WRAPPING UP AND COLLECTING THOUGHTS

**Pasquale Blasi** - Gran Sasso Science Institute

COSMIC RAYS IN THE MULTI-MESSENGER ERA

This is not a new concept for CR physics: the field has been enjoying a wealth of data from radio waves, gamma rays, positrons, antiprotons, nuclei and having in mind the "behind-the-corner" discovery of neutrinos for decades…

The news is that neutrinos are finally here, that they are actually telling us more interesting things that we could have guessed…

and that we detected GW from a bunch of binary systems, and one of them happened to be a gamma ray burst (source of gamma rays, hence a source of non-thermal particles).
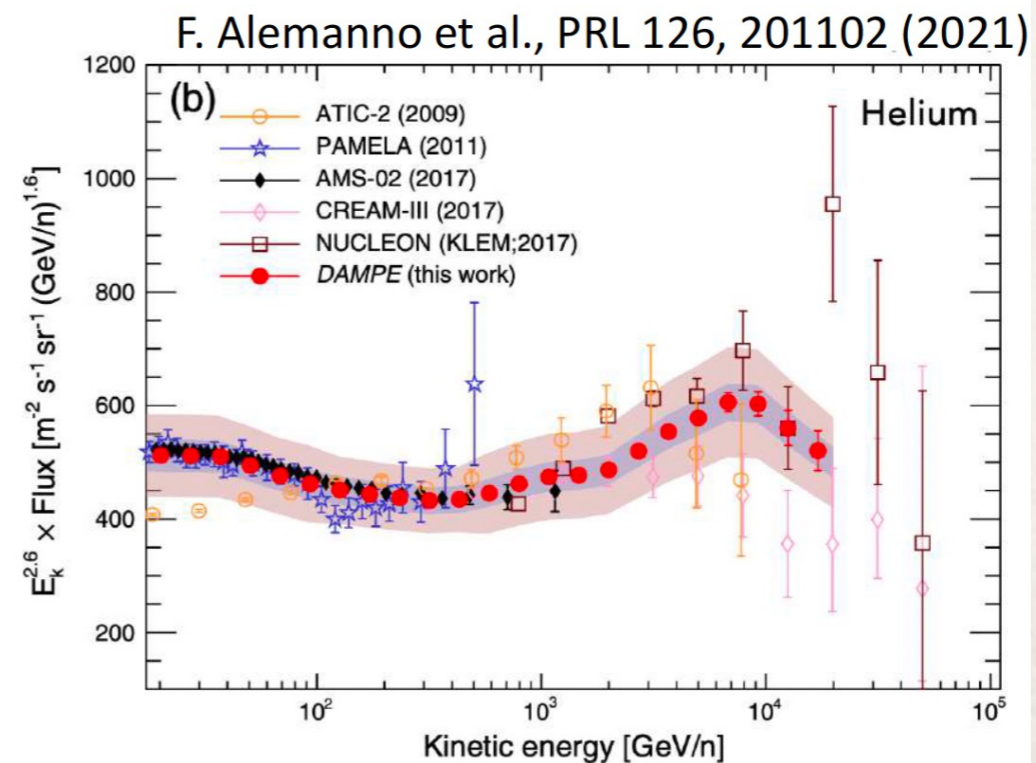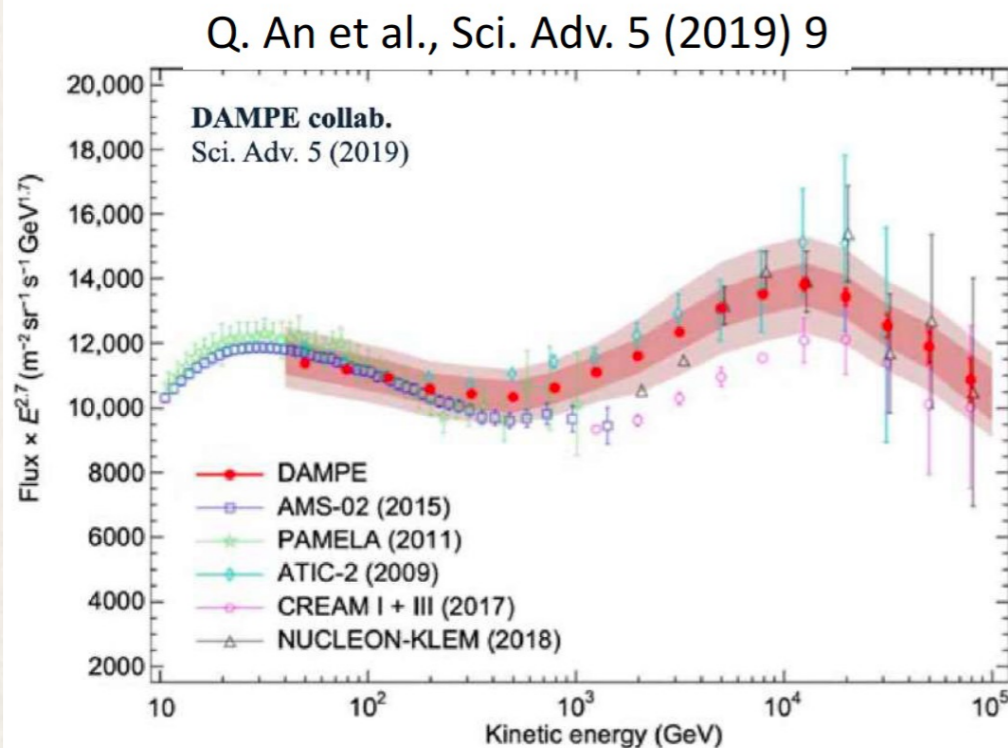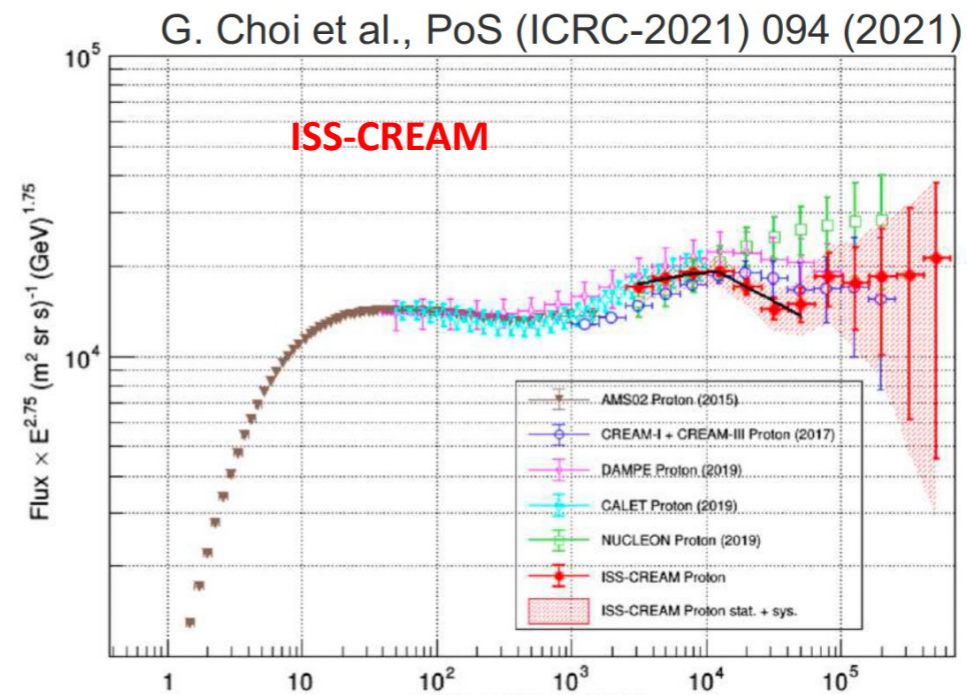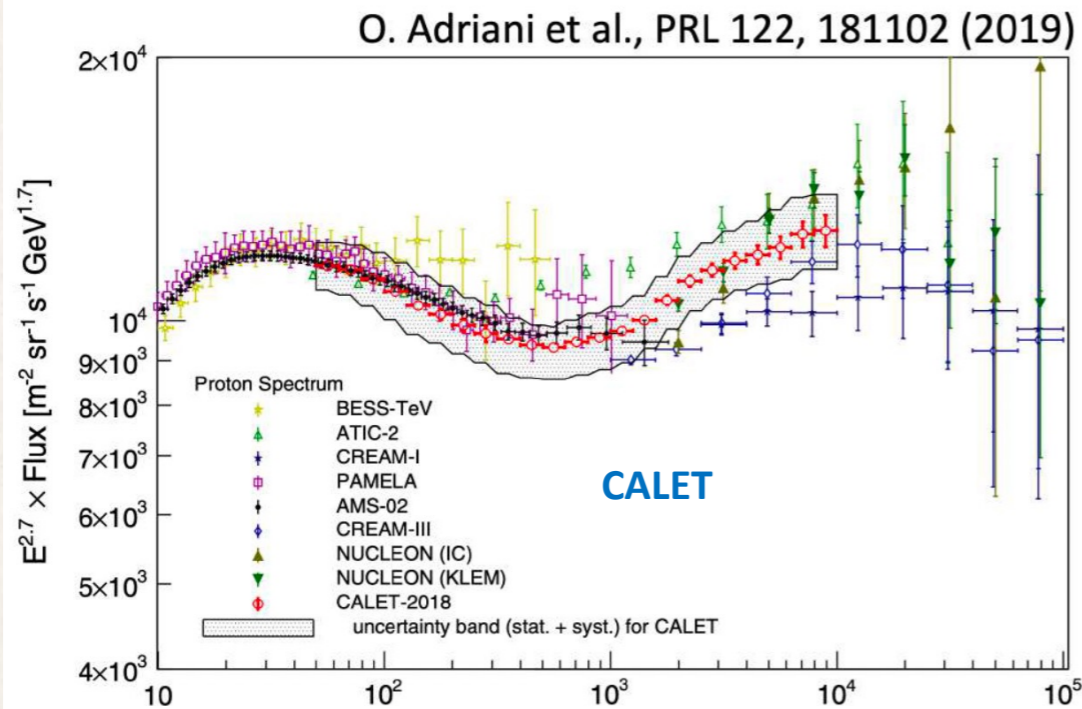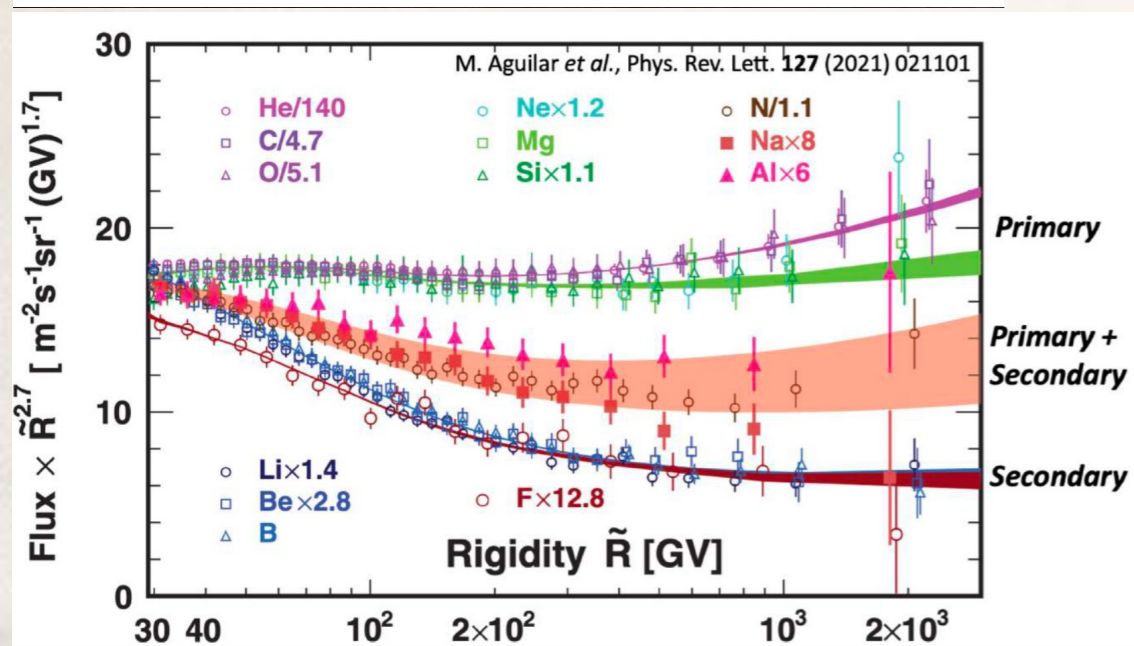
MEASUREMENTS...

J.C. Díaz Vélez
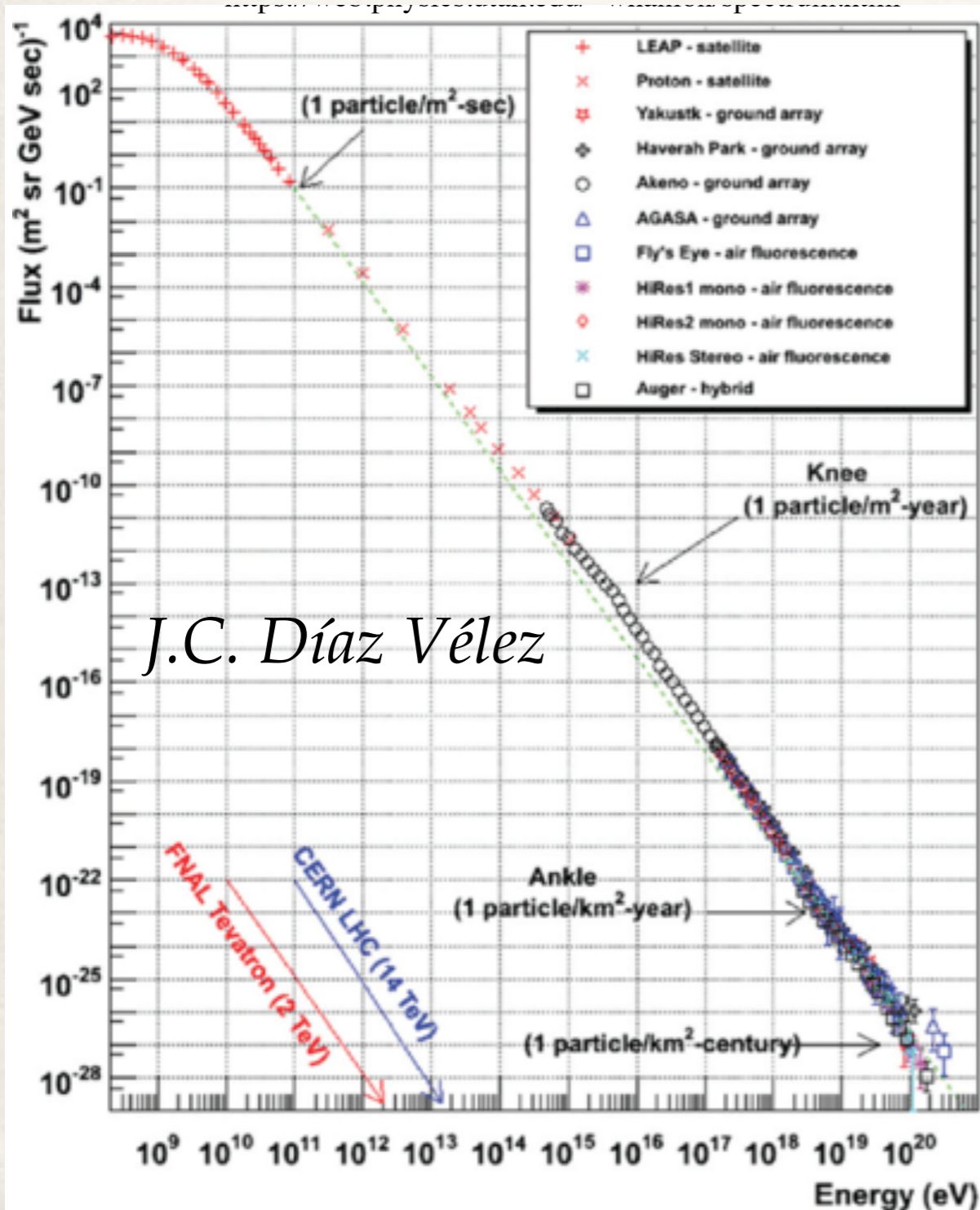
Several speakers have stressed how the situation that measurements are revealing is at odds with the standard model of CR origin

But the theoretical aspects of that model are very simple while this field develops in a very data driven way — it is obvious that while data get better, we understand more of the fine details of the standard model - that is why we are carrying out measurements

Especially important: power laws do not contain scales — it is only when we see deviations (breaks) that we identify scales (remember the knee?)

