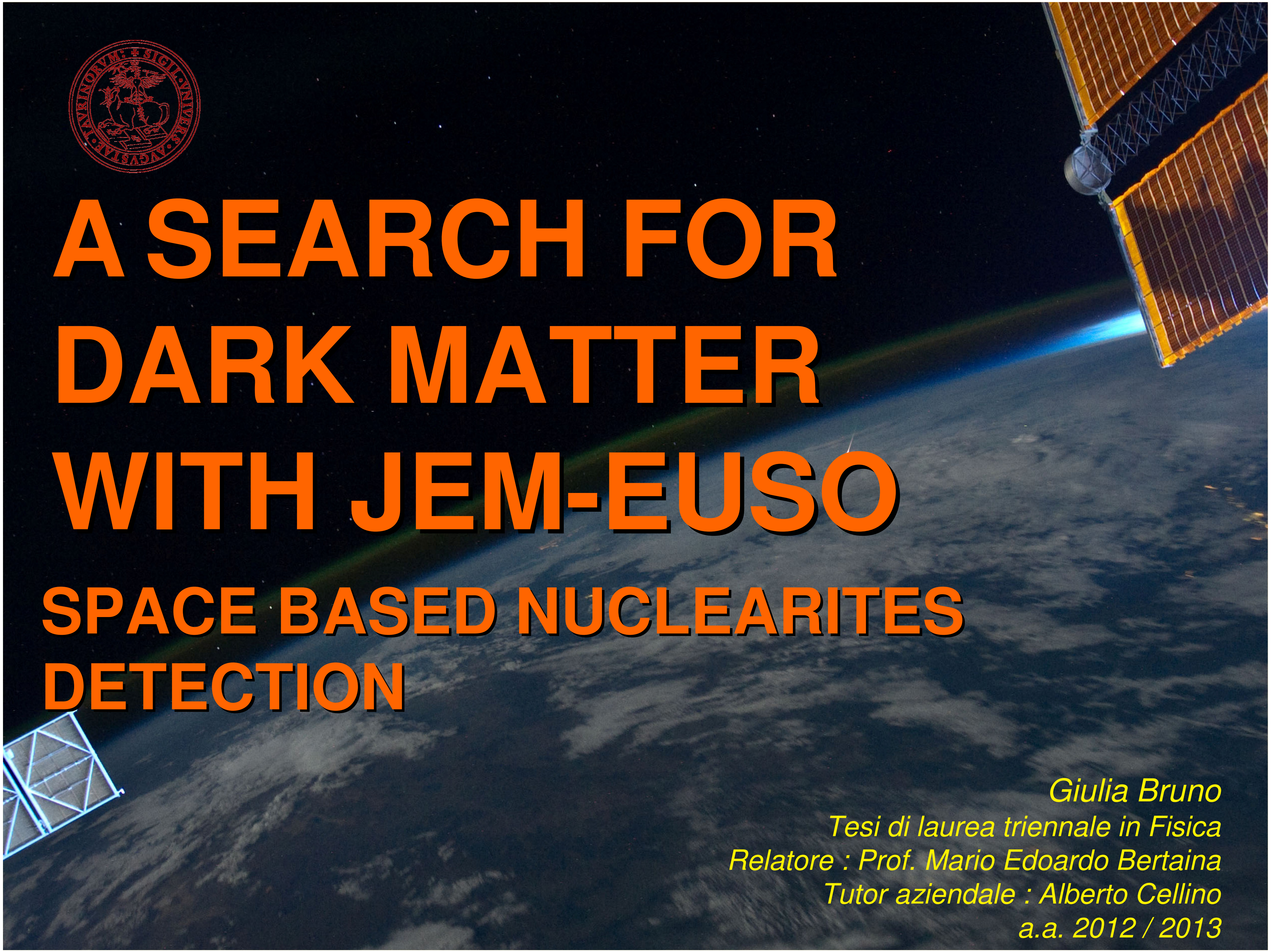

A SEARCH FOR DARK MATTER WITH JEM-EUSO

SPACE BASED NUCLEARITES DETECTION

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Tesi di laurea triennale in Fisica

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What nuclearites are?

Nuggets of Strange Quark Matter (SQM), composed of approximately the same numbers of up, down and strange quarks.

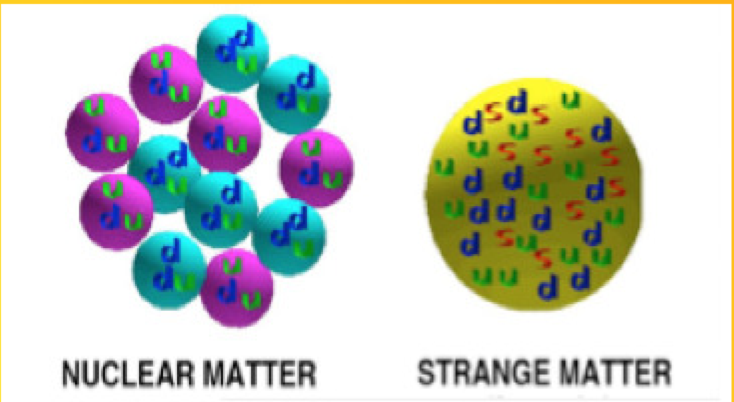
Strange matter is non-luminous and did not partecipate in primordial nucleosynthesis →dark matter

Nuggets appeared shortly after the Big Bang in the QCD transition from a quasi-free quark plasma to a cooler state in which quark are confined.

They are producted by collision of neutron stars and supernovae

→ **strangelets :** core
→ **nuclearites :** core + electron cloud

neutrality ensured by an electron cloud which surrounds the nuclearite core, forming a sort of atom.



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Rate of energy loss

$$\frac{dE}{dx} = -A\rho v^2$$

The principal energy-loss mechanism for a nuclearite passing through matter is by atomic collision.

r : density of traversed medium v : nuclearites velocity A : effective cross-sectional area

Nuclearites having galactic velocity (**250 km/s**) and mass heavier than 10^{-14} g penetrate the atmosphere (those lighter than 0.3 ng will stop in the crust) while those heavier than 0.1 g pass throught an Earth diameter.

Cross-sectional area as a function of mass m

$$A = \begin{cases} \pi \cdot 10^{-16}\,\mathrm{cm}^2 & for\ m < 1.5\ \mathrm{ng} \\ \pi\left(\frac{3m}{4\pi\rho_N}\right)^{2/3} & for\ m > 1.5\ \mathrm{ng} \end{cases}$$

For a small nuclearite of mass less than 1.5 ng the area is controlled by its electronic atmosphere ever smaller than 10^{-8} cm

$\rho_N = 3.5 \cdot 10^{14}$ g/cm^3 : strange matter density m : nuclearite mass

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Some experiments

Technique	Location	Experiment	Observ. Area (m^2)	$Mass_{thr}$ (g)	$Mass_{thr}$ (Gev/c^2)
Thermo-acoustic	Sea level	Explorer	~1	10^{-13}	$>6 \cdot 10^{16}$
Damage	Mountain 5230 m a.s.l.	SLIM	427	$5 \cdot 10^{-14}$	$>3 \cdot 10^{10}$
Light in oil	Underground 3700 hg cm^{-2}	MACRO	~700	$2 \cdot 10^{-10}$	$>10^{14}$
Light in water	Underwater 2500 hg cm^{-2}	ANTARES	$\sim 10^5$	$2 \cdot 10^{-10}$	$>10^{14}$
Earth or moon-quakes	Earth/moon inner	seismometers	10^{11}	$\sim 10^4$	$>6 \cdot 10^{25}$

Fraction of dissipated energy as light is called the luminous efficiency h(w,r)→ **4%**

Does not depend upon radius or velocity.

