CONNECTING UHECR THEORY TO DATA WITH HIERARCHICAL MODELS

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MOTIVATION

- Description of UHECR acceleration, propagation and detection requires **many parameters**

- Models exhibit **non-linearity** and **degeneracy**

- There are many **uncertainties**

HIERARCHICAL MODELS

- Description of UHECR acceleration, propagation and detection requires many parameters

  Organise the parameters into a hierarchy

- Models exhibit non-linearity and degeneracy

  Efficiently evaluate expectation values

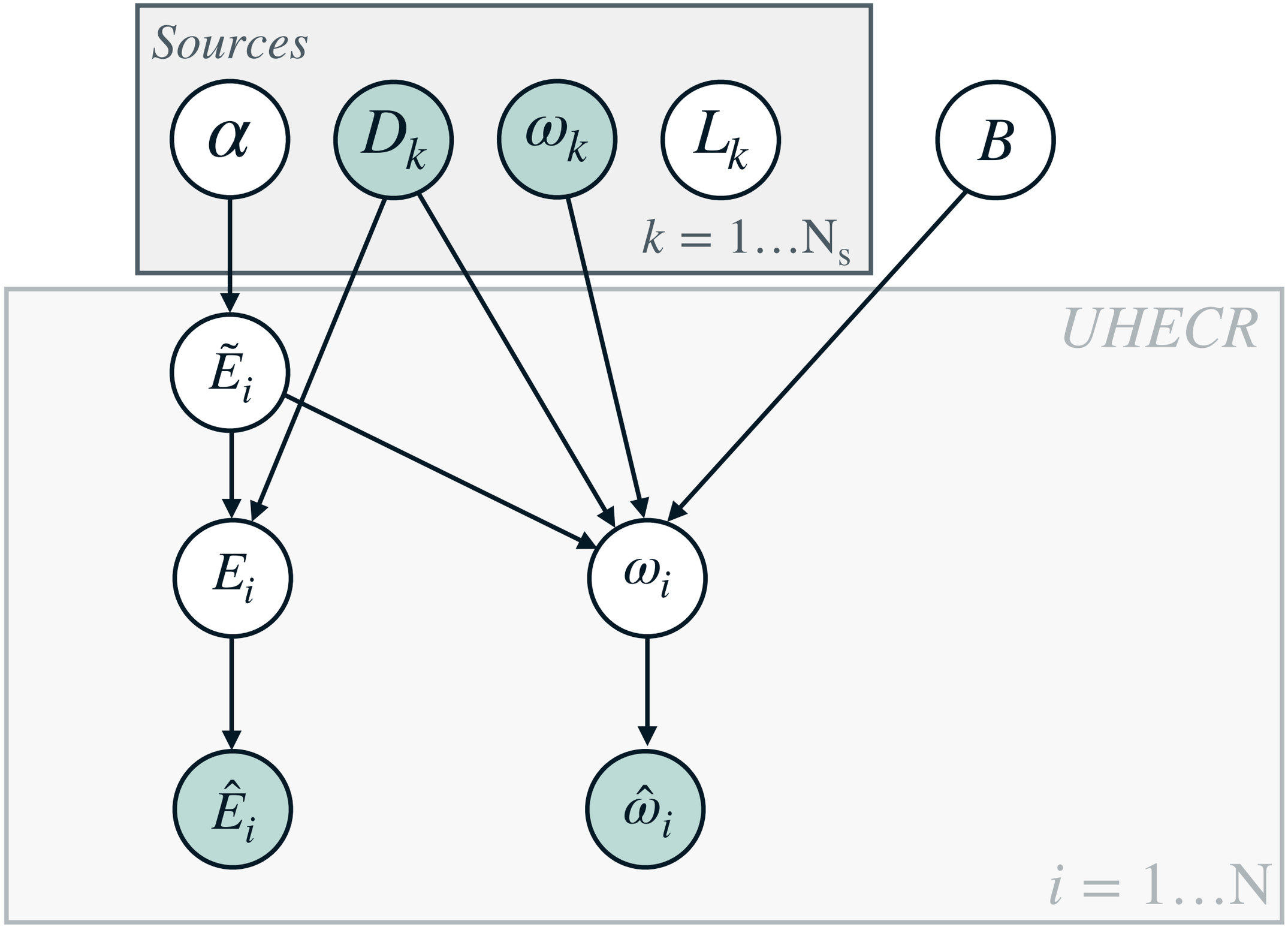
- There are many uncertainties

  Parameterise the uncertainties

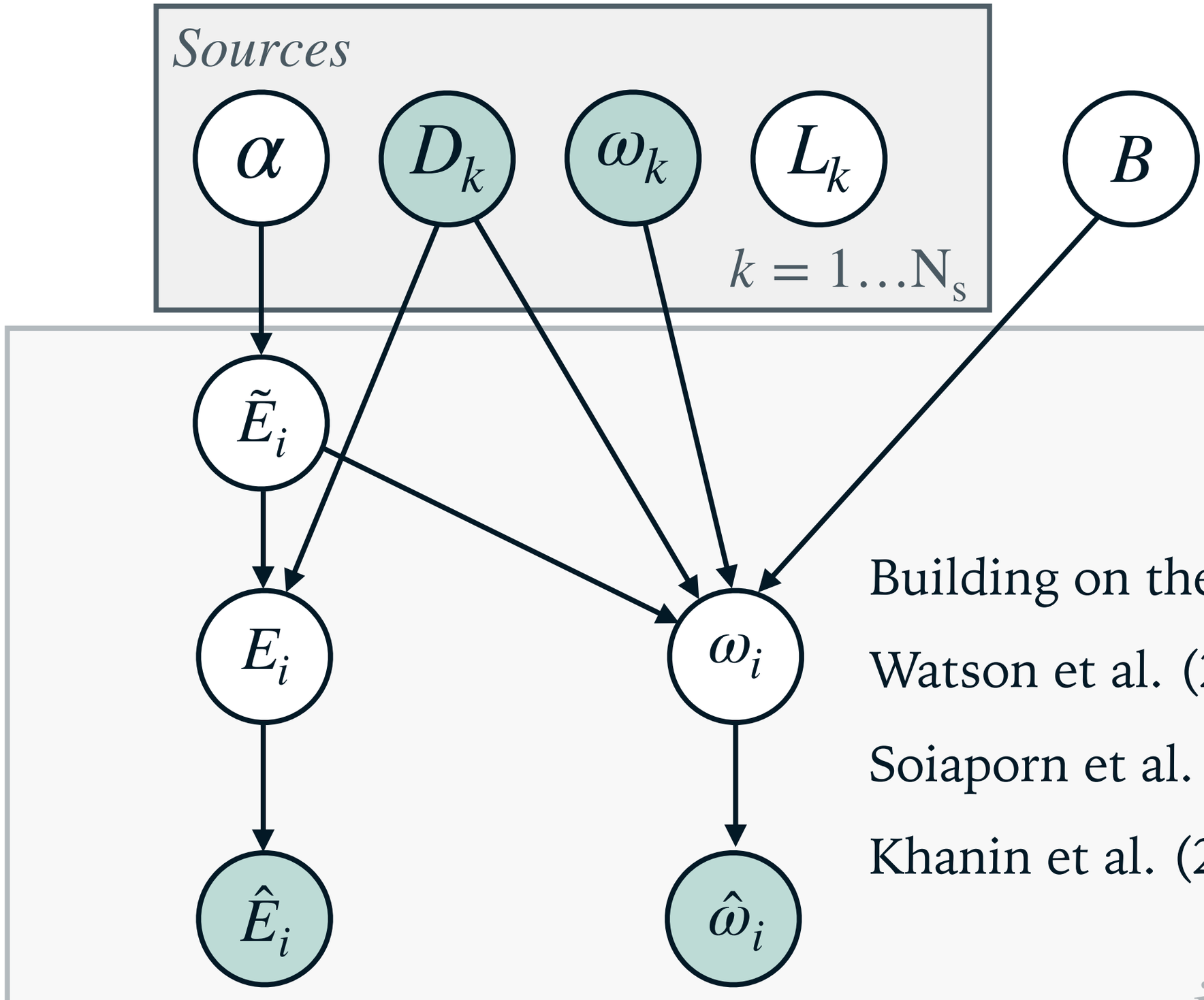
Hierarchical modelling provides an **extendable** framework which can incorporate more of the available information from both **data** and **theory**.

