The High Energy cosmic-Radiation Detection (HERD) Facility onboard China’s Future Space Station
HERD concept

• HERD: a flagship and landmark scientific experiment onboard China's Space Station

• Sciences
  – Indirect dark matter search with unprecedented sensitivity
  – Precise cosmic ray spectrum and composition measurements up to the knee energy
  – Gamma-ray monitoring and full sky survey
Status of electron spectrum measurements

Four direct measurements with three results!
Latest DAMPE result

- A ‘knee’ is first measured at the electron spectrum
- A possible ‘sharp peak’ is detected
- A possible structure at the high energy end of the spectrum

The knee at ~1 TeV is naturally explained by a PWN acceleration and release model; the break at high energy is induced by cosmic ray electron emission at the upstream.

Fang et al. APJ 854 (2018), 57
Measure the total e+- spectrum by HERD

- This is an obvious objective since the present measurements are not consistent
- To test the sharp peak at the DAMPE spectrum which is ~ 3σ but stimulated a lot of interests
Fine structure in the high-E electron spectrum

DM or pulsar can induce different shape of spectrum cutoff → fine structure at the total spectrum.

Simulation shows HERD can find such a feature in ~1 yr & determine the cutoff energy → DM mass!
e$^+$$^-\text{ Propagation distance}$

High energy e$^+$$^-\text{ can only come from nearby sources — the nearby SNR or pulsar induce large anisotropy, DM not}$

If coming from nearby pulsar or SNR they may have possible features at higher energies, DM not
HERD Anisotropy: origin of extra positrons at AMS-02

Fang, k. et al. APJ 2017

A large anisotropy induced by a nearby source
Detect the spectra & anisotropy from nearby sources

HERD can detect the bump $> 10$ s TeV from the local sources $\Rightarrow$ a pulsar origin of positron excess.
Detect DM annihilation gamma ray line

HERD 1 yr, 5.00σ
- $\chi=416\text{GeV}$
- electron+nuclei
- galactic $\gamma$
- extra $\gamma$

Nevents / 5GeV vs Photon Energy (GeV)
Sensitivity for $\gamma$-line of different experiments

Observations of major cosmic ray compositions

- Current status: precise measurements up to TV rigidities by AMS-02
- Goal of HERD: extend the precise measurements of individual species to PeV energies
Proton and Helium spectra

PAMELA, 2011, Science

CREAM (2017)

Break around 10 TV?
Expected HERD Proton and He Spectra

- Well extended to PeV energies
- Critically test any structures between TeV and PeV
- Clearly reveal the knee of light components (Z- or A-dependence)
• AMS-02 data may indicate a break of the B/C ratio around a few hundred GV
• HERD will extend the precise measurement to significantly higher energies
• Li, Be, and B nuclei are secondary products of CRs
• Precise comparison of their spectra at higher energies are very important for particle/nuclear physics, astrophysics, and/or cosmology
Heavy and super-heavy nuclei

- Iron is the end product of stellar synthesis
- CR fluxes of iron and heavier nuclei are crucial to probing the acceleration sites of CRs (e.g., massive stars or supernovae)
HERD’s gamma-ray science goals

- Search for signatures of dark matter
- Studies of Galactic and extragalactic gamma-ray sources
- Galactic and extragalactic diffuse emission
- Gamma-ray transients, e.g. gamma-ray bursts, flares
HERD Gamma-ray sky survey sensitivity

HERD: 1 year
FERMI/LAT: 1 year
LHAASO: 1 year
CTA: 50 hours

Expected HERD gamma-ray sky survey sensitivity (5σ)
Good match between HESS and Fermi (50 GeV-2TeV) maps

HERD will improve this map by a factor of >10!
γ-ray Astronomy Prospects for HERD

• For most of the sky and most of $>10$ GeV energy range, the current Fermi-LAT is limited by photon counting statistics, not background: Linear scaling of HERD improvement with larger acceptance.

• HERD increases the energy reach to 10 TeV, improves the statistical precision, and enhances variability measurements.

• The extreme phenomena seen with Fermi are often rare, so large acceptance of HERD increases the chances of seeing rare activities: meaningful insight of physics behind a variety of high energy phenomenon.
Highlights of HERD potential contributions

• High energy extension in gamma rays:
  – GeV-TeV mapping of the diffuse gamma-ray emission (Galactic and extragalactic)
  – Extragalactic background Light (together with stacked HE sources)
  – GeV-TeV source spectrum (including search for exotic potential sources)
  – Monitoring for transients complementary to Fermi (GRB, GW events, flares, TGF etc.)
  – Extended sources Fermi Bubbles, Cen A lobes, Cygnus region, Supernova remnants
  – TeV point sources!

