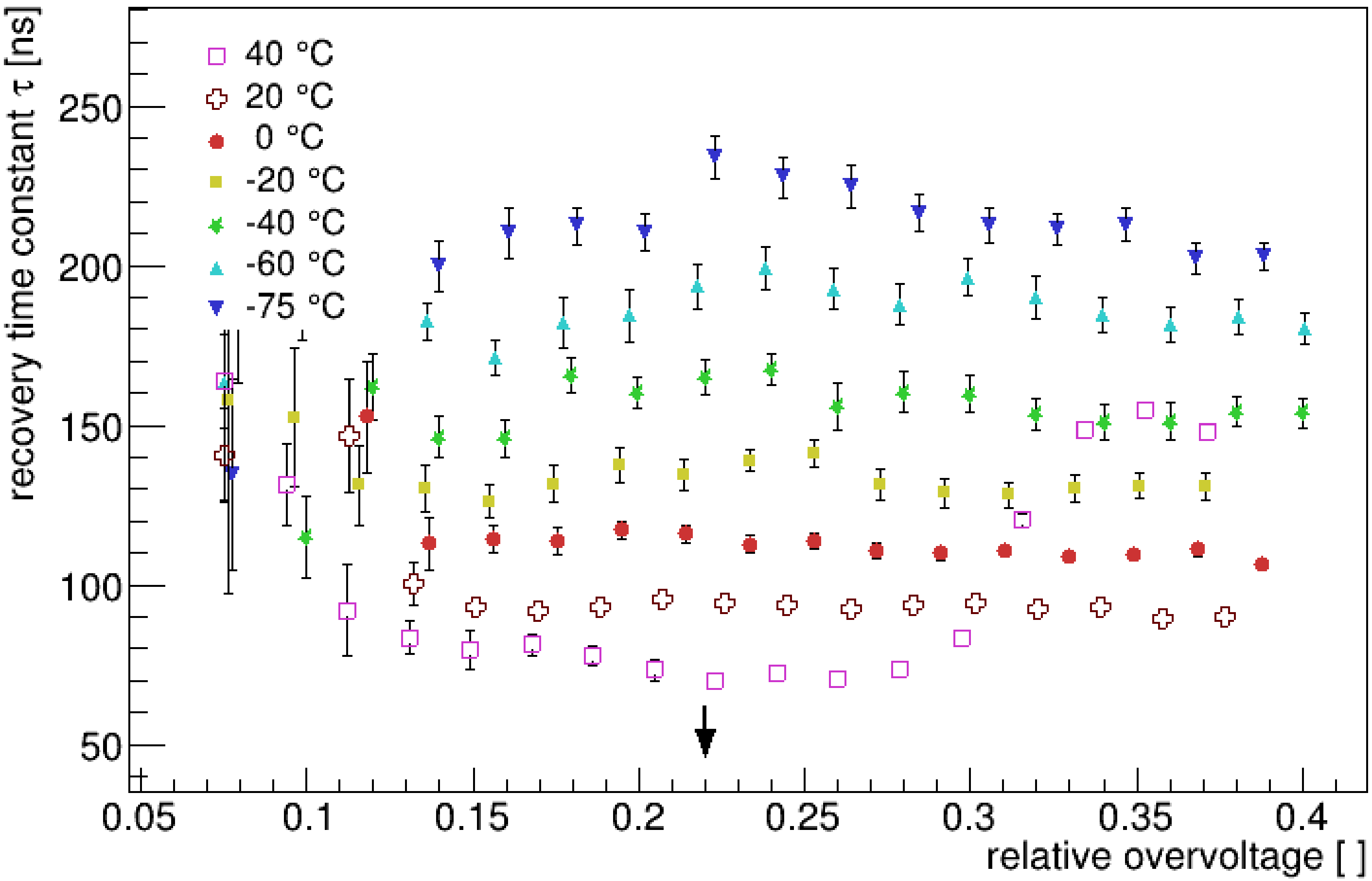

40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
7
6
5
4
3
2
26
28
30
32
34
36


breakdown voltage [V]
27
26.5
26
25.5
25
24.5
24
−80
−60
−40
−20
0
20
40
temperature [°C]
change in breakdown voltage
25.0±0.5 mV/°C

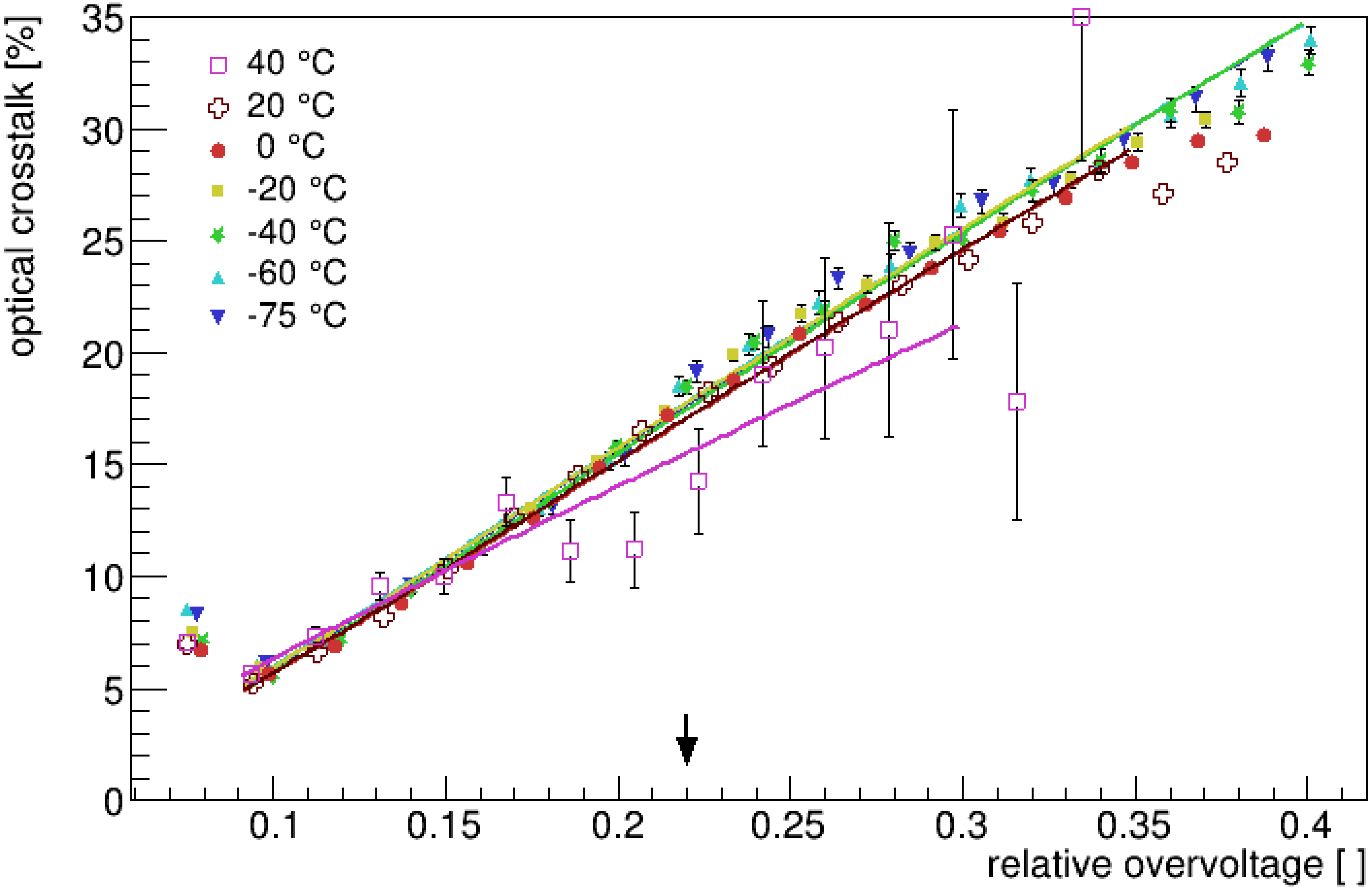

change in eff. capacitance
0.008±0.006 ΔfF/°C
effective cell capacitance [fF]
117
116
115
114
113
112
111
110
109
−80
−60
−40
−20
0
20
40
temperature [°C]



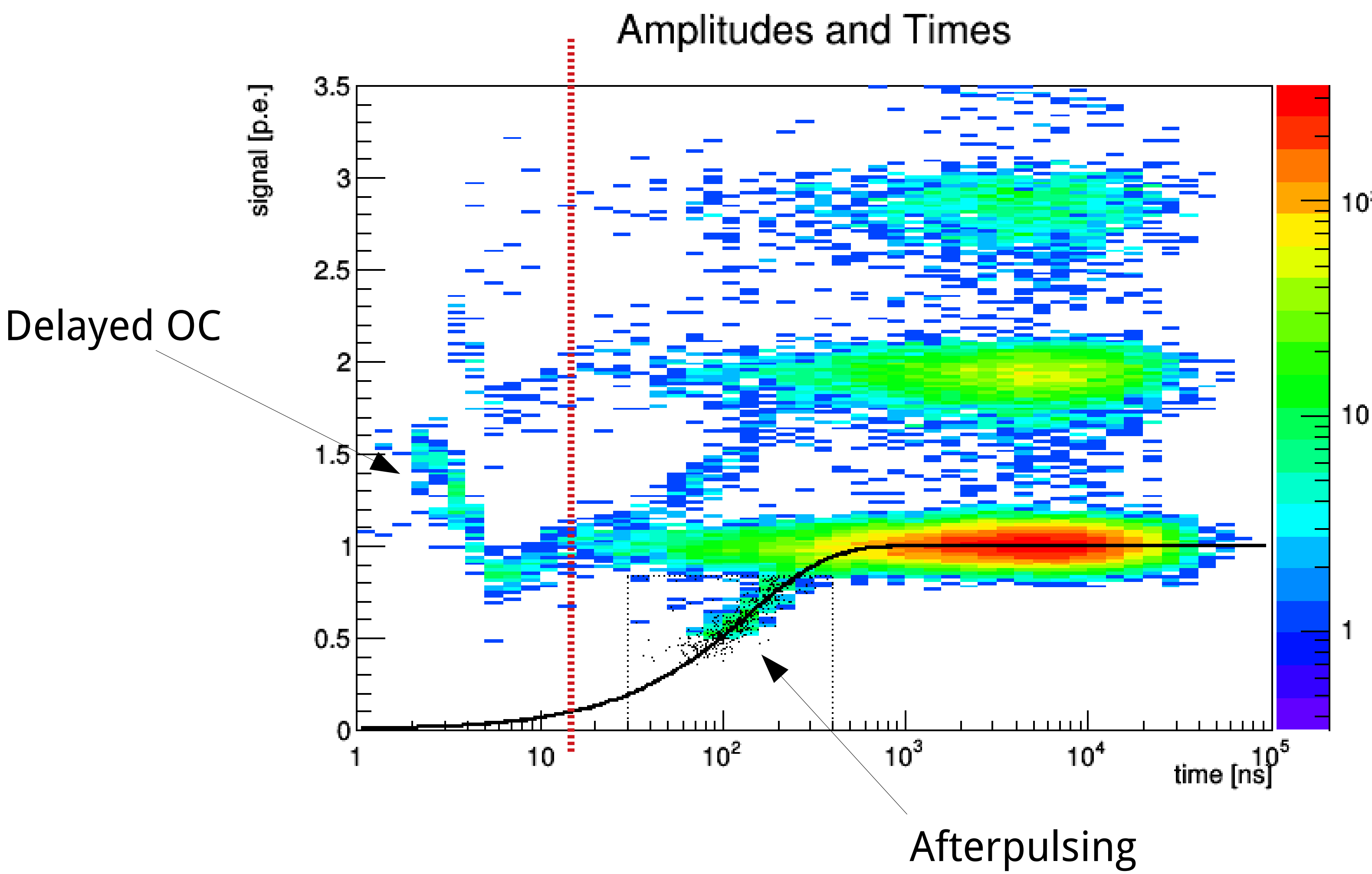
quench resistance [kΩ]
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
−80
−60
−40
−20
0
20
40
temperature [°C]
change in quench resistance
-3652±54 Ω/°C



