SQM-ISS: Update on the activity and ESA implementation

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On behalf of the SQM-ISS group
S. Blin, M. Casolino, D. Pilot, F. Liberatori, A. Marcelli, L. Marcelli, E. Parizot, E. Reali, J. Szabelski et al.

The 37th JEM-EUSO meeting, June 6th 2025, APC - Paris

SQM - stable matter containing strange quarks

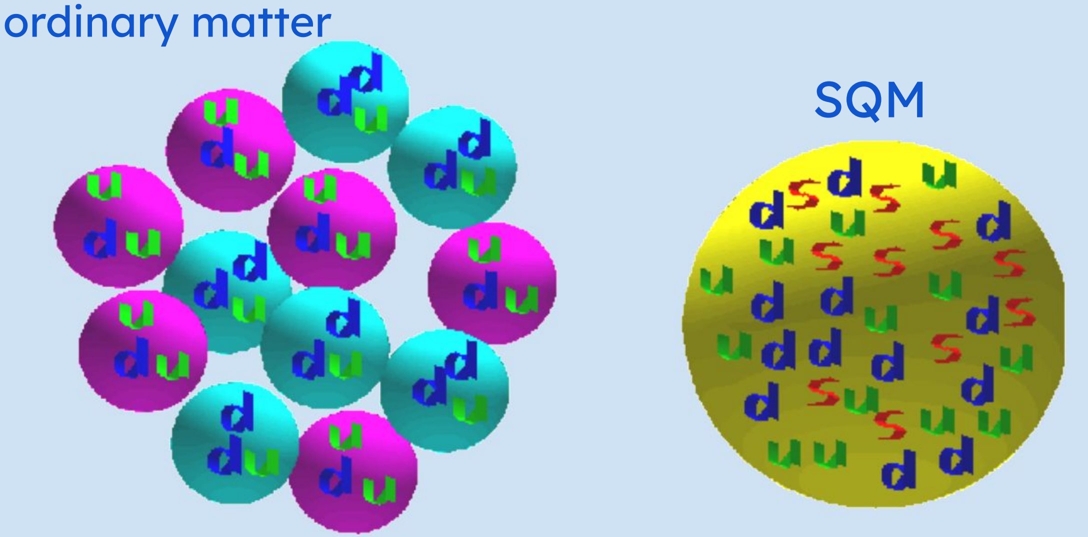
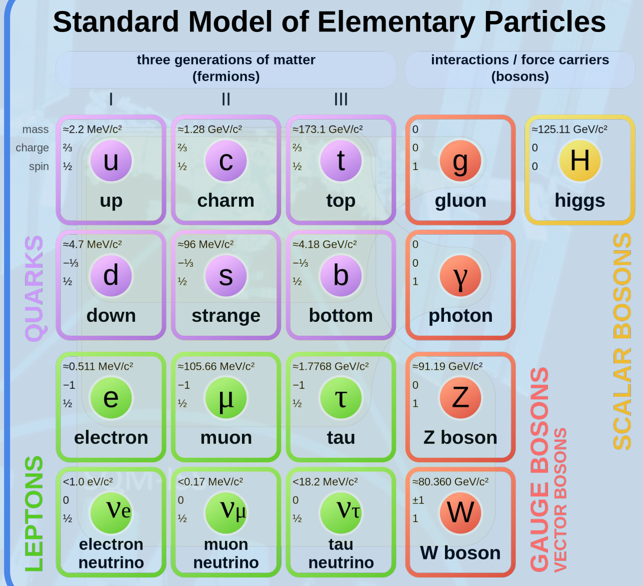


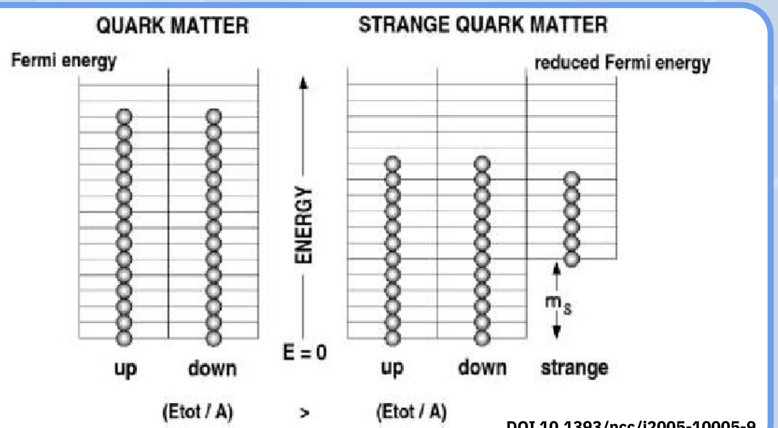
Figure: Finch, E. Strangelets: Who is looking and how?, 2006



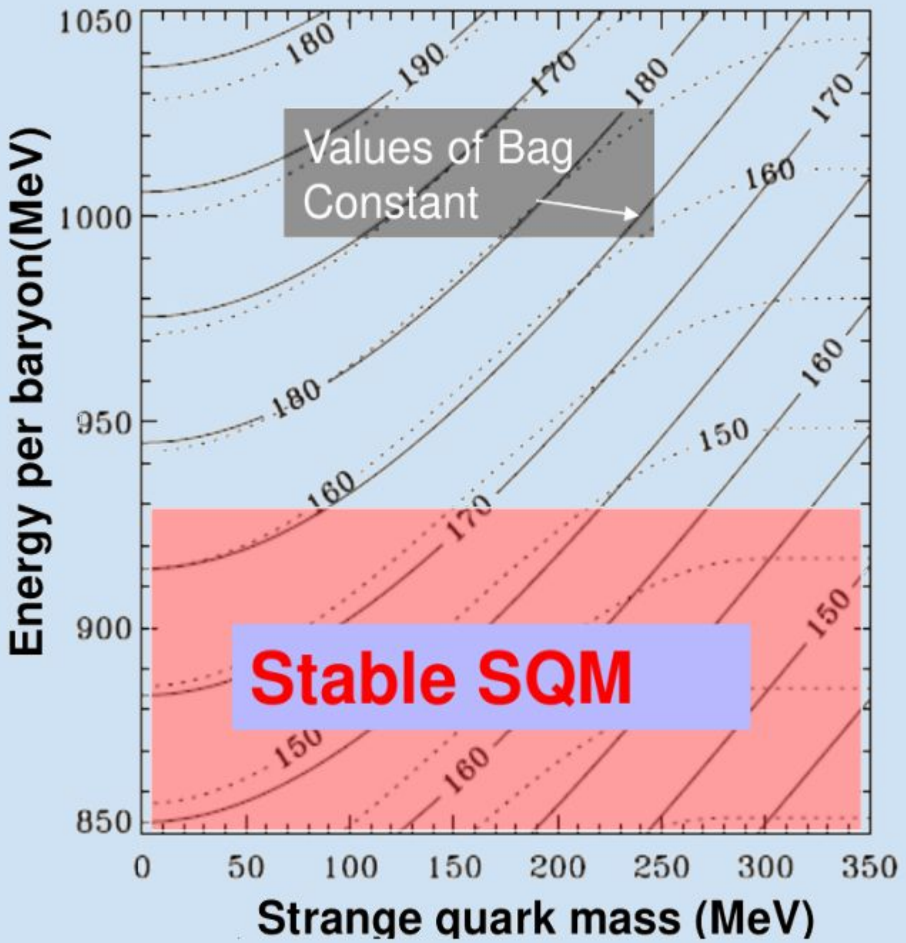
The idea of Strange Quark Matter (SQM) suggests that matter composed of up (u), down (d), and strange (s) quarks can form stable, large droplets due to its potentially lower energy per baryon compared to ordinary nuclear matter. The inclusion of strange quarks, reduces degeneracy pressure and creates a more energetically favorable state. This stability is theorized to occur in extreme astrophysical environments like neutron star cores or remnants from the early universe.

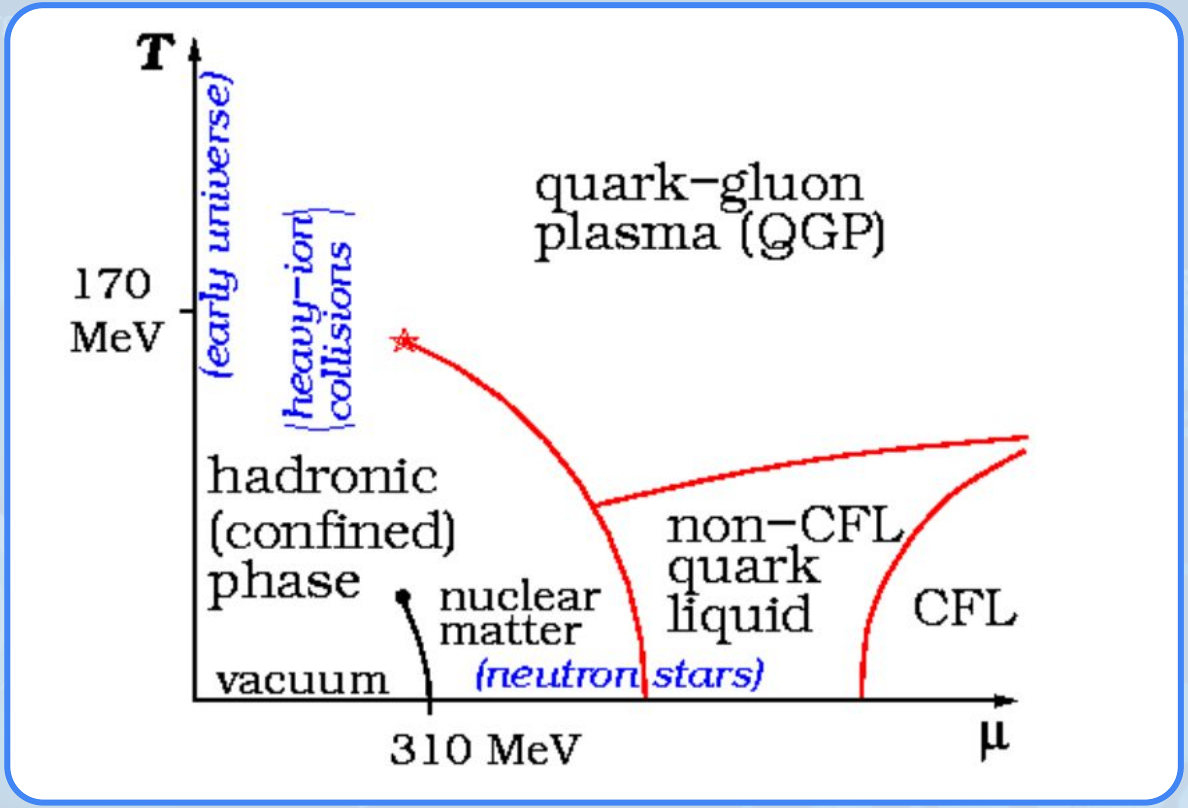
No new physics required

- lower Fermi energy per nucleon with quark s
- lower Z/A due to cancelation of charge
- no limits for A number (possible huge clusters of strange 'baryons')



DOI 10.1393/ncc/i2005-10005-9



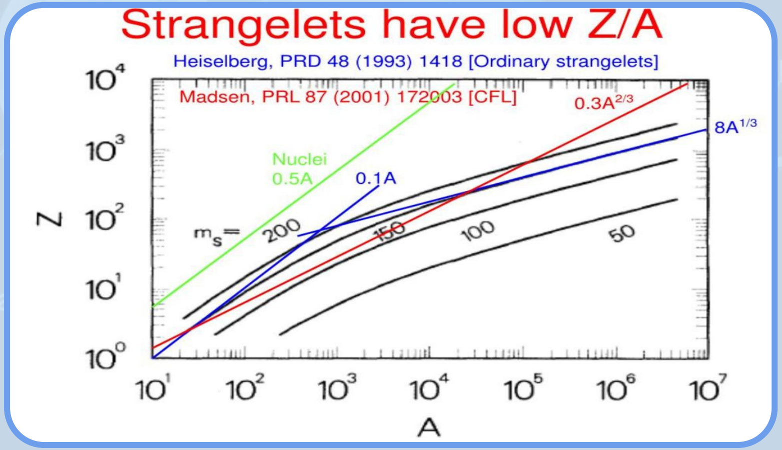


Phase diagram of Quantum Chromodynamics (QCD) as a function of temperature T and baryon chemical potential μ. The diagram shows the transition from the hadronic (confined) phase to the quark-gluon plasma (QGP), including regions of non-CFL and CFL deconfined quark matter. The CFL phase is particularly relevant for the possible stability of SQM at high densities and low temperatures, as found in compact stars.

