Cosmic Ray physics program for the MATHUSLA-CERN Experiment proposal

1.Universidad Autónoma de Chiapas, Mexico
2.Universidad Michoacana de San Nicolás de Hidalgo, Mexico
3.Benemérita Universidad Autónoma de Puebla, Mexico
4. Universidad Mayor de San Andrés, Bolivia
5. University of Toronto, Canada

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Meeting of the Cosmic Rays Division of the Mexican Physical Society
3-5 October 2018
Puebla, México

Outlook

- Motivation
- MATHUSLA detector
- MATHUSLA as a CR's EAS detector
- Cosmic Rays Physics case
- MATHUSLA test
- Simulations for CR in MATHUSLA
- Final remarks

Karen S. Caballero Mora UNACH karen.scm@gmail.com

Motivation

1. Standard Model of particles and interactions (SM):
   a) In very good agreement with most experimental data
   b) But need to be extended as it does not explain

- Dark matter
- Asymmetry of matter-antimatter in the universe
- smallness of neutrino mass
- inflation
- hierarchy problem, etc

2. Physics Beyond the SM is needed to solve these problems they usually require the existence of new particles, e.g. neutral long-lived (**LL**) particles:

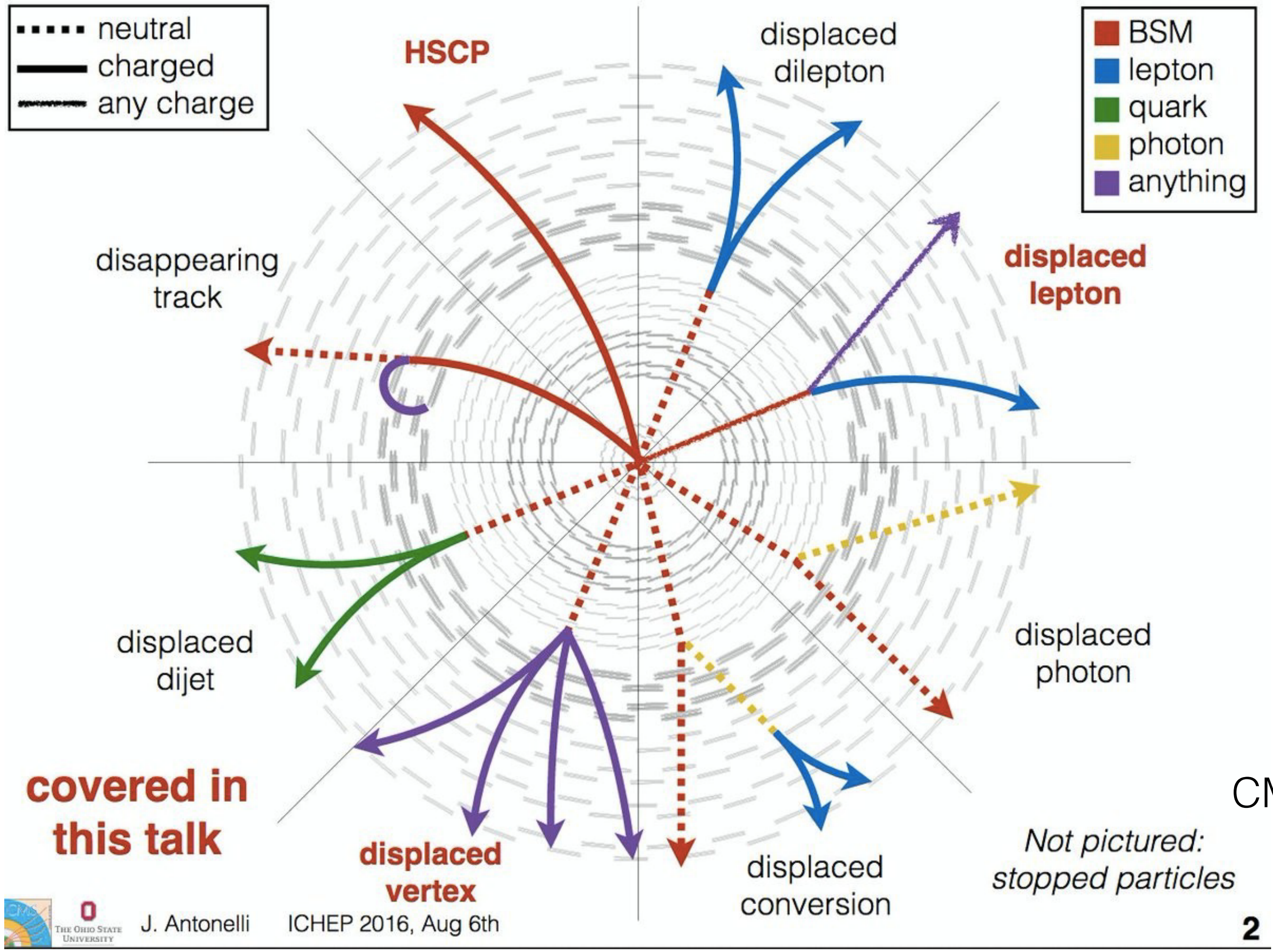
Gluinos, neutralinos, hidden hadrons, etc.

D. Curtin aand Raman Sundrum, Phys. Today 70, 6, 46 (2017)
J.C. Arteaga-Velázquez

Karen S. Caballero Mora UNACH karen.scm@gmail.com

Motivation

3. Neutral LLPs:
   a. Non interacting with SM matter
   b. Only visible once it decays
   c. μm < Decay length (cτ)<10^7-10^8 m (BBN constraint)



CMS Collab., PRD 94 (2016)112004

Motivation

4. Detector size and QCD background constrain LHC searches of neutral LLPs:

a. Ultra long lived particles (**ULLPs**, cτ ~10^7-10^8m) could escape without detection, even if they are detected
b. It would be difficult to determine where they are stable/unstable

J.C. Arteaga-Velázquez

How to detect ULLPs?

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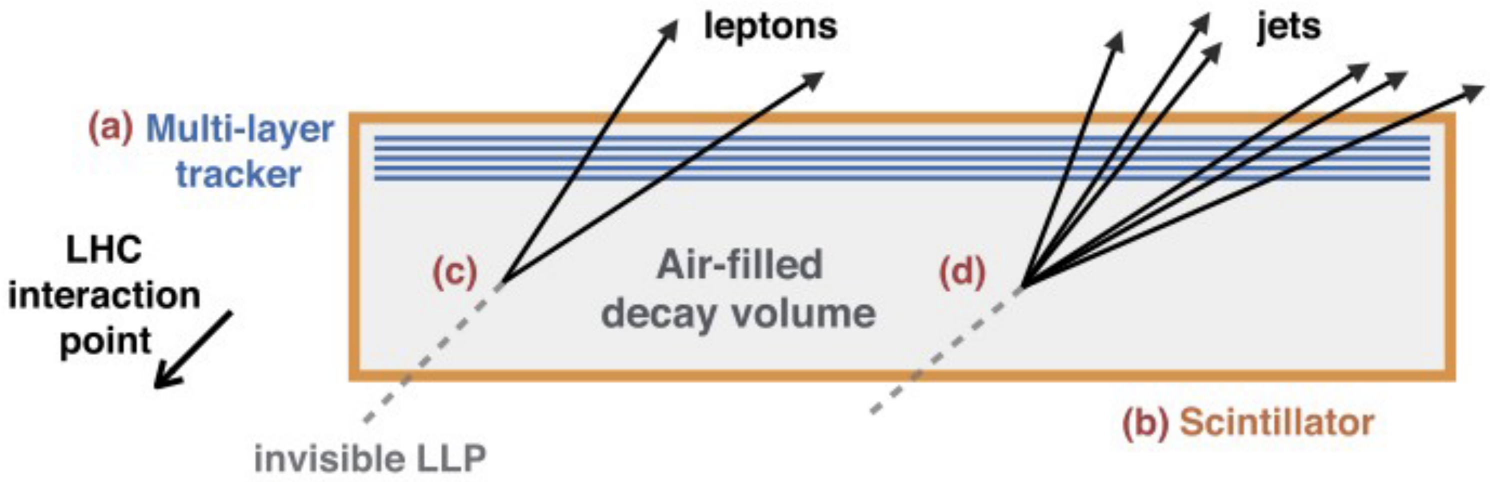
MATHUSLA detector

(**MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutral p**A**rticles)

1. Purpose:
   - Search for LLPs with 10^7m<cτ<10^8 m
   - To complement searches of LLPs at CERN
2. Description:
   - Large volume tracking detector on surface above LHC experiment
3. Instrumentation:
   - RPC tracking layers in a building covered by scintillator layers



RPCs:

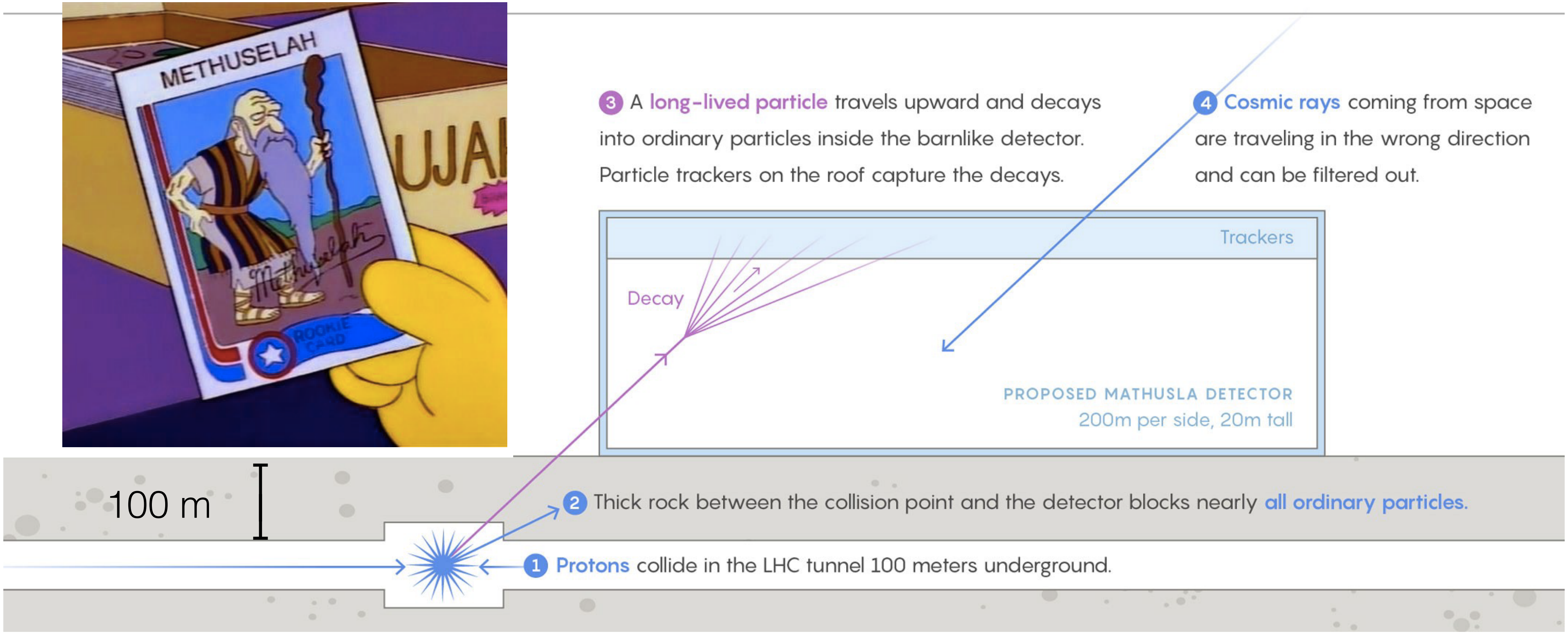
$\sigma x, \sigma y \sim 1$cm

$\sigma t \sim 1$ ns

J.P. Chou, D. Curtin, H.J. Lubatti. Phus. Lett. B 767 (2017)29
D. Curtin and M. E. Peskin, Phys. Rev. D 97, 015006 (2018)

MATHUSLA detector

(**MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutral p**A**rticles)



Quanta Magazine

MATHUSLA detector

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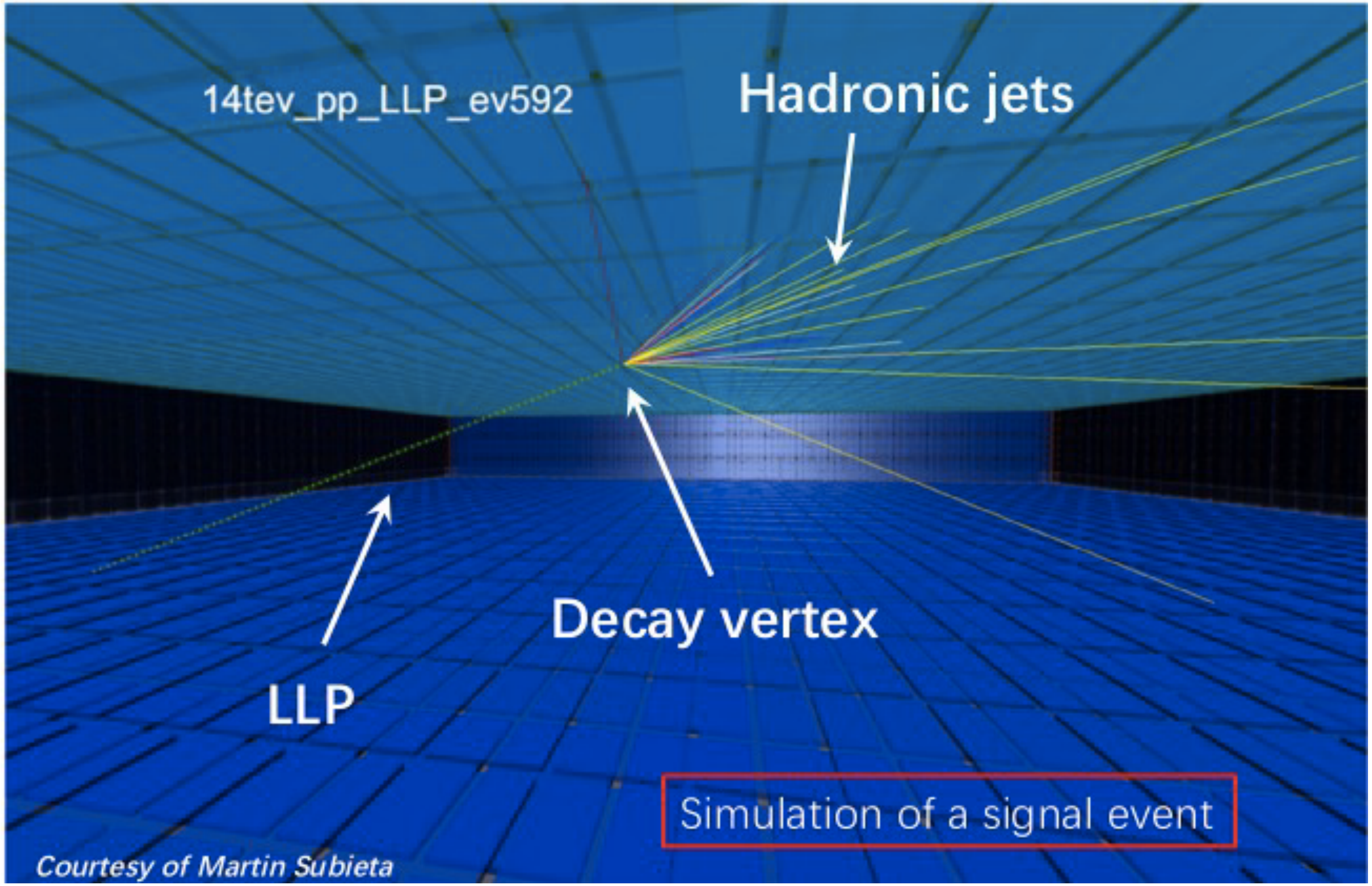
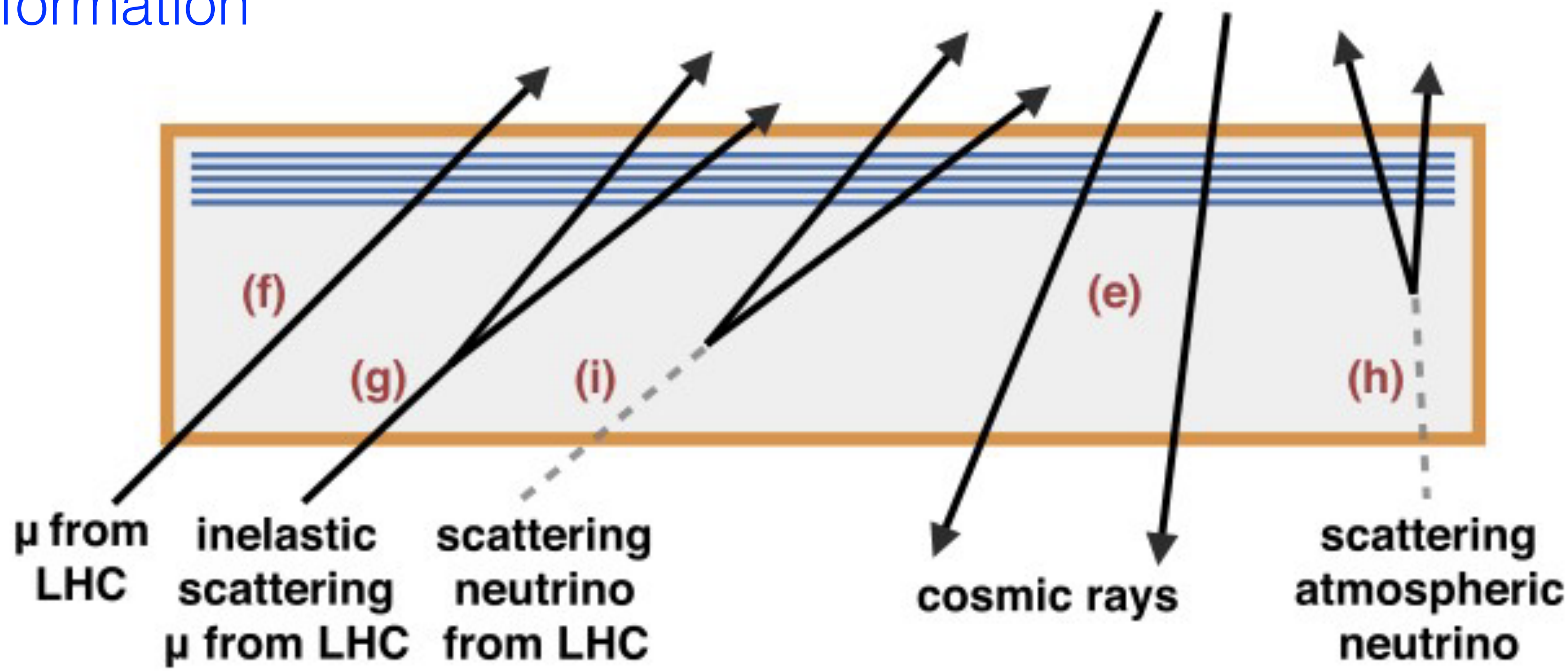