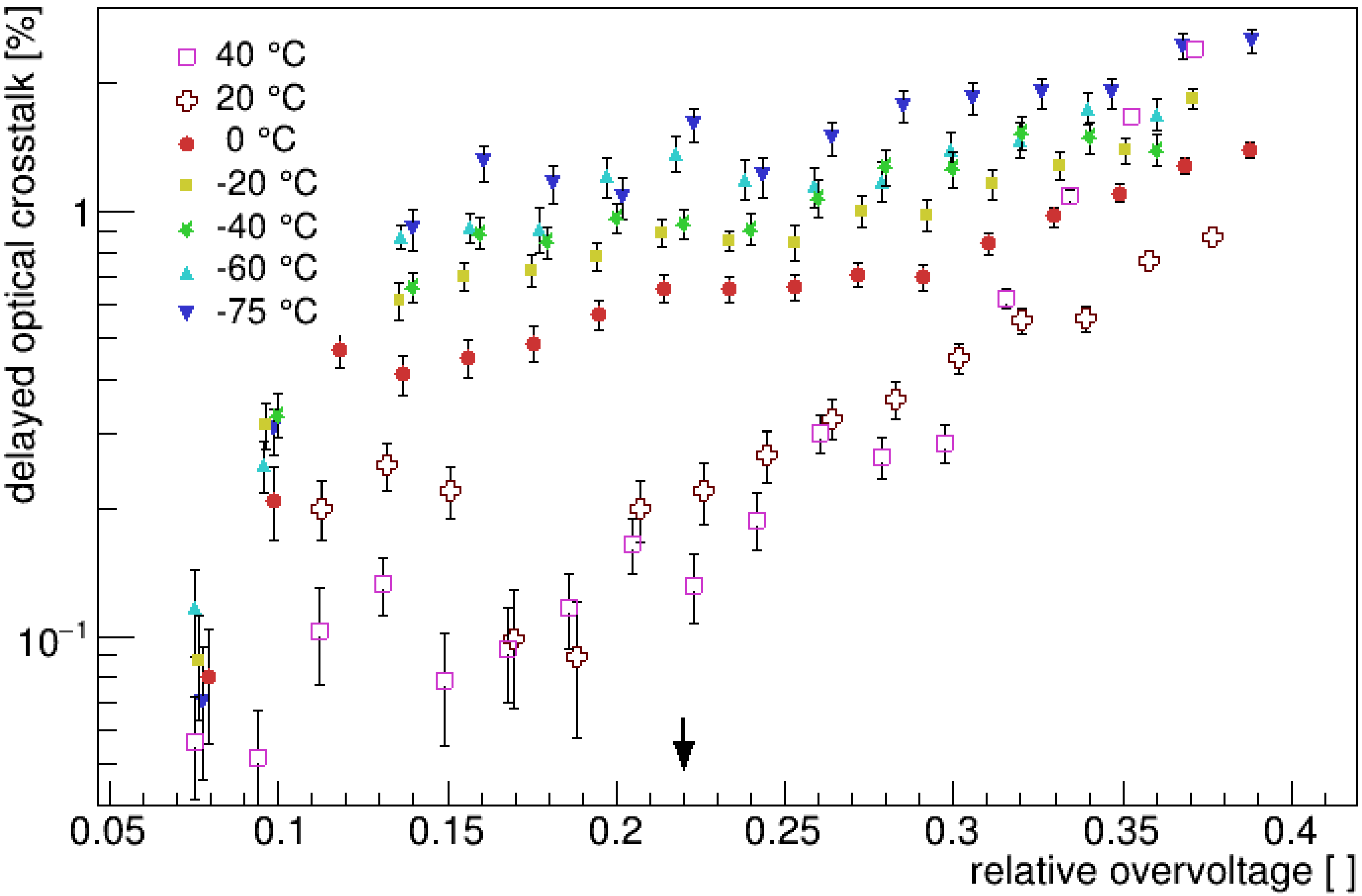
recovery time constant τ [ns]
250
200
150
100
50
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
relative overvoltage [ ]
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C



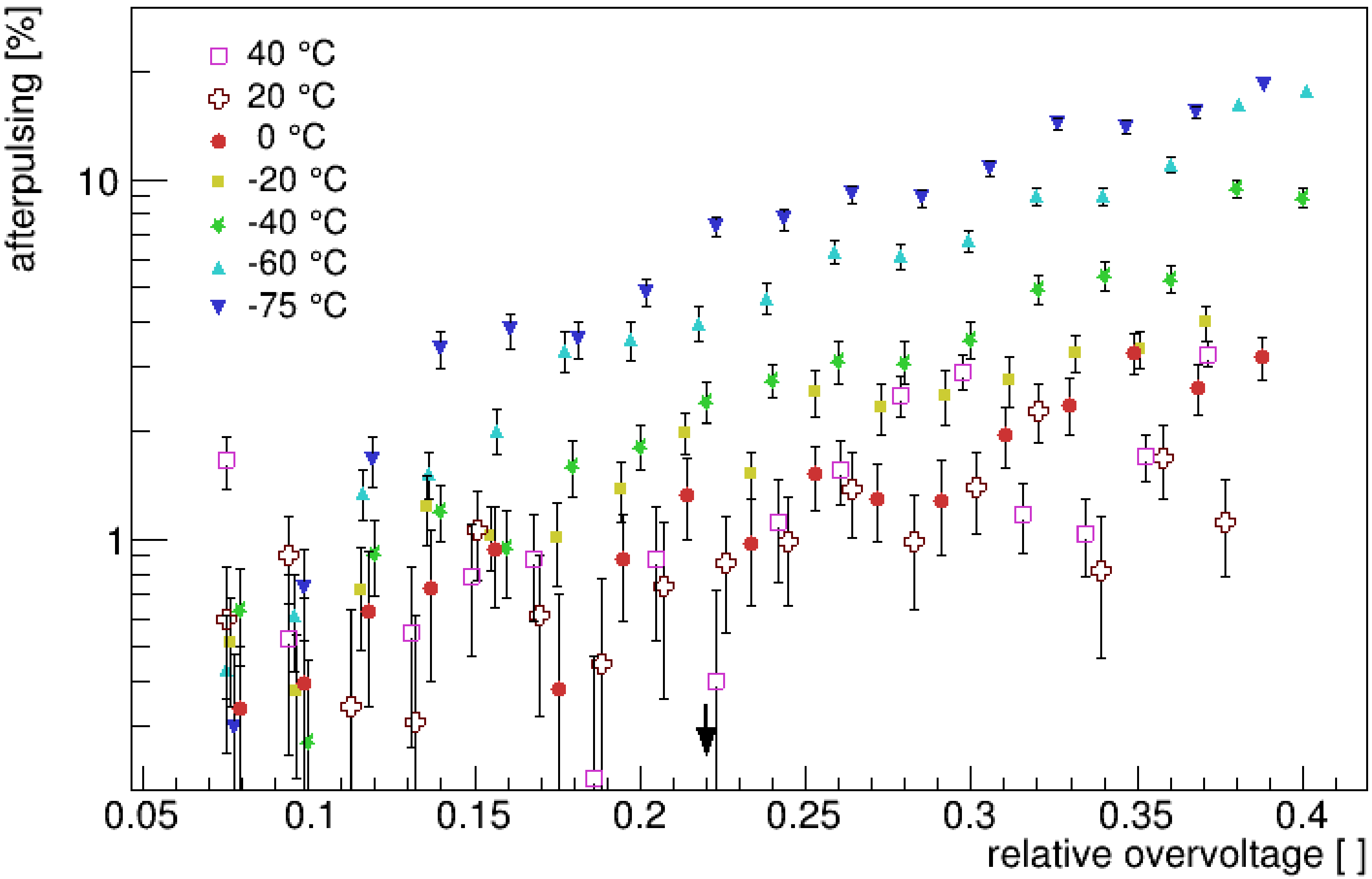
optical crosstalk [%]
35
30
25
20
15
10
5
0
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
0.1
0.15
0.2
0.25
0.3
0.35
0.4
relative overvoltage [ ]



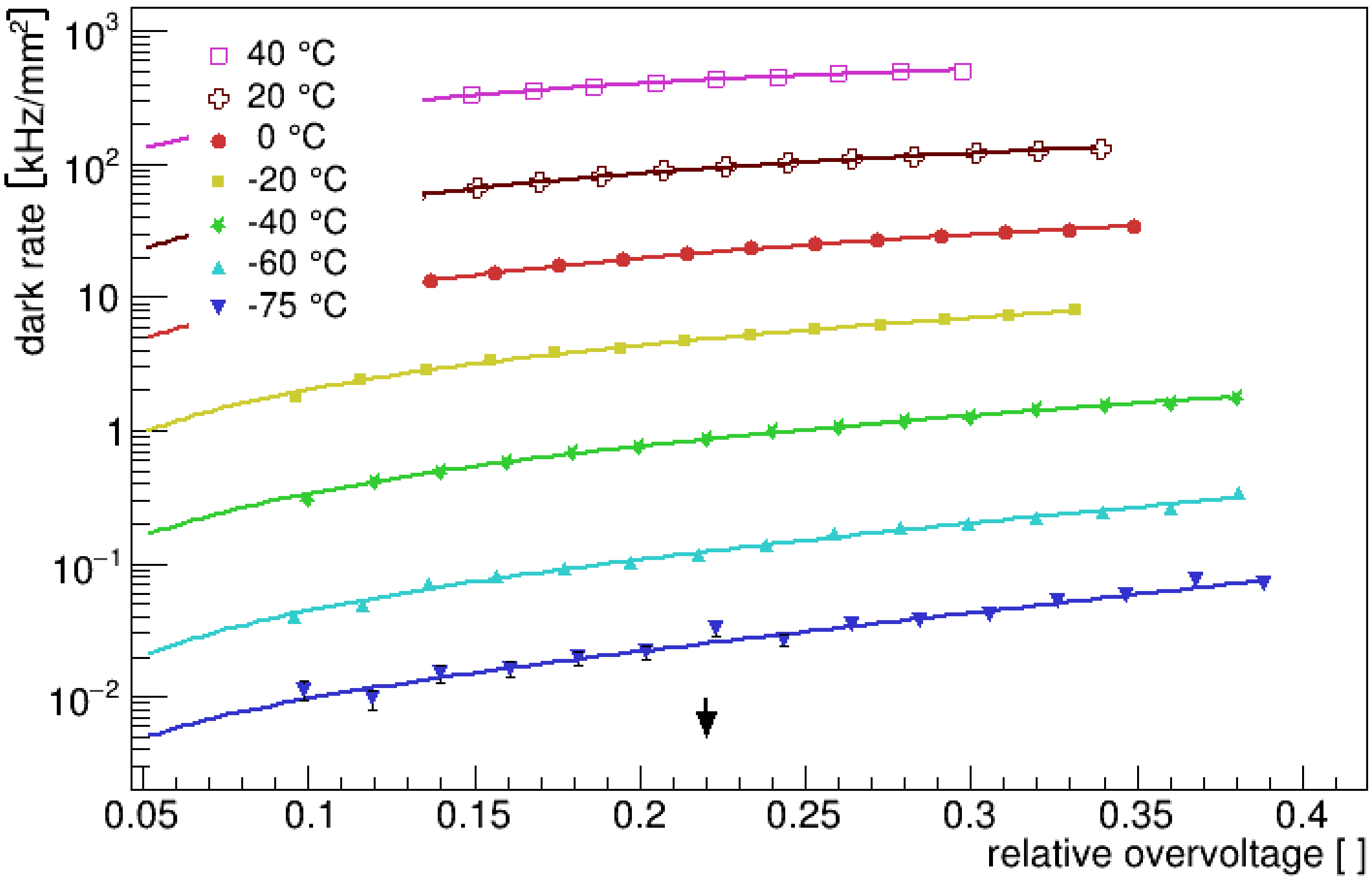
Amplitudes and Times
signal [p.e.]
3.5
3
2.5
2
1.5
1
0.5
0
1
10
10^2
10^3
10^4
10^5
time [ns]
10^2
10
1
Delayed OC
Afterpulsing