Absolute magnitude

$$M = 15.8 - 1.67 \cdot log_{10}(m/1\mu g).$$

From h we deduce an expression for their luminosity as a function of mass and we compute the visual magnitude.

The absolute magnitude of a meteor (or nuclerite) computed as if viewed from a distance of 100 km.

Visual apparent magnitude : 20 g nuclearite at 400 km distance from observer → $M = 6$

Absolute magnitude : 20 g nuclearite → $M = 3.6$

Maximum height

$$h_{max} = 2.7 \ln(m/1.2 \times 10^{-5}\ g)\ \ \text{km}$$

Nuclearites are essentially a phenomenon of lower atmosphere.

10^{-4} g nuclearite → 6 km 10^{4} g nuclearite → 60 km

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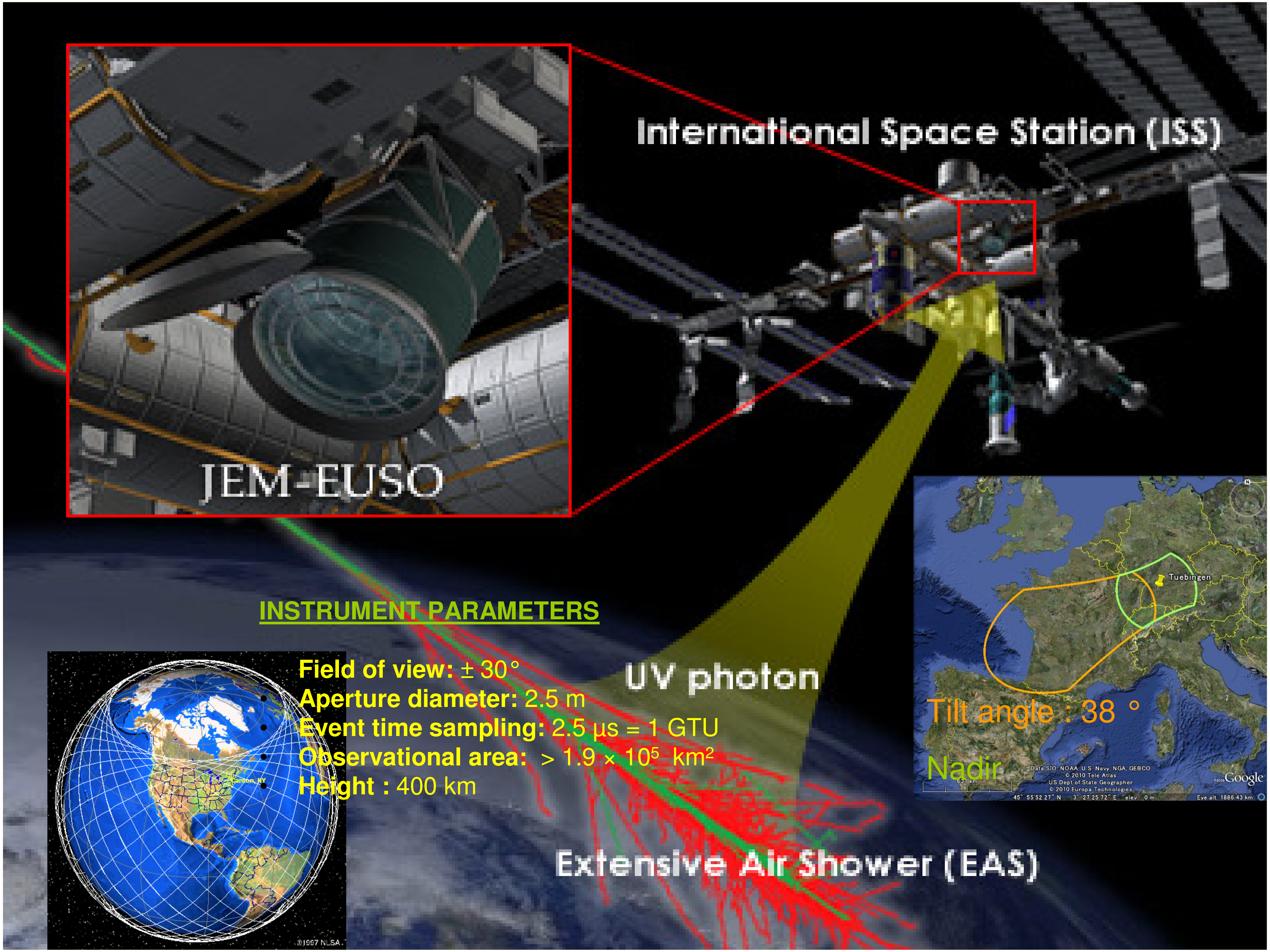
Difference from METEORS

There are three important differences that can help to discriminate between nuclearites and meteors

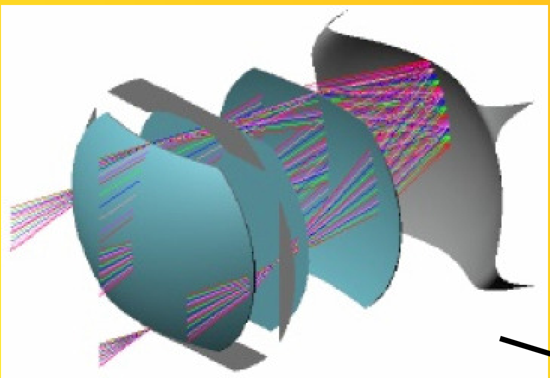
- The absolute value of the nuclearites **velocity** is higher
  (nuclearite max value→ 570 km/s   meteor max value → 72 km/s)
- The **light emitted** by nuclearites is constant at $h \leq h_{max}$
- A nuclearite of mass bigger than 0.1 g **can move upward**



International Space Station (ISS)
JEM-EUSO
INSTRUMENT PARAMETERS
Field of view: ± 30°
Aperture diameter: 2.5 m
Event time sampling: 2.5 μs = 1 GTU
Observational area: > 1.9 × 10^5 km^2
Height : 400 km
UV photon
Tuebingen
Tilt angle : 38 °
Nadir
Google
Extensive Air Shower (EAS)
©1997 NASA

