CERN SUMMER STUDENT - LECTURE I

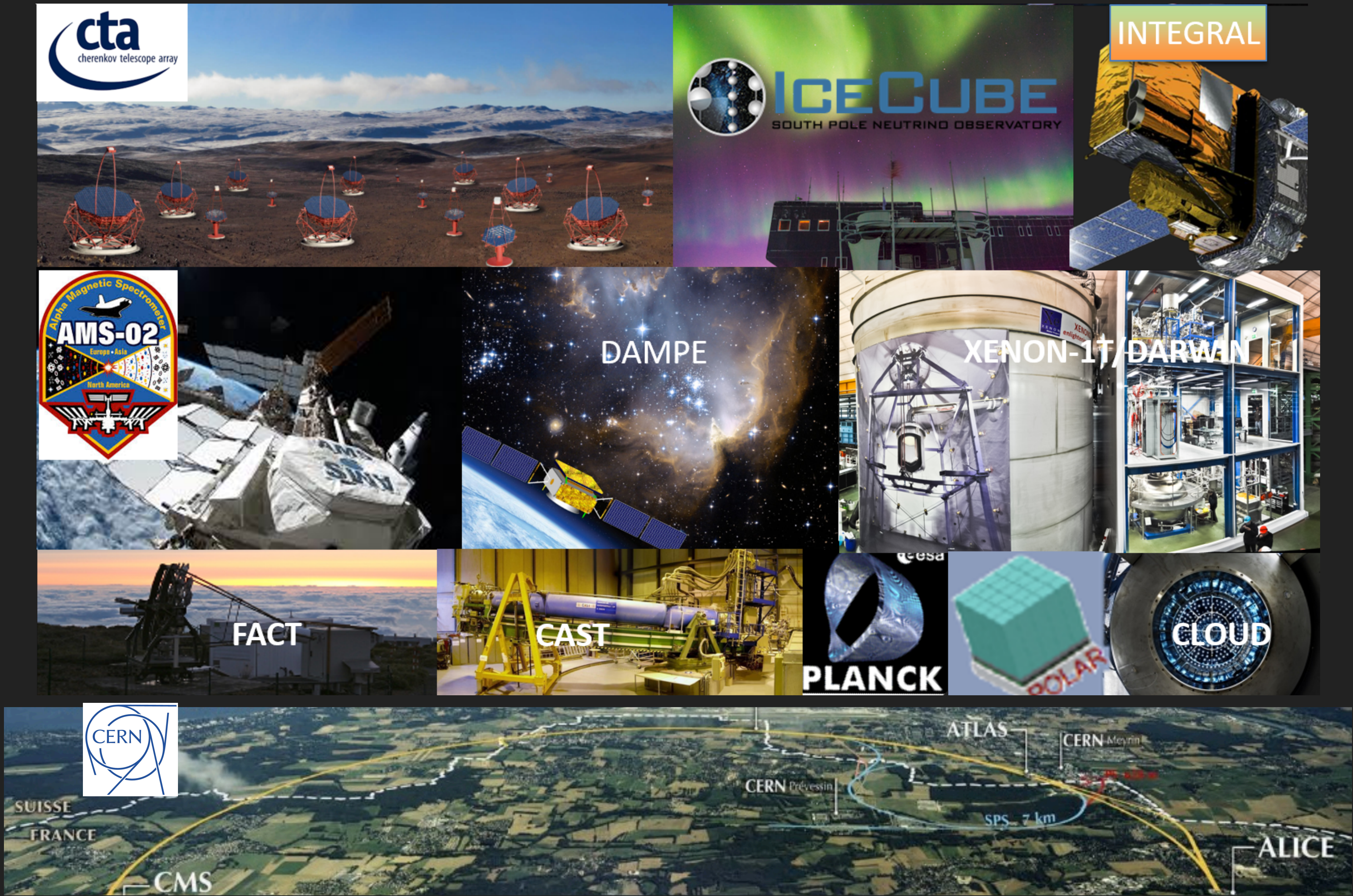
TERESA.MONTARULI@UNIGE.CH

ASTROPARTICLE I

20 JULY 2017

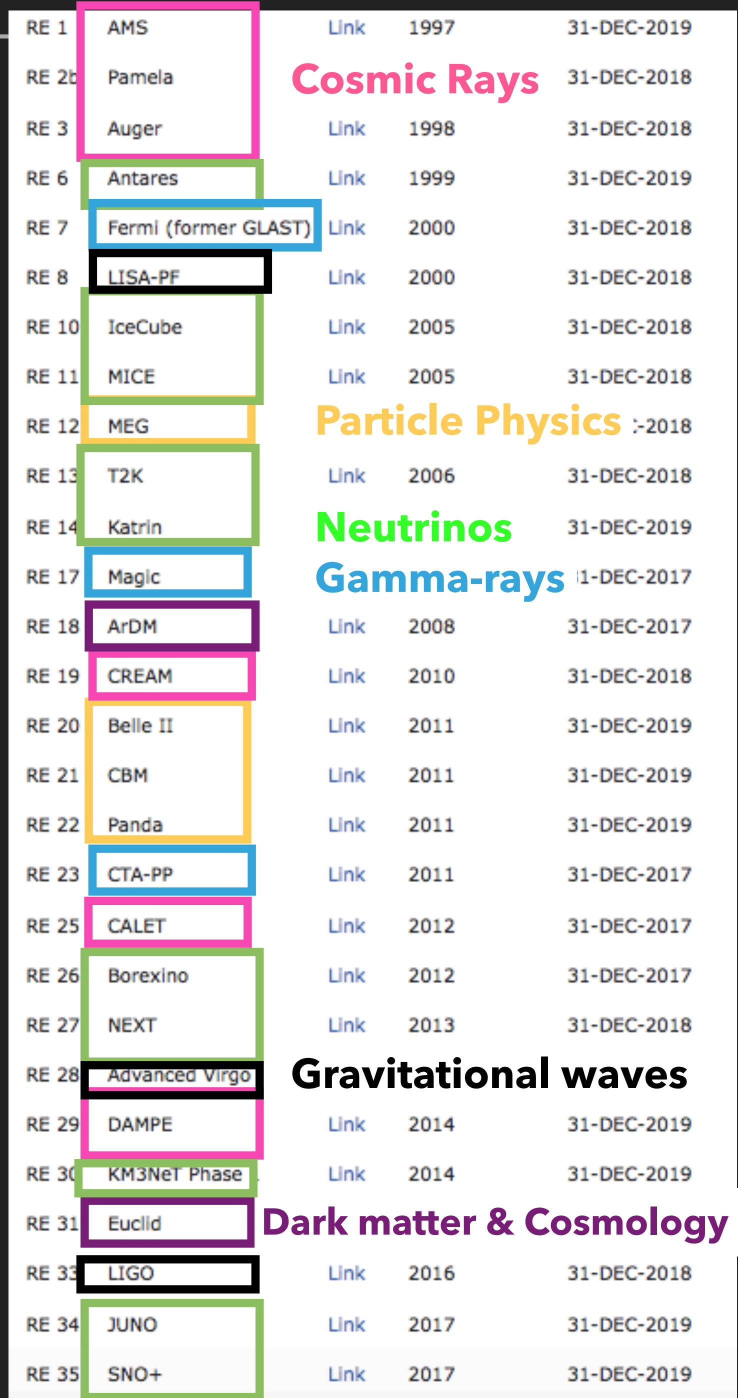
GENEVA...SWITZERLAND...

….AND ASTROPARTICLE



CERN AND ASTROPARTICLE

- Recognised experiments: mostly on neutrinos, particle physics and cosmic rays; also on gamma-rays, gravitational waves and cosmology
- must have substantial presence at CERN and connections to CERN activities
- CERN grants space, administrative, software support,…

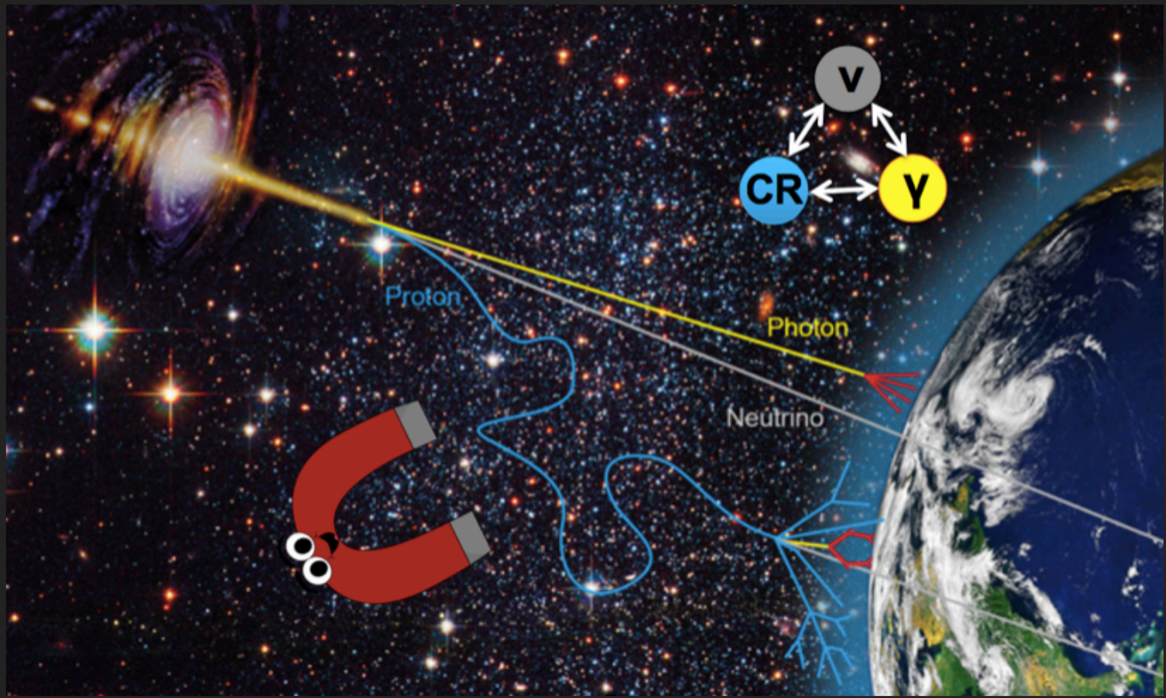


RE 1	AMS	Link	1997	31-DEC-2019
RE 2b	Pamela			31-DEC-2018
RE 3	Auger	Link	1998	31-DEC-2018
RE 6	Antares	Link	1999	31-DEC-2019
RE 7	Fermi (former GLAST)	Link	2000	31-DEC-2018
RE 8	LISA-PF	Link	2000	31-DEC-2018
RE 10	IceCube	Link	2005	31-DEC-2018
RE 11	MICE	Link	2005	31-DEC-2018
RE 12	MEG			:-2018
RE 13	T2K	Link	2006	31-DEC-2018
RE 14	Katrin			31-DEC-2019
RE 17	Magic			1-DEC-2017
RE 18	ArDM	Link	2008	31-DEC-2017
RE 19	CREAM	Link	2010	31-DEC-2018
RE 20	Belle II	Link	2011	31-DEC-2019
RE 21	CBM	Link	2011	31-DEC-2019
RE 22	Panda	Link	2011	31-DEC-2019
RE 23	CTA-PP	Link	2011	31-DEC-2017
RE 25	CALET	Link	2012	31-DEC-2017
RE 26	Borexino	Link	2012	31-DEC-2017
RE 27	NEXT	Link	2013	31-DEC-2018
RE 28	Advanced Virgo			
RE 29	DAMPE	Link	2014	31-DEC-2019
RE 30	KM3NeT Phase	Link	2014	31-DEC-2019
RE 31	Euclid			
RE 33	LIGO	Link	2016	31-DEC-2018
RE 34	JUNO	Link	2017	31-DEC-2019
RE 35	SNO+	Link	2017	31-DEC-2019

http://recognized-experiments.web.cern.ch/recognized-experiments

CONTENTS OF TWO LECTURES

- Radiation from the universe and cosmic rays (CRs)
- Cosmic ray observables: spectrum and composition
- Propagation and sources of cosmic rays
- The connection of CRs to other messengers :
  - Gamma-Rays
  - Neutrinos

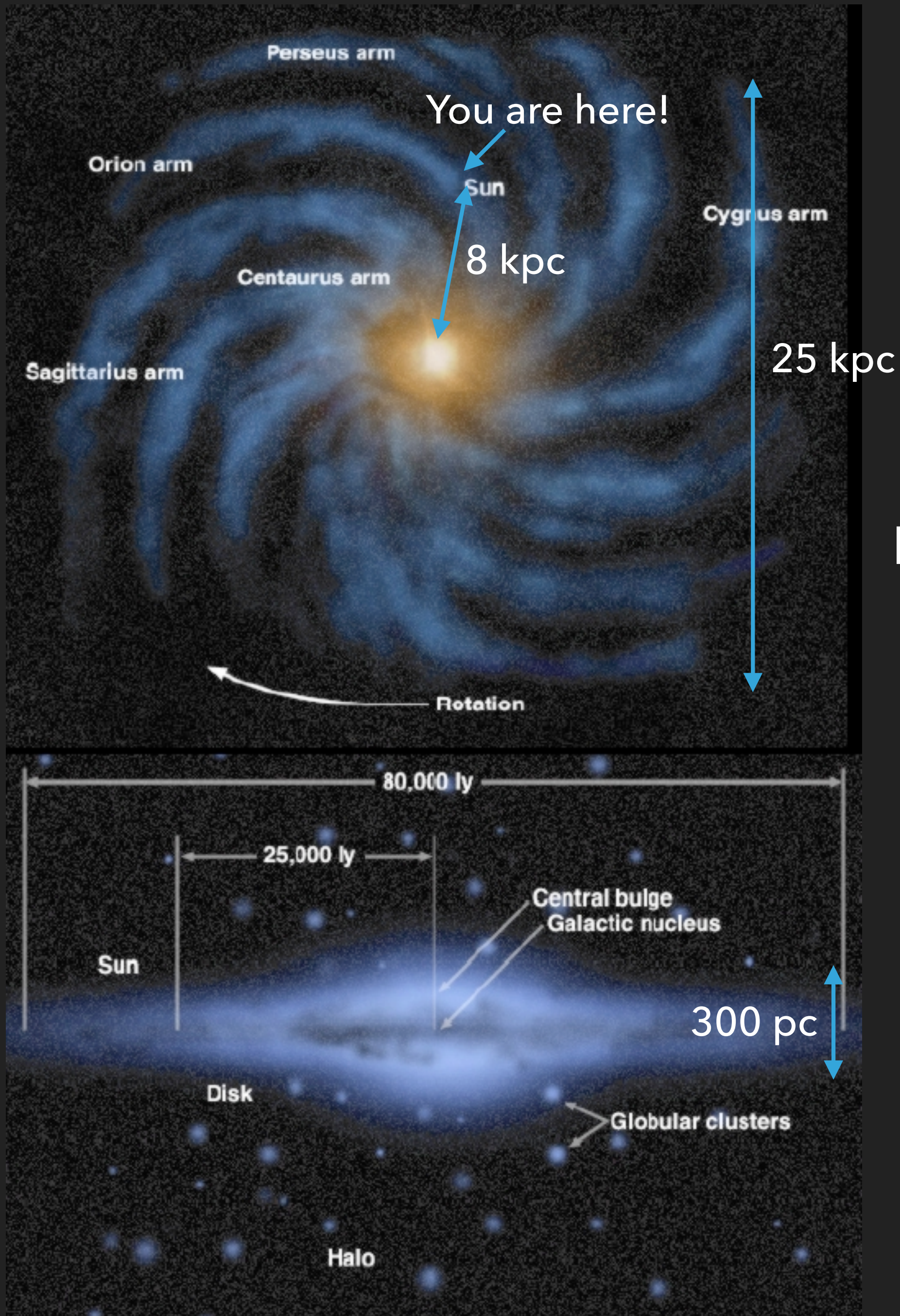


A VIEW TO THE GALAXY…

Thin disk : 25 kpc diameter ~300pc thickness

Surrounded by a halo of ~ 30 kpc

The Sun is located ~ 8 kpc from the Galactic Centre



Moon-Earth 384,000 km = 1.28 ls

Sun -Earth centre8 kpc = 150M km = 8.3 lm

Speed of Sun in the Galaxy around the Galactic centre : 220 km/s

Density of interstellar matter: ρ_{ISM} ~1 proton cm^{-3}

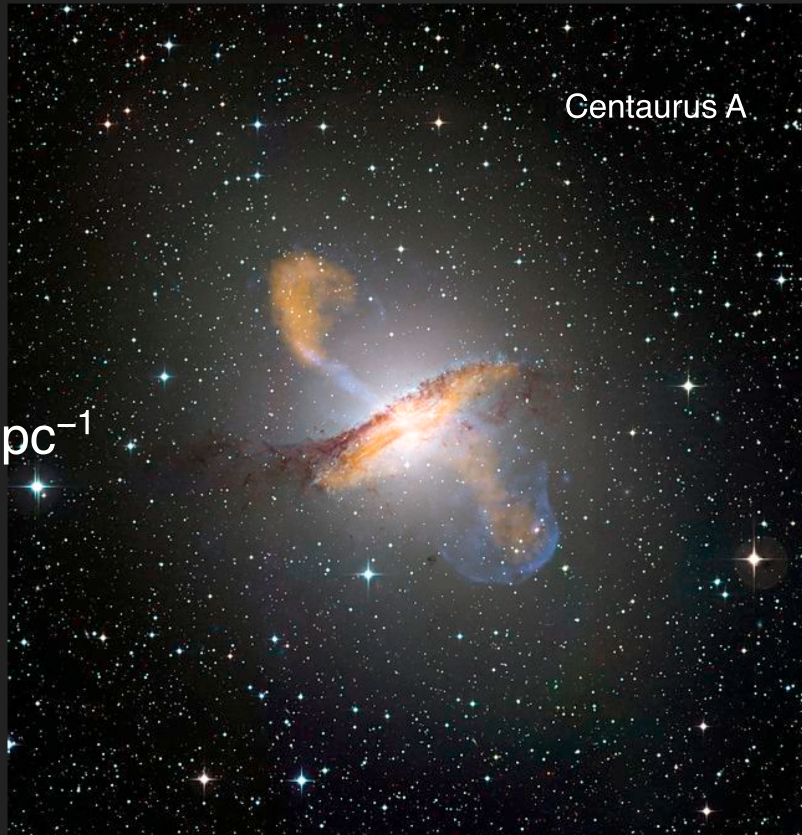
1pc = 3.0857 x 10^{16} m = the distance at which the mean radius of the Earth's orbit about the Sun subtends an angle of 1 sec of arc

1 ly = 2.998 x 10^{8} m/s x 3.156 x 10^{7} s/yr ≈10^{13} km

….AND BEYOND

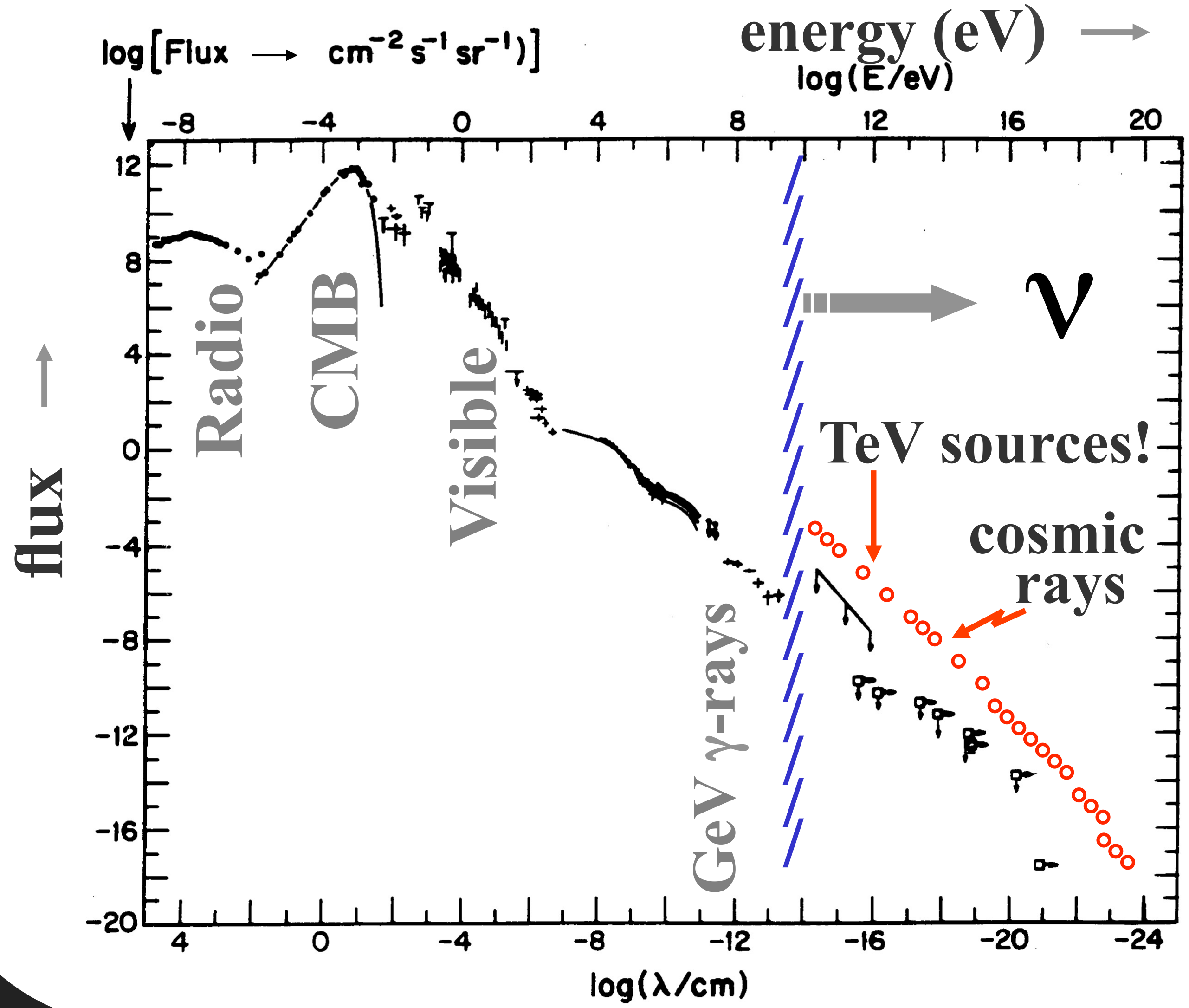
- Proxima Centaury (closest star) 4.3 ly = 1.3 pc
- Large Magellanic Cloud 45 kpc
- Local group (Andromeda M31) 0.78 Mpc
- Active Galactic Nuclei with black holes
  - Cen A 3 Mpc
  - Mrk 421 136 Mpc
  - 3C273. 1 Gpc
- Universe c/H_0 = 13.7 billion yrs ~4 Gpc
- Hubble expansion const. $H_0 = 67.27 \pm 0.66$ km s^{-1} Mpc^{-1}
- T_0 CMBR temperature 2.725 ± 0.001 °K

