Simulation of Galactic Propagation

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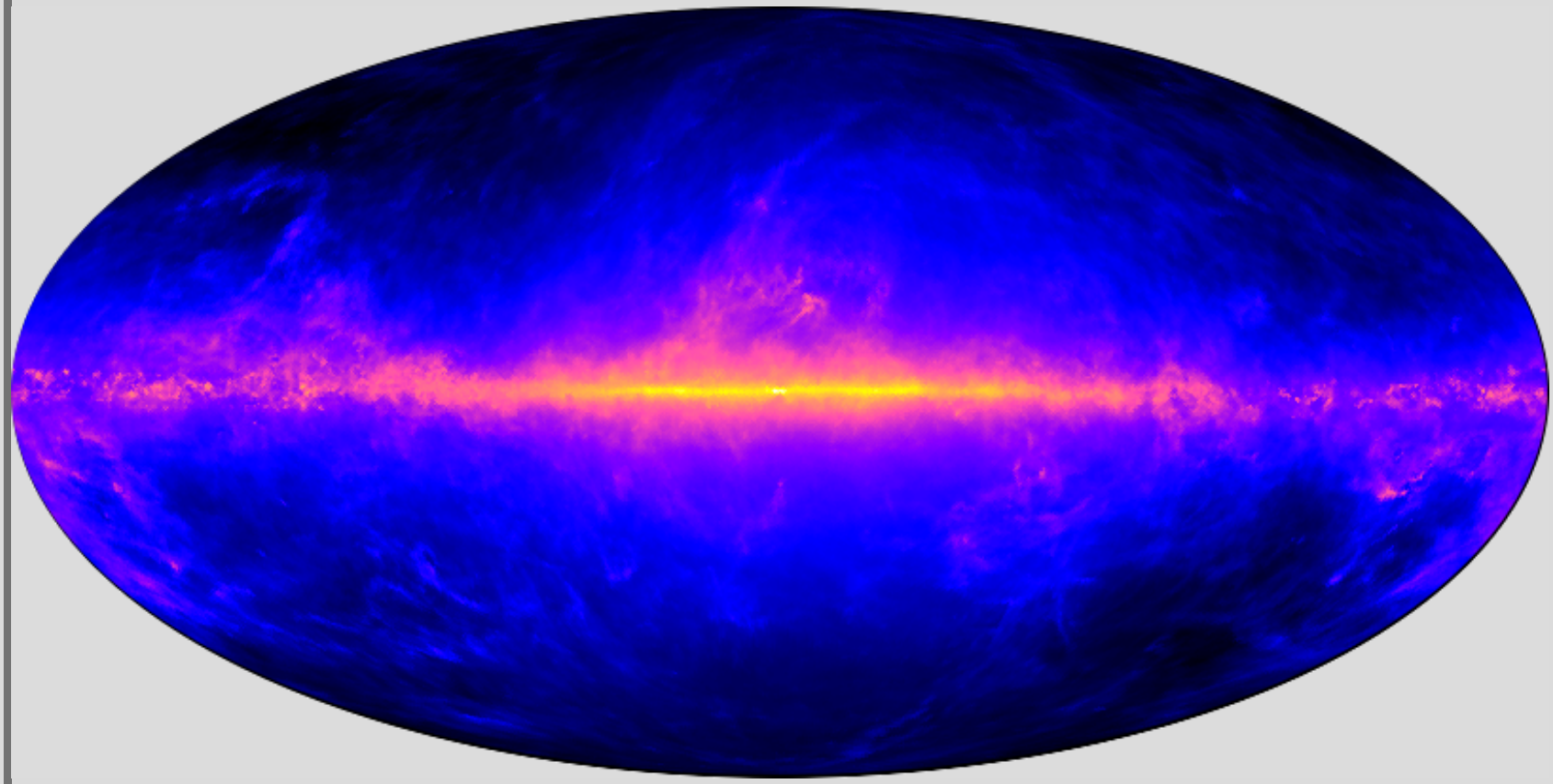

R. Kissmann

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Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration

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Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration

Interaction with ISM

- Spallation cross sections
- Energy loss processes
- Nuclear network

$\leftrightarrow$ Galaxy model

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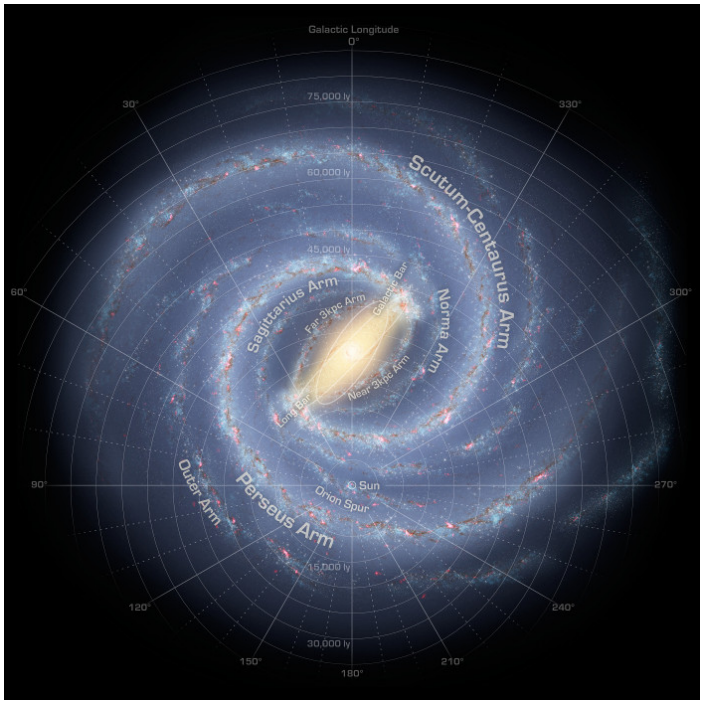
$\leftrightarrow$ Galaxy model

Galaxy Model

- Matter distribution
- ISRF
- Magnetic field

Spiral-Galaxy Model



(Credit: Spitzer / NASA)

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Galaxy Model

- Matter distribution
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- Magnetic field

Secondaries

- Secondary CRs
- Gamma rays
- Neutrinos

Numerical Galactic Transport Models

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Solution Process

CR source distribution

Numerical Galactic Transport Models

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$\leftrightarrow$ Galaxy model

Galaxy Model

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Solution Process

CR source distribution

$\Downarrow$

Transport solver

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Transport Processes

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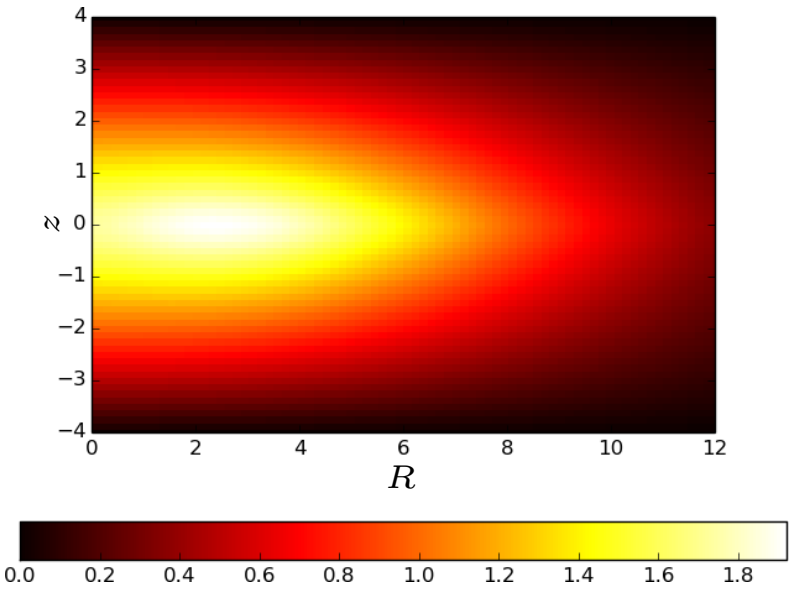
CR Distribution



Solution Process

CR source distribution

⇓

Transport solver

⇓

CR distribution

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Transport Processes

- Convection
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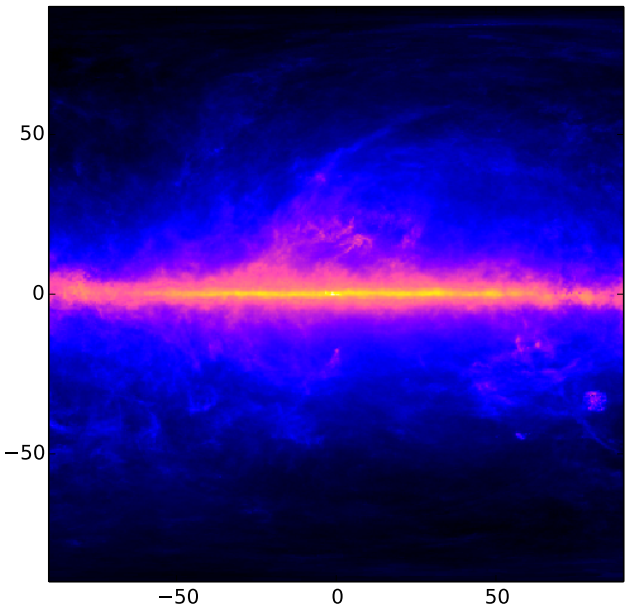
Secondaries

- Secondary CRs
- Gamma rays
- Neutrinos

Gamma-Ray Emission



Solution Process

CR source distribution

⇓

Transport solver

⇓

CR distribution

⇓

Gamma ray emission

Cosmic Particle Transport:

THE NEXT GENERATION

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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

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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.

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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.

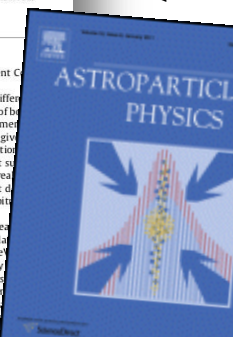
The transport of Galactic Cosmic Rays is a diffusion-loss problem (see [15]). That is we have to find a solution of the partial differential equation:

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

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 solution… different parameters. Analytical methods, however, are not s… 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 arbitr… in configuration- and momentum-space.

With the increasing precision of Galactic Cosmic Ray mea… ments an analytical approach is far from being able to explai… fine details in the measurements. Also a discussion of >1 TeV… 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 Uaxe (see [11]) that use ana… approximations to improve the performance of the code… codes aim at finding the best values for the variables in…



APh Vol.55 (2014)

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Solver

- Steady-state solution
- Explicit time integrator
- MPI-parallel
- Improved nuclear network
- Speed
- Kissmann (2014)

Features of PICARD

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Solver

- Steady-state solution
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Numerical Grid

- 3+1 D
- up to $\sim$75 pc^3 in space

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Solver

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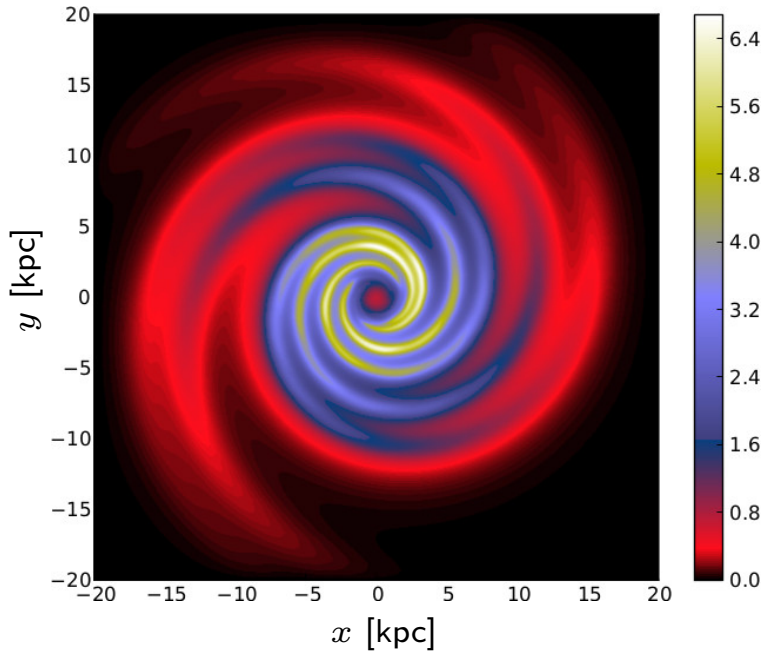
Propagation Physics

- New Radiation Field
- Milkyway as spiral galaxy (Werner et al., 2015)
- Anisotropic diffusion

Example Simulation Results



(Kissmann et al. (2015))

Numerical Grid

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Transport Equation

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

Radiation Field

Transport Equation

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Radiation Field

- Taken from Popescu et al. (2017)
- Propagation: IC losses
- Gamma-rays: IC & bremsstrahlung

Investigated Models

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Galactic Spiral Arms

- Different Models
- Propagation: currently sources only

Investigated Models

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Anisotropic Diffusion

- Spiral arms & X-shape
- Propagation: spatial diffusion

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Radiation Field

- Taken from Popescu et al. (2017)
- Propagation: IC losses
- Gamma-rays: IC & bremsstrahlung

Transport Setup

- Base Setup from Fermi-diffuse II paper

Galactic Spiral Arms

- Different Models
- Propagation: currently sources only

Anisotropic Diffusion

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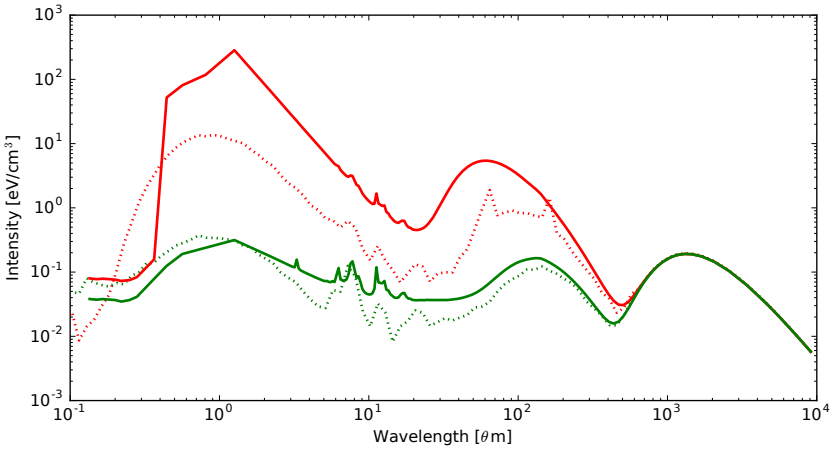
- Propagation: spatial diffusion

New Radiation Field



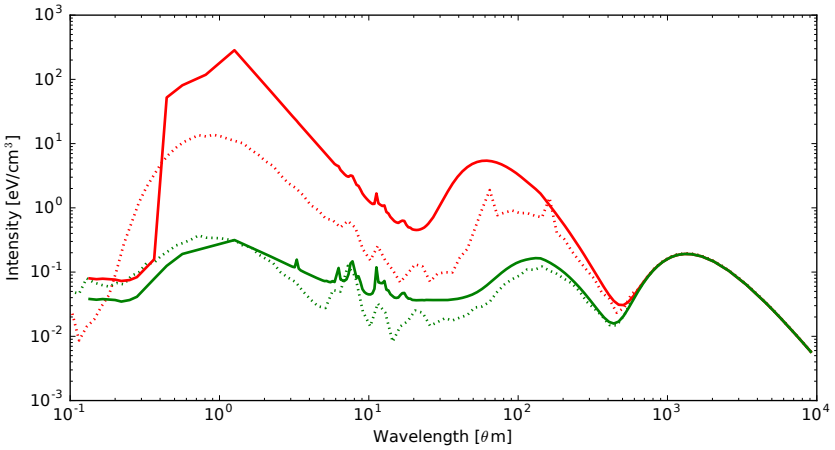
(see Popescu et al. (2017))

Impact of New ISRF

- Considerable changes in GC

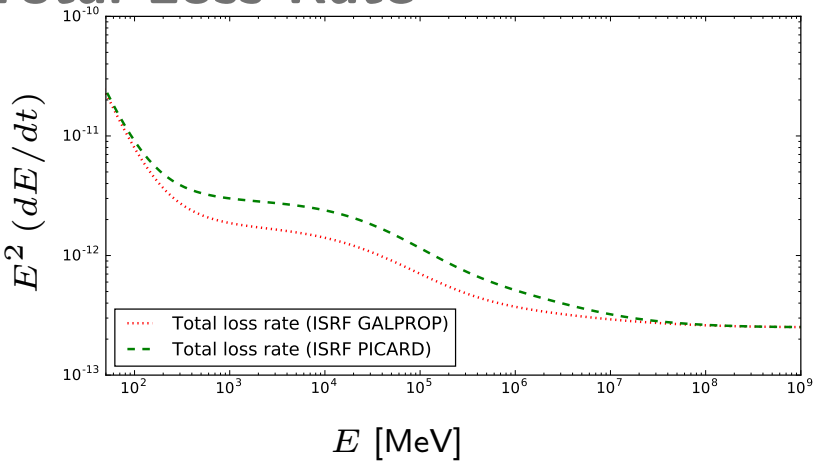
Improved Galactic ISRF

New Radiation Field



(see Popescu et al. (2017))

