Irradiance

What is your sensor really telling you?

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All sensor manufacturers

Introduction

What do you expect from a sensor?

Pyranometer

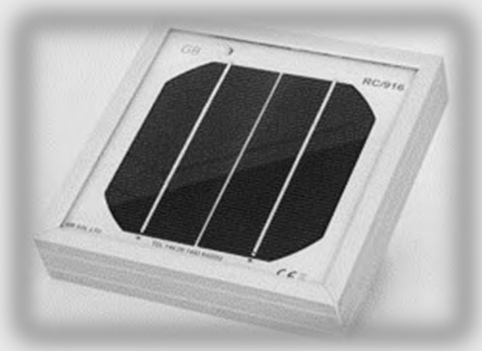
- Radiant intensity
  - Integrated over all directions (hemisphere, Lambertian surface)
  - Integrated over all wavelengths (with some limits)

= *Broadband global irradiance*

Reference cell

- Radiant intensity
  - Weighted integration by direction (IAM)
  - Weighted integration by wavelength (SR)

= *Effective irradiance ?*



There is no *complete* standard or *single* ideal for reference cells!

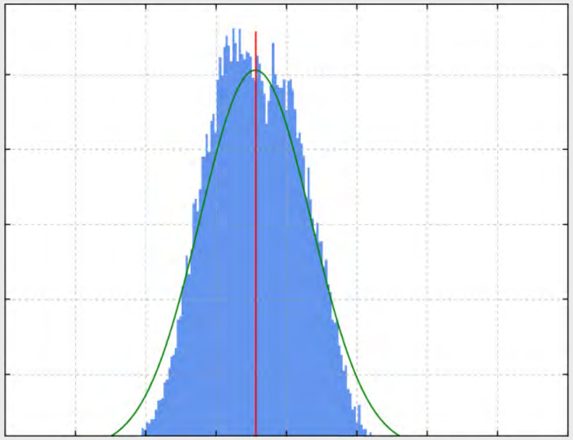
What do you want to know?

820 W/m ^{2}

821.579 W/m ^{2}

822 W/m ^{2} ± 3%

822 W/m ^{2} ± 3%, k=2

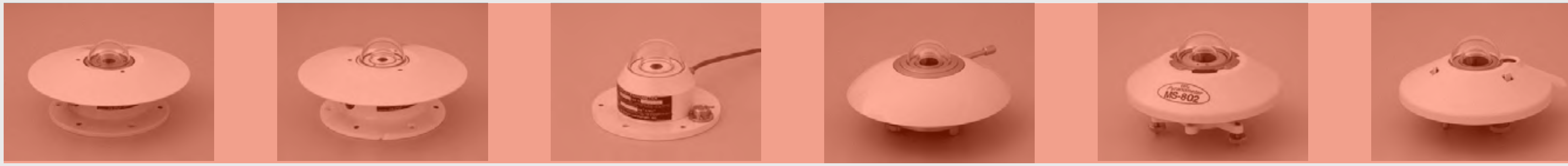


What is possible to know?

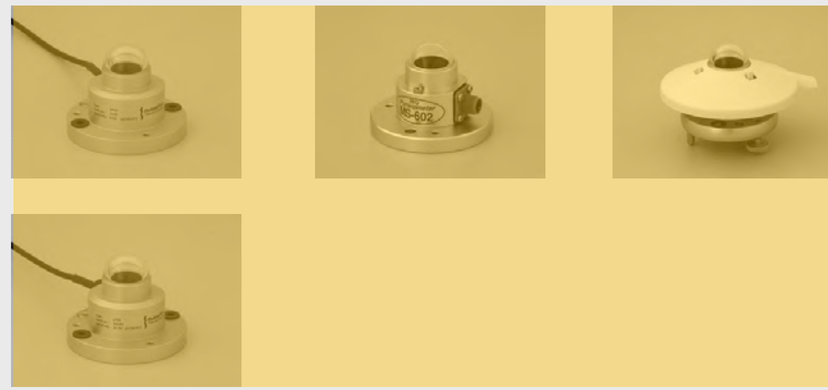
What causes ±

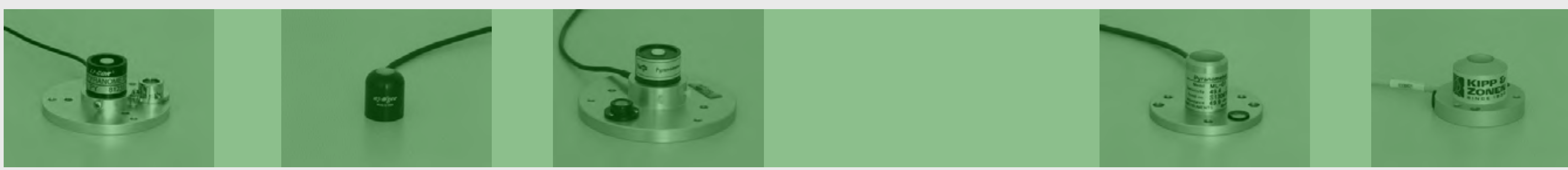
Pyranometers	Reference cells
– Primary characteristics	
• Not-quite Lambertian surface: directional errors	• Yes, but…
• Not-quite flat spectral response: spectral errors	• Yes, but…
– Secondary influences	
• Operating temperature	• Yes, but…
• Temperature rate of change	• No
• Radiant energy losses (sky)	• No
• Influence of tilt angle	• No
• Non-linearity	• Yes
– Operational aspects	
• Calibration and long-term stability	• Yes
• Orientation/leveling	• Yes
• Shading, soiling	• Yes

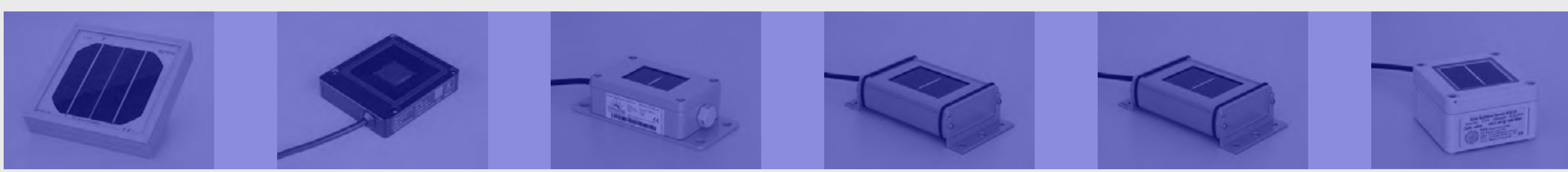
PVSENSOR project: 42 Sensors



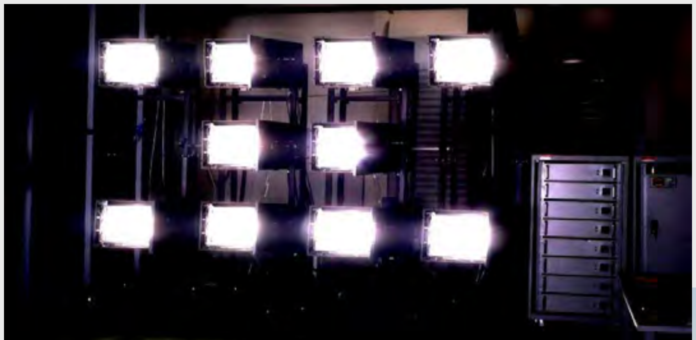
1. Secondary standard thermopile pyranometers
2. Second class thermopile pyranometers
3. Photodiode pyranometers
4. Reference cells

