“La propagation du rayonnement cosmique”

Journées PNHE
29 mars 2016 – Paris

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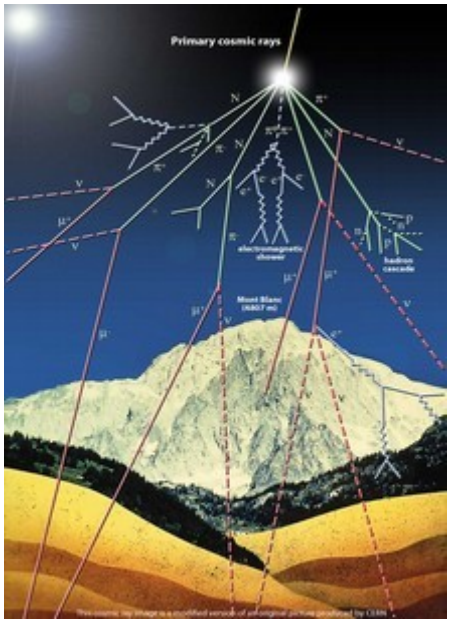
1. Context
2. Diffusion
4. Survey: our needs

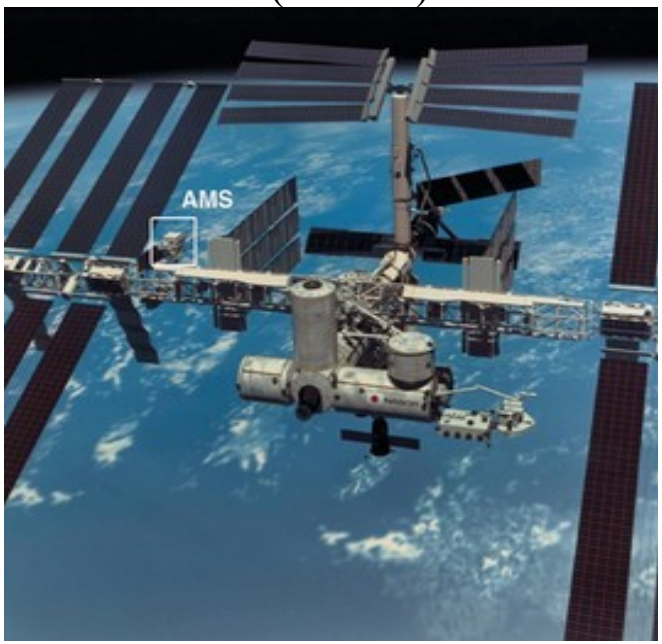
1. Context: a brief history of cosmic rays

Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



CR discovery

Extensive showers

e^-, e^+

Diffuse γ

$\overline{p}$

TeV astronomy

ν

$\overline{d}$?

