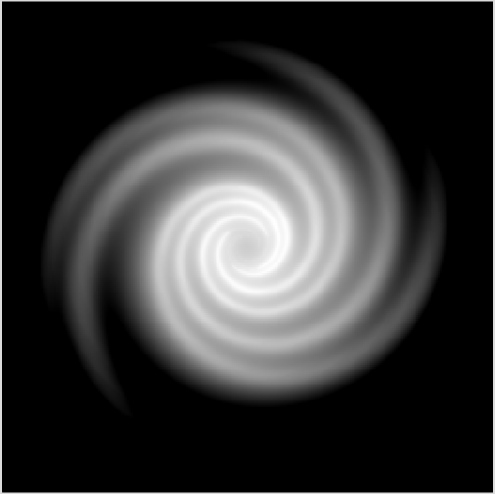
Galactic Cosmic Ray Propagation with PICARD

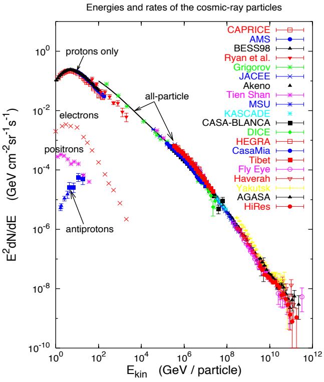


Ralf Kissmann

Innsbruck University

Different Fields

The Cosmic Ray Spectrum

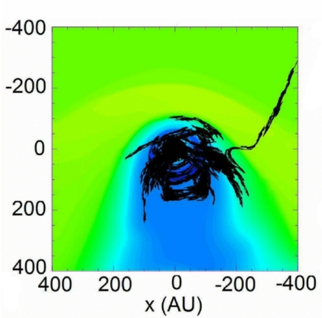


(Hillas (2006))

Different Fields

- Heliospheric physics

CRs in the Heliosphere

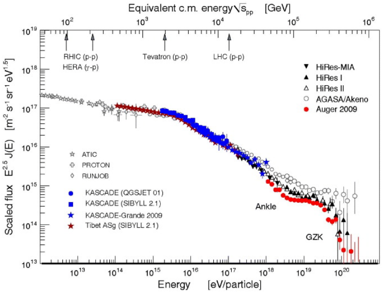


(Strauss et al. (2013))

Different Fields

- Heliospheric physics
- Highest energy CRs

Highest energy cosmic rays



(Matthiae (2010))

Fields of Cosmic Ray Research

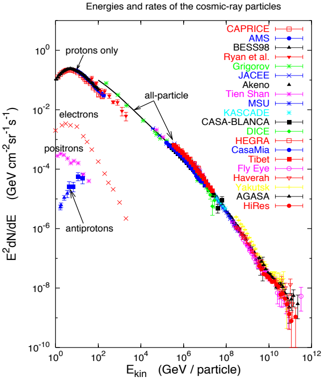
Different Fields

- Heliospheric physics
- Highest energy CRs
- Galactic CRs

Galactic Cosmic Rays

- $E < 10^7$ GeV?
- Sources of CRs?
- Transport of CRs?
- Electrons & Positrons
- Dark Matter...

The Cosmic Ray Spectrum



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Different Fields

- Heliospheric physics
- Highest energy CRs
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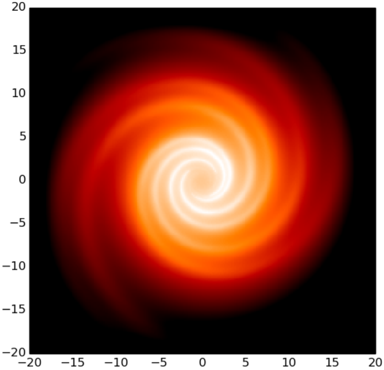
Galactic CR Distribution



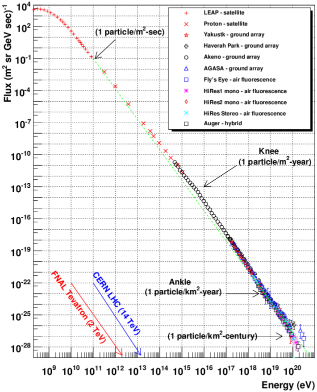
(RK (2014))

AMS-2

Observation techniques

- Lower energies
  - $\rightarrow$ direct detection
- Higher energies
  - Low flux

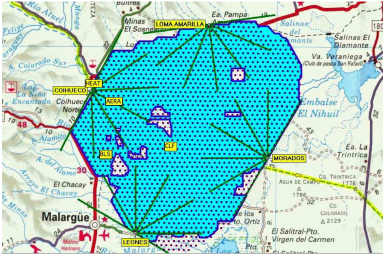
The cosmic ray spectrum



(Swordy (1997))

AMS-2

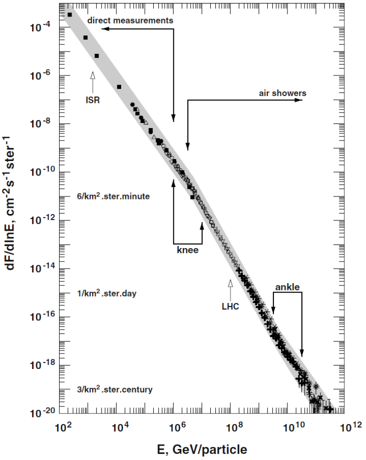
Pierre Auger Observatory



Observation techniques

- Lower energies
  - $\rightarrow$ direct detection
- Higher energies
  - Low flux
  - $\rightarrow$ from air-showers

Local CR Spectrum

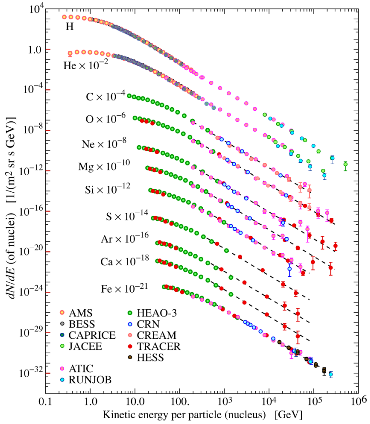


(From *High Energy Cosmic Rays* by Stanev (2009))

Available Data

- Energy dependence

CR Composition

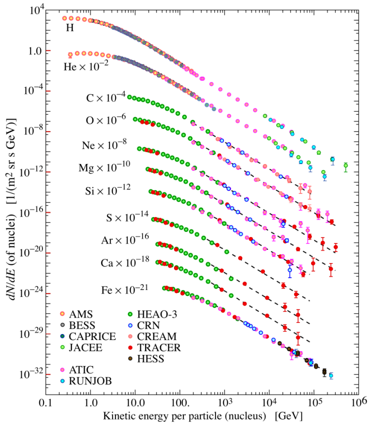


(From *Review of Particle Physics*)

Available Data

- Energy dependence
- Composition
- Secondary to primary ratios

CR Composition



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Available Data

- Energy dependence
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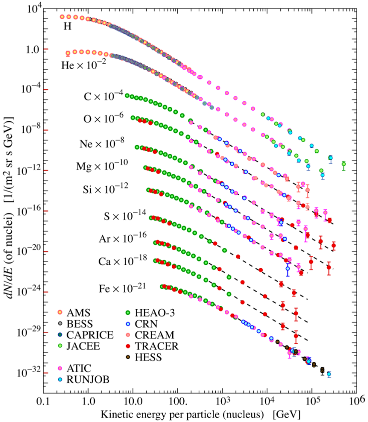
- Secondary to primary ratios

But

- Arrival directions
- Flux at low energies
  - $\leftrightarrow$ solar modulation
- Flux at Earth typical?