Components

Fresnel lenses



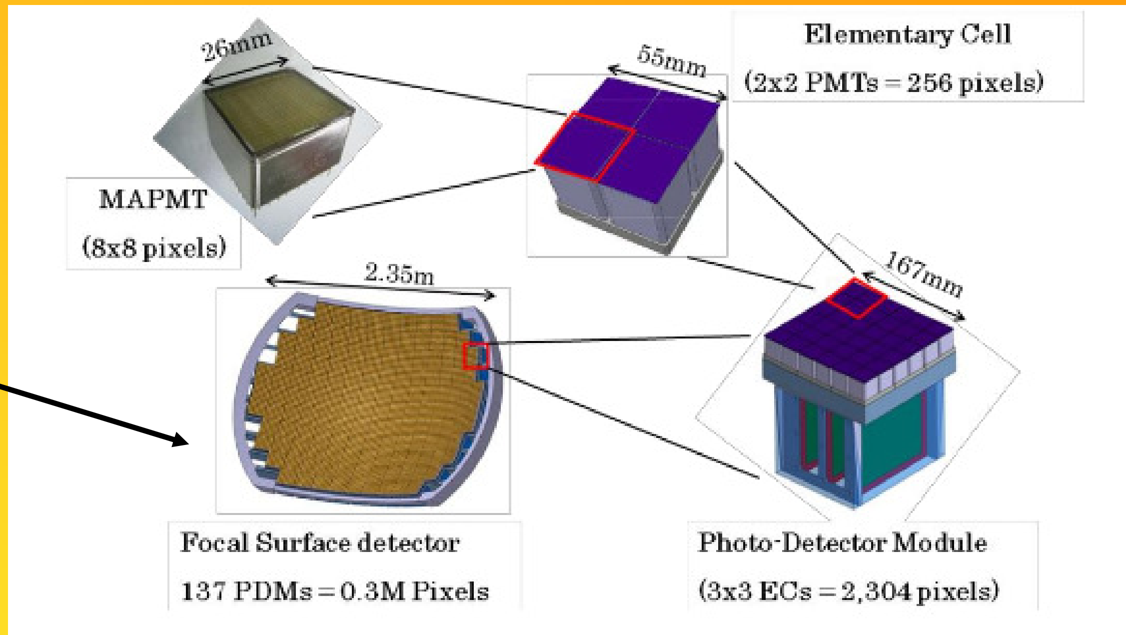
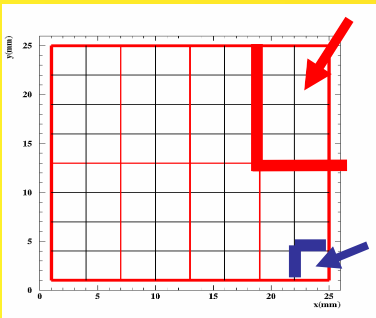


Figure 4.3.1-1. *Focal surface detector and its structure.*

single KI pixel



MAPMTpixel

Working modes:

DIGITAL (MAPMT pixel)

1 – 30 phe/pix/GTU

ANALOG (charge integration)

KI pixels = 4 X 2 MAPMT pixels

10 – 10^6 phe/pix/GTU

Gate Time Unit (GTU) = 2.5 μs

LIGHT CURVE

Meteor : yes/no secondary burst
polynomial coefficients

Nuclearite : M(m) dependence only

ISS

beginning x,y
height of flight
velocity

METEOR / NUCLEARITE

beginning height
yes/no random generation
duration
absolute magnitude / mass
vx, vy, vz

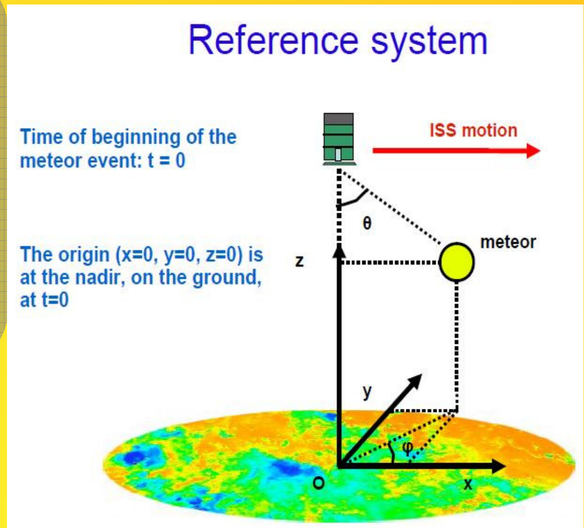
METEOR & NUCLEARITES SIMULATOR

METEOR/NUCLEARITE FROM ISS

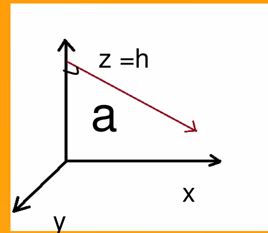
timestep
x, y, z
flux
zenith angle (θ)
azimutal angle (φ)
x, y (pix)

