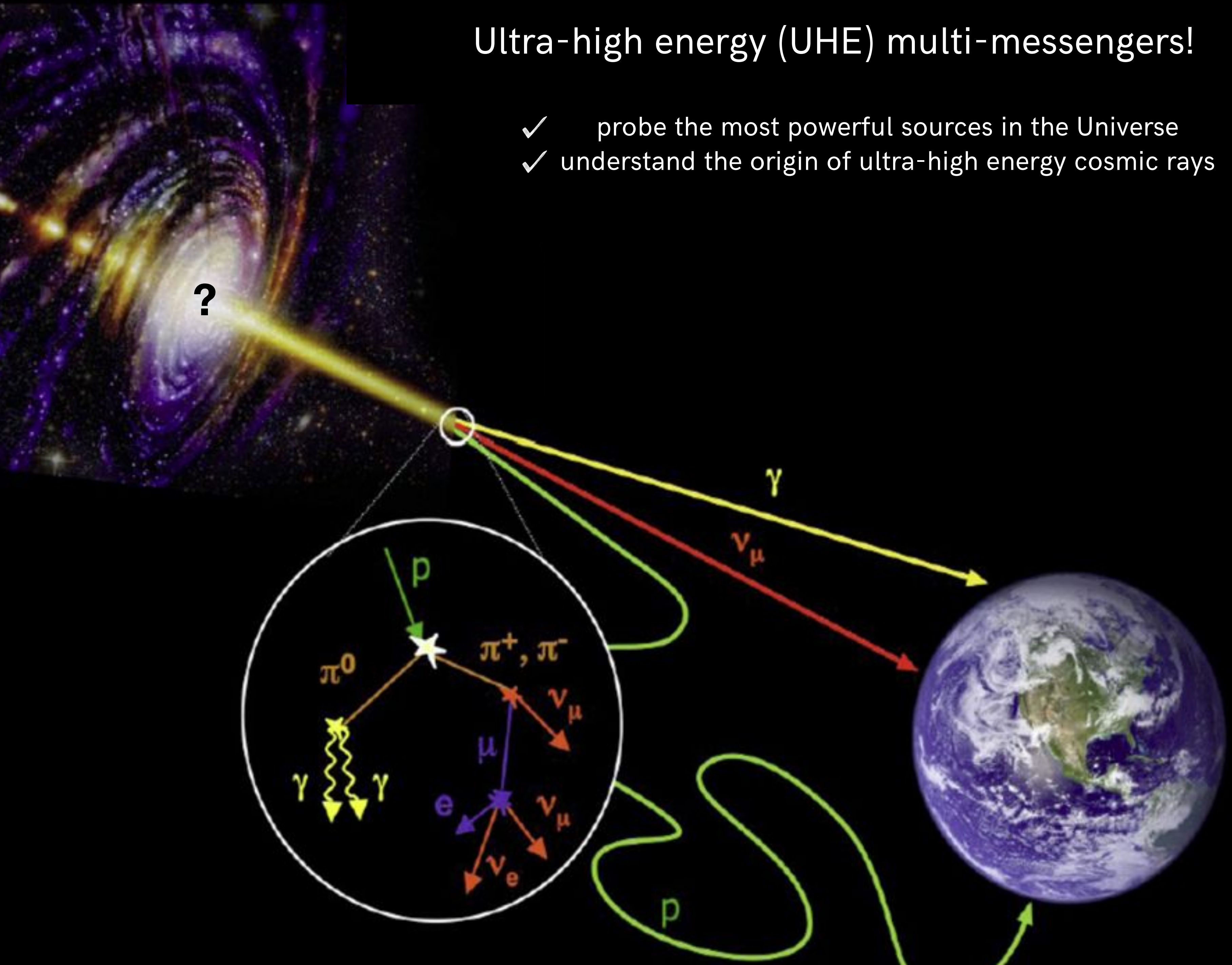
New paradigm and radio signatures for very inclined air showers

Simon Chiche - Institut d’Astrophysique de Paris

Ultra-high energy (UHE) multi-messengers!

- ✓ probe the most powerful sources in the Universe
- ✓ understand the origin of ultra-high energy cosmic rays

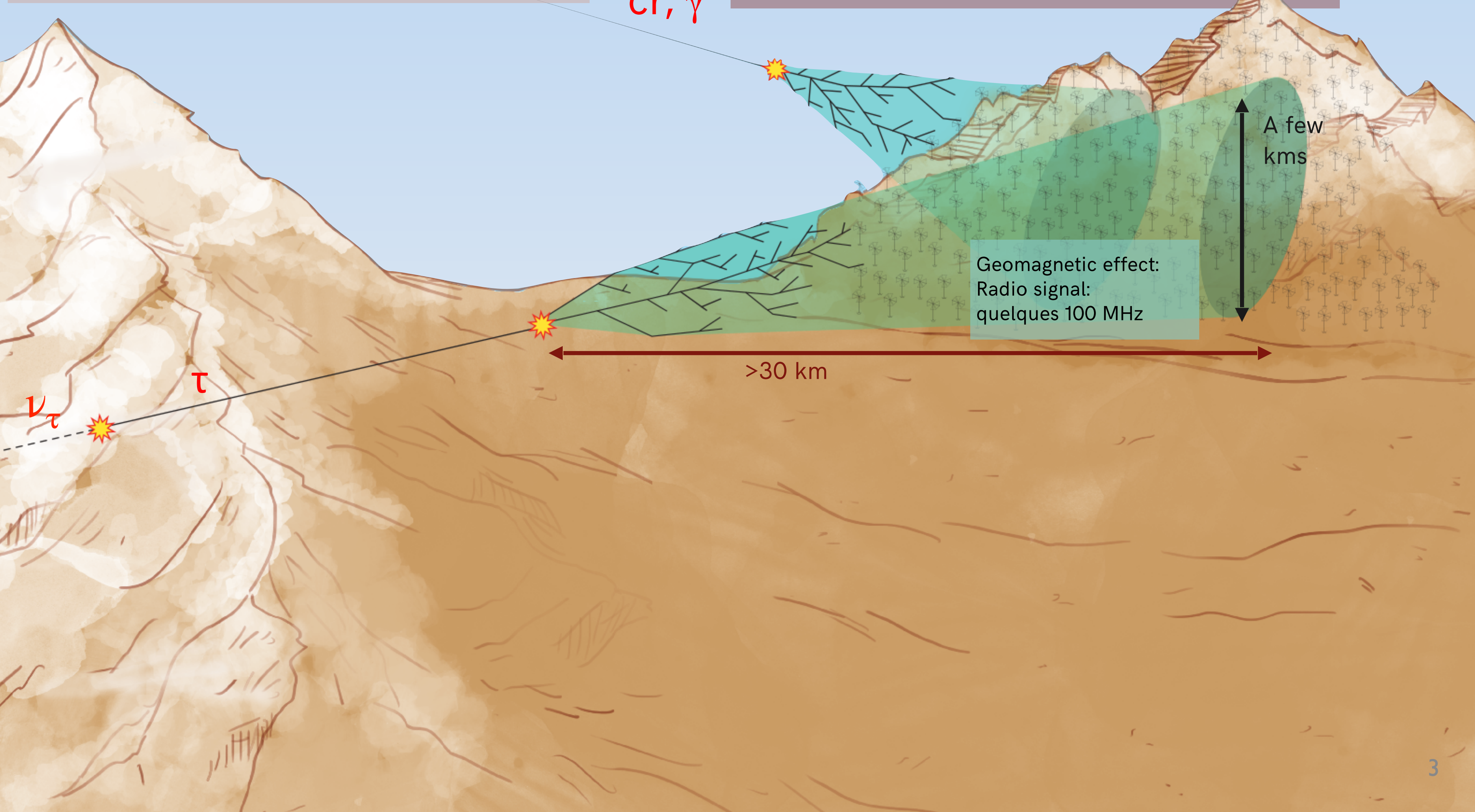


GRAND and GRANDproto300

GRAND: Giant radio array of 200 000 radio antennas over 200 000 km^2

Detection of air showers induced by ultra-high energy astroparticles

Inclined showers with mountains as targets



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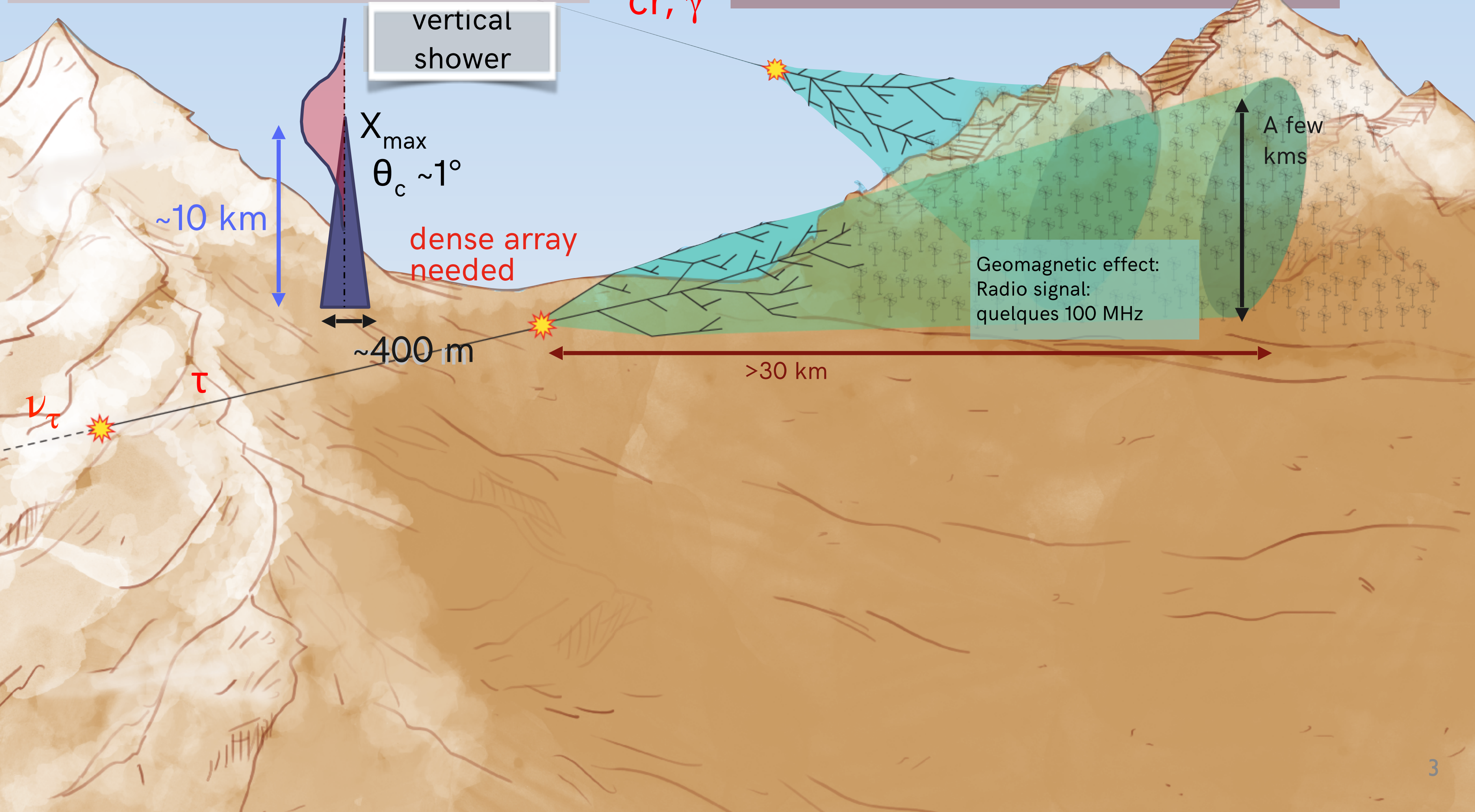