1Mpc = 3.26 Mly = 3.0857×10^{24} cm



RADIATIONS FROM THE UNIVERSE: PHOTONS AND PARTICLES

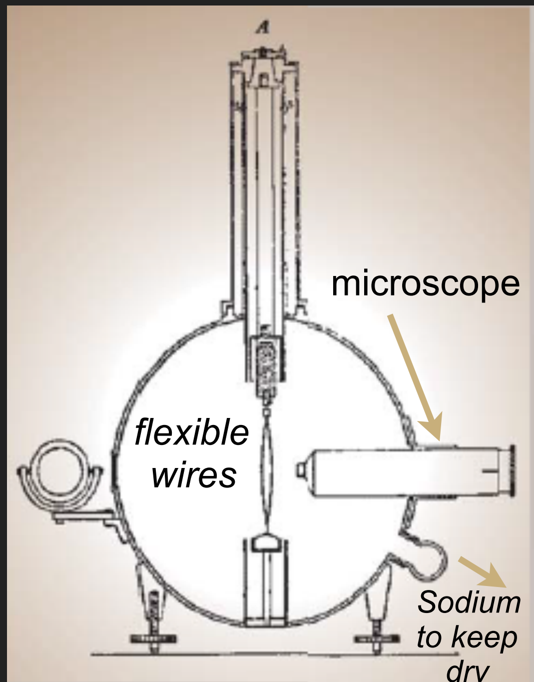
Courtesy of F. Halzen



COSMIC RAY HISTORICAL HINTS

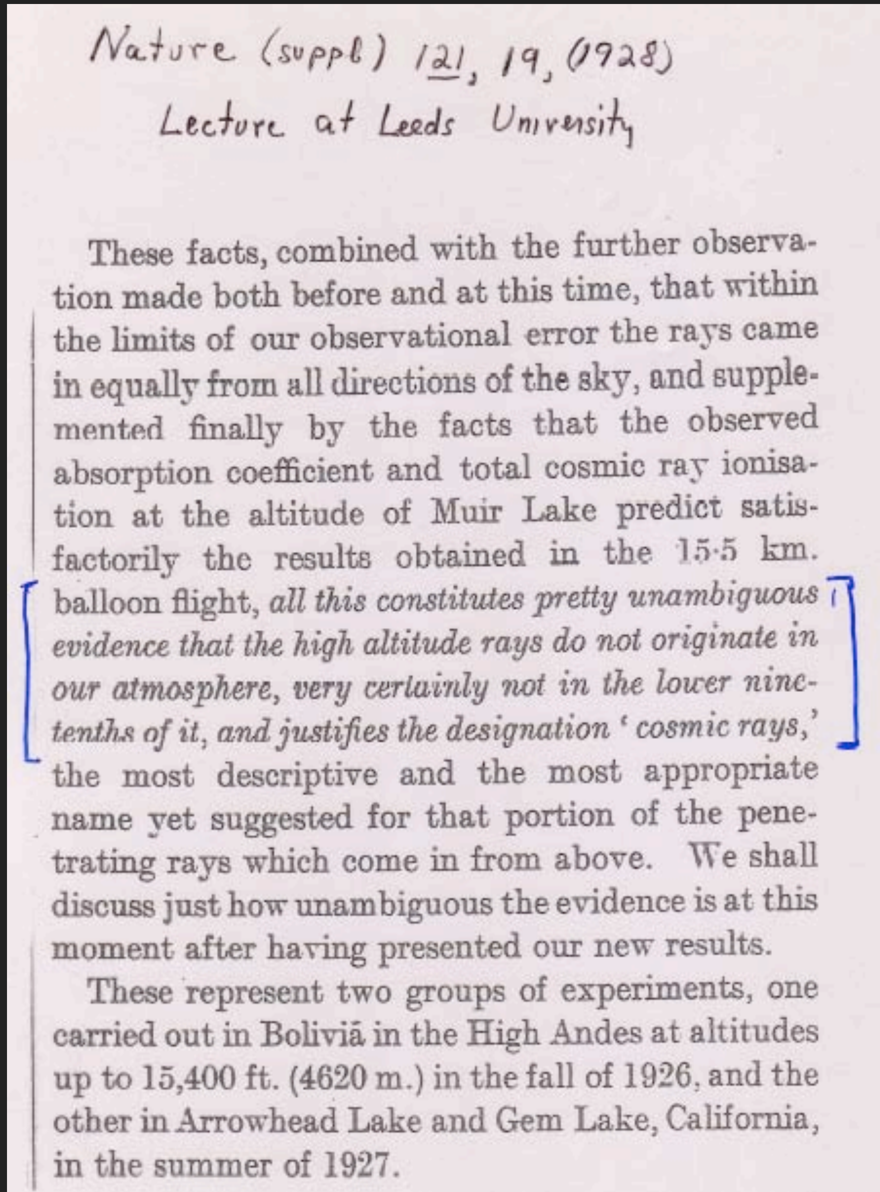
- A. Gockel (Swiss, 1909-1911): with a Wolf-type electroscope on 3 balloon flights discovers that the radiation discharging the electroscopes does not come from ground but increases with altitude. Wrong interpretation: gamma-rays from radioactive sources in the atmosphere
- V.F. Hess (1912, nobel prize with Anderson in 1936) reaches 5000 m altitude and interprets results as due to a ionising radiation that increases with altitude.

http://www.desy.de/2012vhess



COSMIC RAY HISTORICAL HINTS

- Millikan studied the penetration properties in water and atmosphere and called the radiation '**cosmic rays**' (1928)



Nature (suppl) 121, 19, (1928)

Lecture at Leeds University

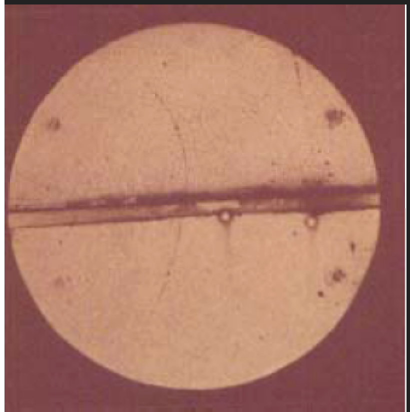
These facts, combined with the further observation made both before and at this time, that within the limits of our observational error the rays came in equally from all directions of the sky, and supplemented finally by the facts that the observed absorption coefficient and total cosmic ray ionisation at the altitude of Muir Lake predict satisfactorily the results obtained in the 15·5 km. balloon flight, *all this constitutes pretty unambiguous evidence that the high altitude rays do not originate in our atmosphere, very certainly not in the lower nine-tenths of it, and justifies the designation 'cosmic rays,'* the most descriptive and the most appropriate name yet suggested for that portion of the penetrating rays which come in from above. We shall discuss just how unambiguous the evidence is at this moment after having presented our new results.

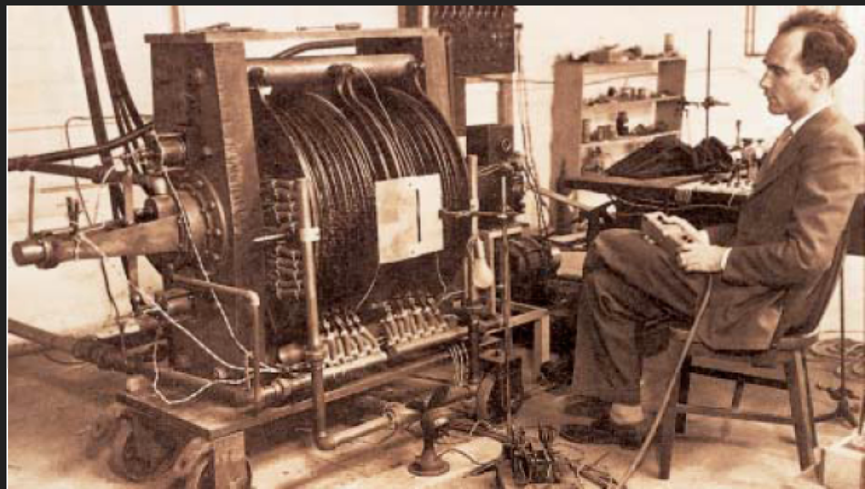
These represent two groups of experiments, one carried out in Boliviā in the High Andes at altitudes up to 15,400 ft. (4620 m.) in the fall of 1926, and the other in Arrowhead Lake and Gem Lake, California, in the summer of 1927.

PARTICLES DISCOVERED IN COSMIC RAYS

- C. Anderson discovers the positron in a bubble chamber (1932) and his results were confirmed by P. Blackett and G. Occhialini that recognised in it the anti-electron of the Dirac theory observing e^+e^- pair production

http://ifjungo.ch/jungfraujoch/





- Auger in the late 30's at the Jungfraujoch (3500 m a.s.l.) concluded that registered particles were secondaries generated in the atmosphere by primary CRs.
- C.F. Powell, G. Occhialini & C. Lattes (1947) observed the pion, predicted by Yukawa, in photographic emulsions. Powell : Nobel prize in 1950.

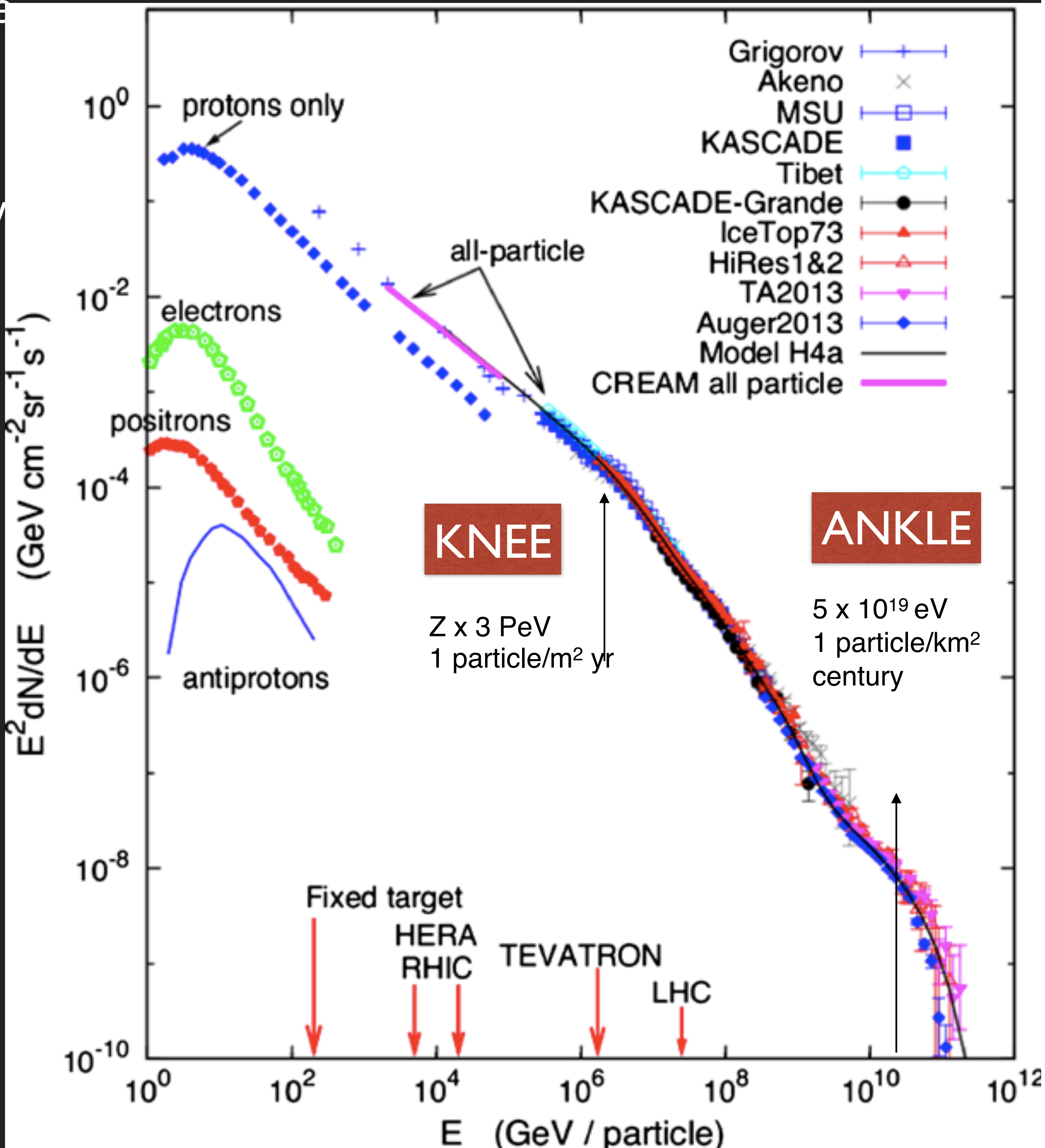
THE COSMIC RAY ALL-PARTICLE SPECTRUM

Particles per unit of surface, unit of time, unit of solid angle, unit of energy $[m^2\ s\ sr\ GeV]^{-1}$.
The spectrum spans 12 orders of magnitude in energy and 24 in intensity

$$\frac{dN}{dE} = 1.8 \times 10^4 (E/1GeV)^{-2.7} \frac{\text{nucleons}}{\text{m}^2\,\text{sr}\,\text{s}\,\text{GeV}}$$

$E_{knee} = Z \times 3$ PeV

$E_{ankle} \cong 5 \times 10^{19}$ eV



COSMIC RAY PHYSICS - LHC PHYSICS

- CR and fixed target nucleus 4-momentum:

$p_1 = (E_1/c, \mathbf{p}_1)$ $p_2 = (m_2 c, \mathbf{0})$

- Total 4-momentum in the lab frame:

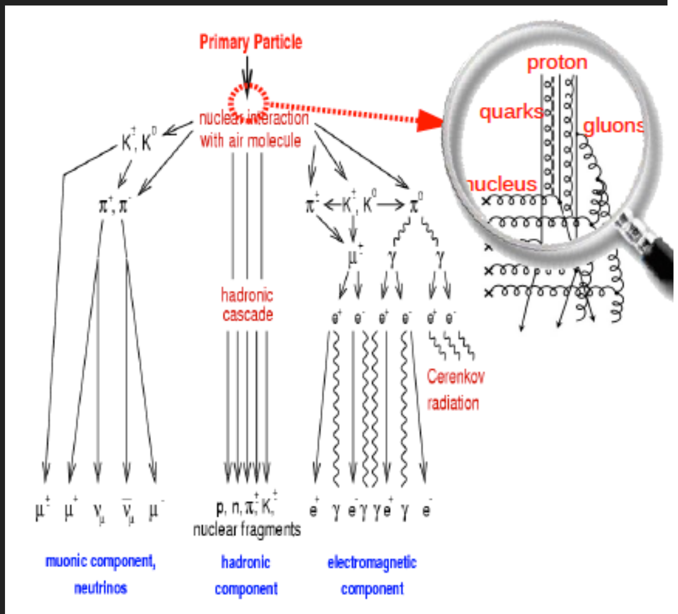
$$p = (E_1/c + m_2 c, \mathbf{p}_1)$$

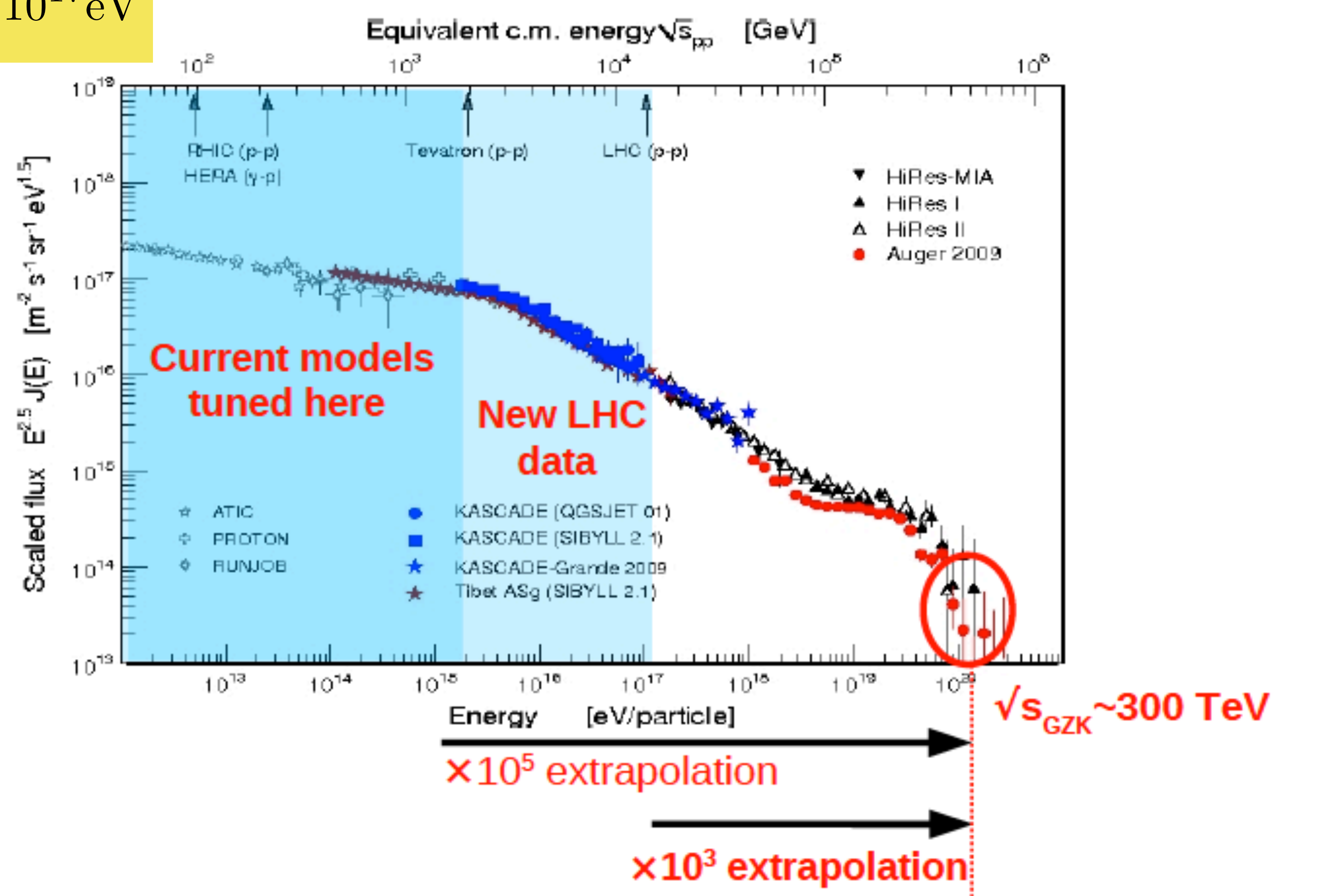
- Total Centre of Mass energy (from invariance of p^2):

$$\mathbf{E^2_{CM} = p^\mu p_\mu c^2 = (m_1^2 + m_2^2)c^4 + 2E_1 m_2 c^2}$$

- LHC and CR physics: E_{CM} = 7TeV+7TeV >> $m_2 = m_p \sim 1$ GeV

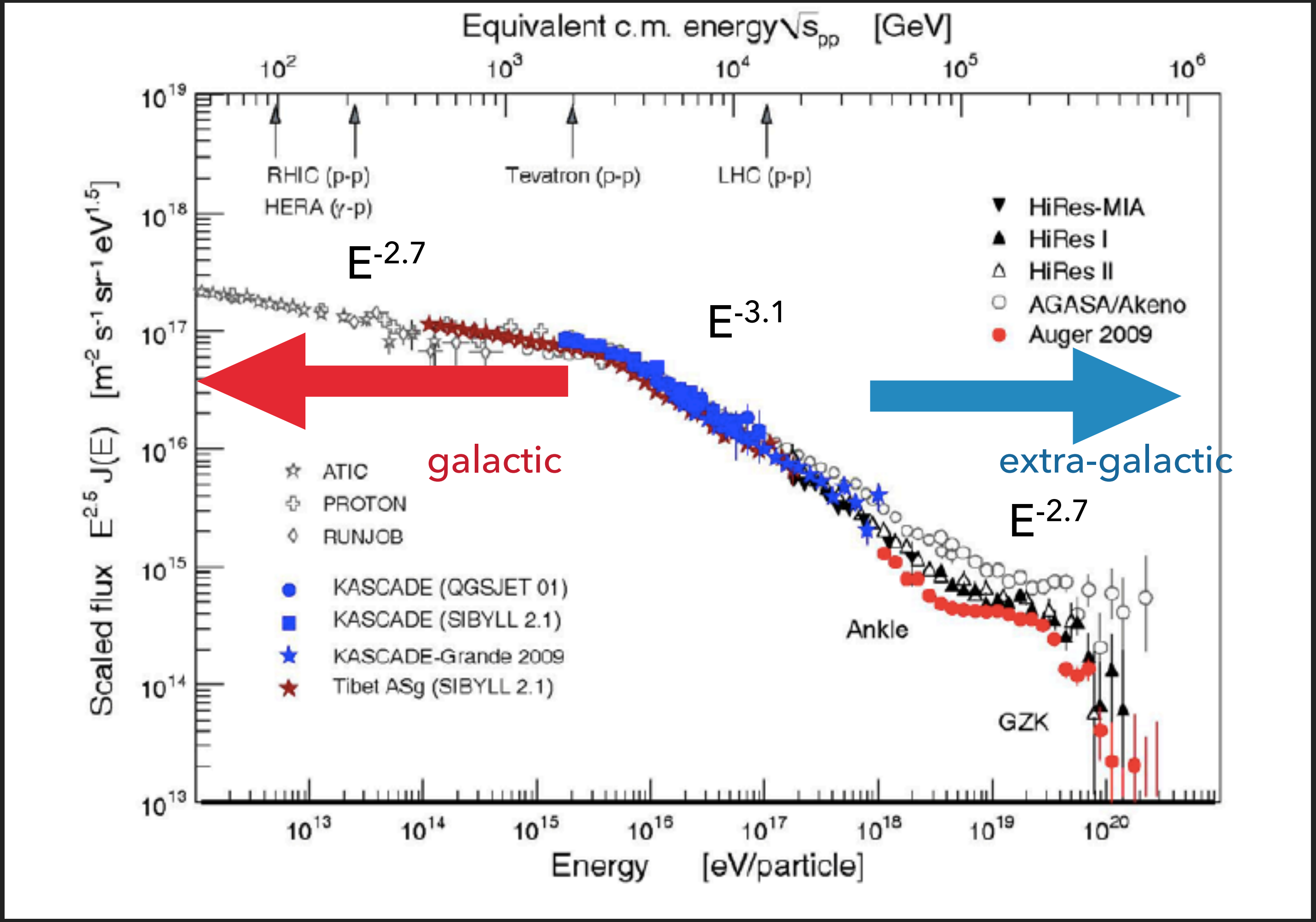
$$E_p \sim \frac{E^2_{CM}}{2m_2c^2} \sim \frac{(14\times10^3)^2}{2} \sim 1\times10^{17}\mathrm{eV}$$





