Data driven search for primordial black holes with VERITAS

- Here we show the outcome of K. Pfrang's PhD work
- A VERITAS paper is under preparation (The following are not official results!)

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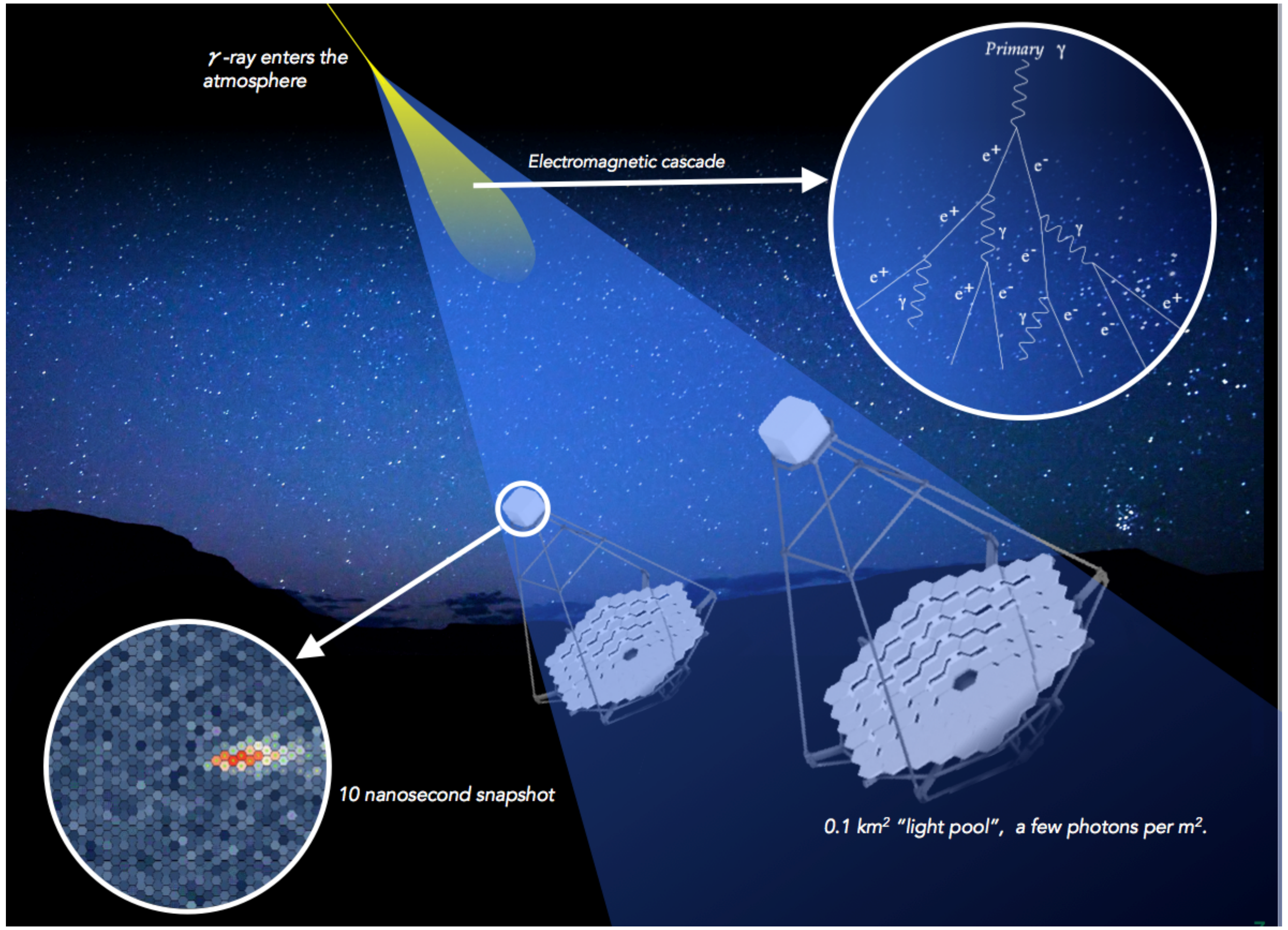
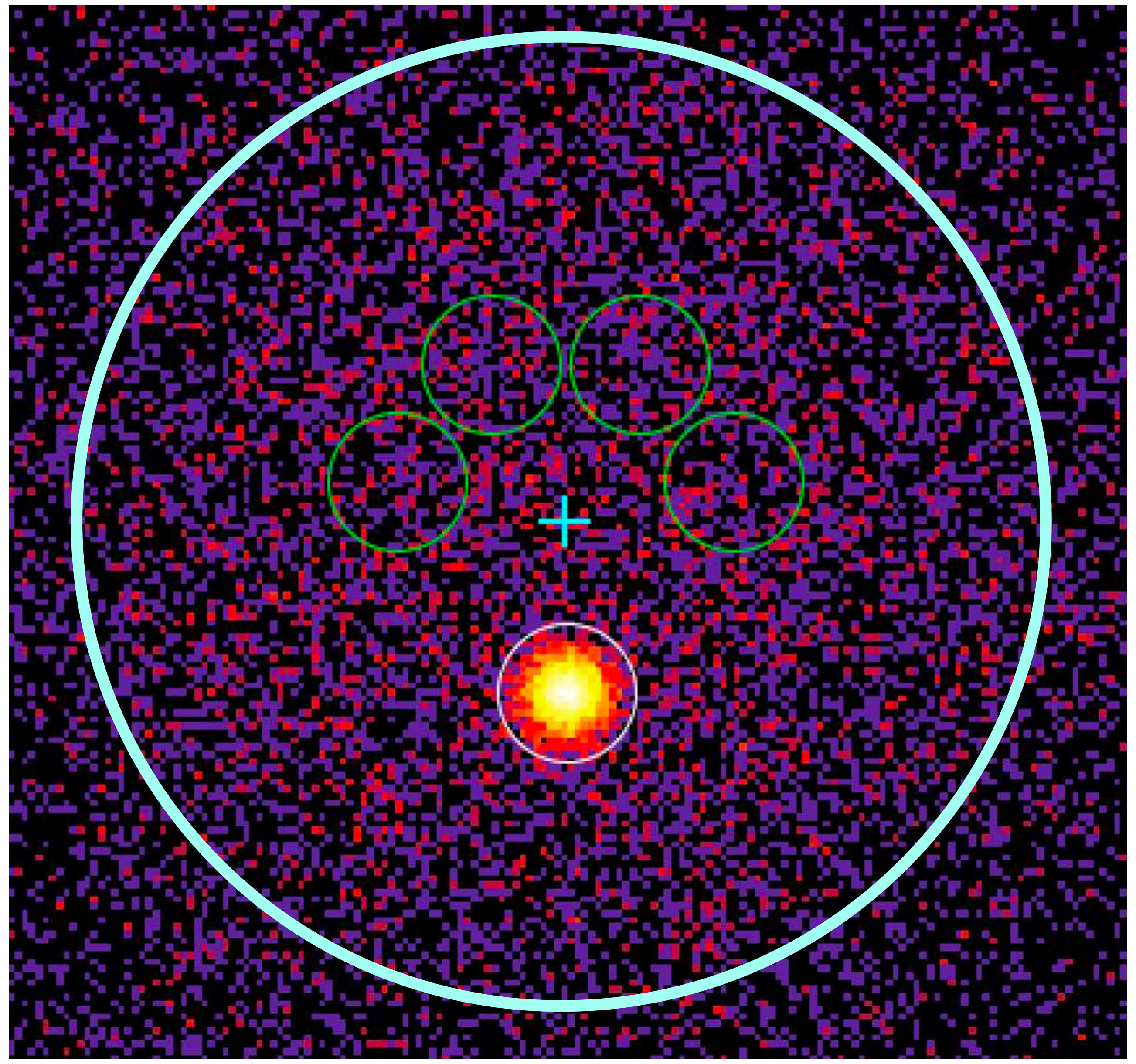
VERITAS

- The VERITAS observatory
  - Fred Lawrence Whipple Observatory, Arizona, USA.
  - Array of 4 Imaging Air Cherenkov Telescopes
  - 12 m diameter aperture; 3.5 degree FoV
  - Indirect γ-ray detection, nominally ∈ 100 GeV - 10 TeV
  - Sensitive to 1% Crab in ~25 h



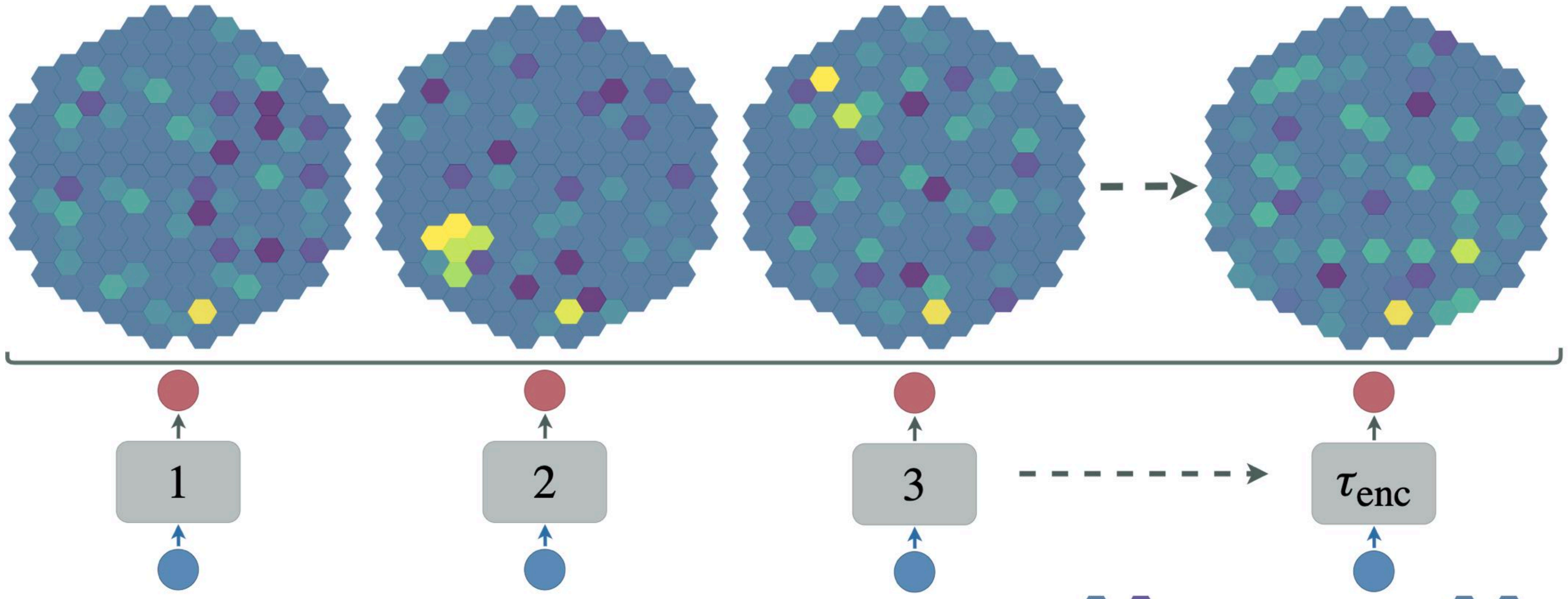
γ-ray source detection à la VERITAS

- **"Classical" approach**
  - Spatial (on/off) strategy
    - Offset the centre of the FoV with respect to the source position
    - Select "off" regions with expected uniform detector response
    - ➜ explicitly subtract background estimation
  - Challenges
    - Uncertainties on instrument simulations (e.g., detector efficiency)
    - Uncertainties on physical backgrounds (e.g., galactic foregrounds)
    - Precise modelling of observing conditions (e.g., clouds, night-sky background)
    - Subtraction of artefacts (e.g., stars, satellites)

