IMPLICATIONS OF TURBULENCE DEPENDENT DIFFUSION ON COSMIC RAY SPECTRA

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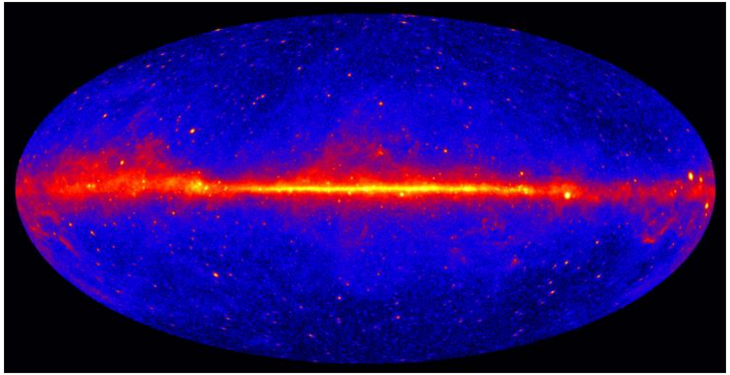
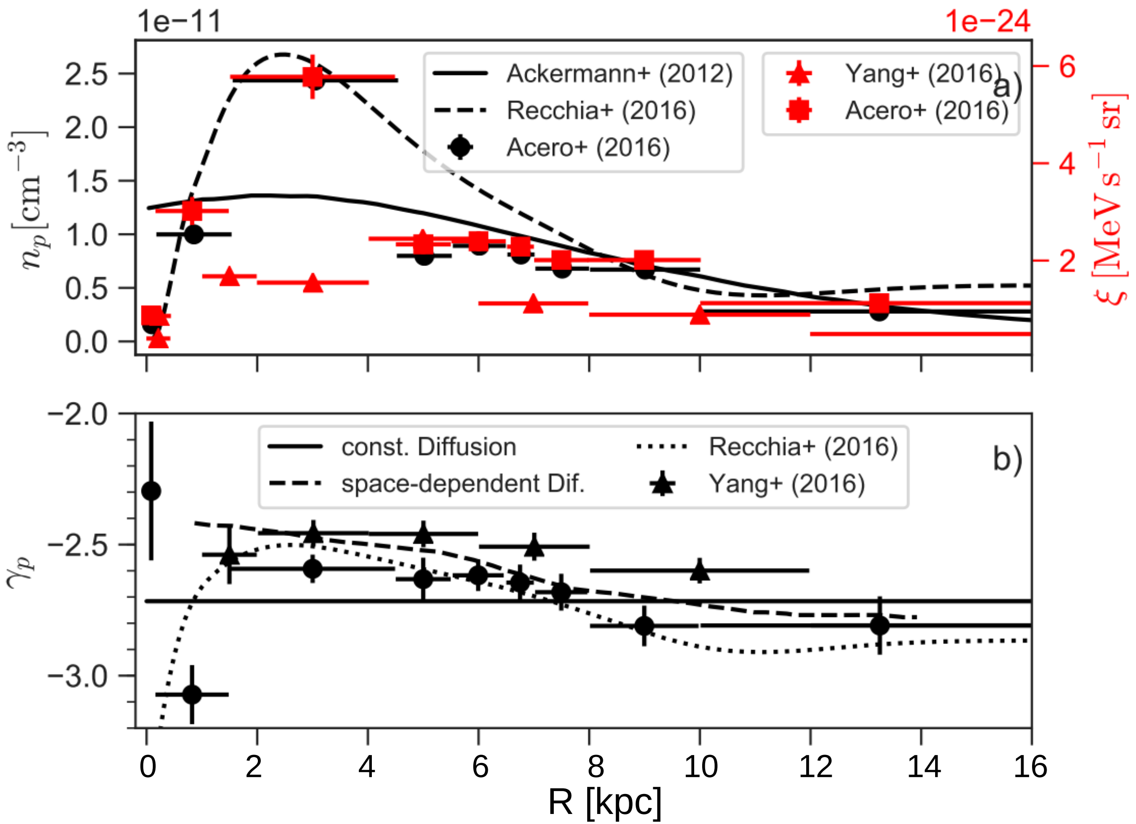
Galactic excess

