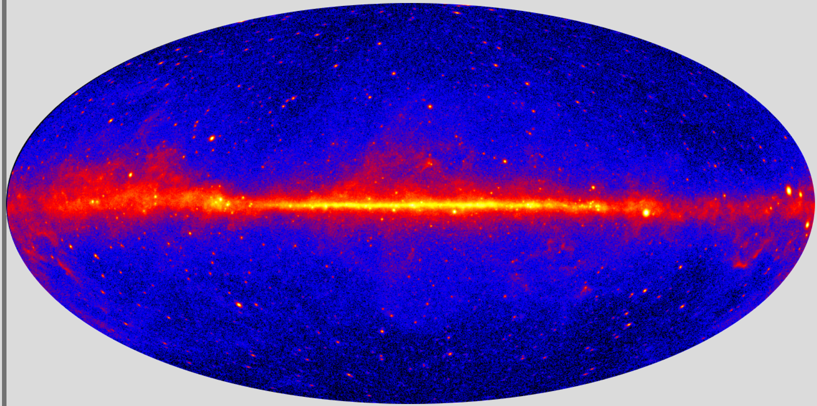
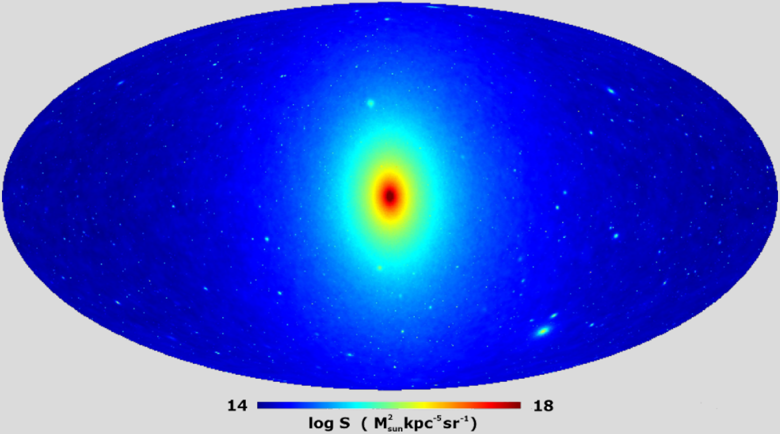
Latest Developments

of Cosmic-ray Propagation Modelling Codes

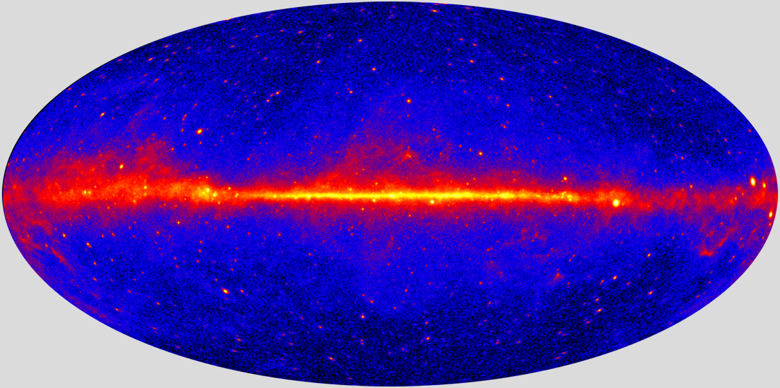


Ralf Kissmann

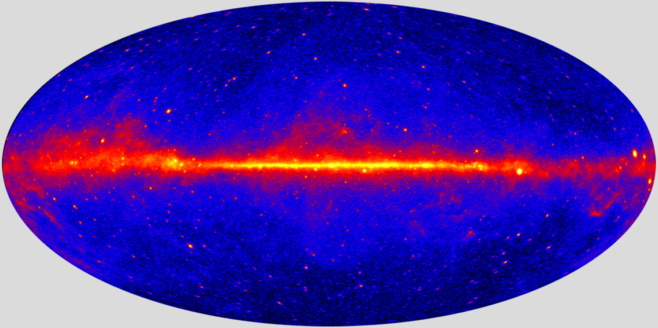
Innsbruck University


14
18
log S (M$^2_{sun}$kpc^{-5}sr^{-1})

The Gamma-ray Sky II: 5 Years of Fermi Data



The Gamma-ray Sky



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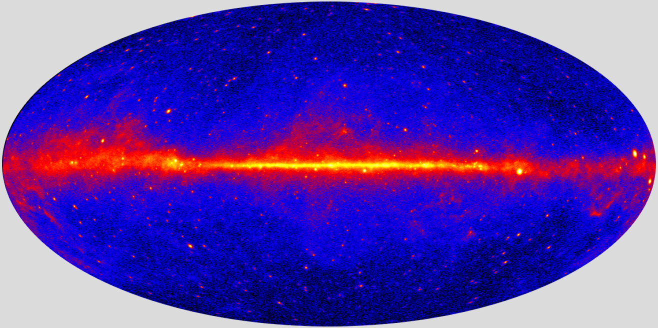

Origin of Gamma Rays

- Sources
- Unresolved sources
- Diffuse emission
- Dark matter

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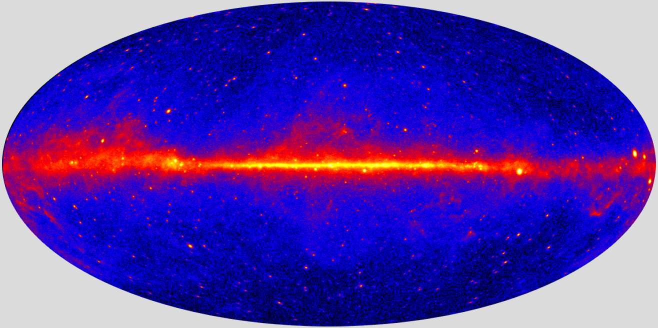

Origin of Gamma Rays

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Connection to Propagation

- Production mechanism of gamma rays
- Info on cosmic rays?

