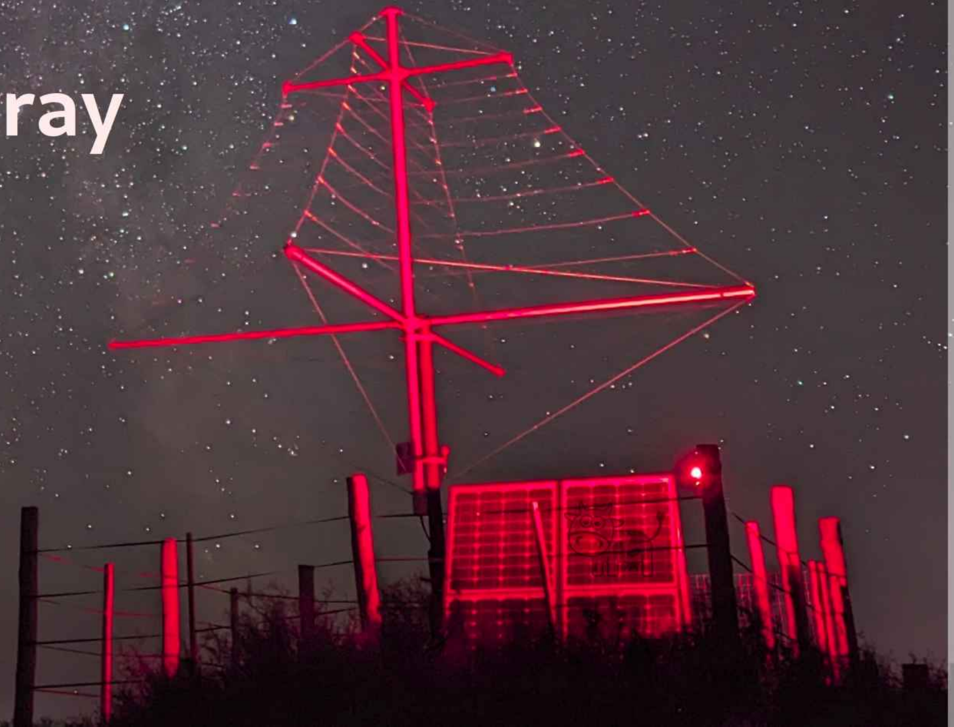
ARENA Workshop
University of Chicago

13th June 2024

Max Büsken for the
Pierre Auger Collaboration

Towards a Cosmic-Ray Energy Scale with the Auger Enigneering Radio Array



ARENA CHICAGO 2024

KIT

UNSAM

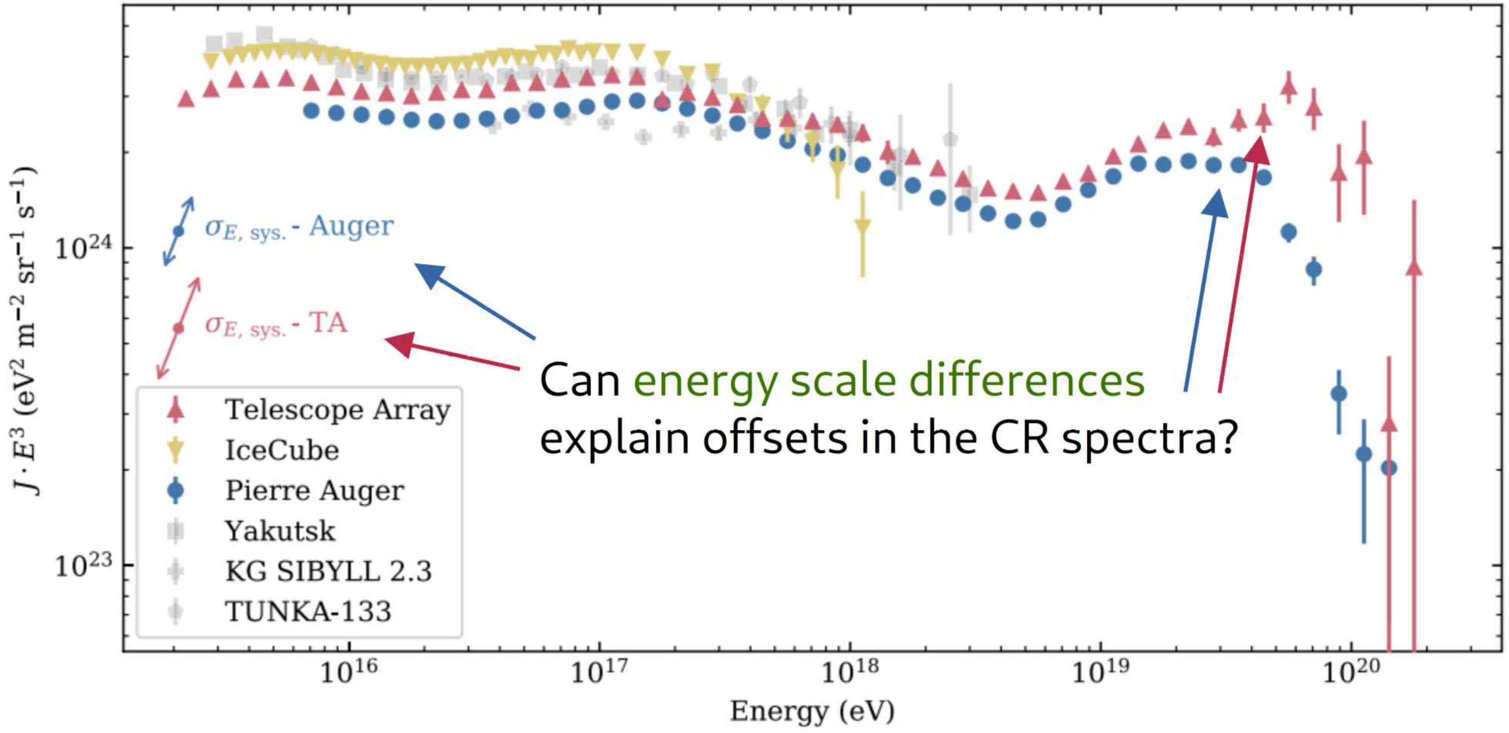
PIERRE AUGER OBSERVATORY · MALARGÜE ·

AERA Auger Engineering Radio Array

HIRSAP

Energy scales of cosmic-ray observatories

[Snowmass White Paper, Astropart. Phys. 149 (2023) 102819]

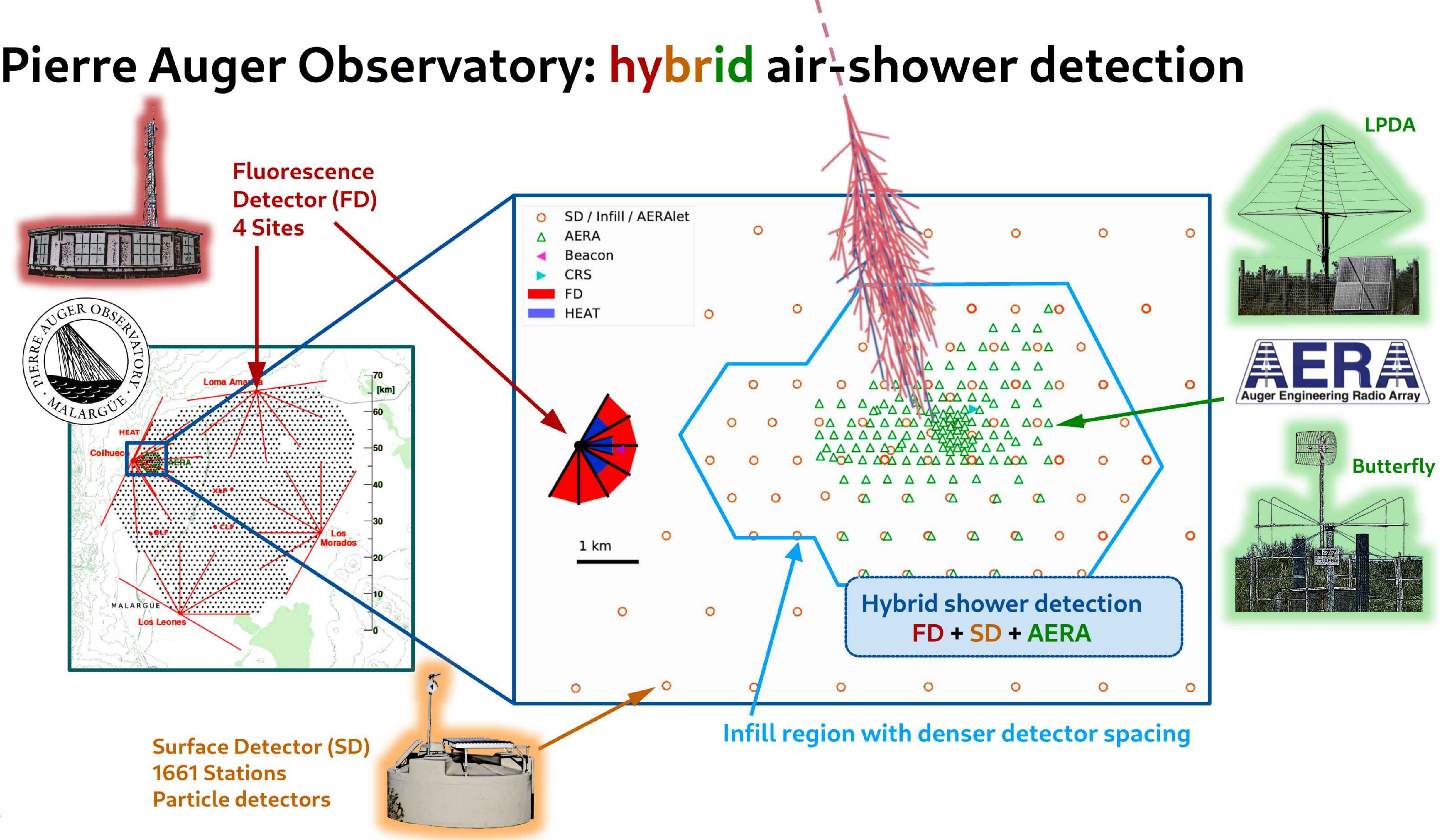


- Each cosmic-ray observatory has an individual energy scale
- Comparison of science results always in view of energy scale differences

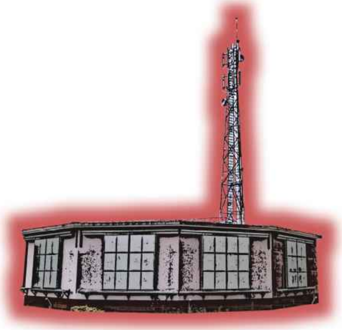
  ↪ Absolute determination of energy scale and its accuracy are crucial

↪ here: cross-check the Auger energy scale using radio

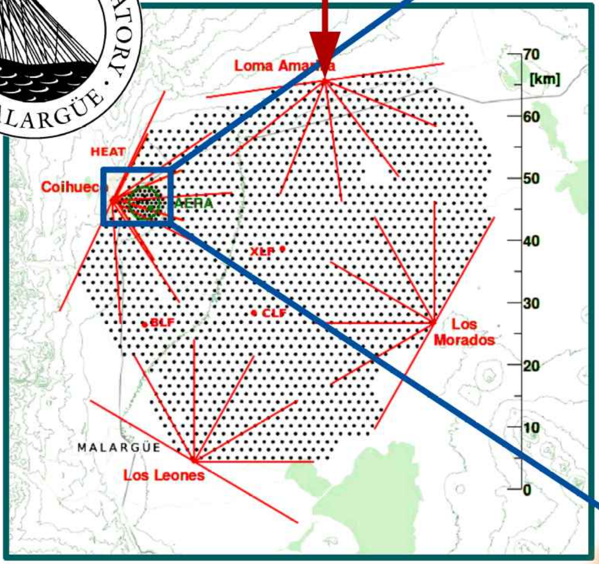
Pierre Auger Observatory: hybrid air-shower detection



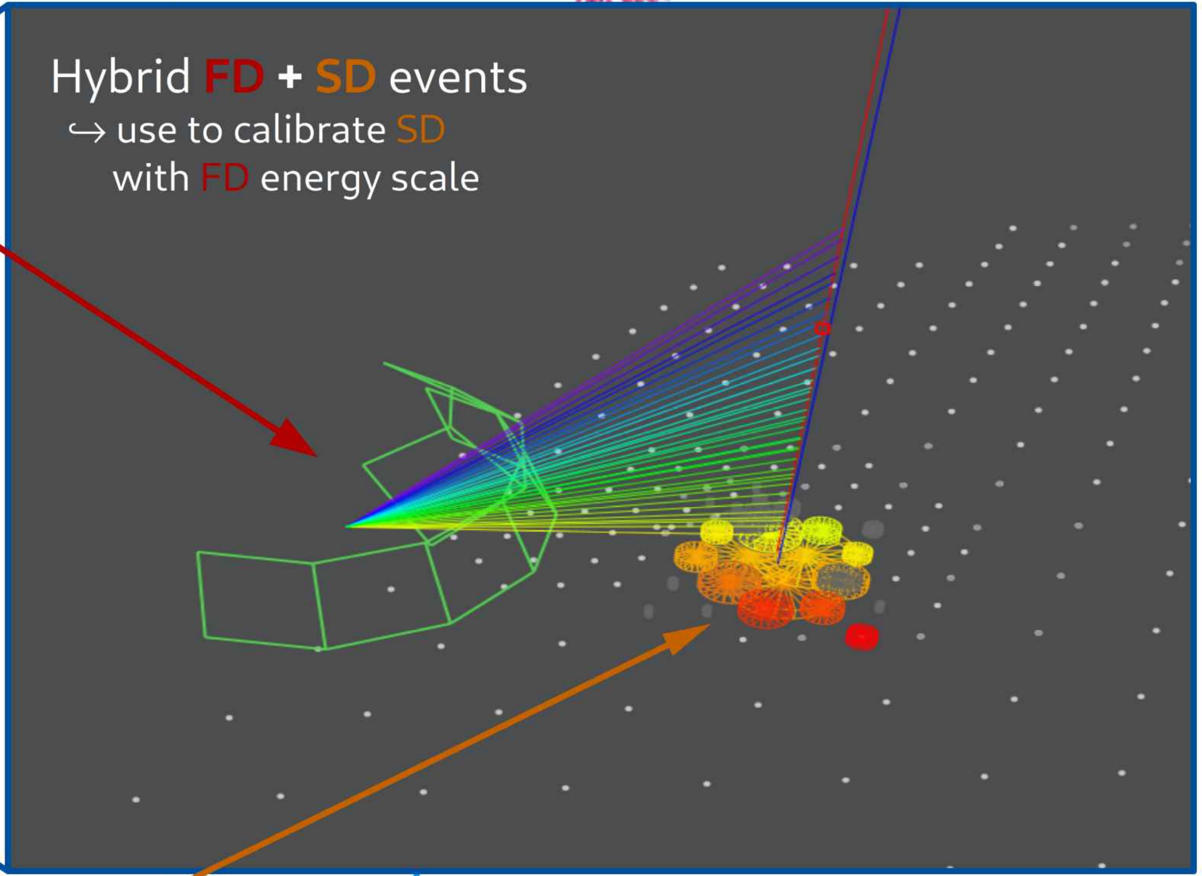
Pierre Auger Observatory: hybrid air-shower detection



Fluorescence Detector (FD)
4 Sites



Example event:

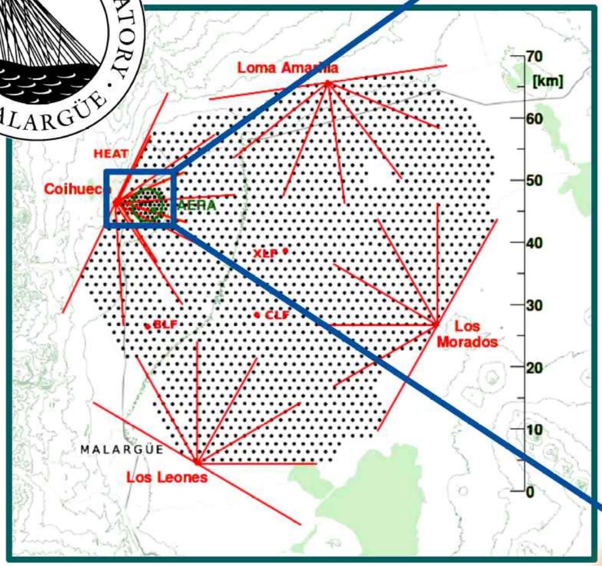


Infill region with denser detector spacing

Surface Detector (SD)
1661 Stations
Particle detectors

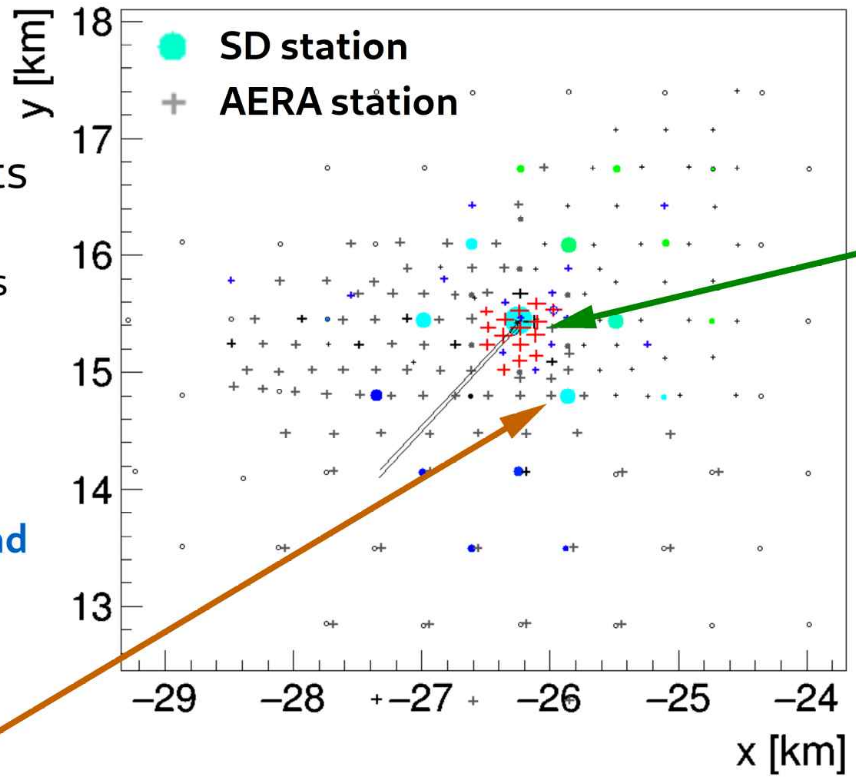
Pierre Auger Observatory: hybrid air-shower detection

Example event:



Hybrid events
SD + AERA
↪ basis for this analysis

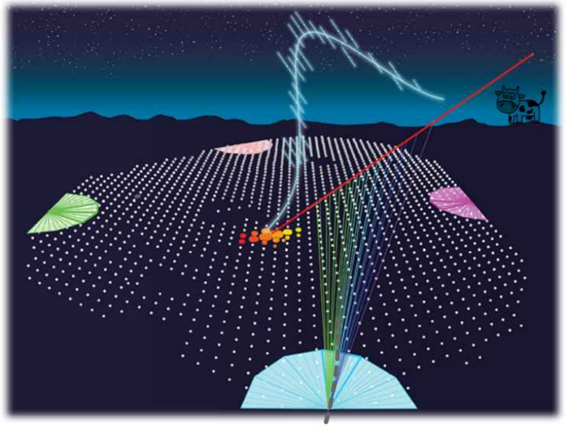
Since 2013:
a **few thousand** high-quality hybrid events recorded
E > $3 \cdot 10^{17}$ eV



Infill region with denser detector spacing

Surface Detector (SD)
1661 Stations
Particle detectors

Energy scales at the Pierre Auger Observatory



Total number of fluorescence photons proportional to cosmic-ray energy

$N_{\gamma,\,\mathrm{fluorescence}} \propto E_{CR}$

Measured in the laboratory
[M. Ave et al., AIRFLY Collaboration Astropart. Phys. 42 (2013) 90.]

