# Propagation of High Energy Particles in Cosmic Magnetic Fields

Rafael Alves Batista

Beercroft Institute for Particle Astrophysics and Cosmology
University of Oxford

rafael.alvesbatista@physics.ox.ac.uk

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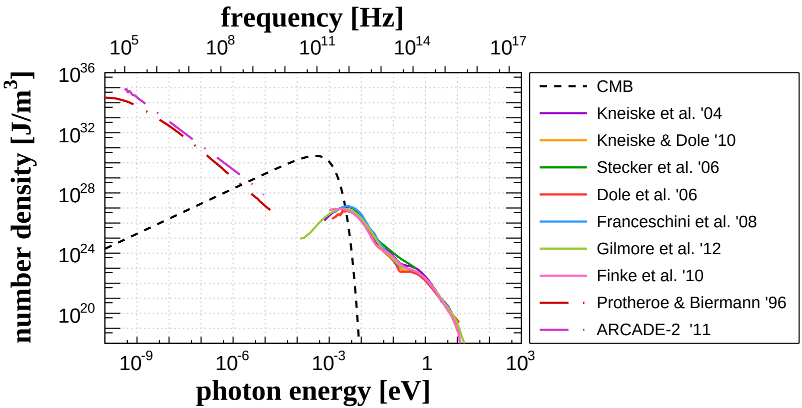
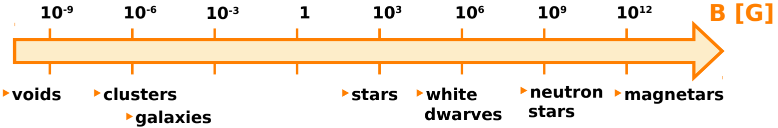
- the presence of photon backgrounds (e.g. CMB, CIB, ...) permeating the universe provide a medium wherein interactions may take place
- cosmic magnetic fields (galactic and extragalactic) can affect the trajectory of particles