Transport Equation

$$\frac{\partial \psi_i}{\partial t} =$$

Reminder: Description of CR Transport

Transport Equation

$$\frac{\partial \psi_i}{\partial t} = q(\vec{r}, p)$$

Individual Terms

- CR sources

Transport Equation

$$\frac{\partial \psi_i}{\partial t} = q(\vec{r}, p) + \nabla \cdot \mathcal{D} \nabla \psi_i$$

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- Spatial diffusion

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- (Adiabatic) energy changes

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- 3+1 dimensions
- Entire Galaxy

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$\rightarrow$ Numerical solution

Available Solution Approaches

Types of Solvers

- Particle-based
  - Monte Carlo
  - SDEs
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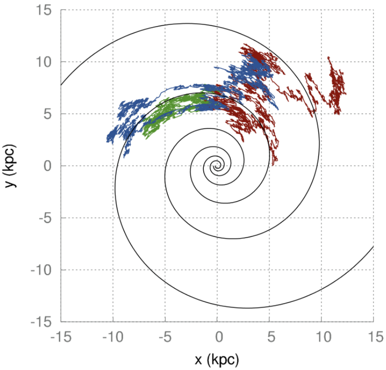
Particle Based Solvers

- Monte Carlo
  - Benyamin, Shaviv et al.

Pseudo Particle Propagation



(Effenberger et al. 2012 A&A **547**,A120)

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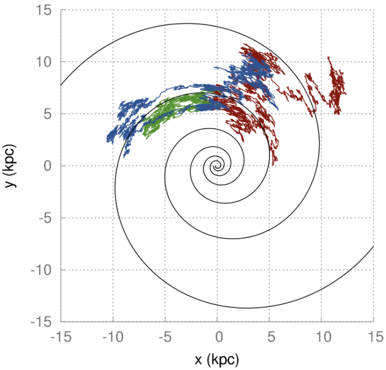

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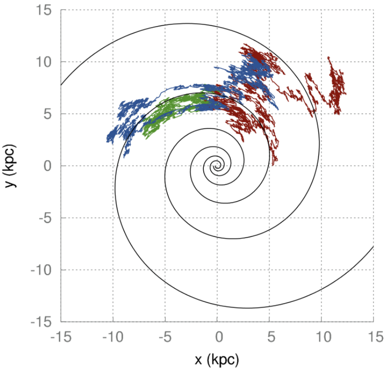

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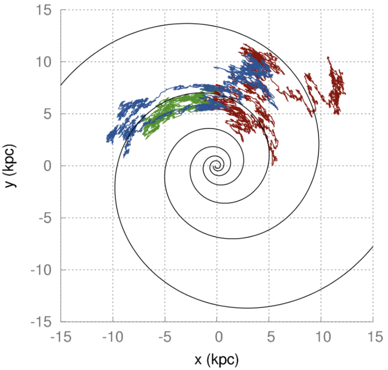

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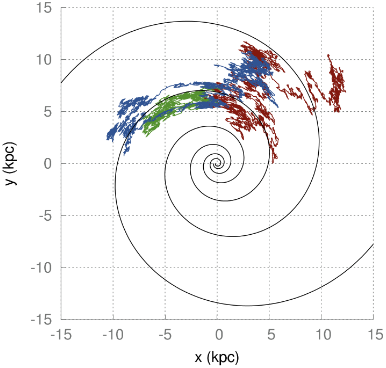

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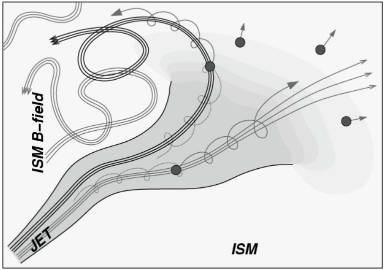
Different Codes

- Semi-analytical:
  - Usine
- Fully numerical:
  - Galprop
  - Dragon
  - Picard

Transport in ISM



(by Heinz & Sunyaev (2002))

Different Codes

- Semi-analytical:
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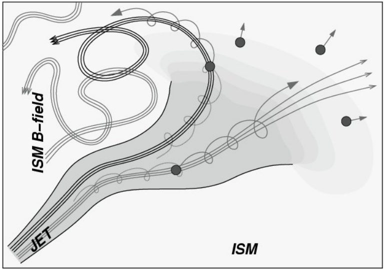
Other Approaches

- Green's functions (Büsching et al.)
- Fluid description (Hanasz et al.)

Transport in ISM



(by Heinz & Sunyaev (2002))

A Typical Numerical Galactic Transport Model

Transport Processes

- Convection
- Diffusion
- Diffusive reacceleration

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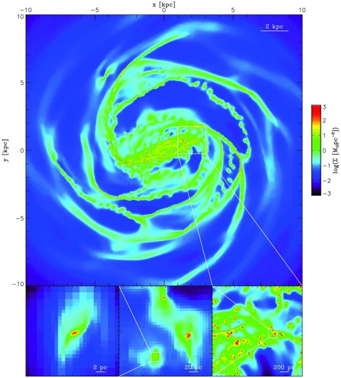
Galaxy Model

- Matter distribution
- ISRF
- Magnetic field

Numerical Galaxy Model



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Interaction with ISM

- Spallation cross sections
- Energy loss processes
- Nuclear network

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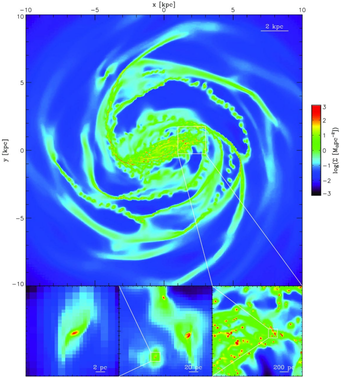