Two phases of SQM

Ordinary SQM (non CFL):

- Potentially produced in accelerators
- High temperature 100 - 300 MeV
- A_{min}: 50-300
- Non-stable, lifetime ~10^{-23}s
- **Charge: Z between 0.1A and $8A^{1/3}$**



Colour-Flavour-Locked SQM:

- Produced in neutron stars
- Low temperature, few MeV
- A_{min}: 10-50
- Stable, lifetime infinite
- **Charge: $Z \sim 0.3A^{2/3}$** **Madsen PRL 87 (2001) 172003**
- **CLF** is the highest-density phase of three-flavor colored matter within the SM

Charged strangelets should give detectable signal in scintillators

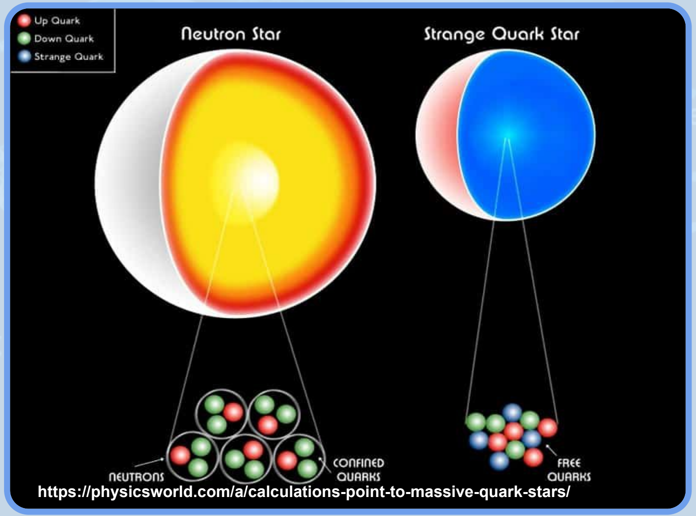
Source:
https://www.slideserve.com/russ/strangelets-and-nuclearites-an-overview

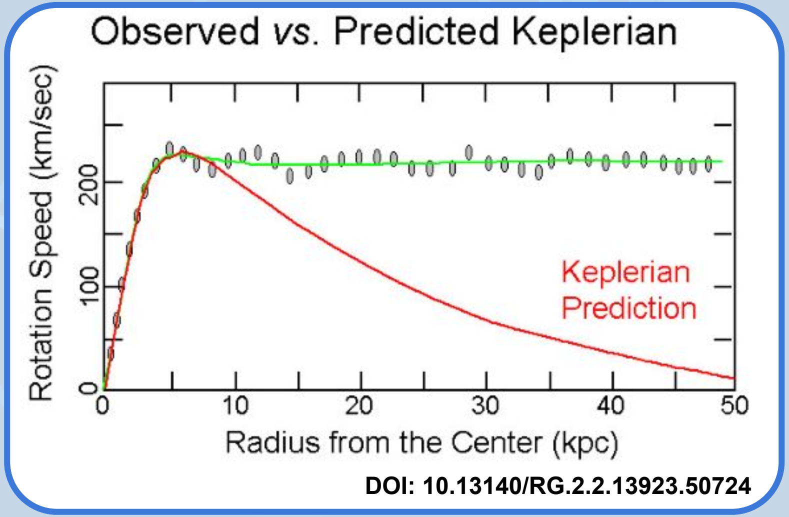
Astrophysical implications of SQM

SQM potentially produced in:

- Big bang
- Neutron stars, collisions
- Quark (strange) stars
- LHC (ALICE), RHIC (STAR)

SQM matter is a good candidate for DM!!!



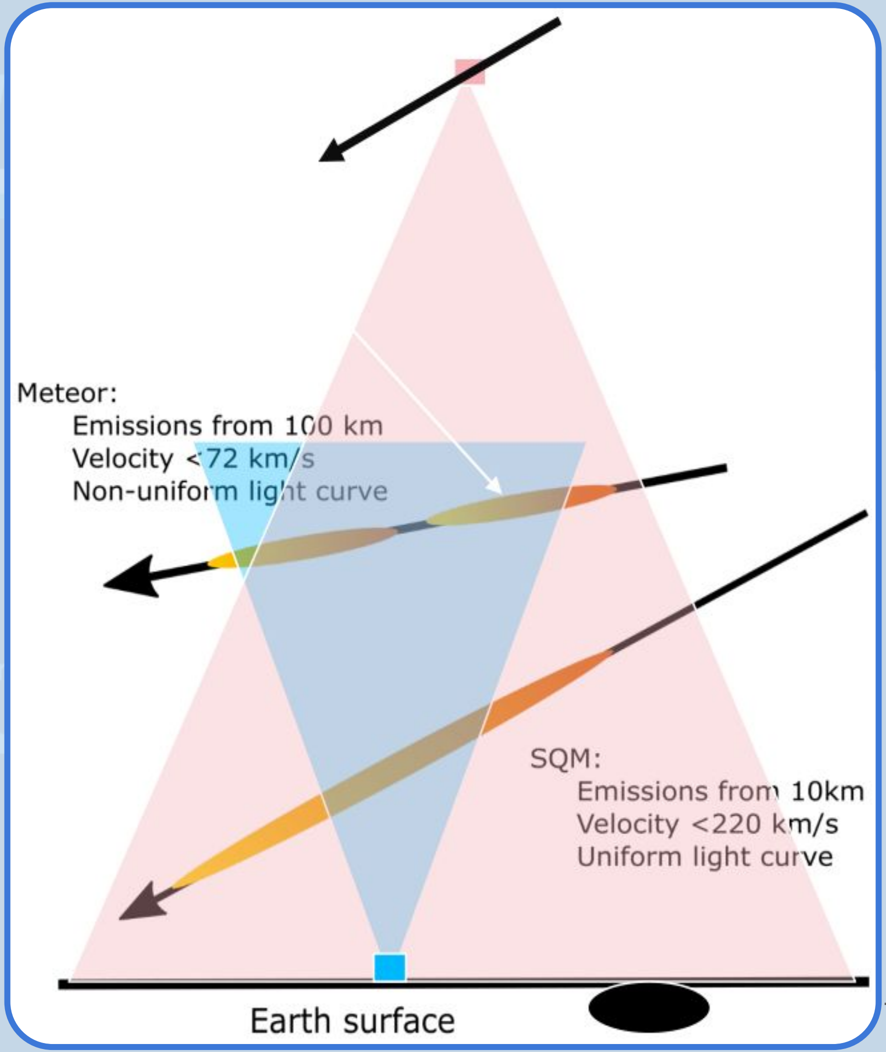


SQM / MACROS detection

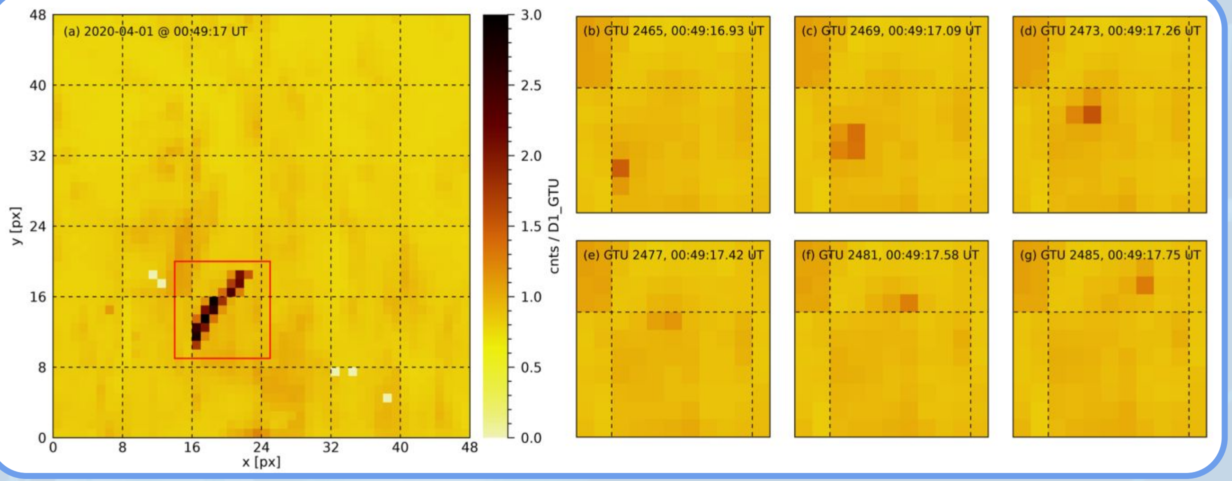
Direct (live)
- PAMELA (2006-2016)
- AMS-02 (2011-now)
- SQM-ISS (proposed/under construction

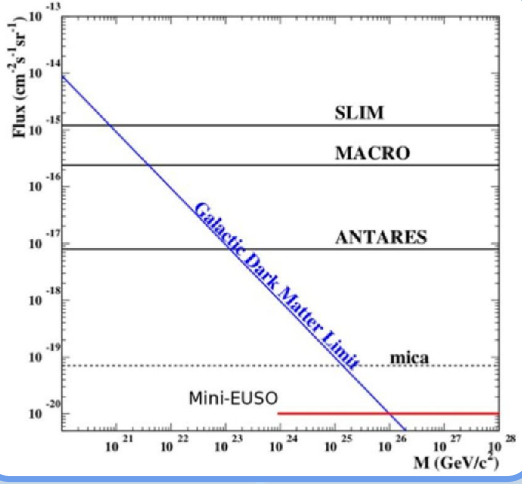
Indirect (atmospheric)
- Mini-EUSO
- DIMS

Direct (“dead/dying”)
- Moon soil
- Earth soil
- Mica tracks
- Impact craters
- Seismometers



Mini-EUSO - meteors and nuclearites

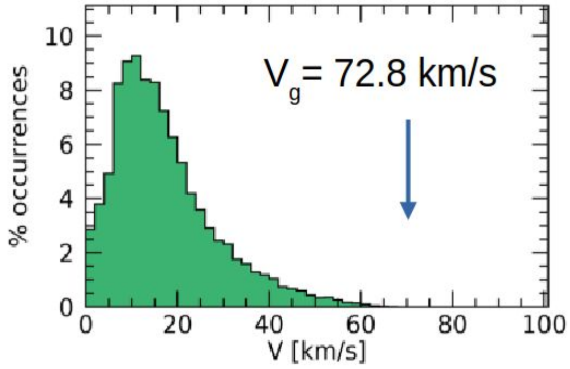




- Intensity range: magnitudes ranging from +7 (limiting magnitude) to approximately -3.
- Dataset: 24,000 meteors recorded during 40 observation sessions.
- Duration: Typical durations ranged from 0.5 to 2.25 seconds.
- **Only three potential interstellar meteors with 85 ± 15 km/s, 87 ± 33 km/s and 98 ± 21 km/s**

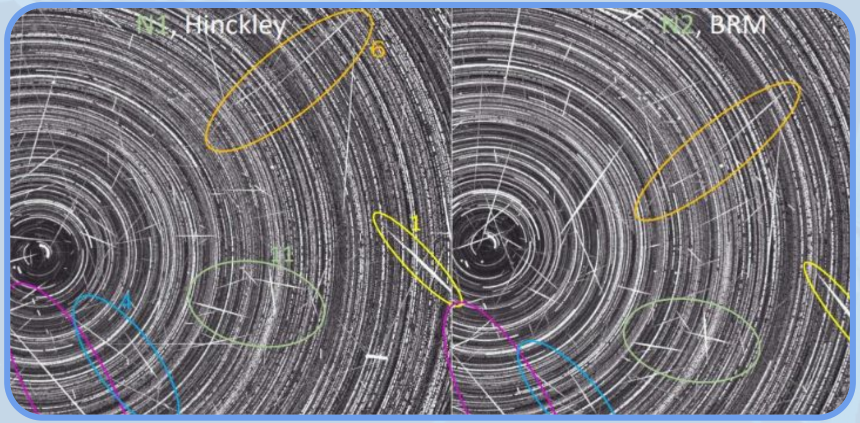
Observation of meteors from space with the Mini-EUSO detector on board the International Space Station A&A, 687, A304 (2024)

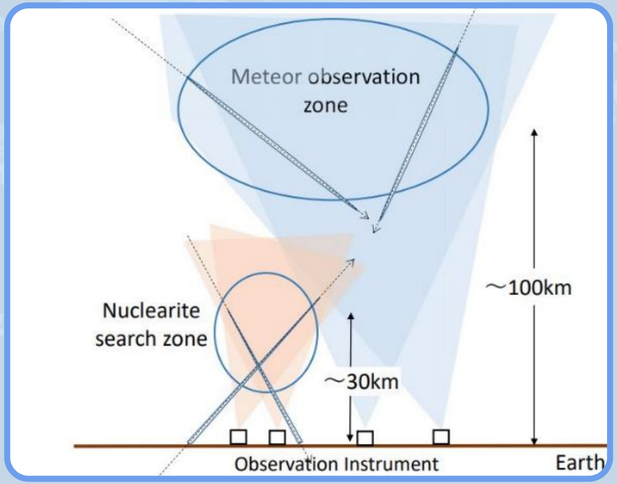
For more details see poster by L. Marcelli, 15.05, 22:14