SPECTRAL BREAKS: CONSISTENT APPEARANCE OF FEATURES IN THE SPECTRA

O. Adriani et al., PRL 122, 181102 (2019)

G. Choi et al., PoS (ICRC-2021) 094 (2021)

Q. An et al., Sci. Adv. 5 (2019) 9

F. Alemanno et al., PRL 126, 201102 (2021)
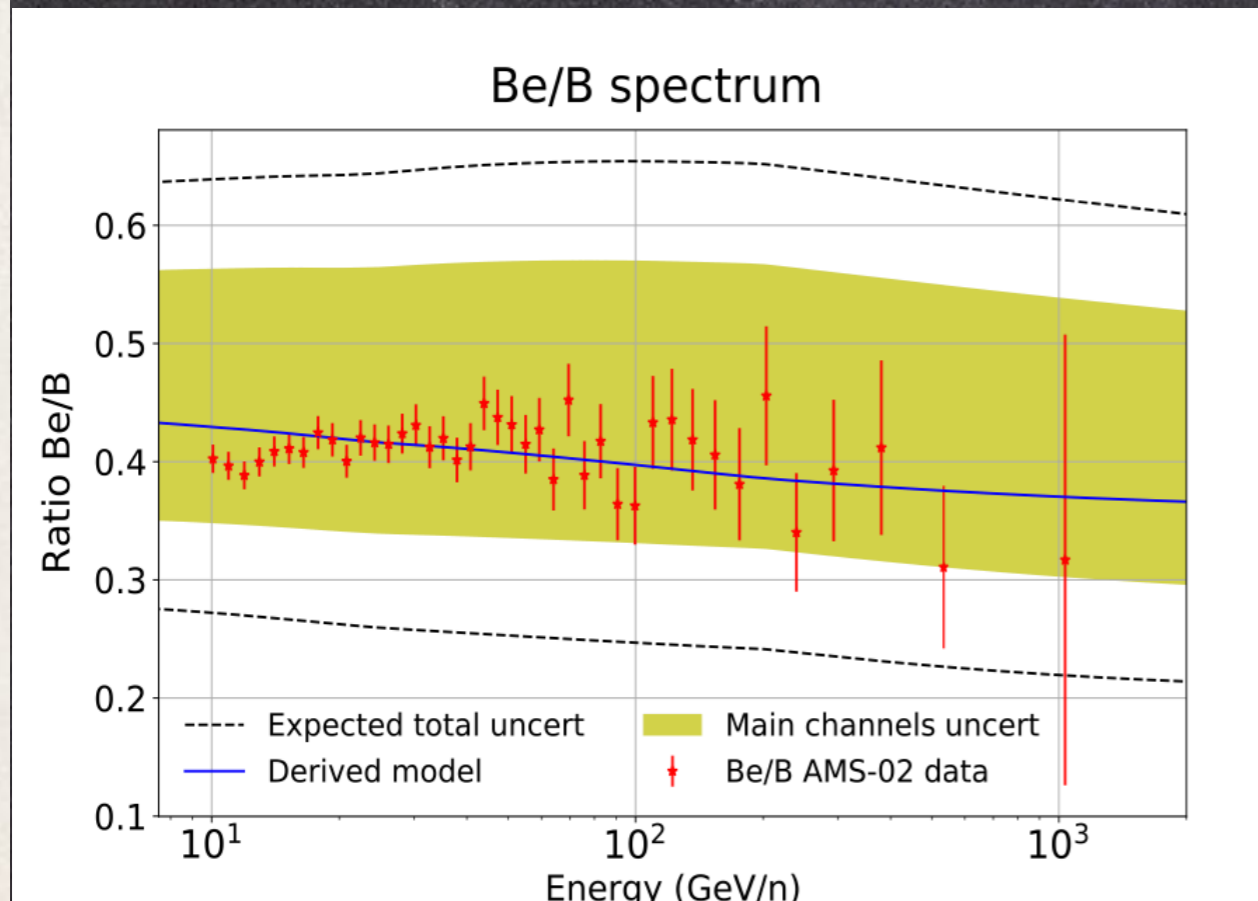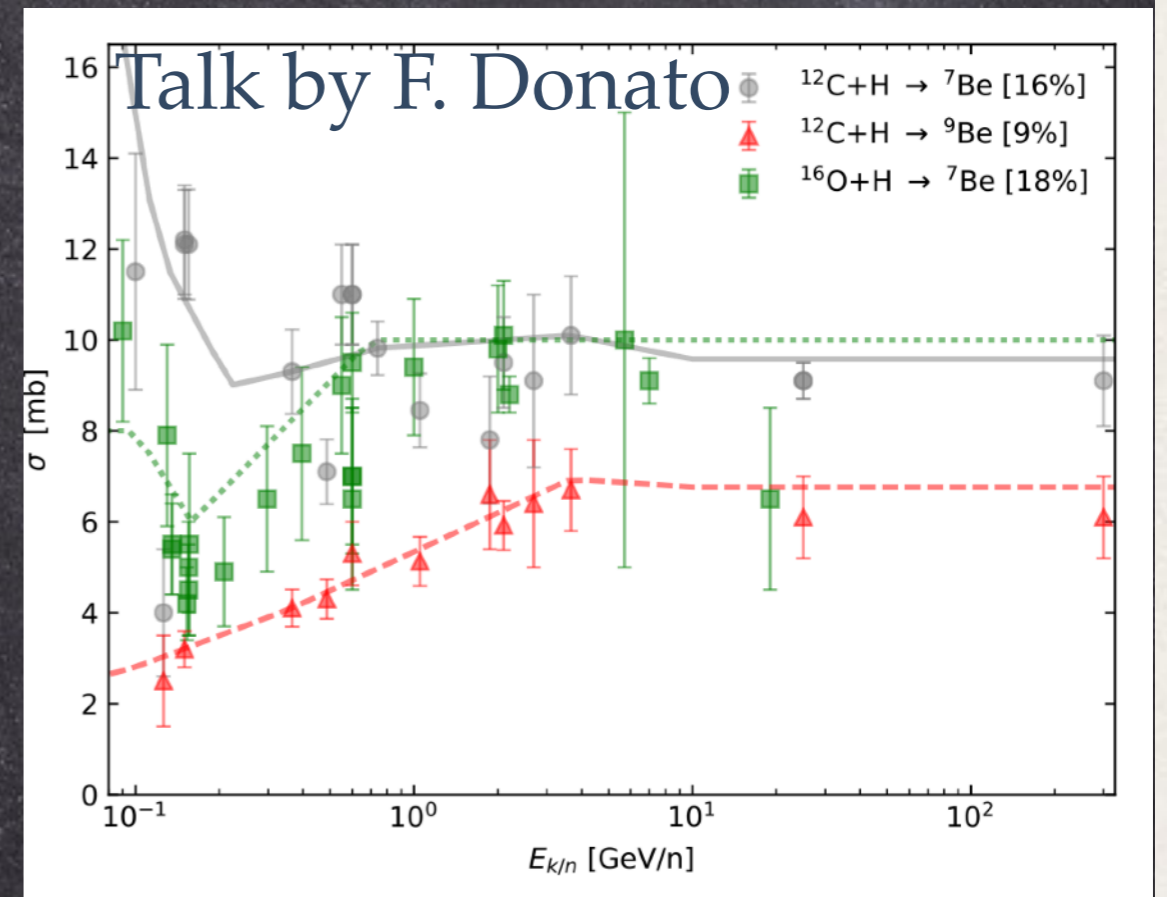
M. Aguilar *et al.*, Phys. Rev. Lett. **127** (2021) 021101
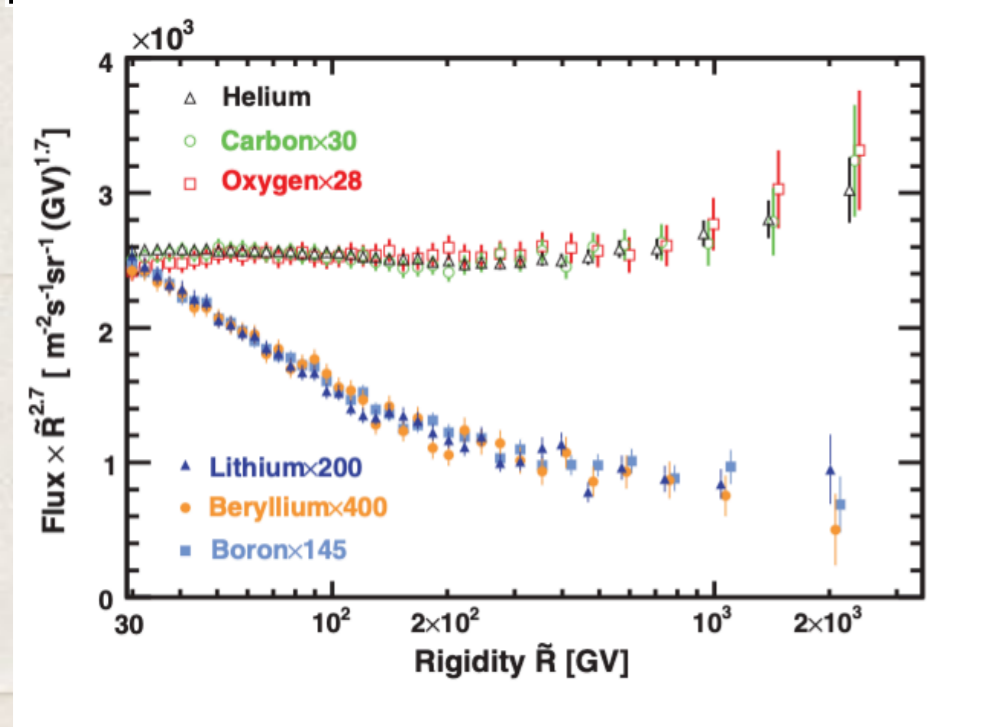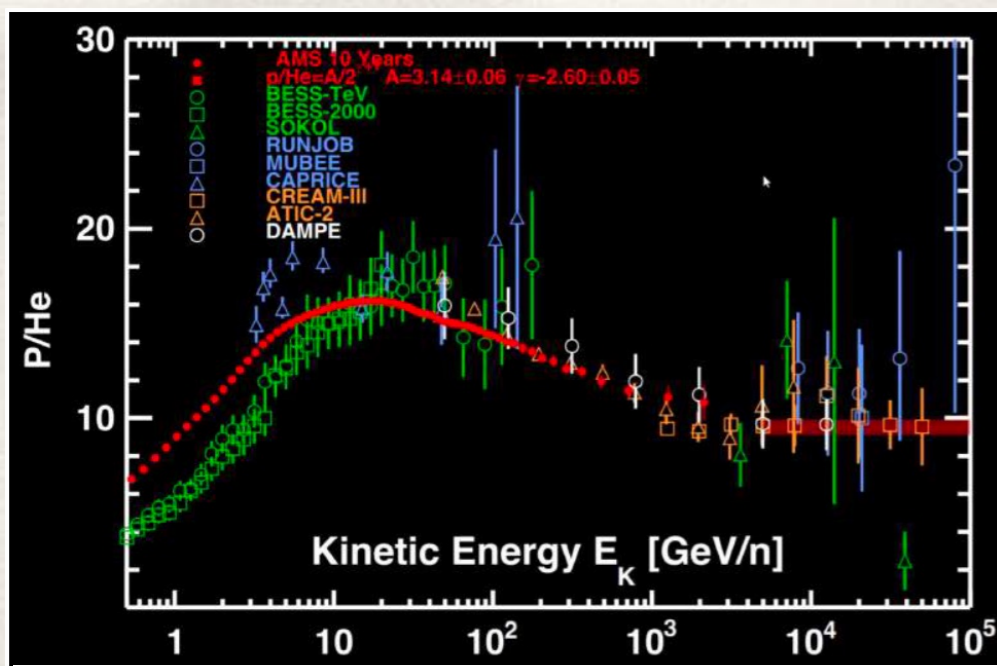
1) VIRTUALLY ALL ELEMENTS HAVE A SPECTRAL BREAK AT FEW HUNDRED GV RIGIDITY, THOUGH LESS EVIDENCE IN HEAVIER NUCLEI, DUE TO A MORE PROMINENT ROLE OF SPALLATION AT LOW ENERGY

2) THE BREAK IS VISIBLE ALSO FOR SECONDARY/PRIMARY RATIOS —> **IT IS DUE TO A CHANGE IN THE TRANSPORT**

3) PROTONS MUST BE INJECTED WITH A STEEPER SOURCE SPECTRUM THAN HELIUM (AND NUCLEI)

4) CARE MUST BE USED IN THE CLASSIFICATION OF ELEMENTS IN PRIMARY AND SECONDARY: VIRTUALLY ALL ELEMENTS ARE NOT PURE, ESPECIALLY THE INTERMEDIATE MASS ONES

5) UNACCEPTABLY LARGE DEPENDENCE OF THE CONCLUSIONS ON PARTIAL CROSS SECTIONS THAT ARE UNCERTAIN (SOME OF THEM) AT THE LEVEL OF 30-50%, WHILE DATA ARE MUCH MORE ACCURATE (TALK BY F. DONATO)

ON THE IMPORTANCE OF MEASURING CROSS SECTIONS

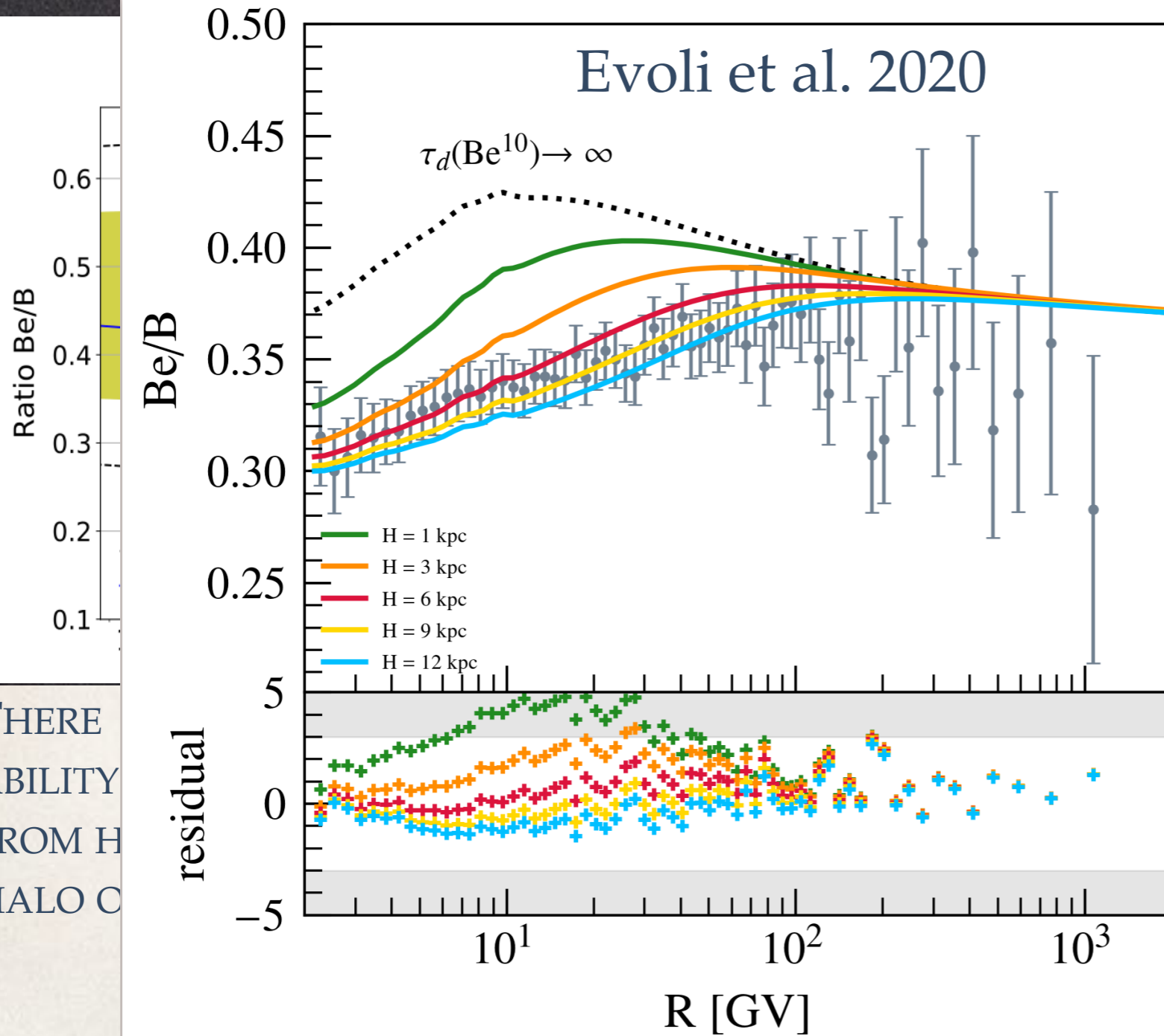THERE ARE MANY INSTANCES IN WHICH THE UNCERTAINTIES IN THE CROSS SECTIONS LIMIT OUR ABILITY TO INFER PHYSICAL INFORMATION. ONE SUCH INSTANCE IS THE PRODUCTION OF BE AND B FROM HEAVIER ELEMENTS —> LIMITS ON HOW WELL WE CAN DERIVE THE SIZE OF THE MAGNETIZED HALO OF THE GALAXY

