HERMES: propagating UHECRs in a magnetized Universe

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“Who” was HERMES?

New (full MC) simulator of:

- UHECR propagation
- Magnetic fields (Gal, XGal)
- Cosmology
- Source distrib., injection

1D of nuclei and \( \nu \), 3D propagation (in regular or turbulent magnetic fields) of nuclei \textbf{without} energy loss: developed and completed by Manlio as part of his PhD thesis (Feb 2012)

COORDINATOR OF PhD: Prof. U. Lombardo

ADVISORS: Prof. A. Insolia
Dr. P. L. Ghia
"Who" is HERMES?

Upgrades!
Merging of existing modules for 3D propagation with energy losses

Upgrades!
Merging with new code ELECA for the propagation of $\gamma$ and $e^+/e^-$
(M.Settimo, M. De Domenico, H. Lyberis, Scineghe 2012)
Part 0: HERMES backbone
HERMES: sketch of modules

xHERMES
- **xLib_Base**: Mathematics and Statistics
- **xLib_CBR**: Extragalactic (CMB,IRB,opt,Radio)
  - Background
  - Radiation
  - Parametrization
- **xLib_CrossSections**: Cross Sections for (\(A,Z\)) + gamma & gamma + gamma interactions
- **xLib_EnergyLoss**: Energy-loss equation solver

EleCa
- **Lib_Base**: Mathematics, Statistics, Methods
- **Lib_CrossSections**: Cross Sections for gamma + gamma & pair/gamma interactions
- **Lib_CBR**: Extragalactic (CMB,IRB,opt,Radio)
  - Background
  - Radiation
  - Parametrization
- **Lib_Cascade**: MC cascade propagation

MagProp
- **Lib_DecayChains**: Handle nuclei decays
  - Stability (PSB) chain
  - Decay network
- **Lib_Particles**: Particle production:
  - Pairs, (multi)pions
  - Photons, neutrinos
  - Inelasticity in ultra-relativistic approx
- **Lib_EnergyLoss**: 1D MC Propagation for nuclei, neutrinos, pairs and photons
  - Interaction lengths \(\lambda\)
  - Energy-loss lengths \(\gamma\)
- **Lib_Mag**: Extragalactic & Galactic Fields
  - Regular & Turbulent
  - Kolmogorov-like
  - BSS, ASS (Sy, Asy)
- **Lib_Propagation**: 3D Propagation for nuclei, neutrinos, pairs and photons in magnetic fields
  - Energy loss due to interactions with background radiation & creation of UHECR cascade in the universe
Part I:
Simulating the propagation of nuclei
Modeling EBR and interaction length

\[ \lambda_{A}^{-1}(z, E) = \mathcal{E}(z) \frac{c}{2 \Gamma_{A}^{2}} \int_{\epsilon_{\text{thr}}/2 \Gamma_{A}}^{\epsilon_{\text{max}}} d\epsilon' \frac{n(\epsilon)}{\epsilon} \int_{\epsilon_{\text{thr}}}^{2 \Gamma_{A} \epsilon} d\epsilon' \sigma(\epsilon') \]

**Model D**

**Star Formation Rate**

**Initial Mass Function**

**Figures: energy density of EBR vs energy of background photons**

HerMES: propagating UHECRs in a magnetized Universe
HERMES: energy losses and particle production

**Cosmology**

- **Fully customizable:** Hubble parameter, energy and matter densities...
- **Source evolution:** Star Formation Rate (SFR), AGN, QSO, GRB and 
  
  \[(1 + z)^m\]

**Energy loss**

Include only those ones having a significant impact on the propagation of UHECR:

- **Adiabatic loss:** expansion of the Universe \([A \geq 1, \gamma, \nu]\) (CEL)
- **Pair production:** creation of \(e^+ / e^-\) pairs \([A \geq 1, \gamma]\) (CEL)
- **(Multi)Photo-pion production:** creation of \(\pi\) \([A \geq 1]\) (MC)
- **Photodisintegration:** fragmentation of the original nucleus, creation of lighter nuclides due to Giant Dipole Resonance and Quasi-Deuteron effect \([A \geq 2]\) (MC)
HERMES: Simulating $A_{\gamma EBR}$ interactions

Cross sections
- Rachen parameterization
- Giant dipole resonance
- Quasi-deuteron effect
- Baryonic resonances
- Multipion production

Energy loss
- Adiabatic
- Pair production
- Photopion production
- Photodisintegration
- CMB + Infrared/Opt

Nuclear rest frame

Squares indicate values from Stanev (p) & Allard (Fe)
The modular structure allows high customization
Default: TALYS v1.2 cross sections and \( \beta \)-stable chain
Any change to TALYS cross-sections can be easily updated

We are in touch with E. Khan (IPNO) for measured cross-sections and chains
HERMES: (many!!) exclusive channels considered

M. De Domenico, H. Lyberis, M. Settimo

HERMES: propagating UHECRs in a magnetized Universe
**HERMES: sources and composition**

**Available options:**

- Continuous/Discrete sources distr.
- Different evolutions
- Power-law injection
- Equal/Different abundances
- Equal/Different luminosity allowed for each source

