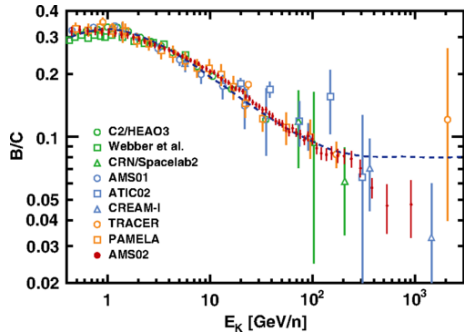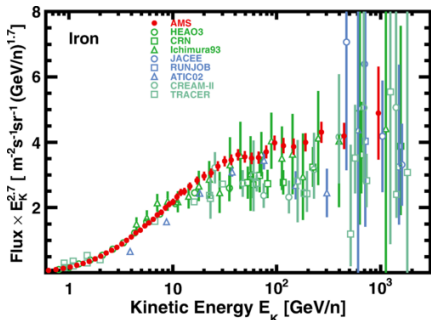R. Kissmann

AMS02 B/C Ratio

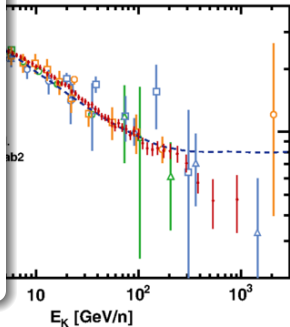(Aguilar et al. (2021a))

AMS02 Iron Flux
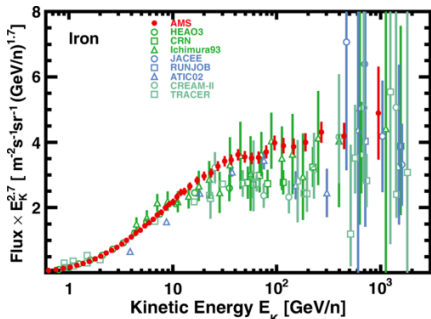

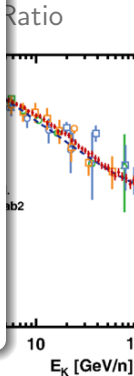(Aguilar et al. (2021b))

Ratio

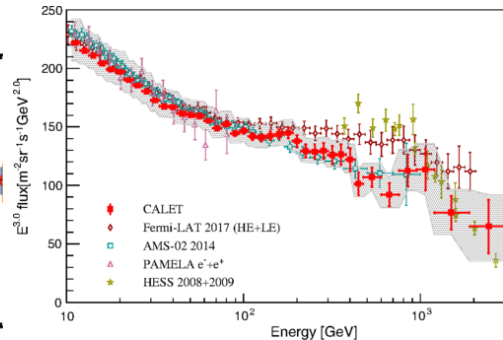(Aguilar et al. (2021a))

AMS02 Iron Flux

(Aguilar et al. (2021b))

...Ratio

(Aguilar et al. (2021a))

CALET Electron Flux

(Adriani et al. (2017))

AMS02 Iron Flux
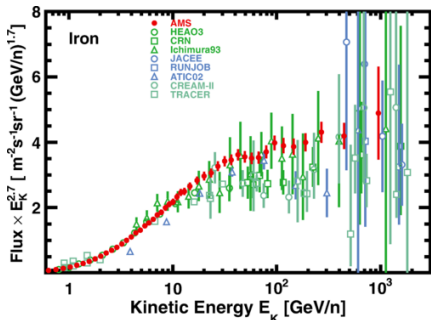
(Aguilar et al. (2021b))
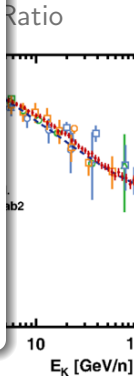
Ratio

(Aguilar et al. (2021a))

CALET Electron Flux
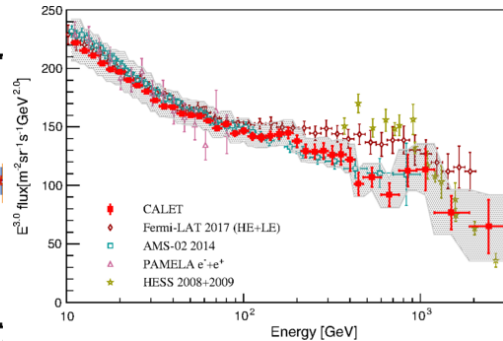
(Adriani et al. (2017))

Properties

- Energy dependence
- Elemental abundances
- Anisotropies

AMS02 Iron Flux

(Aguilar et al. (2021b))

CALET Electron Flux

(Adriani et al. (2017))

Ratio

(Aguilar et al. (2021a))

Properties

- Energy dependence
- Elemental abundances
- Anisotropies

Questions

- Galactic sources
- Transport physics
- Galactic CR distribution

Cas A
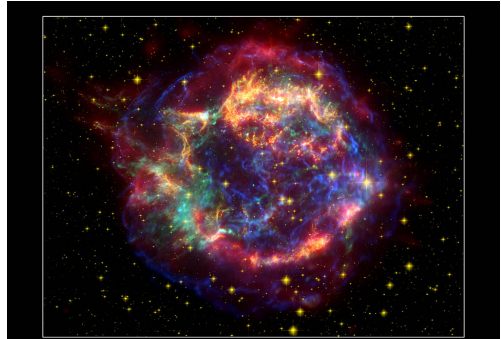
Cassiopeia A Supernova Remnant
NASA / JPL-Caltech / O. Krause (Steward Observatory)
ssc2005-14c

Spitzer Space Telescope • MIPS
Hubble Space Telescope • ACS
Chandra X-Ray Observatory

Crab Nebula

Cas A

Cassiopeia A Supernova Remnant
NASA / JPL-Caltech / O. Krause (Steward Observatory)
ssc2005-14c

Spitzer Space Telescope • MIPS
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Crab Nebula

Cas A

Gamma-Ray Binaries

──Electron/proton-proton interactions──   ──Electron-photon interactions──

Pulsar with Be star

Cometary radio emmission

Pulsar

γ-rays/ν

Pulsar

Disk outflow

Be star

Be star

A

Microquasar

Relativistic jets

Compact object of center

Massive star

Accretion disk

Ultraviolet emission and massive clumpy wind

γ-rays/ν

B

Pulsar with massive star

Pulsar

Ultraviolet emission

Massive star

γ-rays/ν

Observer

C
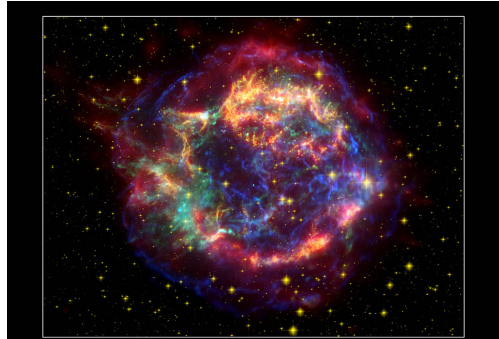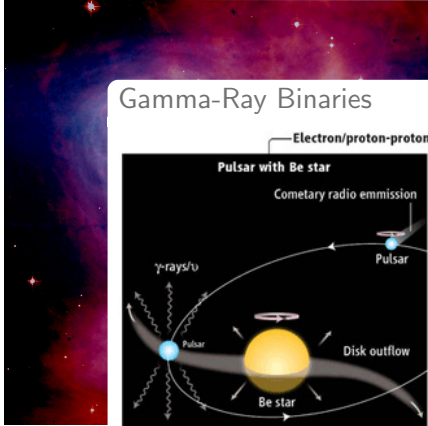
(Mirabel (2012))