C. Zhang, Pekin University, 2017

MATHUSLA detector

(**MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutral p**A**rticles)

4. Background:
   - Neutrinos and muons from LHC, atmospheric neutrinos, cosmic rays
   - Rejected from information of tracking system and timing information



J.P Chou, D. Curtin, H.J.Lubatti, Phys. Lett. B 767 (2017) 29

MATHUSLA detector

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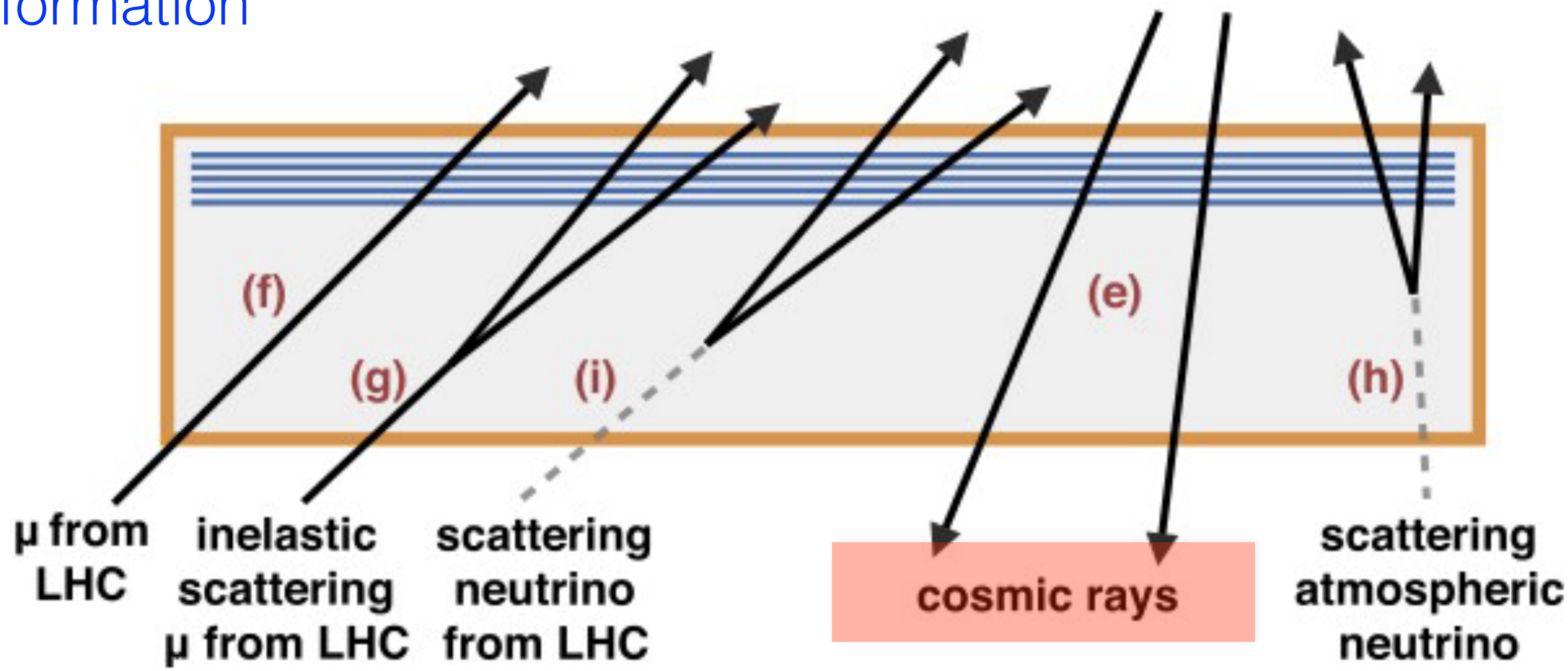

J.C. Arteaga-Velázquez

J.P Chou, D. Curtin, H.J.Lubatti, Phys. Lett. B 767 (2017) 29

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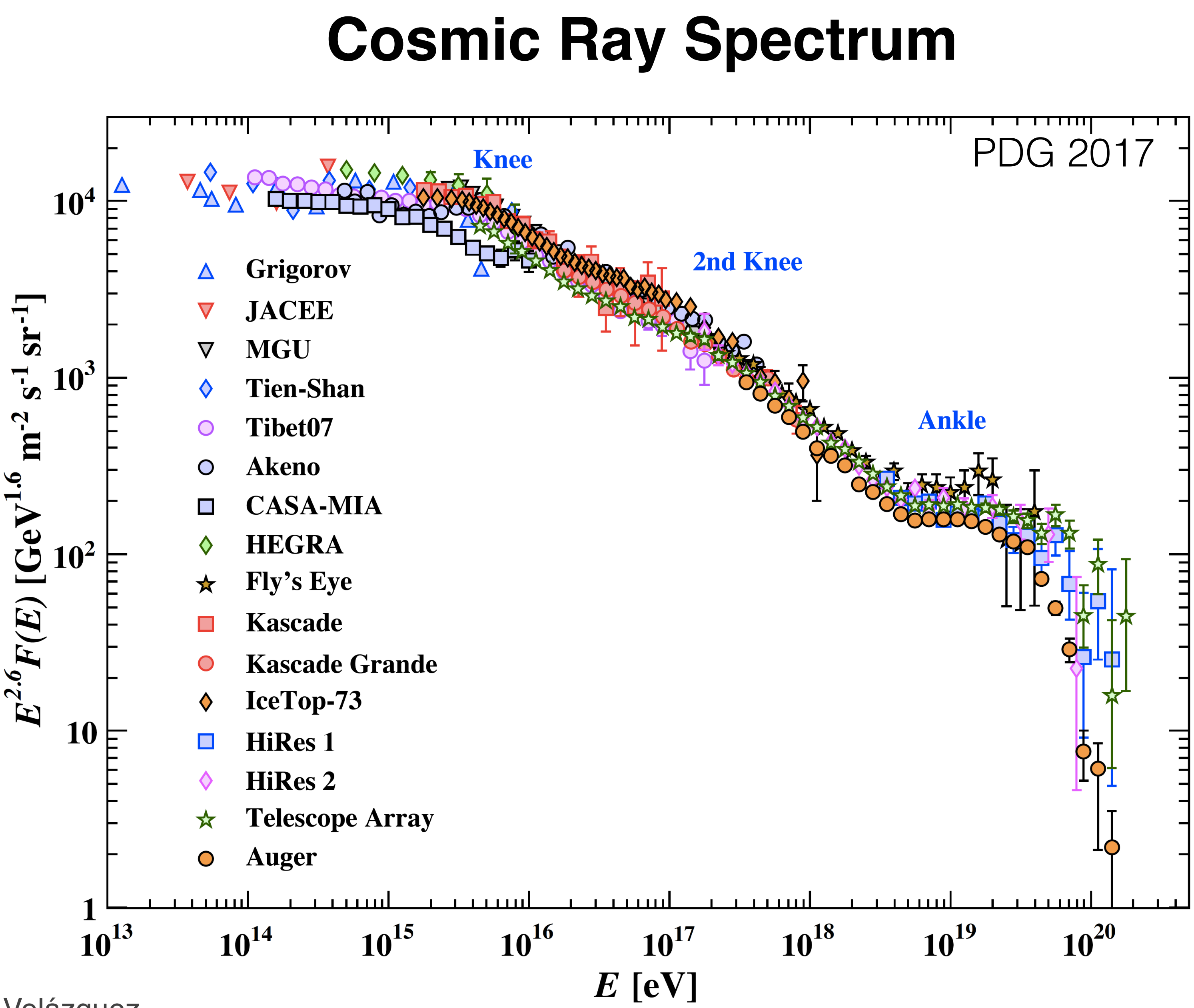
MATHUSLA as a CR's EAS detector



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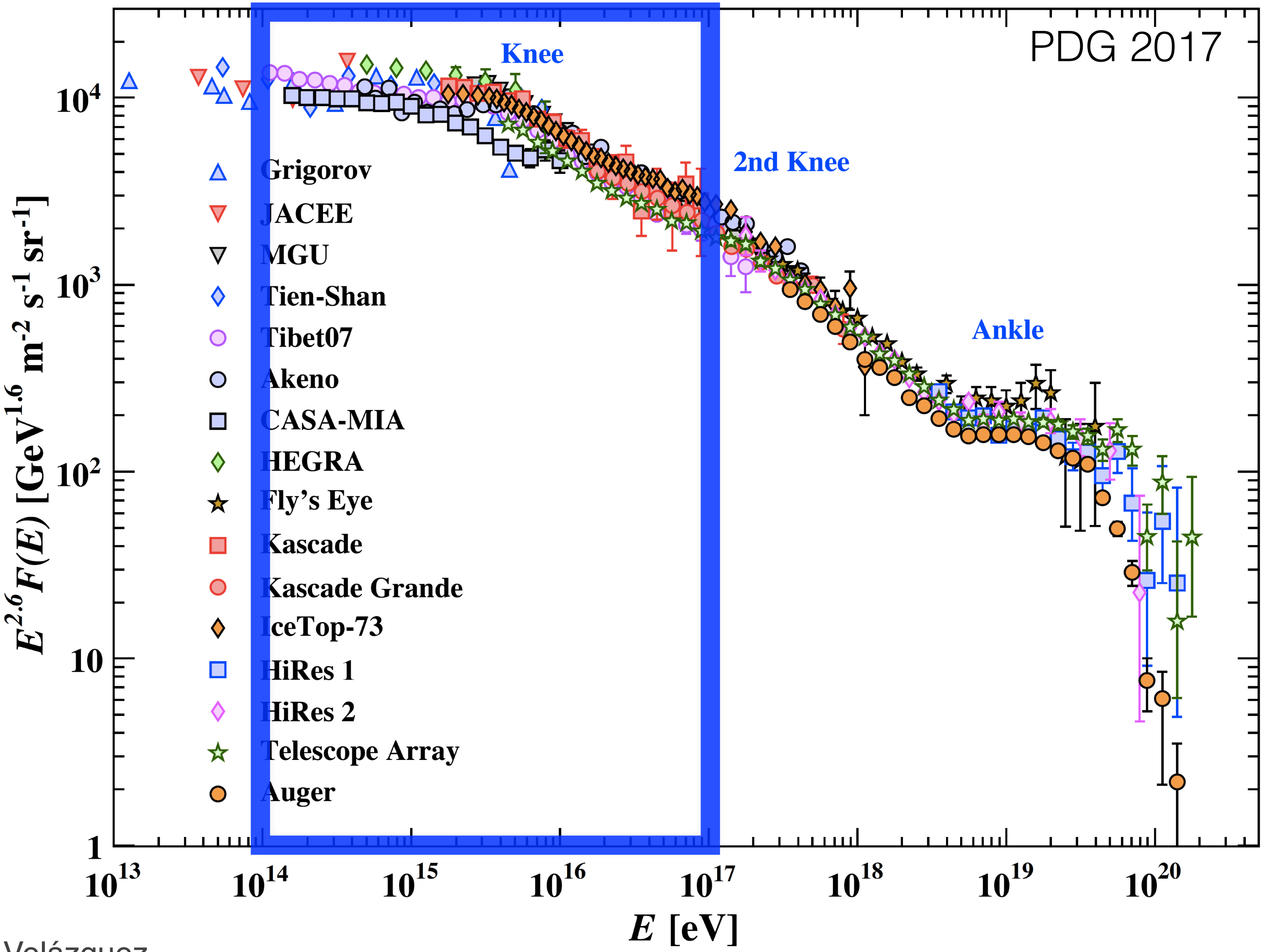
MATHUSLA as a CR's EAS detector

From the size of the instrument and altitude:

Expected energy range: 10^{14} - 10^{17} eV



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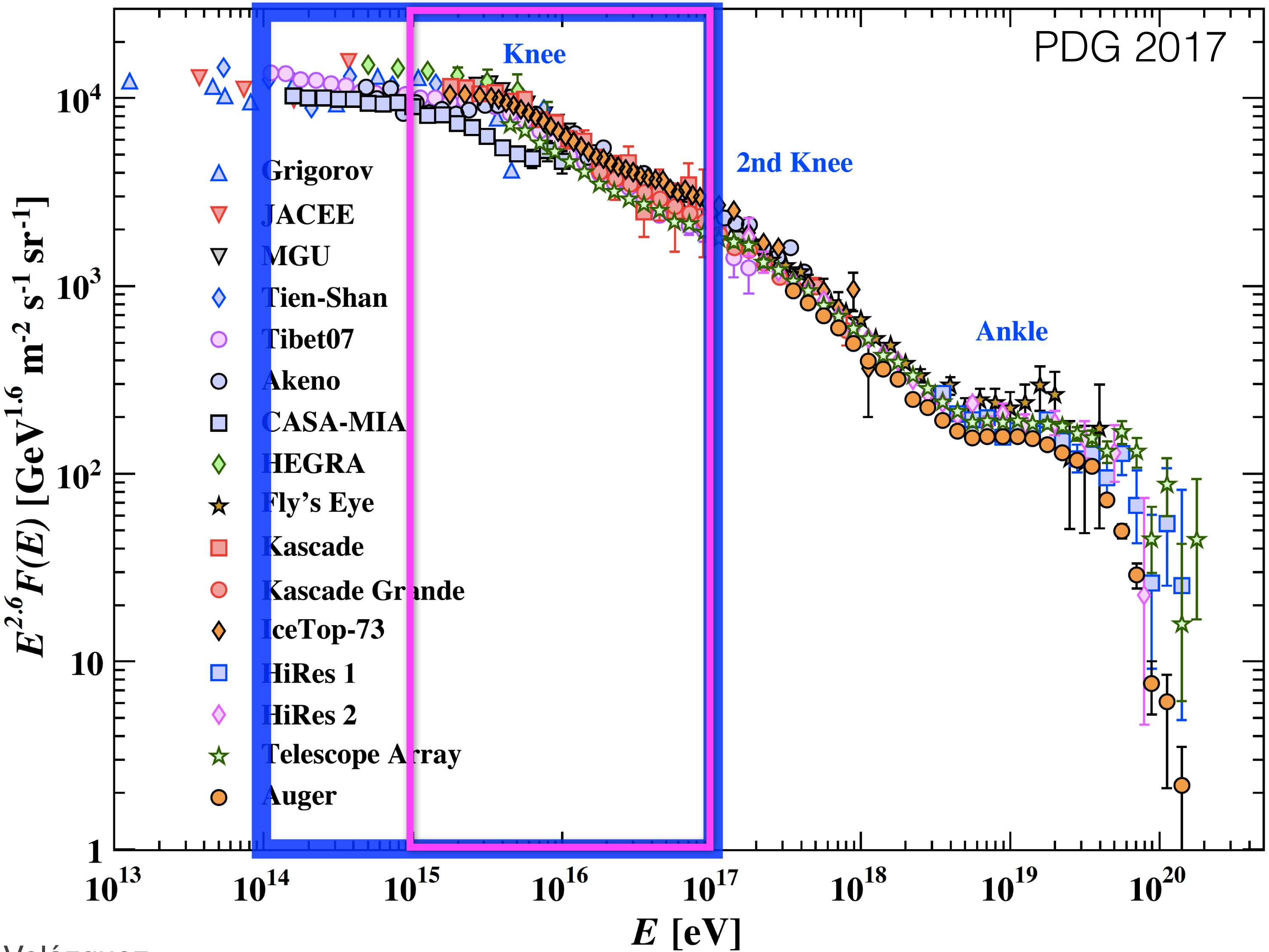
Expected energy range: 10^{14} - 10^{17} eV **Full efficiency >10^{15} eV**



