Local Turbulence and the Dipole Anisotropy of Galactic Cosmic Rays

Yoann Génolini

In collaboration with Markus Ahlers

LAPTh

UNIVERSITÉ SAVOIE MONT BLANC

UNIVERSITY OF COPENHAGEN

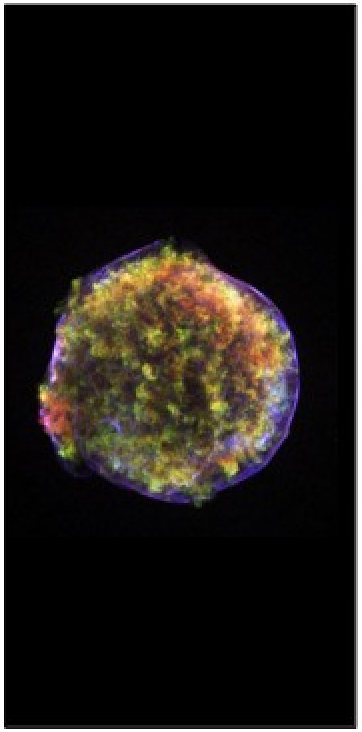
The Niels Bohr International Academy

VILLUM FONDEN

MUST october 2022

Introduction: dipole anisotropy of cosmic rays

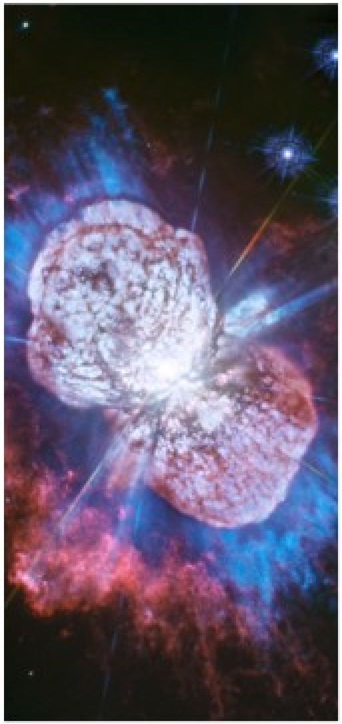
Galactic cosmic-ray sources



SNRs

Star clusters

Pulsar Wind Nebulae



Colliding wind binaries

Protostellar jets microquasars

... and others !

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

Energy

Composition

Direction

Differential flux:

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

Energy

Composition

Direction

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

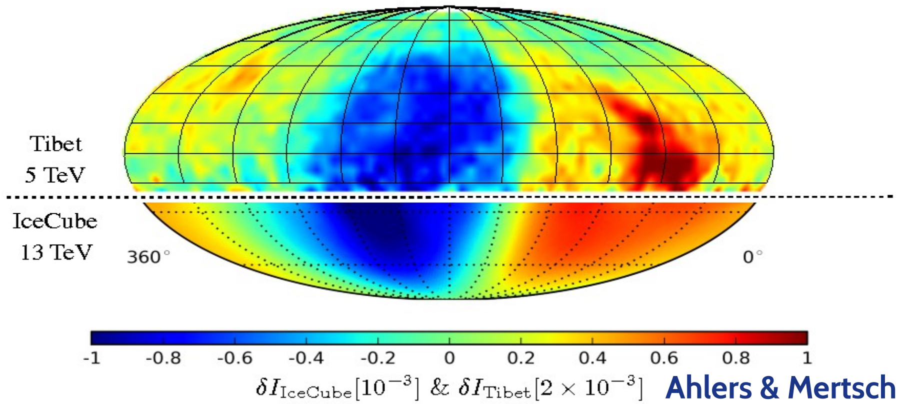
Energy

Composition

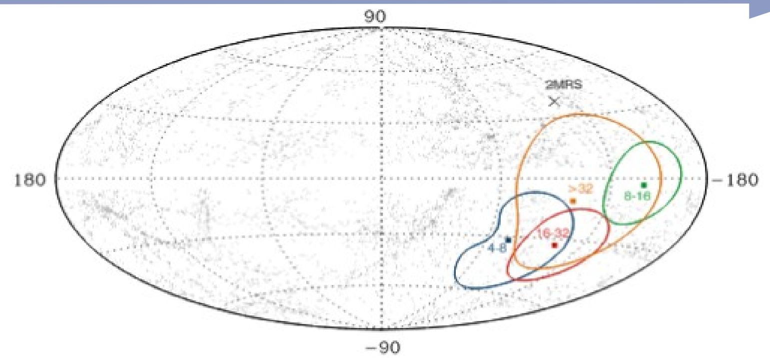
Direction

TeV

EeV



Ahlers & Mertsch PPNP (2016)

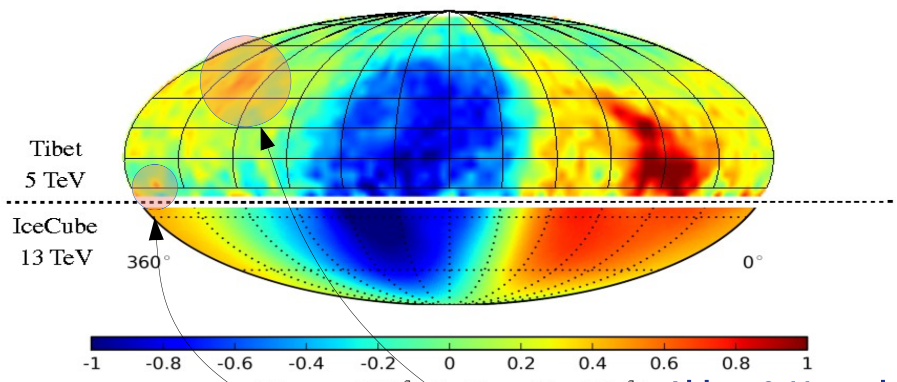


Auger collab. ApJ 868 (2018)

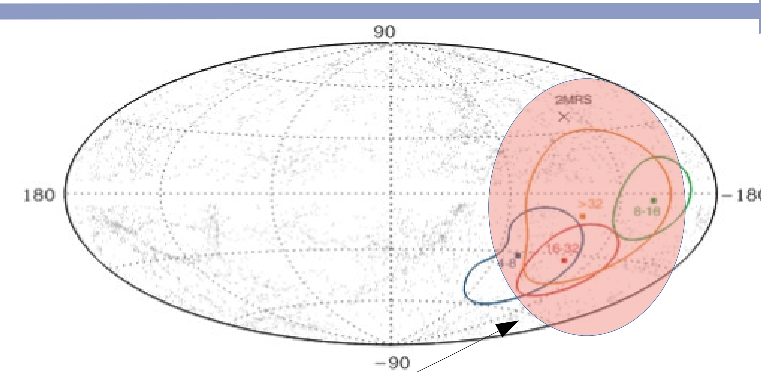
Differential flux: $$\Psi_i = \frac{dN_i}{dE\, dT\, d\Omega\, dS}$$

