Energies and rates of the cosmic-ray particles

- Grigorov
- Akeno
- MSU
- KASCADE
- Tibet
- KASCADE-Grande
- IceTop73
- HiRes1&2
- TA2013
- Auger2013
- Model H4a
- CREAM all particle

- protons only
- all-particle
- electrons
- positrons
- antiprotons

$E_dN/dE$ (GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$)

- Fixed target
- HERA
- RHIC
- TEVATRON
- LHC
All-particle spectrum & simplified description
or in some more detail:
Measuring CR primaries

- Differential fluxes are low, and decrease with energy as $dN/dE \sim E^{-2.7}$
- At $E \lesssim 10^{12}$ eV, balloon experiments can measure primary CRs
- Up to $\sim 10^{14}$ eV, space experiments can measure primary CRs
- For $E \gtrsim 10^{14}$ eV, need to measure from ground
**Direct:** measure primary CRs ($\approx 10^{14}$ eV)

- Spectral index $\alpha = 2.7 \rightarrow$ even at $10^{12}$ eV = TeV, the flux is $\Phi(\text{TeV}) \sim 1 \text{ m}^{-2}\text{day}^{-1}$

- At primary energies $\epsilon \gtrsim 10^{15}$ eV, fluxes are $\Phi(\epsilon) \approx \text{m}^{-2}\text{yr}^{-1}$

- Space experiments: **weight, size & power** limited - although the Space Station (ISS) is somewhat better off than satellites

**Indirect:** measure CR secondaries ($\approx 10^{14}$ eV)

- **Good news:** secondary cascades can be measured from the ground $\rightarrow$ can build **very large** detector arrays, e.g.
  - KASCADE-Grande: 0.5 km$^2$ at $\sim$ PeV energies (knee);
  - Pierre Auger Observatory: 3,000 km$^2$ at EeV-ZeV ($10^{18} - 10^{21}$ eV).

- **Bad news:** inferring the primary CR energy and composition requires **complicated numerical modeling** of the cascade.
\[ E_{\text{primary}} \approx 10^{14} \text{ eV} \]
e.g.

"Cosmic Ray Observatory on the ISS"

AMS Launch
May 16, 2011

ISS-CREAM 2017

CALET Launch
August 19, 2015
- Principle of **PRIMARY** measurement technique

- magnet
- tracker
- time of flight

```
p = γmv from curvature
v from time of flight
q magnitude from energy loss
q sign from direction of curvature
```

$m,q$ identifies particle

Figure 1.19: Schematic of a generic primary CR time-of-flight magnetic tracker detector. Magnetic field points into the picture.
on ISS:

**ISS-CREAM Instrument**

- **4 layer Silicon Charge Detector**
  - Precise charge measurements
  - 380-μm thick 2.12 cm² pixels
  - 79 cm x 79 cm active detector area

- **Carbon Targets (0.5 λ_{int})**
  - Induces hadronic interactions

- **Top & Bottom Counting Detectors**
  - Each with 20 x 20 photodiodes and a plastic scintillator for e/p separation
  - Independent Trigger

- **Calorimeter (20 layers W + Scn Fibers)**
  - Determine Energy
  - Provide tracking
  - Provide Trigger

- **Boronated Scintillator Detector**
  - Additional e/p separation
  - Neutron signals
Below the knee results:

- The spectrum is roughly $\sim E^{-2.7}$
- Composition is mainly protons, heavy elements less abundant
But, above $\sim 10^{14}$ eV:

- Size/Cost forces detectors to the **ground**
- This is, under 10 Km of Earth **atmosphere** (until we can put detectors on the Moon)
- But relativistic CR **collides** with nuclei of atmospheric N, O $\rightarrow$ makes **secondary** particles, to whom it loses its energy
Cosmic ray air shower