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MATHUSLA as a CR's EAS detector

Cosmic Rays

> Spectrum:

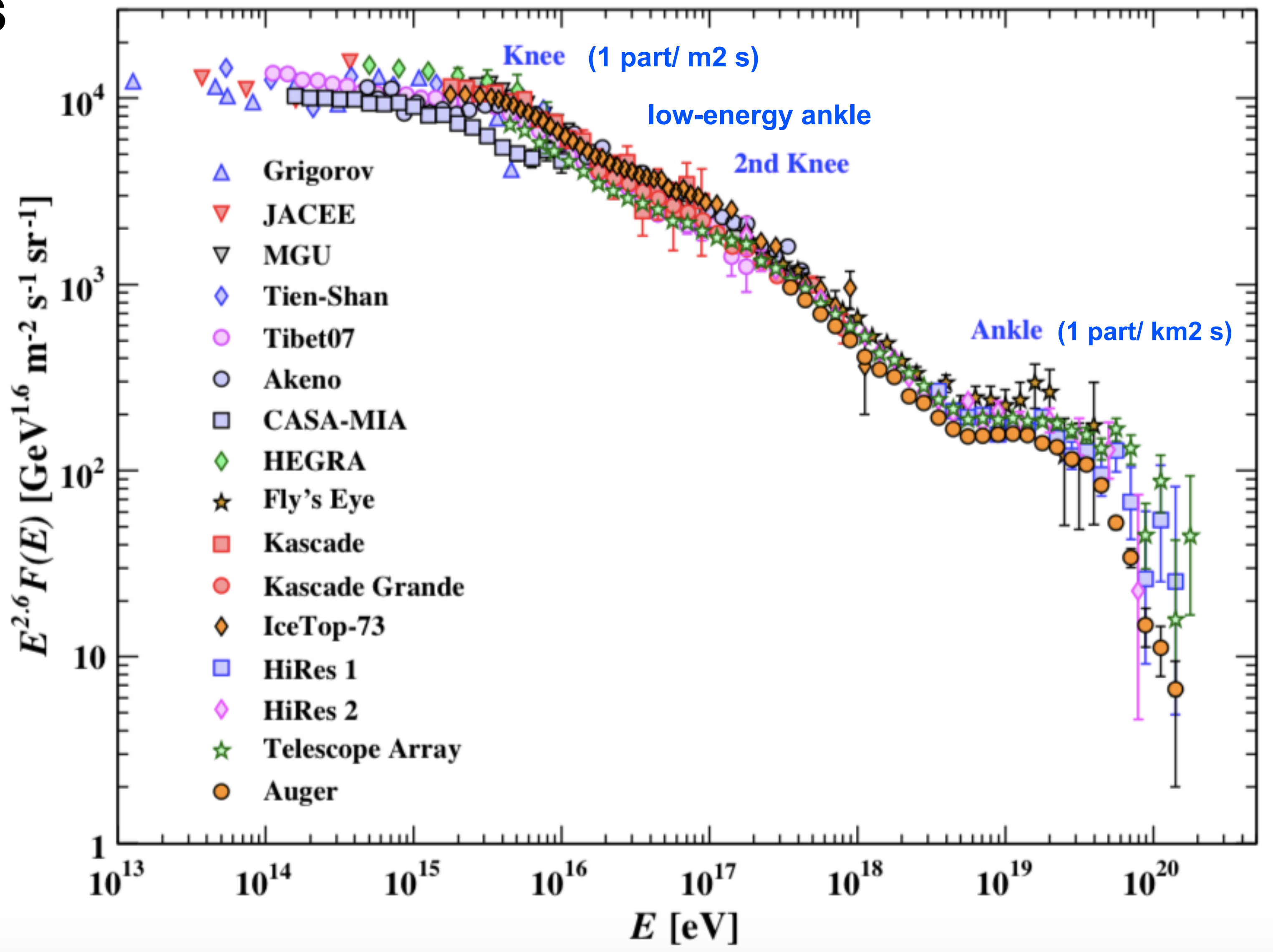
$F(E) = E^{-\gamma}$

> Composition:

1) Electrons (2 %)
2) Atomic nuclei and
3) Neutrons (98 %)

Mainly H (83 %),
He (11%)

Energy spectrum extends from $\mathcal{O}$(100) MeV up to ZeV



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MATHUSLA as a CR's EAS detector

Cosmic Rays

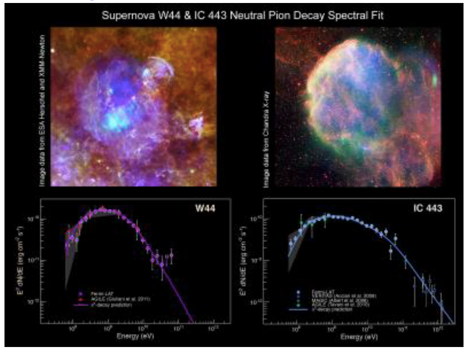
> Origin:

Galactic:

1)Sun

2)SNR

3)?

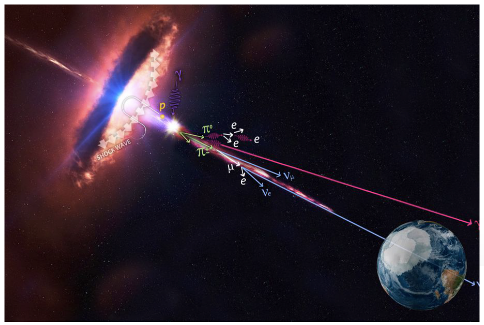


M. Ackermann et al., Science Mag. 339 (2013) 807

Extragalactic:

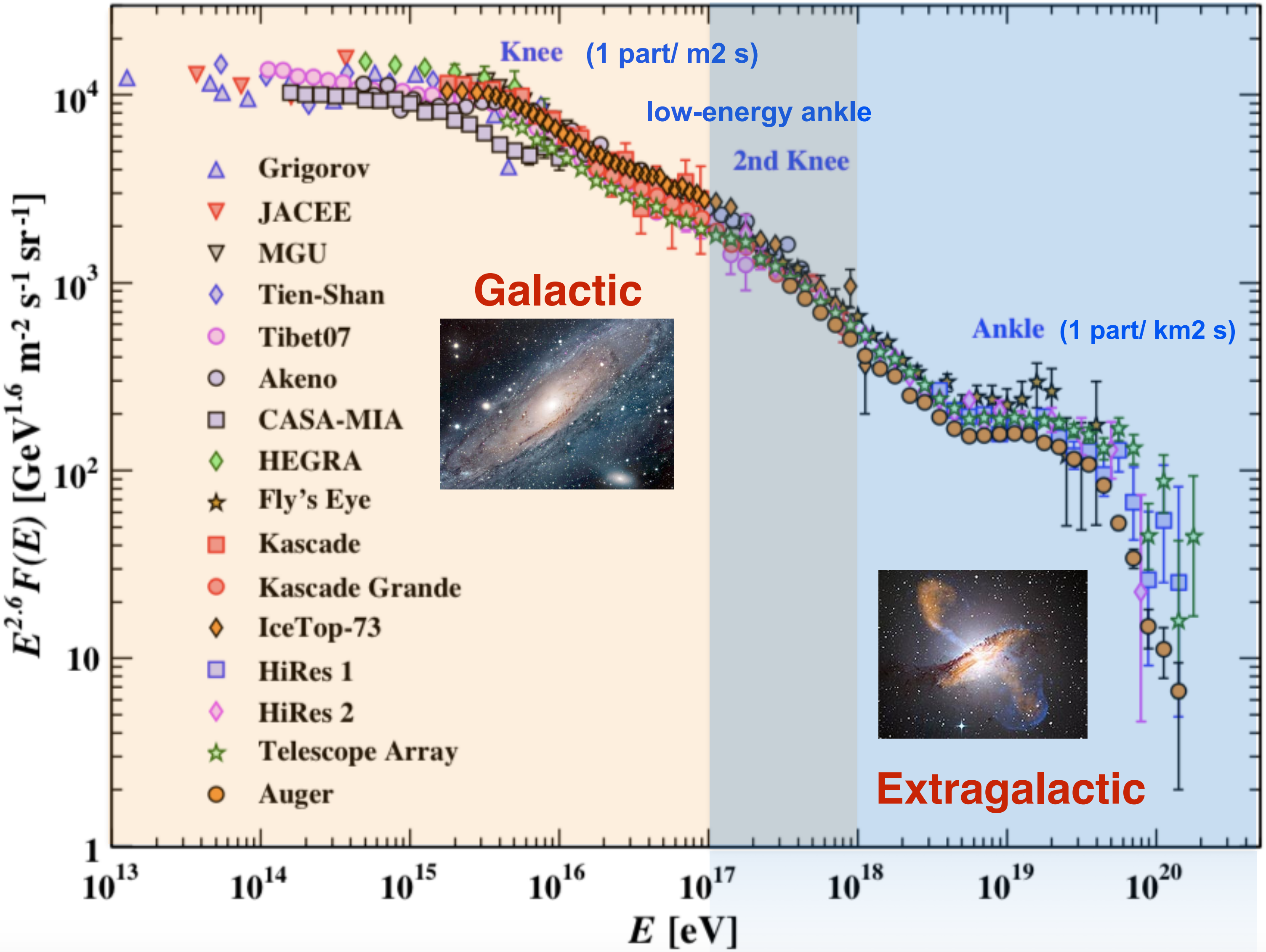
1)Blazars

3)?



ICECUBE/NASA

Energy spectrum extends from $\mathcal{O}$(100) MeV up to ZeV



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MATHUSLA as a CR's EAS detector

Cosmic Rays

> Questions:

1) Origin of structures in spectrum

2)Composition

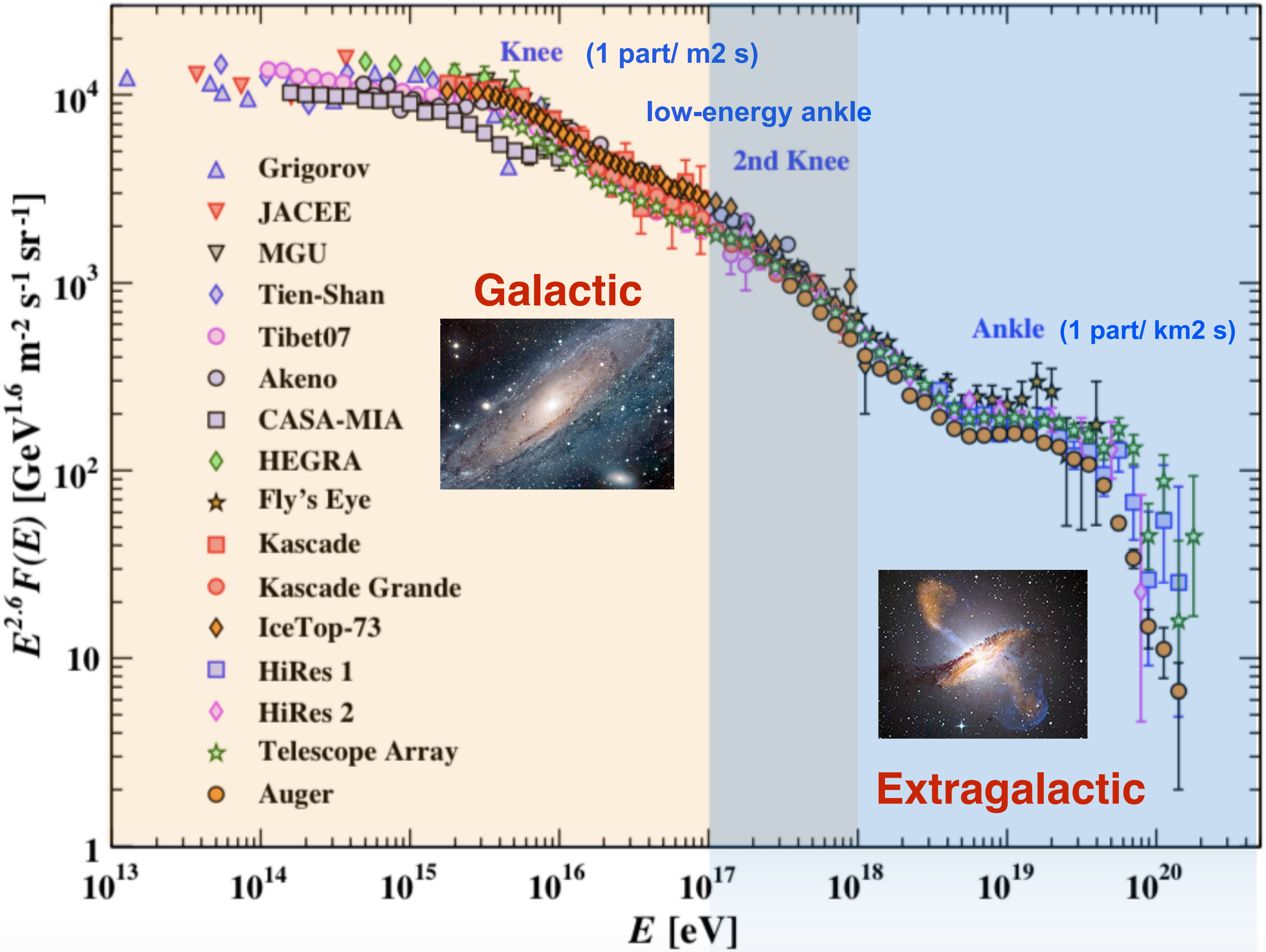
3) Sources

4) Propagation

5) Acceleration Mechanisms

6) Glctic-extraglactic Transition

Energy spectrum extends from $\mathcal{O}$(100) MeV up to ZeV



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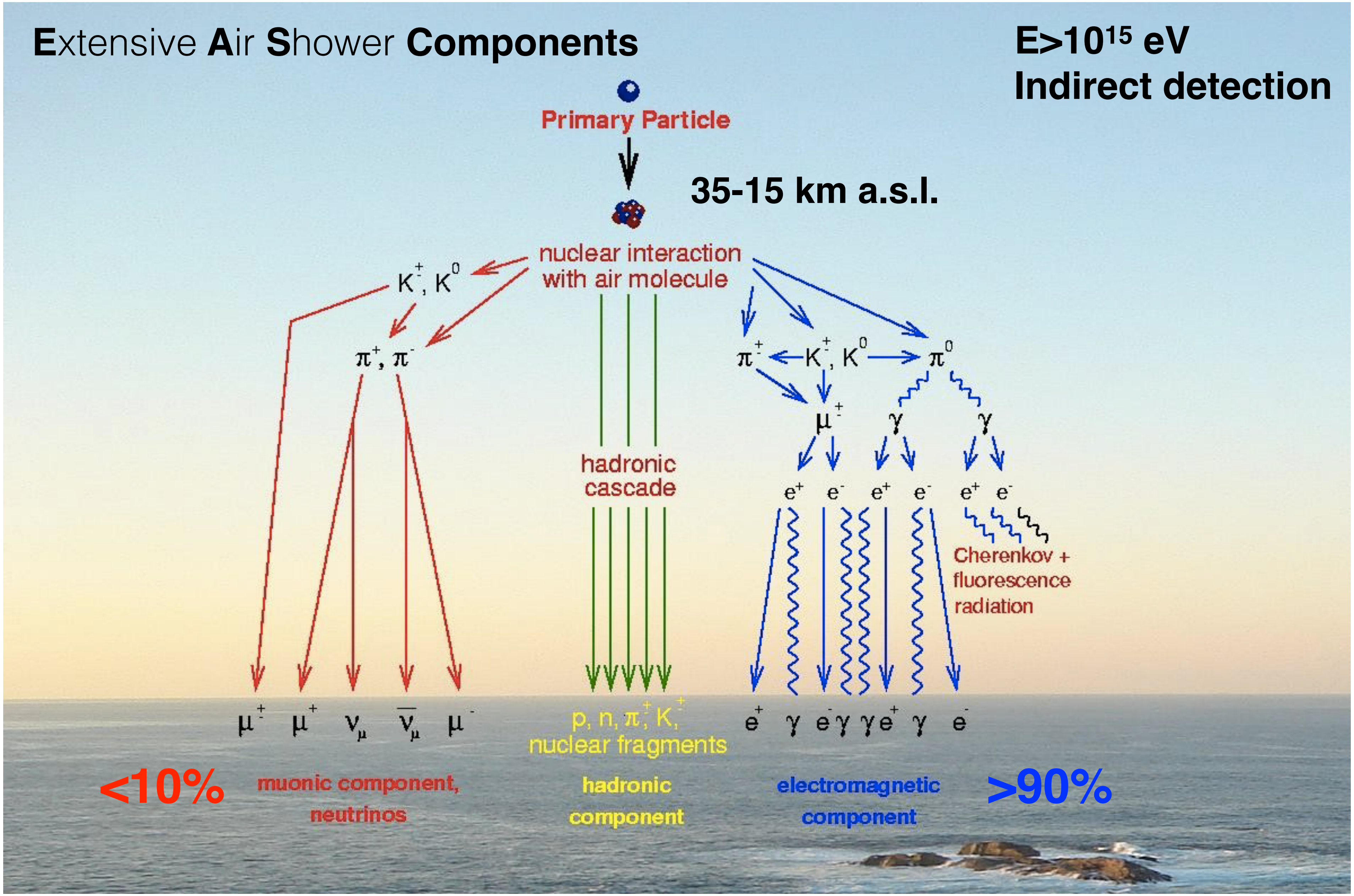

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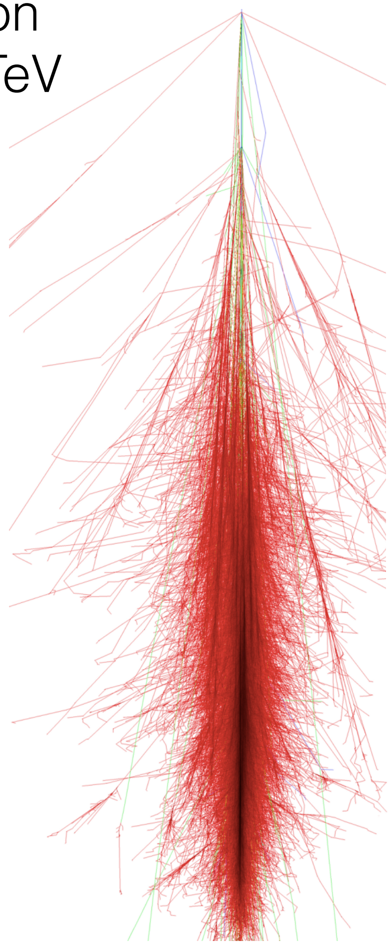
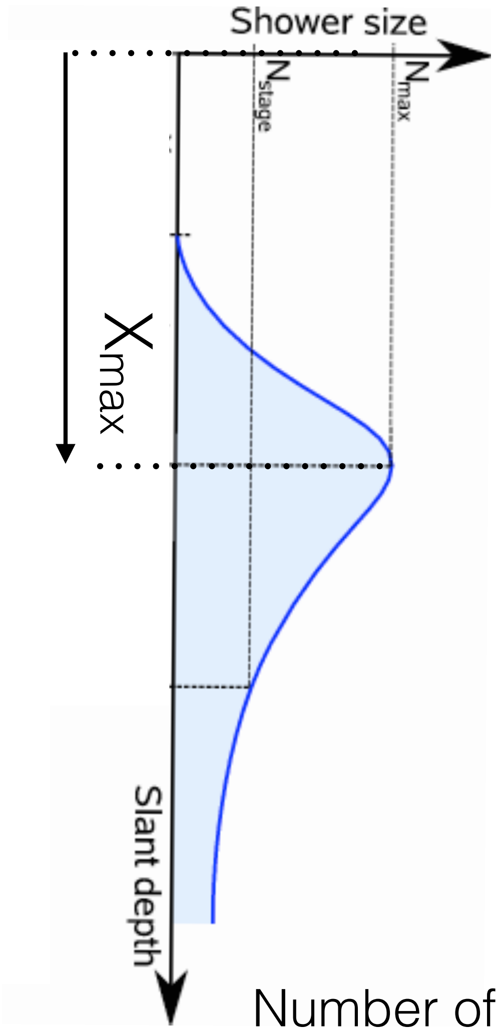
MATHUSLA as a CR's EAS detector

Extensive **A**ir **S**hower **Components**

Longitudinal development

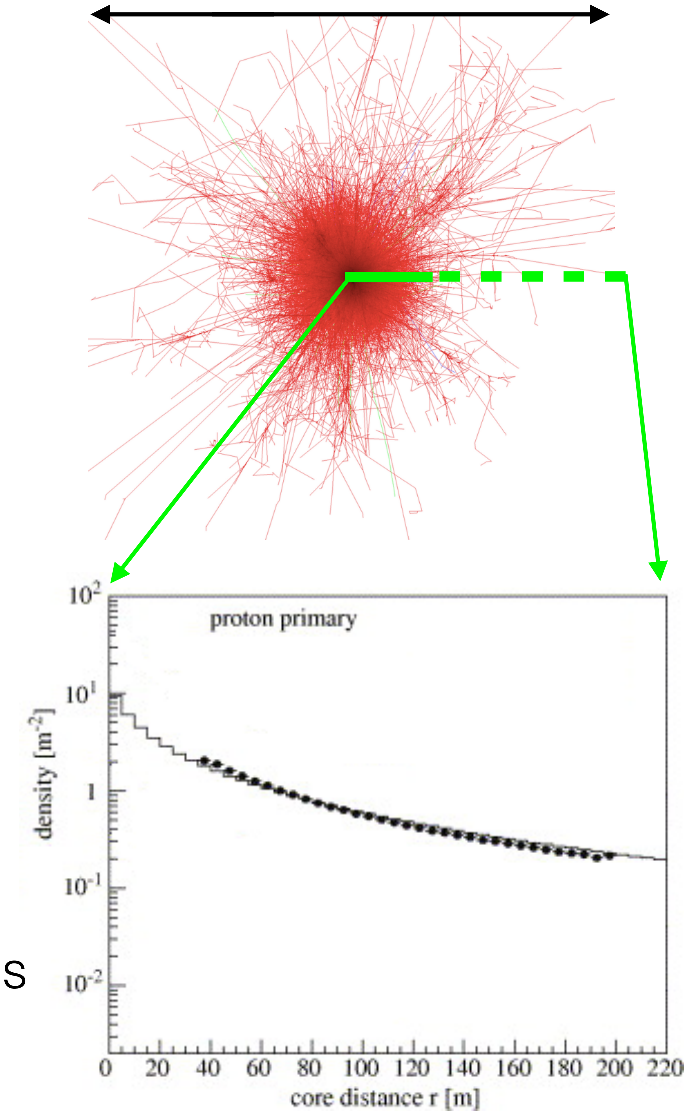
Proton
E= 1TeV





Lateral development

$\mathcal{O}$(0.1 - 1 km)



Number of particles at ground: $N \sim E^{\alpha}$

CORSIKA webpage

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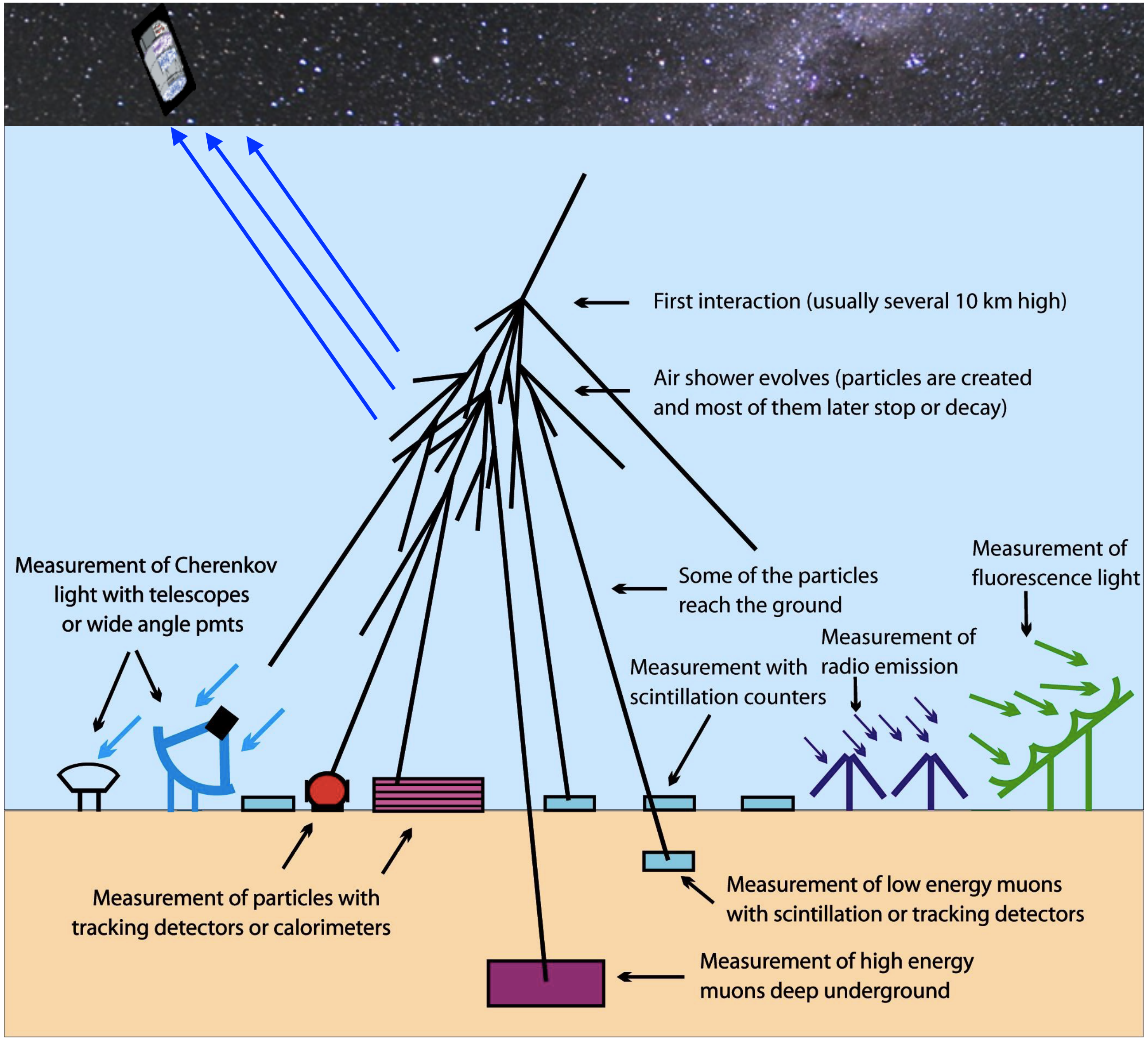
MATHUSLA as a CR's EAS detector

EAS detection from Earth and Space



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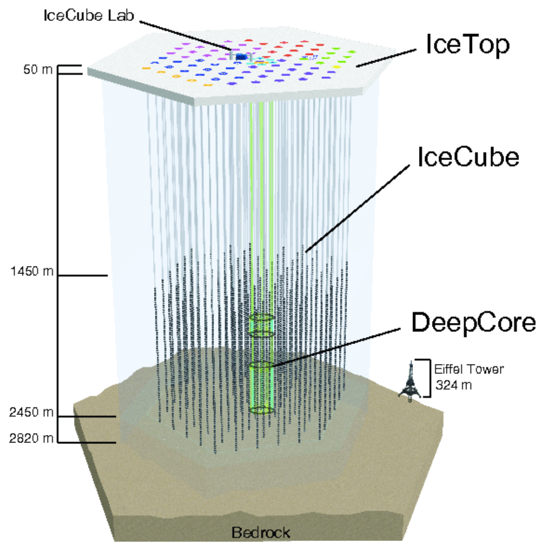
MATHUSLA as a CR's EAS detector

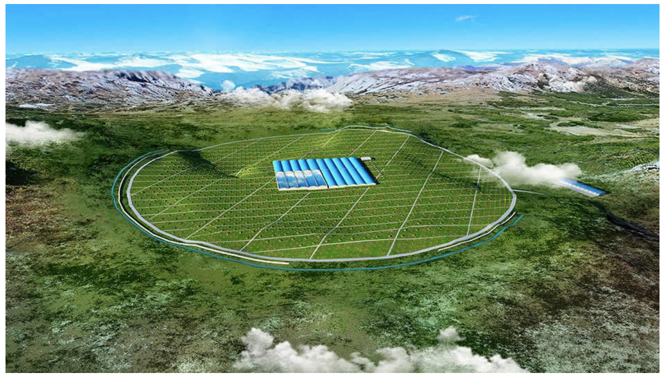
Modern/future experiments sensitive to te energy range of MTHUSLA

Experiment	Energy range (PeV)	Altitude (m a. s. l)	Size (10^4 m^2)	Technique
MATHUSLA-100	(1, 32)	380-436	1	RPC, TD
ARGO-YBJ	(0.1, 3)	4300	0.7	RPC, TD
KASCADE	$(1, 10^2)$	110	4	Sci, TD, CD
HAWC-Outrigger	$(10^{-4}, O(1))$	4100	11	WCD
Taiga	> 0.1	675	25	IACTs
IceTop	$(1, 10^3)$	2835	100	ICD
LHAASO	$(10^{-4}, 10^2)$	4410	100	WCD,AC,Sci.
TALE (TA)	$(30, 10^4)$	1550	10^3	FD, Sci.

HAWC (Mexico)



IceCube/IceTop (Antartica)



LHAASO (China)

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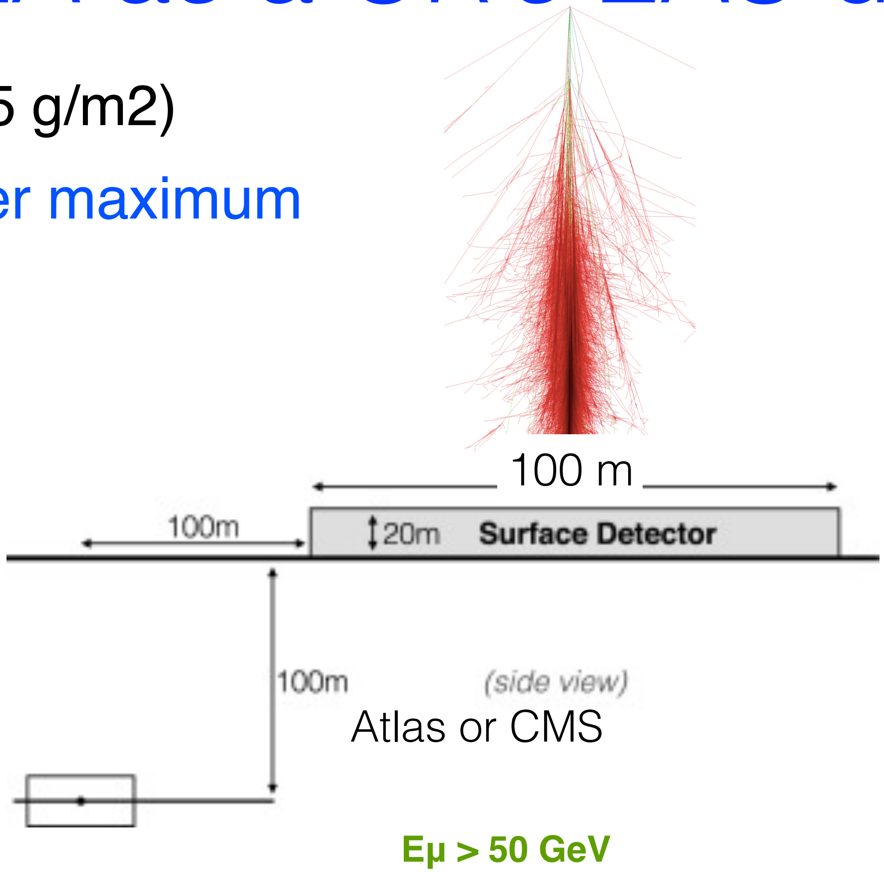
MATHUSLA as a CR's EAS detector

h ~ 436 m a.s.l. (~ 975 g/m2)

Sampling EAS front after maximum



Two modes for EAS sampling:
Stand alone mode (STD): MATHUSLA (scintillator planes and RPC's) alone.
Combined mode (CB): MATHUSLA and the underground detector.