Need precise determination of cosmic-ray energy E_{CR}

established (**FD**):

Energy scale defined by the **fluorescence yield**

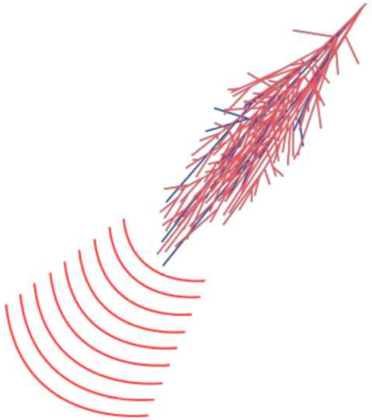
- Needs permanent monit. of atmosphere
  - Aerosol content
  - Clouds
- Long-term drift of telescope components
- Syst. uncertainty: 14%

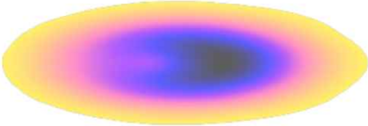
alternative (**Radio**):

Energy scale defined by **classical electrodynamics** in MC air-shower simulations

- Atmosphere transparent
- No significant or relevant ageing
- (At least) competitive syst. uncertainty

Compare the scales





High-precision simulations:

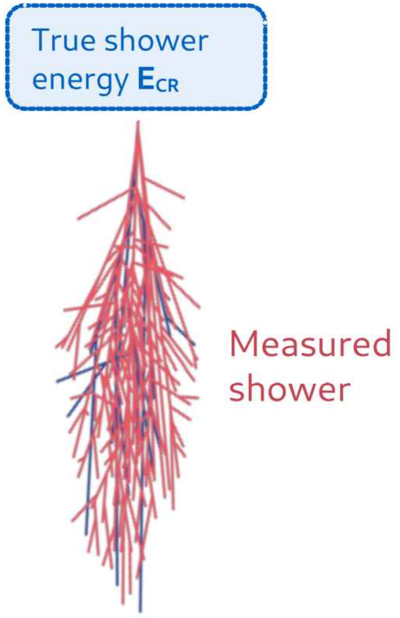
- CORSIKA: particle cascade
- CoREAS: microscopic modeling of radio emission

Quality of radio emission simulations probed extensively
[Gottowik et al., Astropart. Phys. 103 (2018) 87-93]
↪ CoREAS & ZHAireS agreement within **~3%** in cosmic-ray energy

→ More details:
see ARENA talk by T. Huege

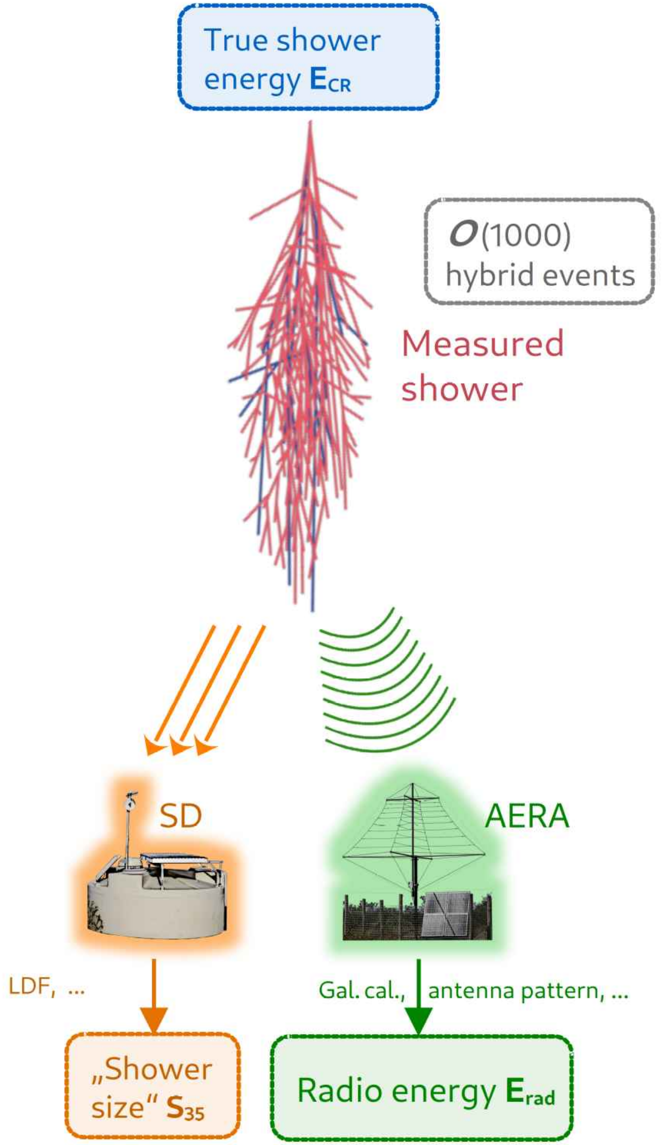
Comparing FD and Radio energy scales

- „Top-down“-like approach



Comparing FD and Radio energy scales

- „Top-down“-like approach
- Hybrid SD – AERA events
  - $E > 3{\cdot}10^{17}$ eV, $\theta < 55°$



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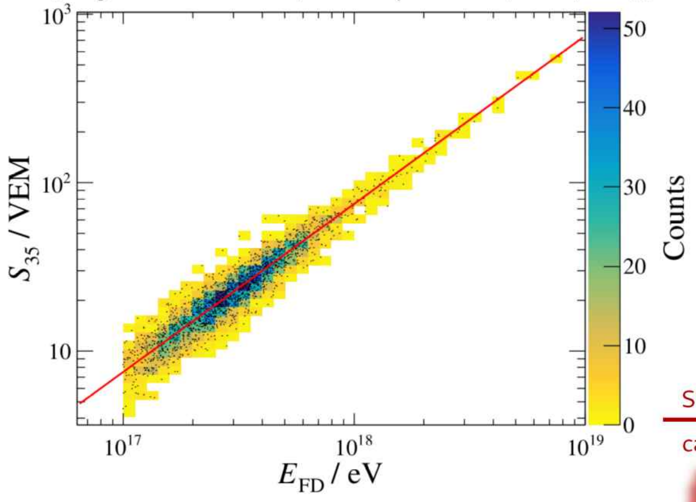
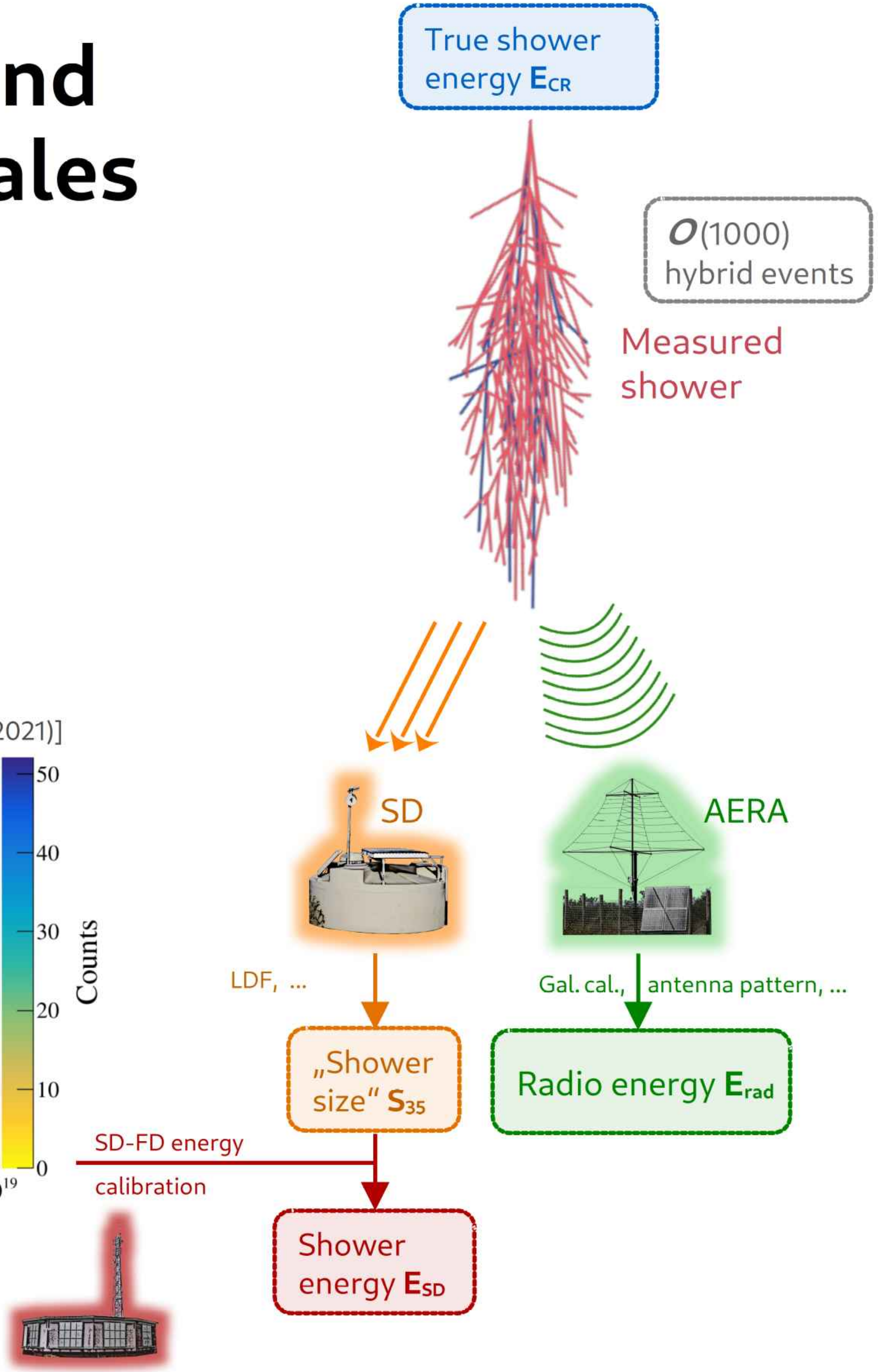
[Auger Collaboration, Eur. Phys. J. C 81, 966 (2021)]



FD energy scale based on **fluorescence yield** measurement



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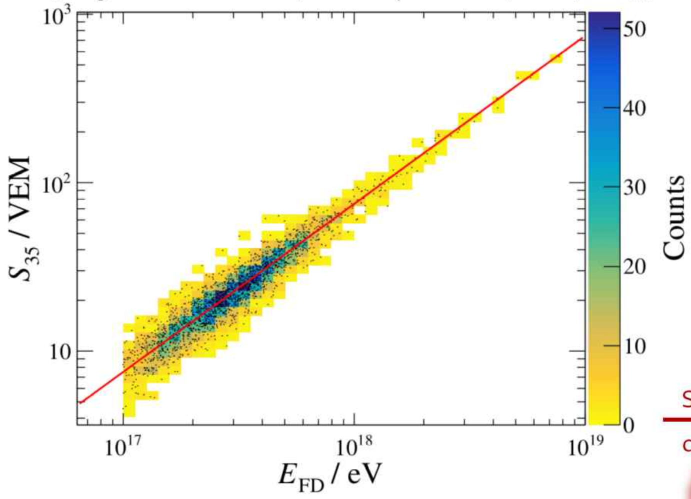

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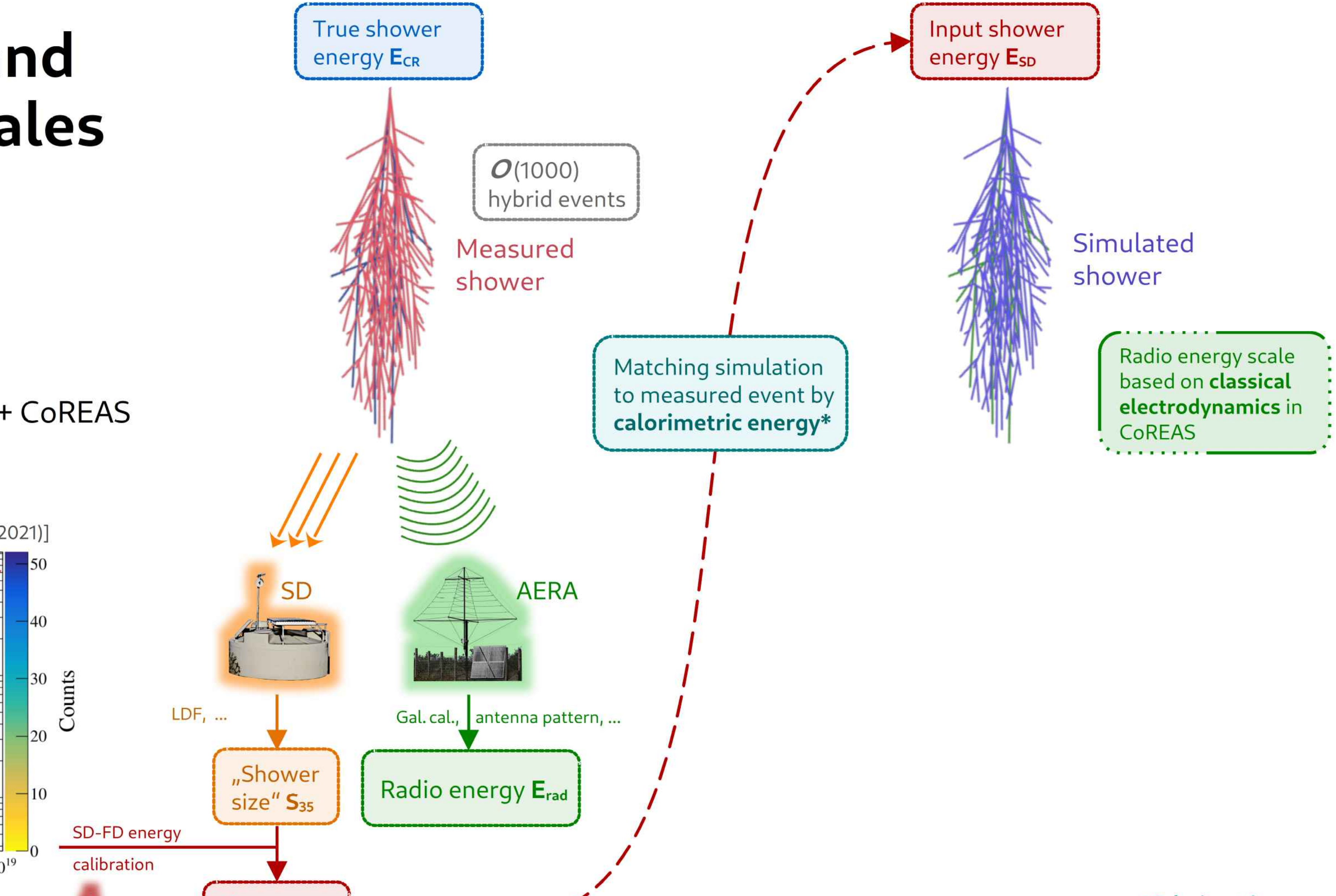

***Calorimetric energy:** all energy deposited by the shower into the atmosphere

Comparing FD and Radio energy scales

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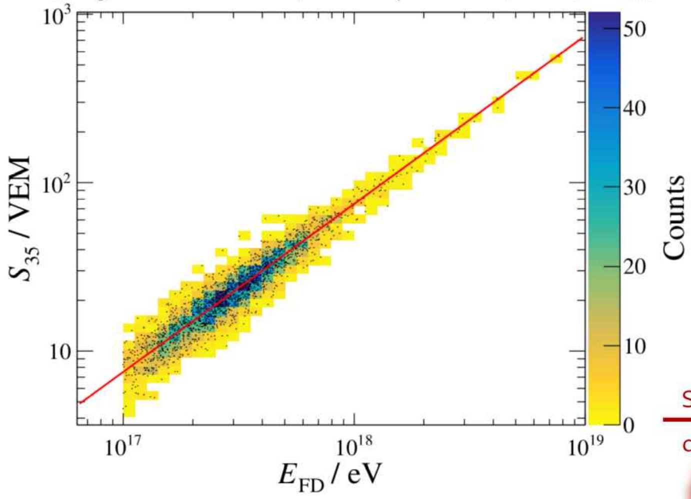

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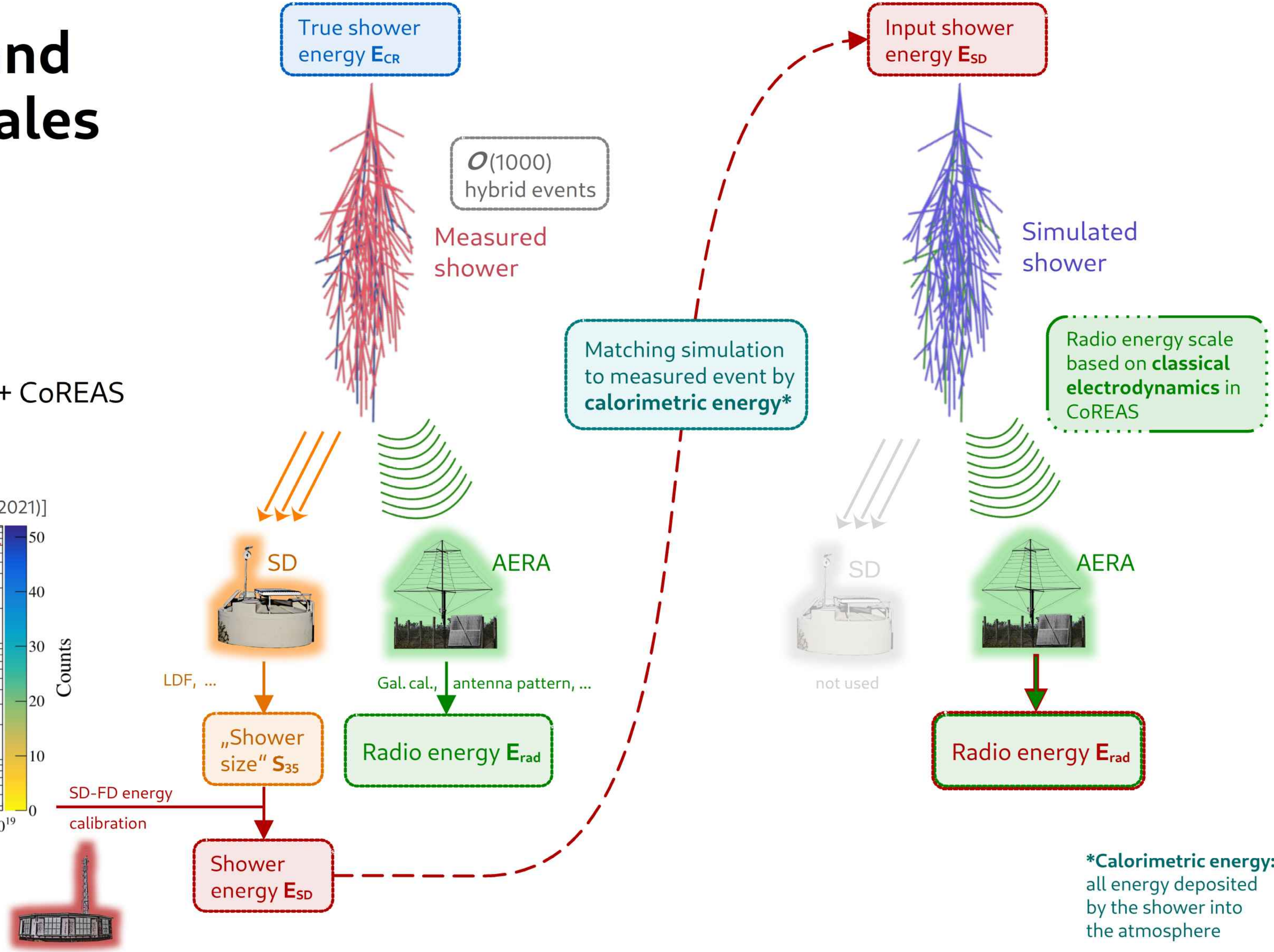

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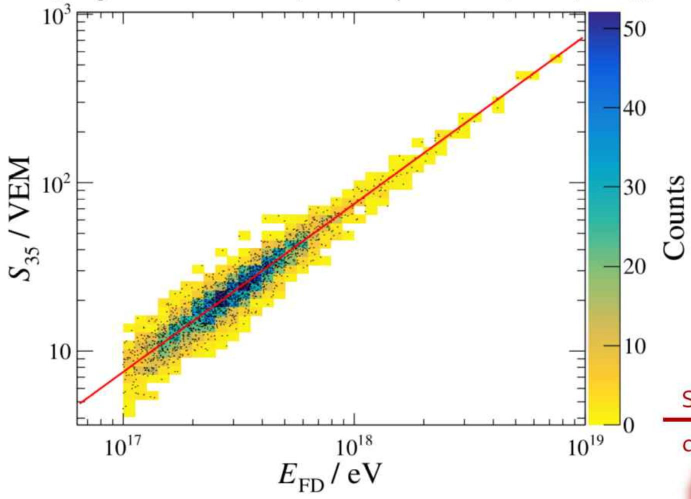