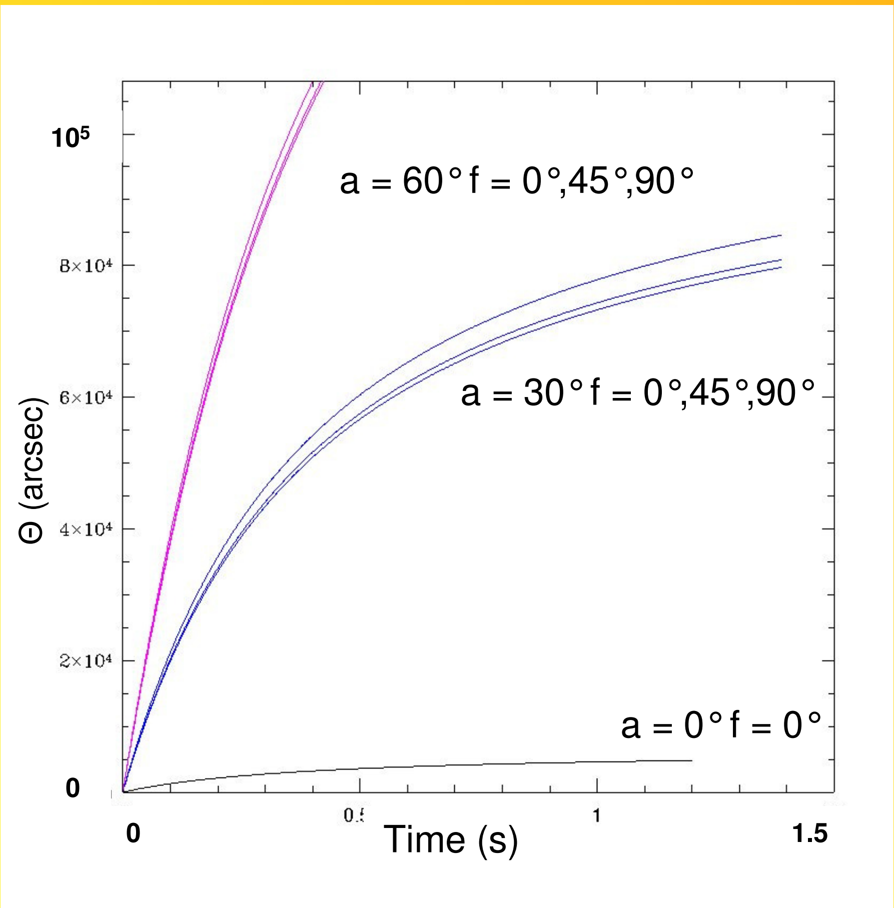
METEOR/NUCLEARITE FROM THE GROUND

timestep
x, y, z
flux
x, y, z of the ISS



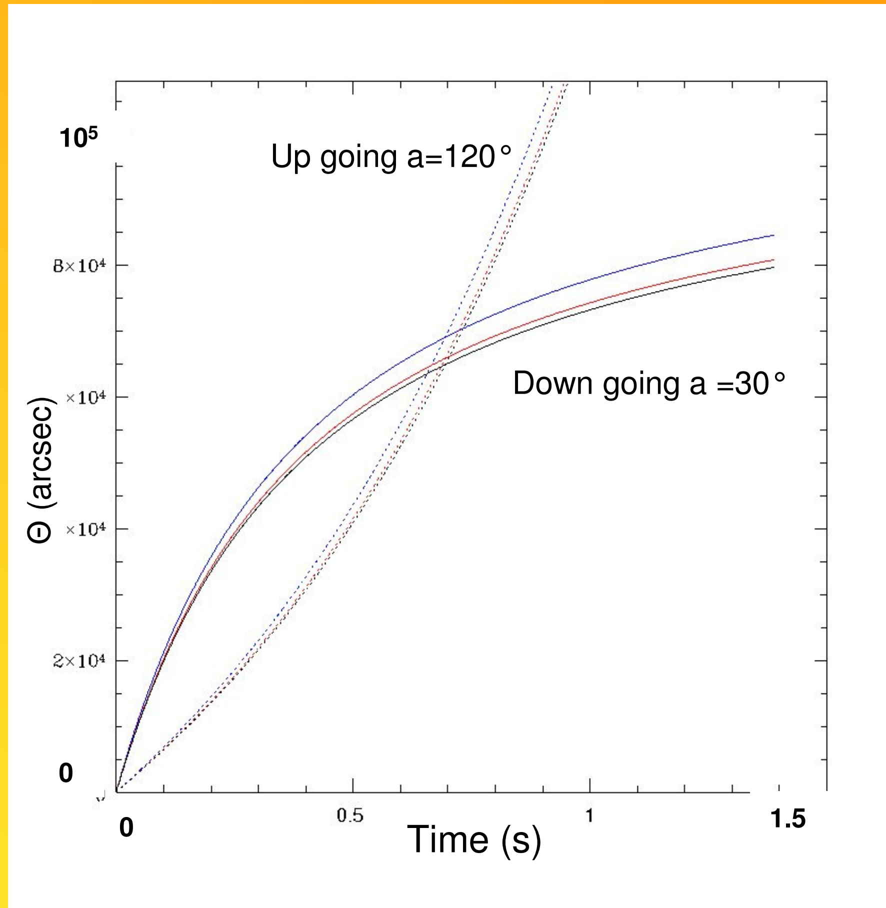
Apparent motion





Down going nuclearites

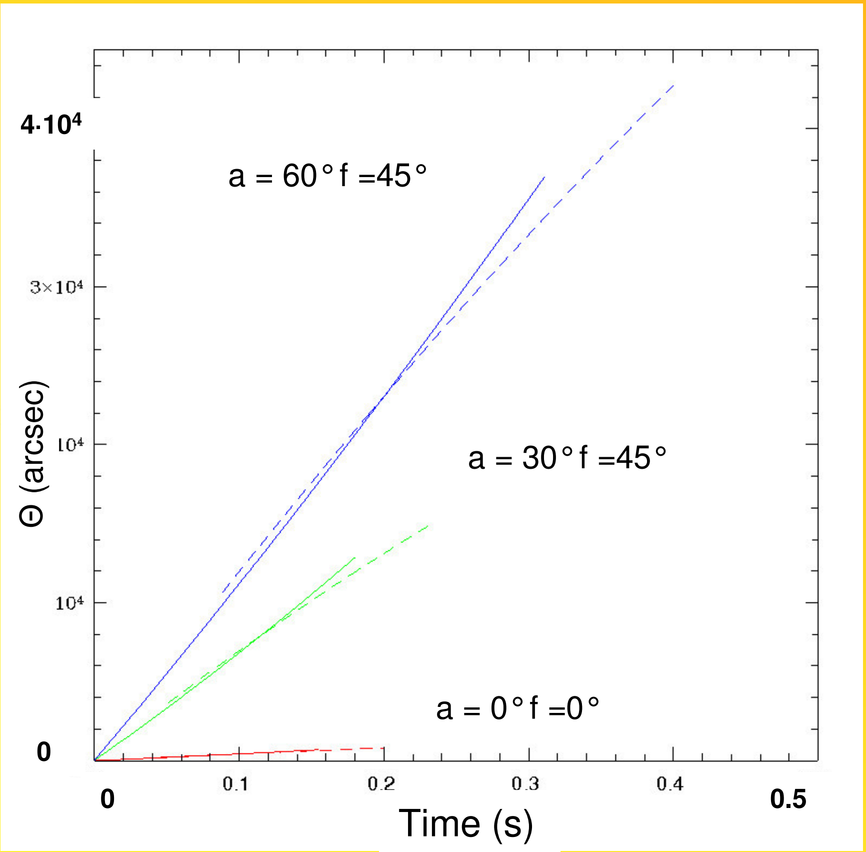
v =250 km/s m = 100 g h = 300 km

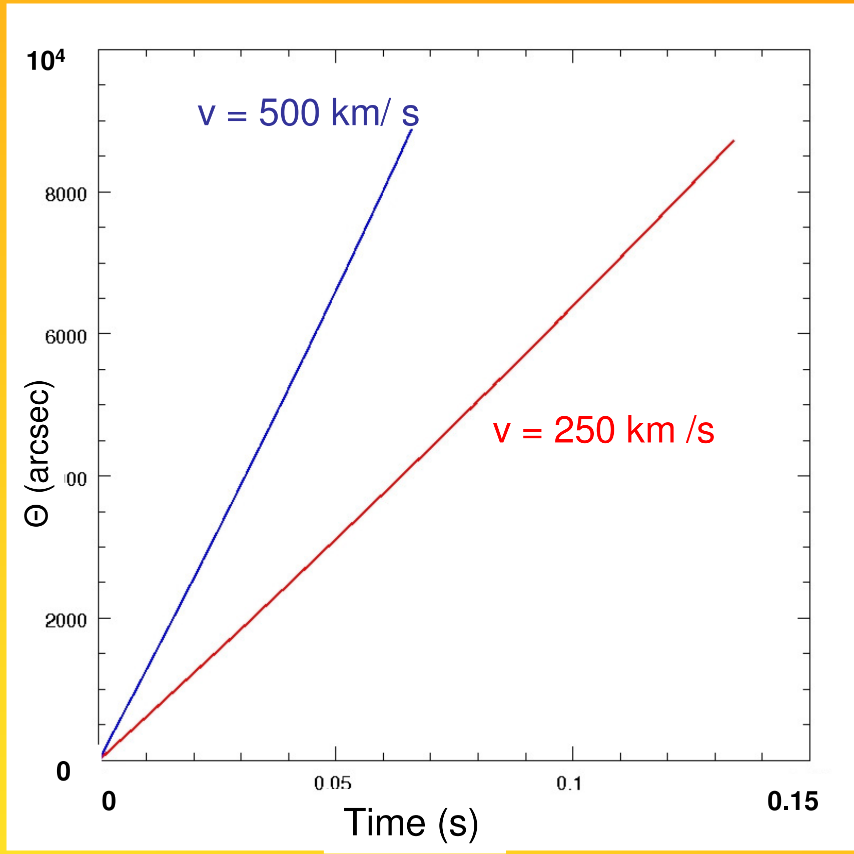


f =0°,45°,90° m = 100 g h = 0 – 300 km

without h_{max}

Apparent motion





Down going nuclearites (dotted)

