Combined fit of UHECRs with jetted AGN

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

Pavlo Plotko

CRpropa 2023

25.09.2023

plotkopavlo.com
pavlo.plotko@desy.de

HELMHOLTZ

DESY.

Who am I?

Xavier Rodrigues

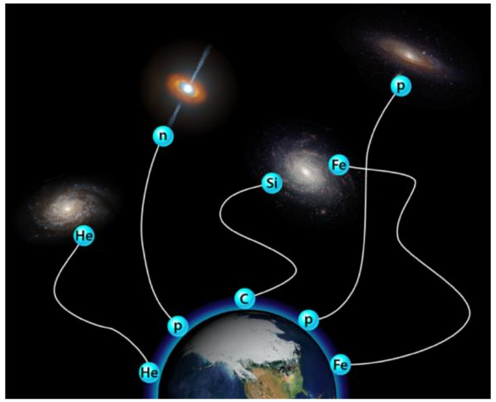
Arjen van Vliet

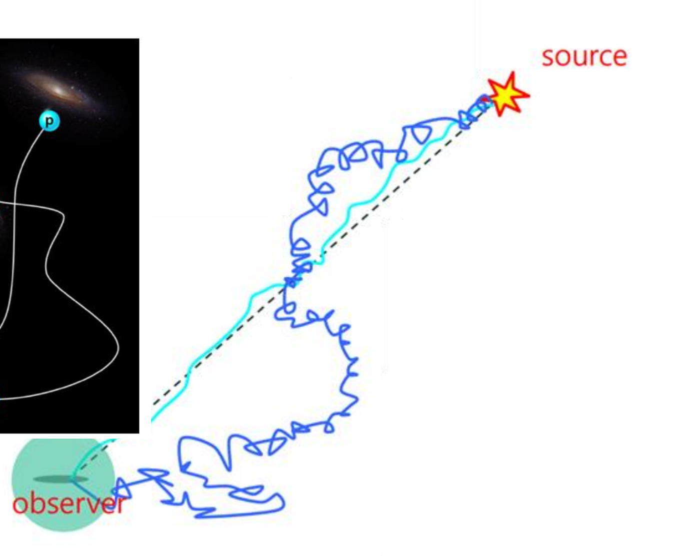
Walter Winter

INTERNATIONAL COSMIC DAY

Astronomy Tournament
Astrophysics Olympiad
Astrophysics Conference

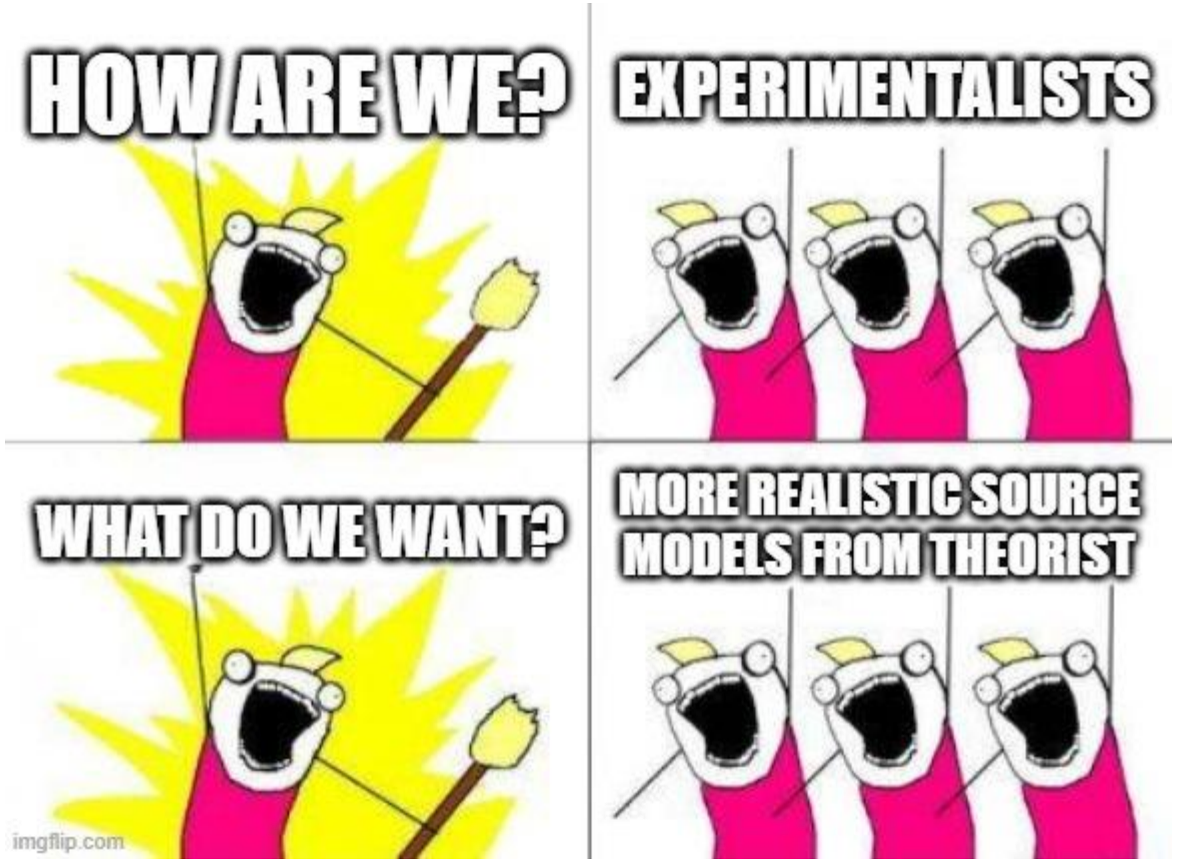
DESY-Ukraine Winter School





(1) From Denise Boncioli, 2022 Varenna

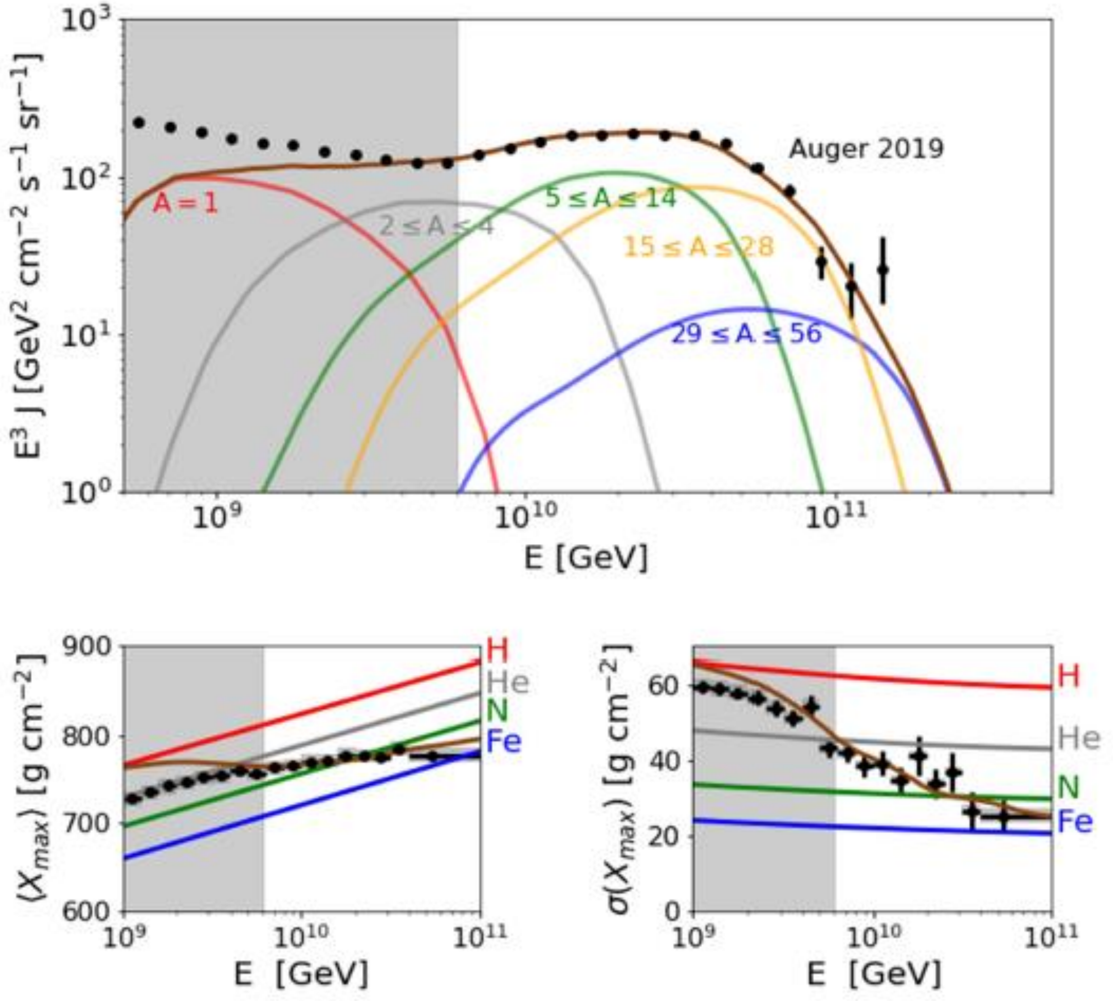
Motivation

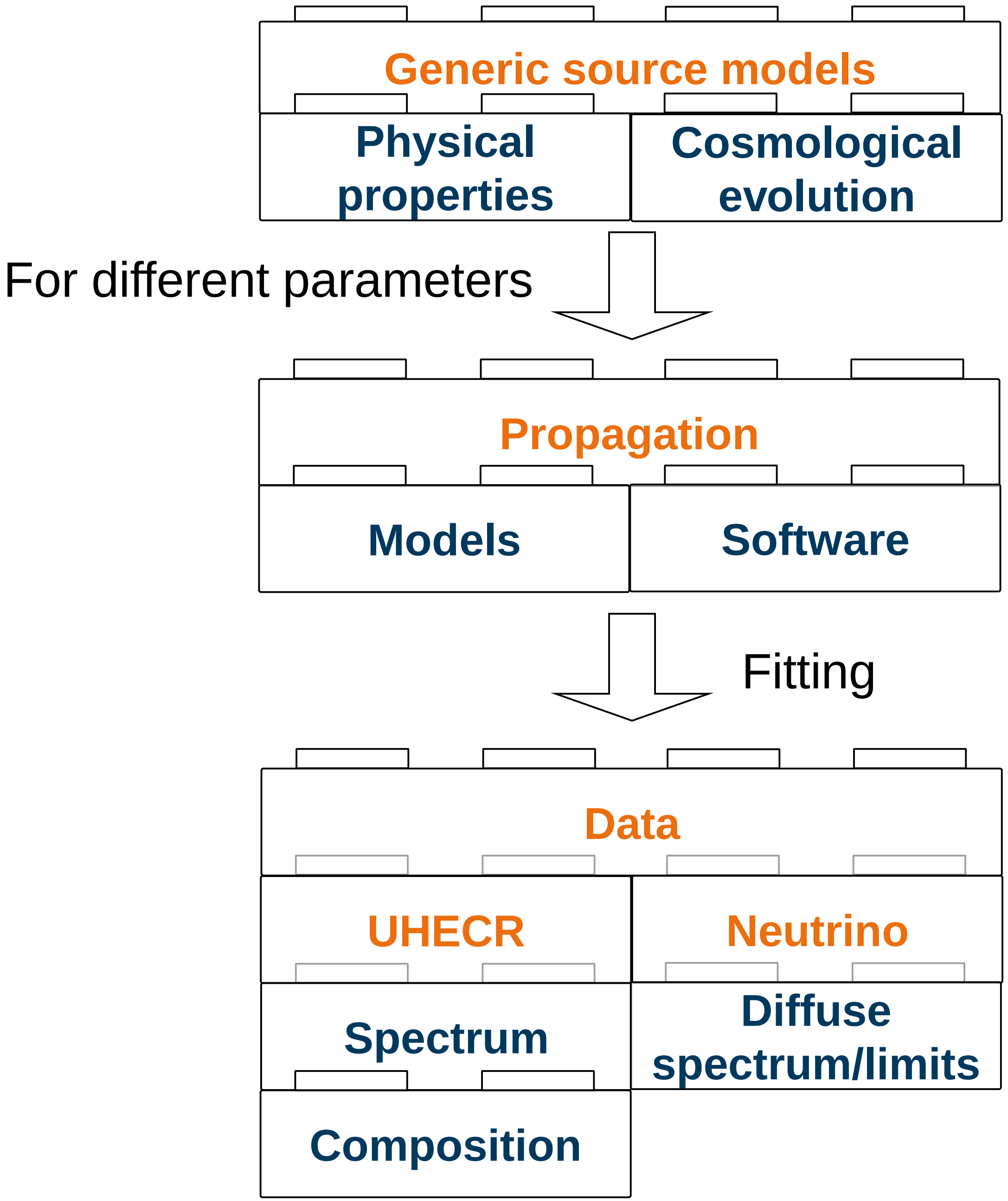


6th International Symposium on Ultra High Energy Cosmic Rays
UHECR
2022
L'Aquila, Italy October 3 - 7 2022