1910 — 1930 — 1950 — 1980 — 2000

e^+, μ, π , K, Λ

Elements up to U

^{10}Be - ^{54}Mn

Cosmic rays = Particle physics

Particle physics Astrophysics

+ Astroparticle physics

1. Context: messengers (spectra, anisotropies...)

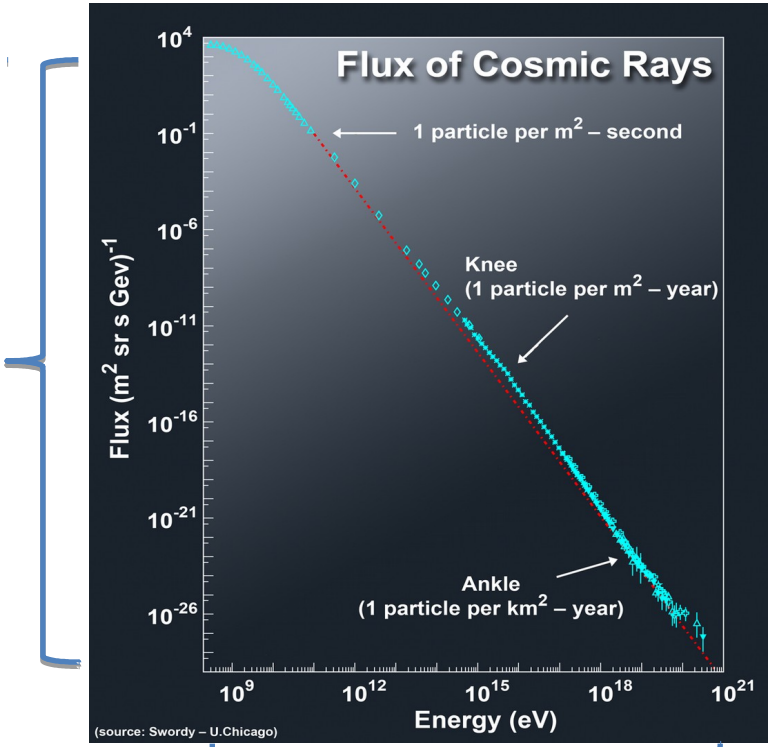
Two categories

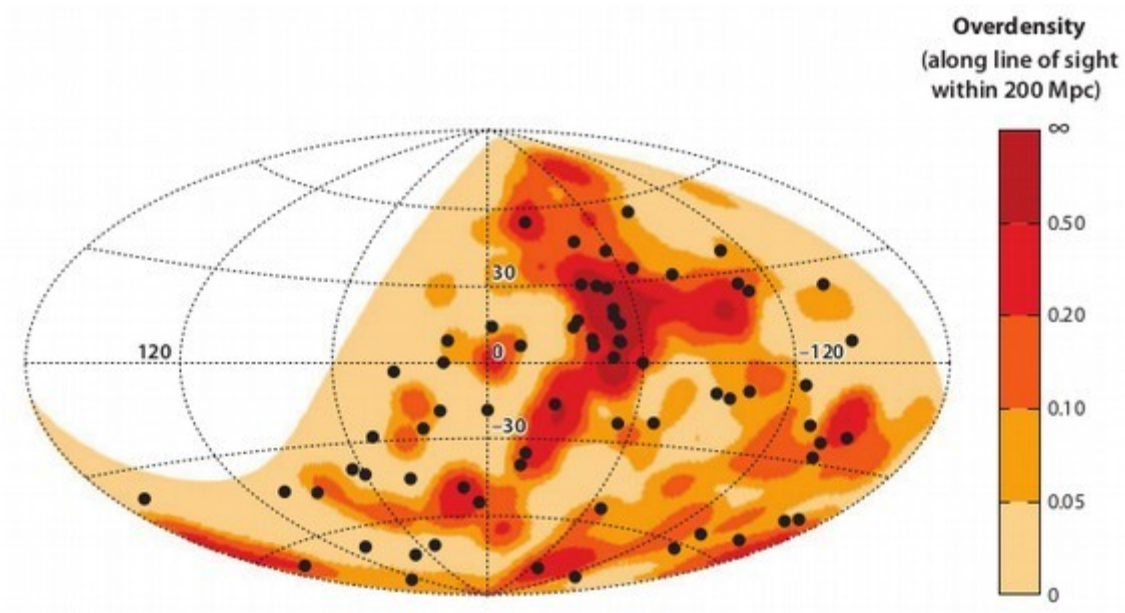
- Neutral species
  - ✔ Gamma-rays
  - ✔ Neutrinos
- Charged cosmic rays
  - ✔ Leptons
  - ✔ Nuclei

Observation type

→ Astronomy: point-like, extended, diffuse emissions

→ Fuzzy (deflection in B fields): spectra and anisotropy maps



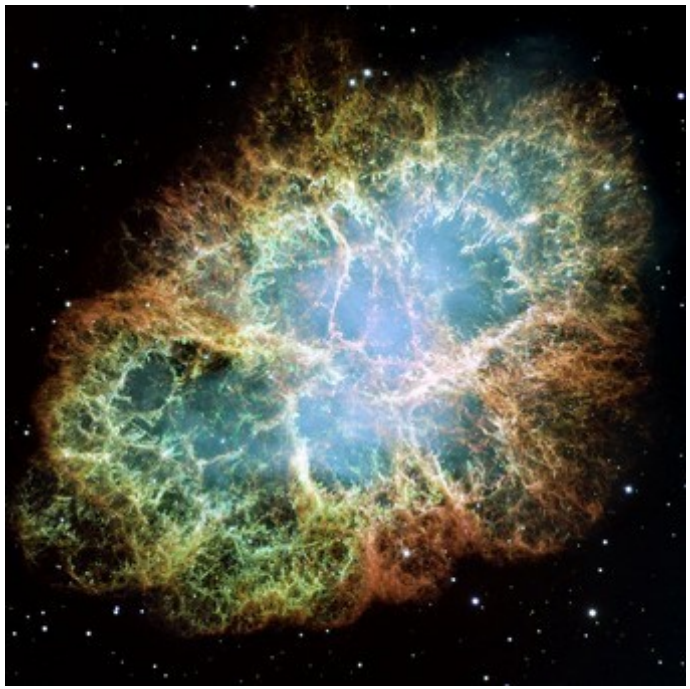


AUGER (arXiv:1306.4998)

→ Multi-messenger approaches
→ Multi-wavelength observations

1. Context: sources of (extra-)galactic CRs?

Crab nebula

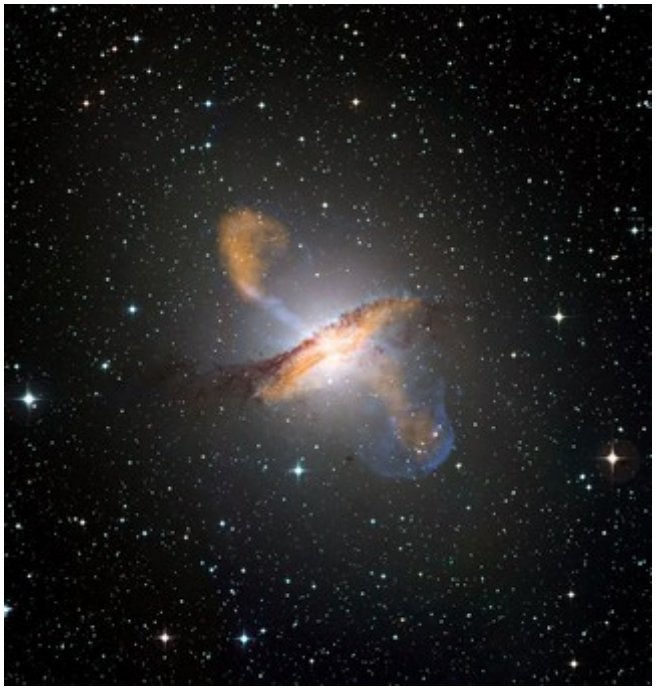


Galactic scale

- Pulsars
- Supernovae
- ...

