MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Discriminating Heavy Cosmic Rays at TeV Energies with MAGIC via Direct Cherenkov Emission

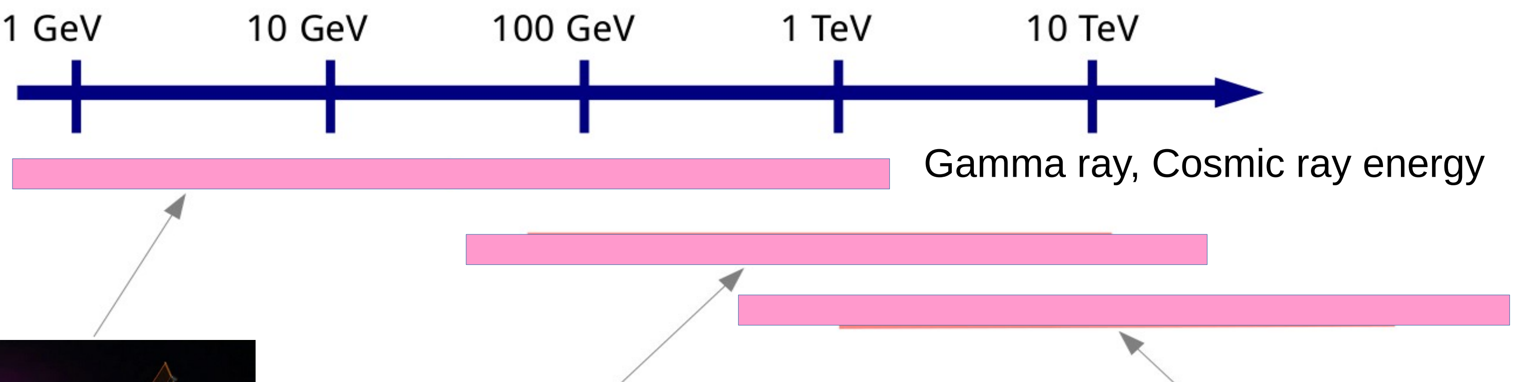
Miguel Molero, Carlos Delgado, Salvatore Mangano
On behalf of the MAGIC collaboration

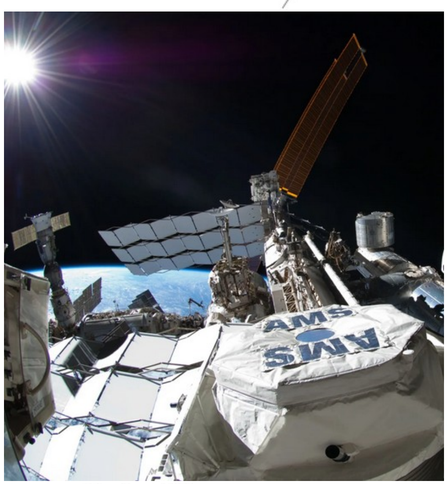
Imaging Air Cherenkov Technique

MAGIC Major Atmospheric Gamma Imaging Cerenkov Telescopes

Earth's atmosphere is opaque for gamma rays and cosmic rays

Direct detection in space ↔ Indirect detection from ground





Satellites

Cherenkov telescopes

Particle detectors

Imaging Air Cherenkov Technique

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Cerenkov Telescopes

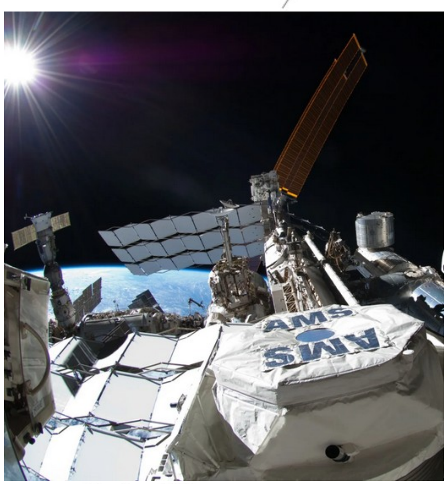
Earth's atmosphere is opaque for gamma rays and cosmic rays

Direct detection in space ⟷ Indirect detection from ground

1 GeV | 10 GeV | 100 GeV | 1 TeV | 10 TeV

Gamma ray, Cosmic ray energy

Overlap and Extend



Satellites

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Why heavy cosmic rays studies?

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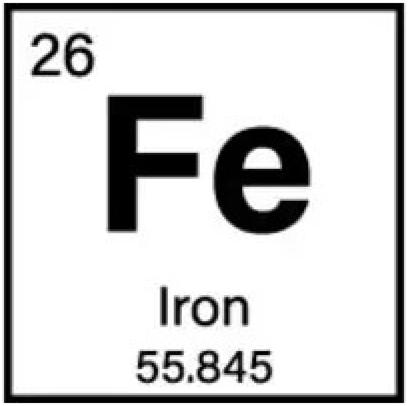
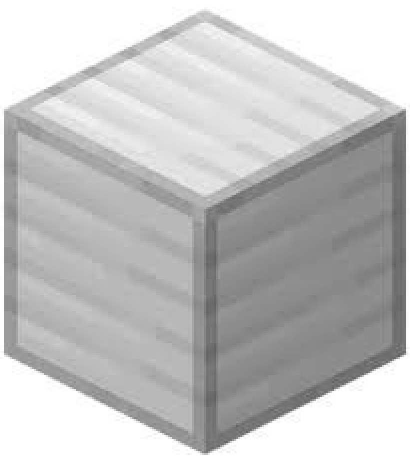


