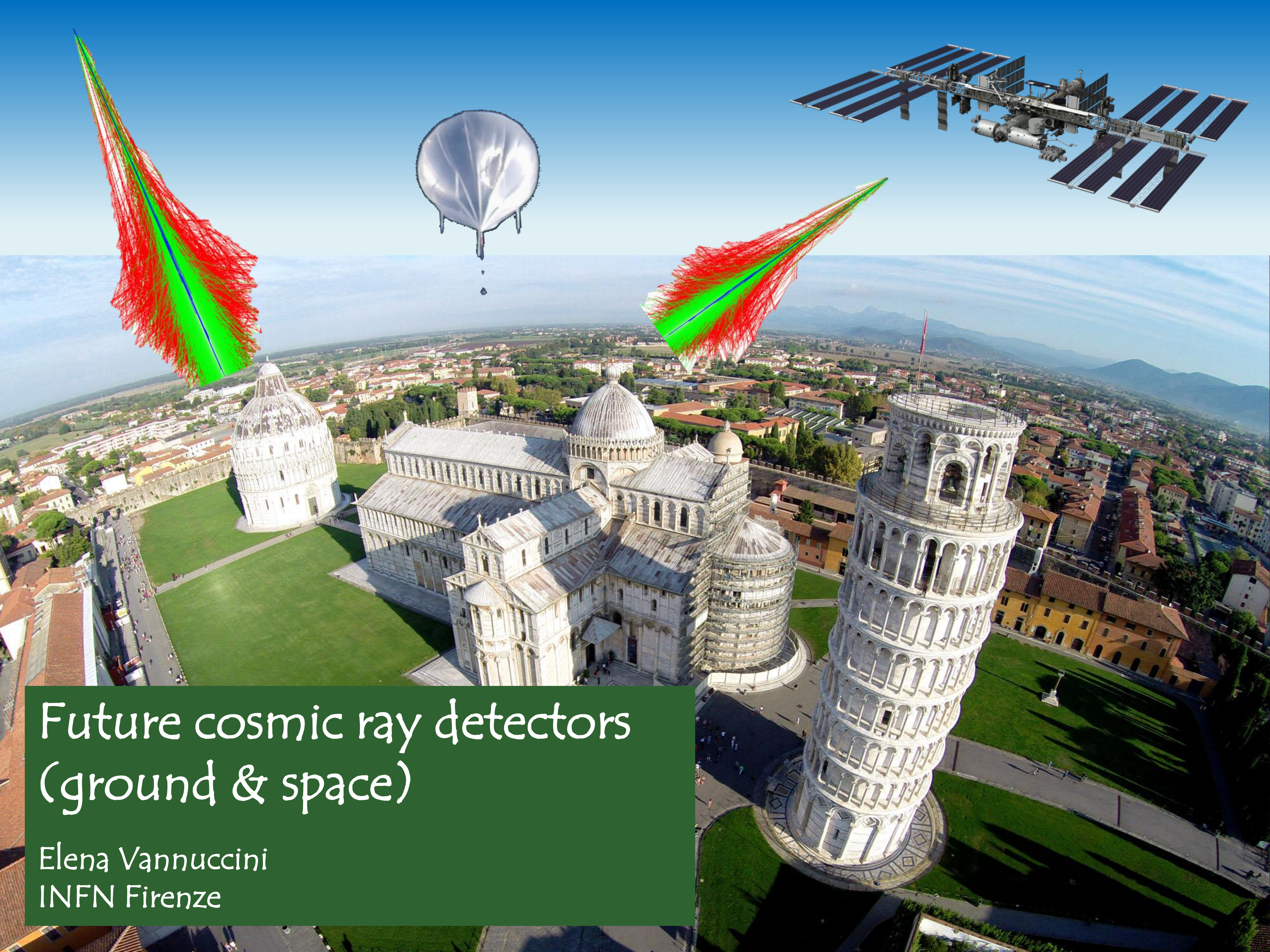


Future cosmic ray detectors (ground & space)

Elena Vannuccini
INFN Firenze

Overview

Energy

- Space
  - Search for antideuterons with GAPS
  - Next generation calorimeter experiments (HERD)
  - Next generation spectrometers
- Ground
  - Advanced composition studies from the knee to the ankle
    - LHAASO
    - EAS radio detection
    - AugerPrime
- Back to space
  - EHECRs with JEM-EUSO

In this talk:

- Focus on experiments that present some «novelties»
- Often superposition with γ-rays and υ. Focus on charged CRs perspectives.

Space experiments

Experiment	e⁺ | e⁻ (present data)	e⁺+e⁻ (Energy range)	CR nuclei (Energy range)	charge Z	gamma	Type	Launch
PAMELA	e⁺ < 300 GeV e⁻ < 625 GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008 Nov 11
AMS-02	e⁺ < 500 GeV e⁻ < 700 GeV	1 GV-1 TV (extendable)	1 GV-1.9 TV (extendable)	1-26 ++	1 GeV-1 TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014/12/26 Dec 26
CALET	-	1 GeV-10 TeV (extendable -> 20TeV)	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV-10 TeV	50 GeV-500 TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1 TeV-1 PeV	1-28 ++	-	ISS	~ 2017
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	~ 2017
GAMMA-400	-	1 GeV-20 TeV	1 TeV-3 PeV	1-26	20 MeV-1 TeV	SAT	~2023-25
HERD	-	10(s) GeV–10 TeV	up to PeV	TBD	10(s) GeV–10 TeV	CSS	~2022-25
HELIX	-	-	< 10 GeV/n	light isotopes	-	LDB	proposal
HNX	-	-	~ GeV/n	6-96	-	SAT	proposal
GAPS	-	-	< 1GeV/n	Anti-p, D	-	LDB	proposal

Compilation by Marrocchesi @ ECRS 2016

Expected:

- Higher-stat. data from AMS02 and Fermi
- Extention of primary spectra to high energy from calorimeter experiments

(Bertucci talk)

Downsized (focus on γ)

Next-generation calorimeters

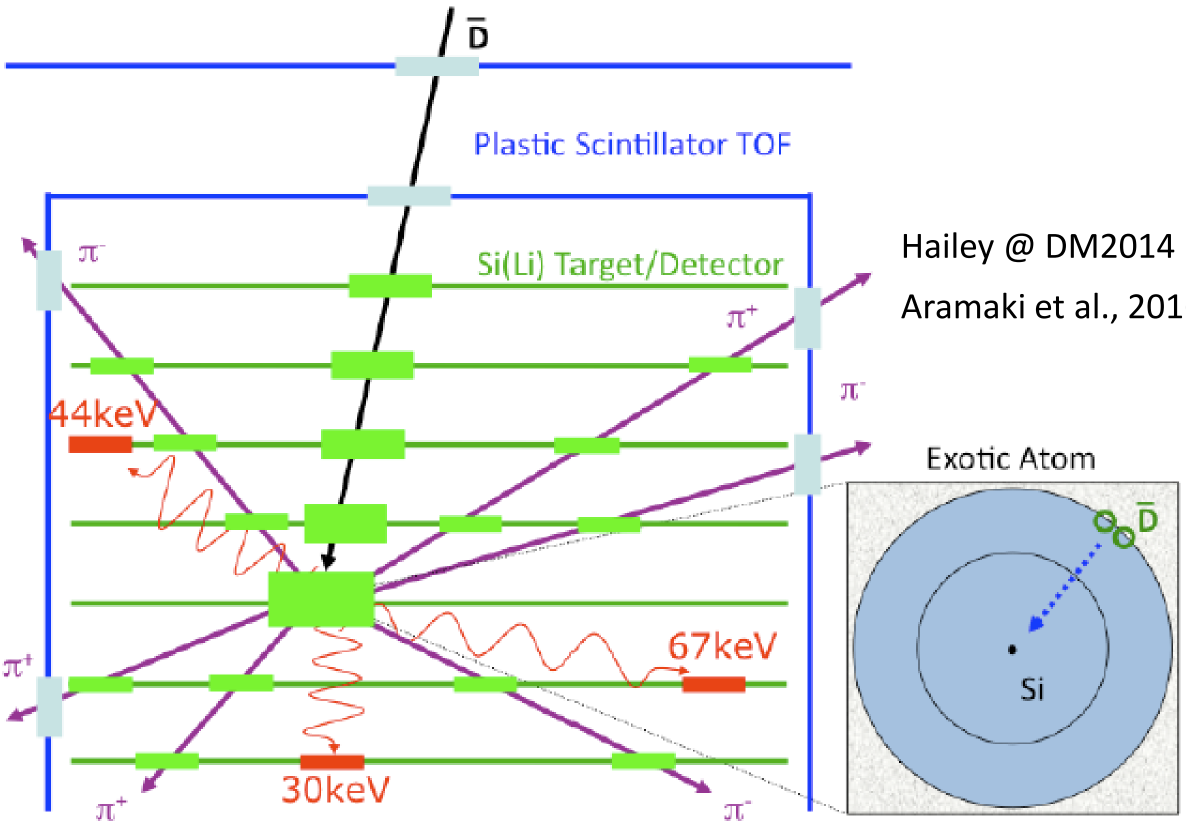
(Now approved) New approach to anti-matter meas.

CR antimatter

Exploring channels with lower astrophysical backgrownd

DM search by $\overline{\mathrm{D}}$ detection

Detection concept



Hailey @ DM2014

Aramaki et al., 2016

$\bar{p}$ / $\bar{D}$ separation based on:

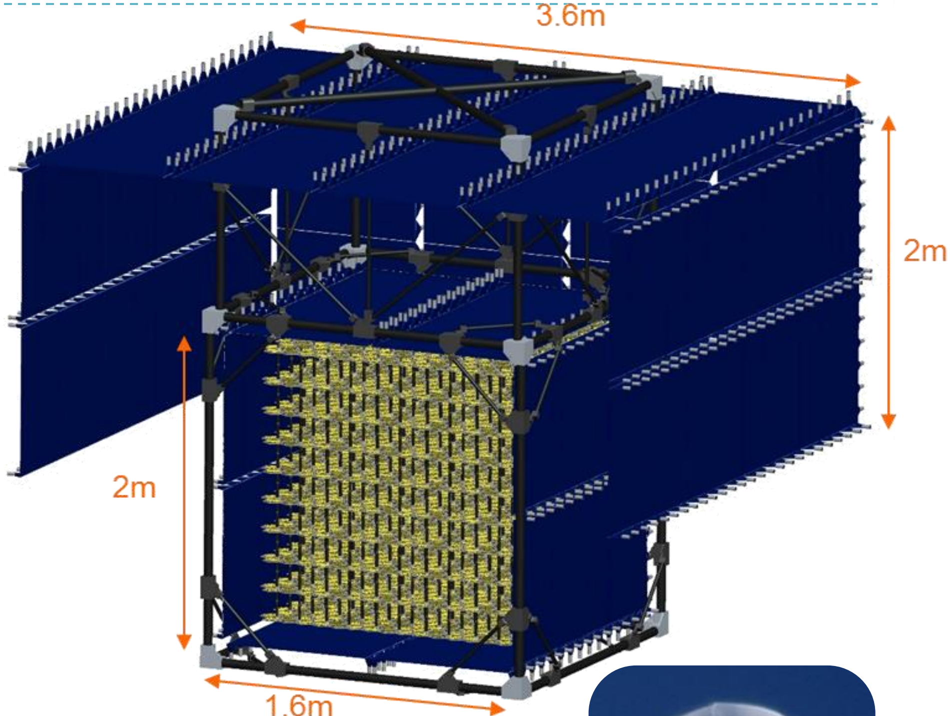
- Time-of-light measurement along antiparticle trajectory
- Multiple dE/dx measurements
- X-ray energies
- Pion/proton multiplicity

Antimatter detection withot a magnet

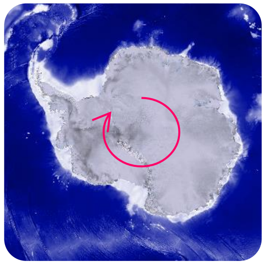
1. Low-energy antiparticles ($\bar{p}$, $\bar{D}$) slow-down and stop in the medium, forming an **exotic atom** in its **excited** state
2. The atom de-excites via emission of **X-rays**
3. The antiparticle undergoes **annihilation** with atomic nucleus, emitting **pions** and **protons**

GAPS

- General Anti-Particle Spectrometer
  - Time-of-flight plastic scintillator
    - 500 ps time resolution
  - 10 layers of Si(Li) detectors
    - 12×12 wafer segmented in 4 strip
      $\rightarrow$ 3D particle tracking
    - 3keV energy resolution
      $\rightarrow$ X-ray spectroscopy
- Measurement of $\bar{p}$ and search for $\bar{D}$ at low energy (<250MeV)
- Status:
  - 1° LDB flight in 2020/2021
  - +2 LDB planned