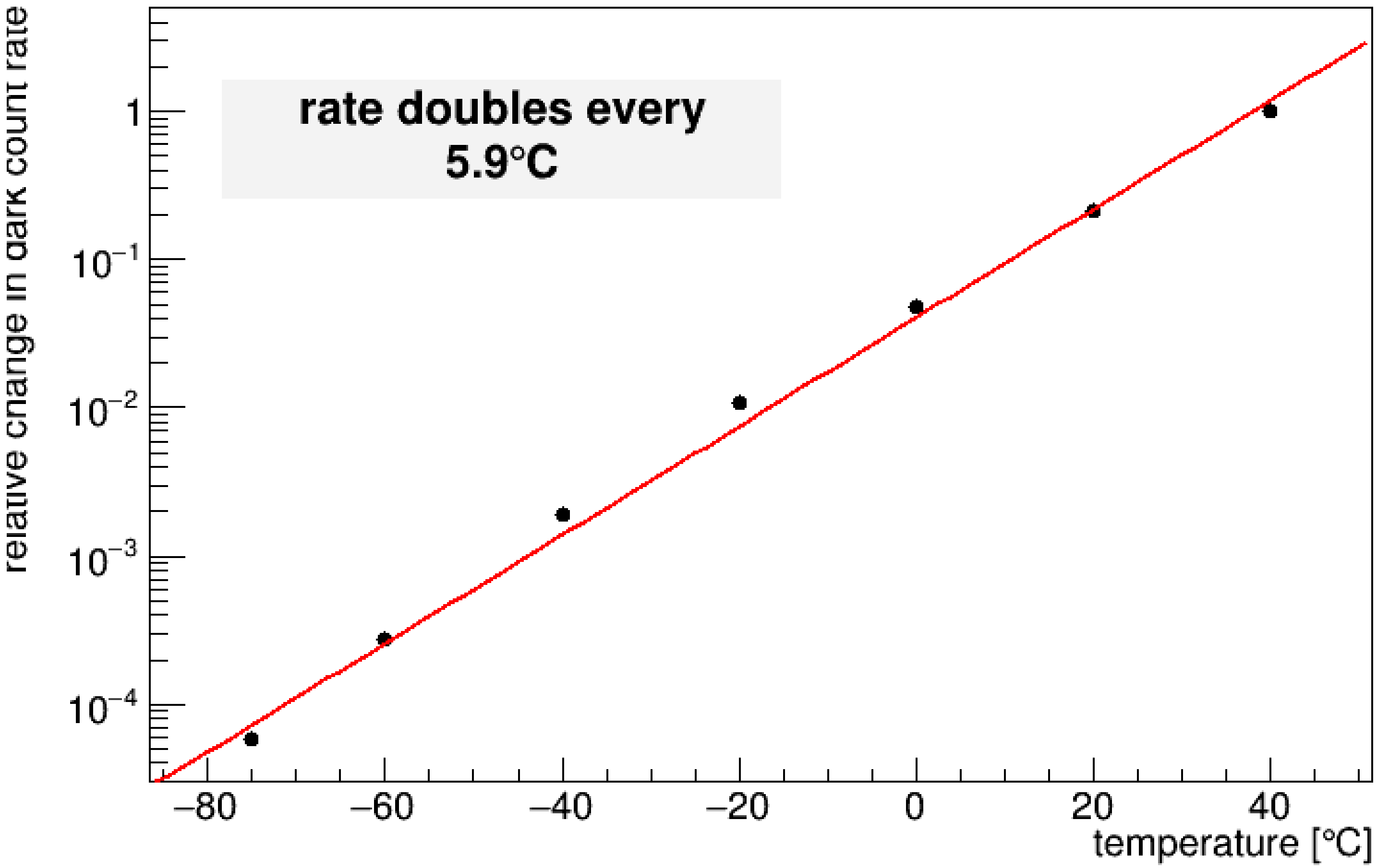
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
delayed optical crosstalk [%]
1
10^{-1}
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
relative overvoltage [ ]



40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
afterpulsing [%]
10
1
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
relative overvoltage [ ]

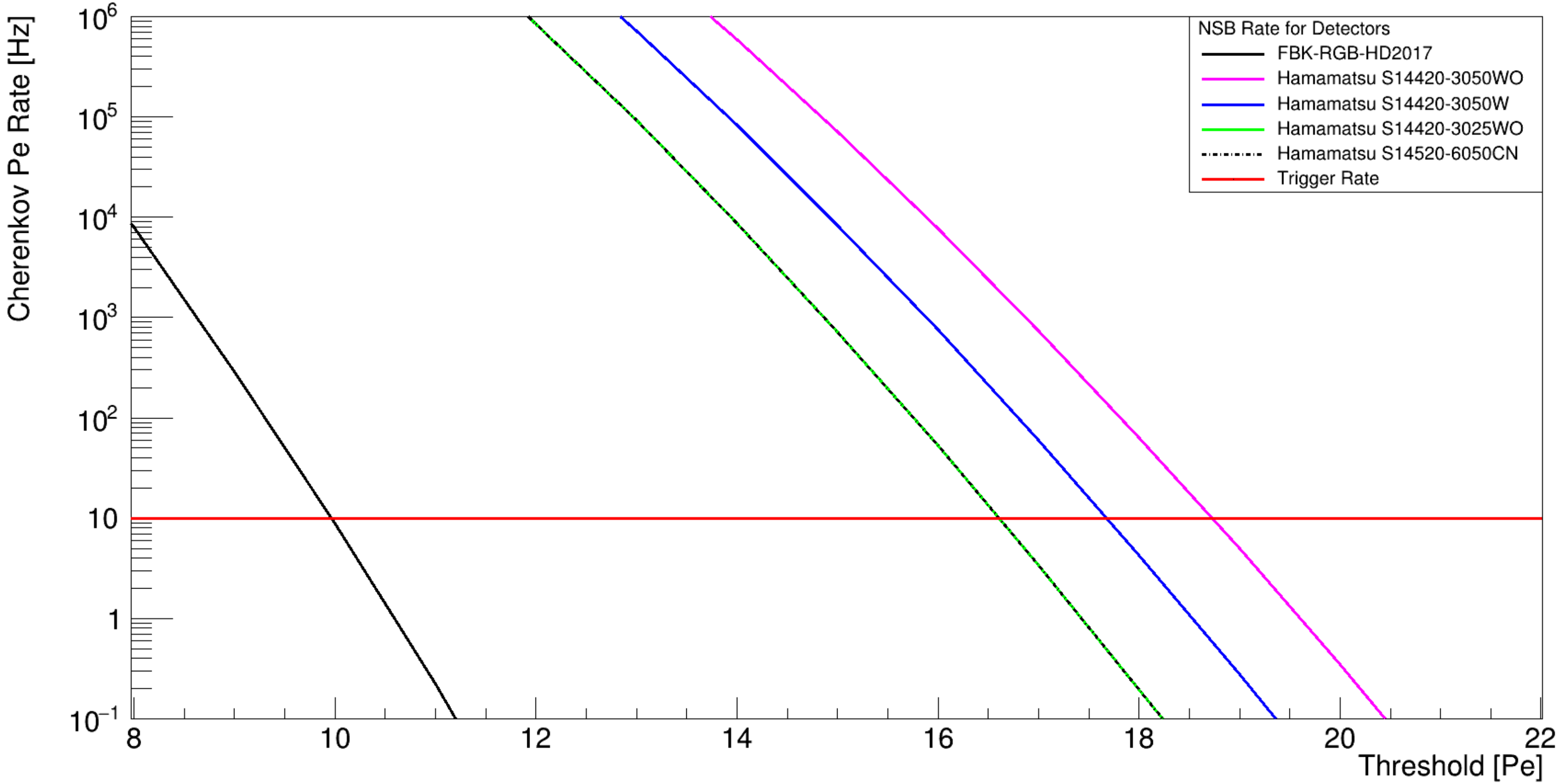


dark rate [kHz/mm^2]
10^3
10^2
10
1
10^{-1}
10^{-2}
40 °C
20 °C
0 °C
-20 °C
-40 °C
-60 °C
-75 °C
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
relative overvoltage [ ]


rate doubles every
5.9°C
relative change in dark count rate
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
−80
−60
−40
−20
0
20
40
temperature [°C]