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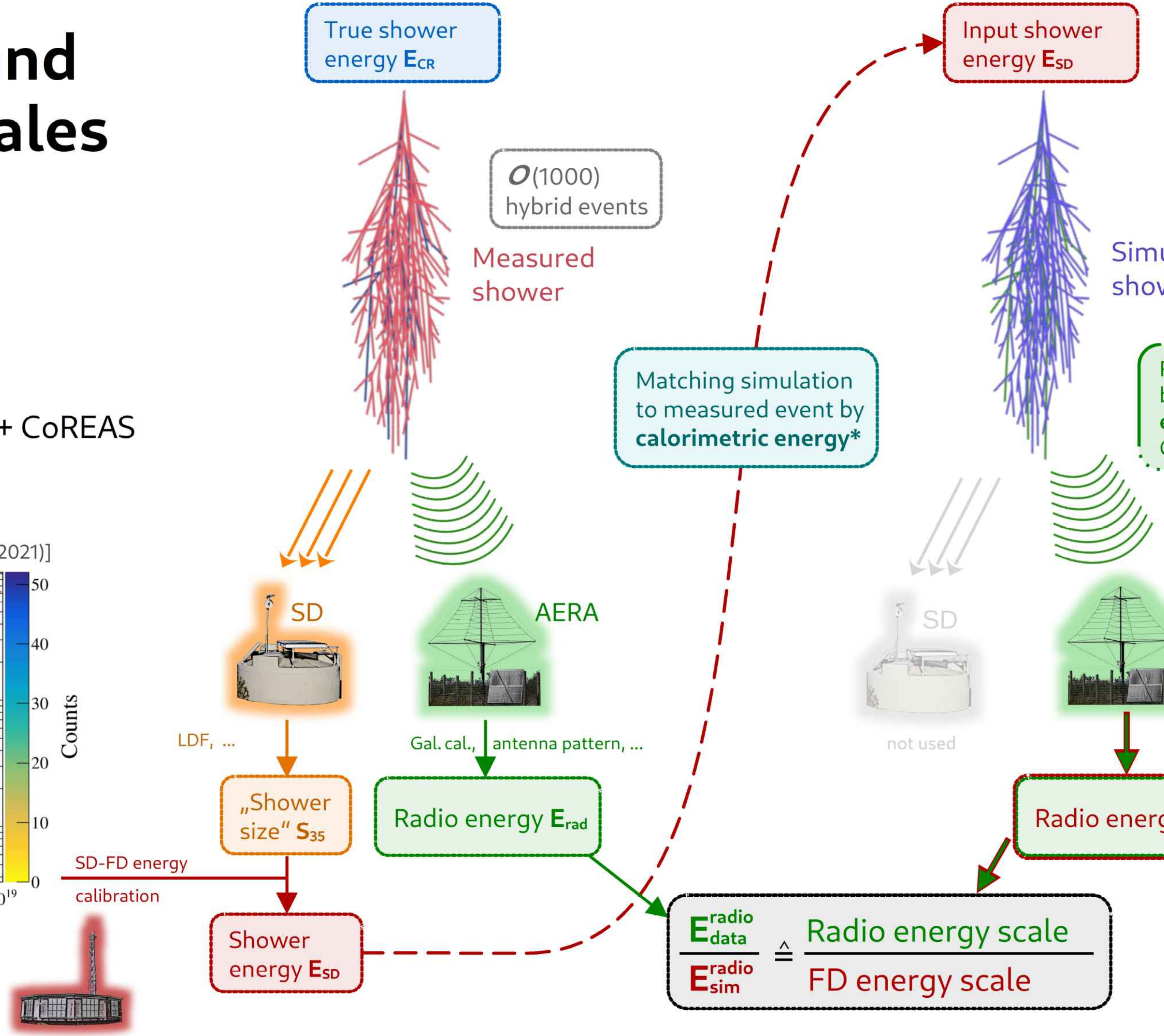
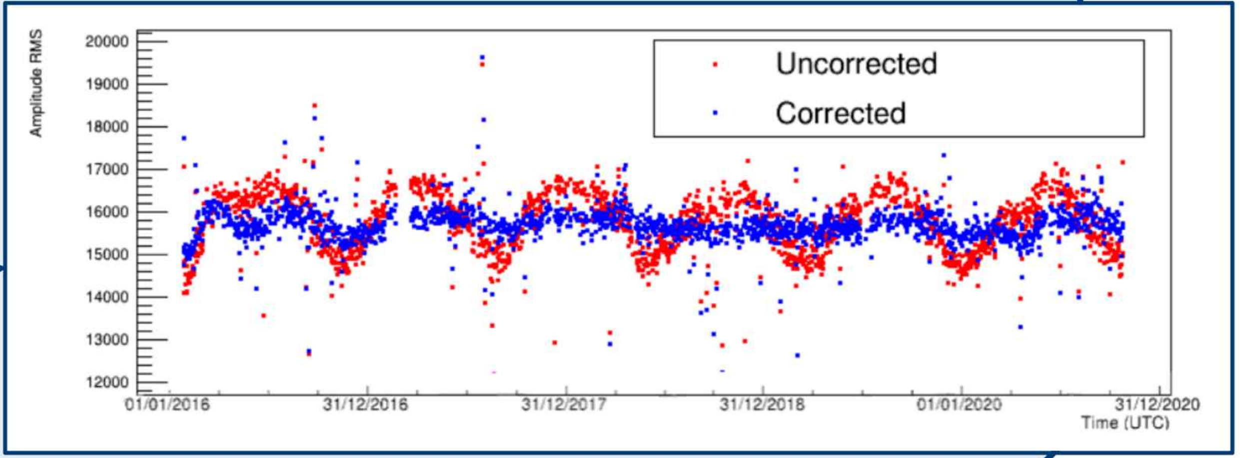


***Calorimetric energy:** all energy deposited by the shower into the atmosphere

Radio event reconstruction with AERA

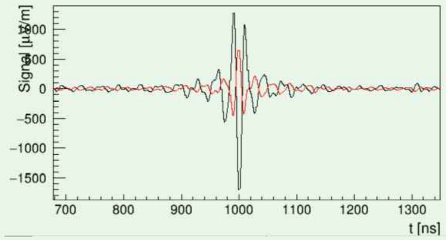
Correcting temperature dependence of amplifier gains

- Temperature-dependent amplifier gains
- Event-by-event fluctuations on CR energy ~4%
- Dependency measured and corrected with temperature data from nearby sensors
    - Fluctuations reduced to ~1% level



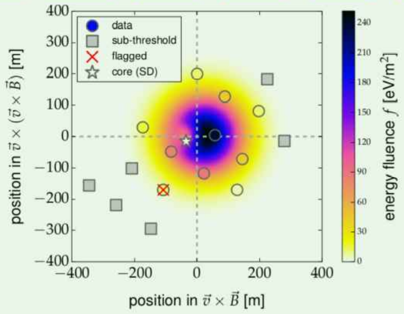
Measured radio traces

Filters, Galactic cal., …



Cleaned & calibrated radio traces

Detector response, …



Reconstructed station signals

Lateral distribution fit, …

Reconstructed radio events

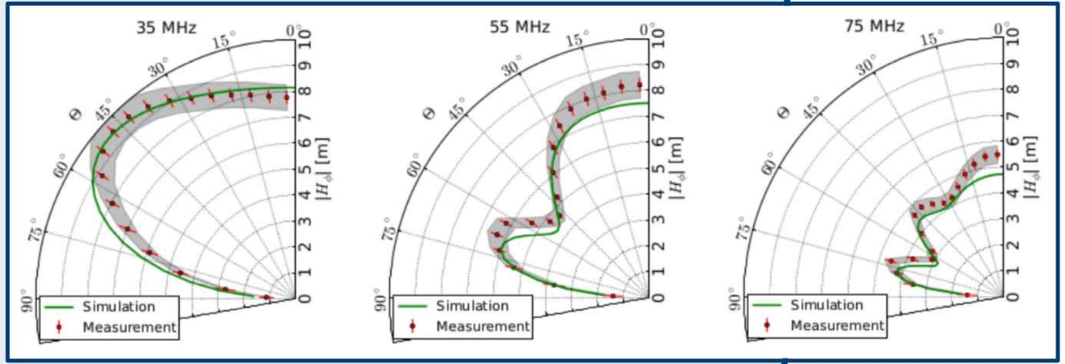
Radio event reconstruction

Radio event reconstruction with AERA

AERA detector response

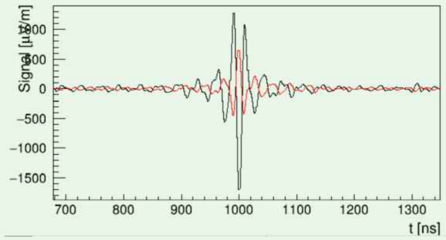
- Signal chain (filters, amplifiers, …) measured in lab
  - Incorporated in signal reconstruction
- Directional antenna response (antenna pattern)
  - LPDA: measured, Butterfly: simulated
  - Verification of patterns with drone-based measurements
  - Small-scale mismatches average out
    Absolute offsets absorbed in Galactic calibration

[Auger Collaboration, 2017 JINST 12 T10005]



Filters,
Galactic cal.,
…

Measured
radio traces



Detector
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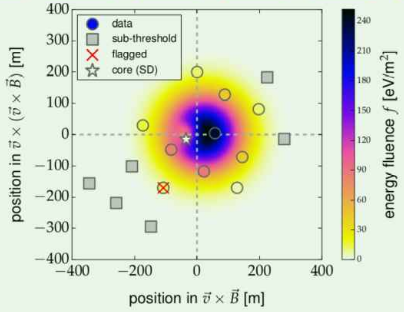


Lateral
distribution fit,
…

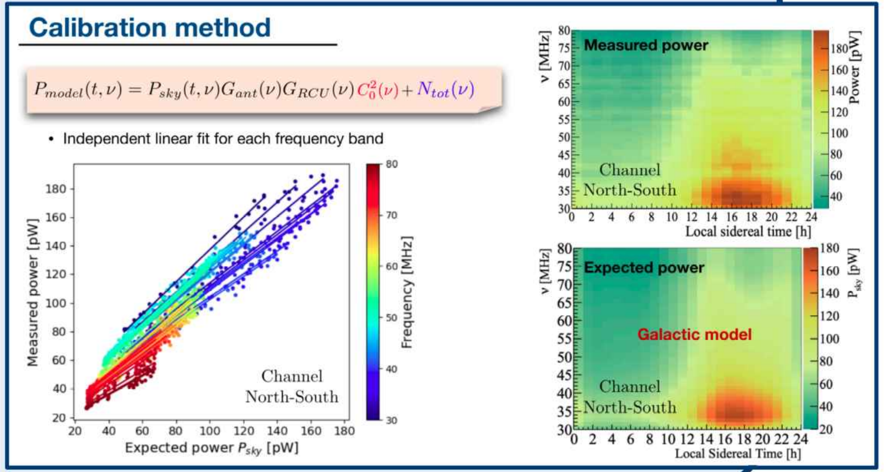
Reconstructed
station signals

Reconstructed
radio events

Radio event reconstruction with AERA

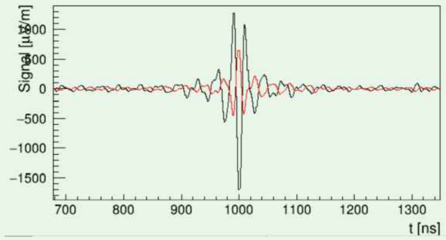
Galactic calibration (see ARENA talk by D. Correia dos Santos / T. Huege)

- Galaxy dominates background signal
- Sky models predict Galactic radio emission
  - Earlyier estimate for absolute scale uncertainty: ~6%
    [MB, T. Fodran & T. Huege, A&A, 679 (2023) A50]
- Fit measured background to prediction
  - Calibrate each channel of each station per freq. & month
  - Including signal chain and AERA detector response
  - Systematic uncertainty of absolute energy scale: ~6%



Measured radio traces

Filters, Galactic cal., ...



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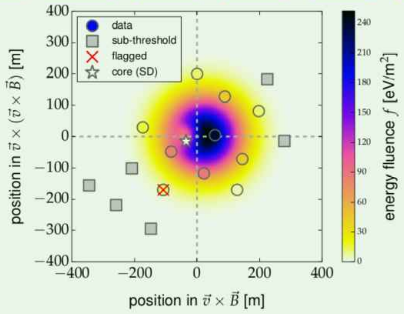
Detector response, ...



Reconstructed station signals

Lateral distribution fit, ...

Reconstructed radio events

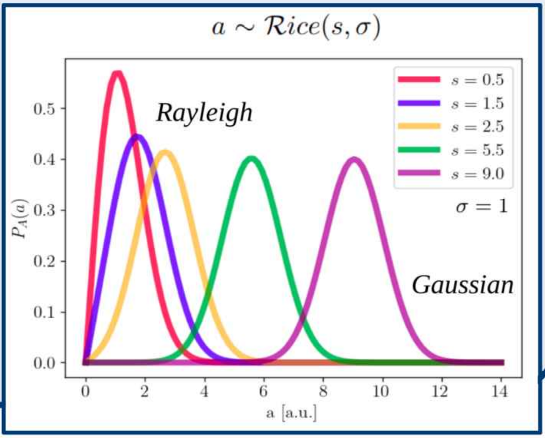
Radio event reconstruction with AERA

Station-signal estimation

Estimation of energy fluence:

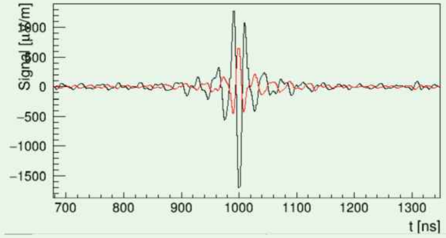
$$f = \epsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$$

- Currently: simple noise subtraction approach
  - Bias (especially for low signals) ⟶ SNR cut necessary
- New development: signal estimation based on Rice distributions (see ARENA talk by S. Martinelli)
  - Lower SNR cut possible with significantly reduced bias



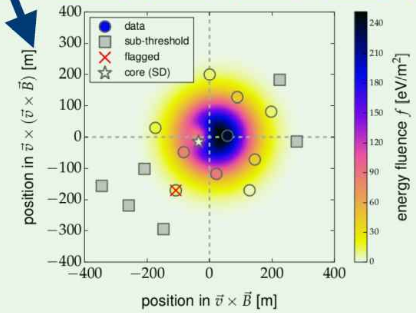
Measured radio traces

Filters, Galactic cal., …



Cleaned & calibrated radio traces

Detector response, …



Reconstructed station signals

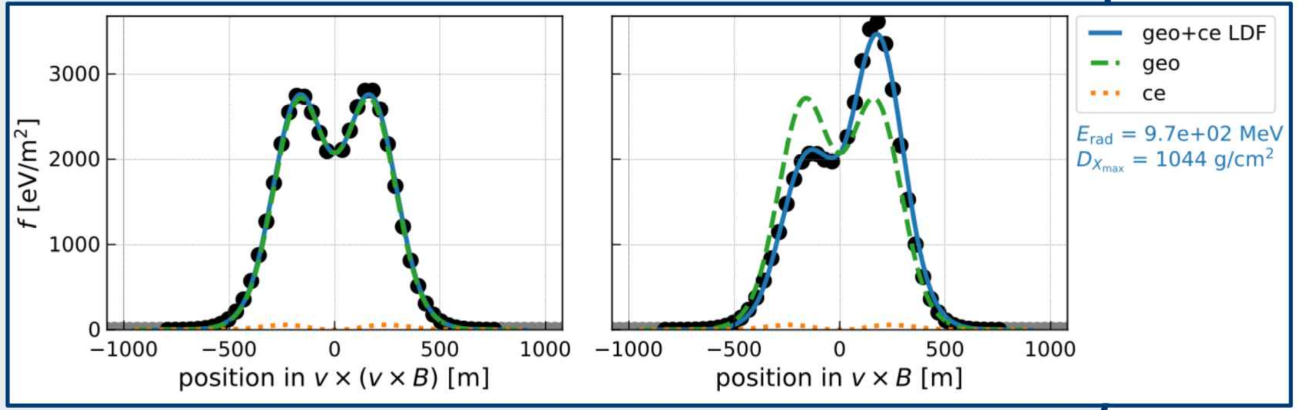
Lateral distribution fit, …

Reconstructed radio events

Radio event reconstruction with AERA

GeoCE LDF [C. Glaser et al. Astropart. Phys. 104 (2019) 64 – 77]

- Fit of signal distribution with model from geomagnetic and charge-excess contributions
- Yields best-fit radiation energy and core pos.
    - Safe against bias in ext. core estimates
- No mass-bias found
- Energy resolution: 2% on CR energy



Filters,
Galactic cal.,
…

Measured
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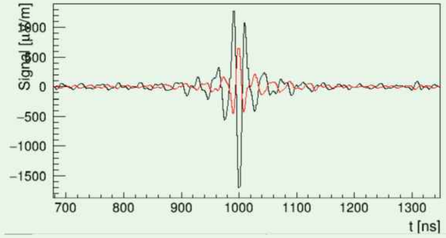

Detector
response,
…

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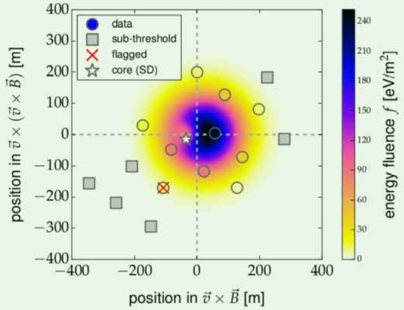


Lateral
distribution fit,
…

Reconstructed
station signals

Reconstructed
radio events

Radio event reconstruction with AERA

Equivalence of data reconstruction & simulation reconstruction

- During reconstruction, biases may be introduced
  - Pulse cleaning, signal estimation, …
- Effects checked to be the same when reconstructing data and simulations

→ **Expect biases to cancel out in event-by-event comparison of data and simulations**

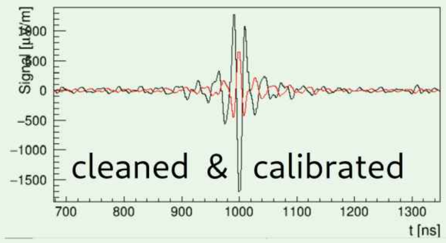
Event simulations (CORSIKA + CoREAS)

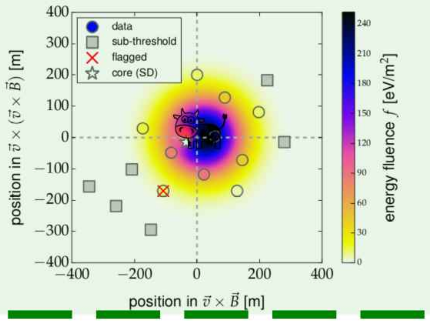
- Matching as close as possible to measured events:
  - Real AERA grid
  - Add measured noise taken close to time of event
  - GDAS atmosphere (time resolution: 3h)

High-precision:

  - Thinning 10^{-6} and STEPFC 0.05

- Per event: 1x proton, 1x iron



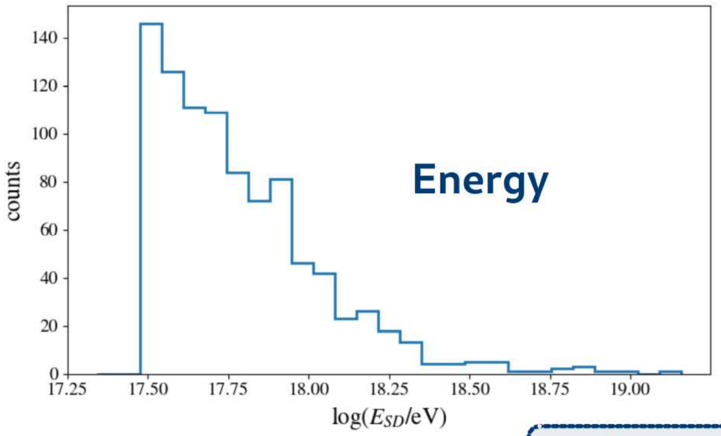


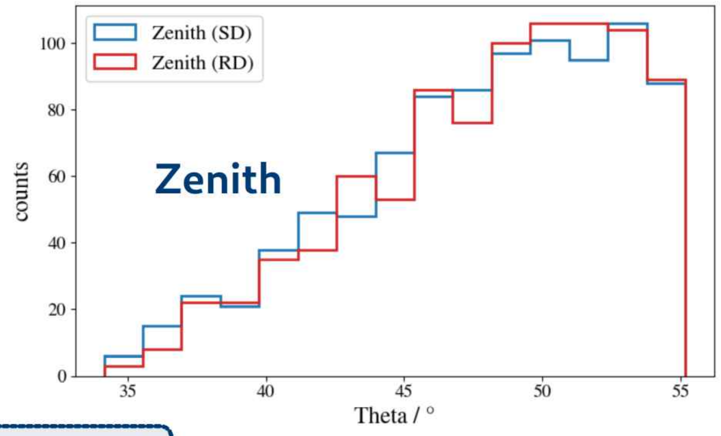
Reconstructed radio events

Radio event reconstruction

Hybrid SD-AERA dataset

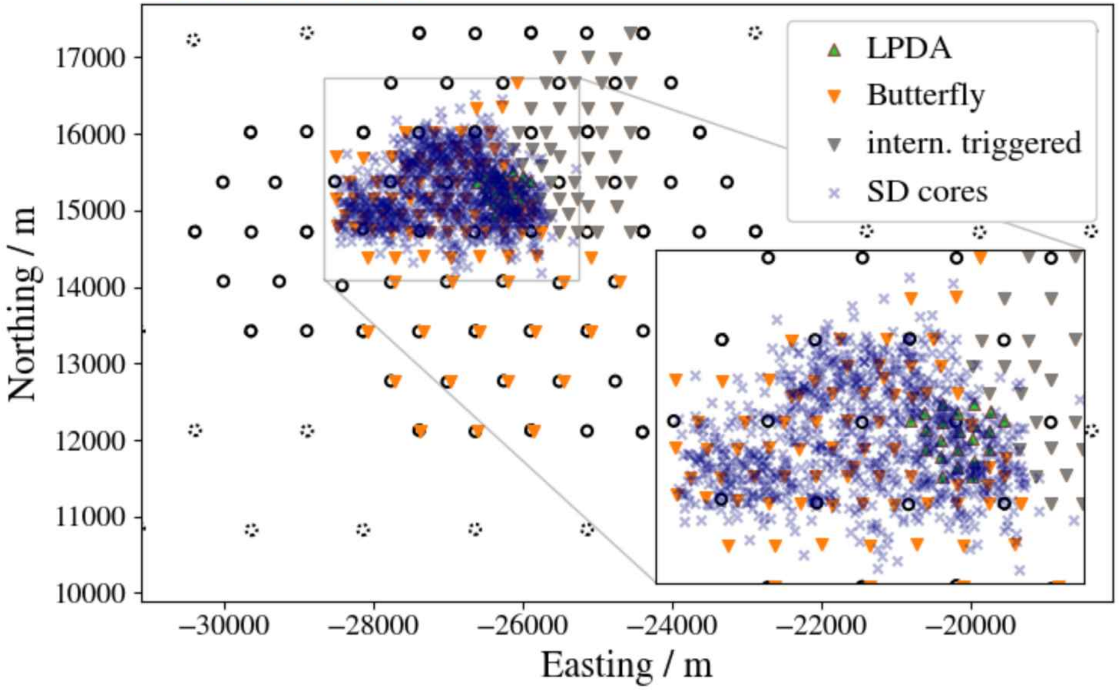
- Years 2013 – 04/2019 are processed
- 05/2019 – 12/2022 to be added soon
  - End of Auger Phase I
- Quality SD cuts (6T5) + quality AERA cuts
  - **5 signal stations + successful LDF fit**
  - **925** high-quality events (+ 50~100% more)
- SD dataset will have defined FD energy scale