- Two components:
  - \(EM\) (\(e^{\pm}, \gamma\)), and - hadronic (\(\pi^{\pm} \rightarrow \mu^{\pm}\))
  - \(EM\): exhausted in upper atmosphere → fluoresc. light
  - Hadronic: muons are harder, they can reach the ground (and the \(\nu_\mu\) reach ground)
• Primary CR (p, He,...heavies) interact at top of atmosphere
• Produce cascade of secondary, lighter particles
• Both EM (e\(^\pm\),\(\gamma\)) and hadronic (N, K, \(\pi\), \(\mu\), \(\nu\)...) cascades
• Secondaries are detected in air or at ground level
Extensive air showers
e.g. at \( \approx \) the knee energies,

**KASCADE-Grande**

KArlsruhe Shower Core Array DETector - Grande

- *Indirect* detection of the primary CRs (\(10^{16}-10^{18}\) eV) via their *secondaries*
- Monte Carlo simulations allow determination of *chemical composition* of primary CRs
- Beyond \(10^{15}\) eV, composition increasingly weighted towards *heavy elements*, He, .., C, O, ..Fe

Located in Karlsruhe, Germany: (Charlemagne’s burial place)
CR spectrum @ $E < 10^{17}$ eV

- Spectrum steepens in a “knee”
- Knee energy depends on charge $Z$
  - For $p$, knee @ $10^{15}$ eV
  - For $Fe$, knee @ $10^{17}$ eV

$$E_{\text{max}} \sim \beta c Z e \text{BL}$$
Newest major project 2018, Dao Cheng plateau, Sichuan:

**LHAASO at Mt. Haizi, Sichuan, China**

N29°21’27.6”, E100°08’19.6”, 4400 m a.s.l.
LHAASO Layout

Main Array:
5242 scintillator detectors every 15 m

&
1146 μ-detectors every 30 m

Water Cherenkov Detector
80,000 m²

CR Detectors:
18 Wide field View Cherenkov telescopes & Large Dynamic WCDA++.
Next energy range:

Ultra-High Energy CRs: (UHECRs)

- UHECRs defined roughly as $E > 10^{18}$ eV (EeV)
- Measurement technique: only indirectly, via their EM and hadronic cascades
- (1) Can image the effects of EM cascade in the upper atmosphere
- (2) Can measure hadronic cascade as it reaches ground
Pierre Auger Observatory

Uses two techniques for detecting CR shower:

- detect air fluorescence photons (light) produced by shower particles with telescopes (FD)
- detect shower particles (muons) on the surface detectors via Cherenkov radiation (SD)
Hybrid FD and SD technique
$FD \rightarrow$
schematic

$\leftarrow FD$
mirrors & prime focus
Fluorescence detector (FD)

Fluorescence detector (FD)

3.4 meter diameter segmented mirror

440 pixel camera

Aperture and optical filter

e± impact on N₂ molecules \rightarrow fluorescence light observed by FD
surface detector

Measure Cherenkov light from charged particles (muons) entering water tanks
Left: SD collecting in its PMTs the Cherenkov light emitted by muon

Right: Geometry of Cherenkov light cone emission by relativistic particle in a medium

FIG. 2: A schematic view of the Cherenkov water tanks, with the components indicated in the figure.
Pierre Auger Observatory: Malargue, Mendoza, Argentina: $E \sim 10^{17} - 10^{21} \text{ eV}$
- 1600 surface detectors: water Cherenkov tanks, 11 kliters ea., 1.5 km apart
- 32 air fluorescence telescopes, 4x8 arrays of 30x30 deg. sky coverage
- Also: tau-nu (horiz.l shower capability: Earth-skimming & through Andes)

Surface detector (SD)
Muons from shower $\rightarrow$ Cherenkov light in water tank, detected by phototubes

Surface detector (SD)
Muons from shower $\rightarrow$ Cherenkov light in water tank, detected by phototubes
Auger: a very large area
Auger Obs. - 3000 km² UHECR detector
Mendoza, Argentina
Auger ≈ inner Beijing
The Pierre Auger Observatory
(in Argentina, Malargue, Prov. Mendoza)