Example: UHECR energies and arrival directions

THE MODEL


Sources
α
D_k
ω_k
L_k
$k = 1 \ldots \mathrm{N_s}$
B
UHECR
$\tilde{E}_i$
E_i
$\hat{E}_i$
ω_i
$\hat{\omega}_i$
$i = 1 \ldots \mathrm{N}$

THE MODEL



Building on the work of:

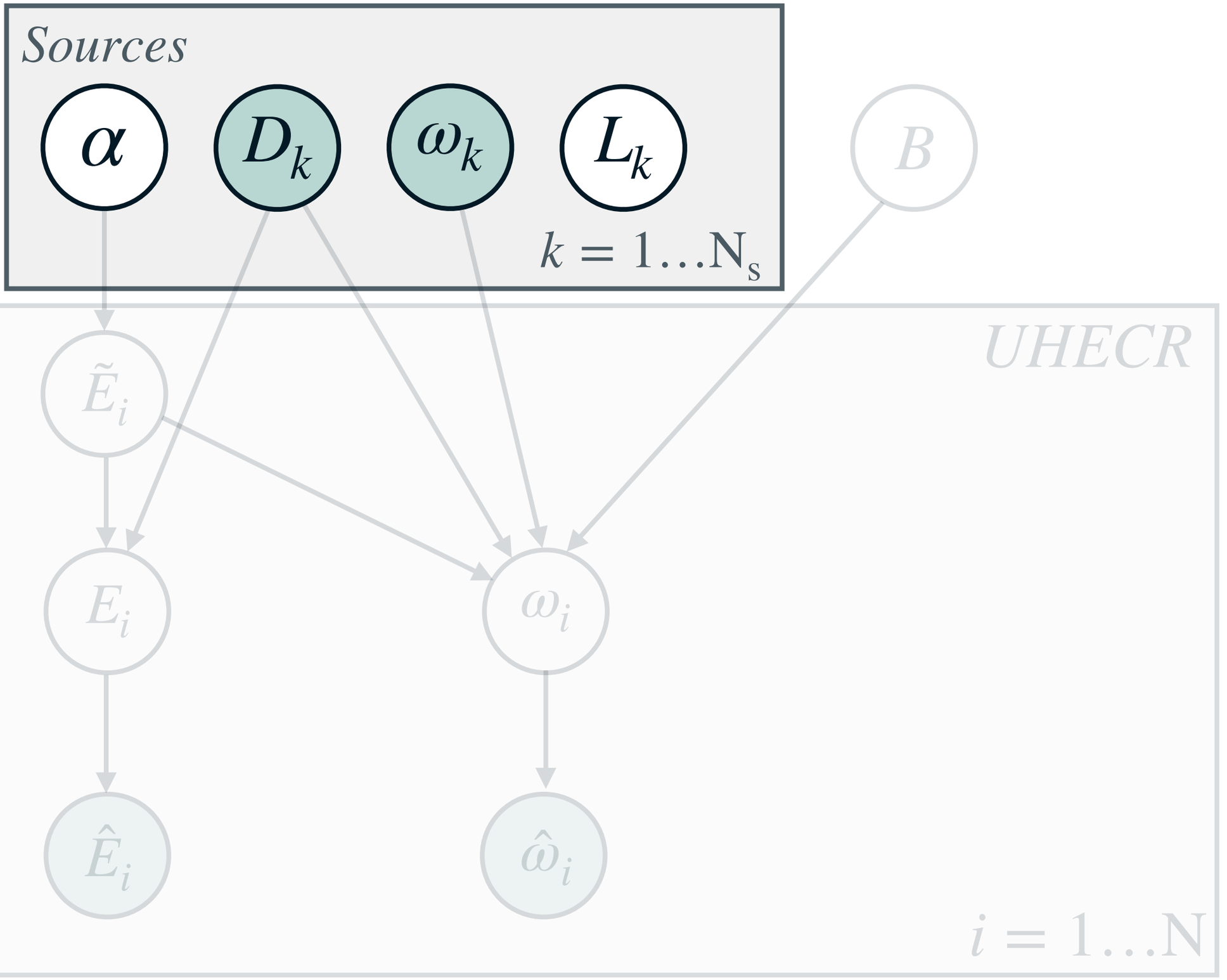
Watson et al. (2012)

Soiaporn et al. (2012)

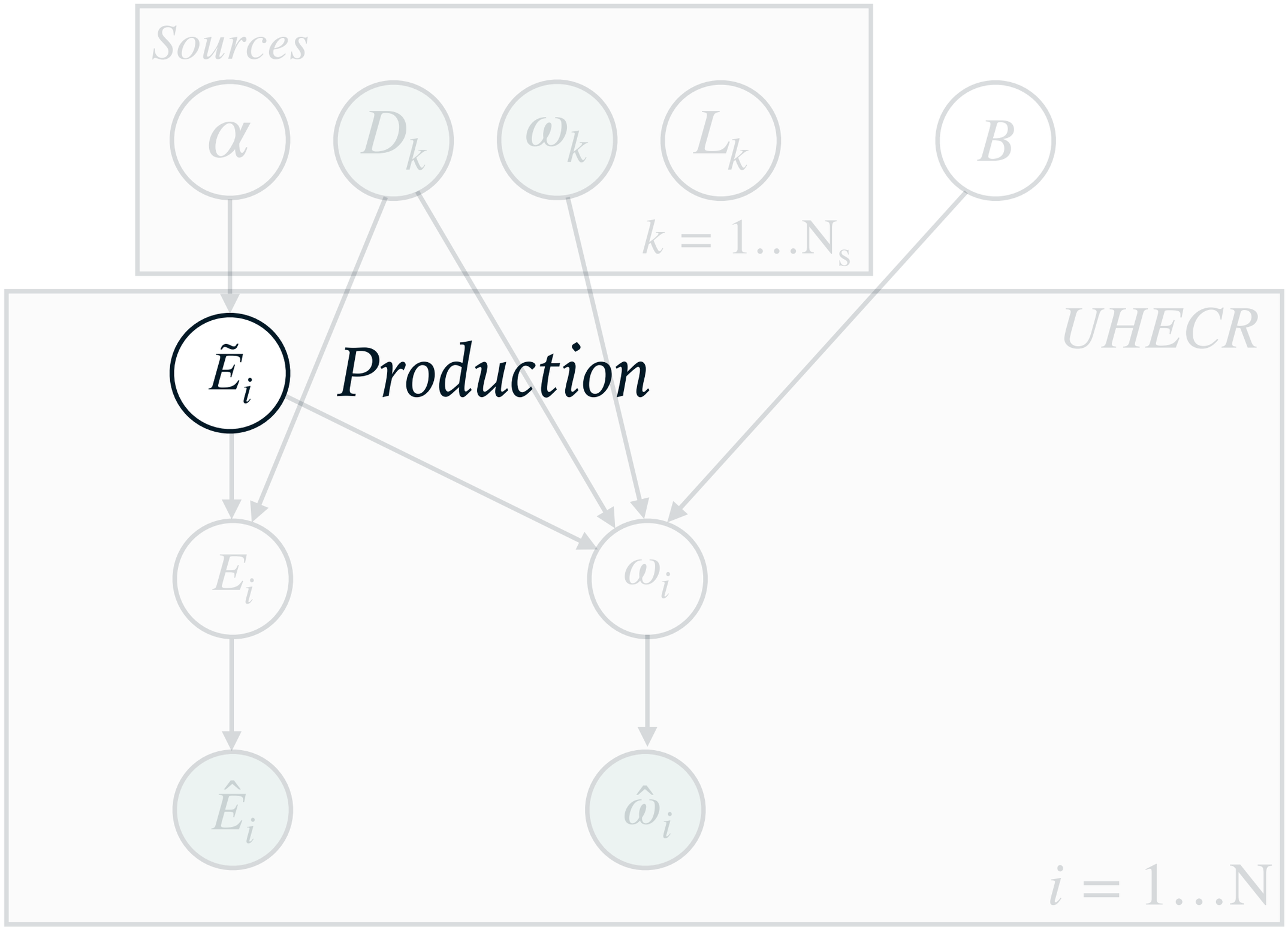
Khanin et al. (2016)