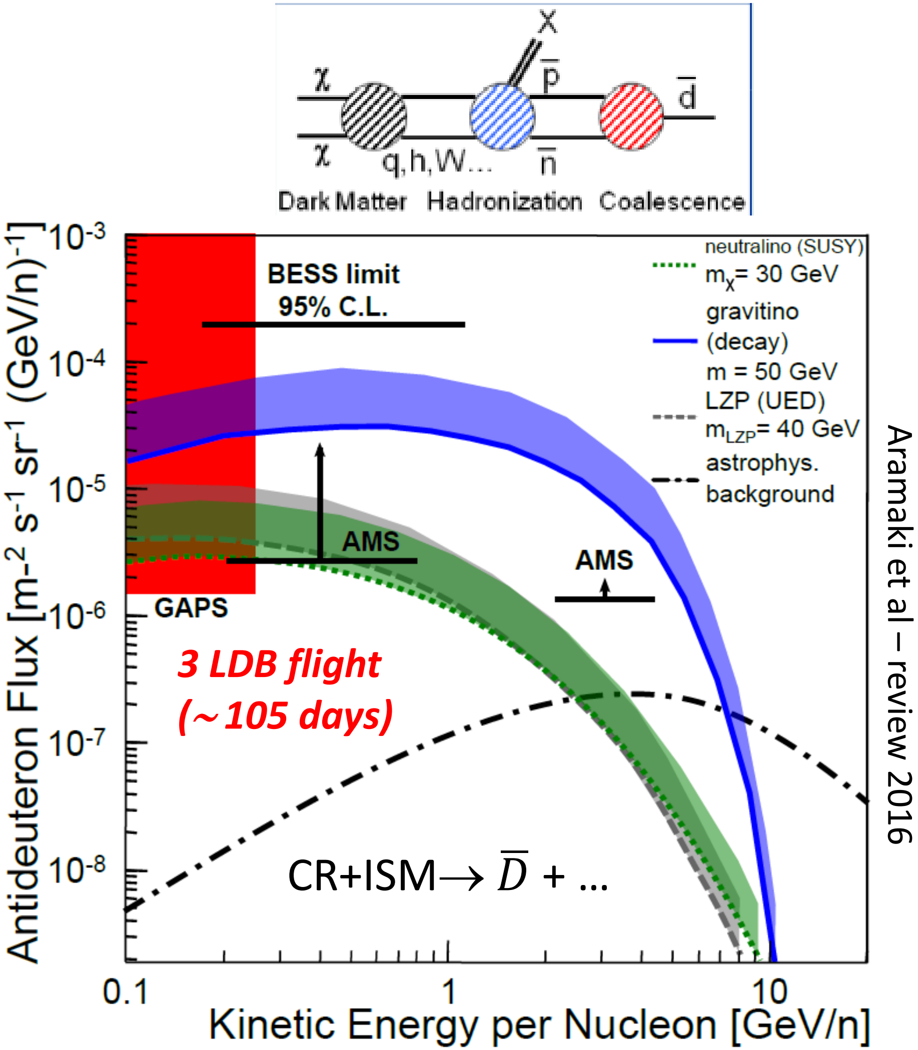


Hailey @ DM2014



Ideal location, due to low geomagnetic cutoff

GAPS science



- Dark-matter search
  - Extremely low astrophysical $\overline{\mathrm{D}}$ background
  - Sizable primary $\overline{\mathrm{D}}$ signal from several DM model
    - Unexplored-phase space
    - Mainly light DM
    - No boosting mechanism required
  - Complementary to other searches
    - collider exp.
    - direct underground exp.
    - other indirect measurementes
  - Aramaki et al – review 2016

Potential breakthrough in DM search by $\overline{\mathrm{D}}$ detection

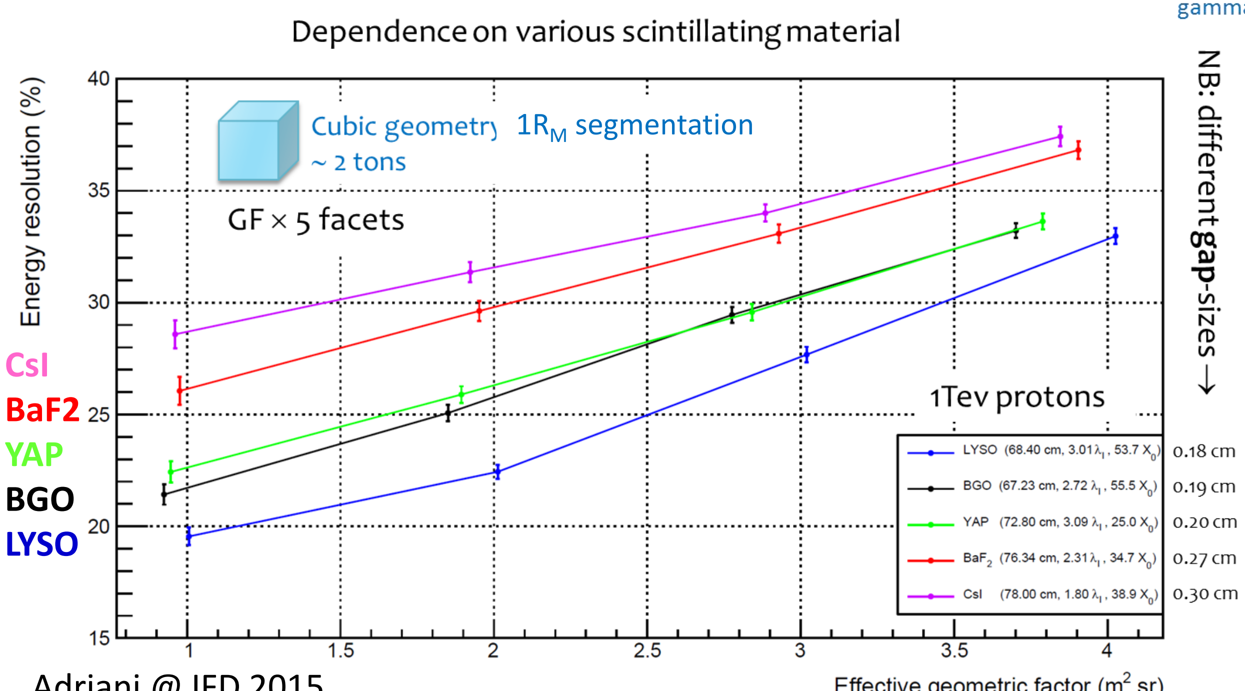
Galactic CR nuclei

Direct measurement of individual-element spectra up the H and He knee

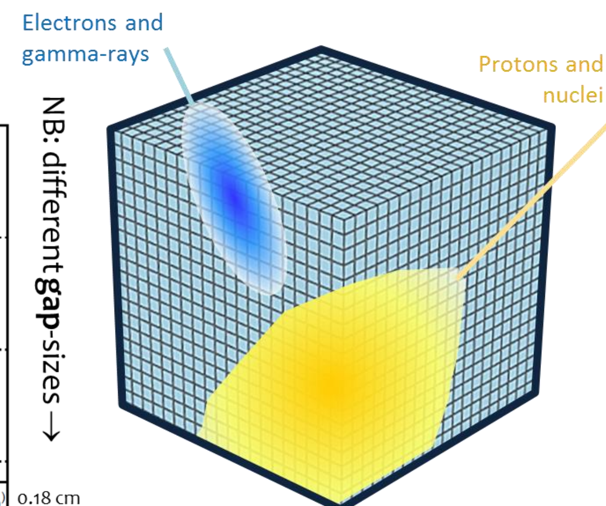
With new-generation large-acceptance calorimeters

CaloCube concept

- INFN r&d project
- Optimization of calorimeter performances with limited mass budget
  - Cubic geometry → 5 facet detection
  - Active absorber → good energy resolution
  - 3D segmentation → shower imaging → leakage correction (hadrons) & e/h separation



Adriani @ IFD 2015



- Up tp 4 m^{2}sr
- Down to 20% energy resolution

HERD

- High-Energy cosmic-Radiation Detector
  - To be installed on board the Chinese in 2020/2021
- Measurement of cosmic- and γ-rays at high energy

Xu @CRIS 2015

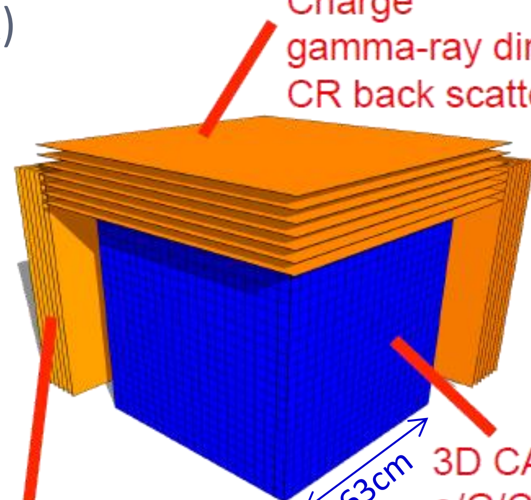
n10X acceptance than others, but weight 2.3 T ~1/3 AMS

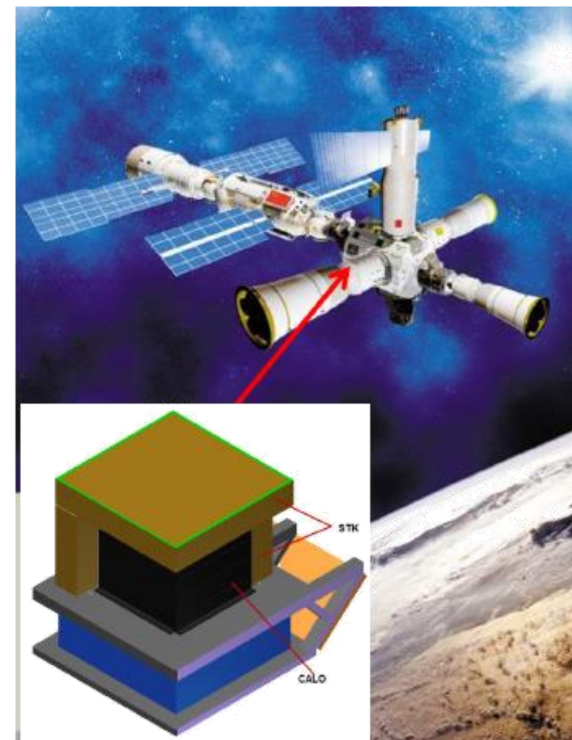
- 3D calorimeter

  ~10k LYSO crystals (3 i.l.)
- Tracker/converter (STK)

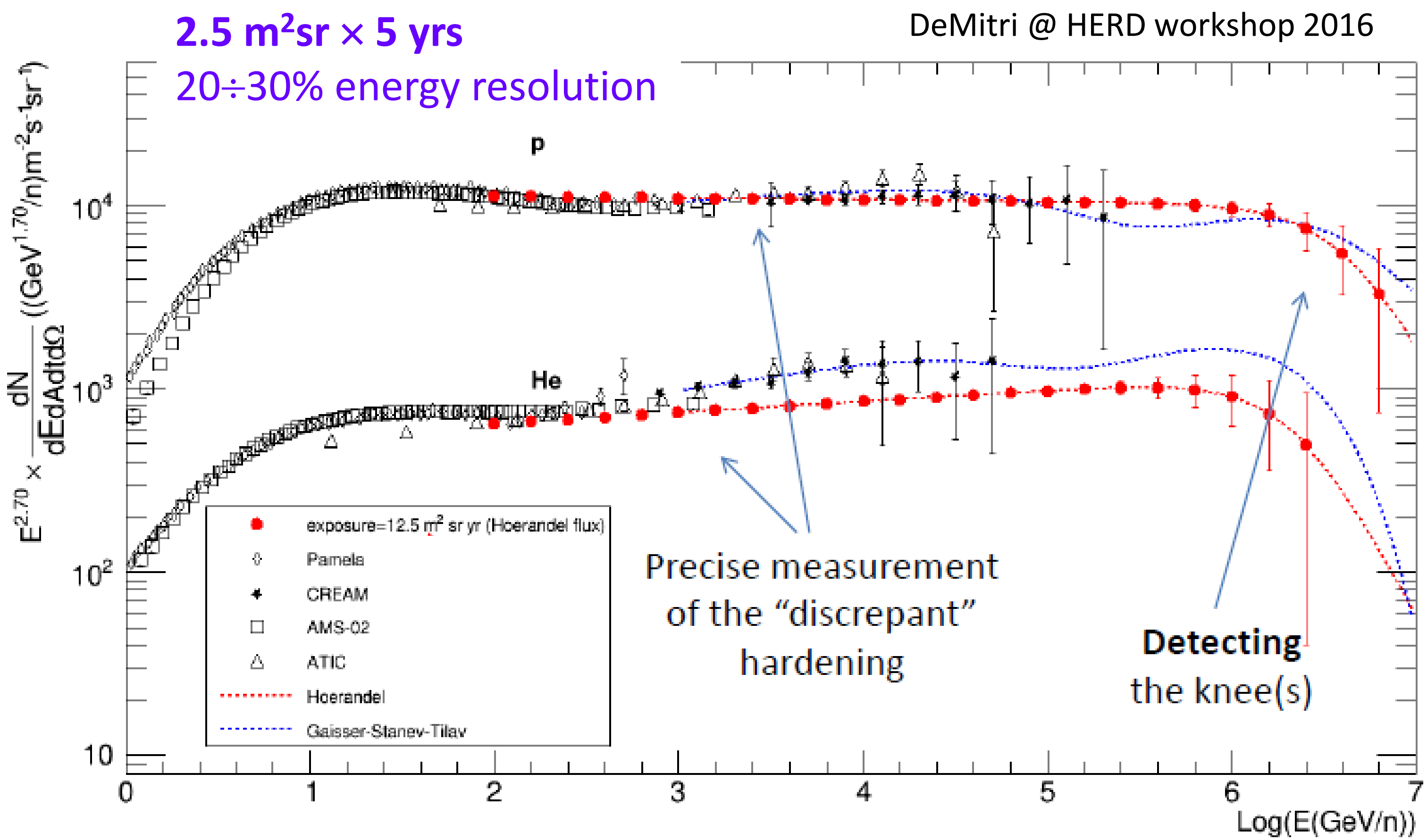
  7 Si/W planes (2 r.l.)
- Very large acceptance