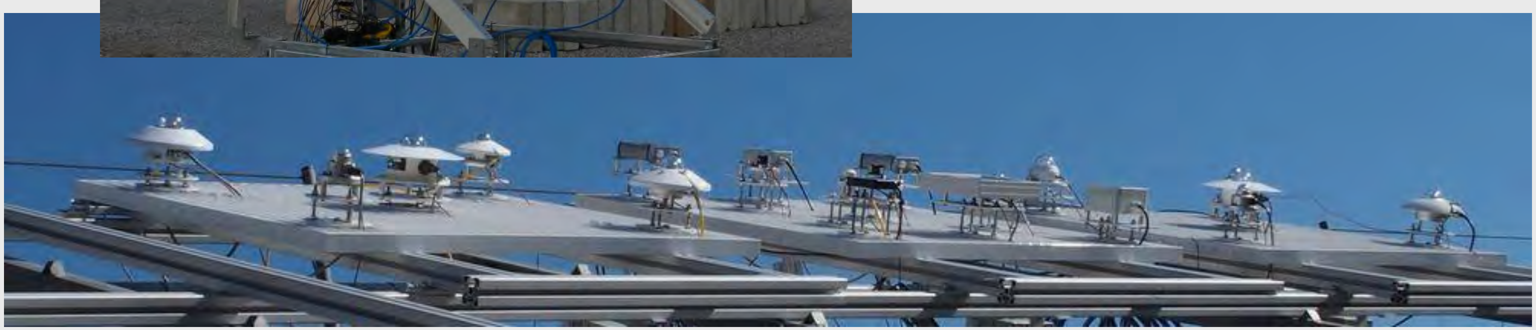




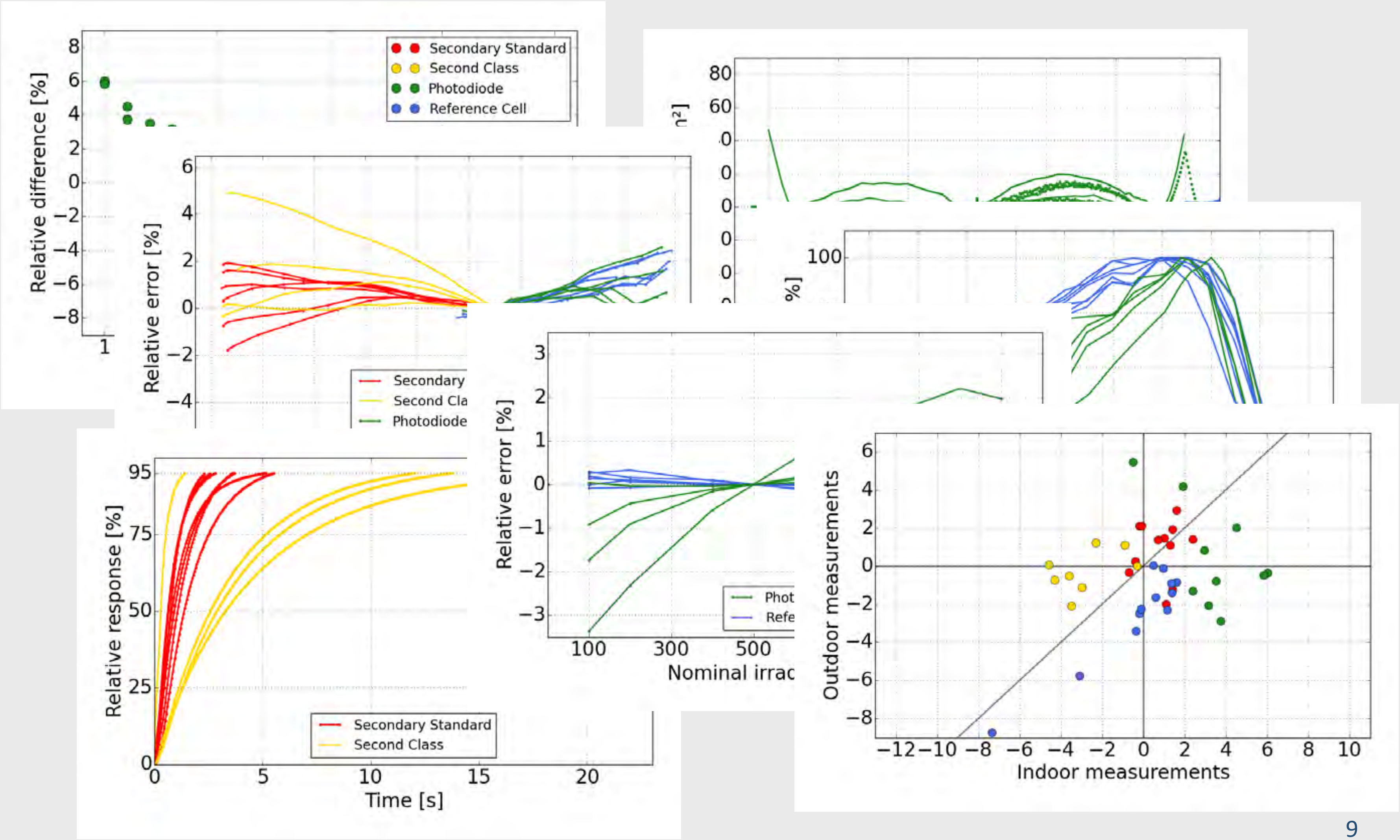


Test facilities



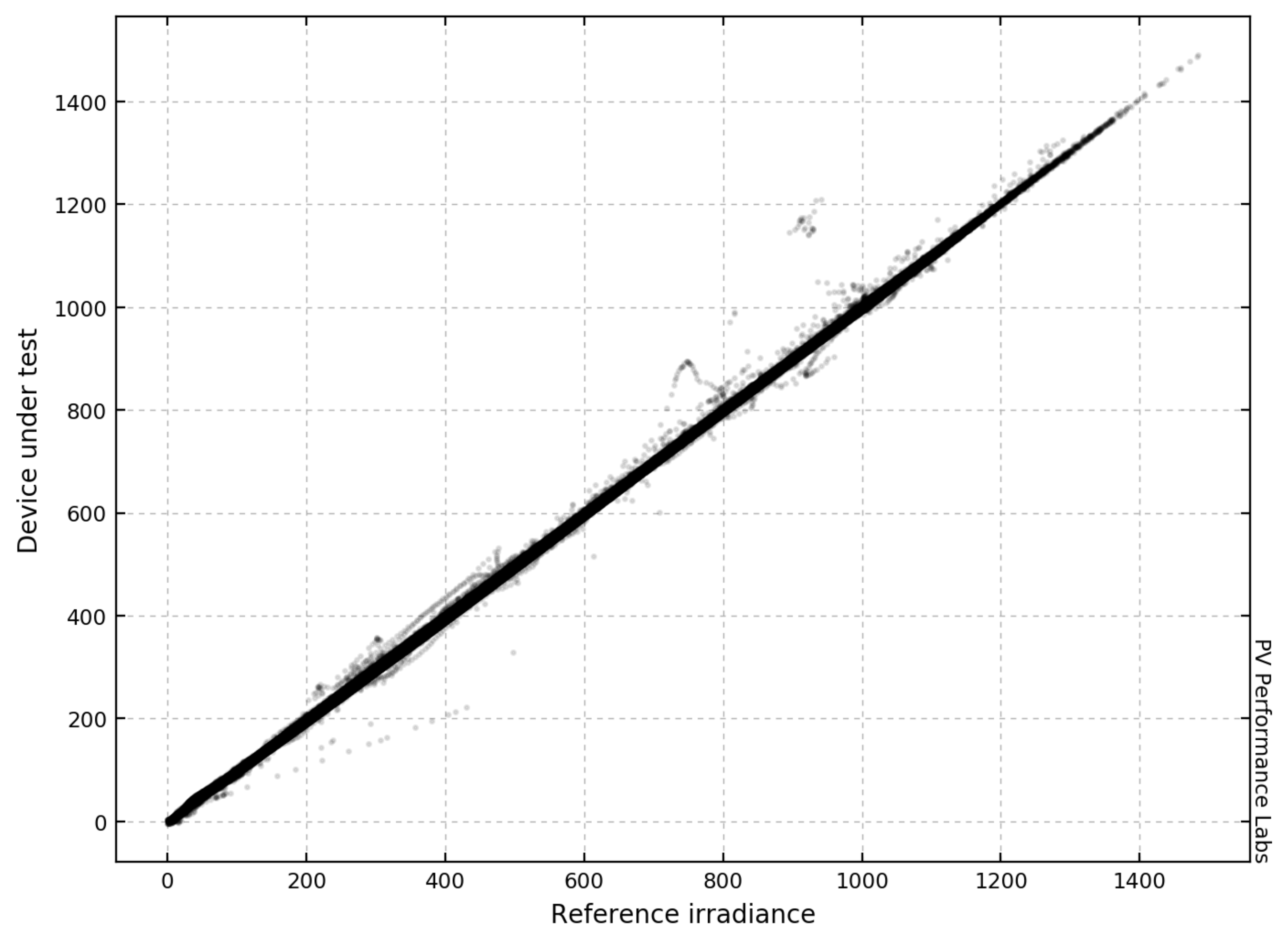


Many characteristics



One-year observations

Secondary standard pyranometer, one-minute averages



One-year observations

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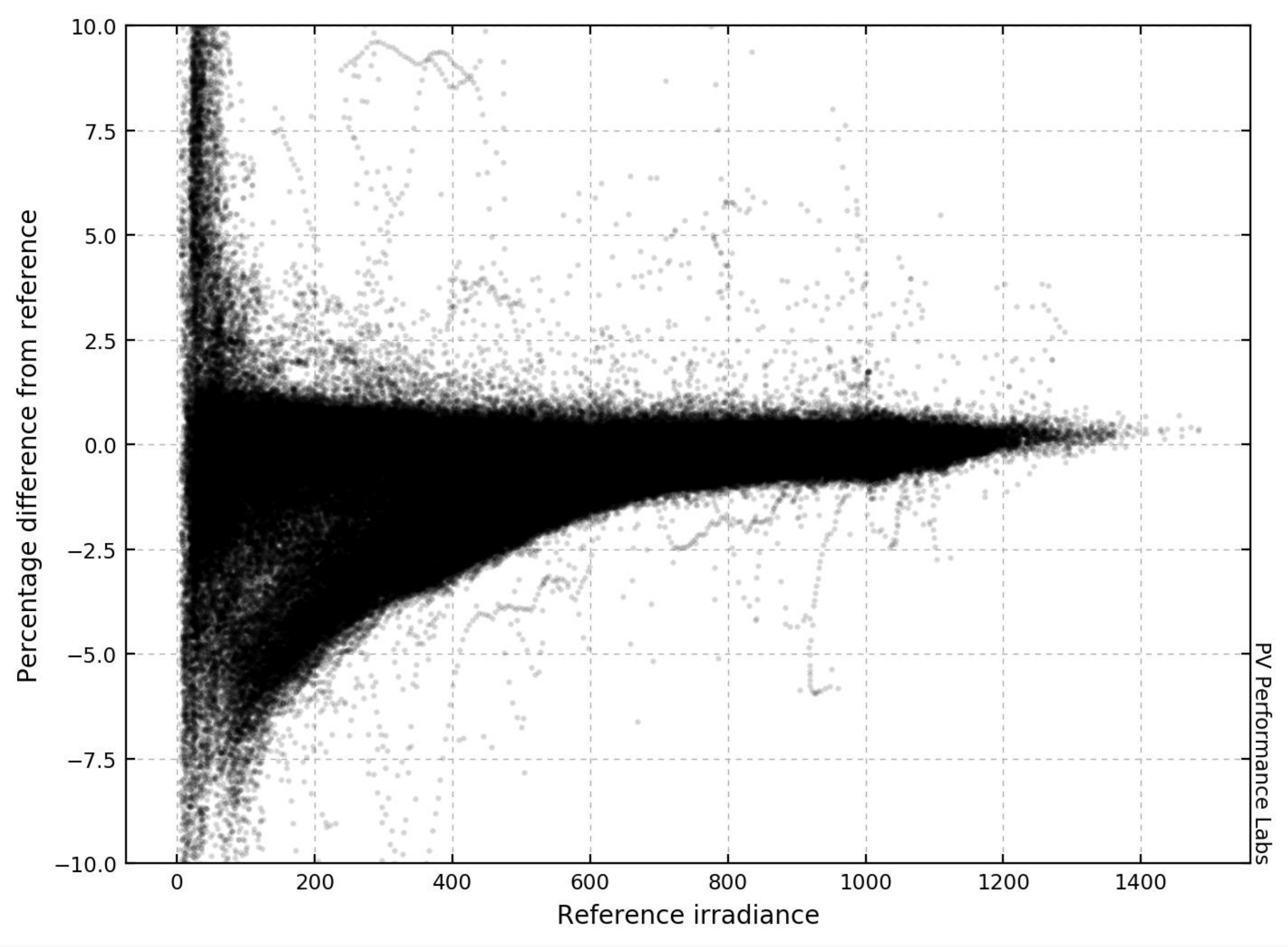
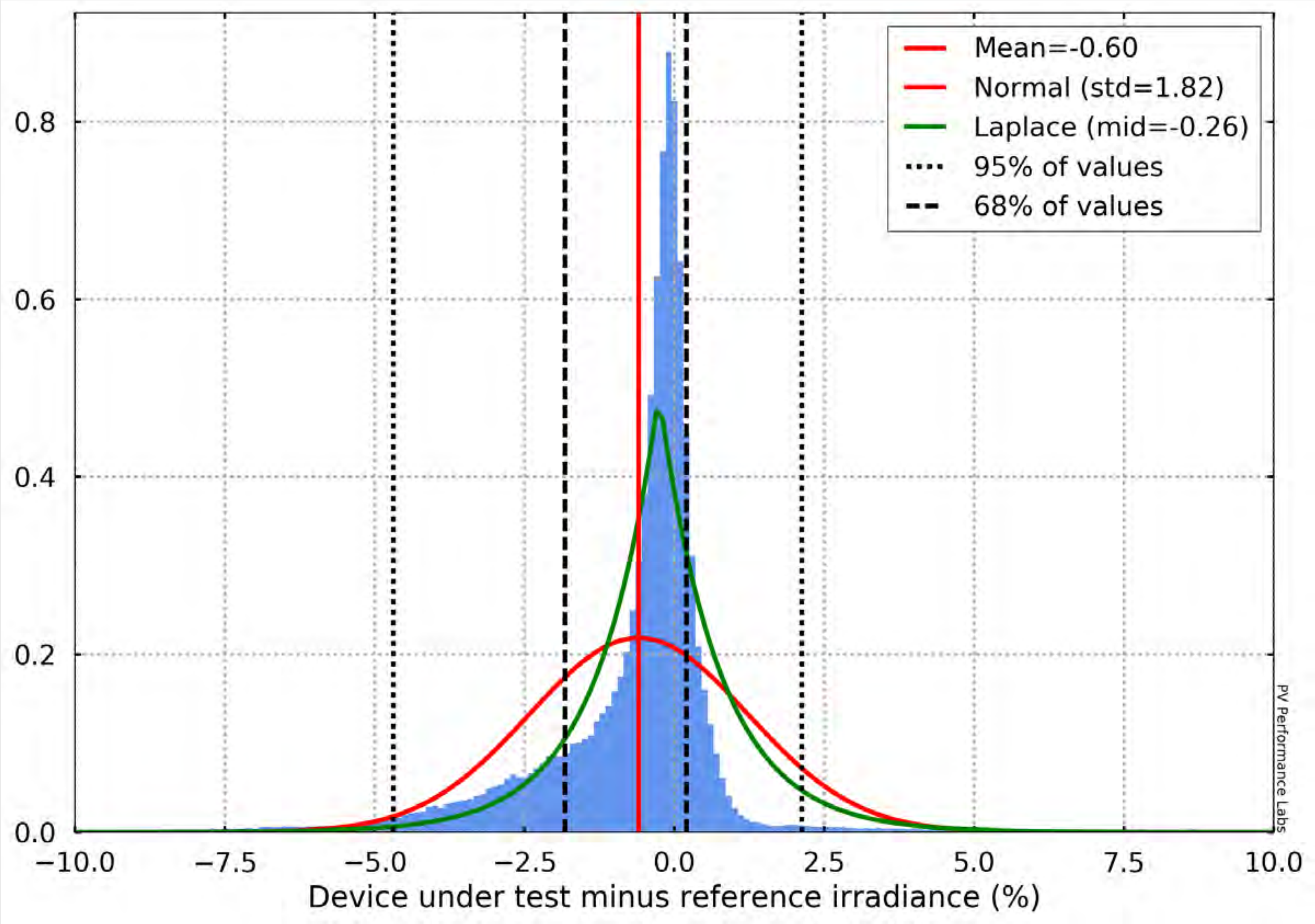