CR Composition



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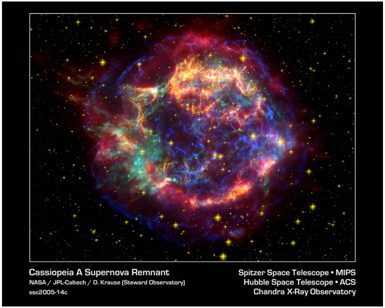
Here

Propagation of CRs

CR Source Candidates

- Supernova remnants

SNR Cas A

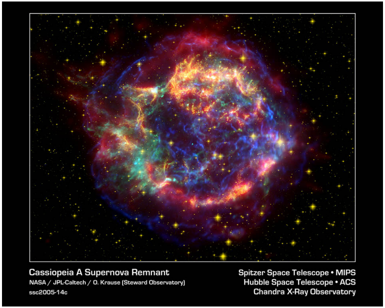


(image by Spitzer)

CR Source Candidates

- Supernova remnants
- Pulsars (PWNs)
- Colliding wind binaries
- ...

SNR Cas A



(image by Spitzer)

Crab Pulsar

(image by Chandra)

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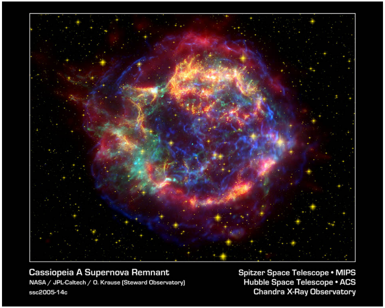


(image by Spitzer)

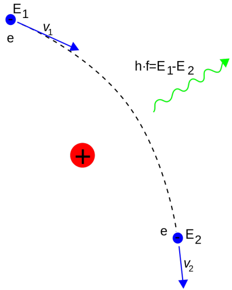
Motivation

- Theoretical arguments
- Gamma-ray emission

Energy Losses

- Ionisation losses
- Coulomb losses
- Bremsstrahlung

Bremsstrahlung Losses



Energy Losses

- Ionisation losses
- Coulomb losses
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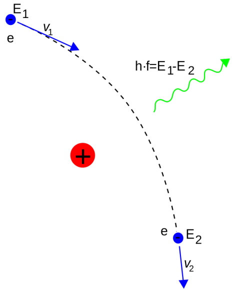
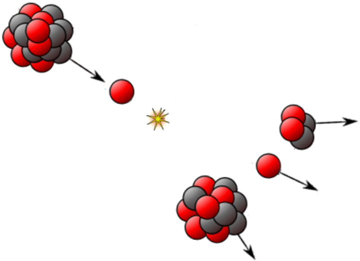
Bremsstrahlung Losses



Spallation Reaction



Inelastic reactions

- Spallation of particles
- Creation of secondaries
- Creation of pions

Energy Losses

- Gyration

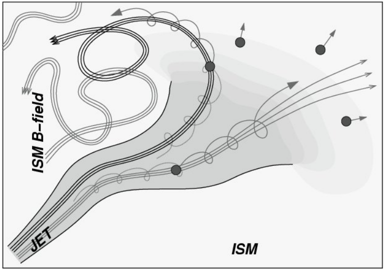
→ synchrotron losses

→ synchrotron radiation

Interaction with Mag. Field

- Energy losses

Transport in ISM



(by Heinz & Sunyaev (2002))

Energy Losses

- Gyration

→ synchrotron losses

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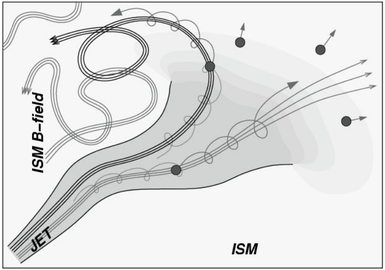
Interaction with Mag. Field

- Energy losses
- Field parallel motion
- Scattering

Transport in ISM



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Propagation: Further Interactions

Energy Losses

- Gyration

→ synchrotron losses

→ synchrotron radiation

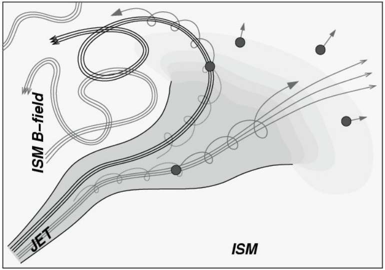
Interaction with Mag. Field

- Energy losses
- Field parallel motion
- Scattering

Resulting CR Motion

- Scattering → diffusion
- Gas motion → convection

Transport in ISM



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Propagation: Further Interactions

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Interaction with Mag. Field

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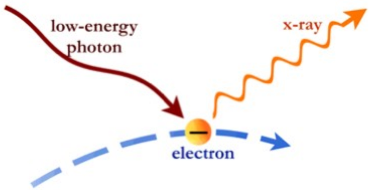
Inverse Compton (IC) Losses



(by S. Bank)

Interaction with Radiation

- IC losses
- Electrons only

Energy Losses – Overview

Energy losses

- Bremsstrahlung (gas)
- Synchrotron losses (magnetic field)
- Inverse Compton losses (radiation)

Energy Losses – Overview

Energy losses

- Bremsstrahlung (gas)
- Synchrotron losses (magnetic field)
- Inverse Compton losses (radiation)

$\rightarrow$ Emission of radiation

Energy losses

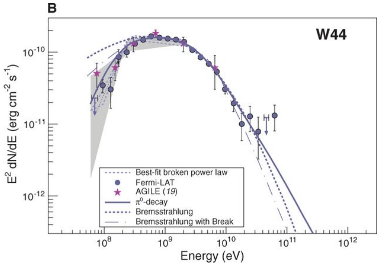
- Bremsstrahlung (gas)
- Synchrotron losses (magnetic field)
- Inverse Compton losses (radiation)

→ Emission of radiation

Additional Channel

- Pion production
- $\pi^0 \rightarrow \gamma + \gamma$

The Pion Bump



(Ackermann et al. (2013))

Energy losses

- Bremsstrahlung (gas)
- Synchrotron losses (magnetic field)
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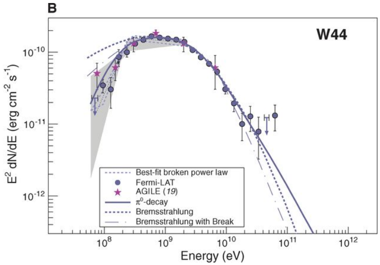
Alternative messenger

gamma-rays

The Pion Bump



(Ackermann et al. (2013))

Energy losses

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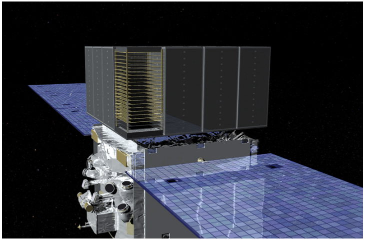
Alternative messenger

gamma-rays

Observation techniques

- Lower energies $\rightarrow$ direct

Fermi GRST



Energy Losses – Overview

Energy losses

- Bremsstrahlung (gas)
- Synchrotron losses (magnetic field)
- Inverse Compton losses (radiation)

$\rightarrow$ Emission of radiation

Additional Channel

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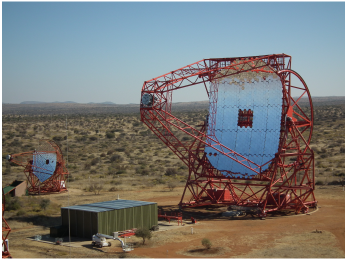
Alternative messenger

gamma-rays

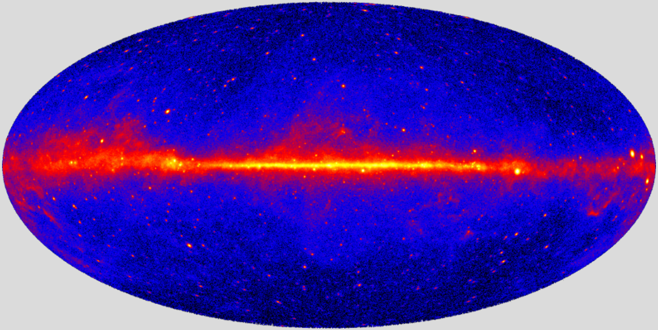
Observation techniques

- Lower energies $\rightarrow$ direct
- Higher energies $\rightarrow$ IACT technique