- Observation by Fermi-LAT
- Radial gradient in CR-density and spectral index

⇒ Diffusion can not be constant in the Galaxy





J. Becker Tjus, L. Merten, Physics Reports **872** (2020)

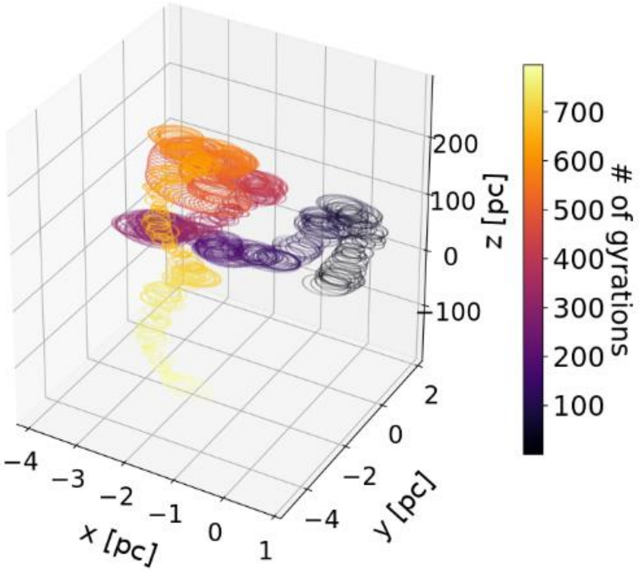
Transport equation

- Most astrophysical environments are dominated by the diffusive motion

$$\frac{\partial n}{\partial t} + \vec{u} \cdot \nabla \mathrm{n} = \boxed{\nabla \cdot (\hat{\kappa}\, \nabla \mathrm{n})} + S(\vec{r}, p, t)$$

Spatial diffusion

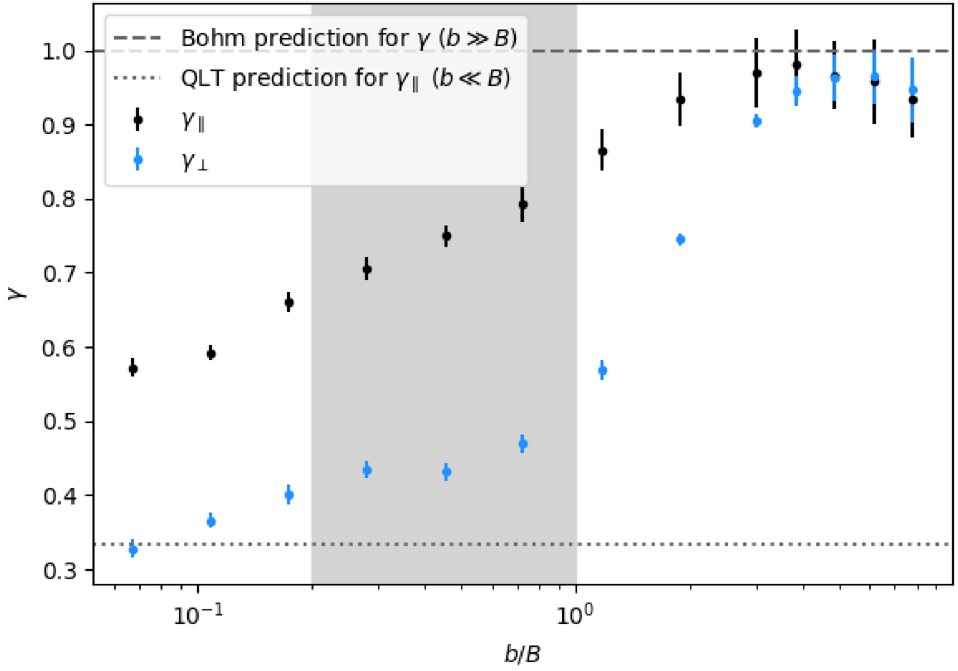
$$\vec{\boldsymbol{B}} = \boldsymbol{B}\, \vec{\boldsymbol{e}_z} \quad \Rightarrow \quad \hat{\boldsymbol{\kappa}} = \begin{pmatrix} \kappa_\perp & 0 & 0 \\ 0 & \kappa_\perp & 0 \\ 0 & 0 & \kappa_\parallel \end{pmatrix}$$