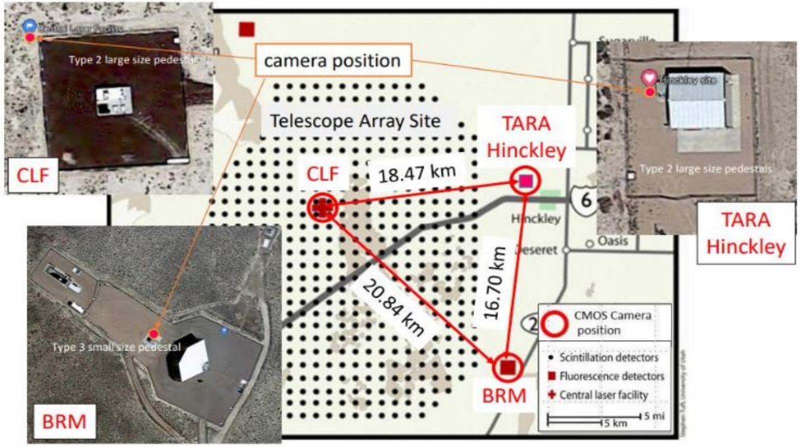


DIMS, F. Kajino, Konan University

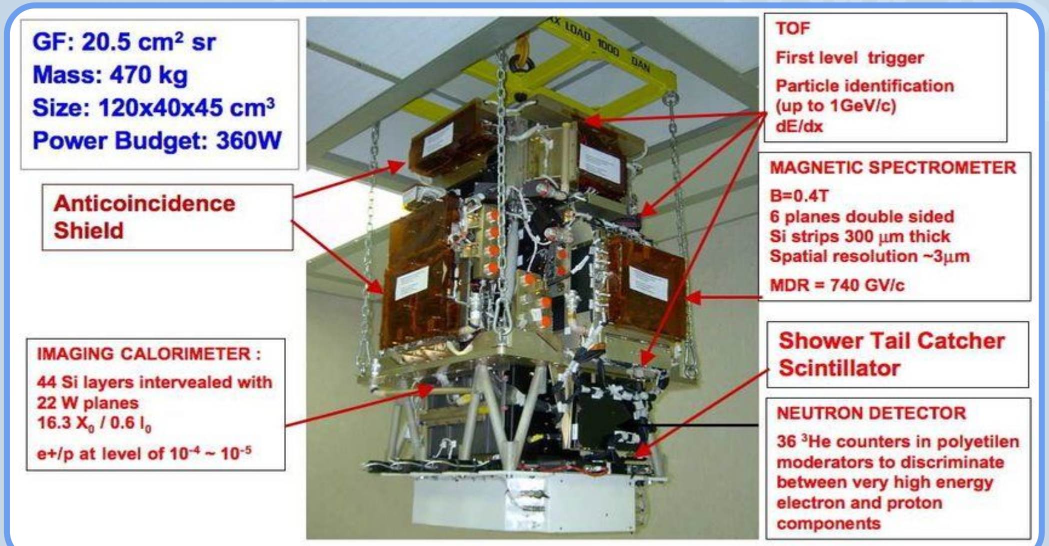
Observation at TA-BRM
Aug. 31, 2019

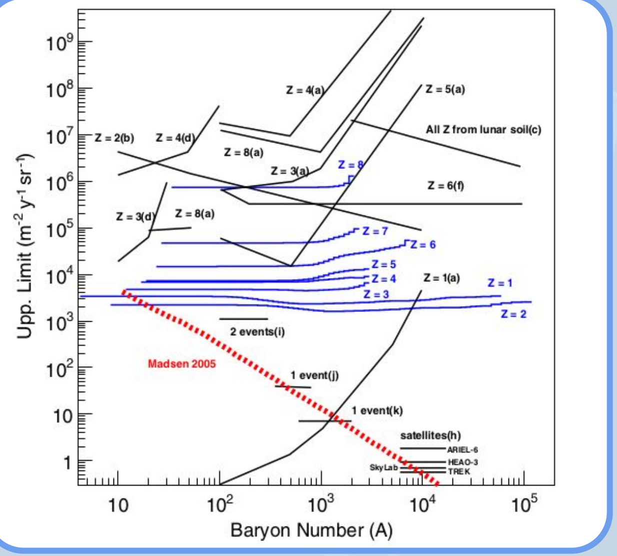


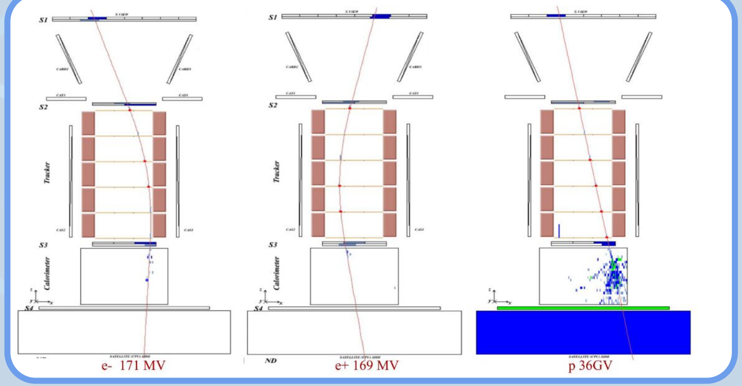




Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

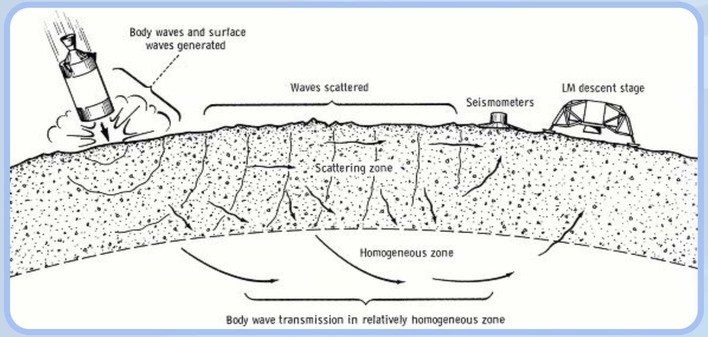




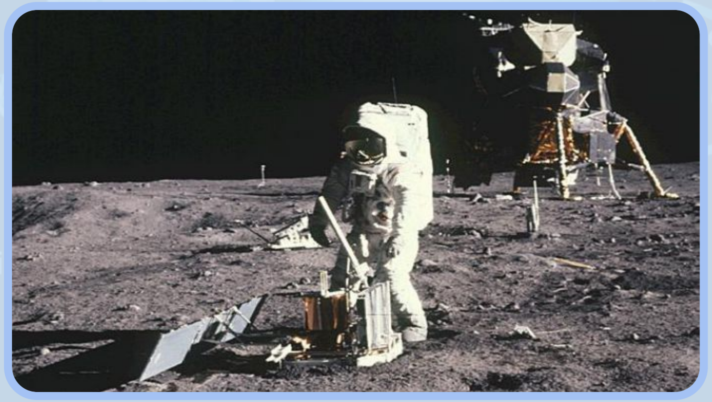


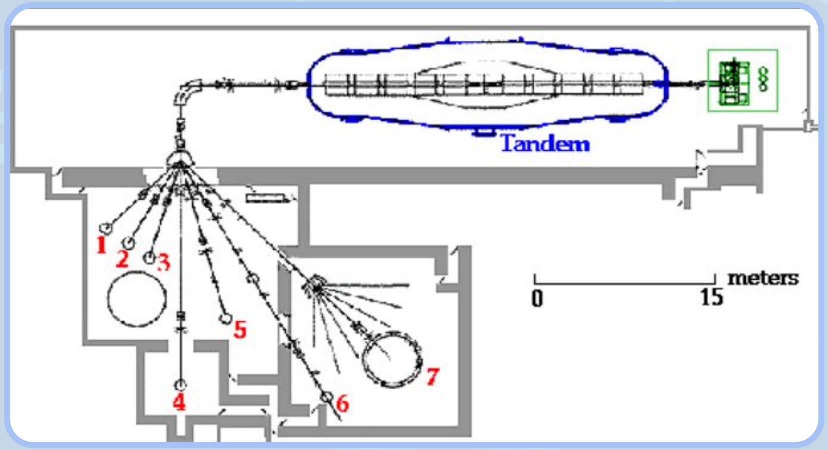
- No evidence of Strange Quark Matter was detected by PAMELA
- Strict upper limit for SQM flux was set at 10^{-8} $cm^{-2}s^{-1}sr^{-1}$ for particles with masses around 10^{-8}g
- SQM is extremely rare or undetectable with current experimental sensitivity
- Detection of high-A particles is challenging due to their low Z/A ratios

Lunar seismometers and soil mass spectrometry

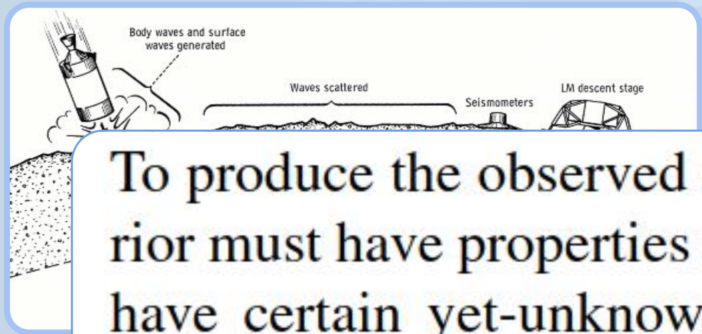


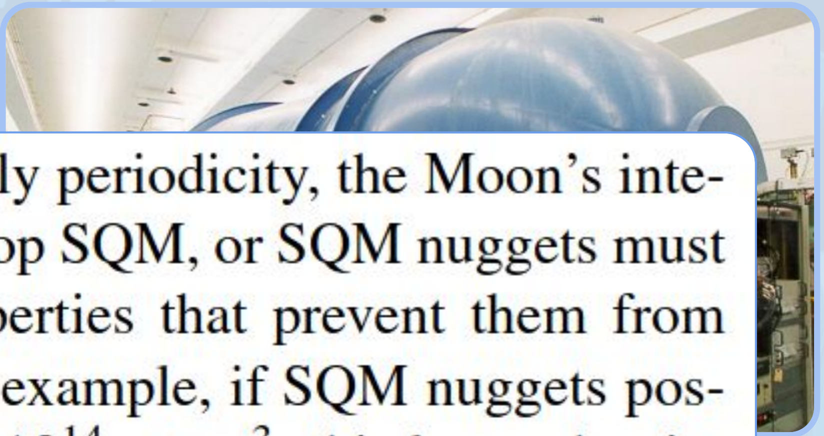
Apollo seismometers, 28 events
Nakamura, Frohlich, Icarus 185 (2006) 21–28



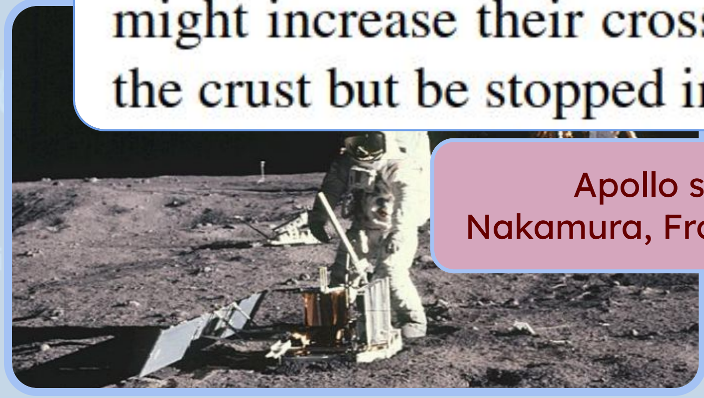


Lunar seismometers and soil mass spectrometry





To produce the observed monthly periodicity, the Moon's interior must have properties that stop SQM, or SQM nuggets must have certain yet-unknown properties that prevent them from passing through the Moon. For example, if SQM nuggets possess a density much lower than 10^{14} g/cm^3, this lower density might increase their cross section and allow them to penetrate the crust but be stopped in the mantle.



