Theoretical astroparticle physics at the IN2P3

Julien Lavalle
(CNRS, LUPM, Montpellier)
as a tentative representative of my IN2P3 colleagues

Conseil Scientifique – June 29-30, 2021

Astroparticle physics: definition/s and national context

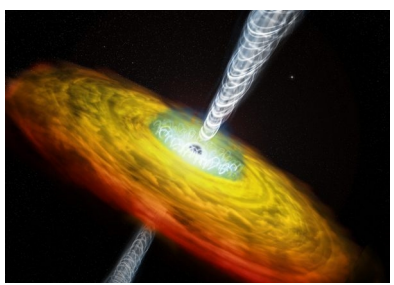
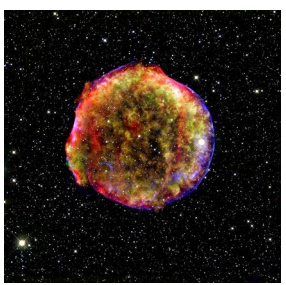
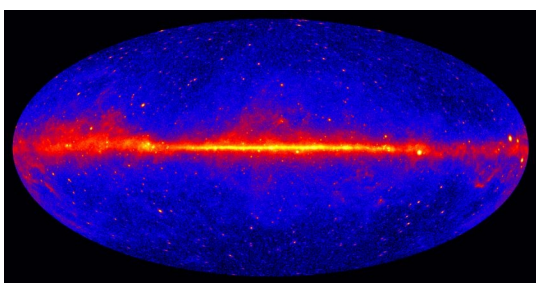
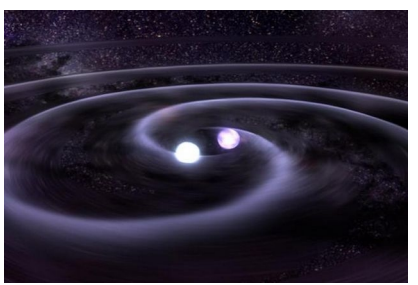
Several definitions depending on communities:

- Astrophysical phenomena/processes in which high-energy particles or radiation are the main players.
- Astrophysical phenomena/processes traced by particles or radiation (cosmic rays, gamma-rays, neutrinos, gravitational waves).
- Understanding of violent/cataclysmic astrophysical events, often leading to high-energy phenomena.
- Particle physics processes or models (often BSM) with astrophysical or cosmological signatures.

=> ***Very often relies on interdisciplinary activities (astrophysics, particle physics, plasmas, GR, cosmology)***

In France:

- Groups from several CNRS/other institutes, depending on topic: INSU (HE astrophysics + all cosmology), INP (new physics), CEA – beside hosting universities.
- IN2P3: groups/scientists internationally visible + usually strongly connected with INSU/INP/CEA.

Astroparticle physics: topics

(Main) Topics
- High-energy astrophysics and cosmic rays (sources, acceleration, transport)
- Neutrinos (process drivers or messengers)
- Other astrophysical phenomena (e.g. axions, IGMF, compact objects)
- Dark matter

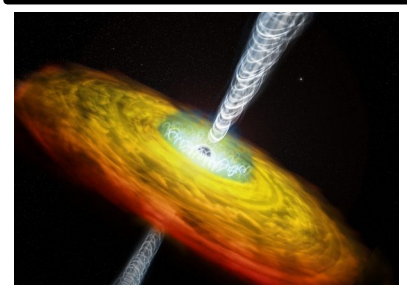
Disciplines
- Quantum field theory/particle physics
- Classical mechanics, electrodynamics, magneto/hydrodynamics, plasmas, transport, radiative transfer
- General relativity

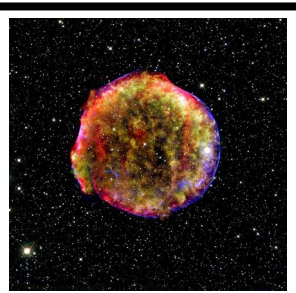
Theoretical methods/tools
- ODEs and PDEs
- Non-linear physics
- Analytical/numerical calculations
- QFT / symmetries
- Numerical simulations

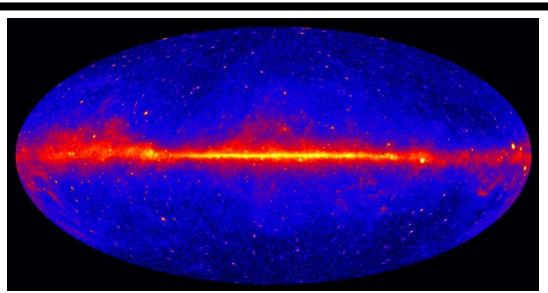
Observables (Galactic/extragalactic)
- Photons (multiwalength, radio ↔ gamma-rays)
- Cosmic rays (HE, UHE)
- Neutrinos (MeV-UHE)
- Gravitational waves
- Point-like/diffuse signals

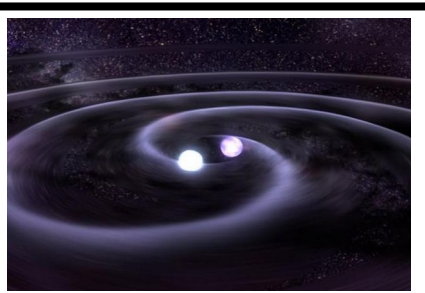
Classes of observables
- Energy spectra / intensity
- Composition
- Anisotropy
- Time variability

Relevant IN2P3 experiments: HESS/CTA, Fermi, AMS, Auger, Antares/KM3, JUNO, Edelweiss, Xenon-1/nt, Planck, LSST, Euclid, **VIRGO**, etc.