Golden events: Local shower μ's sampled with the collider detector for EAS with cores landing on MATHUSLA sensitive area.

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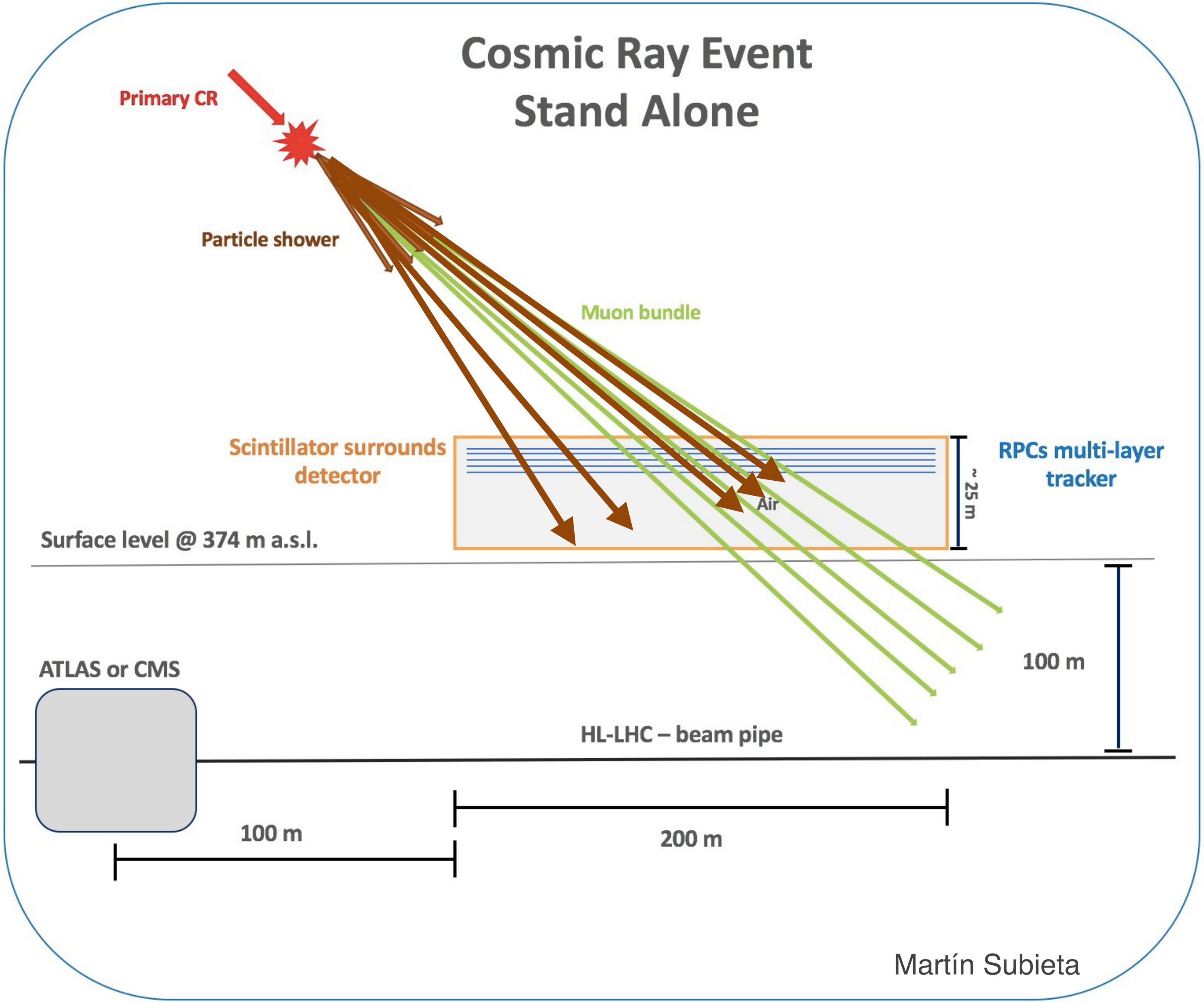
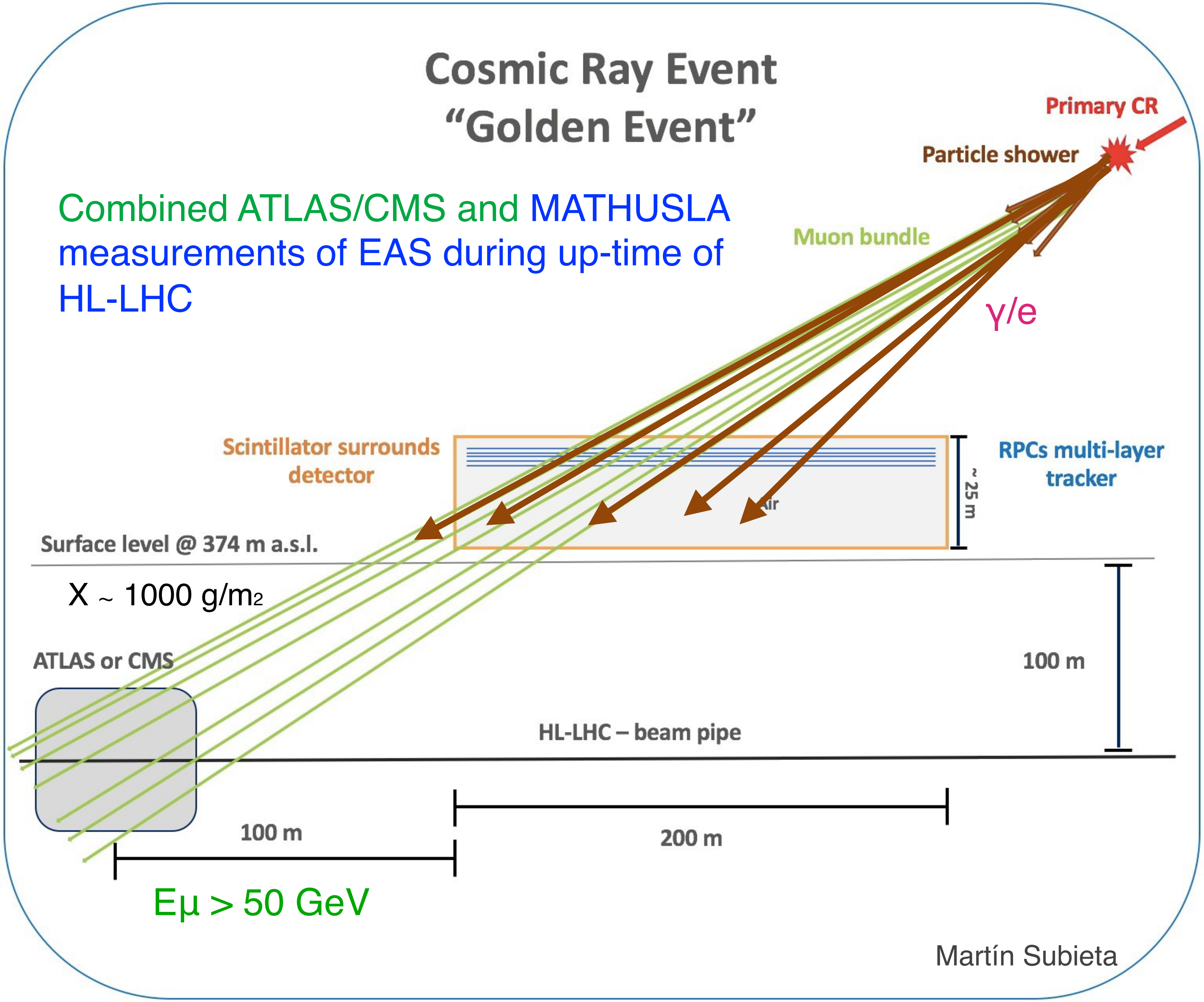
MATHUSLA as a CR's EAS detector



MATHUSLA as a CR's EAS detector



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MATHUSLA as a CR's EAS detector

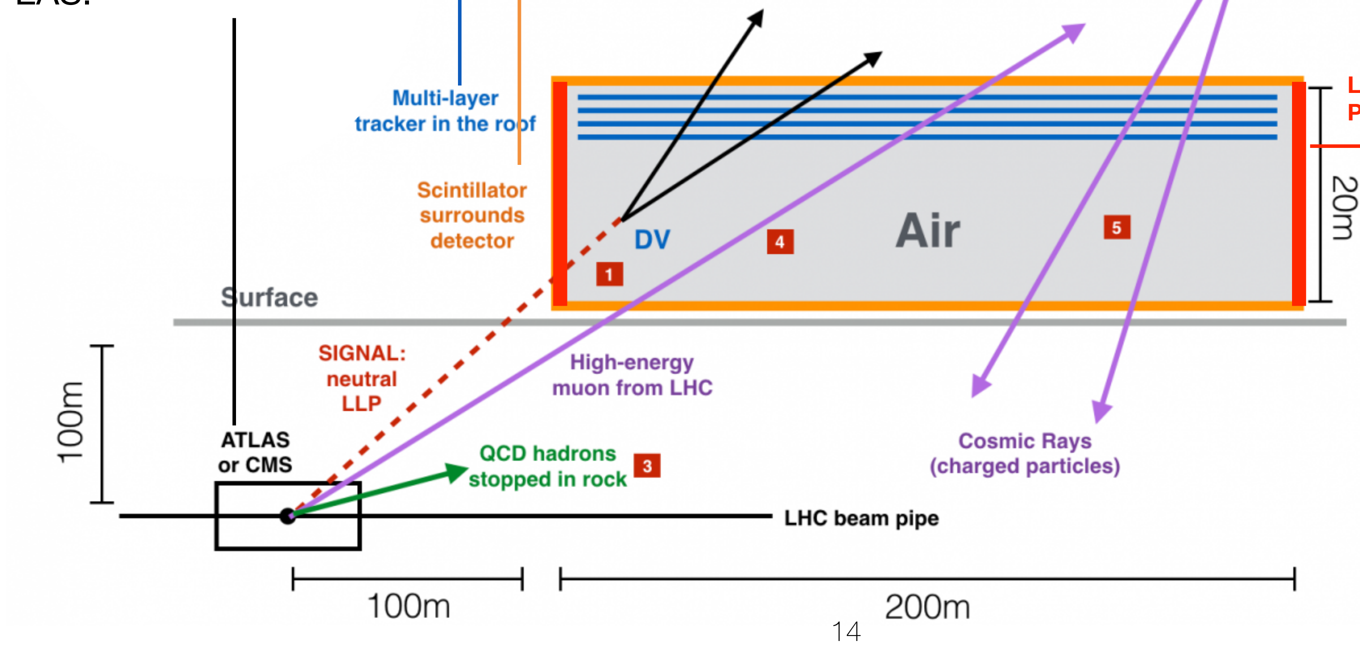
Monitor northern hemisphere, day and night, independent of weather conditions (increased statistics in comparison with Cherenkov arrays)

1.Enhanced angular resolution and better precision in EAS core location than other particles detector arrays.

2.Spatial-temporal measurements of EAS front at the finest level (**it could help for shower particle ID**).

1.Help in the study of μ-bundles.
2.In CB mode will complement MATHUSLA measurements of EAS.

1.Help in reconstruction of arrival direction and core location of air showers.
2.Help to check systematics on EAS observables.



Unique feature to study inclined EAS and look for ν induced events

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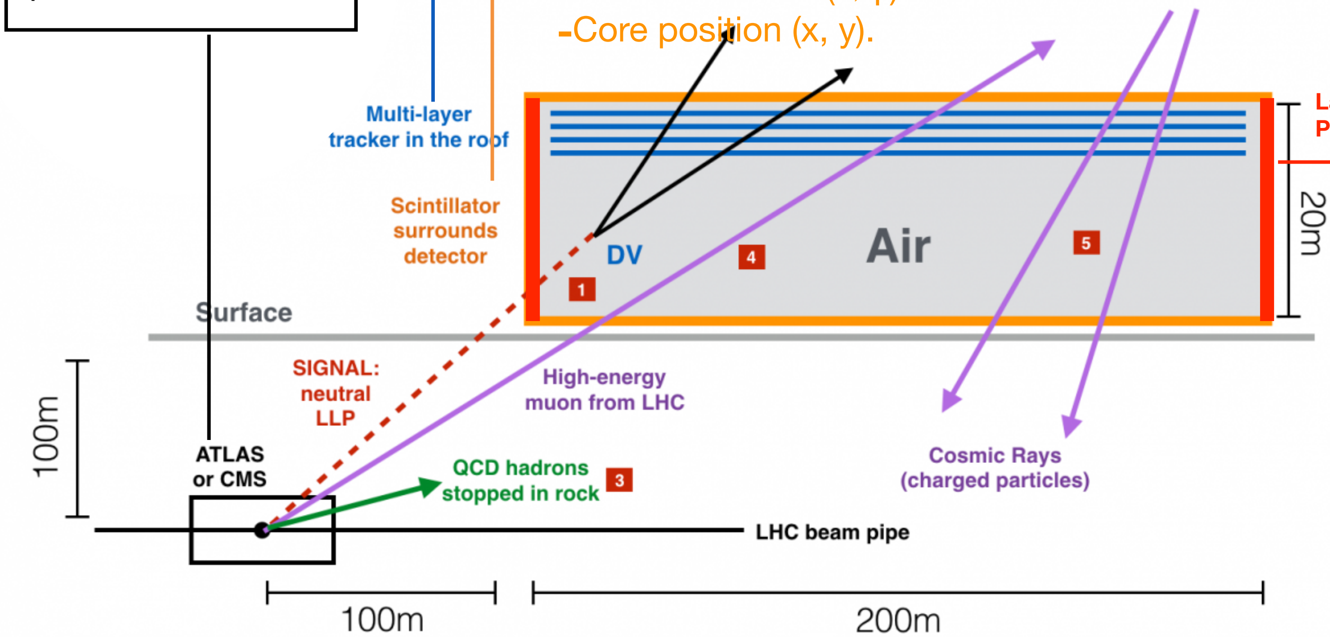
MATHUSLA as a CR's EAS detector

With no e/μ separation

- Lateral density distribution: $\rho_{ch}(r)$.
- Total number of charged particles: N_{ch}.
- Arrival times: t(r).
- Lateral shower age: s.
- Arrival direction (θ, ϕ)
- Core position (x, y).

- μ densities
- μ^+/μ^- ratio
- μ energy spectrum
- μ direction

- Lateral density distribution: $\rho_{ch}(r)$.
- Total number of charged particles: N_{ch}.
- Arrival times.
- Lateral shower age: s.
- Arrival direction (θ, ϕ)
- Core position (x, y).



Inclined EAS
- μ production height: h_μ
- Maximum of μ production depth: X_μ^{max}
- Muon content: N_μ

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Cosmic Rays Physics case

1. Cosmic rays

+ Energy spectrum of cosmic rays

    - Obtain fine details of spectrum

+ Composition

    - Spectra of individual chemical species
    - New light knee ~ 700 TeV as observed by ARGO-YBJ?
    - Fine spectrum of heavy component of CRs

+ Anisotropies

    - Look for point sources
    - Anisotropy maps vs composition? It depends on statistics

2. High energy neutrinos

+ Look for Earth-skimming/atmospheric/cosmic events.

