MULTI-MESSENGER ASTROPARTICLE PHYSICS through HIERARCHICAL MODELLING

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WHAT? Statistical method

WHY? To use more information from both theory and data

RESULT: A more powerful and analysis and insightful results

EXAMPLE

What are the sources of

Ultra-**H**igh-**E**nergy **C**osmic **R**ays?

EXAMPLE

Which sources could be associated with the observed **UHECR**s?

KEY IDEAS

Including physics

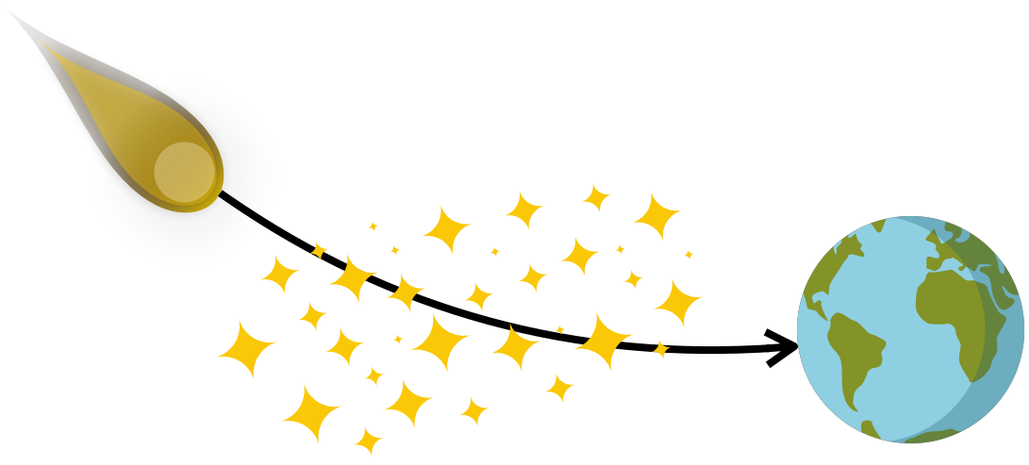
Designing the analysis to answer the question