Dark Matter candidates and induced phenomena

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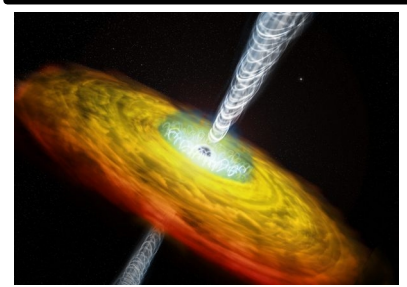
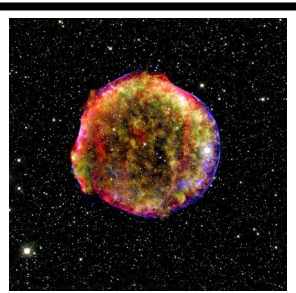
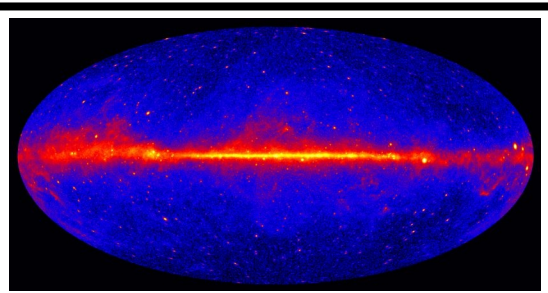
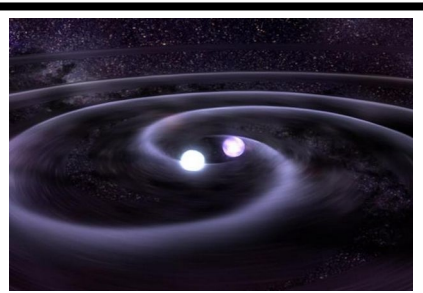
Relevant IN2P3 experiments: (…) **+ many non-IN2P3 experiments/observations**









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Experiment/project != topic !=method

Theoretical research topic => several methods + observables/probes + experiments/surveys

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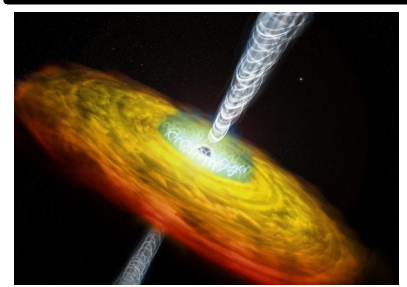
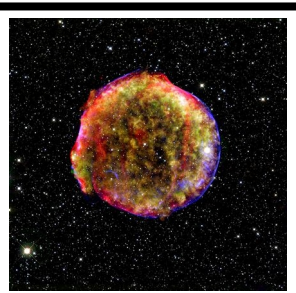
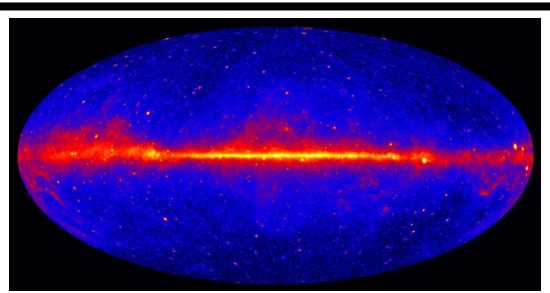
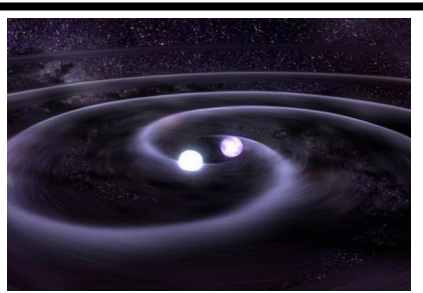








Dark Matter candidates and induced phenomena

Cosmic rays: sources, acceleration, propagation, interpretation of data

(Main) Questions

- Progenitors: accretion disks, stellar environments, etc.
- Acceleration: diffusive shocks, magnetic field amplification, MHD turbulences, plasma instabilities
- Propagation: understand
- Interactions: gas, molecular clouds, etc.

Theoretical methods/tools

- ODEs and PDEs
- Highly non-linear physics
- Analytical/numerical calculations
- Numerical simulations
- Phenomenological modeling

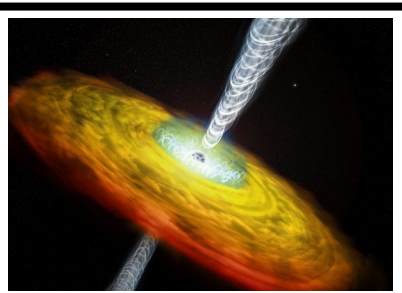
Observables

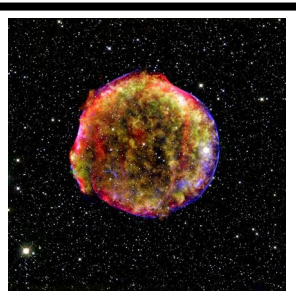
- Spectra of individual sources (mulit-)
- Diffuse emissions (CR-induced + unresolved sources)
- Neutrinos (MeV-UHE)
- Gravitational waves
- Point-like/diffuse signals

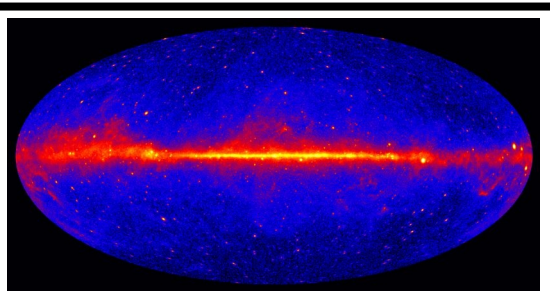
Classes of observables

- Energy spectra / intensity
- Composition
- Anisotropy
- Time variability

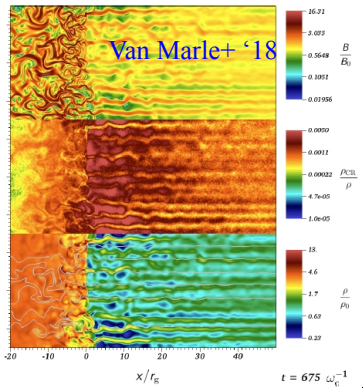
Relevant IN2P3 experiments: HESS/CTA, Fermi, AMS, Auger, Antares/KM3, etc.





