On the detection of nuclearite events with Mini-EUSO experiment

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Framework

We simulate nuclearite events using the De Rujula model

- **Constant density**
  Strange matter is assumed to have the same density as nuclear matter

  $\rho_N = 3.6 \times 10^{14}\,\mathrm{g\,cm^{-3}}$

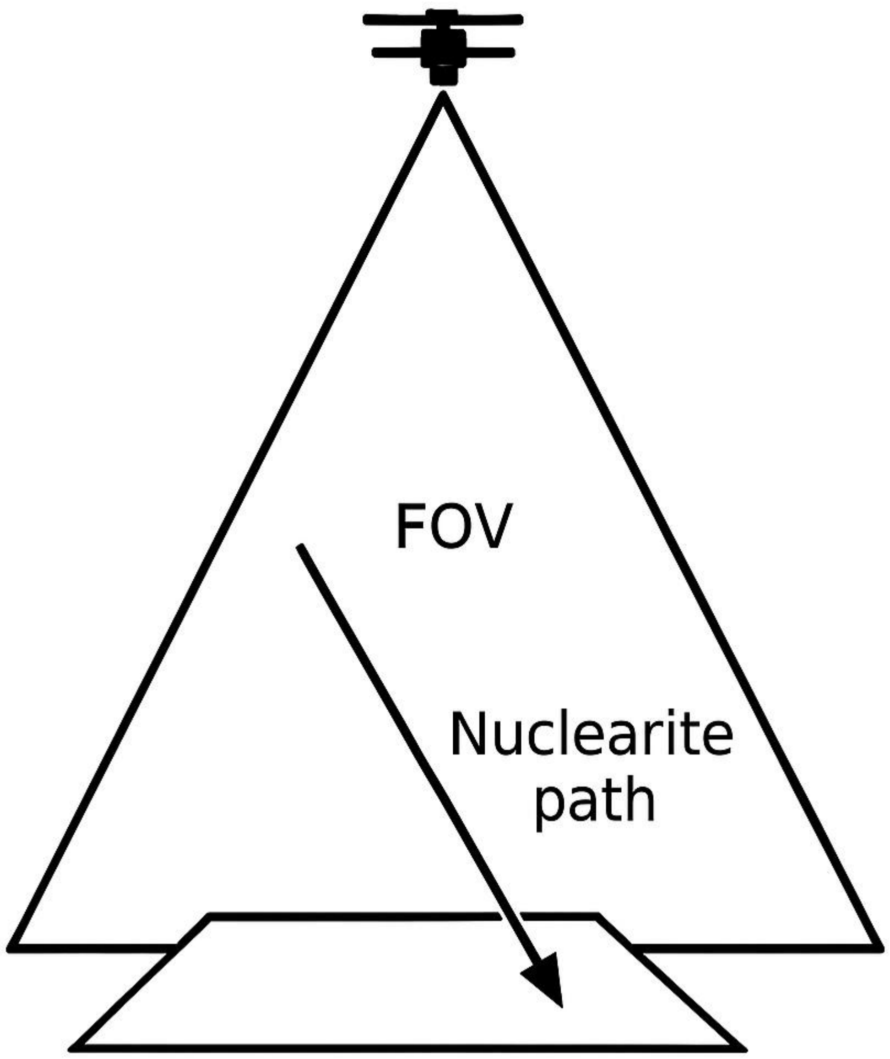
- **Energy-loss mechanism**
  The only dissipation channel is elastic or quasi-elastic scattering with air molecules. A fraction of the energy lost in each collision is converted into light emission.

- **Geometric cross section**

$$\sigma = \begin{cases} \pi\left(\dfrac{3\,M}{4\,\pi\,\rho_N}\right)^{\frac{2}{3}}, & M \geq 1.5\,\mathrm{ng}, \\ \pi \times 10^{-16}\,\mathrm{cm}^2, & M < 1.5\,\mathrm{ng}. \end{cases}$$

- **Quasi-elastic “bolide” scattering**
  The nuclearite is small enough that it does not form an air shell: air molecules interact only with its surface, the thermal velocity of the air is negligible, and the object continues along its path with exponential deceleration.

Velocity distribution	$f(v) = (\pi\, v_{\mathrm{vir}}^2)^{-3/2}\, 4\pi v^2\, \exp\!\big[-(v/v_{\mathrm{vir}})^2\big], \quad v_{\mathrm{vir}} \simeq 250\ \mathrm{km\,s^{-1}}$
Interaction with atmosphere	$\frac{dE}{dx} = -\,\sigma\, \rho_{\mathrm{atm}}\, v^2$
Velocity loss	$v(L) = v_0\, \exp\!\Big[-\frac{\sigma}{M} \int_0^L \rho_{\mathrm{atm}}(x)\, dx\Big]$
Apparent magnitude	$M_{\mathrm{app}} = 2.5\, \ln\!\Big[3.31 \times 10^{11} \left(\frac{1\,\mathrm{km/s}}{v}\right)^3\Big] - 1.67\, \ln\!\Big(\frac{M}{1\,\mu\mathrm{g}}\Big) + 5\, \ln\!\Big(\frac{h}{10\,\mathrm{km}}\Big)$
Minimum mass for emission	$M_{\min} = 122.5 \left(\frac{1\,\mathrm{km/s}}{v}\right)^3\ \mathrm{g}$
Minimum velocity for emission	$v_{\min} = 1\,\mathrm{km/s} \left(\frac{122.5\,\mathrm{g}}{M}\right)^{1/3}$
Maximum emission height	$h_{\max} = 3.3\,\mathrm{km}\ \ln\!\Big[\frac{M}{122.5\,(\frac{1\,\mathrm{km/s}}{v})^3\,\mathrm{g}}\Big]$



Simulation logic – key steps

- **Selection of a valid (M,v)**

  Velocity from galactic Maxwellian distribution f(v), with v mean 250 km/s
  Velocity and mass compatible with the emission condition

