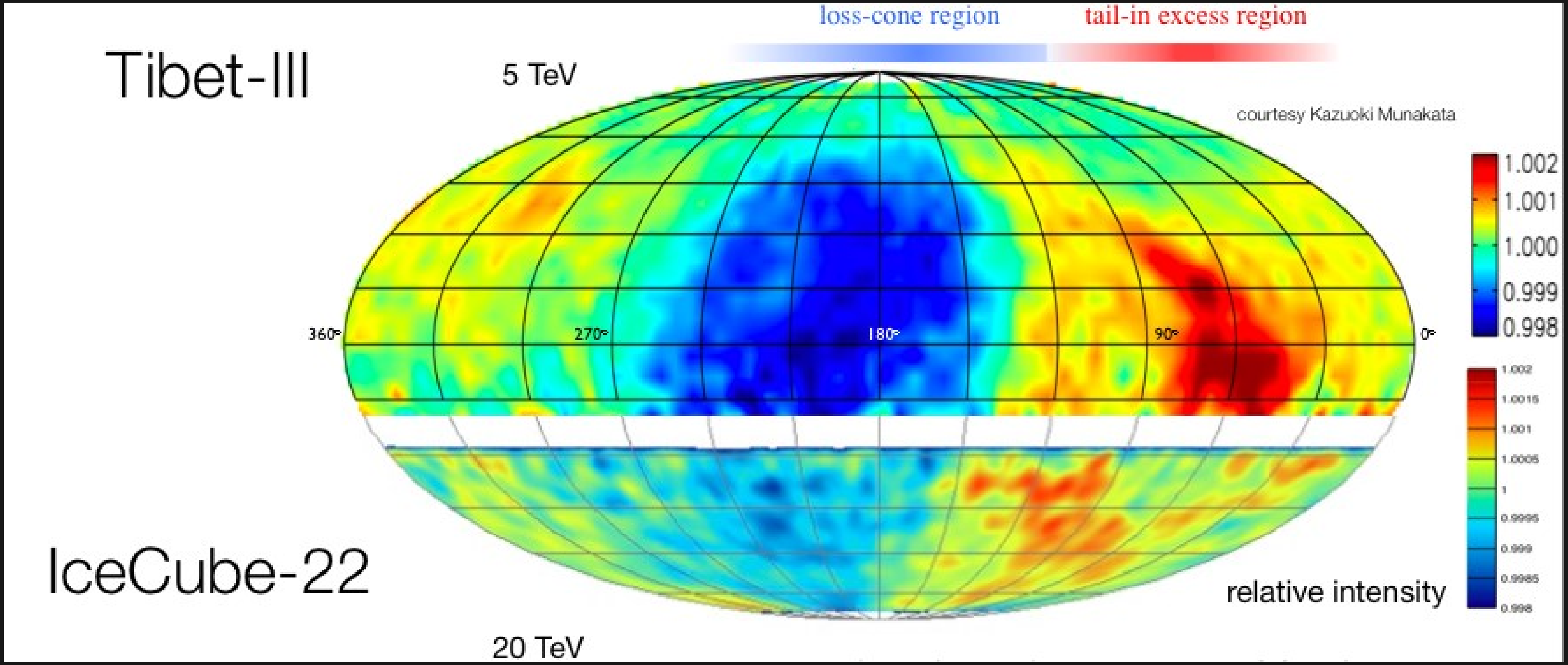
Understanding the anisotropy of cosmic rays at TeV and PeV energies