**Panels:**

- Auger data rescaled by +15%
- HiRes data
- Flux of UHECR from HERMES (lines)
- Uniform source distrib. $10^{-3} \leq z \leq 1.5$
- Equal intrinsic luminosity
- Norm. at $E = 10^{18.8}$ eV

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**Graphs:**

- Pure protons $E_{\text{max}} = 10^{21}$ eV $s = 2.4$
- Auger ICRC11+15%
- HiResI PRL08
- HiResII PRL08
- No Evol.
- Uniform
- SFR
- AGN
- GRB
- QSO

**Legend:**

- Auger ICRC11+15%
- HiResI PRL08
- HiResII PRL08

**Equations:**

- $10^{-3} \leq z \leq 1.5$
- Equal intrinsic luminosity
- Norm. at $E = 10^{18.8}$ eV
**Elongation rate**: Estimation at Earth is due to fast parameterizations based on extreme value theory for 3 different hadronic models ([M. De Domenico, S. Riggi, GAP2012-030](journal paper in preparation))

Panels:
- UHECR from HERMES (lines)
- Uniform source distrib.
  \[10^{-3} \leq z \leq 1.5\]
- Equal intrinsic luminosity
- Check, check & check in progress!

**Preliminary**
HERMES: comparison with other simulators

**Surviving probability**

*Probability to reach the Earth above a given energy $E_{\text{thr}}$

**Protons:**
- Uniform sources
- $E^{-2.7}$ inj.
- $\Lambda$CDM Cosmology
- CMB only

**GZK horizon**

*Nuclei:*
- Uniform sources
- $E^{-2.7}$ inj.
- $\Lambda$CDM Cosmology
- CMB + Infrared/Opt
**Turb. EMF: Kolmogorov 3D**

Turbulent magnetic field: Fisher distribution of deflections as expected!

**Reg. GMF: HMR BSS-S**

Available models:
- Reg. GMF: ASS/BSS
- Harari et al, Stanev, Tyniakov-Tkachev
- Turb. GMF/EMF: Kolmogorov-like $\propto k^{-\gamma}$
- New models can be easily included

Trajectories in turb. GMF (Giacalone-Jokipii isotropic method)

- $E/Z = 10^{17}$ eV
- $E/Z = 10^{18.5}$ eV
- $E/Z = 10^{20}$ eV
Part II: Propagation of secondary particles
HERMES: neutrinos (1D propagation)

Preliminary!
**ELECA: ELEctromagnetic CAscading**

MC code to propagate extragalactic UHE $\gamma$ and $e^+ / e^-$

Main interaction processes with the EBR:

1. **Pair Production** (for photons)
2. **Inverse Compton Scattering and Triple Pair Production** (for $e^+ / e^-$) are treated with a full MC;
3. **Synchrotron and adiabatic energy losses** are treated as continuous processes.

(M.Settimo, M. De Domenico, H. Lyberis, Scineghe 2012)
Conclusions

Summary

A new full MC simulator of UHECRs has been developed:

- 3D Propagation in a magnetized Universe
- Energy losses in the EBR
- Cosmology, Source distribution, UHECR injection
- Propagation of $\nu$, $\gamma$ and $e^+/e^-$
- ASCII configuration file as input: very customizable, about 50 different parameters/options
- Good agreement with existing results

Outlook

1. Nuclei/magnetic fields: final stages of consistency checks
2. ELECA: cross-checks in progress, but promising
3. Public release soon
Acknowledgments

Today HERMES is the result of our joint efforts to build a 3D MC propagator of nuclei including energy loss and the propagation of all secondaries particles, including $\gamma$ and $e^+/e^-$.  

We would like to thank O. Deligny, D. Allard, E. Khan, S. Mollerach, M. Risse, P. Schiffer and T. Winchen for many useful discussions.

We would also like to thank D. Allard, S. Riggi, the Simprop and PARSEC teams for having kindly provided us with simulated particles or tables used for comparisons.
Extra slides
### HERMES: 1D output example

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In the 3D version you have also 3-coords for: **Position, Momentum and Propagation Time**

Output is structured to allow cascade reconstruction...
Friedmann-Robertson-Walker Universe: Homogeneous Isotropic → Friedmann equations

\[ \frac{1}{E} \frac{dE}{dz} = - \frac{dt}{dz} \sum_{\text{process}} \beta_{\text{proc}}(z, E), \quad \text{Energy loss rate} \]

Cosmology \[ - \frac{dt}{dz} = \frac{1}{H_0(1+z)} \left[ \Omega_M(1+z)^3 + \Omega_\Lambda + (1 - \Omega_M - \Omega_\Lambda)(1+z)^2 \right]^{-\frac{1}{2}} \]

\( H_0 \) Hubble param. \( \Omega_M \) Density of cold+baryonic mass \( \Omega_\Lambda \) Density of dark energy

Sum extended to all interactions acting during the propagation. Include only those ones having a significant impact on the propagation of UHECR:

- **Adiabatic loss:** expansion of the universe \([A \geq 1, \gamma, \nu]\) (CEL)
- **Pair production:** creation of \(e^+/e^-\) pairs \([A \geq 1, \gamma]\) (CEL)
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**Available source evolutions:** Uniform, Star Formation Rate, AGN, QSO and GRB