Iron (Fe, Z = 26) most abundant heavy element in cosmic rays
- Tracer of stellar production and evolution

Cosmic rays and gamma rays spectra
- Astrophysical source **location and emission properties**
- **Propagation mechanisms** through interstellar medium



Anisotropy and composition
- Acceleration sites
- Stellar evolution
- Galactic magnetic fields

Multi-messenger and complementary
- Electrons vs. protons vs. irons vs. neutrinos vs. etc.

MAGIC Telescopes

Imaging Atmospheric Cherenkov Telescopes (IACTs)

Canary Island of La Palma Spain

17 m diameter reflector

Gamma ray energy range: ~50 GeV to ~100 TeV

Lightweight for fast slewing to ToOs

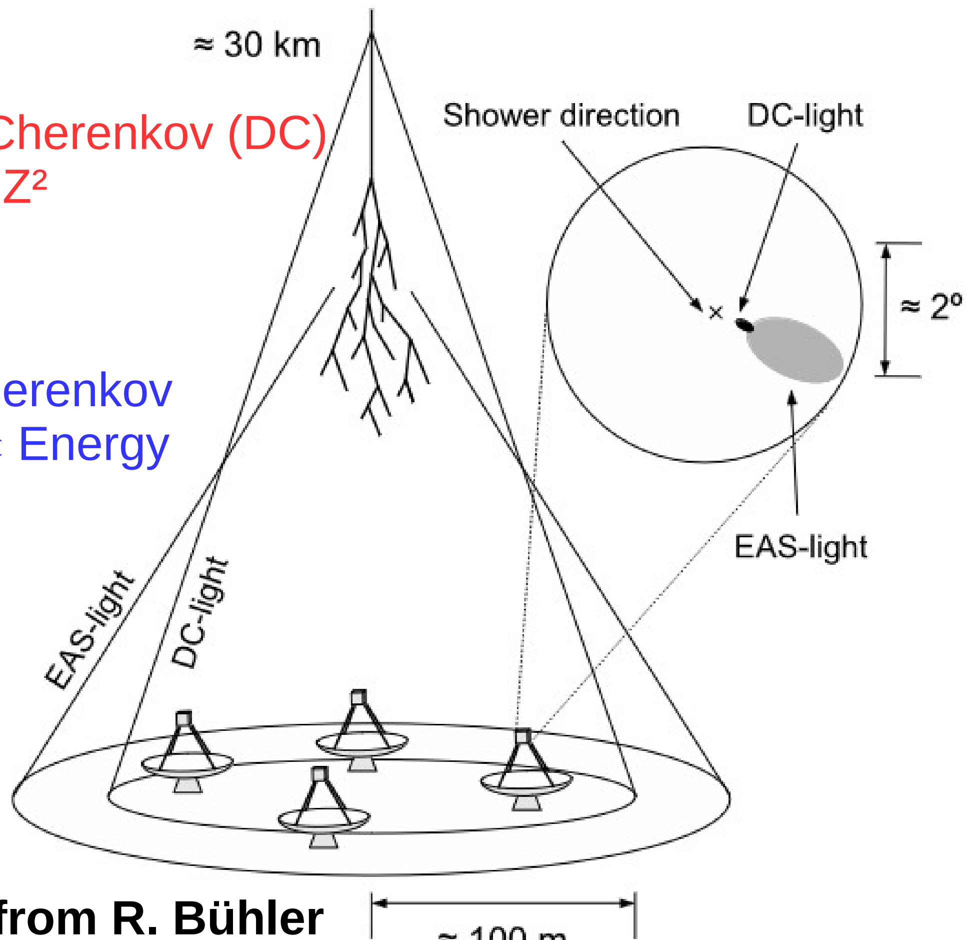
Field of view: 3.5 deg

PSF: 0.1 deg

Direct Cherenkov light emission

Direct Cherenkov (DC) yield ∝ Z^2

EAS Cerenkov yield ∝ Energy



Taken from R. Bühler H.E.S.S. ICRC 2007

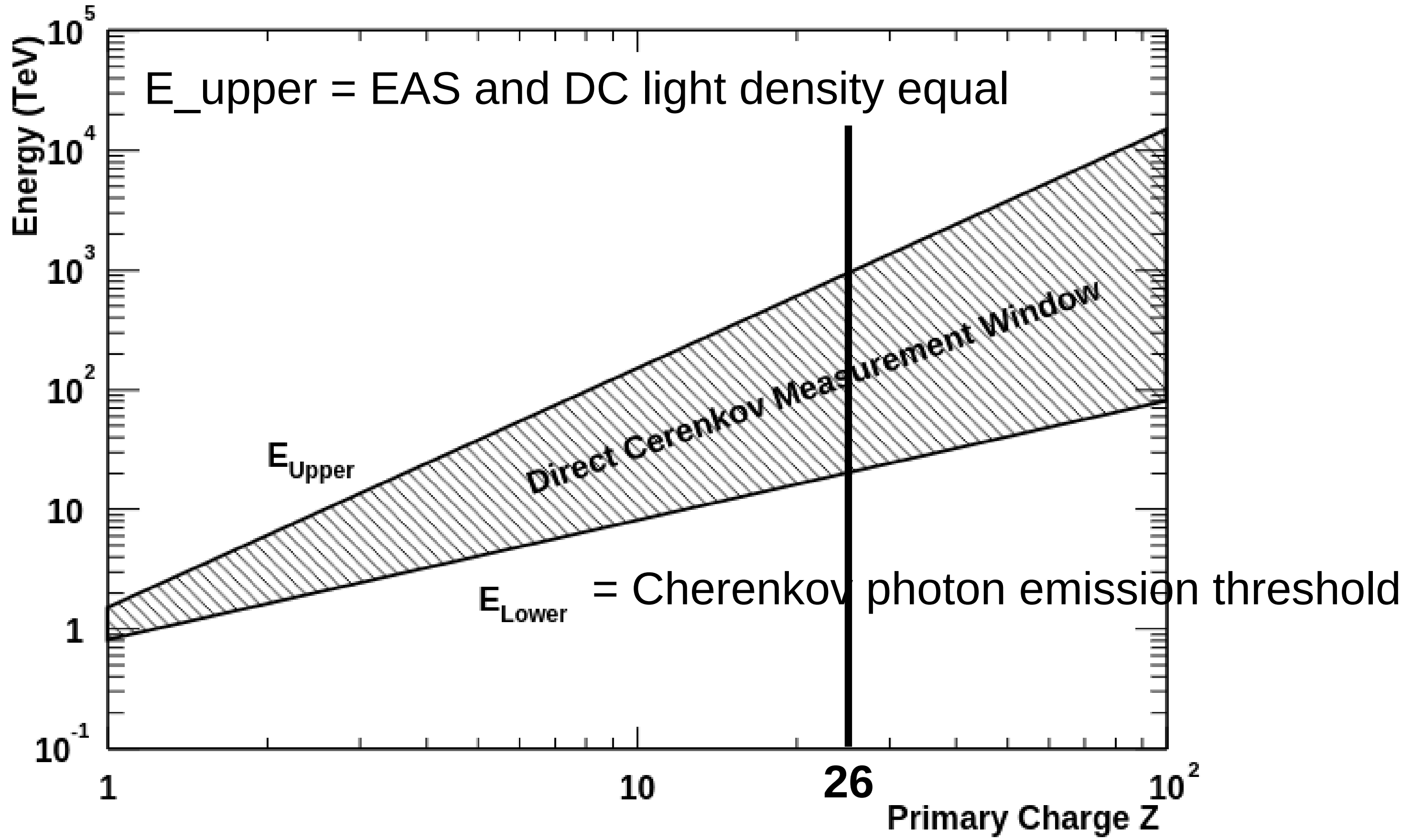
Primary charged cosmic rays emit **Cherenkov light** before their first interaction in atmosphere
→ Direct Cherenkov (DC)
DC light intensity ∝ charge (Z^2)

Primary cosmic rays then interact in upper part of atmosphere
→ Extensive Air Shower (EAS)
EAS light intensity ∝ energy

DC light:
Narrow angular cone with more intense light pool than EAS with wider angular distribution
→ Enables element identification

