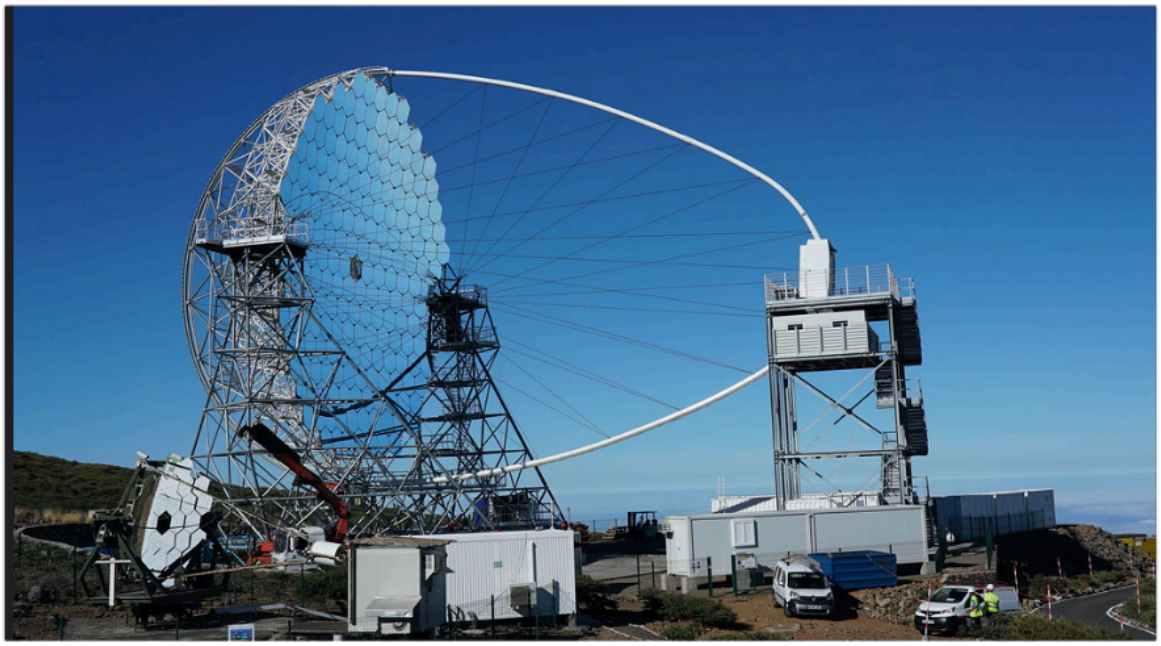


CERN SUMMER STUDENT - LECTURE I

TERESA.MONTARULI@UNIGE.CH

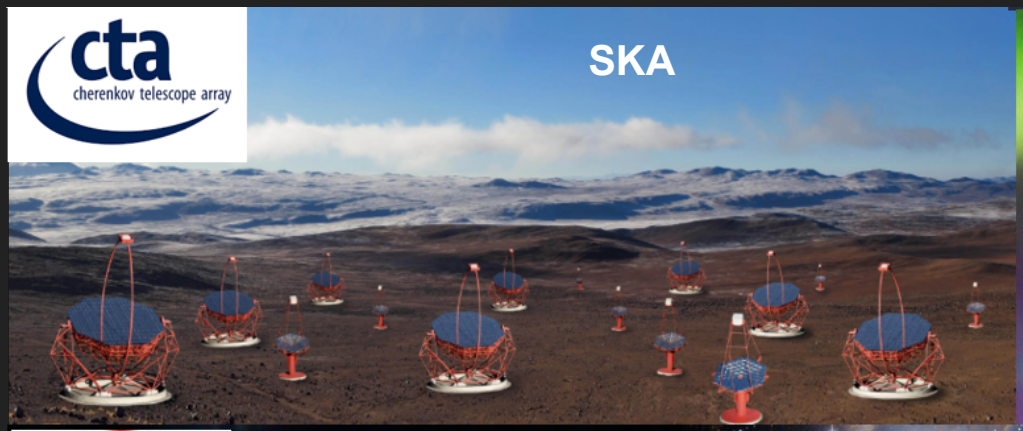
UNIVERSITÉ DE GENÈVE

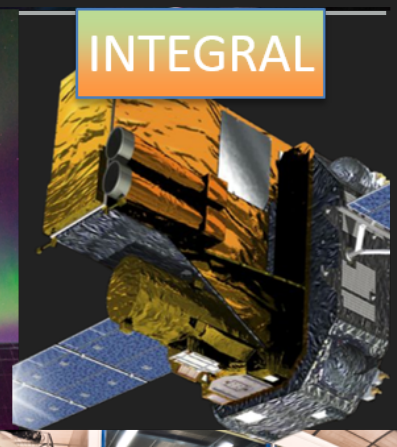
ASTROPARTICLE I

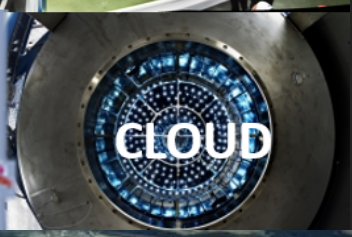
18 July 2019

GENEVA...SWITZERLAND...