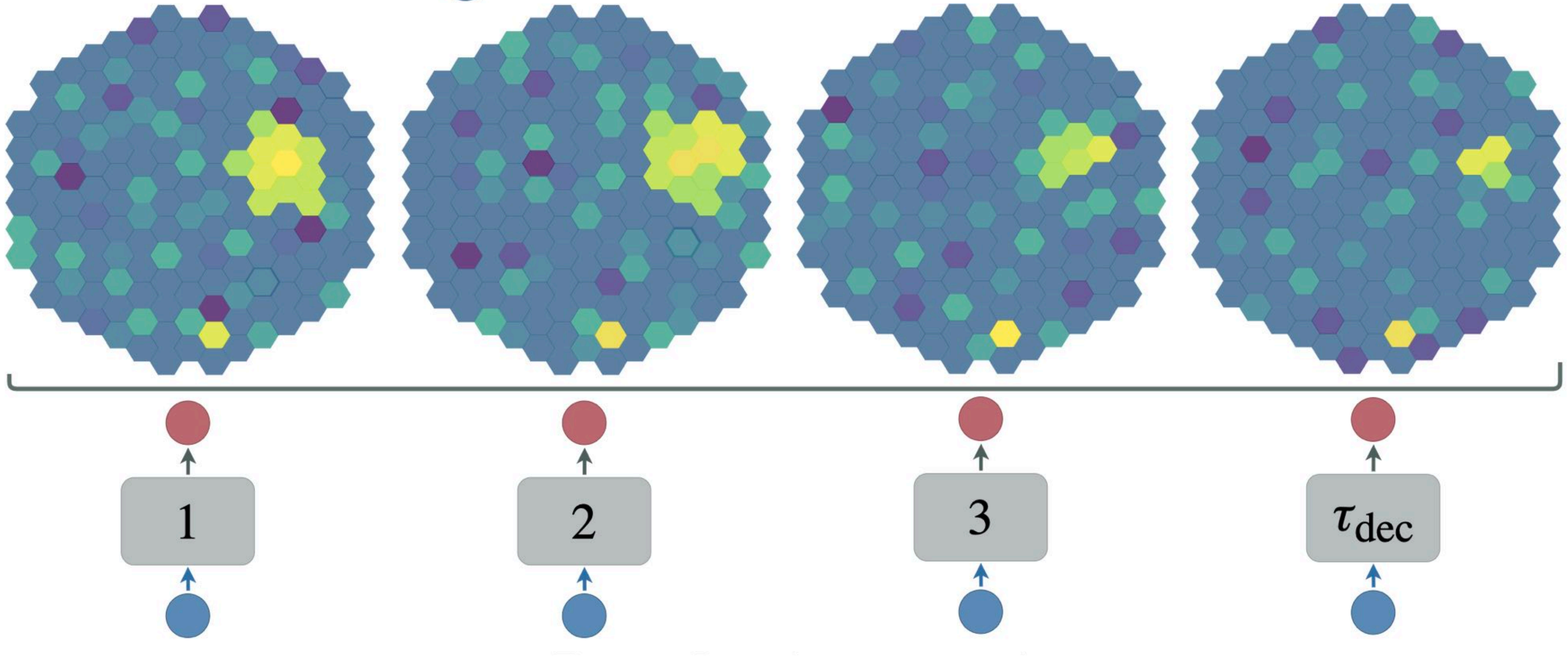


ctools (illustration)

Time-series anomaly detection à la VERITAS



- Background-compatible time series

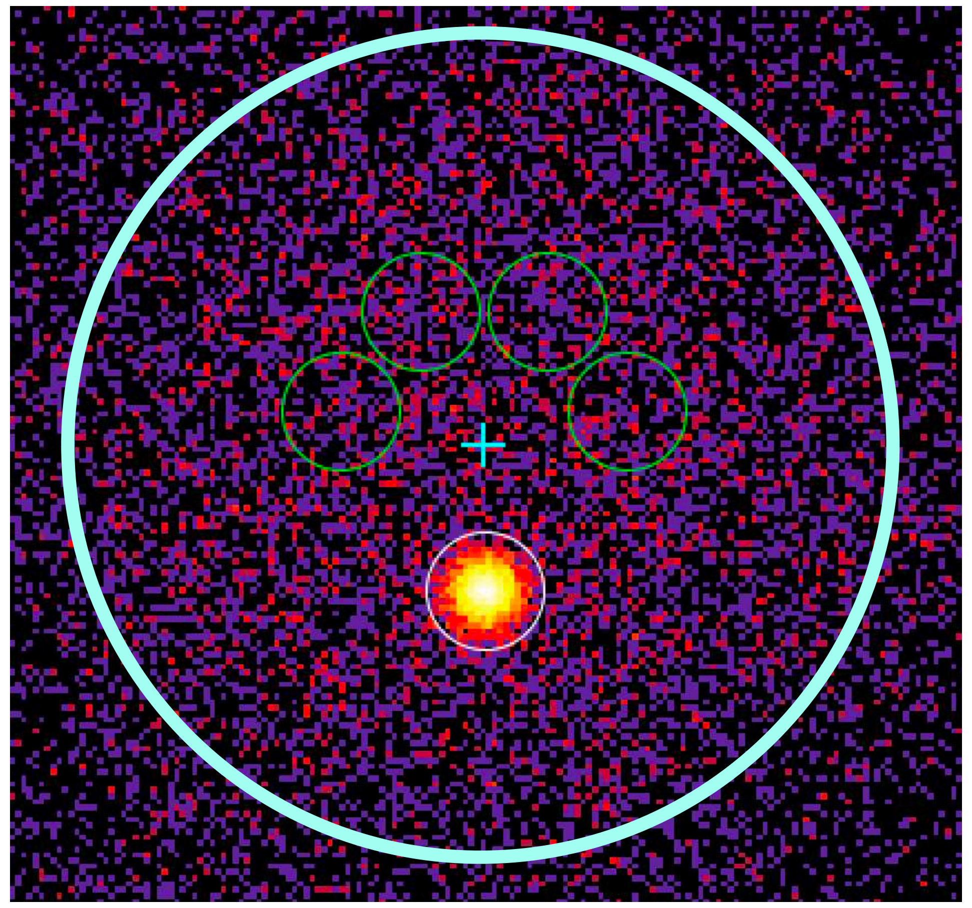


- A possible signal appears within the FoV

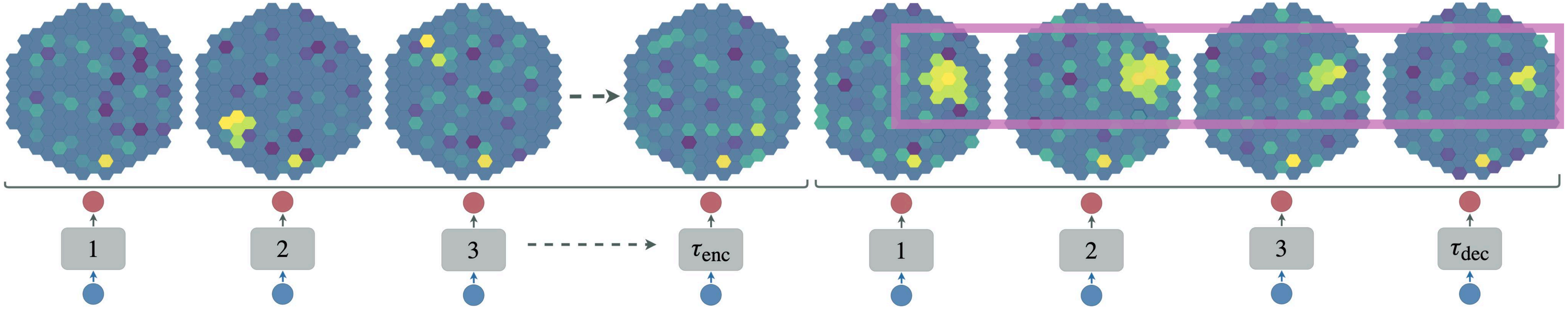
Sadeh (2020) [arxiv:2005.06406](https://arxiv.org/abs/2005.06406)

Time-series anomaly detection à la VERITAS

- **Anomaly detection approach**
  - Temporal strategy
    - Select "off" regions having the same position as the source ➜ offset in time
    - Forecast the expected background distribution
    - ➜ construct a TS based on the forecast background ⊕ actual data
  - Advantage
    - No need for explicit modelling; assumptions on detector response
    - Many systematics factor out, uncertainties reduced
    - Handy for MWL / MMS data fusion & real-time analysis

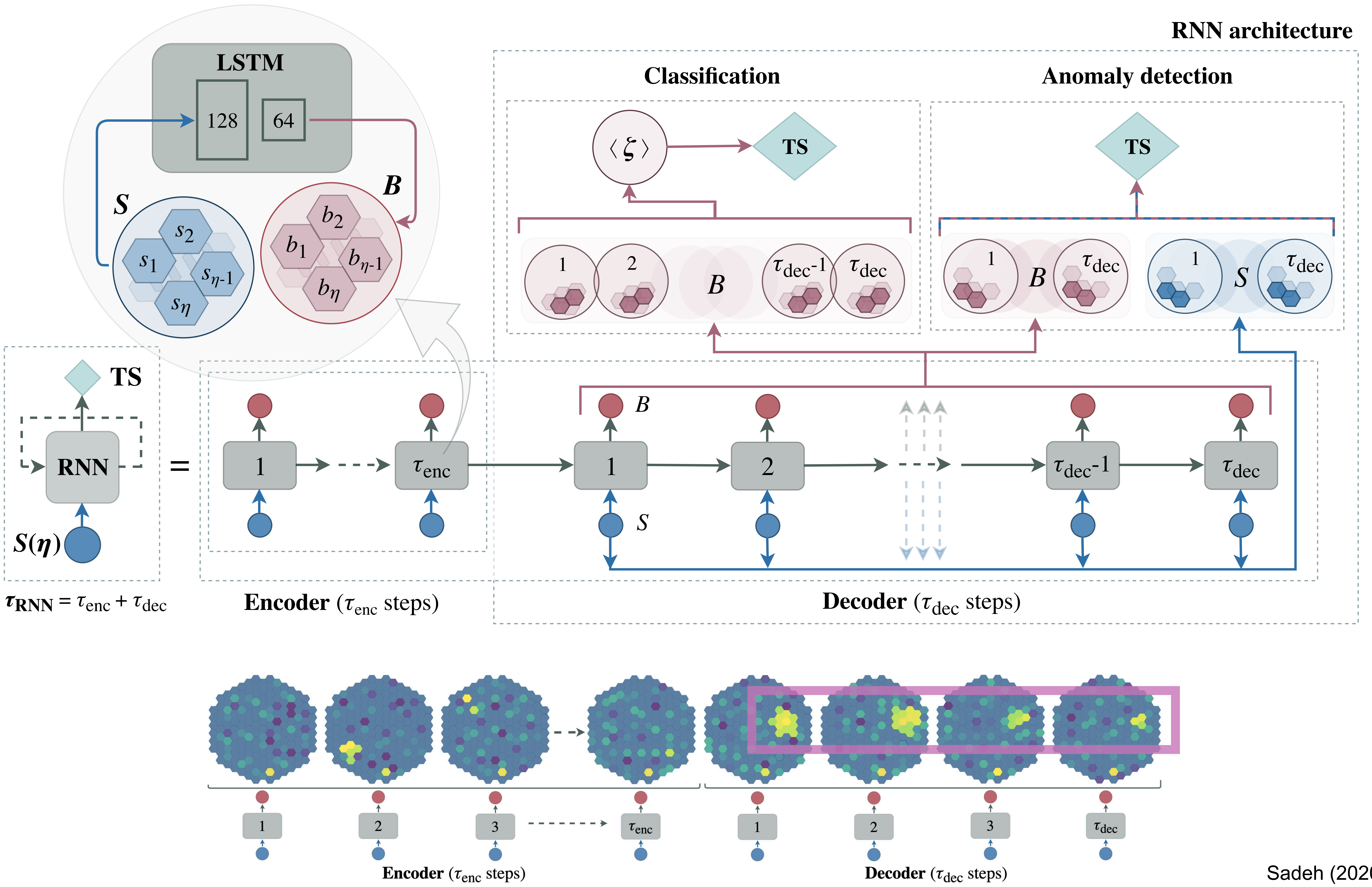


ctools (illustration)