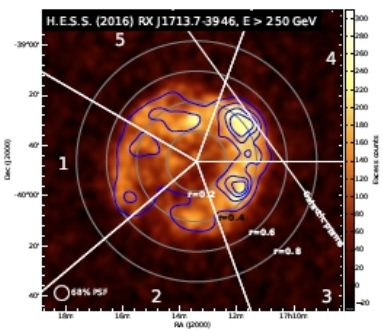


Cosmic rays: sources, acceleration, propagation, interpretation of data



Accretion disks: around compact objects of any mass scale (planets, neutron stars, black holes). Progenitors of high-energy phenomena (jets, etc.).
=> Observational signatures of all compact objects (also exotic ones)
=> Development of GR/MHD (AMR) codes, also coupled to PICs to study supra-thermal particles (e.g. NOVAs project).
=> Tools also used to study CR acceleration

Diffusive shock acceleration (DSA): magnetospheric/heliospheric, supernova remnants (SNRs), pulsar winds (PWNe), gamma-ray bursts (GRBs), active galactic nuclei (AGNi), etc.
=> multi-scale and highly non-linear in space and time ++ sometimes strong gravity => heavy numerical simulations
=> phenomenological approaches for comparisons with data



HESS+17'

Technique	Particle-in-cell	hybrid	Magneto-hydrodynamic	Vlasov / Fokker-Planck
scales	$c/\omega_{pe} \sim L$	$c/\omega_{pe} \ll L$	L =system scale Time > $1/\omega_{ci}$	all (in principle)
based on …	Maxwell + Lorentz force	Maxwell + Lorentz force, electrons as fluid	MHD + Lorentz force	kinetic Eqs for the non-thermal component
geometry	usually 1D, 2D	1-2D rarely 3D	2D rarely 3D	usually 1D

++
Laboratory laser-plasma experiments
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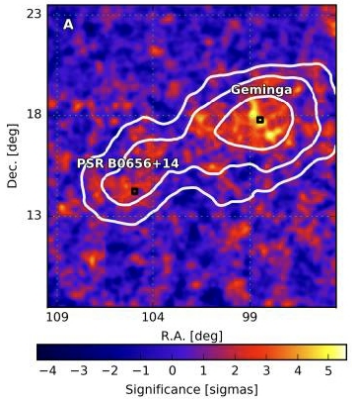
See e.g. Marcowith+ '16 + prospectives Th-IN2P3

Cosmic rays: sources, acceleration, propagation, interpretation of data

HAWC '19



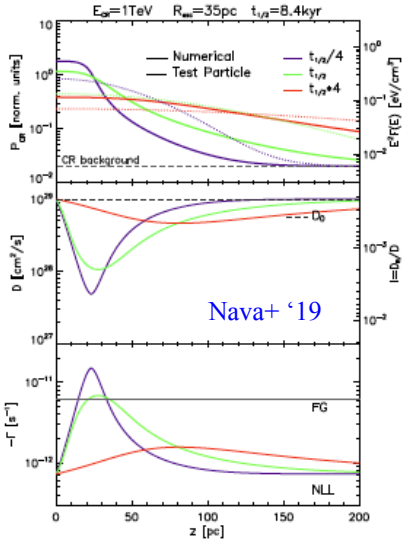
Escape of CRs from their sources:

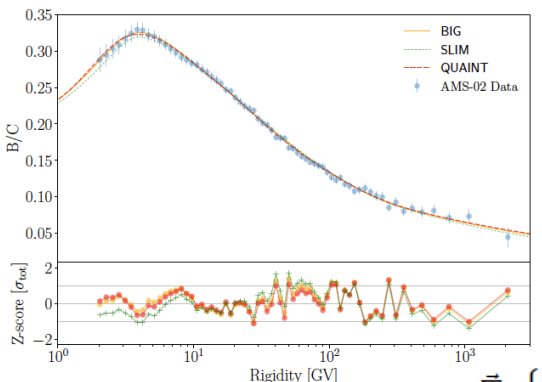
- Still not fully understood
- Important to understand transport + local direct measurements + diffuse emissions
- TeV halos + interactions with close molecular clouds + local HE positrons

A toy model

$$\frac{\partial P_{\rm CR}}{\partial t} + V_{\rm A}\frac{\partial P_{\rm CR}}{\partial z} = \frac{\partial}{\partial z}\left(\frac{D_{\rm B}}{I}\frac{\partial P_{\rm CR}}{\partial z}\right)$$

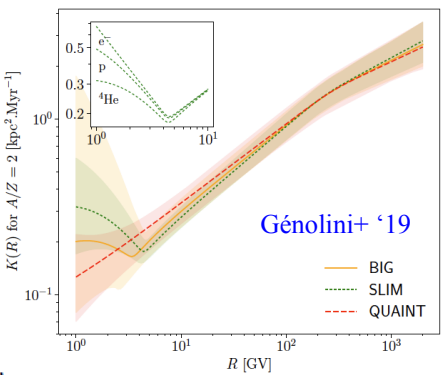
$$\frac{\partial I}{\partial t} + V_{\rm A}\frac{\partial I}{\partial z} = 2(\Gamma_{\rm CR} - \Gamma_{\rm d})I + Q$$





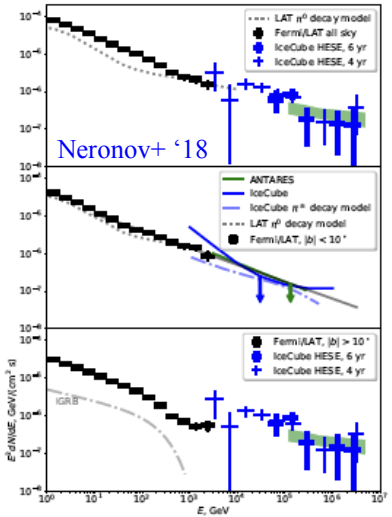
Probes of CR propagation in the Milky Way: secondaries/primaries (B/C)

