

# New features in the radio emission of inclined showers



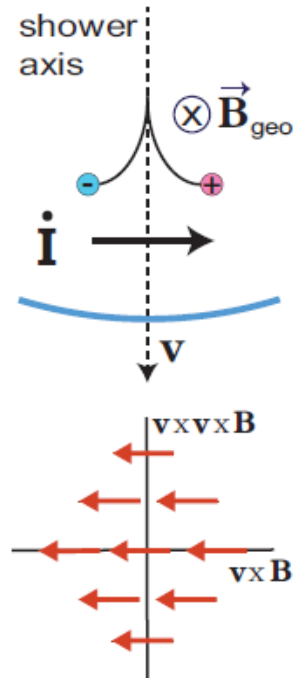
Simon Chiche, Chao Zhang,  
Krijn de Vries, Tim Huege, Kumiko Kotera,  
Simon Prunet, Felix Schlüter, Matias Tueros



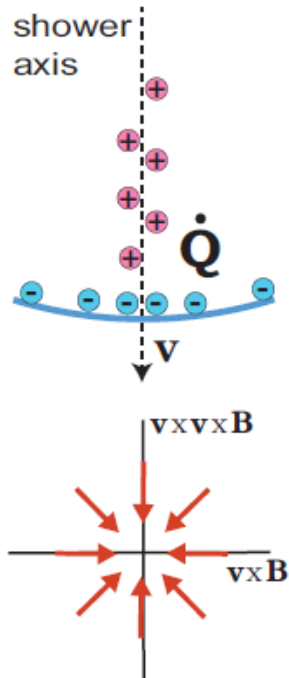
# Radio signal from atmospheric extensive air-showers

## 2 main sources for the radio emission

- Geomagnetic emission
- Induced dipole with  $\vec{B}_{geo}$
  - Polarisation along  $-\mathbf{v} \times \mathbf{B}$
  - Main contribution to the radio signal



Geomagnetic emission



Askaryan emission

- Charge excess emission
- Accumulation of negative charges close to the shower core
  - Radial polarisation
  - $\approx 10\%$  of the amplitude of the total emission for vertical air showers

Schröder (2017)

vertical air-showers: well known, mature and verified

Inclined air showers: still several challenges, trending topic

# The challenge of inclined air-showers

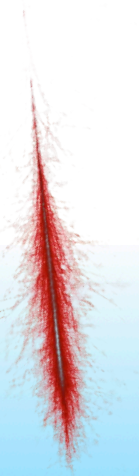
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- High sensitivity required to address the low fluxes at UHE (target of [AugerPrime](#), [Beacon](#), [GCOS](#), [GRAND](#))
- Large footprint: better sensitivity at UHE with sparse arrays

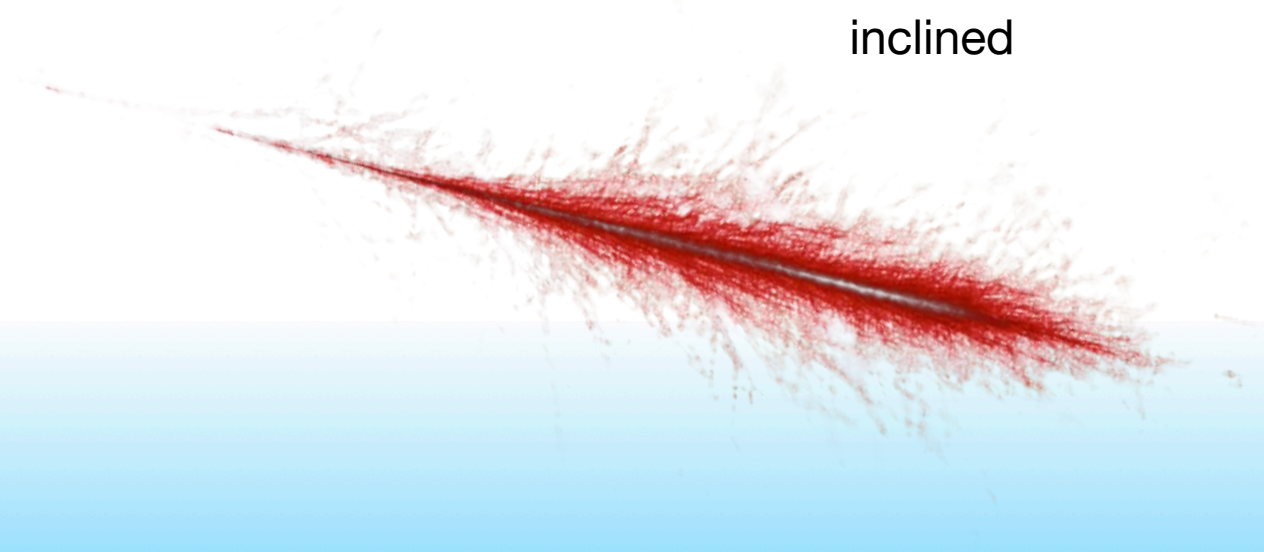
## But several complex characteristics challenging to understand

(Huege et al., 2019, Schlüter et al. 2022, Decoene et al 2021., Chiche et al., 2022)

vertical



inclined



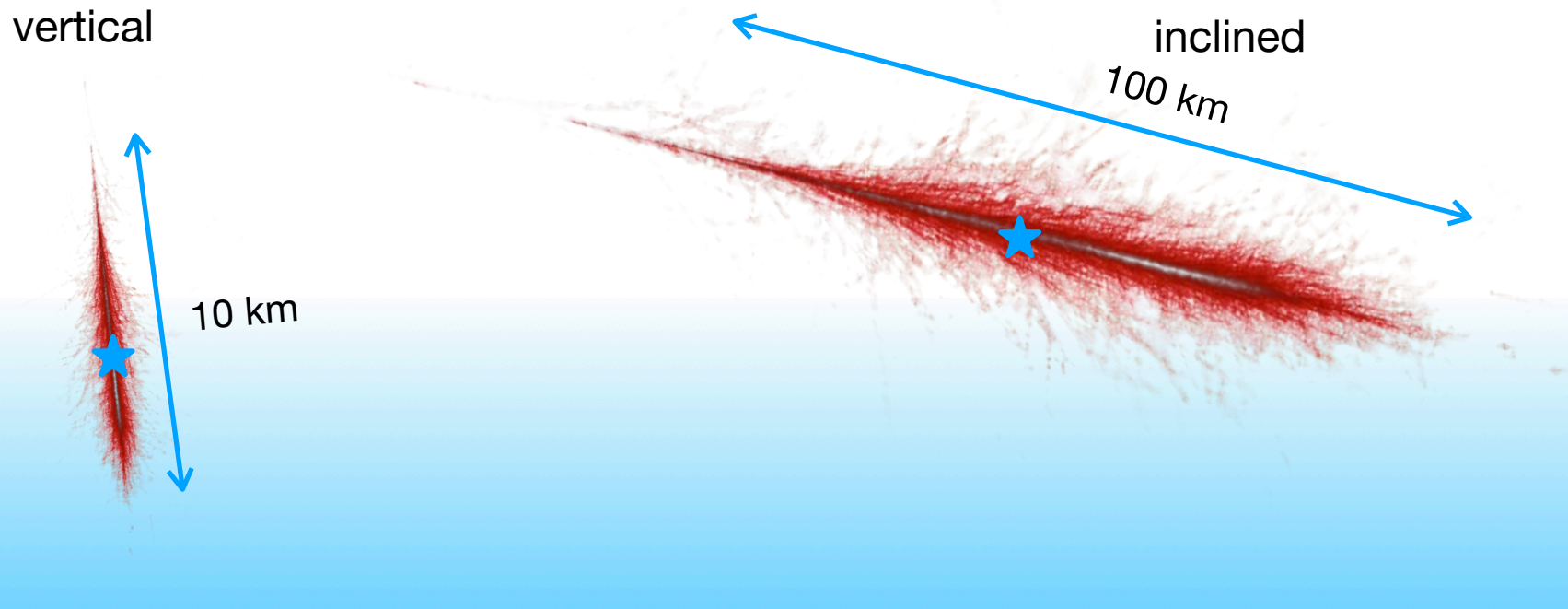
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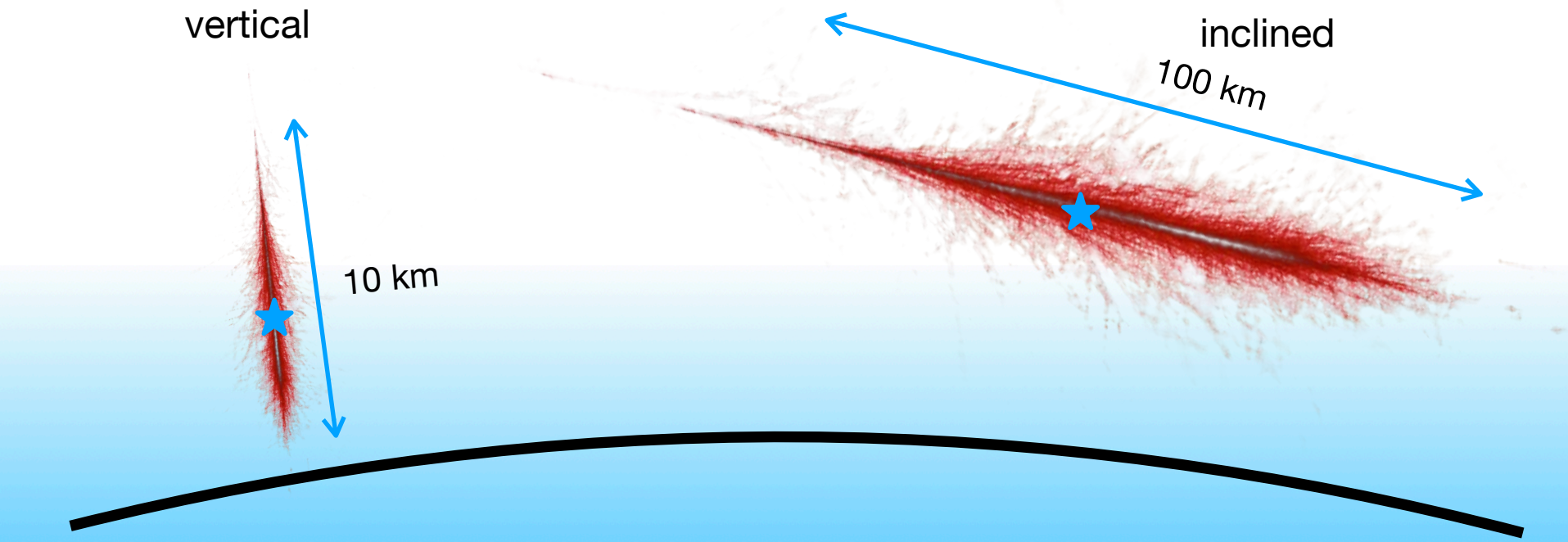
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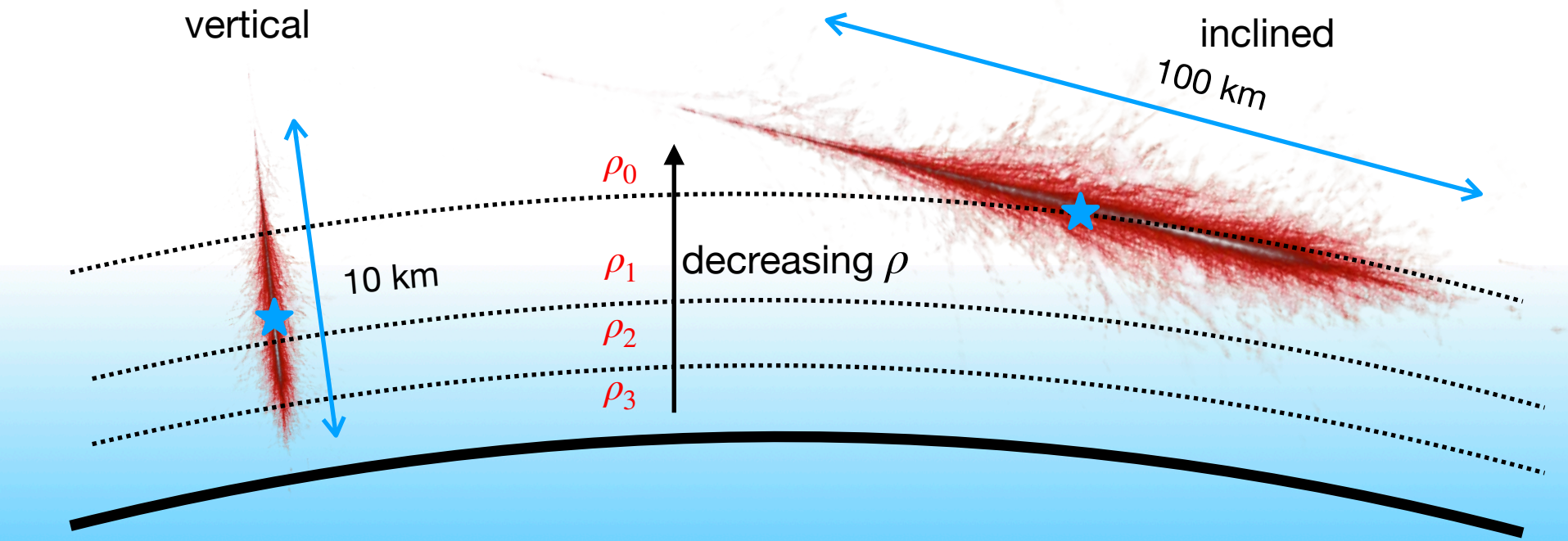
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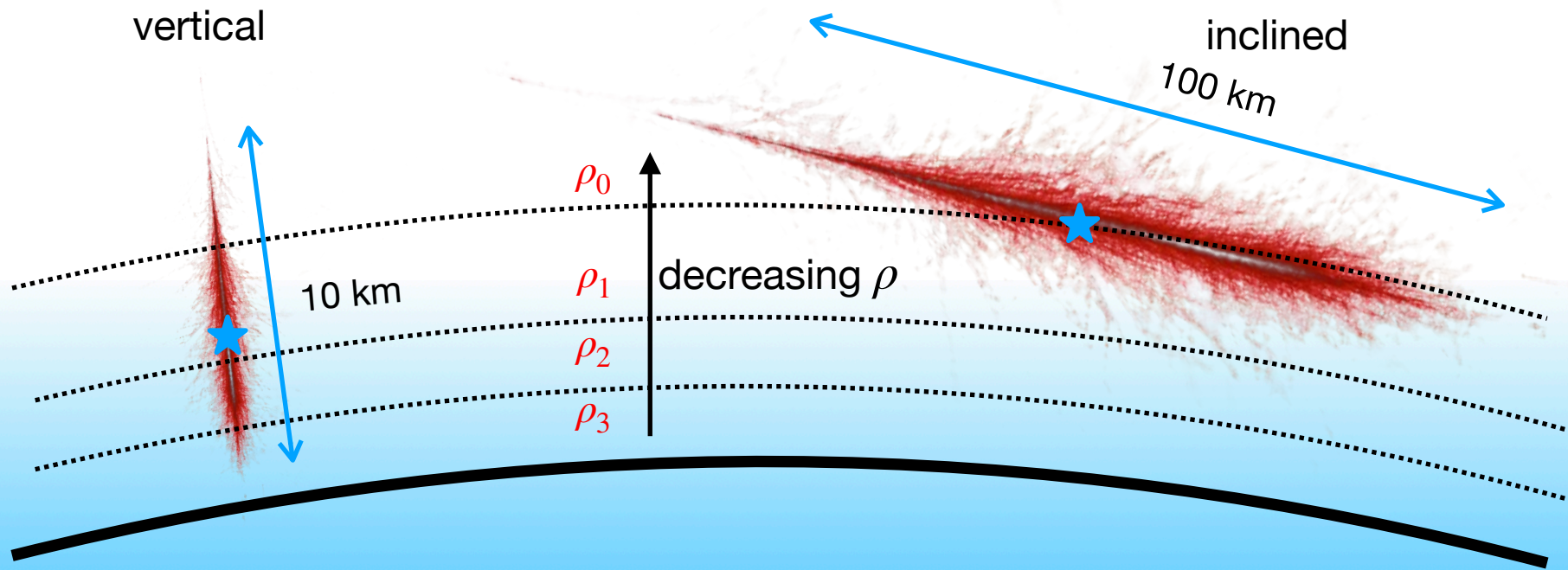
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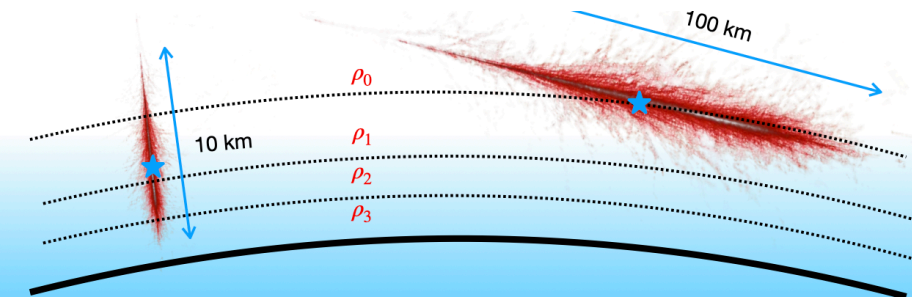
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**How do all these characteristics affect the radio emission?**

