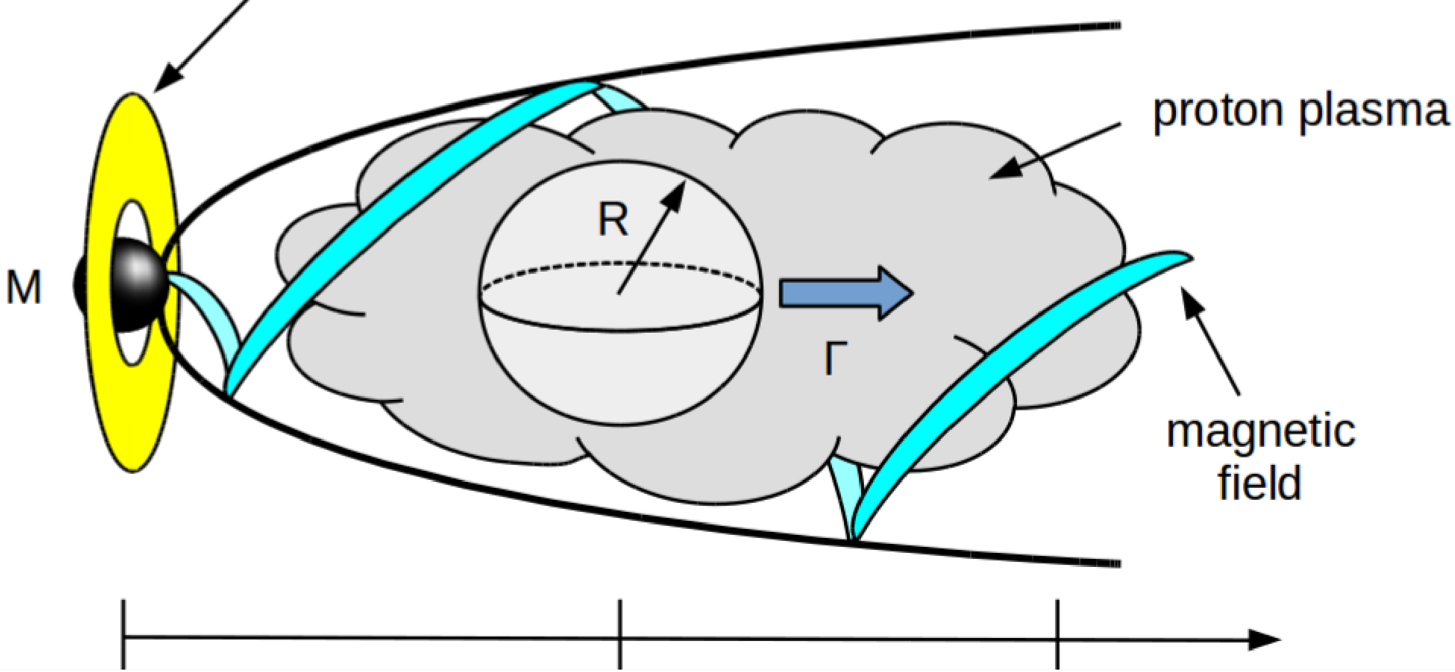

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COINCIDENT NEUTRINO AND GAMMA-RAY EMISSION FROM BLAZARS

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Motivation I – AGN as Multi-Messenger Sources

- **Active Galactic Nuclei (AGN) are one of the most luminous, observable sources**
  - Engine of the cosmic rays with highest energies up to $E_{CR} = 10^{21}$eV ?
- **Modelling is challenging; ambiguous signatures need to be understood via numerical simulation.**

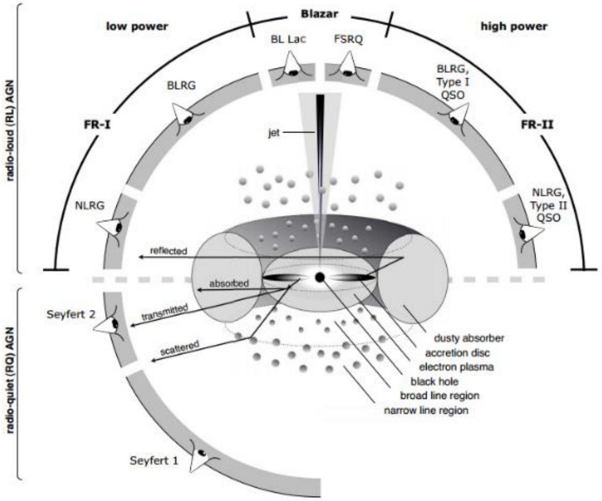

Fig. 1: Unified model of AGN: Classification regarding line of sight, luminosity and radio emissivity. Ref. to: [Beckmann, Shrader POS (2013)]

