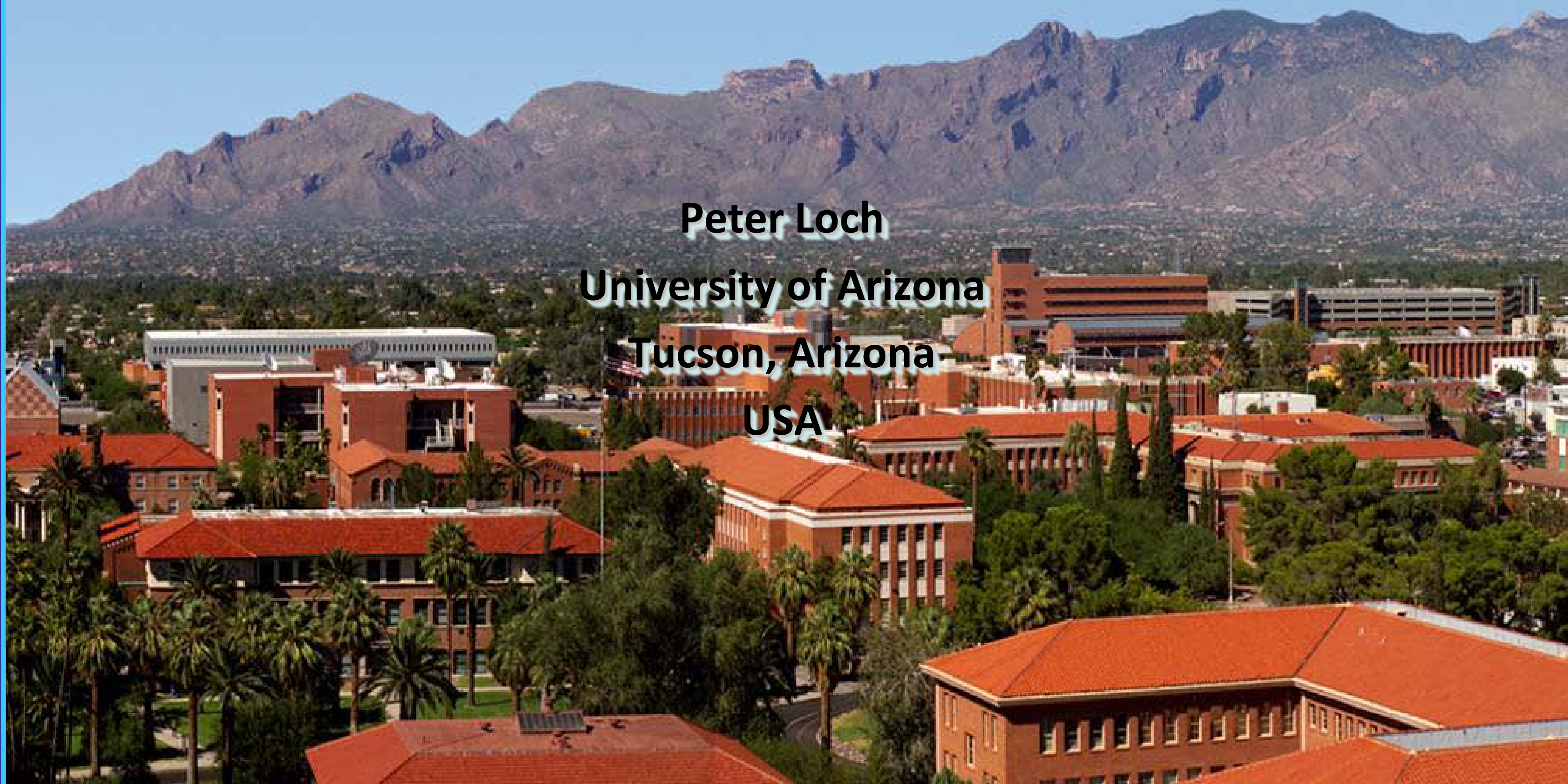
# Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part X)



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# Calorimeter Signal Definitions

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April 6, 2010

## Need to have another look at the calorimeter

- Basically all calorimeters at collider experiments show some level of non-compensation
  - For sure the ones in ATLAS and CMS are!
- Needs to be corrected for jet calibration
  - And all other hadronic final state contributions like isolated hadrons, tau-leptons, and low pT hadronic signals
- Can this be done for highest spatial calorimeter granularity (cells)?
  - Not easy to see – individual cell signal without any other context hard to calibrate in non-compensating calorimeters
- Better to establish a larger context first to find out which calibration the calorimeter cell signal needs
  - Reconstructed jet itself – in ATLAS this is called **Global Calibration**
  - Topological cell clusters without jet context – in ATLAS this is called **Local Calibration**
- Cannot recommend to use cells directly to find jets:
  - High multiplicity on input for jet finders
  - Negative signal treatment required for four-momentum recombination
    - Noise can create E<0 in cells
  - Jets should consistent of significant (relevant) signal objects
    - Cell signal not a good image of the particle flow in jets
- Larger calorimeter signal objects clearly preferred
  - **Towers** of cells – add cell signal up in projective calorimeter towers
  - Topological **clusters** of cells – add cell signals following signal correlations in showers

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# Calorimeter Towers

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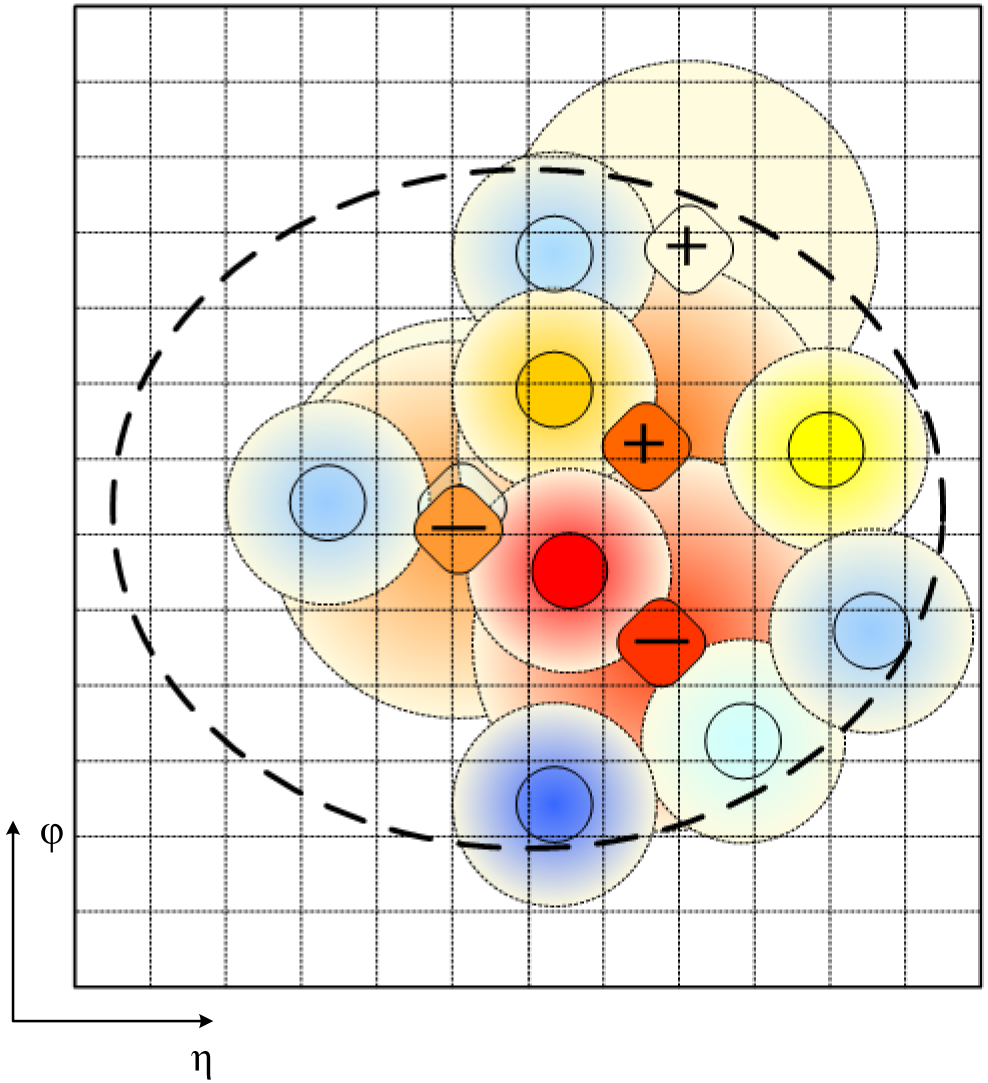

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# Calorimeter Towers

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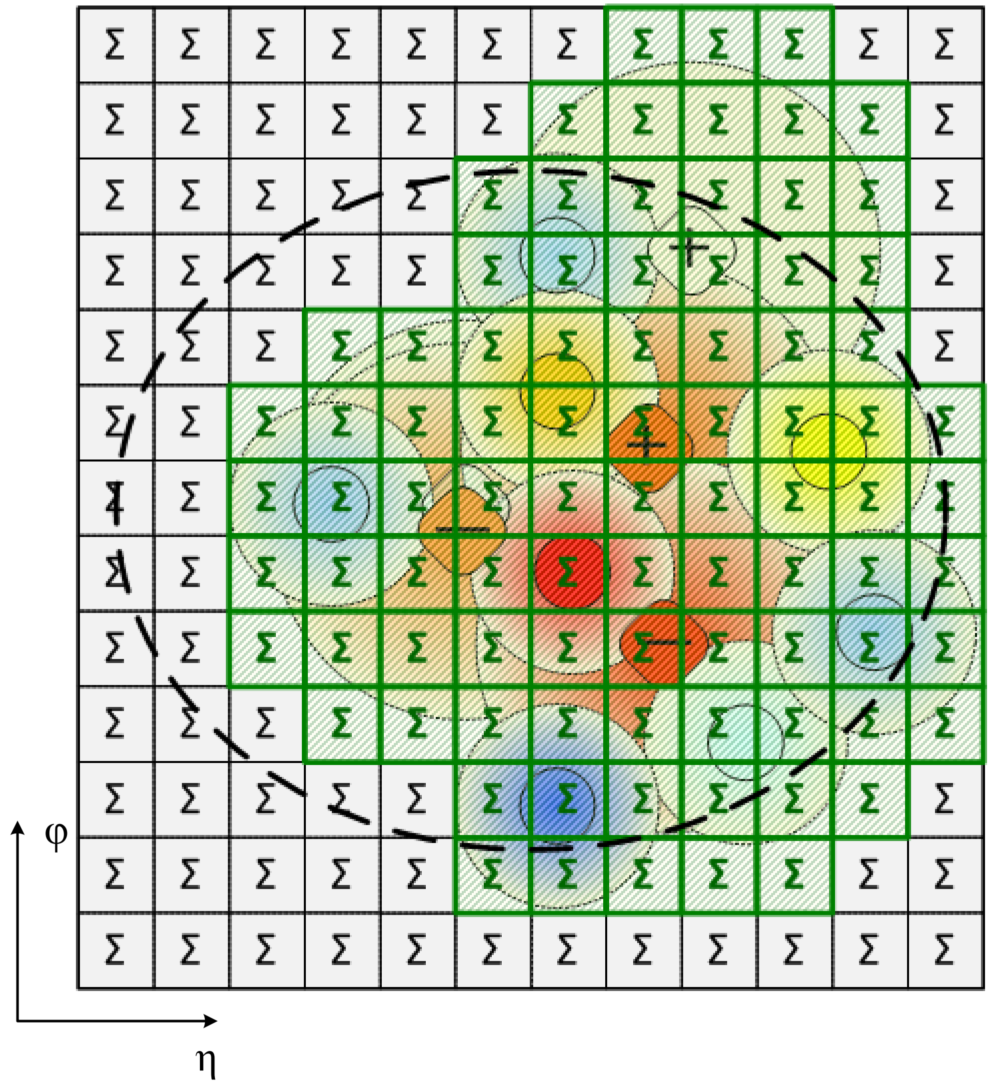

# Calorimeter Towers: Sum Rules

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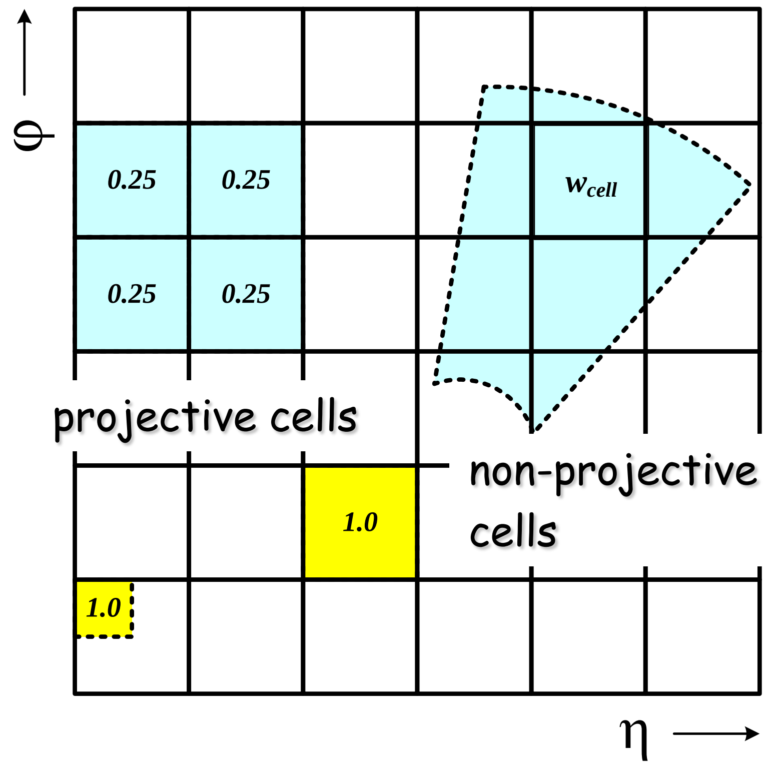
- **Impose a regular grid view on event**
  - $\Delta\eta\times\Delta\varphi = 0.1\times0.1$ grid
  - Motivated by particle Et flow in hadron-hadron collisions
  - Well suited for trigger purposes
- **Collect cells into tower grid**
  - Cells signals can be summed with geometrical weights
    - Depend on cell area containment ratio
    - Weight = 1 for projective cells of equal or smaller than tower size
  - Summing can be selective
    - Noise filter can be applied to cell signals!
- **Towers have massless four-momentum representation**
  - Fixed direction given by geometrical grid center




$$\left(E_{\eta\varphi},\eta,\varphi\right)\mapsto\left(E=p,p_x,p_y,p_z\right)$$

$$p=\sqrt{p_x^2+p_y^2+p_z^2}$$

$$E_{\eta\varphi}=\sum_{\left(A_{\text{cell}}^{\eta\varphi}\cap A_{\eta\varphi}\right)\neq0} w_{\text{cell}}E_{\text{cell}}$$

$$w_{\text{cell}}=\begin{cases}1 & \text{if } A_{\text{cell}}^{\eta\varphi}\leq\Delta\eta\times\Delta\varphi\\ <1 & \text{if } A_{\text{cell}}^{\eta\varphi}>\Delta\eta\times\Delta\varphi\end{cases}$$

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# More On Calorimeter Towers



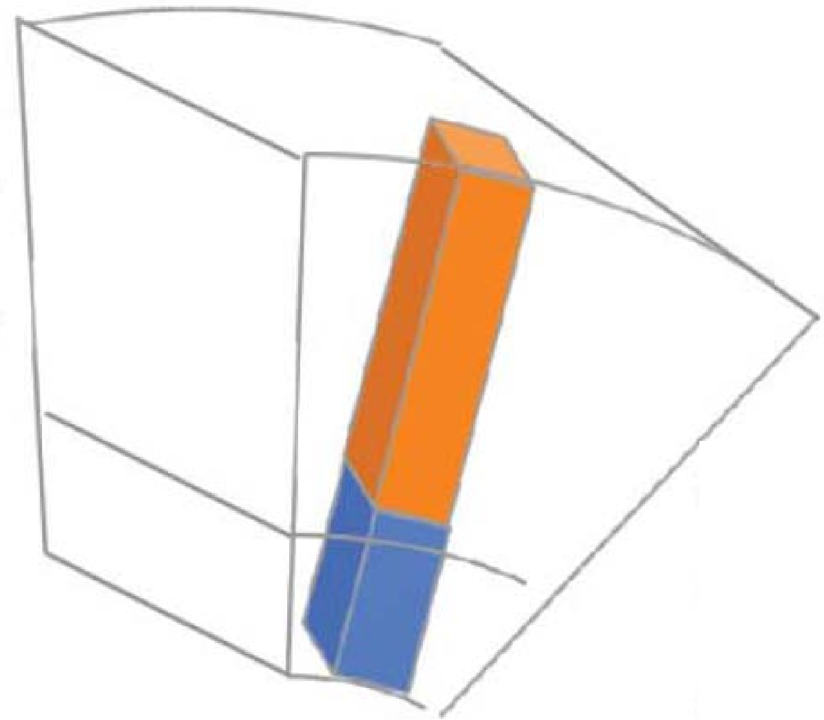
## Signal integration

- Towers represent longitudinally summed cell signals
  - 2-dimensional signal objects
  - Can include partial and complete signals from several particles
- Towers can preserve more detailed signal features
  - Associated information to be collected at tower formation
  - E.g., energy sharing in electromagnetic and hadronic calorimeters
  - Longitudinal signal center of gravity

## Signal splitting

- Towers can split signal from single particles
  - Hadronic shower width can be larger then tower bin, especially at higher pseudo-rapidity
  - Can cause problems with infrared safety
- Can cause problems for seeded jet finders
  - Collateral instability
- Can lead to lost signals cone-like jets
  - Energy in tower bins outside of jet can belong to particle signal in jet

(drawing by K. Perez, Columbia University)



Unbiased calorimeter tower is a "slab" of energy in a regular pseudorapidity-azimuth grid (each tower covers the same area in these coordinates)

# Topological Cell Clusters

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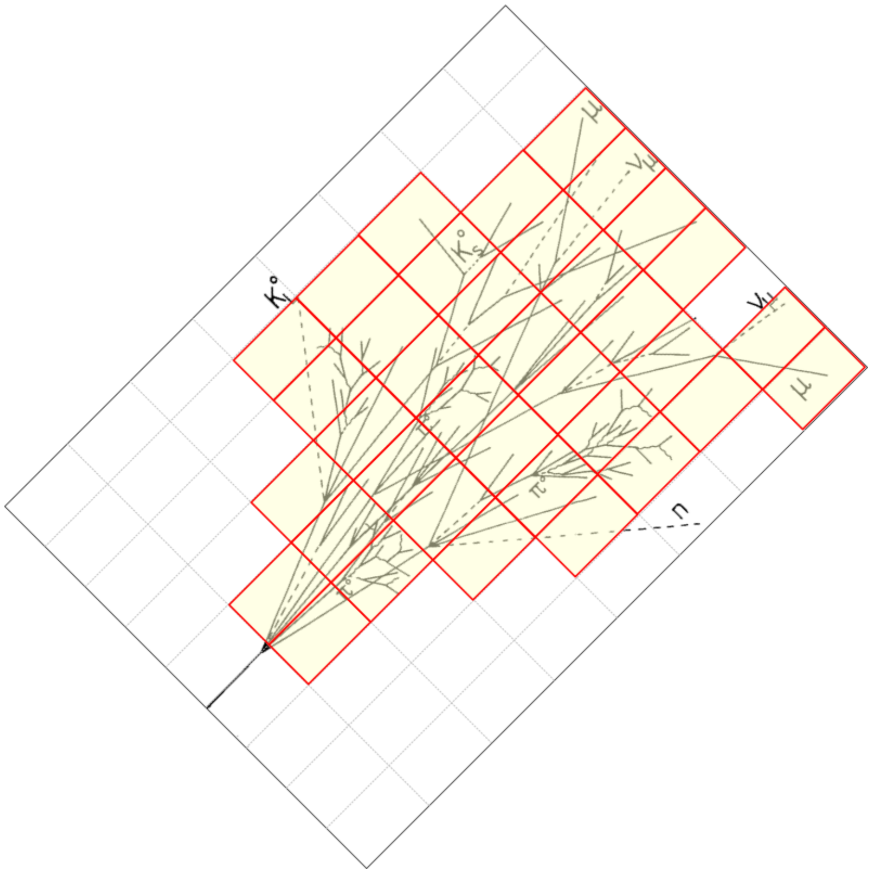
## Collect cell into energy "blobs"

- Idea is to collect all cell signals belonging to a given particle into one cluster of cells
  - Basically reconstruct the shower for each particle entering the calorimeter
- Needs algorithm to form energy blobs at the location of the shower signal in the calorimeter
  - Follow the shower-induced cell signal correlations



## Extract most significant signal from all calorimeter cells

- Cluster formation uses signal significance as guidance
  - Not the total signal – noise changes from calorimeter region to calorimeter region
- Implicit noise suppression in cluster formation
  - Cluster signals should include least amount of noise

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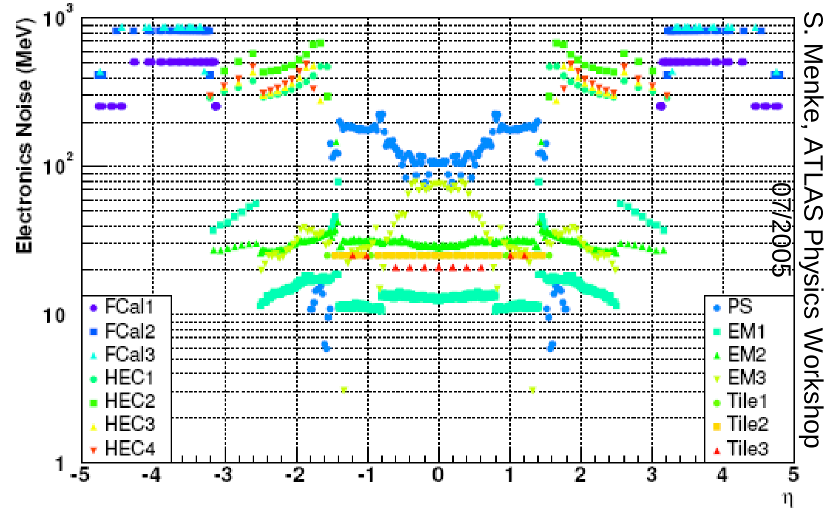
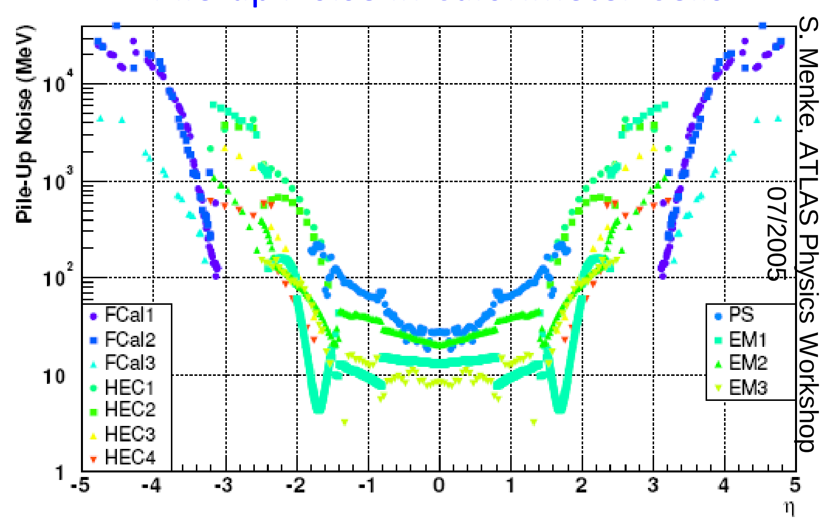
Electronic Noise in Calorimeter Cells




Pile-up Noise in Calorimeter Cells



## Cluster seeding

- Defined by signal significance above primary threshold
  - Cells above this threshold can seed cluster

## Cluster growth

- Defined by signal significance above secondary threshold
  - Cells neighbouring seeds with significance above this threshold drive cluster growths

## Cluster signal

- Defined by cells with significance above basic threshold
  - Cells to be considered in cluster energy sums

## Use of negative signal cells

- Thresholds are considered for the absolute (unsigned) signal magnitude
  - Large negative signals can seed and grow clusters

## Parameters for each stage optimized with testbeam data

- Experimental single pion shower shapes guide cluster algorithm development
  - Clean tuning reference!