# Geomagnetic emission dependency with air-density

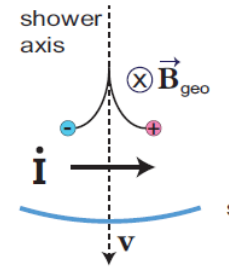
How does the radio emission depend on the  $X_{\max}$  air density/zenith angle?



11000 ZHAireS simulations with various energy and arrival directions

GRAND site  $B_{\text{field}}$  value

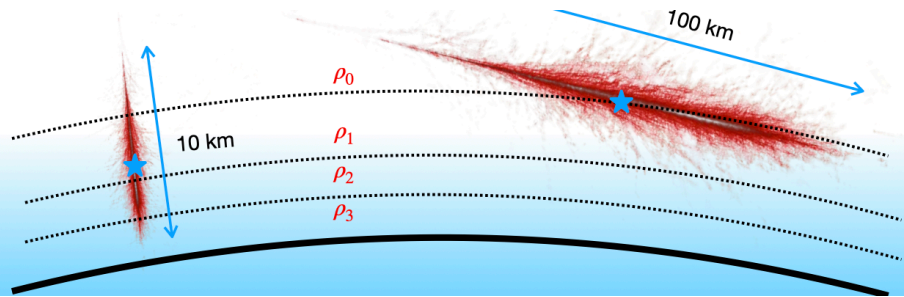
Computation of the geomagnetic energy dependency with  $\rho_{x\max}$





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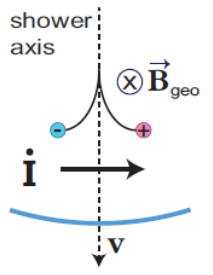
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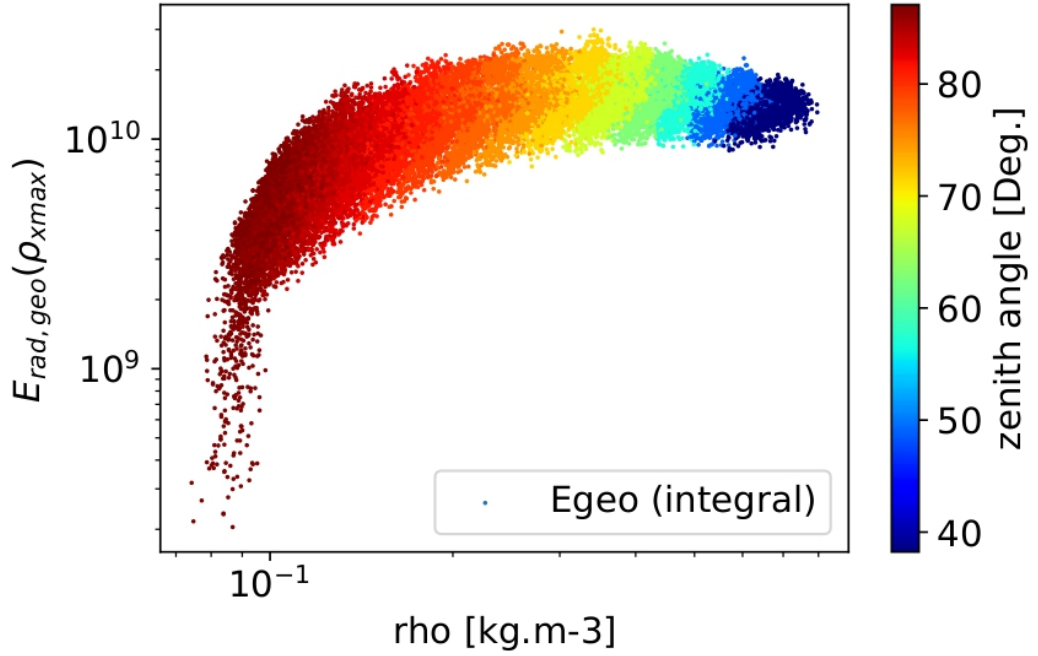
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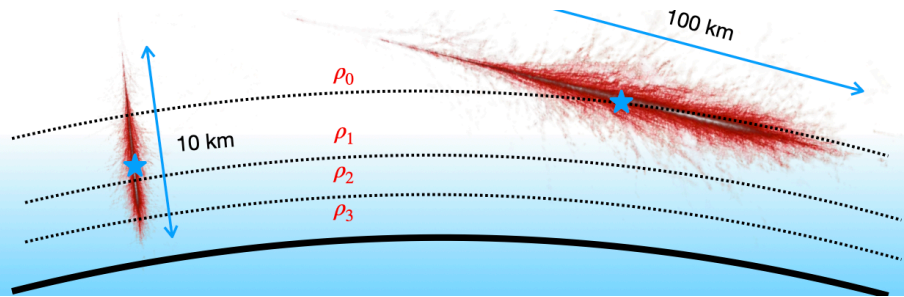


Geomagnetic radiated energy



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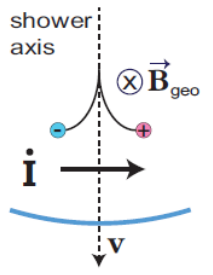
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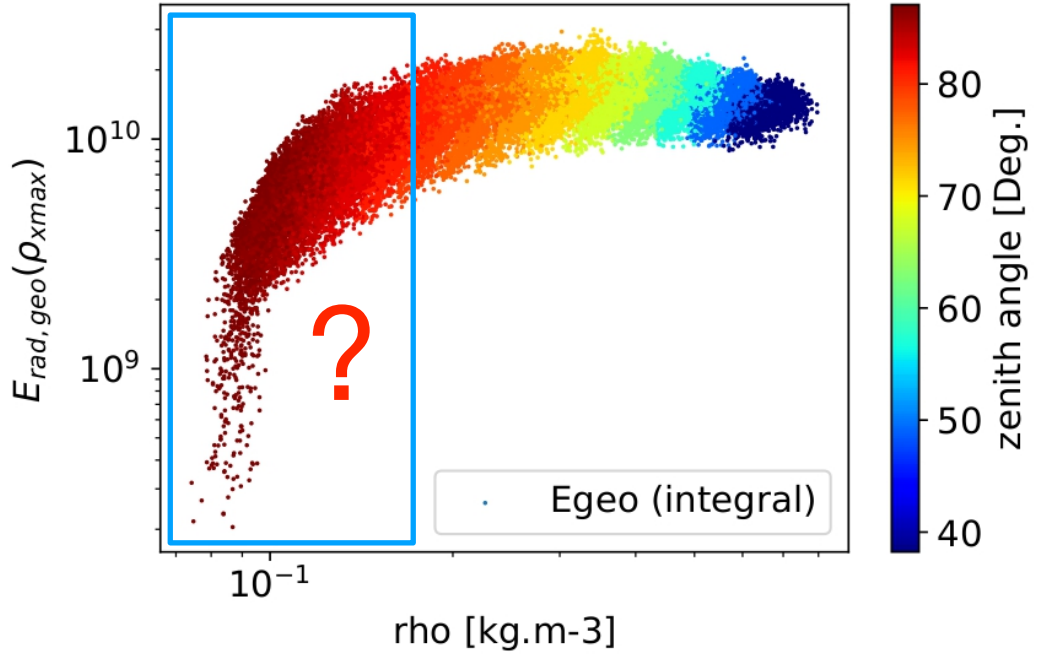
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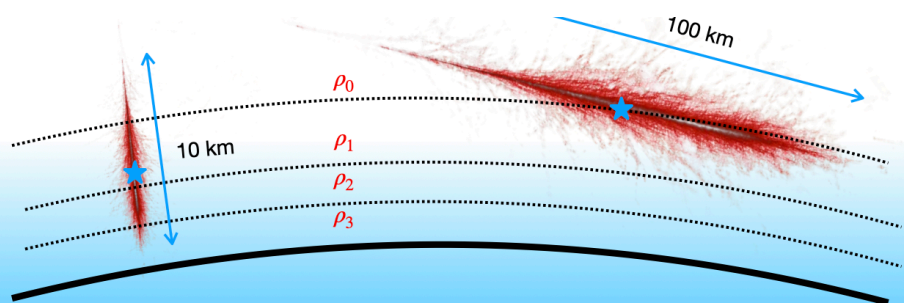


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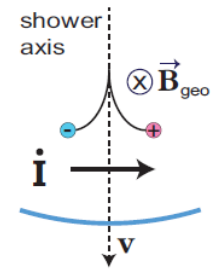
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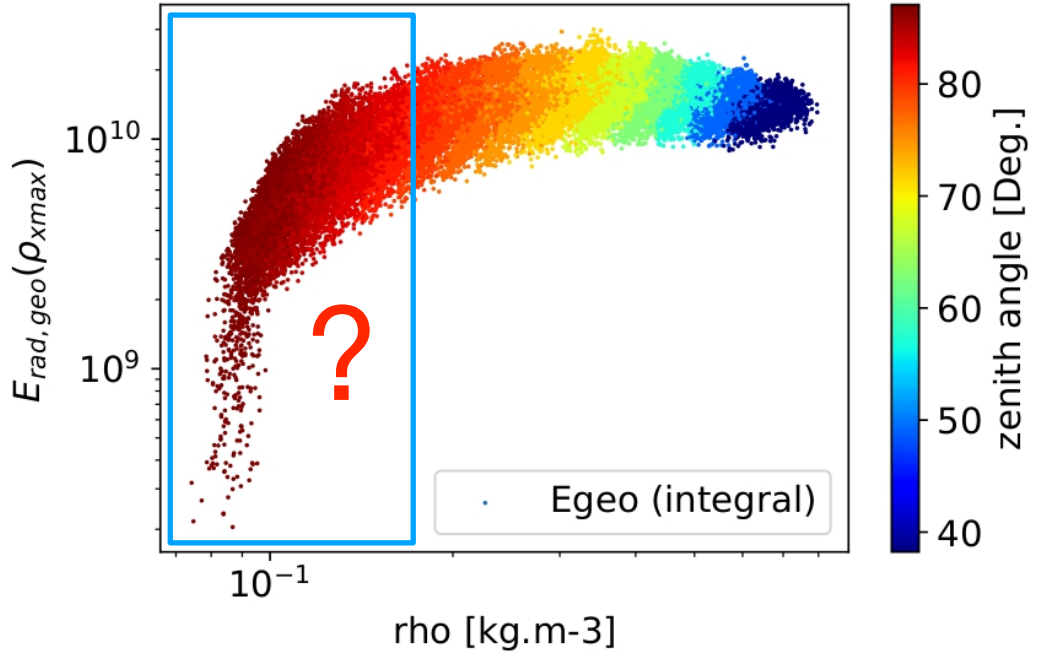
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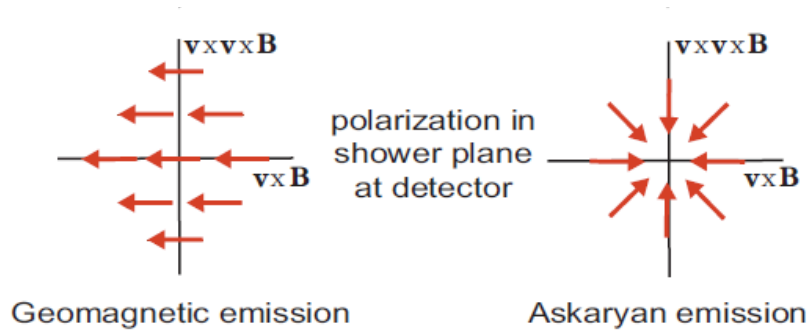
Geomagnetic radiated energy