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Motivation II – γ suppression vs. ν-emission

- **Example: Observations of blazar PKS 1502+106:**
  - Hint onto association of blazar to IceCube-event IC-190730A
- **Long-term survey of gamma-ray and radio fluxes show some correlation**
- **At event time IC-190730A: Deficient gamma-ray flux while de-correlated, strong radio activity**
- **Question: Can we implement models, which reproduce this behavior?**

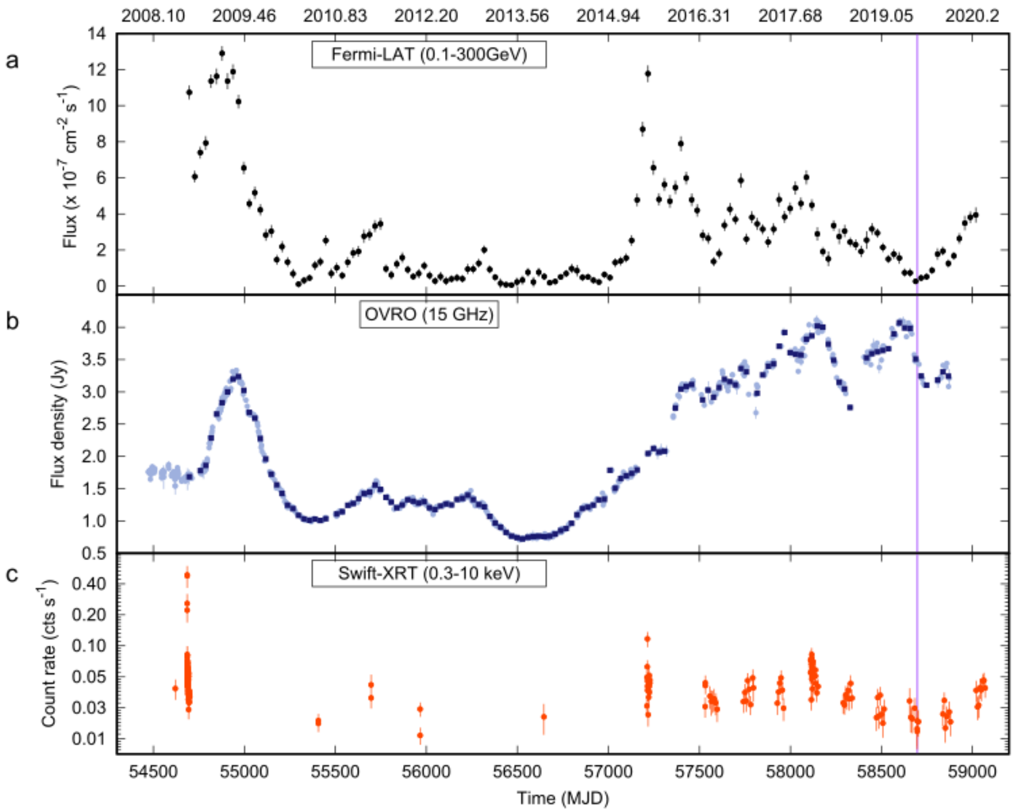

Fig. 2: Photon fluxes in gamma-ray, radio, and x-ray energies, as observed by different observatories. Radio and gamma-ray seem to be correlated, until the neutrino event (violet line). Ref. to: [Kun et al. ApJ (2021)]

Simulation Setup

- **CRPropa (Cosmic Ray Propagation) version 3.1x [Merten et al. JCAP (2017)]**
  - Modified by M. Hörbe and M. Schroller for custom photon fields, temporal scalings of arbitrary choice [Hörbe et al. MNRAS (2020)]
- Various Hadronic interactions
- Ballistic propagation via Cash-Karp or Boris-push method
  - **Different approach: Commonly simulated purely diffusive!**