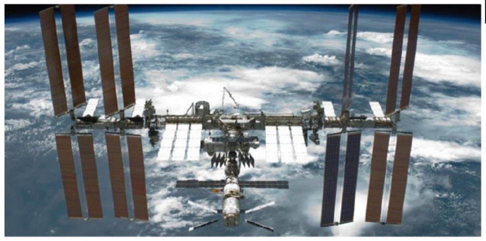
THE SPECTRAL FEATURES

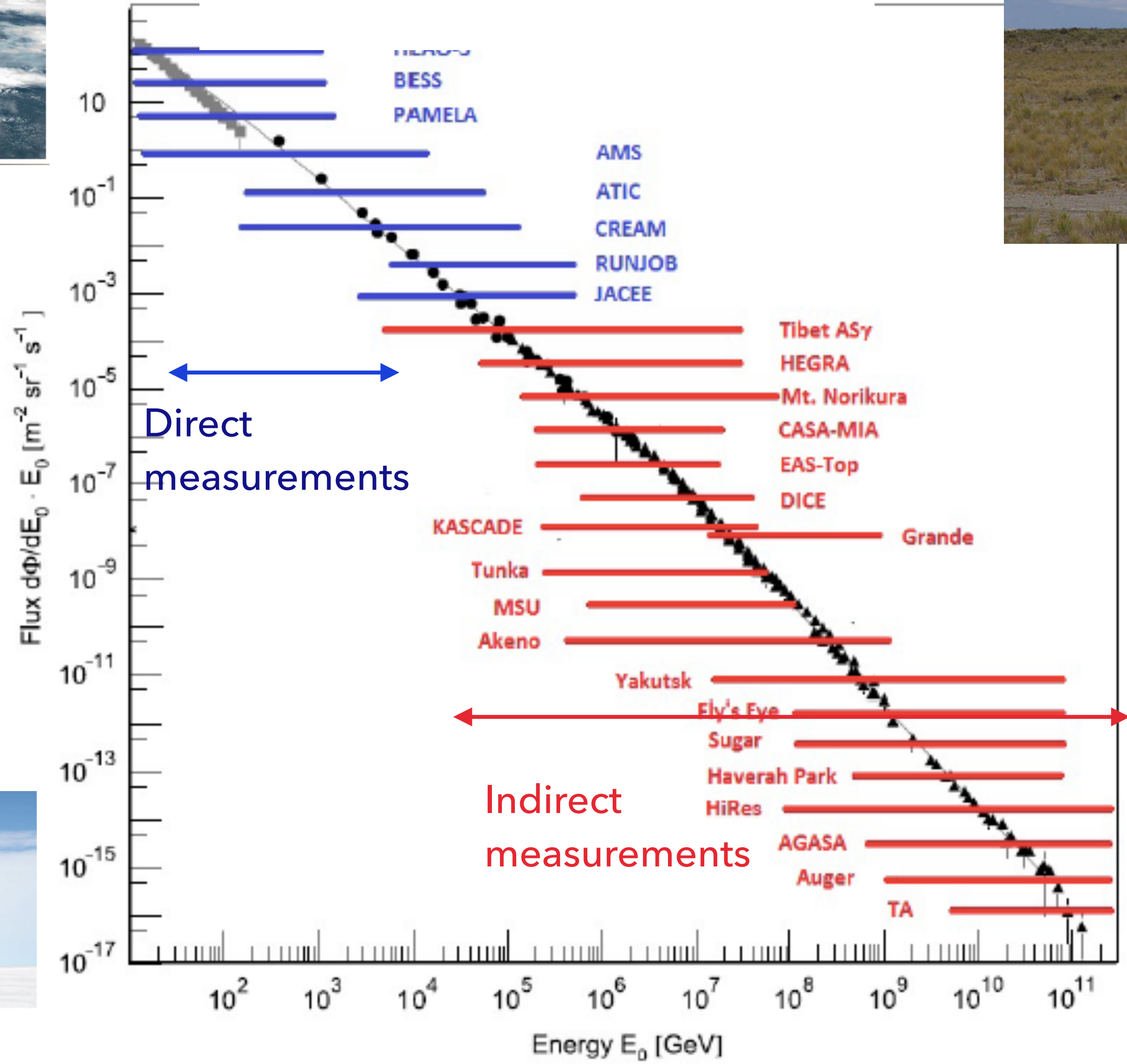
- The power law is explainable through acceleration processes in magnetic fields (Fermi acceleration)
- The changes of slope are connected to changes of sources and/or propagation features

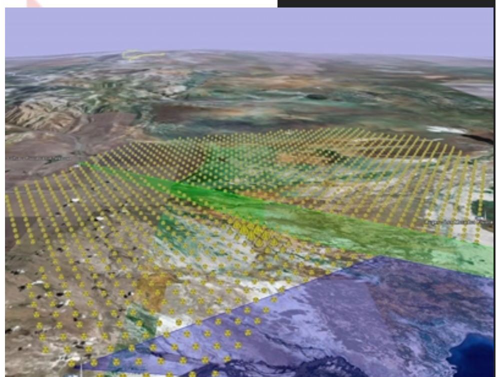


COSMIC RAY MEASUREMENTS

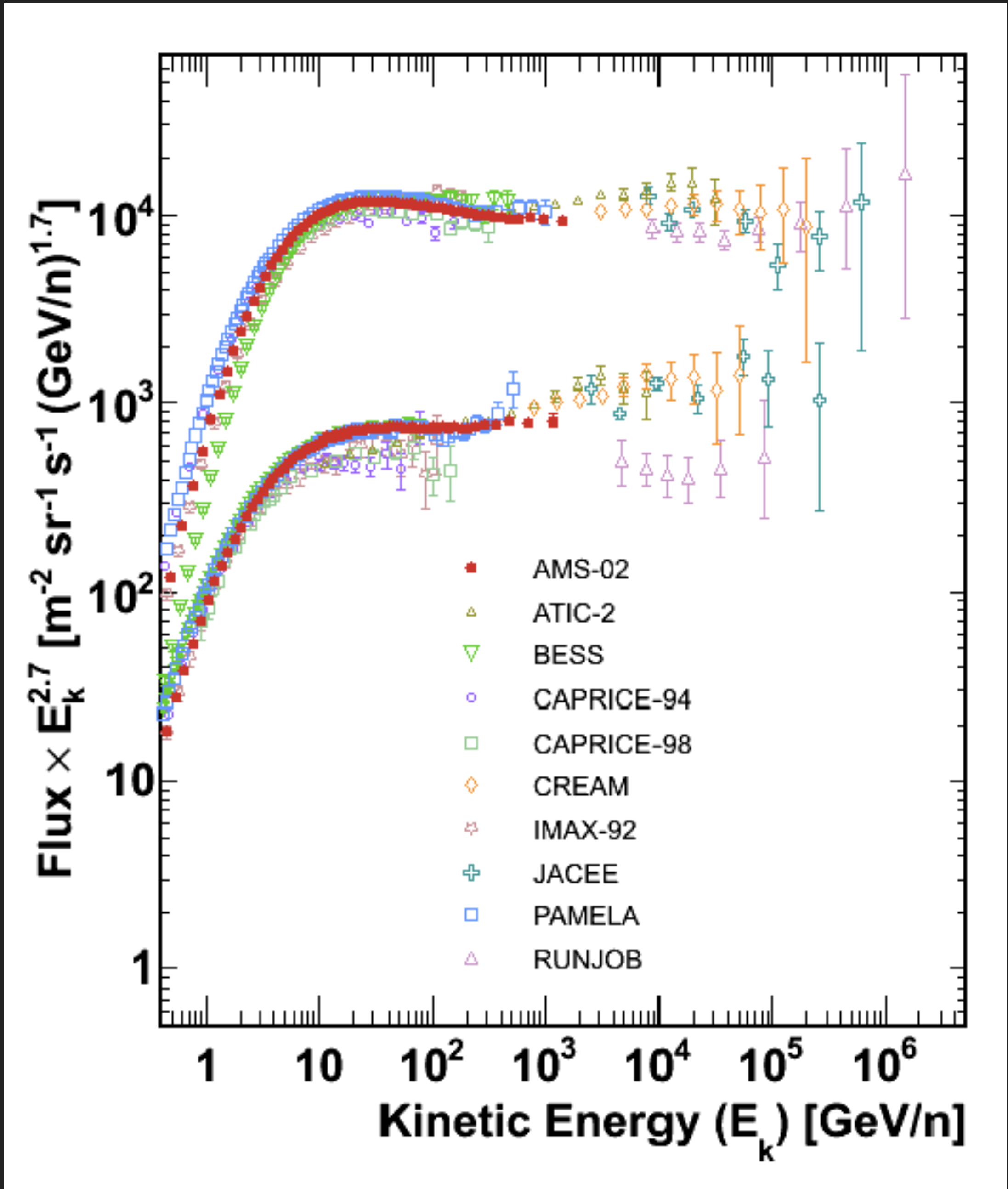
1 gigaelectron-volt= 1 GeV=10^9 eV
1 teraelectron-volt= 1 TeV=10^{12} eV
1 petaelectron-volt= 1 PeV=10^{15} eV
1 exaelectron-volt= 1 EeV=10^{18} eV







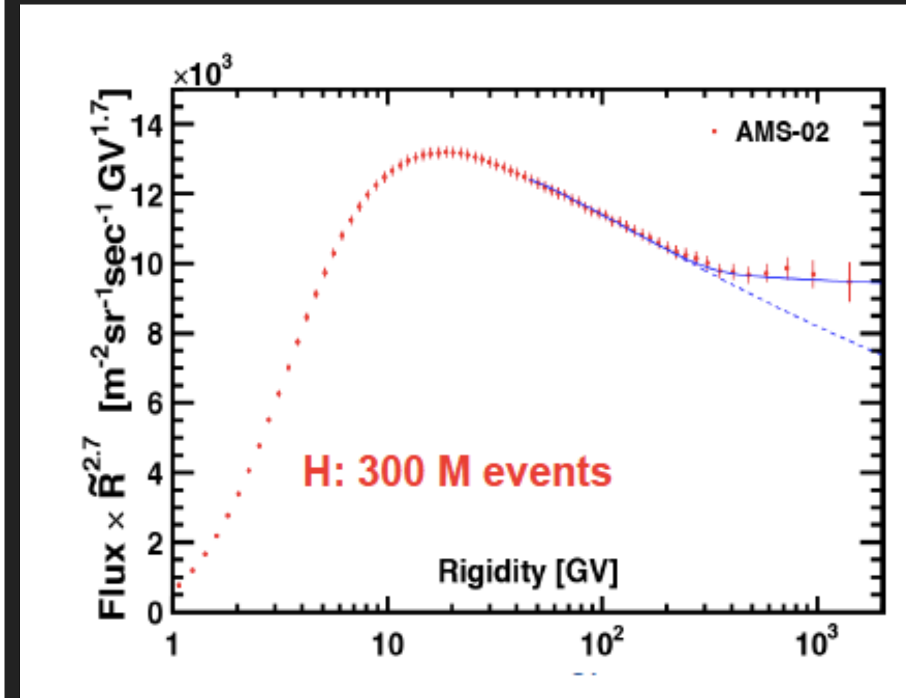
CURRENT BEST KNOWLEDGE OF GALACTIC COSMIC RAYS



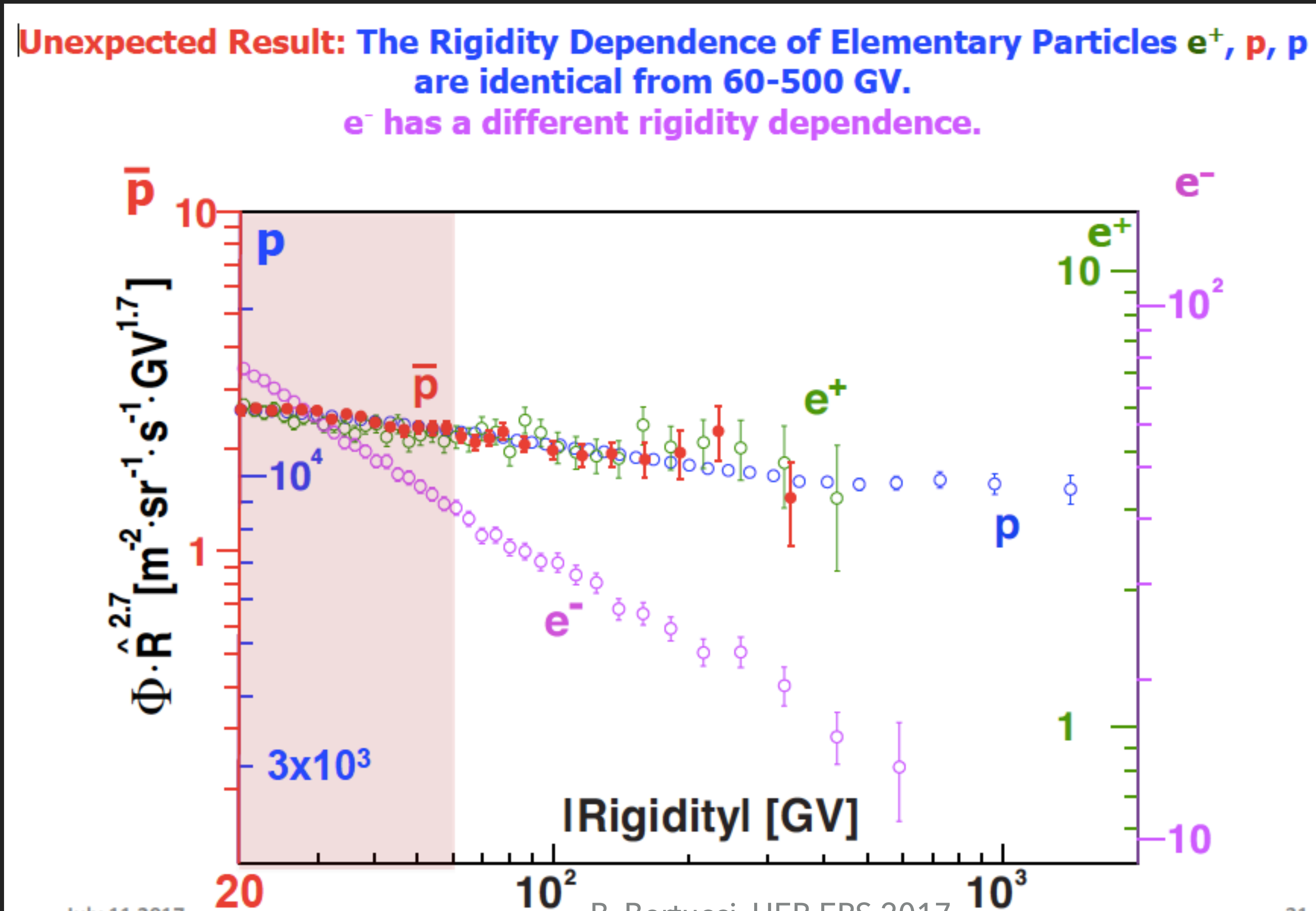
An unexpected kink at 200 GeV/n first detected by Pamela (Science 2011) and confirmed by AMS-02 in the proton and heavier nuclei spectra.

Could hint to young efficient accelerators, propagation effects (arXiv:1704.05696), acceleration mechanism

H and He have not parallel spectra. The knee region could be dominated by He not H.

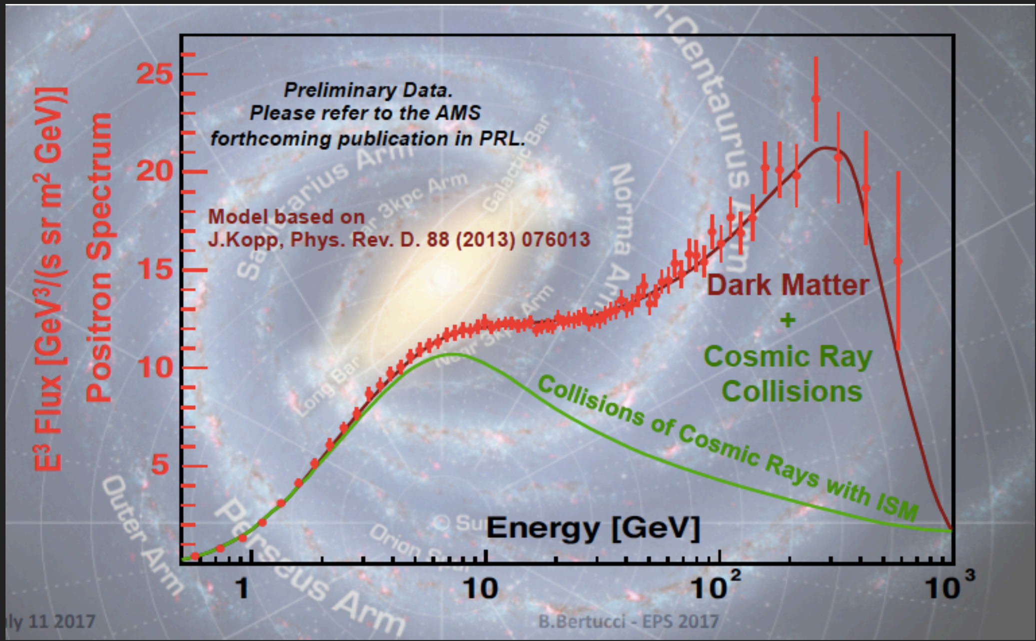


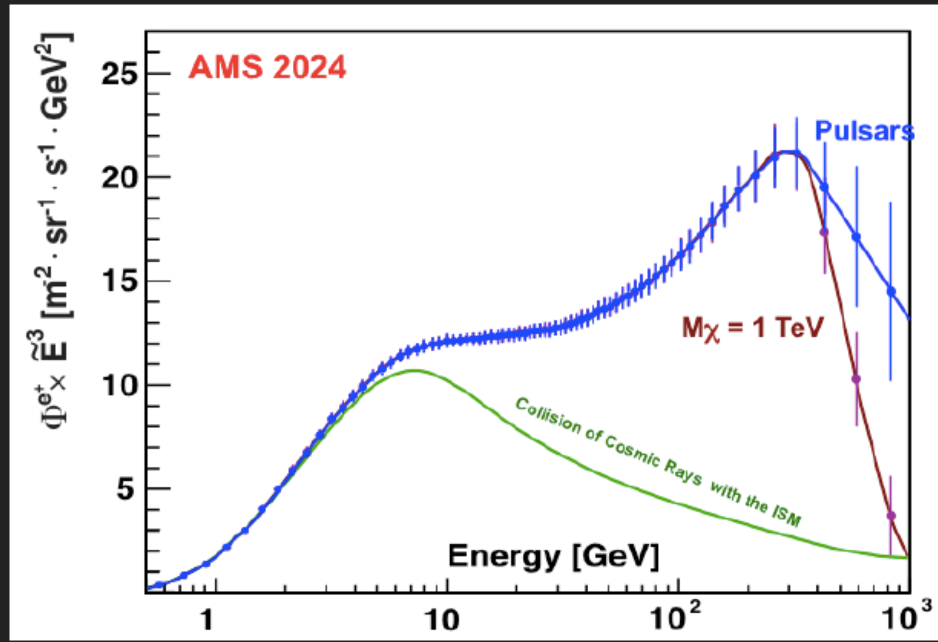
PROTONS AND ELECTRONS AND THEIR ANTIPARTICLES



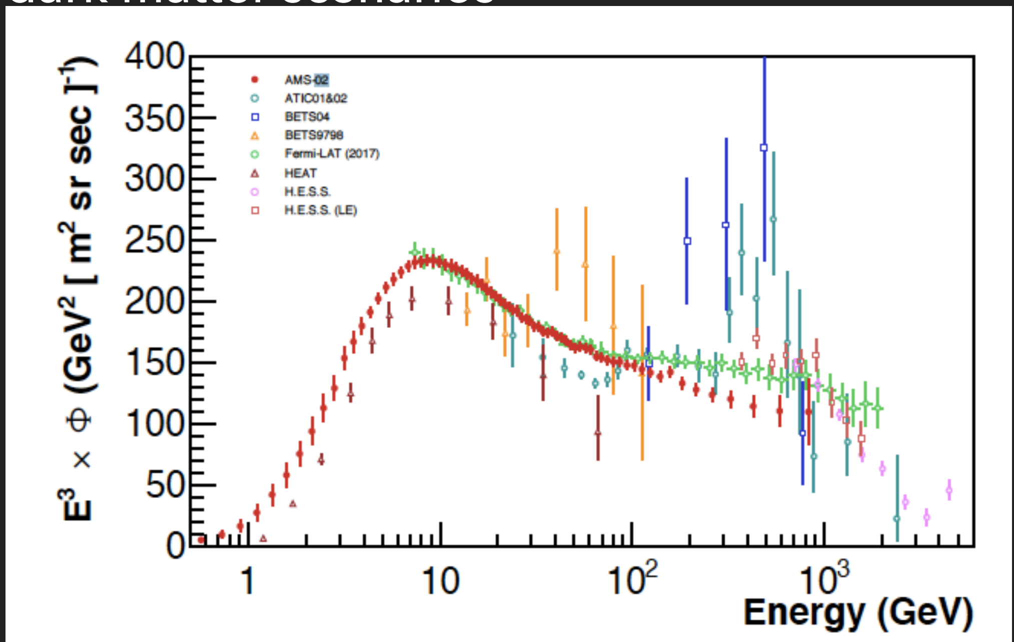
B. Bertucci, HEP-EPS 2017

DARK MATTER HINTS IN COSMIC RAYS? ANTI-ELECTRONS



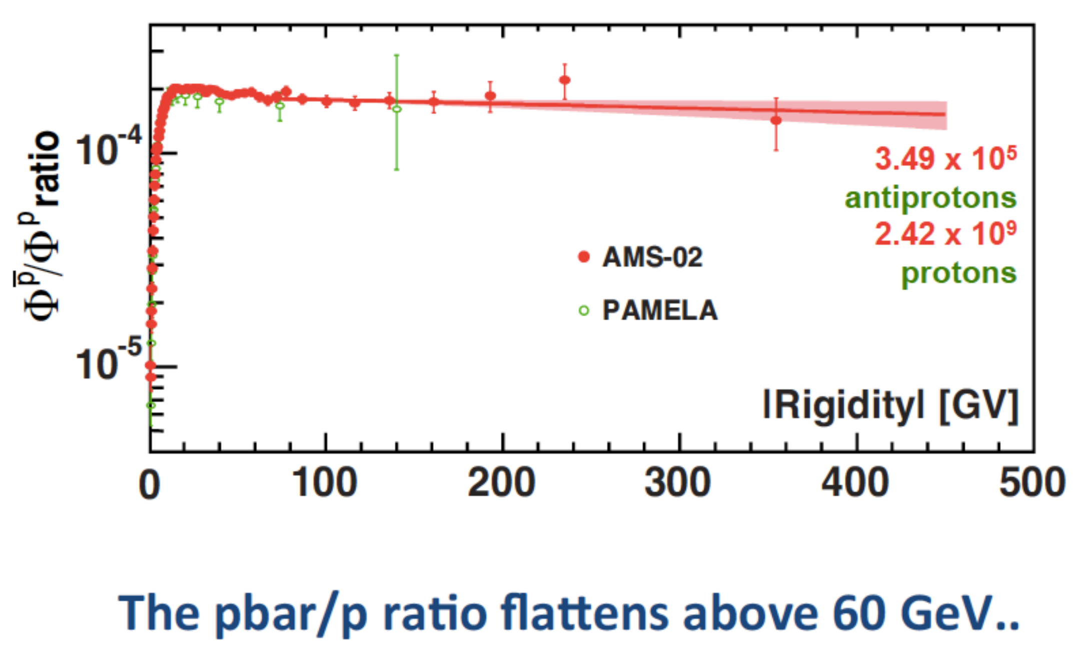


High precision data will allow to discriminate the local source accelerator scenario from dark matter scenarios