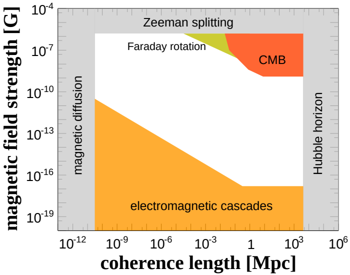
# photon backgrounds

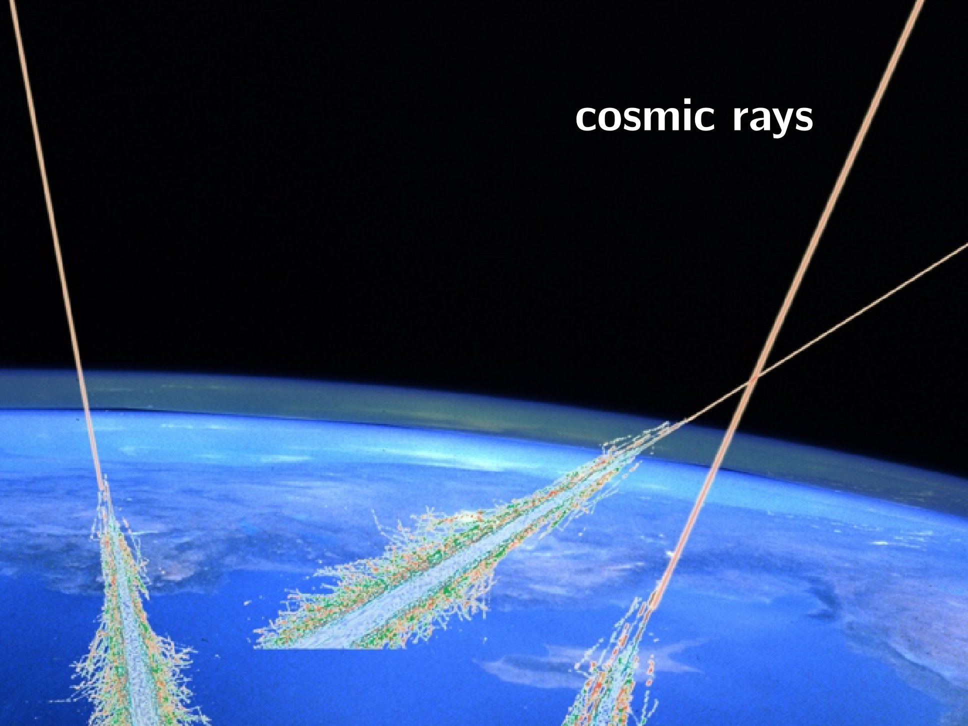


# cosmic magnetic fields




- are there cosmological magnetic fields?
- how did the magnetic fields in the universe came to be?
  - astrophysical scenarios: magnetic fields are generated during structure formation e.g.Biermann battery *[Biermann 1950]* and later amplified by dynamos *[Zeldovich+ 1980]*, …
  - cosmological scenarios: magnetic fields are created during phase transitions (e.g. *[Sigl+ 1997]*), inflation (e.g.*[Turner & Widrow 1988]*) , …
- lower limits from electromagnetic cascades
- upper limits from Zeeman splitting




cosmic rays

# interaction processes and energy losses

## pion production

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

## pair production

$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 (k_B T)^2 f(\Gamma)$$

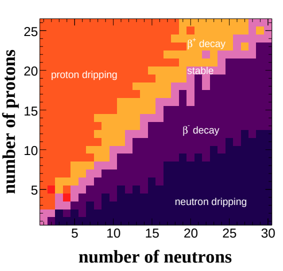
## expansion of the universe

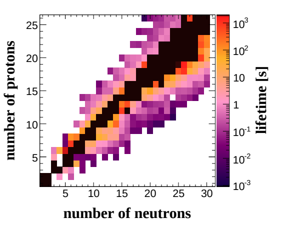
$$-\frac{dE}{dt} = \frac{H_0}{1+z} \frac{1}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}}$$

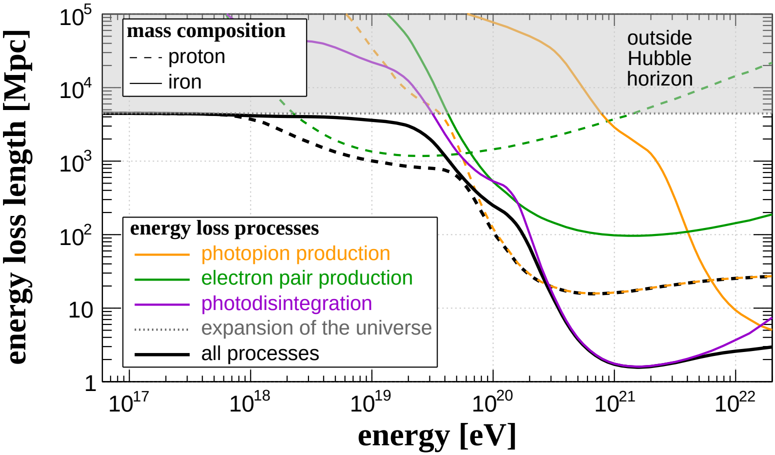
## photodisintegration

$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z) \overline{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon) d\epsilon$$

## nuclear decay

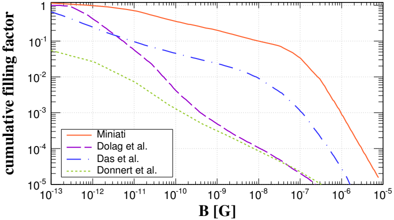


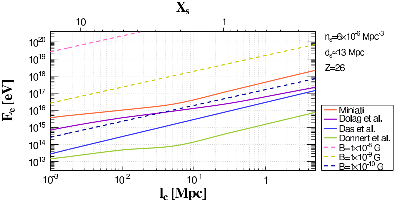




energy loss length [Mpc]
energy [eV]
mass composition
proton
iron
outside Hubble horizon
energy loss processes
photopion production
electron pair production
photodisintegration
expansion of the universe
all processes
1
10
$10^2$
$10^3$
$10^4$
$10^5$
$10^{17}$
$10^{18}$
$10^{19}$
$10^{20}$
$10^{21}$
$10^{22}$