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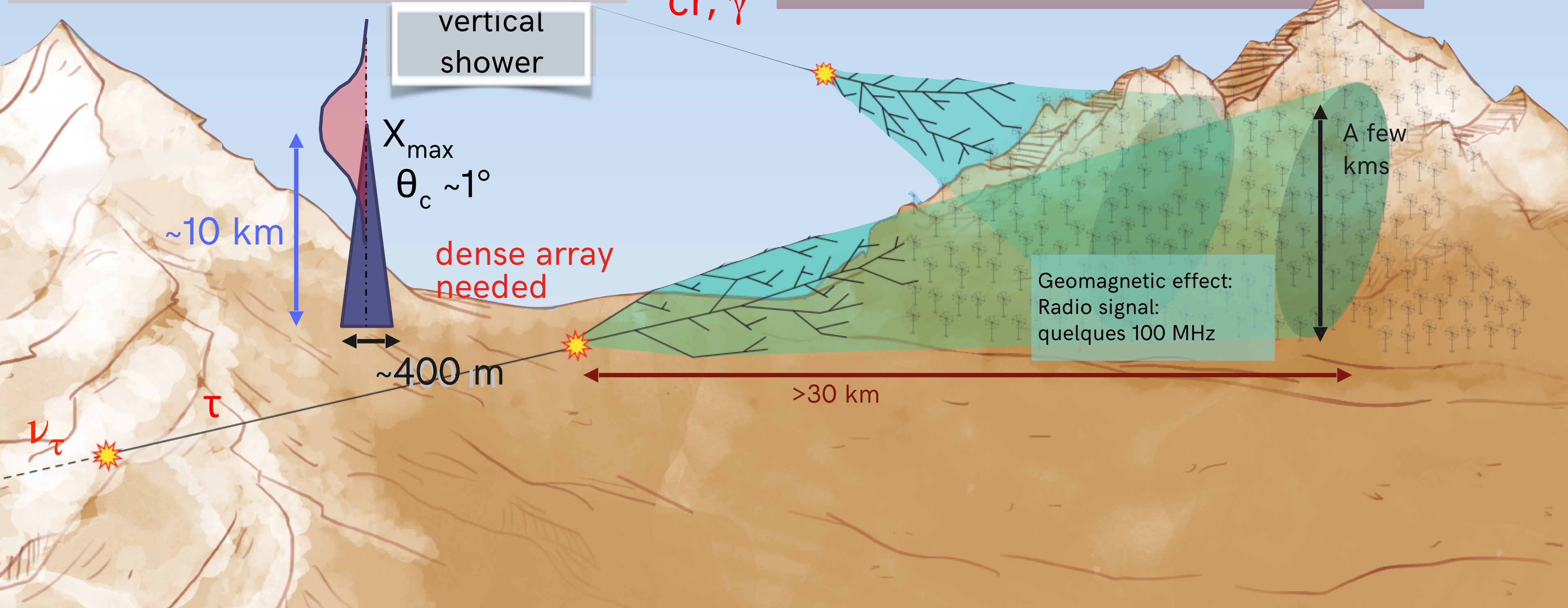


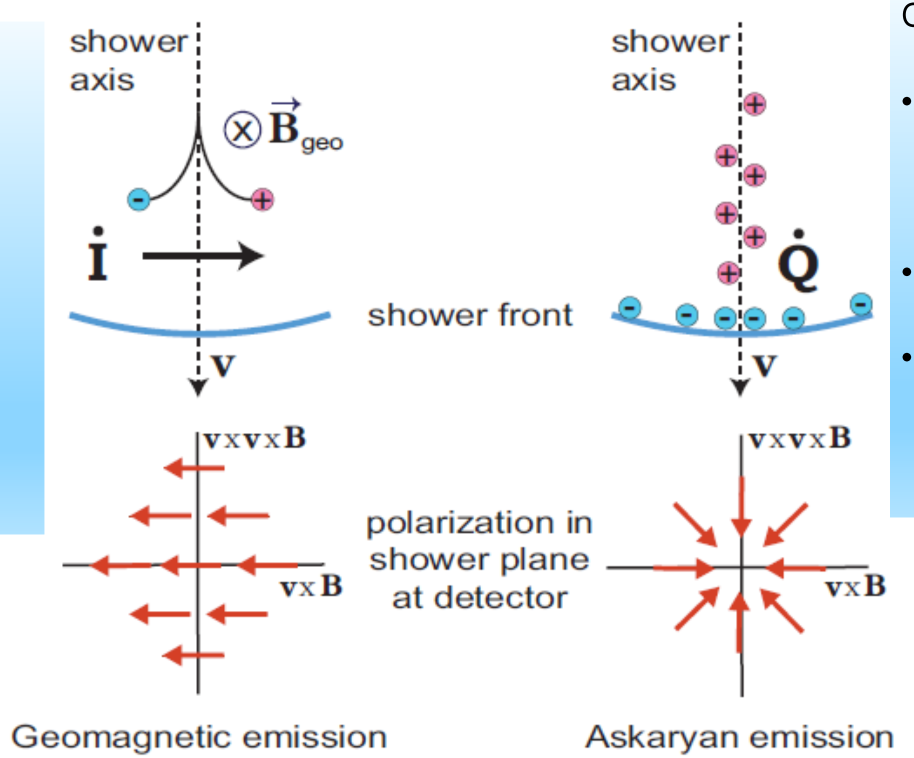
The preparation of GRAND requires a deep understanding of the radio signal emission processes

Radio signal from extensive air-showers - CLASSICAL picture

2 main sources for the radio emission

Geomagnetic emission

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



Schröder (2017)

Charge excess emission

- Accumulation of negative charges close to the shower core
- Radial polarisation
- ≈ 10% of the amplitude of the total emission for vertical air showers

vertical air-showers: well known, mature and verified

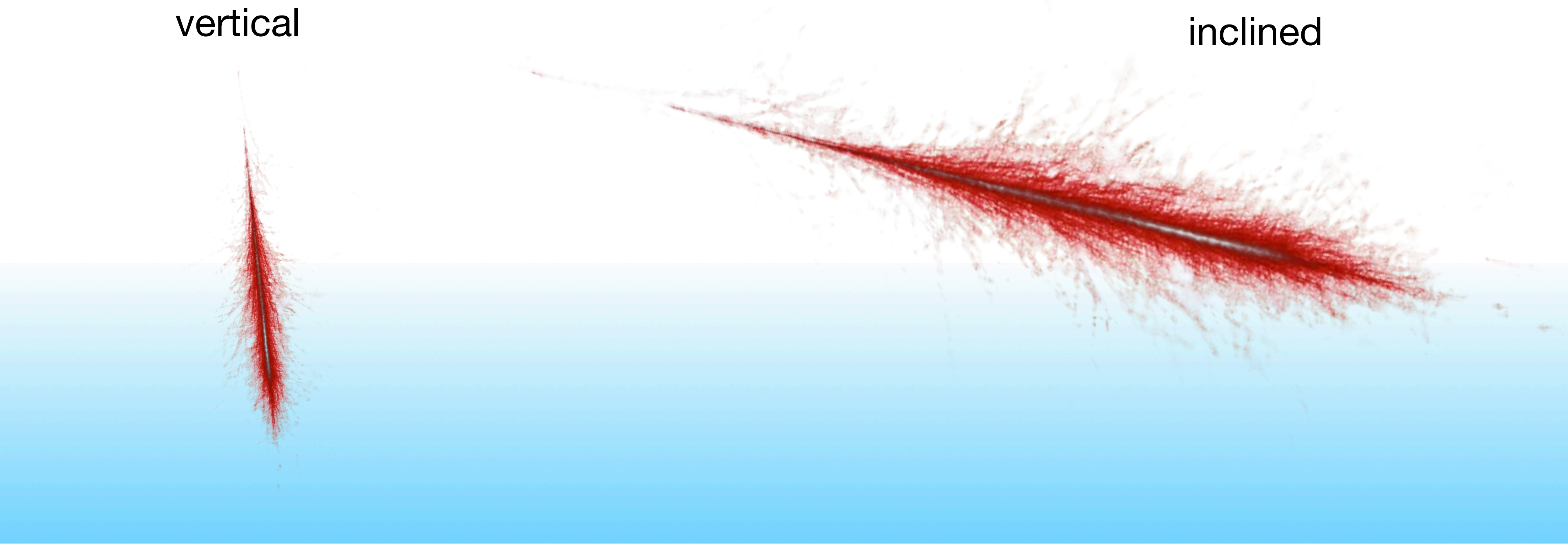
Inclined air showers: still several challenges, trending topic

(Schlüter et al. 2022, Chiche et al. 2022)

Characteristics of inclined air-showers

Next-generation experiments target (GRAND, BEACON, AugerPrime…) very inclined air-showers

- development at **lower air density**
- development over **longer trajectories**



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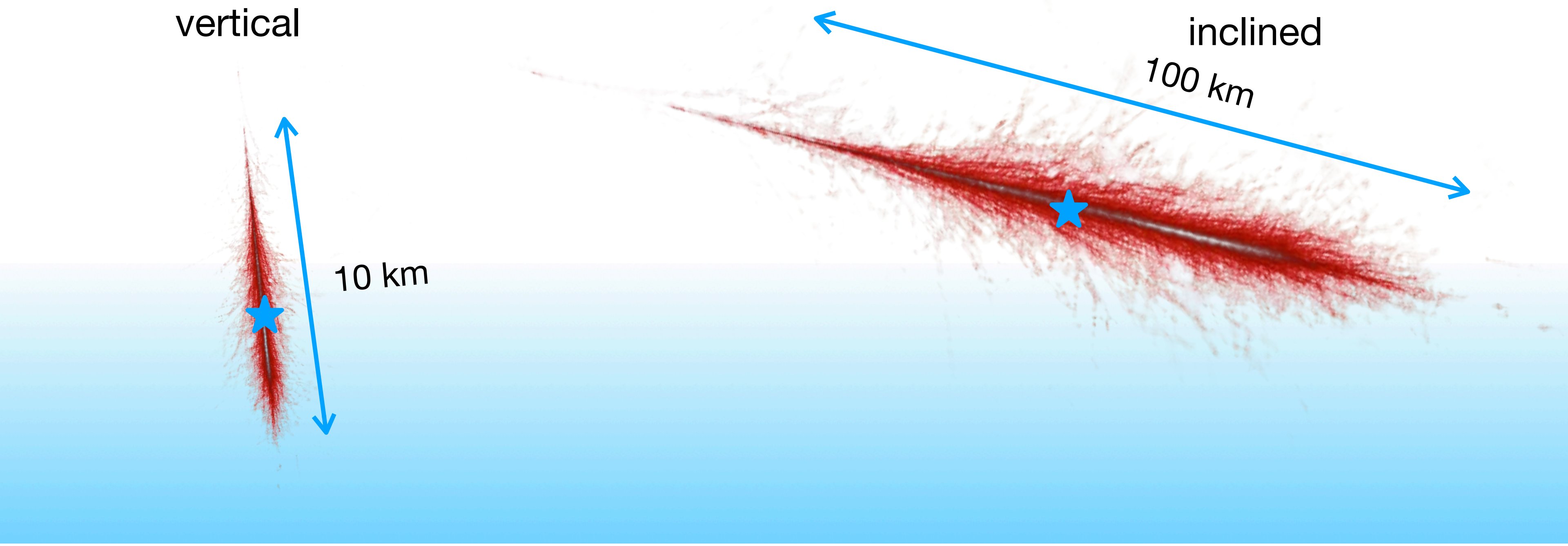

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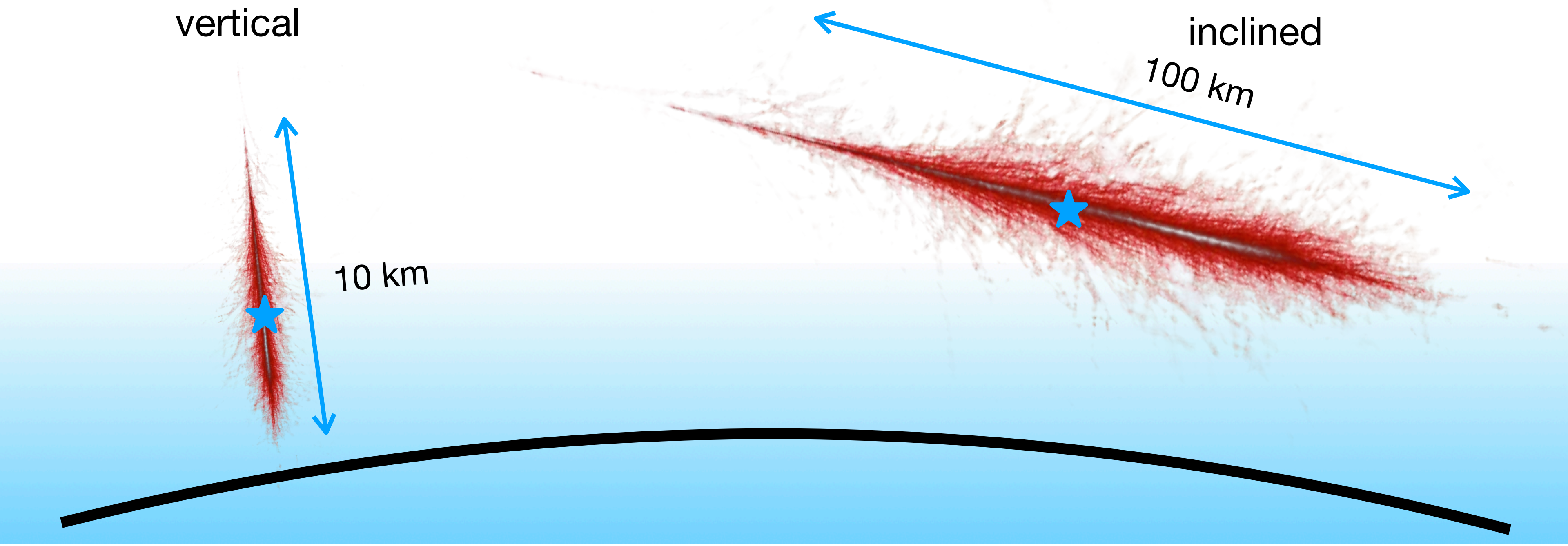

