Picture credit : M. Garlick

ULTRA-HIGH ENERGY COSMIC RAYS

By Léa Marques

Supervised by

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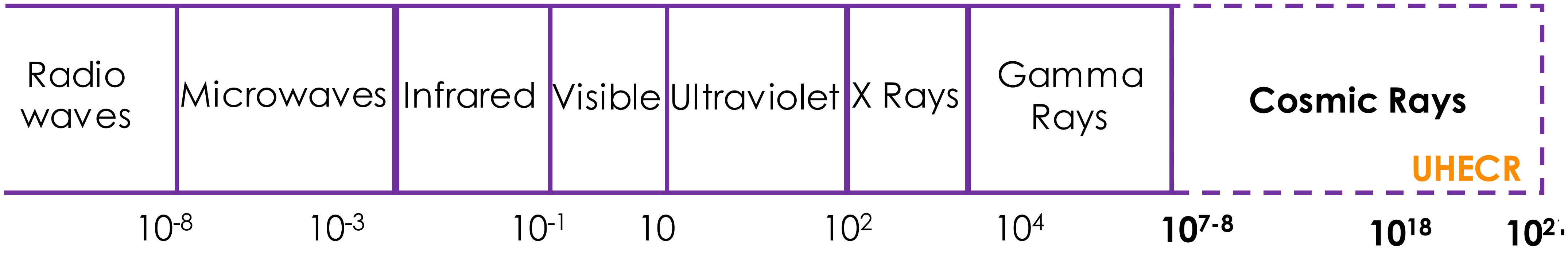
University of Torino, Insituto Nazionale di Fisica Nucleare

Plan

- What are cosmic rays?
- How to study cosmic rays?
- Theoretical background on cosmic ray propagation
- Personal project on arrival directions
- Conclusion

What are cosmic rays?

- **High-energy charged particles** from outer space



Cosmic rays
10^8 eV < E_{CR} < 10^{20-21} eV

Ultra-High Energy Cosmic Rays (UHECR)
E_{UHECR} > 10^{18} eV = 1 EeV

How are they accelerated to such high energies?

Must originate from highly energetic events (SNe, AGN jets, γ ray bursts...)

UHECR likely extragalactic

How to study cosmic rays?

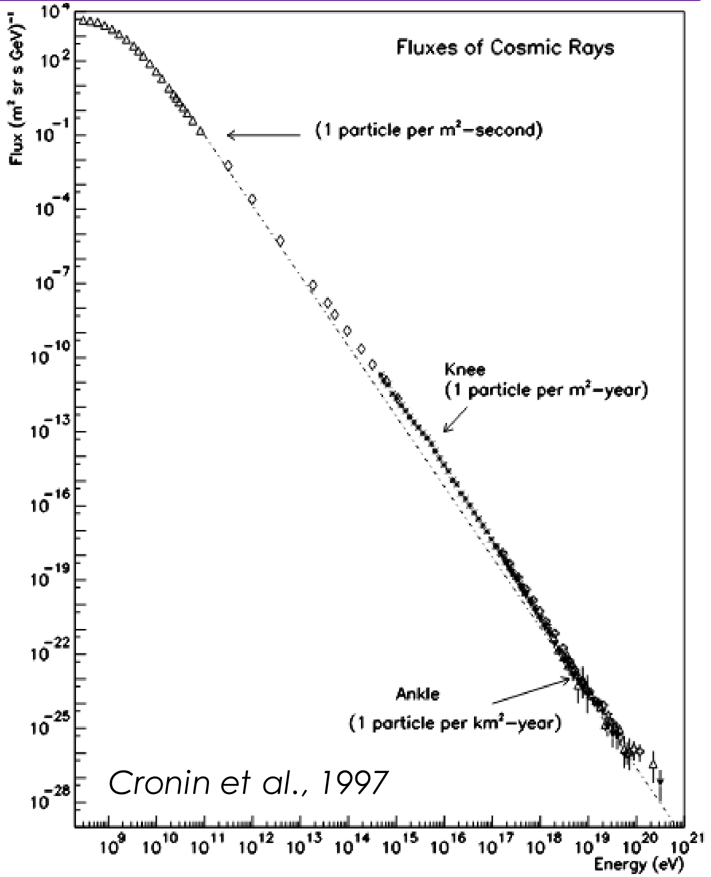
Energy spectrum?

Mass composition?

Arrival directions?

How to study cosmic rays?

Energy spectrum?



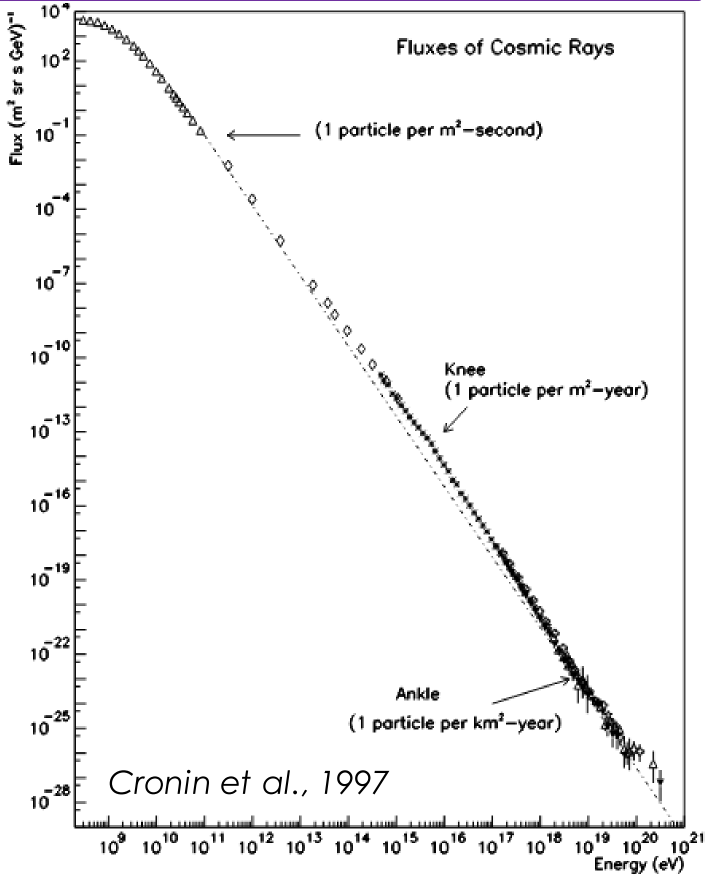
UHECR : 10^2 part./km^2/yr
to 1 part./km^2/mill.

Mass composition?

Arrival directions?

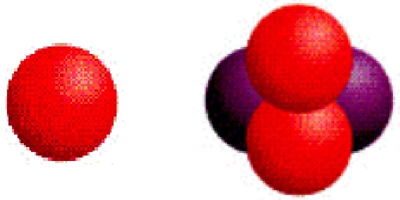
How to study cosmic rays?

Energy spectrum?



UHECR : 10^2 part./km²/yr
to 1 part./km²/mill.

Mass composition?



p?

He?

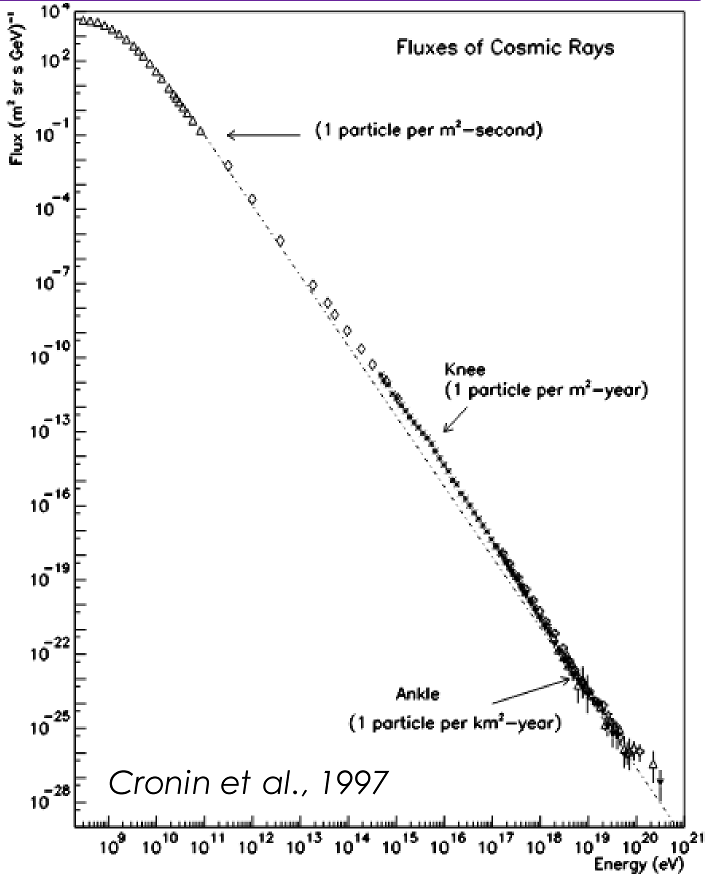
Heavier?