Total Loss Rate



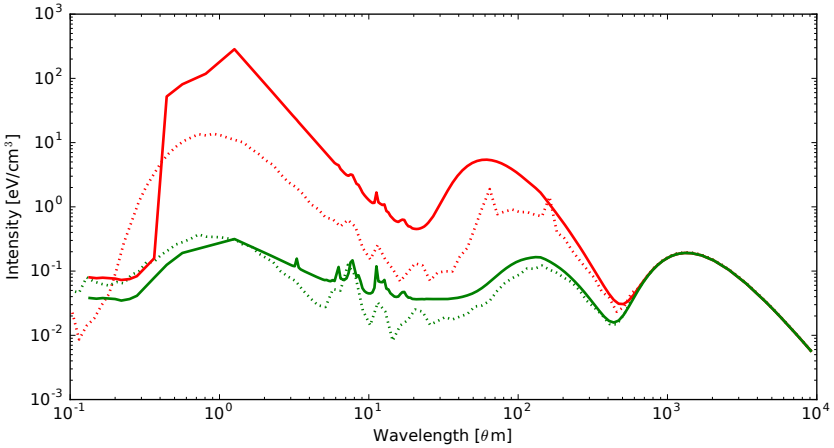
Impact of New ISRF

- Considerable changes in GC

$\rightarrow$ Higher IC losses

Improved Galactic ISRF

New Radiation Field



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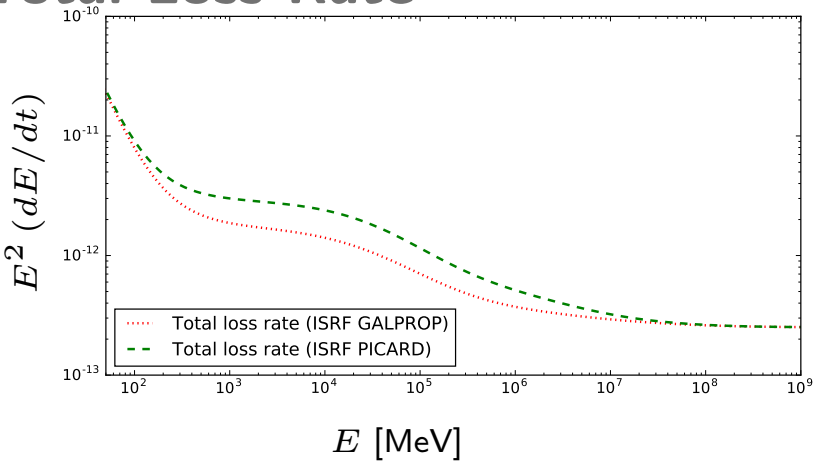
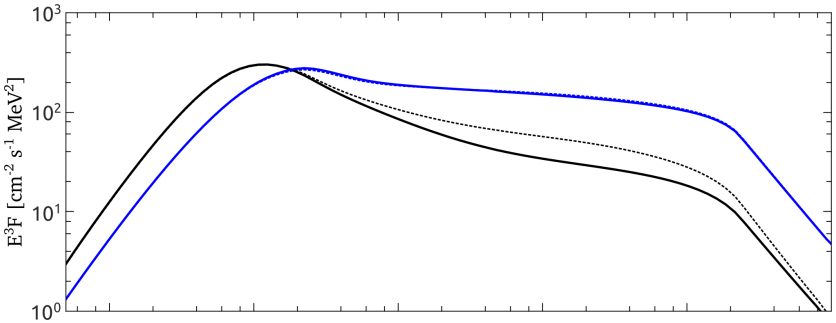


Impact on Particle Spectra



Impact of New ISRF

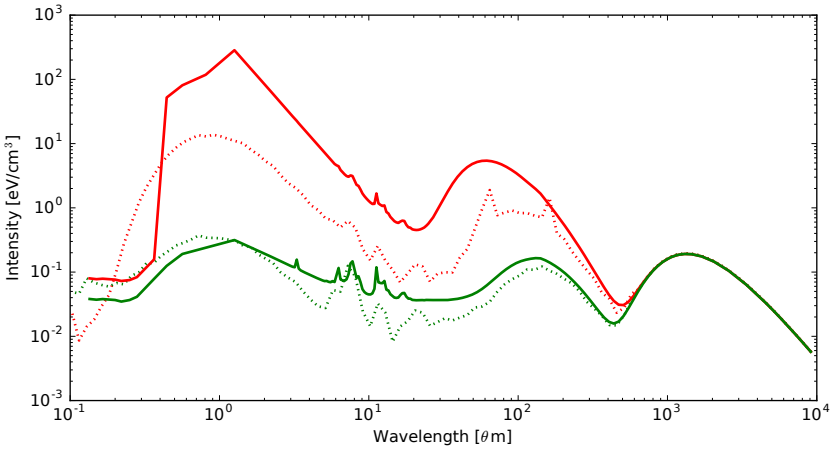
- Considerable changes in GC

$\rightarrow$ Higher IC losses

$\rightarrow$ Softer electron spectrum

Improved Galactic ISRF

New Radiation Field



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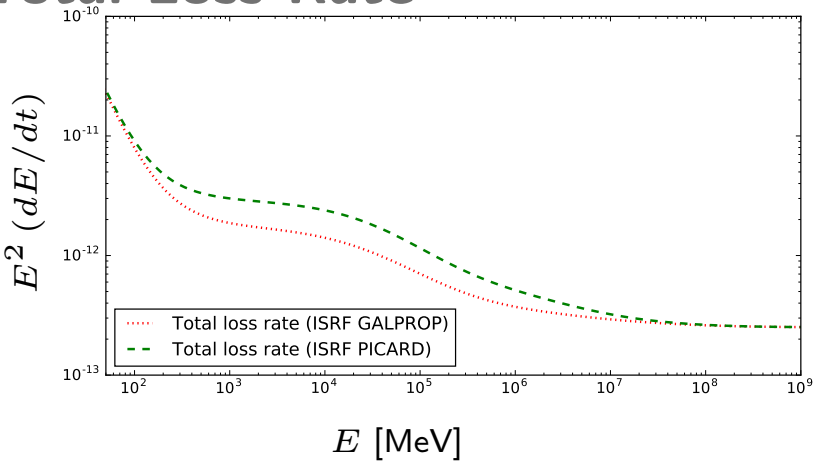
Total Loss Rate



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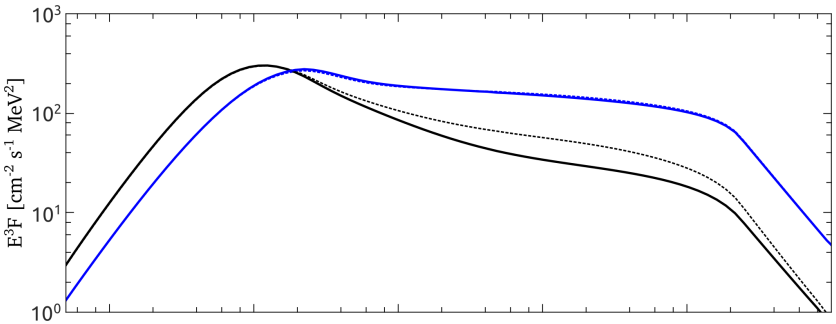


Impact of New ISRF

- Considerable changes in GC

$\rightarrow$ Higher IC losses

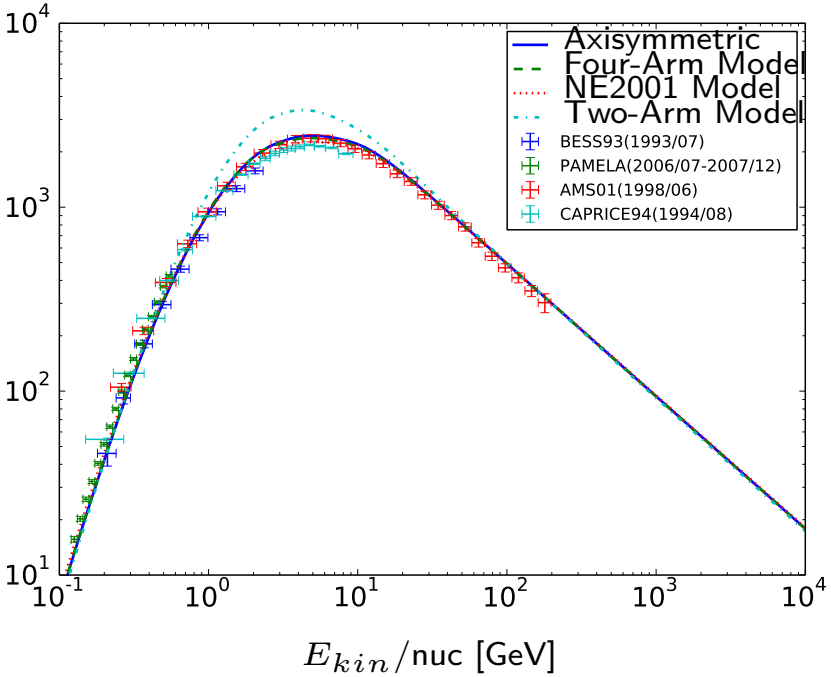
$\rightarrow$ Softer electron spectrum

- No impact at Earth or on nuclei

CR Data

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

CR Proton Flux



(Kissmann et al. (2015))

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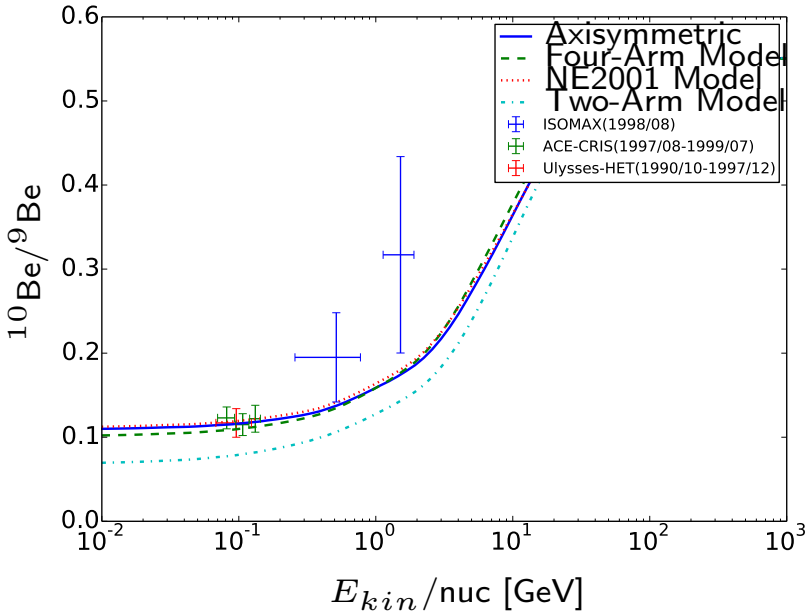
Be-Ratio



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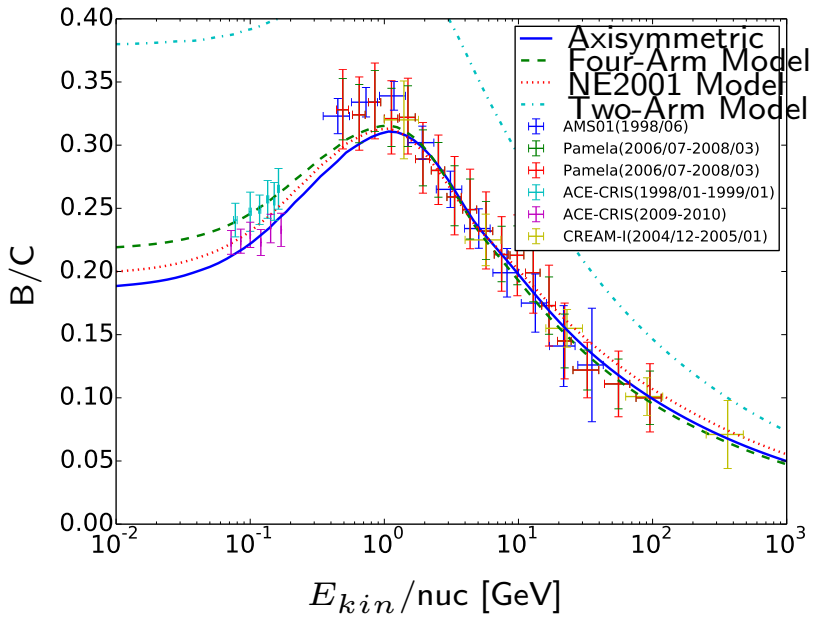
B/C Ratio



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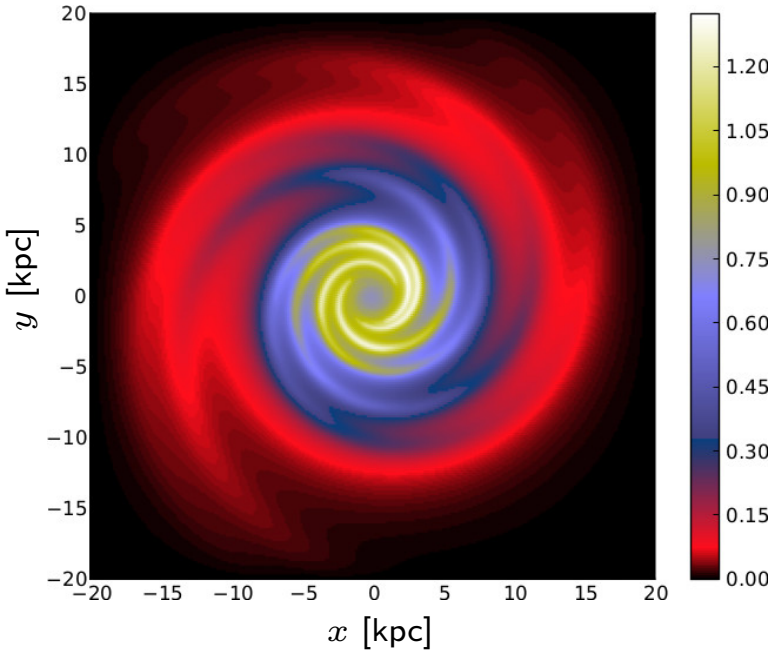
Distribution of Carbon



(Kissmann et al. (2015))

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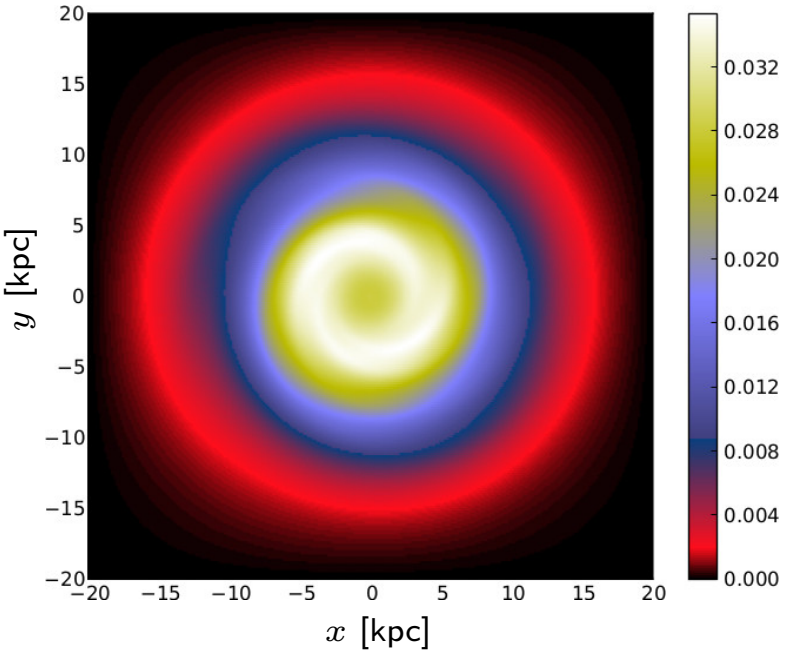
  - B/C Ratio ✓

Distribution of Boron



(Kissmann et al. (2015))

