Acessing the Cosmic-Ray Energy Scale with the *Auger Engineering Radio Array*

DPG Frühjahrstagung
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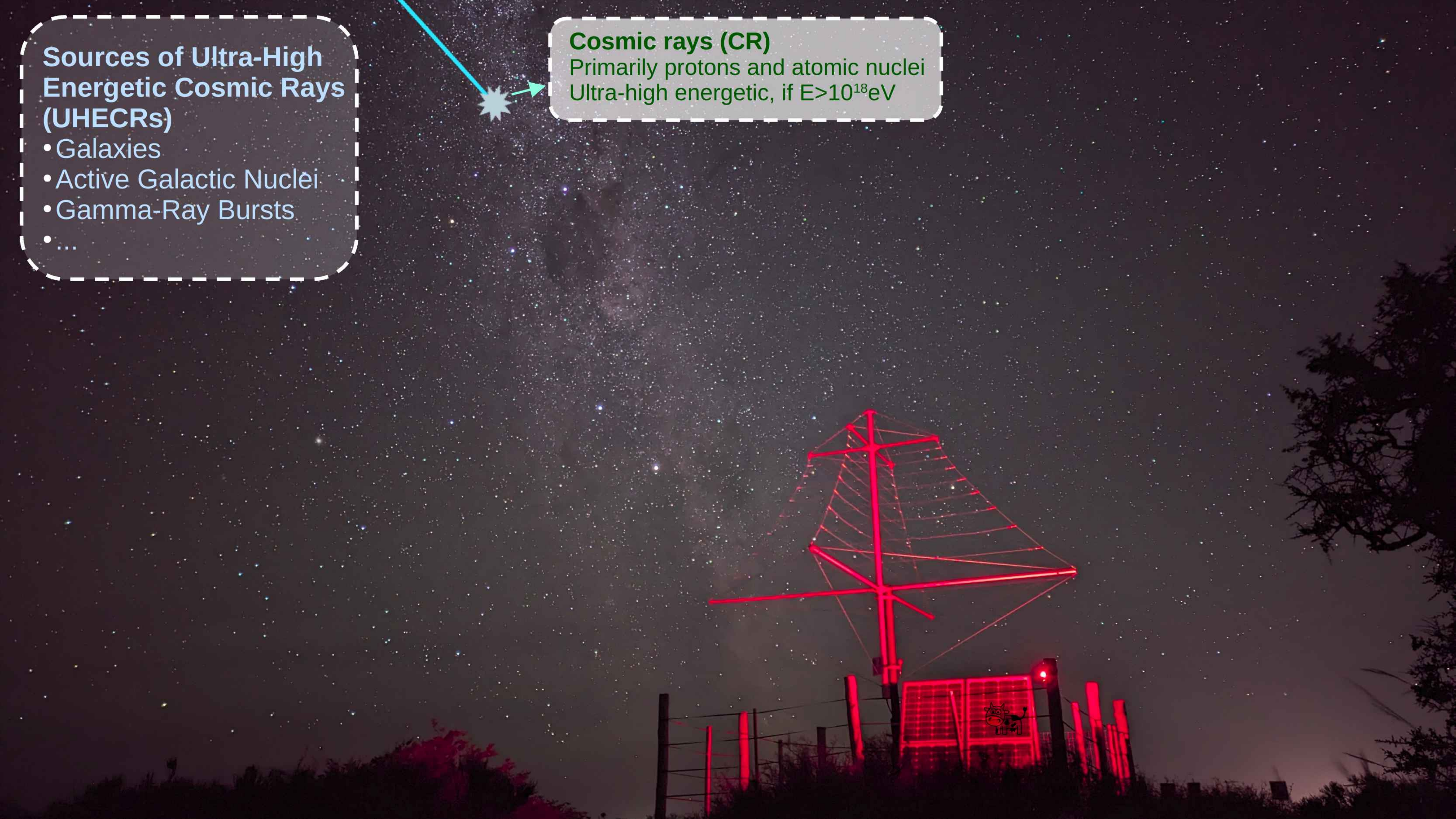
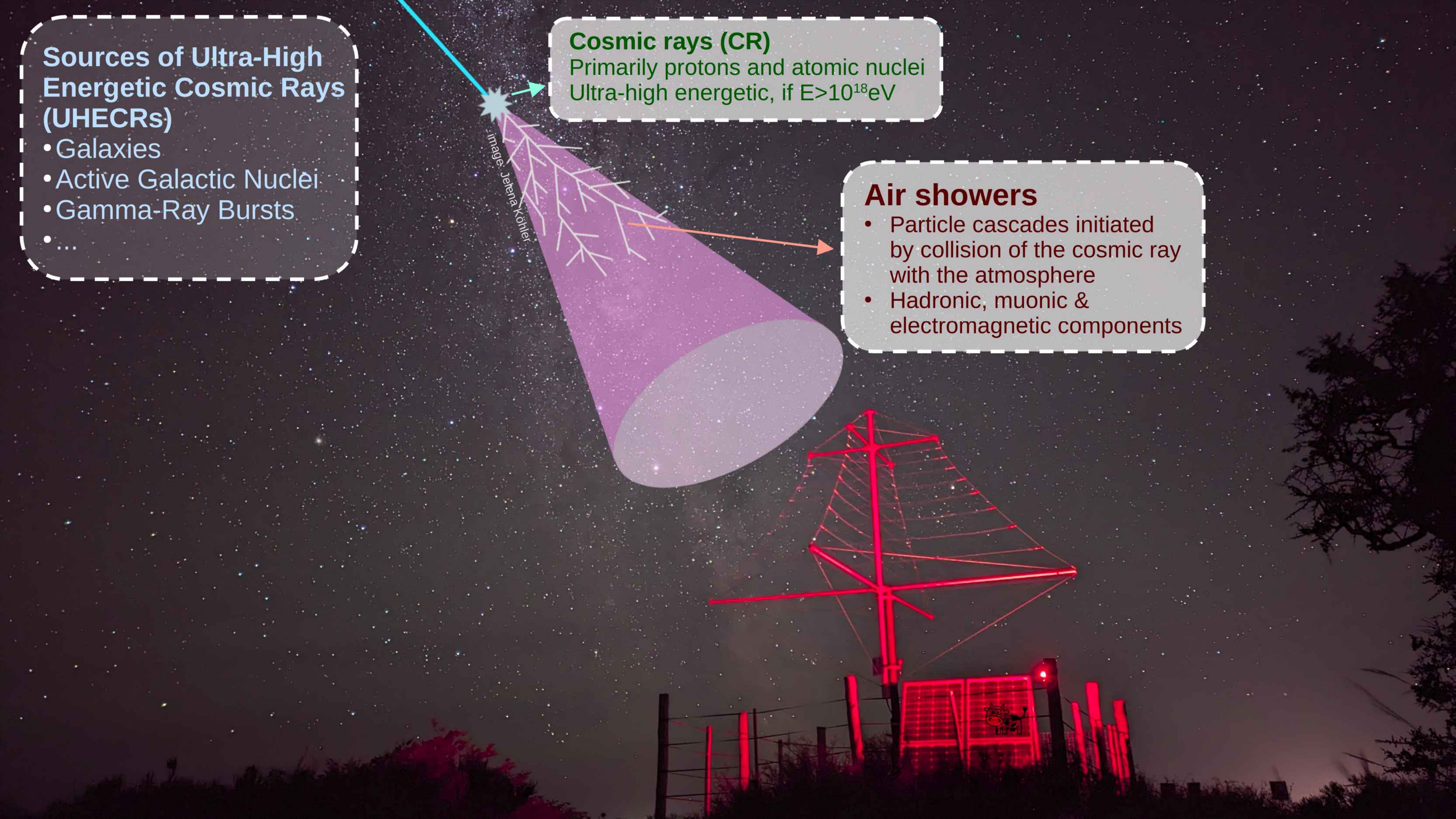
Max Büsken & Tim Huege
for the Pierre Auger Collaboration

Karlsruhe Institute of Technology
UNSAM
PIERRE AUGER OBSERVATORY
HIRSAP
Bundesministerium für Bildung und Forschung



Sources of Ultra-High Energetic Cosmic Rays (UHECRs)
• Galaxies
• Active Galactic Nuclei
• Gamma-Ray Bursts
• ...
Cosmic rays (CR)
Primarily protons and atomic nuclei
Ultra-high energetic, if E>10^18 eV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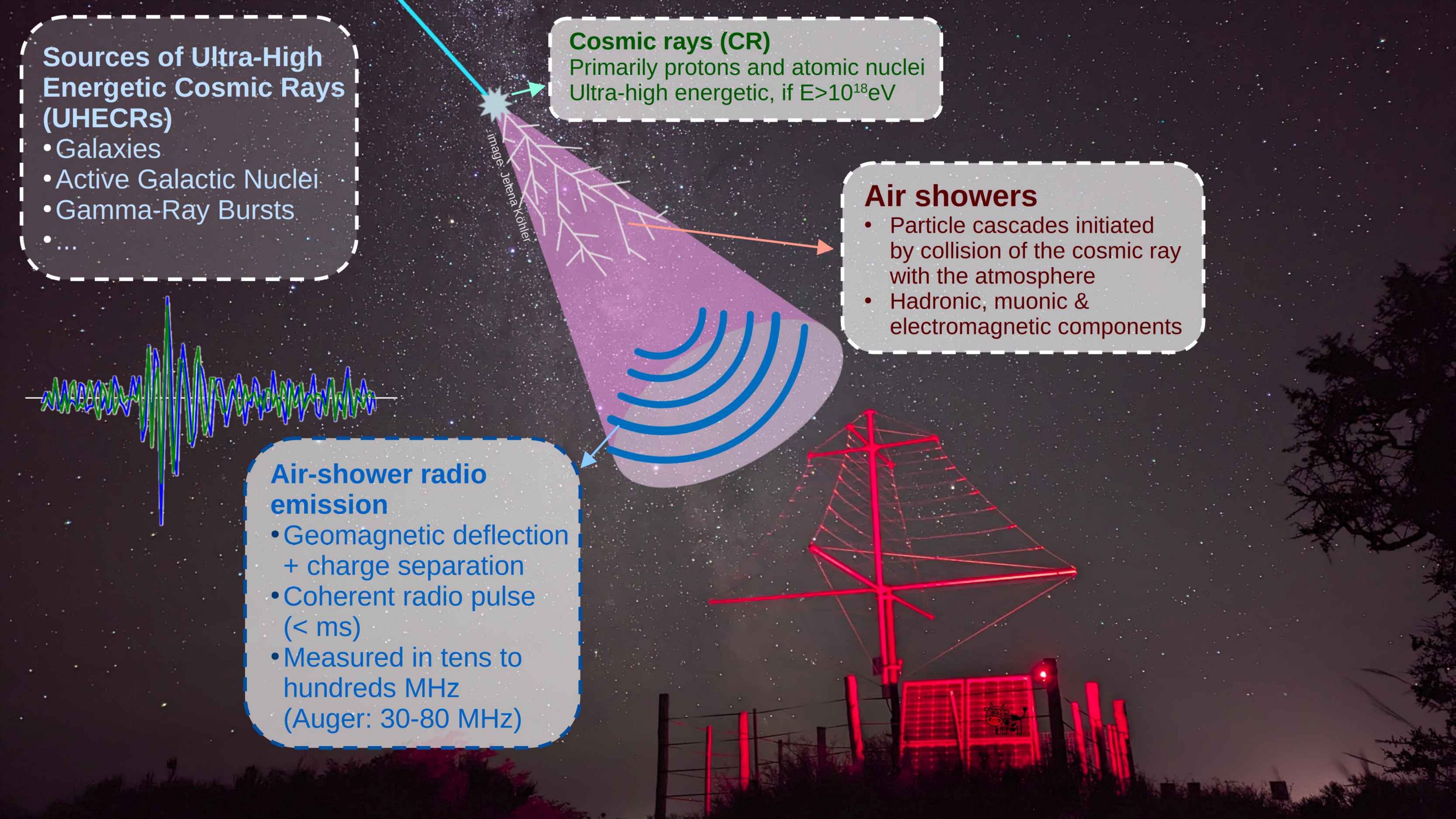
Air showers
• Particle cascades initiated by collision of the cosmic ray with the atmosphere
• Hadronic, muonic & electromagnetic components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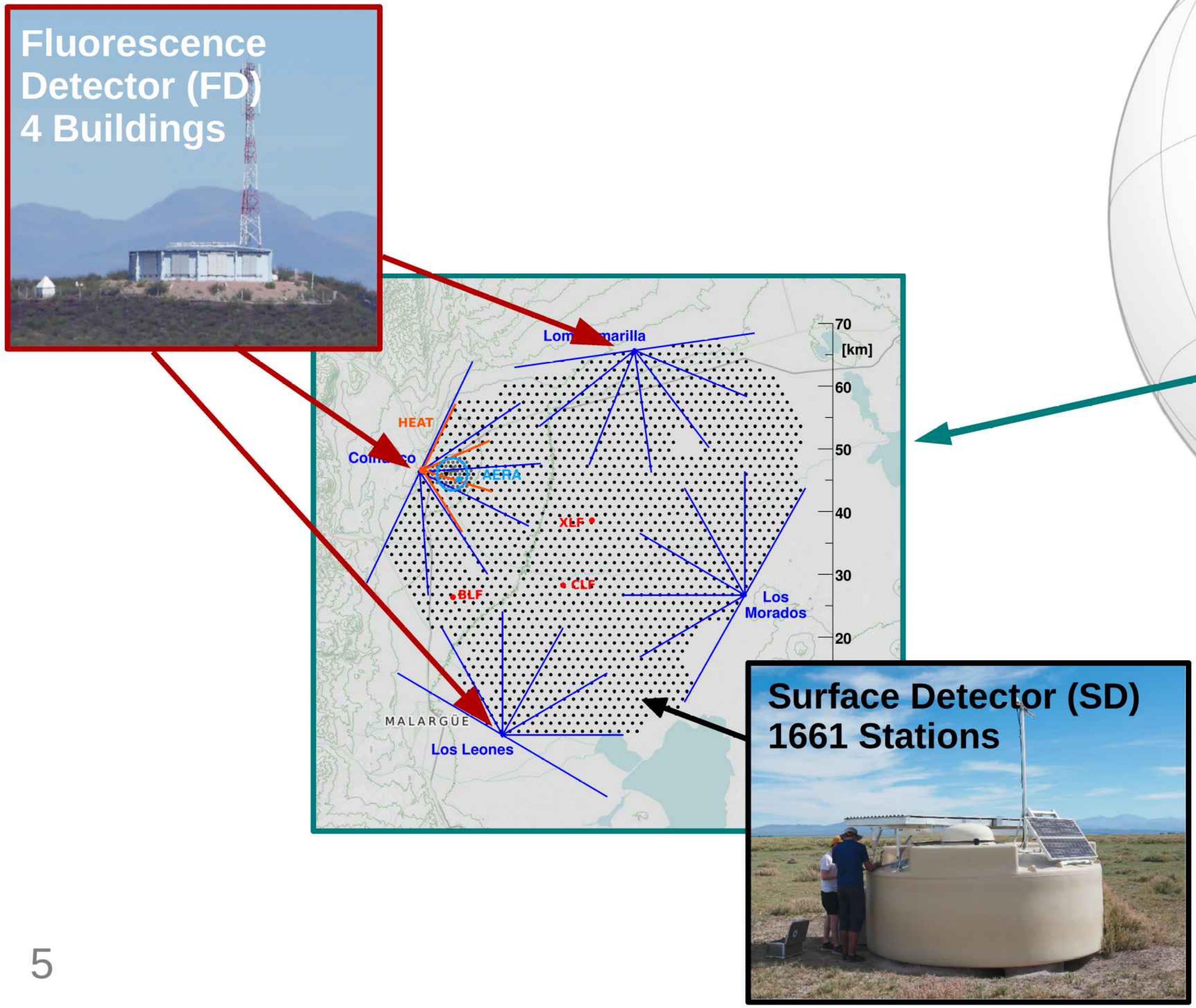
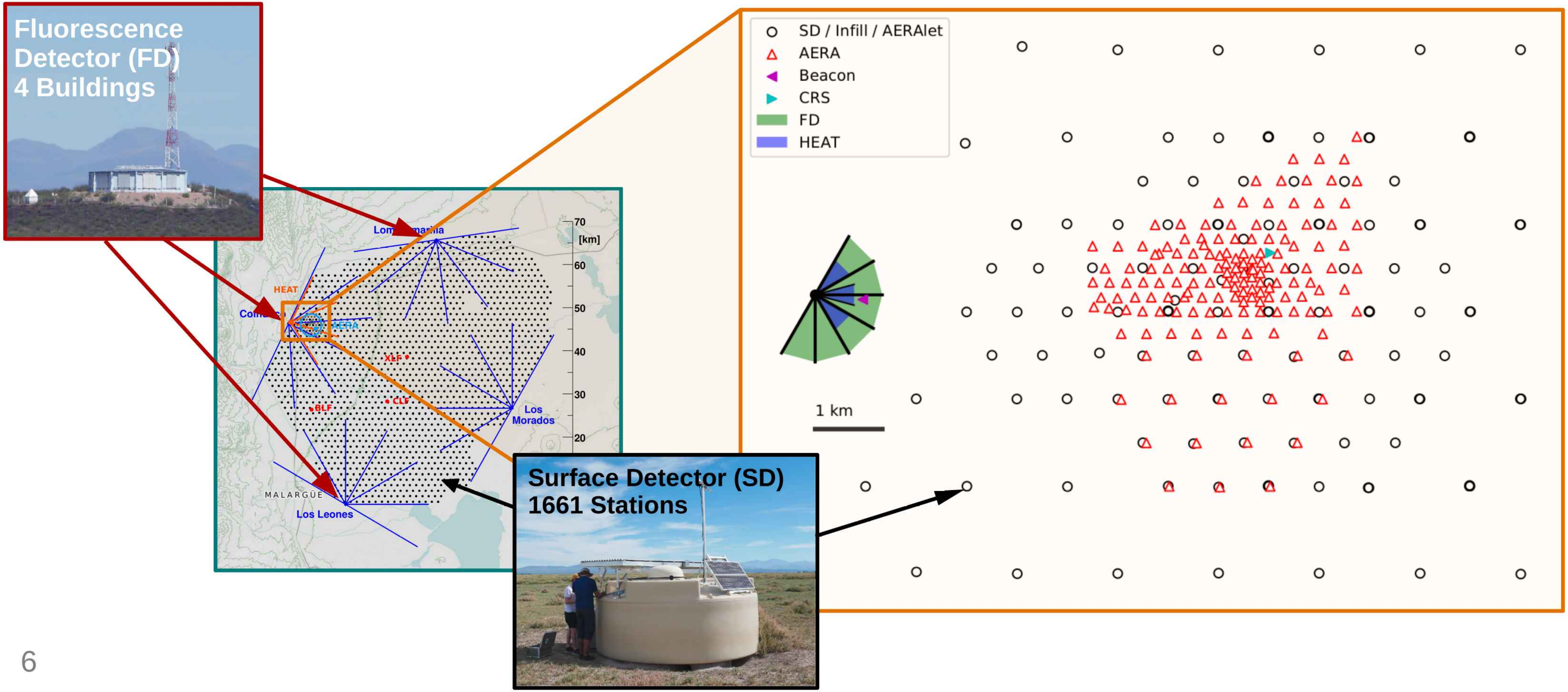
Air showers
• Particle cascades initiated by collision of the cosmic ray with the atmosphere
• Hadronic, muonic & electromagnetic components
Air-shower radio emission
• Geomagnetic deflection + charge separation
• Coherent radio pulse (< ms)
• Measured in tens to hundreds MHz (Auger: 30-80 MHz)

The Pierre Auger Observatory



- Largest ground-based observatory for ultra-high energy cosmic rays (UHECRs)
- Hybrid detection of extensive air showers

The Pierre Auger Observatory



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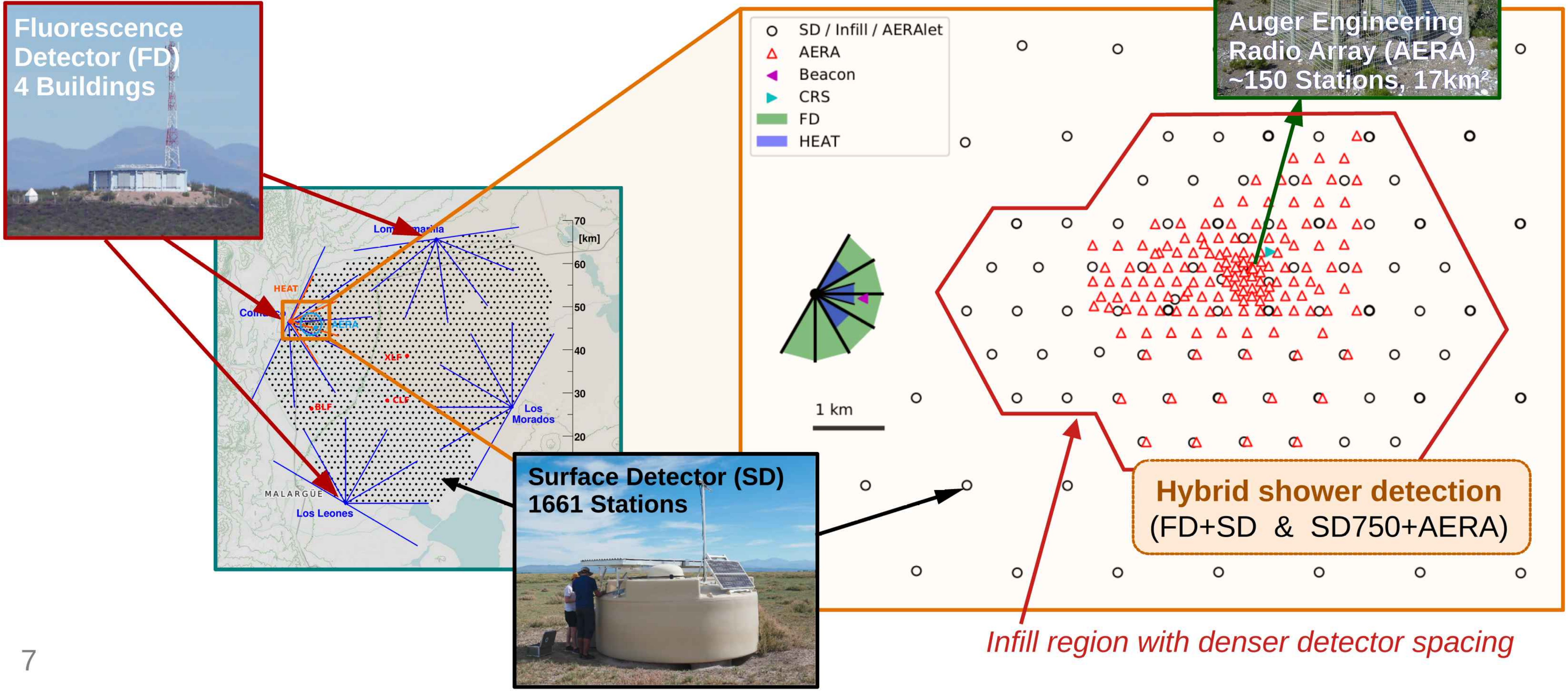
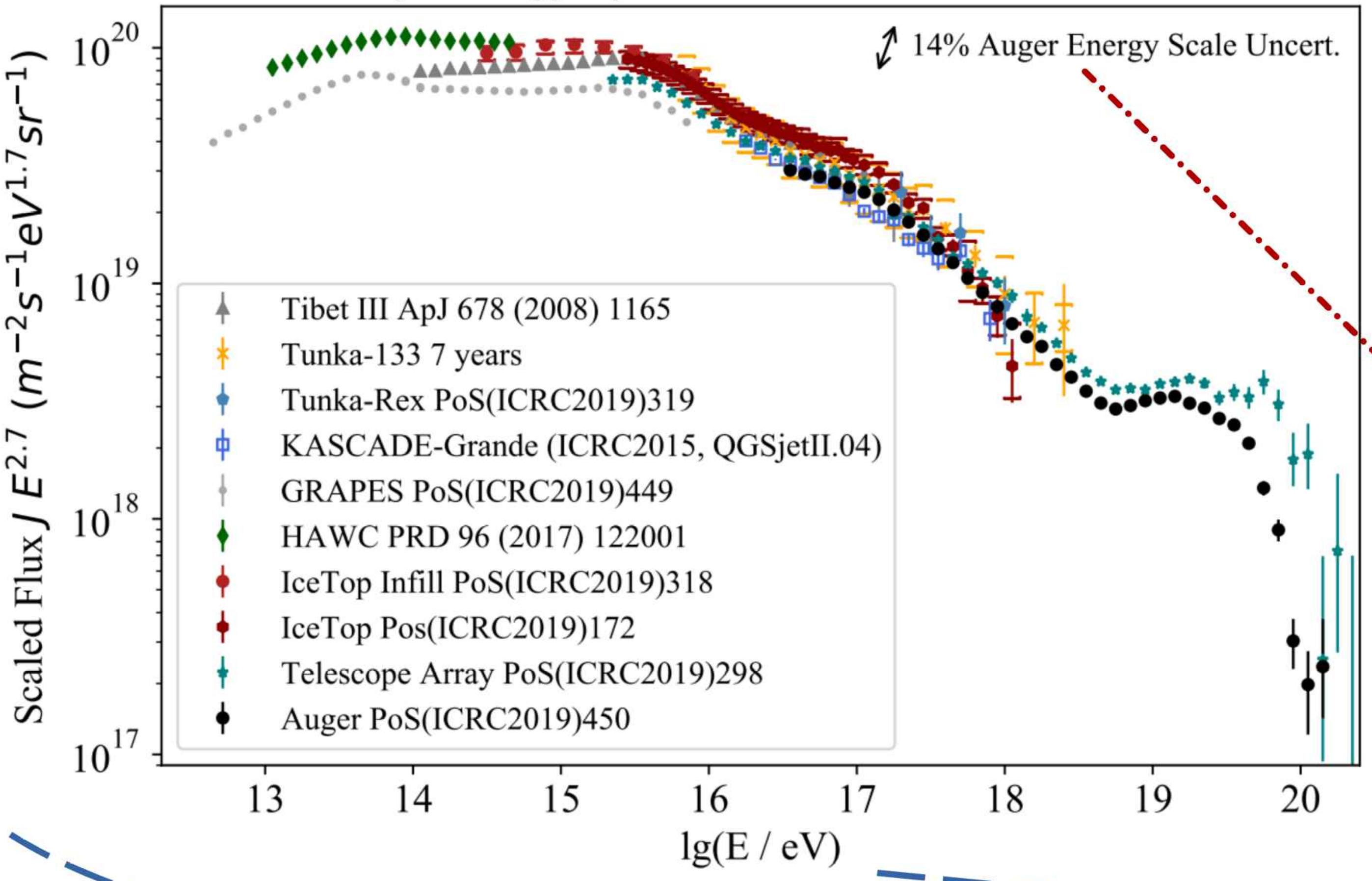


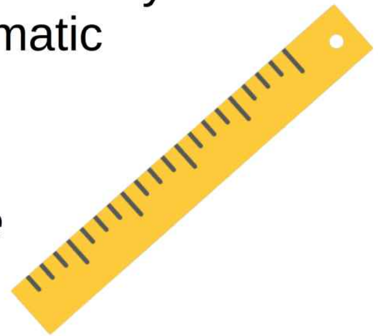
The cosmic-ray energy scale

Cosmic-ray energy spectrum



- Cosmic-ray (CR) energy is base ingredient in many analyses,
  e.g. CR energy spectrum
- Value of reconstructed energy bound to the observatory's energy scale
  - Absolute determination crucial
  - Energy scale uncertainty: Are differences between observatories caused by physics or systematic uncertainties?

i.e. "did we apply the ruler correctly?"