H.E.S.S. Telescopes



Observations of the Gamma Ray Sky



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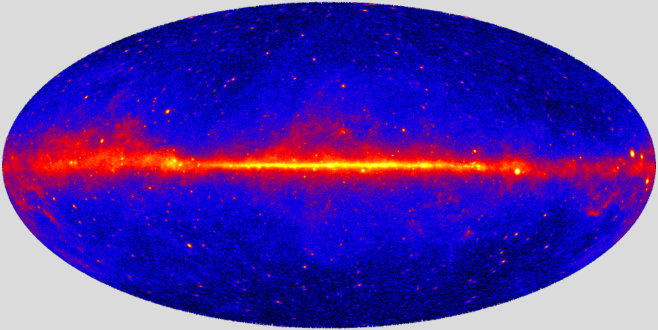
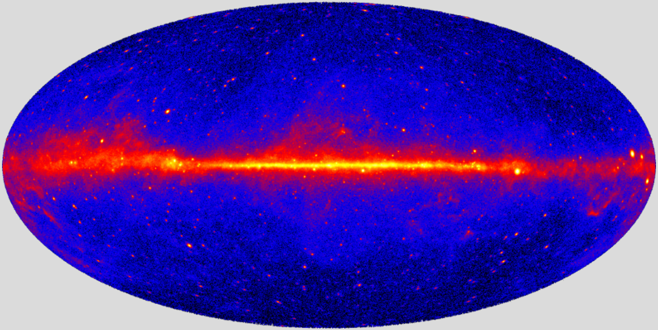


Available Data

- Energy dependence
- Time variation
- Directional information
  - Individual sources
  - Diffuse radiation

Observations of the Gamma Ray Sky



Available Data

- Energy dependence
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Connection to CRs

- Production mechanisms
- Galactic CR distribution
- Convolution with gas, ...

Transport Equation

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

Reminder: Mathematical Description

Transport Equation

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

Individual Terms

- CR sources

Reminder: Mathematical Description

Transport Equation

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

Individual Terms

- CR sources
- Spatial diffusion

Reminder: Mathematical Description

Transport Equation

$$\frac{\partial \psi_i}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot \mathcal{D} \nabla \psi_i + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i$$

Individual Terms

- CR sources
- Spatial diffusion
- Diffusive reacceleration

Transport Equation

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Individual Terms

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- Diffusive reacceleration
- Spatial convection

Reminder: Mathematical Description

Transport Equation

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Individual Terms

- CR sources
- Spatial diffusion
- Diffusive reacceleration
- Spatial convection
- (Adiabatic) energy changes

Reminder: Mathematical Description

Transport Equation

$$\frac{\partial \psi_i}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot \mathcal{D} \nabla \psi_i + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i - \nabla \cdot \mathbf{v} \psi_i - \frac{\partial}{\partial p} \left\{ \dot{p} \psi_i - \frac{p}{3} (\nabla \cdot \mathbf{v}) \psi_i \right\} - \frac{1}{\tau_f} \psi_i - \frac{1}{\tau_r} \psi_i$$

Individual Terms

- CR sources
- Spatial diffusion
- Diffusive reacceleration
- Spatial convection
- (Adiabatic) energy changes
- Catastrophic losses

Reminder: Mathematical Description

Transport Equation

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Individual Terms

- CR sources
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- Catastrophic losses
- Inter-species reactions

Transport Equation

$$\frac{\partial \psi_i}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot \mathcal{D} \nabla \psi_i + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i - \nabla \cdot \mathbf{v} \psi_i - \frac{\partial}{\partial p} \left\{ \dot{p} \psi_i - \frac{p}{3} (\nabla \cdot \mathbf{v}) \psi_i \right\} - \frac{1}{\tau_f} \psi_i - \frac{1}{\tau_r} \psi_i$$

Individual Terms

- CR sources
- Spatial diffusion
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Result

- CR-distribution ψ_i

Reminder: Mathematical Description

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$\rightarrow$ input for computing γ-rays

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$\rightarrow$ input for computing γ-rays

Solution

- Simplifications $\rightarrow$ analytical
- General case $\rightarrow$ numerical

Reminder: Mathematical Description

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$$\frac{\partial \psi_i}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot \mathcal{D} \nabla \psi_i + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_i - \nabla \cdot \mathbf{v} \psi_i - \frac{\partial}{\partial p} \left\{ \dot{p} \psi_i - \frac{p}{3} (\nabla \cdot \mathbf{v}) \psi_i \right\} - \frac{1}{\tau_f} \psi_i - \frac{1}{\tau_r} \psi_i$$

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Transport Processes

- Convection
- Diffusion
- Diffusive reacceleration

Standard Galactic Transport Model

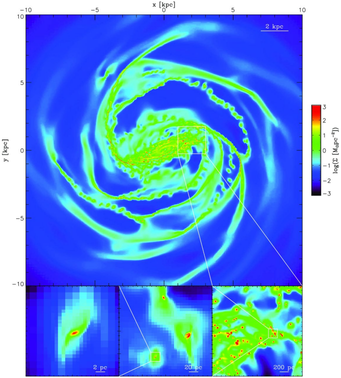
Transport Processes

- Convection
- Diffusion
- Diffusive reacceleration

Galaxy Model

- Matter distribution
- ISRF
- Magnetic field

Numerical Galaxy Model



(Renaud et al (2013))

Standard Galactic Transport Model

Transport Processes

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Galaxy Model

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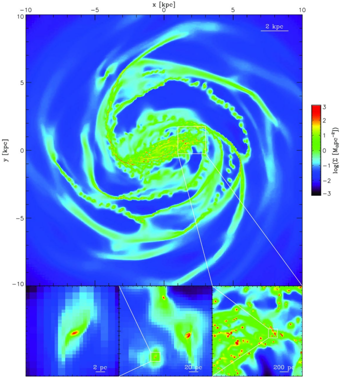
- Magnetic field

Interaction with ISM

- Spallation cross sections
- Energy loss processes
- Nuclear network

Numerical Galaxy Model



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↔ Galaxy model

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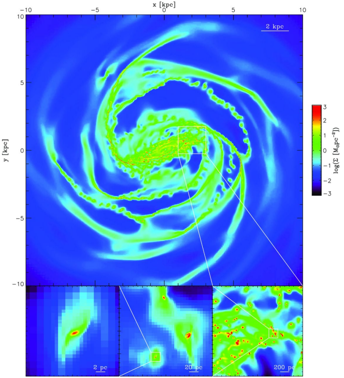

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$\leftrightarrow$ Galaxy model

Secondaries

- Secondary CRs
- Gamma rays

Standard Galactic Transport Model

Transport Processes

- Convection
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↔ Galaxy model

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Solution Process

CR source distribution

Standard Galactic Transport Model

Transport Processes

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- Gamma rays

Solution Process

CR source distribution

$\Downarrow$

Transport solver

Transport Processes

- Convection
- Diffusion
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Secondaries

- Secondary CRs
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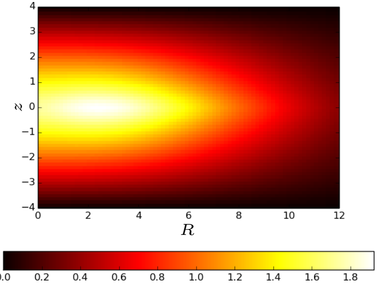
CR Distribution



Solution Process

CR source distribution

$\Downarrow$

Transport solver

$\Downarrow$

CR distribution

Standard Galactic Transport Model

Transport Processes

- Convection
- Diffusion
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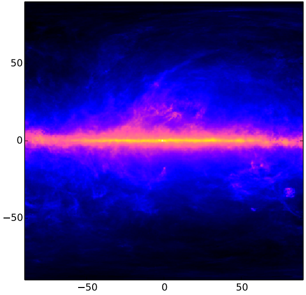
Gamma-Ray Emission



Secondaries

- Secondary CRs
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Solution Process