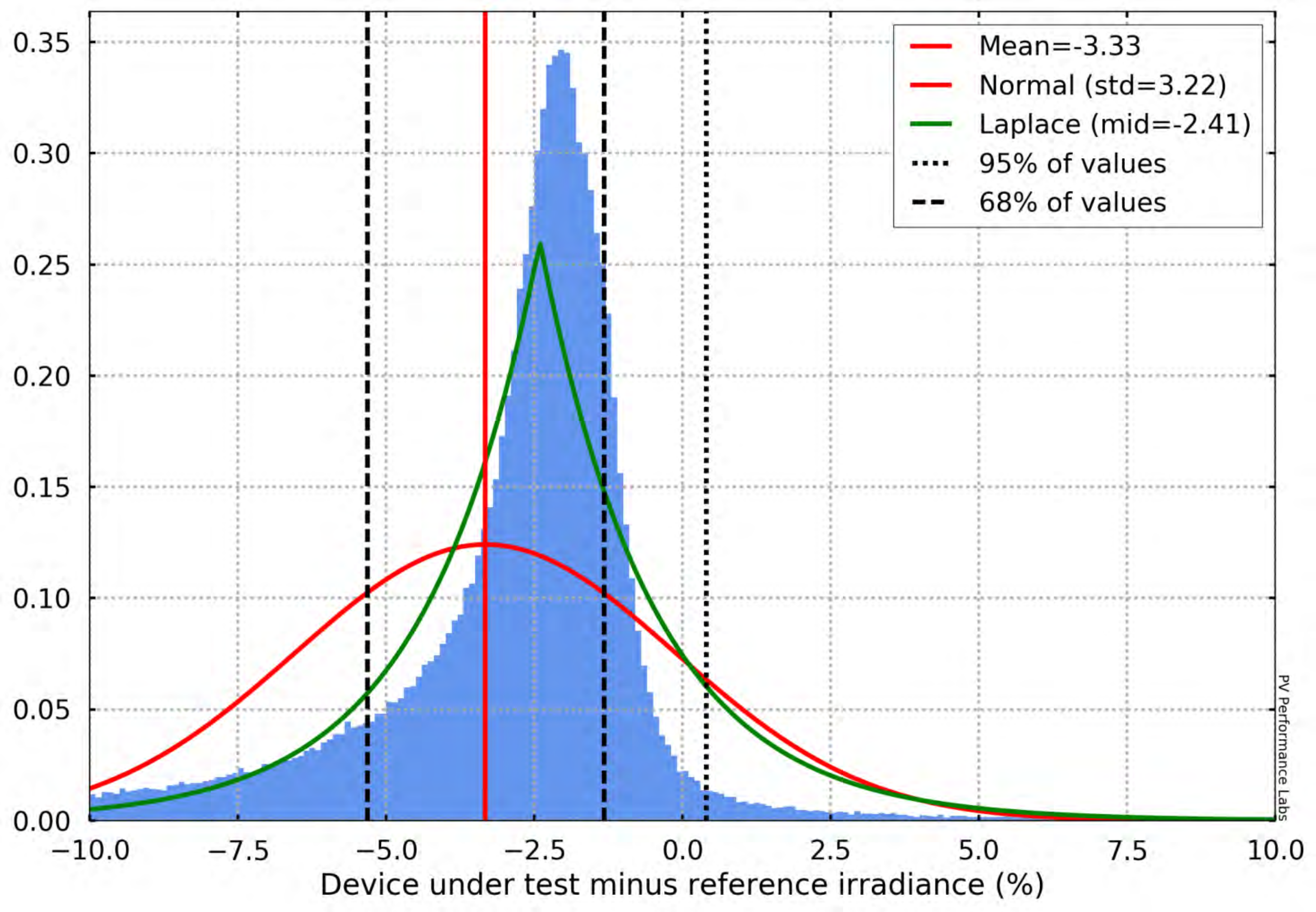
One-year observations

Secondary standard pyranometer, one-minute averages



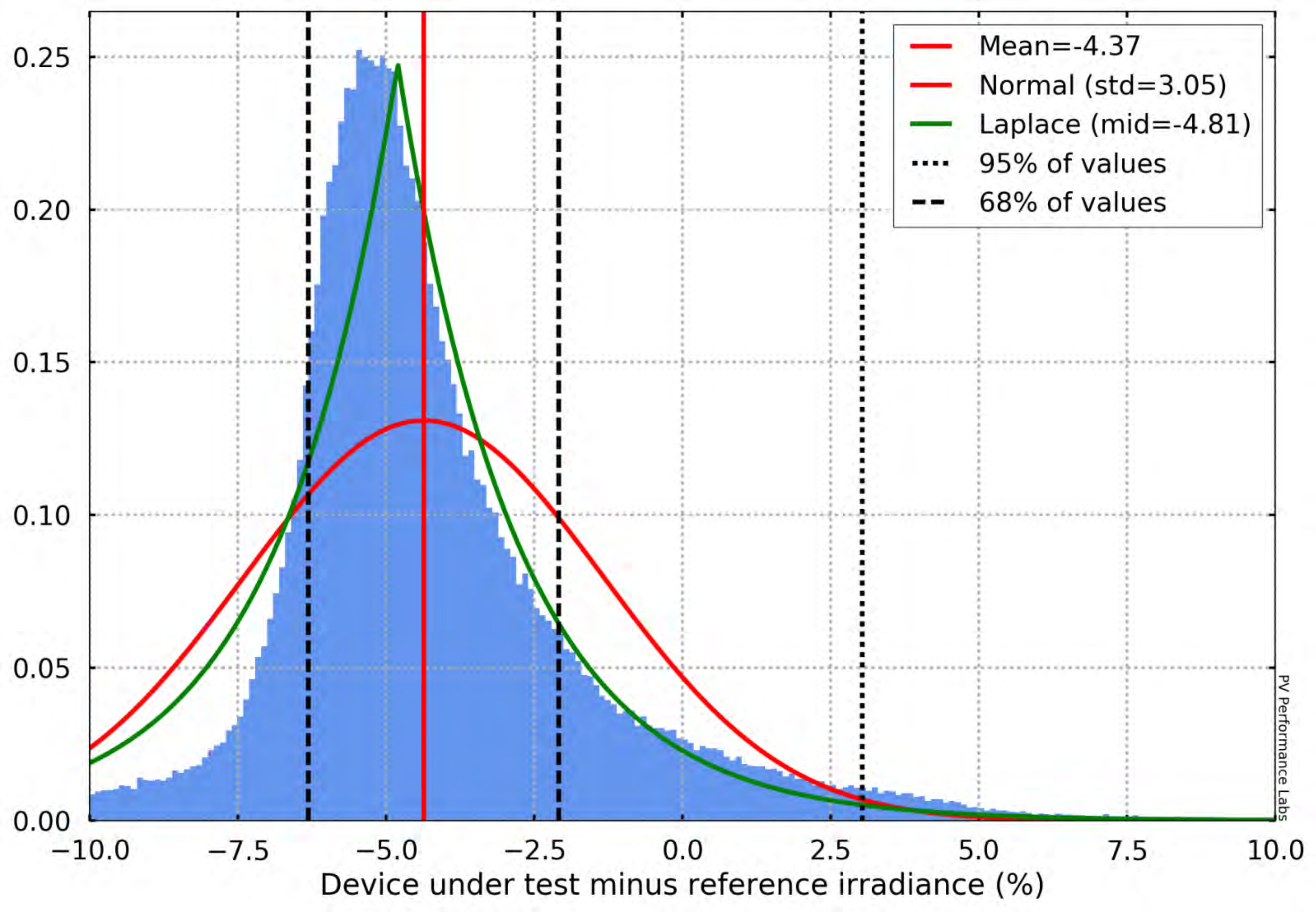
Second-class pyranometer

One-year observations, one-minute averages

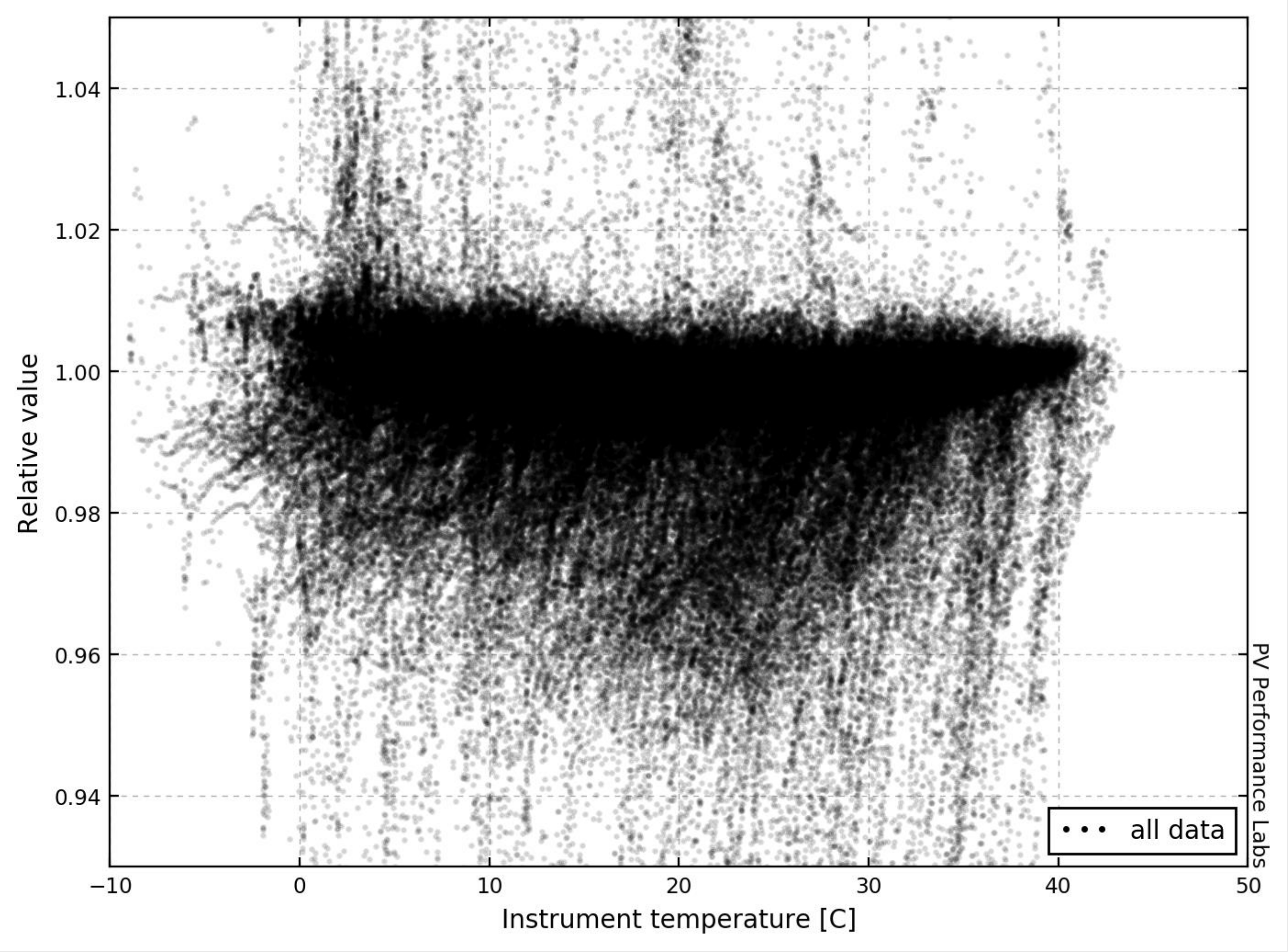


Photodiode pyranometer

One-year observations, one-minute averages



Measurement error vs temperature



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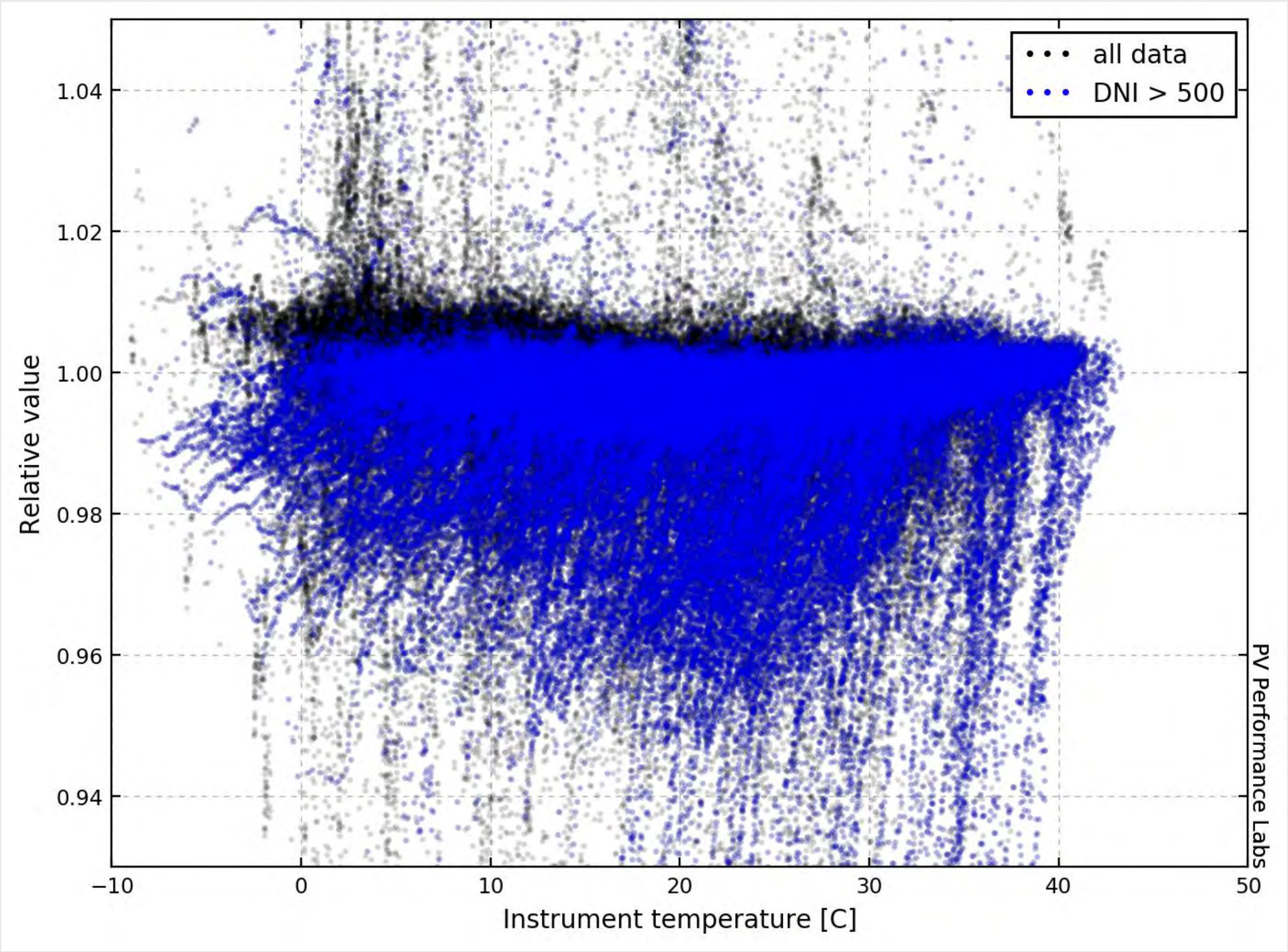
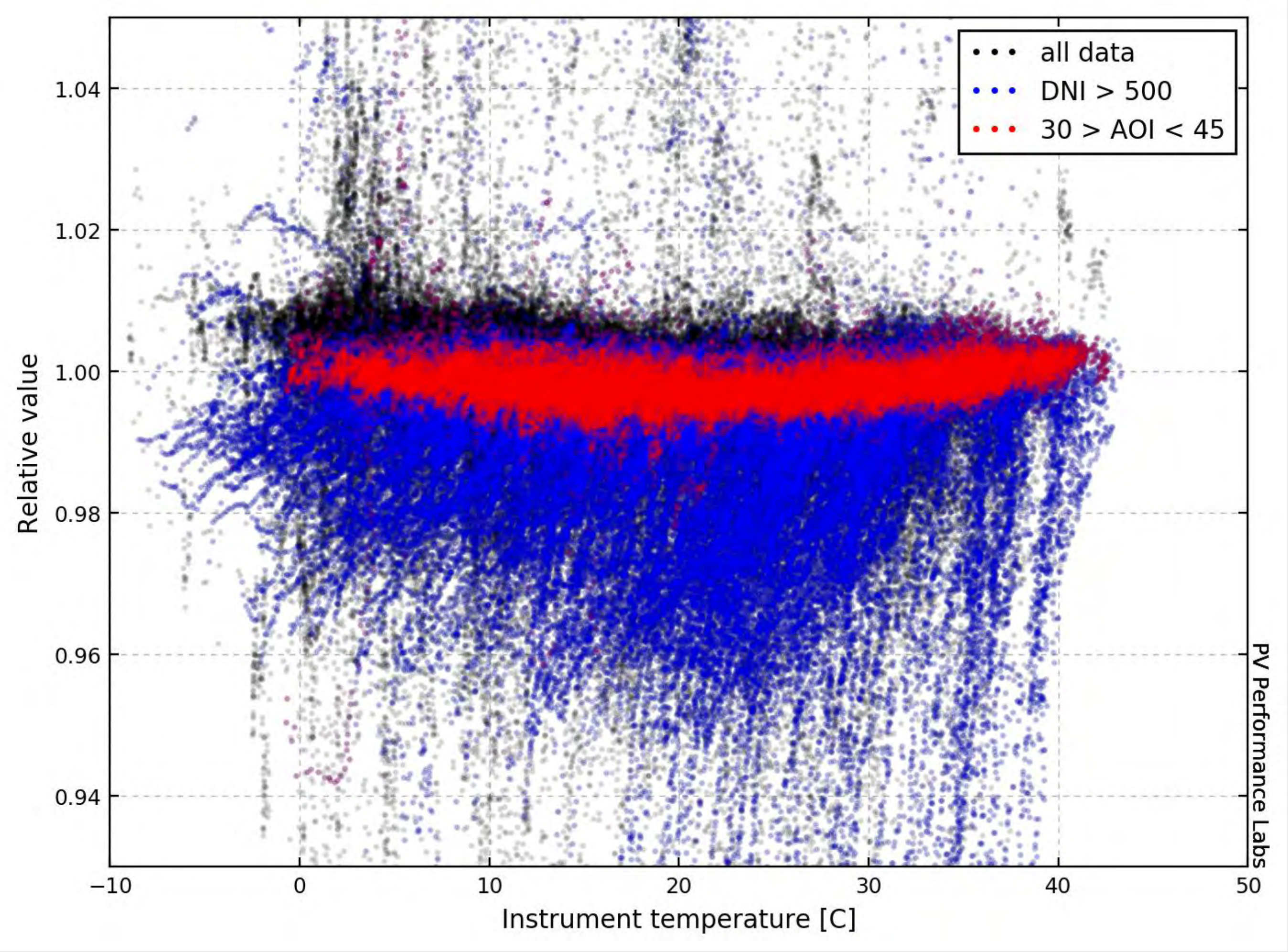


Measurement error vs temperature



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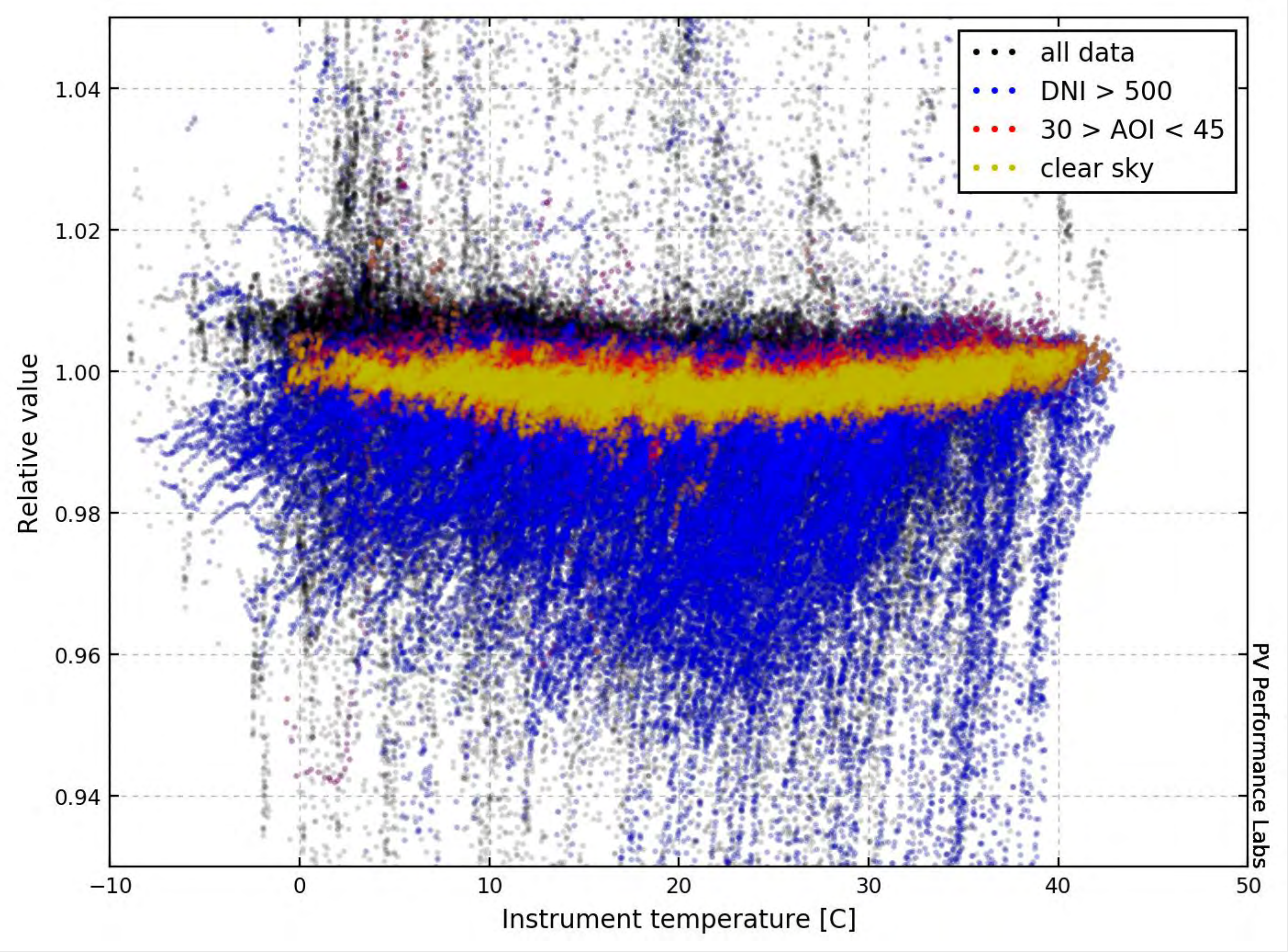