THE MODEL

Sources



THE MODEL


Sources
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D_k
ω_k
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B
UHECR
$\tilde{E}_i$
Production
E_i
ω_i
$\hat{E}_i$
$\hat{\omega}_i$
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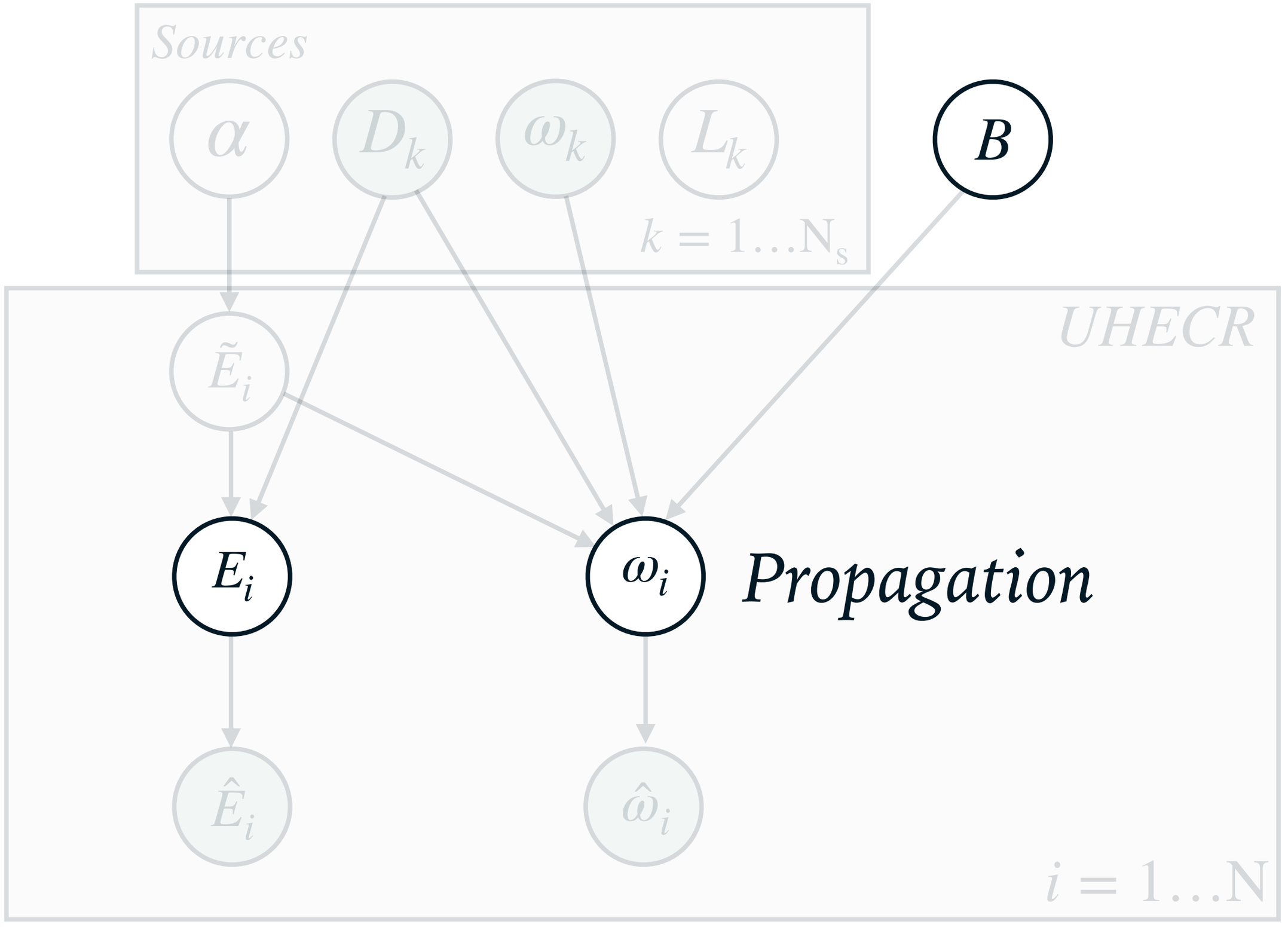
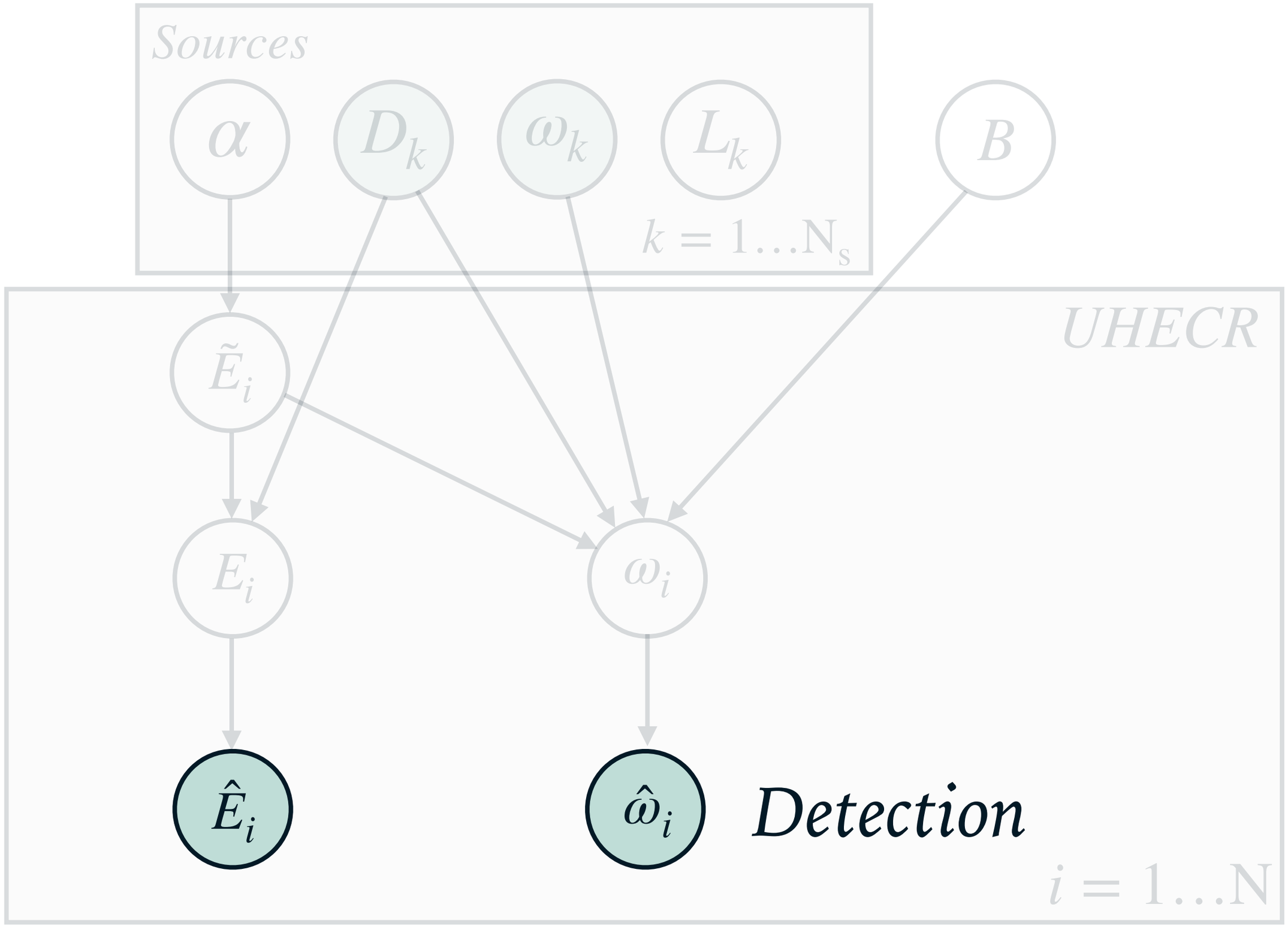
THE MODEL