CR source distribution

$\Downarrow$

Transport solver

$\Downarrow$

CR distribution

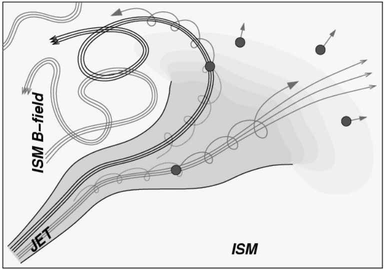
$\Downarrow$

Gamma ray emission

Major Codes

- semi-analytical:
  - Usine

Transport in ISM

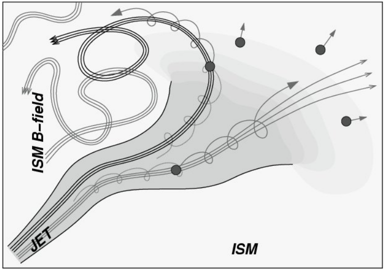


(by Heinz & Sunyaev (2002))

Major Codes

- semi-analytical:
  - Usine
- fully numerical
  - Dragon

Transport in ISM



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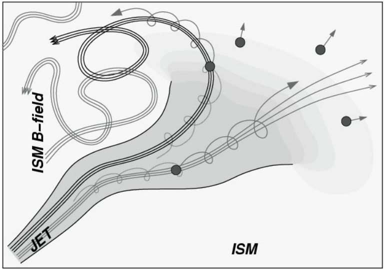

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Major Codes

- semi-analytical:
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  - GALPROP
  - PICARD (this talk)

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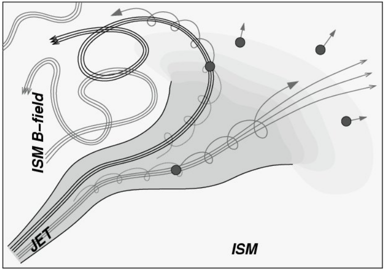

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Galactic Propagation Codes

Major Codes

- semi-analytical:
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- fully numerical
  - DRAGON
  - GALPROP
  - PICARD (this talk)

Other Approaches

- Büsching et al.
- Effenberger et al.
- Hanasz et al. (PIERNIK)

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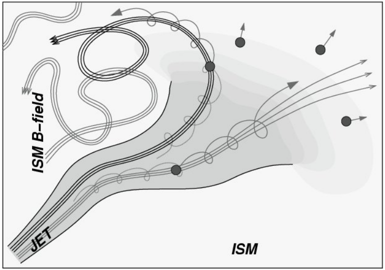

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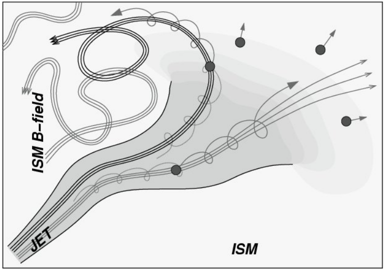

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Issues in Other Models (GALPROP)

Transport Equation

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot (\mathcal{D} \nabla \psi - \mathbf{v}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left\{ \dot{p}\psi - \frac{p}{3} (\nabla \cdot \mathbf{v}) \psi \right\} - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Physics Issues

- Physics as parameters

Issues in Other Models (GALPROP)

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Physics Issues

- Physics as parameters

Transport Parameters

- Source distribution $q(\mathbf{r}, p)$
- Diffusion tensor $\mathcal{D}$
- Momentum diffusion D_{pp}
- Spatial convection $\mathbf{v}$
- Energy losses $\dot{p}$
- Spallation τ_f

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Physics Issues

- Physics as parameters
- Constant in time
- Constant in space

→ Parameter tuning

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Physics Issues

- Physics as parameters
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→ Parameter tuning

Simplified Parameters

- Diffusion, halo height
- Galaxy model
- Convection

Transport Parameters

- Source distribution $q(\mathbf{r}, p)$
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Technical Issues

- Solver
- Local structure ↔ spatial resolution
- Consistency

Simplified Parameters

- Diffusion, halo height
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Issues in Other Models (Galprop)

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Physics Issues

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$\rightarrow$ Parameter tuning

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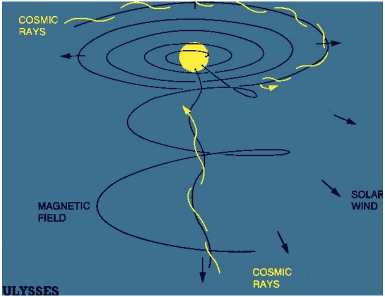
- Galaxy model
- Convection

Diffusion in Galprop

- Isotropic
- No spatial variation

CRs Inside the Heliosphere



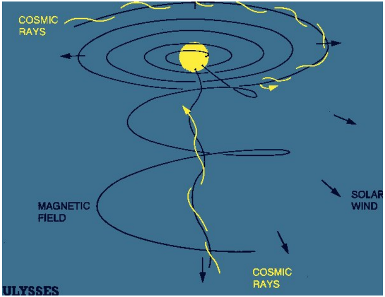
(From Ulysses website)

Example I: Spatial Diffusion

Diffusion in Galprop

- Isotropic
- No spatial variation
- Alternatives:
  - DRAGON, PICARD
  - Effenberger et al.

CRs Inside the Heliosphere



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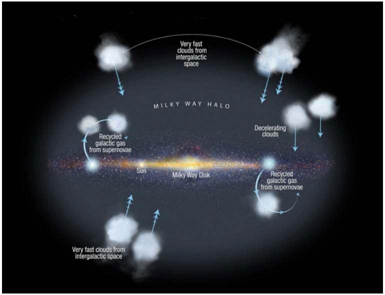
Boundary conditions?

- Diffusion $\leftrightarrow$ advection
- Energy dependence
- Free streaming outside?

The Galaxy



(artist sketch by NASA)

Example I: Spatial Diffusion

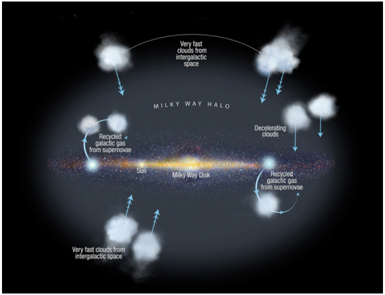
Diffusion in Galprop

- Isotropic
- No spatial variation
- Alternatives:
  - DRAGON, PICARD
  - Effenberger et al.

Boundary conditions?

- Diffusion $\leftrightarrow$ advection
- Energy dependence
- Free streaming outside?
- GALPROP:
  - Restricted to box
  - $\psi = 0$ at boundary

The Galaxy



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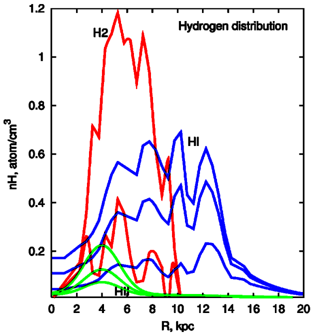
Gas for Propagation



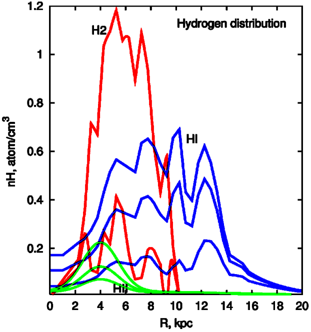
(From Galprop website)

Example II: Consistency

Propagation

- Azimuthally symmetric

Gas for Propagation



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Propagation

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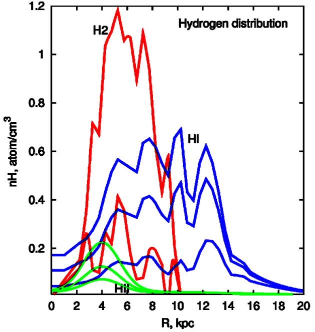
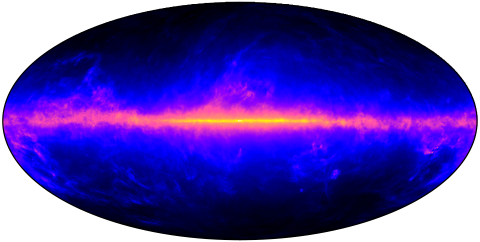
Gas for Propagation



(From Galprop website)

Gamma Ray Map



(PICARD results for 100 GeV gamma rays)

