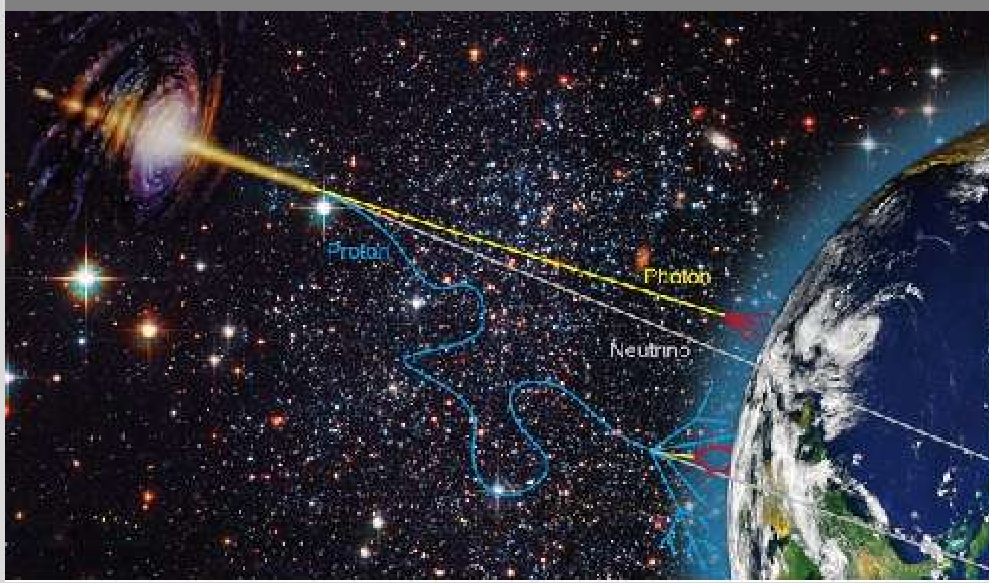
Karlsruher Institut für Technologie

Transport Models for Galactic Cosmic Rays in the Era of PAMELA, FERMI and AMS-02

S. Kunz, W. de Boer, I. Gebauer, F. Keller, M. Weinreuter

Bad Liebenzell 2013

Institute of Experimental Nuclear Physics

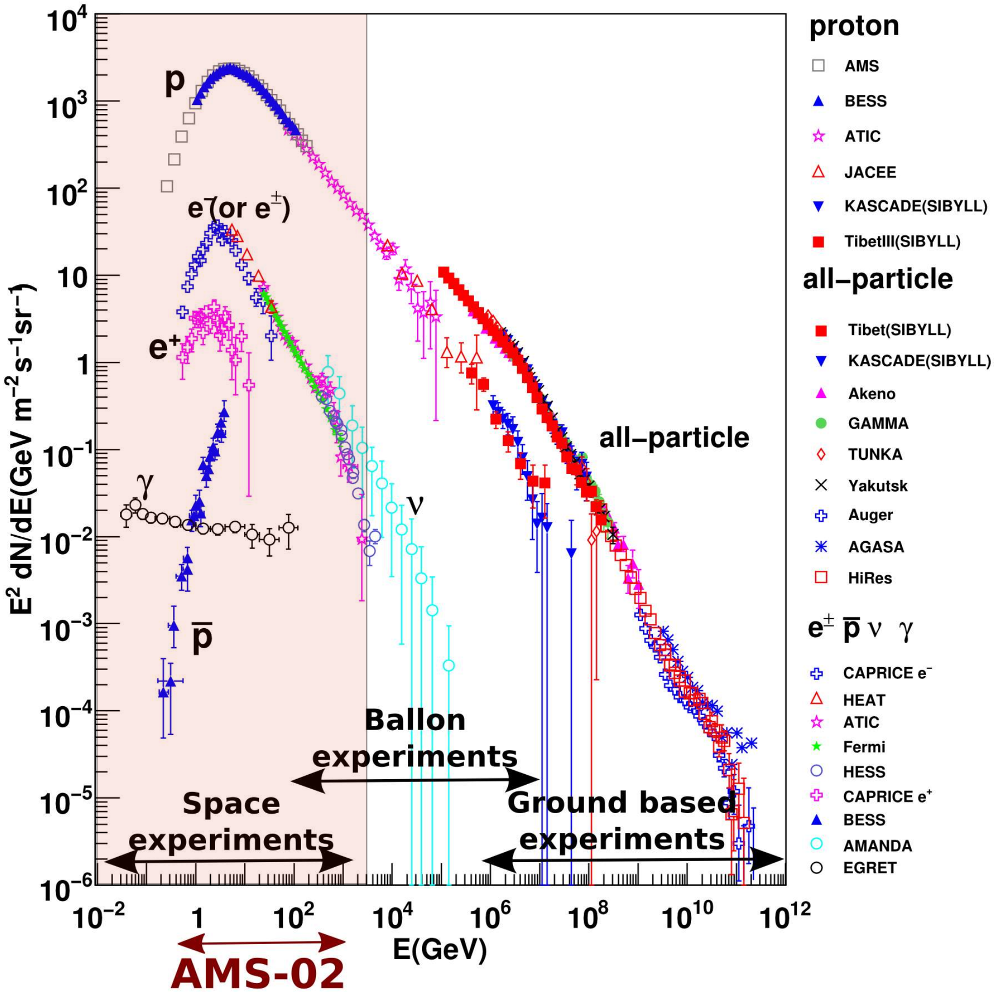


Outline

- Introduction to Cosmic Ray (CR) transport models
- Results of a Markov Chain Monte Carlo (MCMC) study
- Pulsar interpretation of the anomalous rise in the positron fraction
- The local bubble: facts and prospects

Cosmic Ray measurements

Karlsruher Institut für Technologie

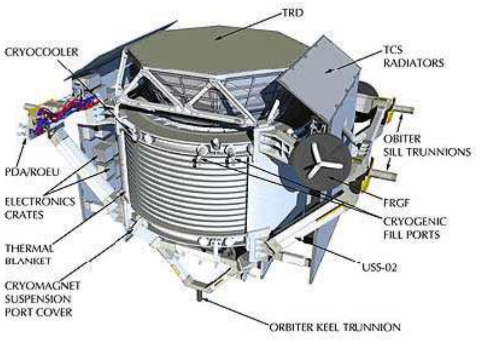


Pamela

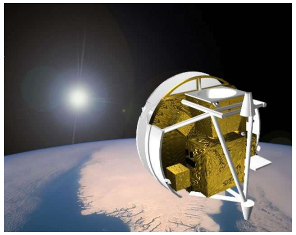
Caprice

Fermi

AMS-02



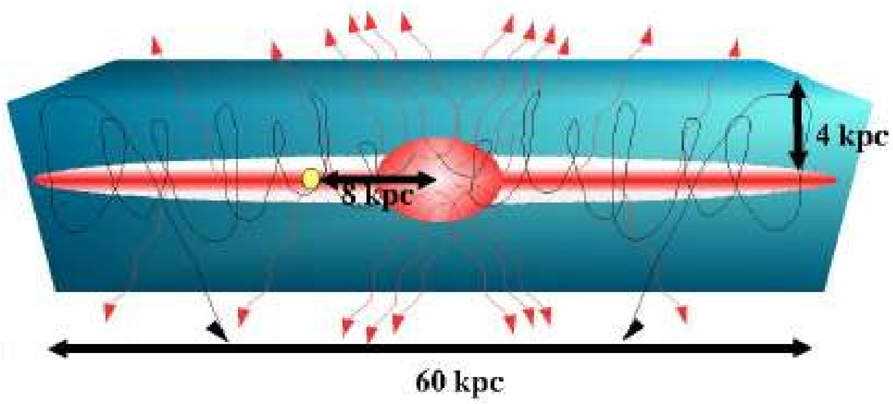
ACE



CREAM

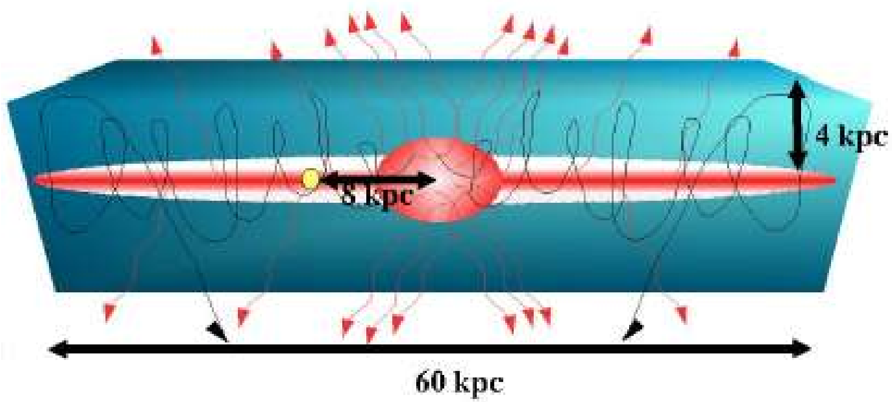
Transport models

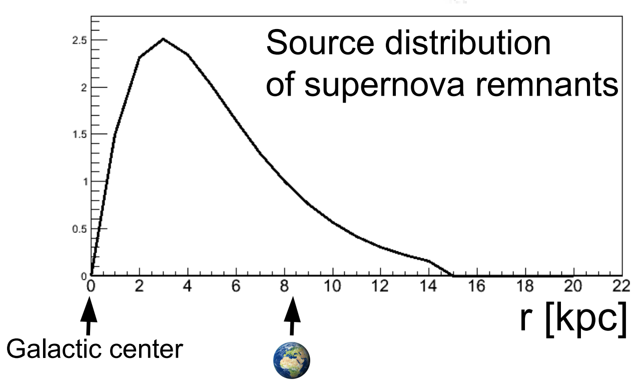
- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)



Transport models

- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)





Source distribution

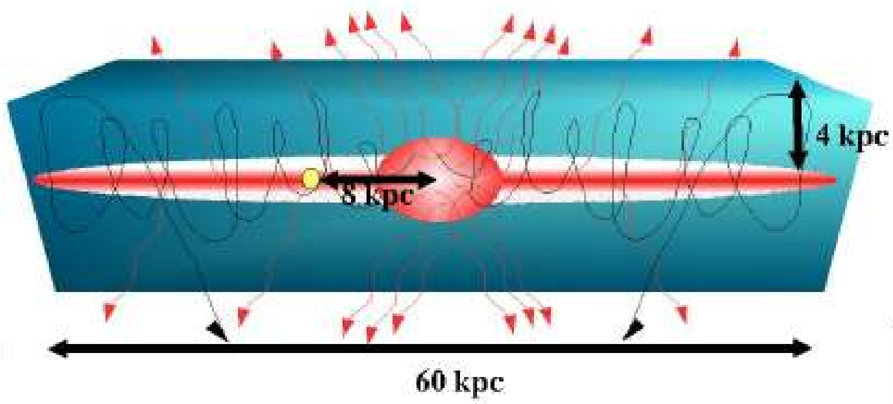
→ Supernova remnants are believed to be the dominant sources for galactic cosmic rays