Unexpected dependency of the geomagnetic emission with air-density

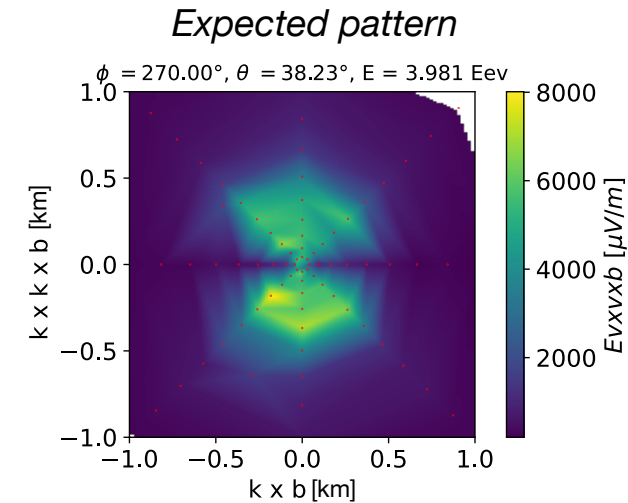
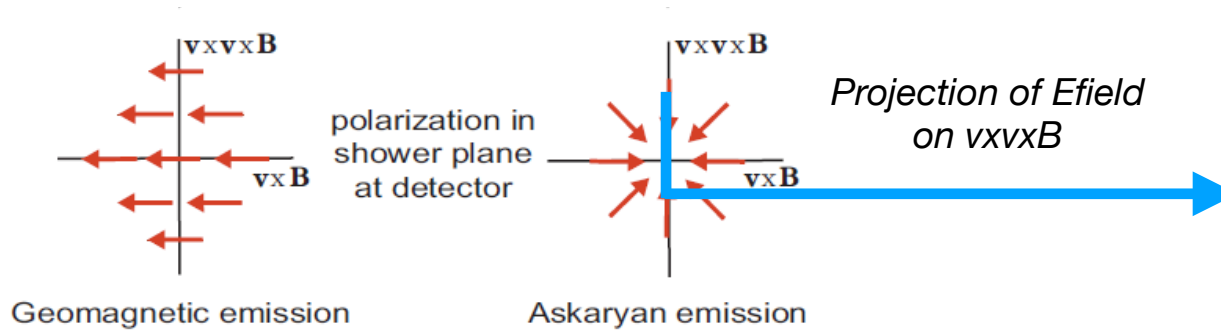
# The clover-leaf pattern: a third type of radio-emission

$\nu \times \nu \times B$  component: dominant contribution of Askaryan emission?



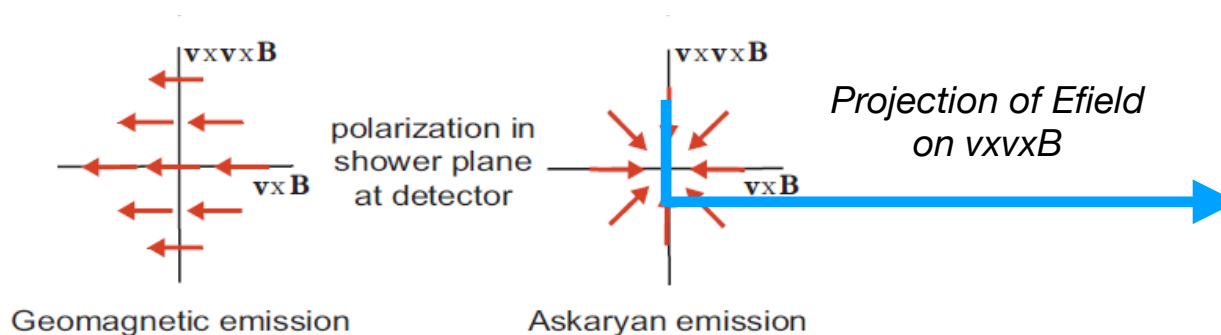
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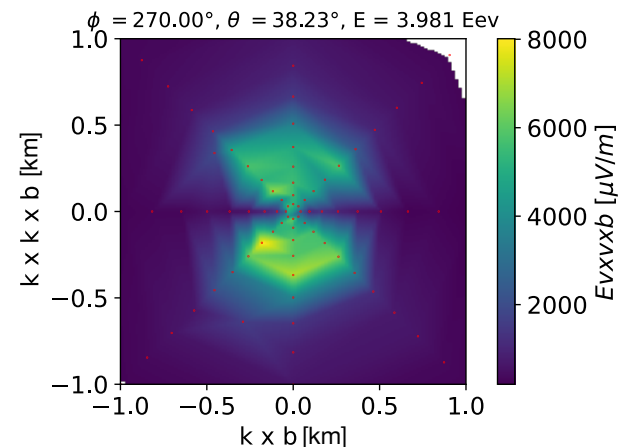


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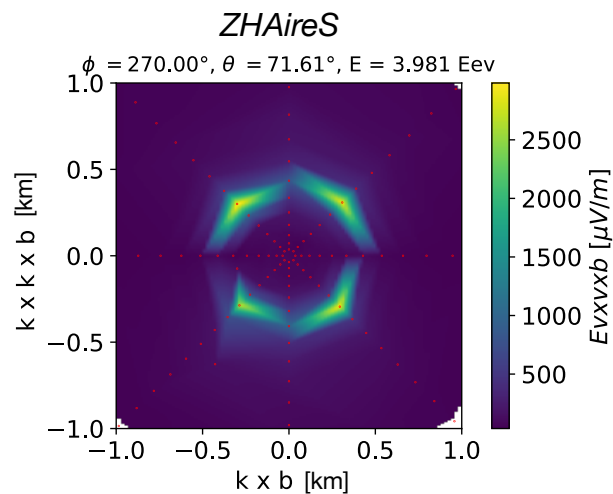
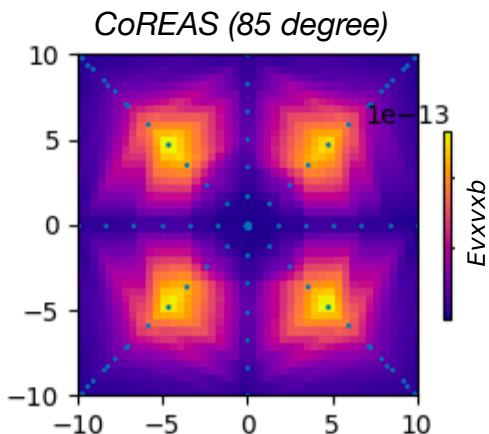
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Expected pattern



Observed pattern: clover-leaf

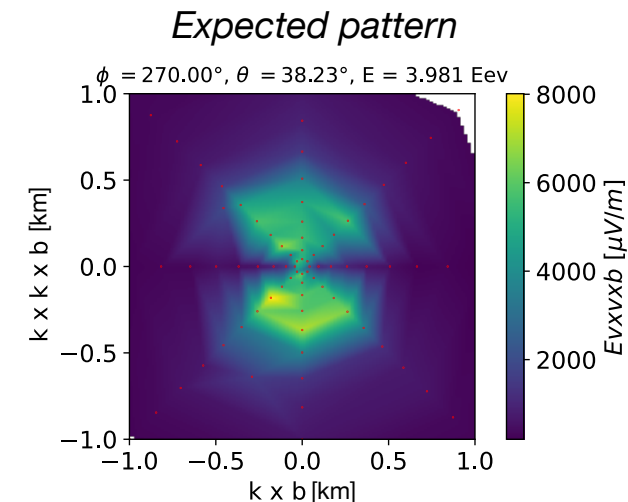
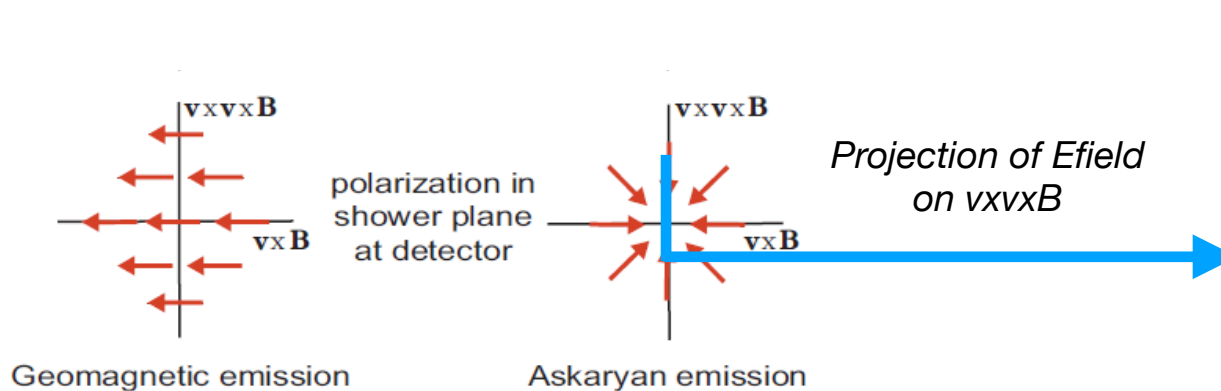


New polarization signature on the  $\nu \times \nu \times B$  component!

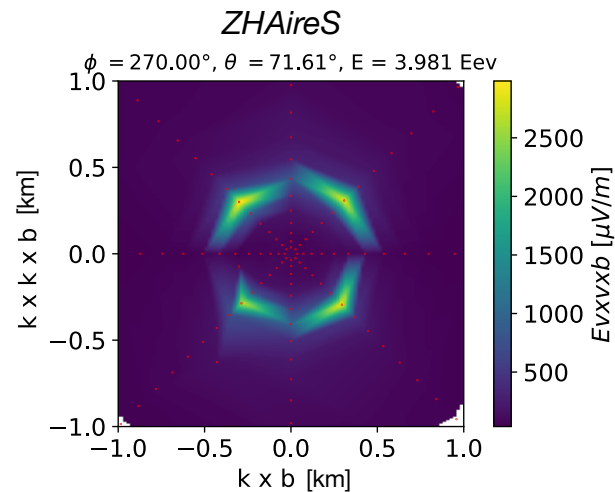
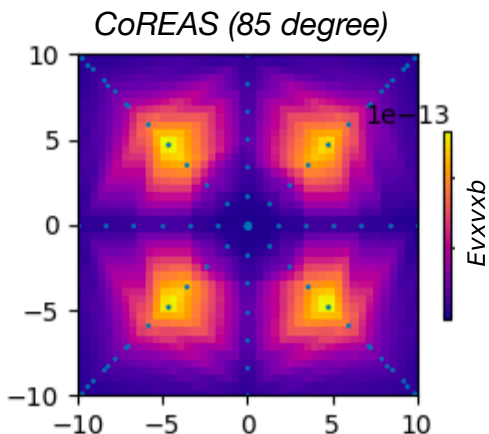
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- Observed in simulations for the 3.4-4.2 GHz band only here  $\mathcal{O}(100 \text{ MHz})$  (Huge 2013, CROME data)

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Observed pattern: clover-leaf