CR Data

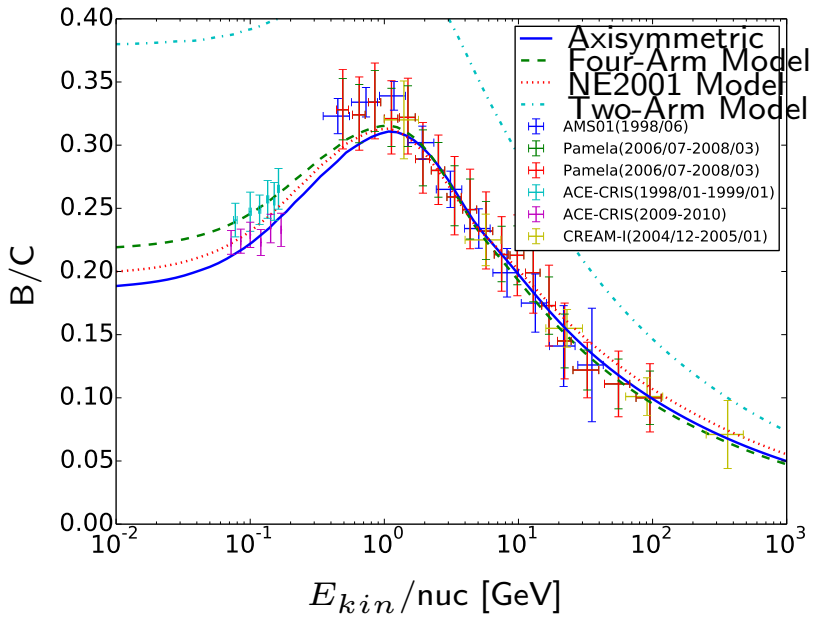
- CR Fluxes ✓
- Secondary / Primary ratios
  - $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ Ratio ✓
  - B/C Ratio ✓

Spiral-Arm Models

1. Adapted parameters
   - Change of D and v_A
   - Relative change $\sim 20\%$
2. Shift of source pattern

- Fit possible

B/C Ratio



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CR Data

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Spiral-Arm Models

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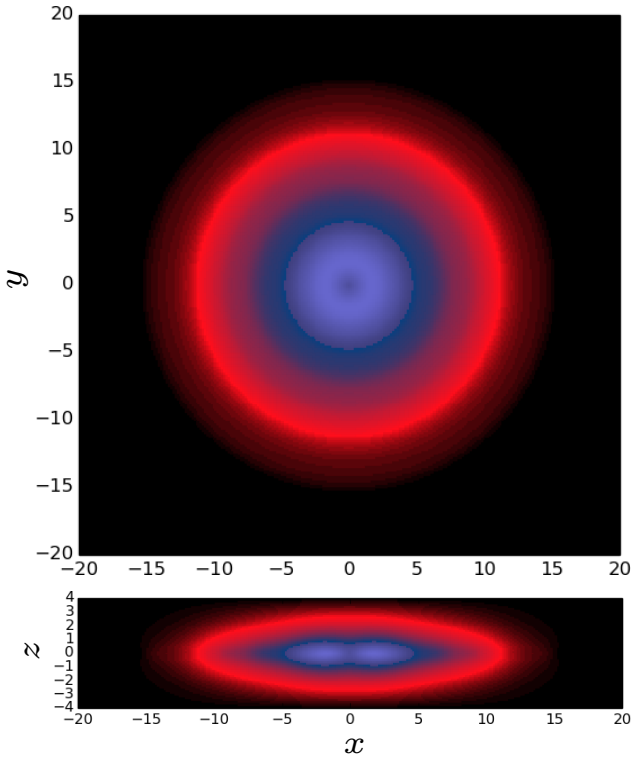
   - Relative change $\sim 20\%$
2. Shift of source pattern

- Fit possible
- Spatial variation

Axially Symmetric Model



(Kissmann et al. (2015))

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Spiral-Arm Models

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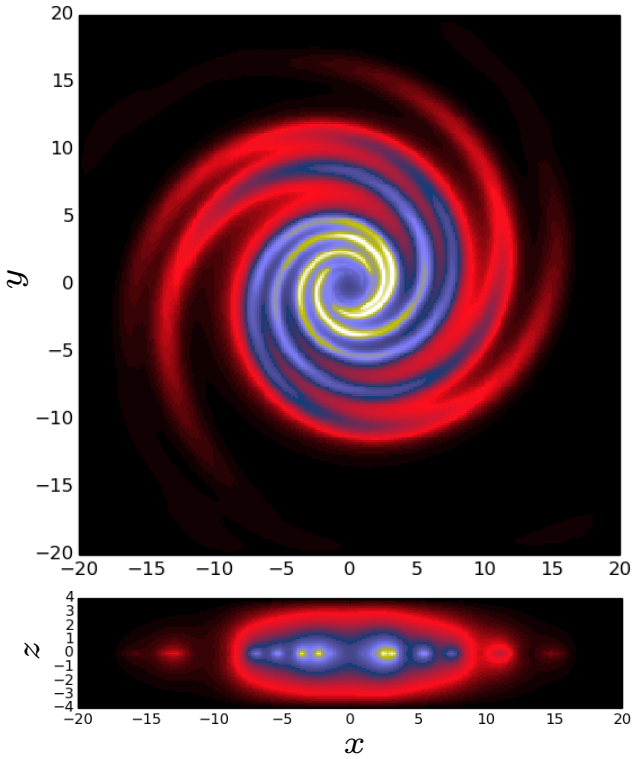
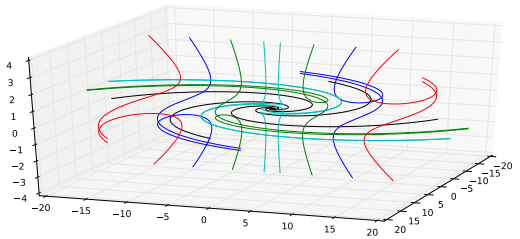
Modified Four-Arm Model



(Kissmann et al. (2015))

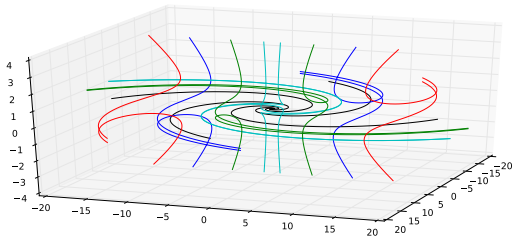
X-shape Magnetic Field



Diffusion Models

1. Isotropic
2. Along spiral arms
3. Along X-shape magnetic field by Ferrière and Terral (2014)

X-shape Magnetic Field



Observation

- No change for spiral-arm diffusion
- Fit possible for X-shape diffusion ($>$ factor 2)

Diffusion Models

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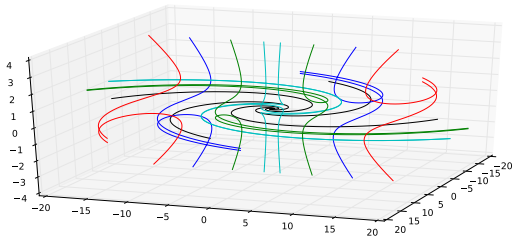
X-shape Magnetic Field



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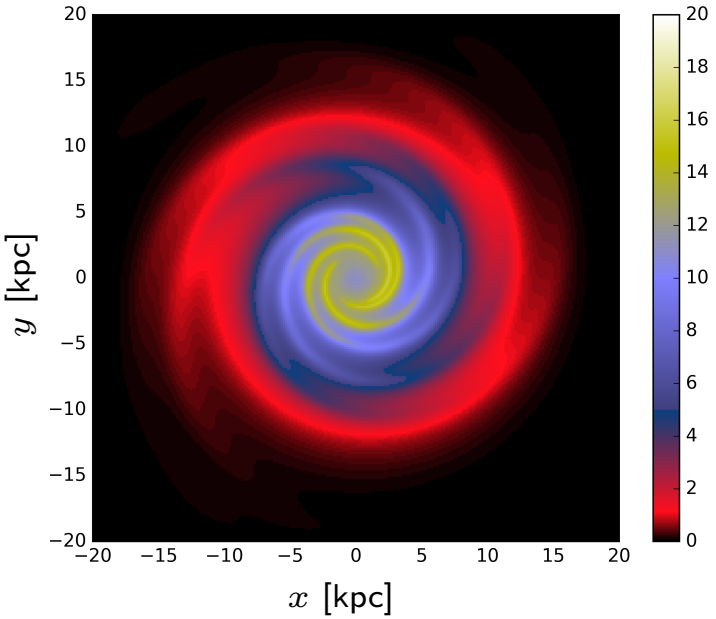
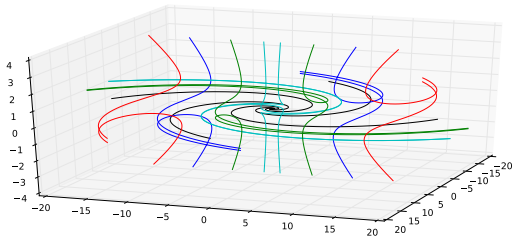
Isotropic Diffusion



X-shape Magnetic Field



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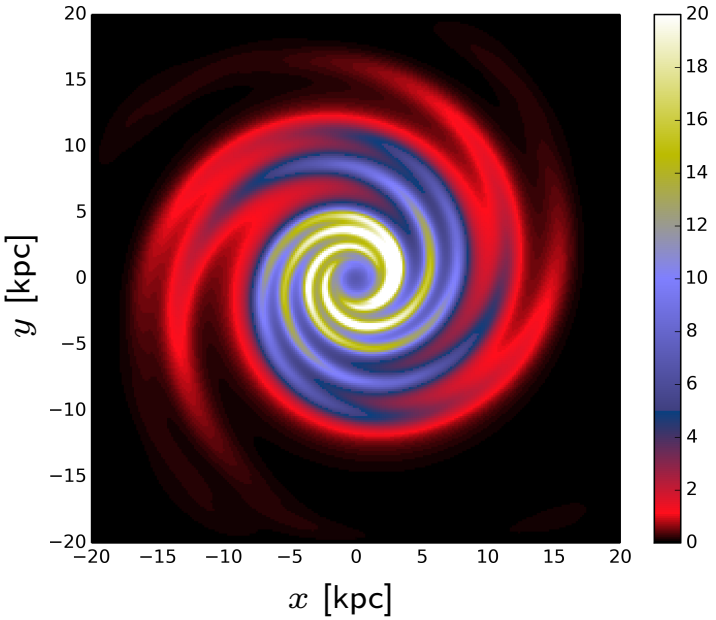
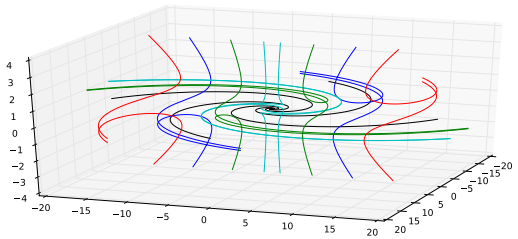
X-shape Diffusion



X-shape Magnetic Field



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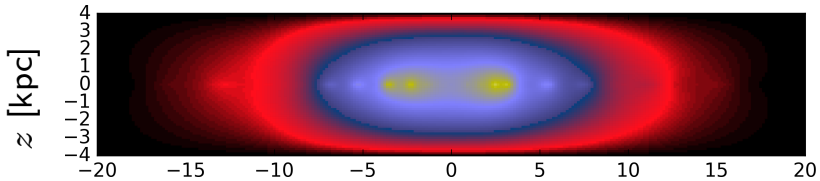
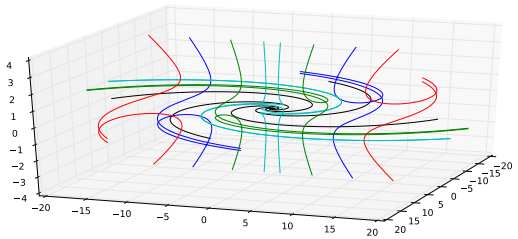
Observation

- No change for spiral-arm diffusion
- Fit possible for X-shape diffusion ($>$ factor 2)

Isotropic Diffusion



X-shape Magnetic Field



Diffusion Models

1. Isotropic
2. Along spiral arms
3. Along X-shape magnetic field by Ferrière and Terral (2014)

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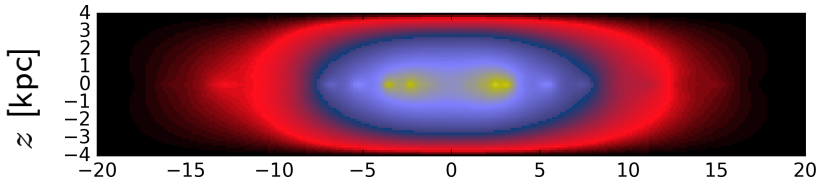
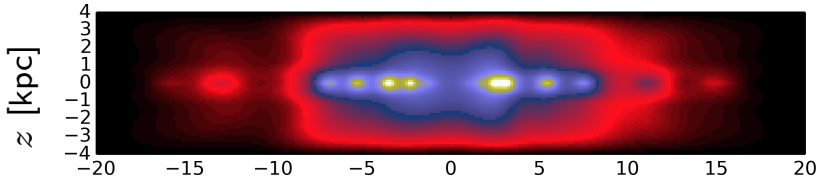
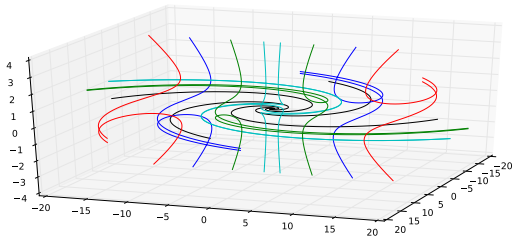
Isotropic Diffusion



X-shape Diffusion



X-shape Magnetic Field



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Diffusion Models

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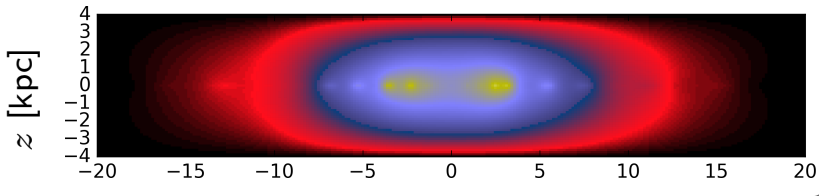
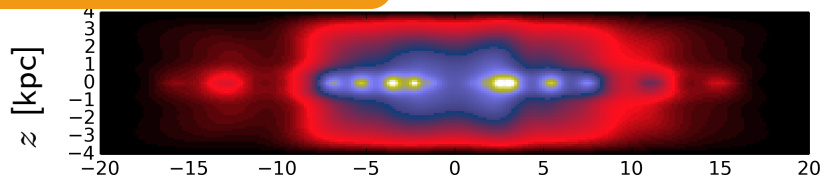
Isotropic Diffusion



Gamma rays?

ion



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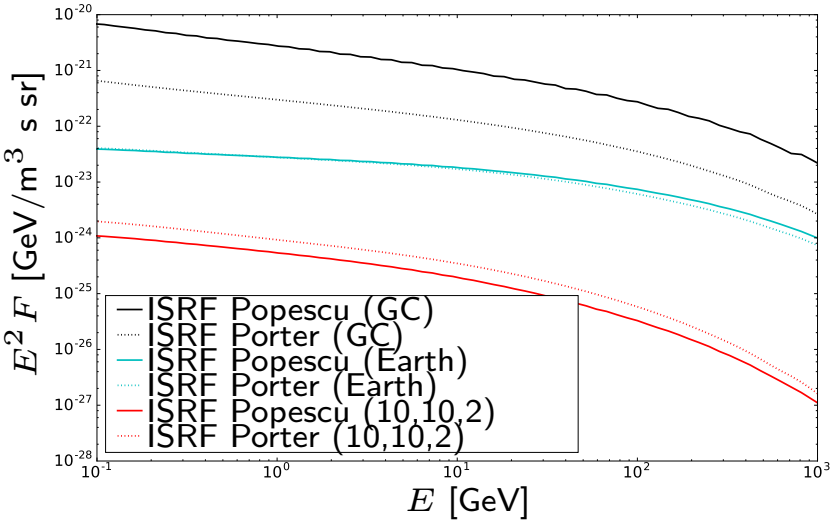
Emissivity



