Accurate module performance characterisation using novel outdoor matrix methods

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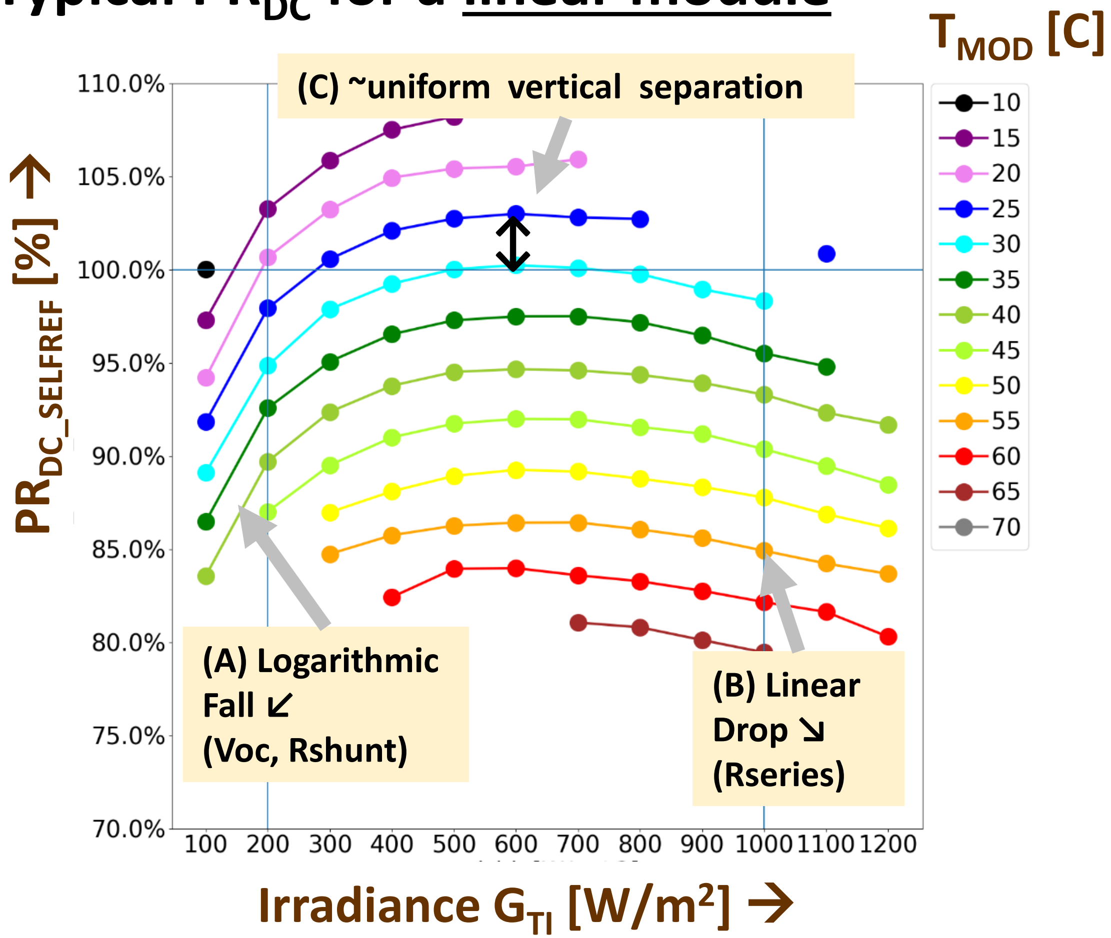
PVSC 48 : 23rd Jun 2021

8D: Characterization and Monitoring of Modules and Systems 4:15 PM eastern time.

How linearly do PV modules behave?

Typical PR_{DC} for a linear module



A module that behaves linearly can be fitted just by functions of irradiance G or temperature T independently

$PR_{DC} = f(G) + f(T)$

i.e. without any "f(G,T) non_linear terms"

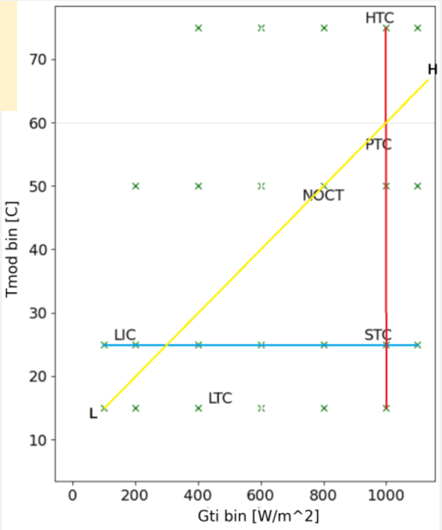
1. Do modules perform linearly?
2. If there are non-linearities, what causes them and how non-linear are they?
3. How can we best model them?

Measuring matrices of $PR_{DC}(G,T)$

$PR_{DC} = P_{MP\_MEAS}/P_{MP\_REF}/G_{SUNS}$

(A) INDOOR (IEC 61853:2011-2018)

(1) IEC 61853
23 point (G,T) Matrix



Temperature Coefficients up to 4 T values ↕

PR_{DC} vs. irradiance Up to 5 G values ↔

Specifies 23 points – could reduce costs with fewer e.g. 6
- → Gives worse modelling accuracy
- → Poorer fitting with inter/extrapolation from only 6 points.
- → No understanding of non linearities

COSTS :
Indoor Matrix ~ \$2800/€2300 + \$700/€580 for AOI

Outdoor measurements :

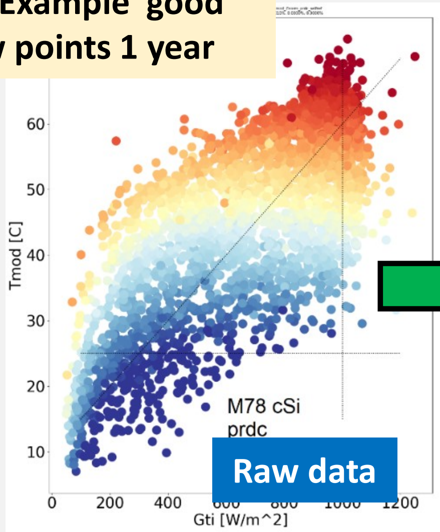
1. Cheaper than indoor ?
2. More matrix bins better for coefficient extraction
3. Quick results with insulation/heating, mesh cover, 2D mistrack

(B) OUTDOOR (GI OTF, Tempe AZ)

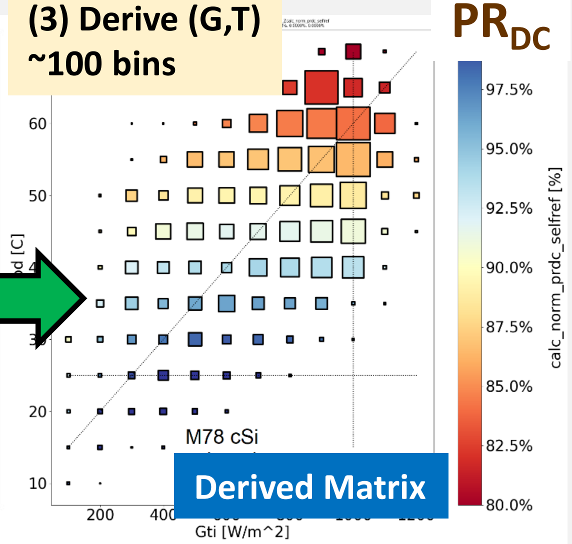
From IV curves or P_{MPP} with real weather
- → 260k measurements/year (if every 1m)
- → Needs data sanitizing and filtering
- → Can give ~100 matrix points (G=100W/m²,T=5C bins)
- → Better analysis possible e.g. any non linearities

