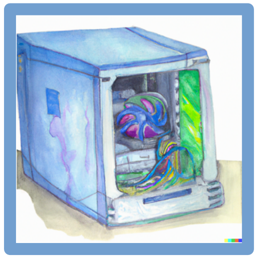
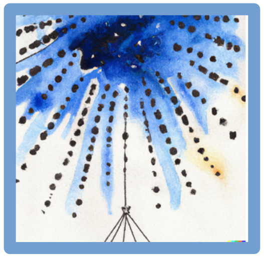
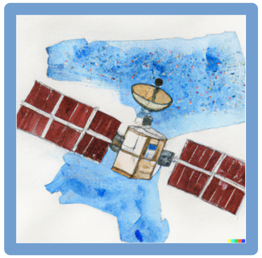
High Performance Computing in astroparticle theory



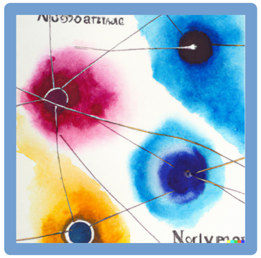
GPUs



Cosmic rays



Gamma rays



Multimessenger

Yoann Génolini

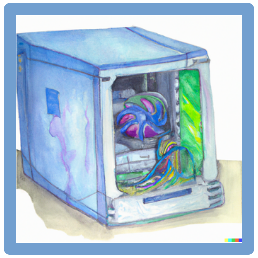
LAPTh

UNIVERSITÉ SAVOIE MONT BLANC

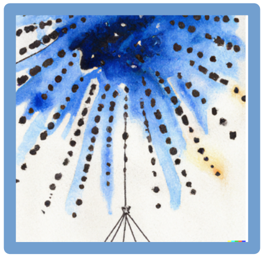
cnrs

Gray Scott Reloaded 2024

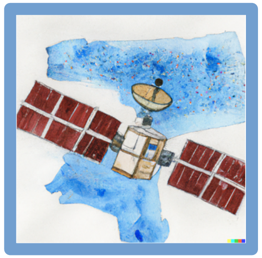
High Performance Computing
in astroparticle theory



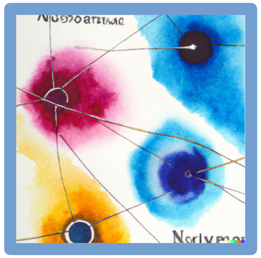
GPUs



Cosmic rays



Gamma rays



Multimessenger

Acknowledgments:

Enigmass & MUST &

Pierre Aubert

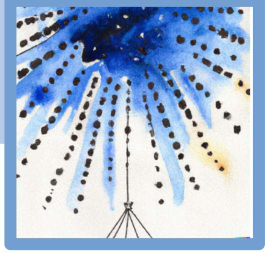
Yoann Génolini

LAPTh

UNIVERSITÉ SAVOIE MONT BLANC

Gray scott school

cnrs



What is the origin of cosmic rays?

(multiples underlying questions)

Direct observable: Local differential flux

$$\Psi_i = \frac{dN_i}{dE\, dT\, d\Omega\, dS}$$

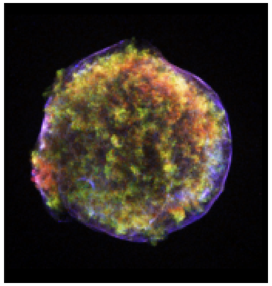
→ Charged particles : Lorentz's force

$$R_L(1\,\mathrm{PeV}) = 1\,\mathrm{pc} \ll 100\,\mathrm{pc}$$

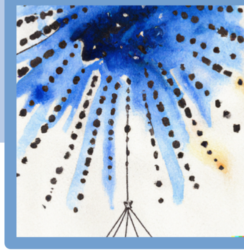
→ What are the generic properties of the CR sources/transport?

→ What is the interstellar B field?

Indirect observables in multi-wavelengths



→ Non-thermal processes: pinpoint potential CR sources
→ What are the environments of acceleration and injection?