Example II: Consistency

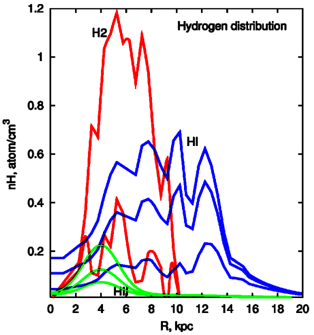
Propagation

- Azimuthally symmetric

Gamma Ray Computation

- Ring distribution

Gas for Propagation



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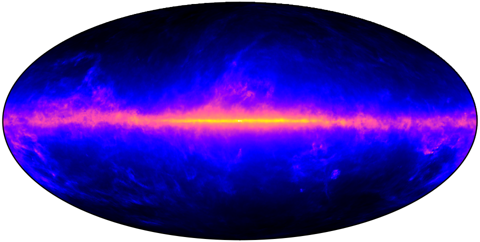
Gamma Ray Map



(PICARD results for 100 GeV gamma rays)

Propagation

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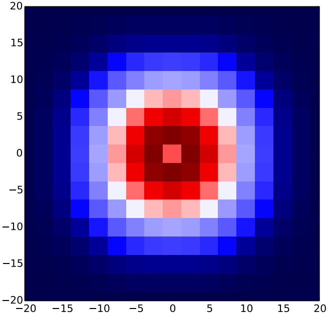
But: CR Distribution



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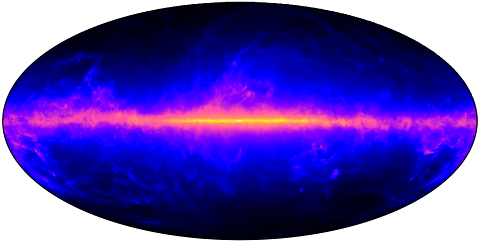

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Transport Equation

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Type of Equation

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Possible Solutions

- Time-dependent
- Steady state

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- Time integration
  - Solve multiple time steps
  - Characteristic time-scales
  - Convergence to steady state

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→ Time-integration solver

Possible Solvers

- SDEs / Monte Carlo
  - (Pseudo-) particles

Steady State Solution via Time-Integration

Possible Solvers

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Steady State Solution via Time-Integration

Possible Solvers

- SDEs / Monte Carlo
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  - Explicit

Explicit schemes

$$\frac{\partial \psi}{\partial t} = f(\psi) \rightarrow \frac{\psi^{n+1} - \psi^{n}}{\Delta t} = f(\psi^{n})$$

- Easy to solve
- Time step restriction

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Implicit schemes

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- Larger time step

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Solution Approach

- Start with empty Galaxy
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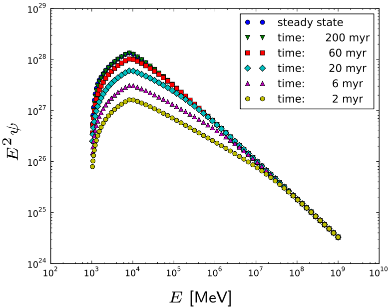
Time Evolution of Spectrum



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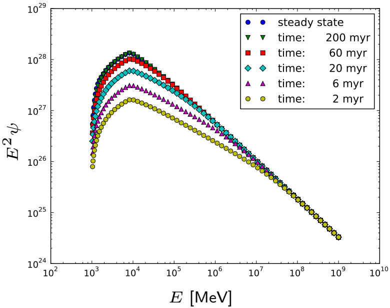

Characteristic time: ~50 yrs

Numerical Implementation

- Crank-Nicolson discretisation
- Time-integration
- Dimensional splitting
- Decreasing timesteps

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Problems

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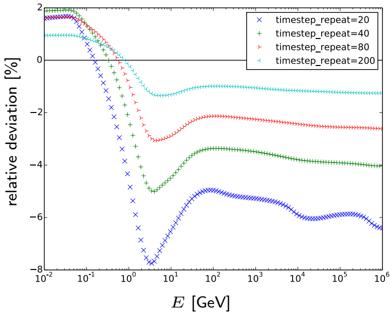
- Timestep control

Time Evolution Parameters



The GALPROP solver

Numerical Implementation

- Crank-Nicolson discretisation
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Problems

- Check for convergence?
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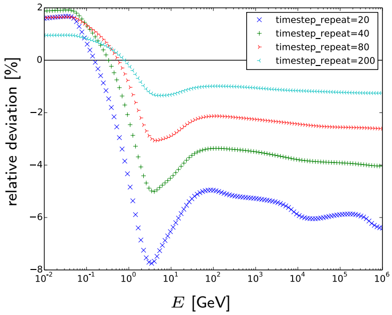
- Problem dependent?

Time Evolution Parameters



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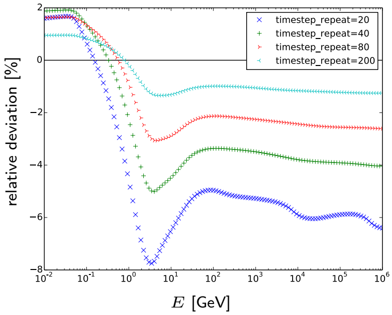

Problems

- Check for convergence?
- Timestep control
- Problem dependent?
- Nuclear reaction network

Numerical Implementation

- Crank-Nicolson discretisation
- Time-integration
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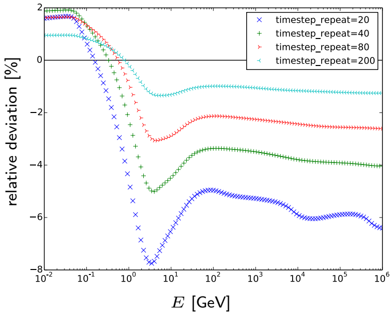
Time Evolution Parameters



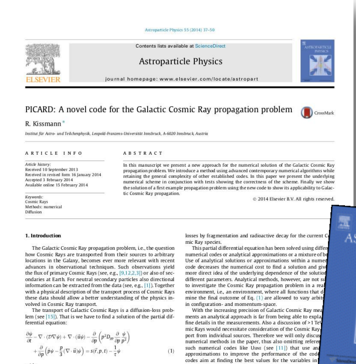
Problems

- Check for convergence?
- Timestep control
- Problem dependent?
- Nuclear reaction network

→ 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

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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.

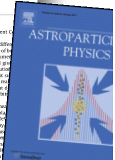
1. Introduction

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:

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

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 discus
numerical methods in the paper, thus also omitting referen
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)

A Different Approach

- Solve steady state problem

Simplified Transport Equation

$$\frac{\partial \psi}{\partial t} = s(\mathbf{r}, p) + \nabla \cdot (\mathcal{D} \nabla \psi - \mathbf{v} \psi) + \frac{\psi}{\tau}$$

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$$0 = s(\mathbf{r}, p) + \nabla \cdot (\mathcal{D}\nabla\psi - \mathbf{v}\psi) + \frac{\psi}{\tau}$$

The Picard Solver

A Different Approach

- Solve steady state problem

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$$0 = s(\mathbf{r}, p) + \nabla \cdot (\mathcal{D}\nabla\psi - \mathbf{v}\psi) + \frac{\psi}{\tau}$$

Difficulty

- Discretisation

Descretisation in 1D

$$\begin{aligned}\nabla\mathcal{D}\nabla\psi =& D_{xx}\frac{\partial^2\psi}{\partial x^2} \\ \simeq& D_{xx}\frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{\Delta x^2}\end{aligned}$$

The PICARD Solver

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- Discretisation
  - $\rightarrow$ Coupled matrix equation

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Descretisation in 2D

$$\begin{aligned}\nabla\mathcal{D}\nabla\psi =& D_{xx}\frac{\partial^2\psi}{\partial x^2} + D_{yy}\frac{\partial^2\psi}{\partial y^2} \\ \simeq& D_{xx}\frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{\Delta x^2} \\ &+ D_{yy}\frac{\psi_{i,j+1} - 2\psi_{i,j} + \psi_{i,j+1}}{\Delta y^2}\end{aligned}$$

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- Iterative solver
  - Multigrid
  - BICGStab

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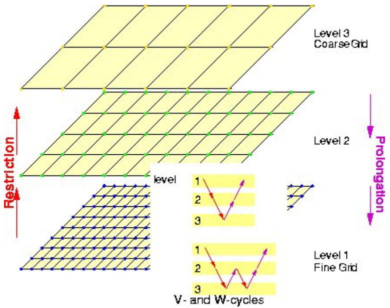
Multigrid Illustration