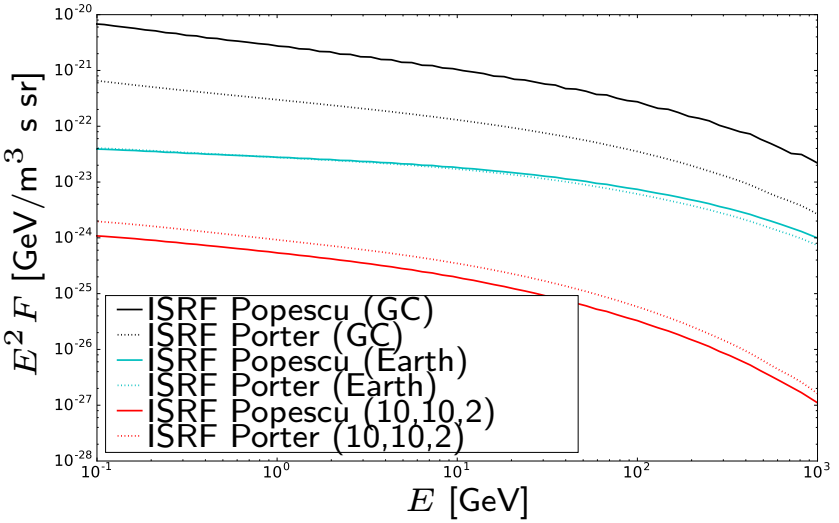
Change of Emissivity

- Small change in halo
- Order of magnitude in GC

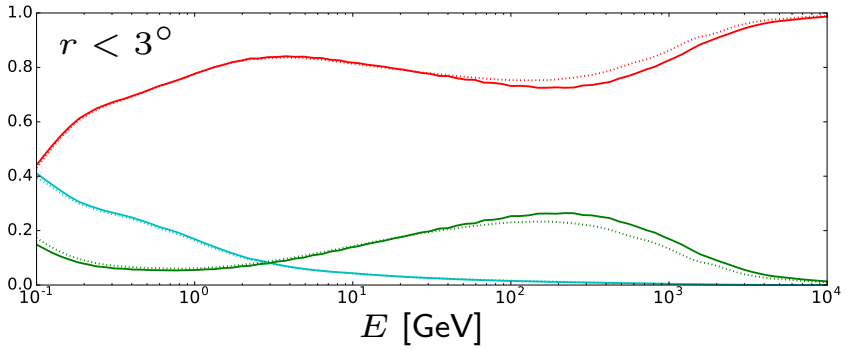
$\rightarrow$ GC modelling

Impact of ISRF

Emissivity



Gamma-ray Flux



Change of Emissivity

- Small change in halo
- Order of magnitude in GC

$\rightarrow$ GC modelling

Change of Gamma-ray Flux

- TeV regime
- Order of a few percent

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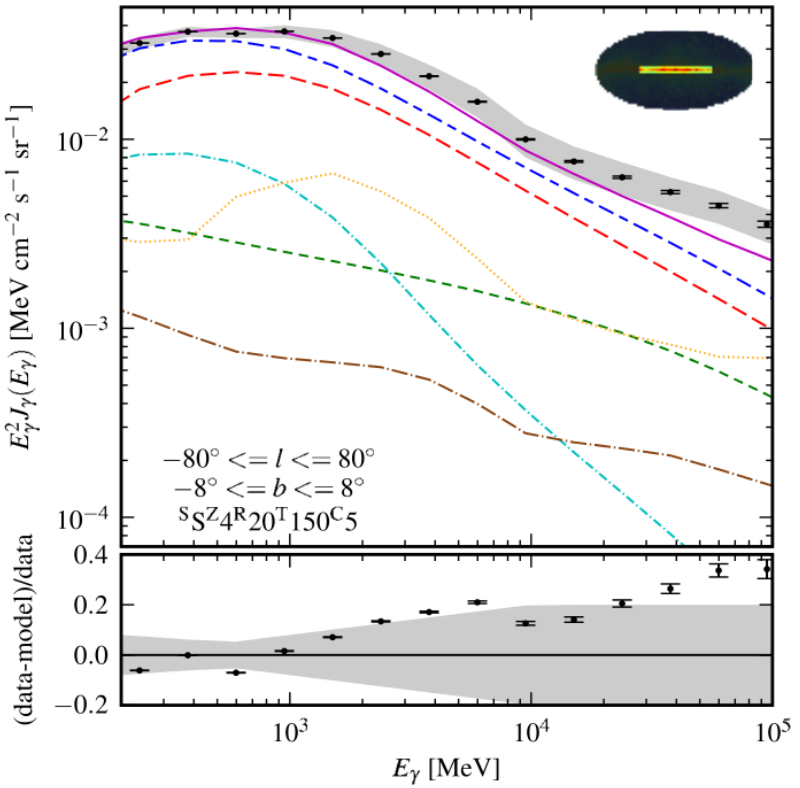
Fermi Diffuse II Paper



((Ackermann et al., 2012))

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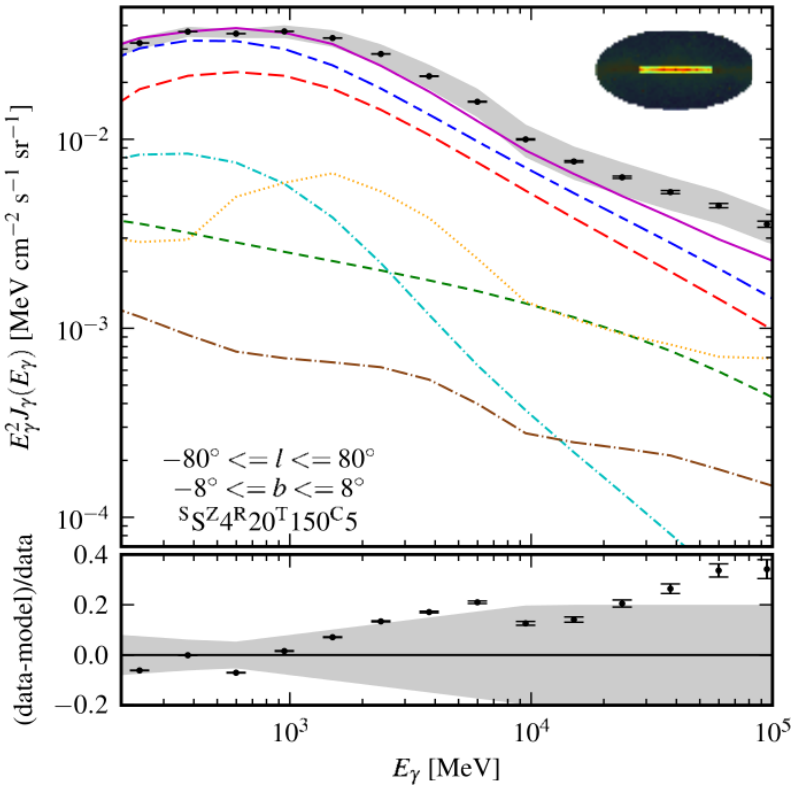
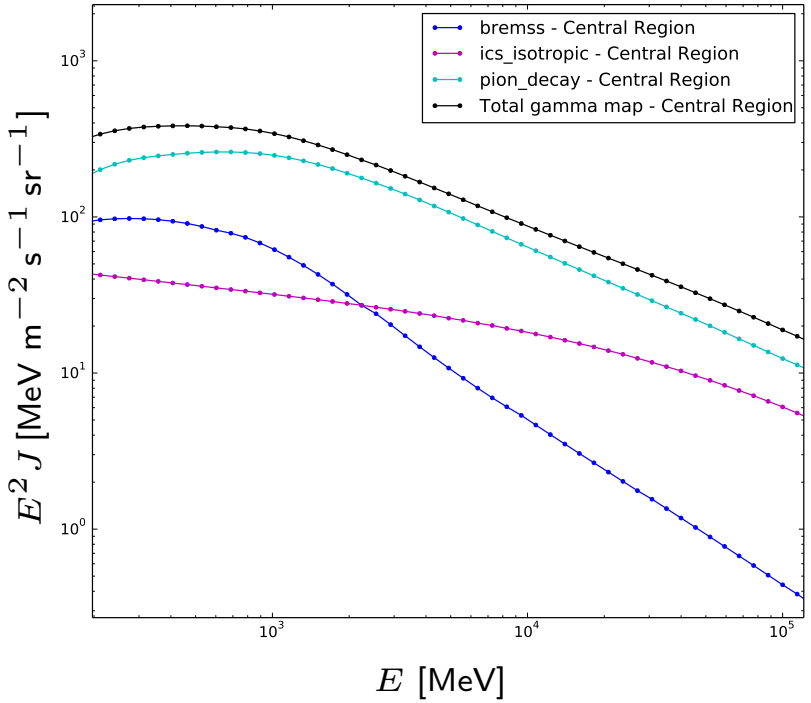
Fermi Diffuse II Paper



((Ackermann et al., 2012))

Picard Four-Arm Model



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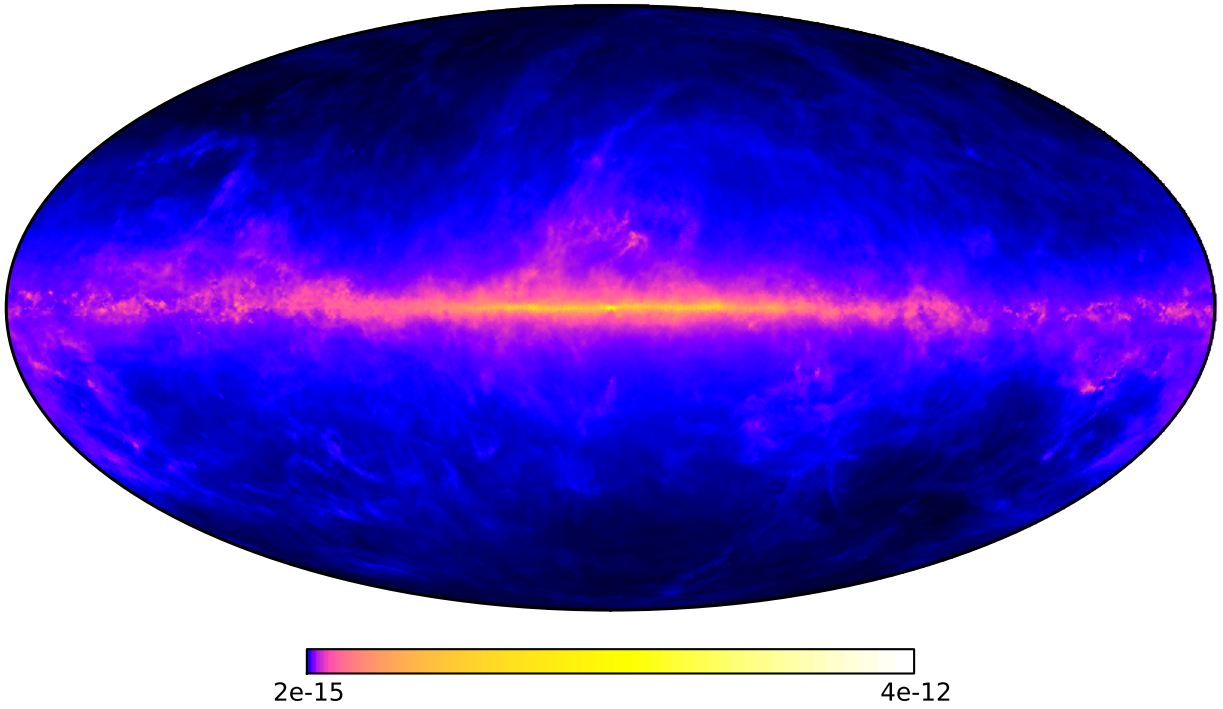
Axi-Symmetric Configuration



Gamma-Ray Data

- ∼100 GeV
- ∼1 TeV

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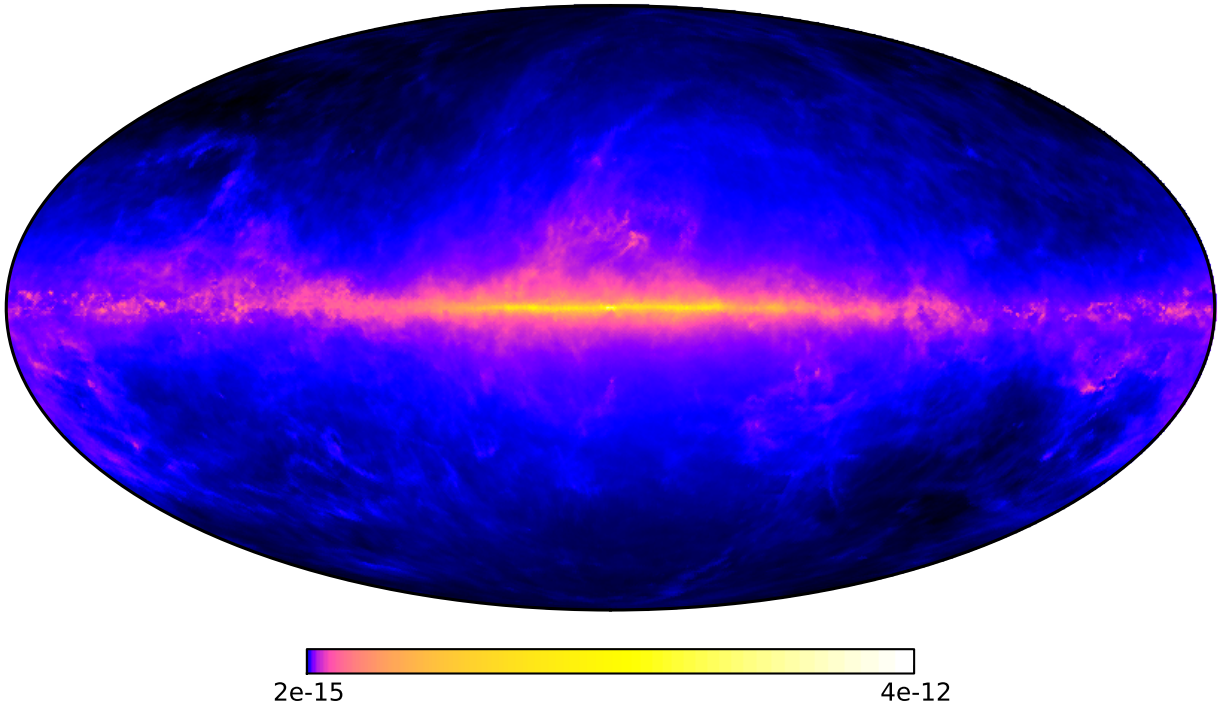
Four-Arm Configuration



Gamma-Ray Data

- ∼100 GeV
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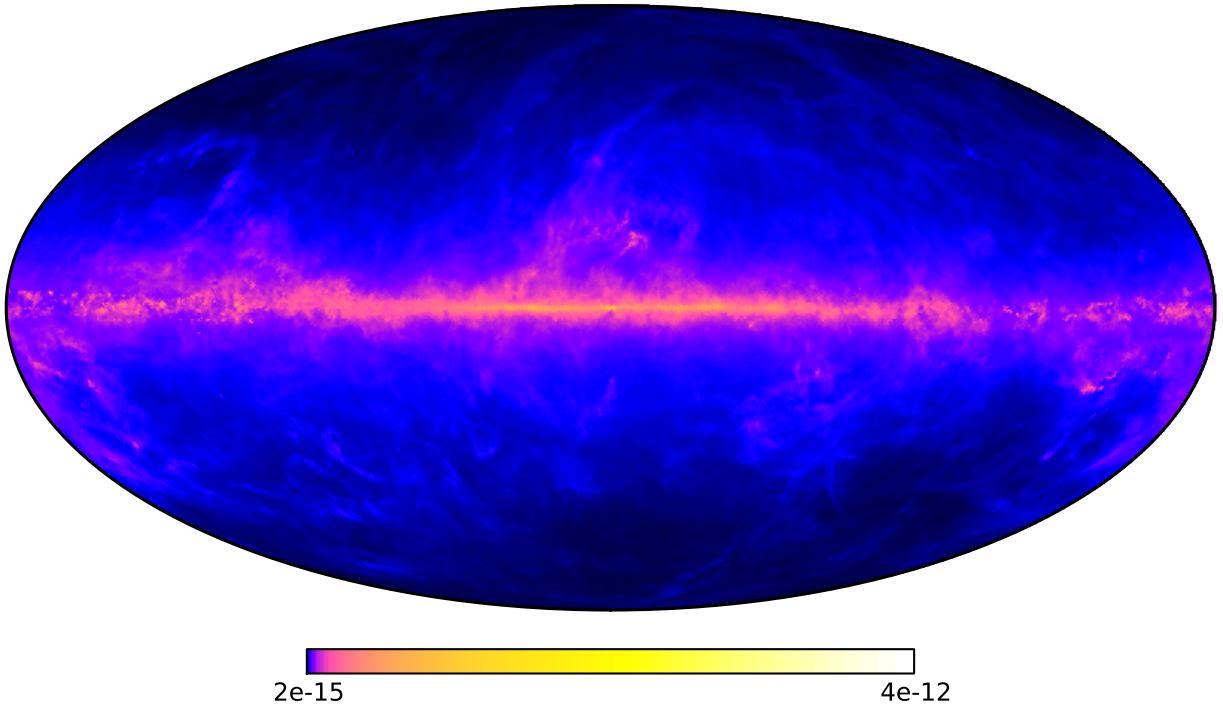
NE2001 Configuration