Crab Nebula
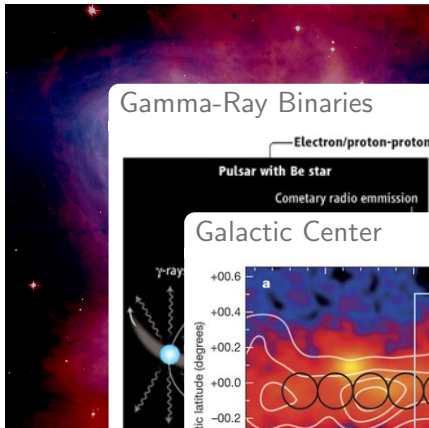
Cas A
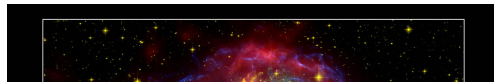
Gamma-Ray Binaries

Galactic Center
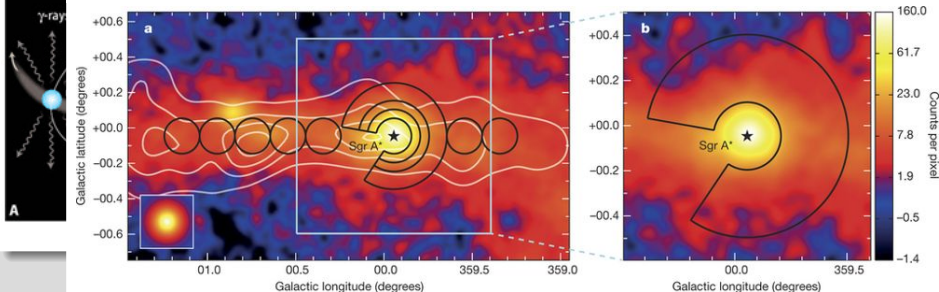
(HESS Collaboration et al. (2016))

Energy Losses

- Ionisation losses
- Coulomb losses
- Bremsstrahlung

Bremsstrahlung Losses

E_1

e

v_1

$h \cdot f = E_1 - E_2$

$+$

e E_2

v_2

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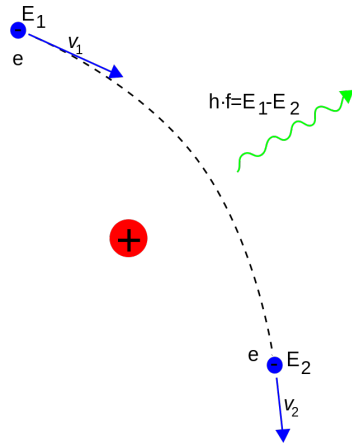
Energy Losses

- Ionisation losses
- Coulomb losses
- Bremsstrahlung

Inelastic reactions

- Spallation of particles
- Creation of secondary CRs
- $X + p \rightarrow X + p + \pi^0$

Spallation Reaction
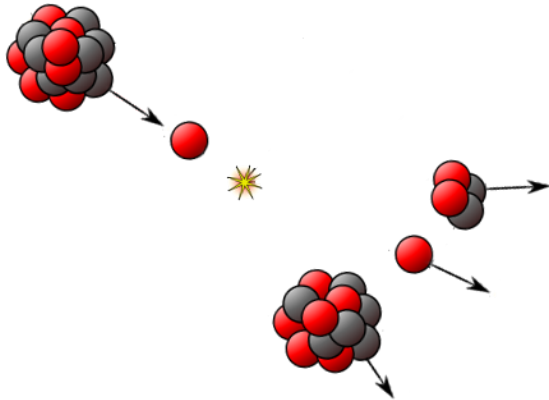
Energy Losses

- Ionisation losses
- Coulomb losses
- Bremsstrahlung
  $\rightarrow$ gamma-rays

Inelastic reactions

- Spallation of particles
- Creation of secondary CRs
- $X + p \rightarrow X + p + \pi^0$
  $\Rightarrow \pi^0 \rightarrow$ gamma rays

Spallation Reaction

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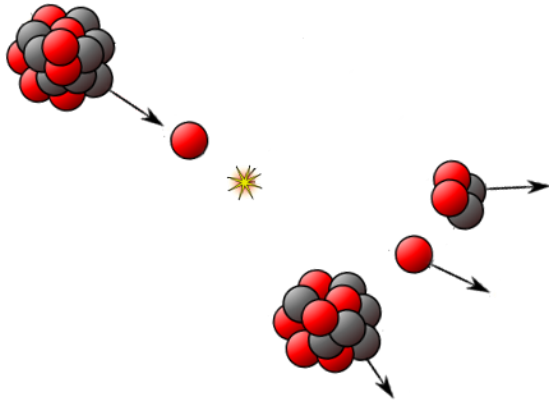
Interaction with Mag. Field

- Energy losses

Transport in ISM
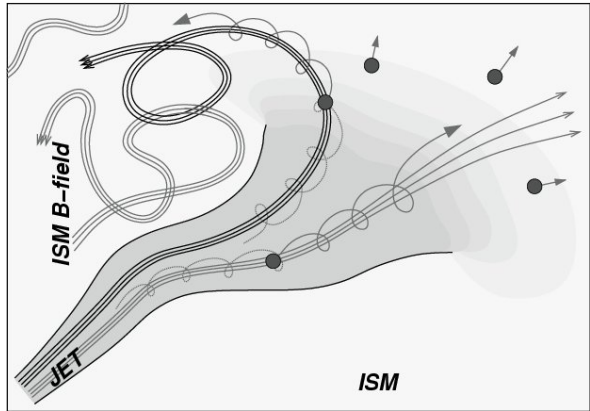
(by Heinz & Sunyaev (2002))

Interaction with Mag. Field

- Energy losses
- Field parallel motion
- Scattering

Transport in ISM

(by Heinz & Sunyaev (2002))

Interaction with Mag. Field

- Energy losses
- Field parallel motion
- Scattering

Resulting CR Motion

- Scattering $\rightarrow$ diffusion
- Gas motion $\rightarrow$ convection

Transport in ISM

(by Heinz & Sunyaev (2002))

Interaction with Mag. Field

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- Field parallel motion
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Resulting CR Motion

- Scattering $\rightarrow$ diffusion
- Gas motion $\rightarrow$ convection

Interaction with Radiation
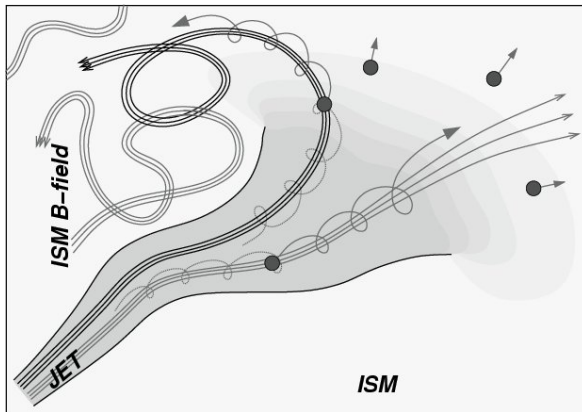
- Electrons only
- IC losses

