# Characterization of irradiated SiPM for the TOP detector at the Belle II experiment

Padova meeting
22/10/2024

Ezio Torassa, Roberto Stroili, Jakub Kandra
INFN Padova

# Tests with irradiated modules in Padova

- Eventually MCP-PMTs with extended lifetime can be replaced by SiPMs in next long shutdown.
- We irradiated 32 SiPM modules with different neutron fluxes, tested by laser, processed and analysed
- Collected data are read from modules and analyzed:
  - Photon spectra fit using two different methods to extract maximum of photons
  - Extraction breakdown voltage using fitting of gain as function of bias voltage
  - Time resolution of first and second peak of photon spectra
  - Dark count rate measurement
- Compare results using modules after annealing (150 °C for 8 weeks) and re-irradiation at level $1.0 \cdot 10^{10}$

| Producer | Code | Index | Dimension [mm×mm] | Pitch [μm] | Neutron 1 MeV eg/cm² fluence |
|---|---|---|---|---|---|
| Hamamatsu | S13360-1350PE | 0 - 7 | 1.3 × 1.3 | 50 | $5.0{\cdot}10^{11}$ - $1.0{\cdot}10^{9}$ |
| FBK | NUV-HD-RH-3015 | 8 - 10 | 3 × 3 | 15 | $1.0{\cdot}10^{10}$ - $1.0{\cdot}10^{9}$ |
| FBK | NUV-HD-RH-1015 | 11 - 14 | 1 × 1 | 15 | $2.0{\cdot}10^{10}$ - $1.0{\cdot}10^{9}$ |
| Hamamatsu | S14160-3050HS | 15, 30, 31 | 3 × 3 | 50 | $1.0{\cdot}10^{9}$, $1.0{\cdot}10^{10}$ |
| Kektek | PM3315-WL | 16, 17 | 3 × 3 | 15 | $1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$ |
| Kektek | PM3335-WL | 18, 19 | 3 × 3 | 35 | $1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$ |
| OnSemi | 10035 | 20, 21 | 1 × 1 | 35 | $1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$ |
| OnSemi | 30035 | 22, 23 | 3 × 3 | 35 | $1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$ |
| Hamamatsu | S13360-3025PE | 24, 25 | 3 × 3 | 25 | $1.0{\cdot}10^{10}$ |
| Hamamatsu | S13360-3050PE | 26, 27 | 3 × 3 | 50 | $1.0{\cdot}10^{10}$ |
| Hamamatsu | S14160-3015PS | 28, 29 | 3 × 3 | 15 | $1.0{\cdot}10^{10}$ |

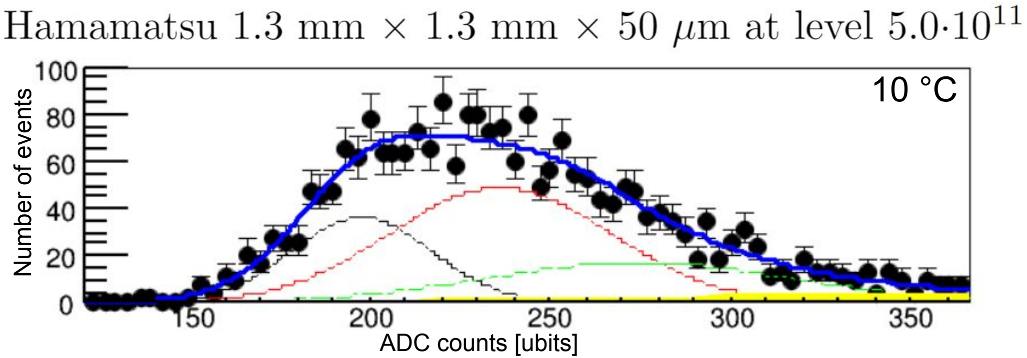
# Tests with irradiated modules in Padova

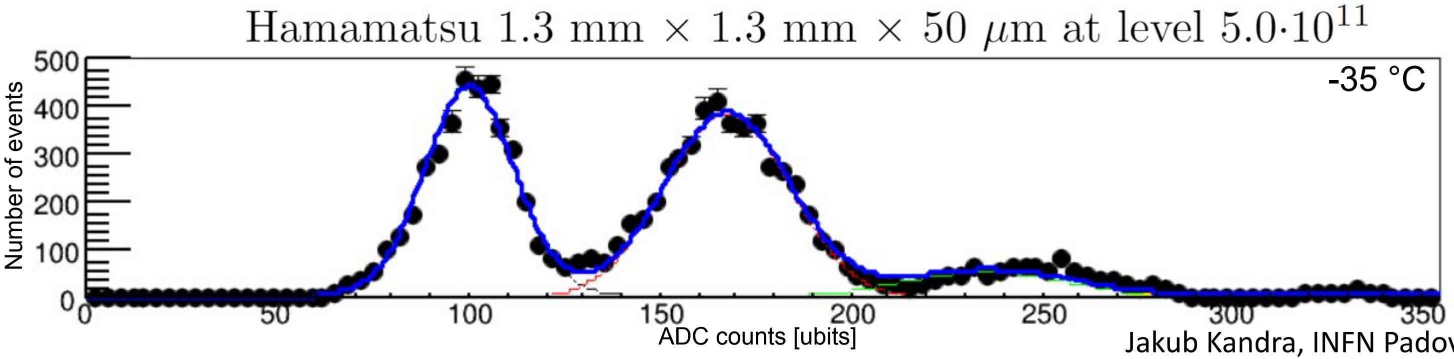
| Producer | Code | Index | Non-irradiated | Irradiated | Annealed | Re-irradiated |
|---|---|---|---|---|---|---|
| Hamamatsu | S13360-1350PE[1] | 0 - 7 | Photon spectra<br>Dark count | Photon spectra<br>Dark count | Dark count | Dark count |
| FBK | NUV-HD-RH-3015[2] | 8 - 10 | Dark count | Dark count | Dark count | Dark count |
| FBK | NUV-HD-RH-1015[3] | 11 - 14 | Photon spectra<br>Dark count | Photon spectra<br>Dark count | Photon spectra<br>Dark count | Photon spectra<br>Dark count |
| Hamamatsu | S14160-3050HS[4,5] | 15, 30, 31 | Photon spectra<br>Dark count | Photon spectra<br>Dark count | Photon spectra<br>Dark count | Photon spectra<br>Dark count |
| Kektek | PM3315-WL[2] | 16, 17 | Dark count | Dark count | Dark count | Dark count |
| Kektek | PM3335-WL[6] | 18, 19 | Photon spectra<br>Dark count | Dark count | Dark count | Dark count |
| OnSemi | 10035 | 20, 21 | Photon spectra<br>Dark count | Photon spectra<br>Dark count | Photon spectra<br>Dark count | Photon spectra<br>Dark count |
| OnSemi | 30035[6] | 22, 23 | Photon spectra<br>Dark count | Dark count | Dark count | Dark count |
| Hamamatsu | S13360-3025PE[7] | 24, 25 | Photon spectra<br>Dark count | | | |
| Hamamatsu | S13360-3050PE[7] | 26, 27 | Photon spectra<br>Dark count | | | |
| Hamamatsu | S14160-3015PS[7] | 28, 29 | Photon spectra<br>Dark count | | | |

[1] No annealing and re-irradiation data, because photon spectra readout device have been broken.
[2] No photon spectra data, because no peaks identified in spectra.
[3] Non-irradiated data is collected using different bias voltage range as others.
[4] For index 17, Non-irradiated data is collected using different bias voltage range as others.
[5] For indices 30 and 31, non-irradiated data is done and others is analysed now.
[6] Non-irradiated data was analysed, in others no peaks was found in photon spectra.
[7] Non-irradiated data is done and others is analysed now.

# Photon spectra fits

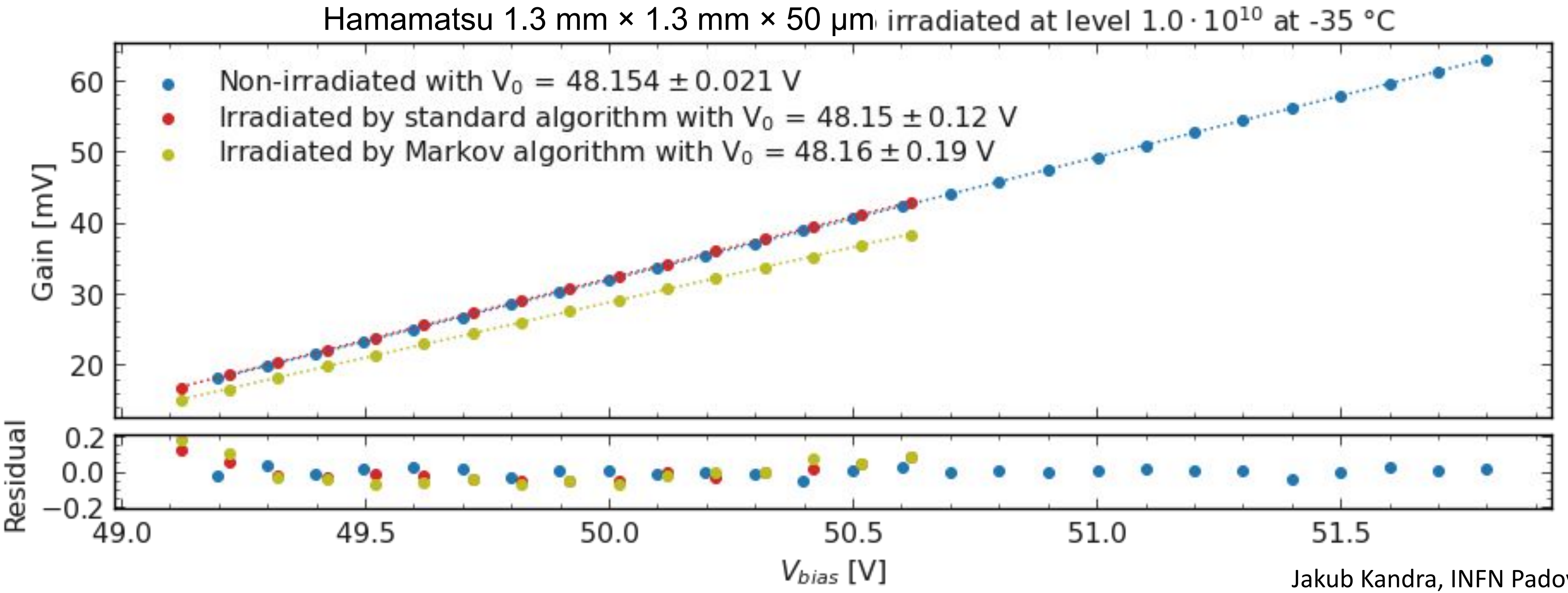
- We are using two different methods for extraction of maximum of photons:
  - Standard algorithm
  - Markov algorithm with background subtraction
- Markov algorithm allows us to provide photon spectra cleaner in harder environments
- Using highly irradiated modules in high temperatures or with large detection area it does not provide sufficient results for photon spectra fit.