  top+lateral particle detection
- 2.5m^{2}sr and 20% en.res. for p @1TeV





HERD: expected performances



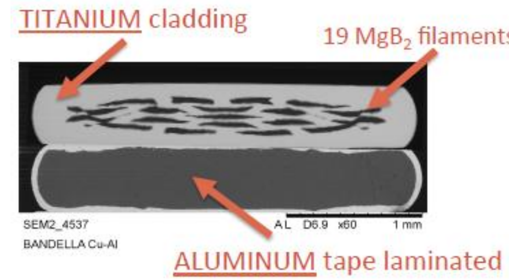
Direct detection fo P and He knee

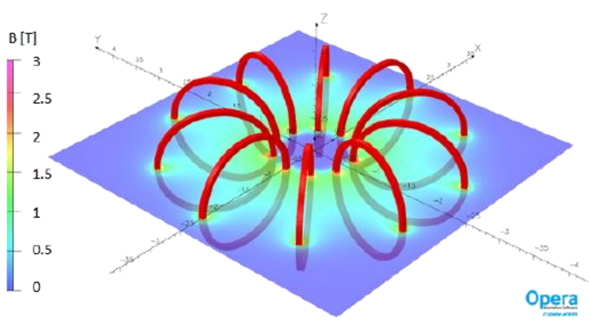
Extending antiparticle measurements at higher energies

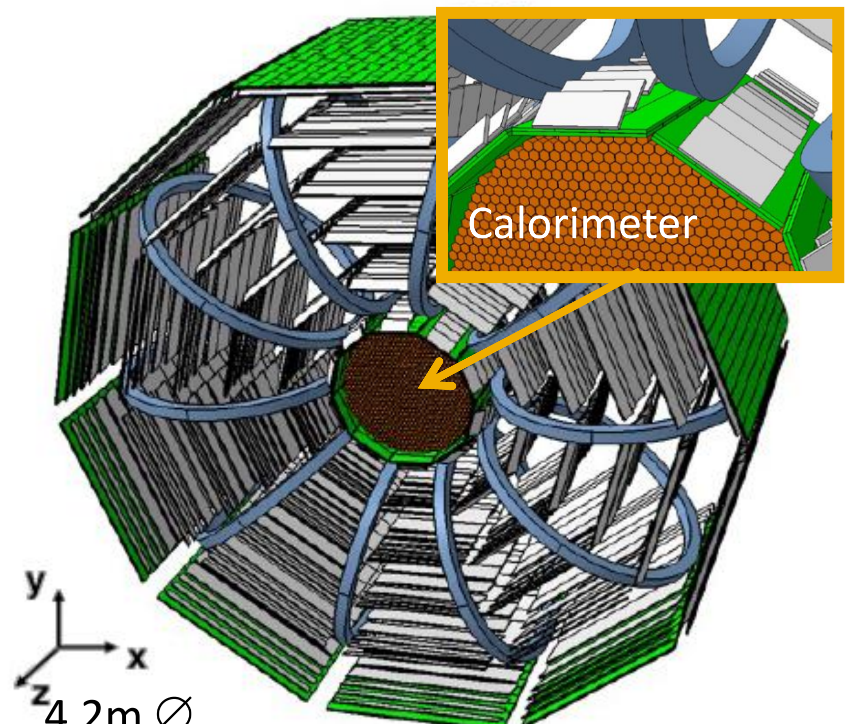
With new-generation spectrometers

Next generation spectrometers

- Must relay on superconducting magnets
- ALADINO magnetic spectrometer
  - Toroidal superconducting magnet
    - 10 coils wound with high-temperature (10s°K) superconductor (MgB_2)
    - $\langle B \rangle \sim 0.8$ T average magnetic field
  - Microstrip silicon tracking system
    - 4 layer with O(μm) spatial resolution
  - MDR ~ 20 TV





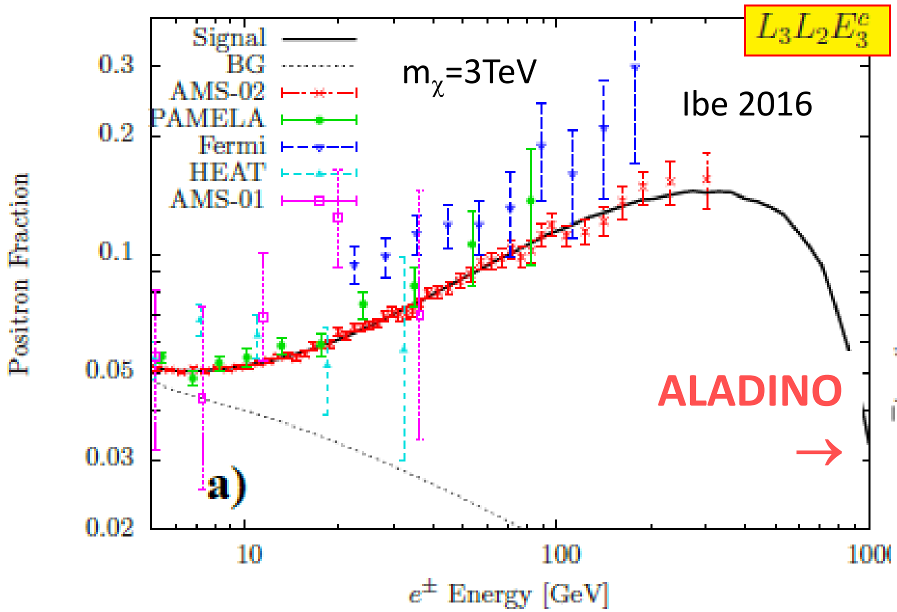


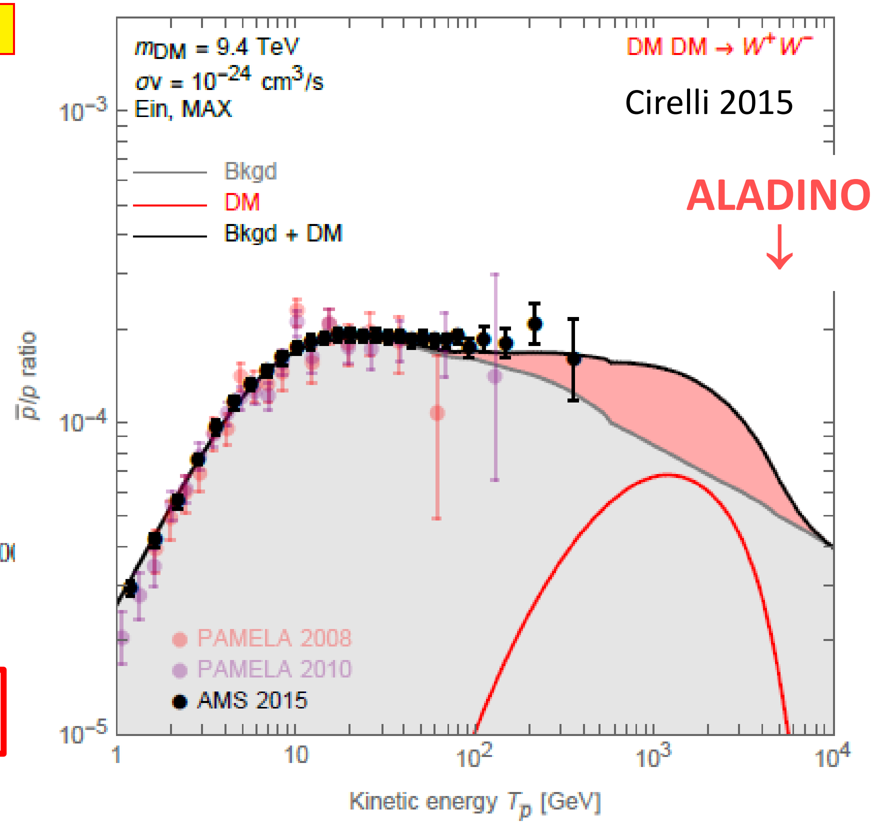
Bertucci (p.c.)

- Proposal submitted to ESA Call for Science Ideas

ALADINO expected performances

PAMELA/AMS02 → MDR~1TV



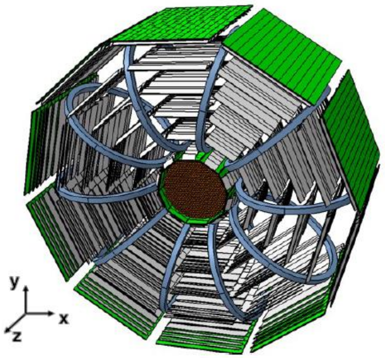


MDR~ 20 TV → e^+ and $\bar{p}$ up to 5TeV !!

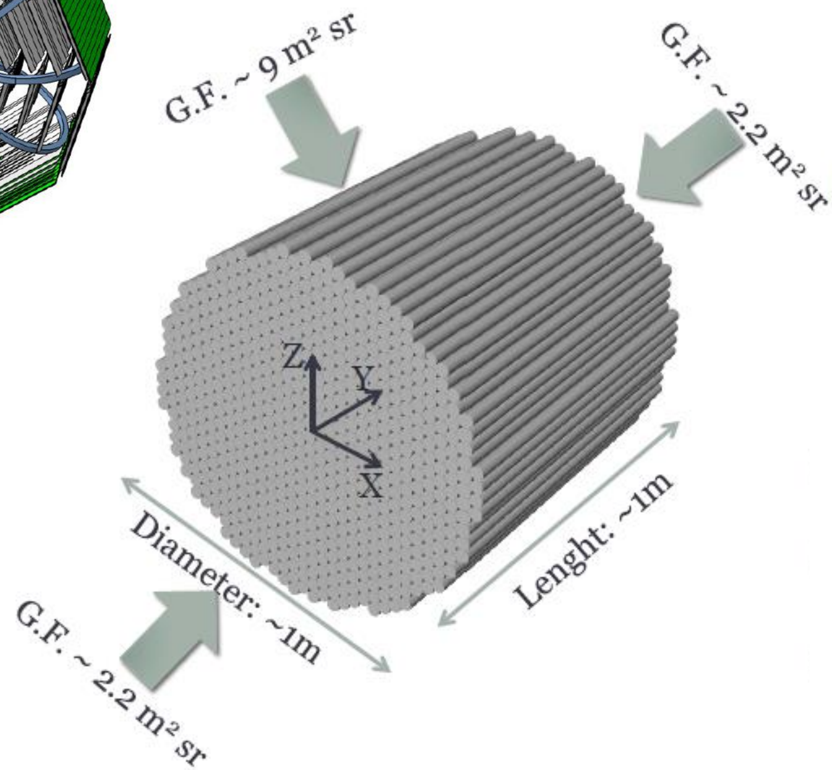
- Examples of contribution to e^+ and $\bar{p}$ CR abundance from DM annihilation

