Discussions on interplay between space/CR and collider experiments
- include some ideas from China Deep Space Exploration Laboratory

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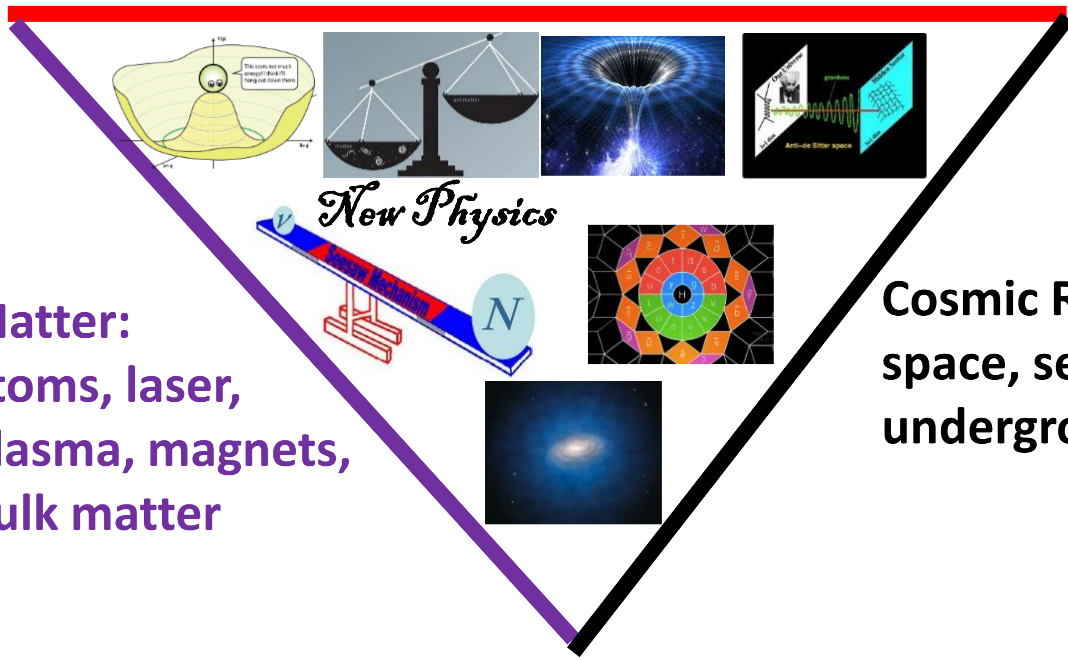
Introduction

- ❑ Finding “new” physics is the key target of particle physics
- ❑ Experimental endeavors being made via different techniques, at various locations, across time
  - ➢ Interplay naturally occurs due to the “same” targets
  - ➢ Leave no stones unturned & Study any new phenomena in a thorough way

Collider/Accelerator/Reactor

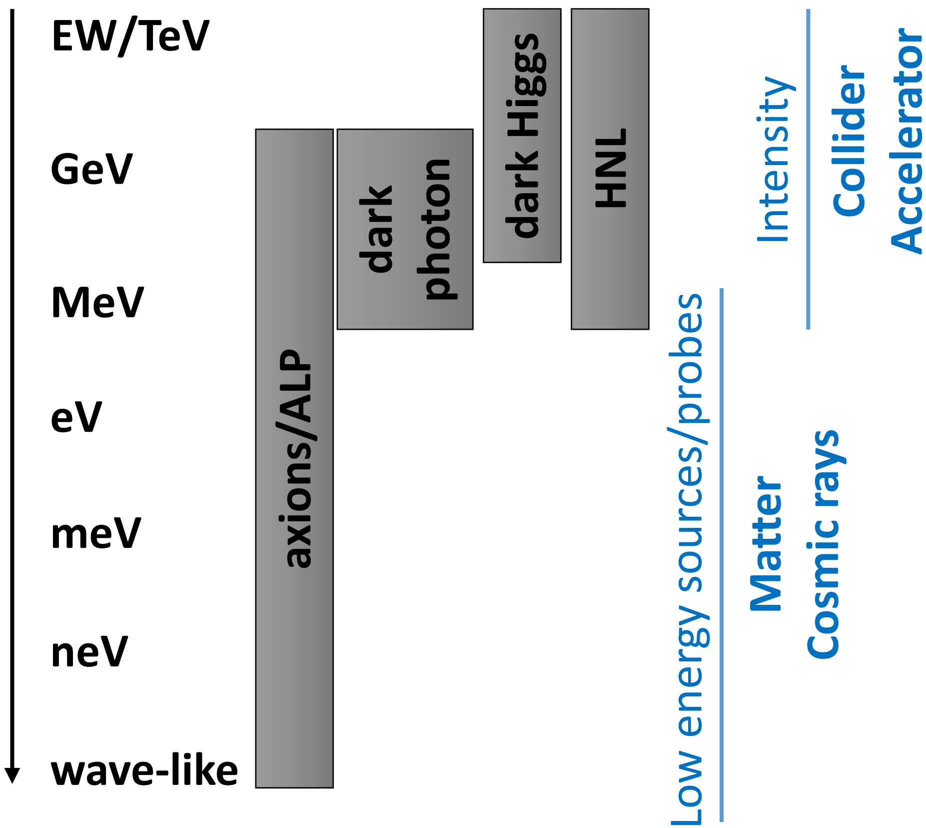


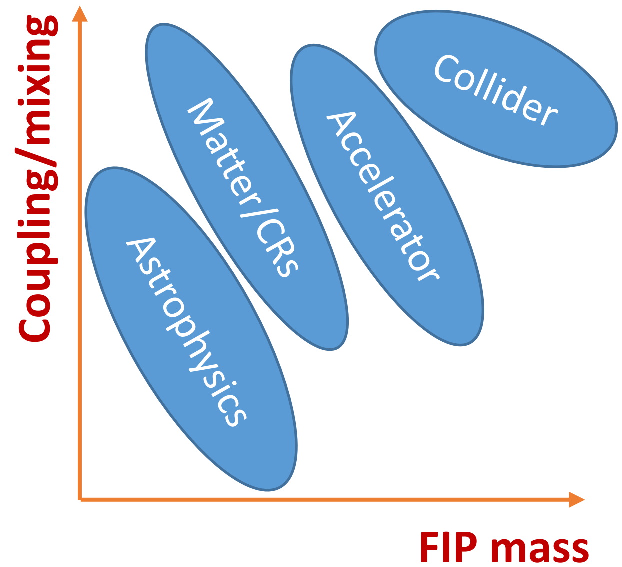
Matter: atoms, laser, plasma, magnets, bulk matter

Cosmic Ray: space, sea level, underground

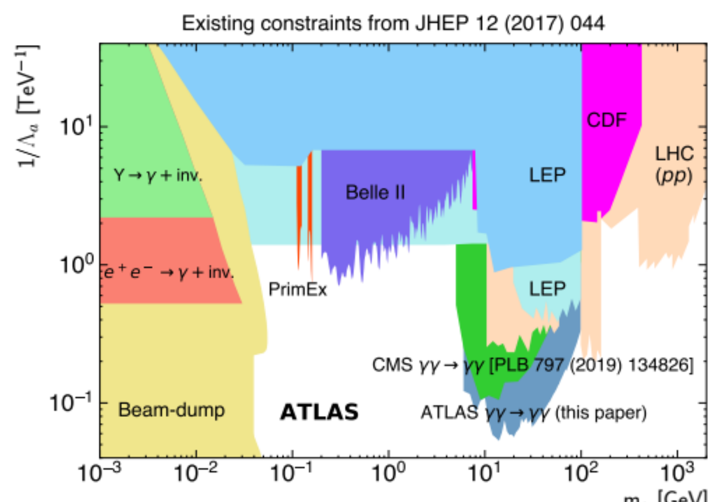
An example on feebly interacting particles