Gamma-Ray Data

- ∼100 GeV
- ∼1 TeV

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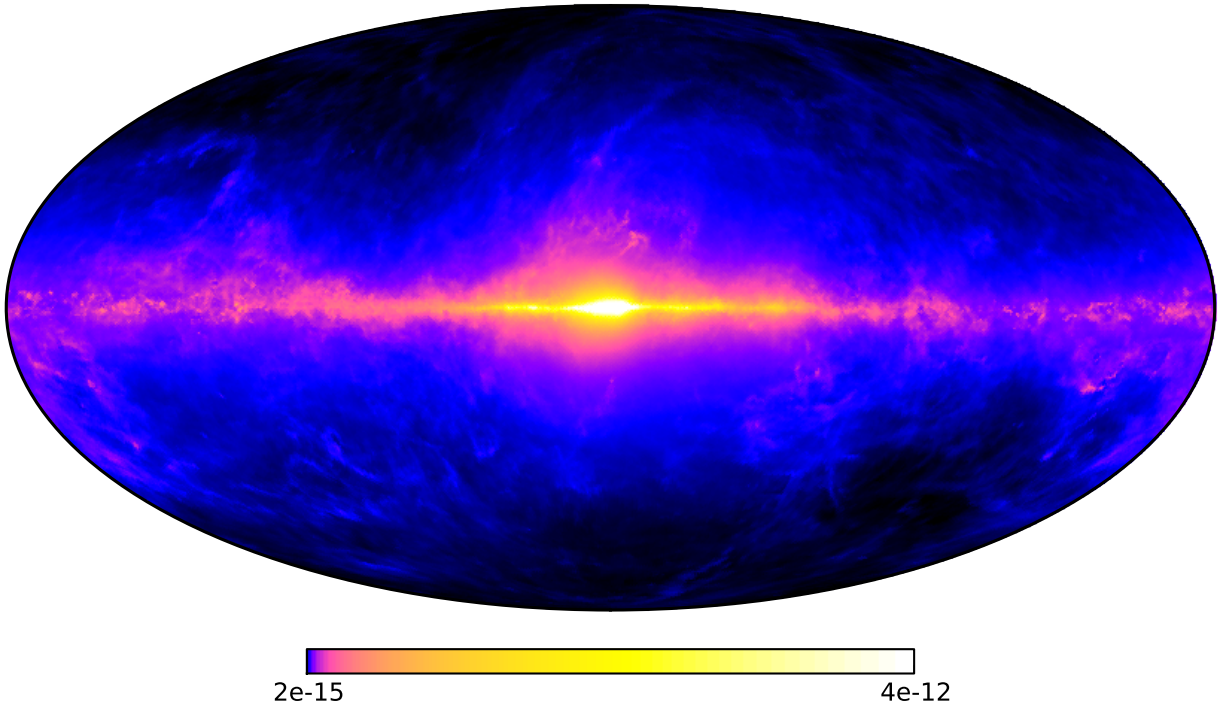
Two-Arm Configuration



Gamma-Ray Data

- ∼100 GeV
- ∼1 TeV

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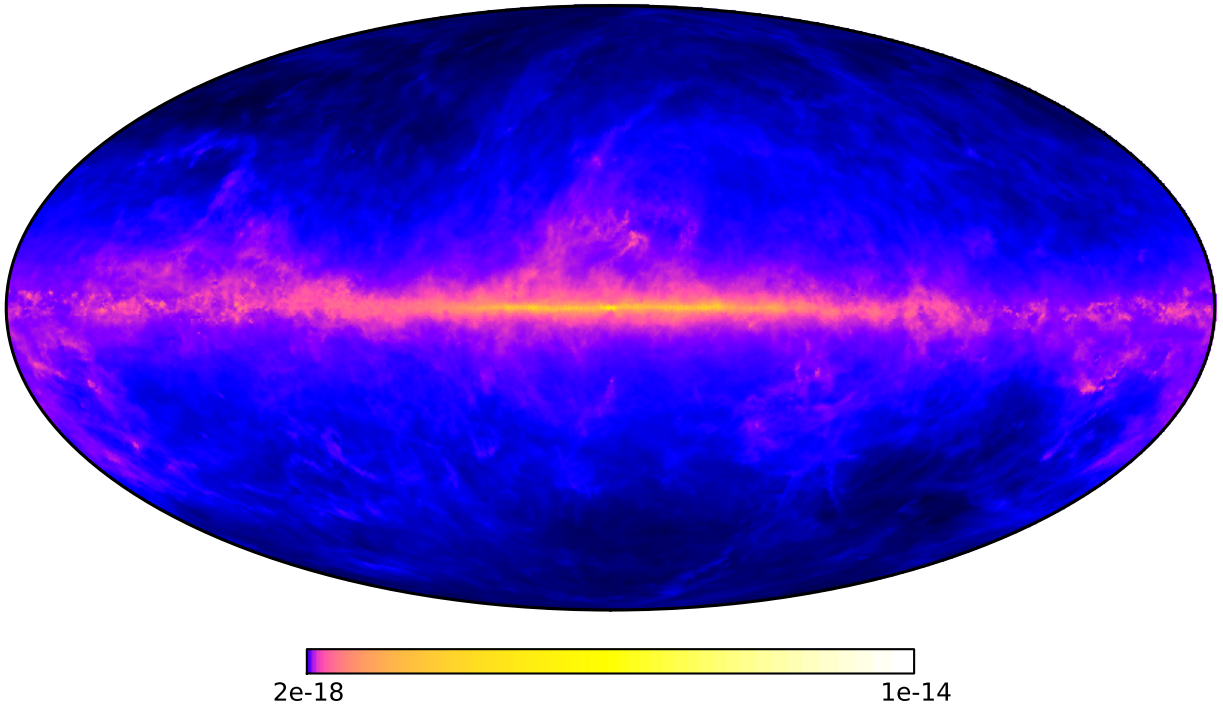
Axi-Symmetric Configuration



Structure

- Tension for two-arm model

Gamma-Ray Data

- ∼100 GeV
- ∼1 TeV

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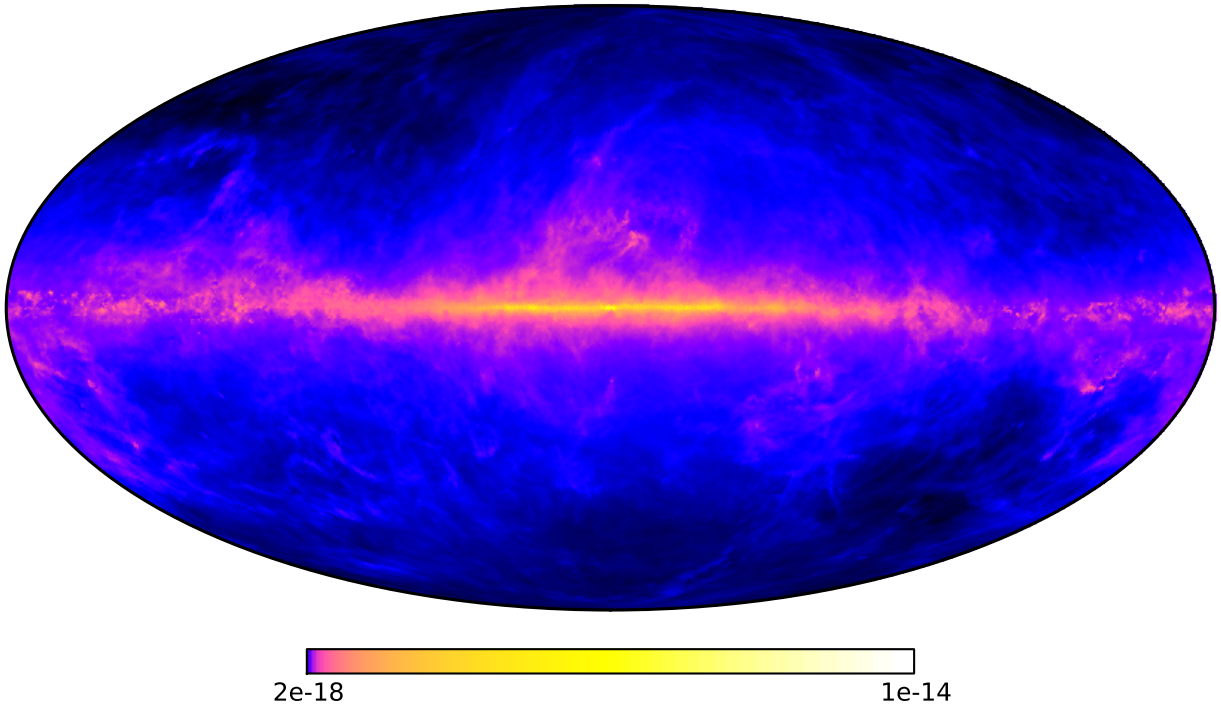
Four-Arm Configuration



Structure

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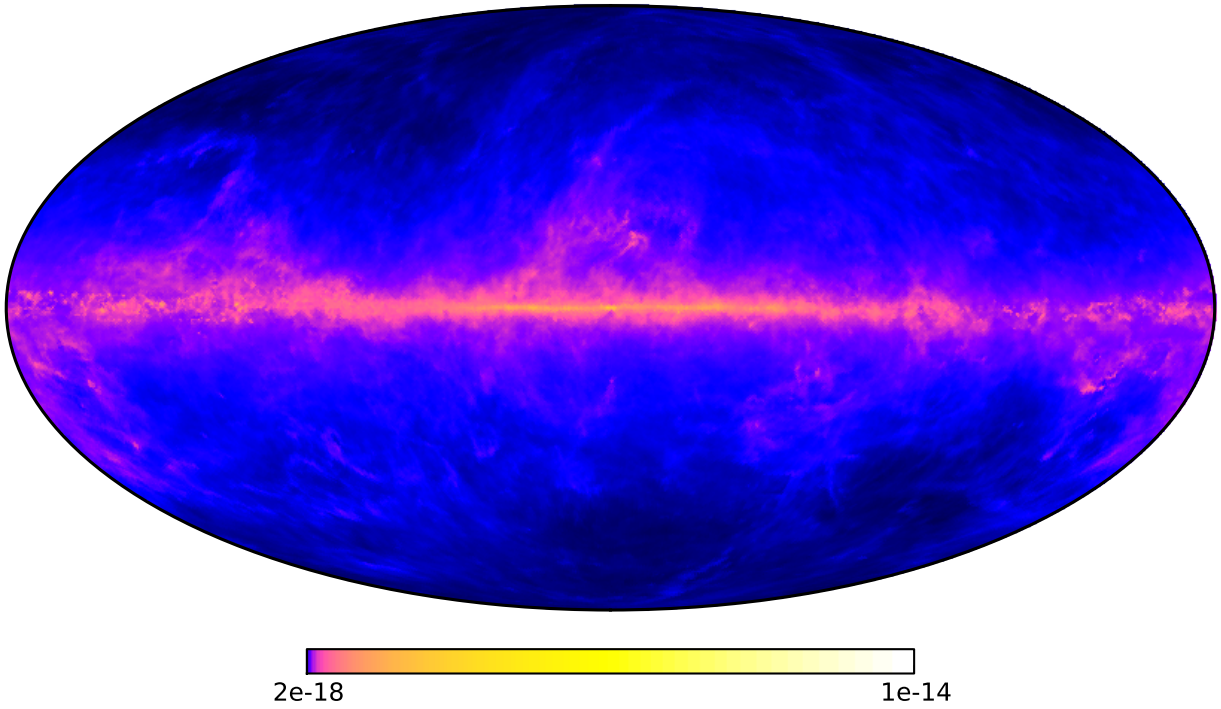
NE2001 Configuration



Structure

- Tension for two-arm model

Gamma-Ray Data

- ∼100 GeV
- ∼1 TeV

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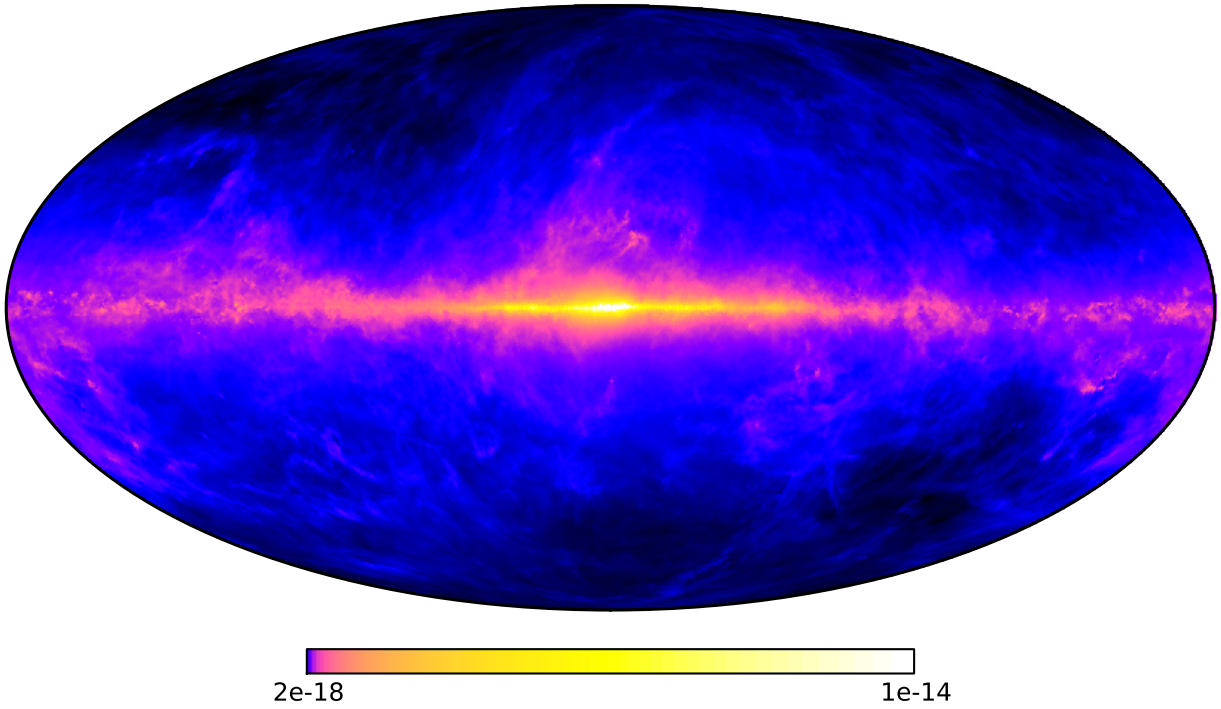
Two-Arm Configuration



Structure

- Tension for two-arm model

Gamma-Ray Data

- ∼100 GeV
- ∼1 TeV

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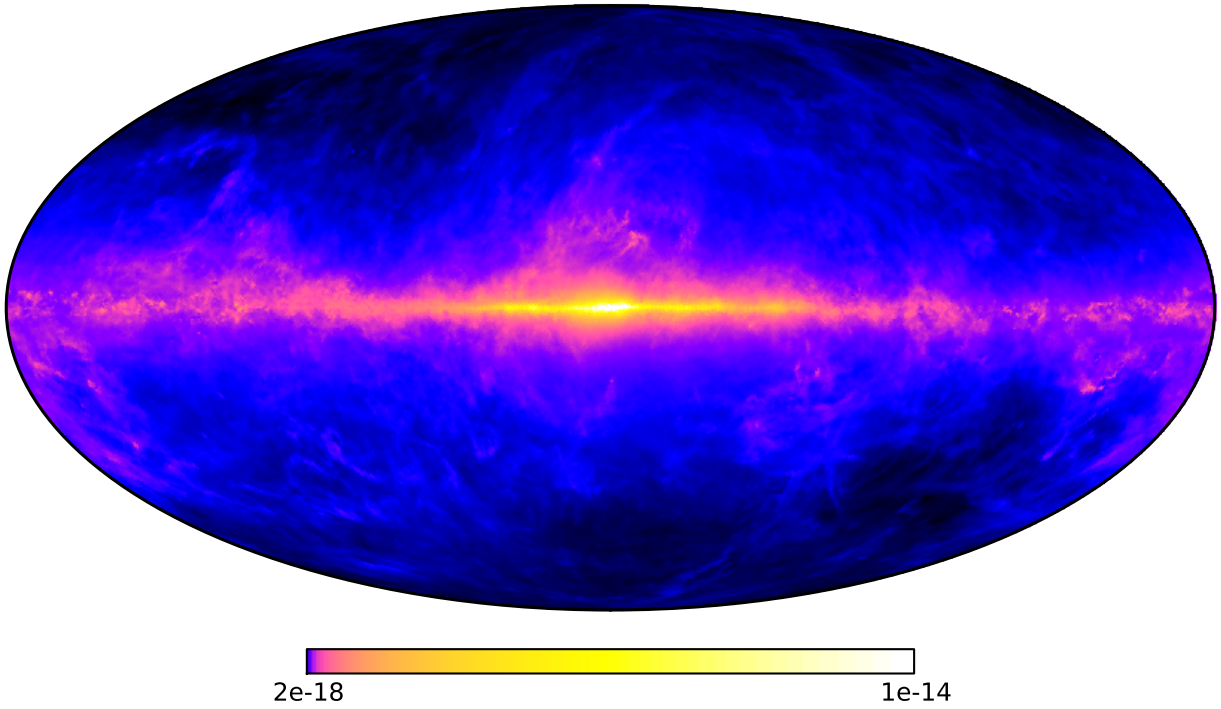
Two-Arm Configuration