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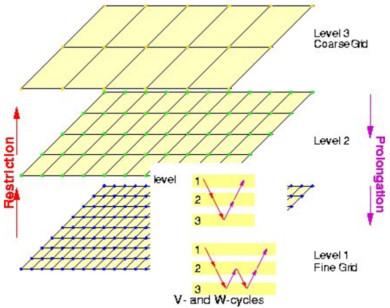


Multigrid Implementation

- Red-black Gauss-Seidel
- Alternating plane Gauss-Seidel

Solver

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

Features of PICARD

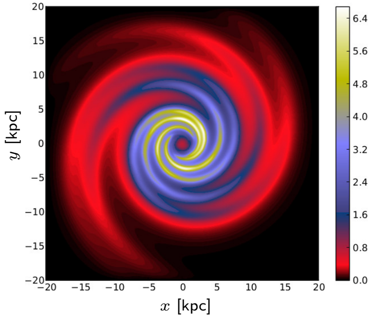
Solver

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

Example Resolution

- Standard GALPROP
  - 2D (1 kpc × 100 pc)
- PICARD
  - 3D (up to ∼75 pc^3)

Example Simulation Results



Features of Picard

Solver

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- Explicit time integrator
- MPI-parallel
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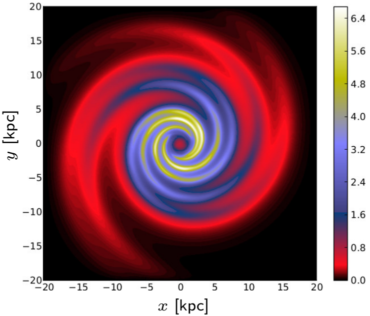
Physics

- 3D source distributions
- Anisotropic diffusion
- tbd...

Example Simulation Results



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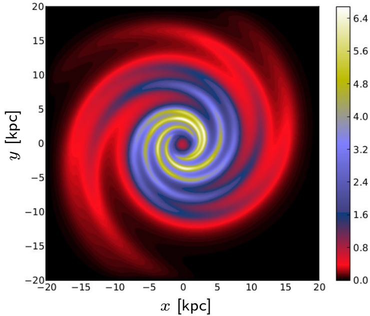

Example results:
Milkyway as spiral galaxy

CR Source Candidates

- Supernova remnants
- Pulars / PWNs
- CWBs

Spiral Arm Cosmic Ray Sources

CR Source Candidates

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- Pulars / PWNs
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→ young objects

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Source Distribution

- Spiral galaxy

→ Spiral arms

→ Galactic bar

Spiral Galaxy NGC1232

Spiral Arm Cosmic Ray Sources

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→ young objects

→ star formation regions

Source Distribution

- Spiral galaxy

→ Spiral arms

→ Galactic bar

- Tracers of spiral structure

→ Variety of models

Spiral Galaxy NGC1232

Model setup

- Spiral arm source dist.
- Standard propagation parameters
- Full nuclear network

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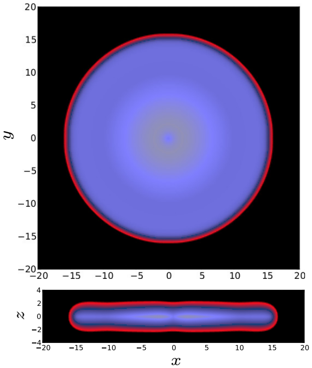
- Standard propagation parameters
- Full nuclear network

Results

- Different source distributions

→ 1 TeV electrons

Axisymmetric Model



(Werner, RK, et al. (2014))

Spiral Arm CR Transport Models

Model setup

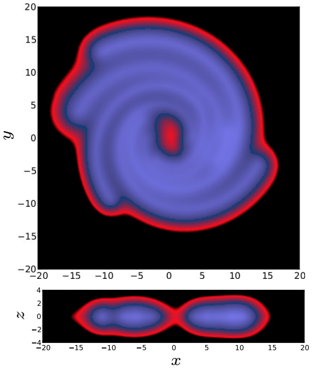
- Spiral arm source dist.
- Standard propagation parameters
- Full nuclear network

Results

- Different source distributions

→ 1 TeV electrons

NE-2001 Model



(Werner, RK, et al. (2014))

Spiral Arm CR Transport Models

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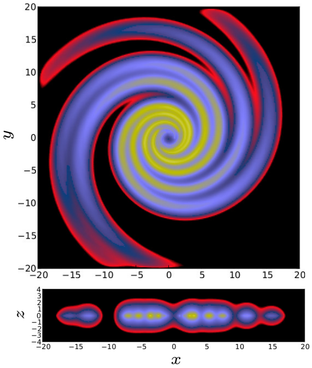
Steiman Four Arm Model



(Werner, RK, et al. (2014))

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Results

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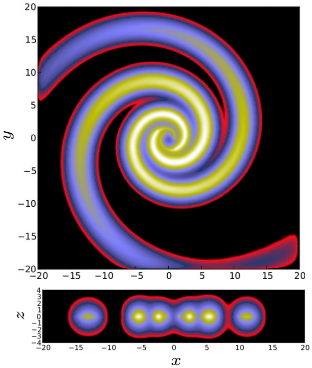
→ 1 TeV electrons

Dame Two Arm Model



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Spiral Arm CR Transport Models

Model setup

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- Full nuclear network

Results

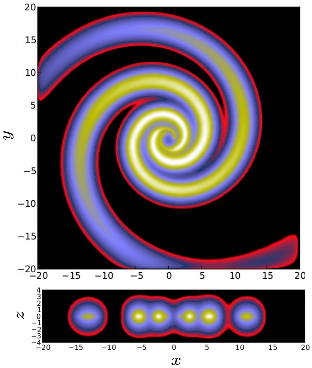
- Different source distributions

→ 1 TeV electrons

- Differences ↔ normalisation

↔ Vicinity of Earth

Dame Two Arm Model



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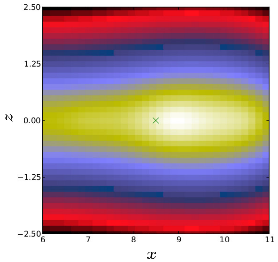

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Model setup

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Results

- Different source distributions

→ 1 TeV electrons

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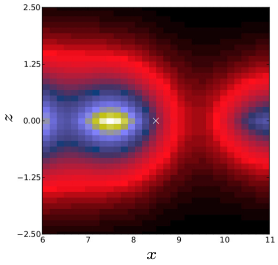
↔ Vicinity of Earth

Other Four Arm Model



(Werner, RK, et al. (2014))

Spiral Arm CR Transport Models

Model setup

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Results

- Different source distributions

→ 1 TeV electrons

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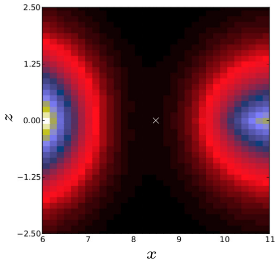
Two Arm Model



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- Standard propagation parameters
- Full nuclear network

Results

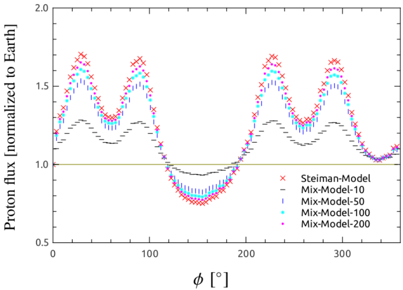
- Different source distributions

$\rightarrow$ 1 TeV electrons

- Differences $\leftrightarrow$ normalisation

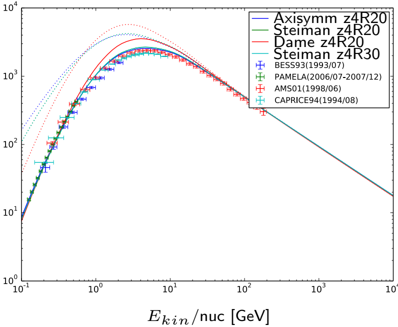
$\leftrightarrow$ Vicinity of Earth

Variation of CR Flux



(Werner, RK, et al. (2014))