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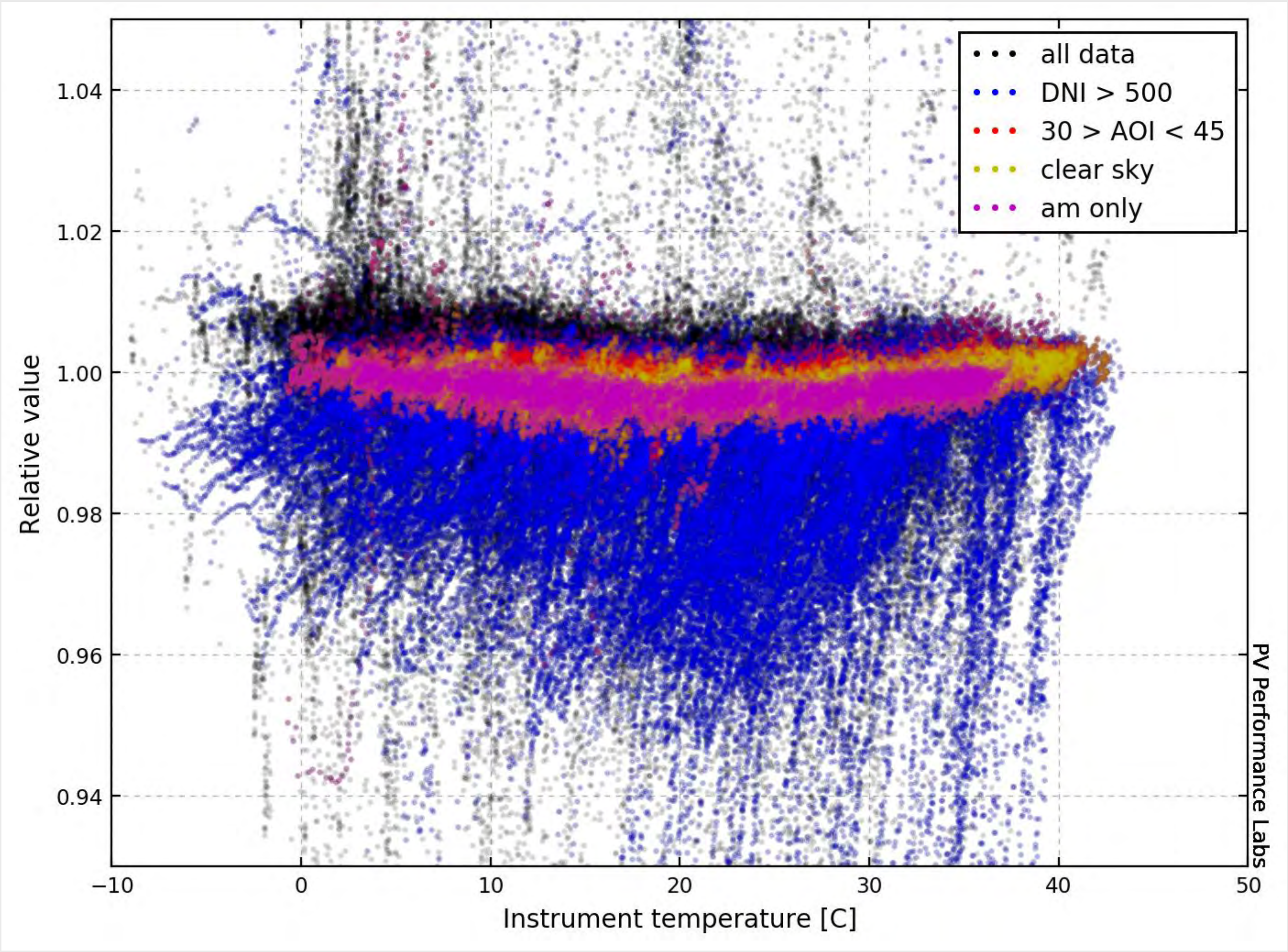

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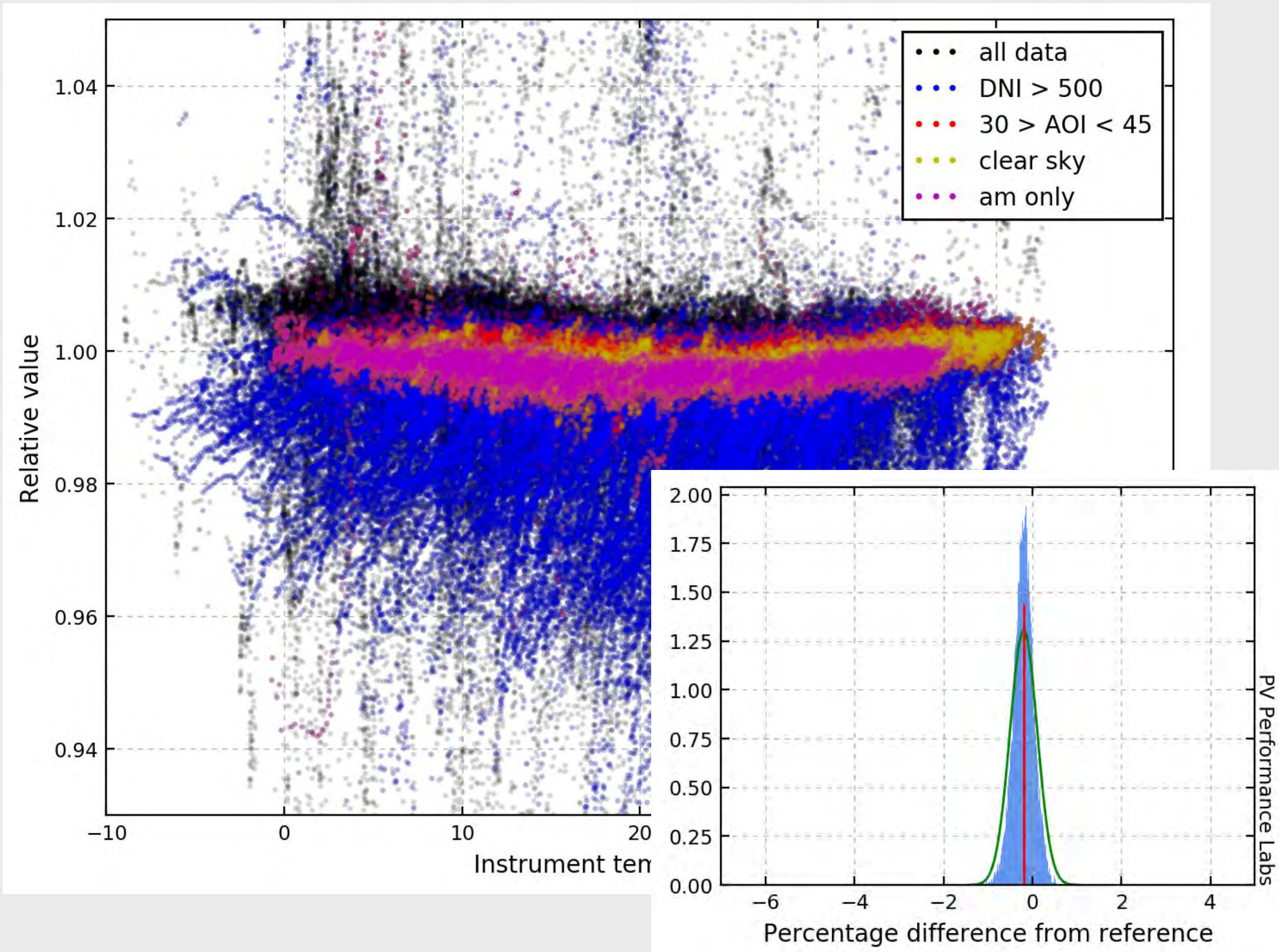
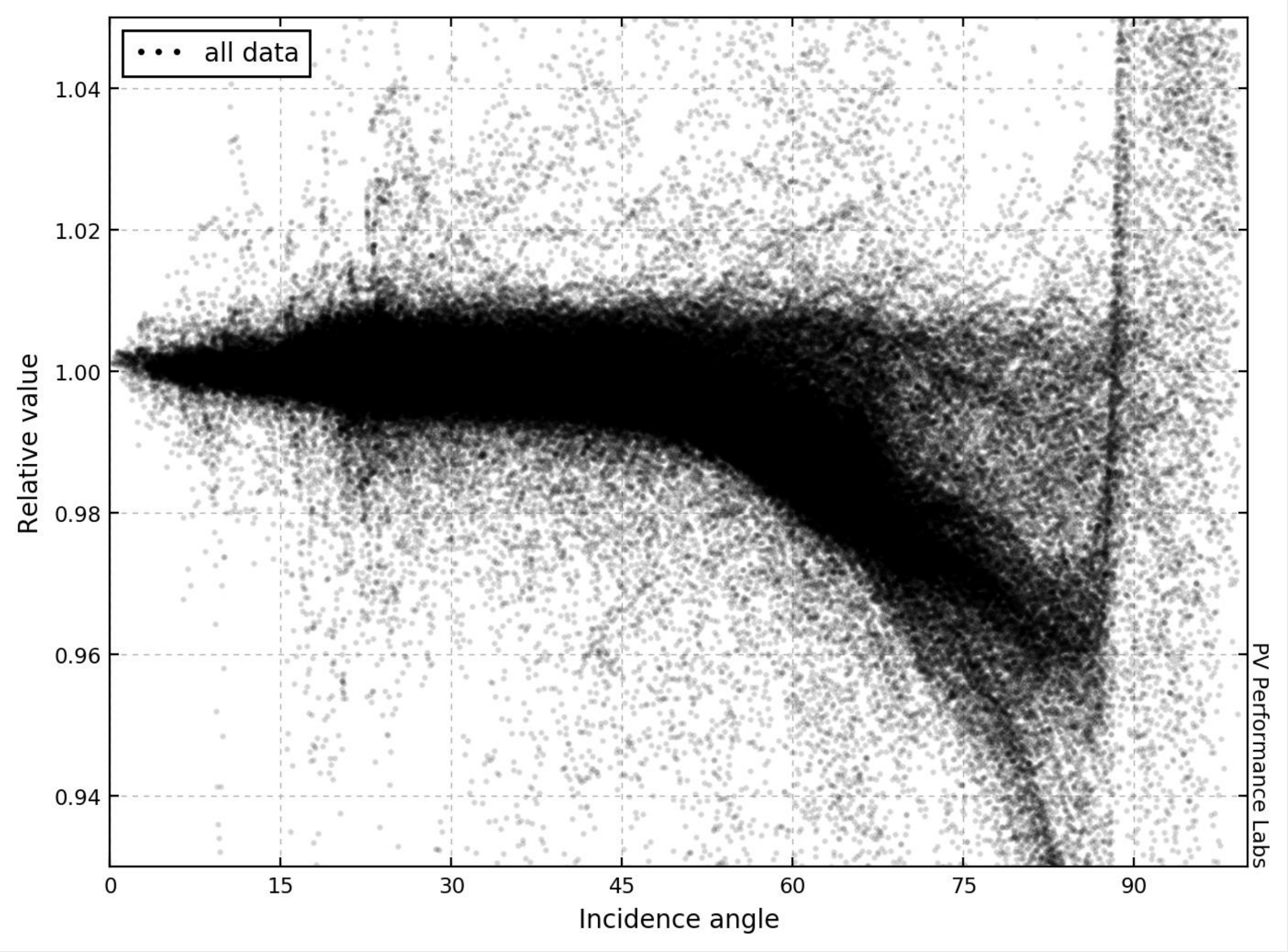
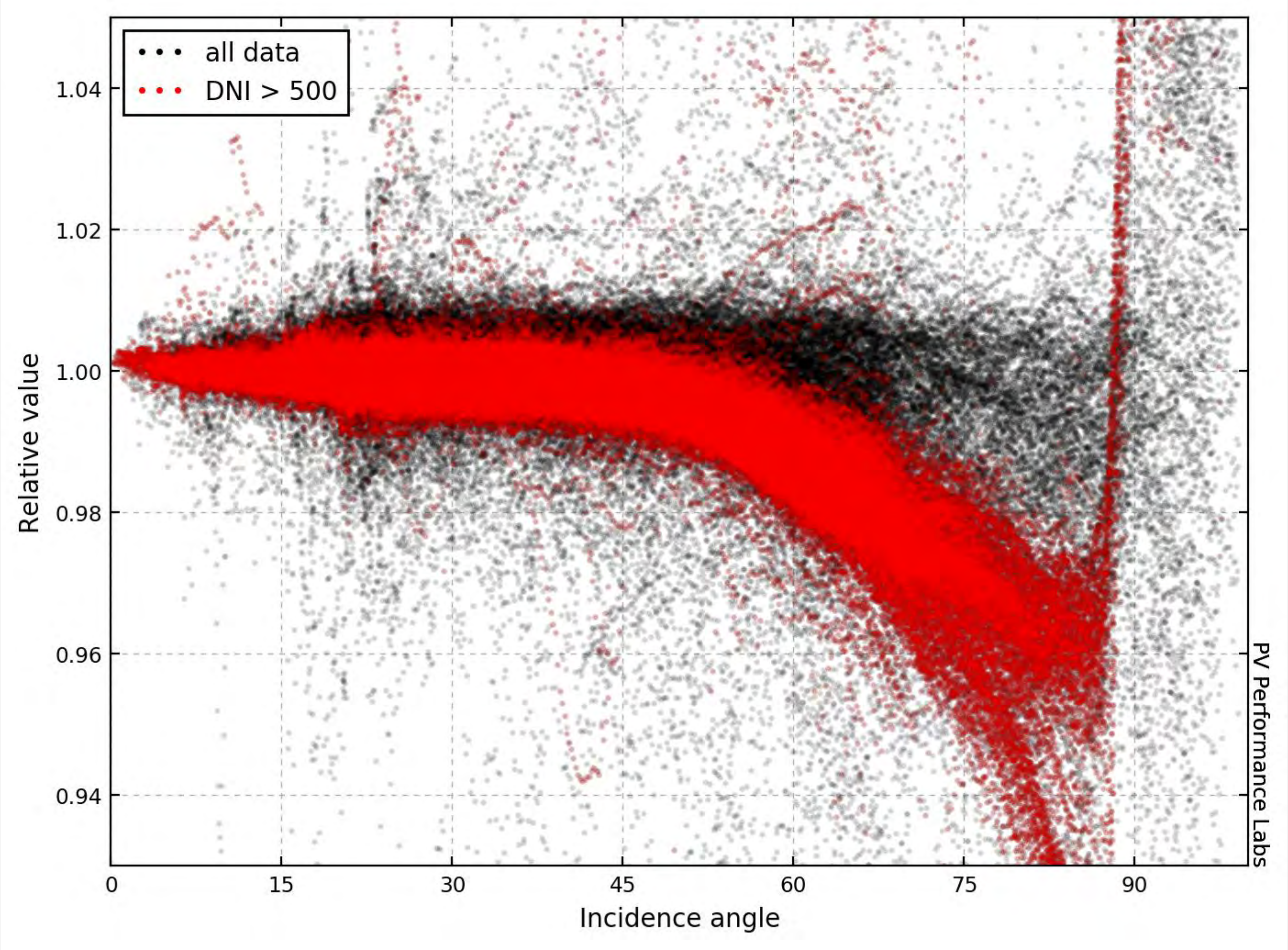