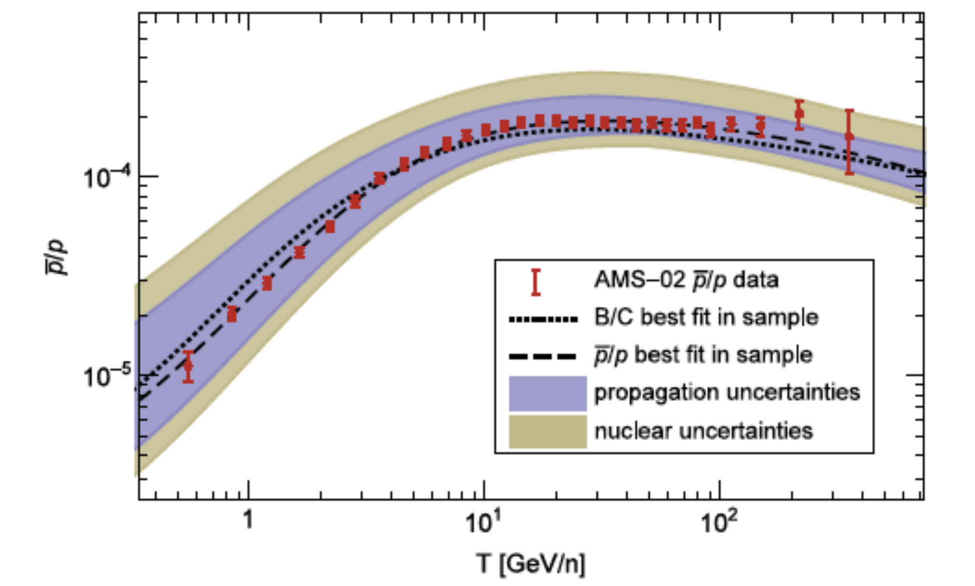


Agreement with Fermi up to 100 GeV in the electron + positron flux. Should be understood. Expected new data: CALET, DAMPE, AMS

DARK MATTER HINTS IN COSMIC RAYS? ANTI-PROTONS

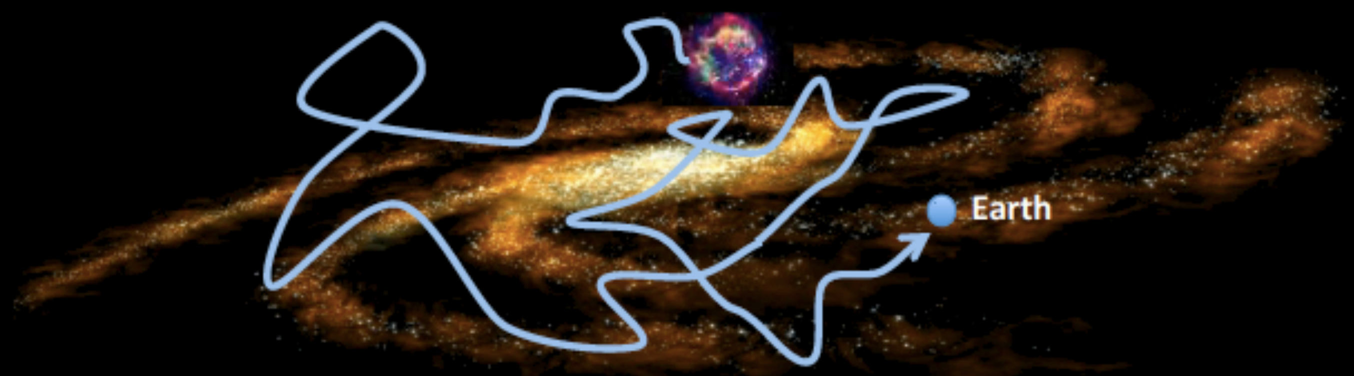


C. Evoli, D. Gaggero and D. Grasso, arXiv:1504.05175 [astro-ph.HE].



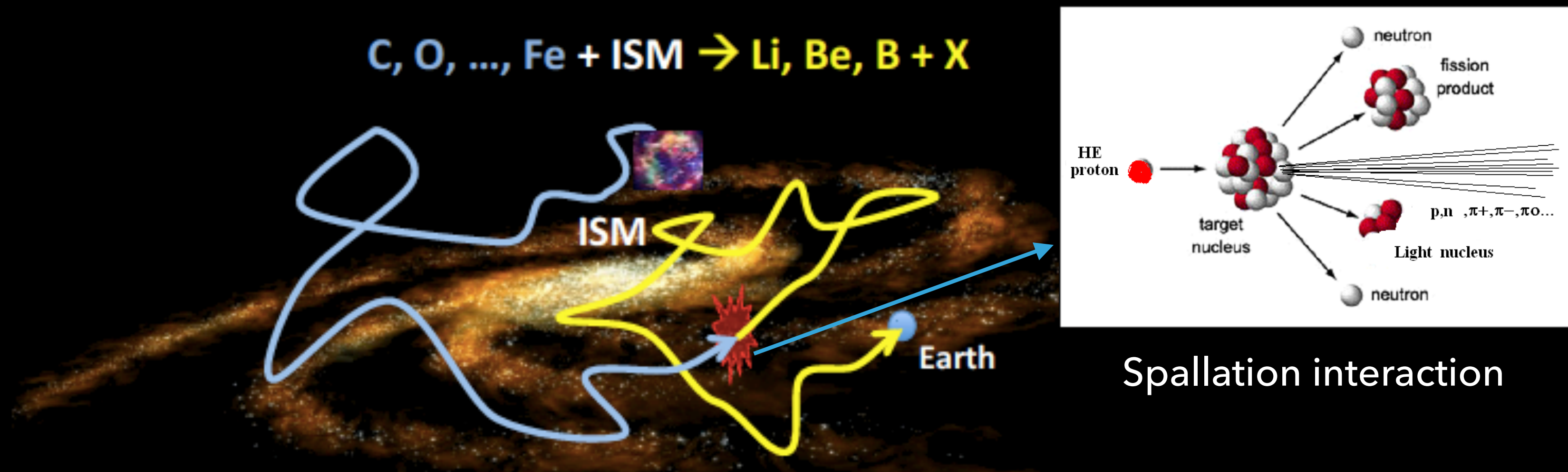
Results are still compatible with secondar production despite a flattening above 60 GeV of the pbar/p ratio

PRIMARY AND SECONDARY COSMIC RAYS



Primary cosmic rays carry information about their original spectra and propagation: high energy e⁻, due to their energy loss ≈ E^2 are sensitive probes to nearby sources

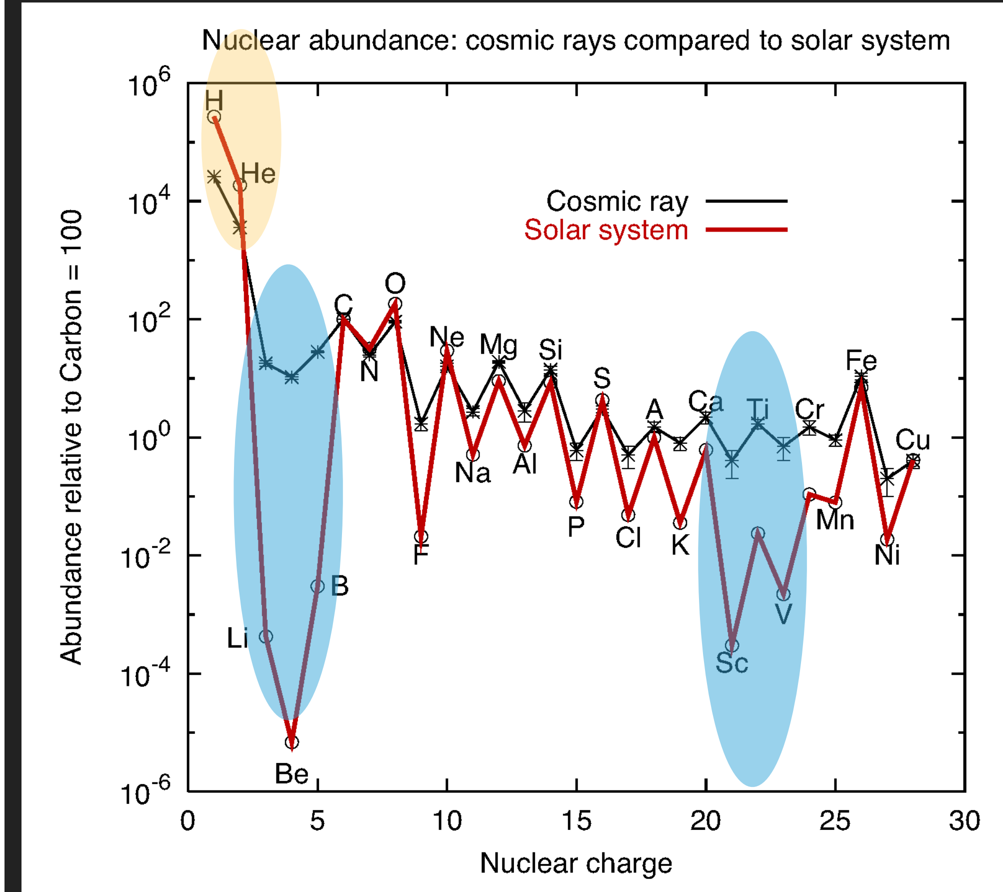
C, O, ..., Fe + ISM → Li, Be, B + X

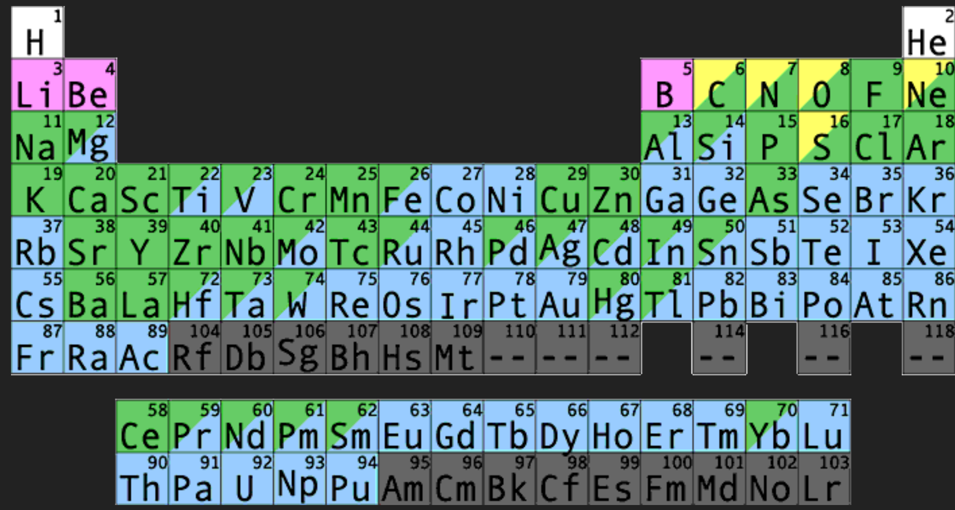


Spallation interaction

Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.

GALACTIC COSMIC RAY COMPOSITION



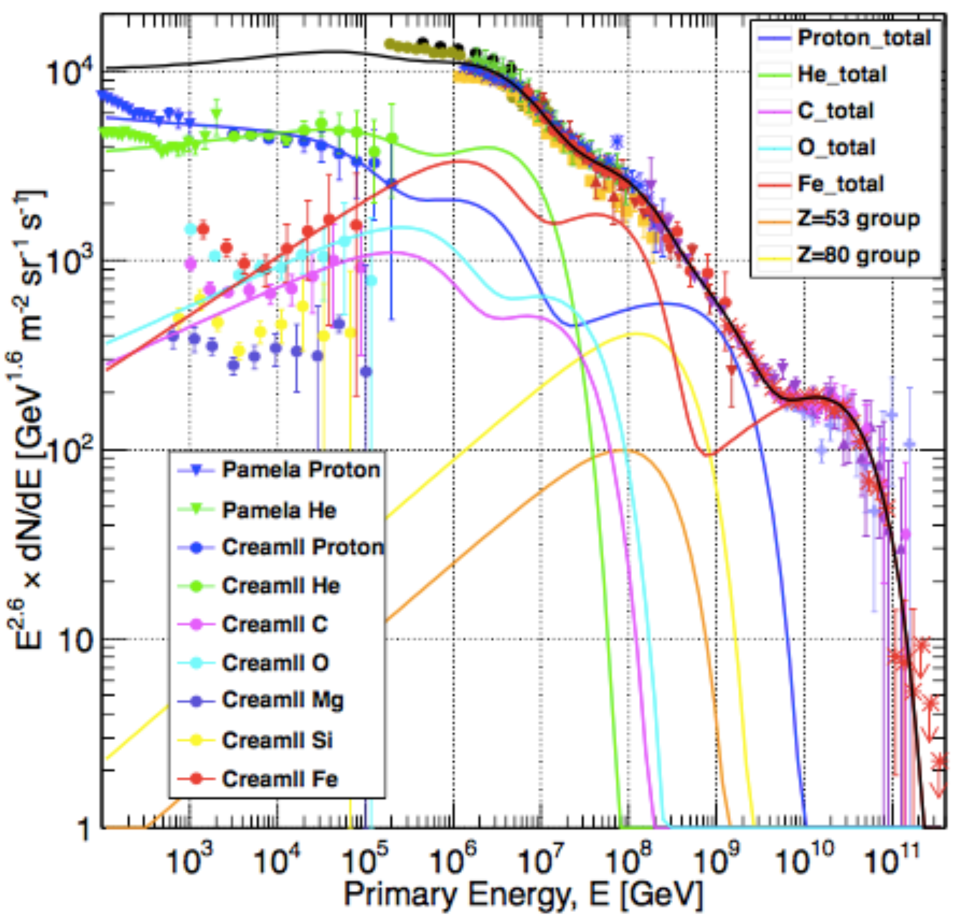


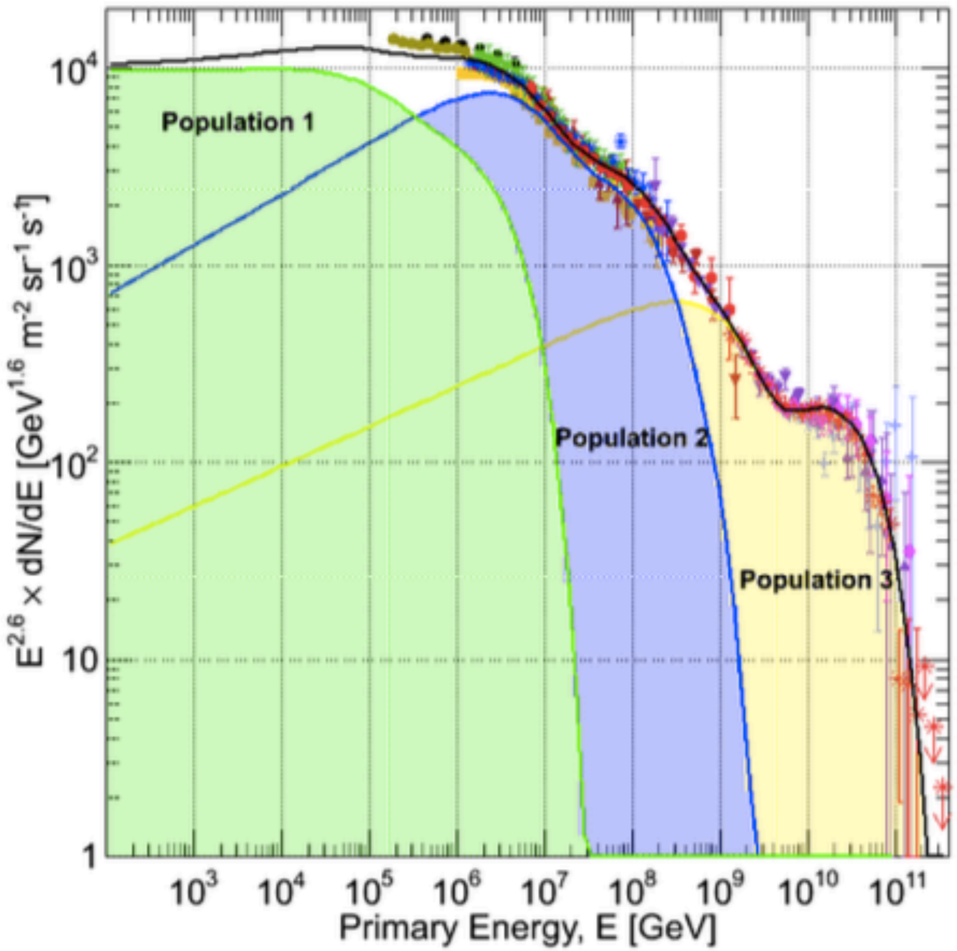
White - Big Bang
Pink - Cosmic Rays
Yellow - Small Stars
Green - Large Stars
Blue - Supernovae

- All stable elements of the periodic table are found in galactic CRs
- The CRs composition is similar to the elements in the Sun indicating that they have stellar origin
- H, He directly accelerated in stars. Li, Be, B are secondary nuclei produced in the spallation of heavier elements (C and O). Also Mn, V, and Sc come from the fragmentation of Fe.
- The zig-zag is due to the fact that nuclei with odd Z and/or A have weaker bounds and are less frequent products of thermonuclear reactions

THE KNEE AND INTERPRETATION OF CR SPECTRUM

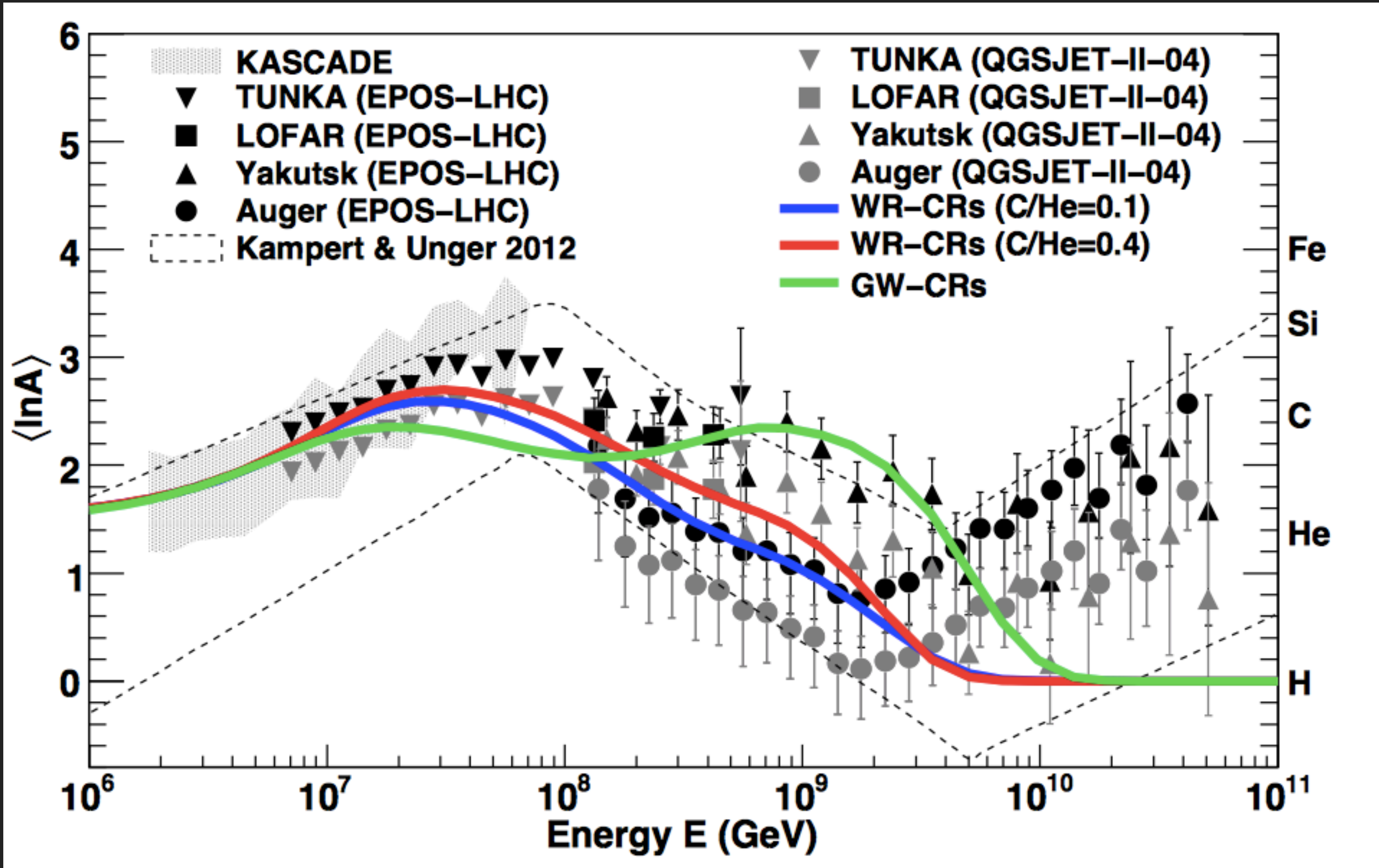
- The all-nucleon spectrum vs E/nucleon is the sum of free protons (about 75%), nucleons bound in He (about 17%) and heavier nuclei (about 8%) between 10-100 GeV/nucleon.
- Peters cycle (first measured by KASCADE): the knee is related to the escape of charged nuclei from a volume hence changes in the spectrum are rigidity-dependent. If there is a characteristic energy at which the proton spectrum steepens E_{knee}, He steepens at $2E_{knee}$, O at 8 E_{knee}, …