Sadeh (2020) arxiv:2005.06406

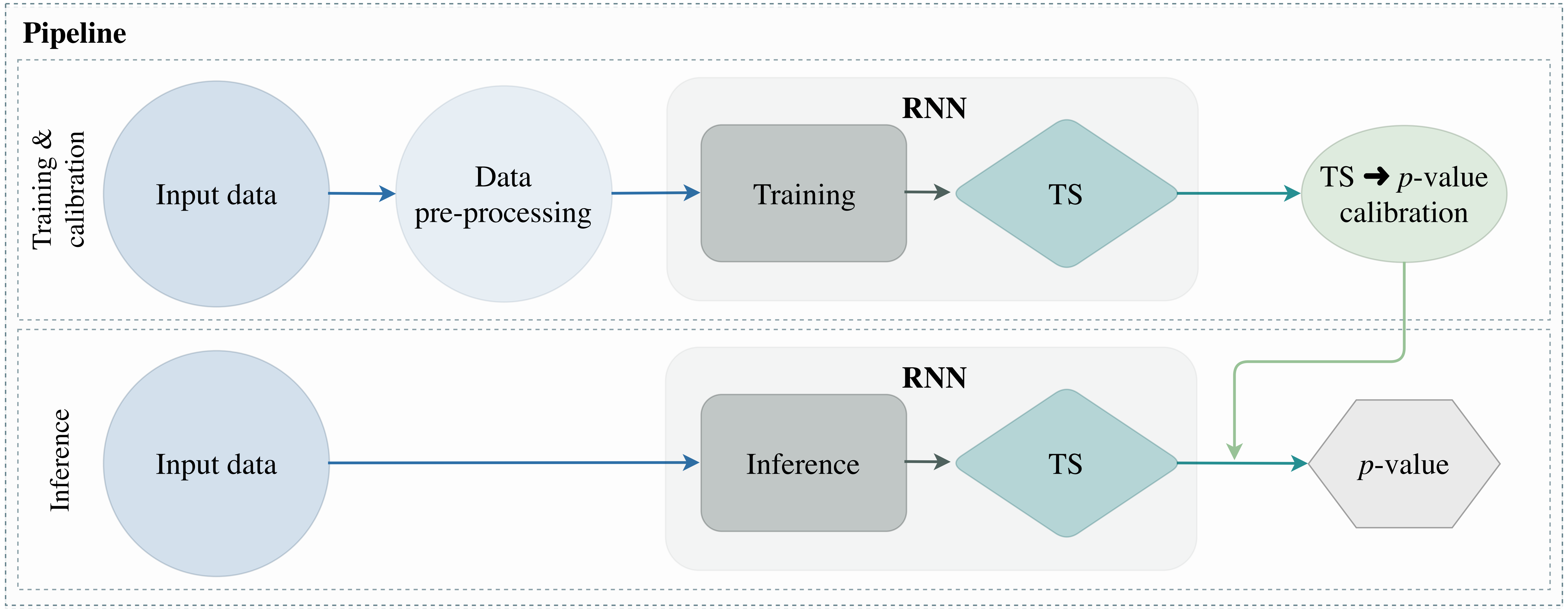
Time-series anomaly detection with RNNs

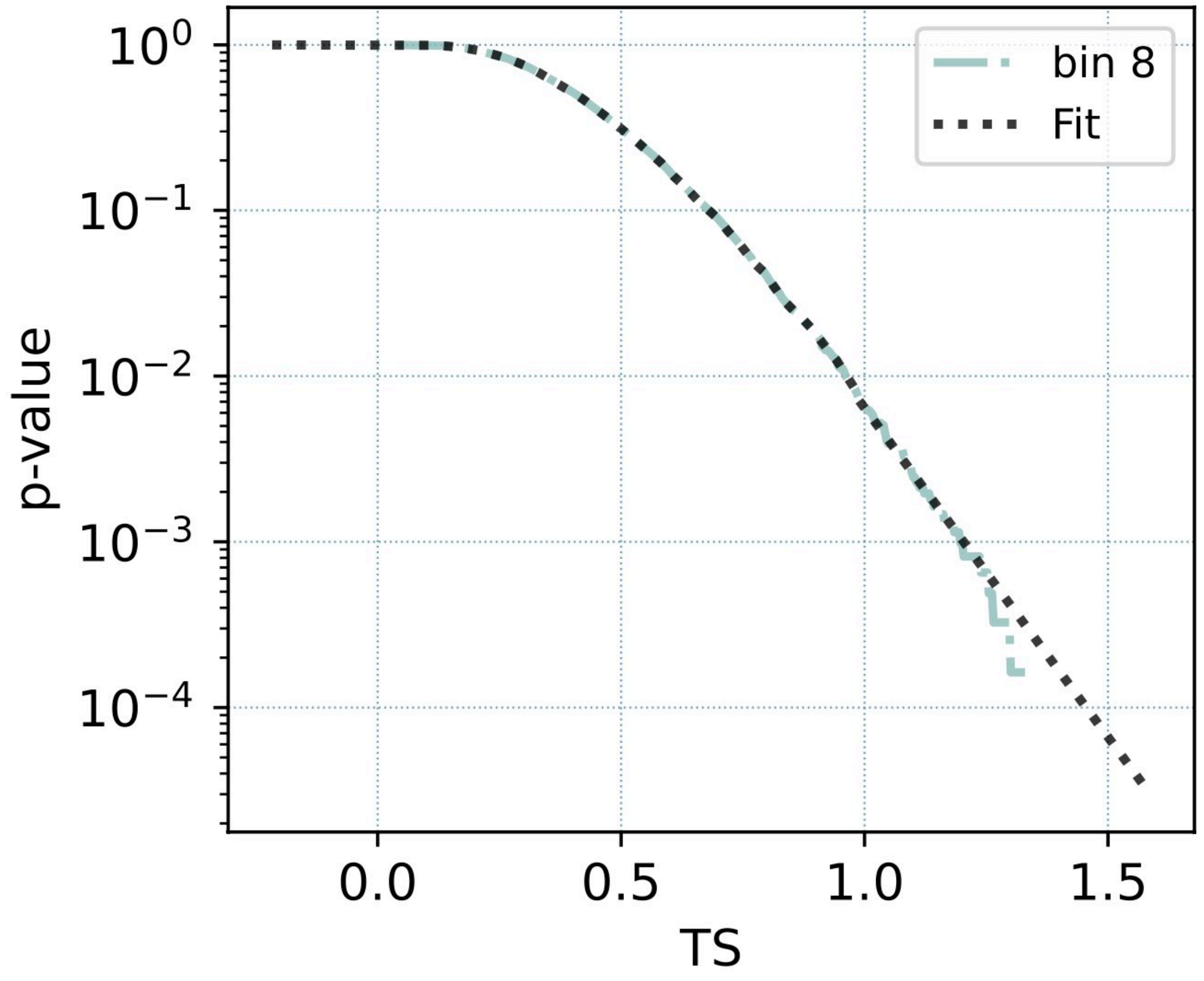


Sadeh (2020) [arxiv:2005.06406](https://arxiv.org/abs/2005.06406)

Anomaly detection ➜ TS calibration

- Automated significance-calibration pipeline
  - Use the RNN to generate background distributions
  - Derive (a hierarchy of successive) TS definitions for a particular analysis
  - Derive numerical [TS ➜ p-value] mappings