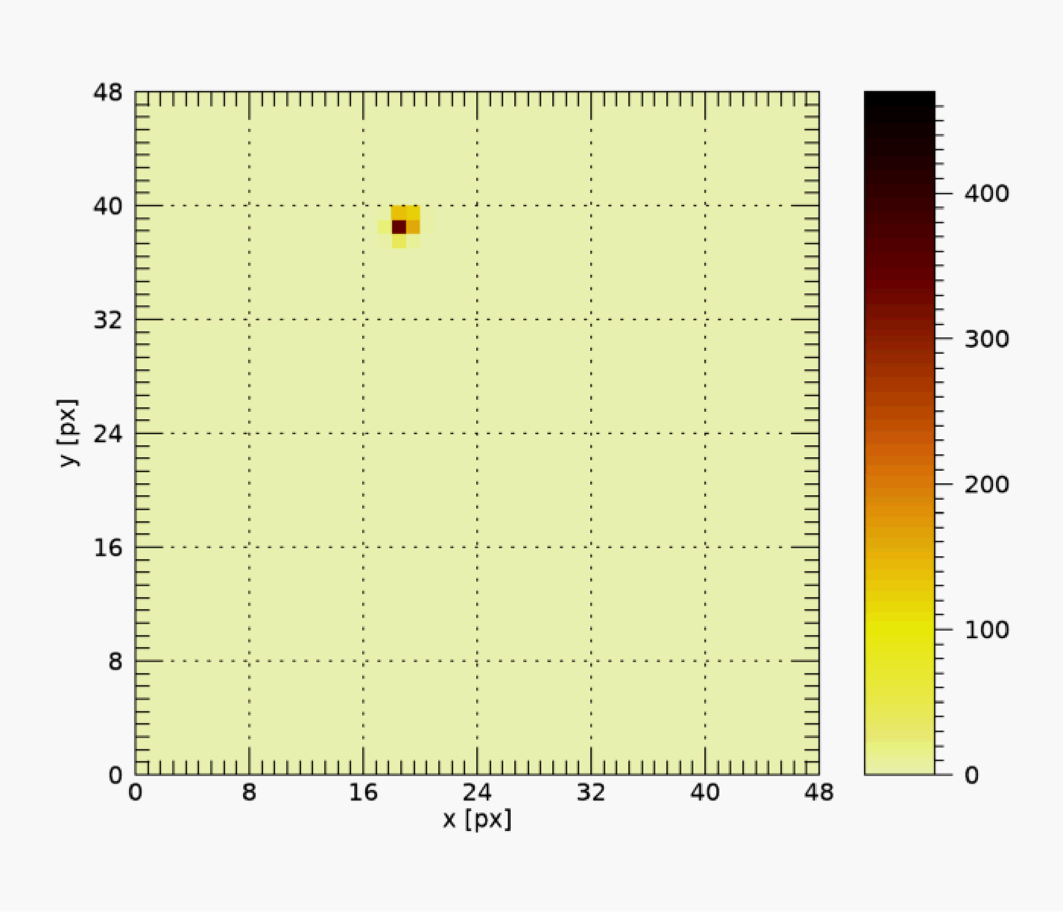
- **Maximum emission height**
  Analytical calculation to delineate the volume of atmosphere in which the nuclearite can actually emit light.

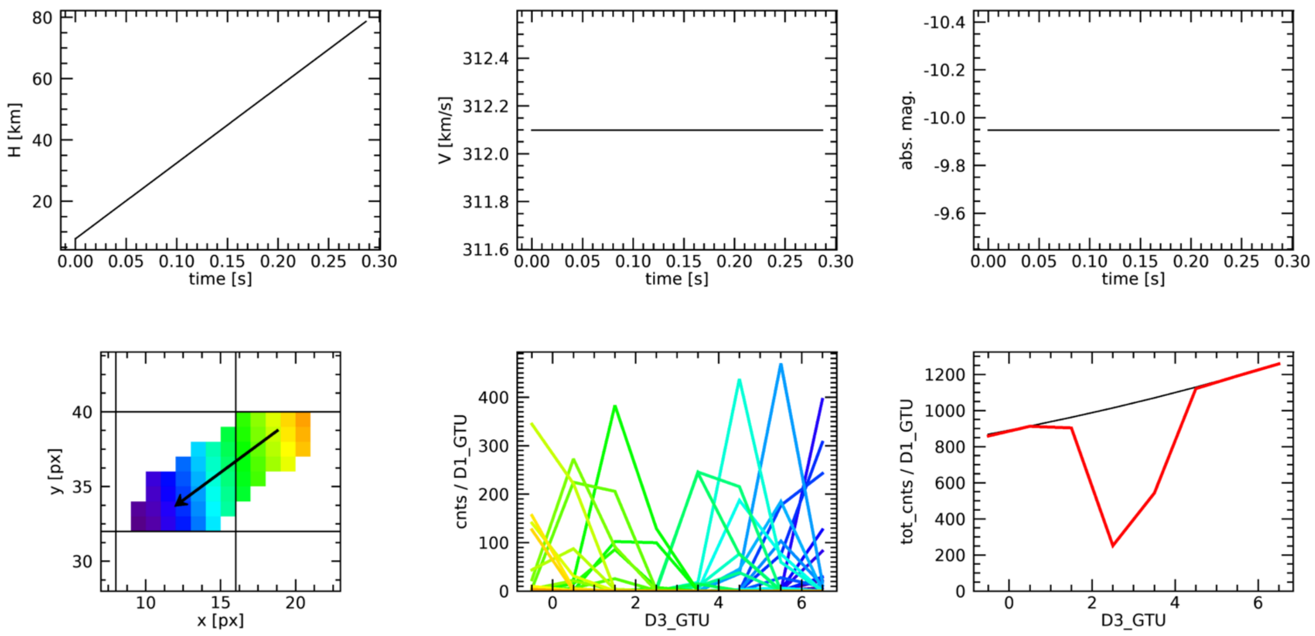
- **Random sampling of start point and direction**

  Starting altitude in the allowed volume
  Horizontal coordinates x,yx,yx,y sampled within the surface set to starting altitude
  Inclination angle and azimuth sampled with a specific logic

- **Forward/backward dynamic integration**
- **FoV Check**
- **Pixel conversion**