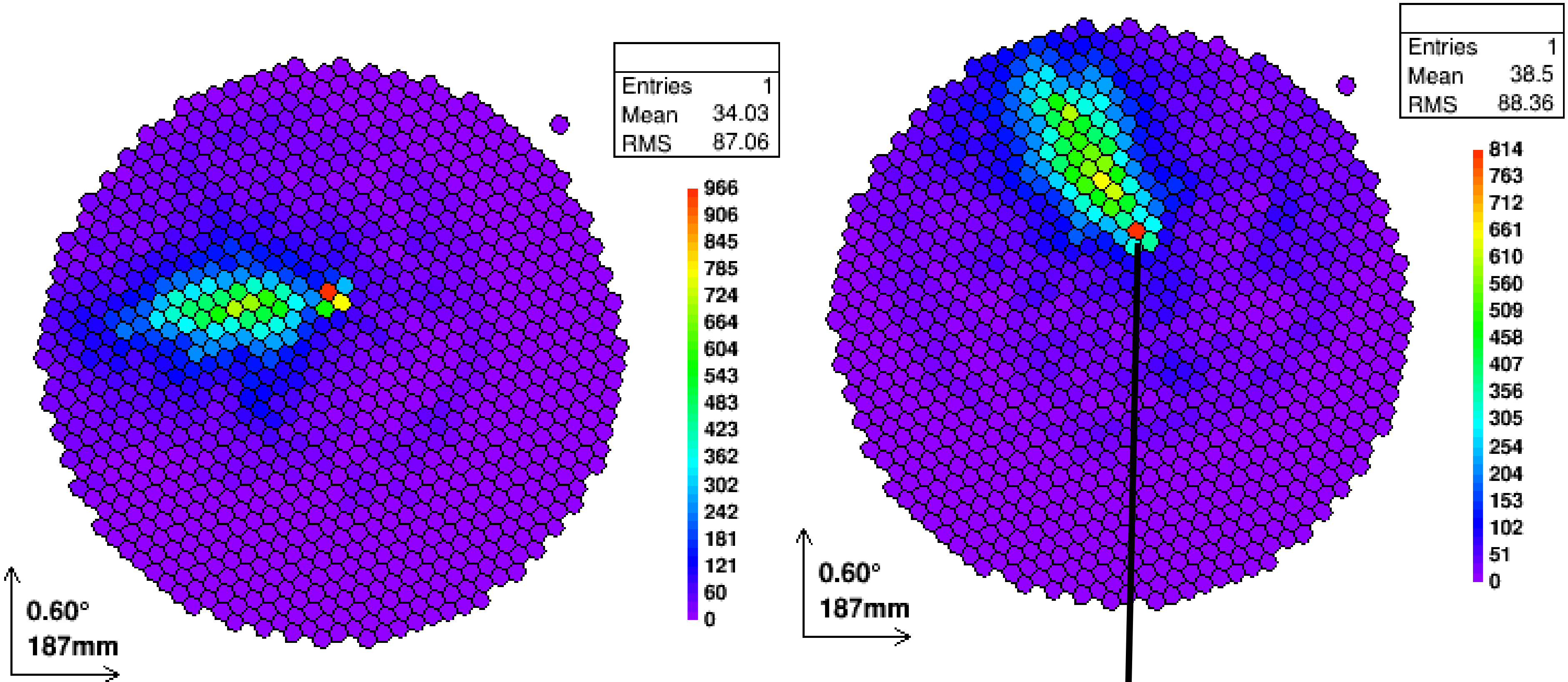
DC light tagging method distinguish light vs. heavy cosmic ray primaries

DC tagging has limited acceptance



DC light only visible from ~10 TeV up to ~150 TeV, **Kieda** et al. (AP 15, 287-303, 2001)
First to propose DC light tagging method for cosmic rays measurement with IACT

DC tagging in MAGIC



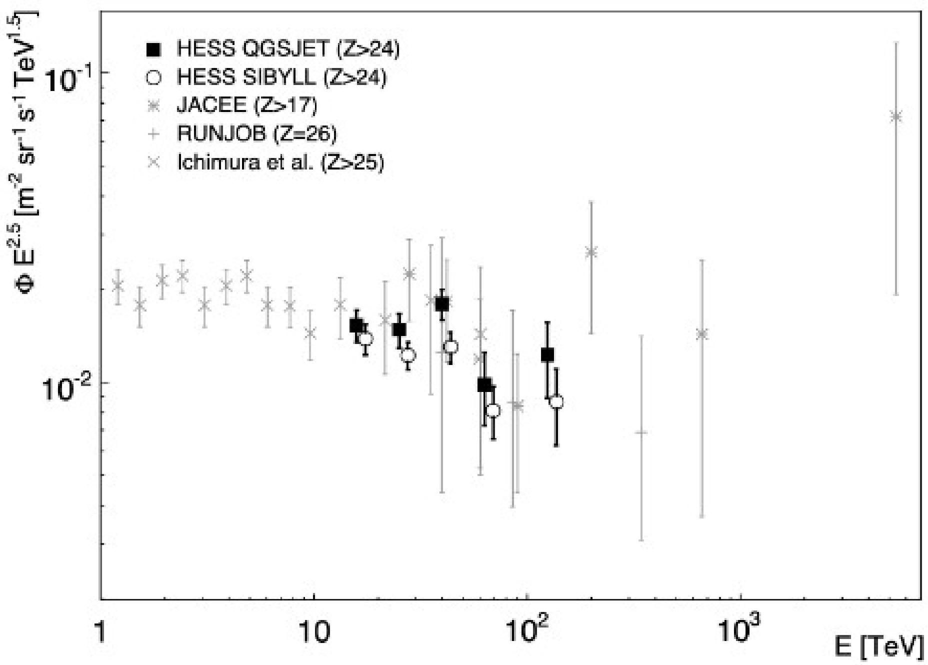
DC light signature in both telescopes:

- Nice reconstructed showers
- Large amount of direct Cherenkov light

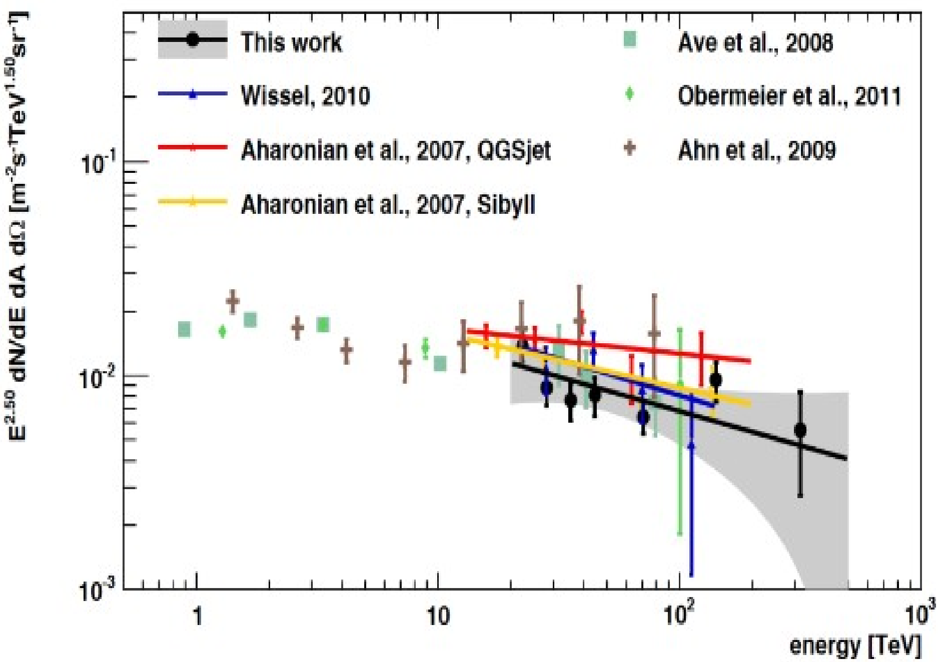
Existing IACTs cosmic ray iron spectrum

H.E.S.S. and VERITAS measured already iron spectrum with DC light tagging

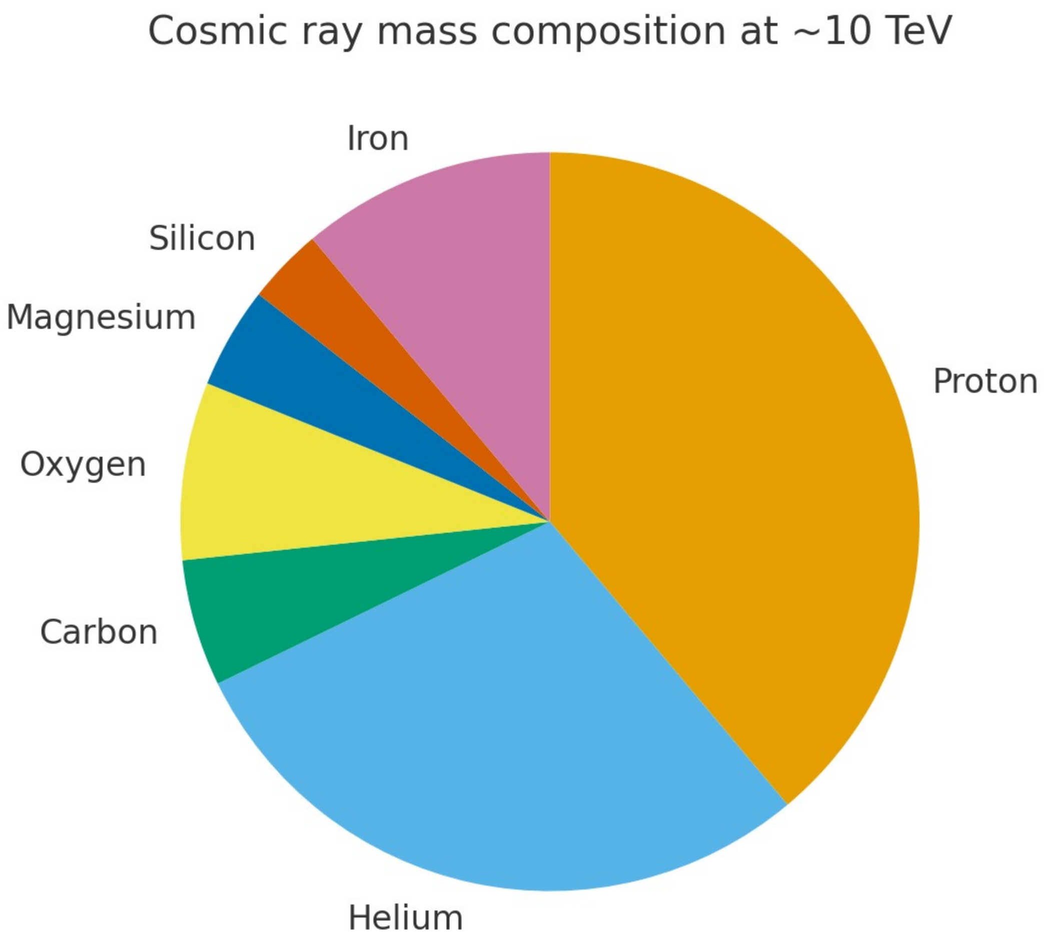
H.E.S.S. (PRD 74, 042004, 2007)



VERITAS (PRD 98, 022009, 2018)



Cosmic ray mass composition



Taken from J. Hörandel (AP, 193-220, 2003)