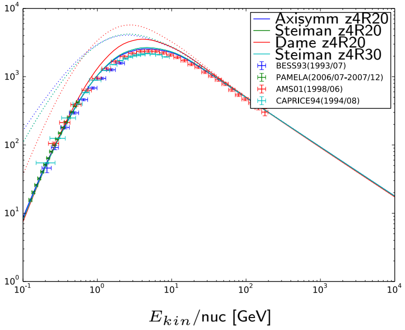
CR Proton Flux



(RK et al. (2014))

Confrontation with CR data

CR Proton Flux



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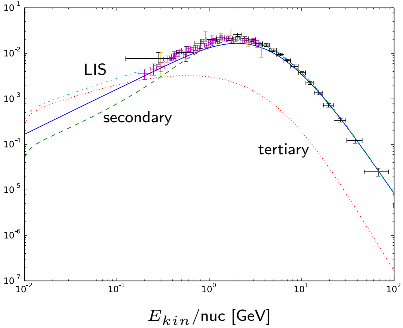
Antiproton Flux



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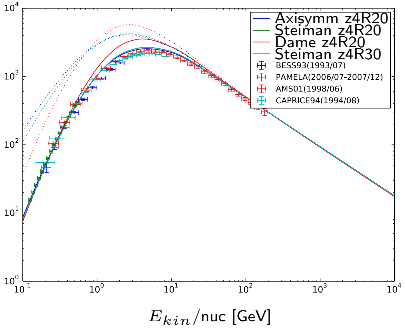

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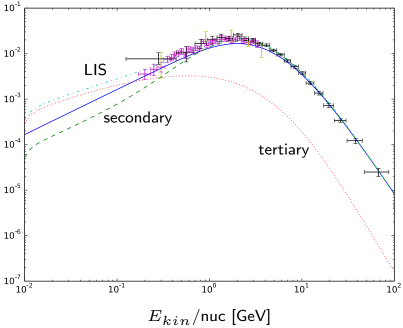
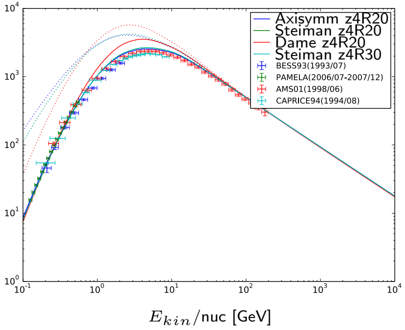


Discussion

- Fit for different models
- Small flux differences

CR Proton Flux



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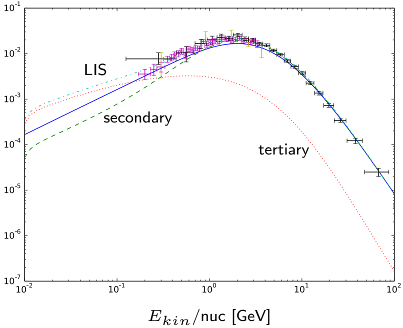

Discussion

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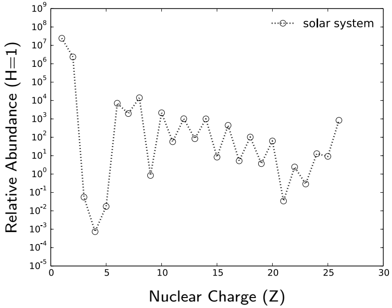
Similarity of CR Spectra

$\rightarrow$ More sensitive constraints

Abundance of Elements



(Solar System data by Lodders (2003))

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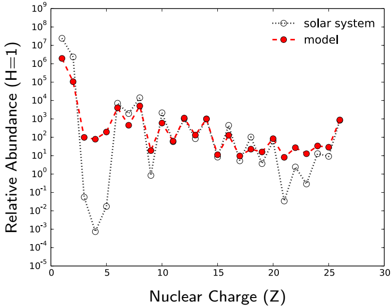

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Distinction

- Primary cosmic rays
  - nucleosynthesis
  - accelerated at sources

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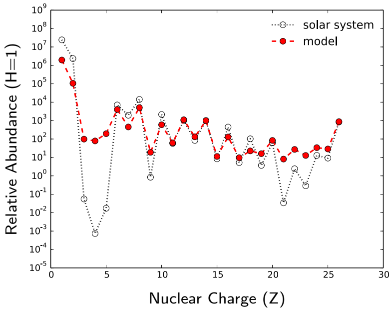

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Secondary Cosmic Rays

Distinction

- Primary cosmic rays
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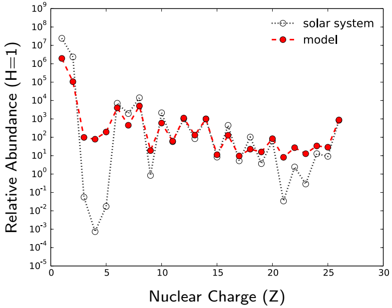
  - accelerated at sources
- Secondary cosmic rays
  - spallation
  - sources = primaries

Abundance of Elements



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Additional Constraint

- Secondary / Primary ratios

→ Distance to sources

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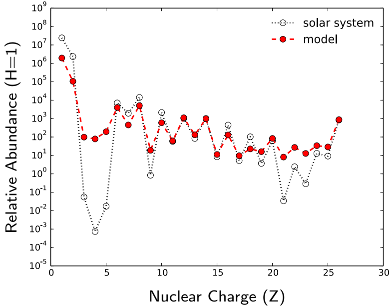

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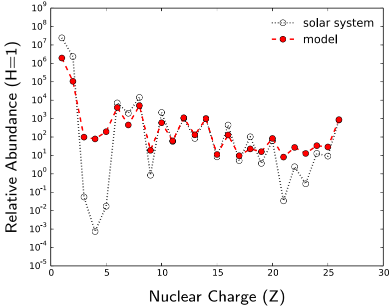

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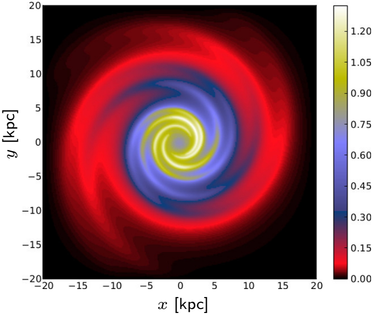
Distribution of Carbon



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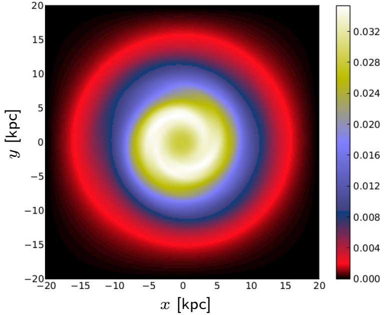
Distribution of Boron



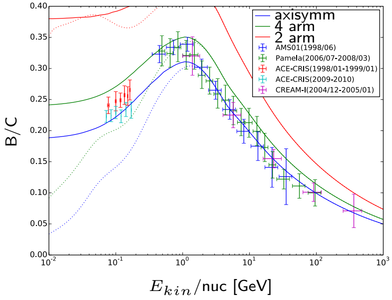
(RK et al. (2014))

B/C in Spiral Arm Models

Discrepancy

- No good fit for spirals $\chi^2_{dof} = 4.56 \leftrightarrow \chi^2_{dof} = 1.04$
- But: propagation tuned to non-spirals
- BC depends on position

Different Models



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- Adapt to spiral arms

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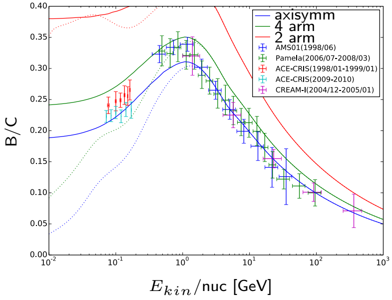