J. Becker Tjus, L. Merten, Physics Reports **872** (2020)

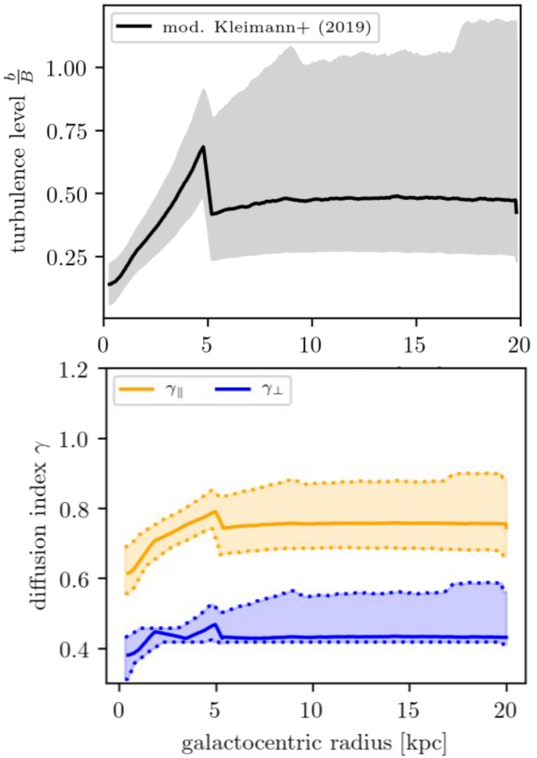
Turbulent dependent diffusion spectra

- Turbulence level $\eta = \frac{b}{B}$
- Based on single particle Simulation
  (Reichherzer, MNRAS, 498, 5051)
- spectral index depend on the turbulence level

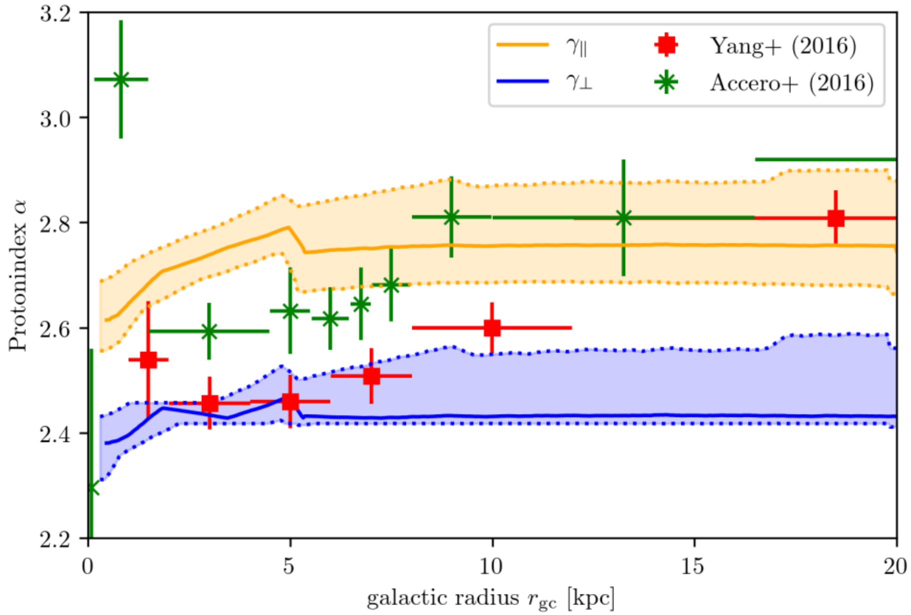


Reichherzer, Merten, **JD** et al.
Nat.Apl.Sc subm. 2021 (**inv.**)

Turbulence in the Milky Way



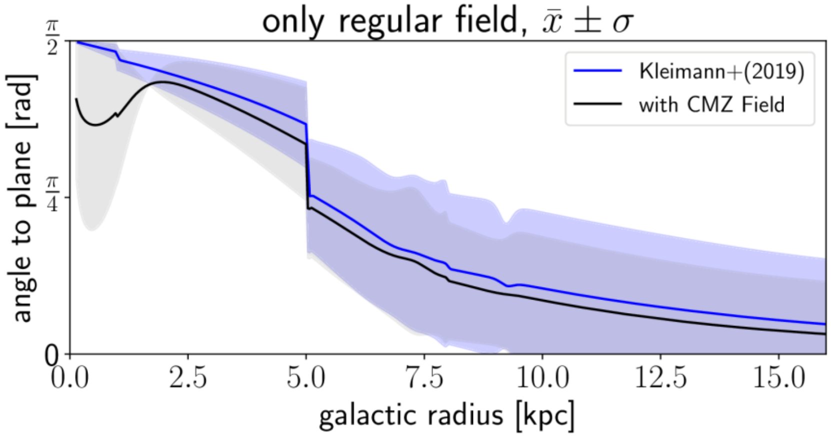
Leaky Box approximation: $\frac{dN}{dE} \propto E^{-\alpha_S - \gamma_i}$ $\alpha_S = 2.0$