. . . AND ASTROPARTICLE







CERN AND ASTROPARTICLE

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

APPEC

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

Cosmic Rays

Particle Physics

Neutrinos

Gamma-rays

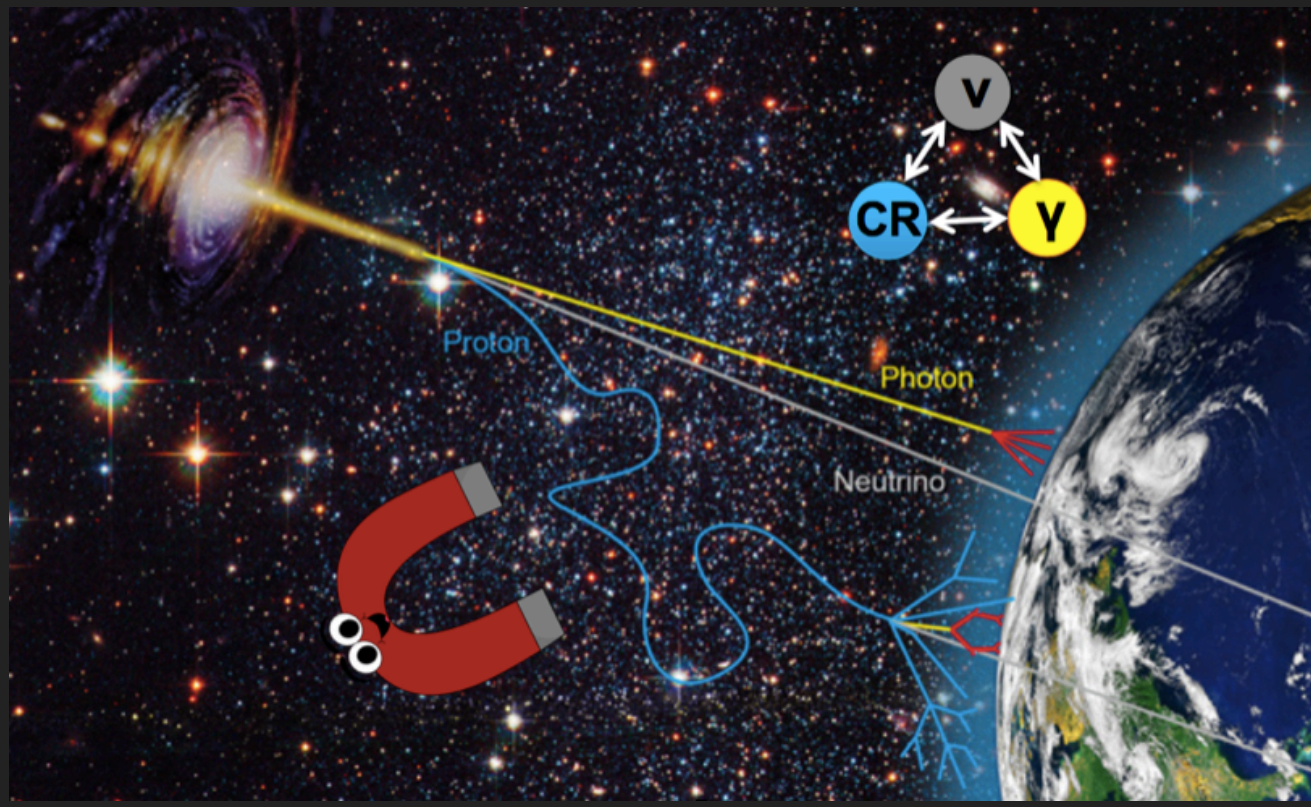
Gravitational waves

Dark matter & Cosmology

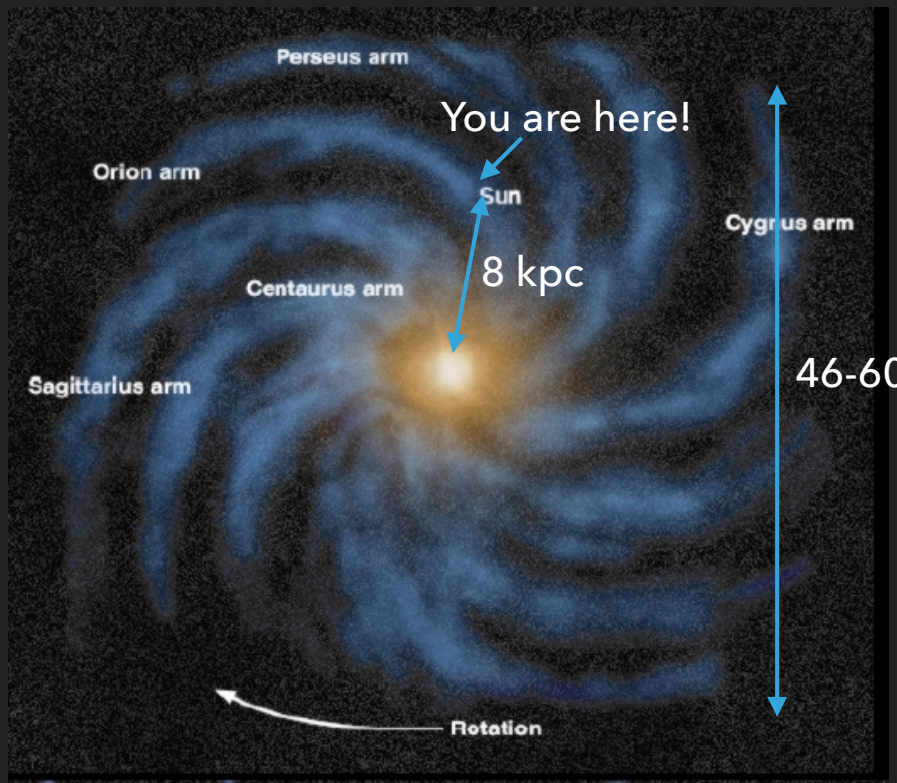
http://recognized-experiments.web.cern.ch/recognized-experiments/

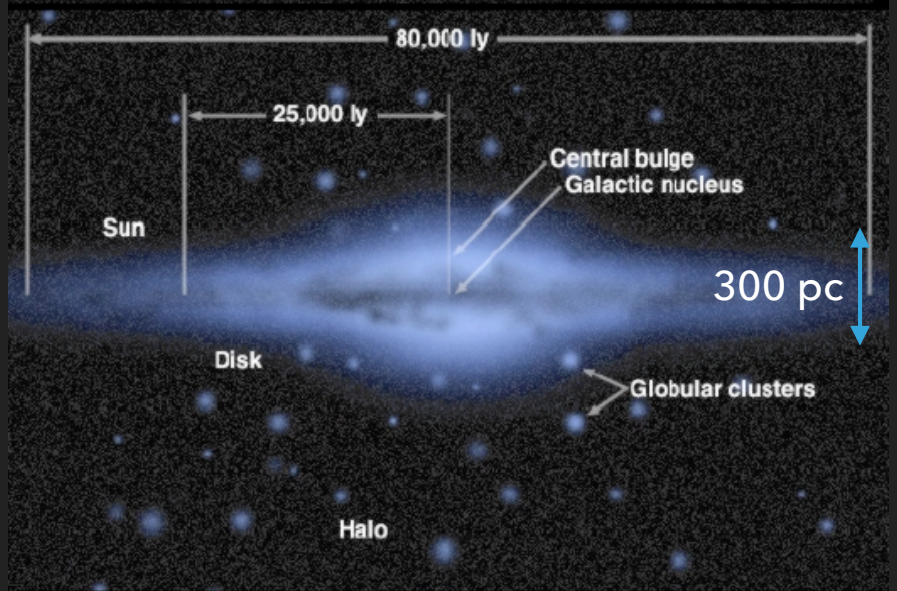
CONTENTS OF TWO LECTURES

- Radiation from the universe and cosmic rays (CRs)
- Cosmic ray observables: spectrum and composition
- Propagation and sources of cosmic rays
- The new astronomy: multi-messenger high energy astrophysics
- The connection of CRs to other messengers :
  - Gamma-Rays
  - Neutrinos
  - Gravitational waves



