

# Technicalities about the LHAASO experiment

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# Abstract

The LHAASO experiment is aimed at detecting highly-energetic particles of cosmological origin within a large range of energies.

The sensitivity of the experimental apparatus can within the frameworks of statistical fluctuations of the background.

Acceleration and lower-energy particles can be analyzed.

The anisotropy mass composition of cosmic rays can analytically described.

The LHAASO Experiment is also suited for detecting particles of cosmological origin originated from the breach (and/or other kinds of modifications) of particle theories paradigms comprehending other symmetry groups.

Some physical implications of anisotropies can be looked for.

The study of anisotropy distribution for particles of cosmological origin as well as the anisotropies of their velocities both in the case of a flat Minkowskian background as well as in the case of curved space-time can be investigated, as far as the theoretical description of the cross-section is concerned, as well as for the theoretical expressions of such quantities to be analyzed.

The case of a geometrical phase of particles can be schematized by means of a geometrical factor.

Particular solutions are found under suitable approximations.

A comparison with the study of ellipsoidal galaxies is achieved.

The case of particles with anisotropies in velocities falling off faster than dark matter (DM) is compared.

The study of possible anisotropies in the spatial distribution of cosmological particles can therefore be described also deriving from the interaction of cosmic particles with the gravitational field, arising at quantum distances, at the semiclassical level and at the classical scales, within the framework of the proper description of particles anisotropies properties.

# Summary

- Some technical properties of the LHAASO Experiment.
- Galactic centers.
- Galactic halos.
- $\gamma$ -ray signal from decaying DM.
- Extensive air showers.
- Background radiation.
- Galaxies scenarios.
- Comparison with anisotropies:
  - position anisotropies;
  - velocity anisotropies;
  - mass anisotropies.
- Comparison with ellipsoidal galaxies:
  - **examples of integration for the detector target recoil momentum.**
- Application of other methods in nuclear recoil for the comparison for **modified Poisson equations**:
  - particle-fields factorization(s);
  - decay rates;
  - form-factors.

## Galactic center

The maximum energy that protons can achieve by diffusive shock acceleration is

$$E_{max} \sim eBR \simeq 10^{14} \left( \frac{B}{G} \right) \left( \frac{M}{4 \cdot 10^4 M_{\odot}} \right) \left( \frac{R}{10R_g} \right) ev \quad (1)$$

- $B$  magnetic field,
- $R$  size of the acceleration region,  
within 10 Schwarzschild radii ( $R_g \sim 10^{12} cm$ ) of the black hole.

# Galactic halos

- Cosmic rays transport and interactions in magnetic halo(s) (in all directions);
- $TeV$  halo surrounding young SNRs;
- High-energy CR's will move earlier and faster than lower-energy CR's: the halo may also have a  $GeV/TeV$  ratio change with distance away from the SNR.

- spatial distribution: - spectral energy distribution
  - diffuse emission from radio to  $\gamma$ -ray bands  $\Rightarrow$  two-dimensional information;
  - emissivity of electron from radio observations:  $\Rightarrow$  three dimensional electron distributions.
- X. Bai *et al.*, arXiv:1905.02773 [astro-ph.HE].

# Gamma-ray signals from decaying DM

- large angular scale diffuse  $\gamma$ -ray flux in multi- $TeV$  – multi- $PeV$  energy range;
- detect the  $\gamma$ -ray signal from DM particles of  $PeV$ - $EeV$  mass decaying on the time scale up to  $3 \cdot 10^{29} s$ .

Signal from Galactic DM halo

$$\frac{dF_{DM}}{d\Omega} = \frac{\Gamma_{DM}}{4\pi} \int_{los} \rho_{DM}(r) dl \quad (2)$$

$\rho_{DM}$  DM density as a function of the radius from the Galactic Center,

$\kappa$  fraction of the rest energy of the DM particles transferred to  $\gamma$ -rays

$\Gamma_{DM} \equiv 1/\tau_{DM}$  the decay width (i.e. the inverse of the DM decay time  $\tau_{DM}$ ).