UHECR:
at least 50% of protons,
then proportion of
heavier seems to
increase with energy
(details uncertain)

Arrival directions?

How to study cosmic rays?

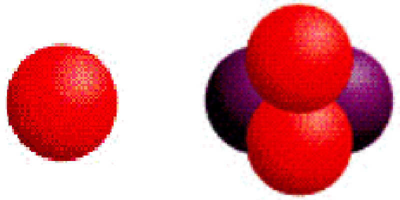
Energy spectrum?



Cronin et al., 1997

UHECR : 10^2 part./km^2/yr to 1 part./km^2/mill.

Mass composition?



p?

He?

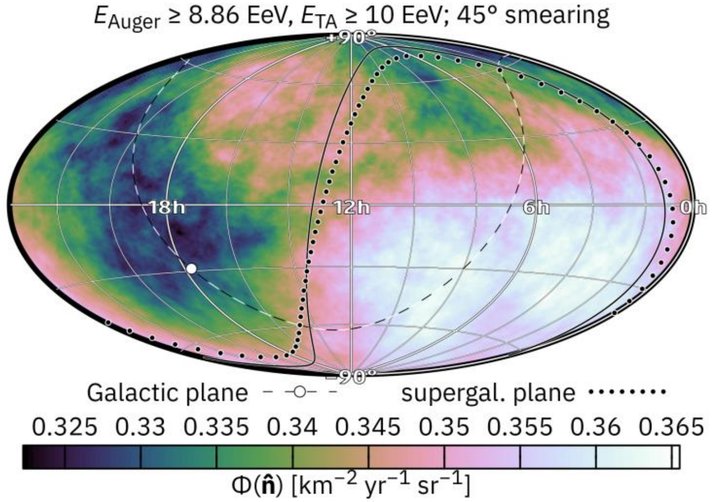
Heavier?

UHECR:
at least 50% of protons, then proportion of heavier seems to increase with energy (details uncertain)

Arrival directions?

Sky distribution of received CR

- ➡ isotropic at low-E
- ➡ anisotropies at UHE



Di Matteo et al., 2019

How to study cosmic rays?

Low-energy

Direct measurements

Simply analyze **primary CR**

👍 information is **direct**
👎 **hard** to detect, especially at very high energies

CERN-AMS on board the ISS, operating since 2017

High-energy

Indirect measurements

CR interacts with the atmosphere: **air showers** ➡ **cascade of particles**

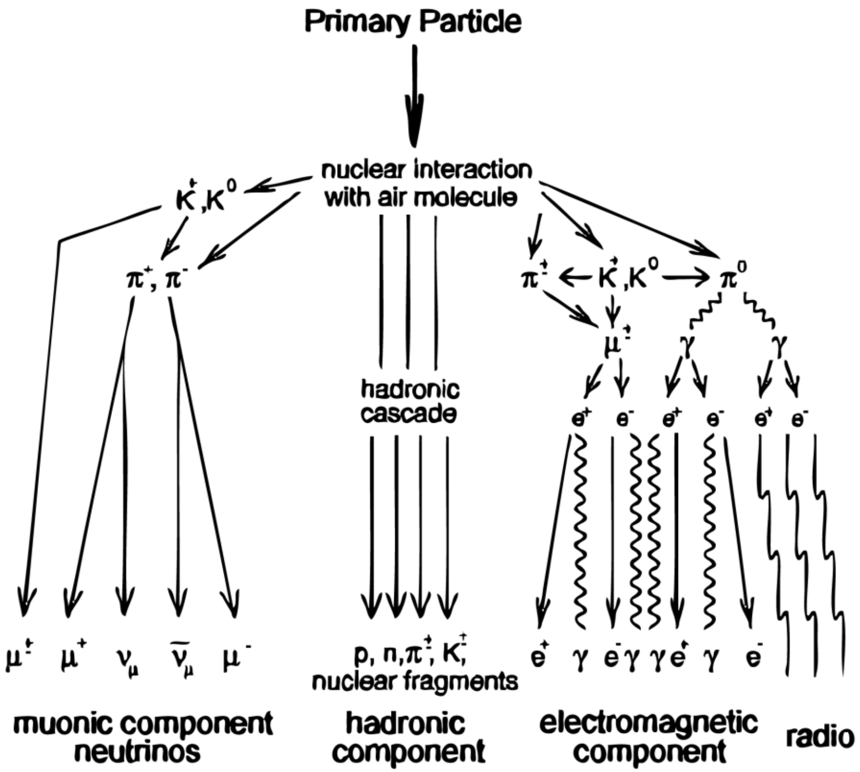
👍 much **more events**
👎 primary parameters are **reconstructed**

Pierre Auger Observatory, Argentina

Telescope Array, Utah, USA

Pierre Auger Observatory detection

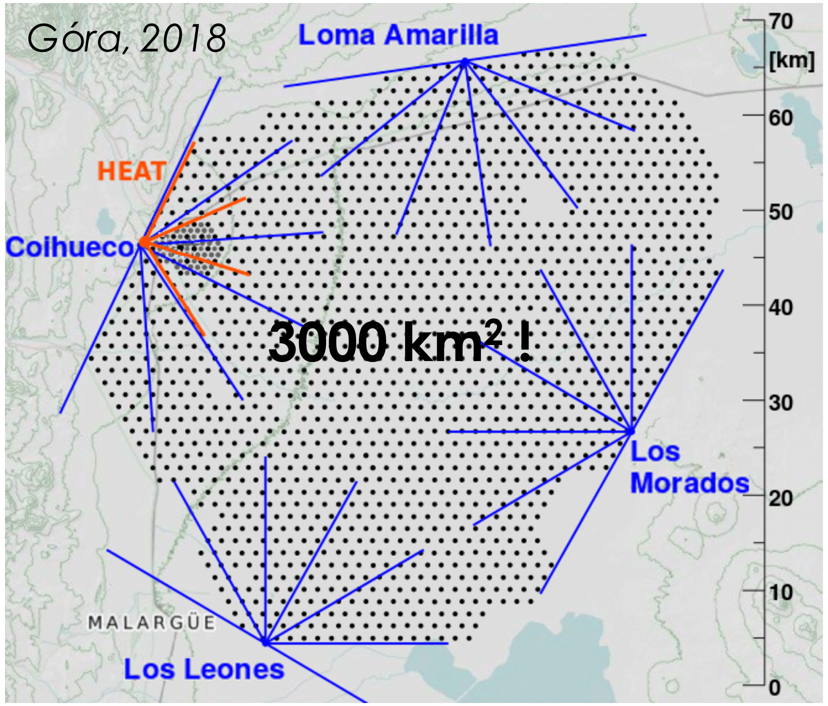
How does Auger detect cosmic rays?



Cascade of particles:

final particles have **ultra-high velocities**

Cherenkov effect in water detectors on Earth!



Auger array of detectors in the Argentina Mendoza province

Cosmic ray propagation in space

AGN, ESA/Hubble
L.Calçada (ESO)

Extragalactic sources

GRB, ESO/A. Roquette

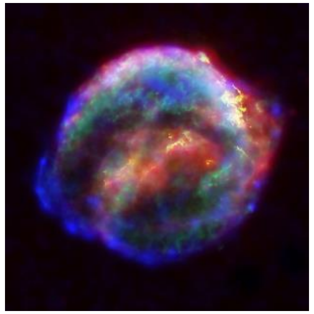
CMB : alters composition + lose energy !

INTERGALACTIC MEDIUM → Milky Way

Intergalactic magnetic field : alters direction !

INTERSTELLAR MEDIUM → Earth

Galactic sources



Kepler SNR,
NASA/ESA/JHU/
R.Sankrit & W.Blair

Cosmic ray propagation in space

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GRB, ESO/A. Roquette

CMB : alters composition + lose energy !

INTERGALACTIC MEDIUM →

Intergalactic magnetic field : alters direction !

Milky Way

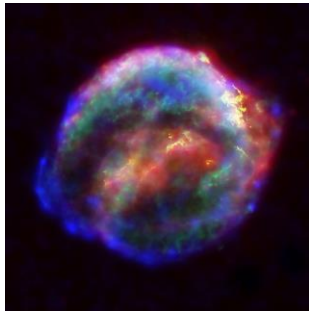
Gas + plasma : alters composition !

INTERSTELLAR MEDIUM →

Galactic magnetic field : alters direction !

