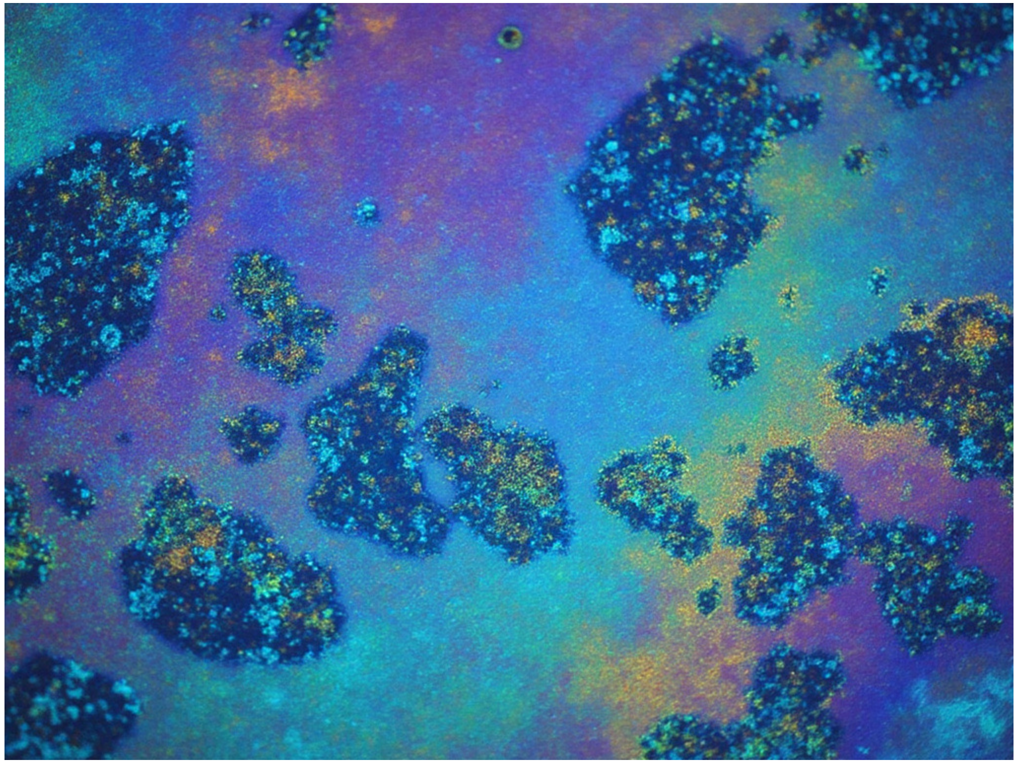
UHECR 2024

– Malargüe, 17th of November 2024 –

What can be learned about UHECRs from anisotropy observations?

Étienne Parizot, Denis Allard, Julien Aublin and Bruny Baret

(APC, Université de Paris)



Some recollection

- My first time in Malargüe was in November 2000

A lot of enthusiasm! => New physics?

=> GZK cutoff or not? (although well established by HiRes in a direct way)

=> top-down models, topological defects, Lorentz symmetry violation, quantum gravity effects…

At the heart of astroparticle physics!

If GZK: only very few, very nearby sources => let's build Auger and TA and get all sources quickly! ("proton astronomy"!)

=> A lot has changed, but it all comes down to one simple thing: **nuclei**

- Indeed, remarkable things have been accomplished from the observational point of view (Auger and TA)!
- Yet here we are ¼ of a century later, still not knowing:
  - What are the UHECR sources? → Not even general information (source density? transient? Etc.)
  - What is their acceleration mechanism?
  - What do they teach us about physics and astrophysics?

=> Have we failed?
Has Nature failed us?

Well, perhaps the astrophysical side of UHECRs had been neglected a bit too much… 😉 **nuclei!**

Some recollection

(I apologize for a somewhat personal introduction)

- I joined Auger in Oct. 2000, coming from High-Energy Astrophysics, particularly **particle acceleration** and light element nucleosynthesis by **spallation during cosmic ray propagation** in the interstellar medium

For anyone with such a background, the first thing that comes to mind is that assuming UHECRs are pure protons makes no astrophysical sense!

The cosmos doesn't know what it accelerates!

Whatever the mechanism, if you are sitting around and you are electrically charged, you will get accelerated!

Nowhere in the universe is there a place with purely protons!

- Does it make a difference? Not necessarily!

H nuclei (protons) are the dominant species anyway!

GZK horizon/cutoff still applies, and GZK works also with nuclei!

- => let's calculate!

With Denis Allard, we realized that most cross sections were missing! (Nuclei propagation had not been investigated since 1976!)

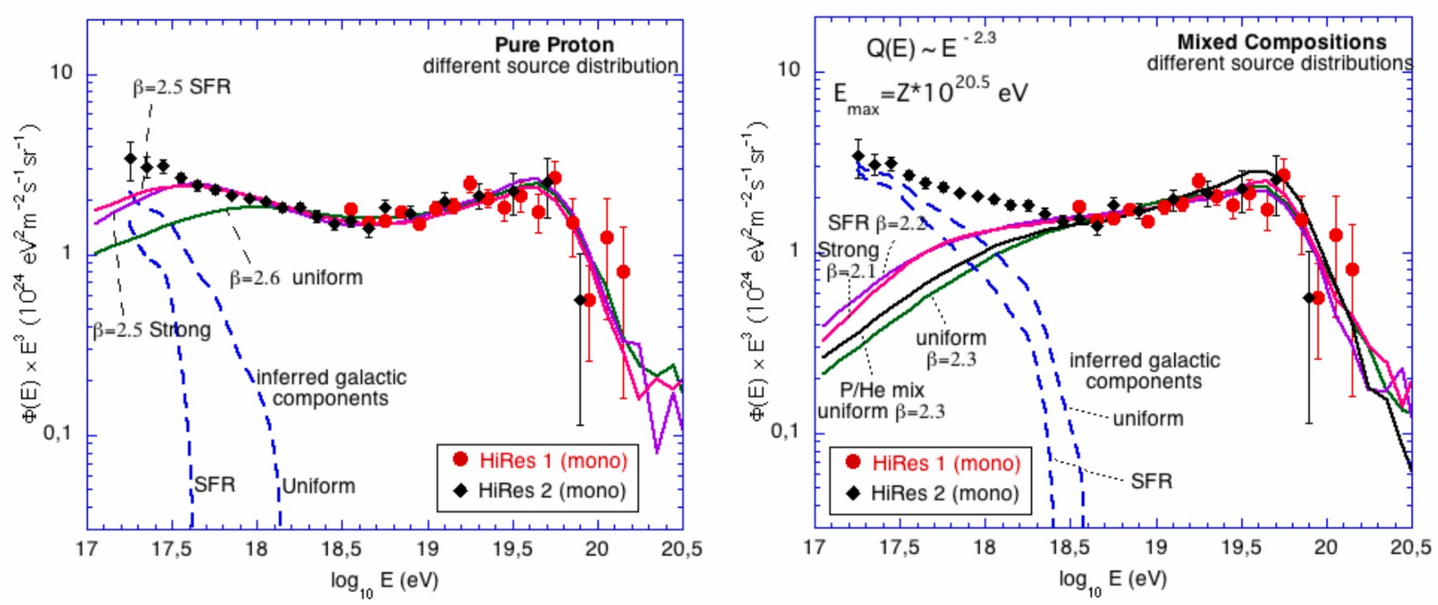
=> Updates and estimates with nuclear physicist at IPN Orsay

=> Detailed propagation scheme for mixed composition UHECRs

=> No electron-positron dip at the ankle! Even with pristine matter coming straight from the primordial universe!

Nuclei among UHECRs

- Even primordial gas with 10% helium breaks the beautiful idea of an electron-positron dip to explain the ankle:



=> end of the hope to use the "dip" as an absolute energy scale!

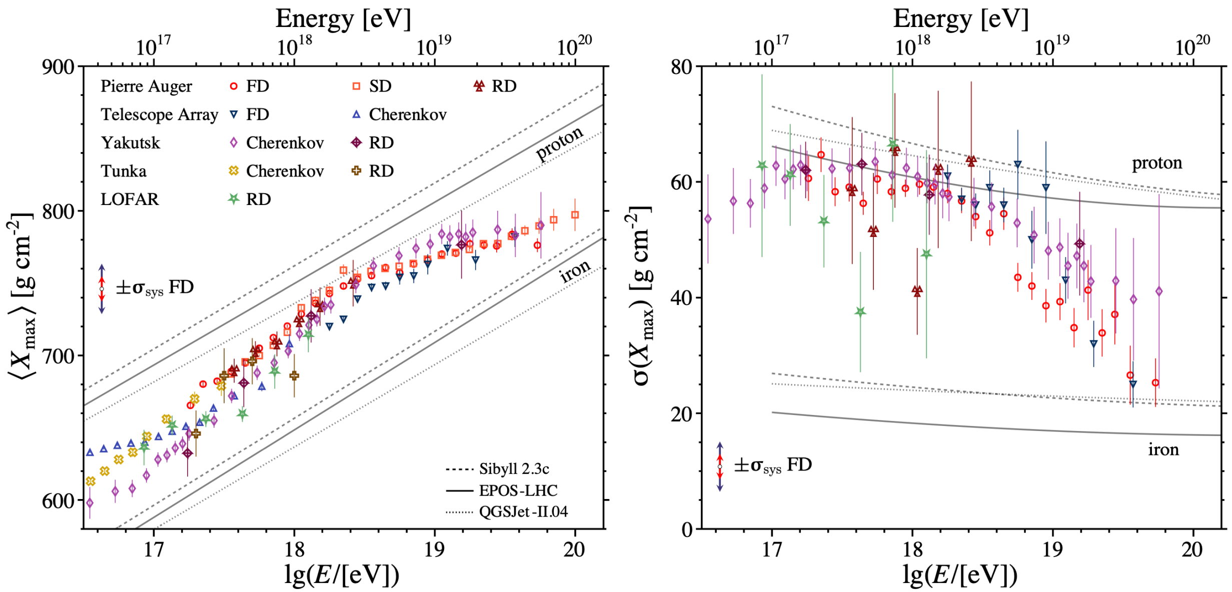
NB: from the astrophysical point of view, this made total sense:

The ankle is in the range where it is expected from cosmic-ray propagation

=> natural transition from Galactic to extragalactic cosmic rays

(NB: more important information about GCRs than about UHECRs!)