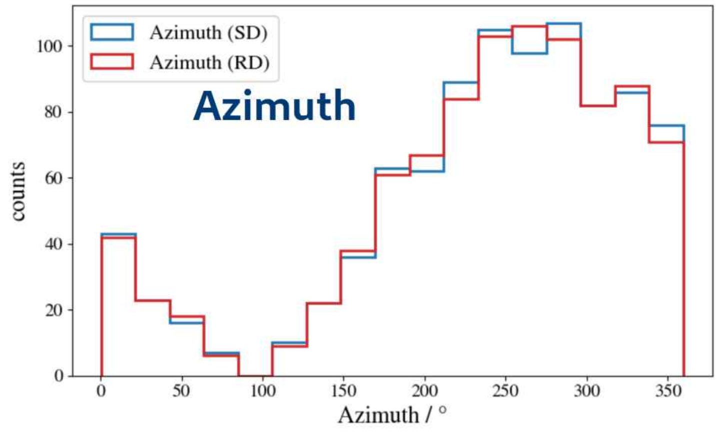


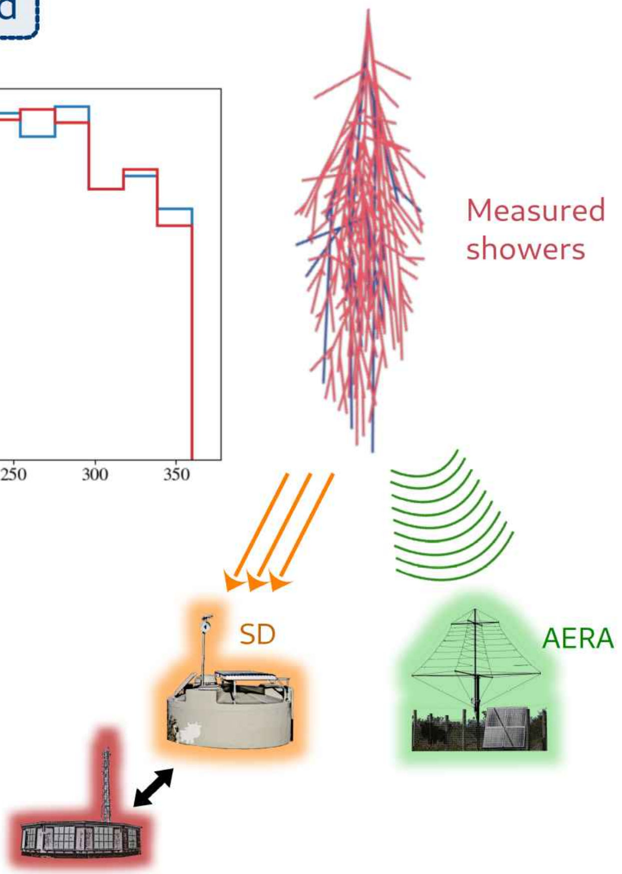


looking as expected

Shower cores

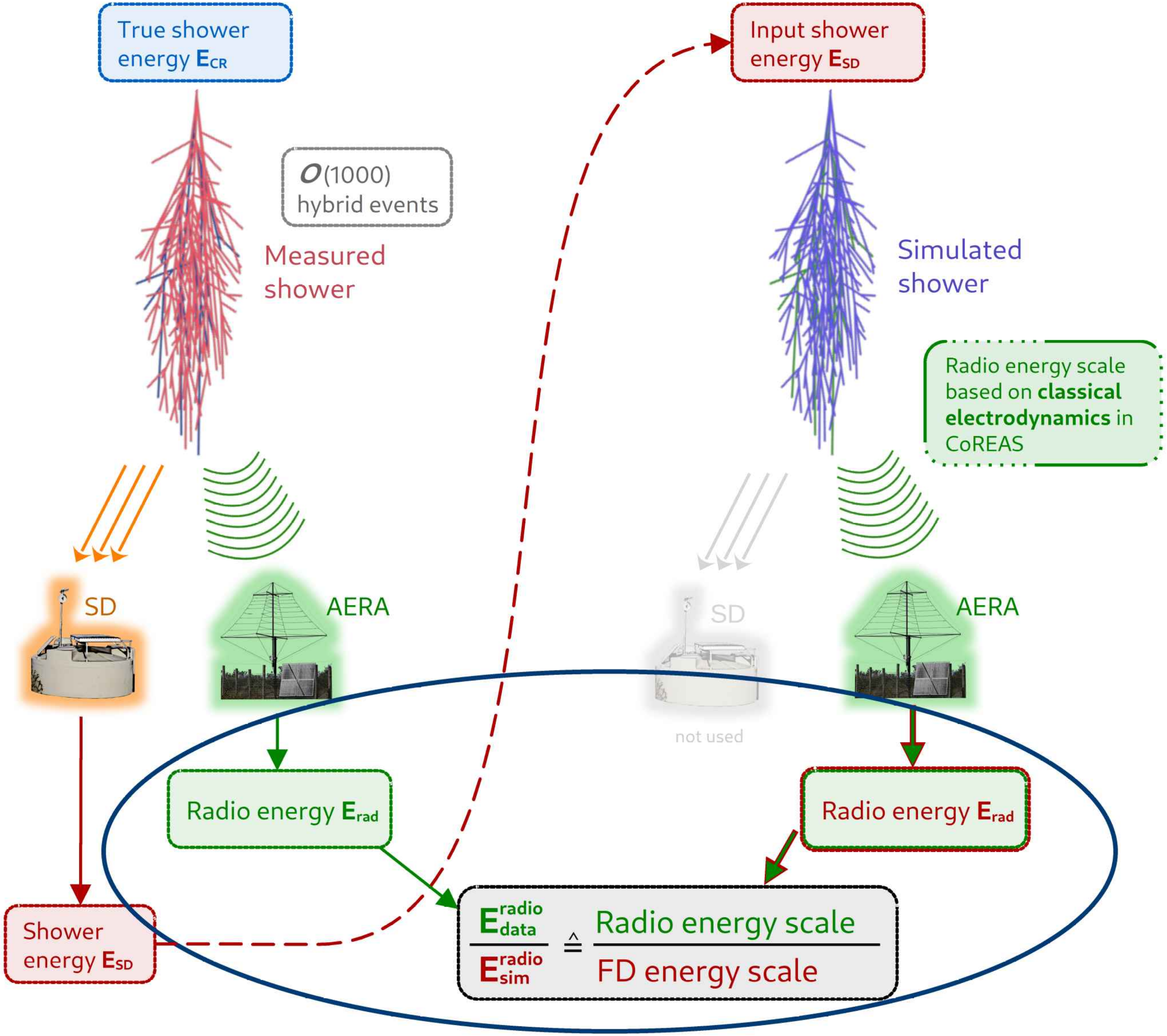






Event cuts:
- E_{SD} > 3e+17 eV
- #Stations(signal) ≥ 5
- distance between SD and RD cores < 400 m
- $\theta > 0.0°$
- $\theta < 55.0°$

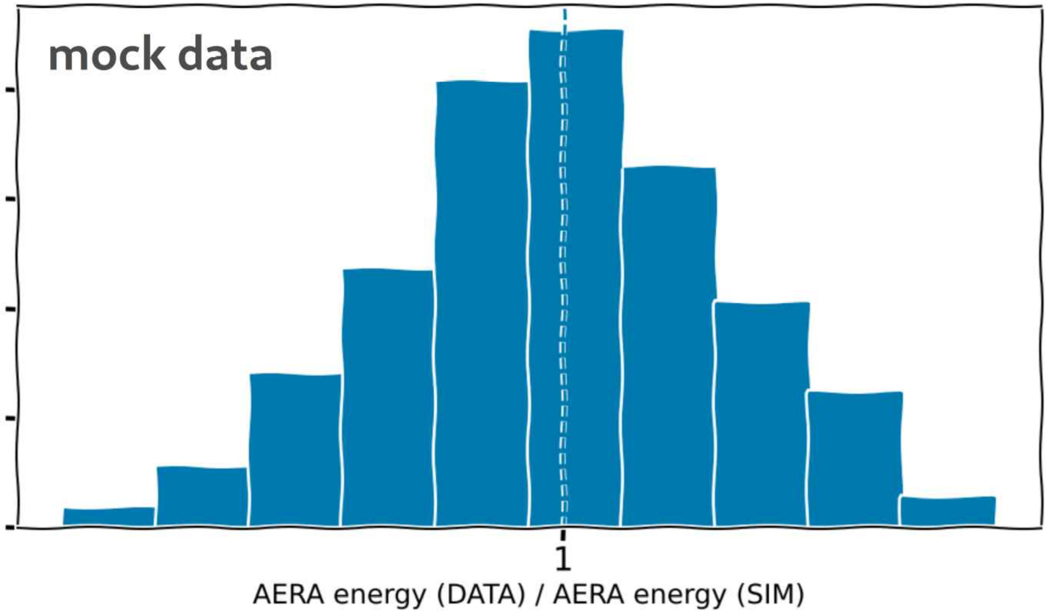
Comparing FD and Radio energy scales



OUTLOOK: Comparison of energy scales

With complete dataset and simulations:

- Currently working on best metric to determine FD-Radio energy scale agreement
- Good statistics will allow to study potential biases and dependencies
    - Antenna type (LPDA-only vs. Butterfly-only)
    - Long-term stability
    - Seasonal variation
    - Frequency, zenith, energy
    - …
- Unfortunately can't show preliminary work



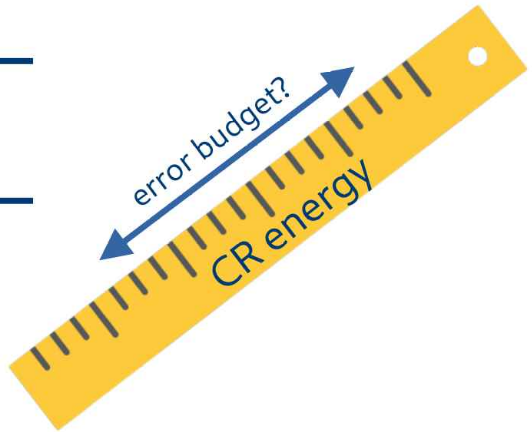
OUTLOOK: Systematic uncertainties of the radio energy scale

- Earlier uncertainty estimate of radio energy scale: 14%

[Auger Collaboration, PRL 116, 241101 (2016)]

→ Aim: reach 10%, competitive with FD

Ingredient	Status	Comment
Radio emission MC	✓	Good CoREAS / ZHAireS agreement ~3%
AERA detector calibration	✓ ✓ ✓	• Lab-calibration of detector response • Amplifier temperature correction • Galactic calibration: ~6% uncertainty
Signal reconstruction	✓ 🚧	• GeoCE LDF resolution 2% • Hopefully soon: improved signal estimation method
Dataset	✓ 🚧	• 925 (+50~100%) high-quality SD-AERA events • Complete dataset very soon
Event simulations	✓ ✓ ✓	• Matched to measured events • Measured AERA noise • GDAS atmospheres



Summary

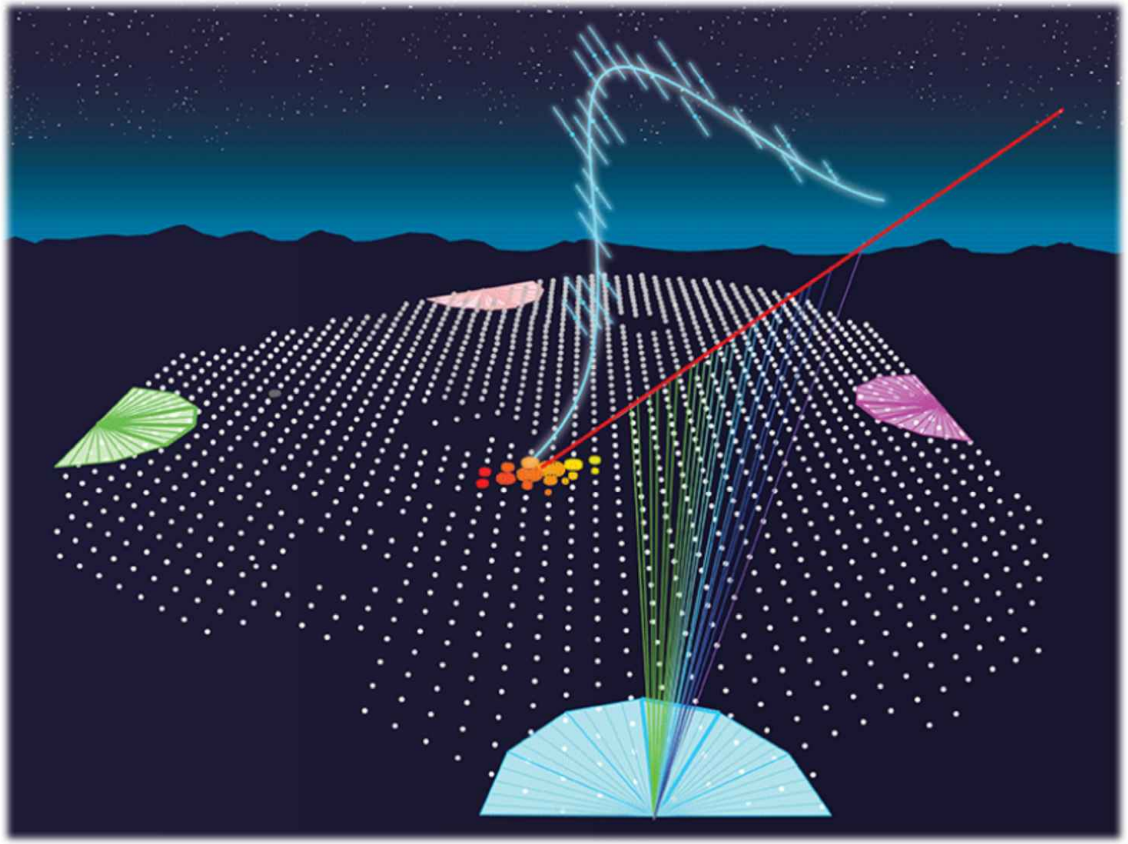
- Anaylsis of CR energy scale with radio
  - Comparison of energy scales at Auger from FD and AERA
  - Hybrid dataset since 2013 → **O**(1000) events
  - „Top-down“ like analysis with high-precision event simulations
- Matured AERA event reconstruction
  - Many ingredients coming together to get events with unprecedented absolute calibration
  - Aim: systematic uncertainties competitive with FD

Outlook

- Preparing simulations → working on metric for comparison
- Results to come!
- **Future:** expanding analysis to the highest energies with the AugerPrime Radio Detector (RD)

Backup

FD Auger energy scale – systematic uncertainties



Systematic uncert. in energy scale	
Fluorescence yield	3.6%
Atmosphere	3.4% – 6.2%
FD calibration	9.9%
FD profile recon.	6.5% – 5.6%
Invisible energy	3% – 1.5%
Energy scale stability	5%
TOTAL	14%

Table 1: Current energy scale systematic uncertainties [4]. A range refers to the change in systematic from 3×10^{18}eV to the highest energies.

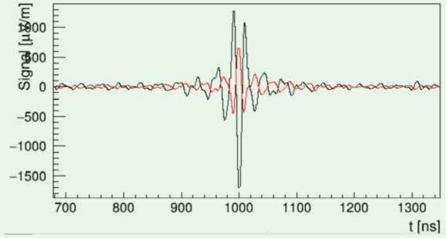
Radio event reconstruction with AERA

New in-situe drone calibration (see ARENA talk by A. Reuzki)

- Sophisticated drone campaign with ext. transmission antenna
- Measurement of directional antenna response
- Expected result:
  - Verification or adjustment of simulated antenna response patterns (LPDA & Butterfly) that are used in station-level signal reconstruction

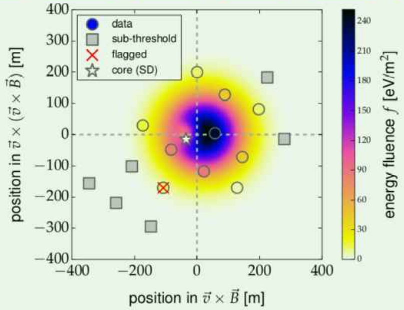
Measured radio traces

Filters, Galactic cal., …



Cleaned & calibrated radio traces

Detector response, …



Reconstructed station signals

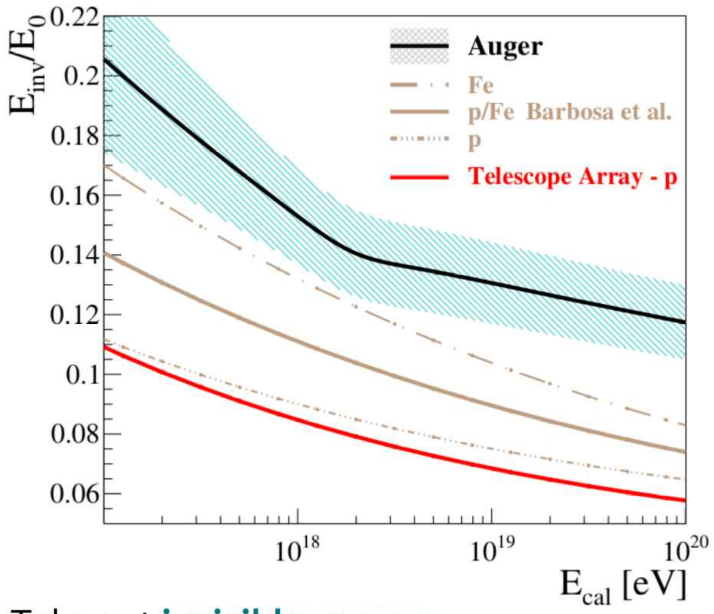
Lateral distribution fit, …

Reconstructed radio events

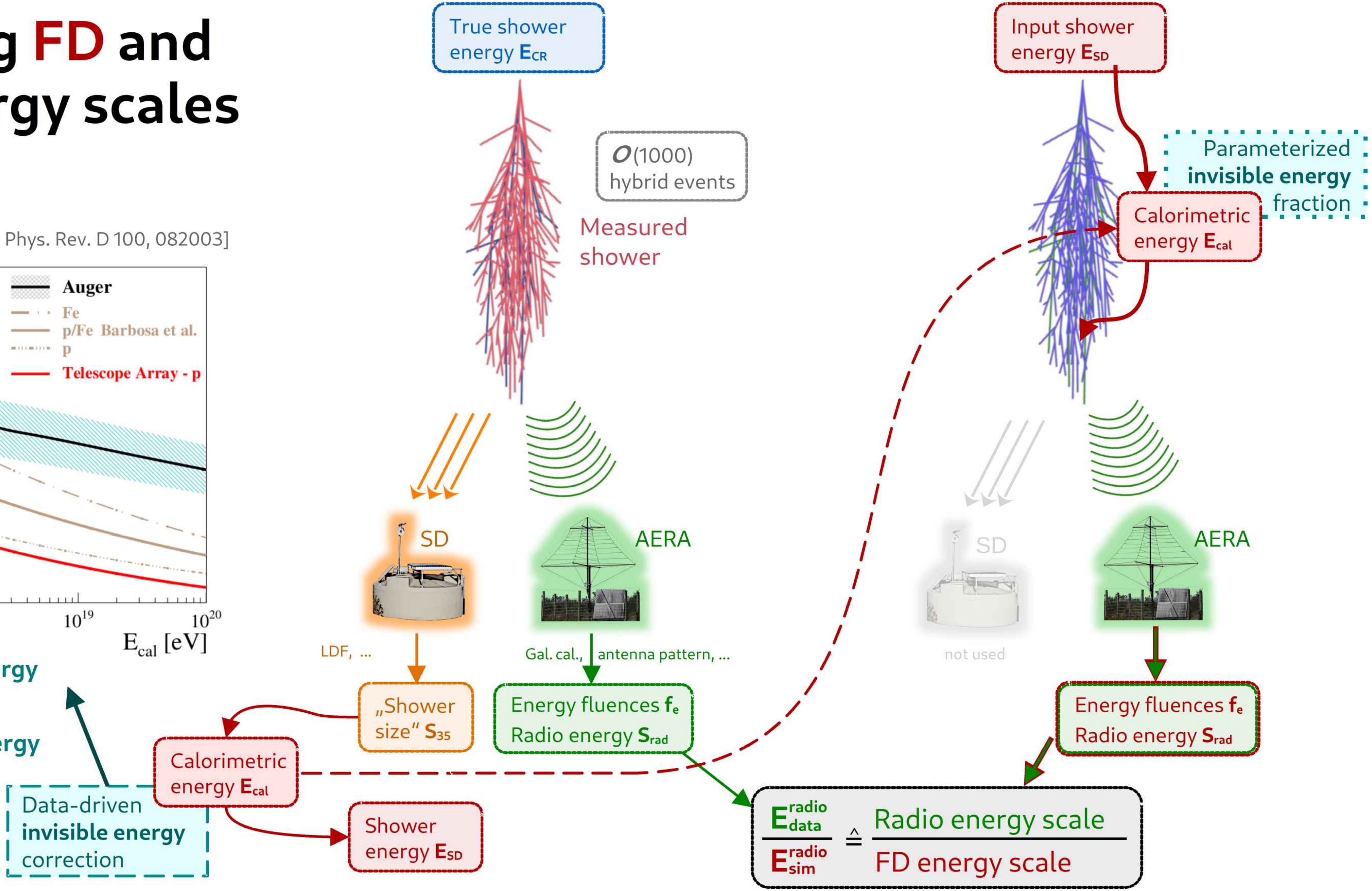
Radio event reconstruction

Comparing FD and Radio energy scales

[Auger Collaboration, Phys. Rev. D 100, 082003]