Setup: Scheme

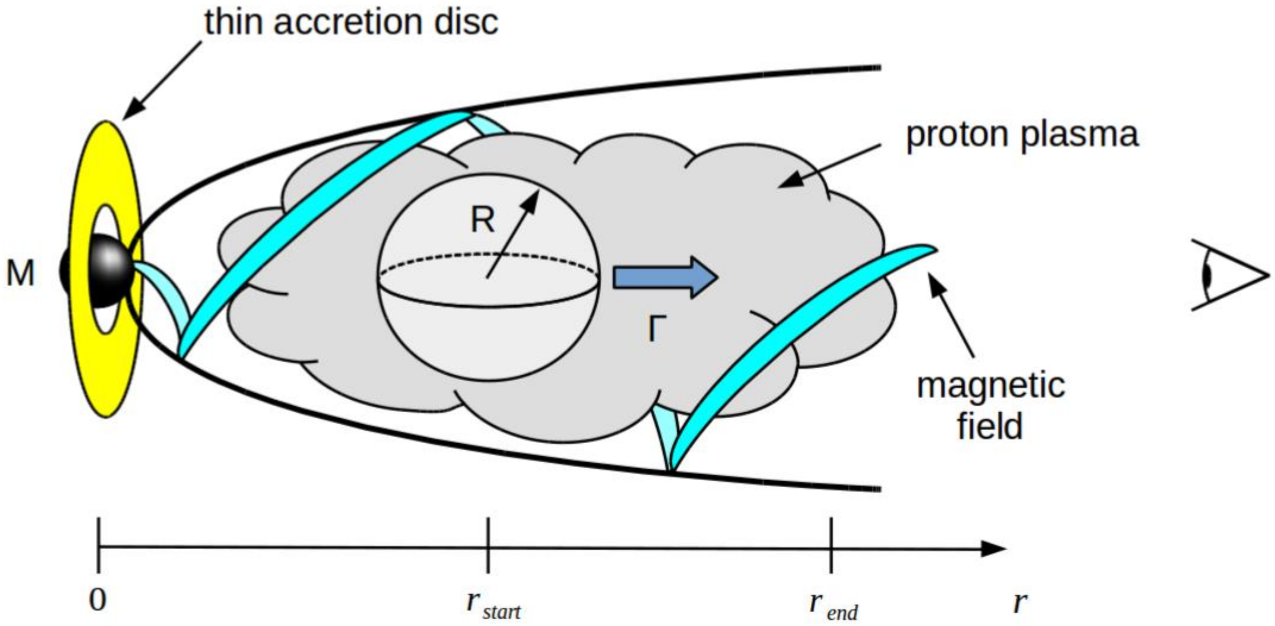

Fig. 3: Propagation of the plasmoid and declarations. Ref. to: [Hörbe et al. MNRAS (2020)]

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Setup: Parameter (excerpt)

Parameter	Symbol	Value
Plasmoid Radius	R	10^{13} m
Plasmoid Propagation Start	r_{start}	10^{14} m
Plasmoid Propagation End	r_{end}	$r_{\text{start}} + 10$ pc
Plasmoid Lorentz Factor	Γ	10
Magnetic Field Initial RMS Value	B_0	1 G
Proton (primary) Initial Energy	$E_{p,\text{inj}}$	10^8 GeV
Proton Target Density (up-scaled)	$n_{0,\text{plasma}}$	10^{15} m^{-3}
Electron Minimal Lorentz Factor	$\gamma_{e,\text{min}}$	10
Electron Maximal Lorentz Factor	$\gamma_{e,\text{max}}$	10^6
Electron Spectral Index	α_e	2.6
Energy Density Ratio U_p/U_e	χ	1/100
Accretion Disc Inner Radius	$3R_s$	$8.86 \cdot 10^{11}$ m
Accretion Disc Outer Radius	R_{acc}	10^{14} m
Accretion Disc Temperature	T_0	10 eV/k$_b$

Tab. 1: Parameter setup for simulation of the plasmoid.
Ref. to: [Hörbe et al. MNRAS (2020)]

Assumptions:

- Equipartition: $U_B = U_p + U_e$
- Purely turbulent field with $l_c = 10^{-2}R$
- Injection monochromatic (Tab. 1) or power law w. spectral index $\alpha_p = 2$;

  $E_{min} = 10^8$ GeV

  $E_{max} = 10^{11}$ GeV
- Instantaneous injection
- Black body field of accretion disk Doppler de-boosted inside plasmoid
- Synchrotron radiation of ambient electrons

Setup: Results (combined messengers)