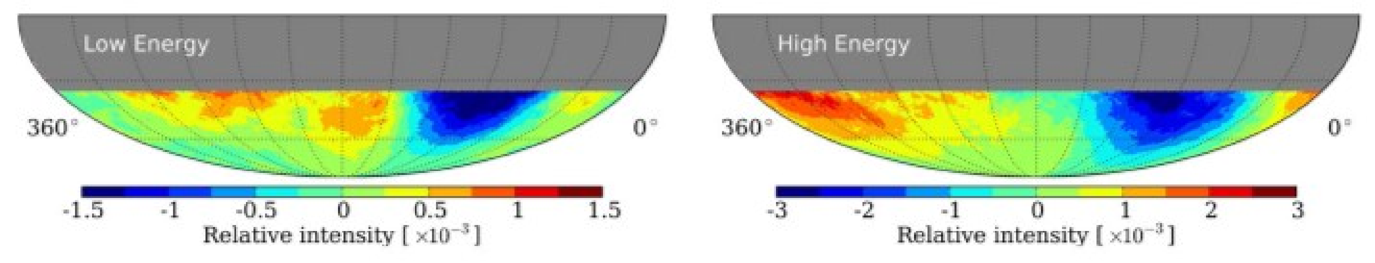
Martin Pohl & Robert Rettig

Anisotropy



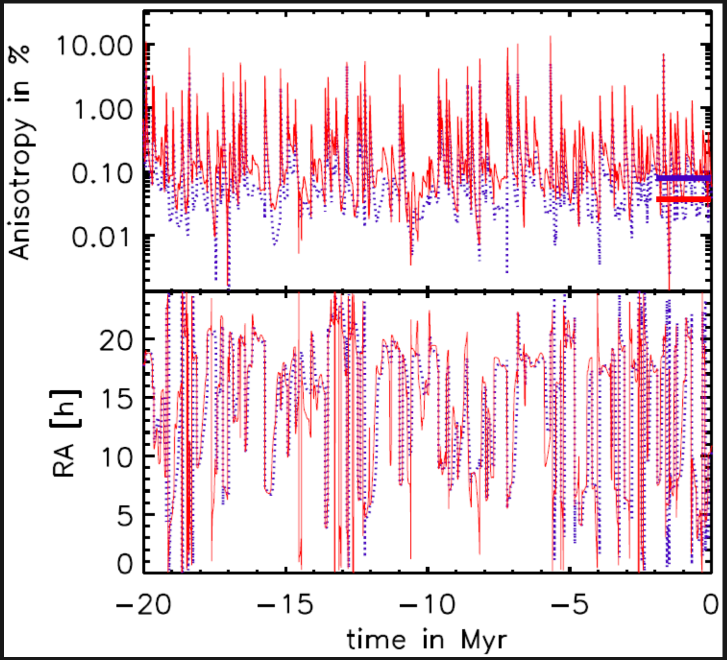
Not a simple dipole

Anisotropy



0.4-2 PeV

(IceTop)



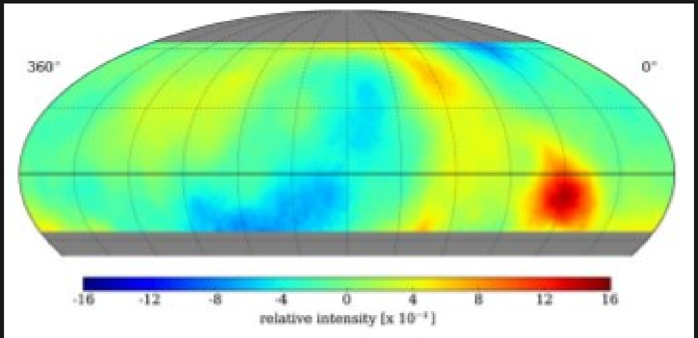
Significant energy dependence in amplitude and direction

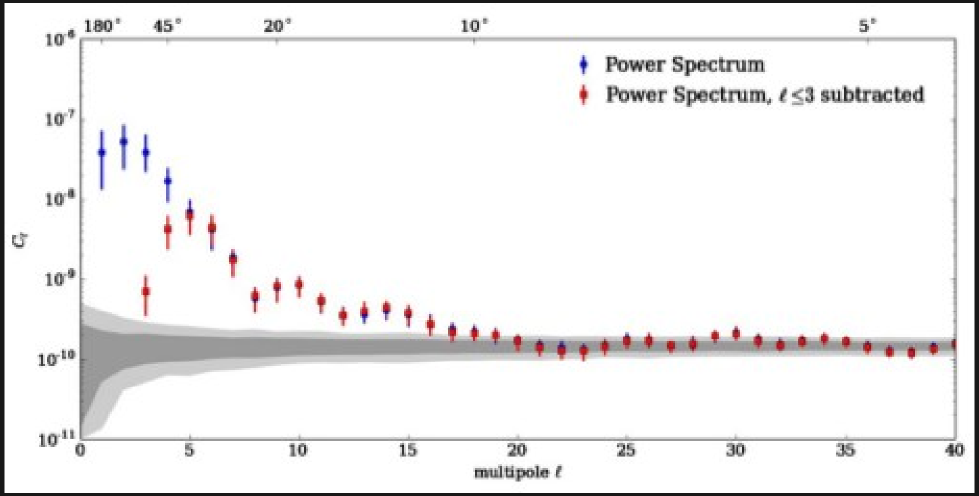
Not unexpected for dipole component as result of source statistics