Sources
α
D_k
ω_k
L_k
$k = 1 \ldots \mathrm{N_s}$
B
UHECR
$\tilde{E}_i$
E_i
ω_i
Propagation
$\hat{E}_i$
$\hat{\omega}_i$
$i = 1 \ldots \mathrm{N}$

THE MODEL


Sources
α
D_k
ω_k
L_k
$k = 1 \ldots N_s$
B
UHECR
$\tilde{E}_i$
E_i
ω_i
$\hat{E}_i$
$\hat{\omega}_i$
Detection
$i = 1 \ldots N$

APPROXIMATIONS

- Protons

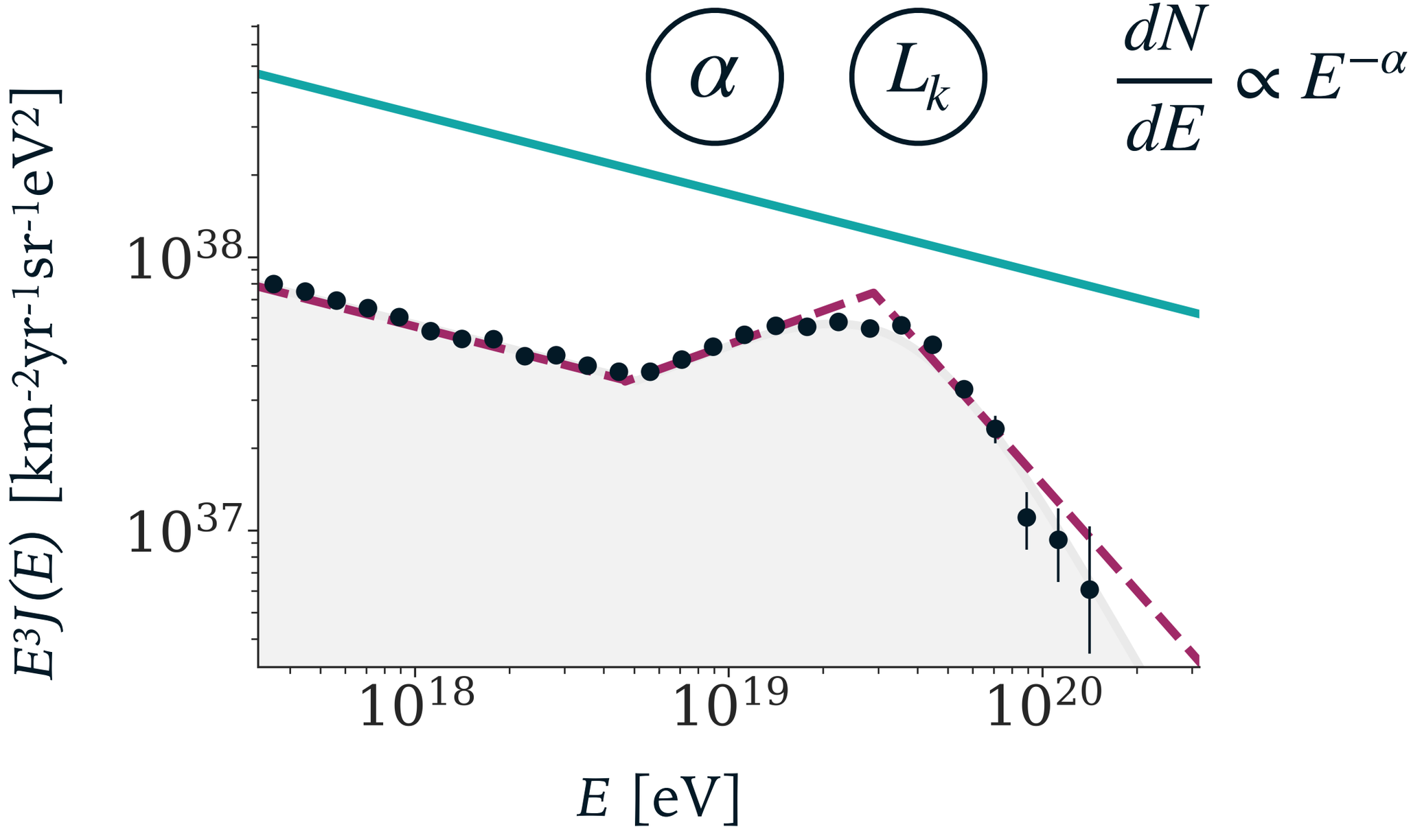
- Injection spectrum

- Continuous energy loss approximation

- Small angle magnetic deflections

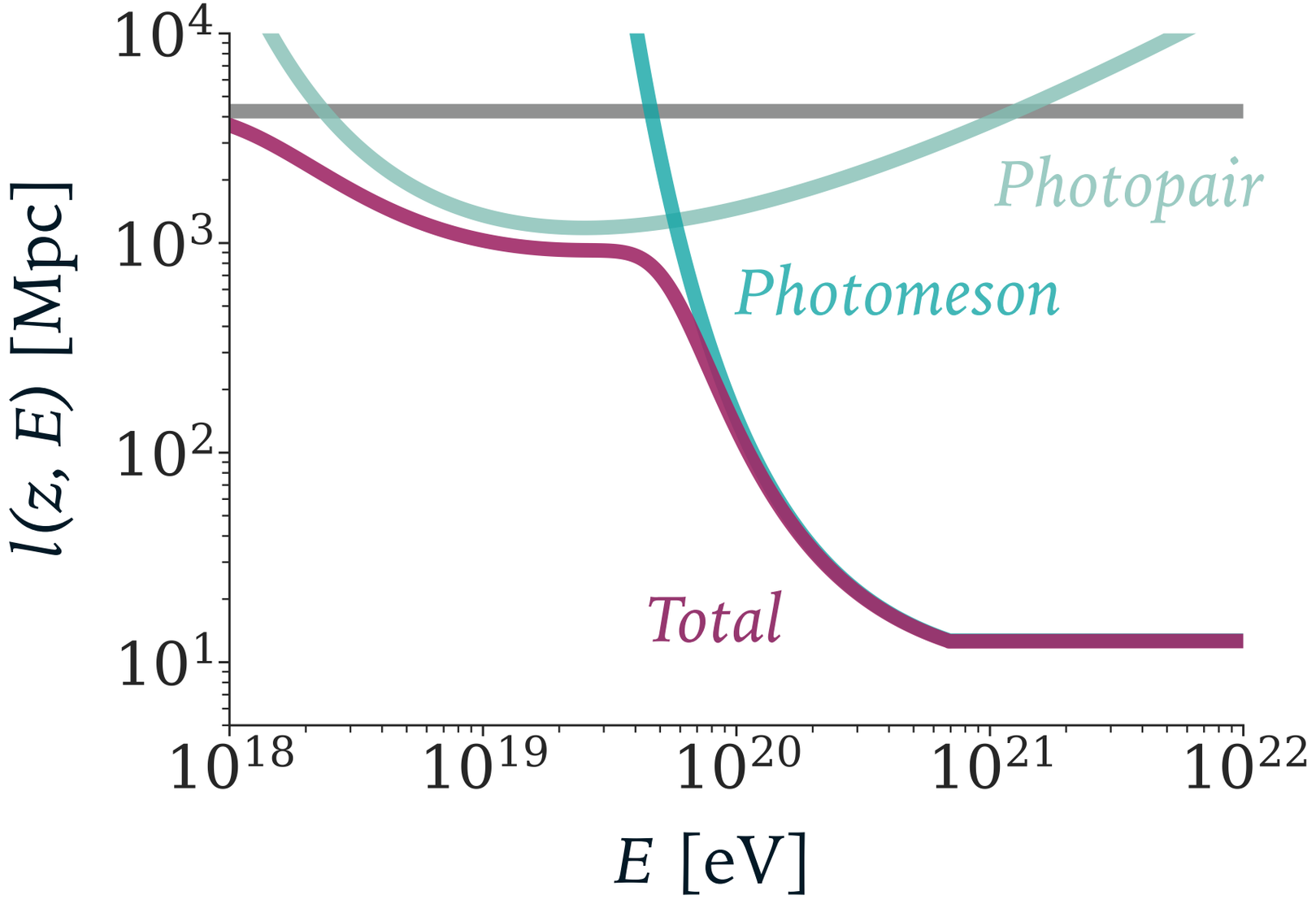
APPROXIMATIONS

