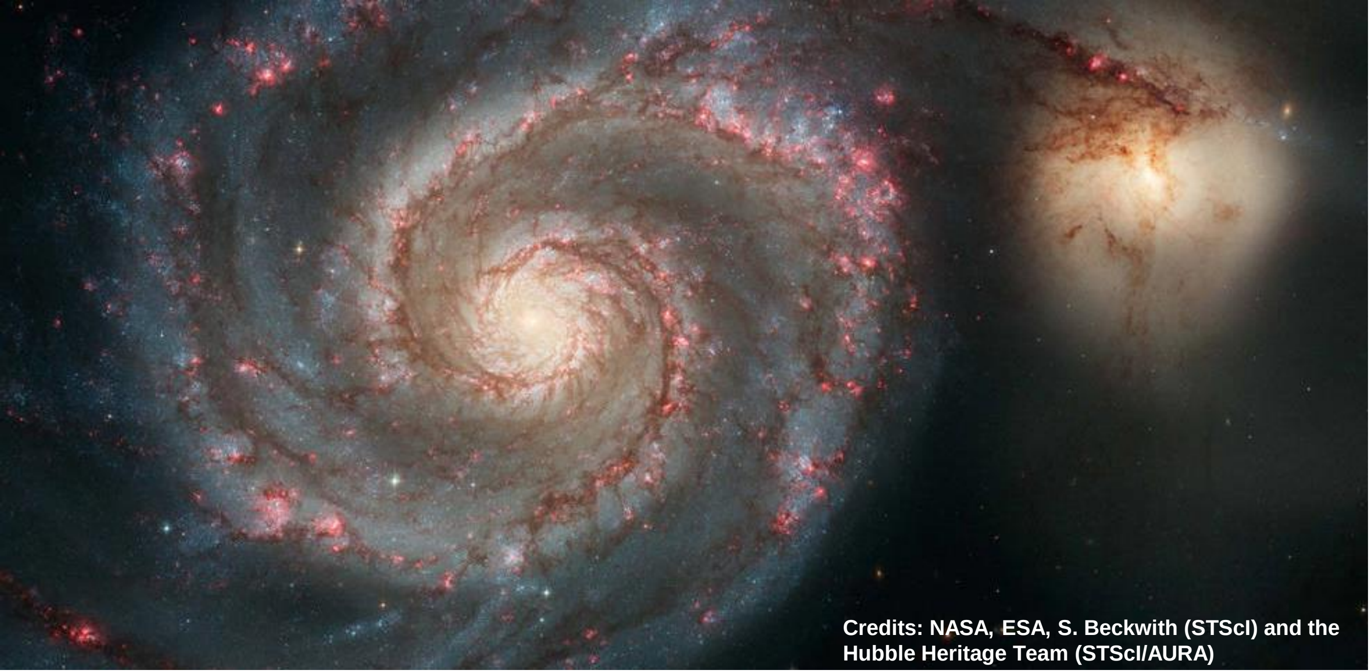


CRC 1491 –
Cosmic Interacting Matters
from source to signal

arXiv:2206.11670

RUHR-UNIVERSITÄT BOCHUM

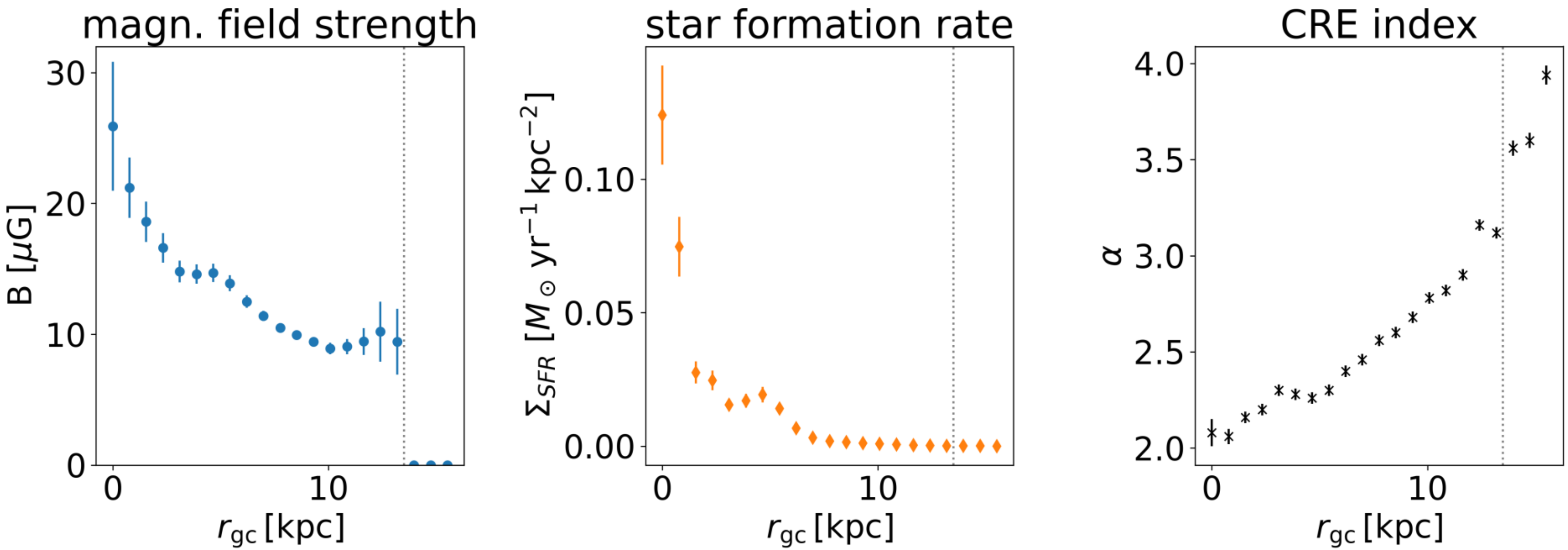
COSMIC RAY ELECTRON TRANSPORT IN THE EXTERNAL GALAXY M51

Julien Dörner | Patrick Reichherzer | Julia Becker Tjus | Volker Heesen

CRPropa Workshop – 14.-16. September 2022 - Madrid

arXiv:2206.11670

M51 observation

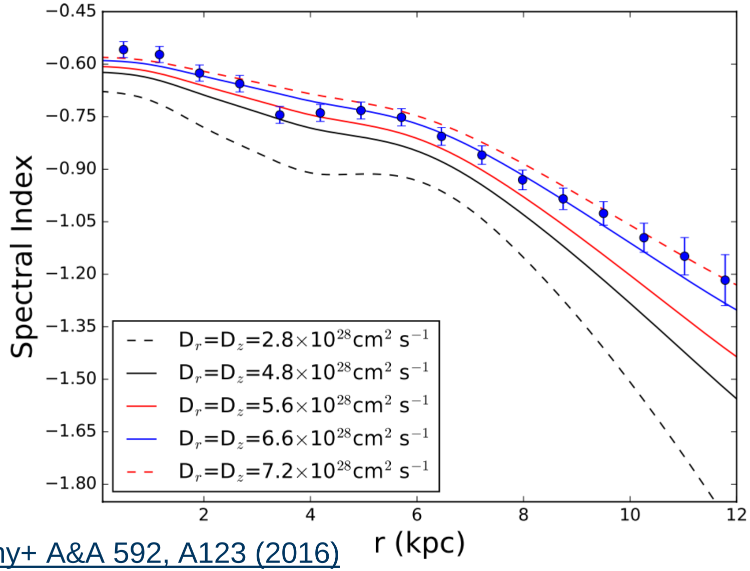


Heesen et al., (2022) arXiv:2208.11068 | Heesen et al., A&A, 622, A8 (2019) | Heesen et al., A&A, 622, A8 (2019)