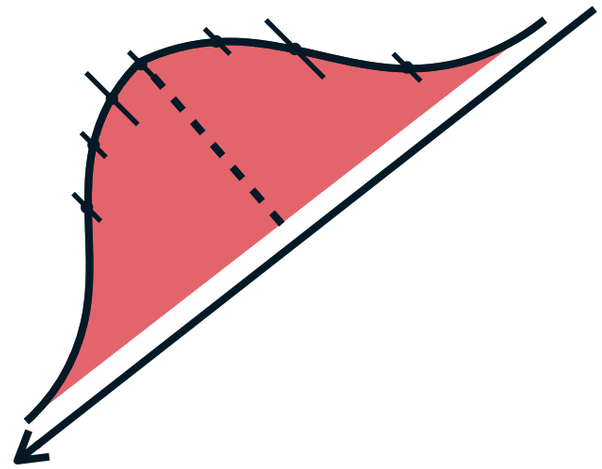
THEORY

- Acceleration
- Propagation
- Detection

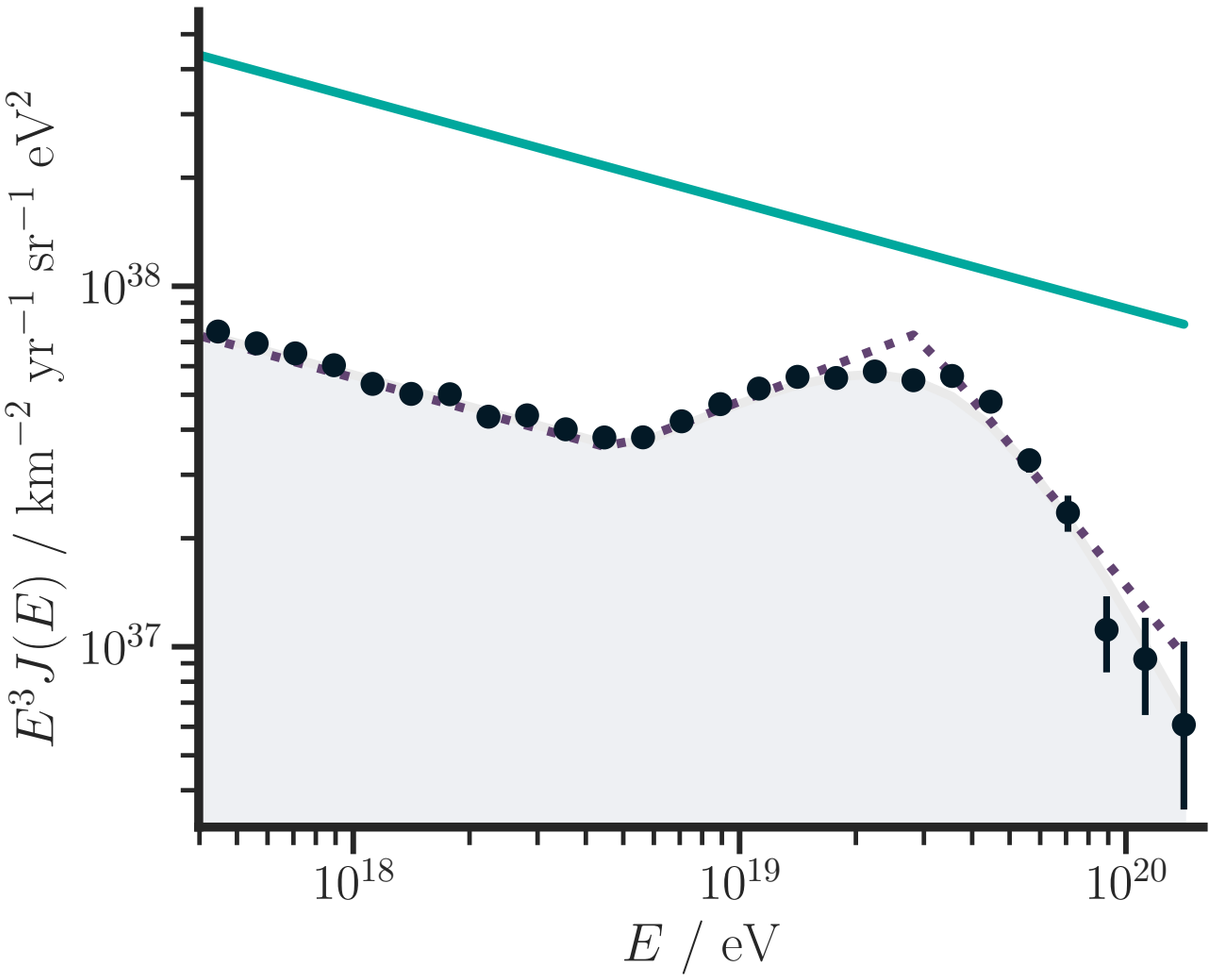
DATA

- Energy
- Arrival direction
- Composition





PHYSICAL MODEL



Protons only

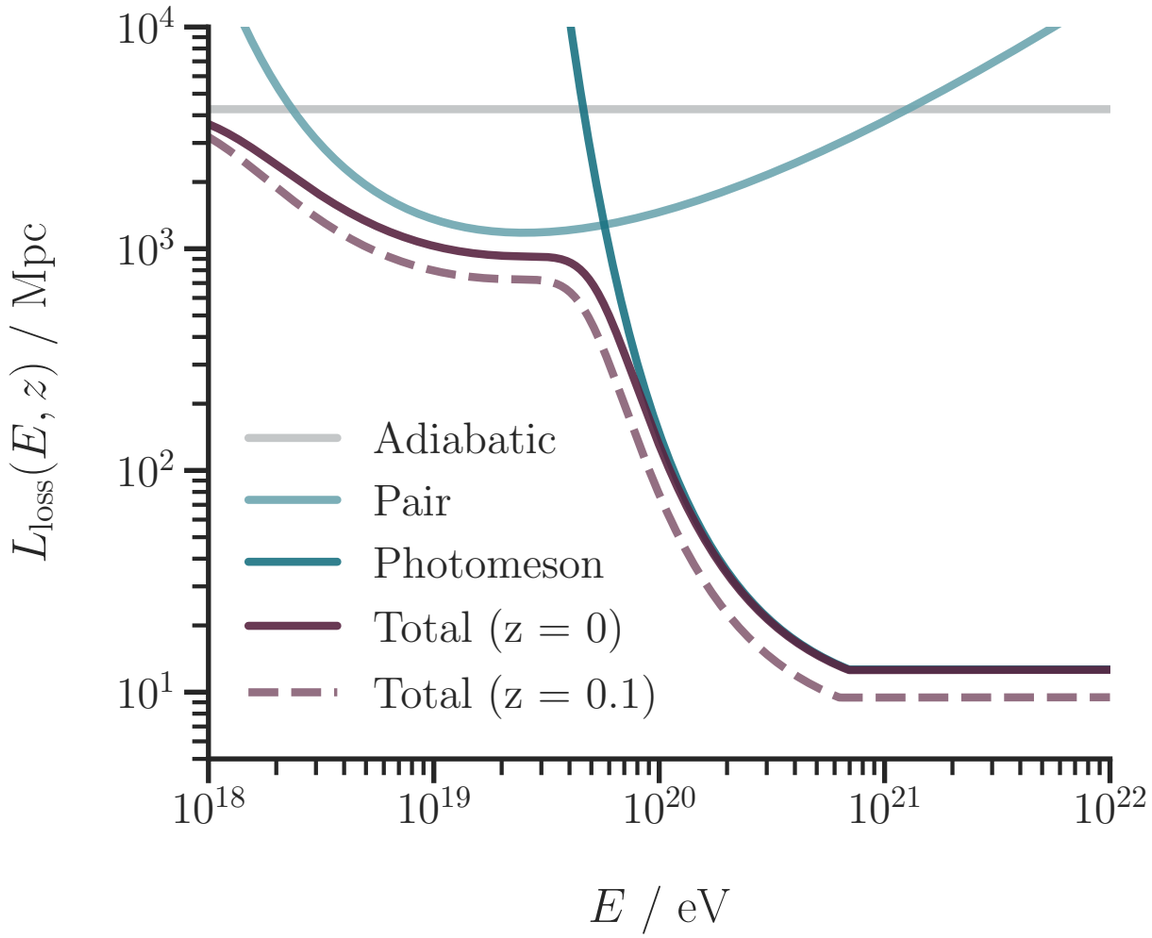
α L

$$\frac{dN}{dE} \propto E^{-\alpha}$$

Source spectrum: power law

PHYSICAL MODEL

Berezinsky+1988
Chodorowski +1992
Anchordorqui+1997