timescale analysis

$$\nabla(\hat{\kappa}\ \nabla n) \approx \left(\frac{\kappa_\parallel}{d_\parallel^2} + \frac{\kappa_\perp}{d_\perp^2}\right) n = -\left(\frac{1}{\tau_\parallel} + \frac{1}{\tau_\perp}\right) n \sim -\frac{n}{\tau_{diff}}$$

Two main dependences



Reichherzer, Merten, Dörner et al.
Nat.Apl.Sc subm. 2021 (**inv.**)

Energy and turbulence

$$\tau_\parallel \propto \left(\frac{b}{B}\right)^2 B_{tot}^{\gamma_\parallel} \quad E^{-\gamma_\parallel}$$

$$\tau_\perp \propto \left(\frac{b}{B}\right)^{-2} B_{tot}^{\gamma_\perp} \quad E^{-\gamma_\perp}$$

Field direction / galactic radius

- Inner Galaxy ($r \leq 5\ kpc$) mainly parallel escape
- Outer Galaxy ($r > 5\ kpc$) mainly perpendicular escape
- Edge of Galaxy ($r \sim 19.5\ kpc$) parallel escape

$$\tau_{diff} \propto \begin{cases} E^{-\gamma_\parallel} & r_{gc} < 5\ kpc \\ E^{-\gamma_\perp} & elsewhere \\ E^{-\gamma_\parallel} & r_{gc} > 19\ kpc \end{cases}$$

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Setup for numerical simulation

- **Magnetic field:**
  global model Kleimann+ (2019)
  galactic center Guenduez+ (2020)

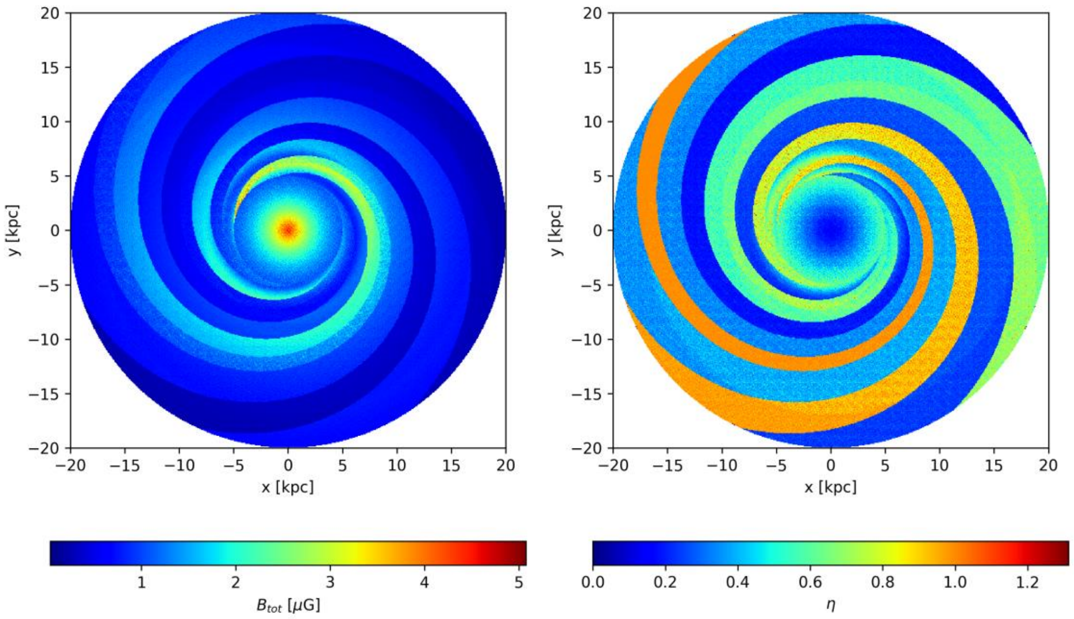
- **Source position follows the SNR distribution**