Nuclei among UHECRs



• Key revolution: discovery of the light-to-heavy transition

=> Big surprise in the room!

=> (Even bigger) surprise when I pointed out that this was actually not a surprise, but the most natural thing to expect!

=> Literally 10 seconds to understand!

Having played so much with nuclei propagation, it was totally clear to us that it could not be a propagation effect!

=> It had to be coming from the sources!

For anyone who had worked on particle acceleration before, it would have just as obvious as it was to me then!

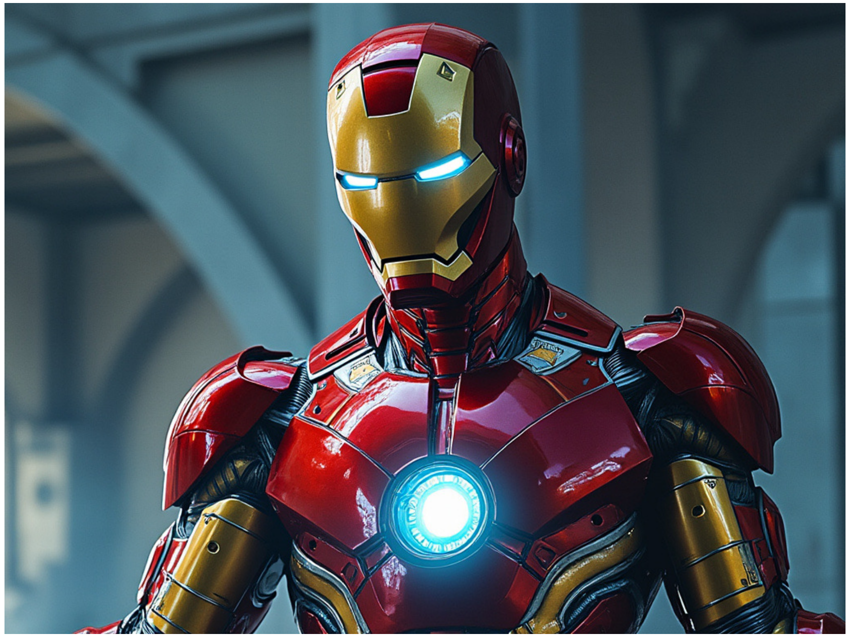
$E_{max} \propto Z$ (A)

=> $E_{max}(p) < E_{max}(CNO) < E_{max}(Si) < E_{max}(Fe)$

=> low proton-E_{max} models!

NB: no pride! Rather shame, actually: we should have predicted it!

Low proton-E_{max} models



Some were working hard trying to find a bias in the data analysis that would lead to a false trend towards heavier nuclei at higher energy.

(In the meantime, I received the nickname of the Iron man! 😉)

But there was very little doubt in my mind, because
from the astrophysical point of view, it all made total sense!

The entire community had been puzzled for years that particles could be accelerated to such high energies: from all that was known about high-energy sources in the universe, that “ZeVatrons” could even exist seemed almost impossible, or at least extremely challenging!

But they had in mind protons! If Fe instead of H, the required maximum rigidity is a factor of 26 lower!!!

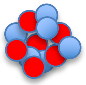
=> It made things much easier! **=> It should really have been predicted!**

With low proton-E_{max} models:
- the acceleration was not so terribly challenging anymore easy to fit.
- the energy spectrum was easy to explain
- the Galactic-to-extragalactic transition was natural
- the absence of UHECR “multiplets” was perfectly natural

Consequences

Emax (nucleus) = Emax (proton) x charge of the nucleus   Fe nuclei: 26 times higher in energy!

proton  $E = 10^{20}$ eV $\Delta\theta \simeq 2°$

Fe nucleus  $E = 10^{20}$ eV $\Delta\theta \simeq 52°$

Corresponds to Emax (proton) only 4 10^{18} eV => almost easy!

So… instead of a handful of sources over the entire sky, with very small deflections,
we have many sources everywhere with large deflections!

=> We are still in the "magnetic mist"…

In addition: the deflections are not known, because the magnetic fields are not known! (GMF, EGMF, regular, turbulent…)

=> the arrival directions of UHECRs are not very talkative

=> what can be learned from UHECR anisotropies?   => So far, not much, apart from this very fact!

Magnetic deflections

Large deflections, even at high energy!

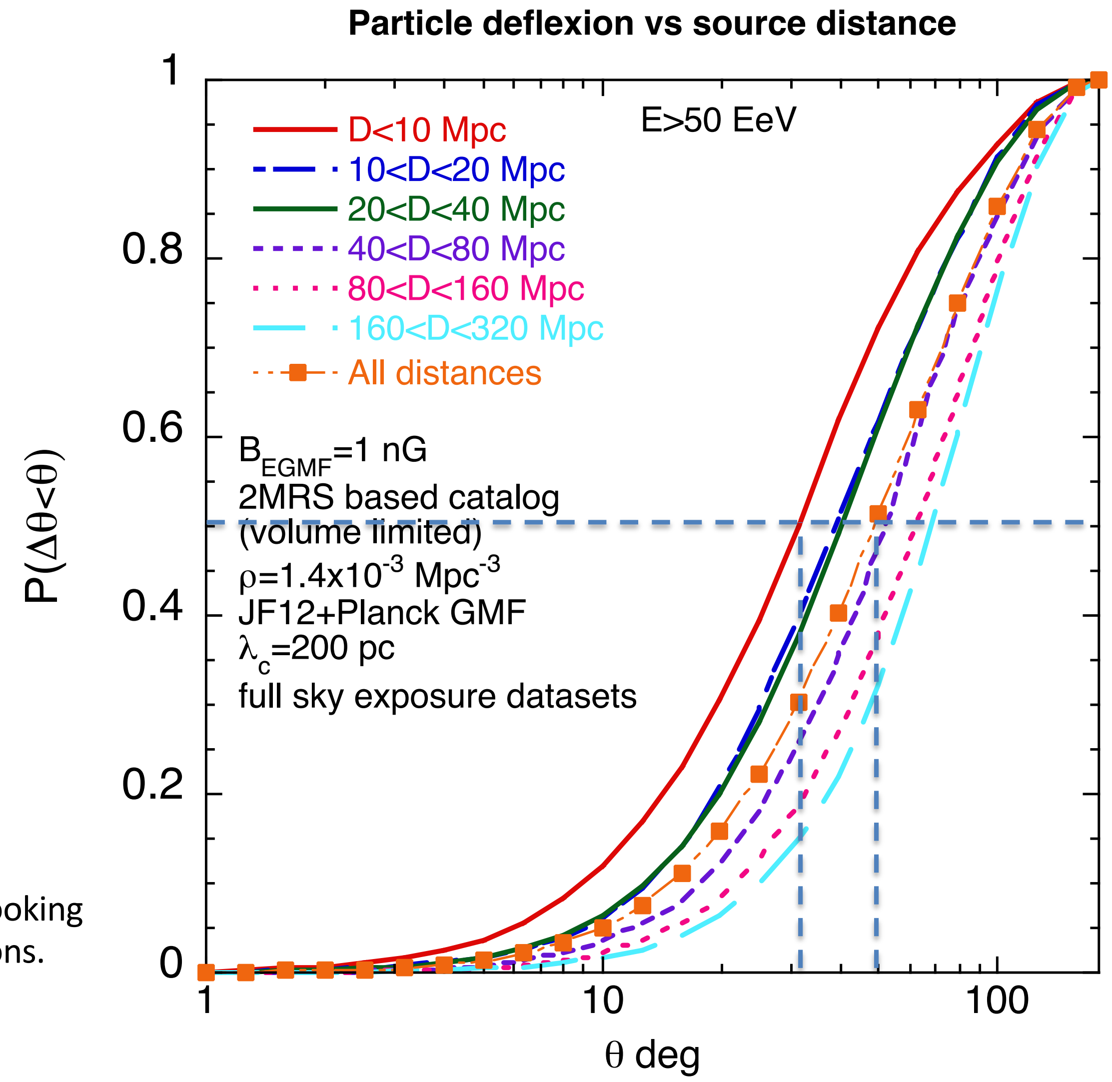
(Cumulative distribution of the deflections of UHECRs above 50 EeV)

50% of the events above 50 EeV are observed more than 50 degrees away from their source!

50% of the events 50 EeV coming from less than 10 Mpc away are observed more than 30 degrees away from their source!

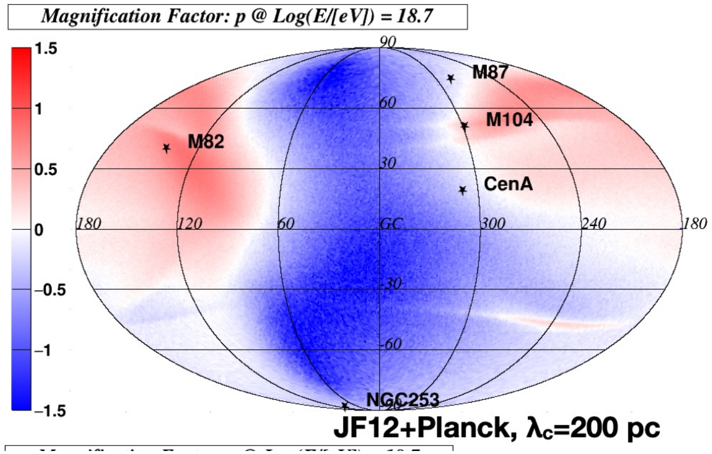
=> Please be very careful with any anisotropy analysis looking for correlations with sources without including deflections.