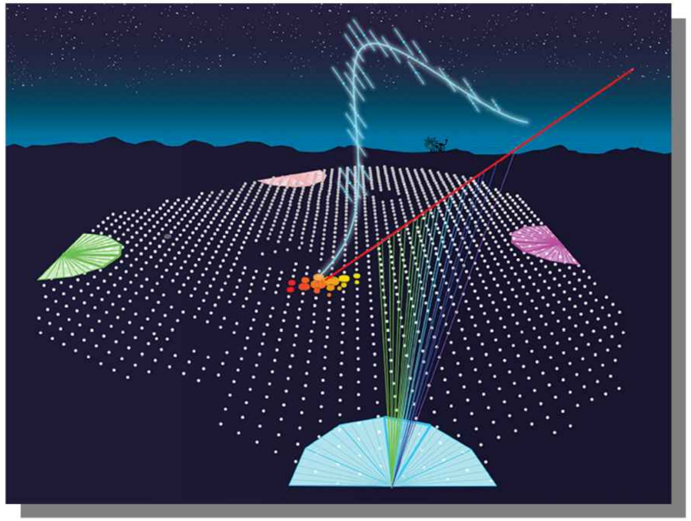


Accessing the cosmic-ray energy scale

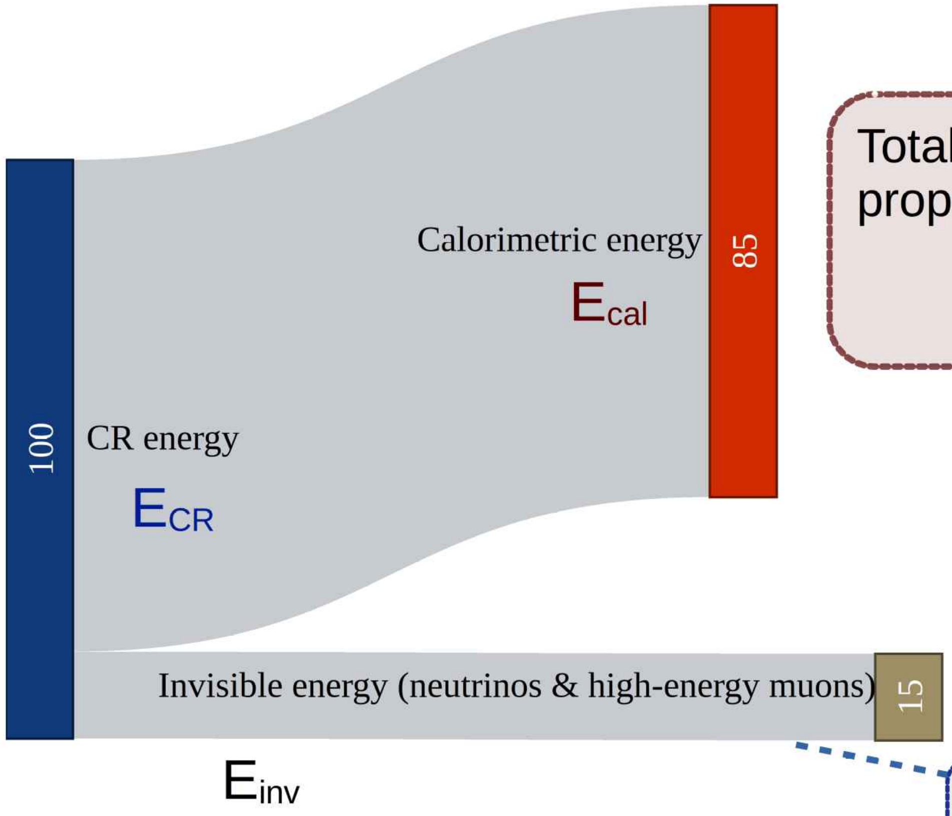
with the Auger Fluorescence Detector (FD)

FD principle:

Shower particles excite air molecules
→ emit fluorescence light



E_{cal}: All energy deposited in the atmosphere



Total number of fluorescence photons proportional to calorimetric energy

$$N_\gamma \propto E_{cal} \propto E_{CR}$$

FD probes absolute CR energy scale

Can be corrected for
Phys. Rev. D 100, 082003 (2019)

Consequence for SD:

SD calibrated from hybrid events
▸ SD inherits FD energy scale

Accessing the cosmic-ray energy scale

with the Auger Fluorescence Detector

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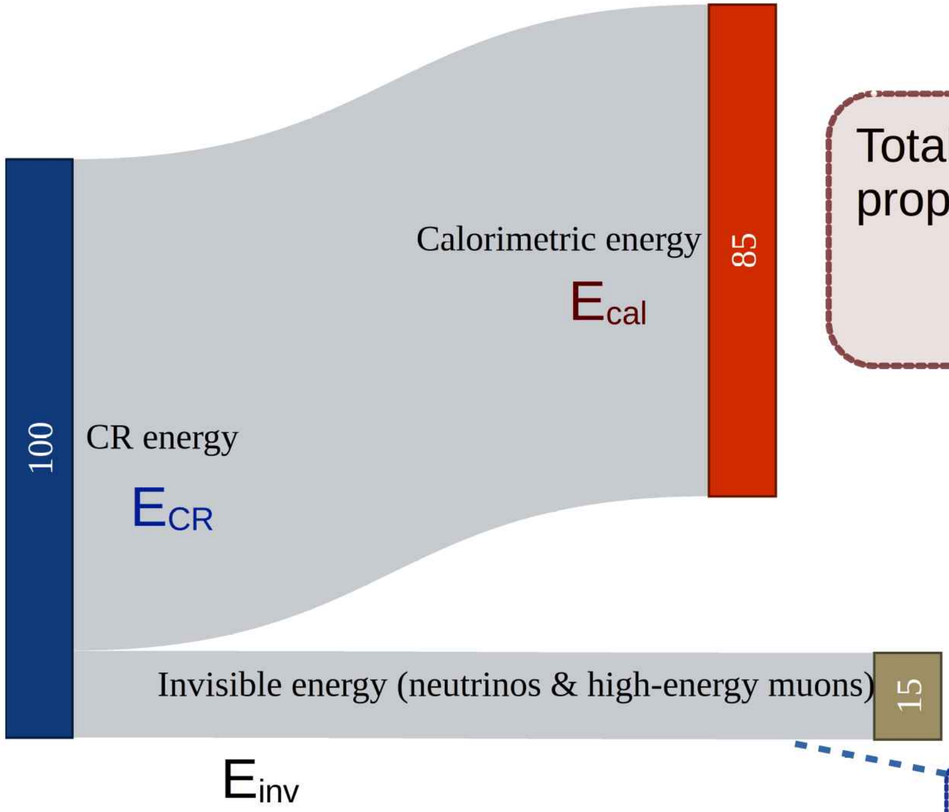

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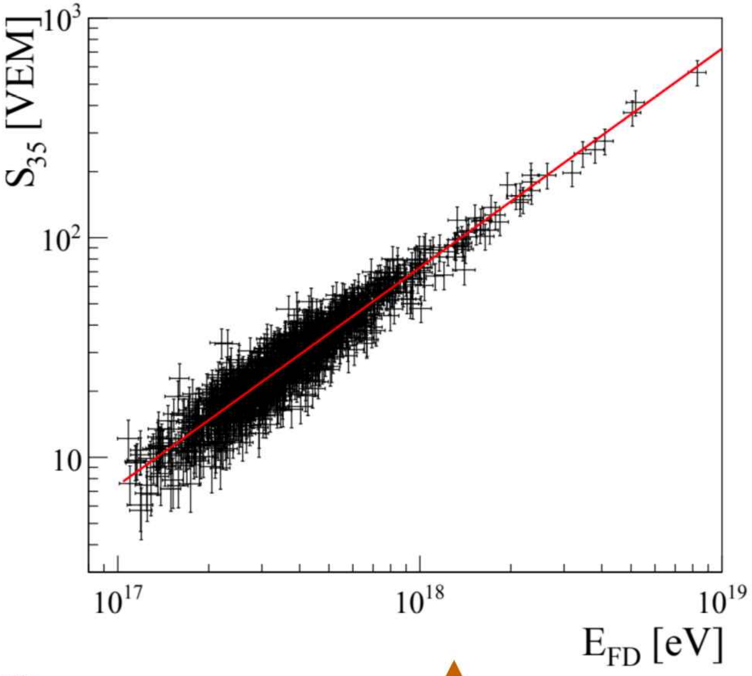
energy estimator from SD



energy estimator from FD

Consequence for SD:

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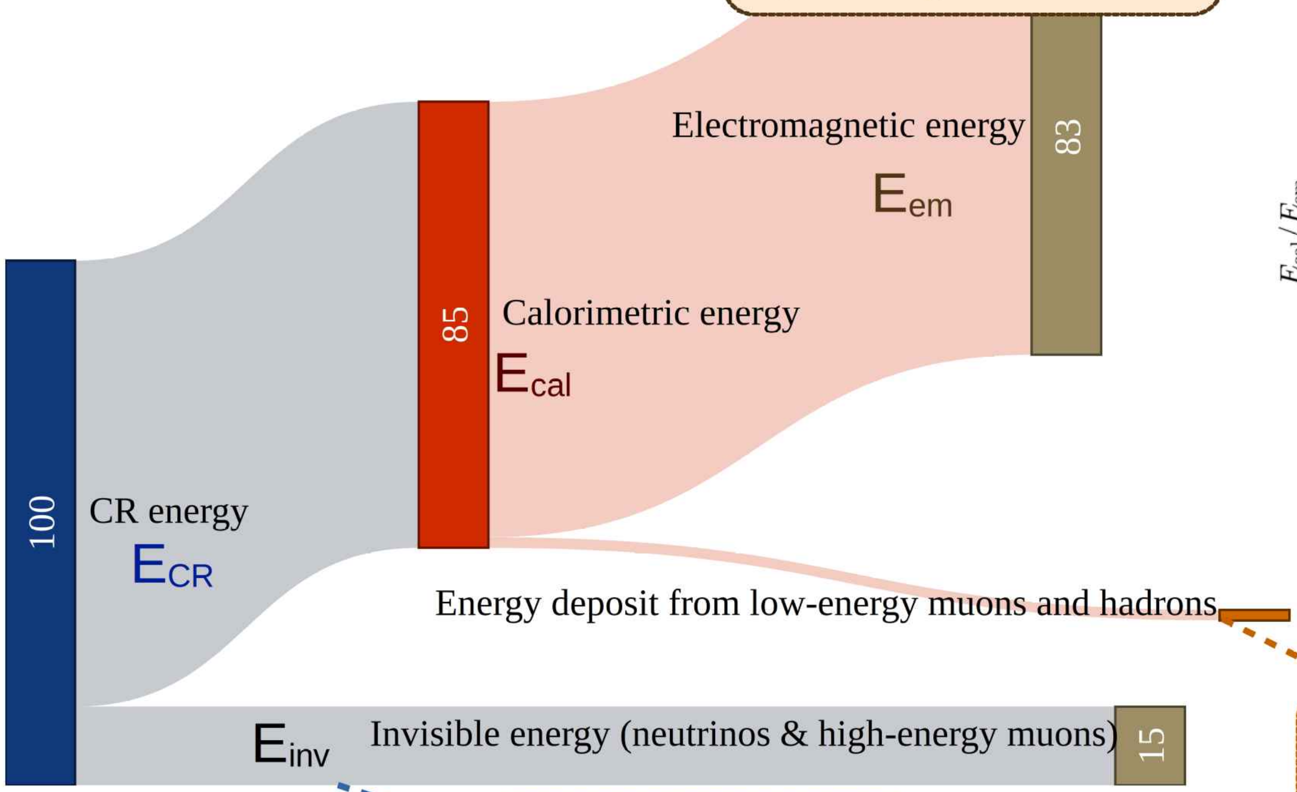
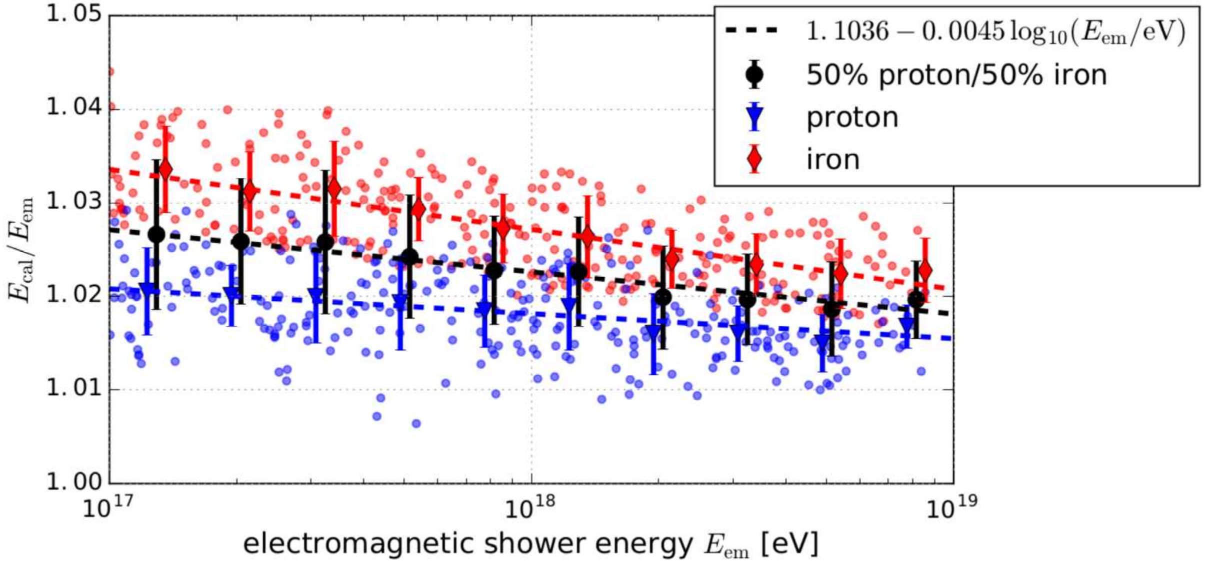
Accessing the cosmic-ray energy scale

with AERA

E_{em}: All energy deposited in the atmosphere
by e⁺, e⁻, ɣ





Can be corrected for

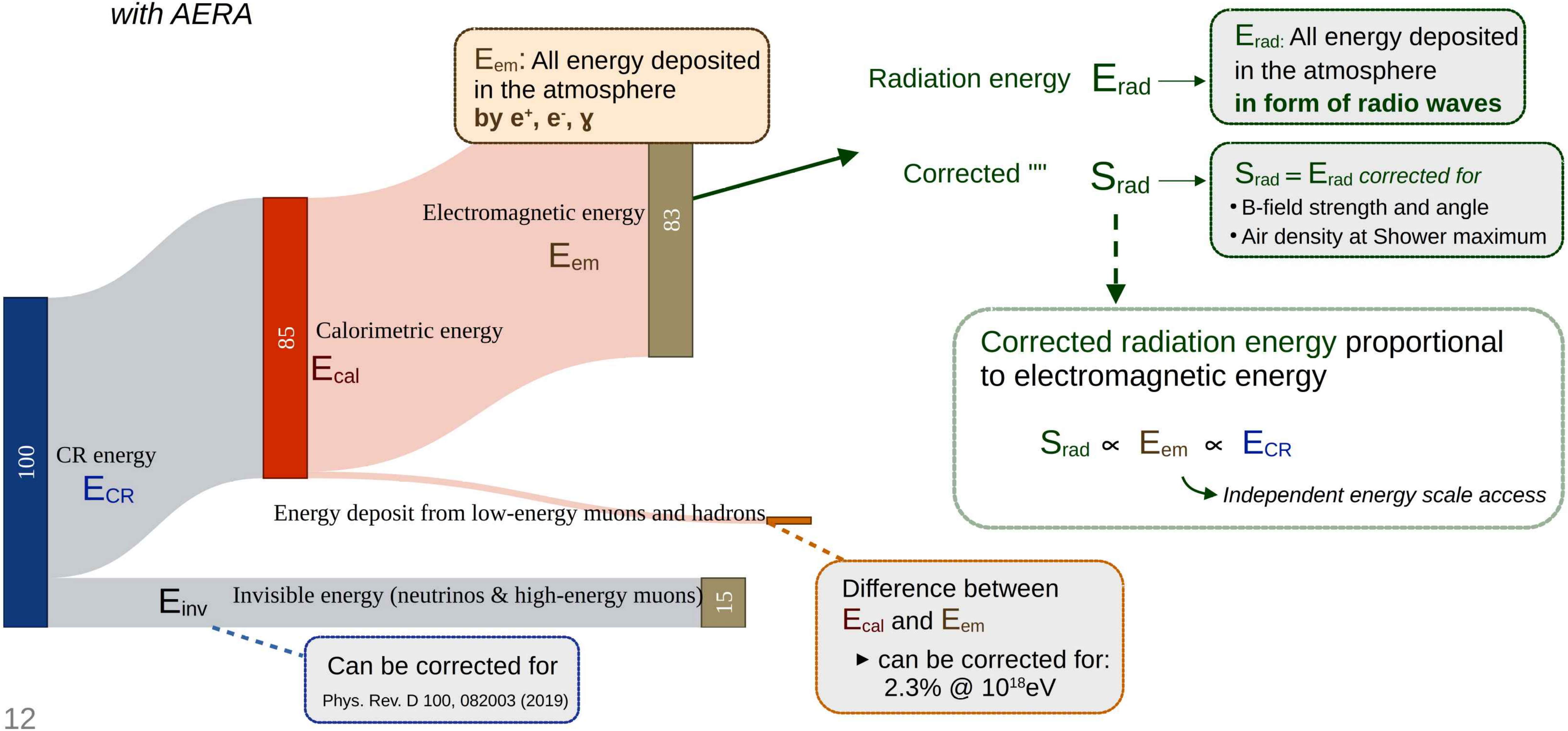
Phys. Rev. D 100, 082003 (2019)

Difference between E_{cal} and E_{em}

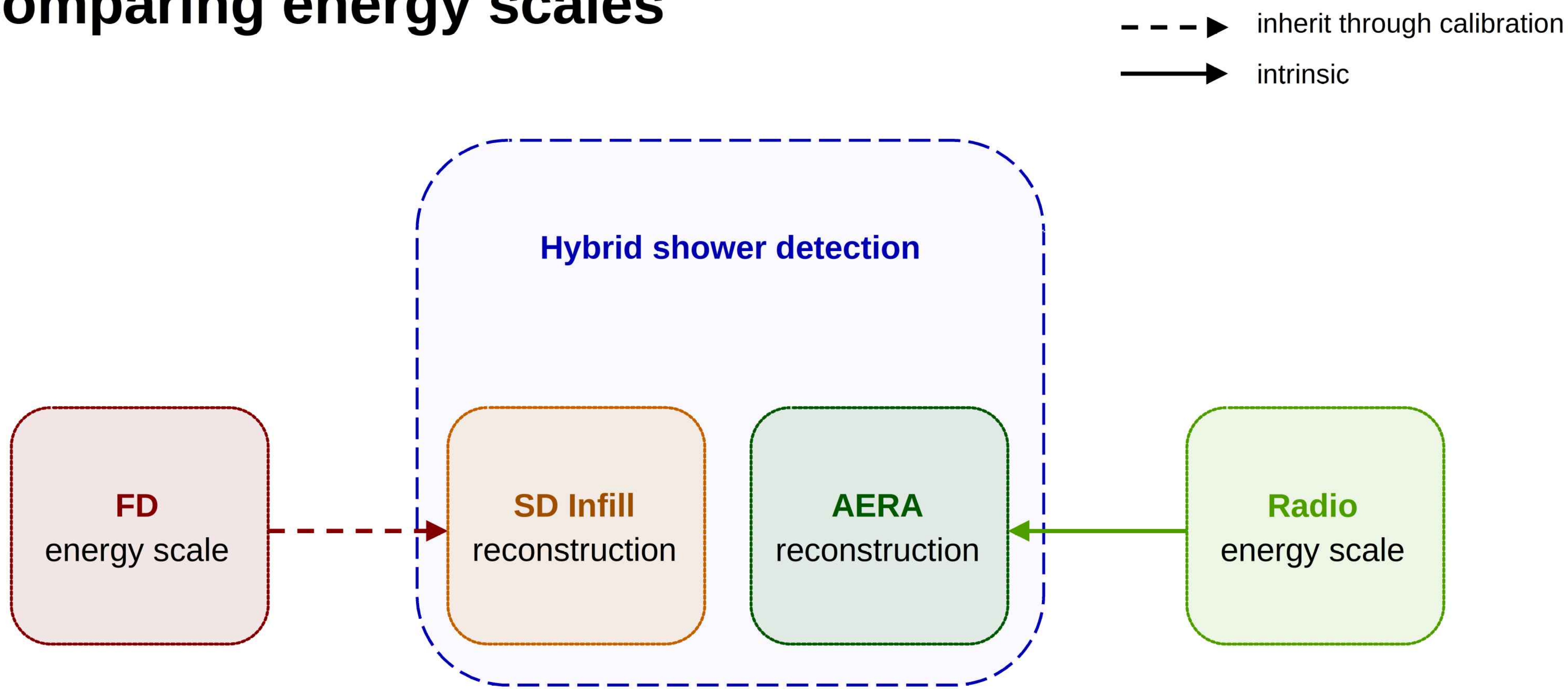
- can be corrected for: 2.3% @ 10^{18}eV

Accessing the cosmic-ray energy scale

with AERA



Comparing energy scales



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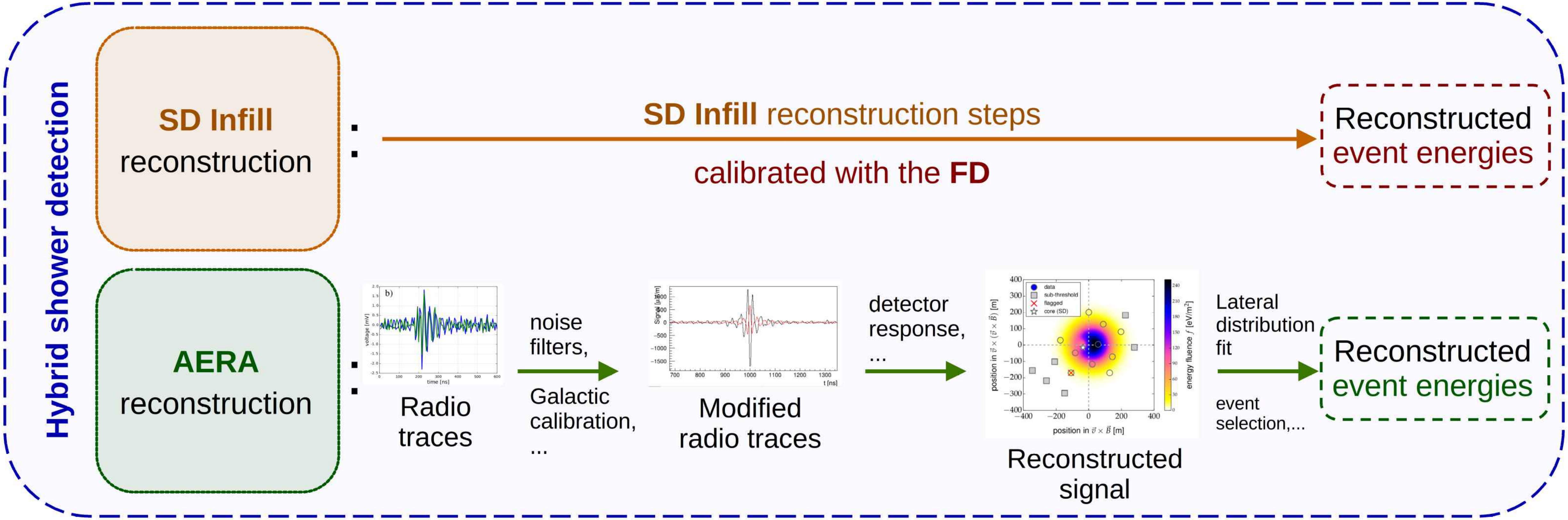

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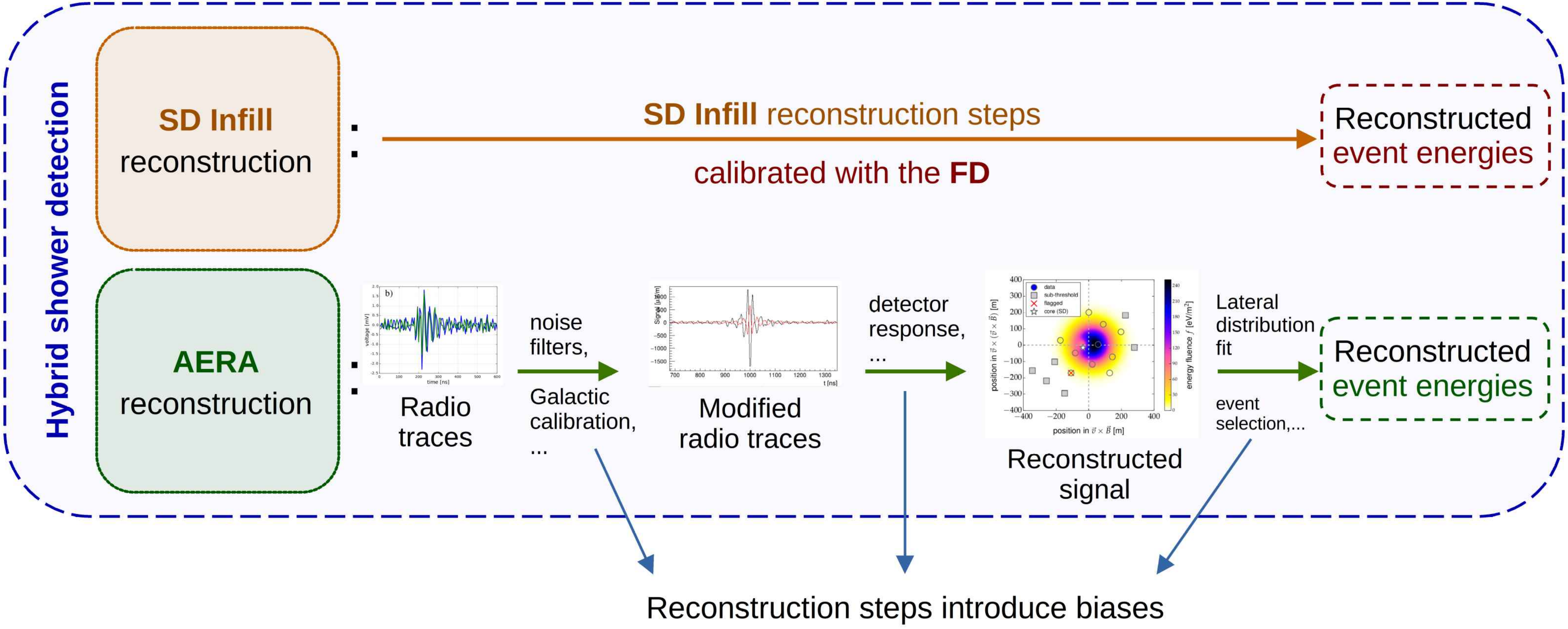

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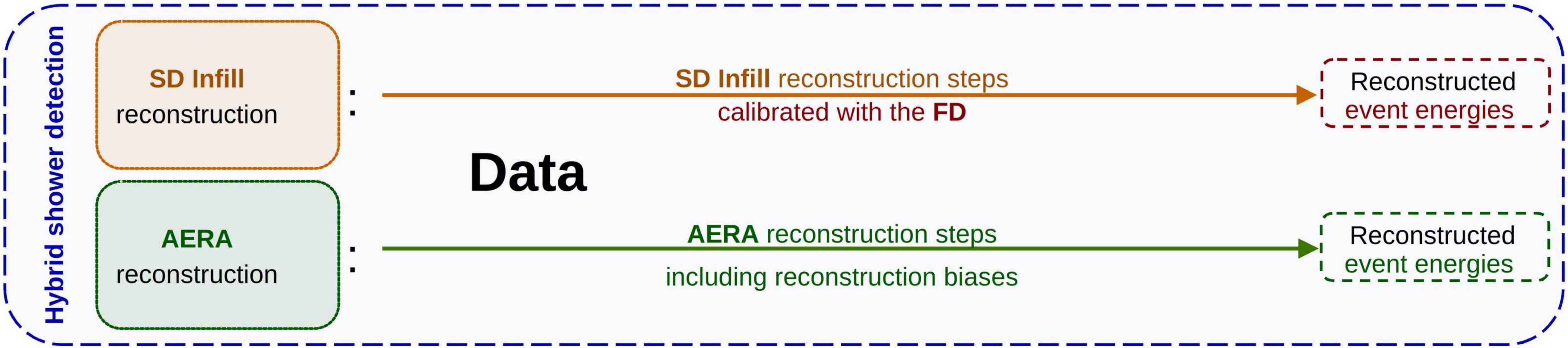

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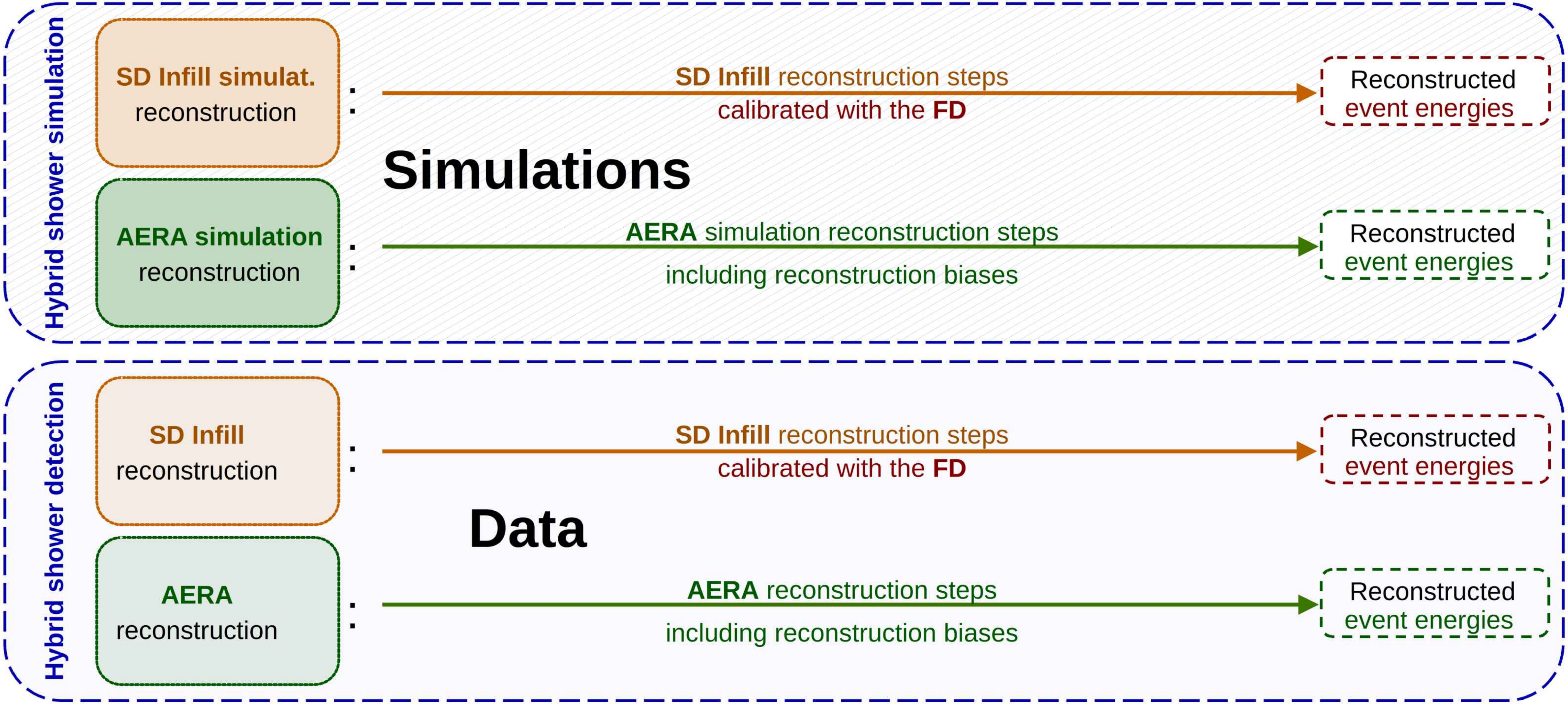