Broad range of possible masses or couplings



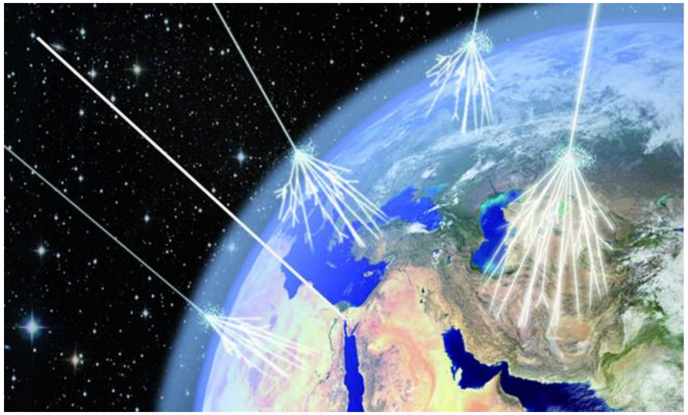


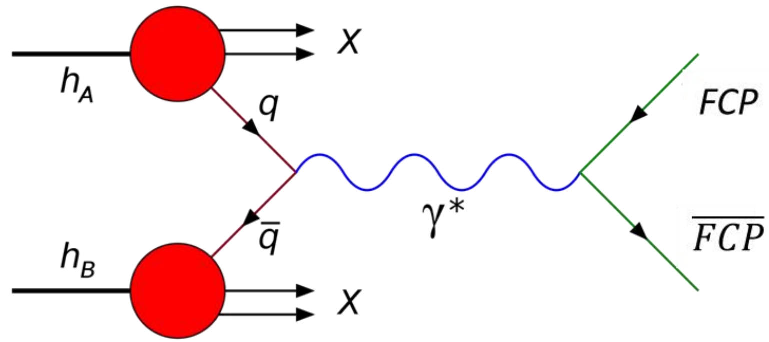
Example of axion searches at MeV → TeV



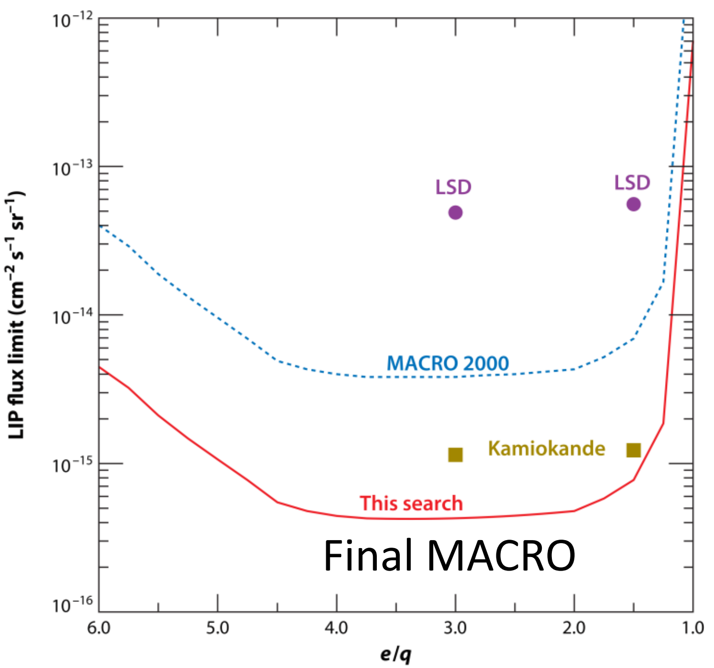
JHEP03(2021)243

An example on fractional charge particles

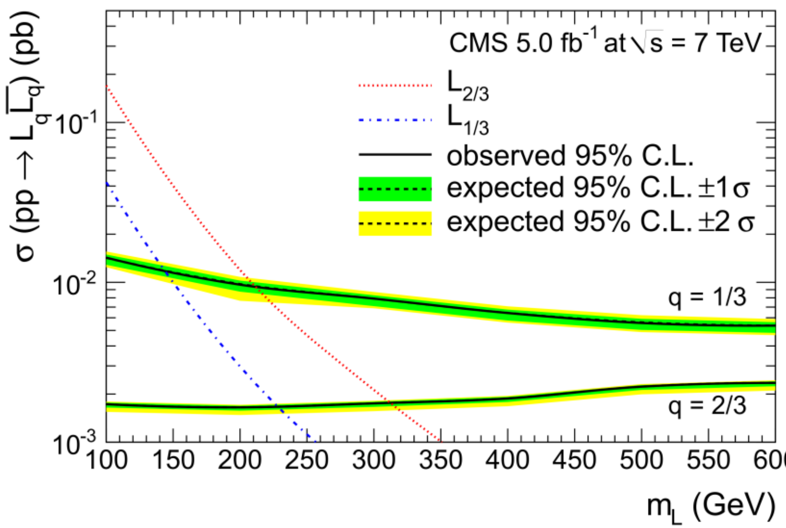




Phys. Rev. D 87 (2013) 092008



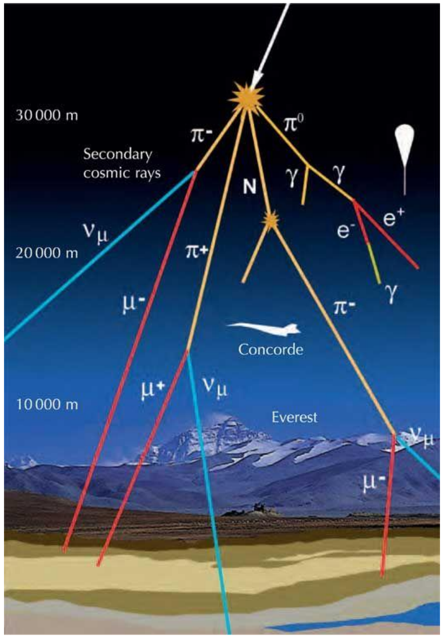
Annu. Rev. Nucl. Part. Sci. 2009.59:47-65



Similarly, but more technically difficult is to directly search for mini-charged particles

Case discussions follow

Disclaimer: this talk serves as an initial, relaxed discussion on those interesting topics, hope to collect inputs, suggestions



Searches via cosmic ray extensive air showers, e.g., at AUGER, LHASSO, etc.