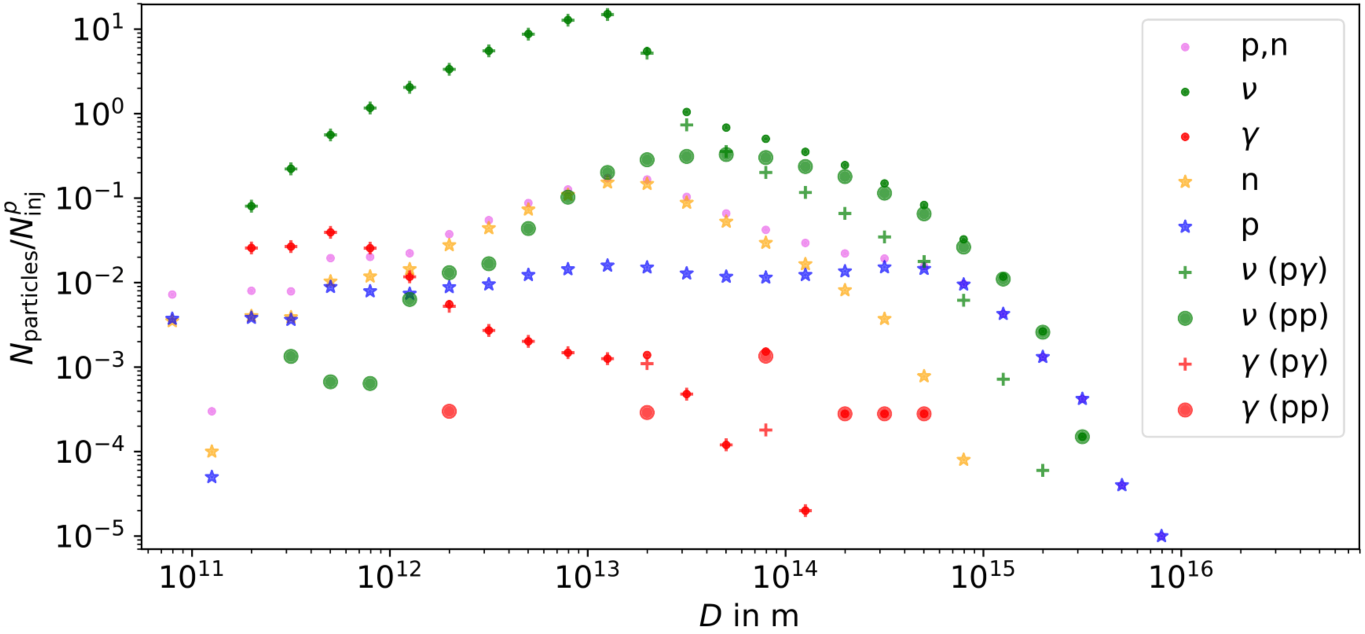

Fig. 4: Relative particle readouts of primary and secondary particles at the plasmoid's surface.

Correlation between γ-rays and Neutrinos

- **Investigation of particle readouts of photons and neutrinos at equal points in time**
  - Can we observe a correlated emission of both messengers?

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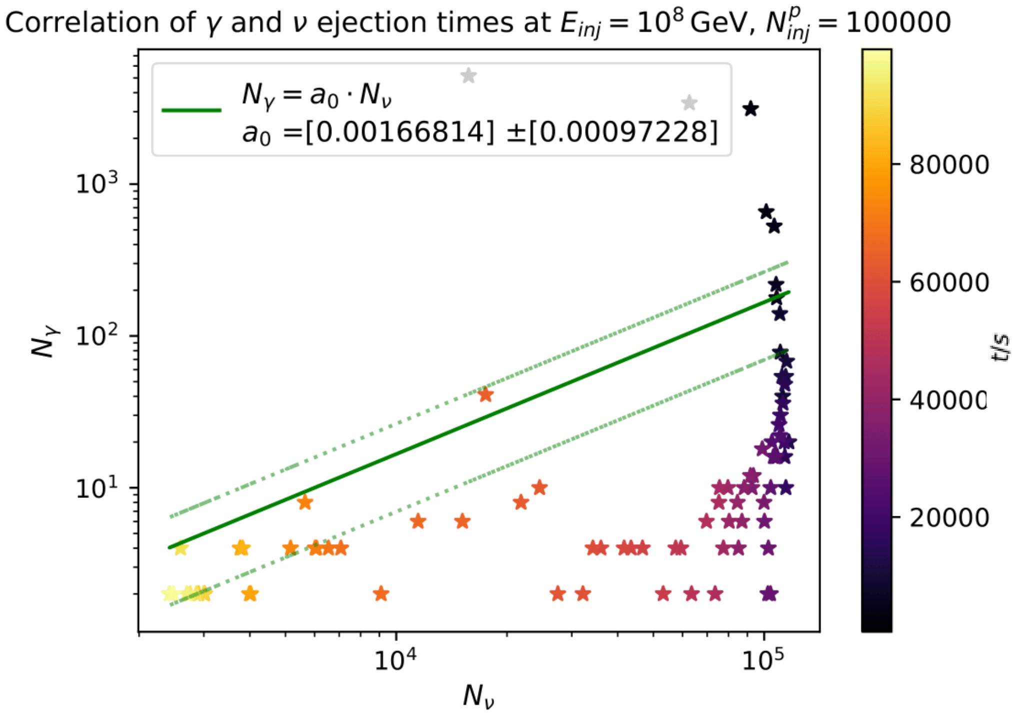