Transport in ISM
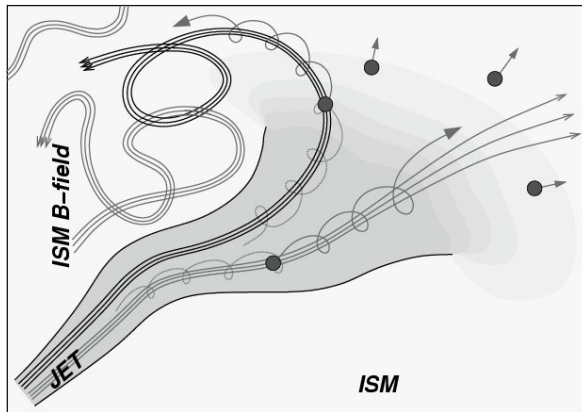
ISM B-field

JET

ISM

(by Heinz & Sunyaev (2002))
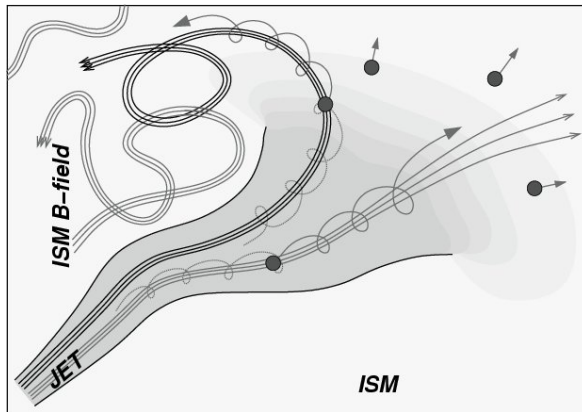
Interaction with Mag. Field

- Energy losses
- Field parallel motion
- Scattering

Resulting CR Motion

- Scattering → diffusion
- Gas motion → convection

Interaction with Radiation

- Electrons only
- IC losses
  → gamma-rays

Transport in ISM
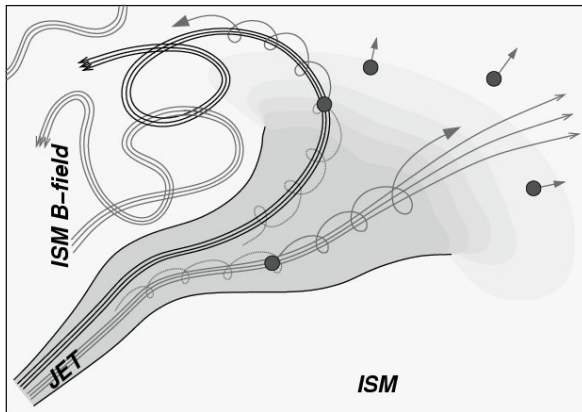
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CR Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration

CR Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration

CR-Interaction with ISM

- Spallation cross sections
- Energy loss processes
- Nuclear network
- $\leftrightarrow$ Galaxy model

CR Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration

CR-Interaction with ISM

- Spallation cross sections
- Energy loss processes
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- $\leftrightarrow$ Galaxy model

Galaxy Model

- Matter distribution
- ISRF
- Magnetic field

Spiral-Galaxy Model

(Credit: Spitzer / NASA)

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CR Transport Processes

- Convection
- Spatial Diffusion
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CR-Interaction with ISM

- Spallation cross sections
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Galaxy Model

- Matter distribution
- ISRF
- Magnetic field

Secondaries

- Secondary CRs
- Gamma rays
- Neutrinos

CR Transport Processes

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Galaxy Model

- Matter distribution
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Solution Process

CR source distribution

CR Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration
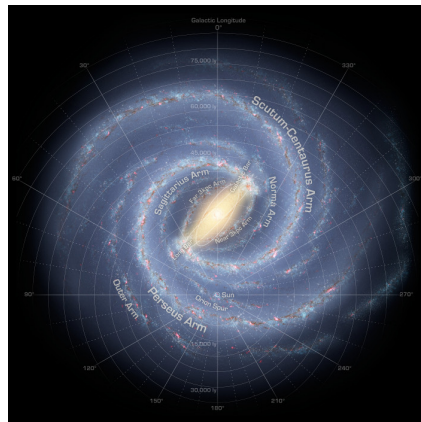
CR-Interaction with ISM

- Spallation cross sections
- Energy loss processes
- Nuclear network
- ↔ Galaxy model

Galaxy Model

- Matter distribution
- ISRF
- Magnetic field

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- Secondary CRs
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Solution Process

CR source distribution

⇓

Transport solver – PICARD

CR Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration

CR Distribution

Secondaries

- Secondary CRs
- Gamma rays
- Neutrinos

Solution Process

CR source distribution

$\Downarrow$

Transport solver – PICARD

$\Downarrow$

CR distribution

CR Transport Processes

- Convection
- Spatial Diffusion
- Diffusive reacceleration

Gamma-Ray Emission

Secondaries

- Secondary CRs
- Gamma rays
- Neutrinos

Solution Process

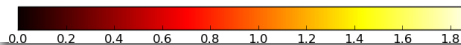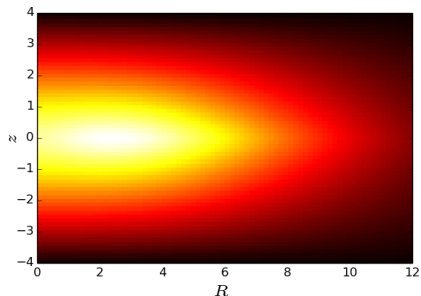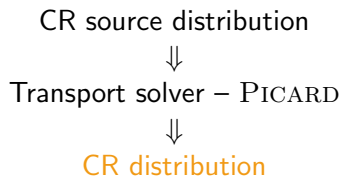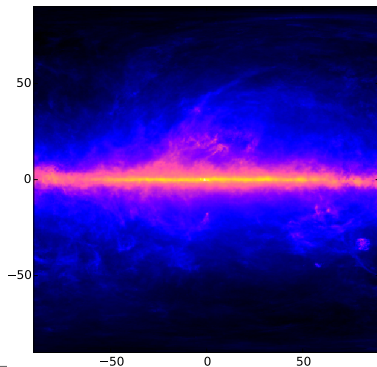CR source distribution
$$\Downarrow$$
Transport solver – Picard
$$\Downarrow$$
CR distribution
$$\Downarrow$$
Gamma ray emission

Transport Equation

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

Transport Equation

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

Transport Parameters

- Source distribution $q(\vec{r}, p)$
- Diffusion tensor $\mathcal{D}$
- Convection $\vec{v}$
- Momentum diffusion D_{pp}
- Energy losses $\dot{p}$
- Spallation τ_f
- Radioactive decay τ_r

Transport Equation

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Usual Parameters

- Diffusion *coefficient* D_0
- Rigidity exponent δ
- Alfvén speed v_A
- Halo height z_H
- Injection index ν
- Convection $v_0, \frac{dv}{dz}$
- Radial / vertical scaleheights

Transport Equation

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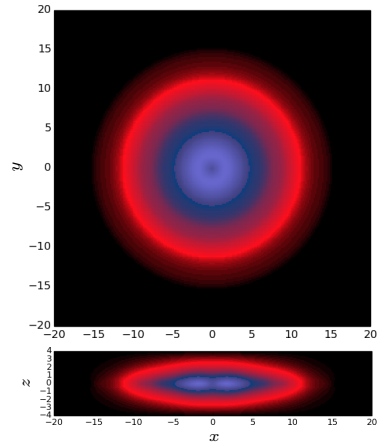- Radioactive decay τ_r

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- ...tion $v_0, \frac{dv}{dz}$
- ... / vertical scaleheights