→ injection spectrum is assumed to be a power law

$$Q \propto E^{-\alpha}$$

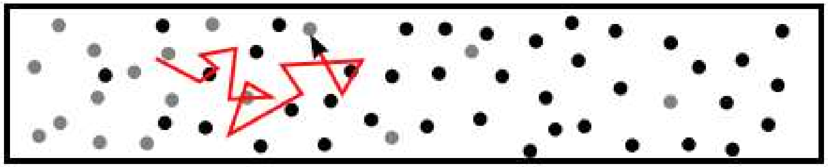
Transport models

- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)



Diffusion

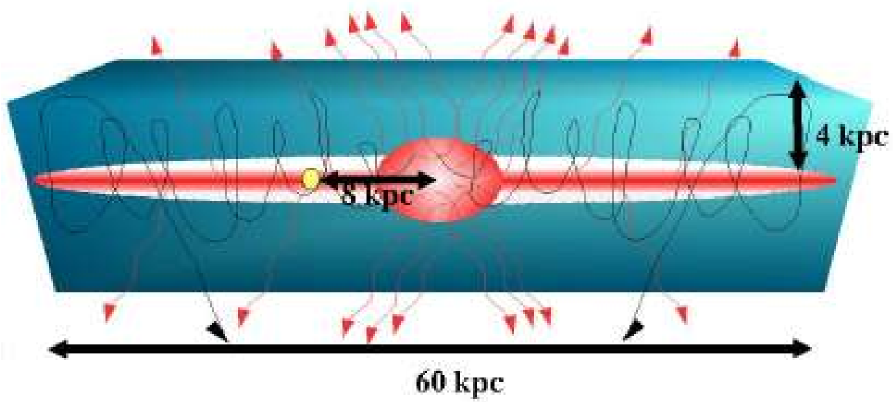
→ CR particles scatter off the turbulences of the magnetic field



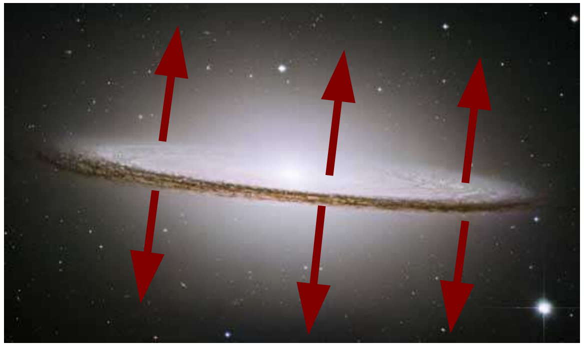
$$D(R) \propto D_0 \cdot R^{\delta}$$

Transport models

- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)



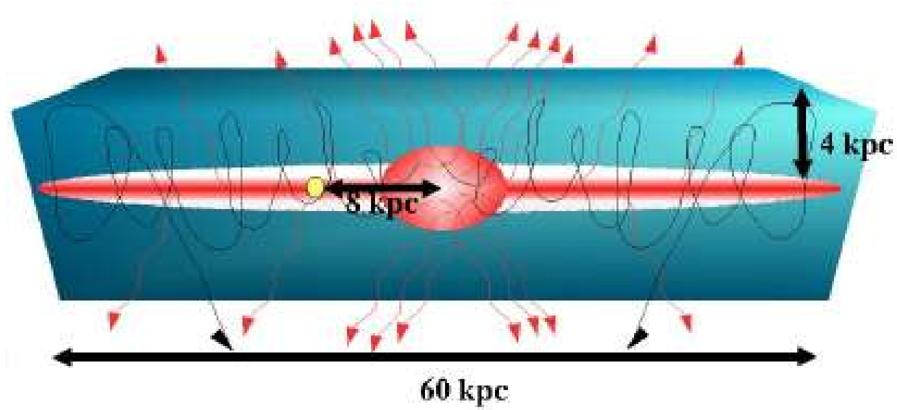
Convection (galactic winds)



$$V\,,\,\frac{dV}{dz}$$

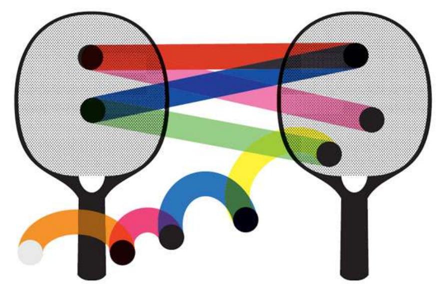
Transport models

- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)



Diffusive reacceleration

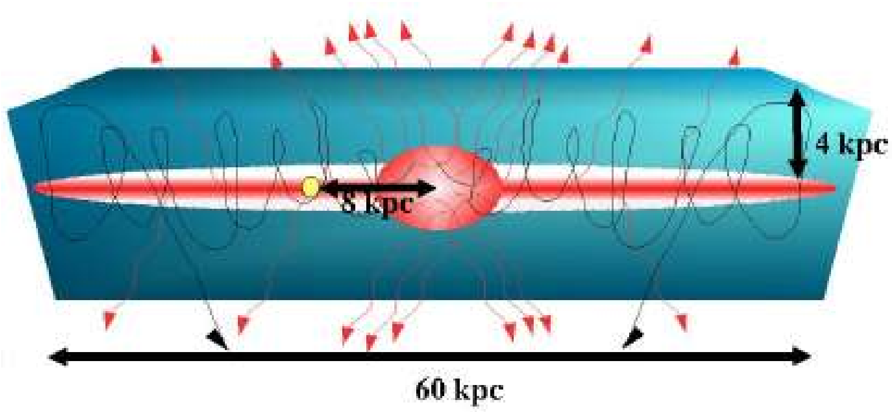
→ CR particles scatter off randomly moving clouds, in which the magnetic fields are frozen



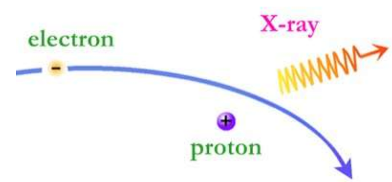
v_{alfven}

Transport models

- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)



Momentum losses



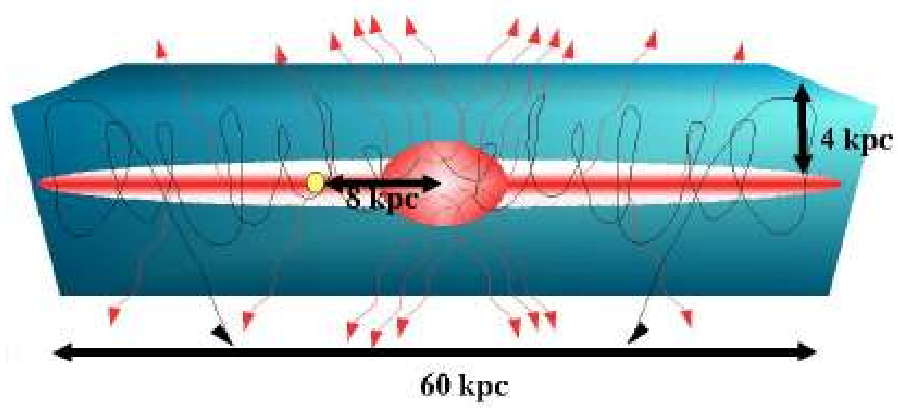
e.g. Bremsstrahlung

Particle losses

- Fragmentation
- Radioactive decays

Transport models

- Aim: Reproduction of the locally measured spectra of cosmic rays
- Modeling of the transport processed the particles underly
- Numerical solution of the transport equation (e.g. Galprop, Dragon)



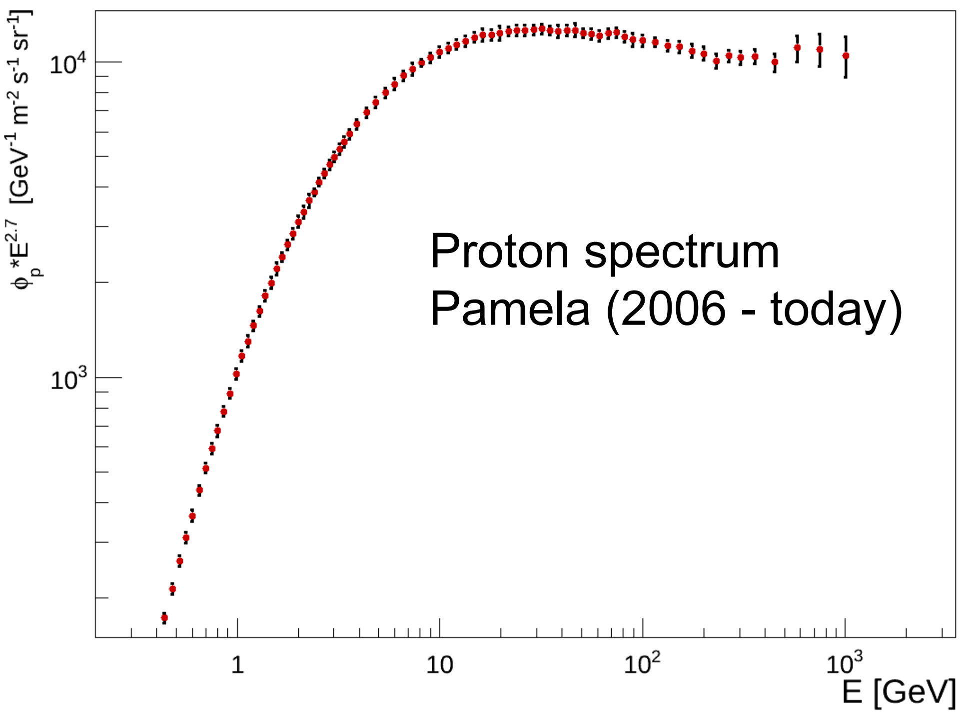
→ **Transport models depend on many unknown parameters! Our model: 16**

e.g. Diffusion strength and rigidity dependence
Halo height
Injection spectrum
...