Primary threshold

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > S, \text{ default } S = 4$$

Secondary threshold

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > N, \text{ default } N = 2$$

Collecting

$$\left|\frac{E_{\text{cell}}}{\sigma_{\text{cell}}}\right| > P, \text{ default}$$

$P = 2$

(note $S \geq N \geq P$)

**Famous "4/2/0" clustering in ATLAS**

# ATLAS Topological Cell Clustering

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## Cluster seeding
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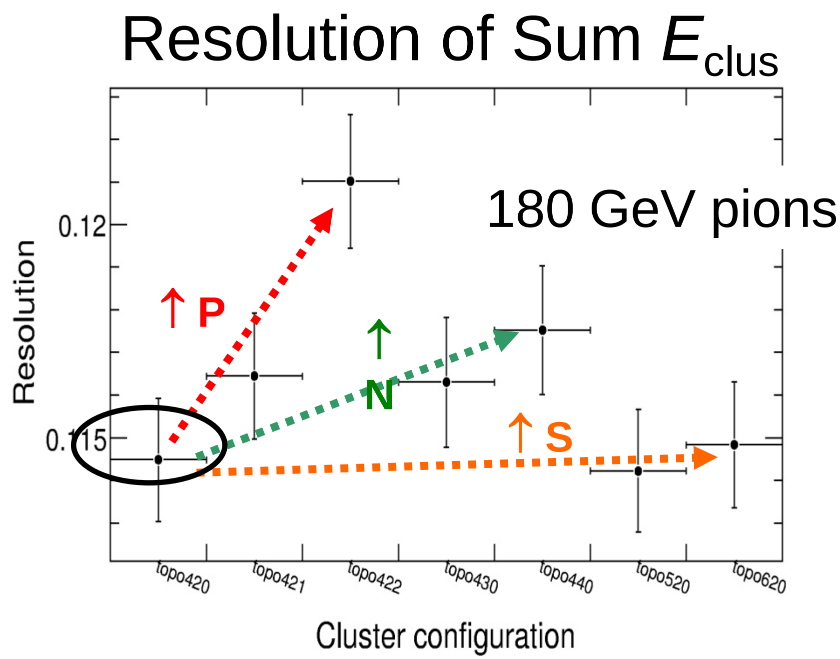


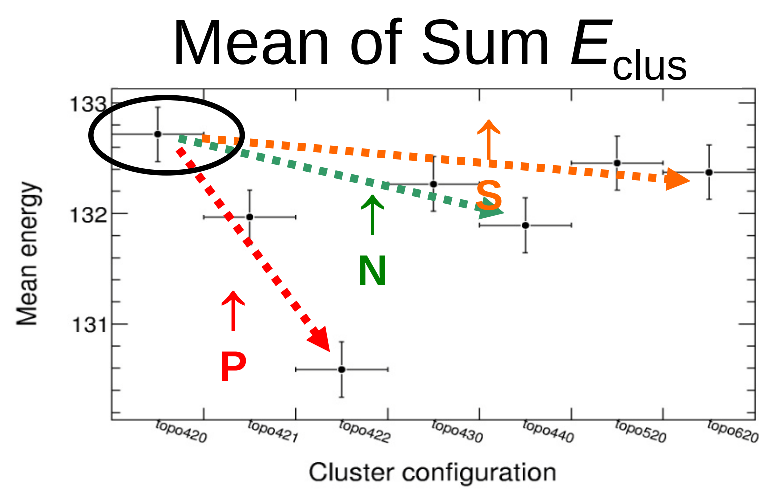

# Clustering Algorithms

1. **Find cell with most significant seed over primary threshold *S***
2. **Collect all cells with significance above basic threshold *P***
   - Consider neighbours in three dimensions
     - Defined by (partly) shared area, (partly) shared edge, or shared corner point
     - E.g., 26 neighbours for perfectly cubed volumes of equal size
   - Neighbours can be in other calorimeter regions or even other calorimeter sub-systems
     - Granularity change to be considered in neighbouring definition
3. **For all cells neighbouring seeds with signal significance above secondary threshold *N*, collect neighbours of neighbours if their signal significance is above *P***
   - Same rules as for collection around primary seed
4. **Continue until cluster does not grow anymore**
   - Automatically generate "guard ring" of small signal cells at cluster margin
     - In three dimensions, of course
5. **Take next not yet used seed cell and collect next cluster**

# Clustering Example

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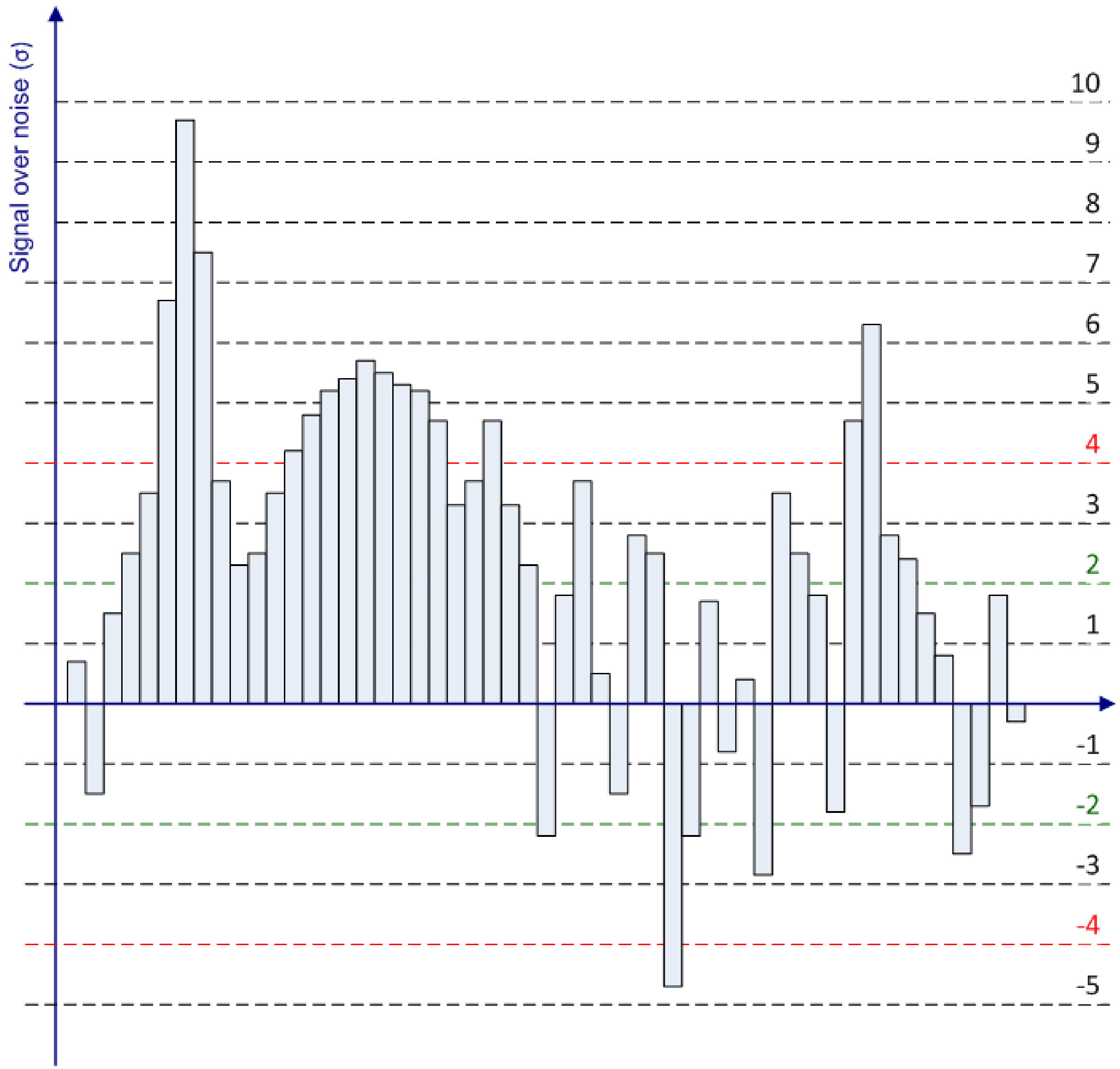

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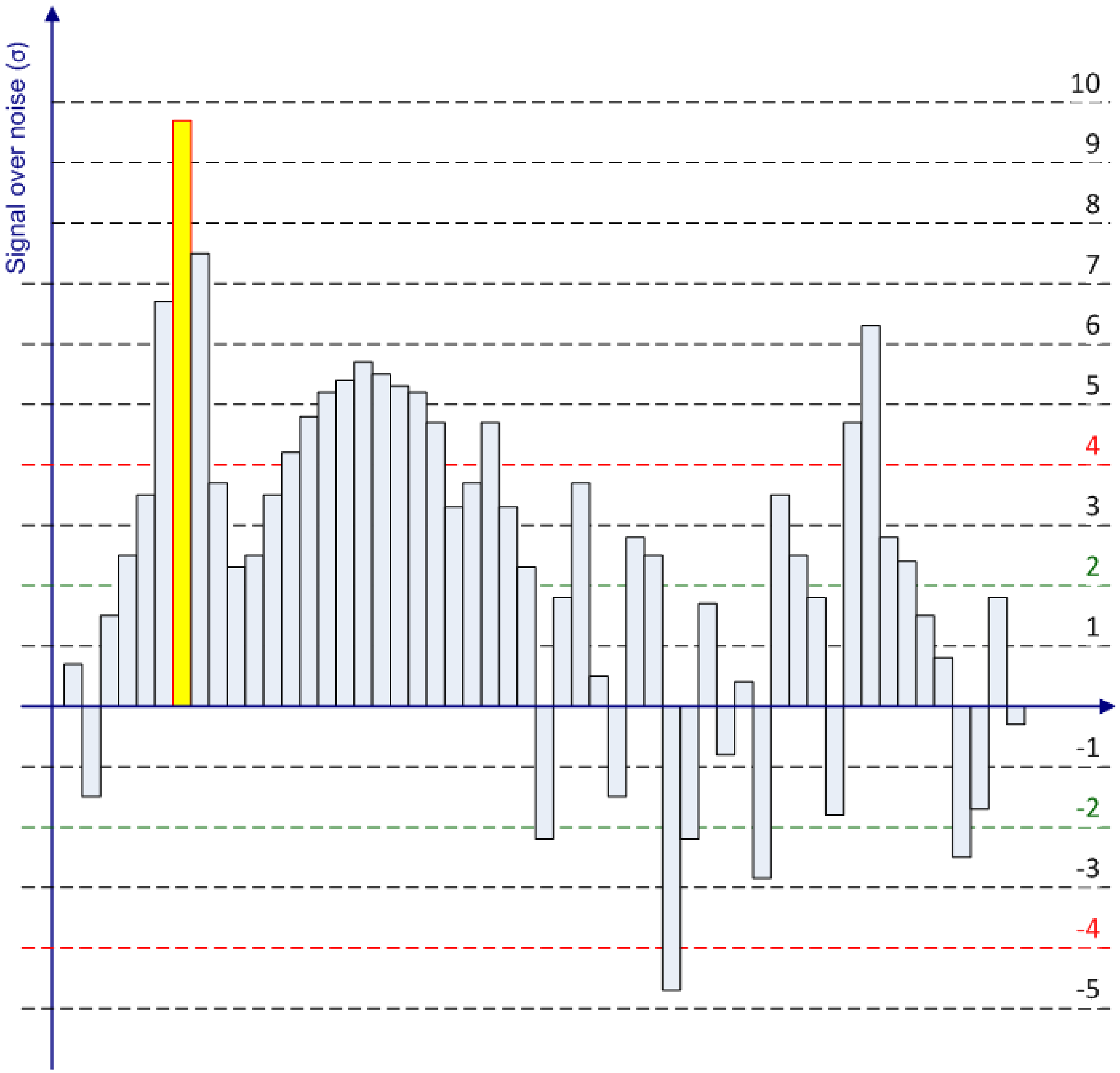

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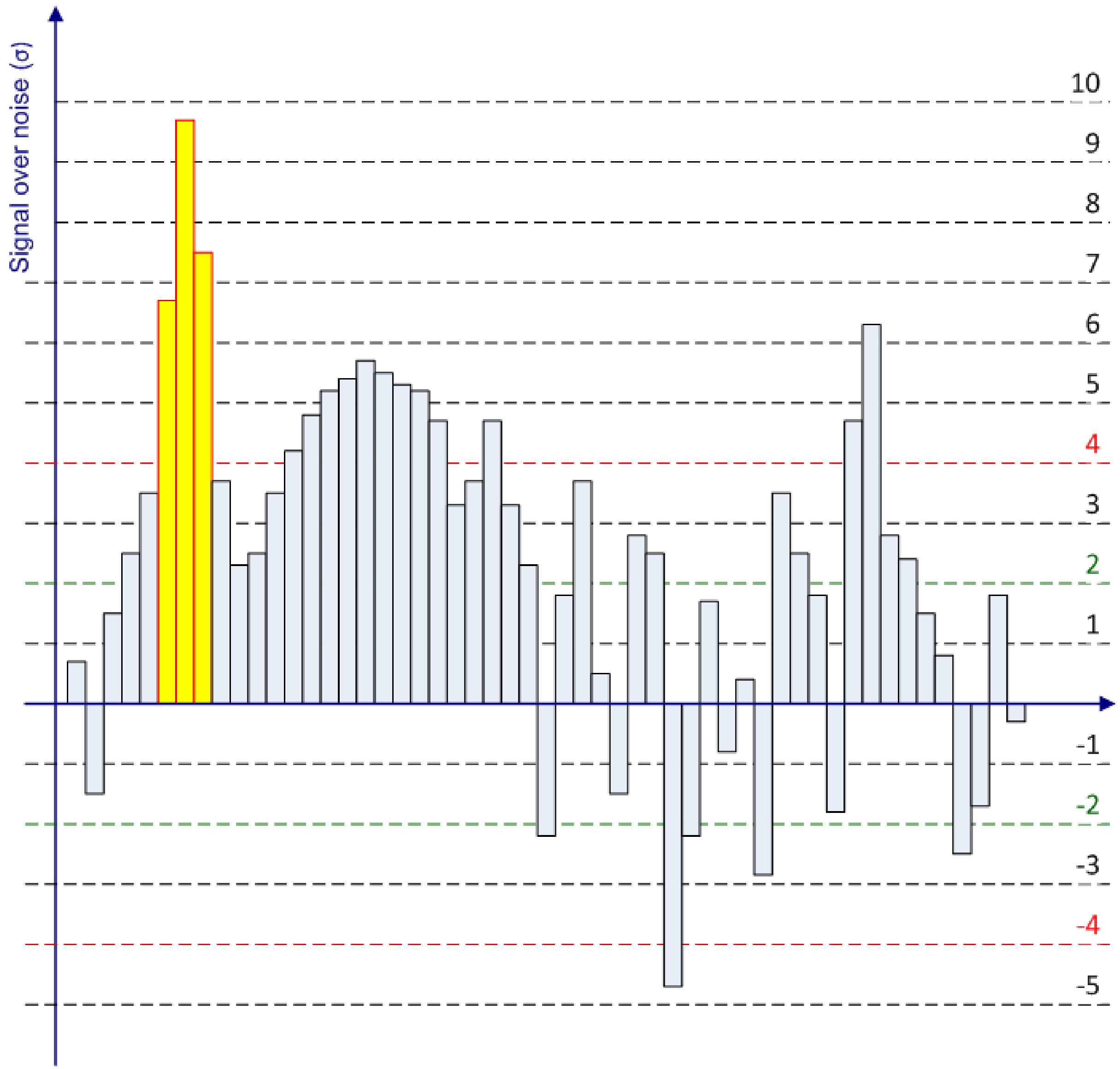


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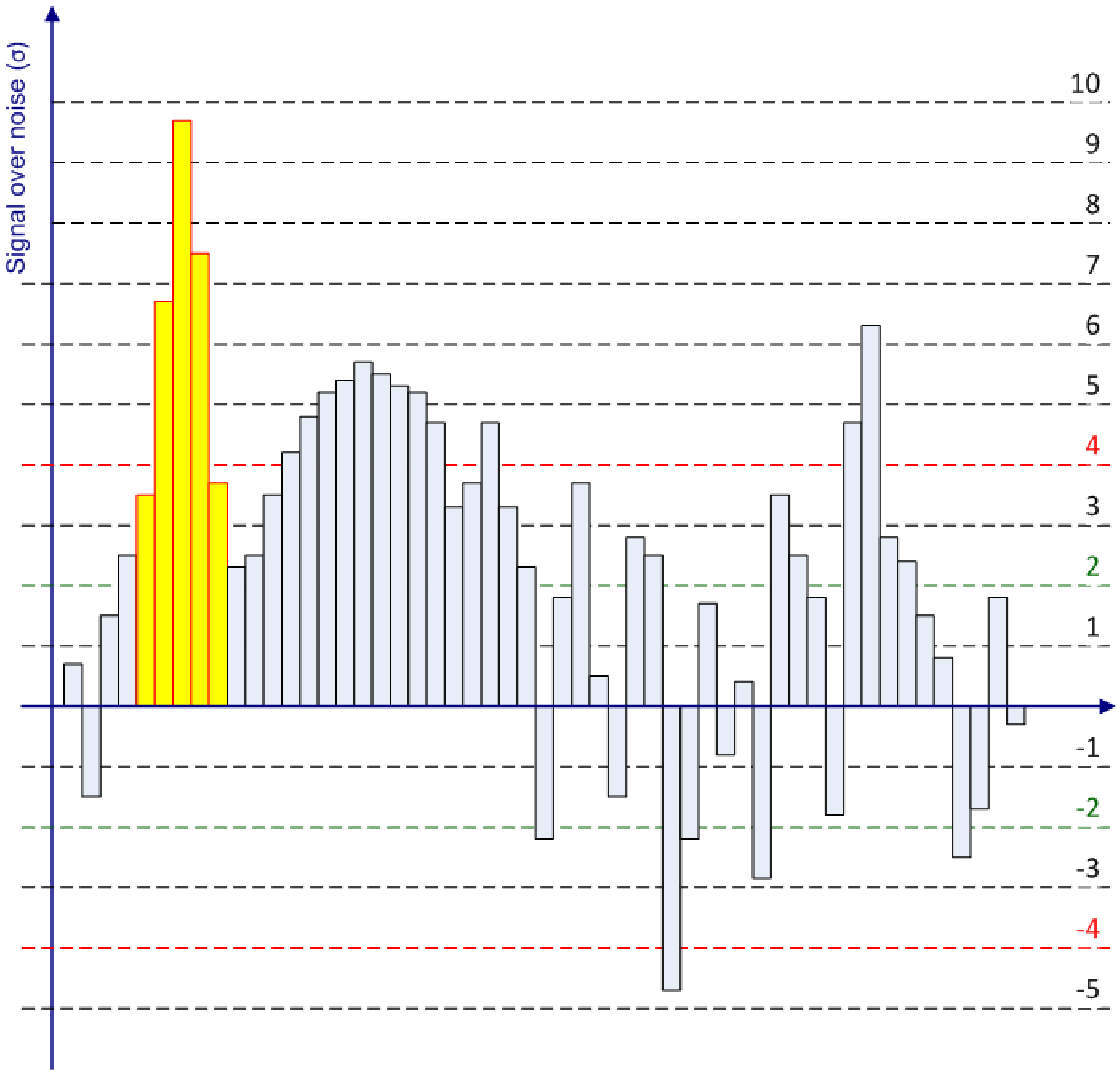


