RUHR UNIVERSITÄT BOCHUM RUB

rls Rosa Luxemburg Stiftung

RAPP Center

A novel analytical model of the magnetic field configuration in the Galactic Center explaining the diffuse gamma-ray emission

Mehmet Guenduez

Julia Becker Tjus

Katia Ferrière

Ralf-Jürgen Dettmar

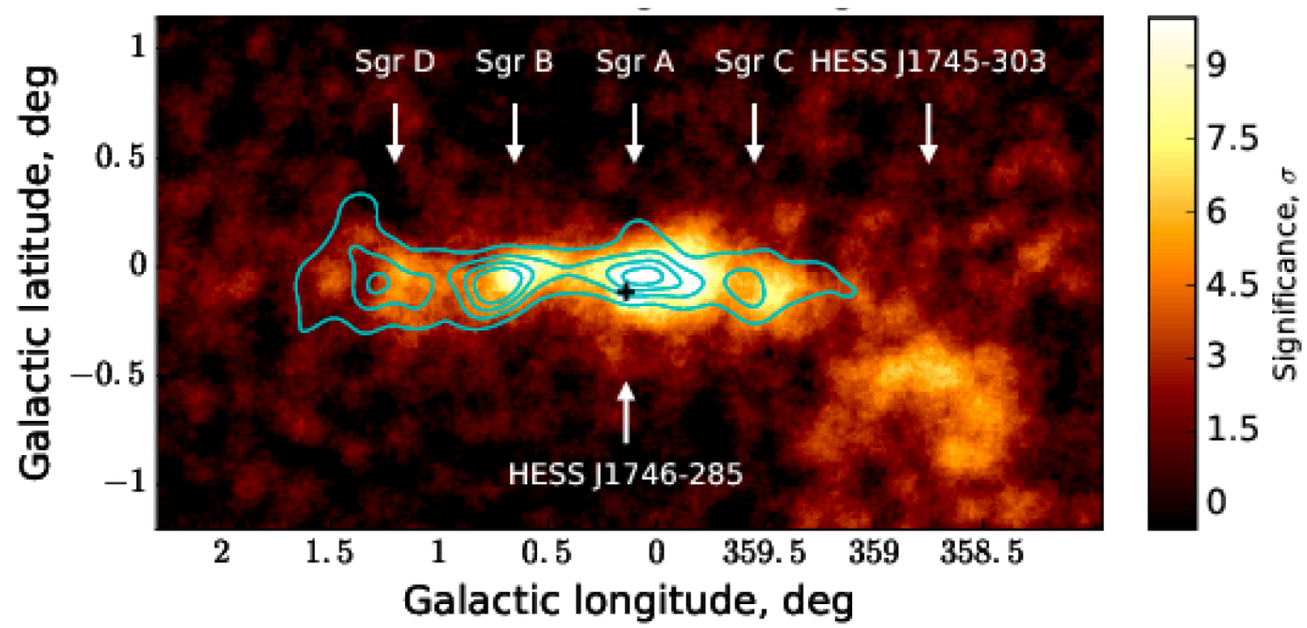
Dominik J. Bomans

Madison

July 26th 2019

Motivation:

- In April 2016 the H.E.S.S. Collaboration reported the detection of a high energy diffuse gamma-ray flux in the Galactic Center from some GeV up to tens of TeV
- No significant allusion to a cut-off

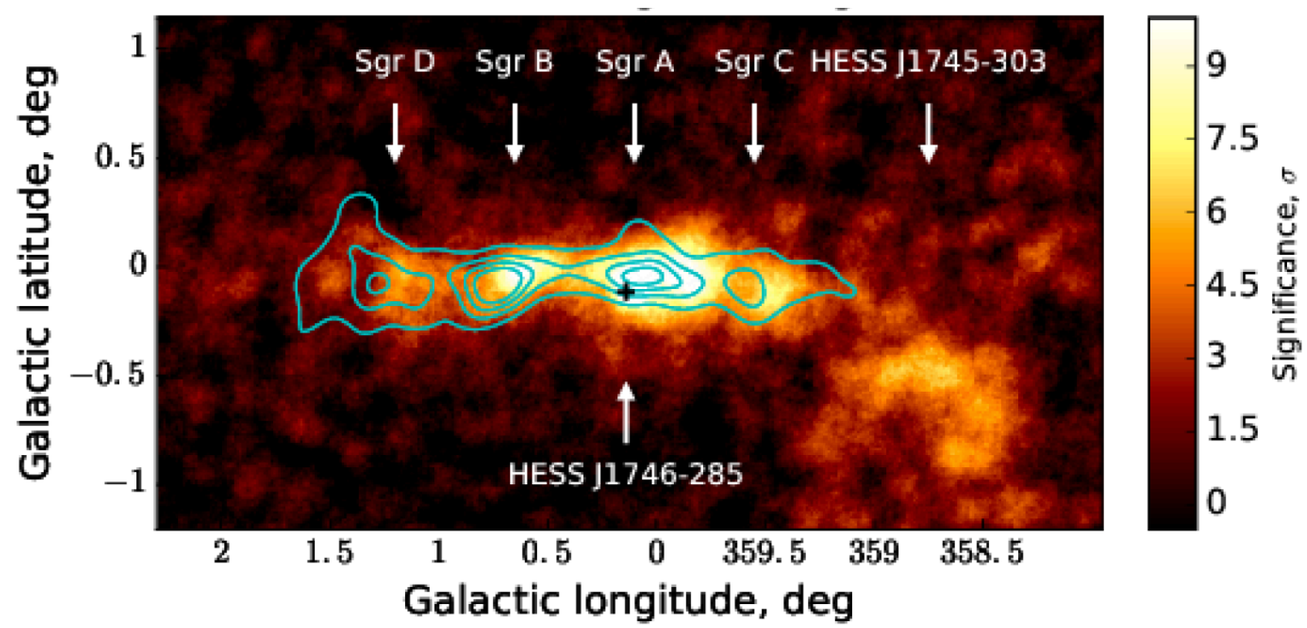


[HESS, A&A, 612, A9, 2018]

Mehmet.Guenduez@RUB.de

Motivation:

- In April 2016 the H.E.S.S. Collaboration reported the detection of a high energy diffuse gamma-ray flux in the Galactic Center from some GeV up to tens of TeV
- No significant allusion to a cut-off



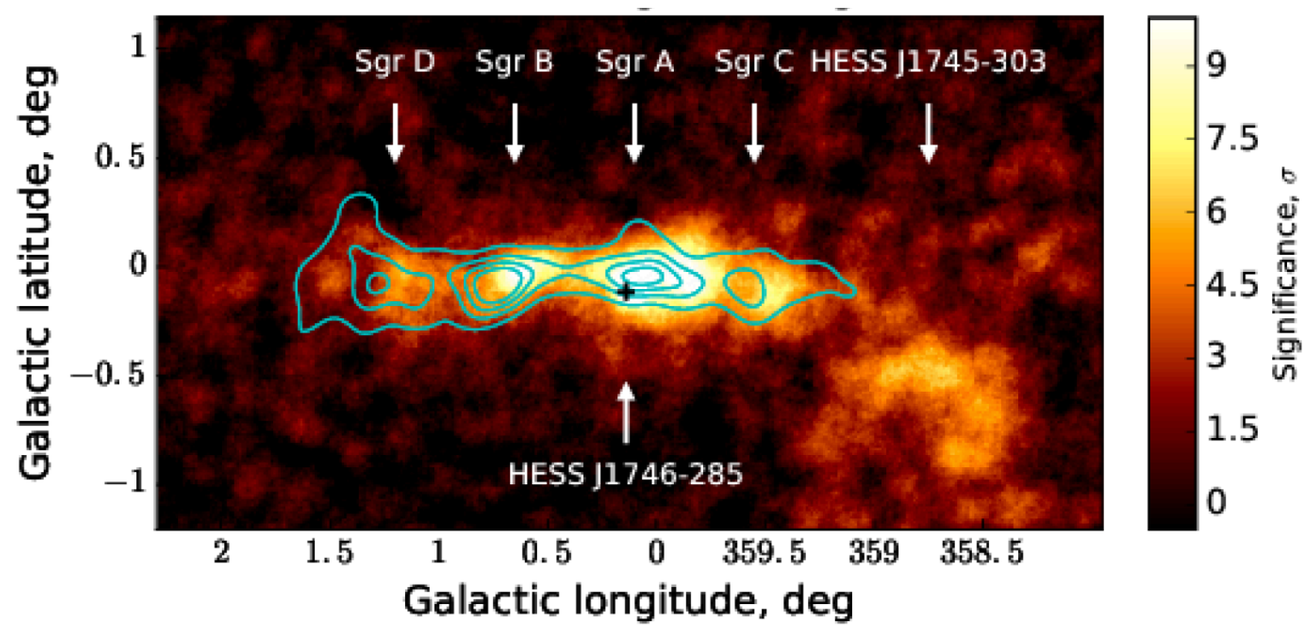
[HESS, A&A, 612, A9, 2018]

PeVatron accelerator

Mehmet.Guenduez@RUB.de

Motivation:

- In April 2016 the H.E.S.S. Collaboration reported the detection of a high energy diffuse gamma-ray flux in the Galactic Center from some GeV up to tens of TeV
- No significant allusion to a cut-off



[HESS, A&A, 612, A9, 2018]

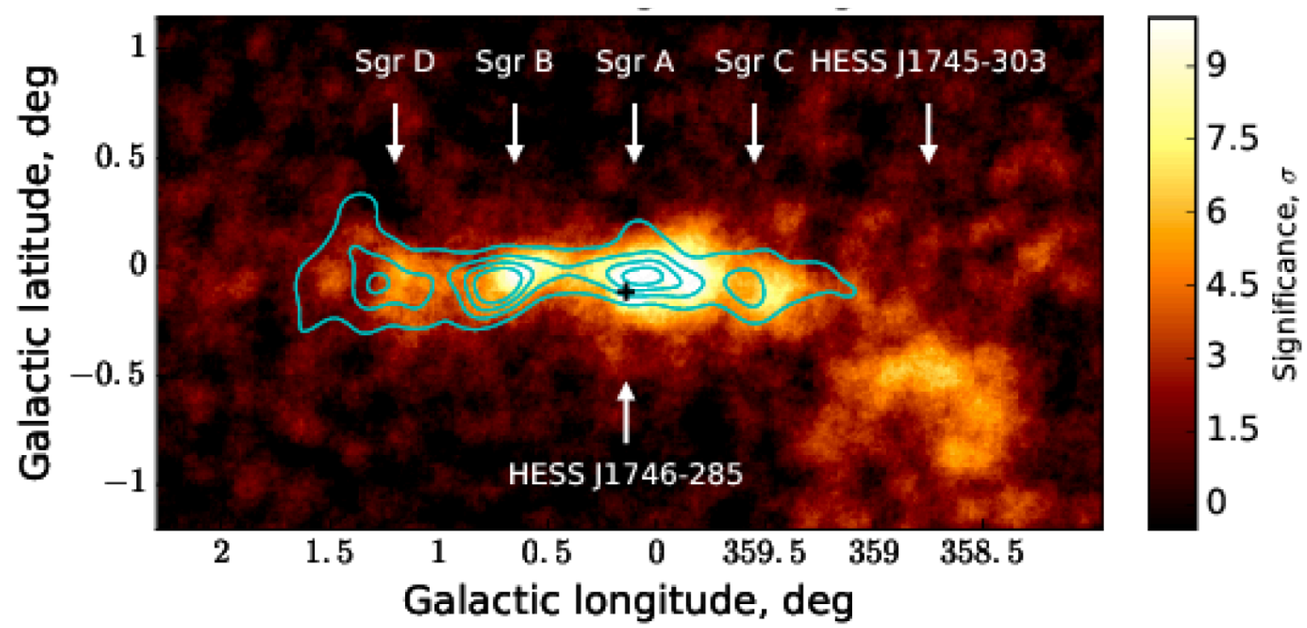
PeVatron accelerator

Semi-analytical model

Mehmet.Guenduez@RUB.de

Motivation:

- In April 2016 the H.E.S.S. Collaboration reported the detection of a high energy diffuse gamma-ray flux in the Galactic Center from some GeV up to tens of TeV
- No significant allusion to a cut-off



[HESS, A&A, 612, A9, 2018]

PeVatron accelerator

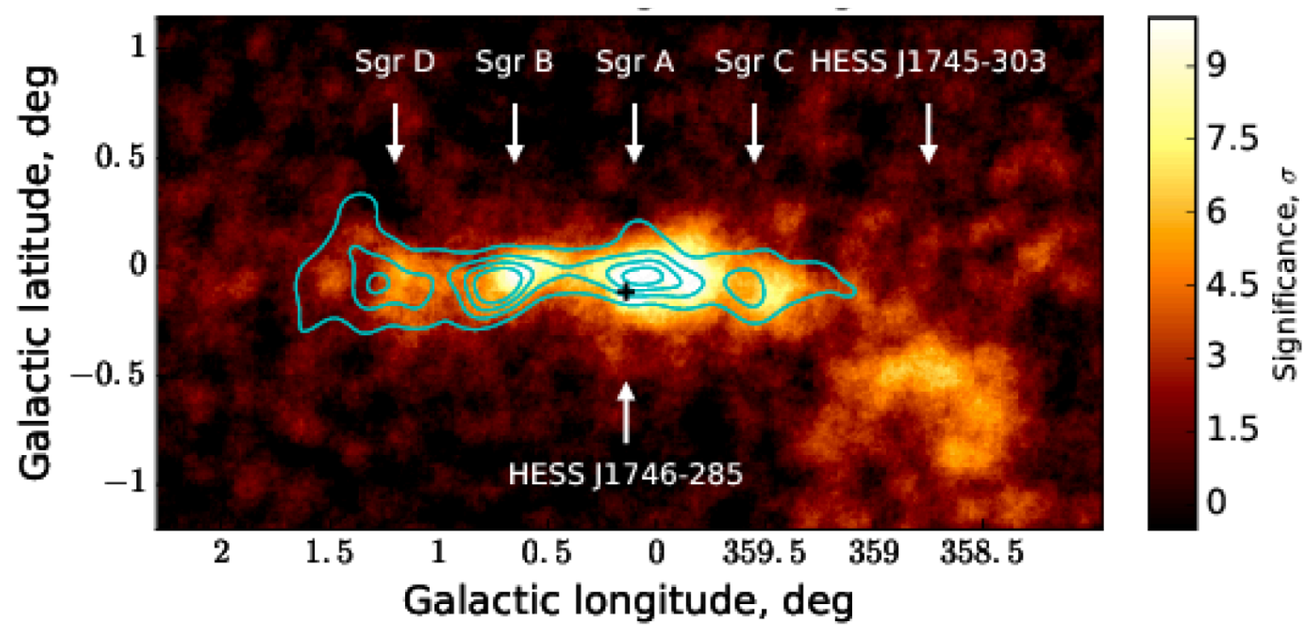
Semi-analytical model

- Diffusion with Kolmogorov spectrum
- spatially and energy dependent continuous loss and source distribution
- static and spherically symmetric
- injection at the center
- Proton-proton interaction