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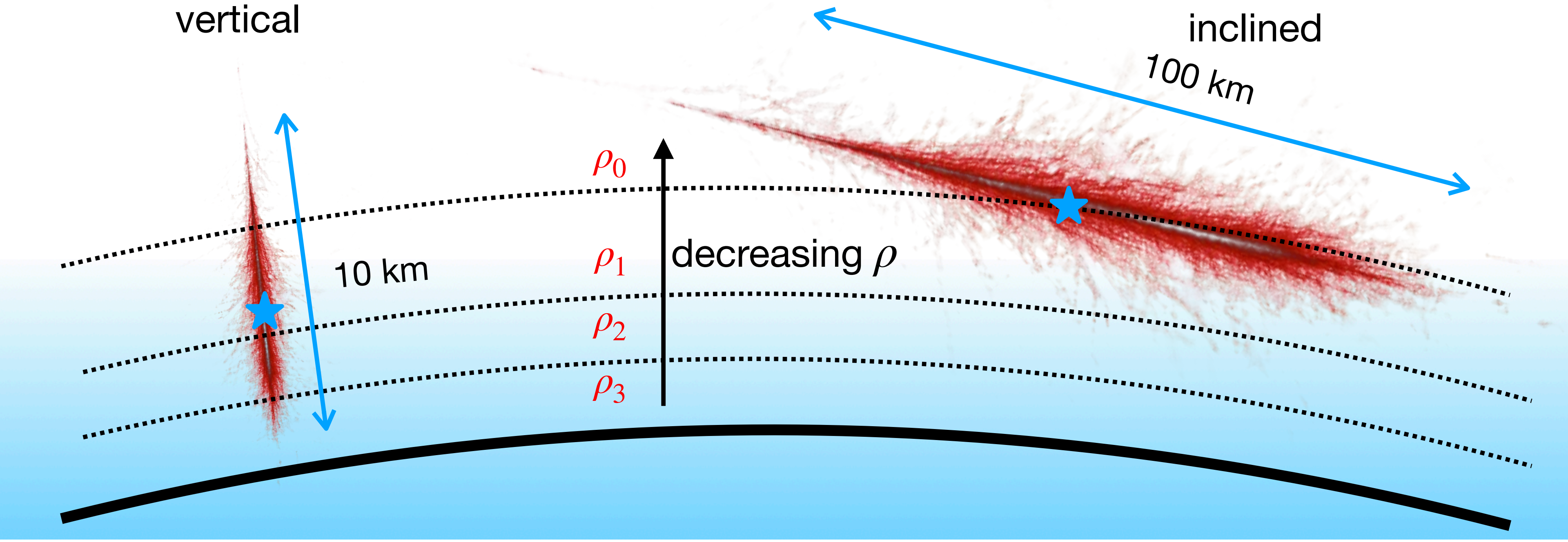

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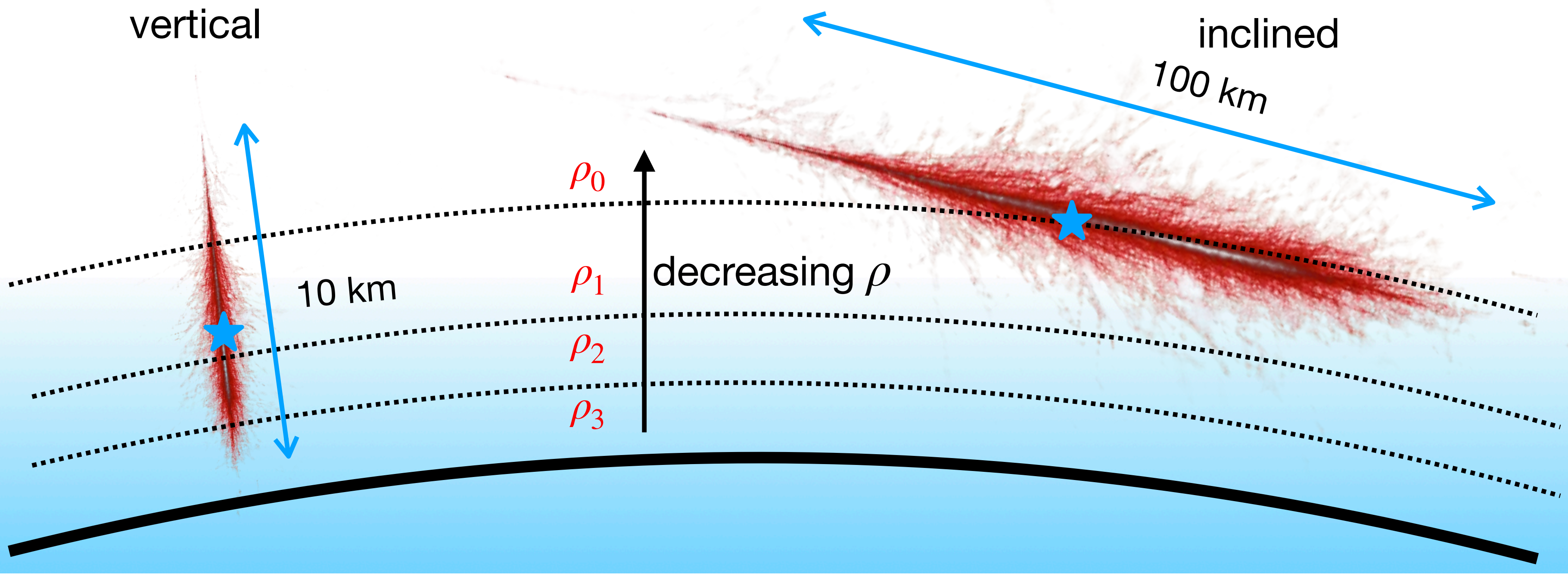

How do all these characteristics affect the radio emission?

Enhanced effect of B!

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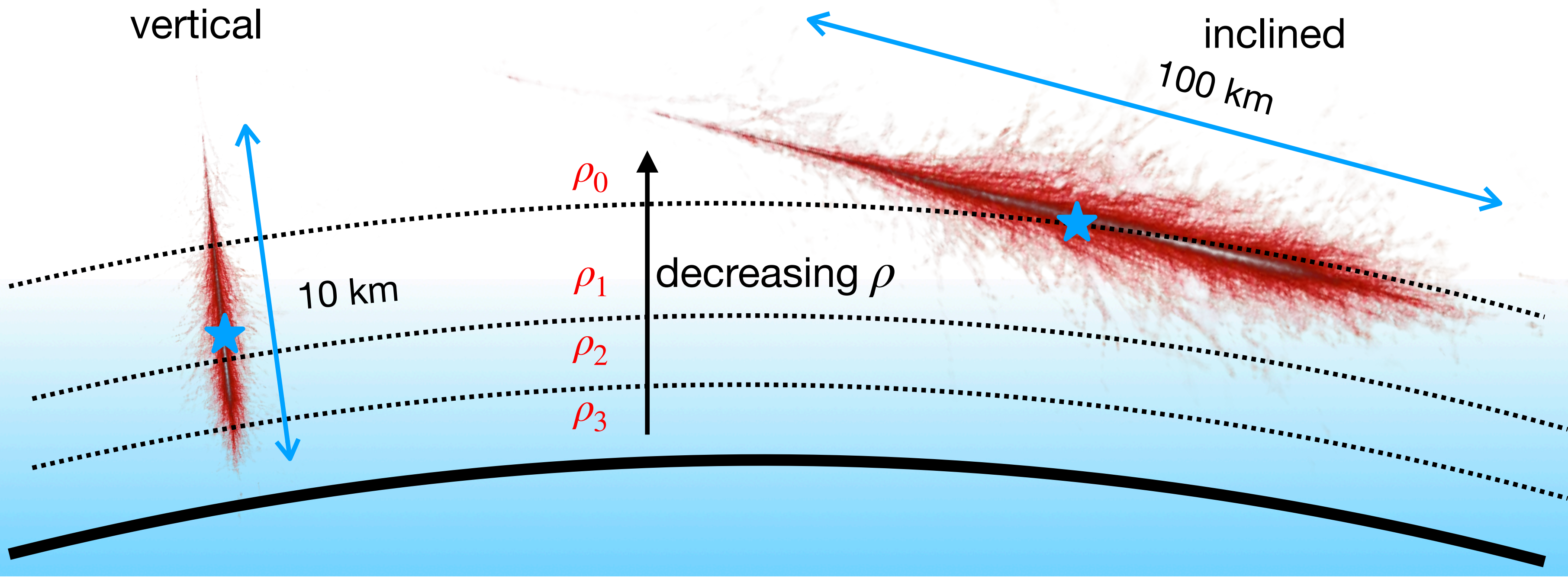

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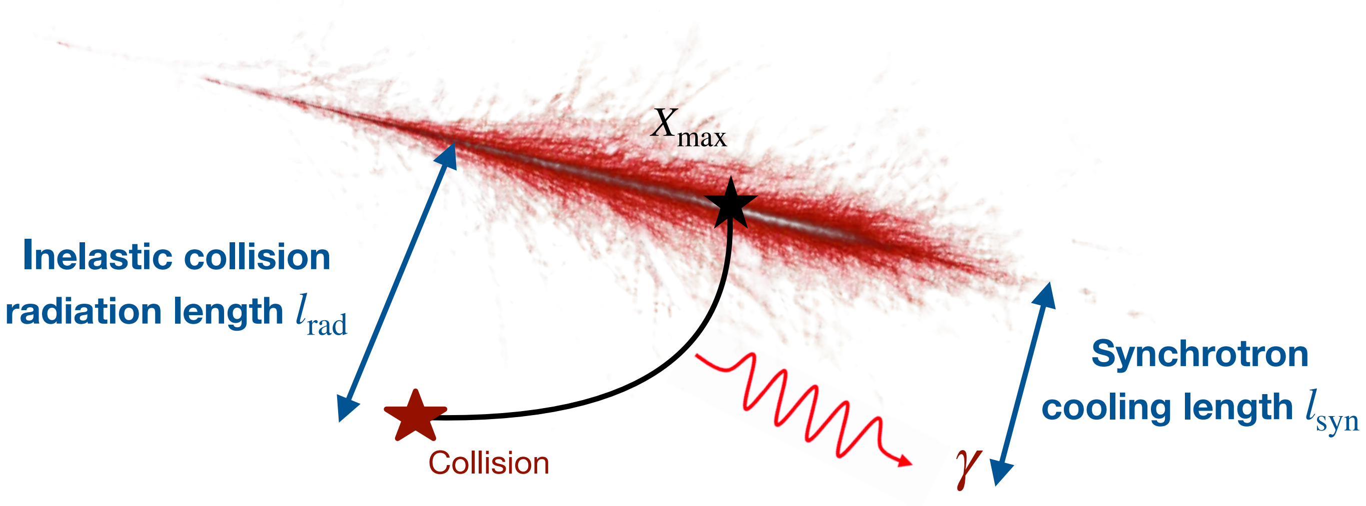
Enhanced effect of B!