Earth

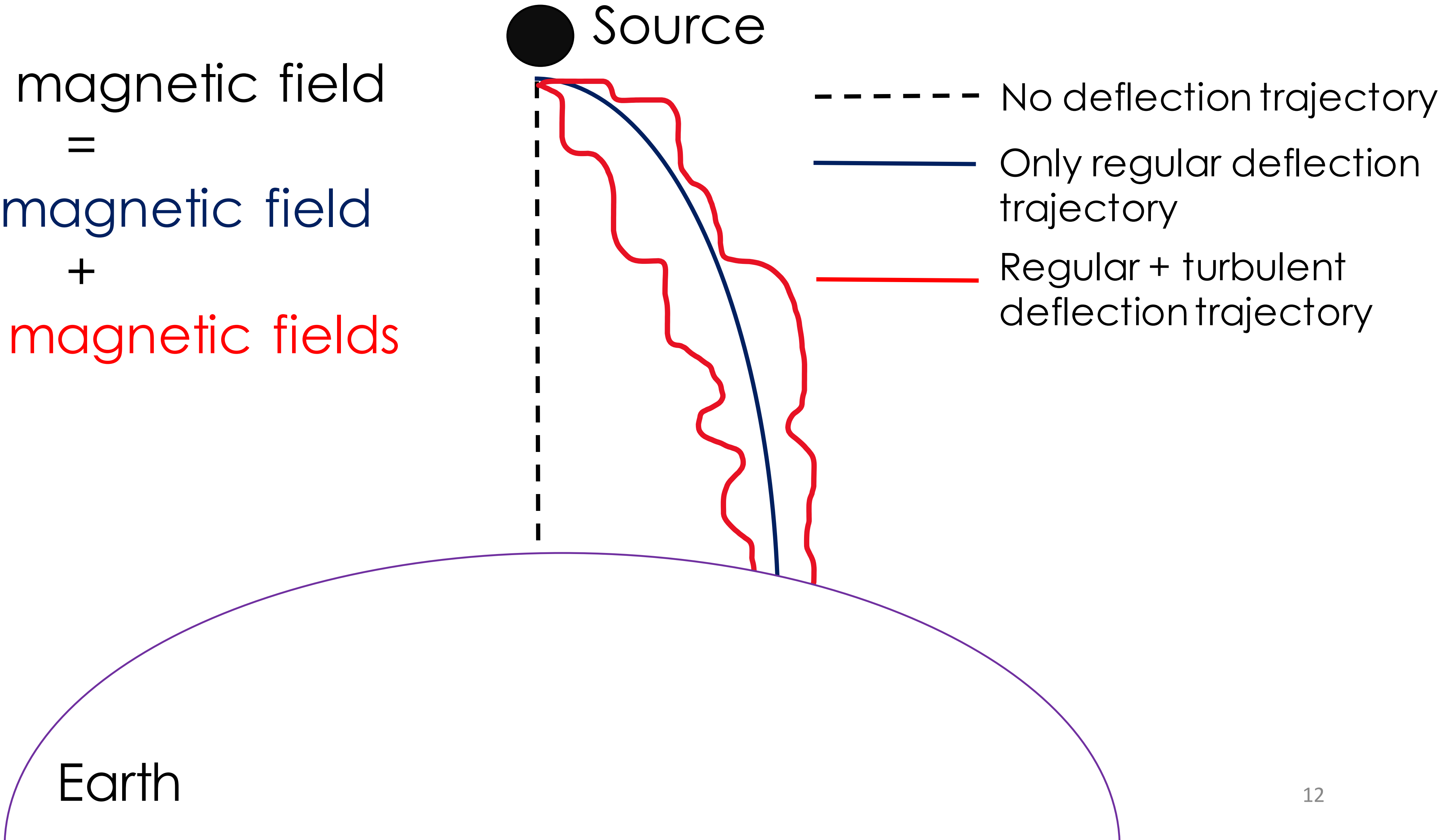
Galactic sources



Kepler SNR,
NASA/ESA/JHU/
R.Sankrit & W.Blair

The Galactic Magnetic Field

Galactic magnetic field
=
Regular magnetic field
+
Turbulent magnetic fields



The Galactic Magnetic Field

Galactic magnetic field

=

Regular magnetic field

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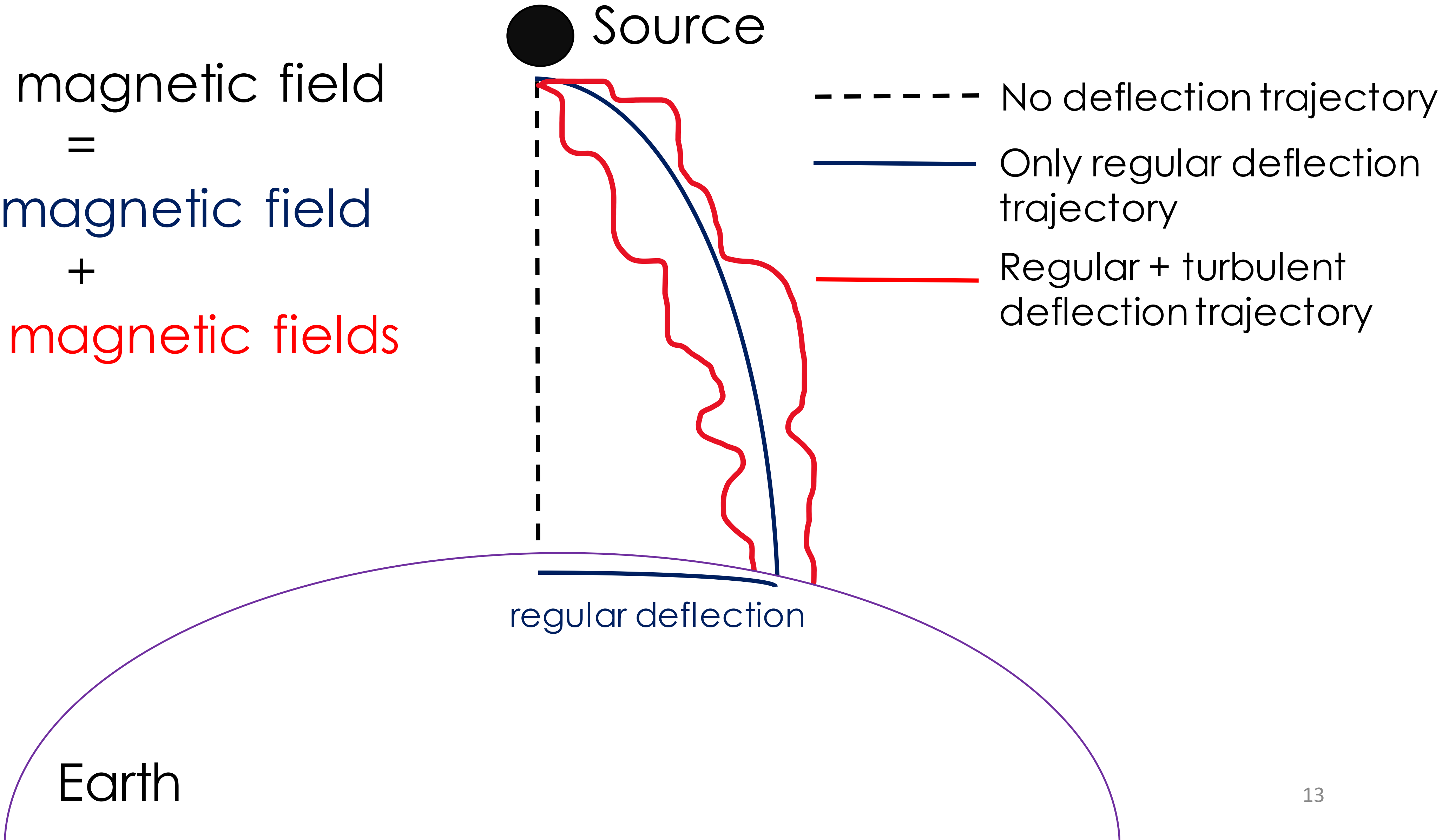
Turbulent magnetic fields