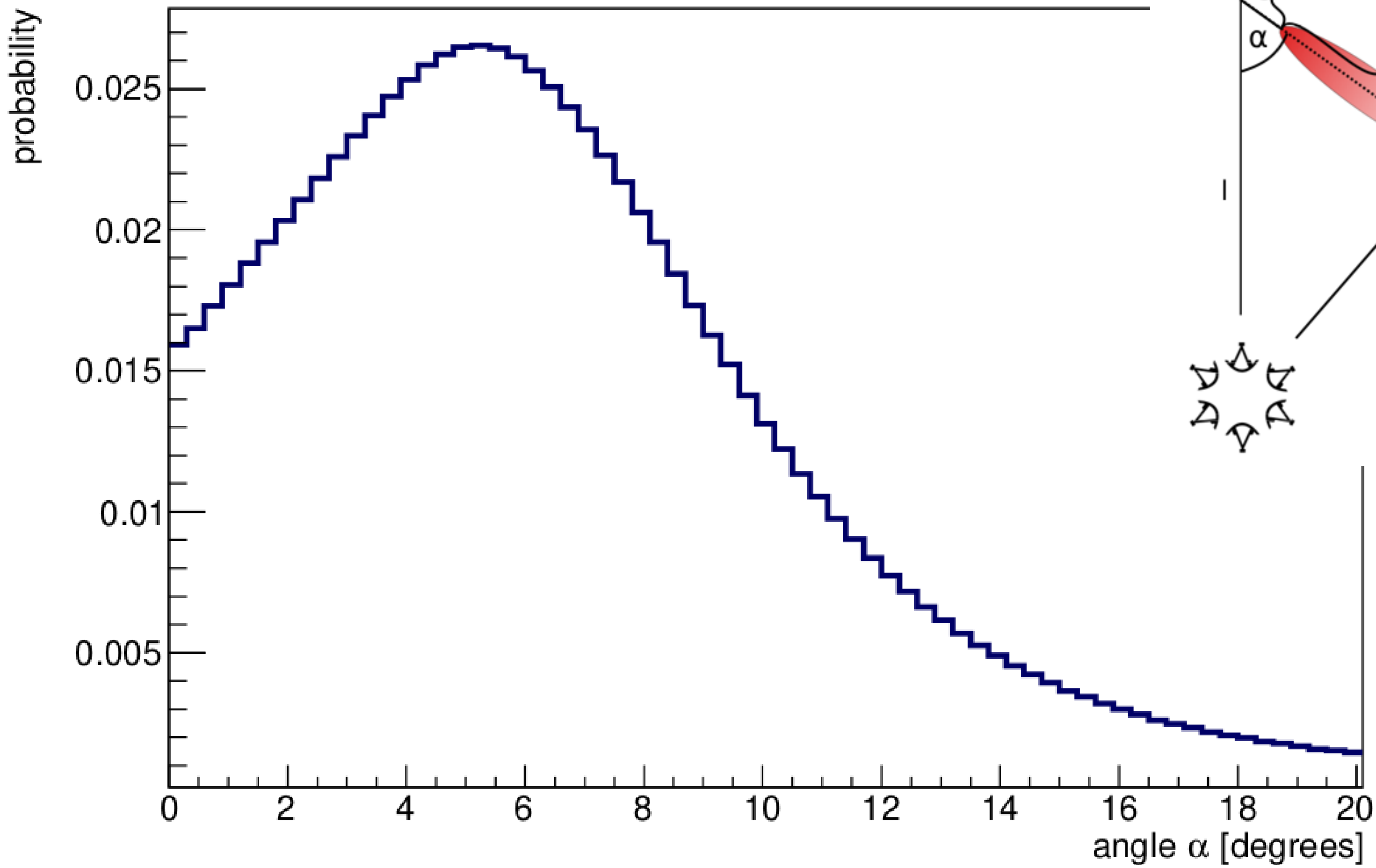
Other backup

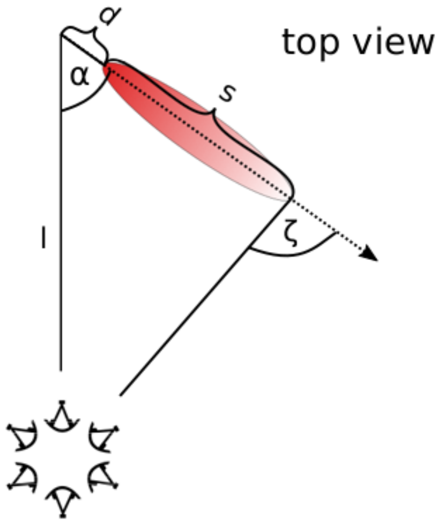
Bias Curves

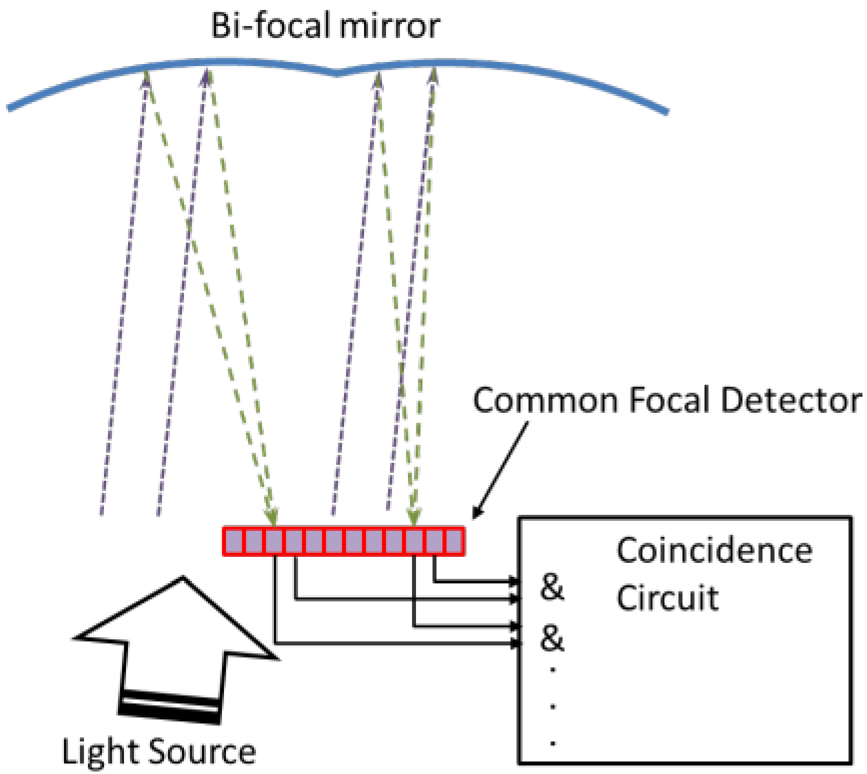


Cherenkov Pe Rate [Hz]
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
8
10
12
14
16
18
20
22
Threshold [Pe]
NSB Rate for Detectors
FBK-RGB-HD2017
Hamamatsu S14420-3050WO
Hamamatsu S14420-3050W
Hamamatsu S14420-3025WO
Hamamatsu S14520-6050CN
Trigger Rate

Triggered Viewing Angles



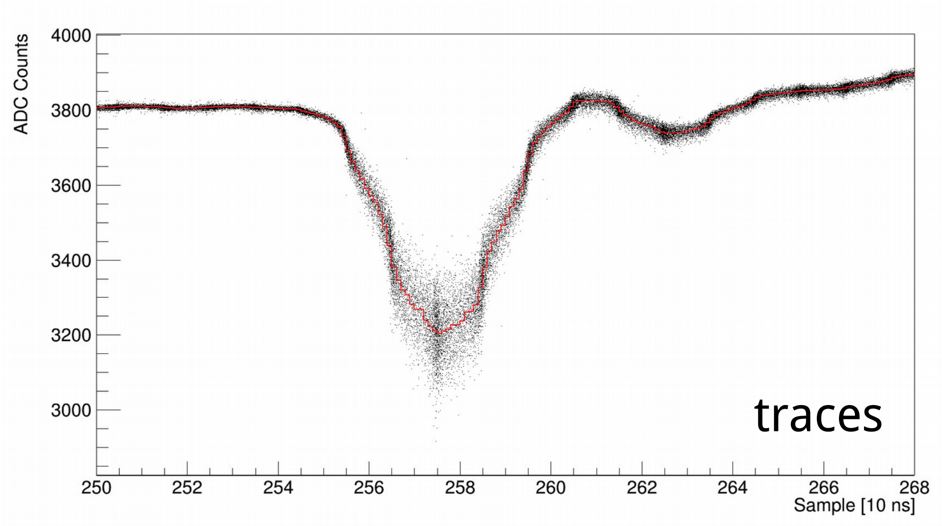


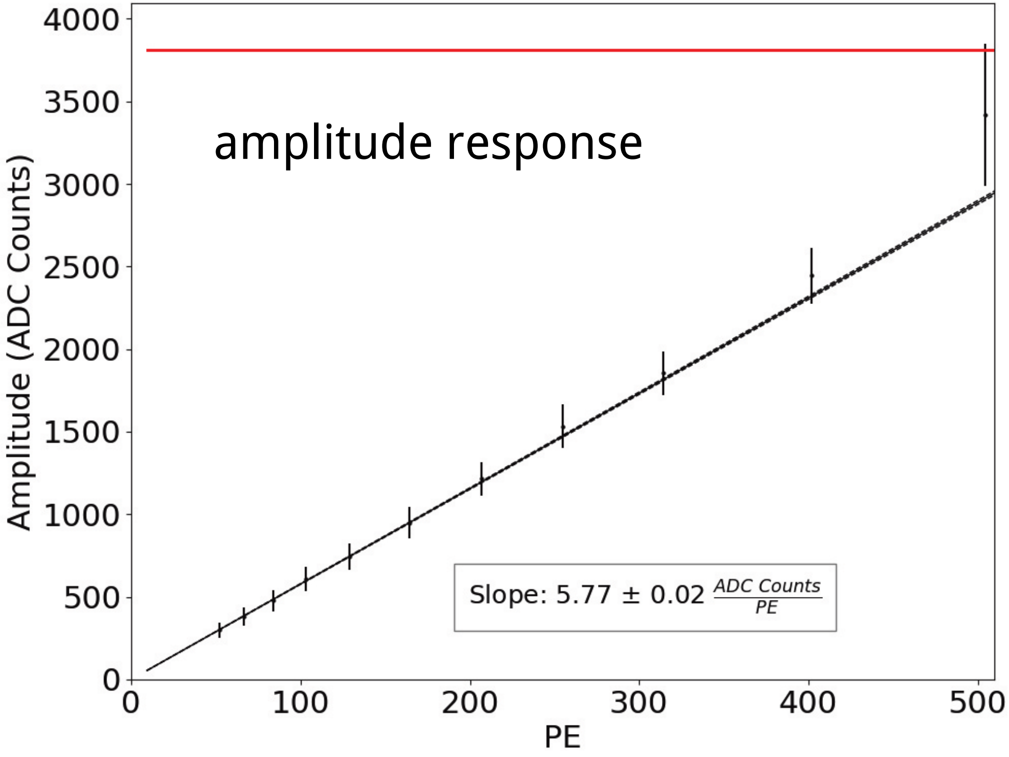

Bi-focal mirror
Common Focal Detector
Coincidence
Circuit
&
&
Light Source

Signal Chain

Same as in NO et al. EUSO-SPB2 PoS(ICRC2019)977

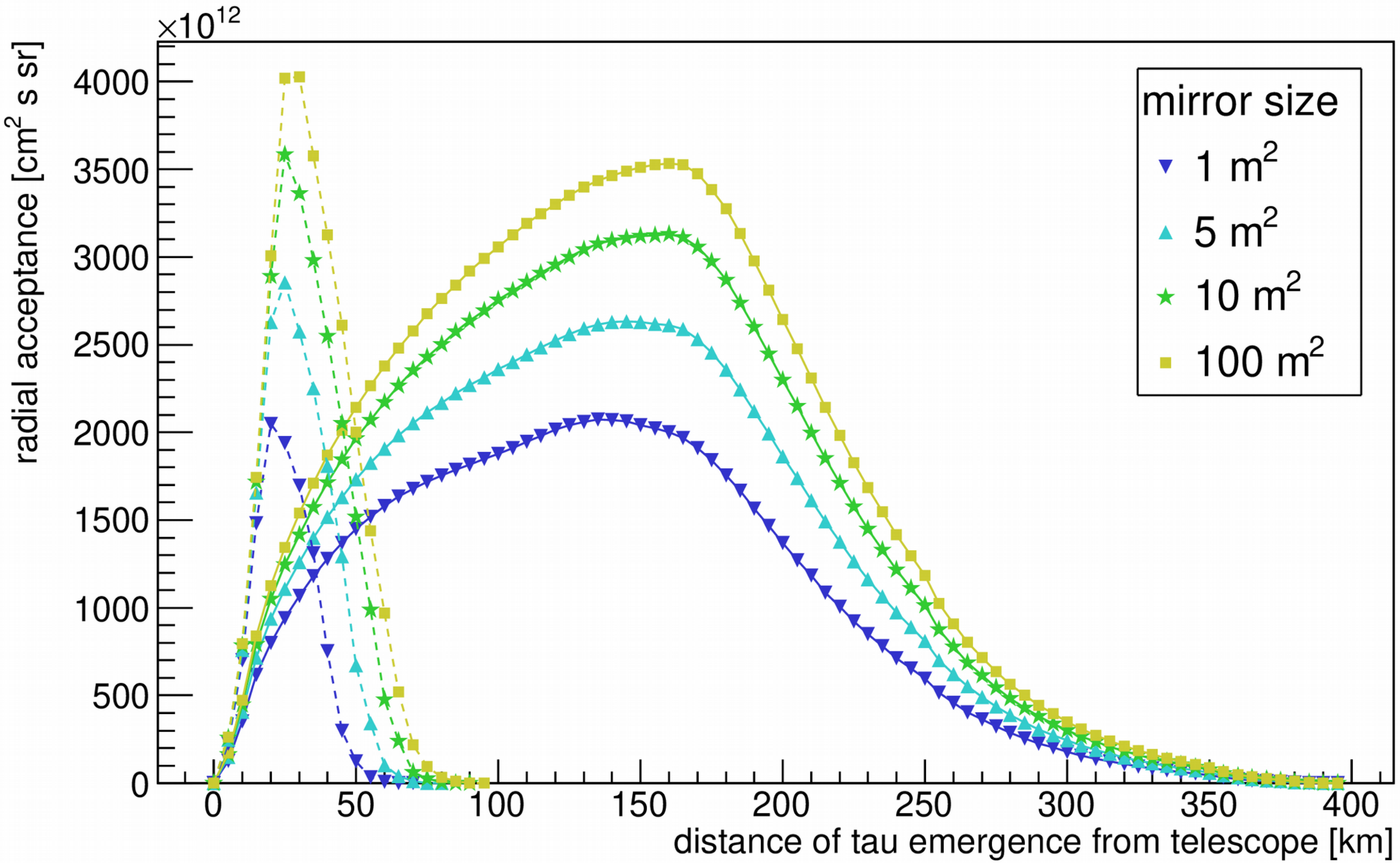
- MUSIC: preamp ASIC developed for IACTs.
- AGET digitizer: 100MS/s, switch capacitor readout, 12 bit.
- \$100 per channel → \$330k per camera