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

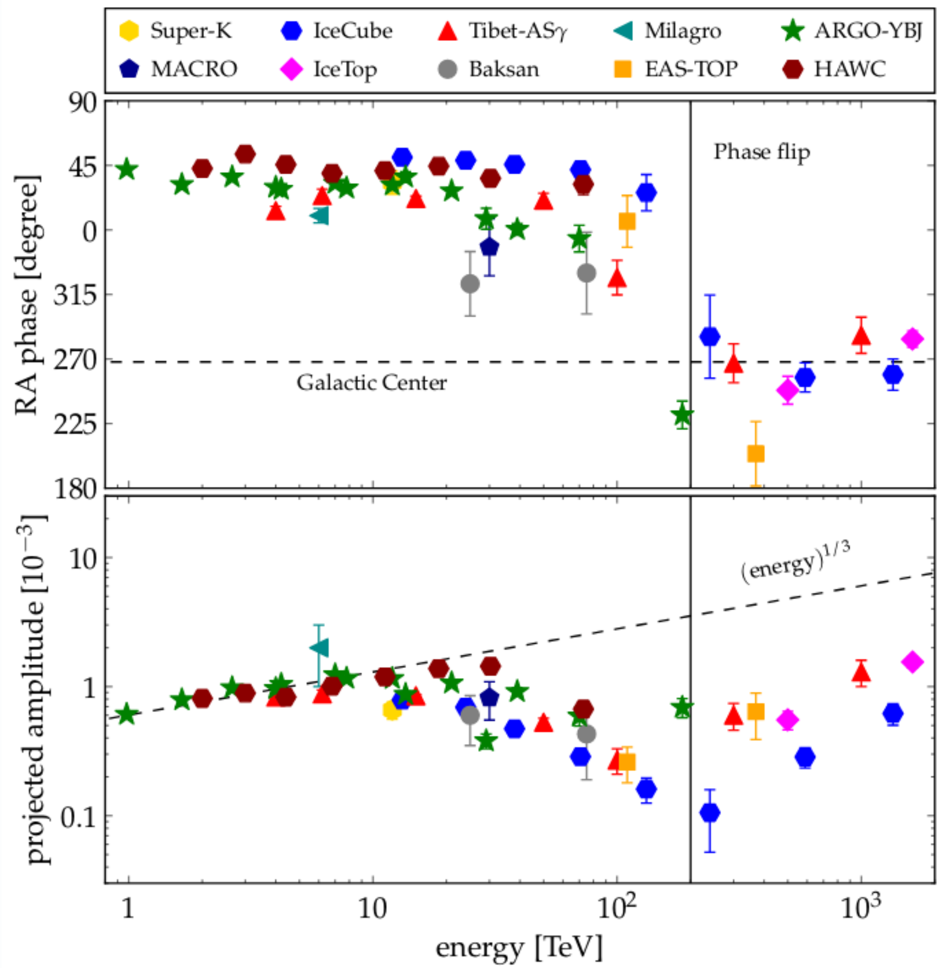
→ Relative intensity can be decomposed as:

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

→ CR observatories sensitive to 2 param.

→ Small dipole anisotropy of GCRs

→ Rapid change of the phase & amplitude with E



Introduction: dipole anisotropy of cosmic rays

Data

→ Relative intensity can be decomposed as:

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

→ CR observatories sensitive to 2 param.

→ Small dipole anisotropy of GCRs

→ Rapid change of the phase & amplitude with E

Interpretation

$$\boldsymbol{\delta} \propto \boldsymbol{j}_{\mathrm{CR}}$$

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

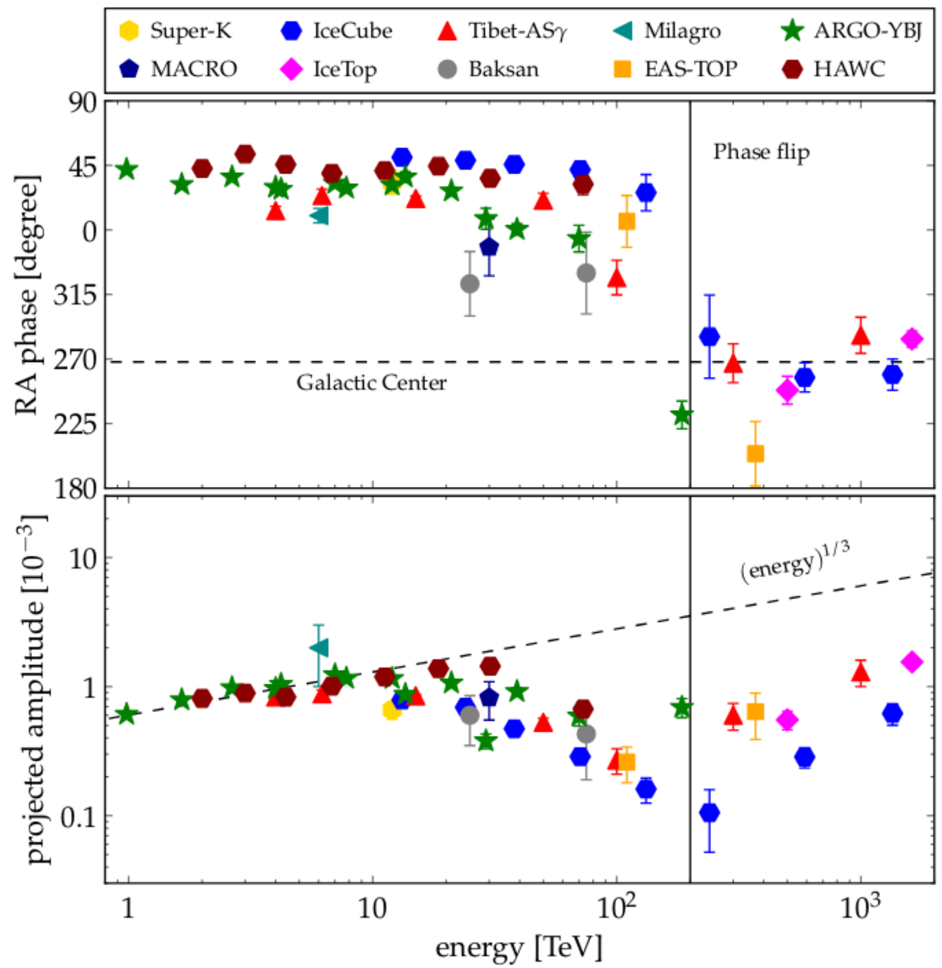
→ Diffusion approximation

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

Energy dependence at odd with diffusion

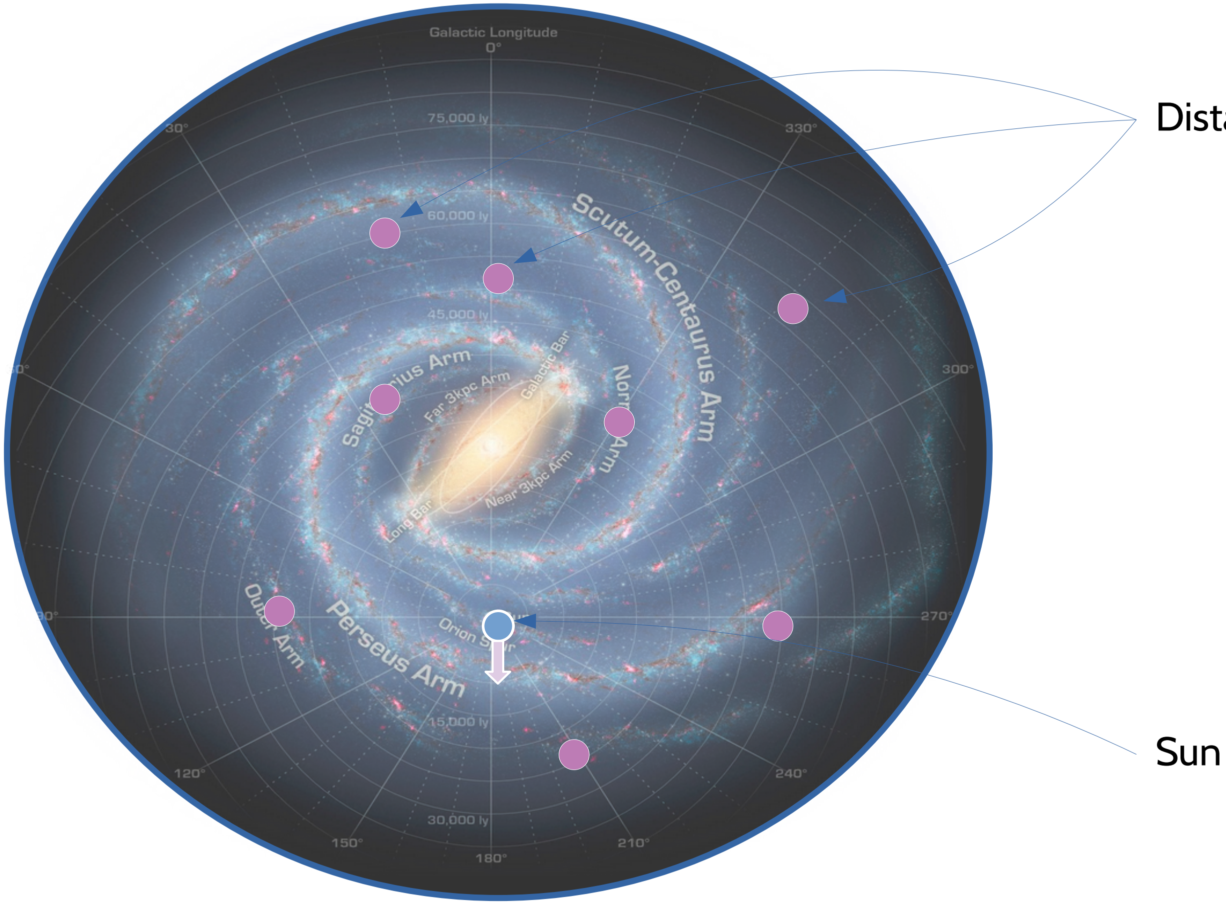
Depends on:
- Distribution of sources and halo geometry halo?
- Structure of local magnetic field?

