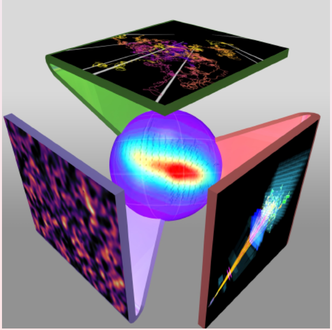
# SFB 1491
# Highlights from the Astro-Theory Projects

Horst Fichtner



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# Highlighting the Astro-Theory Projects

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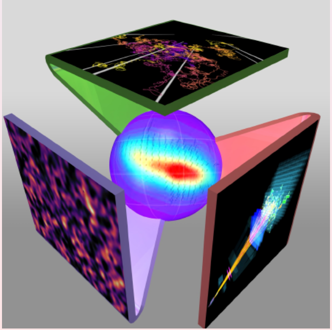

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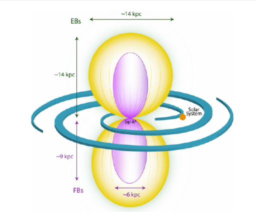

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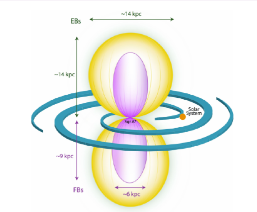


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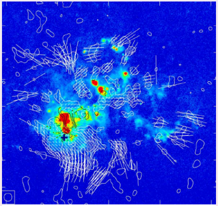

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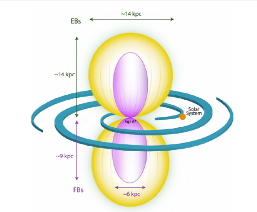


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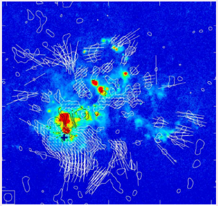

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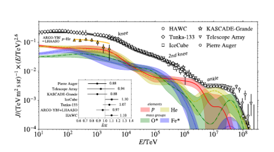

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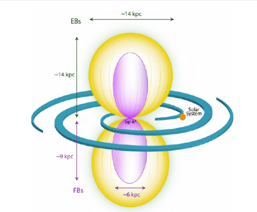


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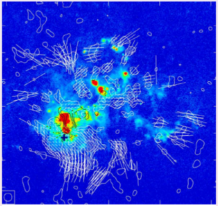

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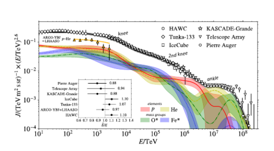
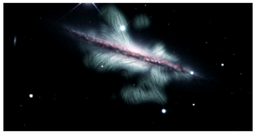



**A4:** Magnetohydrodynamical halos of starforming galaxies



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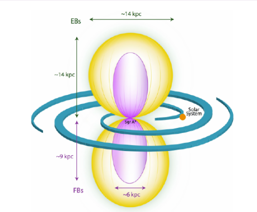


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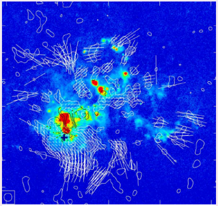

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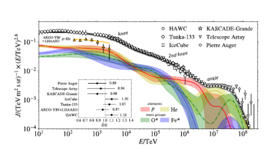


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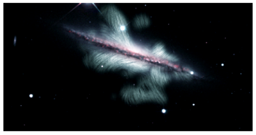

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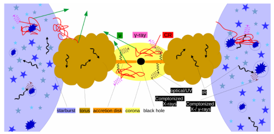

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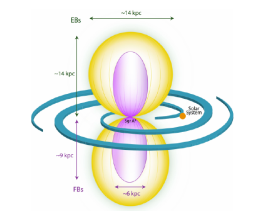


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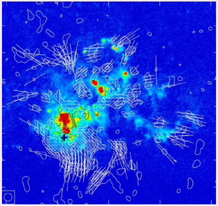