- particles more deflected —> **geo-synchrotron emission?**
- particles more deflected —> larger lateral shower extension —> **coherence loss?**

see also C. James (2022)

The lower air-density for inclined showers should favor geo-synchrotron radiation



$$l_{rad} = X_0/\rho_{air}$$
$$\sim 3.67 \times 10^3\,\mathrm{m}\,(\rho_{air}/1\,\mathrm{g\,cm^{-3}})^{-1}$$

$$l_{syn} \sim 1353\,\mathrm{m}\,(\epsilon_e/88\,\mathrm{MeV})^{\frac{2}{3}}(B/50\,\mu\mathrm{T})^{-\frac{2}{3}}(\nu/50\,\mathrm{MHz})^{-\frac{1}{3}}$$

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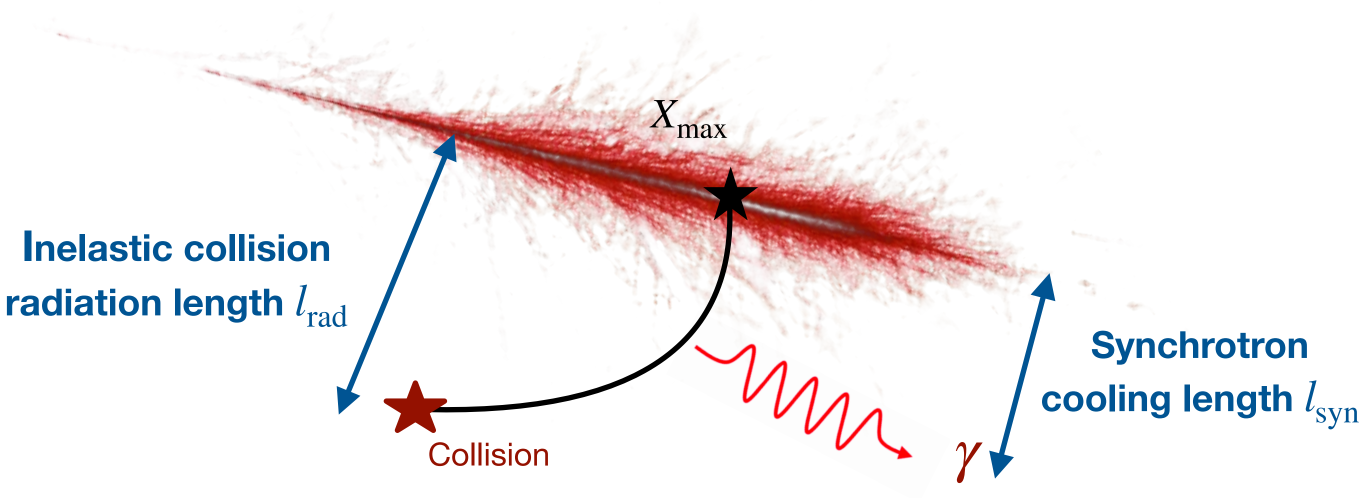

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C. James (2022)

Non negligible synchrotron component expected if:

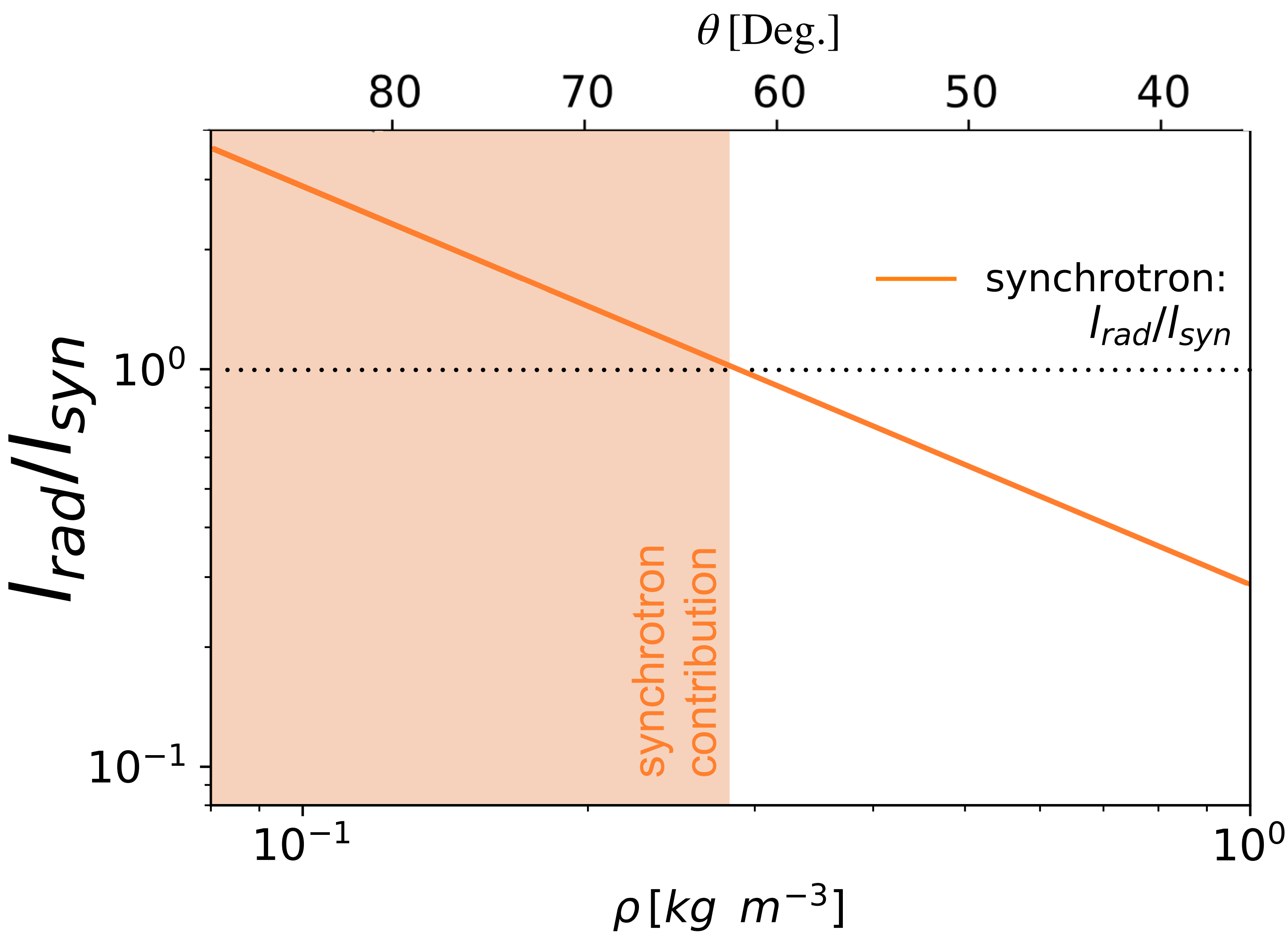
$$l_{\rm syn}(B_{\rm Earth}) < l_{\rm rad}(\rho_{\rm air}) \implies l_{\rm rad}/l_{\rm syn} > 1$$

$$\frac{l_{\rm syn}}{l_{\rm rad}} \sim 3.7 \left(\frac{\epsilon_e}{88\,{\rm MeV}}\right)^{\frac{2}{3}} \left(\frac{B}{50\,\mu{\rm T}}\right)^{-\frac{2}{3}} \left(\frac{\nu}{50\,{\rm MHz}}\right)^{-\frac{1}{3}} \left(\frac{\rho}{1\,{\rm kg\,m^{-3}}}\right)$$

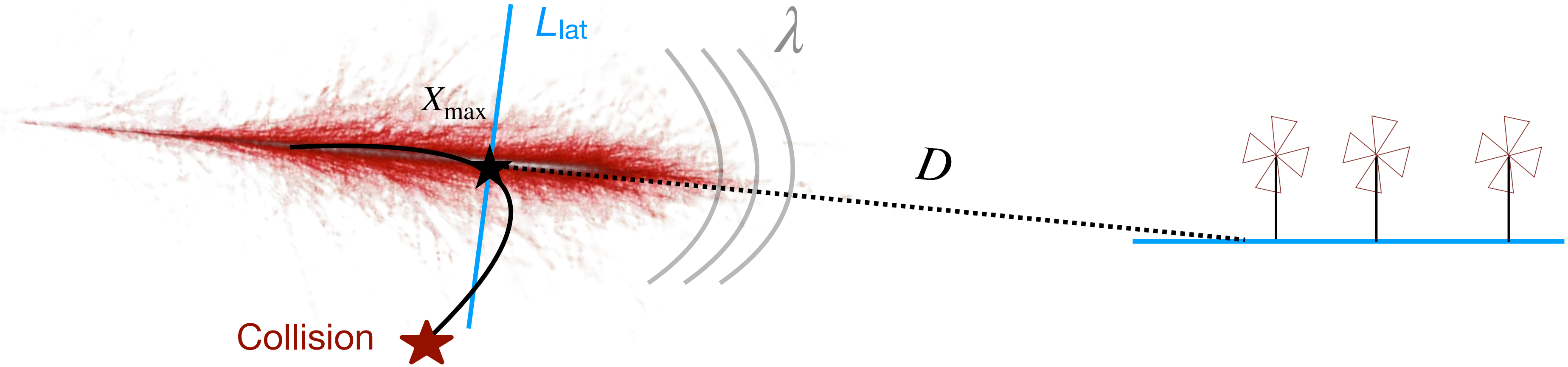
Condition for synchrotron emission

→ **Synchrotron emission if:** $\mathbf{l_{rad}/l_{syn} > 1}$

GRAND frequency band $\nu = \mathcal{O}(50\ \text{MHz})$ and magnetic field (B = 56 μT)



Conditions for a coherent radio signal



Spatial coherence length: $l_c = \lambda D / L_{\text{lat}}$

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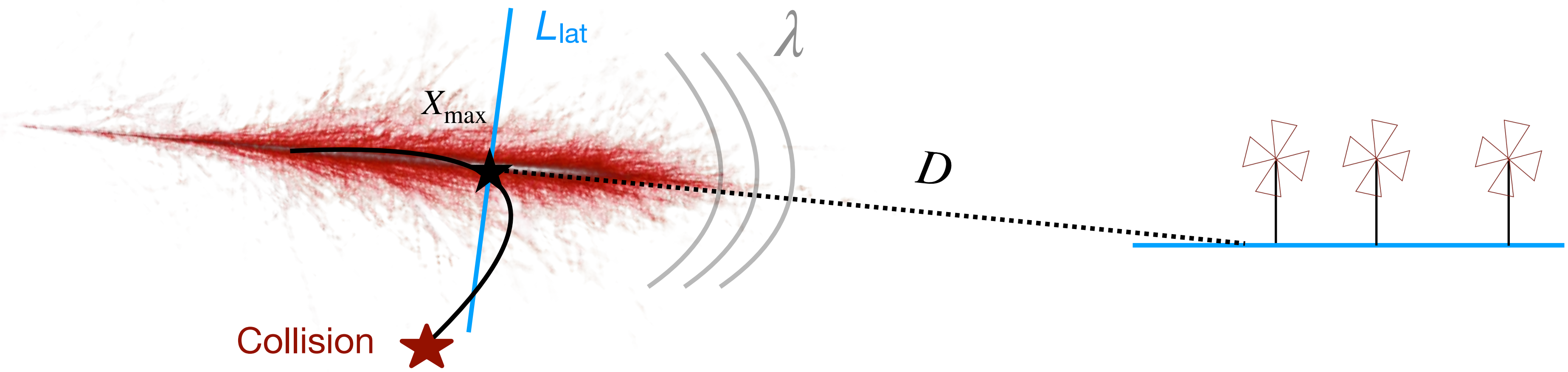

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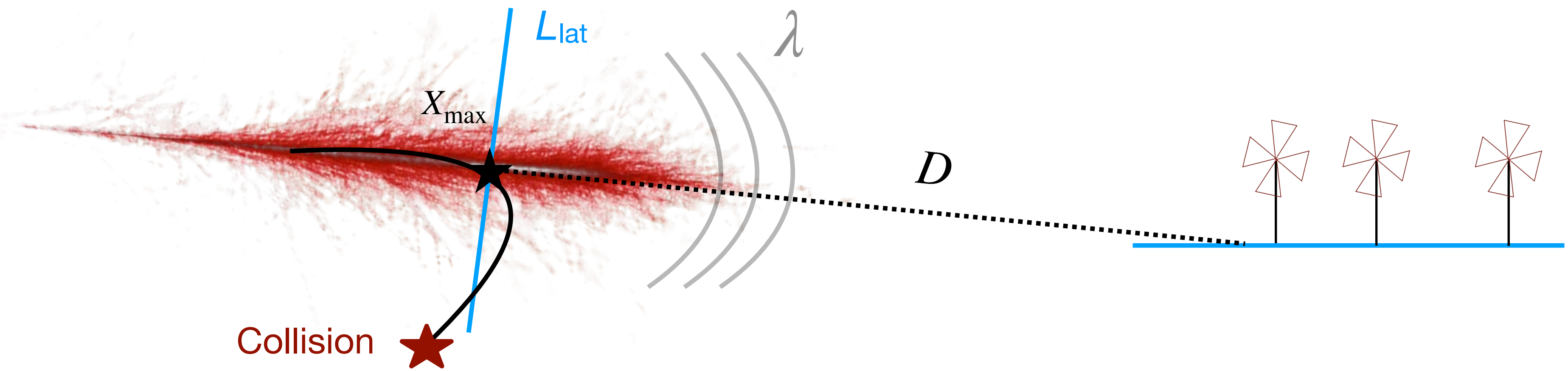