(Please be very careful also if they include deflections, as these are model dependent!)

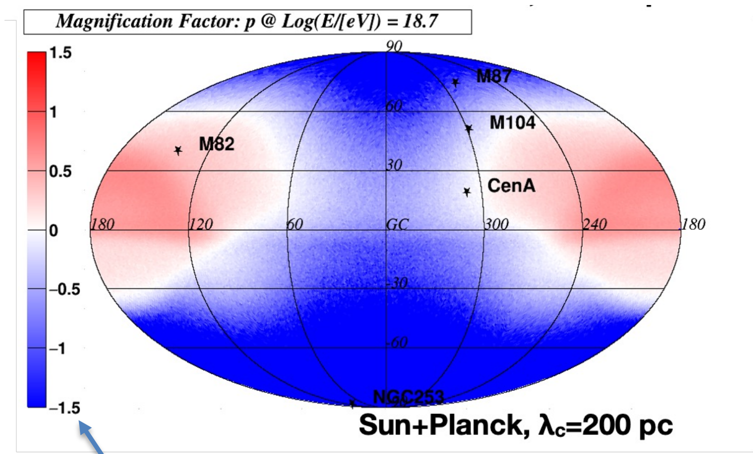


Magnetic magnification

Magnification/demagnification
depending on the source location in the sky…
…and on the magnetic field model!



Jansson & Farrar (2012)



divided by 30 !!!

Sun et al. (2010)

≃ 2/3 sky is demagnified!

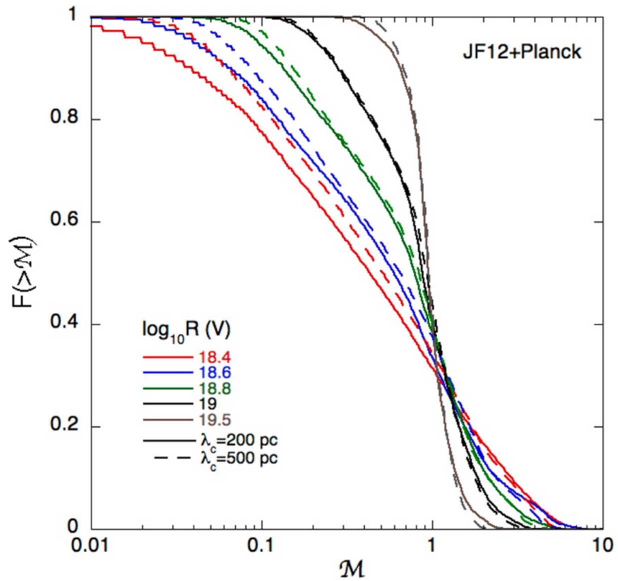


Fig. 4. Fraction of the sky $F(> \mathcal{M})$ filled with magnification factors larger than $\mathcal{M}$ as a function of $\mathcal{M}$. Various rigidities are considered (see legend), the GMF model studied is "JF12+Planck" and the considered coherence lengths are $\lambda_c = 200$ pc (lines) and $\lambda_c = 500$ pc (dashed lines)

Rigidity $10^{18.7}$ V

⇓

- proton at 5 EeV
- CNO at 30–40 EeV
- Si at 70 EeV
- Fe at 130 EeV

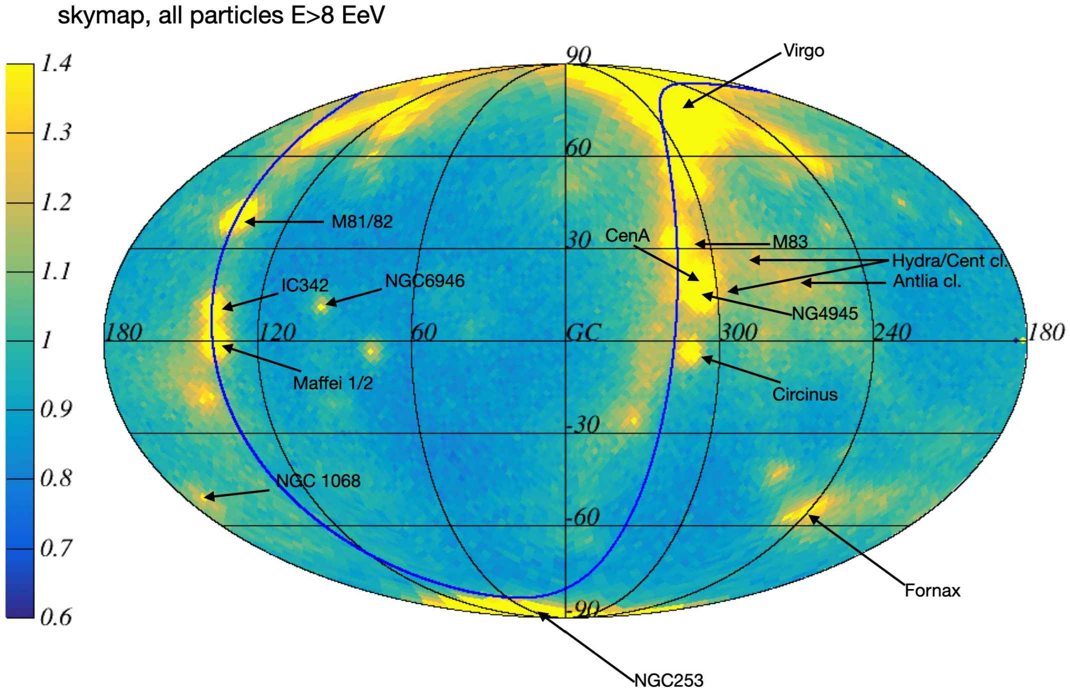
We are blind or almost blind to large parts of the sky.
=> Direct correlations with source catalogs (without deflections) do not make much astrophysical sense…

But remember Liouville's theorem: other sources contribute in the blind spots!

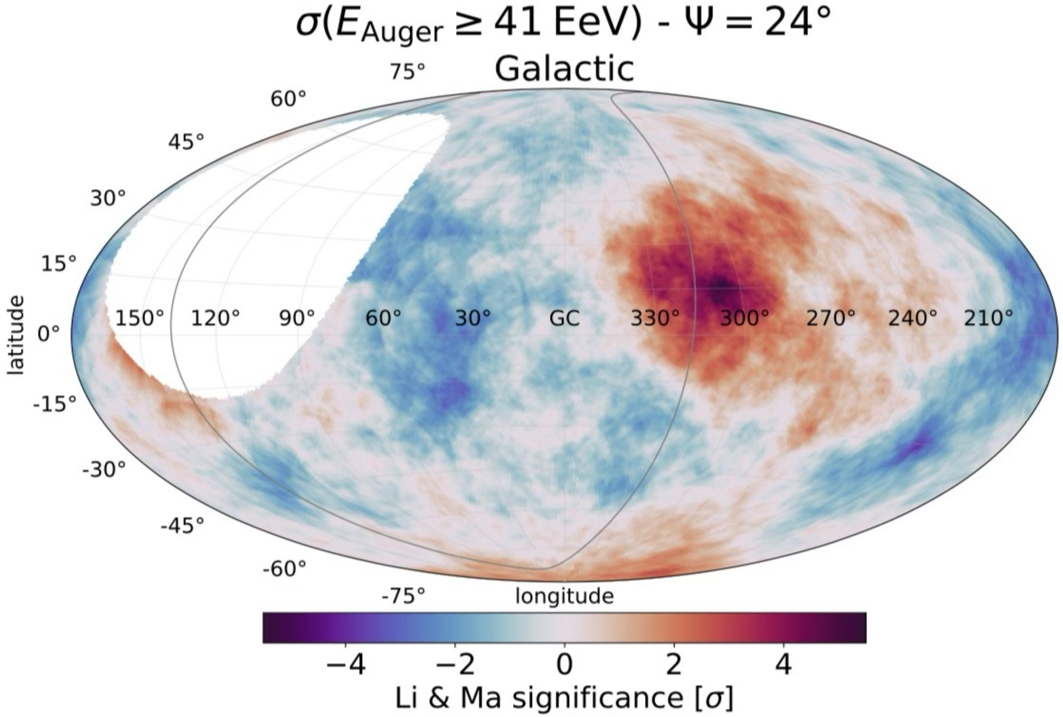
Magnetic deflections

ONE KEY QUESTION: WHERE ARE THE UHECRs FROM VIRGO? (IF ANY!)

Simulated skymap with standard galaxy distribution
without Galactic magnetic field



Li & Ma significance
Auger data (2023)