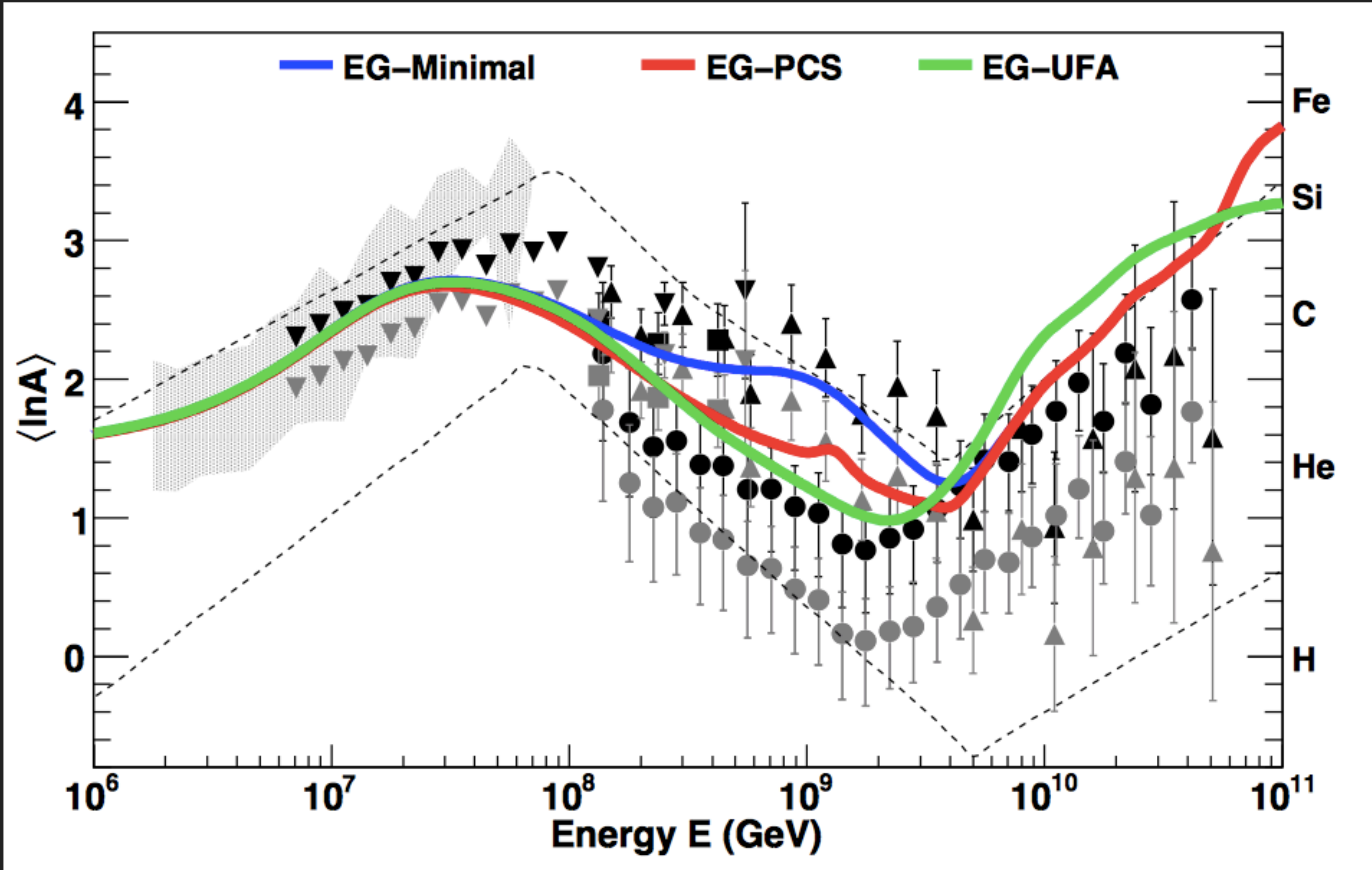
https://arxiv.org/pdf/1303.3565v1.pdf

COMPOSITION OF COSMIC RAYS WITH GALACTIC CR MODELS



https://arxiv.org/pdf/1605.03111.pdf

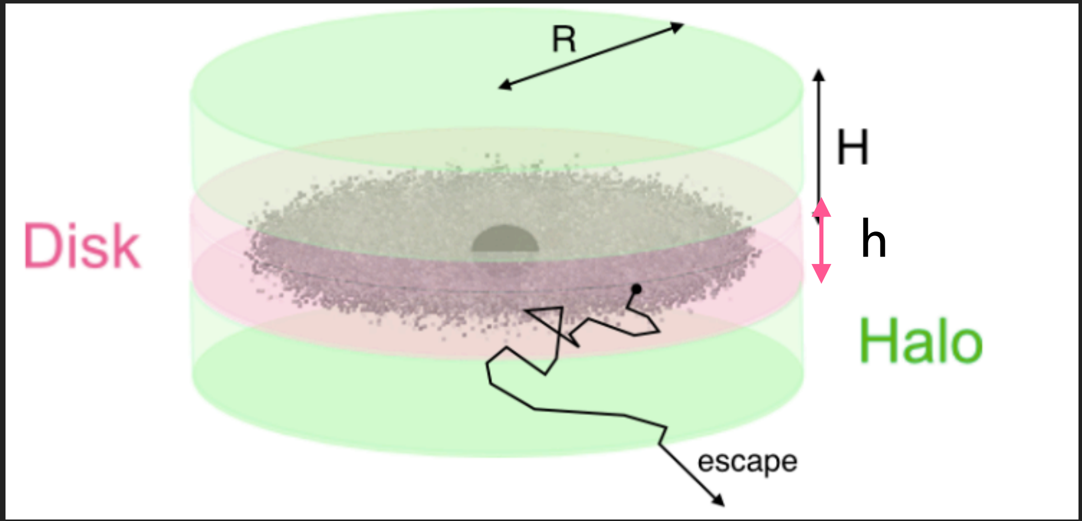
....AND INCLUDING EXTRA-GALACTIC COMPONENTS



LEAKY BOX MODEL

- Leaky box model: sources inject primary CRs and they diffuse in a stationary medium (ISM) escaping the galaxy with an escape probability

$$\tau_{esc} << \frac{c}{h}$$



- CRs undergo losses due to interactions and decay, and gains due to heavier nuclei fragmentation leading to a transport equation:

source term

Loss term due to interactions

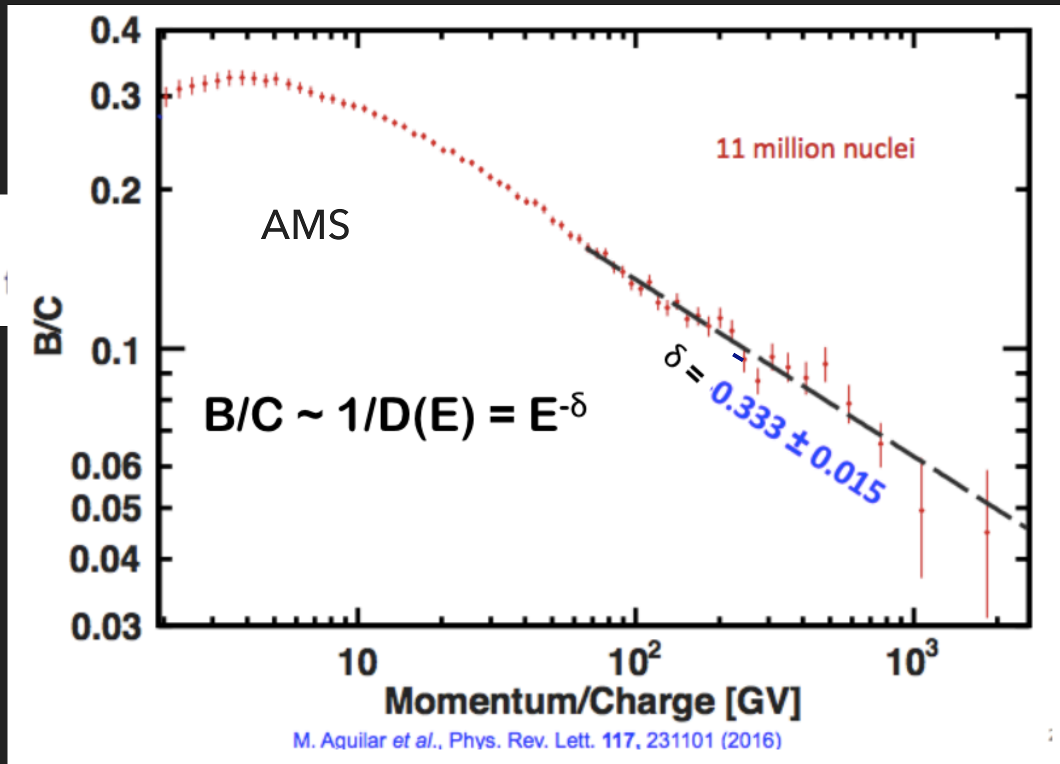
production term due to spallation interactions

$$\frac{n_i(E)}{\tau_{esc}} = q_i(E) - \left[\frac{\beta c \rho}{\lambda_i}\right] n_i(E) + \frac{\beta c \rho}{m_p} \sum_{k \geq i} \sigma_{i,k} n_k(E)$$

THE AGE OF COSMIC RAYS IN THE GALAXY

- The slope of the secondary (B is stable and not directly produced by sources) to primary CRs (C are directly produced in sources) provides a measurement of the energy dependent diffusion coefficient
- δ~ 0.3-0.7 measures the effect of propagation in the galaxy where CRs loose energy. It explains the difference between source - measured spectrum
- The escape time is order of millions and depends on energy

$$\lambda_{esc} = \beta c \rho \tau_{esc} = 10 - 15 \frac{\mathrm{g}}{\mathrm{cm}^2} \beta \left(\frac{4\mathrm{GV}}{R}\right)^{\delta}$$



WHICH ARE THE COSMIC RAY SOURCES? POSSIBLE CANDIDATES

ON SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

In a SN gravitational energy released is transformed into acceleration of particles

→

E^{-2} spectrum

A PARENTHESIS: FLUX AND NUMBER DENSITY RELATIONSHIP

- Flux = rate at which a flux of parallel particles crosses a plane of surface dA perpendicular to the beam

$$\Phi = \frac{dN}{dAdt}$$

- The number density of particles corresponding to the beam of particles is

$$n(\vec{x}) = \frac{dN}{d^3x} = \frac{dN}{dldA} = \frac{1}{\beta c}\frac{dN}{dtdA} = \frac{1}{\beta c}\Phi$$

$$d^3x = dV = dldA \qquad dl = \beta c dt$$

- Considering an isotropic flux in an energy interval E, E +dE and in the full solid angle:

$$\Phi(E) = \frac{dN}{dEdAdtd\Omega}$$

$$n(E,\vec{x}) = \frac{dN}{dEd^3x} = \frac{4\pi}{\beta c}\Phi(E)$$

FLUX AND ENERGY DENSITY RELATIONSHIP

$$Flux\left(\frac{particles}{cm^2 ssr}\right) = \frac{\rho_{CR}\beta c}{4\pi}$$

where n = ρ_{CR} and $\beta \sim 1$

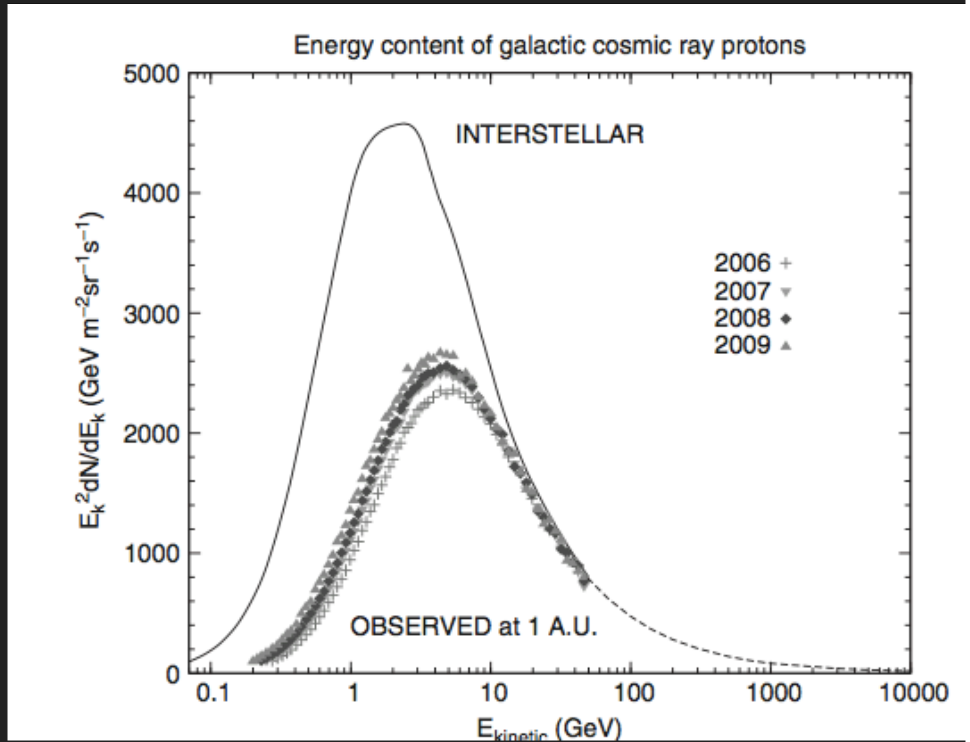
- For galactic CRs (below the knee) the flux is

$$\frac{dN}{dE} = 1.8 \times 10^4 (E/1GeV)^{-2.7} \frac{\text{nucleons}}{\text{m}^2\,\text{sr}\,\text{s}\,\text{GeV}}$$

- The energy density of CRs is provided by a source of power:

$$\rho_E = 4\pi \int \frac{E}{\beta c}\frac{dN}{dE} dE$$

$$\rho_E = \frac{4\pi}{c}\int_{1GeV}^{10^6 GeV} \text{dE}\;\, 1.8 \times 10^4 (E/1GeV)^{-1.7} \sim 1\frac{eV}{cm^3}$$



COSMIC RAYS AND THE GALACTIC MAGNETIC FIELD

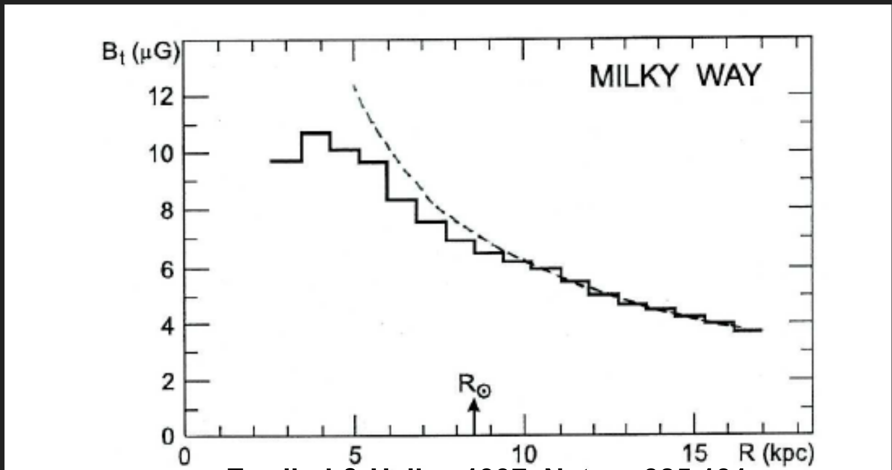
- The energy density of galactic CRs is comparable to the energy density of the galactic magnetic field which on average is 3-6 uG parallel to local spiral arms:

$$\frac{B^2}{8\pi} \sim 4 \times 10^{-13} erg/cm^3 \times 6.24 \times 10^{11} \sim 0.25 eV/cm^3$$

- The magnetic field is frozen into the ionised part of the gas of the Galaxy (ISM: 90% H and 10% He) which forms a magneto-hydrodynamic fluid which supports waves that travel with a characteristic speed called Alfvén velocity.

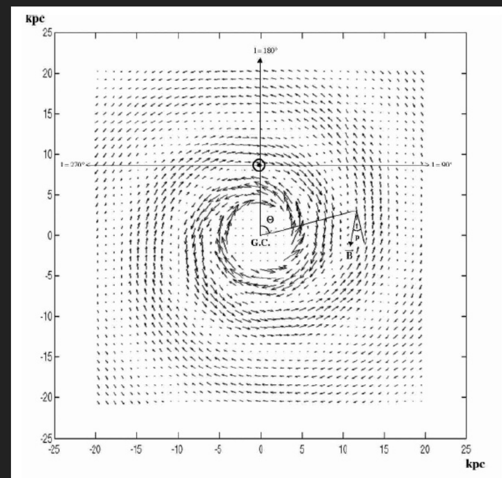
$$\frac{1}{2}\rho v_A^2 = \frac{B^2}{8\pi}$$

- Particles scatter on waves. The B-field and CR are strongly coupled.



Zweibel & Heiles 1997, Nature 385,131

Berdyugin & Teerikorpi 2001, A&A 368,635



COSMIC RAY LUMINOSITY

- The luminosity in galactic CRs is:

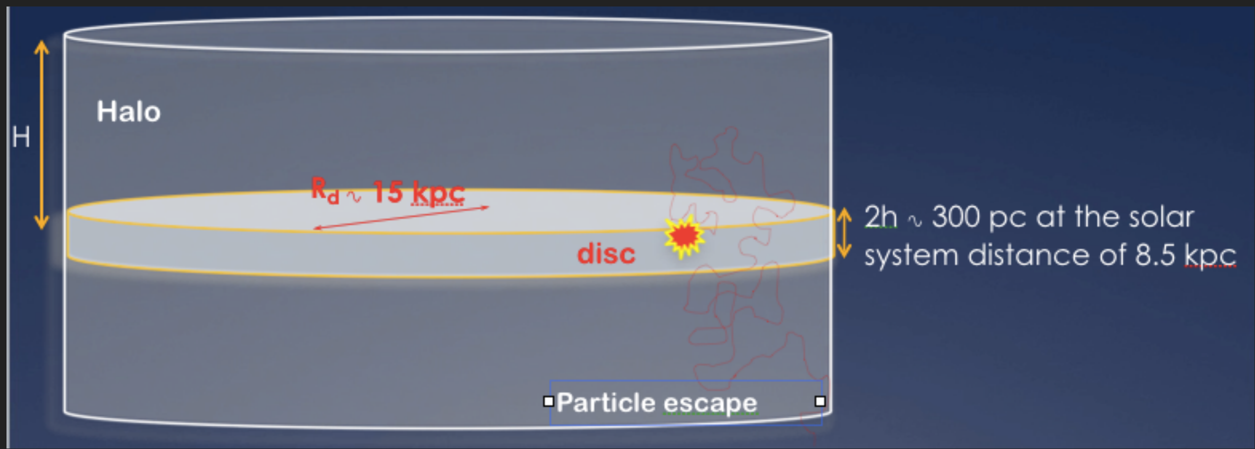
$$L_{CR} = \rho_E \frac{V}{\tau_{esc}} \sim \frac{1\text{eV}/\text{cm}^3}{6.24 \times 10^{11}\text{erg}/\text{eV}} \times \frac{6 \times 10^{66}\text{cm}^3}{3 \times 10^6 yr \times 3.15 \times 10^7\text{s}/\text{yr}} \sim 10^{41}\text{erg}/\text{s}$$

Time cosmic ray spend in the Galaxy

- V = volume of the Galaxy

$$V_{disk} \sim \pi R_{disk}^2 h_{disk}$$
$$\sim \pi [15 kpc]^2 [0.3 kpc]$$
$$\sim 6 \times 10^{66} cm^3$$

1 kpc = 3.0857 × 10^{21} cm



ENERGY BALANCE AND CANDIDATE GALACTIC SOURCES

- Typical galactic supernova kinetic energy in the ejecta for a star of mass M = 10 $M_\odot$ = 10 x 2 x 10^{33} g : K = 10^{51} erg
- Free expansion velocity of ejecta: $V \cong \sqrt{\frac{2K}{M}} = \sqrt{\frac{2 \cdot 10^{51} erg}{10 \cdot (2 \cdot 10^{33} g)}} \cong 3 \cdot 10^{8} cm/s$ $\frac{V}{c} \cong 10^{-2}$

Rate of SN ~ 3 / century

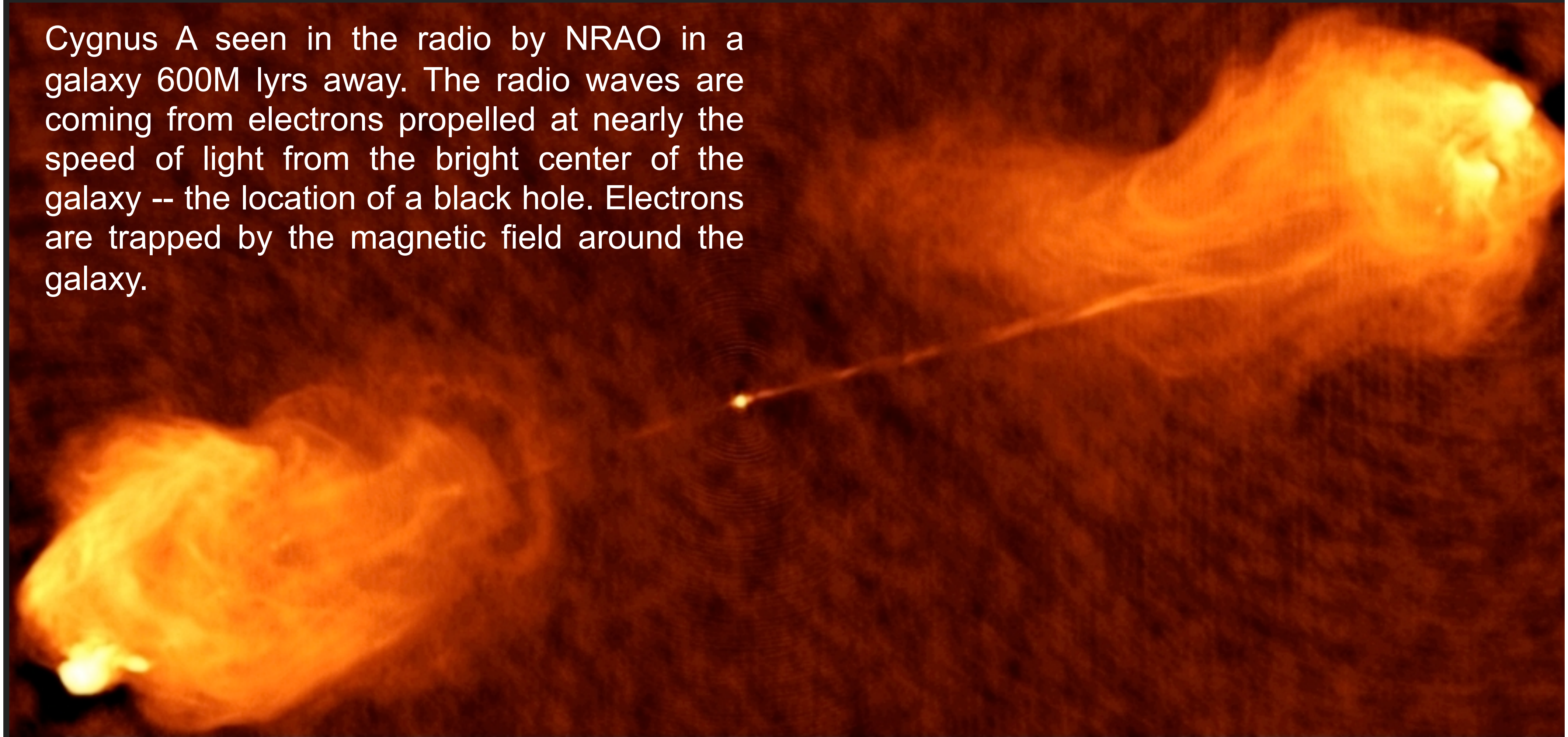
Power = K x rate =

=10^{51} erg x 3/3.15 x 10^{-9} ~ 10^{42} erg/s

5-10% of the energy in the ejecta suffices to produce the measured galactic CR flux

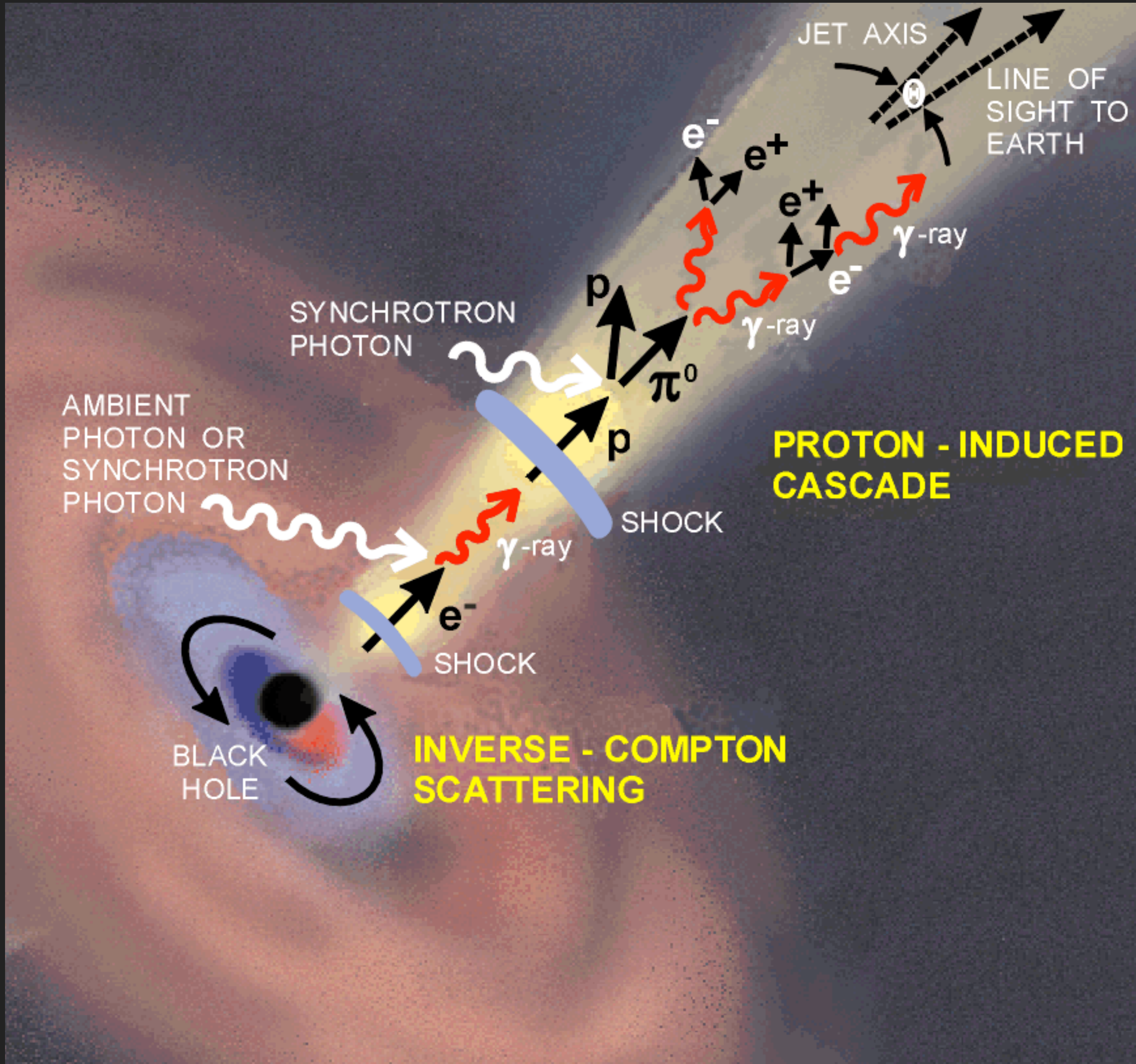
A similar argument was made by Waxman & Bahcall in 1999 for extra-galactic CRs in the ankle region.