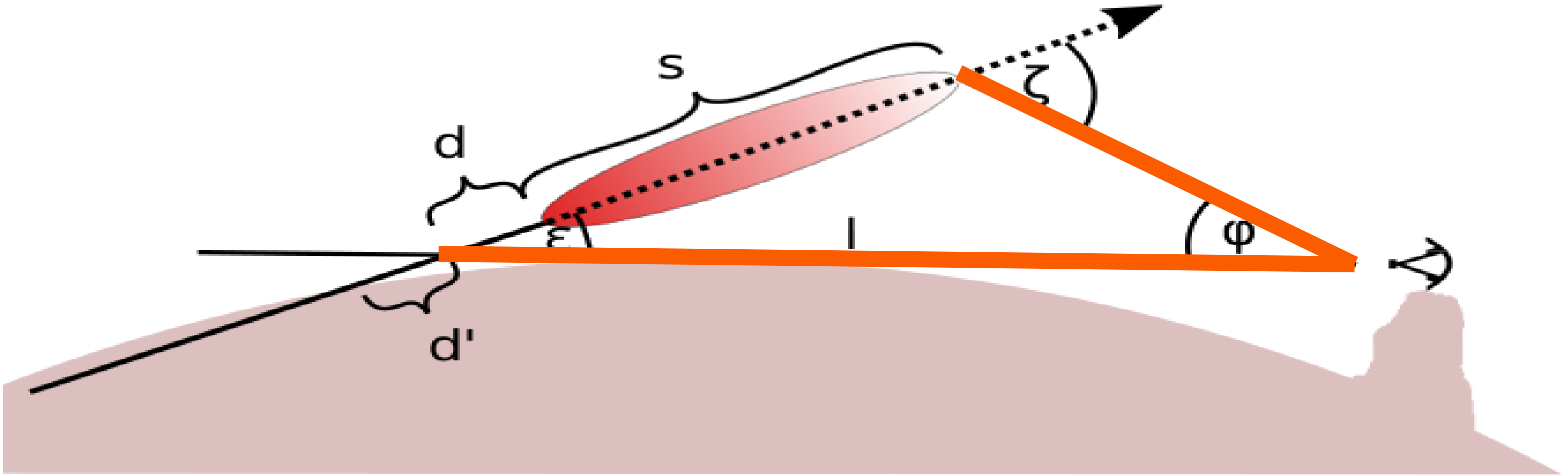


Tested with picosecond laser flashing Hamamatsu S14520 SiPM + MUSIC + AGET

Acceptance vs. Light Collection Area



How much Field of View?



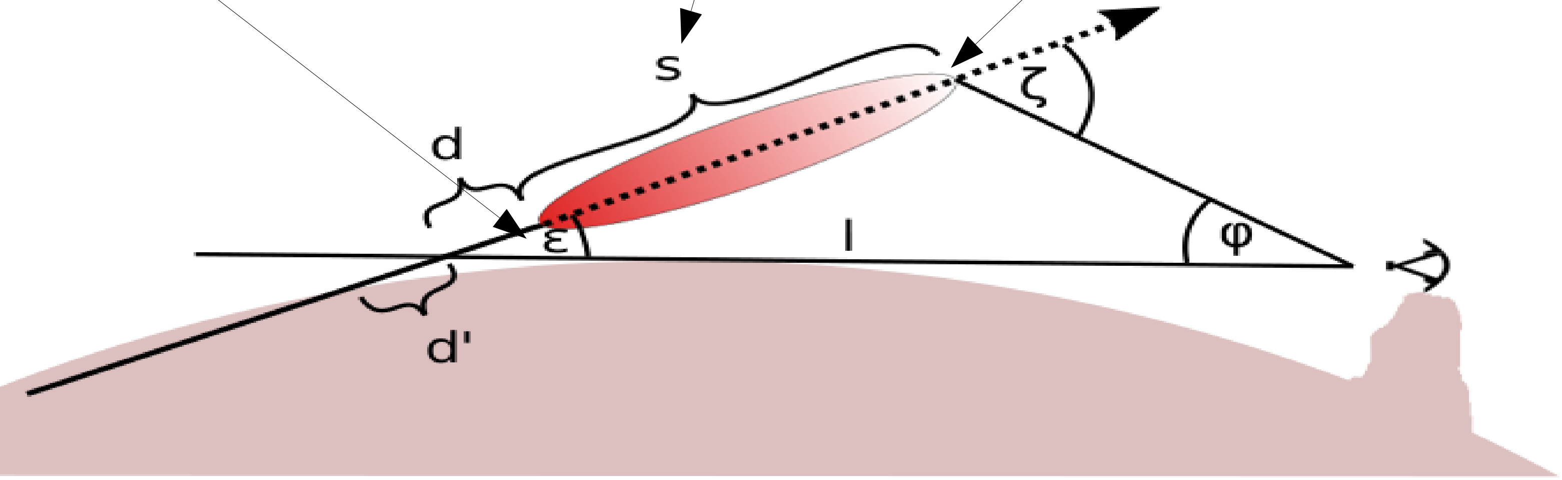
Full image containment is required.

UHE Tau initiated Air-Shower Fun Facts

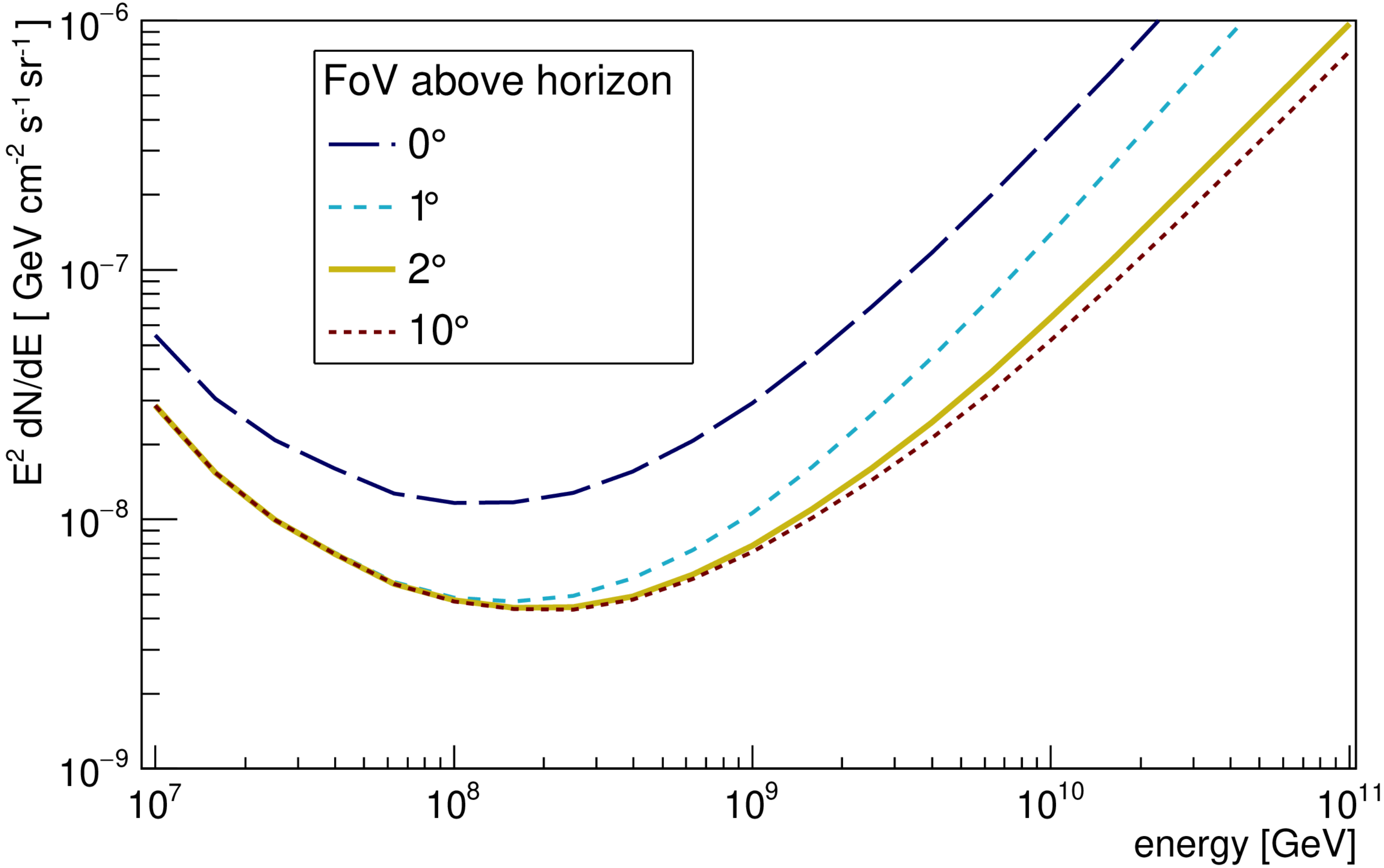
Height of shower tip above ground: ~1 km