Motivation

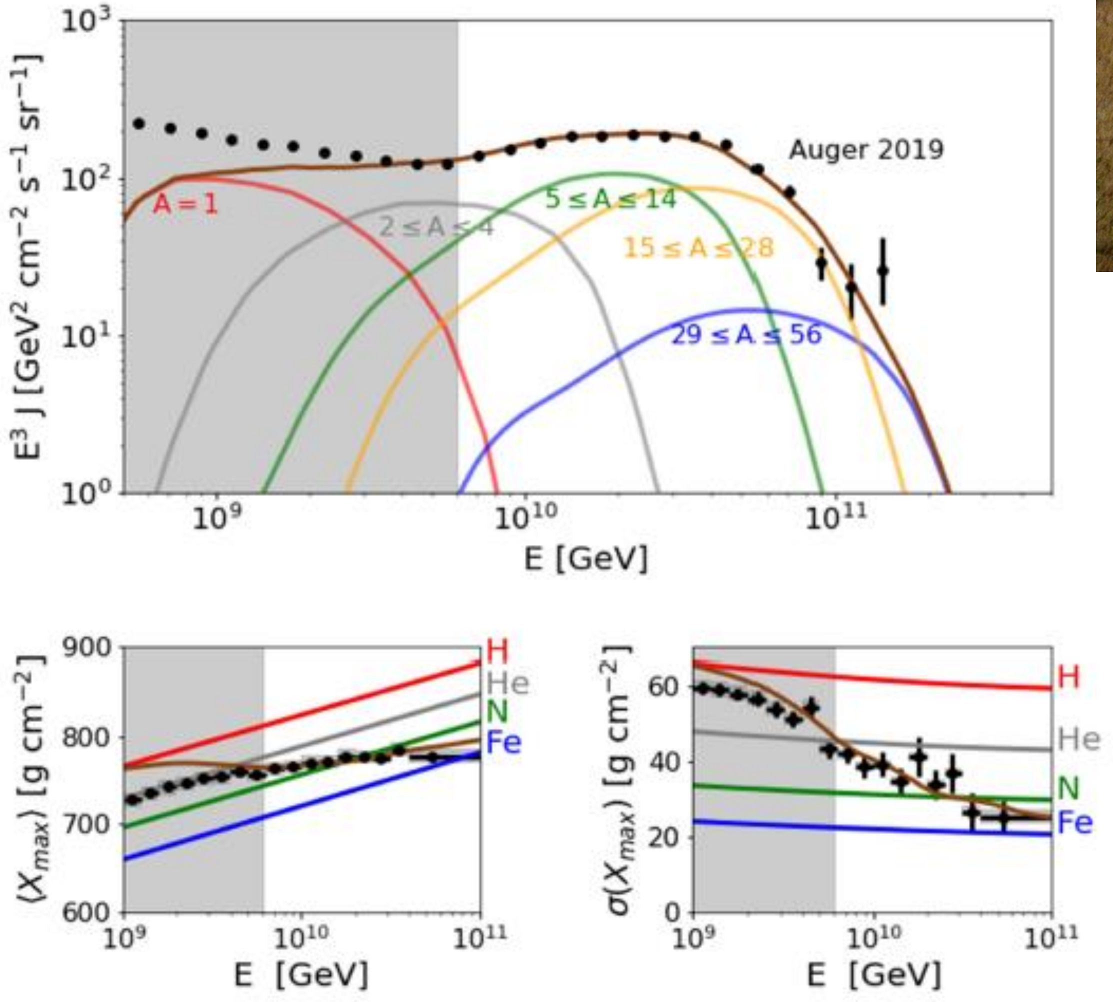
Standard combined fit





Motivation

Standard combined fit



Generic source models

Physical properties | **Cosmological evolution**

nt parameters

Propagation

Models | **Software**

Fitting

Data

UHECR | **Neutrino**

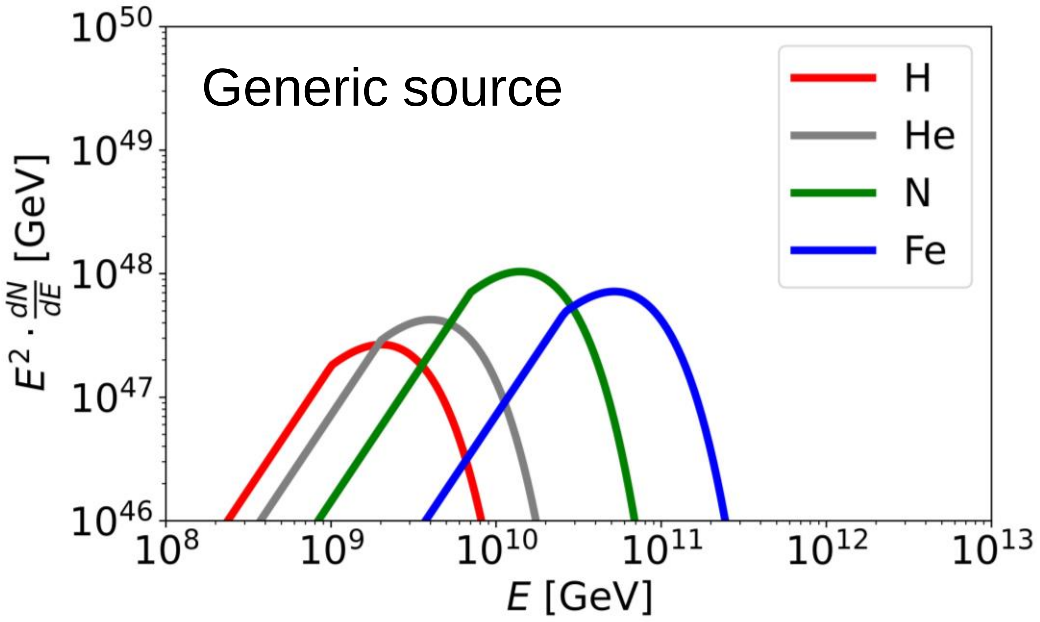
Spectrum | **Diffuse spectrum/limits**

Composition

Motivation

Type of courses

Simple Power-law with rigidity-dependent cut-off:



$J_{source} \sim E^{-\gamma} f_{cut}(E)$

$E_{max} \sim Z$

Generic source models

Physical properties | Cosmological evolution

Propagation

Models | Software

Fitting

Data

UHECR | Neutrino

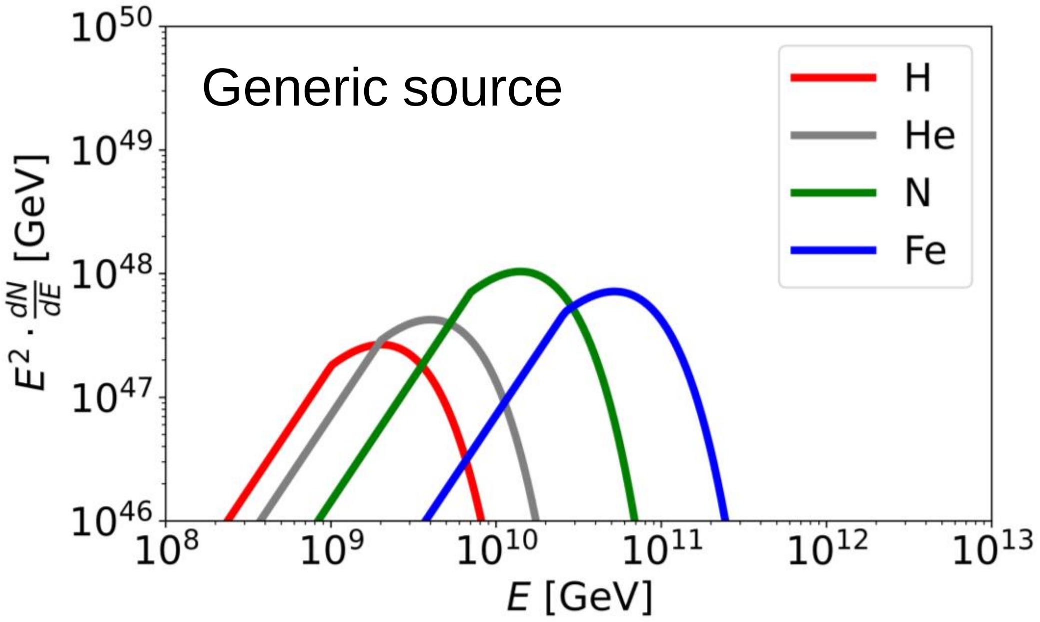
Spectrum | Diffuse spectrum/limits

Composition

Motivation

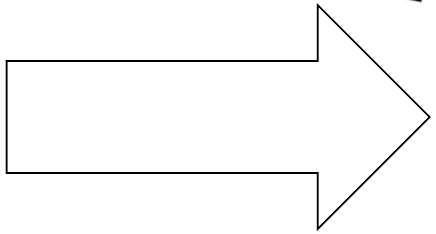
Type of courses

Simple Power-law with rigidity-dependent cut-off:

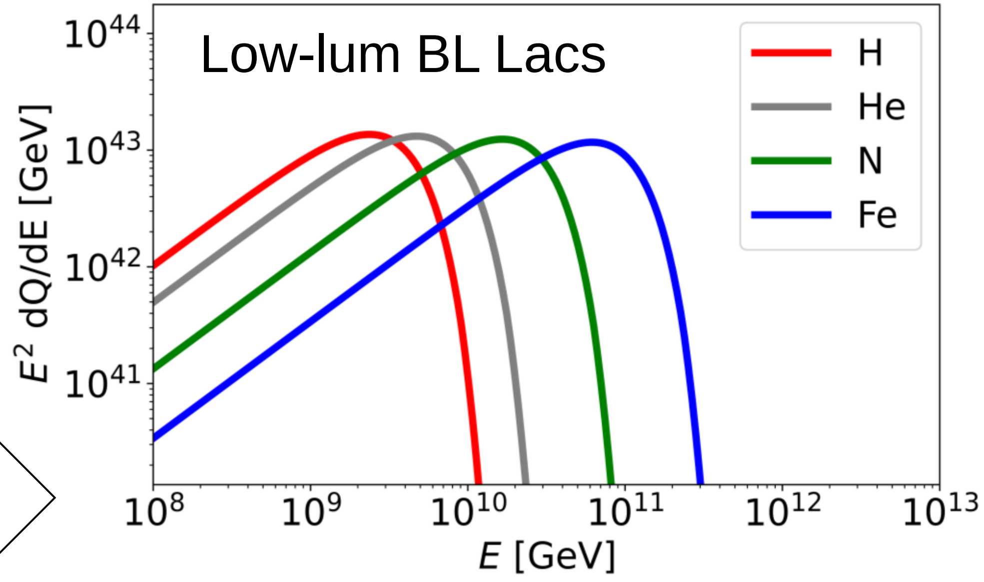


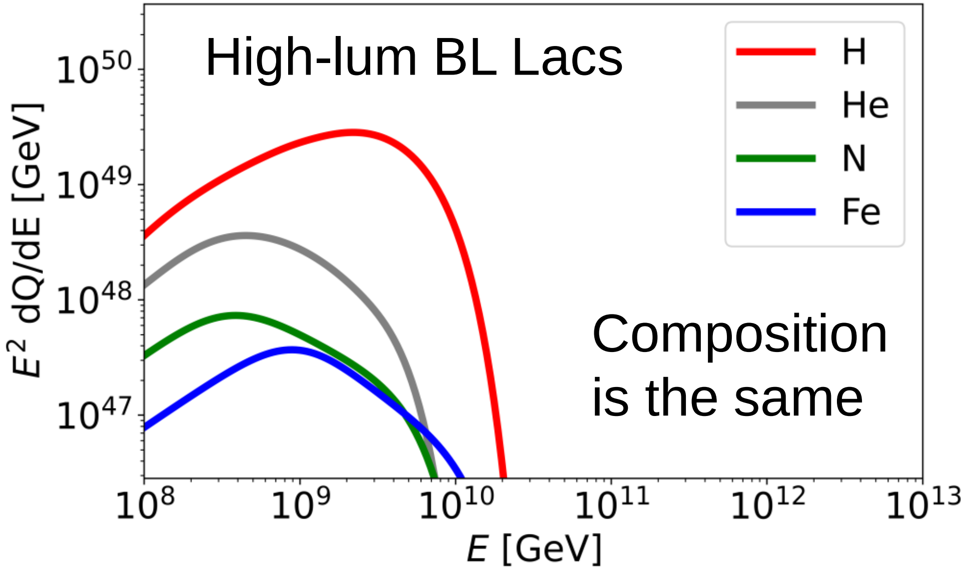
$$J_{source} \sim E^{-\gamma} f_{\text{cut}}(E)$$

$$E_{\text{max}} \sim Z$$



Simulated spectrums of jetted AGN:



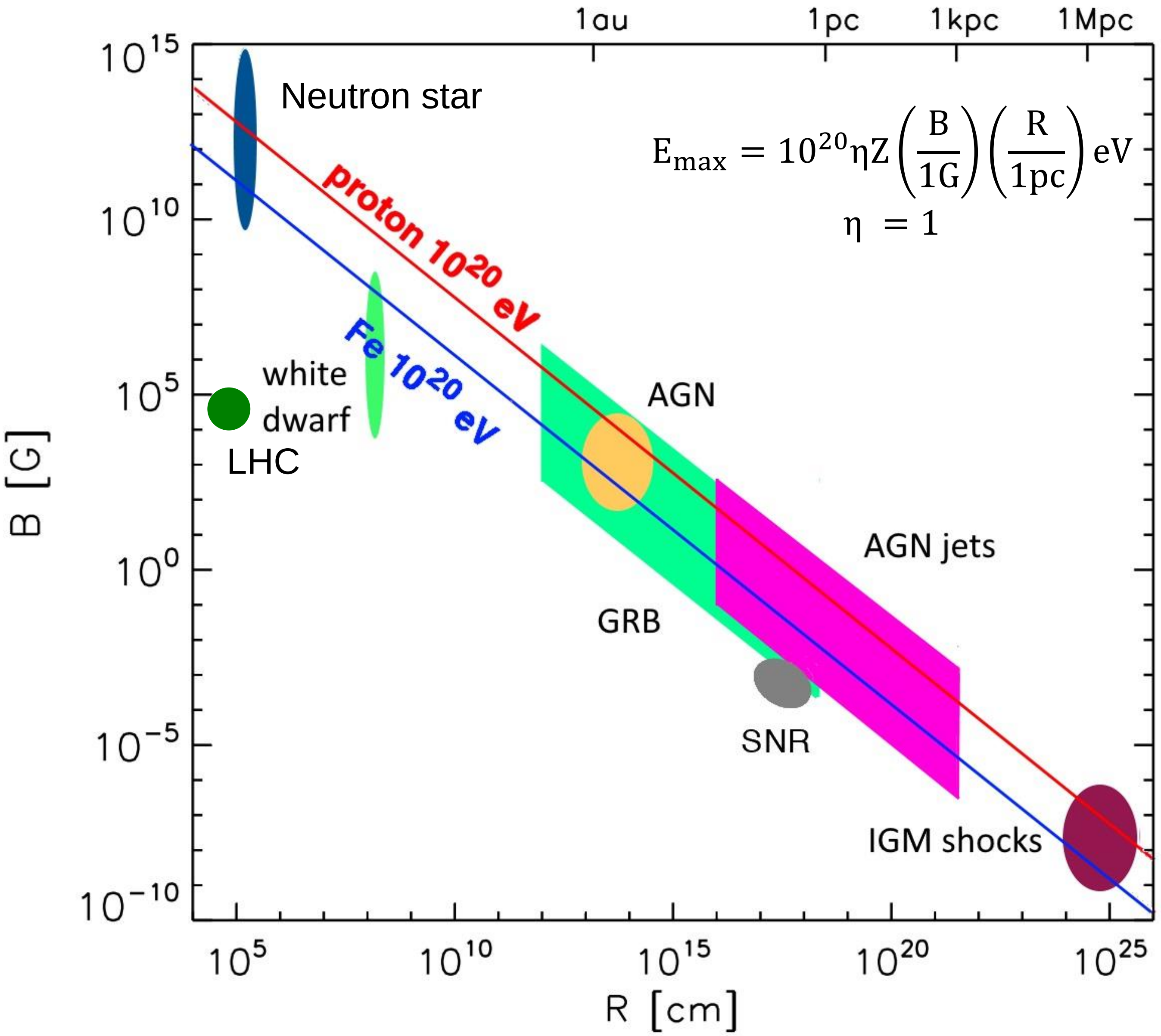


The Hillas criterium

AGNs are the most luminous objects in the universe

Association with neutrino event from IceCube (TXS 0506+056)