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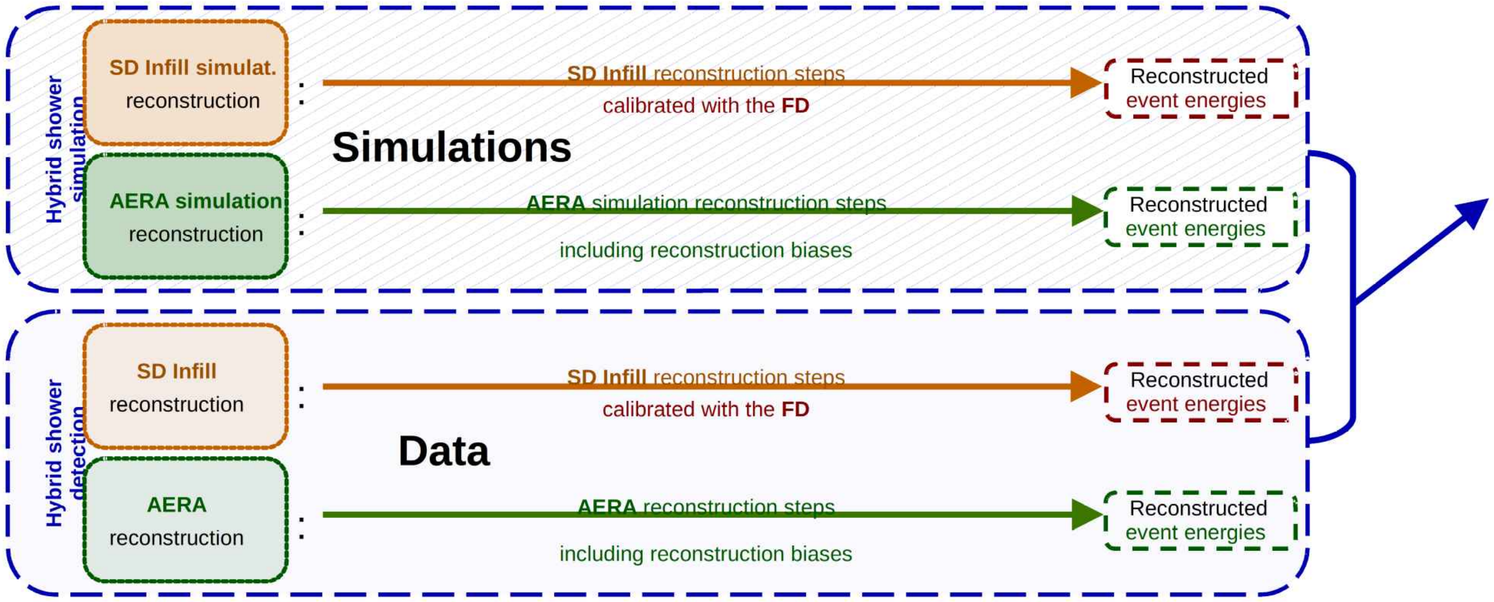
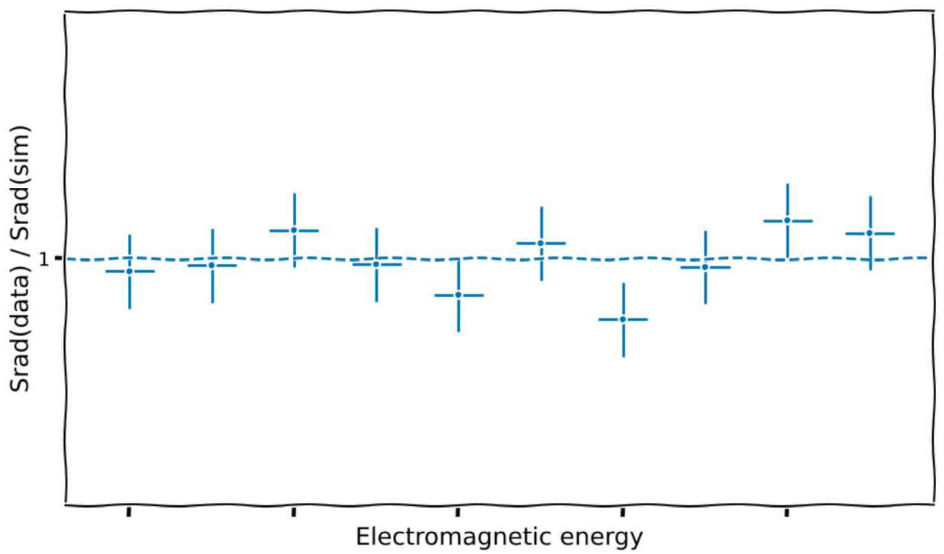




Comparing (biased) SD/AERA measurements with (biased) simulations

Summary

- Radio arrays can independently probe the cosmic-ray energy scale, next to the established access via fluorescence telescopes
- Preparing approach to directly compare CR energy scales at the Pierre Auger Observatory from AERA and the FD:
  - Equalized reconstructions of data and simulations to cancel out rec. biases

Outlook

- Do comparison with new high-precision simulations
- Study systematics
  → biases and uncertainties

Backup

Reconstruction biases in data and simulations

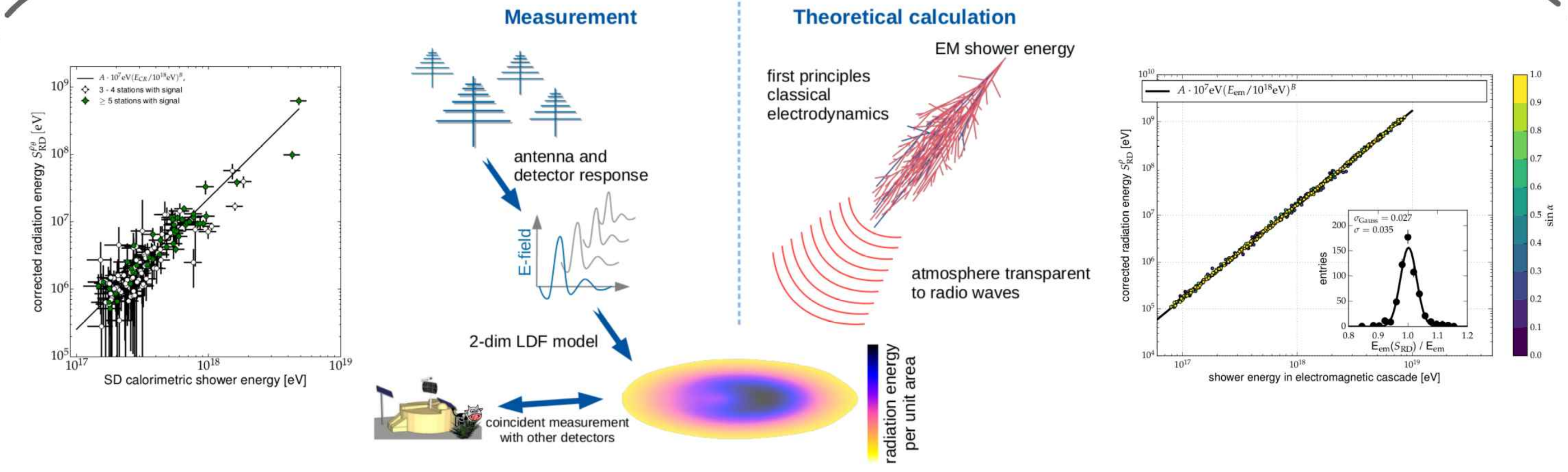
- Steps in AERA reconstruction with multiple choices:
  - Noise filter
  - Signal estimation method (energy fluence)
  - ...
- Tested influence on reconstructed energy
  - Influence very similar for data and simulations

Test	Description	Relative change in rec. energy (data)	Relative change in rec. energy (simulations)
Noise filters	no filter	-	-
	Bandstop	-12.2%	-11.6%
	Sinewave suppressor	-2.9%	-1.9%
Signal estimation methods	Standard method	-	-
	Method with background subtraction	-5.2%	-6.2%

Comparing FD and radio energy scales

- Two individual energy scale accesses call for comparing them
- One recipe worked out by C. Glaser
- Based on hybrid SD-AERA-showers and a high-precision simulation study

Recipe introduced by C. Glaser (PhD thesis, 2017)



$$S_{\mathrm{RD}}^{\rho\theta} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,cal}}}{10^{18} eV}\right)^B$$

Allows to compare CR energy scales from FD and radio

$$S_{\mathrm{RD}}^{\rho\theta} = 1.639 \times 10^7 eV \left(\frac{E_{\mathrm{em}}}{10^{18} eV}\right)^{1.978}$$

Aiming to determine a universal/academic radio energy scale

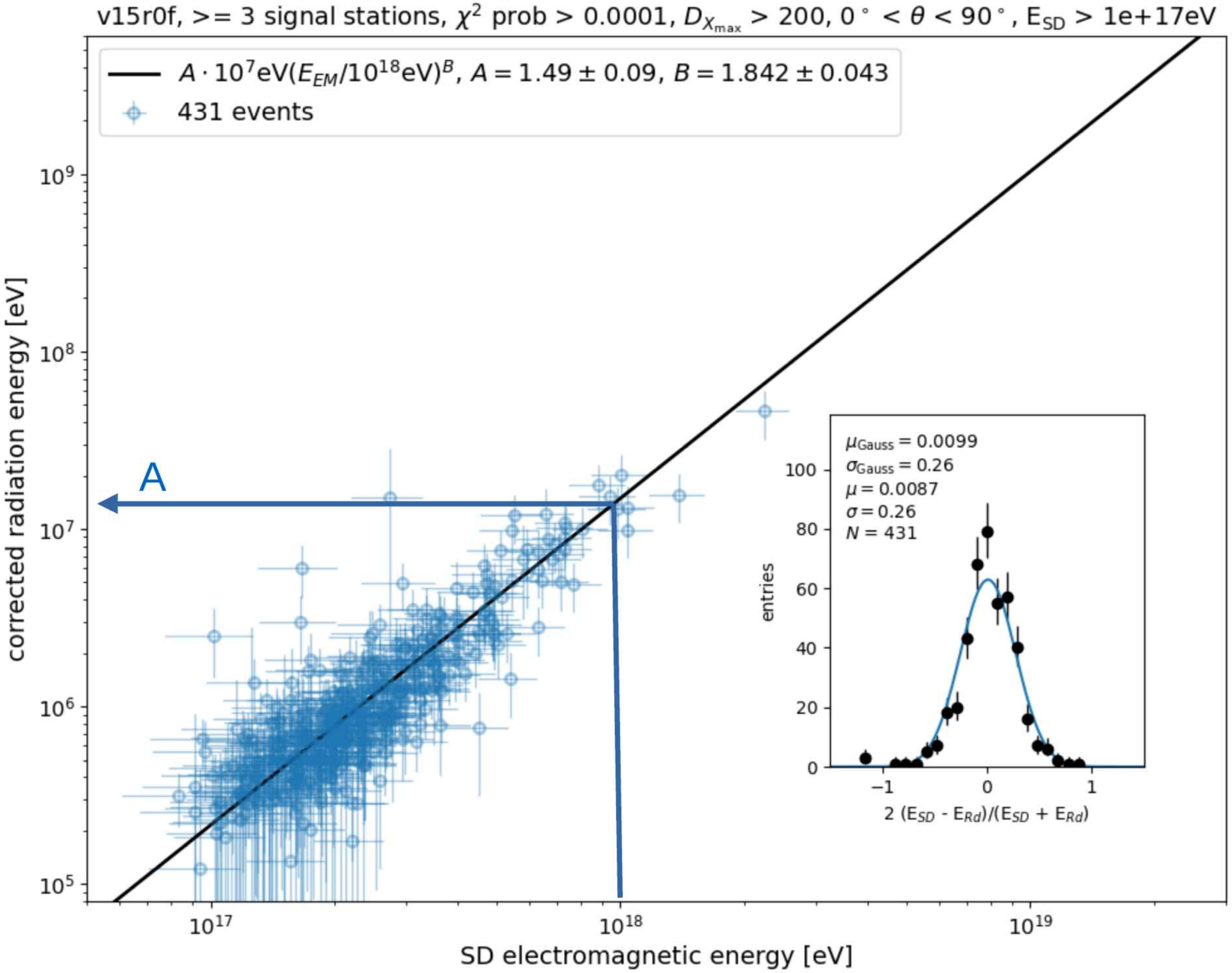
Calibration fit from hybrid showers (SD-AERA)

- Fit S_{rad} from AERA reconstruction to E_{em} from SD reconstruction

$$S_{\mathrm{RD}}^{\rho\theta} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,em}}}{10^{18} eV} \right)^B$$

- A: "how much energy from a 10^{18}eV shower is transformed into radio waves"
- B: Scaling of S_{rad} with E_{em}

Disclaimer: Shown fit values for A and B are very preliminary and not to be compared to previous analyses



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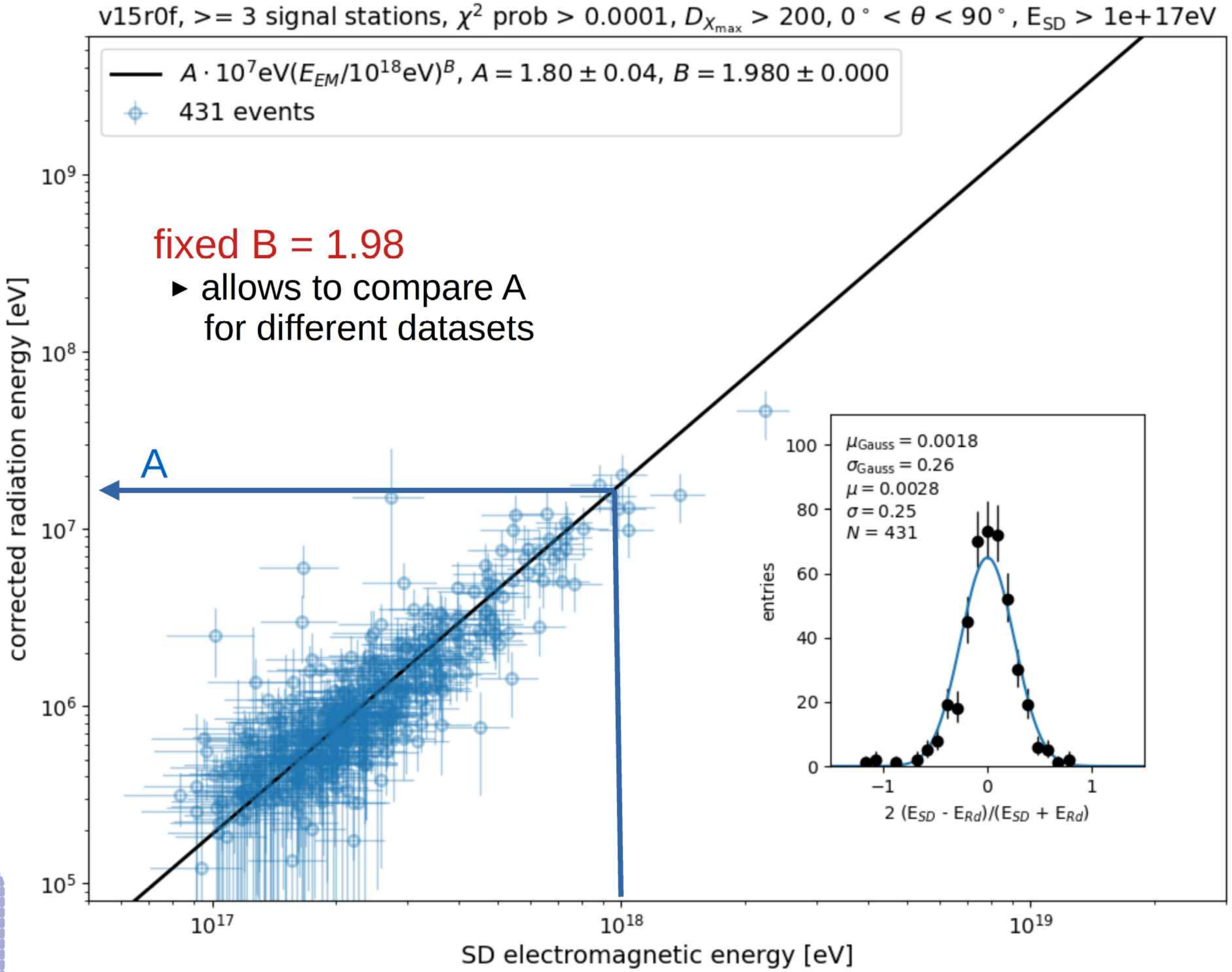
$$S_{\mathrm{RD}}^{\rho\theta} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,em}}}{10^{18} eV}\right)^B$$

- A: “how much energy from a 10^{18}eV shower is transformed into radio waves“
- B: Scaling of S_{rad} with E_{em}

  expectation B = 1.98*
  [JCAP 09(2016)024]

*deviation from quadratic scaling originates from using the zenith angle only to approximate the air density correction, instead of using Xmax



Shift in analysis philosophy

- F. Briechle continued analysis from C. Glaser
  - Observed influence of choice of reconstruction ingredients
    - Signal estimation methods
    - Noise filters
    - ...

F. Briechle PhD thesis 2021

- V. Lenok: full event simulations of F. Briechle's data
  - Observed signal loss through processing pipeline (both in data and simulations)

V. Lenok PhD thesis 2021

Philosophy so far:

- Aiming to compare measurement against academic "truth" / "constant of nature"
- Requires knowledge of all reconstruction biases

Proposed philosophy:

- Aiming to compare (biased) SD/AERA measurements with (biased) simulations
  - ▸ Auger-internal
- Reconstruction biases less critical if equally affecting data and simulations

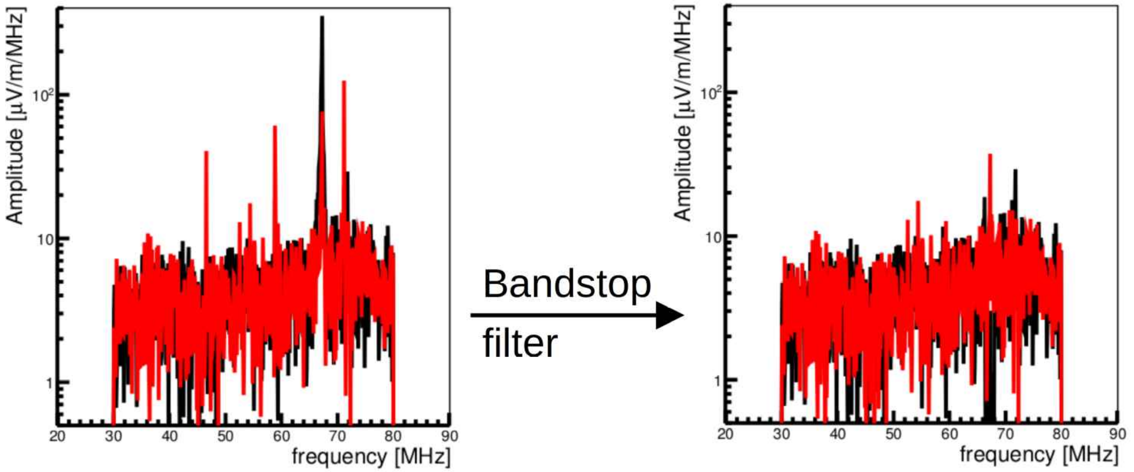
Idea:

- ▸ Directly compare energy scale of FD with AERA, avoid sources of systematics
- ▸ Claiming a universal radio energy scale could be a 'next step'

Reconstruction biases in data and simulations

- Steps in AERA reconstruction with multiple choices:
  - Noise filter
  - Signal estimation method (energy fluence)
  - ...
- Tested SD-AERA calibration fit with fixed B=1.98
  - Check relative change in fitted A
  - Changes very similar for data and simulations

AERA frequency spectra (red + black: 2 polarizations)



by C. Glaser

Test	Description	Relative change in A (data)	Relative change in A (simulations)
Noise filters	no filter	-	-
	Bandstop	-12.2%	-11.6%
	Sinewave suppressor	-2.9%	-1.9%
Signal estimation methods	Offline method	-	-
	Method with background subtraction	-5.2%	-6.2%

General reconstruction improvements & advancements

Updating SD energies ICRC2019 → ICRC2023

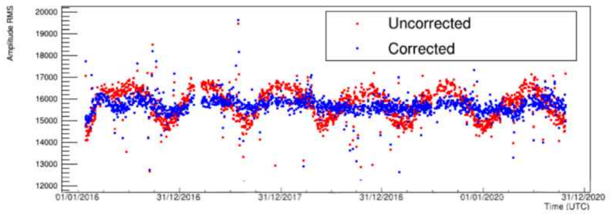
- SD electromagnetic energy from official SDInfill production
    - So far: ICRC2019 incl. quality cuts → comparability to results from F. Briechle
    - Now: move to ICRC2023 incl. quality cuts
        - Final tag production failed
        - Test with icrc23-pre5/pre2 tag
            - Fit results unchanged, but 15% less high-quality events
        - Rerun with final tag planned

Dataset	Events	Relative change in A (data)
ICRC 19	398	-
ICRC 23 (pre)	339	0.6%
	?	✓

Outlook ...for reconstruction.. ...and simulations

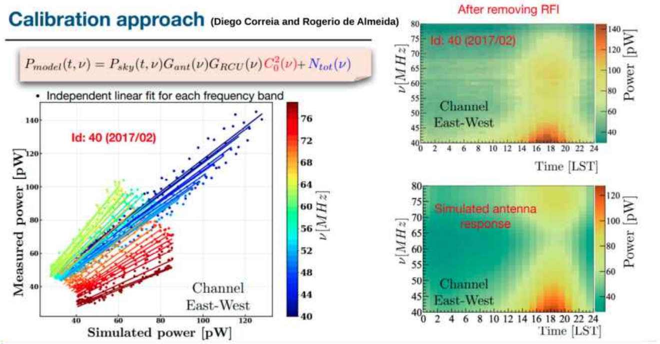
- Correcting for temperature dependence of signal amplifiers

Raluca Smau, Alexandra Saftoiu **GAP** *2023-043*



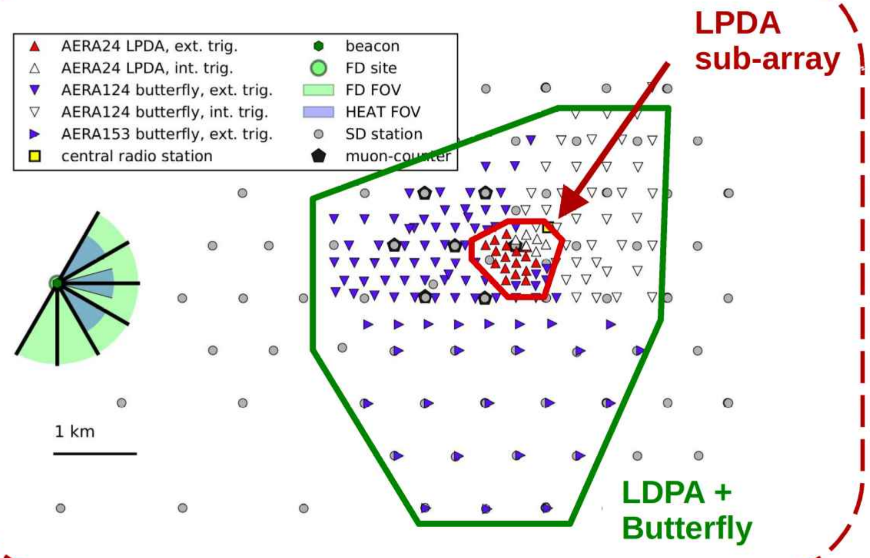
- Galactic calibration of the radio detectors

Diego Correia & Rogerio de Almeida **GAP** *2023-036*



- Improved event selection

Stricter quality cuts to reduce systematic uncertainties / avoid biases



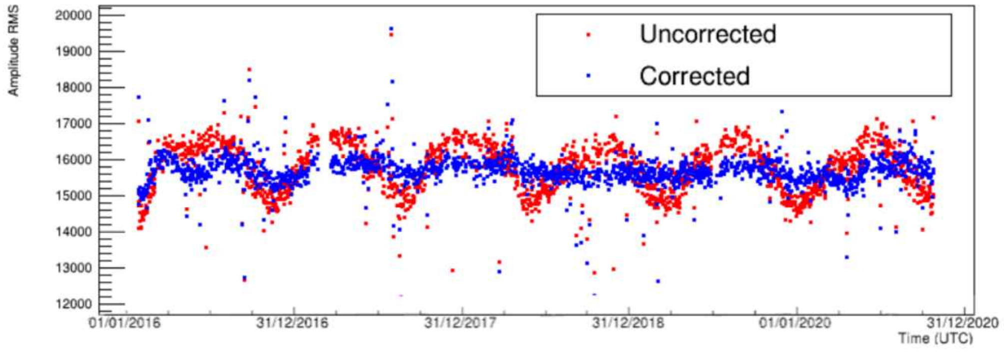
New simulations of measured events with all AERA stations

… and more

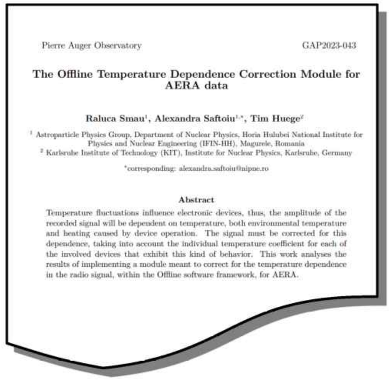
Testing the temperature correction..

Correcting temperature dependence of amplifiers

Raluca Smau, Alexandra Saftoiu



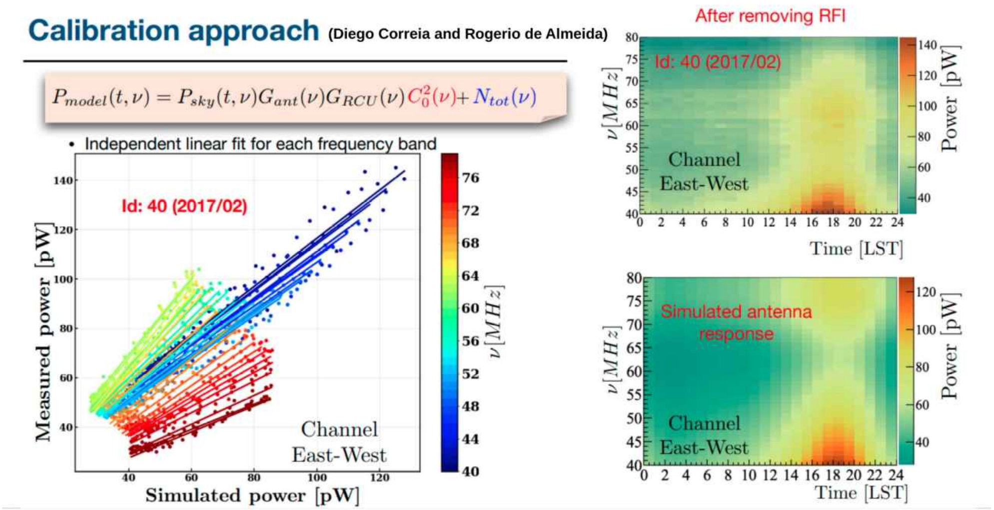
***GAP** 2023-043*



..and Galactic calibration

Absolute calibration using dominating Galactic background as reference

Diego Correia & Rogerio de Almeida



***GAP** 2023-036*

Temperature correction & Galactic calibration

- Offline modules recently finalized
- No big change with temperature correction
- Large influence of sky model choice ☐ in Galactic calibration

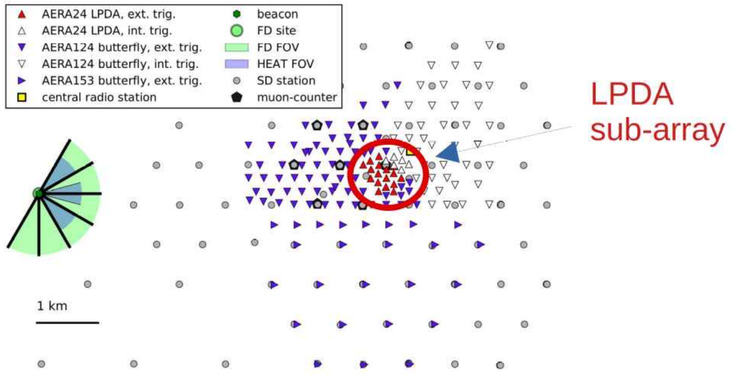
  → will use **average cal. constants** & estimate systematic uncertainties

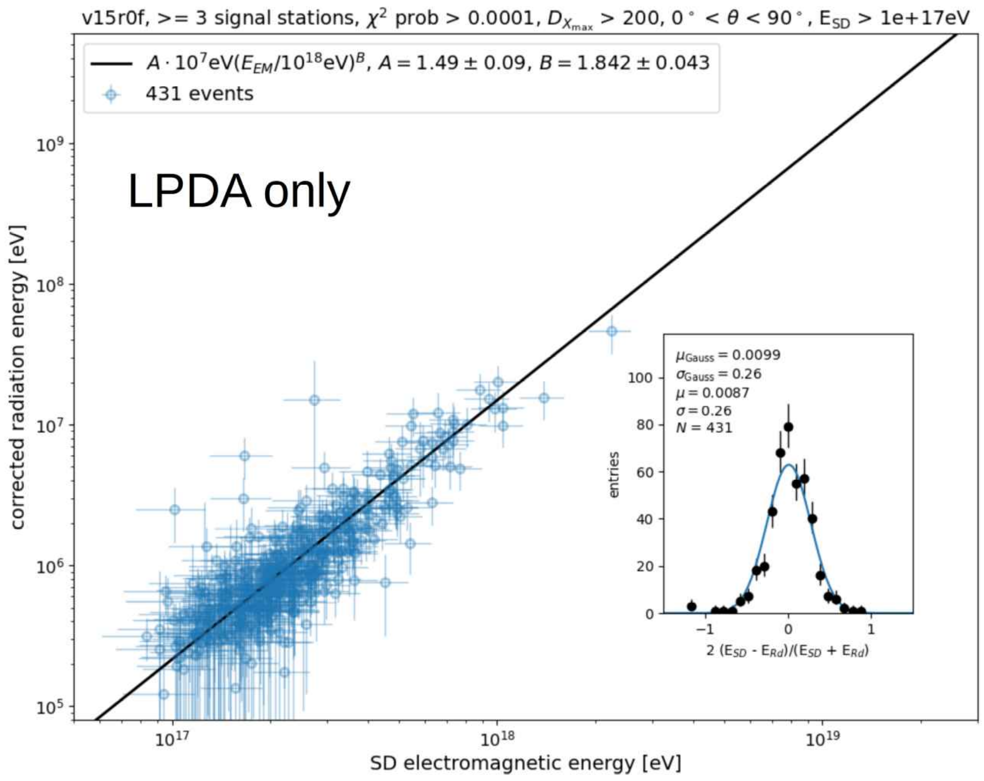
  → average change in A small

description	relative change in A
without temp-corr. & Gal. cal.	-
temp-corr. only	1.8%
LFmap	7.8%
GSM	1.8%
GSM16	-7.7%
LFSM	3.0%
GMOSS	5.4%
SSM	0.0%
ULSA	-10.8%
"Average model"	-3.0%

Fully including Butterfly antennas

- AERA antenna types: LPDA & Butterfly
- So far: basically only used LPDA stations