ON THE IMPORTANCE OF MEASURING CROSS SECTIONS

De La Torre Luque+ JCAP 2021

Weinrich+ A&A 2021

THERE

ABILITY

FROM H

HALO C

THE CASE OF ANTIPROTONS
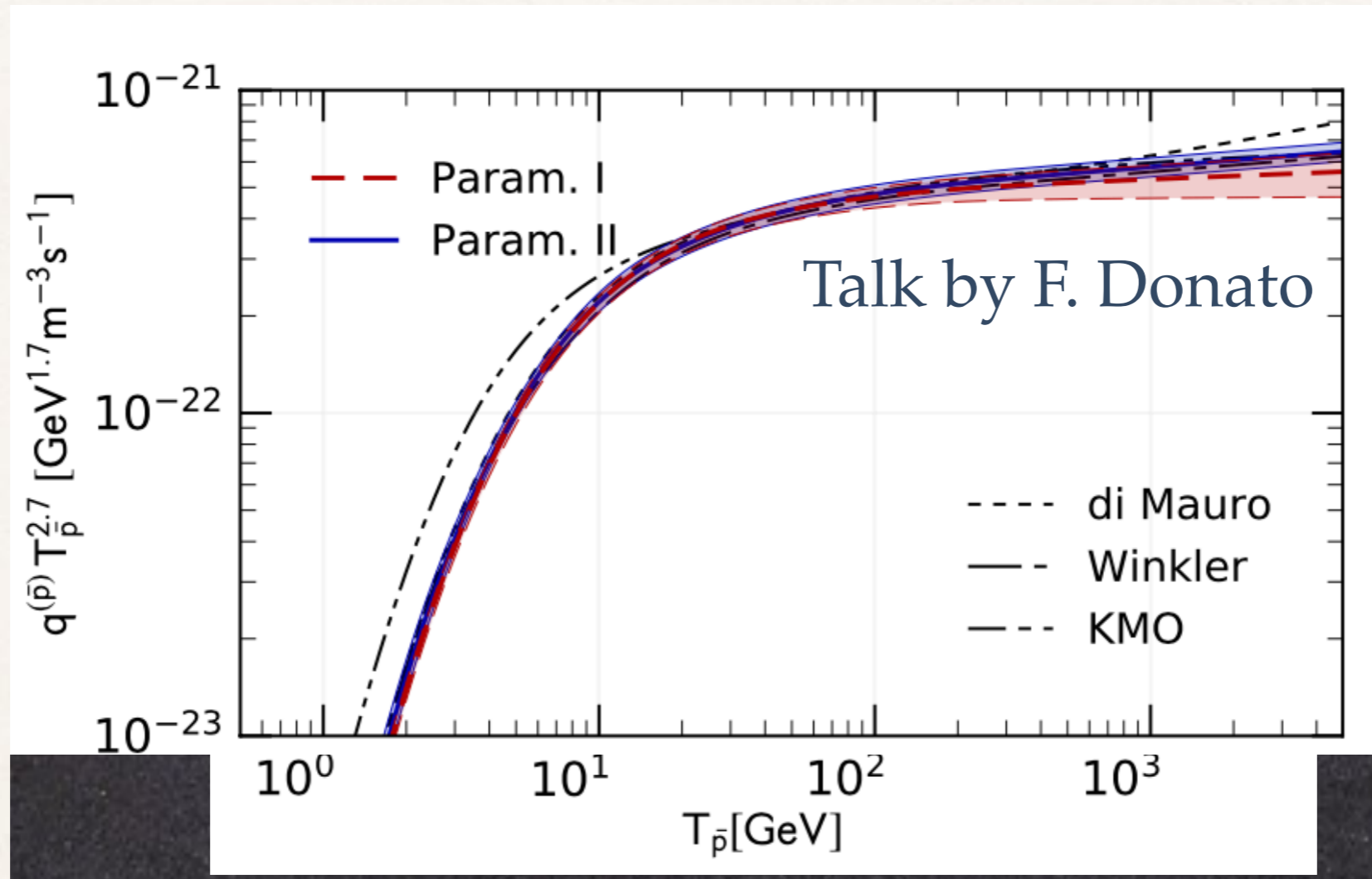
THE PRODUCTION OF ANTIPROTONS IN CR IS HISTORICALLY ONE OF THE MOST IMPORTANT INDICATORS OF TRANSPORT, BUT THE ERROR BAR ON PBAR PRODUCTION CROSS SECTION MAKE THE WHOLE DIFFERENCE BETWEEN STANDARD PICTURE AND REQUIREMENT OF NEW PHYSICS

POSITRONS
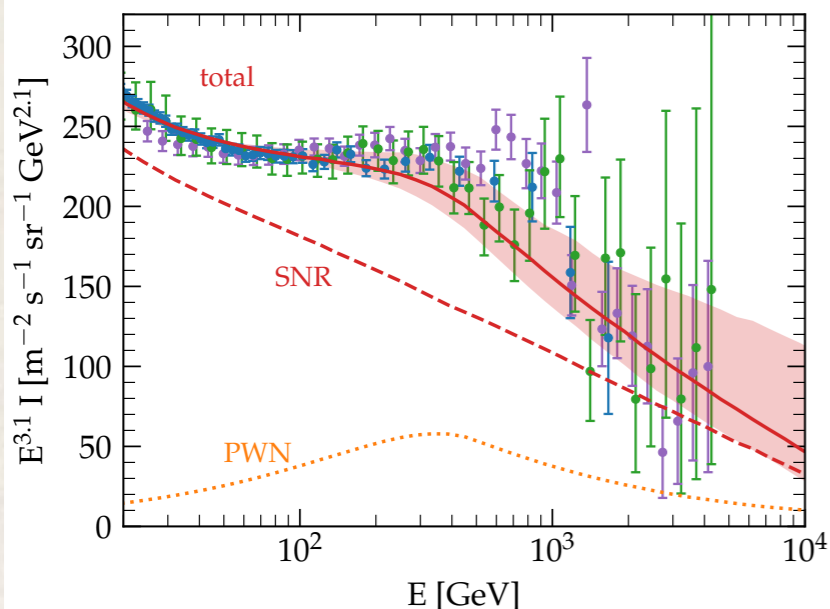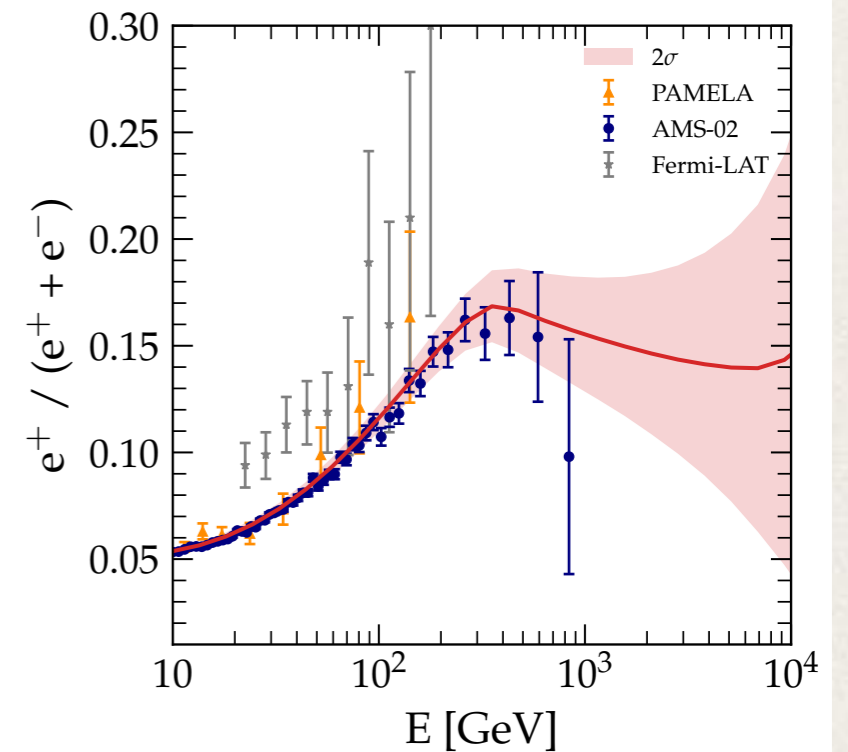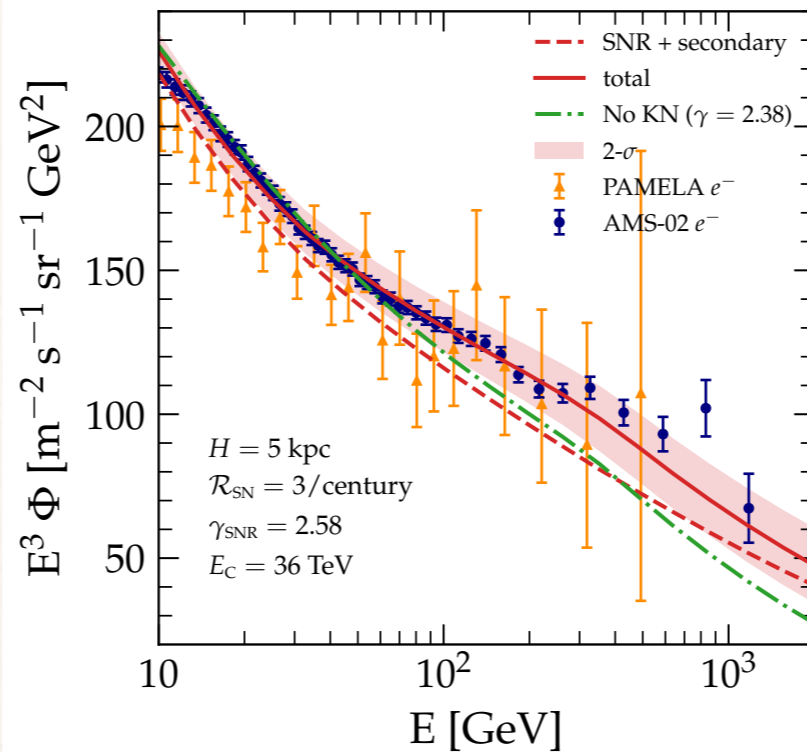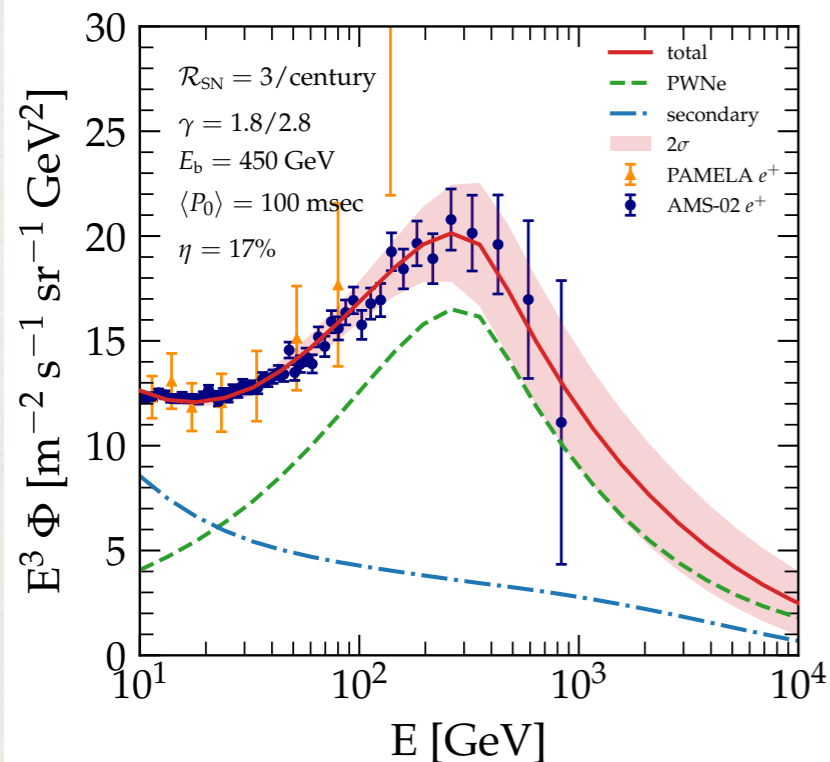
THERE IS LITTLE DOUBT THAT THE OBSERVED POSITRON FLUX AND POSITRON RATIO REQUIRE A SOURCE OTHER THEN SECONDARY PRODUCTION

THE BEST PHYSICALLY JUSTIFIED SOURCES ARE PULSARS (SEE TALK BY N. BUCCIANTINI), FOR WHICH THERE IS INDEPENDENT EVIDENCE OF APPROPRIATE SPECTRA AND PRESENCE OF POSITRONS

HAWC plot: θ = [0.0°, 45.0°], Total, H, He, Heavy; E^2.6 dΦ/dE [m^-2 s^-1 sr^-1 GeV^1.6]

H + He, T=~220 hrs; Flux×E^2.65 (m^2.s.sr)^-1(GeV)^1.65; Energy (GeV)
H+He
ARGO/WFCTA prototype
ARGO/WFCTA-02
ARGO-YBJ
CREAM
KASCADE SIBYLL
KASCADE QGSJET-II 02
Tibet-Phase II QGSJET
Tibet-Phase II SIBYLL

PHYSICAL REVIEW D 92, 092005 (2015)

J. C. Arteaga-Velázquez ECRS 2022

ALL PARTICLE SPECTRUM, δE_syst = ± 9 %
ATIC-02
NUCLEON
ARGO-YBJ
HAWC (This Work)
ICETOP (SIBYLL 2.1)
ICETOP (QGSJET-II-04)
KASCADE (QGSJET-II-02)
KASCADE (SIBYLL 2.1)
TAIGA-HiSCORE
TIBET (QGSJET-01 + HD)
TIBET (QGSJET-01 + PD)
TUNKA-133
Preliminary
Φ E^2.6 (m^2 sr^-1 s^-1) (GeV)^1.6; Energy [GeV/particle]