• Synergy with other high energy and messenger missions: gamma-ray, neutrino, multi-wavelength, GW etc.
HERD completely overlaps the energy range of Cherenkov telescopes by measuring the photons in situ!

**HERD + LHAASO + CTA!**

- HERD extends the Fermi source spectrum to higher energy
- Significantly enhance the detection from Fermi data and reveal NEW sources (especially 1FHL catalog)
- HERD >50 GeV catalog, >100 GeV catalog
- HERD will improve the significance of Fermi sources over a large energy range, improve the source location
- HERD is crucial to provide targets for existing Cherenkov telescopes and future CTA/LHAASO

**HERD produces ToO Alerts:**
  - Sun, AGN, Crab, Novae, binary systems
  - Requires fast onboard data processing or data-downloads
Mission profile – Chinese Space Station

- China Manned Space Program (CMSP)
- Three-step strategy
  - Space ship: send astronauts there!
  - Space lab, including Tiangong-1 and Tiangong-2
  - Space station, to be completed by 2022
Technical conditions of Chinese Space Station

- Chinese Space Station
  - Core Module
  - Experimental Module I
  - Experimental Module II
- Docking for cargo/manned ship
- Suitable for HERD operation
  - Orbit
  - Attitude
  - Observation field
  - Support of astronauts & robotic arm

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission lifetime</td>
<td>≥ 10 years</td>
</tr>
<tr>
<td>Outside environment</td>
<td>Vacuum, -100—+100 °C (TBD)</td>
</tr>
<tr>
<td>Orbit</td>
<td>Altitude 340<del>450 km, inclination 41</del>43 deg</td>
</tr>
<tr>
<td>Measurement accuracy</td>
<td>≤ 0.02° (3σ), ≤ 0.001°/s (3σ)</td>
</tr>
<tr>
<td>Control accuracy</td>
<td>≤ 0.1° (3σ), ≤ 0.005°/s (3σ)</td>
</tr>
<tr>
<td>Micro gravity</td>
<td>≤ 10⁻³g</td>
</tr>
<tr>
<td>Mounting point</td>
<td>Two Mounting points with a distance of 1750 mm</td>
</tr>
<tr>
<td></td>
<td>outside Experimental Module I</td>
</tr>
<tr>
<td>Load</td>
<td>≤ 2 tons per mounting point</td>
</tr>
<tr>
<td>Power supply</td>
<td>≤ 1,500 W per mounting point</td>
</tr>
<tr>
<td>Data transfer</td>
<td>≤ 4 Gbps per FC-AE-1553 fiber</td>
</tr>
<tr>
<td>TC/TM</td>
<td>500<del>1100 Mbps (download), 3</del>9 Mbps(upload)</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Supply by manned or cargo ship; necessary astronaut operation</td>
</tr>
<tr>
<td>Launching site</td>
<td>Wenchang Launching Site</td>
</tr>
</tbody>
</table>
Scientific requirements

- Large exposure (i.e. > m²sr & 10 yrs) -> 3-D CALO
- High particle discrimination power -> Tracker, PSD
- O(%) energy resolution for e/gamma -> Full absorbed CALO
- sub-degree angle resolution for e/gamma -> Tracker
- 20-30% energy resolution for CRs -> Large N.I.L CALO
- Real-time identification of GeV gamma-rays -> PSD
- In-orbit instrumental calibration -> TRD
## HERD specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Energy range (e/γ)</td>
<td>10 GeV-100 TeV(e); 0.5 GeV-100 TeV (γ)</td>
</tr>
<tr>
<td>Energy range (CR)</td>
<td>30 GeV−3 PeV</td>
</tr>
<tr>
<td>Angle resolution</td>
<td>0.1 deg.@10 GeV</td>
</tr>
<tr>
<td>Charge meas.</td>
<td>0.1-0.15 c.u</td>
</tr>
<tr>
<td>Energy resolution (e)</td>
<td>1%@200 GeV</td>
</tr>
<tr>
<td>Energy resolution (p)</td>
<td>20%@100 GeV - PeV</td>
</tr>
<tr>
<td>e/p separation</td>
<td>~10^{-6}</td>
</tr>
<tr>
<td>G.F. (e)</td>
<td>&gt;3 m²sr@200 GeV</td>
</tr>
<tr>
<td>G.F. (p)</td>
<td>&gt;2 m²sr@100 TeV</td>
</tr>
<tr>
<td>Pointing</td>
<td>Zenith</td>
</tr>
<tr>
<td>Field of View</td>
<td>+/-70 deg (targeting +/-90 deg)</td>
</tr>
<tr>
<td>Measure accuracy of attitude</td>
<td>&lt;0.1 deg</td>
</tr>
<tr>
<td>Measure accuracy of angular speed</td>
<td>&lt;0.005 deg/s</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt;10 years</td>
</tr>
</tbody>
</table>
HERD operational concept