arXiv:2206.11670

Transport model

$$\frac{\partial n}{\partial t} = D\,\nabla^2 n + \frac{\partial}{\partial E}\left[\frac{\partial E}{\partial t} n\right] + S(r,E) - \frac{n}{\tau}$$



Mulcahy+ A&A 592, A123 (2016)

Source following SFR $\quad S(r) \propto \Sigma_{SFR}(r)$

Energy loss: $\quad \frac{\partial E}{\partial t} \propto B^2(r)$

Escape via diffusion: $\quad \tau = \frac{h^2}{D}$

RAPP Center

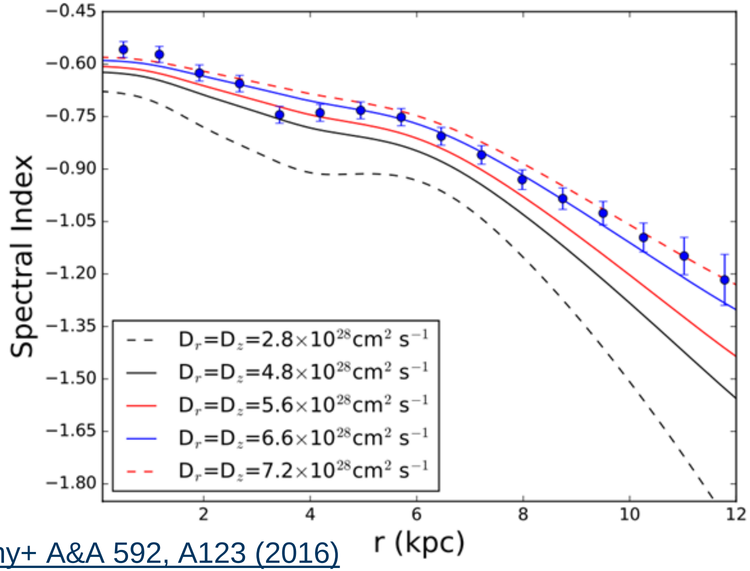
RUB

arXiv:2206.11670

Transport model

move to 3D simulation (DiffusionSDE)