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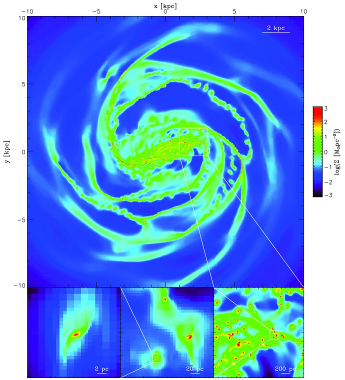

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Secondaries

- Secondary CRs
- Gamma rays
- Neutrinos

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Solution Process

CR source distribution

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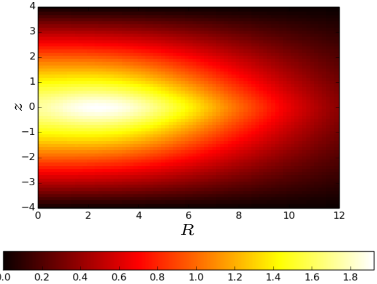
CR Distribution



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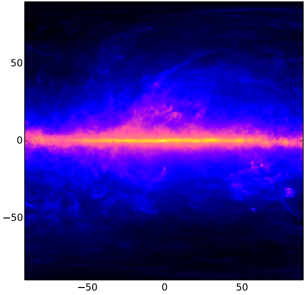
Gamma-Ray Emission



Solution Process

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⇓

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⇓

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⇓

Gamma ray emission

Issues in Previous Approaches

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Physics Issues

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- Constant in time
- Constant in space

$\rightarrow$ Parameter tuning

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Simplified Parameters

- Diffusion, halo height
- Galaxy model
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Technical Issues

- Solver
- Local structure ↔ spatial resolution
- Consistency

→ See discussion in Kissmann et al. (2012)

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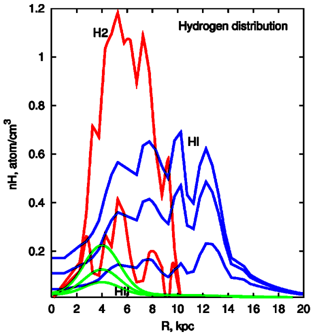
Gas for Propagation

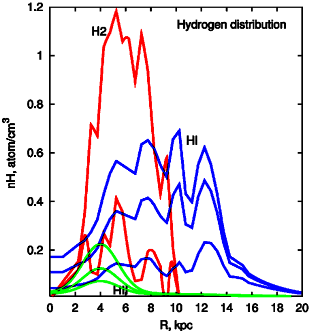


(From Galprop website)

Propagation

- Axially symmetric

Gas for Propagation



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Gamma-ray Computation

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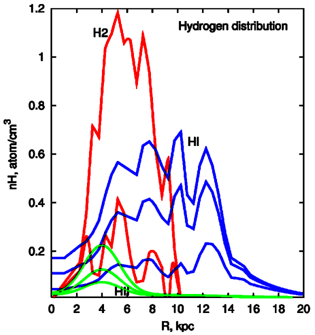
Gas for Propagation



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Gamma-ray Example: Simple Galaxy Model

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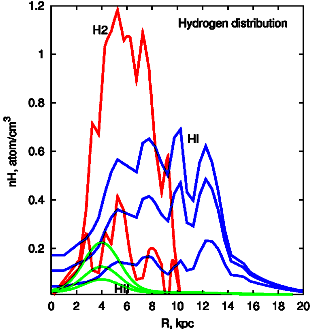

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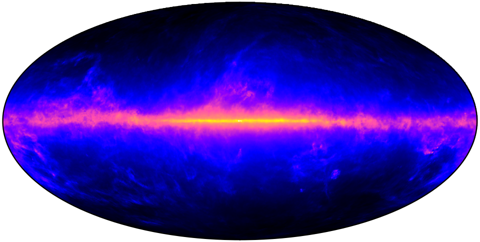
Gamma Ray Map



(PICARD results for 100 GeV gamma rays)

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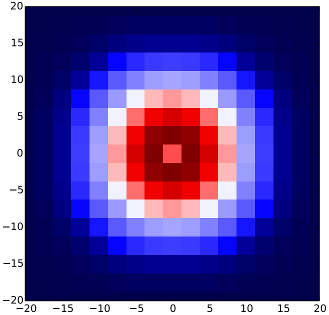
But: CR distribution



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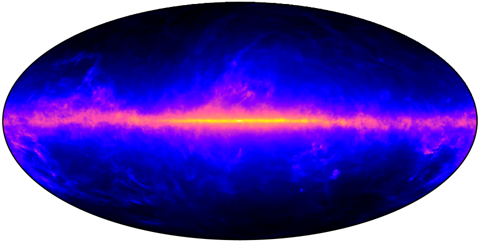

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Idea

- Statistical investigation of propagation
- Fast, simplified simulation models

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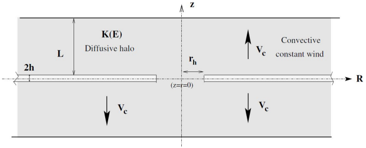


(From Putze et al. (2010) A&A **516**, A66)

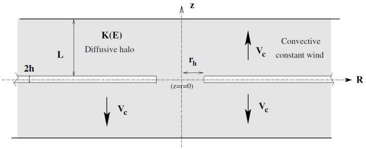
Examples

- Usine (semi-analytical)
- Galprop (very low resolution)

Idea

- Statistical investigation of propagation
- Fast, simplified simulation models

Galaxy Model



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Application

- Statistical analysis
- Estimate on transport parameters
- Effect of cross sections

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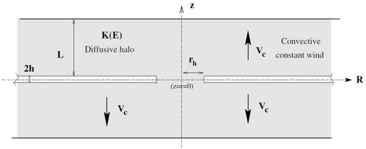

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Application

- Statistical analysis
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- But: CRs only

Examples

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- Galprop (very low resolution)

Development

- Localised sources
- Spatial diffusion:
  - Spatial variation
  - Anisotropy

Transport Physics

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- Spatial diffusion:
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Examples:

- Spiral-arm source distribution
- Diffusion tensor
- Related codes:
  - DRAGON
  - PICARD
  - Effenberger et al.
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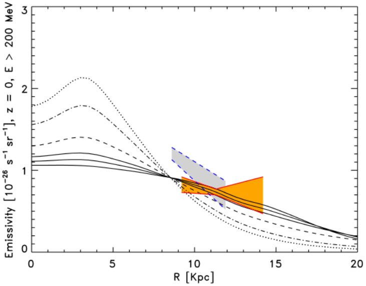
Gamma-ray Emissivity



(From Evoli et al. (2012) PRL **108**, 211102)

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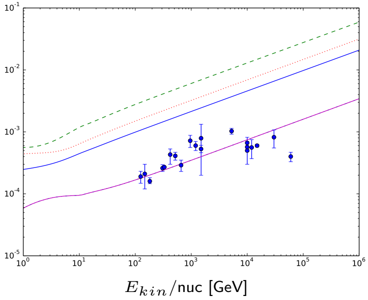
Local CR Anisotropy



(From RK et al. (2015) APh **70**, 39)

The Galprop Solution Approach

Solution Approach

- Start with empty Galaxy
- Advance in time until convergence

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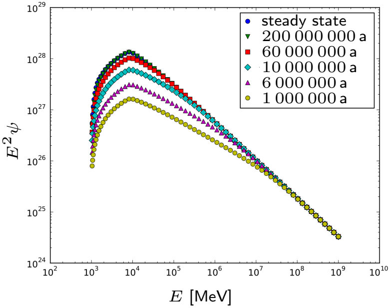
Problem I

- Characteristic timescales
- Convergence timescales

Time Evolution of Spectrum



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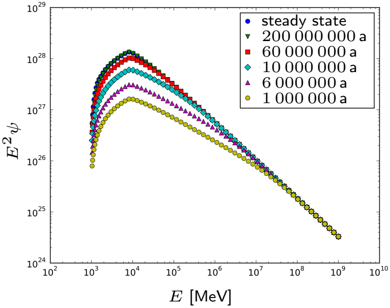

(RK (2014))

Characteristic time: ~50 yrs

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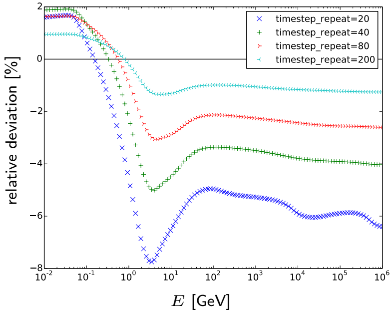
Problem II

- Check for convergence?
- Timestep control

Time Evolution Parameters



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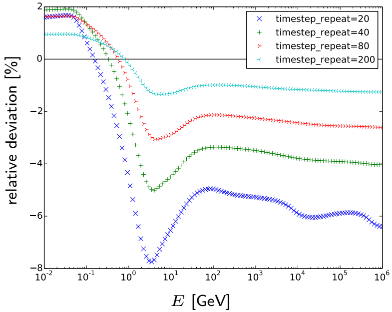

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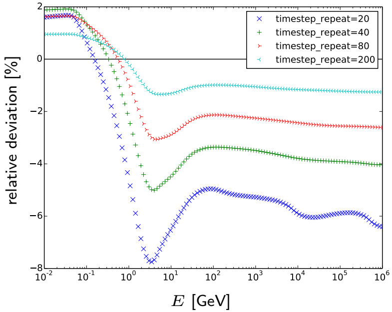
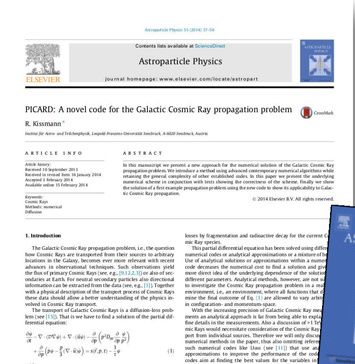


(RK et al. (2014))

→ Let's do better

Cosmic Particle Transport:

THE NEXT GENERATION



Astroparticle Physics 55 (2014) 37–50

Contents lists available at ScienceDirect

Astroparticle Physics

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PICARD: A novel code for the Galactic Cosmic Ray propagation problem

R. Kissmann *

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität Innsbruck, A-6020 Innsbruck, Austria

ARTICLE INFO

Article history:
Received 10 September 2013
Received in revised form 16 January 2014
Accepted 3 February 2014
Available online 15 February 2014

Keywords:
Cosmic Rays
Methods: numerical
Diffusion

ABSTRACT

In this manuscript we present a new approach for the numerical solution of the Galactic Cosmic Ray propagation problem. We introduce a method using advanced contemporary numerical algorithms while retaining the general complexity of other established codes. In this paper we present the underlying numerical scheme in conjunction with tests showing the correctness of the scheme. Finally we show the solution of a first example propagation problem using the new code to show its applicability to Galactic Cosmic Ray propagation.

1. Introduction

The Galactic Cosmic Ray propagation problem, i.e., the question how Cosmic Rays are transported from their sources to arbitrary locations in the Galaxy, becomes ever more relevant with recent advances in observational techniques. Such observations yield the flux of primary Cosmic Rays (see, e.g., [9,12,2,3]) or also of secondaries at Earth. For neutral secondary particles also directional information can be extracted from the data (see, e.g., [1]). Together with a physical description of the transport process of Cosmic Rays these data should allow a better understanding of the physics involved in Cosmic Ray transport.