    - Neutrino oscillations, atmospheric flux, neutrino interactions, etc

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Cosmic Rays Physics case

3. Test of hadronic interaction models

+ Shower particles

- Correlation with N_{μ}, N_h, N_e
- Arrival times of particles
- High energy muon excess
- Attenuation length of shower muons
- Muon production height (MPH)
- Lateral distribution of muons/electrons/hadrons
- For events measured simultaneously with MATHUSLA/underground detector:
  - > Muon bundles and relation with EAS primaries
  - > Local ρ_{μ} (θ, E),   μ+/μ- (θ, E) data for EAS

+ Shower properties

- Investigate fine spatial-temporal structure of EAS
- Study inclined EAS
- Look for exotic EAS events

4. VHE gamma rays

+ Look for γ-ra events —> upper limits

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Cosmic Rays Physics case

Light spectrum of CRs

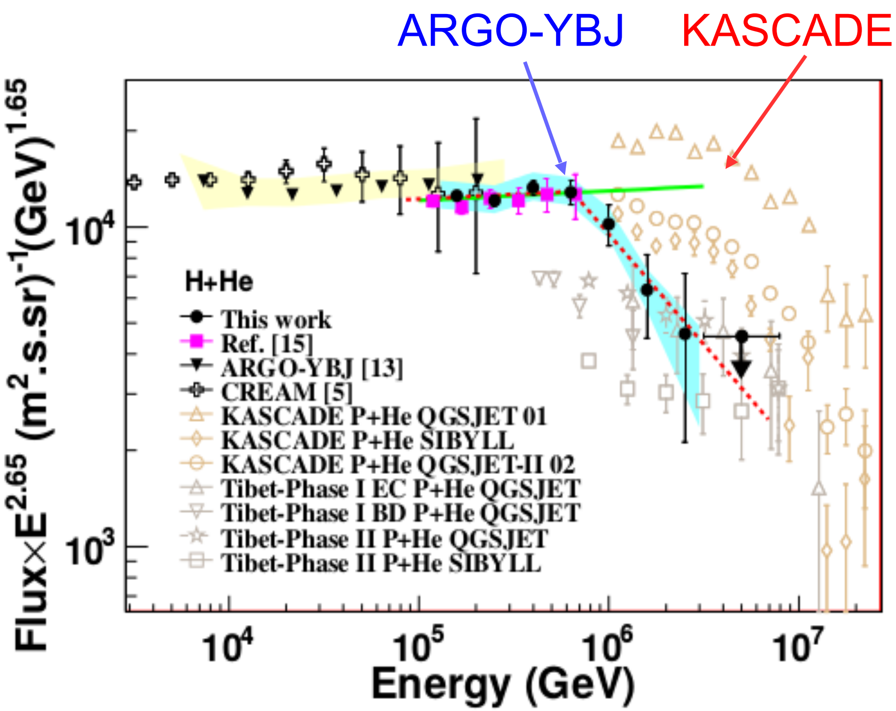
+ Two knees in the PeV light (H+He) spectrum?

+ Hidden systematic error?

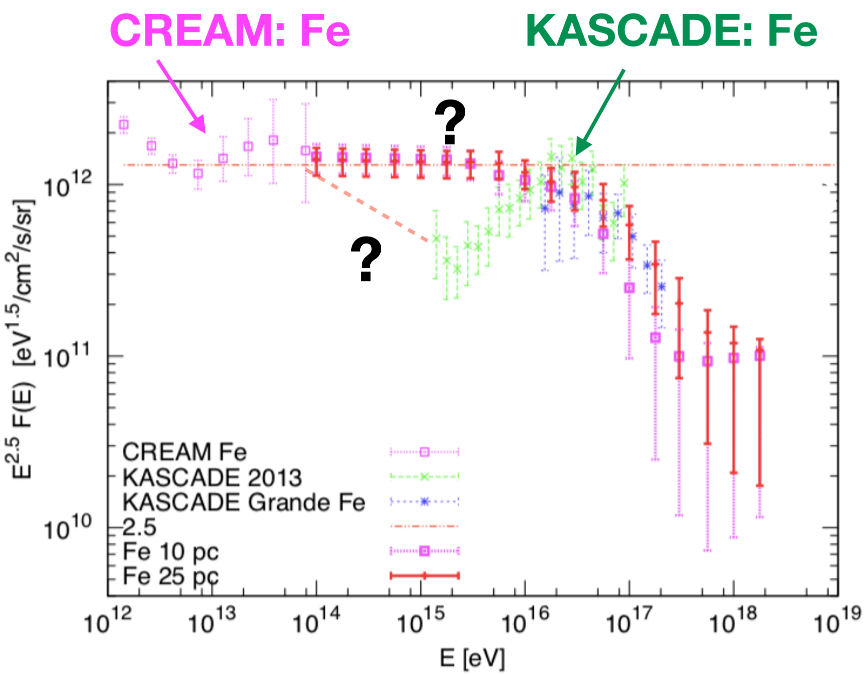
Heavy spectrum of CRs

+ Fine structure in spectrum?

+ Systematic errors?



ARGO-YBJ Collab., astro-ph 1502.03164



Giacinti et al., PRD 91 (2015) 083009

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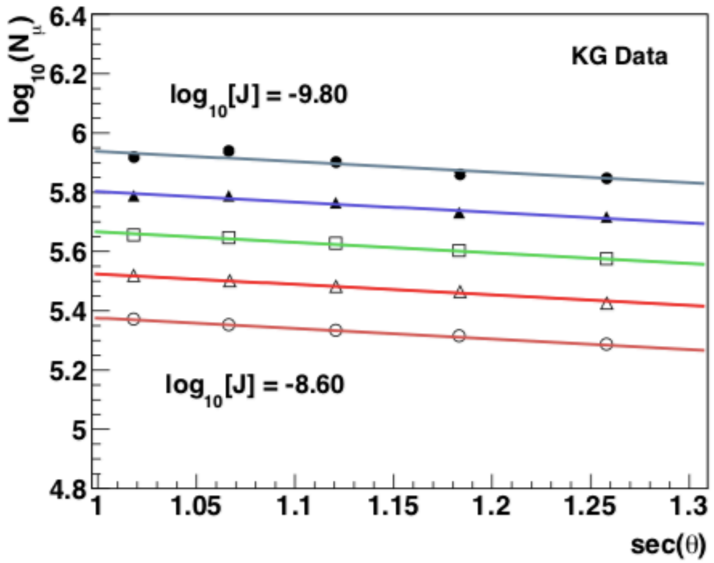
Cosmic Rays Physics case

KASCADE measurements



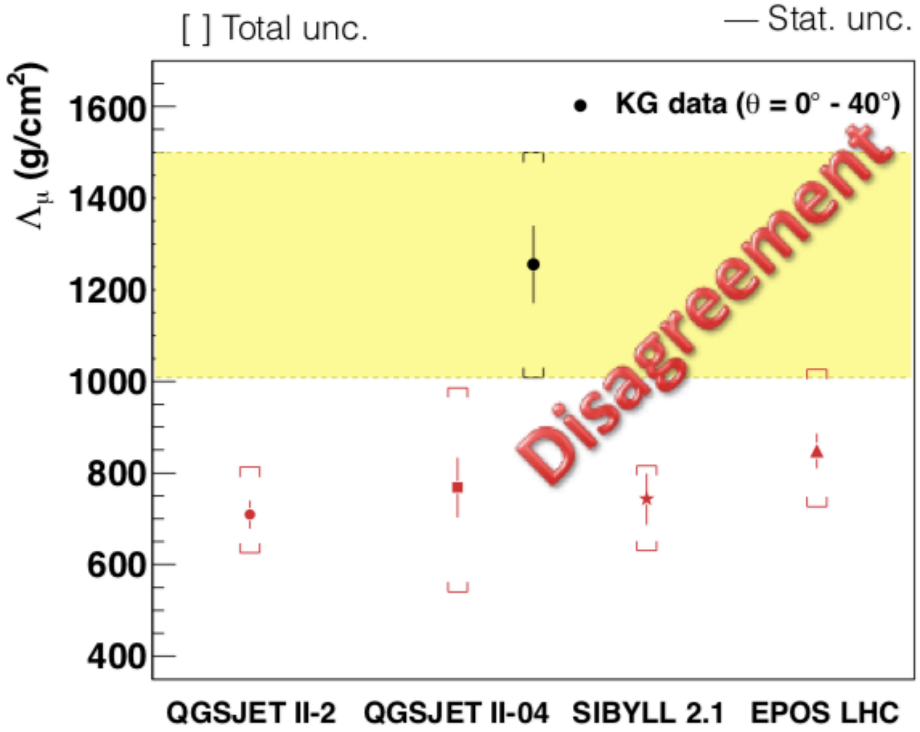
Muon attenuation length (Λ_μ):

$$N_\mu = N_\mu^0 \exp[-X_0 \sec(\theta)/\Lambda_\mu]$$

Measured muon attenuation length (E_{CR} ~ 10^{16} - 10^{17} eV) **is above** MC predictions .

Can we confirm the anomaly around the knee? E dependence?

Muon attenuation length



J.C. Arteaga et al., Astropar. Phys. 95 (2017) 25

Less effective attenuation in exp. data

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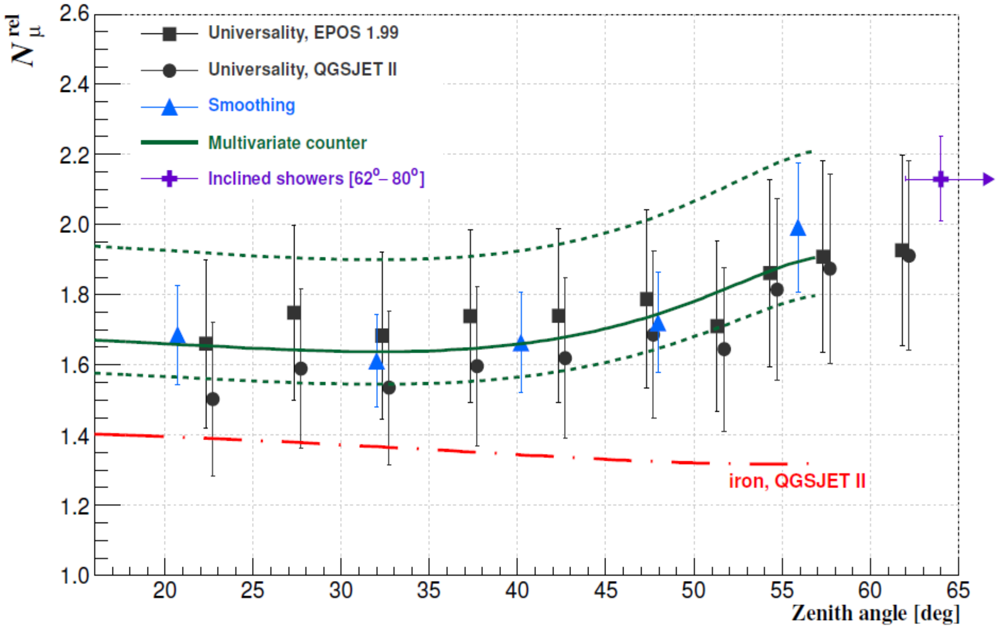
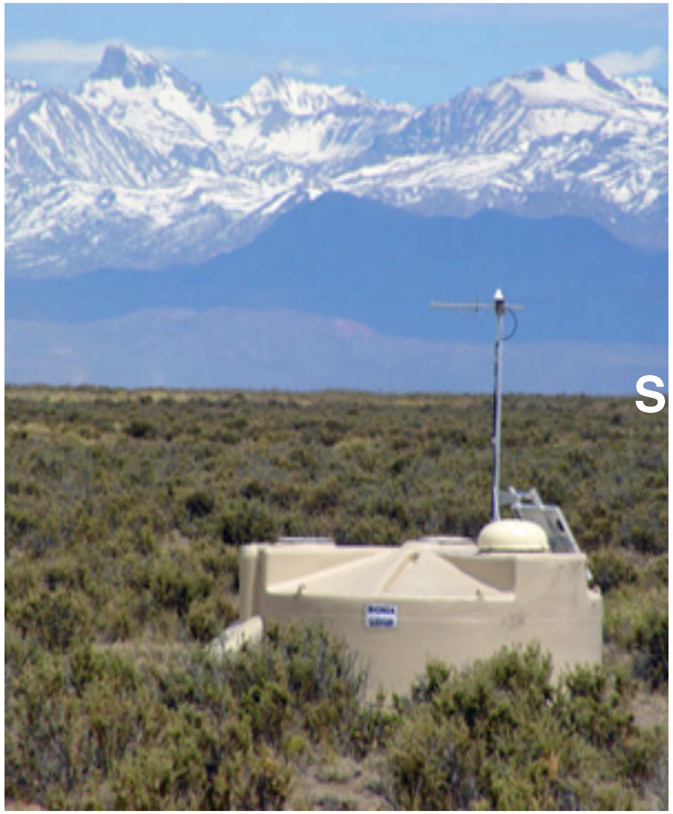
Cosmic Rays Physics case

At ultra-high energies muon discrepancies have been observed by Auger:
Deficit of muons in MC predictions



Relative number of muons (measured data over protons QGSJET-II predictions at 10^{19} eV) at 1000 m from the EAS core.

A. Yushkov et al., Auger Collaboration, EPJ W. of Conf. 53 (2013)



Pierre Auger Observatory

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Cosmic Rays Physics case

Tests of hadronic interaction models

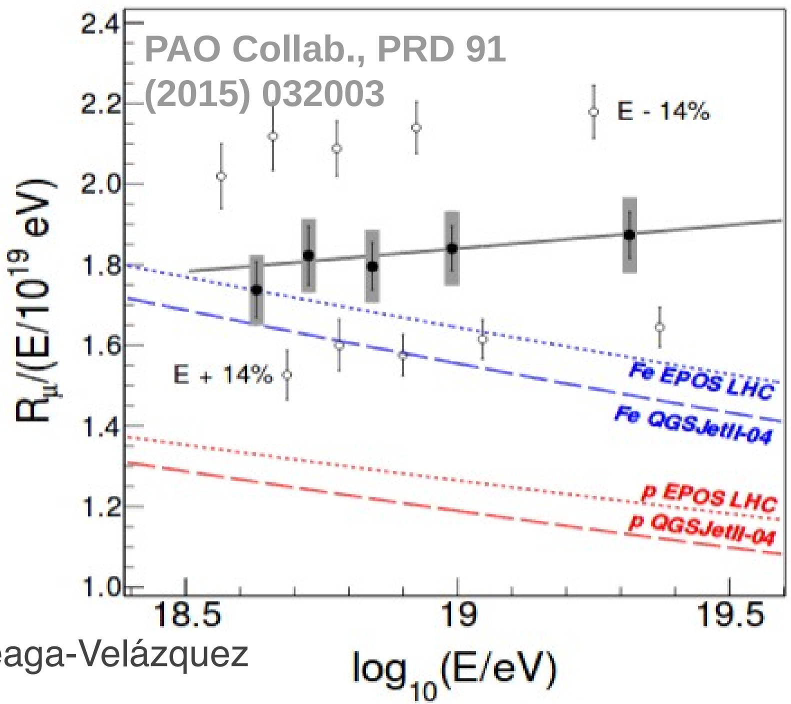
+ Confirm and/or constrain validity of model

Shape of temporal and radial density distributions

Muon content and evolution in EAS

Check possible presence of muon excess in EAS for inclined EAS

Study of muon bundles



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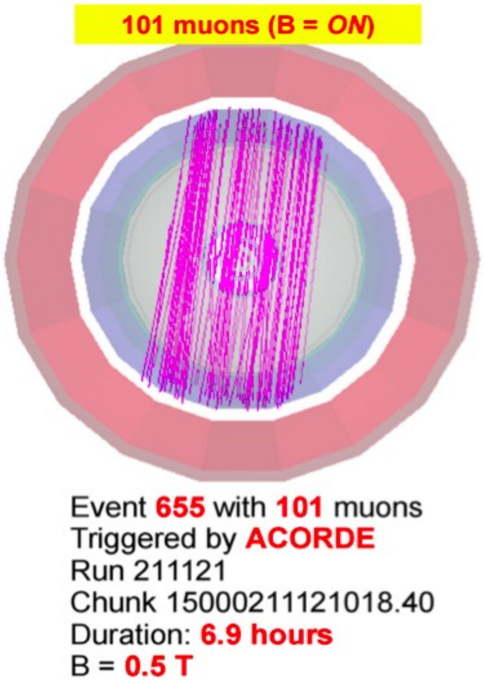


Alice Collab., JCAP01 (2016) 032.