(Pohl & Eichler)

Anisotropy

(HAWC) 1.7—4 TeV





Small-scale anisotropy as result of CR transport in turbulent magnetic field?

Reproduced in backtracing simulations (Giacinti & Sigl)

Predicted as result of forward evolution on account of Liouville's theorem (Ahlers)

Simulations

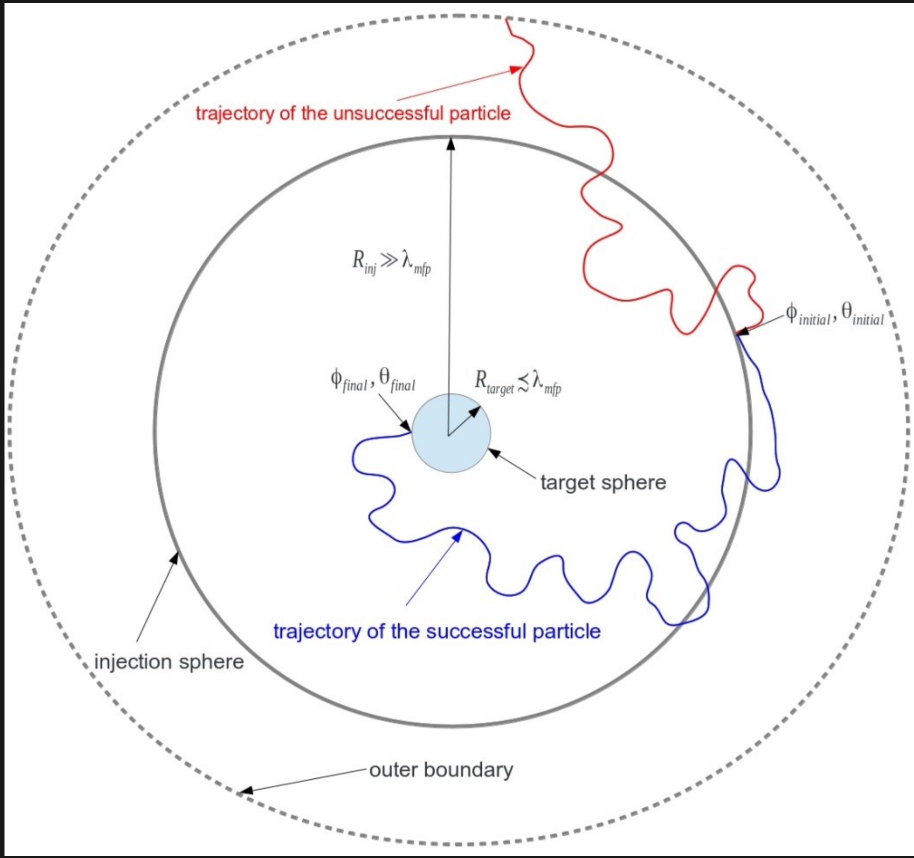
→ **Forward simulations**

Include escape → Liouville‘s theorem may be not applicable

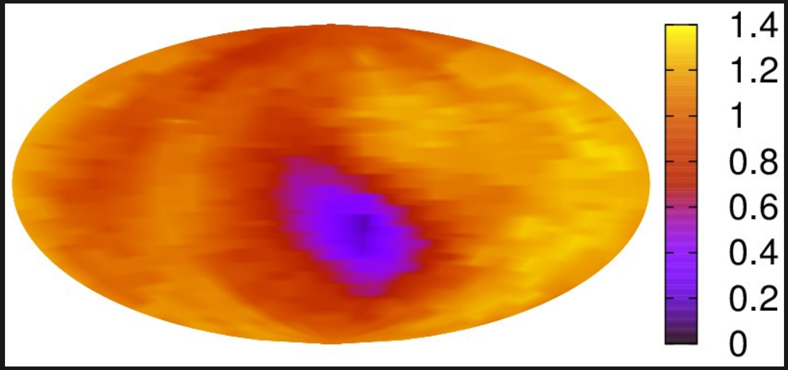
- **New integration algorithm for equation of motion**
- **Standard magnetostatic turbulence generator (Giacalone & Jokipii)**