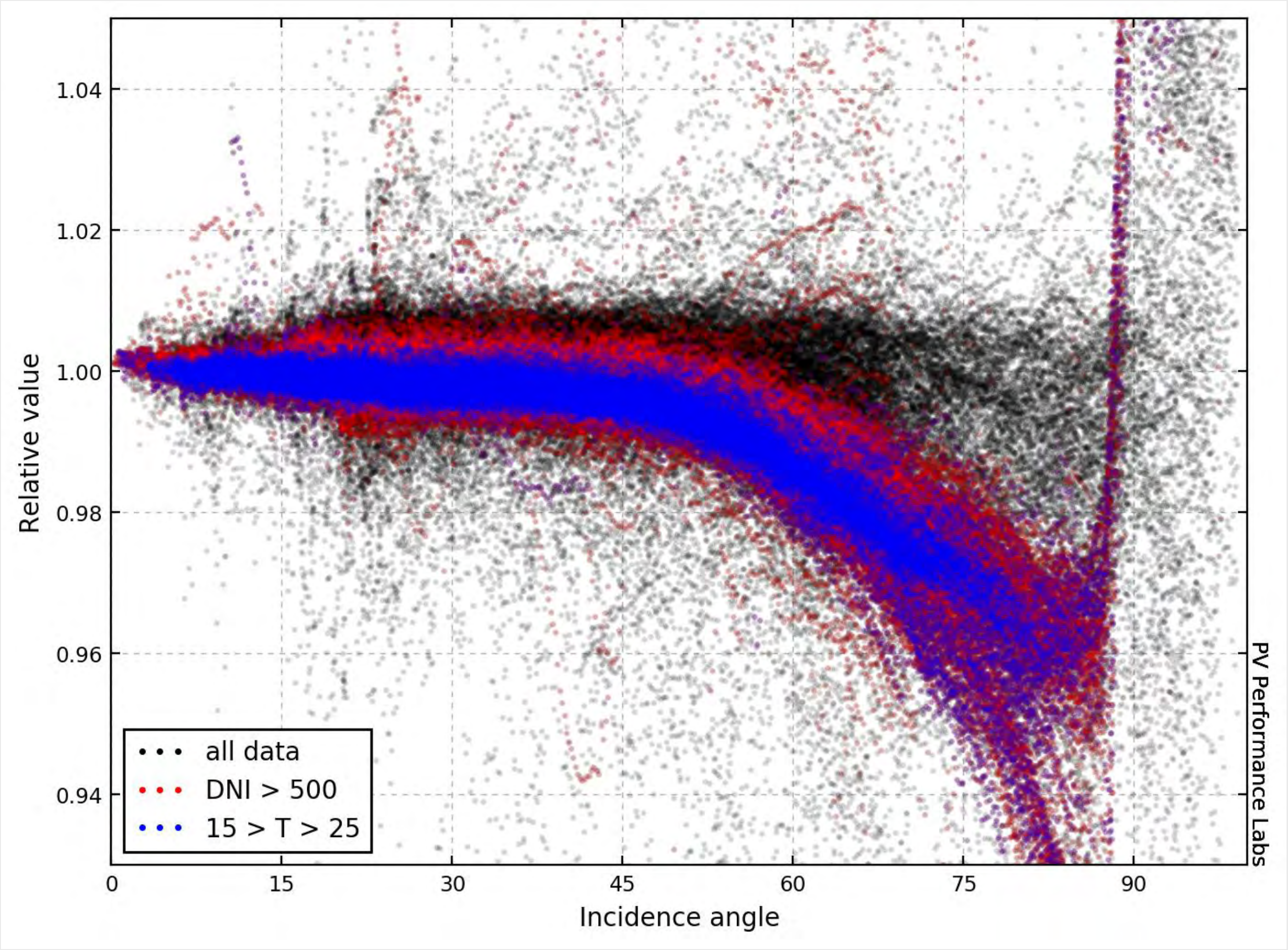
Measurement error vs incidence angle η



Measurement error vs incidence angle



Measurement error vs incidence angle



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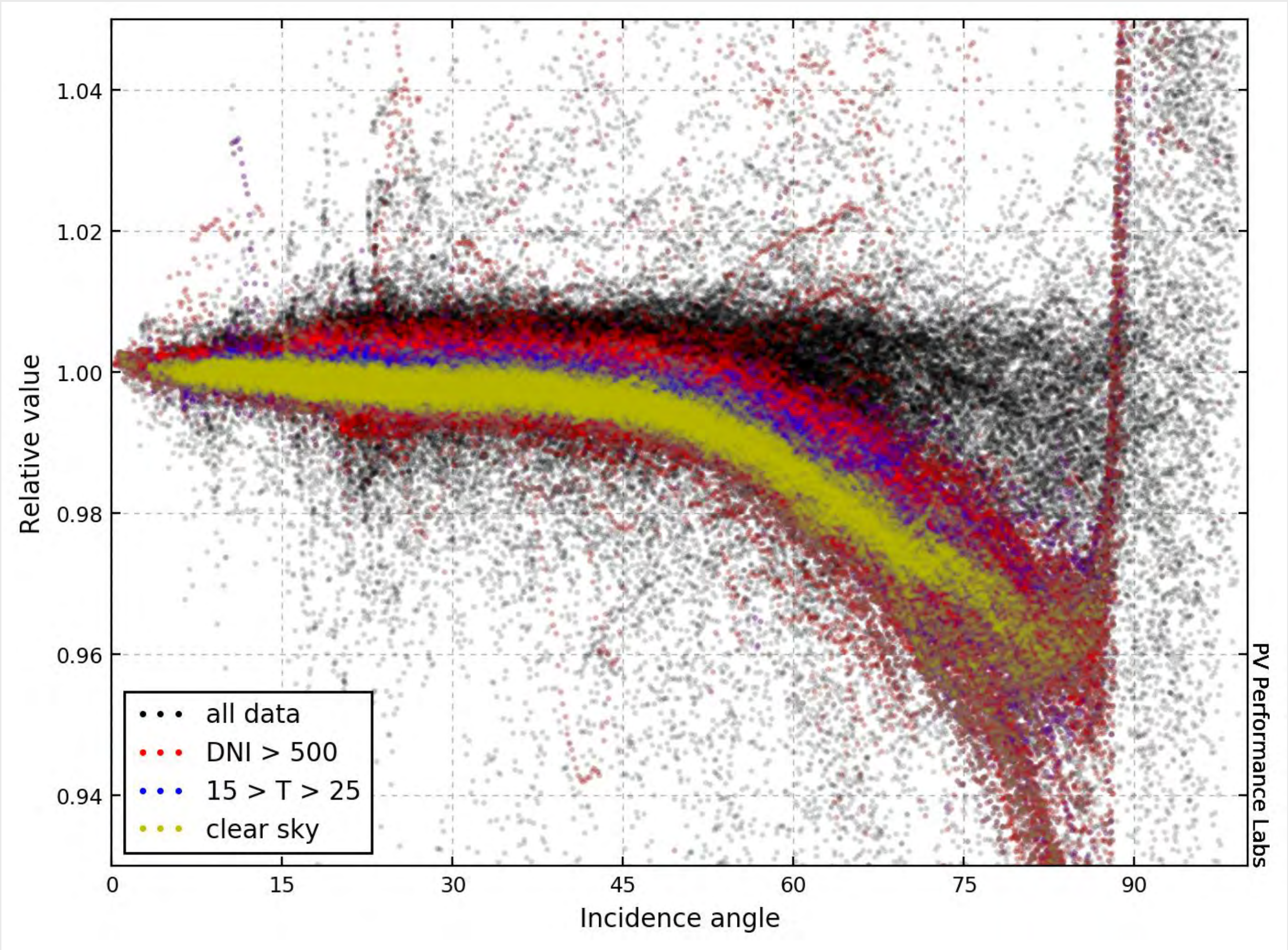

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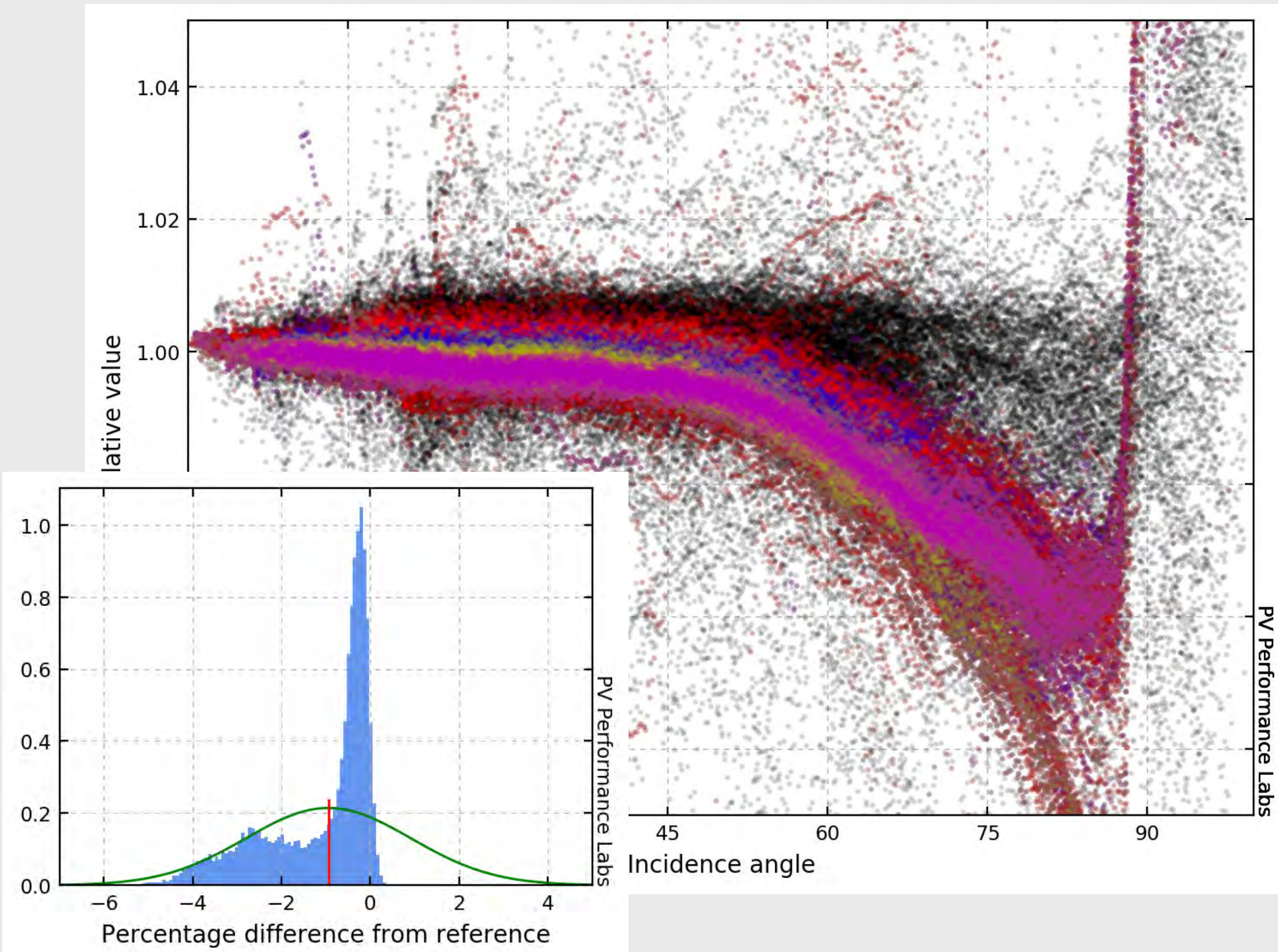


Pyranometer observations

- Systematic errors lead to skewed and non-Gaussian error distributions
- Systematic errors may be specific to
  - Individual instruments
  - Instrument models
  - Instrument categories
- Correlations exist between systematic errors, influencing calculations of total measurement uncertainty

Reference cells

Do reference cells measure effective irradiance?