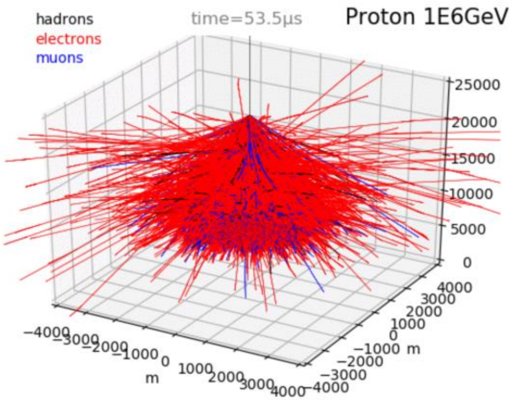
Large exposure, acceptance region, good sensitivity for high-energy particle detection, if EAS can be used to distinguish new and normal particles

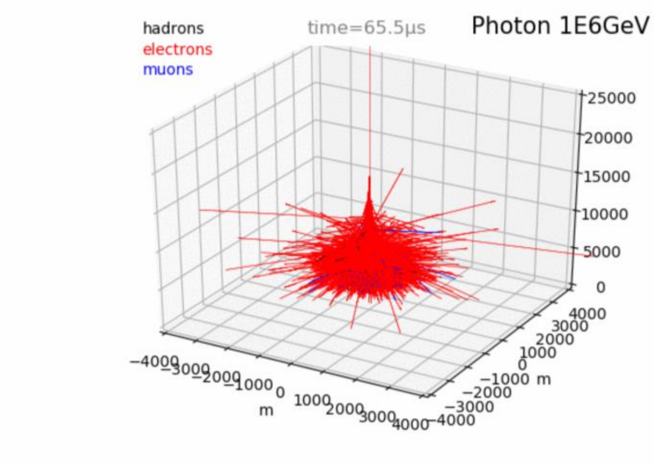
Searches via space experiments, e.g., AMS, DAMPE, FERMI, etc.

Much smaller acceptance, more precise as measuring primary particles directly, good for lower-energy / precision searches;
may be combined with ground exp. for novel purposes (search for wave-like signals)

Case of EAS: Intro

Cosika simulation done by Zhijie Li



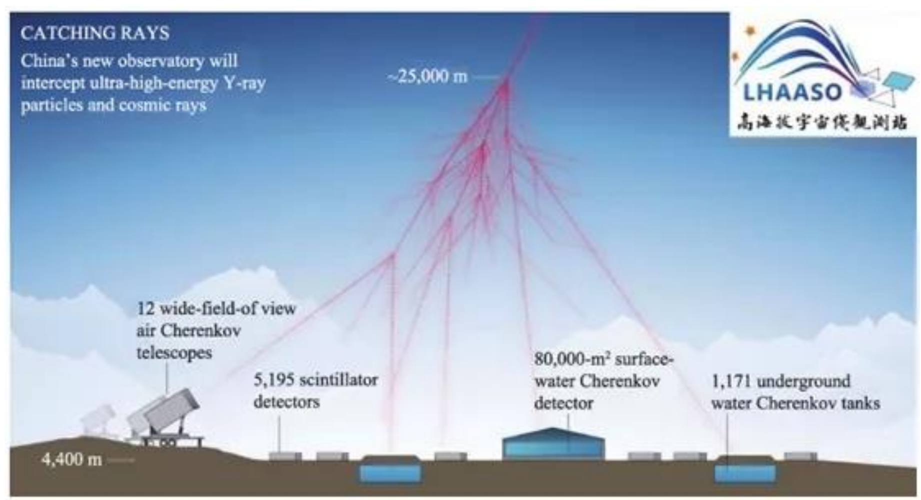


Different primary CR particles leave different EAS (like different calorimeter responses due to different particles at collider exp.)

Particle identification with EAS

- Part reasonably understood (e.g., left shows p v.s. γ), with room for improvement
- Part very difficult (e.g., assume EAS behavior of new physics particles, new models/simulations needed)

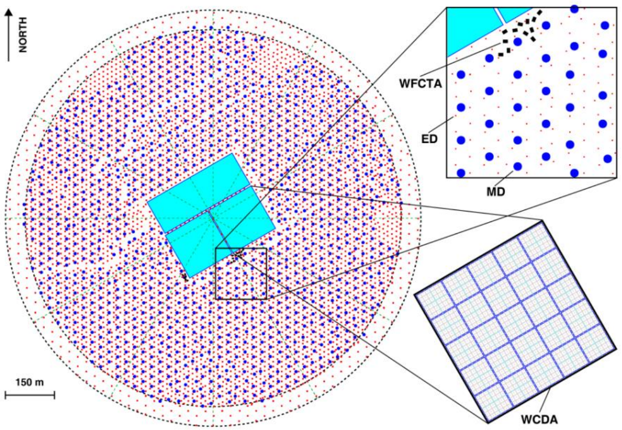
Detector arrays at ~maximum shower depth (e.g., LHASSO) to measure the 2D shower plane, and telescopes to measure the depth profile / energy



Cartoon: LHAASO detector arrays

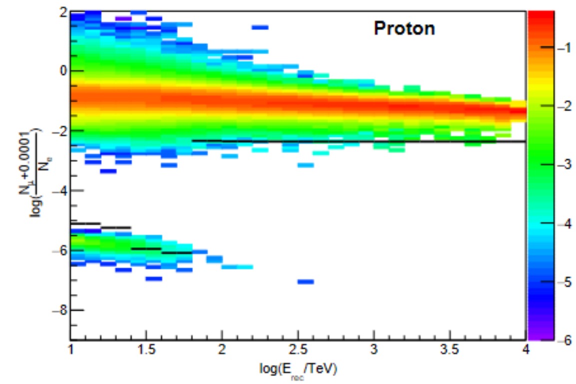
Case of EAS: more on p v.s. γ

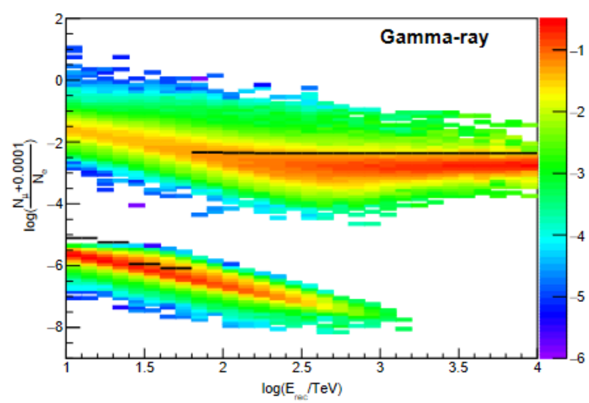
Usual methods from collider experiments have been already tried for EAS pID: topological information, multivariate methods, to help achieve better pIDs



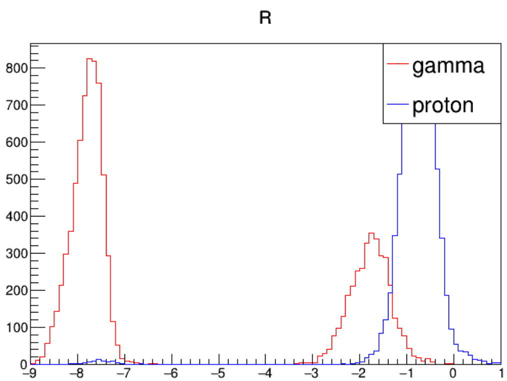
LHASSO detector arrays

Chinese Phys. C 45 025002 (2021)





$\log(N_m/N_e)$: a clear difference can be usually achieved



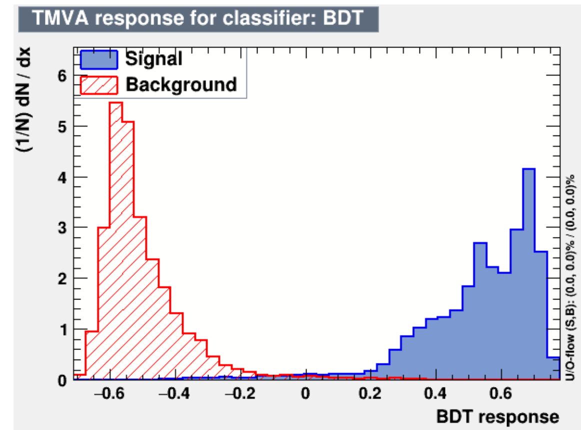
Simulation results from Z. Li, using particles in 10-100 TeV range