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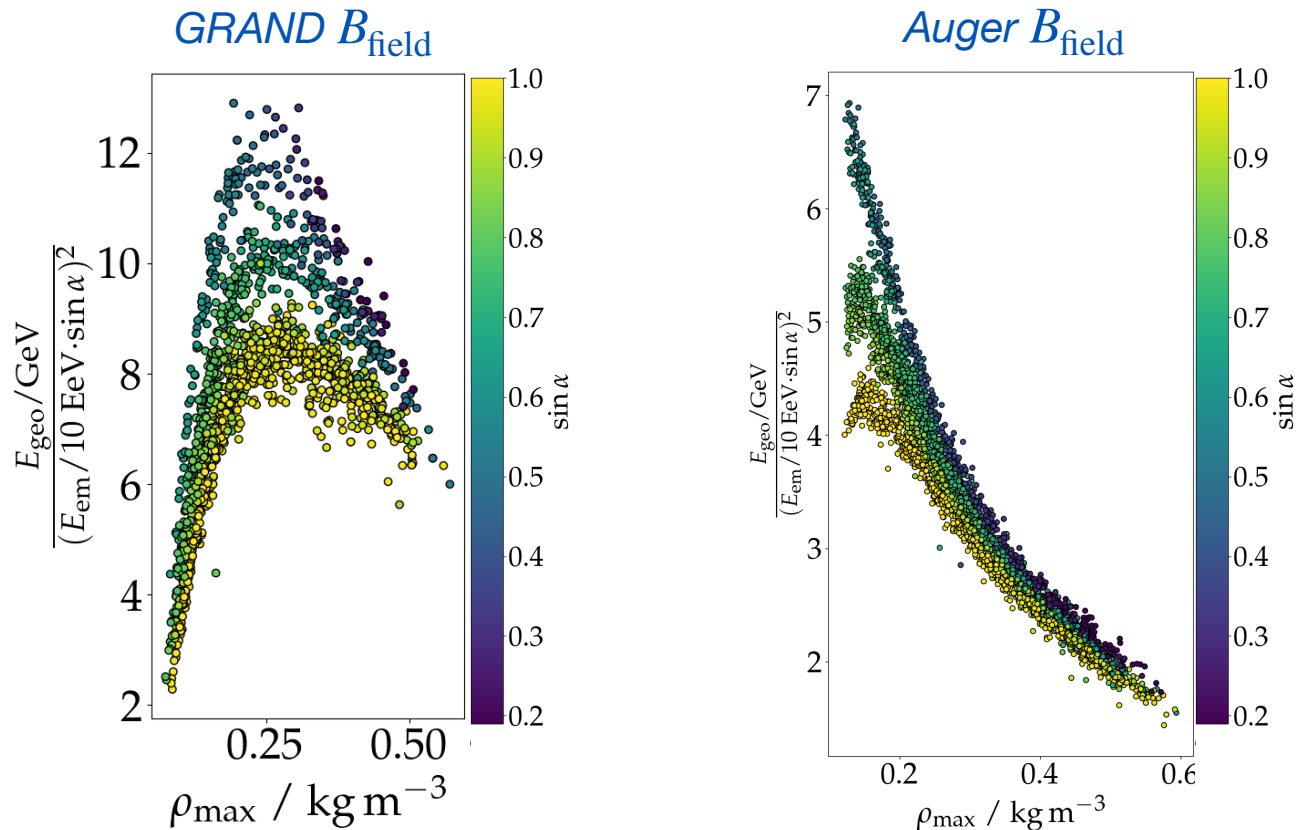
**Clover-leaf pattern: hints for a third type of emission dominant over the Askaryan for inclined EAS**

Where do this Geomagnetic cut-off and the clover-leaf pattern come from? Are they linked?



# Dependency of the cut-off with geomagnetic field

Test of 2 different  $B_{\text{Earth}}$  values with CoREAS simulations



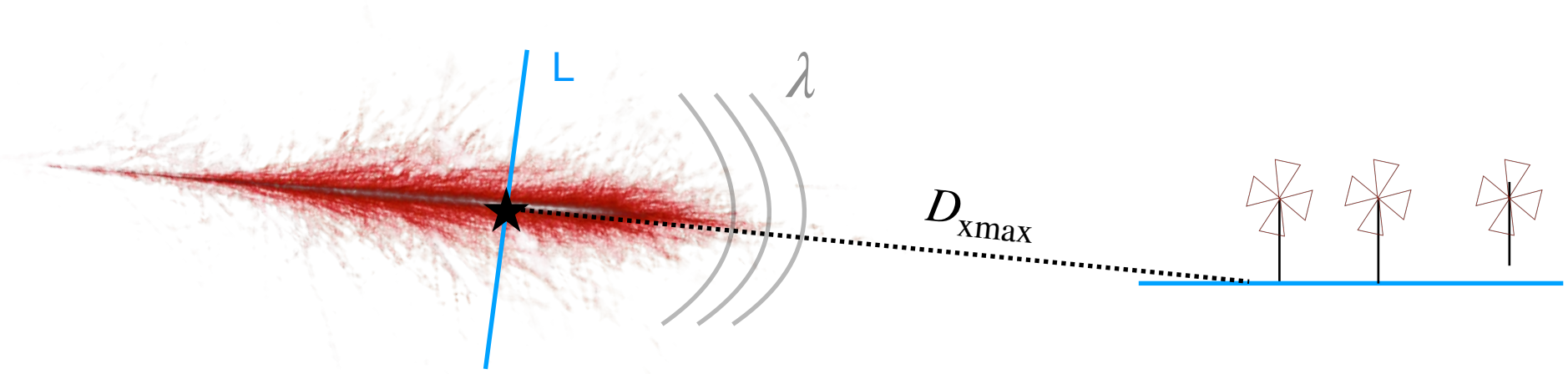
**Almost no cut-off in the geomagnetic emission for Auger  $B_{\text{field}}$ !**

**Scaling does not follow  $E_{\text{rad,geo}} \propto B^2 \sin^2 \alpha$  (Glaser et al., 2016)**

# Spatial coherence of the radio signal

**Geomagnetic cut-off: function of  $\rho_{\text{air}}$  and  $B_{\text{Earth}}$**

→ Could be linked to the shower lateral extent!  $L(\rho_{\text{air}}, B_{\text{Earth}})$