BIG ASSUMPTION: all observed UHECRs are produced by jetted AGN



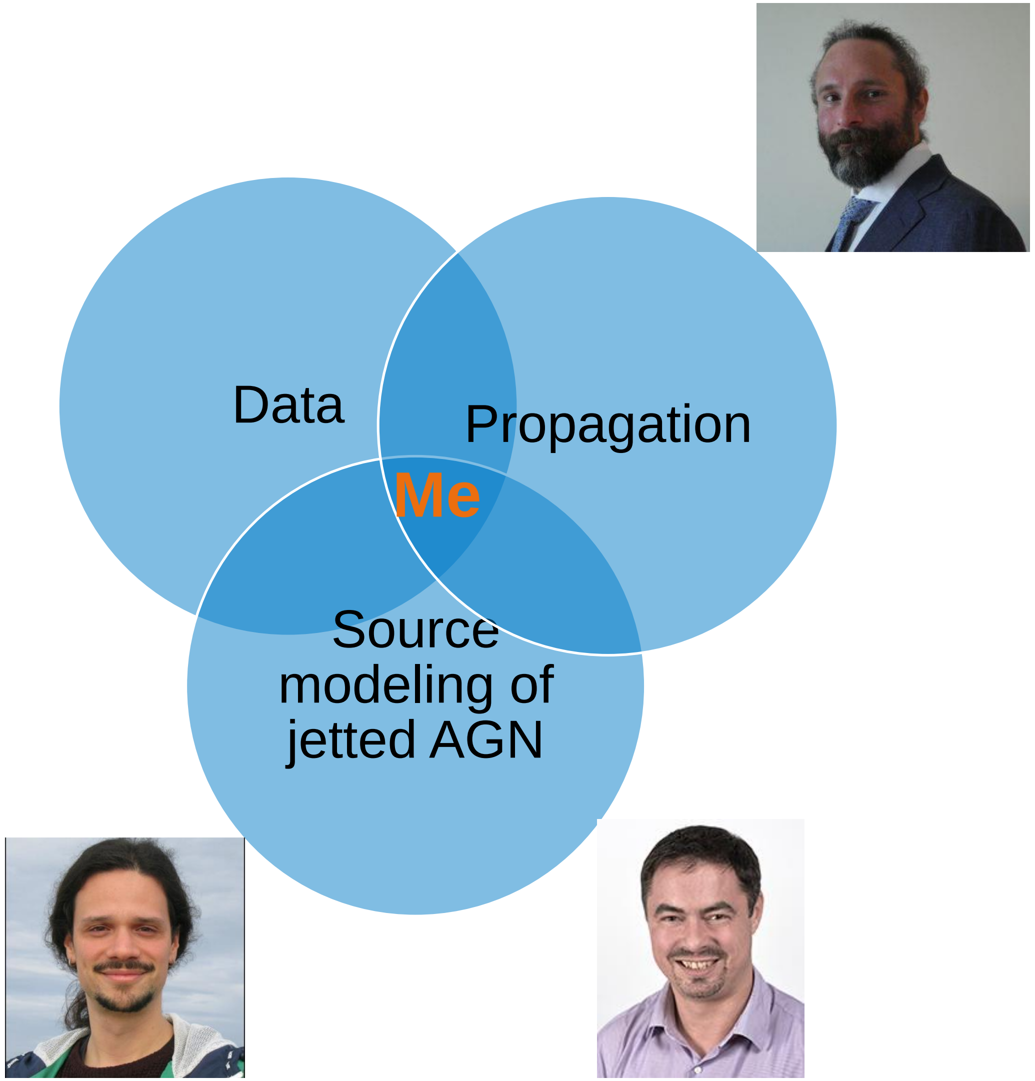
Adapted from Roberto Aloisio 2017

Motivation

1. Switch from generic sources to simulated spectrums from jetted AGN for fitting

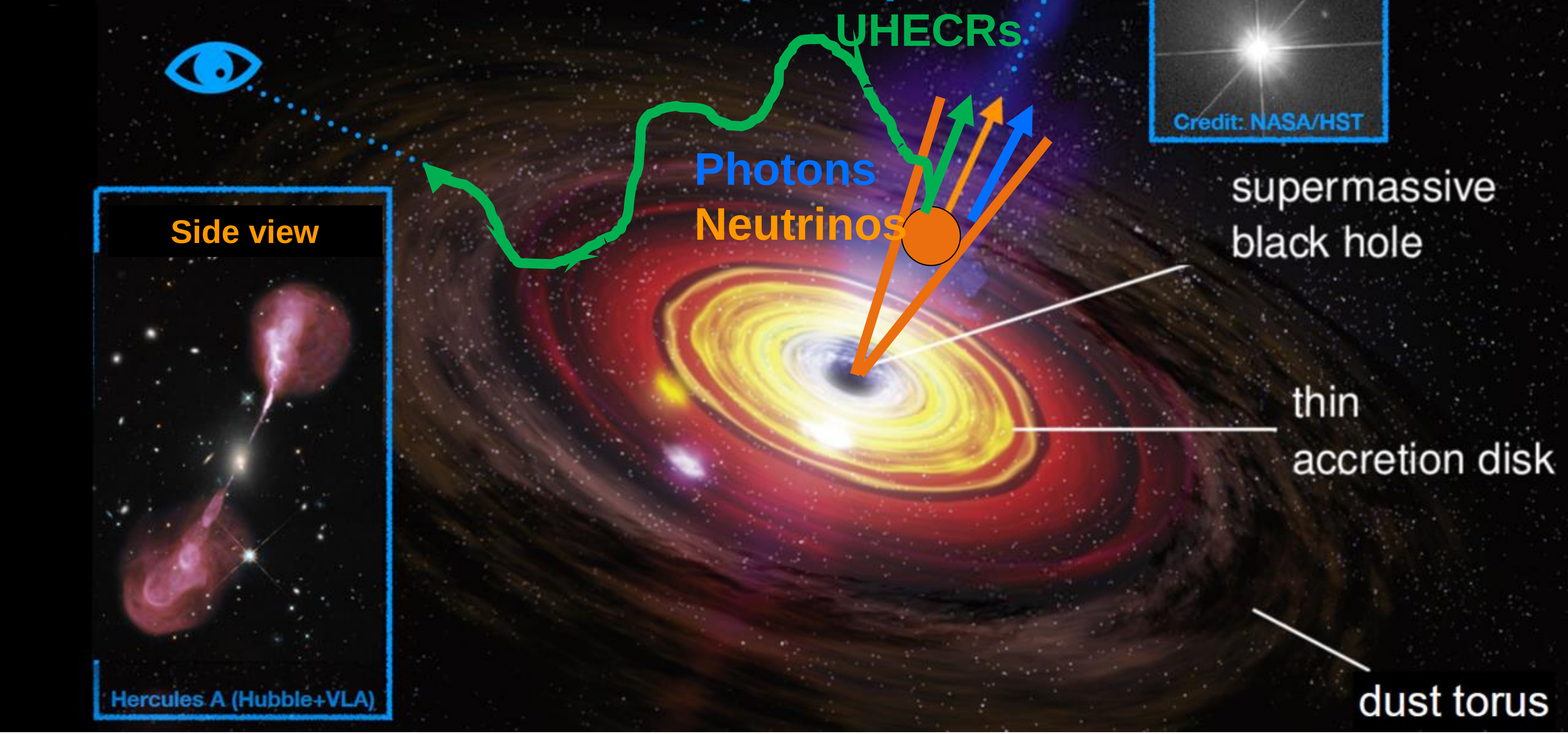
2. Provide constraints on the models using UHECR and neutrino data *

3. Predict cosmogenic and source neutrino flux for future observations



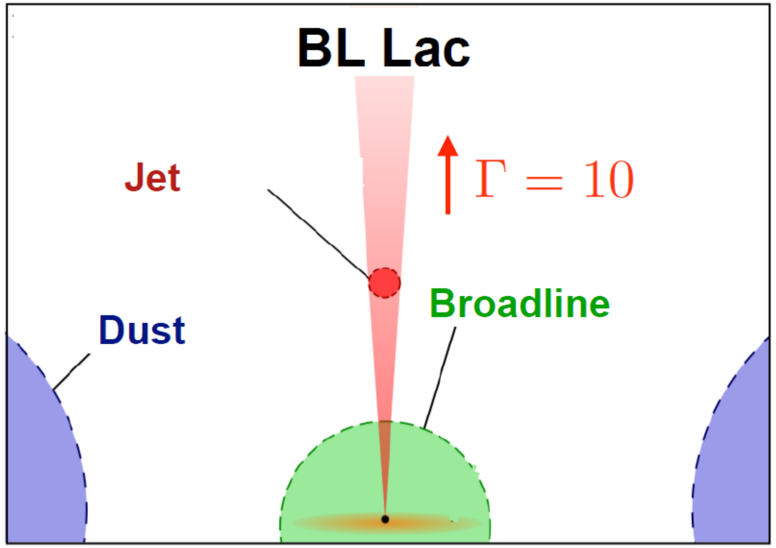
ULTIMATE JETTED AGN MODEL

Jetted Active Galactic Nuclei (AGNs)



Source models

BL Lacs



No evidence of external fields

⇩

One-zone model

Model ingredient list:

Spherical radiation zone with blob size (R)

Injected CR spectrum is power-low with 2 and Maximum energy:

$$E_{max} = 10^{20} \eta Z \left(\frac{B}{1G}\right)\left(\frac{R}{1pc}\right) eV$$

acceleration efficiency (η)

Magnetic field scaling as power law of L_γ

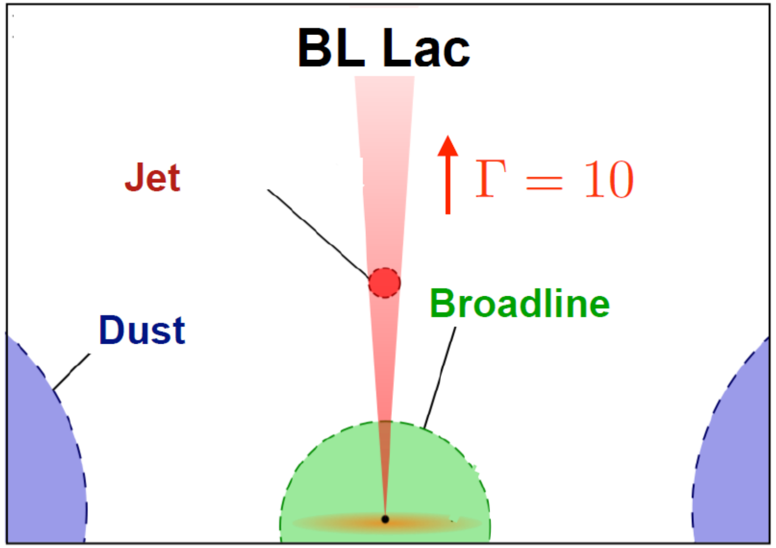
How much energy goes to CR compared to gamma (baryonic loading):