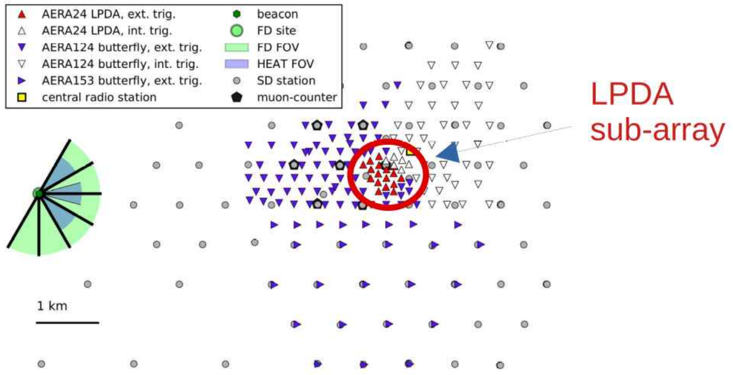


- LPDA:

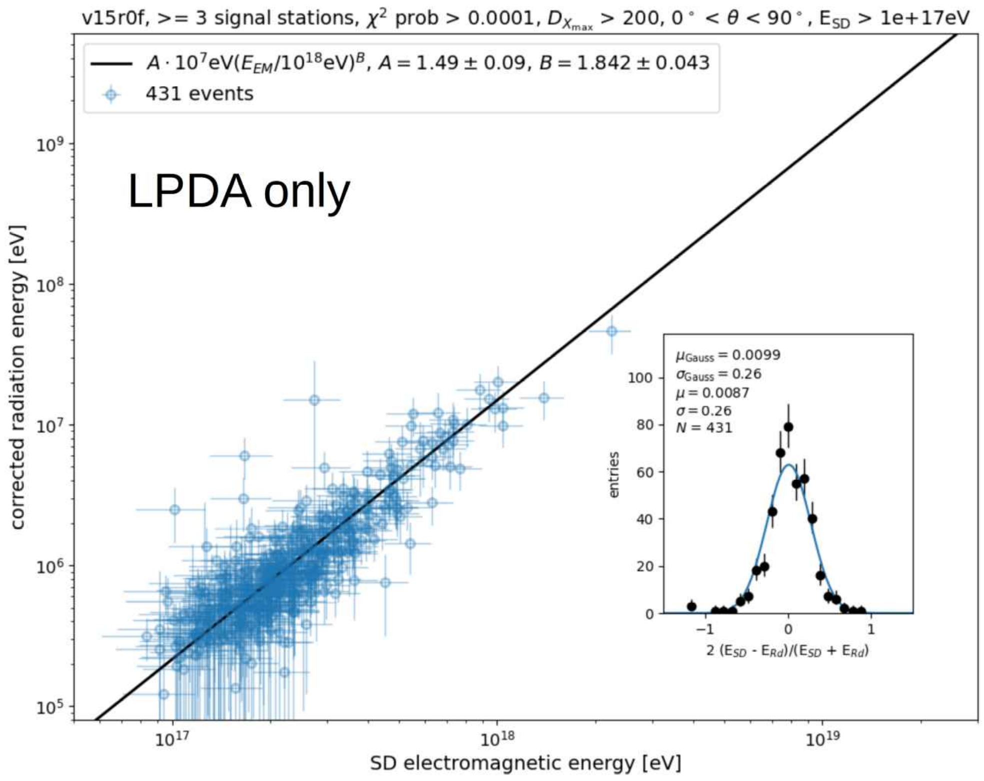
  Antenna response well understood

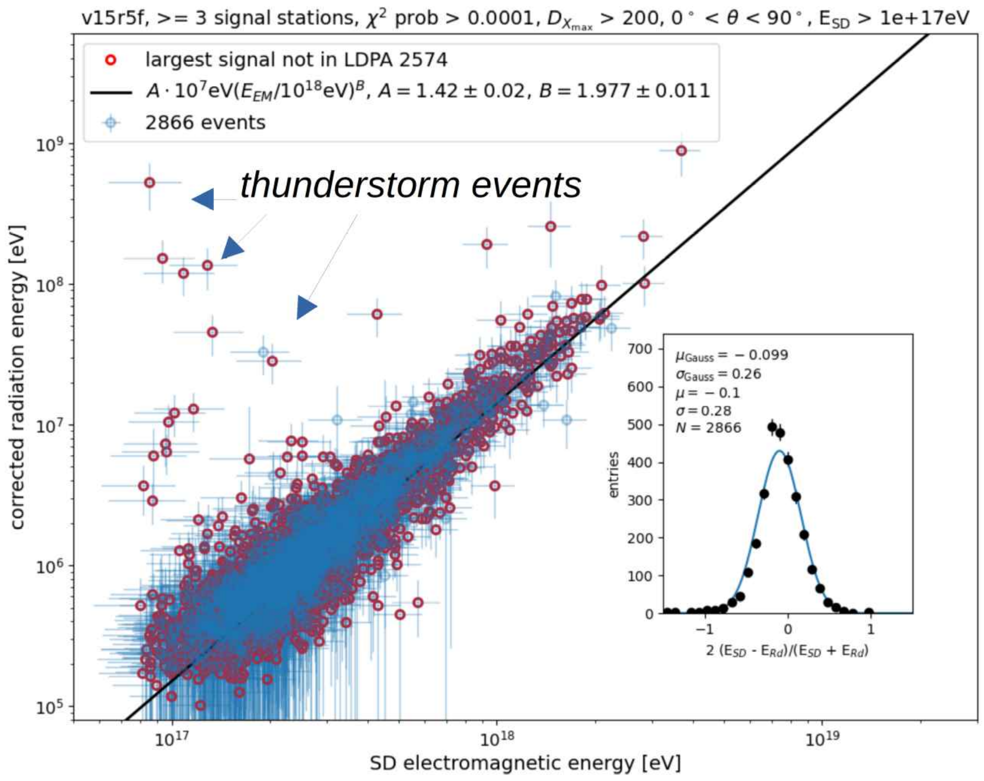
- Butterfly:
  - Previous drone measurement did not agree well with simulated antenna response pattern
    - Several investigations questioning validity of that drone measurement
  - Tests suggest: simulated pattern safe to use
    - To be confirmed from ongoing drone campaign

Fully including Butterfly antennas



- AERA antenna types: LPDA & Butterfly
- So far: basically only used LPDA stations
  - Fully including Butterfly stations increases statistics greatly
  - Gain in statistics allows to set stricter quality cuts / energy threshold





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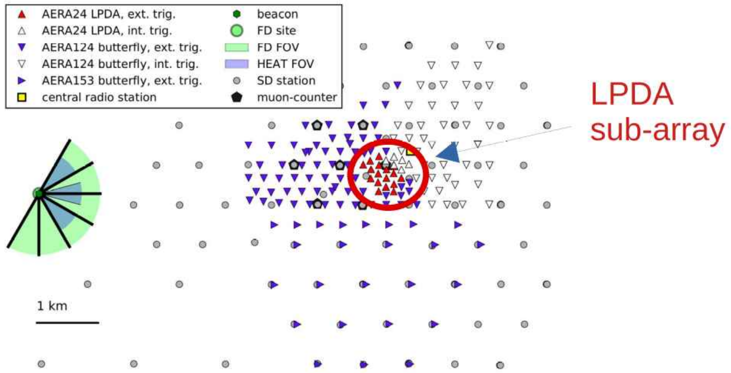

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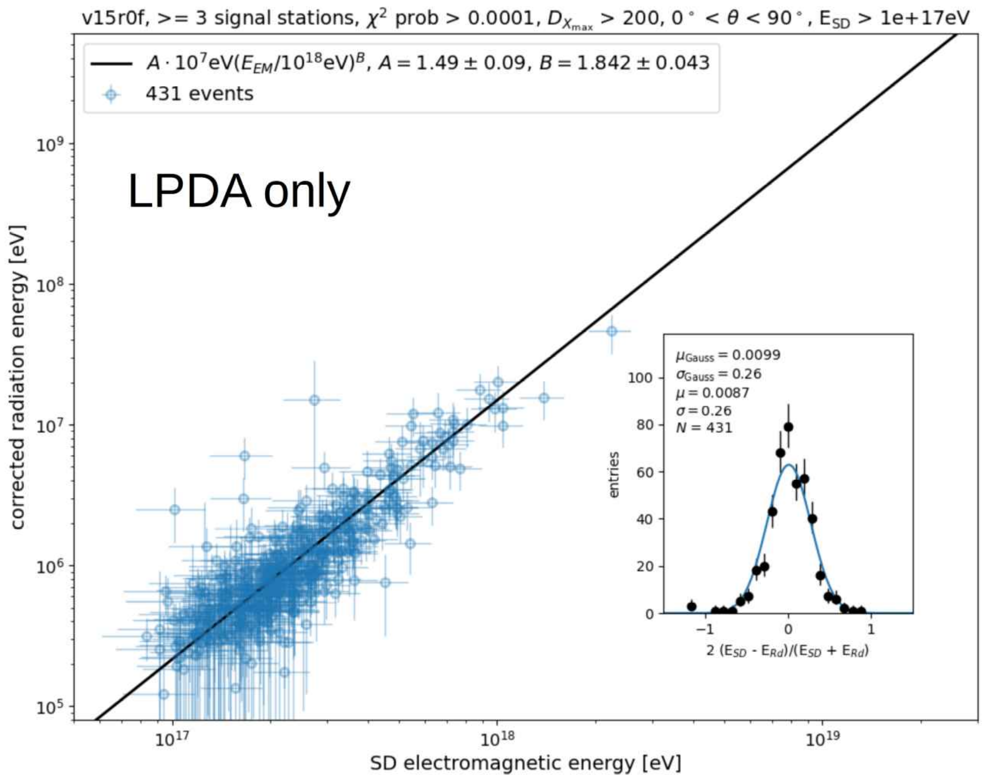

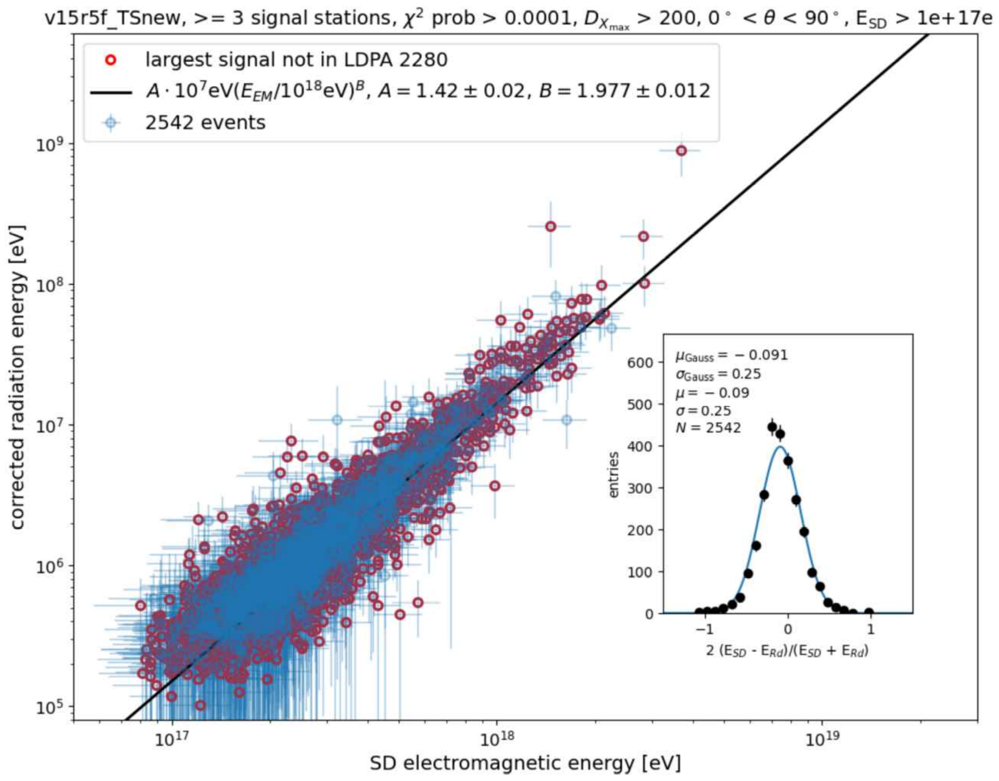

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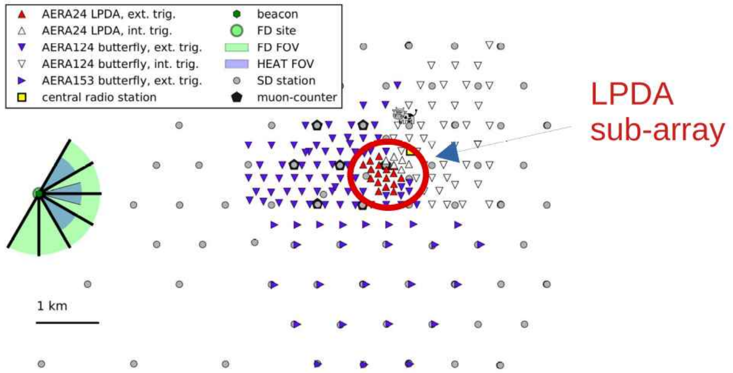

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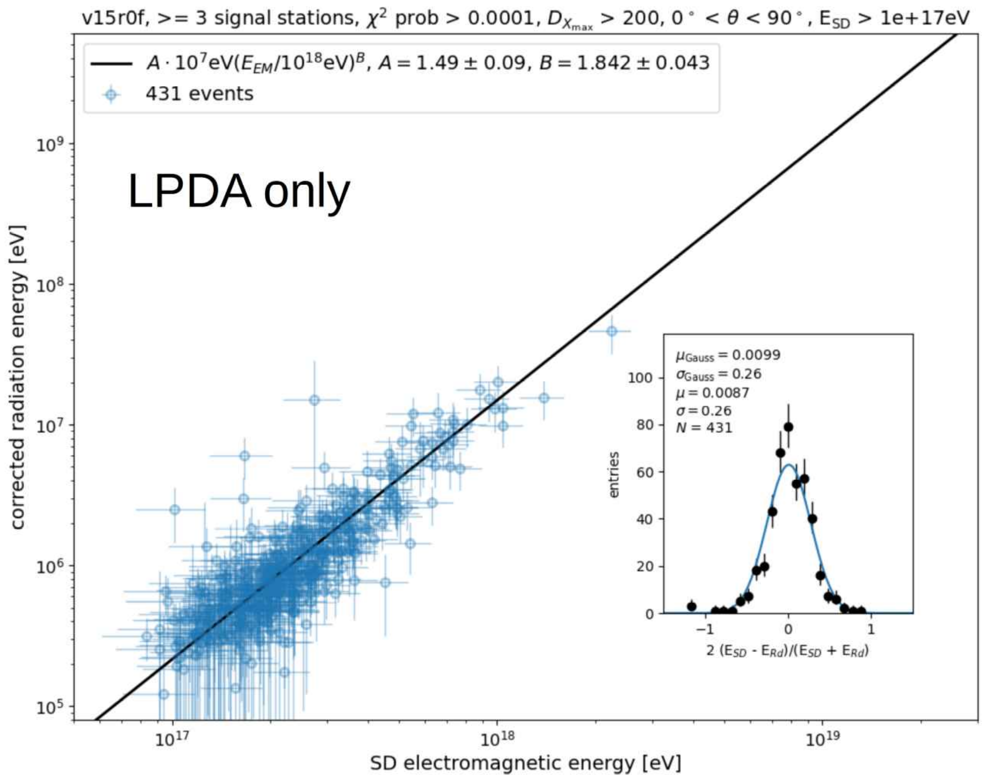
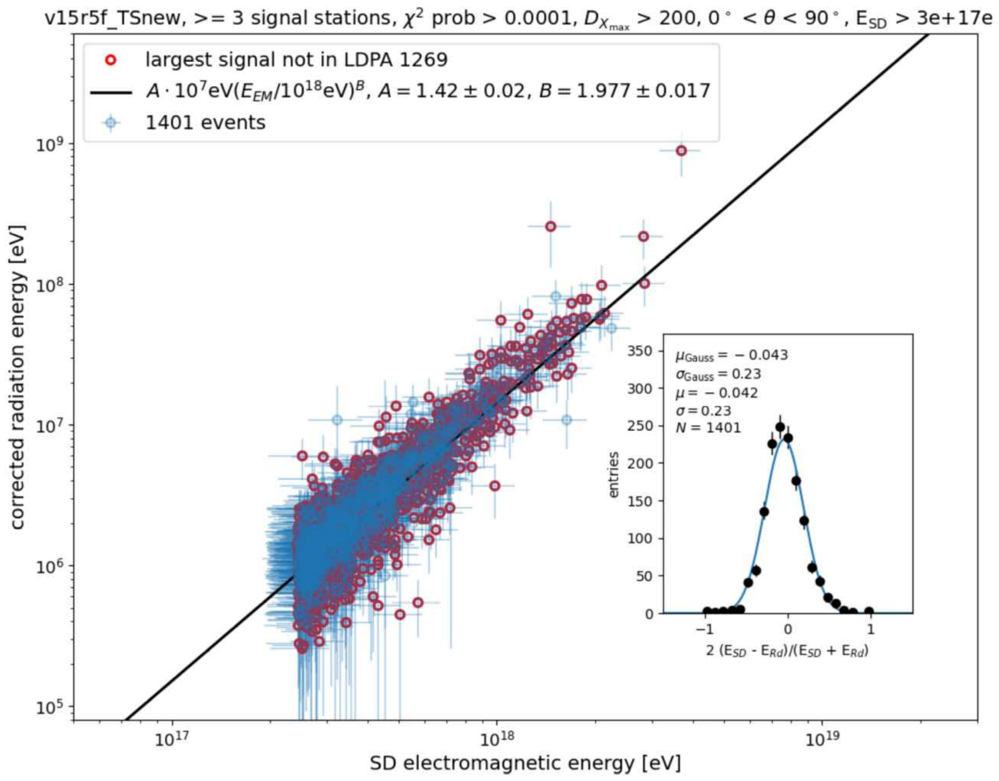
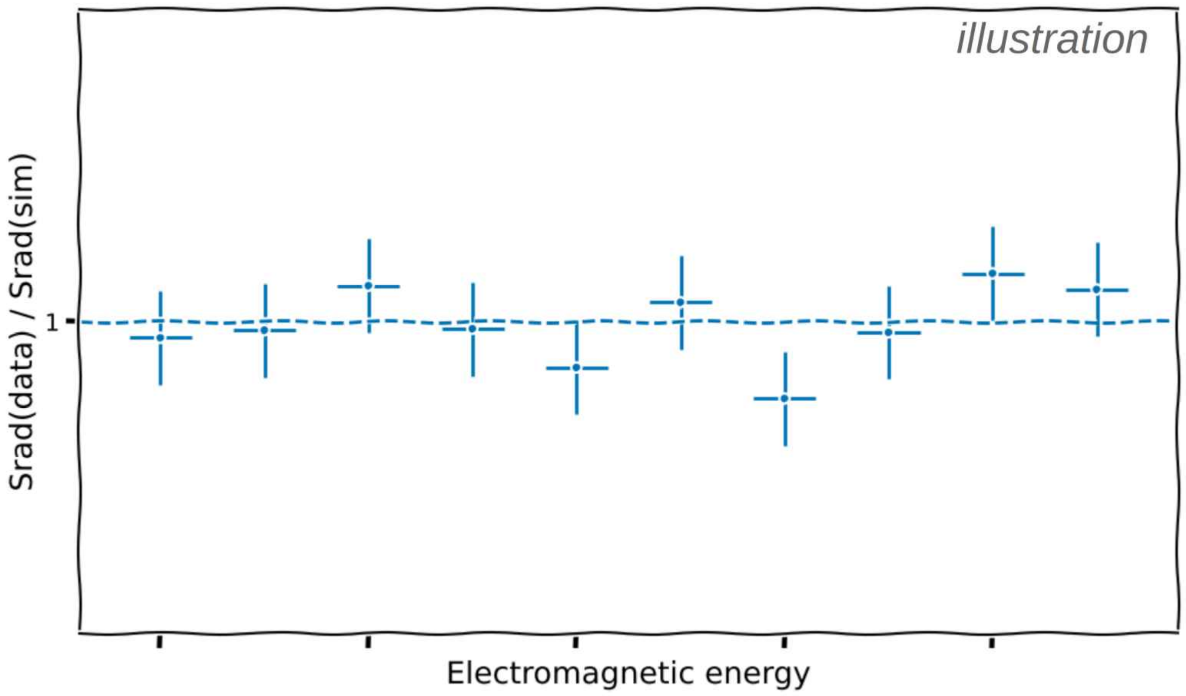




Planned next steps

- Turning away from academic A determination, so far bound to $E_{SD} = 10^{18}$ eV
  - Choose pivot energy such that A and B are less correlated
- Direct comparison of data and simulations:
  - Run new event simulations including Butterfly stations
  - Balance statistics with systematics (e.g. $\geq$ 5 radio signal stations)
  - Evaluate S_{rad} ratio between data and simulations (as function of energy)



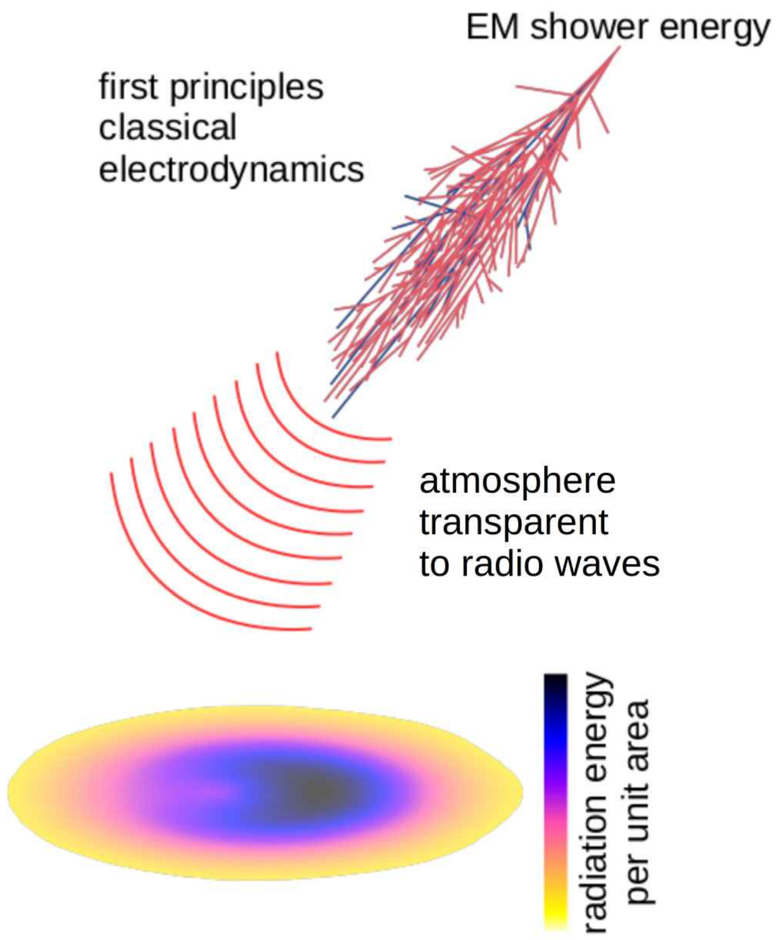
Simulations by V. Lenok

Table 3.2: List of the parameters used for the CORSIKA simulations.

Name of parameter	Set value
Cosmic-ray nuclei (PRMPAR)	H and Fe
Observation level (OBSLEV)	1570 m a.s.l.
High-energy hadron interaction model	QGSJetII-04
Low-energy hadron interaction model	URQMD 1.3cr
Energy cuts for hadrons, muons, electrons, and photons	0.3 GeV 50 MeV
correspondingly (ECUTS)	250 keV 250 keV
Outer radius of NKG electron distribution (RADNKG)	5 km
Electron multiple scattering length factor (STEPF)	0.5
Using NKG and/or EGS4 (ELMFLG)	T T
Muon multiple scattering angle (MUMULT)	T
Magnetic field	according to WMM
Atmosphere model	GDAS, curved

The cosmic-ray energy scale with AERA

Theoretical calculation

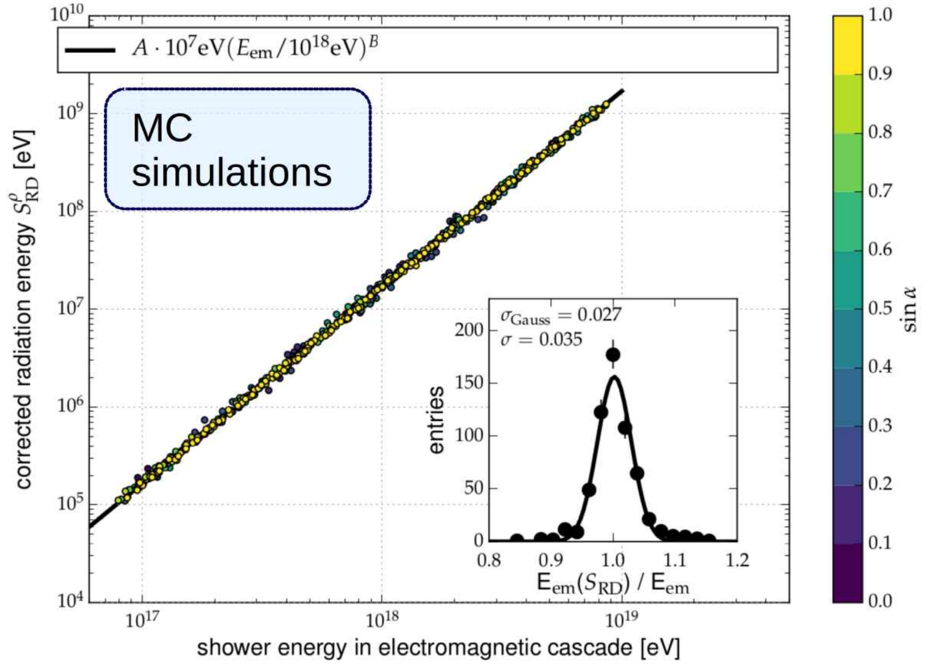


transferable to calorimetric/
cosmi-ray energy

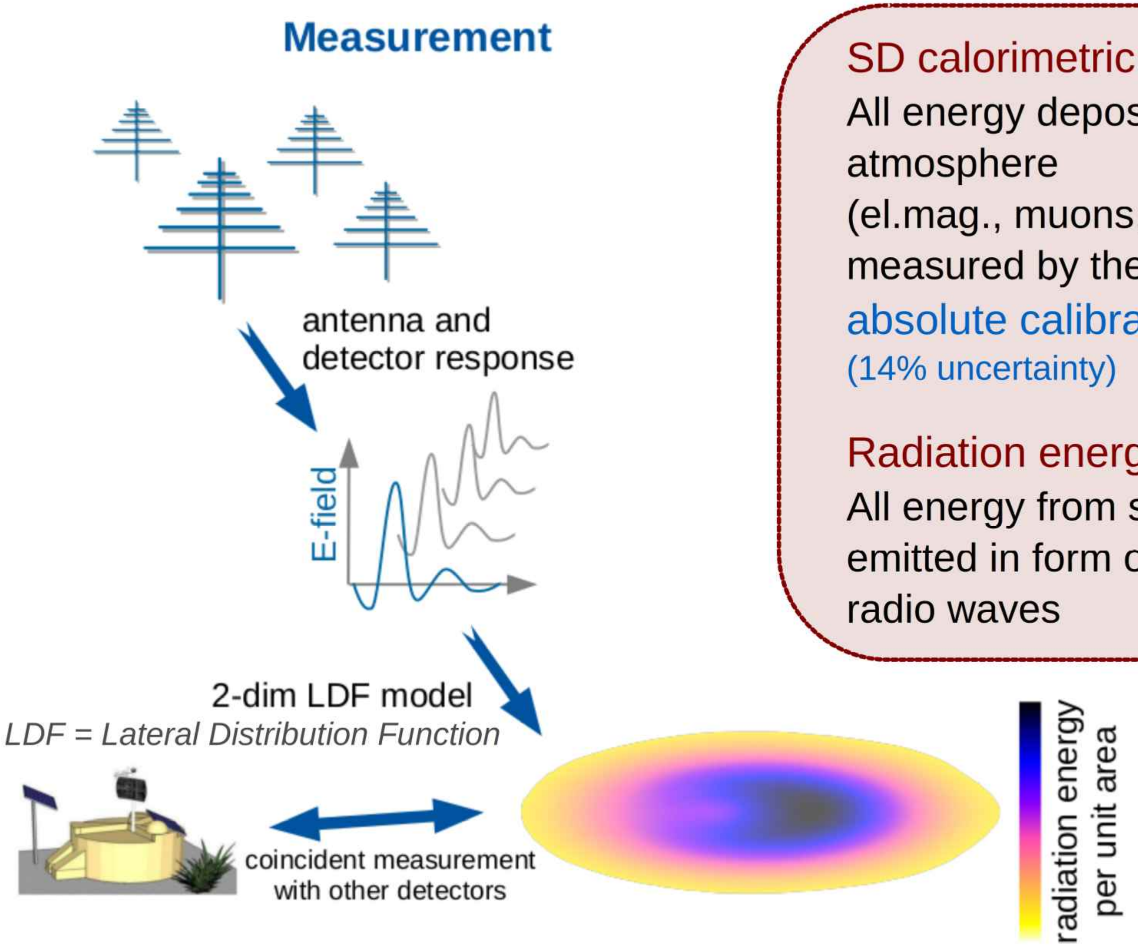
Electromagnetic energy E_{em}
All energy deposited by the electromagnetic shower component (e^-,e^+,γ) in the atmosphere

Radiation energy $S^{\rho\theta}_{RD}$
All energy from shower emitted in form of radio waves

$$S^{\rho\theta}_{\mathrm{RD}} = 1.639 \times 10^7 eV \left(\frac{E_{\mathrm{em}}}{10^{18} eV} \right)^{1.978}$$