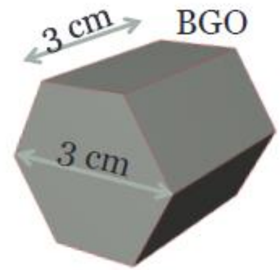
ALADINO calorimeter

A Cylindrical shape calorimeter with 3D hexagonal tesselation



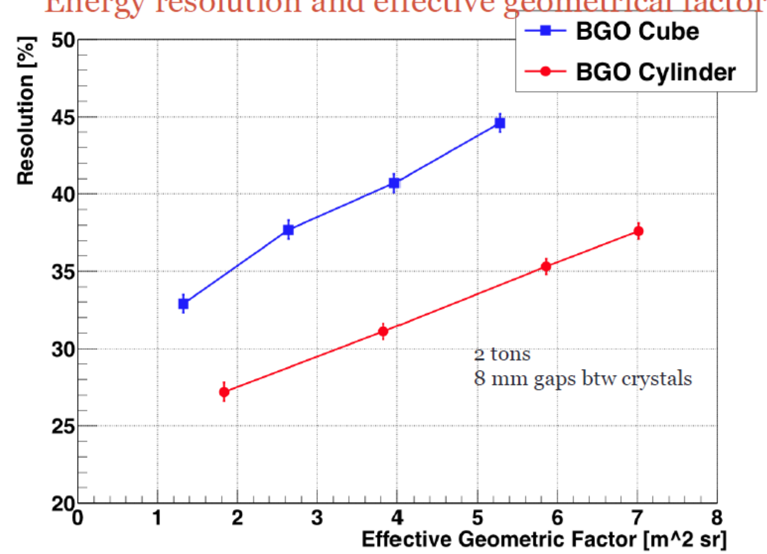
Weight~2000 kg
N. crystals: 15925





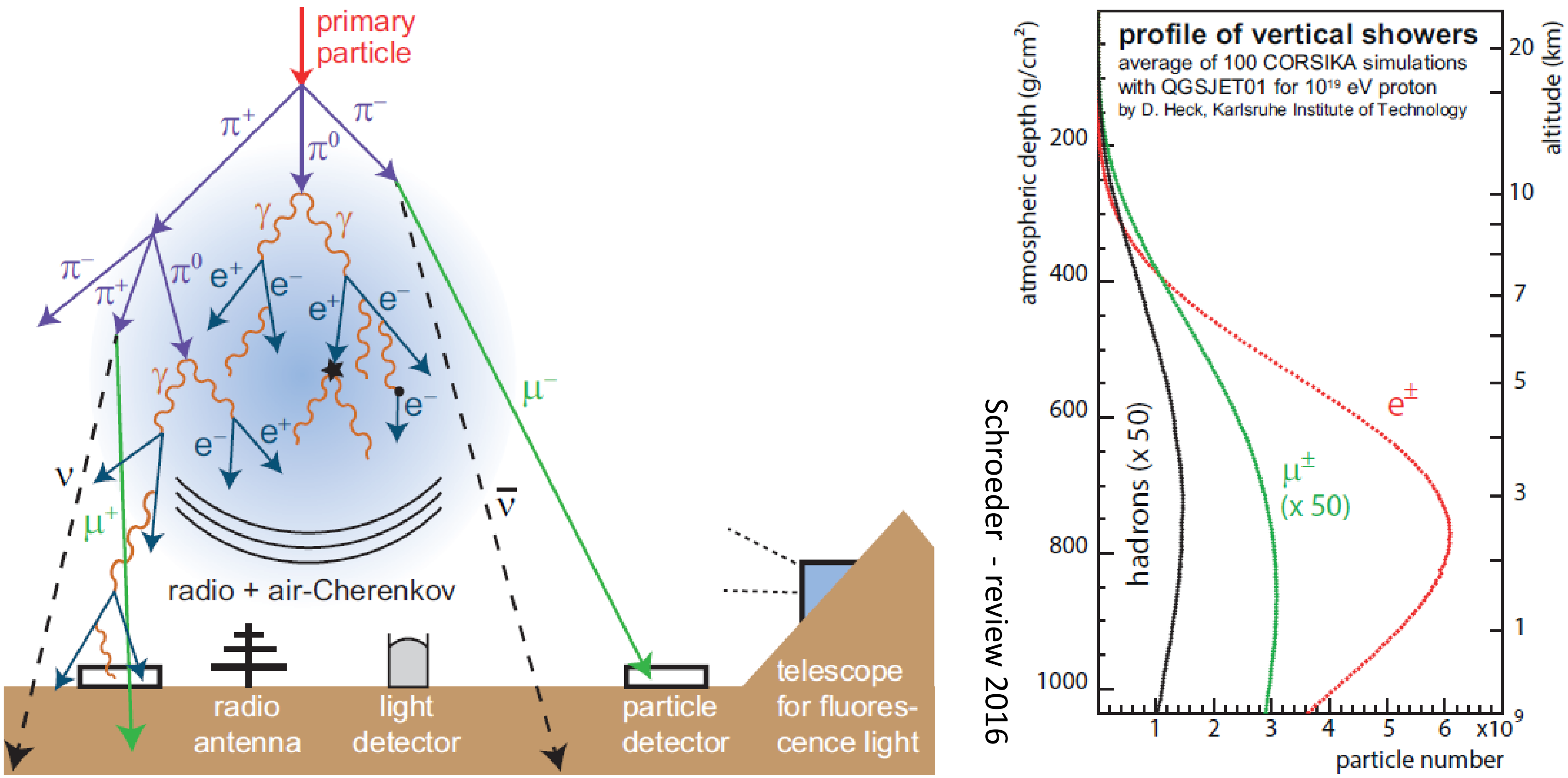
Basic crystal: hexagonal base prisma

1 TeV protons
Energy resolution and effective geometrical factor



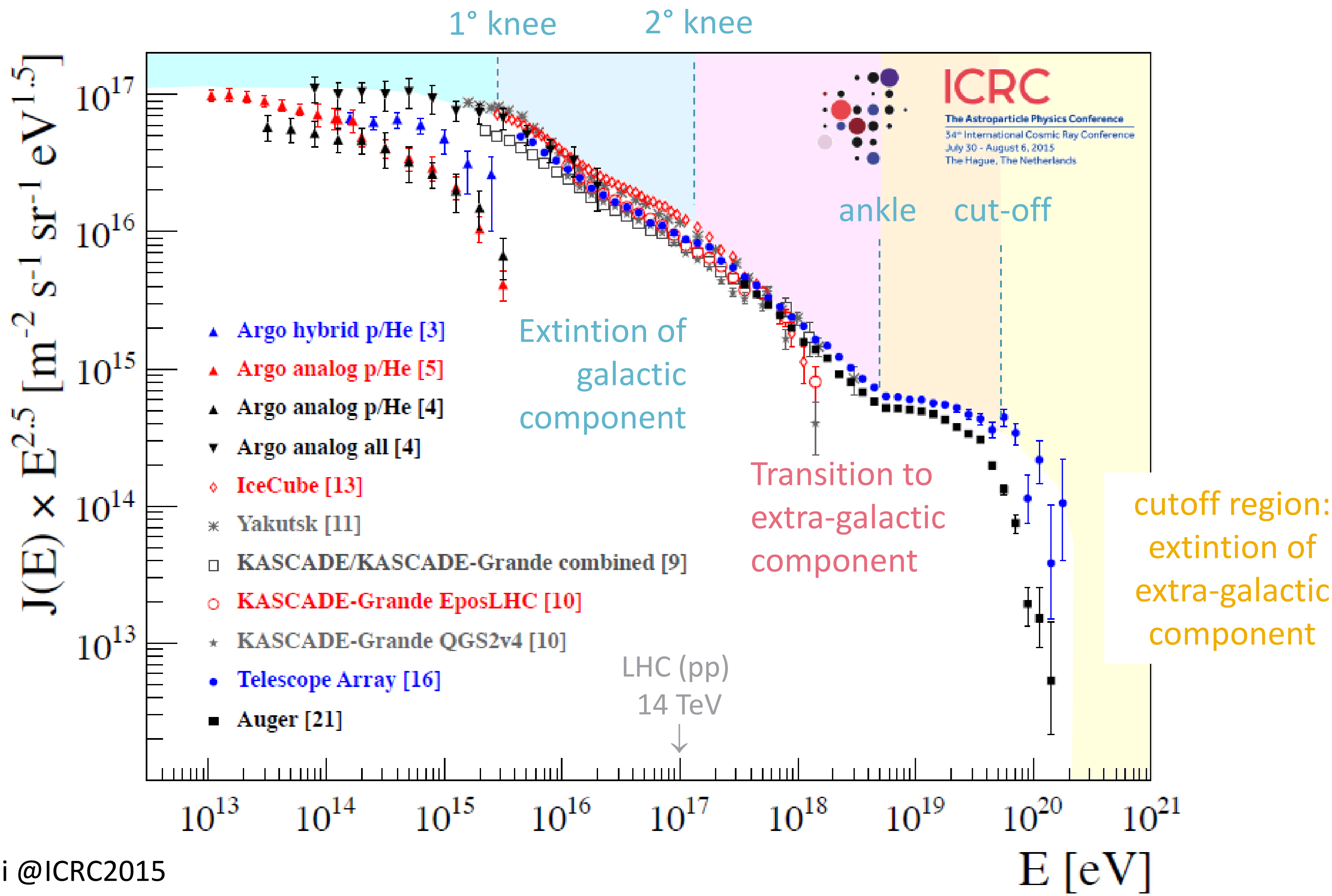
O. Adriani Adriani @IFD 2015 Future Space Challenges

Indirect detection



Schroeder - review 2016

Multi-component approach



Verzi @ICRC2015

Knee region

Bridging direct to higher-energy data with improved performances

Km2-size, high-resolution, multi-component array

LHAASO

- Large High-Altitude Air Shower Observatory
  - Combined study of cosmic- and γ-rays
  - Wide energy range $10^{12} \div 10^{17}$ eV
  - Bridge from direct measurements to most energetic CR particles

Daocheng County, Sichuan, China

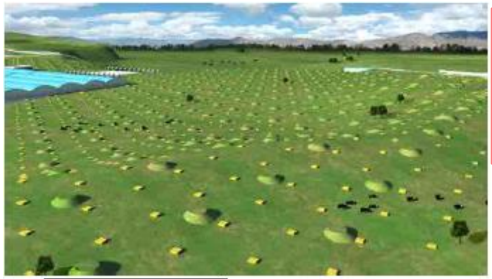
Di Sciascio @ CRIS 2015

	Altitude (m)	e.m. Detection Area (m^2)	Instrumented Area (m^2)	Coverage
KASCADE	110	5×10^2	4×10^4	1.2×10^{-2}
IceTop	2835	4×10^2	10^6	4×10^{-4}
KASCADE-Grande	110	370	5×10^5	7×10^{-4}
LHAASO	4410	5×10^3	10^6	5×10^{-3}
		μ Detection Area (m^2)	Instrumented Area (m^2)	Coverage
KASCADE	110	6×10^2	4×10^4	1.5×10^{-2}
LHAASO	4410	4.4×10^4	10^6	4.4×10^{-2}

(→ ×10 extention with IceTop-2 >2020)

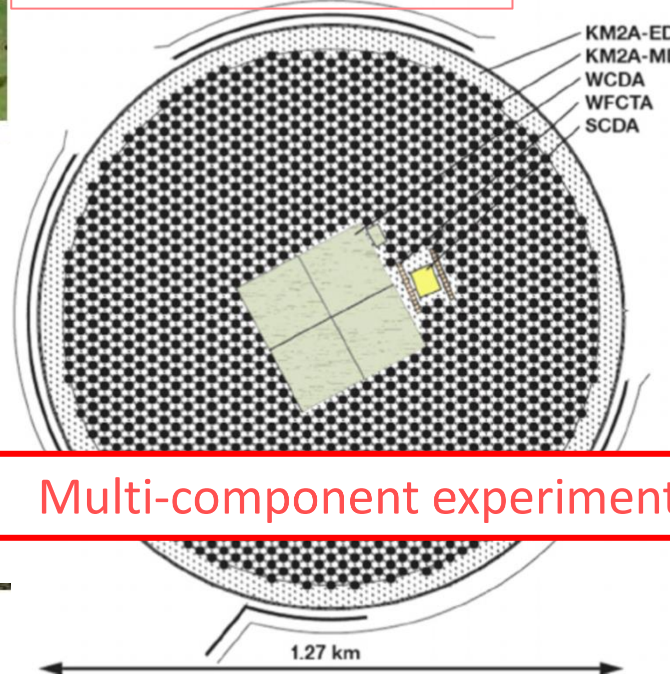
Large coverage (~KASCADE)
Large area (~ IceTop)
High altitude (ARGO-YBJ) → small fluctuations and low energy-threshold