De Domenico+2012



$$\frac{dE}{dz} = -\frac{E}{L_{\rm loss}(E,z)}$$

Propagation: continuous loss approximation

PHYSICAL MODEL

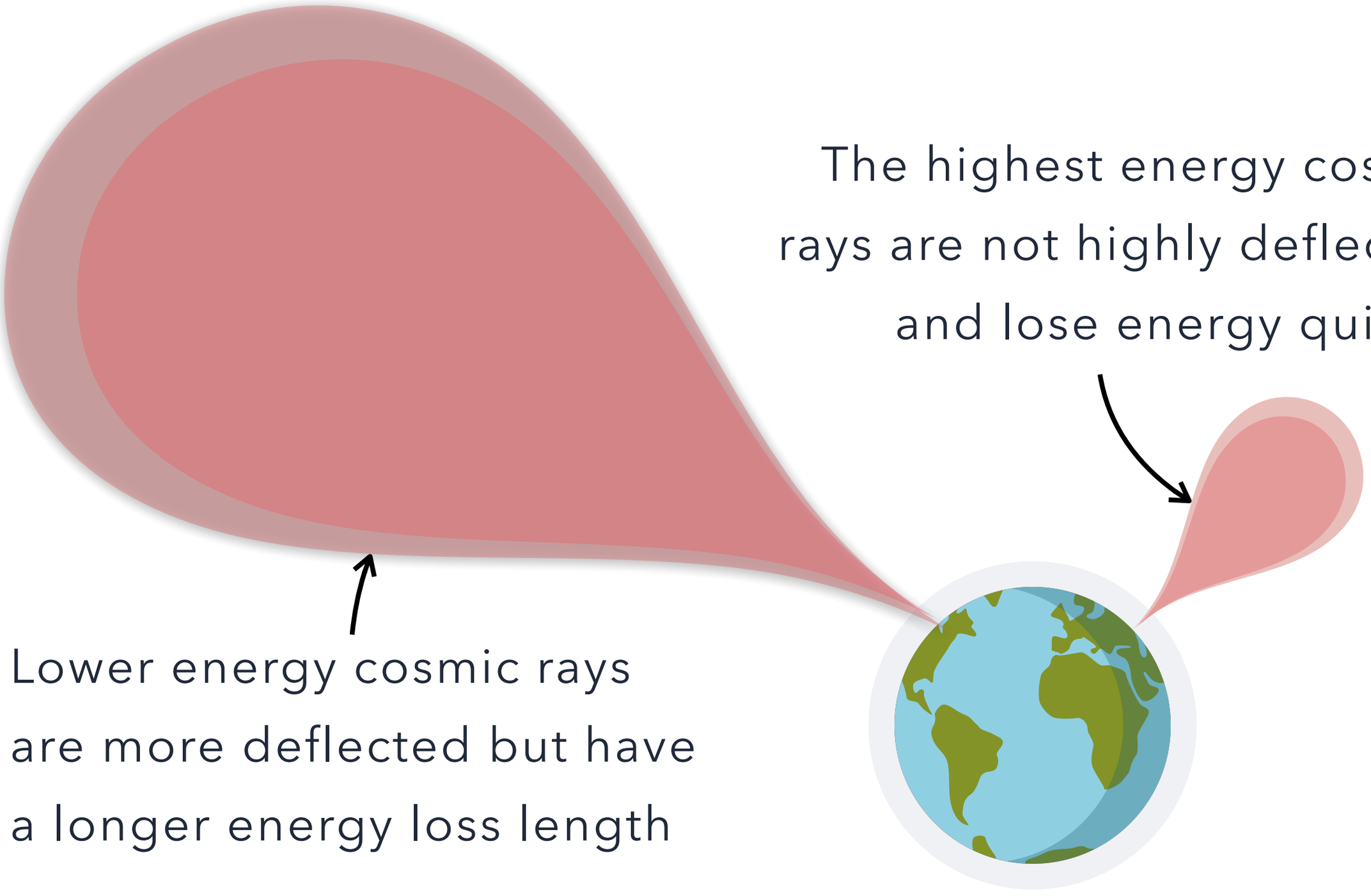
Achterberg+1999
Harari+2002

$$\theta_{\rm rms} \approx 2.3^\circ \left(\frac{E}{50\ {\rm EeV}}\right)^{-1} \left(\frac{B}{1\ {\rm nG}}\right) \left(\frac{D}{10\ {\rm Mpc}}\right)^{1/2} \left(\frac{l_c}{1\ {\rm Mpc}}\right)^{1/2}$$