→ Both!



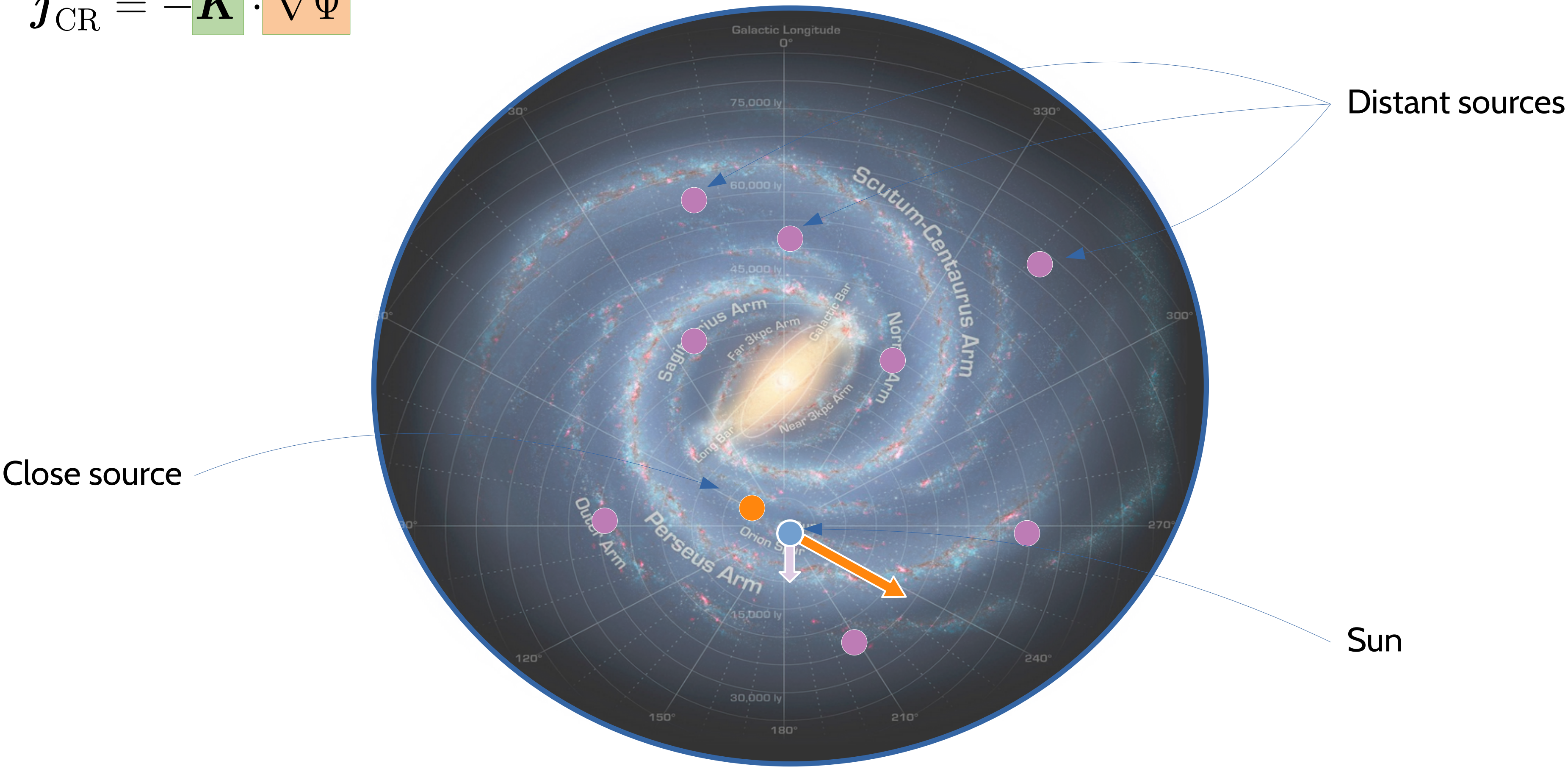
Yoann Génolini

Effect of a local source on the anisotropy



Effect of a local source on the anisotropy

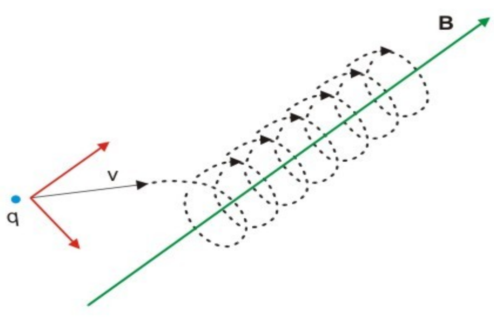
$$j_{\rm CR} = -\boldsymbol{K} \cdot \nabla\Psi$$