FEATURES ALSO ABOUND IN THE REGION BELOW THE KNEE

BUT WE HAVE NO INFORMATION ABOUT THE SECODNDARY/PRIMARY RATIOS AT SUCH ENERGIES, HENCE WE DO NOT KNOW WETHER WE ARE LOOKING AT AN EFFECT OF TRANSPORT OR DIFFERENT TYPES OF SOURCES COMING INTO PLAY
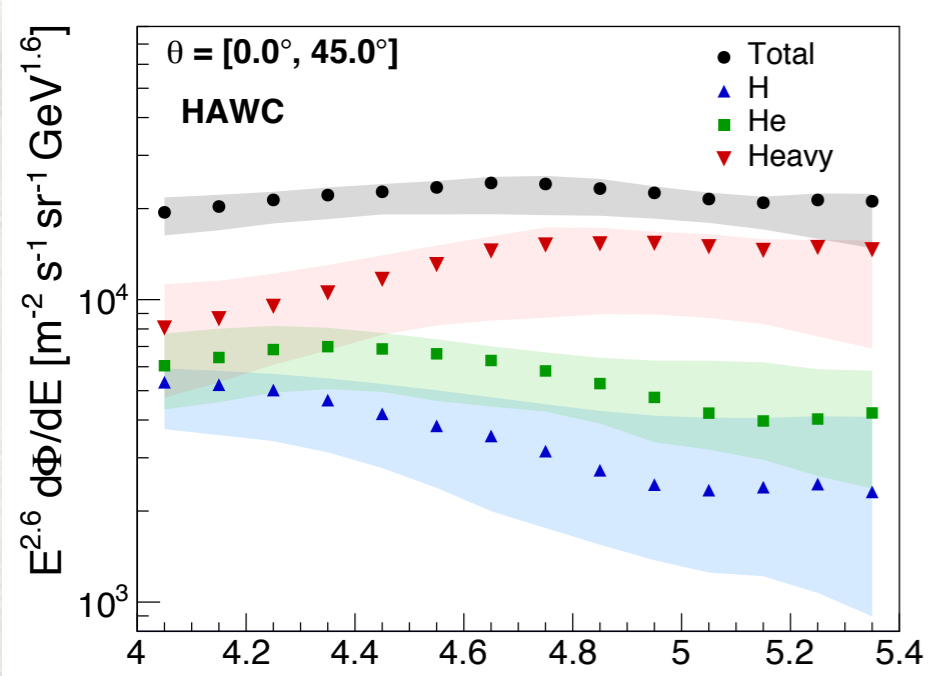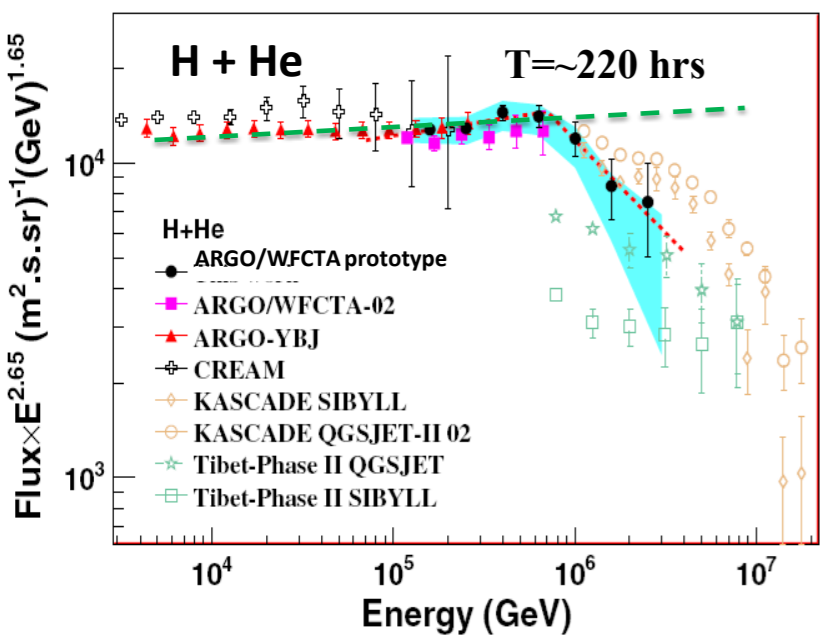
THE MOST PROMINENT FEATURE REMAINS THE KNEE, FOR WHICH THE LONG-STANDING DEBATE PERSISTS: DUE TO A CHANGE IN TRANSPORT OR THE MAXIMUM ENERGY? (TALK BY G. GIACINTI)

	E_0(TeV)	E_1(TeV)	γ_1	γ_2
H	14.1 +2.2/-0.4	103 +1/-4	-2.6 +0.2/-0.5	-3.1 ± 0.3
He	25.3 +1.1/-0.8	152 +11/-9	-2.2 +0.1/-0.3	-3.1 +0.4/-0.
Z > 2	51 ± 1	—	-2.1 ± 0.3	-2.6 +0.04/-0

NOTICE THAT IT REMAINS UNCERTAIN WHETHER THE KNEE IS MADE BY THE LIGHTER COMPONENTS OR THE INTERMEDIATE MASS ONES

HUGE IMPLICATIONS FOR THE TRANSITION TO EXTRA-GALACTIC CR

IT WILL BE A PRECIOUS ADDITION TO HAVE LHASSO MEASUREMENTS IN THE REGION AROUND THE KNEE!

MOVING OUR WAY OUT OF THE GALAXY

Auger 2021, preliminary

- TA SD (2019)
- TA TALE (2018)
- TUNKA-133 (2020)
- Yakutsk (2015)
- Ice Top (2019)
- KAS. Gr. EPOS-LHC (2015)
- KAS. Gr. QGSII-04 (2015)
- Tibet-III (2008)
- GAMMA (2014)

$J(E) \times E^3$ [km^{-2} yr^{-1} sr^{-1} eV^2]

E [eV]

MOVING OUR WAY OUT OF THE GALAXY

Auger 2021, preliminary

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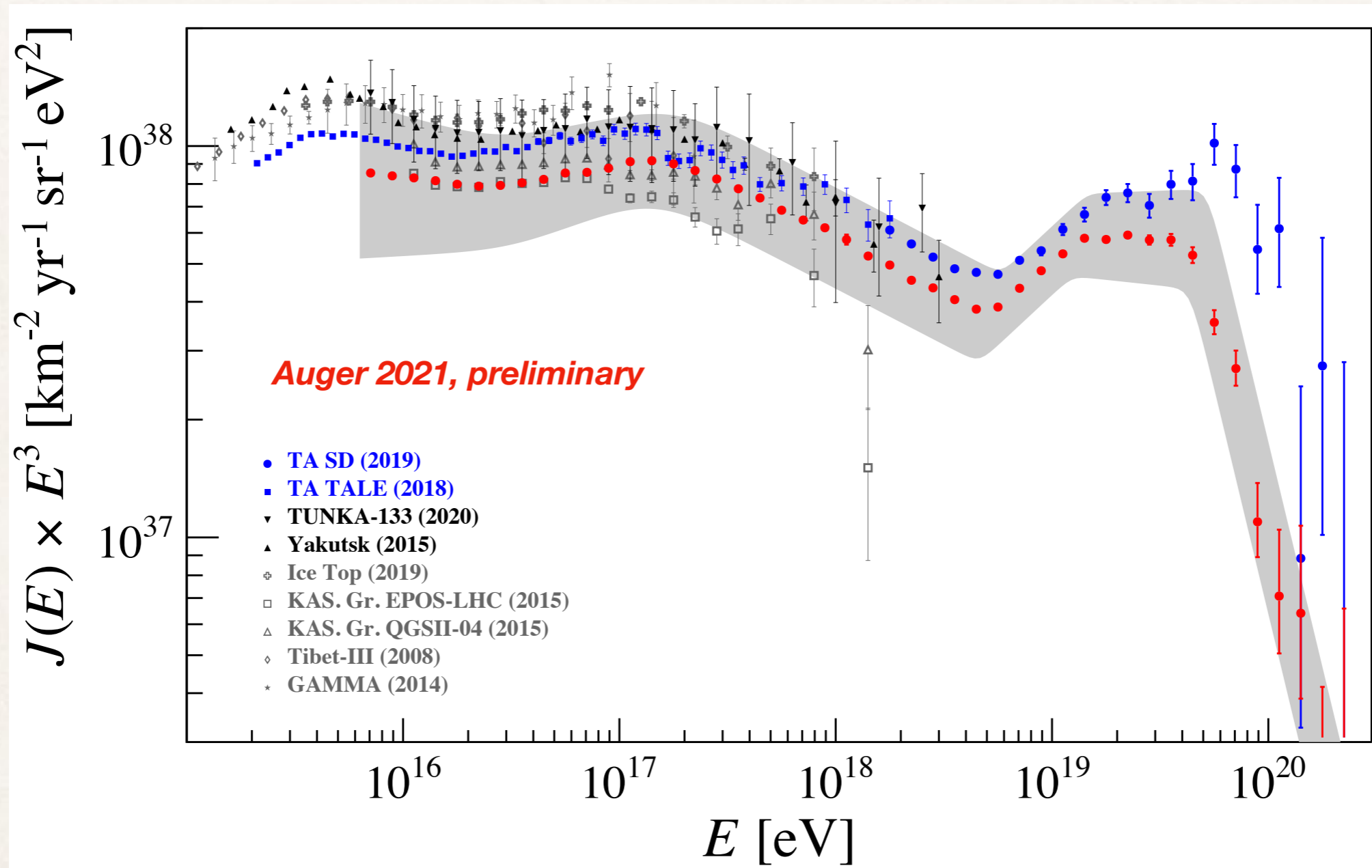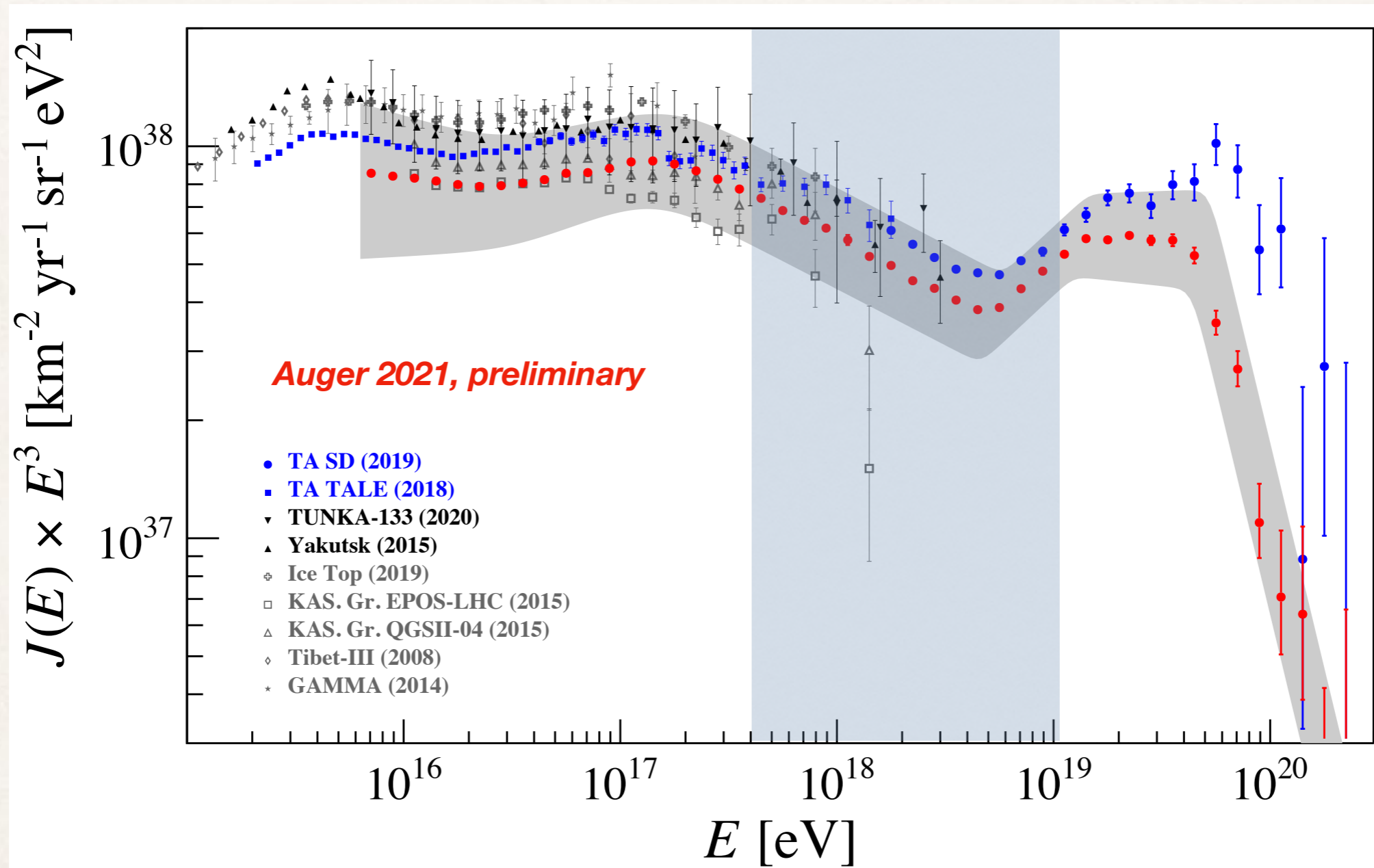
Possibly an "Agreed Upon" picture of mass composition?
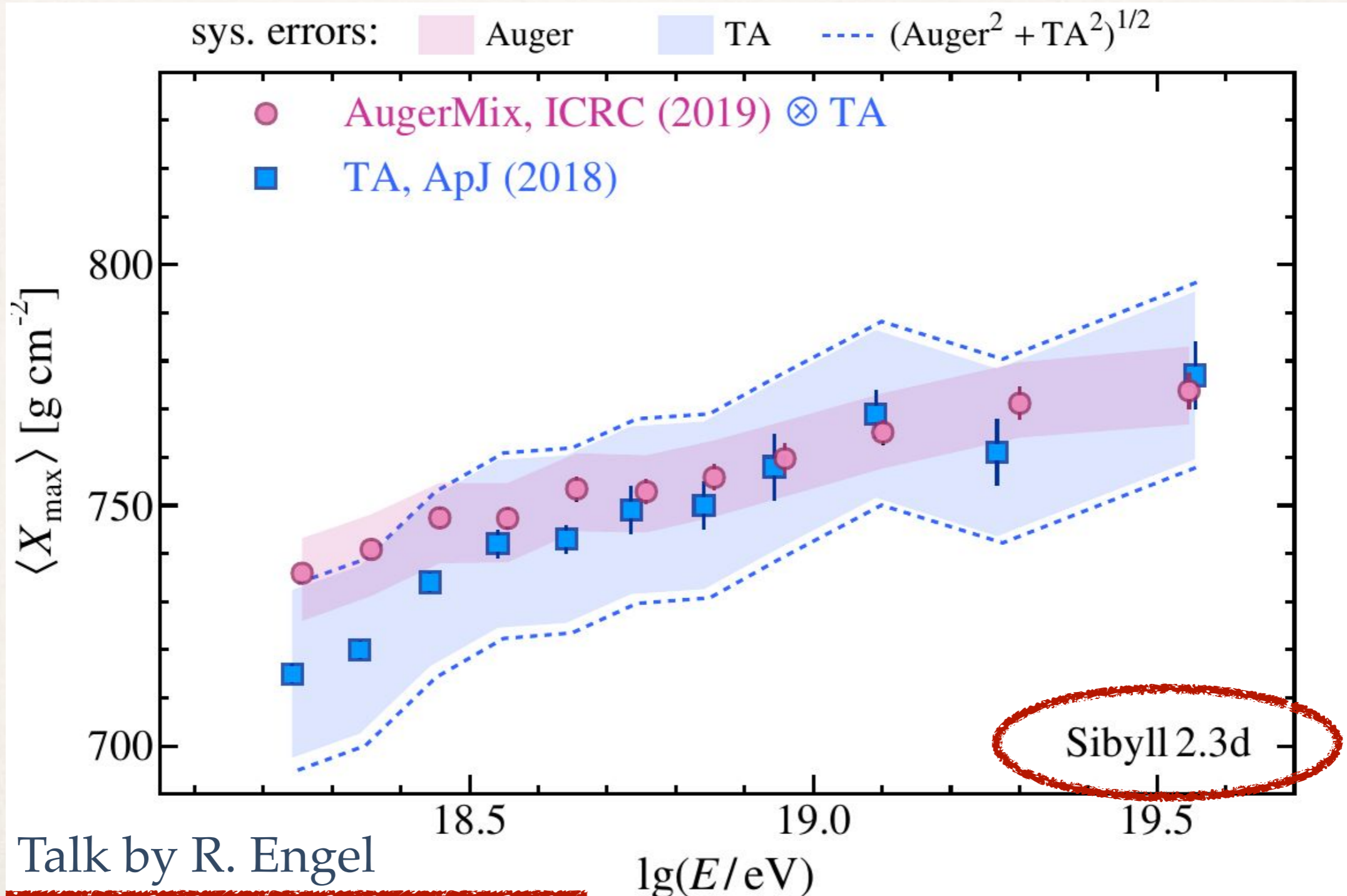
measurements as would have
Talk by R. Engel
high-energy interaction model.