Compare model predictions with experimental data: $p\,,\ \bar{p}\,,\ \frac{\bar{p}}{p}\,,\ \frac{B}{C}\,,\ \frac{^{10}Be}{^{9}Be}$

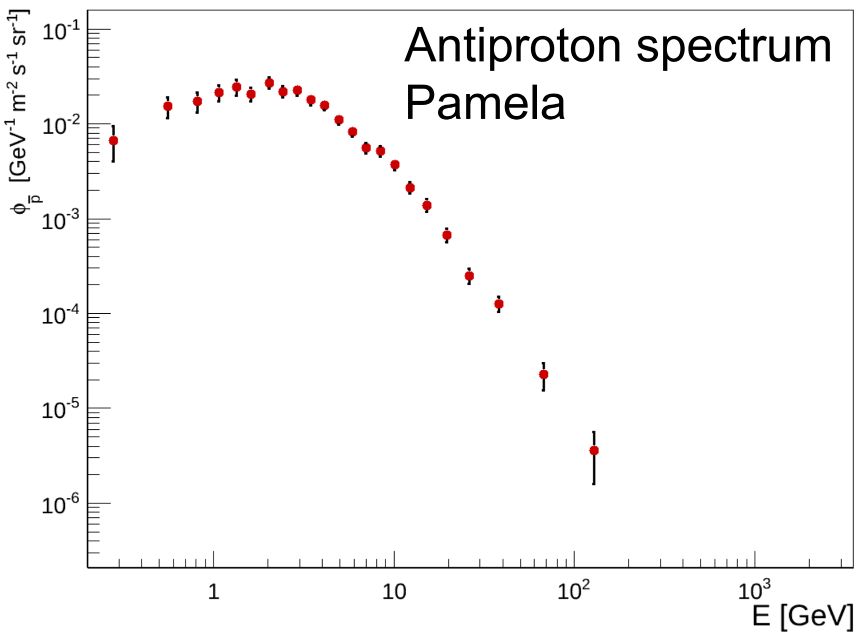
Observables

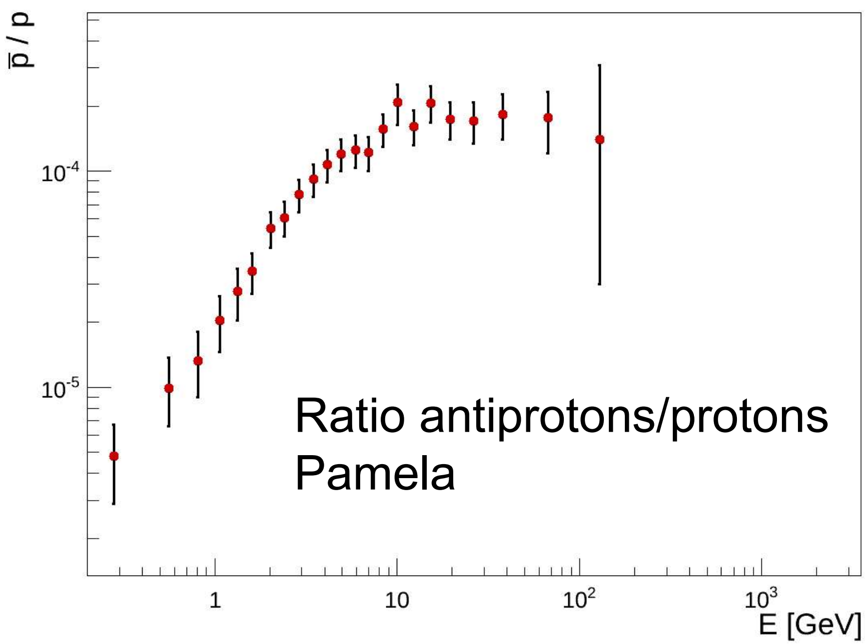
Protons: *primary* CRs, directly produced and accelerated by SNRs



Observables

Antiprotons: *secondary* CRs, produced by interactions of CRs with the interstellar medium (ISM)



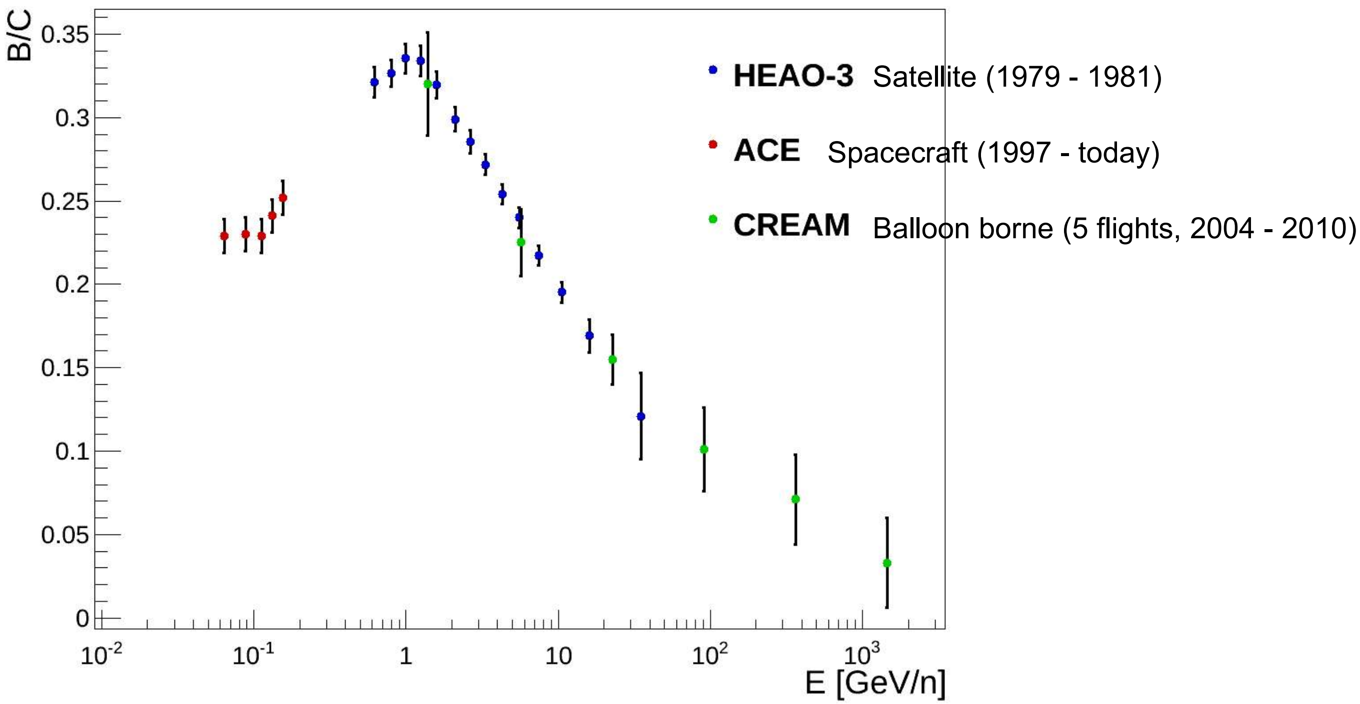


Observables

Boron/Carbon: Secondary-to-Primary ratio

$$C + \text{gas} \rightarrow B + X$$

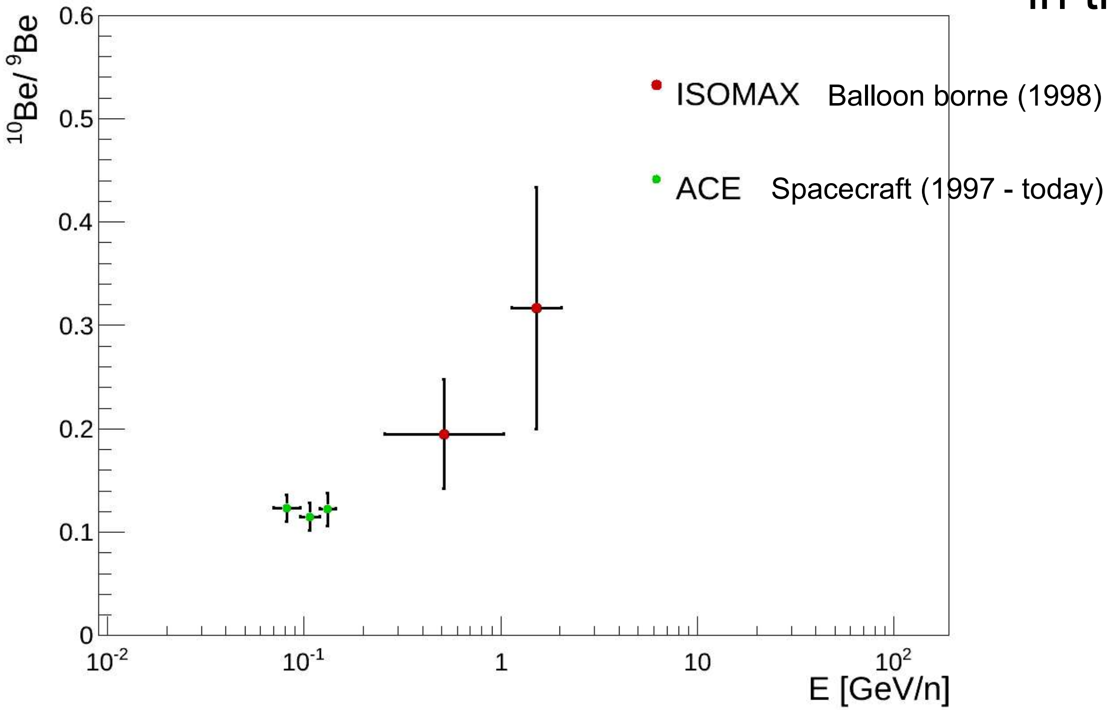
measure for the gas, 'seen' by CRs



Observables

^{10}Be/^{9}Be: Ratio of radioactive nuclei

Half life of **^{10}Be:** 1.39×10^{6} years
^{9}Be: stable



measure for the time, CRs spend in the galaxy: 'Cosmic Clock'

A Markov Chain Monte Carlo approach

Why use MCMC and not a simple minimizing algorithm?

→ not feasible for such a high dimensional problem
Evaluation of a single model takes minutes to hours

→ We do **NOT** just want to find a best fit model, so no fine tuning.
Instead, want to explore wide ranges of parameter space (exotic models?)
Examine the full potential and the limitations of these kind of models