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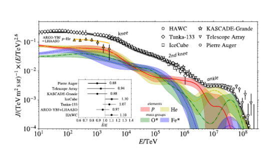


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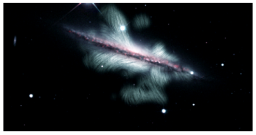

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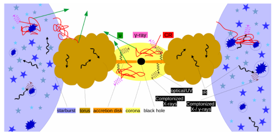
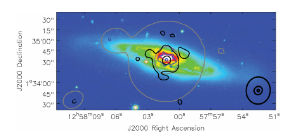



**A6:** Multimessenger signatures of tidal disruption events



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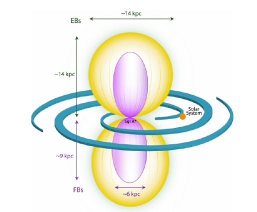


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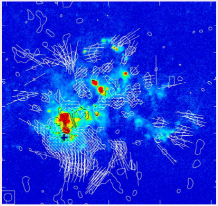

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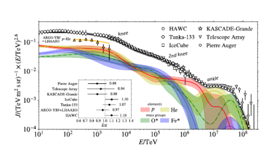


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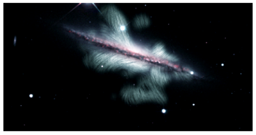

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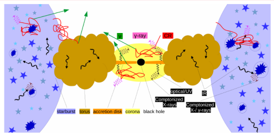
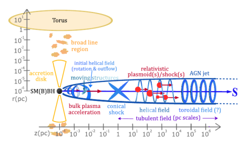
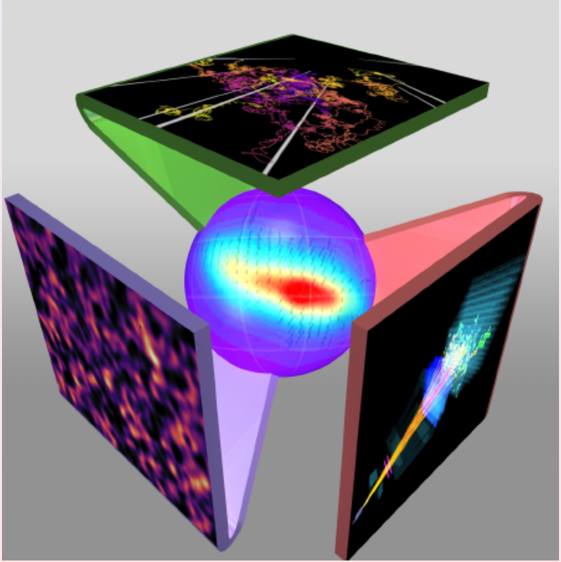



**A7:** Density-dependence of the temporal structure in the multimessenger spectrum of blazars



# The Astro-Theory Projects and the SFB Logo



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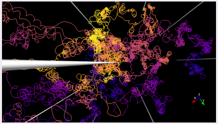
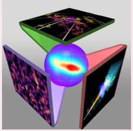


CR transport in turbulent magnetic fields

↑



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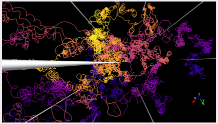

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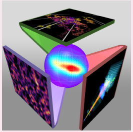

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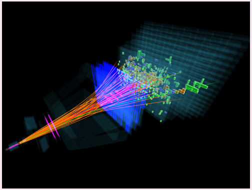

Hadronic interactions in particle physics and astrophysics:
CR signatures

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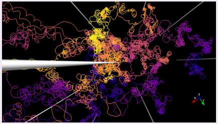

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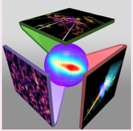

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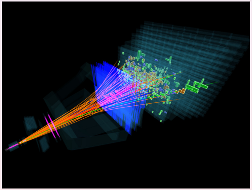