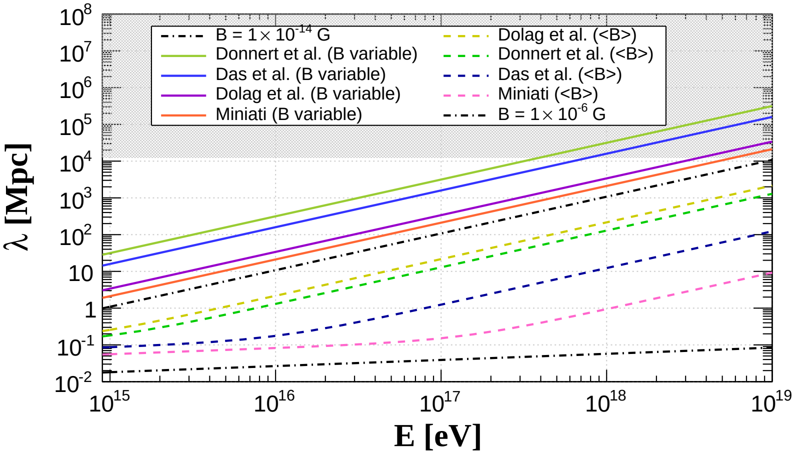
RAB & G. Sigl. JCAP 1411 (2014) 031 [arXiv:1407.6150]

- magnetic horizon effects due to the confinement of cosmic rays in magnetised regions
- "realistic" EGMF models from MHD simulations were used $\rightarrow$ on average, the large fraction of the volume occupied by voids imply large horizons at EeV energies
- in the case of strong magnetic fields, the spectrum is suppressed at $\sim$EeV energies due to the horizon
- this is related to the "hard spectrum problem" $\rightarrow$ the hard spectral indices obtained in combined spectrum-composition fits cannot be explained by magnetic horizons



RAB & G. Sigl. JCAP 1411 (2014) 031 [arXiv:1407.6150]



# simulating the propagation of UHECRs

RAB, D. Boncioli, A. di Matteo, A. van Vliet, D. Walz [arXiv:1508.01824]

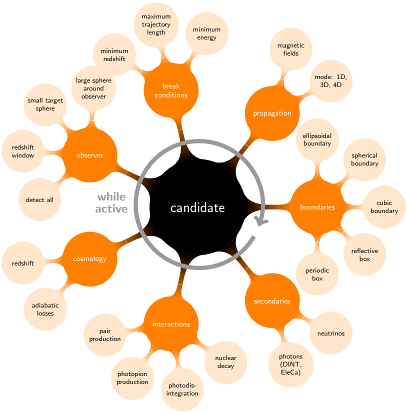
- many public codes: CRPropa *[Armengaud+ 2007, Kampert+ 2013, RAB+ 2013]*, SimProp *[Aloisio+ 2012]*, HERMES *[Domenico 2013]*, TransportCR *[Kalashev & Kido 2015]*
- two treatments:
  - transport equations
  - full Monte Carlo
- magnetic fields are often neglected when simulating only spectrum and composition, but this may not be a good approximation

possible sources of uncertainties

- computational treatment
- stochasticity of photopion production
- uncertainties in EBL models
- photodisintegration cross sections
- scaling of $\alpha$-channels

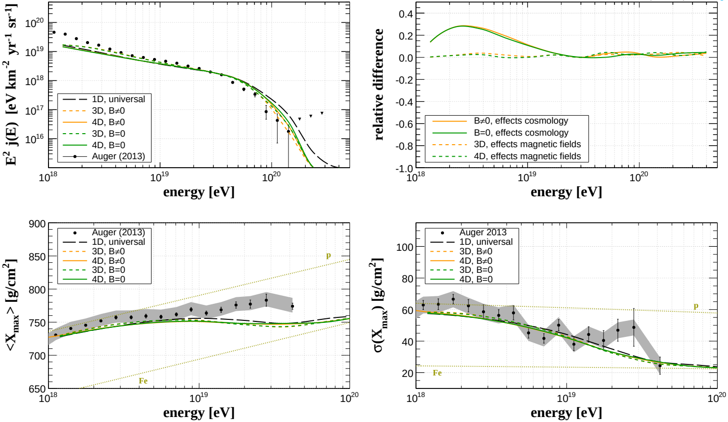
- code available in: `crpropa.desy.de`
- complete redesign of CRPropa 2 *[Kampert+ 2013]*
- modular structure and python steering
- parallel processing with OpenMP®
- 3D simulations with cosmology ("4D mode")
- galactic magnetic field through lenses
- Monte Carlo photon propagation with EleCa code
- more EBL models
- improved interaction rate tables
- updated photodisintegration cross sections
- magnetic field from large scale structure simulations (SPH and AMR)