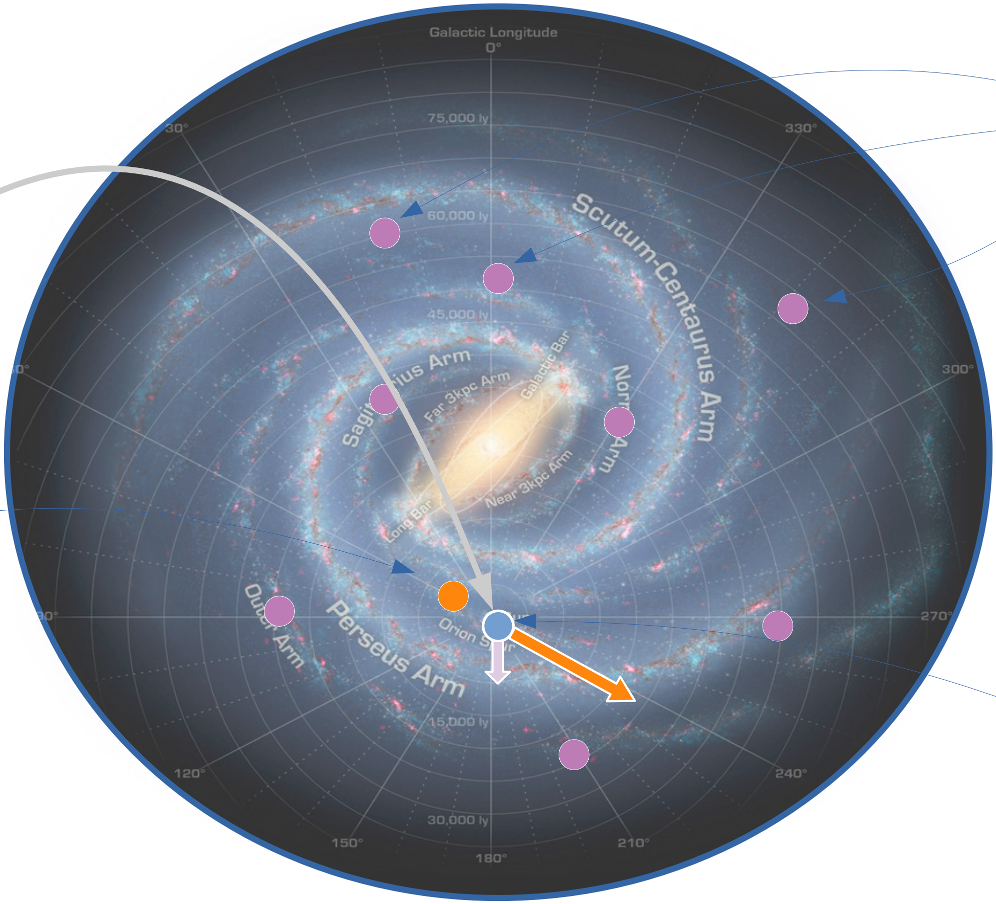
→ Local sources may dominate the dipole but not the flux

Effect of a local source on the anisotropy

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



→ Projection effect



→ Local sources may dominate the dipole but not the flux

Introduction: dipole anisotropy of cosmic rays

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

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

→ We naively write: $K_{ij} = \delta_{ij}\kappa_{\rm iso}$ $\quad \kappa_{\rm iso} = \lim_{\tau\to\infty} \langle \Delta\mathbf{r}^2(\tau)\rangle_{\rm B}/6\tau$

Does it mean that the anisotropy follow the gradient direction?

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

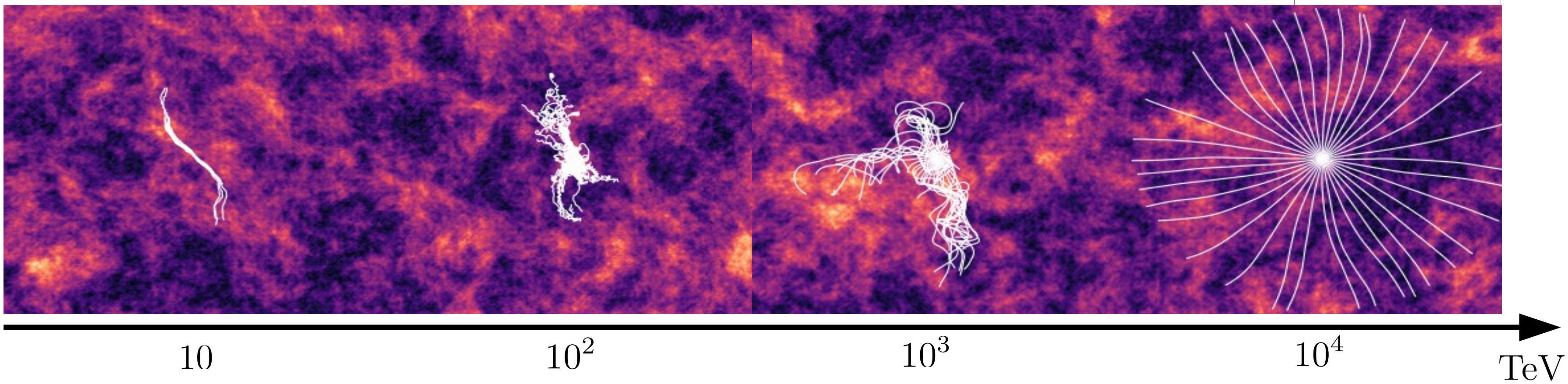
$$\boldsymbol{\delta} \propto \boldsymbol{j}_{\mathrm{CR}} = -\boldsymbol{K} \cdot \nabla\Psi$$

→ We naively write: $K_{ij} = \delta_{ij}\kappa_{\mathrm{iso}}$ $\kappa_{\mathrm{iso}} = \lim_{\tau\to\infty} \langle \Delta \mathbf{r}^2(\tau)\rangle_{\mathrm{B}}/6\tau$

Does it mean that the anisotropy follow the gradient direction?

Test-particle simulations: backtracking in **isotropic turbulence**:

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



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

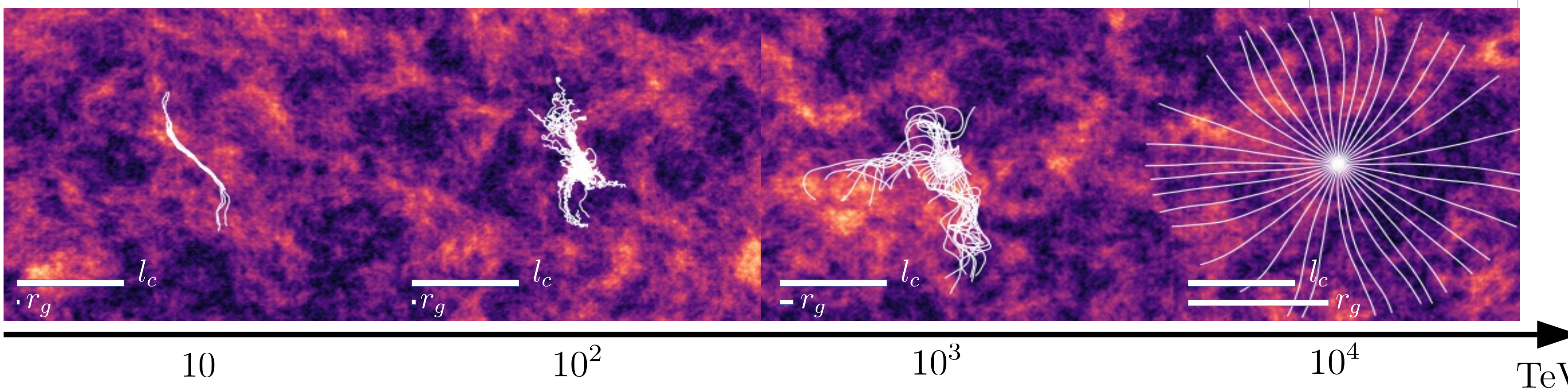
$$\boldsymbol{\delta} \propto \boldsymbol{j}_{\mathrm{CR}} = -\boldsymbol{K} \cdot \nabla\Psi$$

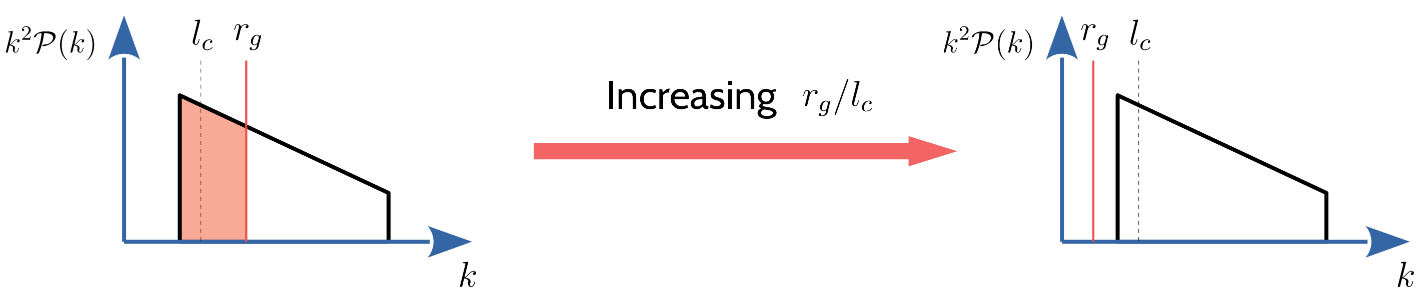
→ We naively write: $K_{ij} = \delta_{ij}\kappa_{\mathrm{iso}}$ $\quad \kappa_{\mathrm{iso}} = \lim_{\tau\to\infty} \langle \Delta\mathbf{r}^2(\tau)\rangle_{\mathrm{B}}/6\tau$

Does it mean that the anisotropy follow the gradient direction?