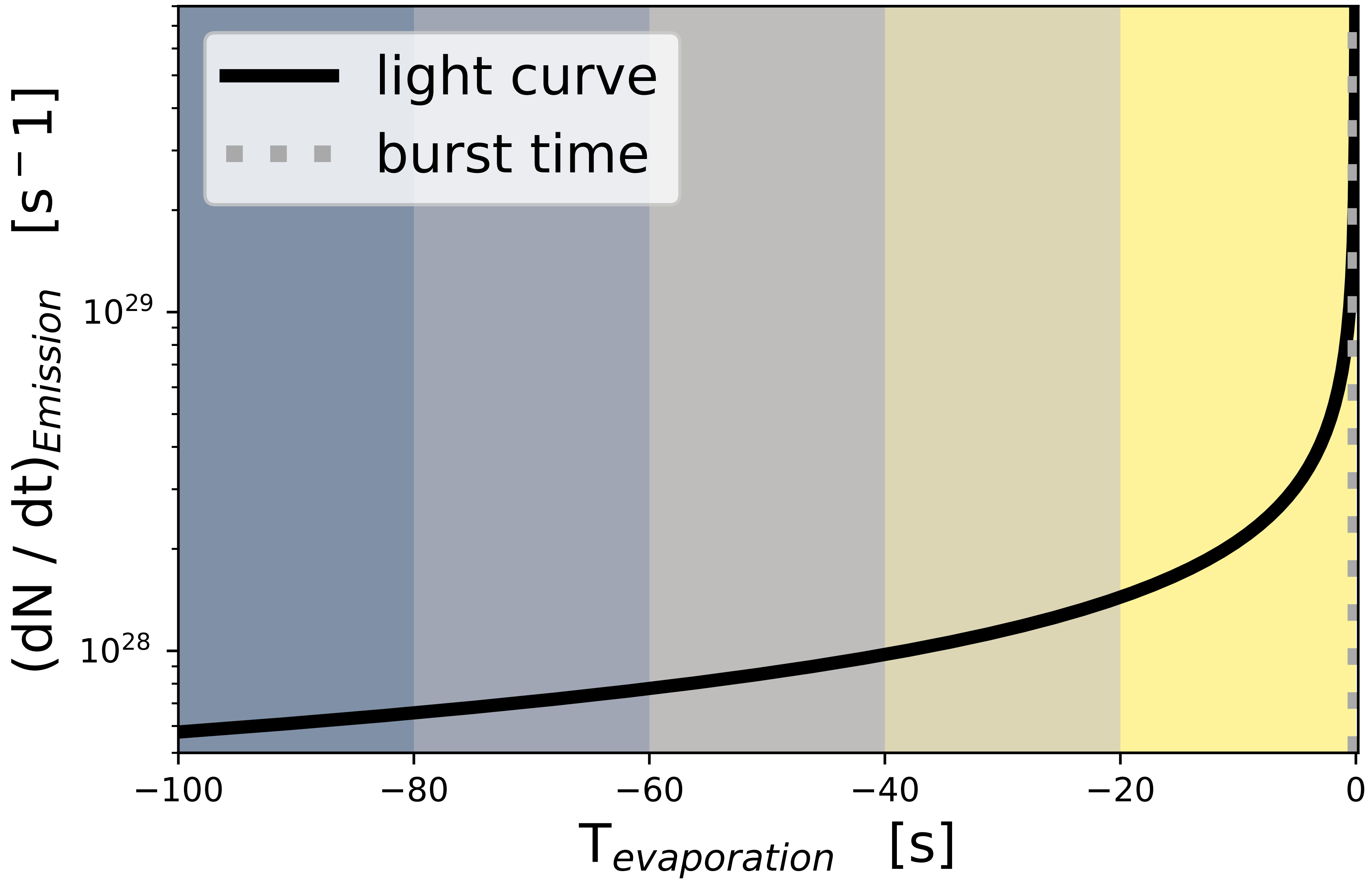


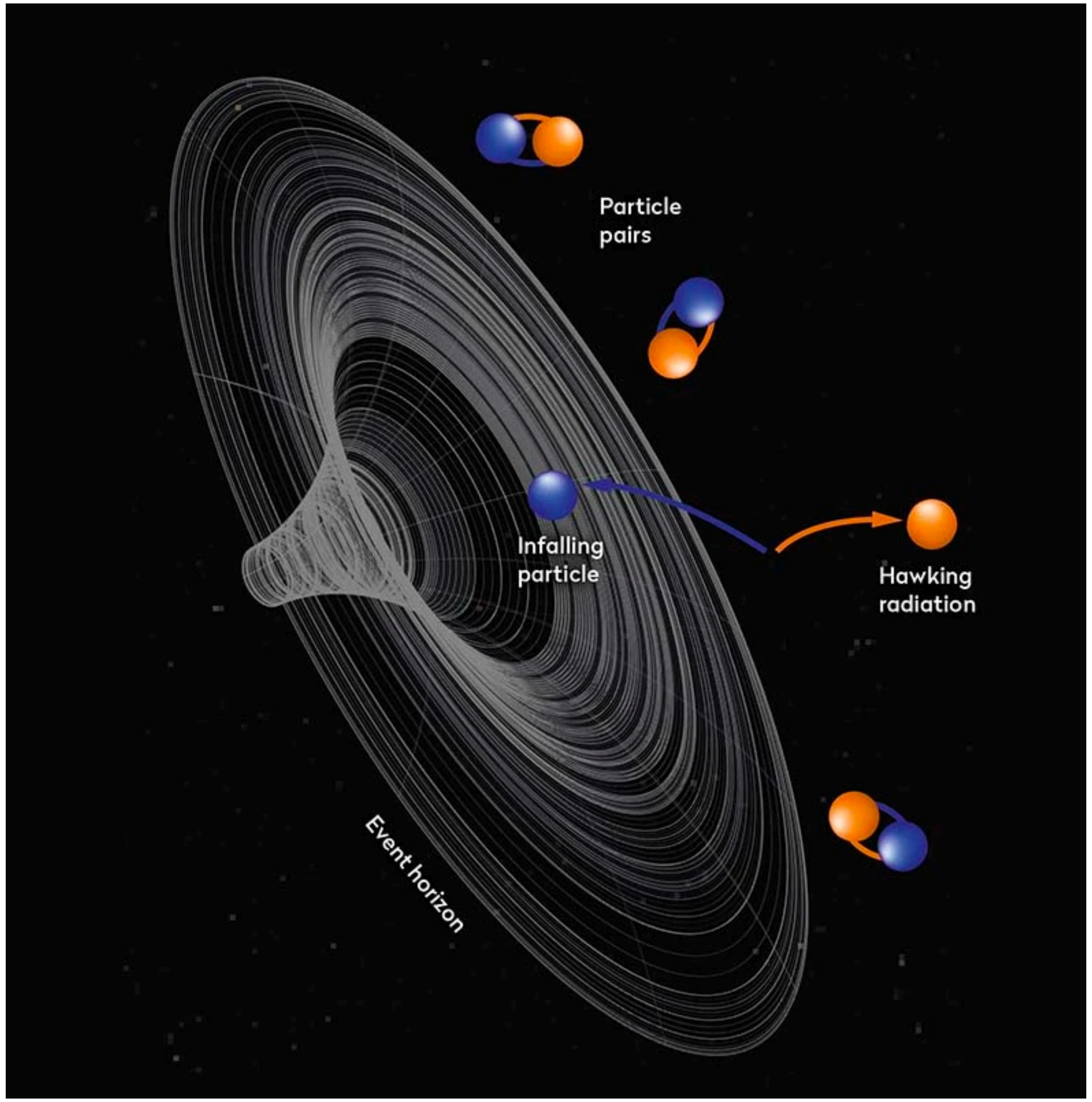


Sadeh (2020) arxiv:2005.06406

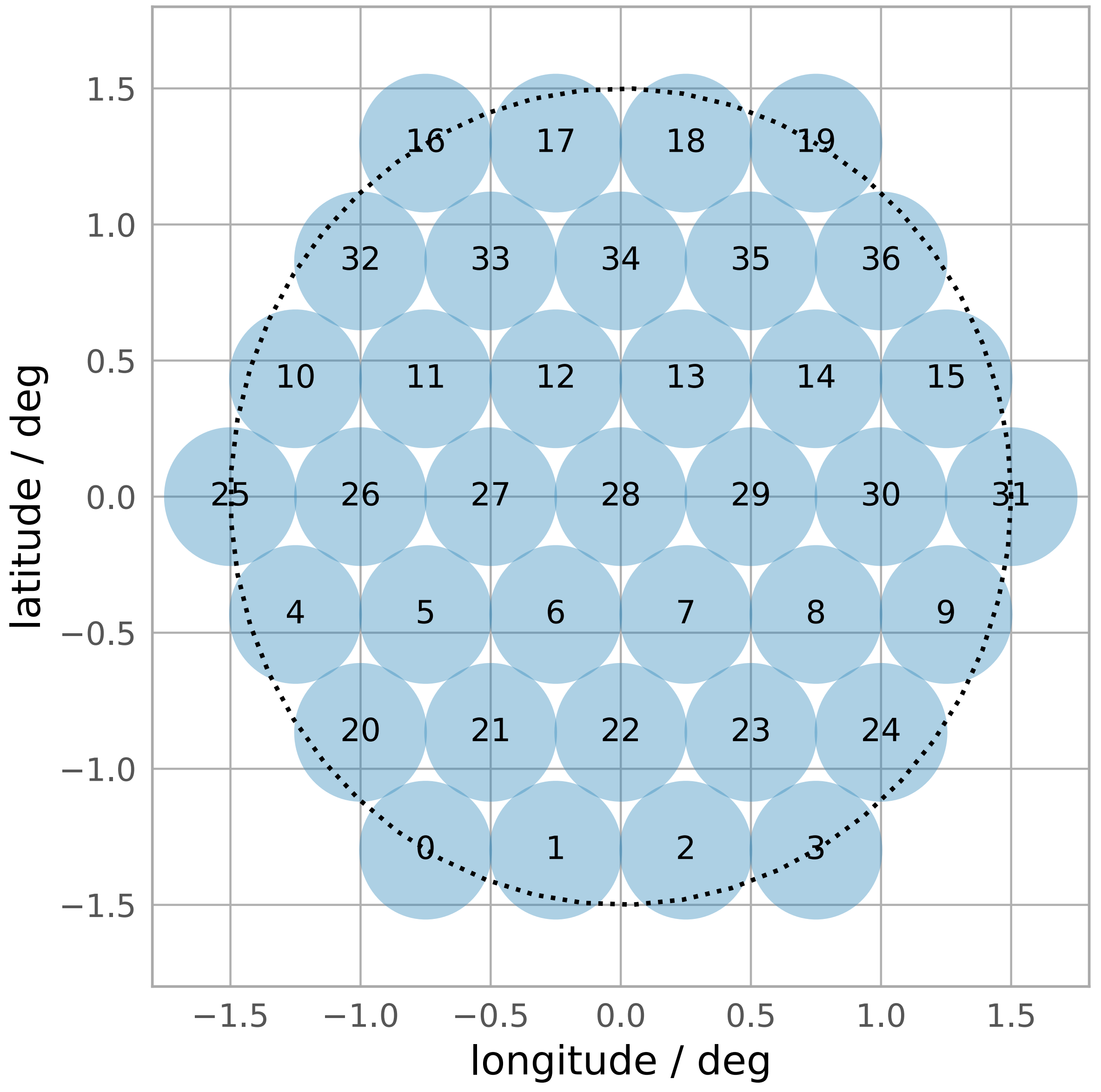
PBH evaporation with VERITAS

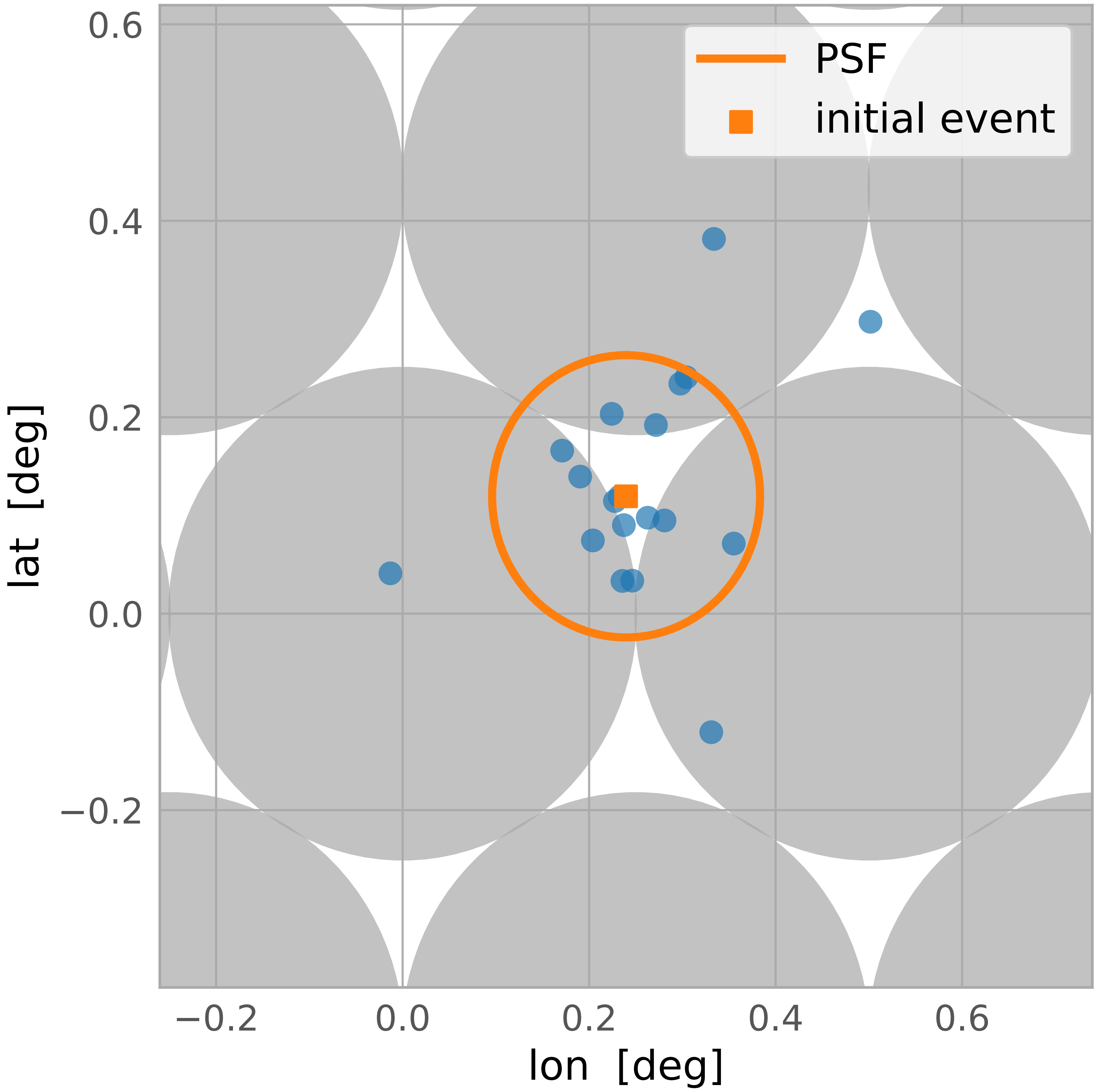
- Evaporation of primordial black holes
  - Many early universe theories predict the creation of PBHs
  - Particles emitted ➜ BH mass decreases ➜ BH temperature increases ➜ emitted radiation increases
  - Probes physics of the early universe, e.g., cosmological density fluctuations below the CMB scale • inflation • HEP • connections between gravitation with thermodynamics ...
  - Signature ➜ flux increases as mass decreases