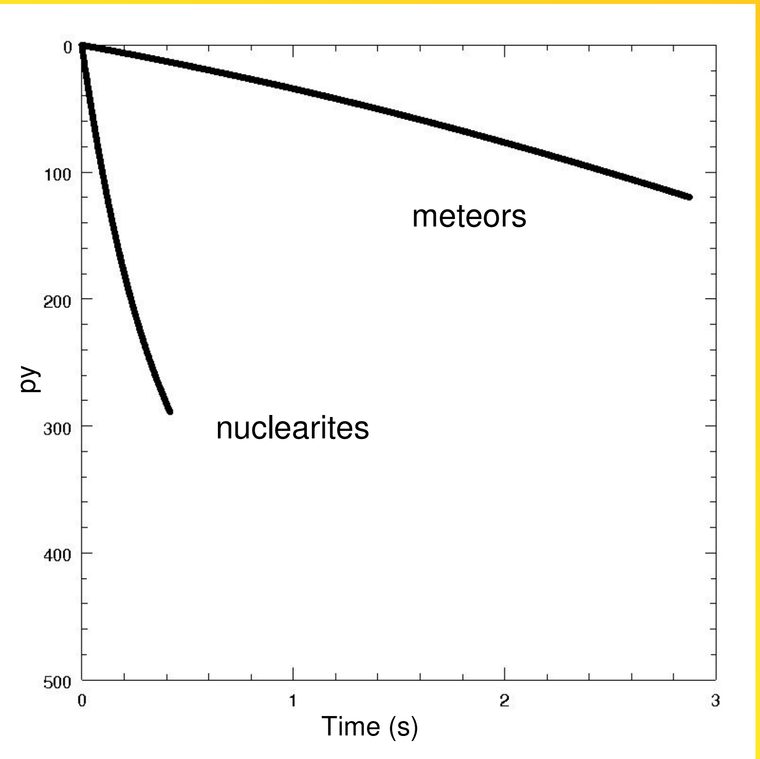
m= 20 g h = 0 - 50 km h_{max} =39 km

Up going nuclearites

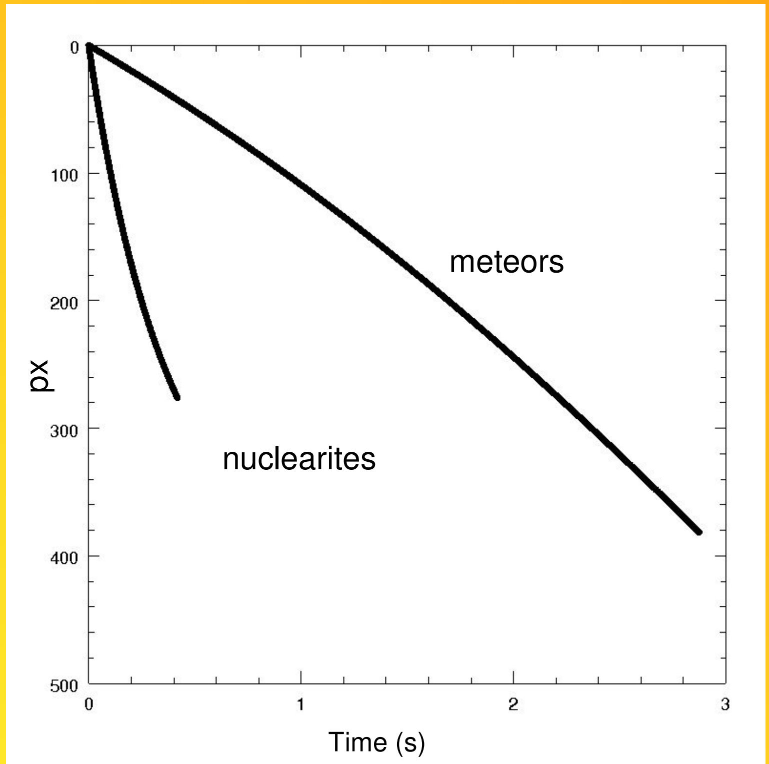
m=0.1 g h_{max} =29 km h=30 km

Comparison between nuclearite and meteor

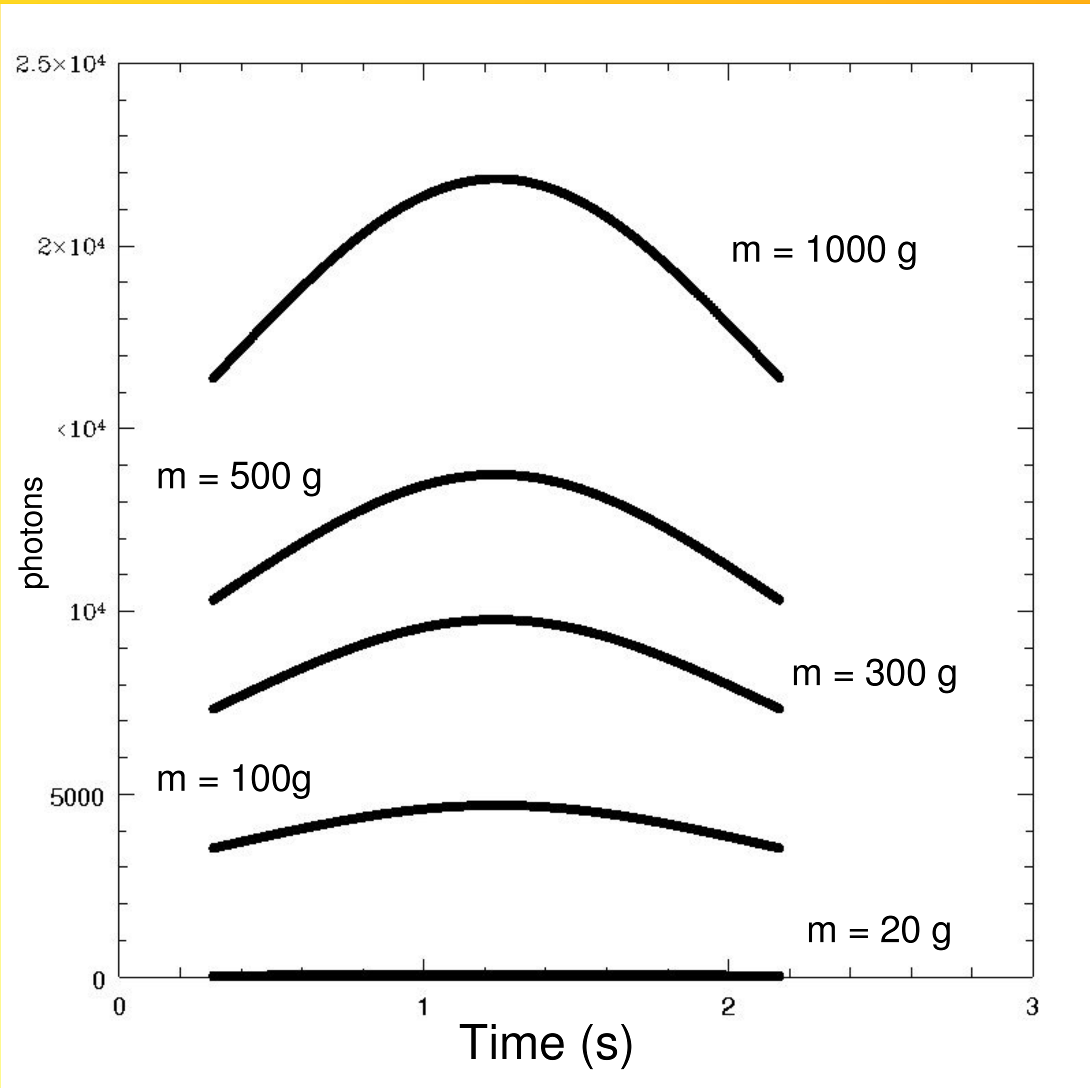
Nuclearite
h = 50 km h_{max}=h
a =60° f= 45°
v = 250 km/s
m = 50 g



Meteor
h = 100 km
a =54° f =30°
vx=46 km/s vy = 12 km/s
vz = 35 km/s →V= 59
M = 1.7