COSTS:
Outdoor /module \$1000/6 months with spectral, AOI

(2) Example good raw points 1 year



(3) Derive (G,T) ~100 bins



All measurement data is from Gantner Instruments' OTF Solutions Tempe, AZ

Further info in published paper, otf@gantner-instruments.com or email authors

PV Module Measurements:

Fixed and 2D track; IV curve every minute, all environmental sensors, spectral parameters
PV Module Power up to 500W/800W
High quality digitalization, current accuracy 0.1% FS, voltage: 0.05% FS
Scalable system (4 .. 48 channels) with raw data access
Local or cloud-based data streaming
Derived parameters using Loss Factors and Mechanistic Performance Models
Integrated Python Jupyter Lab for direct analysis and automatic reporting

Continuous measurements in Arizona since 2010; Other sites available around the world

Trusted by leading PV Module manufacturers, Technology providers and Research Labs

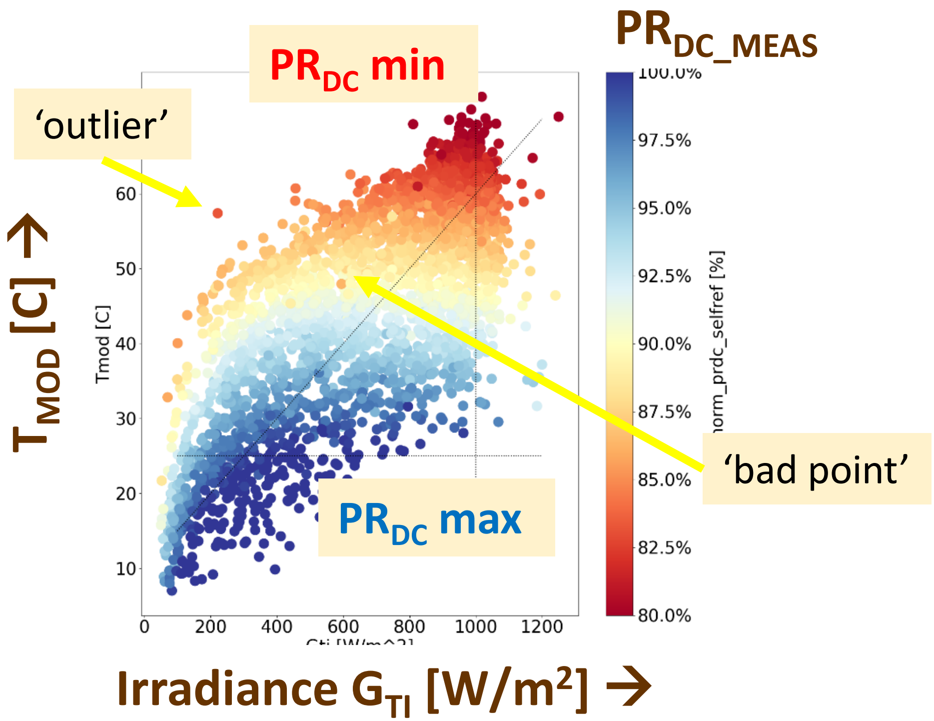
GI OTF MEASUREMENTS

Name	Description	Units
G_H	Global Horizontal Irradiance	kW/m²
D_H	Diffuse Horizontal Irradiance	kW/m²
B_N	Beam Normal Irradiance	kW/m²
G_I	Global Inclined Irradiance (Pyranometers and c-Si ref cells)	kW/m²
T_{AMB}	Ambient Temperature	C
T_{MOD}	Back of Module Temperatures	C
WS	Wind Speed	ms^{-1}
WD	Wind Direction	°
RH	Relative Humidity	%
G(λ)	Spectral Irradiance G(350– 1050nm)	W/m²/nm

How to generate dense performance matrices from good outdoor data 1/3

A) Raw $PR_{DC}(G,T)$

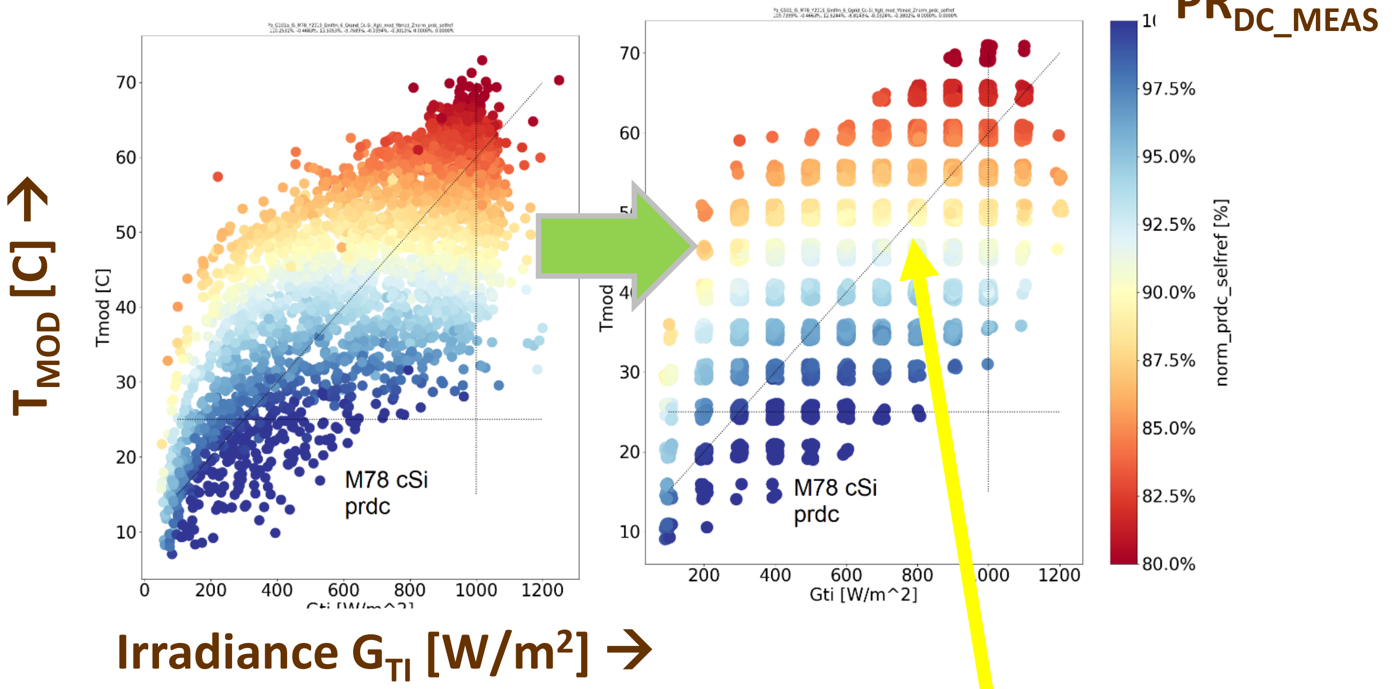
Good points 1 year random 4000 shown



How to generate dense matrix points?