$$\xi_{CR} = \frac{L_{CR}}{L_e} \sim \frac{L_{CR}}{L_\gamma}$$

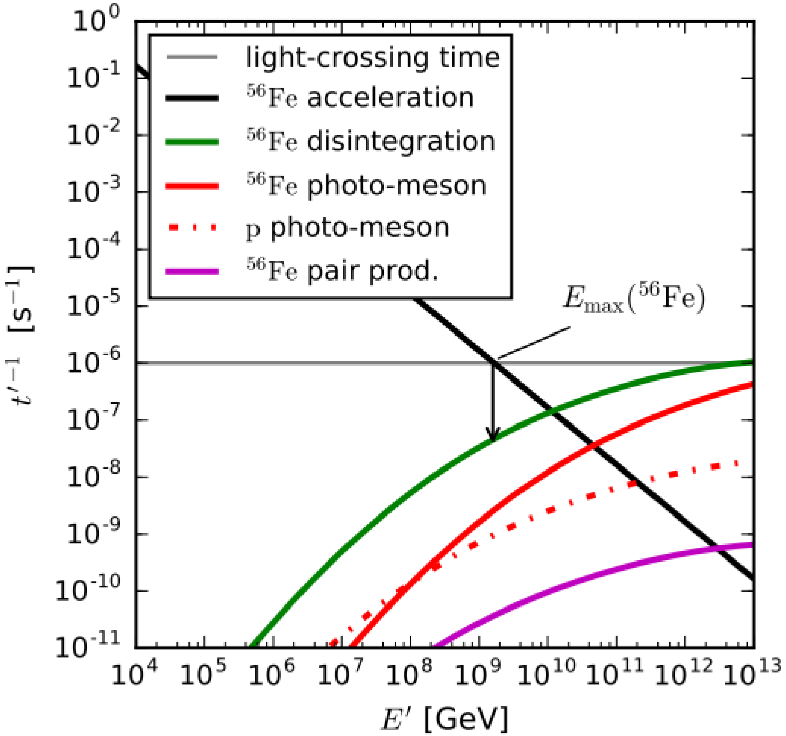
Rodrigues X. et al 2018

Source models

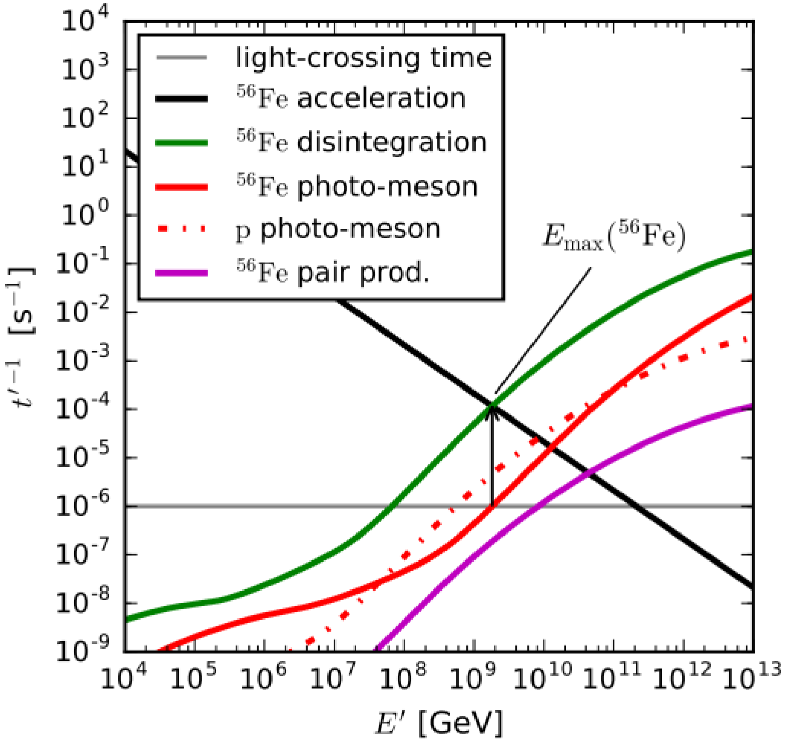
BL Lacs



$L_\gamma = 10^{44.6}\ \mathrm{erg}/s$



$L_\gamma = 10^{48.8}\ \mathrm{erg}/s$



No evidence of external fields

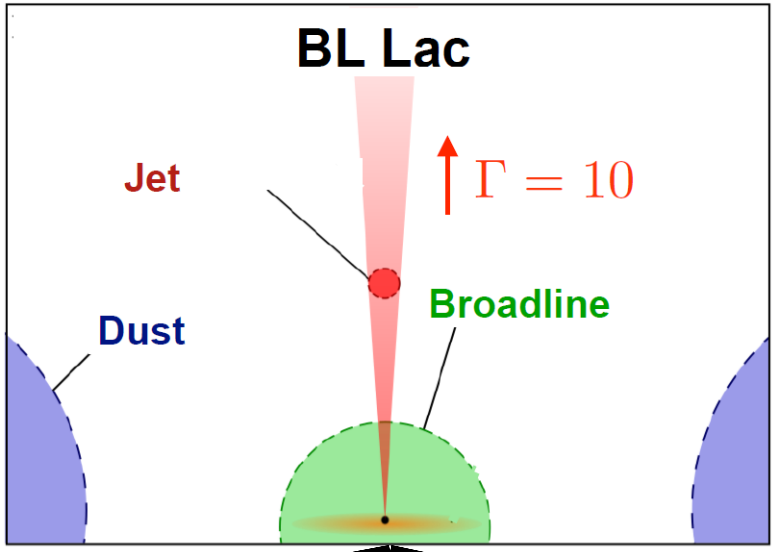
⇩

One-zone model

Rodrigues X. et al 2018

Source models

BL Lacs



Low-lum

$L_\gamma < 10^{45.5}\ {}^{erg}/_{s}$

No interactions

Good CR sources

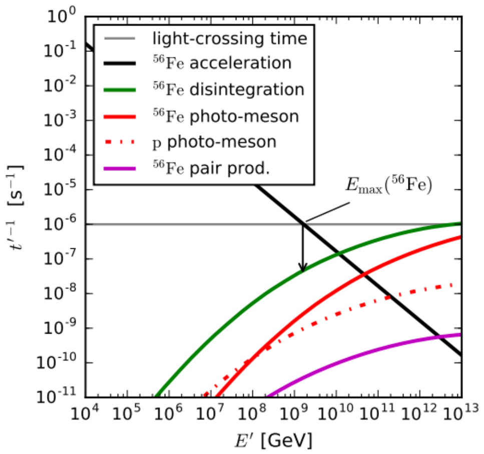
High-lum

$L_\gamma > 10^{45.5}\ {}^{erg}/_{s}$

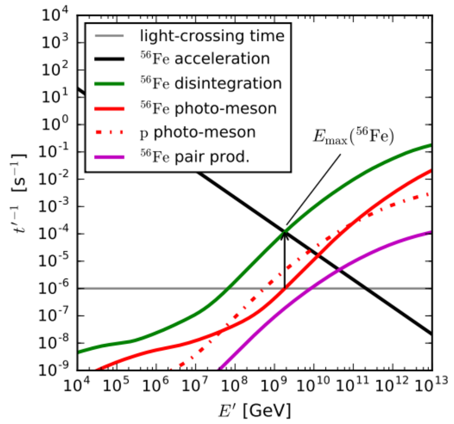
a lot of interactions

Good Nu sources

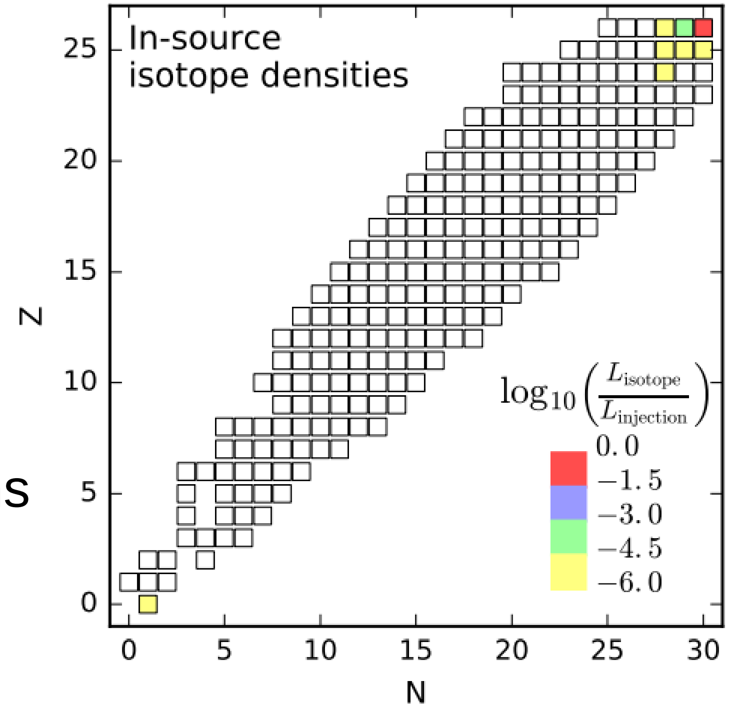
$L_\gamma = 10^{44.6}\ {}^{erg}/_{s}$

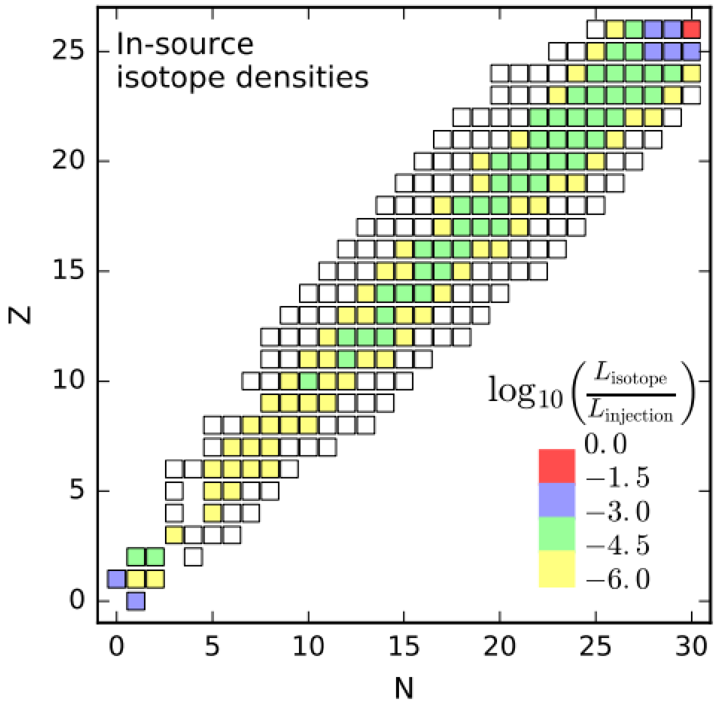


$L_\gamma = 10^{48.8}\ {}^{erg}/_{s}$



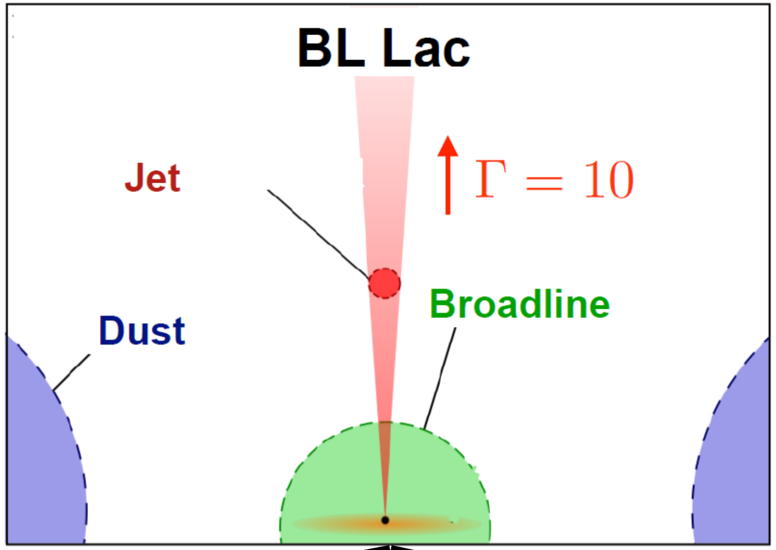
We have to keep the up to 83 spectrum for propagation part





Source models

BL Lacs



Low-lum

$L_\gamma < 10^{45.5}\ \mathrm{erg}/\mathrm{s}$

No interactions

Good CR sources

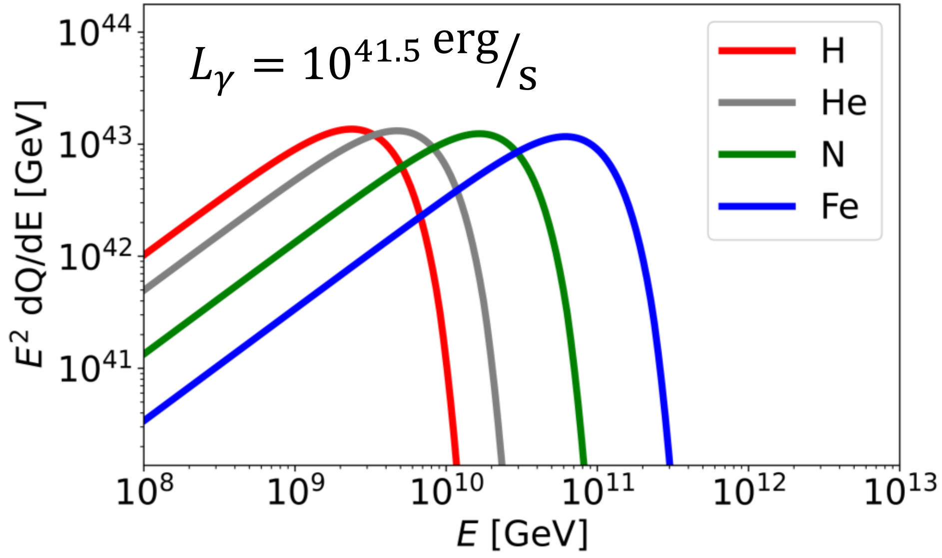
High-lum

$L_\gamma > 10^{45.5}\ \mathrm{erg}/\mathrm{s}$

a lot of interactions

Good Nu sources

Low-lum BL Lacs

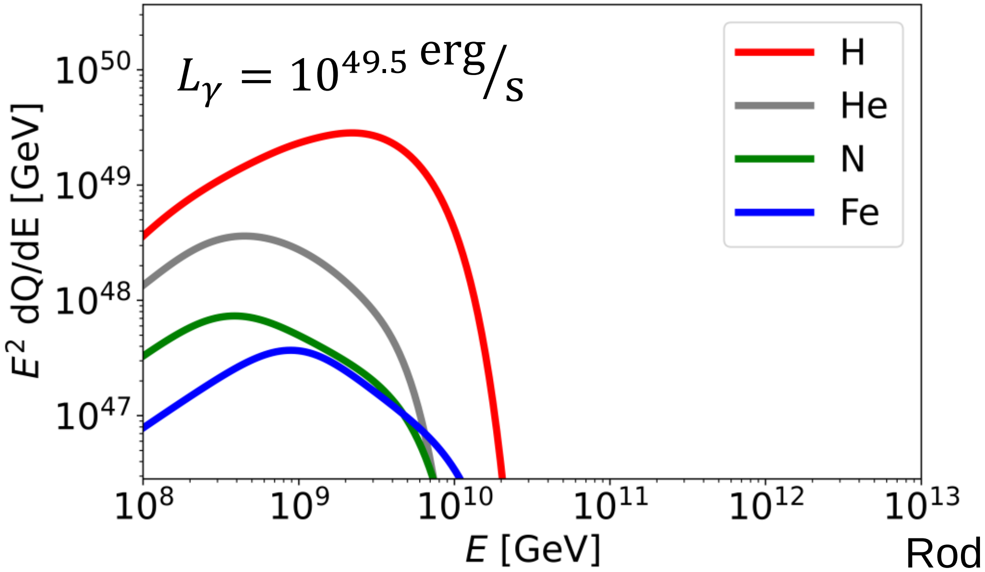


$R = 0.03pc$

$\eta = 0.5$

Bar. loading =100

High-lum BL Lacs



H: 25%

He: 25%

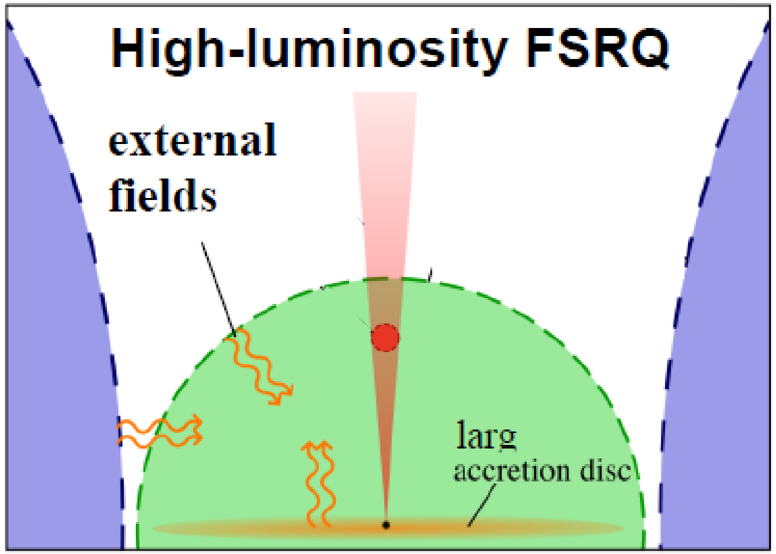
N: 25%

Fe: 25%

Rodrigues X. et al 2018

Source model

Flat-Spectrum Radio Quasars (FSRQ)



Large broadline region and dust torus

⇩

External contributions of target photon field for CR interactions

Model ingredient list:

Spherical radiation zone with blob size (R)

Injected CR spectrum is power-low with 2 and Maximum energy:

$$E_{max} = 10^{20}\eta\left(\frac{B}{1G}\right)\left(\frac{R}{1pc}\right)eV$$

acceleration efficiency (*η)*

Magnetic field scaling as power law of L_γ

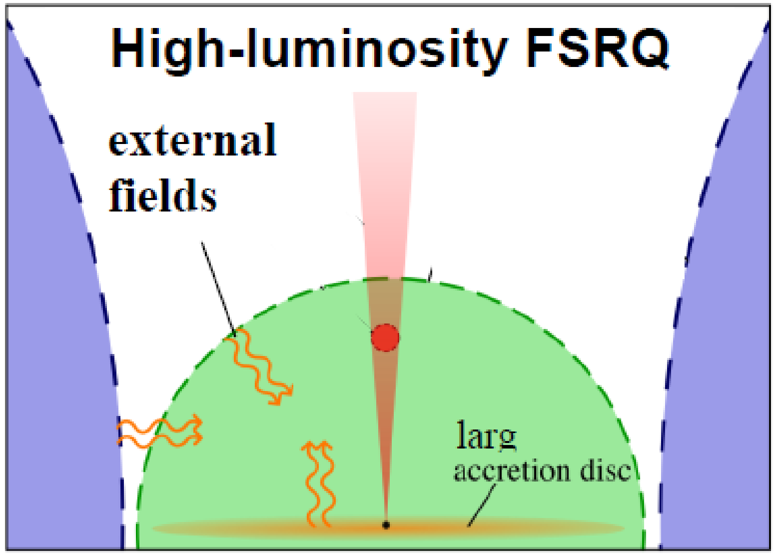
How much energy goes to CR compared to gamma (baryonic loading):

$$\xi_{CR} = \frac{L_{CR}}{L_e} \sim \frac{L_{CR}}{L_\gamma}$$

Rodrigues X. et al 2018

Source model

Flat-Spectrum Radio Quasars (FSRQ)