- Injection spectrum



APPROXIMATIONS

- Continuous energy loss



$$\frac{dE}{dr} = -\frac{E}{l(z, E)}$$

Berezinsky and Grigor'eva (1988), Chodorowski et al. (1992), Anchordorqui et al. (1997),

De Domenico & Insolia (2012),

APPROXIMATIONS

- Small angle magnetic deflections

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

Achterberg et al. (1999), Harari et al. (2002)

APPLICATION

Under the given assumptions, we can learn from the data.

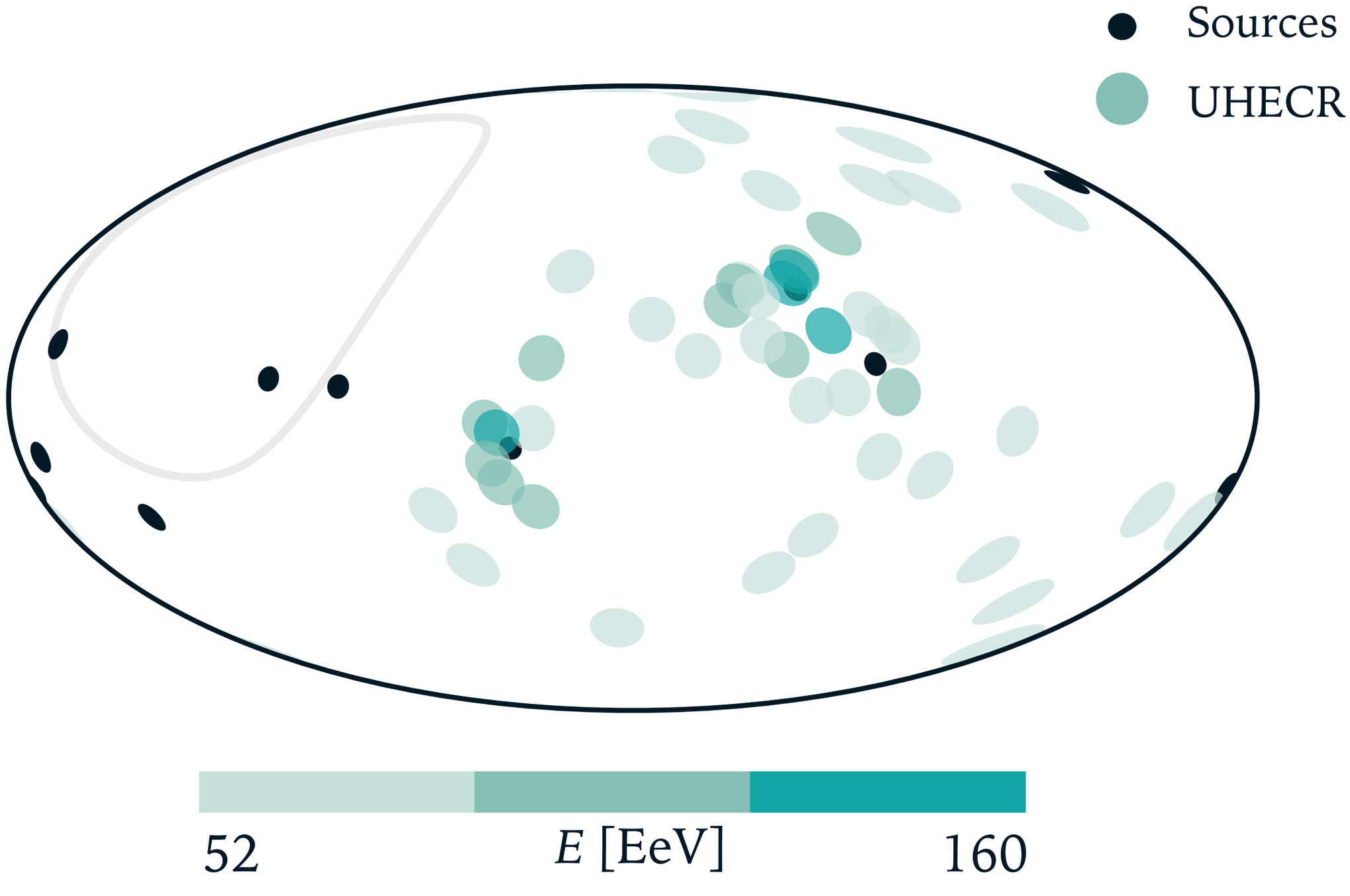
For a given:

- Candidate source catalog
- UHECR dataset and detector

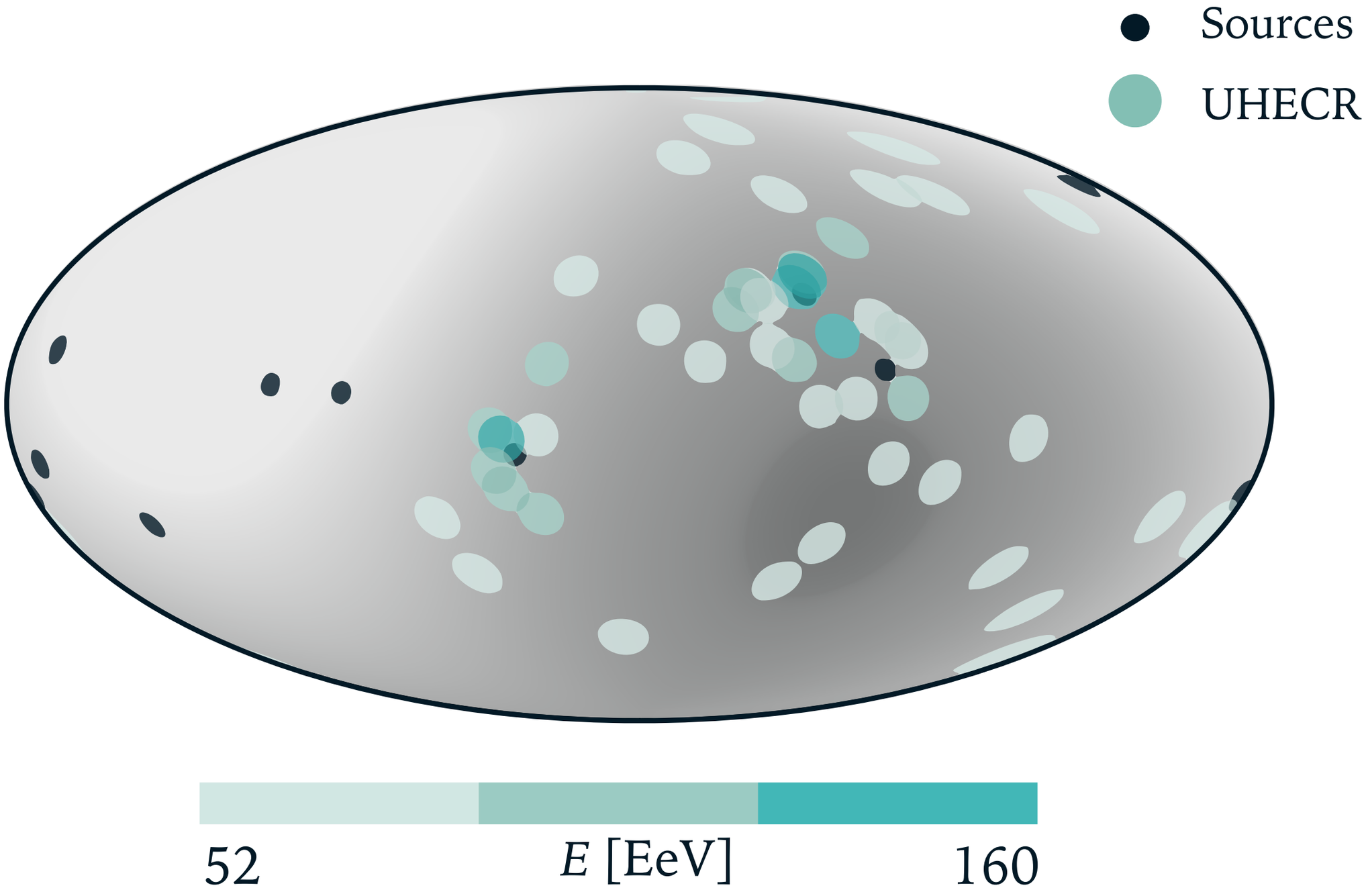
A model fit gives probability distributions for:

- The **fraction** of UHECR associated with the catalog f
- The source **spectral index** and **luminosity** α L_k
- The RMS **magnetic field** strength B
- The association of each UHECR with individual sources λ_i
- *All other parameters, conditioned on the data*

SIMULATIONS

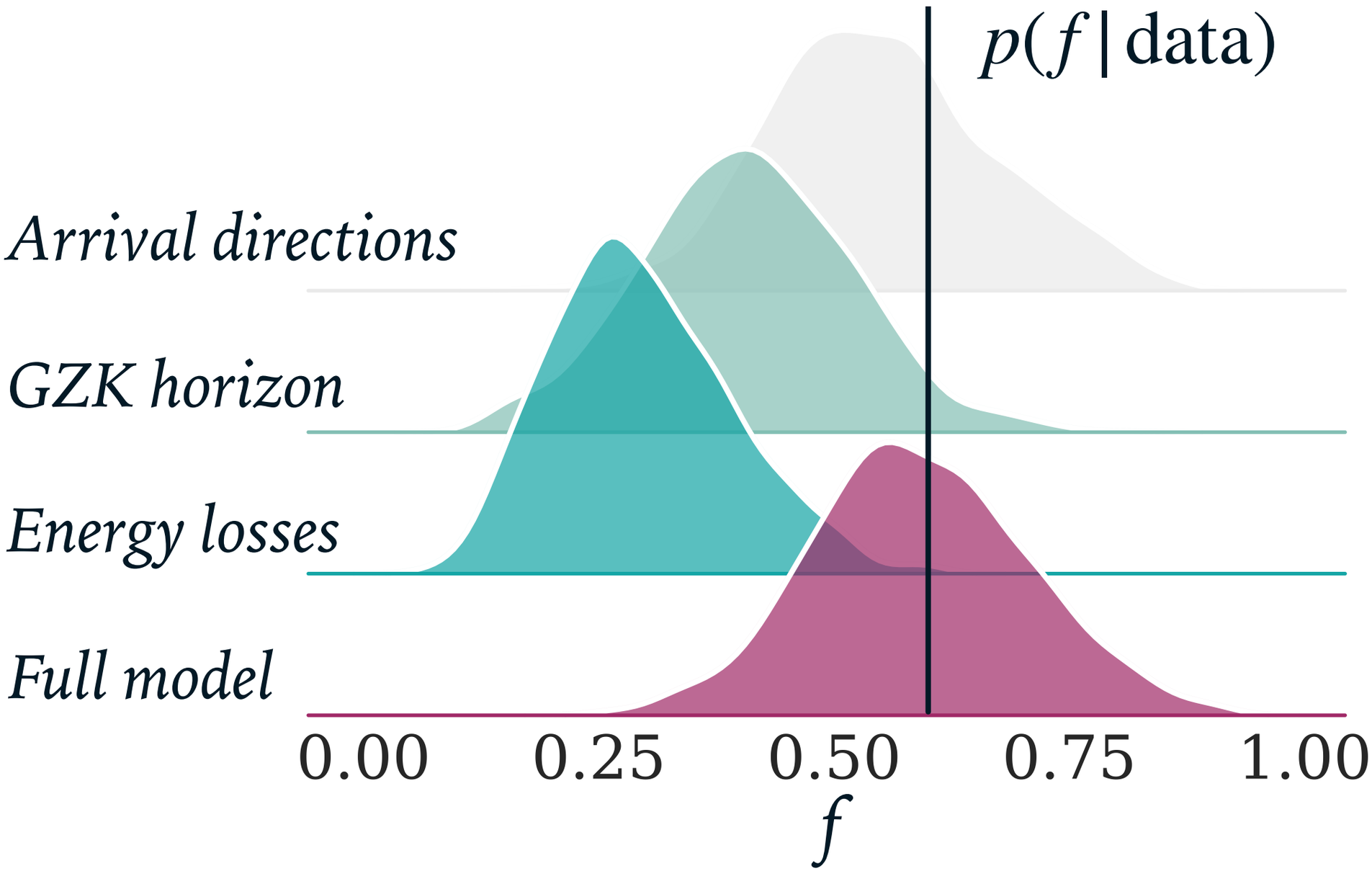


SIMULATIONS



APPLICATION

By including the **energies** into the model, we can recover the input associated fraction, $f = 0.6$.