→ $E_{max} \sim 10^{15}$ eV

Centaurus A



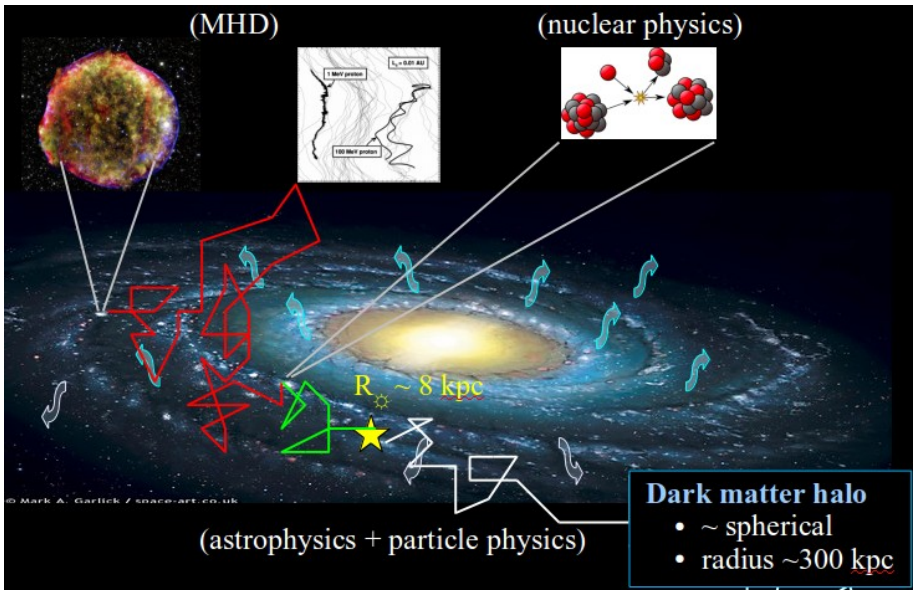
Extra-galactic scale

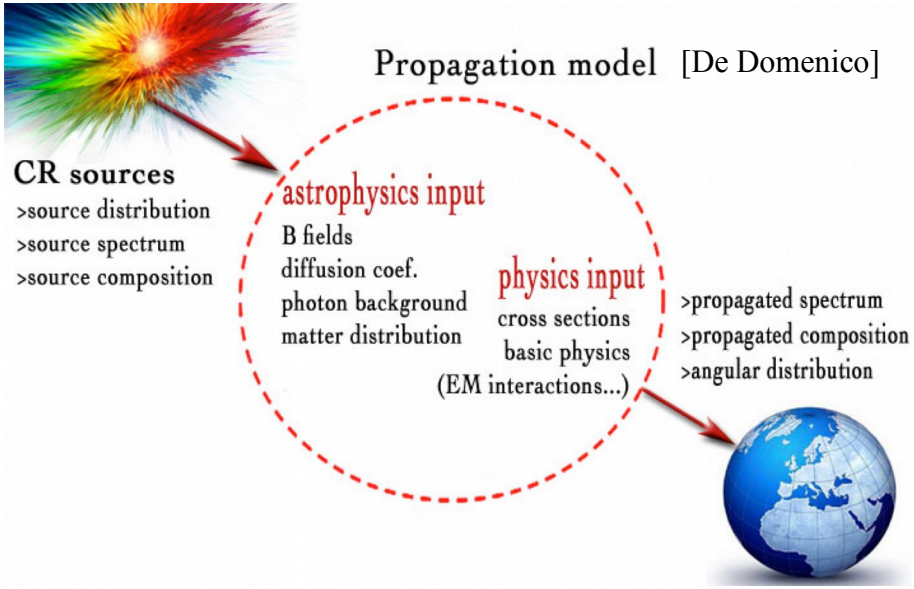
- Gamma-ray bursts
- Quasars
- Active Galaxy Nuclei (AGN)

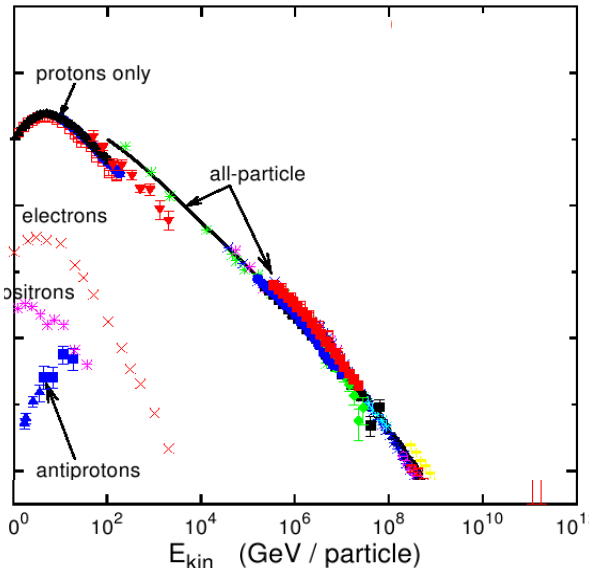
→ $E_{max} \sim 10^{20}$ eV

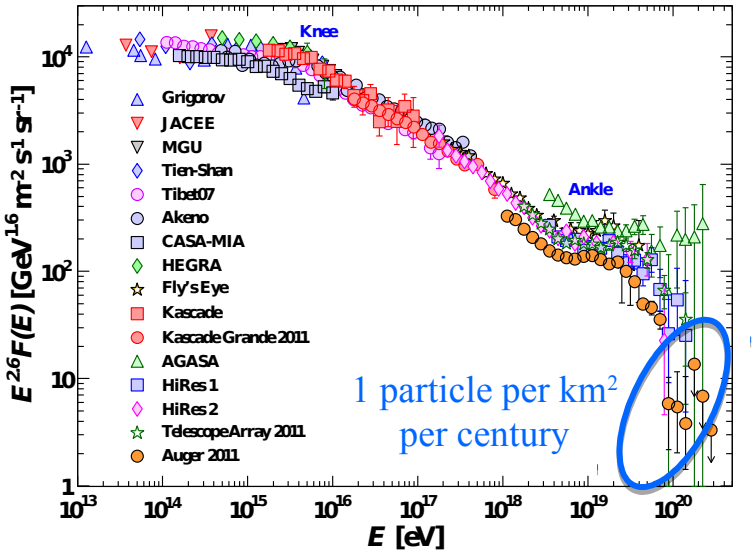
→ One century after their discovery, we still lack a clear evidence of what are the sources for the observed CR spectrum