Auger-TA comparison of Xmax distributions (i)

Mean Xmax shifted to agree between data sets for each energy bin

(UHECR 2022, D. Bergmann for the Auger-TA joint working group)

ANISOTROPIES

For all these searches, most significant signal at **E_{th} = 38-41 EeV** on top...

Evolution of signal: compatible with **linear growth within expected var...**

Most important evidence for UHECR anisotropy around the toe from a s...
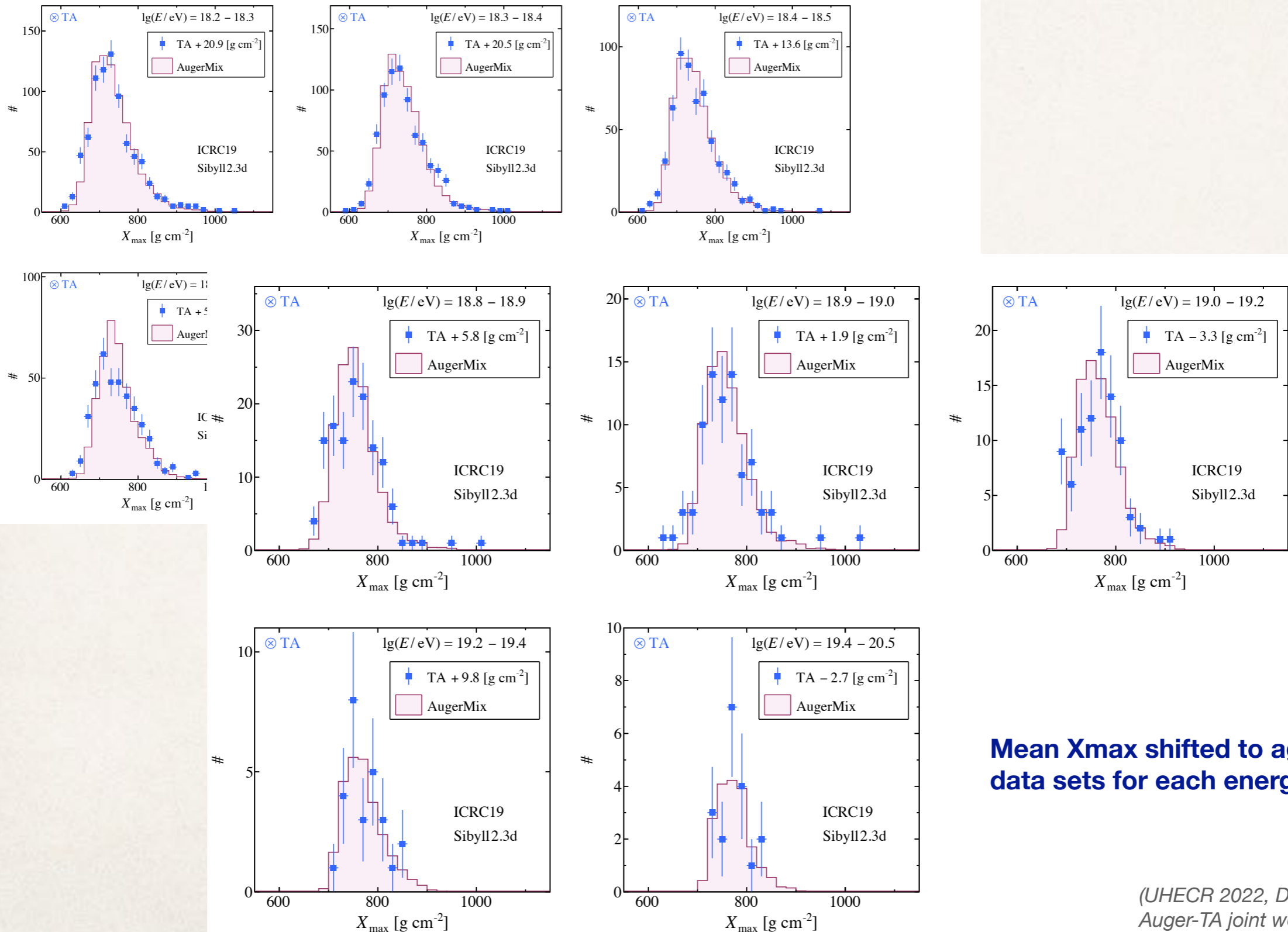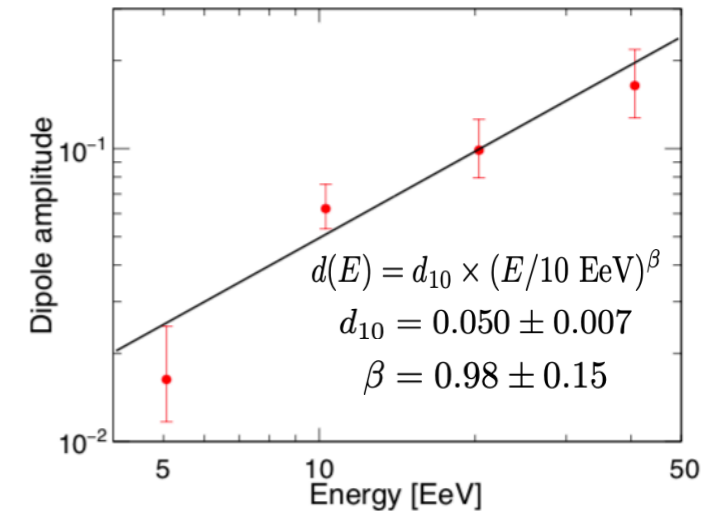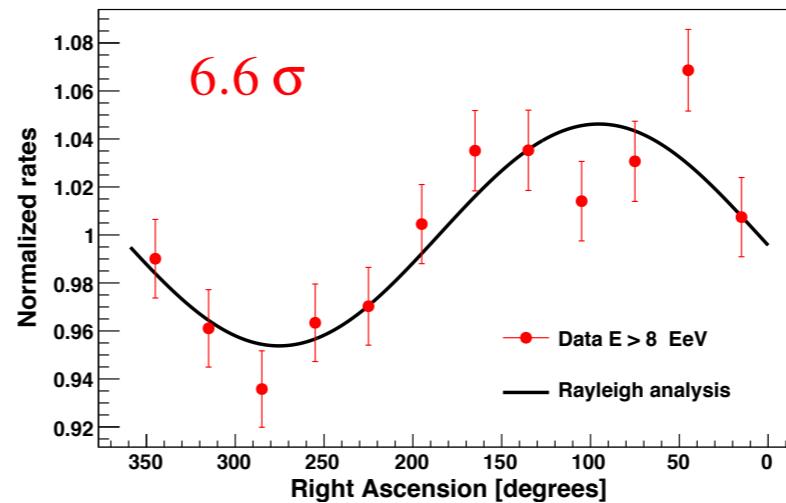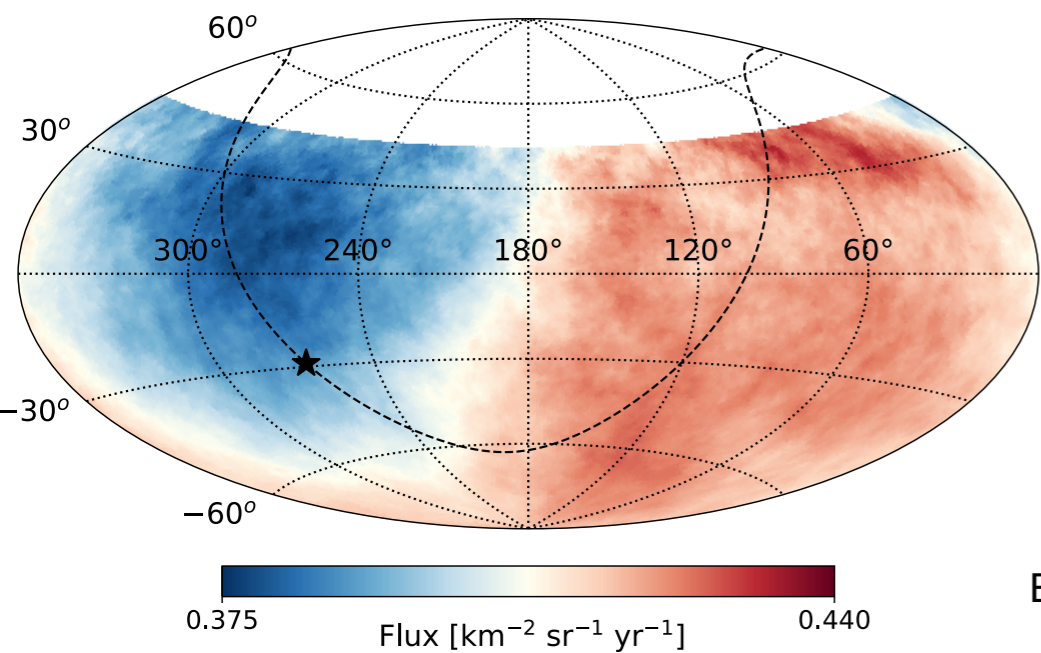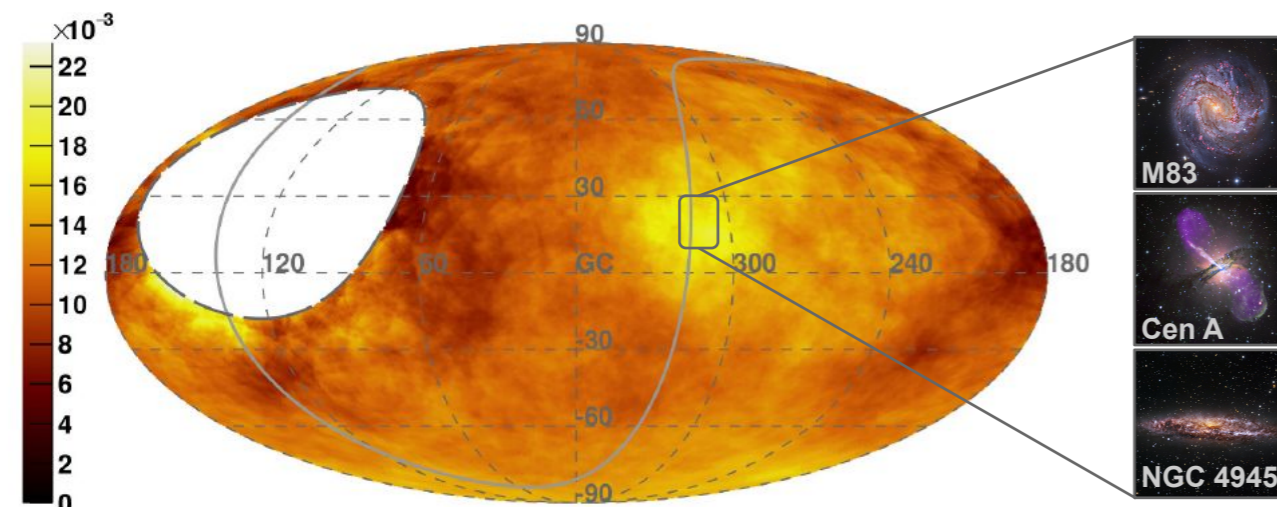
Best-fit parameters and threshold energ...

Fit of attenuated flux pattern + isotropy to data with...

For all four catalogs: most significant signal at E_{th} =...

Post-trial deviation from isotropy: from **3.1σ (jetted...**

Stronger *a priori*: the Centaurus regi...

Evolution of signal with exposure

Starbursts significance: 4.0σ in ApJL 2018...

Motivation

Compatible with **linear growth within...**

of Centaurus region (7% current exposure)

Early sky flagging

Crowded area in the **Council of Giants** (3-6 Mpc)

$\Phi(E_{Auger} > 41$ EeV$)$ [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24°$

Pre-trial Li & Ma $\sigma(E_{Auger} > 41$ EeV$)$ - Galactic coordinates - $\Psi = 24°$

Catalog-based models

$\Phi(E_{Auger} > 41$ EeV$)$ [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24°$

Figure 1: *Left*: The flux map in Galactic coordinates of UHECRs above 41 EeV smoothed with a top-hat profile of radius 24°. *Right*: The associated Li & Ma pre-trial significance map of localized overdensities. The supergalactic plane is shown as a light grey solid line. The edge of the FoV of the Pierre Auger Observatory is shown as a dark grey dashed line.

Model flux map

NOTICE THAT THE POSSIBLE CORRELATION WITH STARBURSTS DOES NOT MEAN THAT THEY ARE THE SOURCES OF UHECR: IN FACT MOST SB GALAXIES DO NOT HAVE ENOUGH JUICE TO EVEN GET CLOSE TO UHE. THIS MAY HAPPEN FOR UFO (TAIL OF SB), BUT THEN...

Jetted AGN (γ-rays) - expected $\Phi(E_{Auger} > 40$ EeV$)$ [km^{-2} sr^{-1} yr^{-1}]

A LOT OF THINGS TO MAKE SENSE OF …

LET'S START FROM THE FEATURES IN THE CR SPECTRA…

AT 300 GV ALL SPECIES WE MEASURE SHOW A CHANGE OF SLOPE…

WE KNOW THAT THIS PHENOMENON IS ALSO PRESENT IN THE SECONDARY/PRIMARY RATIOS, HENCE THIS FEATURE IS INTRINSIC IN THE WAY PARTICLE DIFFUSE IN THE GALAXY

DUE TO THE TRANSITION FROM A SELF-GENERATED TURBULENCE TO A PRE-EXISTING TURBULENCE (PB+2012, …)

NON TRIVIAL SPATIAL DEPENDENCE OF D(E,Z) ON THE HEIGHT UPON THE DISC (Tomassetti 2012, …)

THIS BOILS DOWN TO UNDERSTANDING WHY CRs SCATTER IN THE GALAXY

GOLDEN RULE

IF YOU WANT PARTICLES TO DIFFUSE IN SPACE, YOU NEED **RESONANCES**! NAMELY MAGNETIC FIELD POWER ON PARALLEL WAVENUMBERS[-1] OF LARMOR RADIUS OF THE PARTICLES…

THERE ARE MAINLY TWO SOURCES OF TURBULENCE:

1) **MHD TURBULENCE THAT IS INJECTED AT SOME SCALE AND CASCADES TO SMALLER SCALES**

   COSMIC RAYS STIR MAGNETIC FIELDS ON THE SCALE OF THEIR OWN LARMOR RADIUS
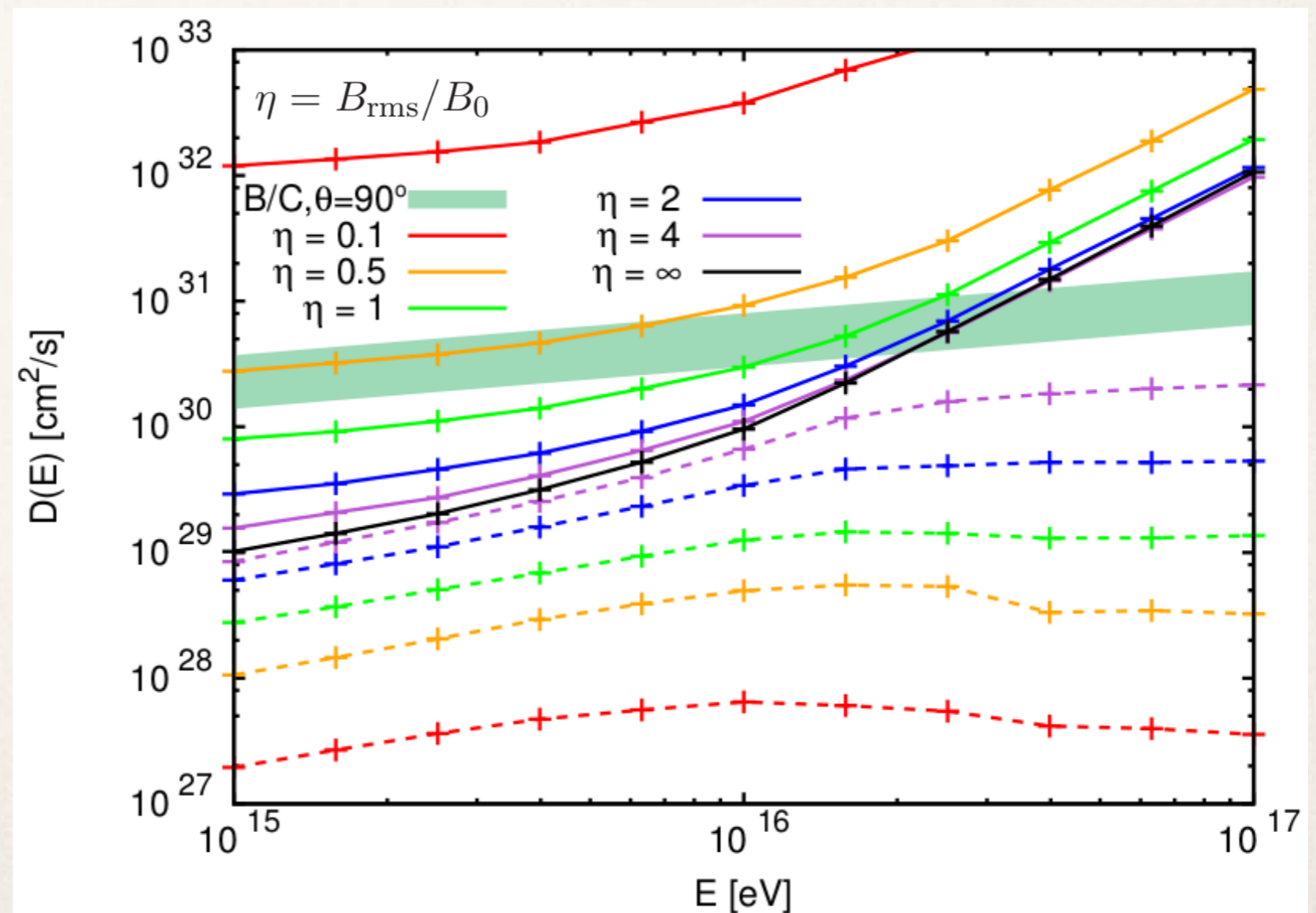
   (STREAMING INSTABILITY)

Similar to
K. Dolag's

2) **TURBULENCE WHICH IS SELF-GENERATED BY COSMIC RAYS THEMSELVES**

THE THING YOU HEAR ABOUT ASSUMING KOLMOGOROV (OR ELSE) TURBULENCE MEANS THAT ENERGY IS INJECTED AT SOME SCALE L AND CASCADES TO SMALLER SCALES
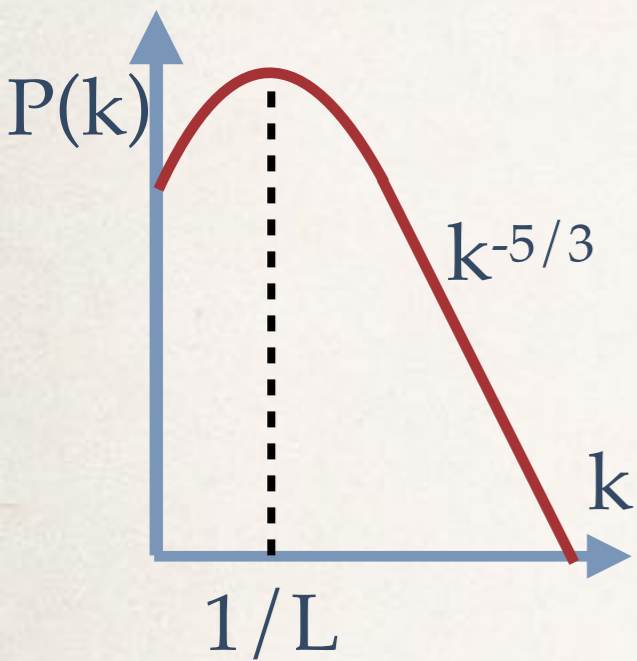
IF $\Delta B/B \ll 1$ (WEAK TURBULENCE) THEN THE DIFFUSION COEFFICIENT PARALLEL TO B IS >> THAN THE PERP ONE

P(k)

$k^{-5/3}$

k

1/L

Talk by G. Giacinti

WARNINGS AND IMPLICATIONS

Turbulence becomes very anisotropic and typically there is no power left to scatter particles with $r_L(E) < \sim 0.1\, L$ — **WHAT IS THE SOURCE OF SCATTERING THEN???**

Yet, if some kind of turbulence does exist, and if there are GALACTIC Accelerators with $E_{MAX} \gg PeV$, then a knee is expected (proposed already in the 60's).
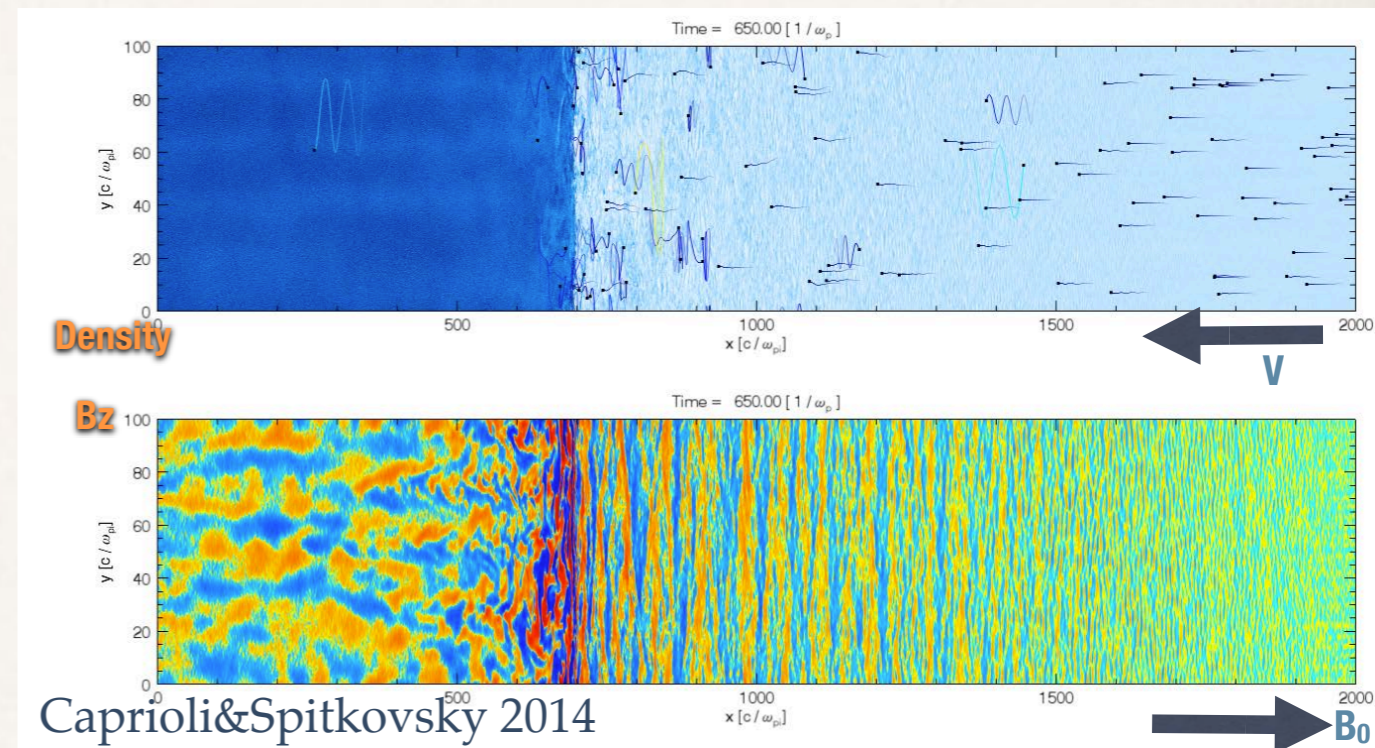

Lmax = 25pc

2.2 injection

2.5 slopes

1.6% of all SNe (rare, extreme CCSNe in dense winds)
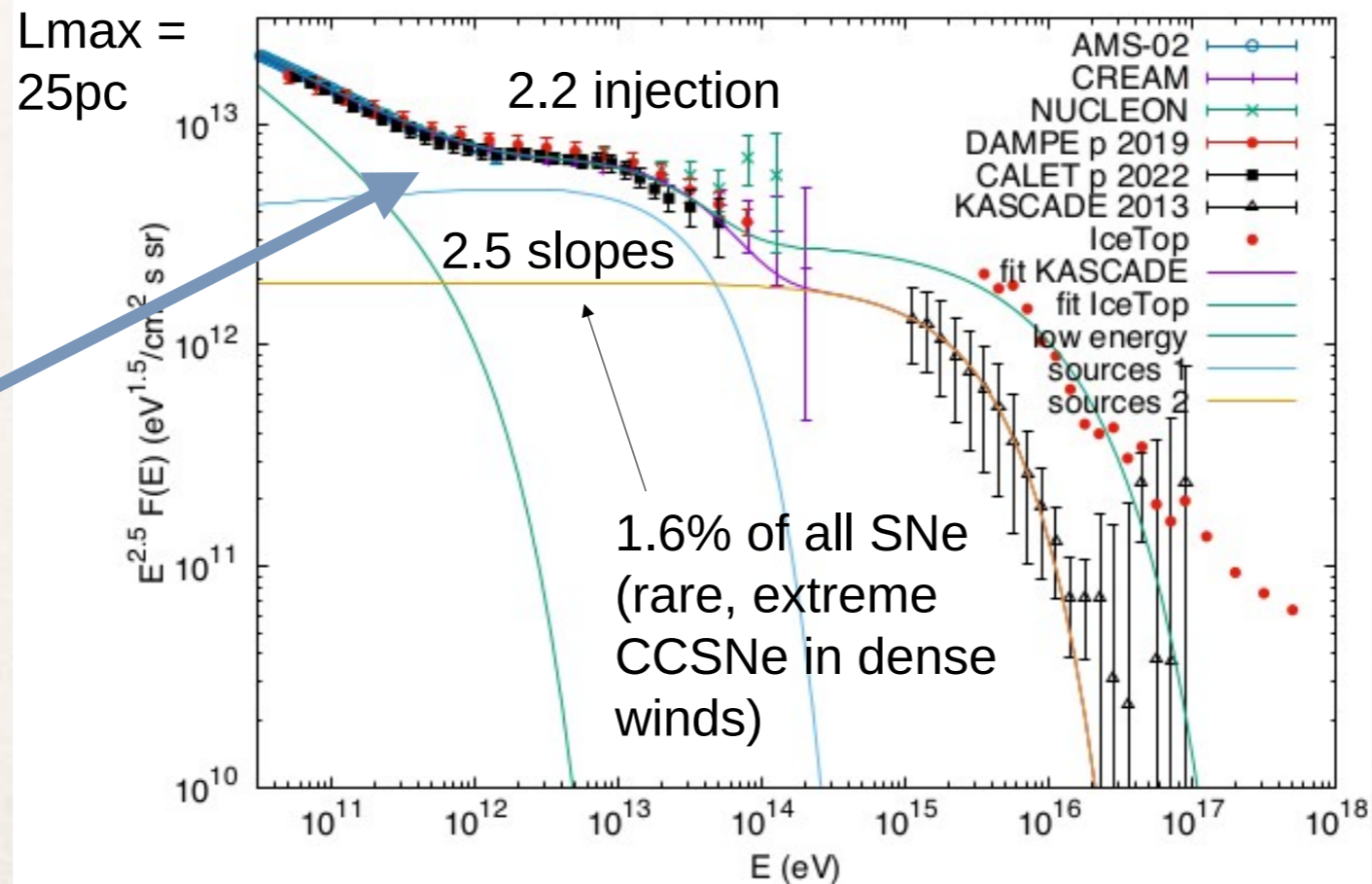
Recall that this is due to transport