Mehmet.Guenduez@RUB.de

Motivation:

- In April 2016 the H.E.S.S. Collaboration reported the detection of a high energy diffuse gamma-ray flux in the Galactic Center from some GeV up to tens of TeV
- No significant allusion to a cut-off

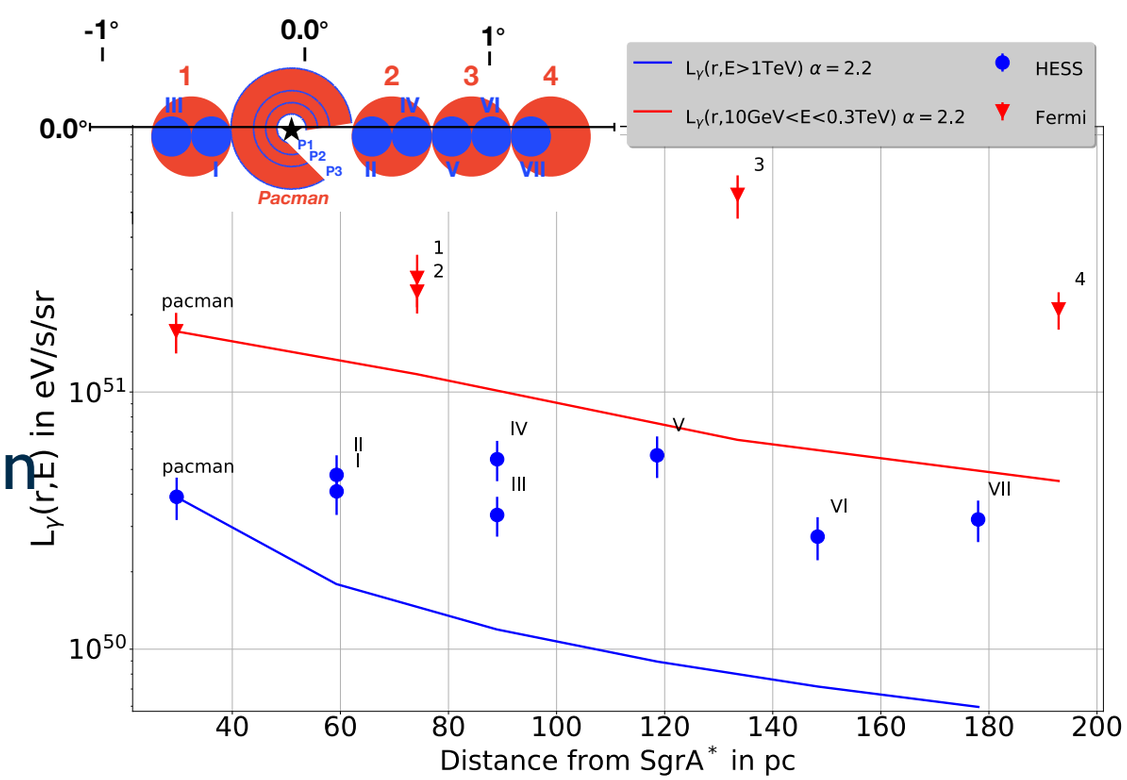


[HESS, A&A, 612, A9, 2018]

PeVatron accelerator

Semi-analytical model

- Diffusion with Kolmogorov spectrum
- spatially and energy dependent continuous loss and source distribution
- static and spherically symmetric
- injection at the center
- Proton-proton interaction



Mehmet.Guenduez@RUB.de

Motivation:

Open questions:

Mehmet.Guenduez@RUB.de

Motivation:

Open questions:

- How many sources are sufficient for the observation?
- How much energy is necessary?
- What is the impact of the ambient conditions?

Mehmet.Guenduez@RUB.de

Problem:

- Larger discrepancies at:
  1. higher longitudes
  2. lower energies

Mehmet.Guenduez@RUB.de

Problem:

- Larger discrepancies at:
  1. higher longitudes
  2. lower energies

→

- dominant horizontal magnetic field
- additional sources?

Mehmet.Guenduez@RUB.de

Problem:

- Larger discrepancies at:
  1. higher longitudes
  2. lower energies

→

- dominant horizontal magnetic field
- additional sources?

Move away from semi-analytical approximation

Mehmet.Guenduez@RUB.de

Problem:

- Larger discrepancies at:
  1. higher longitudes
  2. lower energies

→

- dominant horizontal magnetic field
- additional sources?

Move away from semi-analytical approximation

↓

A novel model of the magnetic field configuration and strength in the Galactic Center

Mehmet.Guenduez@RUB.de

Problem:

- Larger discrepancies at:
  1. higher longitudes
  2. lower energies

→

- dominant horizontal magnetic field
- additional sources?

Move away from semi-analytical approximation

↓

A novel model of the magnetic field configuration and strength in the Galactic Center

↓

Accurate modeling of the gas distribution

Mehmet.Guenduez@RUB.de

Gas distribution

An accurate 3D distribution has not been modeled yet!

Mehmet.Guenduez@RUB.de

Gas distribution

An accurate 3D distribution has not been modeled yet!

New model

Mehmet.Guenduez@RUB.de

Gas distribution

An accurate 3D distribution has not been modeled yet!

Can be split into 3 components:

New model →

1. diffuse medium [Ferrière et al, A&A, 467,611-627, 2007]
2. 10 pc around SgrA* [Ferrière, A&A,540, A50, 2012]
3. molecular clouds

Mehmet.Guenduez@RUB.de

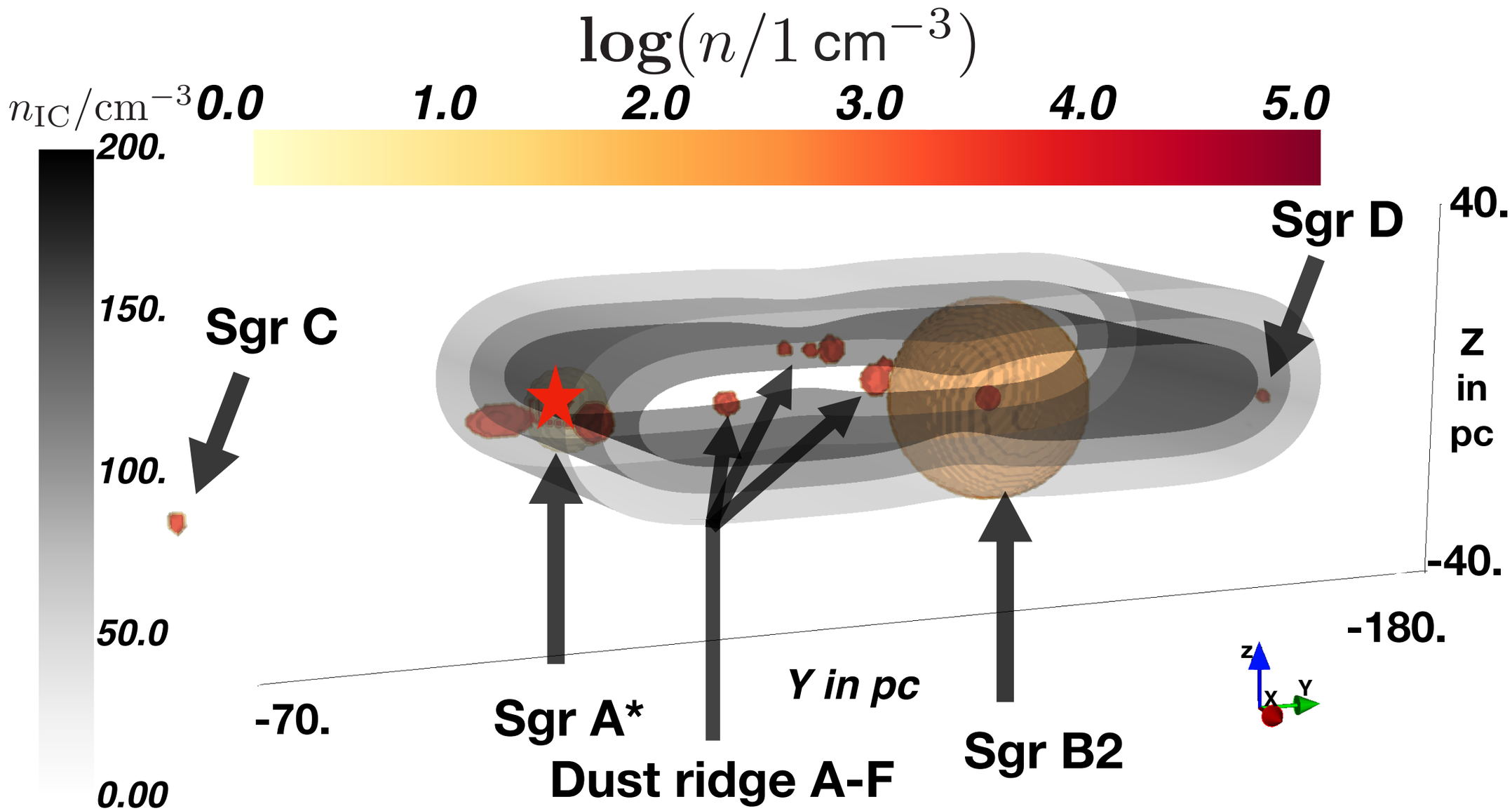
Gas distribution

An accurate 3D distribution has not been modeled yet!

Can be split into 3 components:

New model →

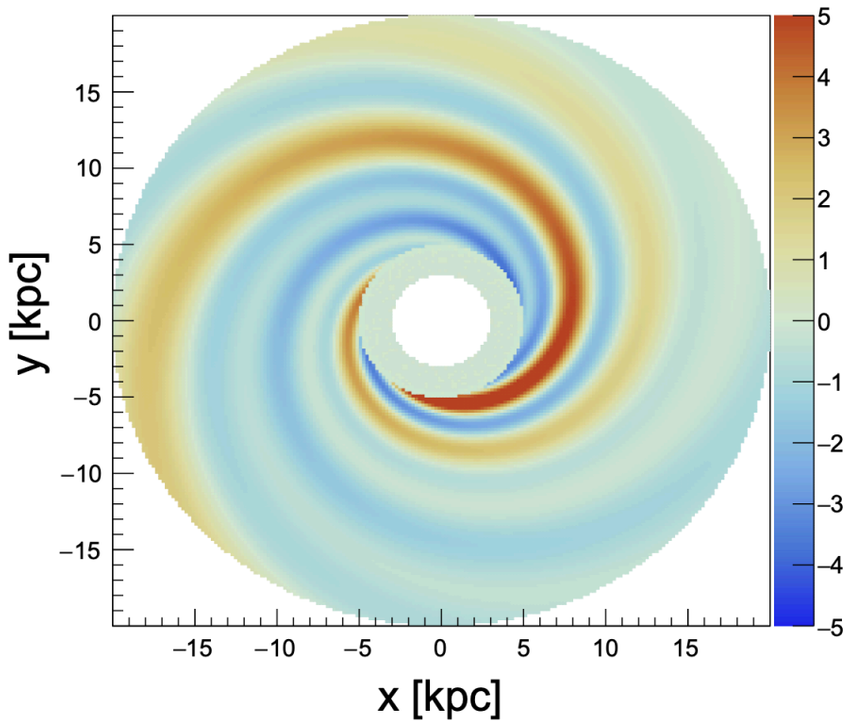
1. diffuse medium [Ferrière et al, A&A, 467,611-627, 2007]
2. 10 pc around SgrA* [Ferrière, A&A,540, A50, 2012]
3. molecular clouds