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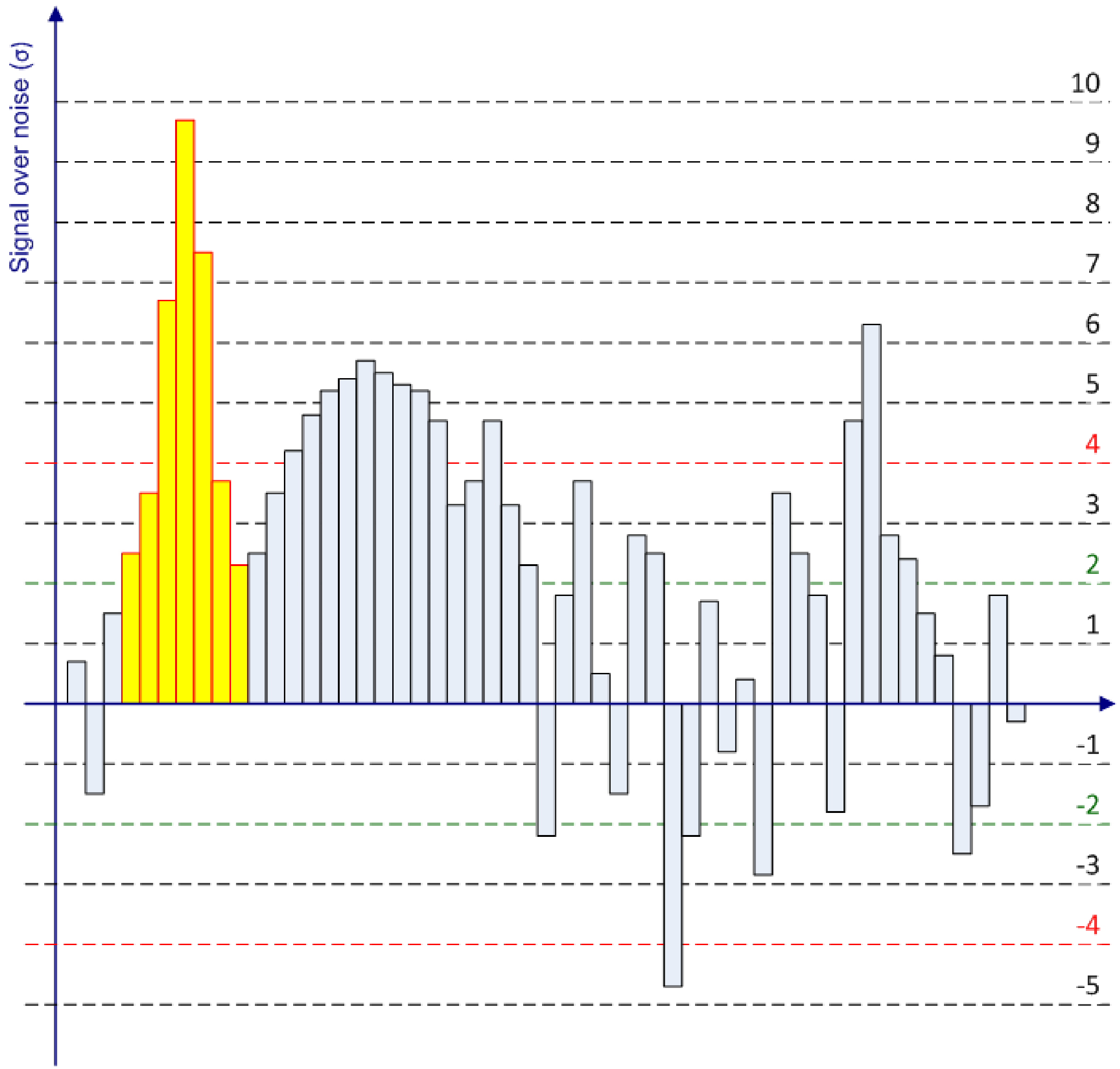


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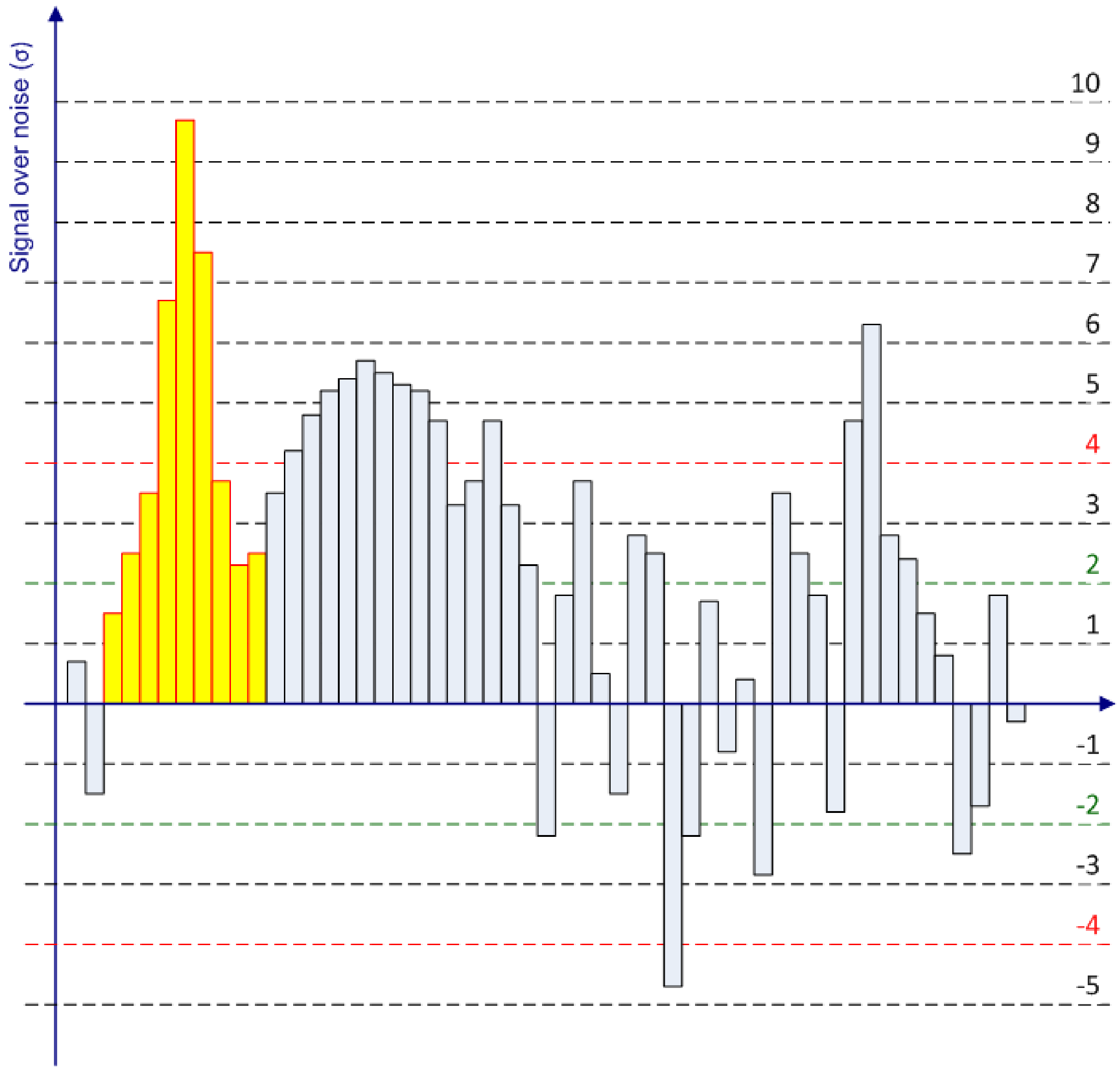

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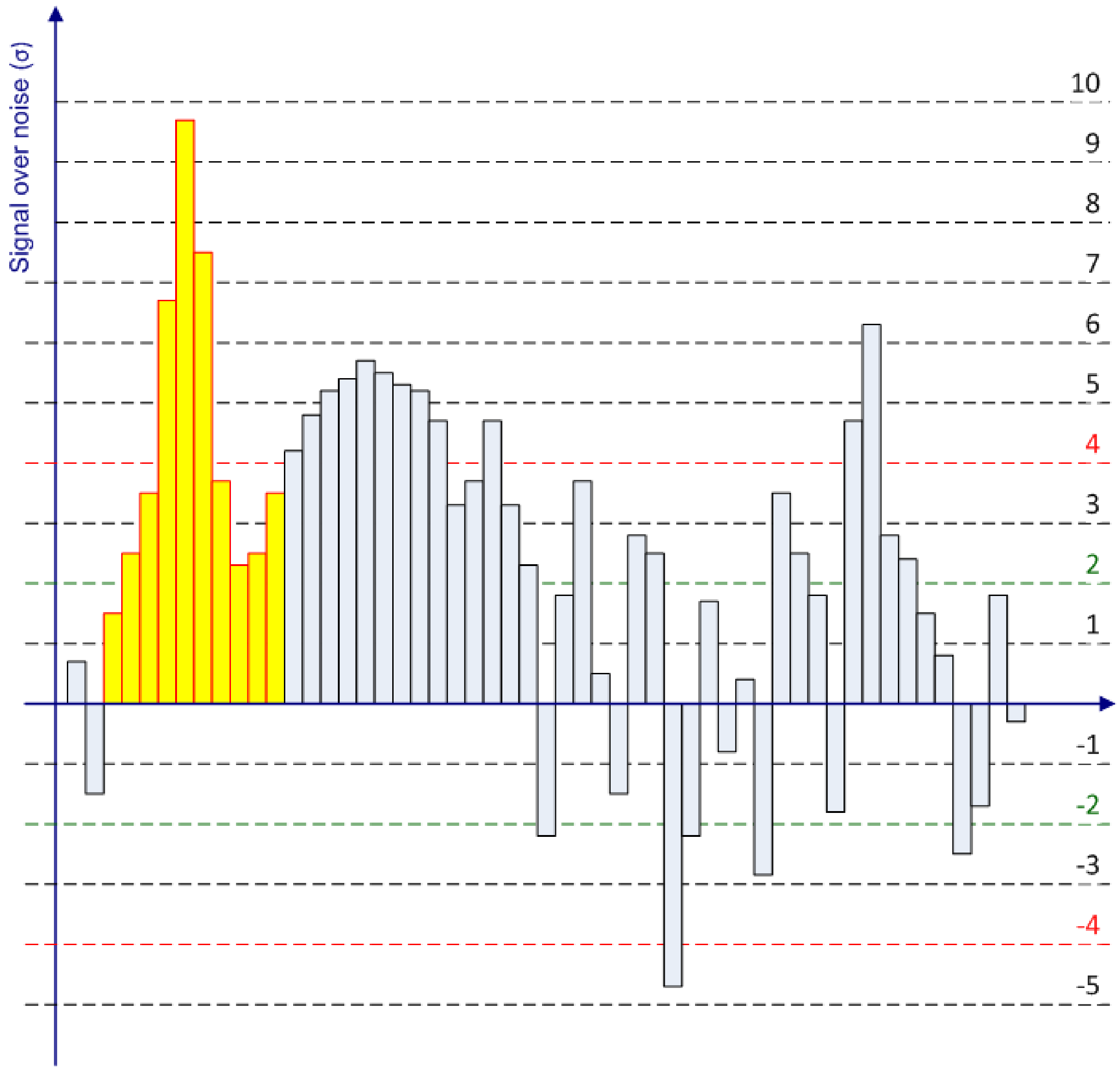


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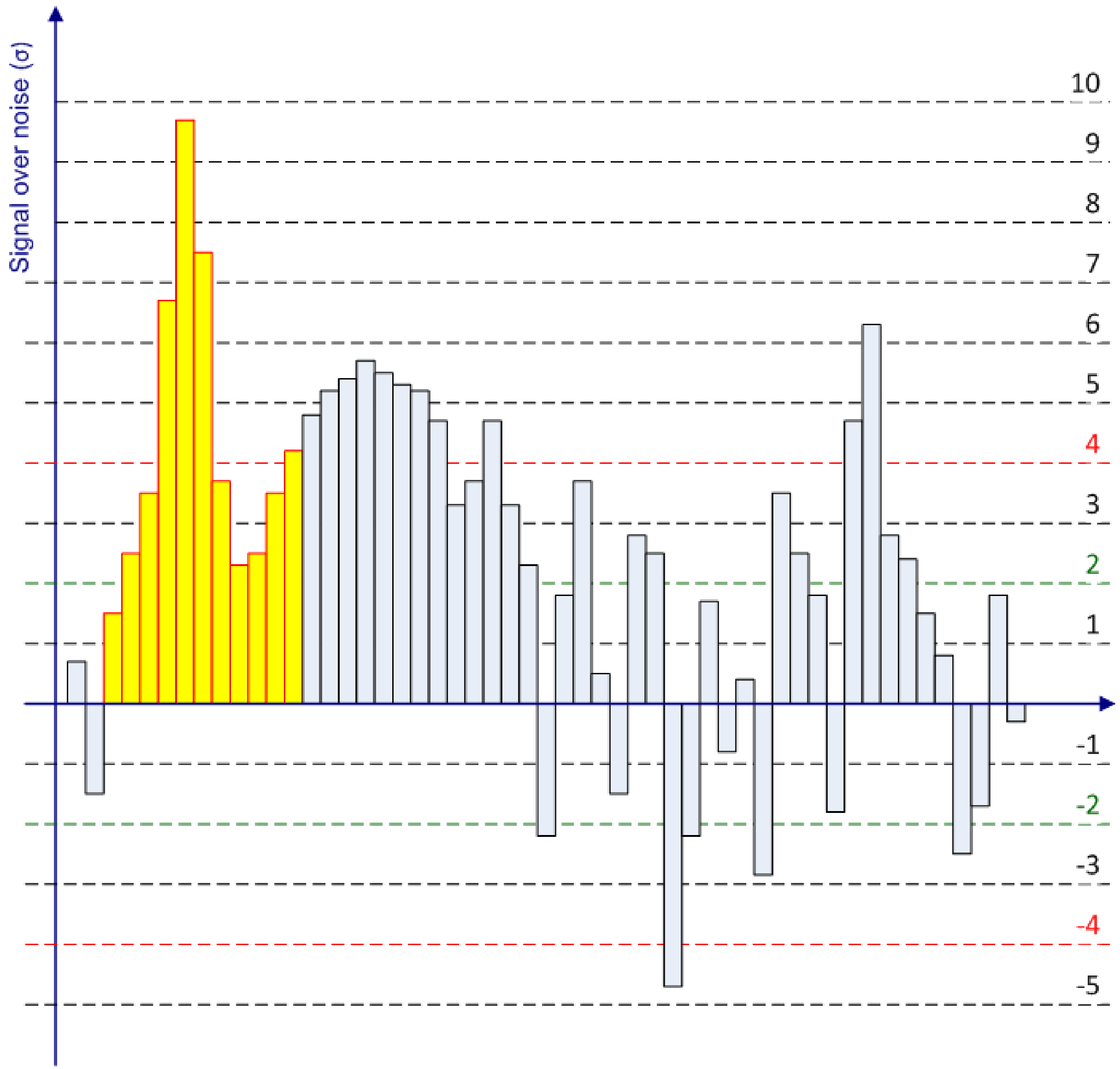

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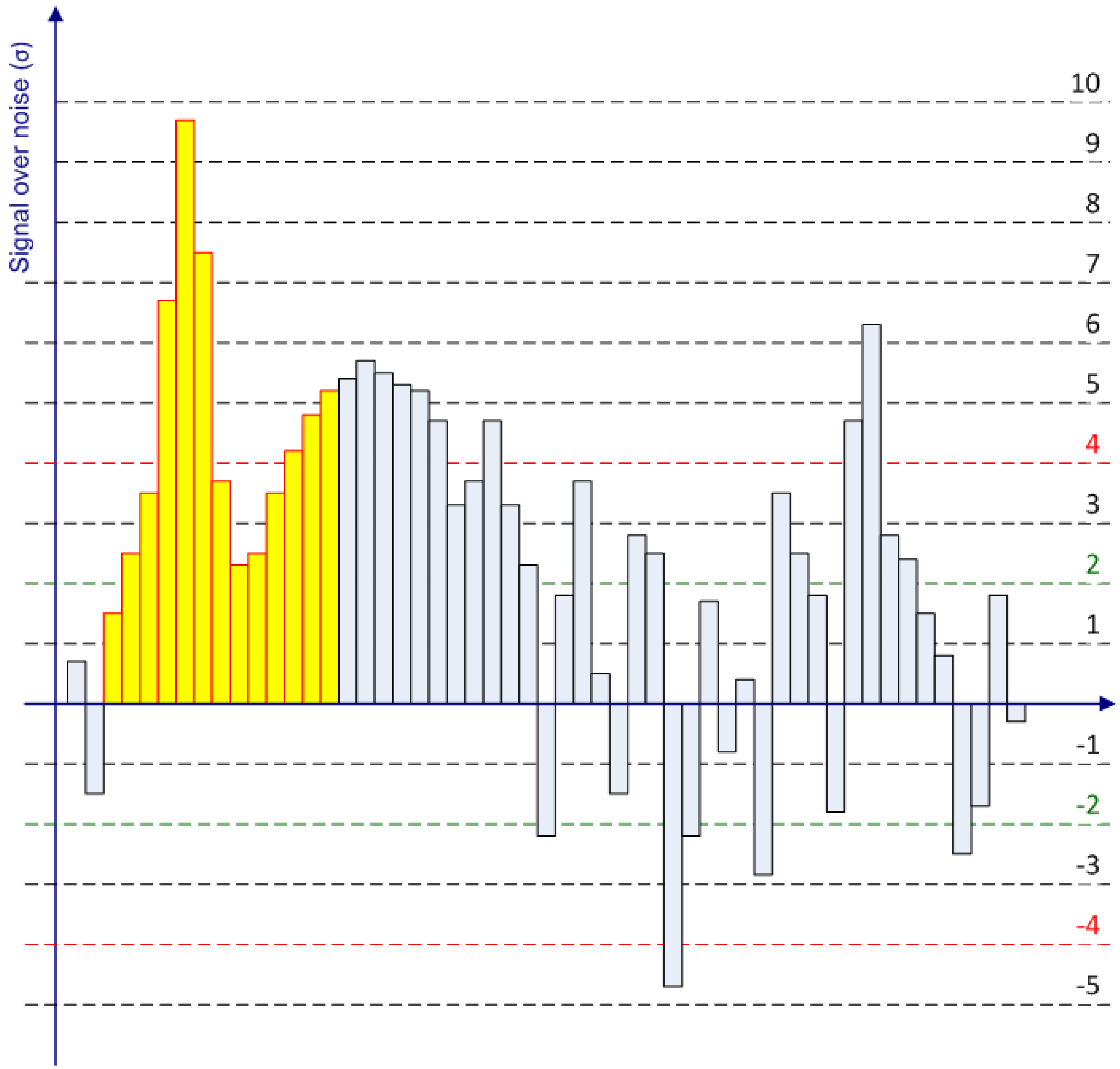

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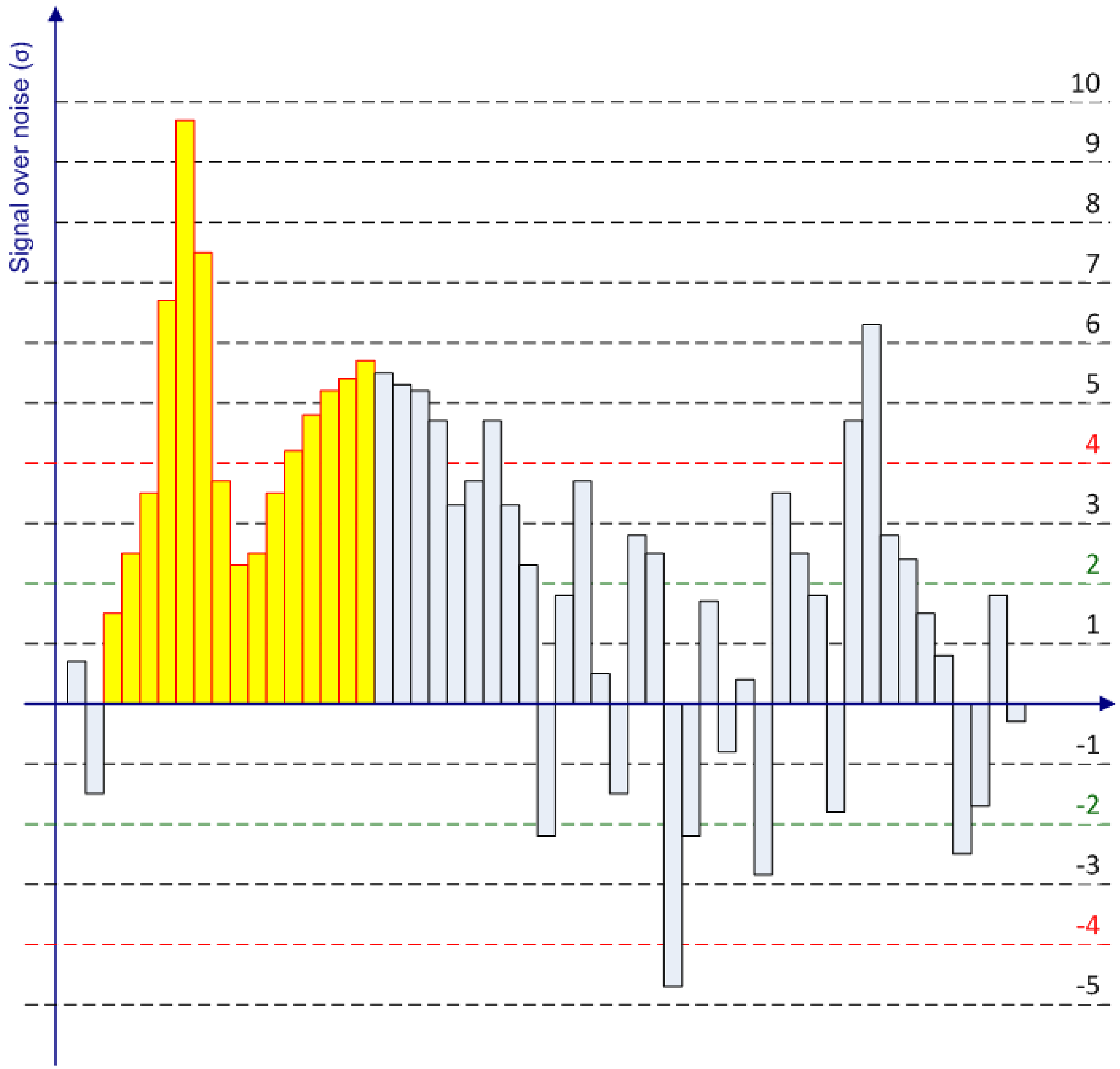

