# High-Energy Astroparticle Theory

Introduction to the course

Carmelo Evoli
Gran Sasso Science Institute (GSSI), L'Aquila
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# About me


## Carmelo Evoli

Associate Professor

GSSI, L'Aquila
INFN, Laboratori Nazionali del Gran Sasso


### Before GSSI

PhD, SISSA, Trieste
Postdoc, NAOC, Beijing
Postdoc, University of Hamburg

### What I work on

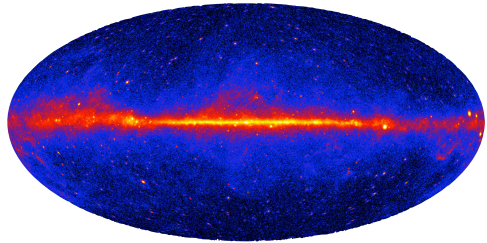
- Galactic cosmic rays
- Milky Way diffuse $\gamma$ rays and neutrinos
- Ultra-high-energy cosmic rays and cosmogenic neutrinos
  Member of the Pierre Auger Collaboration
- Indirect searches for new physics in cosmic rays

# About you



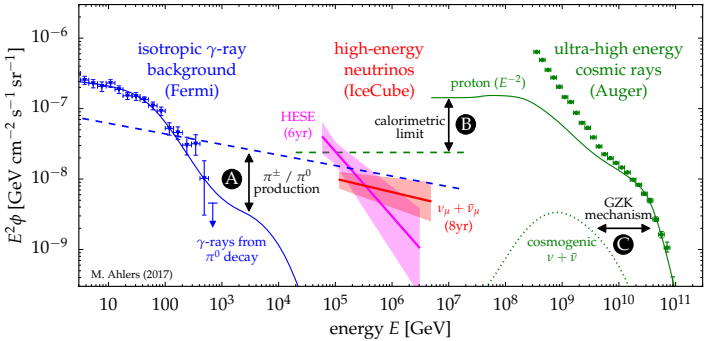
# The big questions

- Where do cosmic rays come from?
- How do they travel from their sources to us?
- How are particles accelerated to PeV energies and beyond?
- What do photons and neutrinos tell us that charged particles cannot?



The $\gamma$-ray sky above 1 GeV. NASA/DOE/*Fermi*-LAT Collaboration

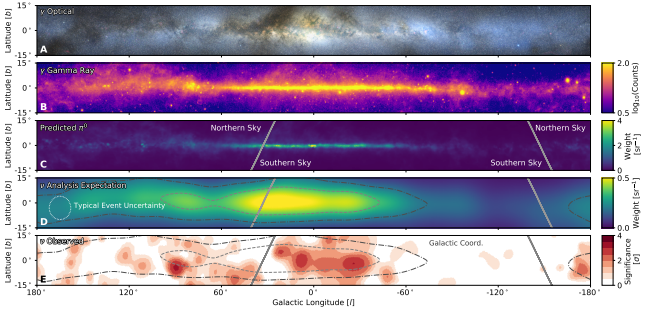
# One population, several messengers




Adapted from M. Ahlers & F. Halzen, Prog. Part. Nucl. Phys. 102, 73 (2018)

Charged particles are deflected by magnetic fields; $\gamma$ rays and neutrinos point back to where they were produced.

# Multi-messenger: The Milky Way in photons and neutrinos




IceCube Collaboration, Science 380, 1338 (2023)

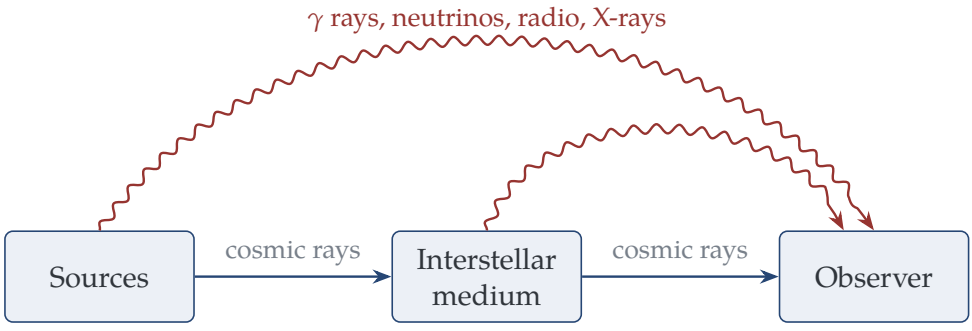
From top: optical, *Fermi*-LAT $\gamma$ rays, predicted $\pi^0$-decay neutrinos, IceCube data. First evidence of neutrinos from the Galactic plane.