Horizontal nuclearites light curves

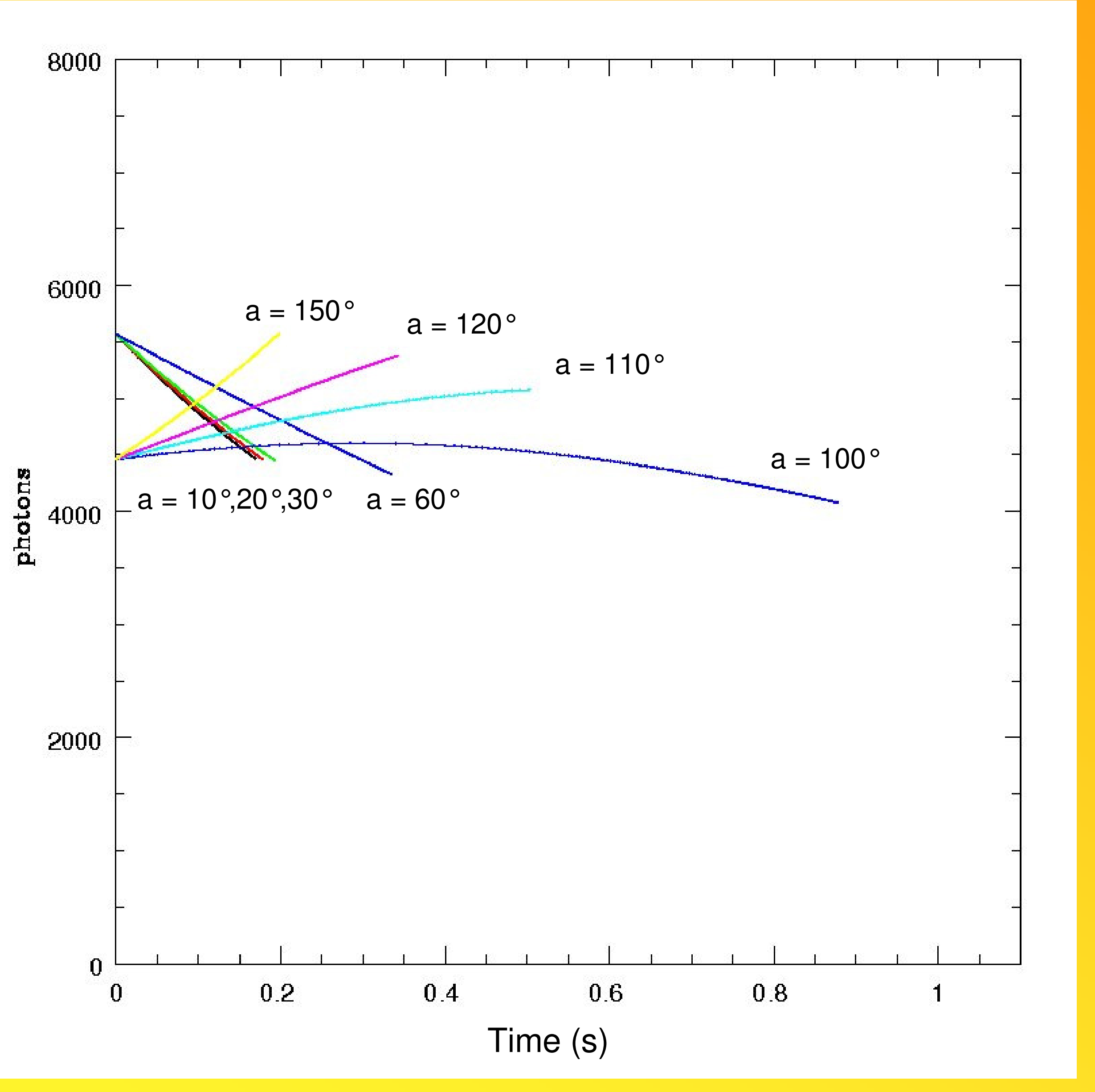


First example of nuclearites light curves who begin to light up at different height.

Changing h_{beg} the light curve becomes shorter or longer.