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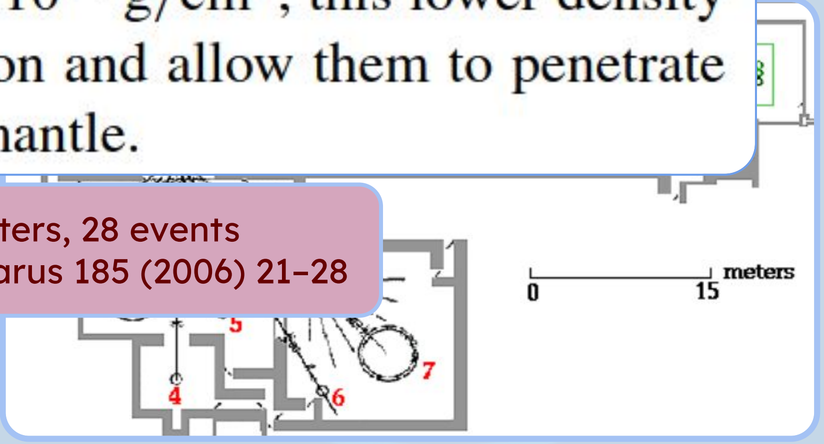
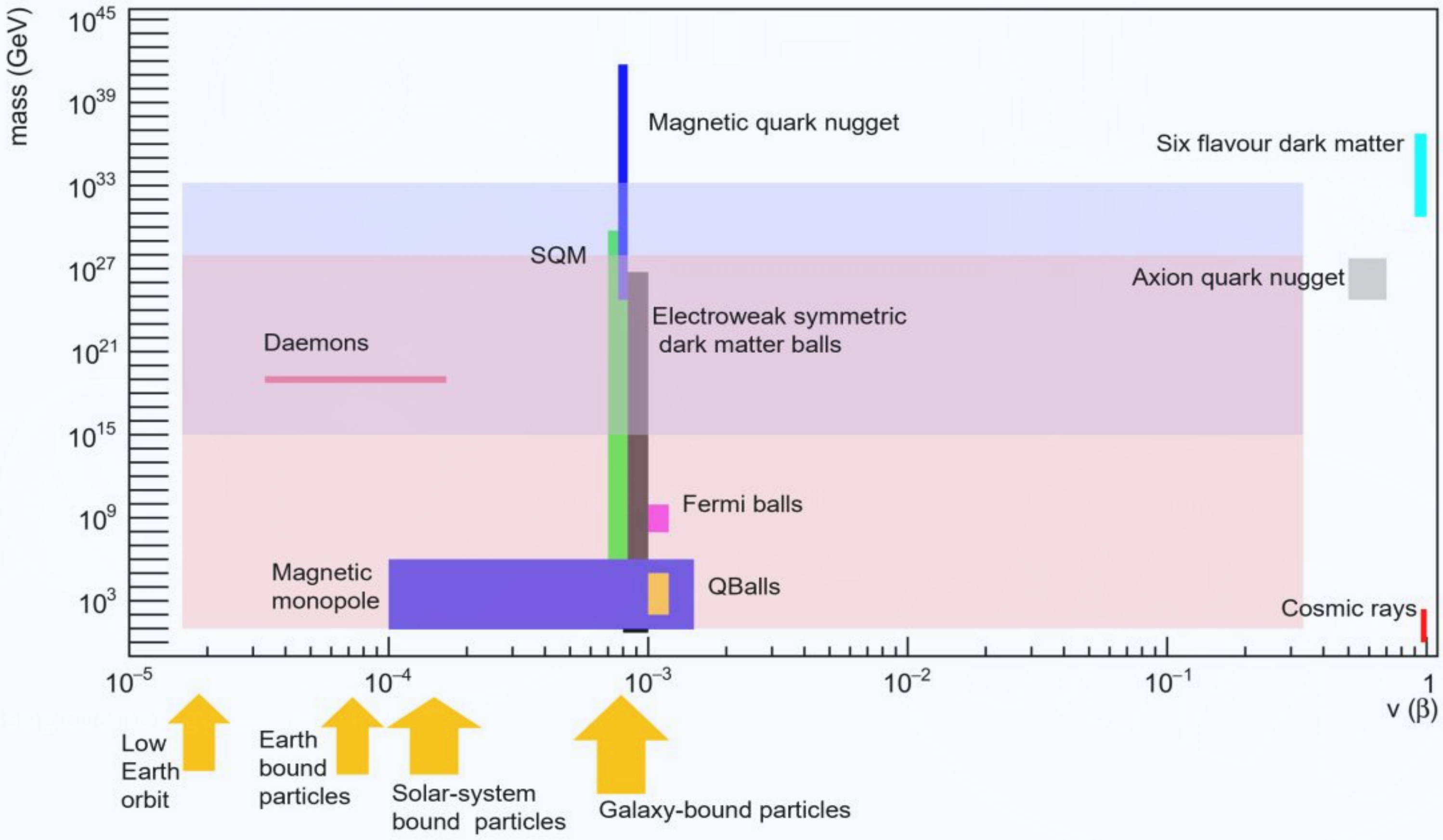
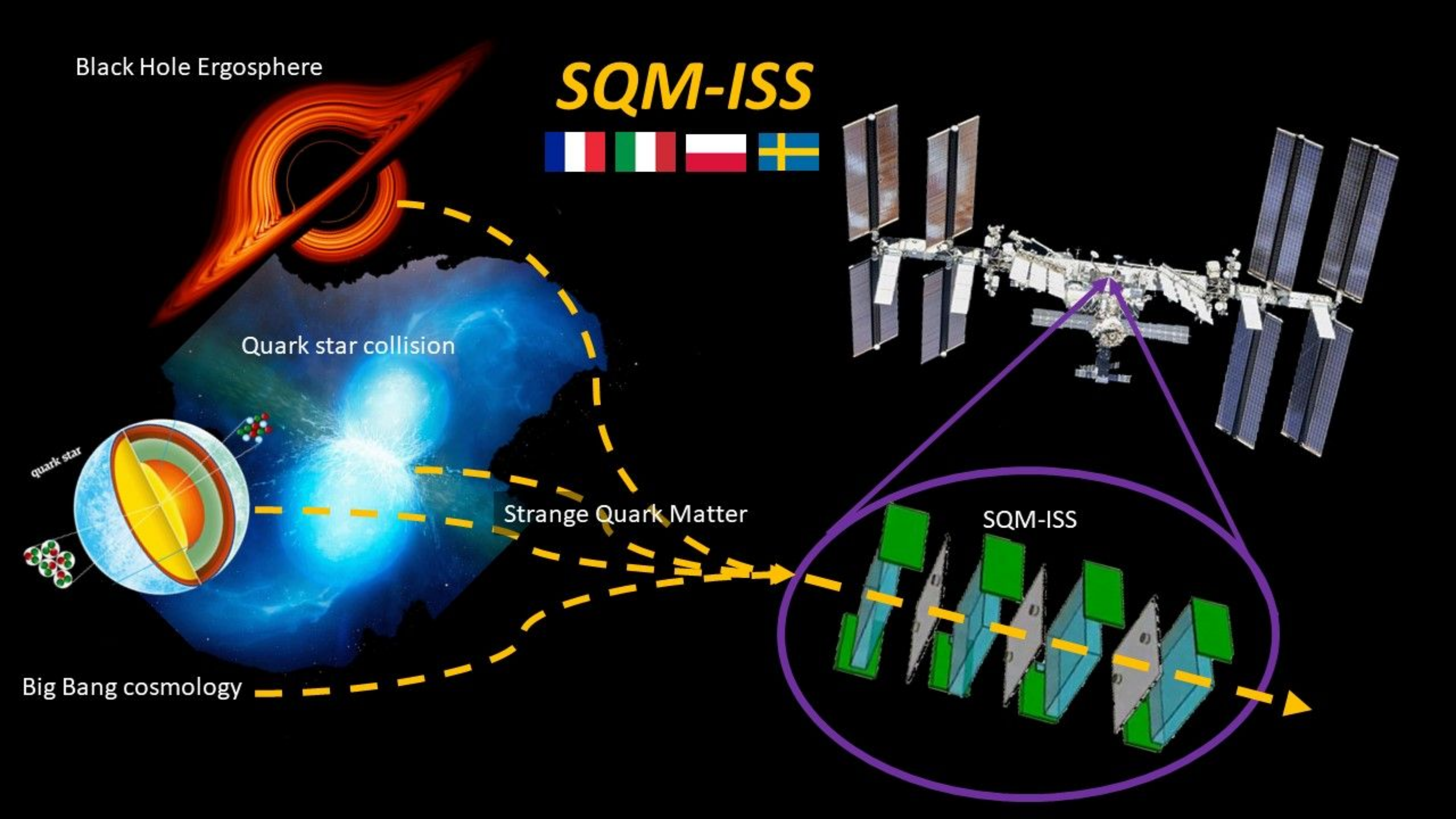
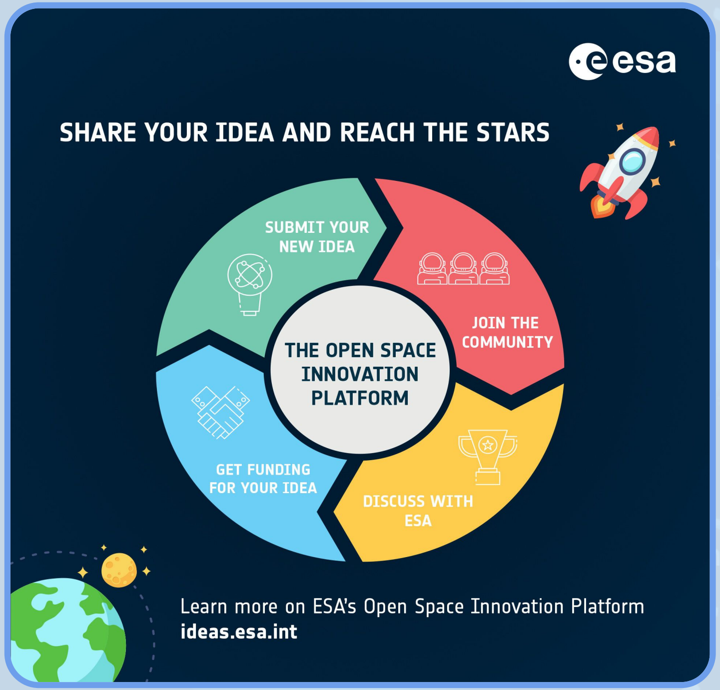


Zoology of slow compact objects



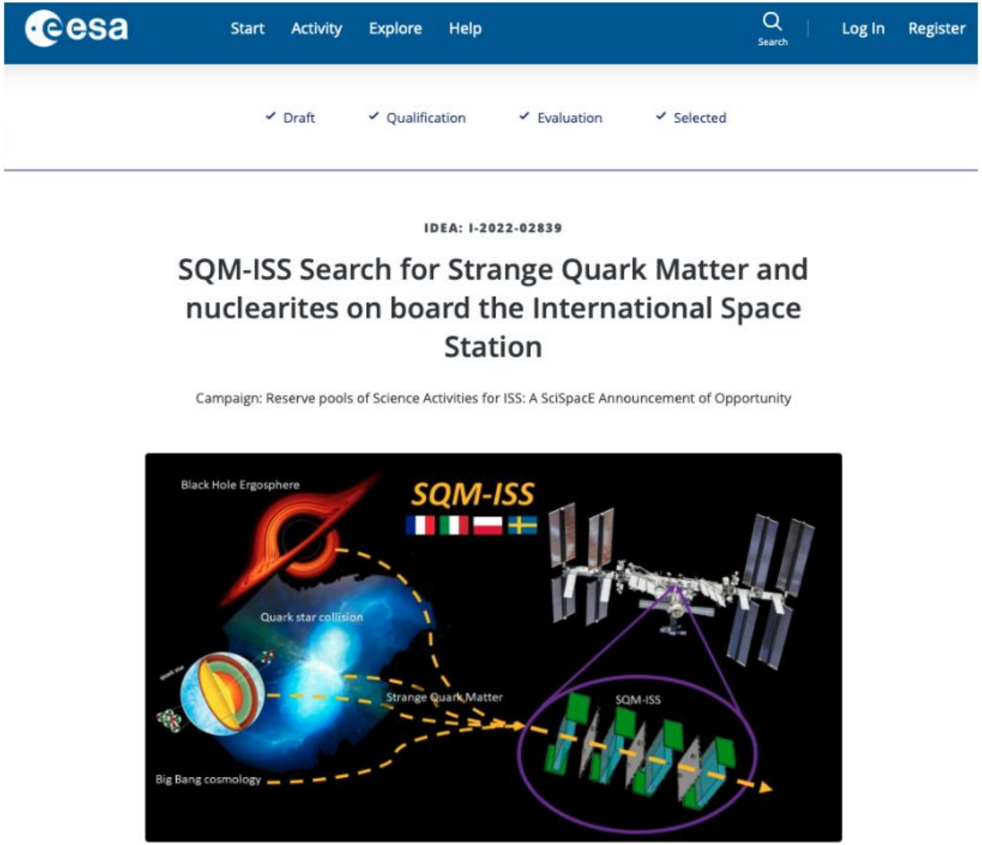

Black Hole Ergosphere
SQM-ISS
Quark star collision
quark star
Strange Quark Matter
SQM-ISS
Big Bang cosmology

SQM-ISS proposal submitted in 2022

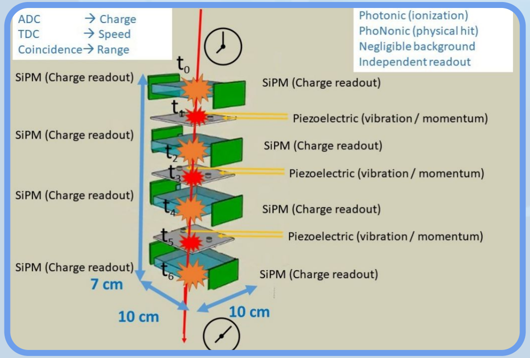


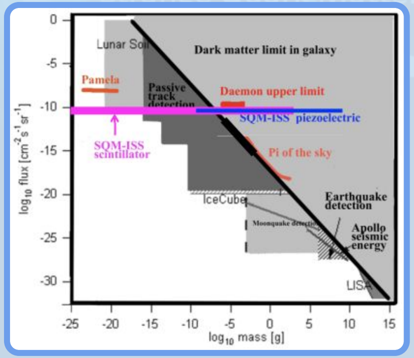
The Open Space Innovation Platform (OSIP)

SQM-ISS selected as “excellent” idea from ESA



SQM-ISS observational approach





sensors

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Search for Strange Quark Matter and Nuclearites on Board the International Space Station (SQM-ISS): A Future Detector to Search for Massive, Non-Relativistic Objects in Space

Massimo Bianchi [1], Francesca Bisconti [1], Carl Blaksley [2], Valerio Bocci [3], Marco Casolino [1,2,4,*], Francesco Di Clemente [5], Alessandro Drago [5], Christer Fuglesang [6], Francesco Iacoangeli [3], Massimiliano Lattanzi [7], Alessandro Marcelli [1], Laura Marcelli [4,*], Paolo Natoli [5], Etienne Parizot [8], Piergiorgio Picozza [1], Lech Wiktor Piotrowski [9], Zbigniew Plebaniak [1,4], Enzo Reali [1], Marco Ricci [10], Alessandro Rizzo [11], Gabriele Rizzo [12] and Jacek Szabelski [13]

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check for updates

Citation: Bianchi, M.; Bisconti, F.; Blaksley, C.; Bocci, V.; Casolino, M.; Di Clemente, F.; Drago, A.; Fuglesang, C.; Iacoangeli, F.; Lattanzi, M.; et al. Search for Strange Quark Matter and Nuclearites on Board the International Space Station (SQM-ISS): A Future Detector to Search for Massive, Non-Relativistic Objects in Space. *Sensors* **2024**, 24, 5090. https://doi.org/10.3390/s24165090