Shower length: ~10 km

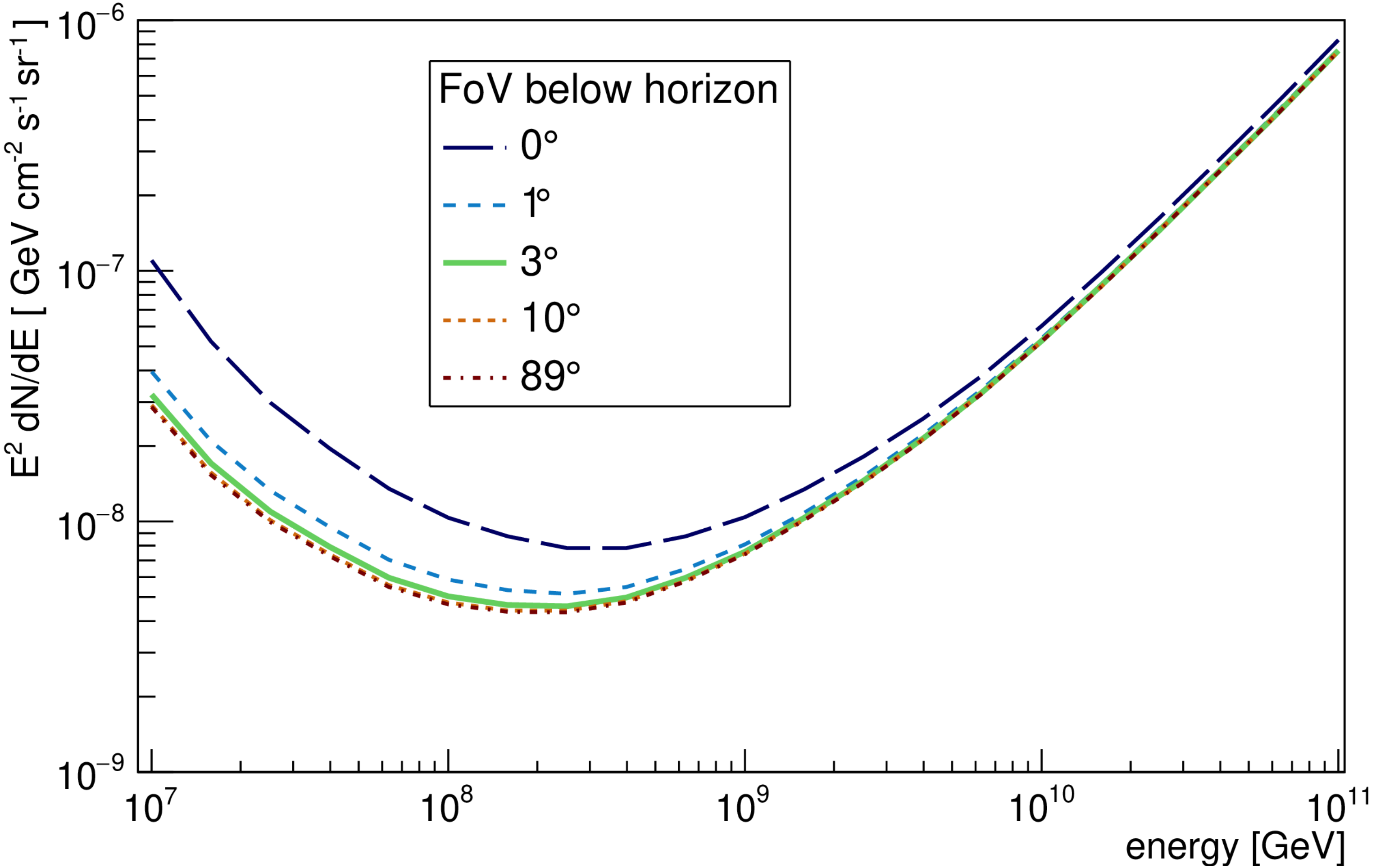
Emergence angle: ~5%



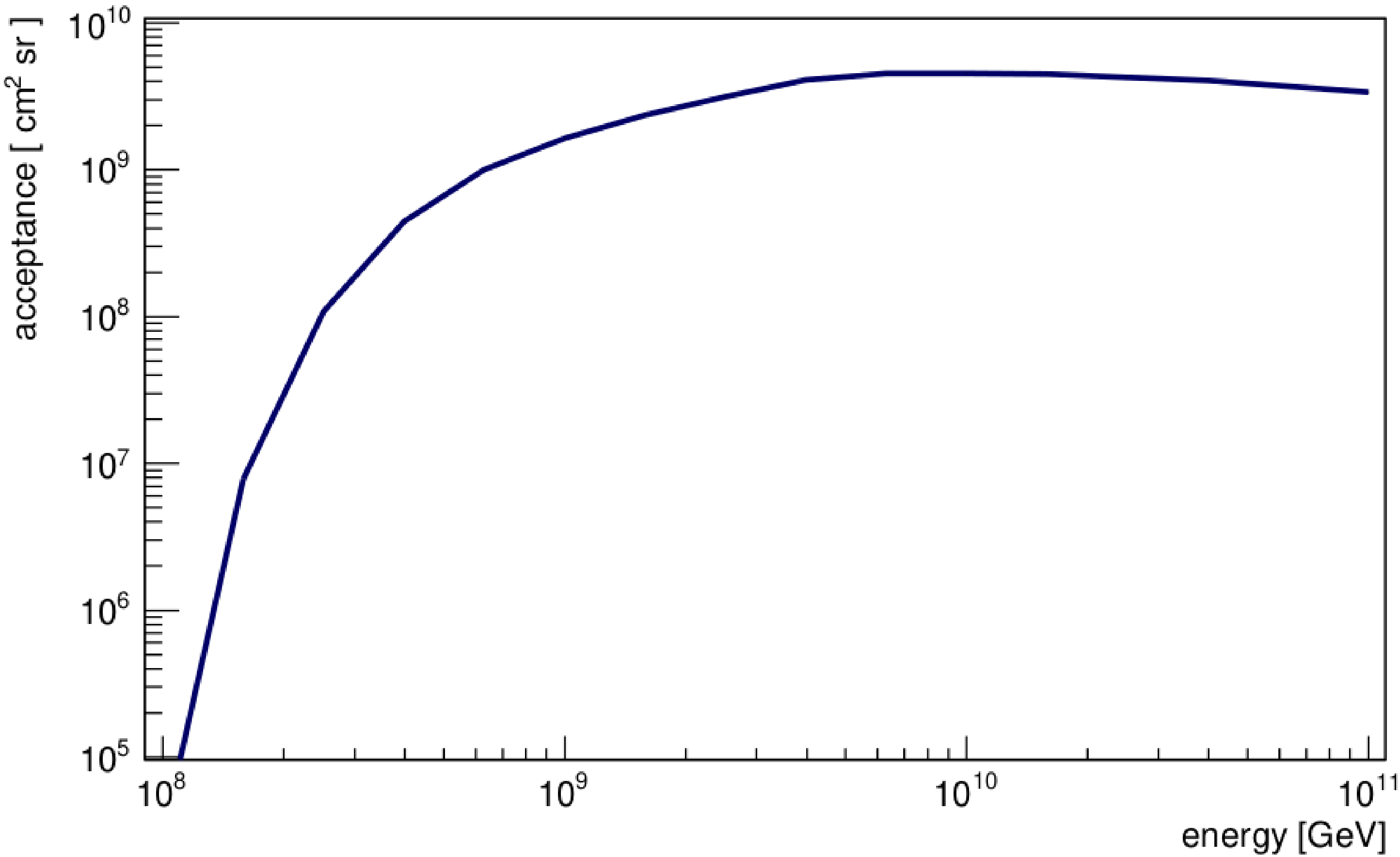
Sensitivity vs. FoV above Horizon



Sensitivity vs. FoV below Horizon

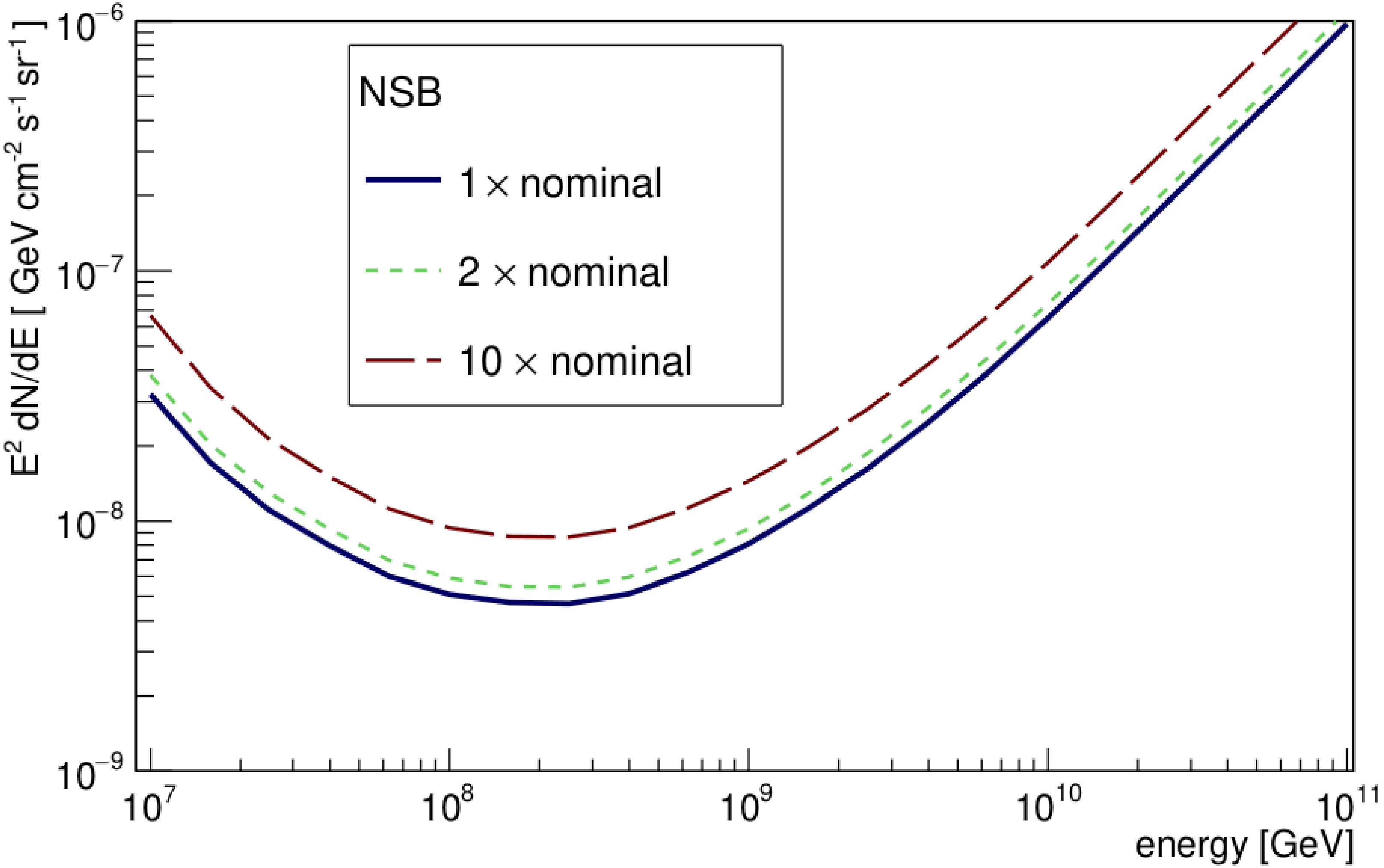


Acceptance

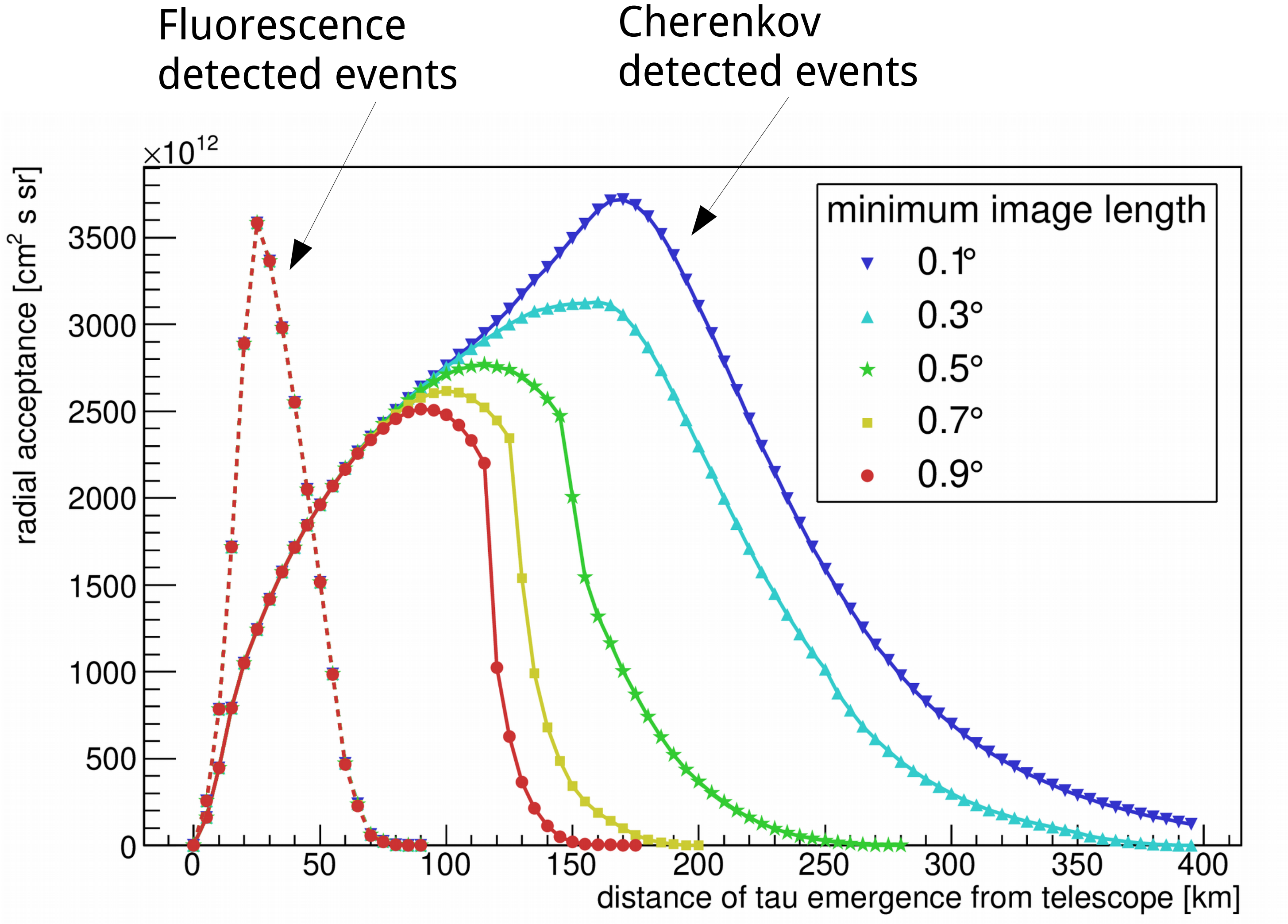


acceptance [cm^2 sr]
10^{10}
10^9
10^8
10^7
10^6
10^5
10^8
10^9
10^{10}
10^{11}
energy [GeV]