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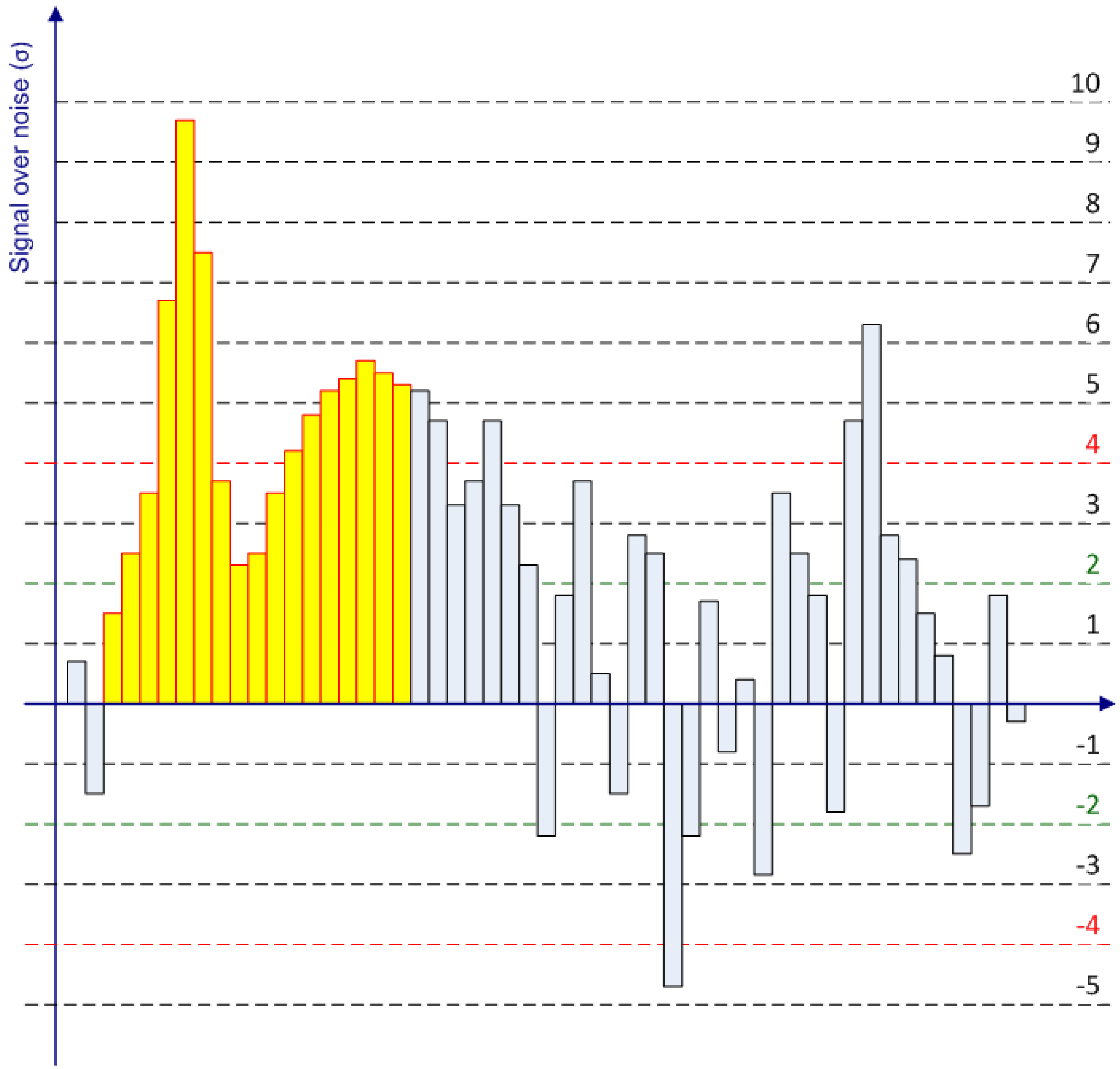

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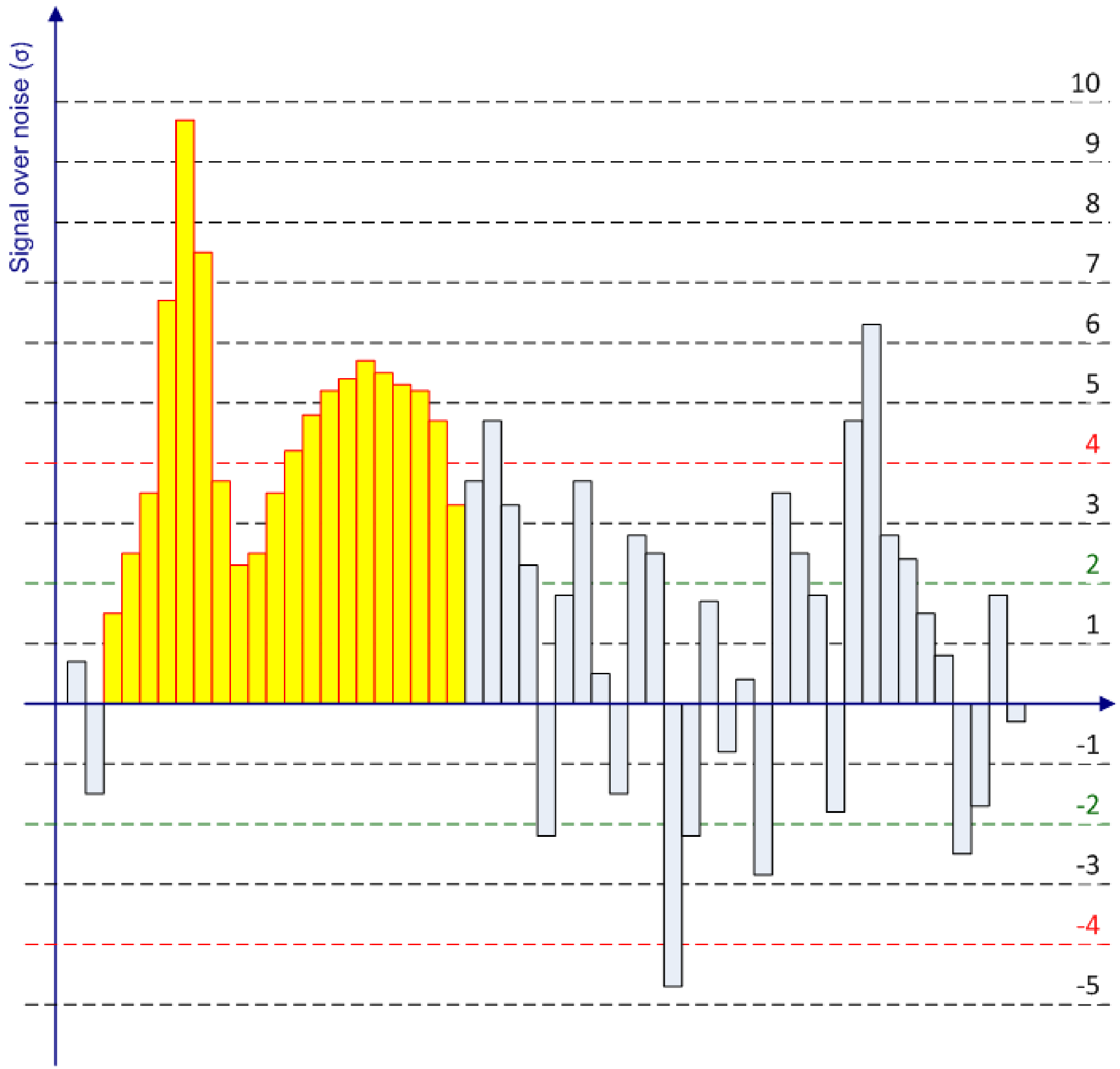

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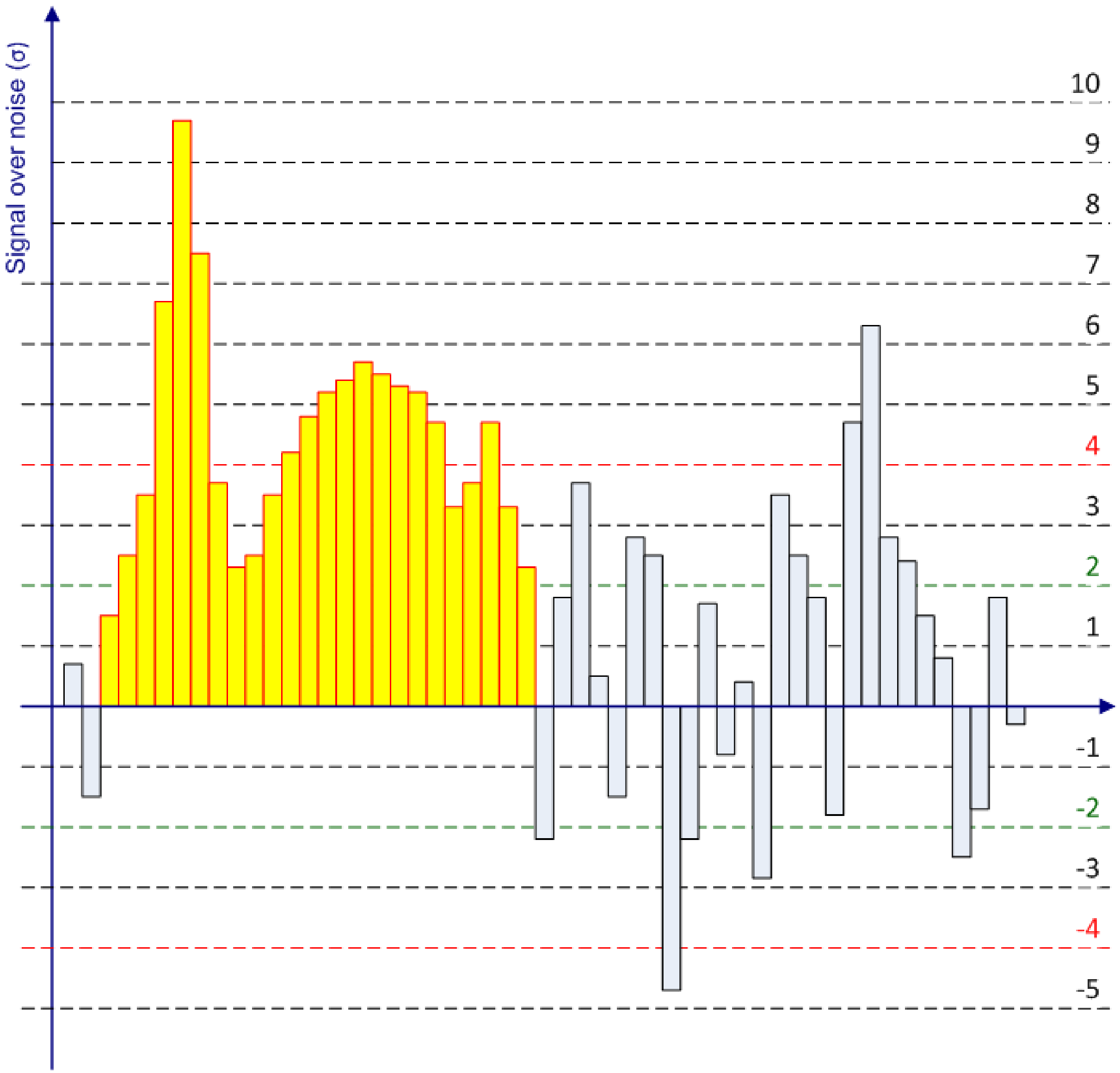


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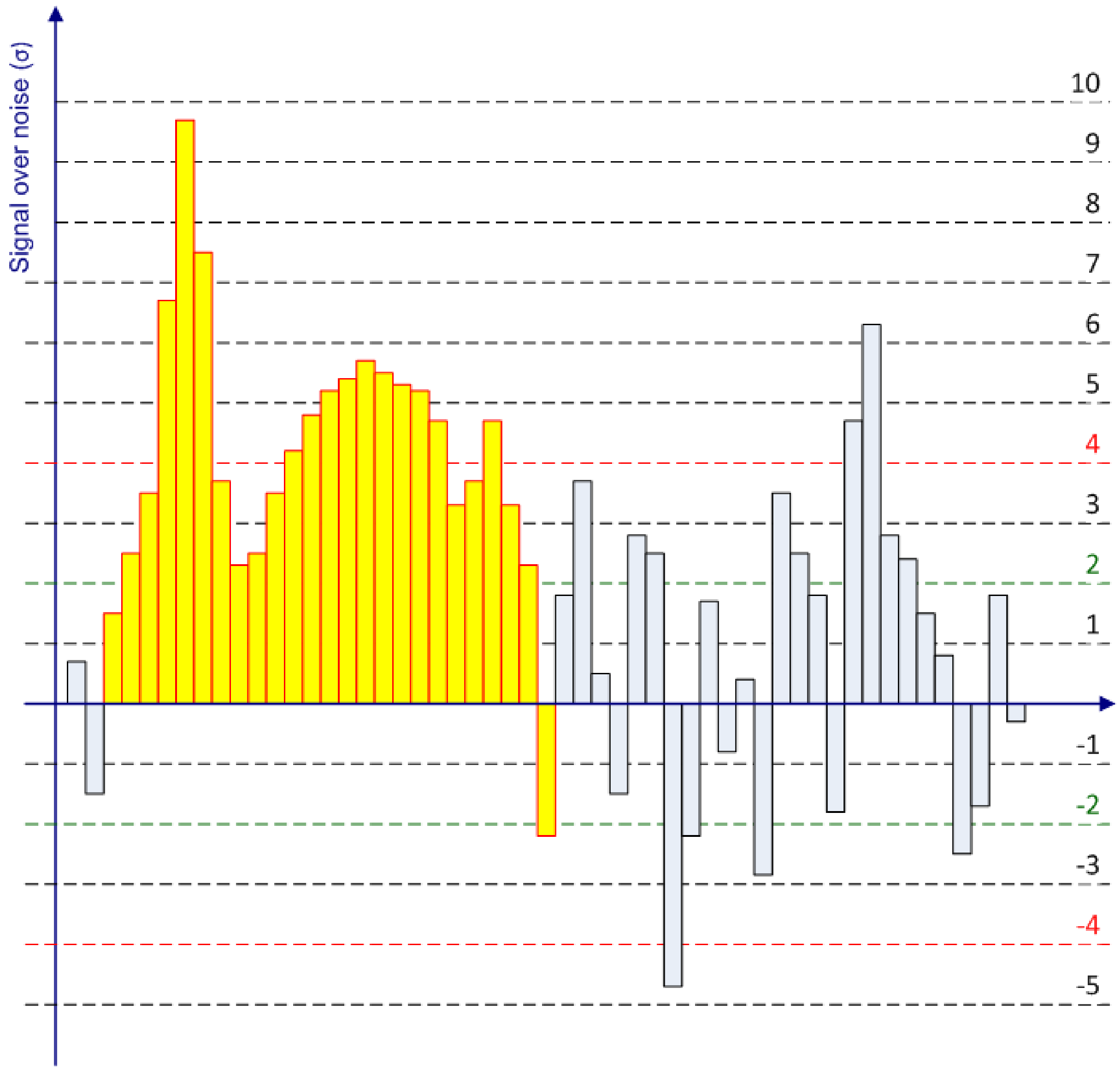


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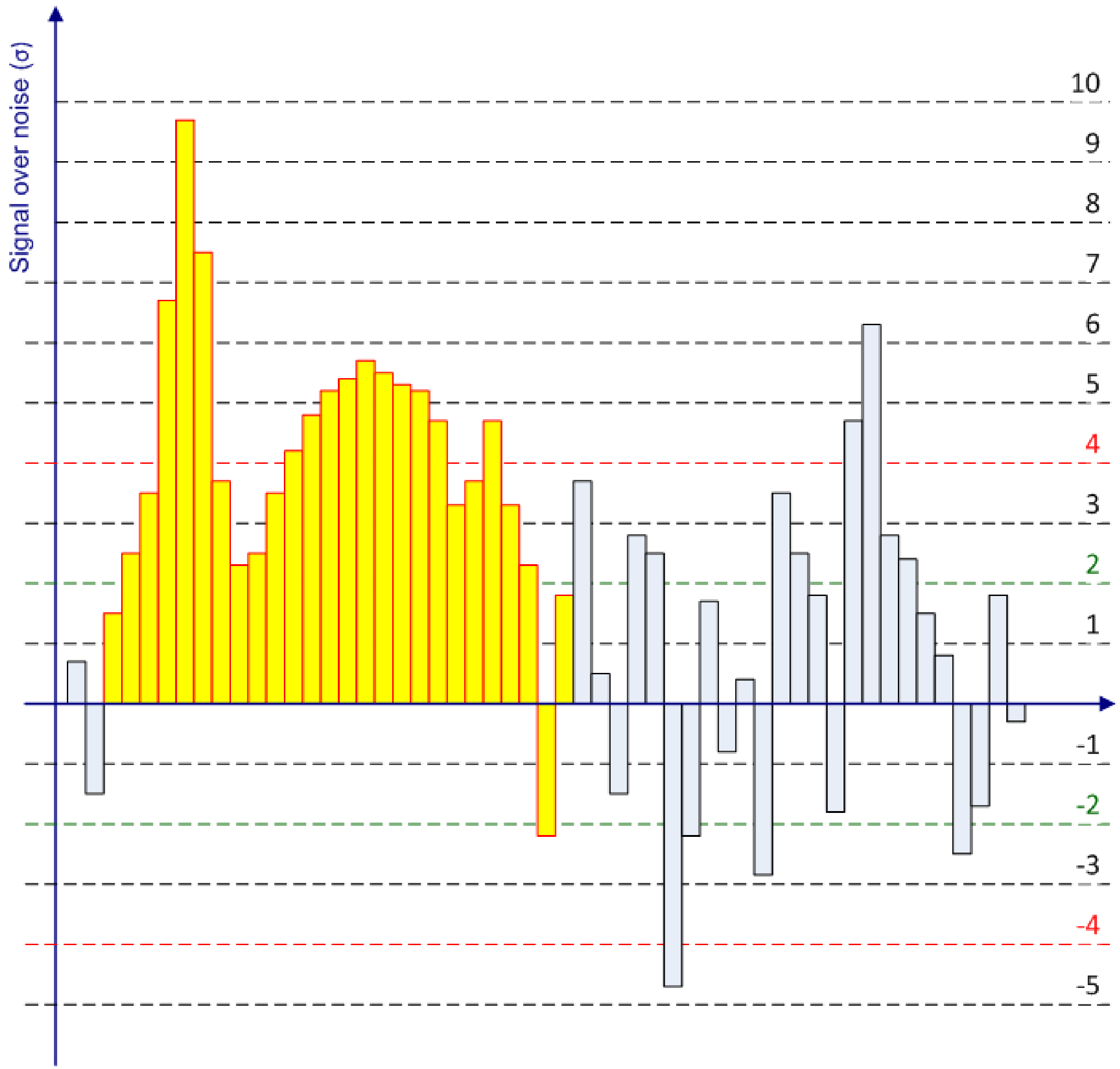


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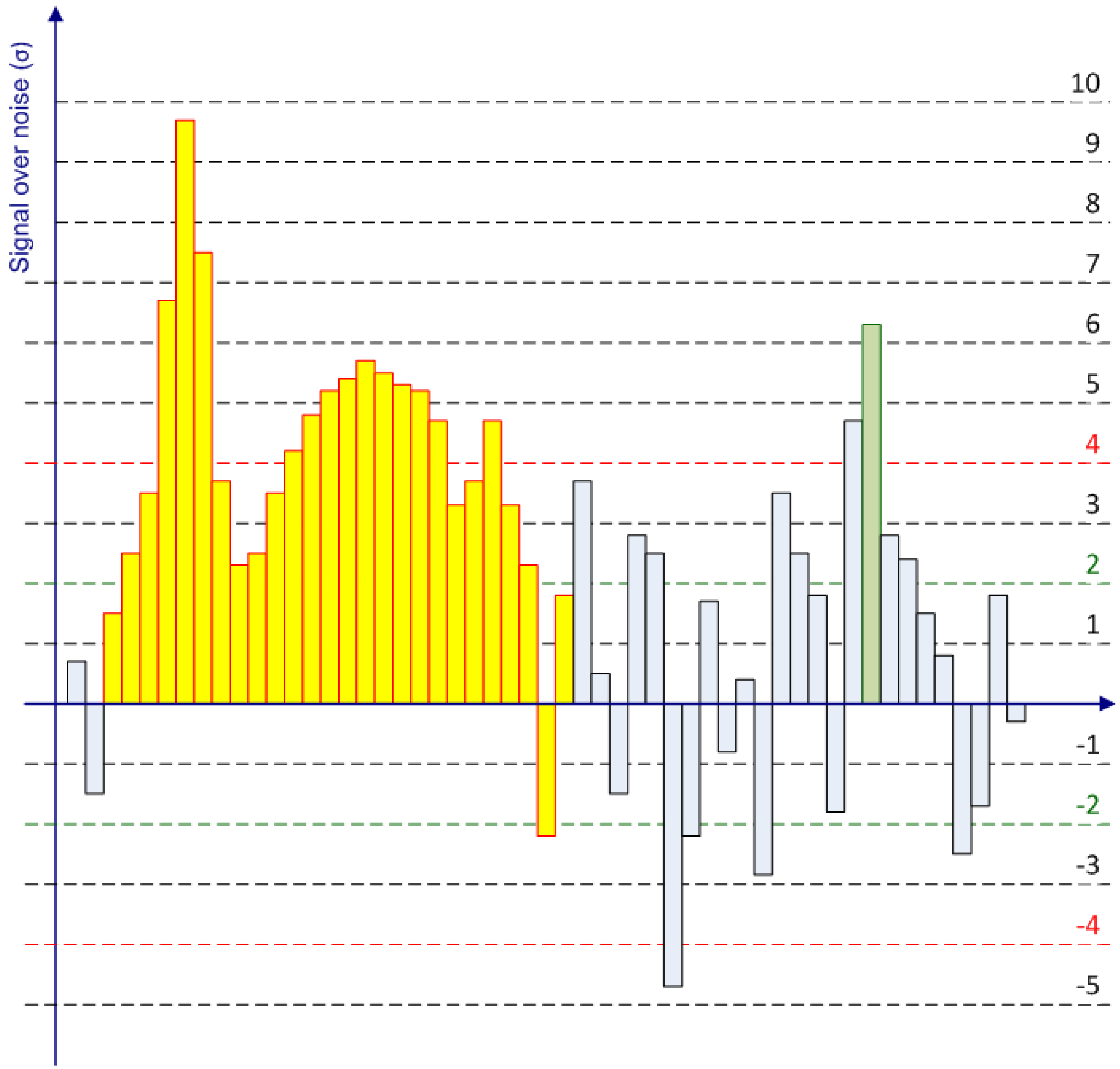