How to generate dense performance matrices from good outdoor data 2/3

A) Raw $PR_{DC}(G,T)$	B) Filter into (G,T) bins
Good points 1 year random 4000 shown	Filter by steady weather, Sanity check e.g. 3sigma, Group into (G,T) bins

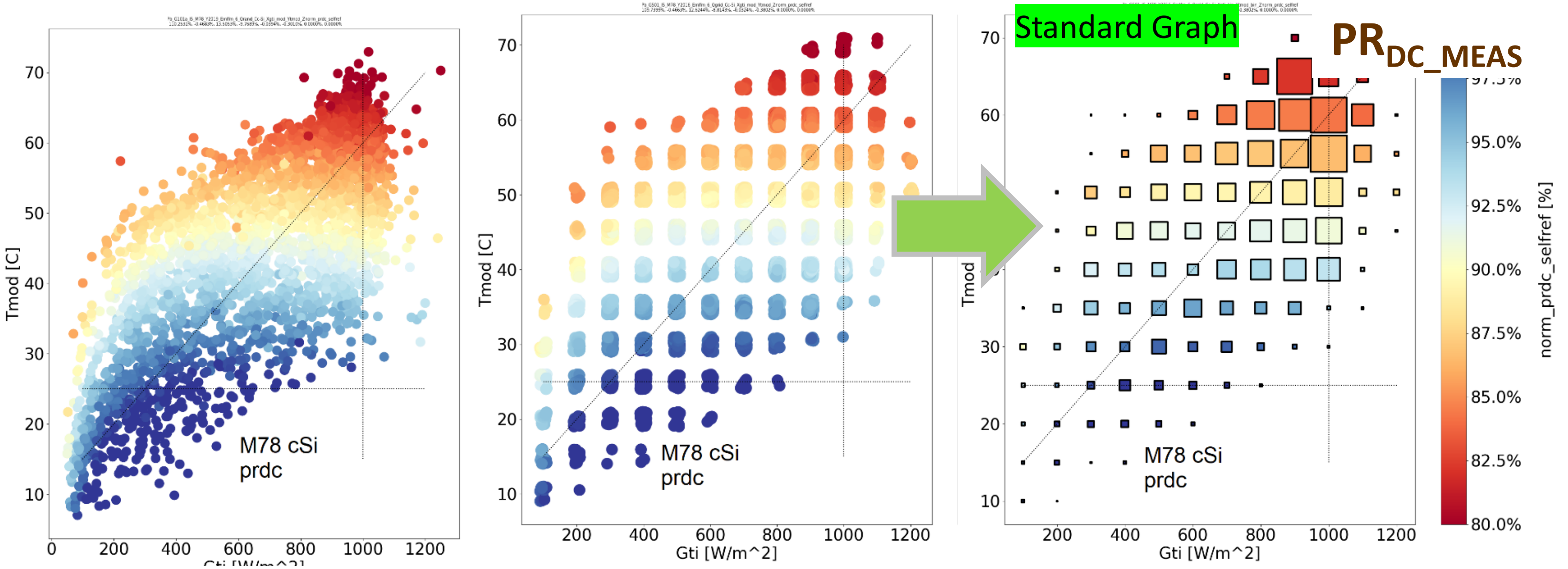


Uniform colour bins prove good non-scattered data

How to generate dense performance matrices from good outdoor data 3/3

A) Raw PR_{DC}(G,T)	B) Filter into (G,T) bins	C) Average, sum per (G,T) bin
Good points 1 year random 4000 shown	Filter by steady weather, Sanity check e.g. 3sigma, Group into (G,T) bins	Colour = Avg(PR_{DC}) /bin Area = Σ(H kWh/m^2) /bin

T_{MOD} [C] →

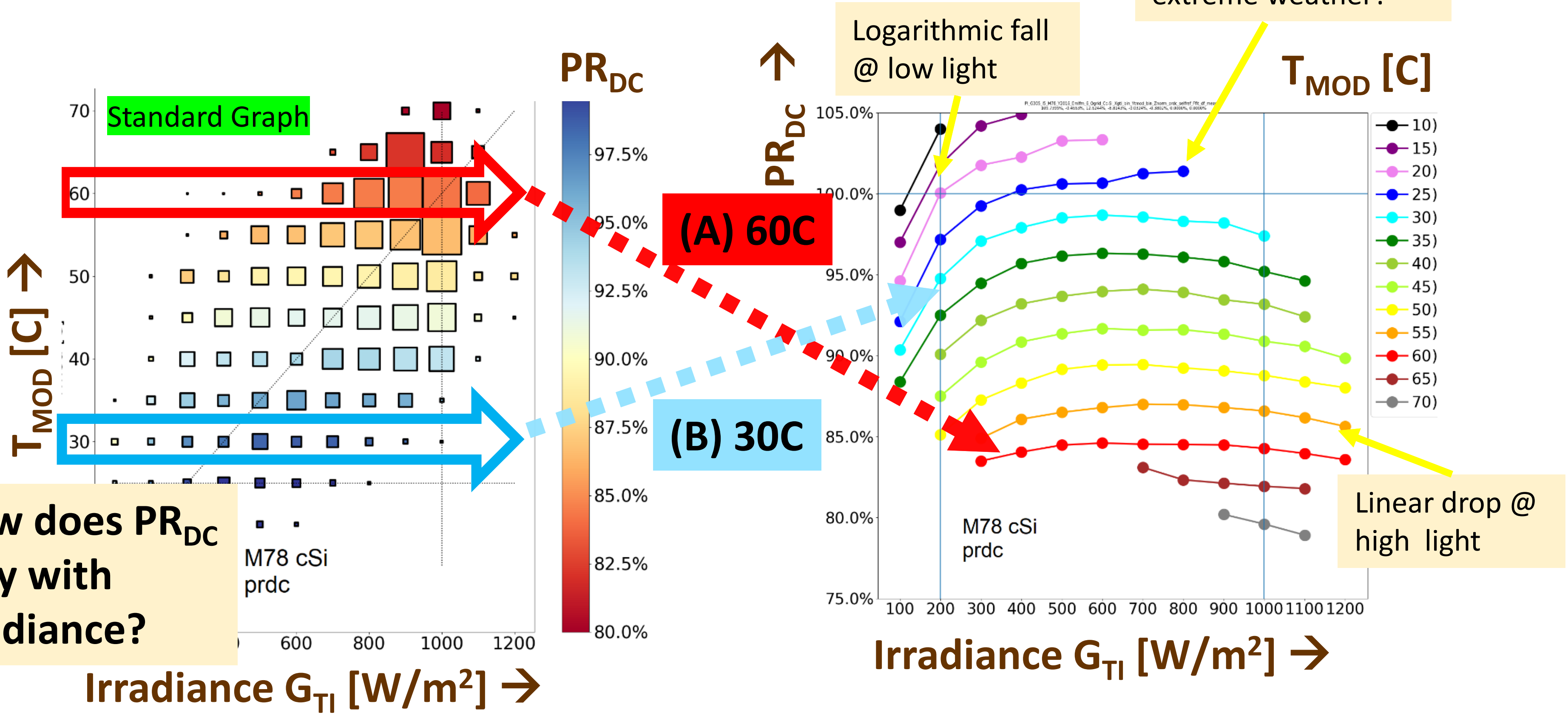


Irradiance G_{TI} [W/m^2] →

Useful standard graph format to be used often showing Performance (colour), Insolation (area) vs. Irradiance→ and Tmodule↑ bins