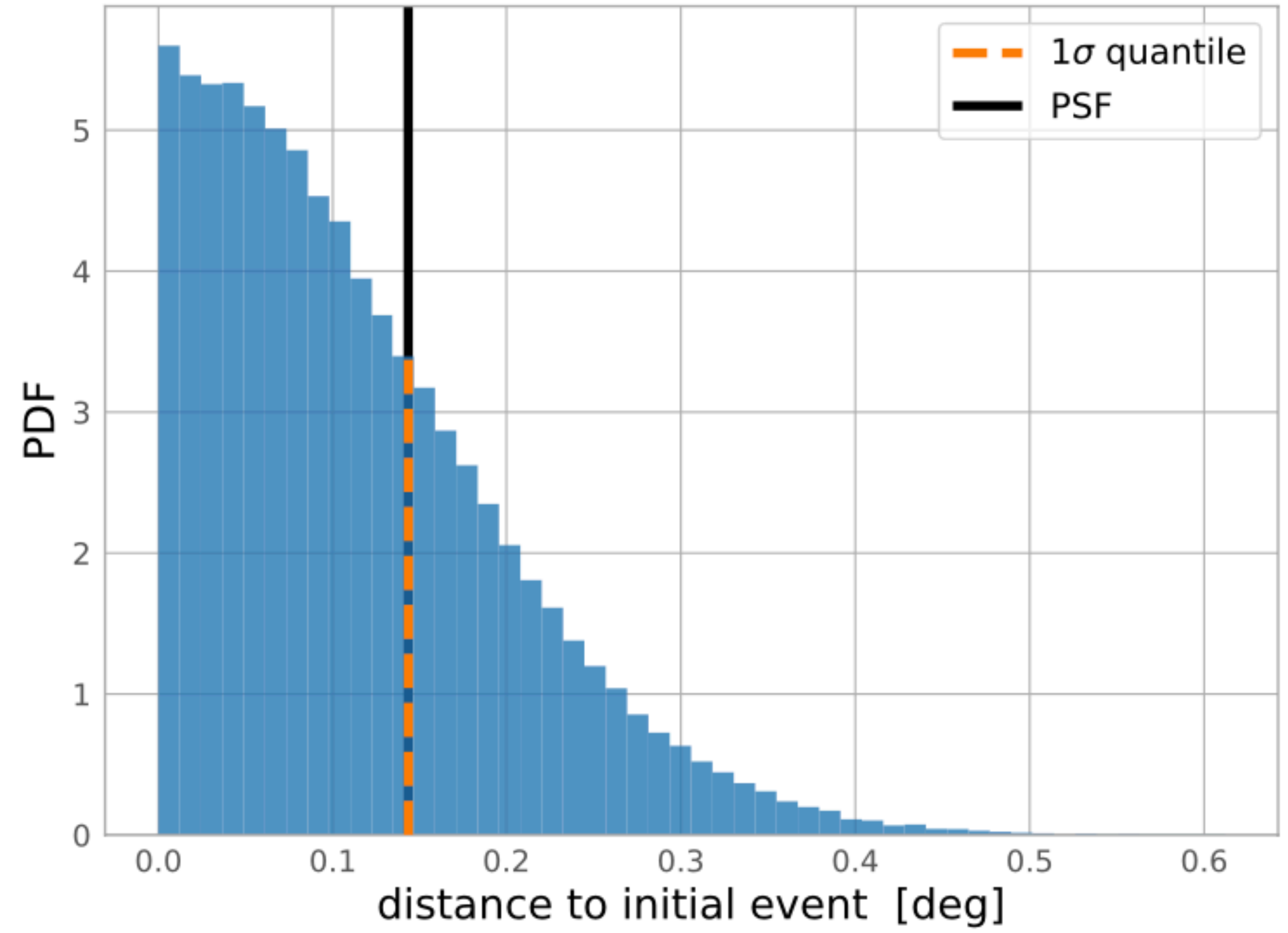


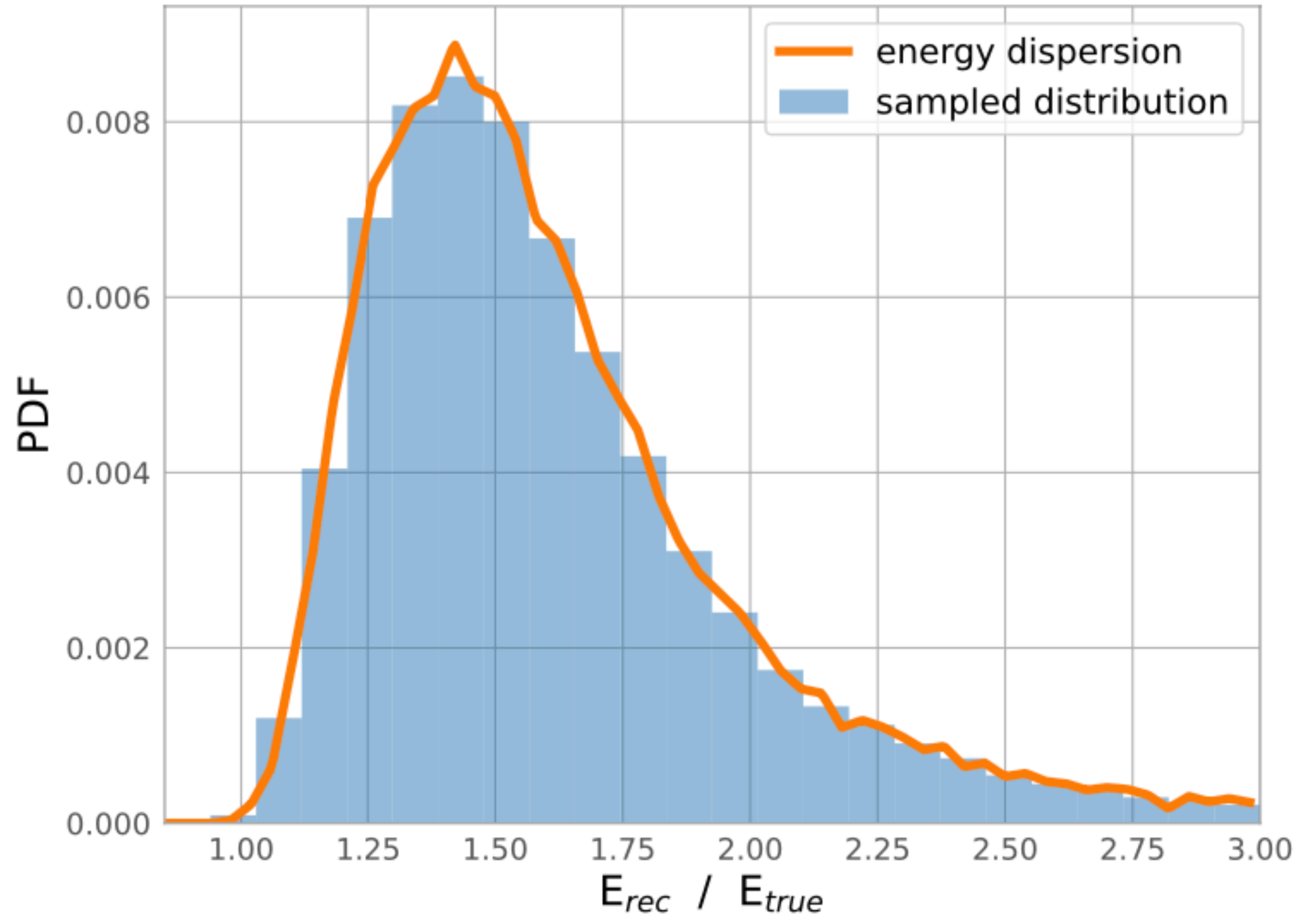


Anomaly detection ➜ oversampling

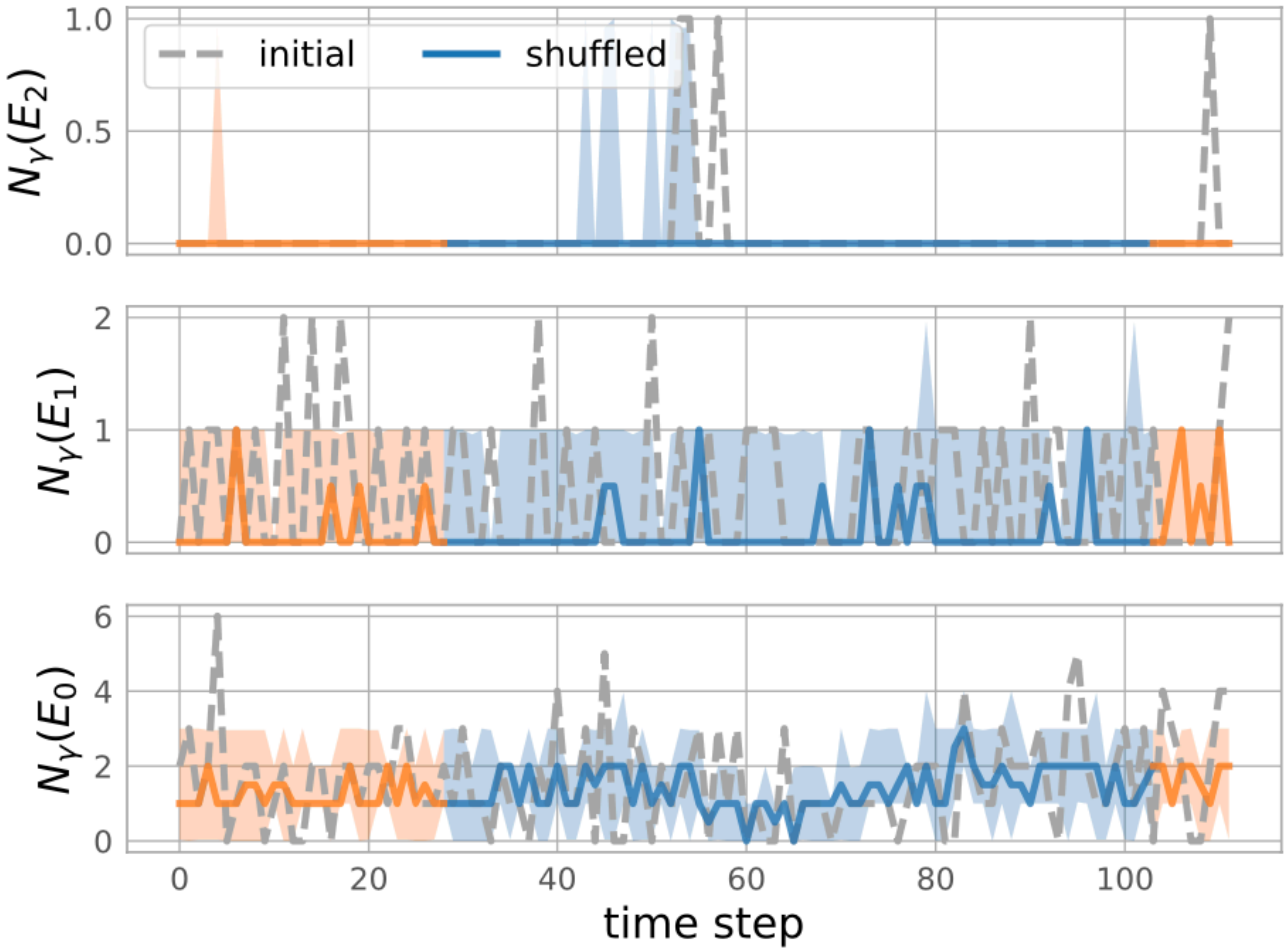




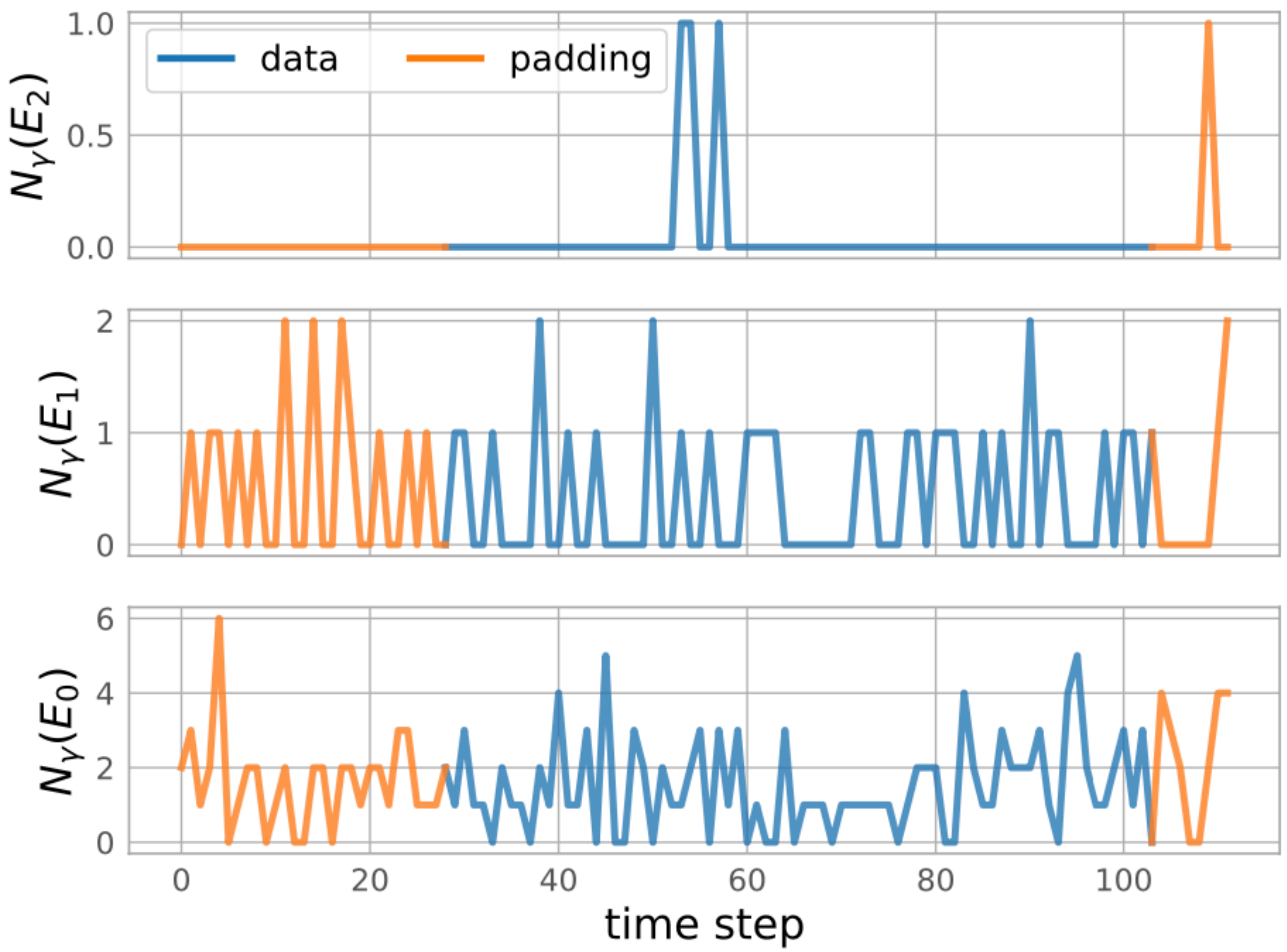




Anomaly detection ➜ shuffling

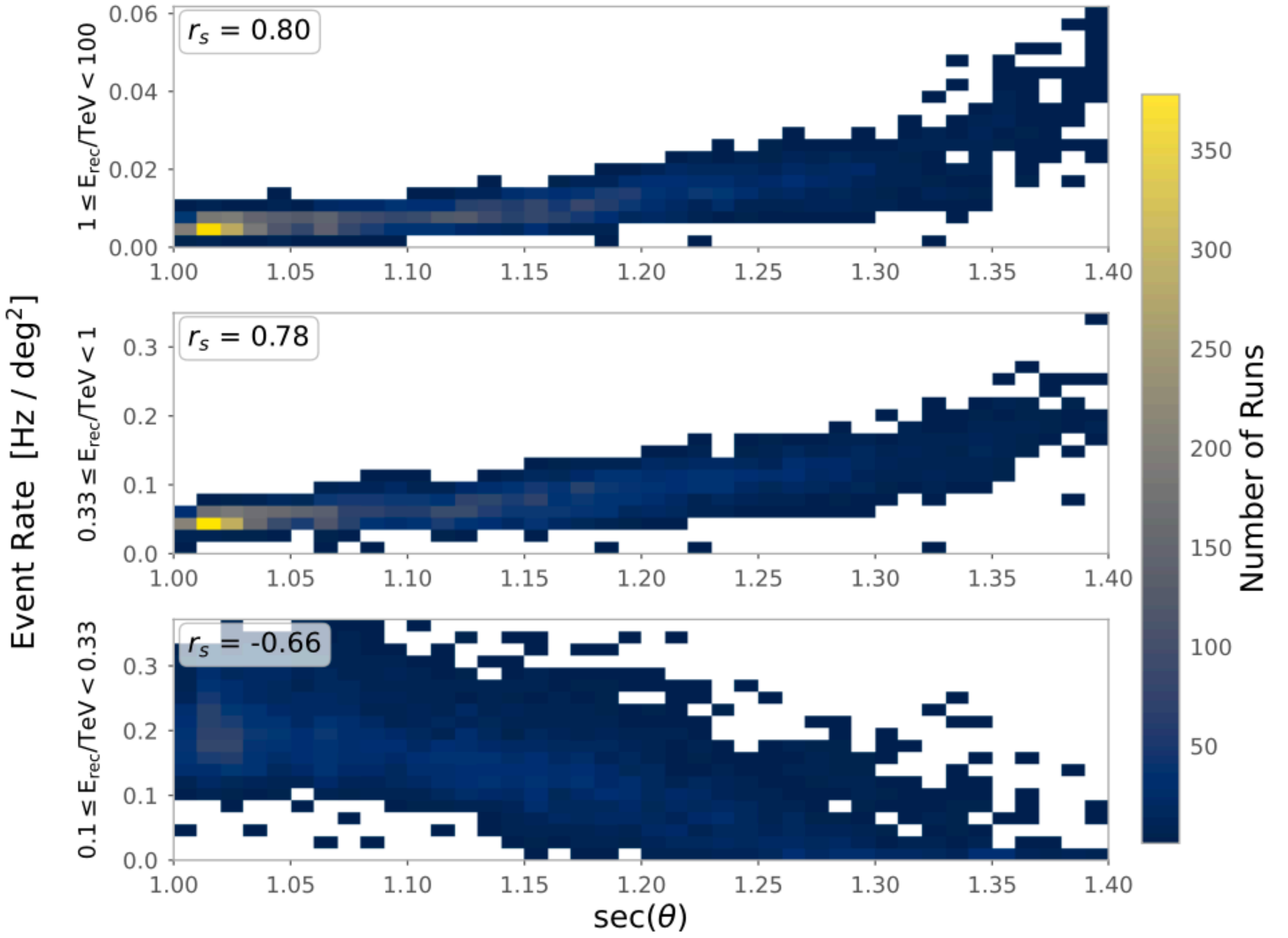


Anomaly detection ➜ padding and sliding window



Anomaly detection ➜ contextual metadata

Parameter	Description
$\sec(\theta)$	Secant of zenith angle of observation
$\lvert\alpha\rvert$	Azimuthal angle observation
ΔT_{ref}	Years after reference point 2012.08.01
l, b	Galactic coordinates
R_{L3}	L3 trigger rate
dead_time	Fraction of time with busy data acquisition
ped_var	Average pedestal variance for complete run
$M(E_{total})$	Average multiplicity in total energy range