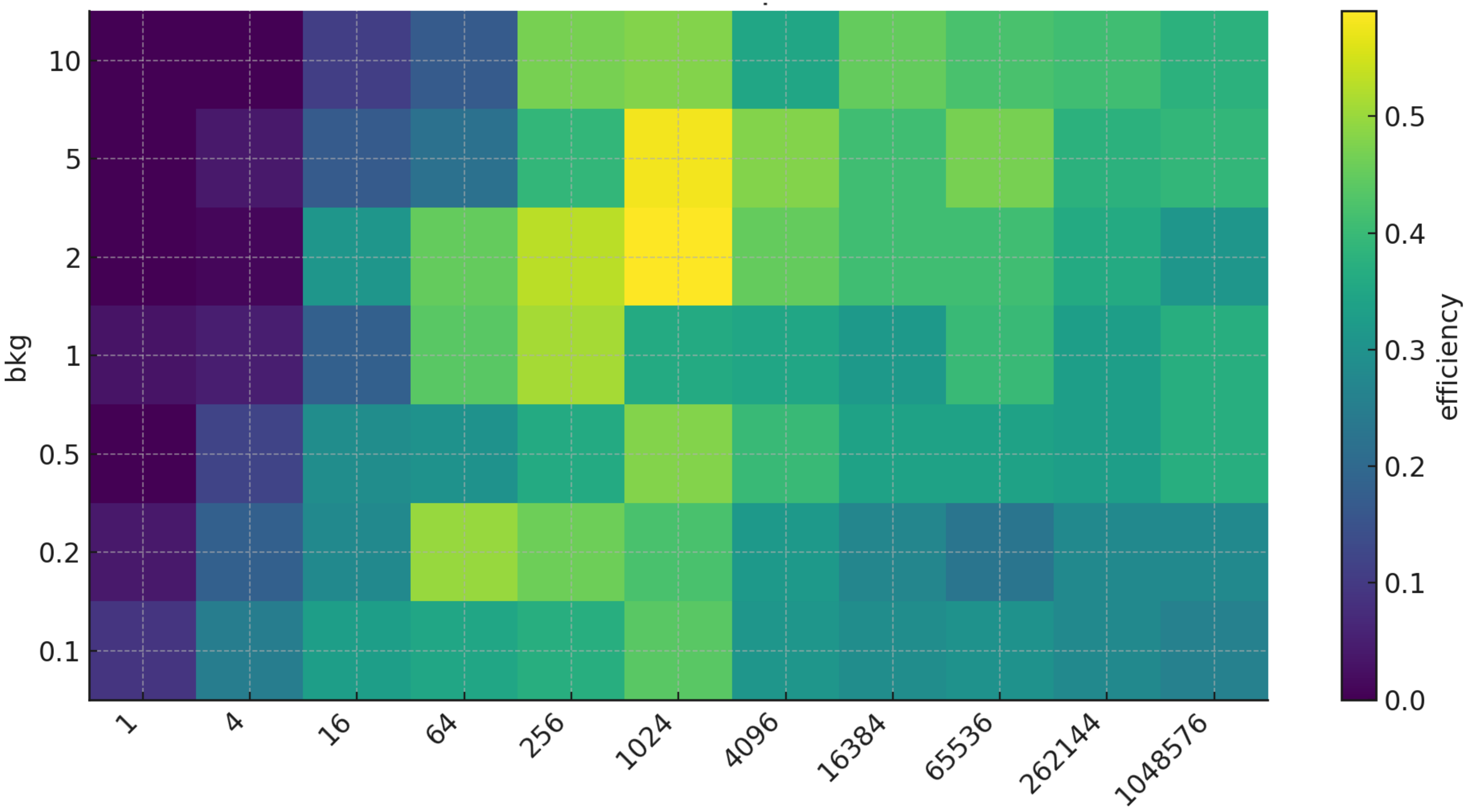
Event example





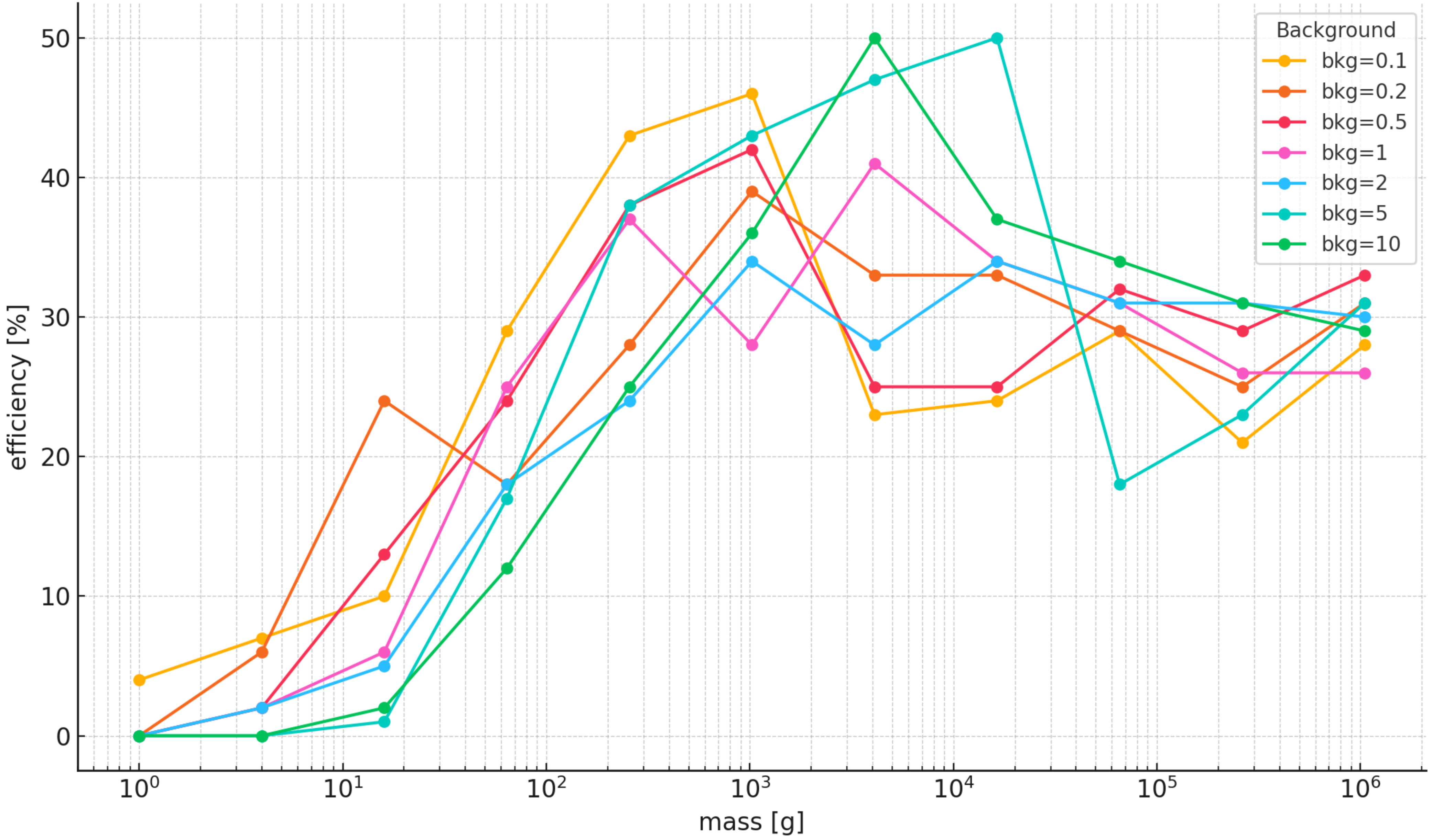
Study of efficiency of the trigger: first analysis

mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	9%	4%	0%	3%	0%	0%	0%
4	25%	18%	12%	5%	1%	4%	0%
16	33%	28%	29%	18%	31%	17%	11%
64	35%	50%	30%	44%	45%	22%	17%
256	37%	46%	36%	51%	53%	39%	47%
1024	44%	42%	48%	36%	59%	58%	48%
4096	31%	32%	40%	35%	45%	48%	35%
16384	29%	27%	34%	32%	41%	41%	45%
65536	30%	23%	34%	40%	41%	47%	42%
262144	28%	28%	33%	33%	36%	38%	41%
1048576	26%	28%	37%	37%	31%	39%	38%