Generated accurate dense measurement matrix with ~100 useful points

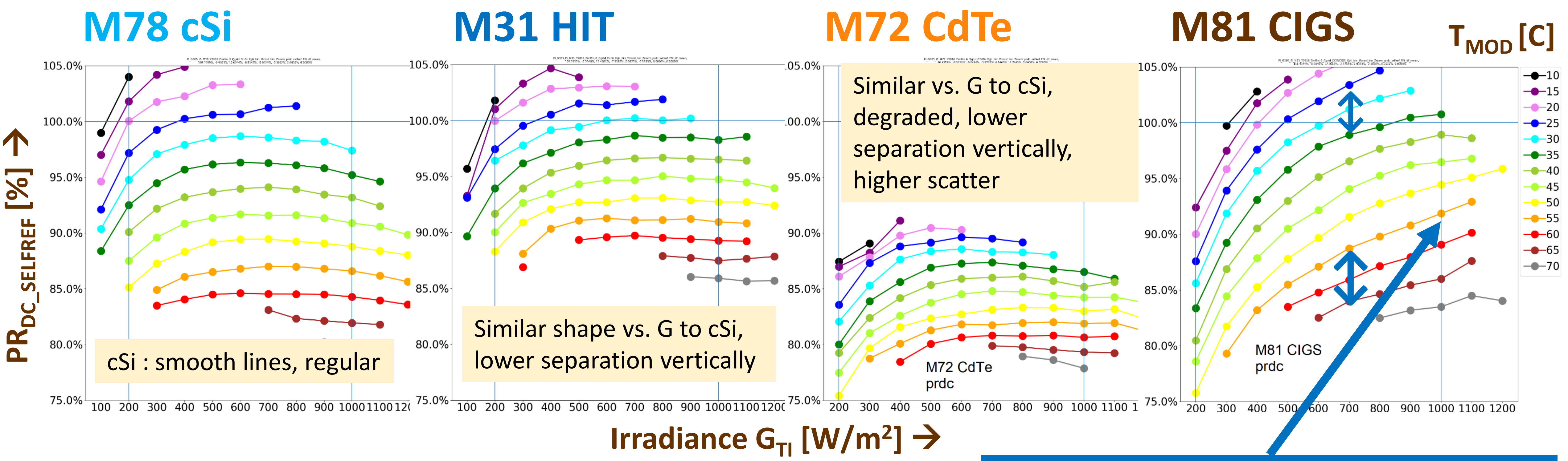
‘PR_{DC} vs. irradiance’ from outdoor matrix



How does PR_{DC} vary with irradiance?

Smooth plots can be generated from good quality outdoor measurements which allow accurate characterisation

‘PR_{DC} vs. irradiance’ for four technologies

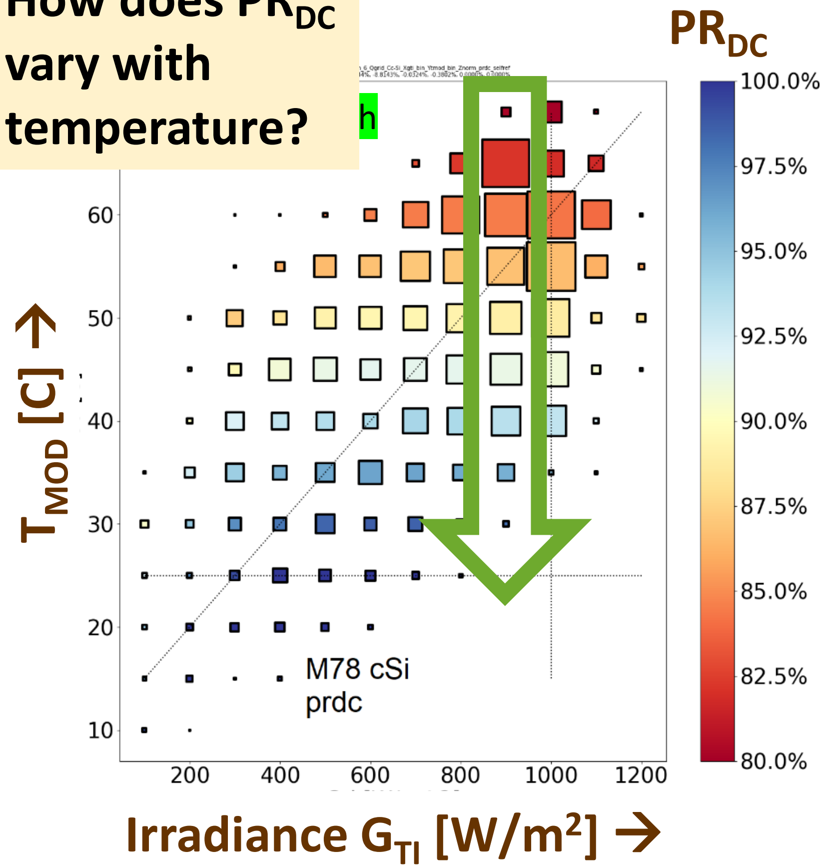


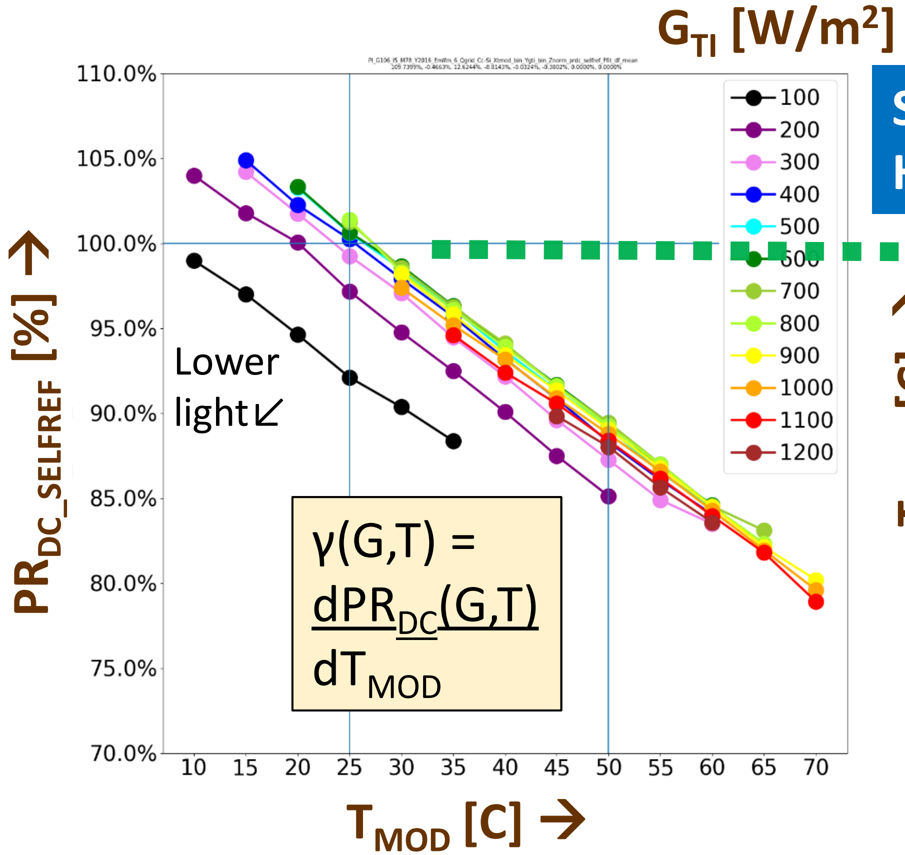
cSi, HIT and CdTe look quite linear over the matrix area
(Extreme weather points may have a little scatter)

This CIGS has a different shape
rising PR_{DC} at high G and larger gamma separation↕ at high temperatures which indicates non-linearity