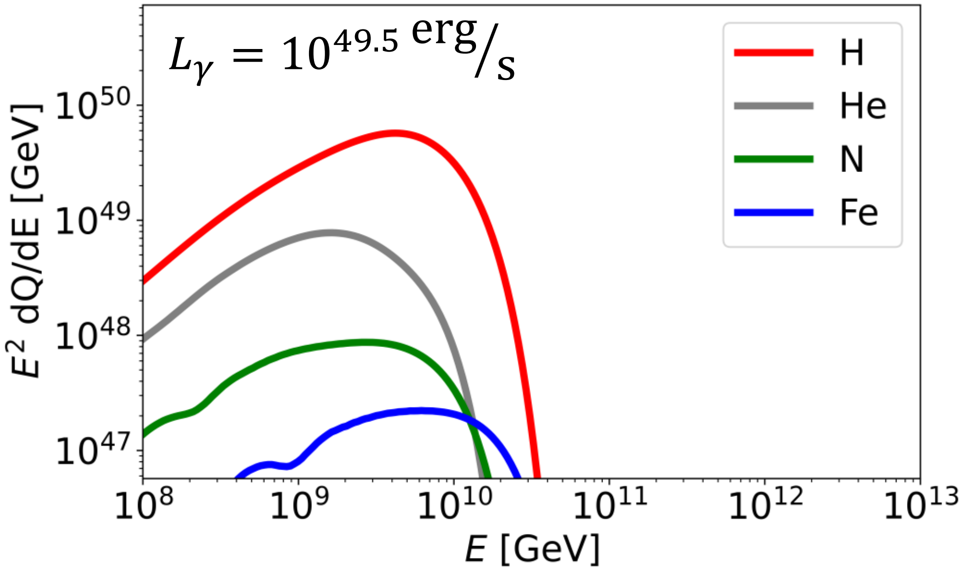


Large broadline region and dust torus

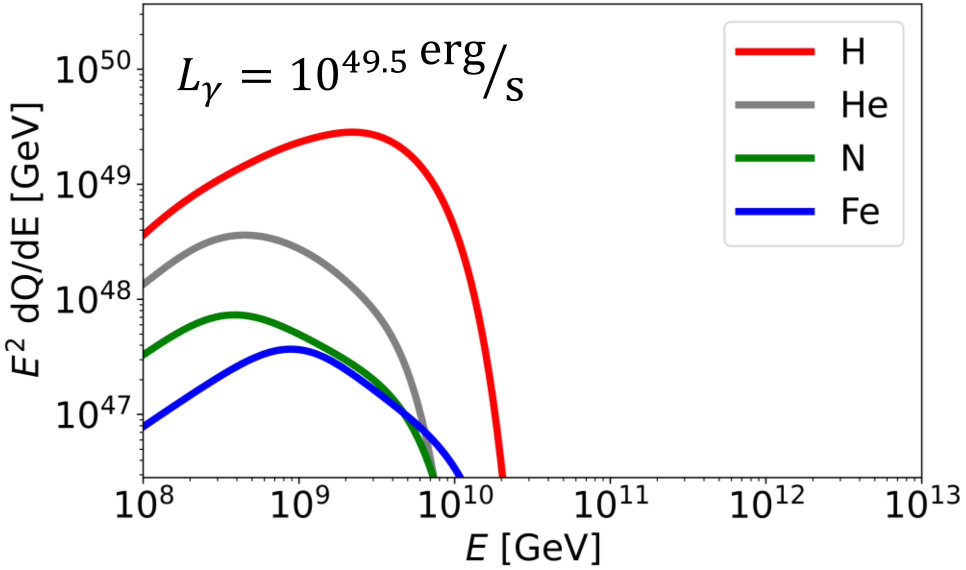
⇩

External contributions of target photon field for CR interactions

FSRQ



High-lum BL Lacs



$R = 0.03pc$

$\eta = 0.5$

Bar. loading =100

H: 25%

He: 25%

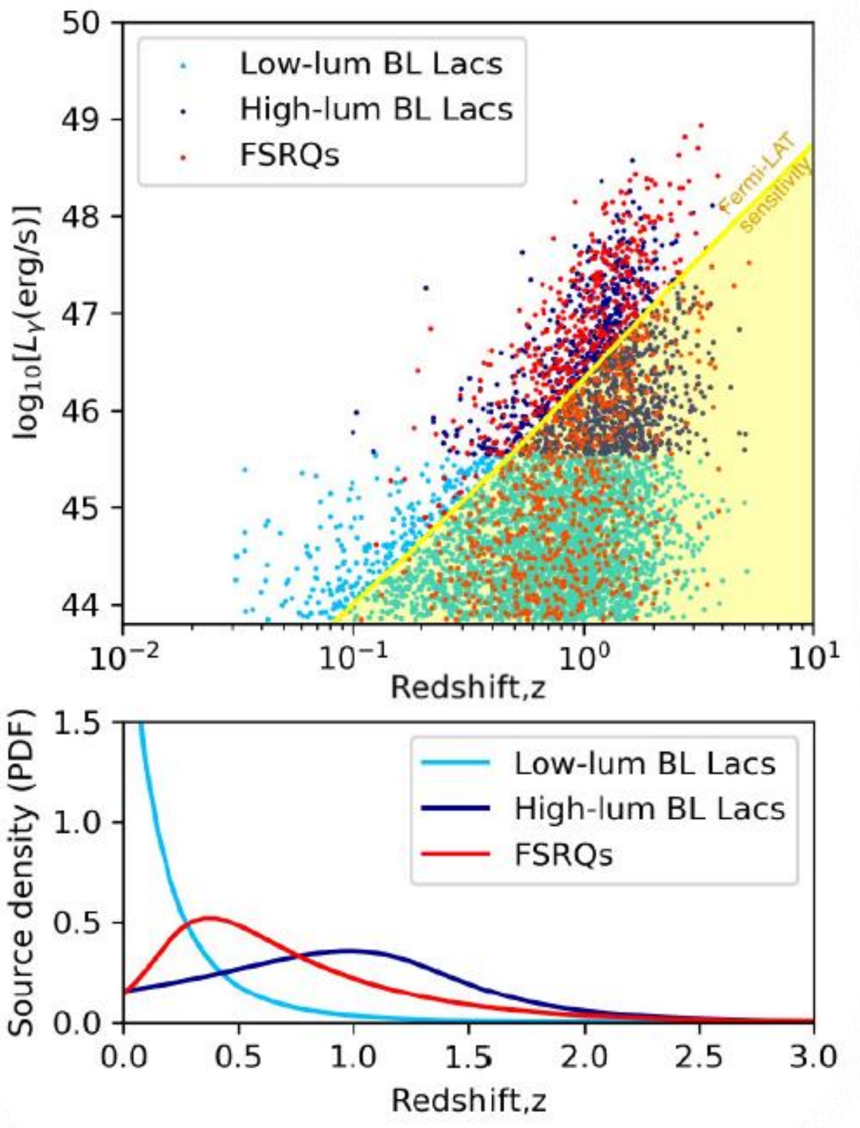
N: 25%

Fe: 25%

Rodrigues X. et al 2018 and 2021

Neutrinos and UHECRs from blazar AGN

Population model



~1500 resolved blazars (above the Fermi flux threshold)

50% of FSRQs resolved by *Fermi*

only 15% of BL Lacs resolved by *Fermi*

Model ingredient list:

- Fermi catalog(3LAC)
- Observed diffuse γ-ray background
- Distributions of FSRQs and BL Lacs (Ajello)

Integrate over L_γ

PriNCe

Propagation including Nuclear Cascade

- Written in pure Python using Numpy and Scipy
- Directly solve the transport equation
- Large speed boost from sparse matrix algorithms
- Public available Analysis tools for parameters scan
- Written for combining source modelling and propagation
- Was developed by Jonas Heinze and Anatoli Fedynitch at DESY

LEGO

Installation: ***pip** install prince-cr*

PriNCe

1D propagation:

- Without MF
- z<5

Photon fields:

- CMB
- EBL (Gilmore)

Interaction:

- Adiabatic cooling
- Pair – production
- Photo-hadronic
- Photo-disintegration

Source:

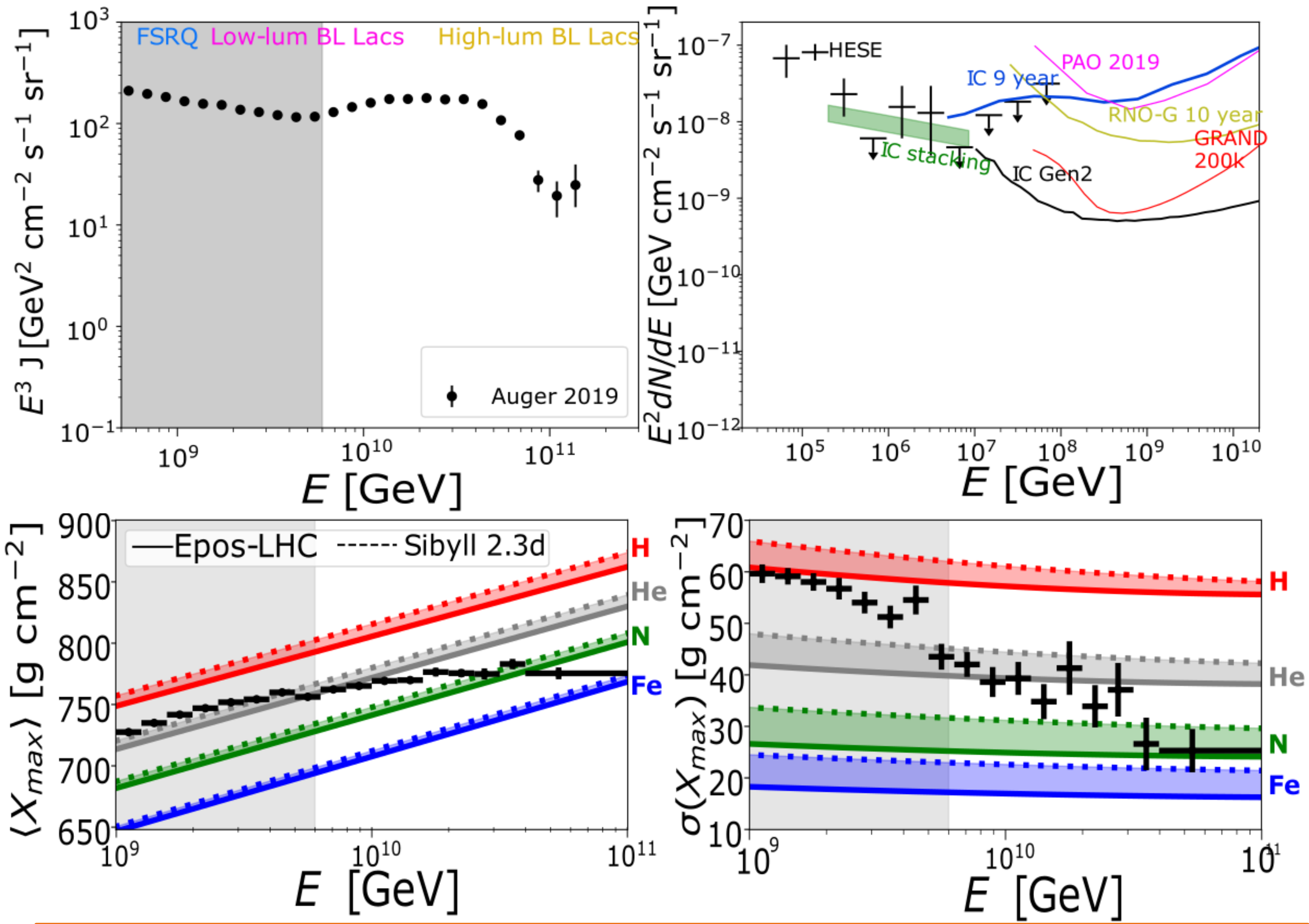
- Direct output from source modeling
- 4 injected elements to jetted-AGN (H, He, N, F)
- Up to 83 except elements
- Energy range: 10^{3}-10^{14} GeV with 8 bins per decade
- Redshift dependency from FSRQ and BL Lacs distributions

Data:

- Auger spectrum and composition 2019
- Ice Cube spectrum and limits

Setup

UHECR and neutrino data



We use EPOS-LHC and SIBYLL2.3d air-shower models

χ^2 used to estimate goodness of fit and find best parameters:

$$\chi^2 = \chi^2_{spectrum} + \\ +\chi^2_{\langle X_{max}\rangle} + \chi^2_{\sigma(X_{max})} \\ +\chi^2_{nu} + \left(\frac{\delta_E}{\sigma_E}\right)^2$$

Spoiler: $\chi^2_{nu} = 0$

Akaike information criterion (AICc) used to compare different models:

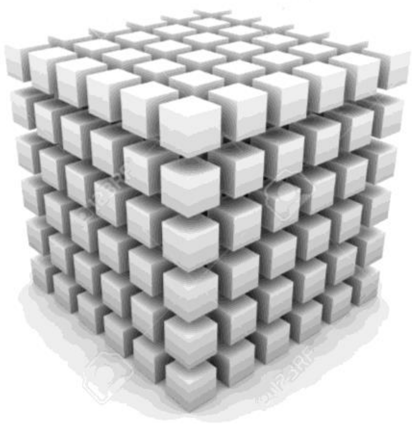
$$AICc = \chi^2 + 2k + \frac{2k^2 + 2k}{N - k - 1}$$

N – number of data points (37)
k – number of free parameters (7-19)

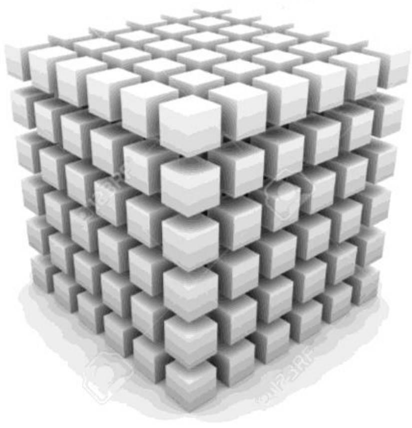
Setup

Parameter scans

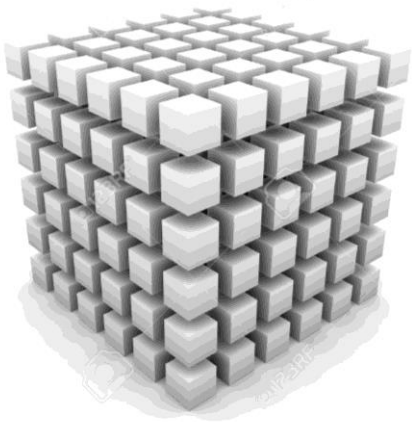
- Jetted AGN
  - Low-lum BL Lacs
    - Blob size
    - Acc efficiency
    - Lum gamma
  - High-lum BL Lacs
    - Blob size
    - Acc efficiency
    - Lum gamma
  - FSRQ
    - Blob size
    - Acc efficiency
    - Lum gamma



H, He, N, Fe



H, He, N, Fe



H, He, N, Fe

4096 simulated model files from source modeling

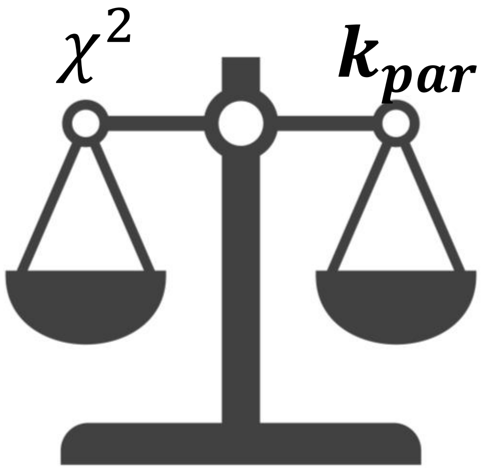
Fe: up to 83 different escaped spectrums