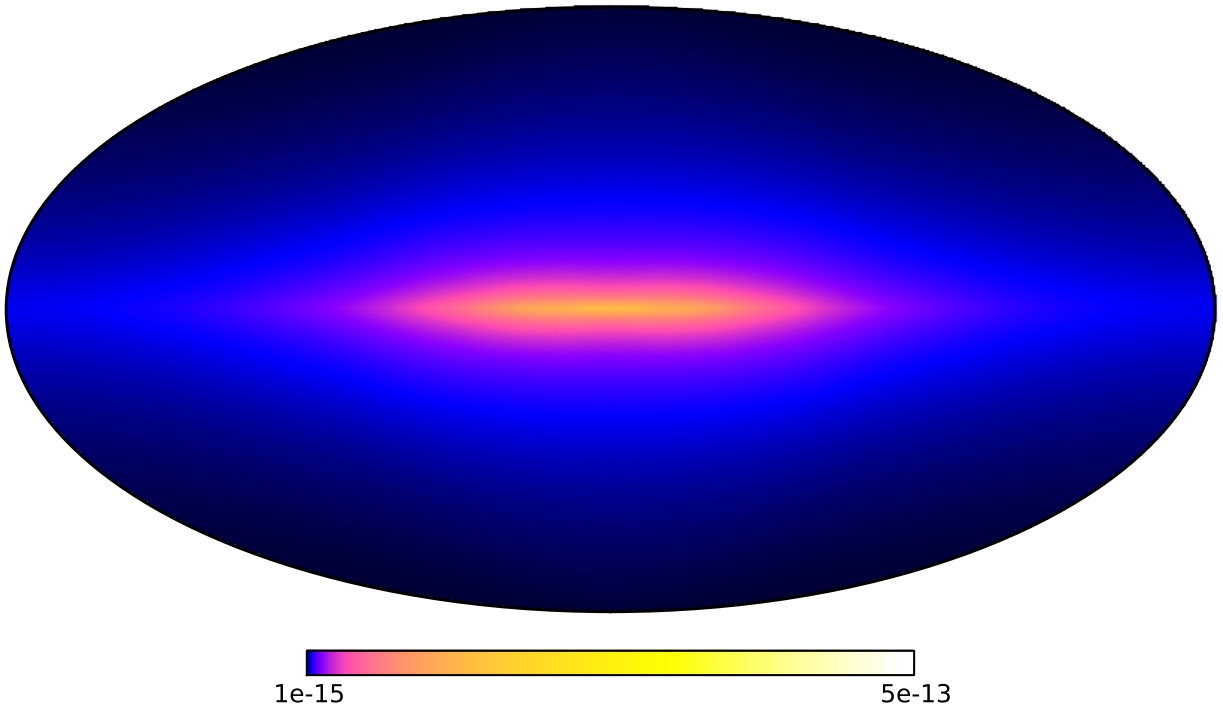
Structure

- Tension for two-arm model
- Imprint of IC component

Gamma-Ray Data

- $\sim$100 GeV
- $\sim$1 TeV

Axi-Symmetric Configuration



IC Data

- $\sim$100 GeV

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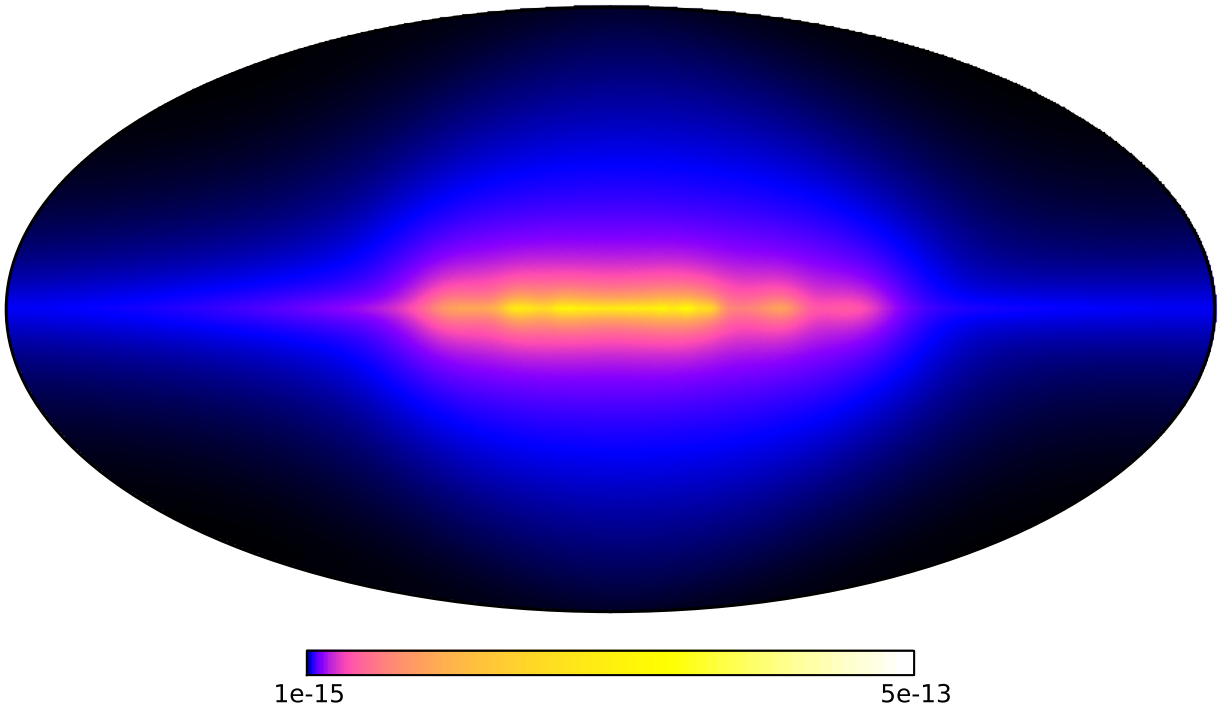
Four-Arm Configuration



IC Data

- ∼100 GeV

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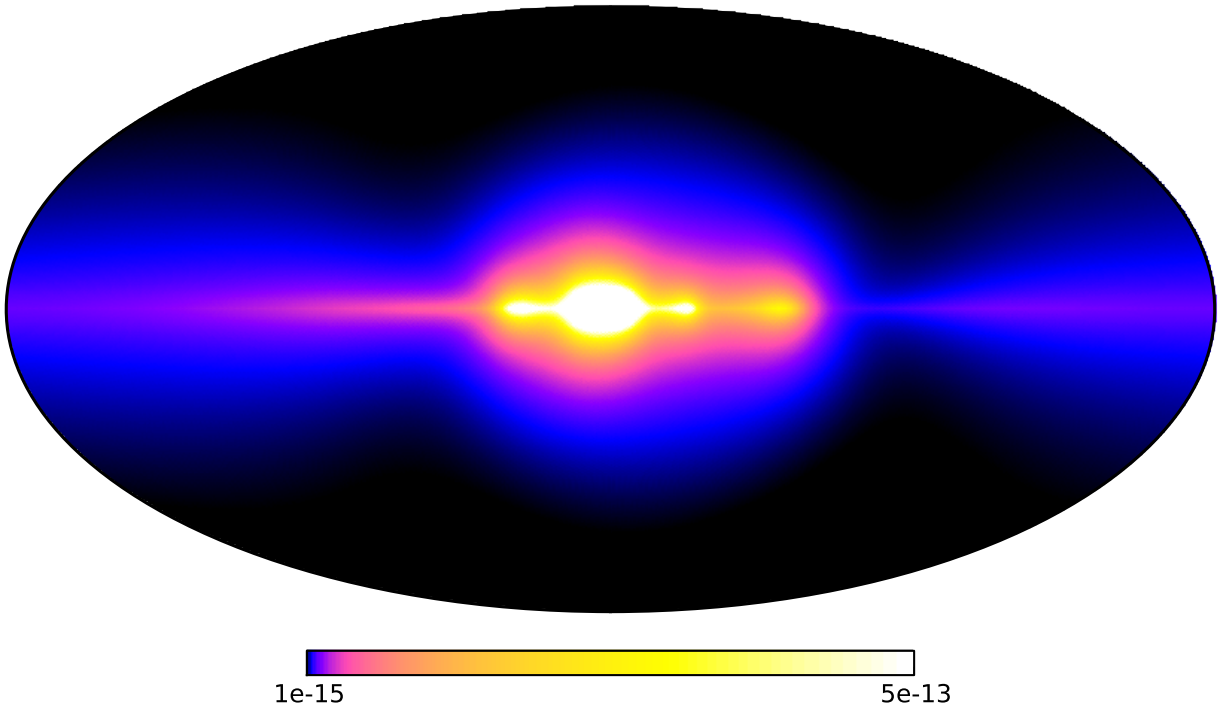
Two-Arm Configuration



Imprint of

- . . . Galactic bar

IC Data

- ∼100 GeV

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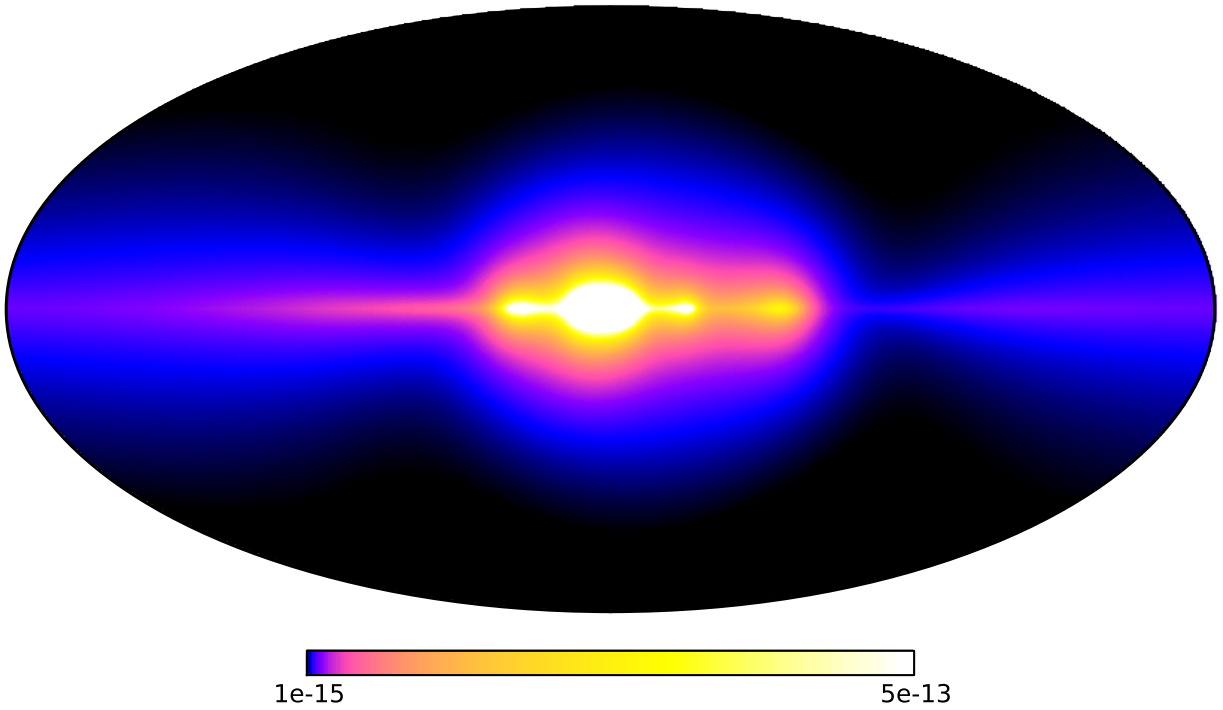
Two-Arm Configuration



Imprint of

- . . . Galactic bar
- . . . Spiral-arm tangents

IC Data

- $\sim$100 GeV

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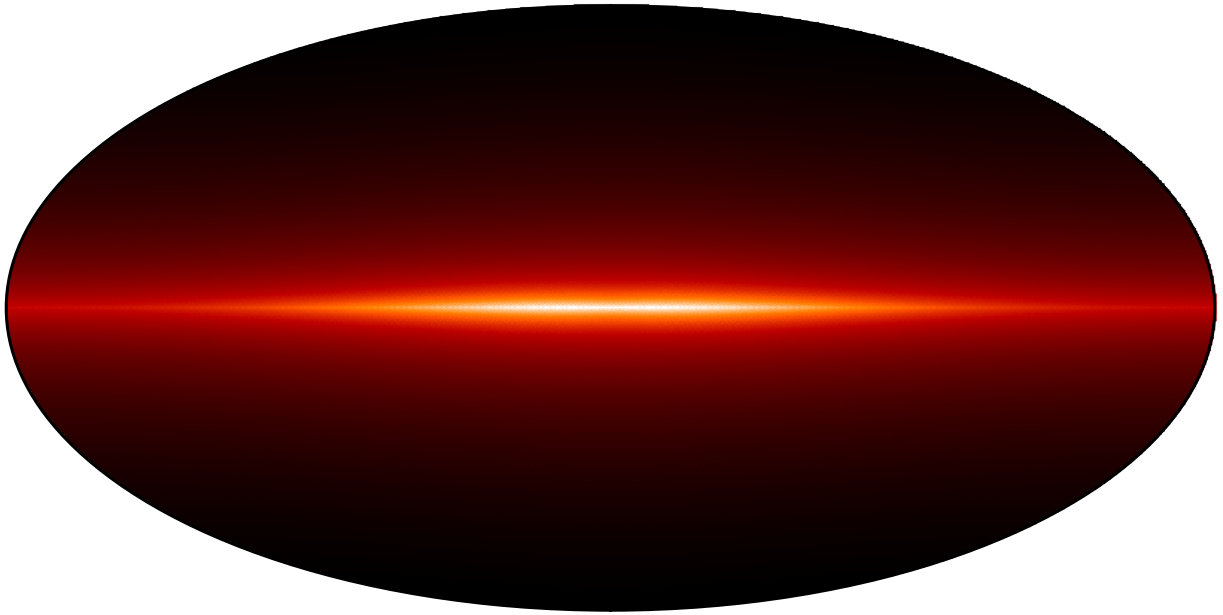
Axi-Symmetric Sources



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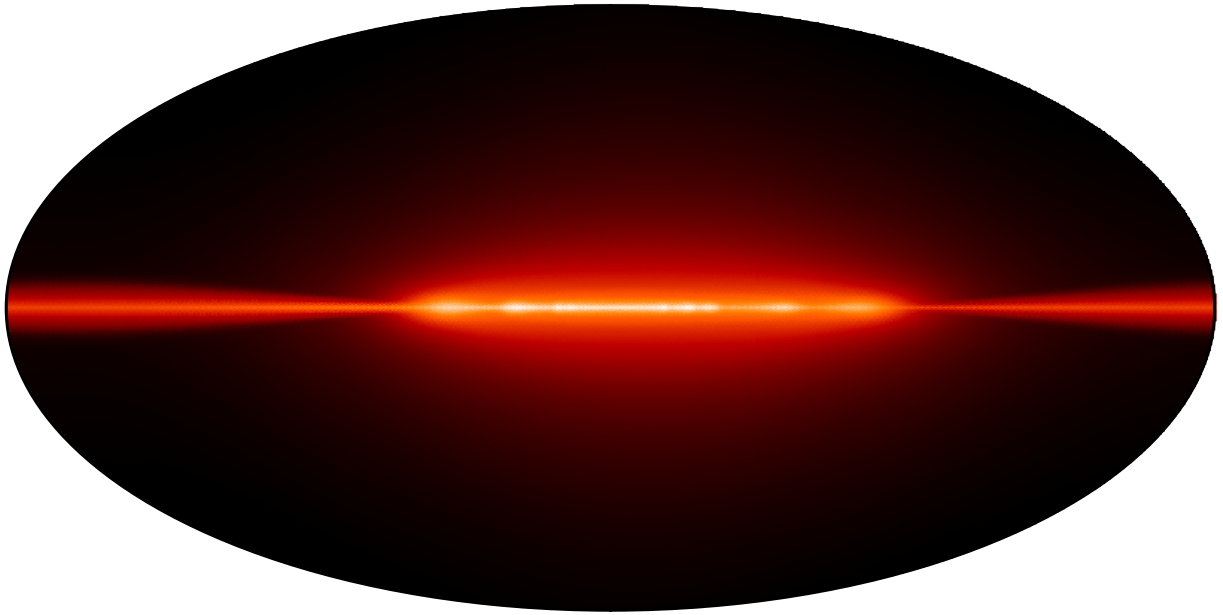
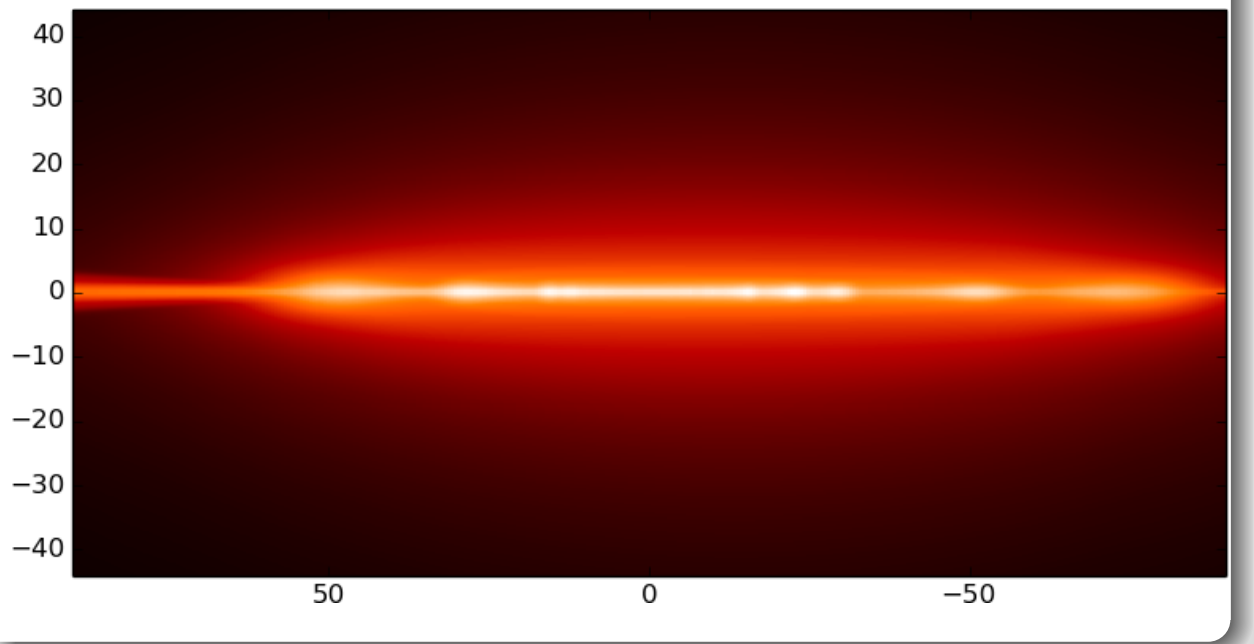
Four-Arm Sources