Possible Improvements
→ Transport & Galaxy model
→ Here: focus on sources

Axially Symmetric Model

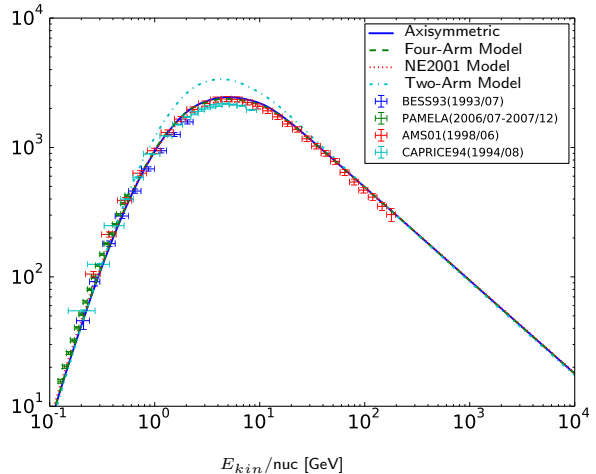(Kissmann et al. (2015))

Four-Arm Model

(Kissmann et al. (2015))

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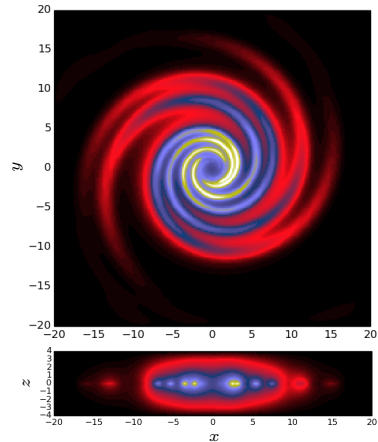
CR Data

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

CR Proton Flux

(Kissmann et al. (2015))

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CR Data

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  - ^{10}Be/^{9}Be Ratio ✓
  - B/C Ratio

Be-Ratio
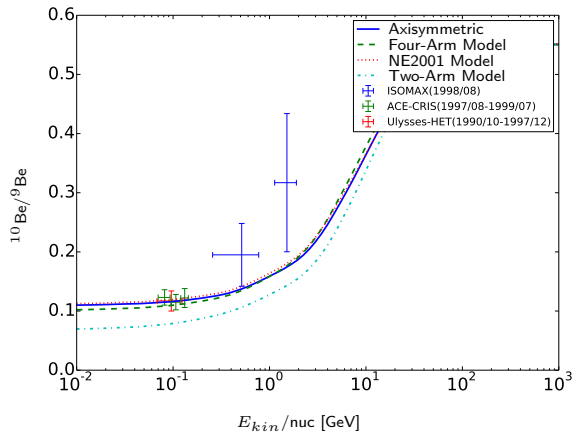
(Kissmann et al. (2015))

CR Data

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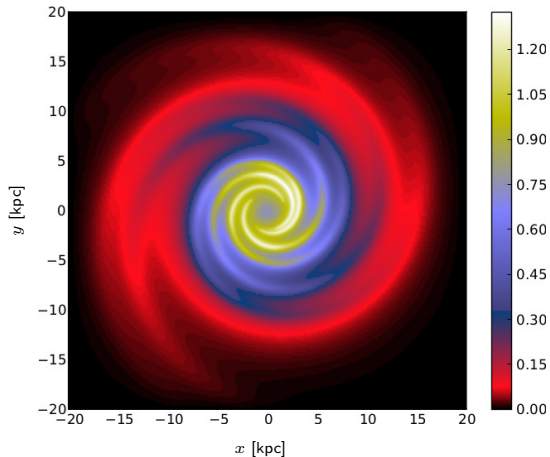 - $^{10}Be/^{9}Be$ Ratio ✓
  - B/C Ratio ✓

B/C Ratio
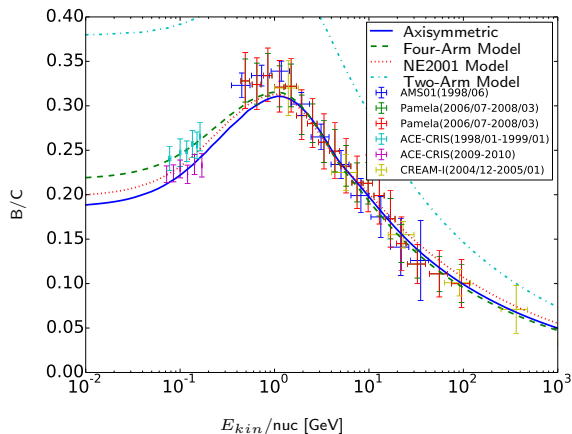
(Kissmann et al. (2015))

CR Data

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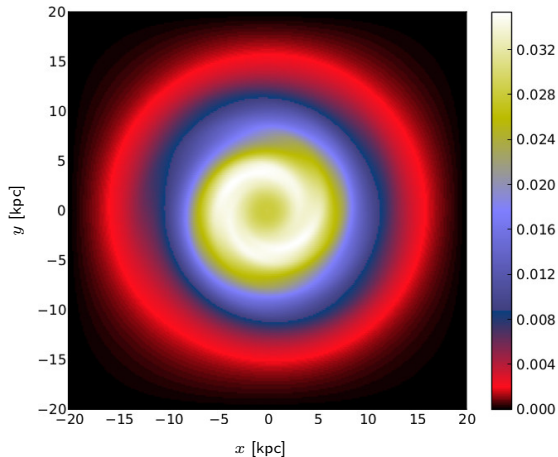 - $^{10}Be/^9Be$ Ratio ✓
  - B/C Ratio ✓

Distribution of Carbon

(Kissmann et al. (2015))

CR Data

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

Distribution of Boron

(Kissmann et al. (2015))

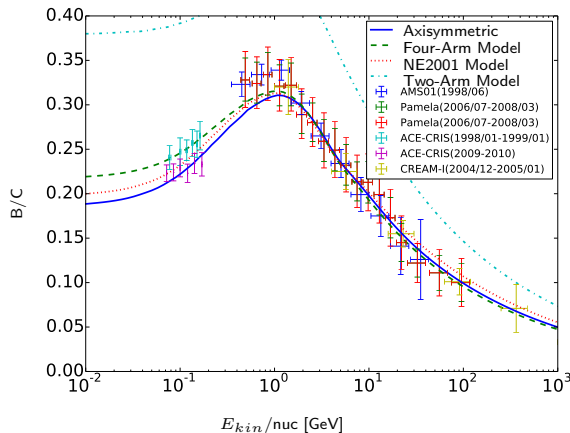**CR Data**

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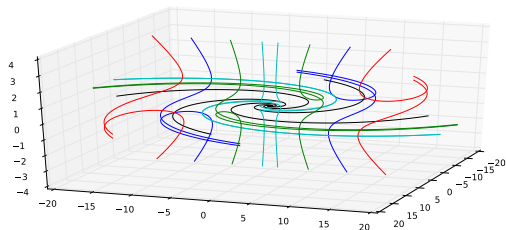 - B/C Ratio ✓

Spiral-Arm Models

1. Adapted parameters
   - Change of D and v_A
   - Relative change $\sim 20\%$
2. Shift of source pattern
- Fit possible
- Spatial variation
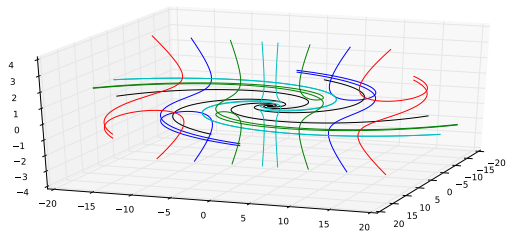
B/C Ratio

(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)