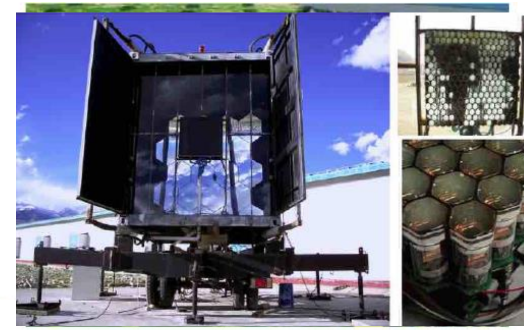
LHAASO



1 KM2A:
5635 EDs
1221 MDs

1 km2 array of
Scintillators
Underground water Ch tanks





WFCTA:
24 telescopes
1024 pixels each

Wide fov air Ch and fluorescence telescopes

WCDA:
3600 cells
90,000 m^2

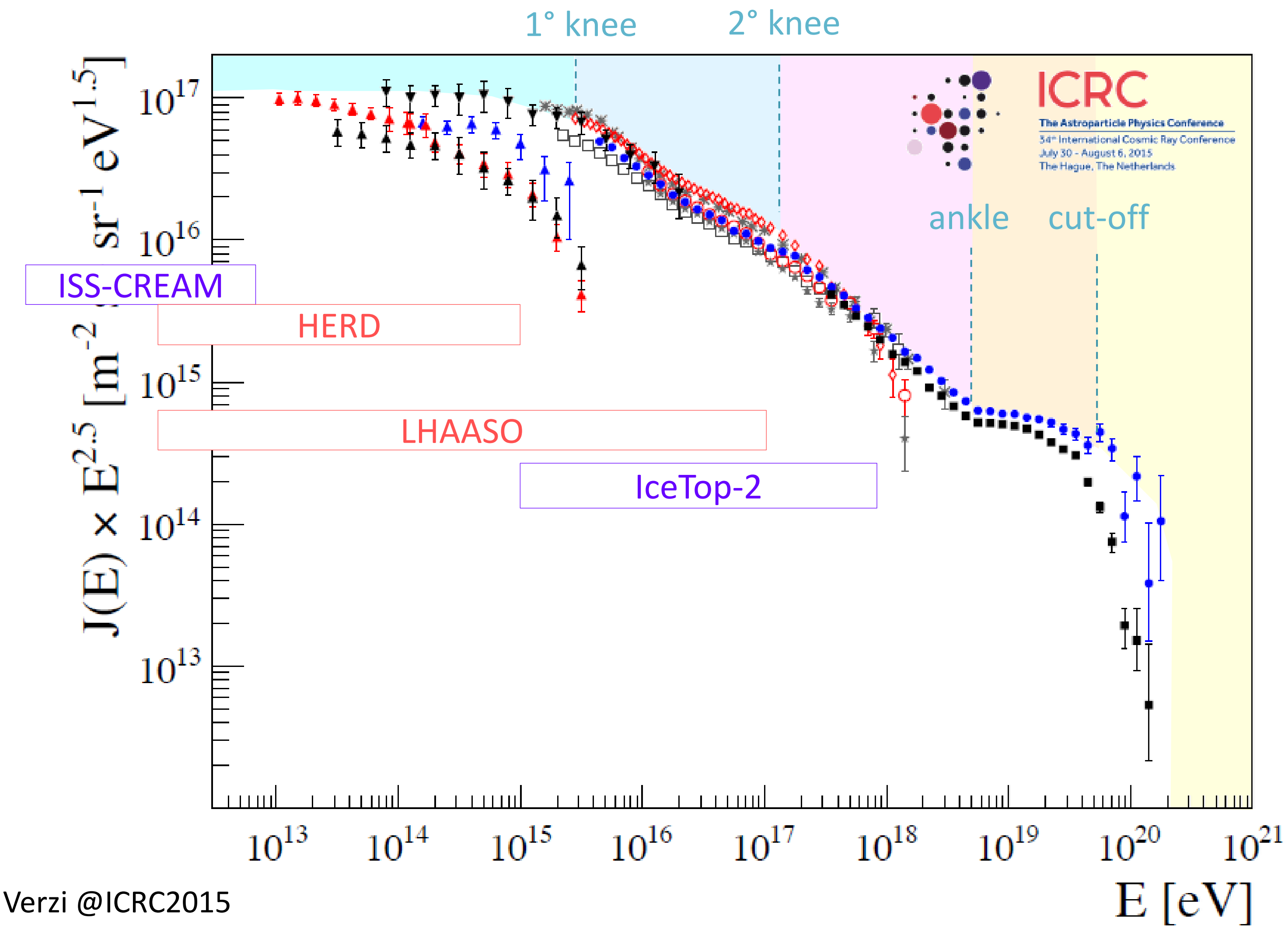
Multi-component experiment

SCDA:
452 detectors

Close-packed surface water-Ch detector facility

Close-packed burst detectors close to the shower core

Future indirect experiments



Verzi @ICRC2015

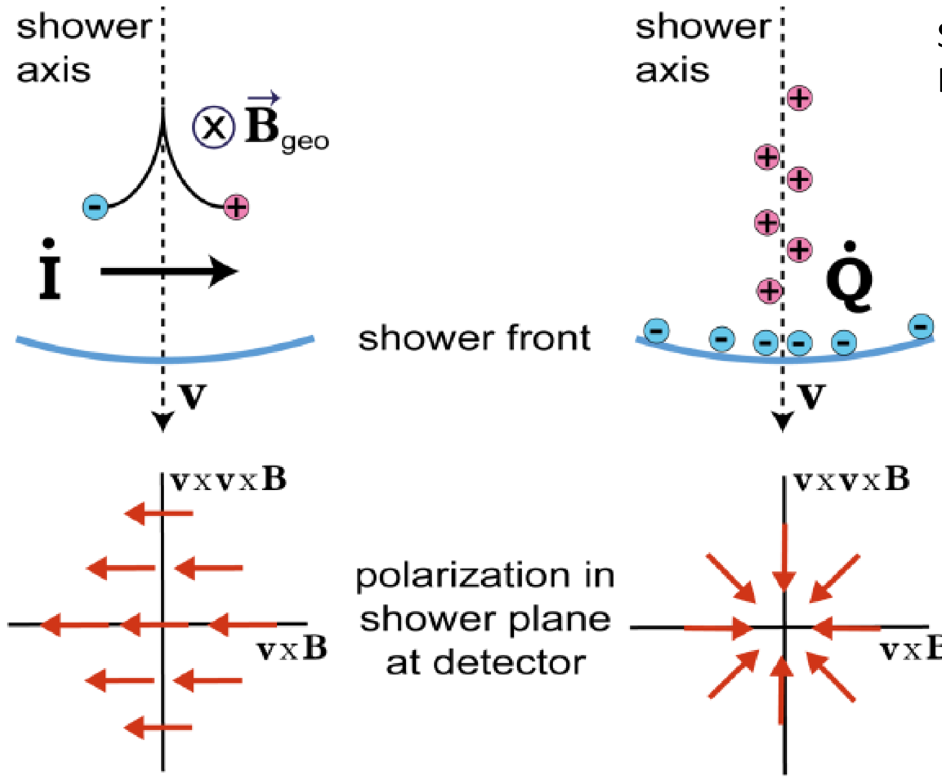
Transition region

An alternative approach to AES detection

→Radio detection

EAS radio emission

Schroeder – review 2016
Huege – review 2016



geomagnetic effect ~ 90%

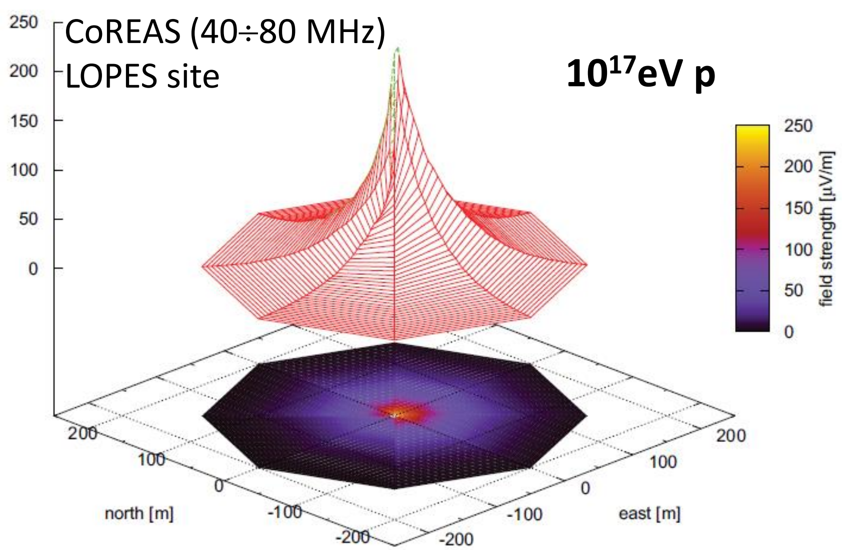
Askaryan effect ~ 10%
(dominant in dense media)

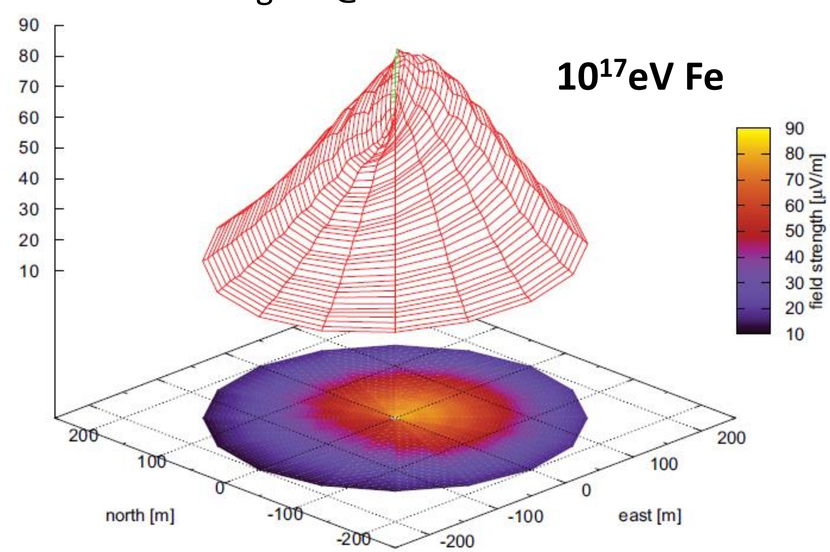
In air, emission region ~1m → coherence and strong amplification below 100 MHz

EAS radio detection

- Total emitted power (< 100 MHz) $\propto N^2 \propto E^2$
  - no significant atmospheric attenuation & only disturbance from thunderstorms
  - Energy threshold ~10^{16}eV (galactic radio bk)
- Footprint dependent on the distance from shower maximum to antennas
- Small footprint limits maximum energy → dense arrays are required

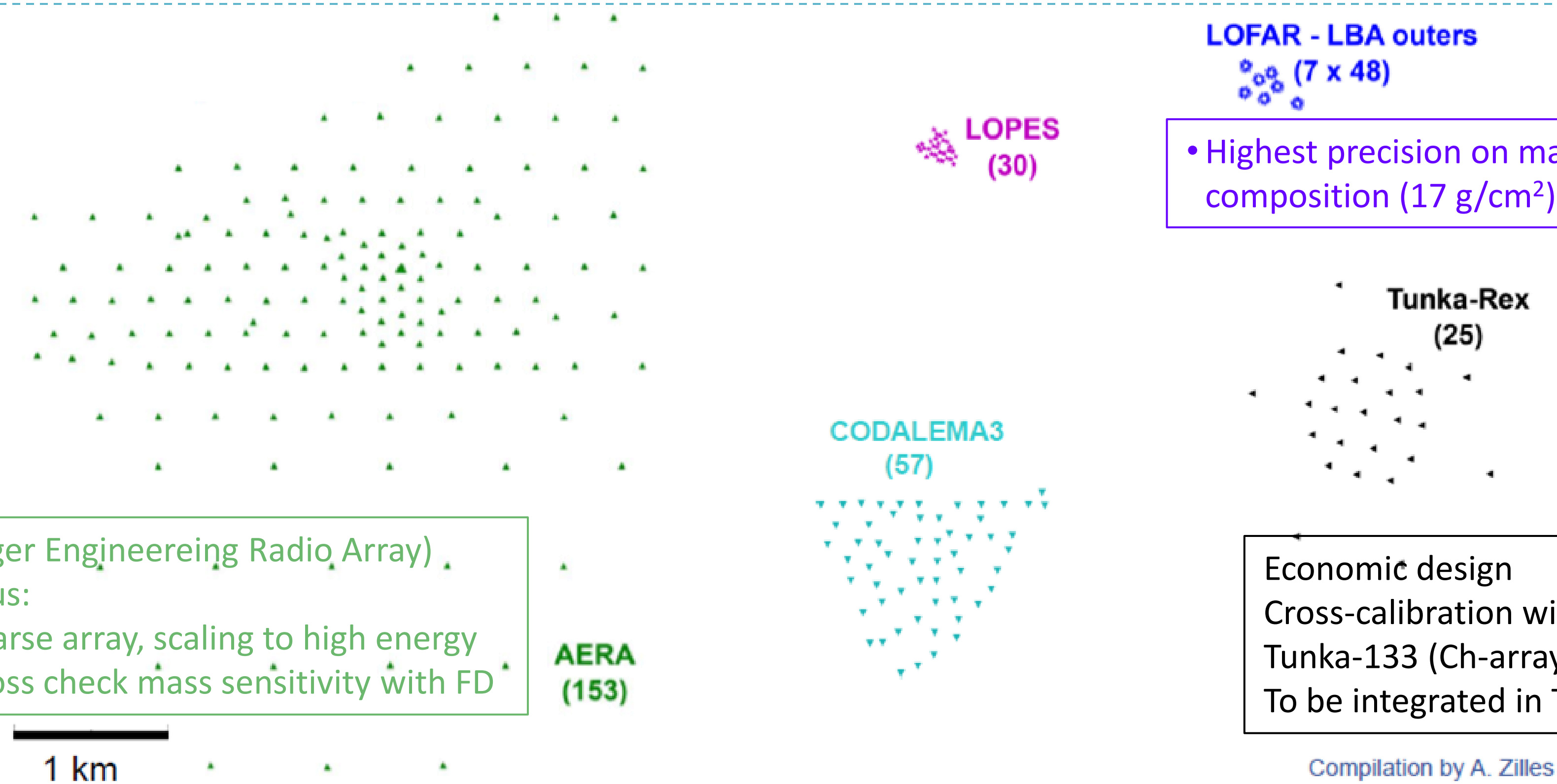
Huege T. @ARENA 2012





- Calorimetric measurement with ~100% duty cycle!!
- Composition sensitivity

Present radio arrays



- Highest precision on mass composition (17 g/cm^2)

(Auger Engineereing Radio Array)
Focus:
- Sparse array, scaling to high energy
- Cross check mass sensitivity with FD

Economic design
Cross-calibration with Tunka-133 (Ch-array)
To be integrated in TAIGA