10
5
2
1
0.5
0.2
0.1
bkg
1
4
16
64
256
1024
4096
16384
65536
262144
1048576
mass [g]
0.0
0.1
0.2
0.3
0.4
0.5
efficiency

H=15, kuL=200, knpmb=64



Check on trigger algorithm

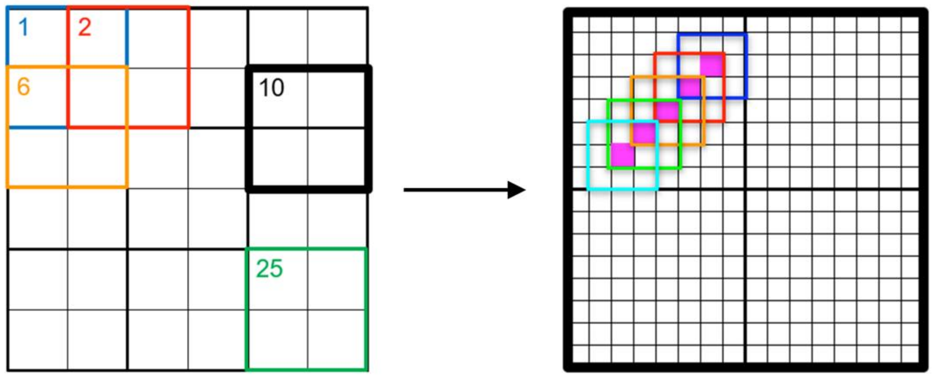
Astronomy & Astrophysics manuscript no. output
April 10, 2024

Observation of meteors from space with the Mini–EUSO detector on board the International Space Station

D. Barghini[1,2,*], M. Battisti[3,4], A. Belov[5,6], M. Bertaina[2,3], S. Bertone[2], F. Bisconti[7], C. Blaksley[8], S. Blin[4], K. Bolmgren[9], G. Cambiè[7,10], F. Capel[11], M. Casolino[7,8,10], A. Cellino[1], I. Churilo[12], A. G. Coretti[2,3], M. Crisconio[13], C. De La Taille[14], T. Ebisuzaki[8], J. Eser[15], F. Fenu[13], G. Filippatos[15], M. A. Franceschi[16], C. Fuglesang[9], D. Gardiol[1], A. Golzio[17], P. Gorodetzky[9], F. Kajino[18], H. Kasuga[8], P. Klimov[5], V. Kungel[19], V. Kuznetsov[12], M. Manfrin[2,3], L. Marcelli[7], G. Mascetti[13], W. Marszał[20], M. Mignone[3], H. Miyamoto[2,3], A. Murashov[6], T. Napolitano[16], H. Ohmori[8], A. Olinto[15], E. Parizot[4], P. Picozza[7,10], L. W. Piotrowski[21,**], Z. Plebaniak[7,10,20], G. Prèvôt[4], E. Reali[7,10], F. Reynaud[2], M. Ricci[16], G. Romoli[7,10], N. Sakaki[8], S. Sharakin[6], K. Shinozaki[20], J. Szabelski[22], Y. Takizawa[8], V. Vagelli[13], G. Valentini[13], M. Vrabel[20], L. Wiencke[19], and M. Zotov[6]

(Affiliations can be found after the references)

Received ; accepted



(a) Scan 25 «virtual» ECs (Elementary Cells) over 9 «physically existing» ECs

(b) Trigger: excess on the neighbouring pixels lasting 4 consecutive GTUs

Trigger 1 (Miyamoto et al. 2019)

- Divides the PDM focal surface into 25 overlapping virtual Elementary Cells (ECs), each formed by a 2 × 2 MAPMT array.
- For every pixel, continuously computes the background mean (μ) and standard deviation (σ) over the previous 16 GTUs and sets the threshold T = $\mu + 3\,\sigma$.
- Scans each EC: a trigger is issused
  if in any area of 3x3 pixels T is exceeded in 4 consecutive GTUs
- On trigger, records a buffer of 64 GTUs before and 64 GTUs after threshold crossing.

Meteor vs Nuclearite speed

Typical meteor speed: 40 km/s --> 6 km/pix / 40 km/s = 150 ms/pix ~ **4 D3GTU/pix**

Typical nuclearite speed: 250 km/s --> 6 km/pix / 250 km/s = 24 ms/pix ~ **0.6 D3GTU/pix**

Parameter `kUL`

- The parameter `kUL` (upper-limit) sets a cap on the "sigma-excess" that each pixel can contribute to the trigger:

$$\frac{\mathrm{count}_{\mathrm{trg}} - \overline{N}}{\sigma}$$

- If this value exceeds `kUL`, the event is discarded (or that contribution is ignored).
- In effect, `kUL` limits the trigger's response to overly bright events, preventing a single flash from saturating the algorithm or producing false positives.

$\boxed{\text{Parameter kNpixMaxBox}}$

- The parameter `kNpixMaxBox` regulates the maximum number of pixels, within a single Virtual EC (16×16 pixels), that can exceed the threshold simultaneously.
- If the number of above-threshold pixels in that cell exceeds `kNpixMaxBox`, the entire event is discarded as "too extensive" (typical of large-scale luminous phenomena such as lightning or reflections).
- This filter discriminates point-like meteors (few pixels) from larger, more diffuse optical structures.

We conducted different sets of efficiency simulations for nuclearites:

- kUL=1e9 and kNpixMaxBox=64.
- kUL=200 and kNpixMaxBox=257.
- kUL=1e9 and kNpixMaxBox=257.

Table 2: Trigger efficiency for detection of nuclearite events without cloud thresholds - Parameters kUL = 200 knpixmaxbox = 257

mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	7%	5%	0%	1%	0%	1%	0%
4	22%	15%	11%	8%	1%	1%	1%
16	38%	27%	28%	15%	30%	14%	12%
64	33%	56%	27%	42%	44%	21%	21%
256	36%	45%	41%	48%	49%	42%	49%
1024	47%	41%	48%	35%	52%	54%	49%
4096	27%	36%	42%	34%	49%	46%	36%
16384	31%	33%	38%	38%	38%	42%	47%
65536	30%	30%	39%	39%	42%	46%	40%
262144	29%	23%	34%	37%	34%	37%	39%
1048576	30%	30%	40%	34%	34%	40%	41%

Table 3: Trigger efficiency for detection of nuclearite events without cloud thresholds - Parameters kUL = 1.00E+09 knpixmaxbox = 64