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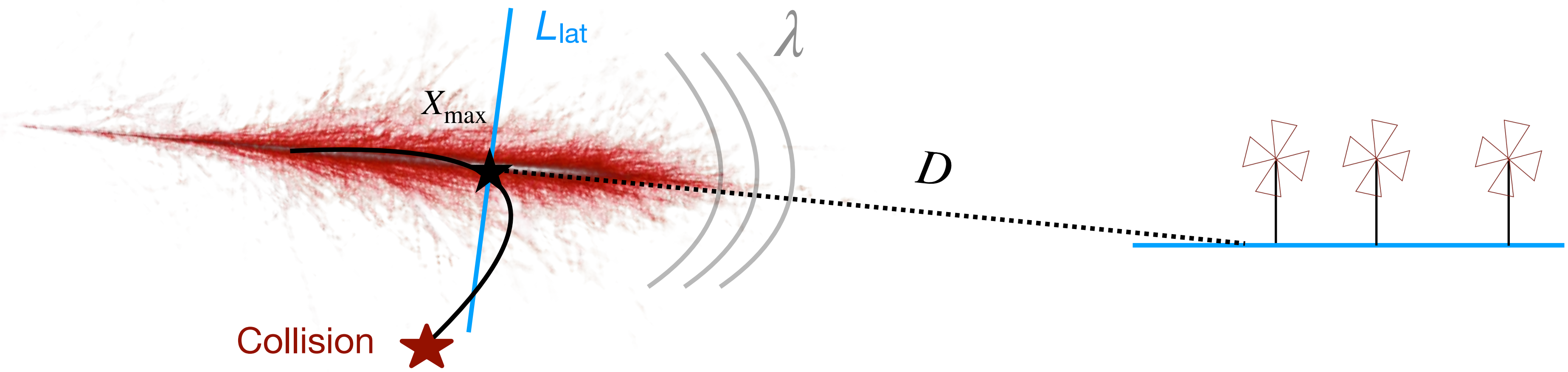

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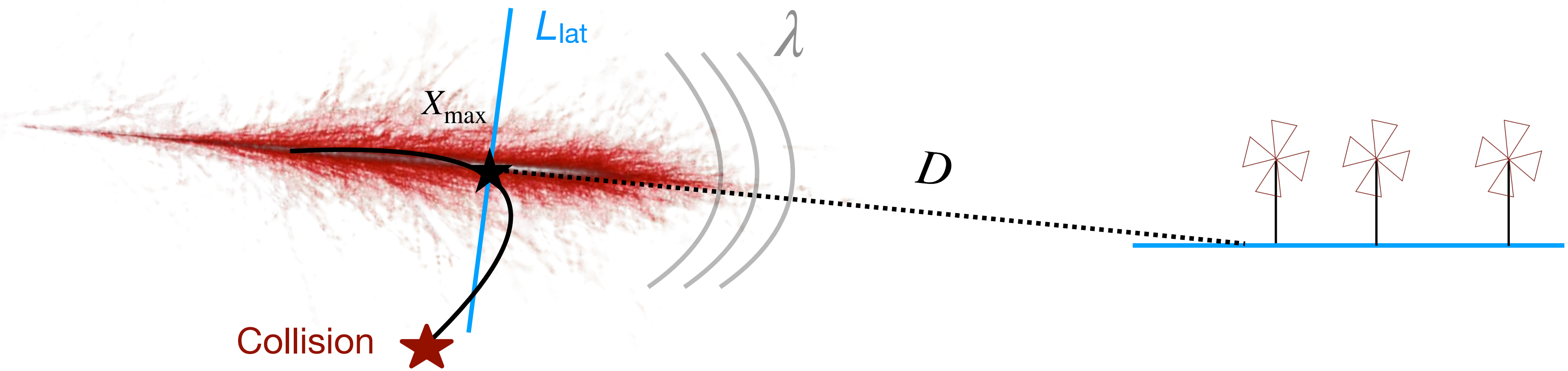

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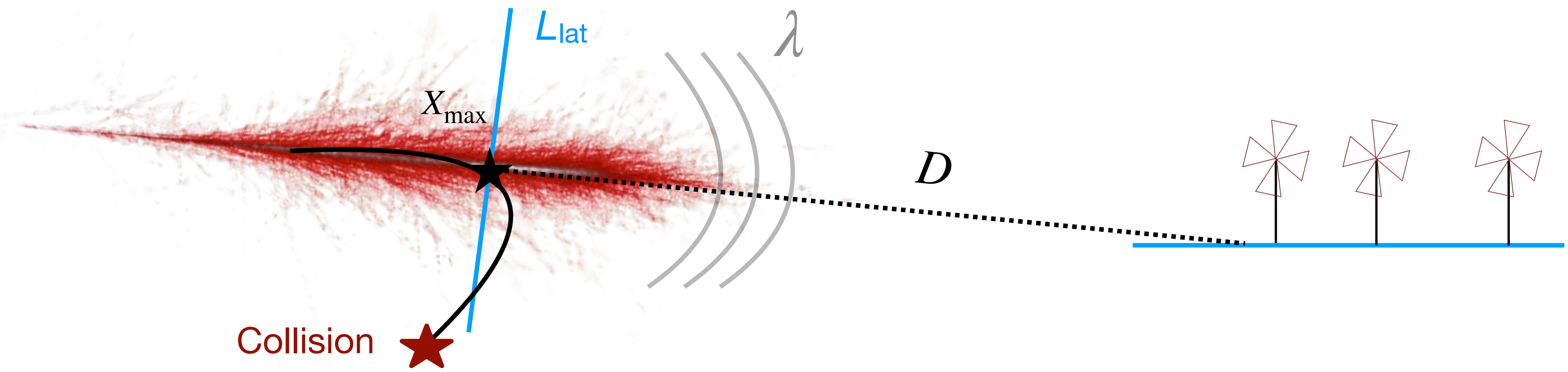

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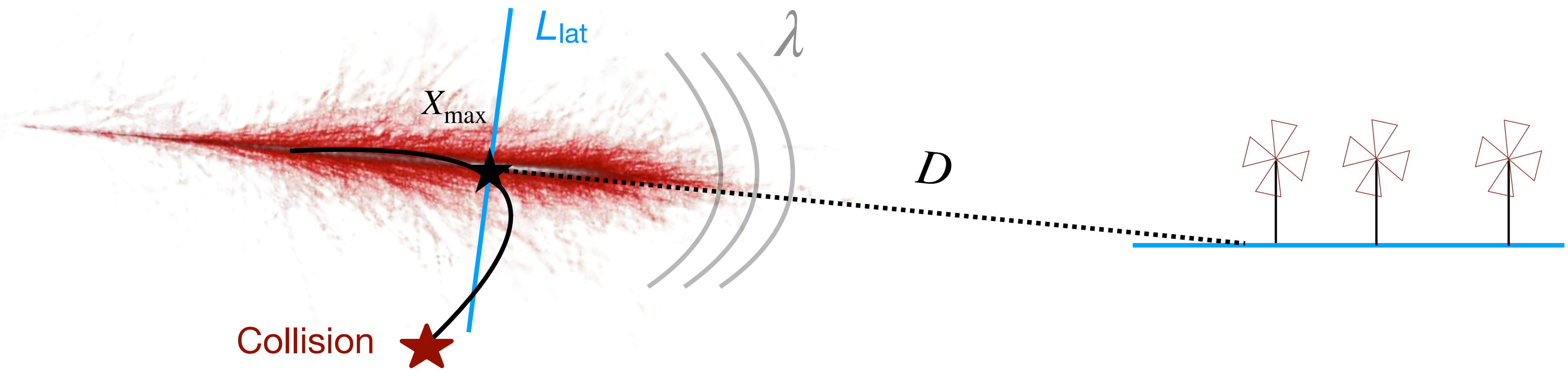

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τ: characteristic time of inelastic collision

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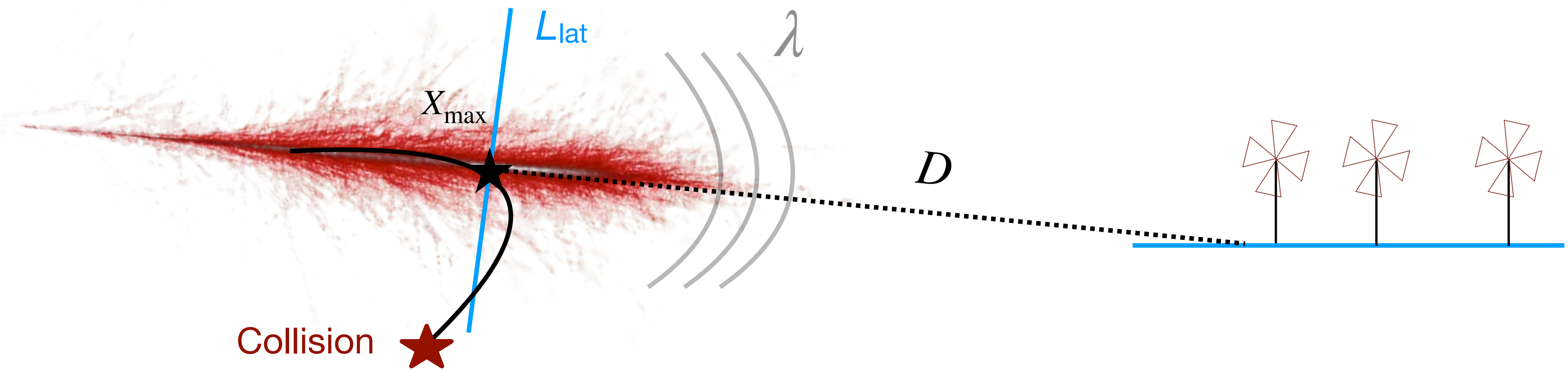

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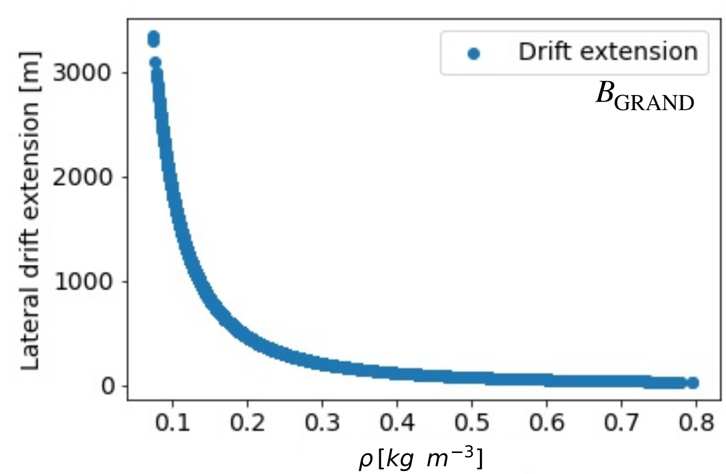
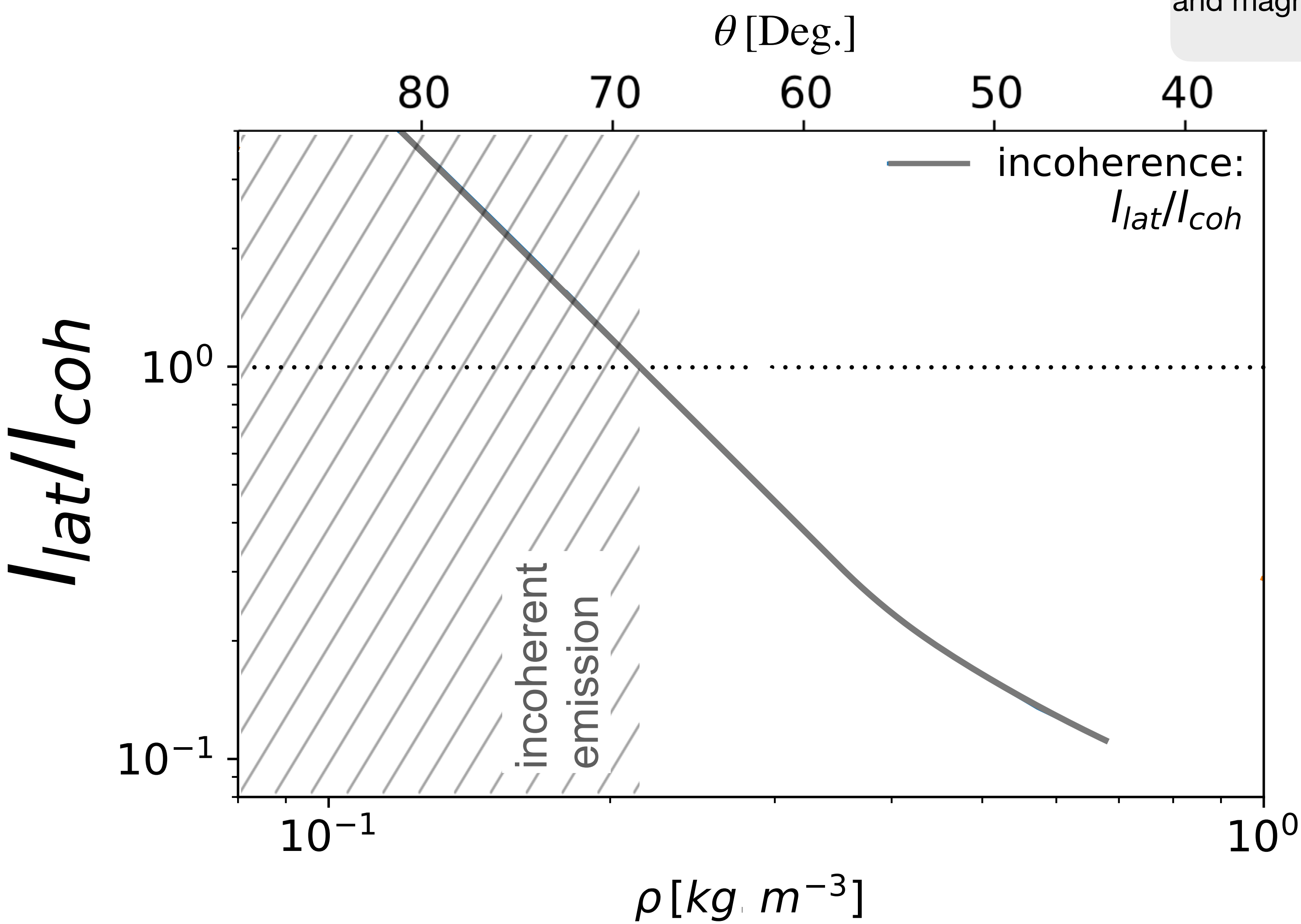