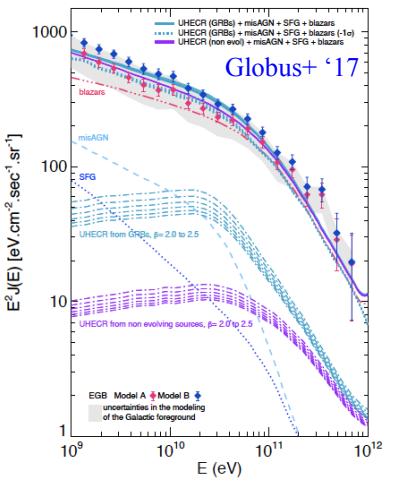
- Spectral breaks in diffusion coefficient
- Calibration of phenomenological propagation models
- Experimental systematics must be dealt with
- Large uncertainties from nuclear cross sections



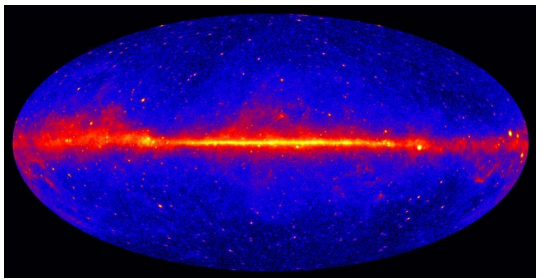
$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \vec{V}_{\rm c}\psi_\alpha\right\} + \frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\,\psi_\alpha - \beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\} + \sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha$$
$$= q_\alpha + \sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha}\right\}\psi_\beta\ .$$

Cosmic rays: sources, acceleration, propagation, interpretation of data





Fermi 10 yrs

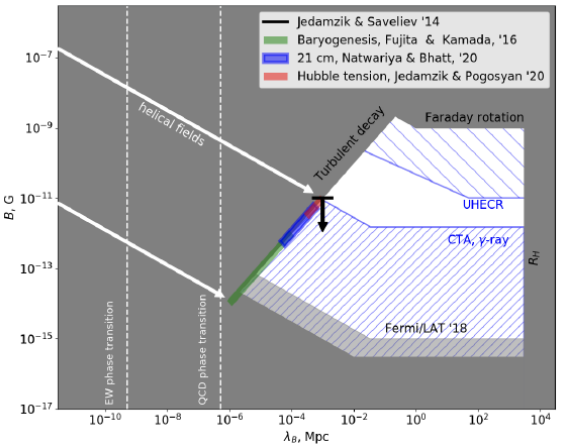


Other topics include:

- Diffuse emissions as probes of transport + ISM + B-field (complementarity with neutrinos)
- Galactic/extragalactic origin of Icecube neutrinos
- Diffuse EGB as probe of UHECR models
- CR anisotropy as probe of diffusion + local sources
- Transition btw Galactic/extragalactic
- …

Cosmological implications

- TeV gamma-rays from blazars as probes of IGMB
- CR pressure in galaxies + AGN feedback
- Etc.



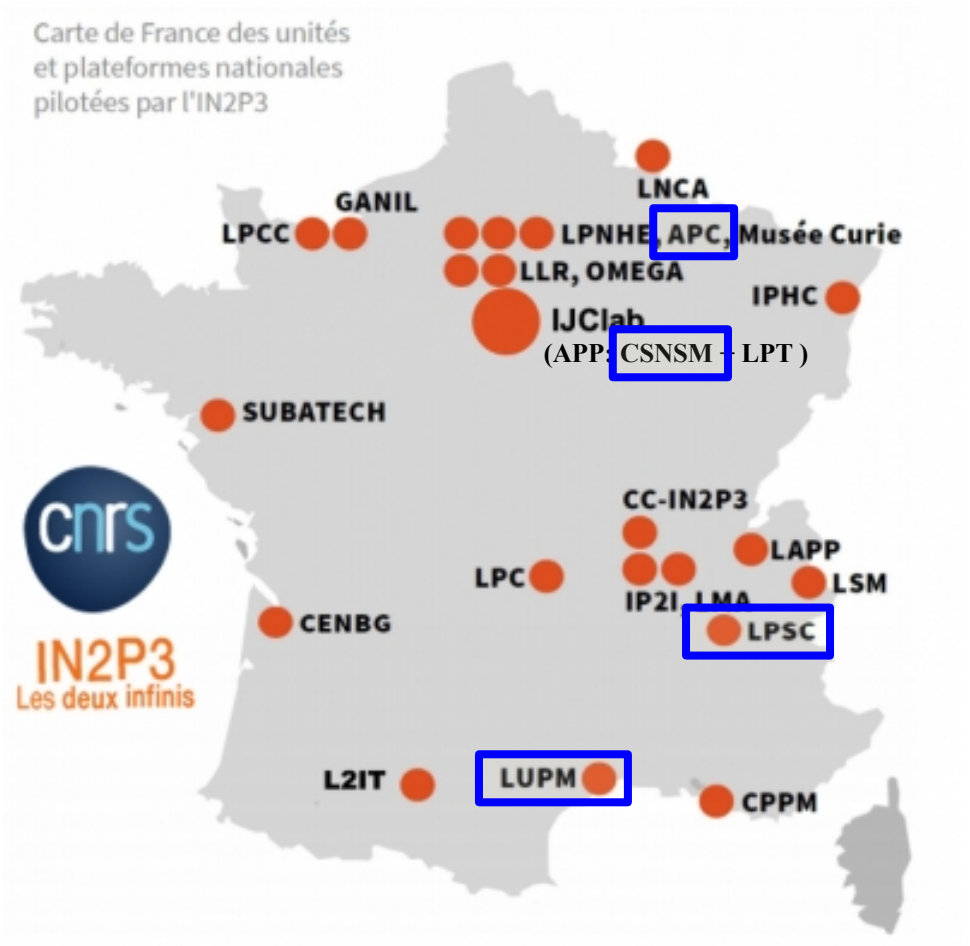
Koroshkin+ '20

Cosmic rays: sources, acceleration, propagation, interpretation of data

Miscellanea:

- Numerical codes: e.g. MHD-PIC-GR (AMR), USINE, etc.
- Prospects:
  - Th: simulations + compare with laser experiments
  - Improve links btw th/ph
- Ph: strong impact of observational data (CR: Voyager, AMS02 + diffuse) + (sources: Fermi, HESS/CTA, neutrinos)