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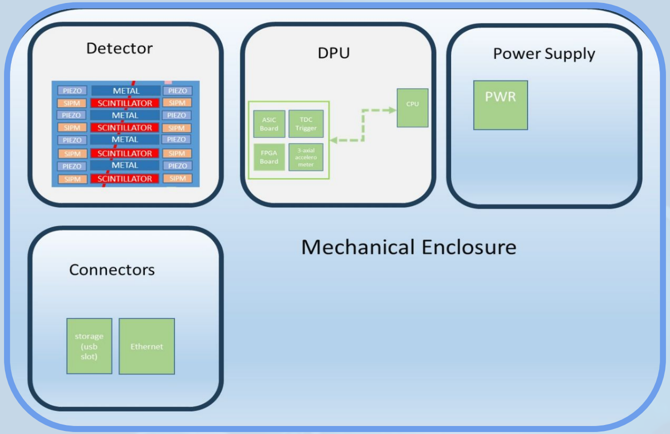
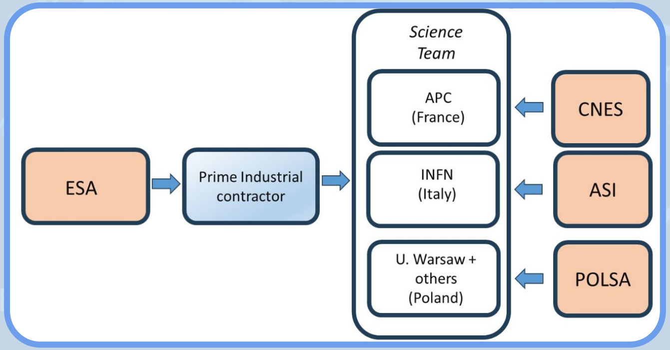
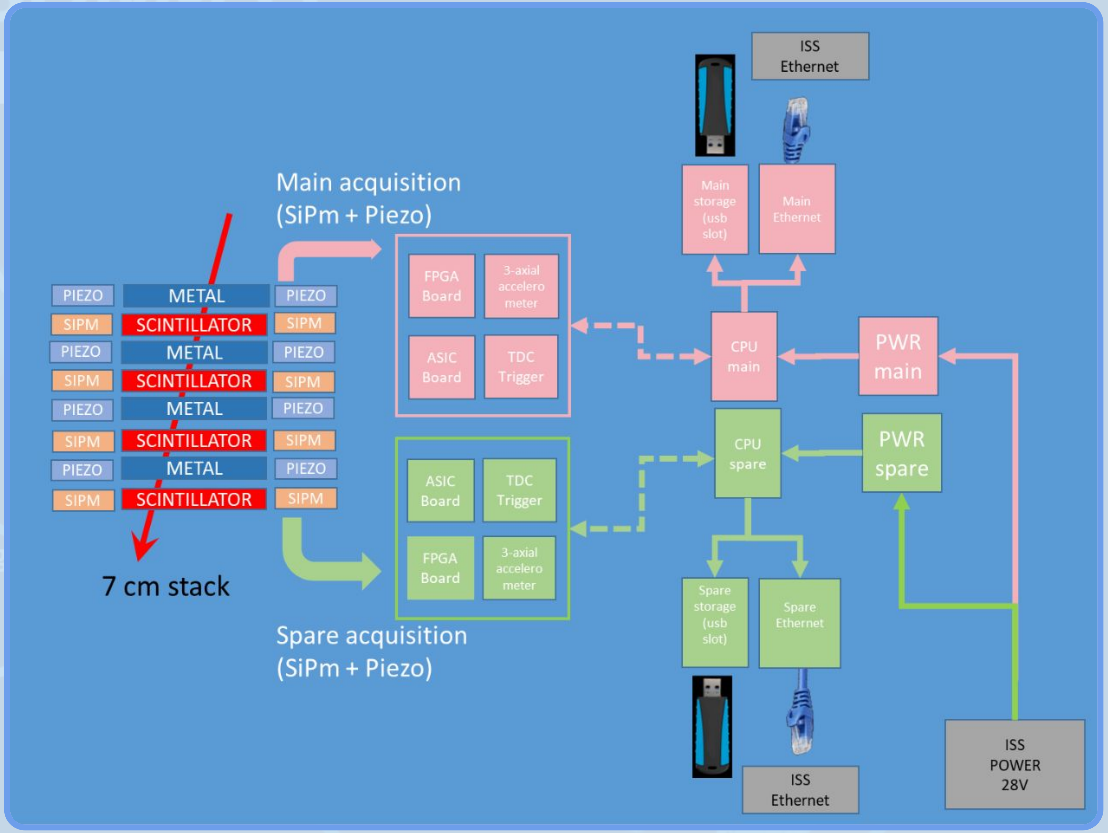
Abstract: SQM-ISS is a detector that will search from the International Space Station for massive particles possibly present among the cosmic rays. Among them, we mention strange quark matter, Q-Balls, lumps of fermionic exotic compact stars, Primordial Black Holes, mirror matter, Fermi balls, etc. These compact, dense objects would be much heavier than normal nuclei, have velocities of galaxy-bound systems, and would be deeply penetrating. The detector is based on a stack of scintillator and piezoelectric elements which can provide information on both the charge state and mass, with the additional timing information allowing to determine the speed of the particle, searching for particles with velocities of the order of galactic rotation speed ($v \lesssim 250$ km/s). In this work, we describe the apparatus and its observational capabilities.

Keywords: strange quark matter; SQM; ISS; space detector

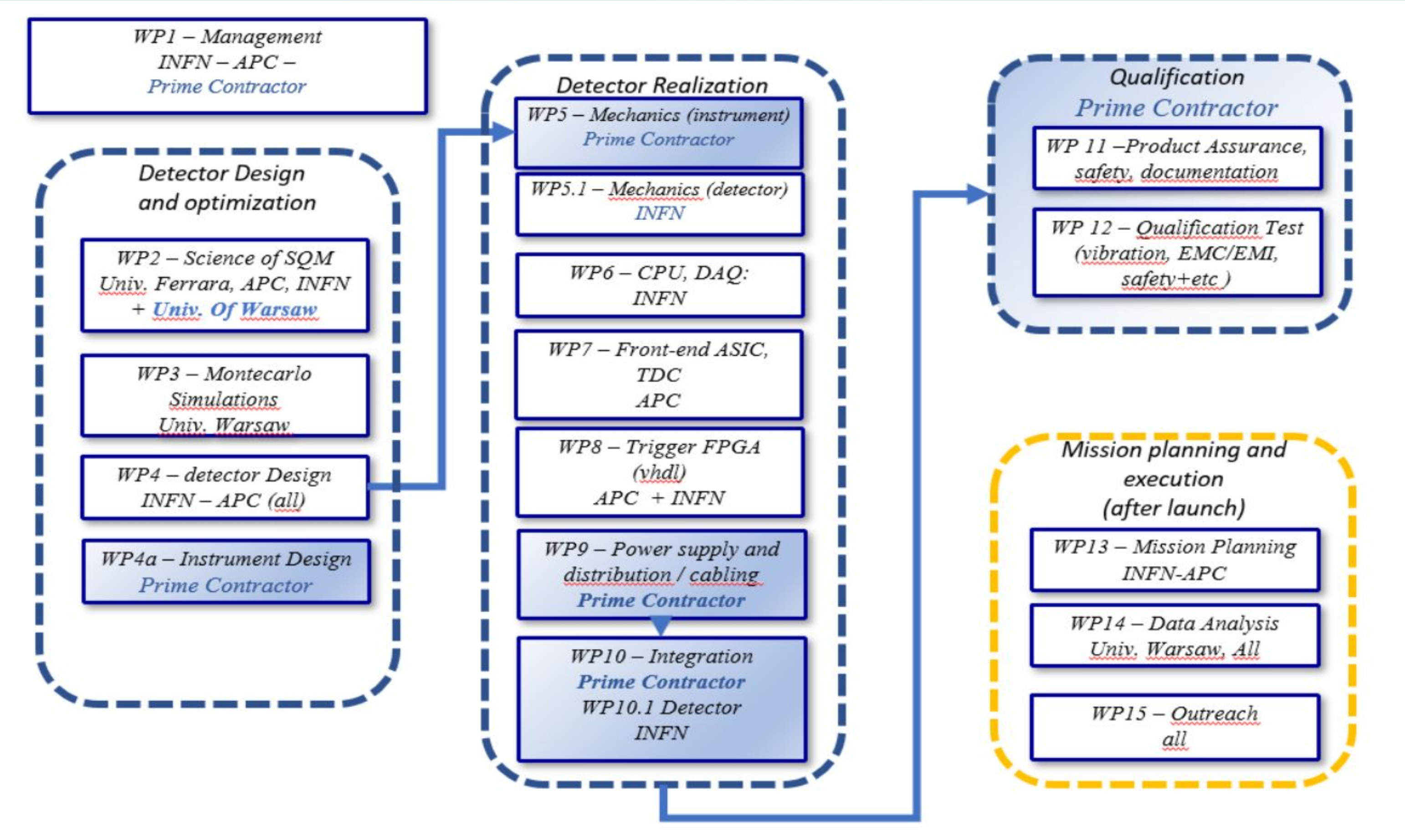
SQM-ISS - block and the functional schemes



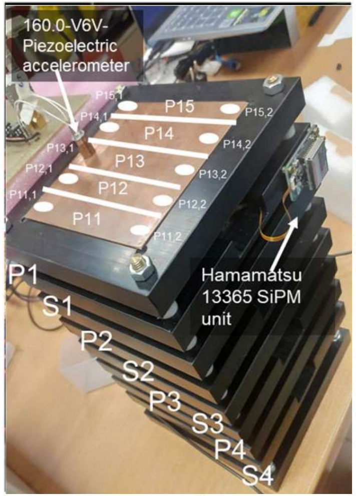


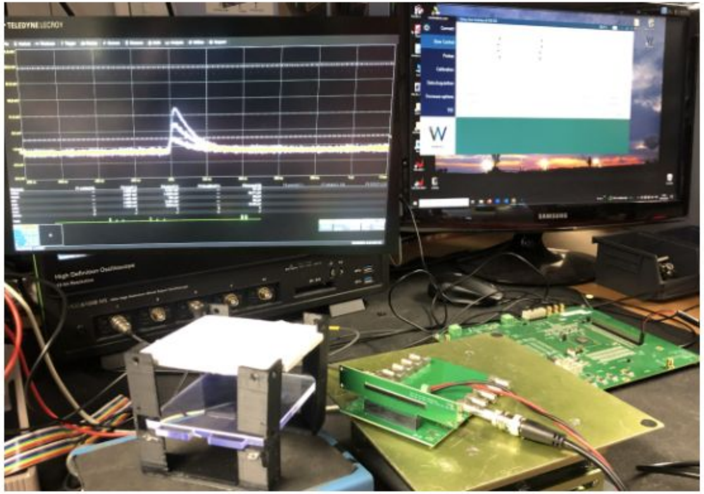


SQM-ISS Work Breakdown Structure



SQM-ISS laboratory model in preparation



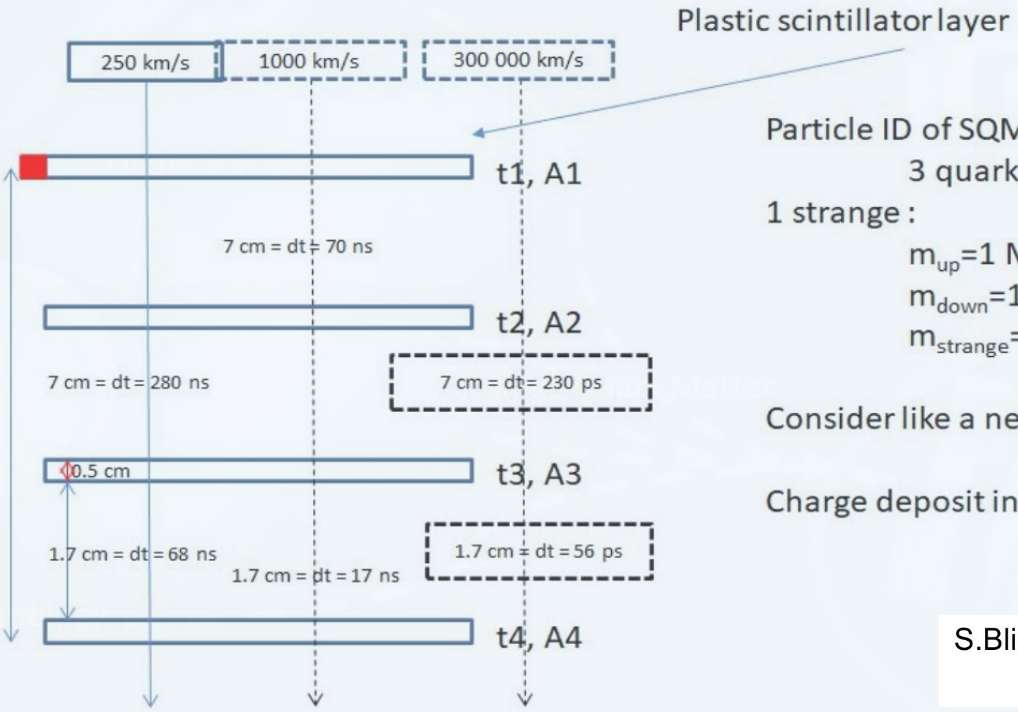


- Geometrical factor: 111cm^{2}sr for 4 plates, 154cm^{2}sr for three plates coincidence
- Each scintillator plate is read by 10 SiPMs, two per strip
- ToF window between 2.5 - 25 µs for particles at SEECHO, NEACHO, and GESCO
- Power consumption ~35W
- Minimal charge Z≥4 to eliminate background, low energy protons (e.g. SAA)

Scintillating detector and Time of Flight - first tests

« Timing science » ?