Propagation: magnetic deflections

IMPORTANCE OF ENERGY

The highest energy cosmic rays are not highly deflected and lose energy quickly



Lower energy cosmic rays are more deflected but have a longer energy loss length

HIERARCHICAL MODEL

Watson+2012

Soiaporn+2013

Khanin+2016

Energy

Arrival direction

$$e^{-\bar{N}} \prod_i r(\hat{\omega}_i, \hat{E}_i)$$

Joint fit of the **energies** and **arrival directions**

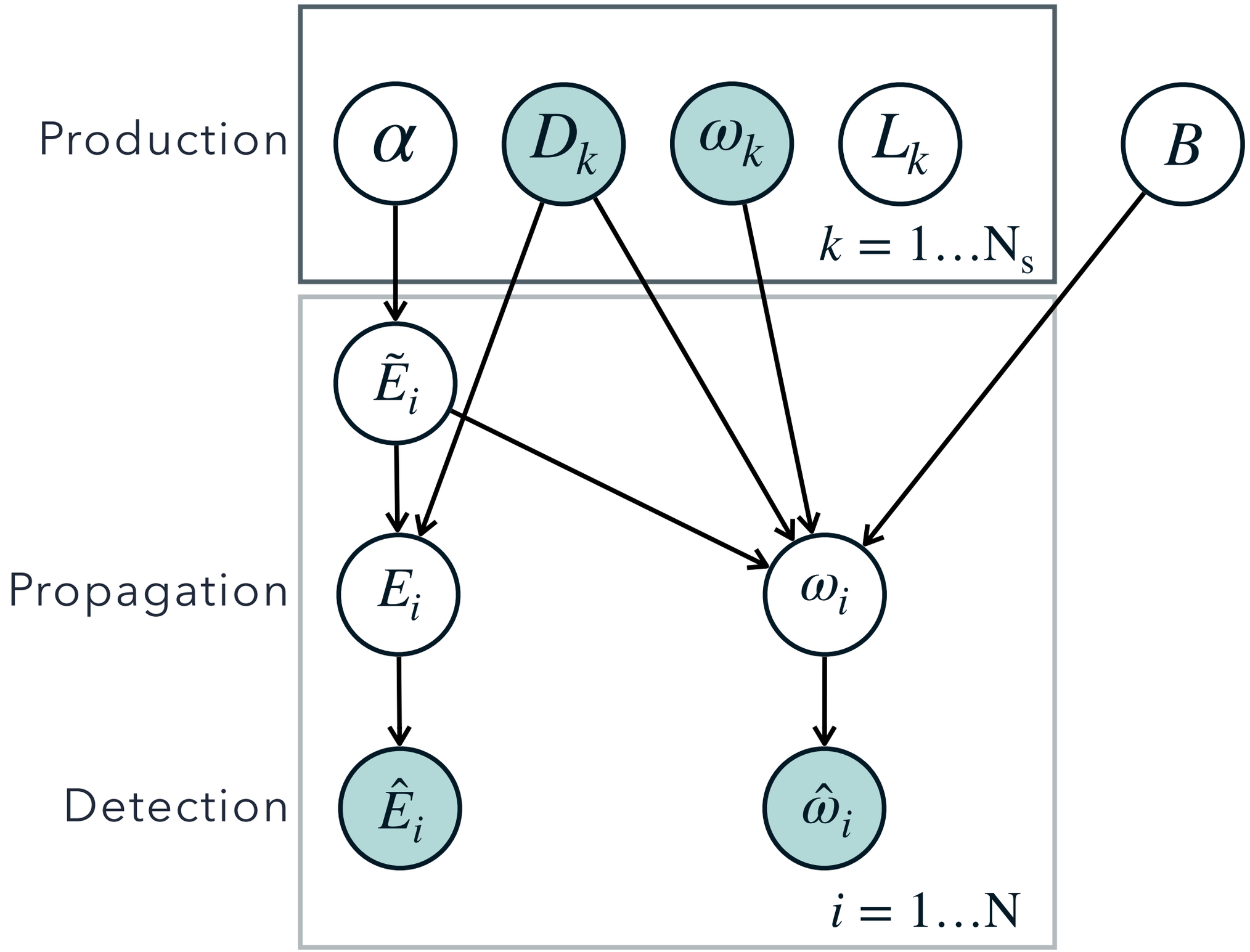
HIERARCHICAL MODEL

Mixture model over sources

$$e^{-\bar{N}} \prod_i \sum_k p(\hat{\omega}_i, \hat{E}_i \,|\, k)$$

Depends on direction, energy, distance travelled, magnetic field strength...

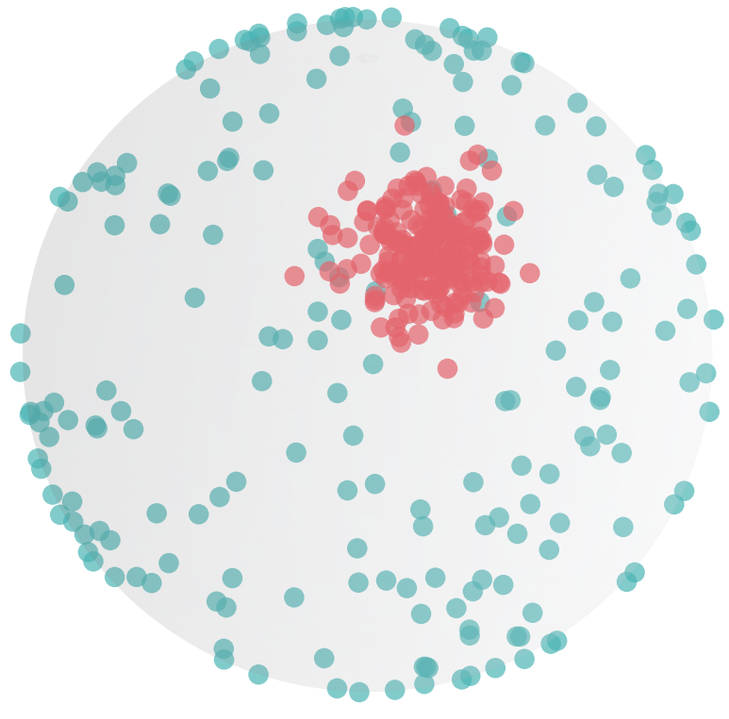
HIERARCHICAL MODEL



HIERARCHICAL MODEL

Which sources could be associated with the observed UHECRs?