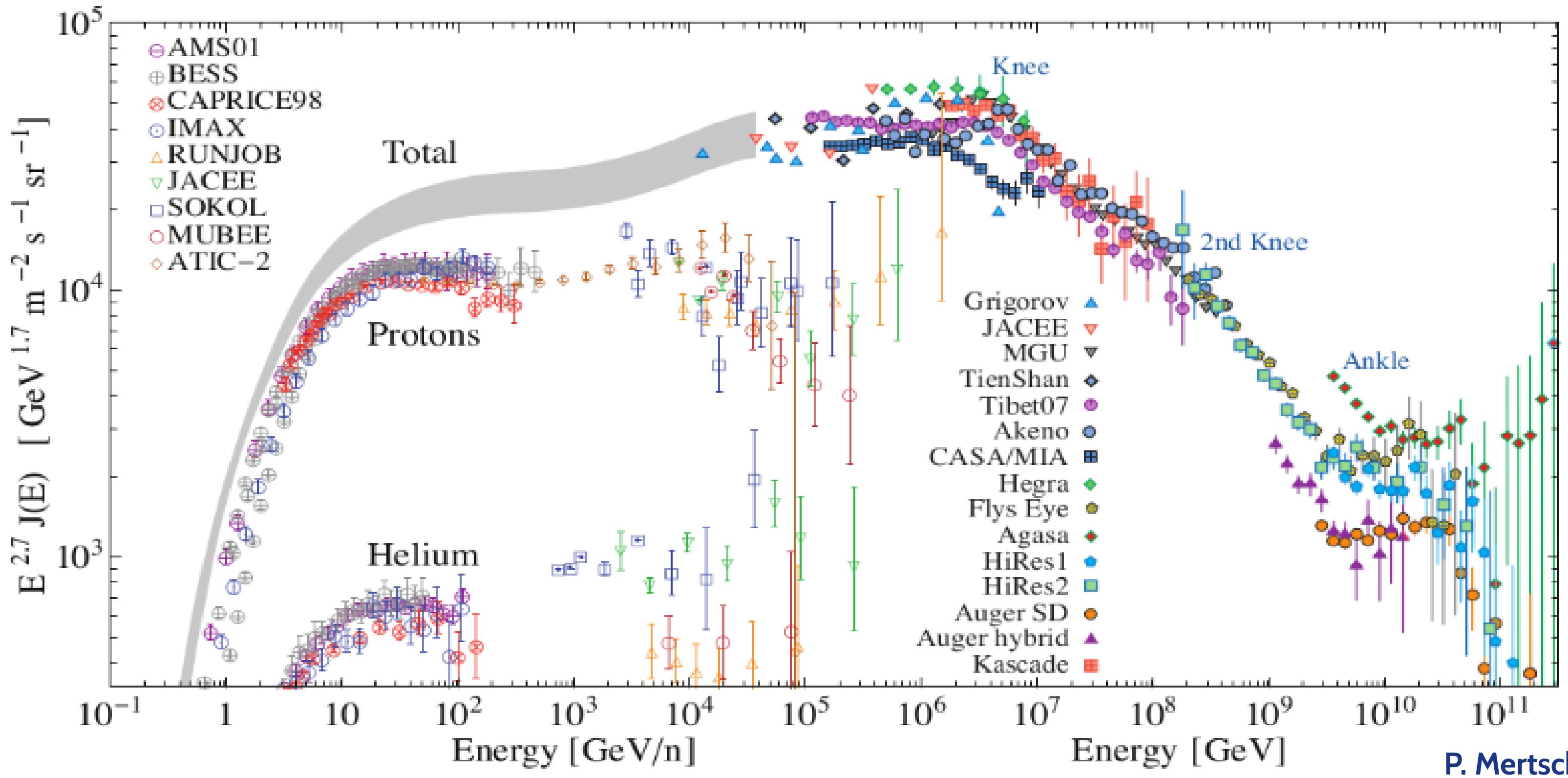


Differential flux:
$$\Psi_i = \frac{dN_i}{dE\,dT\,d\Omega\,dS}$$

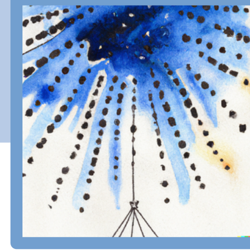
Energy

Composition

Direction



P. Mertsch PhD (2010)



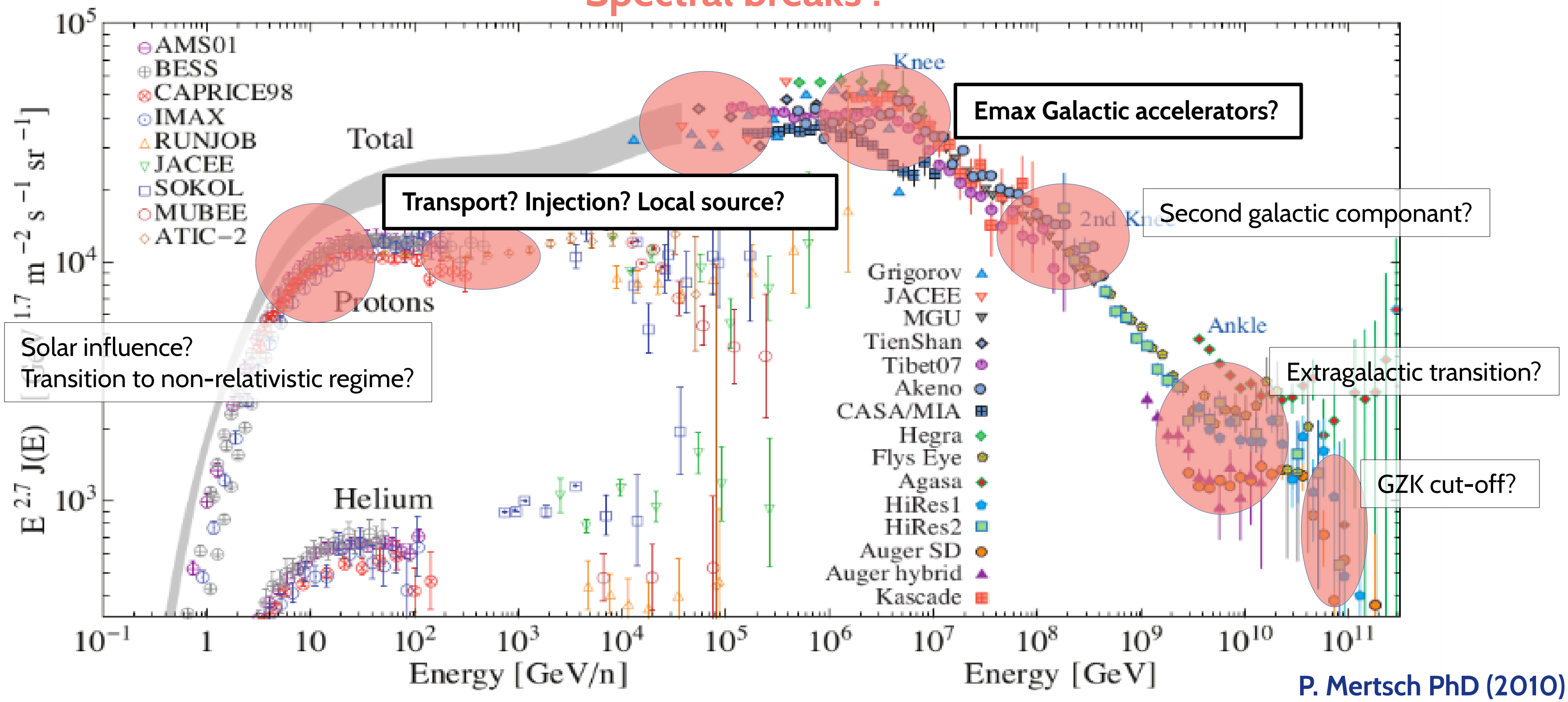
Differential flux: $$\Psi_i = \frac{dN_i}{dE\, dT\, d\Omega\, dS}$$

Energy

Composition

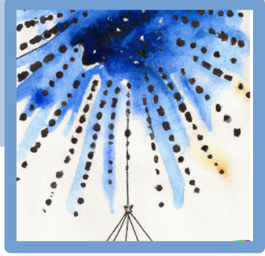
Direction

Spectral breaks !



P. Mertsch PhD (2010)

Introduction

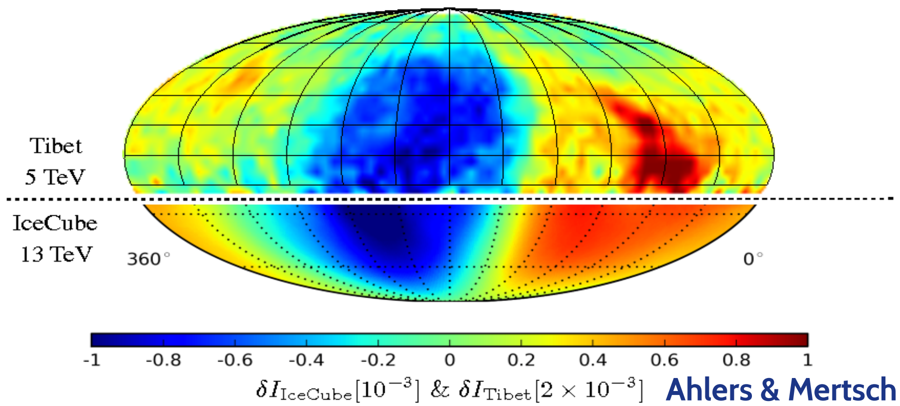


Differential flux:

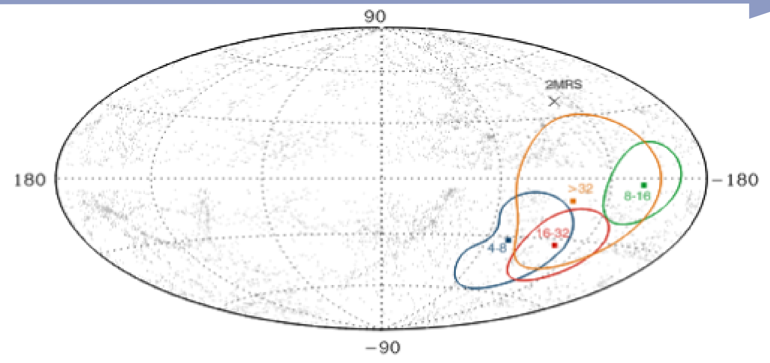
$$\Psi_i = \frac{dN_i}{dE\,dT\,d\Omega\,dS}$$

Energy | **Composition** | **Direction**

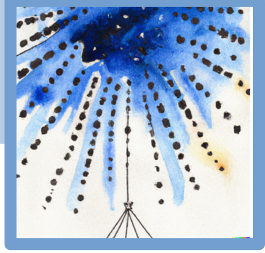
TeV | EeV



Ahlers & Mertsch PPNP (2016)



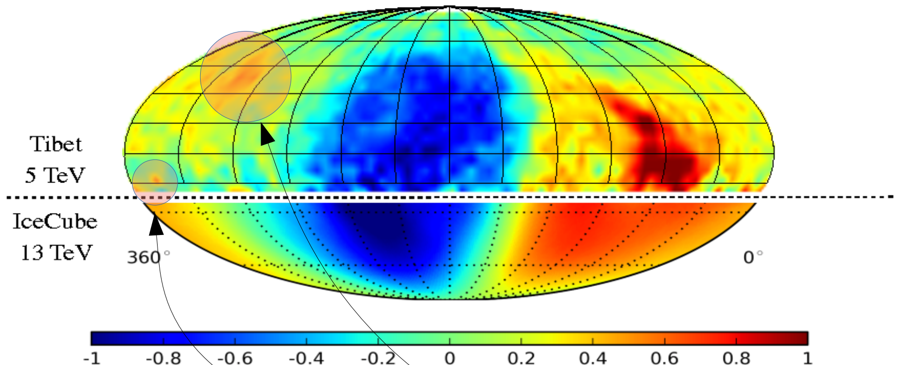
Auger collab. ApJ 868 (2018)



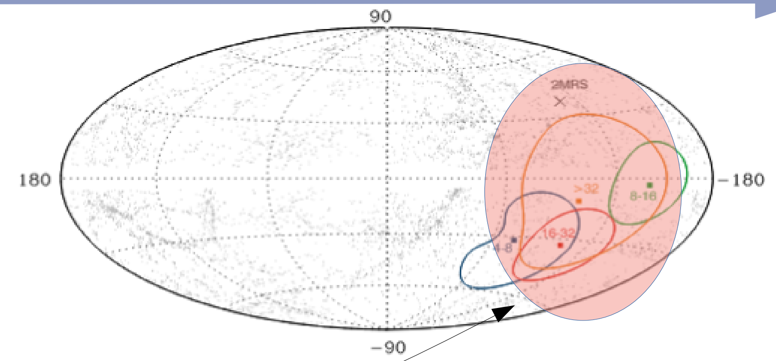
Differential flux: $$\Psi_i = \frac{dN_i}{dE\,dT\,d\Omega\,dS}$$

Energy | **Composition** | **Direction**

TeV → **EeV**



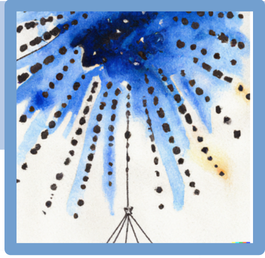
Ahlers & Mertsch PPNP (2016)



Auger collab. ApJ 868 (2018)