'PR$_{DC}$ vs. Temperature' from outdoor matrix

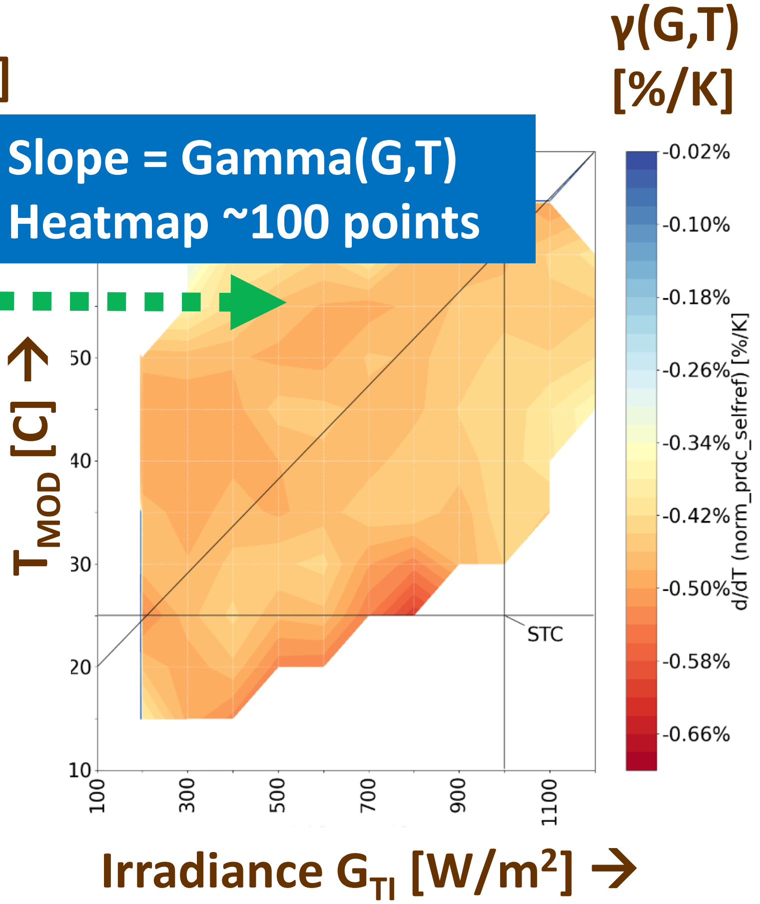
How does PR$_{DC}$ vary with temperature?





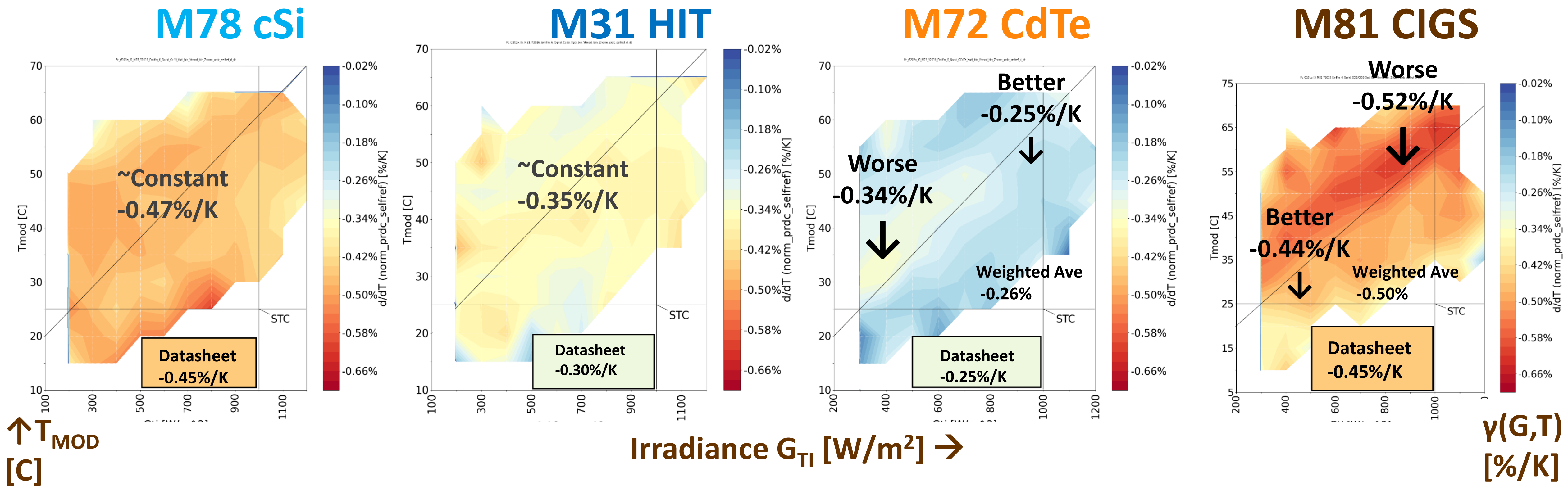
$\gamma(G,T) = \frac{dPR_{DC}(G,T)}{dT_{MOD}}$

Slope = Gamma(G,T)
Heatmap ~100 points



Datasheets usually report 1 constant gamma value
This plot will quantify any non-linear behaviour

Gamma(G,T) heatmaps for four modules



cSi, HIT : ~constant γ(G,T)

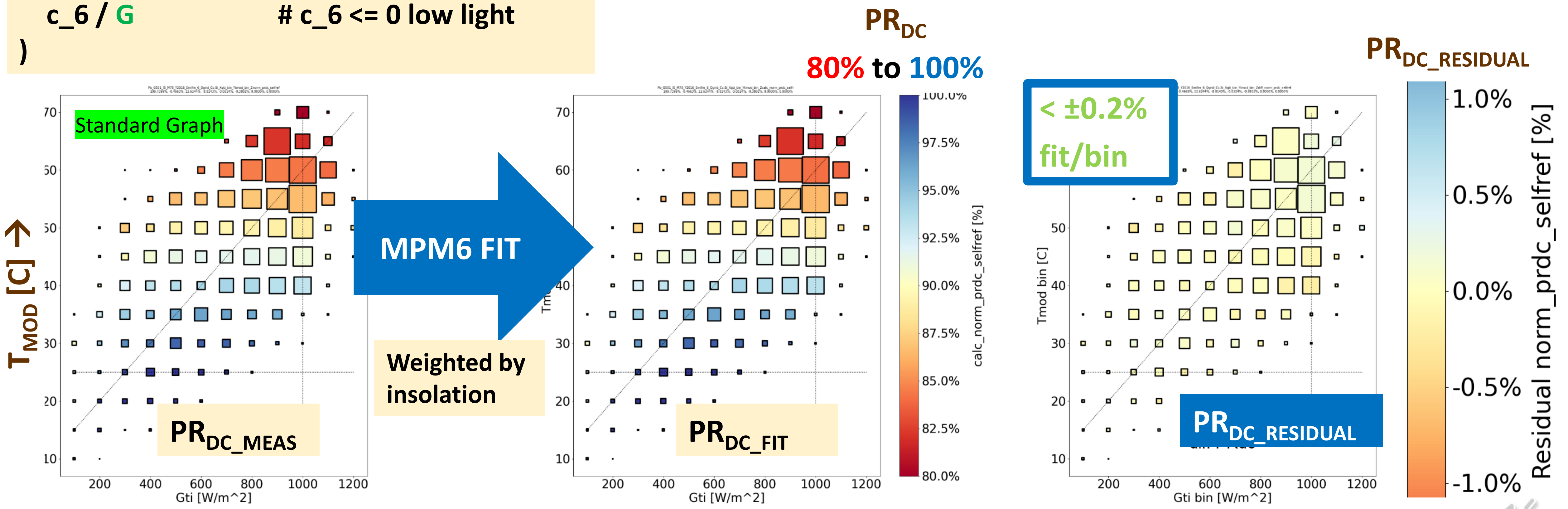
→ "A constant temperature coefficient means a linear device"