Surface Array
1663 detector stations
1.5 km spacing
3000 km²

Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 (+3) Telescopes total

Jim Cronin
Alan Watson
GZK spectral cut-off

• “GZK” = Greisen-Zatsepin-Kuz’min (1967)
• “UHECR” = ultra-high energy cosmic ray, roughly $10^{18}-10^{21}$ eV = $10^{-2} - 10$ $E_{GZK}$
• $E_{GZK} \sim 10^{20}$ eV $\equiv$ 100 EeV (Exa-electron-Volt) $\approx 1.6 \times 10^8$ erg $\approx 16$ Joule $\approx 4$ calories
• $E_{GZK} \approx$ fast-serve *tennis ball* ($\sim 130$ km/h), or $\sim 1/10$ the energy of a *bullet* (7.65 mm, .32 cal)
• Significance: $E \gtrsim E_{GZK}$ protons encountering a $\sim 10^{-3}$ eV cosmic microwave background photon undergoes *photo-hadronic* losses, $p + \gamma \rightarrow \pi + n$
Major UHECR features expected

- **GZK cut-off** expected @ $10^{19.5}$ eV (CMB)
- Below $\sim 10^{18.5}$ eV CRs may be *galactic* origin (Larmor radius $r_L$ in $B \sim \mu G \ll$ size of galaxy)
- At $\geq 10^{18.5}$ eV CRs must be *extragalactic* origin ($r_L > R_{gal}$), could have $\neq$ *spectrum*
- Depth of maximum atmospheric penetration $X_{max}$ is expected to be *shallower for heavy* nuclei (and with less variance) than for protons
Figure 2: The unfolded spectrum for the SD 1500 vertical sample. The number of events is shown for each bin. The error bars represent statistical uncertainties. The upper limits correspond to the 84% C.L.
Depth of maximum penetration for light & heavy CRs (Monte Carlo)

Photon, Proton and Iron Induced Air Showers

Vertical (z-) axis range is 30 km. First interaction at a height of 30 km. The shower is projected onto the x-z plane. Horizontal (x-) axis range is +/- 5 km around the shower core. Energy: 100 TeV. Vertical injection of the cosmic ray particle. Colors: e+, e-, photons (red) / muons (green) / hadrons (blue) (red+green -> yellow) (www.ast.leeds.ac.uk/~fs/showerimages.html)
Shower development

- Vertical depth \( X_v \) slant depth \( X \)
- Fe and p shower maximum vs. \( X \)
- \( X_{\text{max}} \) vs. energy for \( \gamma \), p and Fe

\begin{align*}
\text{Number of particles} & \quad 6 \\
\text{Fe} & \quad \text{proton}
\end{align*}

\( X \) Slant depth (g/cm\(^2\)) \( (E_0=10^7 \text{ GeV}) \)

\begin{align*}
\langle X_{\text{max}} \rangle & \quad [\text{g/cm}^2] \\
\gamma & \quad \text{p} & \quad \text{Fe}
\end{align*}

\( E \) [eV]

\( 10^{15} \quad 10^{16} \quad 10^{17} \quad 10^{18} \)
Auger ICRC 17

Spectrum & composition, $[X_{\text{max}}, \text{Var}(X_{\text{max}})]$
Phenomenological fit to Auger data

An *ad-hoc spectral and composition* best-fit using EPOS-LHC hadronic model (Mollerach & Roulet 2017) where atomic numbers $A$:

- $A=1$: red
- $A=2-4$: grey
- $A=5-22$: green
- $A=23-38$: cyan
Raw interpretation of Auger data phenom. fit:

- Transition gal-extragal @ $10^{18.7}$ eV favored
- Injection spectral slope $s \sim 1$ favored above ankle (hard slope!)
- $s \sim 2$ strongly disfavored by $X_{\text{max}}$ distribution
- $X_{\text{max}}$ and $\sigma(X_{\text{max}})$ favor significant fractions of medium-high $A$ (heavy) elements
- EPOS-LHC favored over Sybill2.1, QGSJet04
Can interpret a spectrum+composition fit with physically motivated sources?