Sources in Galactic Centre Region



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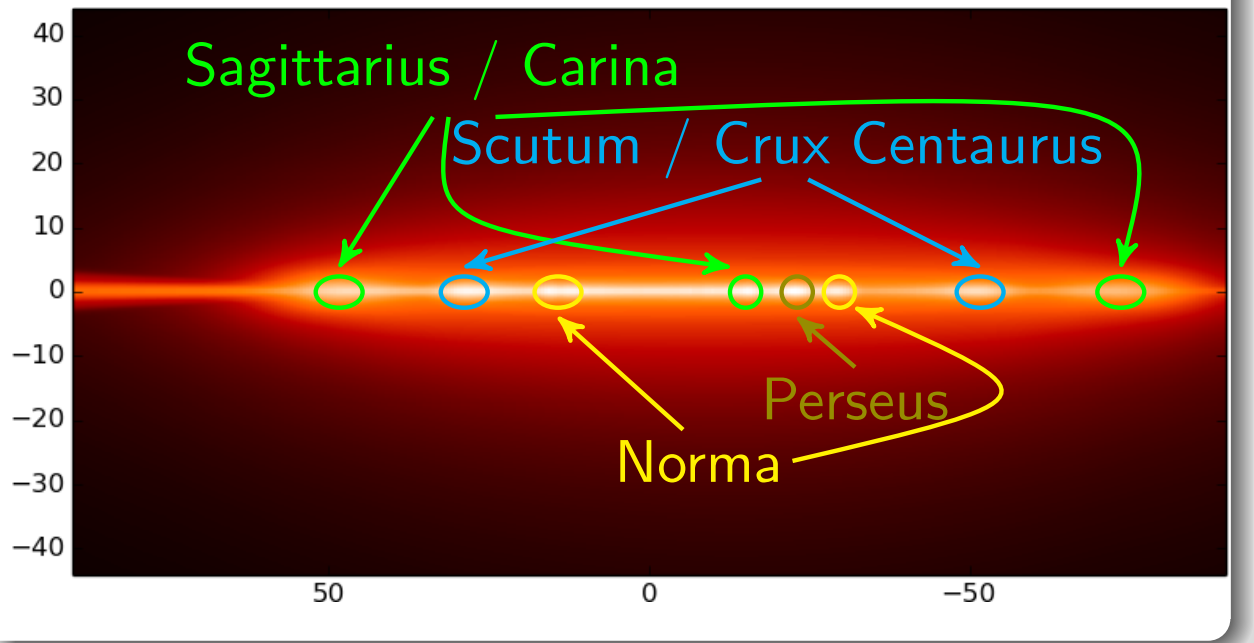
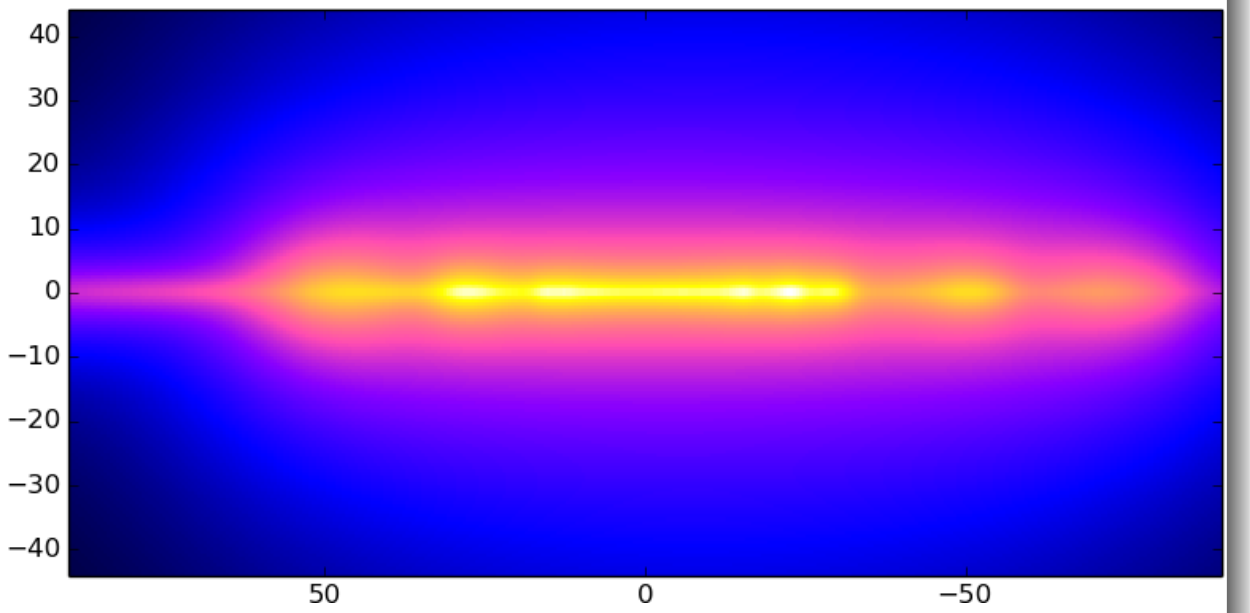
Sources in Galactic Centre Region



IC Emission Map



Gamma-Ray Data At

- ∼100 GeV
- ∼1 TeV

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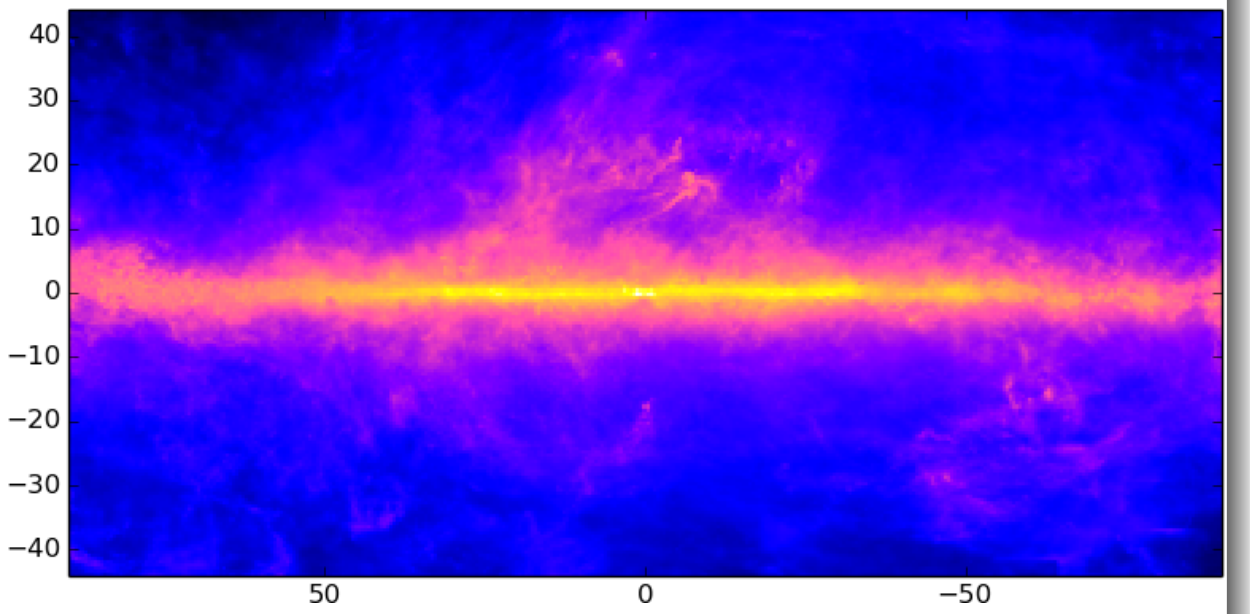
Total Gamma Emission Map



Gamma-Ray Data At

- ∼100 GeV
- ∼1 TeV

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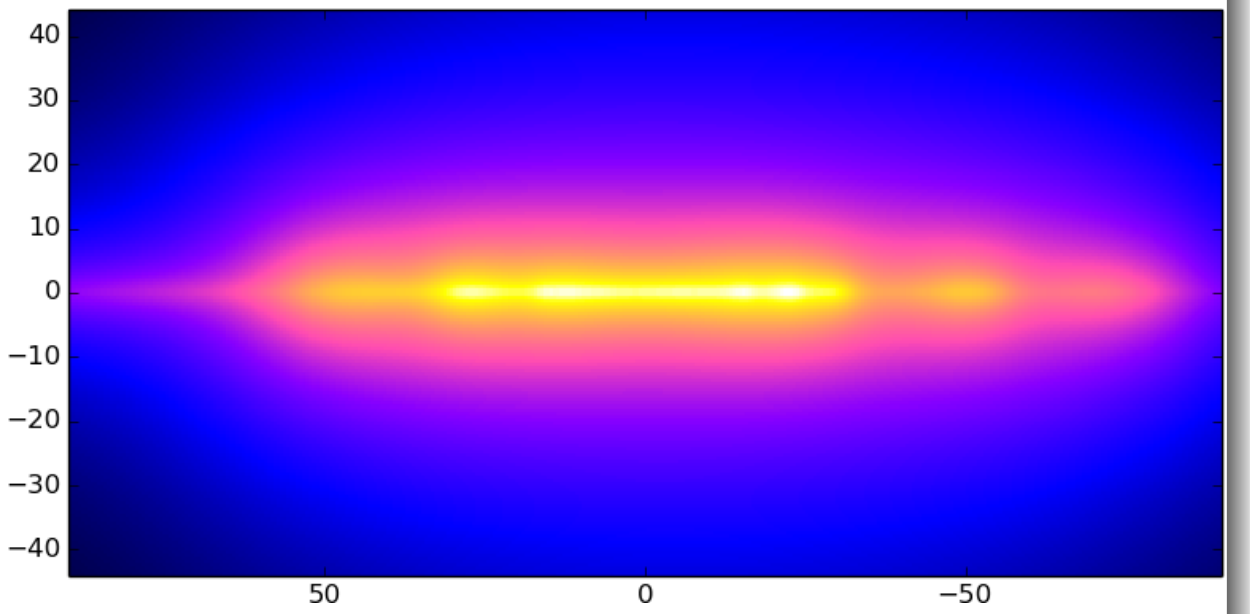
IC Emission Map



Spiral-arms

- . . . visible in IC

Gamma-Ray Data At

- ∼100 GeV
- ∼1 TeV

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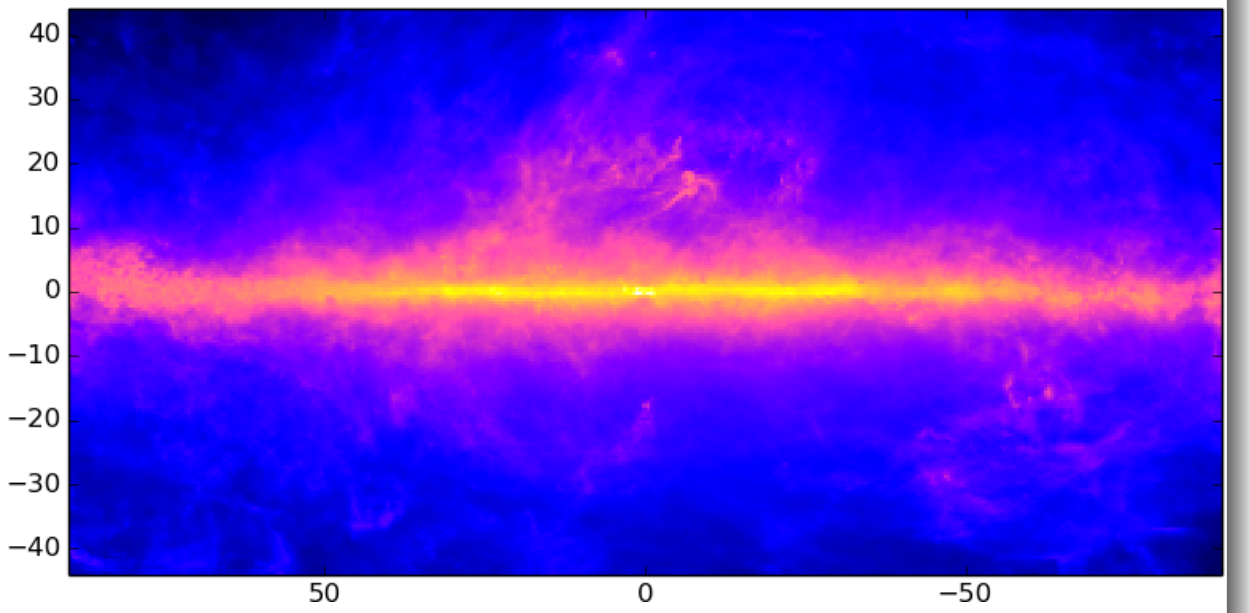
Total Gamma Emission Map



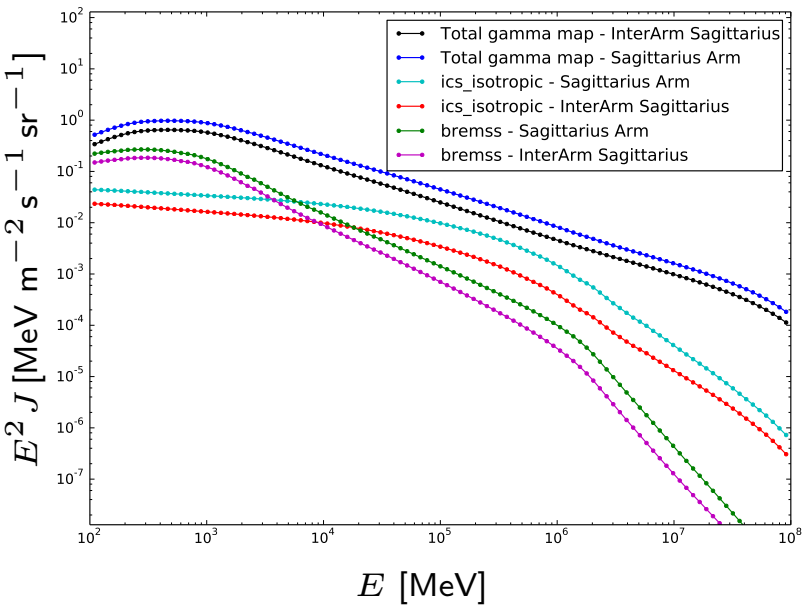
Spiral-arms

- . . . visible in IC
- Total spectrum?