Effective irradiance

- "Effective irradiance is total plane of array (POA) irradiance adjusted for angle of incidence losses, soiling, and spectral mismatch. In a general sense it can be thought of as the irradiance that is "available" to the PV array for power conversion." [pvpmc.sandia.gov]

$$E_e = \frac{I_{sc}}{I_{sc0}\left\{1 + \alpha_{Isc}\left(T_c - T_0\right)\right\}}$$

- "E_e = The 'effective' solar irradiance as previously defined by Equation (7). This value describes the fraction of the total solar irradiance incident on the module to which the cells inside actually respond." [SAND2004-3535]

- "Ee = 'Effective' irradiance to which the PV cells in the module respond, (dimensionless, or 'suns')" [SAND2004-3535]

Alpha is key

“Hard to measure”

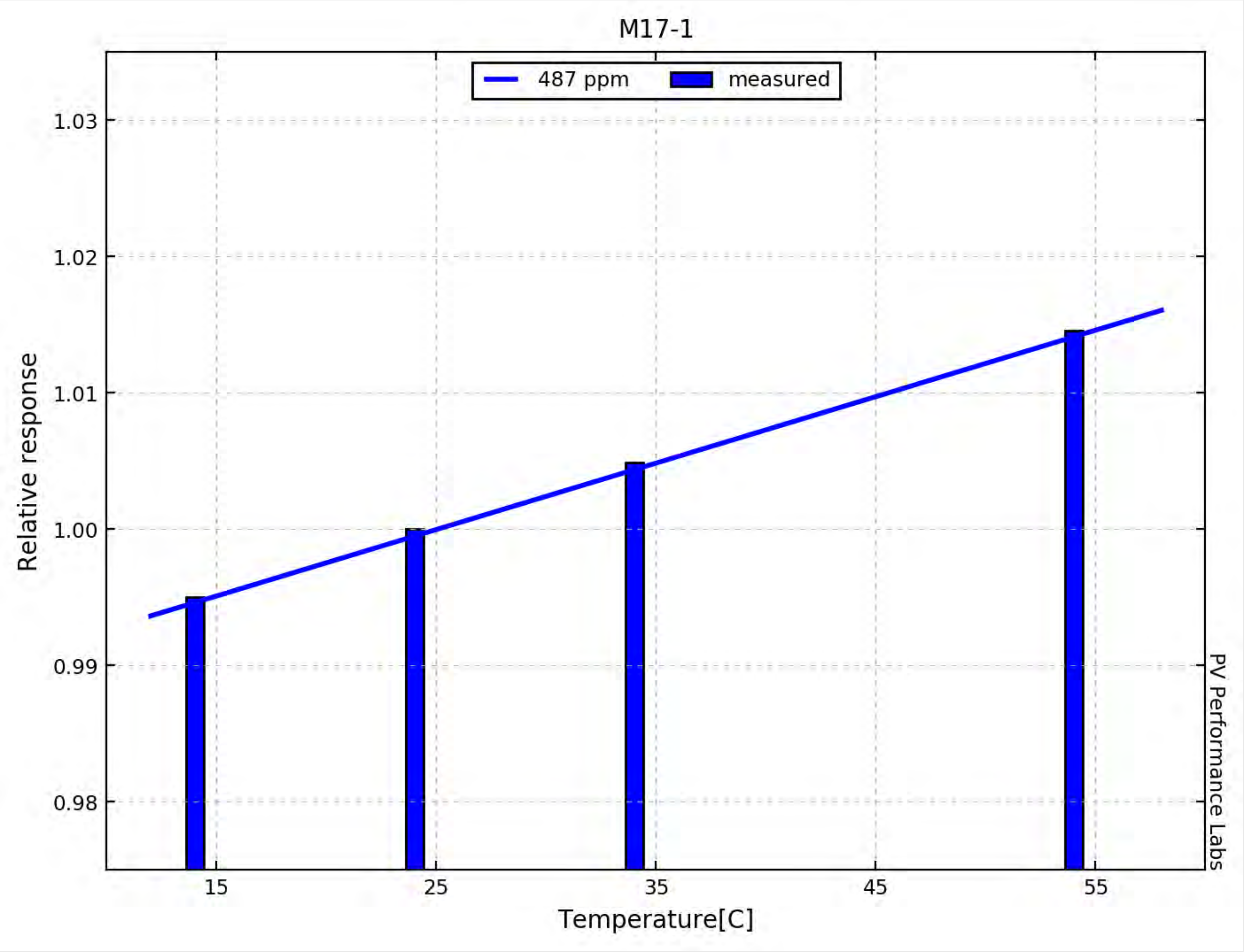
“Large uncertainty”

“Inconsistent results”

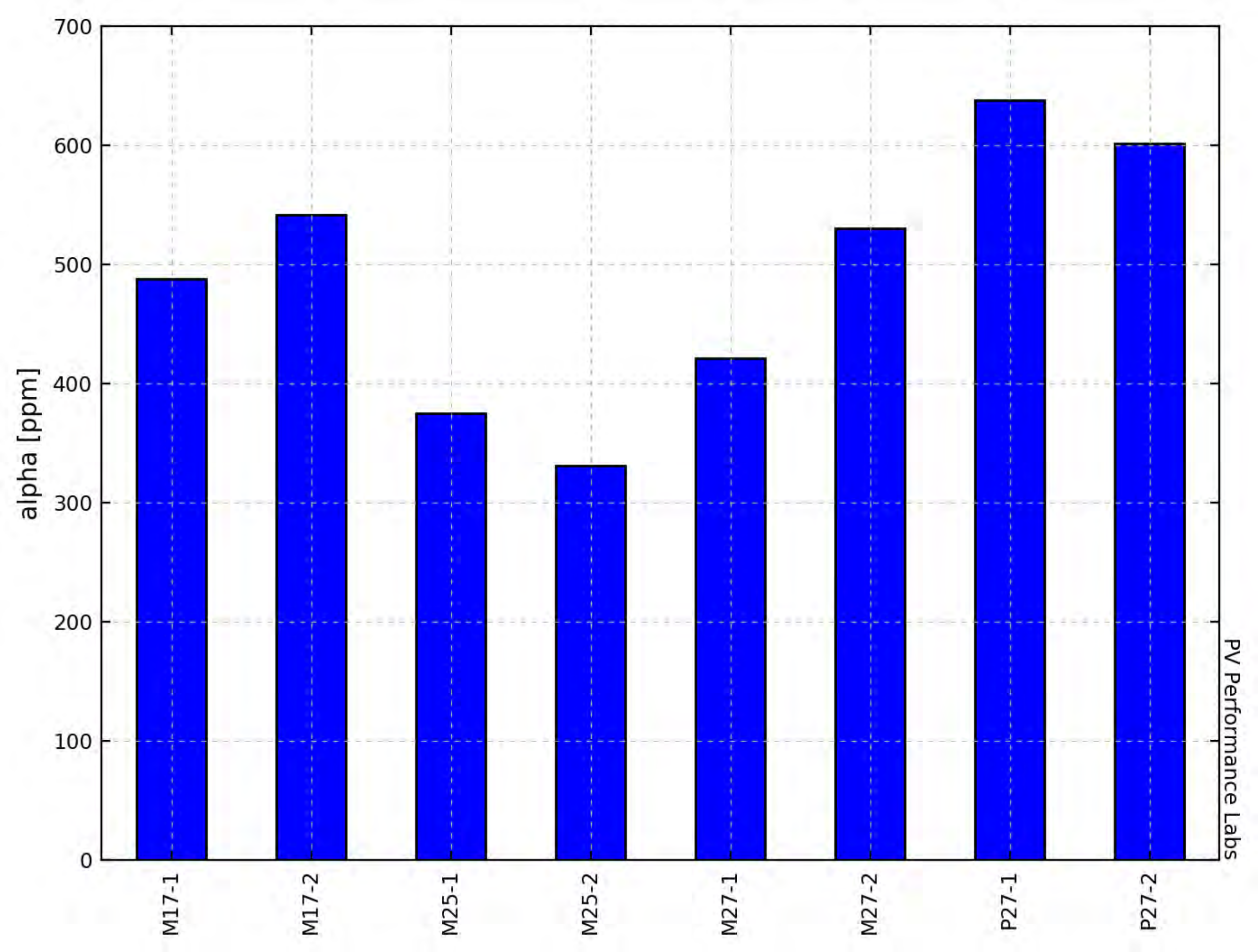
Let’s try it!

4 pairs of custom reference cells

I_{sc} at different temperatures -> alpha

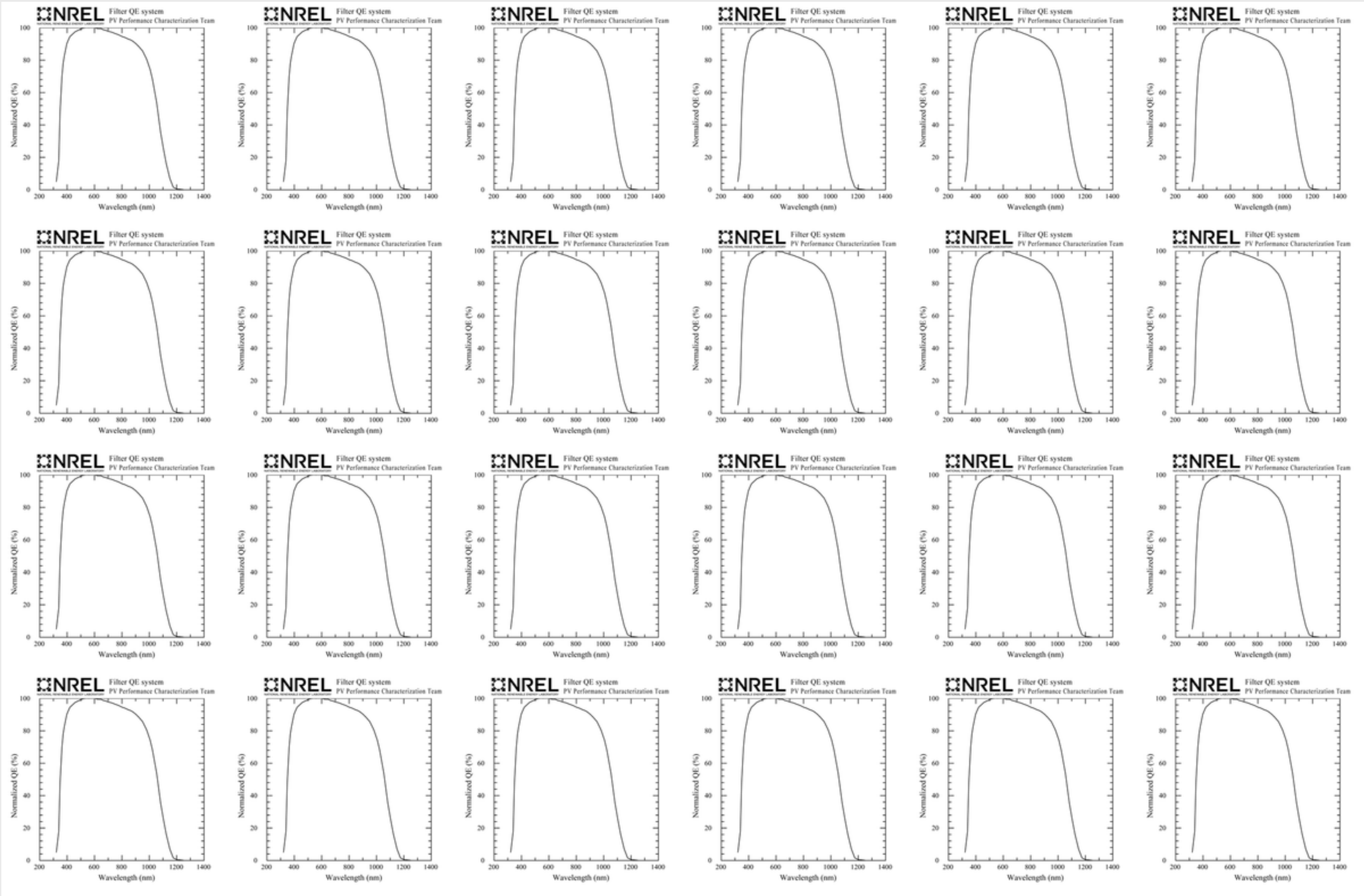


Alpha for 4 pairs of cells

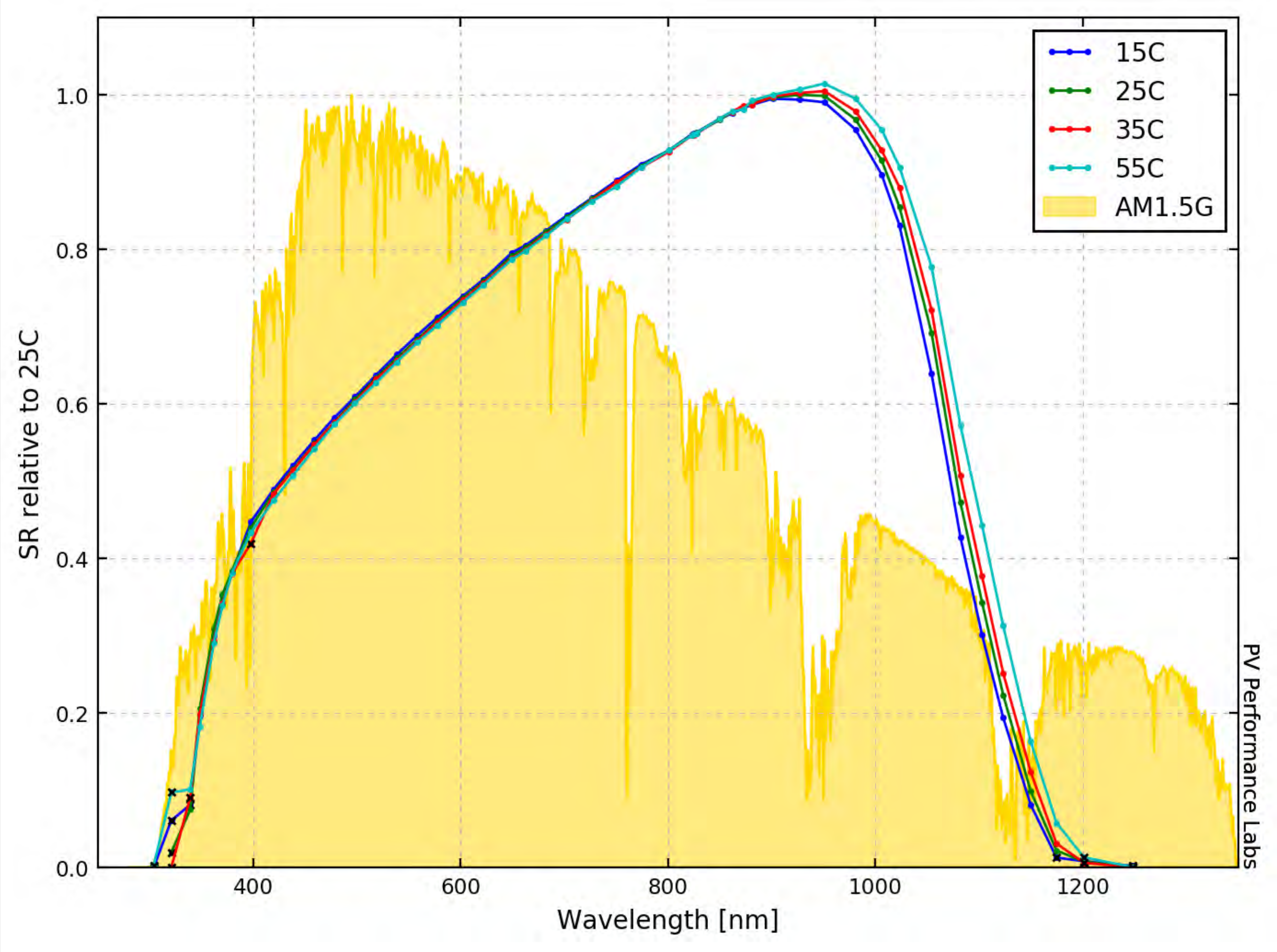


What causes alpha?