A.Fernández Téllez, M. Cahuatzin, Alice warms with cosmics, Alice Matters,March 2015

MATHUSLA test

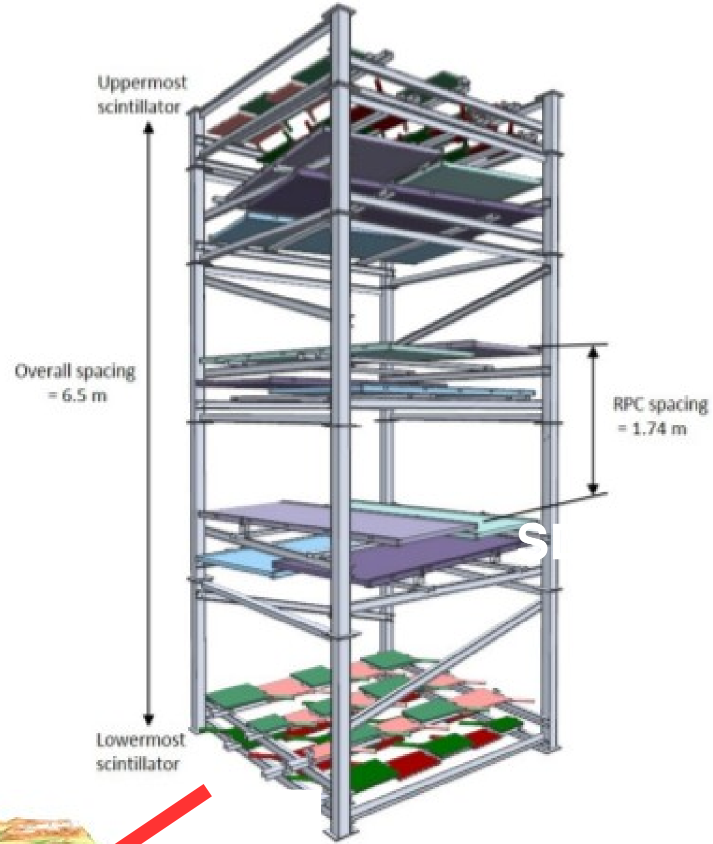
+ Installed at ground level in the ATLAS SX1 building at CERN in November 2017.

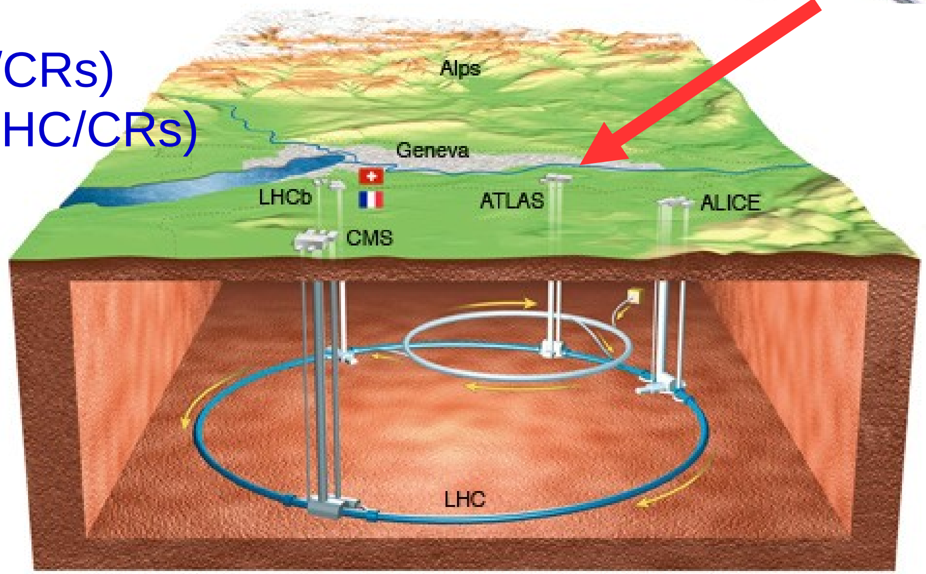
+ Tests up to end of LHC Run 2.

+ 2 layers of scintillators and three of RPCs.
  6.5 m high
  2.5 m x 2.5 m area

+ Triggers for upward/downward going particles.

+ Provide information for:
  - Measure background (LHC/CRs)
  - Test rejection capabilities (LHC/CRs)
  - Improve final design





MATHUSLA Collab., MATHUSLA physics white paper (2018)

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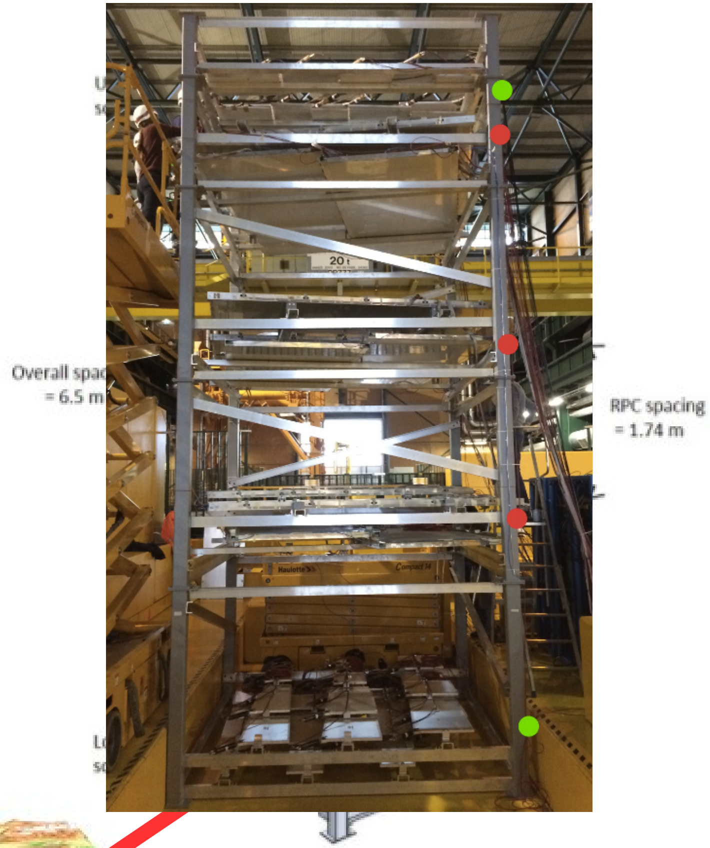
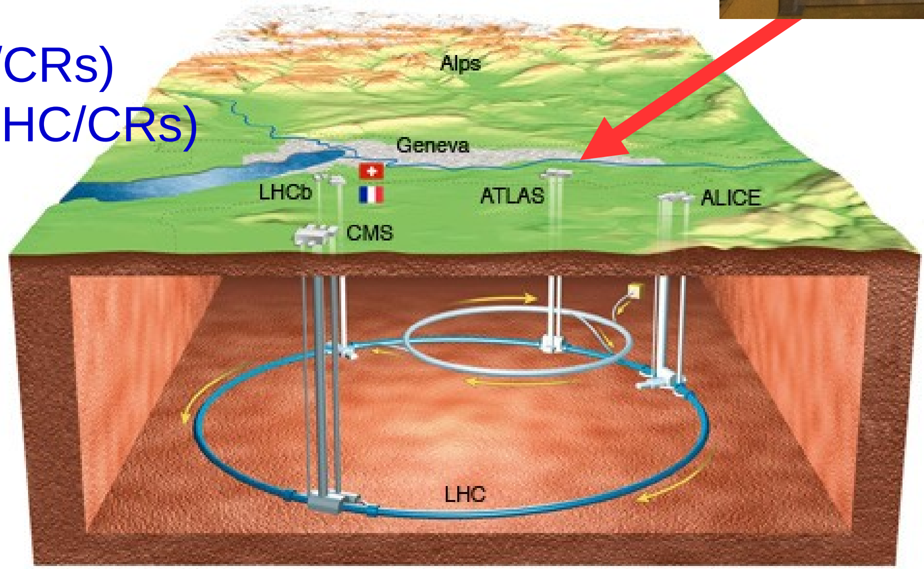




MATHUSLA Collab., MATHUSLA physics white paper (2018)

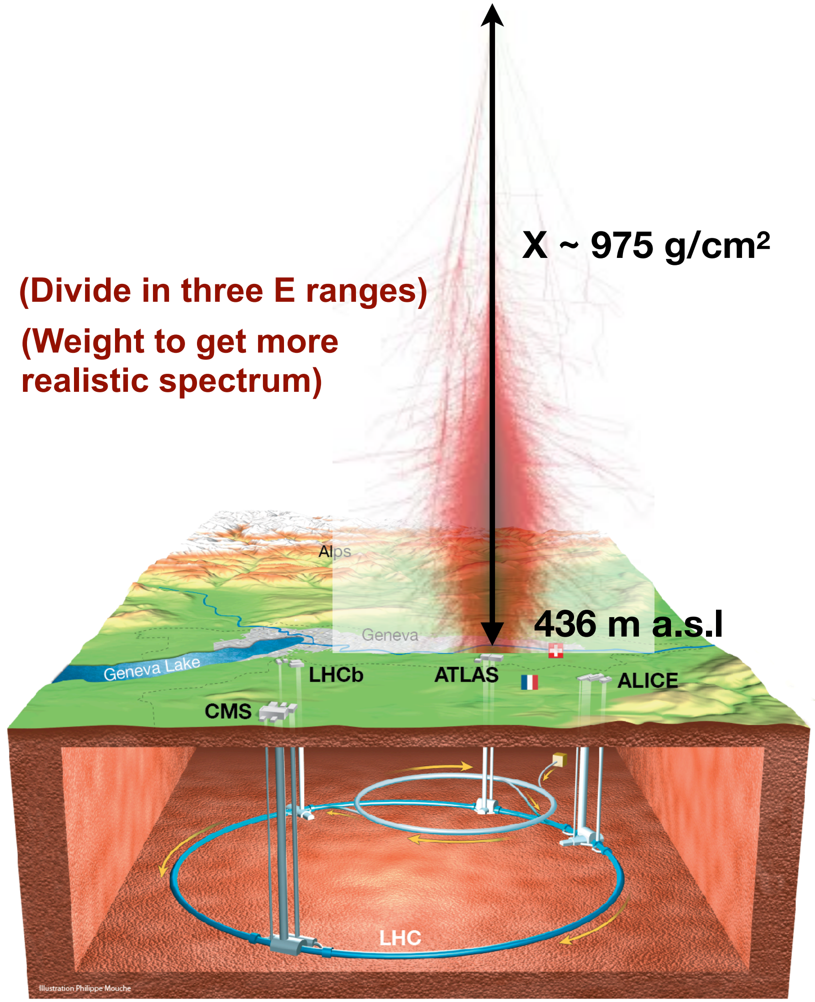
Simulations for CR in MATHUSLA

CORSIKA 7.6400	
High-energy hadronic model (E_h > 200 GeV)	QGSJET-II-04 EPOS-LHC SIBYLL 2.3
Low-energy model	Fluka Geisha
Mass groups	H, He, C, Si, O, Fe
Primary energy range	$\log_{10}$ (E/GeV) = 0.5 - 9
Primary spectrum	E^{-2}
Zenith angle range	0^{o} - 90^{o}
Energy cuts	hadrons (100 MeV) μ's(100 MeV) e's (3 MeV) γ's (3 MeV)
Atmosphere	Standard U.S. model, curved
Site	ATLAS
Magnetic field at site NOAA https://www.ngdc.noaa.gov/	(Bx, Bz) = (22.1, 41.6) μT
Detector Geometry	Flat/volume geometry

At the moment 14 x 10^6 simulations with QGSJET-II-04/Geisha

(Divide in three E ranges)

(Weight to get more realistic spectrum)



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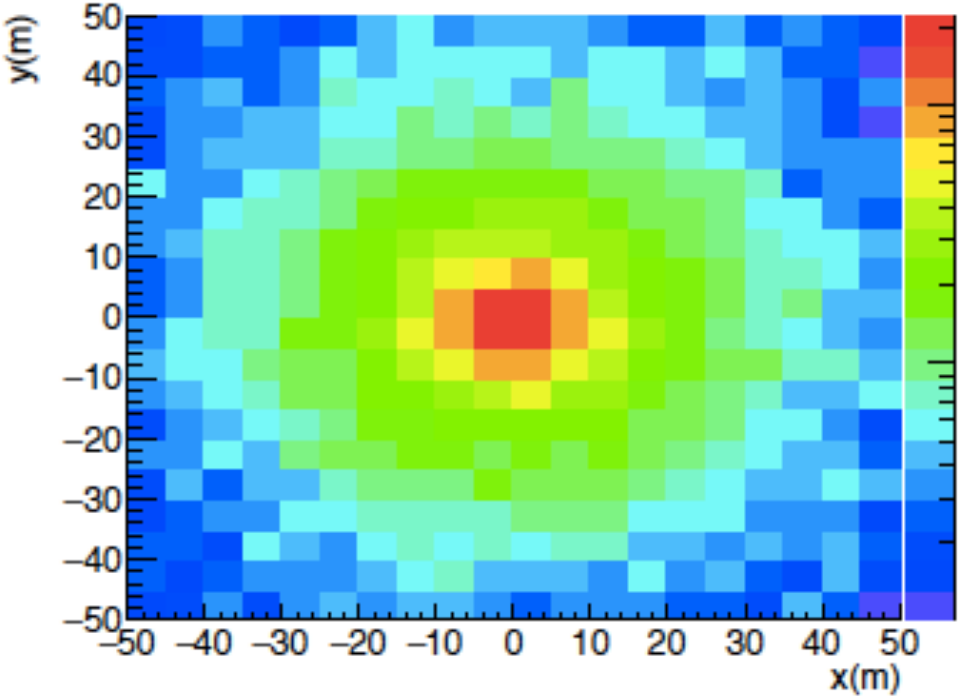
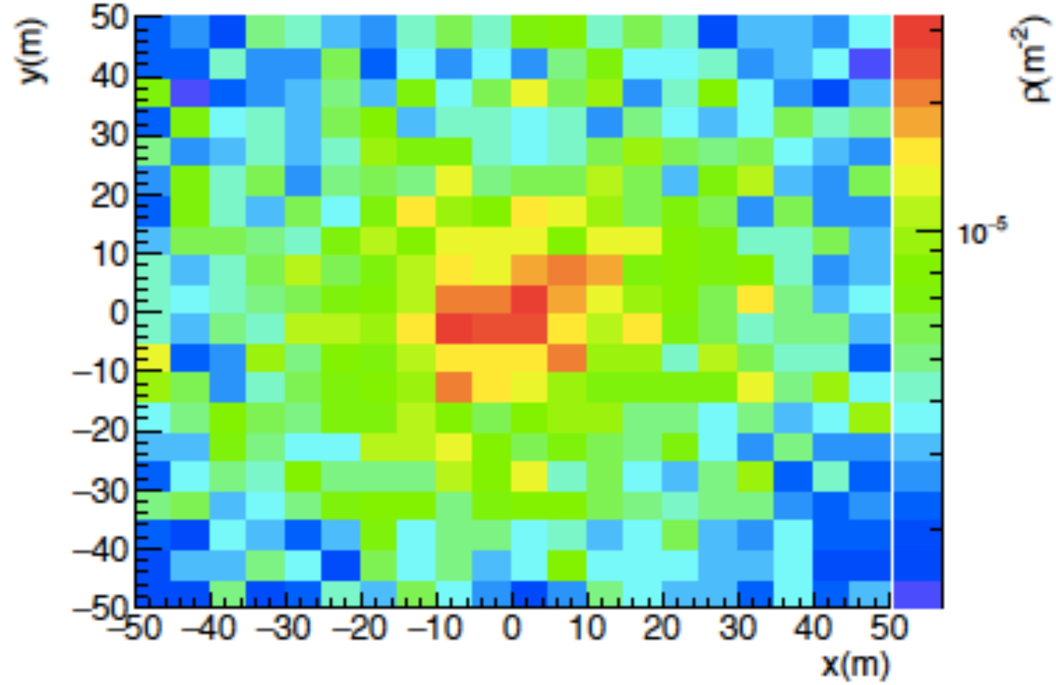
Simulations for CR in MATHUSLA

Lateral density distributions of EAS above ATLAS



θ<20°



55°<θ<60°

Primary protons with energies log10(E/GeV)= [6,6.5]