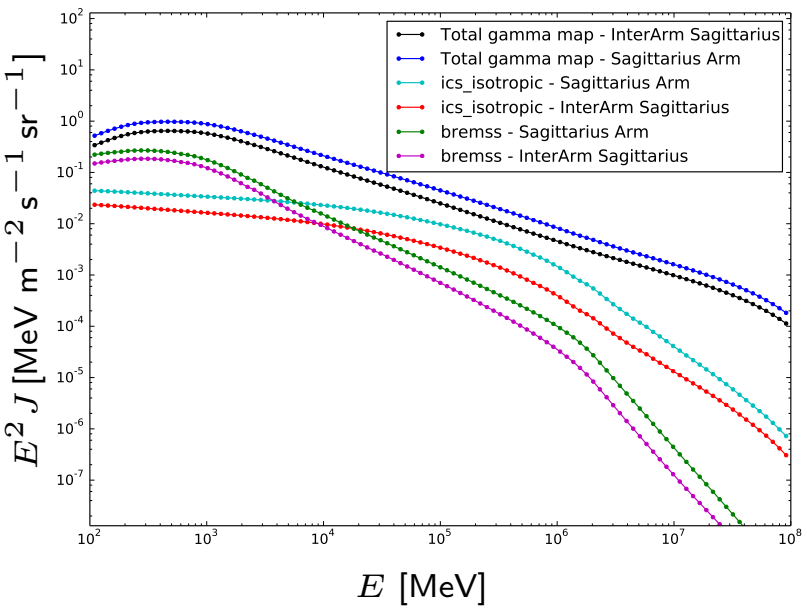
Gamma-Ray Data At

- ∼100 GeV
- ∼1 TeV

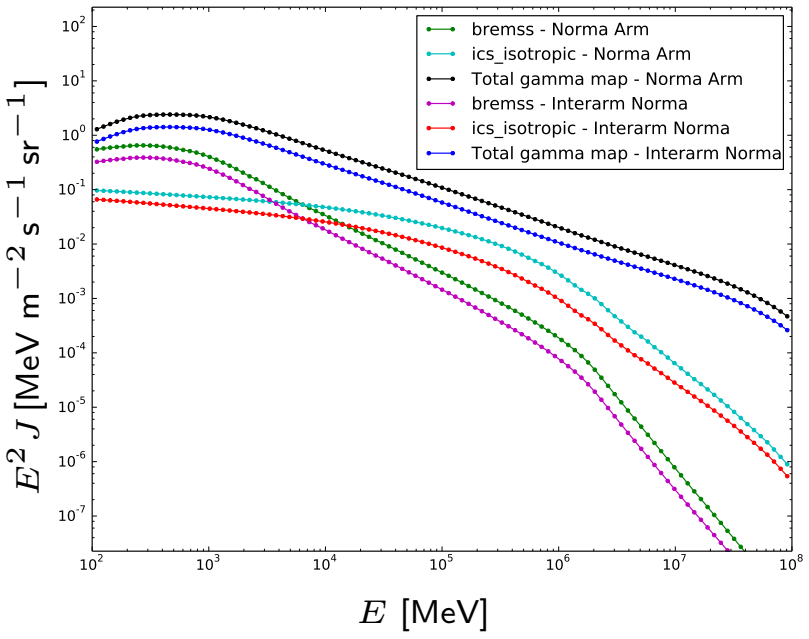
Sagittarius Arm



Sagittarius Arm



Norma Arm



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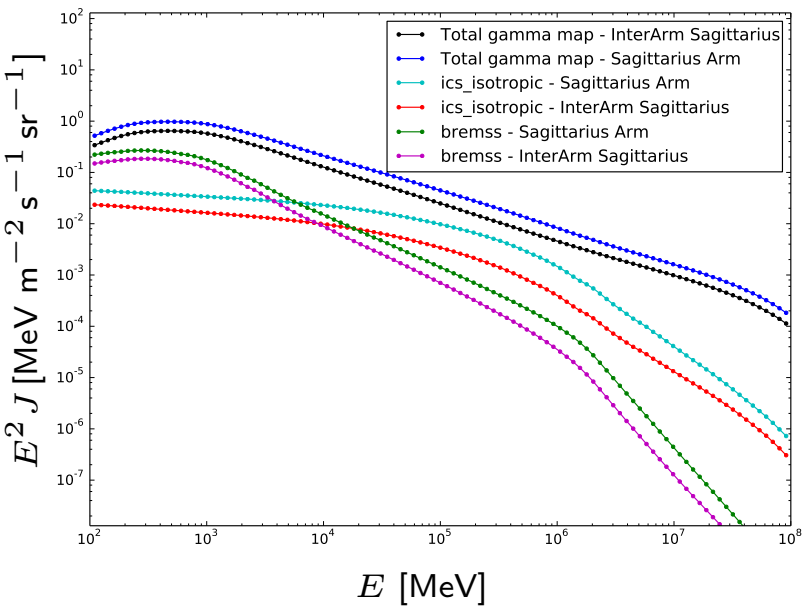
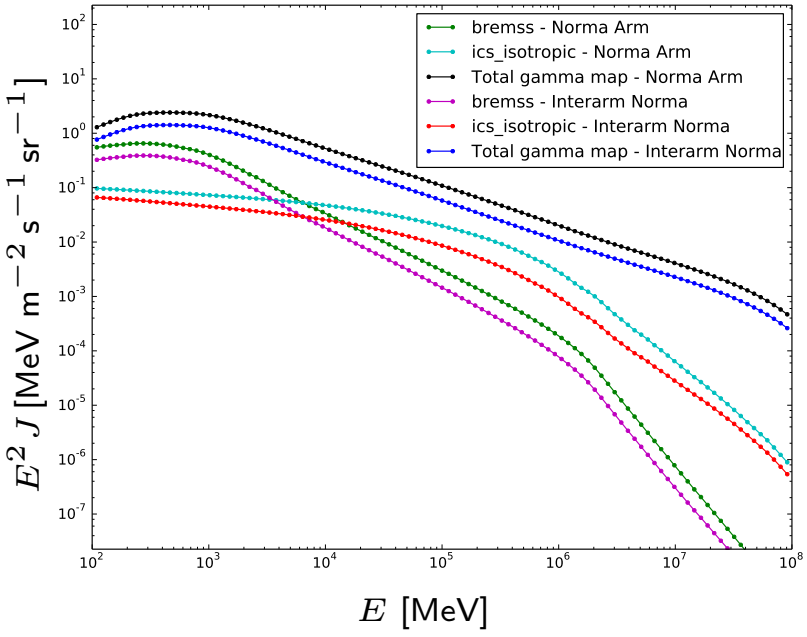
Sagittarius Arm



Norma Arm



Observations

- Higher on-arm flux
- Harder on-arm spectra
  - up to 0.1 for IC
  - slightly for π^0

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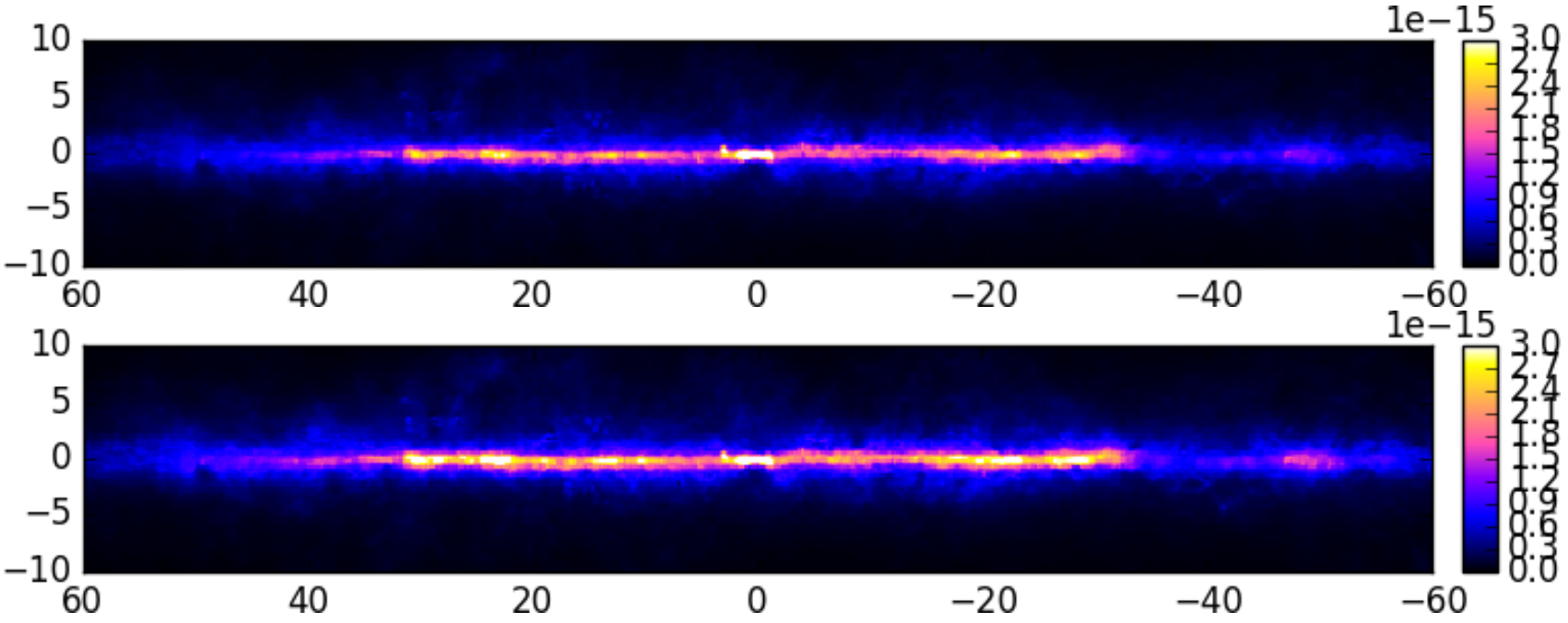
Gamma-ray Emission



Preliminary: Anisotropic Diffusion

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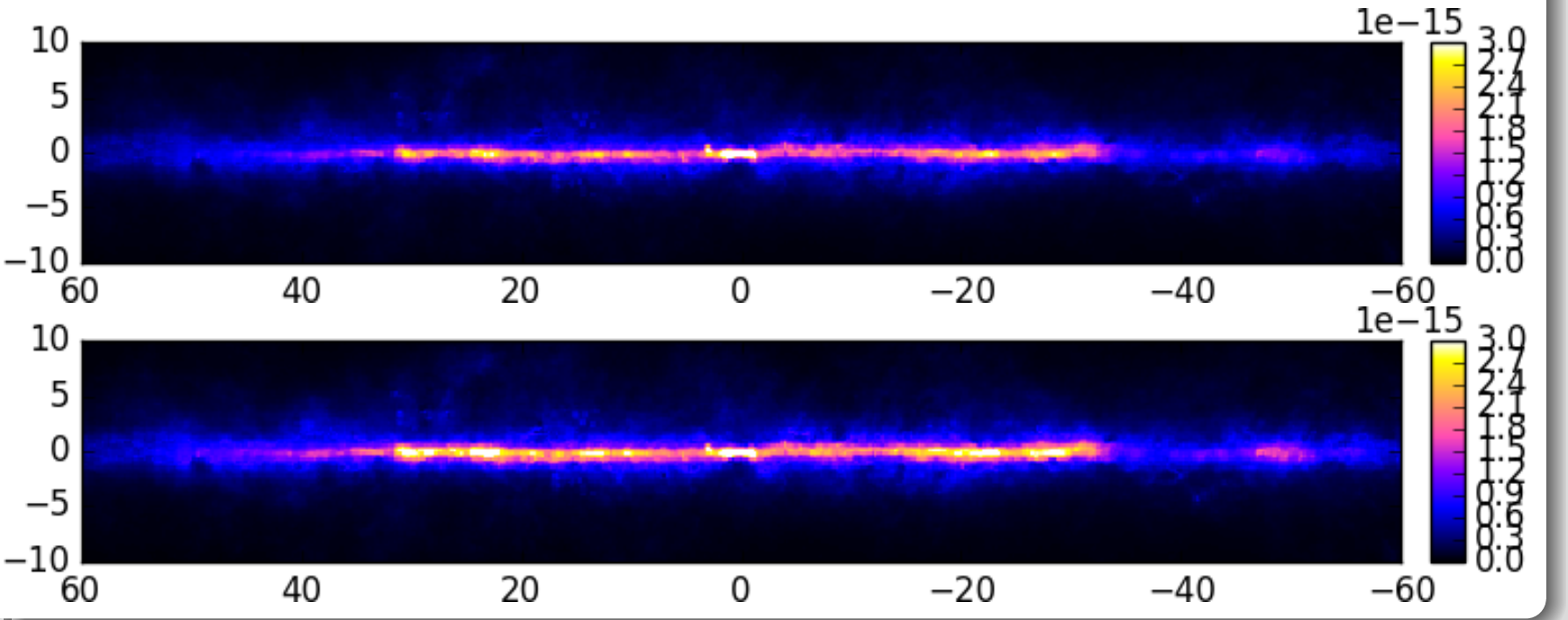
Gamma-ray Emission



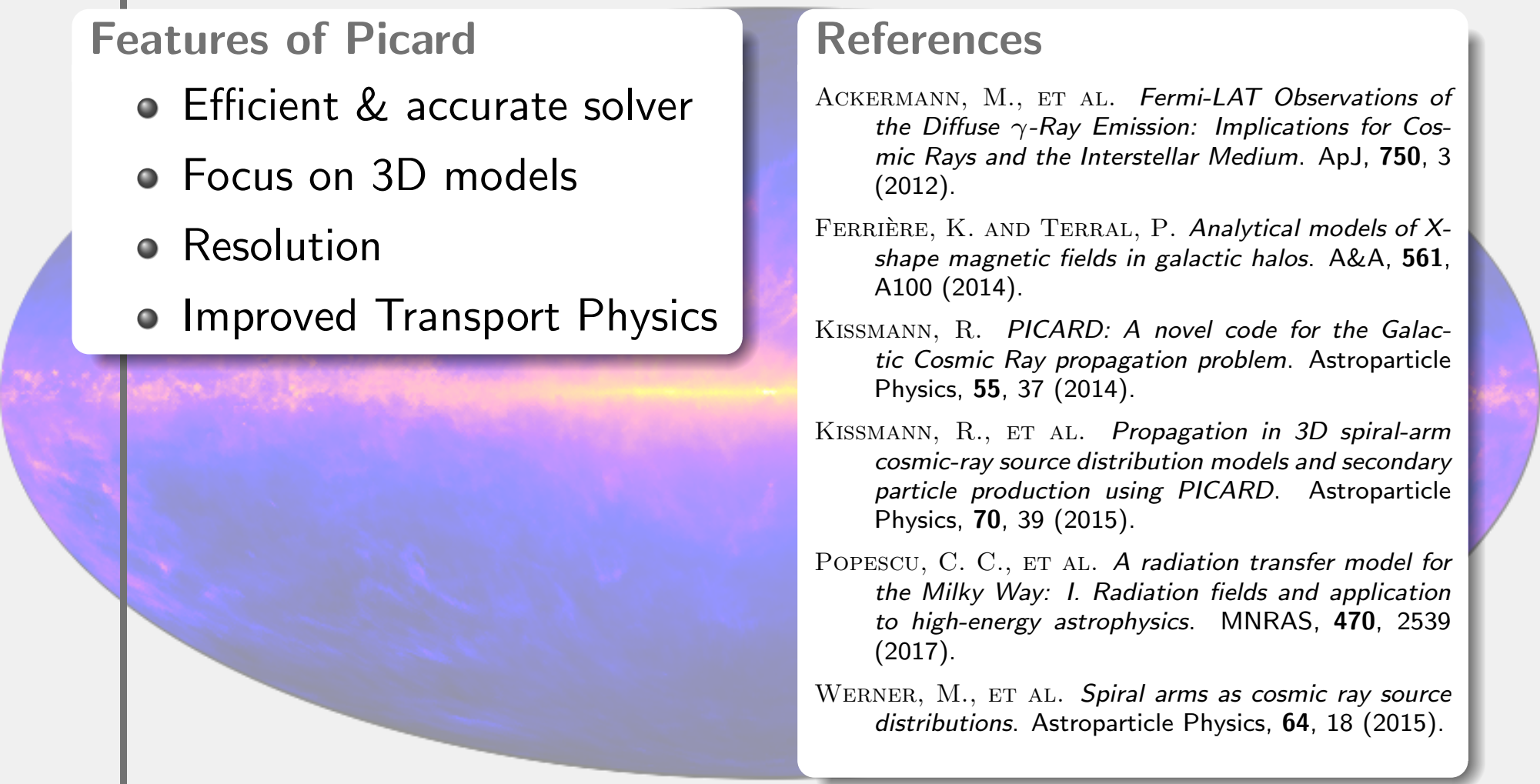
Impact

- Enhanced local structure
- Analysis ongoing

Conclusion

Features of Picard

- Efficient & accurate solver
- Focus on 3D models
- Resolution
- Improved Transport Physics



References

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Conclusion

Features of Picard

- Efficient & accurate solver
- Focus on 3D models
- Resolution
- Improved Transport Physics

Applicability

- Galactic-center physics
- Energies up to the knee
- Propagation near sources
- Locally changing diffusion
- Neutrino messenger*

References

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