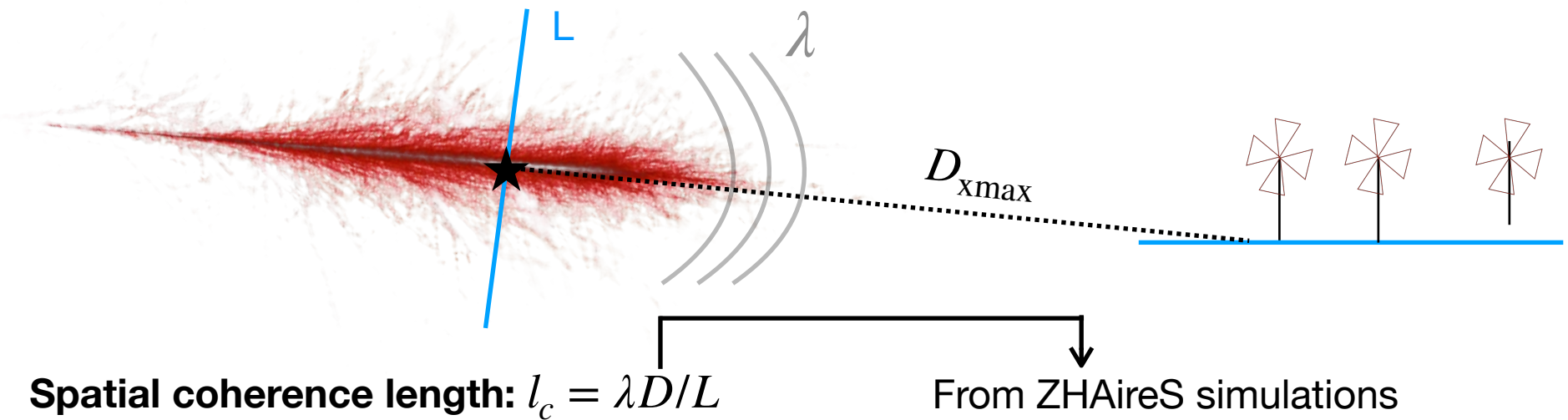


**Spatial coherence length:  $l_c = \lambda D/L$**

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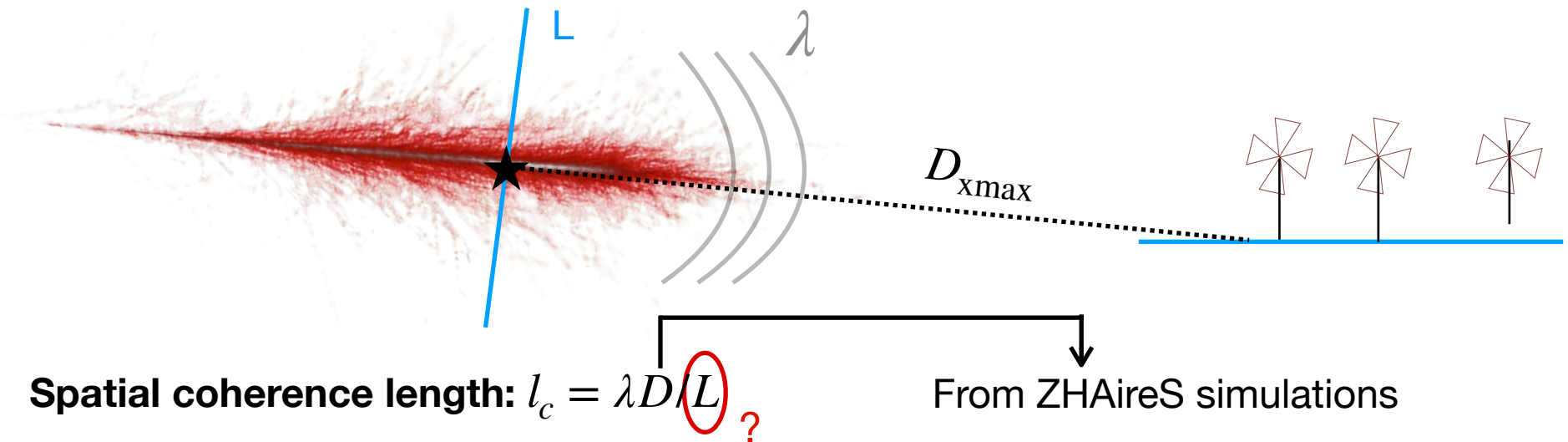
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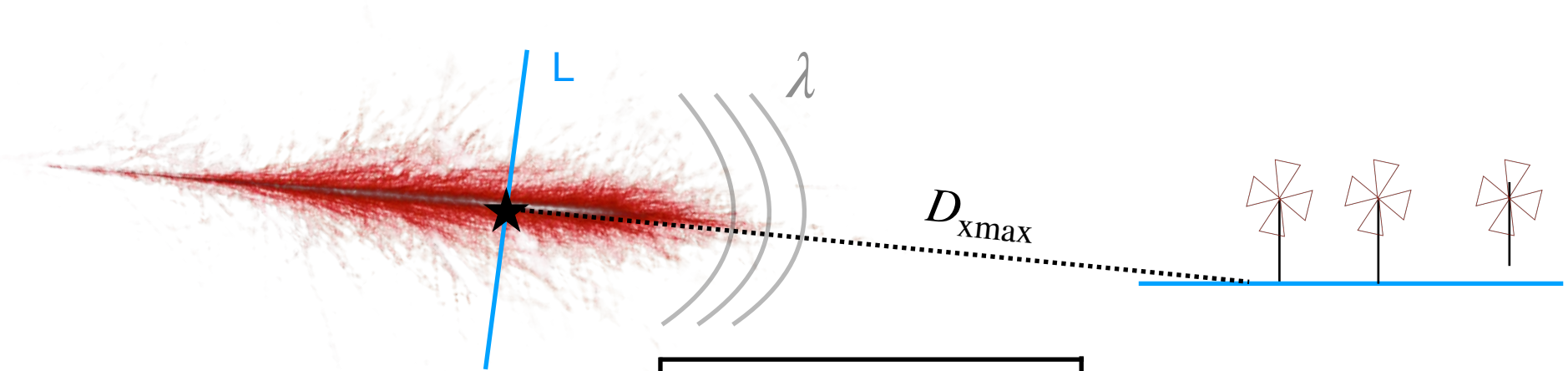
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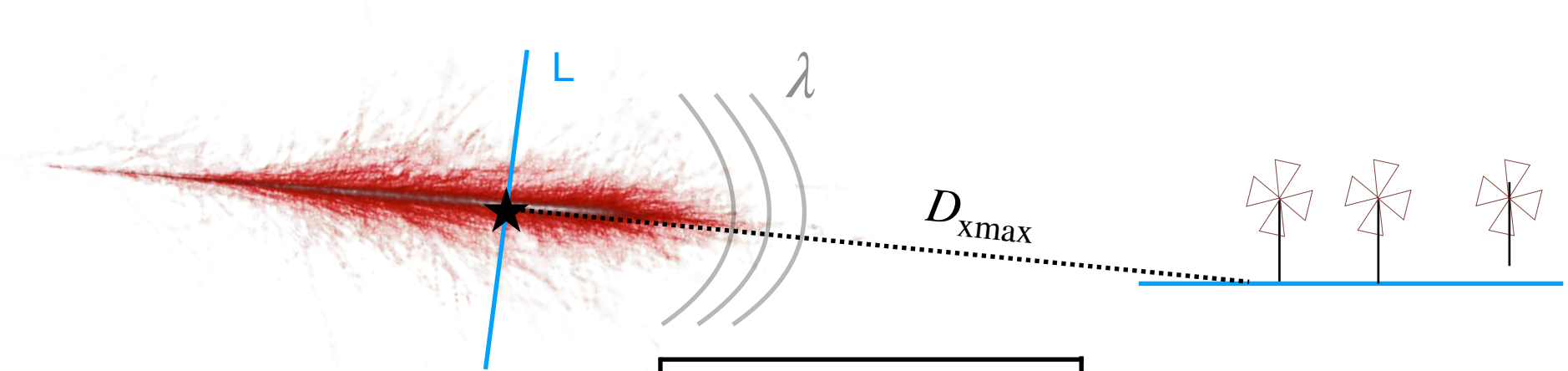
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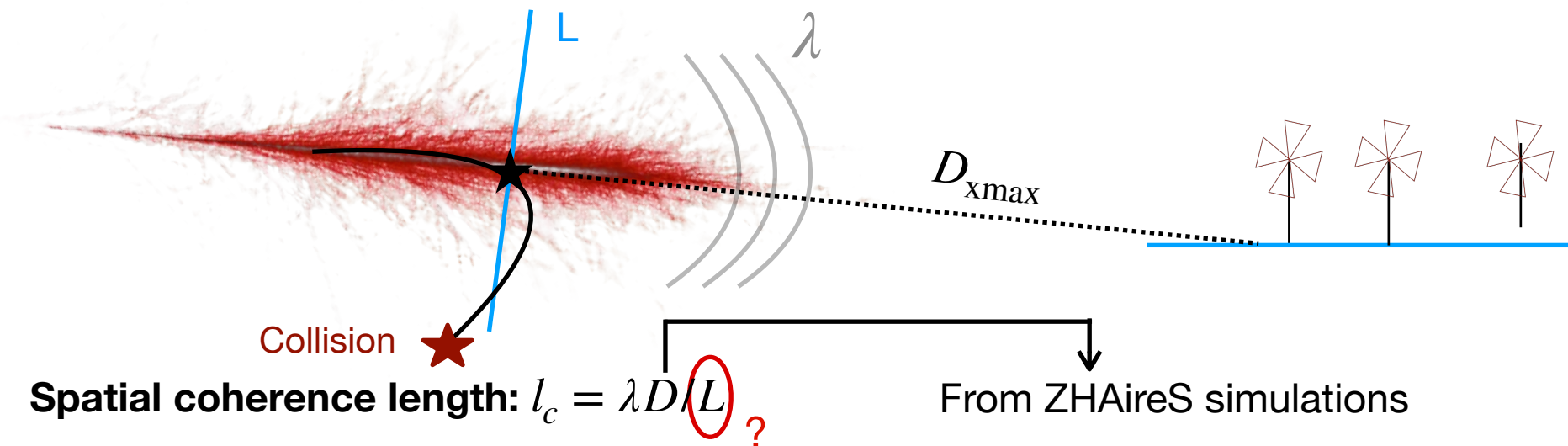
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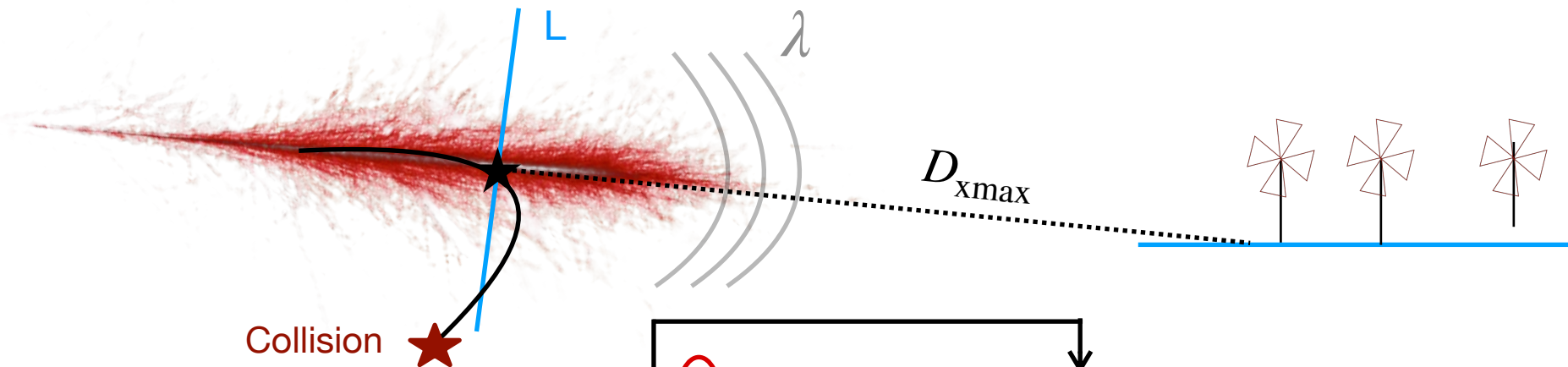
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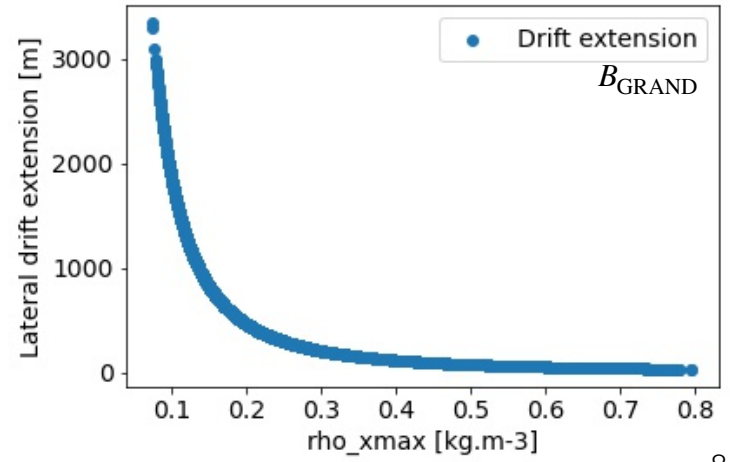
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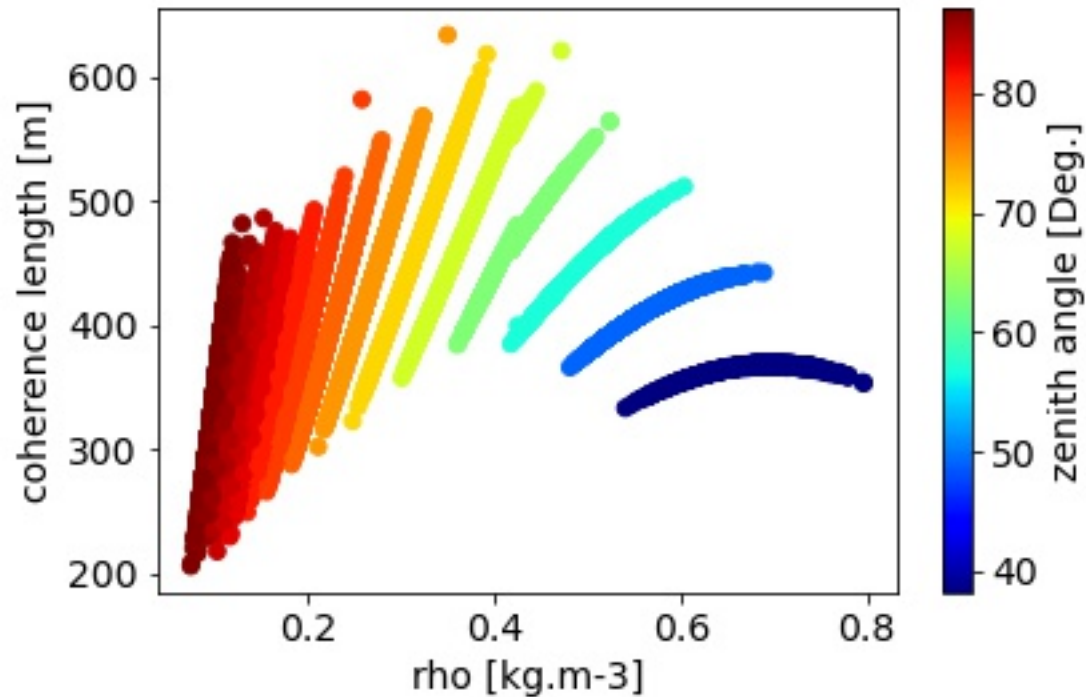




# Spatial coherence of the radio signal

**Spatial coherence length:**  $l_c = \lambda D/S$

GRAND magnetic field value



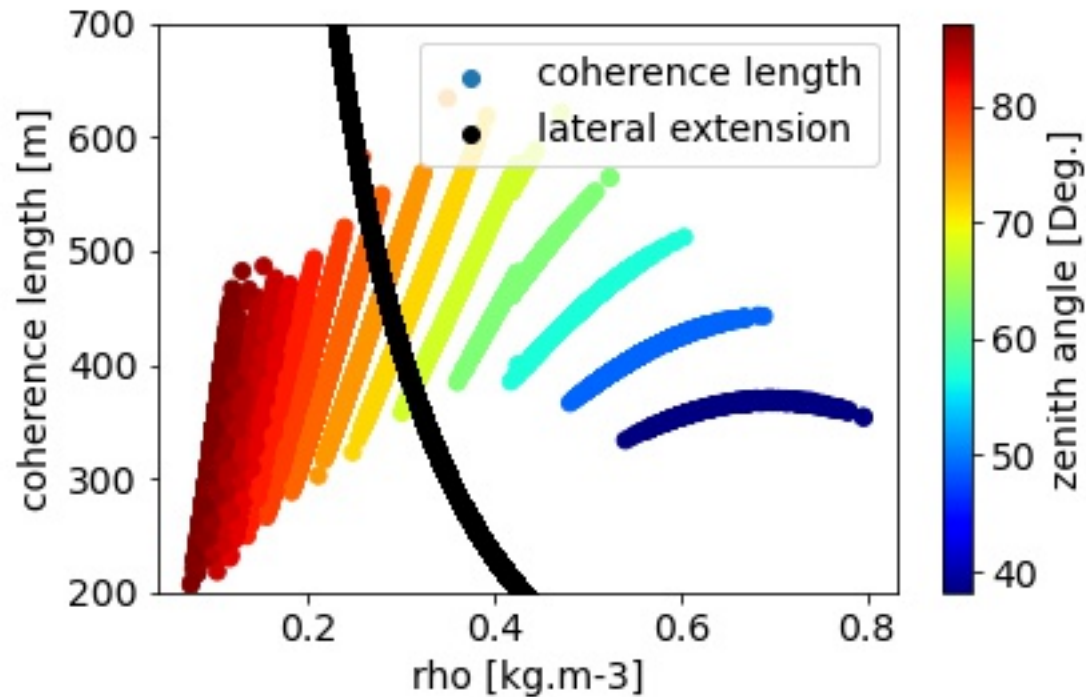
Loss of spatial coherence for inclined showers!

**Could efficiently model the geomagnetic cut-off**

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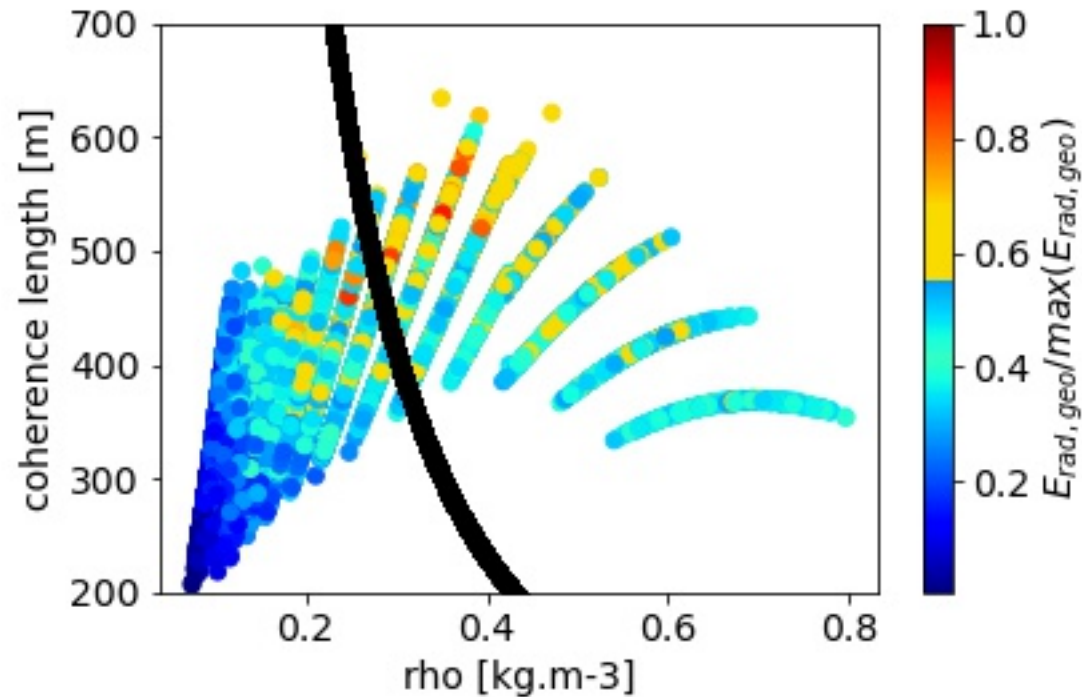
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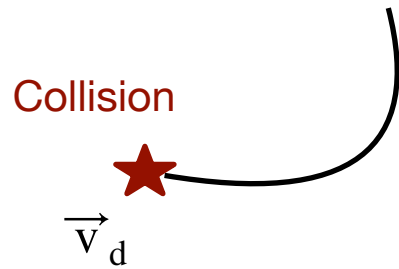
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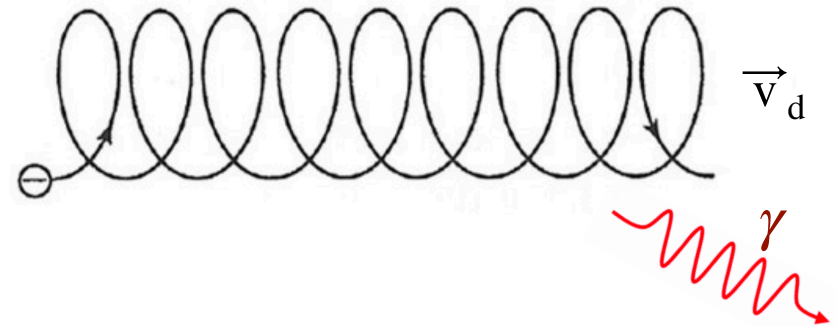
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The geomagnetic emission process becomes less efficient at low density