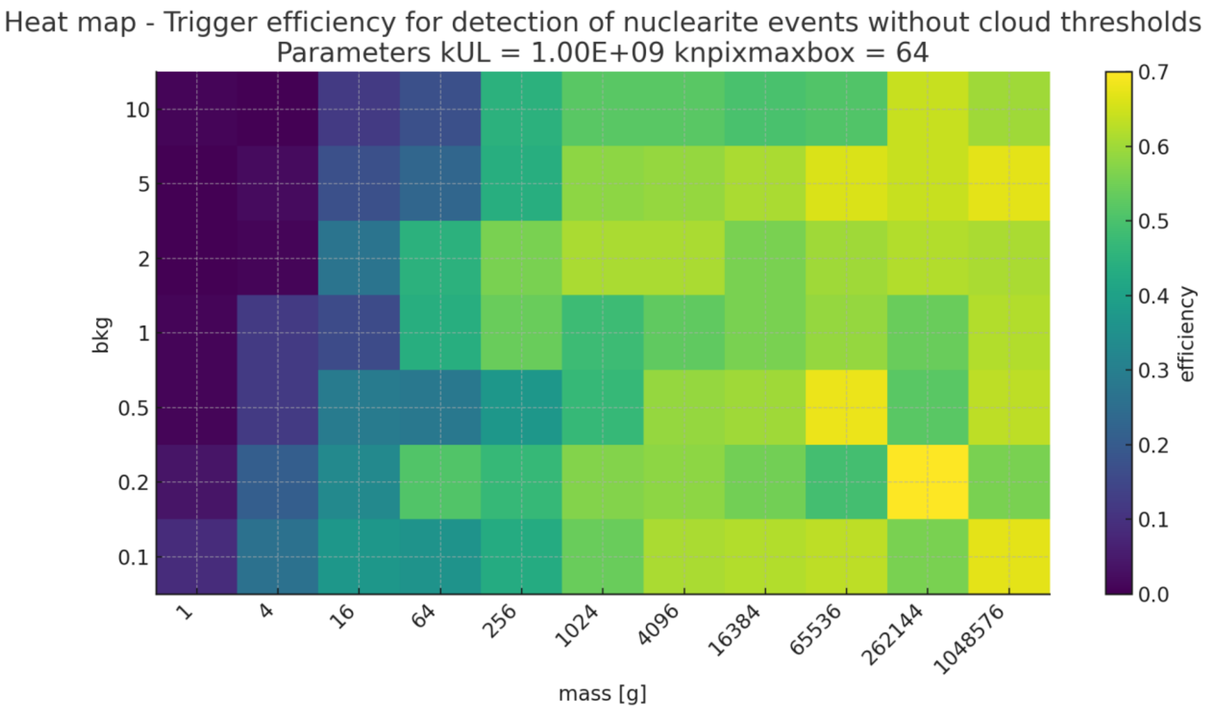
mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	9%	4%	1%	1%	0%	0%	1%
4	26%	21%	12%	12%	1%	2%	0%
16	37%	33%	29%	16%	27%	17%	12%
64	36%	51%	28%	44%	45%	23%	17%
256	43%	47%	37%	54%	56%	44%	45%
1024	54%	57%	47%	48%	61%	58%	52%
4096	61%	58%	59%	53%	61%	59%	52%
16384	62%	55%	60%	56%	56%	61%	50%
65536	63%	49%	68%	59%	60%	66%	51%
262144	56%	70%	52%	54%	62%	64%	64%
1048576	67%	56%	63%	62%	61%	67%	60%

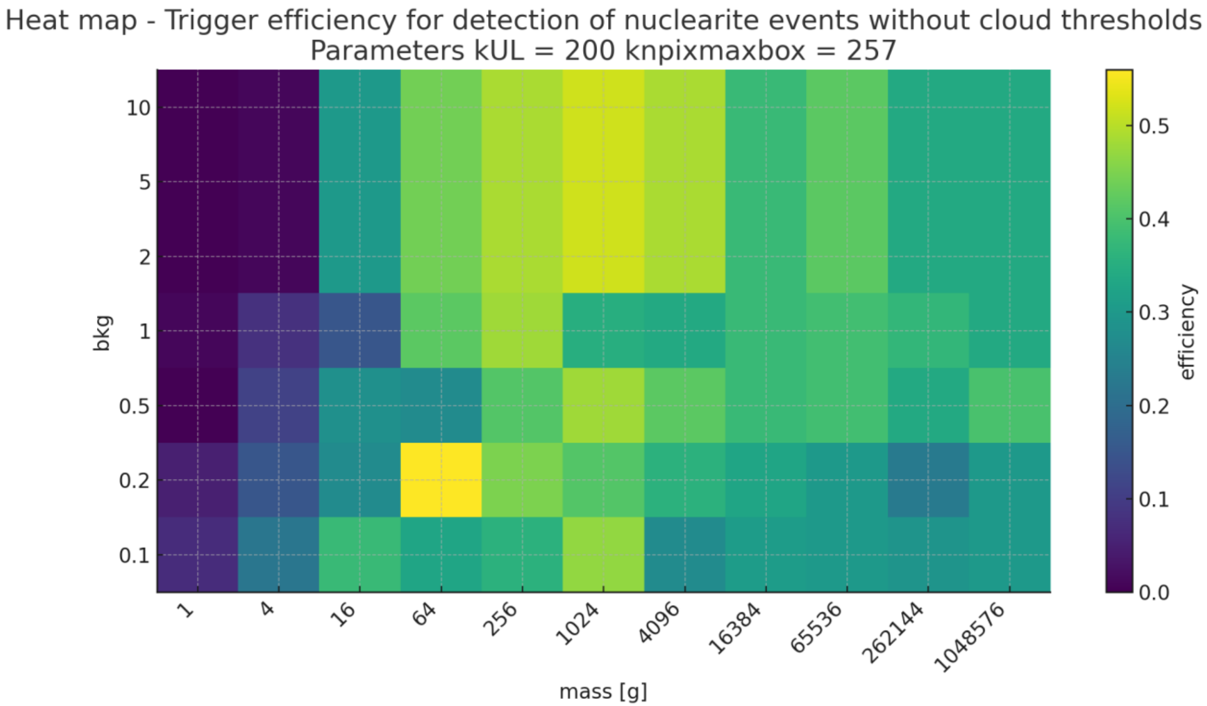
Table 4: Trigger efficiency for detection of nuclearite events without cloud thresholds - Parameters kUL = 1.00E+09 knpixmaxbox = 257