EXTRAGALACTIC ACCELERATORS

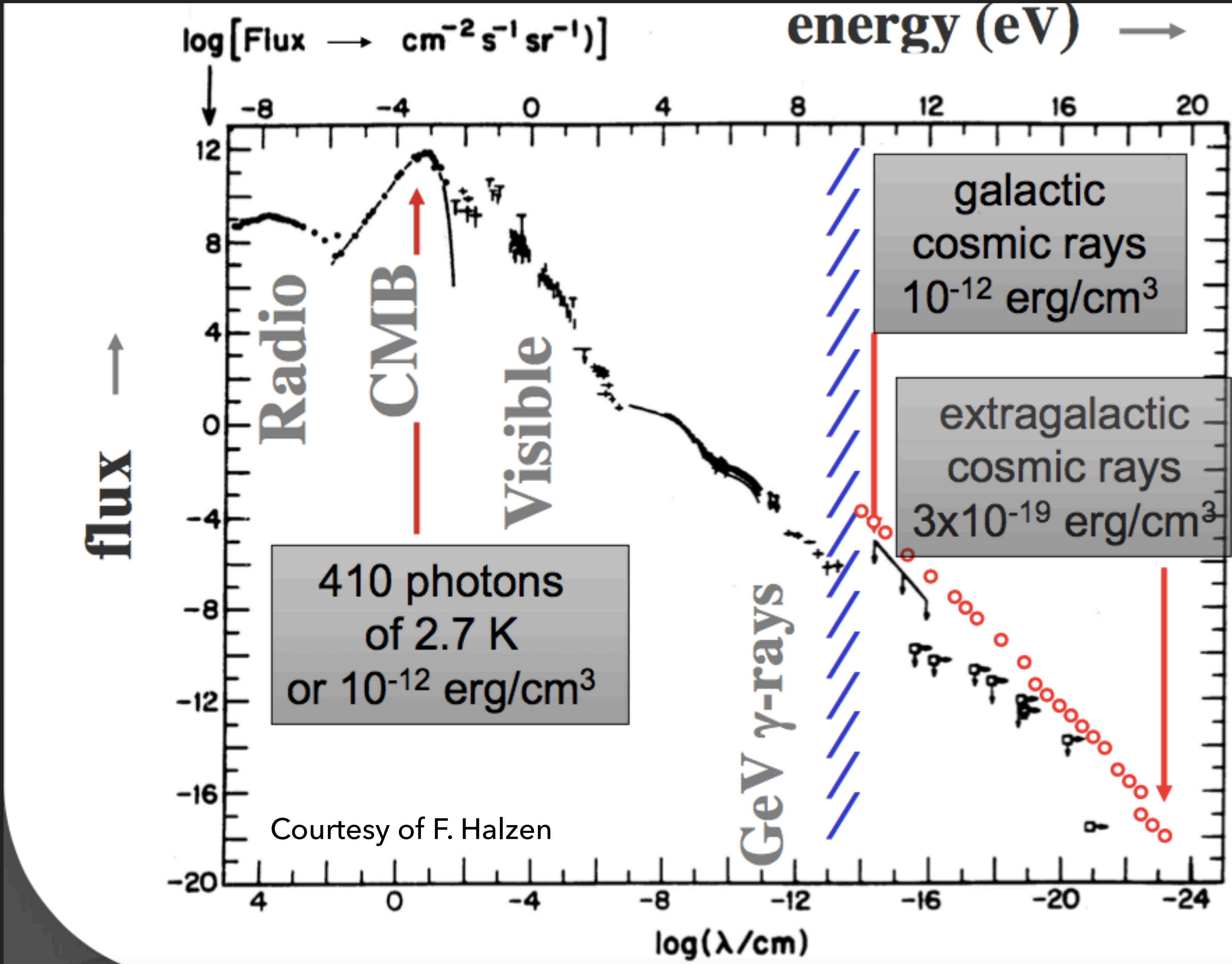


Cygnus A seen in the radio by NRAO in a galaxy 600M lyrs away. The radio waves are coming from electrons propelled at nearly the speed of light from the bright center of the galaxy -- the location of a black hole. Electrons are trapped by the magnetic field around the galaxy.

WHAT CAN BE ACCELERATED: LEPTONIC AND HADRONIC SCENARIO



RADIATION FROM THE UNIVERSE

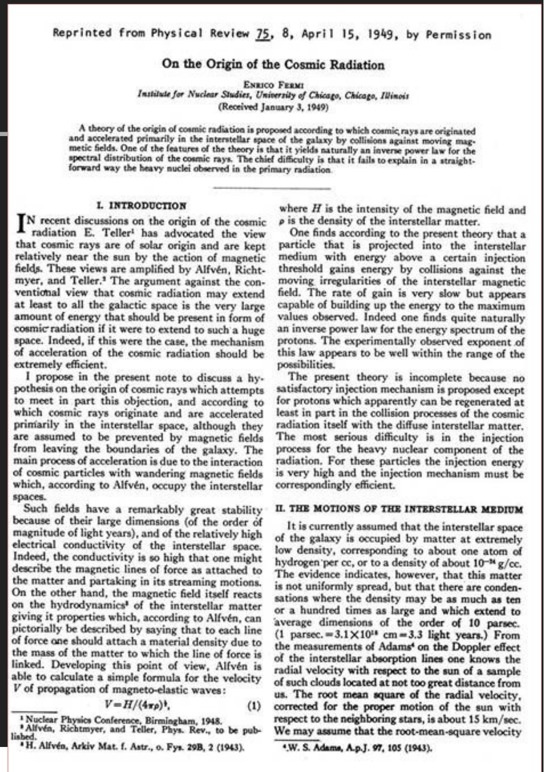


THE FERMI ACCELERATION OF PARTICLES

Acceleration within magnetic clouds (2nd order) or in the magnetic field of a SN shock (1st order).

The energy increase is $\Delta E/E_0=\xi$ and β is the non relativistic speed of the cloud or the shock in units of c = speed of light.

Considering that after k interactions the energy of the particle is $E_k = E_0(1+\xi)^k$ and that the remaining number of particles is $N_k = N_0 P_k = N_0(1-P_{esc})^k P_{esc}$ a power law spectrum comes out naturally



Reprinted from Physical Review 75, 8, April 15, 1949, by Permission

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept relatively near the sun by the action of magnetic fields. These views are amplified by Alfvén, Richtmyer, and Teller.[2] The argument against the conventional view that cosmic radiation may extend at least to all the galactic space is the very large amount of energy that should be present in form of cosmic radiation if it were to extend to such a huge space. Indeed, if this were the case, the mechanism of acceleration of the cosmic radiation should be extremely efficient.

I propose in the present note to discuss a hypothesis on the origin of cosmic rays which attempts to meet in part this objection, and according to which cosmic rays originate and are accelerated primarily in the interstellar space, although they are assumed to be prevented by magnetic fields from leaving the boundaries of the galaxy. The main process of acceleration is due to the interaction of cosmic particles with wandering magnetic fields which, according to Alfvén, occupy the interstellar spaces.

Such fields have a remarkably great stability because of their large dimensions (of the order of magnitude of light years), and of the relatively high electrical conductivity of the interstellar space. Indeed, the conductivity is so high that one might describe the magnetic lines of force as attached to the matter and partaking in its streaming motions. On the other hand, the magnetic field itself reacts on the hydrodynamics[3] of the interstellar matter giving it properties which, according to Alfvén, can pictorially be described by saying that to each line of force one should attach a material density due to the mass of the matter to which the line of force is linked. Developing this point of view, Alfvén is able to calculate a simple formula for the velocity V of propagation of magneto-elastic waves:

$$V = H/(4\pi\rho)^{\frac{1}{2}}, \quad (1)$$

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar medium with energy above a certain injection threshold gains energy by collisions against the moving irregularities of the interstellar magnetic field. The rate of gain is very slow but appears capable of building up the energy to the maximum values observed. Indeed one finds quite naturally an inverse power law for the energy spectrum of the protons. The experimentally observed exponent of this law appears to be well within the range of the possibilities.

The present theory is incomplete because no satisfactory injection mechanism is proposed except for protons which apparently can be regenerated at least in part in the collision processes of the cosmic radiation itself with the diffuse interstellar matter. The most serious difficulty is in the injection process for the heavy nuclear component of the radiation. For these particles the injection energy is very high and the injection mechanism must be correspondingly efficient.

II. THE MOTIONS OF THE INTERSTELLAR MEDIUM

It is currently assumed that the interstellar space of the galaxy is occupied by matter at extremely low density, corresponding to about one atom of hydrogen per cc, or to a density of about 10^{-24} g/cc. The evidence indicates, however, that this matter is not uniformly spread, but that there are condensations where the density may be as much as ten or a hundred times as large and which extend to average dimensions of the order of 10 parsec. (1 parsec. $=3.1\times10^{18}$ cm $=3.3$ light years.) From the measurements of Adams[4] on the Doppler effect of the interstellar absorption lines one knows the radial velocity with respect to the sun of a sample of such clouds located at not too great distance from us. The root mean square of the radial velocity, corrected for the proper motion of the sun with respect to the neighboring stars, is about 15 km/sec. We may assume that the root-mean-square velocity

[1] Nuclear Physics Conference, Birmingham, 1948.
[2] Alfvén, Richtmyer, and Teller, Phys. Rev., to be published.
[3] H. Alfvén, Arkiv Mat. f. Astr., o. Fys. 29B, 2 (1943).
[4] W. S. Adams, A.p.J. 97, 105 (1943).

$$\frac{dN}{dE} \propto E^{\frac{ln(1-P_{esc})}{ln(1+\xi)}-1} = E^{-\gamma-1}$$

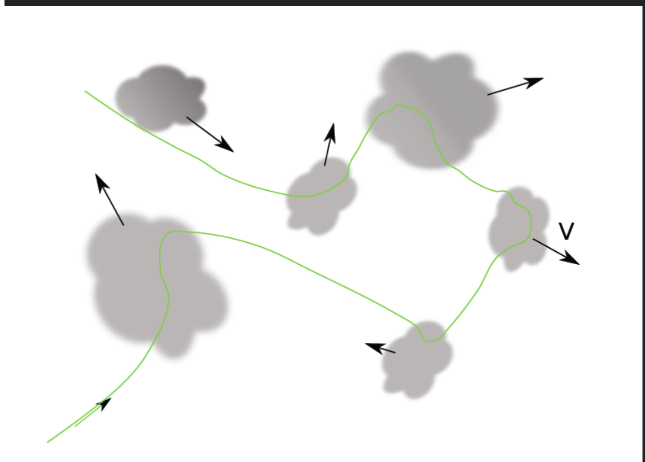
$$\gamma \sim \frac{-P_{esc}}{\xi}$$

$$\xi = \frac{\Delta E}{E_0} \sim \frac{4}{3}\beta^2$$

γ > 1 (inefficient)

$$\xi = \frac{\Delta E}{E_0} \sim \frac{4}{3}\beta$$

γ ∿ 1 (efficient)



THE SIMPLE EXPLANATION

A particle of velocity v collides perpendicularly on a shock front of speed u_1.

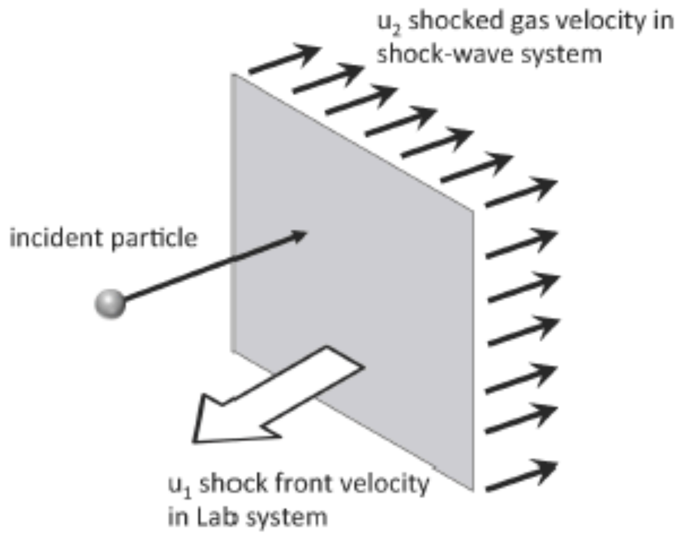
Behind the shock, the gas recedes at a speed u_2 so in the lab the gas has speed of u_1 - u^2. As the particle is reflected back it gains the kinetic energy of the shocked gas.

The gain is:

$$\Delta E = \frac{1}{2}m(v + (u_1 - u_2))^2 - \frac{1}{2}mv^2$$
$$= \frac{1}{2}m(2v(u_1 - u_2) + (u_1 - u_2)^2)$$

Assuming $v \gg u_1, u_2, u_1 > u_2$ then:

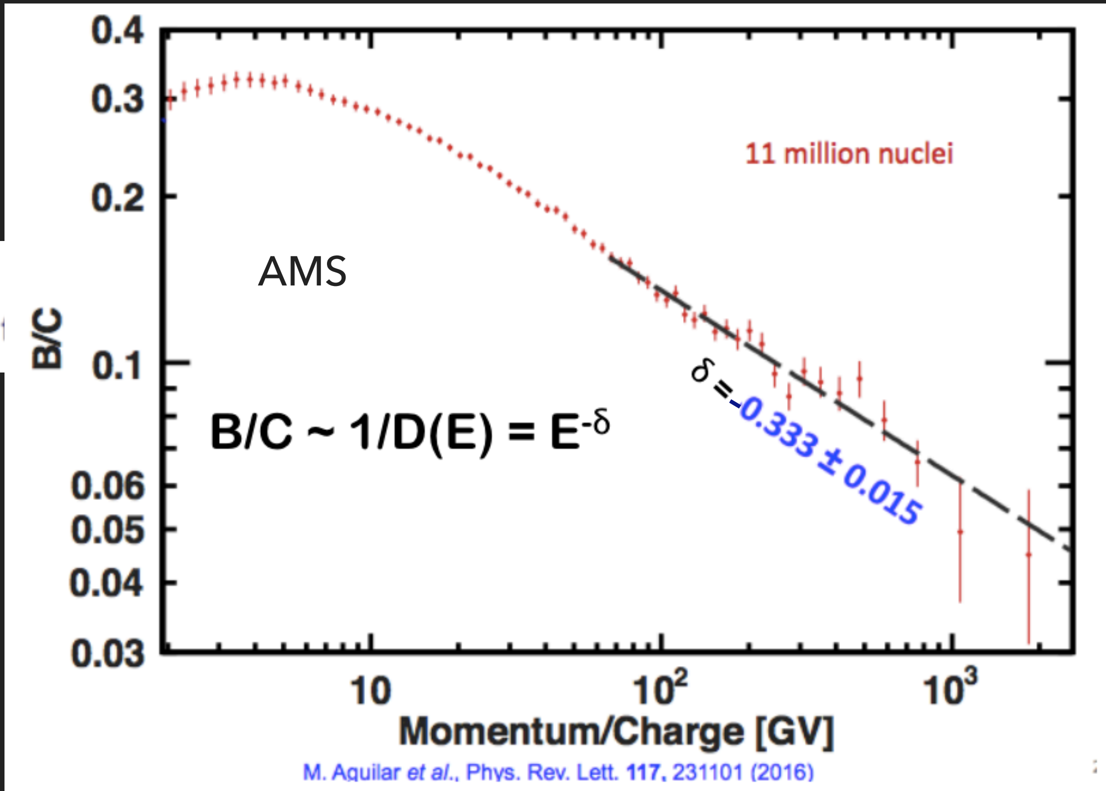
$$\frac{\Delta E}{E} \approx \frac{2(u_1 - u_2)}{v}$$



SOURCE SPECTRA AND MEASURED SPECTRA

- Diffusive Shock Acceleration (DSA) predicts: $$\frac{dN}{dE} \propto E^{-(\gamma+1)} = E^{-2}$$
- The observed CR spectrum is steeper: $E^{-2.7}$
- The slope of the secondary (B is stable and not produced by sources) to primary CRs (C are directly produced in sources) δ~ 0.3-0.7 measures the effect of propagation in the galaxy where CRs loose energy and explains the difference between source and measured spectrum

$$\lambda_{esc} = \beta c \rho \tau_{esc} = 10 - 15 \frac{\mathrm{g}}{\mathrm{cm}^2} \beta \left(\frac{4\mathrm{GV}}{R}\right)^{\delta}$$



THE 1ST ACCELERATION MECHANISM FEATURES

- If the Fermi accelerator has finite lifetime T_A the maximum acceleration energy

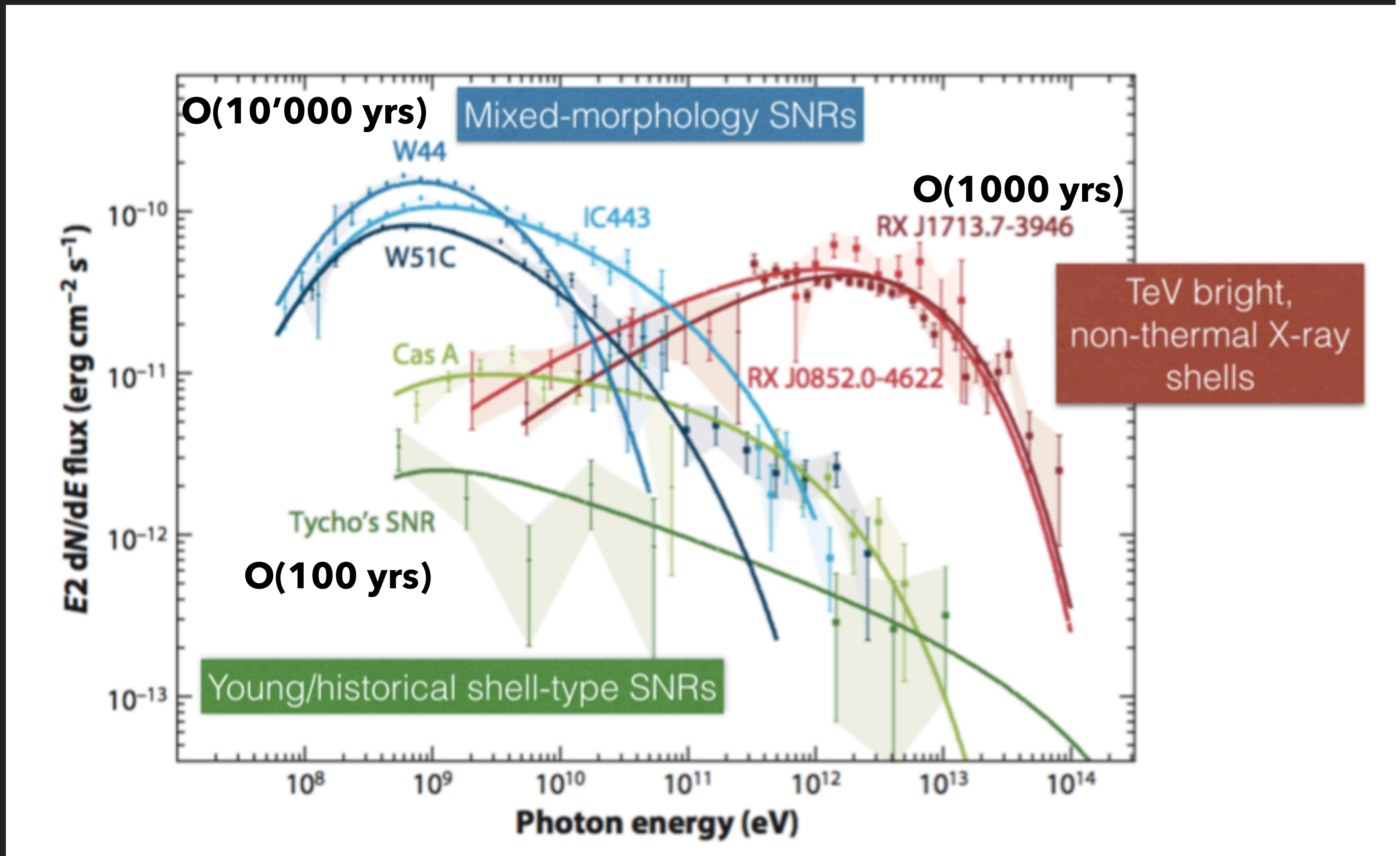
$$E \leq E_0(1+\xi)^{T_A/T_{cycle}}$$

T_{cycle}: time the particle takes to cross back and fourth the shock

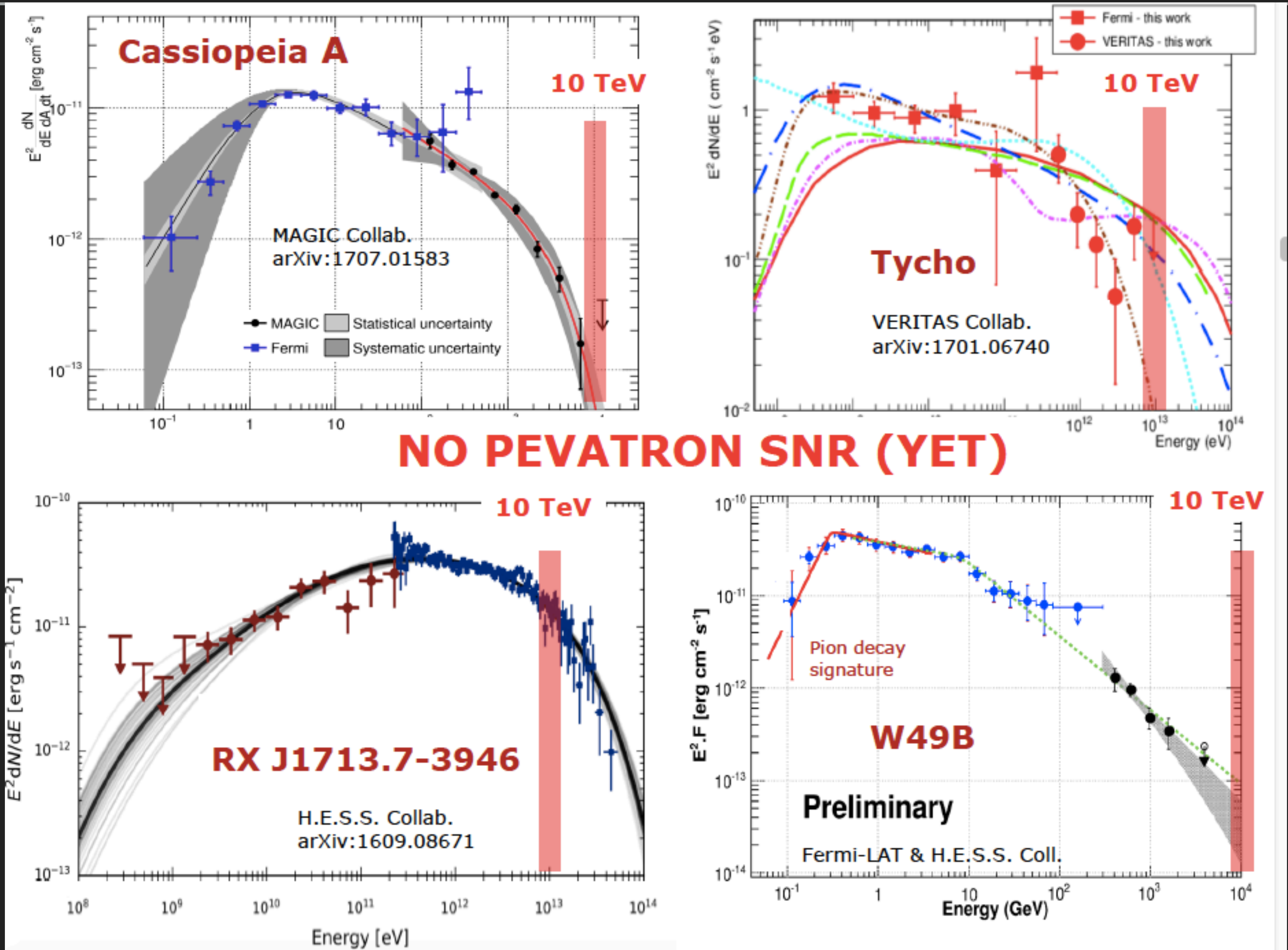
- For a SN the shock is an efficient accelerator until the density of ejecta becomes comparable to the density of ISM in the Galaxy (order of 100-1000 yrs) => E_{max} ~ 100 TeV x Z

- This energy is about an order of magnitude lower than the knee… PROBLEM!