Multi-scale anisotropies

→ In the following we focus on the dipole anisotropy



Data

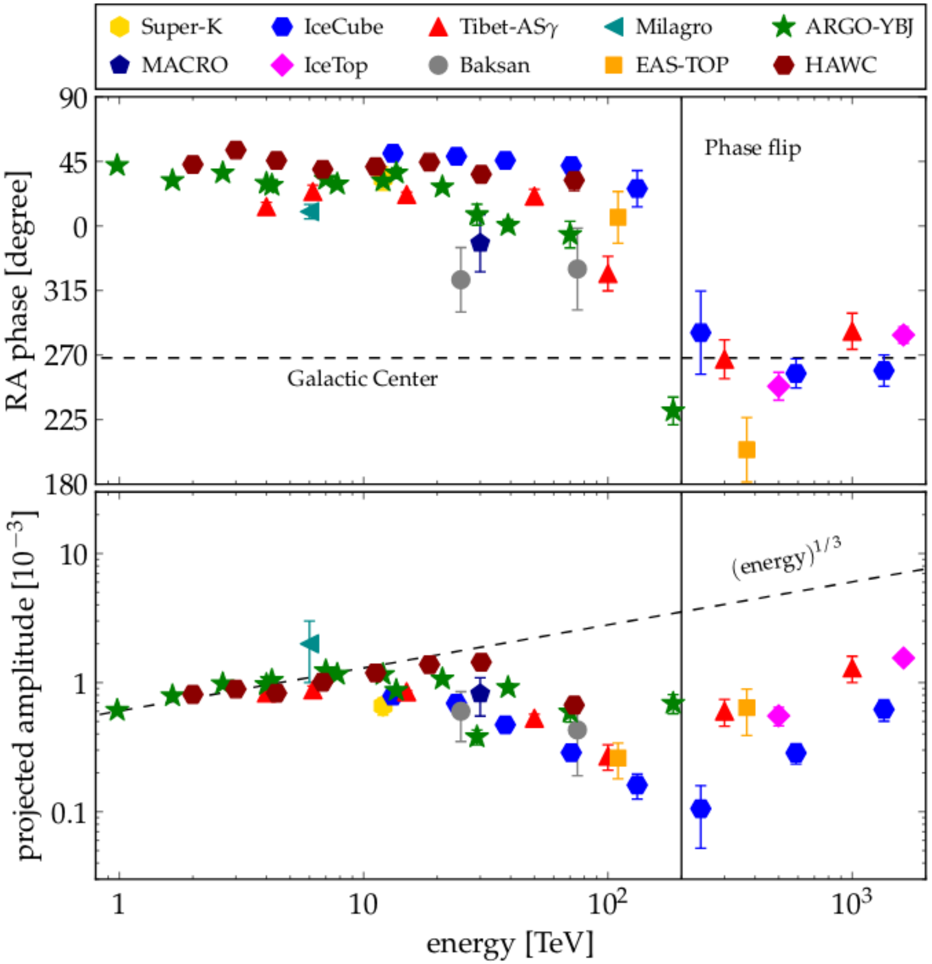
→ Relative intensity can be decomposed as:

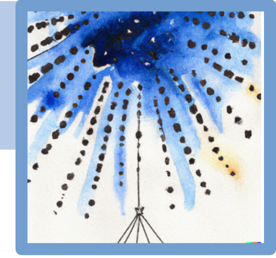
$$I(\boldsymbol{n}) = 1 + \boldsymbol{\delta} \cdot \boldsymbol{n} + \mathcal{O}(Y_{l>1})$$

→ CR observatories sensitive to 2 param.

→ Small dipole anisotropy of GCRs

→ Rapid change of the phase & amplitude with E





Data

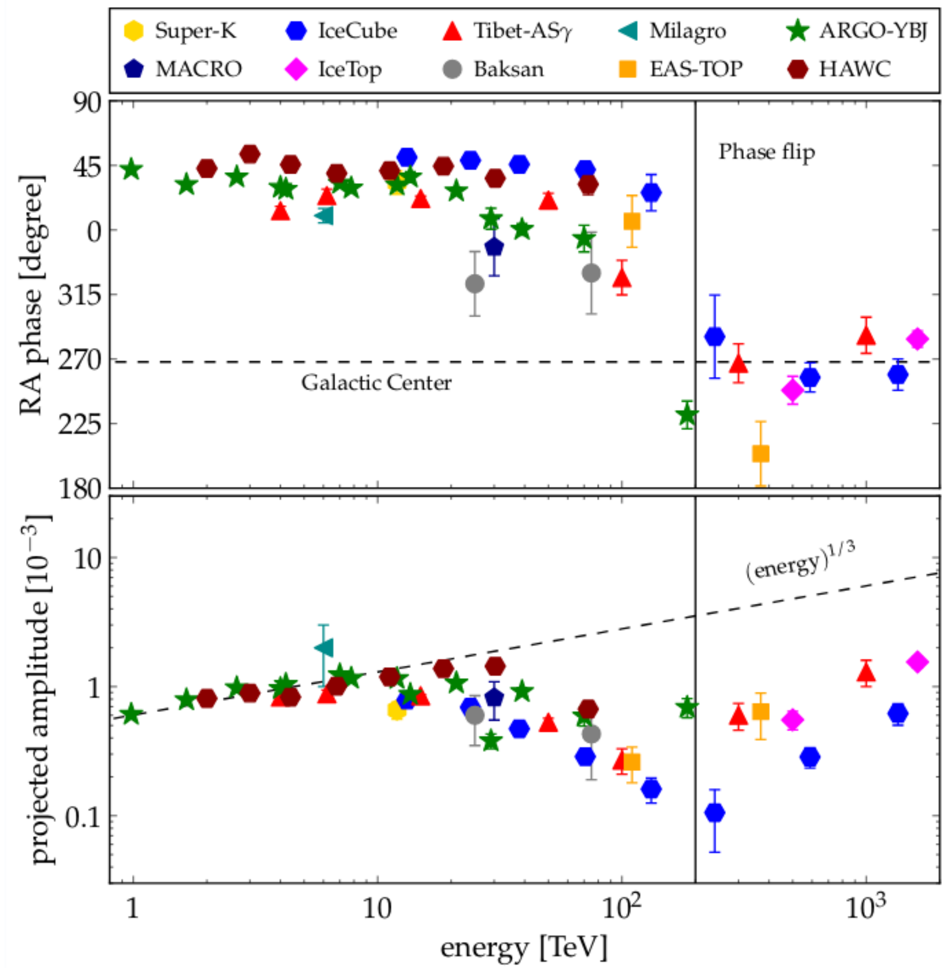
→ Relative intensity can be decomposed as:

$$I(\boldsymbol{n}) = 1 + \boldsymbol{\delta} \cdot \boldsymbol{n} + \mathcal{O}(Y_{l>1})$$

→ CR observatories sensitive to 2 param.