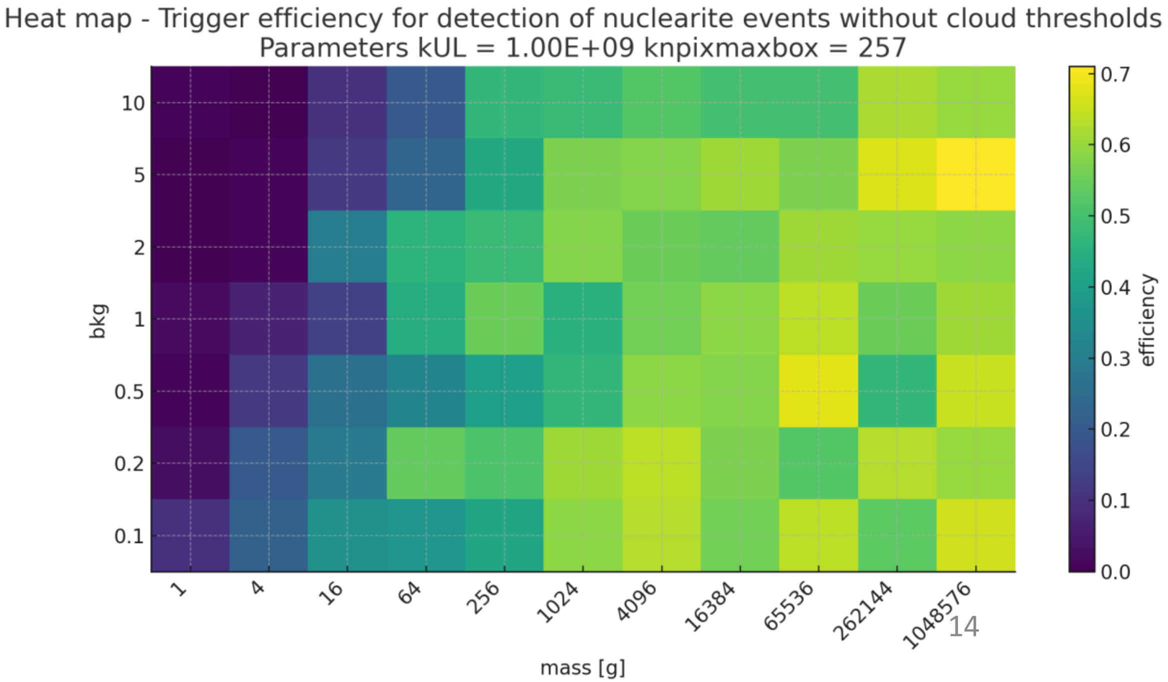
mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	10%	3%	1%	2%	0%	0%	1%
4	22%	20%	12%	7%	1%	1%	0%
16	36%	29%	26%	14%	30%	12%	10%
64	37%	54%	32%	44%	46%	23%	20%
256	42%	51%	40%	55%	48%	43%	47%
1024	59%	61%	47%	45%	58%	57%	48%
4096	63%	64%	59%	56%	55%	58%	52%
16384	56%	57%	58%	59%	54%	61%	50%
65536	64%	52%	68%	64%	61%	57%	50%
262144	53%	63%	47%	55%	60%	67%	62%
1048576	66%	60%	65%	61%	59%	71%	60%

We conducted different sets of efficiency simulations for nuclearites:

- kUL=1e9 and kNpixMaxBox=64.
- kUL=200 and kNpixMaxBox=257.
- kUL=1e9 and kNpixMaxBox=257.







- Conclusion

For very large masses the counts become so high that the "σ-excess" exceeds the limit of 200 and is clipped, reducing the efficiency. By resetting k_{UL} to a virtually unlimited value (10^9), this filter no longer intervenes and high-mass events are correctly triggered.

- We also studied the case with cloud threshold set (h > 15 km)

Table 5: Trigger efficiency for detection of nuclearite events with cloud thresholds set to 15 km - Parameters kUL = 200 knpixmaxbox = 64

mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	4%	0%	0%	0%	0%	0%	0%
4	7%	6%	2%	2%	2%	0%	0%
16	10%	24%	13%	6%	5%	1%	2%
64	29%	18%	24%	25%	18%	17%	12%
256	43%	28%	38%	37%	24%	38%	25%
1024	46%	39%	42%	28%	34%	43%	36%
4096	23%	33%	25%	41%	28%	47%	50%
16384	24%	33%	25%	34%	34%	50%	37%
65536	29%	29%	32%	31%	31%	18%	34%
262144	21%	25%	29%	26%	31%	23%	31%
1048576	28%	31%	33%	26%	30%	31%	29%

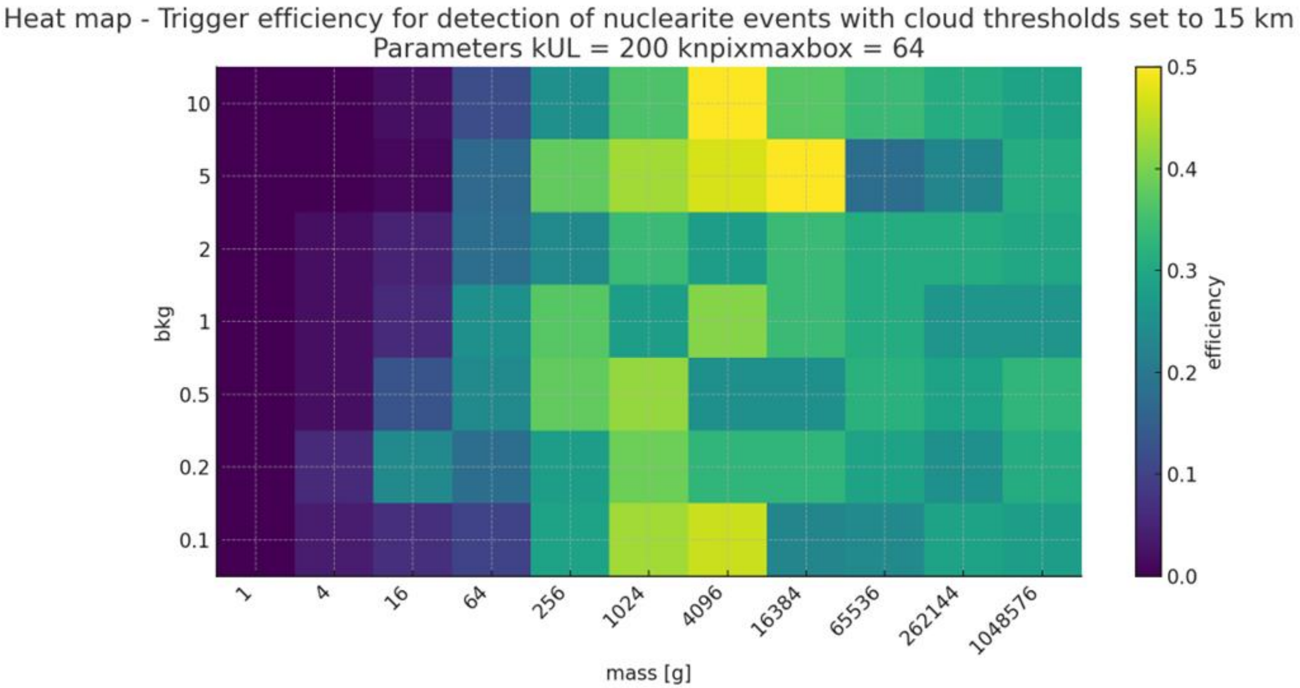


Table 6: Trigger efficiency for detection of nuclearite events with cloud thresholds set to 15 km - Parameters kUL = 200 knpixmaxbox = 257

mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	2%	0%	0%	0%	0%	0%	0%
4	8%	4%	3%	1%	1%	0%	0%
16	10%	21%	17%	8%	5%	2%	3%
64	32%	22%	26%	29%	17%	20%	12%
256	43%	26%	41%	32%	27%	36%	27%
1024	46%	32%	42%	31%	32%	41%	39%
4096	23%	30%	29%	39%	35%	45%	48%
16384	22%	29%	28%	28%	34%	47%	34%
65536	24%	28%	32%	31%	30%	26%	33%
262144	22%	22%	27%	22%	32%	24%	29%
1048576	29%	25%	36%	28%	29%	32%	29%