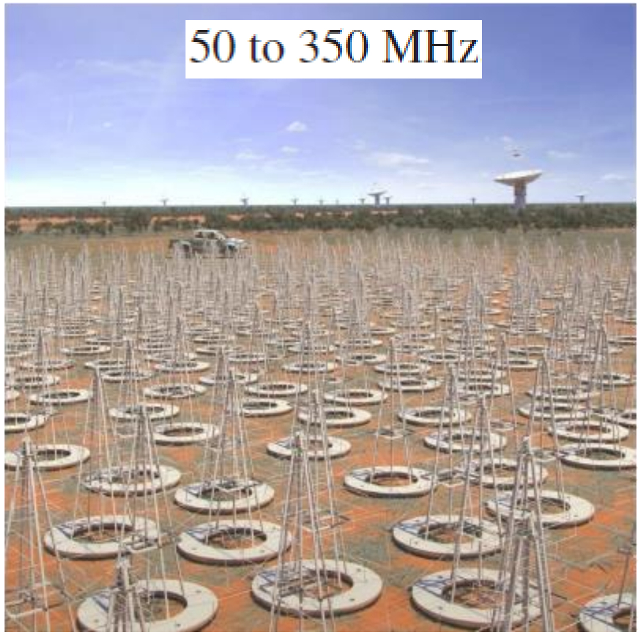
- Strongest potential in combination particle detectors
- Just crossed the threshold from proof-of-principle to science application
- Resolution: Energy < 20% Angle < 0.7° Maximum-depth < 20g/cm^2

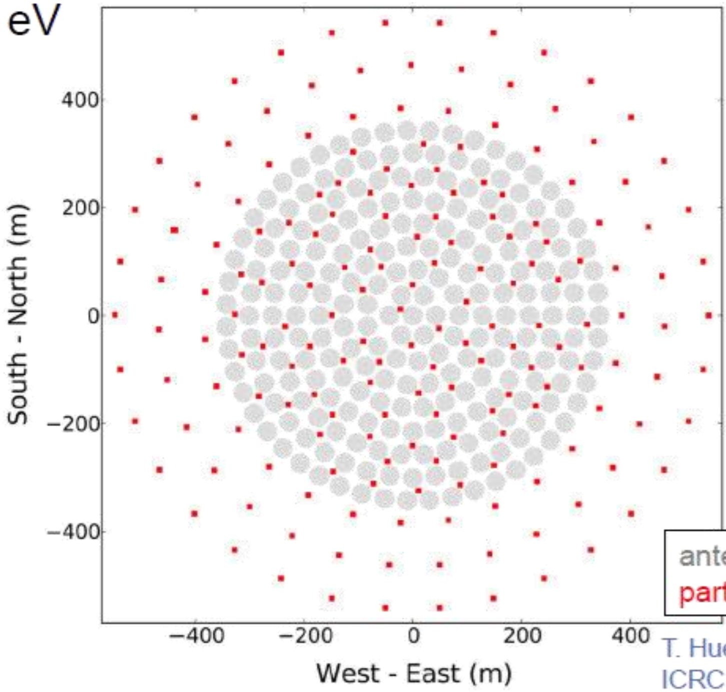
Accuracy in shower parameters competitive to fluorescence technique

SKA-low

Low-frequency core of the Square Kilometer Array

- Phase 1: ~ 60,000 antennas on ½ km²
- Scintillator array planned for E > 10^{16} eV



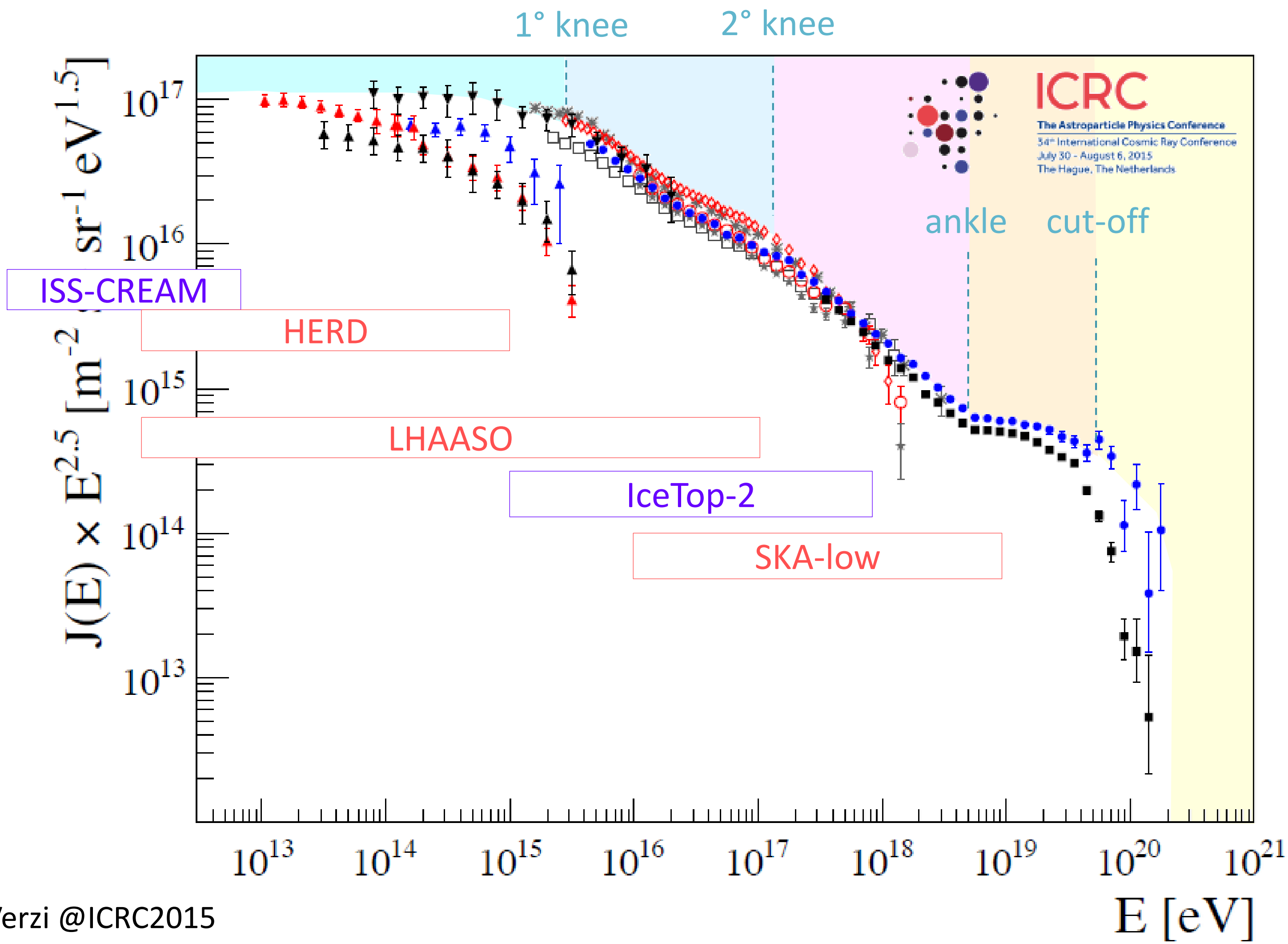


T. Huege et al., ICRC 2015, Den Haag

Start of construction >2018, in Australia

10 g/cm² resolution on shower maximum, with 100% duty cycle

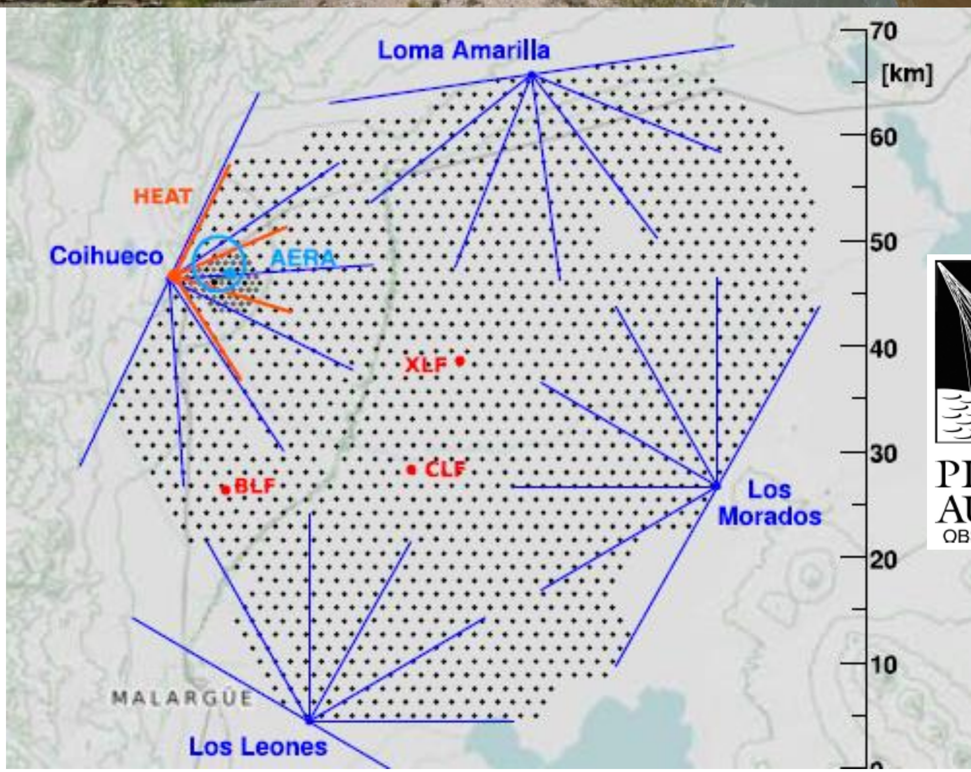
Future indirect experiments



Verzi @ICRC2015

Improving mass-composition sensitivity in the cut-off region

→ e/μ mass identification technique



PIERRE AUGER OBSERVATORY

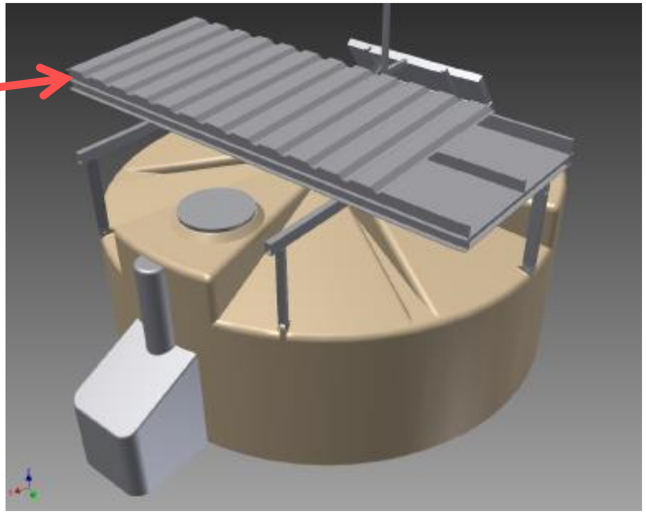
15 g/cm2 resolution >10^{19}eV
< 10g/cm2 on absolute scale
Duty cycle 15%
12% energy resolution >10EeV

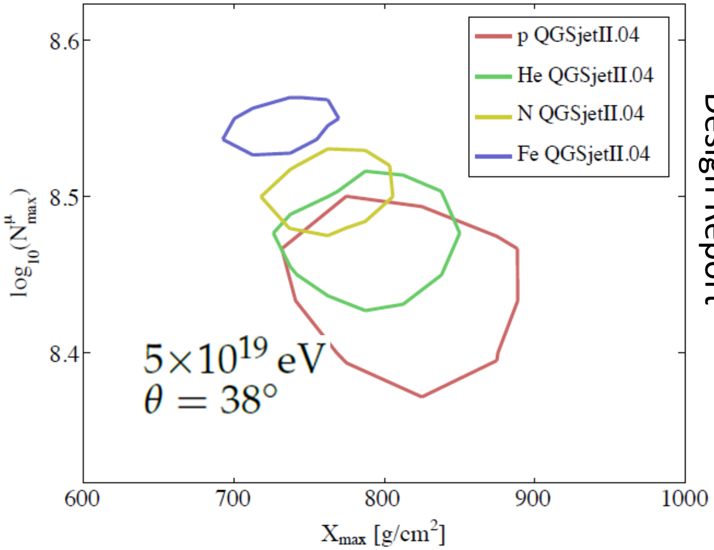
Auger

- 1660 Water-Cherenkov particle Detector (WCD) stations (1.5 km spacing) over 3000 km^2
- 4×6 fluorescence telescopes (FDs)
- Low-energy (10^{17} eV) enhancements
  - 3 High Elevation Auger Telescopes (HEATs)
  - Auger Muon and Infill Groung Array (AMIGA) : 61 WCDs(750m spacing) + prototype underground scintillators
  - Auger Engineering Radio Array (AERA)

AugerPrime

- Proposed upgrade to Auger
  - Scintillator plane above the existing WCDs
    - E.m.-vs-muon EAS components
    - Direct comparison with TA
  - Upgrade of WCD electronics
    - Timing & dynamic range
  - Completion of the AMIGA array
    - Muon shower content
  - Possible extention of FD operation to high night-sky bk conditions
    - 50% duty-cycle increase
- Study of the mass composition of UHECRs
- Status
  - start deployment in 2017, full-upgrade data from 2018, statistics more than doubled by 2024