1. Context: HE and UHECR propagation









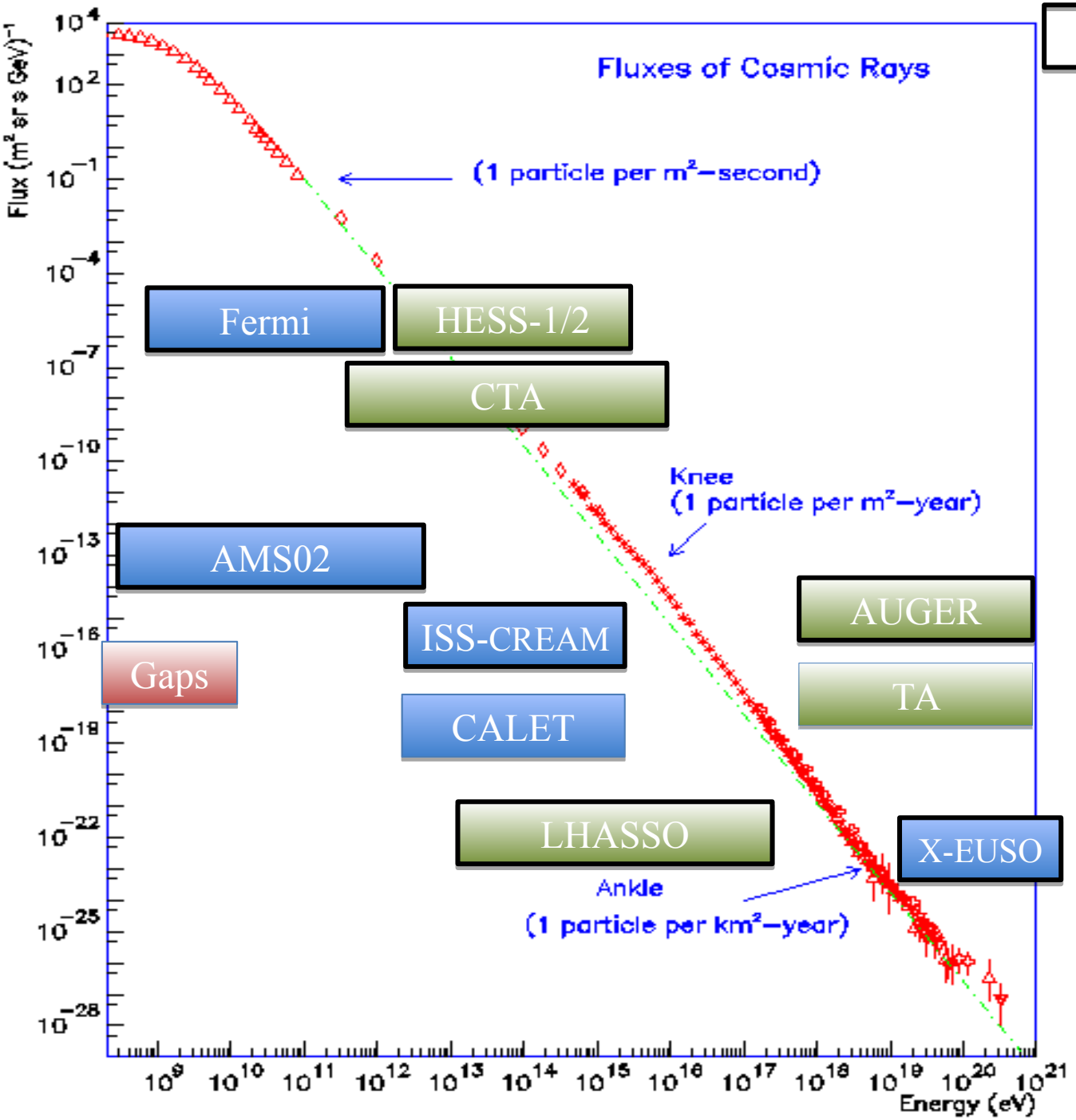
- pbar, diffuse γ-rays, e^- and e^+ (and sources)
- anisotropy<10^{-3} for ≠ energies and ≠ species

→ searching for sources, understanding transport, looking for dark matter

- Messengers of the high energy universe
- E>accessible at man-made accelerators

→ Origin of flux suppression at the highest E, mass composition, Lorentz invariance tests, etc.

1. Context: experiments vs energy (~ in 2019)



Participation IN2P3

Space

Balloon

Ground

(Courtesy L. Derome)

1. Context: CRDB (Cosmic-Ray DataBase)

http://lpsc.in2p3.fr/crdb

Welcome | Experiments/Data | Data extraction | Links | New data

Database of Charged Cosmic Rays

New release V2.1 - June 20

D. Maurin (LPSC), F. Melot (LPSC), R. Taillet (LAPTh)

Last code modification: 20/06/2014

If you use this database, please cite Maurin, Melot, Taillet (arxiv.org/abs/1302.5525).

Description

This database is a compilation of experimental cosmic-ray data. The database includes electrons, positr
below the knee. If you spot any errors or omissions, want to contribute, or simply comment on the conten
the database to Z>30 and to higher energy ground measurements and any help is welcome.

Warning: several sets of Solar modulation values are provided per sub-experiment. We refer the user to
complete discussion, and only give below a brief description of the different sets of modulation paramete

Current version / Latest data added / Acknowledgements

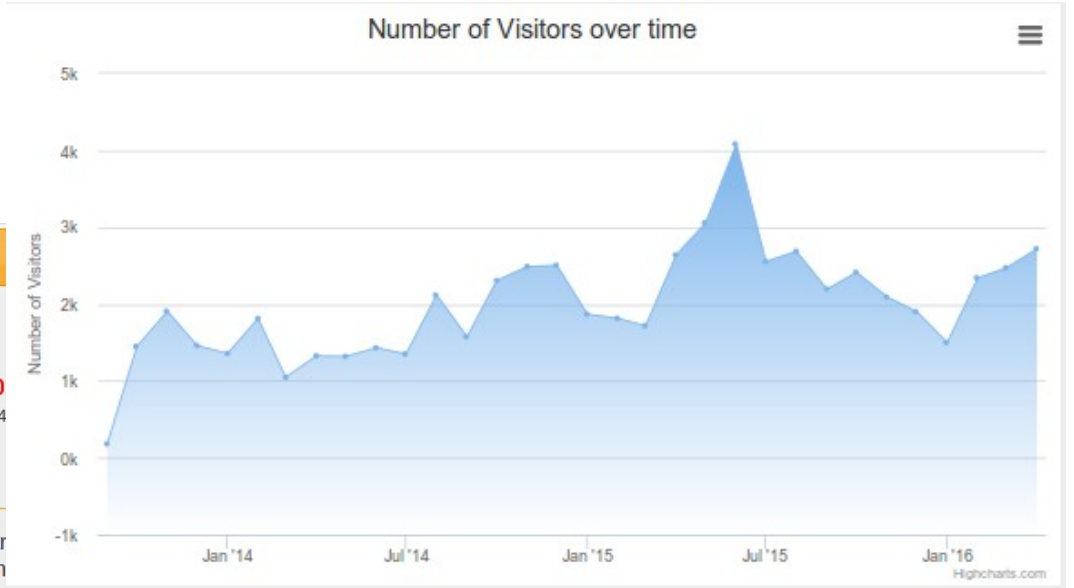
Structure of the database

This is a mySQL database containing lists of experiments (name, dates of flight, experimental technique
link to the ADS database), and all available data points (fluxes and ratios of leptons, nuclides, and anti-p
whenever available).