The Galactic Magnetic Field

Galactic magnetic field

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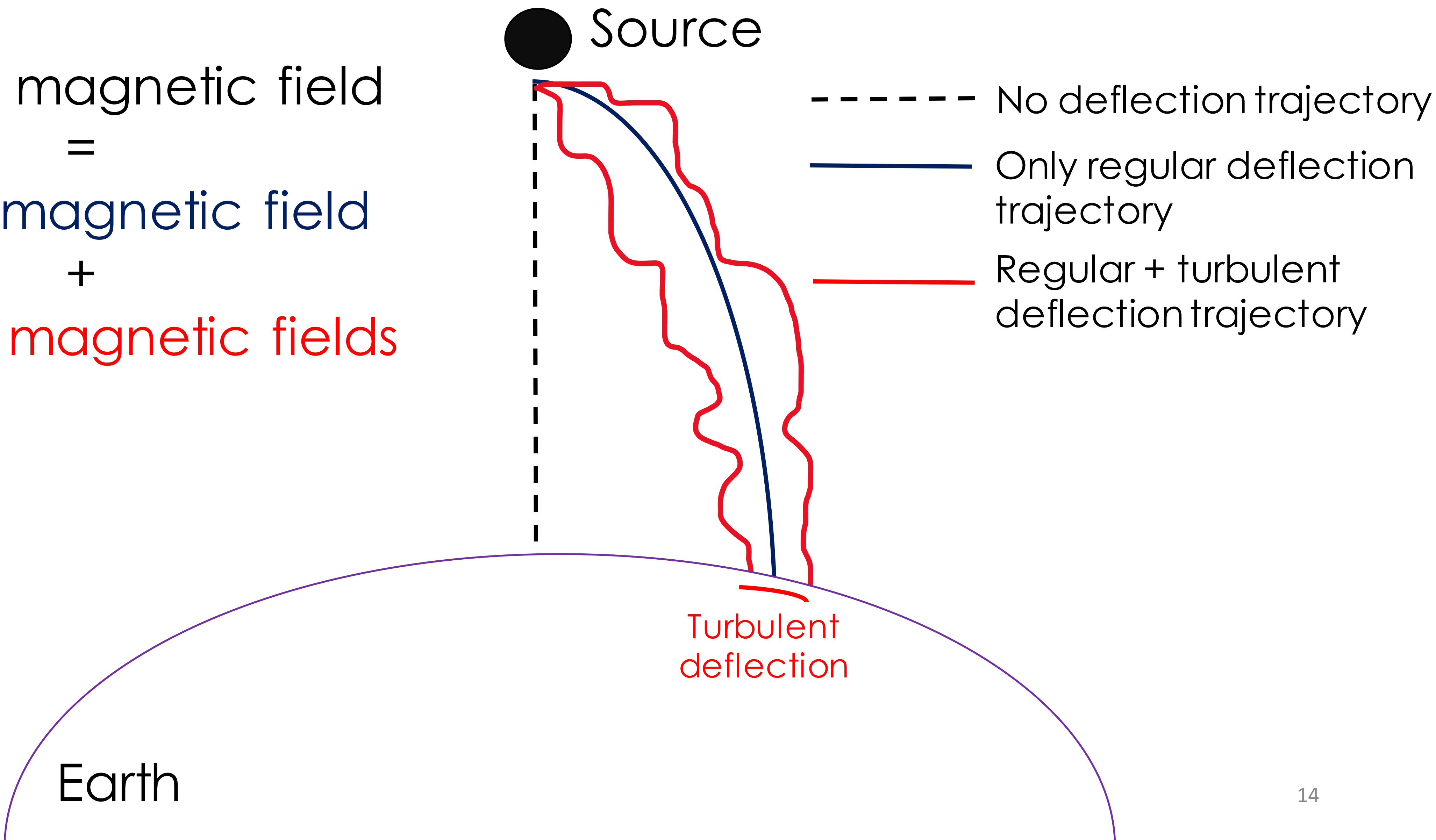
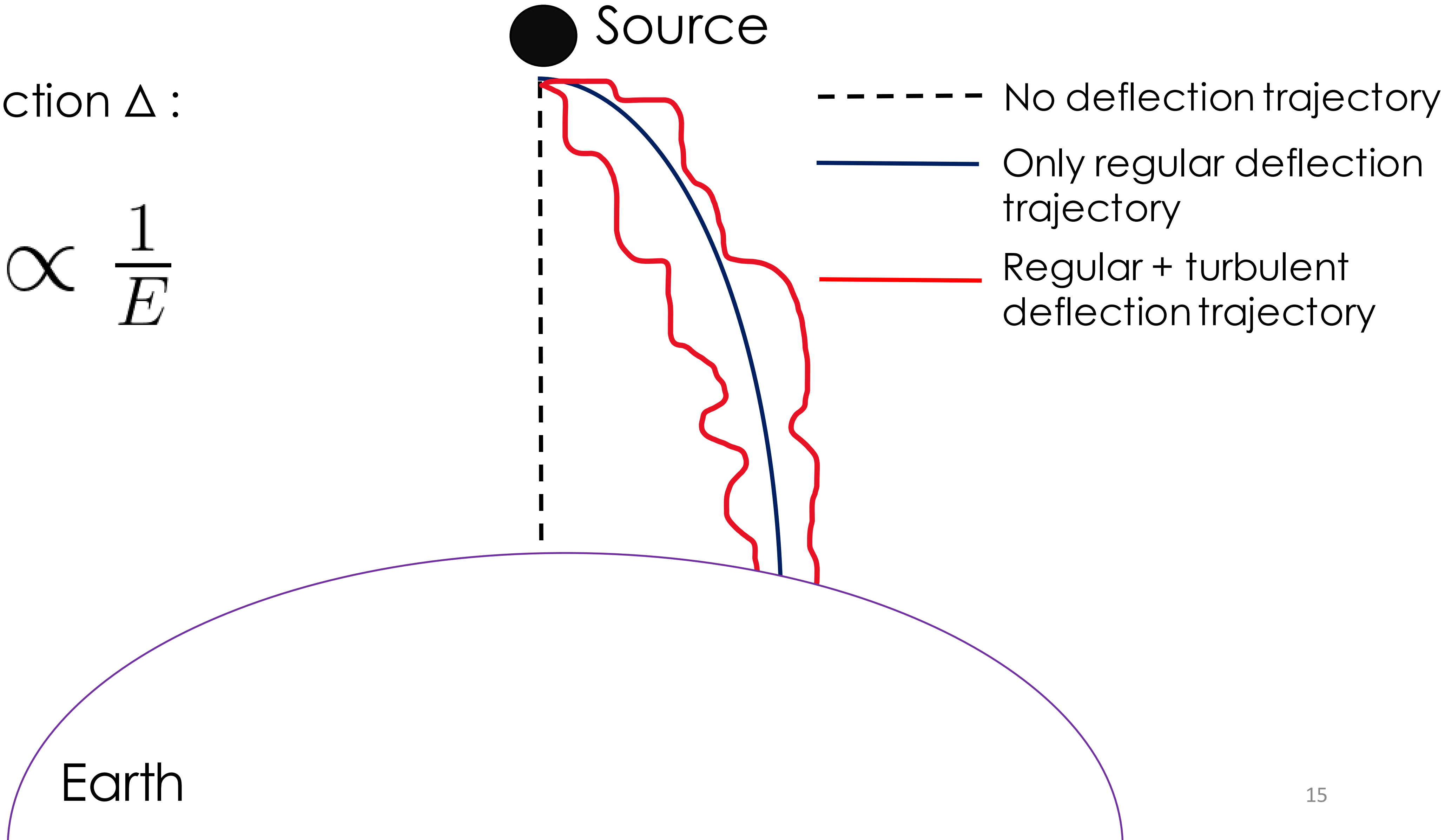


The Galactic Magnetic Field

Deflection Δ :