# Extraction breakdown voltage

- Gains and breakdown voltage are extracted from photon spectra fit, gain as function of bias voltage, respectively.
- Extracted breakdown voltage after irradiation is consistent with results before irradiation
- Markov algorithm provides precise result as standard algorithm in highly irradiated environment with small difference in slope





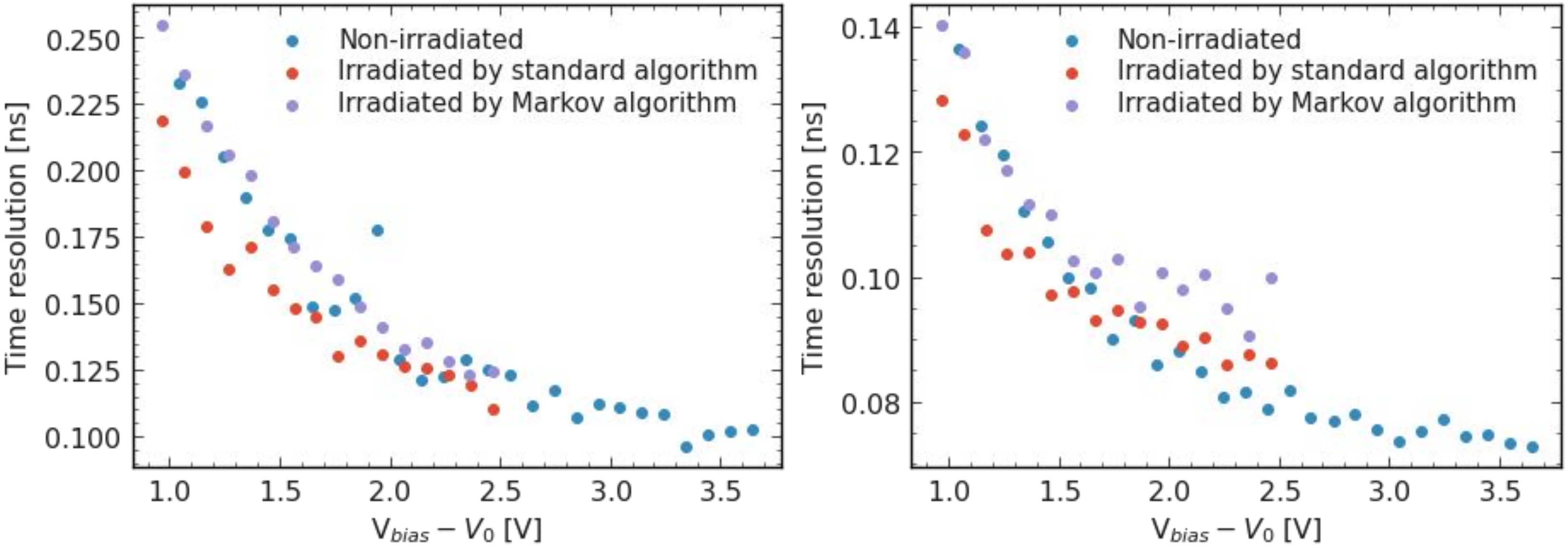

Jakub Kandra, INFN Padova

# Time resolution

- Then we check time resolution using first and second photons of photon spectra
- Time resolution studies demonstrate time resolution is consistent before and after irradiation

Hamamatsu 1.3 mm × 1.3 mm × 50 μm irradiated at level $1.0 \cdot 10^{10}$ at -35 °C

First peak of photon spectra　　　　Second peak of photon spectra

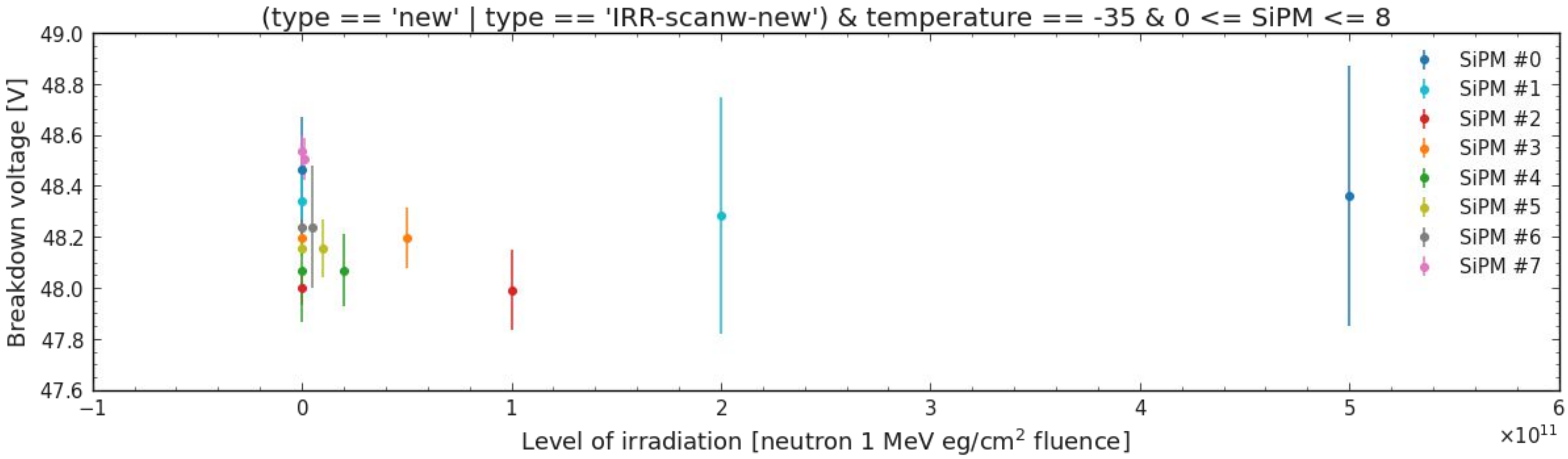





Jakub Kandra, INFN Padova

# Breakdown voltage as function of irradiation

- Breakdown voltages can be presented as function of irradiation level
- Breakdown voltages are consistent before and after irradiation for several high irradiation levels
- The high uncertainty of the breakdown voltages come from a fact, in high irradiated environment is more difficult extract clear photon spectra.

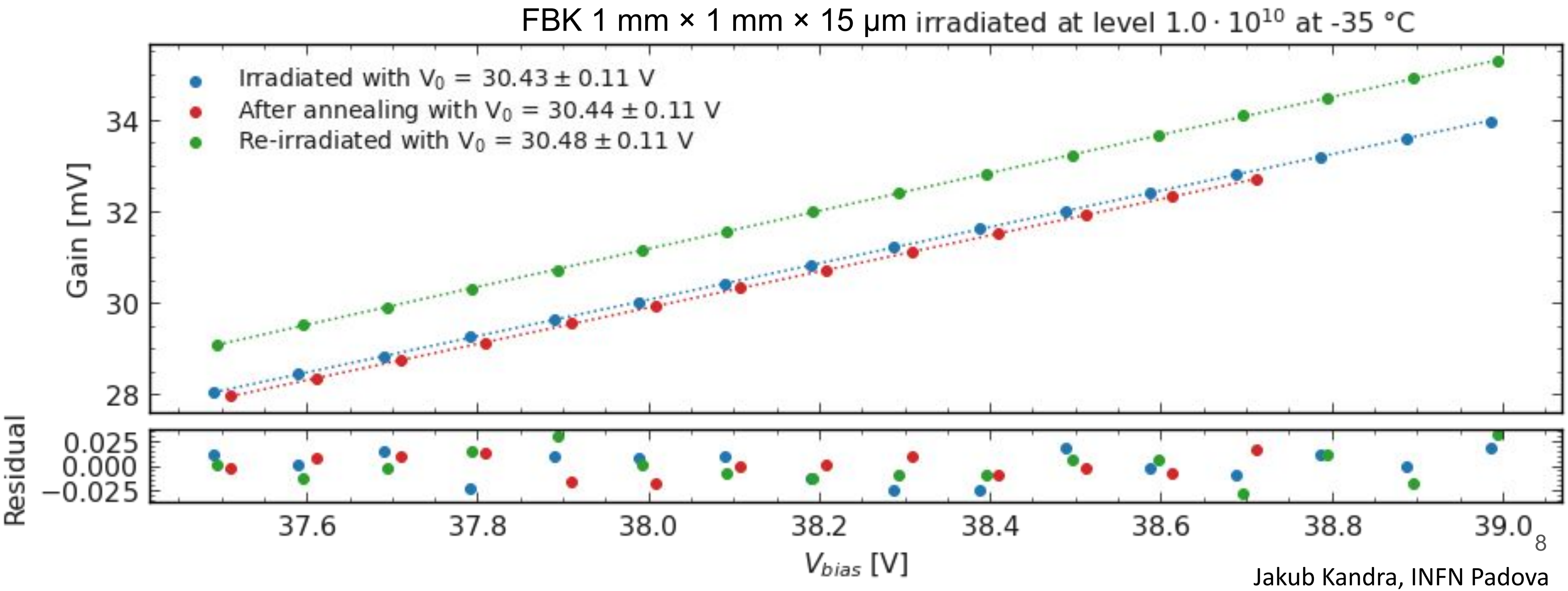





Jakub Kandra, INFN Padova

# Annealing and re-irradiation

- This module has been irradiated at level $1.0 \cdot 10^{10}$, then annealed and re-irradiated at same level
- No significant difference between irradiated annealed and re-irradiated data has been observed