Impact of Night Sky Background

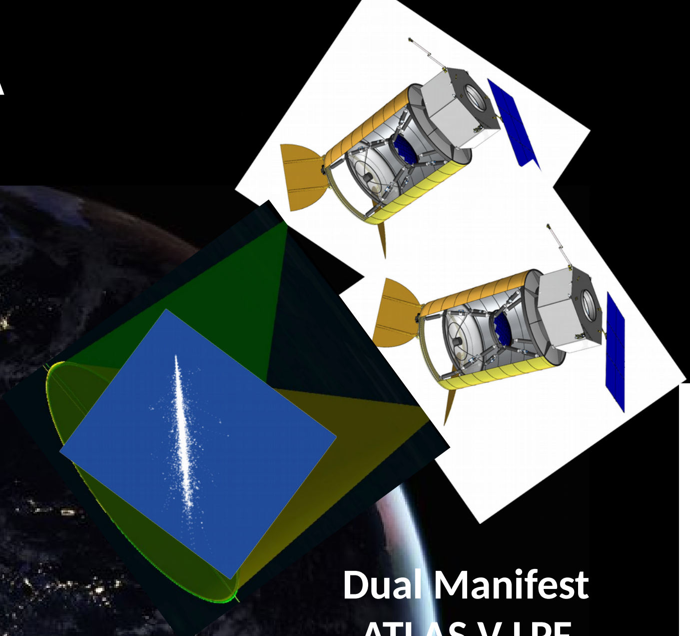


Angular Resolution



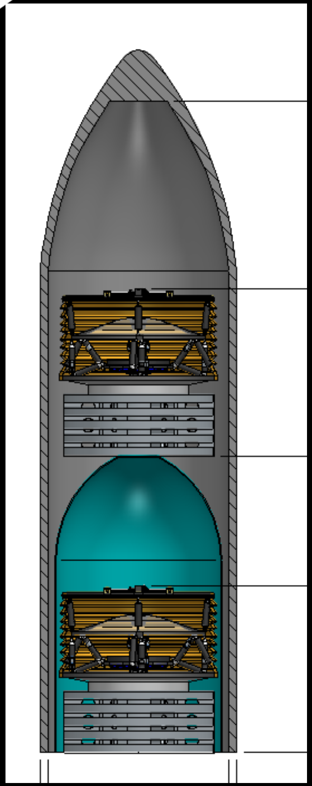
Thin-Glass Mirrors

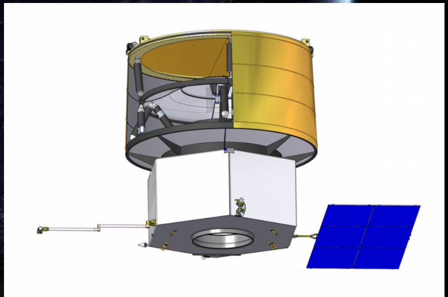
POEMMA MISSION



Mission Lifetime: 3 years (5 year goal)
Orbits: 525 km, 28.5° Inc
Orbit Period: 95 min
Satellite Separation: ~25 km – 1000+ km
Satellite Position: 1 m (knowledge)
Pointing Resolution: 0.1°
Pointing Knowledge: 0.01°
Slew Rate: 8 min for 90 °
Satellite Wet Mass: 3860 kg
Power: 2030 W
Data: 1 GB/day
Data Storage: 7 days
Communication: S-band (X-band if needed)
Clock synch (timing): 10 nsec

Dual Manifest
ATLAS V LPF





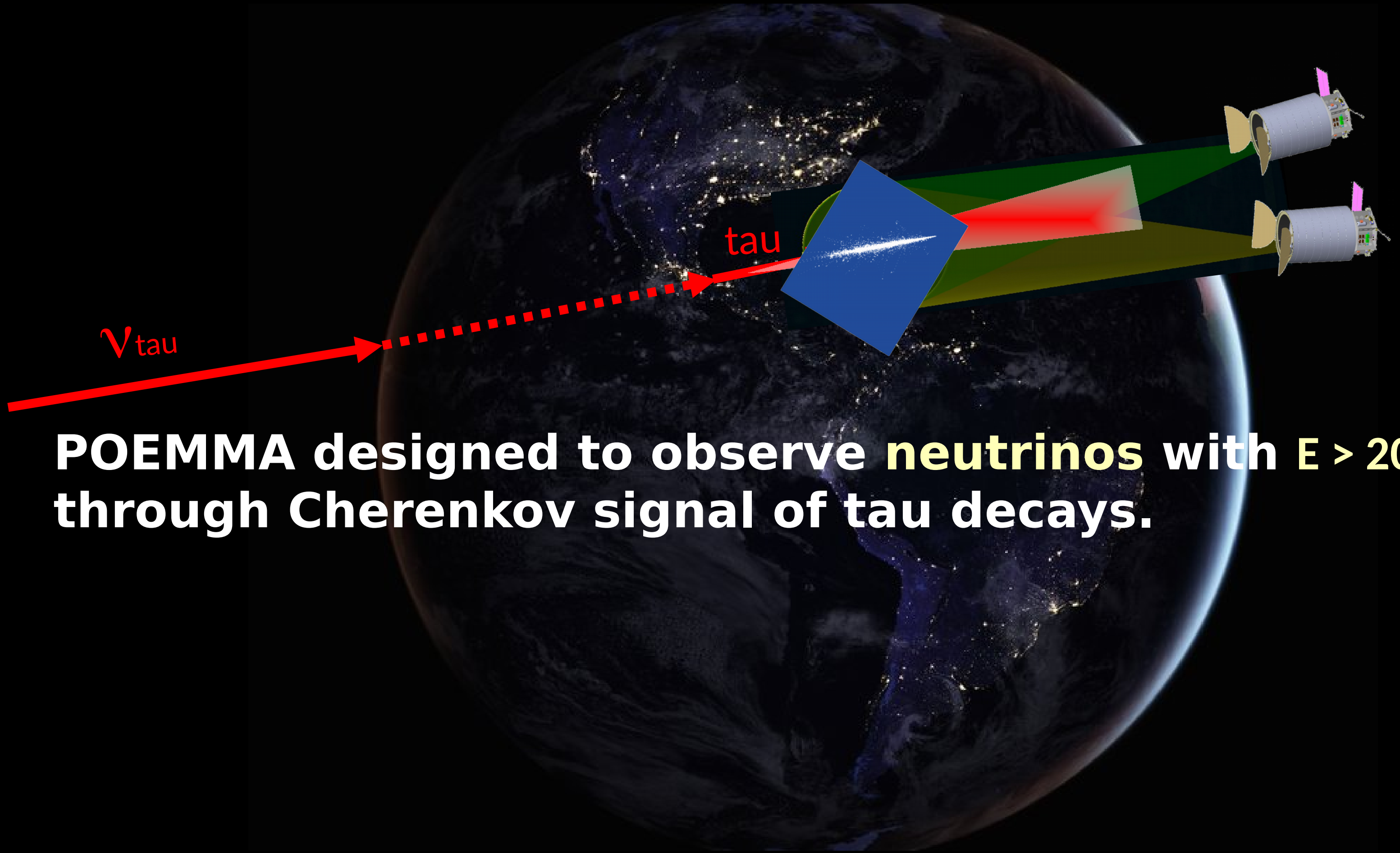
Operations:

- Each satellite collects data autonomously
- Coincidences analyzed on the ground
- View the Earth at near-moonless nights, charge in day and telemeter data to ground
- ToO Mode: dedicated com uplink to re-orient satellites if desired

POEMMA: study collaboration

USA: University of Chicago: *Angela V. Olinto (PI)*, R. Diesing
NASA/GSFC: John Krizmanic (deputy PI), E. Hays , J. McEnery, J. W. Mitchell, J. S Perkins, F. Stecker, T. M. Venters
NASA/MSFC: P. Bertone, M.J. Christl, R. M. Young,
University of Alabama, Huntsville: J. Adams, E. Kuznetsov, P. Reardon,
University of Utah: D. R. Bergman
Colorado School of Mines: J. Eser, F. Sarazin, L. Wiencke,
City University of New York, Lehman College: L. Anchordoqu, T. C. Paul, J. F. Soriano
Georgia Institute of Technology: A. N. Otte
Space Sciences Laboratory, University of California, Berkeley: E. Judd
University of Iowa: M. H. Reno
DENMARK: NBI: M. Bustamante
FRANCE: APC Univerite de Paris 7: E. Parizot, G. Prevot; IAP, Paris: C. Guepin
GERMANY: KIT: R. Ulrich, M. Unger; ESO: F. Oikonomou
ITALY: Universita di Torino: M. E. Bertaina, F. Bisconti, F. Fenu, A. Liberatore, K. Shinozaki:
Gran Sasso Science Institute: R. Aloisio, A. L. Cummings, I. De Mitri; INFN Frascati: M. Ricci
JAPAN: RIKEN: M. Casolino, Y. Takizawa
SLOVAKIA: IEP, Slovak Academy of Science: S. Mackovjak
SWITZERLAND: University of Geneva: A. Neronov

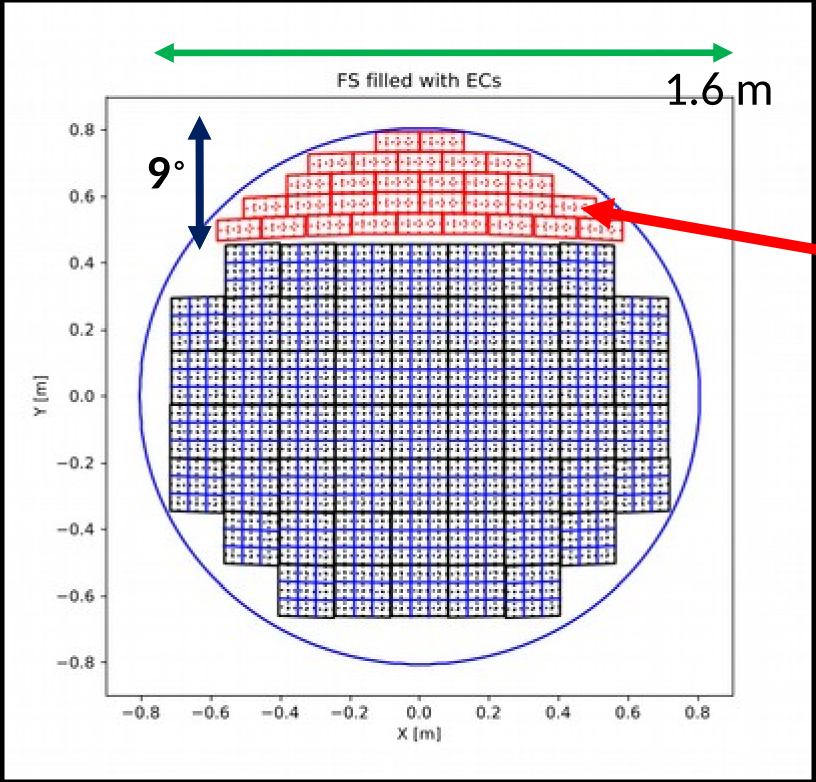
POEMMA Neutrinos



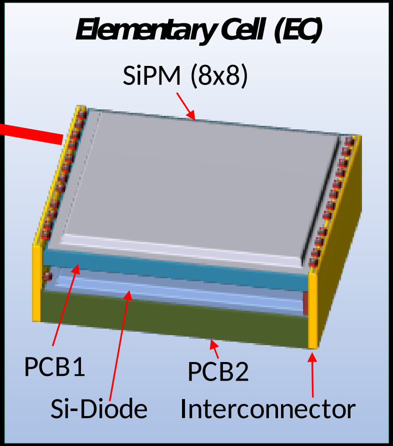
POEMMA designed to observe neutrinos with E > 20 PeV through Cherenkov signal of tau decays.