- **Alternatively, dynamical turbulence with fixed v_ϕ**
- **HealPix representation of results**

Simulations

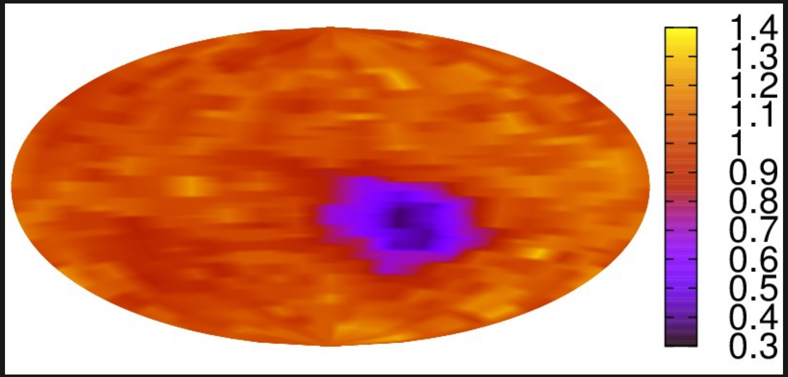
1. Launch particles on sphere
   initially isotropic
2. Define field realization,
   important: r_L / λ_{max}
3. Determine λ_{mfp}
4. Escape at outer boundary
5. Count particle at target sphere



Results for δE=0



Statistical uncertainty 3.2% and 5.8%

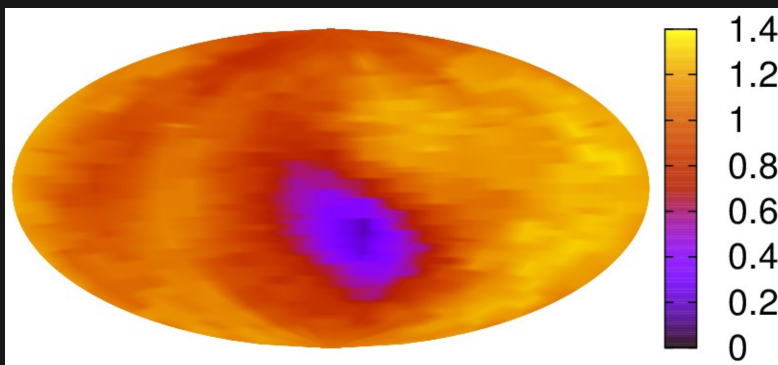


Target sphere with radius halved

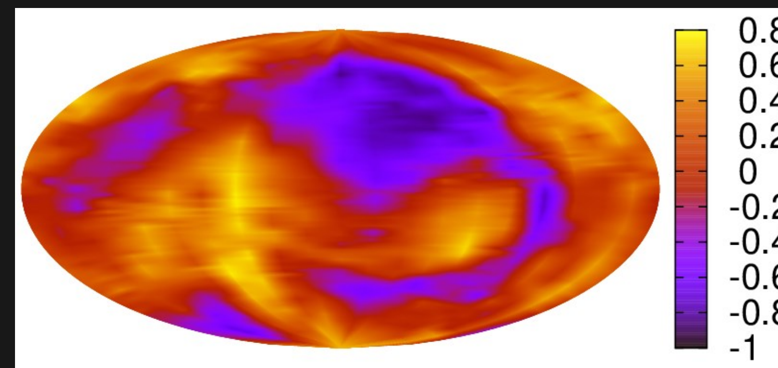
1 PeV energy, λ_{max} =10 pc, λ_{mfp} = 0.94 pc, r_L = 0.35 pc