→ Small dipole anisotropy of GCRs

→ Rapid change of the phase & amplitude with E



Interpretation

$$\boldsymbol{\delta} \;\propto\; \boldsymbol{j}_{\rm CR}$$

→ Compton Getting effect?
Small in the local standard of rest

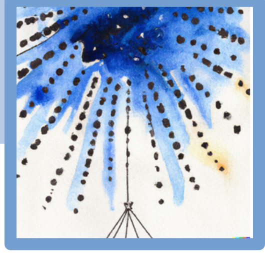
→ Diffusion approximation

Fick's law: $\boldsymbol{j}_{\rm CR} = -\boldsymbol{K} \cdot \nabla\Psi$

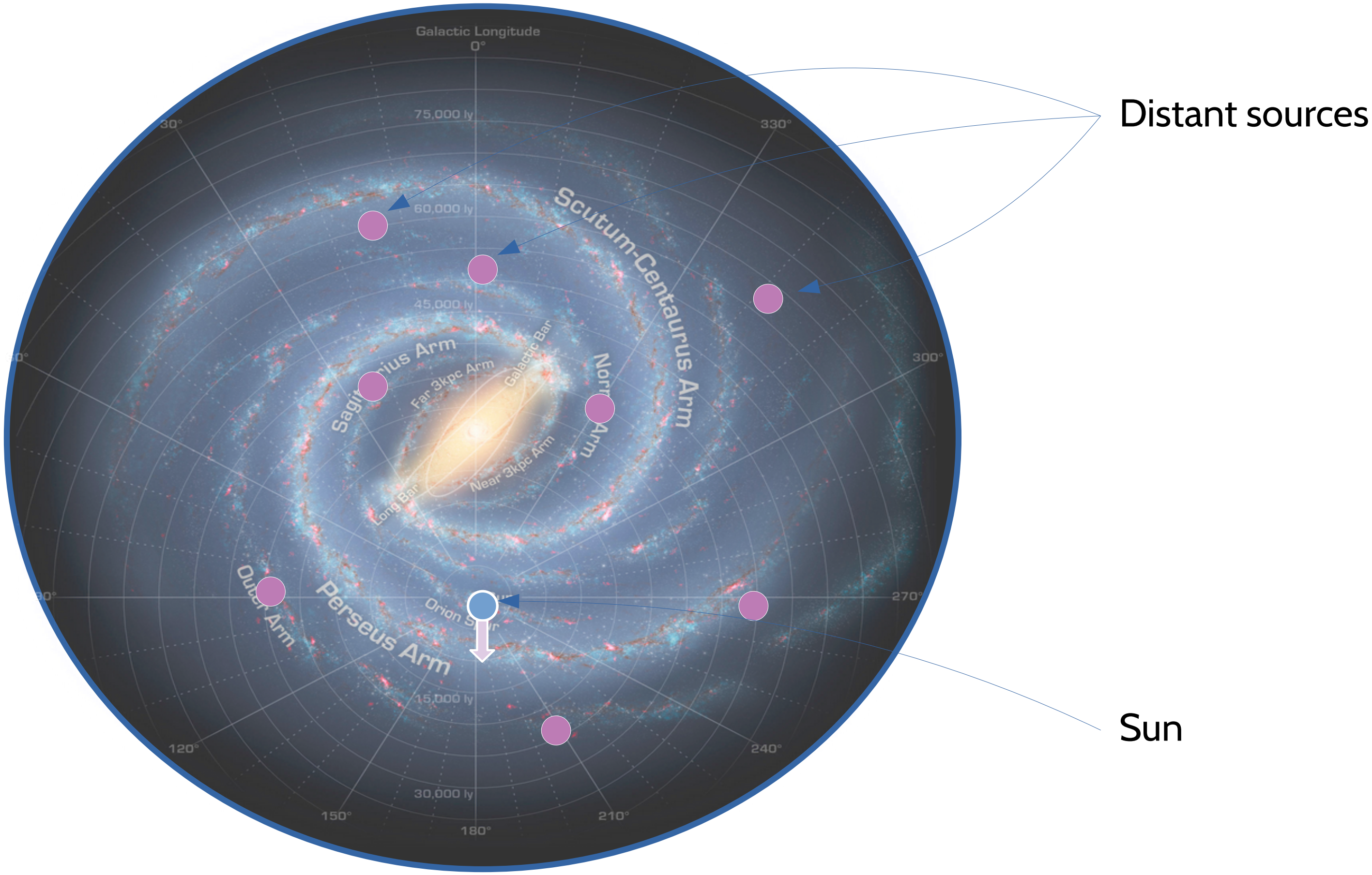
Energy dependence at odd with diffusion

Depends on:
- Distribution of sources and halo geometry halo?
- Structure of local magnetic field?

→ **Both!**

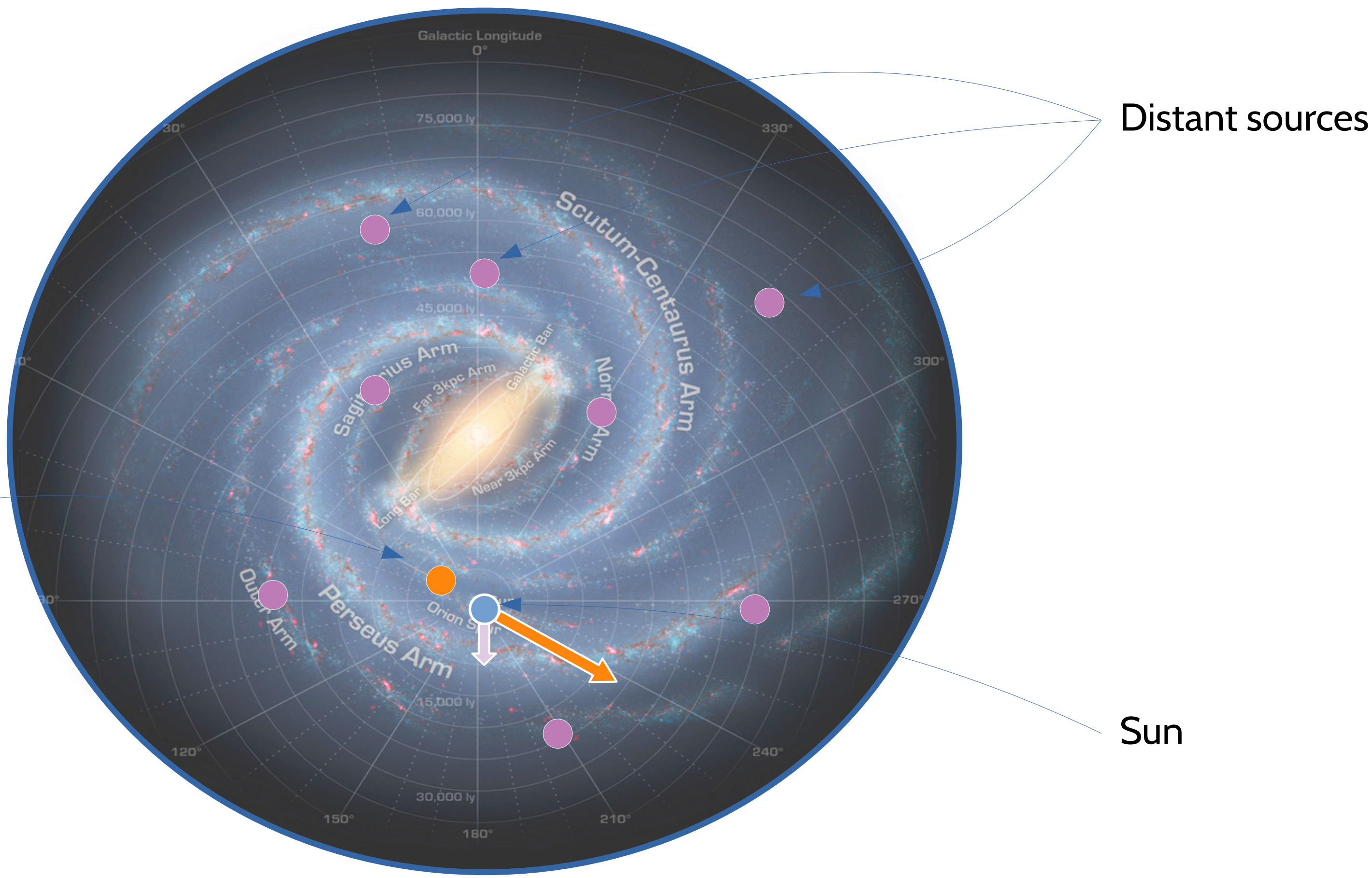


Effect of a local source on the anisotropy

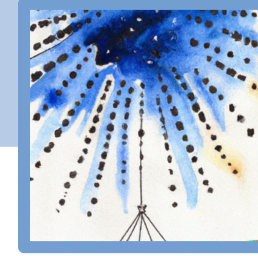


Effect of a local source on the anisotropy

$$j_{\mathrm{CR}} = -\boldsymbol{K} \cdot \nabla\Psi$$

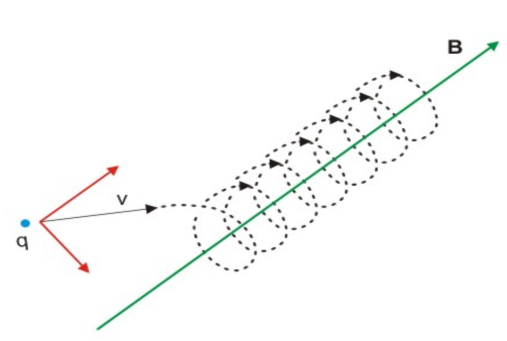


→ Local sources may dominate the dipole but not the flux



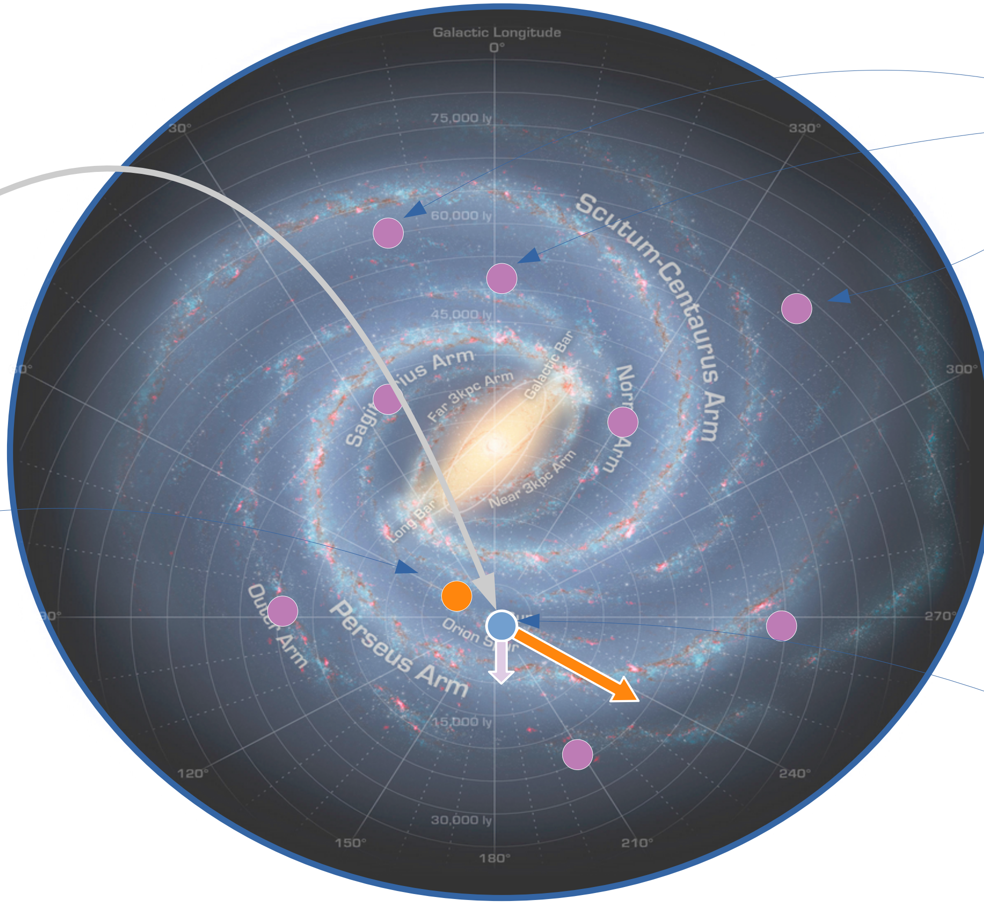
Effect of a local source on the anisotropy