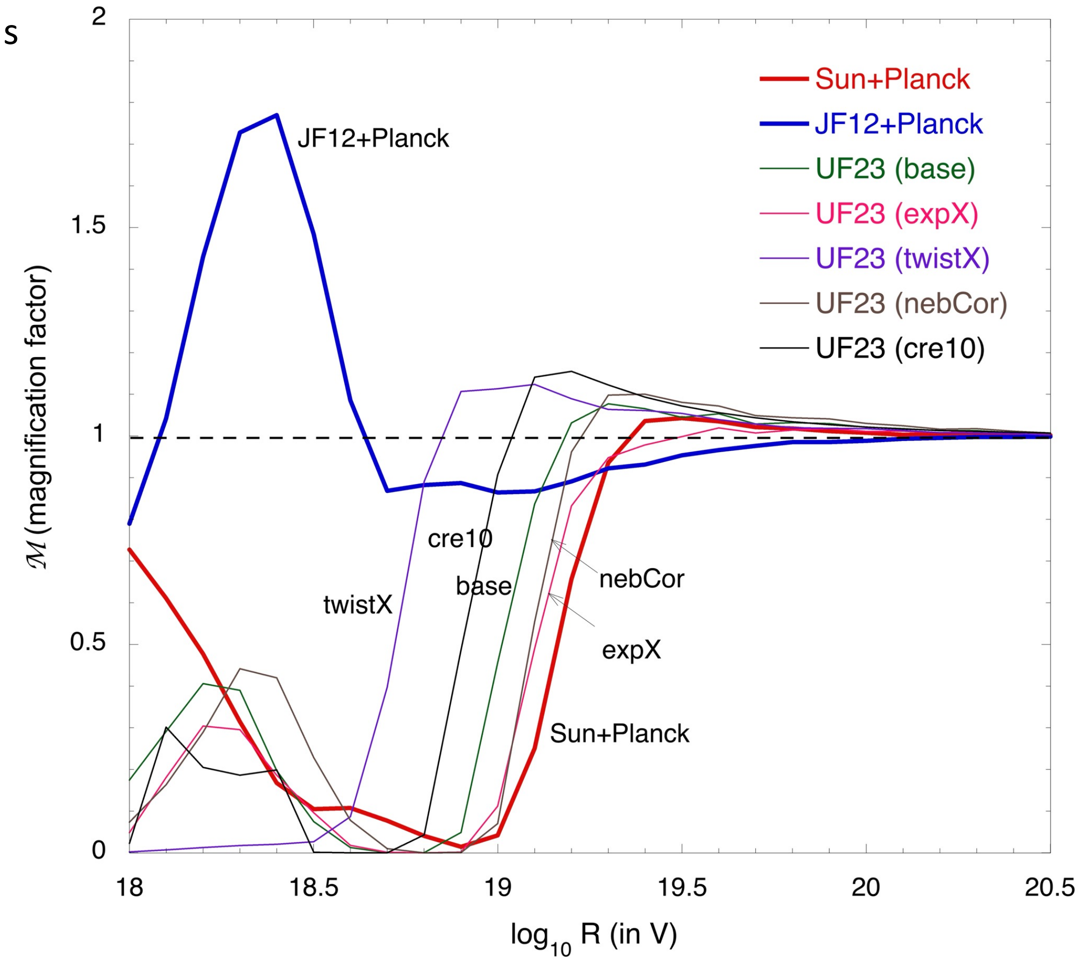


Magnetic magnification in the direction of the Virgo cluster

Unger and Farrar (2023): several versions

=> Jansson and Farrar 2012 appears very specific

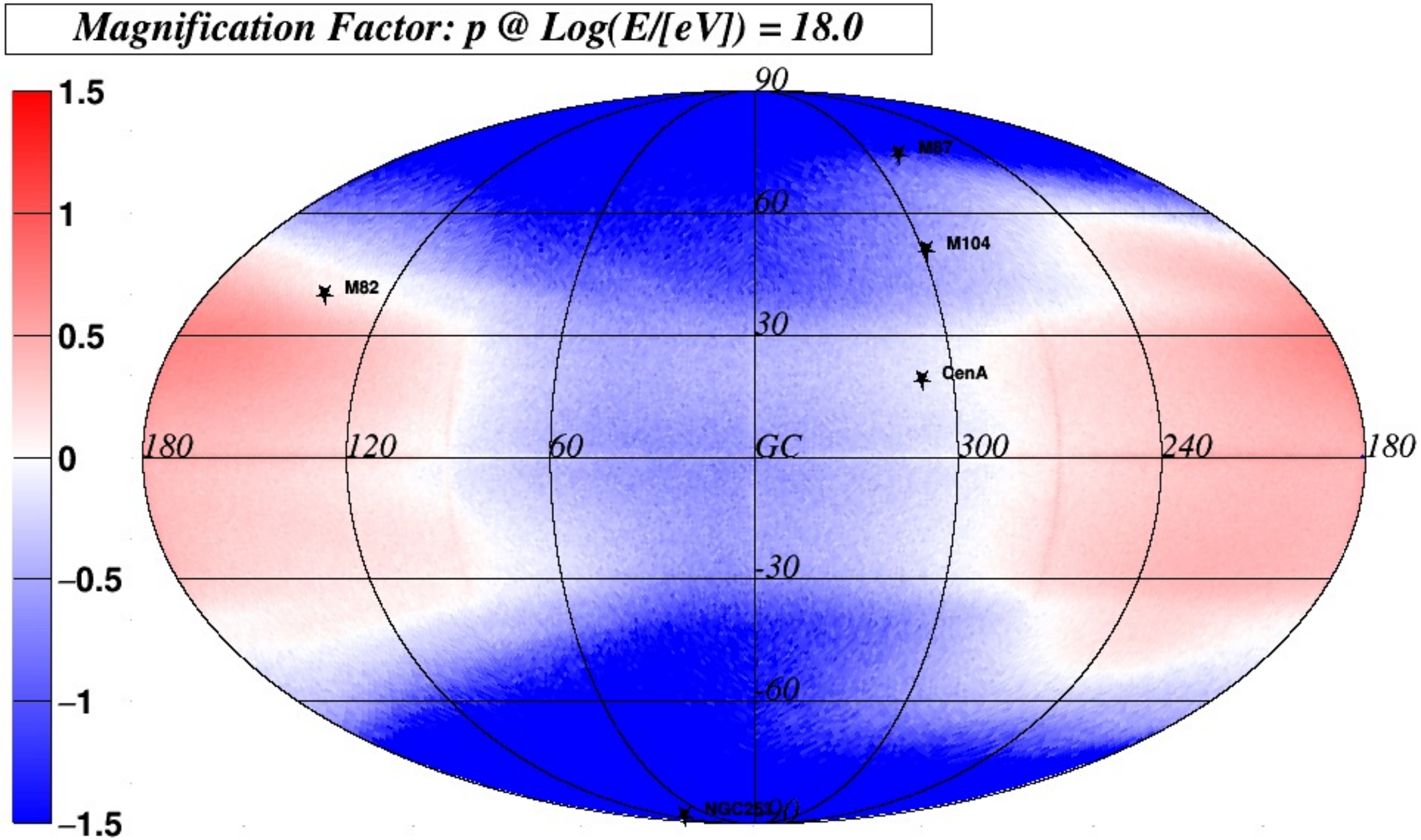
=> Unger and Farrar 2023: much closer to Sun et al. (2010)



Magnetic magnification maps

(Depends on rigidity!)

Unger & Farrar (2023): "base" model, with λ_c = 50 pc



UHECR anisotropies

1. Dipole (and quadrupole…)
2. Correlations with specific catalogs of putative sources
3. Hot spots (flux excesses or deficits)

Clean results!
High quality data!

But no clear useful implications for the quest of UHECR origin! (unfortunately!)

NB: DETECTING ANISOTROPIES IS NOT A GOAL IN ITSELF!

There is no point in proving that the UHECRs are not isotropic with ever more statistical significance.

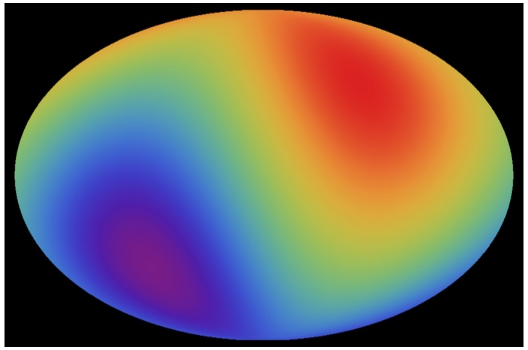
- "UHECRs are not isotropic" → Of course!
- "ever more statistical significance" → Of course!

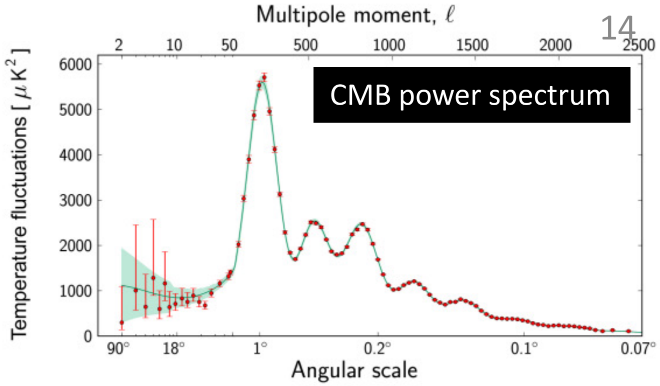
=> Focus on what is meaningful, i.e. what can provide astrophysical insight.

So far, unfortunately, the UHECR observations appear rather natural…
=> essentially no independent information

UHECR anisotropies: dipole

1





NB: not a dipole in the sense of the CMB dipole

Merely a non-zero power in the dipole component of the distribution of the UHECR arrival directions.

→ Of course!

Contrary to CMB: no particular meaning or prediction of the dipole amplitude
no particular meaning or prediction of the C(l) power

<u>But it does have to be reproduced by the models!</u>

Unfortunately: 1) This is rather "easy" Source models can easily adjust parameters to reproduce the dipole amplitude

2) It depends on many parameters:

- source composition
- source density
- EGMF amplitude
- GMF coherence length
- actual position of the source
- spread in the source intrinsic power
- Etc.

=> Cannot be disentangled without external reliable input (currently not available!)