Conditions for a coherent radio signal

→ Strong radio emission only if shower lateral extent shorter than coherence length

$$L_{\rm lat}(\rho_{\rm air}, B_{\rm Earth})/l_{\rm coh} < 1$$

GRAND frequency band
$\nu = \mathcal{O}$(50 MHz)
and magnetic field (B = 56 μT)



Synchrotron and incoherence regimes

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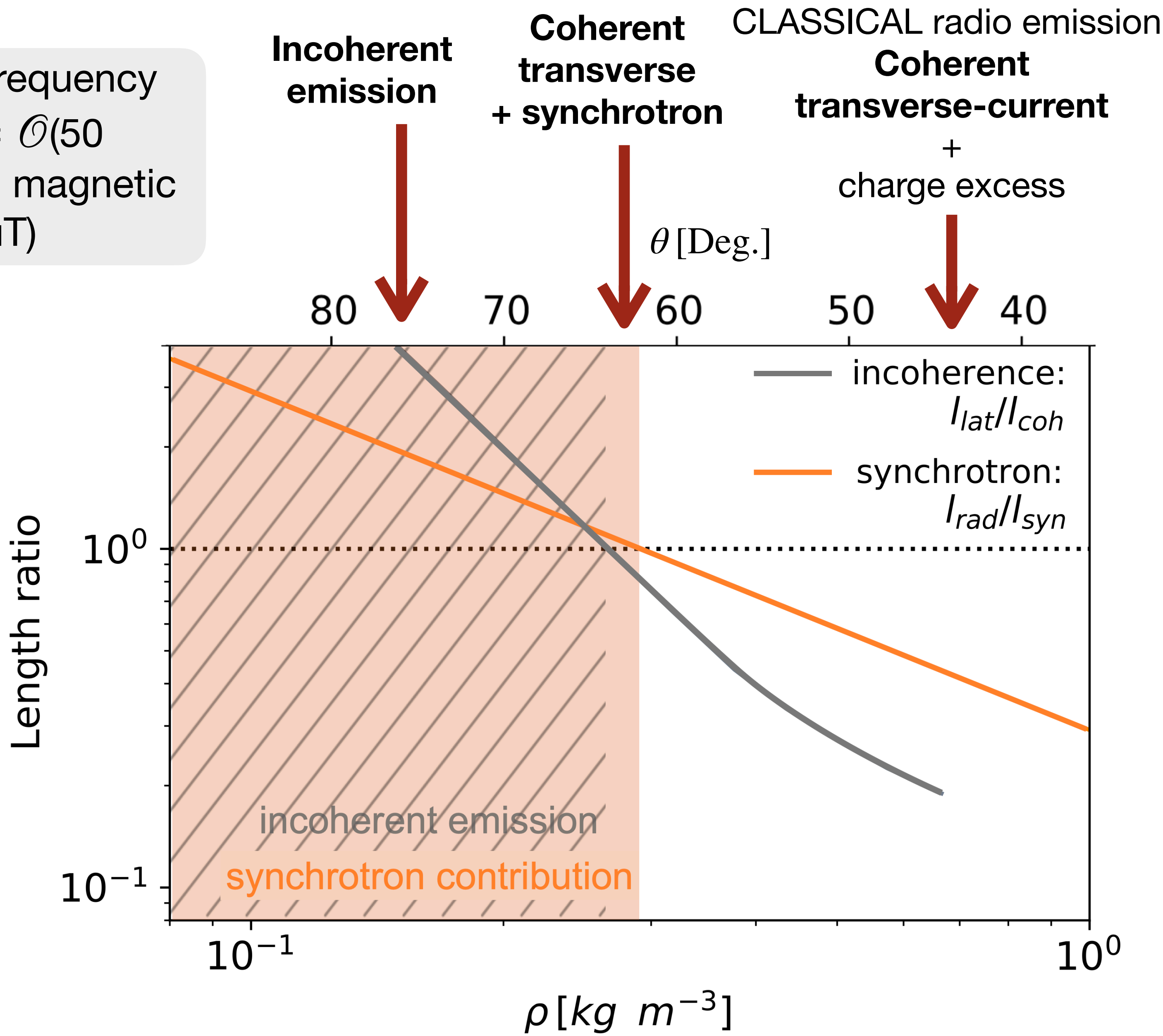
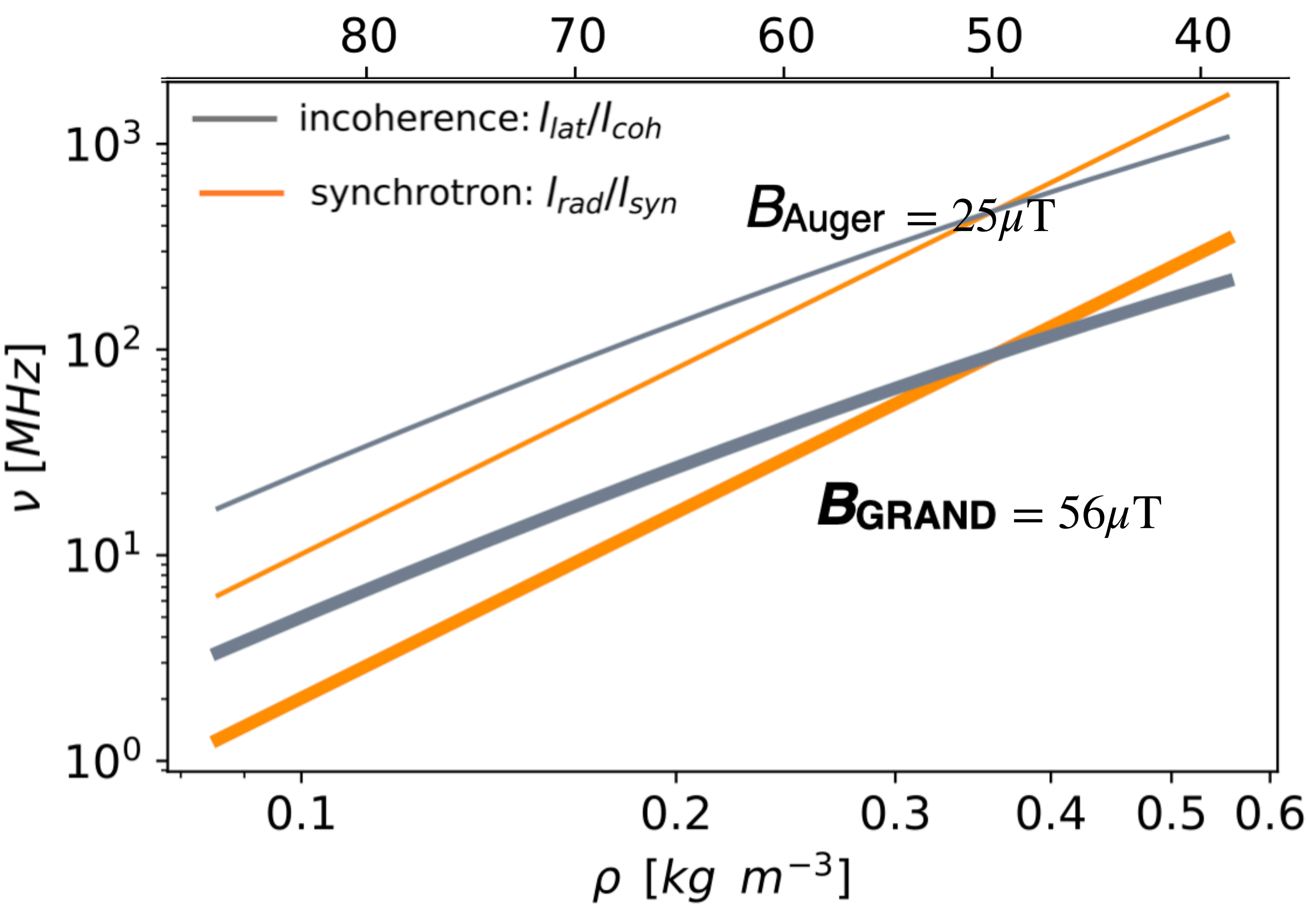


Synchrotron and incoherence regimes

Incoherence? $\frac{l_{\rm lat}}{l_{\rm coh}} \sim 0.018 \left(\frac{\nu}{50\,{\rm MHz}}\right)\left(\frac{B}{50\,\mu{\rm T}}\right)^{2}\left(\frac{\epsilon_e}{88\,{\rm MeV}}\right)^{-2}\left(\frac{\rho}{1\,{\rm kg\,.\,m^{-3}}}\right)^{-4}\left(\frac{d_{\rm obs}[\rho]}{10\,{\rm km}}\right)^{-1}$

Synchrotron? $\frac{l_{\rm syn}}{l_{\rm rad}} \sim 3.7 \left(\frac{\epsilon_e}{88\,{\rm MeV}}\right)^{\frac{2}{3}}\left(\frac{B}{50\,\mu{\rm T}}\right)^{-\frac{2}{3}}\left(\frac{\nu}{50\,{\rm MHz}}\right)^{-\frac{1}{3}}\left(\frac{\rho}{1\,{\rm kg\,m^{-3}}}\right)$

synchrotron and incoherence transition regimes

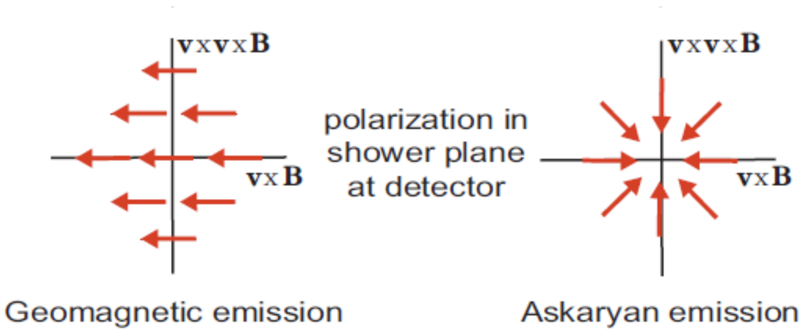


- synchrotron or/and incoherence is expected for low ρ (high θ), and high ν
- A smaller $B_{\rm geo}$ shifts the transition to higher frequencies