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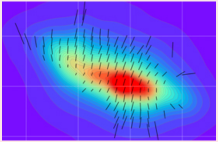
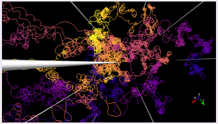
M82: magnetic fields in dynamical halos



# The Astro-Theory Projects and the SFB Logo

Dark matter in and around galaxies



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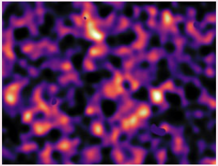
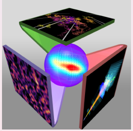
$\uparrow$



$\leftarrow$



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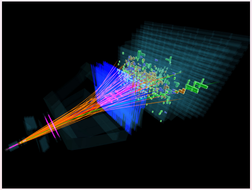

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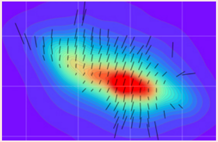

Hadronic interactions in particle physics and astrophysics:
CR signatures

# Outline of the Talk

- Introduction (✓)
- CR transport in turbulent magnetic fields
- Turbulent dynamical halos of galaxies
- Dark matter signatures?

# Cosmic Ray Transport in Turbulent Magnetic Fields

# The CR transport equation

$$\frac{\partial n}{\partial t} = \nabla \cdot \left[ \overleftrightarrow{D} \nabla n - \vec{U} n \right]$$ spatial diffusion & advection

$$+ \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \left( \frac{n}{p^2} \right) \right]$$ momentum diffusion

$$- \frac{\partial}{\partial p} \left[ \left( \frac{dp}{dt} - \frac{p}{3} (\nabla \cdot \vec{U}) \right) n \right]$$ momentum loss & adiab. changes

$$- \frac{n}{\tau_f} - \frac{n}{\tau_d} + S$$ fragmentation & radioactive decay & sources

$n = n(\vec{r}, p, t)$, $\overleftrightarrow{D} = \overleftrightarrow{D} (\vec{r}, p, t)$, $\vec{U} = \vec{U}(\vec{r}, t)$, $D_{pp} = D_{pp}(\vec{r}, p, t)$,
$S = S(\vec{r}, p, t)$

*Schlickeiser [2002], Becker-Tjus & Merten et al. [2020]*

## The CR transport equation

$$\frac{\partial n}{\partial t} = \nabla \cdot \left[\overleftrightarrow{D} \nabla n - \vec{U} n\right] \qquad \text{A1, A2, A3, A4, A5, A7}$$

$$+ \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} \left(\frac{n}{p^2}\right)\right] \qquad \text{A1, A5}$$

$$- \frac{\partial}{\partial p} \left[\left(\frac{dp}{dt} - \frac{p}{3} (\nabla \cdot \vec{U})\right) n\right] \qquad \text{A1, A2, A3, A5, A7}$$

$$- \frac{n}{\tau_f} - \frac{n}{\tau_d} + S \qquad \text{A1, A2, A3, A5, A7}$$

$n = n(\vec{r}, p, t)$, $\overleftrightarrow{D} = \overleftrightarrow{D}(\vec{r}, p, t)$, $\vec{U} = \vec{U}(\vec{r}, t)$, $D_{pp} = D_{pp}(\vec{r}, p, t)$,
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*Schlickeiser [2002], Becker-Tjus & Merten et al. [2020]*

# The Central Transport Quantity: The Diffusion Tensor

Study of large-scale transport requires transformation of the diffusion tensor from a (field-aligned) local to a global system:

- Which local system is the most 'natural' one?

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- The correct choice of the 'perpendicular' directions is important for the case of anisotropic perpendicular diffusion.