$$j_{\mathrm{CR}} = -\boxed{\boldsymbol{K}} \cdot \boxed{\nabla\Psi}$$



→ Projection effect

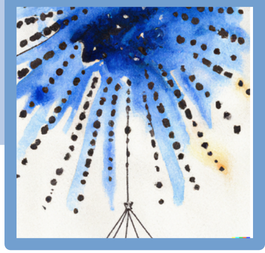
Close source



Distant sources

Sun

→ Local sources may dominate the dipole but not the flux



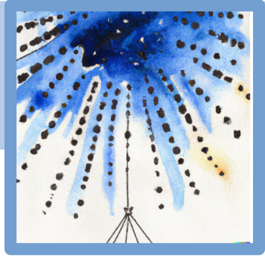
Formalism

Angular power spectrum of CR arrival directions:

$$\frac{C_\ell}{4\pi} \simeq \int \frac{\mathrm{d}\widehat{\mathbf{p}}_1}{4\pi} \int \frac{\mathrm{d}\widehat{\mathbf{p}}_2}{4\pi} P_\ell(\widehat{\mathbf{p}}_1 \widehat{\mathbf{p}}_2) \lim_{\tau\to\infty} \left(\Delta r_{1i}(-\tau)\Delta r_{2j}(-\tau)\right) \frac{\partial_i n \partial_j n}{n^2}$$

Ahlers & Mertsch AJL (2015)

CR dipole power: $\frac{C_1}{4\pi} \simeq \mathrm{S}_{ij} \frac{\partial_i n \partial_j n}{n^2}$ with $\mathbf{S} \equiv \mathcal{K}^T \mathcal{K}$ and $\mathcal{K}_{ij} \equiv \lim_{\tau\to\infty} \langle \widehat{p}_i(0) \Delta r_j(-\tau) \rangle_\Omega$



Formalism

Angular power spectrum of CR arrival directions:

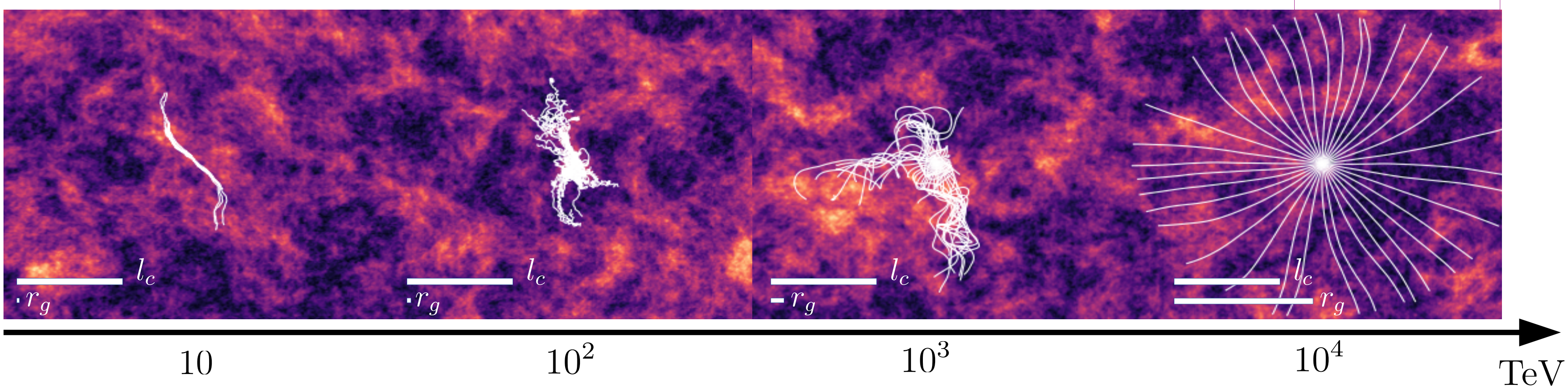
$$\frac{C_\ell}{4\pi} \simeq \int \frac{\mathrm{d}\widehat{\mathbf{p}}_1}{4\pi} \int \frac{\mathrm{d}\widehat{\mathbf{p}}_2}{4\pi} P_\ell(\widehat{\mathbf{p}}_1 \widehat{\mathbf{p}}_2) \lim_{\tau\to\infty} (\Delta r_{1i}(-\tau)\Delta r_{2j}(-\tau)) \frac{\partial_i n \partial_j n}{n^2}$$

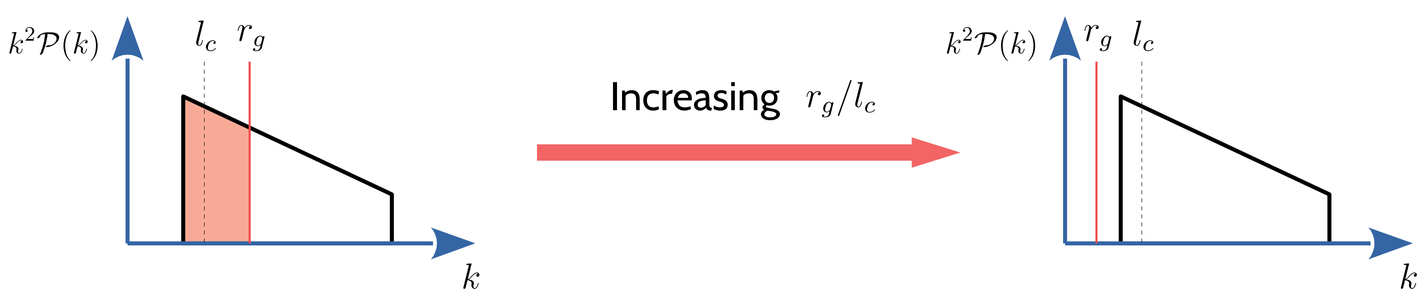
Ahlers & Mertsch AJL (2015)

CR dipole power: $\frac{C_1}{4\pi} \simeq \mathrm{S}_{ij} \frac{\partial_i n \partial_j n}{n^2}$ with $\mathbf{S} \equiv \mathcal{K}^T \mathcal{K}$ and $\mathcal{K}_{ij} \equiv \lim_{\tau\to\infty} \langle \widehat{p}_i(0) \Delta r_j(-\tau)\rangle_\Omega$

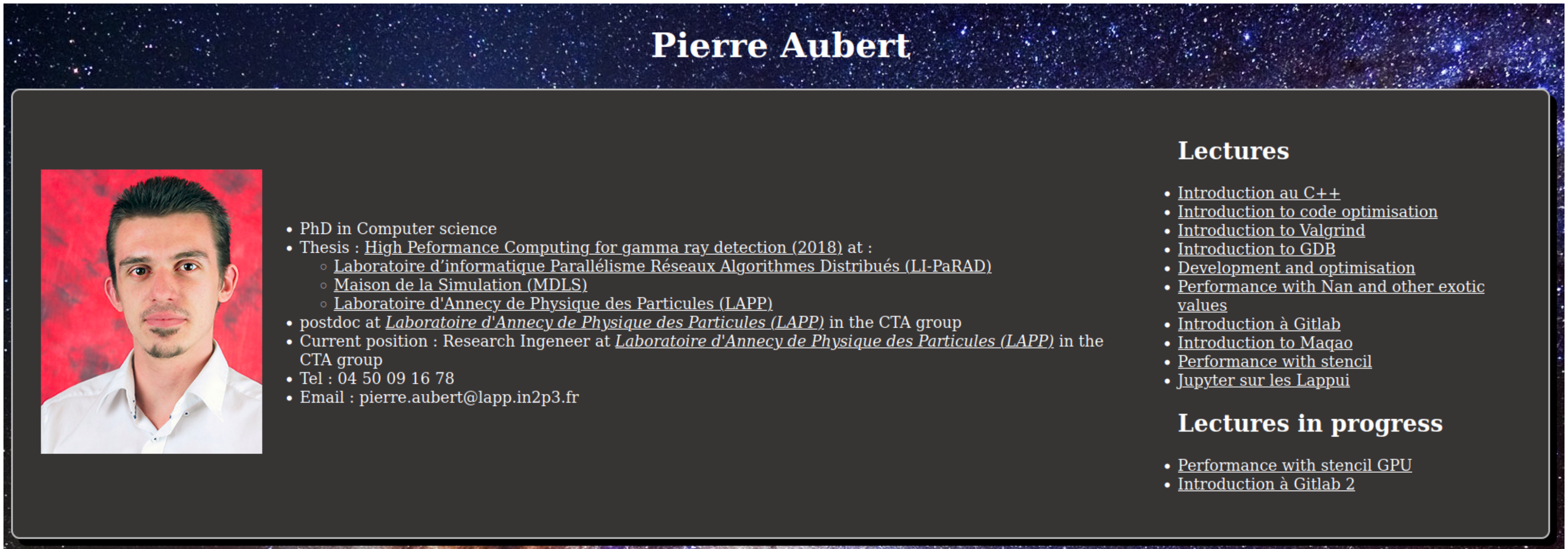
→ **Study the diffusion tensor with test-particle simulations**: backtracking in **isotropic turbulence**