CdTe, CIGS : can have <u>Non-linear temperature coefficients</u> which will affect $PR_{DC}(G,T)$

1st Pass : Fitting performance matrices with a linear model (mpm6)

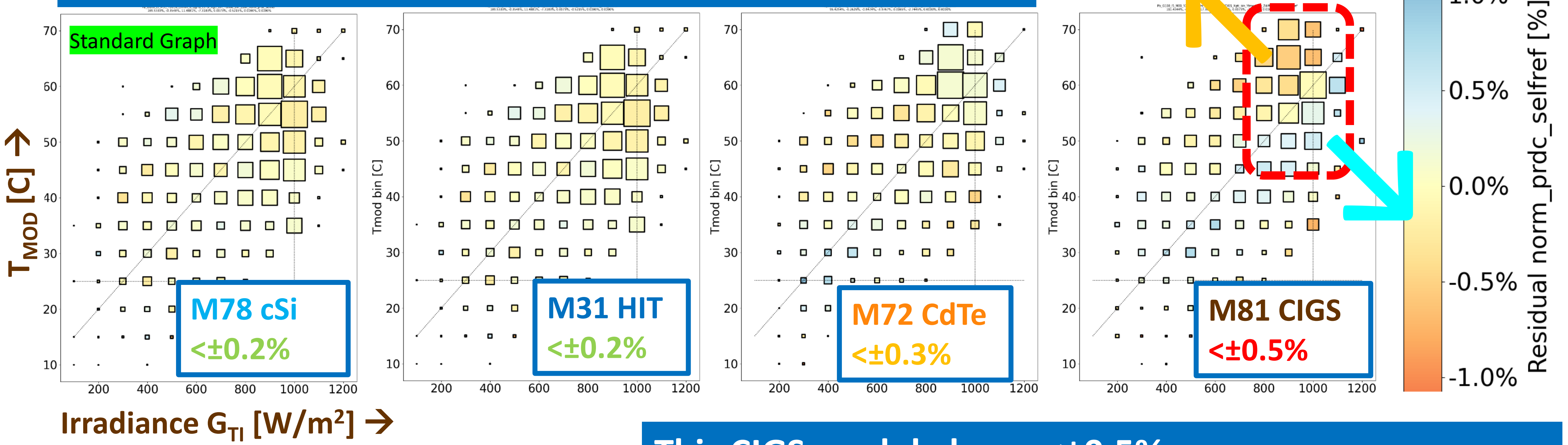
```
def mpm_6(G, dT, WS) = (
    c_1 +              # constant
    c_2 * dT +         # temp. coeff
    c_3 * log10(G) +   # low light ~Voc, Rshunt
    c_4 * G +          # high light ~Rseries
    c_5 * WS +         # windspeed ~0
    c_6 / G            # c_6 <= 0 low light
)
```

MPM6 is a linear model :
(each coefficient is only a function of G , T or WS)
G = irradiance [kW/m^2] ;
dT = delta temperature (Tmod – 25) [C] ;
WS = windspeed [ms^{-1}]



Typical outdoor linear model residual fit error $PR_{DC(MEAS-FIT)}$ four modules

cSi, HIT, CdTe :
Fit very well (because they are linear)

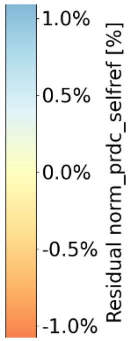


This CIGS module has a <±0.5%
Monotonic residual error between
high ↔ low temperature indicating a Non-linearity
(as expected from the gamma heatmap)

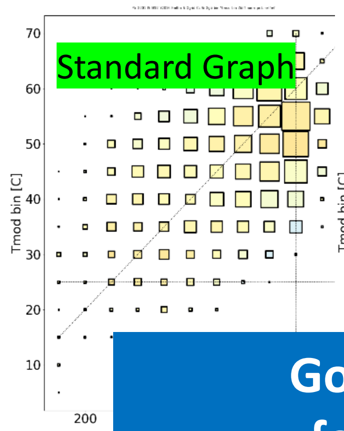
Gantner instruments
www.steveransome.com
SRCL Steve Ransome Consulting Limited

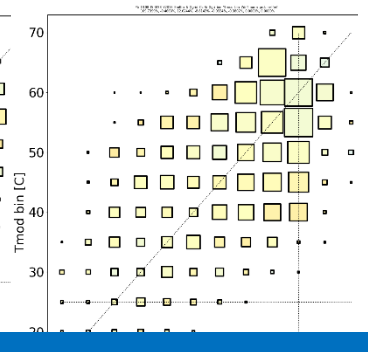
Many more modules were studied linear mpm6 residual fit error

$PR_{DC\_RESIDUAL}$ -1% to +1%

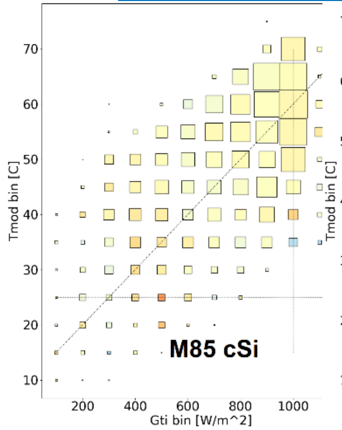


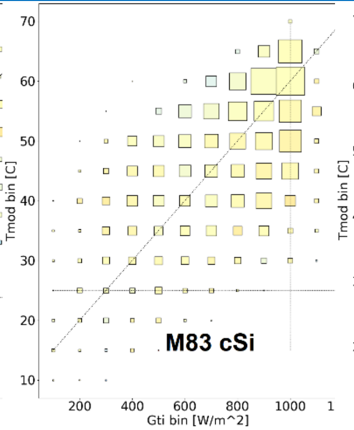
5 × cSi

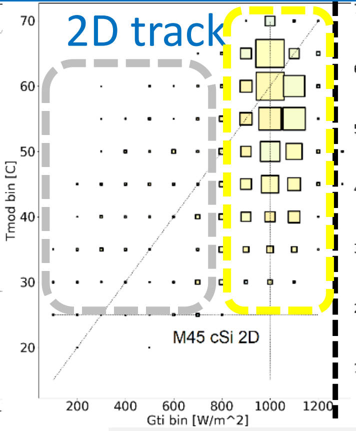




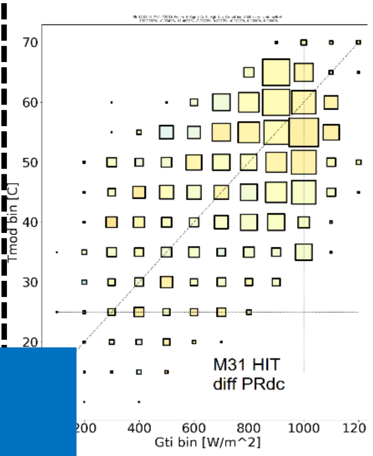
Good fits $PR_{DC}(G,T)$ <±0.2% for all c-Si and HIT tested