SR measurements at 15, 25, 35, 55C



Evolution of the absolute SR



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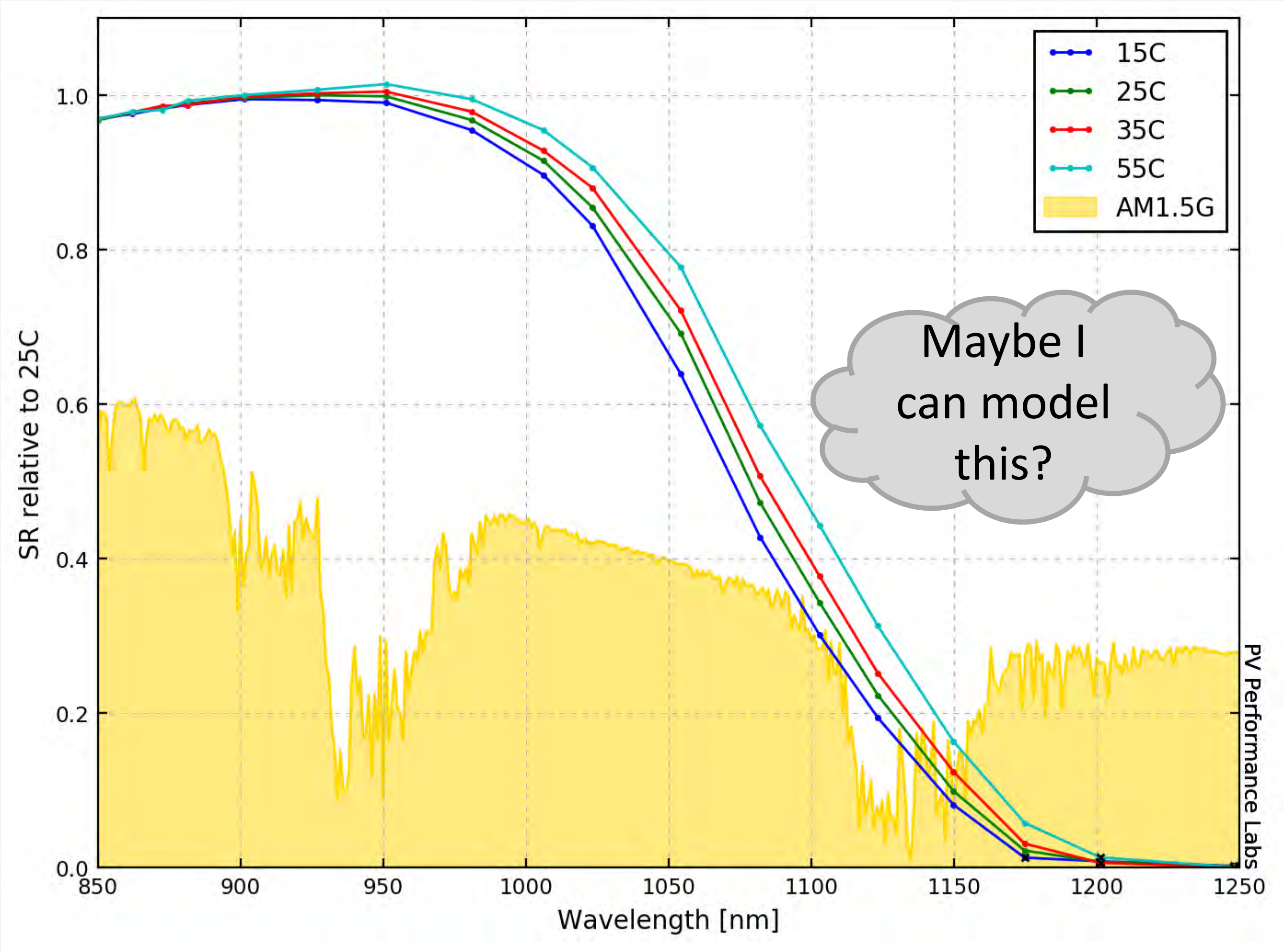
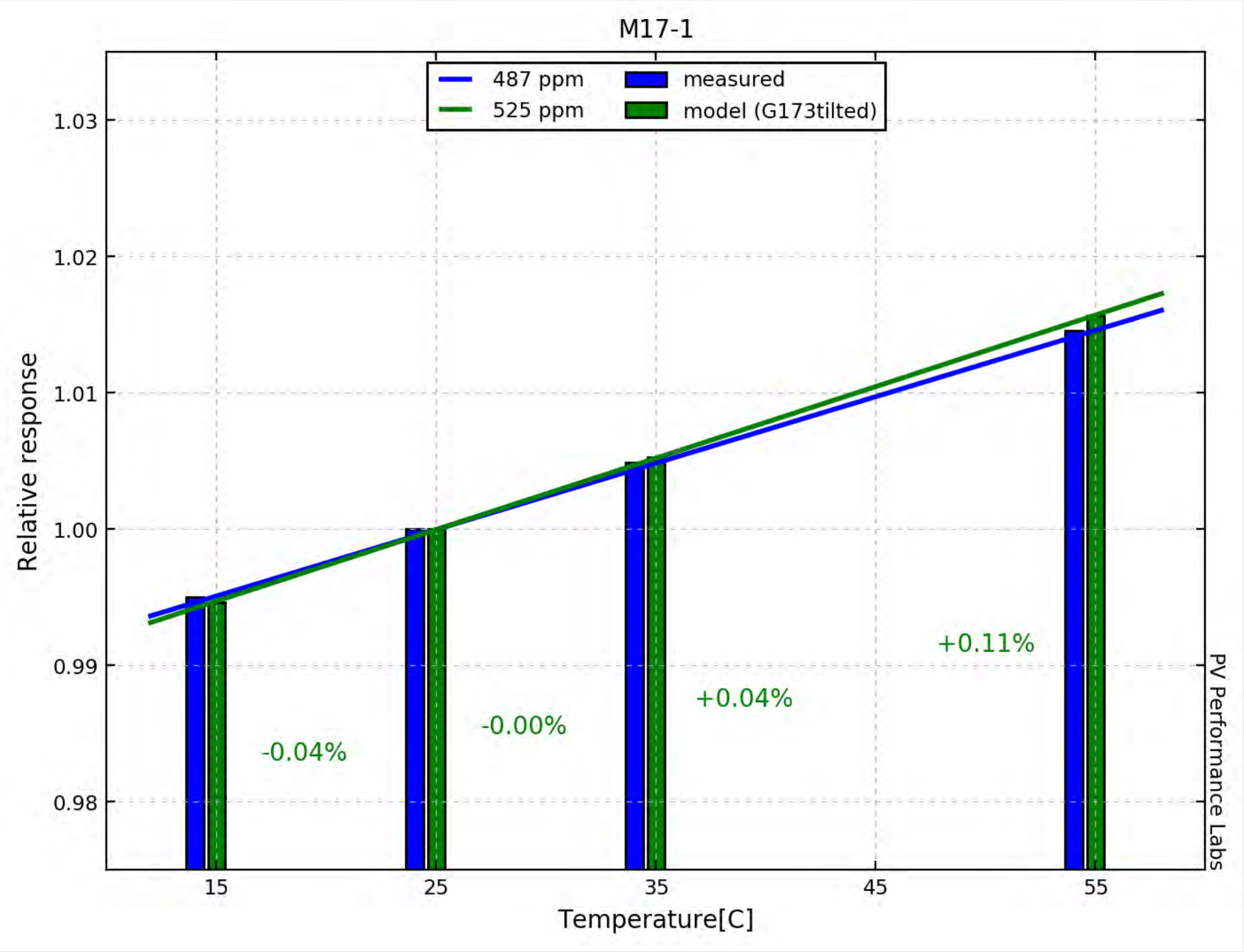
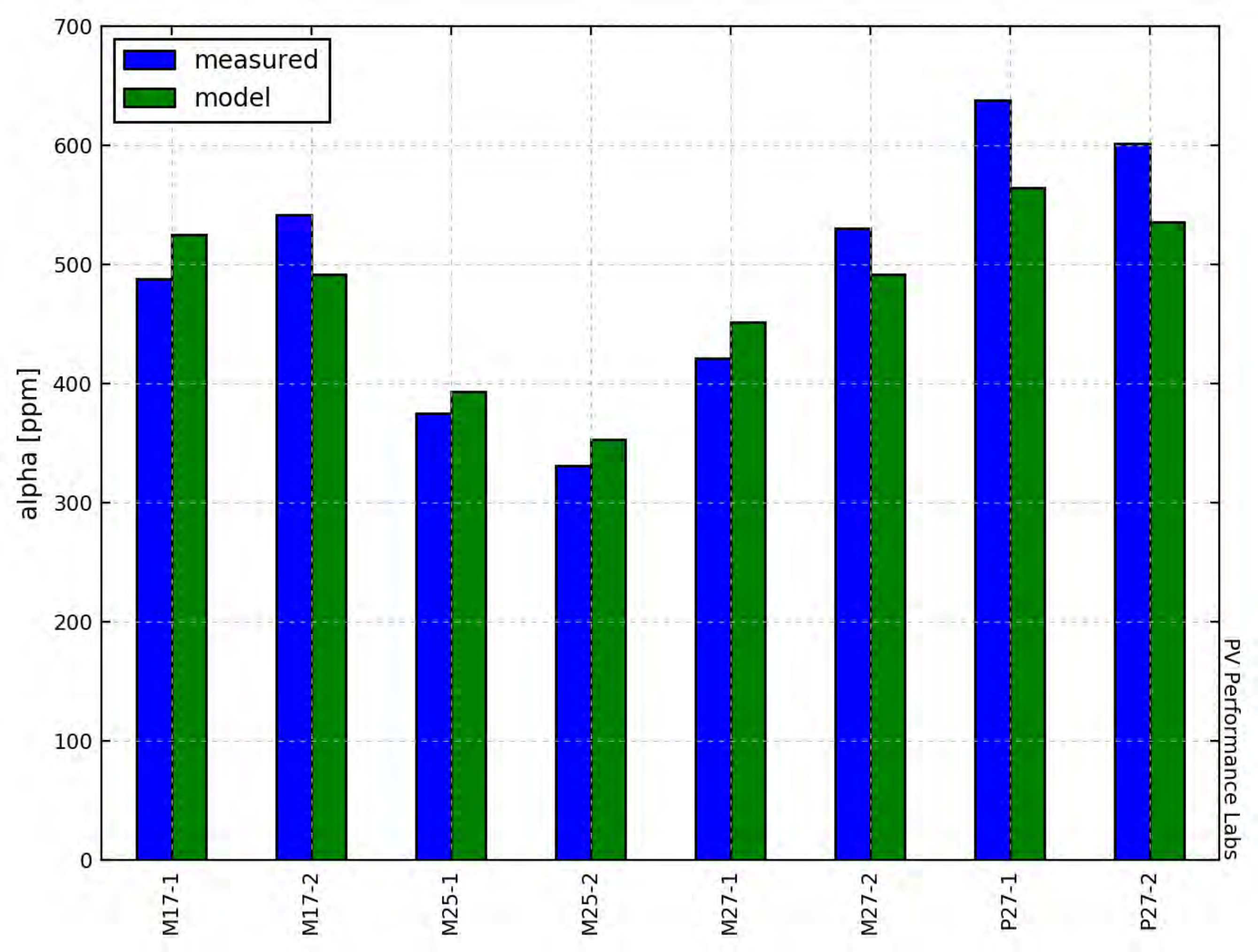