- Self-structuring community:
  - INTERCOS Project (IN2P3)
  - Workshop series CFRCOS



Neutrinos in astrophysics

(Main) Questions

- Masses and mixings
- Role in stellar evolution / supernovae
- MSW + self-interactions in dense astrophysical media + strong gravity + decoherence-induced suppression of flavor oscillation
- Signatures of astrophysical processes (e.g r-processes)
- Neutron star properties from SN neutrino events
- Sterile neutrinos / leptogenesis / dark matter

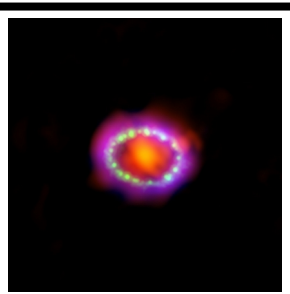
Theoretical methods/tools

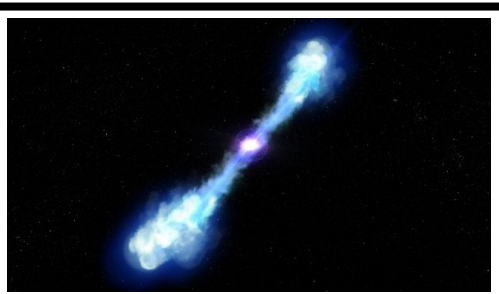
- QFT + symmetries (BSM)
- Quantum kinetic equations
- Many-body techniques (nuclear physics)
- Analytical/numerical methods

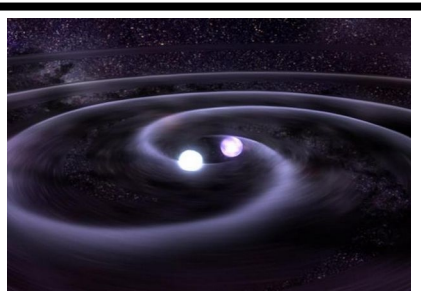
Observables

- MeV astrophysical neutrinos (diffuse + individual SNe)
- Complementarity with gravitational waves (mergers of neutron stars – kilonovae)
- Neutrino beam detectors
- Neutrinos in cosmology (Neff + LSS power spectrum)
- ...

Relevant IN2P3 experiments: Antares/KM3, JUNO, T2K, SuperNEMO, Planck, **VIRGO**, etc.







Richness and complexity of interdisciplinary or transversality,

bring new ideas, solutions to open problems and open novel directions

Neutrino Physics

Experiments

Low energy beta-beam

Volpe, Journ. Phys. G30, 2004

Ganil, GSI, Isolde

Cosmology

Neutrino properties, flavor mechanisms, cosmological neutrino detection

Lazauskas, Vogel, Volpe, J.Phys.G. 35, 2008

neutrino quantum kinetic equations

Froustey, Pitrou, Volpe, JCAP 12, 2020

Neff = 3.0440

Nuclear Physics

neutrino-Pb cross section, SN signal

Volpe et al, PRC65, 2002; Engel et al, PRD67, 2003

HALO (SNOLAB)

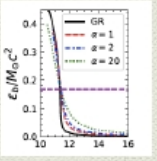
Gravitation

Gravity effects - ex. neutrino decoherence

Chatelain, Volpe, PLB 801, 2020

Neutrinos and EGR

Gallo Rosso, Abbar, Vissani, Volpe, JCAP 12, 2018

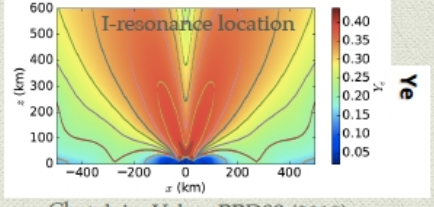


Neutrino astrophysics

many-body approaches (BBGKY) and neutrino propagation

Volpe et al, PRD87, 2013

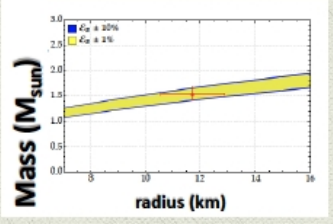
Flavor conversion, non-standard properties and the r-process



Chatelain, Volpe, PRD98 (2018)

Astroparticle physics

Properties of neutrinos or of astrophysical sources - ex. mass-radius of NS



Gallo Rosso, Vissani, Volpe, JCAP11, 2017

Neutrinos in astrophysics

Miscellanea:

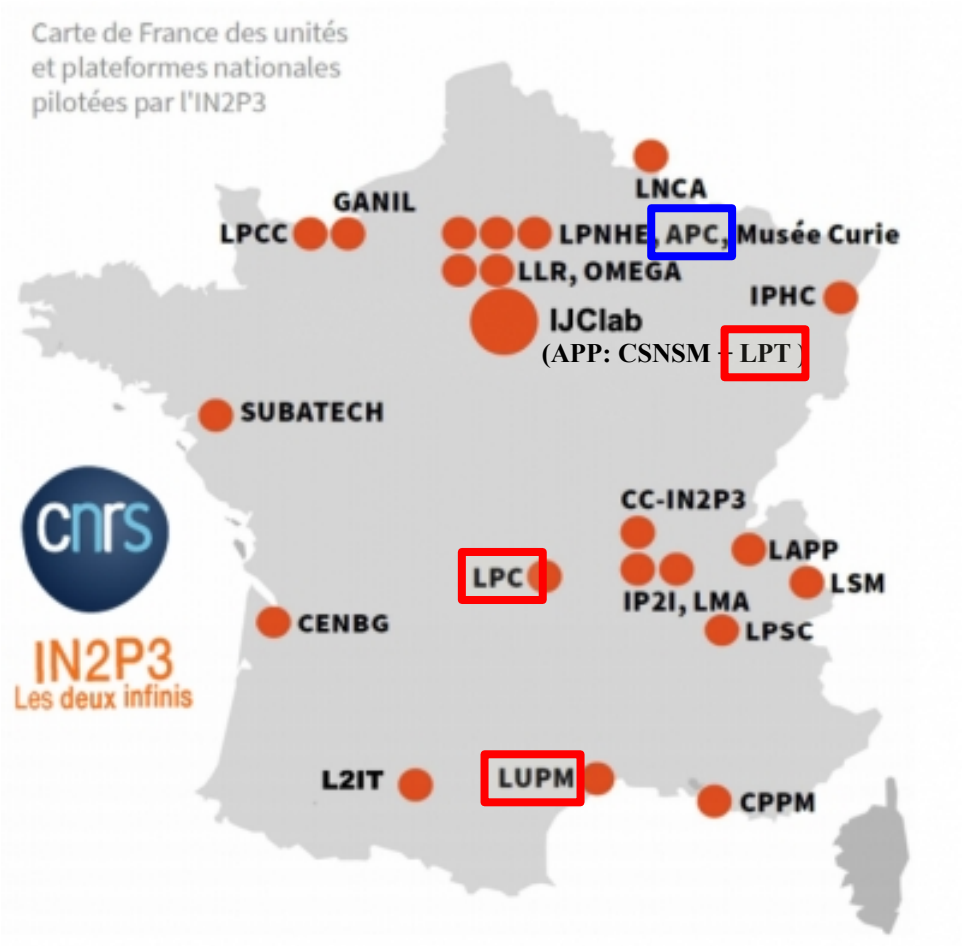
- MeV neutrinos: historical connexion with nuclear physics + astro of dense/compact objects