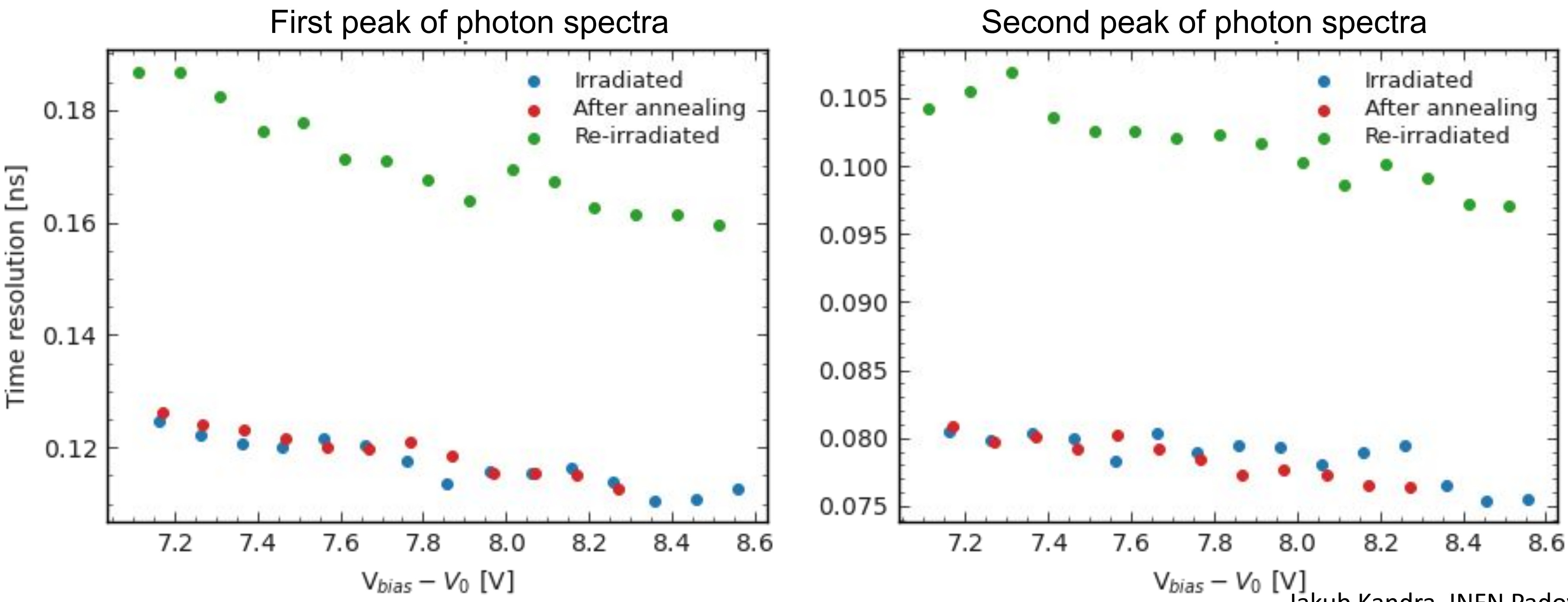



Jakub Kandra, INFN Padova

# Annealing and re-irradiation

- This module has been irradiated at level $1.0 \cdot 10^{10}$, then annealed and re-irradiated at same level
- No significant difference between irradiated annealed and re-irradiated data has been observed

FBK 1 mm × 1 mm × 15 µm irradiated at level $1.0 \cdot 10^{10}$ at -35 °C

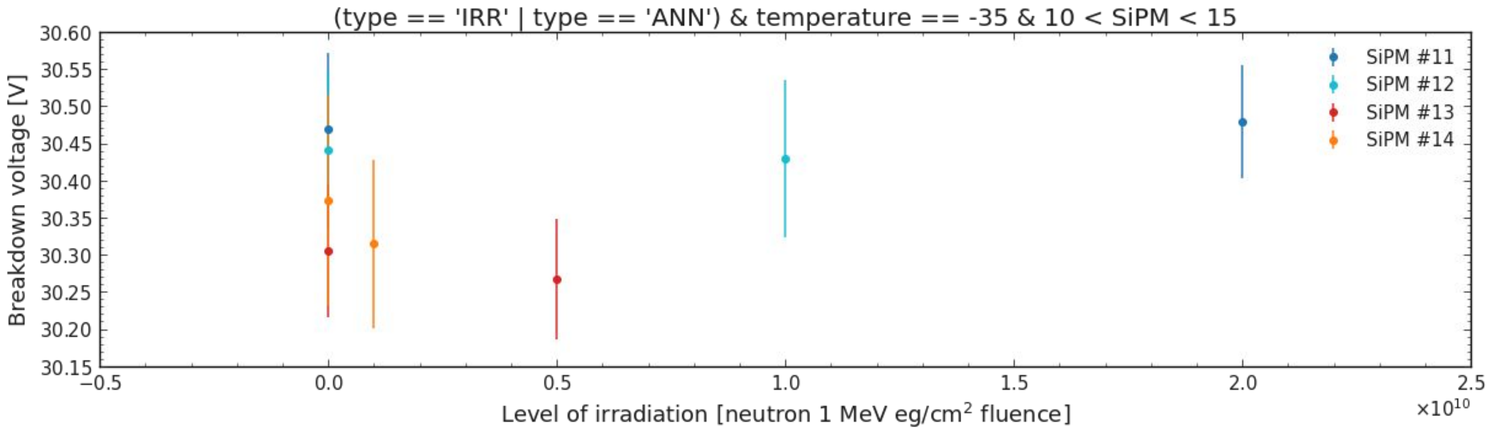


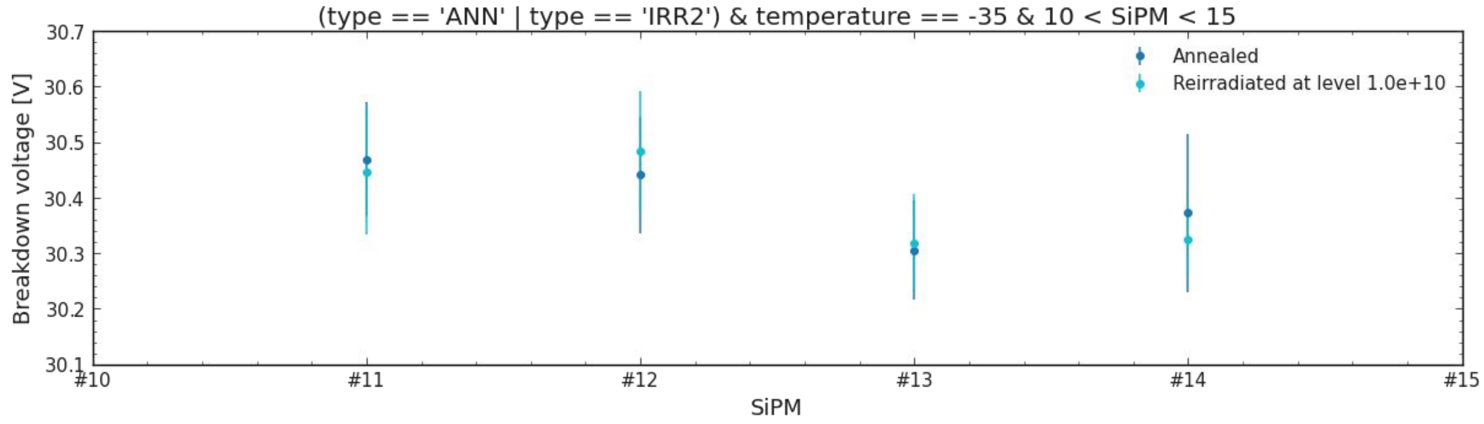



Jakub Kandra, INFN Padova

# Breakdown voltage as function of irradiation

- Breakdown voltages are consistent irradiated, annealed and re-irradiated data for several high irradiation levels



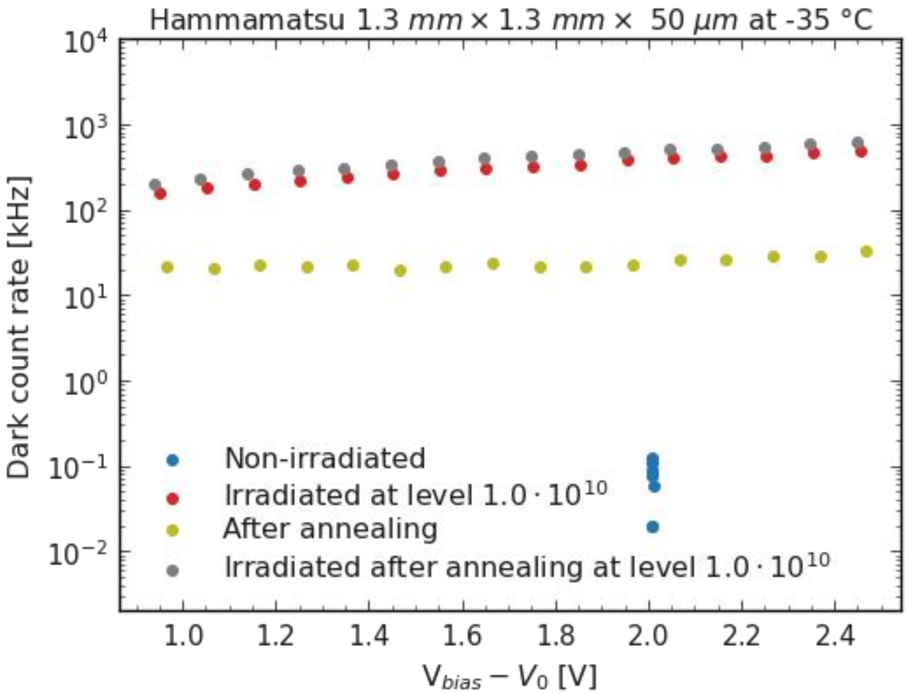






Jakub Kandra, INFN Padova

# Dark count rates

- We provide dark count rate measurements using non-irradiated, irradiated, annealed data and re-irradiated
- Annealing helps to reduce dark count rates in several magnitudes
- Results of re-irradiated are consistent with previous observations