Test-particle simulations: backtracking in **isotropic turbulence**:

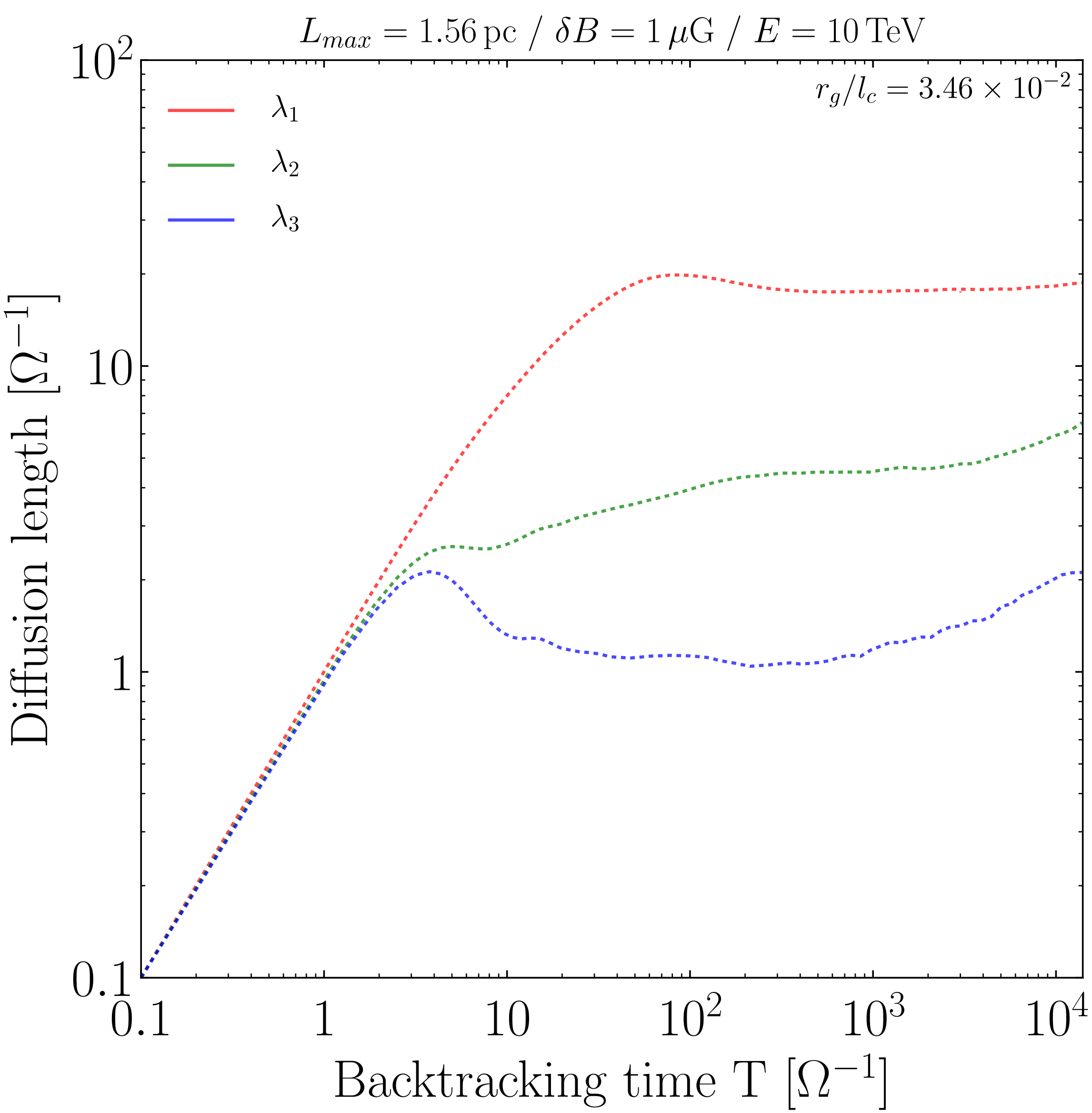
$l_c = 2\,\mathrm{pc}$
$B_{\mathrm{rms}} = 4\mu\mathrm{G}$





→ **At low energies particles stream along the local magnetic field**

Results



Conventional diffusion tensor

$$\kappa_{lm}(T) = \langle \Delta r_l(-T) \Delta r_m(-T) \rangle_\Omega / 2T$$

→ Isotropic diffusion length

$$\lambda^{\text{iso}} = \frac{1}{3} \langle \text{Tr}(\kappa_{lm}(T)) \rangle_{\text{B}}$$

→ Convergence of the eigen values:

$$\lambda_i^{\text{iso}} = \langle \text{EigenValue}_{\,\text{i}} \, [\kappa_{lm}] \rangle_{\text{B}} \rightarrow \lambda^{\text{iso}}$$

In agreement with **Giacinti et al. PRL (2012)**

Local diffusion tensor

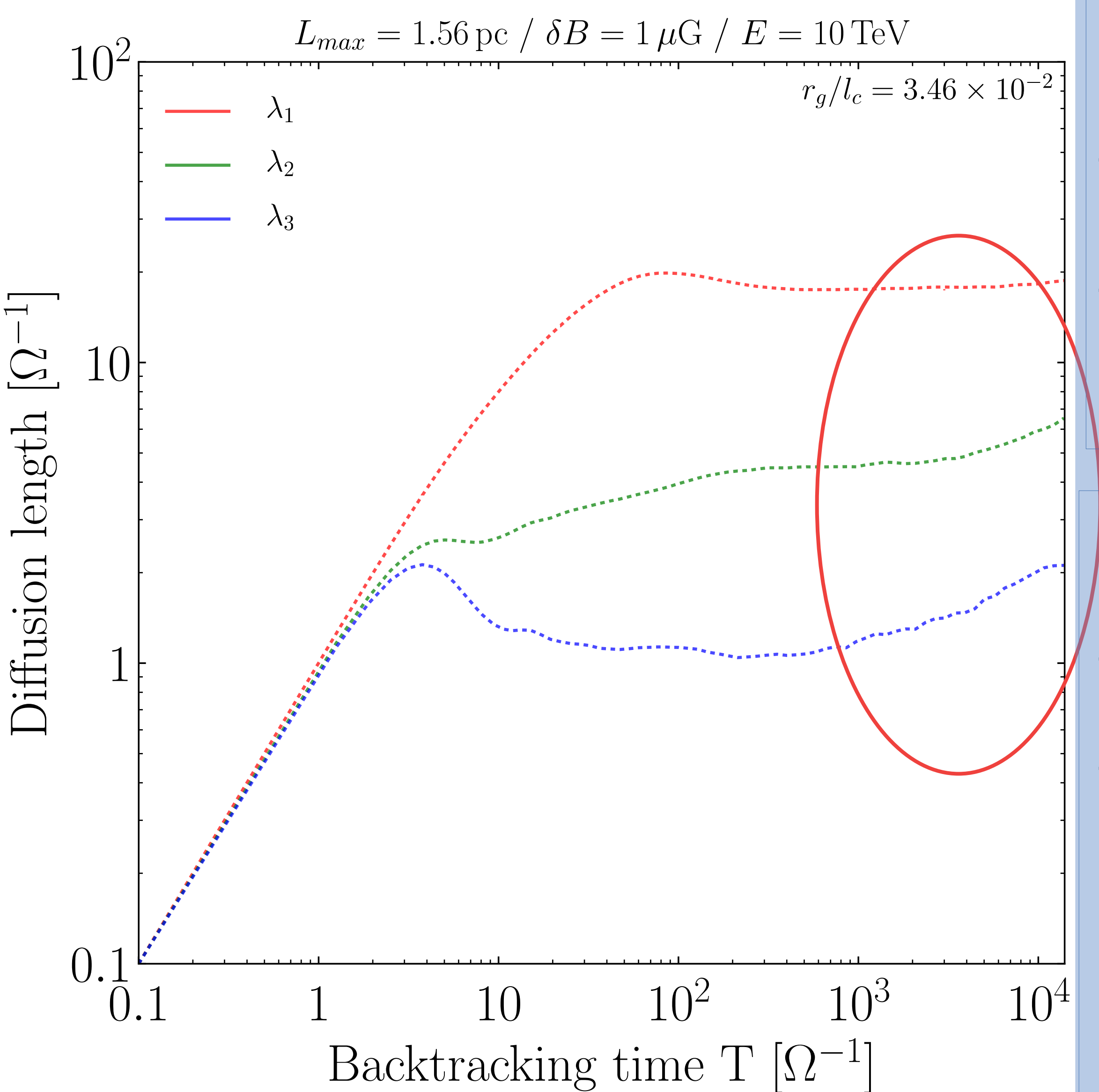
$$\mathcal{K}_{lm}(T) \equiv \langle \widehat{p}_l(0) \Delta r_m(-T) \rangle_\Omega$$