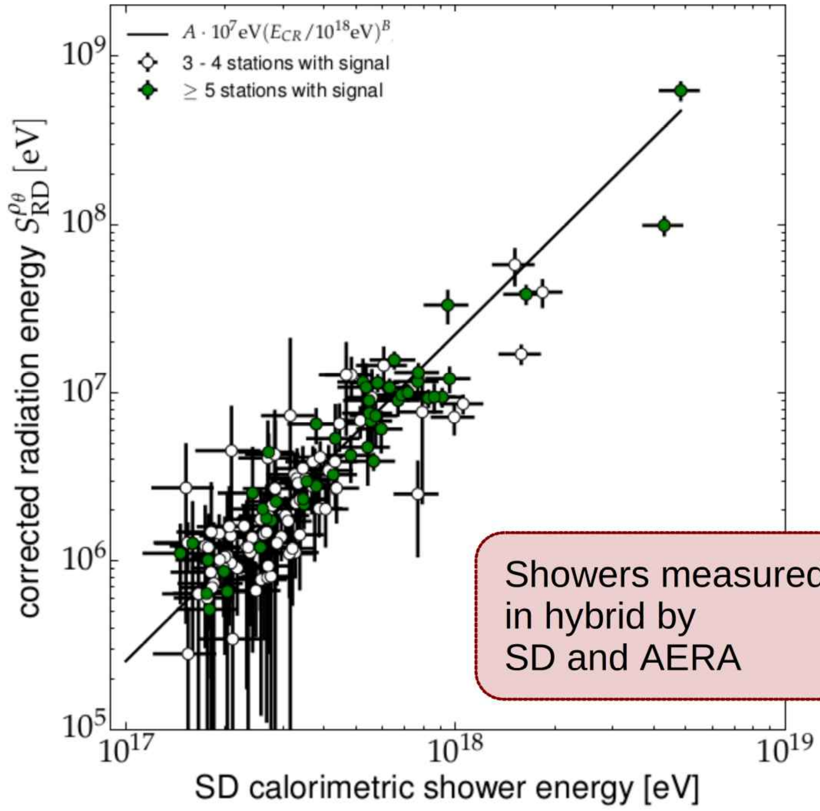
The cosmic-ray energy scale with AERA



SD calorimetric energy $E_{SD,cal}$
All energy deposited in the atmosphere
(el.mag., muons, hadrons)
measured by the SD
absolute calibration from FD
(14% uncertainty)

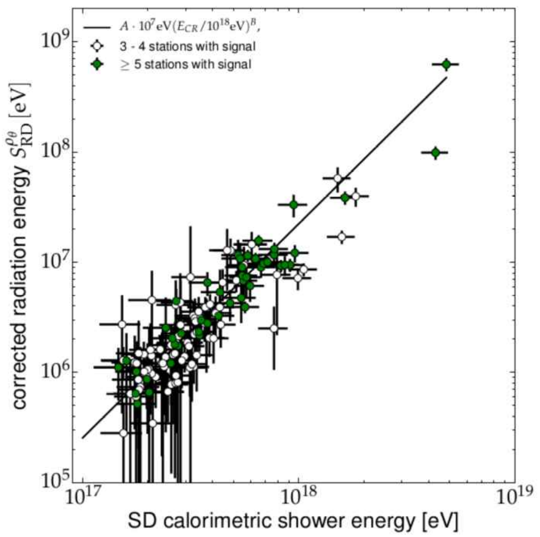
Radiation energy $S^{\rho\theta}_{RD}$
All energy from shower emitted in form of radio waves

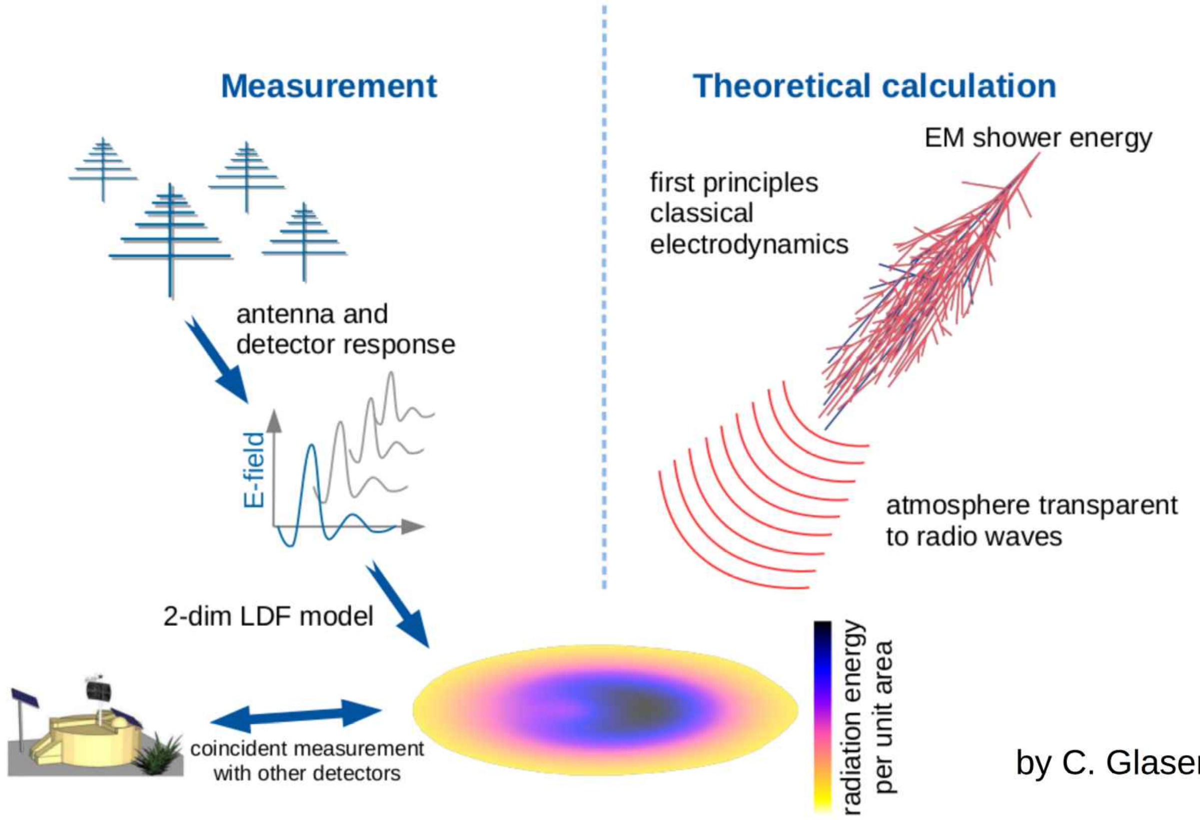
$$S^{\rho\theta}_{\mathrm{RD}} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,cal}}}{10^{18} eV}\right)^B$$

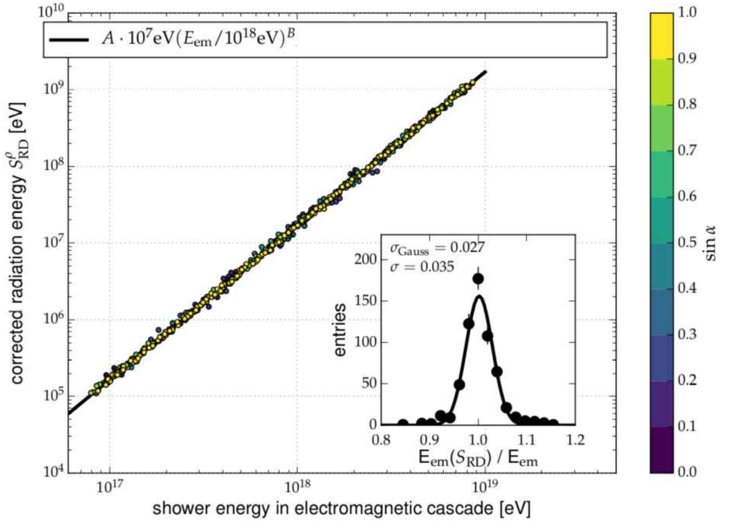


Showers measured in hybrid by SD and AERA

The cosmic-ray energy scale with AERA







by C. Glaser

$$S_{\mathrm{RD}}^{\rho\theta} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,cal}}}{10^{18} eV}\right)^B$$

Allows to compare CR energy scales from FD and radio

$$S_{\mathrm{RD}}^{\rho\theta} = 1.639 \times 10^7 eV \left(\frac{E_{\mathrm{em}}}{10^{18} eV}\right)^{1.978}$$

Testing different methods for estimating the energy fluence

Energy fluence estimation methods

Standard method

$$f = \epsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$$

- Assume white noise
- Subtract content of noise window from content of signal window
- Simplistic but straight-forward

➜ Choise to use for now

Method with background subtraction ("Fabrizia's method")

$$M(\nu)^2 = (S(\nu) + B(\nu)\cos\phi)^2 + B(\nu)^2 \sin^2\phi$$

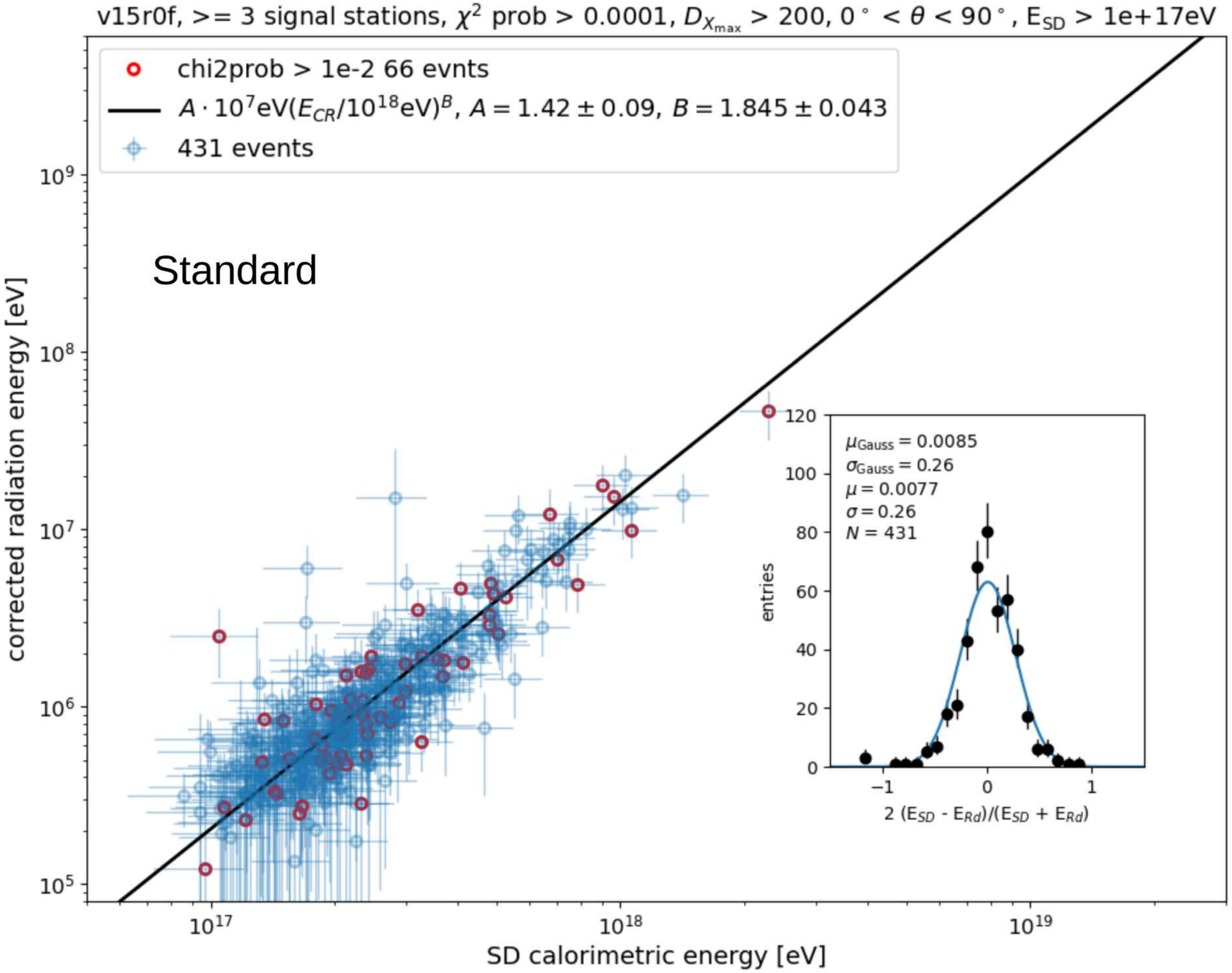
measurement signal background

↳ $$f_{rec} = \epsilon_0 c \Delta t \left(\sum_{\nu_{min}}^{\nu_{max}} S_{rec}(\nu)^2 \right)$$

- Consider phase difference between signal and background
- Involved formalism
- Sophisticated but complex, apparently not completey flawless

Fit comparison v15r0f vs 15r1f

- **Data reconstruction**
- Test influence of signal estimation method
  - v15r0f: standard reco
  - v15r1f: reco with background subtraction
- No filters applied
- Slightly more events with standard reconstruction (Significantly more with a very good fit, by chi²)
- With Fabrizia's method, B is much closer to 1.98, within 1.5 sigma (fit uncertainty); 3.5 sigma for standard reco
- Spread of residuals slightly smaller for standard reco and mean slightly closer to 0
- Methods reasonably compatible in A, but less compatible in B (2 sigma in either direction)



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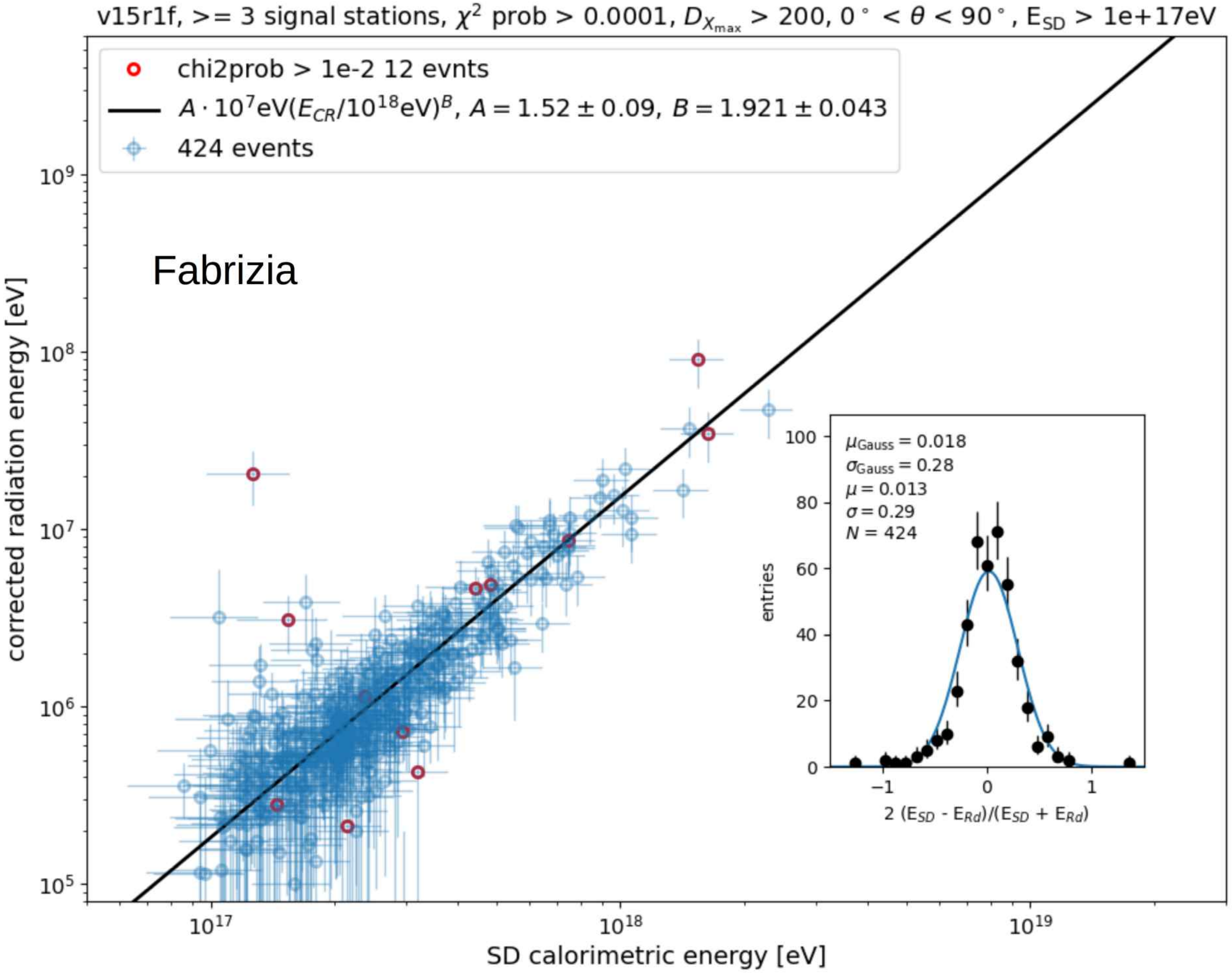
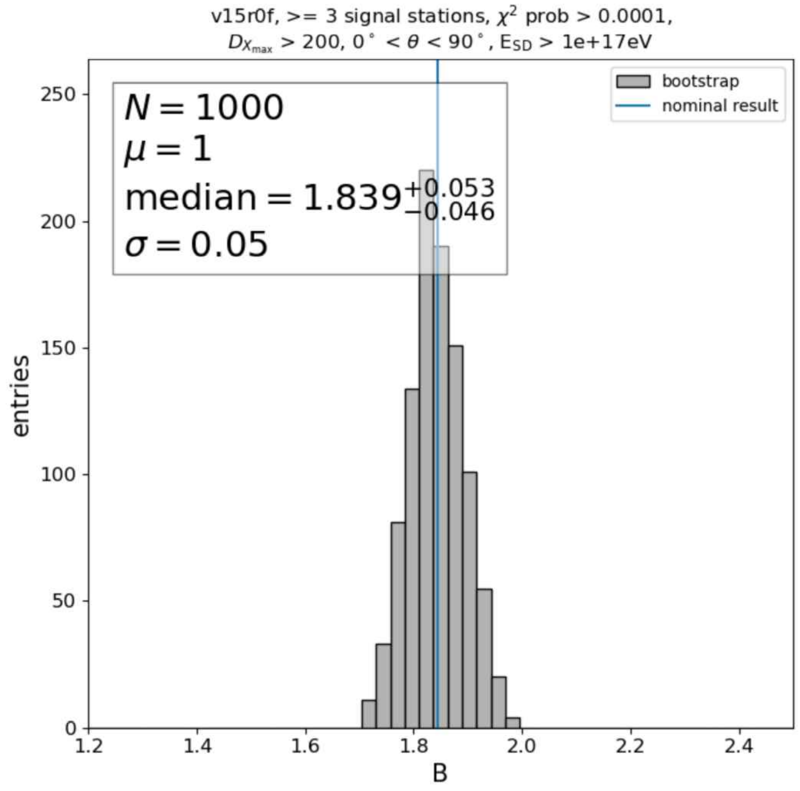


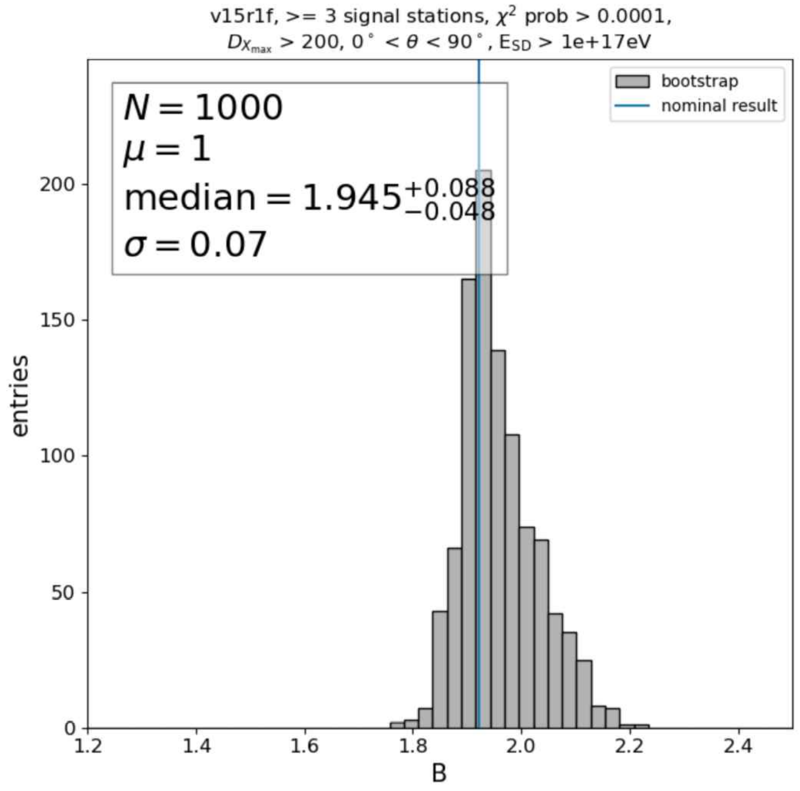
Bootstrapping uncertainties

- Uncertainties from bootstrapping on B only slightly larger, except for upwards uncertainty with Fabrizia’s method
  - Fabrizia’s method even better compatible with B=1.98
  - Methods still not well compatible

Standard



Fabrizia



Fit comparison v15r0f vs 15r1f

- **Data reconstruction**
- Test influence of signal estimation method
  - v15r0f: standard reco
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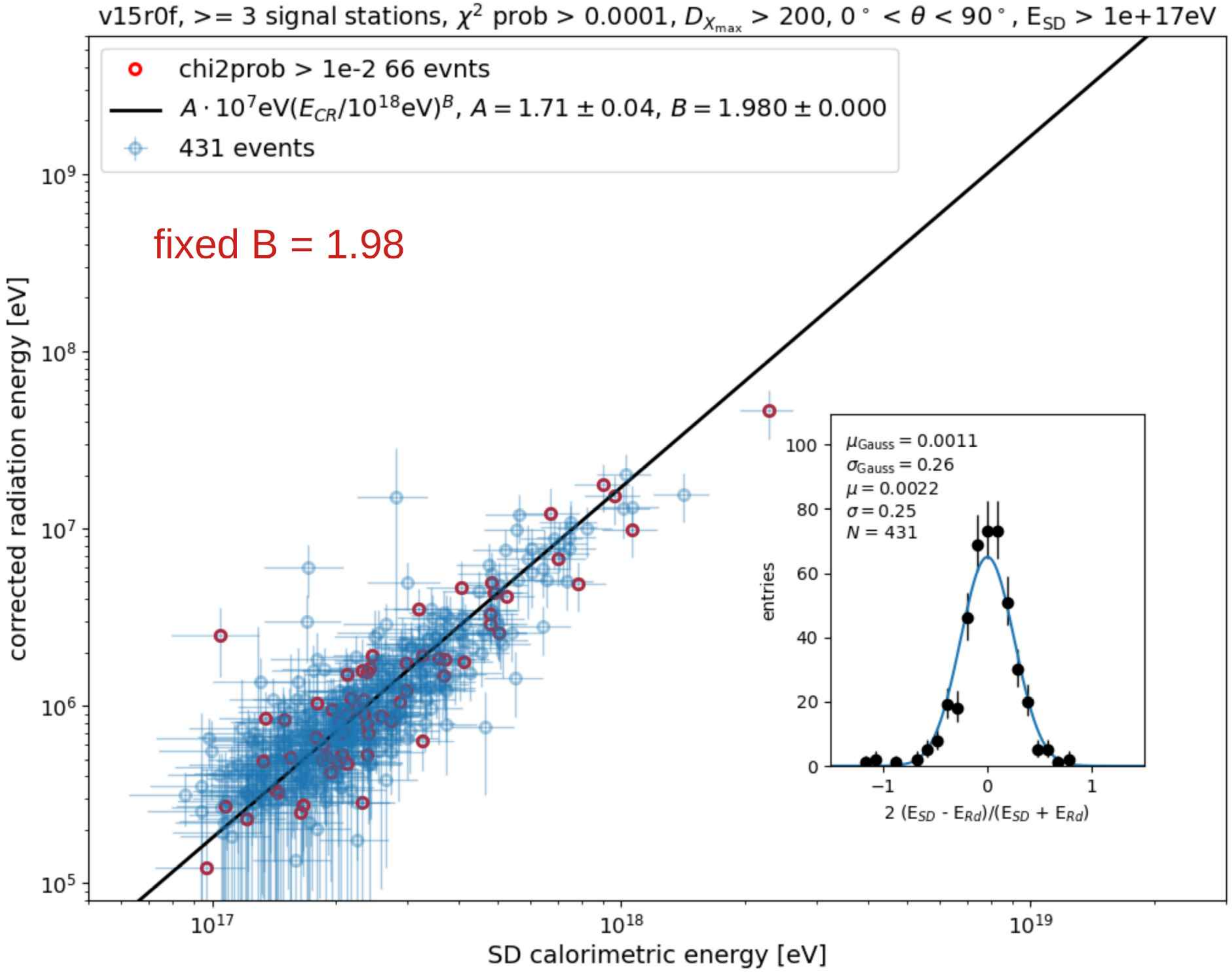
- No filters applied
- Also with B fixed to 1.98, fit values for A not well compatible
  → systematic shift



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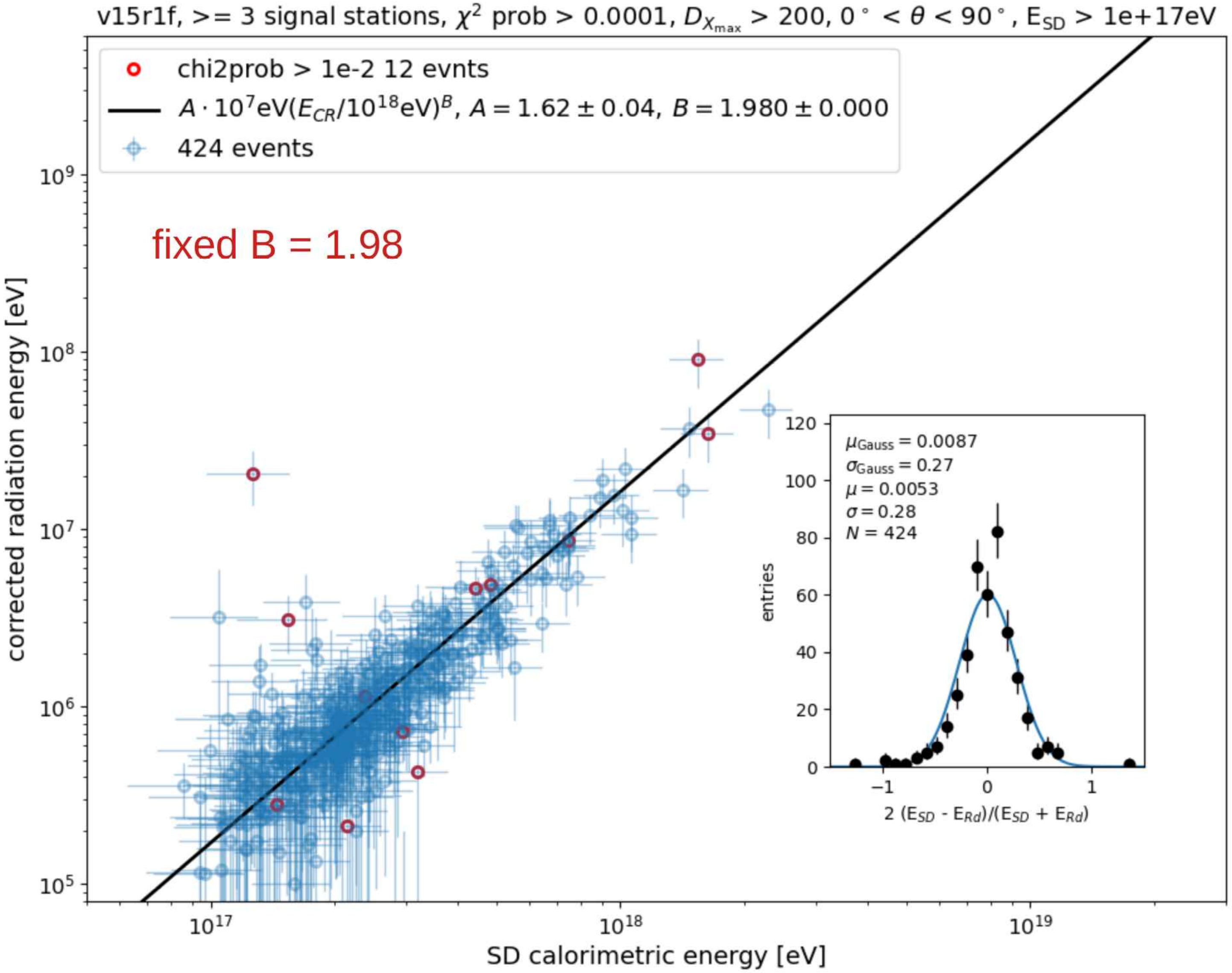
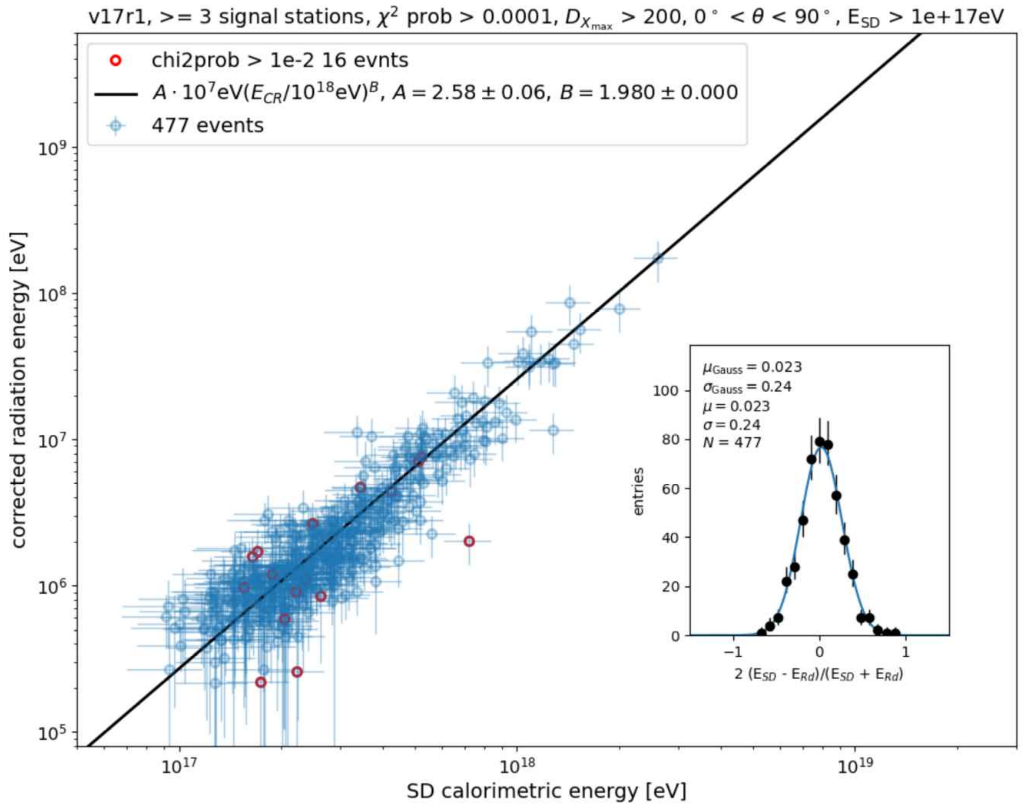