- Take out **invisible energy** correction **in data**
- Factor in **invisible energy** **in simulations**

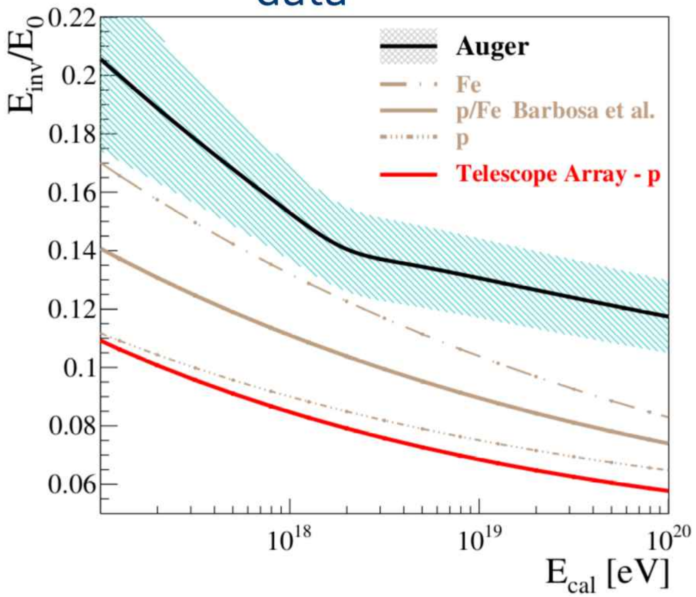


Event simulations

- CORSIKA + CoREAS event simulations
  - SD energy as input
  - SD shower geometry as input
    ↪ No dependency on radio reconstruction
  - Sibyll 2.3d + UrQMD
  - THINNING 1e-6
  - STEPFC 0.05
  - GDAS atmosphere
  - 2 simulations per shower: p + Fe
  - AERA station grid

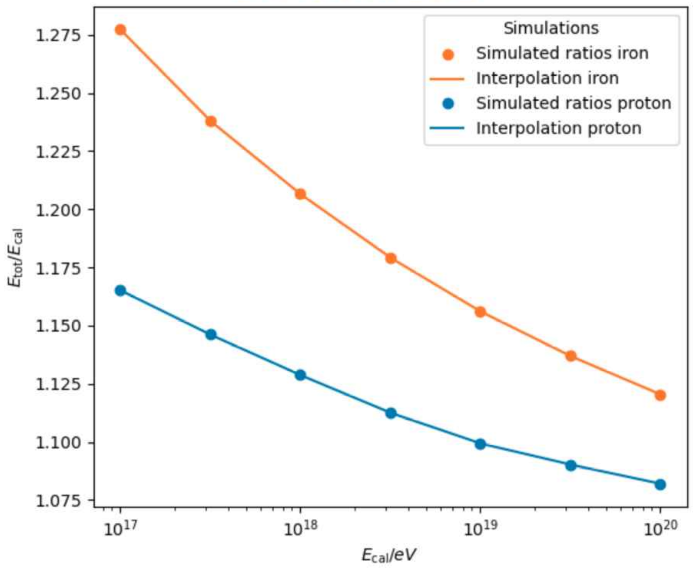
invisible energy

data

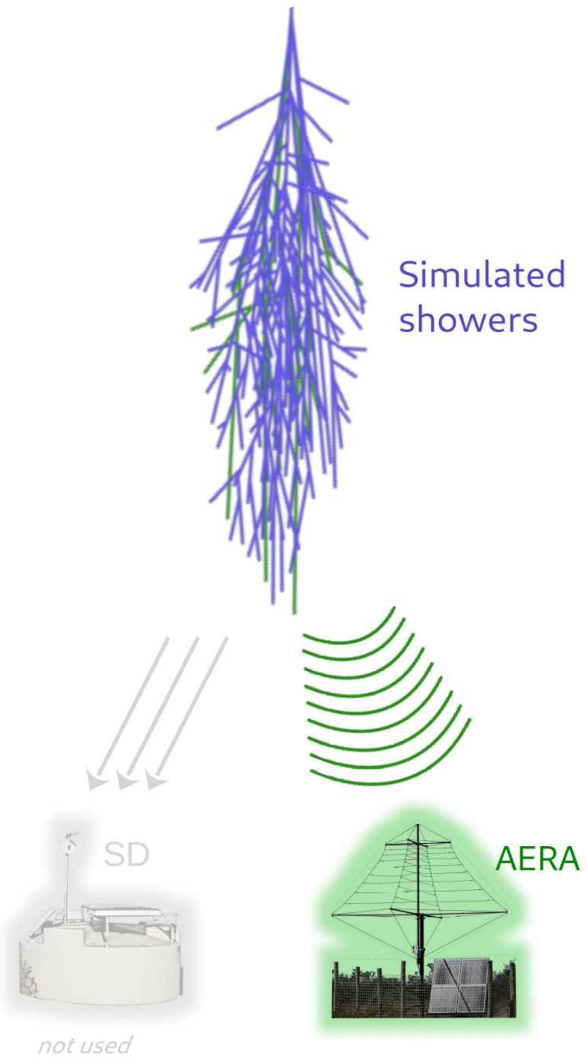


Data-driven **invisible energy** correction

simulations



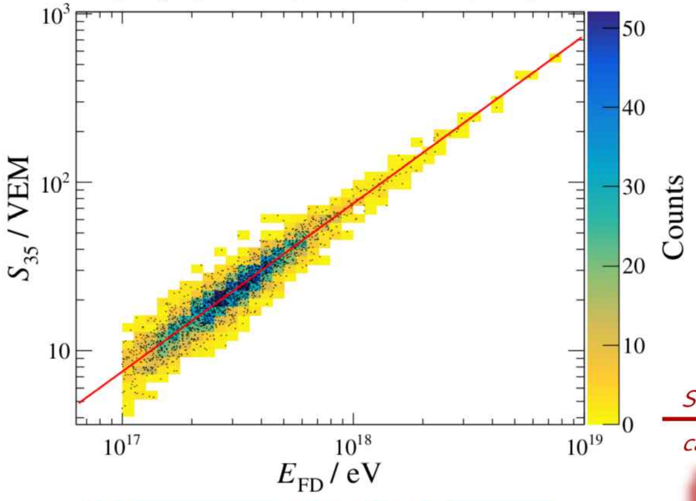
Parameterized **invisible energy** fraction



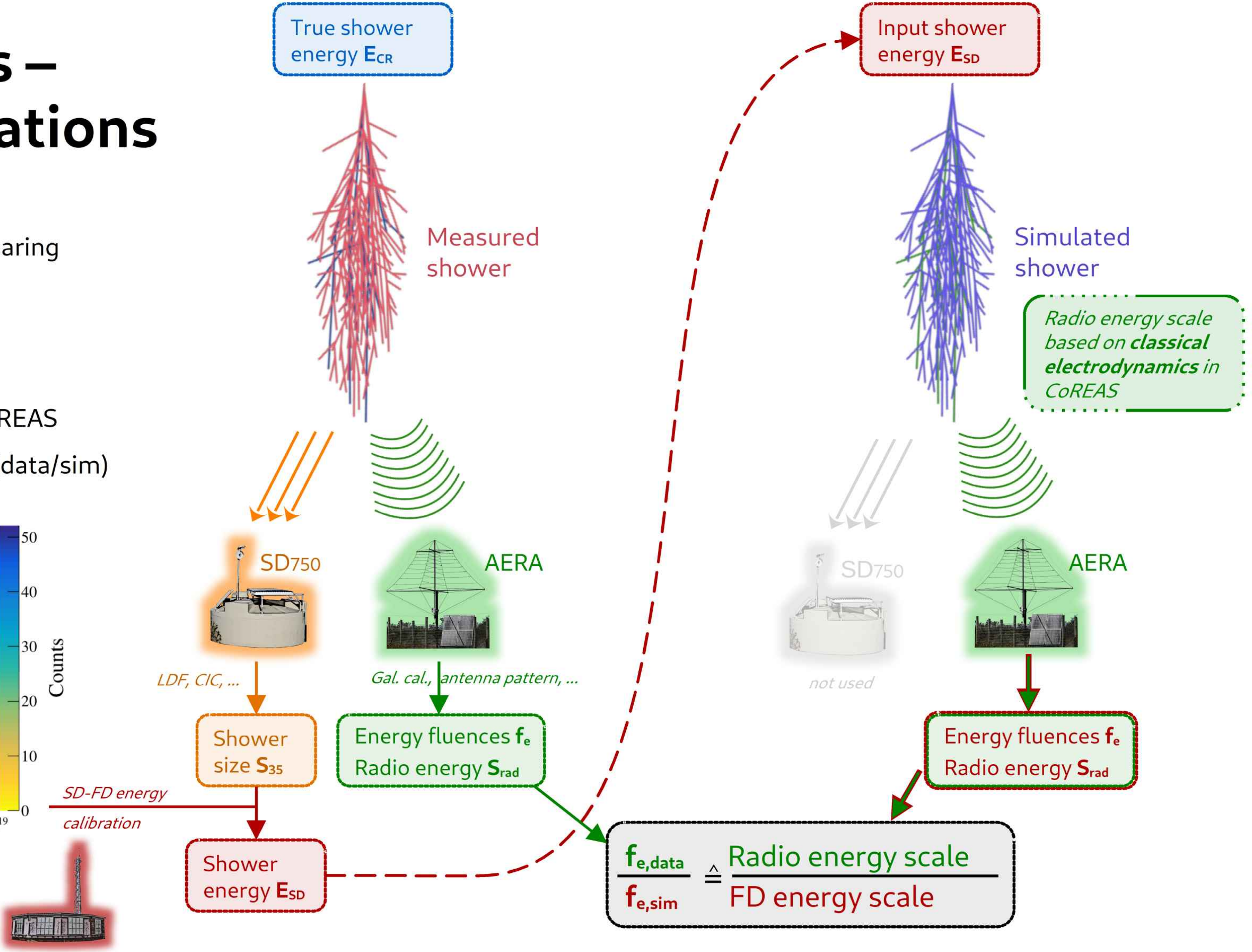
Hybrid Showers – Data and Simulations

- Proposed methodology for comparing FD & Radio energy scales
- Hybrid SD750 – AERA events
  - $\theta < 55°$
- Event simulations CORSIKA + CoREAS
- Ratio/difference of radio energy (data/sim)

[Auger] Eur. Phys. J. C 81, 966 (2021)



*FD energy scale based on **fluorescence yield** measurement*



Hybrid Showers – Data and Simulations

Potential source for a bias?

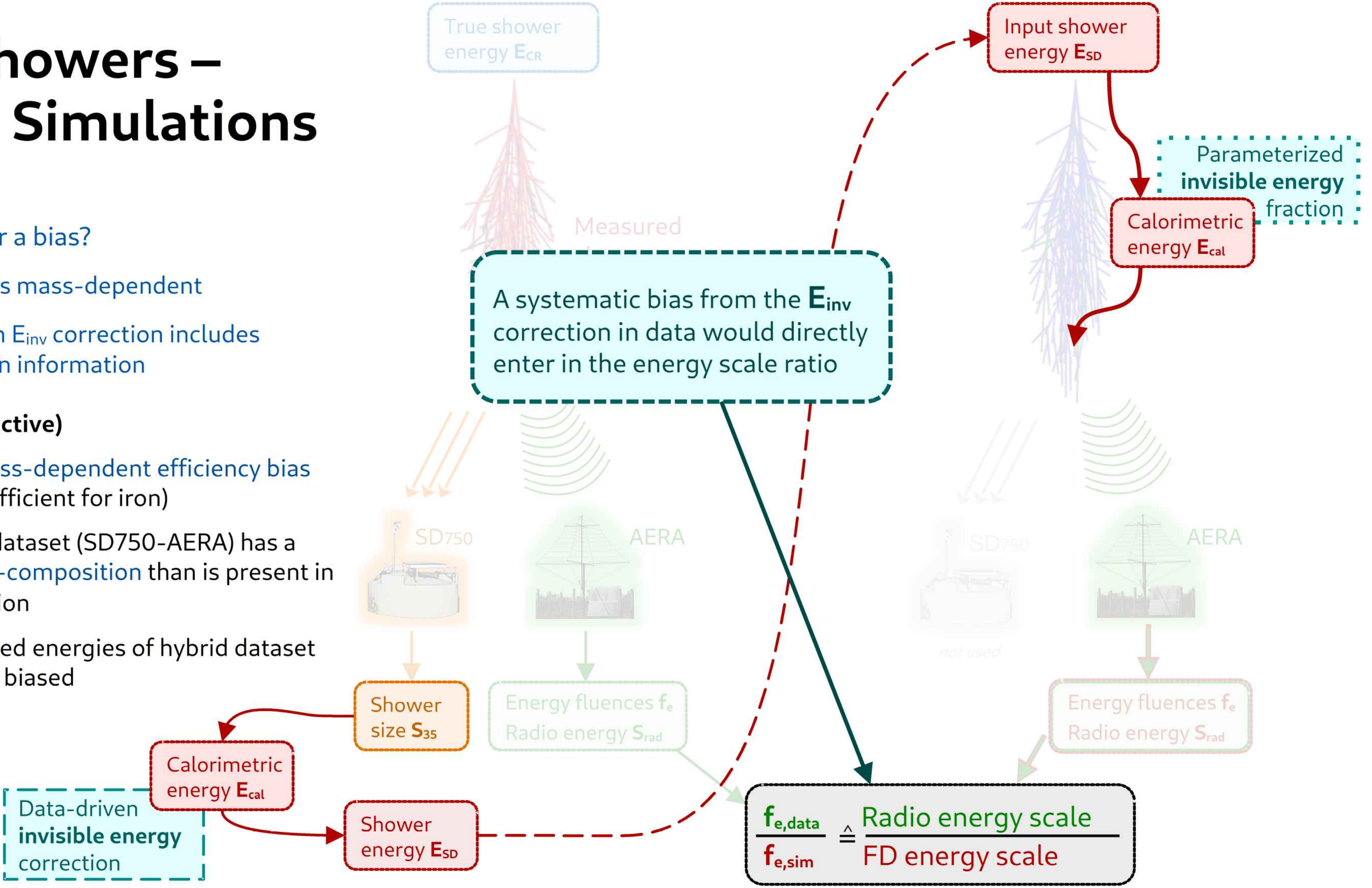
- E_{inv} / E_{CR} fraction is mass-dependent
- Auger data-driven E_{inv} correction includes mass-composition information

Scenario: (subjunctive)

AERA has a mass-dependent efficiency bias (e.g. not fully efficient for iron)

↪ The hybrid dataset (SD750-AERA) has a different mass-composition than is present in the E_{inv} correction

↪ Reconstructed energies of hybrid dataset are on average biased



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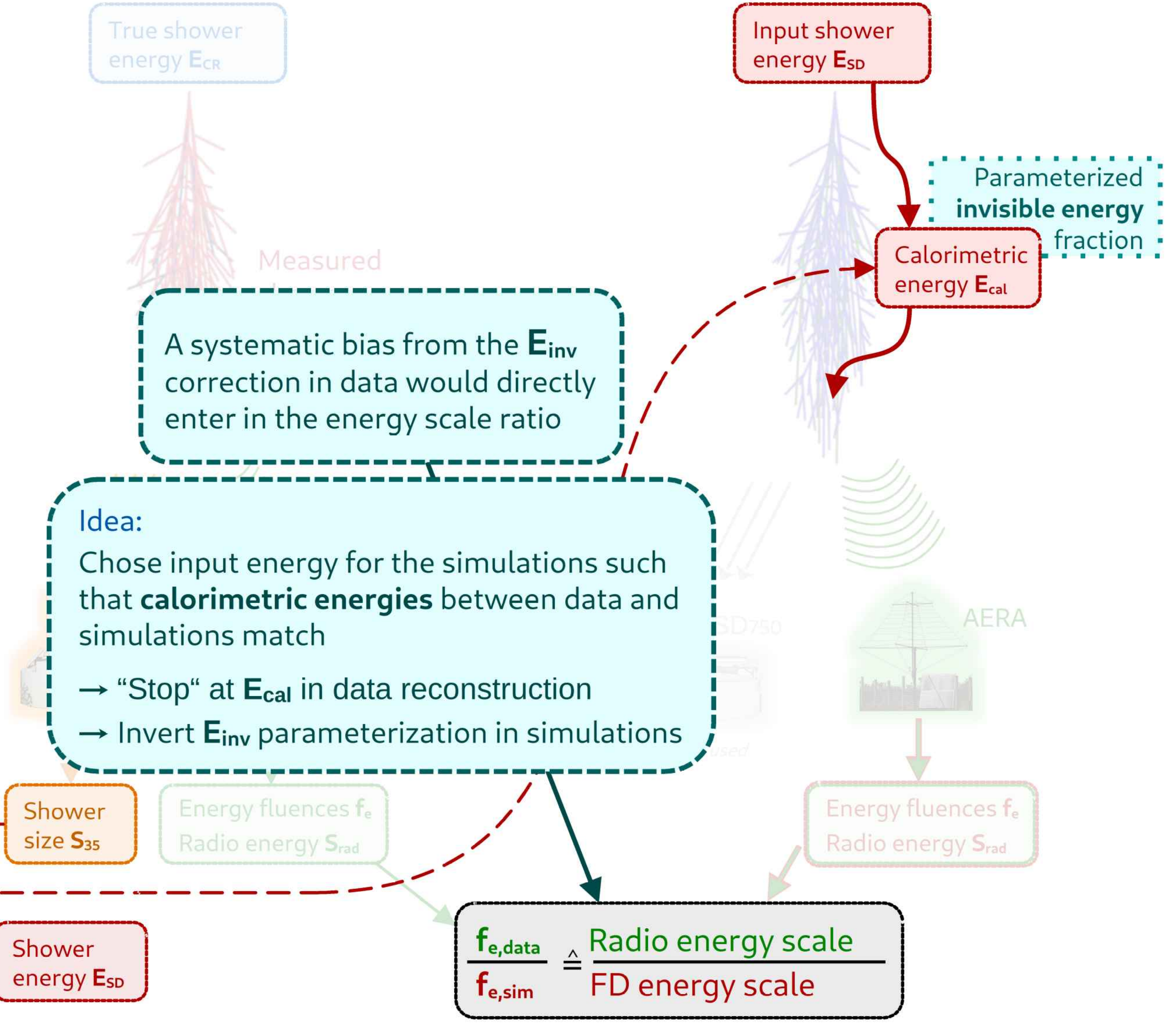
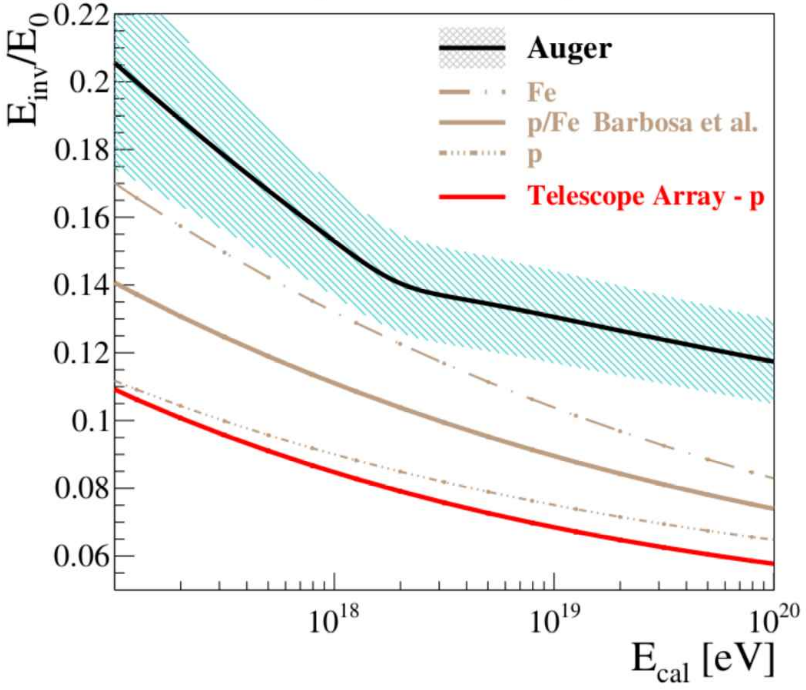
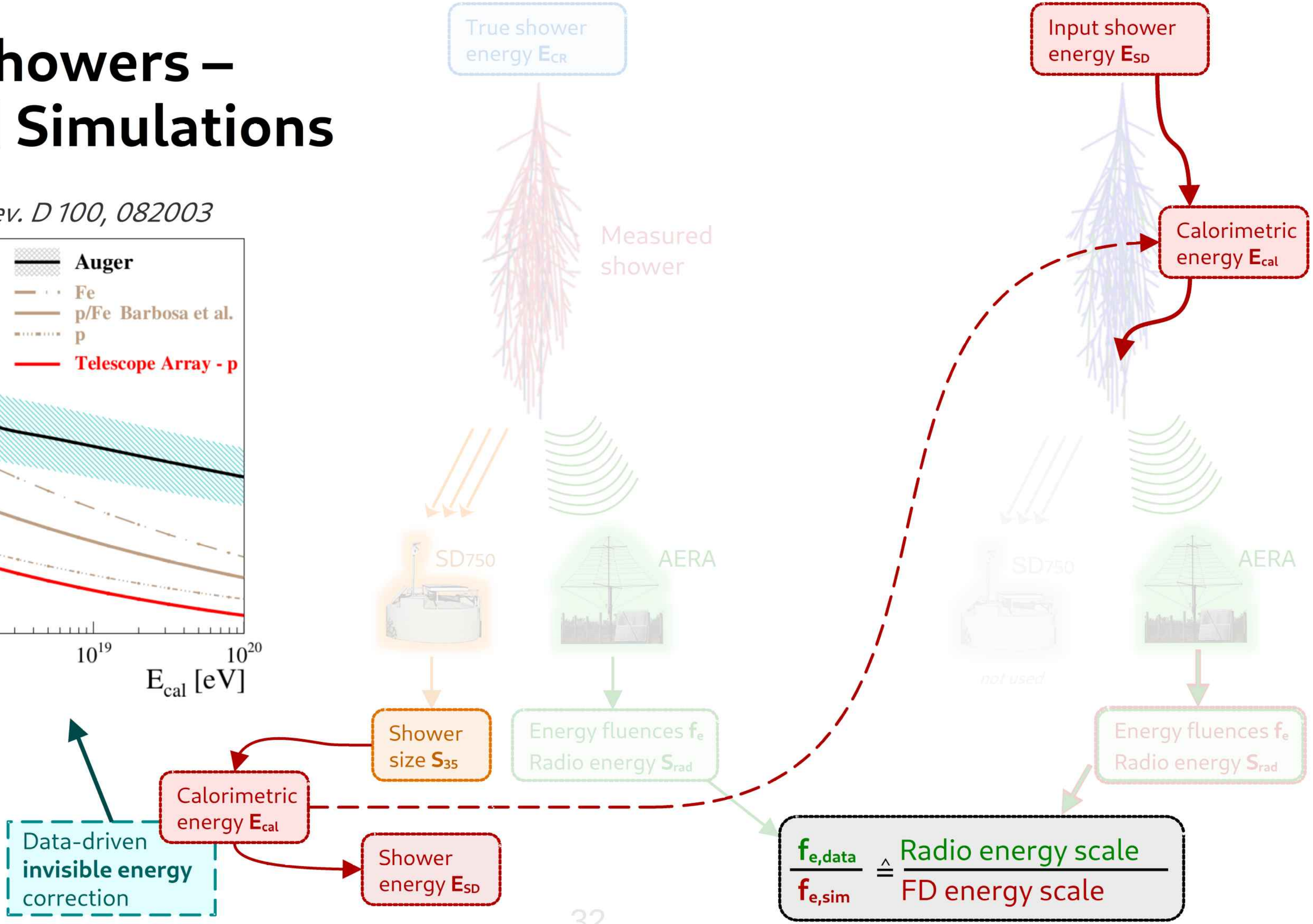