=> Strongly interdisciplinary + links with experiments

- Activities in BSM neutrinos more focused on LFV + leptogenesis + dark matter.

Astro/cosmo/nuclear aspects

BSM neutrinos



Dark matter in astroparticle physics

(Main) Questions

- Links with other fundamental issues?
- Interaction properties with visible/dark sectors
- Production mechanisms in early universe
- Astrophysical signatures: annihilation/decay, (other types if PBHs), stellar capture/evolution.
- Astrophysical backgrounds
- Phase-space distribution + structuring on small scales
- Mixed scenarios

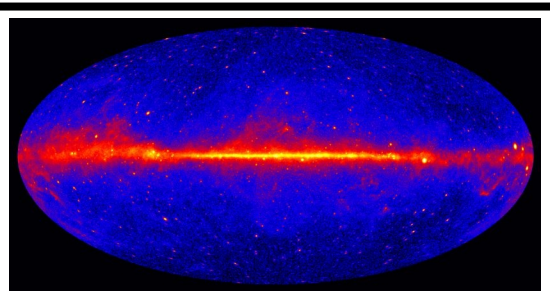
Theoretical methods/tools

- BSM model building (top-down)
- Simplified model approaches (tree-level interactions – bottom-up)
- Evolution of phase-space DFs in early universe or astrophysical systems (abundance, free-streaming, DFs in galaxies)
- Structure formation + subhalos
- Newtonian dynamics
- (all the physics relevant to deal with astrophysical backgrounds)

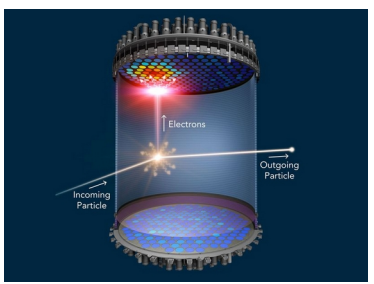
Observables

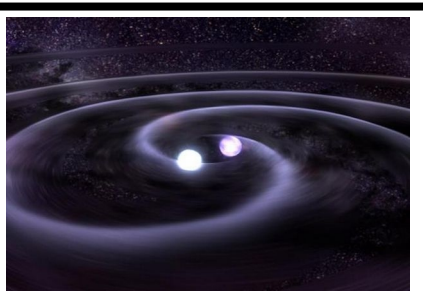
- Multimessenger astrophysical spectra (indirect detection)
- Observation of identified DM targets
- Direct detection
- Complementarity with collider + cosmological probes

Relevant IN2P3 experiments: LHC, HESS/CTA, Fermi, AMS, Antares/KM3, JUNO, Edelweiss, Xenon-1/nt, Planck, LSST, Euclid, **VIRGO**, etc.



Dark Matter candidates and induced phenomena





Dark matter in astroparticle physics

Can hardly be separated from cosmology

Evolutive context

- No new physics observed at the LHC so far
- WIMP parameter space being explored by experiments/observations
- Small-scale "problems" of the cold dark matter (CDM) paradigm: baryonic effects or DM properties?
- Cosmological tensions: impact of DM?
- Ligo/Virgo events: primordial black holes (PBHs) as a "background noise"

Particle physics landscape

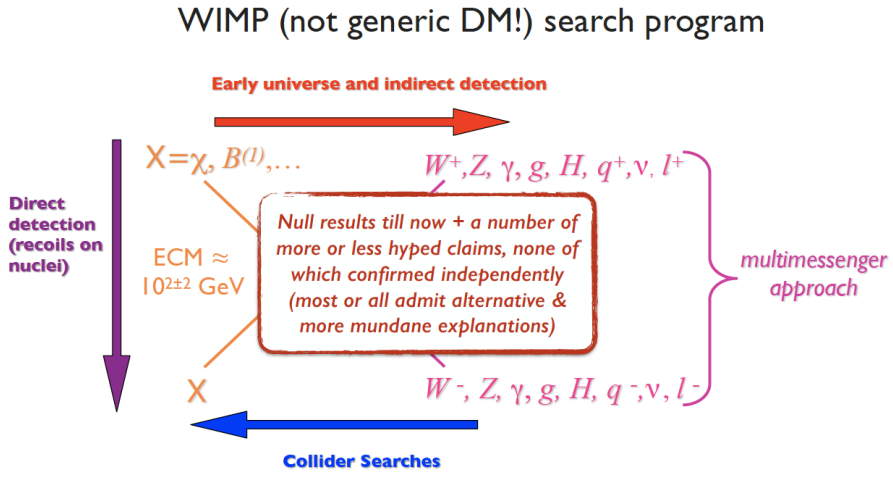
- Long-standing expertise in BSM model building related to the EW hierarchy pb: supersymmetry, extra-dims, compositeness
- Increasing interest in other frameworks: axions (CP strong) and sterile neutrinos (masses/leptogenesis)
- Effective approaches