$$l_c = 2\,\mathrm{pc}$$
$$B_{\mathrm{rms}} = 4\mu\mathrm{G}$$





WANTED!!



Pierre Aubert

- PhD in Computer science
- Thesis : High Peformance Computing for gamma ray detection (2018) at :
  - Laboratoire d'informatique Parallélisme Réseaux Algorithmes Distribués (LI-PaRAD)
  - Maison de la Simulation (MDLS)
  - Laboratoire d'Annecy de Physique des Particules (LAPP)
- postdoc at *Laboratoire d'Annecy de Physique des Particules (LAPP)* in the CTA group
- Current position : Research Ingeneer at *Laboratoire d'Annecy de Physique des Particules (LAPP)* in the CTA group
- Tel : 04 50 09 16 78
- Email : pierre.aubert@lapp.in2p3.fr

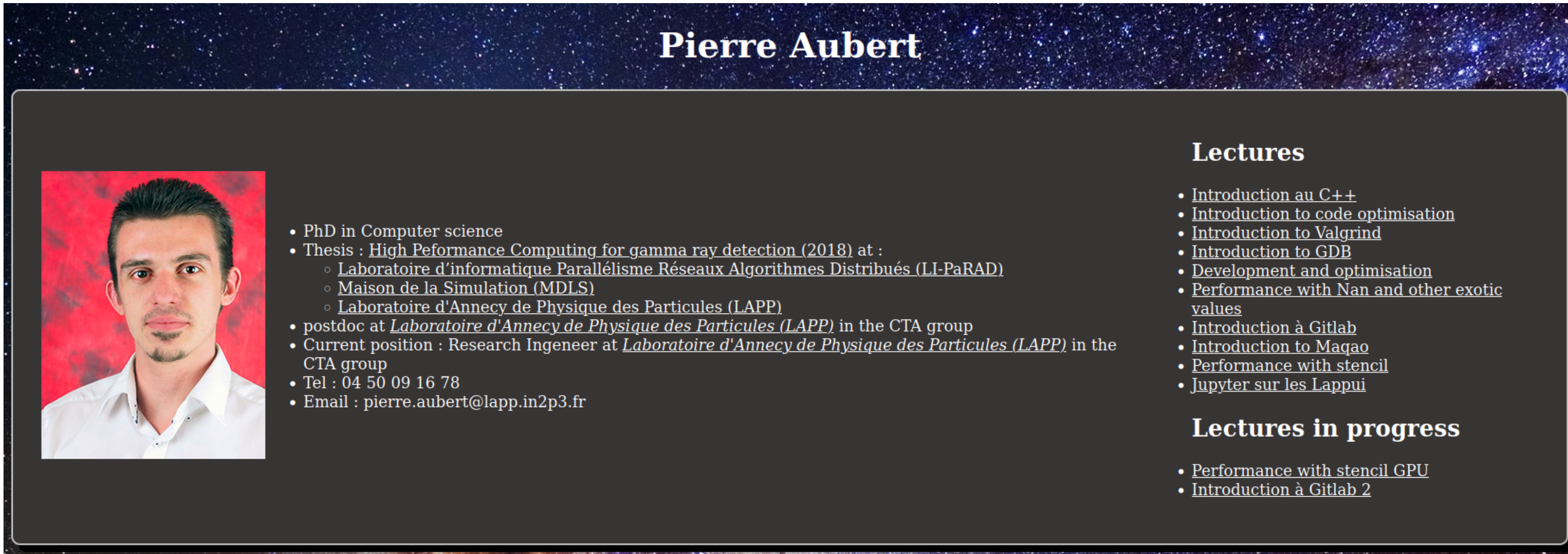
Lectures

- Introduction au C++
- Introduction to code optimisation
- Introduction to Valgrind
- Introduction to GDB
- Development and optimisation
- Performance with Nan and other exotic values
- Introduction à Gitlab
- Introduction to Maqao
- Performance with stencil
- Jupyter sur les Lappui

Lectures in progress

- Performance with stencil GPU
- Introduction à Gitlab 2

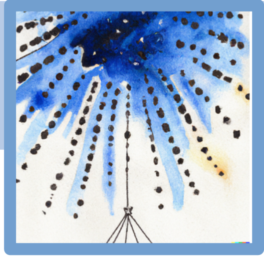
WANTED!!

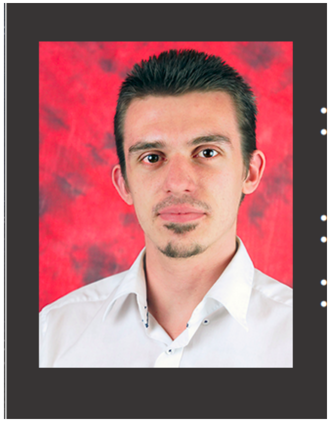


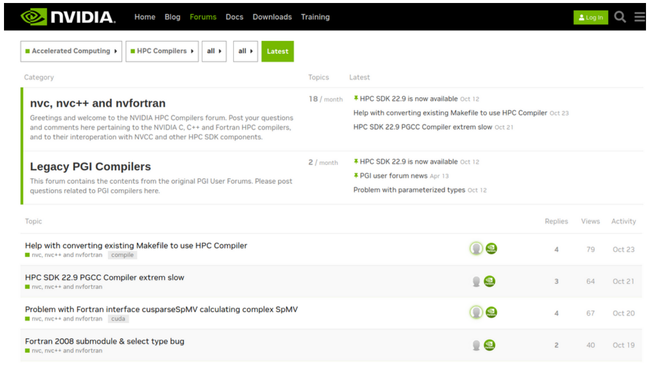
https://lappweb.in2p3.fr/~paubert/

Rewrite your code introducing the functions of the algorithm library (C++ 17):
→ https://en.cppreference.com/w/cpp/algorithm

Compile with NVC++
→ Done!





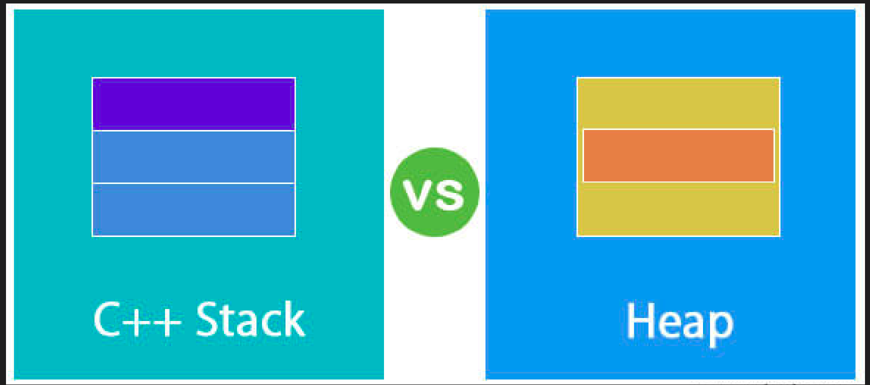


https://forums.developer.nvidia.com/c/accelerated-computing/hpc-compilers/299

Solutions!