$M(E_0)$, $M(E_1)$, $M(E_2)$	Average multiplicity per energy bin
ζ	Offset angle relative to center of FoV



- Zenith

Anomaly detection ➜ contextual metadata

Parameter	Description
$\sec(\theta)$	Secant of zenith angle of observation
$\lvert\alpha\rvert$	Azimuthal angle observation
ΔT_{ref}	Years after reference point 2012.08.01
l, b	Galactic coordinates
R_{L3}	L3 trigger rate
`dead_time`	Fraction of time with busy data acquisition
`ped_var`	Average pedestal variance for complete run
$M(\text{E}_{\text{total}})$	Average multiplicity in total energy range
$M(\text{E}_0), M(\text{E}_1), M(\text{E}_2)$	Average multiplicity per energy bin
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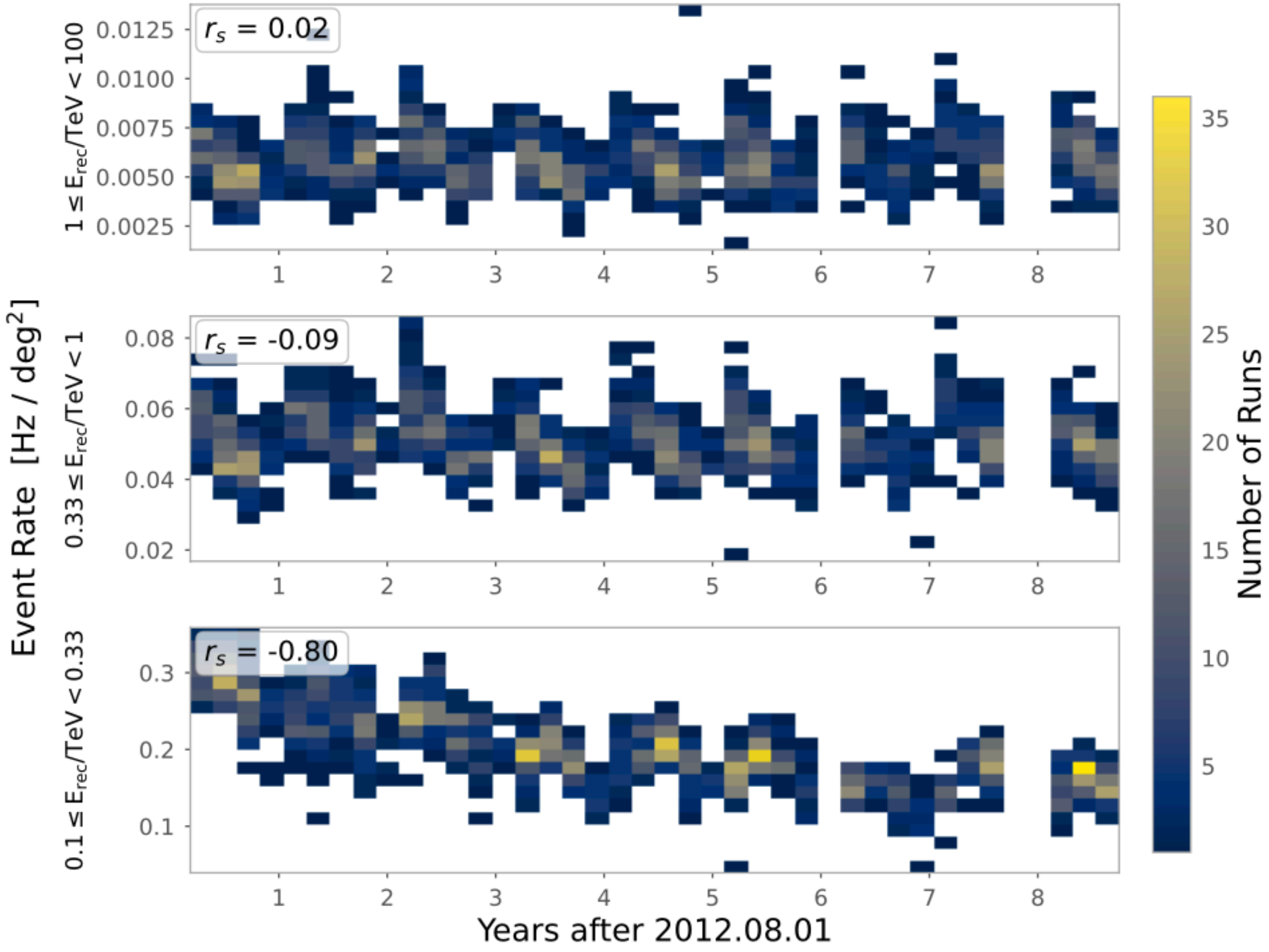
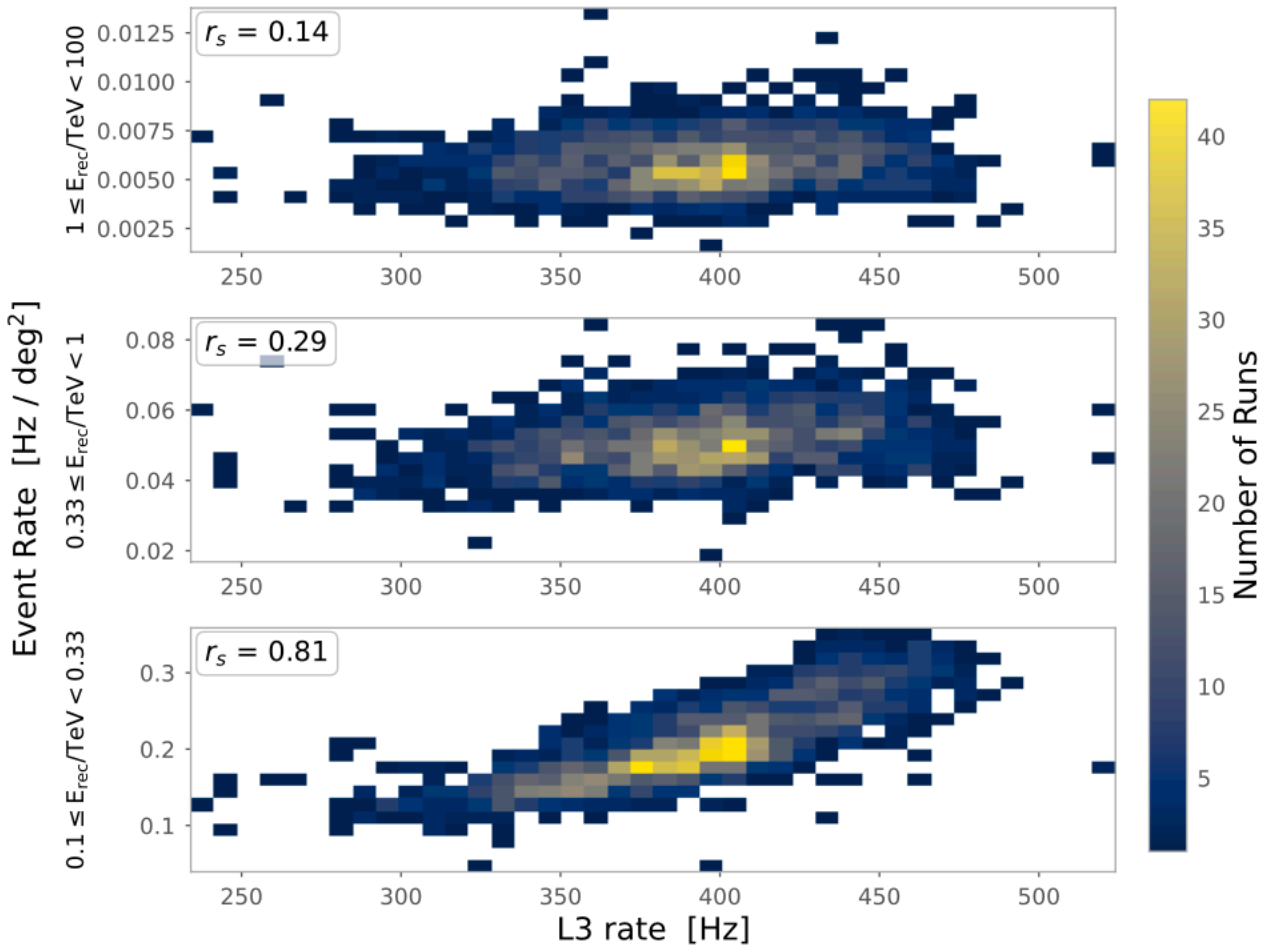