High density



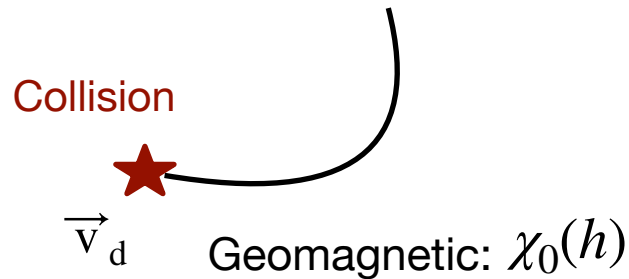
Low density



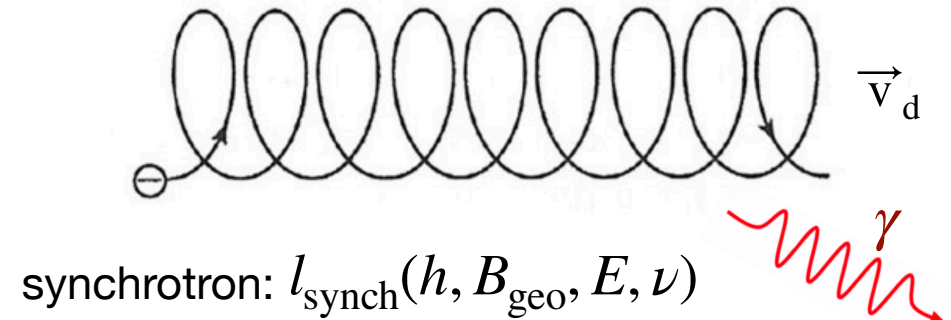
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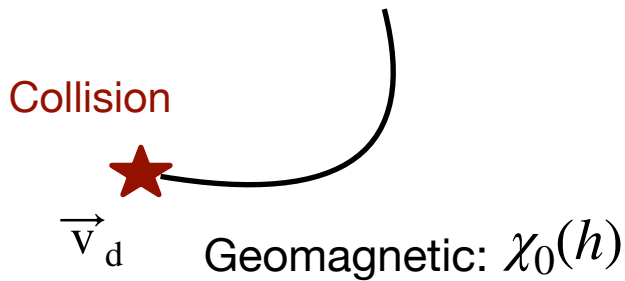
$$l_{\text{synch}}(h, B_{\text{geo}}, E, \nu) = \chi_0(h): \text{transition geomagnetic/synchrotron emission}$$

C. James (2022)

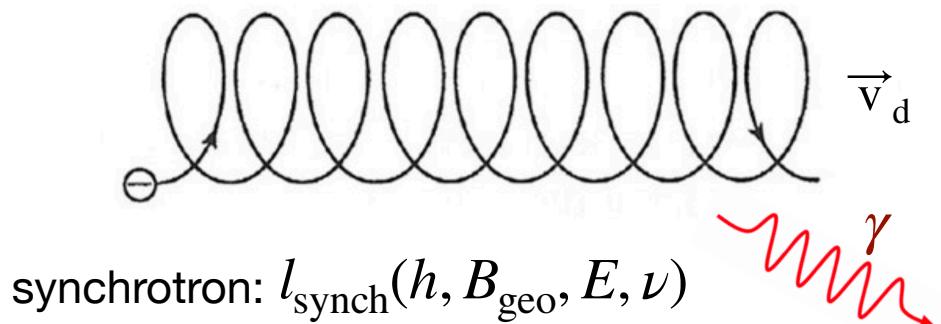
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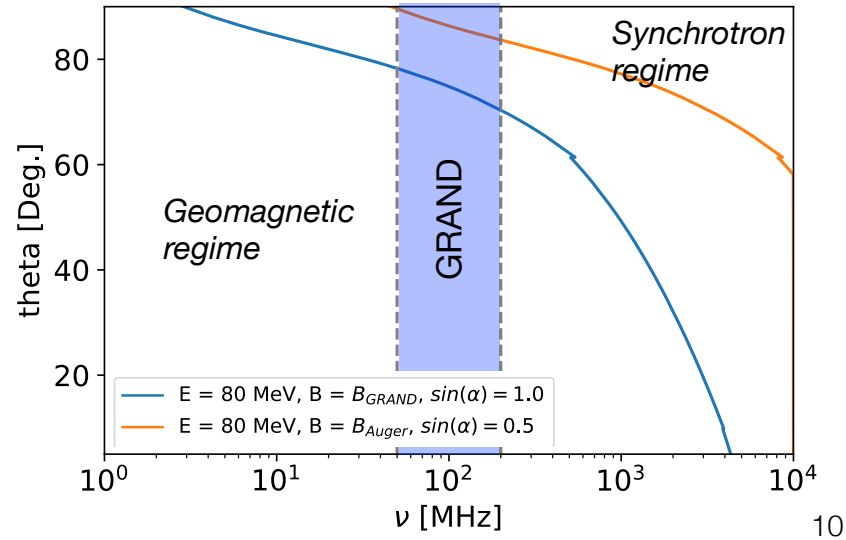


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C. James (2022)

**80 degree shower: transition regime at ~100 MHz for GRAND and ~ 1 GHz for Auger**

**Synchrotron emission visible with GRAND but hardly with Auger**

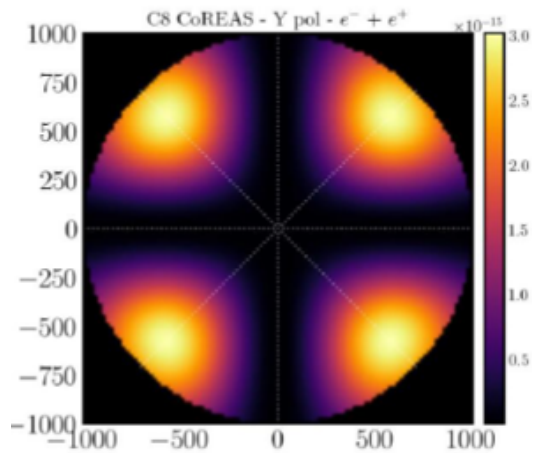


# The clover-leaf pattern: hints of a synchrotron emission

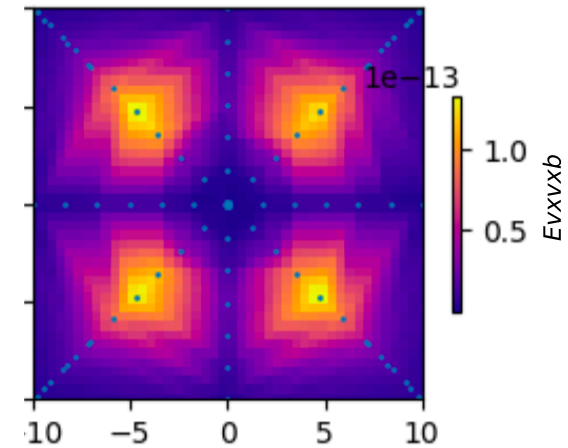
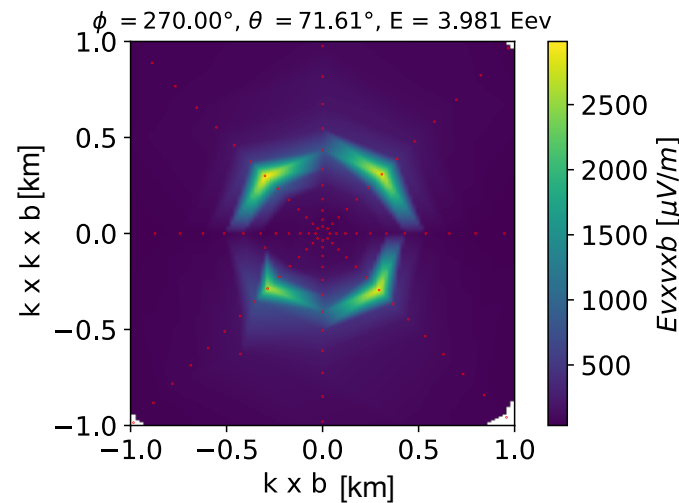
## Simulation of an $e^{+/-}$ pair in a uniform $B_{\text{field}}$ with Corsika8

Particles with same energy, starting vertically downwards, observer on the symmetry axis

*Synchrotron predictions*



*Clover-leaf pattern*



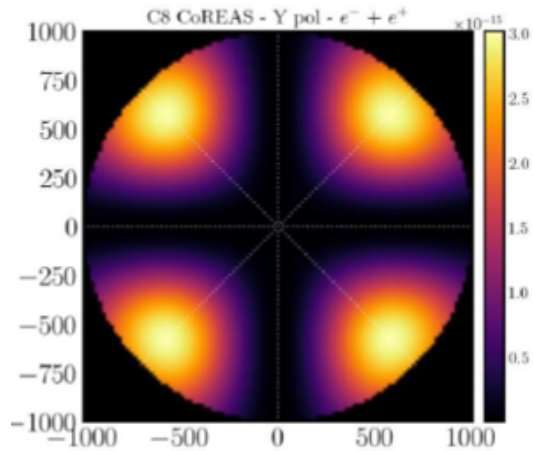
Credits to Nikolaos Karastathis

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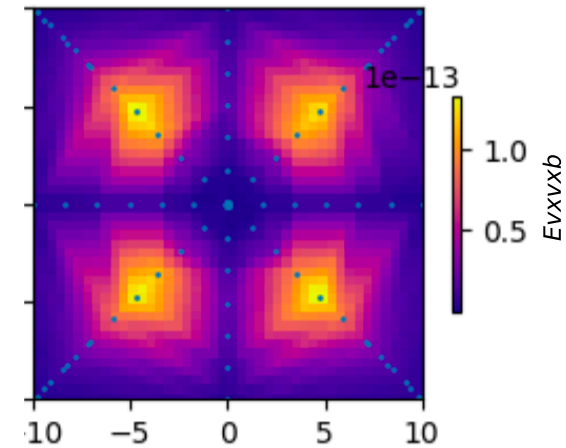
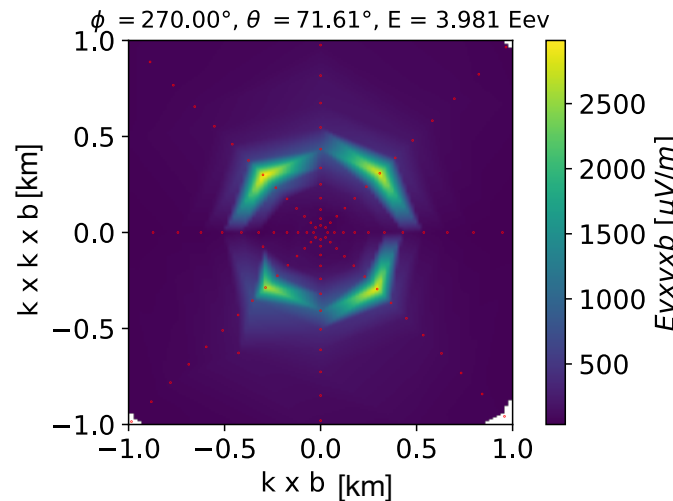
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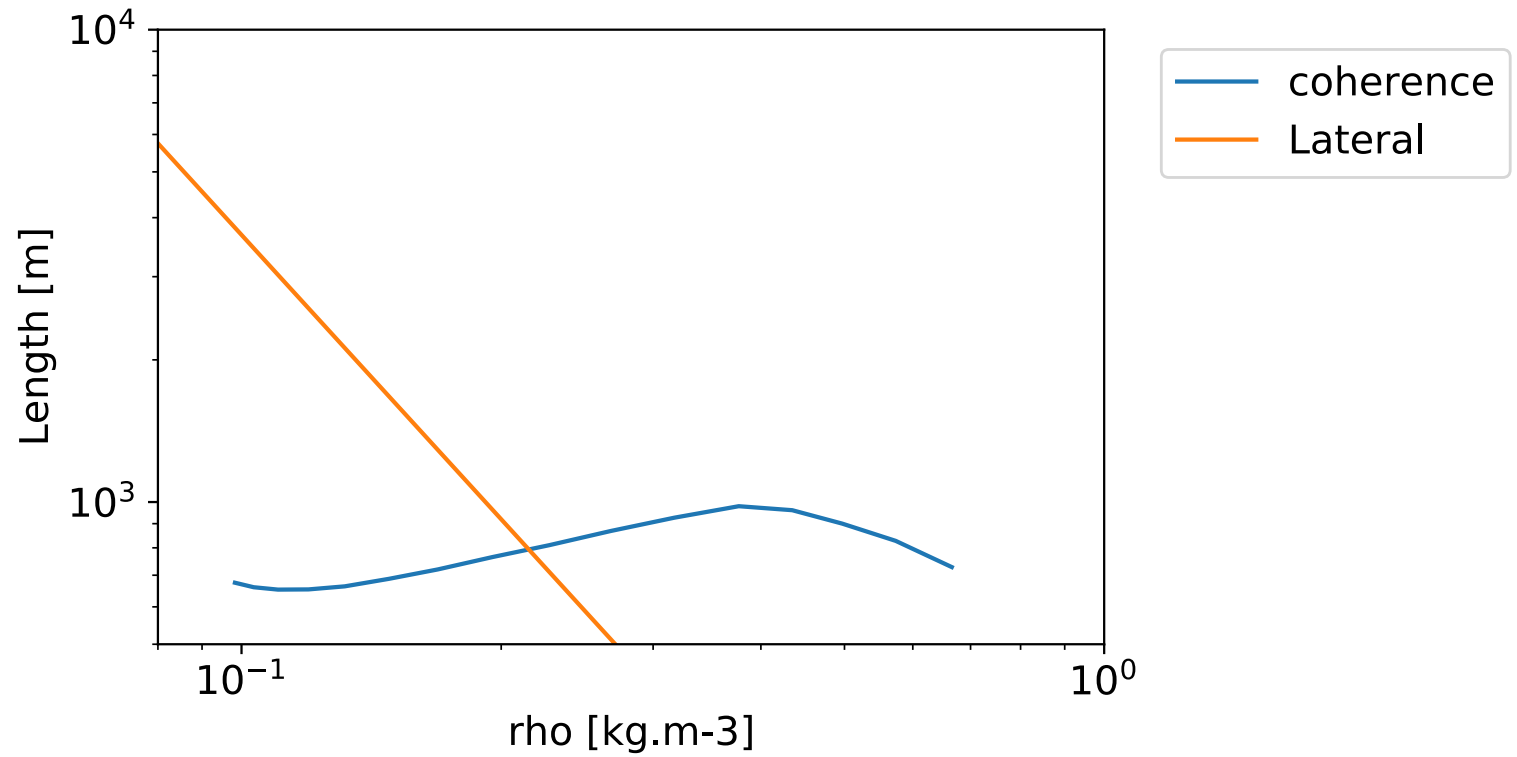