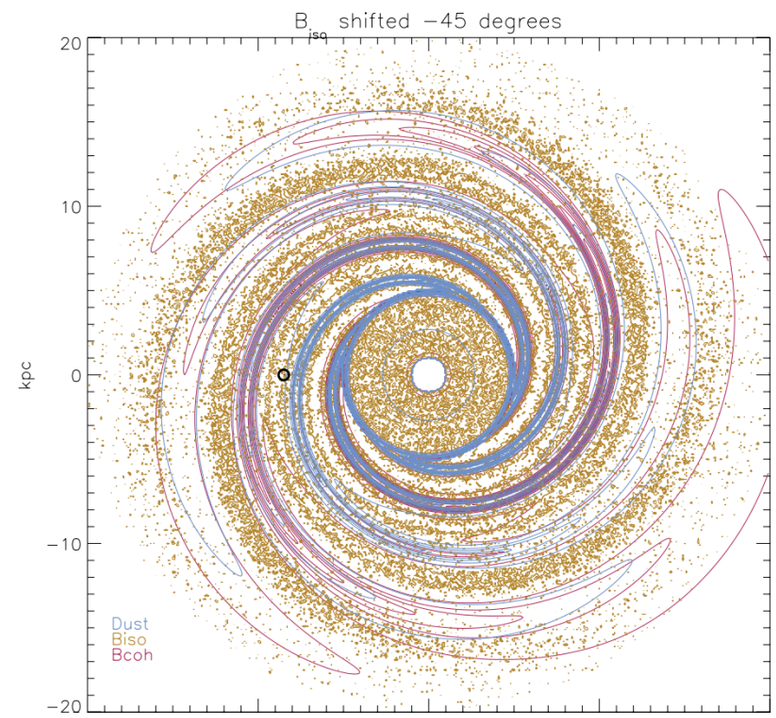
Mehmet.Guenduez@RUB.de

Magnetic Field in the GC

Status of research:



[Unger & Farrar, EPJWC, 210, 4005, 2019]



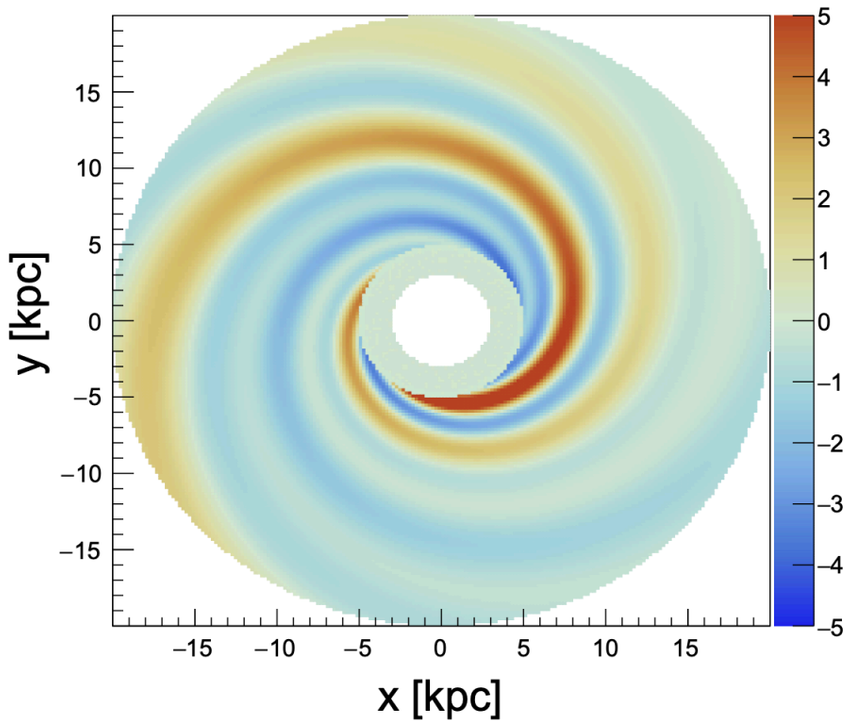
[Jaffe et al., MNRAS, 431, 683, 2013]

...

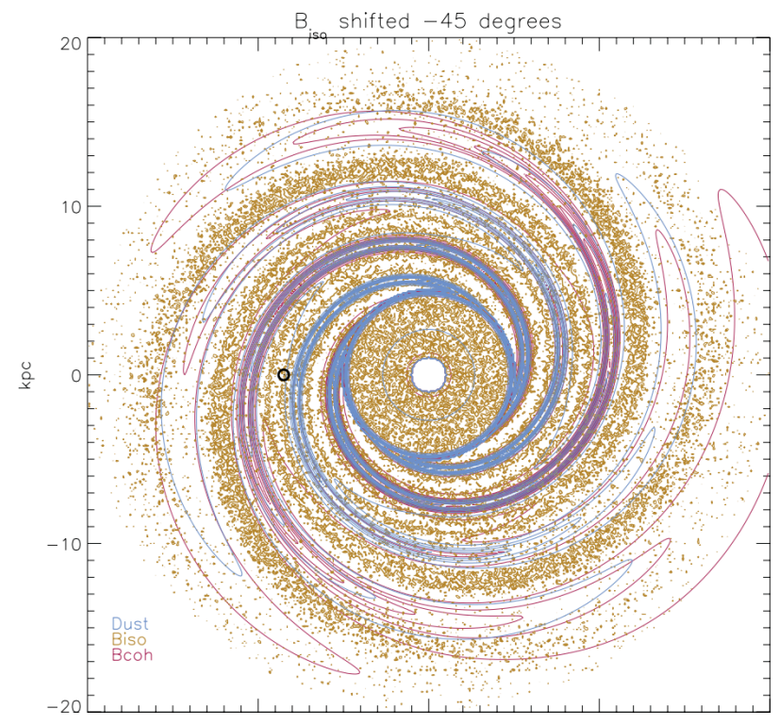
Mehmet.Guenduez@RUB.de

Magnetic Field in the GC

Status of research:

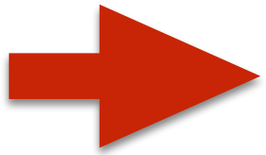


[Unger & Farrar, EPJWC, 210, 4005, 2019]



[Jaffe et al., MNRAS, 431, 683, 2013]

...



lack in the Galactic Center

Mehmet.Guenduez@RUB.de

Magnetic Field in the GC- *GBFD19*

- Variation range between ~1e-5 G and ~5e-3G
- **Large-scale** magnetic field in the GC initially **poloidal**
- Then, inside **molecular clouds** were sheared out **horizontally**

Mehmet.Guenduez@RUB.de

Magnetic Field in the GC- *GBFD19*

- Variation range between ~1e-5 G and ~5e-3G
- **Large-scale** magnetic field in the GC initially **poloidal**
- Then, inside **molecular clouds** were sheared out **horizontally**

Has not been modeled yet!

Mehmet.Guenduez@RUB.de

Magnetic Field in the GC- *GBFD19*

- Variation range between ~1e-5 G and ~5e-3G
- **Large-scale** magnetic field in the GC initially **poloidal**
- Then, inside **molecular clouds** were sheared out **horizontally**

Has not been modeled yet!

Can be split into 2 components:

1. Poloidal:
   - Intercloud medium (ICM) → large scale field
   - Non-thermal filaments (NTFs) → local field

2. Horizontal:
   - Dense molecular clouds (MCs) → local field

Mehmet.Guenduez@RUB.de

Poloidal field

From Ferrière et al. (2014) we consider Model C (FT14-C)}

Mehmet.Guenduez@RUB.de

Poloidal field

From Ferrière et al. (2014) we consider Model C (FT14-C)}

→ analytical and divergence-free

Mehmet.Guenduez@RUB.de

Poloidal field

From Ferrière et al. (2014) we consider Model C (FT14-C)}

→ analytical and divergence-free

$$\mathbf{B}^C = \begin{pmatrix} B_r \\ B_\phi \\ B_z \end{pmatrix} = \begin{pmatrix} \frac{2\,a\;z}{(1+a\,z^2)^3} \\ 0 \\ \frac{1}{(1+a\,z^2)^2} \end{pmatrix} \cdot B_1 \cdot e^{-r/L \cdot \frac{1}{(1+a\,z^2)}}$$

Mehmet.Guenduez@RUB.de

Poloidal field

From Ferrière et al. (2014) we consider Model C (FT14-C)}

→ analytical and divergence-free

$$\mathbf{B}^C = \begin{pmatrix} B_r \\ B_\phi \\ B_z \end{pmatrix} = \begin{pmatrix} \frac{2\,a\;z}{(1+a\,z^2)^3} \\ 0 \\ \frac{1}{(1+a\,z^2)^2} \end{pmatrix} \cdot B_1 \cdot e^{-r/L \cdot \frac{1}{(1+a\,z^2)}}$$

- a → opening of field lines away from the z-axis
- L → exponential scale length
- B_1 → normalization factor

Mehmet.Guenduez@RUB.de

Poloidal field

From Ferrière et al. (2014) we consider Model C (FT14-C)}

→ analytical and divergence-free

$$\mathbf{B}^C = \begin{pmatrix} B_r \\ B_\phi \\ B_z \end{pmatrix} = \begin{pmatrix} \frac{2\,a\;z}{(1+a\,z^2)^3} \\ 0 \\ \frac{1}{(1+a\,z^2)^2} \end{pmatrix} \cdot B_1 \cdot e^{-r/L \cdot \frac{1}{(1+a\,z^2)}}$$

a → opening of field lines away from the z-axis
L → exponential scale length
} → geometry

B_1 → normalization factor } → observation

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$$

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Consider the zonal plane → $B_z = 0$ → $\beta = 1$

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Consider the zonal plane → $B_z = 0$ → $\beta = 1$

$$\rightarrow \quad \vec{B} = \begin{pmatrix} B_r \\ B_\phi \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial}{\partial\phi}\alpha \\ -\frac{\partial}{\partial r}\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial\phi}\Big|_r \\ -\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial r}\Big|_\phi \\ 0 \end{pmatrix}$$

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Consider the zonal plane → $B_z = 0$ → $\beta = 1$

$$\rightarrow \quad \vec{B} = \begin{pmatrix} B_r \\ B_\phi \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial}{\partial\phi}\alpha \\ -\frac{\partial}{\partial r}\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial\phi}\Big|_r \\ -\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial r}\Big|_\phi \\ 0 \end{pmatrix}$$

$|B_r/B_\phi| = \frac{1}{r} \cdot dr/d\phi|_{\psi,\rho} \stackrel{!}{=} \eta$ depends on the MC characteristics

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Consider the zonal plane → $B_z = 0$ → $\beta = 1$

$$\rightarrow \quad \vec{B} = \begin{pmatrix} B_r \\ B_\phi \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial}{\partial\phi}\alpha \\ -\frac{\partial}{\partial r}\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial\phi}\Big|_r \\ -\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial r}\Big|_\phi \\ 0 \end{pmatrix}$$

$|B_r/B_\phi| = \frac{1}{r} \cdot dr/d\phi|_{\psi,\rho} \stackrel{!}{=} \eta$ depends on the MC characteristics

$$\rightarrow \quad \psi = \phi \pm \eta^{-1} \ln(r/\rho) \quad \rightarrow \quad \partial\alpha/\partial\psi = \rho \cdot B_r(\psi)$$

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Consider the zonal plane → $B_z = 0$ → $\beta = 1$

→ $$\vec{B} = \begin{pmatrix} B_r \\ B_\phi \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial}{\partial\phi}\alpha \\ -\frac{\partial}{\partial r}\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial\phi}\Big|_r \\ -\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial r}\Big|_\phi \\ 0 \end{pmatrix}$$

$|B_r/B_\phi| = \frac{1}{r} \cdot dr/d\phi|_{\psi,\rho} \stackrel{!}{=} \eta$ depends on the MC characteristics

→ $\psi = \phi \pm \eta^{-1} \ln(r/\rho)$ → $\partial\alpha/\partial\psi = \rho \cdot B_r(\psi)$

we define: $B_r(\psi) = B_1 \cdot \cos(\psi) \cdot h(z)$

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Consider the zonal plane → $B_z = 0$ → $\beta = 1$

→ $$\vec{B} = \begin{pmatrix} B_r \\ B_\phi \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial}{\partial\phi}\alpha \\ -\frac{\partial}{\partial r}\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial\phi}\Big|_r \\ -\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial r}\Big|_\phi \\ 0 \end{pmatrix}$$

$|B_r/B_\phi| = \frac{1}{r} \cdot dr/d\phi|_{\psi,\rho} \overset{!}{=} \eta$ depends on the MC characteristics

→ $\psi = \phi \pm \eta^{-1} \ln(r/\rho)$ → $\partial\alpha/\partial\psi = \rho \cdot B_r(\psi)$

we define: $B_r(\psi) = B_1 \cdot \cos(\psi) \cdot h(z)$

→ net magnetic flux=0 → *h(z)* is arbitrary

Mehmet.Guenduez@RUB.de

Horizontal field

Starting with Euler's potentials:

$\vec{B} = \vec{\nabla}\alpha \times \vec{\nabla}\beta$ → analytical and divergence-free

Consider the zonal plane → $B_z = 0$ → $\beta = 1$

→ $$\vec{B} = \begin{pmatrix} B_r \\ B_\phi \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial}{\partial\phi}\alpha \\ -\frac{\partial}{\partial r}\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \frac{1}{r}\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial\phi}\Big|_r \\ -\frac{\partial\alpha}{\partial\psi}\frac{\partial\psi}{\partial r}\Big|_\phi \\ 0 \end{pmatrix}$$

$|B_r/B_\phi| = \frac{1}{r} \cdot dr/d\phi|_{\psi,\rho} \overset{!}{=} \eta$ depends on the MC characteristics

→ $\psi = \phi \pm \eta^{-1} \ln(r/\rho)$ → $\partial\alpha/\partial\psi = \rho \cdot B_r(\psi)$