Talk by G. Giacinti

ACCELERATION/SOURCES

Talks by A. Spitkovsky
&
V. Tatischeff

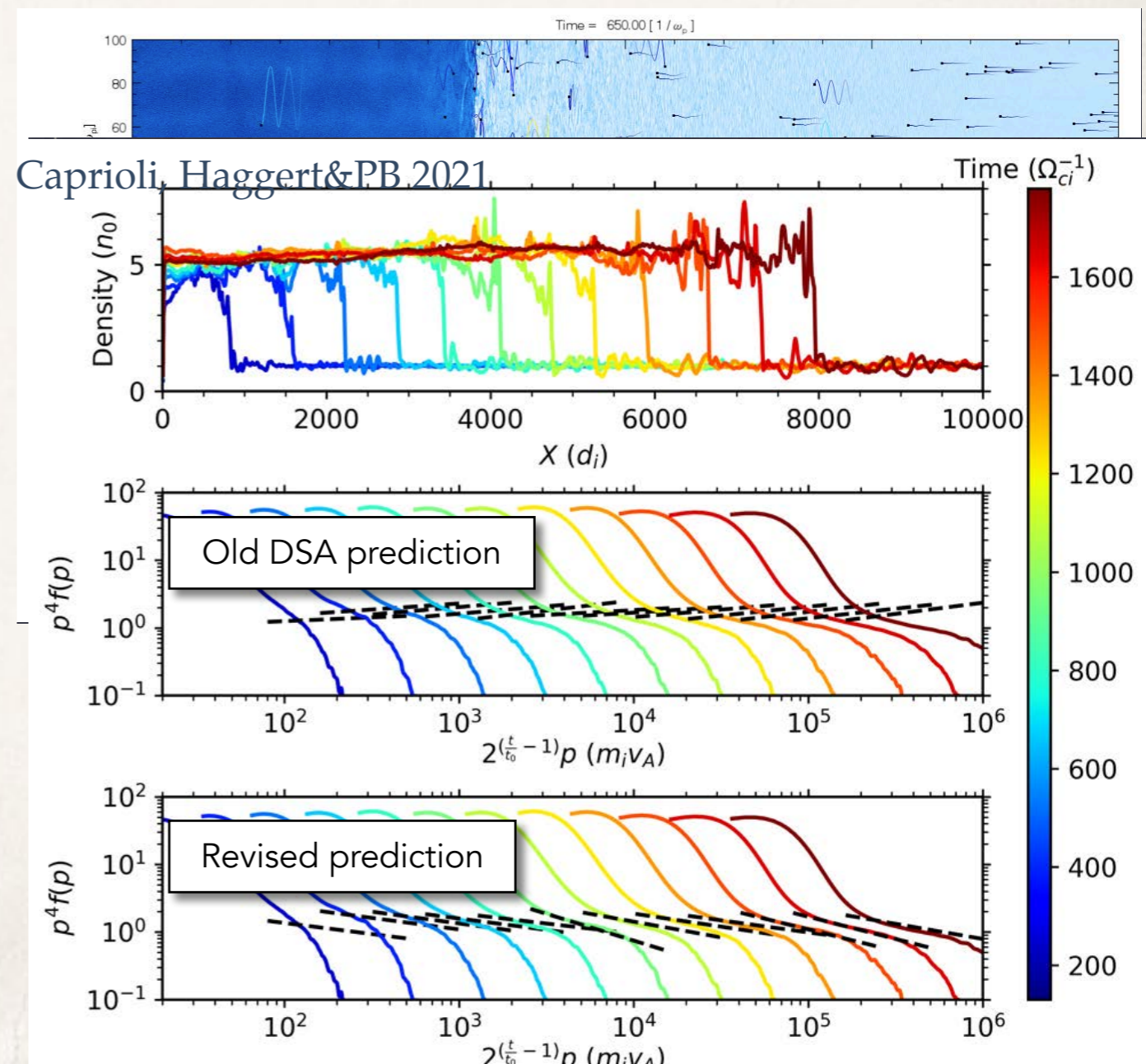## FOR GALACTIC CR IT APPEARS CLEAR THAT SHOCKS PLAY A CENTRAL ROLE

1. SHOCKS IN MOST ASTROPHYSICAL SITUATIONS ARE COLLISIONLESS (MEDIATED BY E.M. INSTABILITIES)

2. THE INJECTION OF PARTICLES AT THE SHOCK IS SEVERELY DEPENDENT UPON INCLINATION ANGLE (SUPPRESSED FOR >45DEG)

3. THE SHOCK ACCELERATES EFFECTIVELY ONLY IN THE PRESENCE OF SELF-GENERATED WAVES (STREAMING INSTABILITY)

4. THE ROLE OF THESE WAVES TO SHAPE THE SPECTRUM HAS BEEN RECENTLY STUDIED

Caprioli&Spitkovsky 2014

ACCELERATION/SOURCES

Talks by A. Spitkovsky
&
V. Tatischeff

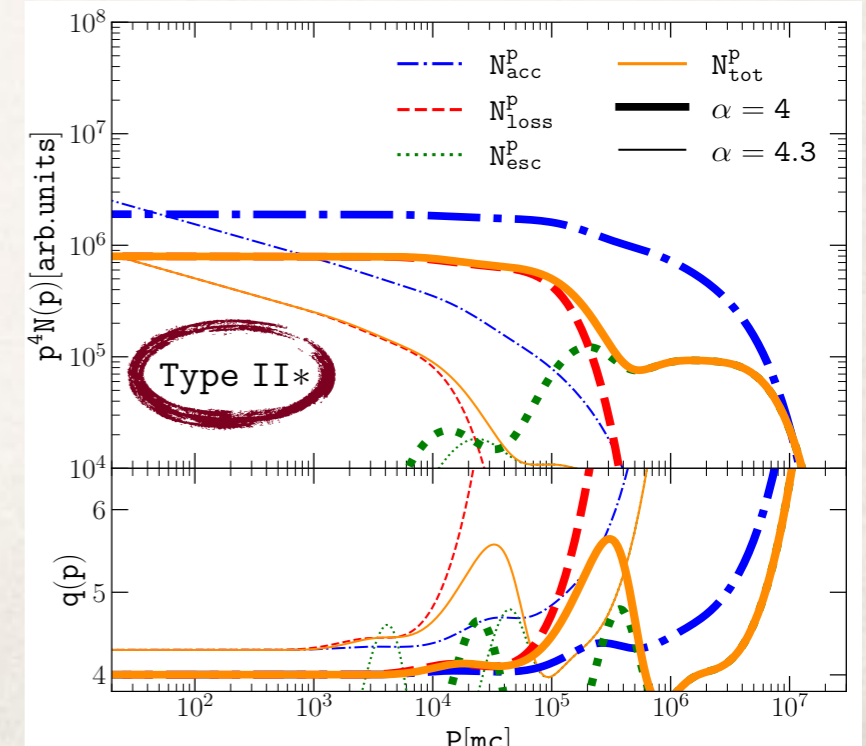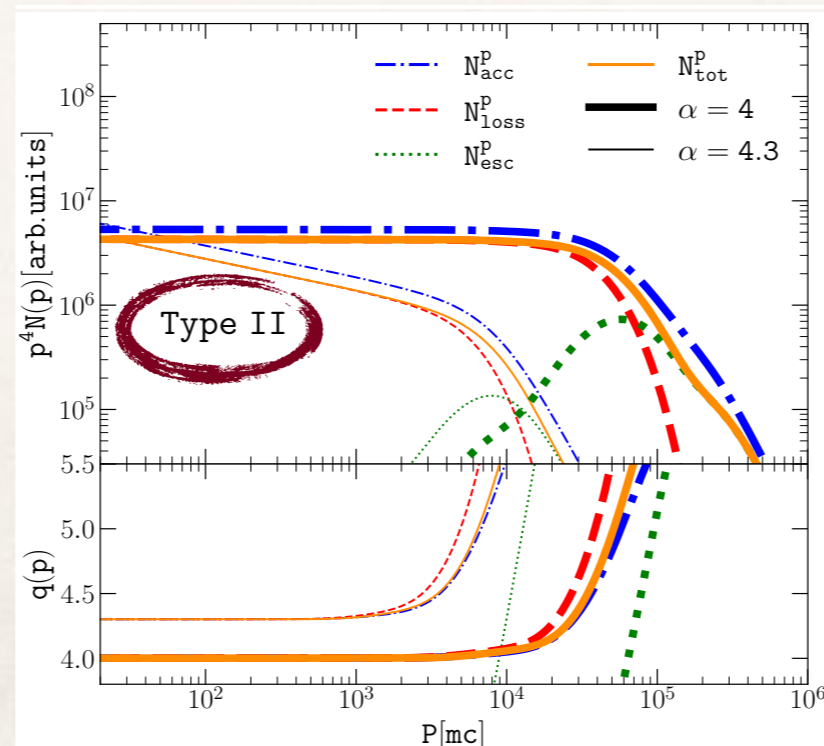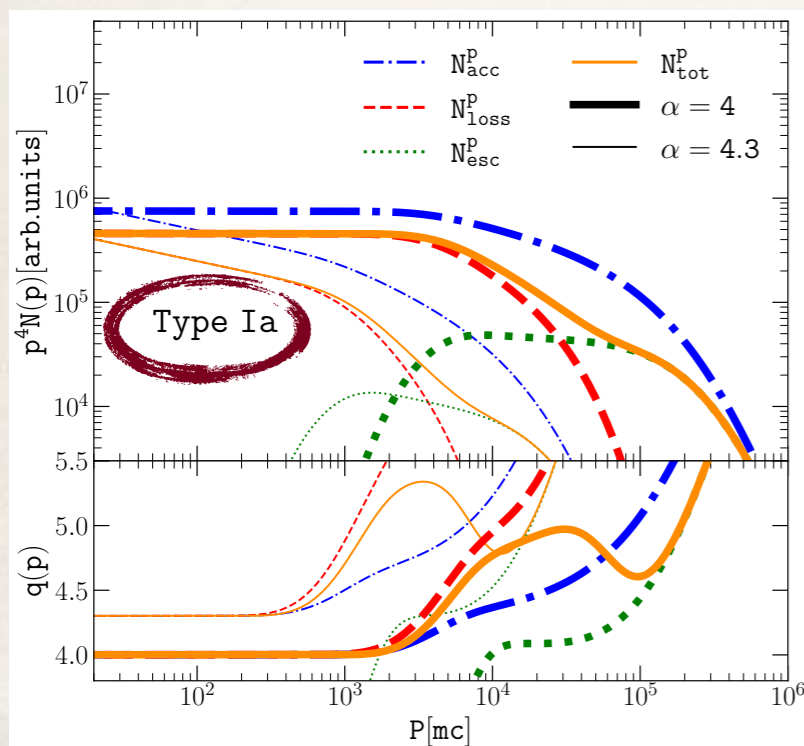## FOR GALACTIC CR IT APPEARS CLEAR THAT SHOCKS PLAY A CENTRAL ROLE

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Caprioli, Haggert&PB 2021

Old DSA prediction

Revised prediction

Acceleration/sources

❖ SNR are effective accelerators, as also shown by the large B field in the X-ray rims. The highest effective E_{max} is reached at the beginning of Sedov phase

❖ For SN-Ia E_{max} is typically around 100 TeV

❖ For SN-II exploding in the wind of the pre-SN star E_{max} can be a bit higher but still <<knee

❖ Only in rare, very energetic core collapse SNe one can get up to the knee region
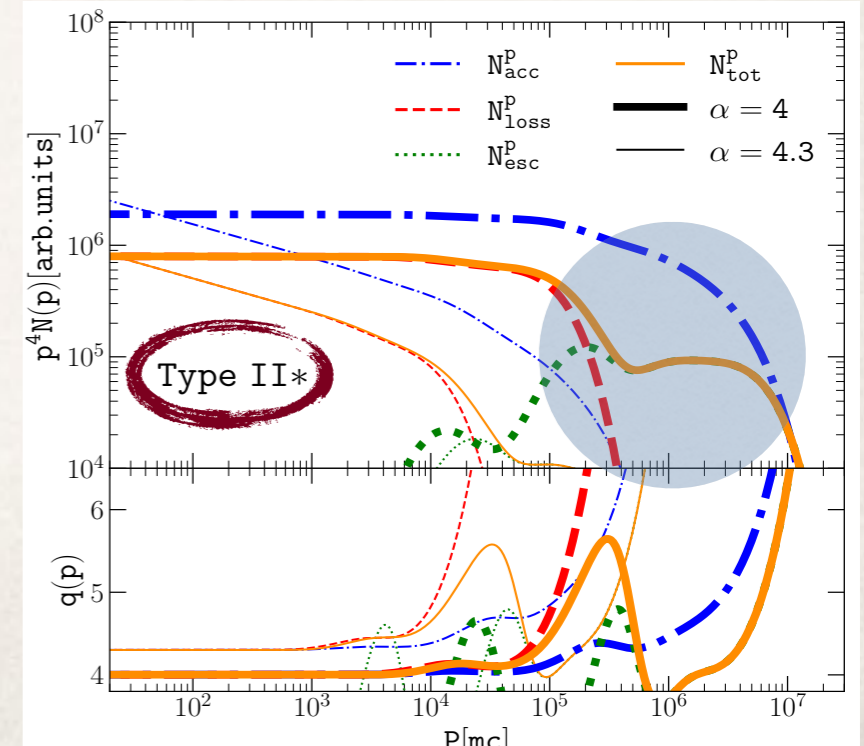
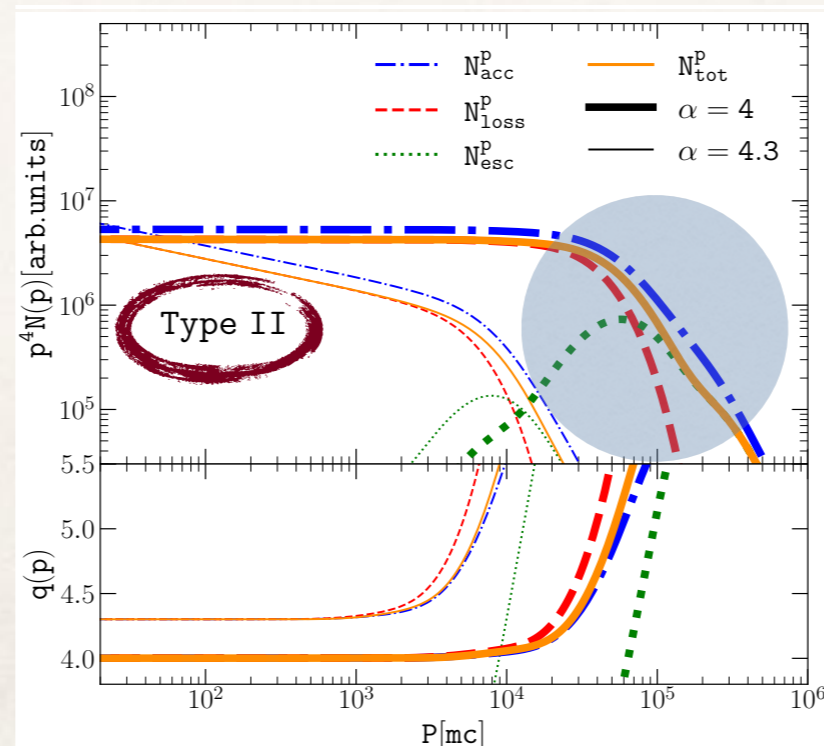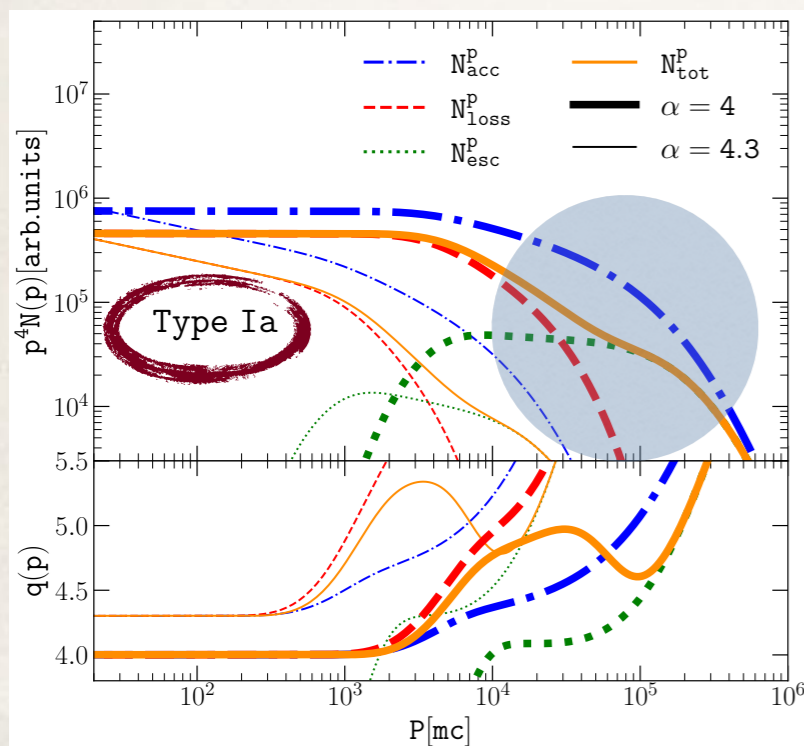❖ But the spectrum is all but trivial