Case of EAS: more on p v.s. γ

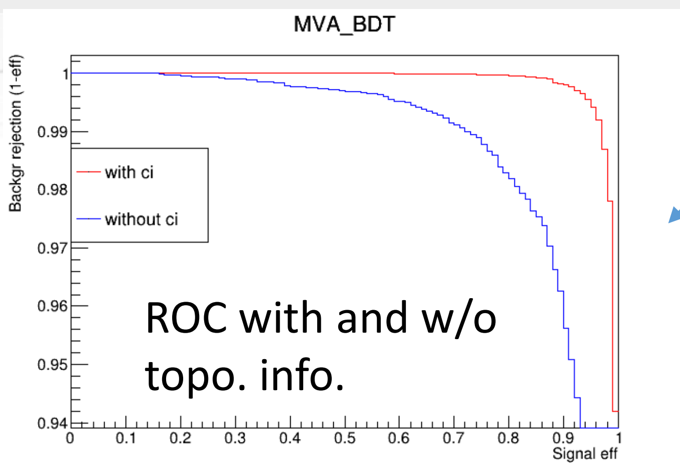
Usual methods from collider experiments have been already tried for EAS pID: topological information, multivariate methods, to help achieve better pIDs

Studies from Z. Li, based on simulation data

- In addition to Nμ/Ne, we investigate the potential with topological variables.
- Compactness $C = \frac{N_{hit}}{CxPE40}$, A.U. Abeysekara et al. / Astroparticle Physics 50-52 (2013)
  - Nhits: number of PMTs
  - CxPE40: PE numbers in largest signal PMT outside 40m of shower core.
- PINCness $P = \frac{1}{N}\sum\frac{(\xi i - <\xi>)^2}{\sigma_\xi^2}$, A.U. Abeysekara et al. The Astrophysical Journal (2017)
  - ξ: log10(effective charge)
- Azimuth non-uniformity $C_k = \frac{1}{2n(n-1)<S>}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}(Si - Sj)^2$
  - n: number of detectors
  - k: lable of regions
  - S: collected signals in each detector



Adding topo. info. on top of event counting



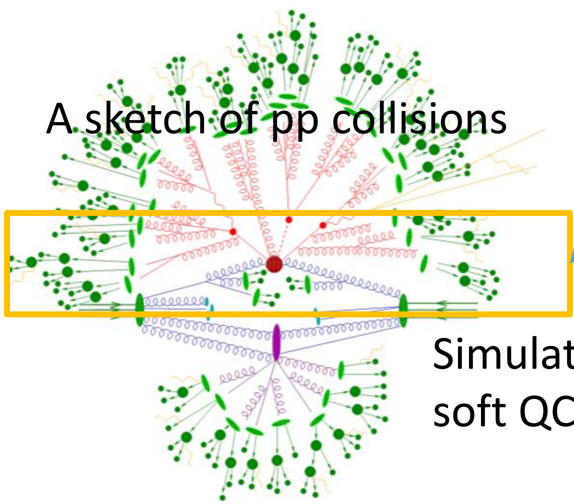
ROC with and w/o topo. info.

Preliminary studies demonstrate a potential improvement
More can be tuned, and experience, methods from collider physics studies could help

Case of EAS: modelling of hadronic processes

Any optimization and interpretation of array detections relies on the simulation of hadronic processes of EAS induced by primary particles

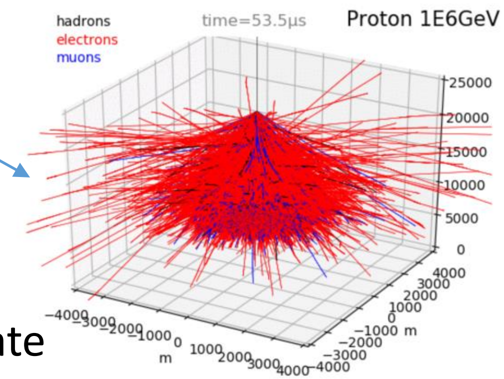
A sketch of pp collisions



Hadronic interaction models:
EPOS LHC, QGSJETII
Sibyll, DPMJETIII

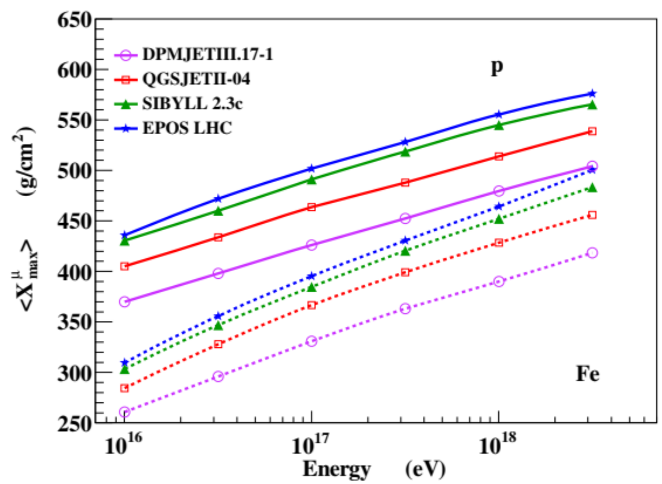
Simulate minibias, soft QCD, diffractive…

Simulate EAS



- Forward pp interactions at LHC is relevant for EAS of primary particles up to CR knee ~ 10^{17} eV
- Abundant data collected in soft QCD, inelastic pp, diffractive regime already

EPJ Web of Conferences 208, 02002 (2019)

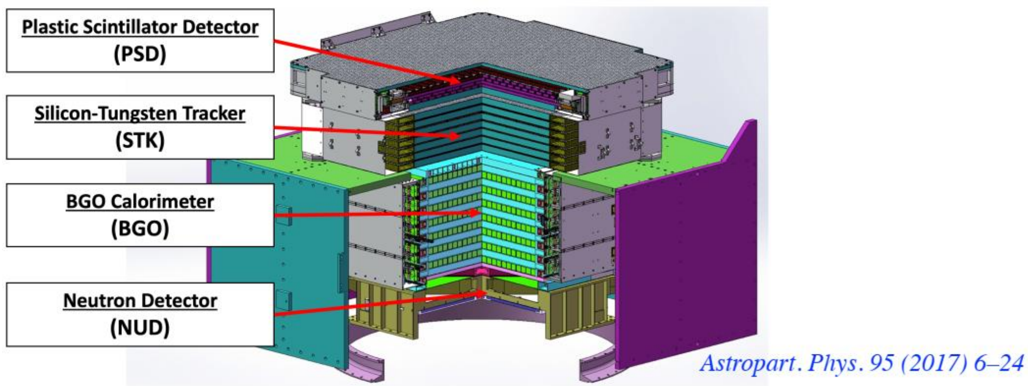


- Model uncertainty is sizable in EAS observables
- Thorough analysis of LHC forward data (w forward detectors) will help refine these models, and bring new insights