$$f = \frac{F_s}{F_0 + F_s}$$



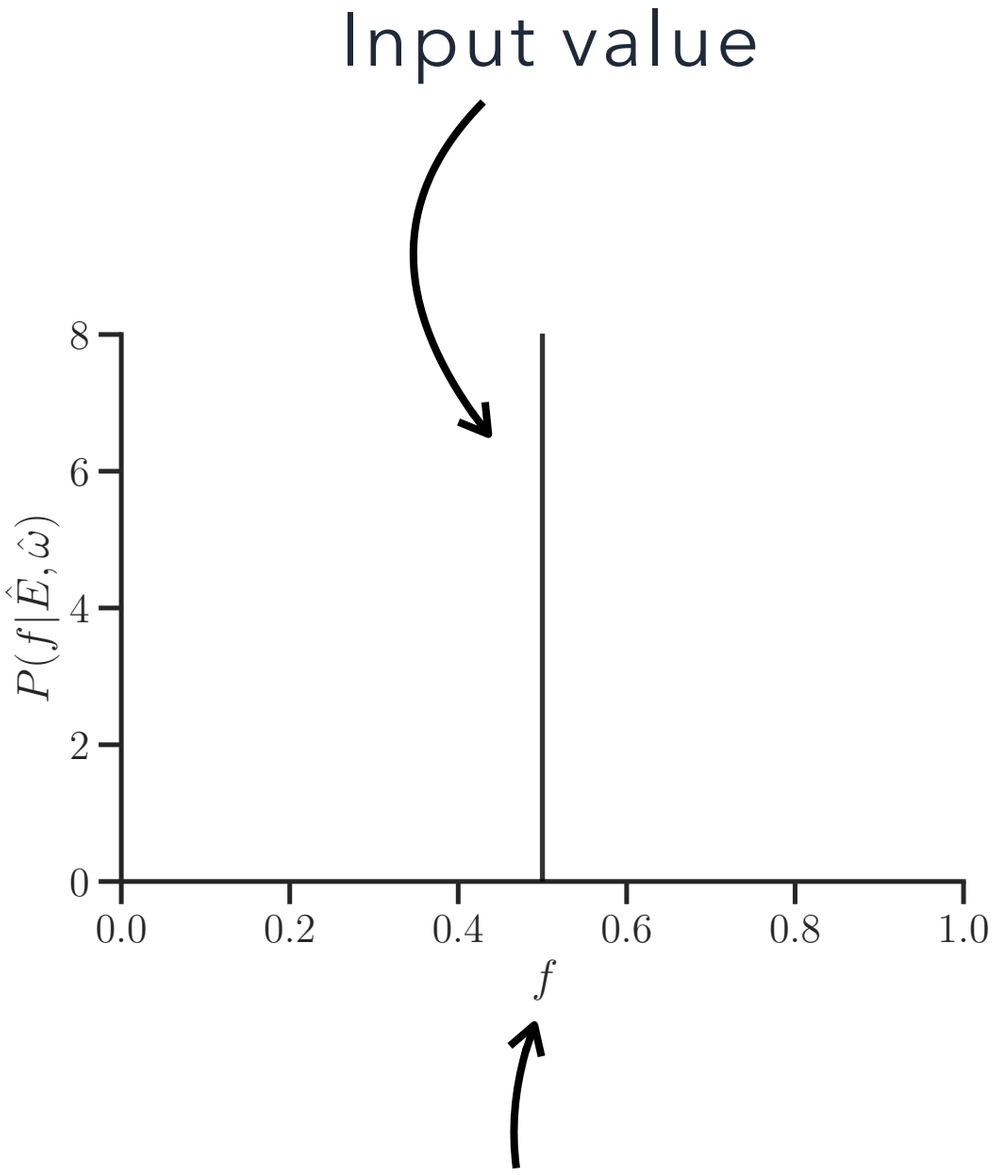
HIERARCHICAL MODEL

Include physical parameters

Parameterise uncertainties

VERIFICATION

- Choose input parameters
- Simulate data
- Fit → correct answer



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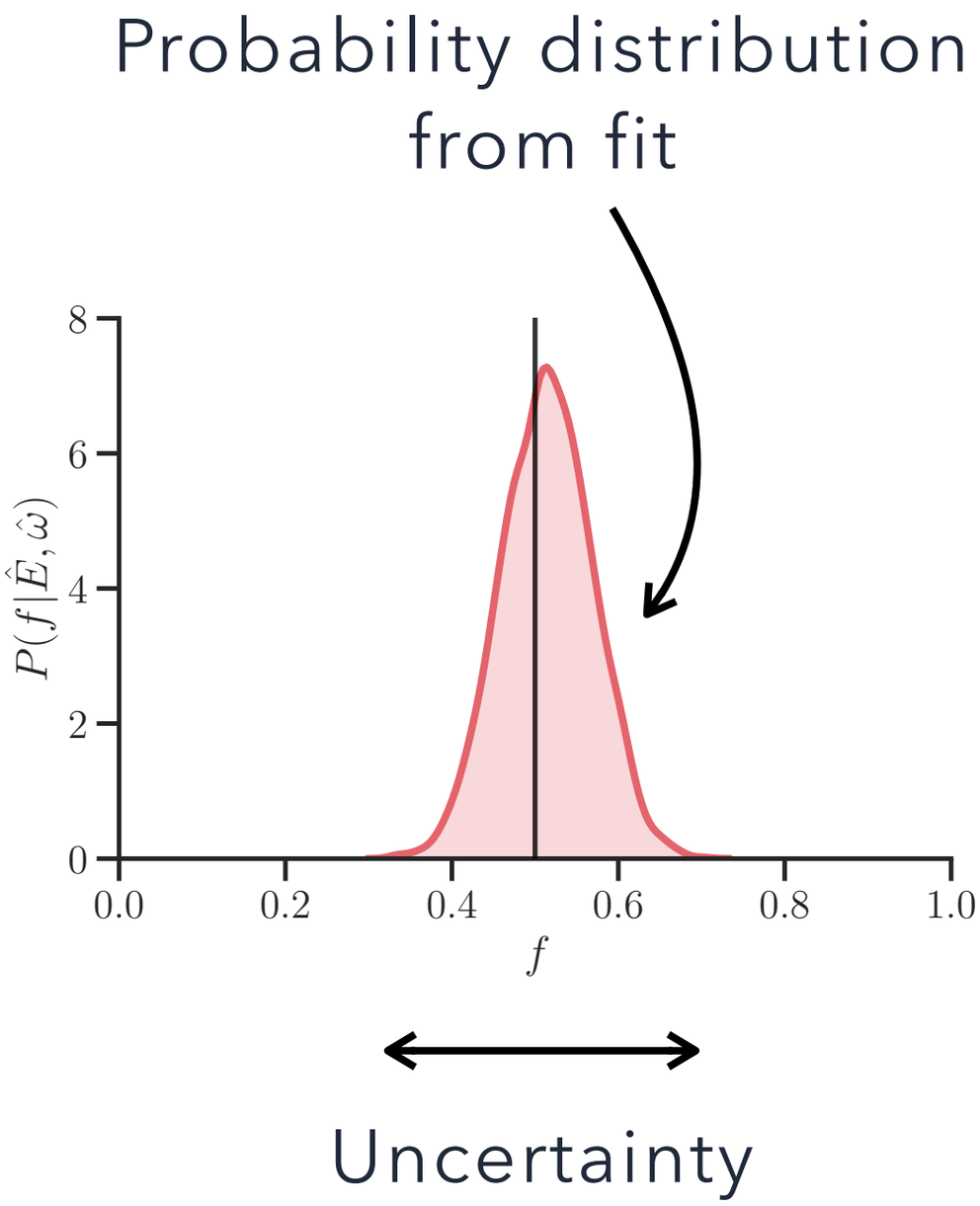

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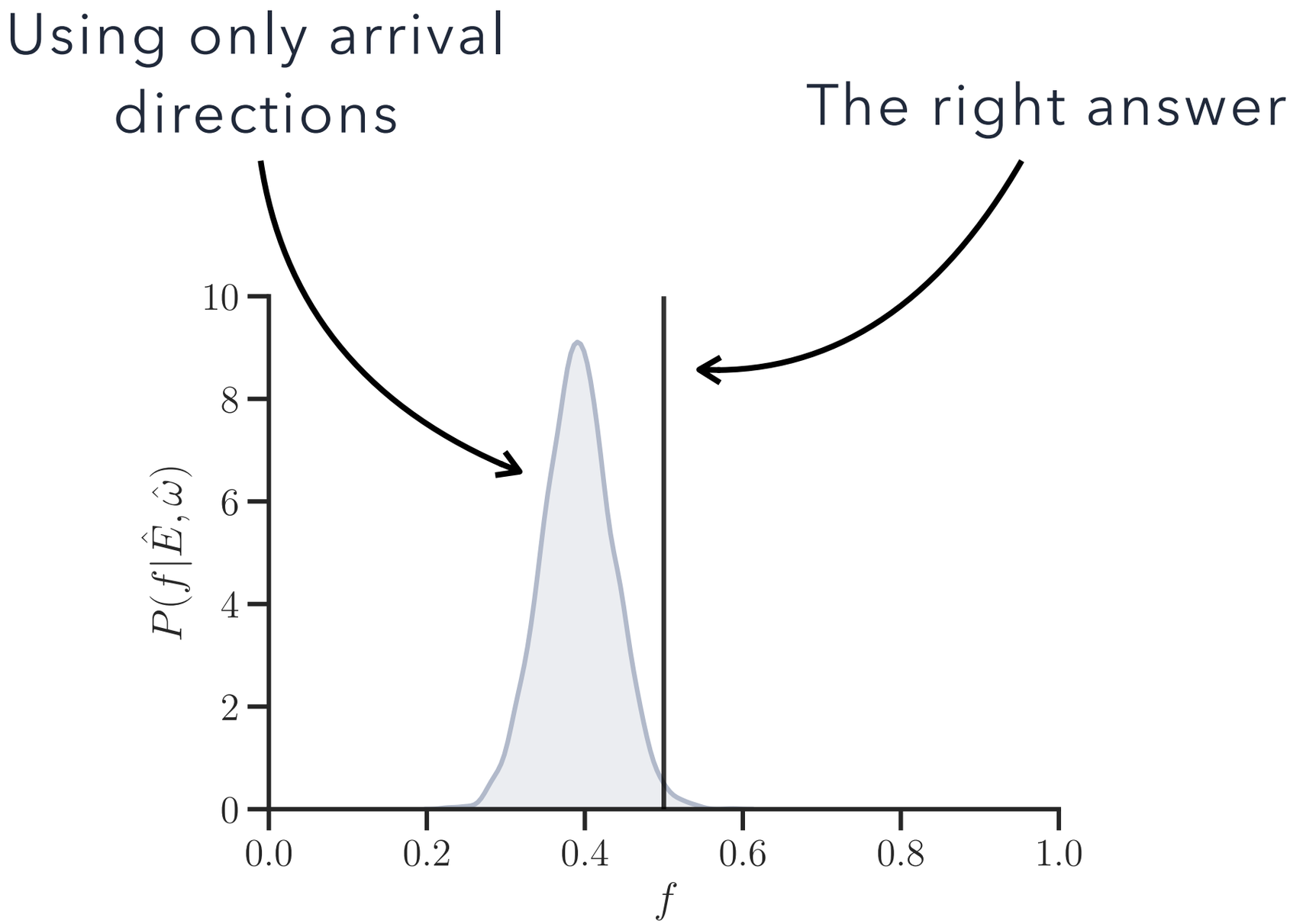