Single ns required for SQM



Particle ID of SQM :
3 quarks : 1 up, 1 down et
1 strange :
m_{up}=1 MeV
m_{down}=1 MeV
$m_{strange}$=150 MeV

Consider like a neutral particle

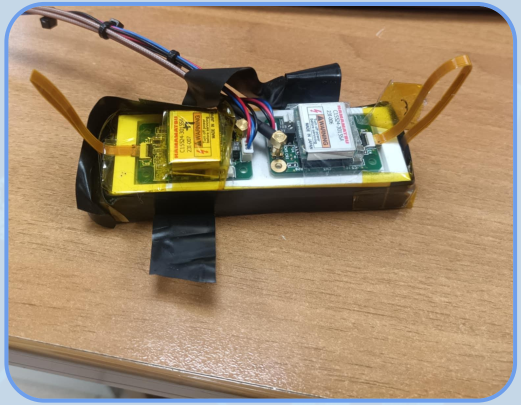
Charge deposit in plastic by SQM ?

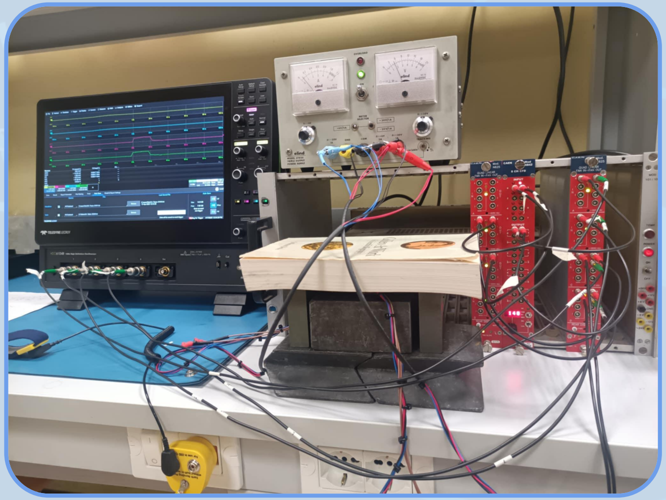
S.Blin, E.Parizot, D.Pailot
APC

Scintillating detector and Time of Flight - first tests of laboratory model

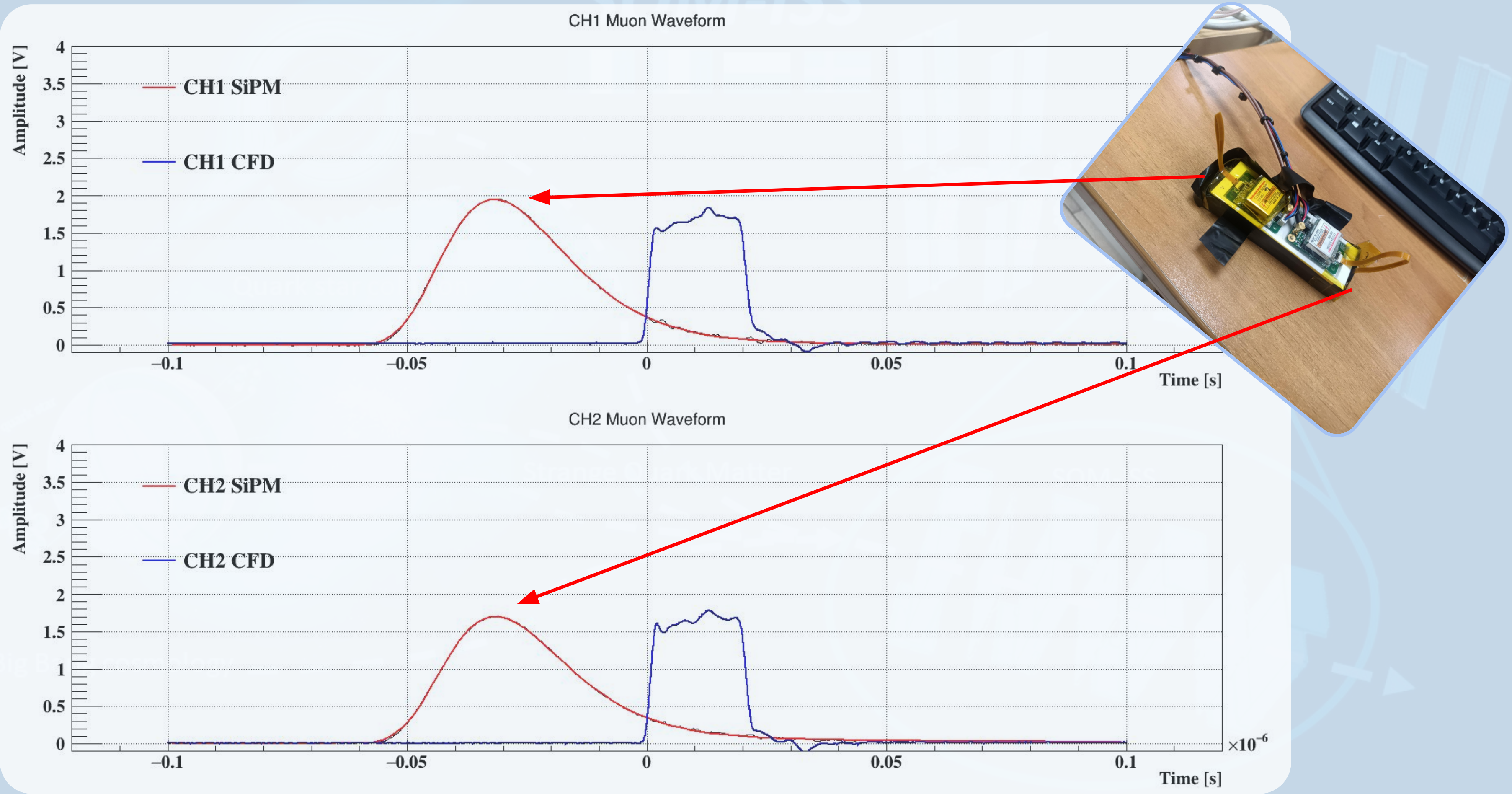
ToF characteristic

- One scintillating plate will be divided into 4 bars (10 cm long, 2SiPM) - 4x5x2 = 40 SiPMs
- SiPMs: Hamamatsu C15524
- CAEN N842 CFD module
- TDC board: xHPTDC8-PCIe by Cronologic with ~20ps resolution
- Scintillator: EJ-208

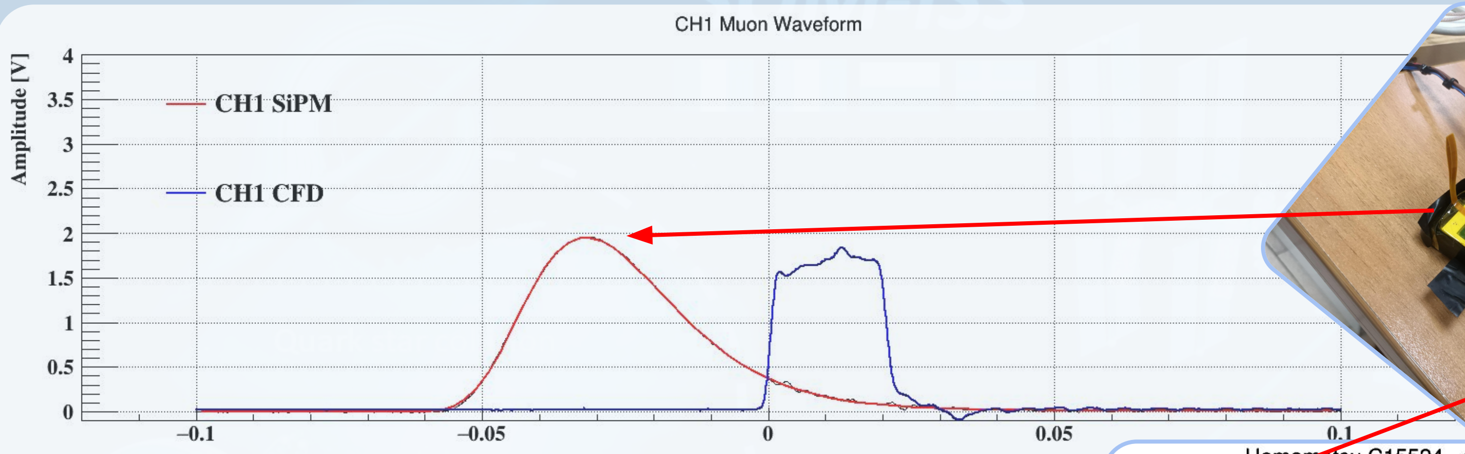


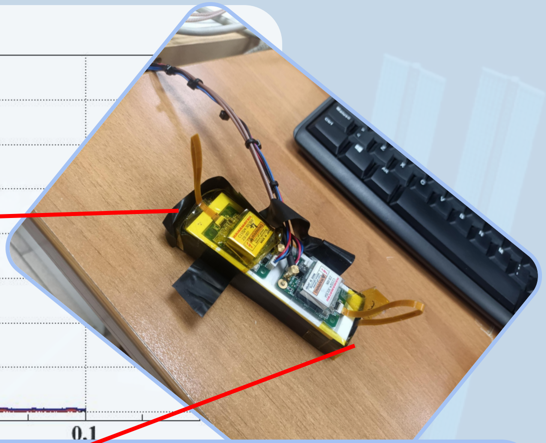


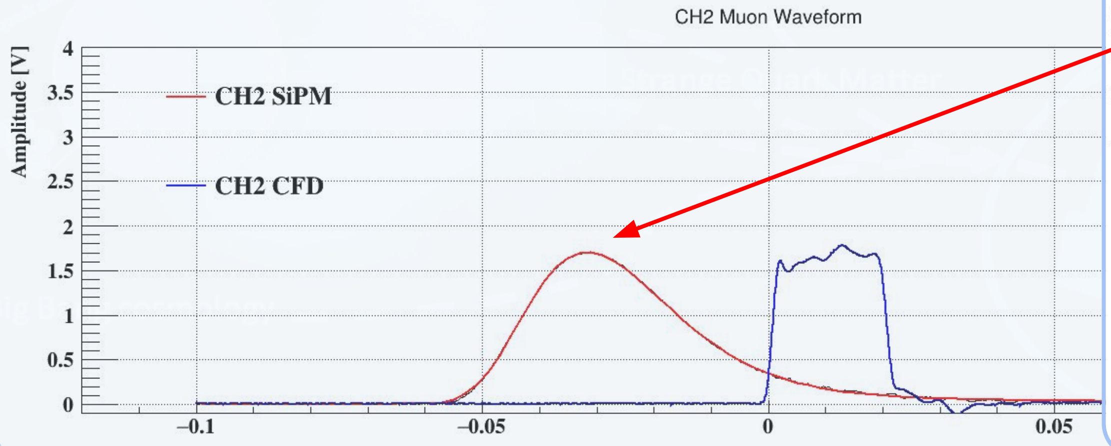
Scintillating detector and Time of Flight