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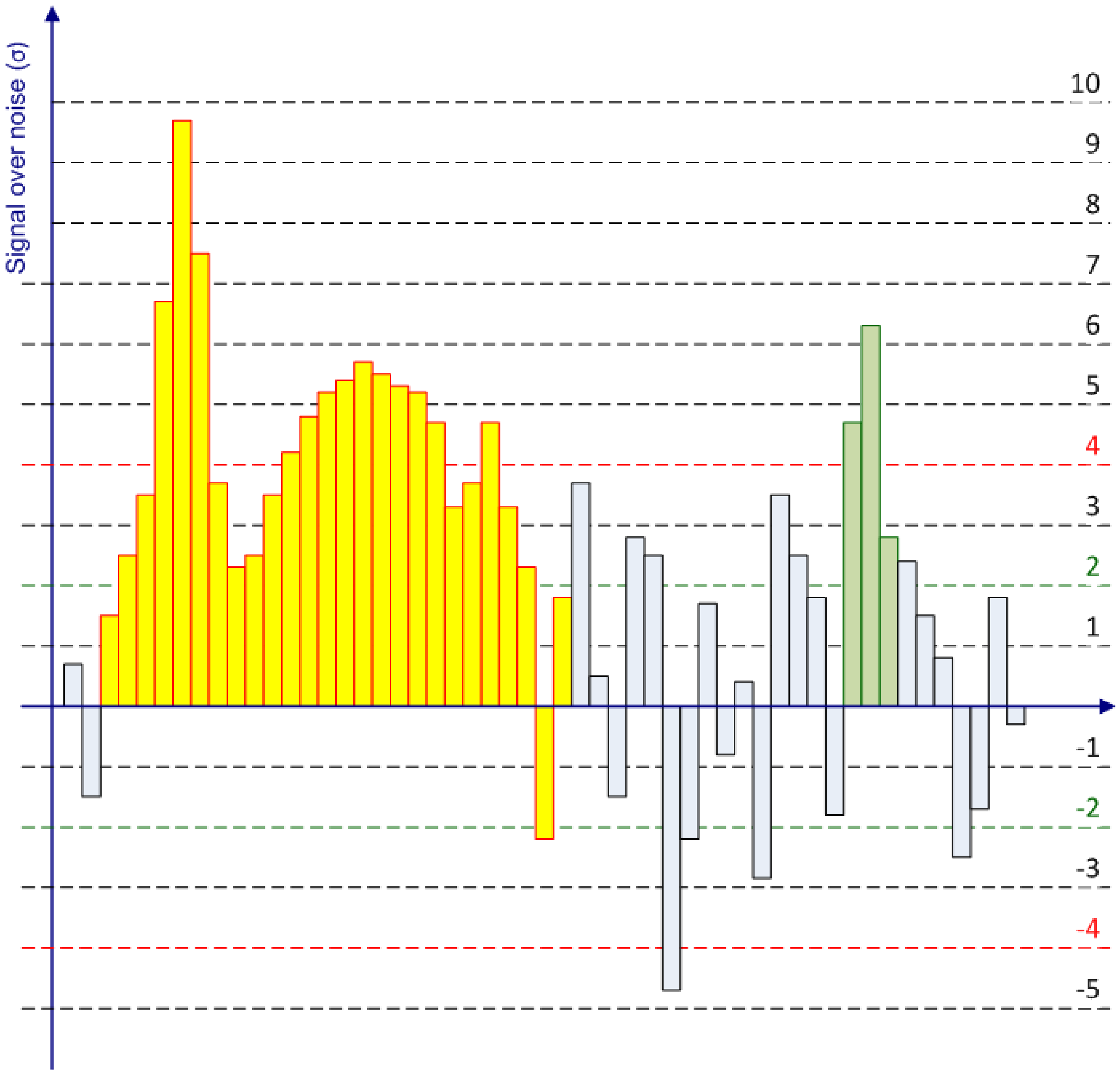

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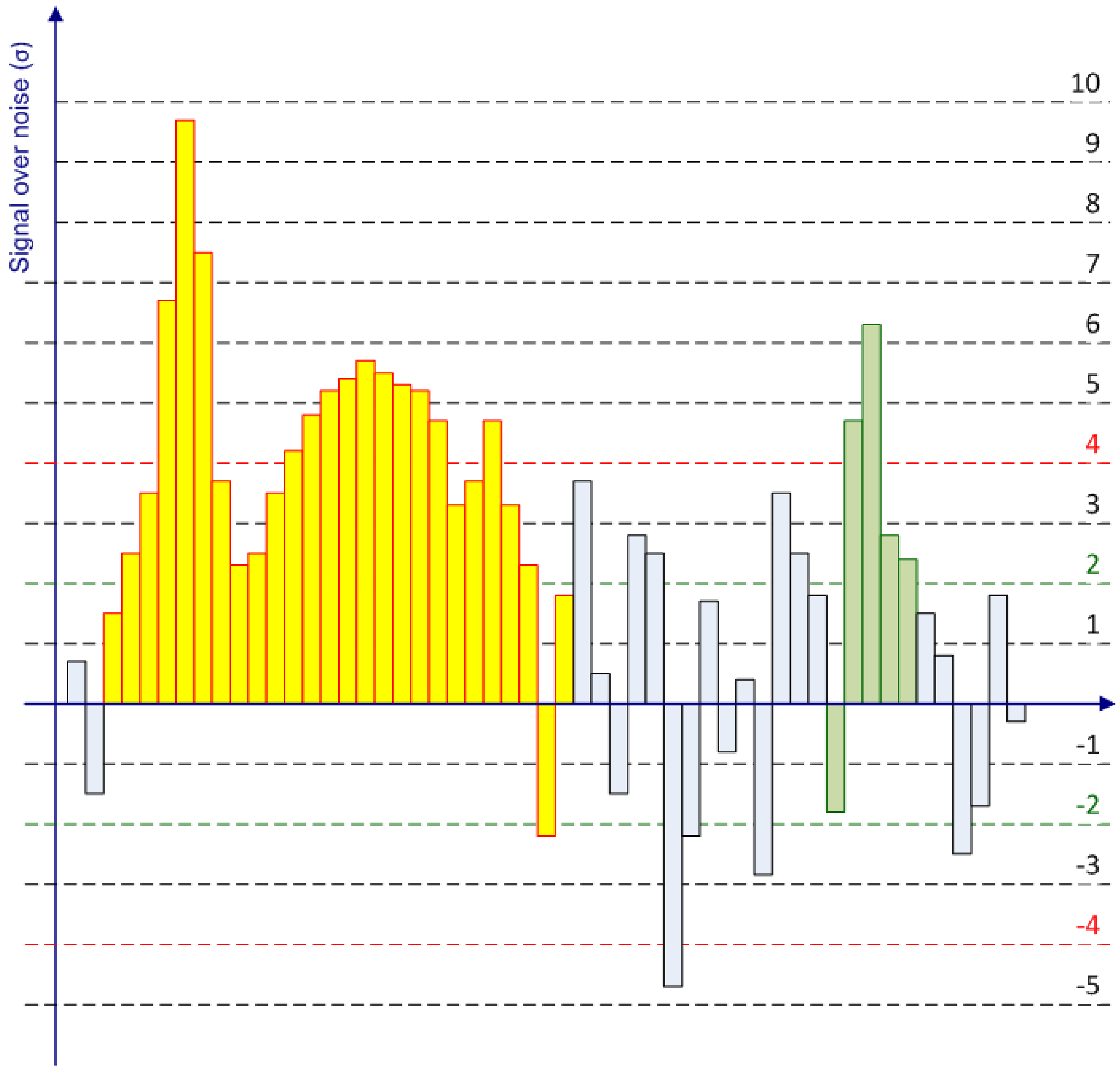

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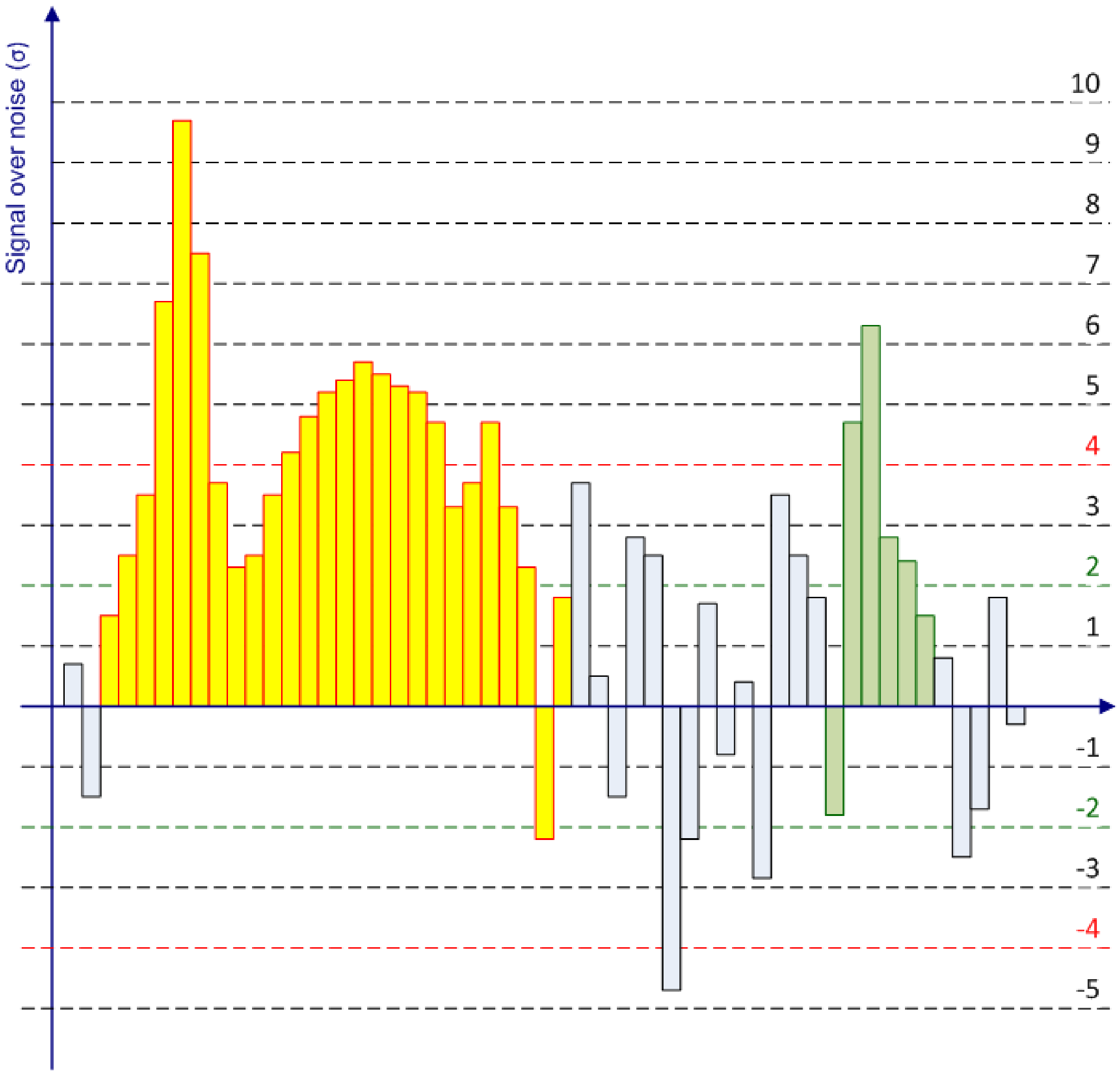

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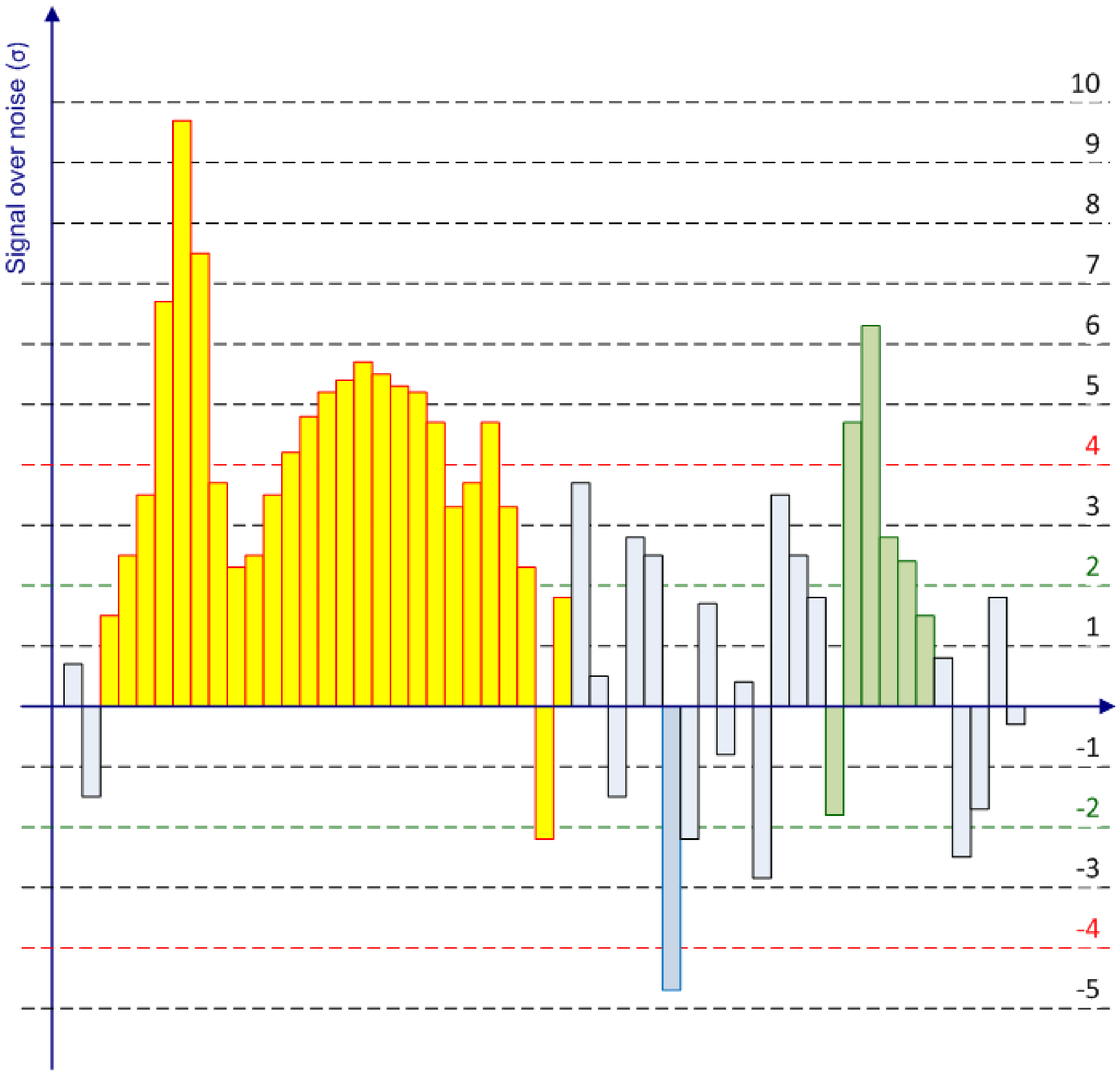


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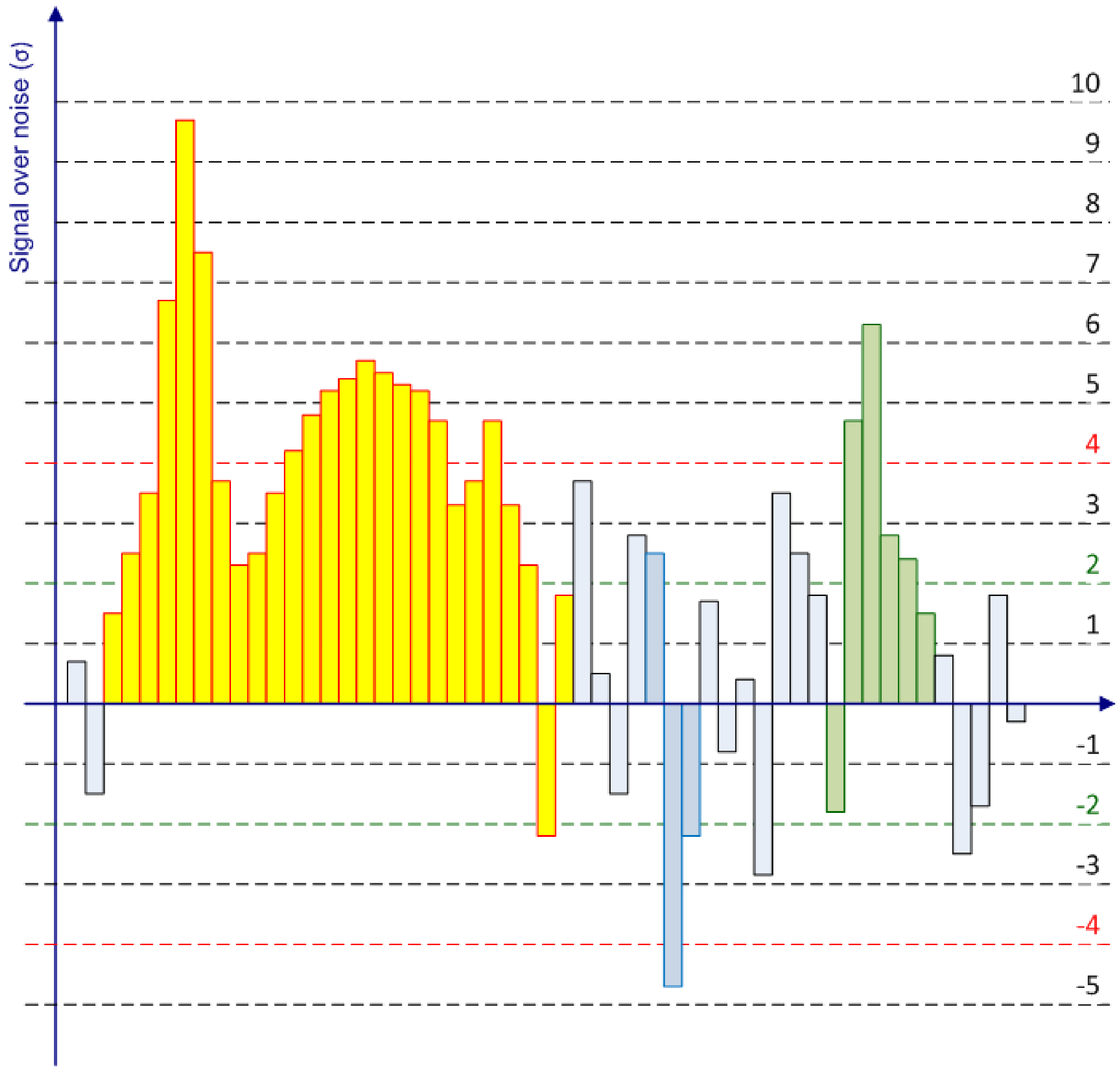


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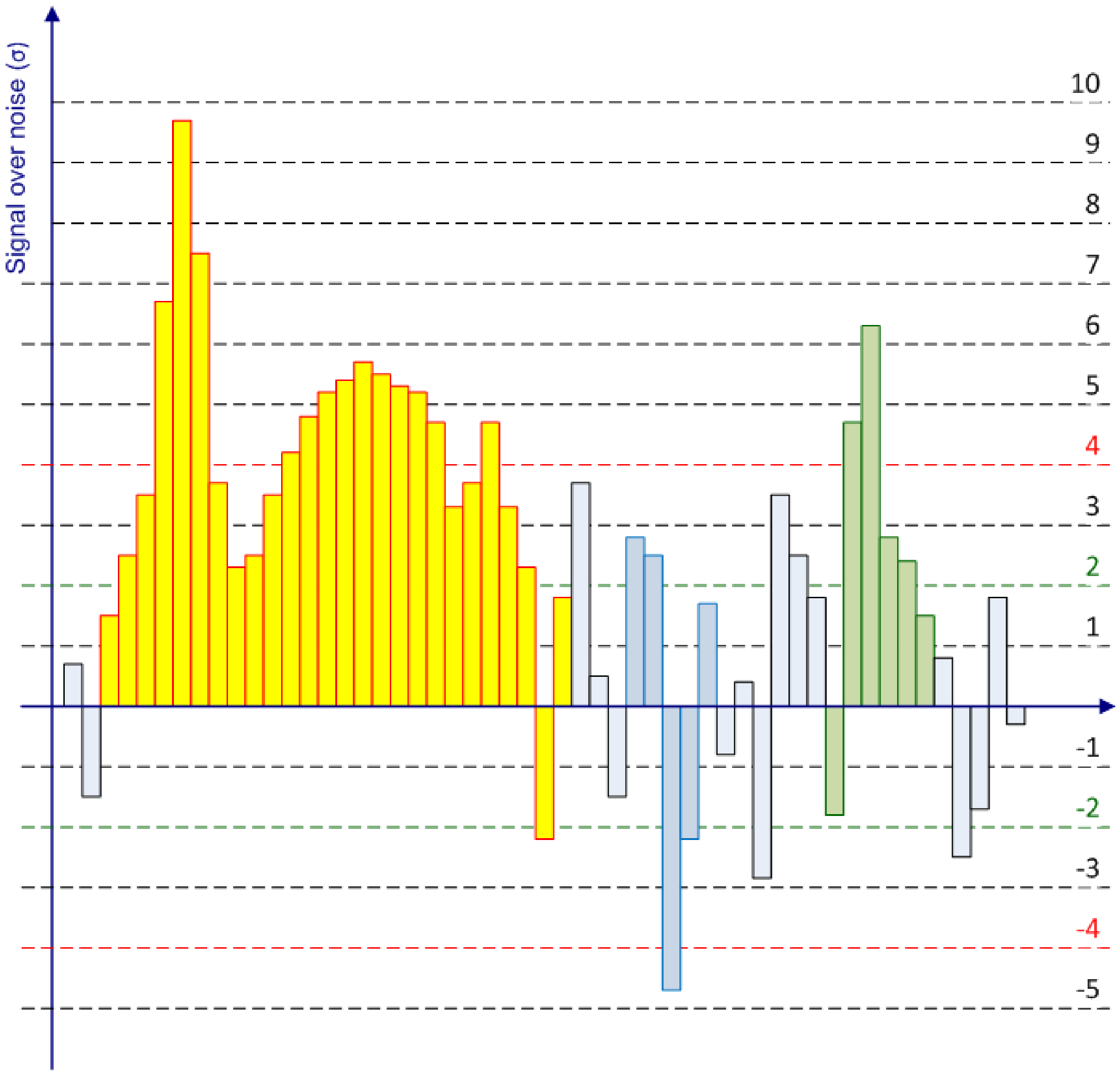