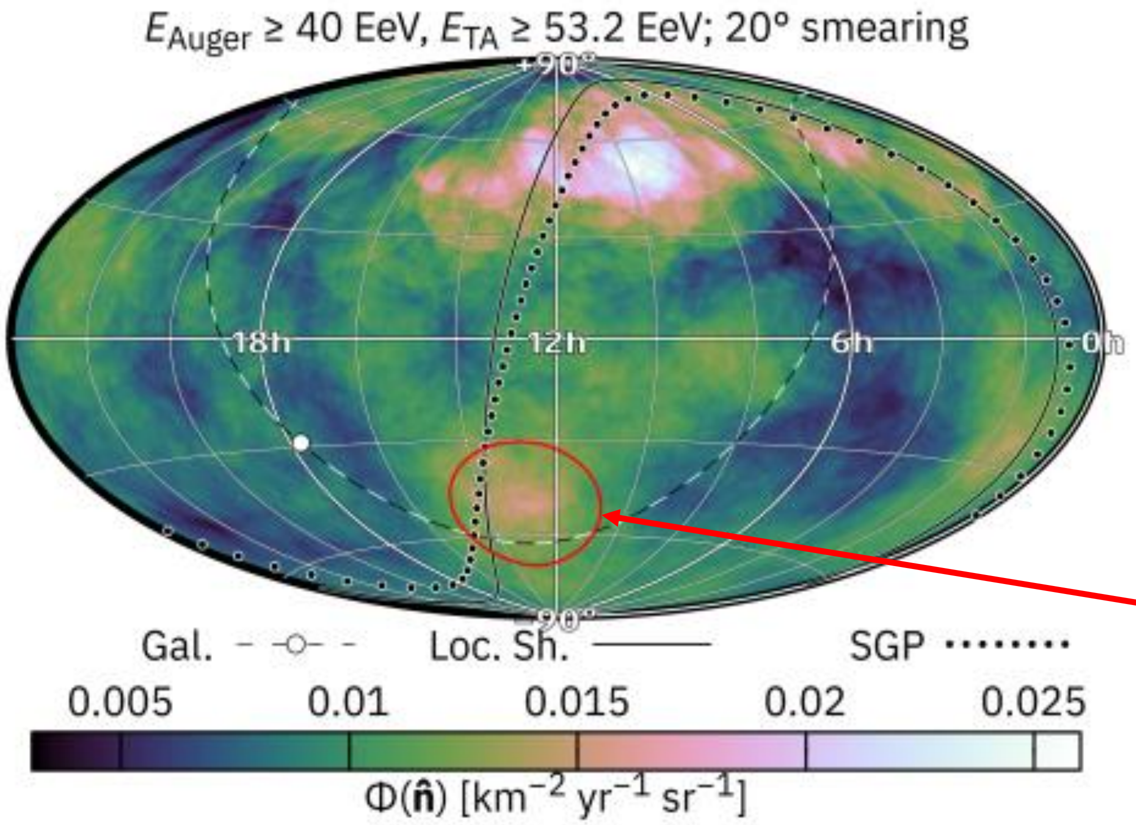
$$\Delta \propto \frac{1}{E}$$



Literature on UHECR sky anisotropies

Combination of Auger and TA data by Di Matteo et al., 2019

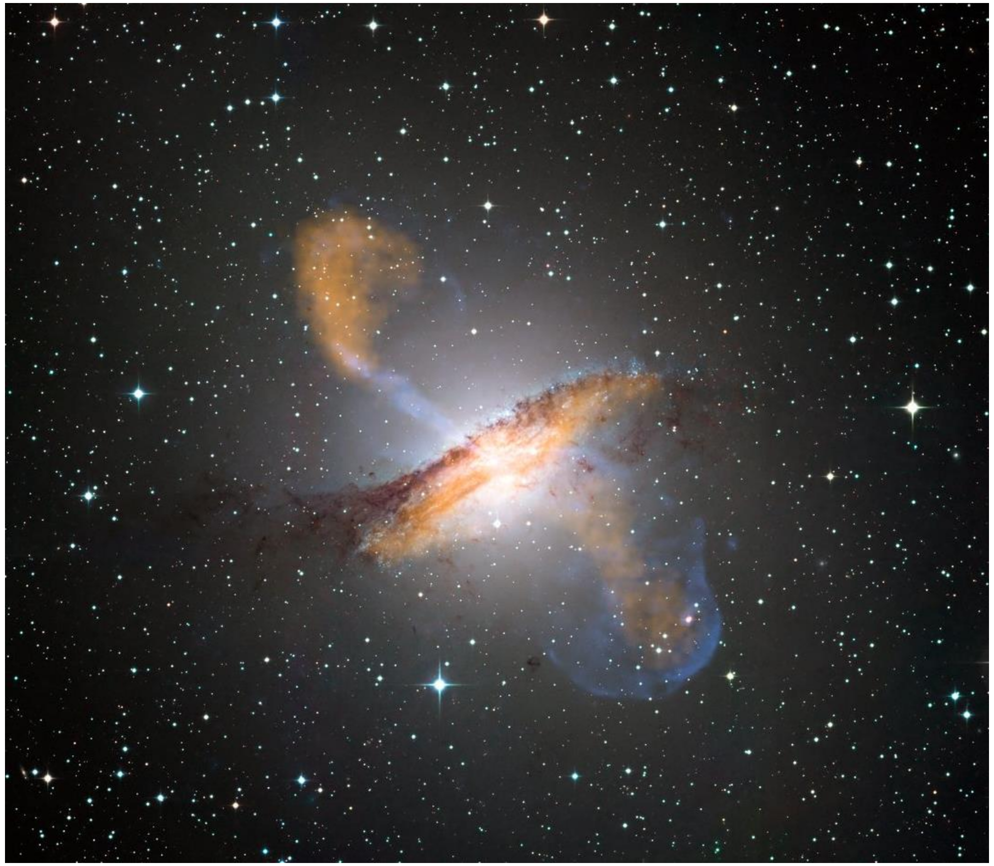
High-energy : E ≳ 40 EeV



Localized anisotropies at various **smaller scale**, which coincide with local **energetic objects** (e.g. radio galaxies)

Hotspot near active galaxy Centaurus A

Project : anisotropies with 10% of Auger?



Centaurus A, active galaxy located in the southern hemisphere

Image credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

Only 10% ≈ 1 year of Auger data is public.

Project

With only 10% of Auger data :

- **What conclusions could be drawn on magnetic deflections?**
- **How significant would those results be?**

Method

- focus on **Cen A = closest AGN**
- **Blind search** = look for hotspot in UHECR **flux map**

How to plot a flux map?

Flux ϕ of cosmic rays in a region R of the sky: $$\phi(R) = \frac{N_{events}(R)}{\omega_{Auger}(R)}$$

How to plot a flux map?

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Exposure of region R

=

number of particles expected to be observed with arrival direction R = (Ra, Dec)

→ in $\mathrm{km}^2.\mathrm{sr}.\mathrm{yr}$

→ depends on **observatory location**

→ Earth rotation ➡ **constant in Ra**

How to plot a flux map?

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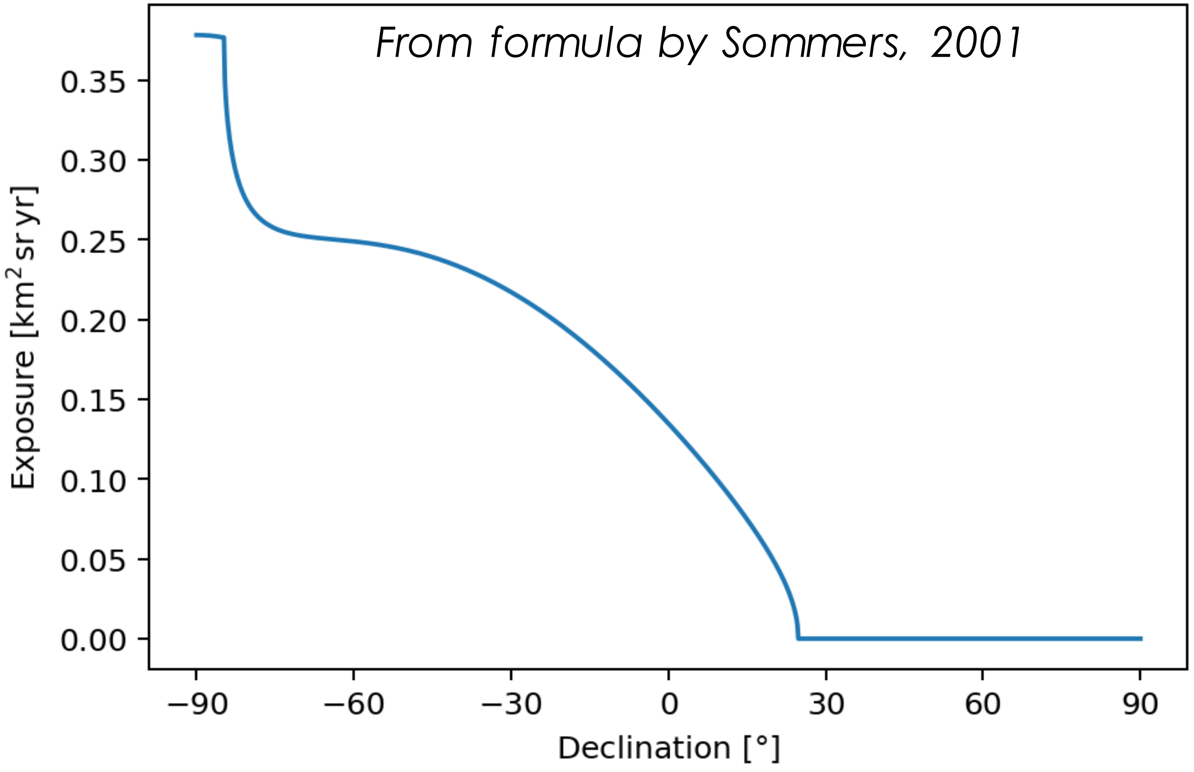

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→ in $\mathrm{km^2.sr.yr}$

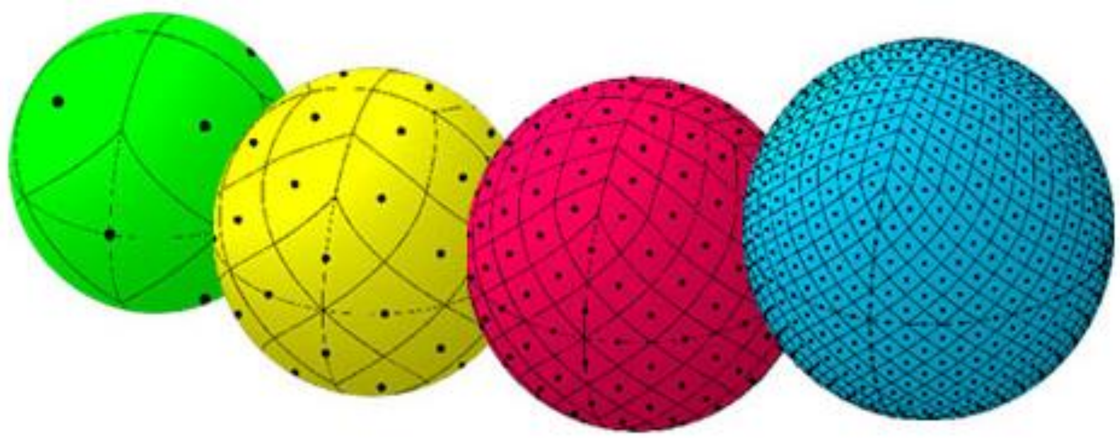
→ depends on **observatory location**

→ Earth rotation ➡ **constant in Ra**

How to plot a flux map?