# The Central Transport Quantity: The Diffusion Tensor

Study of large-scale transport requires transformation of the diffusion tensor from a (field-aligned) local to a global system:

- Which local system is the most 'natural' one?
- One principal direction aligned with magnetic field.
- The correct choice of the 'perpendicular' directions is important for the case of anisotropic perpendicular diffusion.
- The most natural directions are defined with the Frenet-Serret trihedron, i.e. by the curvature and torsion of a magnetic field:

$$\vec{t} = \vec{B}/B \quad ; \quad \vec{n} = (\vec{t} \cdot \nabla)\,\vec{t}/k \quad ; \quad \vec{b} = \vec{t} \times \vec{n}$$

# The Central Transport Quantity: The Diffusion Tensor

The **general transformation** reads: (*Effenberger et al. [2012b]*)

$$\overleftrightarrow{D}_{global} = A^T \overleftrightarrow{D}_{local} A$$

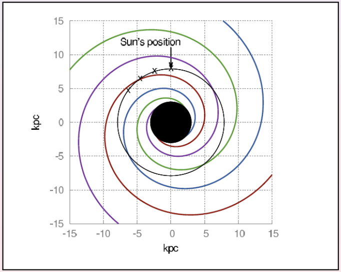
with $A = \begin{pmatrix} n_1 & b_1 & t_1 \\ n_2 & b_2 & t_2 \\ n_3 & b_3 & t_3 \end{pmatrix}$ and $\overleftrightarrow{D}_{local} = \begin{pmatrix} D_{\perp 1} & 0 & 0 \\ 0 & D_{\perp 2} & 0 \\ 0 & 0 & D_{\|} \end{pmatrix}$

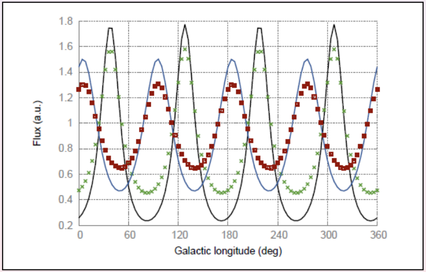
resulting in

$$\begin{aligned}
D_{11} &= D_{\perp 1}\, n_1^2 + D_{\perp 2}\, b_1^2 + D_{\|}\, t_1^2 \\
D_{12} &= D_{\perp 1}\, n_1\, n_2 + D_{\perp 2}\, b_1\, b_2 + D_{\|}\, t_1\, t_2 \\
D_{13} &= D_{\perp 1}\, n_1\, n_3 + D_{\perp 2}\, b_1\, b_3 + D_{\|}\, t_1\, t_3 \\
D_{22} &= D_{\perp 1}\, n_2^2 + D_{\perp 2}\, b_2^2 + D_{\|}\, t_2^2 \\
D_{23} &= D_{\perp 1}\, n_2\, n_3 + D_{\perp 2}\, b_2\, b_3 + D_{\|}\, t_2\, t_3 \\
D_{33} &= D_{\perp 1}\, n_3^2 + D_{\perp 2}\, b_3^2 + D_{\|}\, t_3^2
\end{aligned}$$

# Impact of Anisotropic Diffusion on Galactic Propagation

Orbit of the Sun through the spirally structured galactic cosmic ray (proton) distribution:




black, green: 1, 100 GeV at 7.9 kpc

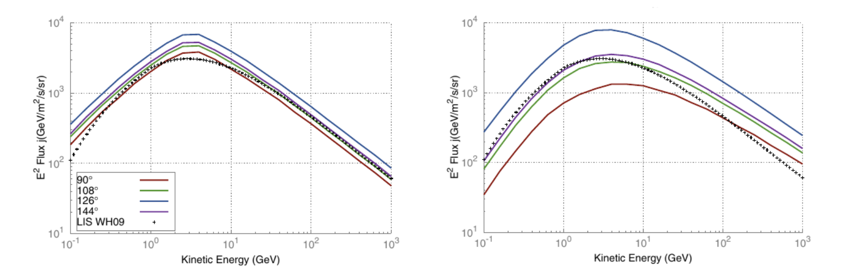
blue, red: 1, 100 GeV at 5.0 kpc

- stronger intensity variations for anisotropic spatial diffusion
- higher absolute intensities for anisotropic diffusion