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X-shape Magnetic Field

Diffusion Models

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

Observation

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

X-shape Magnetic Field

Diffusion Models

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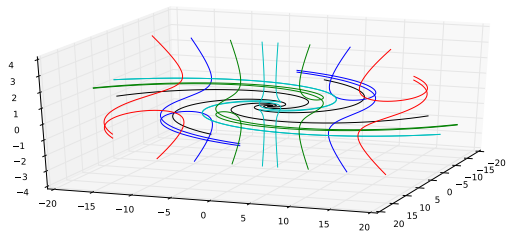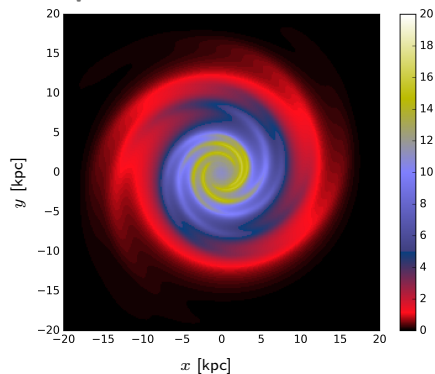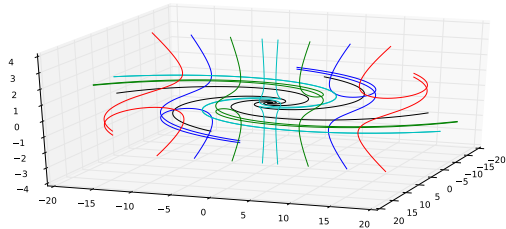3. Along X-shape magnetic field by Ferrière and Terral (2014)

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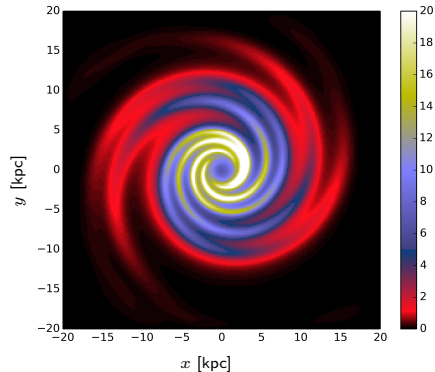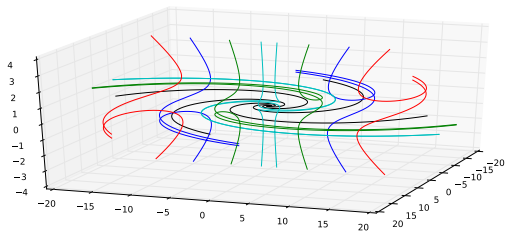## Isotropic Diffusion

X-shape Magnetic Field

Diffusion Models

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X-shape Magnetic Field

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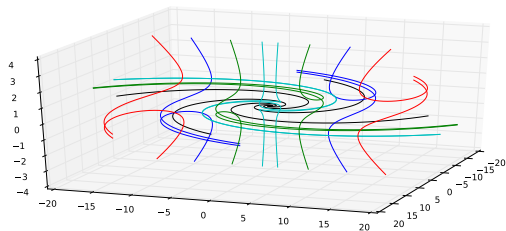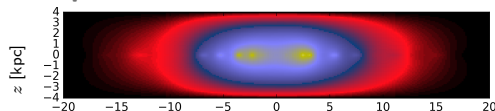
Isotropic Diffusion
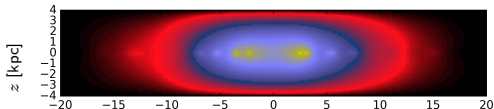
X-shape Magnetic Field

Diffusion Models

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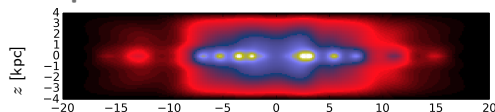3. Along X-shape magnetic field by Ferrière and Terral (2014)

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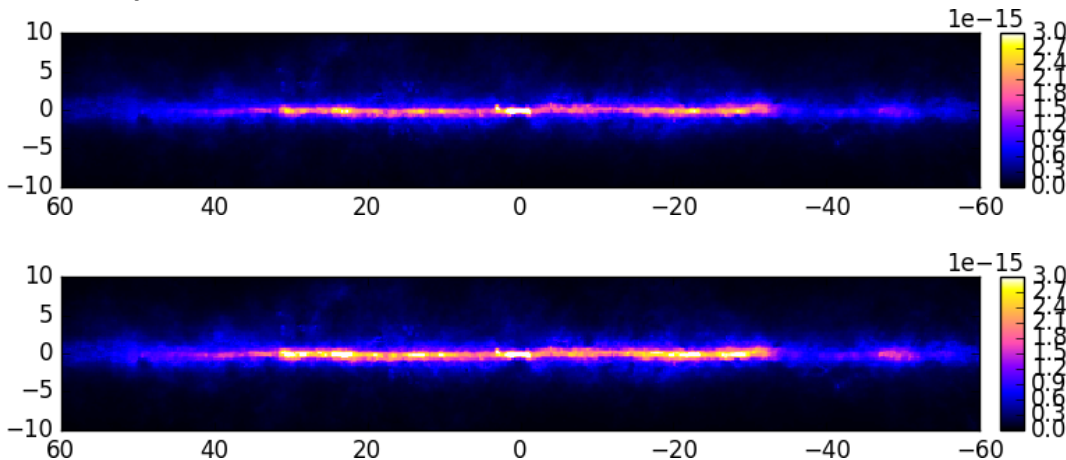- Fit possible for X-shape diffusion ($>$ factor 2)