A. Neronov and D. Semikoz, [arXiv:2001.11881 [astro-ph.HE]].

## Extensive air showers

- Delayed thermal neutrons and by the soft ( $30\text{--}50\text{keV}$   $\gamma$  rays):
- tens of milliseconds in the case of neutron component, and up to a few whole seconds for gamma rays
  - delayed accompaniment of low-energy radiation particles with mean level of background counting rate to study the interaction of the hadronic component

$$\Delta R(t) = R(t) - R_{bckgr}. \quad (3)$$

with  $R(t)$  the amplitude of the average intensity functions of the time distributions of soft  $\gamma$  radiation detected with the lowest energy threshold ( $E_\gamma > 30\text{keV}$ ) around the core ( $r \leq 10\text{m}$ ) and at periphery ( $r \geq 20\text{m}$ ) of the extensive air showers with different sizes with respect to the background radiation intensity, with  $R_{bckgr}$  due to the background.

A. Shepetov *et al.*, Eur. Phys. J. Plus **135**, no. 1, 96 (2020), [arXiv:1912.13173 [astro-ph.HE]].

## More about background radiation

Compare the results with the analysis of slow thermal neutrons. Slow thermal neutrons have been demonstrated not to have much influence on the temporal behaviour of the neutrons diffusing inside the monitor (of the particular experimental device) or on the distribution of  $\gamma$ -radiation taking place during the absorption of the latter, but can from the outer environment can only have a secondary role in the origin of (any) prolonged distributions.

A. P. Chubenko, A. L. Shepetov, V. P. Antonova, P. A. Chubenko and S. V. Kryukov,

J. Phys. G **35** (2008) 085202, arXiv:1912.13356v1 [astro-ph.HE] .

## Particular galaxy scenarios

- jetted active galaxies whose jets are directed towards Earth (blazars):

- radiation peak at TeV energies;
- hard intrinsic spectrum of the component radiated at sub-TeV energies;
- leptonic interactions

to be compared with CMB photons interactions

-  $\gamma$  rays at  $\sim 10\text{TeV}$

- to be detected by Cherenkov detectors arrays

J. Biteau *et al.*, *Nat. Astron.* **4**, no. 2, 124 (2020) [arXiv:2001.09222 [astro-ph.HE]].

## Anisotropies in cosmic rays masses

Cosmic ray nuclei above  $200\text{GeV}$  followed by softenings around  $10\text{TeV}$

- complexities of the origin and transportation of Galactic cosmic rays;

- anisotropy features of different mass composition (or mass groups) of cosmic rays;

spatially-dependent distribution

spherical geometry with infinite boundary conditions

$$\phi(r, \hat{R}, t) = \frac{q_{inj}(\hat{R})}{(\sqrt{2\pi}\sigma^3)} e\left(-\frac{r^2}{2\sigma^2}\right) \quad (4)$$

$q_{inj}\delta(t)\delta(R)$  instantaneous injection spectrum with cut-off law, originating from a point source,

$D(\hat{R})$  diffusion coefficient nearby the Solar System

$\sigma(\hat{R}, t) \equiv \sqrt{2D(\hat{R})t}$  effective diffusion length within time  $t$ .

B. Q. Qiao, W. Liu, Y. Q. Guo and Q. Yuan, JCAP **1912**, no. 12, 007 (2019),

[arXiv:1905.12505 [astro-ph.HE]].

# Particle-fields factorization

For a broken  $O(3)$  space symmetry, the geometrical phase  $\varphi(x)$  for a particle field  $\phi(x)$  can be factorized as  $\Phi(x)$ , i.e.

$$\Phi(x) \equiv e^{-i\varphi(x)}\phi(x) \quad (5)$$

M.V. Berry, Proceedings of the Royal Society A. 392, 1802: 45–57 (1984).

# Velocity anisotropy

The velocity anisotropy is defined as

$$\beta(\vec{r}) = 1 - \frac{\zeta_y^2 + \zeta_z^2}{2\zeta_x^2}; \quad (6)$$

for  $\beta = 0$ , isotropy is restored.

It can be detected by a ionization chamber able to recover the track parameters  $(X, Y, Z, \theta, \phi, S)$ .

The velocity dispersion tensor  $\zeta(\vec{v})$  is diagonal, i.e.

$$\zeta(\vec{v}) \equiv \text{diag}[\zeta_x, \zeta_y, \zeta_z] \quad (7)$$

where  $\vec{v}_{\odot}$  the Earth orbital velocity around the Sun.

The velocity anisotropy therefore encodes the solution to the EFE's.