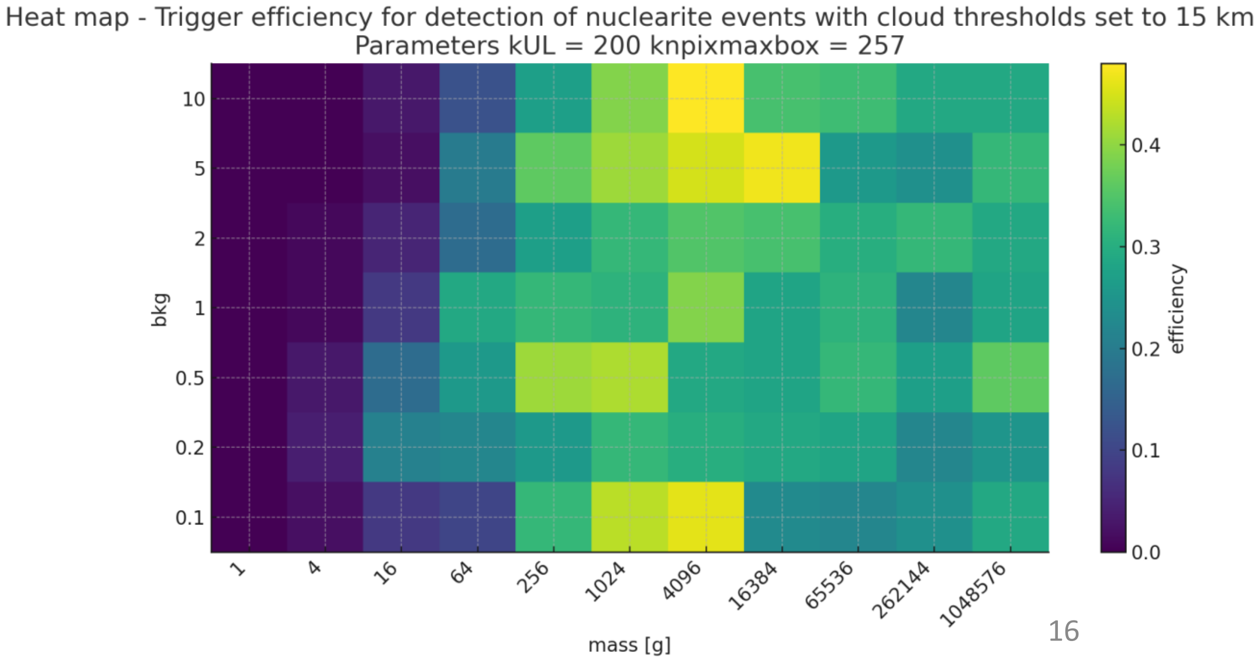


Table 7: Trigger efficiency for detection of nuclearite events with cloud thresholds set to 15 km - Parameters kUL = 1.00E+09 knpixmaxbox = 64

mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	1%	0%	0%	0%	0%	0%	0%
4	5%	5%	2%	3%	0%	0%	0%
16	13%	24%	14%	5%	6%	1%	4%
64	30%	22%	24%	30%	20%	20%	12%
256	52%	32%	41%	33%	28%	39%	26%
1024	57%	44%	57%	39%	41%	44%	37%
4096	36%	56%	43%	64%	39%	58%	56%
16384	52%	50%	53%	61%	50%	59%	53%
65536	57%	59%	49%	60%	51%	43%	50%
262144	52%	45%	56%	60%	64%	45%	61%
1048576	56%	59%	68%	55%	51%	53%	45%

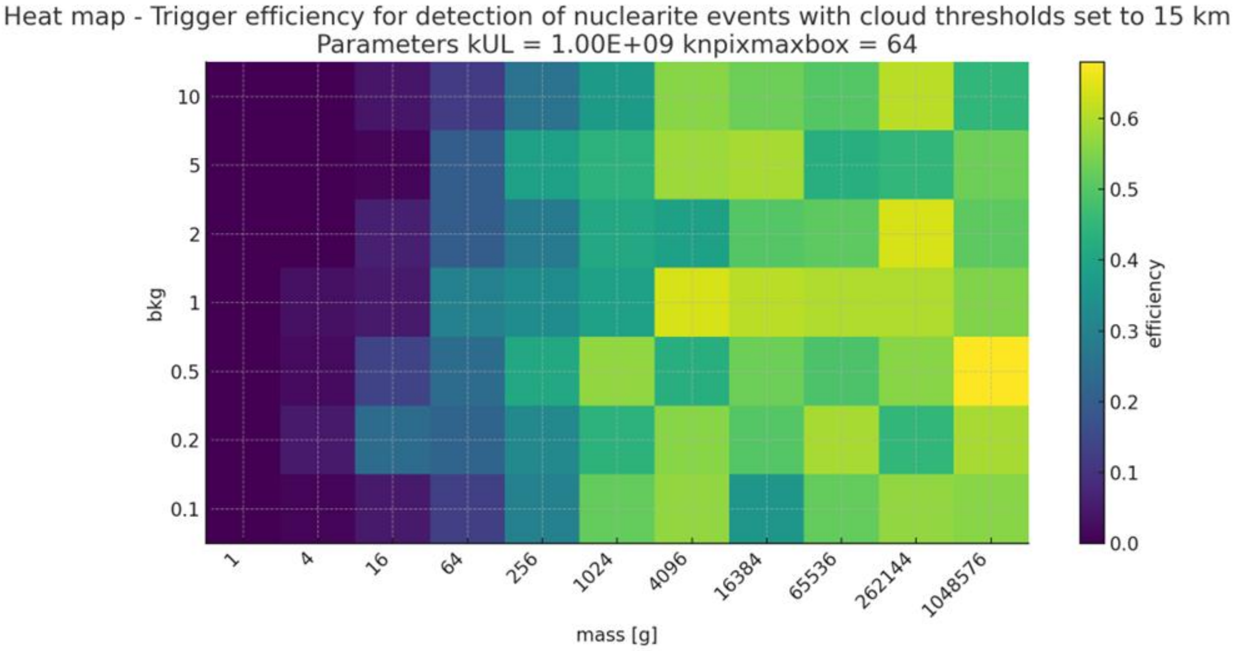
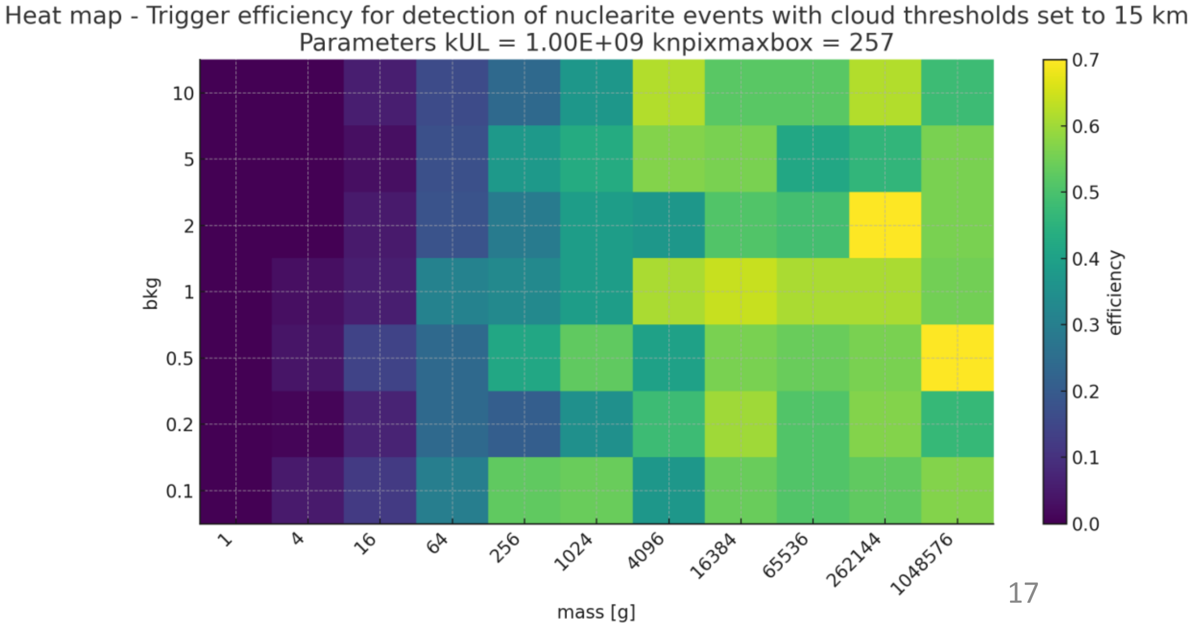