- **Source energy**

$$50\ GeV \leq E \leq 100\ TeV$$

- **Hadronic Interaction p-p**

CRPropa



Testing different diffusion models

Quasi-Linear Theory

$$\kappa_{\parallel}^{A}(E) = \kappa_0 \cdot \left(\frac{E}{4\ GeV}\right)^{\frac{1}{3}} \qquad \kappa_{\perp}^{A}(E) = \epsilon \cdot \kappa_{\parallel}^{A}$$

with turbulence dependence: $\boldsymbol{\eta = \frac{b}{B}}$

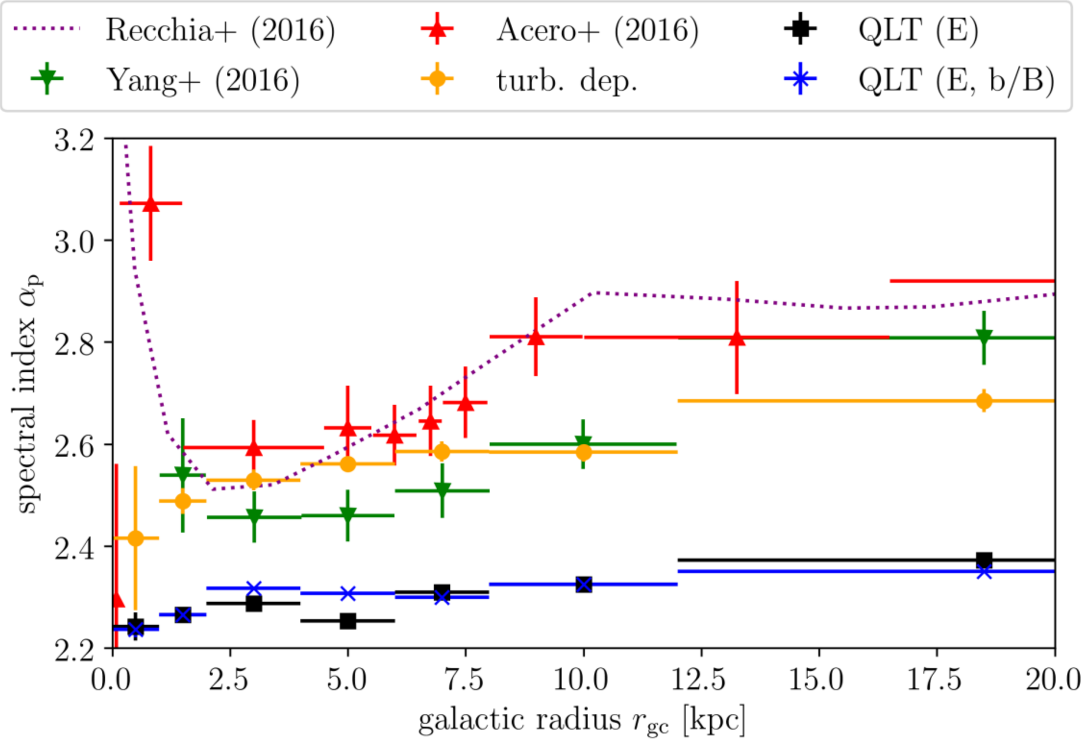
$$\kappa_{\parallel}^{B}(E,\eta) = \kappa_0 \cdot \left(\frac{\eta}{\eta_0}\right)^{-2} \left(\frac{E}{4\ GeV}\right)^{\frac{1}{3}} \qquad \kappa_{\perp}^{B}(E,\eta) = \kappa_0 \cdot \eta^2 \eta_0^2 \cdot \left(\frac{E}{4\ GeV}\right)^{\frac{1}{3}}$$

Full turbulence dependend:

$$\kappa_{\parallel}^{C}(E,\eta) = \kappa_0 \cdot \left(\frac{\eta}{\eta_0}\right)^{-2} \left(\frac{E}{4\ GeV}\right)^{\gamma_{\parallel}} \qquad \kappa_{\perp}^{C}(E,\eta) = \kappa_0 \cdot \eta^2 \eta_0^2 \cdot \left(\frac{E}{4\ GeV}\right)^{\gamma_{\perp}}$$

$\gamma_i = \gamma_i(\eta)$ (interpolated after Reichherzer et al. 2021)