- Launch, Transportation and Installation
- Operation
- In-orbit replacement
CALO - from bars to cubes

ATIC

FERMI

AMS-02

ATIC

HERD (and CALOCUBE)

CALET

DAMPE

3-d calorimeter significantly increases GF, improve particle discrimination & reduce systemic error (O. Adriani et al. 2017)
HERD payload baseline design

CALO + TRACKER

TIC

WLSF+IsCMOS

photo diode

Long bar

Square tile

Silicon

Fiber+SiPM

MWPC

TPC

Black: baseline design

Gray: alternative approach
Payload design - CALO

- **CALOrimeter (3 N.I.L. and 55 R.L.)**
  - A 3-d crystal array (~7500 LYSO)
  - IsCMOS camera
  - Trigger sub-system

- **Novel readout method**
  - WLSF + IsCMOS
  - Linearity of LYSO+WLSF is verified.
  - Energy measurement of WLSF + IsCMOS is verified.

Alternative/complementary approach: Photo diode readout
CALO – ISCMOS sub-system

- **IsCMOS** to collect WLSF photons
  - Faster: Global shutter; ROI readout
  - Lower noise
- **Accurate energy measurement**
  - 1 fiber ~ 20*20 pixels
  - Saturation effect to increase DR
CALO – trigger sub-system

- To provide common trigger signal
  - Core/shell regions + PMTs
- Coarse energy measurement

- HERD working mode
  - Normal mode (150cps)
    - HE trigger
    - LE photon
    - LE electron
    - Unbiased trigger
  - Calibration mode (350cps)
    - MIP trigger

Trigger logic
## STK

- Charge measurement
- CR/e trajectory
- Gamma ray conversion & tracking

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tbody>
<tr>
<td>Coverage ratio</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>Z measurement</td>
<td>(Z = 1 - 20) (26); 0.1-0.15 c.u</td>
</tr>
<tr>
<td>Angle resolution</td>
<td>0.1 deg.@10 GeV</td>
</tr>
<tr>
<td>Layers of SSD</td>
<td>6 X/Y (top); 3/6 X/Y (Lateral)</td>
</tr>
<tr>
<td>Active converter</td>
<td>1 R.L.</td>
</tr>
<tr>
<td>Dead time</td>
<td>&lt;2 ms</td>
</tr>
<tr>
<td>Working mode</td>
<td>External trigger</td>
</tr>
<tr>
<td>Eff. Area (top)</td>
<td>~133 cm*133 cm</td>
</tr>
<tr>
<td>Eff. Area (lateral)</td>
<td>~114 cm*66.5 cm</td>
</tr>
<tr>
<td>Channels</td>
<td>~240,000/368,000</td>
</tr>
</tbody>
</table>

Alternative/complementary: Fiber Tracker (FIT) using SiPMs
PSD

- Low energy gamma identification
- Charge measurement
- Design
  - 1 X/Y layer on top and 4 lateral sides
    - X layer for LE photon trigger
    - X & Y layers for Z measurement and e/gamma discrimination
  - 1 X layer on bottom side
  - SiPM + IDE3380 ASIC
    - Low & high range to cover Z=1-26
    - Redundancy SiPMs

PS bar readout by $2^*(3+1)$ SiPMs

Alternative approach: tile geometry
TRD

- Energy calibration of TeV protons and other nuclei
- A complete calibration in 2-3 months in-orbit operation

MWPC energy response to [2.25, 2.5] TeV protons

2 months simulated observation, ~6300cm² TRD.
Technical analysis – mechanical & thermal

• Structural design & analysis
  – Total weight ~ 4 tons
  – Main structure with inner frame, outer frame, main panel and device container
  – FEA results on main structure is reasonable and acceptable.