J. Billard, F. Mayet, J. F. Macias-Perez, D. Santos, Phys.Lett.B691:156-162,2010, arXiv:0911.4086 [astro-ph.CO];

J. Billard, F. Mayet and D. Santos, Phys. Rev. D **83** (2011) 075002, [arXiv:1012.3960 [astro-ph.CO]].

## Anisotropic velocity distribution

The velocity-distribution function  $f_v$  for the velocities  $v$  characterizing the wavepackets is given by

$$f_v = \frac{1}{8\pi^3 \det[(\zeta_v)^2]} \exp \left[ -\frac{1}{2} (\vec{v} - \vec{v}_\odot)^T \zeta_v^{-2} (\vec{v} - \vec{v}_\odot) \right] \quad (8)$$

# Ellipsoidal Galaxies

For logarithmic ellipsoidal models, the potential  $\widehat{\Phi}$  can be parameterized as

$$\widehat{\Phi}(x, y, z) = \frac{1}{2}v_C^2 \ln (x^2 + y^2p + z^2q). \quad (9)$$

The geometrical phase  $\varphi(x)$  for a particle field  $\Phi(x)$

$$\widetilde{\Phi}(x)(r; \mu, \nu) \equiv e^{-i\widetilde{\varphi}(g(x; \mu, \nu))} \phi(x) \quad (10)$$

The directional recoil is evaluated as

$$\frac{d^2 R}{dE_R d\Omega_R} = \frac{\rho_0 \sigma_0}{4\pi m_\chi m_r^2} F^2(E_R) f(v_{min}, \hat{q}) \quad (11)$$

with  $\hat{q}$  the recoil (versor) direction solid angle,  $d\Omega_R$  the differential solid angle  $d\Omega_R = 2\pi d \cos \theta$ ;

$F(E_R)$  the form factor and  $v_{min}$  the minimal WIMP velocity required to produce a nuclear recoil of energy  $E_R$ .

$$\frac{d\sigma}{d^2 s d\Omega_q} = \frac{d\sigma}{dq^2} \frac{1}{2} \delta(\cos \theta - \frac{q}{2\mu v}) = \frac{\sigma_0 S(q)}{8\pi \mu^2 v} \delta(v \cos \theta - \frac{q}{2\mu}) \quad (12)$$

$$v_q = \frac{q}{\mu} = \sqrt{\frac{ME}{2\mu^2}} \quad (13)$$

P. Gondolo, Phys. Rev. D **66** (2002) 103513, [hep-ph/0209110];

N. W. Evans, C. M. Carollo and P. T. de Zeeuw, Mon. Not. Roy. Astron. Soc. **318** (2000) 1131, [astro-ph/0008156].

For a given  $\rho$  self-consistent density, the differential rate for a WIMP distribution is expressed as

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{2m_x m_r} F^2(Q) \int_{v_{min}}^{\infty} \frac{f_s(v)}{v} \quad (14)$$

with

$$F(Q) = e\left[-\frac{Q}{2Q_0}\right] \quad (15)$$

nuclear form factor, with  $Q_0$  the nuclear coherence energy and

$$N_{min} \equiv \left[ \frac{Q m_N}{2m_r^2} \right]. \quad (16)$$

associated with  $v_{min}$ .

The total event rate is integrated as

$$R = \int_{E_T}^{\infty} \frac{dR}{dQ} dQ \quad (17)$$

with  $E_T$  the threshold energy.

The velocity distribution calculated in the Earth rest reference frame admits the approximation as a triaxial Gaussian

$$f = \frac{1}{(2\pi)^{3/2} \sigma_R \sigma_\phi \sigma_z} e^{-\frac{v_R^2}{2\sigma_R^2} - \frac{(v_\phi + v_\oplus)^2}{2\sigma_\phi^2} - \frac{v_z^2}{2\sigma_z^2}} \quad (18)$$

which is integrated as

$$f_s(v) = \frac{v^2}{(2\pi)^3} \int_0^{2\pi} d\hat{\alpha} \int_0^\pi d\hat{\beta} \left[ -\frac{v^2 \sin^2 \alpha \sin^2 \beta}{2\sigma_R^2} - \frac{(v_\alpha + v_\oplus)^2}{2\sigma_\phi^2} - \frac{v_z \sin^2 \alpha \cos^2 \beta}{2\sigma_z^2} \right], \quad (19)$$

with  $\hat{\alpha}$  and  $\hat{\beta}$  the proper (to be specified) integration angles, and  $v_\oplus$  the velocity of the Earth with respect to the Galaxy rest frame.