A PARENTHESIS: VIEW TO THE MILKY WAY…





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 arcsec~ 3 x 10^{-4}°

1 ly = 2.998 x 10^{8} m/s x 3.156 x 10^{7} s/yr ≈10^{13} km ~ 0.3 pc

Moon-Earth 384,000 km = 1.28 ls

Thin disk: 30 kpc diameter ~300 pc thickness
Sun at ~8 kpc from Galactic Centre

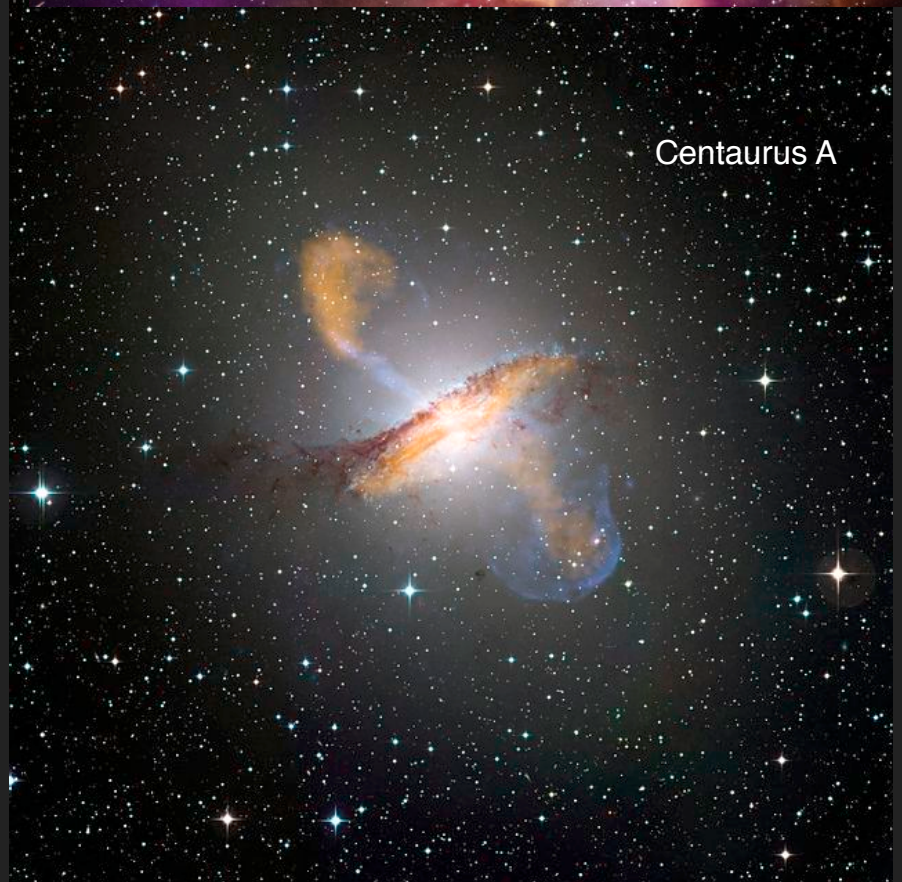
Speed of Sun in the Galaxy around the Galactic centre : 220 km/s

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

. . . 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
- Visible universe: sphere limits from which light can reach us due to finite speed of light during the life of the universe: c/H_0 ~13.8 Glyr ~ 4 Gpc (Planck from cosmic MW background)
- Observable universe (since the beginning of cosmological expansion): diameter ~28Gpc (~2% larger)
- Hubble expansion const. H_0 ~70 km s^{-1} Mpc^{-1}
- T_0 CMBR temperature 2.725 ± 0.001 °K

1Mpc = 3.26 Mly = 3.0857×10^{24} cm



WHY THE SKY IS DARK?

Olber's paradox (XIX century): In a static, infinite Universe every line of sight should eventually intercept the surface of a star, so the sky should be as bright as a stellar surface.

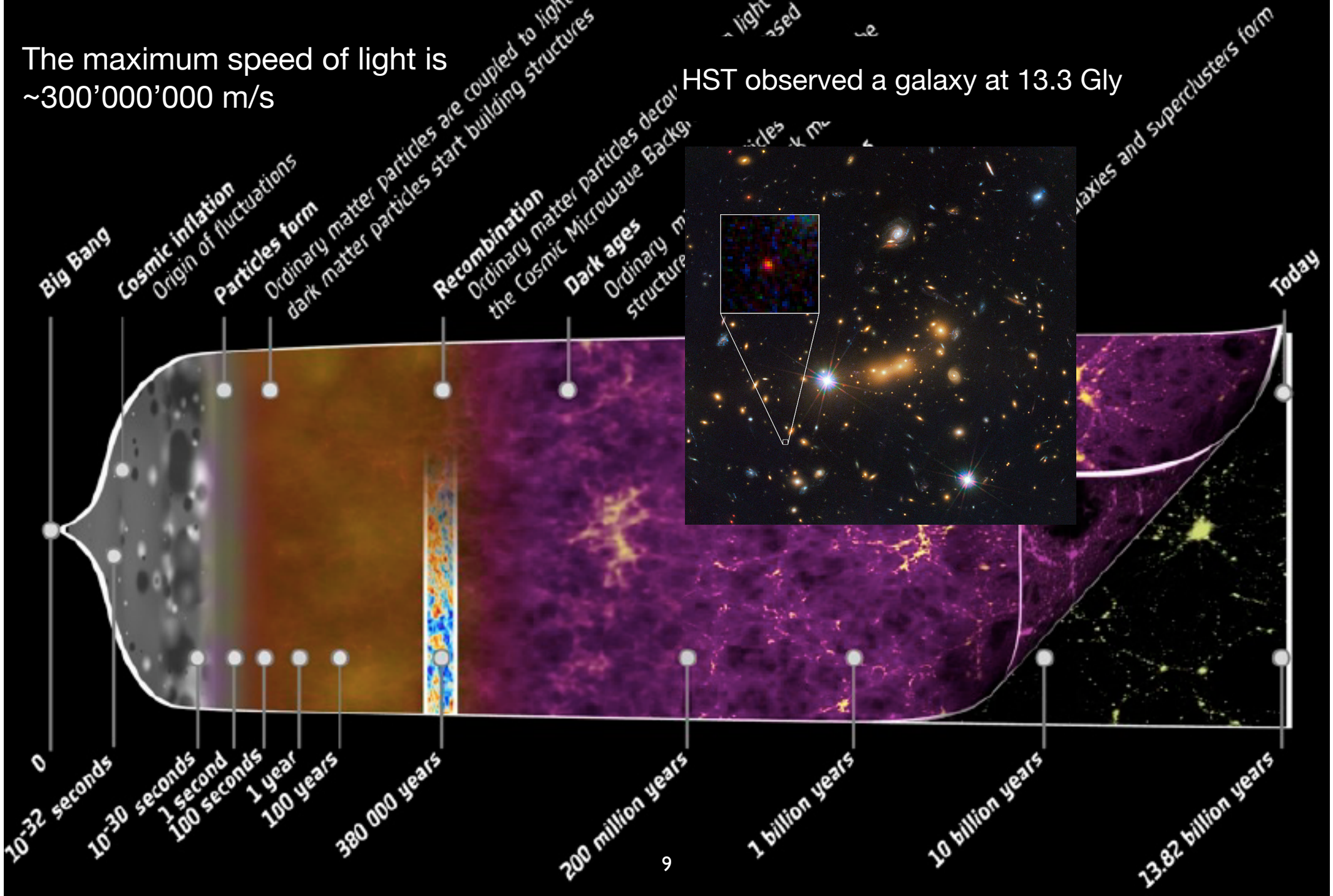
Solution:

- finite speed of light : we can see only galaxies where light has had the time to reach us;
- Finite age of universe in the Big Bang cosmology;
- Expansion of the universe: stars only radiate for finite time, limiting the energy density of the background light)

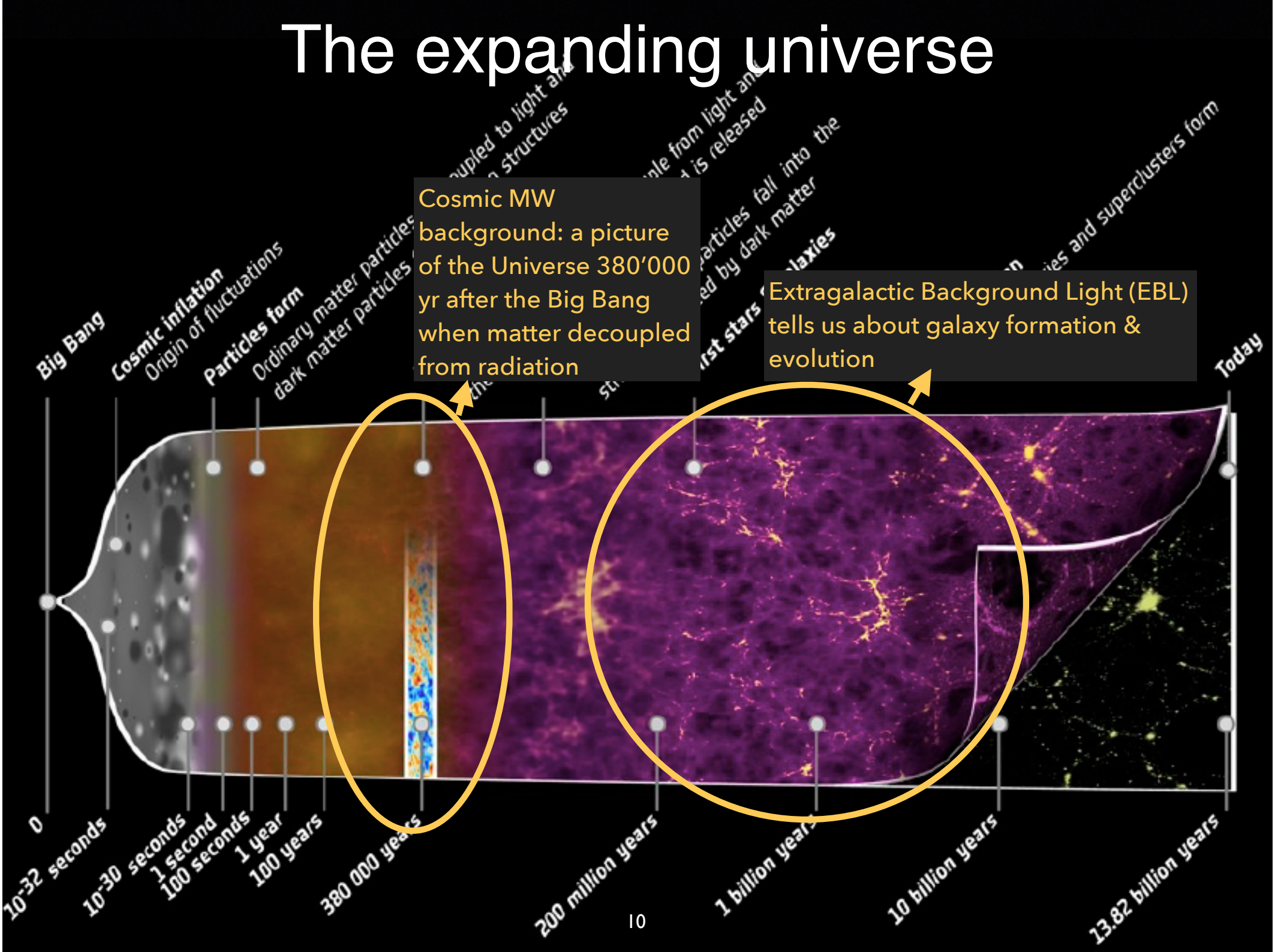
The expanding universe

The maximum speed of light is ~300’000’000 m/s