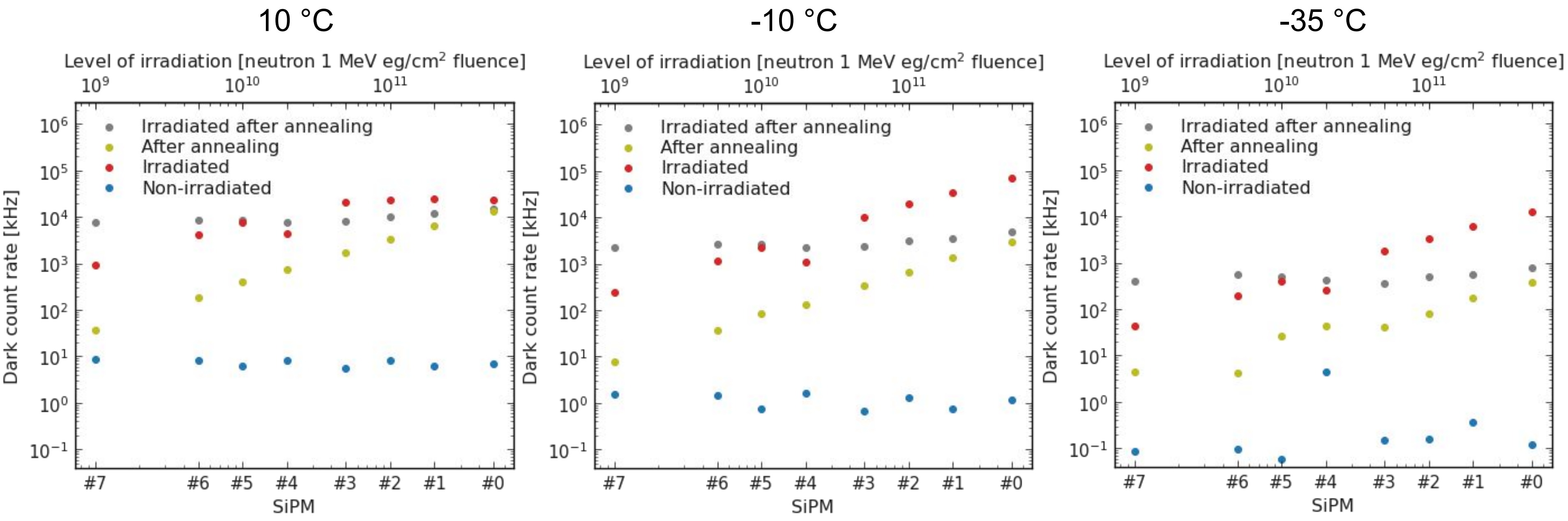





Jakub Kandra, INFN Padova

# Dark count rates as function of irradiation level

Hamamatsu 1.3 mm × 1.3 mm × 50 µm

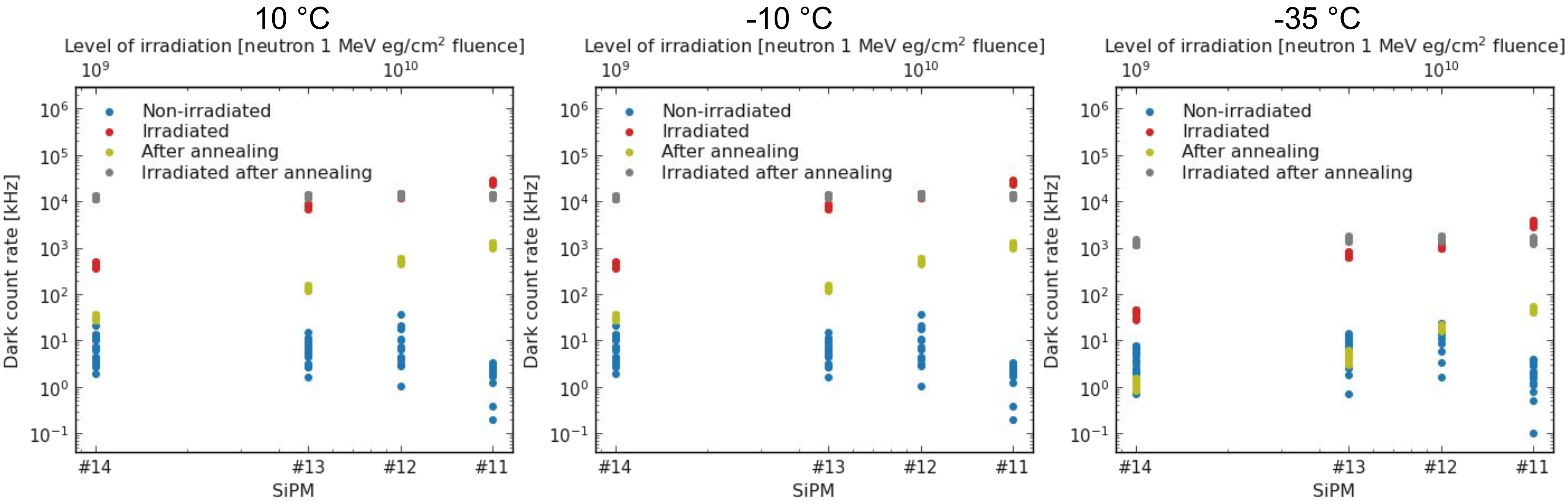



- Dark count rates can be recovered by annealing, but not to the level before irradiation.


Jakub Kandra, INFN Padova

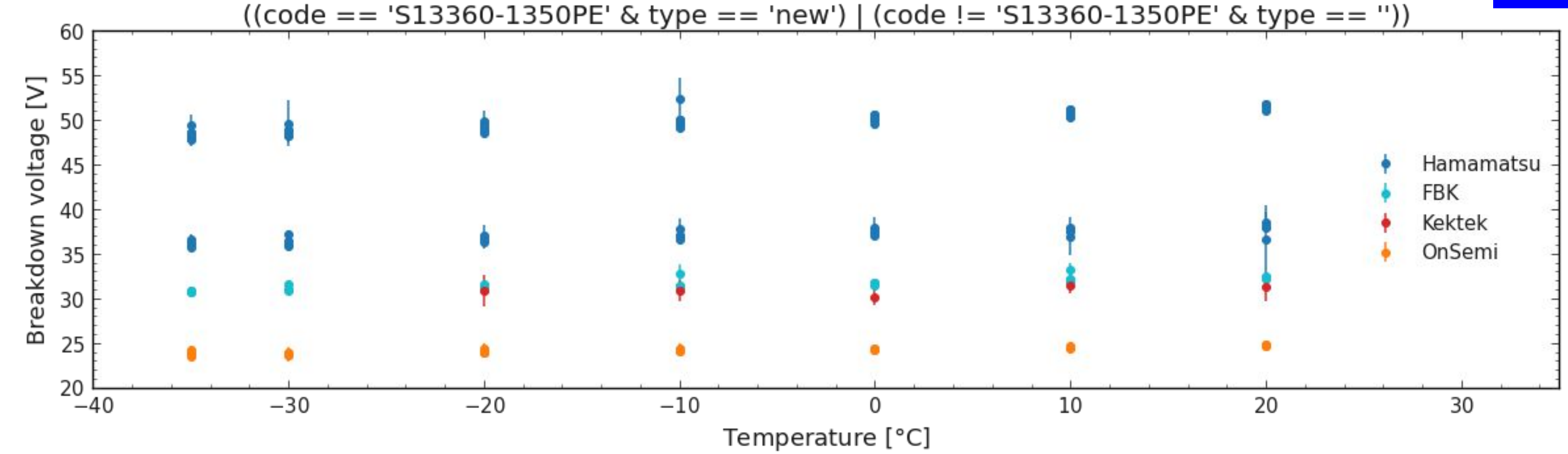
# Dark count rates as function of irradiation level

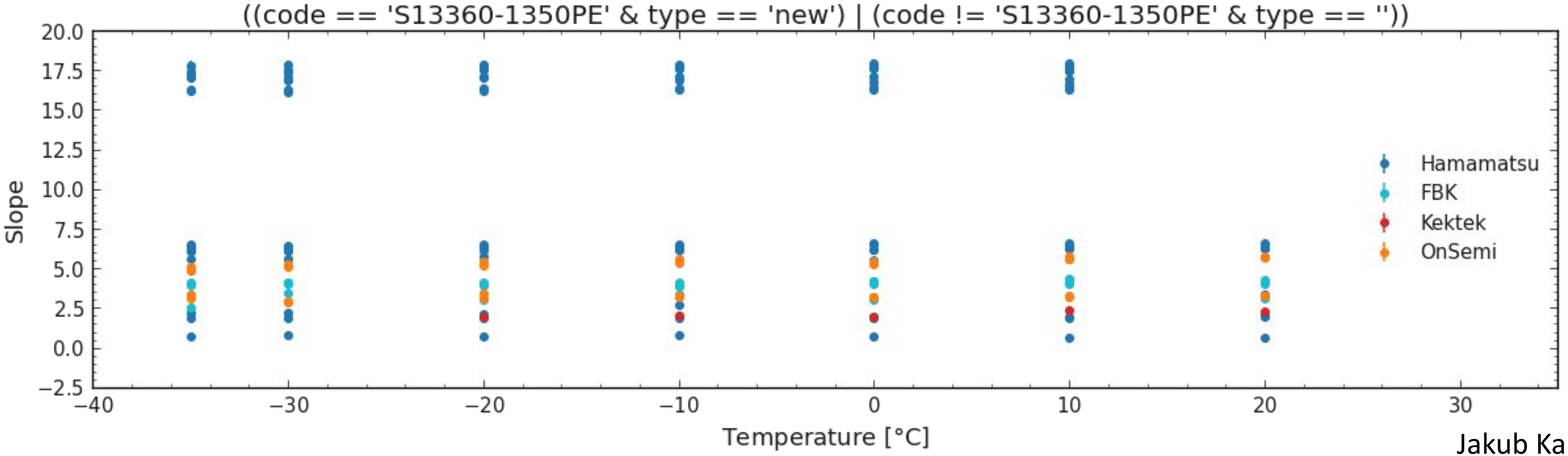
FBK 1 mm × 1 mm × 15 μm




- Dark count rates can be recovered by annealing, but not to the level before irradiation.