Simulation X-check v17r1 vs 17r3

- **Simulations (V. Lenok)**
- same number of events
  - slightly more with good chi^2 in standard reco
- Good agreement in A (absolute values not to be compared to data though)
- B values closer to 1.98 for both methods, but similarly incompatible as for data (~2 sigma difference)



dataset	description	events	A [10^7eV]	B	bootstrap A	bootstrap B	A (fix B)	relative change in A
v15r0f	standard method	431	1.42 ± 0.09	1.845 ± 0.043		$1.839^{+0.053}_{-0.046}$	1.71 ± 0.04	
v15r1f	Fabrizia's method	424	1.52 ± 0.09	1.921 ± 0.043		$1.945^{+0.088}_{-0.048}$	1.62 ± 0.04	-5.2%
v17r1 (sim)	standard method	477	2.35 ± 0.11	1.905 ± 0.037			2.58 ± 0.06	
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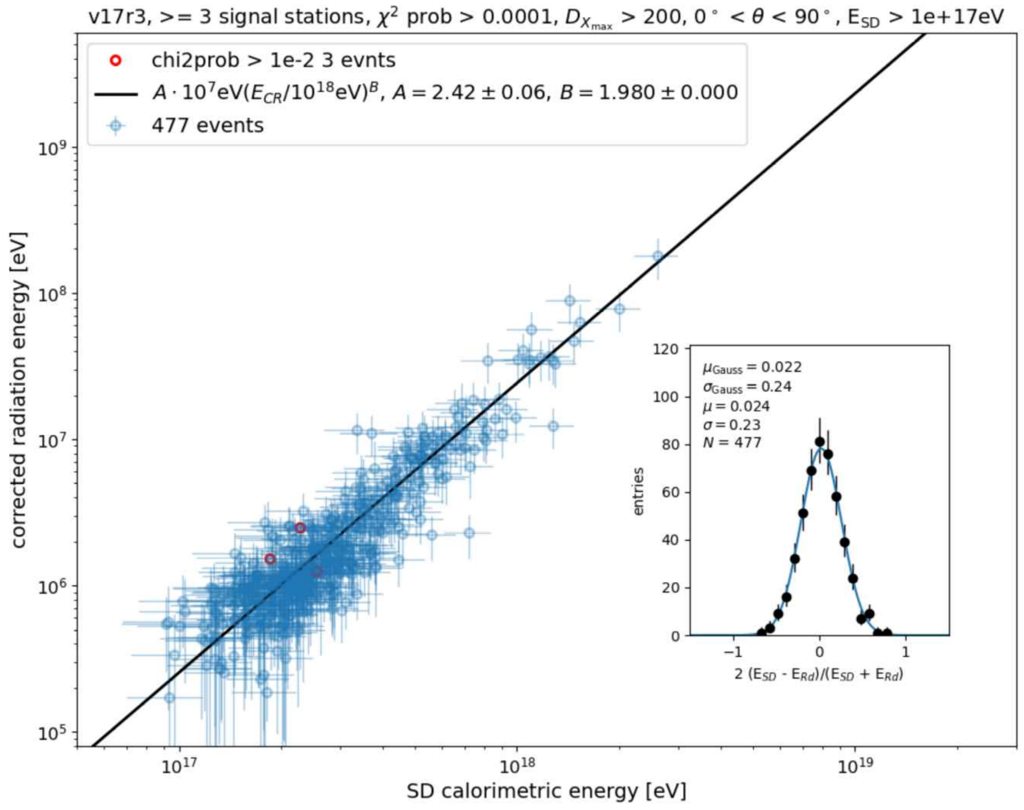

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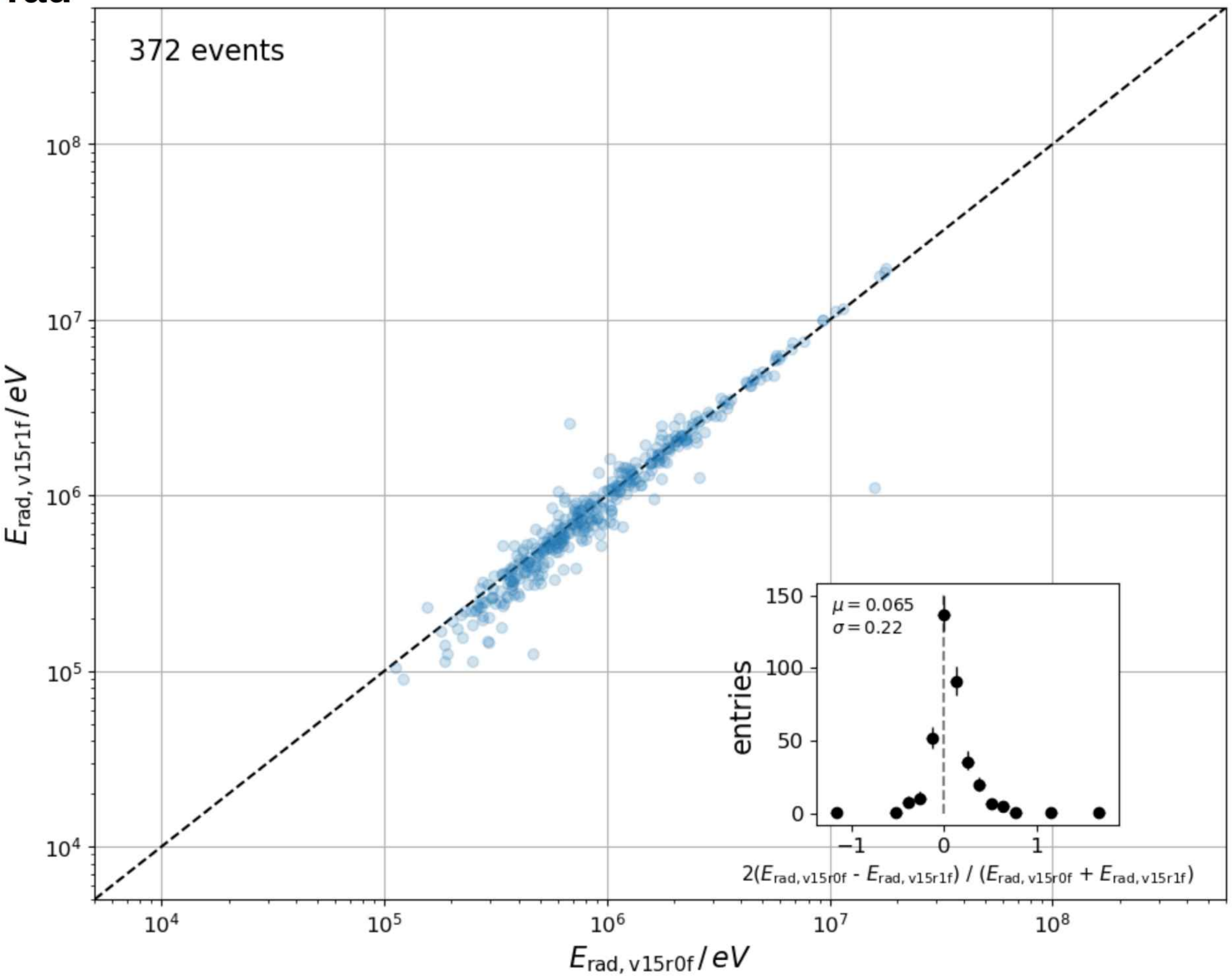
Dataset comparison - E_{rad}

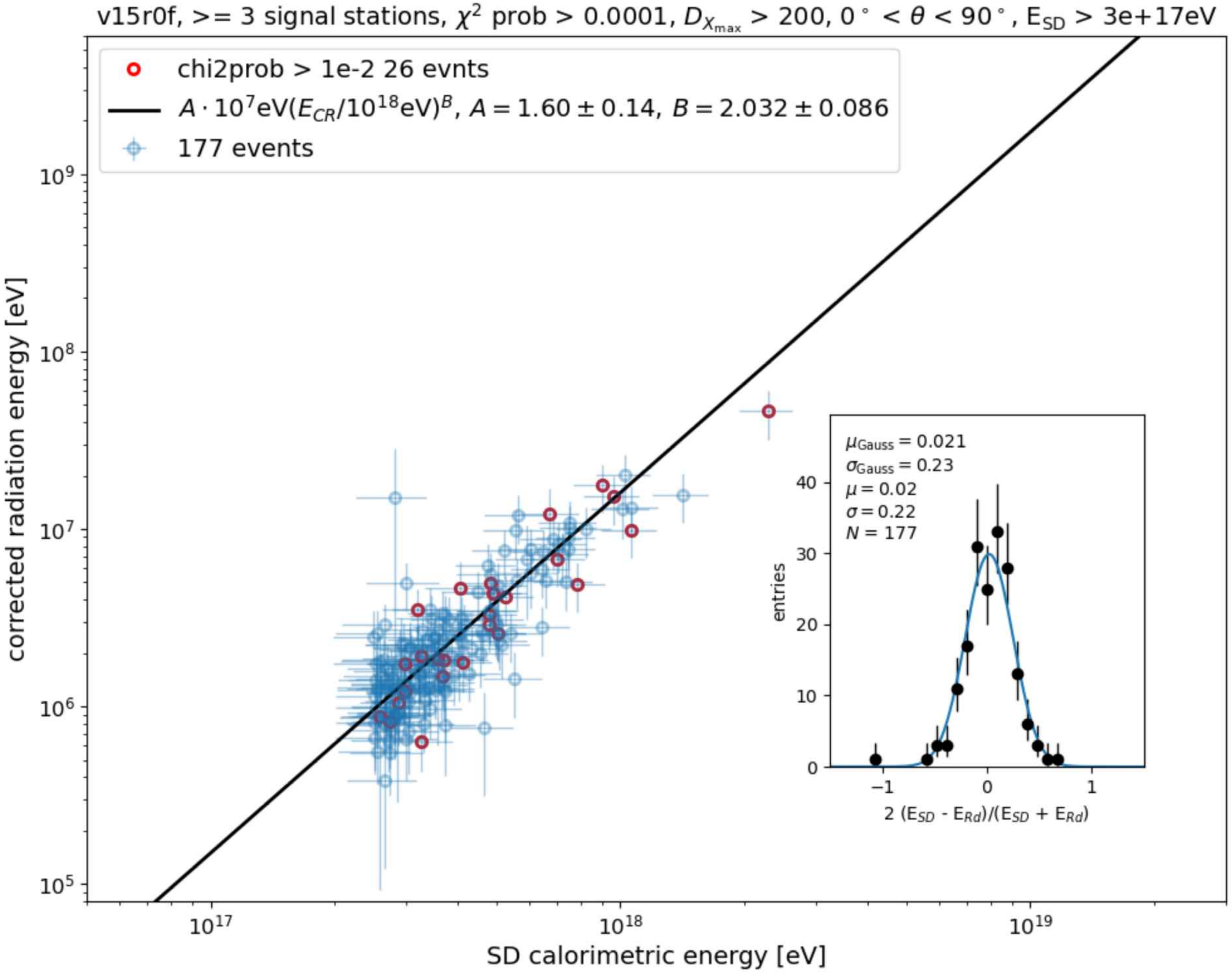
- **E_{rad} event-by-event (dataset overlap)**
- Good agreement above ~2.4x10^17 eV
- Below 2.4x10^17 eV, standard reco estimates are higher compared to reco with background subtraction
- Energy-dependent systematic
  - Could absorb in a systematic uncertainty



Fit comparison v15r0f vs 15r1f

- **Energy cut E_{SD} > 3x10^17 eV**
- Other settings unchanged

- Methods well compatible
- B > 2, although well within 1 sigma of B = 2



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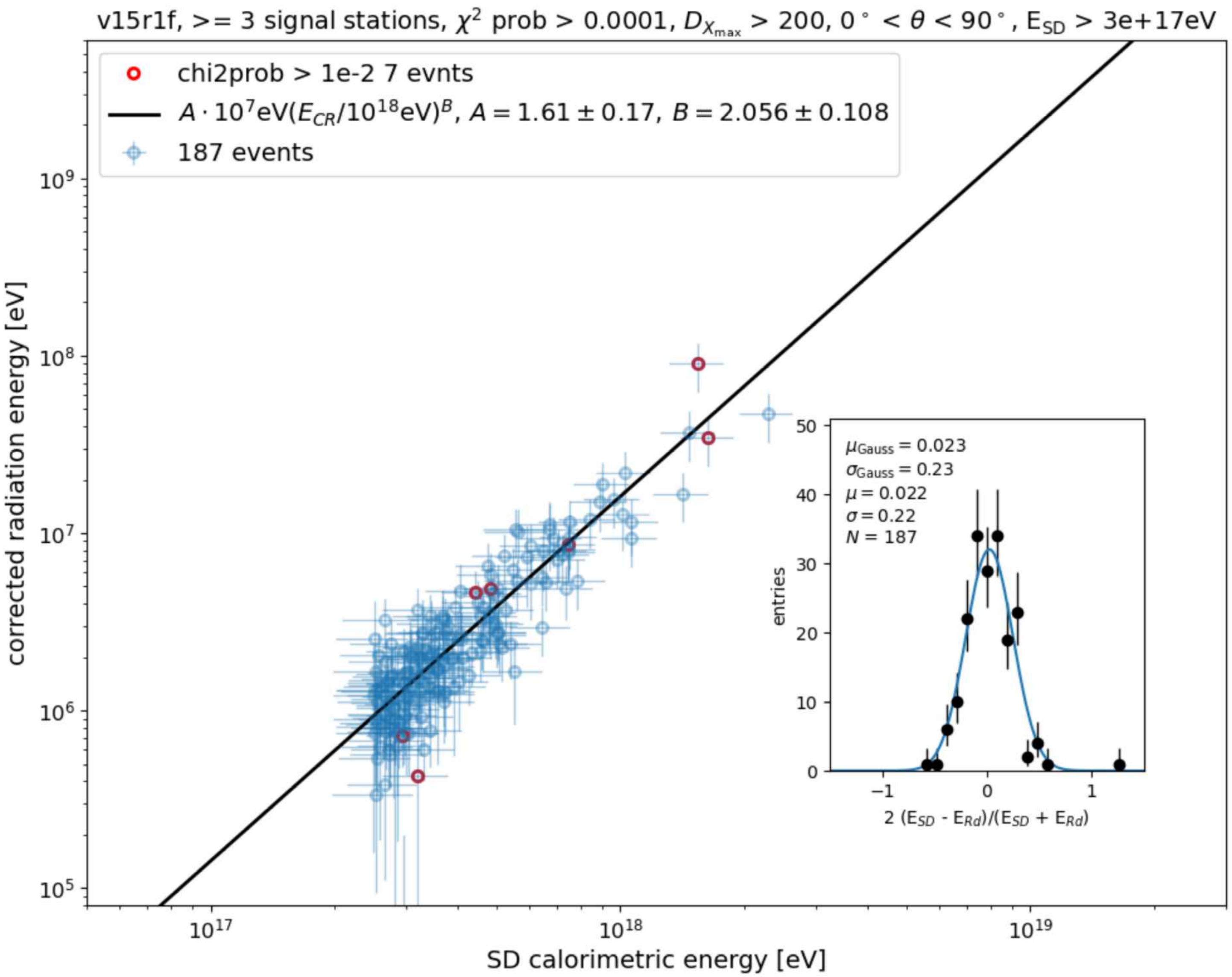
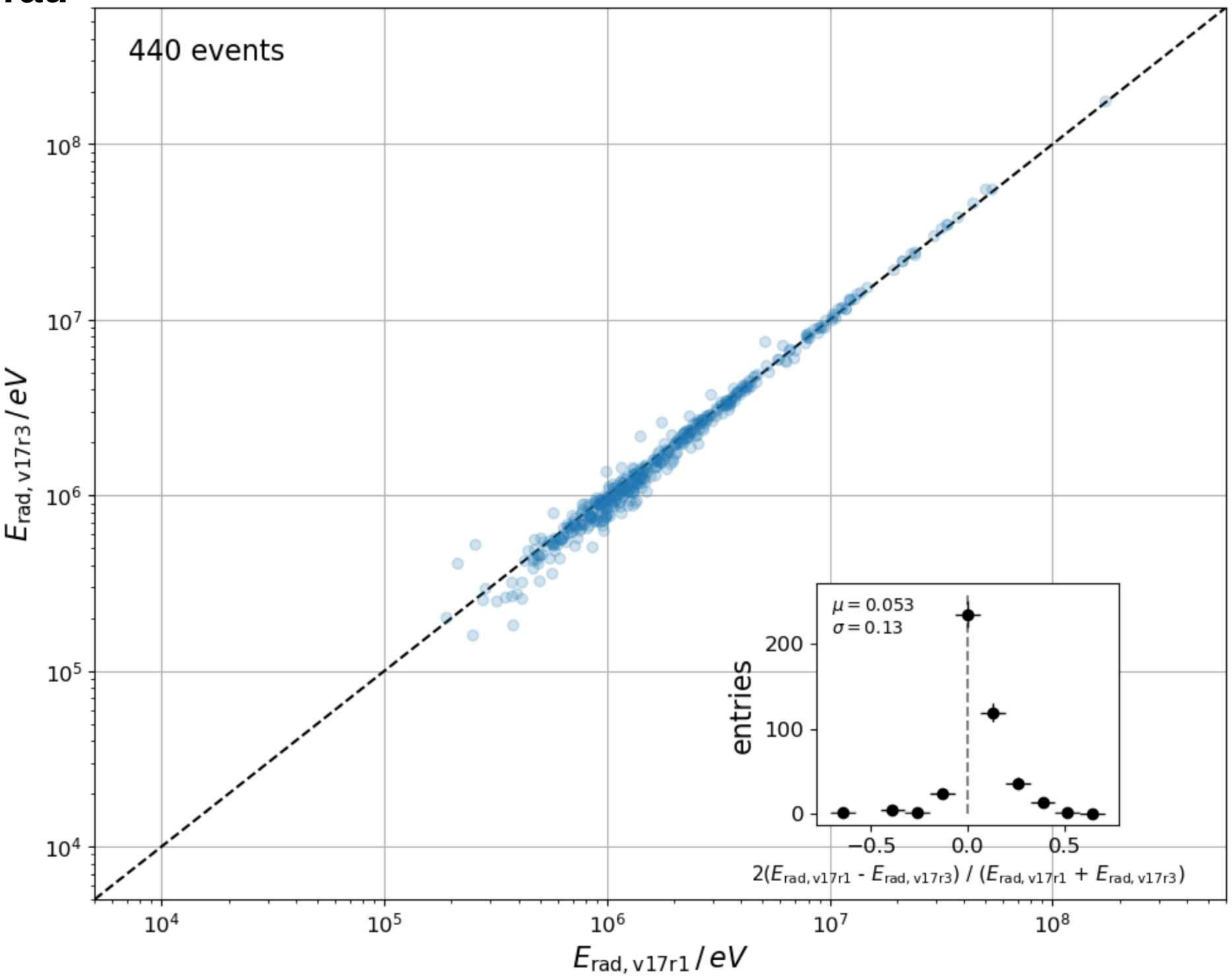


Sim.set comparison - E_{rad}

- **E_{rad} event-by-event (simset overlap)**
- Good agreement at higher energies
- Below ~3x10^6 eV in E_{rad}, energy estimate with Fabrizia's method is systematically lower than with the standard method

  → same as for data



Testing different filters

Signal filter (remove RFI)

Bandstop filter

- Fourier transform of signal (per channel)
- Exceeding frequency bins set to zero
- Good at removing RFI, but also cuts away signal

Sinewave suppressor

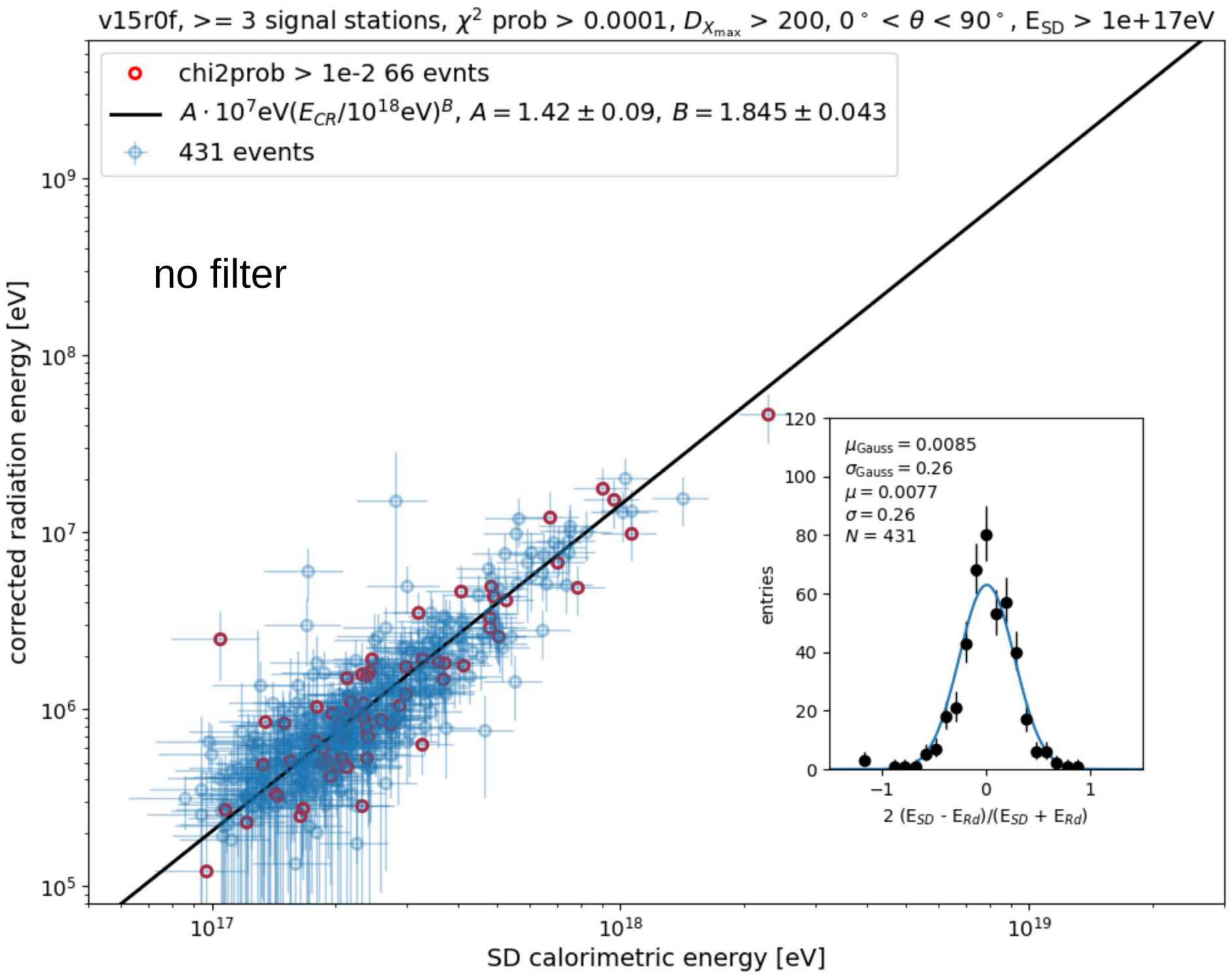
- Outside signal window, sine waves are fit to the trace
- Determine amplitude, frequency and phase of RFI
- Remove from signal window
- More sophisticated

No filter

- Leaves trace as it is, incl. any left RFI
- Much of the noise should be removed during signal calculation anyway

Fit comparison v15r0f vs v14r0f vs v15r2f

- **Data reconstruction**
- Test influence of niose filter
  - v15r0f: no filter
  - v14r0f: Bandstop filter
  - v15r2f: Sinewave suppressor
- Standard method for energy fluence estimation
- Event number reduced with Bandstop filter compared to no filter or Sinewave supp.
- Difference in fitted B within 1 sigma, differences in A slightly larger
- Lowest A value for bandstop filter (11% less than without filter),
  also observed by Florian: bandstop filter cuts out part of the spectrum, so not only noise but also signal
- Energy estimates also slightly lower for Sinewave suppressor compared to no filter



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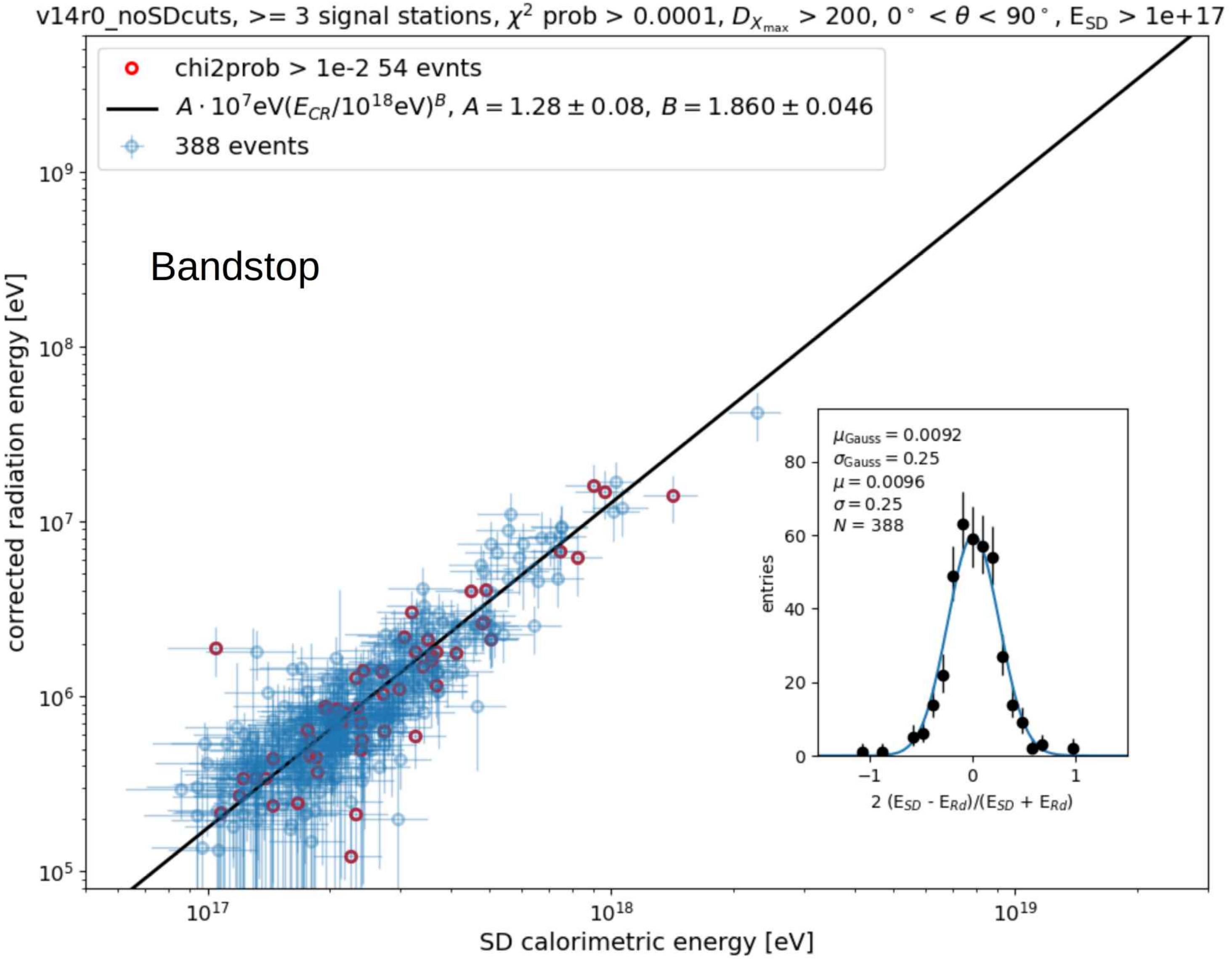