Accessing the database

- Experiments/Data: list of experiments, publications, data
- Data extraction: selection by flux/ratio/energy range... (on this web site or via a REST interface)
- Export database content in USINE or GALPROP compliant format (ASCII files)
- Get all bibtex entries and Latex cite (by sub-experiment)

Acknowledgements: this project has been financially supported by the PNHE



2. Diffusion: from microphysics to diffusion

[Adapted from R. Tautz (CRISM 2014)]

- **Physics problem:** motion in a turbulent field
- **Ansatz:** diffusion equation $\frac{\partial f}{\partial t} - S = \nabla \cdot \left(\kappa_{nj} \cdot \nabla f - \boldsymbol{v}\, f \right) + \frac{\partial}{\partial \boldsymbol{p}} \left(p^2 D_p \frac{\partial}{\partial \boldsymbol{p}} \frac{f}{p^2} - \dot{\boldsymbol{p}}\, f \right) + \ldots$

$$\boldsymbol{\kappa} = \begin{pmatrix} \kappa_\perp & \kappa_A & 0 \\ -\kappa_A & \kappa_\perp & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix}$$

$\kappa_{||}$: Diffusion *along*[2] $\boldsymbol{B}$
$\kappa_\perp$: Diffusion *across*[3] $\boldsymbol{B}$
κ_A: Drift effects[4]

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κ_A: Drift effects[4]

Analytical calculation

- Mean free path $\lambda_{||} \propto \kappa_{||} \propto \int_{-1}^{1} \mathrm{d}\mu \, \frac{(1-\mu^2)^2}{D_{\mu\mu}(\mu)}$

  Pitch angle $\mu = \cos(\widehat{\boldsymbol{v}, \boldsymbol{B}_0})$

- Fokker-Planck coefficient $D_{\mu\mu} = \int_0^\infty \mathrm{d}t \, \langle \dot{\mu}(t)\, \dot{\mu}^\star(0) \rangle$

  Taylor-Green-Kubo formula

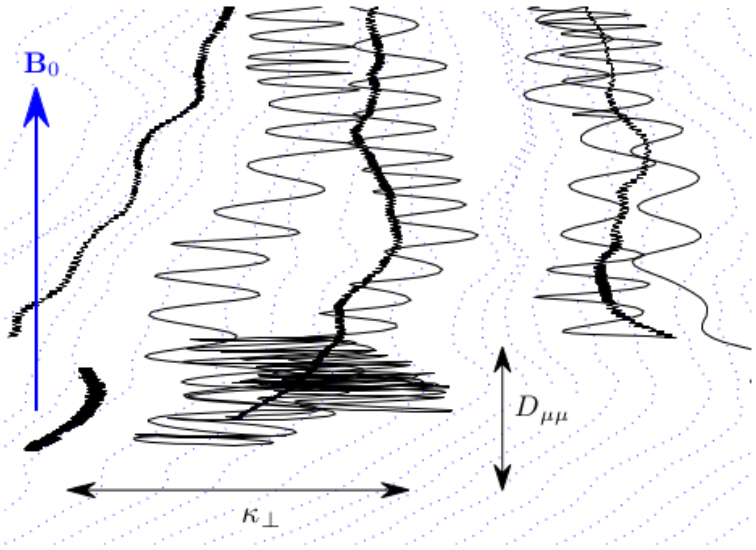
- Equation of motion (Lorentz) $\dot{\mu} = \frac{\partial}{\partial t} \left(\frac{v_{||}}{v} \right) \overset{\text{static}}{=} \frac{\dot{v}_{||}}{v}$

  Unknown $v_{x,y}$*, unknown position in* $\delta B_{x,y}$ $= \frac{\Omega}{v} \left(v_x \frac{\delta B_y}{B_0} - v_y \frac{\delta B_x}{B_0} \right)$

→ Can only be solved in ideal situations
- Quasi-Linear Theory (δB ≪B): QLT
- 2nd order QLT: SOQLT
- Non-linear guiding centre: NLGC

Numerical simulations

Reality: resonant wave-particle interaction with stochastic motion



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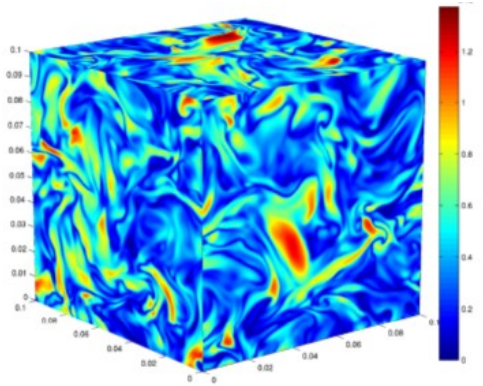
- 2nd order QLT: SOQLT
- Non-linear guiding centre: NLGC

Numerical simulations

Reality: resonant wave-particle interaction with stochastic motion... turbulence model requires:

- Energy spectrum (diff.eq. for wave!): $W \propto k^{-s}$
- Geometry
- Dynamical behaviour
  - Instabilities
  - Damped waved
  - Intermittency



Diffusion in MHD turbulence

3. Survey: “propagation” community/activity/needs

Survey March 22-25

[sent to 40 persons whose activity may be linked to CR propagation: 9 answers]

- Not really representative of the whole French community
- No answer from post-docs (my bad, only one post-doc in my mailing list)