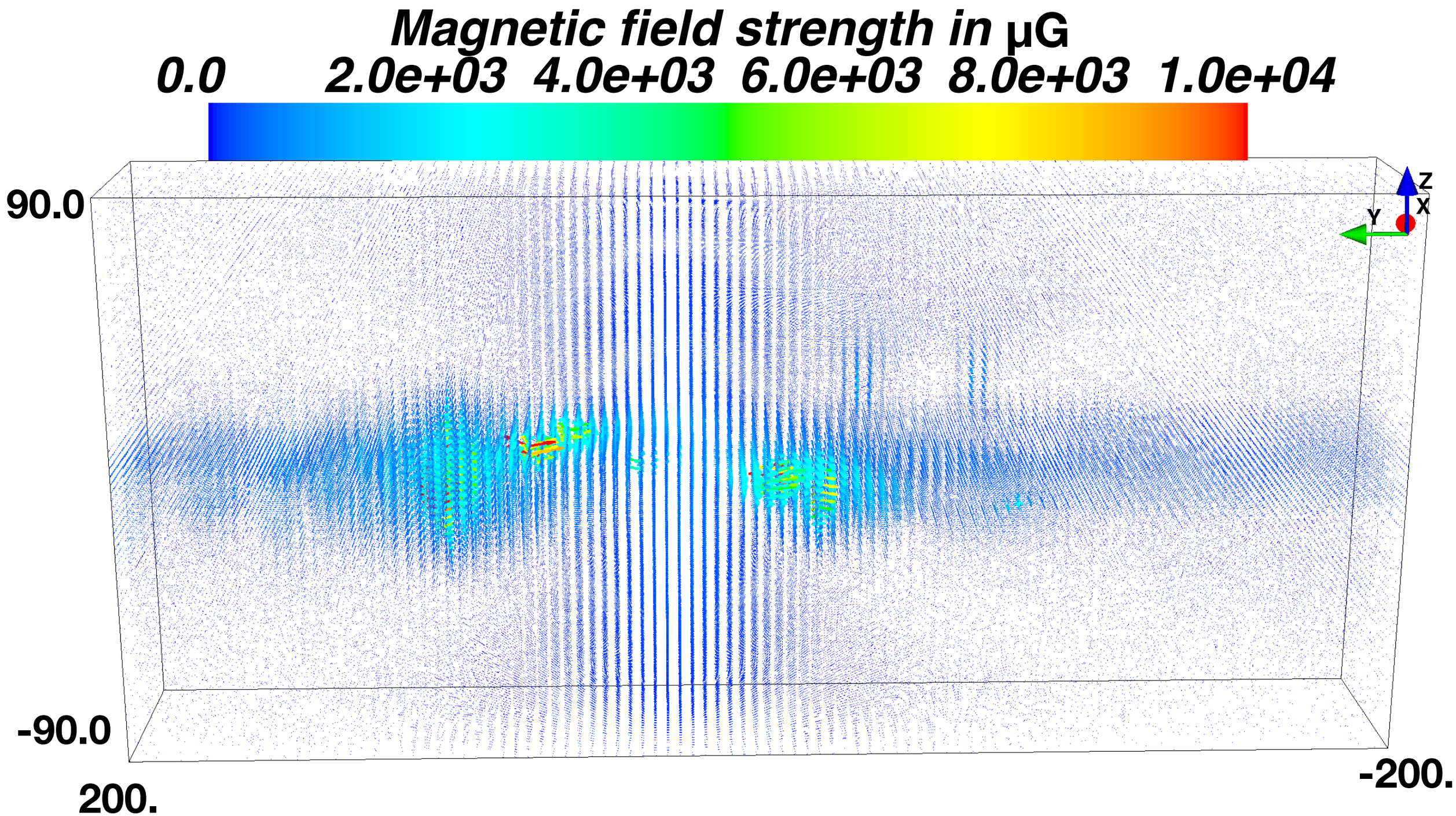
we define: $B_r(\psi) = B_1 \cdot \cos(\psi) \cdot h(z)$

→ net magnetic flux=0 → *h(z)* is arbitrary

$$\mathbf{B}_{\mathrm{tot}} = \mathbf{B}^C_{\mathrm{IC}} + \sum_{i=1}^{8} \mathbf{B}^C_{\mathrm{NTF,i}} + \sum_{i=1}^{12} \mathbf{B}_{\mathrm{MC,i}}$$