With  $\rho$  obeying the potential equation  $4\pi G\rho = \nabla^2\phi$ ,

$$\rho(r; \mu, \nu) = \frac{h(\mu, \nu)}{r^\alpha} \quad (20)$$

where  $h(\mu, \nu)$  is an arbitrary function:

- for  $\alpha = 2$ ,  $\rho$  is therefore a self-consistent density for the corresponding Poisson equation,

and  $g_{\mu\nu}$  is the solution for the proper Einsteinian-gravity field equations,

i.e. also for the (possible) geometrical phase(s) in Eq.'s (5) and (10);

- differently, other possibilities can be examined.

The techniques here exposed can be implemented for the investigation of the nature of particles arising from galactical activity, and can be specialized as well for the study of the part of the Galaxies from which they originate by suitably choosing the integration regions in the cross sections and in the differential rates. Comparison with other experimental techniques is therefore possible.

The **Recoil momentum spectrum** allows one to acquire information about the anisotropic velocities of particles of galactic origin:

by assuming relativistic particles of mass  $m_0$  of galactic origin with anisotropies in velocities reaching with relativistic velocities the target at rest in the laboratory frame (with velocities oriented in the direction of one cartesian axes  $i$  in the laboratory frame)

$$\frac{dR}{d\Omega_{\hat{q}}} = \int_0^{v_{esc}} dv F^2[E_R] f(v_{min, i, \hat{q}}) m_0 c^3 [\arctan(\hat{\gamma}) - \hat{\gamma}] \quad (21)$$

with  $\hat{\gamma}$  the Lorentzian relativistic factor and  $v_{esc}$  the escape speed.

It is here nevertheless possible to use the solid-angle versors calculated between the Galaxy rest reference frame and the Earth laboratory reference frame:

due to the choice of spherical galaxies or elliptic galaxies, the information modulo  $\pi$  in the solid-angle versor integration can be here specified as

$$\frac{dR}{d\Omega_{q_r, \hat{f}'_s}} = \int_0^{v_{esc}} dv F^2[E_R] f(v_{min}, i, \hat{q}) m_0 c^3 [\arctan(\hat{\gamma}) - \hat{\gamma}] \quad (22)$$

with  $q_r, \hat{f}'_s$  the considered portion of solid angle.

By assuming

- a constant velocity-dispersion tensor  $\zeta(\vec{v})$  for particles of galactic origin without a geometrical phase and

- a constant form factor  $F(q)$ ,

the recoil momentum spectrum is integrated by elliptical functions on the Galaxy-lab portion of solid angle.

For  $\alpha \neq 2$  in Eq. (20), the relativistic properties applied in Eq. (21) do not hold any more, and different schematizations have to be adopted.

## Comparison with other experimental techniques

The majority of experiments are based on ionization, scintillation, low temperature phonon techniques, or some combination of these. They have in common the same basic theoretical interpretation. In the case the **differential energy spectrum** of such nuclear recoils is expected to be featureless and smoothly decreasing, with (for the simplest case of a detector stationary in the Galaxy), it might admit the typical form:

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-R/E_0 r} \quad (23)$$

## event rate per unit mass

$$dR = \frac{N_0}{A} \sigma v dn \quad (24)$$

- with  $\sigma$  the cross section,
- target of atomic mass  $A$
- $N_0$  Avogadro number

$\sigma \equiv \sigma_0 = \text{const} \Leftrightarrow$  zero-momentum transfer.  
J. D. Lewin and P. F. Smith, *Astropart. Phys.* **6** (1996) 87.

smoothly decreasing differential energy spectrum of nuclear recoils for the simplest case of a detector stationary in the Galaxy

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{E_R/E_0 r} \quad (25)$$

$r = \frac{4M_{DM}M_T}{(M_{DM}+M_T)^2}$  target nucleus of mass  $M_T$ :

$E_R$  recoil energy,

$E_0$  most probable kinetic energy of a DM particle of mass  $M_{DM}$ ,

$R$  is the event rate per unit mass,

$R_0$  the total event rate.

within a range  $10 - 1000 \text{ GeV}c^{-2}$

recoil energy  $1 - 100 \text{ KeV}$

Normalized differential particle density distribution

$$dn = \frac{n_0}{\tilde{k}} f(\vec{v}, \vec{v}_E) d\vec{v}, \quad \tilde{k} : n_0 = \int_0^{v_{esc}} dn \quad (26)$$

$$\frac{dR(v_E, \infty)}{dE_R} = c_1 \frac{R_0}{E_0 r} e^{-c_2 E_R / E_0 r} \quad (27)$$

with

$$\frac{c_1}{c_2} = \frac{R(v_E, \infty)}{R_0} \quad (28)$$

$$R(E_1, E_2) = R_0 \frac{c_1}{c_2} e^{-c_1 E_1 / E_0 r} - e^{-c_2 E_2 / E_0 r} \quad (29)$$