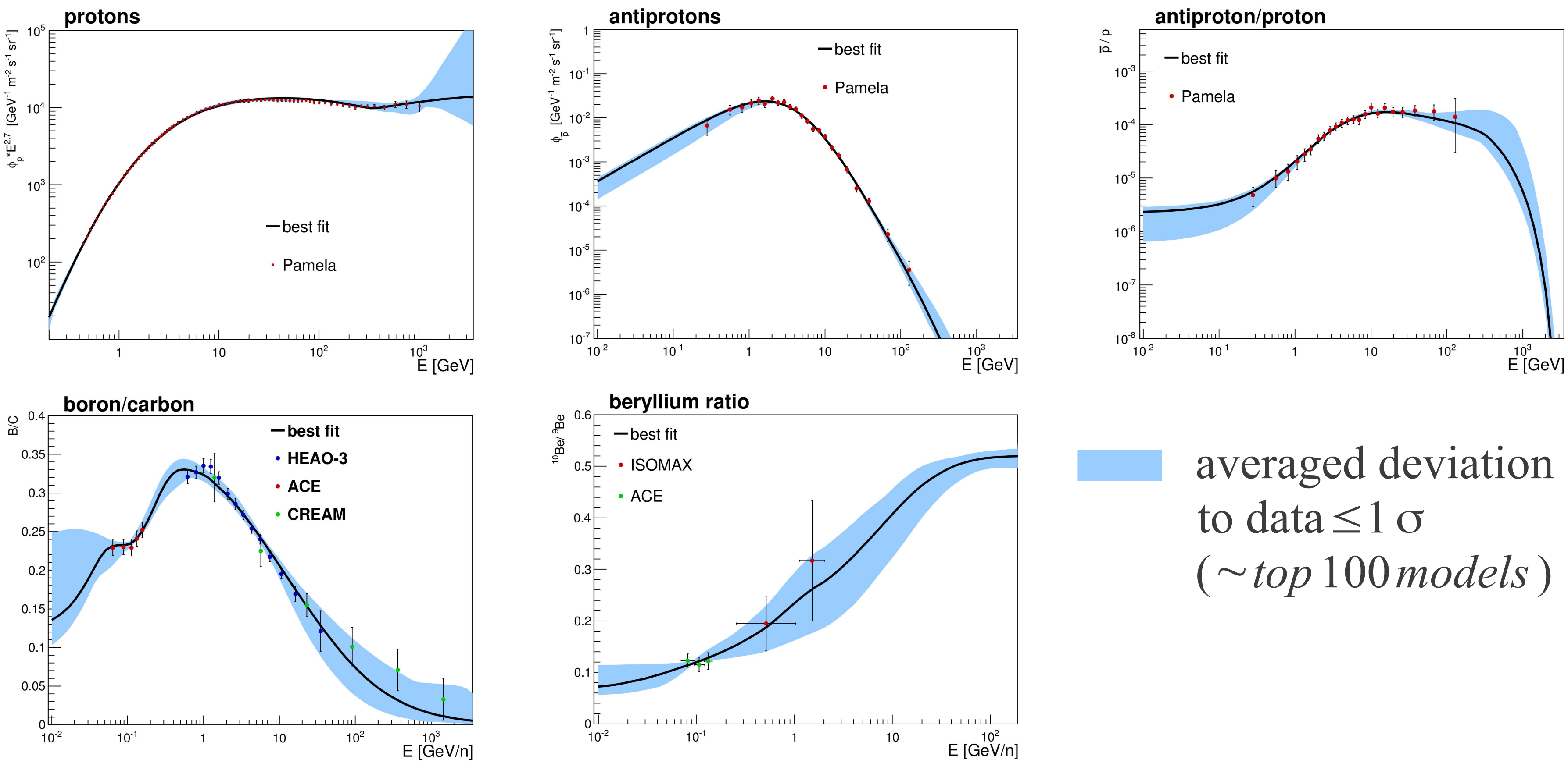
→ Use **MCMC** in order to **sample** the parameter space efficiently

Results are based on ~ **10 Mio. Models**

> 1 year with ~ 1.500 CPU cores

MCMC Results

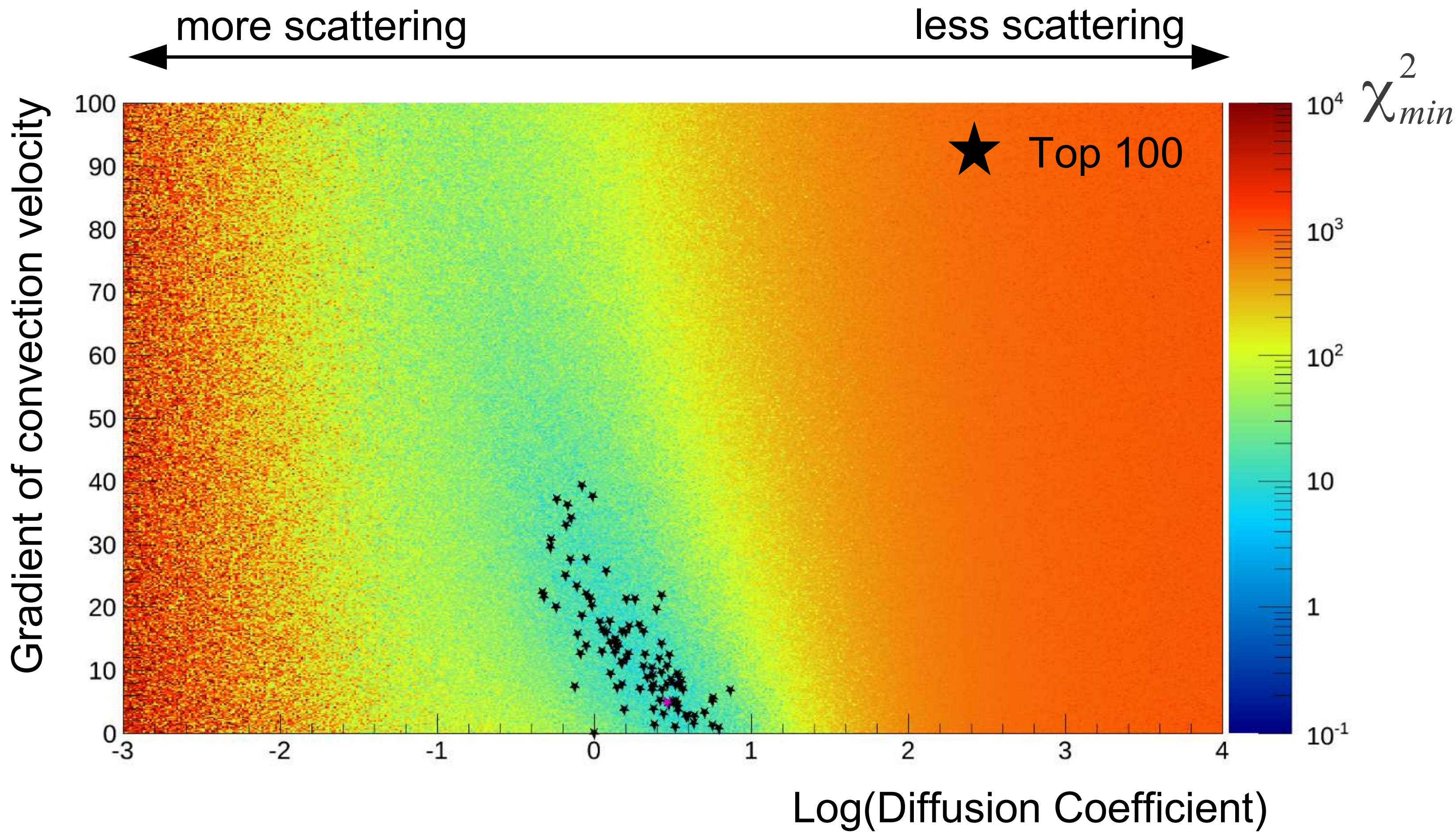
Karlsruher Institut für Technologie



How well are the transport parameters constrained by these data sets?

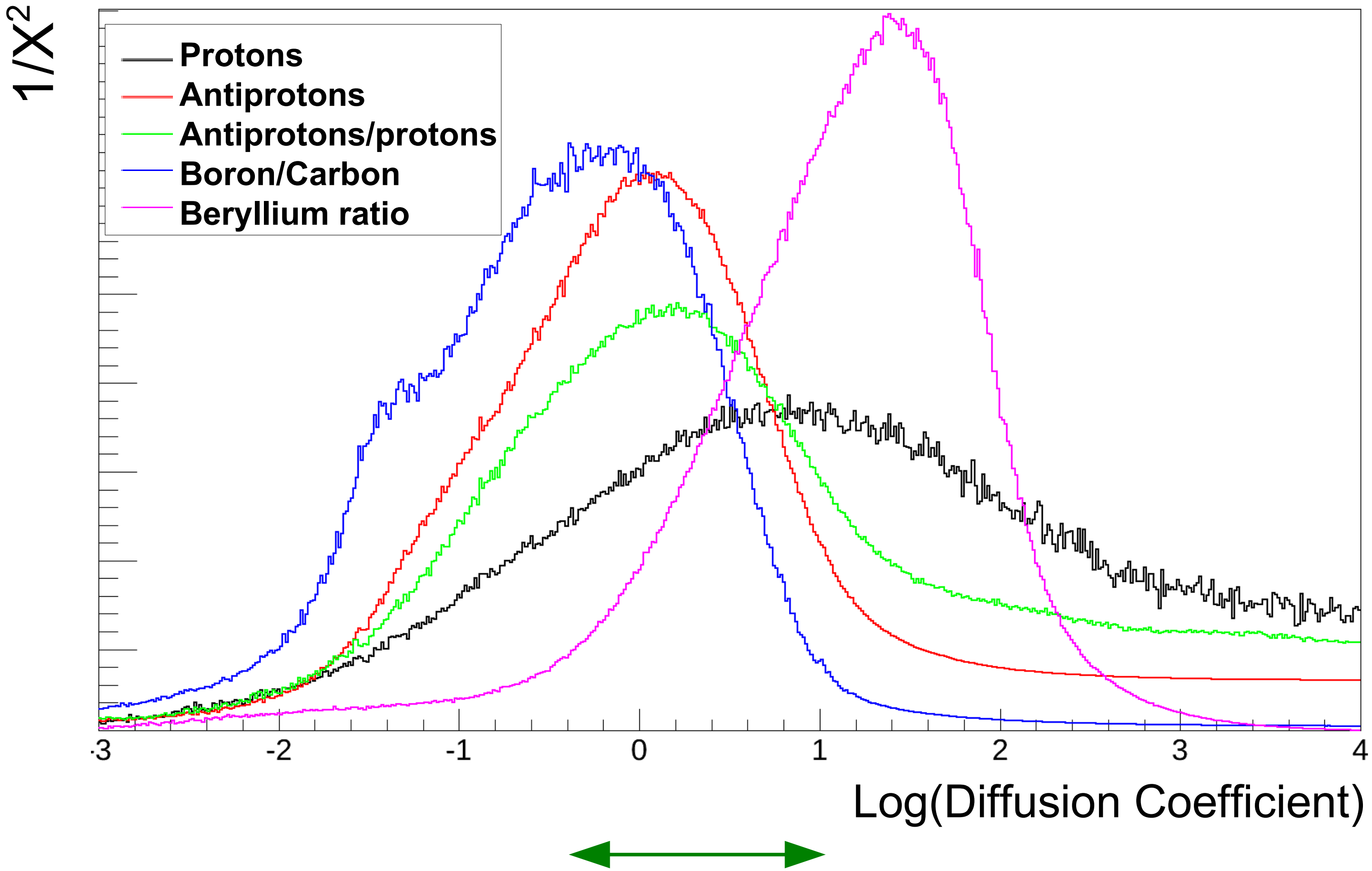
MCMC Results

How well are the transport parameters constrained by the data sets?