HST observed a galaxy at 13.3 Gly



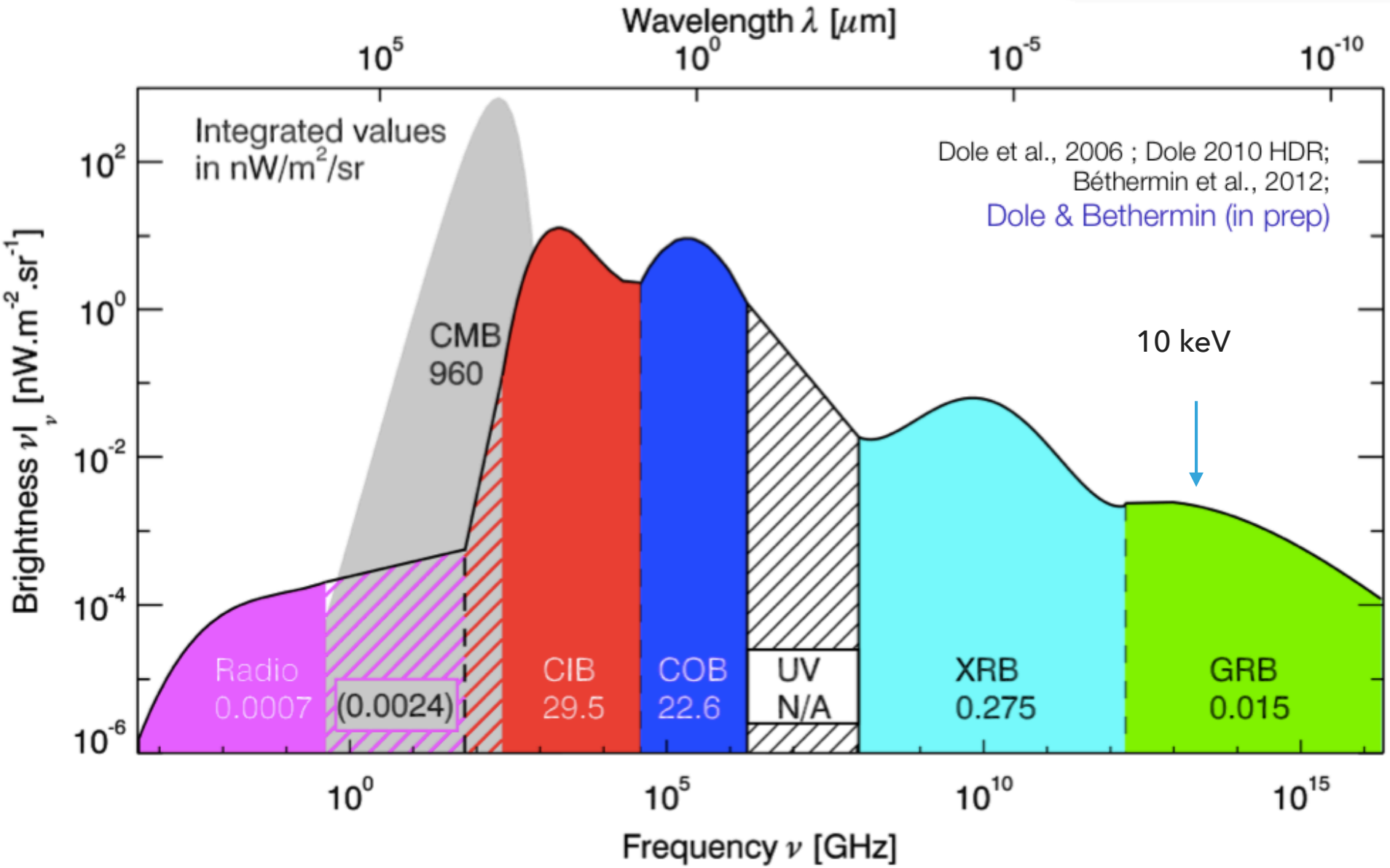
The expanding universe



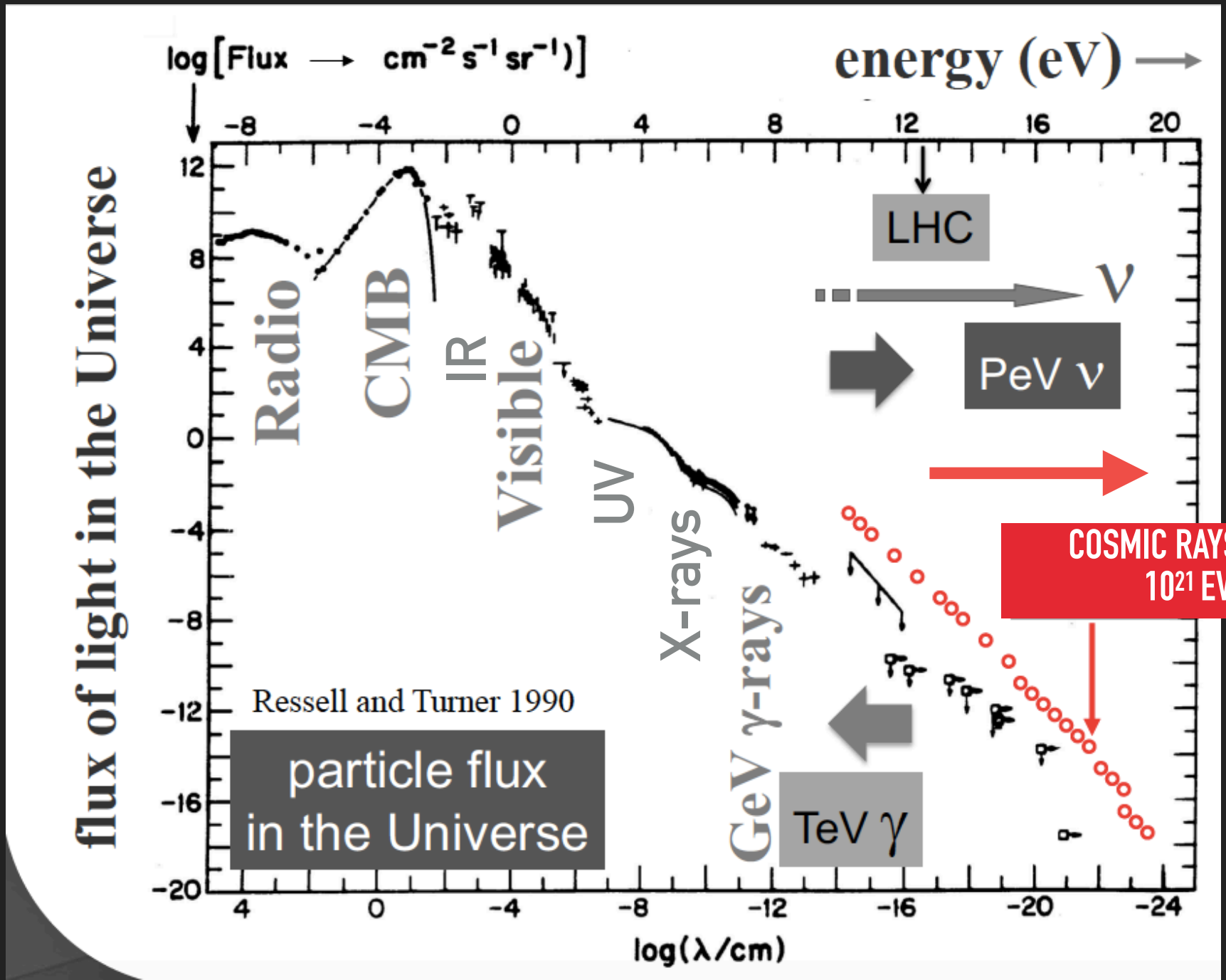
BEING FINITE THE SKY SHINES!

The CMB is a picture of the Universe 380’000 yr after the Big Bang

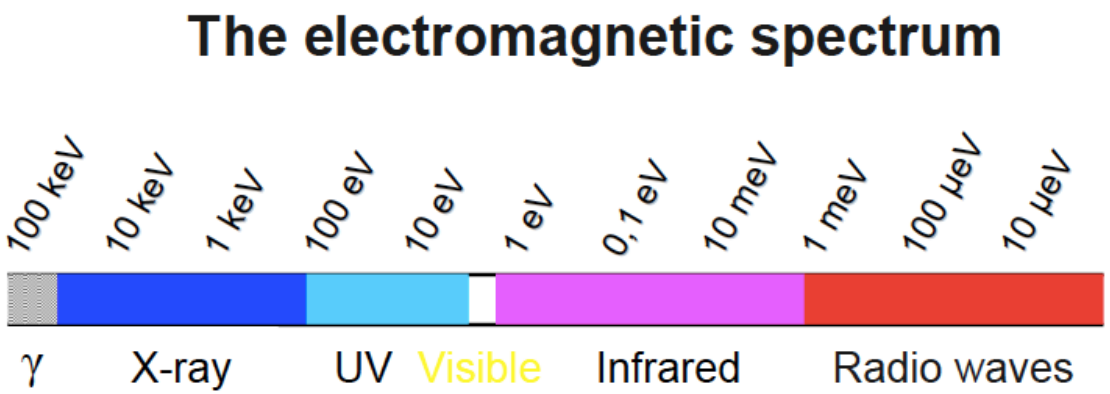
The Extragalactic Background Light (EBL) encodes the output of galaxy formation evolution