- SN efficiency is age dependent



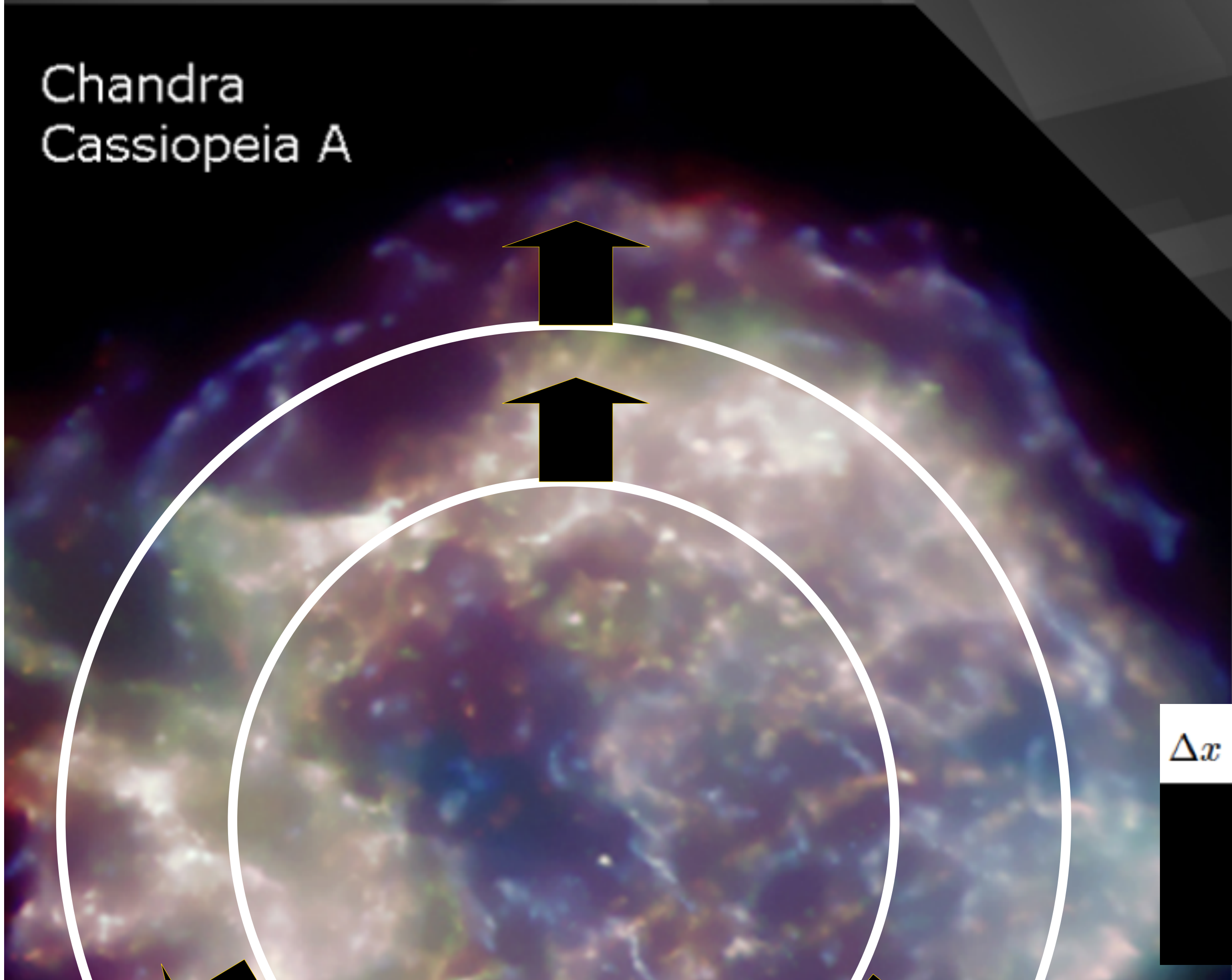
NOT YET A SNR PEVATRON OBSERVED BY GAMMA-RAY EXPERIMENTS

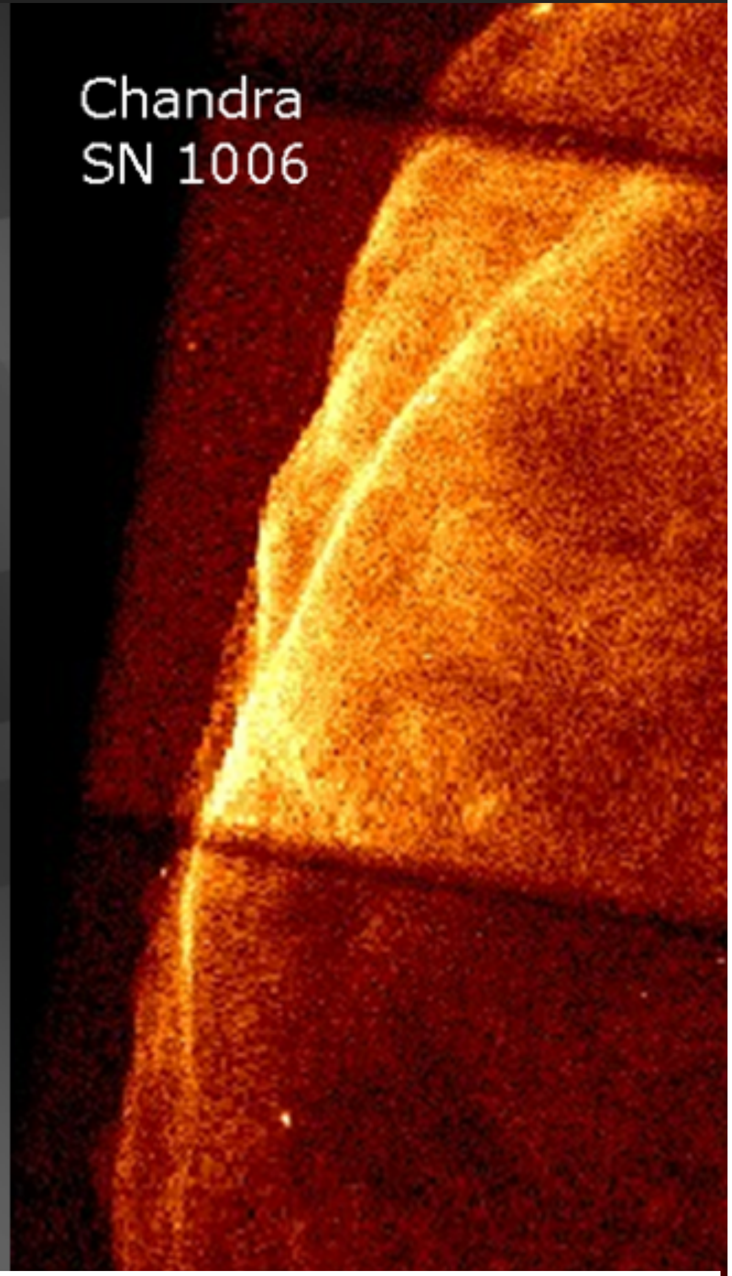


W. Hoffman, HEP-EPS 2017

BEYOND DSA

Non-linear DSA (dynamical connection between CRs being accelerated and the background plasma) is in agreement with observed filaments due to synchrotron emission of electrons of dimensions of 10^{-2} pc. They imply large B-fields of the order of 100 uG



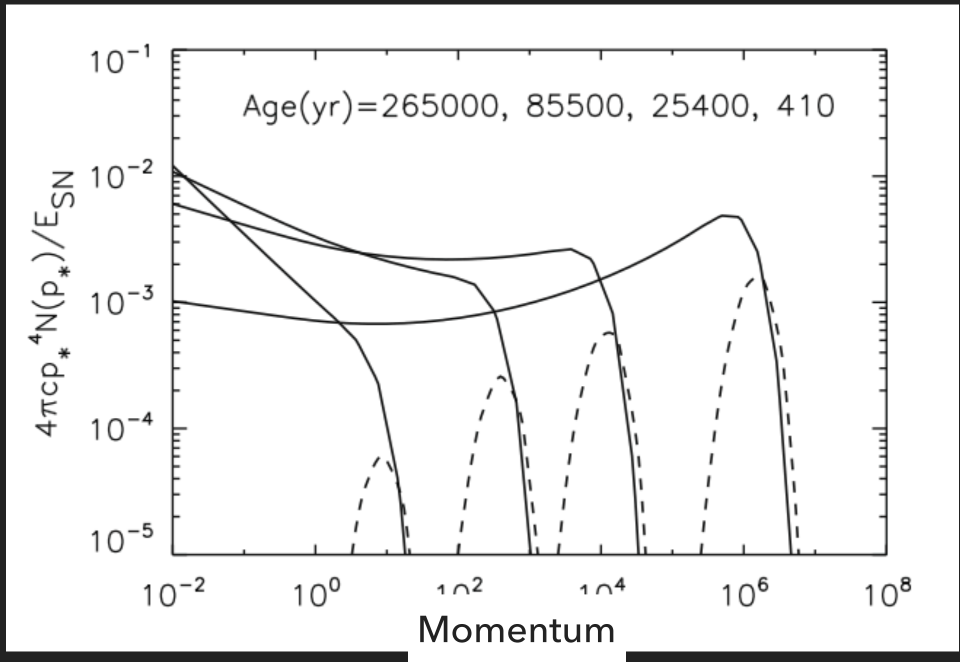


$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

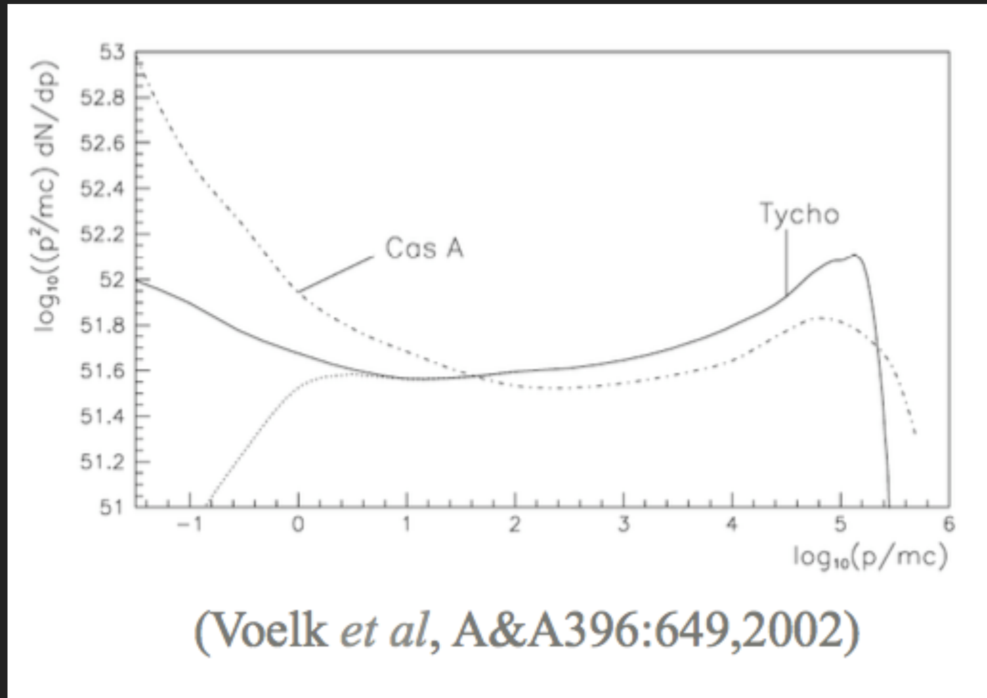
$$B \approx 100\ \mu\mathrm{Gauss}$$

SPECTAL DISAGREEMENT WITH DSA

- Observed spectra are softer than what predicted by DSA (E^{-2}) and on-linear DSA (concave shape)

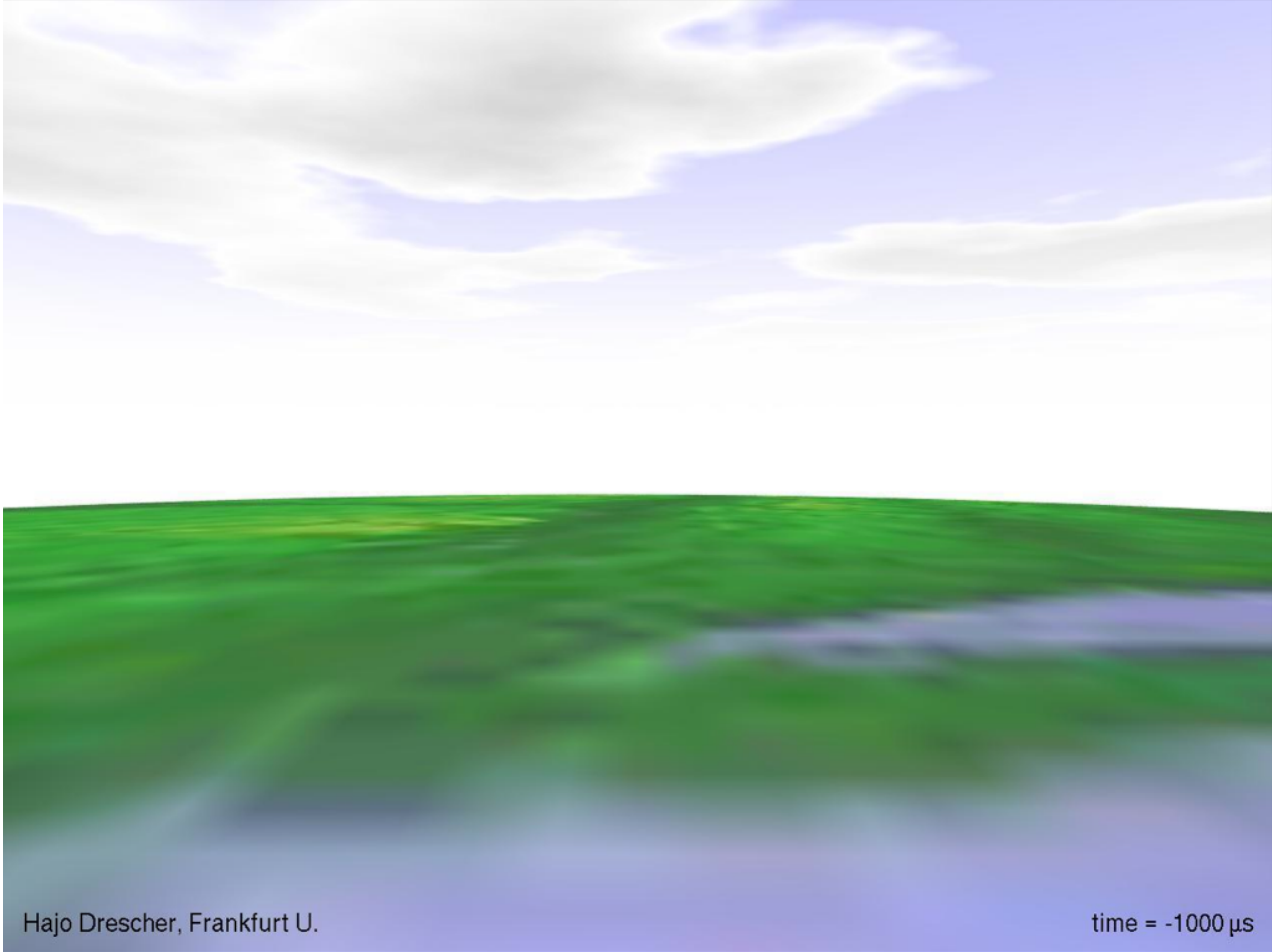


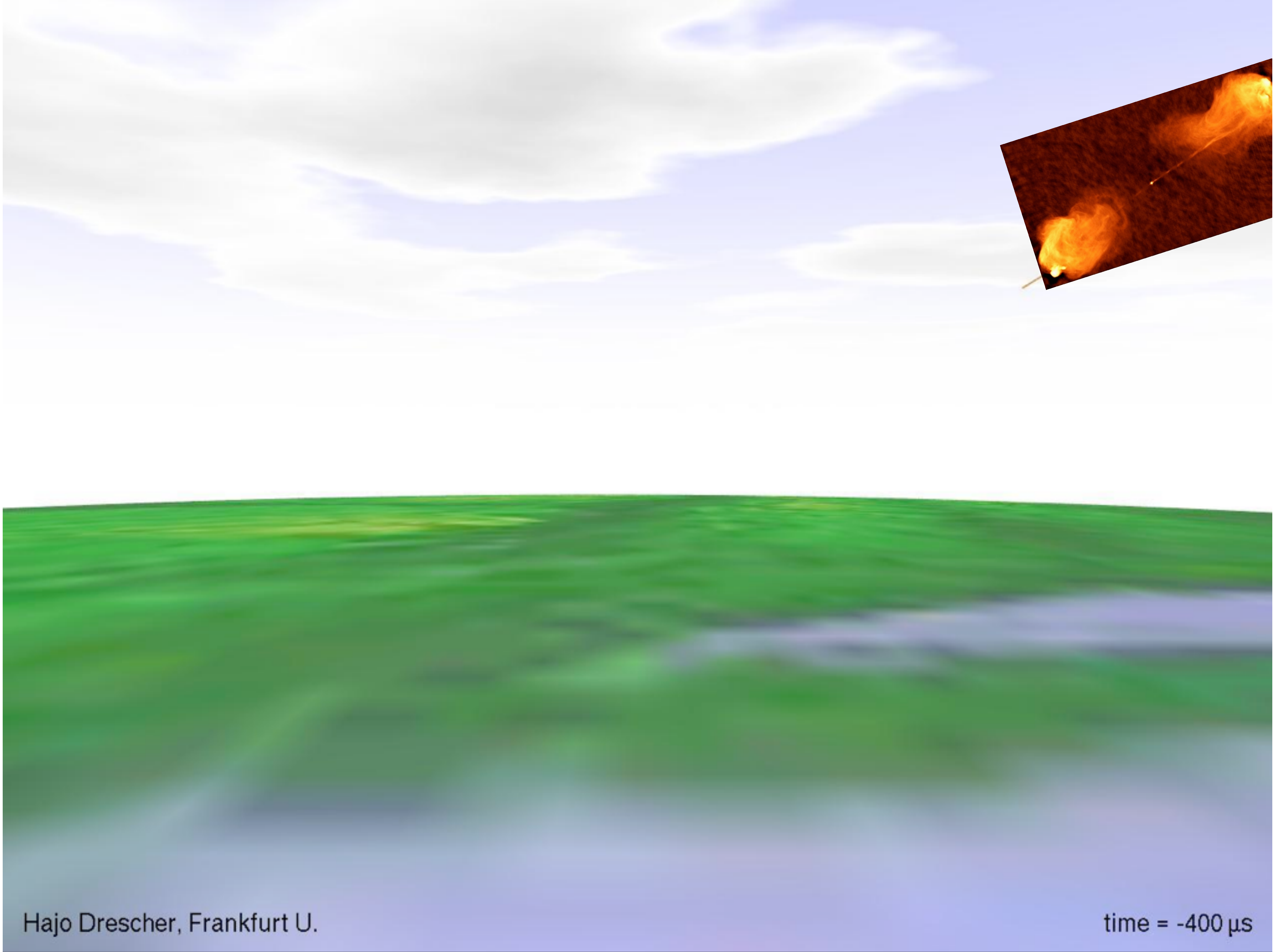
D. Caprioli et al. / Astroparticle Physics 33 (2010) 160–168