- Most previous arguments considered **HL GRBs**, the “classical”, high-luminosity GRBs
  
  • **In favor** of this: HL GRBS have shock accelerators, right energies, source numbers (Waxman’95, …)

  • **Against**: for HL GRBs one expects a HENU-UHECR connection: **IceCube** say that HLGRB/HENU are **not** correlated, providing limits on UHECR contribution

  • **However**: this is GRB model-dependent, to resolve issue need more data (Waxman, He+, Hummer+)
Other variations on the **HL** GRB theme:

- HL GRBS: high $\tau_{p\gamma}$ makes HENU but kills CRs, while low $\tau_{p\gamma}$ allows CR escape without HENU (Rachen+, Bustamante+, etc)

- HL GRBs: high photon (high $\tau_{p\gamma}$) regions making photons could be $\neq$ from shocks where CR are accelerated (Asano+PM)
Or, a different alternative?

- **LL GRBs** (instead of HL GRBs) can also produce UHECR and $\nu$s
- Source rate much higher than for HLGRBs
- Energetics, $T_{\gamma \gamma}$ appear to be adequate ✔
- They are $\gamma$-faint, i.e. EM detection difficult ✔
consider then more seriously

*Low-luminosity GRBs as the sources of UHECR nuclei (heavies too)*

GRB progenitor stellar models

(Woosley & Heger’06)

Several fast-rotating pre-supernova WR *, ≠ initial chem. comp.
← e.g. a Si-poor one

Top: chemical comp. vs. radius
Bot: specific ang. momentum
\( J_{\text{ISCO}} \) at ISCO vs. radius

\[
J_{\text{ISCO}} = \frac{2GM_{BH}}{3^{3/2}c} \left[ 1 + 2 \left( \frac{r_{\text{ISCO}}}{r_g} - 2 \right)^{1/2} \right]
\]
But:

- ≠ progenitor models lead to ≠ chemical (A) distribution vs. radius, and
- also ≠ $J_{\text{ISCO}}$ vs. radius distrib.
- ← e.g., Si-rich model Si-R-1
Thus,

Jet chemical composition is characterized by that of the progenitor star at $\sim r_{\text{ISCO}}$

$$J_{\text{ISCO}} = \frac{2GM_{\text{BH}}}{3^{3/2}c} \left[ 1 + 2 \left( \frac{r_{\text{ISCO}}}{r_g} - 2 \right)^{1/2} \right]$$

where $r_g = GM_{\text{BH}}/c^2$ and

$$r_{\text{ISCO}} = \frac{GM_{\text{BH}}}{c^2} \{ 3 + z_2 - [(3 - z_1)(3 + z_1 + 2z_2)^{1/2}] \},$$

with

$$z_1 = 1 + (1 - a_{\text{BH}}^2)^{1/3}[(1 + a_{\text{BH}})^{1/3} + (1 - a_{\text{BH}})^{1/3}],$$

and

$$z_2 = (3a_{\text{BH}}^2 + z_1^2)^{1/2}.$$

- $J_{\text{ISCO}} = \text{spec. mom. of last inner stable circular orbit, occurs at } r_{\text{ISCO}}$
- Inside $r_{\text{ISCO}}$ matter falls in
- Jet launched from $r > r_{\text{ISCO}}$
- Chemical comp. of jet is that of star at $r > r_{\text{ISCO}}$
GRB Pre-SN models used

(from Woosley & Heger)

<table>
<thead>
<tr>
<th>MODELS</th>
<th>$M_{\text{init}}$</th>
<th>$M_{\text{final}}$</th>
<th>$J_{\text{core}}$</th>
<th>$r_{\text{e}}$</th>
<th>$M_{\text{e}}$</th>
<th>C</th>
<th>O</th>
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<th>Mg</th>
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<td>14.80</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.006</td>
<td>0.710</td>
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</table>

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Si-F indicate Si-free (Si-poor) init. stellar models
Si-R indicate Si-rich (by comparison to the Si-F)

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*a* Presupernova models calculated in Ref. [67].

*b* The initial mass of GRBs progenitors.

*c* The final mass of GRBs progenitors at the onset of core collapse.

*d* The angular momentum of the iron core at core collapse.

*e* Critical radius in the progenitors where accreting material starts to form the accretion disk.

*f* Enclosed mass within the critical radius $r_c$.