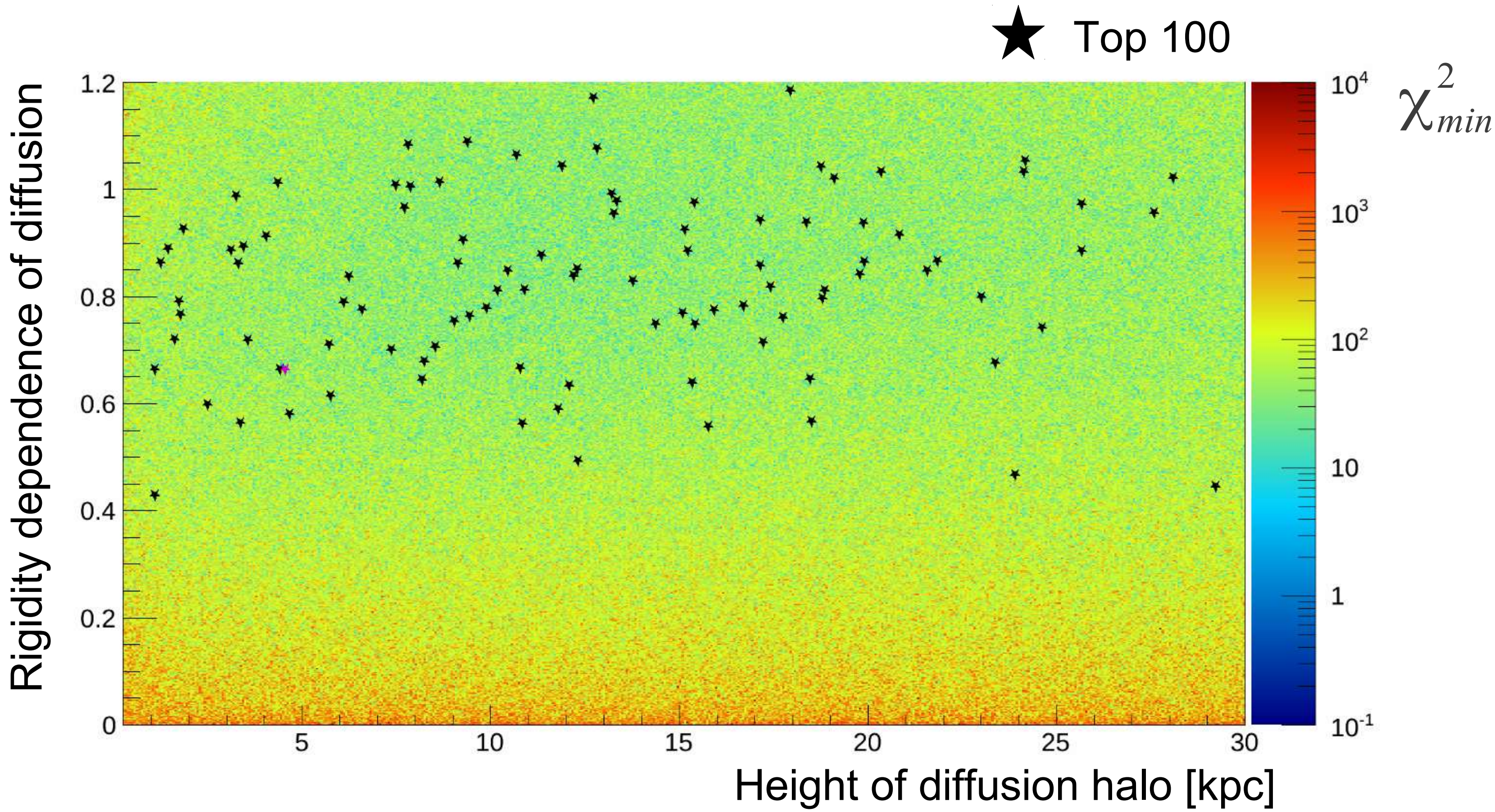
MCMC Results

Preferred diffusion coefficient by the **single** observables



Range of agreement

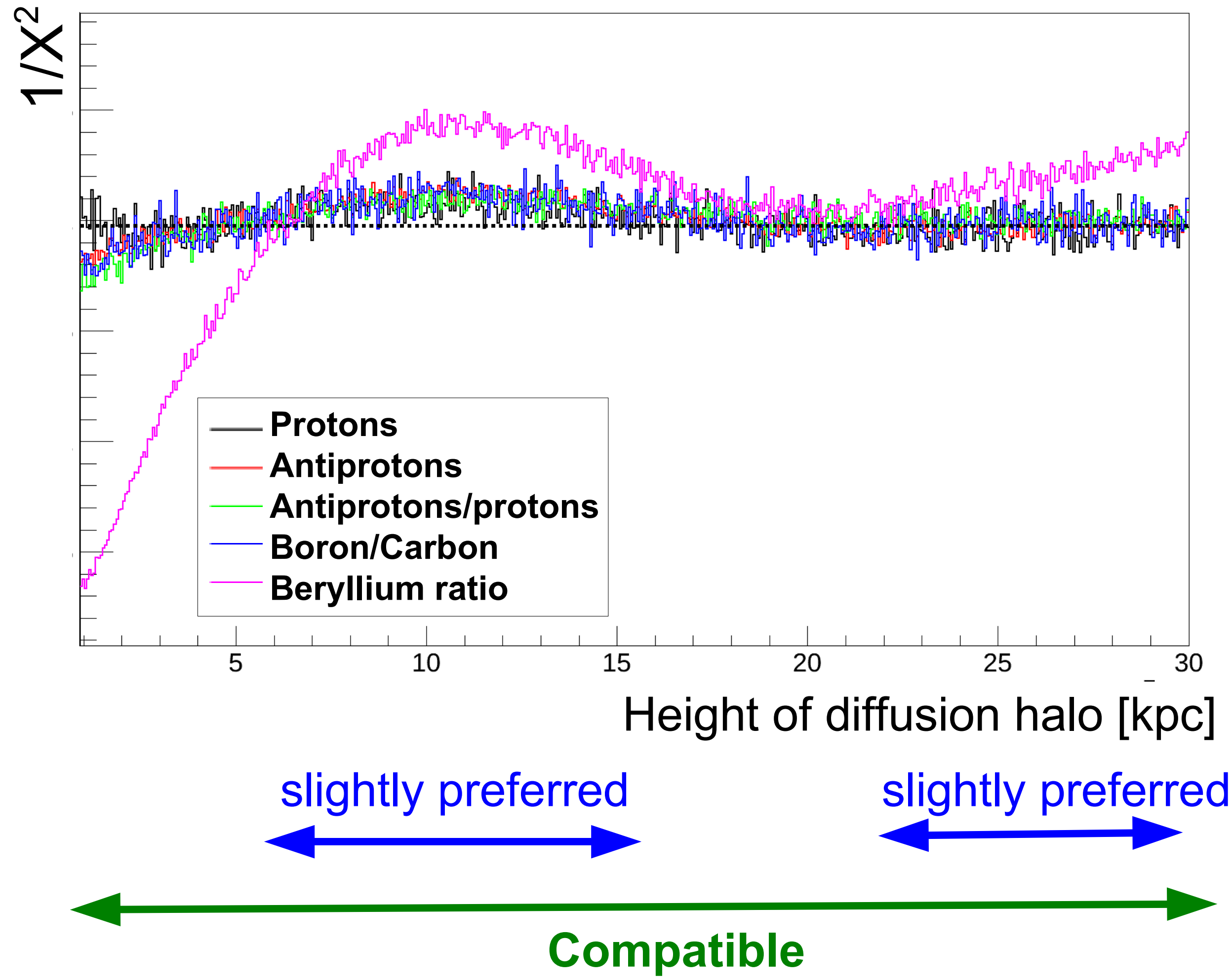
MCMC Results



Compatible

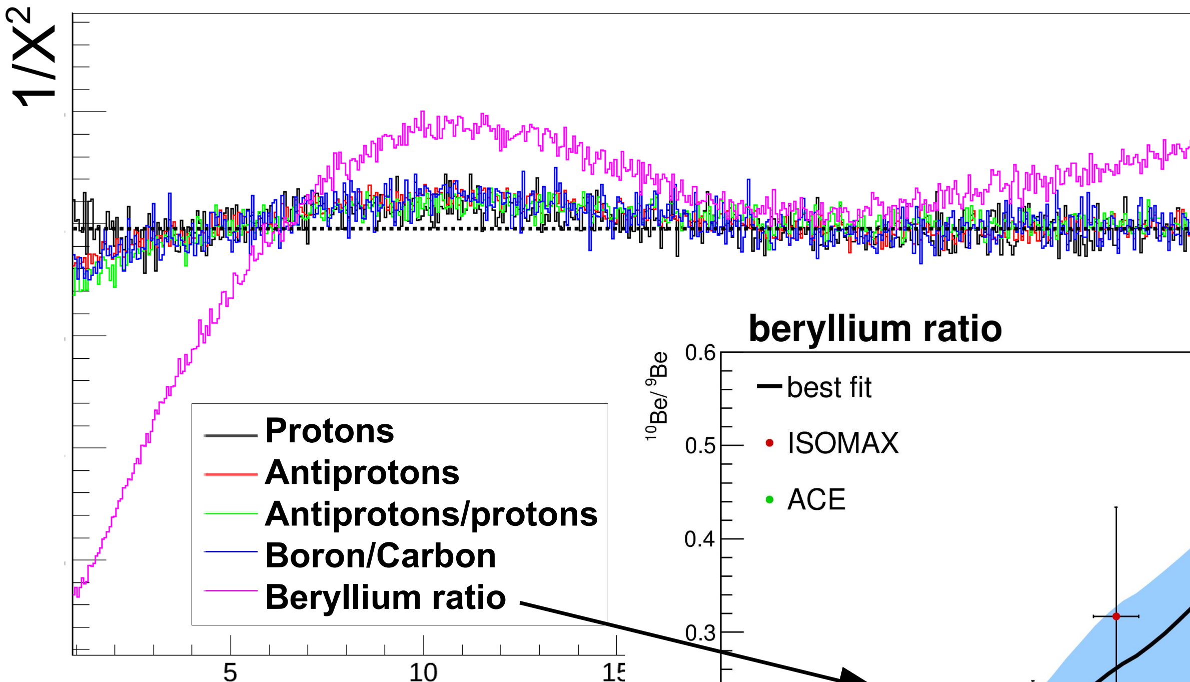
MCMC Results

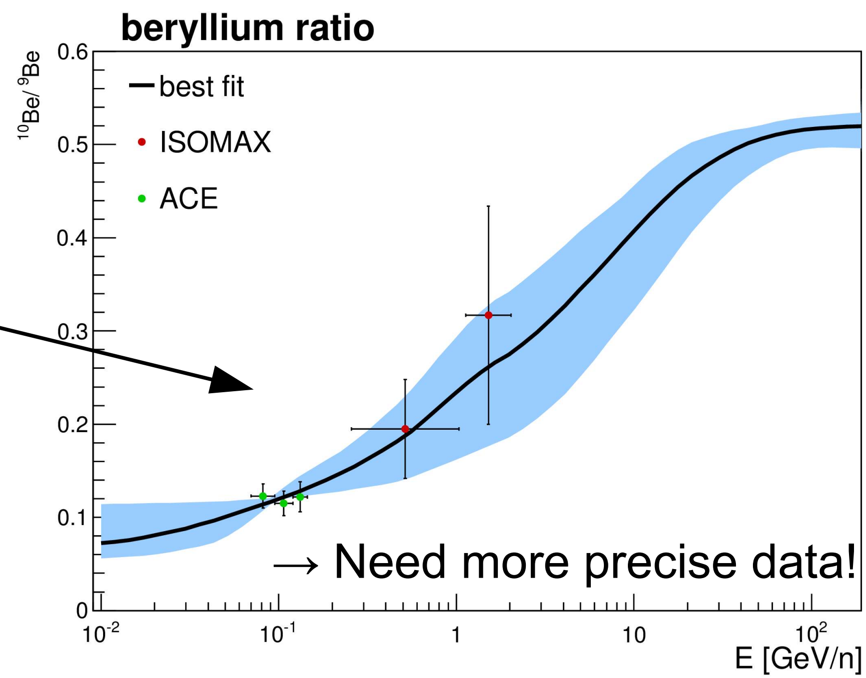
Preferred halo size by the **single** observables