Hybrid Showers – Data and Simulations

from *Phys. Rev. D 100, 082003*





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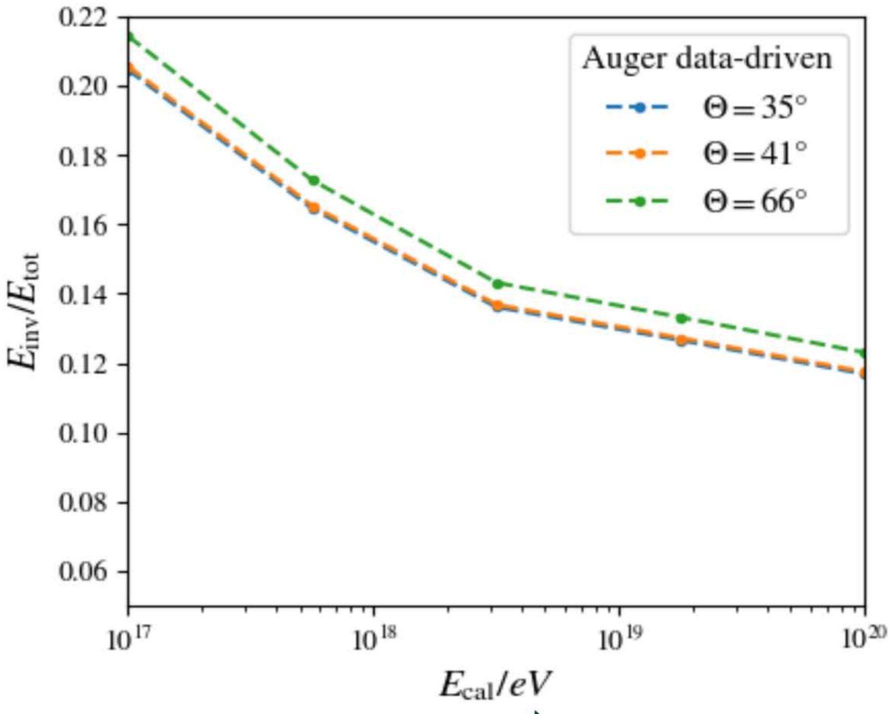

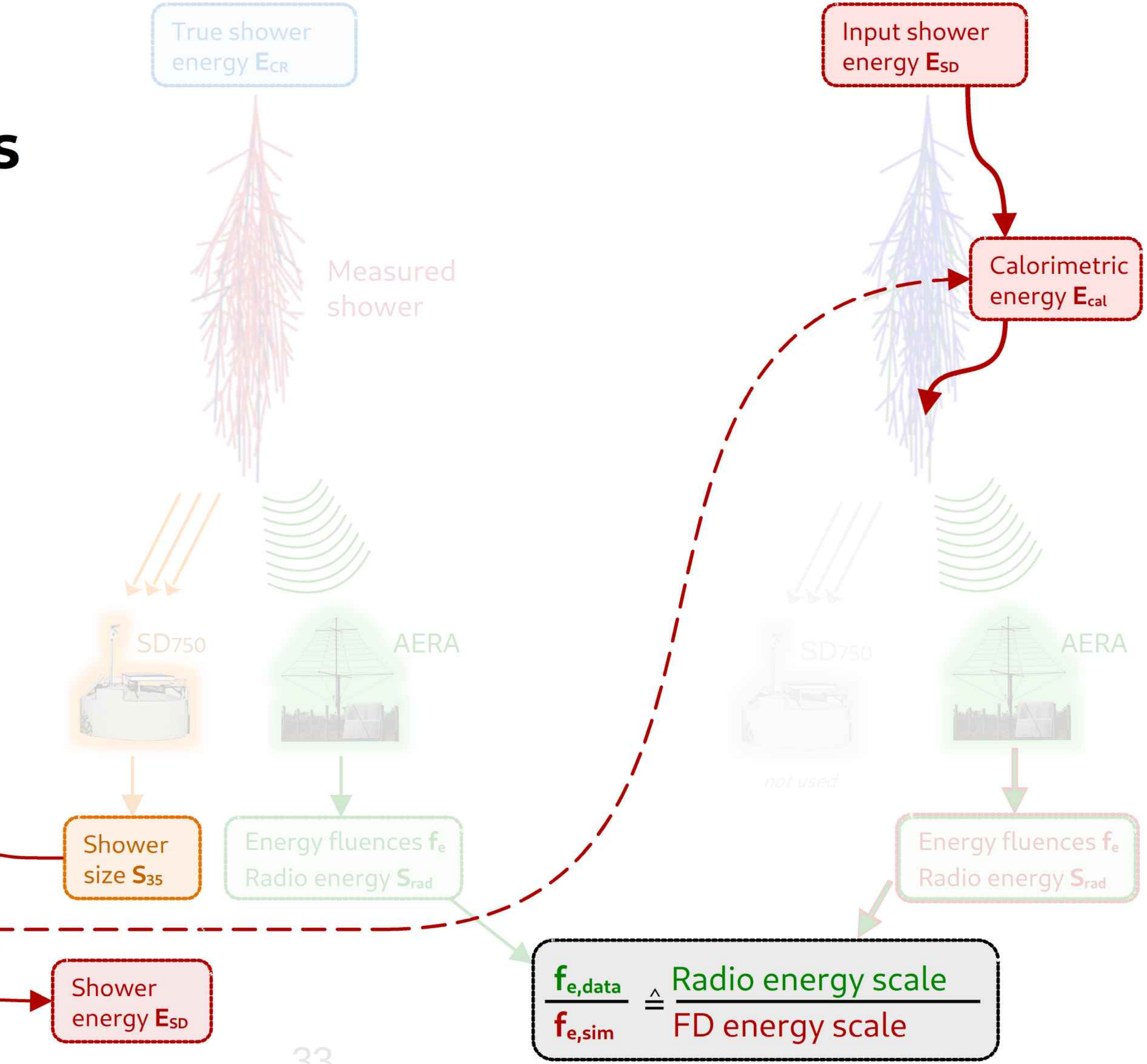

Hybrid Showers – Data and Simulations

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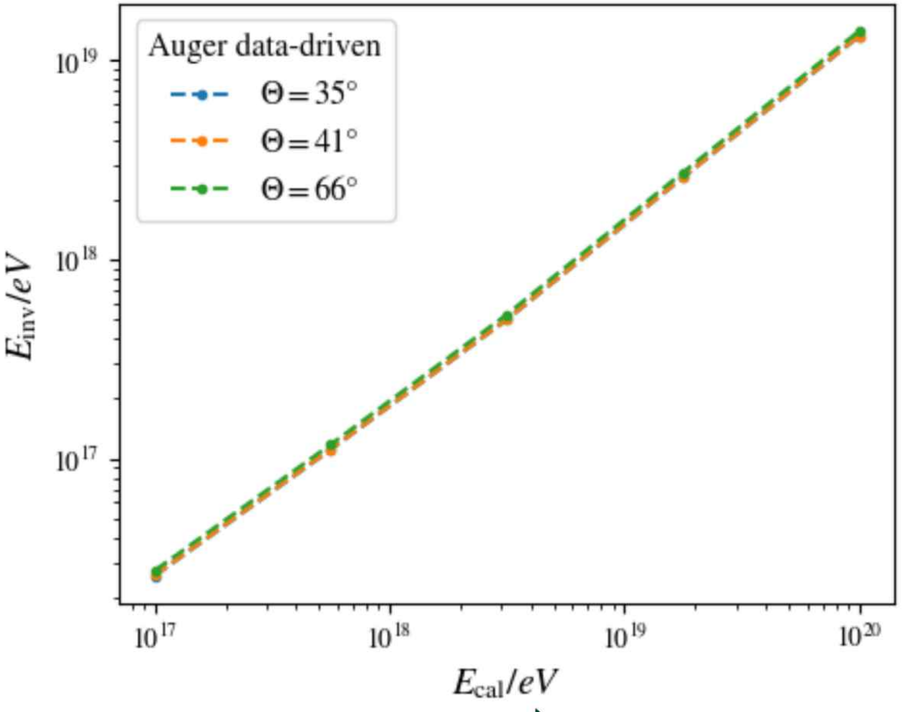
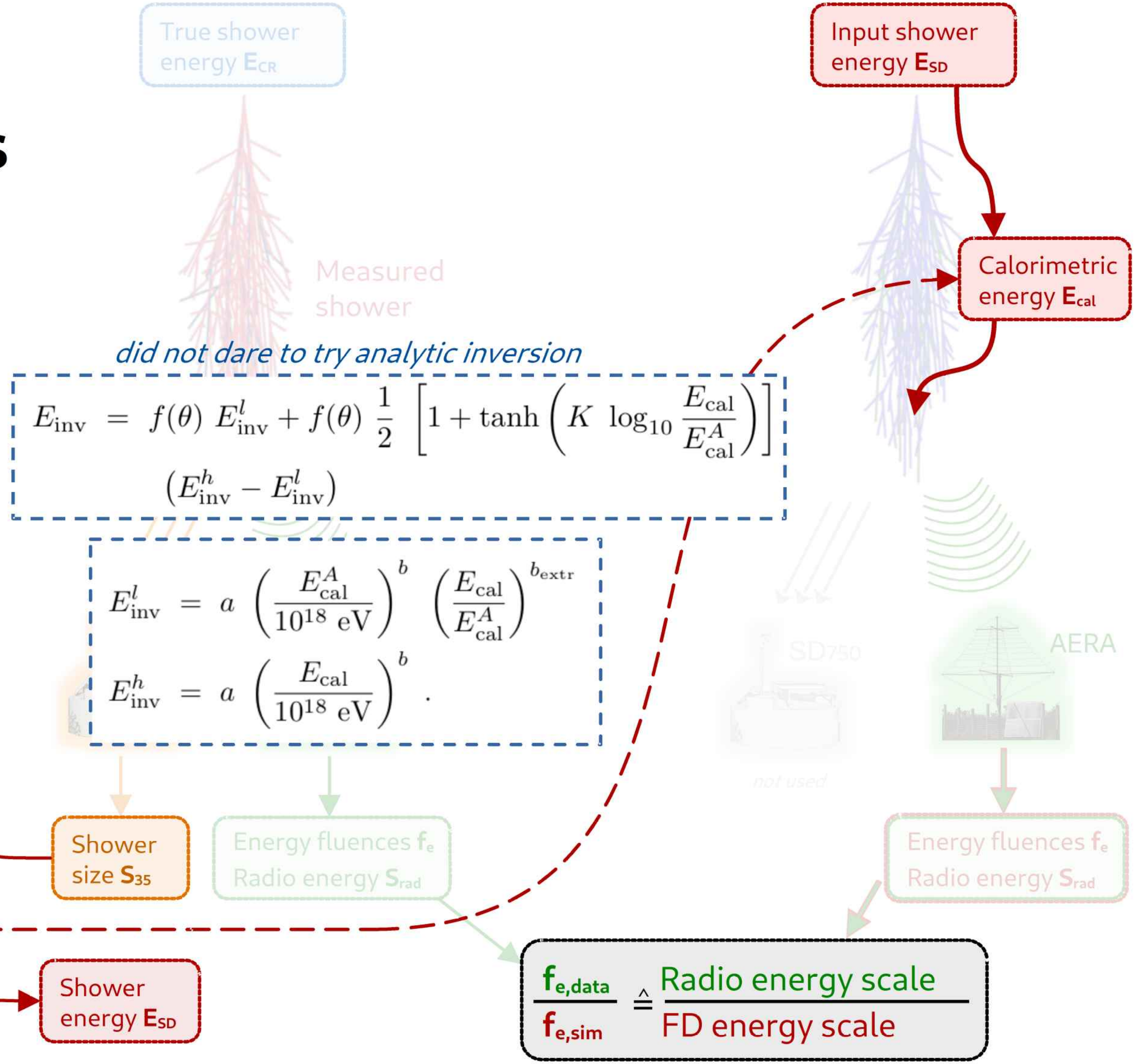


did not dare to try analytic inversion

$$E_{inv} = f(\theta)\, E^l_{inv} + f(\theta)\, \frac{1}{2} \left[1 + \tanh\left(K \, \log_{10} \frac{E_{cal}}{E^A_{cal}}\right)\right] (E^h_{inv} - E^l_{inv})$$

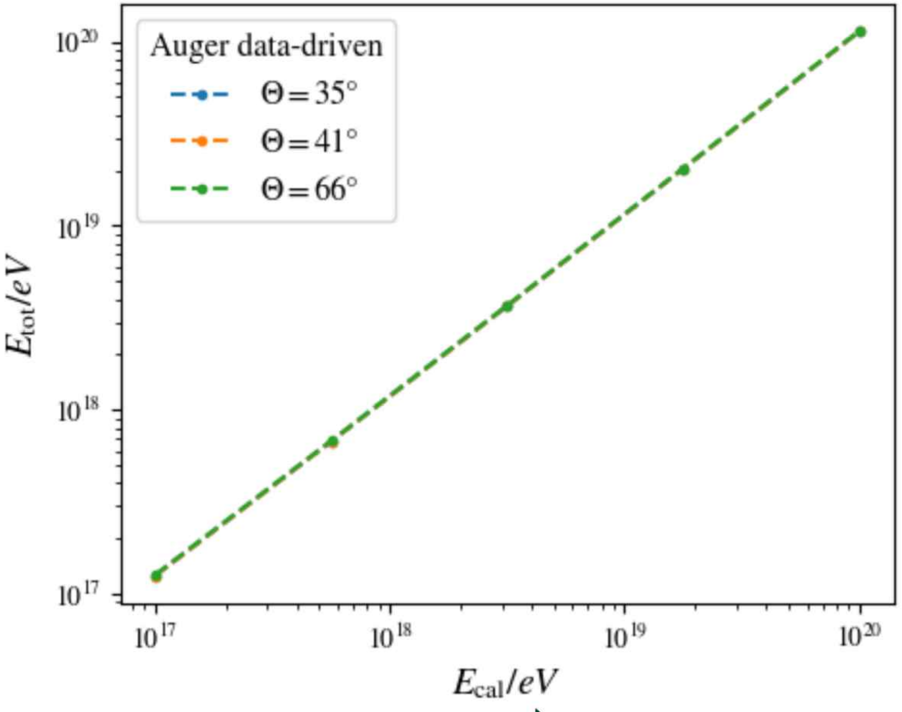
$$E^l_{inv} = a \left(\frac{E^A_{cal}}{10^{18}\ \mathrm{eV}}\right)^b \left(\frac{E_{cal}}{E^A_{cal}}\right)^{b_{extr}}$$