Comparison with Monte-Carlo simulations

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

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



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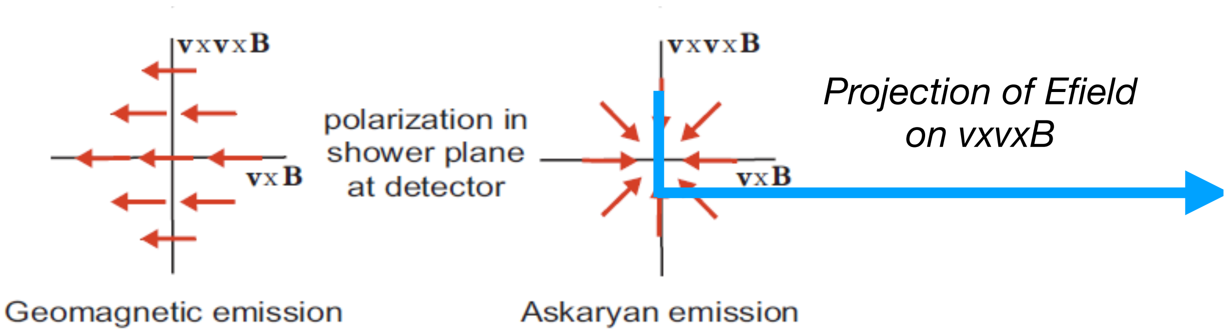
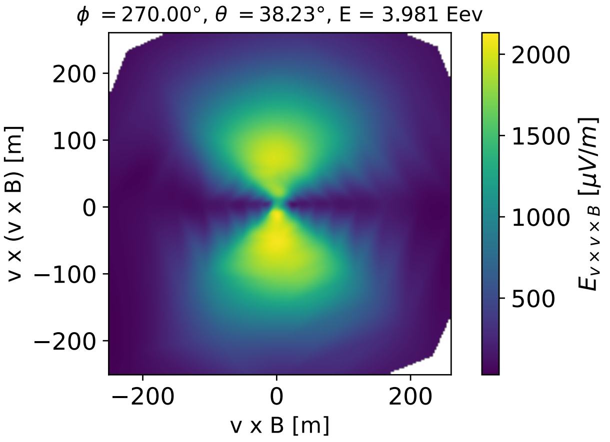


Expected pattern



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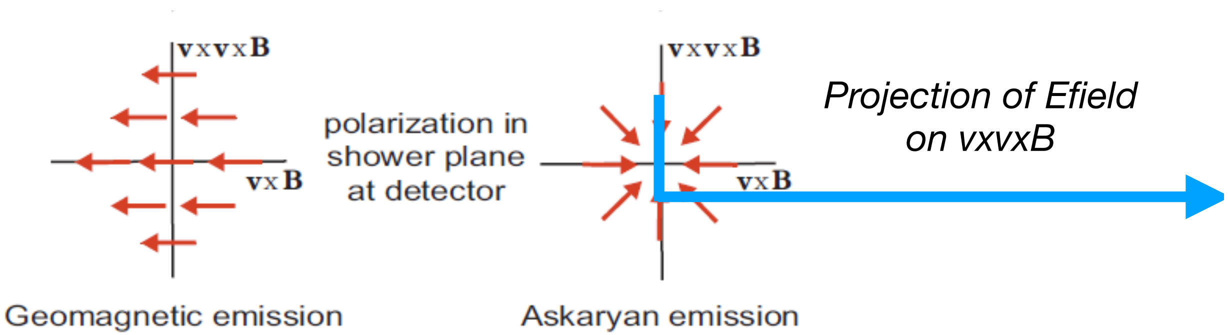

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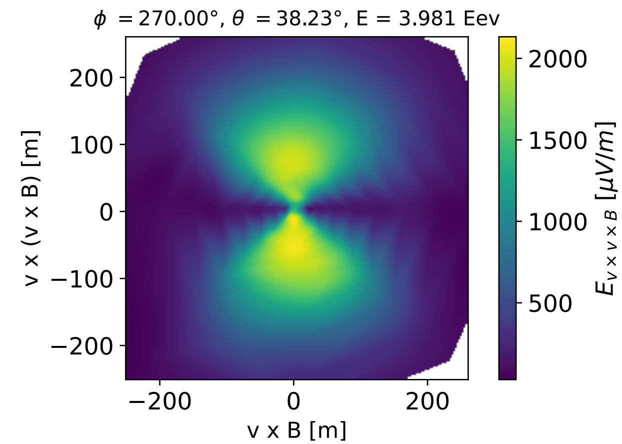
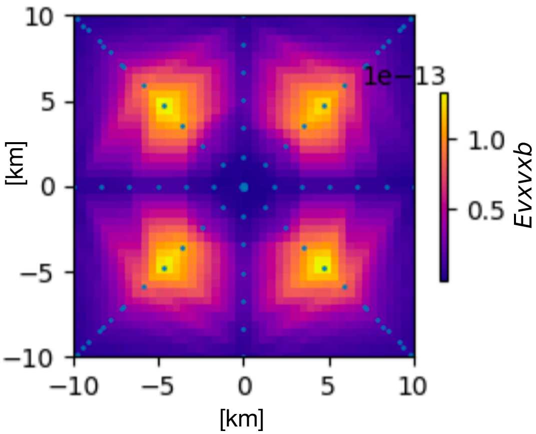
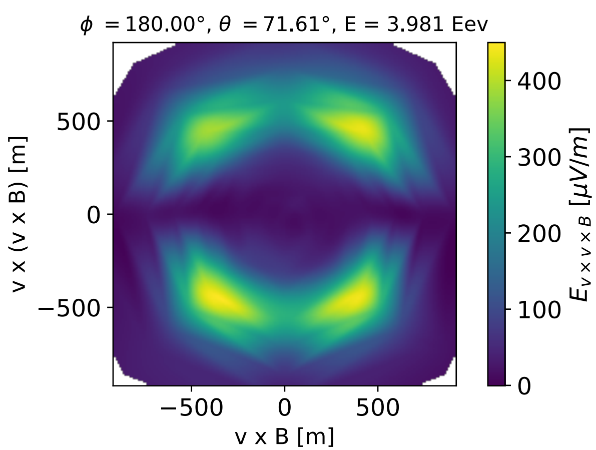


Observed pattern: clover-leaf

CoREAS (85 degree)



ZHAireS

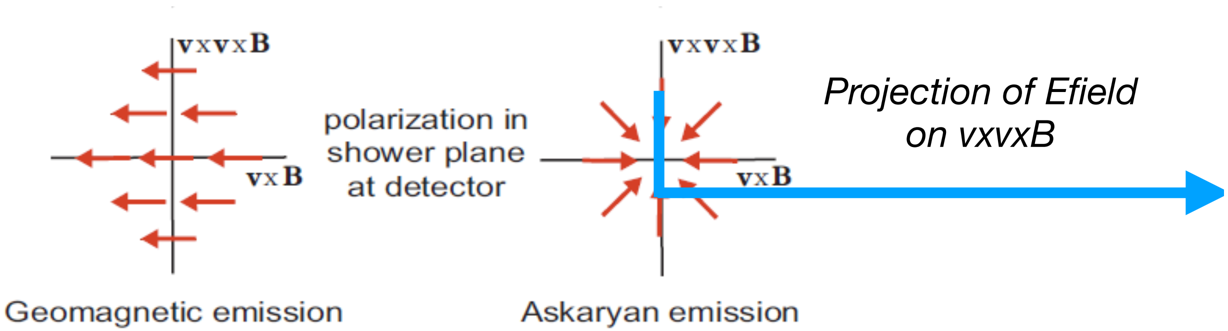


New polarization signature on the $v \times v \times B$ component!

- ~ 10% of the total emission for inclined showers

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

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



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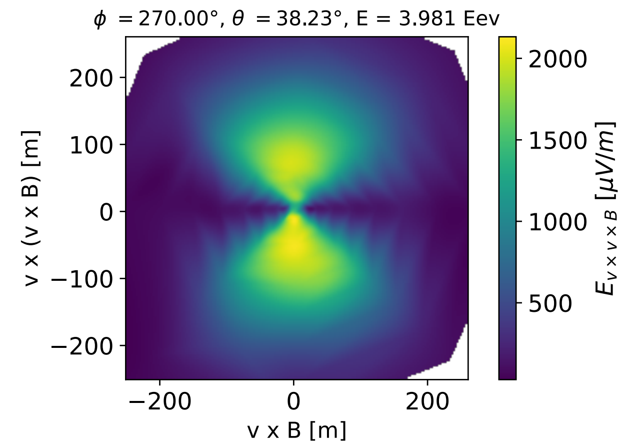

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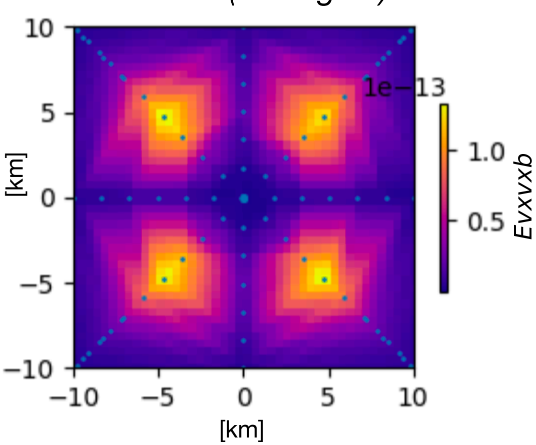

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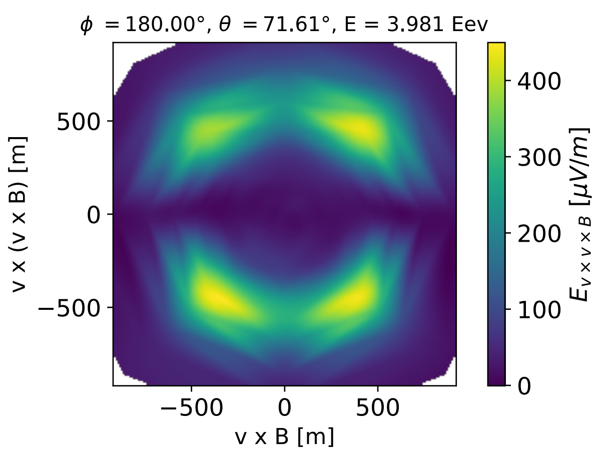

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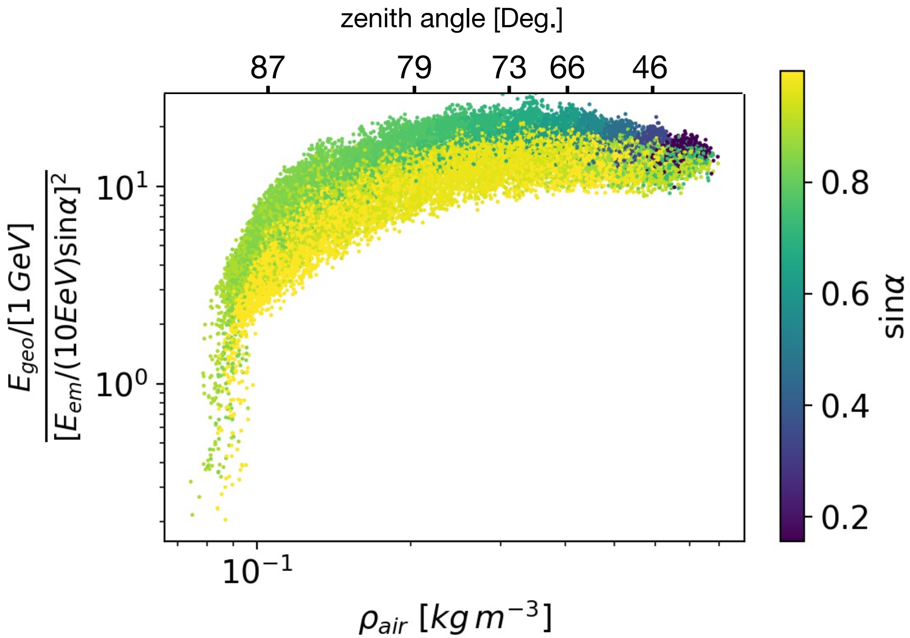
Clover-leaf pattern: hints for a third type of emission that could come from a synchrotron emission

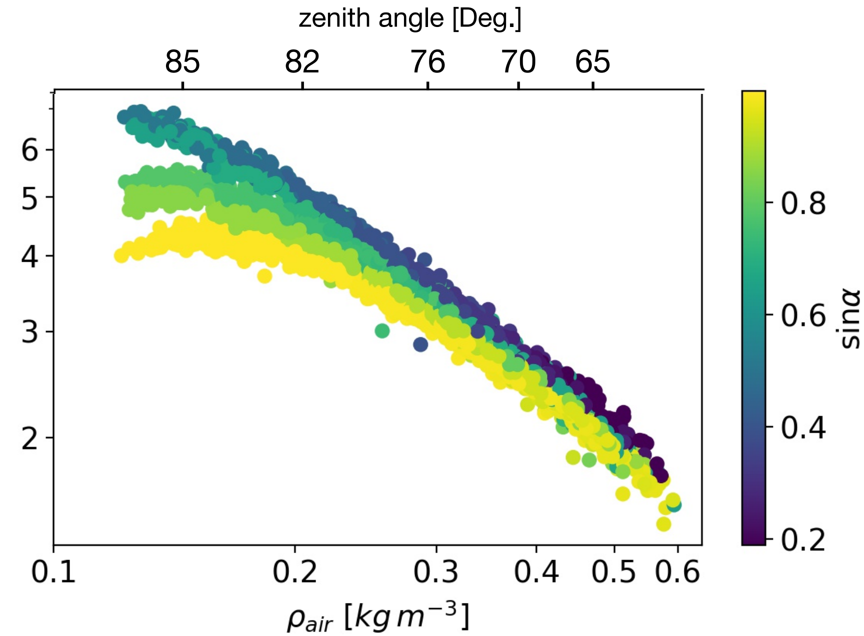
Radiation energy as a function of the air density from Monte-Carlo simulations

$$E_{\text{rad}} = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\infty} r\mathrm{d}r f(r,\phi)$$ (Glaser et al., 2016)