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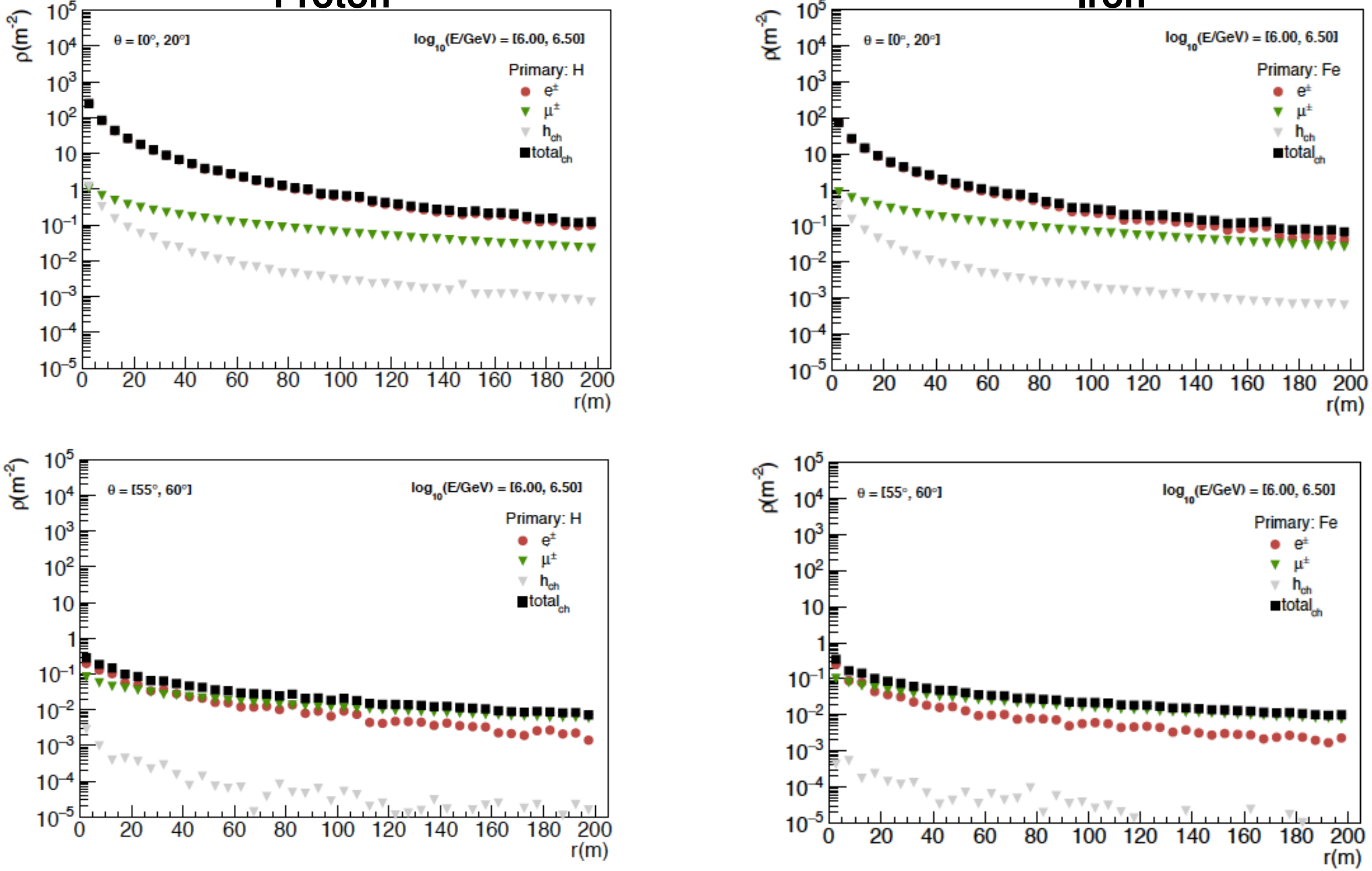
Simulations for CR in MATHUSLA

Mean radial density profile of EAS

Proton **Iron**



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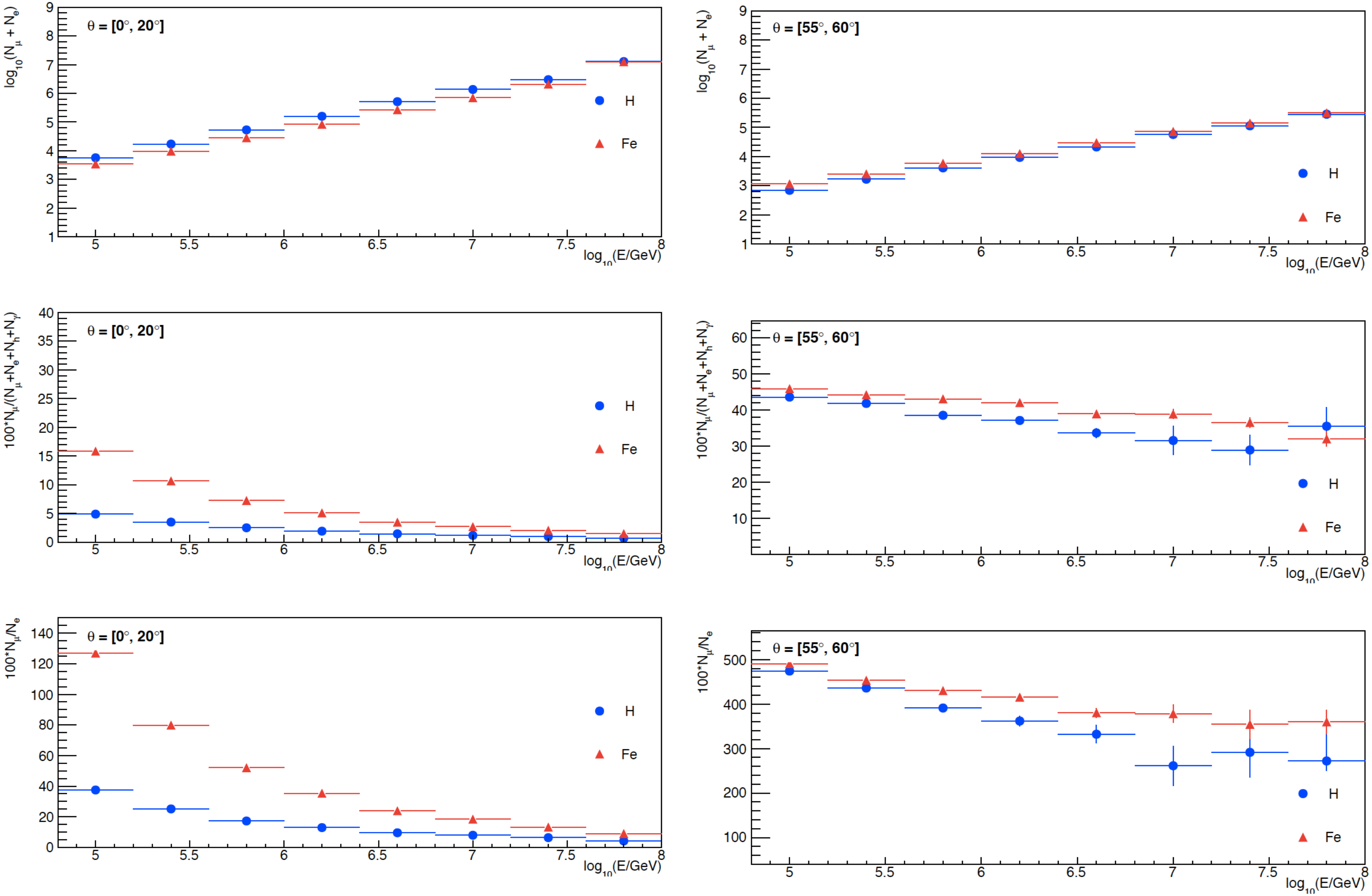
Simulations for CR in MATHUSLA

Mean particle production at observation level of MATHUSLA-100



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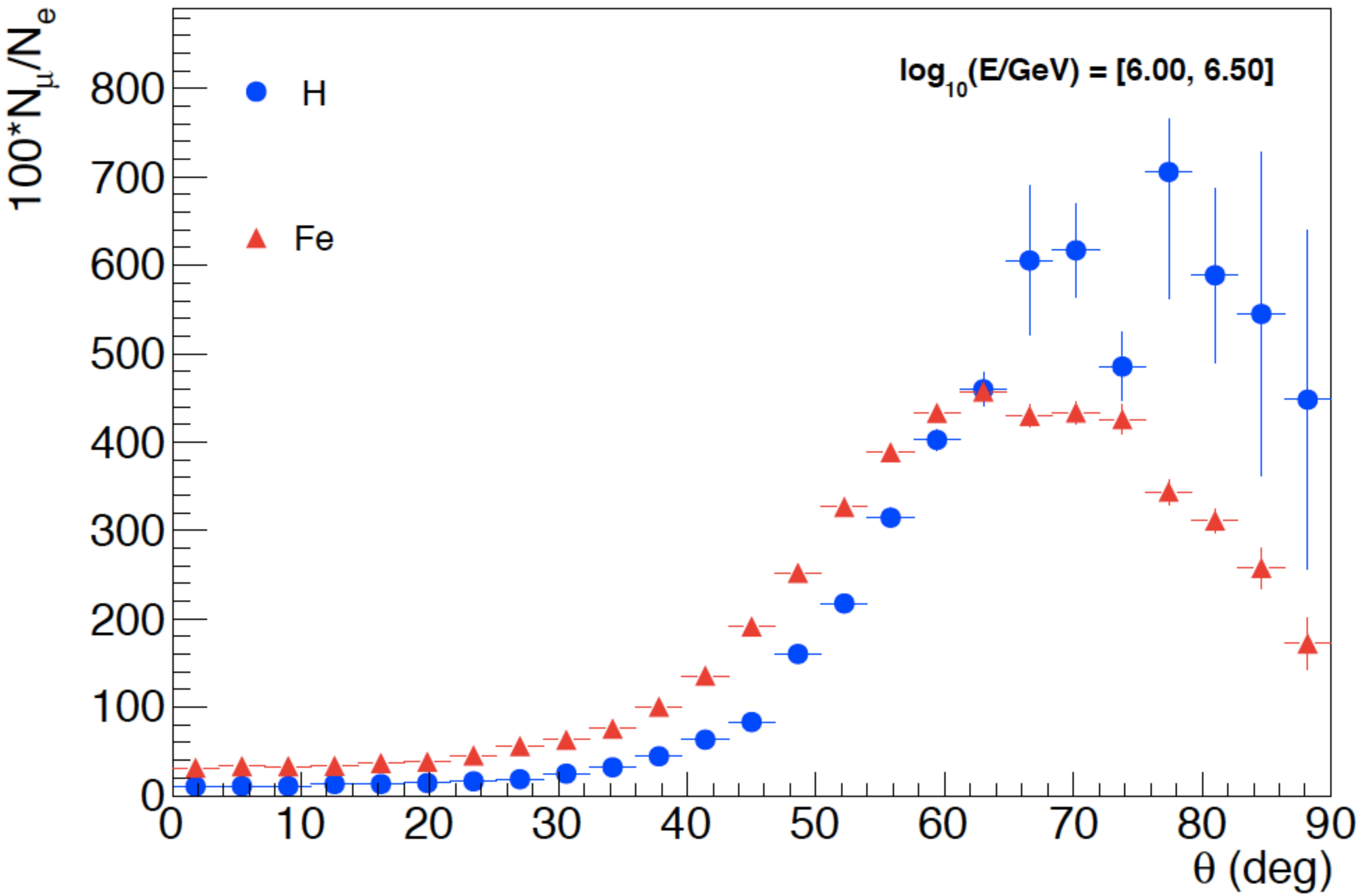
Simulations for CR in MATHUSLA

Mean ratio of total shower N_μ to N_e at observation level of MATHUSLA-100



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Final remarks

- A detector like MATHUSLA would complement the **Long Lived Particle Searches** at the LHC
- It is also possible that MATHUSLA would also allow to **study several open issues** in astroparticle physics (**Cosmic rays, dark matter, gamma-rays, neutrinos,…**)
- It would provide quality data on **extensive air showers** with **unprecedented precision at PeV energies**
- It would permit to **validate/test predictions of hadronic interaction models** at very high energies with cosmic rays
- **White paper** for the MATHUSLA physics case (and intro to the Cosmic Ray potential) has been finished*****, **CR MATHUSLA white paper** is in preparation
- Final design is under study

*Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case arXiv:1806.07396v1

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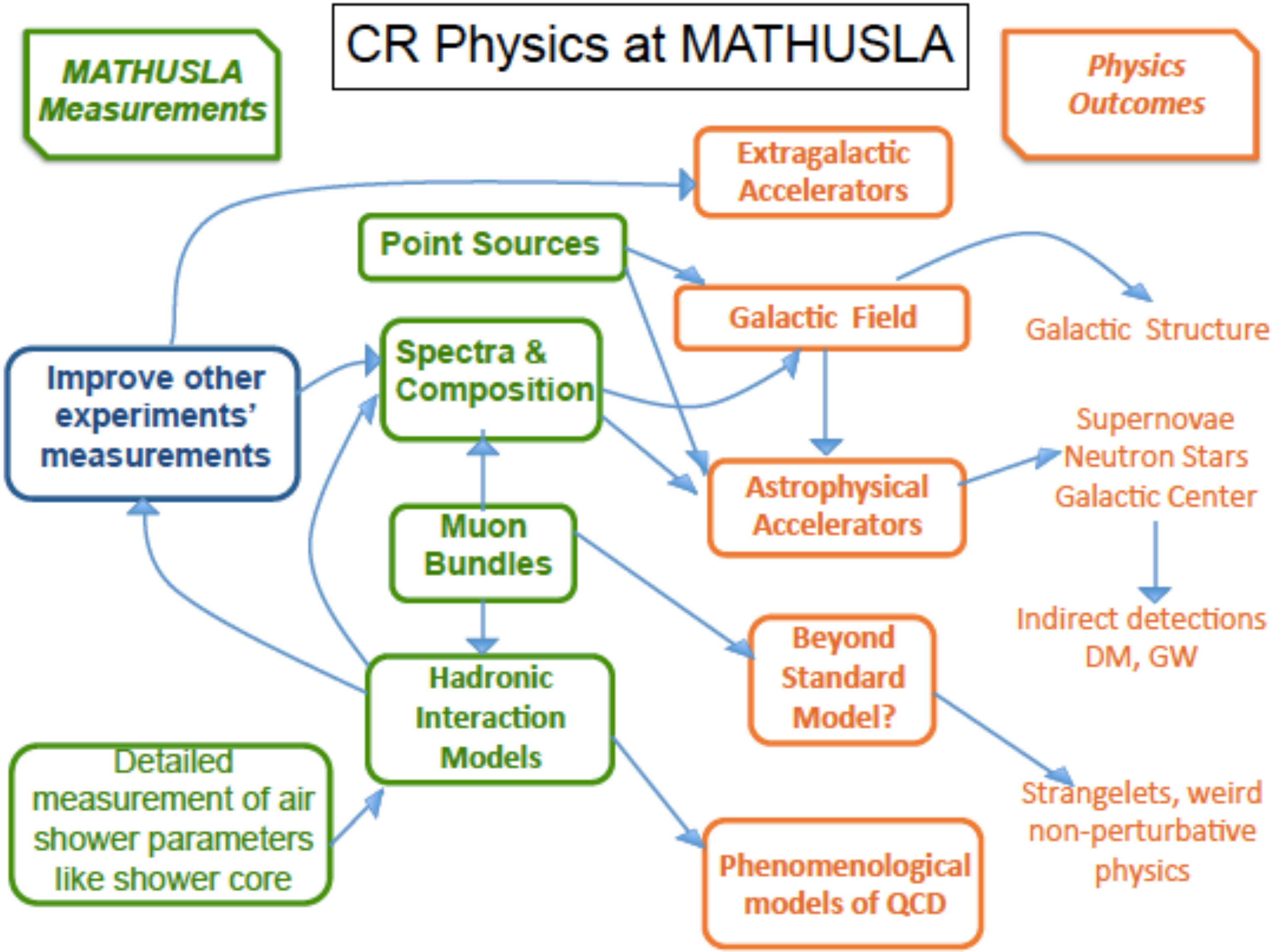
Final remarks



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Thank you!

Meeting of the Cosmic Rays Division of the Mexican Physical Society

3 Oct 2018, 08:30 → 5 Oct 2018, 17:30 America/Mexico_City

Puebla, Mexico

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