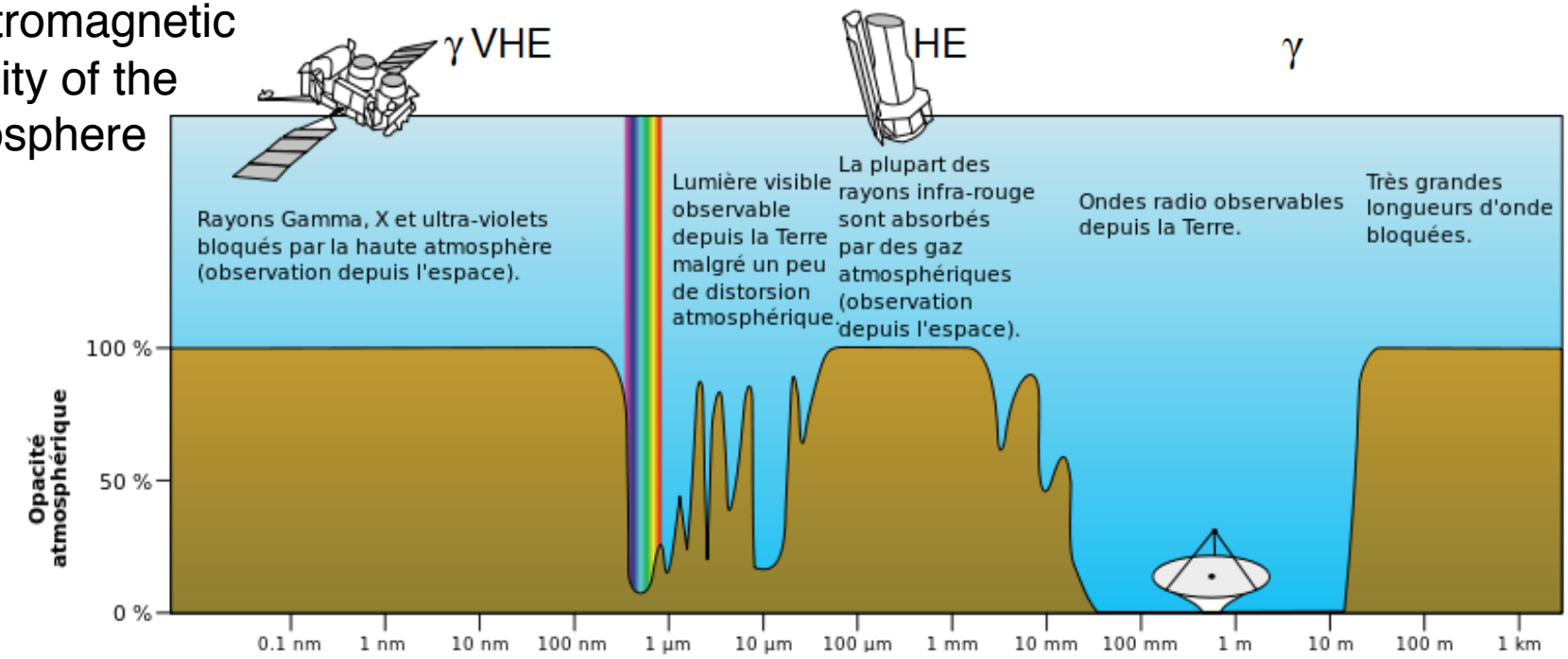
. . . AND PARTICLES!



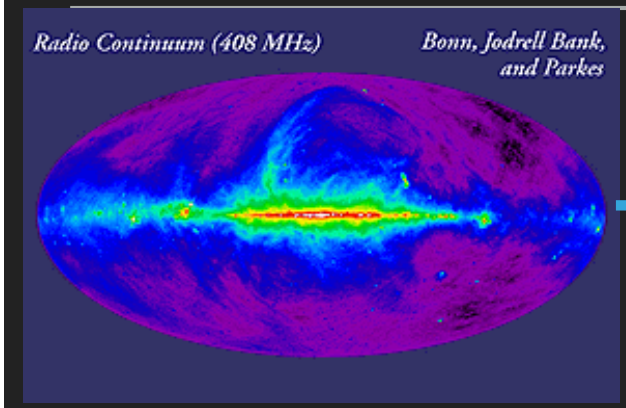
MULTI-WALENGTH ASTRONOMICAL OBSERVATIONS

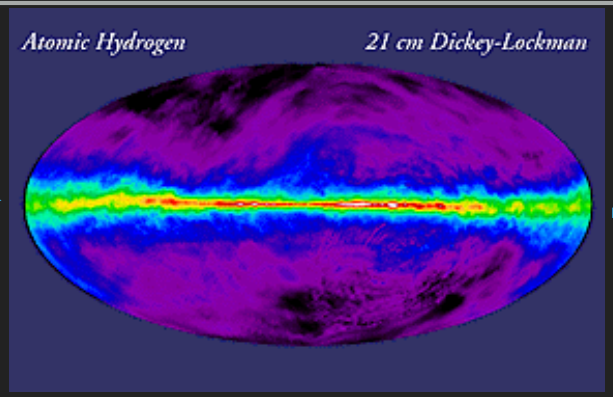


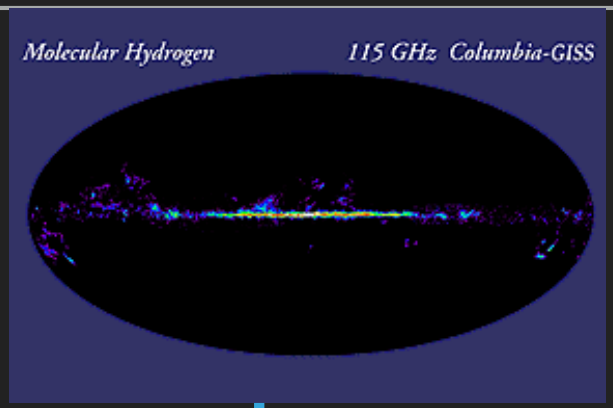
Electromagnetic opacity of the atmosphere