3. Survey: who are we?

Survey March 22-25

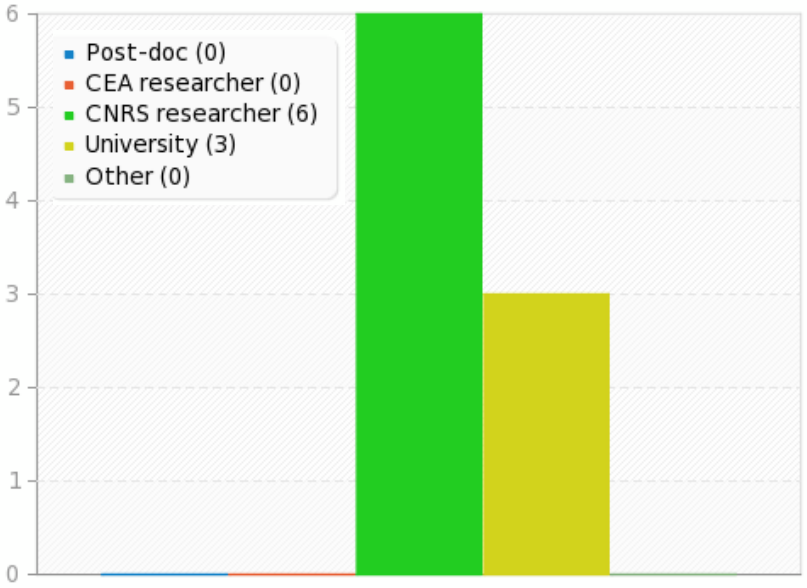
[sent to 40 persons whose activity may be linked to CR propagation: 9 answers]

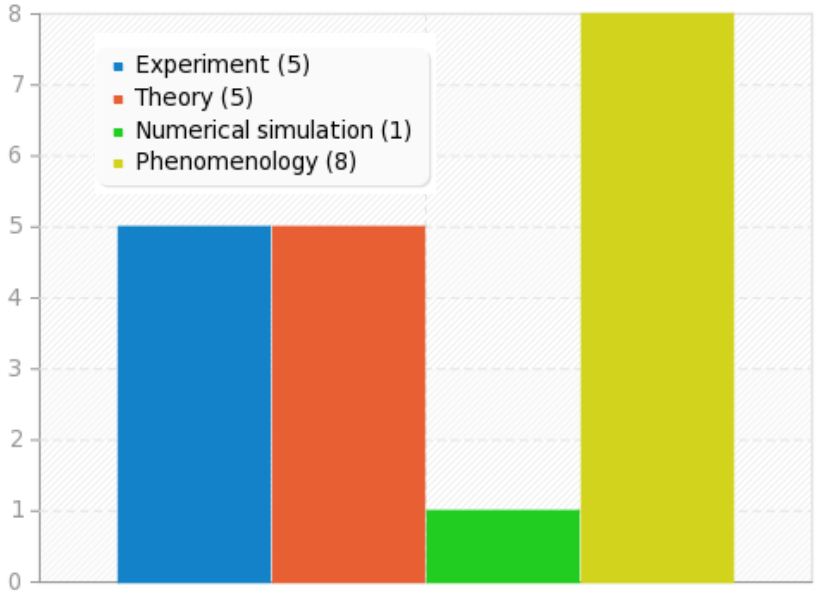
- Not really representative of the whole French community
- No answer from post-docs (my bad, only one post-doc in my mailing list)

BUT

→ Biased (hopefully) towards researchers the most concerned/involved in PNHE actions

→ "Fair" geographic/topical/institute coverage





Lab.	#	City	Institute
AIM	1	Saclay	CEA, INSU
APC	2	Paris	IN2P3, INP, INSU
IRAP	2	Toulouse	INSU, INS2I, INSIS
LAPTh	1	Annecy	INP
LPSC	1	Grenoble	IN2P3, INSIS, INSU
LPTHE	1	Paris	INP
LUPM	1	Montpellier	IN2P3, INP, INSU

3. Survey: (related to) propagation of CRs

Topics we work on

Galactic/ extragalactic CRs

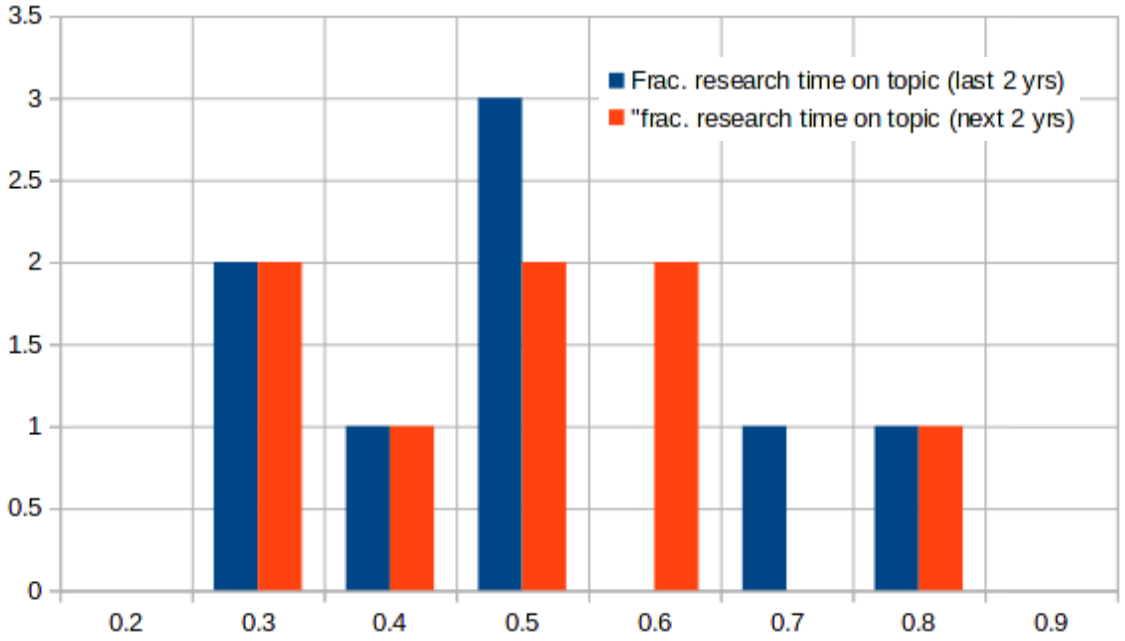
- Diffusive/bended transport
- Sources (and escape from sources)
- Interstellar/intergalactic medium
- Dark matter indirect detection