The transport of Galactic Cosmic Rays is a diffusion-loss problem (see [15]). That is we have to find a solution of the partial differential equation:

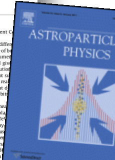
$$\frac{\partial\psi}{\partial t} - \nabla\cdot(D\nabla\psi) + \nabla\cdot(\vec{u}\psi) - \frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right) + \frac{\partial}{\partial p}\left(\dot{p}\psi - \frac{p}{3}(\nabla\cdot\vec{u})\psi\right) = s(\vec{r},p,t) - \frac{1}{\tau}\psi \quad (1)$$

losses by fragmentation and radioactive decay for the current C
mic Ray species.

This partial differential equation has been solved using differ
numerical codes or analytical approximations or a mixture of b
Use of analytical solutions or approximations within a numer
code decreases the numerical cost to find a solution and giv
more direct idea of the underlying dependence of the solutio
different parameters. Analytical methods, however, are not su
to investigate the Cosmic Ray propagation problem in a rea
environment, i.e., an environment, where all functions that d
mine the final outcome of Eq. (1) are allowed to vary arbit
in configuration- and momentum-space.

With the increasing precision of Galactic Cosmic Ray mea
ments an analytical approach is far from being able to expla
fine details in the measurements. Also a discussion of >1 Te
mic Rays would necessitate consideration of the Cosmic Ray
port from individual sources. Therefore we will only discu
numerical methods in the paper, thus also omitting refere
such numerical codes like Usine (see [11]) that use an
approximations to improve the performance of the cod
codes aim at finding the best values for the variables in

APh Vol.55 (2014)



Solver

- Steady-state solution
- Explicit time integrator
- MPI-parallel
- Improved nuclear network
- Speed

Features of Picard

Solver

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- Explicit time integrator
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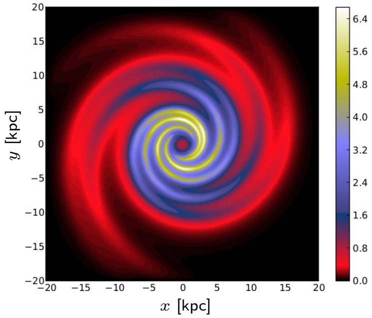
Example Resolution

- Standard CR simulation (e.g., Fermi Diffuse Paper)
  - 2D (1 kpc $\times$ 100 pc)
- Picard
  - 3D (up to $\sim$75 pc^3)

Example Simulation Results



(RK et al. (2014))

Features of PICARD

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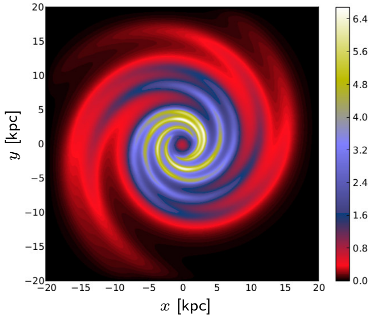

(RK et al. (2014))

Example results:
Milkyway as spiral galaxy

Spiral-Arm Cosmic Ray Sources

CR Source Candidates

- Supernova remnants
- Pulsars
- Gamma-ray binaries

Spiral-Arm Cosmic Ray Sources

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$\rightarrow$ young objects

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- Pulsars
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→ young objects

→ star formation regions

Source Distribution

- Spiral galaxy

→ Spiral arms

→ Galactic bar

Spiral Galaxy NGC1232

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Source Distribution

- Spiral galaxy

→ Spiral arms

→ Galactic bar

- Tracers of spiral structure

→ Variety of models

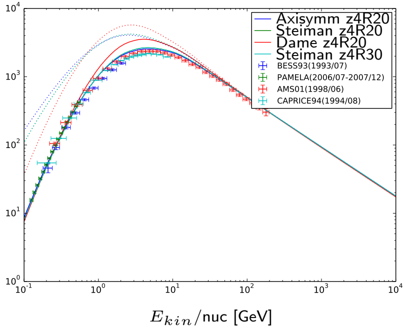
Spiral Galaxy NGC1232

Confrontation with CR Data

CR Data

- CR Fluxes ✓
- Secondary / Primary ratios
  - ^{10}Be/^{9}Be Ratio
  - B/C Ratio

CR Proton Flux



(RK et al. (2014))

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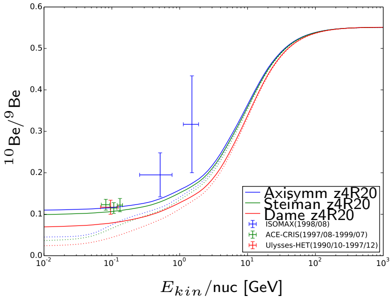
Be-Ratio



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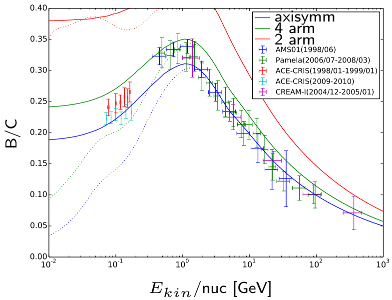

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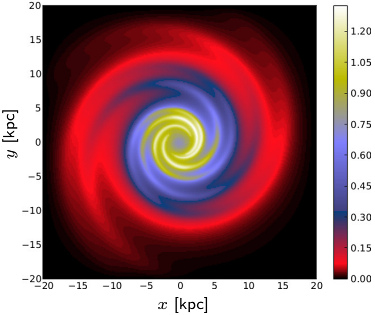
Distribution of Carbon



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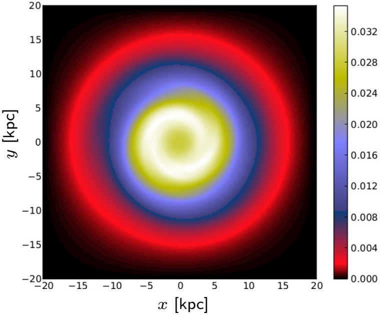

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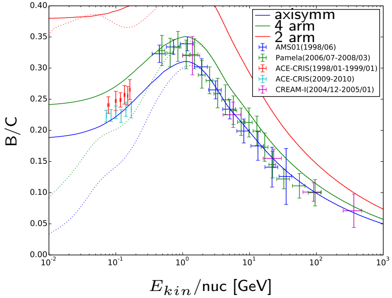
Four-Arm Model