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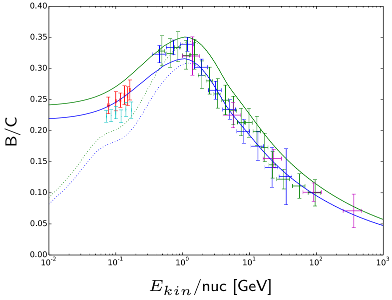
Modified Parameters



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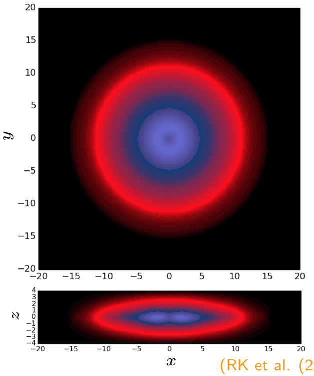
Conclusion

- Fit possible

Axially Symmetric Model



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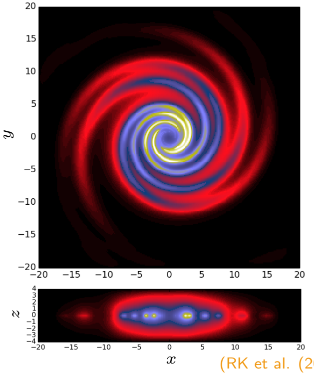
- $\chi^2_{dof} = 0.9$

Conclusion

- Fit possible

Modified Four-Arm Model



(RK et al. (2014))

B/C in Spiral Arm Models

Discrepancy

- No good fit for spirals
  $\chi^2_{dof} = 4.56 \leftrightarrow \chi^2_{dof} = 1.04$
- But: propagation tuned to non-spirals
- BC depends on position

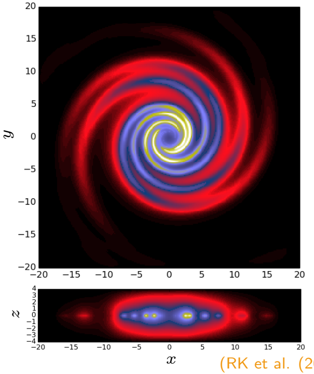
Alternative Parameters

- Adapt to spiral arms
- $\chi^2_{dof} = 0.9$

Conclusion

- Fit possible
- Flux variation

Modified Four-Arm Model

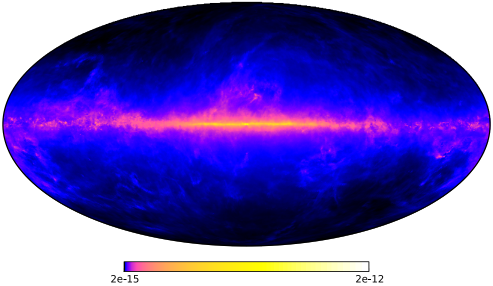


(RK et al. (2014))

Need additional constraints

Outlook: Gamma-rays with PICARD

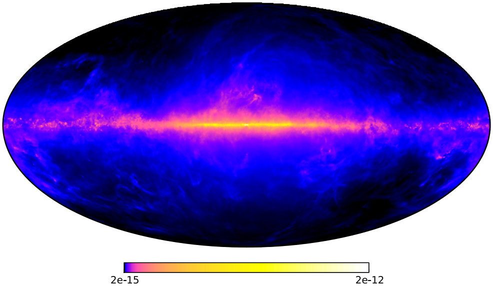
Axisymmetric Configuration



Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Four-Arm Configuration

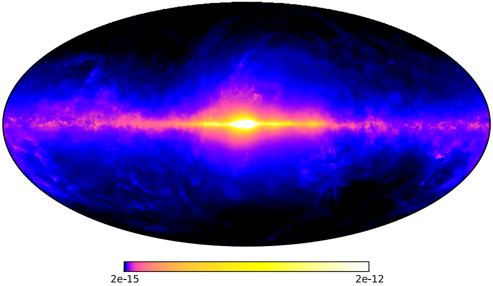


Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Outlook: Gamma-rays with Picard

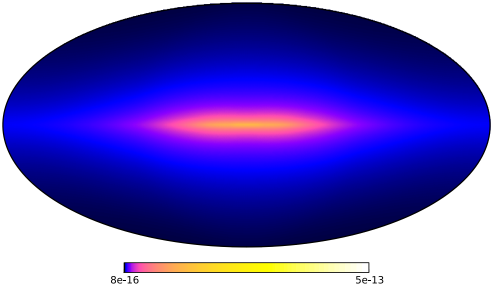
Two-Arm Configuration



Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Axi-Symmetric Configuration – IC

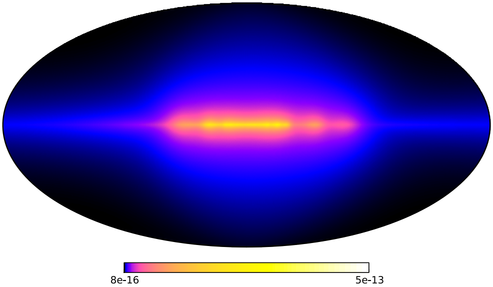


Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Outlook: Gamma-rays with PICARD

Four-Arm Configuration – IC

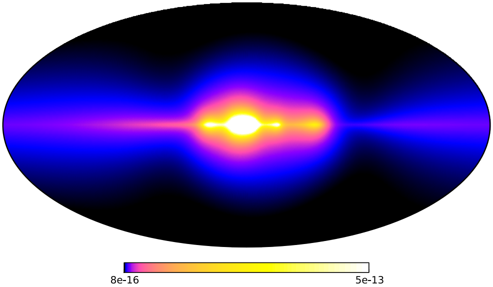


Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Outlook: Gamma-rays with PICARD

Two-Arm Configuration – IC



Preliminary Results

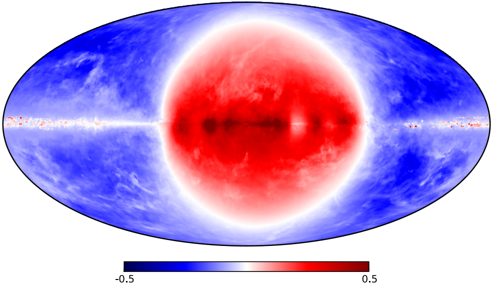
- Increase of IC emission

Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Outlook: Gamma-rays with PICARD

Residual – Four-Arm Configuration



Preliminary Results

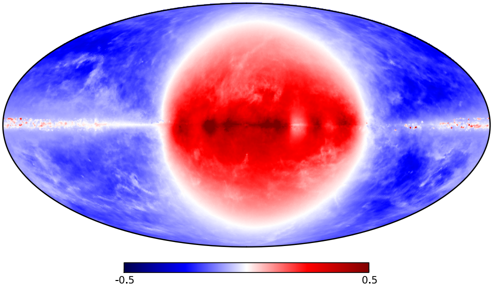
- Increase of IC emission
- Major differences

Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Outlook: Gamma-rays with Picard

Residual – Four-Arm Configuration



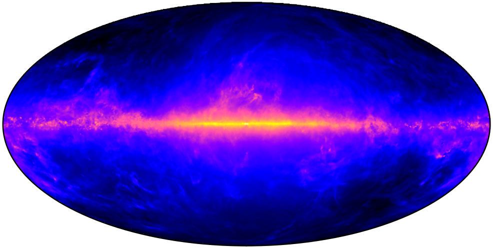
Preliminary Results

- Increase of IC emission
- Major differences
- Relevant constraint

Global Constraint

- Gamma-ray all-sky emission
- Example: 100 GeV

Four-Arm Configuration

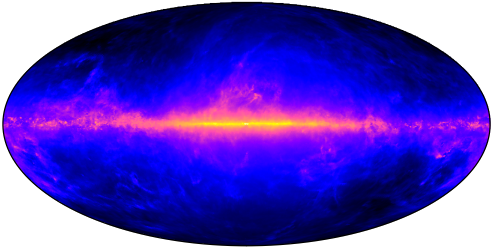


The PICARD Solver

- Introduced in 2014
- More detailed propagation models

Conclusion

Four-Arm Configuration



Application of PICARD

- CR data at Earth ✓
- Alternative propagation models ✓
- Gamma-ray emission (✓)

The PICARD Solver

- Introduced in 2014
- More detailed propagation models