- Epoch (obs. period)

Anomaly detection ➜ contextual metadata

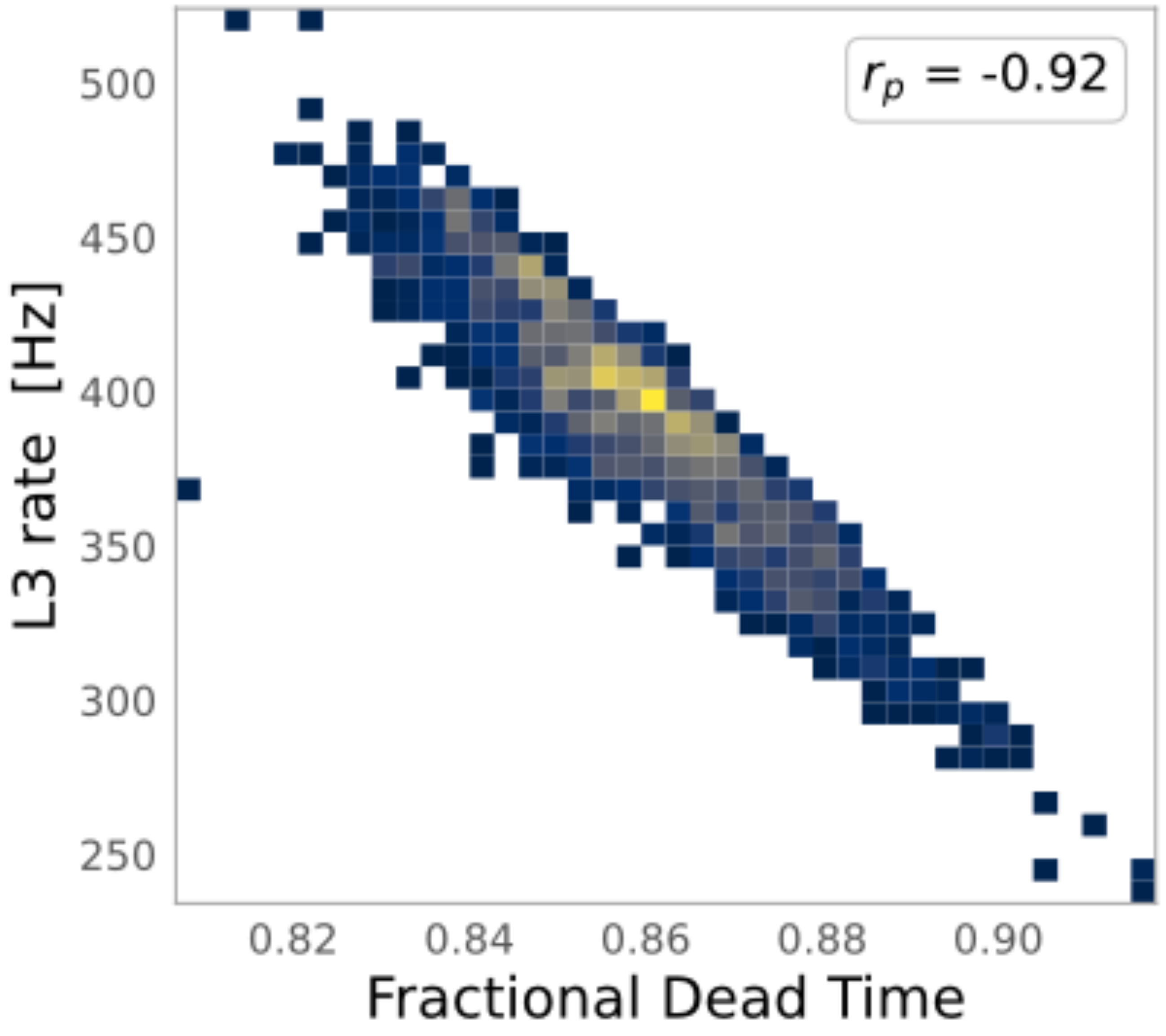
Parameter	Description
$\sec(\theta)$	Secant of zenith angle of observation
$\|\alpha\|$	Azimuthal angle observation
ΔT_{ref}	Years after reference point 2012.08.01
l, b	Galactic coordinates
R_{L3}	L3 trigger rate
`dead_time`	Fraction of time with busy data acquisition
`ped_var`	Average pedestal variance for complete run
$M(\mathrm{E_{total}})$	Average multiplicity in total energy range
$M(\mathrm{E_0}), M(\mathrm{E_1}), M(\mathrm{E_2})$	Average multiplicity per energy bin
ζ	Offset angle relative to center of FoV



- L3 trigger rate

Anomaly detection ➜ contextual metadata

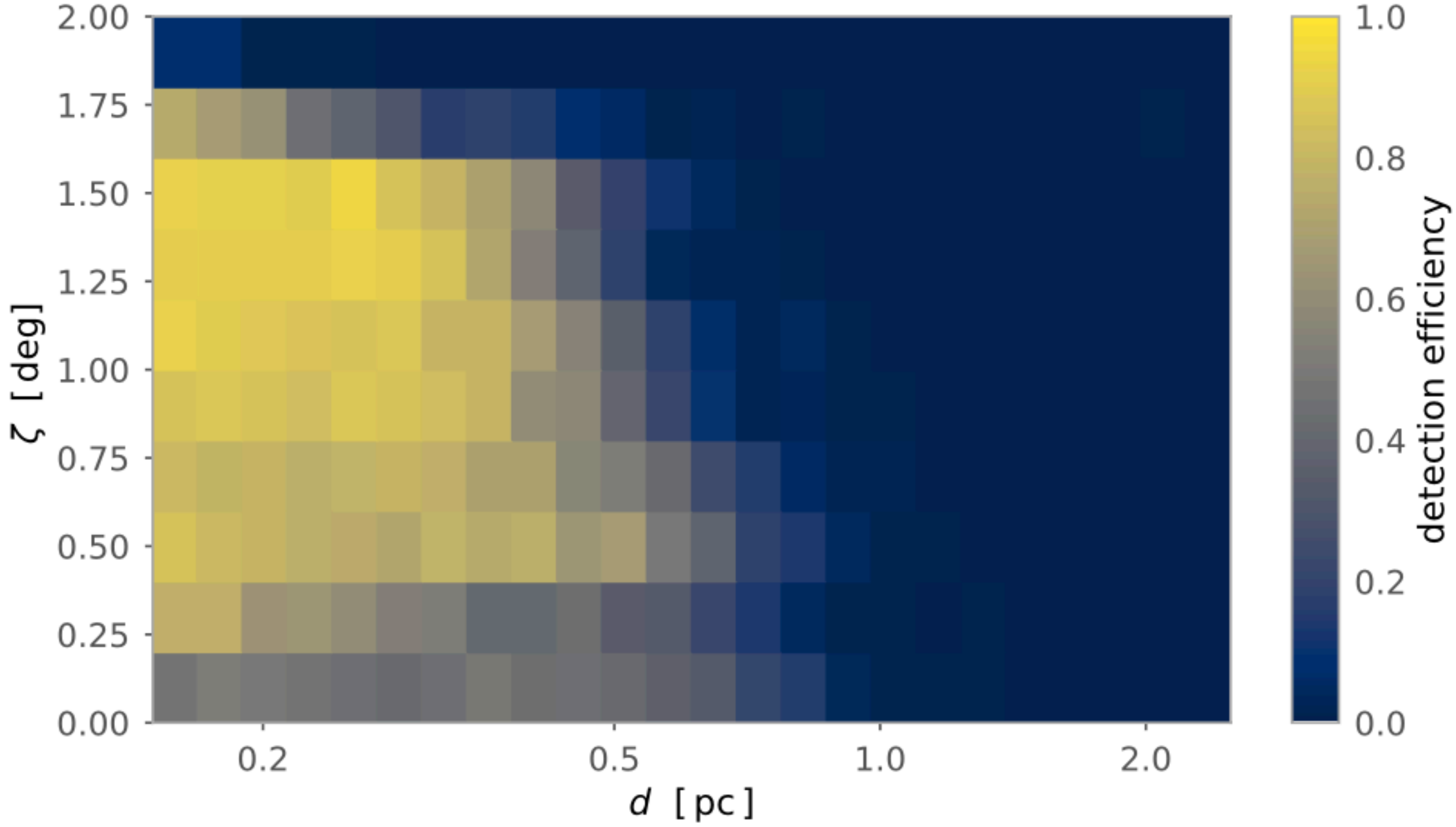
Parameter	Use	Intra-run	Comments
$\sec(\theta)$	✓	✓	Propagation length of atmospheric showers
$\|\alpha\|$	✓	✓	Effects on lateral shower development by geomagnetic field
ΔT_{ref}	✓	✓	Long-term degeneration of instrument
l, b	✗	✗	Observations in the galactic plane are excluded
R_{L3}	✓	✓	Intra-season changes of the instruments
`dead_time`	✗	✓	Redundant due to linear correlation to L3 rate
`ped_var`	✗	✗	Only accessible as average number for run
$M(\mathrm{E_{total}})$	✓	✓	Description of time dependent NSB to replace `ped_var`
$M(\mathrm{E_0}), M(\mathrm{E_1}), M(\mathrm{E_2})$	✗	✓	Correlation to $M(\mathrm{E_{total}})$, limited by low statistic
ζ	✓	✗	Radial acceptance for different ROIs



Parameter		Time Dependent Auxiliary Parameter
ΔT_{ref}	✗	→ Constant starting point of observing run
$\sec(\theta)$	✓	
$\|\alpha\|$	✓	
$\tilde{R}_{\mathrm{L3}}$	✓	
$M(\mathrm{E_{total}})$	✗	→ Mean multiplicity spanning the full observing run