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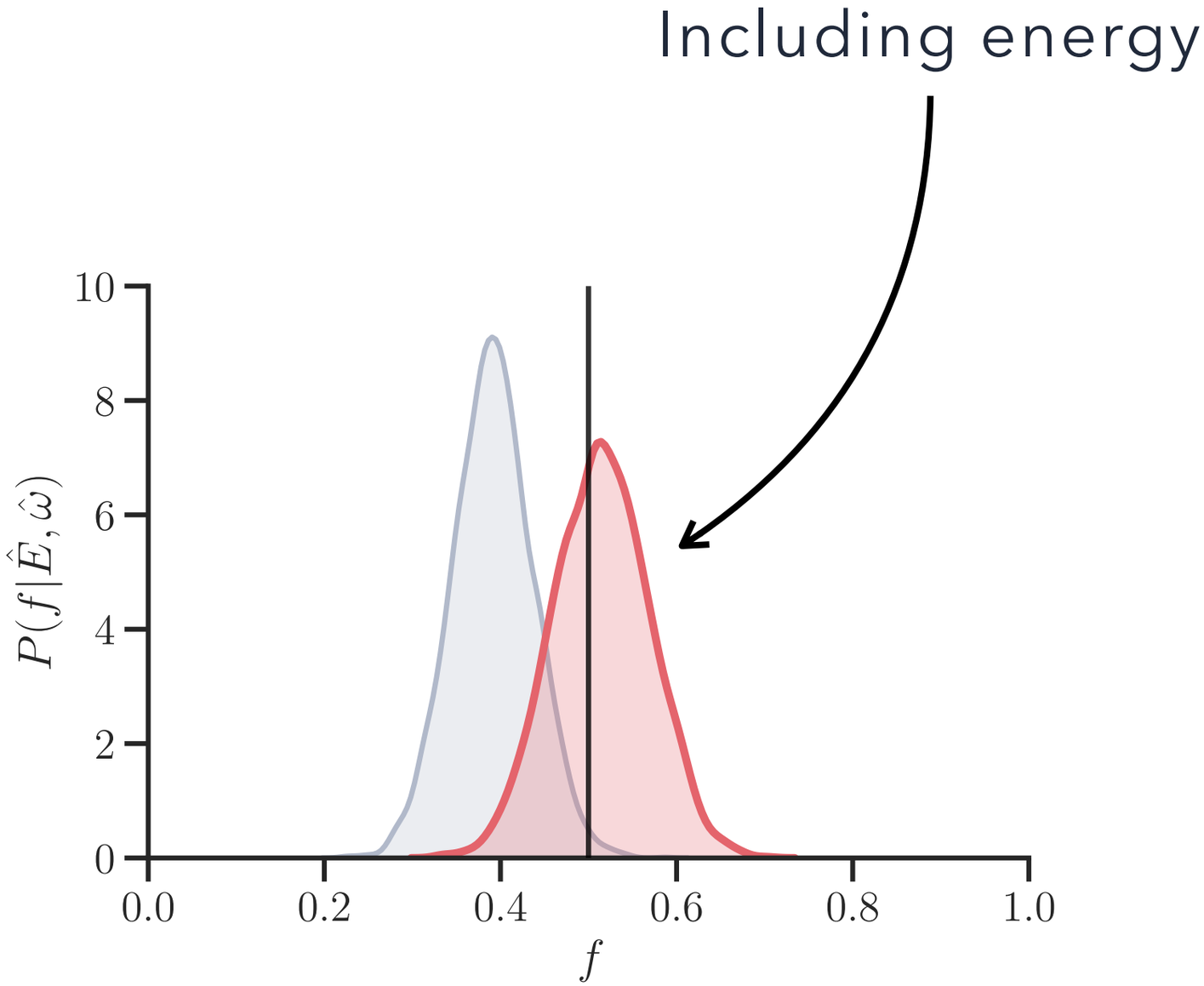
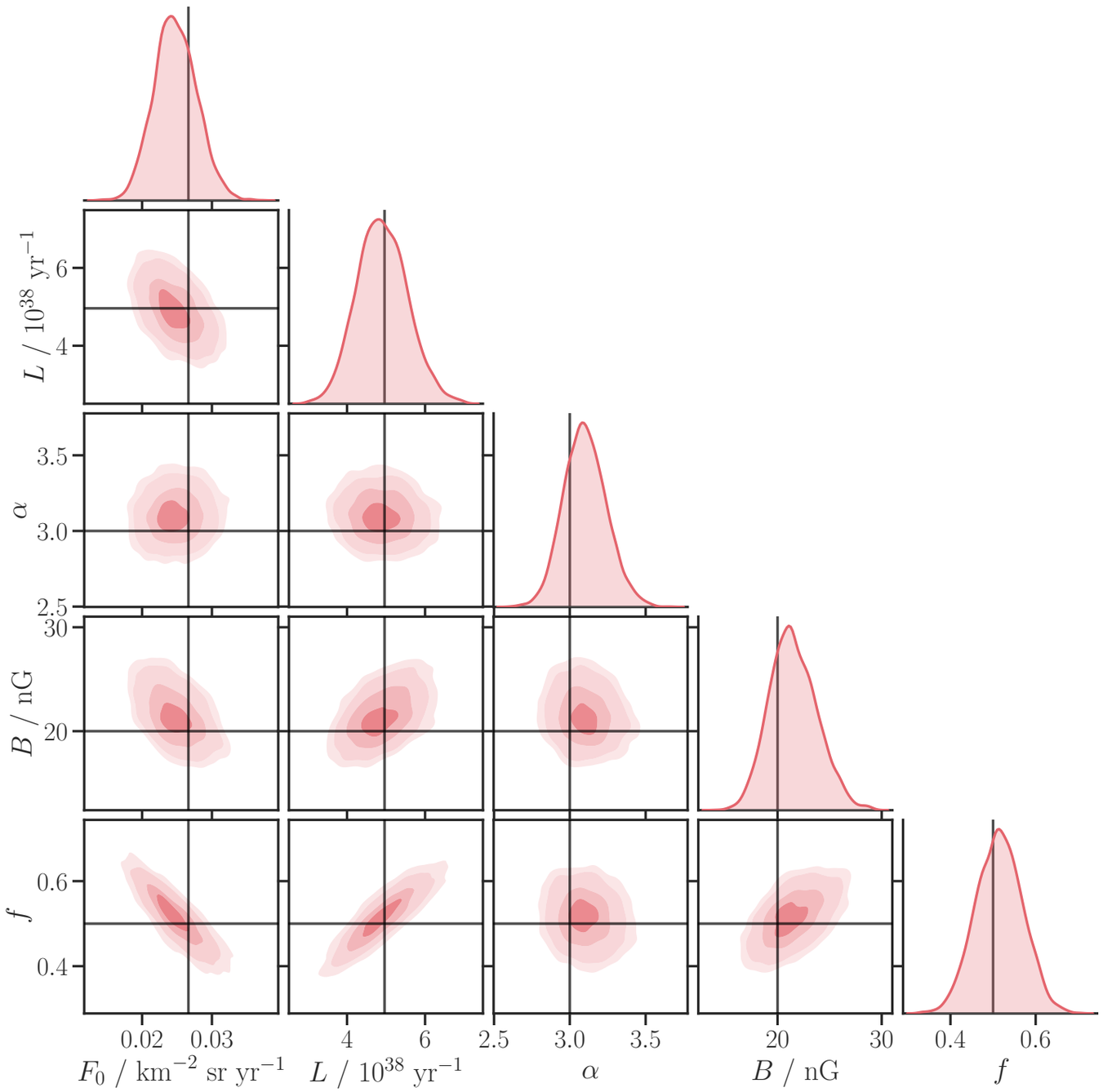
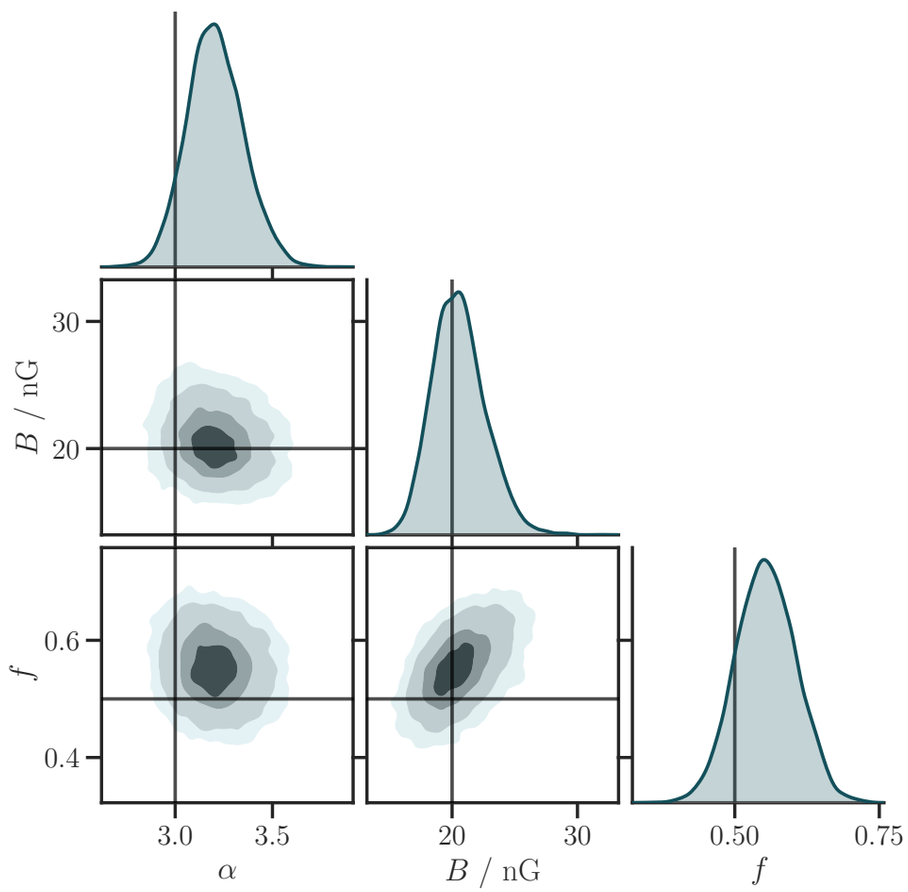