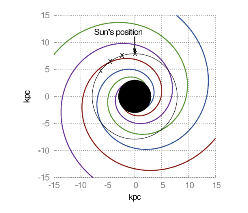
  (isotropic: $D_{\perp 1} = D_{\perp 2} = D_{\perp} = D_{\parallel}$; anisotropic: $D_{\perp} = 0.01 D_{\parallel}$)

# Impact of Anisotropic Diffusion on Galactic Propagation

... and a different local interstellar spectrum:




$D_\perp = D_\parallel$ $\qquad$ $D_\perp = 0.01 D_\parallel$




*Effenberger et al. [2012b]*

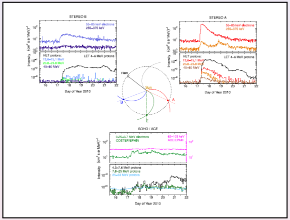
# Anisotropic Interstellar Diffusion

**Anisotropic spatial diffusion** of cosmic ray protons in the interstellar medium...

- ... causes **stronger intensity variations**;
- ... leads to **higher absolute fluxes** due to a confinement effect;
- ... **influences the local interstellar spectrum**

... at the location of the Sun / Heliosphere in the Galaxy.

# The Central Transport Quantity: The Diffusion Tensor




*Dresing et al. [2012]*

**turbulence is crucial for the transport of energetic particles**

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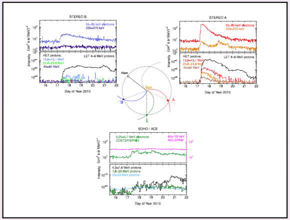


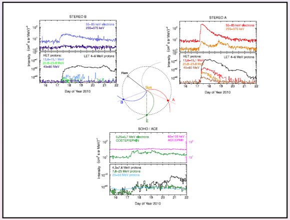

*Dresing et al. [2012]*

**turbulence is crucial for the transport of energetic particles**

but: $\overbrace{\delta B^2}^{1-comp.\ model}$

| *transport process* | *1-comp. model* | |
|---|---|---|
| *parallel diffusion* $D_{\parallel}$ | $\sim B^2/\delta B^2$ | |
| *perpendicular diffusion* $D_{\perp}$ | $\sim \delta B^2/B^2$ | |
| *drifts* $D_A$ | $= D_A\left(\delta B^2/B^2\right)$ | |
| *momentum diffusion* $D_{pp}$ | $= D_{pp}\left(\delta B^2/B^2\right)$ | |

# The Central Transport Quantity: The Diffusion Tensor



*Dresing et al. [2012]*

**turbulence is crucial for the transport of energetic particles**

but: $$\overbrace{\delta B^2}^{1-comp.\ model} = \overbrace{\underbrace{\delta B^2_{2D}}_{\substack{\text{'quasi-2D'} \\ \text{low frequency} \\ k \approx k_\perp}} + \underbrace{\delta B^2_{sl}}_{\substack{\text{'slab/wave-like'} \\ \text{high frequency} \\ k \approx k_\parallel}}}^{2-comp.\ model}$$

| *transport process* | *1-comp. model* | |
|---|---|---|
| *parallel diffusion* $D_\parallel$ | $\sim B^2/\delta B^2$ | |
| *perpendicular diffusion* $D_\perp$ | $\sim \delta B^2/B^2$ | |
| *drifts* $D_A$ | $= D_A\left(\delta B^2/B^2\right)$ | |
| *momentum diffusion* $D_{pp}$ | $= D_{pp}\left(\delta B^2/B^2\right)$ | |

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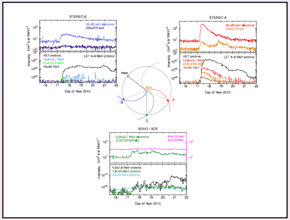


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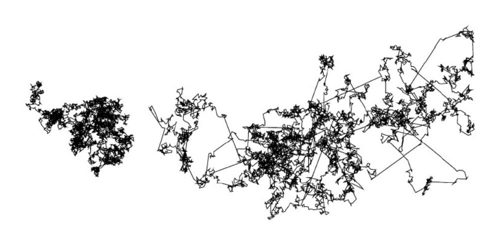
## What if transport is non-diffusive?