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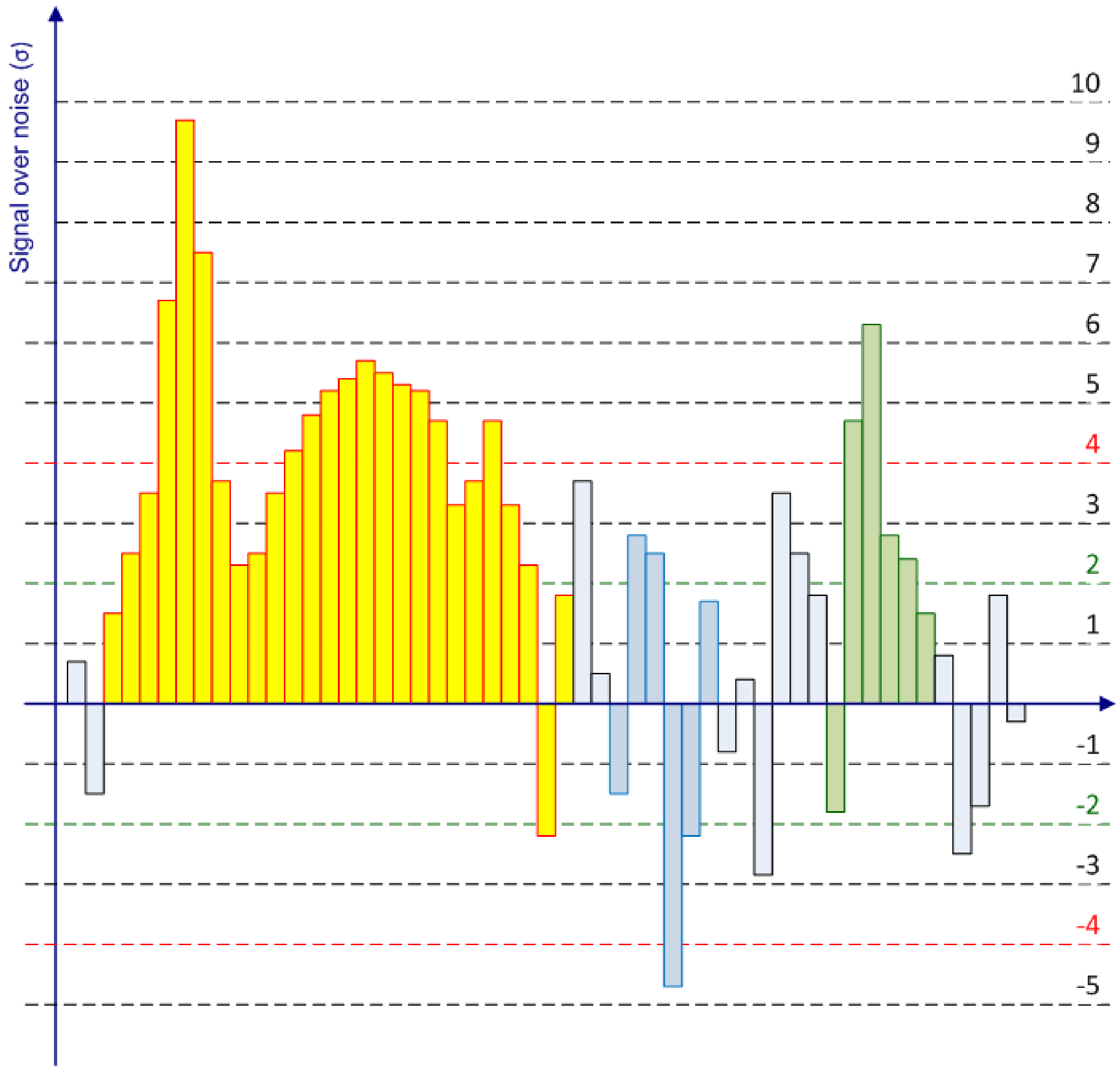


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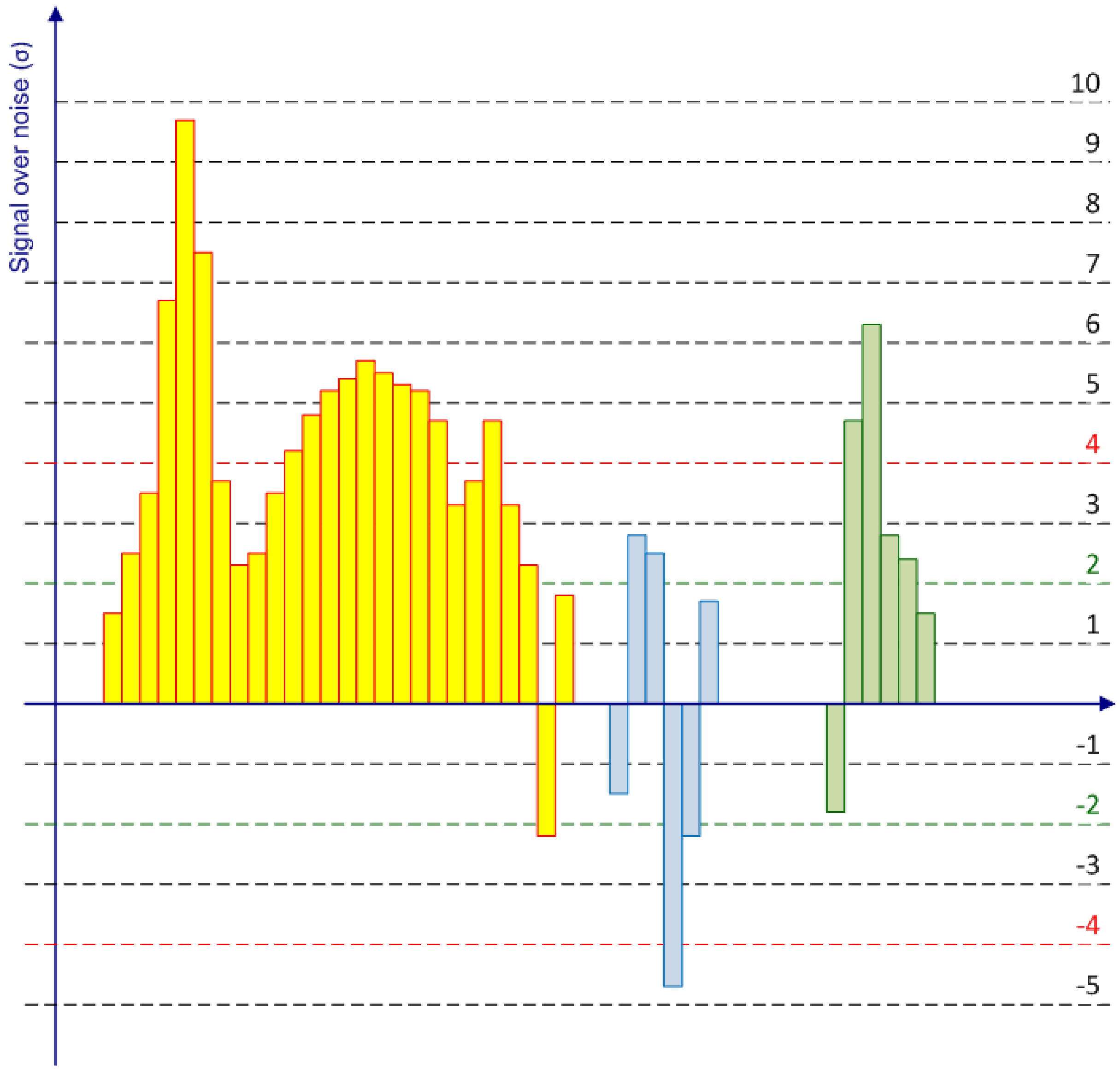


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# Effect Of Strict Nearest Neighbour Approach

**Large topologically connected regions in calorimeter can lead to large cell clusters**

- Lost particle flow structure can introduce problems for jets
  - Infrared safety, in particular
- Need to refine the clustering algorithm
  - Try to match single particle shower shapes better

**Splitting the clusters**

- Examine spatial cluster signal structure – find local signal maxima
  - "hill and valley" structural analysis in three dimensions
- Split cluster between two maxima
  - In three dimensions, of course!
- Share energy of cells in signal valleys
  - Needs sharing rules – introduces "geometrically" weighted cell energy contribution to cluster signal
- Introduces new tunable parameter
  - Local signal maximum threshold is defined in units of energy, not significance!

# Cluster Splitting

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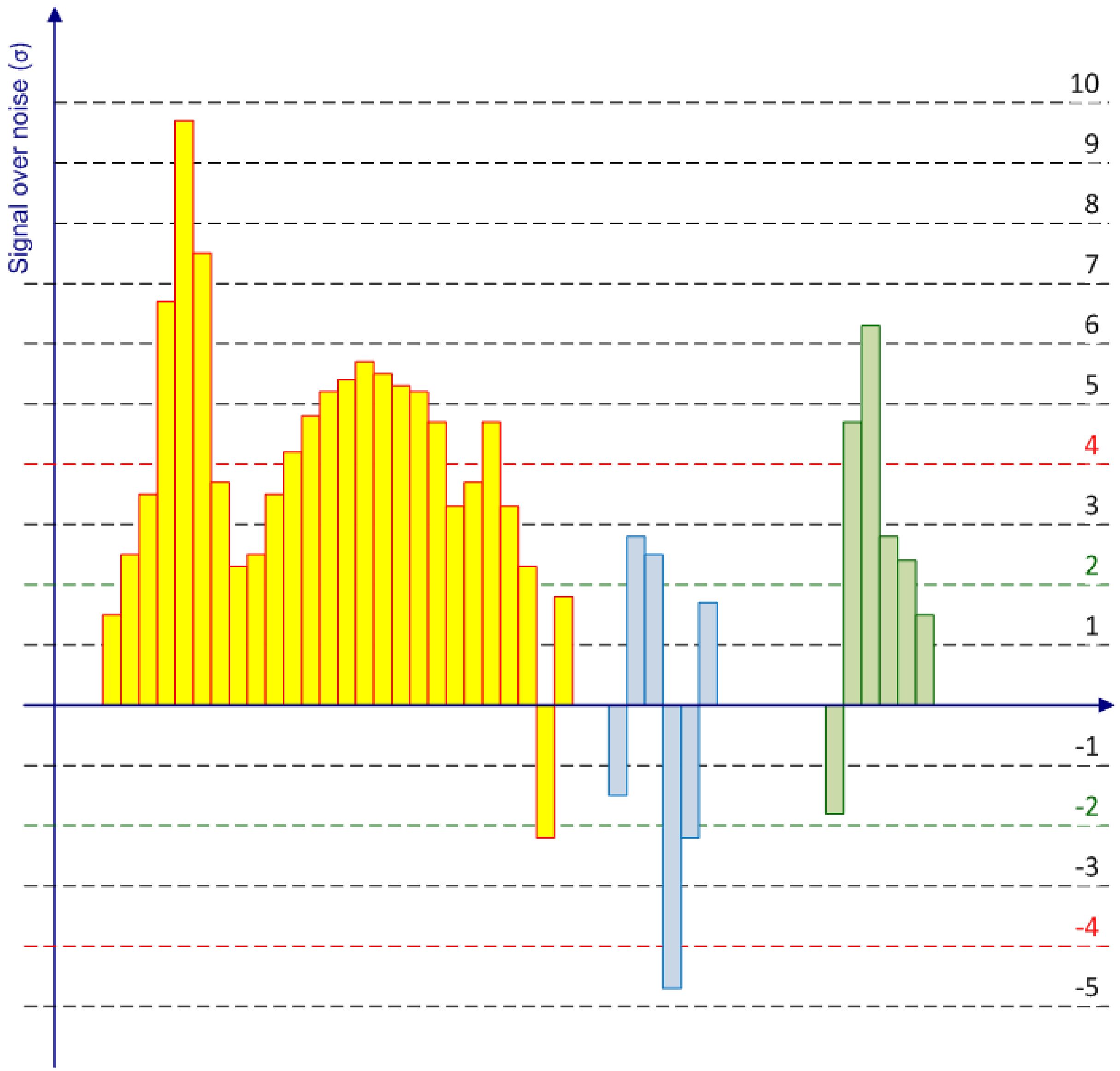

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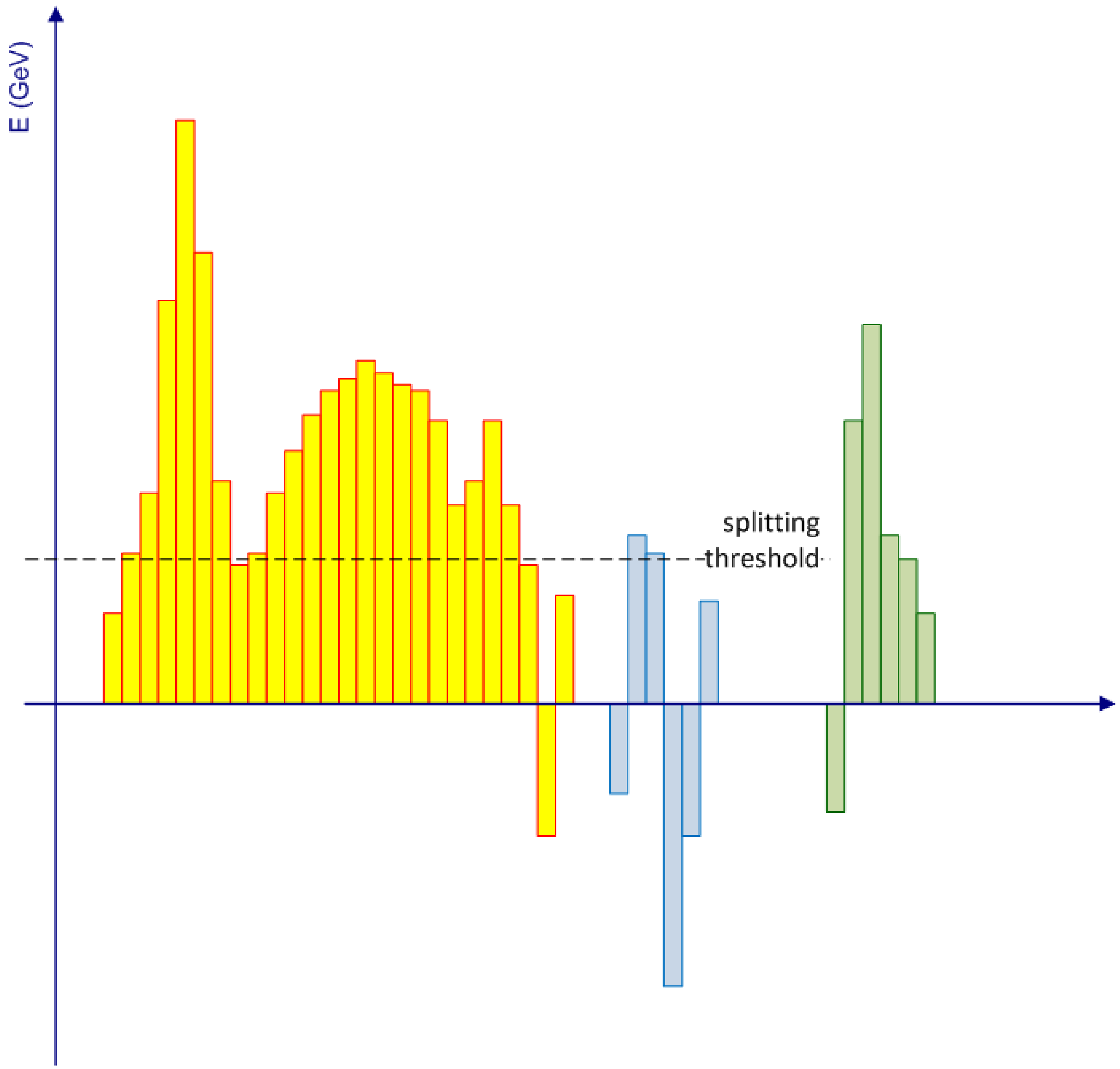

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# Cluster Splitting

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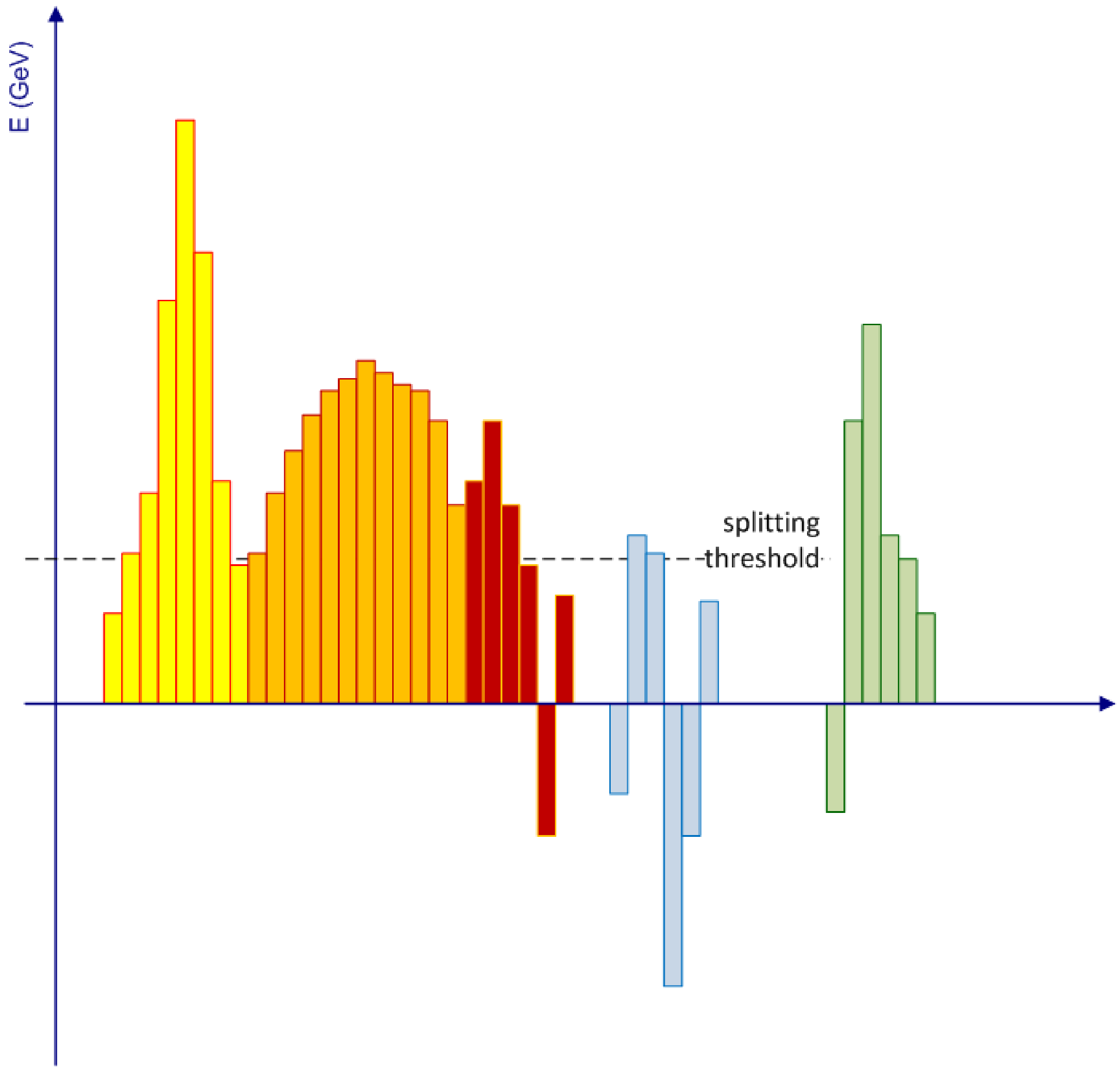


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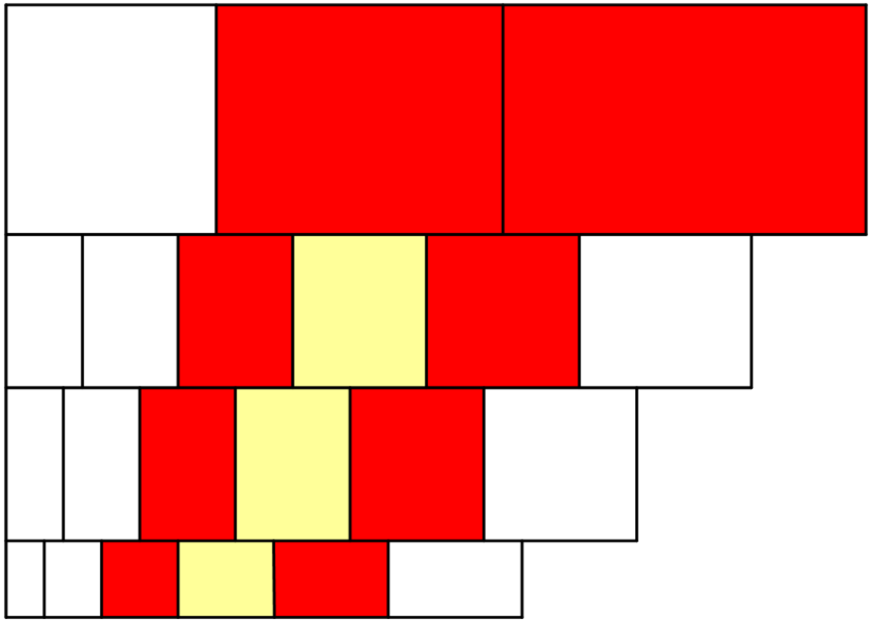
# Splitting & Cell Energy Sharing



## Splitting technique

- Guided by finest calorimeter granularity
  - Typically in electromagnetic calorimeter
- Allows to split larger cell signals without signal valley
  - Typically in hadronic calorimeters