Setup

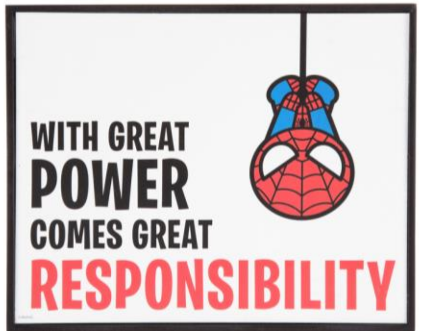
Jetted AGN

- Low-lum BL Lacs
  - Blob size
  - Acc efficiency
  - Composition

15 models
x 2 air-shower model
500 CPU days



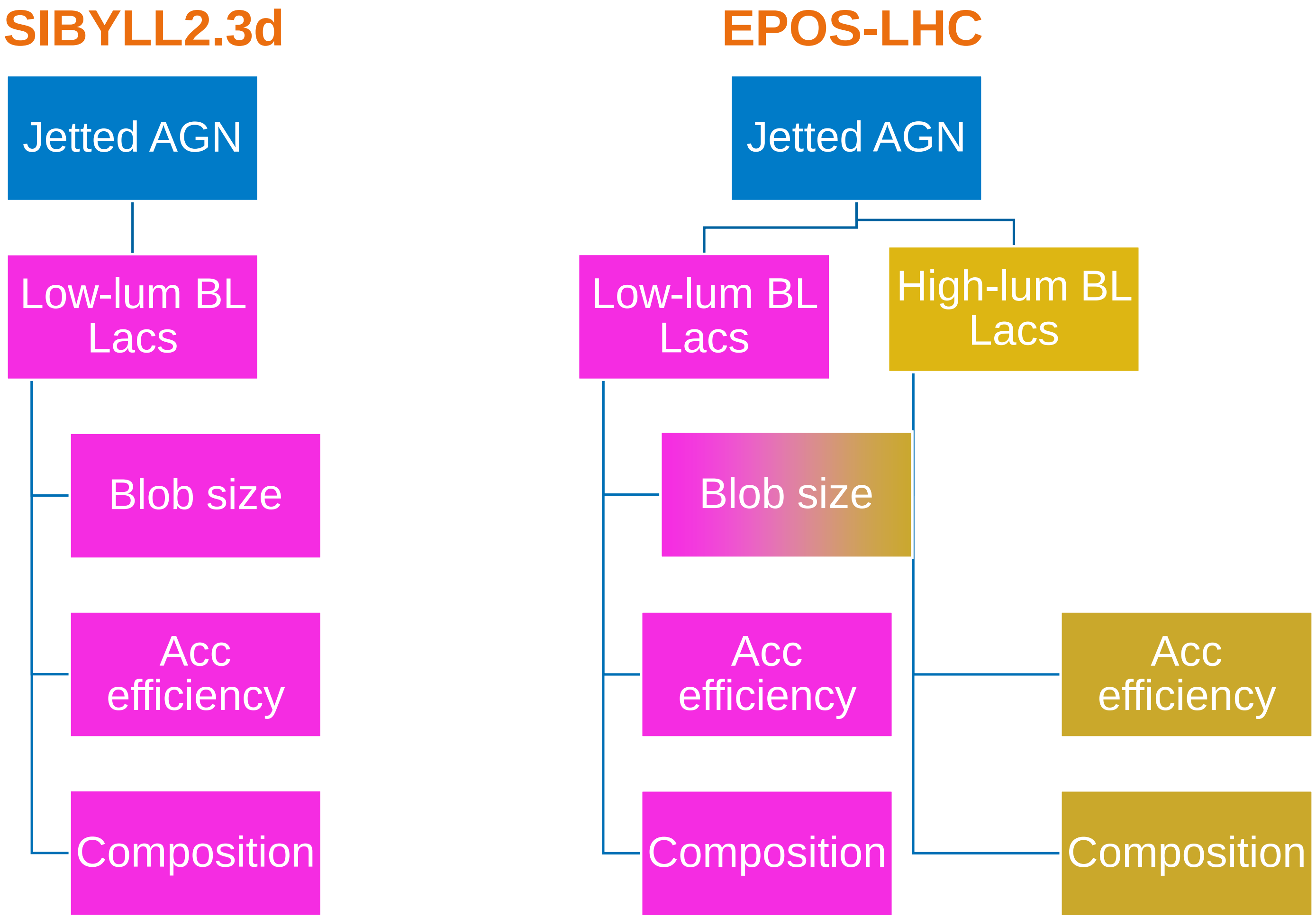
Akaike information criterion



Jetted AGN

- Low-lum BL Lacs
  - Blob size
  - Acc efficiency
  - Composition
- High-lum BL Lacs
  - Blob size
  - Acc efficiency
  - Composition
- FSRQ
  - Blob size
  - Acc efficiency
  - Composition

Results



$$\chi^2 / d.o.f. \approx 89.2 / 30$$

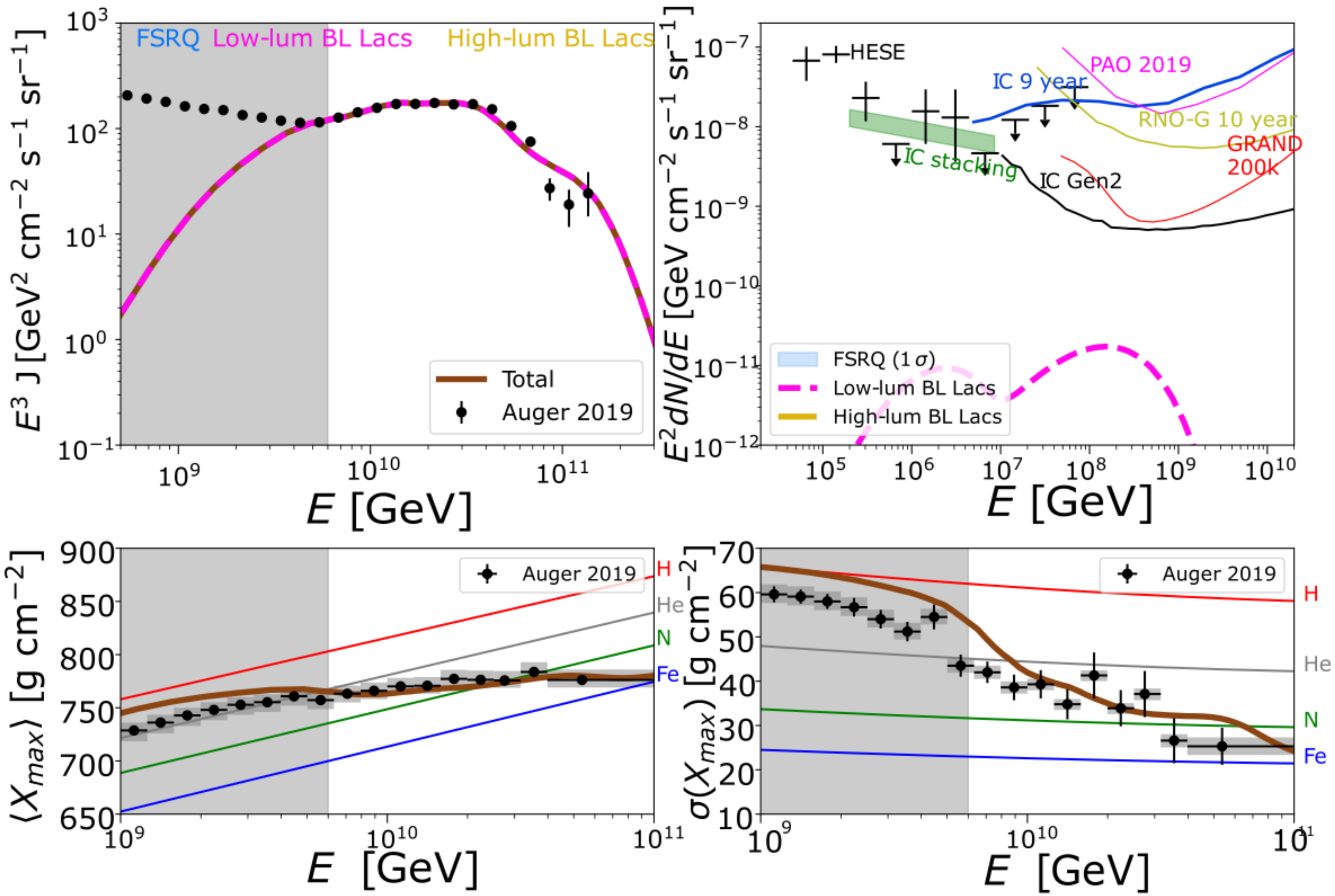
$$\chi^2 / d.o.f. \approx 91.5 / 25$$

1. Results strongly depend on the air shower model.
2. Low-lum BL Lacs are the main source of UHECR (local sources)
3. FSRQs are excluded for both scenarios
4. The fits are not sensitive to some elements

Plotko P. et al. in preparation

Results

SIBYLL2.3d: best fit



1. Low-lum BL Lacs can explain UHECR data
2. No diffuse neutrinos

Baryonic loading 42.5

H: 21 %

He: not sensitive

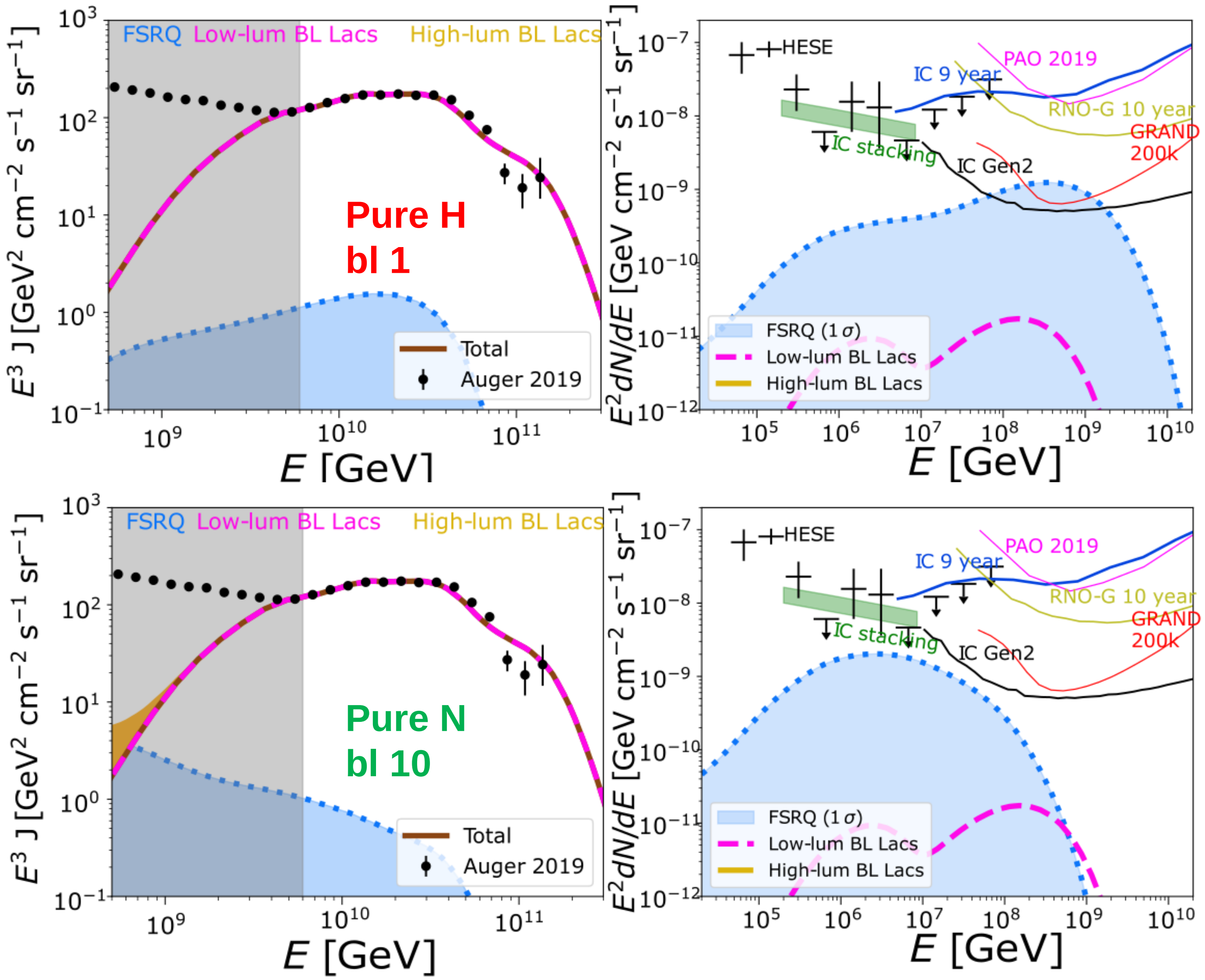
N: not sensitive

Fe: 79%

Plotko P. et al. in preparation

Results

SIBYLL2.3d: FSRQ limits

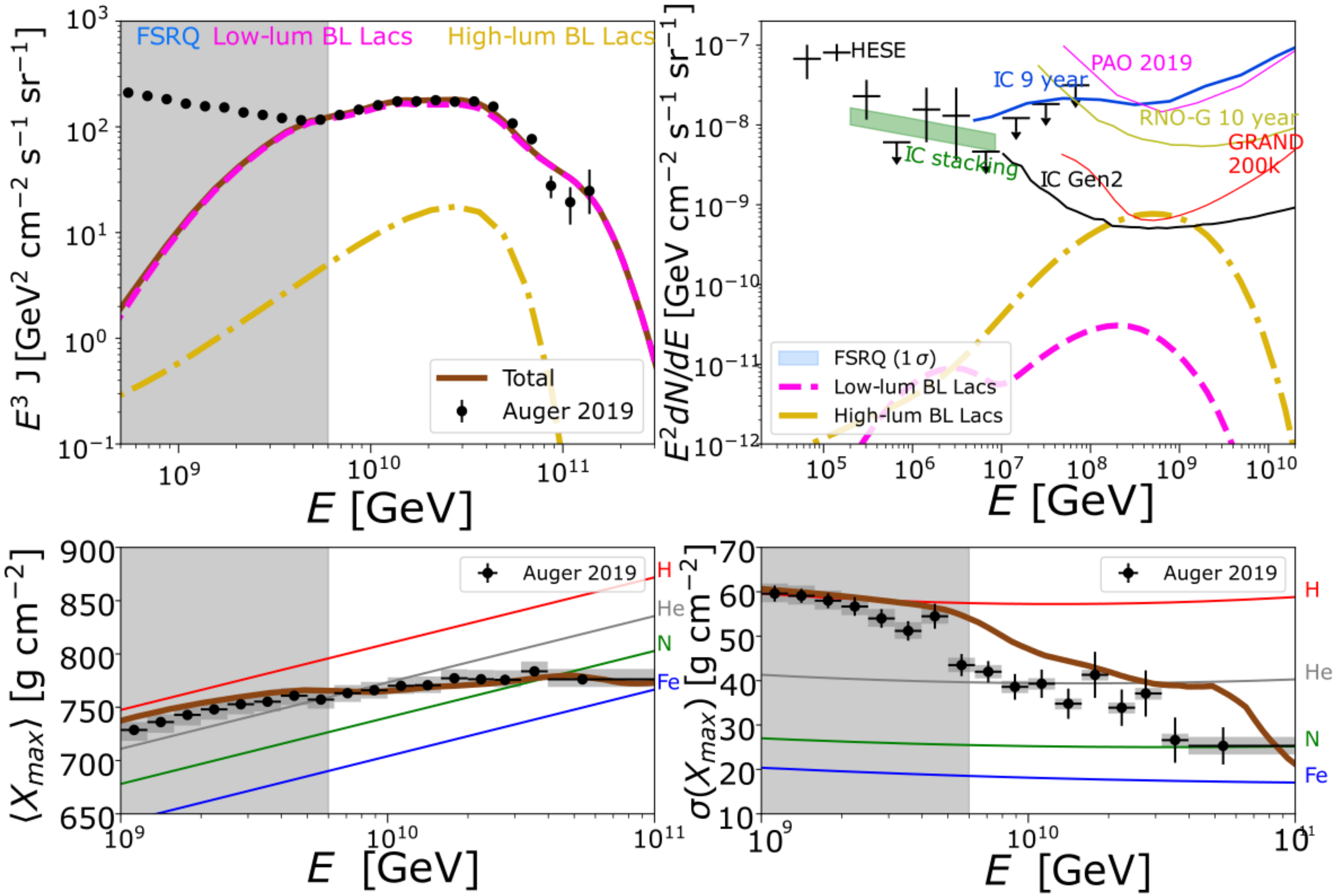


1. Low-lum BL Lacs can explain UHECR data
2. No diffuse neutrinos
3. FSRQs are free source of neutrinos
4. FSRQs have the same parameters as Low-lum BL Lacs
5. Neutrino flux depends on composition