RAB et al. CRPropa paper - in preparation - coming soon
RAB et al. EPJ Web of Conferences 99 (2015) 13004 [arXiv:1411.2259]
RAB et al. J. Phys.: Conf. Ser. 608 012076 [arXiv:1410.5323]
RAB et al. Proceedings ICRC 2013 [arXiv:1307.2643]

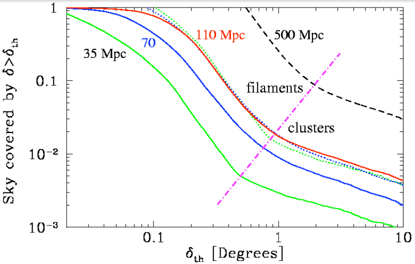


# cosmological effects in 3D simulations

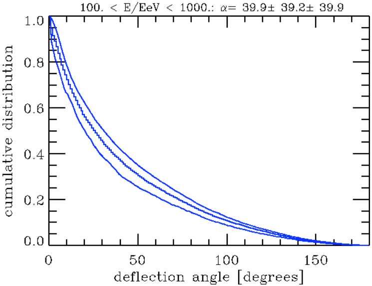
RAB, P. Schiffer, G. Sigl. NIM A 742 (2014) 245 [arXiv:1407.6150]




- "benchmark scenario": distribution from Dolag *et al.* *[Dolag+ 2004]* modulated by the magnetic field-density profile from Miniati *[Miniati 2002]*
- cosmological effects are indeed relevant → "4D" simulations needed



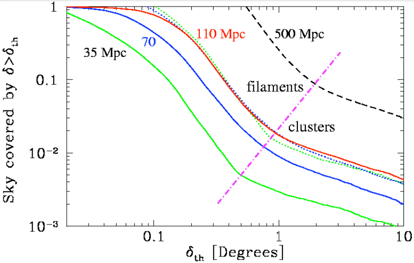

[Dolag+ 2004]



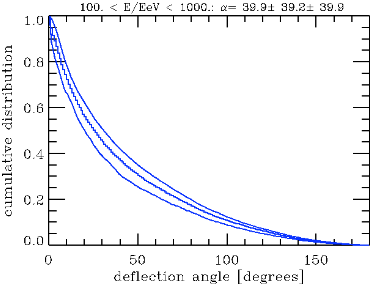

[Sigl+ 2004]

- plots show cumulative deflections
- Sigl+ 2004: deflections are large → UHECR astronomy might not be possible
- Dolag+ 2004: deflections are small → UHECR astronomy might be possible
- depending on the composition deflections can be even higher!

# is cosmic ray astronomy possible?




[Dolag+ 2004]

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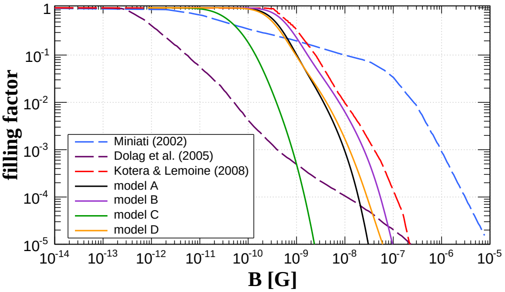
will we ever be able to identify the sources of UHECRs?

# simulations of the magnetised cosmic web

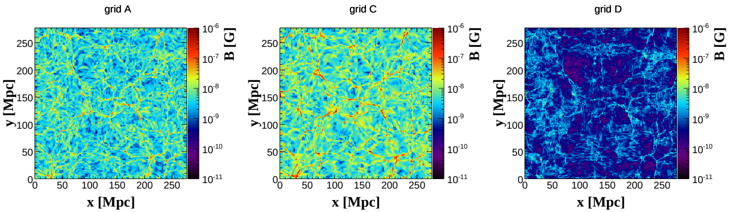
RAB, M.-S. Shin, J.Devriendt, D. Semikoz, G. Sigl. In preparation.