=> No clue about the UHECR sources

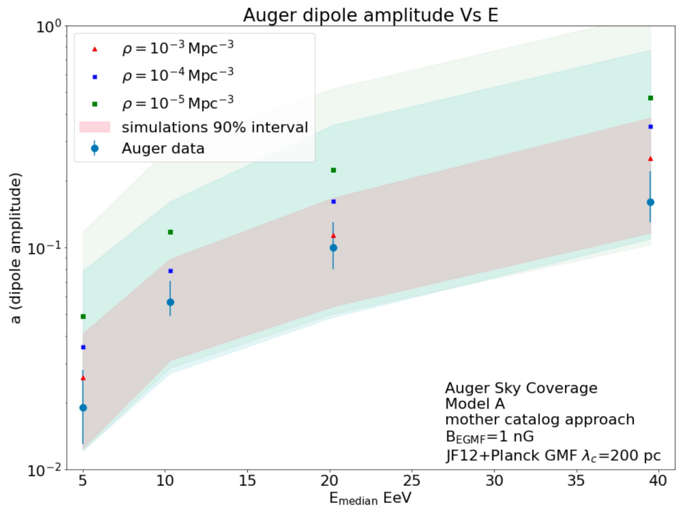
UHECR anisotropies: dipole

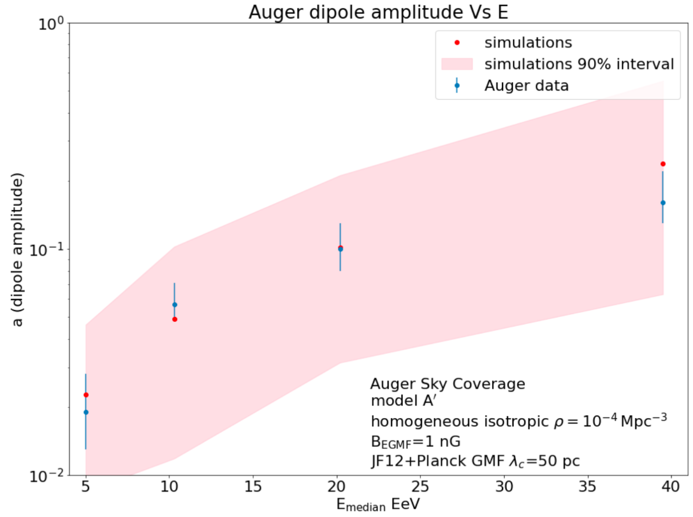
1

Possible interest:

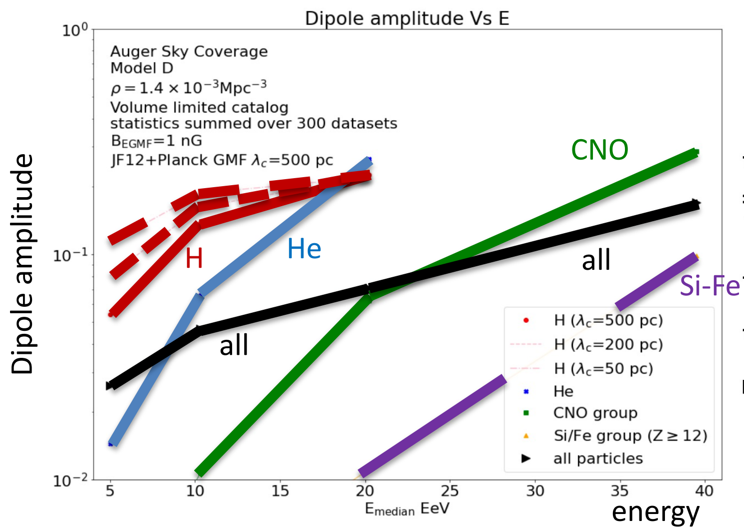
energy evolution of the dipole

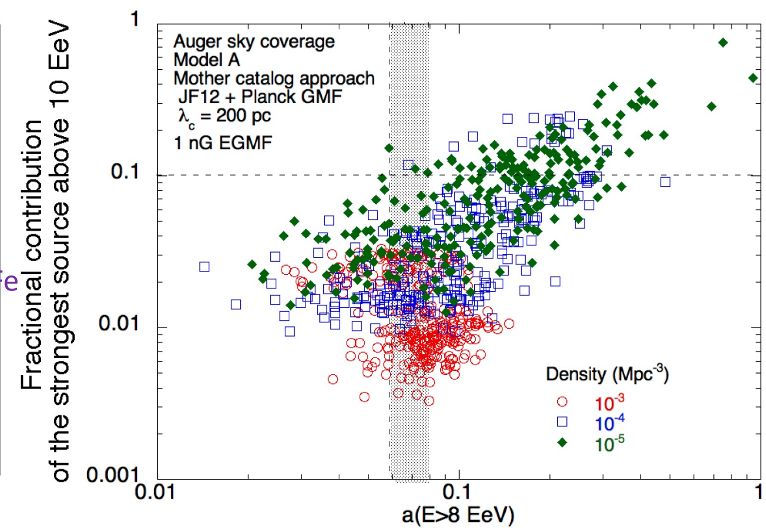
NB: large dispersion expected at current statistics





NB: some sensitivity to the composition, but unfortunately not independently of other assumptions





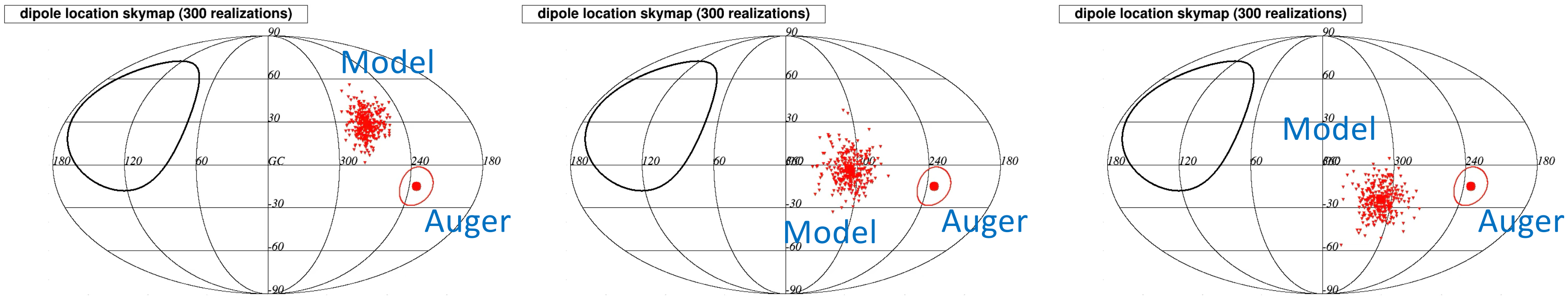
UHECR anisotropies: dipole

1

All galaxies in 2MRS above 1.2 10^{10} $L_{\odot}$ (i.e. $n_s \simeq 7.6\ 10^{-3}$ Mpc^{-3})

300 datasets with Auger statistics

=> tension with the Auger dipole position at high source density, because of the low cosmic variance



Jansson & Farrar (2012)
λ_c = 200 pc

Sun et al. (2010)
λ_c = 200 pc

Unger & Farrar (2023) (base)
λ_c = 50 pc

=> The Auger dipole position is not very natural => could contain some useful information!

But because a UHECR dipole has no intrinsic physical or astrophysical meaning, its reconstructed direction is most probably not the best handle on that information!

Many astrophysically different source distributions and UHECR arrival distributions would give the same dipole direction => not necessarily meaningful

(Even for a given GMF model !)

=> Beware to interpretation and conclusions

[+ Hand waving explanation]

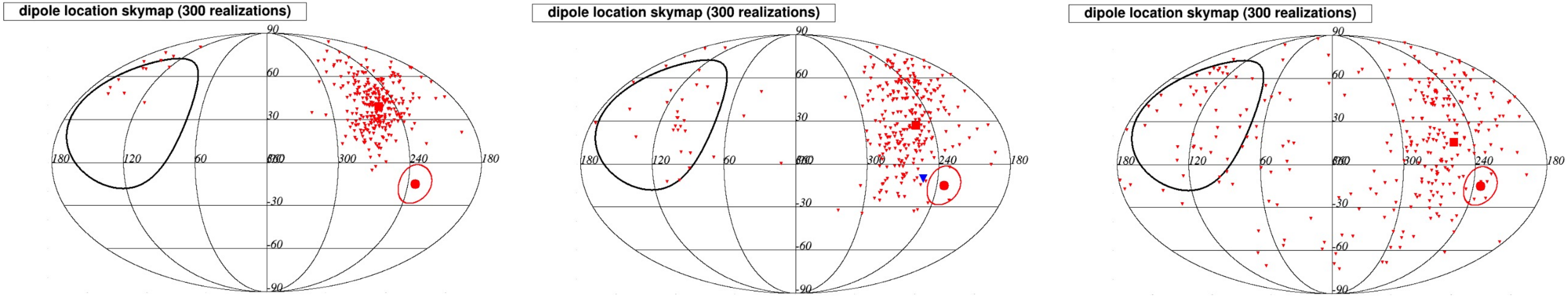
NB: saying that the dipole direction proves that UHECRs are extragalactic is wrong!

UHECR anisotropies: dipole

1

Subsample of all galaxies in 2MRS above 1.2 10^{10} $L_{\odot}$

300 datasets with Auger statistics (JF12+Planck, λ_c = 200 pc)



$n_s = 10^{-3}$ Mpc^{-3} **$n_s = 10^{-4}$ Mpc^{-3}** **$n_s = 10^{-5}$ Mpc^{-3}**

$\simeq$ 40 sources within 100 Mpc!
Large cosmic variance

In sum, what do we learn from the dipole: not much!

Amplitude is OK: easy to reproduce, including its energy evolution, but highly degenerate.

Could contain some info about the composition, but not precise and degenerate

Tension with the position if source density is very large.

but cosmic variance has to be important, because we have only one sky!

=> Position OK if one opens cosmic variance, but then no information from the dipole direction!

In any case, the dipole position cannot be the best handle!

(just a crude summary of the actual distribution of UHECRs, highly degenerate…)

UHECR anisotropies: correlations with specific catalogs of putative sources

2

BEWARE: just a test of isotropy!

Only to exclude isotropy with largest possible significance => no astrophysical meaning!

In what sense?

types of galaxies from the *Swift*-BAT and 2MASS surveys, have been investigated for comparison. The sky model of cosmic-ray density constructed using each catalog has two free parameters, the fraction of events correlating with astrophysical objects and an angular scale characterizing the clustering of cosmic rays around extragalactic sources. A maximum-likelihood ratio test is used to evaluate the best values of these parameters and to quantify the strength of each model by contrast with isotropy. It is found that the starburst model fits the data better than the hypothesis of isotropy with a statistical significance of 4.0σ, the highest value of the test statistic being for energies above 39 EeV. The three alternative models are favored against isotropy with

Well, that's not a fit…

Gives the wrong impression that "starburst" galaxies have been shown by the data to have something to do with UHECRs.