# Breakdown voltage as function of temperature

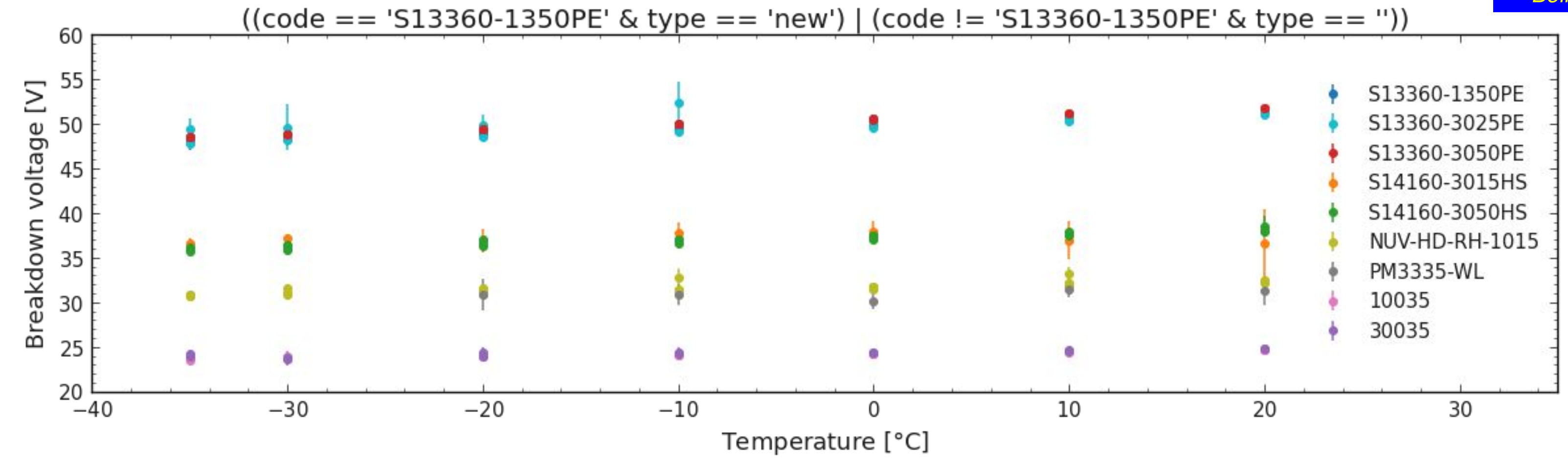


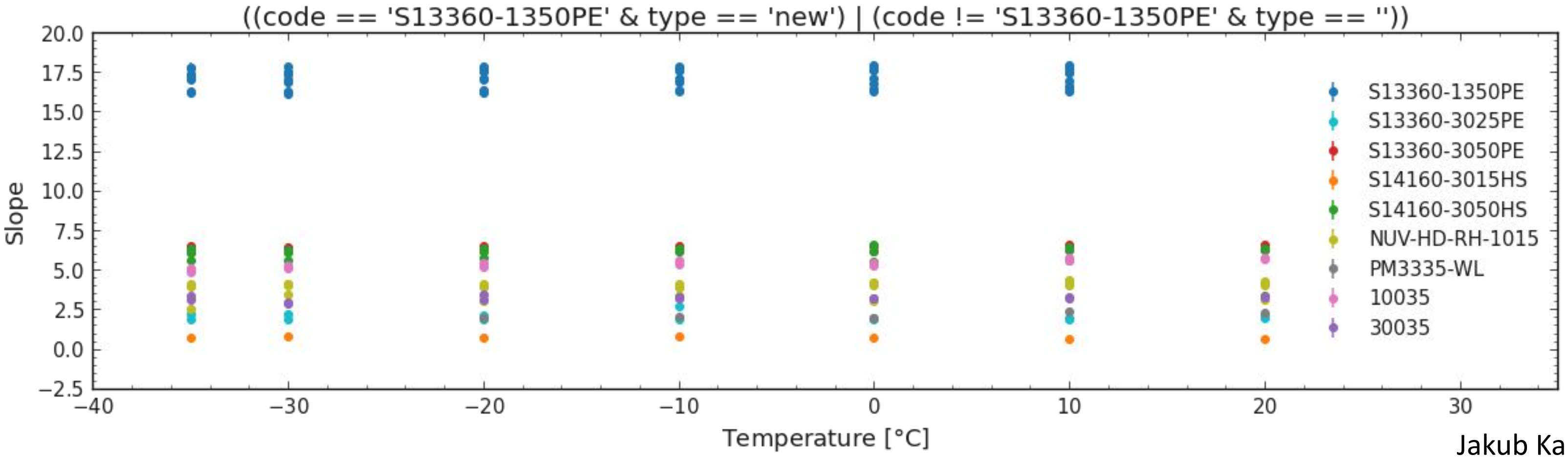






Jakub Kandra, INFN Padova

# Breakdown voltage as function of temperature



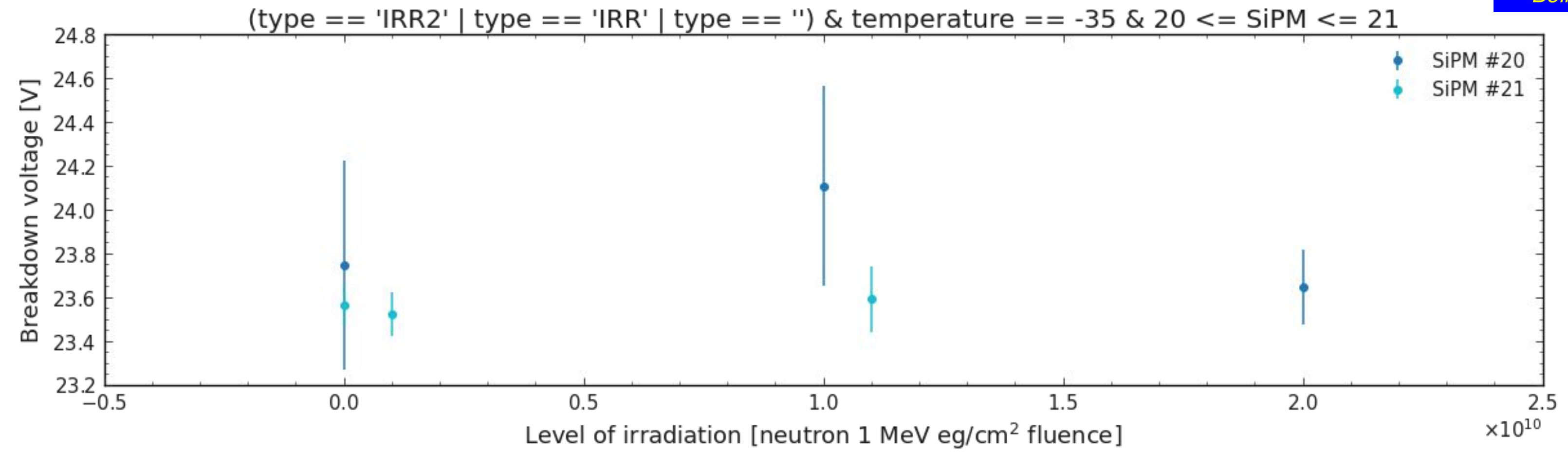



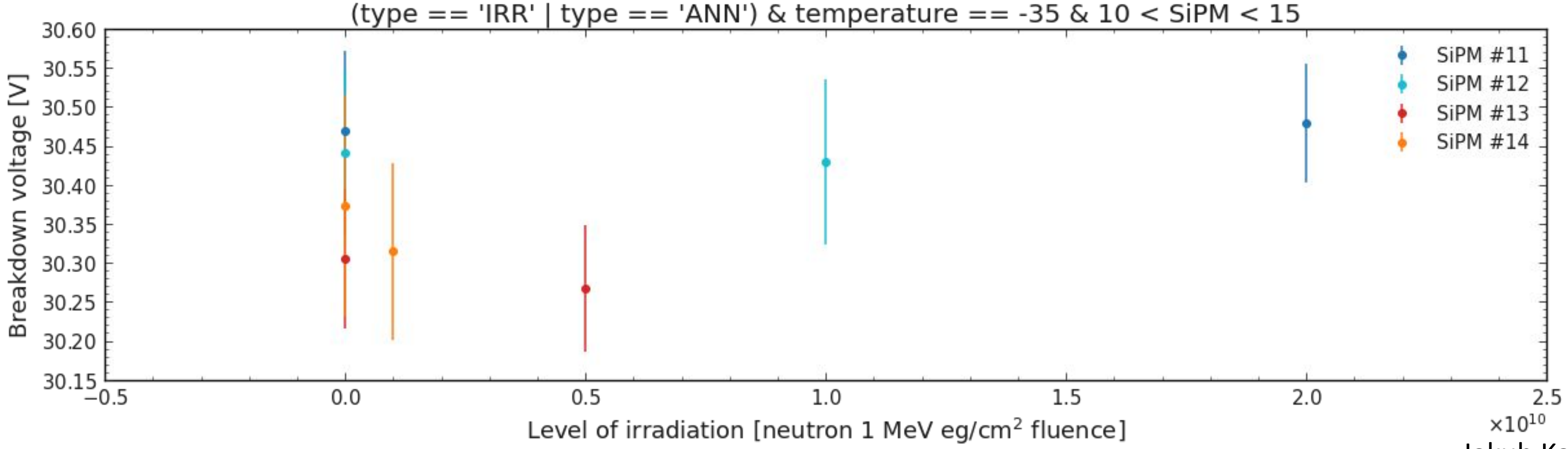
# Conclusions and outlook

- We irradiated 32 SiPM modules with different neutron fluxes and tested by laser.
- All of them are processed to study their response.
- Modules were annealed (at 150 °C for 8 weeks) and processed again
- Then modules were re-irradiated at level $1.0 \cdot 10^{10}$ and processed again
- Collected data are read from modules and analyzed:
  a. Photon spectra fit using two different methods to extract maximum of photons
     - Highly irradiated modules with big sensitive area or at high temperatures worse fitted
  b. Extraction breakdown voltage using fitting of gain as function of bias voltage
     - Results are consistent before, after irradiation, after annealing and after re-irradiation
  c. Time resolution of first and second peak of photon spectra
     - Results are consistent before, after irradiation, after annealing and after re-irradiation
  d. Dark count rate measurement
     - Annealing reduce rates but not to level before irradiation
     - Re-irradiation consistent with previous observations
  e. We see some differences dependence on produces or SiPM's code

# Backup

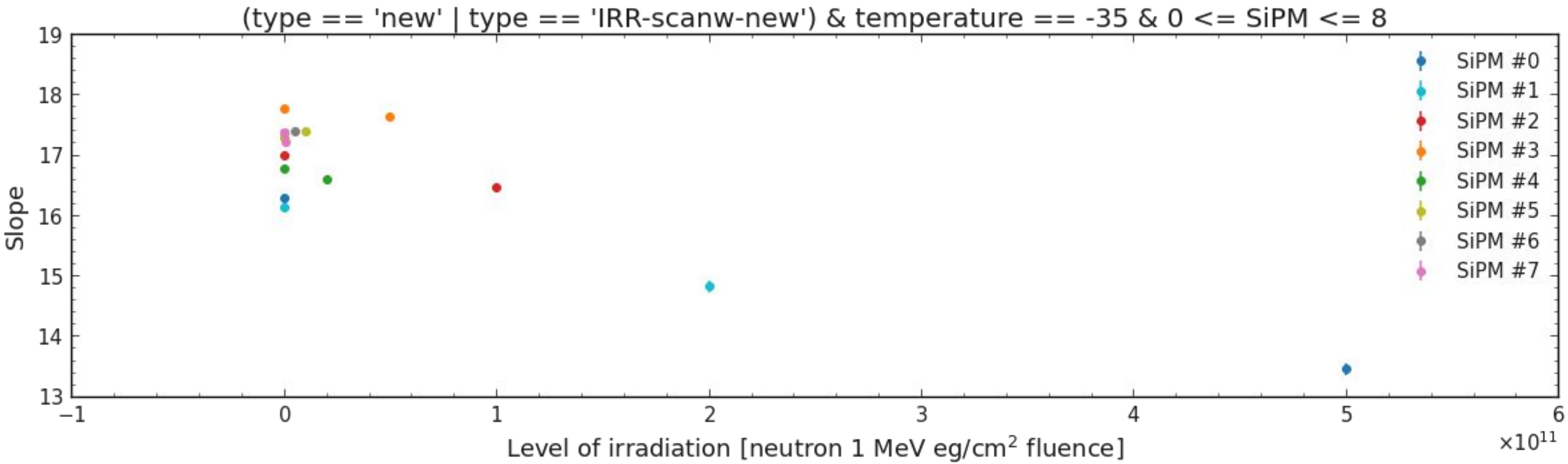
# Breakdown voltage as function of irradiation



# Breakdown voltage as function of irradiation

- Breakdown voltages can be presented as function of irradiation level
- Breakdown voltages are consistent before and after irradiation for several high irradiation levels
- The high uncertainty of the breakdown voltages come from a fact, in high irradiated environment is more difficult extract clear photon spectra.