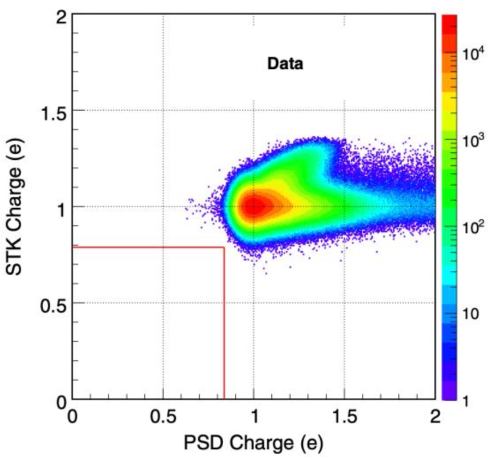
Case of Space experiment

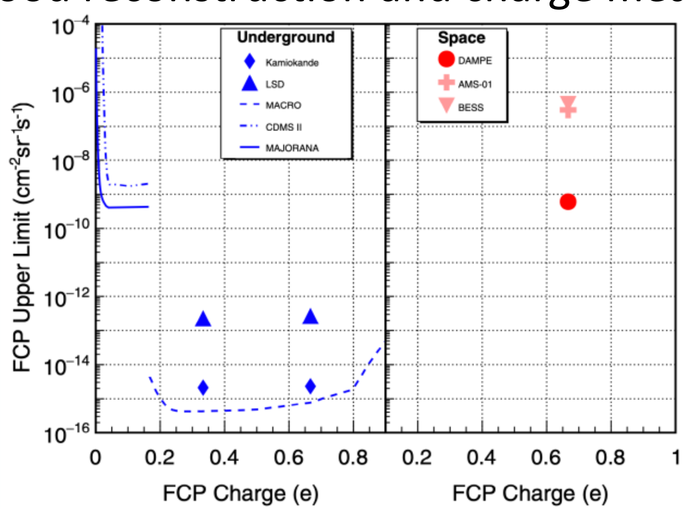
Experiments conducted at satellites, space stations, and on moons in the future
⇒ Exploration of "particles" out-of-earth: anti-matter, dark matter, CR components …
⇒ AMS, FERMI, DAMPE, HERD, …

Use FCP search at DAMPE as an example



Search for FCPs relies on good reconstruction and charge measurements



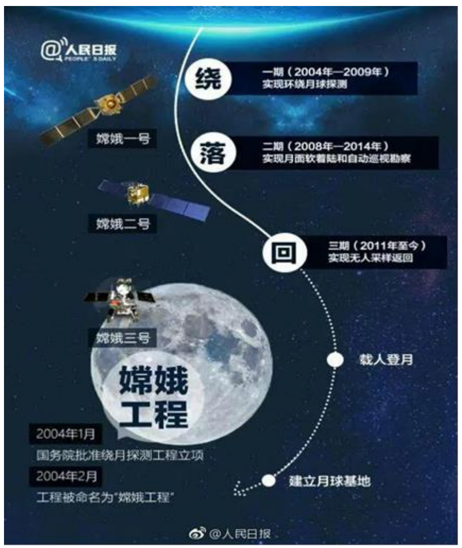


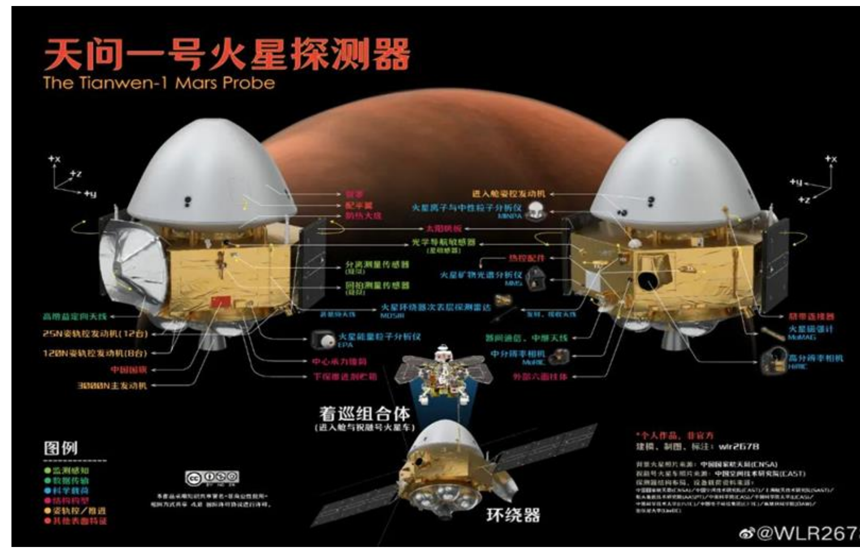
Interplay with collider between usual space exp.: detector methodology, test beam studies, reconstruction, data analysis techniques …

Phys. Rev. D 106, 063026 (2022)

Space Exploration Program

Explore directly objects in the solar system (e.g., moon, Mars, …) to
- Extend human knowledge and presence on these objects
- Investigate the potentials of human habitation
- Importantly also on science exploration (space science, biology, chemistry, astrophysics, particle physics, …)





China has become a main player in space exploration (successful operation of moon missions, Mars probe, etc.), with a particular emphasis on science exploration:
=> Bring new, complementary opportunities for us to think about interesting particle physics experiments along the long-term efforts

China Deep Space Exploration Laboratory (DSEL)

A new laboratory founded by three parties: China National Space Administration; Anhui Province, China; University of Science and Technology of China
=> To support future China space missions, and especially **R&D on science exploration**

DSEL
DEEP SPACE EXPLORATION LAB
深空探测实验室

- Location: Hefei, Anhui, China
- Construction of office, laboratory spaces started years ago
- Science projects intended for international collaboration
- Ongoing: call for science proposals, and recruitment of staff members (several K positions in about 10 years)

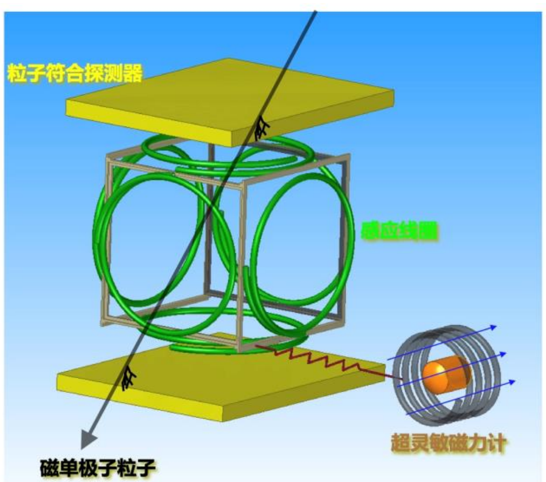
Related early DSEL projects

Search for new physics at deep space environment

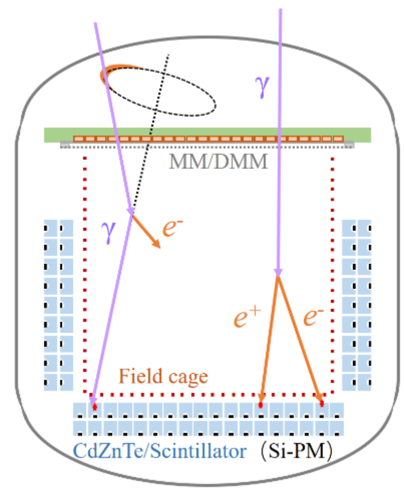
<u>Considering factors</u>

- With a target to operate the experiments on moon station, and intermediate prototype to be constructed on the earth or orbit
- Pursue something new (techniques, directions) with science significances
- Harsh limits on transportation load (e.g., <= 1ton) and operating environment (radiation environment, temperature, …)
- Benefits of operating in deep space