Plotko P. et al. in preparation

Results

EPOS-LHC: best fit



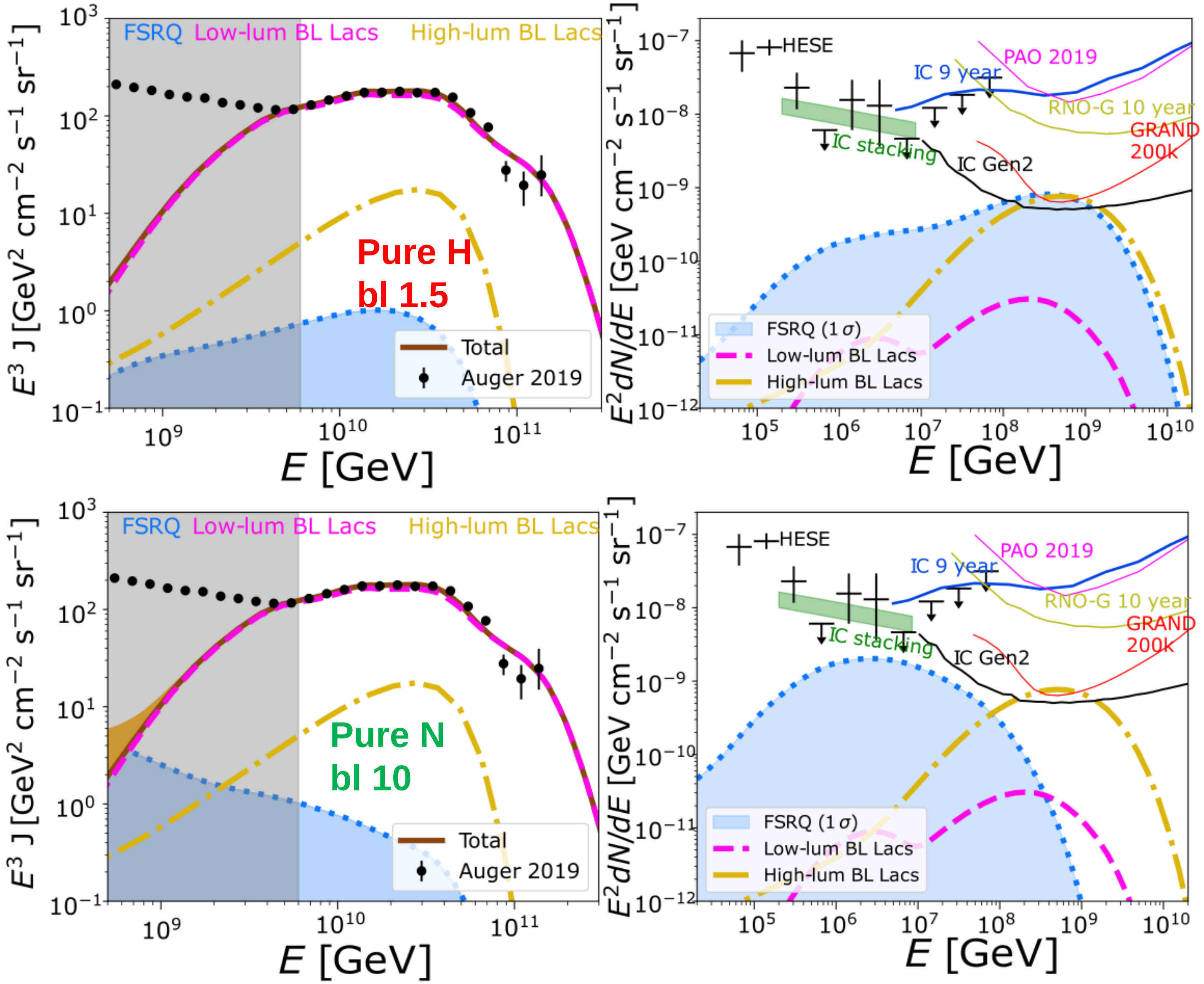
1. Low-lum BL Lacs is explain contributor of UHECRs
2. Small fraction of High-lum BL Lacs is needed
3. Diffuse neutrino from High-lum Bl Lacs

	Low-lum	High-lum
bl:	35.8	1.8
H:	9 %	100%
He:	not sensitive	not sensitive
N:	85%	not sensitive
Fe:	6%	not sensitive

Plotko P. et al. in preparation

Results

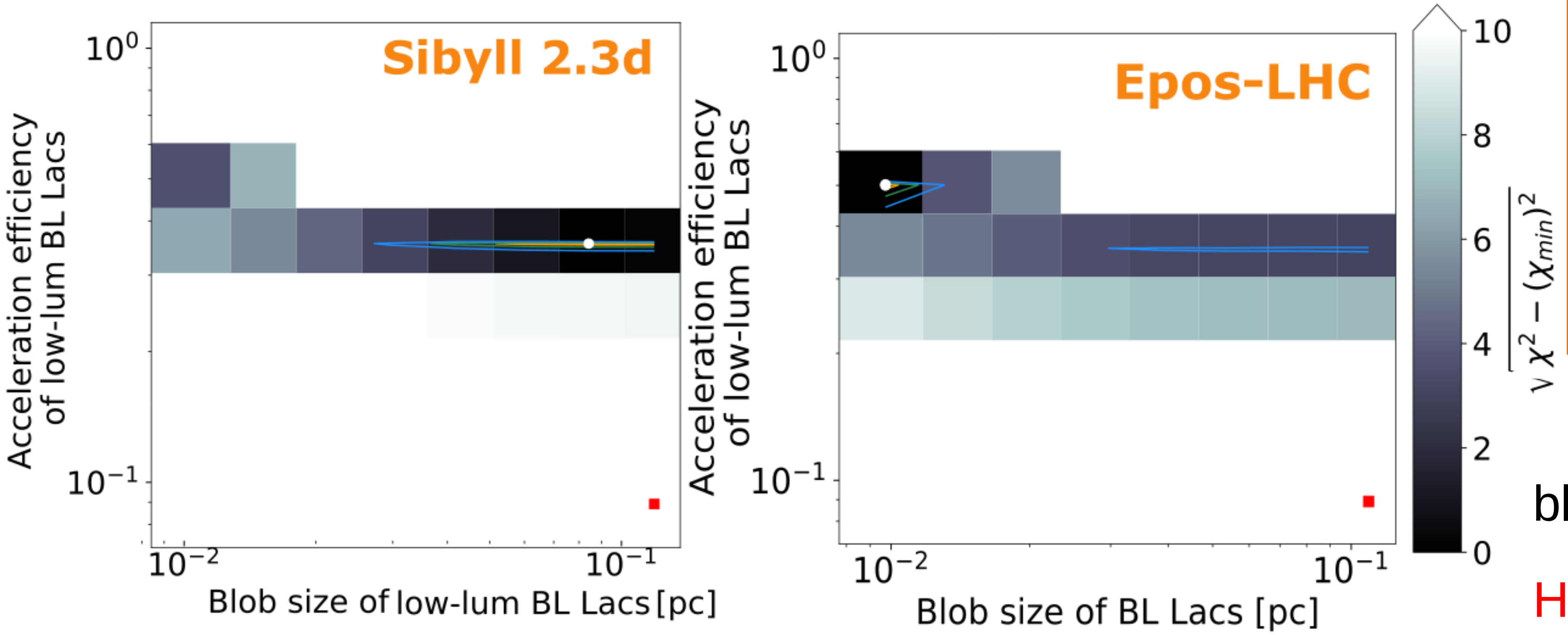
EPOS-LHC: FSRQ limits



1. Low-lum BL Lacs is explain contributor of UHECRs
2. Small fraction of High-lum BL Lacs is needed
3. Diffuse neutrino from High-lum Bl Lacs
4. FSRQs are free source of neutrinos
5. FSRQs have the same parameters as Low-lum BL Lacs
6. Neutrino flux depends on composition

Results

Parameters of low-lum BL Lacs



■ represents
the parameters
from Rodrigers et al. 2021

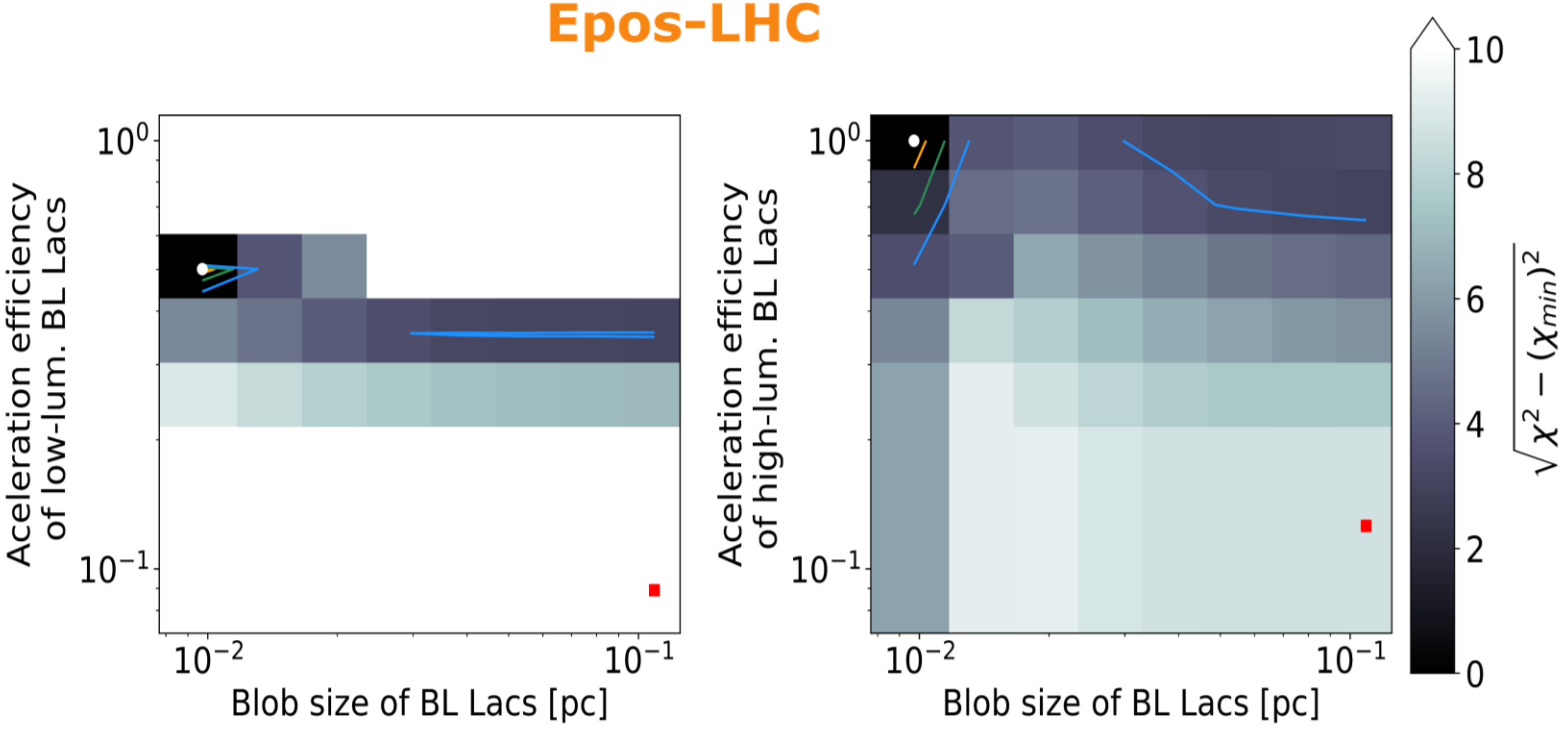
1. Good constraints on acceleration efficiency
2. Blob size is different for two air-shower models
3. Parameters are different

	Sibyll2.3d	Epos-LHC
bl:	<42.5	<35.8
H:	21 %	9 %
He:	not sensitive	not sensitive
N:	not sensitive	85%
Fe:	79%	6%

Results

Parameters of high-lum Bl Lacs

Epos-LHC



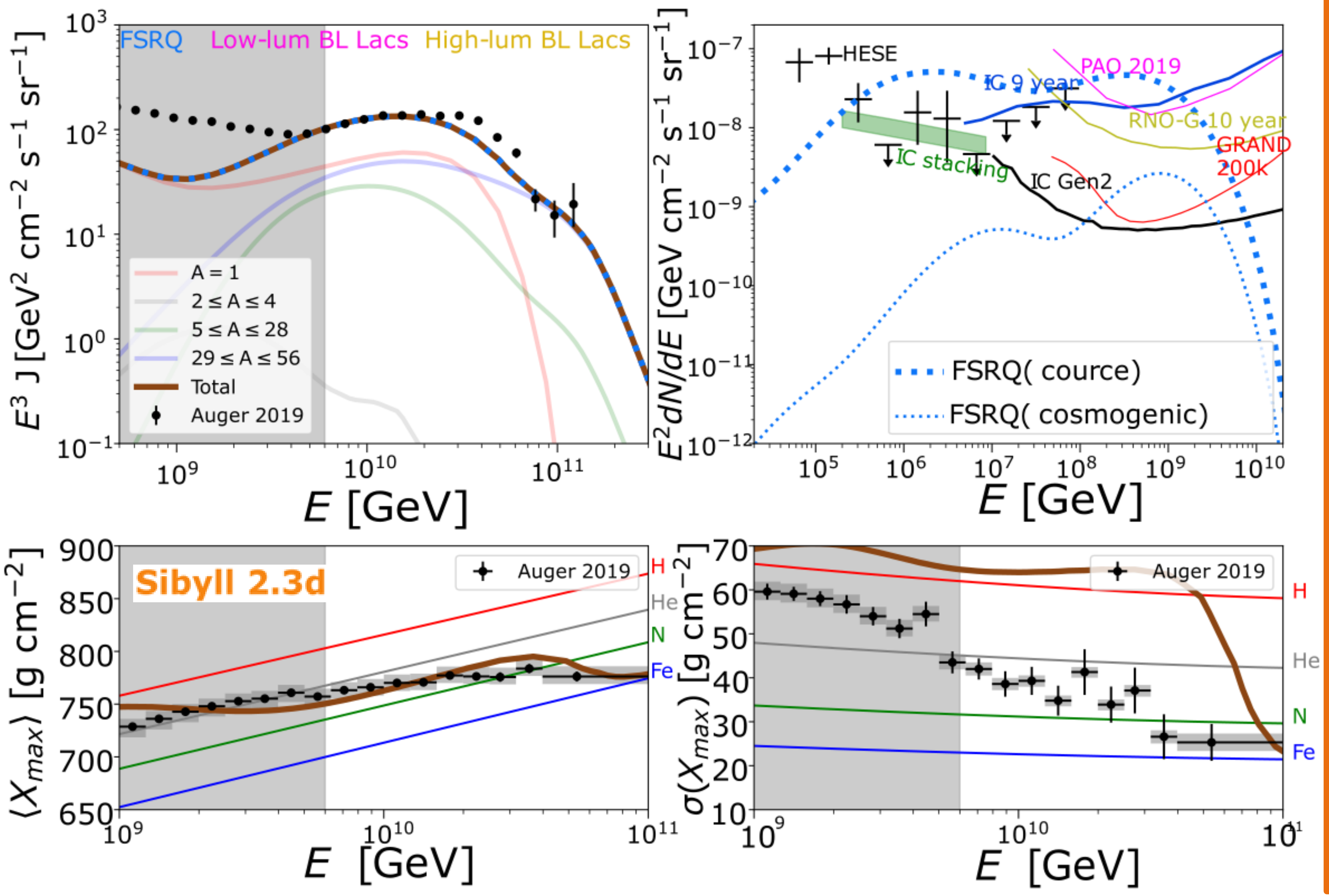
1. Constrains on high-lum BL Lacs
2. Parameters are different