**Idea:** The particles are not diffusing normally (= 'Gaussian') but anomalously:

$$\langle \Delta x^2 \rangle \sim \begin{cases} t, & \text{Gaussian diffusion} \\ t^{\zeta}, & \text{anomalous diffusion} \begin{cases} 0 < \zeta < 1, & \text{subdiffusion} \\ 1 < \zeta < 2, & \text{superdiffusion} \end{cases} \end{cases}$$

(sub-) diffusion: (extended 'waiting times')



super- diffusion: 'Levy flights'

Levy flights $\Rightarrow$ **power law distributions**

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- ballistic motion: equation of motion

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Fokker Planck eq.

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- anom. diff. motion: $\frac{\partial f}{\partial t} = {}_0 D_t^{1-\alpha} \left( \hat{D}_\mu \frac{\partial^\mu f}{\partial x^\mu} \right)$

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- diffusive motion: $\frac{\partial f}{\partial t} = D\frac{\partial^2 f}{\partial x^2}$ $\Leftrightarrow$ $dX(t) = D^{1/2}dW(t)$
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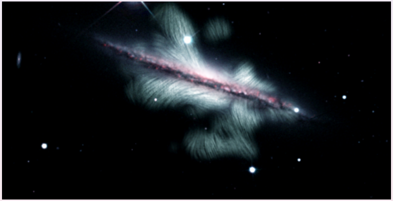
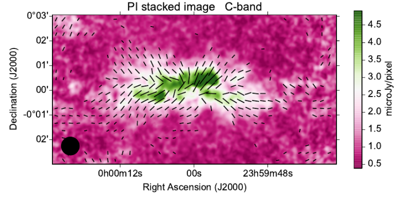
Simulation framework **CRPropa** (to be used extensively in the SFB) offers a ‘unifying’ treatment regarding transport and energy regimes

$\longrightarrow$ **see talks by P. Reichherzer and J. Dörner**

# Turbulent Dynamical Halos

# Dynamical Halos






polarized intensity of NGC 4217

stacked images of 28 CHANG-ES galaxies

⟶ **see talk by M. Stein**

# MHD Description

- large-scale equations:

$$\partial_t \rho + \nabla \cdot (\rho \vec{U}) = 0$$

$$\partial_t(\rho \vec{U}) + \nabla \cdot \left[ \rho \vec{U}\vec{U} + \left( p + \frac{|\vec{B}|^2}{2} + p_{\mathrm{w}} \right) \mathbb{1} - \left( 1 + \frac{\sigma_D \rho Z^2}{2B^2} \right) \vec{B}\vec{B} \right] = -\rho \vec{g}$$

$$\partial_t e + \nabla \cdot \left[ e\vec{U} + \left( p + \frac{|\vec{B}|^2}{2} \right) \vec{U} - (\vec{U} \cdot \vec{B})\vec{B} \right] + \vec{q}_{\mathrm{H}} - \frac{\rho H_{\mathrm{c}}}{2} \vec{V}_{\mathrm{A}}$$
$$= -\rho \vec{U} \cdot \vec{g} - \vec{U} \cdot \nabla p_{\mathrm{w}} - (\vec{V}_{\mathrm{A}} \cdot \nabla \rho) \frac{H_{\mathrm{c}}}{2} + \frac{\rho Z^3 f}{2\lambda}$$
$$+ \vec{U} \cdot (\vec{B} \cdot \nabla) \left[ \frac{\sigma_D \rho Z^2}{2B^2} \vec{B} \right] - \rho \vec{V}_{\mathrm{A}} \cdot \nabla H_{\mathrm{c}}$$