1. Divide the celestial sphere in **pixels** : healpy python library

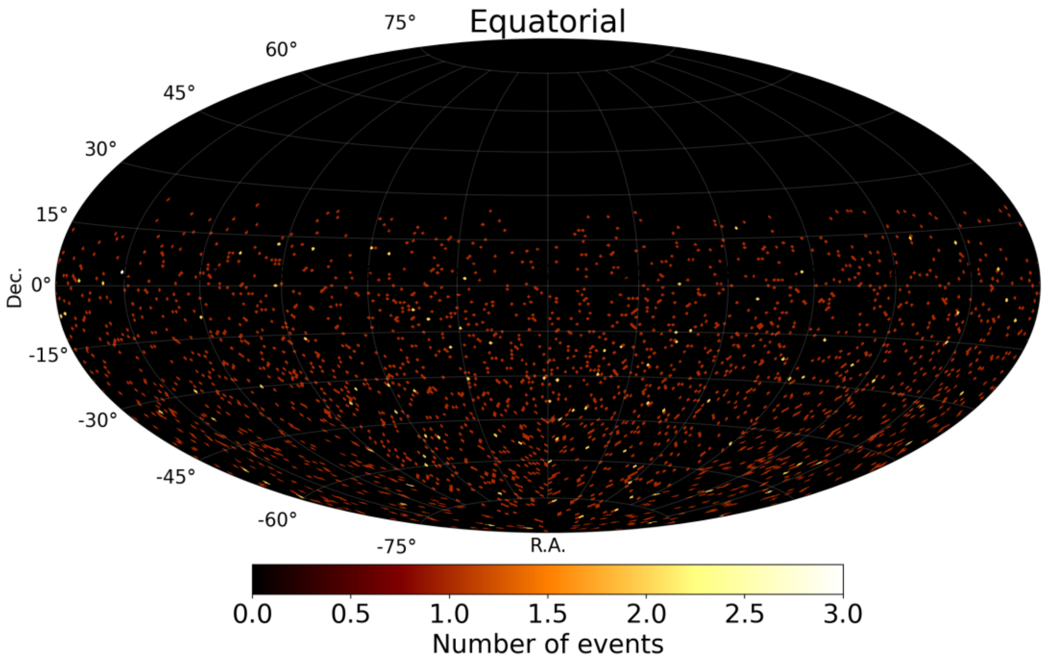
- Same surface area for each pixel
- Resolution : 0.9°

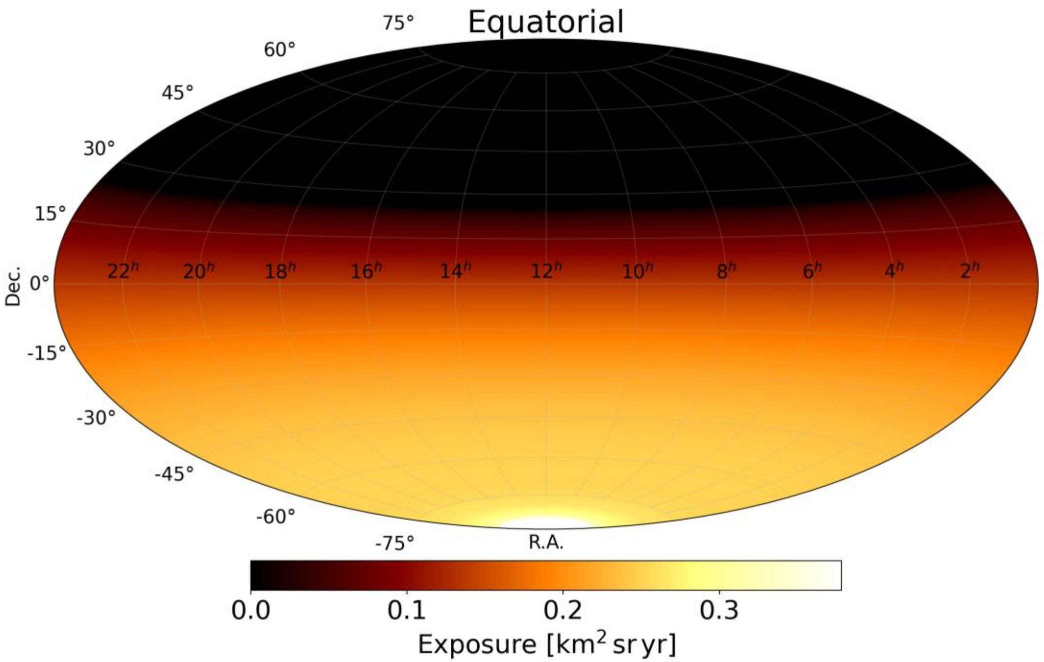


How to plot a flux map?

1. Divide the celestial sphere in **pixels** : healpix python library

2. For each pixel, **count** the number of events and calculate the **exposure**



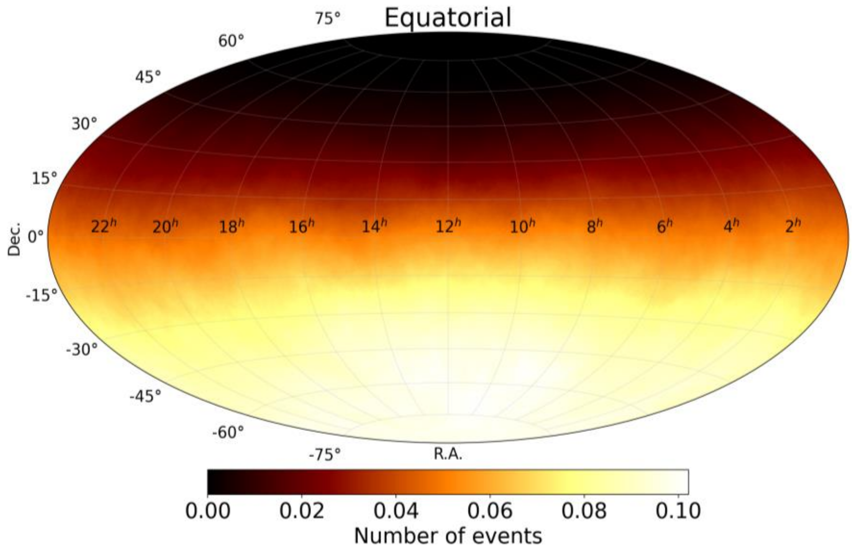


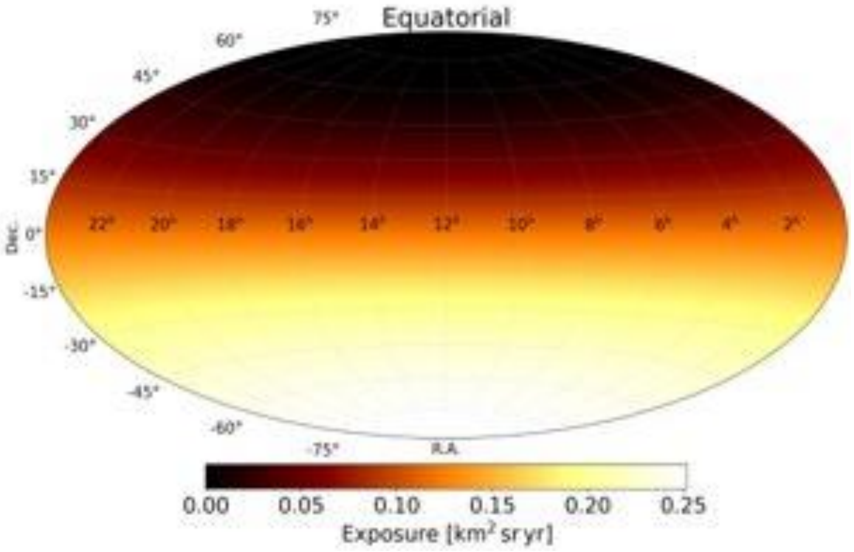
How to plot a flux map?

1. Divide the celestial sphere in **pixels** : healpix python library

2. For each pixel, **count** the number of events and calculate the **exposure**

3. **Smoothing** both the number of counts and the exposure per pixel over the scale of interest : **uniform** filtering





How to plot a flux map?

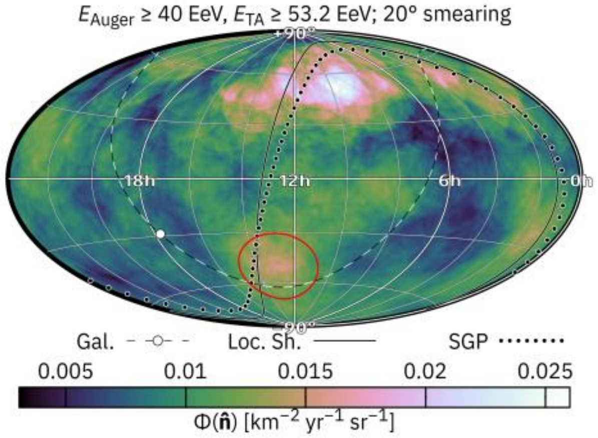
1. Divide the celestial sphere in **pixels** : healpix python library