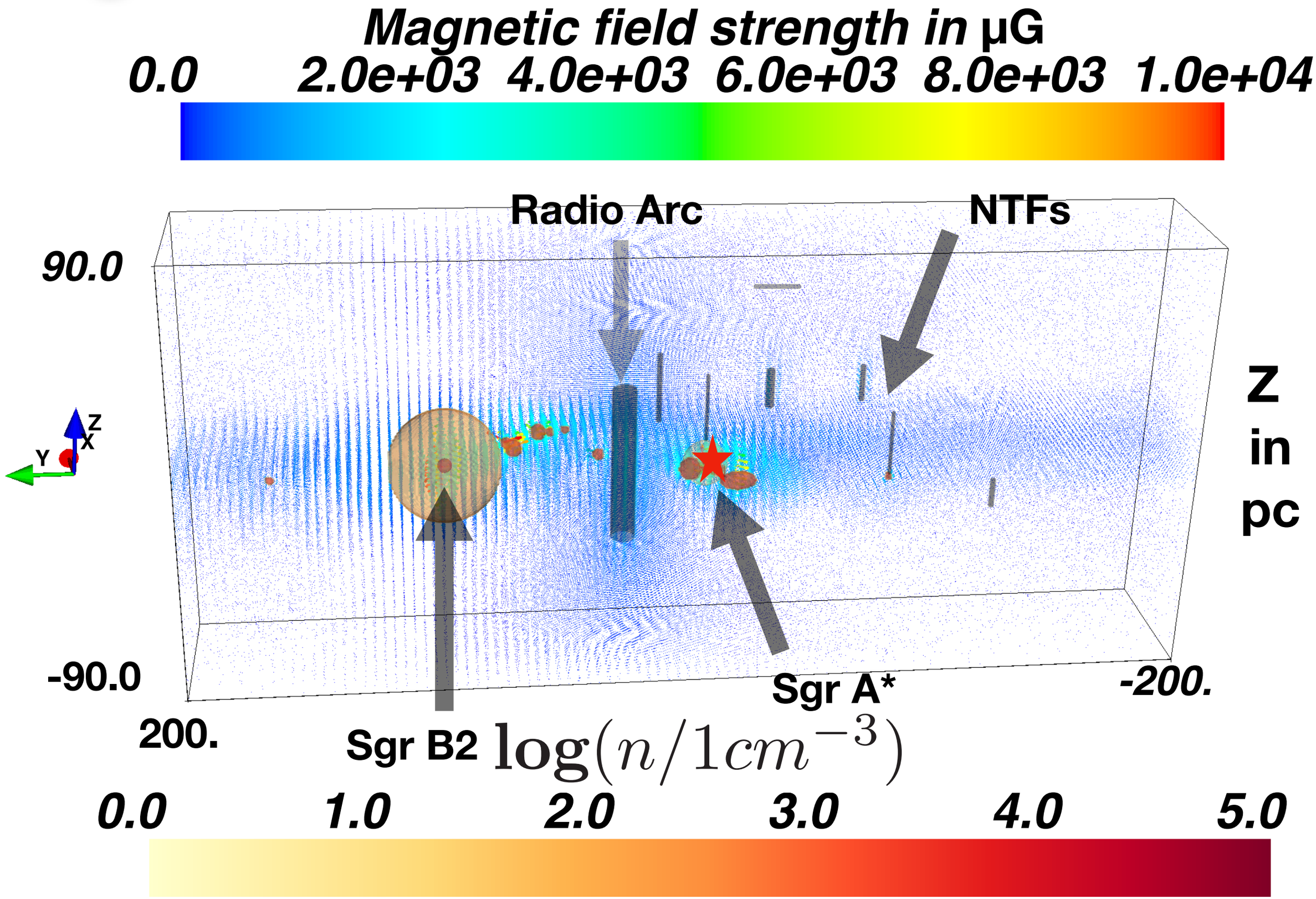
Mehmet.Guenduez@RUB.de

Magnetic Field in the GC - *GBFD19*



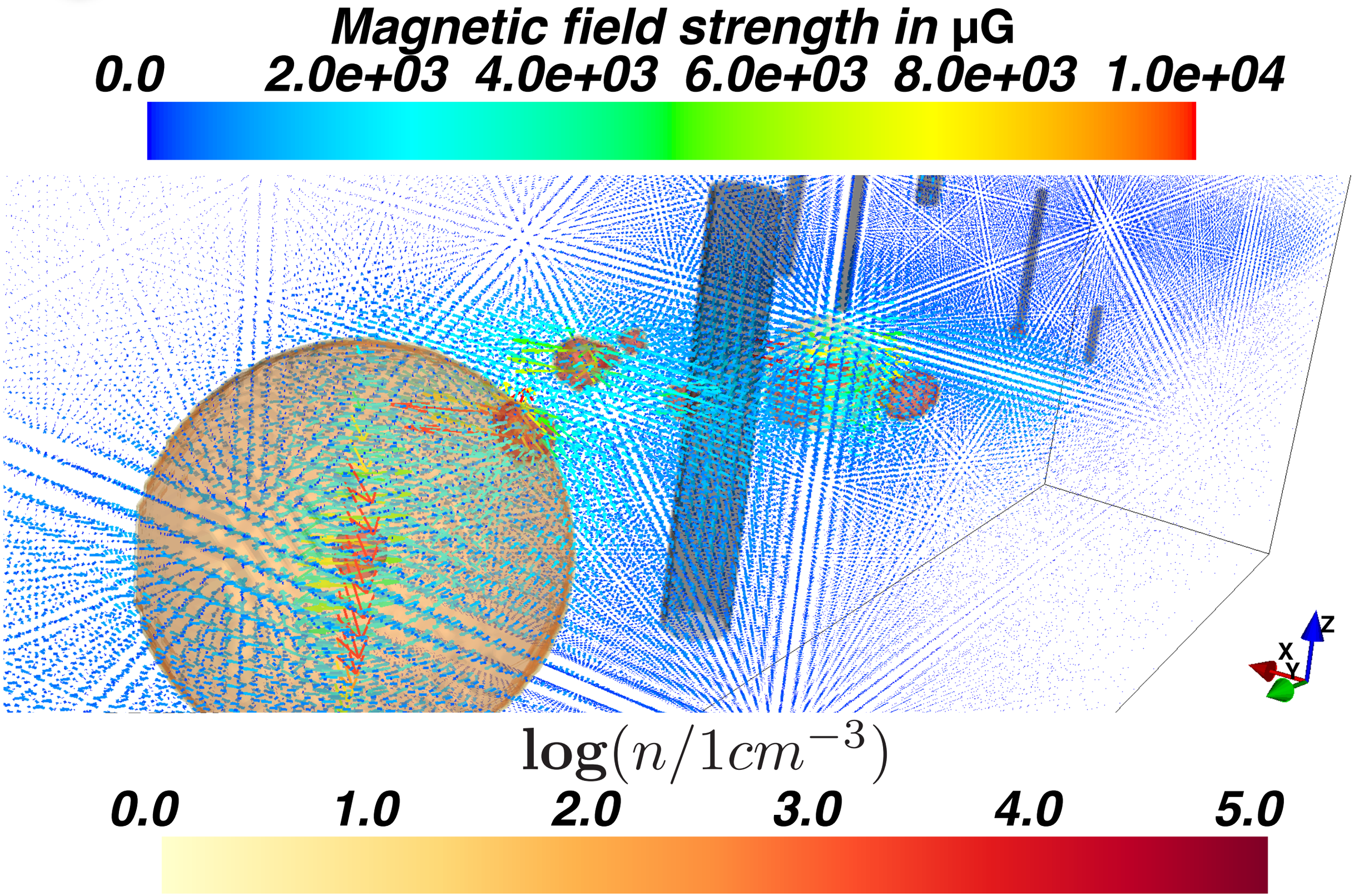
Mehmet.Guenduez@RUB.de

Magnetic Field in the GC - *GBFD19*



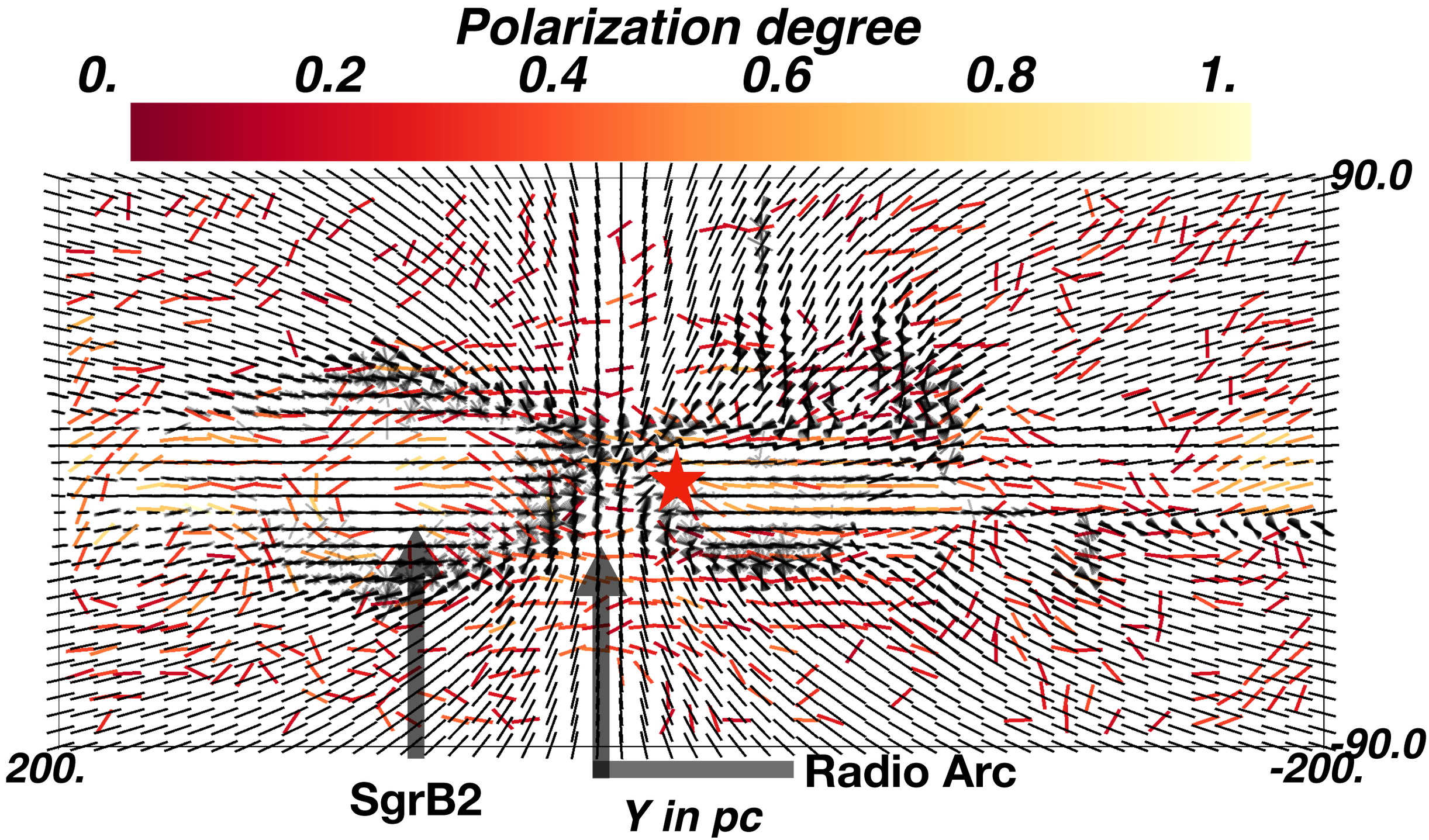
Mehmet.Guenduez@RUB.de

Magnetic Field in the GC - *GBFD19*



Mehmet.Guenduez@RUB.de

Magnetic Field in the GC - *GBFD19*

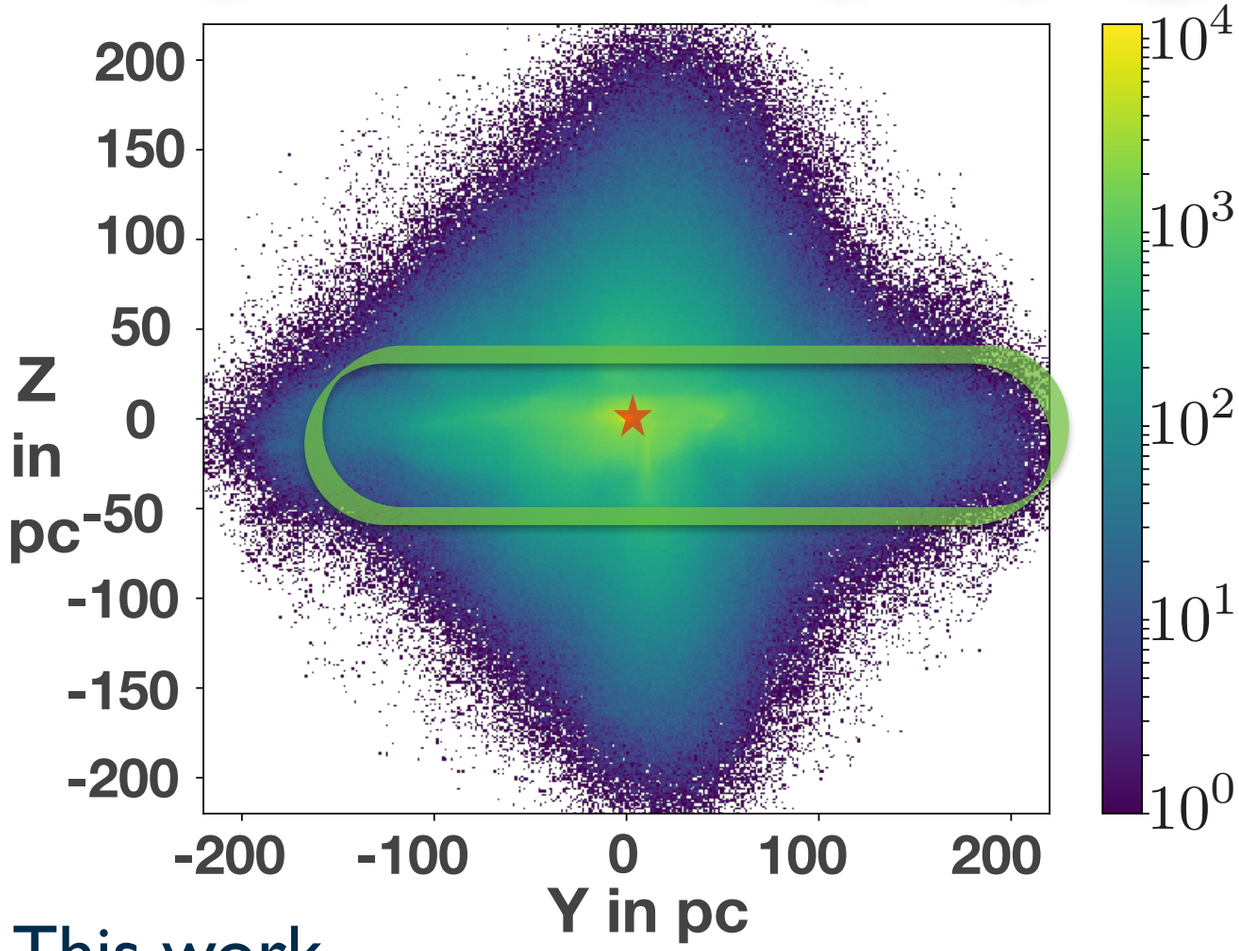


Colored data from [Nishiyama et al., APJ Letters, 712, L23, 2010]

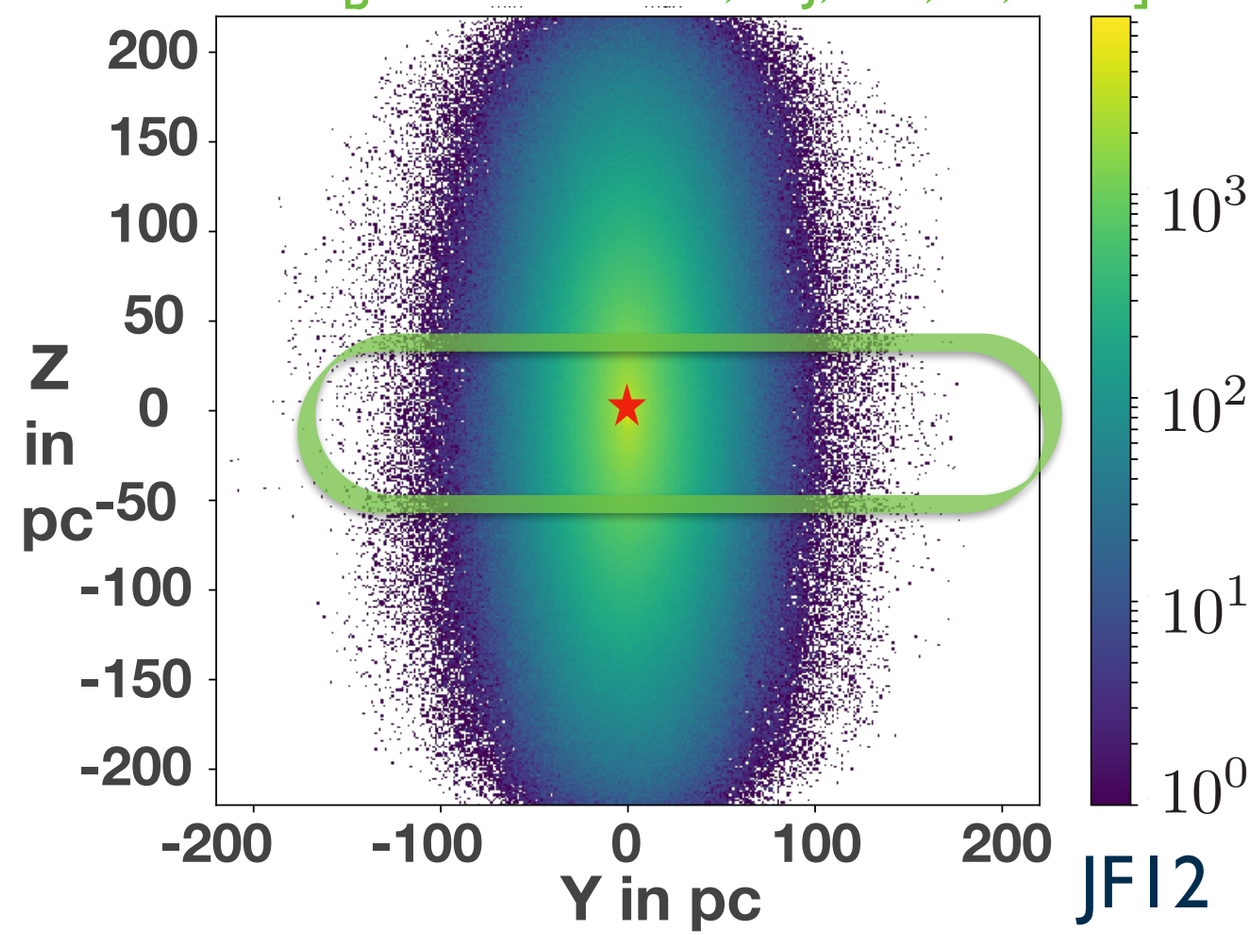
Mehmet.Guenduez@RUB.de

Impact on CR propagation

[Jansson & Farrar, APJ, 757, 14, 2012]