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- small-scale equations:

$$\partial_t Z^2 + \nabla \cdot (\vec{U} Z^2 + \vec{V}_{\mathrm{A}} H_{\mathrm{c}}) = \frac{Z^2(1 - \sigma_D)}{2} \nabla \cdot \vec{U} + 2\vec{V}_{\mathrm{A}} \cdot \nabla H_{\mathrm{c}} + \frac{Z^2 \sigma_D}{|\vec{B}|^2} \vec{B} \cdot (\vec{B} \cdot \nabla) \vec{U} - \frac{\alpha Z^3 f^+}{\lambda} + S$$

$$\partial_t H_{\mathrm{c}} + \nabla \cdot (\vec{U} H_{\mathrm{c}} + \vec{V}_{\mathrm{A}} Z^2) = \frac{H_{\mathrm{c}}}{2} \nabla \cdot \vec{U} + 2\vec{V}_{\mathrm{A}} \cdot \nabla Z^2 + Z^2 \sigma_D \nabla \cdot \vec{V}_{\mathrm{A}} - \frac{\alpha Z^3 f^-}{\lambda}$$

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$$p_w = \delta B^2 = (1+\sigma_D)\rho Z^2/4 \Rightarrow \overleftrightarrow{D}$$

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# MHD Simulation Output

- large-scale eqs: velocity field, magnetic field, ... $\rightarrow$ A1, A2
- small-scale eqs: turbulence... $\rightarrow$ F1 $\rightarrow$ (modified) diffusion tensor
  $\longrightarrow$ **see talk by F. Effenberger**

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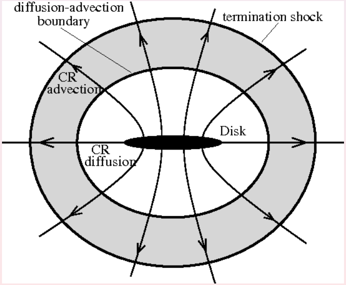
- assume intergalactic medium

  $\longrightarrow$ bow shock as a consequence of a galactic wind $\rightarrow$ A3




$\longrightarrow$ **see talk by A. Kääpä**

*Jokipii & Morfill [1985], Völk & Ziraqashvili [2003], Merten et al. [2018]*

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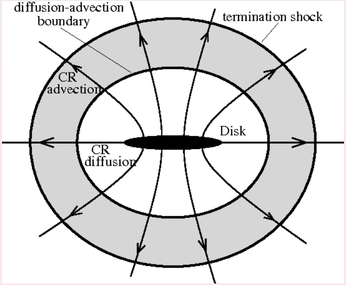


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*Jokipii & Morfill [1985],*

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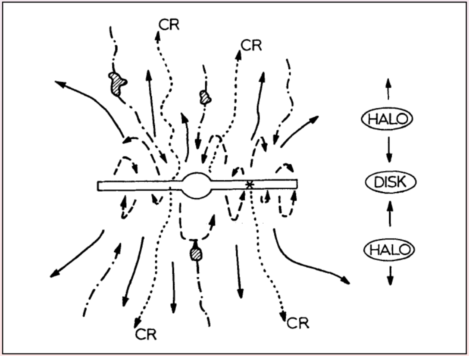
In the MHD code **Cronos** the large- and small-scale equations are implemented already (originally for heliospheric applications)

# Dark Matter

# Consequences of Dark Matter

- A1: Dark matter signature from Galactic center?
- A2: Dark matter signatures from dwarf galaxies?
- A4: Impact on halo dynamics?

$\longrightarrow$ global winds, partial winds, fountains, ... ?