- Adapt parameters

B/C Ratio



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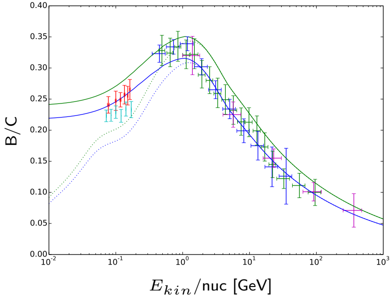
Four-Arm Model

- Adapt parameters
- Fit possible

Modified Parameters



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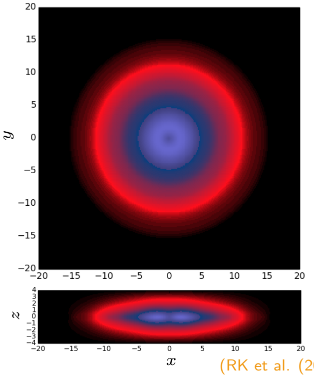
Four-Arm Model

- Adapt parameters
- Fit possible
- Spatial variation

Axially Symmetric Model



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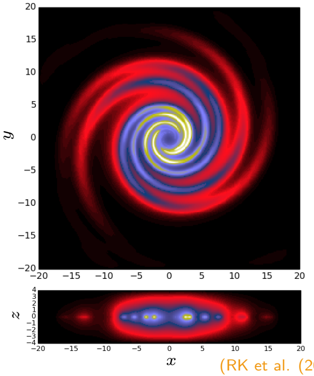

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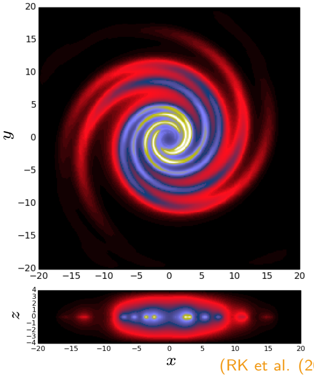

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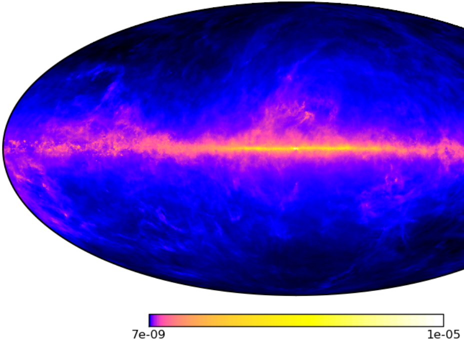
Impact on gamma rays?

Impact on Gamma Rays – Preliminary

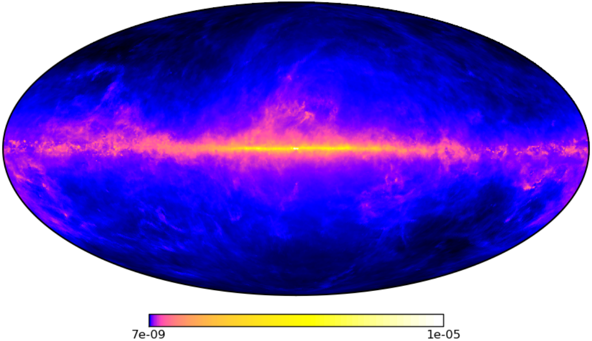
Axi-Symmetric Configuration



Gamma-Ray Data

- ∼200 MeV
- ∼1 GeV
- ∼100 GeV

Four-Arm Configuration



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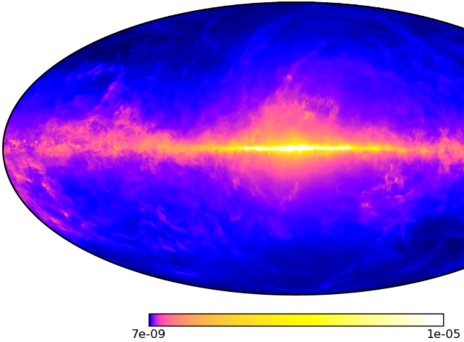

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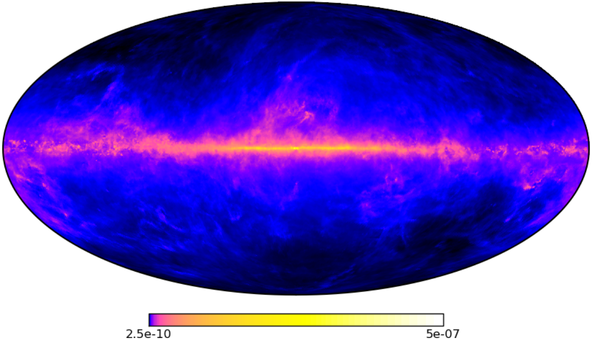

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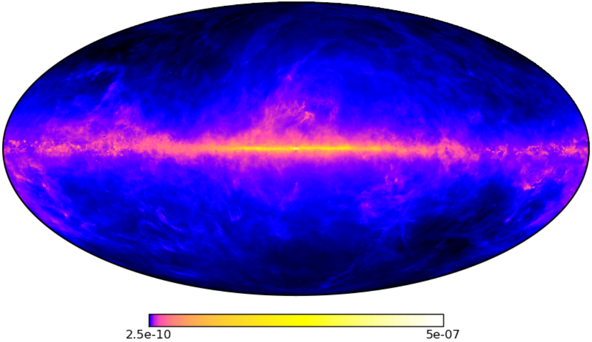