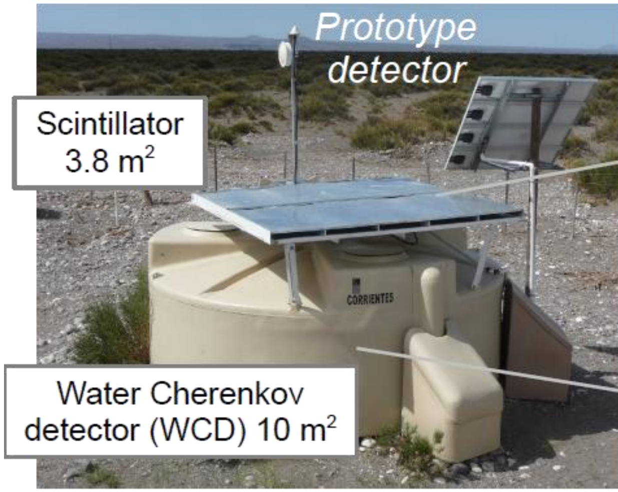


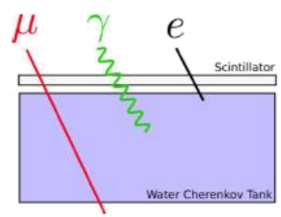


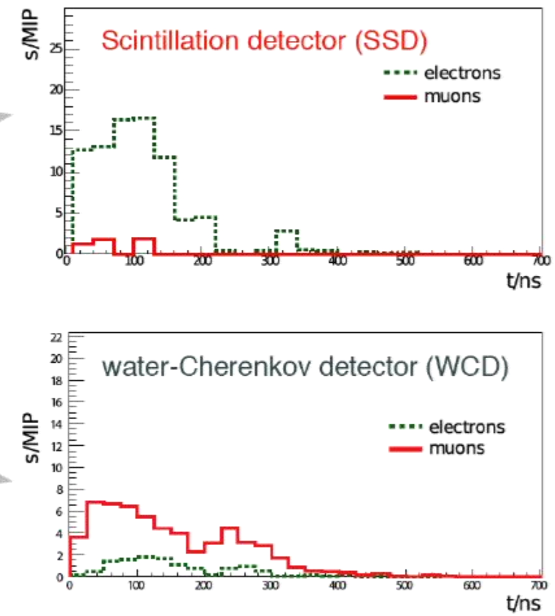
Design Report

Surface detector upgrade

100% duty cycle







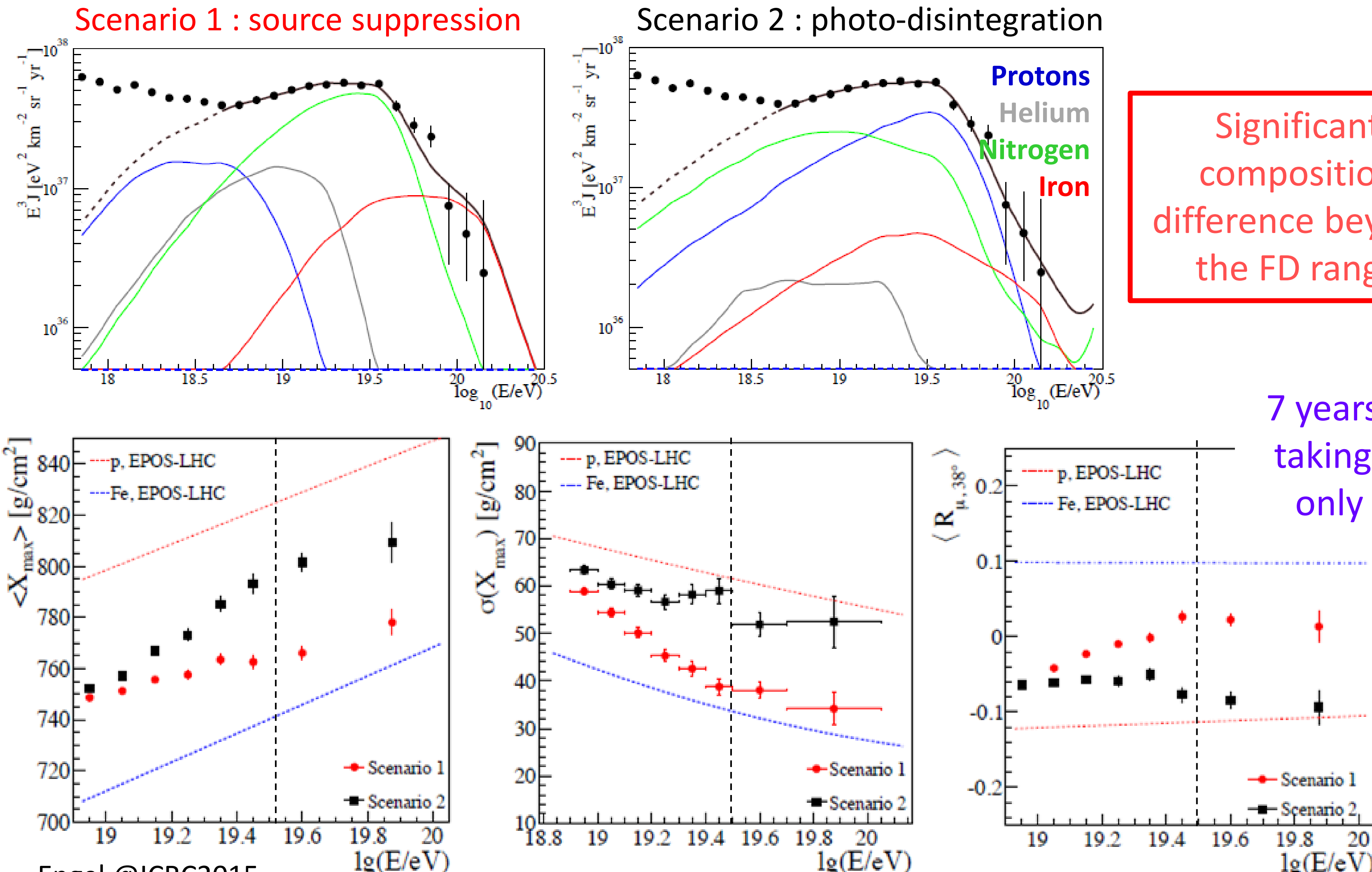
Smida @UHEAP 2016

- Complementary particle response used to discriminate e.m. and muon EAS components
  - Cross-check with direct mu content from AMIGA
- Composition studies with 100% duty cycle
  - Composition info on a event-by-event basis
  - Sensitivity to proton component down to a fraction of 10%

Composition up to 10^{20}eV

Composition-enhanced anisotropy study

AugerPrime: expected performances

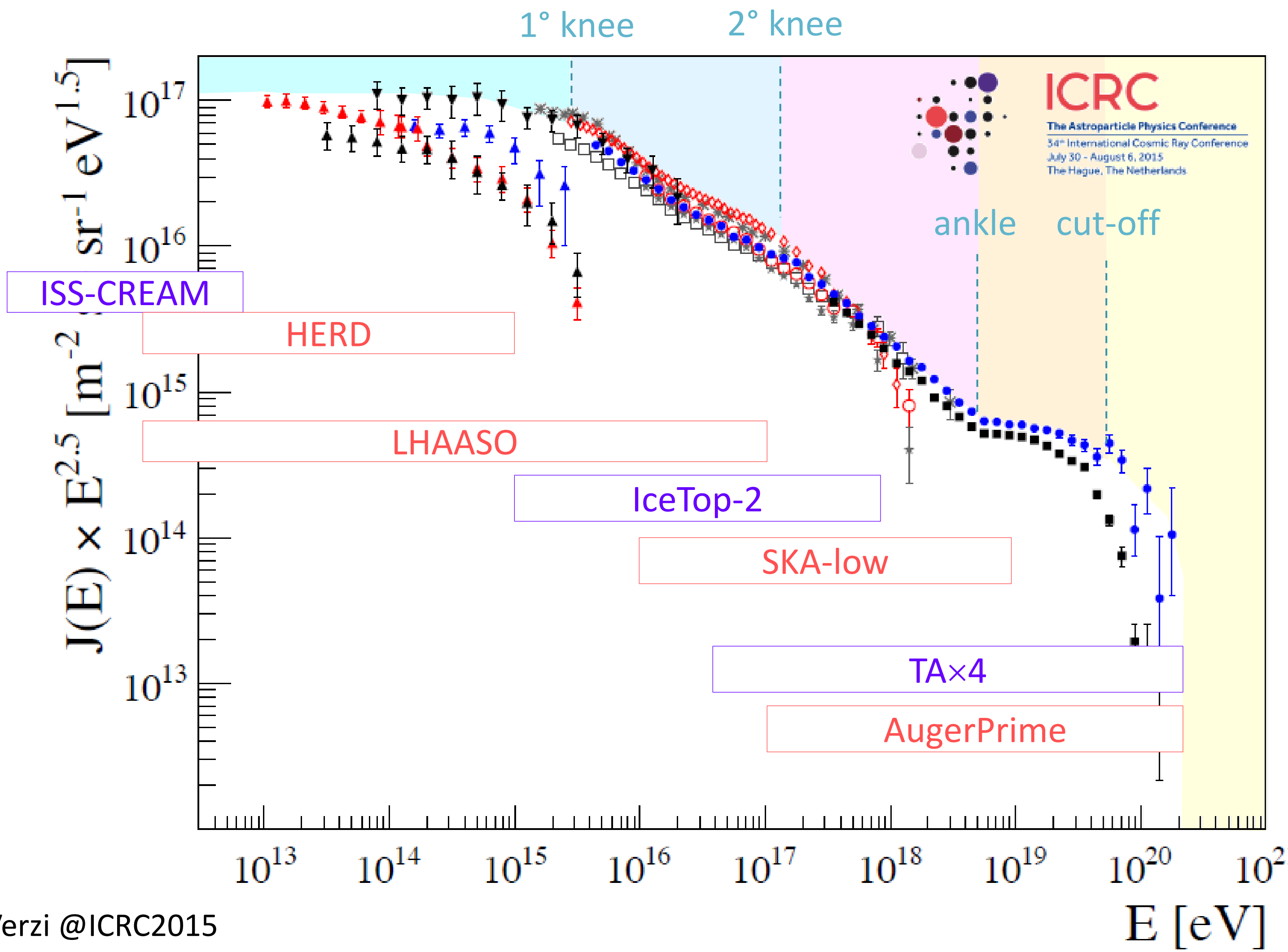


Significant composition difference beyond the FD range

7 years data taking with only SDs

Engel @ICRC2015

Future indirect experiments



Verzi @ICRC2015

EHECRs

Search for CRs above the cutoff

$\rightarrow$ Increasing the exposure by an order of magniture

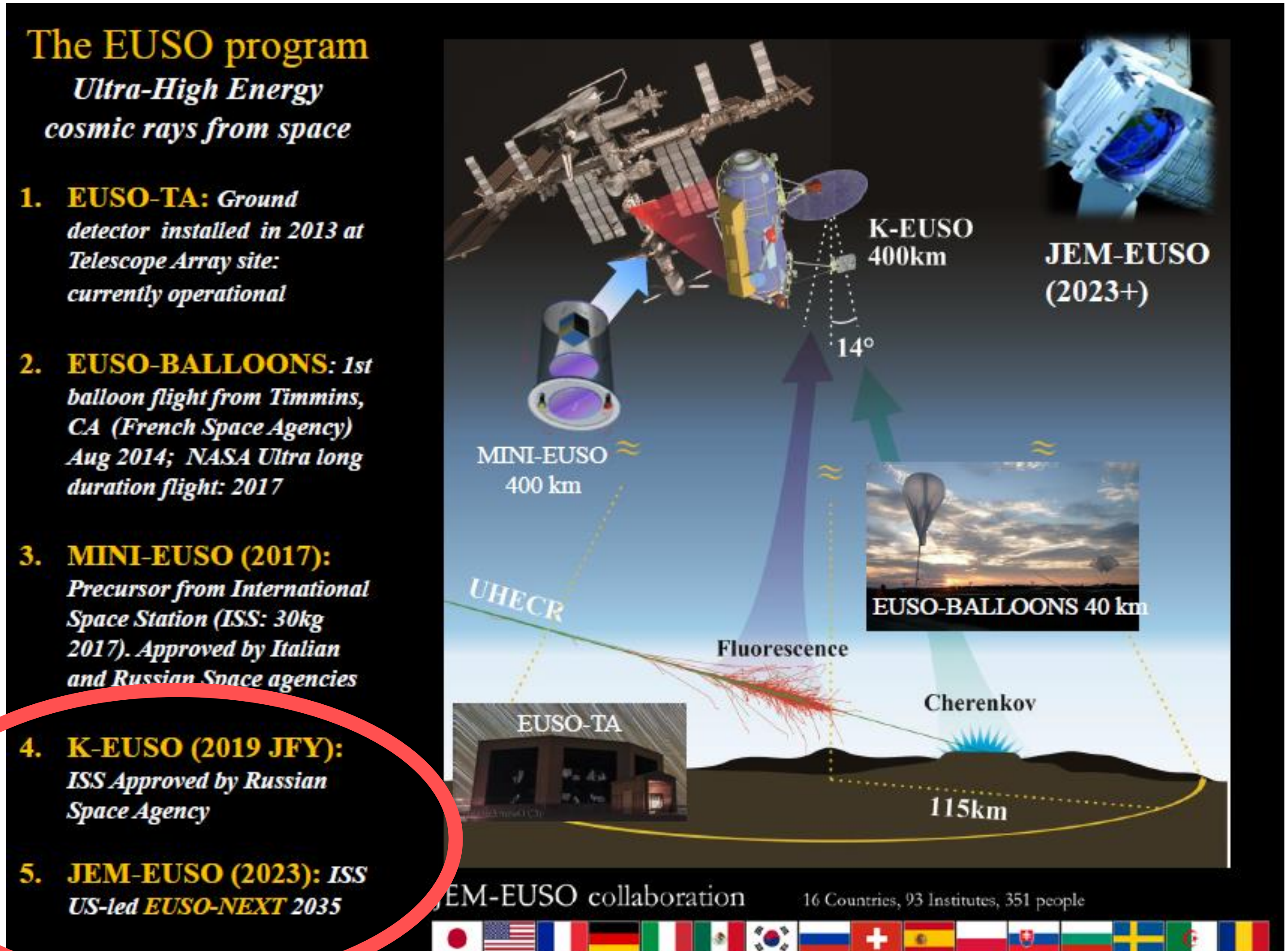
JEM-EUSO

- Extreme Universe Space Observatory
  - to be installed on board the Japanese Experiment Module of the ISS
- EAS fluorescence-light detection from space
  - Wide fov (60°) near-UV telescope of 2.5m∅
  - 2 Fresnel lenses + foca surface PMTs