GRAND



Auger



Signature of coherence loss

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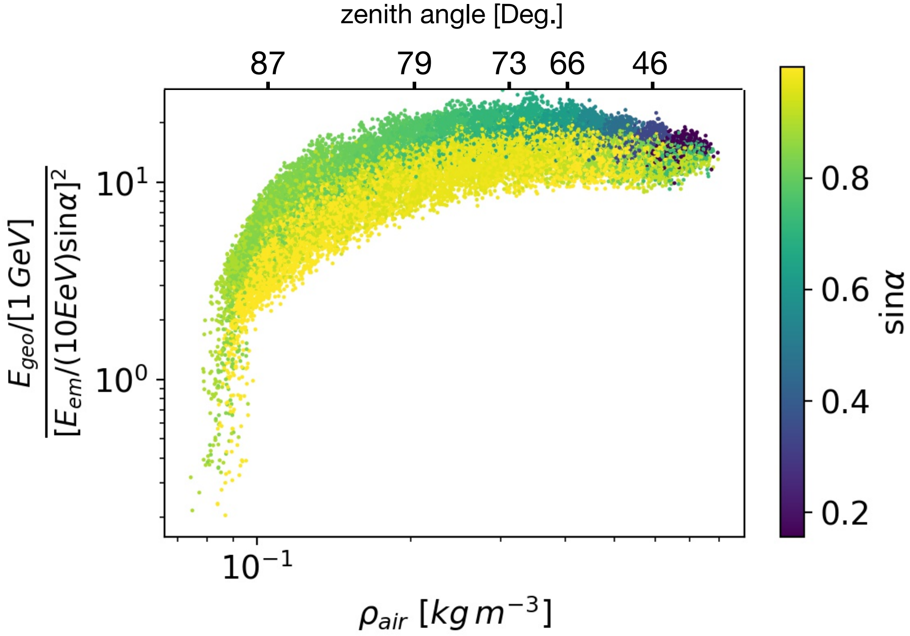

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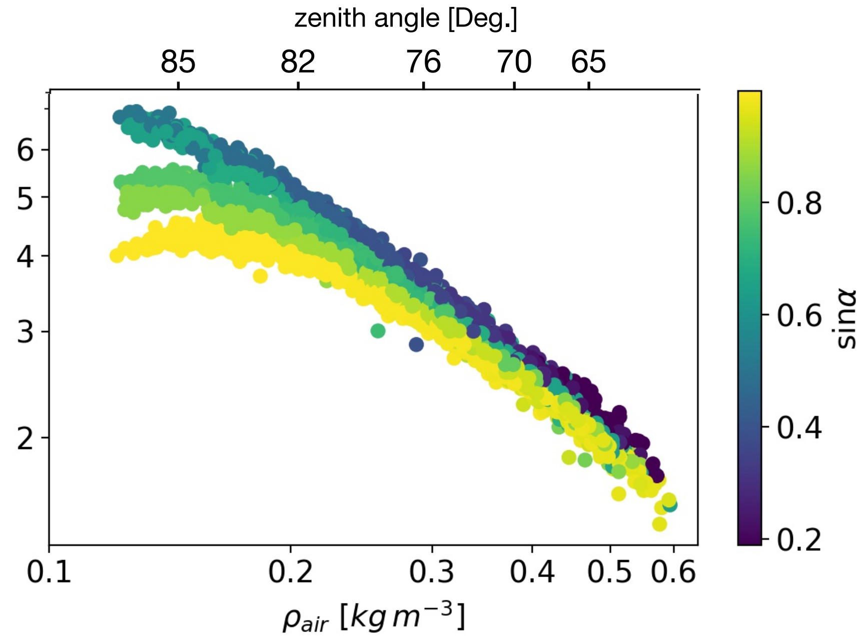


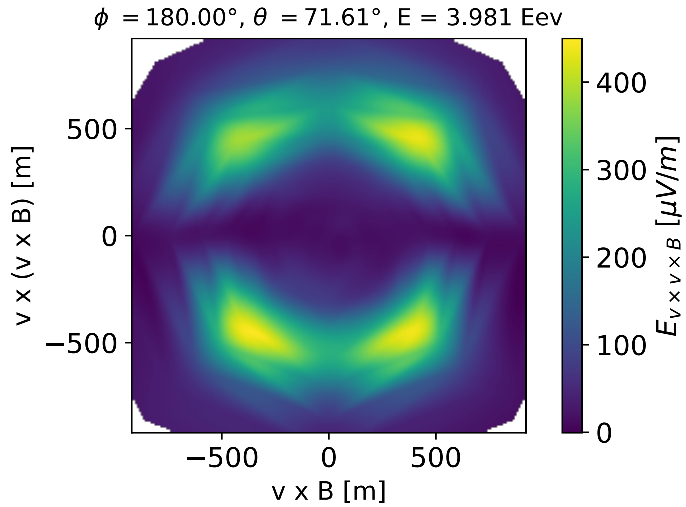
Suppression in the radiation energy of inclined showers for GRAND magnetic field

Almost no suppression of the radiation energy for Auger

Summary

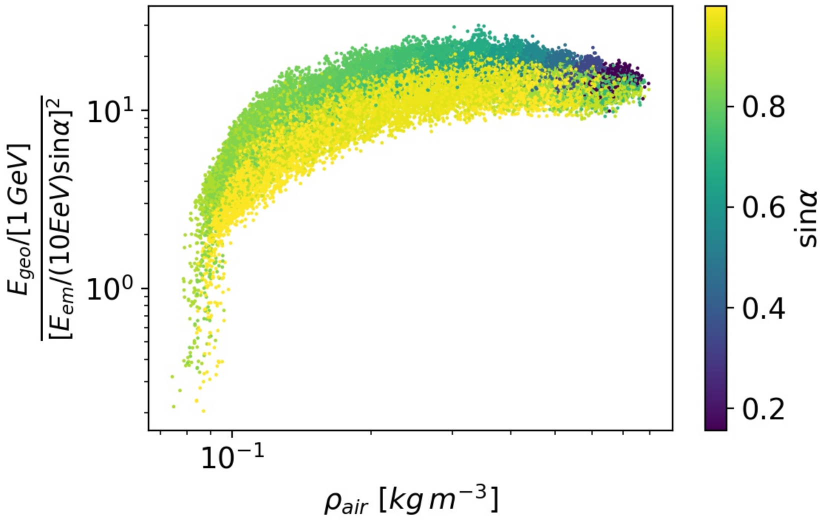
2 major new features in the radio emission of very inclined showers

Clover-leaf pattern



Linked to synchrotron radiation

Radiation energy cut-off



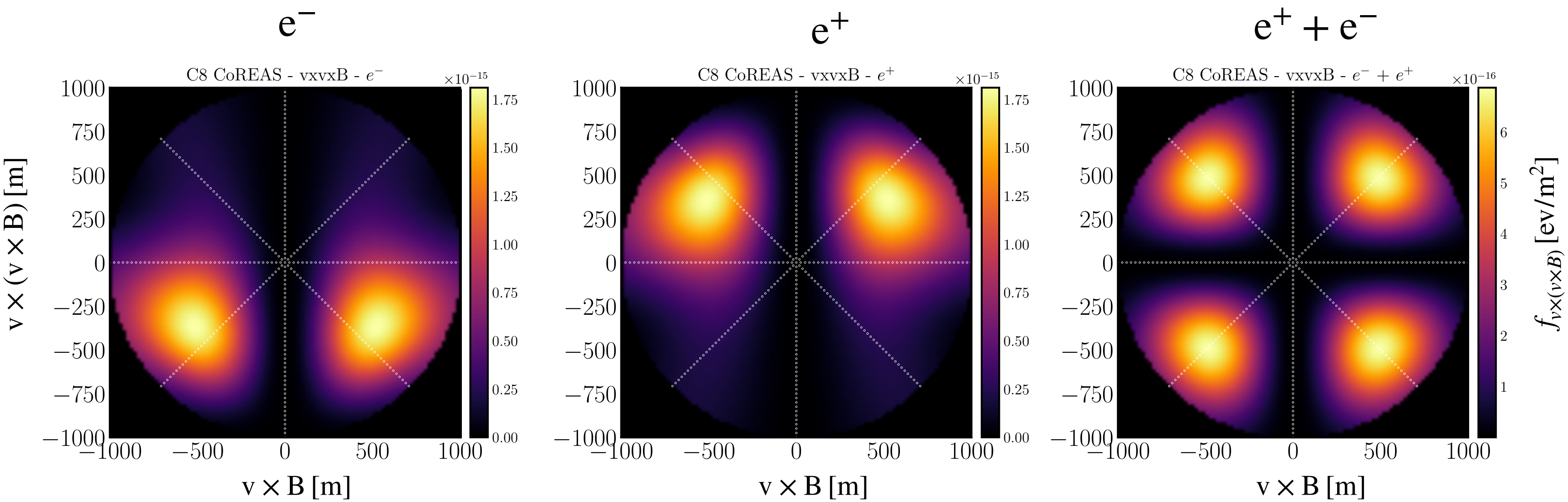
Linked to a loss of coherence

Could strongly affect detection/reconstruction strategies of future experiments

Refine our understanding of the radio emission: Transverse-current + Askaryan description no more valid

Could help for cosmic-ray/neutrino discrimination

CORSIKA8 simulation of an electron/positron pair in a uniform magnetic field



(Credits to Nikolaos Karastathis)

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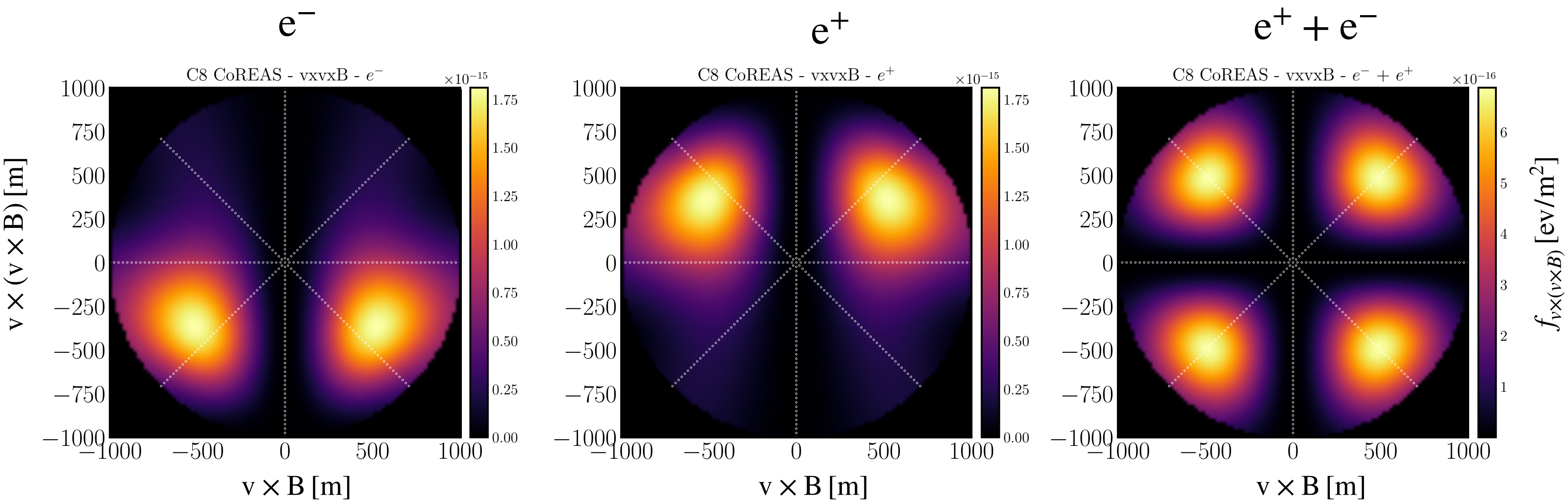

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The magnetic deflection of an e^-/e^+ pair give rise to clover-leaf emission pattern