- **Significant anisotropy on many scales**
- **Anisotropy pattern reasonably stable (also for larger target sphere)**
- **Correlation with MF?**

Results for $\delta E=0$



Anisotropy



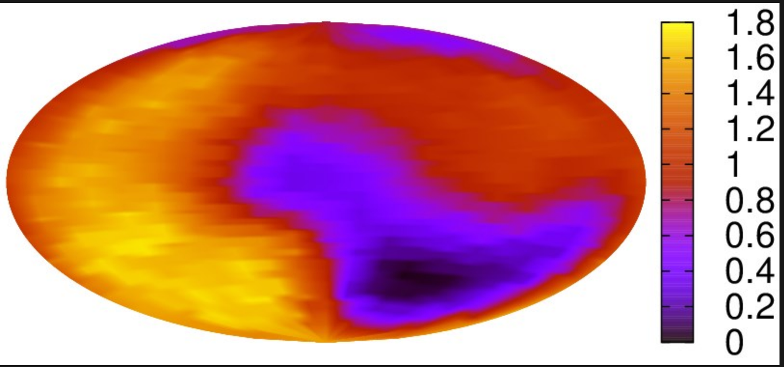
$< \cos \theta >$ of magnetic field

$< \cos \theta >$ = +/- 1 indicates homogeneous field along line of sight

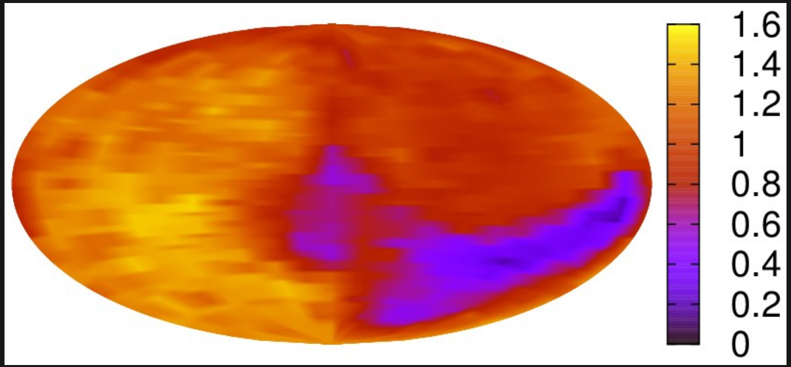
Average over 1-10 target radii

→ no correlation with anisotropy pattern
→ Is there really a correlation with local interstellar field?