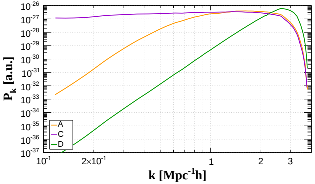


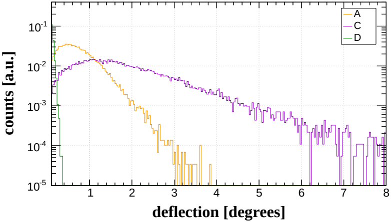

A: $256^3$, fiducial run
B: $256^3$, B seed $10^5$ times higher than model A
C: $256^3$, power in large $k$ values
D: $256^3$, power in small $k$ values
E: $512^3$, fiducial-like run with higher resolution

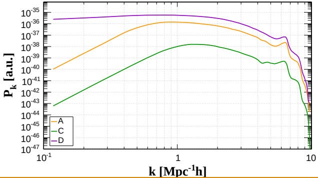
- box size $= 200h^{-1}$ Mpc, with 10 levels of refinement
- MHD simulations being done by J. Devriendt (Oxford) and M.-S. Shin (KASI)
- adaptative mesh refinement (AMR) using the RAMSES code
- models A and B $\rightarrow$ can we rescale the magnetic field? YES
- models A and E $\rightarrow$ convergence for higher resolution? ROUHGLY
- models A, C and D $\rightarrow$ does the initial seed of the magnetic field affect the distribution of magnetic fields? A LOT
- how do the results depend on the normalisation of the filling factors?

# effects of seed fields



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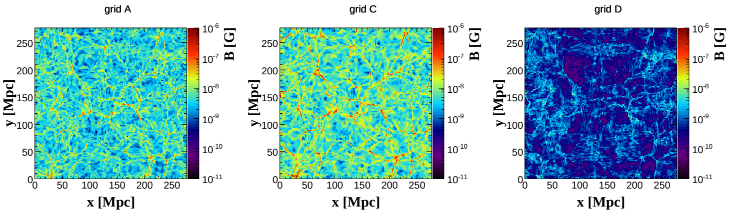
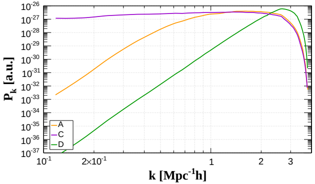
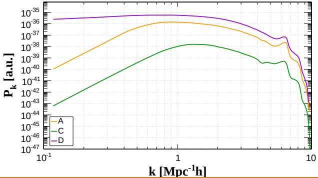
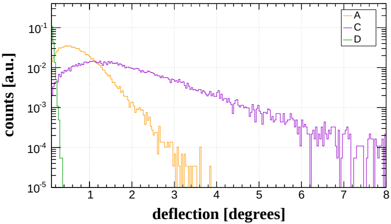


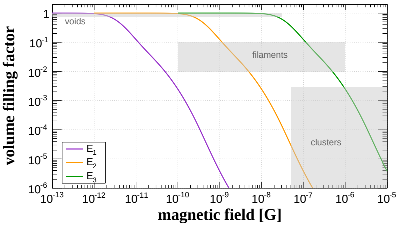



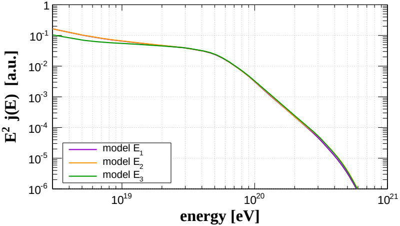

**can we use UHECRs to constrain magnetic fields?**

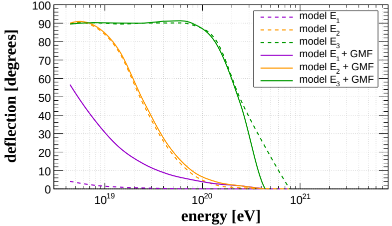
# effects of the magnetic field normalisation