MCMC Results

Preferred halo size by the **single** observables





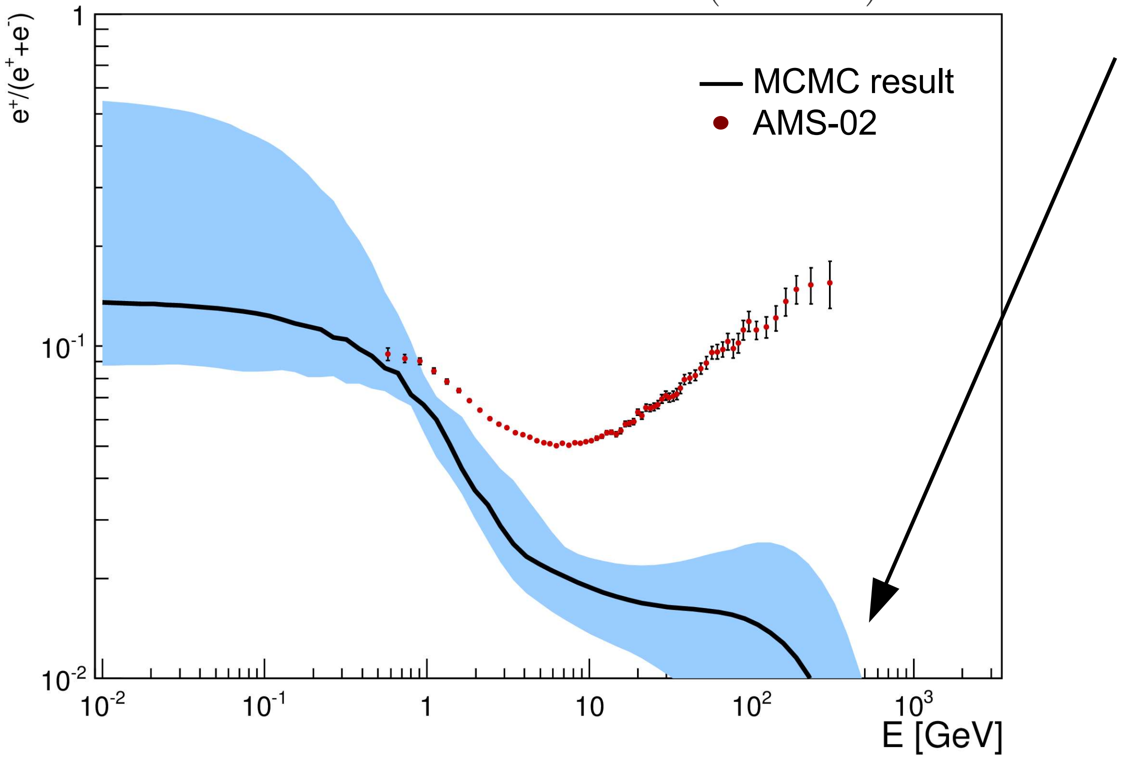
Halo size cannot be constrained

MCMC Results
Summary

- Sampling of parameter space using MCMC
- Some transport parameters can and some cannot be constrained by the experimental data
- The preferred models can be used as background models and allow predictions for other observables
  → Leptons

Leptons

positron fraction: $\frac{e^+}{(e^+ + e^-)}$



Downgoing behaviour expected from standard CR transport

Impossible to mimic with a pure secondary production of positrons!

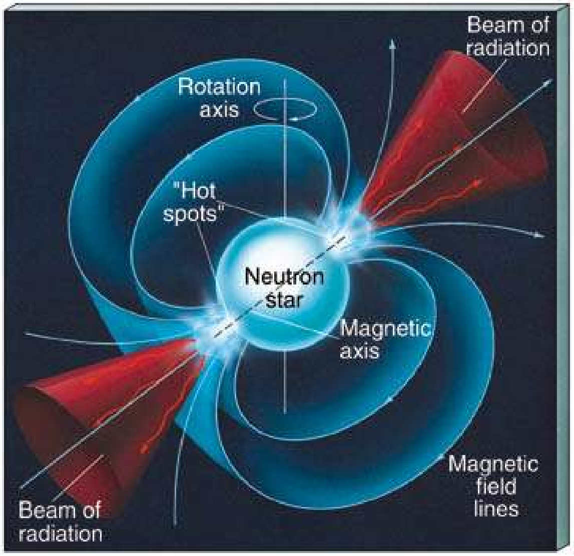
Most favored explanations are additional primary positrons by:
- Pulsars
- Dark matter annihilation
  (not covered in this talk)

Pulsars

→ highly magnetized, rotating neutron stars
Electrons are extracted from the surface by electric fields and later transformed into electron-positron pairs through electromagnetic cascading

Expected flux can be modeled[1], but large uncertainties due to

- transport
- pulsar properties: distance, age, energy output, injection, efficiency, ...



[1] e.g. arXiv:1001.4540

Pulsars

→ highly magnetized, rotating neutron stars
Electrons are extracted from the surface by electric fields and later transformed into electron-positron pairs through electromagnetic cascading

Expected flux can be modeled[1], but large uncertainties due to

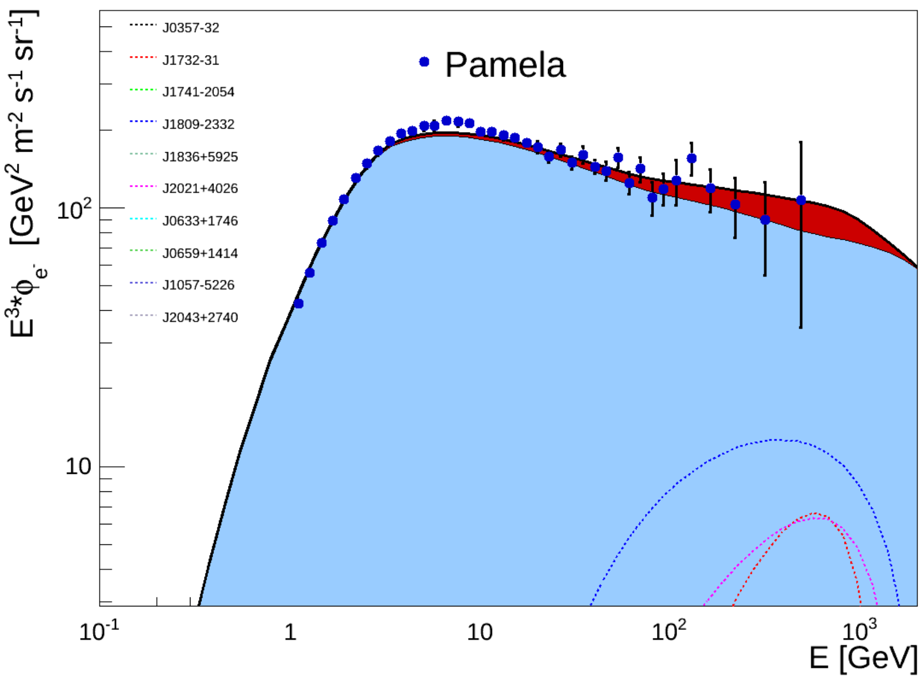
- transport
- pulsar properties: distance, age, energy output, injection, efficiency, ...

Fit to data:
- use the 10 most contributing (known) pulsars
- allow pulsar parameters to vary inside their observational limits
- use the very latest data of Pamela, Fermi and AMS-02
- fit the available e^+, e^- data sets simultaneously: e^-, e^+, $(e^+ + e^-)$, $e^+ /(e^+ + e^-)$