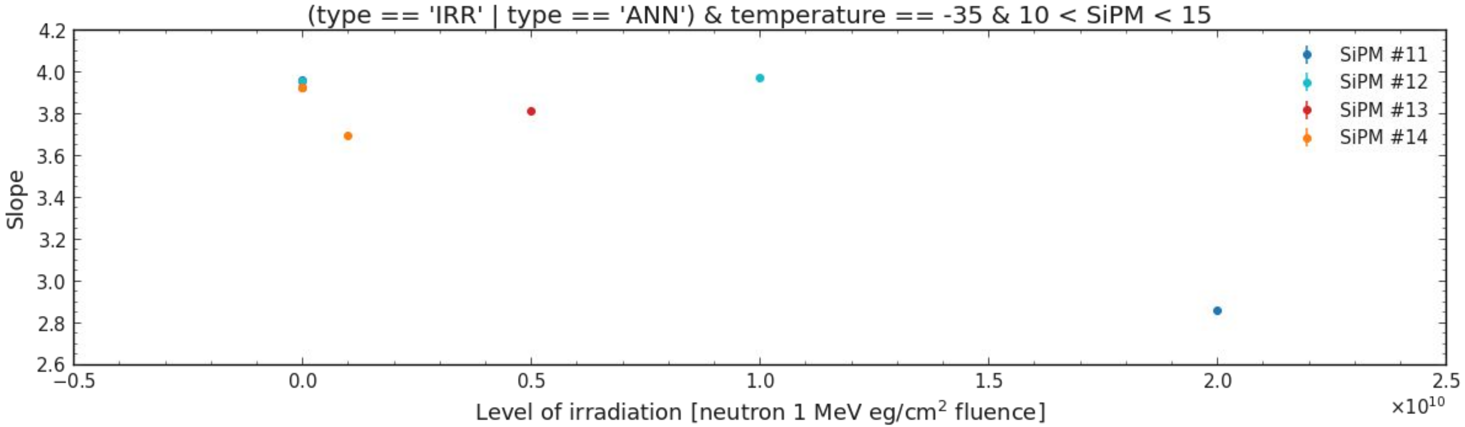


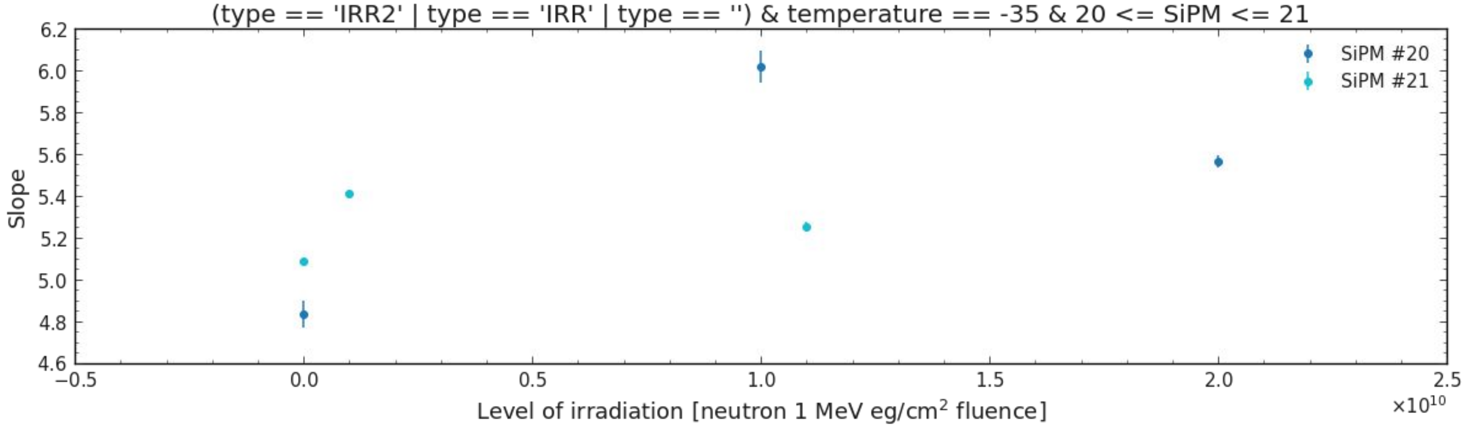



Jakub Kandra, INFN Padova

# Breakdown voltage as function of irradiation

- Breakdown voltages are consistent irradiated, annealed and re-irradiated data for several high irradiation levels