$$\frac{\partial n}{\partial t} = D\,\nabla^2 n + \frac{\partial}{\partial E}\left[\frac{\partial E}{\partial t} n\right] + S(r,E) - \frac{n}{\tau} - \vec{v}\cdot\nabla n$$



Mulcahy+ A&A 592, A123 (2016)

Source following SFR $S(r) \propto \Sigma_{SFR}(r)$

Energy loss: $\frac{\partial E}{\partial t} \propto B^2(r)$

Escape via diffusion: $\tau = \frac{h^2}{D}$

CRPropa setup for 3D simulation - Diffusion

$$\frac{\partial n}{\partial t} = D\, \nabla^2 n + \frac{\partial}{\partial E}\left[\frac{\partial E}{\partial t} n\right] + S(r,E) - \vec{v} \cdot \nabla n$$

Isotropic diffusion $\hat{D} = \mathrm{D} \cdot \mathbb{E}_3$

Energy independent

$$D_0 = 2 \cdot 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}}$$

$$D_1 = 6 \cdot 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}}$$

Energy dependent

$$D_2 = 6.1 \cdot 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}} \left(\frac{E}{4\,\mathrm{GeV}}\right)^{\frac{1}{3}}$$

$$D_3 = 2 \cdot 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}} \left(\frac{E}{4\,\mathrm{GeV}}\right)^{1/3}$$

arXiv:2206.11670

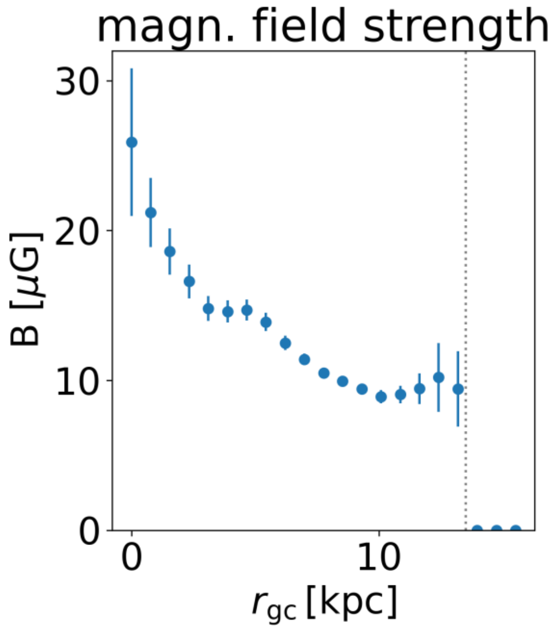
CRPropa setup for 3D simulation - Energy loss

$$\frac{\partial n}{\partial t} = D\,\nabla^2 n + \frac{\partial}{\partial E}\left[\frac{\partial E}{\partial t} n\right] + S(r,E) - \vec{v}\cdot\nabla n$$

- Synchrotron and IC
- Continuous energy loss approximation

$$\frac{\partial E}{\partial t} = \alpha\left(U_{rad} + \beta\,\frac{B^2(\vec{r})}{8\pi}\right)E^2$$

$$B(\vec{r}) = B_0(r_{gc})\cdot\exp\left(-\frac{|z|}{h_B}\right)$$



CRPropa setup for 3D simulation - Sources

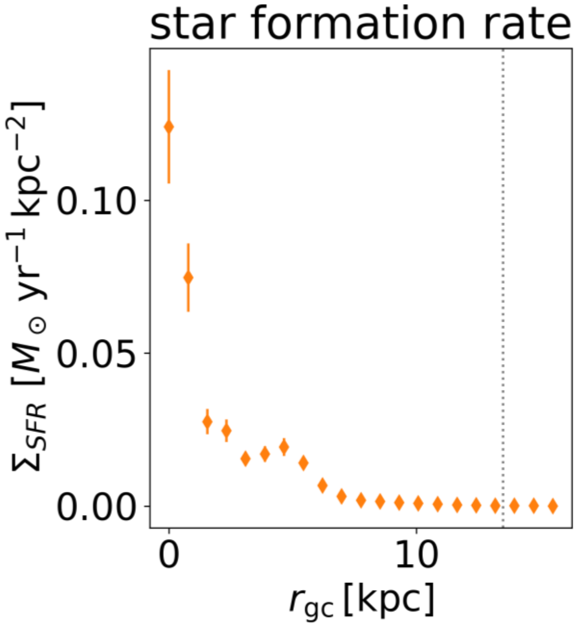
$$\frac{\partial n}{\partial t} = D\,\nabla^2 n + \frac{\partial}{\partial E}\left[\frac{\partial E}{\partial t} n\right] + S(r,E) - \vec{v}\cdot\nabla n$$