Example : one of my problems...

```cpp
/***************************************
	Auteur : Pierre Aubert
	Mail : pierre.aubert@lapp.in2p3.fr
	Licence : CeCILL-C
*****************************************/

#include <iostream>
#include <vector>

#include <algorithm>

//Some doc at : https://en.cppreference.com/w/cpp/header/execution
#include <execution>

int main(int argc, char** argv){
	size_t nbElement(100000000);
	std::vector<float> tabX, tabY, tabRes;
	tabRes.resize(nbElement);
	for(size_t i(0lu); i < nbElement; ++i){
		tabX.push_back(i*19lu%11);
		tabY.push_back(i*27lu%19);
	}

	std::vector<float> test;
	test.resize(2);
	test[0]=1.;
	test[1]=2.;

	double q = 10.0;

	float * test_ptr = test.data();

	std::transform(std::execution::par_unseq, std::begin(tabX), std::end(tabX), std::begin(tabY), std::begin(tabRes),
			[test_ptr, q](float xi, float yi){ test_ptr[0]=5.0; return test_ptr[1]*xi*yi; });

	std::cout << "x = " << tabX.front() << ", y = " << tabY.front() << ", res = " << tabRes.front() << ", test_yo = "<< test[0] << std::endl;
	return 0;
}
```

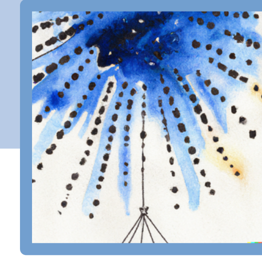


https://www.youtube.com/watch?v=wJ1L2nSIV1s

The GPU can only acess allocated (heap) memory (It relies on CUDA Unified Memory)

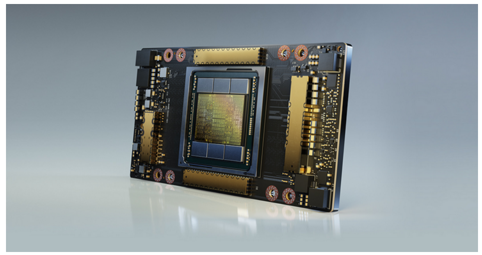
Need to pass the pointer of vectors and not the vector (stack variable)

Tests de performance



GPU *vs* **CPU**

(Graphics Processing Units) — (Central Processing Unit)

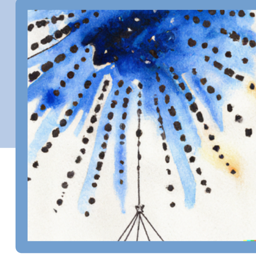


GPU A100
40 x 3145728 particules/38 min → 55188 part/seconde → **gain = 155**

GPU V100
3145728 particules/14 min → 5242 part/seconde → **gain = 15**

GPU P6000
3145728 particules/44 min → 1191 part/seconde → **gain = 3.4**

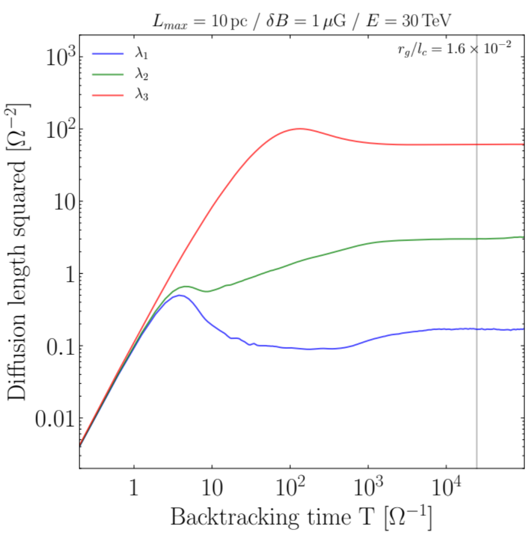
My computer (with tbb, 8 threads 2.4 GHz)
49152 particules/140 secondes → 354 part/seconde → **gain = 1**

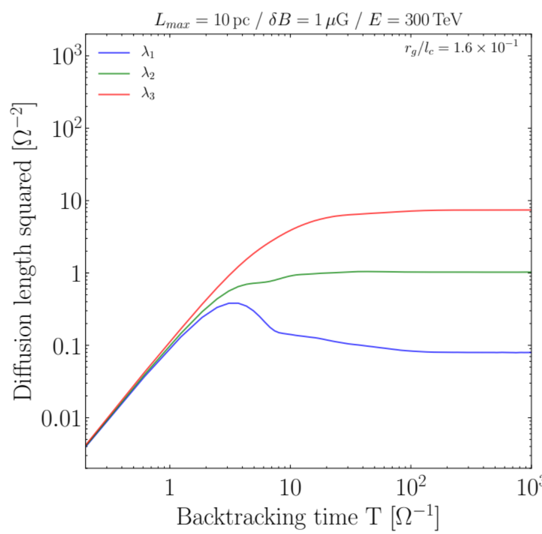


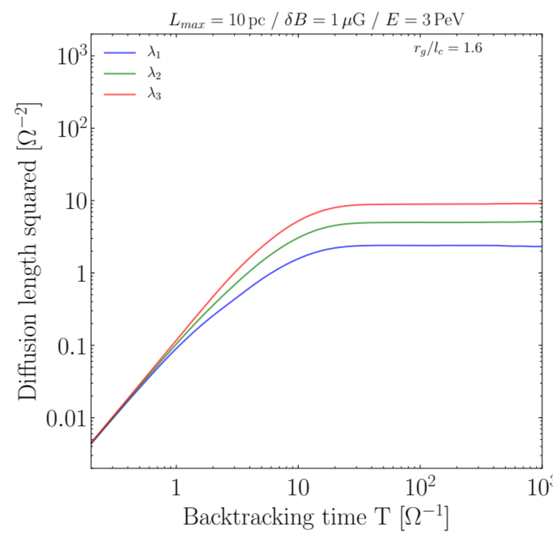
How does behave the CR dipole in **isotropic turbulence**?

$$\boldsymbol{\delta} \propto \boldsymbol{j}_{\mathrm{CR}} = -\boldsymbol{K} \cdot \nabla\Psi$$

$$K_{local} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

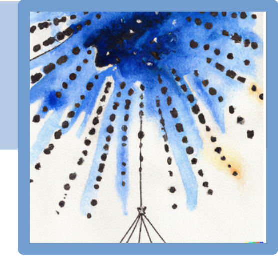


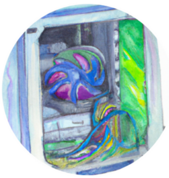




10 10^2 10^3 10^4 TeV

HPC and Cosmic-Ray Physics





High Performance Computing
Particle-test simulations

Local cosmic-ray current

→ Methodology to study the dipole anisotropy
→ Related phenomenology

Collaboration with:

- M. Ahlers (NBI)

UNIVERSITY OF COPENHAGEN

Beyond Quasi-Linear-Theory

→ Numerical study of diffusion
→ Theoretical developments
→ Related phenomenology

Collaboration with:

- A. Marcowith (LUPM)

- P. Mertsch (RWTH)

LUPM LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

RWTH AACHEN UNIVERSITY

Bridging with microphysics

→ Diffusion in MHD turbulence
→ Non-linearities and instabilities

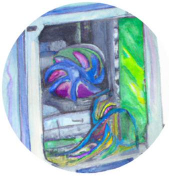
Collaboration with:

- A. Marcowith (LUPM)

- S. Cerri (OCA)

OBSERVATOIRE DE LA CÔTE D'AZUR UNIVERSITÉ CÔTE D'AZUR

Supports: **AAP USMB 2022&2023** | **PNHE 2023** Possible PhD 2024 | **ANR project 2024** (PI: S. Cerri)



@ LAPTh

High Performance Computing at LAPTh

Project run on Must GPUs

MUST

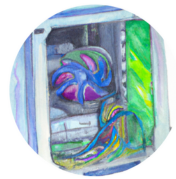
→ Machine Learning

Eckner, C., & Calore, F. PRD (2022)
Caron, S., Eckner, C., et al. JCAP (2023)

→ Solving cascade equation

Hooper, D., **Juan, J. I.**, & Serpico, P. D. PRD. (2023)

CoopIntEER CNRS-UChicago



High Performance Computing at LAPTh

Project run on Must GPUs

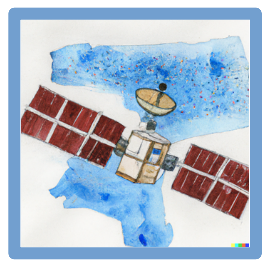
→ Machine Learning

Eckner, C., & Calore, F. PRD (2022)
Caron, S., Eckner, C., et al. JCAP (2023)

→ Solving cascade equation

Hooper, D., **Juan, J. I.**, & Serpico, P. D. PRD. (2023)

CoopIntEER CNRS-UChicago



Gamma rays

High Performance Computing at LAPTh

Project run on Must GPUs

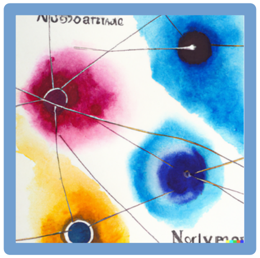
→ Machine Learning

Eckner, C., & Calore, F. PRD (2022)
Caron, S., Eckner, C., et al. JCAP (2023)

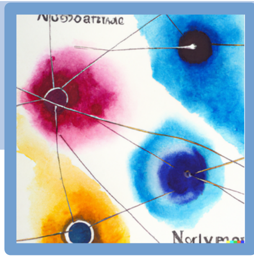
→ Solving cascade equation

Hooper, D., **Juan, J. I.**, & Serpico, P. D. PRD. (2023)

CoopIntEER CNRS-UChicago



Multimessenger



Hooper, D., **Juan, J. I.**, & Serpico, P. D., PRD (2023)

Motivation

$$\Delta a_\mu \equiv a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 251(59) \times 10^{-11}$$

T. Aoyama et al., Phys. Rept. 887, 1 (2020)

4.2σ discrepancy!