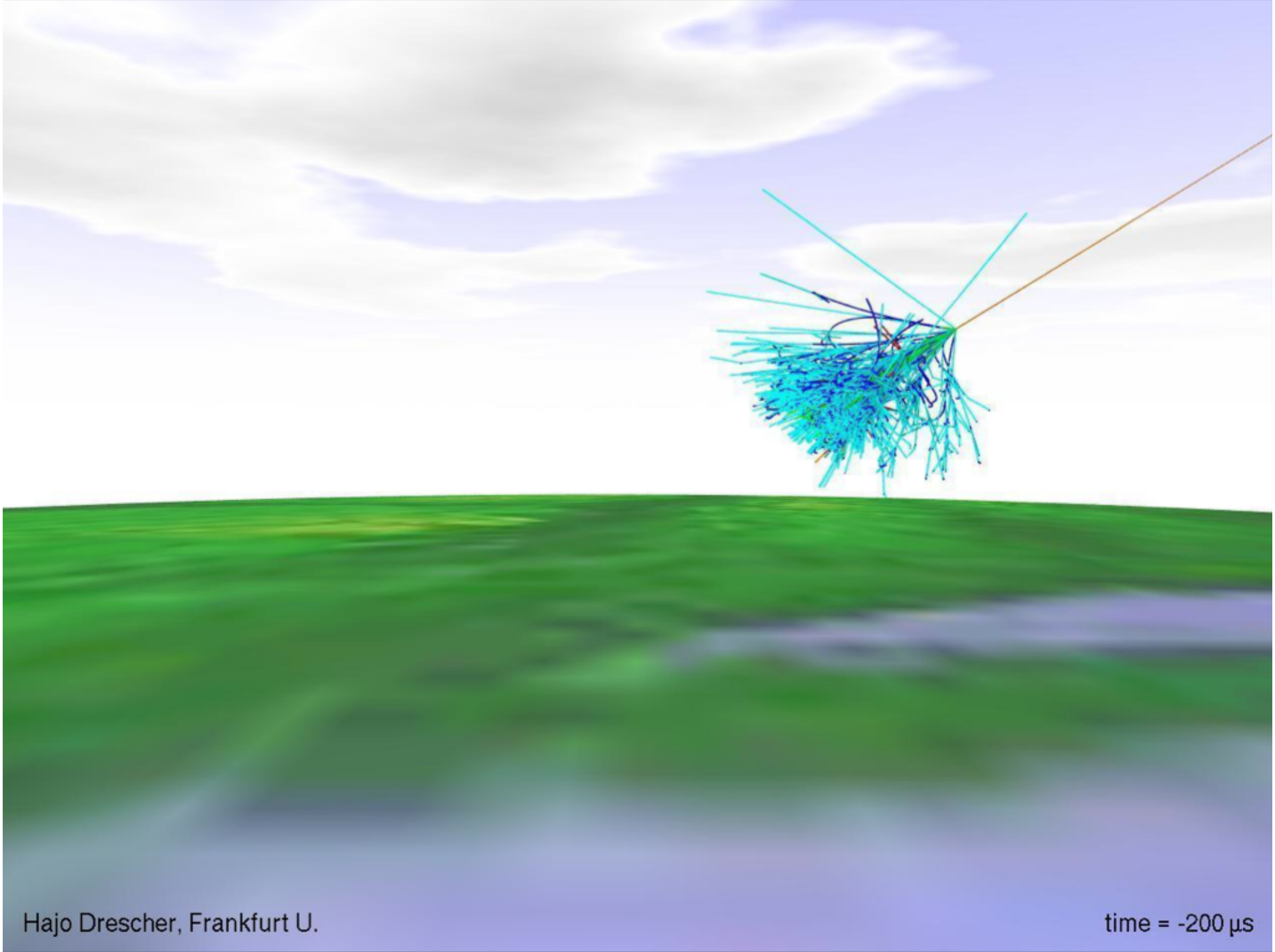
- Alternative source scenarios are possible: BH PeVatron in the Galactic Centre (H.E.S.S. arXiv:1603.07730) being more efficient accelerator or superbubbles

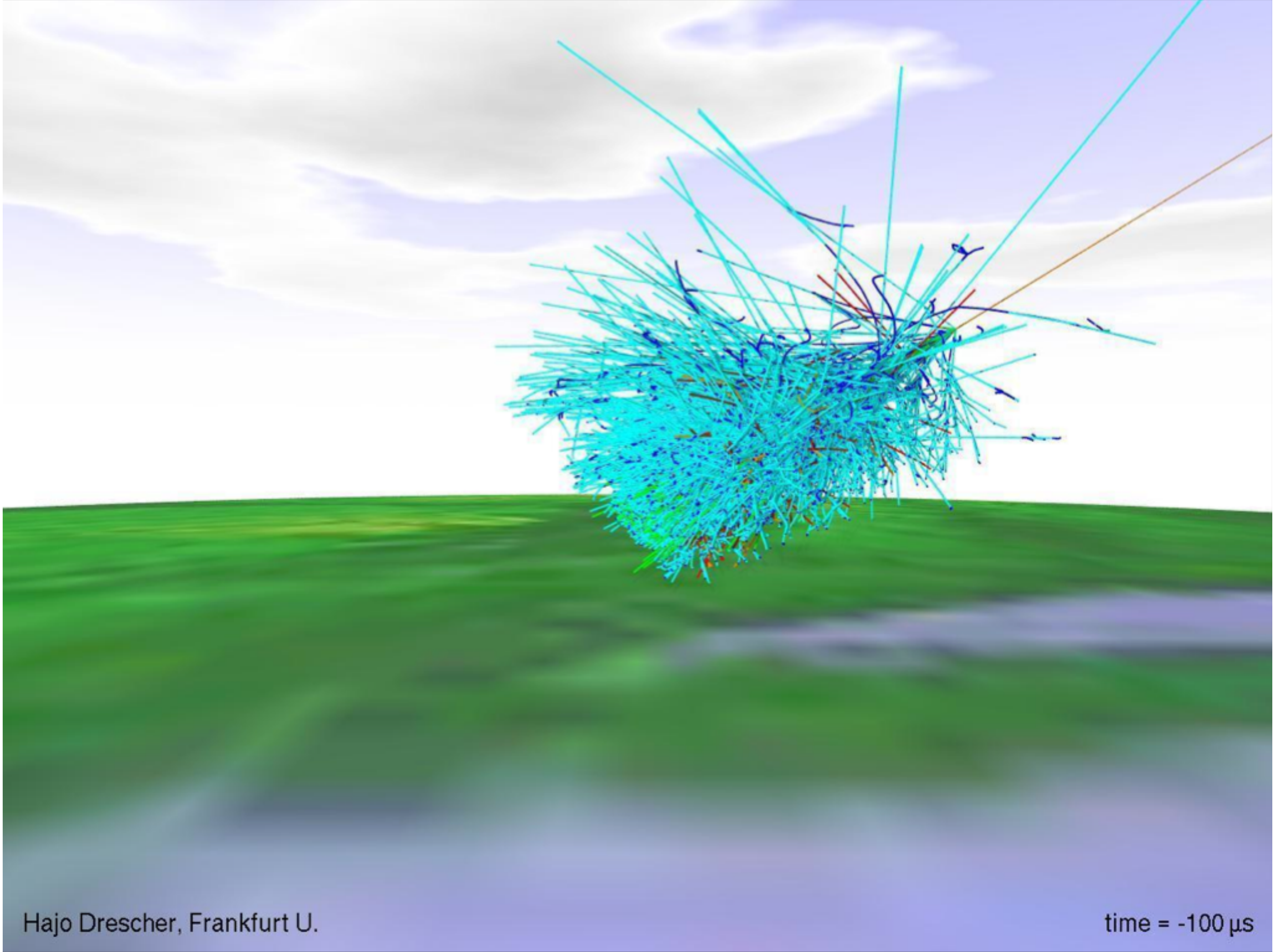
http://www.nature.com/nature/journal/v460/n7256/full/nature08127.html


Hajo Drescher, Frankfurt U.
time = -1000 µs

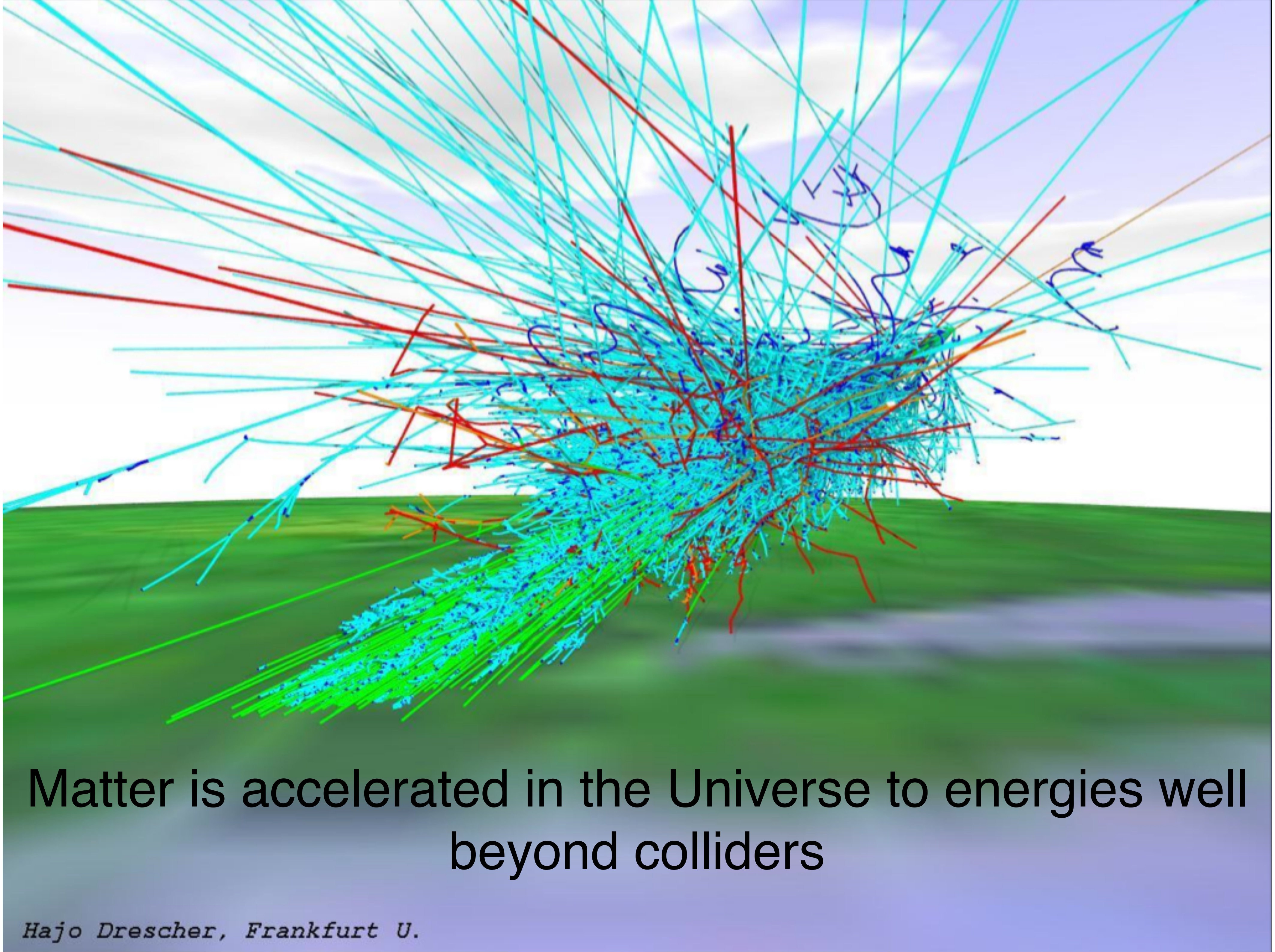

Hajo Drescher, Frankfurt U.
time = -400 µs


Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
time = -200 µs



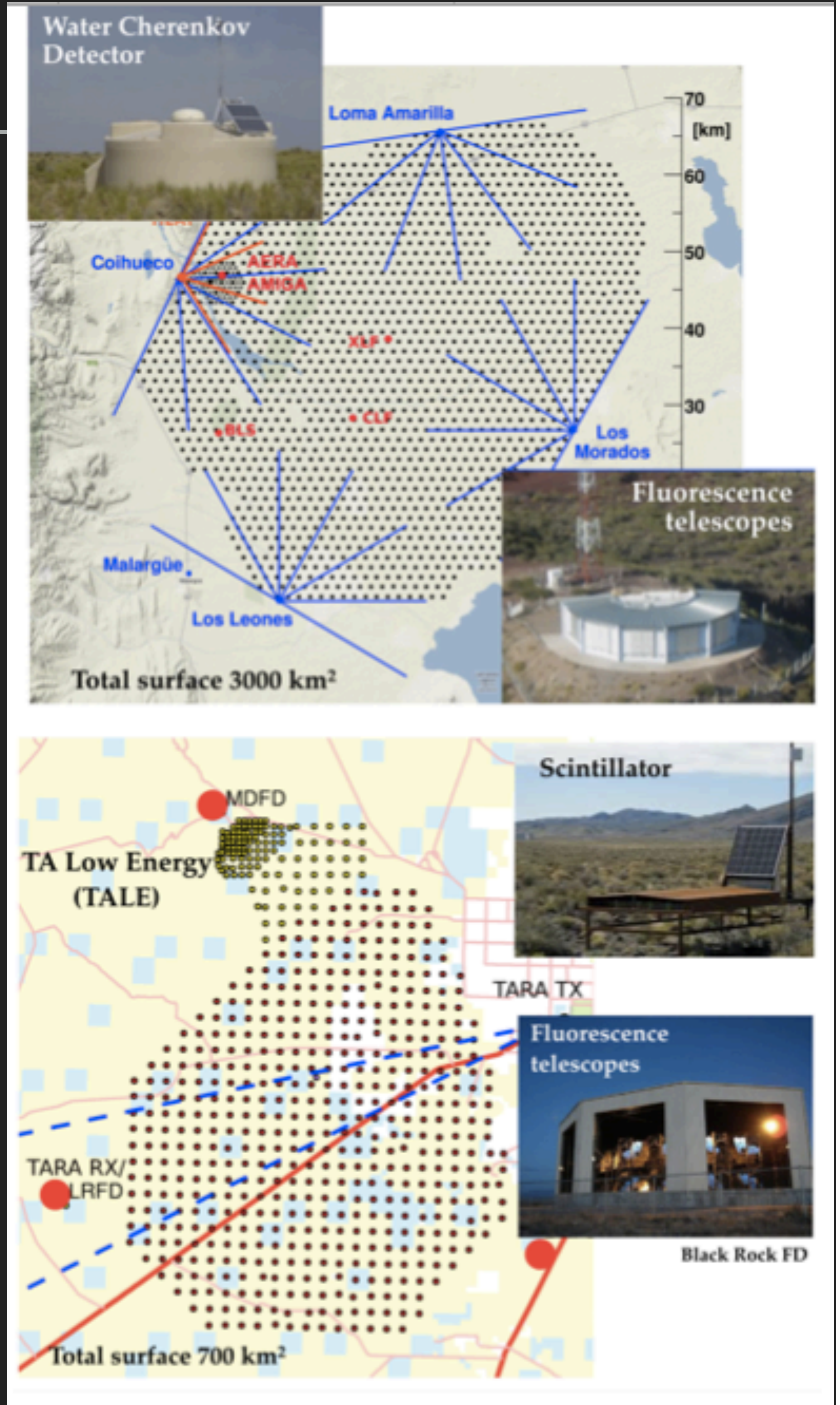
Hajo Drescher, Frankfurt U.
time = -100 µs



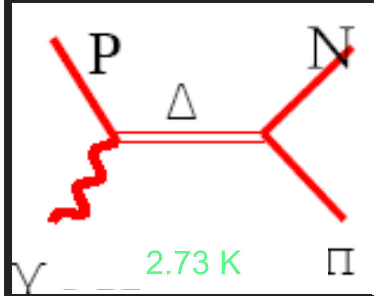
Matter is accelerated in the Universe to energies well beyond colliders

THE LARGEST EXPERIMENTS…

Use shower sampling and fluorescence techniques



THE ANKLE REGION: THE GZK CUT-OFF

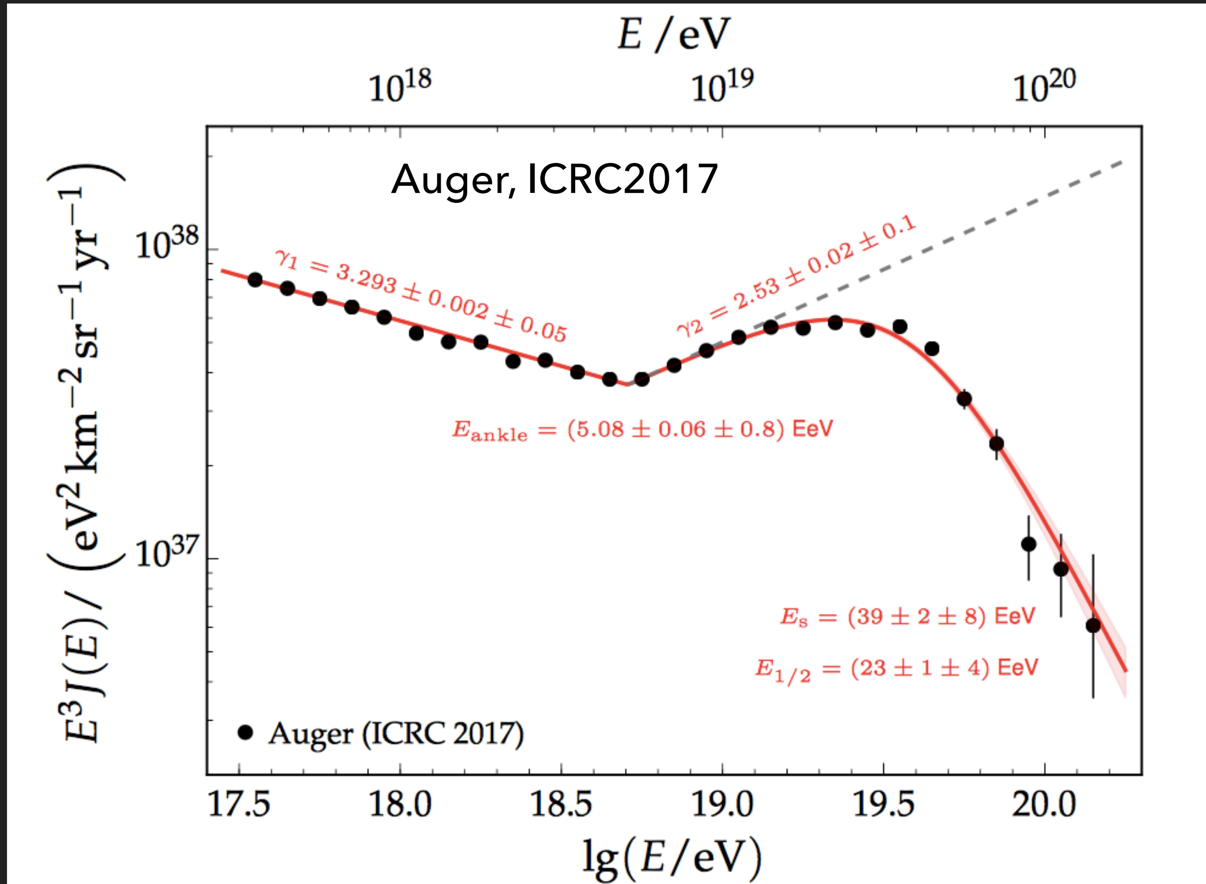


$$\gamma + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

$$\gamma + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

The GZK cut-off is due to proton interactions. The threshold for production of delta resonance is around 5 x 10^{19} eV.

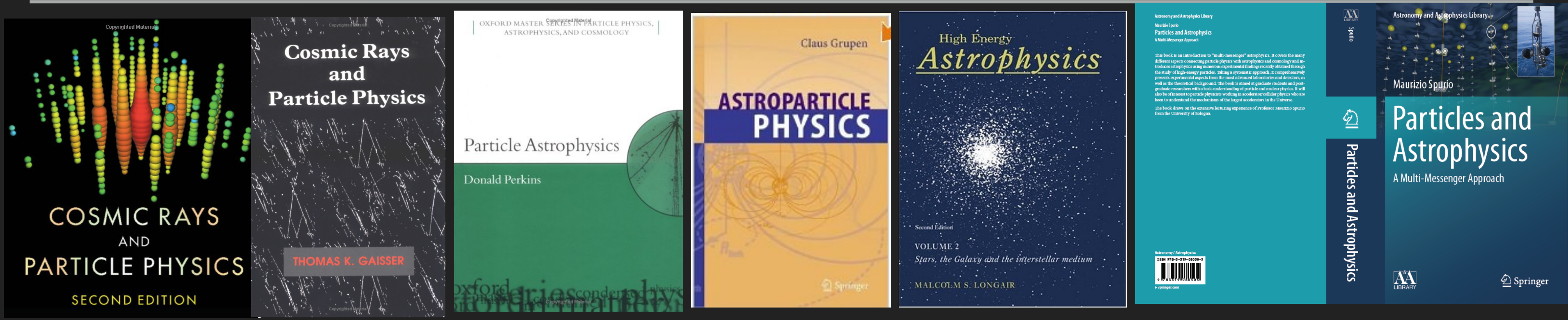
The end of the spectrum of CRs could be due to this effect but we cannot disentangle the effect of sources exhausting their energy.



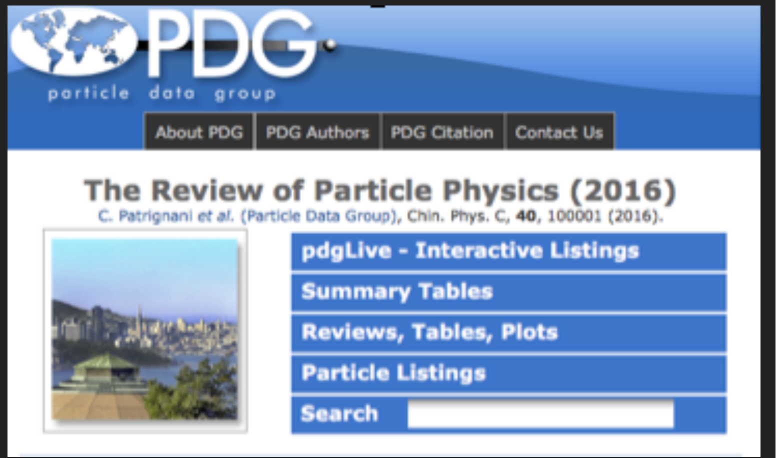
Moreover, the composition in the UHECR region is still very debated…

If UHECR are not light then astronomy with them will be not easy due to magnetic fields deflections during propagation in the Galaxy and outside.

SOME REFERENCE TEXTBOOK



- T.K. Gaisser et al. Cosmic Rays and Particle Physics
- D. Perkins, Particle Astrophysics
- C. Grupen, Astroparticle Physics
- M.S. Longair, High Energy Astrophysics
- S. Rosswog & M. Brüggen, High Energy Astrophysics
- M. Spurio, Particle Astrophysics
- L. Bergstrom & A. Goobar, Cosmology and Particle Astrophysics
- Data Particle Book: http://pdg.lbl.gov



ONLINE MATERIAL

- **Cosmic Rays:**

  http://web.mit.edu/redingtn/www/netadv/Xcosmicray.html; M. Settimo, Review on extragalactic cosmic rays detection, https://arxiv.org/pdf/1612.08108.pdf; Gaisser, Stanev, Tilav, Cosmic Ray Energy Spectrum from Measurements of Air Showers, https://arxiv.org/pdf/1303.3565v1.pdf; Kotera and Olinto, The Astrophysics of Ultrahigh Energy Cosmic Rays, https://arxiv.org/abs/1101.4256; Blümer, Enger and Hörandel, Cosmic Rays from the Knee to the Highest Energies, https://arxiv.org/pdf/0904.0725v1.pdf;

  Drury's review at ICRC2017: https://indico.snu.ac.kr/indico/event/15/session/11/contribution/457/material/slides/0.pdf

- **Neutrinos:**

  All: http://www.nu.to.infn.it;

  Neutrino Astronomy: http://web.mit.edu/redingtn/www/netadv/Xnuastroph.html; https://arxiv.org/pdf/1511.03820.pdf

  Atmospheric Neutrinos: https://arxiv.org/abs/1605.03073

- **Gamma-ray Astronomy:**

  http://web.mit.edu/redingtn/www/netadv/Xgamma.html

- **Gravitational Waves**: http://web.mit.edu/redingtn/www/netadv/Xgraviradi.html