→ Hierarchy between the eigen values:

$$\lambda_i = \langle \text{EigenValue}_{\,\text{i}} \, [\mathcal{K}^T \mathcal{K}] \rangle_{\text{B}}^{1/2}$$

Yoann Génolini

Results



Conventional diffusion tensor

$$\kappa_{lm}(T) = \langle \Delta r_l(-T) \Delta r_m(-T) \rangle_\Omega / 2T$$

→ Isotropic diffusion length

$$\lambda^{\mathrm{iso}} = \frac{1}{3} \langle \mathrm{Tr}(\kappa_{lm}(T)) \rangle_{\mathrm{B}}$$

→ Convergence of the eigen values:

$$\lambda_i^{\mathrm{iso}} = \langle \mathrm{EigenValue}_{\,\mathrm{i}} \, [\kappa_{lm}] \rangle_{\mathrm{B}} \rightarrow \lambda^{\mathrm{iso}}$$

In agreement with **Giacinti et al. PRL (2012)**

Local diffusion tensor

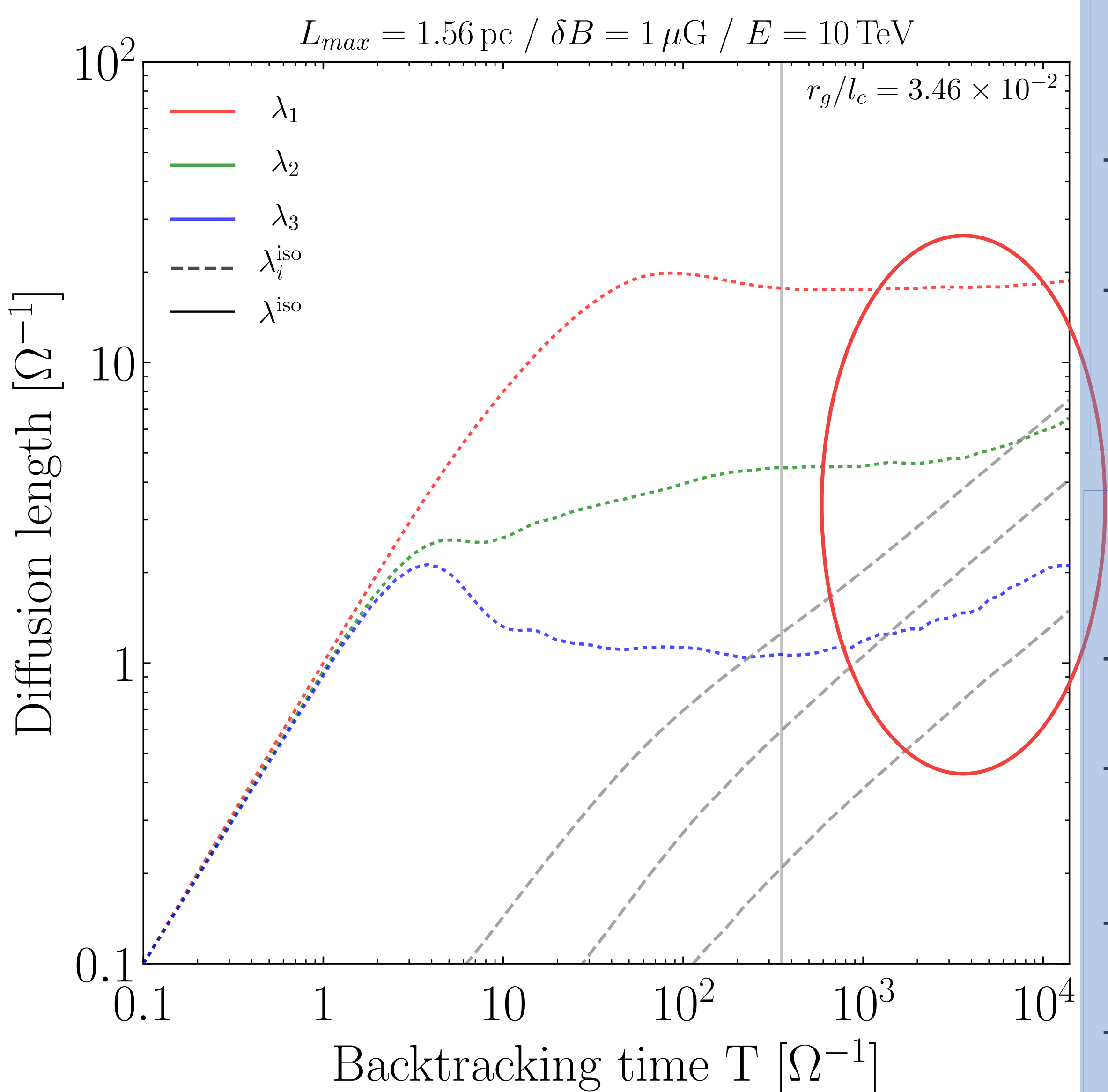
$$\mathcal{K}_{lm}(T) \equiv \langle \widehat{p}_l(0) \Delta r_m(-T) \rangle_\Omega$$

→ Hierarchy between the eigen values:

$$\lambda_i = \left\langle \mathrm{EigenValue}_{\,\mathrm{i}} \left[\mathcal{K}^T \mathcal{K} \right] \right\rangle_{\mathrm{B}}^{1/2}$$

→ Numerical noise from finite directions sampling

Yoann Génolini



Conventional diffusion tensor

$$\kappa_{lm}(T) = \langle \Delta r_l(-T)\Delta r_m(-T)\rangle_\Omega / 2T$$

→ Isotropic diffusion length

$$\lambda^{\mathrm{iso}} = \frac{1}{3}\langle \mathrm{Tr}(\kappa_{lm}(T))\rangle_{\mathrm{B}}$$