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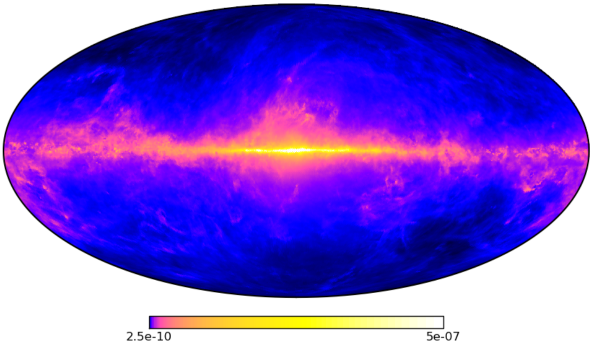

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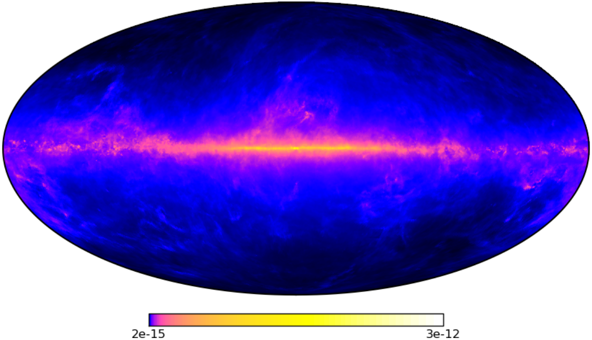

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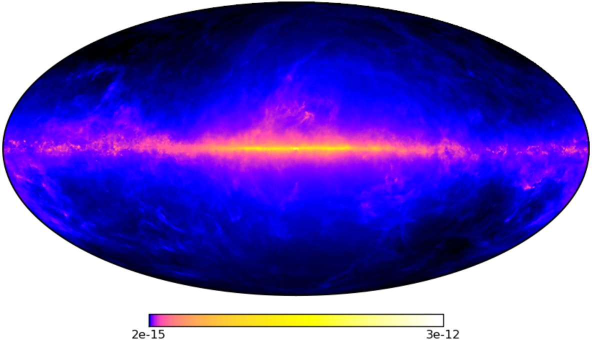

Preliminary Conclusion

- Imprint of IC component

Gamma-Ray Data

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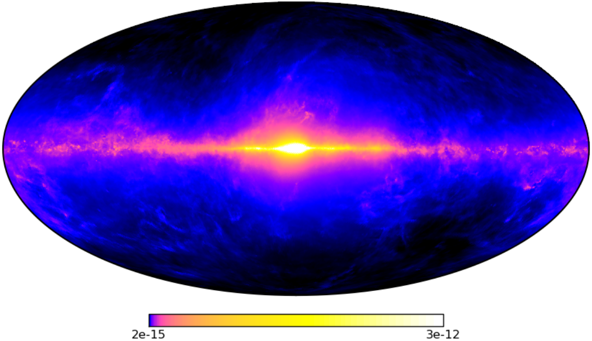
- ∼100 GeV

Two-Arm Configuration



Preliminary Conclusion

- Imprint of IC component
- Two-arm model excluded?

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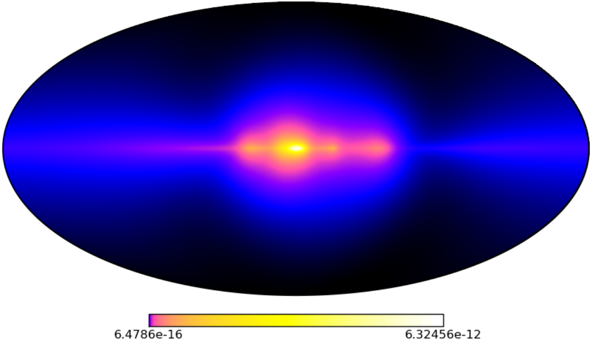
Impact on Gamma Rays – Preliminary

Two-Arm Configuration (IC only)



Preliminary Conclusion

- Imprint of IC component
- Two-arm model excluded?
- Galactic centre?

Gamma-Ray Data

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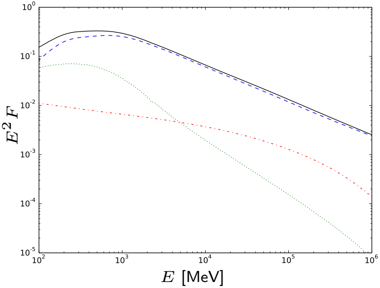
Preliminary Results

- At Galactic centre
- Different source models
- No ISRF scaling yet (see Fermi Diffuse Paper)

Axi-Symmetric Model



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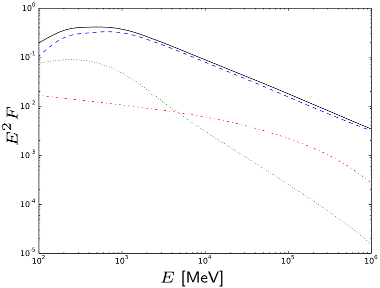

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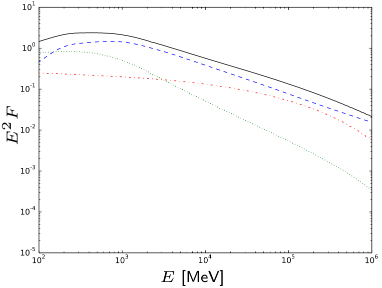

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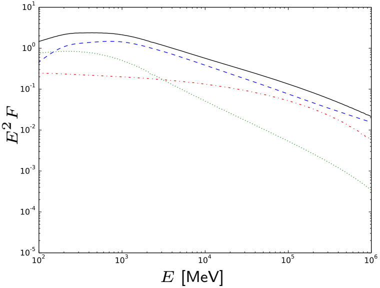

Observation

- Change in total flux
- Impact of electrons
- Inverse compton

Preliminary Results

- At Galactic centre
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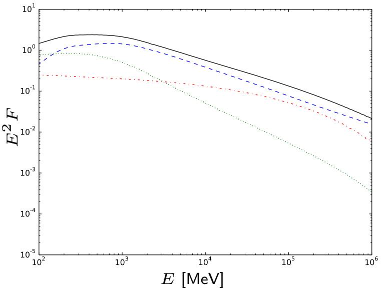
Conclusion

- Dependence on source model
- Other transport parameters
- Numerics?