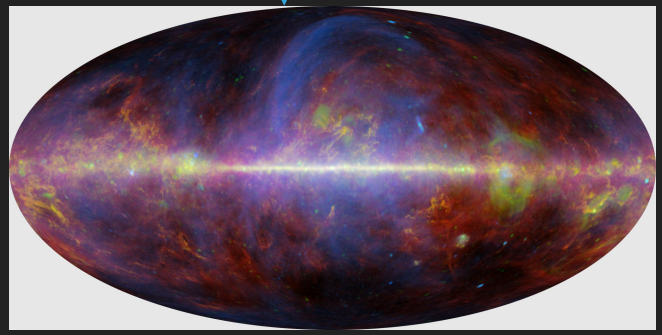
THE MULTI-WALENGTH SKY

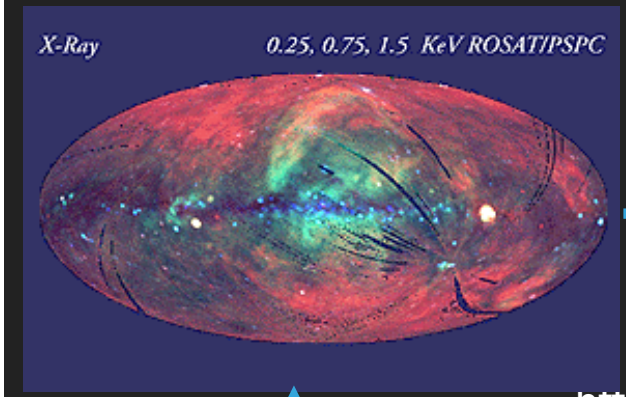


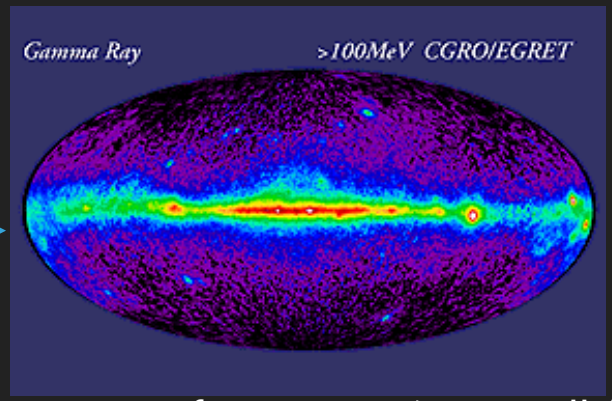




Planck 10-0.3 mm

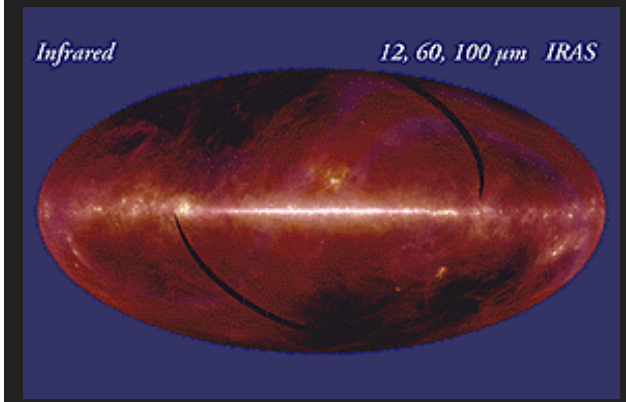


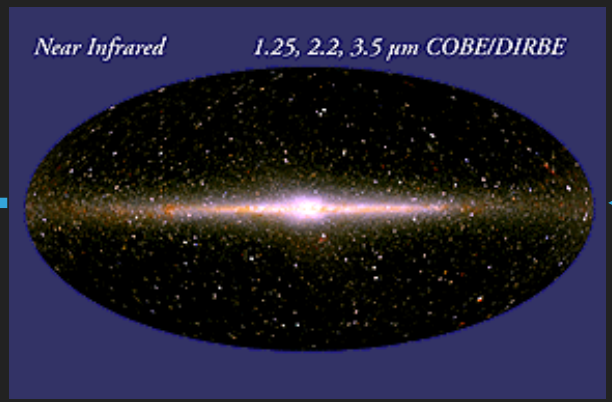


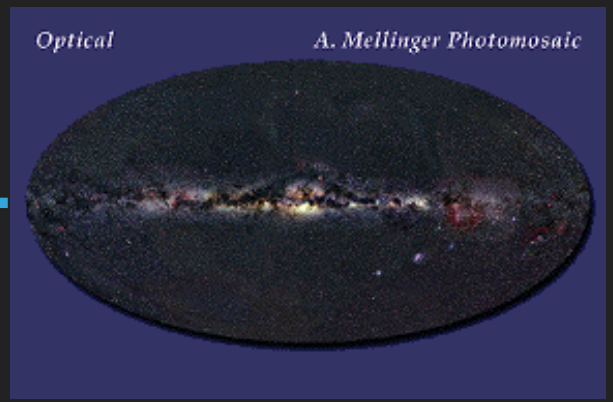


https://mwmw.gsfc.nasa.gov/mmw_allsky.html

http://www.chromoscope.net

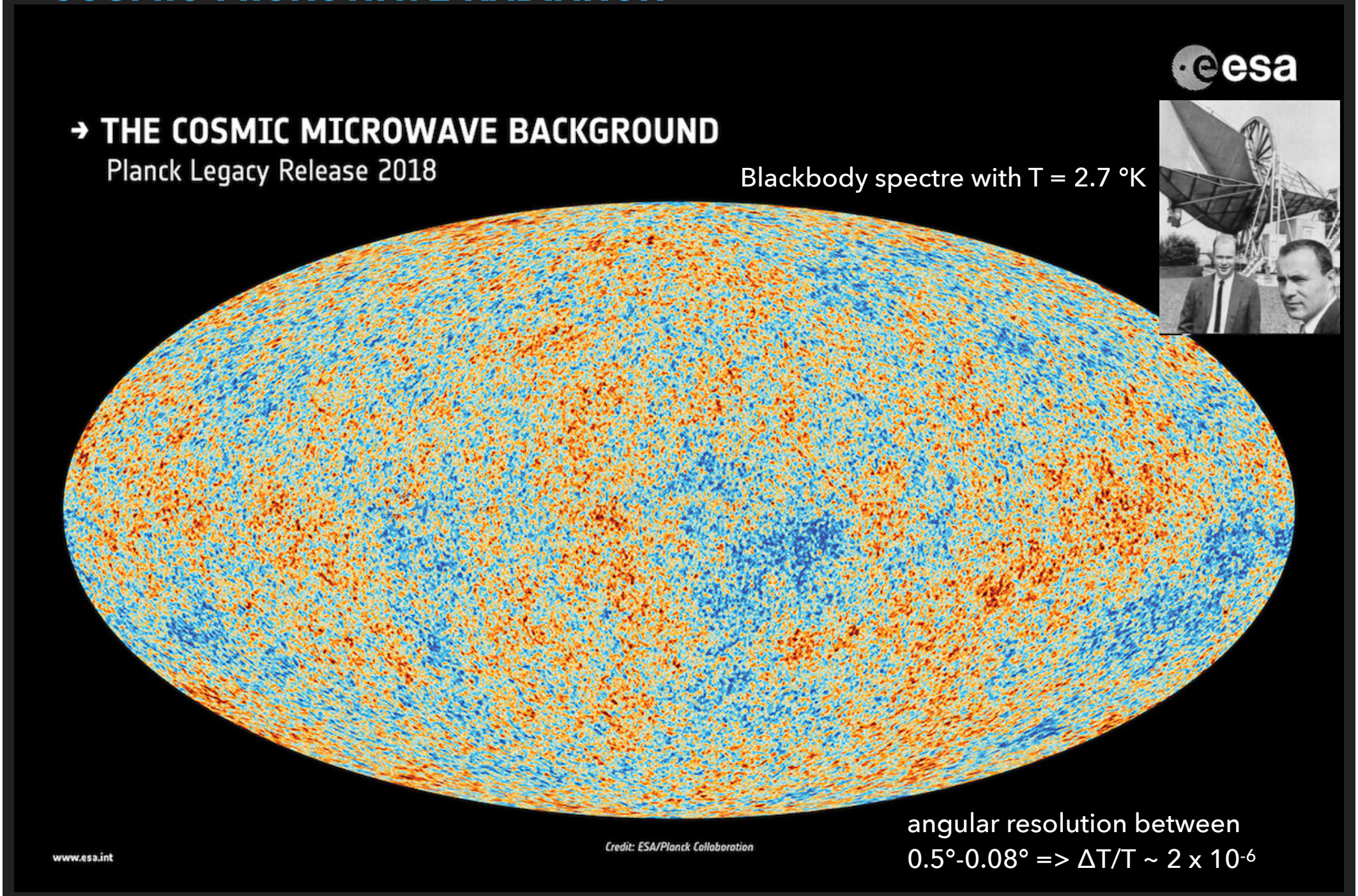




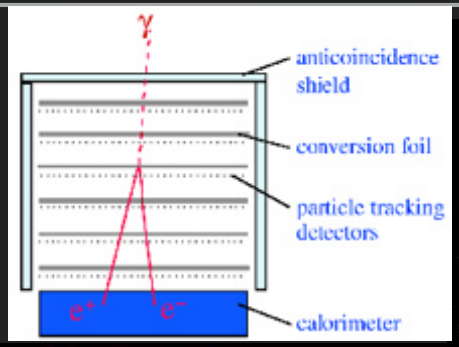


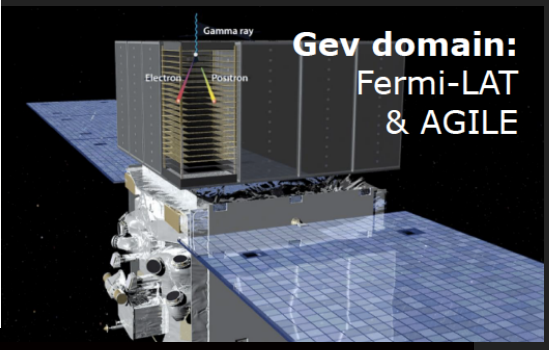