This work

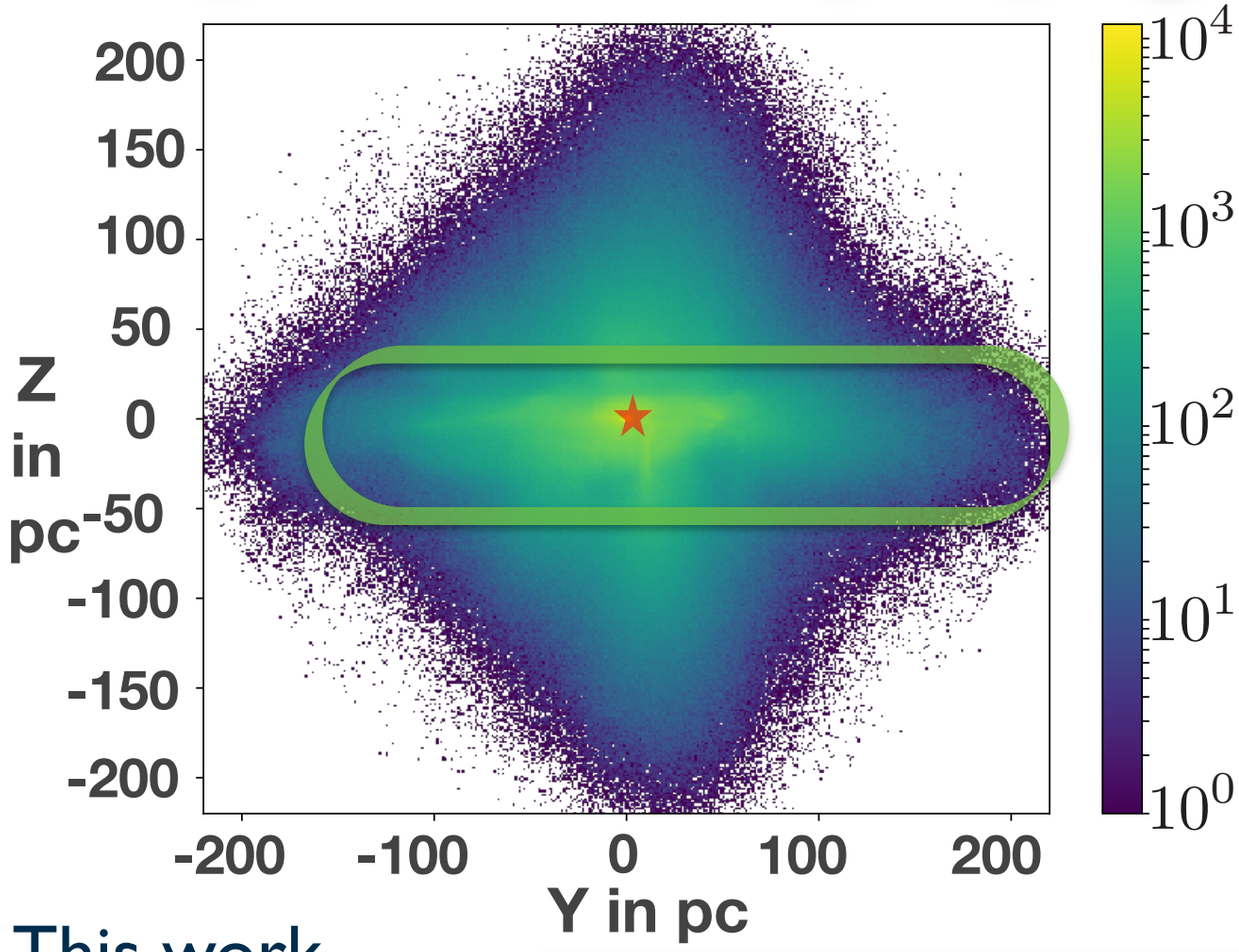


JF12

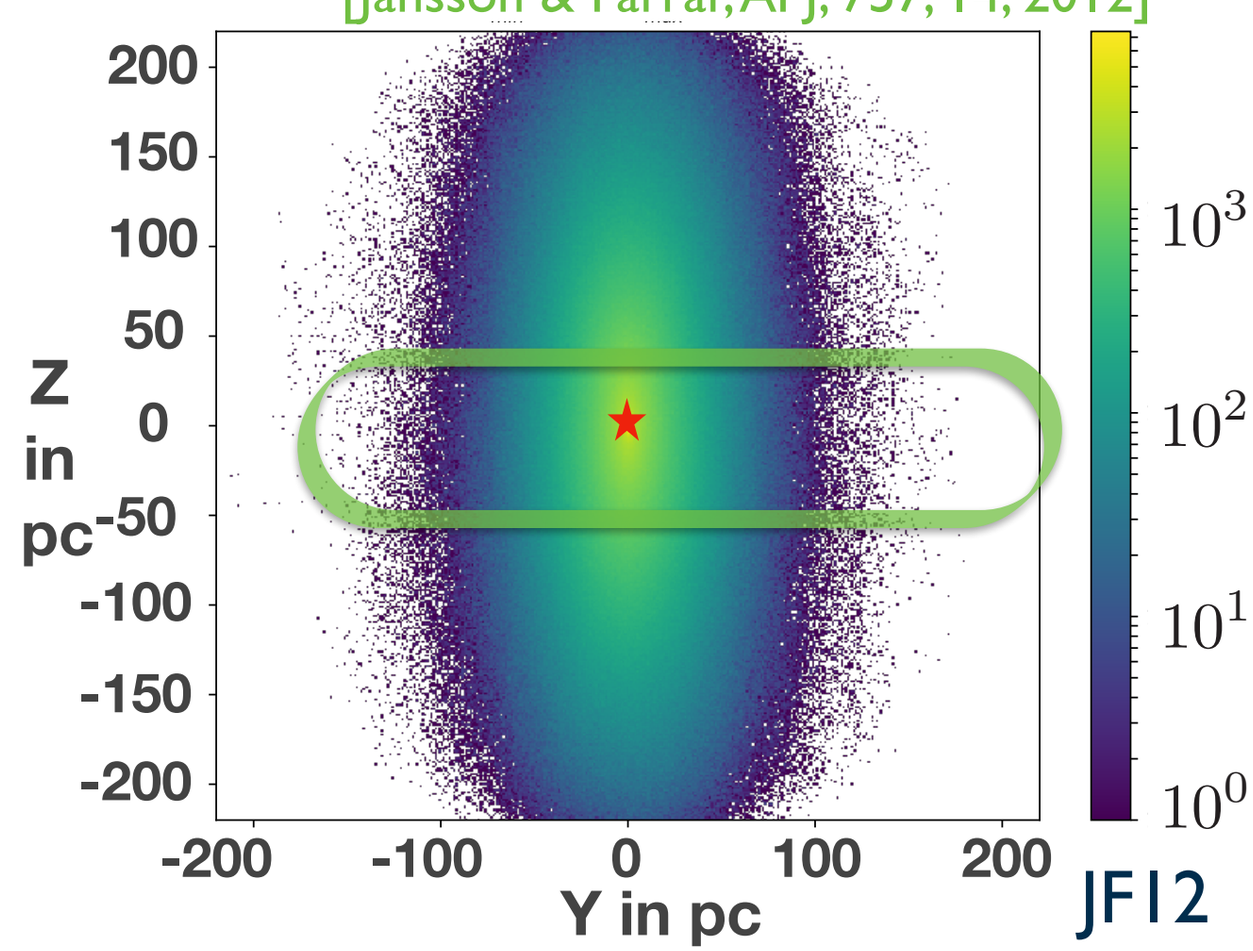
Mehmet.Guenduez@RUB.de

Impact on CR propagation

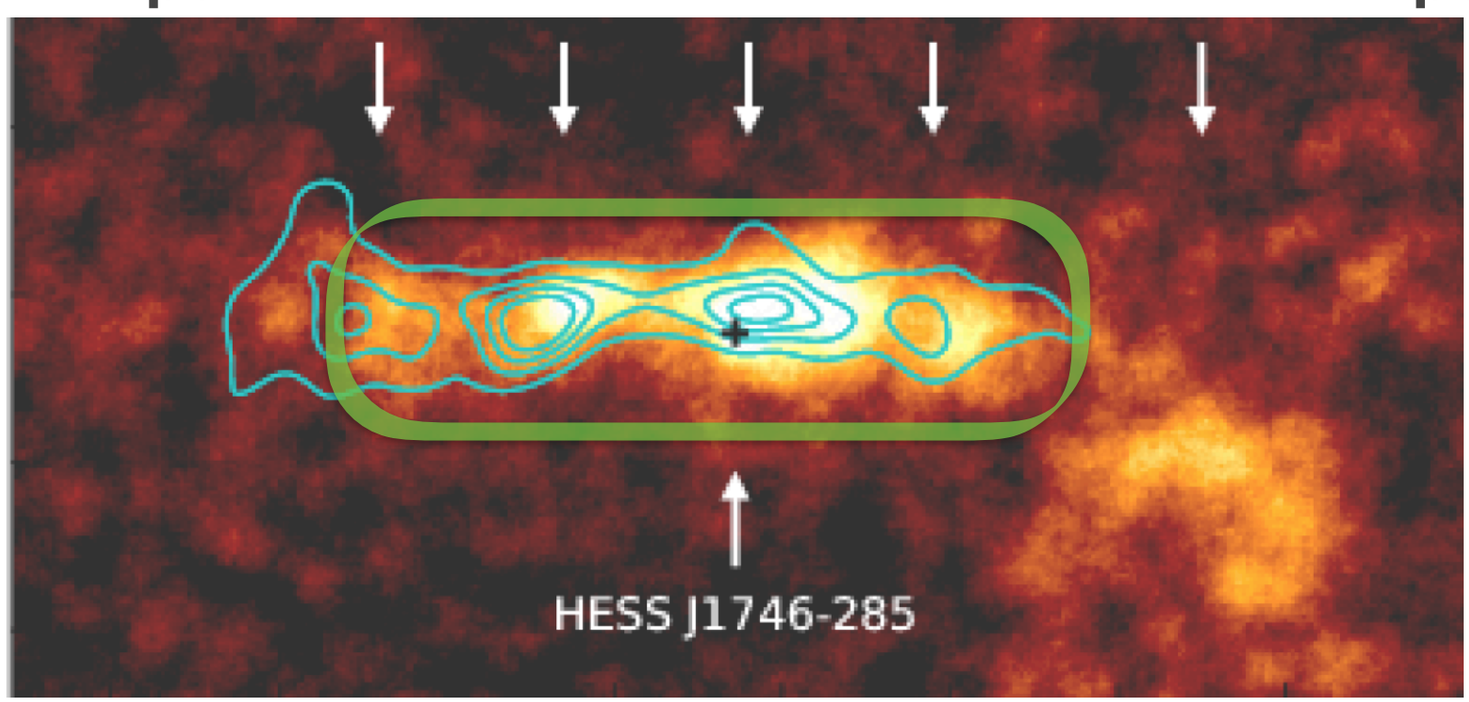
[Jansson & Farrar, APJ, 757, 14, 2012]



This work



JF12



Mehmet.Guenduez@RUB.de

Summary and conclusion

- A centrally located source is not easily sufficient for the observed gamma-ray emission
- *GBDF19*:
  - could explain the diffuse gamma-ray emission caused by a single centralized source
  - is strong in non-thermal filaments and molecular clouds
  - is compatible with polarization data and corresponds to the observations
  - has a significant impact on the longitudinal profiles of CR propagation
  - can be combined with any other Galactic B-field models
- The 3D gas distribution and *GBDF19* make a more accurate calculation accessible for the GC investigators
- For detailed modeling: M.Guenduez et al. 2019 Submitted to A&A, arXiv:1906.05211

Mehmet.Guenduez@RUB.de

Backup slides

- Proton as primary cosmic-rays injected from SgrA* at the origin
- spherically symmetric description
- diffusion dominated scenario is favored
- spatial and energy dependent source
- energy dependent continuous loss
  For the first time:
  - we include a spatially dependent term in the hadronic pion production interaction term

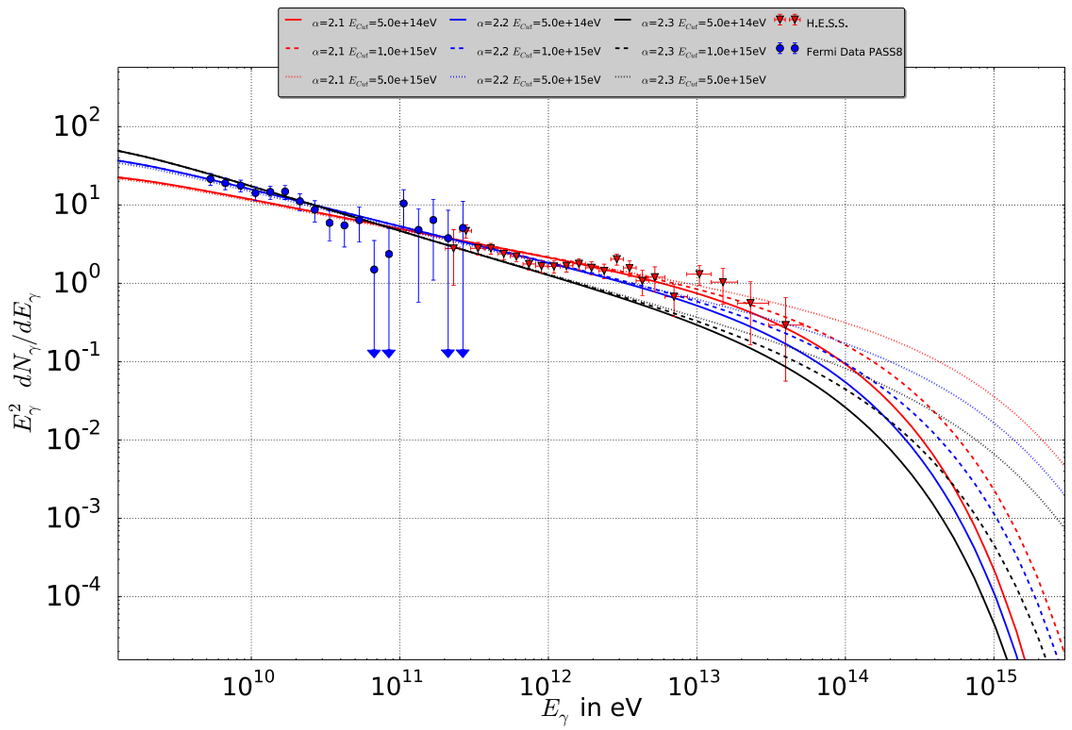
$$-D_0\,\gamma^{\nu}\frac{2}{r}\frac{\partial}{\partial r}n(r,\gamma) - D_0\,\gamma^{\nu}\frac{\partial^2}{\partial r^2}n(r,\gamma) - \frac{\partial}{\partial\gamma}\underbrace{b(r)}_{\propto r^{-2}}\gamma^{1+\mu}\,n(r,\gamma) = Q(r,\gamma)$$

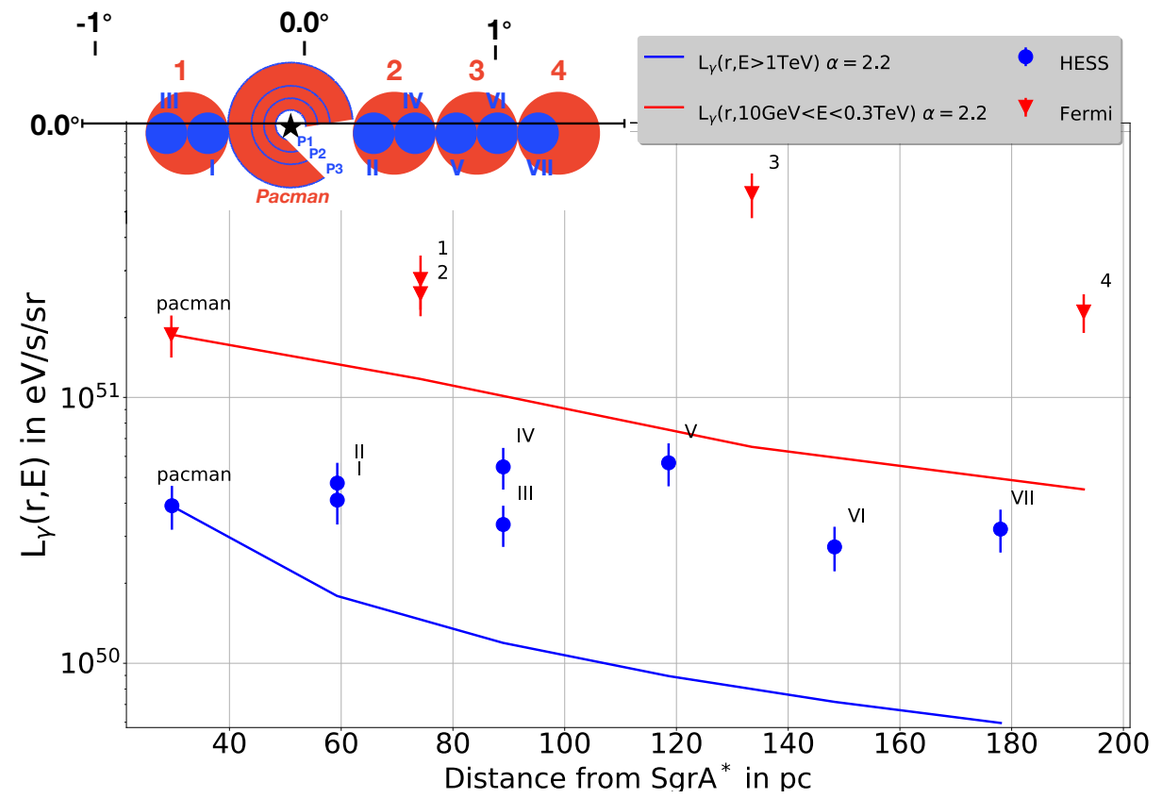
Solution:

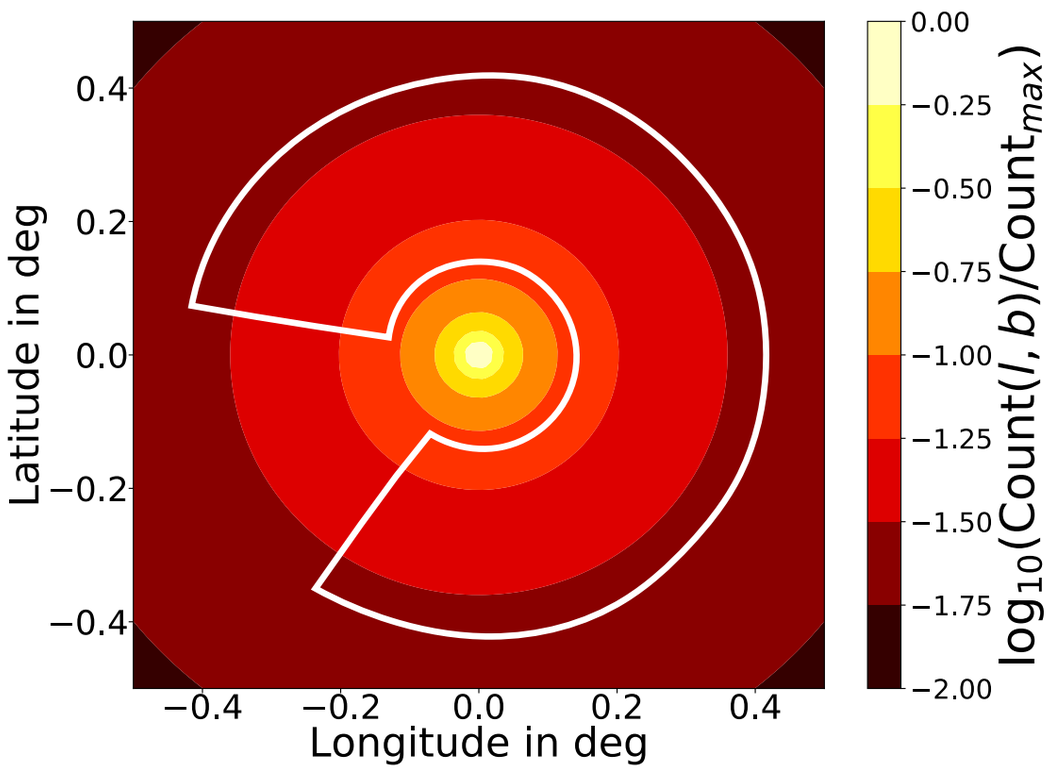
$$n(r,\gamma) = \gamma^{-1-\mu}\int\int\frac{r_0^{\frac{3}{2}}\,H[r-r_0]\cdot H[\gamma_0-\gamma]}{\sqrt{4\pi\cdot D_0\cdot b_0\cdot r_c^2}}\cdot\frac{\gamma_0^{\mu+2\nu}}{\sqrt{\frac{\gamma^{\nu}-\gamma_0^{\nu}}{\nu}}}\cdot\exp\left(-\frac{D_0}{4\nu\cdot b_0\cdot r_c^2}(\gamma^{\nu}-\gamma_0^{\nu})\right)\cdot$$
$$\left[\exp\left(-\frac{\log(\sqrt{r_0})^2\nu\cdot b_0\cdot r_c^2}{D_0\cdot(\gamma^{\nu}-\gamma_0^{\nu})}\right)-\exp\left(-\frac{\log(\frac{r}{\sqrt{r_0}})^2\nu\cdot b_0\cdot r_c^2}{D_0\cdot(\gamma^{\nu}-\gamma_0^{\nu})}\right)\right]\cdot Q(r_0,\gamma_0)\mathrm{d}r_0\mathrm{d}\gamma_0$$

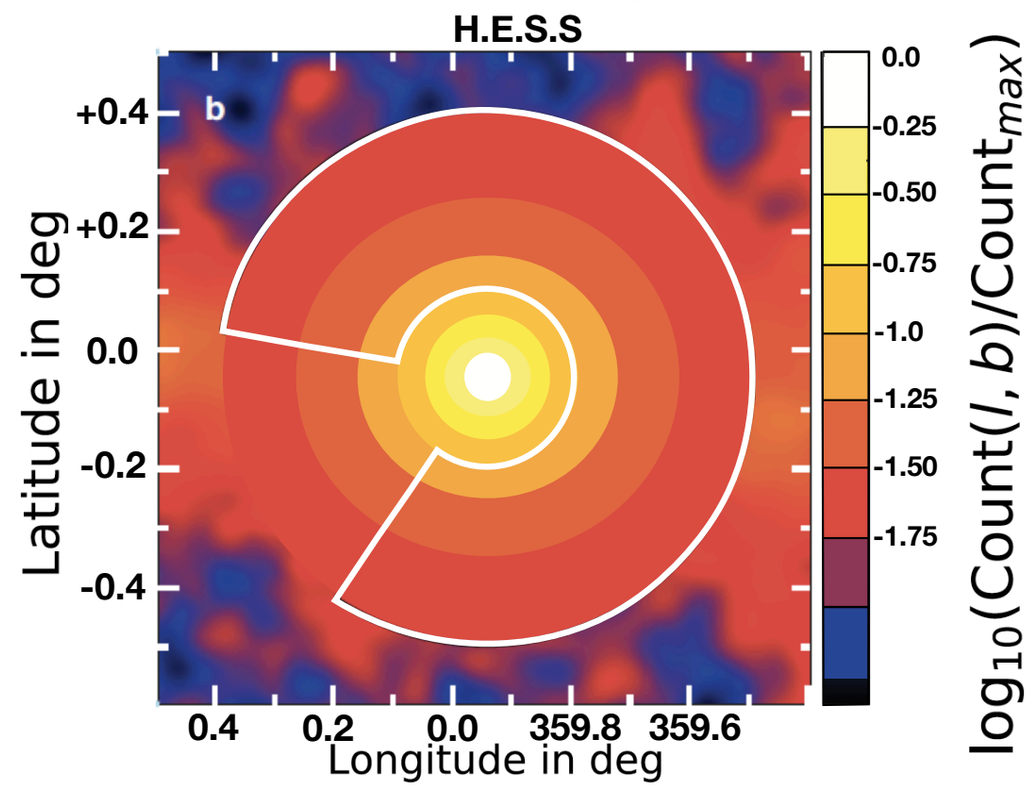
Mehmet.Guenduez@RUB.de

Backup slides



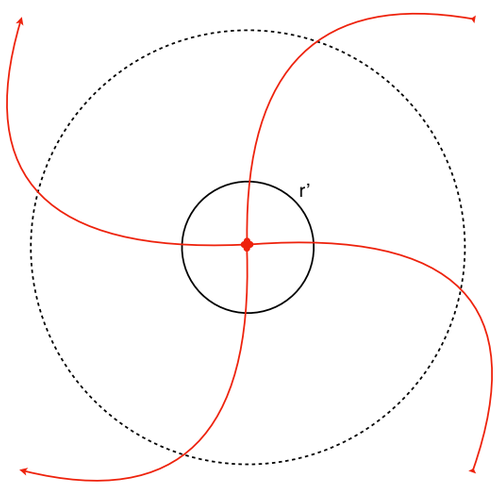


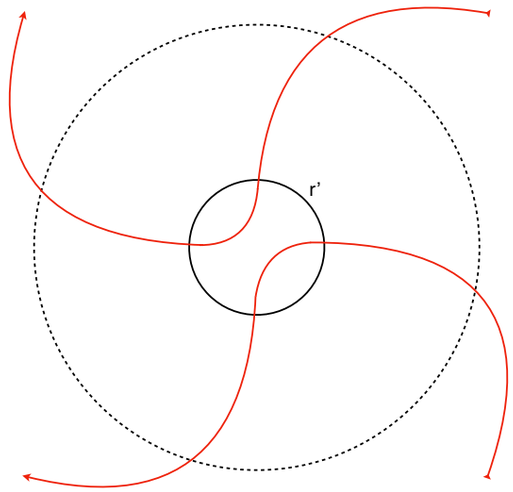




Mehmet.Guenduez@RUB.de

Backup slides





$$\vec{B}_{\mathrm{MC}}^{r>r'} = \beta \cdot \begin{pmatrix} \frac{R}{r} \\ \mp\eta^{-1}\frac{R}{r+b} \\ 0 \end{pmatrix}$$

$$\beta = B_1 \cdot \cos\left(\pm v(r) + m \cdot \phi\right) \cdot \exp\left(-\frac{z^2}{H_c^2}\right)$$

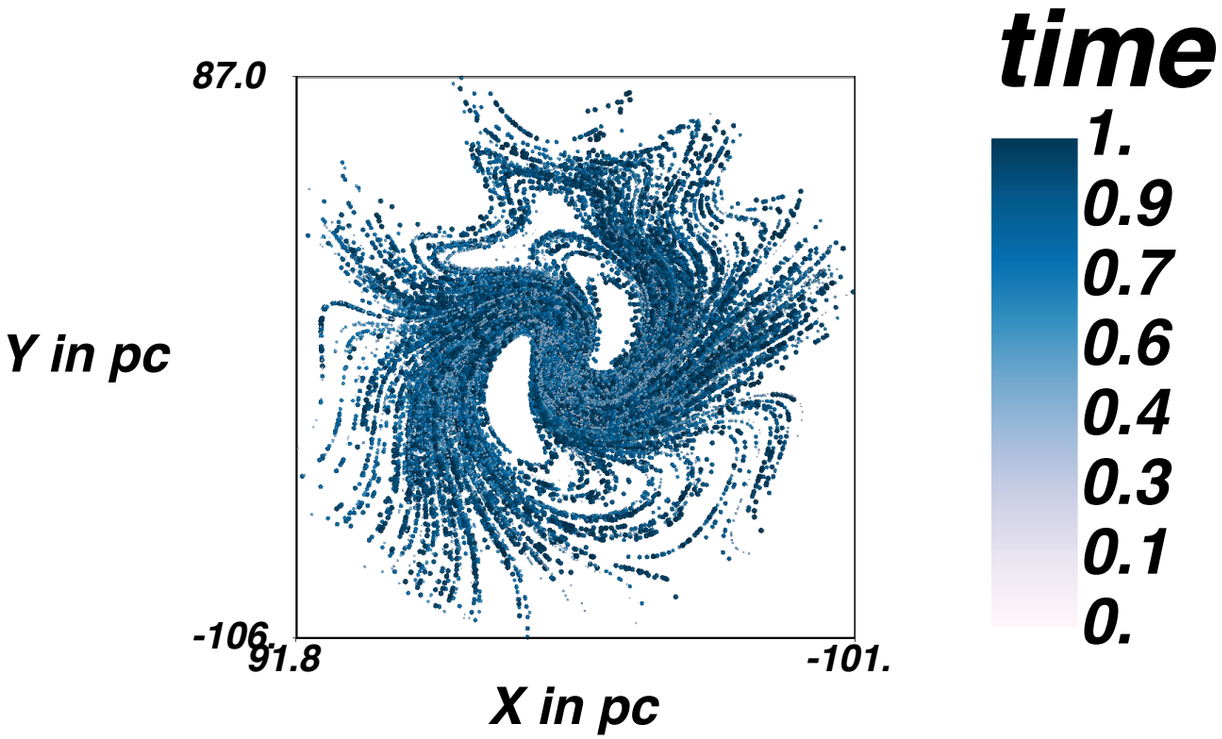
$$v(r) = \frac{1}{\eta} \cdot \ln\left(\frac{r+b}{R+b}\right)$$

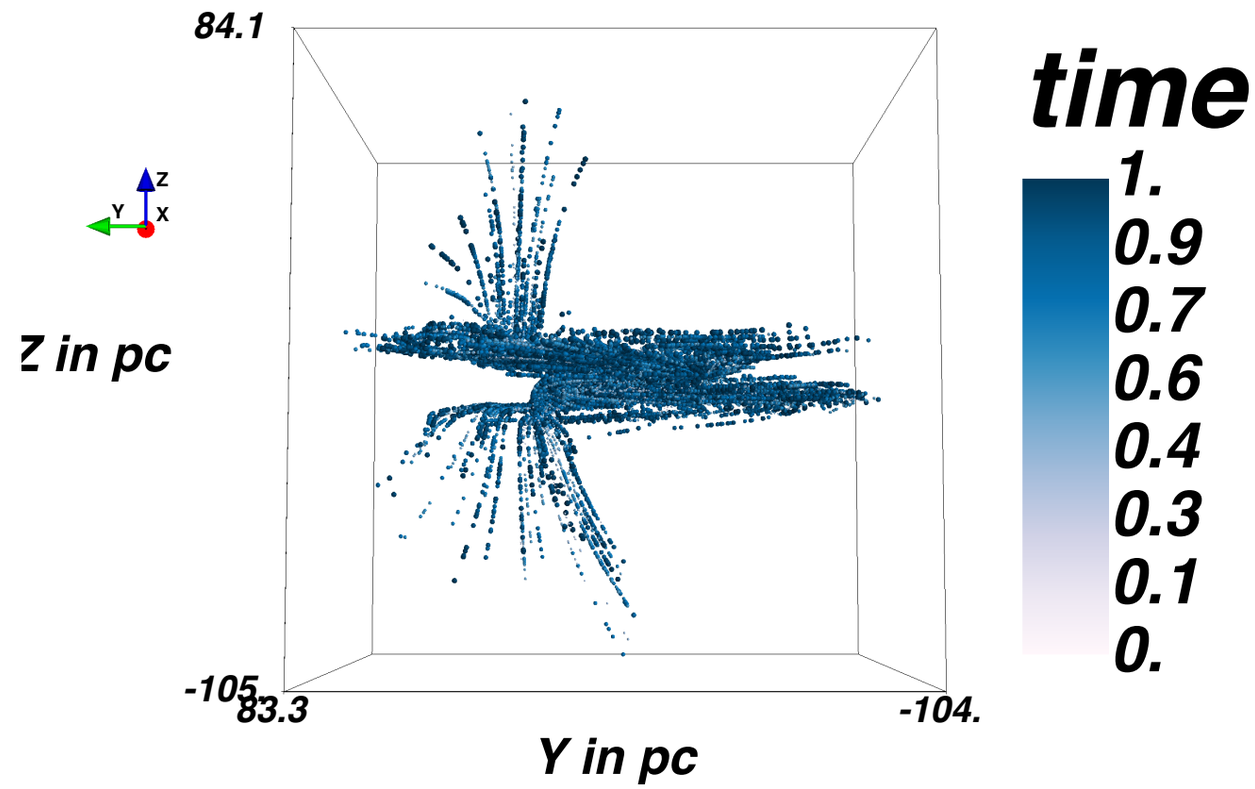
$$\vec{B}_{\mathrm{MC}}^{r<r'} = \beta \cdot \frac{R}{r'}\left(\frac{3r}{r'} - \frac{2r^2}{r'^2}\right) \begin{pmatrix} 1 \\ \mp\frac{r}{\eta(r+b)}\left(1 + \frac{6(r-r')}{2\,r-3\,r'}\left(\frac{\sin(\pm v(r)+m\phi)-\sin(\pm v(r))}{\cos(\pm v(r)+m\phi)}\right)\right) \\ 0 \end{pmatrix}$$