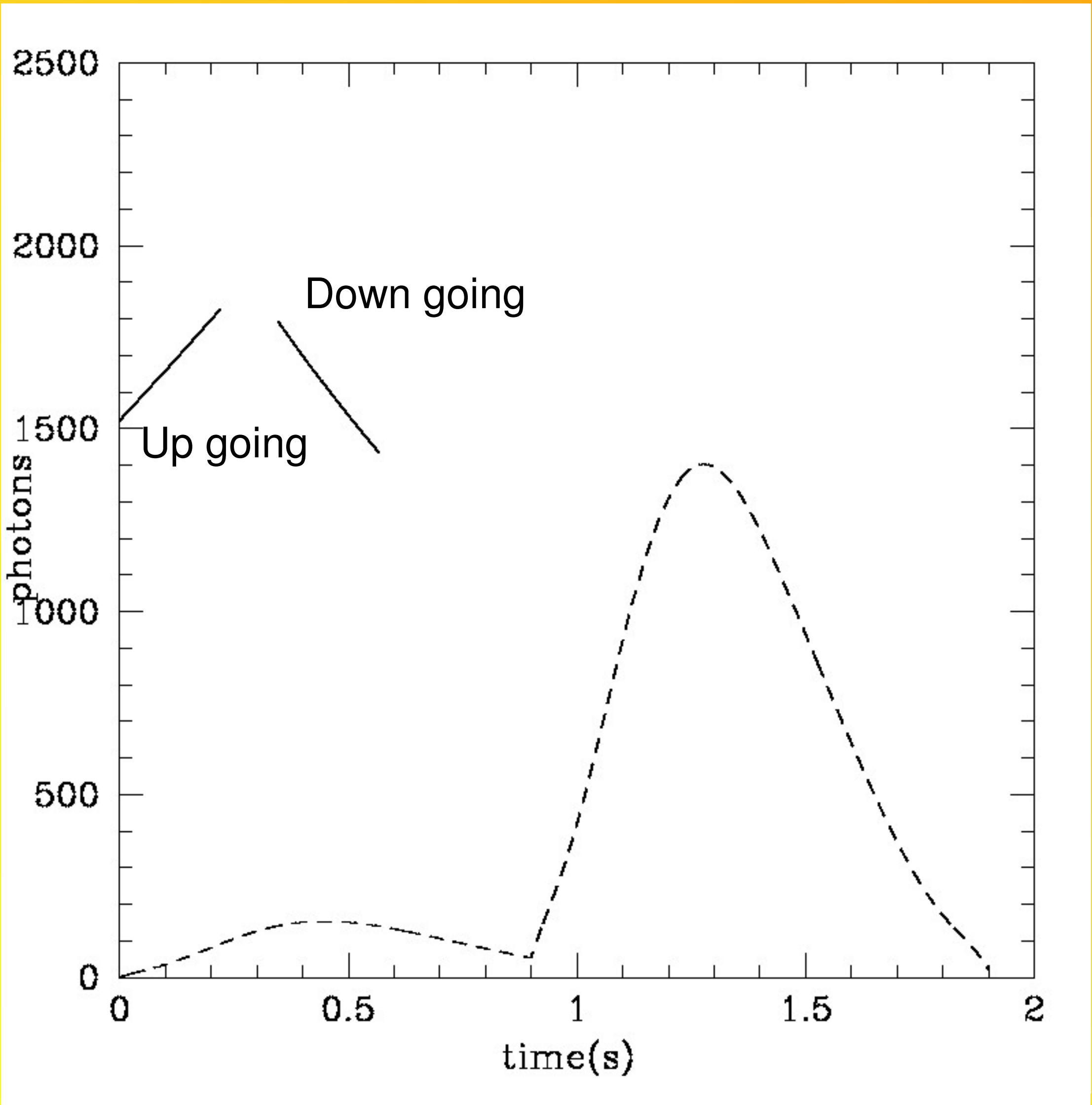
h_{beg}= 20 km

Light curves



m = 100 g → h_{max} = 43 km

Nuclearites and meteors comparison



f = 0°

a = 45°

Nuclearites

v = 250 km/s

m = 20 g → h_{max}= 39 km

h = 40 km, 0.0001 km

Meteor *(dotted)*

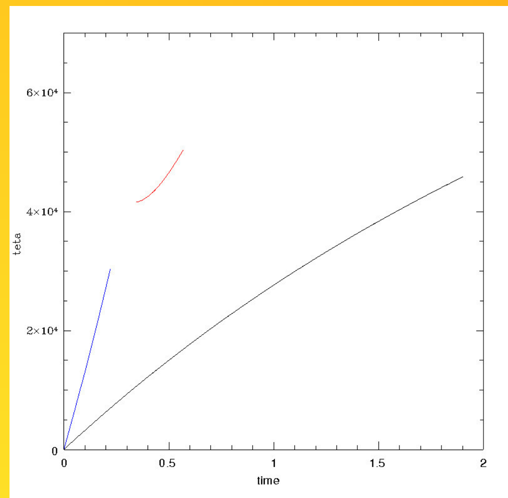
v = 70 km/s h = 100 km

Abs mag =1.7

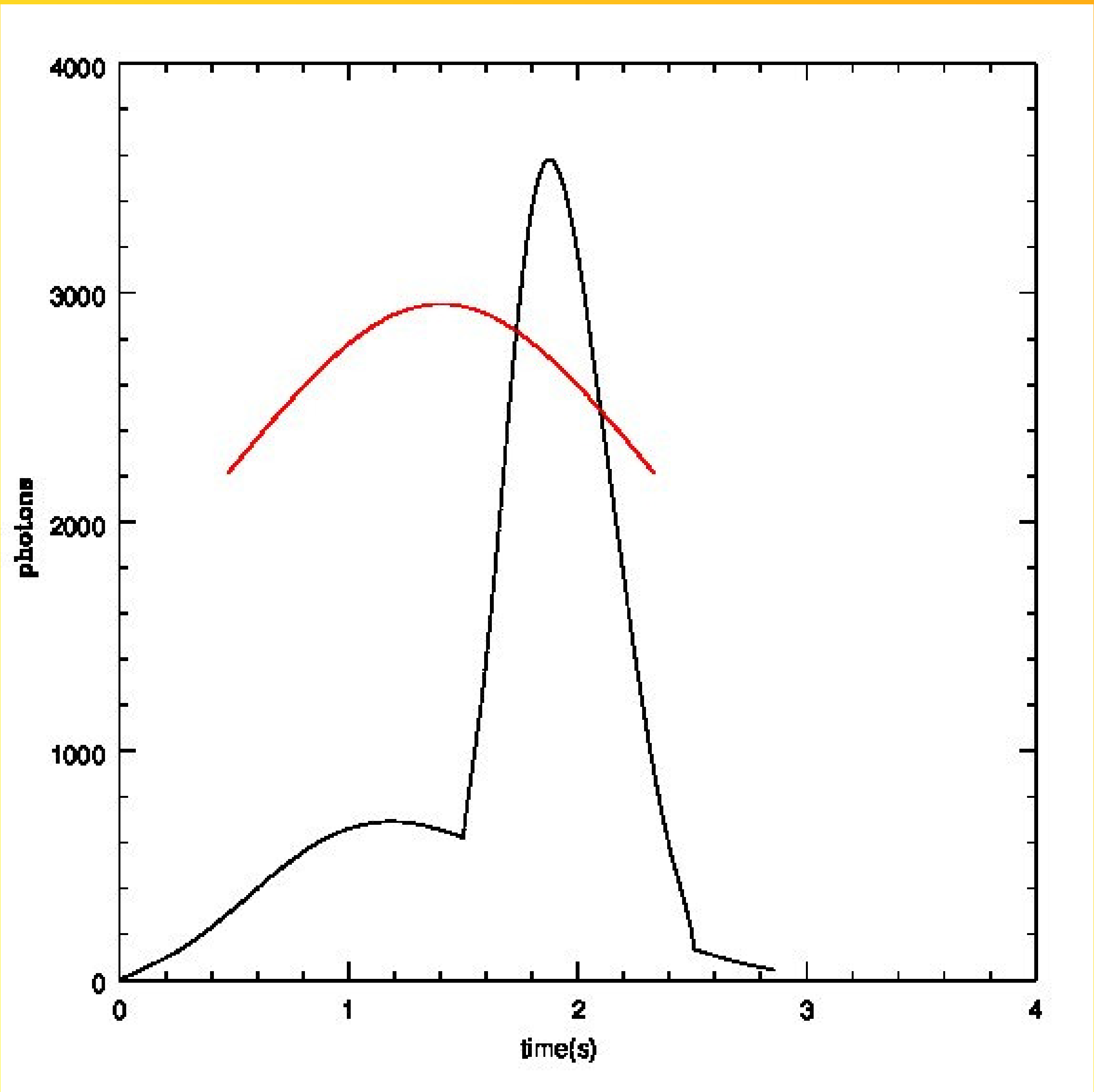
Abs mag sec burst = -1

Instant of beginning sec burst = 0.9 s

Duration = 1.2 s

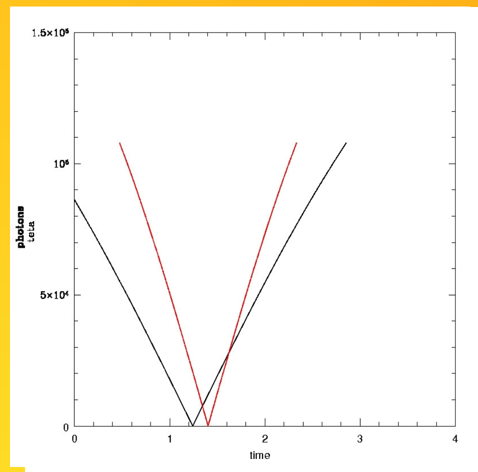


Nuclearites and meteors comparison

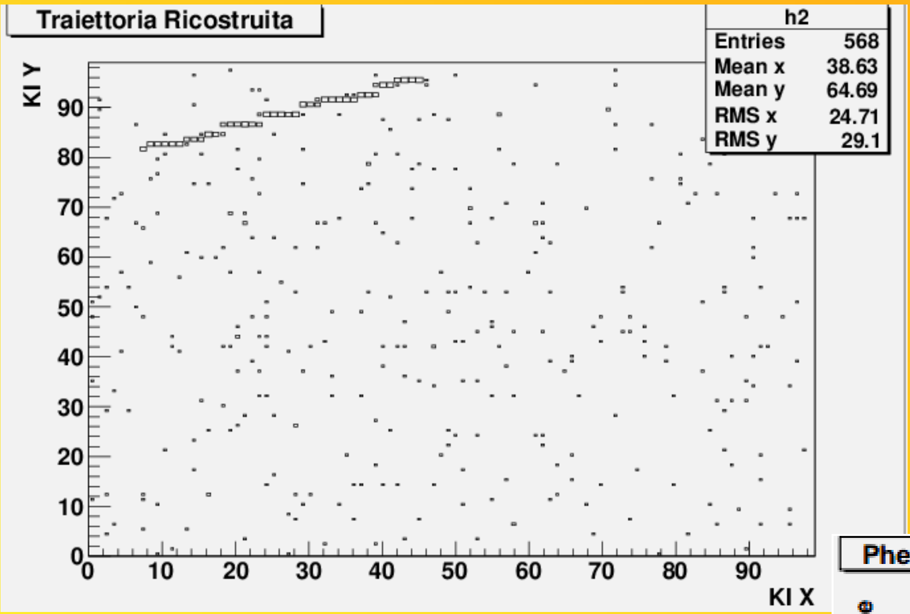


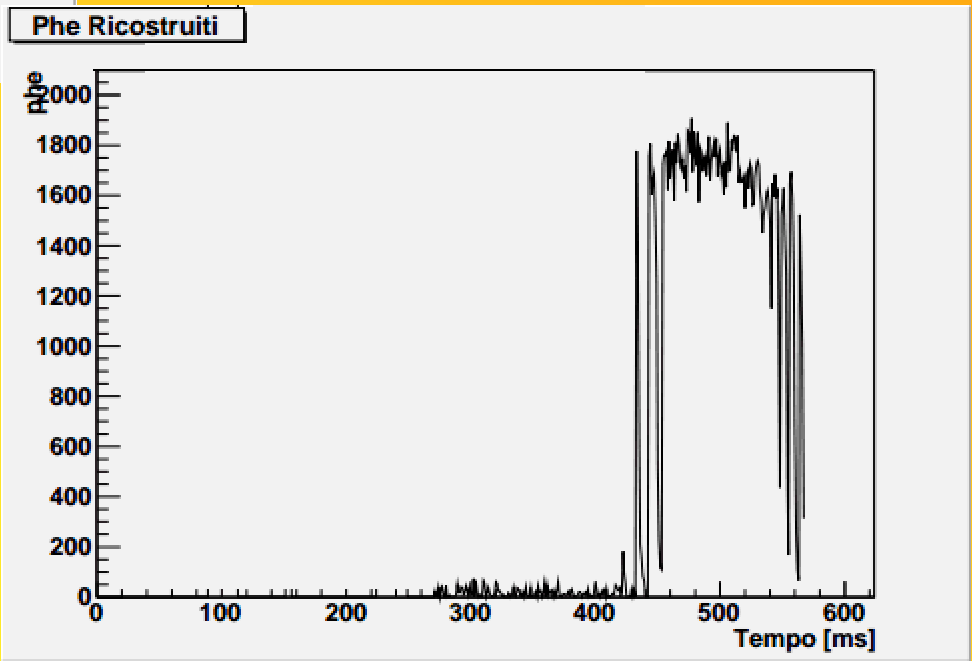
NUCLEARITE
m = 50 g
v = 250 km/s
hmax = 41 km
h = 10 km

METEOR
h=120 km
v=72 km/s
mag= 2.2



Detector results





Meteor limits on flux

magnitude (M)	U-band flux (erg/s/cm^2/A)	photons (s^{-1})	photo-electrons (GTU=2.5μs)$^{-1}$	mass (g)	collisions in JEM-EUSO FoV
7	$6.7 \cdot 10^{-12}$	$4.3 \cdot 10^{7}$	4	$2 \cdot 10^{-3}$	1/s
5	$4.2 \cdot 10^{-11}$	$2.7 \cdot 10^{8}$	23	10^{-2}	6/min
0	$4.2 \cdot 10^{-9}$	$2.7 \cdot 10^{10}$	2300	1	0.27/orbit
-5	$4.2 \cdot 10^{-7}$	$2.7 \cdot 10^{12}$	$2.3 \cdot 10^{5}$	100	6.3/year

m > 3 g

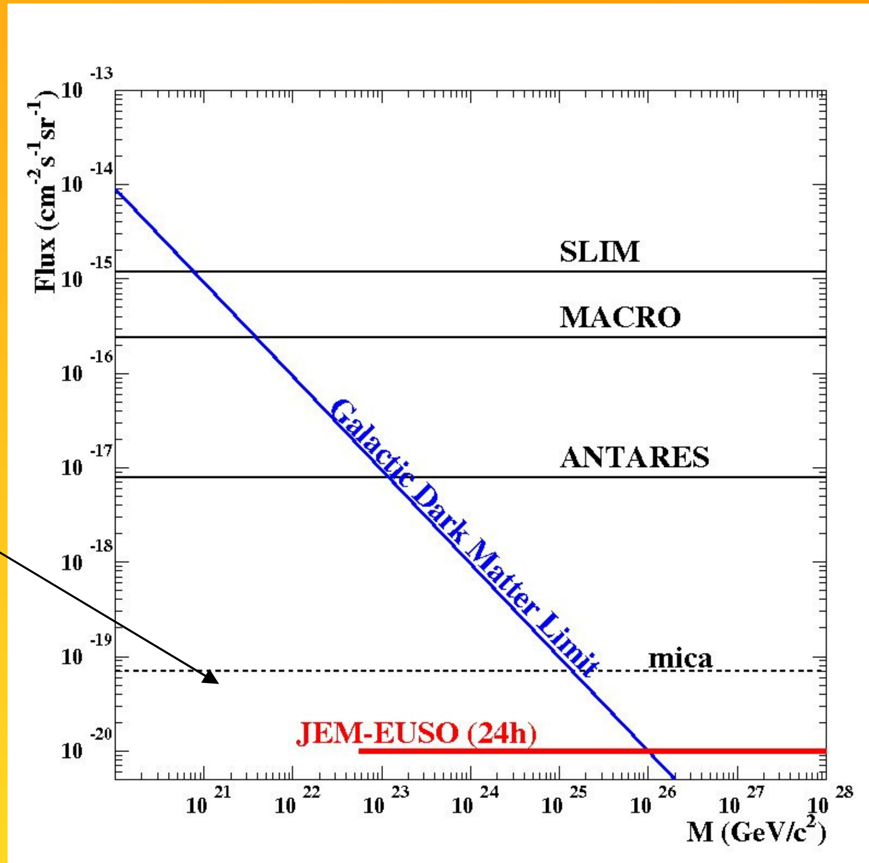
m > 0.1 g

$$M = 15.8 - 1.67 \cdot log_{10}(m/1\mu g).$$