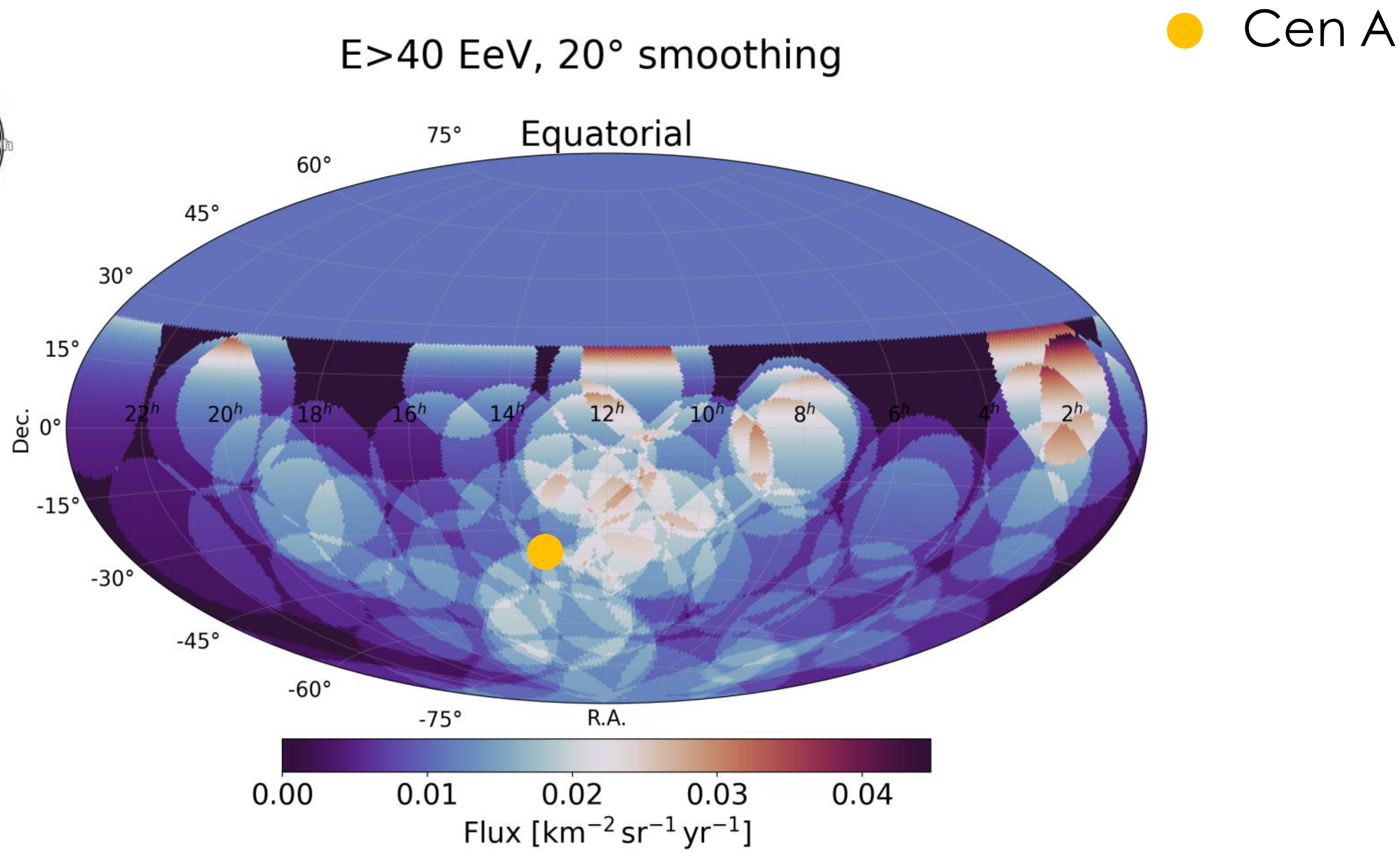
2. For each pixel, **count** the number of events and calculate the **exposure**

3. **Smoothing** both the number of counts and the exposure per pixel over the scale of interest : **uniform** filtering

4. **Divide** the smoothed count by the smoothed exposure

Flux map : high energy



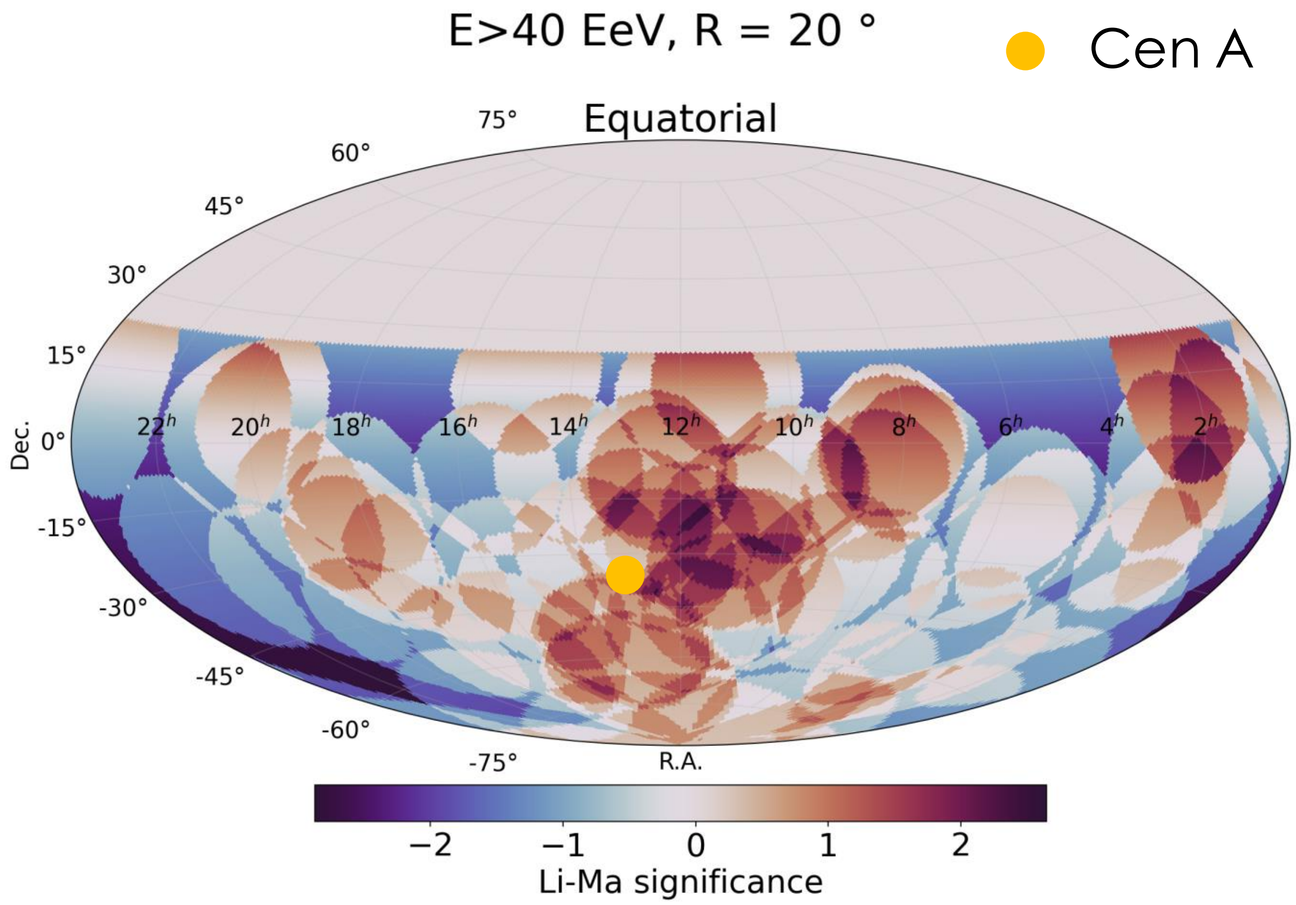


How significant is the hotspot,
i.e. originating from noise or from a real source?

Local significance map

Li-Ma significance (Li & Ma, 1983)

For each pixel, comparison between the flux inside and outside of the smoothing region



Presence of a hotspot with a Li-Ma significance of 2.6 at RA = 158°, Dec = -29°

Implications on the magnetic field

Hypotheses

1. Cen A = **only source** of the hotspot

⇨ Hotspot **distance with Cen A** = result of **regular magnetic deflections**

2. Cen A is a **point source at RA=201°, Dec=-43°**

⇨ Hotspot **width** = result of **turbulent magnetic deflections** only

Implications on the magnetic field

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	My work
Position of hotspot	RA = 158°, Dec = -29°
Size of hotspot	(30 ± 6)°
Conclusions	
Regular B deflections	(43 ± 8)°
Turbulent B deflections	(30 ± 6)°

Implications on the magnetic field

Hypotheses

1. Cen A = **only source** of the hotspot

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2. Cen A is a **point source at RA=201°, Dec=-43°**

⇨ Hotspot **width** = result of **turbulent magnetic deflections** only

	My work	Di Matteo et al., 2019
Position of hotspot	RA = 158°, Dec = -29°	RA = 192.5°, Dec = -50°
Size of hotspot	(30 ± 6)°	(35 ± 3)°
Conclusions		
Regular B deflections	(43 ± 4)°	(9 ± 2)°
Turbulent B deflections	(30 ± 6)°	(30 ± 6)°