Results for $\delta E=0$



Statistical uncertainty 3.0% and 5.3%

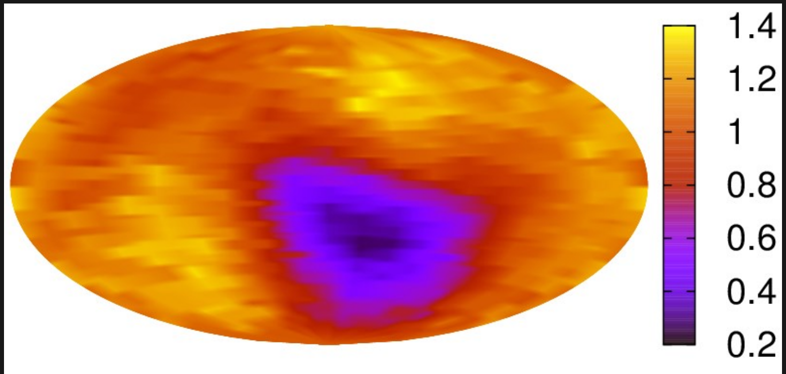


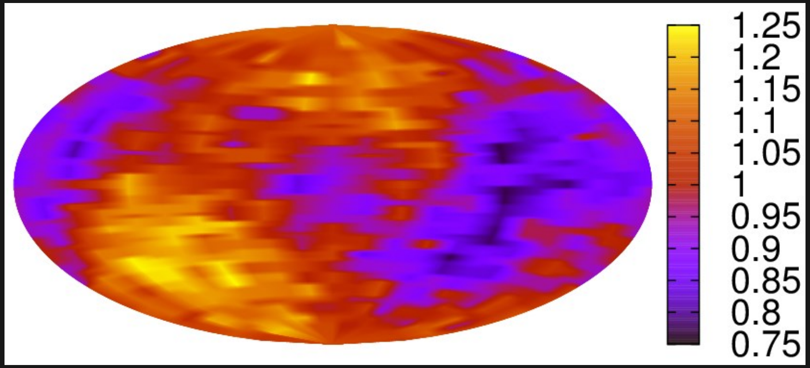
Target sphere with radius halved

1 PeV energy, λ_{max} =100 pc, λ_{mfp} = 1.85 pc, r_L = 0.3 pc

- **Significant anisotropy**
- **Anisotropy pattern changes little on small scales**
- **Weak, if any, correlation with local magnetic field**

Results for finite δE





Statistical uncertainty 4.6% and 4.7%

v_ϕ=100 km/s → v_ϕ=1000 km/s

1 PeV energy, λ_{max} =10 pc, λ_{mfp} = 0.94 pc, r_L = 0.35 pc

- **Significant distortion of anisotropy by dynamics of turbulence**
- **Local MF environment changes on timescales 300 λ_{wave} / c**
- **Everything should average out, unless $\lambda_{wave} > 5\,\lambda_{mfp}$ is decisive range**

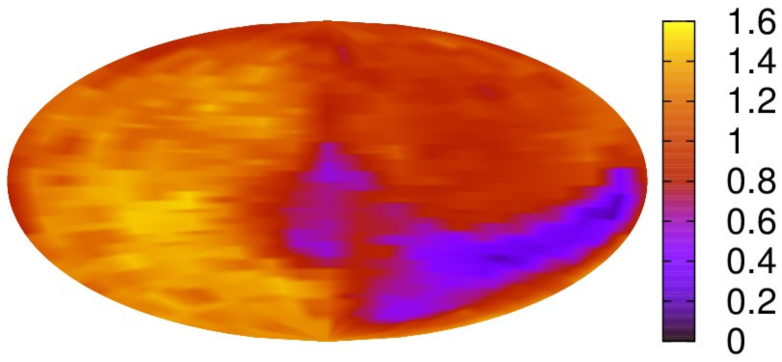
Conclusion

Forward simulation of cosmic-ray trajectories

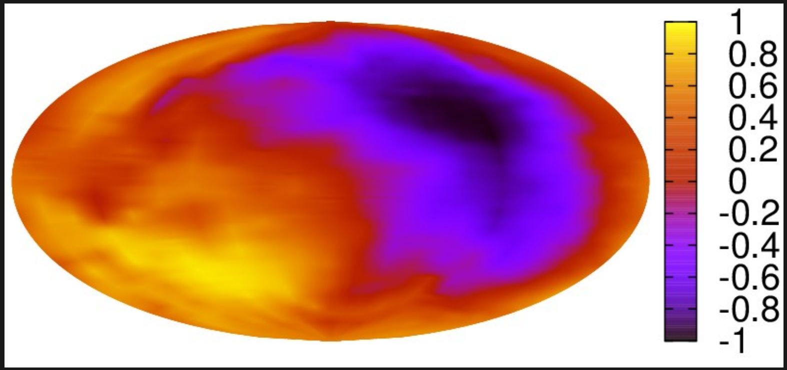
- **Anisotropy is created *ex nihilo*, no initial dipole is needed**
- **Complicated patterns that do not stronly depend on $\lambda_{mfp} / \lambda_{max}$**
- **Little, if any, correlation with magnetic field orientation**
- **Little wash-out with dynamical turbulence,**

magnetic-field structure on largest scales is decisive

Results for $\delta E=0$



Anisotropy



$< \cos\theta >$ of magnetic field

For large λ_{max}