# Splitting & Cell Energy Sharing

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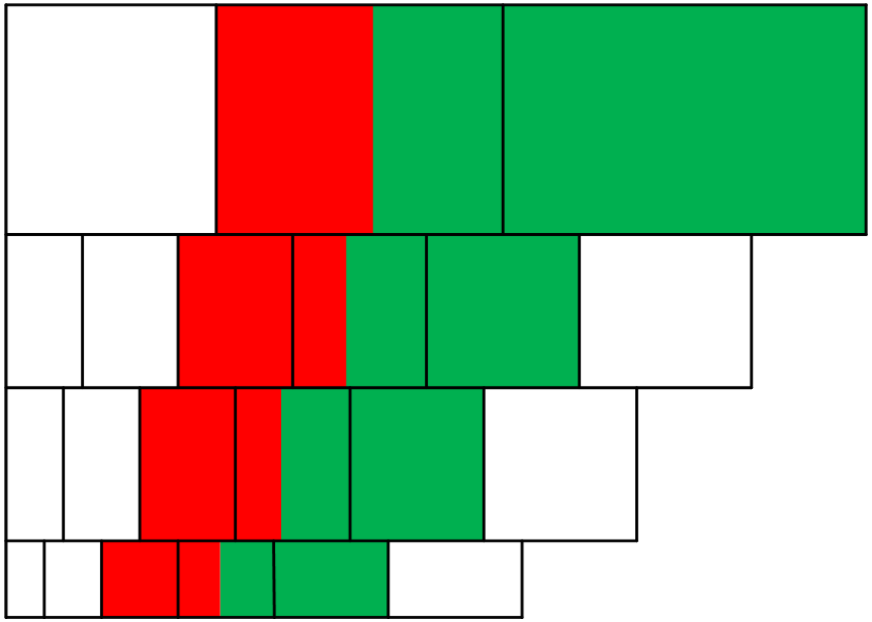

Rule for energy sharing (ATLAS example):

$$w_1 = \frac{E_1}{E_1 + rE_2}$$

$$w_2 = 1 - w_1$$

$$r = e^{d_1 - d_2}$$

($d_i$ is the distance of the cell from the centroid of cluster $i$)

Each cell can only appear in up to two clusters

# Cluster Shapes

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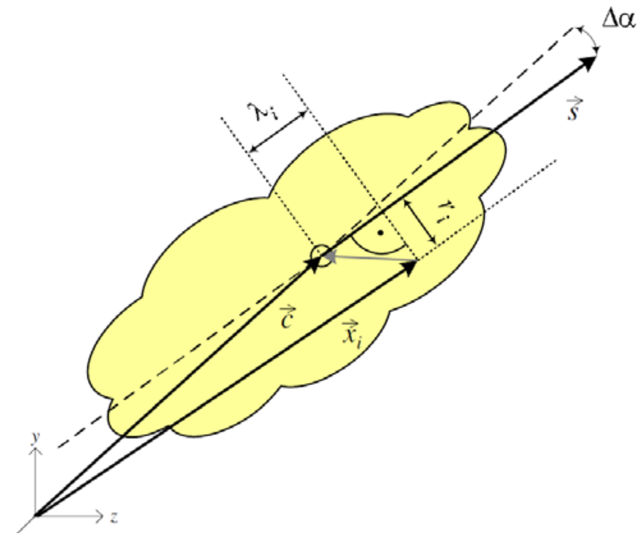
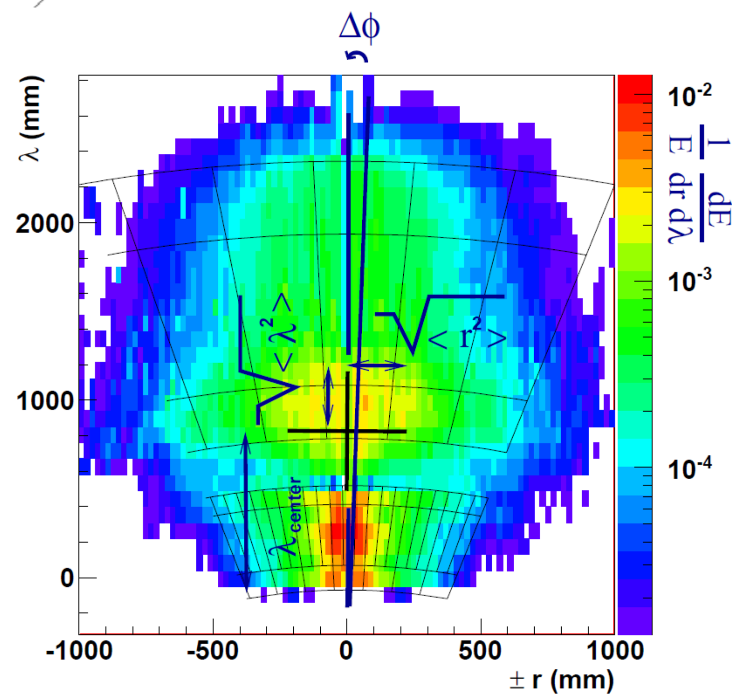
## Clusters have shapes

- Geometrical moments and sizes
  - Lateral and longitudinal
- Tilt of principal axis
  - With respect to direction extrapolation from primary vertex (magnetic field!)
- Density and compactness measures
  - Cluster energy distribution in cells
- Energy sharing between calorimeter segments and modules
  - Shower structures

## Useful for cluster calibration

- Exploit shape sensitivity to shower character
  - Hadronic versus electromagnetic



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# Cell Signal Significance Spectrum

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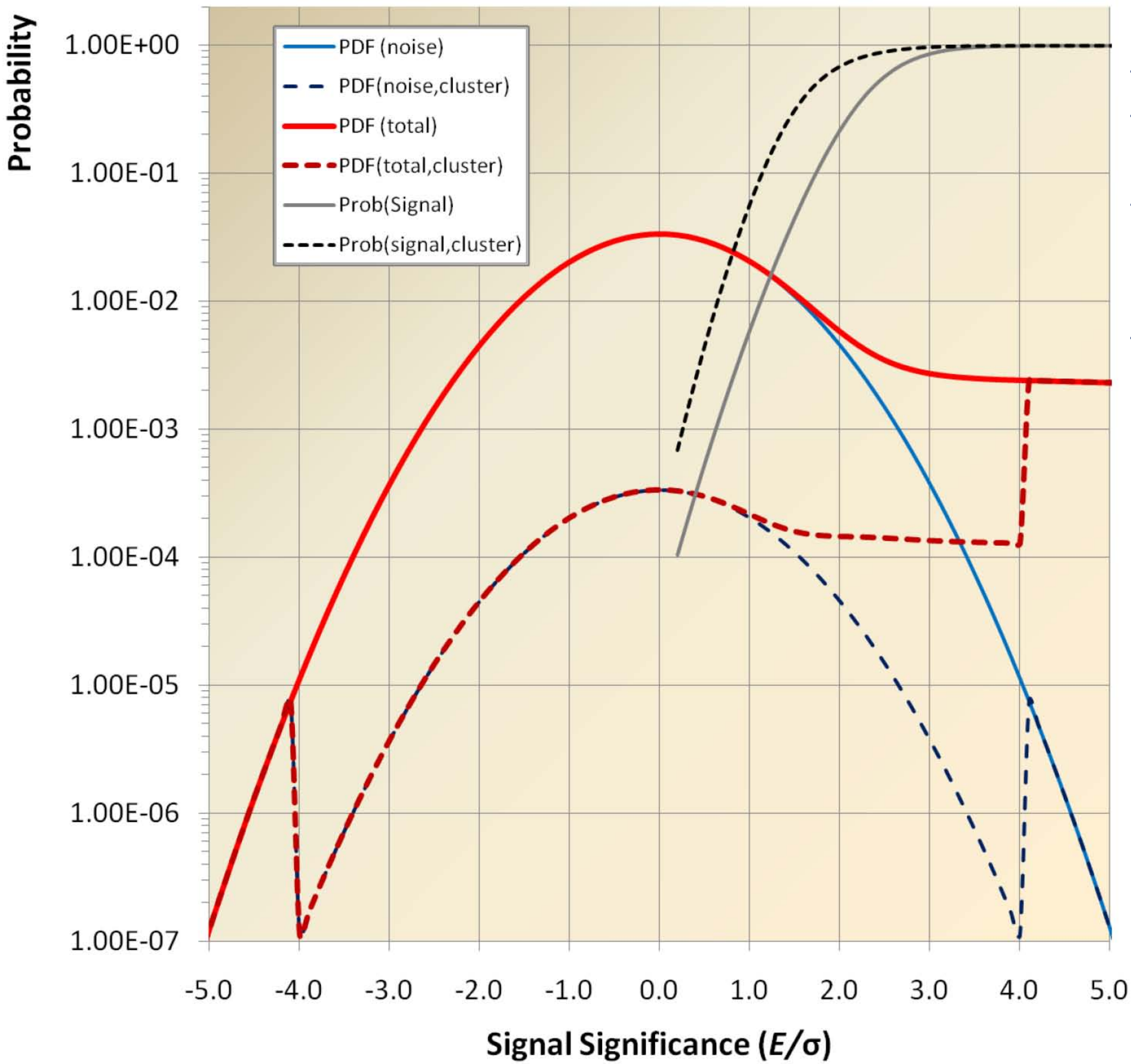


Modeled effect of topological clustering on the cell signal significance spectrum, for purposes of illustration here with only the primary (seed) threshold, no secondary (growth) threshold.

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# Cell Signal Significance Spectrum

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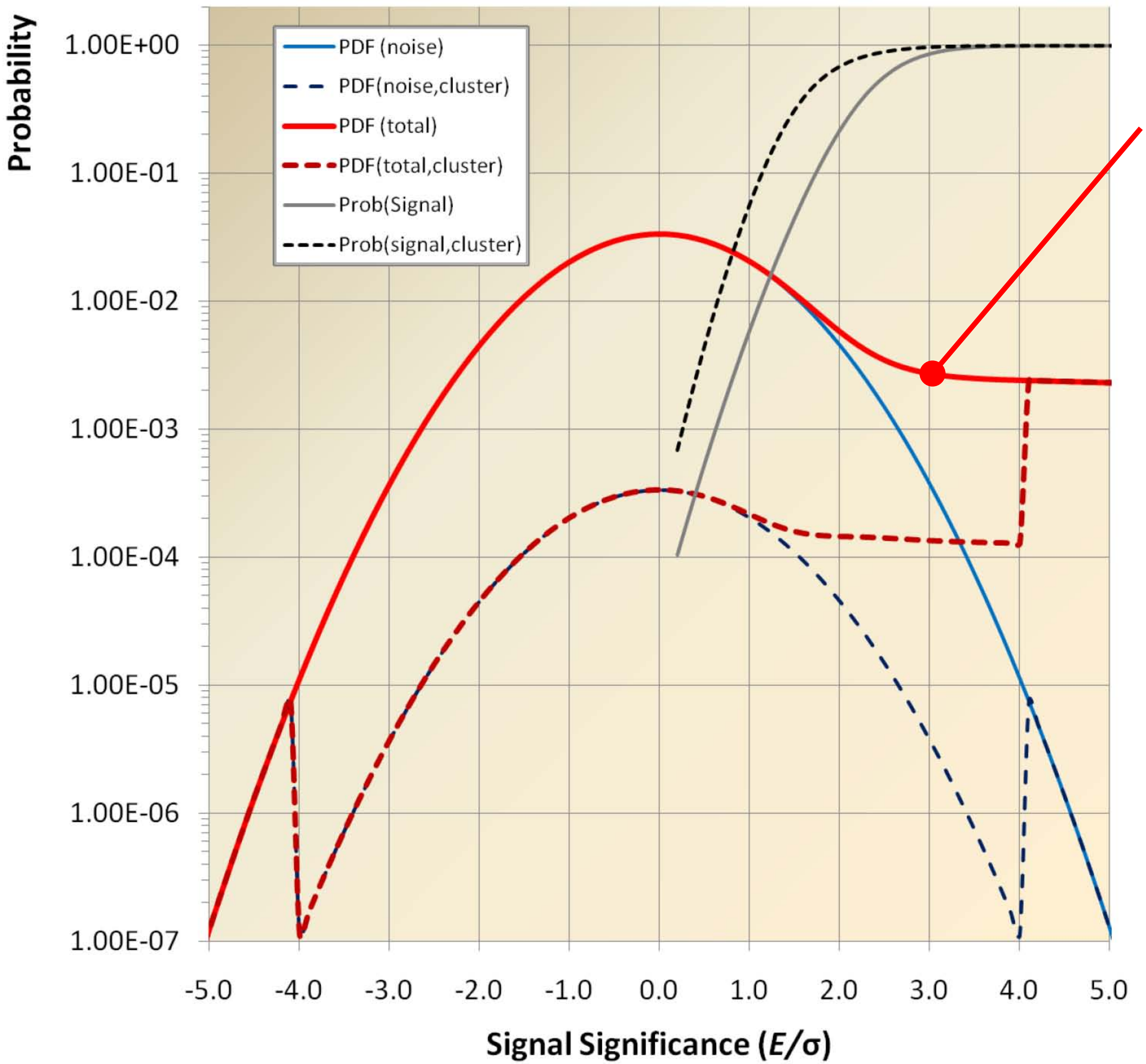


no clusters, cells with signal & noise

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# Cell Signal Significance Spectrum

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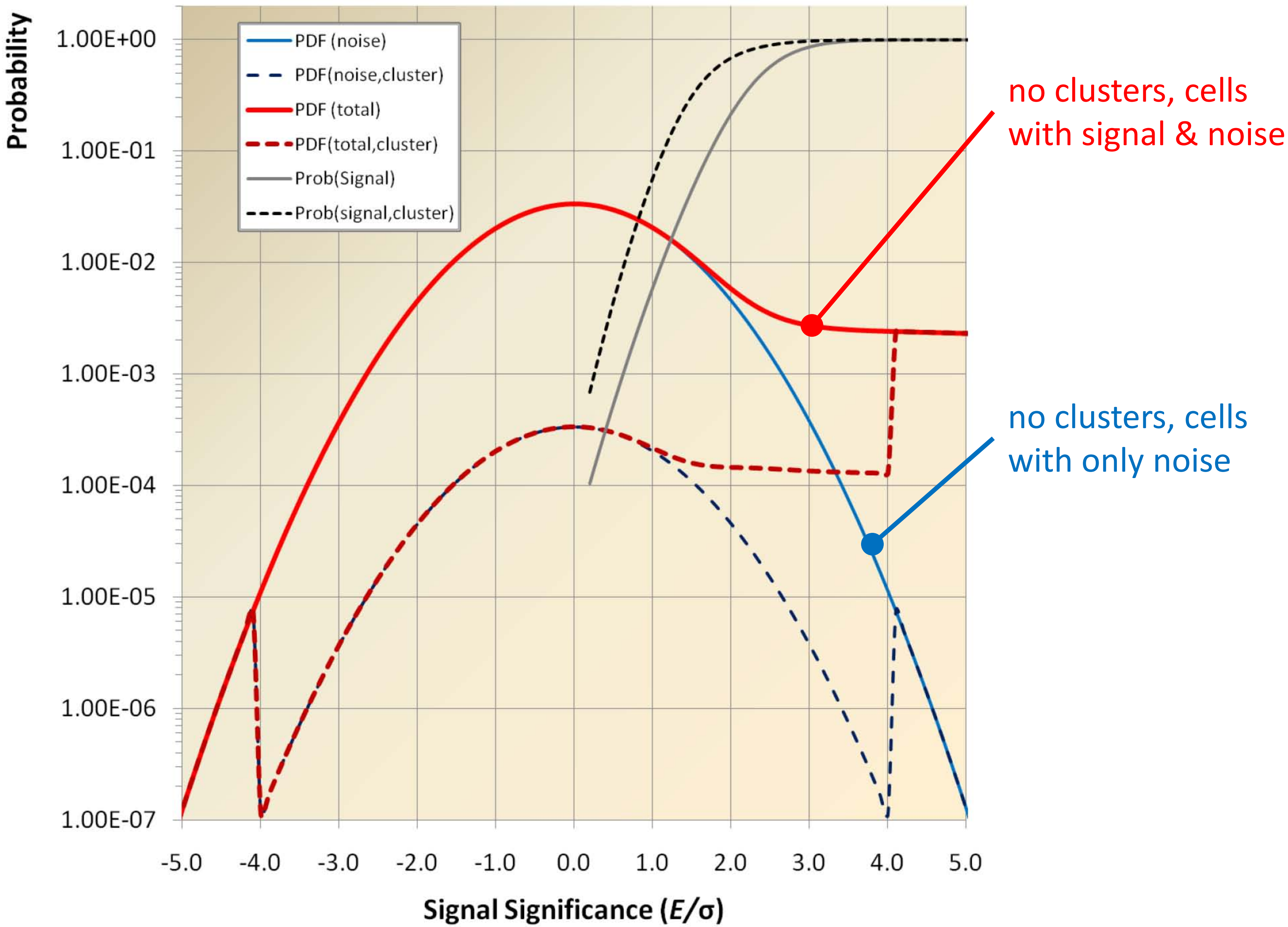

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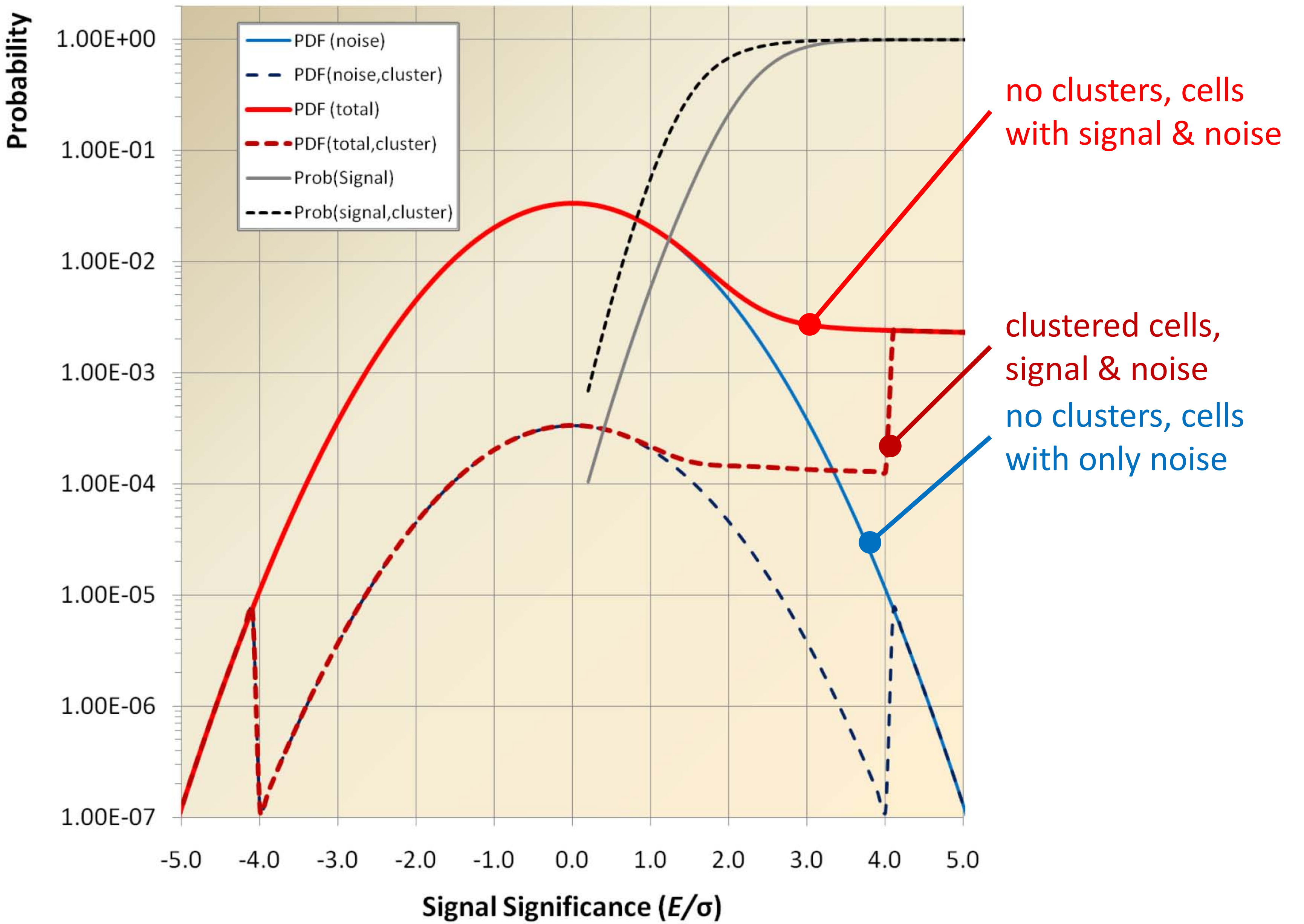
# Cell Signal Significance Spectrum