Credits to Nikolaos Karastathis

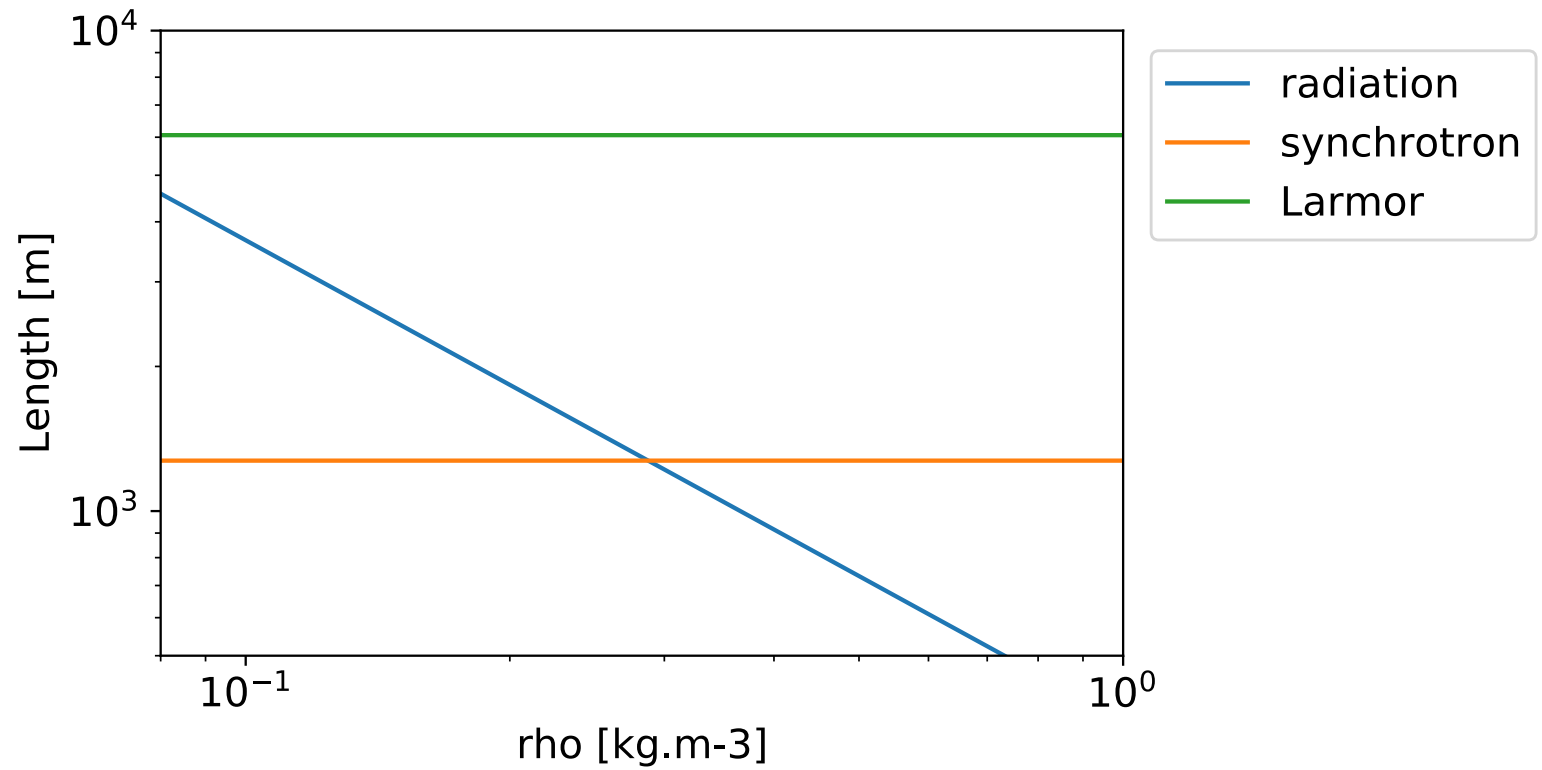
**➔ Synchrotron emission of an  $e^{+/-}$  pair leads to a clover-leaf like polarization pattern!**