- Source position

$$S(\vec{r}) = S_0(r)\cdot\exp\left(-\frac{z^2}{h_s}\right) \qquad h_s = 80\ \mathrm{pc}$$

- Energy distribution $\frac{\mathrm{dN}}{\mathrm{dE}} \propto E^{-2}$

$$E \in [0.1\ \mathrm{GeV}, 50\ \mathrm{GeV}]$$



RAPP Center
RUB

CRPropa setup for 3D simulation - Advection

$$\frac{\partial n}{\partial t} = D\,\nabla^2 n + \frac{\partial}{\partial E}\left[\frac{\partial E}{\partial t} n\right] + S(r,E) - \vec{v}\cdot\nabla n$$

ection

$\frac{\mathrm{km}}{\mathrm{s}} \left(\Sigma_{SFR}(r_{gc})\right)^{0.41} \hat{e}_z$

- Only winds in z-direction

$$\vec{v}(\vec{r}) = \pm 10^{3.23}\,\frac{\mathrm{km}}{\mathrm{s}} \left(\Sigma_{SFR}(r_{gc})\right)^{0.41} \hat{e}_z$$

, **476**, 158 (2018)

Heesen et al., MNRAS, **476**, 158 (2018)

RAPP Center

RUB

arXiv:2206.11670

Geometry and Observer

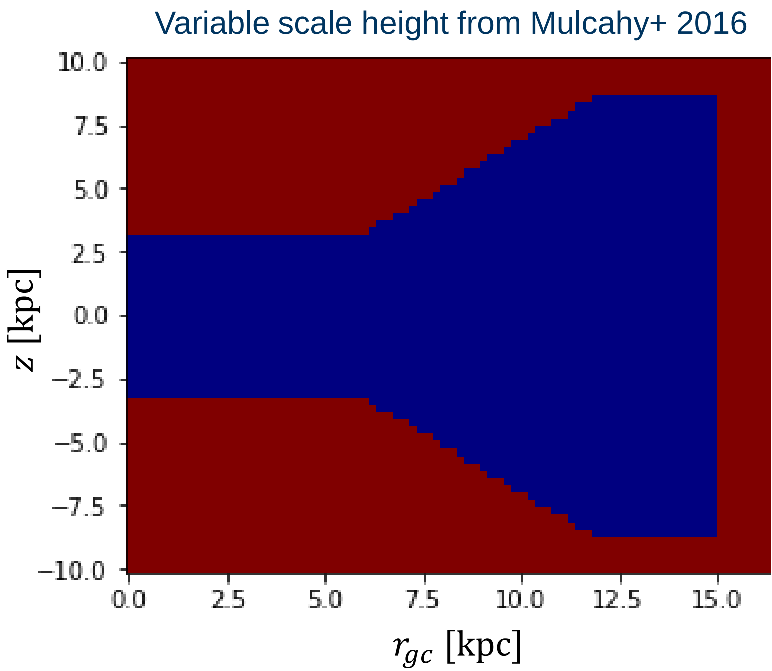
spherical shape

$r \in [0, 15\ \text{kpc}] \qquad z \in [-h_d, h_d]$

parameter	model A	model B	model C
h_B	7 kpc	6 kpc	$h(r)$
h_d	7 kpc	3 kpc	$h(r)$

ObserverTimeEvolution:

$N_{step} = 1000 \qquad \Delta T = 500\ \text{kyr}$

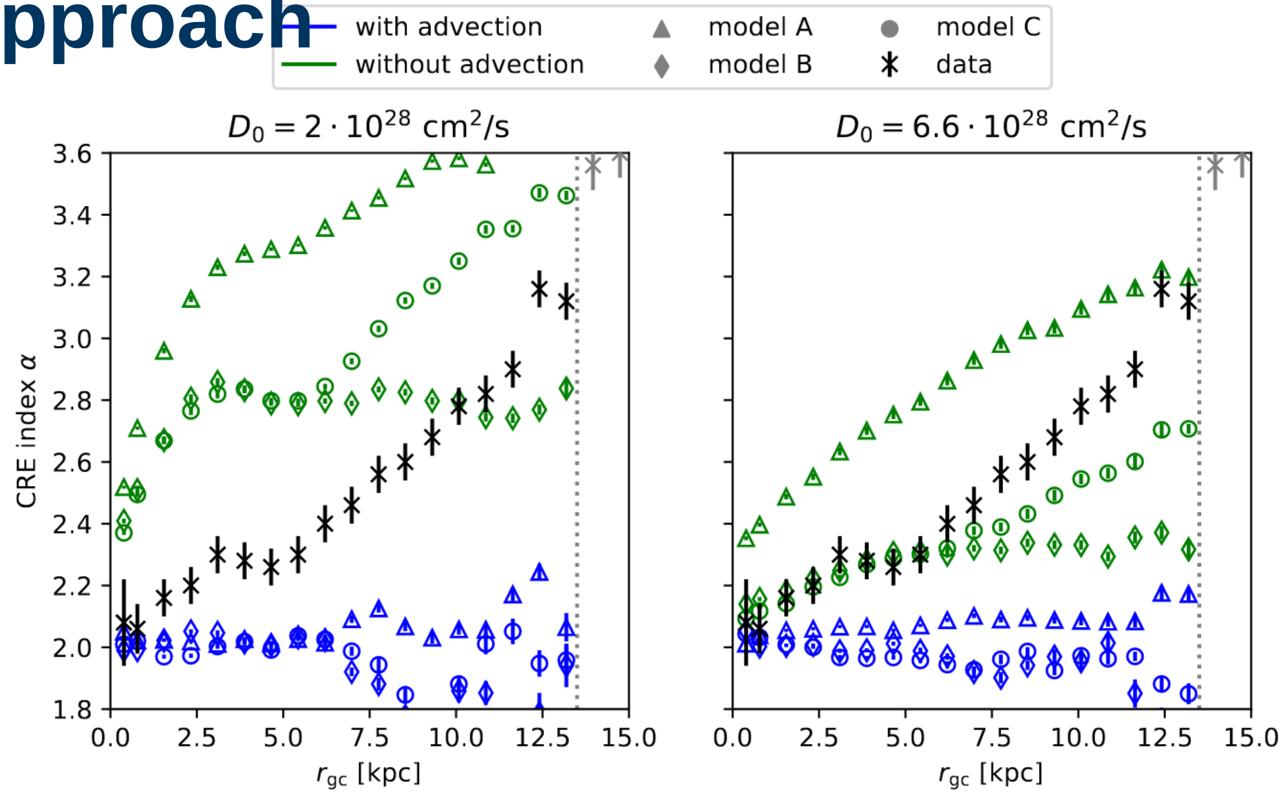


First model approach

Escape time is

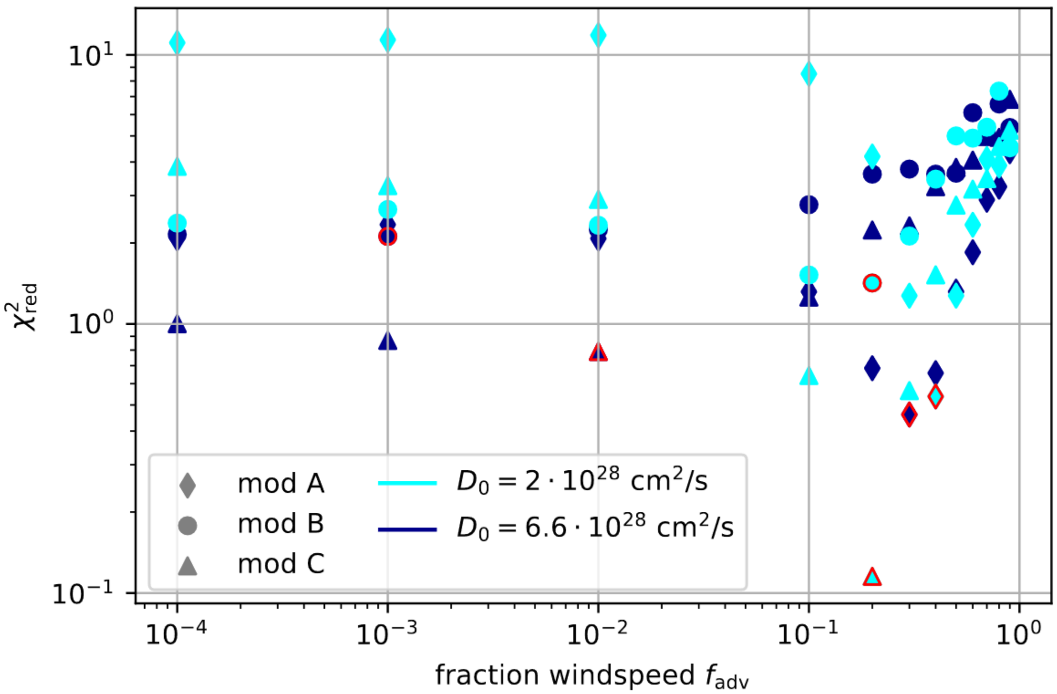
- too short when including advection
- to high for lower diffusion coefficient