Fig 7.: The correlation between neutrino and gamma-ray emission at equal points in time, which are color-coded by the bar on the right-hand side. Gamma-rays are absorbed by the dense photon fields, while neutrinos escape.

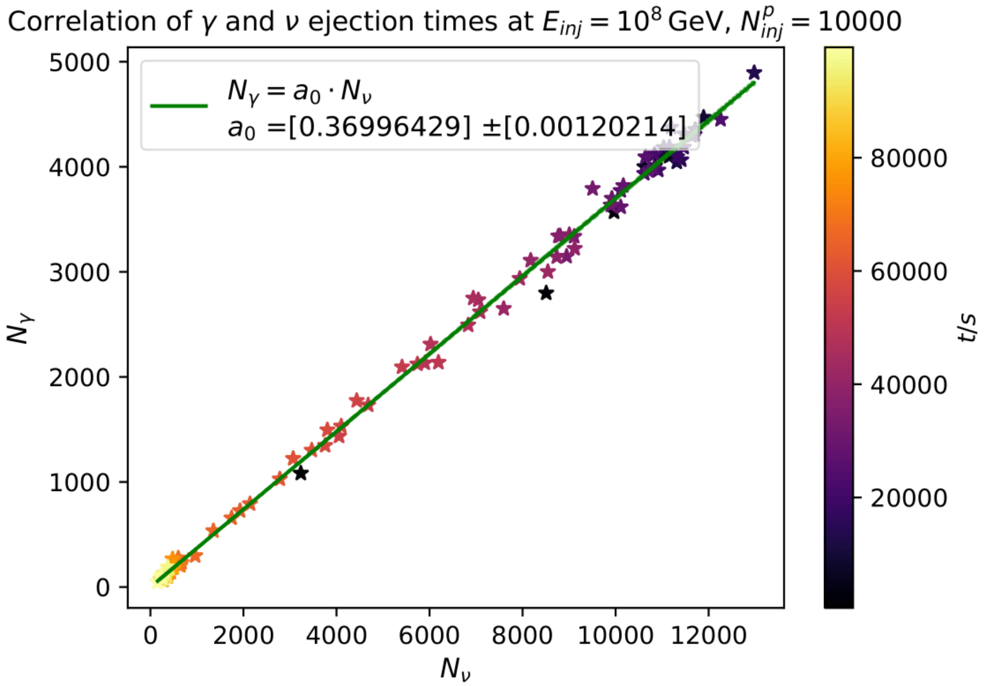

Fig 8.: The correlation between neutrino and gamma-ray emission at equal points in time, which are color-coded by the bar on the right-hand side. In this unphysical view-case, the Breit-Wheeler pair production of secondary γ-rays with background photons is disabled for visualization.

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Summary

- **A simulation scheme is established for the ballistic propagation of hadronic plasmoids traveling along an AGN jet axis.**
- **A first analysis of simultaneous γ-ray and neutrino emission has been performed.**
- **For a full analysis of temporal correlation of gamma-ray and neutrino emission in absorbing environments, higher statistics is needed.**