PBH evaporation with VERITAS

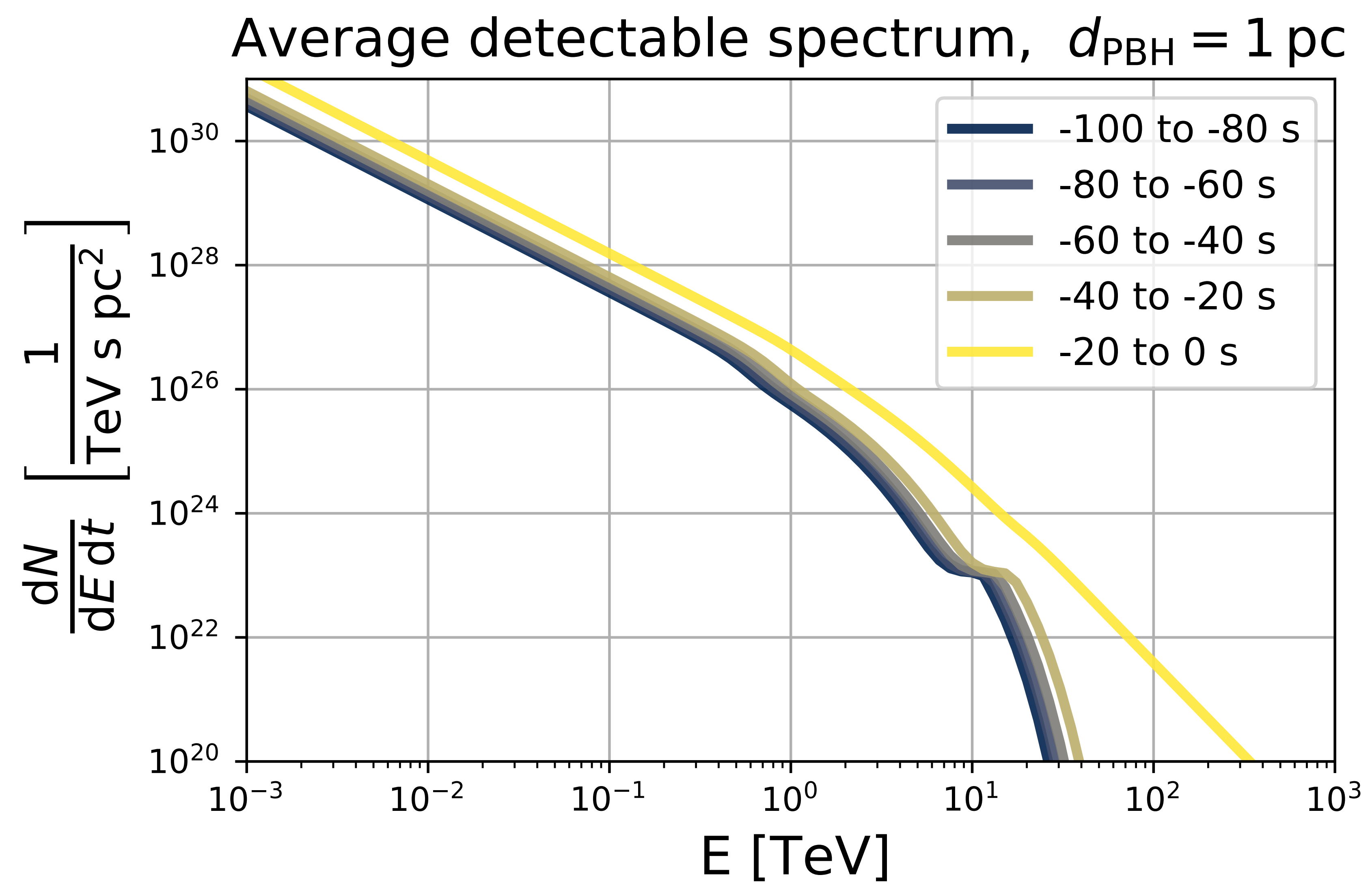
- Detection efficiency for simulated PBH evaporations within a particular metadata bin of the analysis

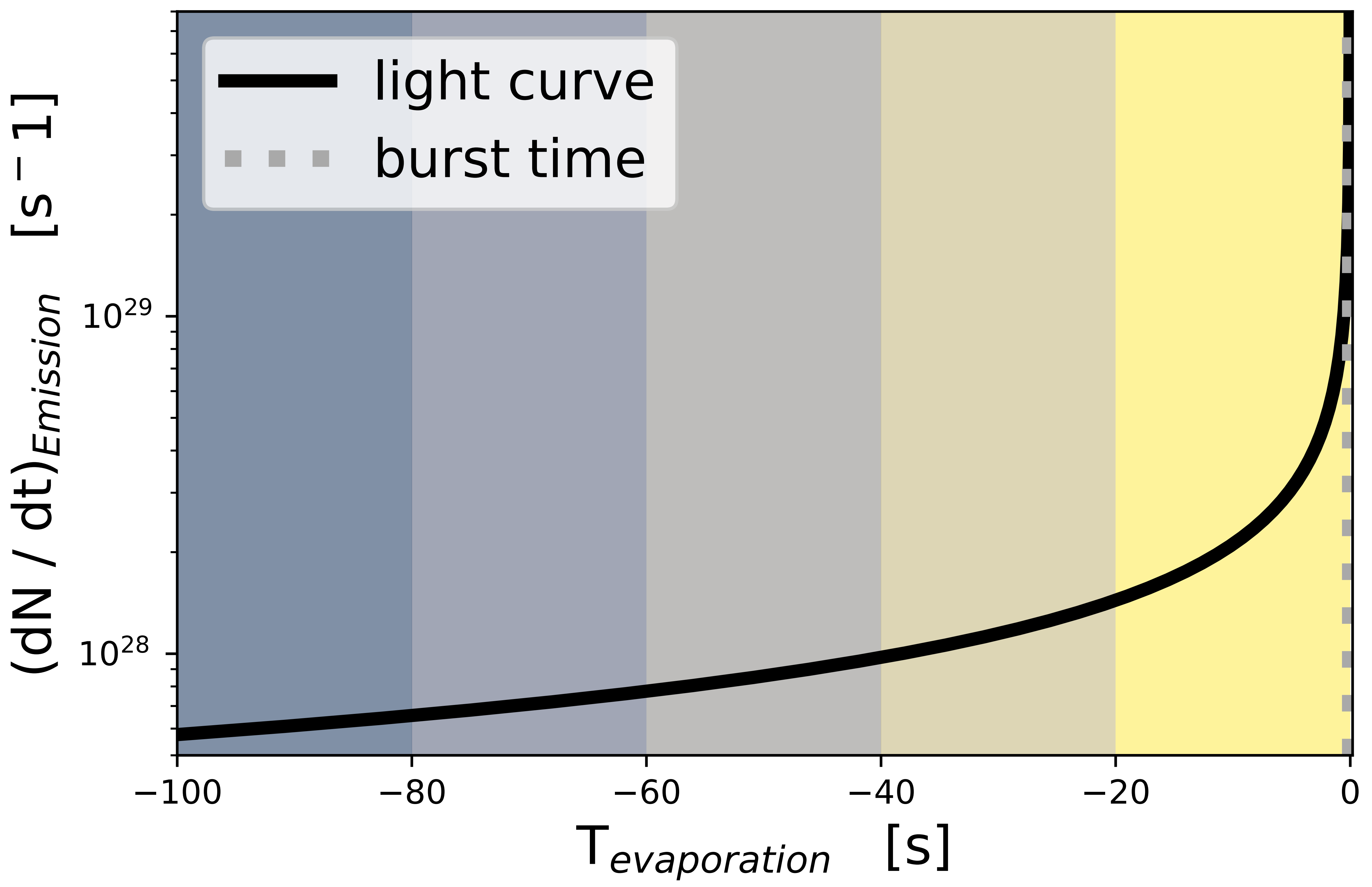


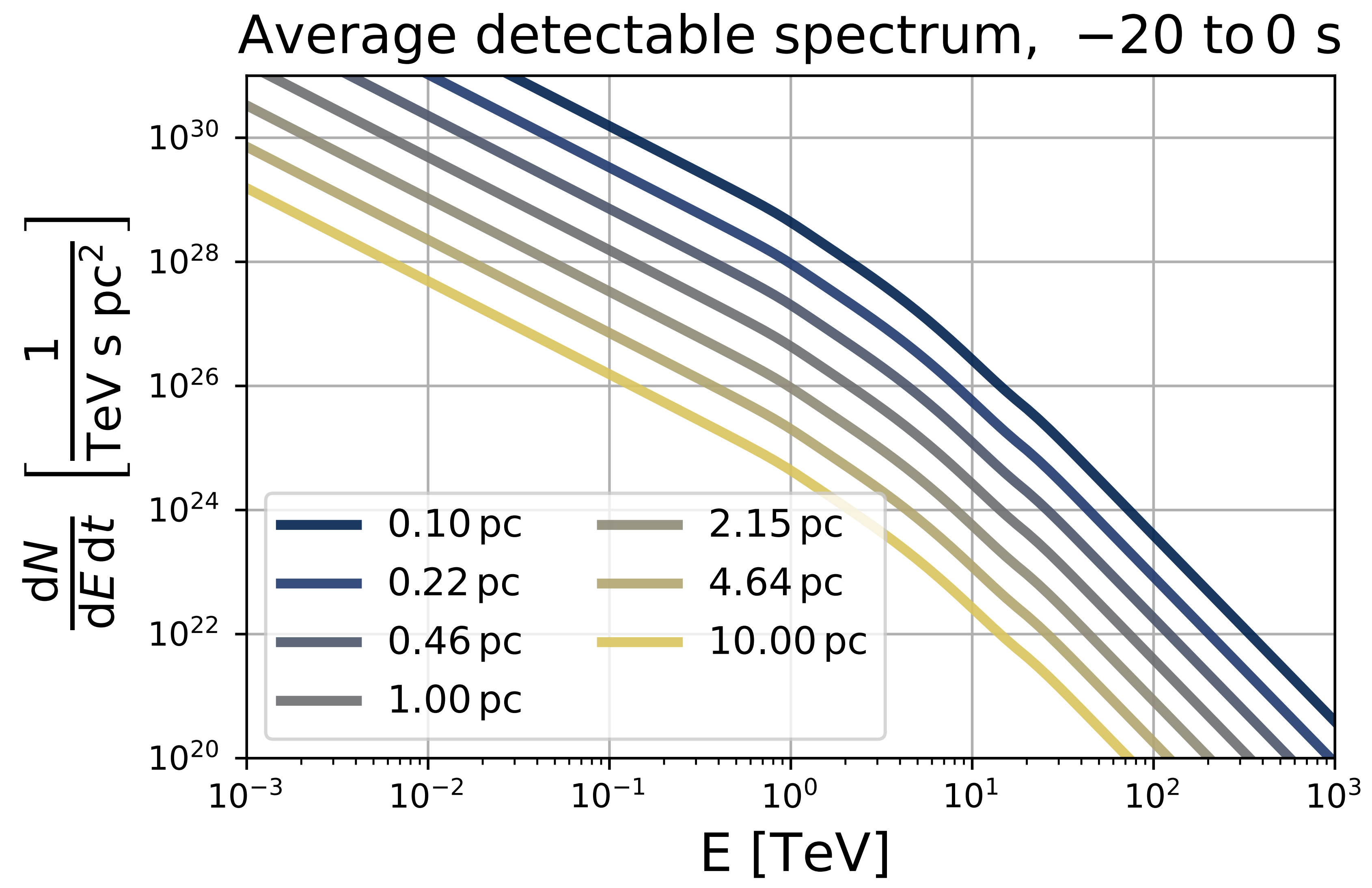
Extras

PBH evaporation with VERITAS

- Evaporation of primordial black holes
  - Eligible for evaporation today ➜ ~10^{15} g
  - γ-ray emission (model dependent) via Hawking radiation
    - Signature ➜ flux increases as mass decreases







PBH evaporation with VERITAS

- Data preparation
  - Observers during the night ➜ next-day analysers ➜ automated data checks:
    - Trigger rate & calibration devices ➜ monitor:
      - Rate spikes • weather fluctuations • background illumination (e.g., moonrise, passing car)
  - Stricter selection criteria for training / calibration, compared to inference (the actual search)