→ Convergence of the eigen values:

$$\lambda_i^{\mathrm{iso}} = \langle \mathrm{EigenValue}_{\,\mathrm{i}}\,[\kappa_{lm}]\rangle_{\mathrm{B}} \rightarrow \lambda^{\mathrm{iso}}$$

In agreement with **Giacinti et al. PRL (2012)**

Local diffusion tensor

$$\mathcal{K}_{lm}(T) \equiv \langle \widehat{p}_l(0)\Delta r_m(-T)\rangle_\Omega$$

→ Hierarchy between the eigen values:

$$\lambda_i = \langle \mathrm{EigenValue}_{\,\mathrm{i}}\,[\mathcal{K}^T\mathcal{K}]\rangle_{\mathrm{B}}^{1/2}$$

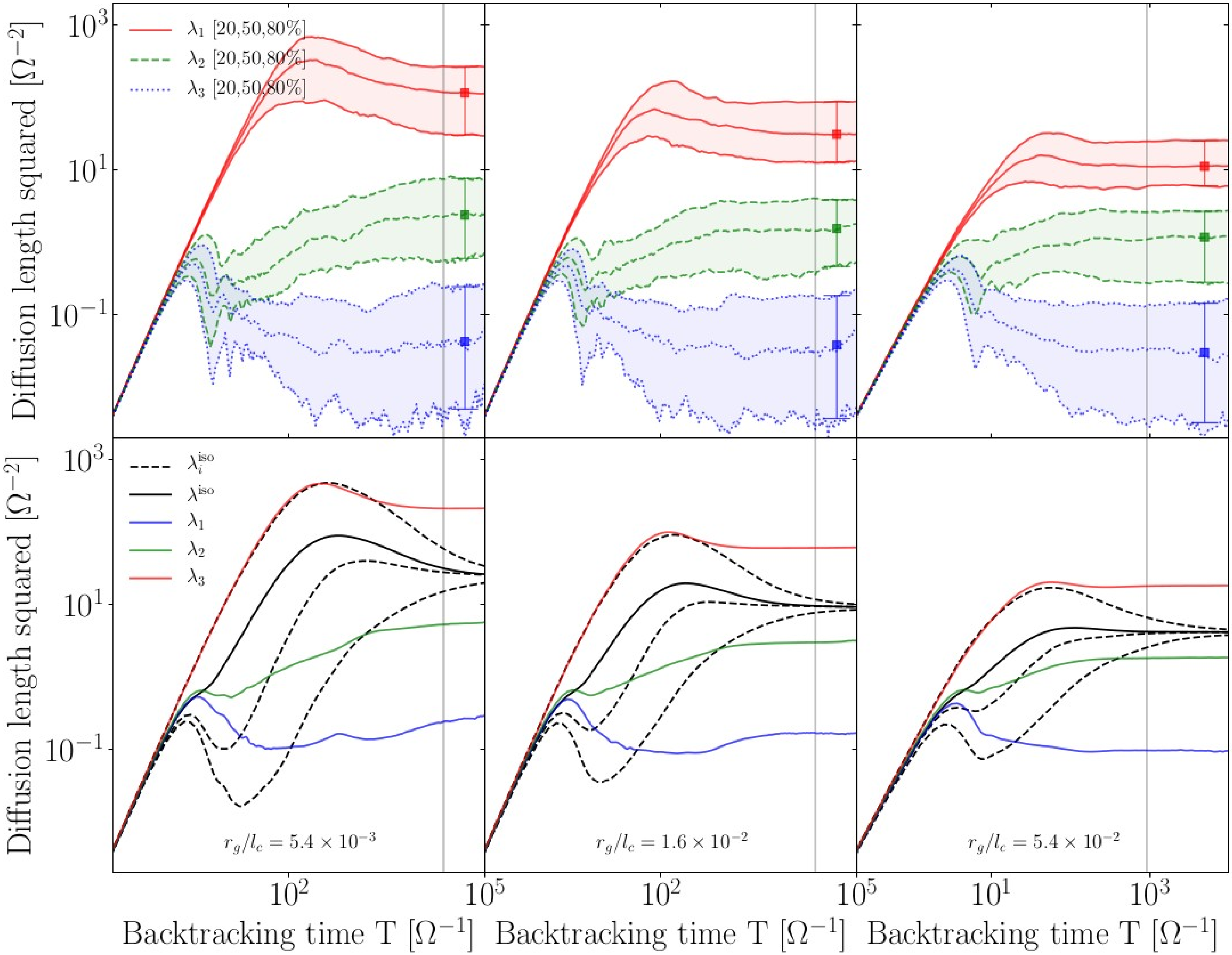
→ Numerical noise from finite directions sampling

Estimated via $\widetilde{\mathcal{K}}_{ij}(\boldsymbol{\xi}) = \frac{1}{N_{\mathrm{pix}}}\sum_{n=1}^{N_{\mathrm{pix}}} \widehat{p}_{\xi_n i}(0)\Delta r_{nj}(-\tau)$

→ Total noise well under control
But noise on each eigen value not known

→ Rescaling of the noise via a fit with constraints

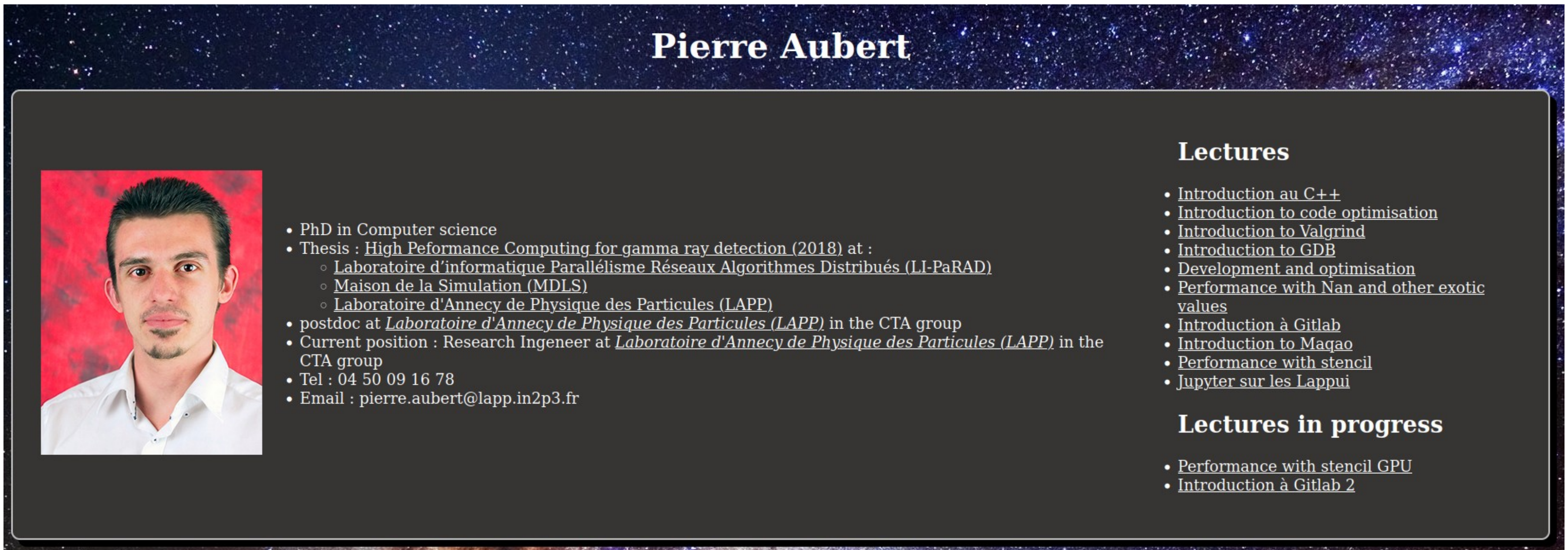
$$\lambda_i \rightarrow \widehat{\lambda}_i$$