# Modified Poisson equations

A Poisson equation with  $\alpha \neq 2$  is consistent with a modification of the decay rate

$$c_i \rightarrow c_i \alpha \Rightarrow \frac{c_1(\alpha)}{c_2(\alpha)} \simeq \frac{c_1}{c_2} + \tilde{c}(\alpha) \quad (30)$$

$$R(E_1, E_2; \alpha) \sim R(E_1, E_2) + R_0 \tilde{c}(\alpha) \left[ e^{-c_1 E_1 / E r_0} e^{-c_1(\alpha) E_1 / E_0 r} - e^{-c_2 E_2 / E} - e^{-c_2(\alpha) E / E_0 r} \right] \quad (31)$$

$$R(v_E, \infty; \alpha) \sim R(v_E, \infty) + \hat{f}(v_E; \alpha) \quad (32)$$

with the modification

$$\sigma \equiv \sigma(0)(\alpha) \simeq \sigma(0) + \tilde{\sigma}_\alpha \quad (33)$$

and addend is obtained

$$\frac{dR}{dQ} \simeq \frac{\rho_0}{2m_\chi m_r^2} F^2[Q] \int_{v_{min}}^{\infty} \sigma_0(\alpha) \frac{f_s(v; \alpha)}{v_\alpha} dv_\alpha \quad (34)$$

$\alpha$ -energy-spectrum modifications

nuclear form-factor corrections  $F_\alpha$ :

form factor modifications momentum transfer modifications

$$q = M_T E_R$$

modifications of the cross section as  $\sigma(qr_n) \Rightarrow \sigma(0)F^2(qr_n; \alpha)$

$r_n$  effective nuclear radius all the modifications obtained must be kept separated (i.e. after spectral analysis) with possible other (statistical errors) contributions

## $\alpha$ -energy-spectrum modifications in directional detection

$$\frac{dR(v_E, \infty)}{dE_R} \Big|_{\parallel} = \int_{-1}^{+1} |\cos \psi| \frac{d^2 R(v_E, \infty)}{dE_R d \cos \psi} d \cos \psi \quad (35)$$

$$\frac{dR(v_E, \infty)}{dE_R} \Big|_{\perp} = \int_{-1}^{+1} (1 - \cos^2 \psi)^{1/2} \frac{d^2 R(v_E, \infty)}{dE_R d \cos \psi} d \cos \psi \quad (36)$$

$$\frac{1}{R_0} \frac{dR(v_E, \infty)}{dE_R} = \frac{1}{2} \left[ e^{-(v_1 - v_e \cos \psi)^2 / v_0^2} - e^{-(v_2 - v_e \cos \psi)^2 / v_0^2} \right] +$$

$$\frac{\sqrt{\pi} 2 v_E \cos \psi}{v_0} \left[ \operatorname{erf} \left( \frac{v_2 - v_e \cos \psi}{v_0} \right) - \operatorname{erf} \left( \frac{v_1 - v_e \cos \psi}{v_0} \right) \right] \quad (37)$$

with  $v_i \equiv \sqrt{E_i E_0} r v_0$ ; the first two integrations obtained numerically - the results have to be compared with those obtained by the restrictions on the solid-angle integration previously obtained; - only two components can be evaluated in the latter calculation, as one degree of freedom is kept by the Poisson-like equation.

# Outlook

- Technical detail of the LHAASO experiment:
  - Galactic Centers;
  - Galactic Halos;
- Analysis of further phenomena possibly interacting with the detection techniques;
- Comparison with other detection techniques;
- Comparison with anisotropies properties of relativistic particles, including velocity anisotropies, mass anisotropies and anisotropies due to possible geometrical phases of the particle fields, and phenomena due to anisotropies in the galactic region;
- **Examples of integration of the recoil rate of the detector target for relativistic particles of galactical origin with anisotropies in velocities for determining the number of events (particles).**
- **Comparison with the results obtained in the cases of ellipsoidal galaxies containing DM regions and DM particles form the halo falling off faster than DM have been determined.**

Thank You for Your attention.

## Further References

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