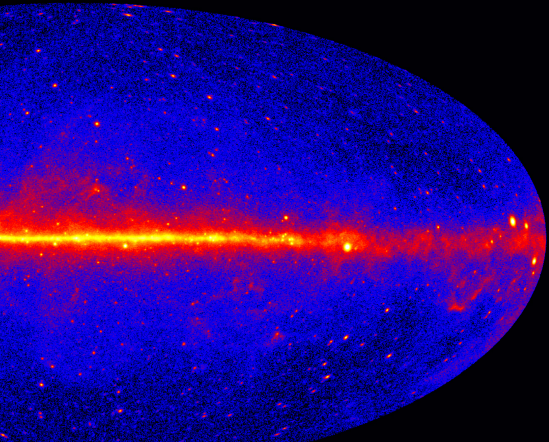
RAB, M.-S. Shin, J.Devriendt, D. Semikoz, G. Sigl. In preparation.




- three models derived from model E were tested
- above $10^{19}$ eV deflections are high, even if GMF is neglected
- spectrum is affected by the normalisation of the field
- example shown is for iron primaries



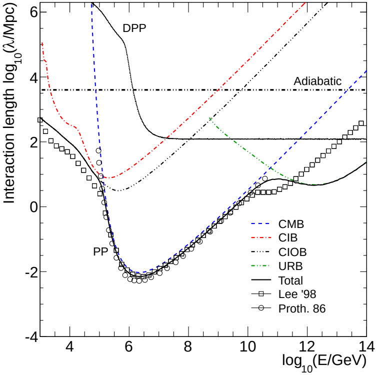





gamma rays

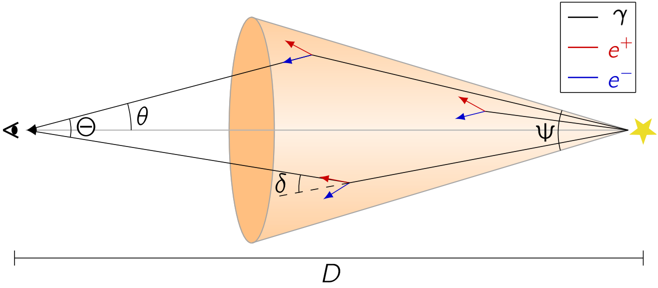
# energy losses and interactions

- expansion of the universe
- inverse Compton scattering
- synchrotron losses
- pair production
- double pair production
- triple pair production




[Settimo+ 2012]

# gamma-ray induced electromagnetic cascades

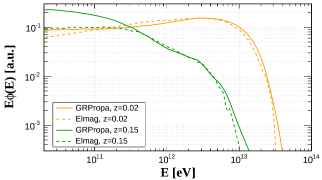



- gamma rays produce $e^+e^-$ pairs
- $e^\pm$ scatter background photons via inverse Compton
- therefore: point-like sources will appear extended [Plaga 1994]
- cascades $\rightarrow$ lower limit on the strength on IGMF [Neronov & Semikoz 2009]
- cascades may explain the observed flux suppression at $E \sim 1\,\mathrm{GeV}$ [Neronov & Semikoz 2009, Vovk+ 2012]
- controversial issue: plasma instabilities may squelch the development of the cascades [Schlickeiser+ 2012, Broderick+ 2013, Saveliev+ 2013]
- electromagnetic cascades can also be induced by cosmic rays

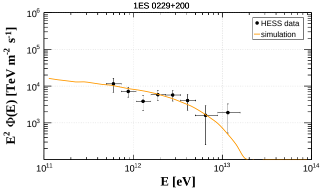
# GRPropa

- there are several computational tools for propagating electromagnetic cascades in the intergalactic medium (e.g. Elmag code [Kachelrieß+ 2012])
- most codes are 1D and mimick magnetic deflections using the small angle approximation, including cosmological effects
- other codes are more complete and do the full 3D propagation, but they neglect cosmological effects
- GRPropa is a Monte Carlo package based on CRPropa 3.0 that allows full 3D simulations including cosmological effects ("4D mode")
- https://github.com/rafaelab/GRPropa
- arbitrary magnetic field configurations, source distributions, spectrum, and contains > 7 different EBL models