Diffusion length squared [Ω^{-2}]
λ_1 [20,50,80%]
λ_2 [20,50,80%]
λ_3 [20,50,80%]
λ_i^{iso}
λ^{iso}
λ_1
λ_2
λ_3
$r_g/l_c = 5.4 \times 10^{-3}$
$r_g/l_c = 1.6 \times 10^{-2}$
$r_g/l_c = 5.4 \times 10^{-2}$
Backtracking time T [Ω^{-1}]

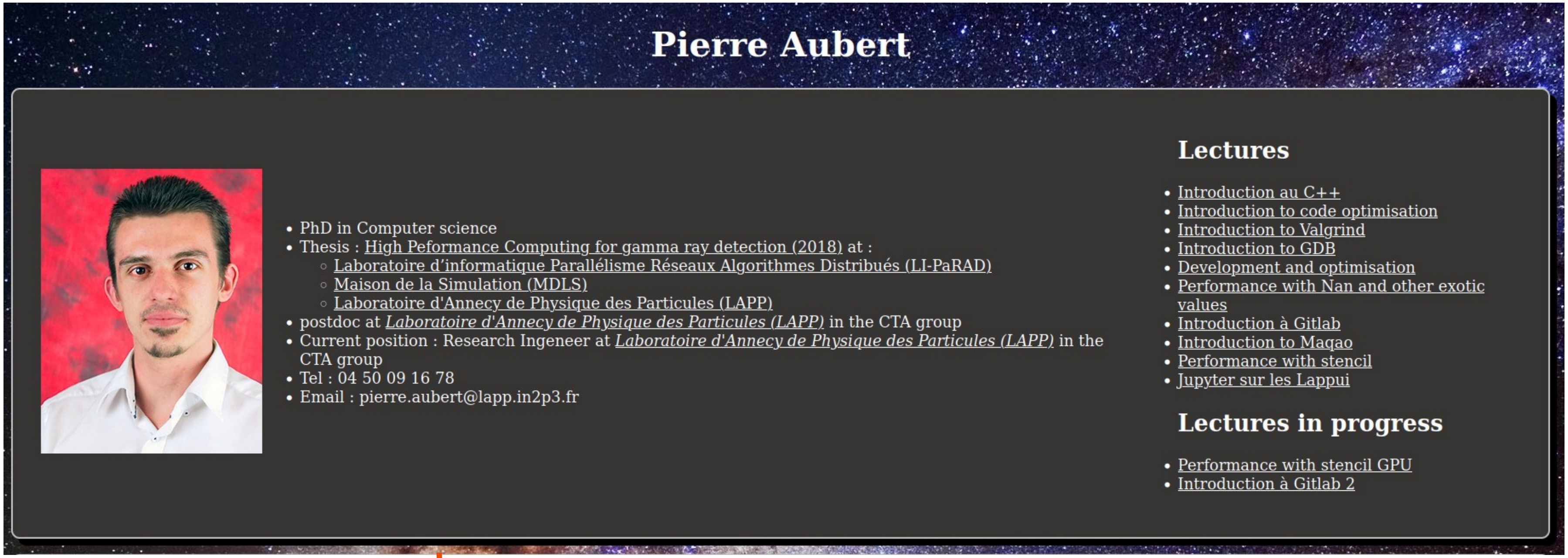
How to deal with MUST GPUs?

(A personal viewpoint)

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!!

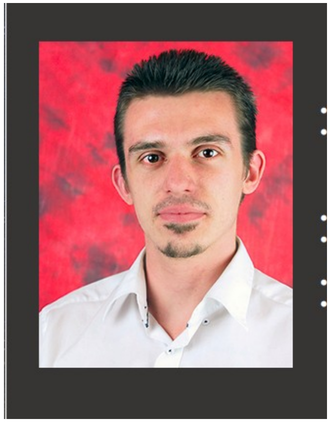


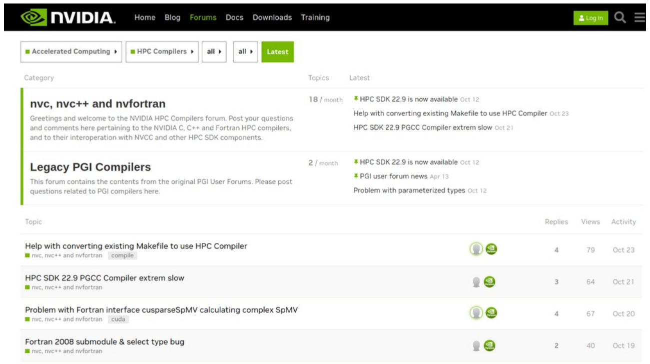
https://lappweb.in2p3.fr/~paubert/

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

Compile with NVC++
→ Done!

Facing problems?

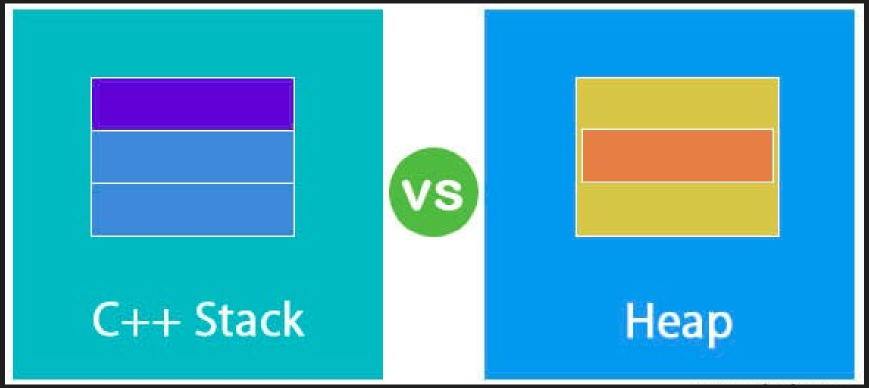




https://forums.developer.nvidia.com/c/accelerated-computing/hpc-compilers/299

Solutions!

```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 A100
40*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**

Conclusion & Prospect in 2021 !!!

CR dipole observations

→ Rapid phase flip and reduced dipole in the TeV-PeV range

Investigating local diffusion in isotropic turbulence

→ New methodology to study local diffusion (Nested grid & Backtracking)

→ In isotropic turbulence local diffusion is strongly anisotropic for $r_g/l_c < 1$

→ Evolution with particle rigidity towards isotropy for $r_g/l_c > 1$

Prospects

→ Challenges to remove the numerical noise for smaller r_g/l_c

→ Other magnetic configurations to probe

Conclusion & Prospect in 2021 !!!

CR dipole observations

→ Rapid phase flip and reduced dipole in the TeV-PeV range

Investigating local diffusion in isotropic turbulence

→ New methodology to study local diffusion (Nested grid & Backtracking)

→ In isotropic turbulence local diffusion is strongly anisotropic for $r_g/l_c < 1$

→ Evolution with particle rigidity towards isotropy for $r_g/l_c > 1$

Prospects

→ Challenges to remove the numerical noise for smaller r_g/l_c

→ Other magnetic configurations to probe

Done!
Thank you :
@Pierre Aubert!
@MUST!

Conclusion & Prospect about LAPTh GPU

Deployment @LAPTh

→ Christopher Ekner used A100 for machine learning
→ Joaquim Iguaz used V100 already to solve a cascade equation

Good news from Enigmass R&D booster LAPTh AstroComo team

→ New A100 + dedicated server is coming

Prospects

→ Open up new projets! Extensive MCMC, machine learning, ...

→ People are exciting to hear about new trainings

Thank you!

Yoann Génolini