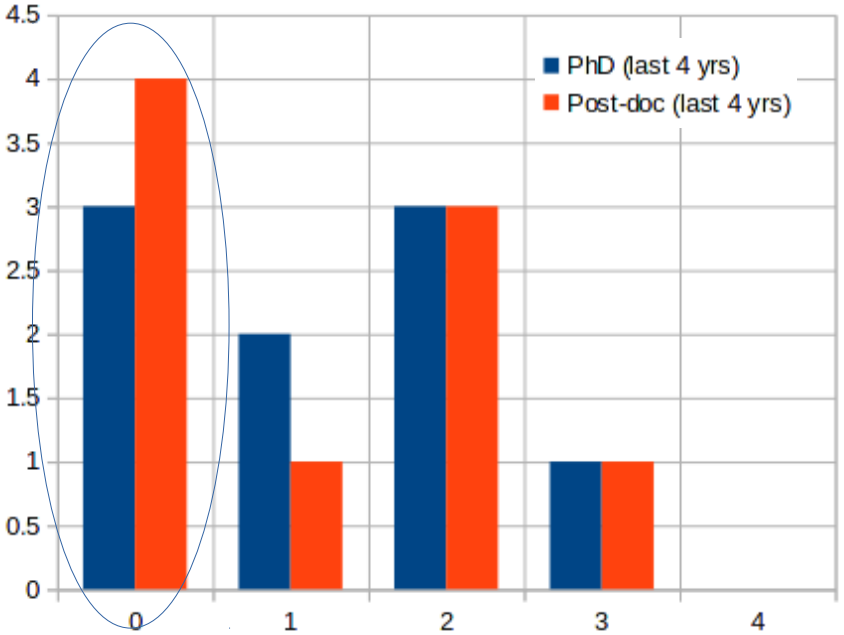
Galactic γ-ray emissions

- Diffuse emissions
- Spectra @ different places in Galaxy
- CR penetration in molecular clouds
- HE emission from novae

3. Survey: workforce?

Fraction of our time spent on these topics (last and next 2 years)
+
Number of PhD/Post-docs working on this topic (last 4 years)





# of PhD/post-doc in last 4 years (per researcher)

- half of our time on average (last 2 years)
- Will stay stable in the next 2 years

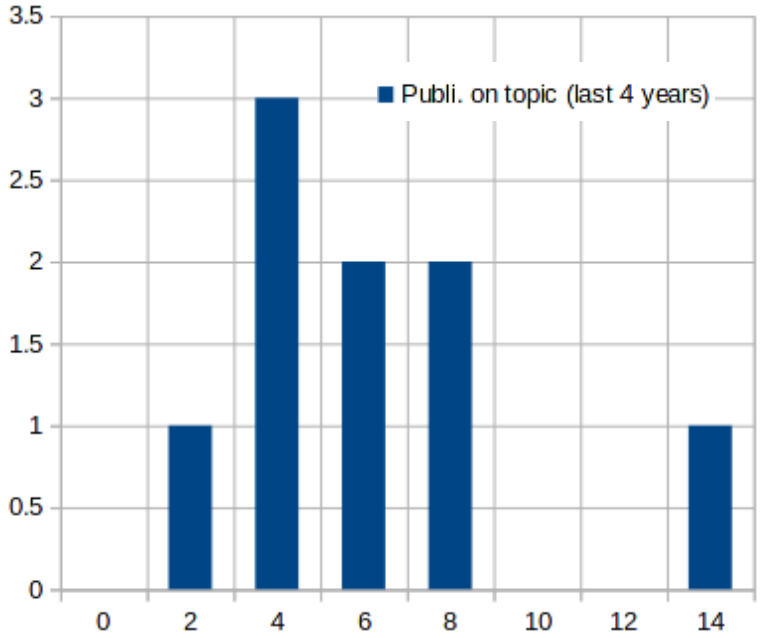
- ~ 1 PhD + 1 post-doc on average
- But 1/3 had no PhD/post-doc (last 4 years)

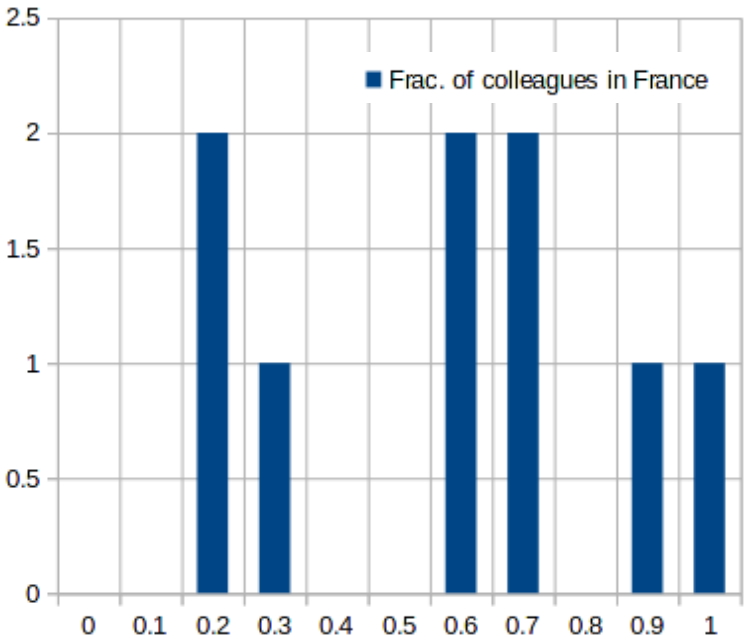
3. Survey: active? French/international collaborations?