Simulation result



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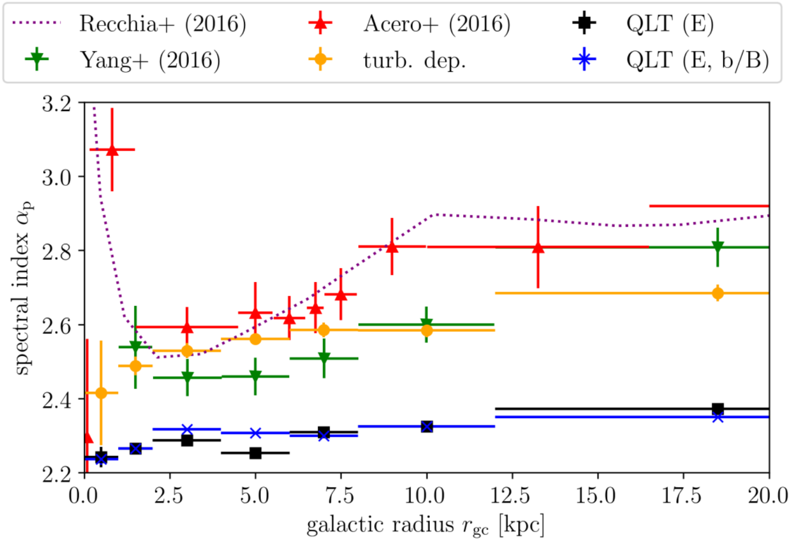
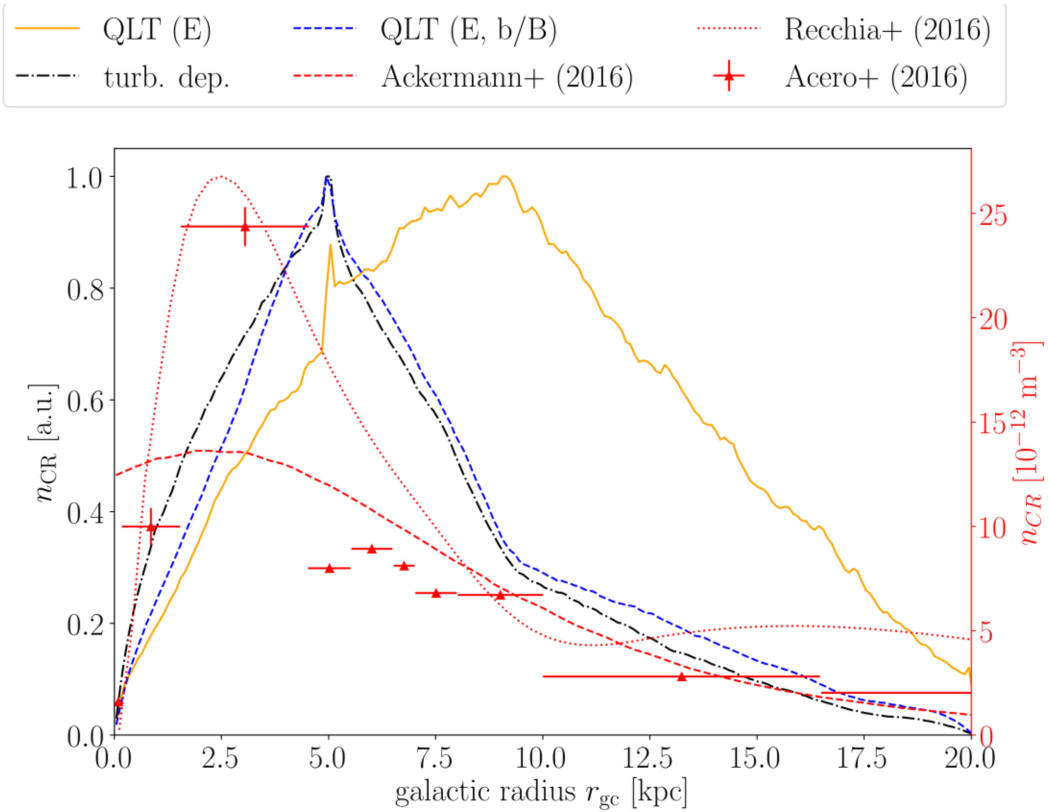
Simulation result





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Conclusions

Summary

- QLT is not a good prediction for galactic turbulence levels
- Turbulent dependence changes the CR density
- Transition in the spectral index

Outlook:

- Contribution by the galactic outflow for the GC needed