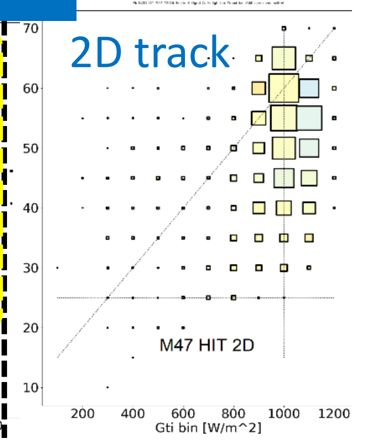






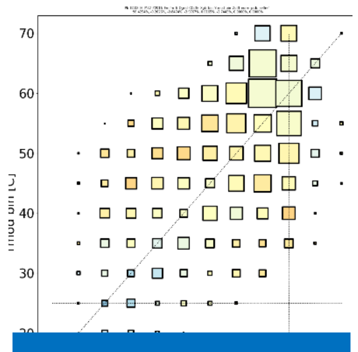
2 × HIT



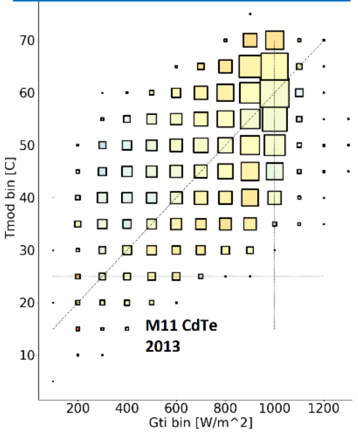


AZ has "little insolation at low light" 2D tracker worse choice for matrix unless mistracked

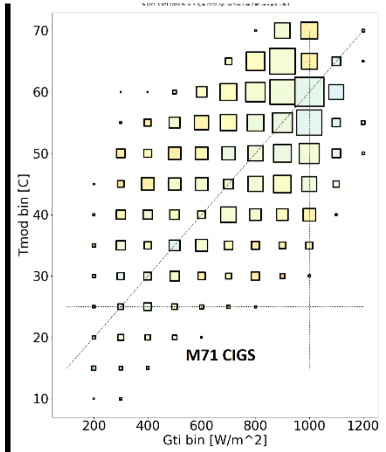
2 × CdTe

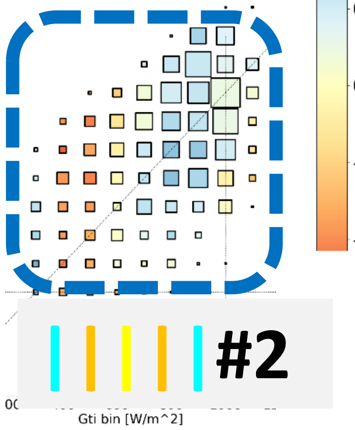


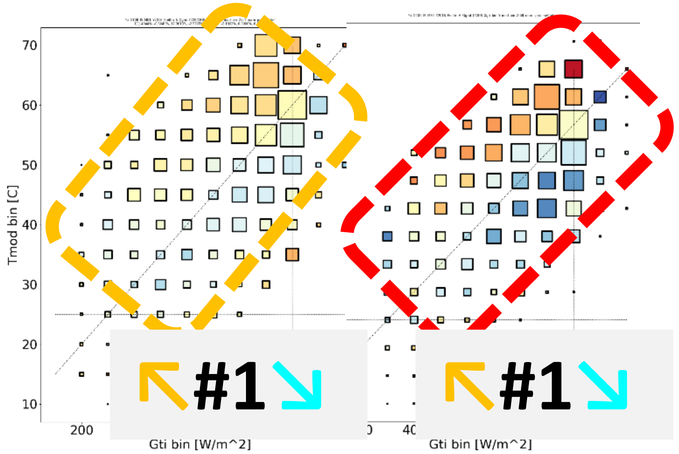
CdTe <±0.3% almost linear



4 × CIGS

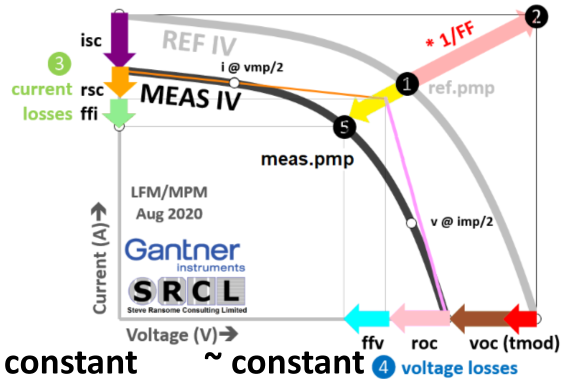






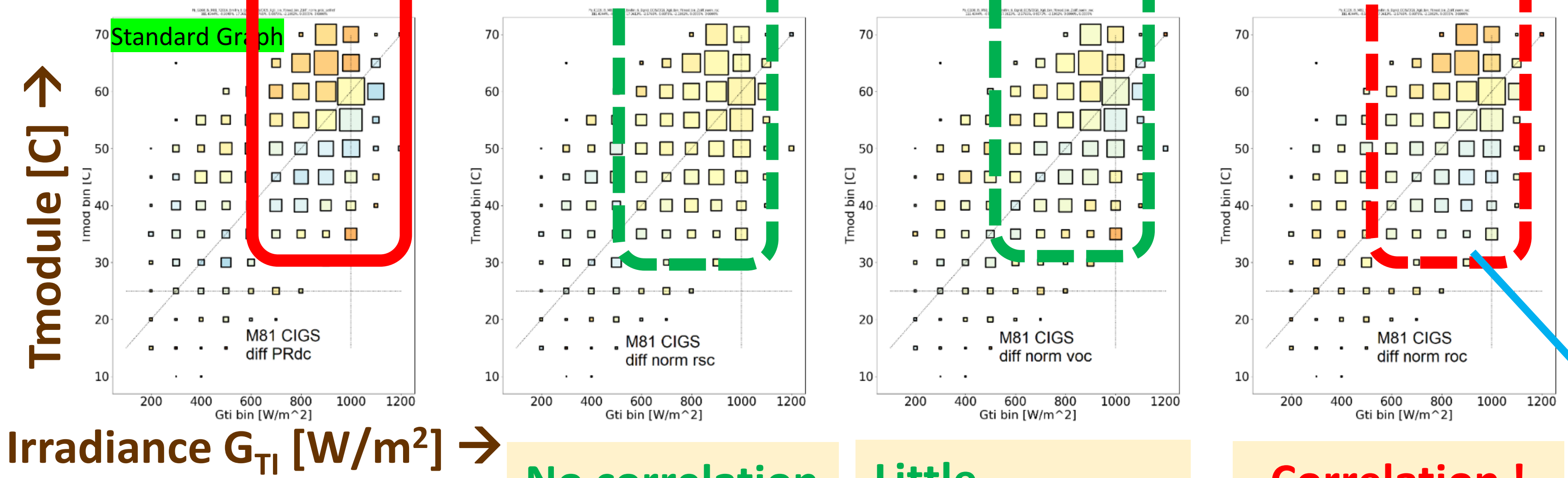
Non-linearities for some CIGS
Different shapes #1, #2 shown

Which LFM parameter(s) cause non-linearity #1 ?