Isotropic Diffusion
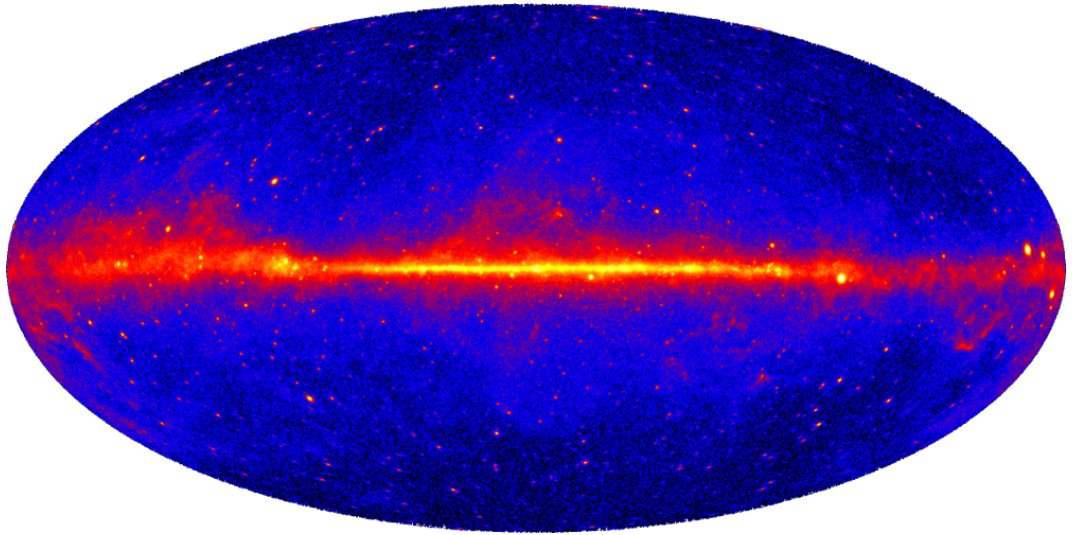

X-shape Diffusion
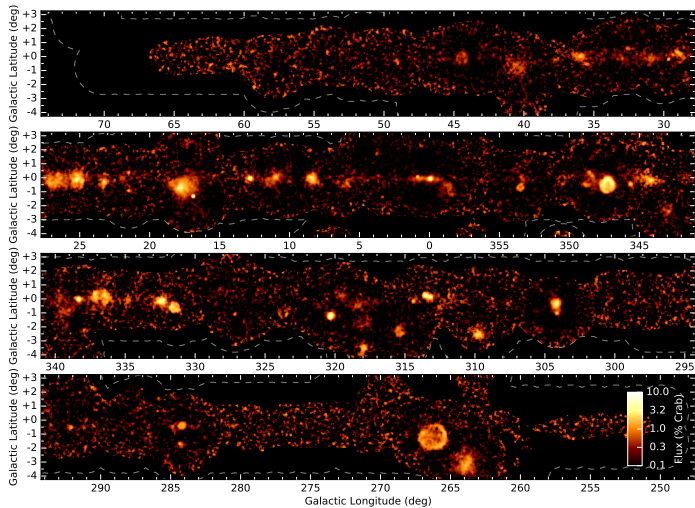
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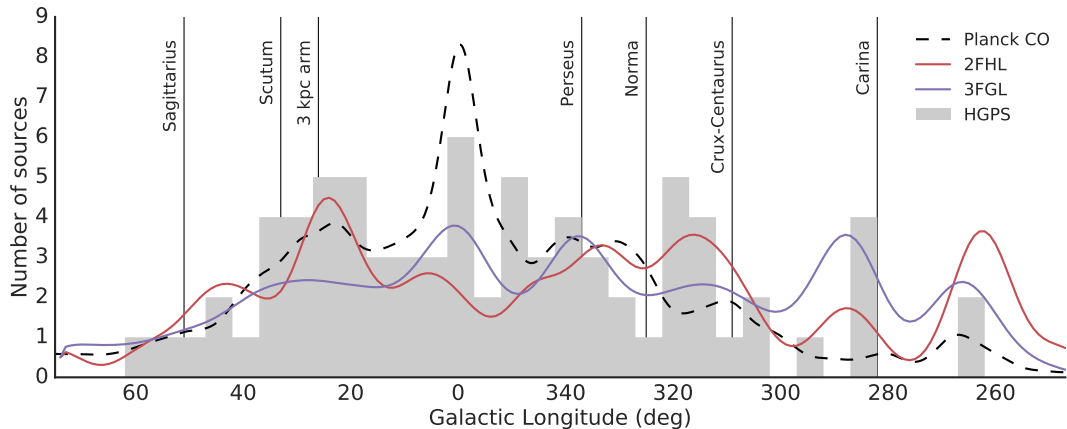Gamma-ray Emission

(Picard (2017))

5 Years of Fermi Data

H.E.S.S. Galactic Plane Survey

(H. E. S. S. Collaboration et al. (2018))

H.E.S.S. Galactic Plane Survey and Spiral Arms

(H. E. S. S. Collaboration et al. (2018))

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Active CR Sources

- Use observations
- Here: HGPS

Number of HGPS Sources

(H. E. S. S. Collaboration et al. (2018))
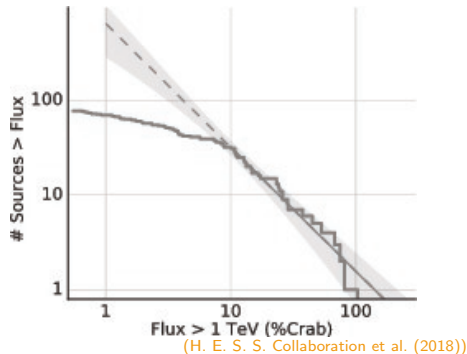
HGPS Sensitivity Limits
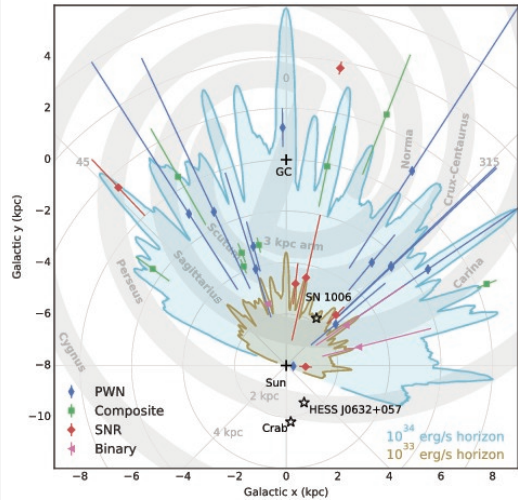
PWN
Composite
SNR
Binary

10^{34} erg/s horizon
10^{33} erg/s horizon

(H. E. S. S. Collaboration et al. (2018))

Observed Sources

- HGPS catalog (relative fluxes)
- Identified source (distance)
- Distinction: leptonic $\leftrightarrow$ hadronic

Implemented Source Model

Observed Sources

- HGPS catalog (relative fluxes)
- Identified source (distance)
- Distinction: leptonic $\leftrightarrow$ hadronic

Simulated Source Population

- Model by Steppa and Egberts (2020)
- Distribution from Steiman-Cameron et al. (2010)
- Replace simulated sources by observed ones.

Monte-Carlo Source Distribution
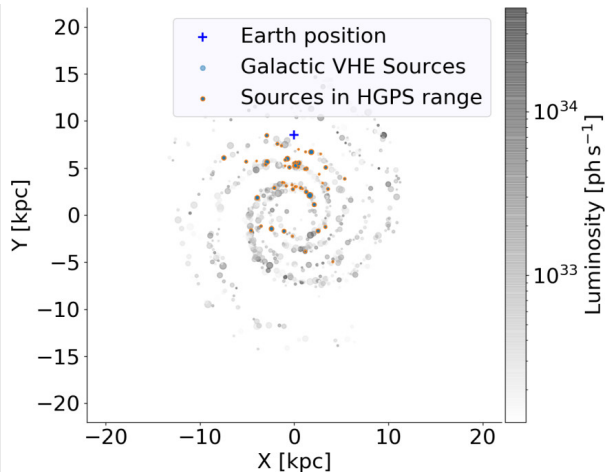

(Steppa and Egberts (2020))

Observed Sources

- Hgps catalog (relative fluxes)
- Identified source (distance)
- Distinction: leptonic $\leftrightarrow$ hadronic
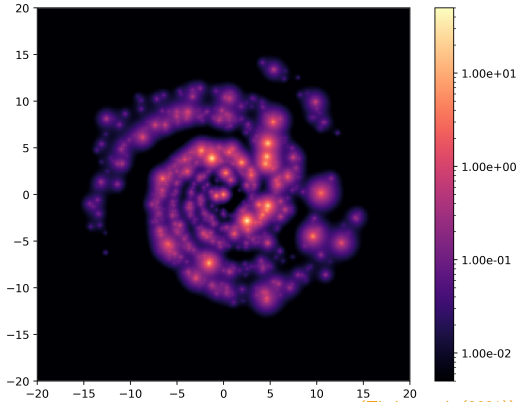
Simulated Source Population

- Model by Steppa and Egberts (2020)
- Distribution from Steiman-Cameron et al. (2010)
- Replace simulated sources by observed ones.
- Use measured $\log N - \log S$ $\rightarrow$ only high-energy sources