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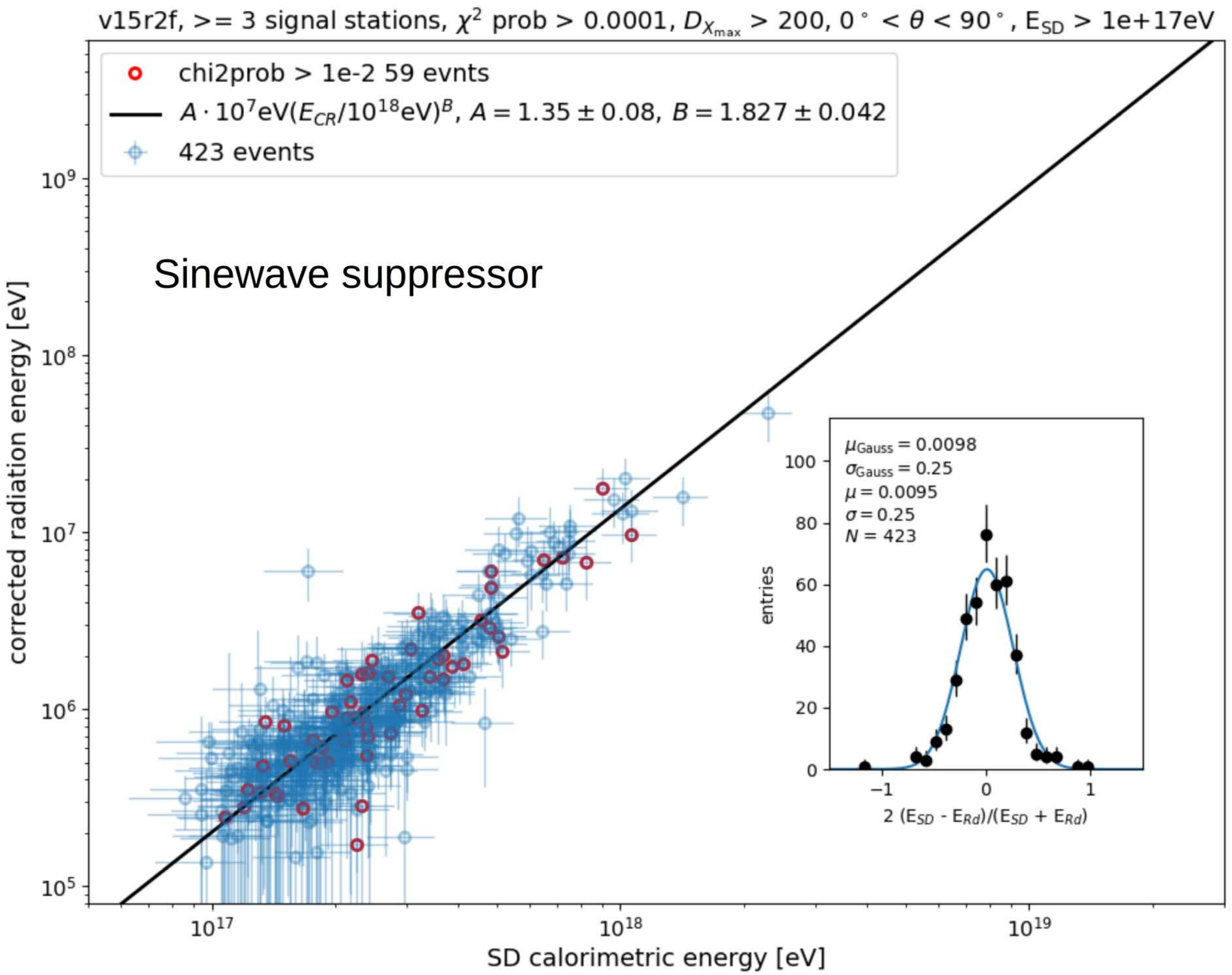
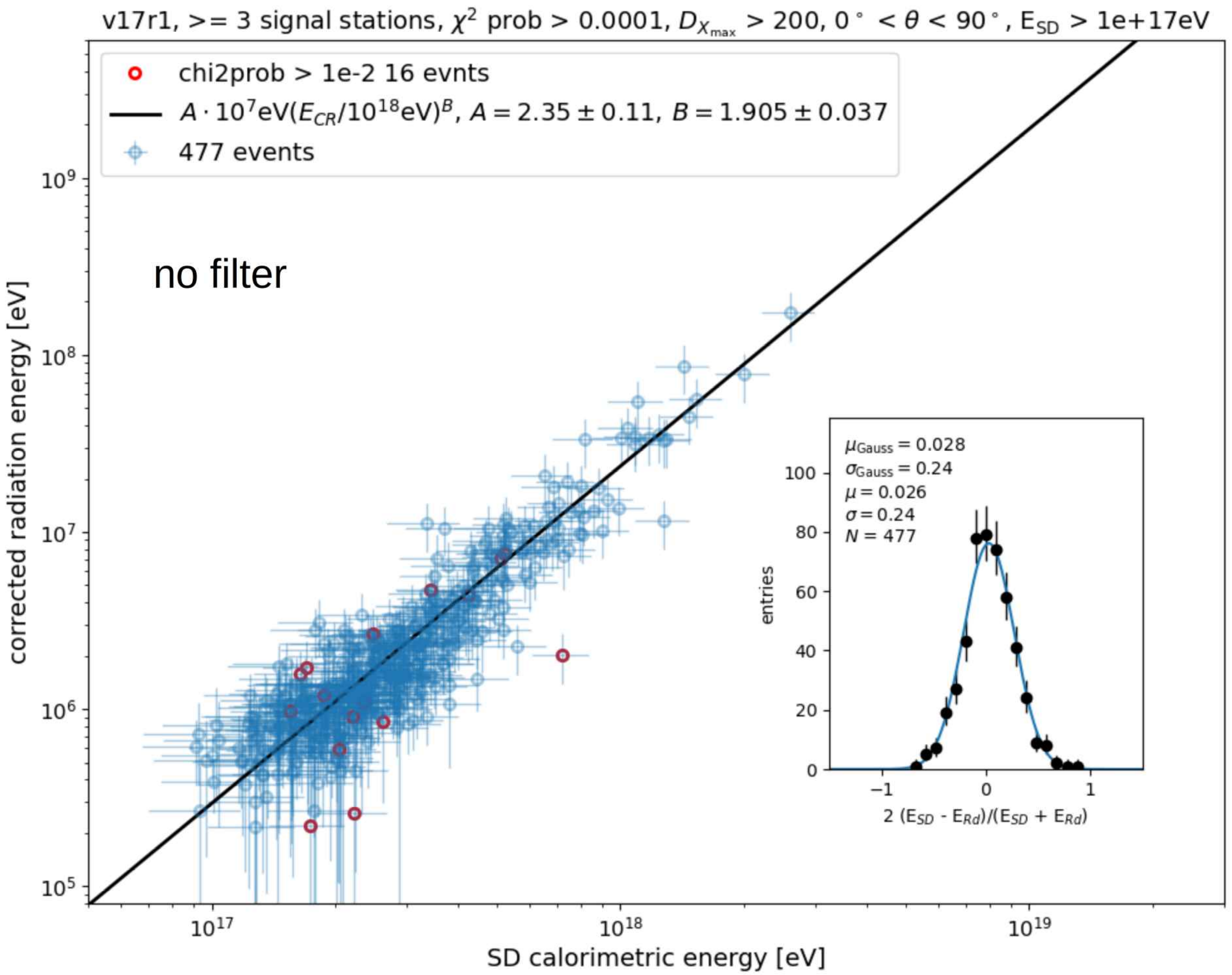


Sim comparison v17r1 vs v17r0 vs v17r2

- **Simulation reconstruction**
- Cross-check influence of niose filter
  - v17r1: no filter
  - v17r0: Bandstop filter
  - v17r2: Sinewave suppressor
- Standard method for energy fluence estimation
- Fewest events without any filter, not by much but still suprising?
- Both filter methods agree well in B, less in A (2 sigma)
- Without filter, B is lower by ~1 sigma, A is smaller than for signal suppressor. Lowest A for bandstop



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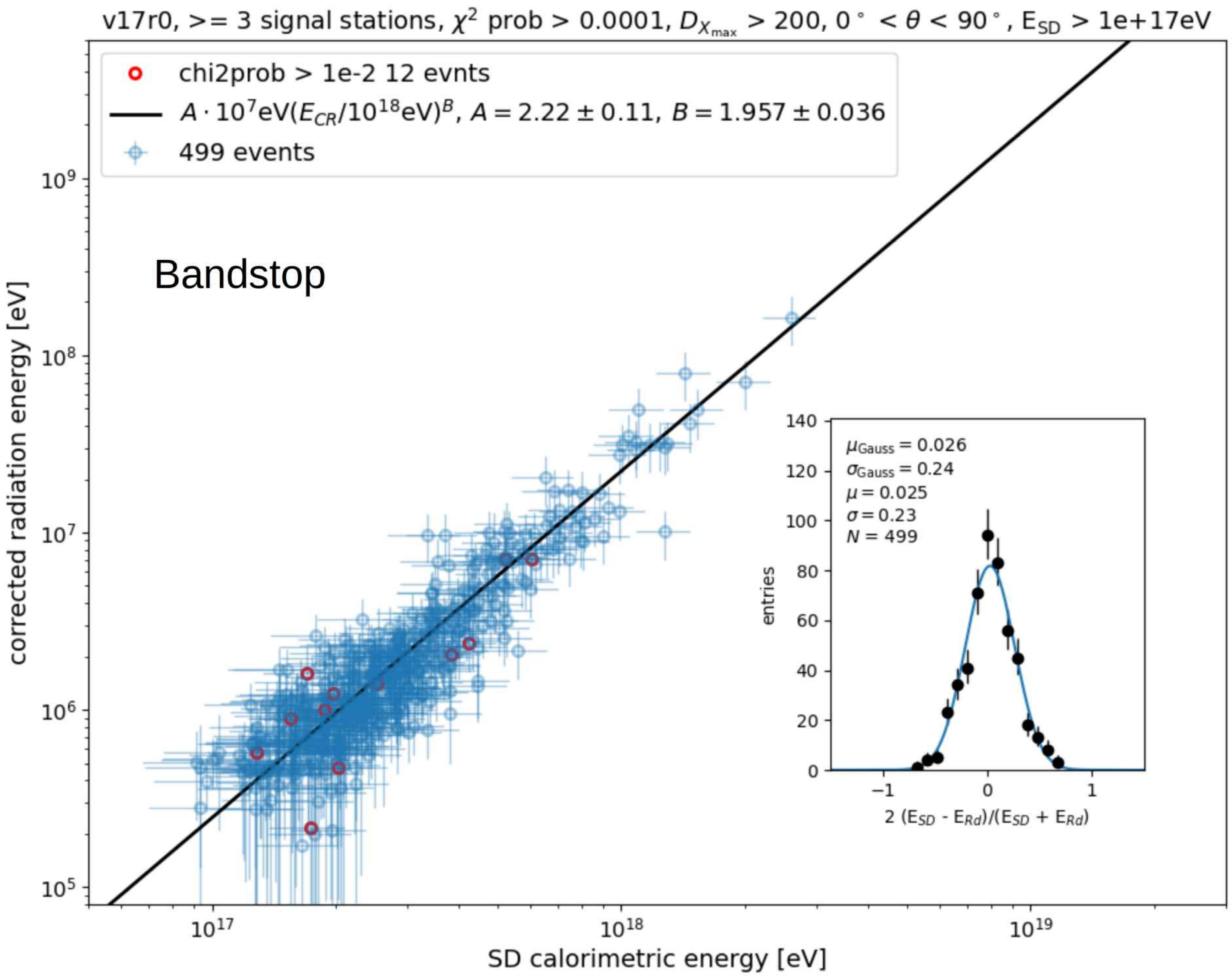

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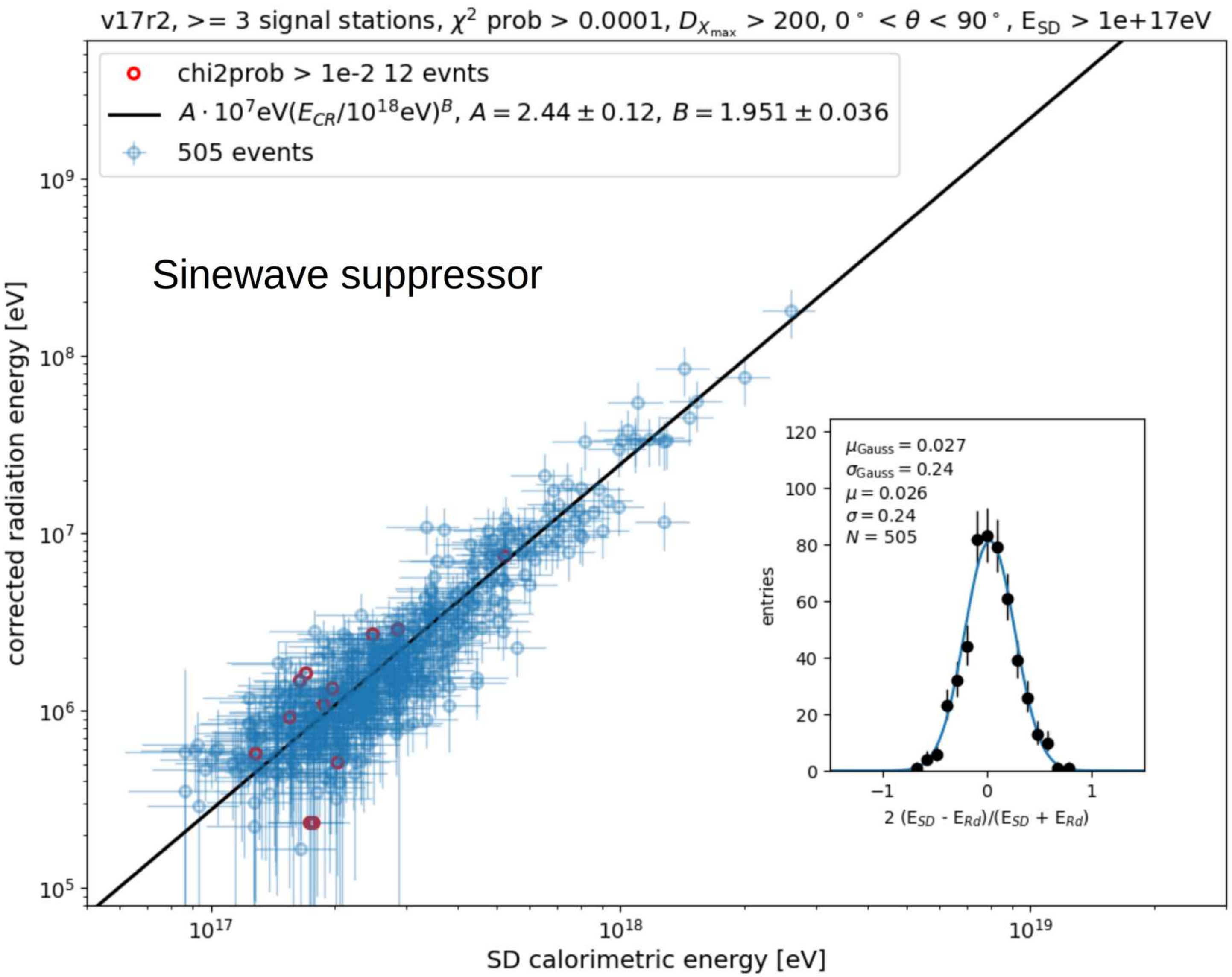

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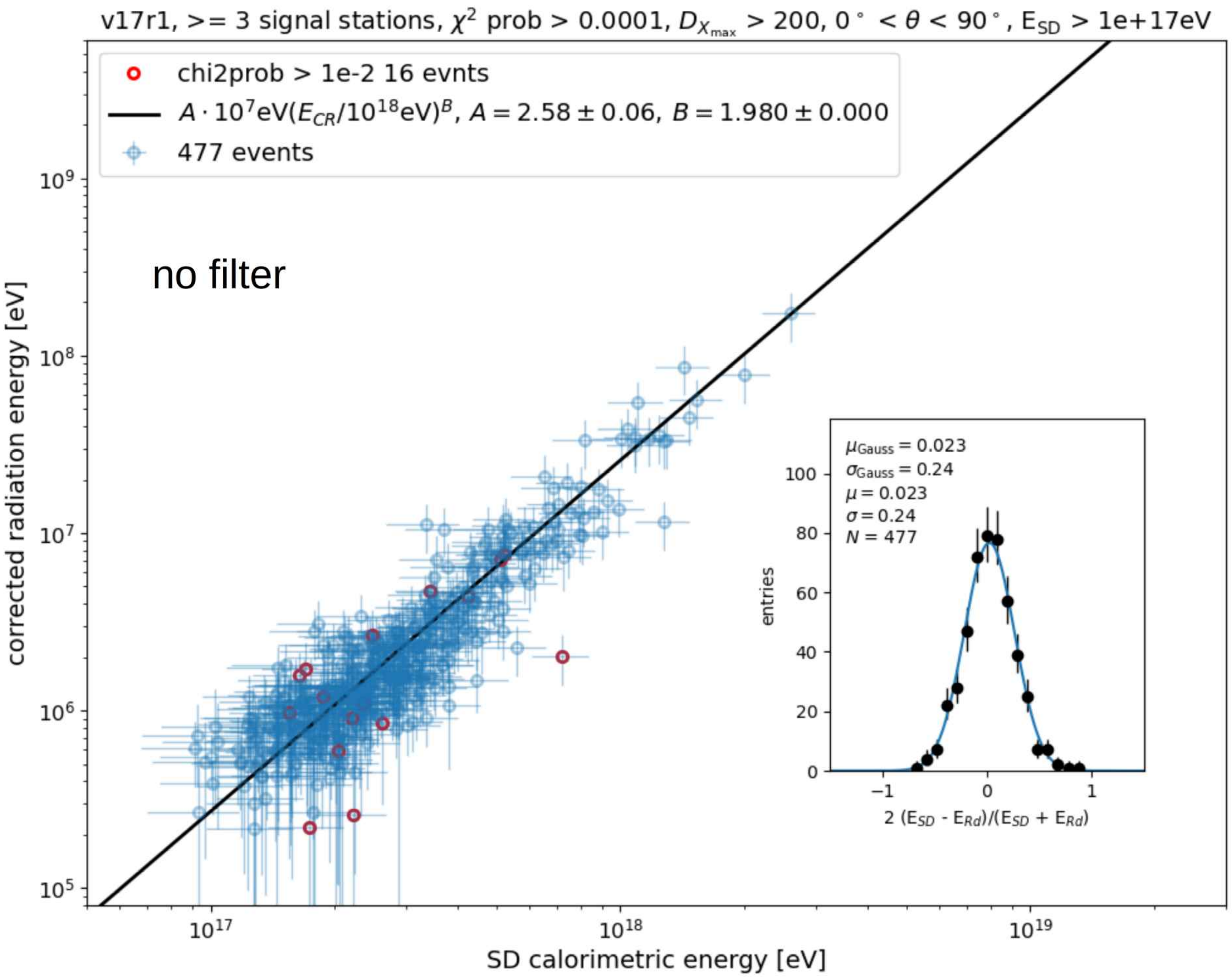
- With B=1.98 fixed, fit values for A relate more distinctly:
  - Sinew. supp. only slightly smaller than without filter
  - for bandstop significantly smaller
  - similar picture for sims. and data



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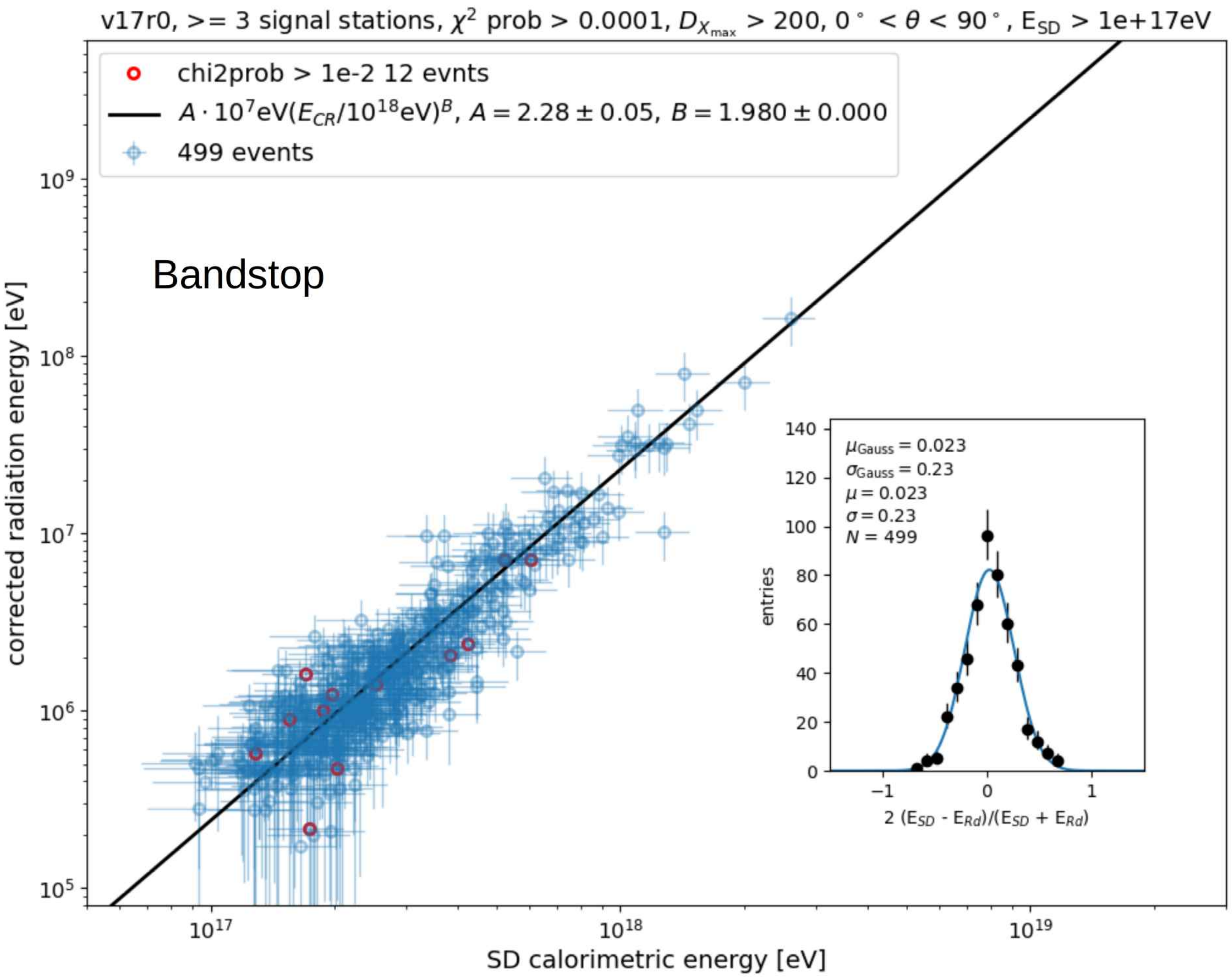

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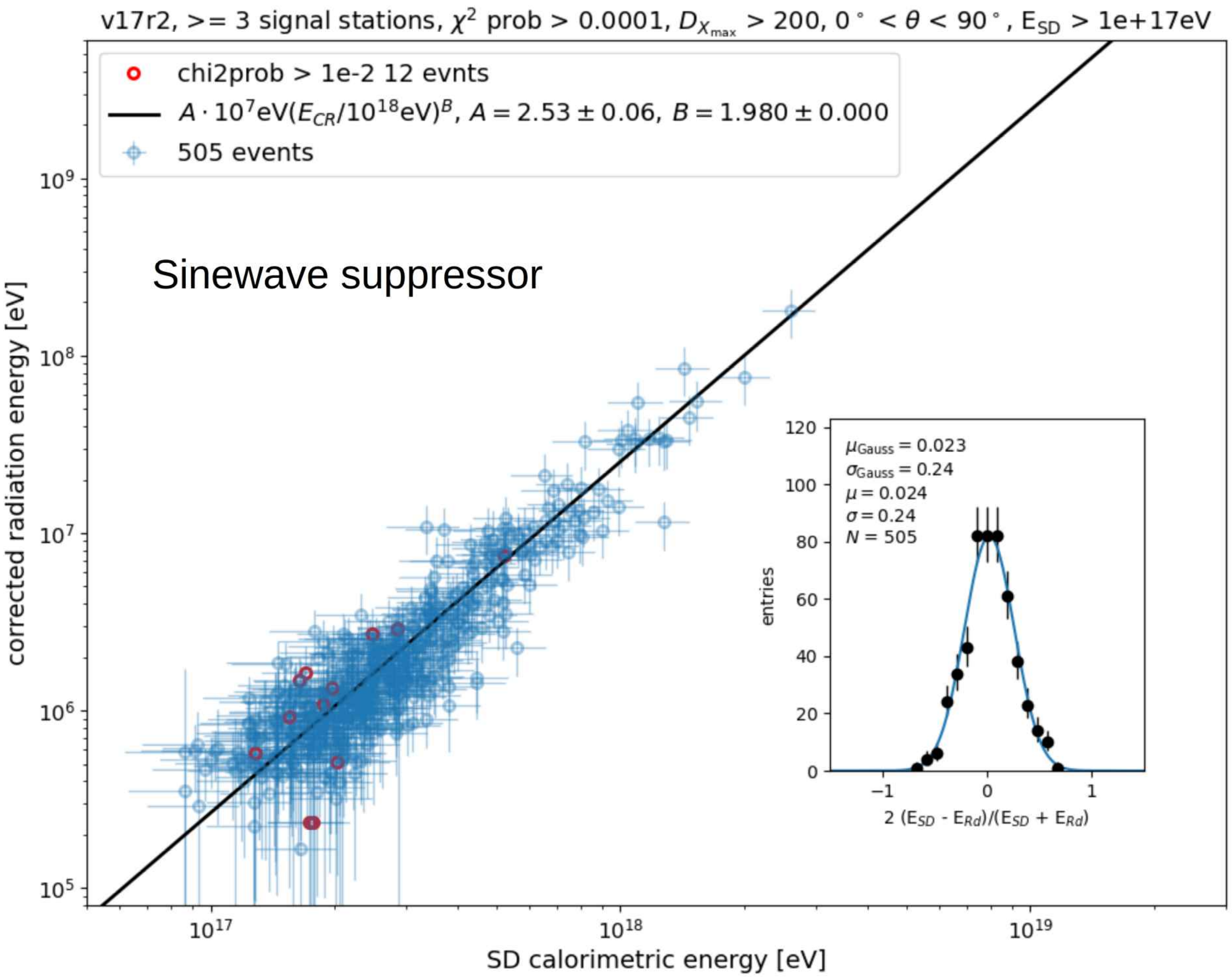


Influence of signal estimation method

- Currently two methods available: The "standard method" and "Fabrizia's method"
- ~5% difference on fitted A value (B=1.98 fixed)
    - Largest difference for showers below $3x10^{17}$eV
- Similar difference observed for simulations

	dataset	description	events	A [10^7 eV]	B	bootstrap A	bootstrap B	A (fix B)	relative change in A
Data →	v15r0f	standard method	431	1.42 ± 0.09	1.845 ± 0.043		$1.839^{+0.053}_{-0.046}$	1.71 ± 0.04	
	v15r1f	Fabrizia's method	424	1.52 ± 0.09	1.921 ± 0.043		$1.945^{+0.088}_{-0.048}$	1.62 ± 0.04	-5.2%
Simulations →	v17r1 (sim)	standard method	477	2.35 ± 0.11	1.905 ± 0.037			2.58 ± 0.06	
	v17r3 (sim)	Fabrizia's method	477	2.45 ± 0.12	1.988 ± 0.038			2.42 ± 0.06	-6.2%

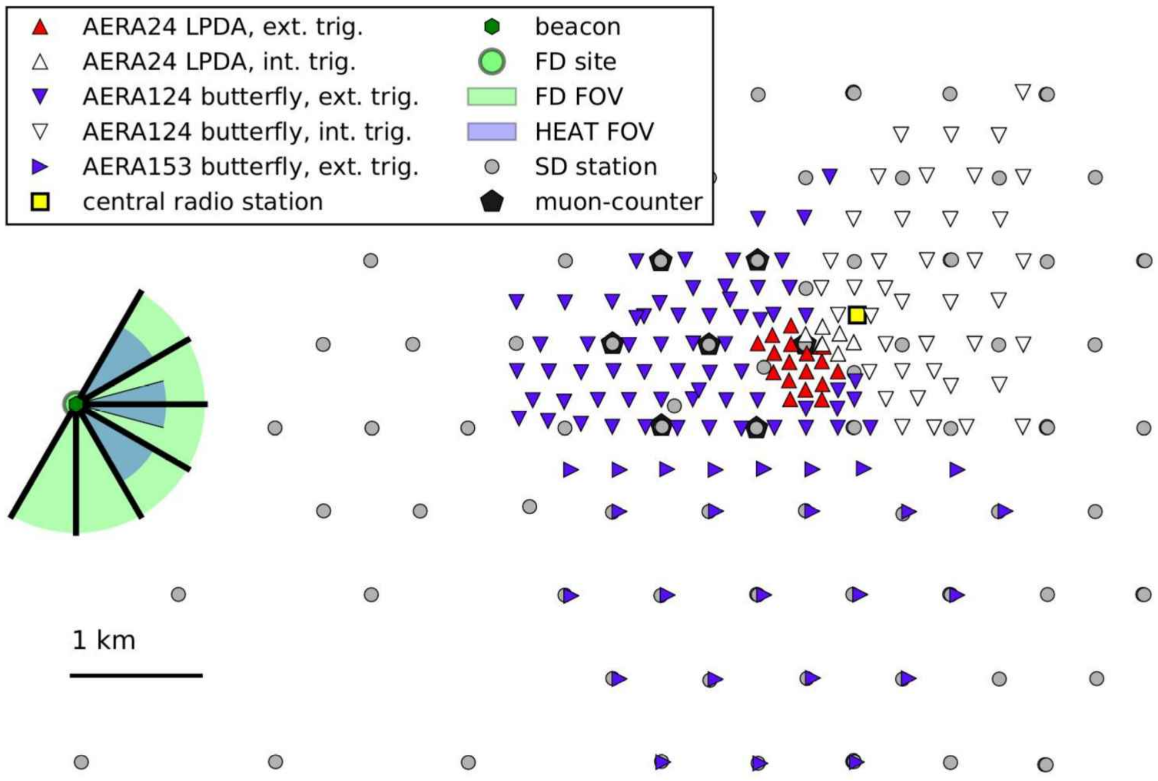
Influence of noise filter

- 3 choices for applying a noise filter: no filter / bandstop filter / sinewave suppressor
- Influence on A value expected
- Similar for data and simulations

	dataset	description	events	A [10^7 eV]	B	bootstrap A	bootstrap B	A (fix B)	relative change in A
Data →	v15r0f	no filter	431	1.42 ± 0.09	1.845 ± 0.043		$1.839^{+0.053}_{-0.046}$	1.71 ± 0.04	
	v14r0f	Bandstop	388	1.28 ± 0.08	1.860 ± 0.043			1.50 ± 0.04	-12.2%
	v15r2f	Sinewave	423	1.35 ± 0.08	1.827 ± 0.042			1.66 ± 0.04	-2.9%
Simulations →	v17r1 (sim)	no filter	477	2.35 ± 0.11	1.905 ± 0.037			2.58 ± 0.06	
	v17r0 (sim)	Bandstop	499	2.22 ± 0.11	1.957 ± 0.036			2.28 ± 0.05	-11.6%
	v17r2 (sim)	Sinewave	505	2.44 ± 0.12	1.951 ± 0.036			2.53 ± 0.06	-1.9%