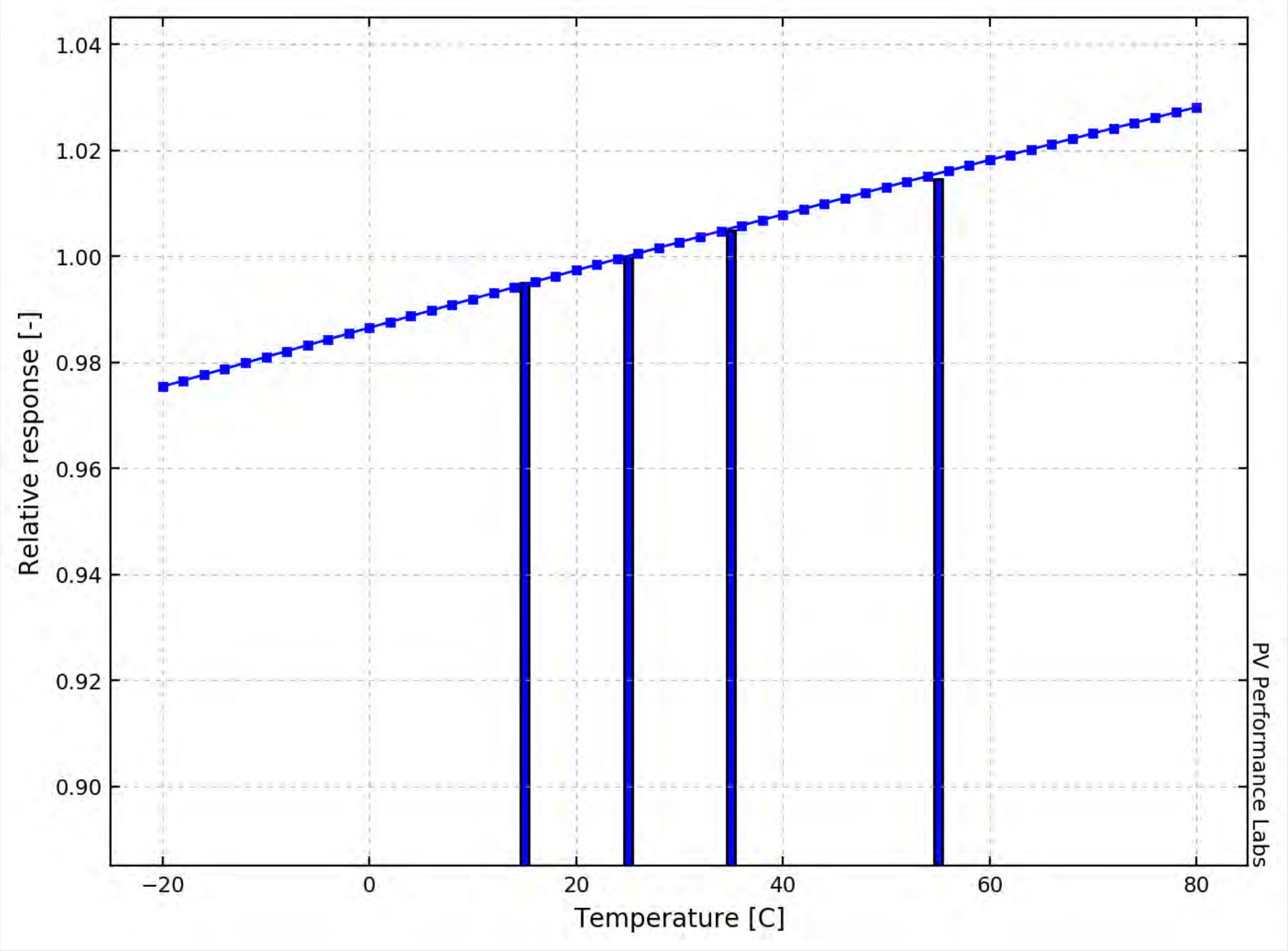
Measured and modeled Isc



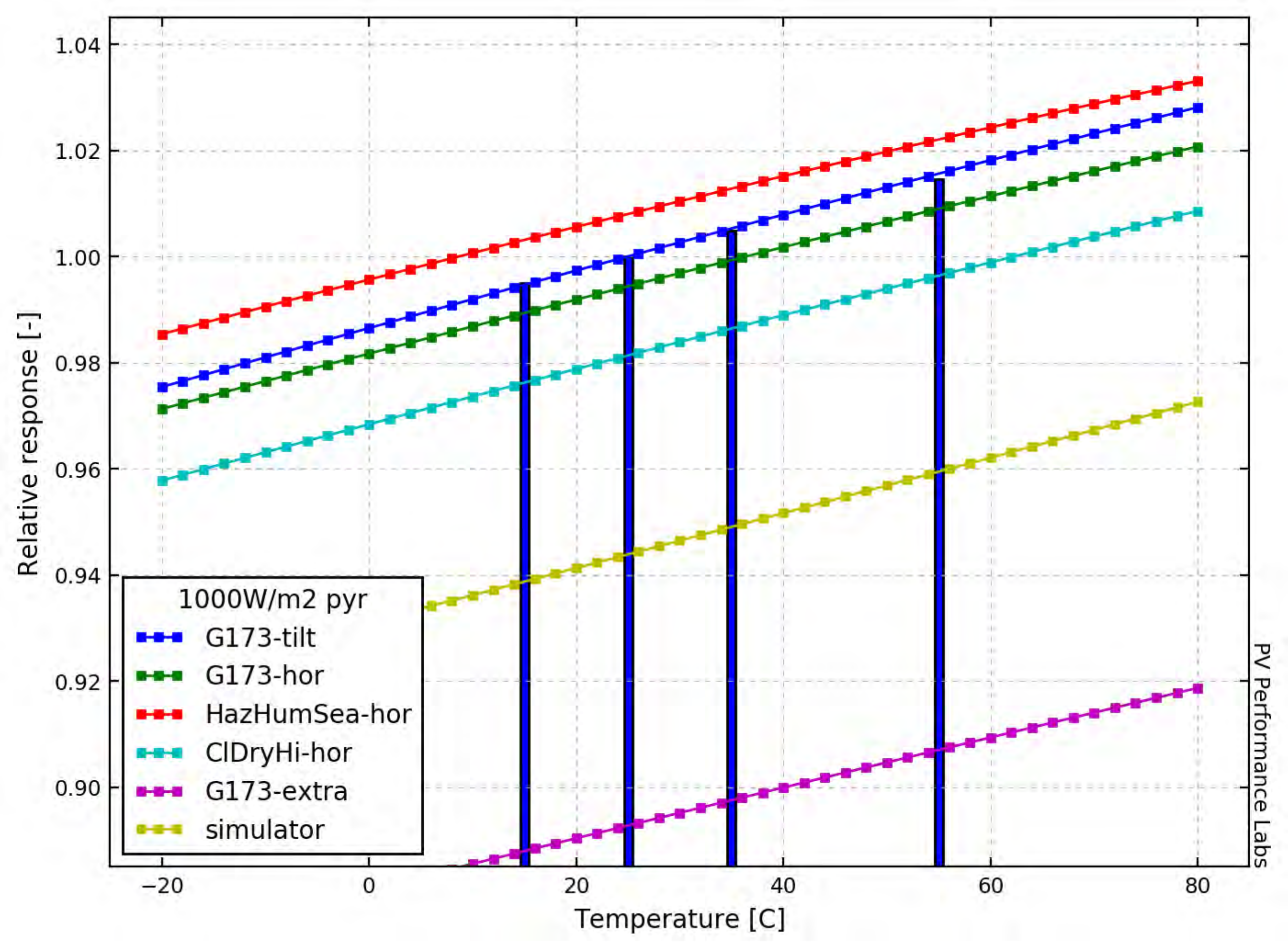
Measured and modeled alpha



Extrapolation using the model



Isc under different spectra



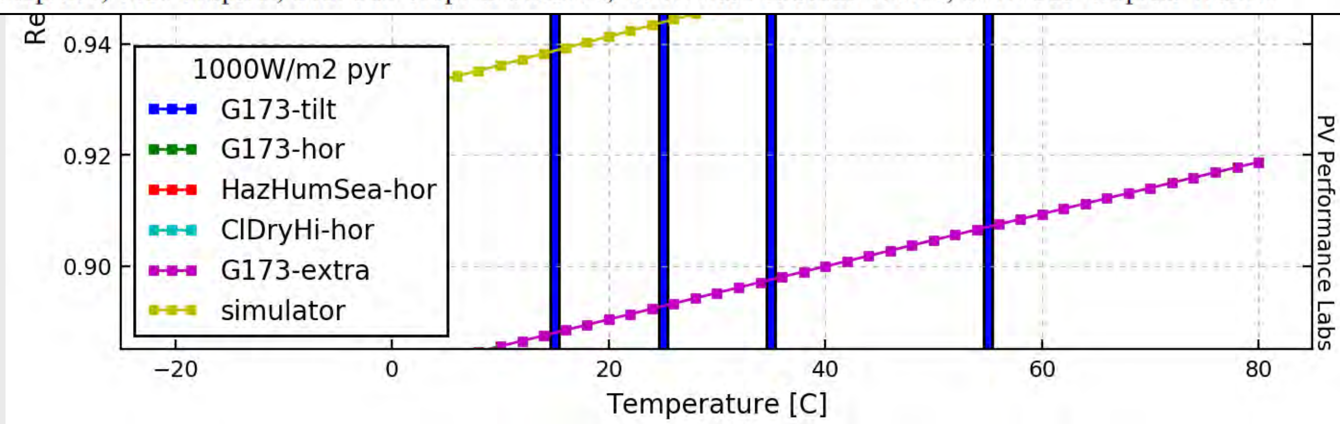
Isc under different spectra

W. Jessen et al. Solar Energy xxx (xxxx) xxx–xxx

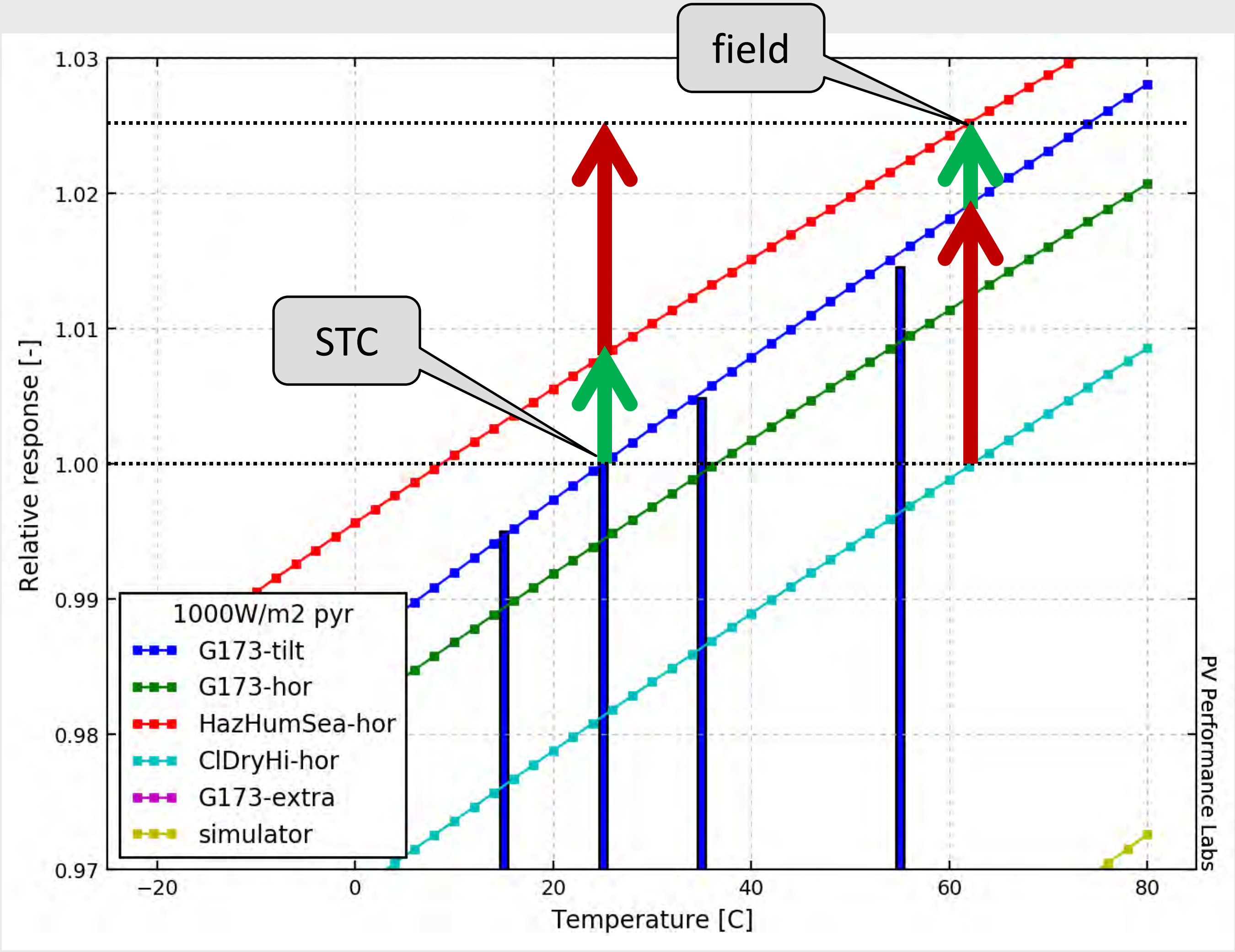
Table 1
Atmospheric conditions (Gueymard et al., 2016) proposed for the creation of the tested and subordinate standard spectra, in addition to the reference values (first row) used in (IEC, 2016).

Short name	Description	Elev. (m)	AOD@500 nm	Aerosol model	PW (cm)	Albedo	Atmosphere/Temperature
IEC 60904	Reference (IEC 60904-3)	0	0.084	RURAL	1.416	Light sandy soil	USSA
SemClMedHum	Semi-clean, medium humidity, sea level	0	0.27	RURAL	1.416	Light sandy soil	USSA
SemClHum	Semi-clean, humid, sea level	0	0.27	RURAL	4.115	Light sandy soil	TRL
HazMedHum	Hazy, medium humidity, sea level	0	0.54	RURAL	1.416	Light sandy soil	USSA
DustyMedHum	Dusty, medium humidity, sea level	0	0.54	DESERT_MAX	1.416	Dune sand	STS
HazHum	Hazy, humid, sea level	0	0.54	RURAL	4.115	Light sandy soil	TRL
ClDryHi	Clean, dry, high elevation	1500	0.084	RURAL	0.708	Light sandy soil	MLW
SemClDryHi	Semi-clean, dry, high elevation	1500	0.27	RURAL	0.708	Light sandy soil	MLW
HazDryHi	Hazy, dry, high elevation	1500	0.54	RURAL	0.708	Light sandy soil	STW

USSA: US Standard Atmosphere, TRL: Tropical, STS: Sub Tropical Summer, MLW: Mild Latitude Winter, STW: Sub Tropical Winter.

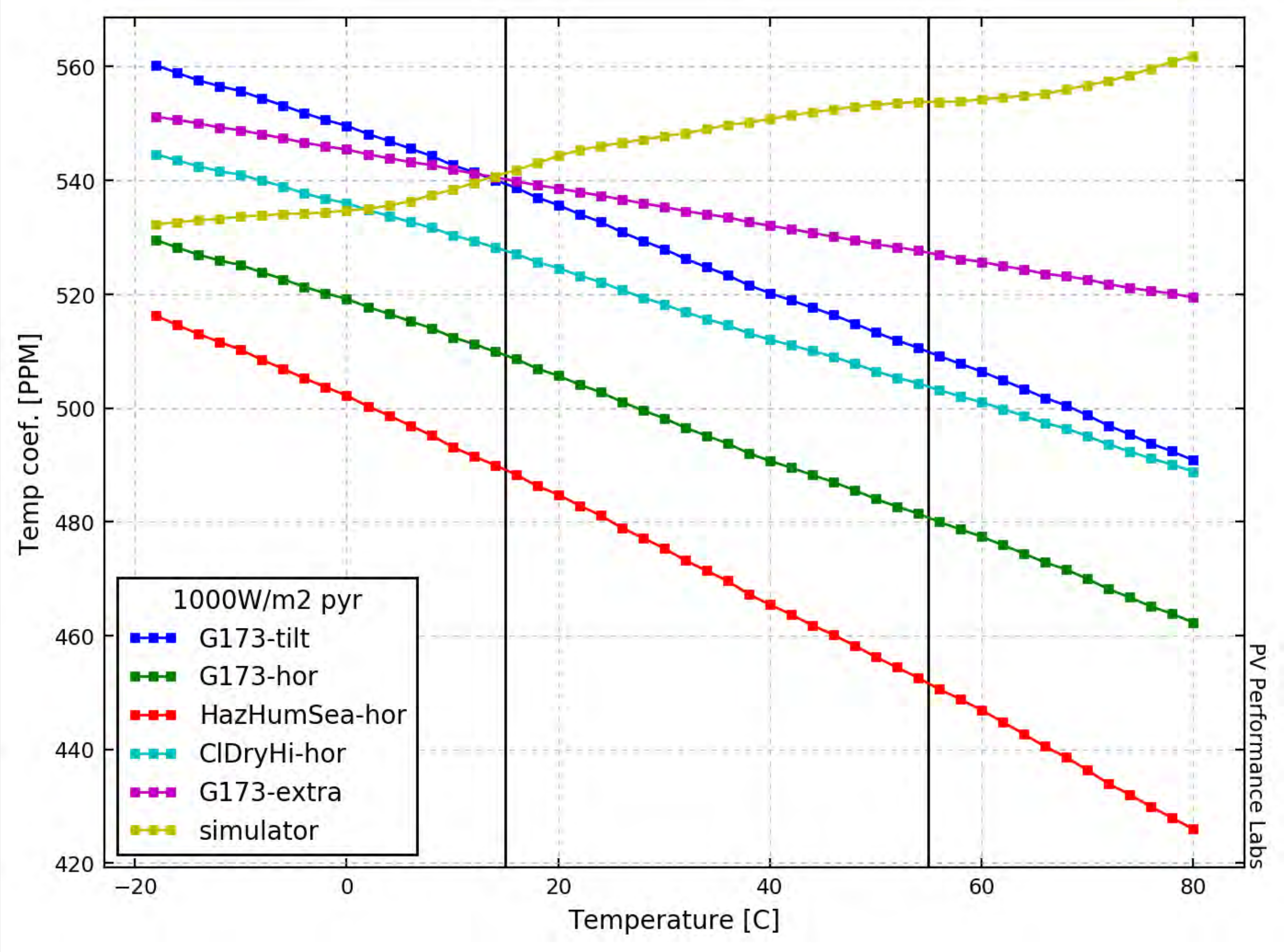


STC vs field conditions



Two ways to separate temperature effects (red arrows) and spectral (green)

Alpha under different spectra



Reference cell observations

- The observed ***alpha*** is primarily the result of a change in spectral response with cell temperature
- Measured Isc depends on both cell spectral response and spectrum, ergo ***alpha*** does too
- In the field, temperature and spectral effects cannot be completely separated
- The best spectral match is obtained when a reference cell and PV array operate at the same temperature

Final slide

To understand what your sensor is really telling you:

- know how your sensor works
- consider the context in which your sensor measured
- don’t believe everything it says

This is a workshop so let’s discuss!