$$\vec{v}(\vec{r}) = f_{adv}\, v_{SFR}(r)\, \vec{e}_z$$



arXiv:2206.11670

Optimization of the reduction factor

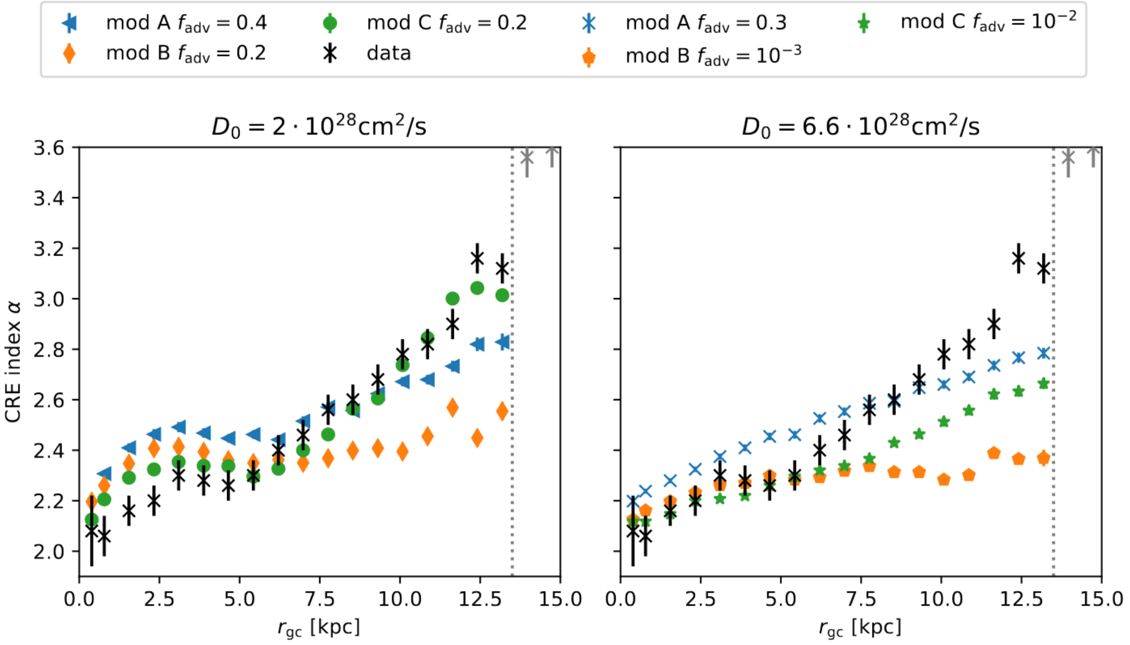


- preferred lower diffusion coefficient
- preferred variable scale height
- sharp minimum