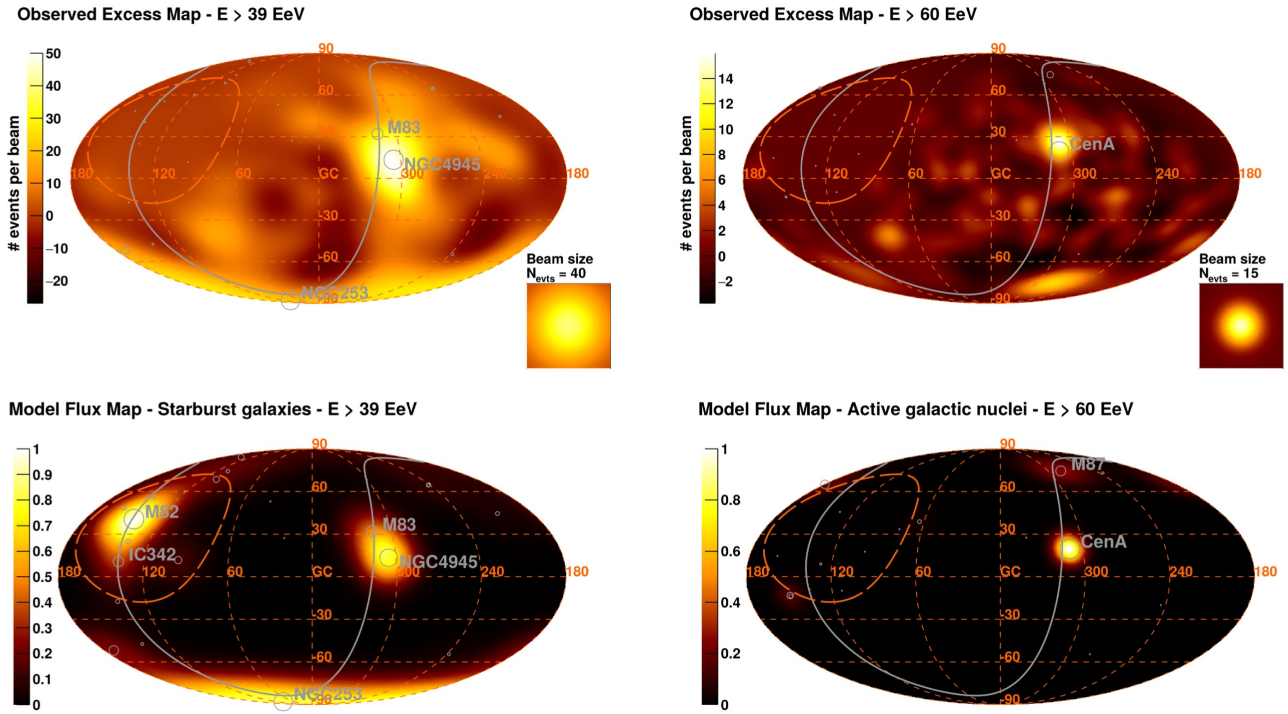
This is simply NOT the case!

In sum, what can be learned from this study? Not much… UHECRs are not isotropic.

(Which is a surprise to no one, but cannot as such be used to get any insight into the UHECR sources, unfortunately…)

UHECR anisotropies: correlations with specific catalogs of putative sources

2



NB: given the flux excess in the region of Cen A, any source model with sources in that region will be favored by the Likelihood test!

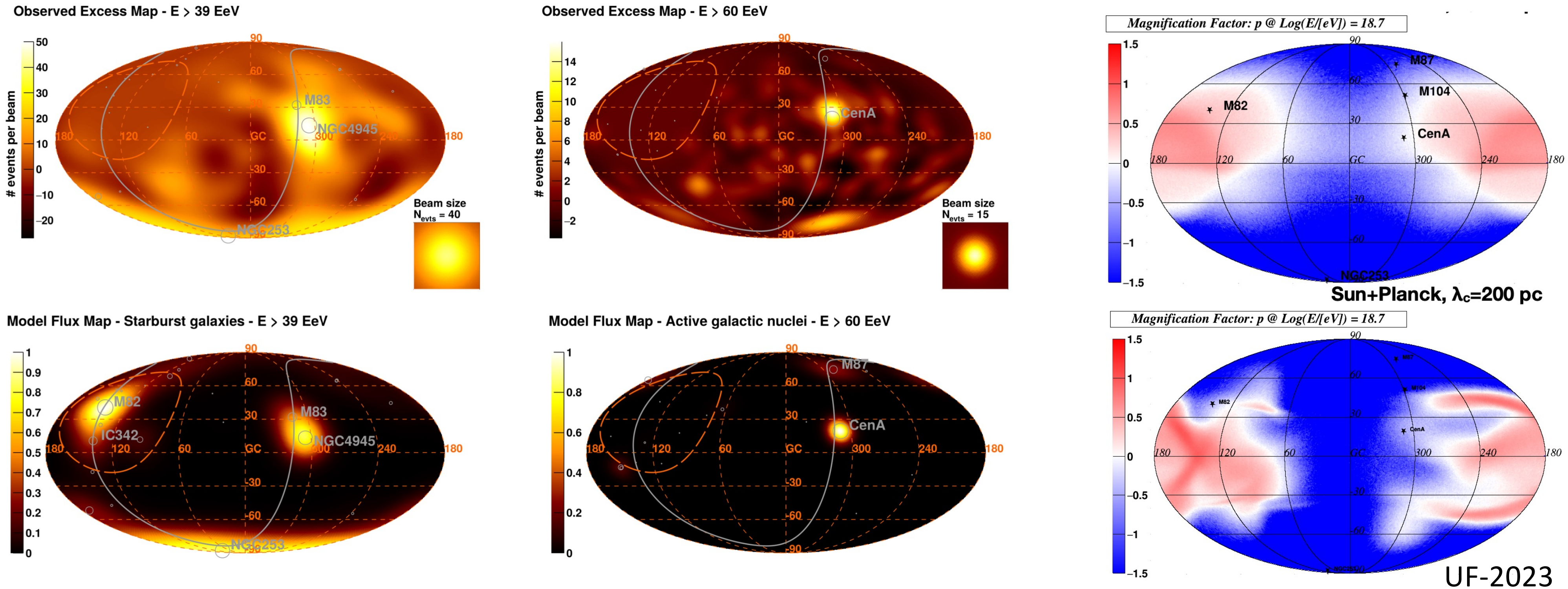
=> known from the start!

=> no new information

=> no astrophysical value

UHECR anisotropies: correlations with specific catalogs of putative sources

2



NB: NGC253 plays a big role in the "superiority" of the "starburst model" compared to the "AGN model"
(in excluding isotropy)

Yet these events most probably DO NOT COME from NGC253!

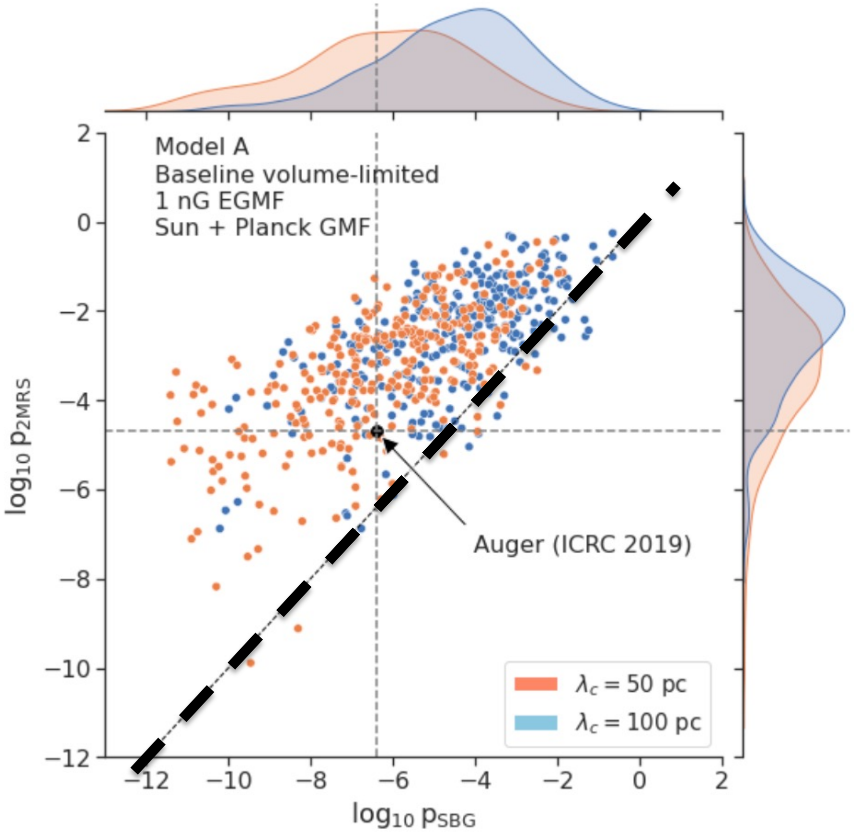
This study, which does not take into account deflections/magnifications, cannot provide insight into UHECR source models!