■ represents the parameters from Rodrigers et al. 2021

Plotko P. et al. in preparation

Results

High-lum BL Lacs and FSRQ

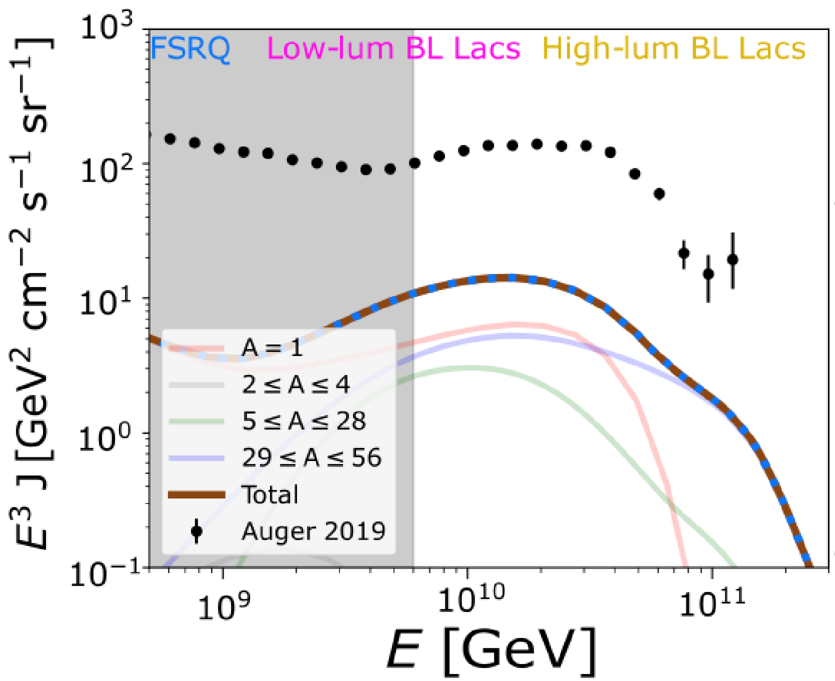


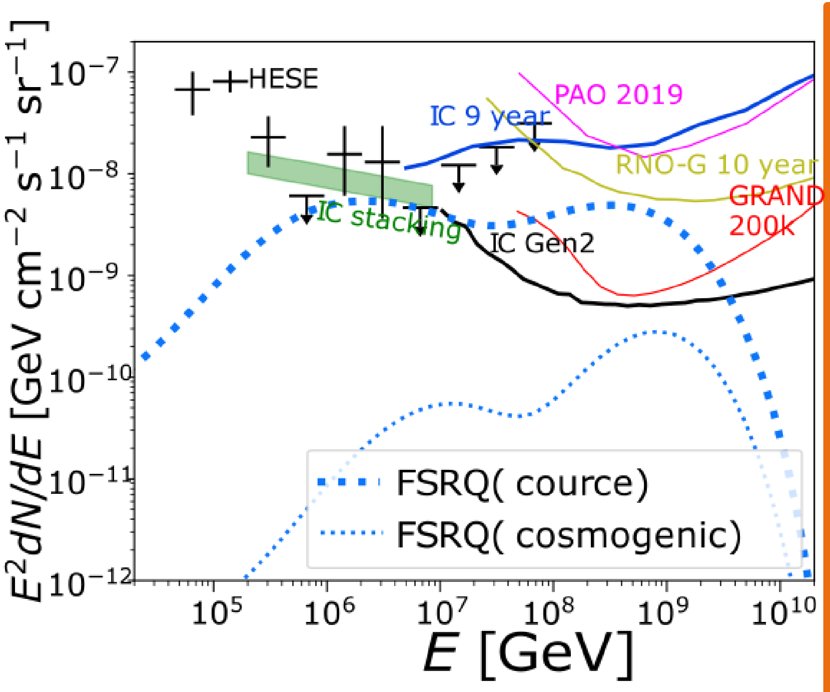
1. FSRQ can not be UHECR source
2. $\chi^2/_{d.o.f.} \approx {}^{1084}/_{30}$

Plotko P. et al. in preparation

Results

High-lum BL Lacs and FSRQ





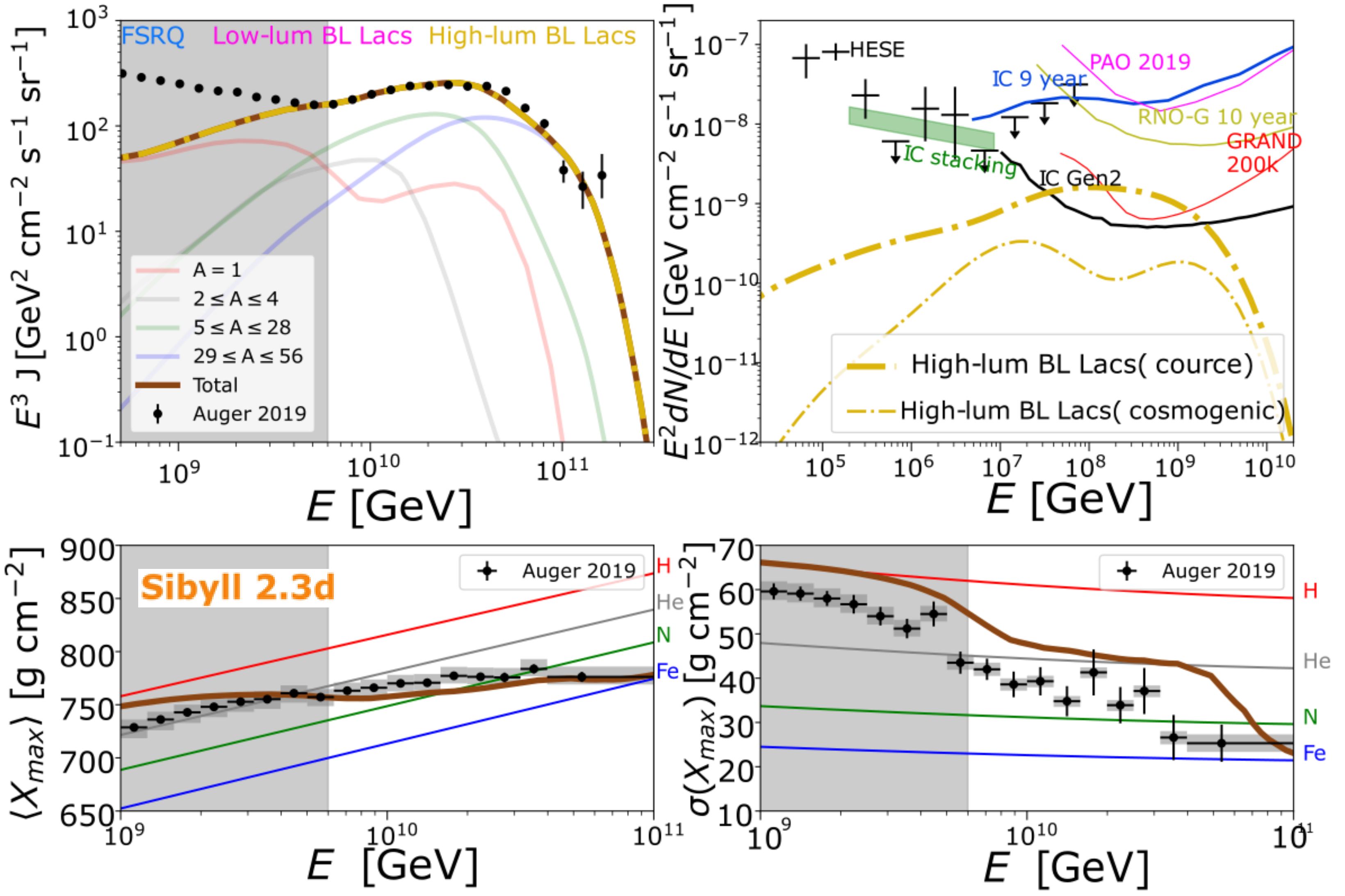
Sibyll 2.3d

1. FSRQ can not be UHECR source
2. $\chi^2 / _{d.o.f.} \approx {}^{1084}/_{31}$
3. Baryonic loading <40

Plotko P. et al. in preparation

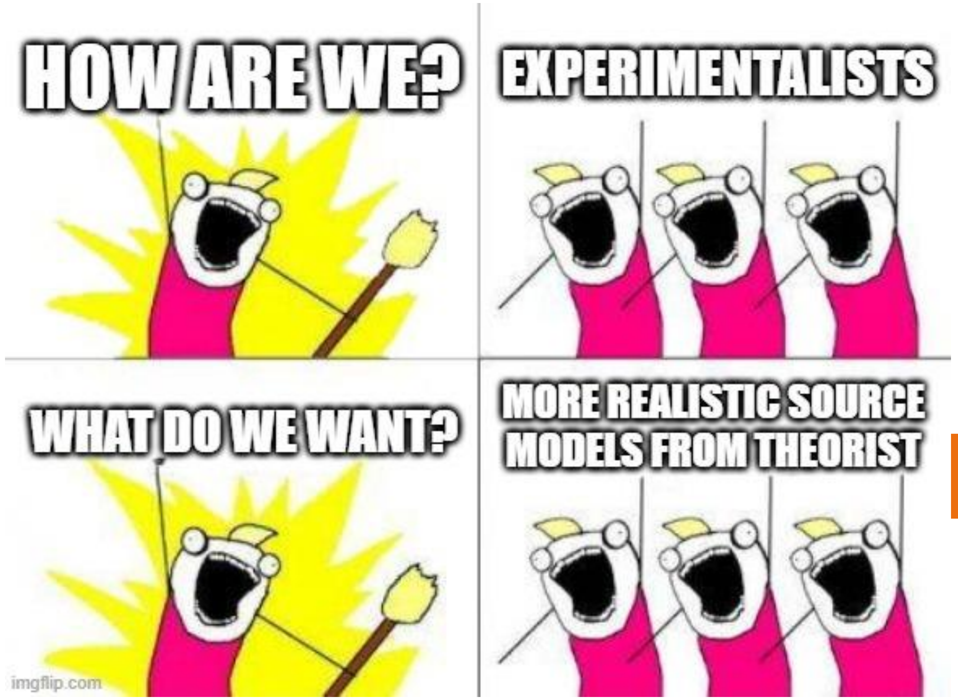
Results

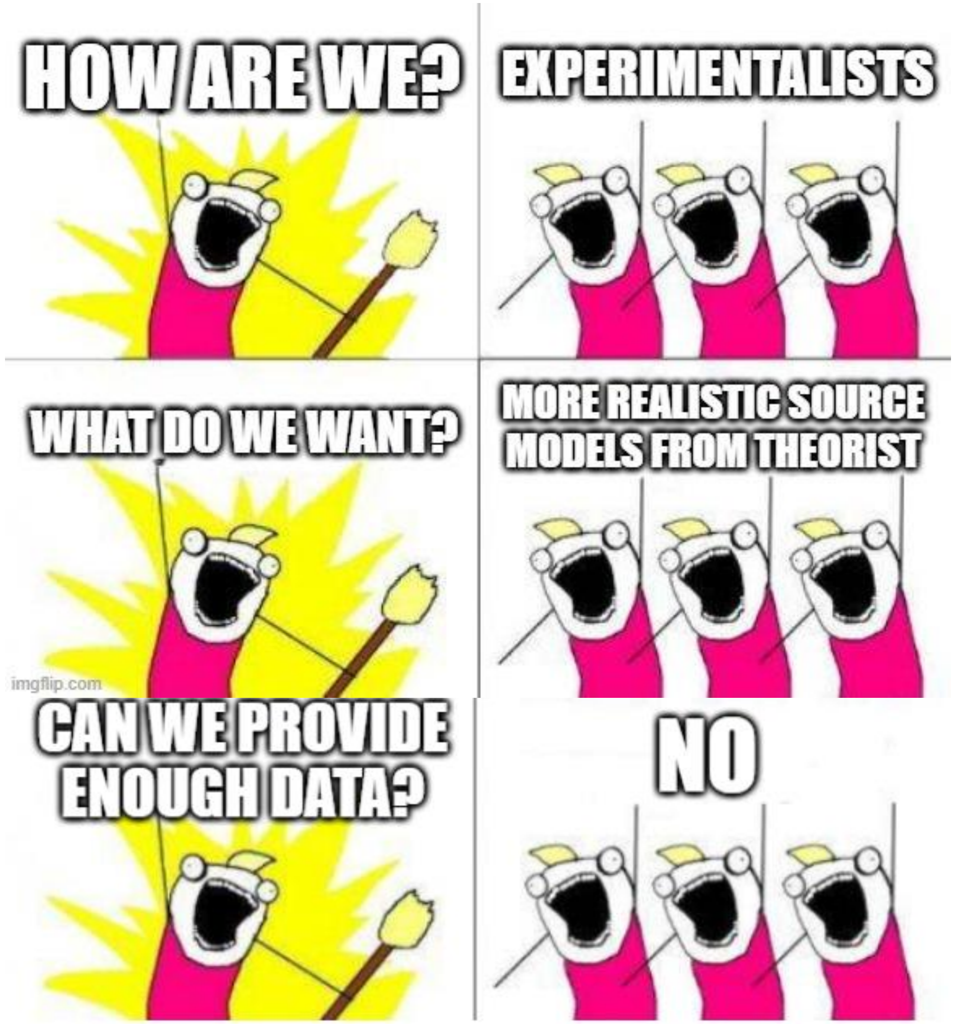
High-lum BL Lacs and FSRQ



1. FSRQ can not be UHECR source
2. $\chi^2/_{d.o.f.} \approx {}^{188.4}/_{30}$
3. Baryonic loading < 243
4. Cosmogenic flux from jetted AGN is too low for all cases

Take-home messages





Take-home messages

Jetted AGN can explain the UHECR data

Results strongly depend on air shower model

EPOS-LHC:	**SIBYLL 2.3d:**
1. UHECR from Low- and High-lum BL Lacs 2. High neutrino flux	1. UHECRs from Low-lum BL Lacs 2. Low neutrino flux

FSRQs are free source of neutrinos

I am looking for sponsors/support for Ukrainian Astronomy and Astrophysics projects

APPEC
DESY.
esa
Astronomische Gesellschaft
German Astronomical Society
ESO
Max-Planck-Institut
für Radioastronomie
KIT
Karlsruher Institut für Technologie
AIP
Leibniz-Institut für
Astrophysik Potsdam

Open technical questions

- How to compare models to each other. “ This model A is 3 sigma better compared to model B”
- How to calculate composition errors and consider the correlation between the fraction of injected elements.
- How properly put upper limits on contributions of FSRQ