VERIFICATION

Simulation under model assumptions



CRPropa 3



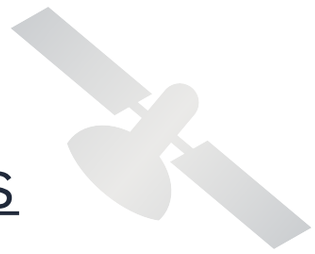
APPLICATION: REAL DATA

UHECR data

Pierre Auger Observatory results (2014)

231 UHECRs above **52 EeV**

Source catalogs

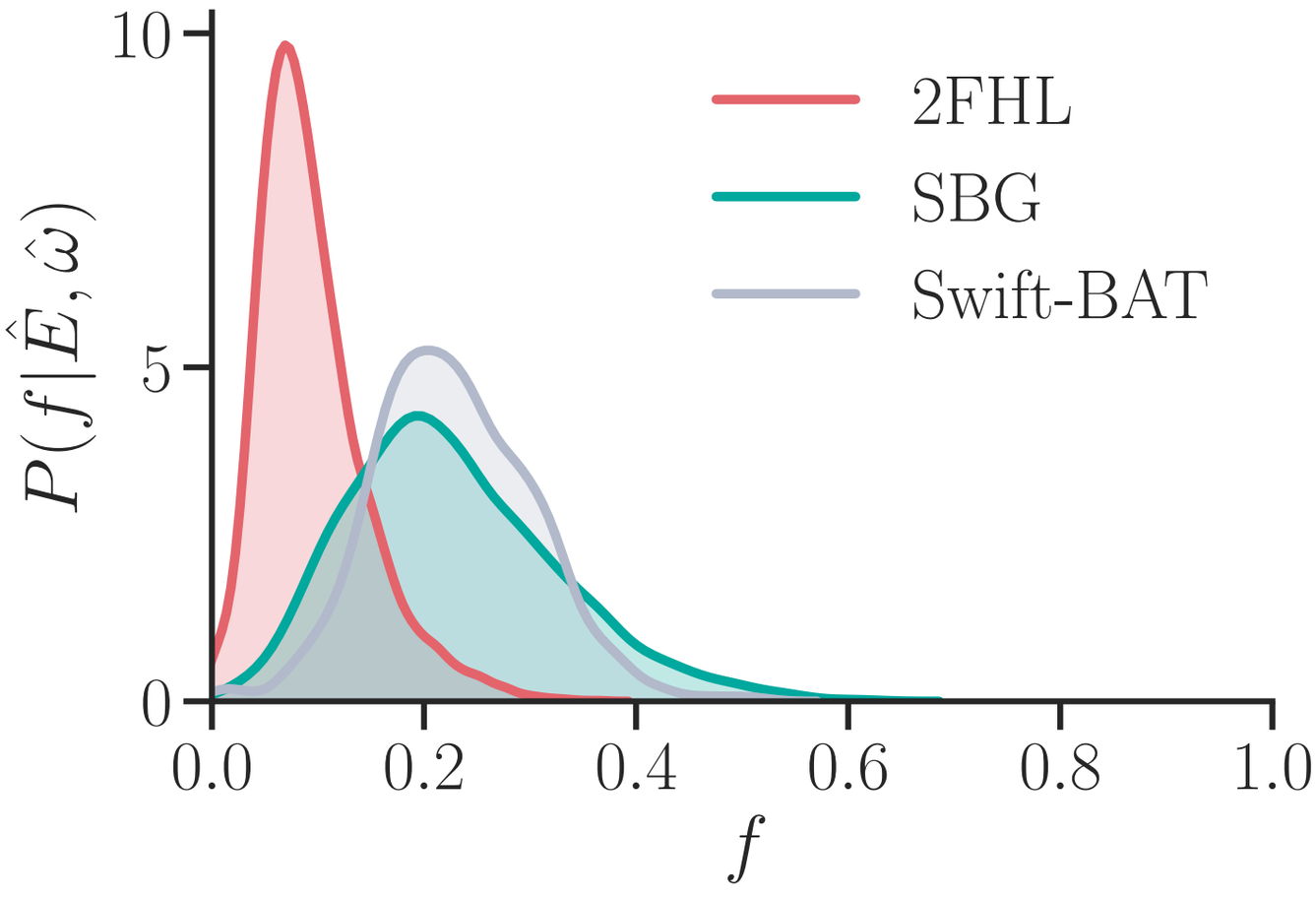


Fermi-LAT **2FHL** gamma-ray catalog

Fermi-LAT starburst galaxy search - **SBG**

Swift-BAT X-ray survey

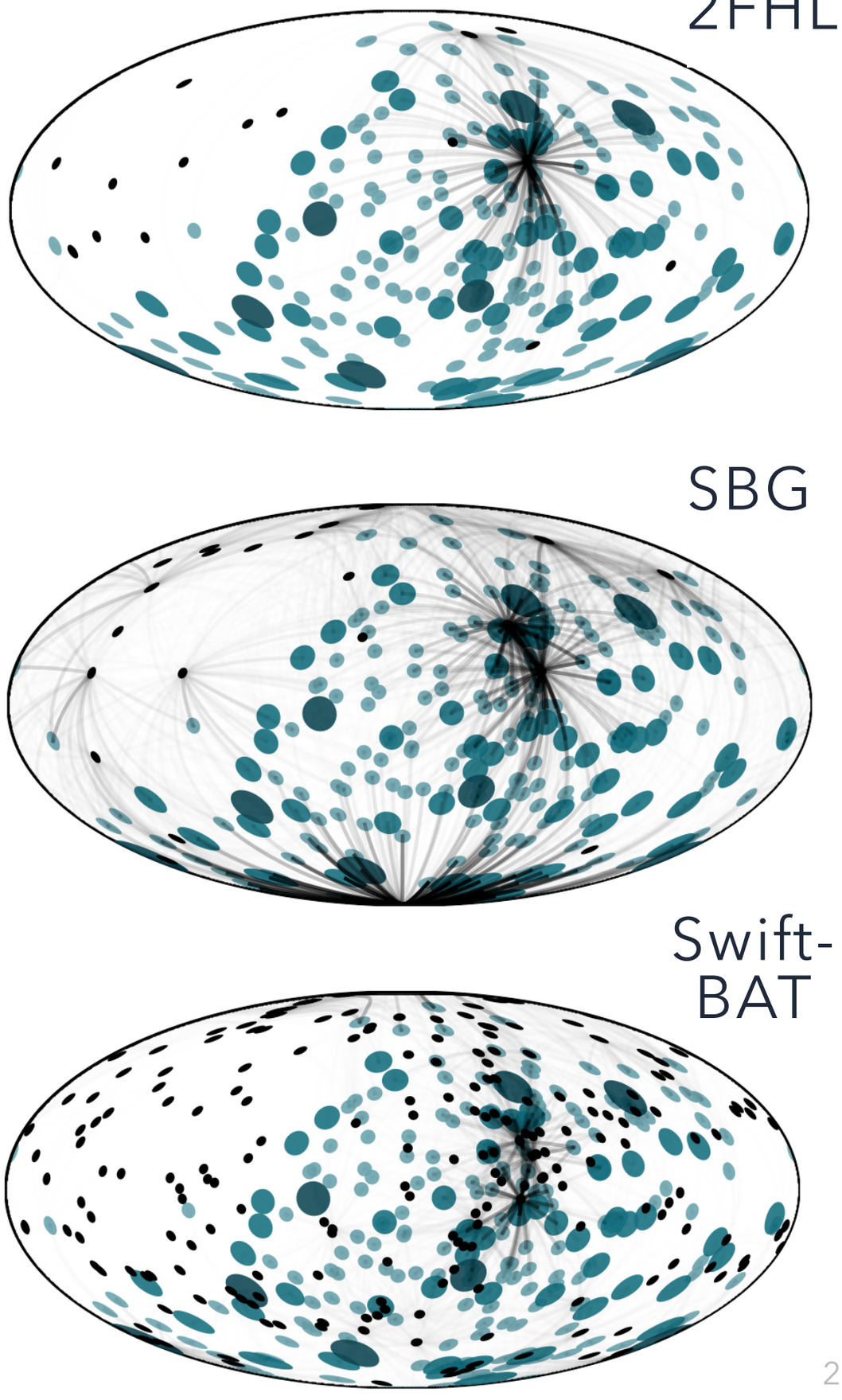
RESULTS



10-20% of UHECRs could be associated with sources

RESULTS

- Catalogs with more or nearby sources have larger associations
- Cen A, M87, M83...
- Highest energy particles are without associations!



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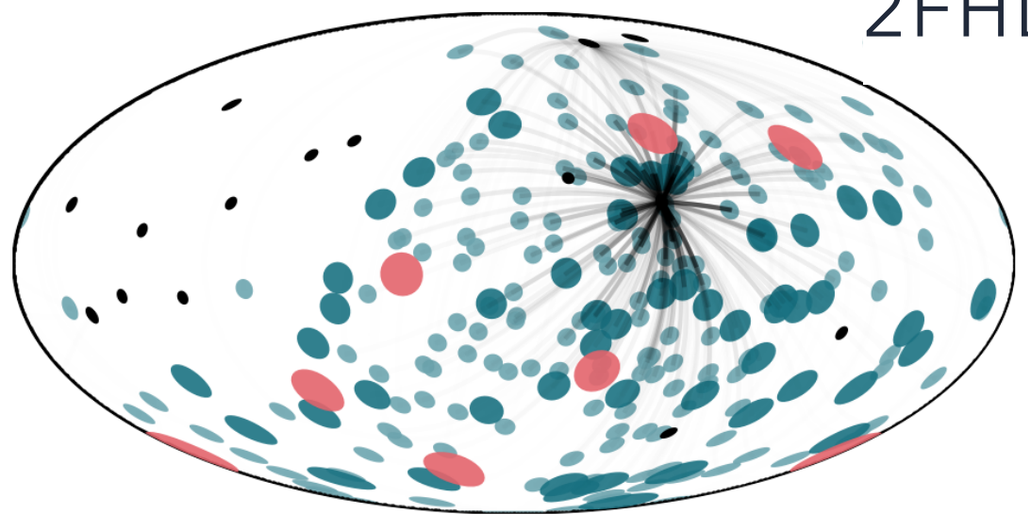