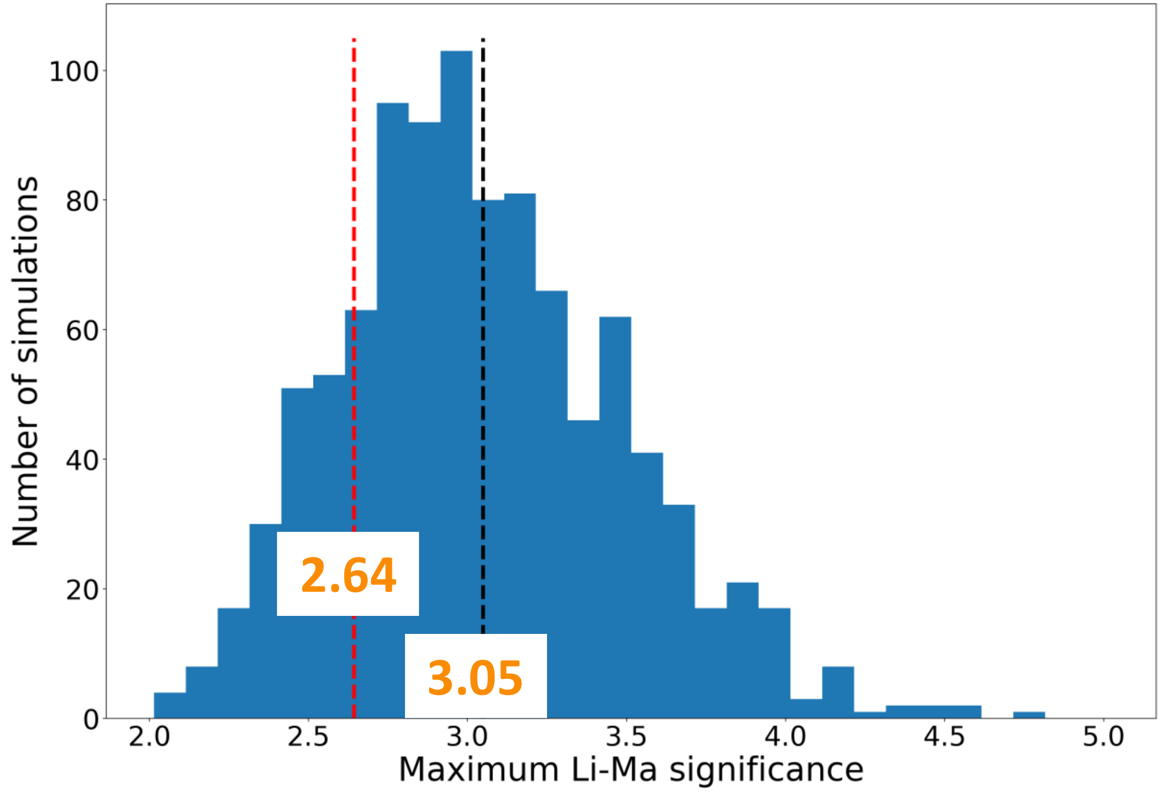
Measured by me

Is 1 year of Auger data enough?

Could an isotropic flux produce such a hotspot?

Monte Carlo simulation

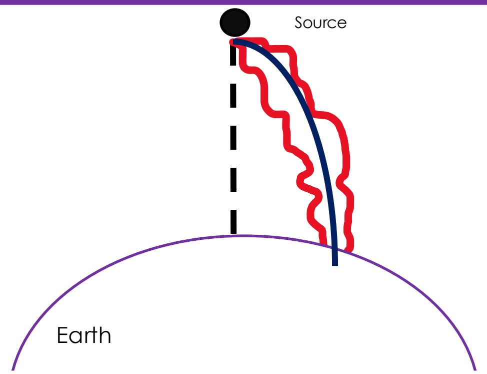
- **1000 simulations**
- Each simulation has:
  - The **same number of events** as was observed above 40 EeV
  - The **Auger exposure**
  - An **isotropic flux**
  - The **same** Li-Ma significance **analysis**



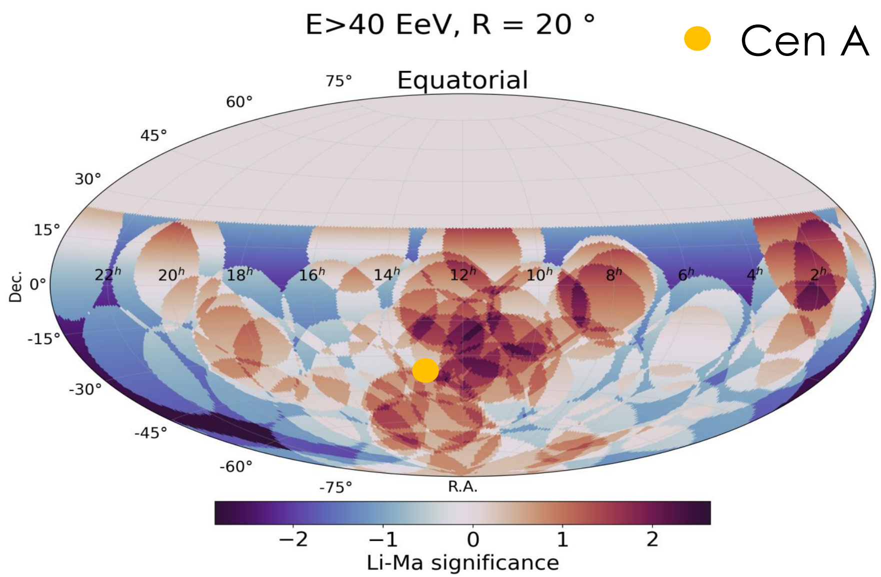
$$\widehat{S_{simu}} - S_{obs} = 0.9\sigma$$

Not enough data to draw conclusions

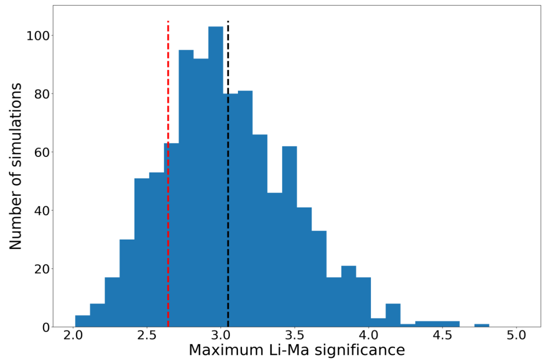
Conclusion



- **UHECR** arrival directions can **point near sources** outside the Milky Way.



- With **10% of Auger** Observatory data :
  - **Hotspot** near the region of Cen A
  - Induced regular magnetic deflections **off compared to literature**



- Monte-Carlo simulation shows **dataset is not enough** to produce significant results.

To try: targeted search of a hotspot near Cen A

Appendix : More details on Auger

Location: Mendoza Province, Argentina
35.2° S, 69.2° W, 1 400 m a.s.l. (≈ 880 g/cm^2)

Main array for UHE taking data since 01 Jan 2004:

SD: 1 600 water Cherenkov detectors on a
1.5 km-spacing triangular grid (3 000 km^2 total)

FD: 4 sites on edge of SD array (24 telescopes total)

Low-energy extension (HEAT and AMIGA):

- 3 extra FD telescopes at higher elevation
- 61 extra SDs with 750 m spacing

Aperture: $\theta_{zenith} < 80°$ (declination $\delta < +44.8°$)

Systematic uncertainty on energy scale: ±14%

Di Matteo, 2021

Appendix : Galactic magnetic field

Regular magnetic field

- Large scale

Turbulent magnetic field

- Small scale
- Random
- Supernovae + other outflows + hydrodynamic turbulence
- Striated random fields : aligned orientation over large scale, but sign and strength vary
  - differential rotation of a medium containing small-scale random fields
  - levitation of bubbles of hot plasma carrying trapped randomly oriented fields away from the disk

Lots of models, often parametrized on a lot of observables
Order of magnitude : 3 mG

Appendix : Magnetic field deflections

For GMF: Calculate R, compare with values from article (?), scale with energy since defl propto E

IGMF : upper bound is lowest GMF lower bound (upper bound found in an article)

	10 EeV	**50 EeV**
Proton	15 – 40 °	3 – 8 °
CNO	100 – 250 °	20 – 50 °
Heavy nuclei	diffusive	80 – 200 °

Table of Galactic magnetic deflections with respect to composition and energy
A. di Matteo, 2021 *from* Šmída, 2015 *simulations*

Appendix : Li-Ma significance

$$S_{LM} = -2\ln\left(\frac{P_r(X|E_0,\hat{T}_c)}{P_r(X|\hat{E},\hat{T})}\right) \sim \chi^2(r)$$

- X : observed data ***N***
- (E, T) : unknown parameters
  E = N_s = number of counts originating from Cen A
  T = N_B = number of counts originating from the isotropic background
- E_0 : null hypothesis (the observed data are a result of noise) **E = <N_s> = 0**
- ^ : maximum likelihood estimates of parameters E and T
- : maximum likelihood estimate of parameter T for E = E_0
- $\hat{T}_c$ r : number of parameters involved in the null hypothesis (here 1)

Appendix : Other possible sources

- NGC 5090 : radio galaxy

Appendix : More details on air showers

- The different final particles
- What they teach us about primary cosmic rays
- How parameters are reconstructed