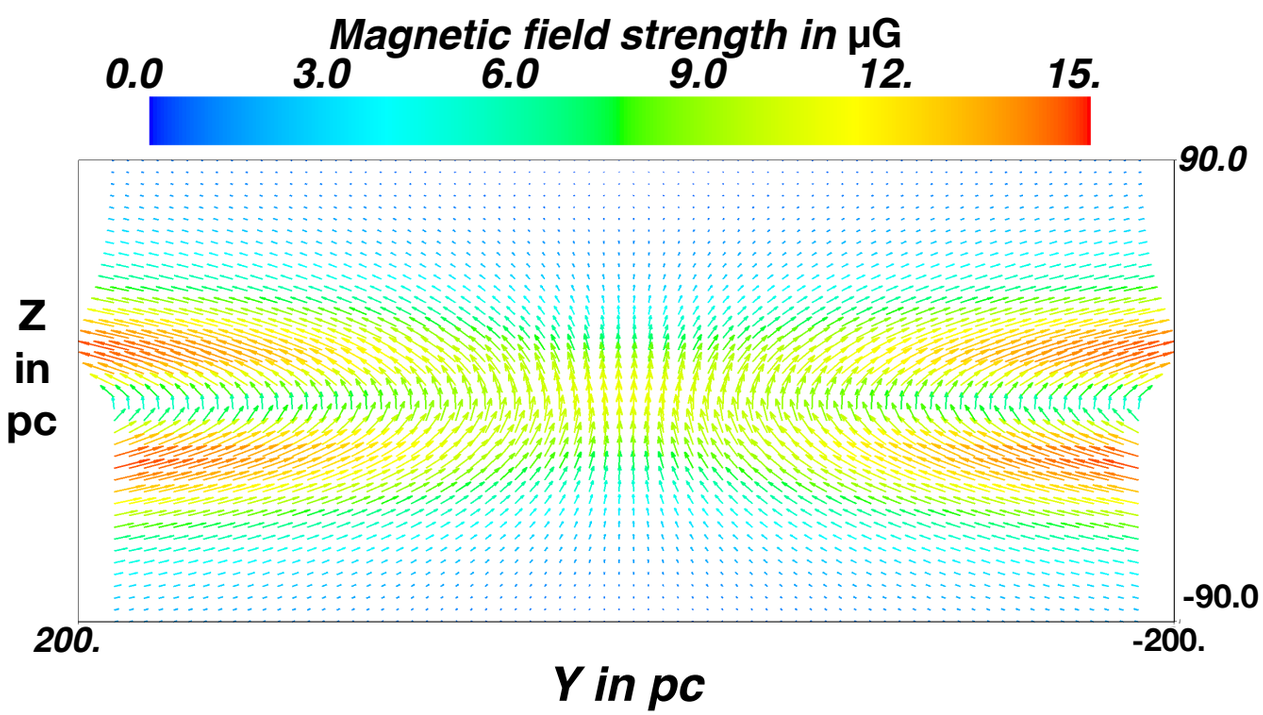
$$\mathbf{B}_{\mathrm{tot}} = \mathbf{B}_{\mathrm{IC}}^{C} + \sum_{i=1}^{8} \mathbf{B}_{\mathrm{NTF,i}}^{C} + \sum_{i=1}^{12} \mathbf{B}_{\mathrm{MC,i}}$$

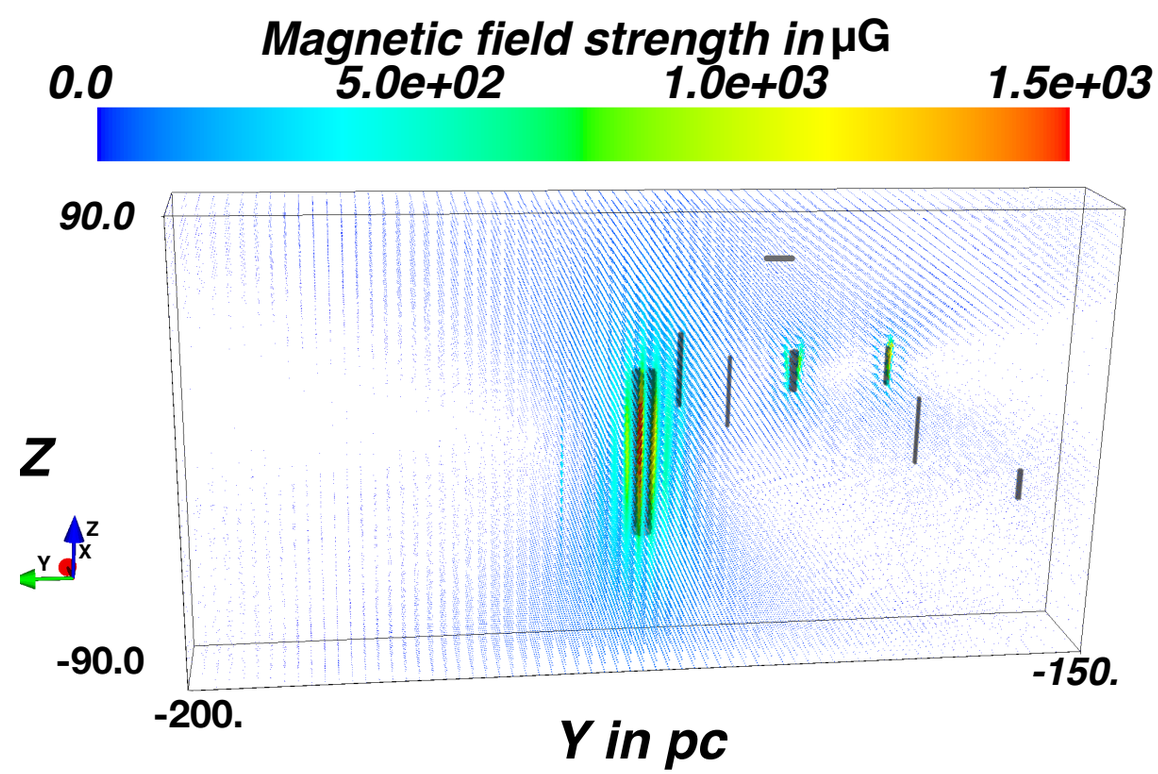
Mehmet.Guenduez@RUB.de

Backup slides



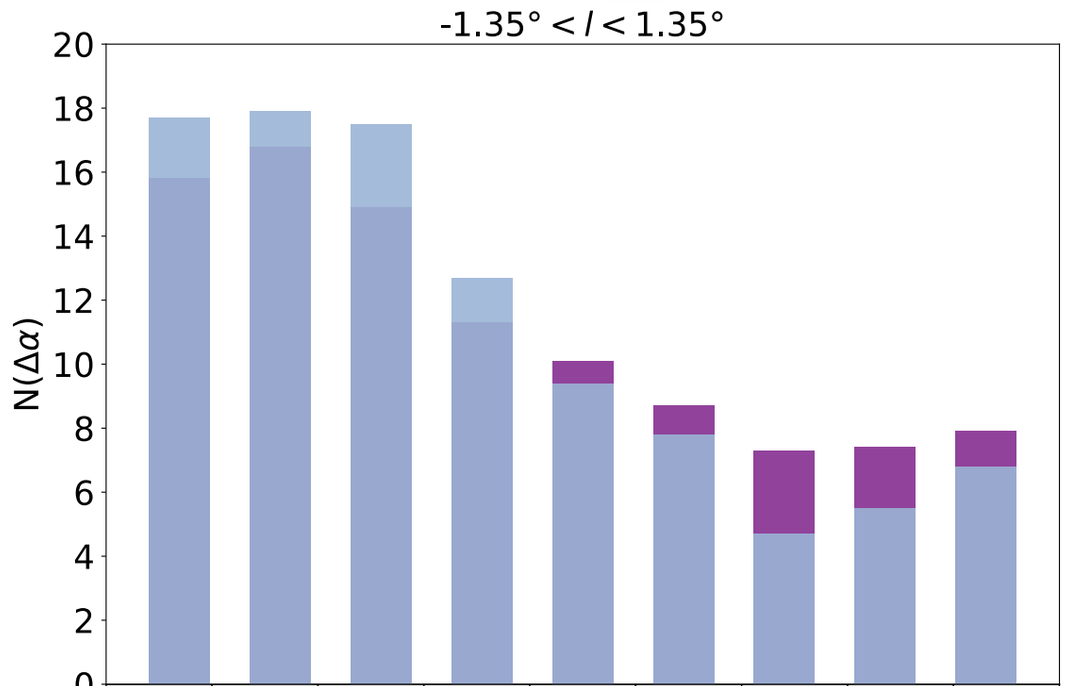




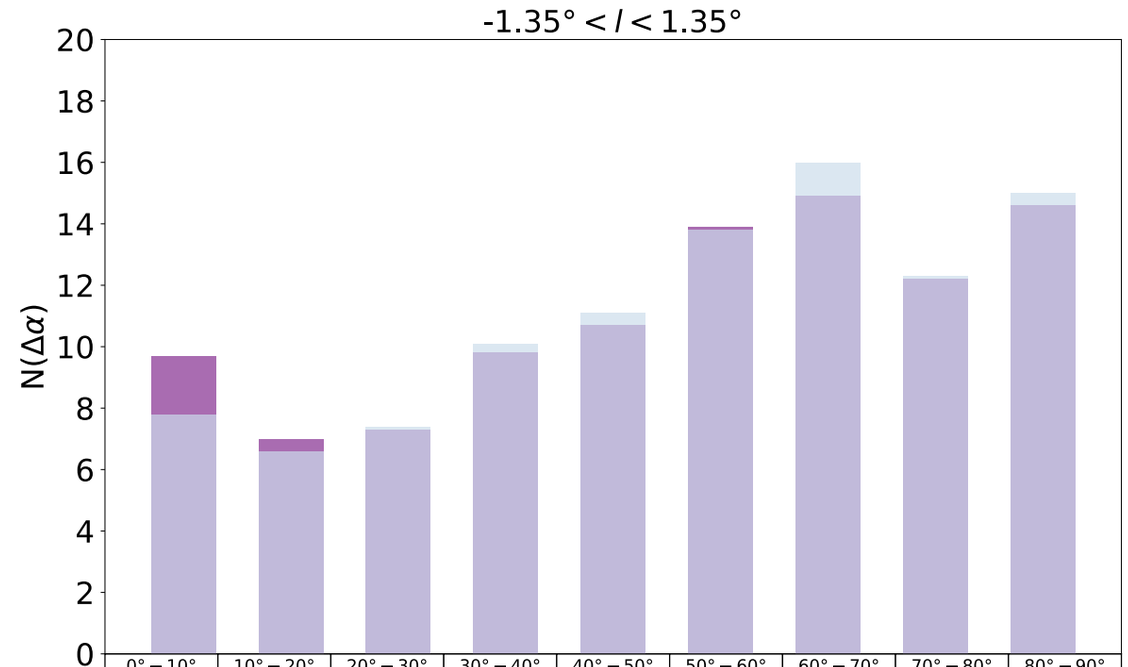


Mehmet.Guenduez@RUB.de

Backup slides



	0° – 10°	10° – 20°	20° – 30°	30° – 40°	40° – 50°	50° – 60°	60° – 70°	70° – 80°	80° – 90°
-0.6° ≤ b ≤ 0.6°	15.8	16.8	14.9	11.3	10.1	8.7	7.3	7.4	7.9
-0.3° ≤ b ≤ 0.3°	17.7	17.9	17.5	12.7	9.4	7.8	4.7	5.5	6.8



	0° – 10°	10° – 20°	20° – 30°	30° – 40°	40° – 50°	50° – 60°	60° – 70°	70° – 80°	80° – 90°
≤ b ≤ 0.6°	9.7	7.0	7.3	9.8	10.7	13.9	14.9	12.2	14.6
≤ b ≤ 0.3°	7.8	6.6	7.4	10.1	11.1	13.8	16.0	12.3	15.0

Mehmet.Guenduez@RUB.de