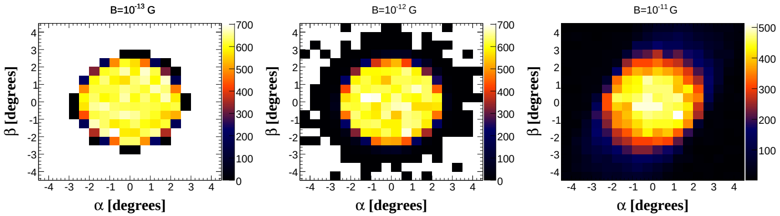
comparison with Elmag




fitting source spectrum



# blazar pair halos



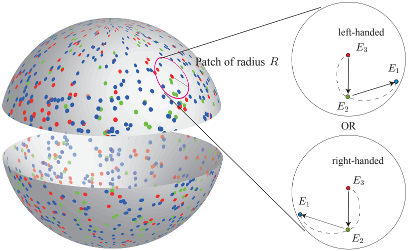

- pair halos can be detected by the next generation of imaging air Cherenkov telescopes (e.g. CTA)
- non observation of pair halos → upper limit on the strength of IGMFs
- observation of pair halos → favours cosmological origin of seed fields

# helical magnetic fields

- magnetic helicity

$$\mathcal{H} = \int_V d^3r\, \vec{A} \cdot \vec{B}$$

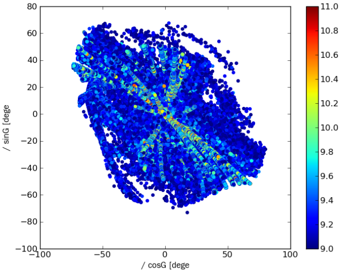
- helicity is related to the topology of the field, and is approximately conserved ($\partial\mathcal{H}/\partial t \approx 0$)
- helicity may be a signature of CP violation during matter baryo- and leptogenesis
  - baryogenesis $\rightarrow$ right-handed helicity *[Vachaspati 2001]*
  - leptogenesis $\rightarrow$ left-handed helicity *[Long+ 2013]*
- can we infer the helicity of IGMFs from gamma ray observations? *[Long+ 2013]*

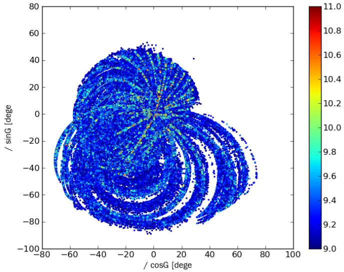



Patches of radius $R$ are centred on the highest energy gamma rays; the distribution of lower energy (GeV) photons along spirals indicates the helicity *[Tashiro+ 2013, Tashiro+2014]*

# signatures of helical fields in 3D simulations

GRPropa simulations, B = 10 fG, $dN/dE \propto E^{-2}$ [PRELIMINARY]




R. Alves Batista, A. Saveliev, G. Sigl, T. Vachaspati. In preparation.

# conclusions and outlook

- it is difficult to come up with models to explain the three main observables (spectrum, composition and arrival directions) $\rightarrow$ fast computational tools $\rightarrow$ CRPropa
- our limited knowledge of cosmic magnetic fields is a limiting factor for identifying the sources of UHECRs
- new MHD simulations of the local universe suggest that UHECR astronomy might not be possible with current facilities such as Auger (maybe never??)
- imprints of IGMFs in the arrival directions of UHECRs $\rightarrow$ can we constrain these fields using cosmic rays?
- magnetic horizons of UHECR depend on the distribution of magnetic fields in the universe

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- imprints of IGMFs in the arrival directions of UHECRs → can we constrain these fields using cosmic rays?
- magnetic horizons of UHECR depend on the distribution of magnetic fields in the universe
- GRPropa: new code for propagating gamma rays in the universe considering arbitrary configurations of magnetic fields
- observation of blazar pair halos → limits on the strength of IGMFs ← new generation of IACTs
- we have shown the feasibility of inferring magnetic helicity from arrival directions of gamma rays → cosmological magnetogenesis