=> Input: self-consistent particle models, interaction cross sections (abundance + searches), constraints from colliders

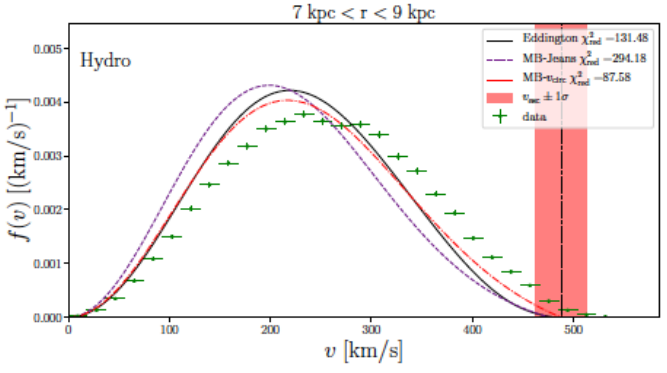
Astrophysics/cosmology

- Evolution of phase-space distribution functions in various environments: early universe (production + thermal/chemical contact/decoupling), galaxies (velocity distribution of particles – DD, p-wave Sommerfeld effect, etc.)
- Impact of interactions in primordial plasma perturbations
- Dark matter distribution in (and identification of) astrophysical targets: halo shapes
- Structuring on small scales: subhalos
- Multimessenger astrophysical probes + astrophysical backgrounds
- Non-particles: PBHs, classical fields

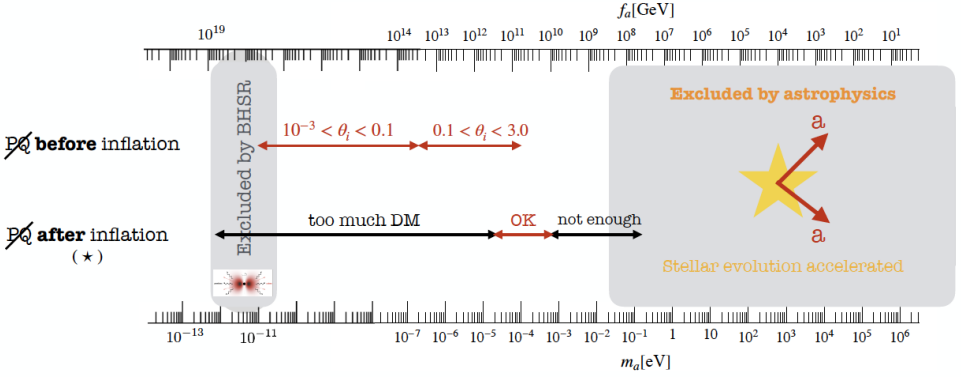
Dark matter in astroparticle physics



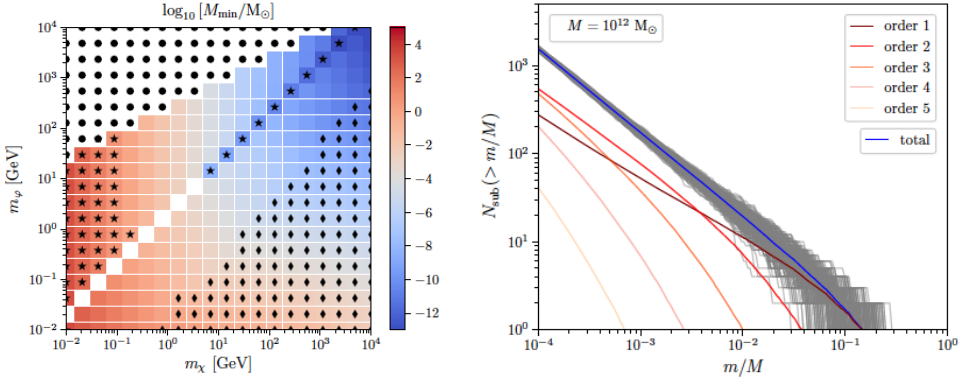
P. Serpico @ atelier théorie: try building from gravitational hints



Lacroix+'18: predictions of v DFs vs. simulations
=> theoretical errors in DD + v-dependent signals



Axions: J. Quevillon @ atelier théorie ++++ Strong links with GrAHal (haloscope @ LPSC)



Facchinetti+'21: analytical models of subhalos
=> accounts for PP properties + structure formation (excursion set theory)