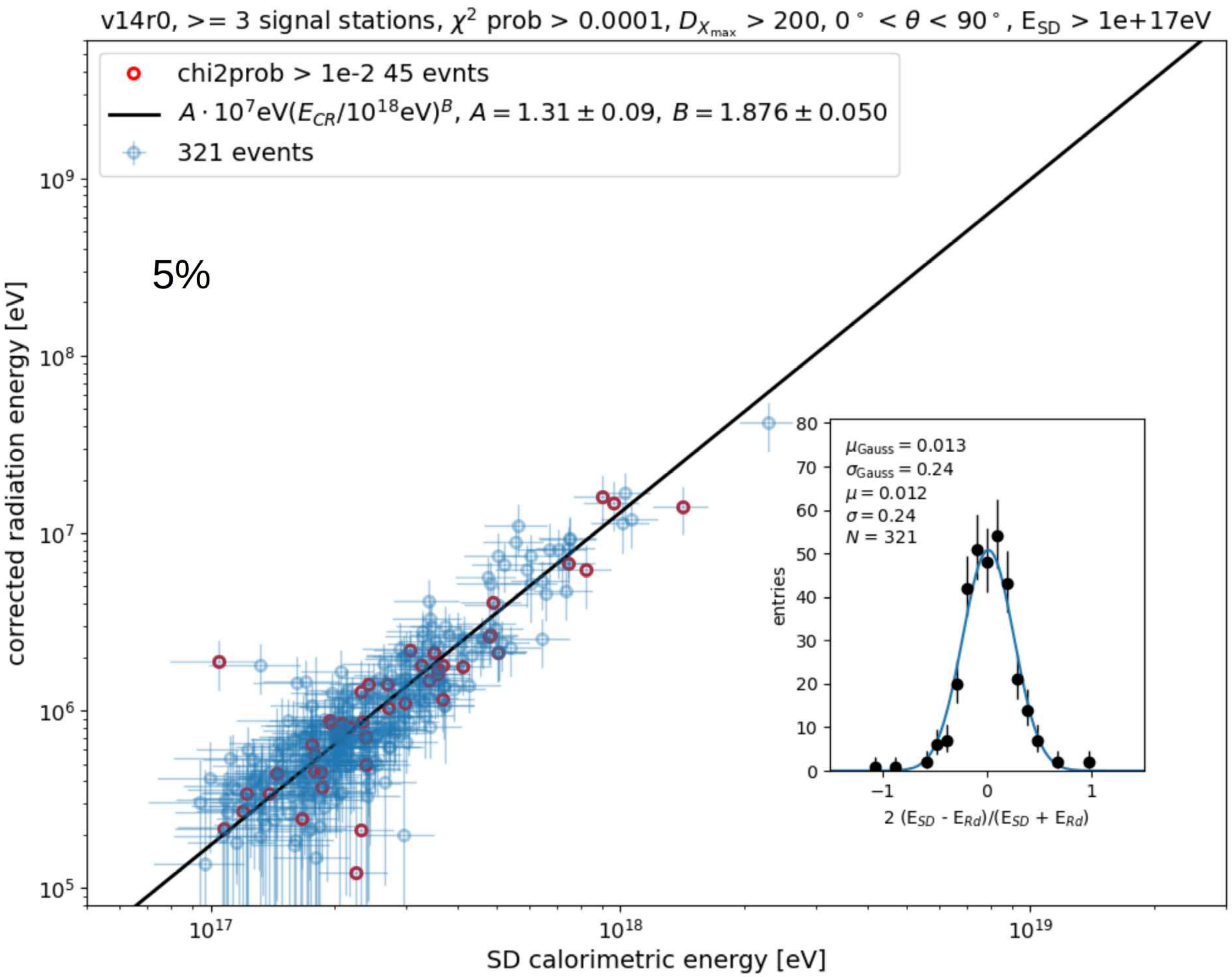
Testing Butterfly weighting

Currently the antenna-to-antenna uncertainty in the signal reconstruction is set to 5% for the Butterfly antennas (ref.: master thesis F. Schlüter), but C. Glaser and F. Briechle weighted them down by using 10%



Fit comparison v14r0 vs v14r3

- **Data reconstruction**
- Test influence of Butterfly weighting
  - v14r0: 5%
  - v14r3: 10%
- Standard method for energy fluence estimation
- Event numbers and fit parameters almost idendtical, well compatible within uncertainties



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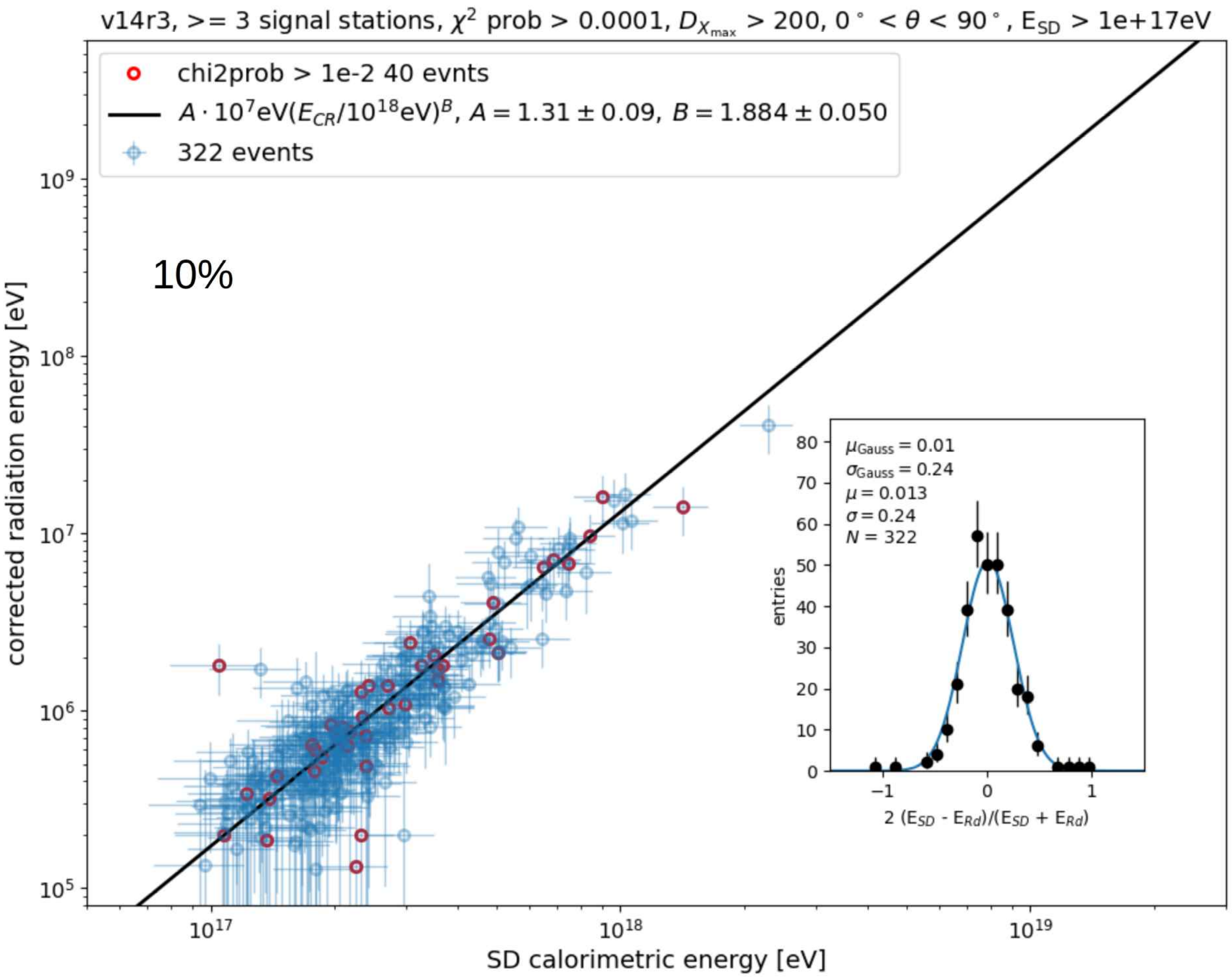


Fit comparison v14r0 vs v14r3

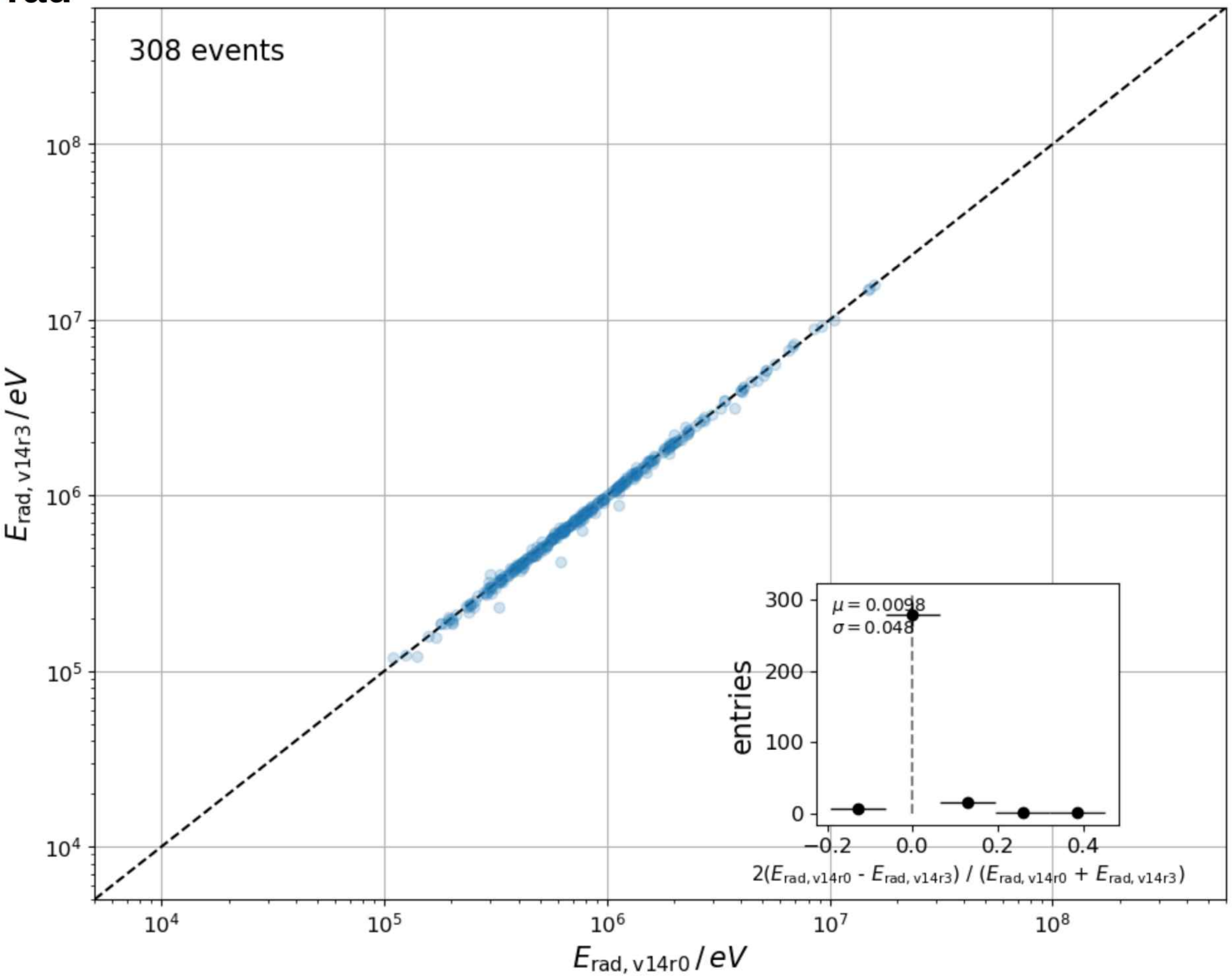
- **Data reconstruction**
- Test influence of Butterfly weighting
  - v14r0: 5%
  - v14r3: 10%
- Standard method for energy fluence estimation
- Event numbers and fit parameters almost idendtical, well compatible within uncertainties
- **Can safely use Butterflys with full weight**

- **Ensuing questions:**
  - Do we trust our Butterfly description?
    - Drone calibration campaign
  - Do we want to lift the requirement for showers to be contained in the LPDA array (AERA24)?

dataset	description	events	A [10^7 eV]	B	bootstrap A	bootstrap B	A (fix B)	relative change in A
v14r0	5% unc.	321	1.31 ± 0.09	1.876 ± 0.050			1.50 ± 0.04	
v14r3	10% unc.	322	1.31 ± 0.09	1.884 ± 0.050			1.49 ± 0.04	-0.6%

Dataset comparison - E_{rad}

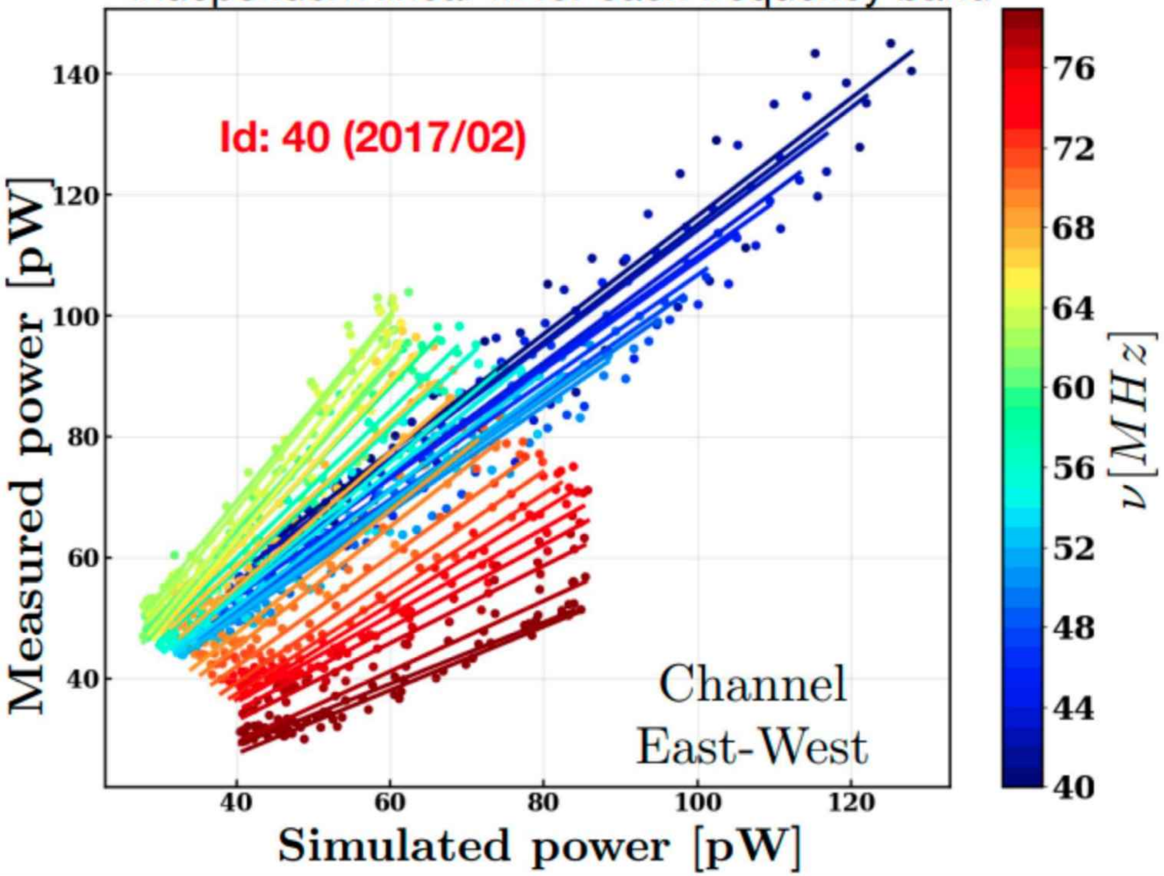
- **E_{rad} event-by-event (dataset overlap)**
- Very good overlap and agreement: 5% spread
- Larger uncertainty on Butterflys causes on average 1% reduction of E_{rad}

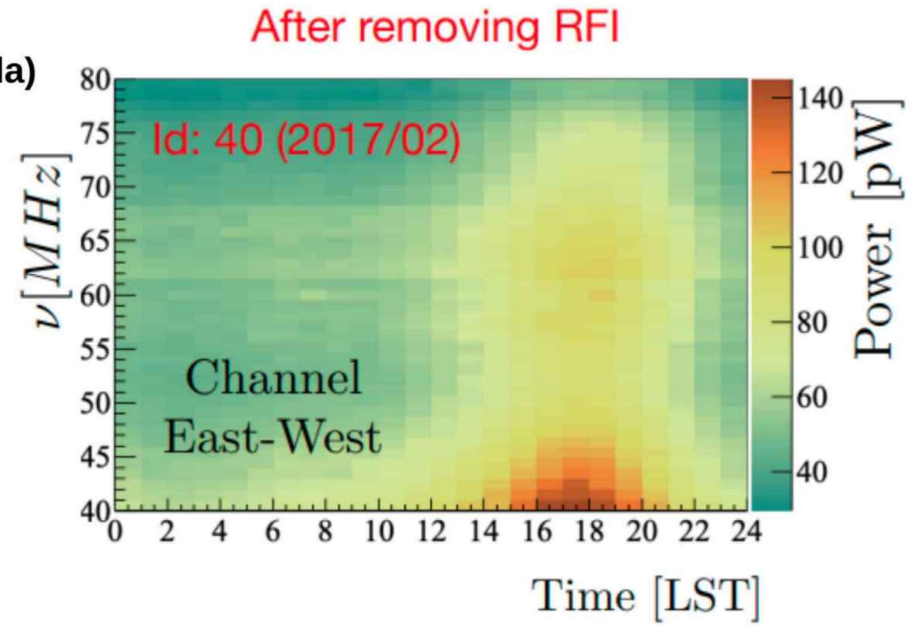


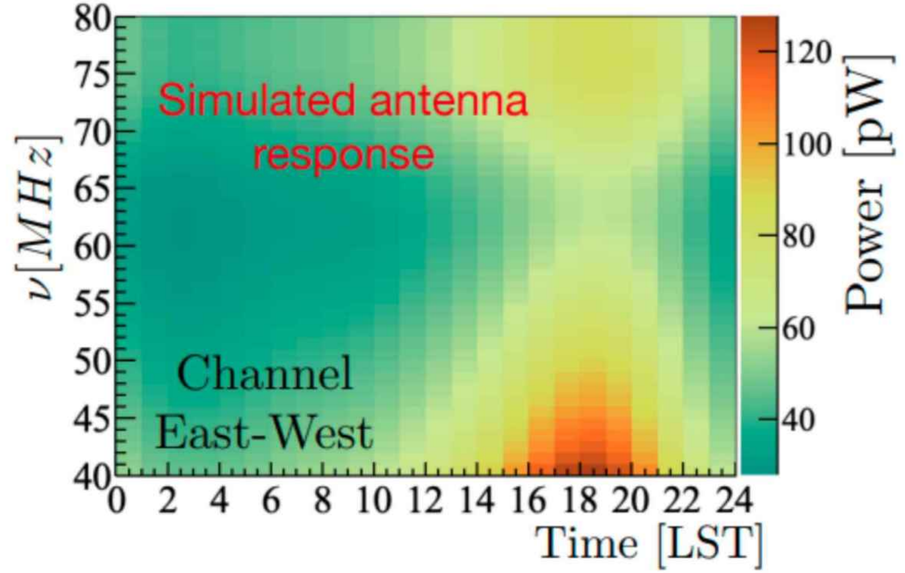
Calibration approach (Diego Correia and Rogerio de Almeida)

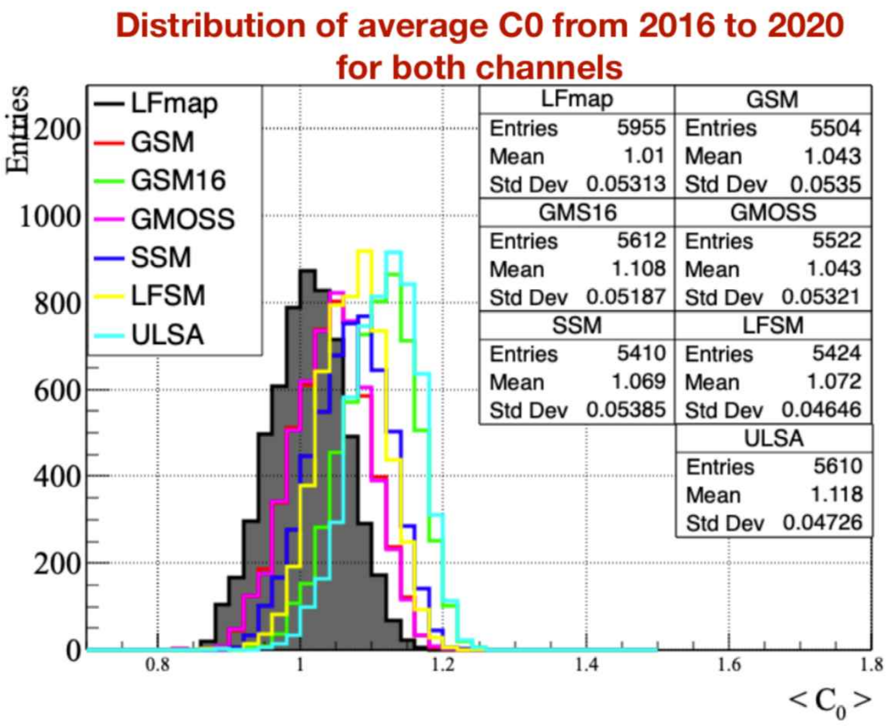
$$P_{model}(t,\nu) = P_{sky}(t,\nu)G_{ant}(\nu)G_{RCU}(\nu)C_0^2(\nu) + N_{tot}(\nu)$$

- Independent linear fit for each frequency band





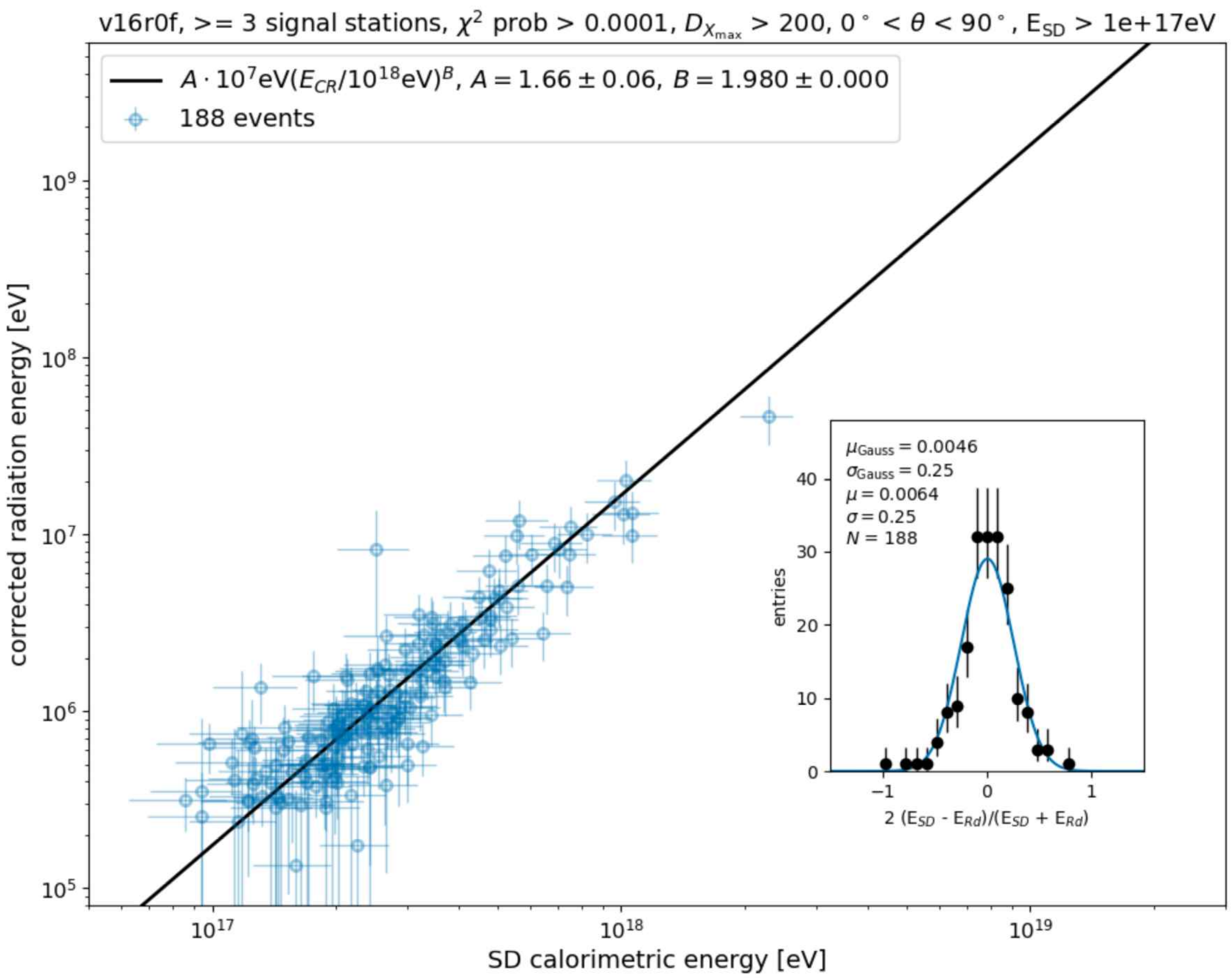




dataset	description	events	A [10^7eV]	B	dataset overlap with 16r0f	A (fix B)	relative change in A
v16r0f	-	398	1.42 ± 0.09	1.868 ± 0.046		1.64 ± 0.04	
v16r1f	temp-corr. only	364	1.48 ± 0.10	1.889 ± 0.047		1.67 ± 0.04	1.8%
v16r3f	LFmap	233	1.90 ± 0.19	2.008 ± 0.076	187	1.79 ± 0.07	7.8%
v16r4f	GSM	230	1.72 ± 0.19	1.969 ± 0.084	189	1.69 ± 0.06	1.8%
v16r5f	GSM16	230	1.60 ± 0.16	1.980 ± 0.073	190	1.55 ± 0.06	-7.7%
v16r6f	LFSM	232	1.62 ± 0.16	1.987 ± 0.075	192	1.70 ± 0.06	3.0%
v16r7f	GMOSS	231	1.74 ± 0.20	1.973 ± 0.086	190	1.76 ± 0.06	5.4%
v16r8f	SSM	235	1.68 ± 0.18	1.956 ± 0.081	195	1.68 ± 0.06	0.0%
v16r9f	ULSA	224	1.46 ± 0.17	1.938 ± 0.085	186	1.48 ± 0.05	-10.8%

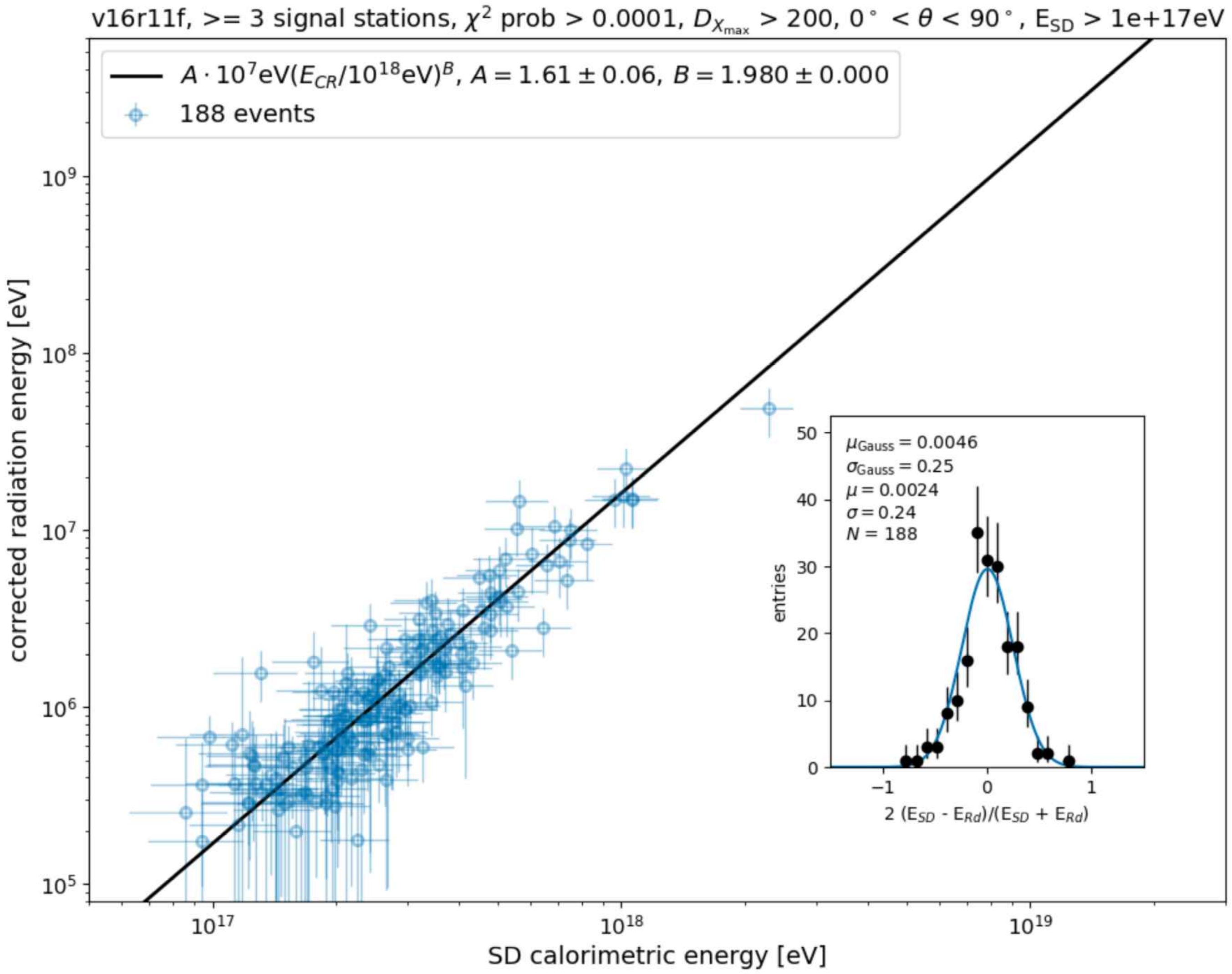
Fit comparison

- **Without temp-corr. and Gal. calibration**



Fit comparison

- **With temp-corr. and Gal. calibration using average calibration constants from all models**



Fit A parameter → shift pivot point from 1e18 eV

- v15r5f_TSnew allButterflys, E_{SD} > 3e17 eV

A = 1.422e+00 +/- 2.091e-02
B = 1.977 +/- 0.017
covariance: [[0.00043713 0.00022645]
 [0.00022645 0.00028478]]
corr coeff = 0.64

  - median energy: 3.73e+17

A = 2.434e-01 +/- 3.396e-03
B = 1.982 +/- 0.020
covariance: [[1.15341170e-05 -2.57505972e-05]
 [-2.57505972e-05 4.16850615e-04]]
corr coeff = −0.37

  - mean energy: 4.87e+17

A = 3.797e-01 +/- 4.606e-03
B = 1.978 +/- 0.020
covariance: [[2.12128536e-05 -9.15127913e-07]
 [-9.15127913e-07 3.86199216e-04]]
corr coeff = −0,01

  - test: 5.0e+17

A = 3.802e-01 +/- 4.440e-03
B = 1.977 +/- 0.019
covariance: [[1.97094339e-05 -1.48991668e-06]
 [-1.48991668e-06 3.50072208e-04]]
corr coeff = -0.02

  - test: 8.0e+17

A = 1.397e+00 +/- 4.070e-02
B = 2.011 +/- 0.030
covariance: [[0.00165653 0.00098887]
 [0.00098887 0.00087801]]
corr coeff = 0.82

10^{19} eV event