$$E^h_{inv} = a \left(\frac{E_{cal}}{10^{18}\ \mathrm{eV}}\right)^b .$$



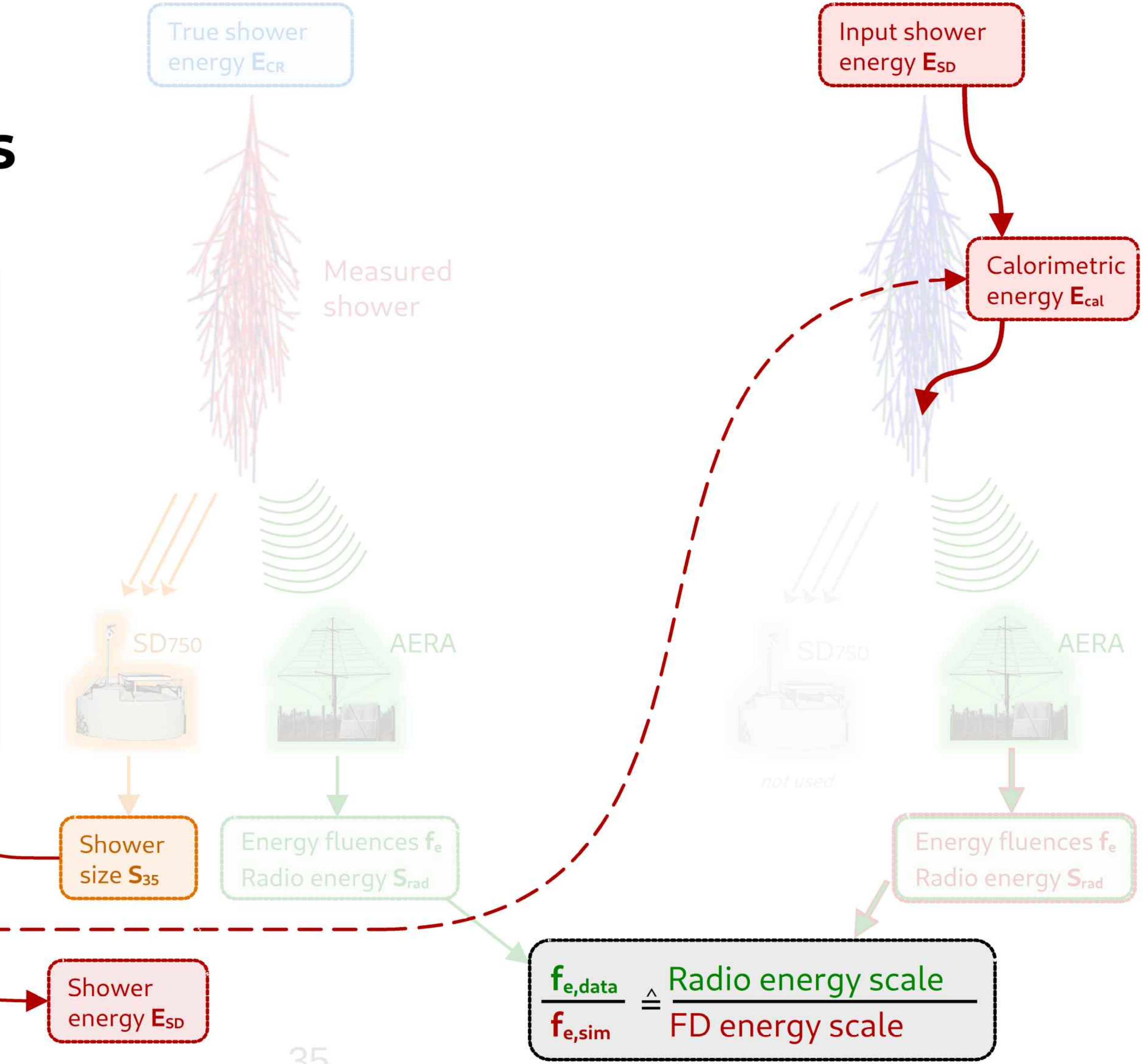
Hybrid Showers – Data and Simulations

from *Phys. Rev. D 100, 082003*



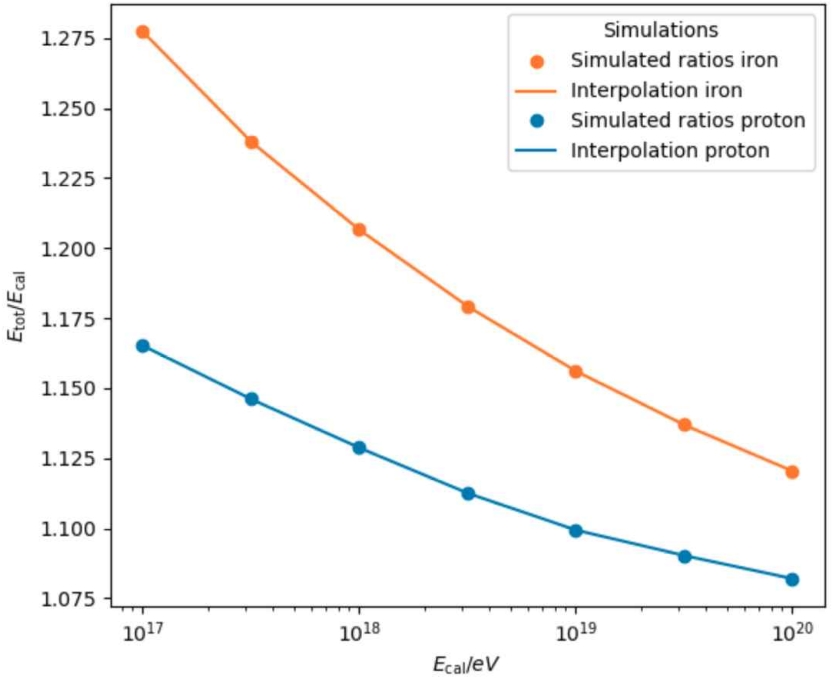
interpolate inverse relation
to “recalculate“ E_{cal}

↪ $E_{cal}(E_{tot})$

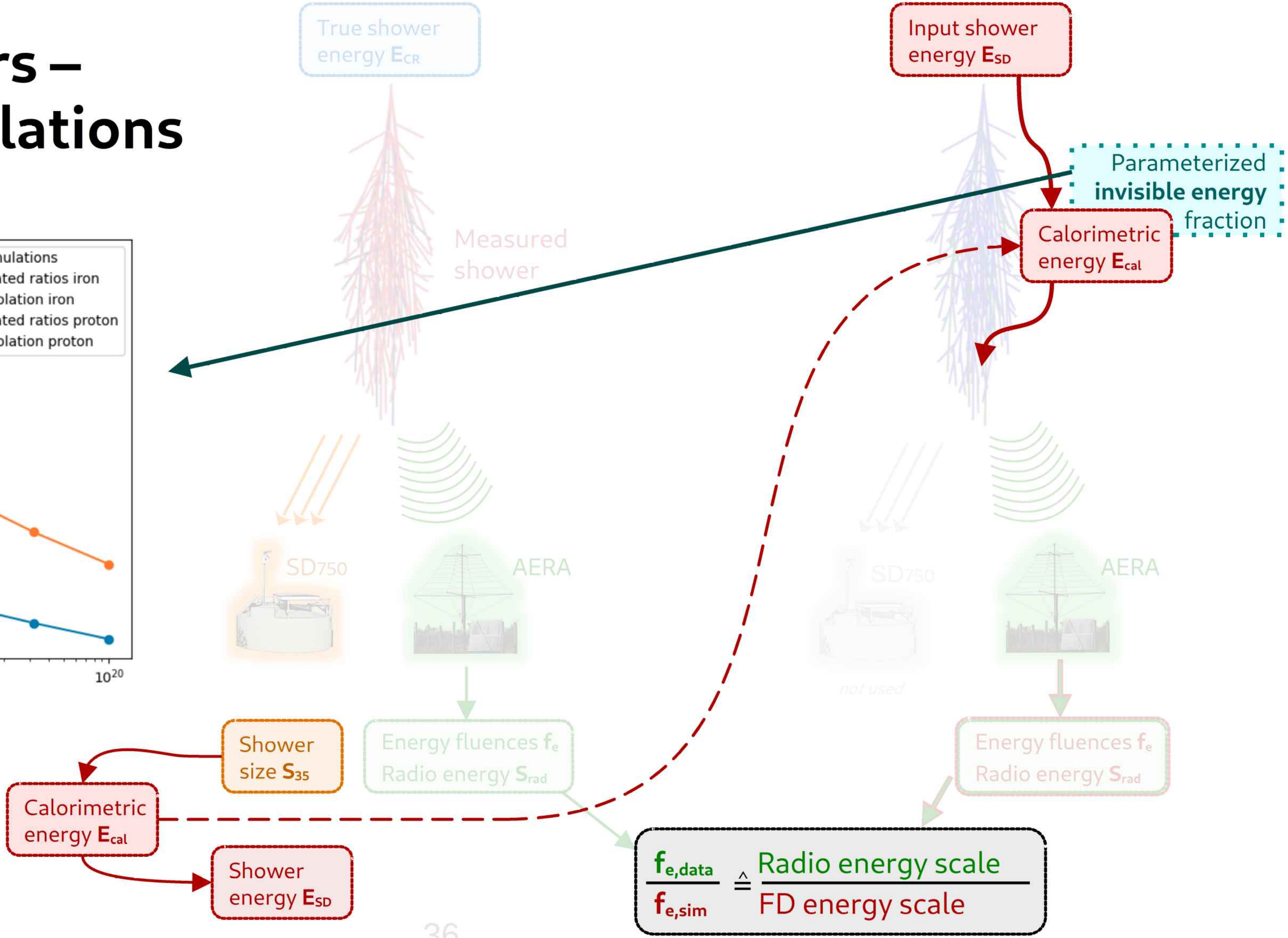


Hybrid Showers – Data and Simulations

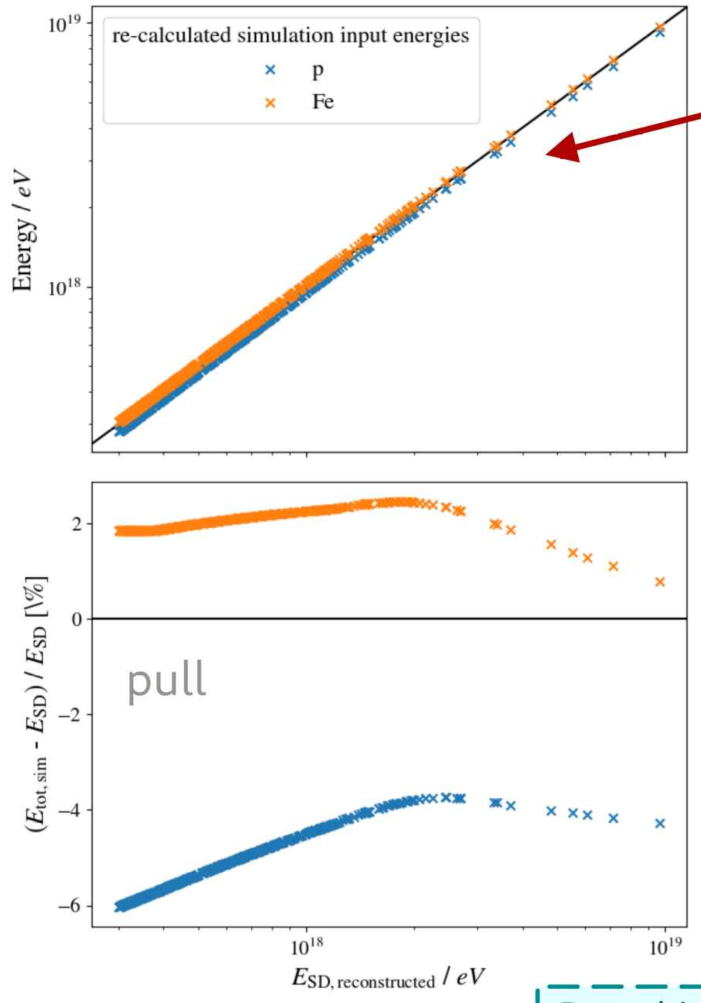
provided by T. Pierog



interpolate to calculate E_{tot}, which is expected to produce desired E_{cal}
(separate for proton and iron)



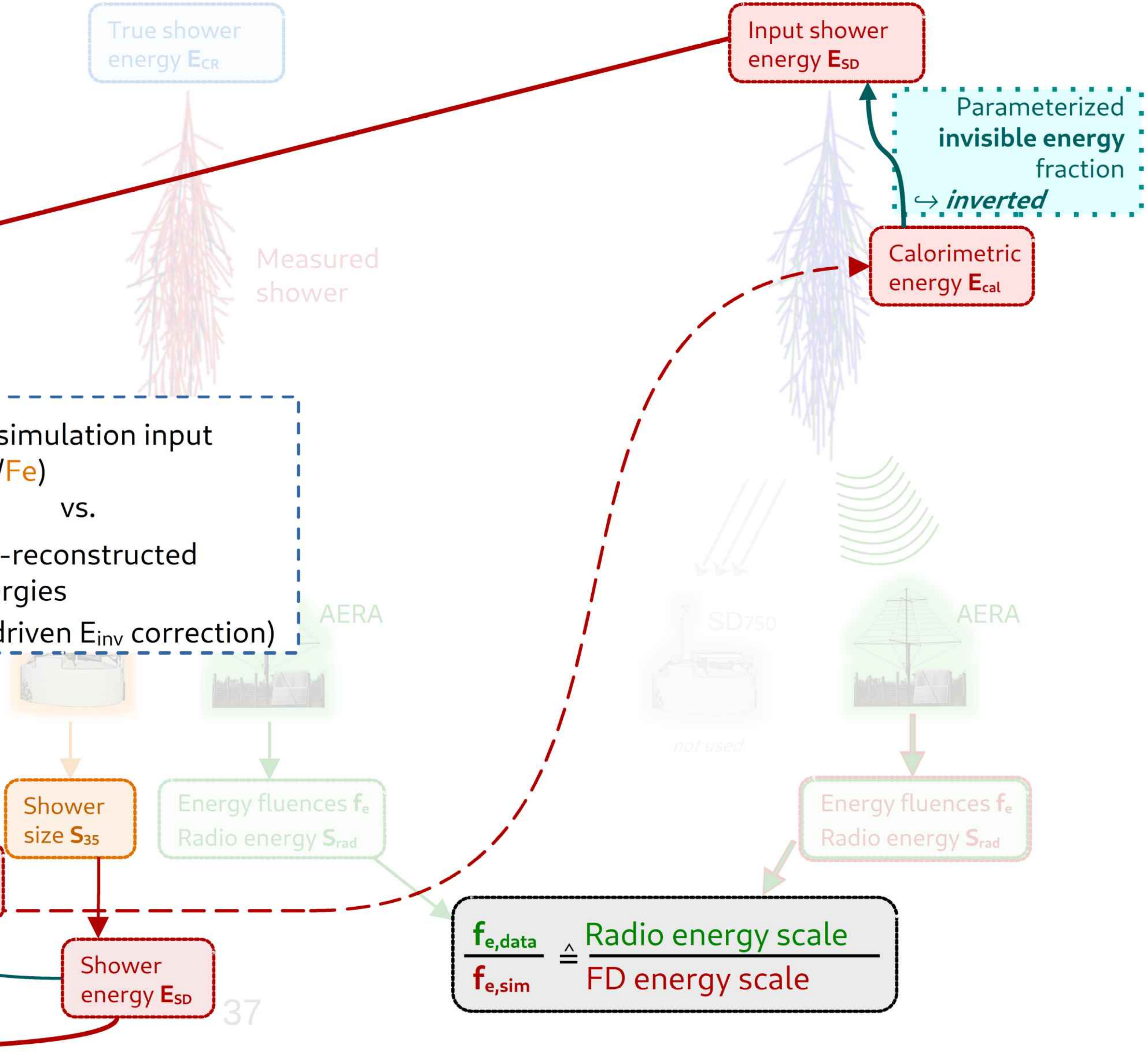
Hybrid Showers – Data and Simulations



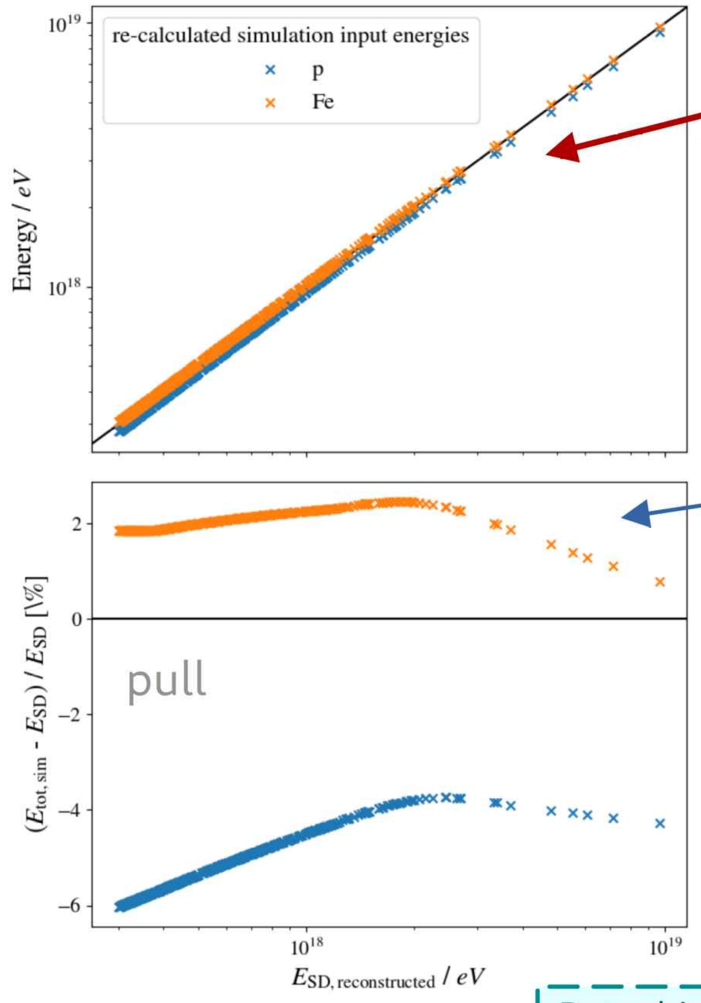
Calculated simulation input energies (p/Fe)

vs.

Original SD-reconstructed shower energies (incl. data-driven E_{inv} correction)

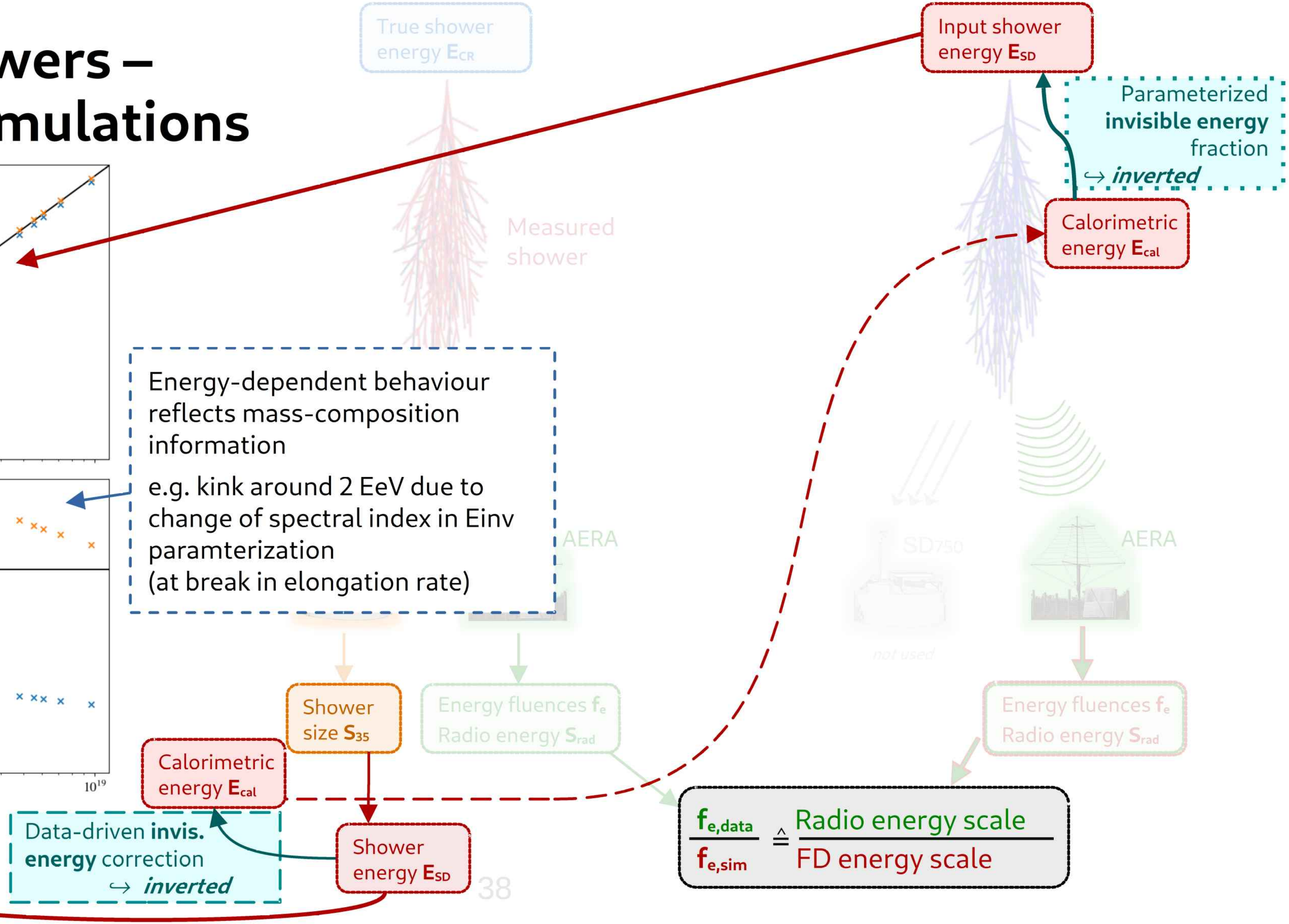


Hybrid Showers – Data and Simulations



Energy-dependent behaviour reflects mass-composition information

e.g. kink around 2 EeV due to change of spectral index in Einv paramterization
(at break in elongation rate)



Hybrid Showers – Data and Simulations

Plan B?