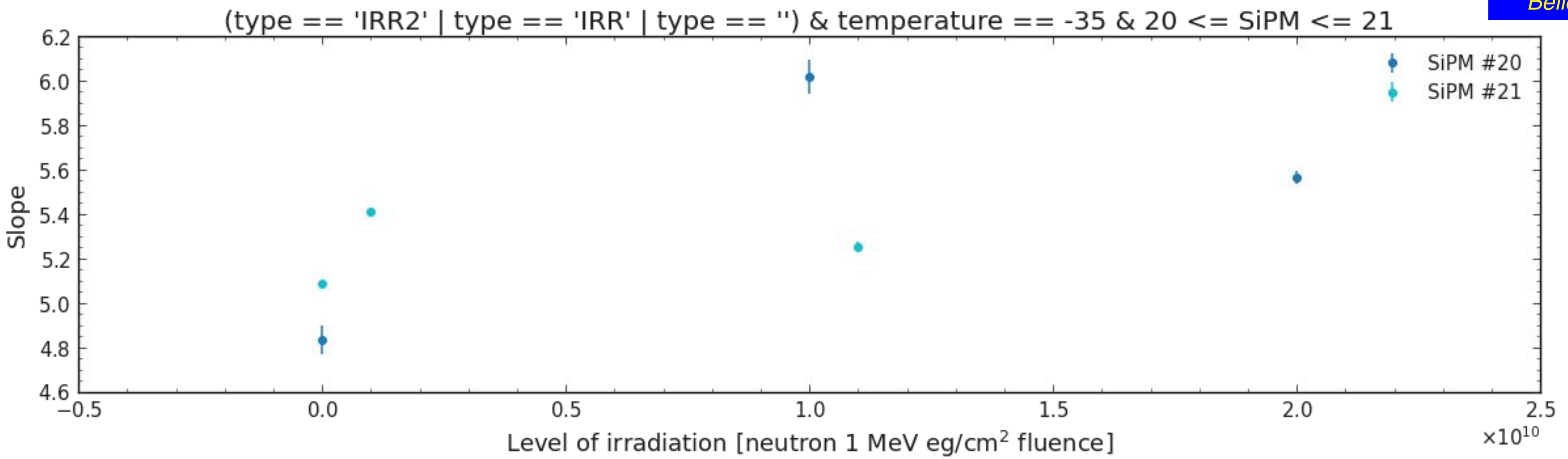


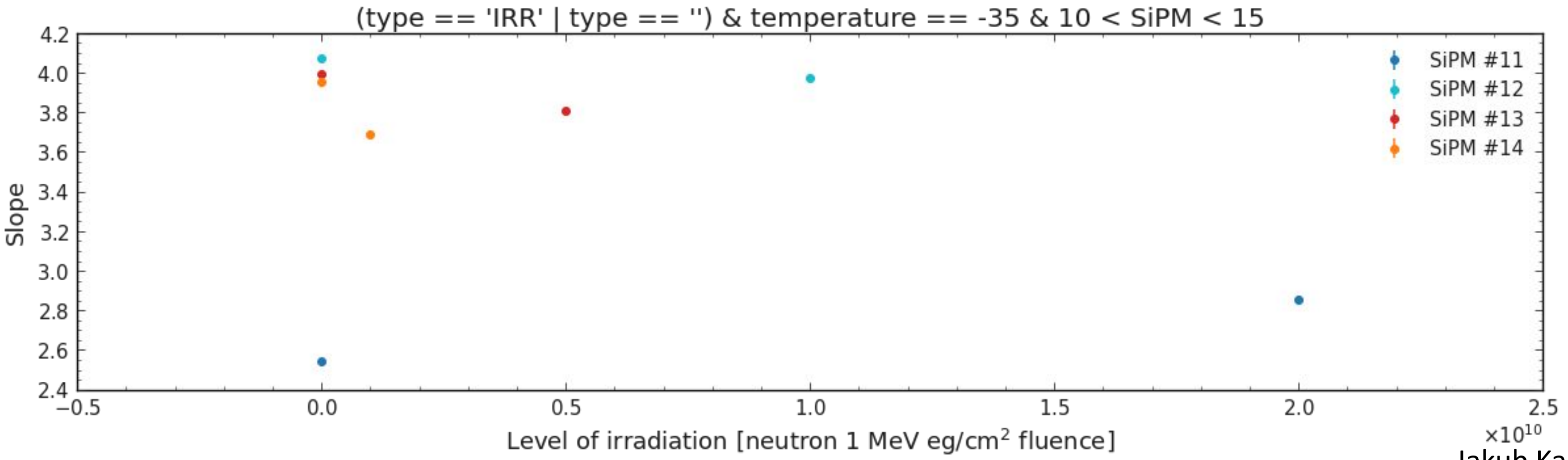






Jakub Kandra, INFN Padova

# Breakdown voltage as function of irradiation



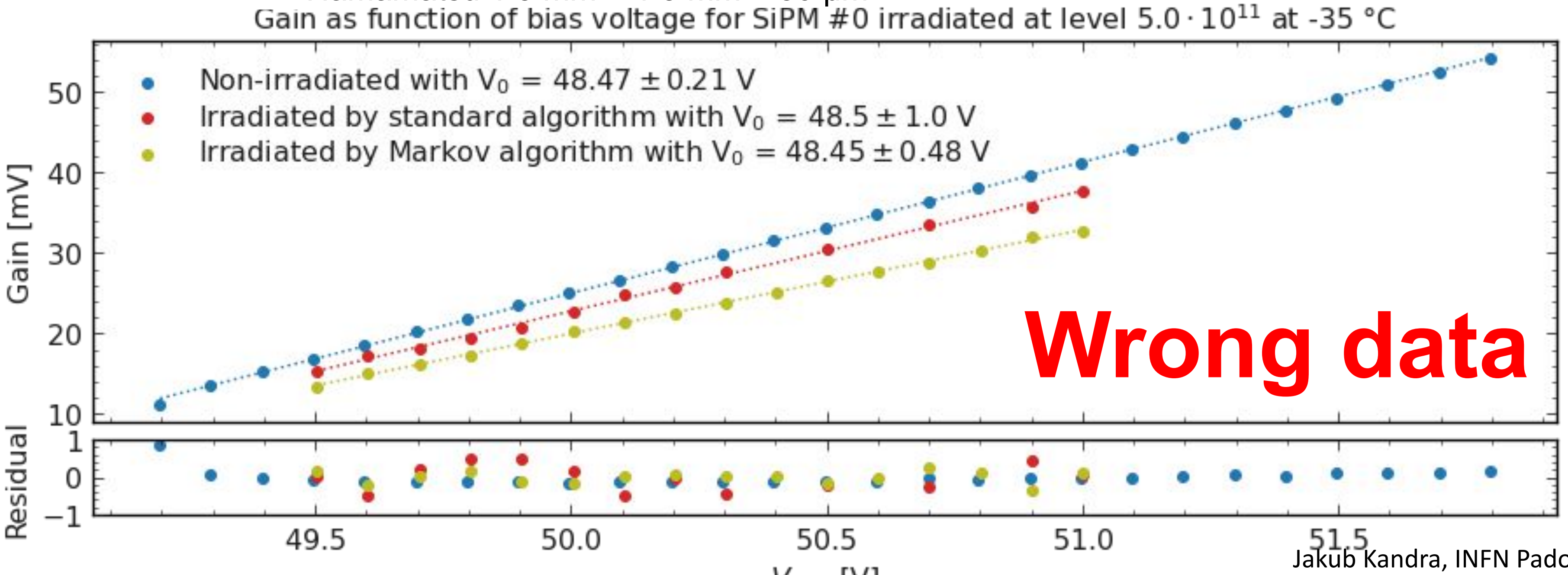


Jakub Kandra, INFN Padova

# Extraction breakdown voltage

- From photon spectra fit gains are extracted and breakdown voltage is extracted from gain as function of bias voltage
- Extracted breakdown voltage after irradiation is consistent with results before irradiation
- Markov algorithm provides precise result as standard algorithm in highly irradiated environment

Hamamatsu 1.3 mm × 1.3 mm × 50 µm



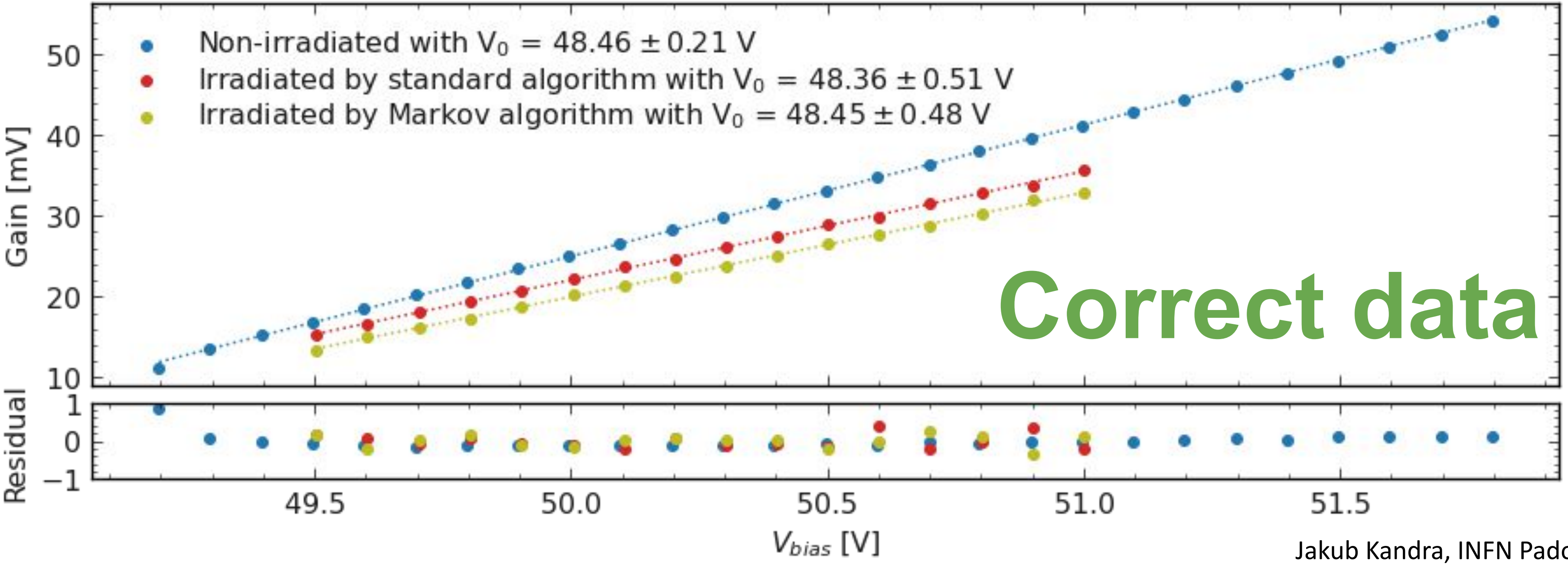



Jakub Kandra, INFN Padova

# Extraction breakdown voltage

- From photon spectra fit gains are extracted and breakdown voltage is extracted from gain as function of bias voltage
- Extracted breakdown voltage after irradiation is consistent with results before irradiation
- Markov algorithm provides precise result as standard algorithm in highly irradiated environment

Hamamatsu 1.3 mm × 1.3 mm × 50 µm irradiated at level $5.0 \cdot 10^{11}$ at -35 °C

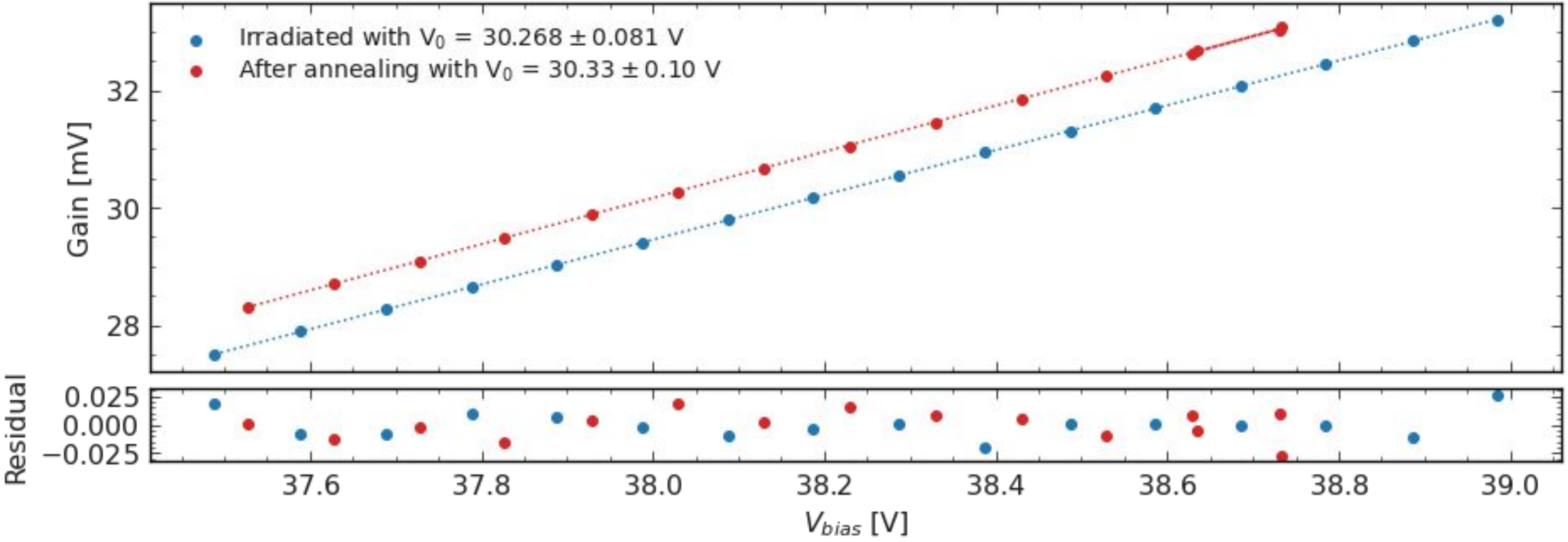





Jakub Kandra, INFN Padova

# Effect of annealing to breakdown voltage

FBK 1 mm × 1 mm × 15 μm irradiated at level $5.0 \cdot 10^9$ at -35 °C



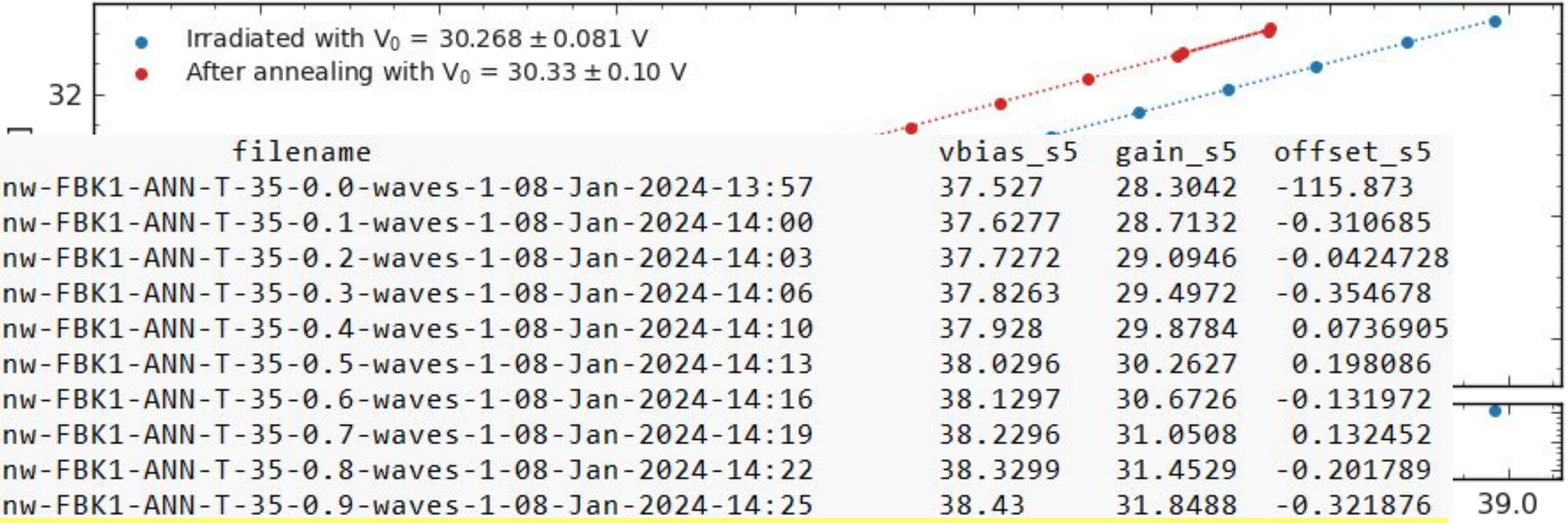

- Additional test has been provided using FBK modules, where photon spectra has been fitted before and after annealing to test if annealing process affect breakdown voltage extraction
- No significant difference has been observed after annealing