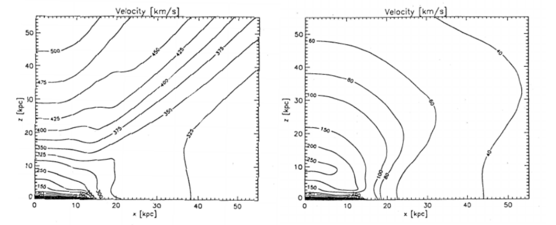



*Völk et al. [1989]*

# Consequences of Dark Matter

Adding a (spherical/axisymmetric/triaxial) dark halo potential (determined in F6) may also result in *breeze solutions*:

Wind Breeze




*Fichtner & Vormbrock [1997], Taylor & Giacinti [2017]*

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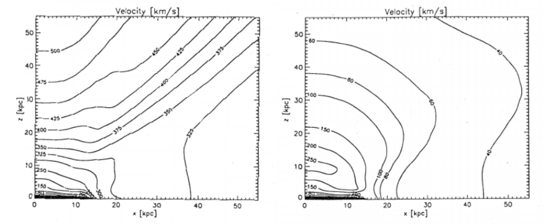


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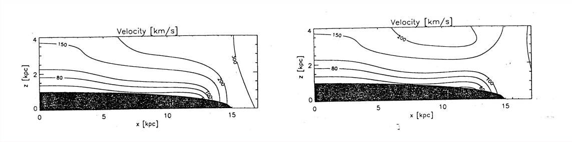
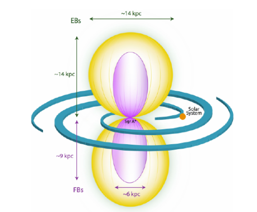


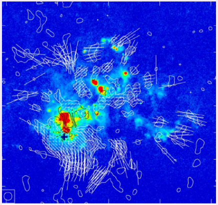
# Résumé

# Well... instead of a Résumé: Check the next Annual Meeting ☺

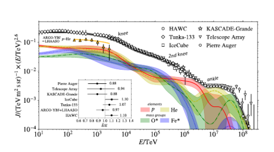
**A1:** Multimessenger signatures of Gal. CR transport



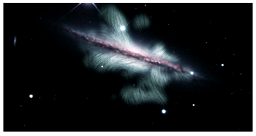

**A2:** CR signatures in dwarf galaxies



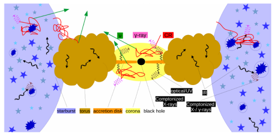
**A3:** CR transport in the transition region from Galactic to extragalactic origin



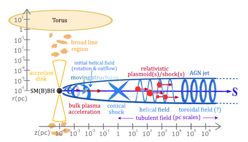

**A4:** Magnetohydrodynamical halos of starforming galaxies



**A5:** Disentangling cosmic-ray signatures in AGN-starburst composites




**A7:** Density-dependence of the temporal structure in the multimessenger spectrum of blazars



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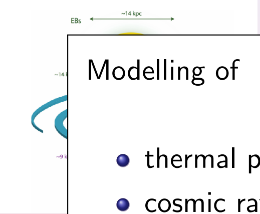


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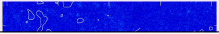

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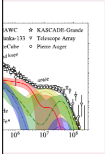


Modelling of

- thermal plasma dynamics
- cosmic ray transport
- turbulence
- multimessenger signatures

not new in all aspects but new in this coordinated fashion

**A4:** M
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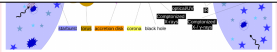


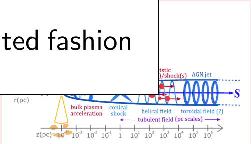

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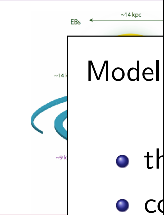


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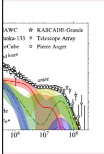
**A3:** CR transport in the transition region from ... c to extragalactic




**A4:** M... ical h... galaxie...

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