POEMMA

Hybrid MM Focal Surface



Cherenkov Detection with SiPMs: 20 nsec sampling



30 SiPM focal surface units
Total 15,360 pixels
512 pixels per FSU (64x4x2)
Si-Diode for LEO radiation backgrounds rejection

POEMMA

Observing Modes

Nadir for UHECR:

Radius 200-400 km

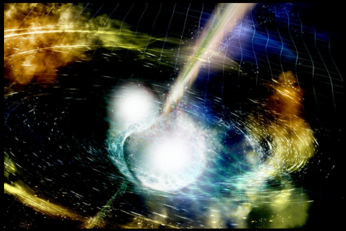
Limb for Neutrinos & UHECRs

Radius 2.6-3.7 10^3 km

POEMMA Neutrino TOO

(Targets of Opportunity)

Venters et al. arXiv: 1906.07209

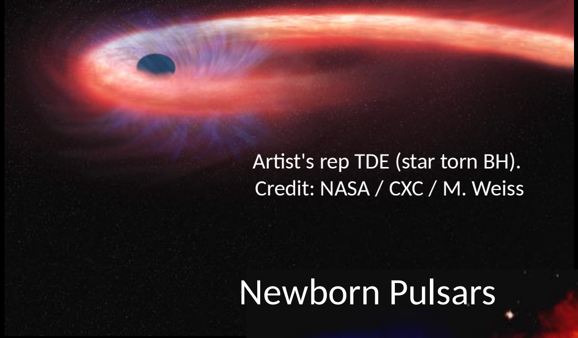


Artist's rep NS-NS merger.
Credit: Credit: NSF/LIGO/ SSU/A. Simonnet.

Transient Events
few to 100 Million neutrinos/event

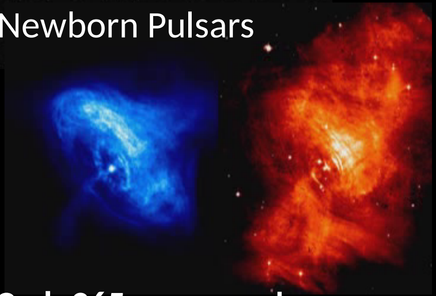
10 neutrinos up to 120 Mpc!

Tidal Disruption Events



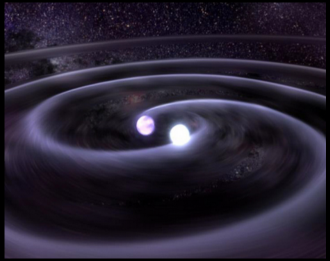
Artist's rep TDE (star torn BH).
Credit: NASA / CXC / M. Weiss

Newborn Pulsars



Crab 965 years ago!

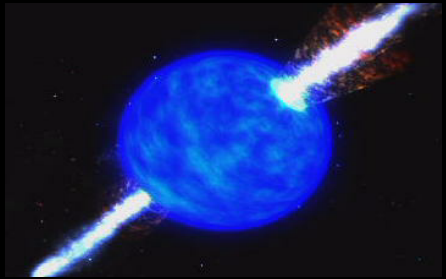
Credit: Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.



Artist's rep WD-WD merger
Credit: Ars Technica

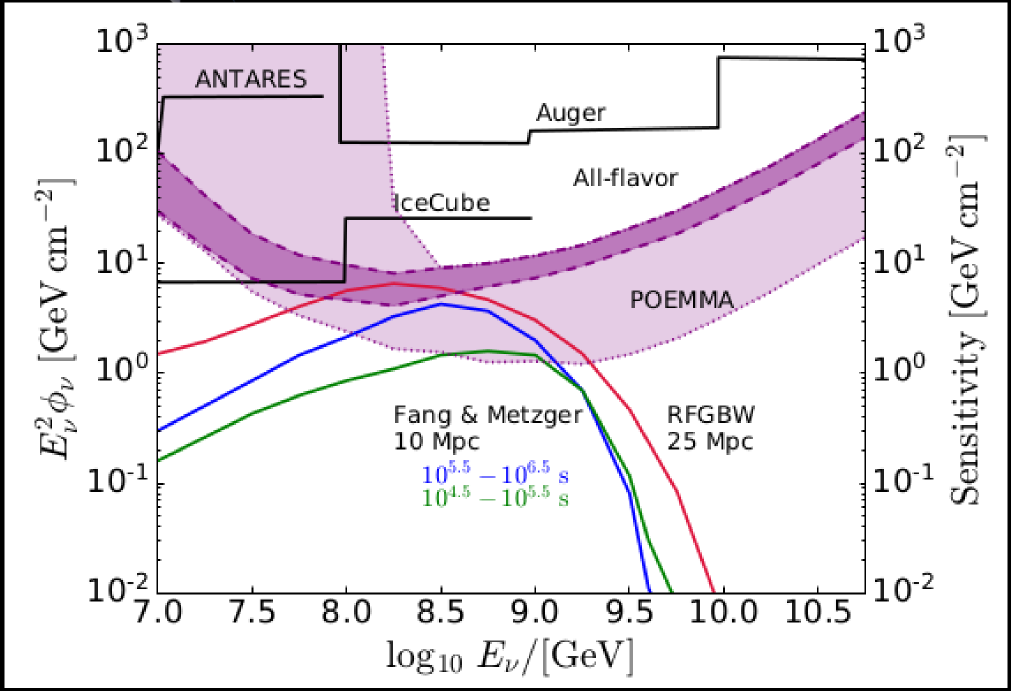
Binary Coalescence

Source Class	No. of ν's at GC	No. of ν's at 3 Mpc	Largest Distance for 10 ν's per event	Model Reference
TDEs	10^6	7	2.5 Mpc	Dai & Fang (2017) average
TDEs	5×10^6	35	5.6 Mpc	Dai & Fang (2017) bright
TDEs	2×10^8	1668	40 Mpc	Lunardini & Winter (2017) $M_{\rm SMBH} = 5 \times 10^6 M_\odot$
TDEs	NA	16000	120 Mpc	Lunardini & Winter (2017) $M_{\rm SMBH} = 1 \times 10^5 M_\odot$
Blazar Flares	NA	1400	35 Mpc	Rodrigues et al. (2018) – FSRQ proton-dominated advective escape model
BH-BH merger	6×10^7	400	20 Mpc	Kotera & Silk (2016) – $t_{\rm dur} \sim 10^4$ s
BH-BH merger	3×10^{10}	212297	400 Mpc	Kotera & Silk (2016) – $t_{\rm dur} \sim 10^{6.7}$ s
NS-NS merger	3×10^7	188	13 Mpc	Fang & Metzger (2017)
WD-WD merger	39000	0.3	500 kpc	Xiao et al. (2016)
Newly-born pulsars	8000	0.06	226 kpc	Fang (2015)



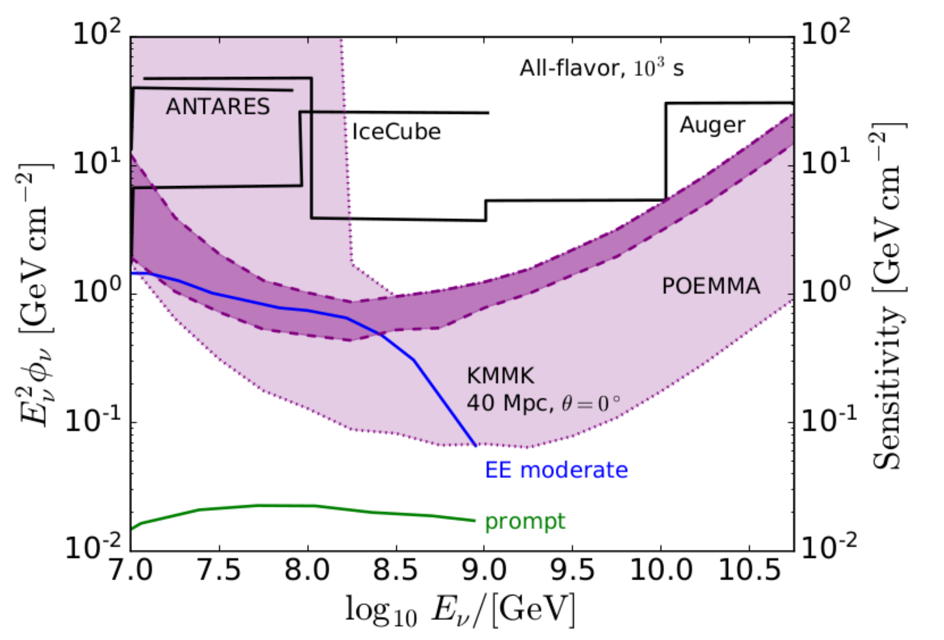
Gamma-Ray Bursts, Blazar Flares

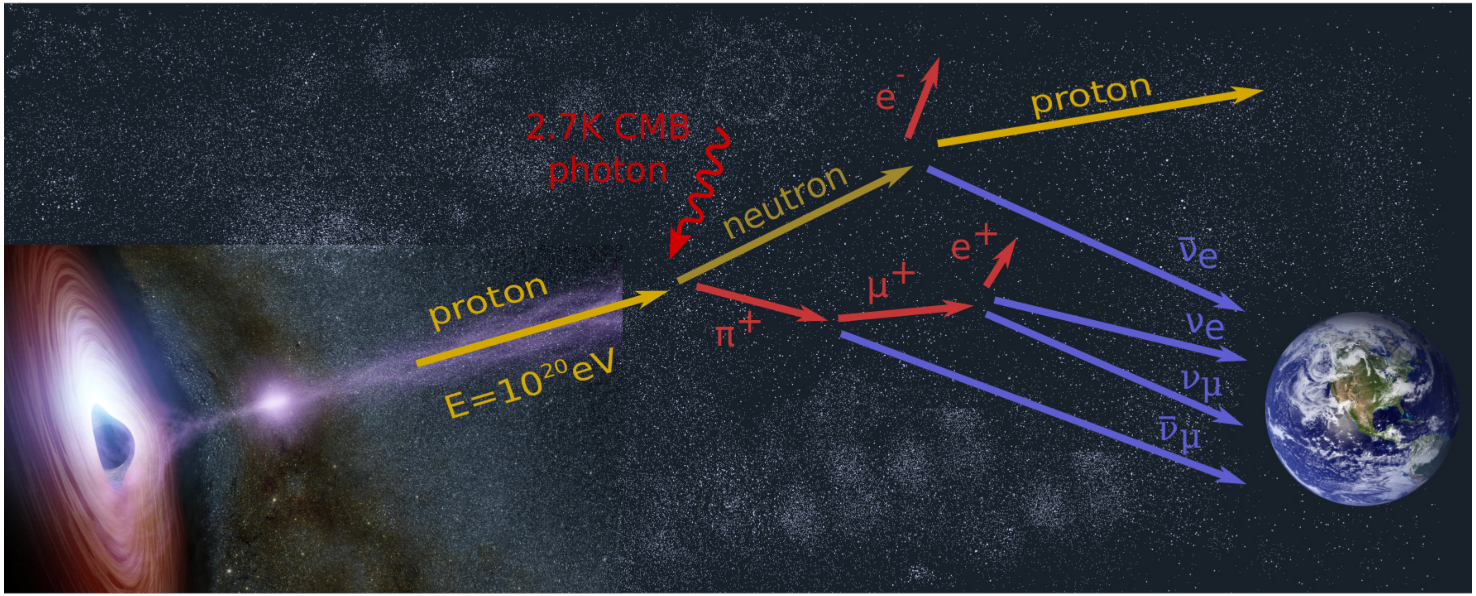
GW170817 follow up with POEMMA arXiv:1906.07209



Long bursts

Short bursts





Science Motivation:

- **What is the composition of UHECR?**
- **What are the sources of UHECR?**
- **Extension of IceCube detected ν flux to 10^9 GeV?**
- **Search for "new" physics**

Three year sensitivity