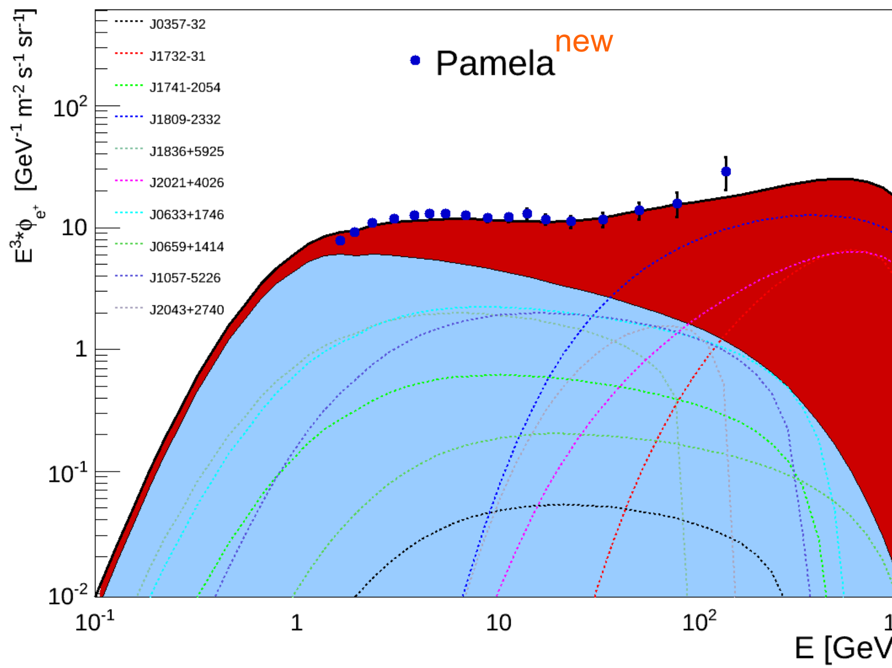
[1] e.g. arXiv:1001.4540

Pulsars Fit Results

Electrons



Positrons



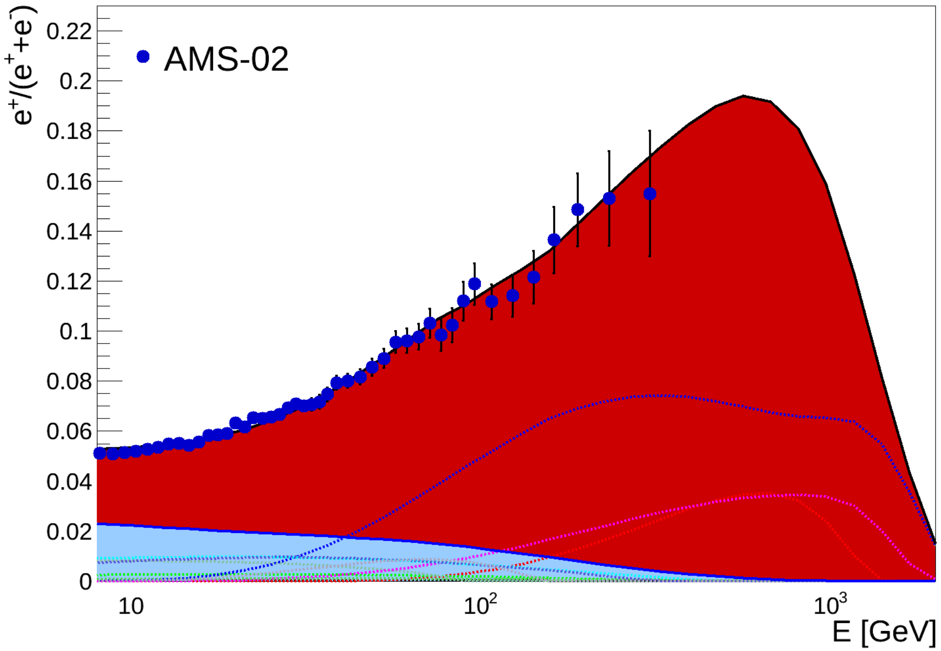
Background

Additional pulsar contribution

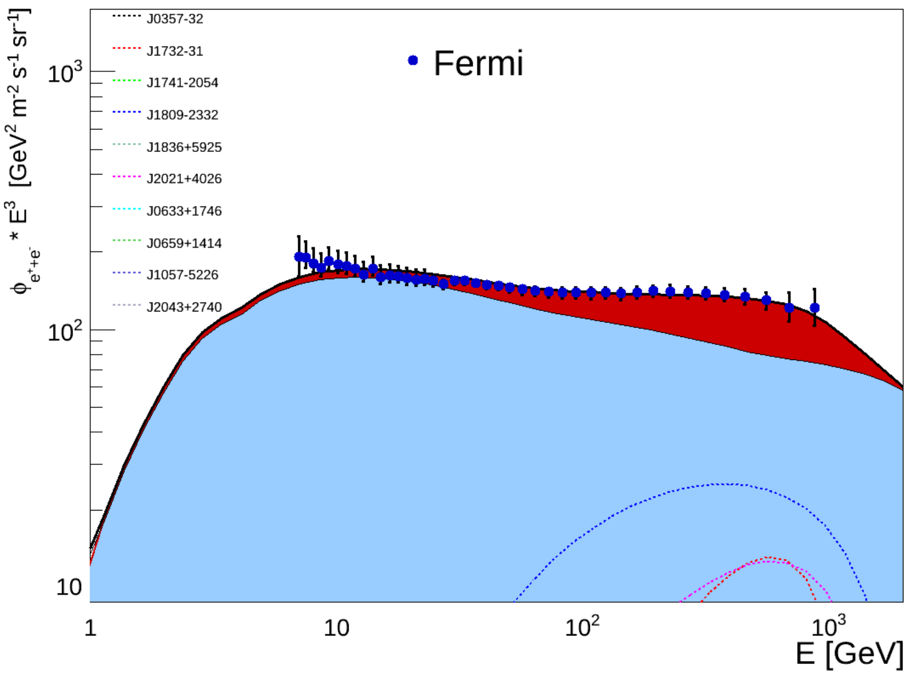
Same for e^+ and e^-

Pulsars Fit Results

Positron fraction



Electrons + Positrons



Background

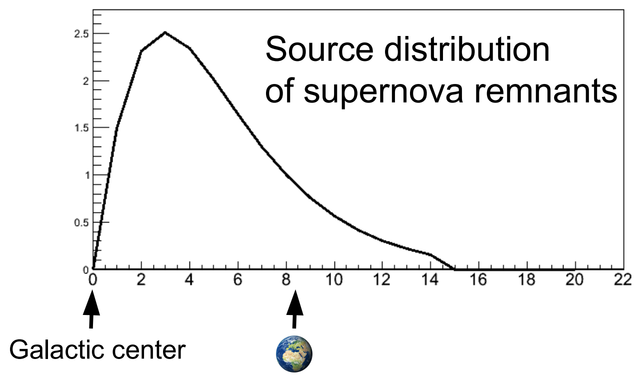
Additional pulsar contribution

Is there a way to disprove the pulsar/point like source explanation?

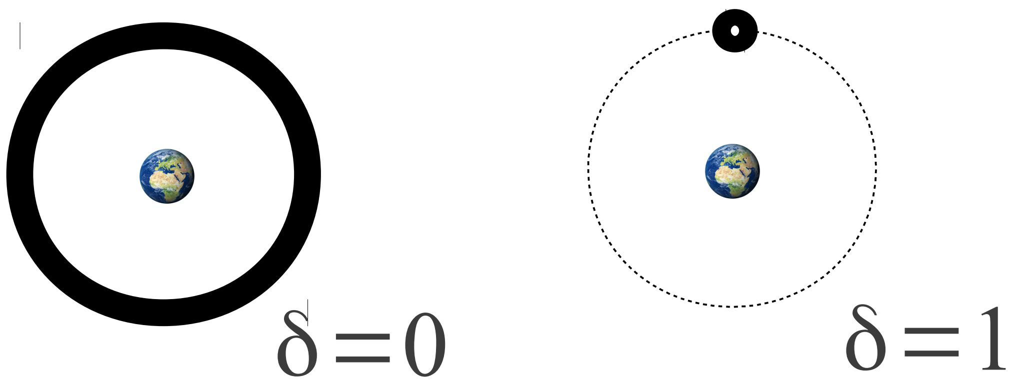
Anisotropy of Pulsars

- Most of the SNR (the sources of 'usual' CRs) are located towards the galactic center at ~ 4 kpc

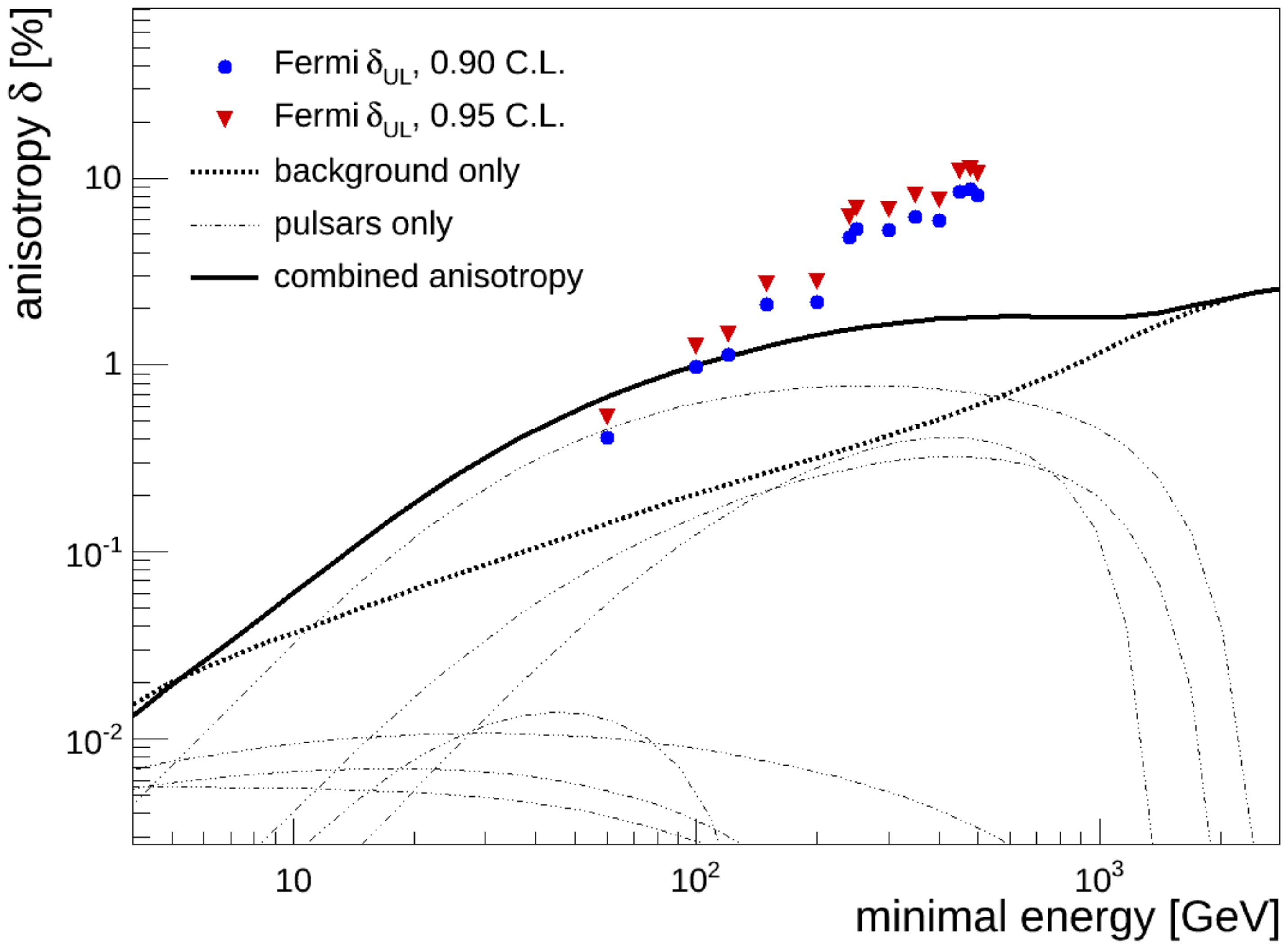
  → Expect dipole anisotropy of background itself



- Anisotropies of several pulsars can cancel each other completely



Anisotropy of ($e^+ + e^-$)