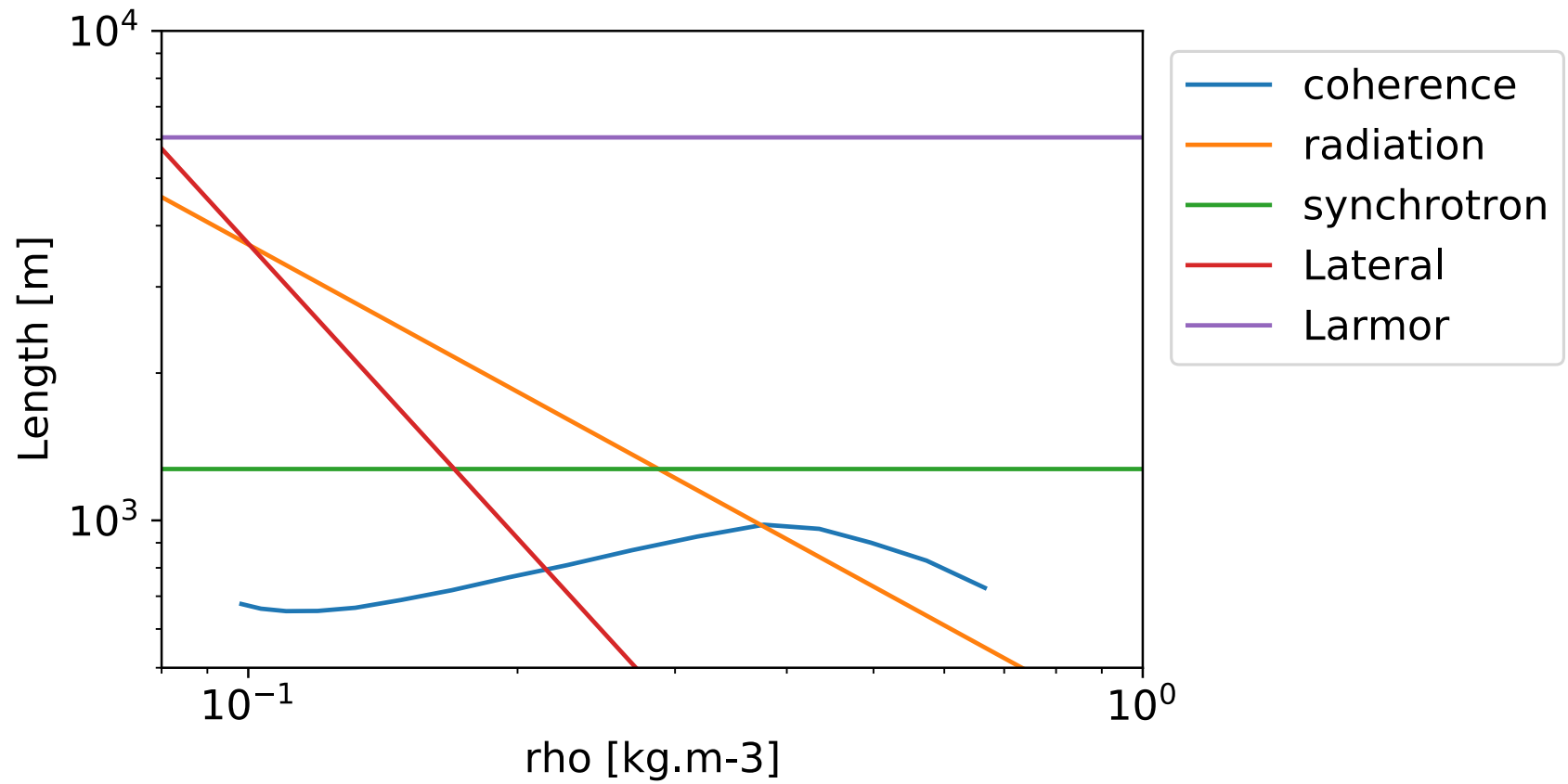
# Characteristic lengths



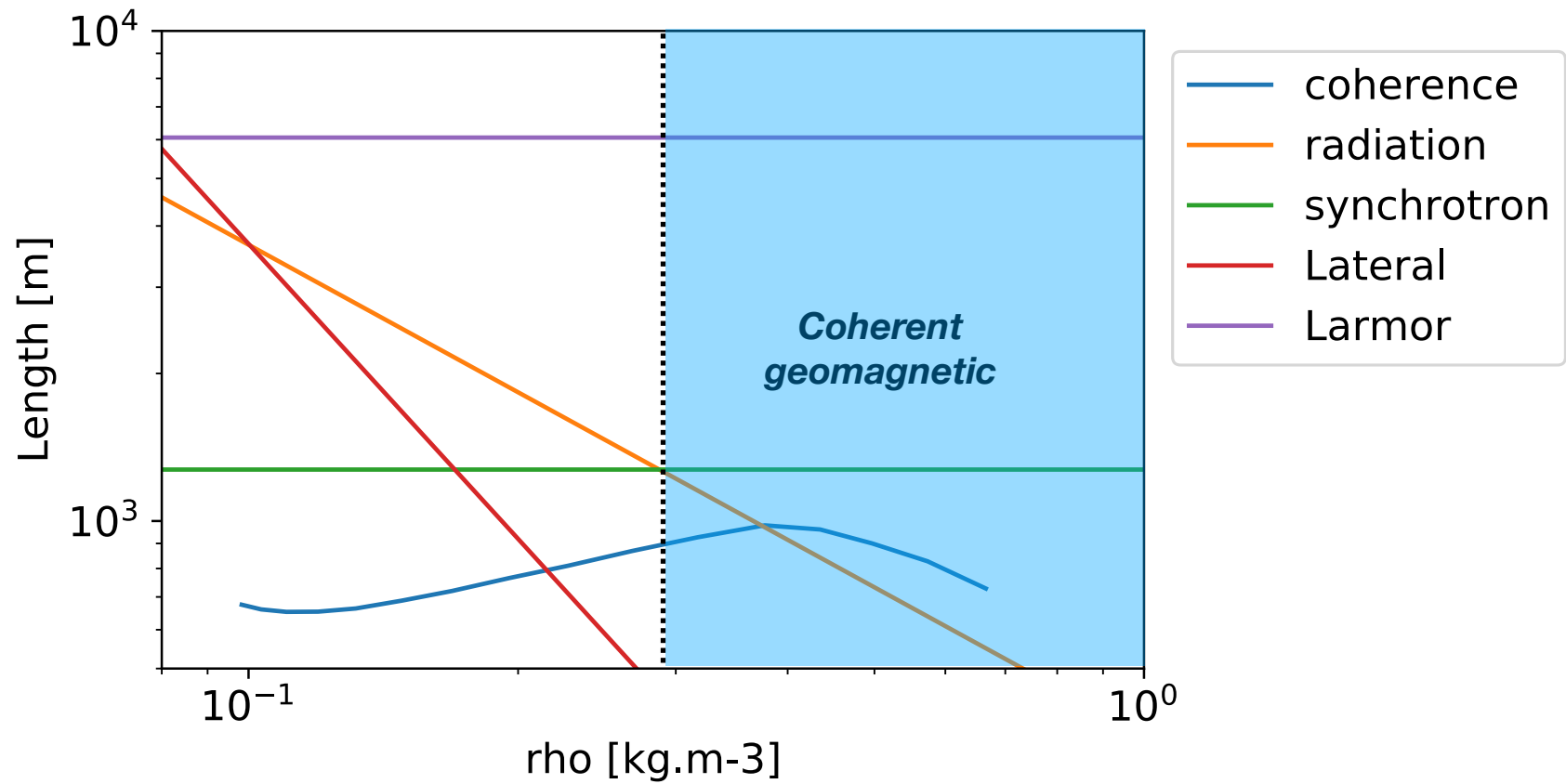
# Characteristic lengths



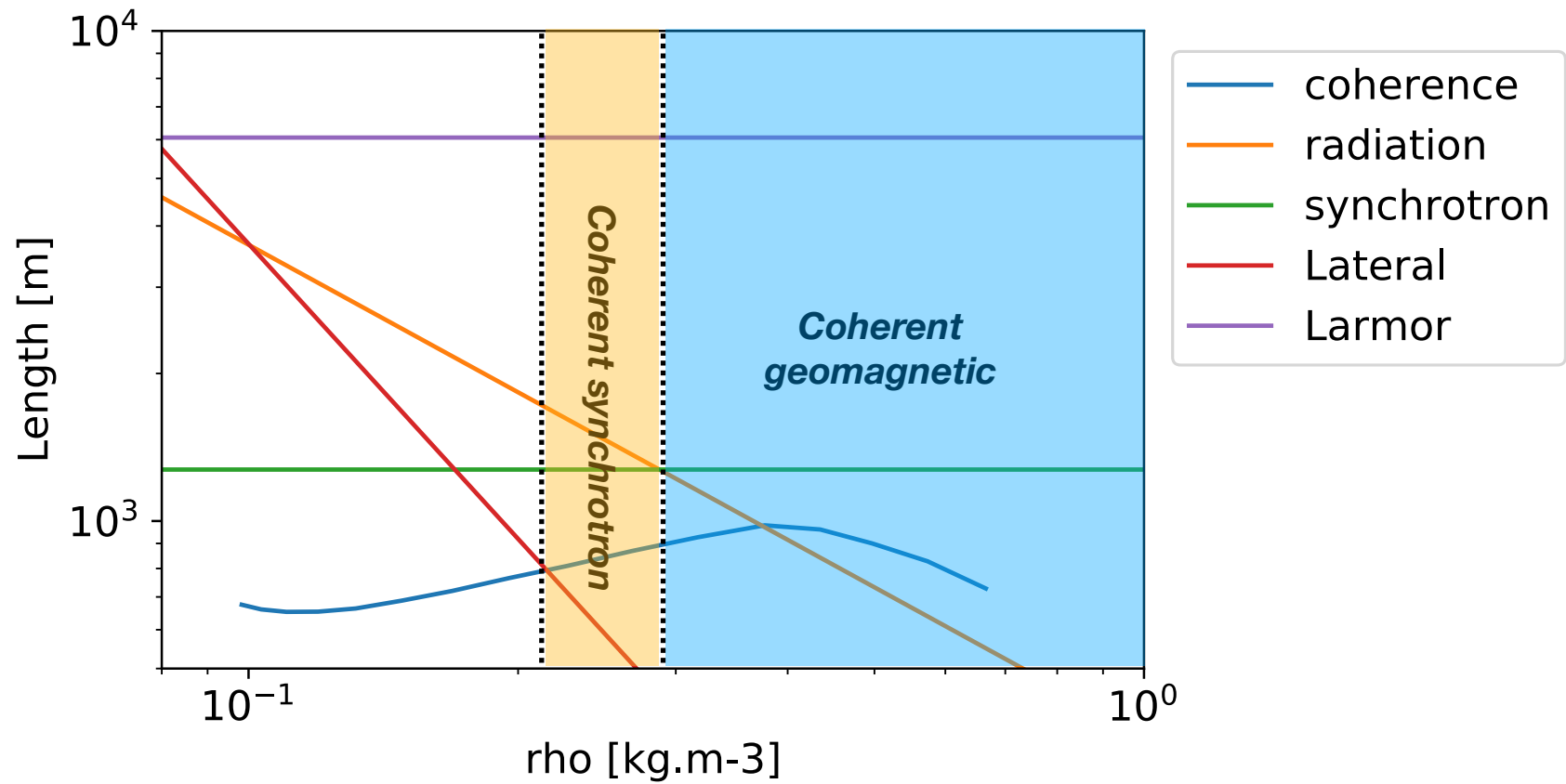
# Characteristic lengths



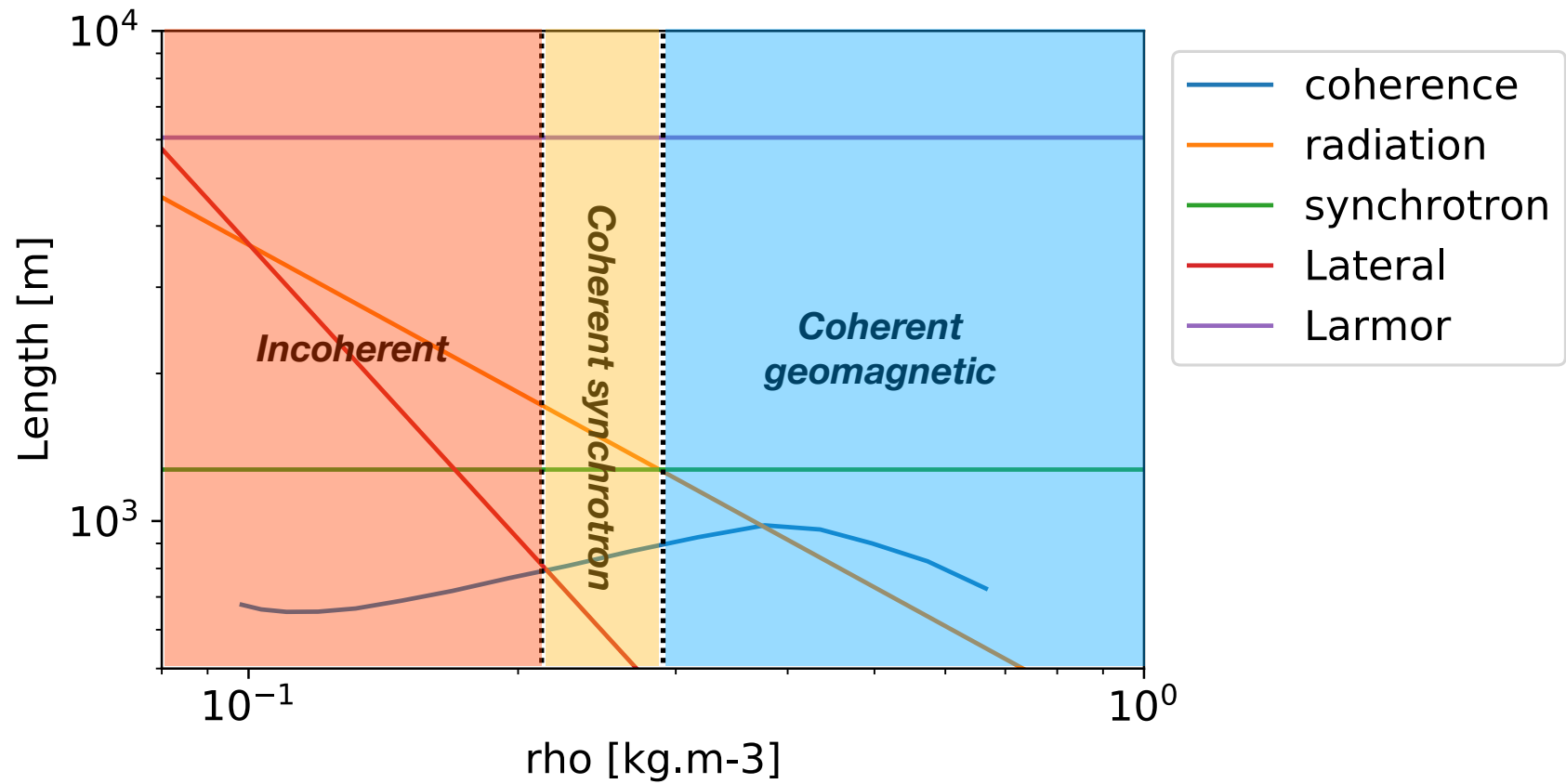
# Characteristic lengths



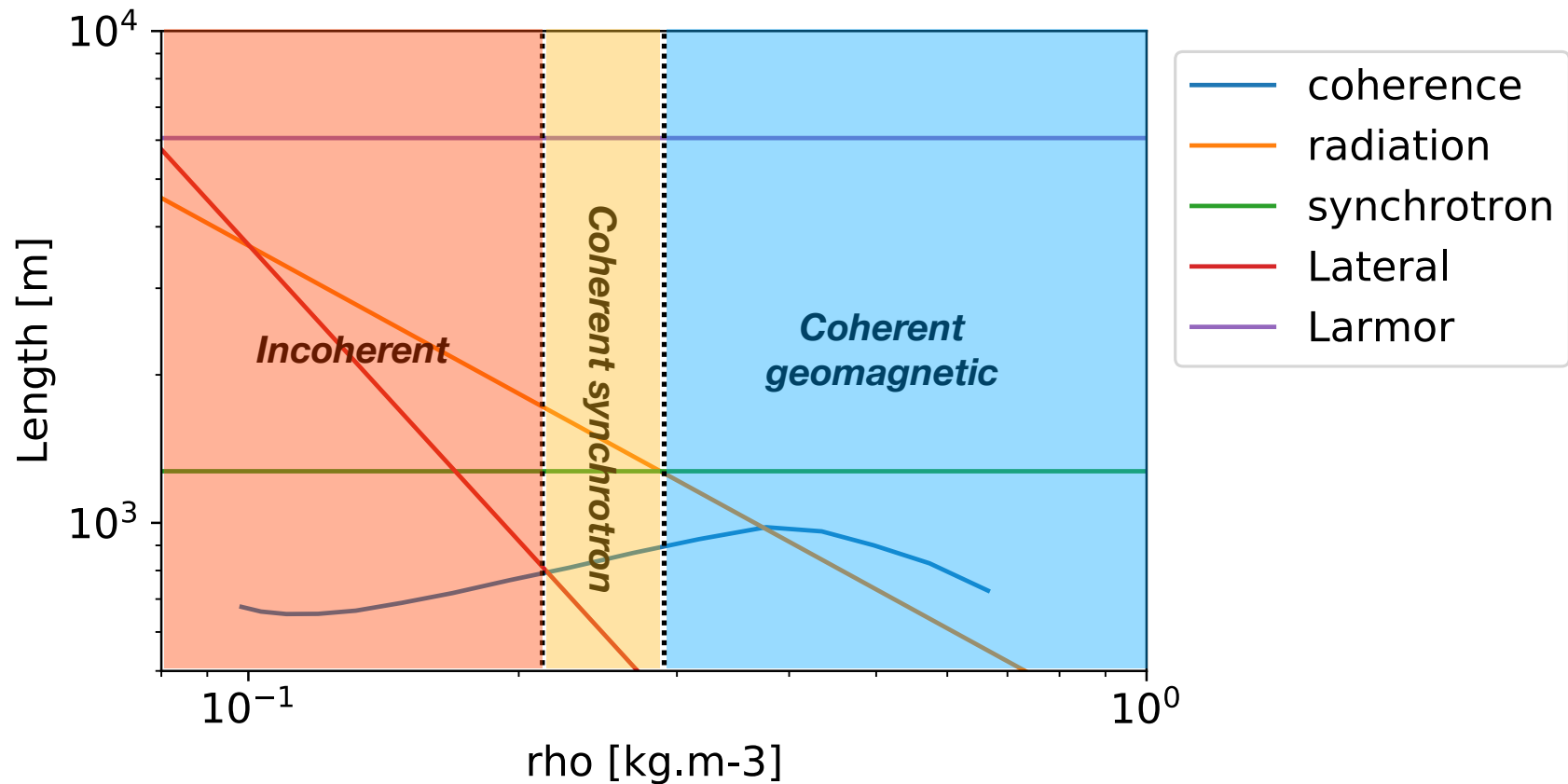
# Characteristic lengths



# Characteristic lengths



# Characteristic lengths



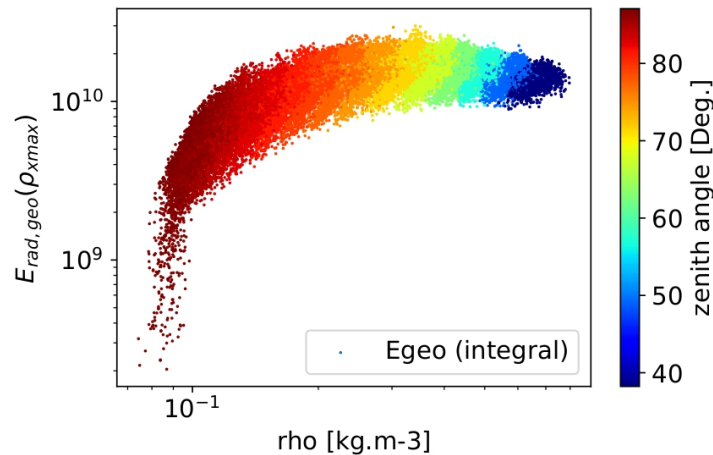
**3 distinct regimes as a function of air density**

**Explain the geomagnetic cut-off and the clover-leaf pattern!**

# Conclusion

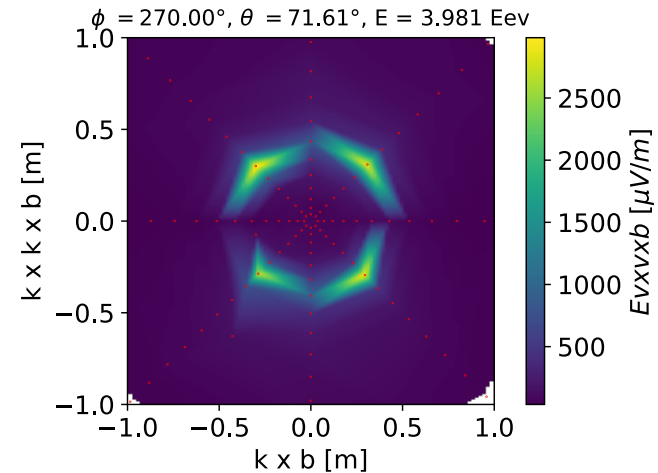
## 2 major new features in the radio emission of very inclined showers

*Geomagnetic cut-off*



Linked to a loss of coherence

*Clover-leaf pattern*



Linked to synchrotron radiation

**Refine our understanding of the radio emission: Geomagnetic + Askaryan description no more valid**

**Could strongly affect detection strategies of future experiments**

**Could help for cosmic-ray/neutrino discrimination**