Using hybrid FD-AERA events would simplify the logic and maybe save us some sources of systematics

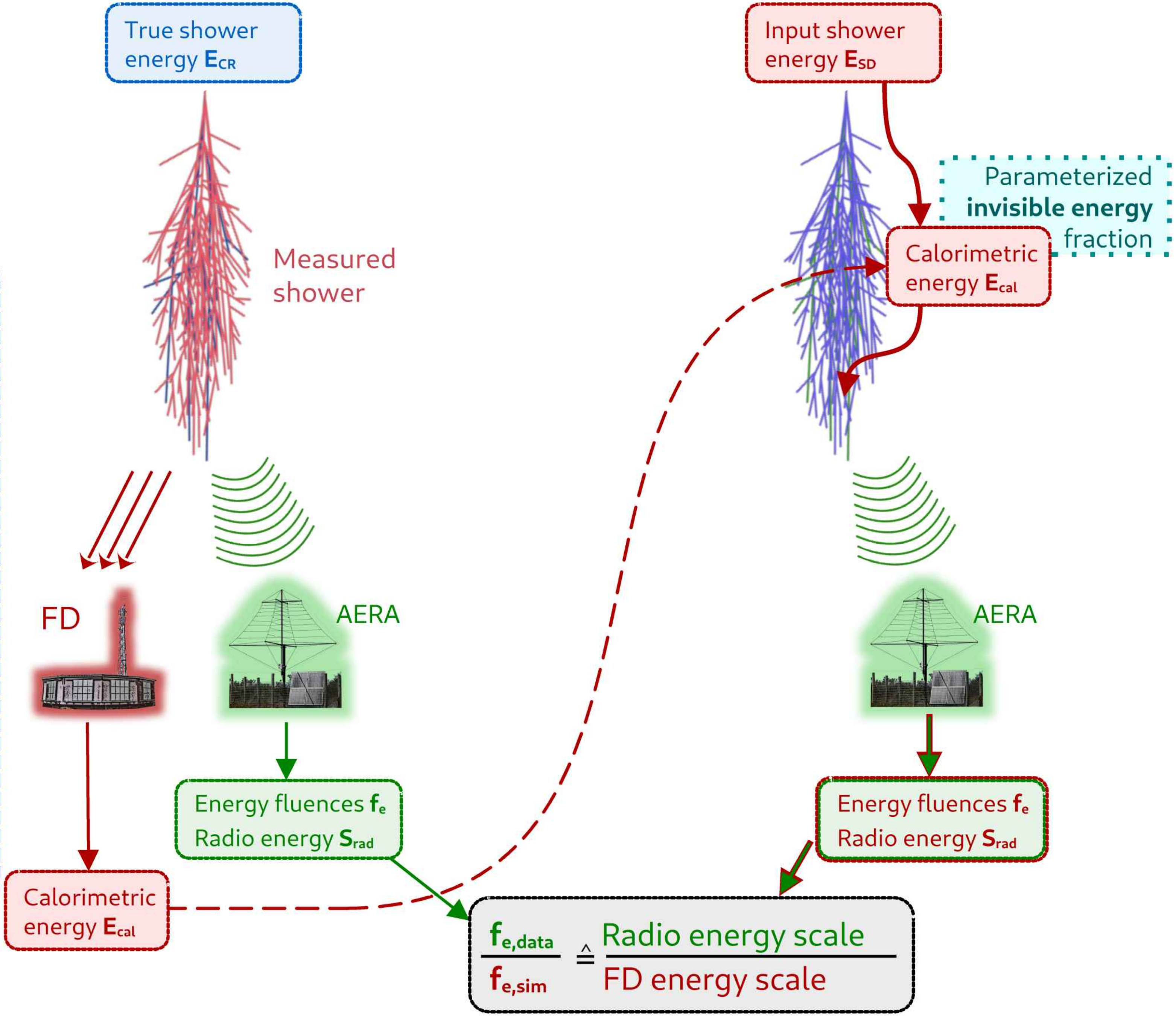
- Downside: low statistics
  - How many events available?

↓

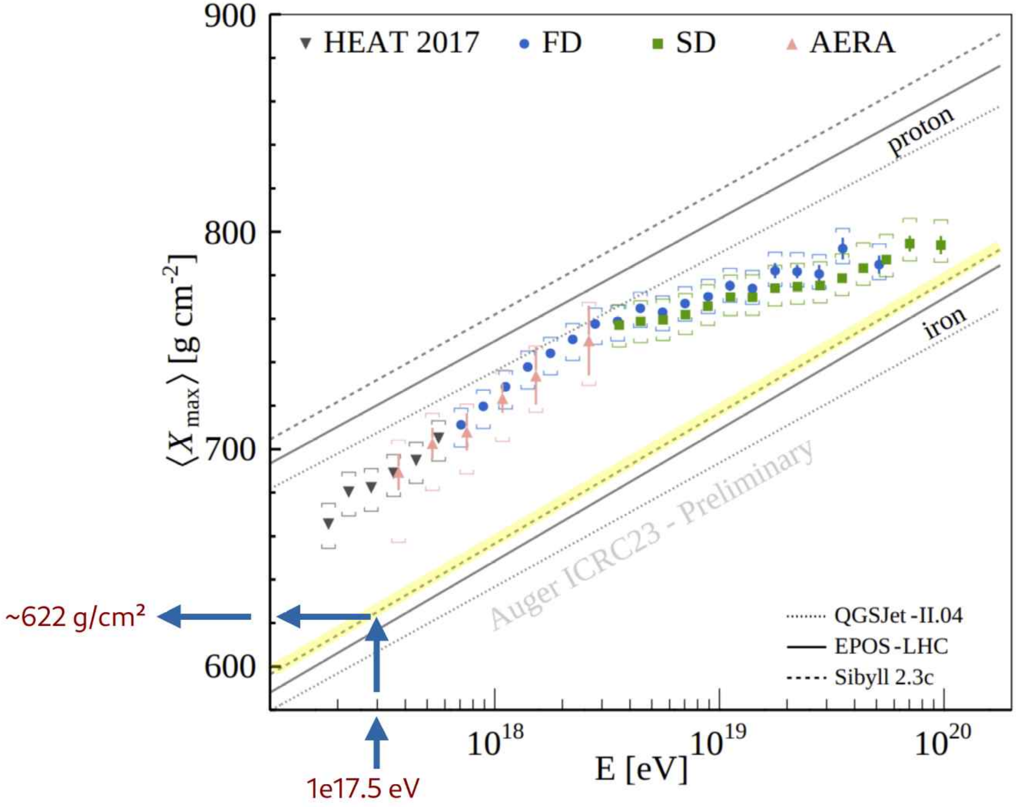
- Hybrid AERA-GoldenInfill events 2013 – 04/2019
  - standard SDInfill cuts (6T5)
  - energy calibration FD cuts (with some relaxations)
  - quality radio cuts

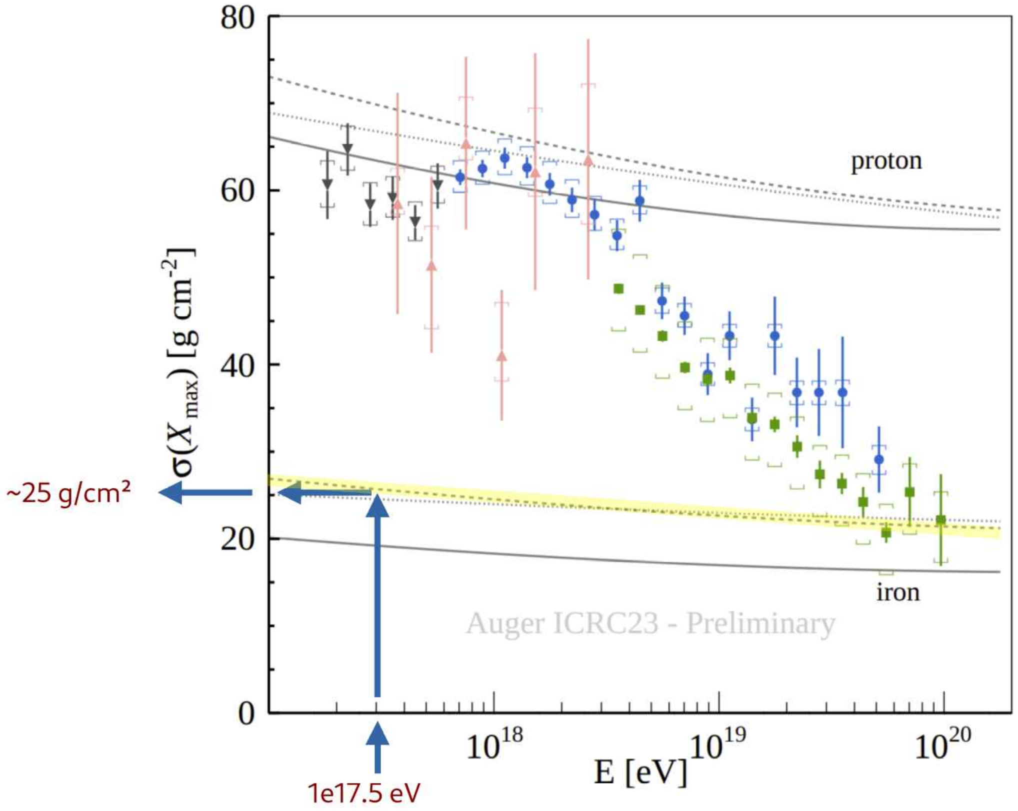
  ↪ ~**16** events remaining

+ ~50-100% with newer data



AERA station selection for CoREAS simulations



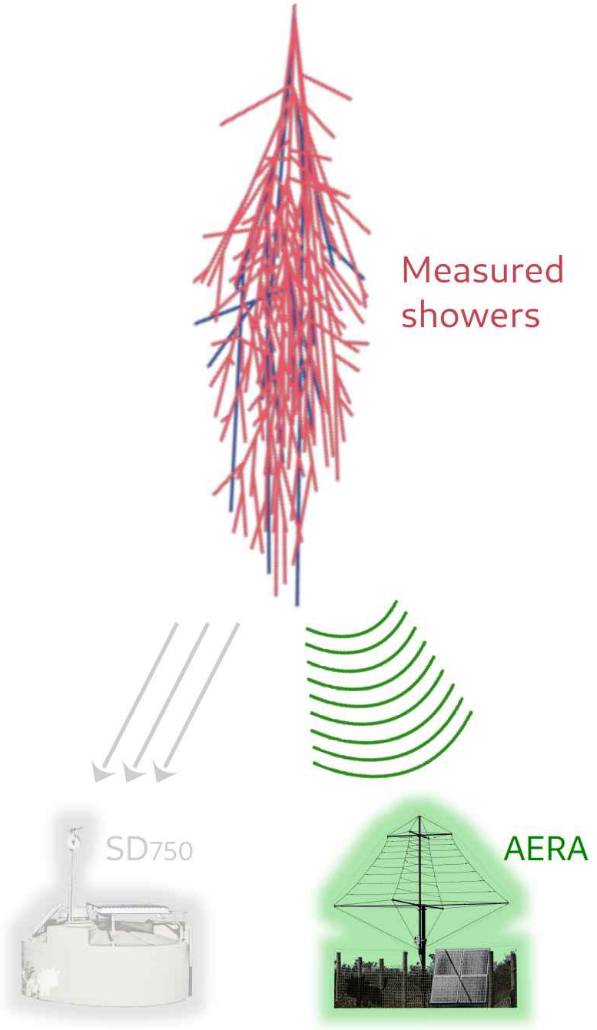


Lowest expected Xmax value in considered E range: ~622 g/cm² ± 25 g/cm² → use 600g/cm² for station cut

Hybrid data – GeoCeLDFFitter performance

- 2013 – 2018:
  - 18111 events
  - 595 events (3%) without converged GeoCeLDF fit → no E_{rad} estimate
  - 5437 events (30%) without uncertainty estimate on E_{rad}
  - 11297 events (62%) without Rd core fit in GeoCeLDF fit

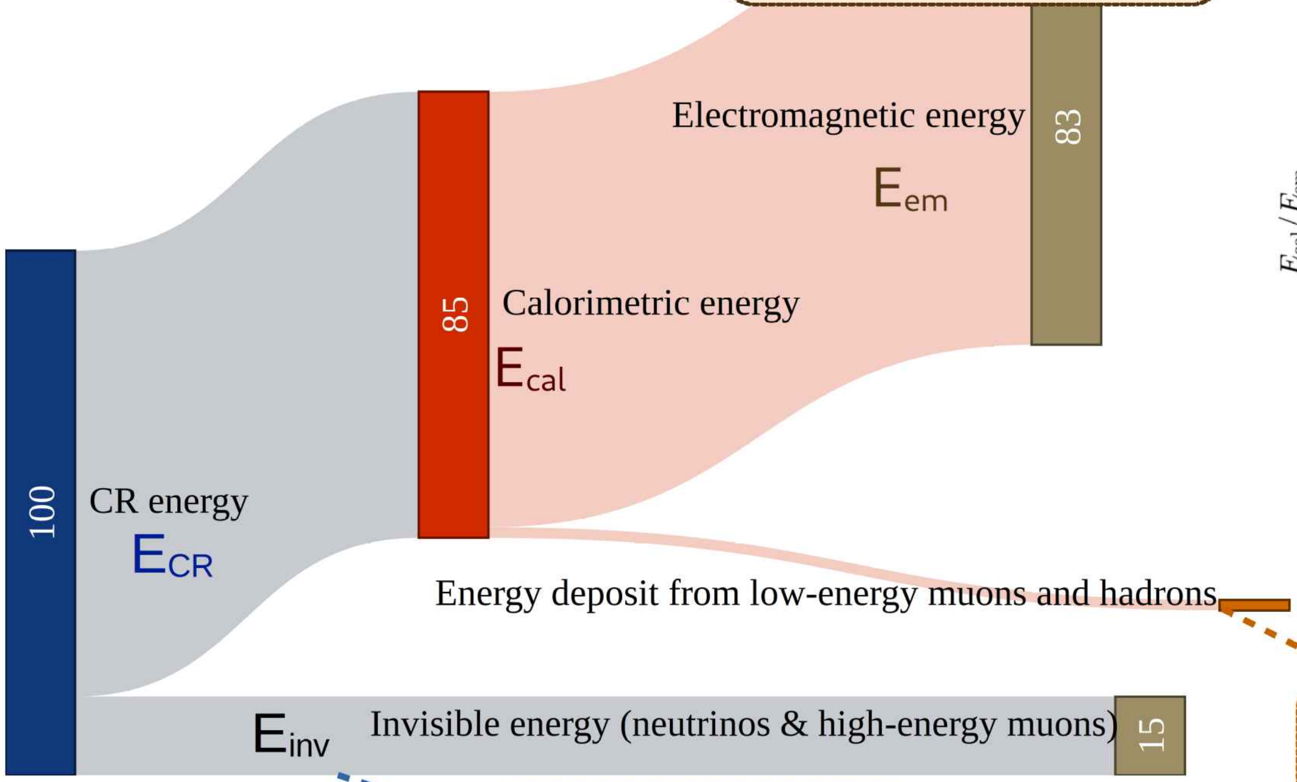
- Allowing events with 5+ signal stations (RD) only: (vs. 3+)
  - 2% without converged GeoCeLDF fit → no E_{rad} estimate
  - 19% without uncertainty estimate on E_{rad}
  - 2% without Rd core fit in GeoCeLDF fit

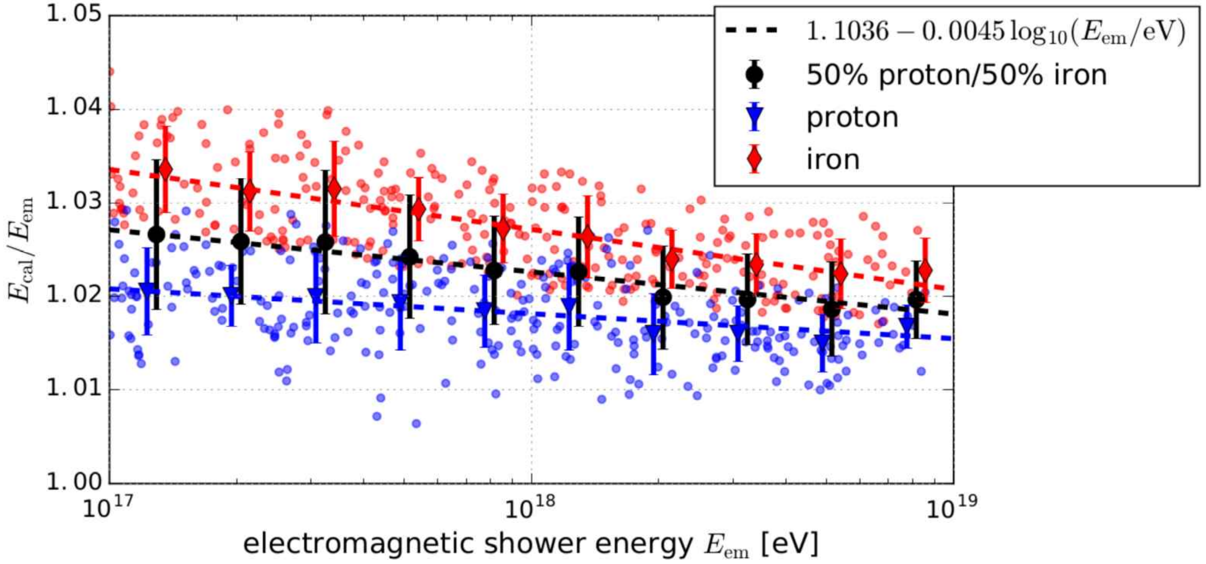


Accessing the cosmic-ray energy scale

with AERA

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





Can be corrected for

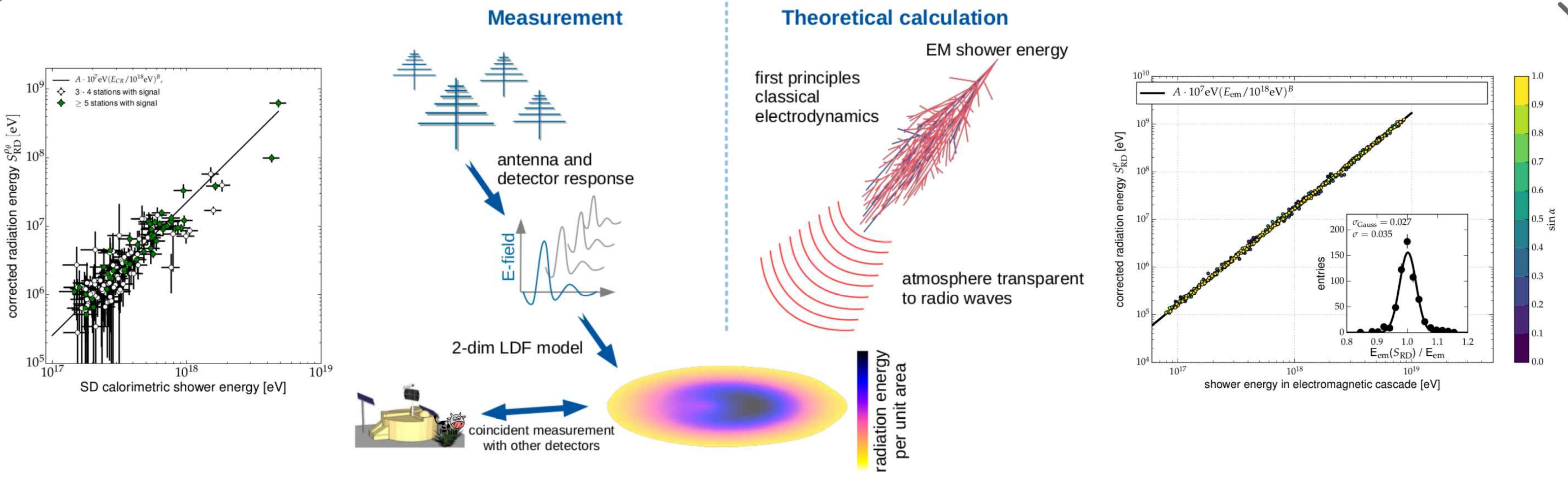
Phys. Rev. D 100, 082003 (2019)

Difference between E_{cal} and E_{em}

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

Comparing FD and radio energy scales

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

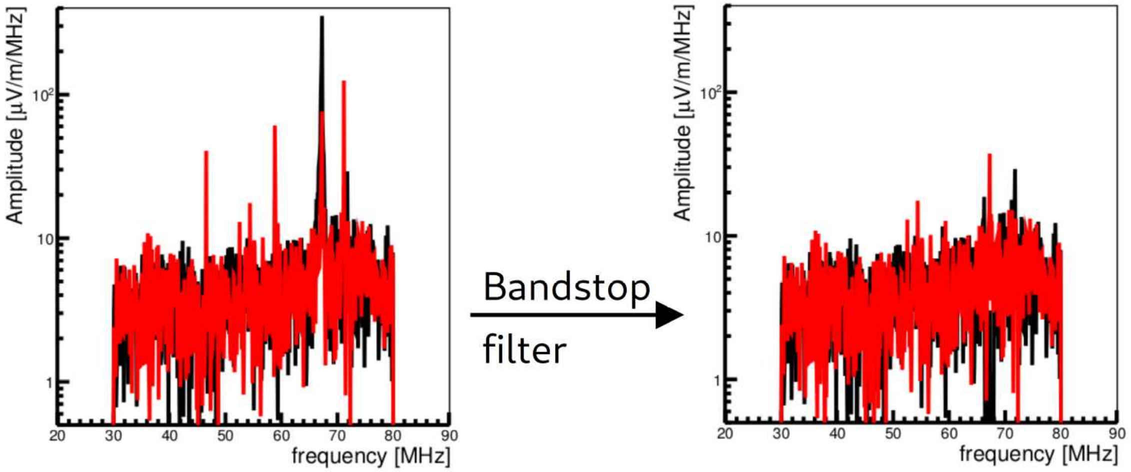
$$S_{\mathrm{RD}}^{\rho\theta} = 1.639 \times 10^7 eV \left(\frac{E_{\mathrm{em}}}{10^{18} eV}\right)^{1.978}$$

Aiming to determine a universal/academic radio energy scale

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%