Two initial projects being studied



Search for monopoles using quantum technologies and particle detectors

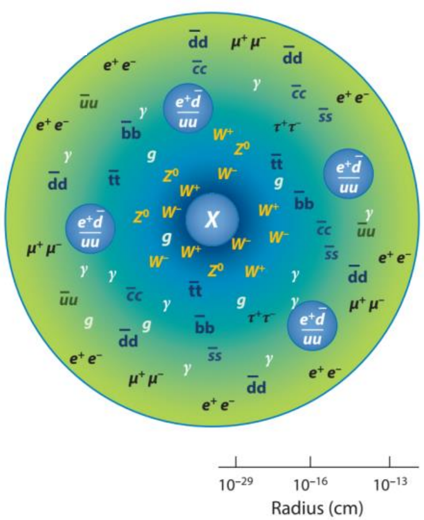


Measurement of MeV gamma rays for astrophysics and dark matter search

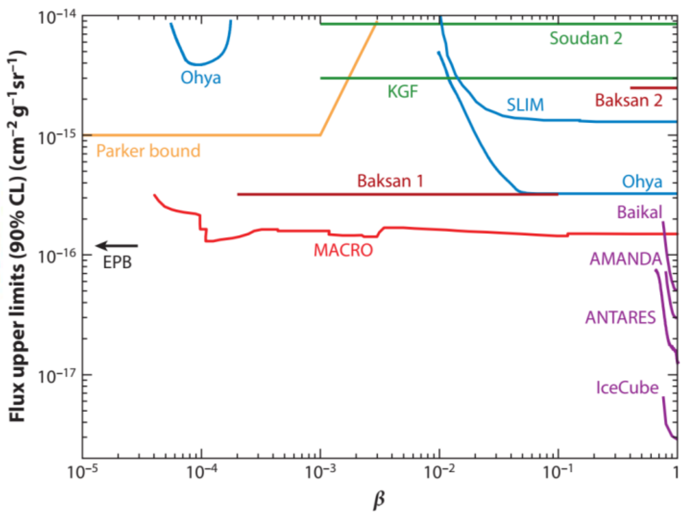
Monopole searches

Search for magnetic monopoles is a long-lasting program since Dirac’s time

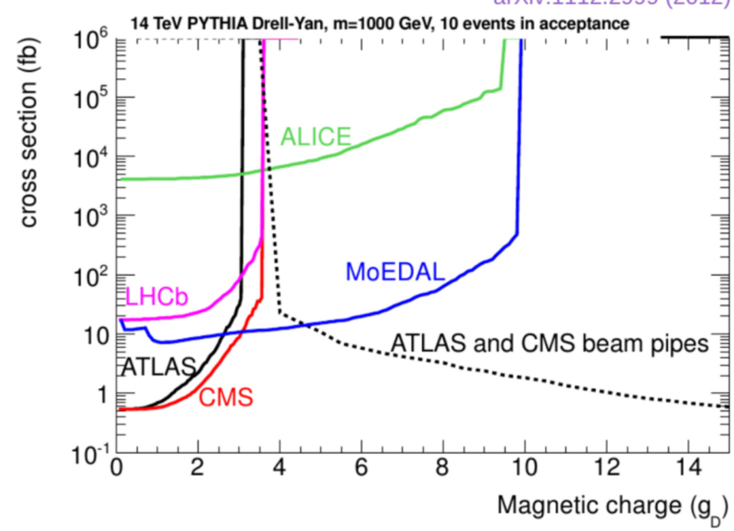
- Classic or GUT monopoles, with masses potentially unconstrained, but may prefer extremely large energies beyond the reach of LHC
- Theoretically could be related to early Universe evolution, quantization of electric charge, dark matter, …
- Experimentalists look for MMs: cosmic rays, bulk matter, collider => nature place for interplays to occur, different methodologies complementary to each other



Annu. Rev. Nucl. Part. Sci. 2015.65:279-302



arXiv:1112.2999 (2012)

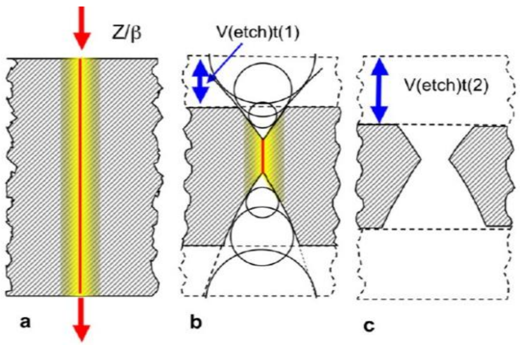


Relatively old figures to demonstrate the search results, variations on the markets.

Search Methodology

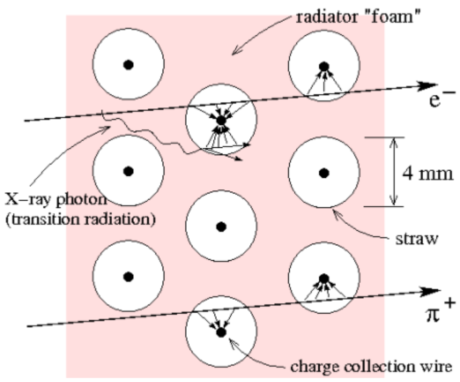
In a nutshell: monopoles are heavy (and therefore may be slow), carrying only magnetic charges, effectively be more active when propagating through materials (larger dE/dx)