Cristofari, PB & Caprioli 2021, Cristofari, PB & Amato 2020

Acceleration/sources

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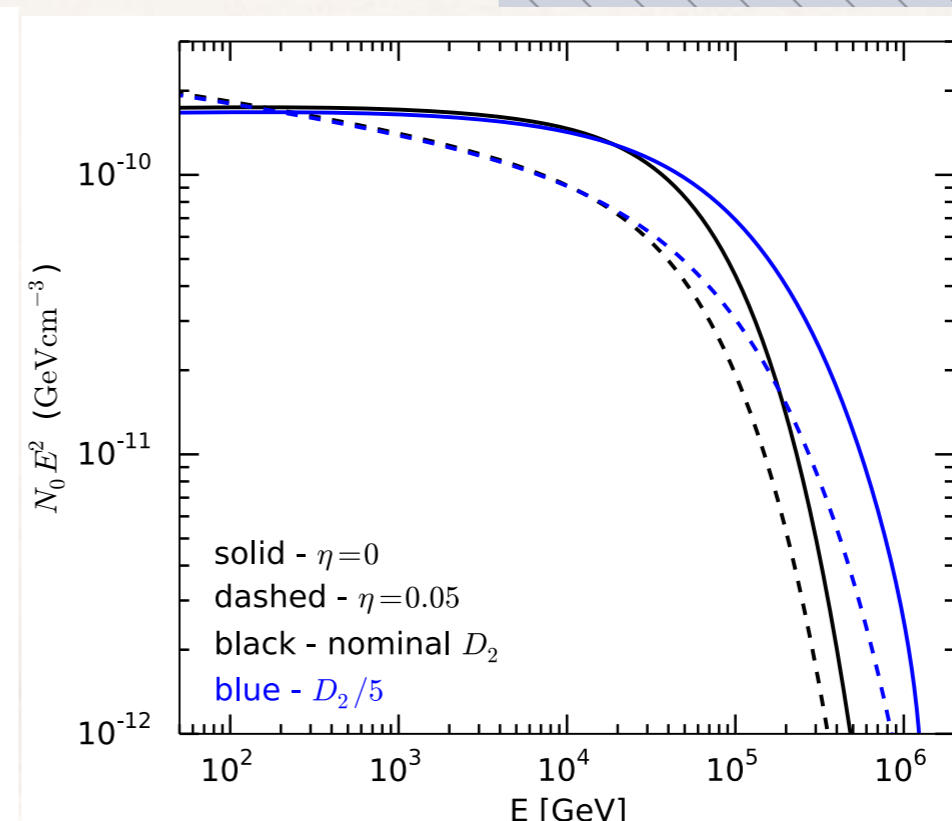
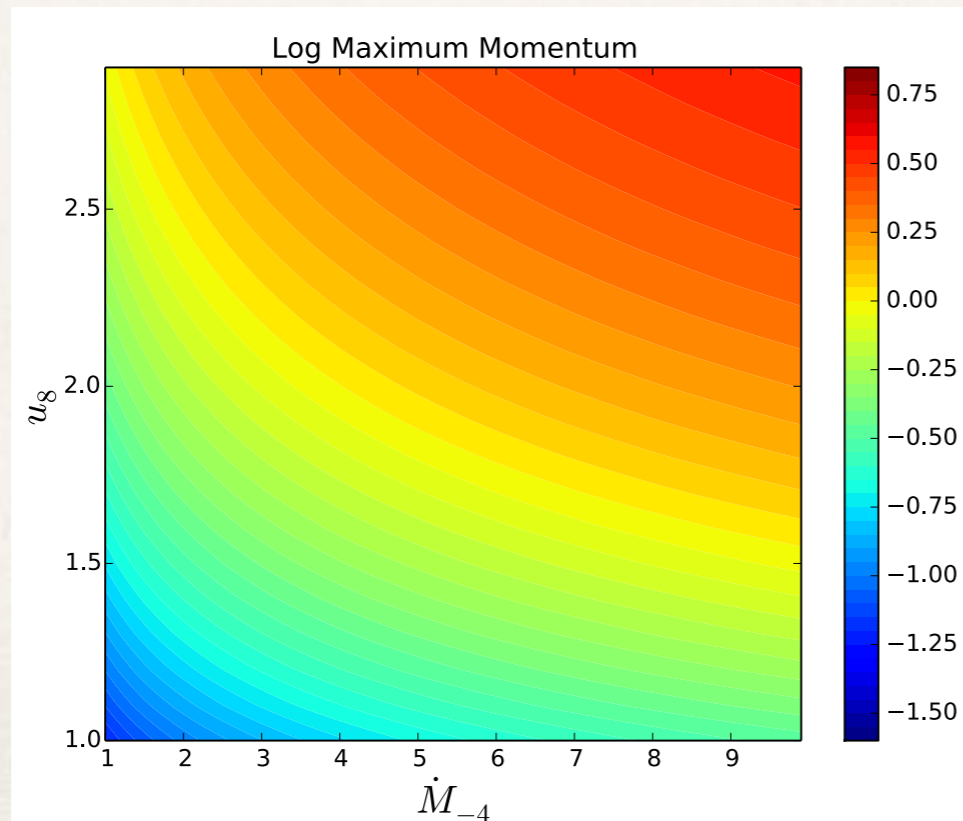- But the spectrum is all but trivial

Cristofari, PB & Caprioli 2021, Cristofari, PB & Amato 2020

Acceleration/sources

❋ Star clusters/superbubbles may in principle be efficient accelerators — DSA but in spherical symmetry (Talk by E. Peretti)

❋ As discussed by V. Tatischeff these structures would address and probably solve the ^{22}Ne problem

❋ The E_{max} can be estimated as:

$$E_{max} \approx 4 \times 10^{14} \, \eta_B^{1/2} \dot{M}_{-4}^{4/5} v_8^{13/5} \rho_1^{-3/10} t_{10}^{2/5} \left(\frac{L_c}{2pc} \right)^{-1} \, eV$$

ed by a star cluster
ck, R_{cd} the contact

utors to the flux

Acceleration/sources - UHE

Muzio et al 2
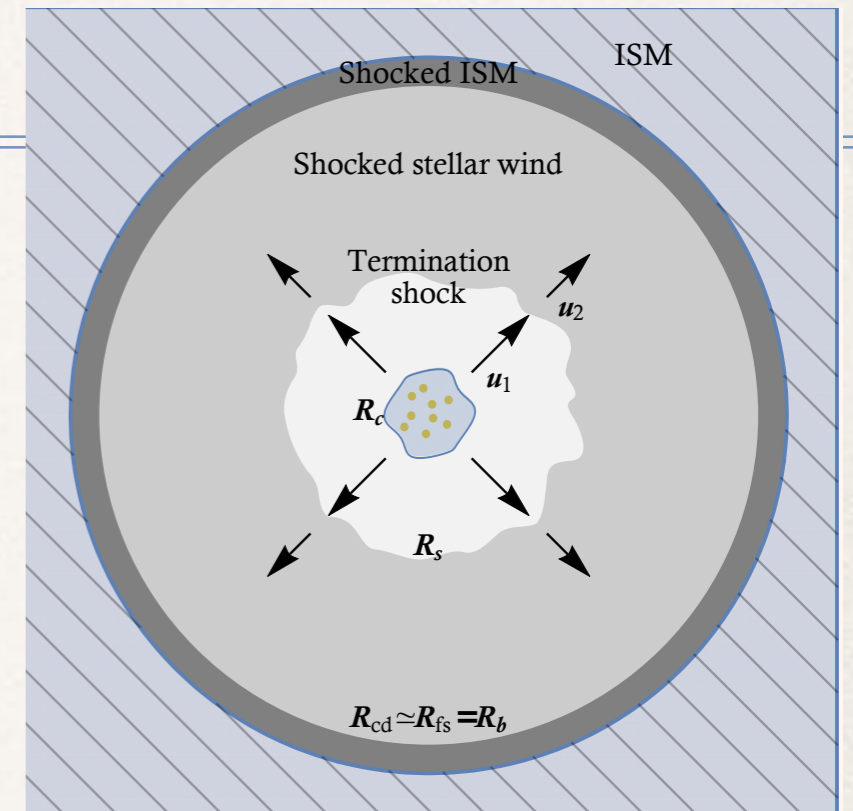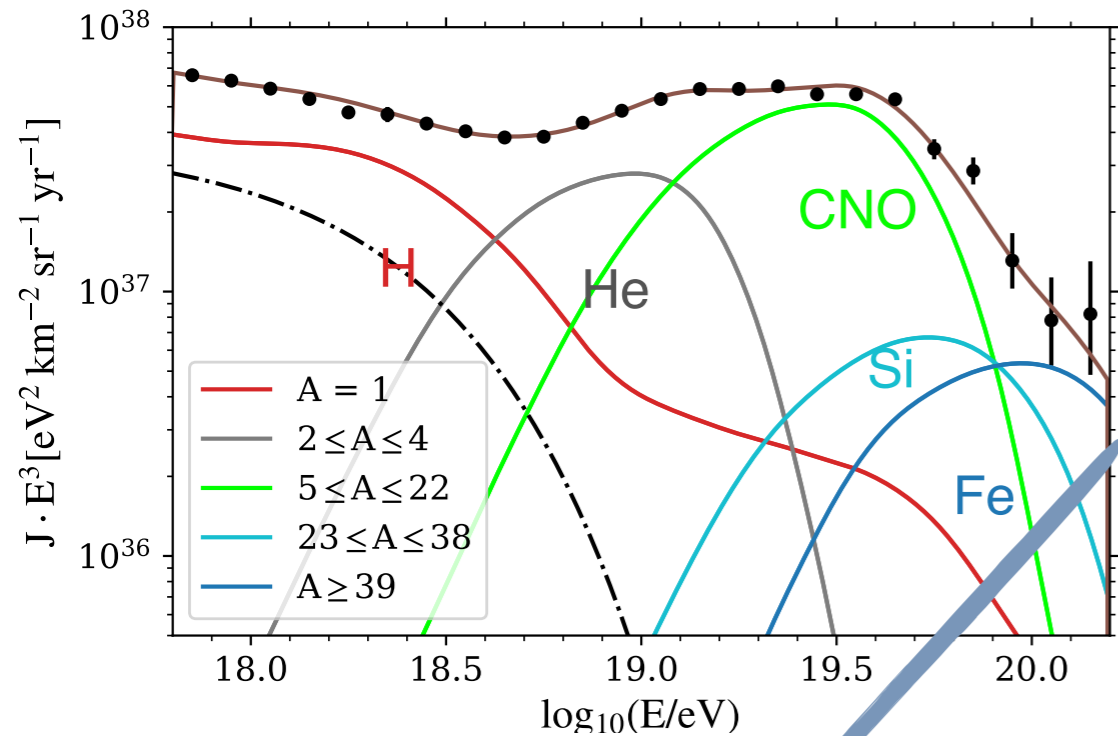
IN ORDER TO MAKE SENSE OF THESE DATA ONE HAS TO ASSUME A FEW THINGS:

- THE SOURCES MUST PRODUCE A MIXED MASS COMPOSITION (HARD TO IMAGINE THIS MAY HAPPEN IN THE STANDARD IGM)
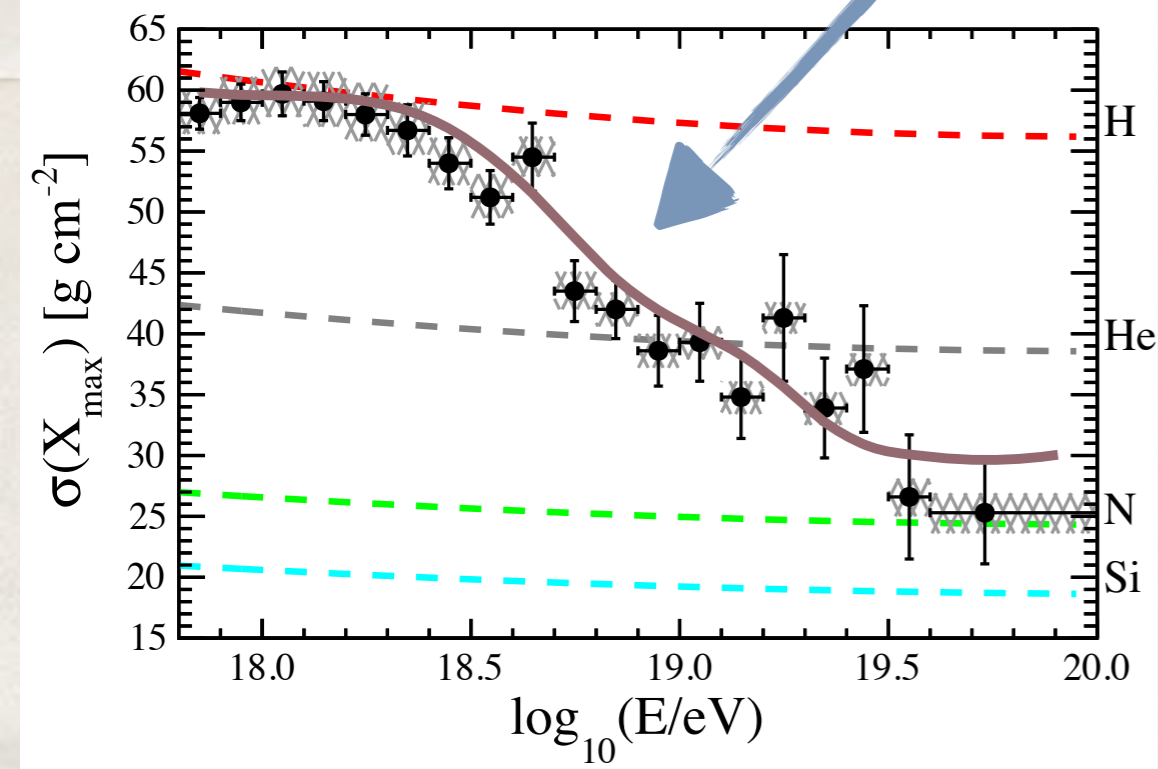- FAST TRANSITION BETWEEN COMPONENTS
- THE MAX ENERGY CANNOT HAVE A WIDE SPREAD (F. OIKONOMOU TALK)
- THE SOURCES MUST INJECT CR WITH VERY HARD SPECTRUM

THE HARD SPECTRA MAY RESULT FROM ACCELERATION IN NON-STANDARD CONDITIONS, FOR INSTANCE LIKE THE ONES SHOWN BY A. SPITKOVSKY IN 3D RECONNECTION (IN GRB? IN RADIO GALAXIES?)

…OR BUT THE HARD SPECTRA MIGHT REFLECT ENERGY LOSSES IN THE SOURCES+ENERGY DEPENDENT ESCAPE (MODEL OF FARRAR, UNGER) OR CONFINEMENT EFFECTS DUE TO MAGNETIC FIELDS (TALK BY B. EICHMANN)

…OR SELF-CONFINEMENT AROUND THE SOURCES (ASK QUESTIONS IF YOU DEEM NECESSARY)

ntribution (dot-dashed line) and the extragalactic

e) to the energy spectrum at the top of atmosphere.

a function of the energy.

Acceleration/sources - UHE

ONE SHOULD APPRECIATE HOW THE SITUATION CHANGED IN THE LAST TWENTY YEARS

WE WENT FROM A SITUATION IN WHICH DATA SHOWED THAT PROTONS SHOULD BE ACCELERATED TO ZeV ENERGIES, TO A SITUATION IN WHICH THE MAX RIGIDITY CANNOT BE HIGHER THAN ~2 EeV.

CLEARLY THE PROBLEM OF ACCELERATING PARTICLES HAS BECOME MUCH LESS DEMANDING

YET THERE ARE CONSTRAINT: FOR INSTANCE THE BULK OF STARBURSTS DO NOT HAVE ENOUGH POTENTIAL TO ACCELERATE UP TO SUCH RIGIDITY — PERHAPS UFO MAY BE A RARE EXCEPTION (TALK BY E. PERETTI)

BUT DO NOT FORGET ACCRETION SHOCKS (AROUND CLUSTERS — K. DOLAG TALK), RADIO GALAXIES (TALK BY B. EICHMANN), GRBs (INTENSE RADIATION FIELD)

General Remarks

✤ EXPERIMENTS GOT SO SENSITIVE THAT STATISTICS IS RARELY A PROBLEM, BUT SYSTEMATICS OFTEN LIMITING FACTOR (THINK OF C AND O SPECTRA)

✤ A TOPIC THAT HERE WAS BASICALLY UNCOVERED BUT IT IS PROBABLY ONE OF THE HOTTEST TOPICS IS THE EXISTENCE OF TeV HALOS AND SUPPRESSED DIFFUSION NEAR SOURCES

✤ THE SELF-GENERATION OF TURBULENCE IS CENTRAL TO ACCELERATION, TO ESCAPE FROM SOURCES AND TO TRANSPORT ON GALACTIC SCALES, AS WELL AS LIKELY FOR ESCAPE OF UHECR FROM THEIR SOURCES - NOT DISCUSSED HERE

General Remarks

* THESE ARE CONSIDERATIONS THAT PLAY A CRUCIAL ROLE NOT ONLY FOR THEORY BUT OBSERVATION (THINK OF THE DISTINCTION BETWEEN DIFFUSE FLUX AND NEAR-SOURCE INTERACTIONS, OR UHECR SUPPRESSION AT LOW E)

* AS SHOWN BY C. EVOLI, LOOKING AT ELECTRONS, IT SEEMS CLEAR NOW THAT LEPTONS LOSE ENERGY AS THEY ARE SUPPOSED TO (LIMITS TO ALTERNATIVE MODELS OF CR TRANSPORT TAILORED ON POSITRONS) — STILL, SOME FRACTION OF THE GRAMMAGE COULD BE ACCUMULATED NEAR THE SOURCES (THIS AFFECTS RESULTS EVEN MORE THAN CROSS SECTION UNCERTAINTIES)

* IT IS BECOMING CLEAR THAT B-FIELDS ON COSMOLOGICAL SCALES MAY PLAY A CRUCIAL ROLE IN SHAPING THE UHECR SPECTRUM (MAGNETIC HORIZON)…YET THERE ARE INDICATIONS THAT THE UNIVERSE IS LIKELY FILLED WITH EXTREMELY LOW VALUES OF B (VOIDS) [SEE CASE OF GRB221009A]