Number of publications (last 4 years)

+

Fraction of these publications done with colleagues working in France





- ~1.5 pub. (per yr, per person) on average
- Reminder: 50% of total time on this topic

- On average, ~60% French collaborators
- But also international collaborations

3. Survey: (related to) propagation of CRs

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Questions in survey

- Topics we work on?
- Important questions of the field?
- Recent developments?
- Which instruments?
- Objectives in next 4 years?
- Support expected from PNHE?

3. Survey: (related to) propagation of CRs

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Recent developments?

GCR charged species (GeV-TeV)

- Instruments: PAMELA, AMS-02 → H, He break ~ 300 GeV/n, pbar, e+…
- MHD turbulence (semi-analytical calculations and numerical sims): transport and mean free path (Lazarian + Shalshi groups), D⊥vs D//, escape from sources
- Transport modelling: surprises from cross sections (nbar~1.5 pbar), better grasp on nuclear uncertainties, contributions from point sources, more evolved propagation models and statistical framework for analysis

UHECR

- Instruments: Auger, Telescope Array and KASCADE data
- Constraints on magnetic fields
- More evolved models (variety of sources, multi-species, etc.)

γ-rays (GeV-TeV):

- Instruments: Fermi-LAT, H.E.S.S., ...
- Emissions from: 1 symbiotic + 5 classical novae, Cygnus cocoon, Fermi bubbles, starburst galaxies (GeV-TeV), HESS ridge

Multi-wavelength analyses

- Molecular clouds and link between LE and HE: mm-range for CR ionization rate, γ-rays for CR intensity and spectrum
- Fermi-Bubble and other emissions: from radio to γ-rays
- B Gal.: Planck/WMAP (synchrotron) + radio surveys +...

3. Survey: (related to) propagation of CRs

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Recent developments?

[Which instruments?]

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LE: Voyager, AMS-02, PAMELA – *VHE*: ISS-CREAM, CALET

UHECR

- Instruments: Auger, Telescope Array and KASCADE data
- Constraints on magnetic fields
- More evolved models (variety of sources, multi-species, etc.)

UHE: Kascade-Grande, Auger, JEM-EUSO, LHAASO

γ-rays (GeV-TeV):

- Instruments: Fermi-LAT, H.E.S.S., ...
- Emissions from: 1 symbiotic + 5 classical novae, Cygnus cocoon, Fermi bubbles, starburst galaxies (GeV-TeV), HESS ridge

LE: Astrogam, Compair – *HE*: Fermi-LAT – *VHE*: H.E.S.S., TA, CTA

Multi-wavelength/messenger analyses

- Molecular clouds and link between LE and HE: mm-range for CR ionization rate, γ-rays for CR intensity and spectrum
- Fermi-Bubble and other emissions: from radio to γ-rays
- B Gal.: Planck/WMAP (synchrotron) + radio surveys +...

Wavelength: LOFAR, SKA, ALMA – *Messenger*: Icecube, KM3net, Ligo/Virgo

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Most important questions?

Turbulence and transport

- *Microphysics:* nature of turbulence, feedback CRs/turbulence/ISM phase?
- *CR sources*: escape from the sources?
- *Galactic scale*: spatial dependent and anisotropic diffusion?
- *Elsewhere*: transport in other galaxies (e.g., starburst), solar modulation?

CR spectra (source and transport)

- *Features in spectra*: origin of breaks at ~300 GeV/n? Breaks at higher energies?
- *Transition galactic/extragalactic*: mass composition, anisotropy?
- *Anomalies w.r.t. astrophysics*: pbar, e+, dbar measurement, ν HE spectrum?
- *Multi-λ*: leptonic or hadronic origin of γ-rays, γ-rays in novae
- *Multi-messengers*: counterparts/constraints for UHECRs

CR phenomenology

- Improve models with limited #params? Reliable uncertainties spectra/anis.?
- Improve ingredients (nuclear cross sections, magnetic fields, radiation field)
- Properties of LE transport (E < GeV)
- Impact of star formation regions on CR spectrum and propagation? Impact of superbubbles nearby massive star clusters (acceleration/reacceleration?)
- Impact of local environment on transport (e.g., for galactic centre, LISM, etc.)

3. Survey: (related to) propagation of CRs

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Most important questions?

[Objectives in next 4 years?]

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Streaming instability (PIC-MHD): close to sources (escape), around molecular clouds
B diffusion and D⊥ (MHD) sub/super Alfvénic + CRs and ISM (MHD bi-fluid)

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- *Multi-λ*: leptonic or hadronic origin of γ-rays, γ-rays in novae
- *Multi-messengers*: counterparts/constraints for UHECRs

Detailed modelling acceleration/emission + thesis CRs from cocoons (ANR CriBs)
Fermi-LAT pass8 data for diffuse (Galaxy and LMC) + be prepared for CTA
Bridging low (<GeV) and high energy (GeV-TeV) CRs

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GeV-TeV: AMS-02 data interpretation, solar modulation, astro. back. uncertainties
Integrate realistic D predictions (from sims) in propagation codes
TeV-Eev: interpret current data, scientific case for JEM-EUSO, KM3Net
Observables/constraints on sources (persistent vs transient, gal. vs extra-gal.)

Actions and support the PNHE could provide?

Summary

- *Topics of interest:* CR transport (LE to HE), galactic to extra-galactic, MHD to feedback, codes
- *Interdisciplinary*: plasma physics, phenomenology, simulations, theory, observations

Possible support

- Missions (for interdisciplinary collaborations)
- Working group
  - CR source and transport?
  - Interdisciplinary propagation?
  - Perspectives for CTA/SKA/future experiments?
- Thematic school (too rare)?
- Reactivate together with other PN the ASSNA initiative (on numerical sims)?
  - PCMI: ionisation from CRs, ISM dynamics
  - PNST: LECRs
- PhD and post-doc founding?

Community benefits from PNHE support: more support crucial to realise many projects/ideas

- Various expertises (multi-institutes, interdisciplinary, multi-λ, multi-messenger)
- Expertises recognised at national/international level
  → Propagation-related studies vivid field of research, very active members
  → Probably too loose ties between members for now, but strong shared interests