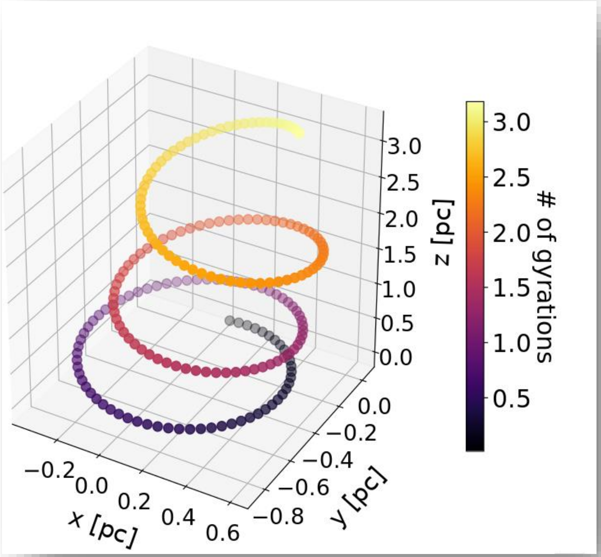
Outlook

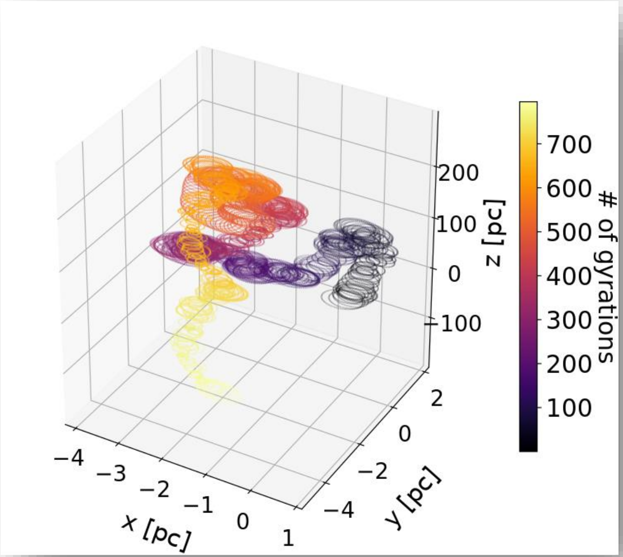
- **Inclusion of radio-emission to the particle readouts**
- **Transformation of signatures to the observer's frame**
- **… and many more ideas for projects!**

Thank you for your attention!

BACKUP

Transport in Turbulent Fields: Ballistic vs. Diffusive





$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{v} \times \boldsymbol{B})$$

$$\frac{\delta n}{\delta t} = \nabla \cdot \left(\widehat{D} \cdot \nabla n\right) - \vec{u} \cdot \nabla n + Q$$

Propagation modes. Ref. to: [Merten et al. JCAP (2017)]

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Transport in turbulent fields: Criteria

Following [Reichherzer et al. MNRAS (2020)]:

The reduced rigidity $\rho = \frac{r_g}{l_c} = \frac{E}{qcB\,l_c}$

- Reduced rigidity ρ can be used as criterion to distinguish between the necessity to either propagate ballistically or diffusively:
  - Ballistic motion for $\rho > 1$
  - Diffusive propagation for ${}^{l_{min}}/_{l_{max}} \leq \rho \leq 1$

System: parameter comparison

i	P_i	former Value V_i	new value W_i
1	Radius of plasmoid R	1e13 m	1e13 m
2	Spacing Δs	2*R	2*R
3	timestep Δt	33358 s	33358 s
4	# timesteps N_t	308557	308557
5	# spatial steps $N_{x,y,z}$	2	2

Magnetic field: former parameter

i	P_i		V_i	W_i
6	# of gridpoints	N_{Gr}	256	512
7	Spacing	Δs_B	R / (128)	R /(256 * 64)
8	Root Mean Value	B_0	1 G	1 G
9	Correlation length	l_c	10^(-2) R	10^(-2) R
10	Lmin	l_{min}	R / (64)	R / (256 * 32)
11	Lmax	l_{max}	R / (32)	R / (32)
12	# of spatial scalings	$N_{x,y,z}^B$	2	4
13	# of temporal scalings	N_t^B	308557	617114
14	Scaling: spacing	Δs^B	2 * R	R
15	Scaling: timesteps	Δt^B	33358 s	16679

Propagation and energy: comparison parameter

i	P_i		V_i	W_i
16	Propagation method	P	CK	BP
17	Min. step size	Δx_{min}	10^(-2) R	10^(-5) R
18	Max step size	Δx_{max}	10^(-2) R	10^(-3) R
19	Precision	ε	10^(-3)	10^(-3)
20	Injection energy	E	10^(8) GeV	10^(8) GeV
21	Max. trajectory length	d	10 pc	10 pc
22	Minimum energy	E_{min}	10^(2) GeV	10^(2) GeV
23	# of particles	N	10000	10000