*g* Jet nuclear composition. The blank space means that nuclei have mass fraction less than 0.01. The last row represents the hypernova ejecta composition.
Another possible model for jet composition:

Jet through Hypernova

- In hypernovae heavy nuclei may be synthesized in the semi-relativistic shocked ejecta.
- If semi-relativistic ejecta is launched before the jet goes through it, jet will entrain a nuclear mass fraction similar to that of the ejecta.
- Used ejecta model CO138E50 (Nakamura+ '01) which reproduces light curve of SN1998bw.
Heavy nuclei acceleration & survival in jet

- Assume usual internal shock Fermi acceleration of protons and nuclei of atomic weight $A$

- Jet photon luminosity $L_{\gamma,\text{iso}}$ determines survival of nuclei $A$ against photodesintegration and photomeson

- Broken power law (Band) photon spectrum

$$\frac{dn}{d\varepsilon} = \frac{(L_{\gamma\text{iso}}/5)e^{-\varepsilon/\varepsilon_{\text{max}}}}{4\pi r^2 \Gamma^2 c\varepsilon_b^2} \left\{ \begin{array}{ll} (\varepsilon/\varepsilon_b)^{-1} & (\varepsilon_{\text{min}} \leq \varepsilon < \varepsilon_b) \\ (\varepsilon/\varepsilon_b)^{-2.2} & (\varepsilon_b \leq \varepsilon \leq \varepsilon_{\text{max}}) \end{array} \right.$$
Constraint on initial $L_{\gamma,\text{iso}}$

$f_{A\gamma} = \text{energy loss efficiency}; \quad \tau_{A\gamma} = \text{opt. depth (interaction efficiency)}; \quad r_0 = \text{base of jet}$
Thus, for survival of heavies, want:

- Low luminosities $L_\gamma$ (relatively)
- Low bulk Lorentz factors $\Gamma$ (relatively)
- Moderately large initial radii $r_0$

First two requirements: Low-luminosity GRBs ✔

(Alternatively: if destroy heavies, ⇒ make neutrinos! )
Luminosity function: LL and HL

- LL GRB: $L_{\gamma,iso} \leq 10^{49}$ erg/s
- LF for LLGRB + HLGRB $\leftarrow$ (Liang, Zhang, Dai ’07)
- Contribution is dominated by LL GRB, but HL GRB can also contribute
- Nuclei destruction dep. on $L_{\gamma,iso}$, $\Gamma$ and $r_0$ ($r_{ISCO}$)

$$\frac{d\rho_0}{dL} = A_0 \left[ \left( \frac{L}{L_b} \right)^{\alpha_1} + \left( \frac{L}{L_b} \right)^{\alpha_2} \right]^{-1}$$
CR injection & escape spectrum

• Max. energy $Z E'_{p,max} \sim 10^{18.2} Z L_{\gamma,iso}^{1/2}$ eV

• Fermi I: injection spectrum is typically power law $dN'_A/dE' \sim E'^{-s}$ with $s \sim 2$
  (but for large angle scatt. or magnetic reconnection; may have $s \sim 1.5$)

• Escape spectrum may be $\neq$ than injection

• I) assume only CRs of max. energy escape

• II) or, assume escape spectrum $\sim$ injected
CR Propagation & flux at Earth

- **CRPropa-3** Monte Carlo propagation of nuclei A
- The CMB and EBL fields as function of z lead to photodesintegration, Bethe-Heitler, photomeson
- Flux of nuclei A at Earth given by

\[
\Phi_A(E) = \sum_{A'} \frac{c}{4\pi} \int_{z_{\text{min}}}^{z_{\text{max}}} dz \left| \frac{dt}{dz} \right| F_{\text{GRB}}(z) \\
\times \int_{L_{\text{min}}}^{L_{\text{max}}} \frac{d\rho_0}{dL} \int_{E'_{\text{min}}}^{E'_{\text{max}}} dE' \frac{dN_{A'}}{dE'} d\eta_{AA'}(E, E', z)
\]

where \( F_{\text{GRB}}(z) \) is the redshift distribution parameter of long GRBs which trace the star formation history (SFH) [37], \( \rho_0 \) is the local event rate of GRBs, \( d\rho_0/dL \) is the GRB luminosity function in the local universe [35], and \( \eta_{AA'}(E, E', z) \) is the fraction of generated cosmic rays of mass \( A' \) and energy \( E' \) from parent particles of mass \( A \) and energy \( E \) [28]. The redshift range is from \( z_{\text{min}} = 0.0005 \) to \( z_{\text{max}} = 2 \). We use the same method as in Ref. [28] to calculate the final spectrum and the distribution of \( \langle X_{\text{max}} \rangle \) and \( \sigma(X_{\text{max}}) \) [7]. In this work,
Results:

PRD’18, in press, 1712.09984
Spectrum, \( X_{\text{max}}, \sigma(X_{\text{max}}) \)

*from Silicon-poor \( E_{\text{max}} \) escape models*

- Si-F-1 Si-poor model
- Blue data points: Auger, magenta data points: TA
- \( ZE'_{p,\text{max}} \approx 10^{18.2} ZL_{\gamma,\text{iso}}^{1/2} \text{ eV} \)
- Fit \( \chi^2 \) not good (same for other for Si-poor models)
Spectrum, $X_{\text{max}}$, $\sigma(X_{\text{max}})$

from Silicon rich $E_{\text{max}}$ escape models

- Si-R-1 Si-rich model
- Blue data points: Auger, magenta data pts: TA
- Fit $\chi^2$ is now better
- Also better for Si-R2, 3
Spectrum, $X_{\text{max}}, \sigma(X_{\text{max}})$

**Hypernova $E_{\text{max}}$ escape model**

- Blue data points: Auger, magenta data pts: TA
- Fit $\chi^2$ is also OK
Spectrum, \( X_{\text{max}}, \sigma(X_{\text{max}}) \)

**Si-rich PL spectrum escape model:**

- Si-R-2 Si-rich model but with escape power law spectrum index \( s_{\text{esc}} = 0.5 \) (injection \( s_{\text{inj}} = 1/5 \))

- Blue data points: Auger, magenta data pts : TA

- Fit \( \chi^2 \) is also OK
summary of RESULTS for UHECR

- LL GRBs from *Si-R* progenitors, or from *hypernova* models can explain the Auger spectrum and composition: $X_{\text{max}}$, $\sigma(X_{\text{max}})$,

- Either in $E_{\text{max}}$ escape model, or hard PL model, favor having a hard $s_{\text{inj}} < 1.5$.

Thanks!
What about neutrinos?

- Intra-source $p\gamma$ neutrinos can be estimated from

$$E^2 \Phi_\nu \approx \frac{c}{4\pi H_0} \frac{3}{8} \xi_z f_{\text{sup}} \min[1, f_{p\gamma}(E_A/A)f_{A\gamma}(E_A)]$$

$$+ f_{\text{mes}}(E_A)(1 - f_{A\gamma}(E_A)) E_A^2 \frac{dN_A}{dE_A} \rho_{0\text{LL}}$$

$$\sim 2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \min[1, f_{p\gamma}] f_{\text{sup}}$$

$$\times \left( \frac{\xi_{\text{CR}}/R}{1} \right) \left( \frac{\xi_z}{3} \right) \left( \frac{\xi_{\text{iso}}}{10^{50} \text{ erg}} \right) \left( \frac{\rho_{0\text{LL}}}{200 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right)$$

- If $f_{\text{mes}} \sim f_{p\gamma}$, this **could** give the IceCube observed flux **if** have $f_{p\gamma} \sim 1$, i.e., if all nuclei are destroyed (no CRs)

- But two-zone model where $\nu$s come from inner radii and UHECR from outer radii **might** explain both
LHAASO:
Zhen Cao summary slide from 2016 (Vulcano)

- Absolute Energy Scale at 10TeV could be established by using moon shadow technique
- Great opportunity for cross-calibration with space-borne Measurements
- Separation between species can be done at energy of 0.1-10 PeV
- The Knees at 0.7, 1.4, ~3 PeV ... and 18 PeV are expected to be fixed on the individual spectra
- The schedule is fixed:
  - Civil construction is finished by April, 2017
  - Construction of No.1 pool & tanks: start around April, 2017
  - Detector installation starts by the end of 2017
  - Physics data taking in 2018 with ¼ LHAASO array