Table 8: Trigger efficiency for detection of nuclearite events with cloud thresholds set to 15 km - Parameters kUL = 1.00E+09 knpixmaxbox = 257

mass [g]	bkg = 0,1	bkg = 0,2	bkg = 0,5	bkg = 1	bkg = 2	bkg = 5	bkg = 10
1	0%	1%	0%	0%	0%	0%	0%
4	5%	7%	4%	3%	0%	0%	0%
16	12%	24%	14%	6%	5%	3%	6%
64	30%	21%	24%	31%	18%	17%	16%
256	53%	35%	42%	33%	29%	38%	24%
1024	54%	48%	53%	39%	39%	43%	37%
4096	37%	60%	40%	61%	37%	57%	62%
16384	54%	51%	56%	64%	51%	56%	52%
65536	51%	57%	54%	61%	49%	42%	52%
262144	53%	47%	56%	61%	70%	46%	62%
1048576	57%	57%	70%	55%	56%	56%	48%



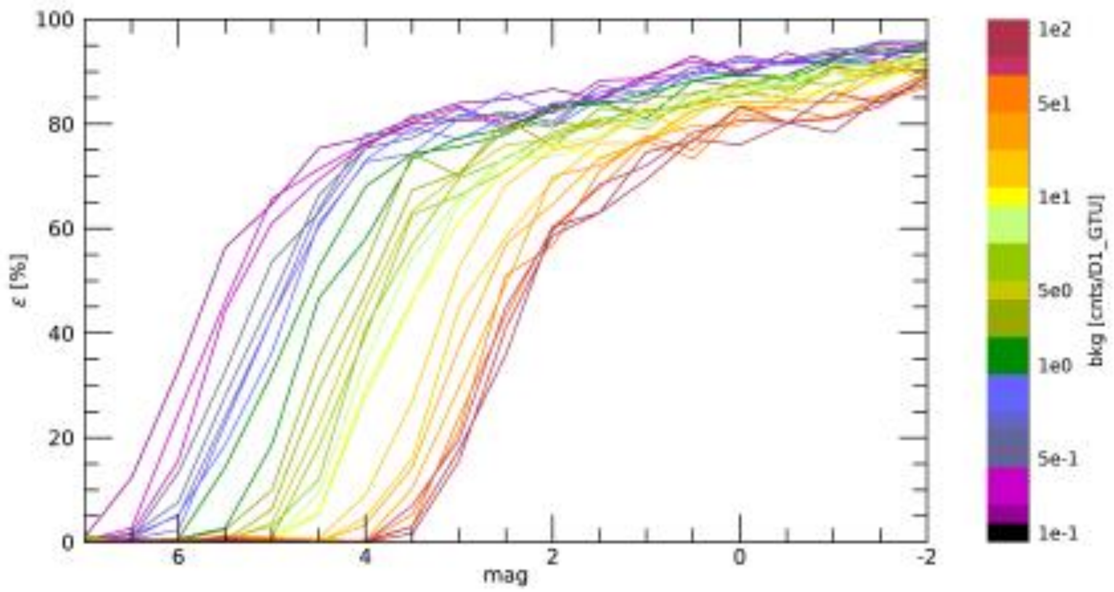
Next step: further consideration for flux estimation

- **Fraction of events in the Mini-EUSO FoV**
  Assume trajectory events are isotropically distributed within a sphere, and model the Mini-EUSO field of view as a cone (or pyramid) inscribed in that sphere. A first, naive estimate gives theoretical fraction: 0.46704**,** numerical result: 0.4669.
- **Fraction of sub-threshold–velocity events**
  Compute the fraction of events whose velocity falls below the minimum required for emission. An initial estimate—by integrating the Maxwellian speed distribution—yields approximately zero.
- **Altitude-restricted fraction within the FoV**
  Of the events inside the FoV, determine the fraction occurring between the cloud threshold at **15 km** and the maximum emission altitude.

Flux calculation
Apply the detector's efficiency estimate to this final fraction to obtain the expected flux.

Next step: curve fit of nuclearite efficiency

- The goal is to derive a parametric fit for the efficiency so that, for any given mass and background level, we can directly estimate the corresponding efficiency.
- $\in = \in\ (mass, bkg)$
- The same study Dario Barghini made with meteor efficiency



$$\epsilon(\mathcal{M}) = \epsilon_M + \frac{\epsilon_m - \epsilon_M}{\left[1 + (2^{\nu} - 1)e^{-B(\mathcal{M}-\mathcal{M}_0)}\right]^{1/\nu}},$$

Thank you