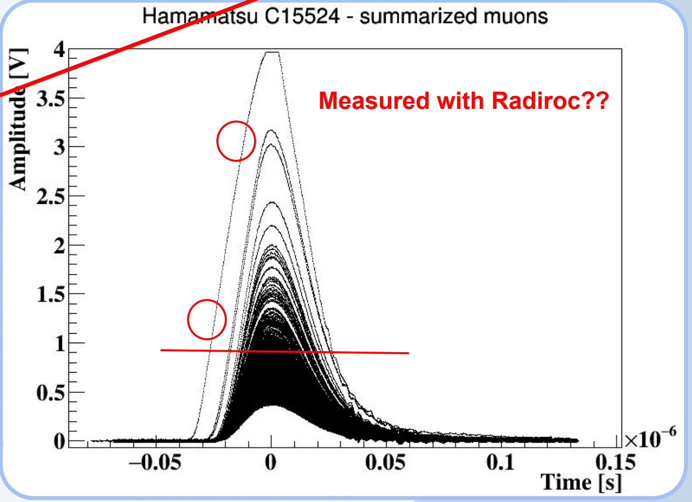


Scintillating detector and Time of Flight

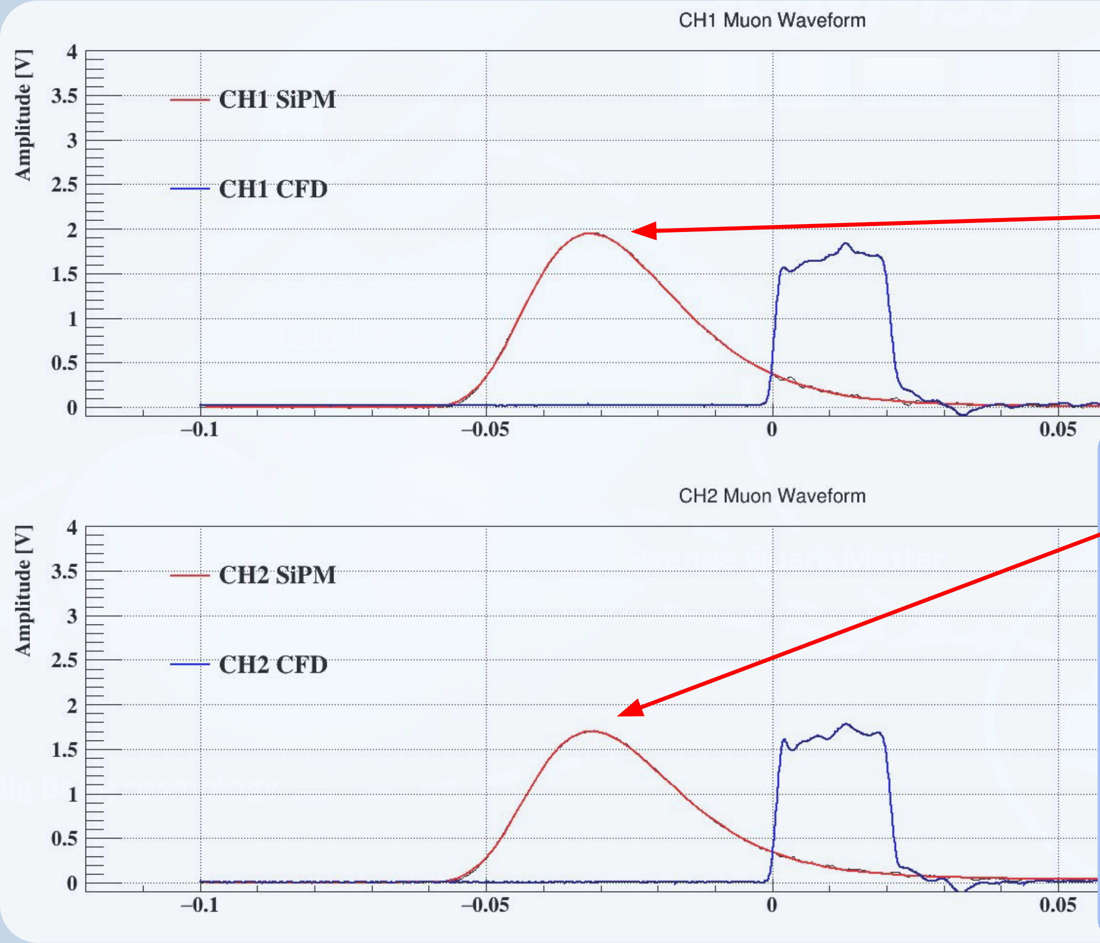


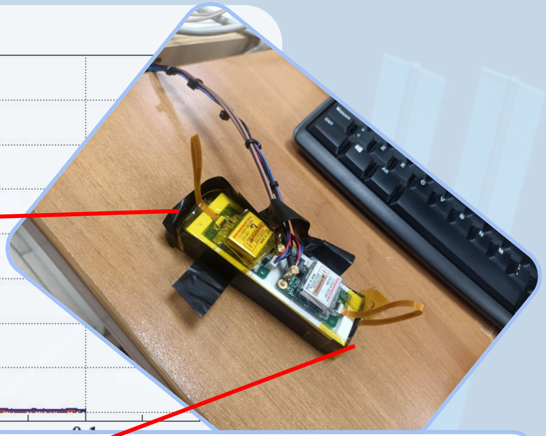


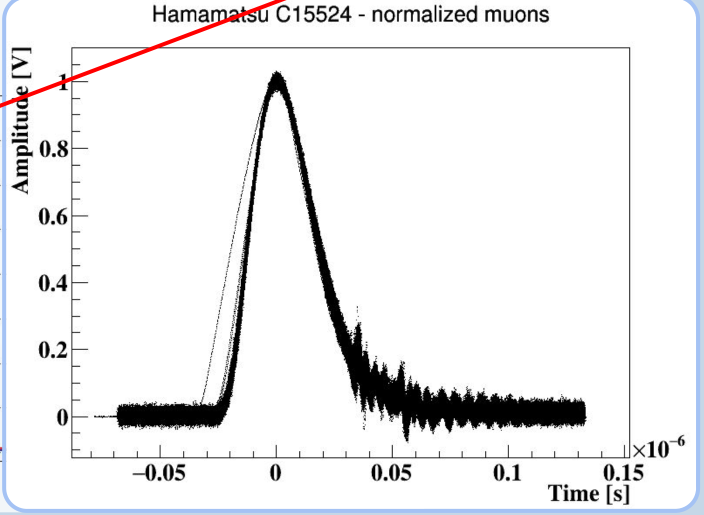




Scintillating detector and Time of Flight



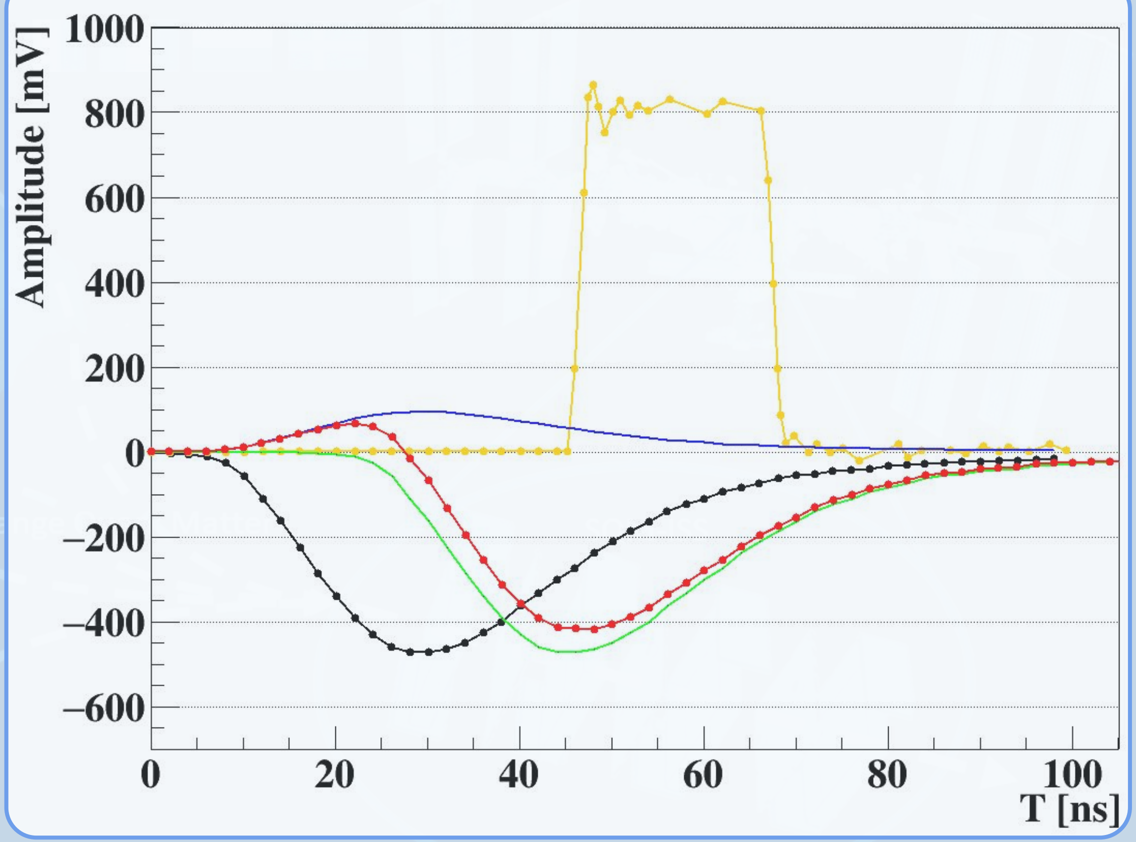




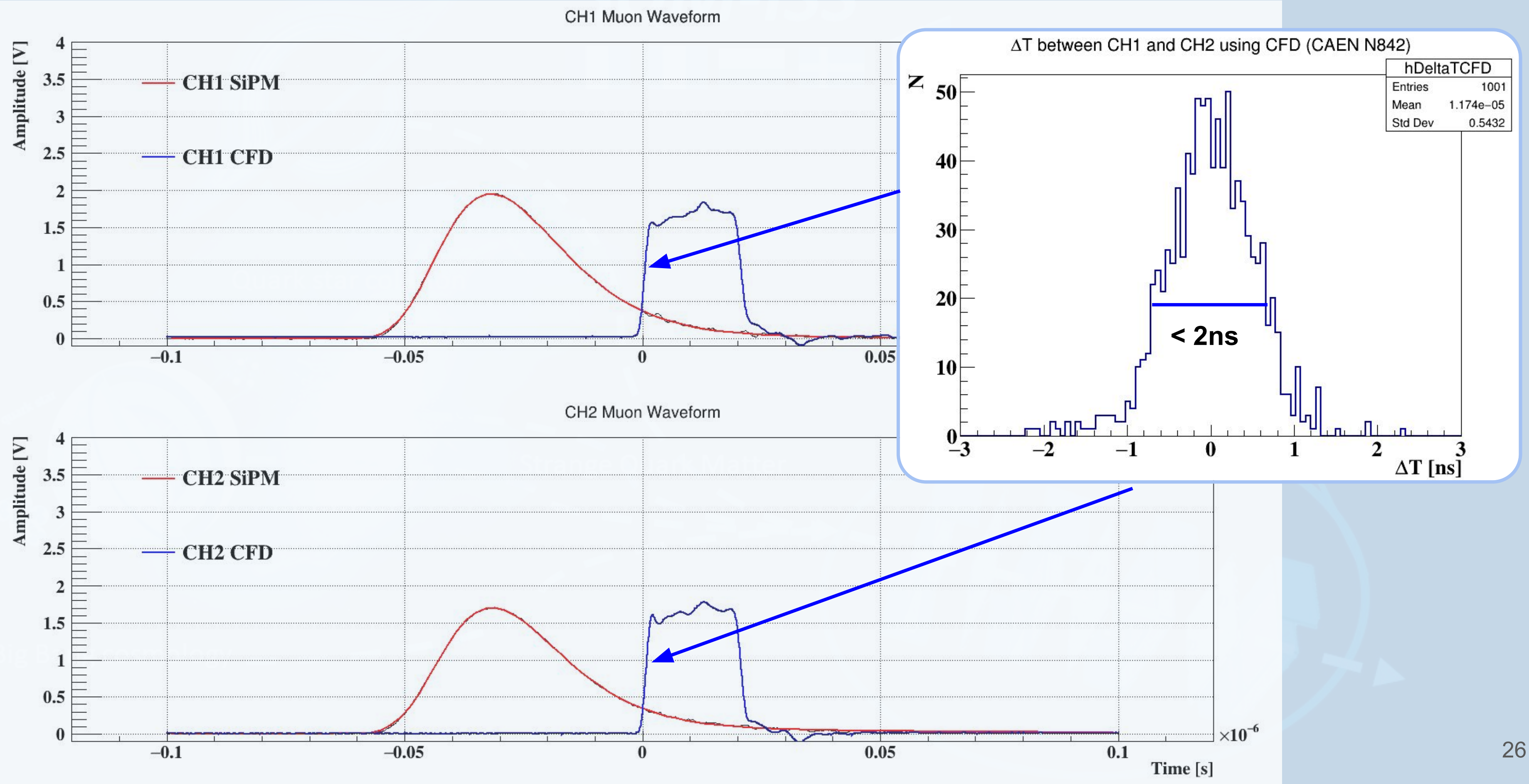
Scintillating detector and Time of Flight - CFD

Constant Fraction Discriminator

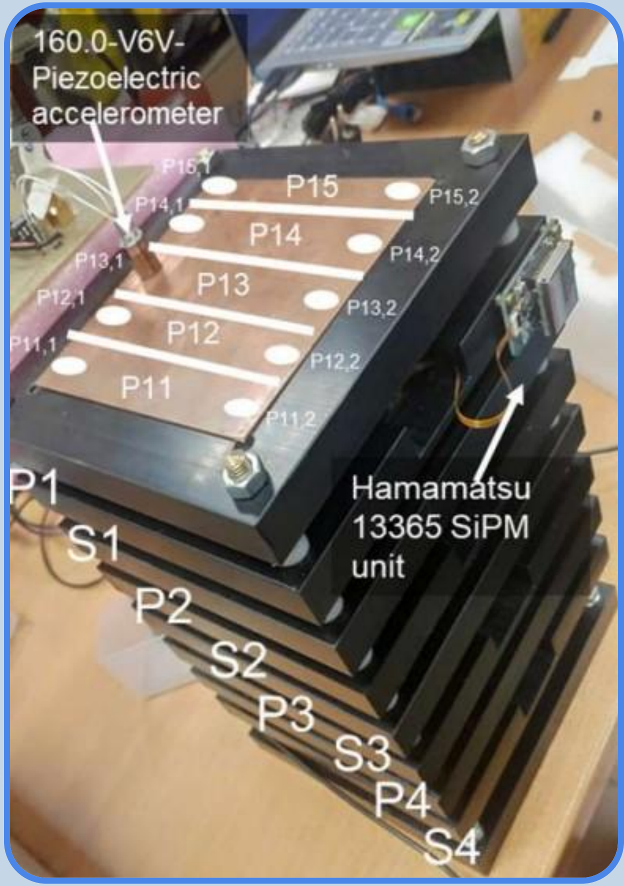
- CAEN N842 used in laboratory model
- Not sensitive to the amplitude in defined range
- Gives timing of the signals with similar shapes
- May be problematic if the signal amplitude has high variability
- In flight model we can use Mesytec MCFD-16, Twin_Peaks_CFD1 or similar module for integration