P. Loch
U of Arizona
April 6, 2010

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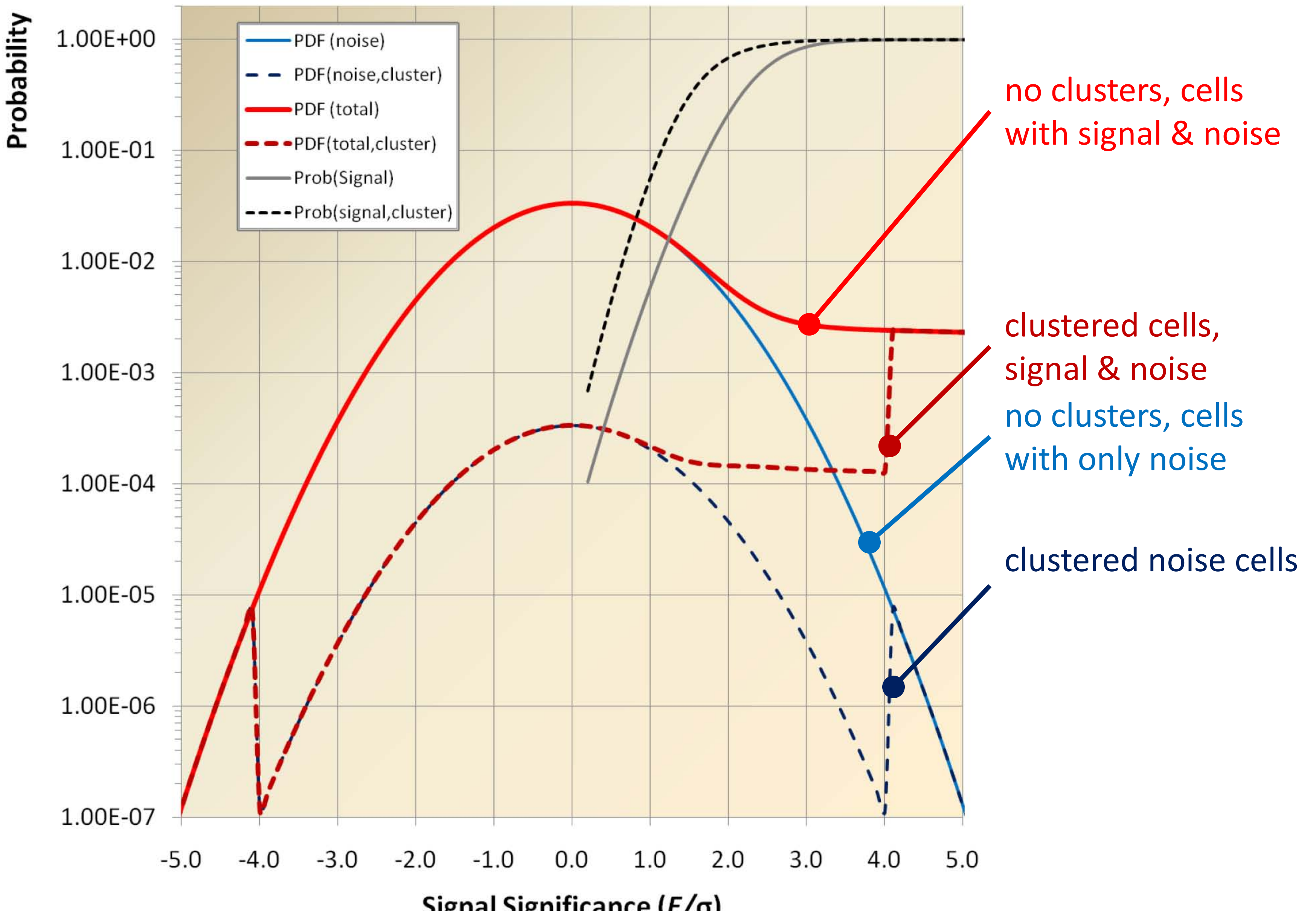

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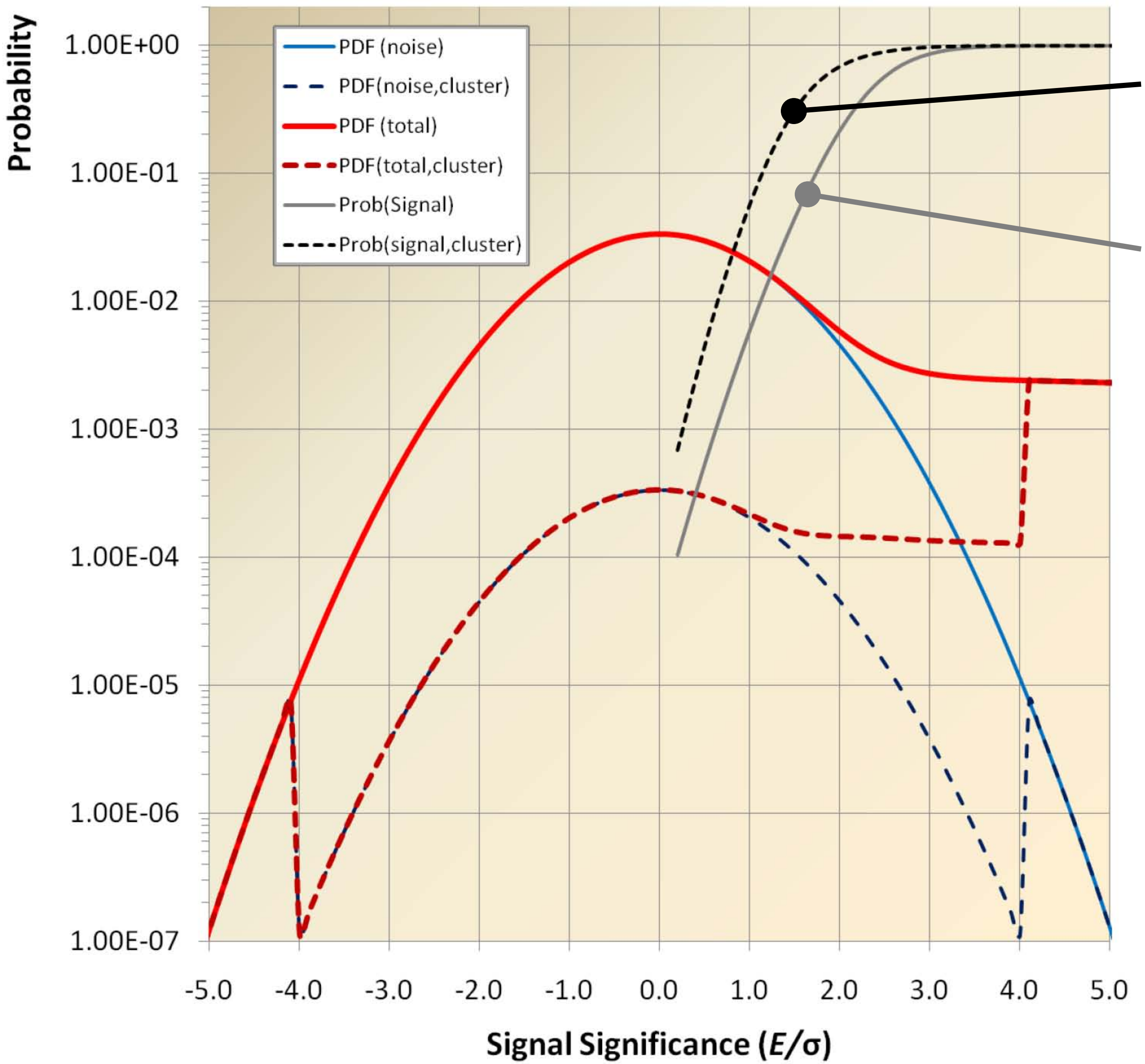


probability for "true" signal for clustered cells

probability for "true" signal for all cells

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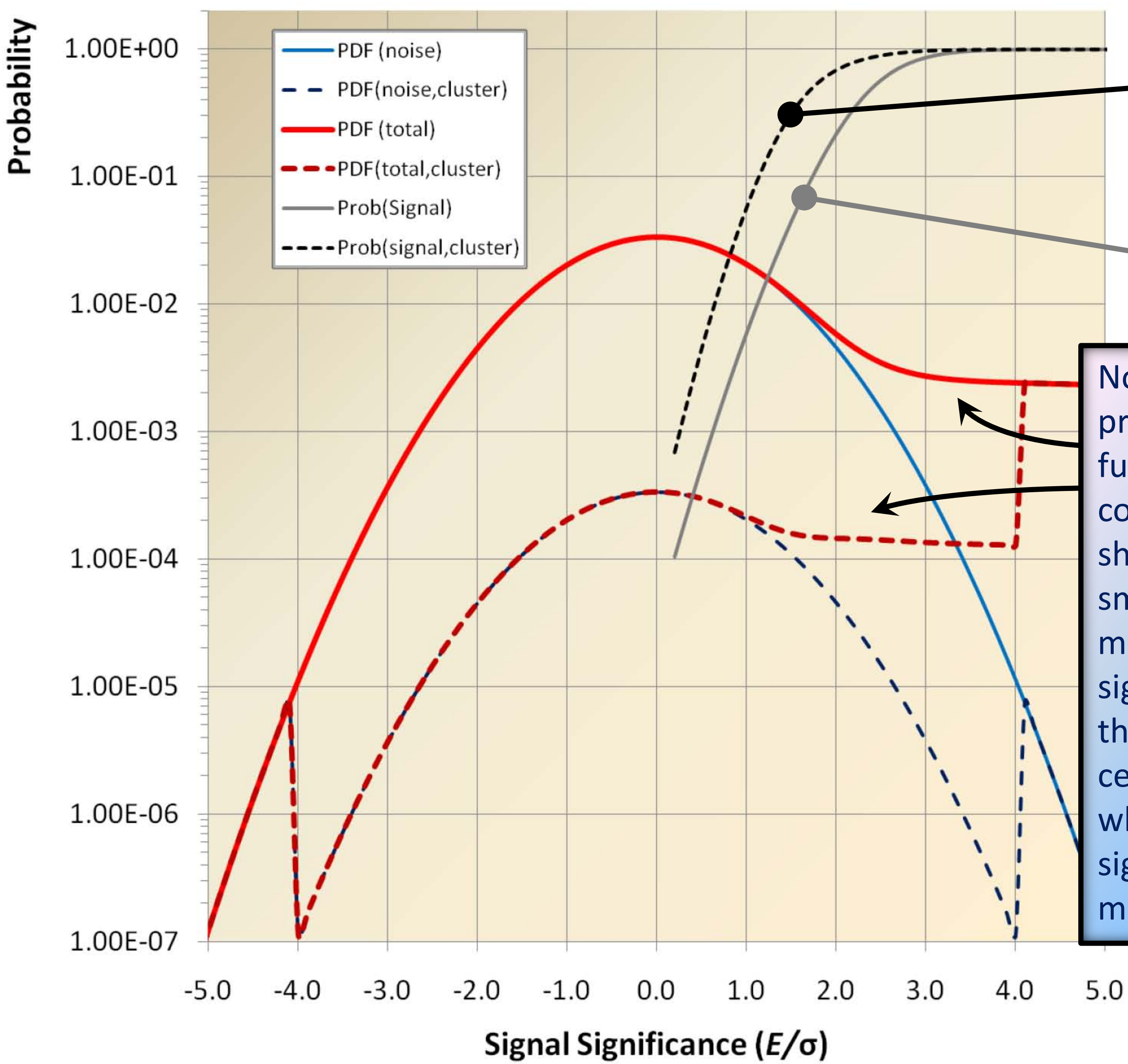


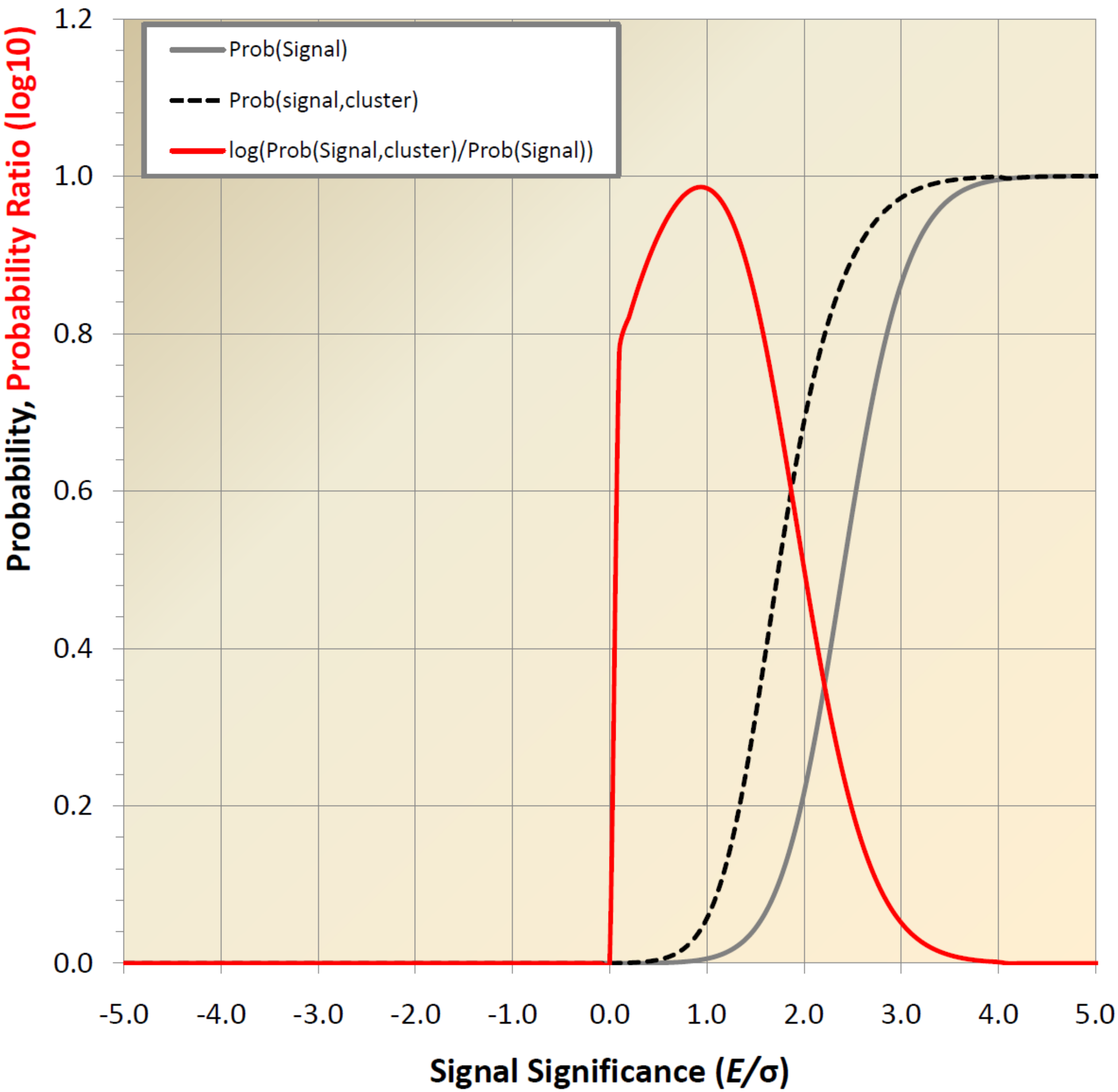

probability for “true” signal for clustered cells

probability for “true” signal for all cells

Note change of shape of probability density function due to correlations introduced by showering – clustered small signal cells have more likely some true signal because they are in the neighbor-hood of a cell with significant signal, while cells with the same signal from noise only are more often suppressed!

# Probably For Cell To Have True Signal






Significant boost of likelihood that small signals are generated by particles (rather than noise) in clustered cells!

# Cluster Kinematics



## Cluster signal

- Sum of clustered cell energies
  - Possibly with geometrical weight introduced by cluster splitting

## Cluster direction & location

- Barycenter in (η,φ) from energy weighted cell directions
  - Negative signal cells contribute with absolute of their signal
  - Small effect on direction of final cluster from particles – negative signals are noise, i.e. small!
- Consistent approach for direction calculation
  - Leaves true signal and noise clusters at the right direction
- Same approach for geometrical signal center
  - "center of gravity"

## Cluster four-momentum

- Massless pseudo-particle approach similar to tower
  - Consistent with cluster idea of reconstructing showers rather than particles

Total cluster signal:

(electromagnetic energy scale)

$$E_{0,\mathrm{cluster}} = \sum_{\text{clustered cells}} w_{\text{cell, cluster}} E_{0,\text{cell}}$$

(with $w_{\text{cell, cluster}} \neq 1$ only for cells shared between clusters)

Direction and location:

$$\eta_{\text{cluster}} = \frac{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\text{cell}}\right| \eta_{\text{cell}}}{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\text{cell}}\right|}$$

$$\varphi_{\text{cluster}} = \frac{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\text{cell}}\right| \varphi_{\text{cell}}}{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\text{cell}}\right|}$$

$$\left(x_{\text{cluster}}, y_{\text{cluster}}, z_{\text{cluster}}\right) = \frac{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\text{cell}}\right| \left(x_{\text{cell}}, y_{\text{cell}}, z_{\text{cell}}\right)}{\sum_{\text{clustered cells}} w_{\text{cell, cluster}} \left|E_{0,\text{cell}}\right|}$$

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Cluster four-momentum

(electromagnetic energy scale)

$$\left(E_{\text{cluster}},\vec{p}_{\text{cluster}}\right) = E_{0,\text{cluster}} \begin{pmatrix} 1 \\ \cos\varphi_{\text{cluster}}/\sinh\eta_{\text{cluster}} \\ \sin\varphi_{\text{cluster}}/\sinh\eta_{\text{cluster}} \\ \tanh\eta_{\text{cluster}} \end{pmatrix}$$

with:

$$E_{\text{cluster}} = \left|\vec{p}_{\text{cluster}}\right| = p_{\text{cluster}}$$

# Cluster Features



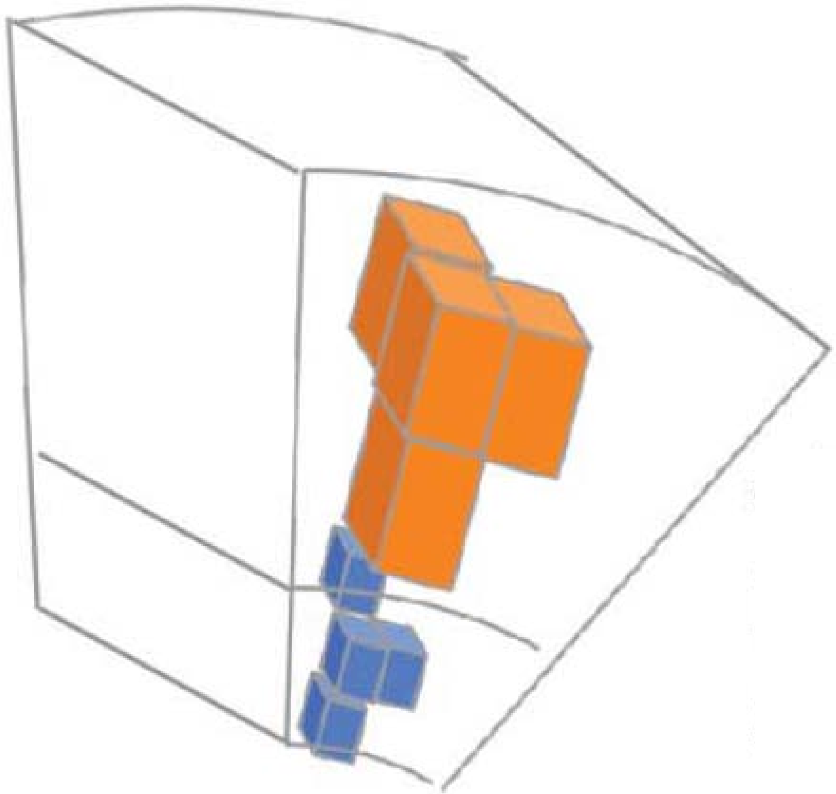
## Signal integration

- Clusters sum cell signals without grid
  - 3-dimensional signal objects
  - Can include partial and complete signals from several particles
- Clusters preserve some detailed signal features
  - Associated information to be collected at cluster formation
  - E.g., energy sharing in electromagnetic and hadronic calorimeters
  - Longitudinal signal center of gravity
  - Shapes

## Signal splitting

- Topological clusters need splitting algorithm
  - Cannot follow individual showers perfectly in jet environments
  - Can cause problems with infrared safety
- Few problems with seed and energy leakage
  - Can include energy from cells even outside of jet cone

(drawing by K. Perez, Columbia University)



Topological cell cluster is a "blob" of energy dynamically located inside the calorimeter (even crossing sub-detector boundaries)

# Noise Suppressed Tower Signals



## Signal formation

- Fill towers with cells from topological clusters
  - These survived noise suppression
- Same energy collection as unbiased towers

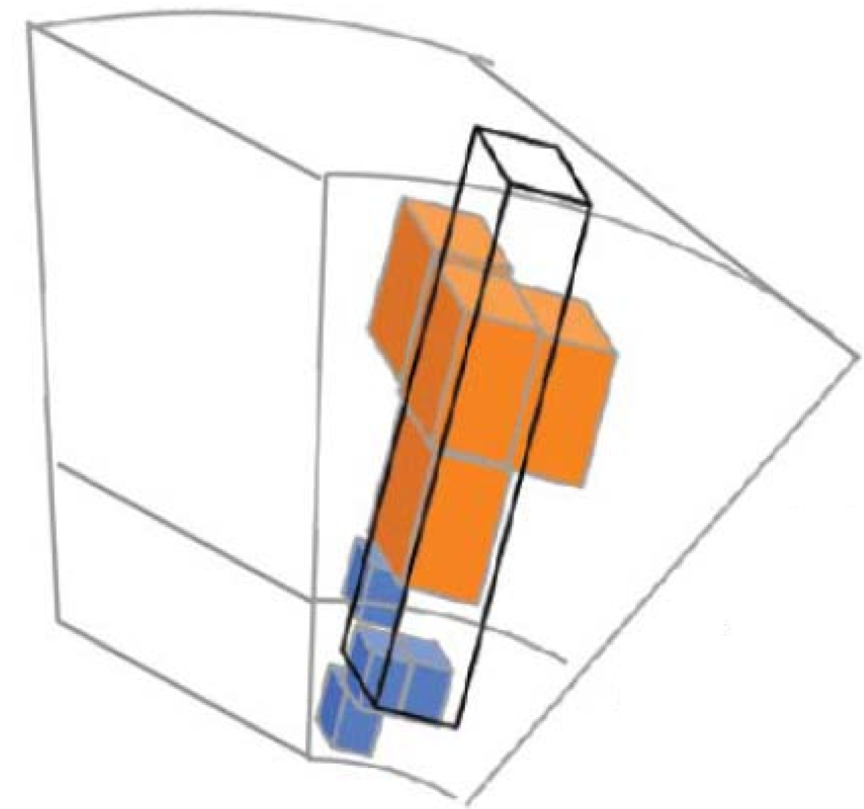
## Signal integration

- Sum cell signals on tower grid
  - 2-dimensional signal objects
  - Can include partial and complete signals from several particles
- Same additional signal features as unbiased towers
  - Associated information to be collected at tower formation
  - E.g., energy sharing in electromagnetic and hadronic calorimeters
  - Longitudinal signal center of gravity

## Signal splitting

- Can split showers, have problems with seeds, and cell energy "leakage"
  - Same problems as unbiased tower
- Applies regular geometrical splitting
  - Transverse energy flow motivated energy distribution
  - Avoid splitting threshold parameter

(drawing by K. Perez, Columbia University)



**Noise suppressed towers are sparsely populated slabs of energy in a regular pseudorapidity-azimuth grid (each tower covers the same area in these coordinates)**