1 eV = $1.6 \cdot 10^{-19}$ J

0.1 g = $1 \cdot 10^{-4}$ Kg = 10^{22} GeV/c^2

v_{proj}^{min} (km s^{-1})	a_{min} (deg.)	R_{acc} (%)
100	23.6	84
130	31.3	73
160	39.8	59
190	49.5	42
220	61.6	23



$$P(\lambda \leq \lambda_0) \int_0^{\lambda_0} T \exp(-\lambda T)\, d\lambda = 1 - \exp(-\lambda_0 T)$$

l_0 : *flux limit* → $\lambda_0 = -\frac{1}{T} \ln(1 - \mathrm{CL})$ → **~$1 \cdot 10^{-20}$ $cm^{-2} \cdot s^{-1} \cdot sr^{-1}$**

T : *geometrical factor* $T = S \cdot t \cdot sr$ → $5.4 \cdot 10^{20}$ $cm^2 \cdot s \cdot sr$ ⟶ **T = $2.27 \cdot 10^{20}$ $cm^2 \cdot s \cdot sr$**

S : surface = **$2 \cdot 10^{15}$ cm^2**

t : acquisition time = **86000 s**

sr : solid angle = **p**

CL : *confidence level* → 0.9

Conclusions

Nuclearites are noticeable from meteors (ligth curves, θ(t))

*JEM-EUSO will be sensitive to nuclearites with mass higher than a few 10^{22} GeV/c^2 and will be able, **after a run time of only 24 h**, to provide limits on nuclearite flux lower by **one order of magnitude** with respect to the limits of the experiments carried out so far, and lower than the dark matter limit.*

Limits on flux will be improved by one or two orders of magnitude after a run time of one or two years.

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