SOLUTION: NEW PHYSICS?

New particle with an **MeV-scale mass** coupling to muons with $g \sim 10^{-4}$

C.-Y. Chen et al., Phys. Rev. D 95, 115005 (2017)
P. Fayet, Phys. Rev. D 75, 115017 (2007)

Model

New broken abelian $U(1)$ symmetry

Grand Unified Theory: D. London et al., Phys. Rev. D 34, 1530 (1986)
Little Higgs: N. Arkani-Hamed et al., JHEP 08, 021 (2002)
Extra dimensions: M. Carena et al., Phys. Rev. D 68, 035010 (2003)

New Z' massive boson

$(L_\mu - L_\tau)$

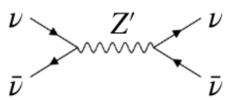
X. G. He et al., Phys. Rev. D 43, 22 (1991) and Phys. Rev. D 44, 2118 (1991)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} Z'^{\alpha\beta} Z'_{\alpha\beta} + \frac{m_{Z'}^2}{2} Z'_\alpha Z'^\alpha + Z'_\alpha J^\alpha_{\mu-\tau}$$

$$J^\alpha_{\mu-\tau} = g_{Z'} \left(\bar\mu \gamma^\alpha \mu + \bar\nu_\mu \gamma^\alpha P_L \nu_\mu - \bar\tau \gamma^\alpha \tau - \bar\nu_\tau \gamma^\alpha P_L \nu_\tau \right)$$

Signatures

$\nu - \nu$ **SCATTERING**



Resonant scattering!

$$\sigma(\nu_i \bar\nu_j \to \nu\bar\nu) = \frac{2 g_{Z'}^4 s \left(U^\dagger_{\mu i} U_{\mu j} - U^\dagger_{\tau i} U_{\tau j}\right)^2}{3\pi \left[(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2\right]}$$

$U_{\alpha i}$ is the PMNS matrix

Credits: Joaquim Iguaz

Hooper, D., **Juan, J. I.**, & Serpico, P. D., PRD (2023)

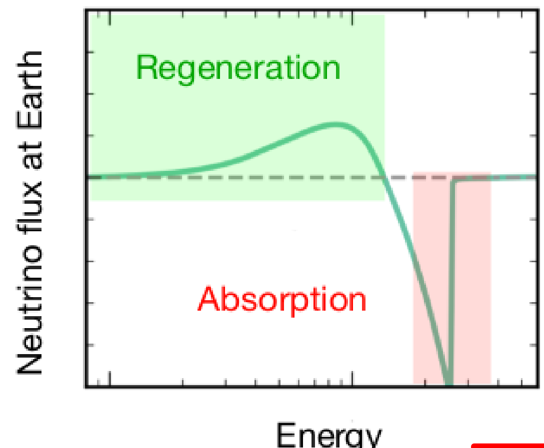
$\nu - \nu$ scattering: Absorption & Regeneration

The neutrino spectrum that reached Earth follows:

CνB

$$-(1+z)\frac{H(z)}{c}\frac{\mathrm{d}\tilde{n}_i}{\mathrm{d}z} = \underbrace{J_i(E_0,z)}_{\text{SOURCE}} \underbrace{- \tilde{n}_i \sum_j \langle n_{\nu j}(z)\sigma_{ij}(E_0,z)\rangle}_{\text{ABSORPTION}} \underbrace{+ P_i \int_{E_0}^{\infty} \mathrm{d}E' \sum_{j,k} \tilde{n}_k \left\langle n_{\nu j}(z)\frac{\mathrm{d}\sigma_{kj}}{\mathrm{d}E_0}(E',z)\right\rangle}_{\text{REGENERATION}}$$

High-energy neutrinos scattering off neutrinos from CνB

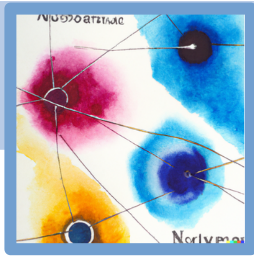


$$\tilde{n}_i \equiv \frac{\mathrm{d}N_i}{\mathrm{d}E}(E_0,z),$$

$$P_i \equiv \sum_l \mathrm{Br}(Z' \to \nu_l \nu_i)$$

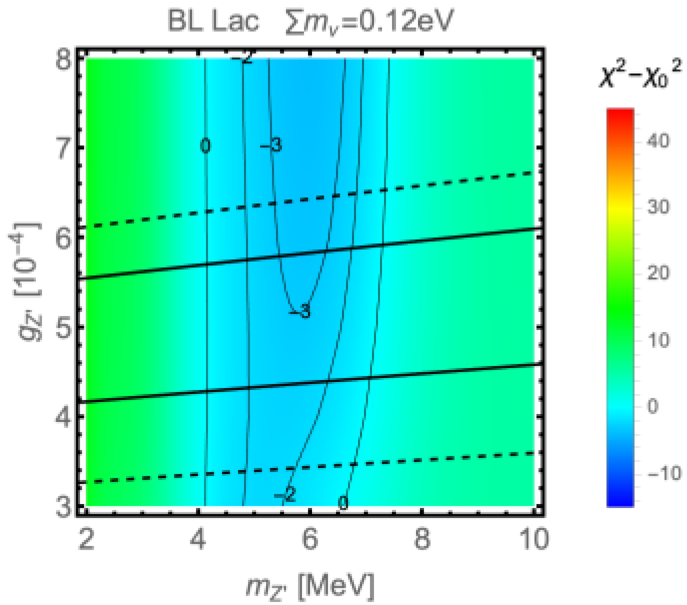
Credits: Joaquim Iguaz

CPU: ~ 1 day **vs** GPU: ~ few min

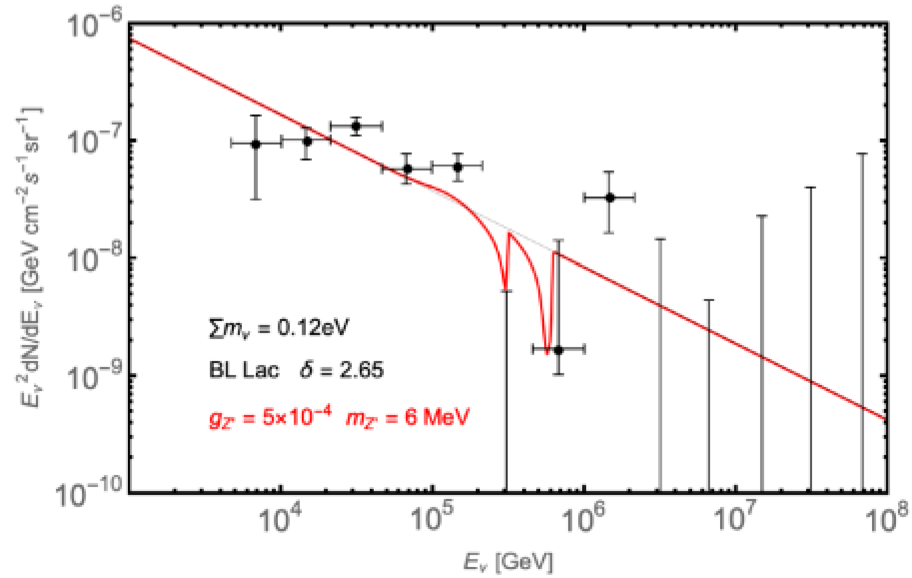


Hooper, D., **Juan, J. I.**, & Serpico, P. D., PRD (2023)

BL Lac distribution



(Normal hierarchy)



Credits: Joaquim Iguaz

@ LAPTh

High Performance Computing at LAPTh

Project run on Must GPUs

MUST

→ Machine Learning

Eckner, C., & Calore, F. PRD (2022)
Caron, S., Eckner, C., et al. JCAP (2023)

→ Solving cascade equation

Hooper, D., **Juan, J. I.**, & Serpico, P. D. PRD. (2023)

CoopIntEER CNRS-UChicago

Enigmass R&D booster LAPTh AstroComo team

Enigmass
The enigma of mass

→ New A100 Nvidia GPU
→ 80Gb
+ dedicated server

→ Organised trainings:
e.g. https://indico.in2p3.fr/event/29755/
https://indico.in2p3.fr/event/30939/

→ Also open for other groups
Now operating

Future activities !

→ GCE with Swift!

→ Open up new projects
e.g. Extensive MCMC, Machine learning

→ Benefit to new CNRS CPJ
Azadeh Moradinezhad
cosmological simulations