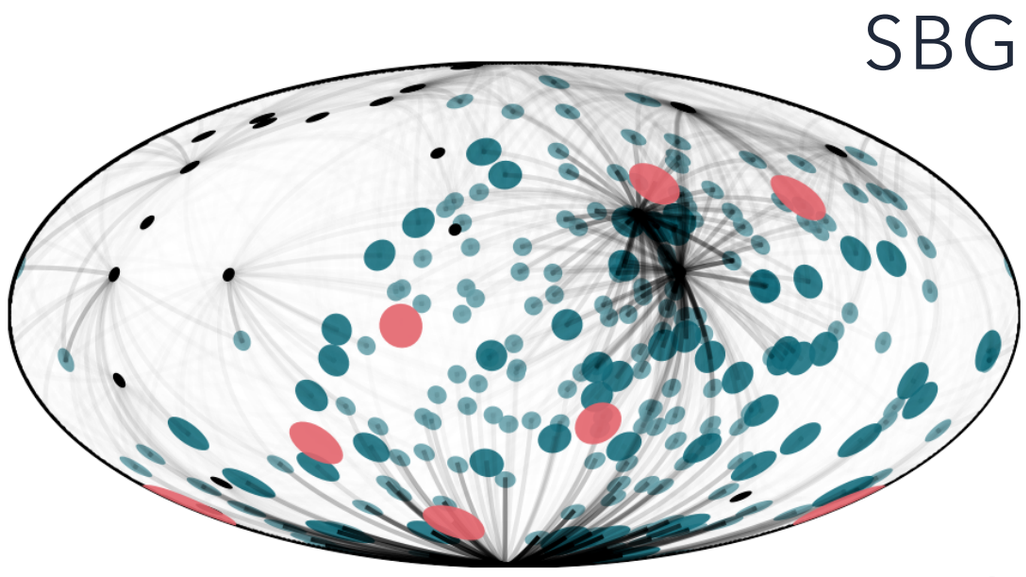

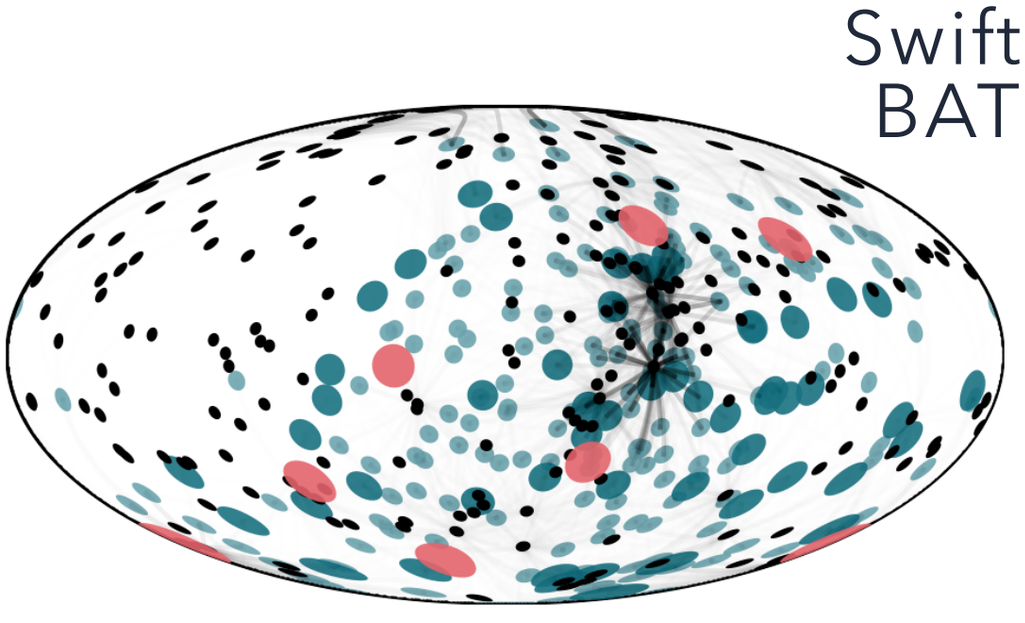

PAPER

Bonus material

Impact of using the ultrahigh-energy cosmic ray arrival energies to constrain source associations

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ABSTRACT

We present a Bayesian hierarchical model which enables a joint fit of the ultrahigh-energy cosmic ray (UHECR) energy spectrum and arrival directions within the context of a physical model for the UHECR phenomenology. In this way, possible associations with astrophysical source populations can be assessed in a physically and statistically principled manner. The importance of including the UHECR energy data and detection effects is demonstrated through simulation studies, showing that the effective GZK horizon is significantly extended for typical
verify the ability of the model to fit and recover physical
ons. Finally, the model is used to assess the fraction of the
HECRs detected by the Pierre Auger Observatory which
FHL catalogue, a set of starburst galaxies, and *Swift*-BAT
hard X-ray sources. We find association fractions of $9.5^{+2.4}_{-5.9}$, $22.7^{+6.6}_{-12.4}$, and $22.8^{+6.6}_{-8.0}$ per cent

arXiv:1811.06464 - Now with code!

CONCLUSION

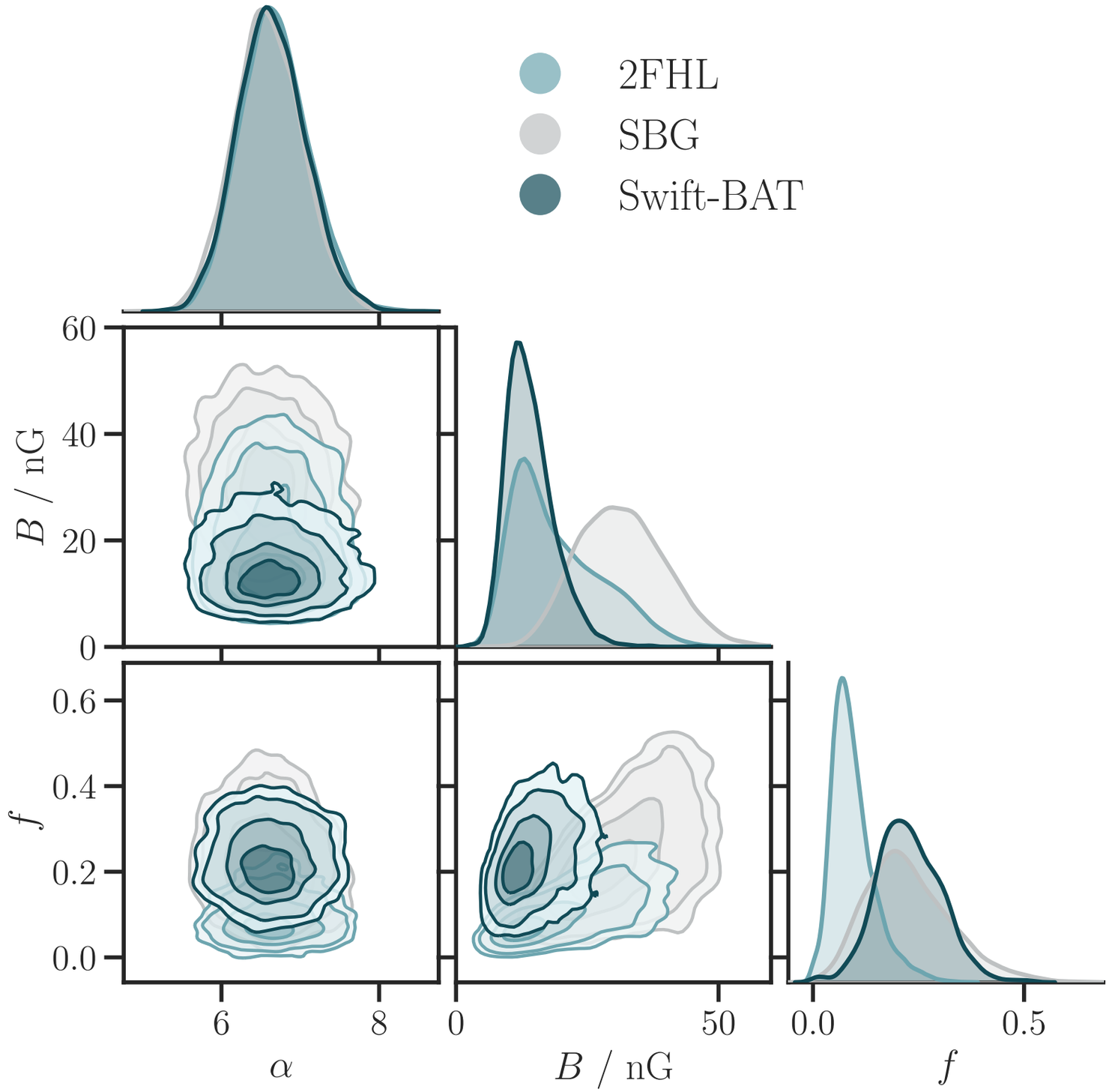
- Including energies is **more informative** and **removes unphysical associations**

- Complementary to other methods

- The **composition** data can also be included!

- Same concept can be extended to **multiple messengers**
    - Neutrinos and cosmic rays
    - Neutrino population constraints


THANK
YOU!


2FHL
SBG
Swift-BAT
60
40
20
0
B / nG
0.6
0.4
0.2
0.0
f
6
8
α
0
50
B / nG
0.0
0.5
f