Number of Sources

(Steppa and Egberts (2020))
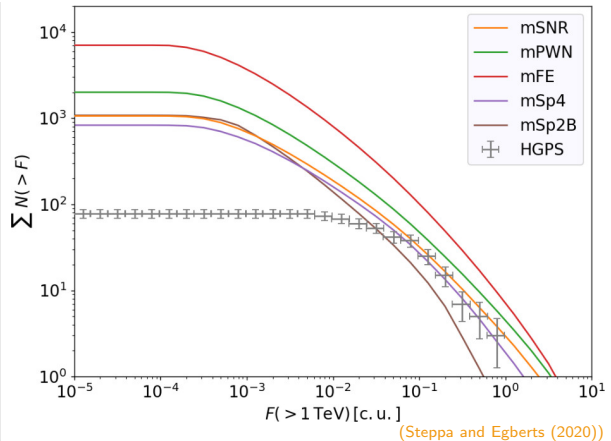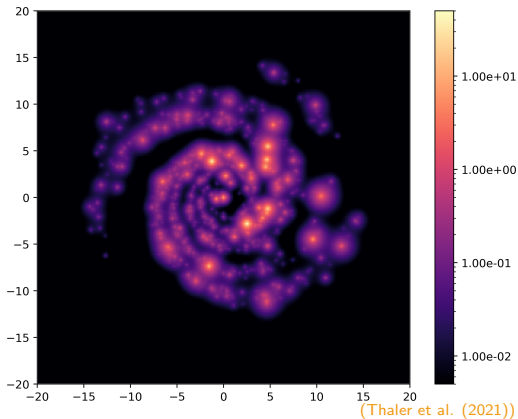
Electrons in Galactic Plane

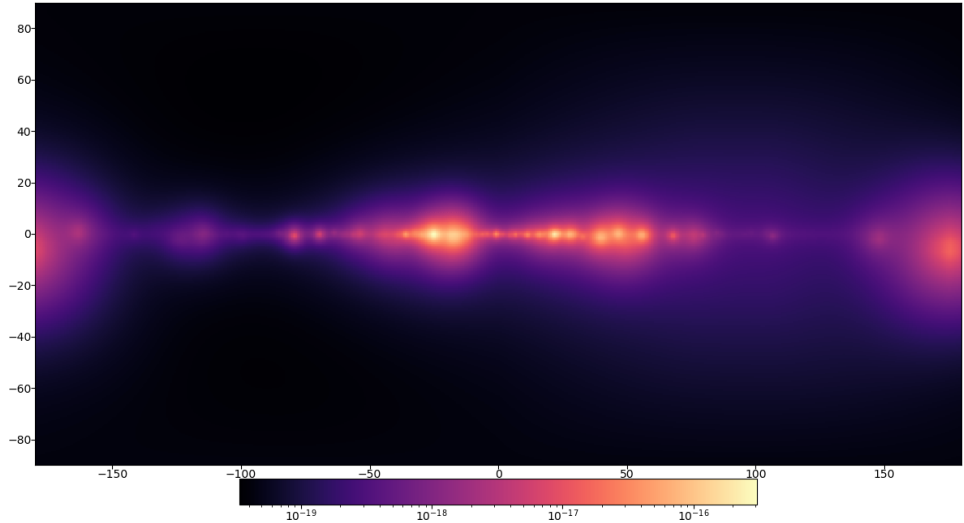(Thaler et al. (2021))

Electrons in Galactic Plane

Carbon in Galactic Plane
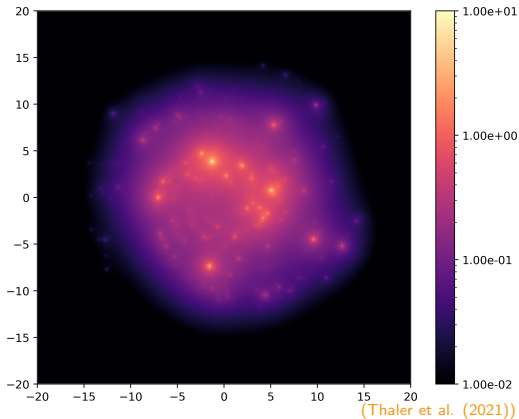
(Thaler et al. (2021))

Inverse-Compton Emission at 1.6 TeV

(Thaler et al. (2021))
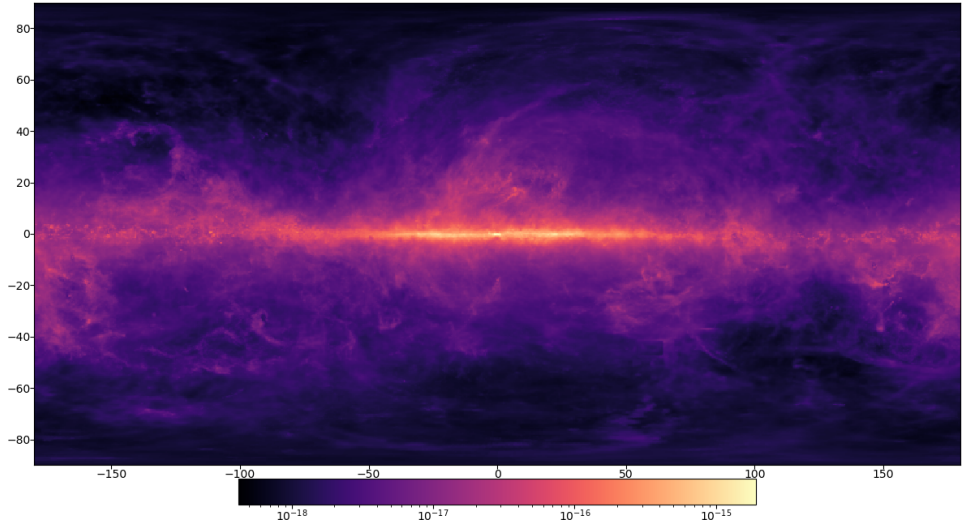
Pion-Decay Emission at 1.6 TeV
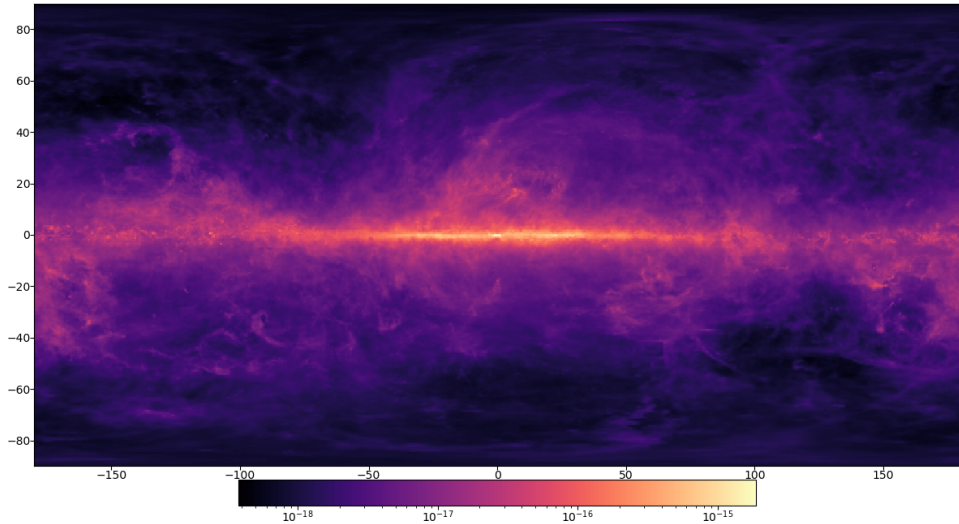
(Thaler et al. (2021))