Jakub Kandra, INFN Padova

# Effect of annealing to breakdown voltage

FBK 1 mm × 1 mm × 15 µm irradiated at level $5.0 \cdot 10^9$ at -35 °C

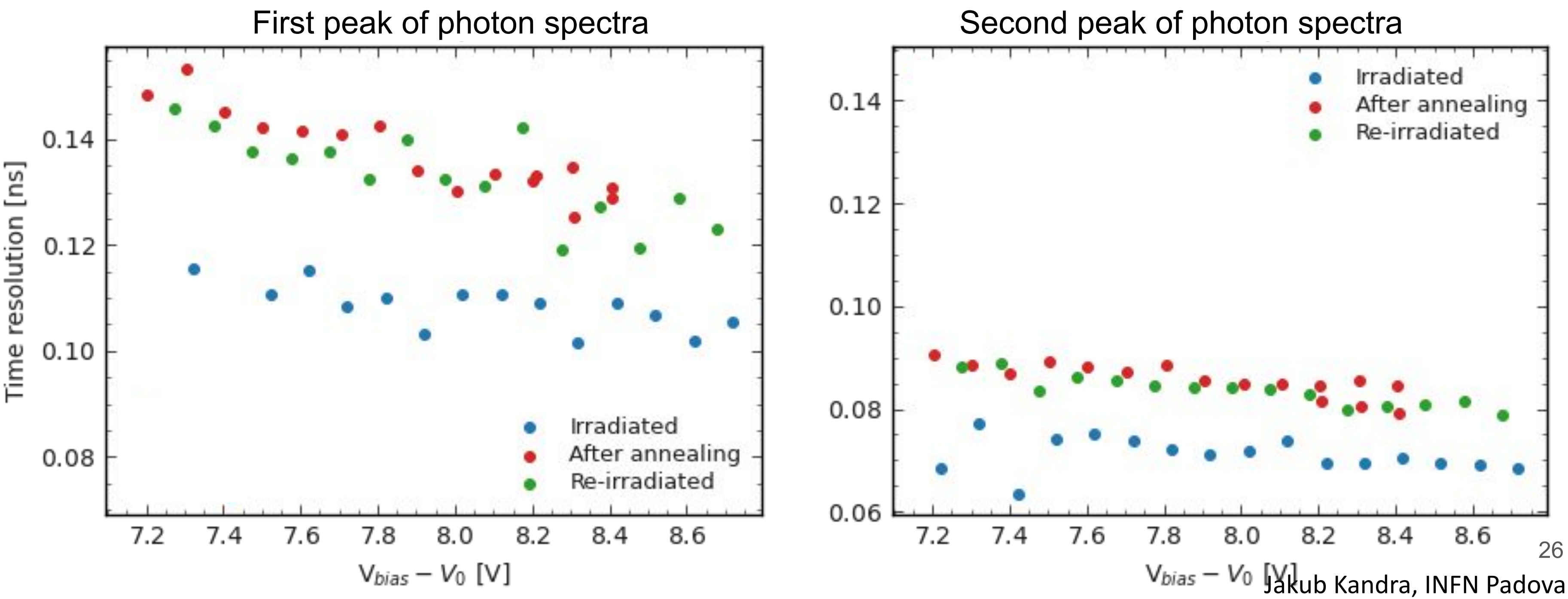



| filename | vbias_s5 | gain_s5 | offset_s5 |
|---|---|---|---|
| scanw-FBK1-ANN-T-35-0.0-waves-1-08-Jan-2024-13:57 | 37.527 | 28.3042 | -115.873 |
| scanw-FBK1-ANN-T-35-0.1-waves-1-08-Jan-2024-14:00 | 37.6277 | 28.7132 | -0.310685 |
| scanw-FBK1-ANN-T-35-0.2-waves-1-08-Jan-2024-14:03 | 37.7272 | 29.0946 | -0.0424728 |
| scanw-FBK1-ANN-T-35-0.3-waves-1-08-Jan-2024-14:06 | 37.8263 | 29.4972 | -0.354678 |
| scanw-FBK1-ANN-T-35-0.4-waves-1-08-Jan-2024-14:10 | 37.928 | 29.8784 | 0.0736905 |
| scanw-FBK1-ANN-T-35-0.5-waves-1-08-Jan-2024-14:13 | 38.0296 | 30.2627 | 0.198086 |
| scanw-FBK1-ANN-T-35-0.6-waves-1-08-Jan-2024-14:16 | 38.1297 | 30.6726 | -0.131972 |
| scanw-FBK1-ANN-T-35-0.7-waves-1-08-Jan-2024-14:19 | 38.2296 | 31.0508 | 0.132452 |
| scanw-FBK1-ANN-T-35-0.8-waves-1-08-Jan-2024-14:22 | 38.3299 | 31.4529 | -0.201789 |
| scanw-FBK1-ANN-T-35-0.9-waves-1-08-Jan-2024-14:25 | 38.43 | 31.8488 | -0.321876 |
| scanw-FBK1-ANN-T-35-1.0-waves-1-08-Jan-2024-14:28 | 38.5285 | 32.2513 | -0.446562 |
| scanw-FBK1-ANN-T-35-1.1-waves-1-08-Jan-2024-14:31 | 38.6295 | 32.631 | -0.307714 |
| scanw-FBK1-ANN-T-35-1.2-waves-1-08-Jan-2024-14:34 | 38.7303 | 33.0258 | -0.391451 |
| scanw-FBK1-ANN-T-35-1.3-waves-1-10-Jan-2024-13:52 | 38.5344 | 32.2894 | -0.370892 |
| scanw-FBK1-ANN-T-35-1.4-waves-1-10-Jan-2024-13:55 | 38.634 | 32.6616 | -0.175506 |
| scanw-FBK1-ANN-T-35-1.5-waves-1-10-Jan-2024-13:58 | 38.7328 | 33.0714 | -0.452139 |

# Effect of annealing to time resolution

- Then modules was irradiated again at level $10.0 \cdot 10^{10}$ to test affect to time resolution
- Time resolution results keep consistent as before

FBK 1 mm × 1 mm × 15 μm irradiated at level $2.0 \cdot 10^{10}$ at -35 °C





Jakub Kandra, INFN Padova

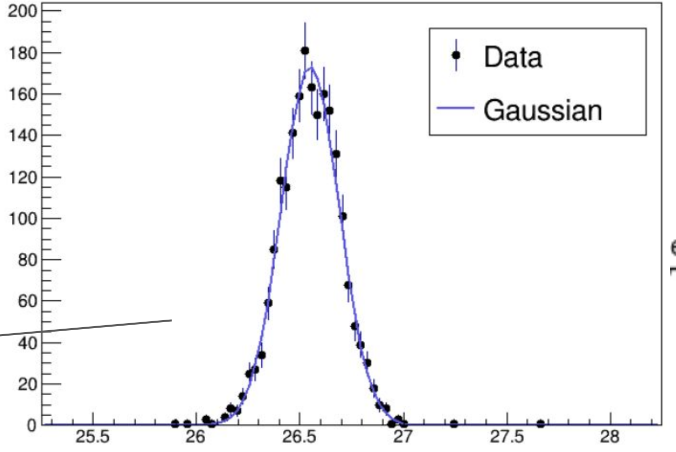
# Effect of annealing to time resolution

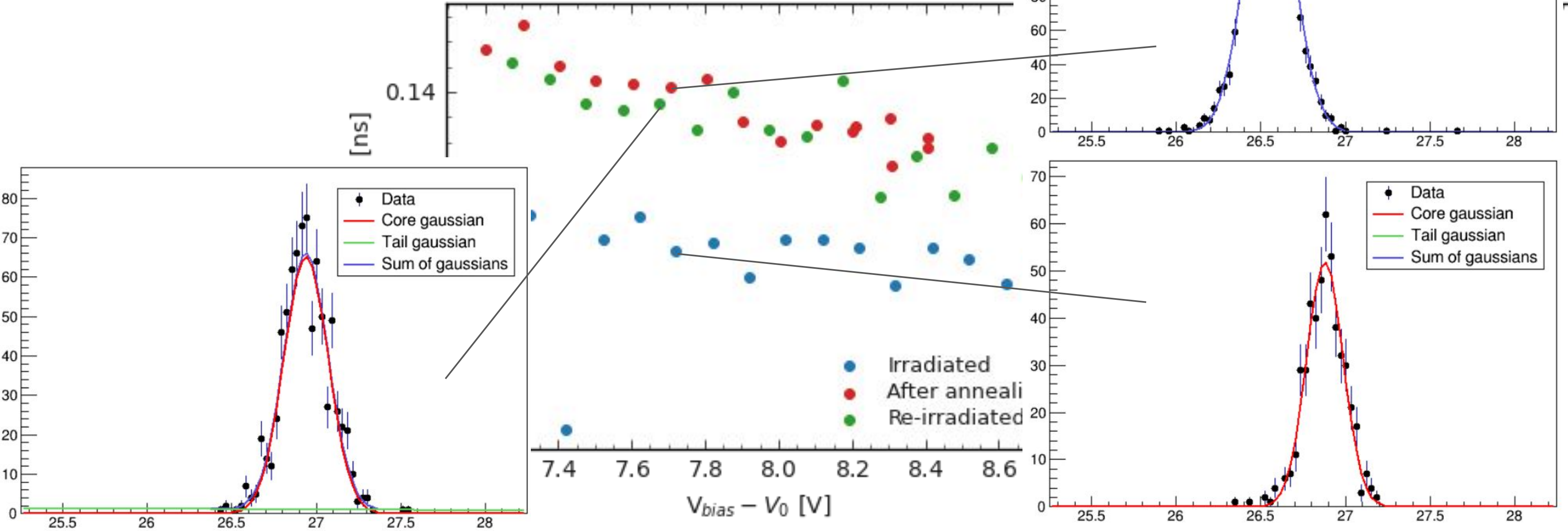
- Then modules was irradiated again at level $10.0 \cdot 10^{10}$ to test a
- Time resolution results keep consistent as before

FBK 1 mm × 1 mm × 15 μm irradiated at level 2.

First peak of photon spectra

Sec



# Effect of annealing to time resolution

- Then modules was irradiated again at level $10.0 \cdot 10^{10}$ to test
- Time resolution results keep consistent as before

FBK 1 mm × 1 mm × 15 μm irradiated at level 2

First peak of photon spectra Se