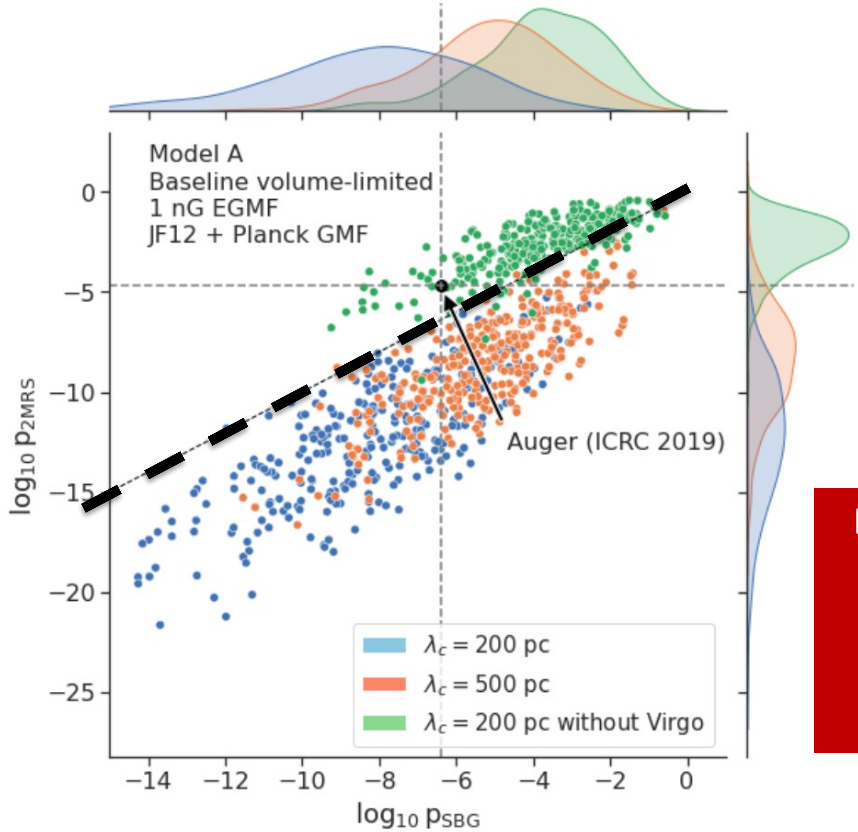
UHECR anisotropies: correlations with specific catalogs of putative sources

2

NB: for the same astrophysical source model, the “preference” for star forming galaxies vs. standard galaxies completely depends on the assumed magnetic field (notably through the demagnification or not of Virgo)

Above the line: standard galaxies preferred





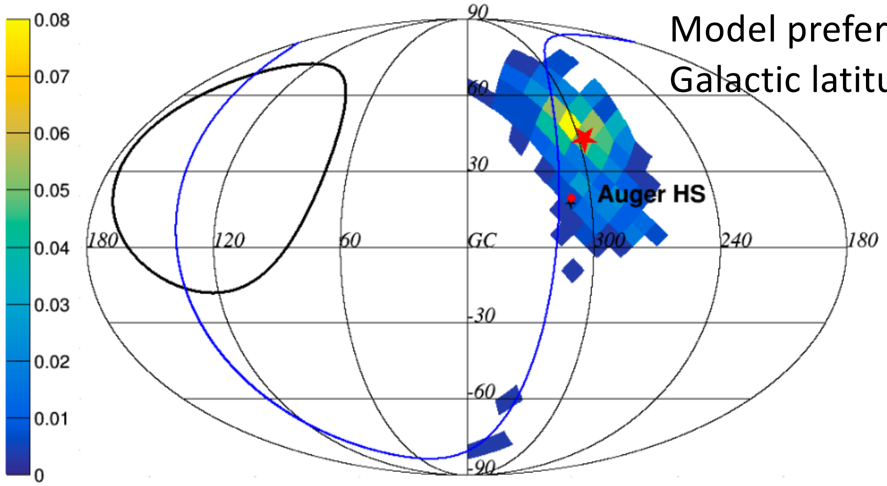
Below the line: star forming galaxies preferred

UHECR anisotropies: hot spots

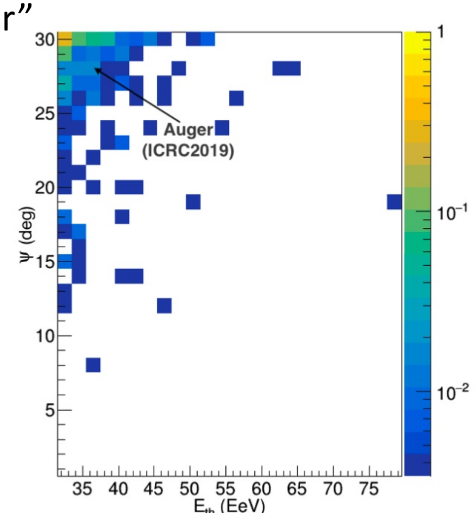
3

Searching for flux excesses… (or deficits!)

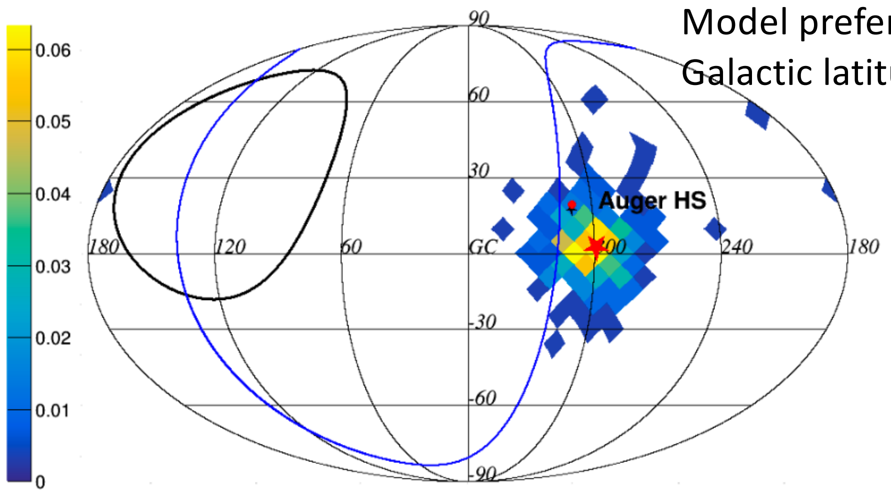
Jansson&Farrar



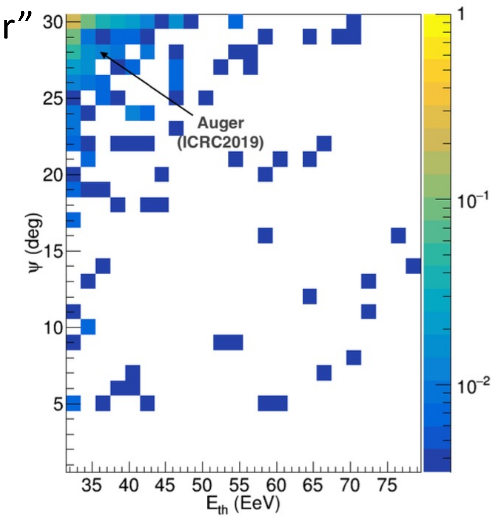
Model prefers "higher" Galactic latitudes



Sun et al.



Model prefers "lower" Galactic latitudes



How was the minimum energy of the scan chosen?

Please open the scan to lower energies…

Essentially all models expect higher significances at lower energy and higher angular scales

Please do not attribute too much meaning to current values of the parameters for the moment

(+ not really discriminating for source models)

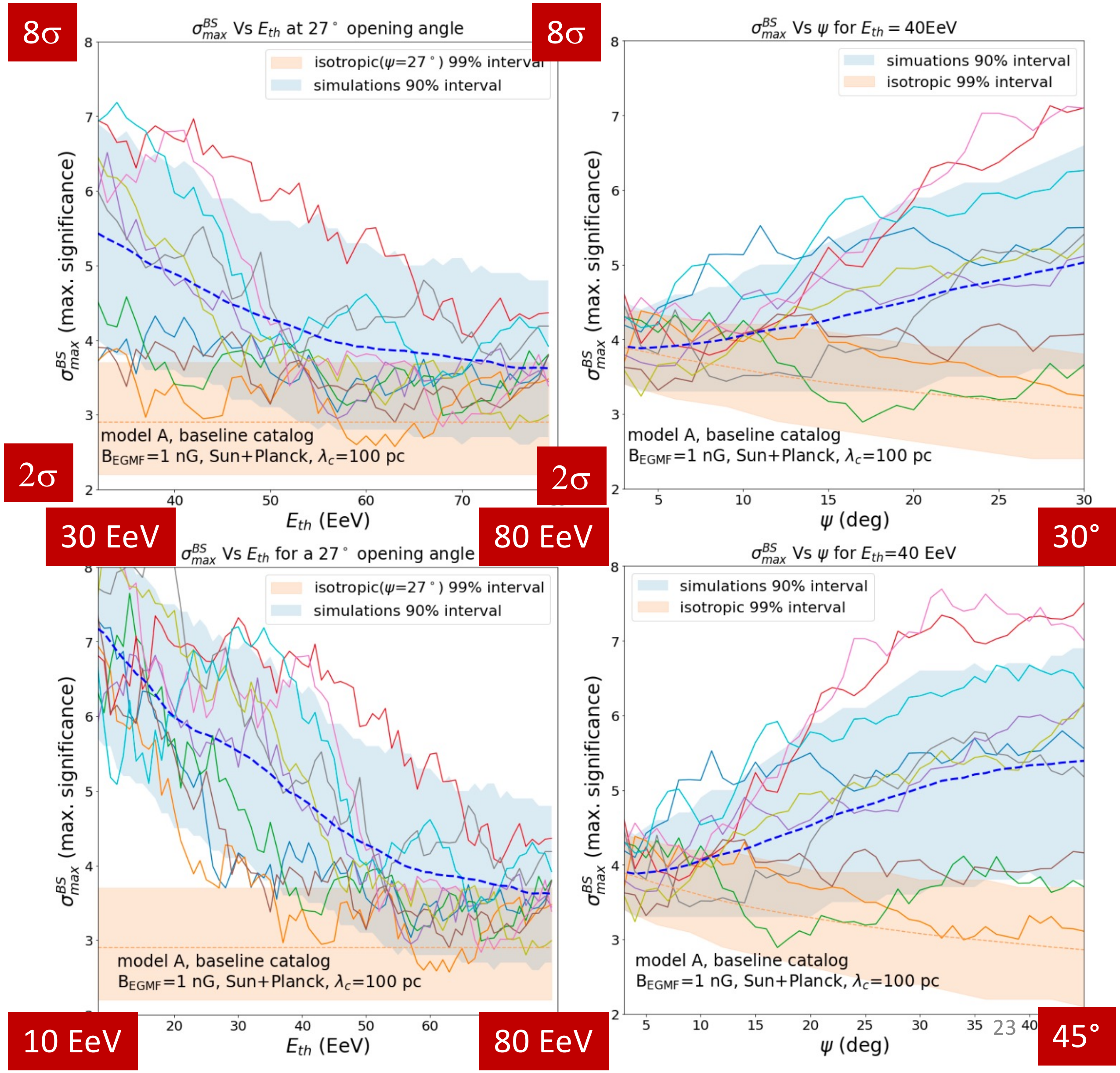
UHECR anisotropies: hot spots

3

A lot of variations at the current statistics!