Two Arm Model



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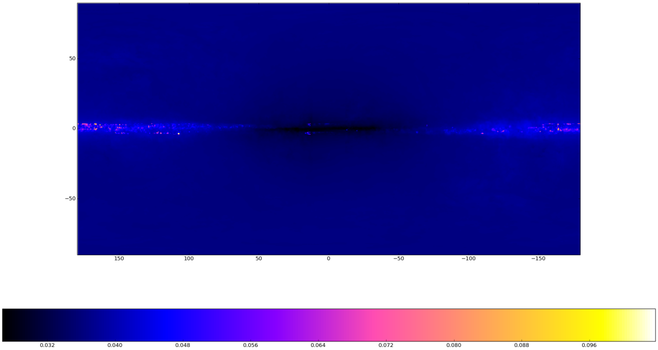
Effect of Convergence

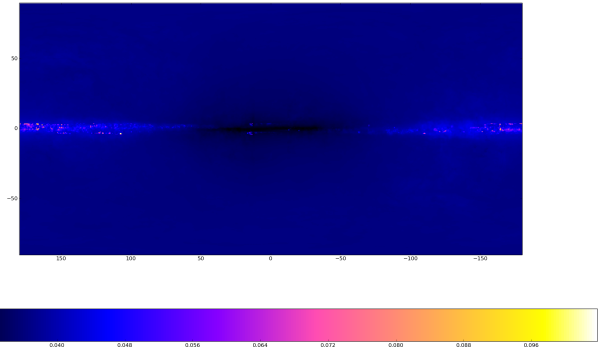
Residuum for bremsstrahlung



Setup

- Different GALPROP time-integration parameters

Residuum for bremsstrahlung

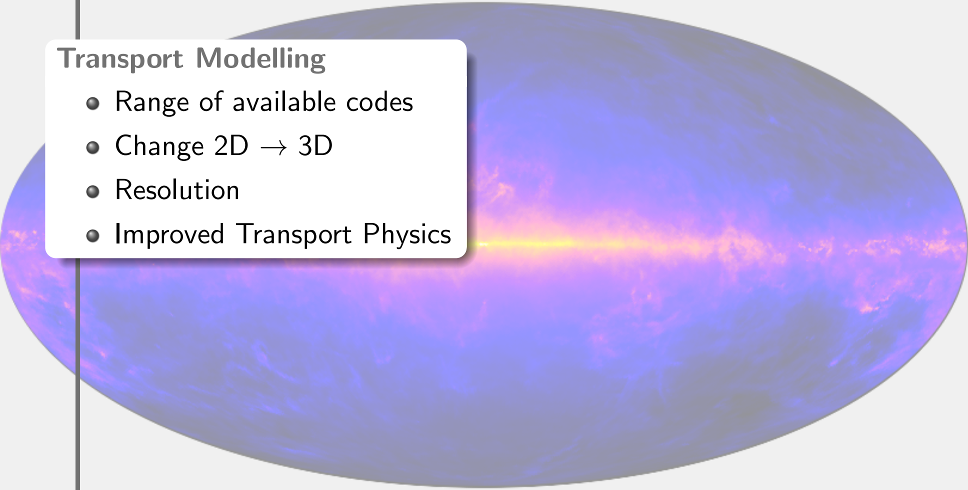


Setup

- Different GALPROP time-integration parameters

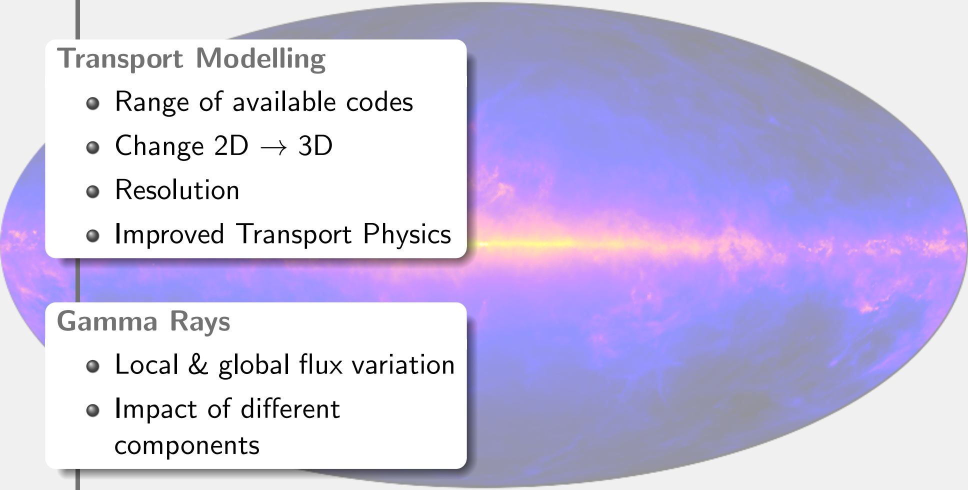
Result

- Global shift
- Local structure



Transport Modelling

- Range of available codes
- Change 2D $\rightarrow$ 3D
- Resolution
- Improved Transport Physics



Transport Modelling

- Range of available codes
- Change 2D $\rightarrow$ 3D
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Gamma Rays

- Local & global flux variation
- Impact of different components

Conclusion

Transport Modelling

- Range of available codes
- Change 2D $\rightarrow$ 3D
- Resolution
- Improved Transport Physics

Gamma Rays

- Local & global flux variation
- Impact of different components

Galactic Centre

- Here: localised sources
- Possibilities:
  - Anisotropic diffusion
  - Re-acceleration
  - Unresolved sources
  - Matter / Radiation
  - Galactic Wind
- Problems:
  - 2D models insufficient
  - Spatial resolution