→ Current and upcoming upper limits may challenge the pulsar explanation

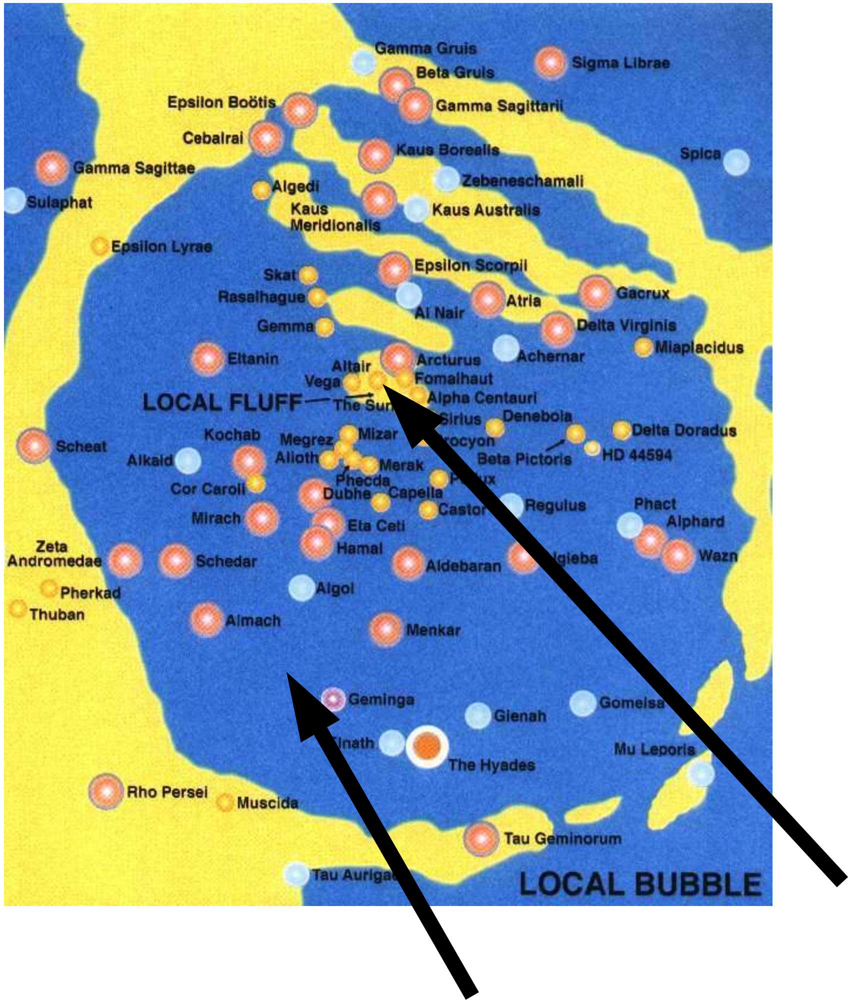
Local transport

→ e^+ and e^- suffer from large energy losses due to synchrotron radiation and inverse compton scattering
→ loose energy much faster than e.g. protons

→ short propagation lengths of 0.5 – 1 kpc
Protons: few kpc

→ *local transport:* highly affected by the local environment

The local bubble



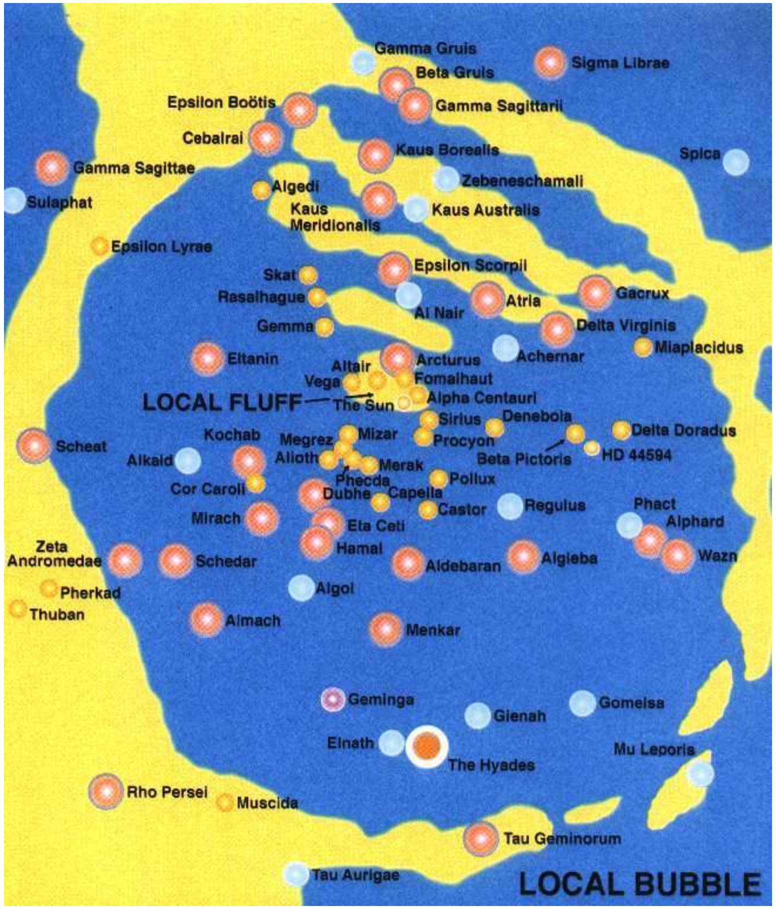
- lower gas density, factor 100–1000
- irregular shape, radii 50-150 pc
  → very local!
- Age: 5 –12 Myr
- Origin: SN explosions

This structure could significantly affect the transport of local CRs!

Sun

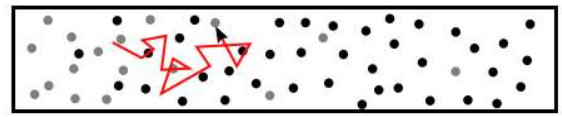
Underdense region

The local bubble



Lower gas density → Effect on diffusion?

Reminder: CR particles scatter off the turbulences of the magnetic field



Connection between turbulences and gas density?

less turbulence being washed out:
→ more scattering?

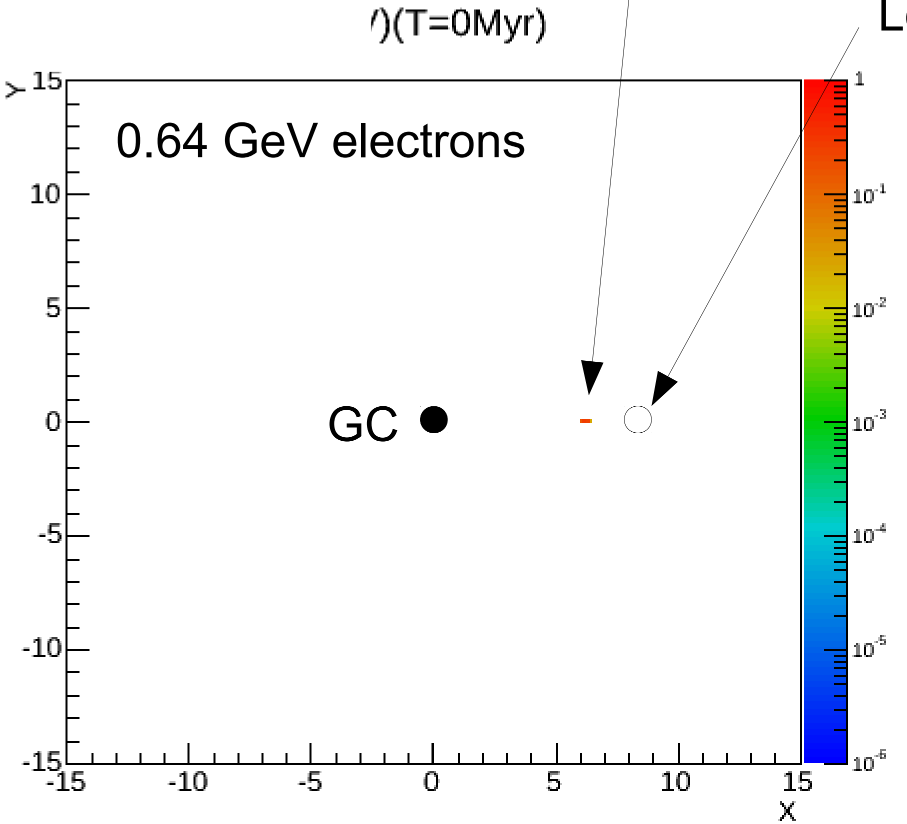
or

less magnetic focus points:
→ less scattering?

The local bubble

Point source

Local bubble: R = 0.3 kpc, $D_{LB} / D_{out} = 0.1$
→ more scattering centers



M. Weinreuter

Electrons are blocked out of the bubble!
A possible isotropizer?

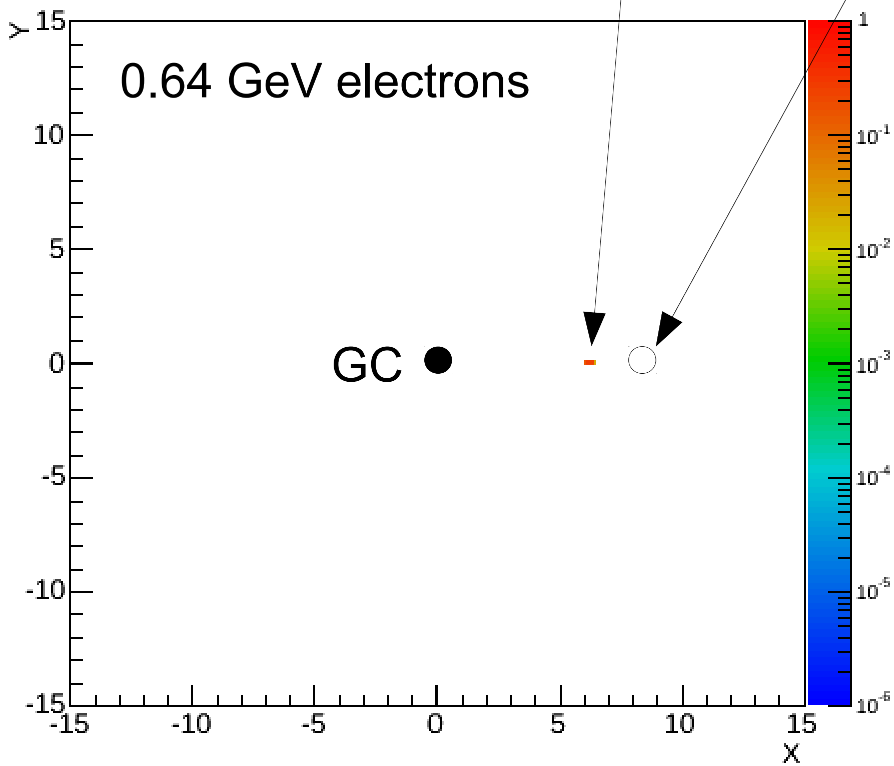
Work in progress...

The local bubble

Point source

Local bubble: $R = 0.3$ kpc, $D_{LB} / D_{out} = 10$

→ less scattering centers



M. Weinreuter

Electrons are pulled into the bubble

Work in progress...

Summary

- By using MCMC sampling, the parameter space of transport parameters was studied

- Positron fraction cannot be described with the assumption of a pure secondary production of positrons
  → Additional positron sources are needed

- Nearby pulsars could explain the positron fraction and lead to an anisotropy, which may challenge the pulsar explanation with upcoming upper limits

- The local environment could significantly affect the transport of local CRs and the expected anisotropies. Work in progress...