Particle detection methods



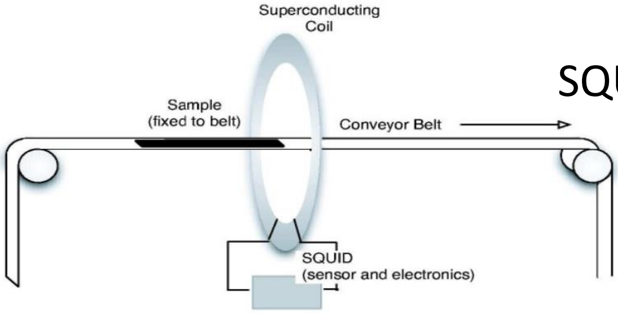
Nuclear tracking detector

Gas/solid-state tracking, scintillators

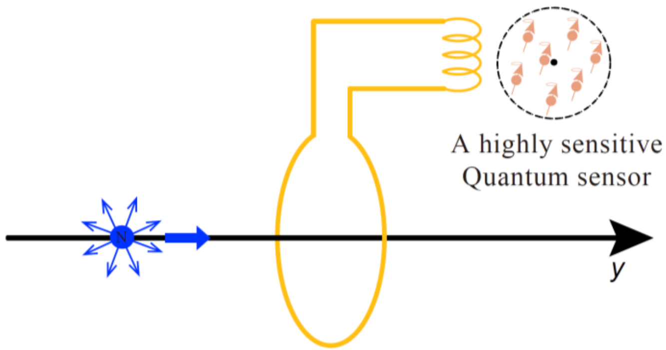


LHC (ATLAS, CMS, MoEDAL)
MACRO
IceCube,
…

Magnetic field detection methods



SQUID

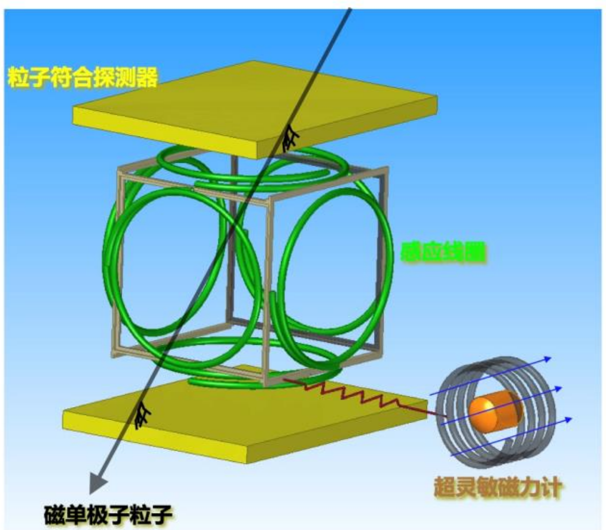


Induction method, rely on high-sensitive electronical measurement; induction or direct B field measurement via quantum sensors

Monopole search at DSEL

Ideas:

- limit-size device at first stage to demonstrate the detection principles at ground-level
- Induction circuits (convert moving magnetic charge to electric current, which can be already measured for detection) + conversion circuits (convert induced current to magnetic fields) + quantum sensor (high precision measurement of magnetic fields)
- Outside: potential deployment of traditional detectors for triggering/coincidence
- Advantages: may benefit from low temperature, vacuum, no air showers, weak B field
- Sensitivity: limited acceptance, but sensitive to a range of speed of MMs (10^{-6} and beyond)



Interdisciplinary cooperation ongoing:

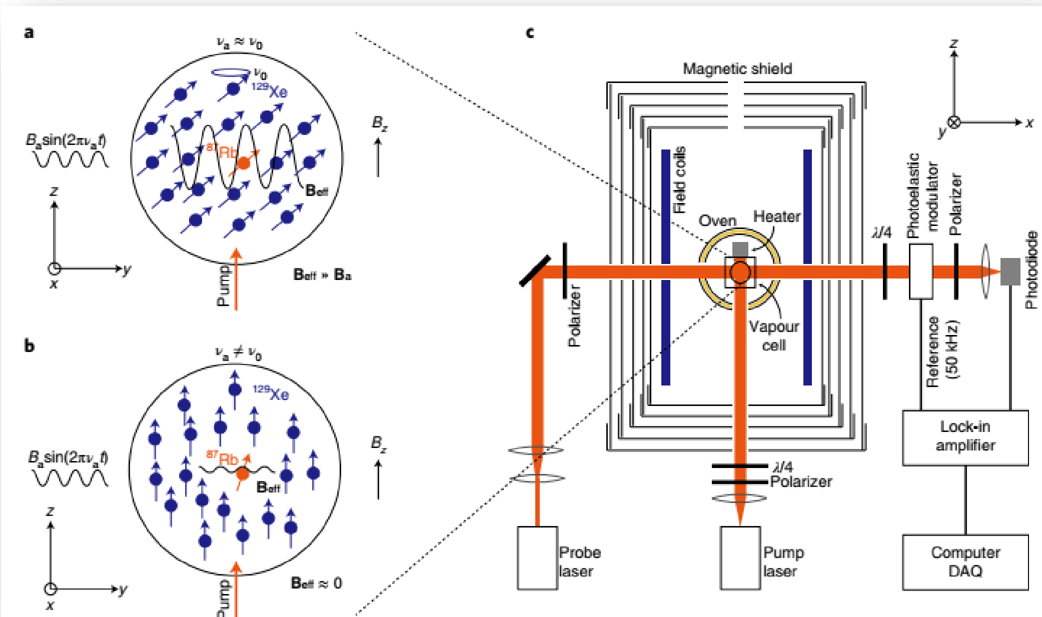
- Detailed study of DC/AC behaviors of circuits important for understanding the signal prorogation chain and help design (electronics expert)
- Simulation of full system, detection, and reconstruction (particle physicists)
- Quantum sensors (quantum experts)
- Prototype (all)

Q. Lin, L. Zhao, M. Jiang, Z. Cao, Y. Wu, etc.

Monopole search at DSEL (Contd)

Numbers from simulation (for a sense of precision needed):

- MM with unit Dirac charge at speed of 10^{-5} may induce nA currents, and convert to **pT** magnetic field to be measured (circuit parameter dependent)



Min Jiang, etc. Nature Physics volume 17, pages 1402–1407 (2021)

The chosen technique was used for axion searches recently (assuming A-nucleus coupling inducing weak B field)

⇒ Demonstrated superior sensitivity of pT per $Hz^{1/2}$

Ongoing steps:

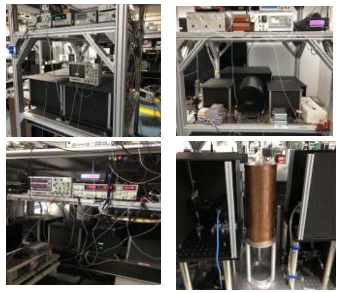
- Electronic simulation of full system and validation run (solenoid to induce weak B fields)

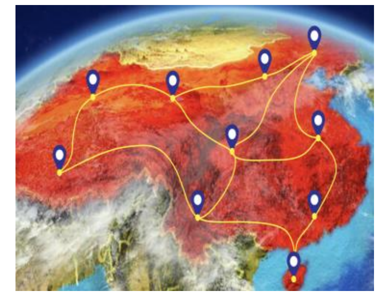
Experiment Name:

Search for Cosmic Exotic Particles (SCEP)

Monopole search at DSEL (more)

Min Jiang etc.