Power law E^{-3}

Composition at ~10 TeV:

35 % Proton
26 % Helium
5 % Carbon
7 % Oxygen
4 % Magnesium
3 % Silicon
10 % Iron

Abundances varies slightly with energy

Data and MC simulation

Data:
- Pixel-wise information (intensity and arrival time)
- Zenith Range: 5-35° with good atmospheric conditions
- Total effective exposure time amounts to 305 hours

MC:
- Corsika simulation with similar conditions as data (preserve pixel-wise information)
- High statistics of cosmic ray simulations to distinguish iron from lighter elements

Source	Exposure Time [h]
M15	54.5
M87	60.3
Cyg-X3	36.7
Draco	34.1
Crab Nebula	72.3
Mrk421	47.1

Particle	Z	Gen. Events $[\times 10^6]$
Proton	1	2.0
Helium	2	2.0
Oxygen	8	1.5
Magnesium	12	1.5
Silicon	14	3.0
Iron	26	10

DC light reconstruction and selection

DC light variables and set of strong cuts to select

clean golden heavy element sample with high purity but small efficiency

Use of MAGIC standard software with addition of pixel-information
Calibration, energy reconstruction, Hillas variables, effective area

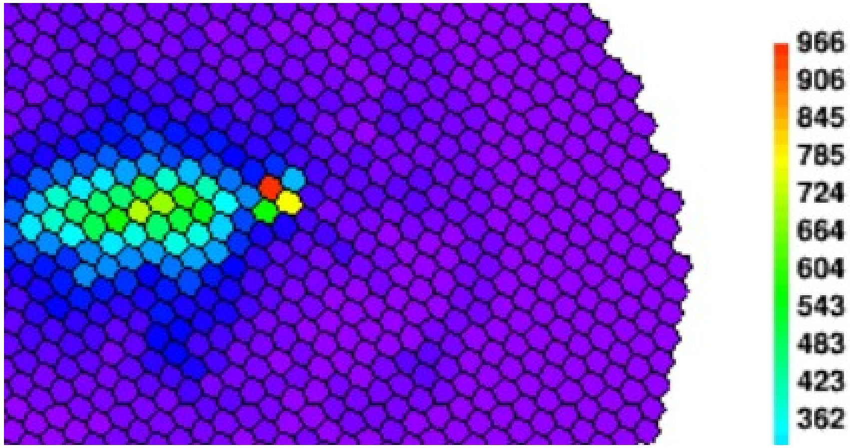
Select nice showers with quality cuts + heavy element identification:

DC ratio:

$$Q_{DC} = \frac{< I_{neigh} >}{I_{pixel}}$$

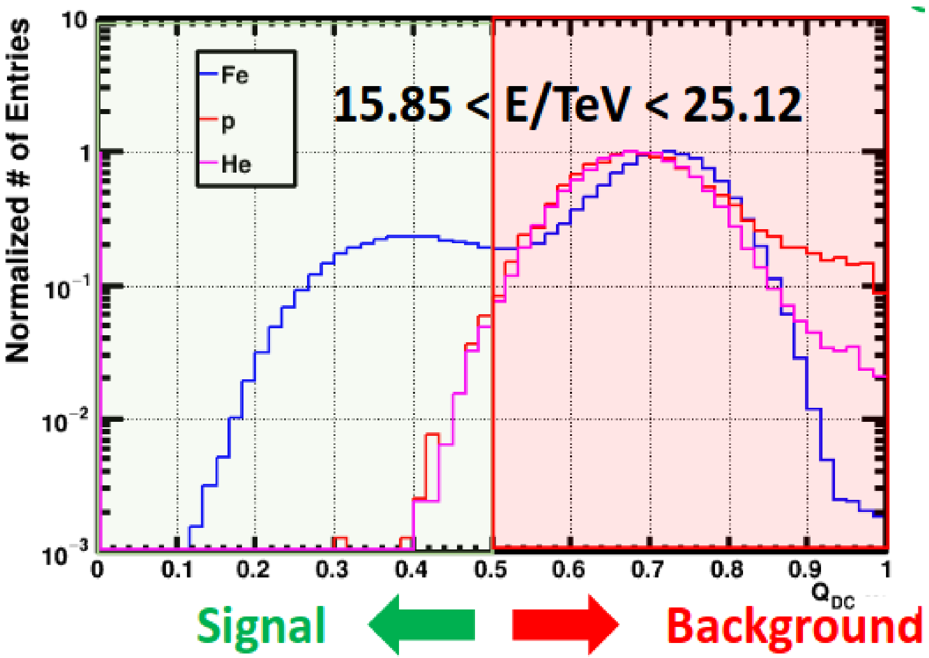
DC light:

$$I_{DC} = I_{pixel} - < I_{neigh} >$$

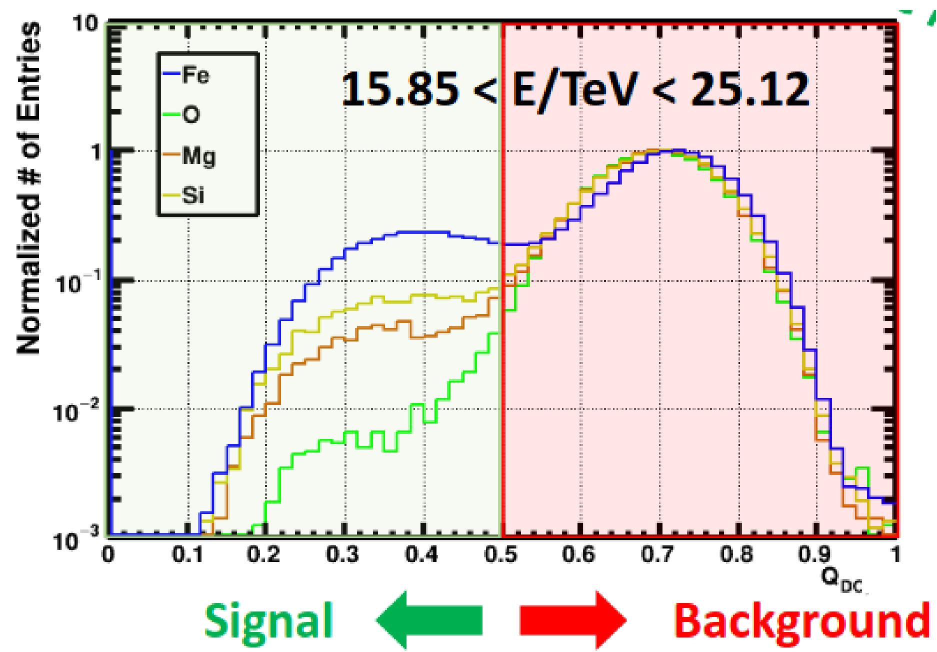


DC ratio selection

Fixed cut in DC ratio (Q_{DC}) for different reconstructed energy ranges in both telescopes



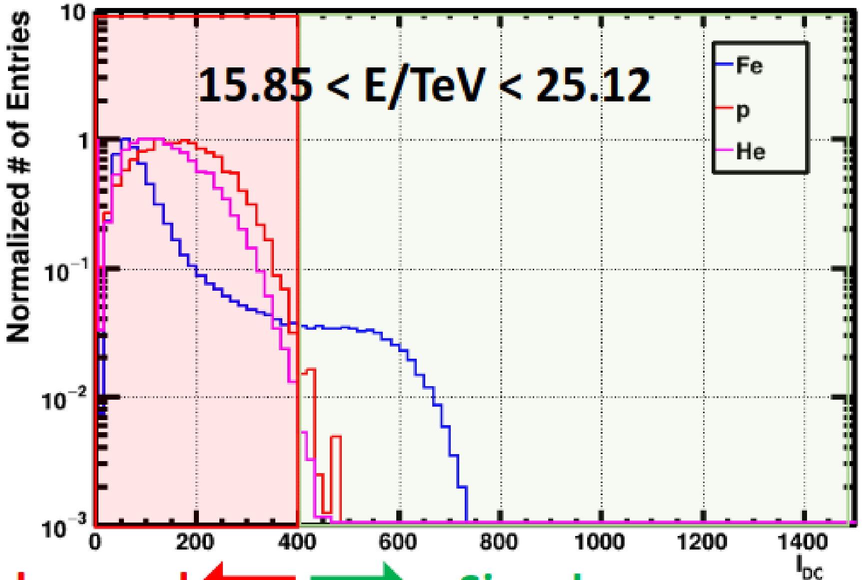
Good rejection of proton and helium events



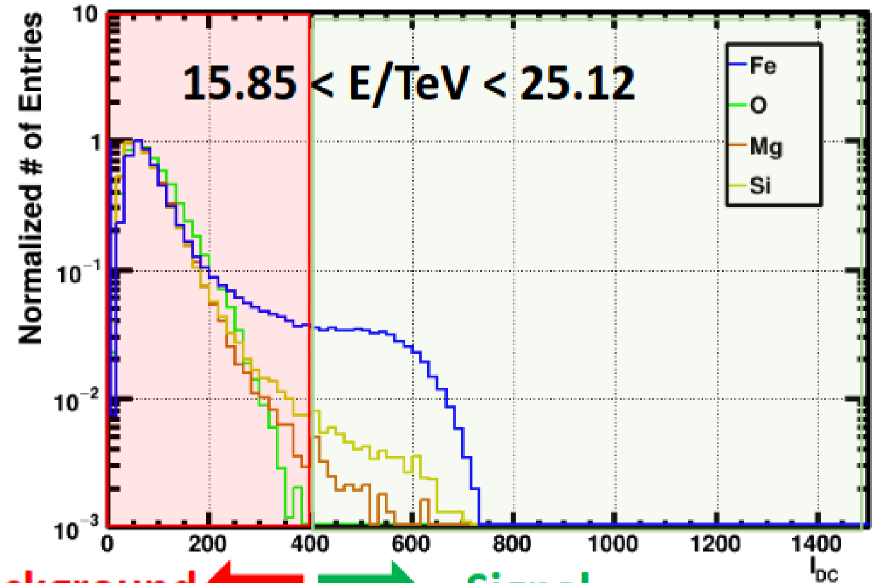
Poorer rejection of mid elements

DC light selection

Fixed cut in DC light (I_{DC}) for different reconstructed energy ranges in both telescopes