Please show larger energy and angular range

Or better: make data public! 😉

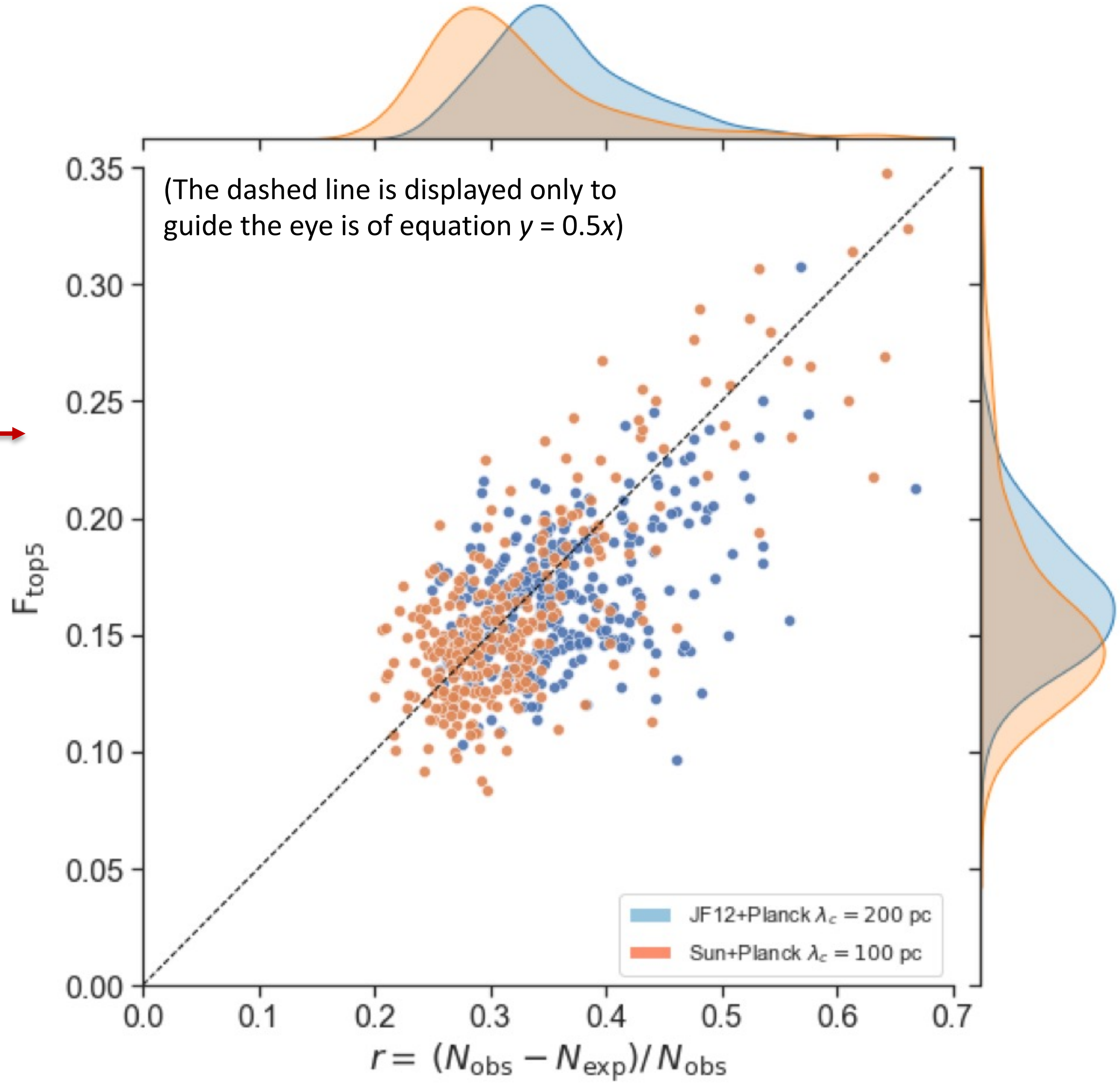


UHECR anisotropies: hot spots

3

BEWARE: AN EXCESS IS NOT A SOURCE!

Fraction of events coming from the 5 dominant sources (together) in the BS maximum window vs. the relative flux excess, *r* in that window (according to "standard" simulations)



NB: model expectations usually assume standard candles, or at least same spectrum and same composition for all sources

WE ALL KNOW IT'S WRONG!

UHECR anisotropies: ASTROPHYSICALLY MEANINGFUL RESULTS?

Dipole, hot spot, catalog correlation:
does not help identifying the sources (so far)

NB: UHECR observables should be reproduced TOGETHER (not one by one…)

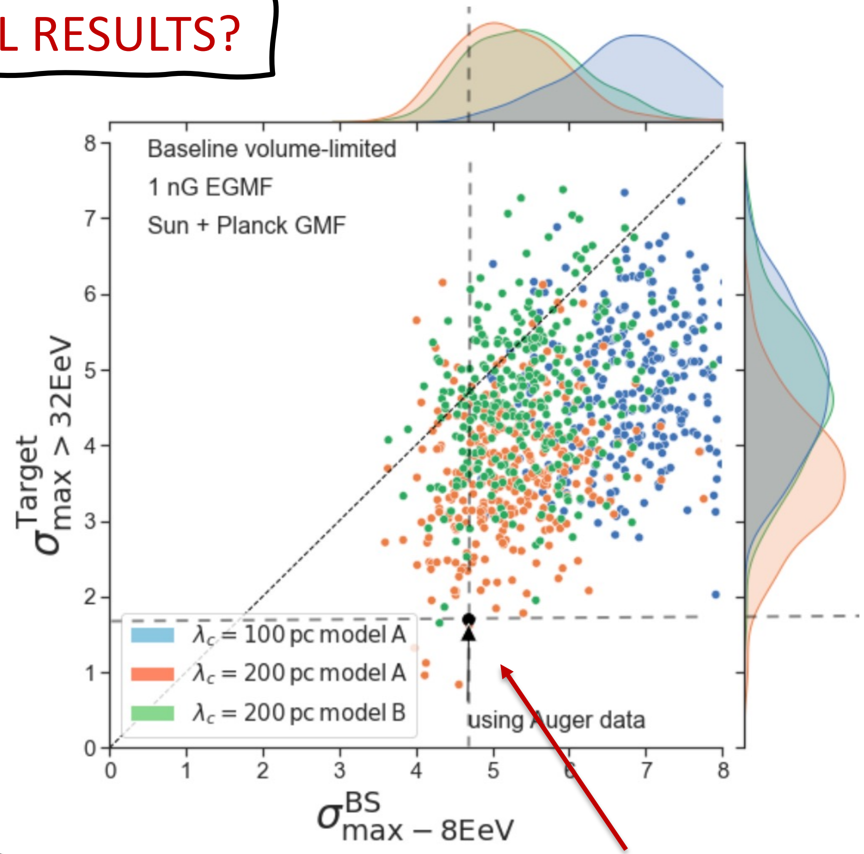
**MORE PROMISING (in our humble opinion):
ENERGY EVOLUTION OF THE UHECR SKY MAPS !!!!**

PLEASE PUBLISH THE DATA!!!!!!!!!!!!!!!!!!

Dipole could be dominated by a component that is disappearing at the highest energies…

For instance… Fornax!

Higher statistics over the entire sky would help => keep growing (=> JEM-EUSO!)



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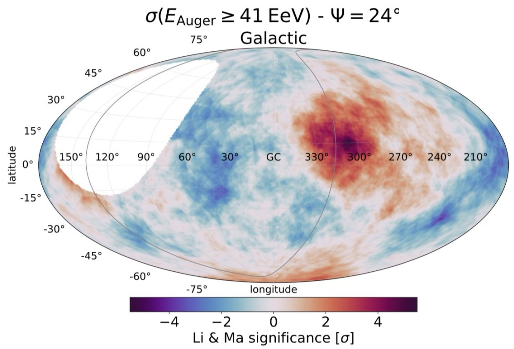

Last comments…

★ Main thing we learned so far from UHECR anisotropies is that they do not teach us much (so far!)

Once it was understood that UHECRs are mostly heavy at the highest E, immediate conclusions were:

1) It is not such a difficult task for a source to produce them, so there can be "numerous" sources
2) Deflections are probably quite large => overlap of many sources in any direction of the sky
3) Correlation studies are largely meaningless without an assumption on the magnetic fields
4) Knowledge of the magnetic fields is currently too poor for any clear conclusion (e.g. Virgo?)

★ Don't give up now!

Things have been more difficult than expected. But mostly because our expectations were wrong.

No crisis yet. On the contrary!

Observations are globally compatible with typical expectations => not very informative

★ Astrophysics condemned us (nuclei!)
Salvation will come from astrophysics too!

Better knowledge of the magnetic fields
[UHECRs from Virgo?]

Better understanding of the potential sources
[Multi-messenger astrophysics!]

★ Keep accumulating data!

Auger Prime   TA x 4

★ Need to increase statistics at the highest energies with full sky coverage => JEM-EUSO !!!

Nevertheless, it is better to study UHECR anisotropies than asking AI where the UHECR come from…

According to Grok's generative AI:

Please draw an image corresponding to 'Where do the UHECRs come from?'.

According to Grok's generative AI:

'Show what we can learn about UHECRs from anisotropy studies'

Go figure!

!!!

Maybe we are not bold enough!

😉