Total Gamma-Ray Emission at 1.6 TeV

(Thaler et al. (2021))

Typical Resolution (130 pc)
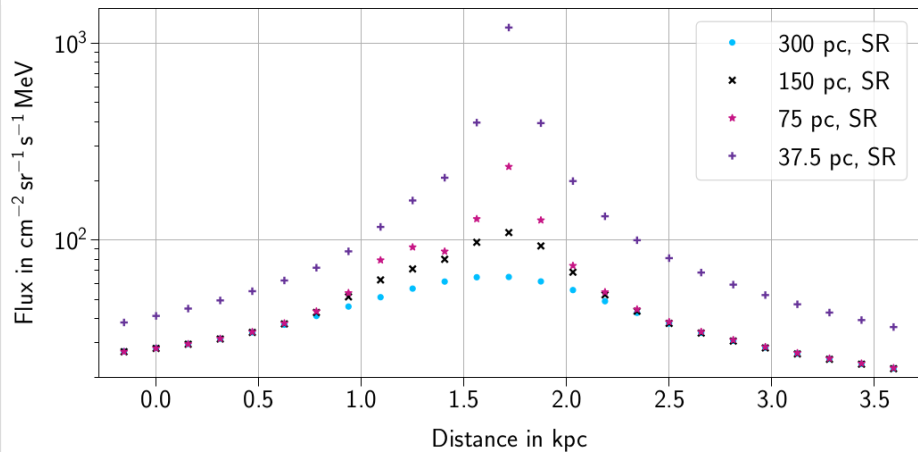
(Zangerl (2021))

Typical Resolution (130 pc)
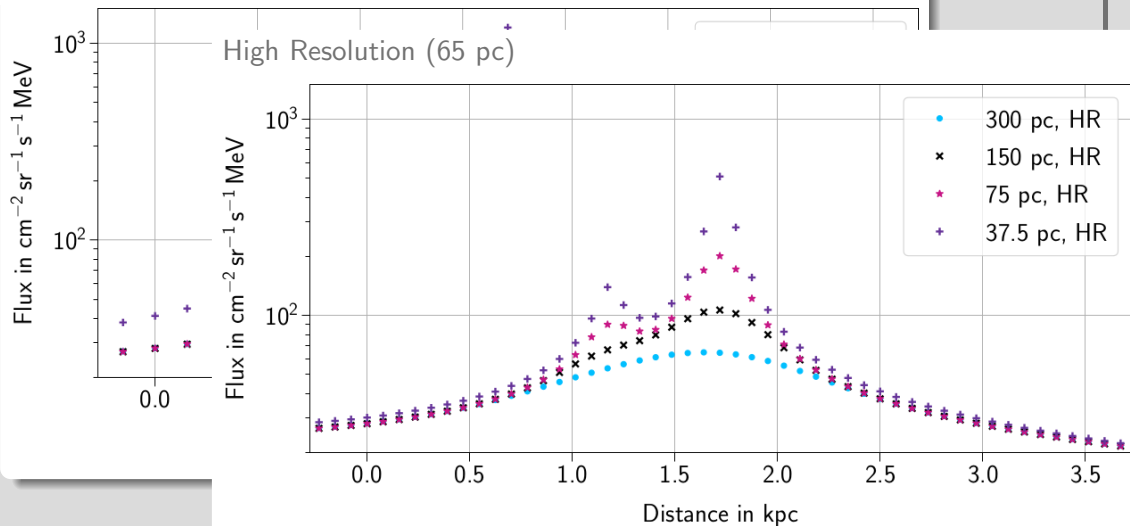
High Resolution (65 pc)

(Zangerl (2021))

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Outlook: Galactic CR Transport

- 3D Structure
- Galactic Center
- Dynamical Evolution
- Anisotropic Transport
- Individual Sources

Outlook: Galactic CR Transport

- 3D Structure
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- Dynamical Evolution
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- Individual Sources

Individual Sources

- Here: $>$TeV energies
- Diffuse Emission for CTA?
- To Do:
  - Normalization
  - $\log N - \log S$
  - Near-Source Transport
  - Anisotropic Diffusion

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Outlook: Galactic CR Transport

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Individual Sources

- Here: $>$TeV energies
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- To Do:
  - Normalization
  - $\log N - \log S$
  - Near-So
  - Anisotro

Transport Near Geminga

Transport Near Geminga

(López-Coto and Giacinti (2018))

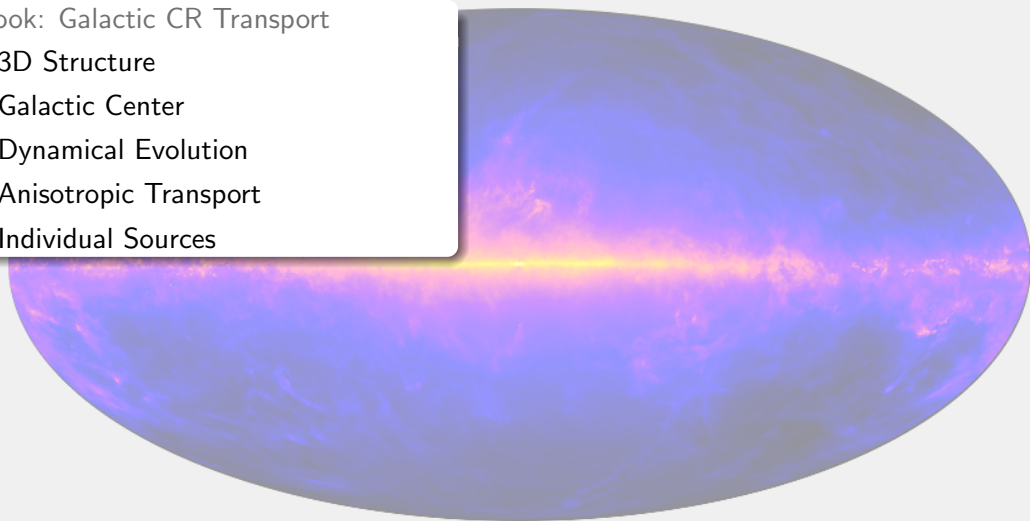(Hooper et al. (2017))

Outlook: Galactic CR Transport

- 3D Structure
- Galactic Center
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- Individual Sources

PICARD

- Accuracy of solver
- Energies up to the knee
- (Locally) high resolution
- Locally changing diffusion
- Neutrino messenger*

Individual Sources

- Here: >TeV energies
- Diffuse Emission for CTA?
- To Do:
    - Normalization
    - $\log N - \log S$
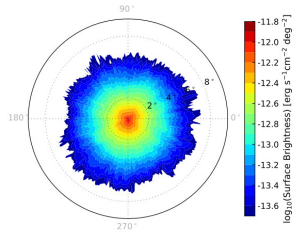   - Near-Source Transport
    - Anisotropic Diffusion
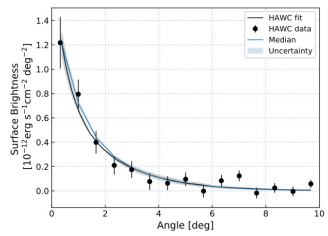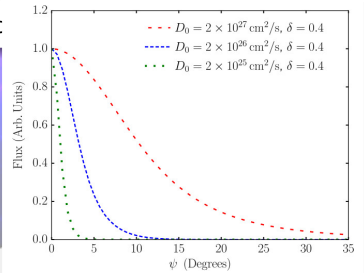
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