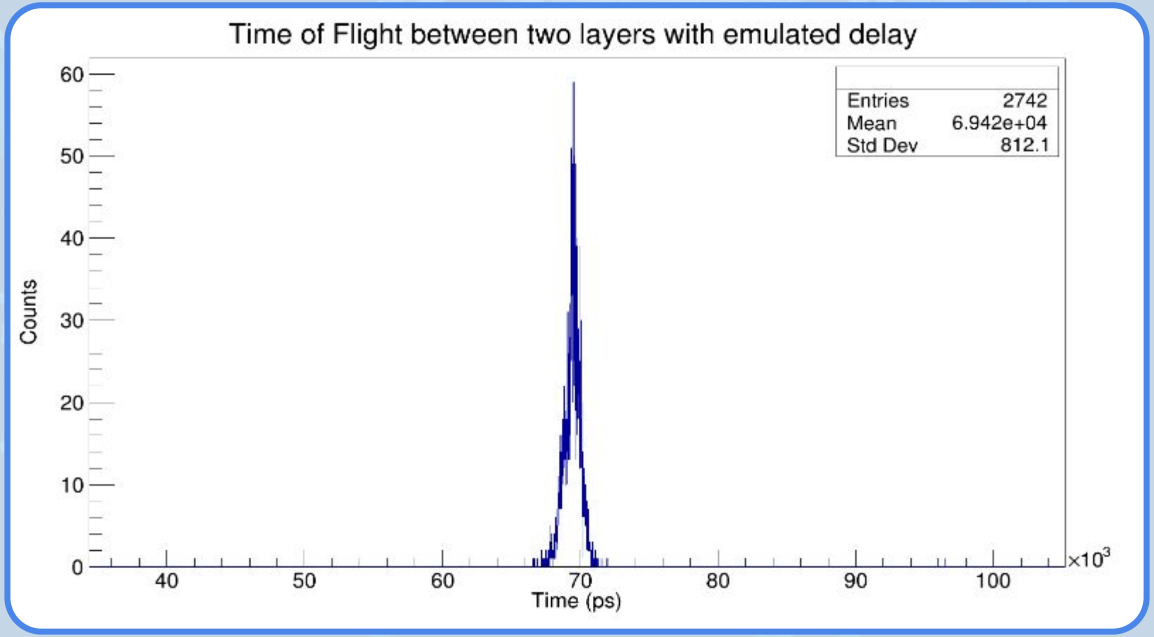
Scintillating detector and Time of Flight



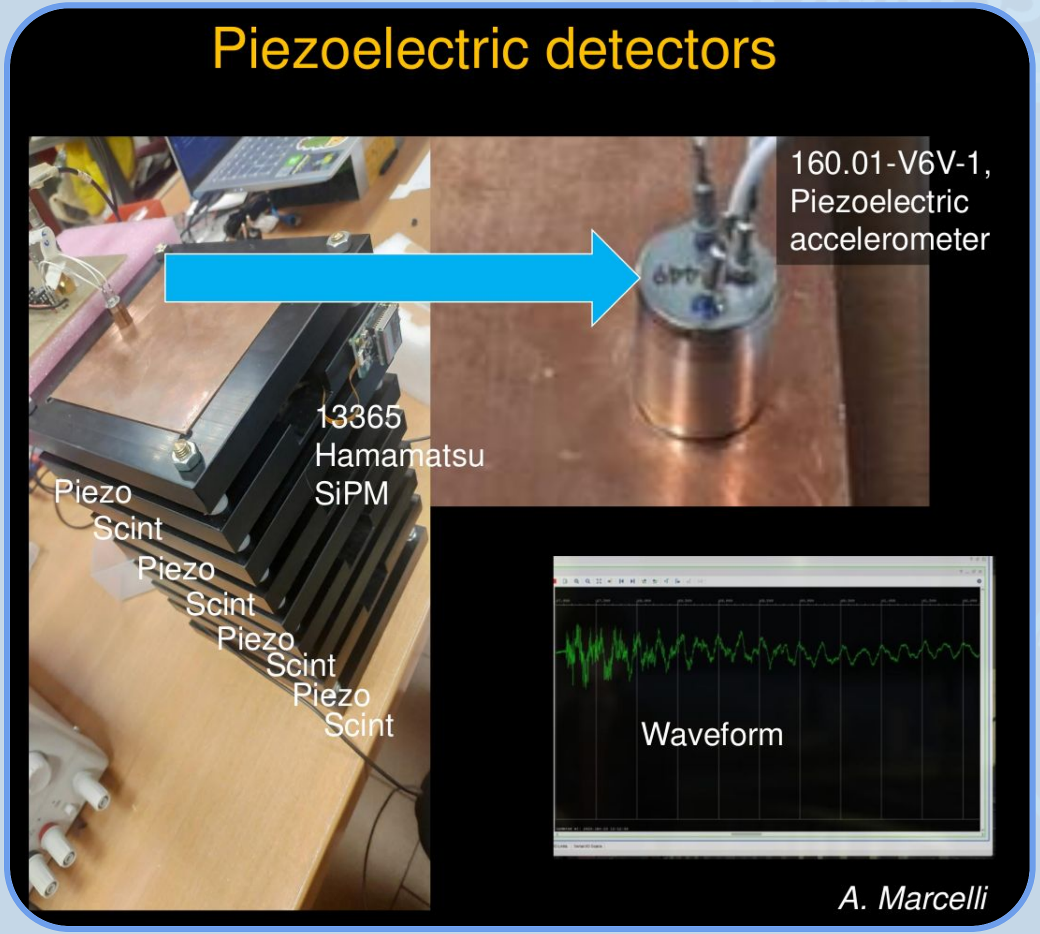
ToF - delayed signal

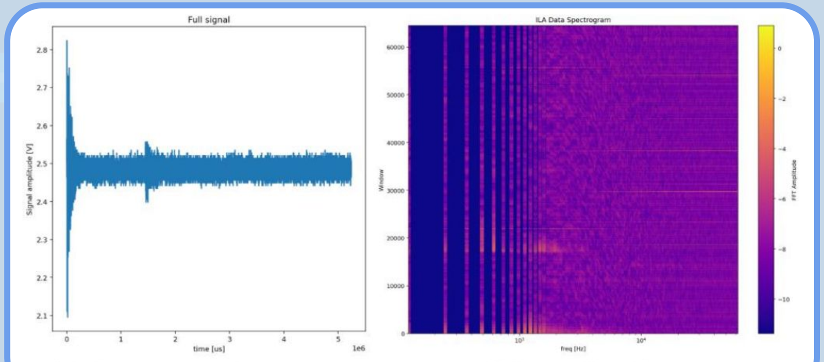


Signal from the second plane delayed to 70ns and measured by TDC



SQM-ISS piezoelectric detector





(a) Dido ball from 150 mm height response
(b) Corresponding spectrogram

Piezoelectric Accelerometer

- Two sensors per plate
- Three or four piezoelectric plates
- E_{min} ~ 100 nJ
- Mass range: > 10^{-9} g
- Barionic mass: $A>10^{14}$
- **Propagation time: ~20μs**

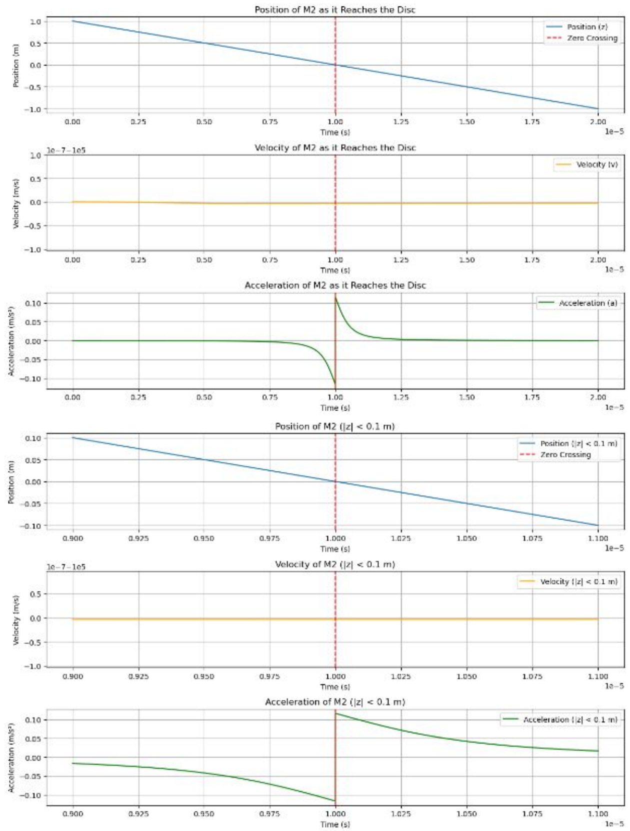
Detection of PBHs - work by F. Liberatori and M. Casolino

Primordial black holes (PBHs), hypothetical black holes formed from high-density fluctuations in the early universe, remain unconfirmed, but the **SQM-ISS** detector is designed to capture their gravitational signals and could potentially detect them via piezoelectric channel

$$a_{\min} = \frac{5\,\mathrm{mV}}{S} = \frac{5\,\mathrm{mV}}{100\,\mathrm{mV}/g} = 0.05\,g \approx 0.49\,\mathrm{m/s^2}.$$

$$a(z) = \frac{F_z}{M} = -\mathrm{sign}(z)\frac{2Gm_{bh}}{R^2}\left(1 - \frac{z}{\sqrt{R^2+z^2}}\right) \qquad a(z) \geq a_{\min}$$

The minimum acceleration of **0.49 m/s²**
is related to **minimal measurable mass of PBH** of **5 x 10⁶ kg**



SQM-ISS conclusion and perspectives

- We have already produced elements of the lab model. We expect the flight within 2 years
- The ToF solutions already tested with resolution <2ns. Piezoelectric part and front-end electronic should be designed by the end of 2025
- The project is interdisciplinary, considering the diversity of hypotheses about the existence of objects it may detect
- We are finalizing **System Requirements and Activity Requirements** documentation

Thank you for your attention

Backup slides

SQM predictions are strongly model dependent

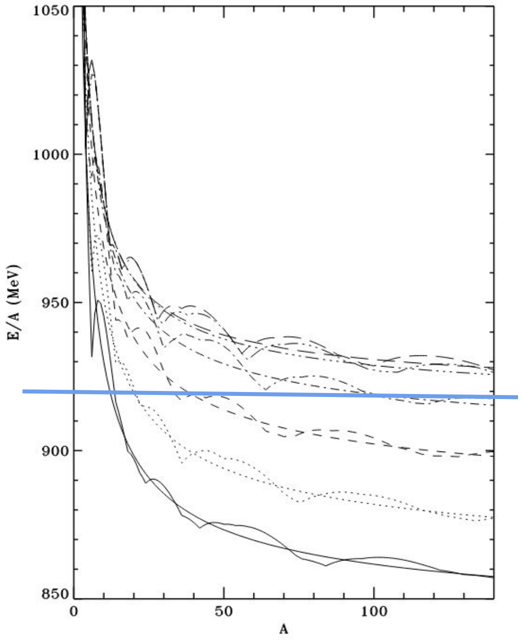


FIG. 1. Energy per baryon as a function of baryon number for $B^{1/4} = 145$MeV and s-quark mass from 50–300 MeV in steps of 50 MeV (higher curves have higher m_s). Spiky curves are based on direct mode-filling calculations, smooth curves on the smoothed density of states from the multiple reflection expansion. The smooth curves are thus not fits to the shell model calculations, but derived from a smoothing procedure *within* the MIT bag model.

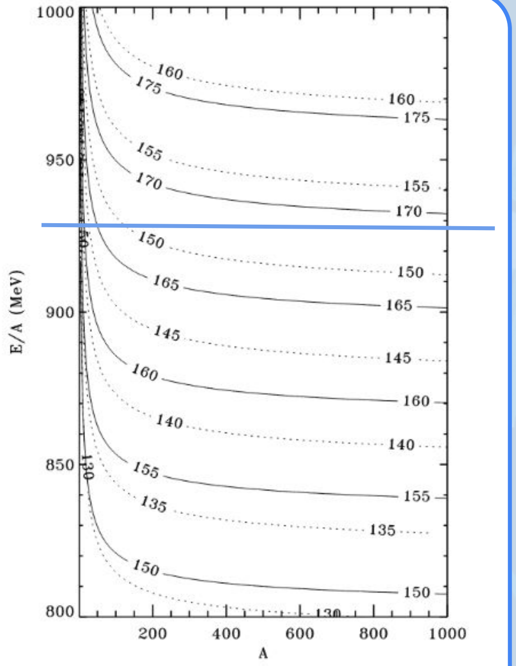


FIG. 2. Energy per baryon in MeV as a function of A for CFL-strangelets (full curves) and ordinary strangelets (dashed curves) with $B^{1/4}$ in MeV as indicated, $\Delta = 100$MeV and $m_s = 150$MeV.

J. Madsen, 1995,
https://arxiv.org/pdf/hep-ph/9502242

J. Madsen, 2001,
https://arxiv.org/pdf/hep-ph/0108036