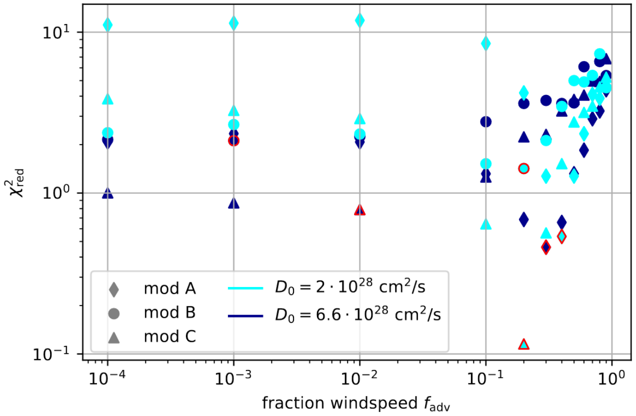
RAPP Center
RUB

arXiv:2206.11670

Optimization of the reduction factor

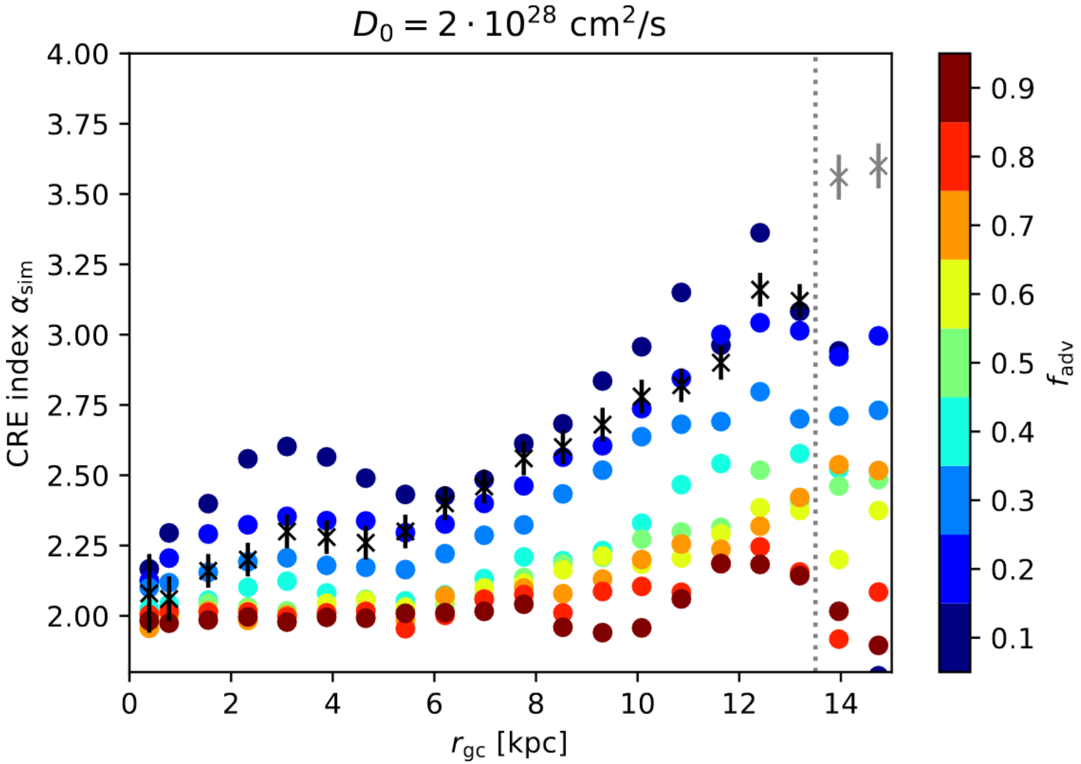


- preferred lower diffusion coefficient
- preferred variable scale height
- sharp minimum

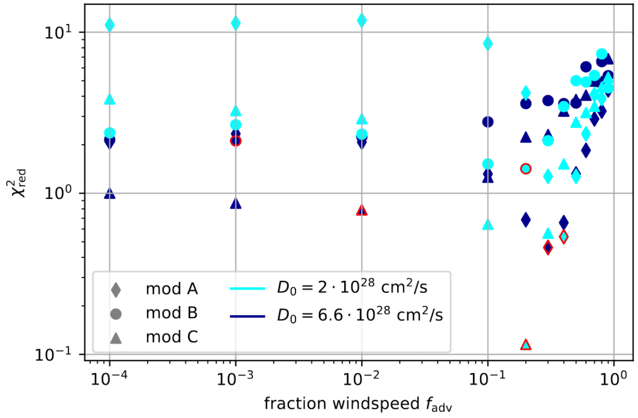


arXiv:2206.11670

Optimization of the reduction factor



- preferred lower diffusion coefficient
- preferred variable scale height
- sharp minimum