APPLICATION

UHECR data:

Pierre Auger Observatory data (Auger Collaboration, 2014)

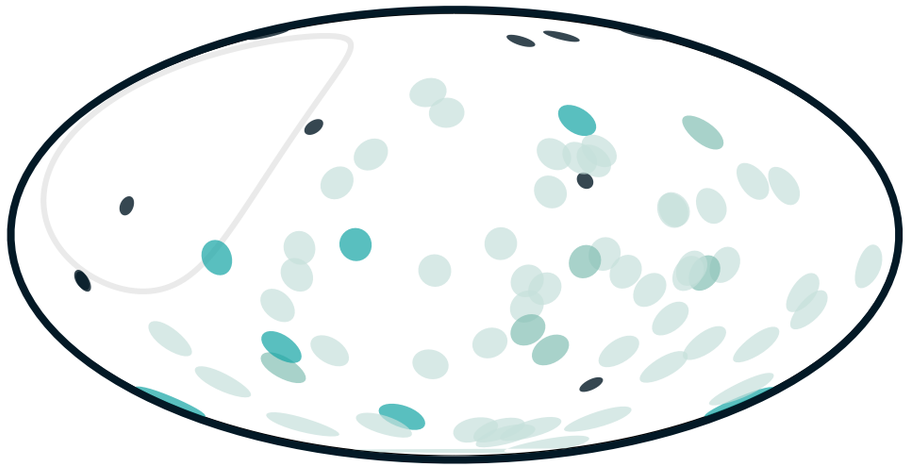
Candidate source catalogs:

- Fermi-LAT 2FHL (Ackermann et al., 2016)
- Fermi-LAT starburst galaxy search (Ackermann et al., 2012)
- Swift BAT survey (Oh et al., 2018)

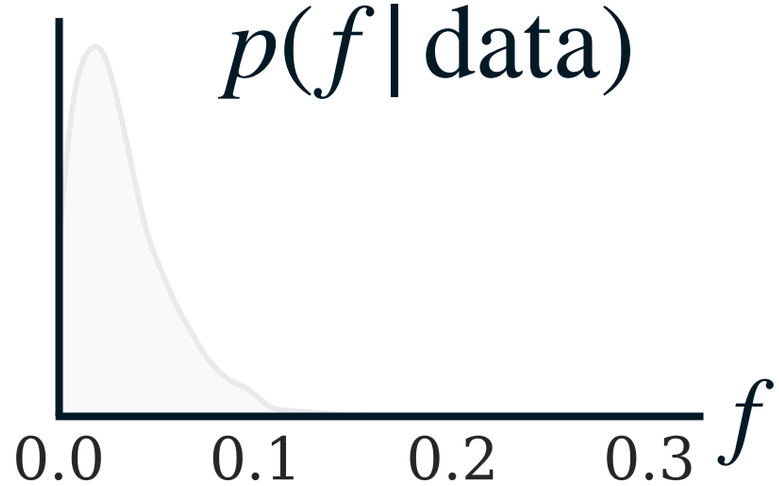
Following Auger Collaboration (2018).

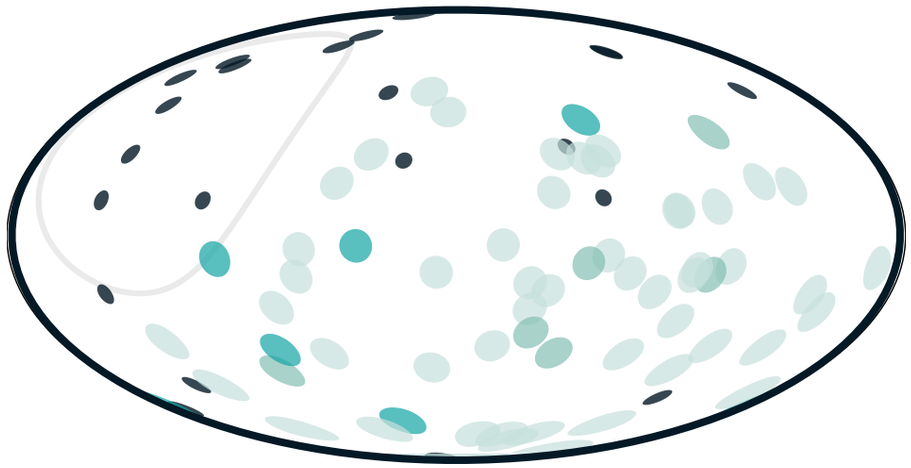
Sources within **150 Mpc** and UHECR above **70 EeV**.