• Thermal design
  – Total power ~1200W
  – No fixed surface for radiator
  – **Liquid cooling system** by using the big coolant tank inside CSS cabin
The GPU of ISU will help processing the frame images and tracker data including event selection, shower discrimination, track identification, data suppression. The downloaded HERD data are then reduced to be within 100 Mbps.

Payload test and debugging software can be embedded inside the ISU to make real-time calculation of working parameters of instruments, e.g. pedestals and noise level.
System requirements – launch, transportation & installation

- To Launch HERD in a **full-open cargo ship** for a single launch opportunity by LM-7 rocket
- To Dock the cargo ship with HERD on the **windward end of the Core Module**
- To transport HERD using **enhanced robotic arm** to Experimental Module I
- To install HERD onto **two neighbor mounting points** outside Experimental Module I
- To install HERD as high as possible from Experimental Module I
System requirements – operation

• Orbit & attitude
  – CSS orbit and three-axis stabilization attitude system is suitable.
  – Two star trackers will be mounted on the main body of HERD, allowing to have data with high quality pointing information without strong requirements on CSS.

• Power
  – Continuous primary power of ~1200 W is required.
  – A coolant tank inside Experimental Module I is required to make thermal dissipation and temperature stabilization for HERD instruments.

• Telemetry
  – ISU is required to do event selection and data compression.
  – ISU is required to do real-time calculation of instrument parameters and refresh the parameters firmware automatically.
  – Relay satellites and enough ground stations are required to download data with an average data rate of 100 Mbps.
System requirements – in-orbit replacement

• The upgrade of IsCMOS camera will greatly improve capabilities of HERD instruments and bring to us more fruitful scientific outputs.
• Upgrade or replacement of onboard devices will rely on the joint operation of small robotic arm and astronauts.
• Similar replacement may also happen for the TRD detectors, because of gas leakage in the detectors.
HerD consortium

- The HerD consortium includes 120+ scientists from China and Europe.
- Most of the members have been collaborating on AMS-02 and DAMPE experiments in science and hardware development.
- Most of the team has space experience in astroparticle research.
- Since 2012, the HerD international consortium has organized six international workshops in China and Europe on the related scientific topics and technological developments of HerD.
- Together with European colleagues, two CERN beam tests on HerD have been successfully implemented for the verification of novel design and performances.
- Joint Working Group on space science and utilization between ASI and CSU in Feb. 2018, including HerD Joint Working Team.
- The HerD proposal was submitted to the Review Board in April, 2018, review meeting on May 11th 2018 at ASI.
International collaboration (120+ colleagues)

- **China**: CSU, IHEP, XIOPM, PMO, USTC, IGG, XAO, NAOC, TSU, GXU, PKU, NJU, YNU, NBU, SYSU, University of Hong Kong (HKU), National Central University (NCU)
- **Italy**: INFN Perugia, University & INFN Firenze, University & INFN Bari, University & INFN Pisa, University & INFN Trento, University of Salento and INFN Lecce, IAPS/INAF, University & INFN Catania, University & INFN Napoli, University & INFN Trieste, GSSI
- **Switzerland**: University of Geneva; **Sweden**: KTH; **Spain**: CIEMAT
- **Germany**: KIT; **Russia**: Lebedev Physical Institute
- **Japan**: University of Tokyo

4th HERD workshop
ASI HQs, Roma, Italy 2017.2.9
HERD product tree (current)

- HERD is jointly led by CSU and IHEP, who take respective responsibilities in the engineering and payload/science of the project.
- CMSA: launcher, cargo ship, launching, operation and service, data service
- CSU: general design of HERD and coordination with other systems.
- ASI/INFN: lead European participation with payload/science
HERD project schedule

- Phase A, 2018.09 - 2020.02 (18 months)
- Phase B, 2020.02 - 2021.06 (16 months)
- Phase C, 2021.06 - 2022.10 (16 months)
- Phase D, 2022.10 - 2024.10 (24 months)
- Expected launch: 2025.
Summary

• HERD: China-led mission with key European contribution led by Italy, & flagship and landmark scientific experiment, taking full advantages of China's Space Station

• Important and frontier scientific objectives in DM search, CR observation and gamma-ray astronomy
  – Distinguish between possible DM and astrophysical origins of positron/electron excess measured by AMS-02
  – Confirm & distinguish possible origins of the features in high-E electron spectrum found by DAMPE, and extend the energy range up to 100 TeV
  – Direct measurements of CR composition > PeV
  – Large acceptance & sensitive high-E γ-ray sky monitoring

• Novel 3-D calorimeter, verified at two CERN beam tests
• Expected launch time around 2025.