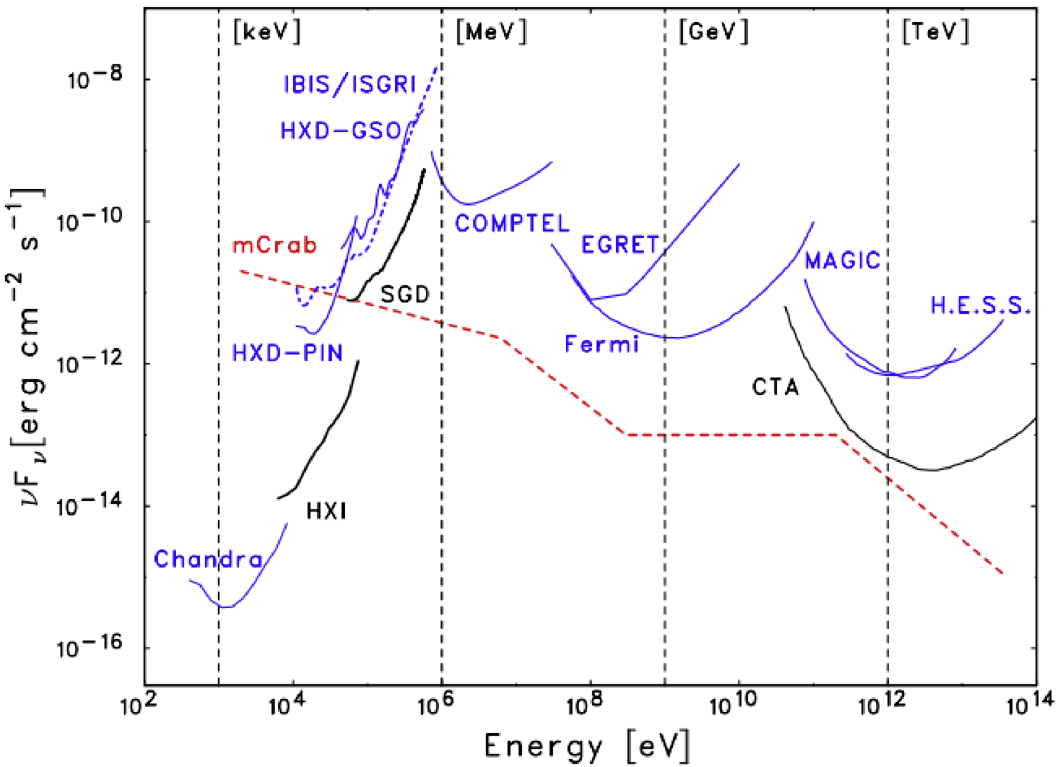
2019-2020 2021 2022 2023-

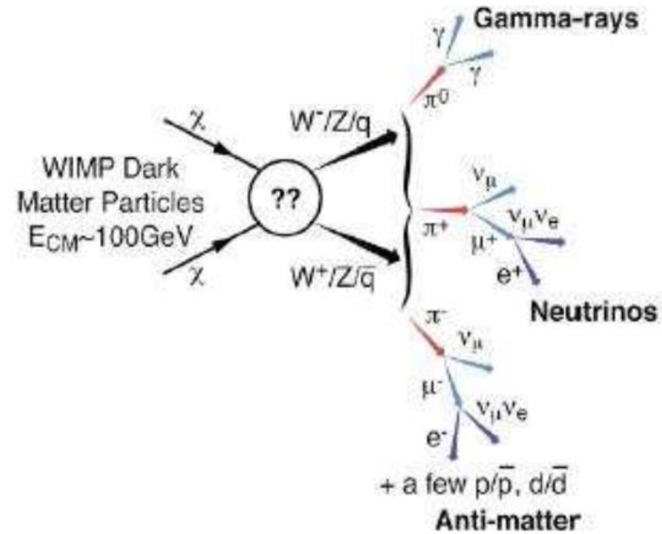
Quantum sensor itself has been used for detecting axion-nucleus coupling, long-range network has been built for more affirmative searches at low masses
➔ Coined as “Spin Amplifier for Particle PHysIcs Research”

Comment: quantum sensor searches combined between ground-level and moon-based will open a new territory in such a direction (in future DSEL considerations)

MeV gamma ray measurement at DSEL

Gamma astronomy: MeV range much less constrained



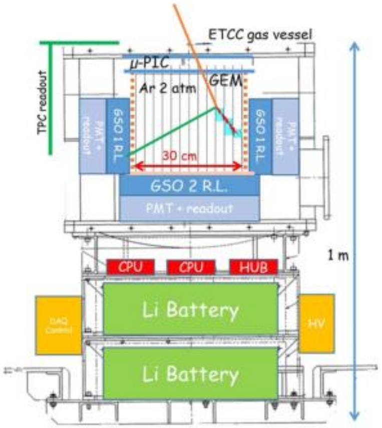


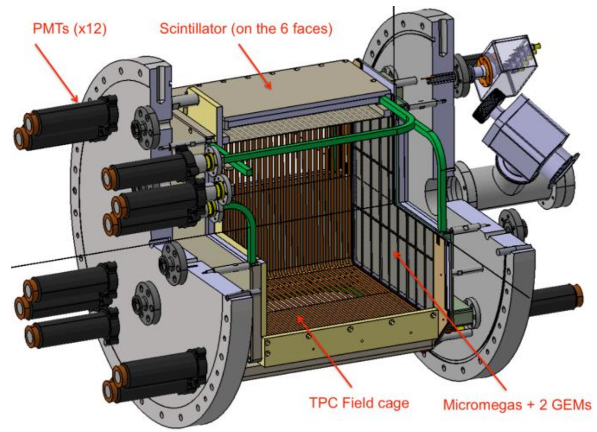
Also provide indirect search for dark matter induced photons at MeV

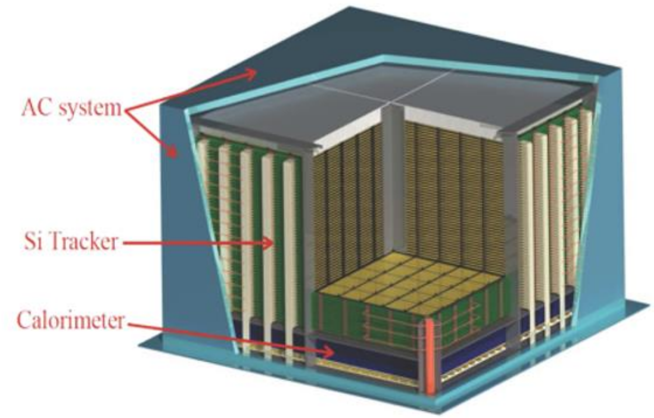
In addition, MeV is the range of nuclear emission lines, sensitive for studying Nuclear astrophysics

A small, low-cost MeV gamma ray detector can be interesting to put in space

Current Techniques



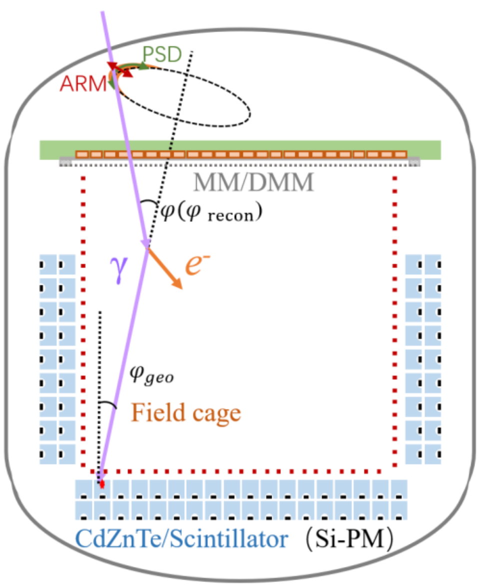




SIMLES, 0.3-3 MeV
Compton scattering; TPC

HAPRO, MeV - GeV
Pair production; TPC

e-ASTROGAM, 0.3 MeV – 3 GeV, silicon detector



This project (Z. Zhang, L. Xu, R. Yang, J. Li, Y. Cai, etc.)

- Precision TPC to measure track of scattered electron precisely => gamma direction
- CdZnTe or similar calorimeter to measure the energy precisely

Aim to achieve a next generation precision (degree resolution on the electrons)

Currently, work on detector mini-prototypes

Summary

- Interplay between different experimental searches targeting for a same new signal naturally have interplays
- potentials of using cosmic ray EAS measurements for searches may be enhanced after further understanding of EAS-based pIDs, and intrinsic hadronic models, where LHC/collider/accelerator has important contributions
- new opportunities with space experiments, considering increasing space exploration program, e.g., China DSEL
- Initial search program is under study at DSEL, which emphasizes on interdisciplinary collaboration, new techniques, new directions. More concrete simulation / validation studies are yet to come.
  - Interests, suggestions are welcomed!

Thanks for your attention!

Backup