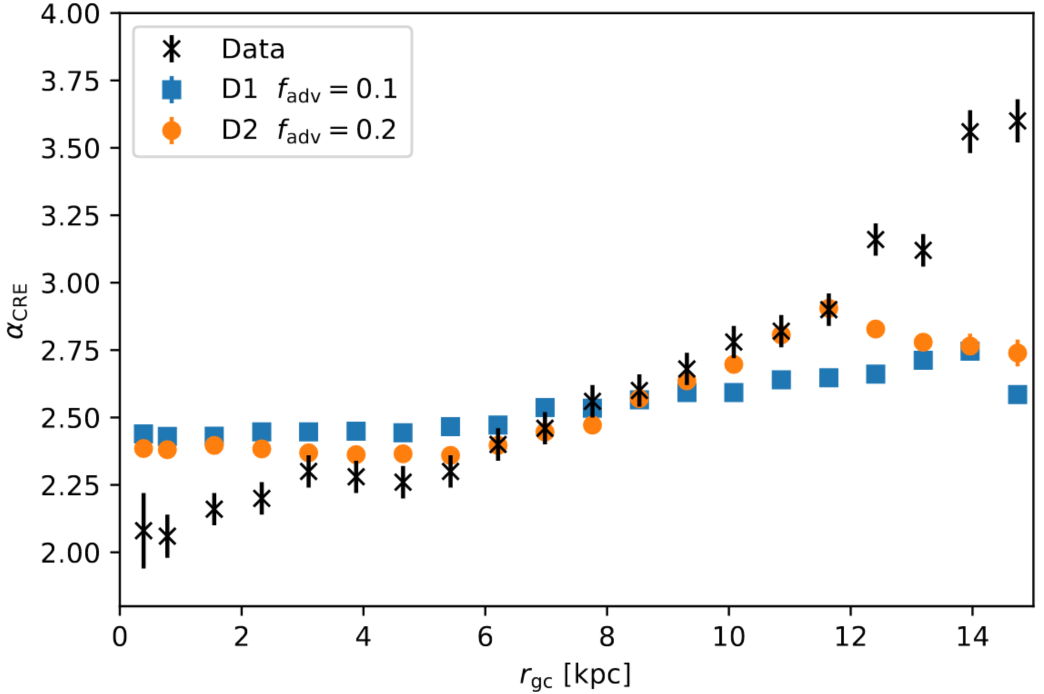


Domparing energy dependent models

$$D_1 = 6.1 \cdot 10^{28} \frac{\mathrm{cm}^2}{\mathrm{s}} \left(\frac{E}{4\ \mathrm{GeV}}\right)^{\frac{1}{3}}$$

$$D_2 = 2 \cdot 10^{28} \frac{\mathrm{cm}^2}{\mathrm{s}} \left(\frac{E}{4\ \mathrm{GeV}}\right)^{1/3}$$

No good agreement in the inner galaxy



RAPP Center RUB

arXiv:2206.11670

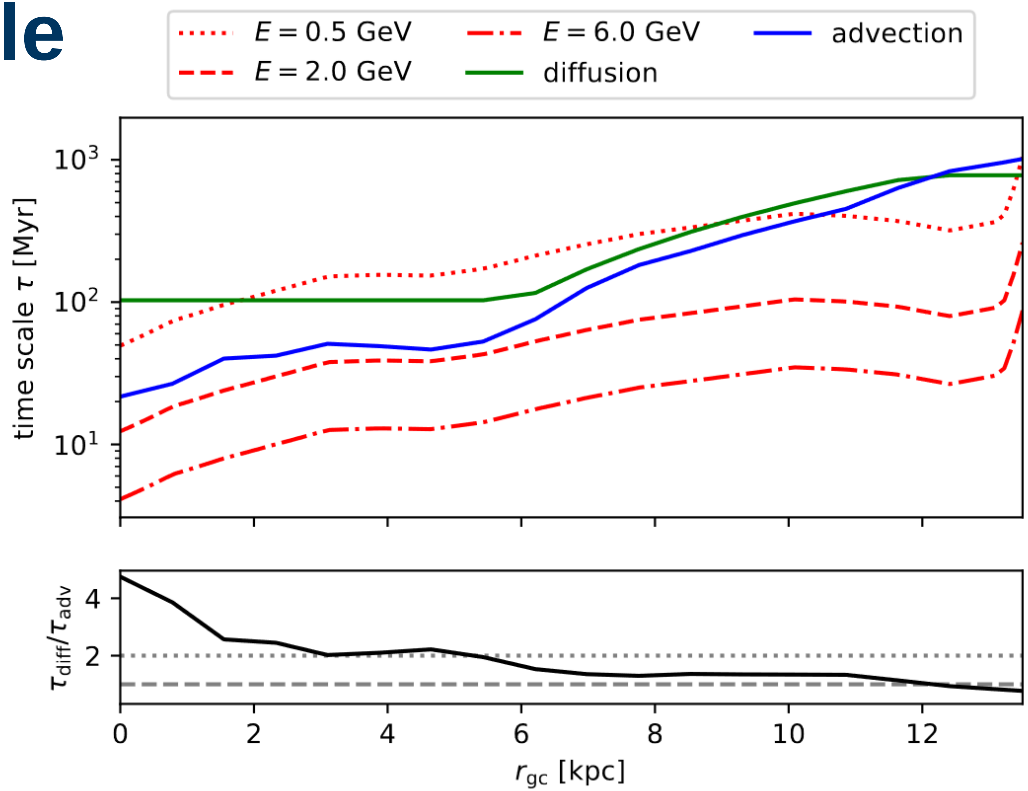
Dominating timescale

Escape:

- Central galaxy dominated by advection
- Outer galaxy mixture of advection and diffusion

Energy loss dominate escape

⇒ should lead to a break in the CRE spectrum



RAPP Center RUB

Conclusion

3-dimensional modelling gives insights in (not observable) galactic winds

- Energy independent diffusion with $D_0 = 2 \cdot 10^{28}\,\frac{\mathrm{cm}^2}{\mathrm{s}}$ in good agreement with the data
- Variable scale height for the escape of CRE
- Advection speed must be reduced by 5