# Open questions

- **The knee.** The cosmic-ray spectrum steepens at a few PeV. Are supernova remnants able to reach it? LHAASO now sees $\gamma$ rays above 100 TeV from many Galactic sources.
- **Spectral features.** Protons and helium harden at a few hundred GV (PAMELA, AMS-02) and soften again at $\sim$ 10 TeV (DAMPE). Simple power laws no longer describe the data.
- **Antimatter.** The positron fraction rises above $\sim$ 10 GeV (PAMELA, AMS-02). Pulsars? Something else?
- **Neutrinos.** IceCube detects a diffuse astrophysical flux and the Galactic plane. Which sources, and through which interactions?

This course gives you the theory needed to address these questions.

# The course in one picture



# Syllabus: 15 lectures of two hours

## Part I · radiative processes

1. Introduction to high-energy astroparticle physics
2. Synchrotron emission
3. Inverse Compton scattering and $\gamma$-ray absorption
4. Hadronic radiative processes
5. Diffuse emission and multi-messenger connections

## Part II · transport

6. Primary cosmic rays and grammage
7. Secondary cosmic rays
8. Scattering in turbulent magnetic fields

## Part II · transport (continued)

9. From pitch-angle scattering to spatial diffusion
10. Magnetohydrodynamic foundations
11. Transport theory and cosmic-ray anisotropy

## Part II · acceleration

12. General principles of particle acceleration
13. Shock waves in astrophysics
14. Supernova remnants and diffusive shock acceleration
15. Diffusive shock acceleration: transport view and observational tests

# What I assume, and what I don't

### Assumed

- Classical electrodynamics: Maxwell's equations, Lorentz force, radiation from accelerated charges
- Special relativity: four-vectors, invariants, Lorentz transformations
- Statistical mechanics: distribution functions
- Basic astrophysics

### Built from scratch

- Plasma physics and magnetohydrodynamics
- Interaction cross sections, introduced when needed

### Conventions

- Gaussian units: $e^2/\hbar c \simeq 1/137$
- Energies in eV, distances in pc, magnetic fields in $\mu$G
- Order of magnitude first, then the calculation

# By the end of the course you will be able to

- compute the emission of a population of relativistic particles: synchrotron, inverse Compton, $\pi^0$ decay;
- estimate energy-loss and escape times, and decide which one shapes a spectrum;
- derive the diffusion equation and solve it for primary and secondary nuclei;
- relate the diffusion coefficient to magnetic turbulence;
- explain how shocks accelerate particles, and why the spectrum is close to $E^{-2}$;
- use these tools to interpret data: B/C, positrons, diffuse $\gamma$ rays, neutrinos.

# Material

### Lecture notes

- C. Evoli, *Lecture notes on High-Energy Astroparticle Theory*, updated during the course

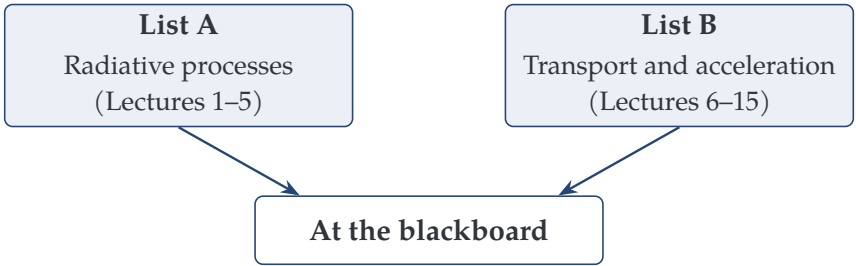
### Reviews the notes are based on

- P. Blasi, A&ARv 21, 70 (2013)
- S. Gabici, C. Evoli et al., IJMPD 28, 1930022 (2019)
- D. Boncioli; C. Evoli & U. Dupletsa; P. D. Serpico: Proc. Enrico Fermi School, Course 208, Varenna (2022)

### Textbooks

- G. B. Rybicki & A. P. Lightman, *Radiative processes in astrophysics* (1986)
- T. K. Gaisser, R. Engel & E. Resconi, *Cosmic rays and particle physics* (2016)
- M. Vietri, *Foundations of high-energy astrophysics* (2008)

# The exam




1. Choose one problem from each list.
2. Solve both on your own.
3. Present your solutions at the blackboard.

# How to contact me

| | |
|---|---|
| Room | Zenith building, P2.16 |
| Office hours | anytime on appointment |
| Contact | carmelo.evoli@gssi.it |
| Notes, slides | carmeloevoli.github.io/teaching |