(2) Correlating shapes of colours 'Cause' PR_{DC} behaviour

Dependency	~ Rshunt		~ Voc		~ Reseies	~ constant	~ constant	~ constant
(1) PR_{DC} = [	nR_{SC}	×	nV_{OC}	×	nR_{OC}	× nI_{SC}	× nFF_I	× nFF_V]

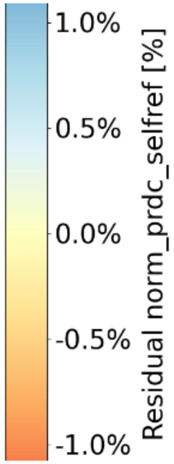


No correlation

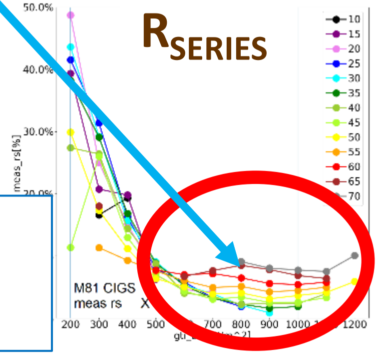
Little correlation

Correlation !

Find cause of non-linearity from pattern matching PR_{DC} with LFM fits



$PR_{DC\_RESIDUAL}$
-1% to +1%



(3) Cause found :
Atypical R_{SERIES}~T_{MOD}
Only at High LIght

>3 Different types of "<1%/bin" perturbations have been seen so far

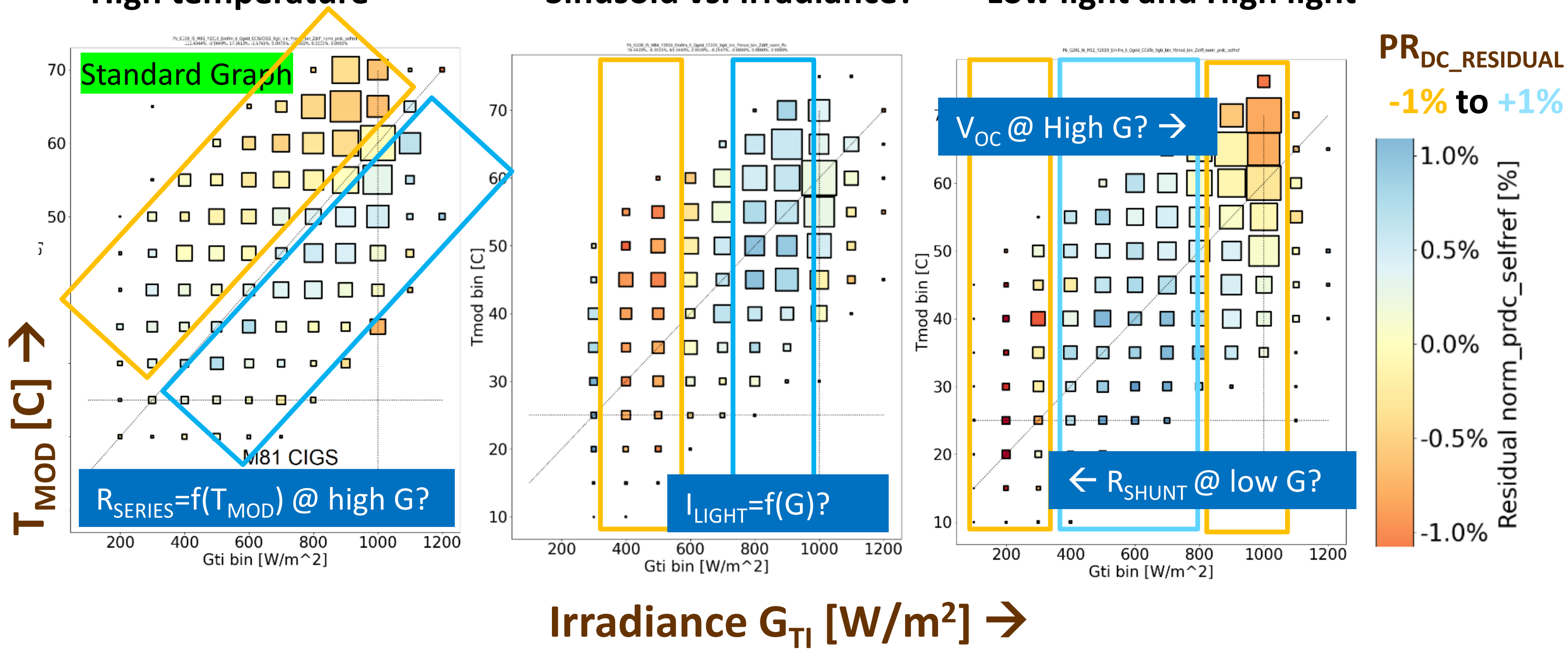
(1st Pass) use linear fit to identify and quantify any non-linearities

(2nd Pass) simple device dependent corrections <~0.5-1.0% if needed

Perturbation #1 : High temperature

Perturbation #2: "Sinusoid vs. irradiance?"

Perturbation #3: "Low light and High light"

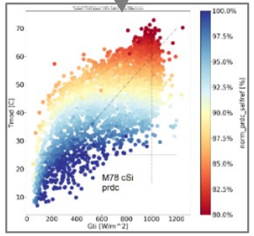


No single non-linear model can fit all different behaviours perfectly

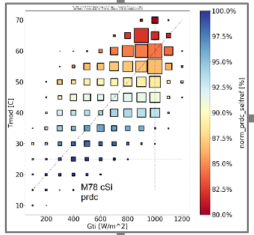
Small technology dependent perturbation coefficients can be added to mlfm6 for optimum fit if needed as most fits are < ±0.5-1.0%/bin

Summary of this work

1) From high Quality outdoor data (e.g. Gantner's OTF)



2) 100+ point matrices of PR_{DC} or any LFM e.g. nR_{SC}, nV_{OC}



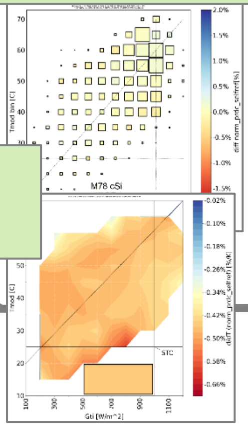
3) 1st pass Linear Model fit = f(G) + f(T) …

4) Residual (measured- fit) matrices

7) Database of normalised coefficients

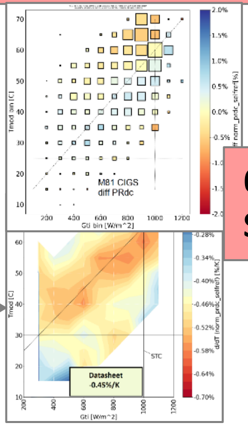
Tech	mod	c_1	c_2	c_3	c_4	STC
CIS/CIGS	81	110.6%	-0.50%	14.2%	-1.5%	106.6%
CdTe	72	96.4%	-0.26%	-0.8%	-4.0%	89.7%
cSi	78	109.6%	-0.47%	12.5%	-8.7%	100.5%
HIT	31	109.5%	-0.35%	11.5%	-7.3%	101.7%

fit <±0.2% ?



5) Linear : cSi, HIT

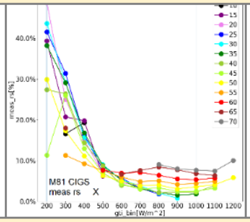
fit >±0.5% ?



6) ~Non_Linear : Some cigs

8) Temperature coefficient heatmaps

9) 2nd pass with non-linear coeffs



10) Quantify small perturbations Identify cause

Thank you for your attention !

Contact us for OTF enquiries and high-quality data sets for your own research

www.gantner-instruments.com/products/software/gi-cloud/