- Extremely large exposure
- Full-sky coverage

JEM-EUSO status

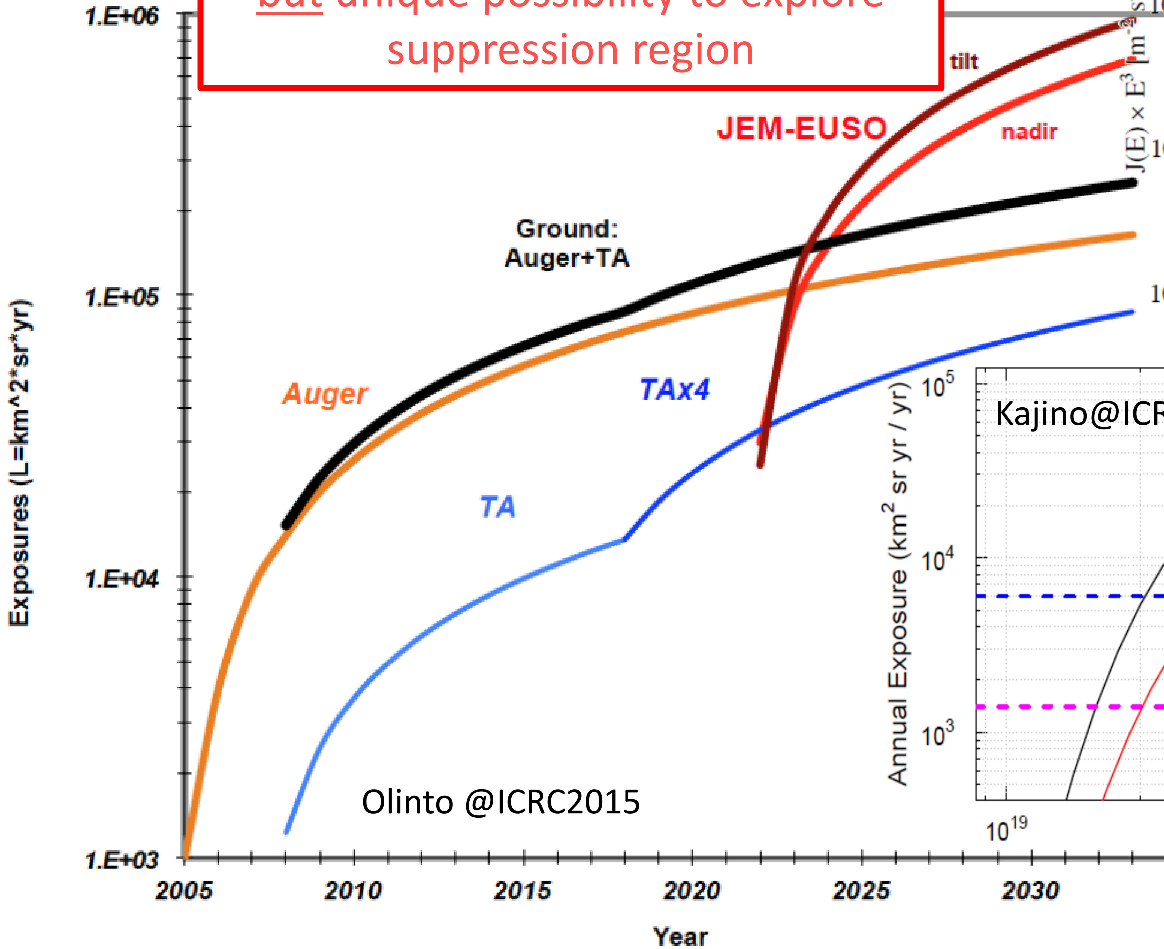
Scientific missions

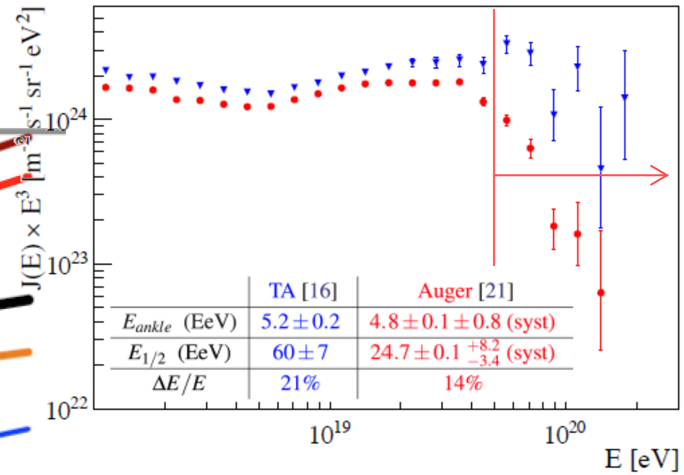


Casolino @UHEAP 2016

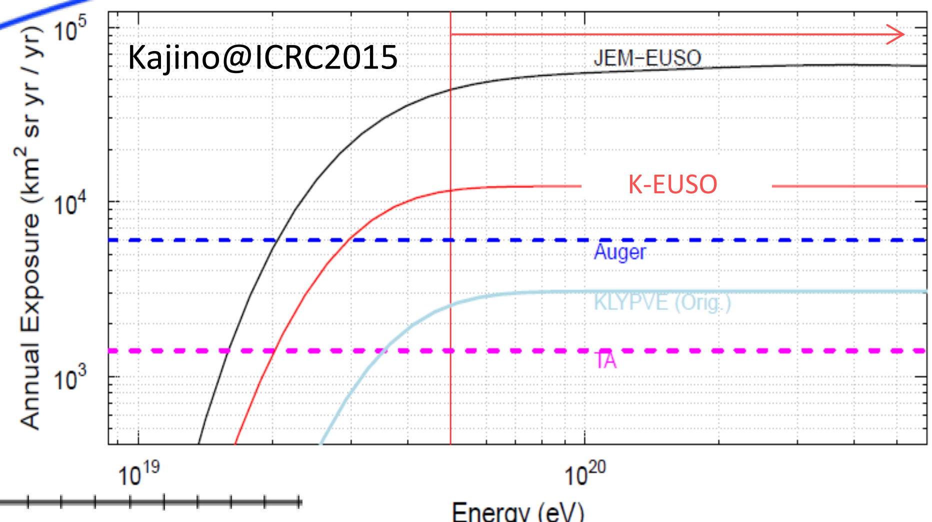
JEM-EUSO: expected performances

No mass sensitivity, high threshold, <u>but</u> unique possibility to explore suppression region

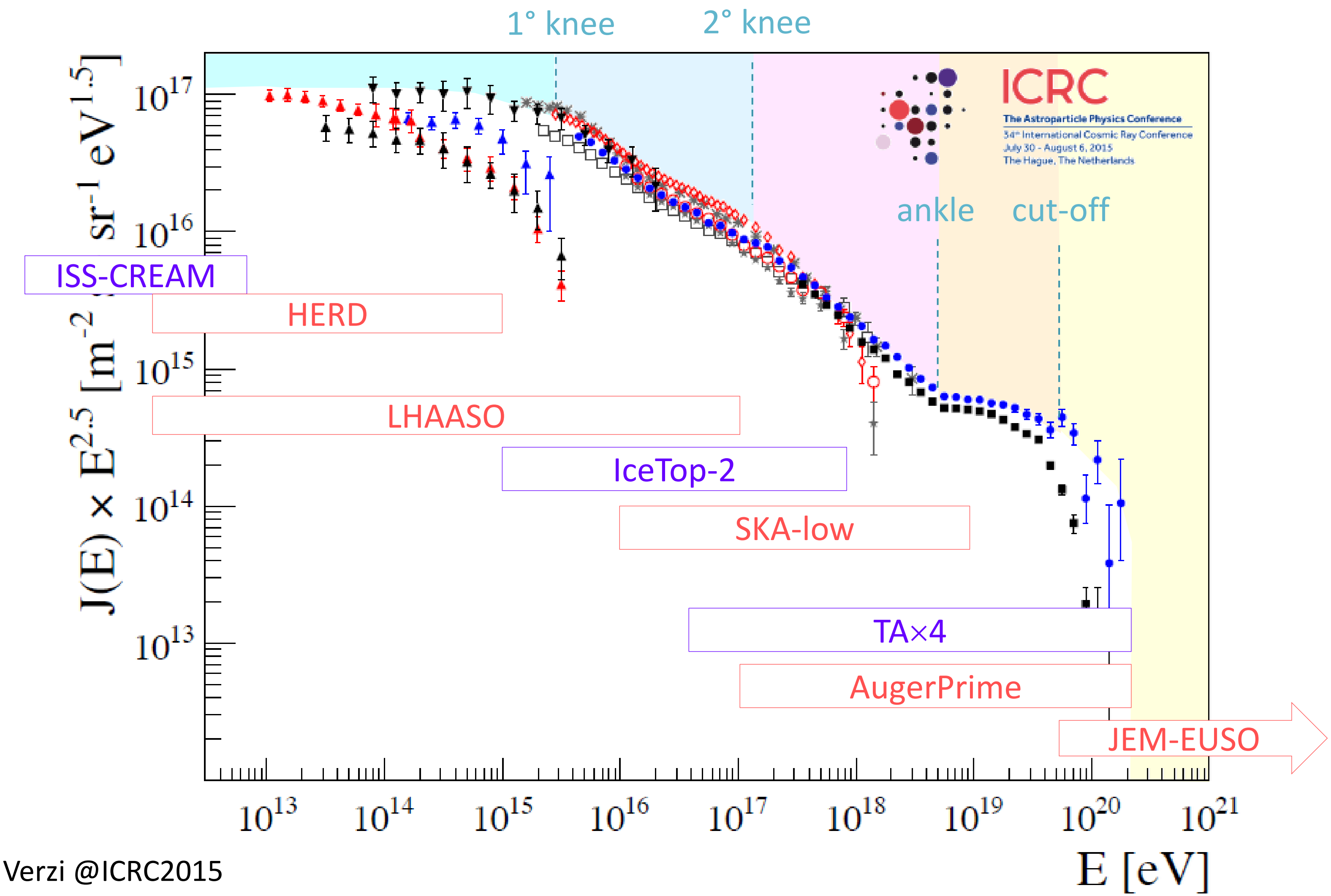




	TA [16]	Auger [21]
E_{ankle} (EeV)	5.2 ± 0.2	$4.8 \pm 0.1 \pm 0.8$ (syst)
$E_{1/2}$ (EeV)	60 ± 7	$24.7 \pm 0.1 ^{+8.2}_{-3.4}$ (syst)
$\Delta E/E$	21%	14%



Future indirect experiments



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Conclusions

- Future directions in CR research (with some «technological» novelty)

1. Low-background indirect DM search with $\overline{D}$ by GAPS
   - Possible breakthrough by $\overline{D}$ detection
2. Calocube as possible approach for next generation calorimeter experiment in space (HERD?)
   - Locate the H/He «knee»
3. A possible approach to next generation spectrometer experiment in space
   - High-energy e^+ and $\bar{p}$ measurement. Solution to e^+ excess puzzle?
4. Km2, high-resolution, multi-component EAS array @knee (LHAASO)
   - Composition-enhanced anisotropy study.
   - Understanding the role of confinement- and source-limits in determining GCR extintion
5. Radio detection as complementary approach to EAS detection
   - Competitive to standard techniques $\rightarrow$ better understanding/modeling of EAS properties
   - Composition-enhanced measurements in the transition regions
6. e/μ mass discrimination technique applied @UHE (AugerPrime)
   - Composition-enhanced measurements in the cutoff region.
   - Understanding the extra-GCR extintion mechanism
7. Observation of EAS from space (JEM-EUSO)
   - Search for EHECRs above the cutoff region

Thanks!!