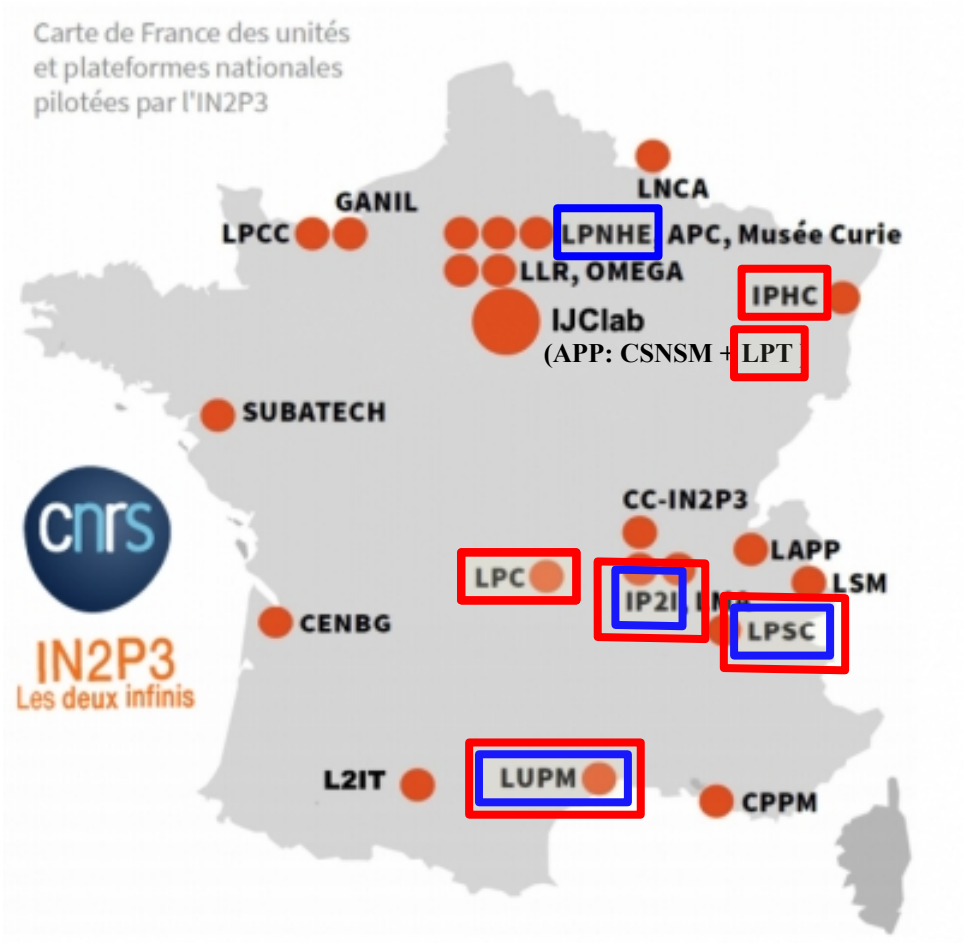
Dark matter

Miscellanea

- Strongly interdisciplinary + inter-institute (INSU/IN2P3/INP/CEA)
- Particle physics aspects covered by IRN Terascale
- IN2P3-Projects on axions (PI @ LPSC) and production (PI @ IJCLab)
- Public codes: NMSSMTools, SuperISO, MARTY, AlterBBN, BlackHawk, Clumpy
- Astro/cosmo on the way of structuring itself

Astro/cosmo aspects

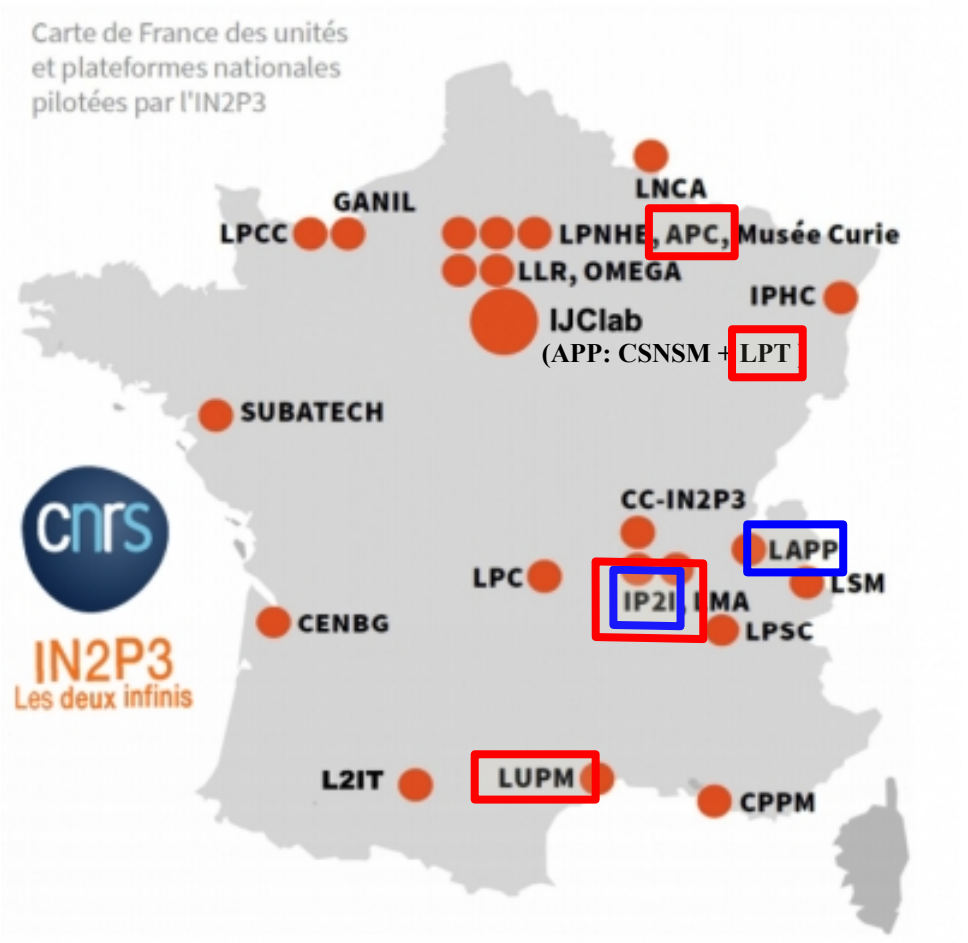
Particle Physics aspects



Dark matter / PBHs

Miscellanea

- Revived interest with GWs
- Long-standing expertise @ IN2P3
- Links with inflation
- Astrophysical backgrounds = astrophysical compact objects



GR + standard astro

PBHs / modified grav.

Summary

General comments:

- Activities spread over IN2P3+INSU+INP+CEA => small collaborations rather easy
- IN2P3 scientists happy with IN2P3 environment – difficulties may come when bridging with other institutes (except PNx-INSU)
- "APP community" rather diverse, structuring depends on topics
- Groups have international impact in all fields
- Non-linear th aspects: heavy simulation tools developed (extreme environments, instabilities, multi-scale in space and time, etc.).
- Links with experiments/projects rather strong in CR astrophysics (ph), neutrinos, axions.
- Dark matter = multi-candidates + multi-probes
- **Strongly interdisciplinary approaches:**
  - CRs = Astro + plasma + electrodynamics + nuclear interactions
  - Neutrinos = PP + oscillation in dense media + nuclear physics
  - DM = astro + cosmo + PP

  => sometimes difficult for young scientists looking for jobs