RESULTS

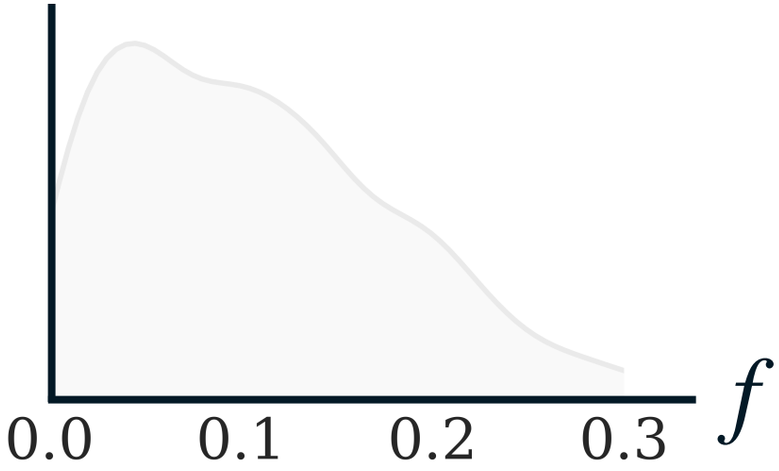


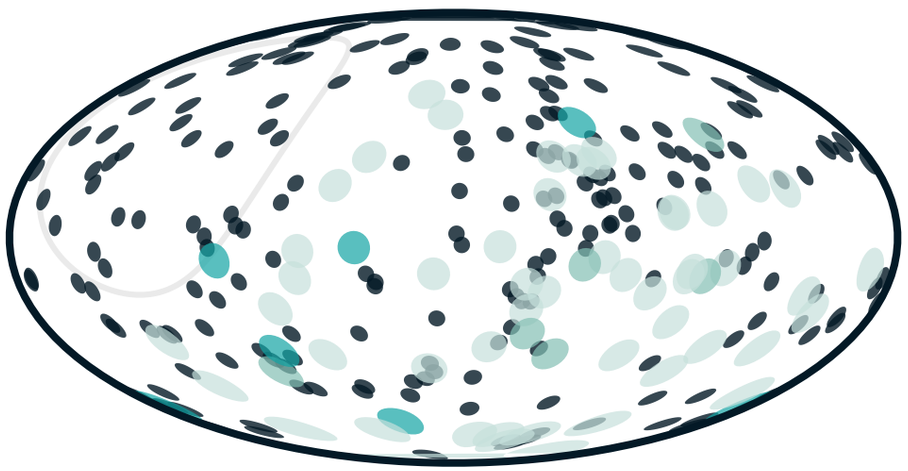
2FHL



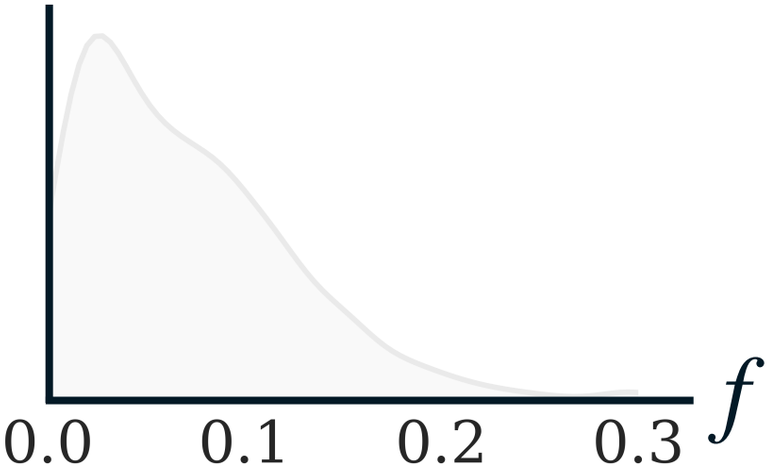


SBG

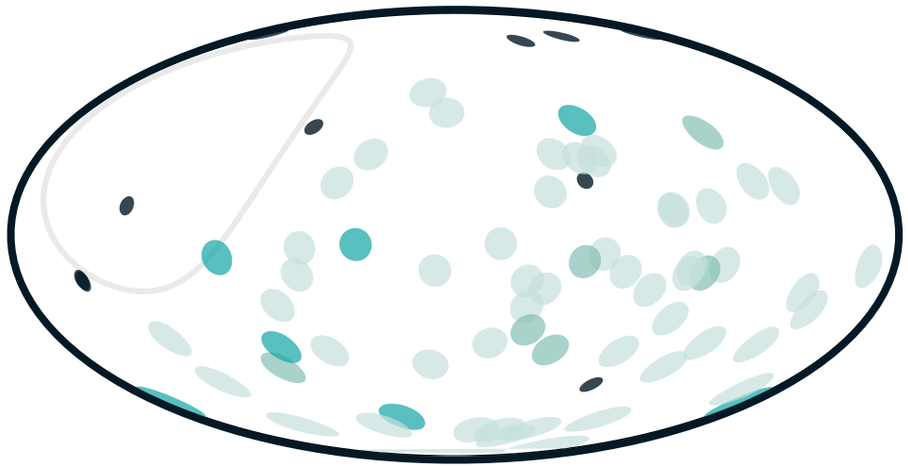




Swift BAT



RESULTS



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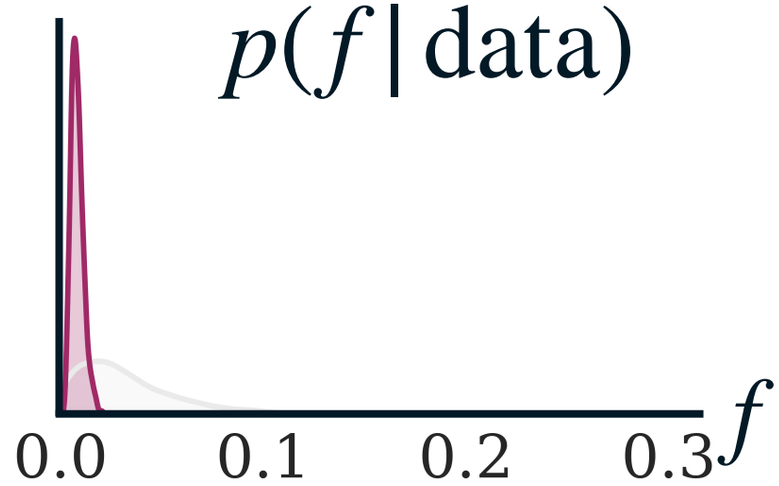

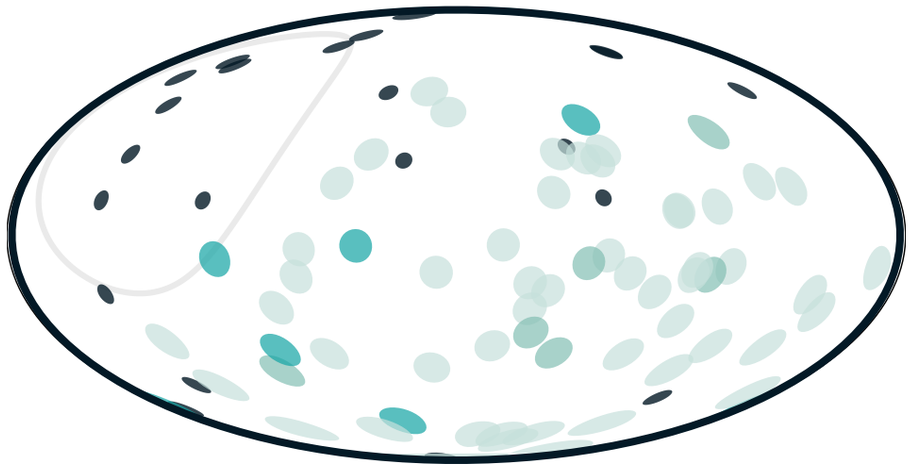

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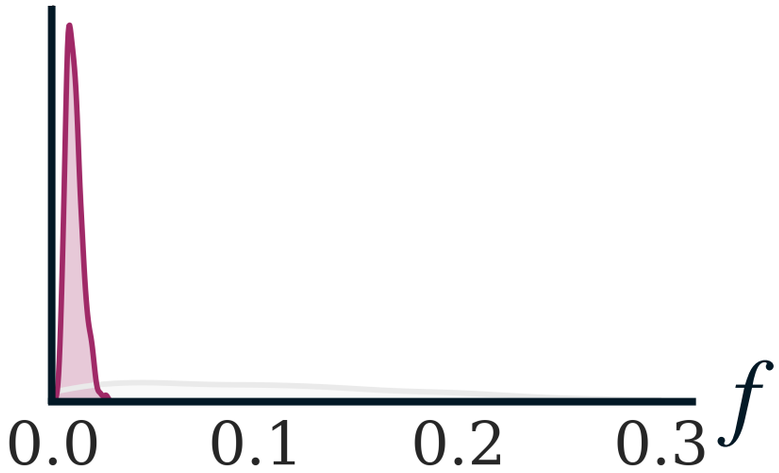

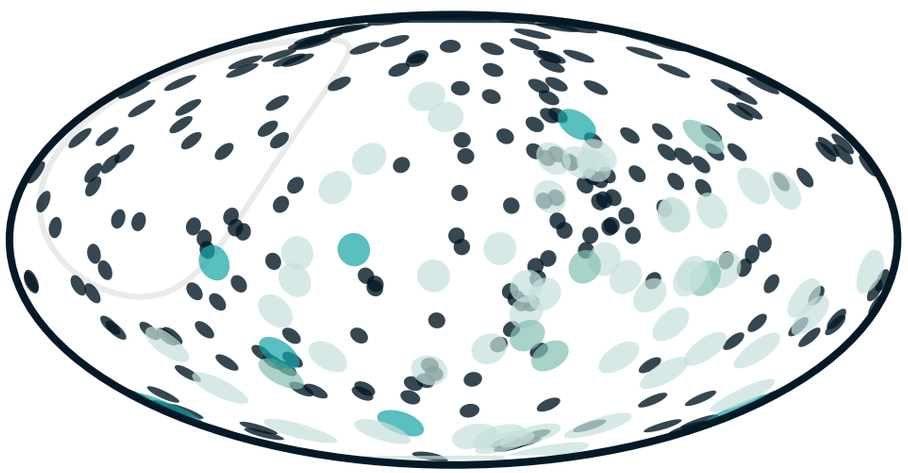

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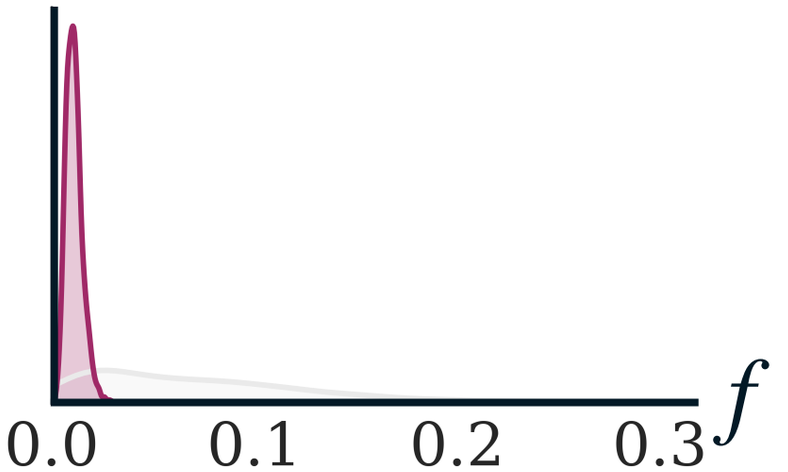

Arrival direction

Including energy

CONCLUSIONS

1. Including energies into the fit is more **constraining** and more **informative**
2. A simple model with protons **cannot** represent the observed data
3. The framework presented is extendable and **composition/X_{max}** data could be included
4. Similar concepts could be applied to multi-messenger data