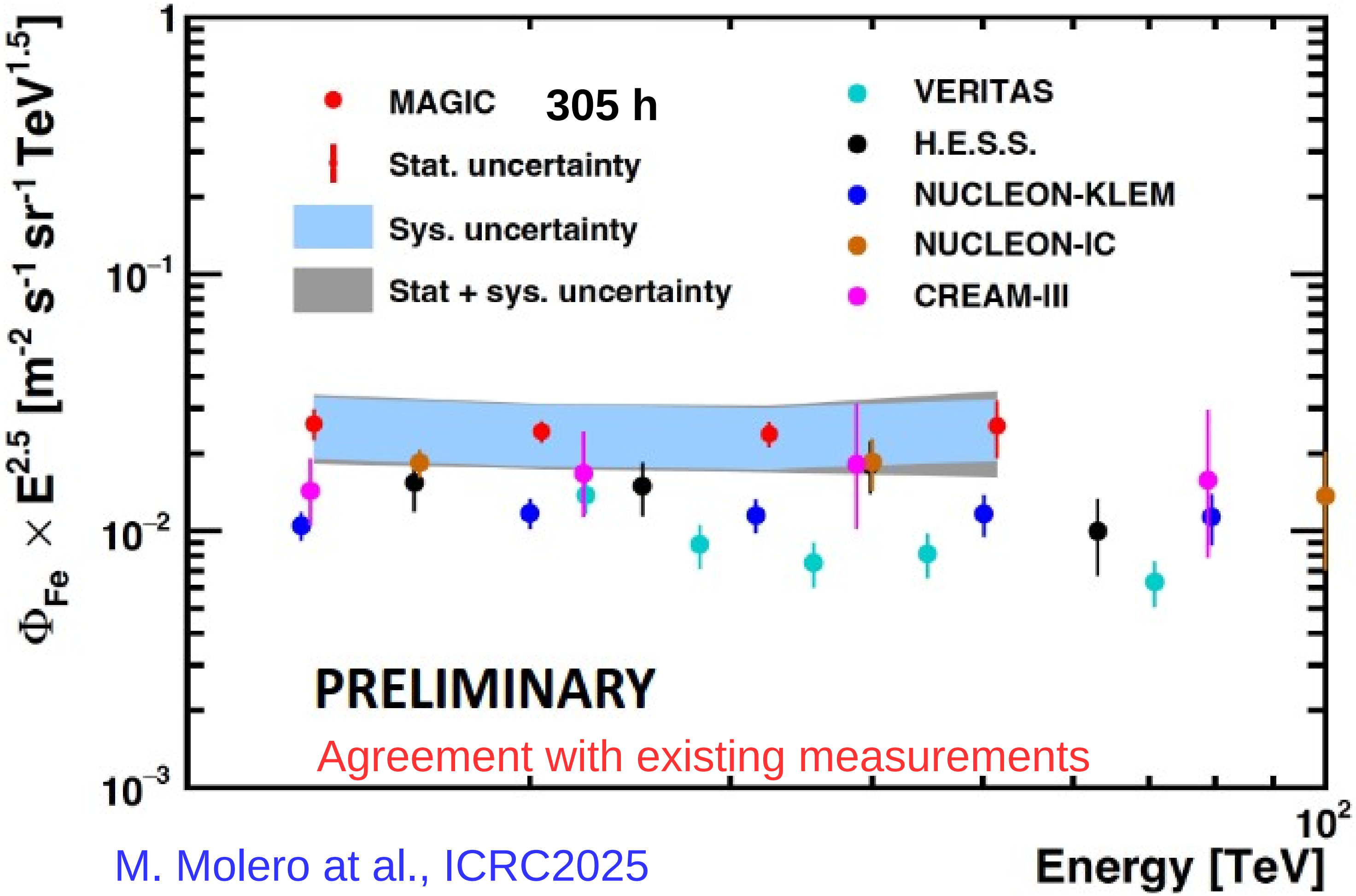
Background ⟵ ⟶ Signal



Background ⟵ ⟶ Signal

Fixed cuts in both variables Q_{DC} and I_{DC} provide reasonable suppression of mid elements

Comparison with existing experiments



M. Molero at al., ICRC2025

Largest contribution to systematic uncertainty from misclassified elements

Conclusion

Direct Cherenkov (DC) light tagging with MAGIC
- Distinguish heavy (e.g. Fe) from light cosmic ray nuclei
- Measured in energy range from 10 to 60 TeV using DC emission

Dedicated cosmic ray simulations (Corsika) performed to assess
- Iron tagging efficiency
- Contamination from lighter elements

Preliminary MAGIC heavy cosmic ray flux consistent with IACTs results
- “Golden” iron sample with high purity but low efficiency (~1 event/hour)

Inclusive tagging approaches needed to increase statistics
- Higher statistics enables to increase energy range and study anisotropy