COSMIC MICROWAVE RADIATION

Penzias&Wilson, 1965

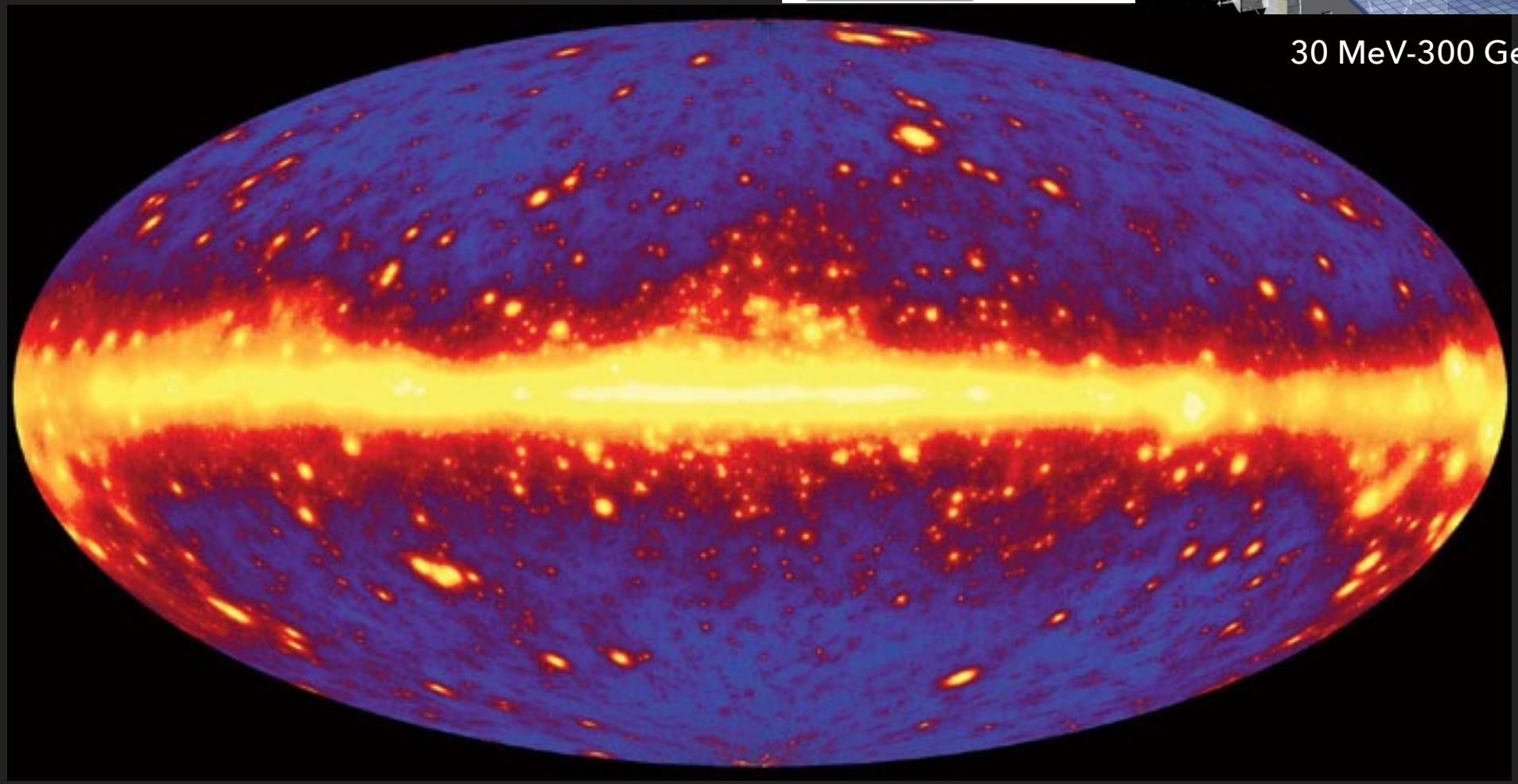


THE ACCELERATORS SKY IN THE TEV SEEN BY FERMI-LAT





30 MeV-300 GeV



http://www.nasa.gov/mission_pages/GLAST/news/gammaray_best.html

THE MULTI-WALENGTH OBSERVATIONS: THE CRAB NEBULA

Hystorical Supernova remnant observed in the year 1054 by Chinese Astronomers

X-ray	Optical	Infrared	Radio
~ 10^4 eV	~ few eV	~ 1 eV	~ 10^{-4} eV

Credit: NASA/CXC/SAO (X-ray), Paul Scowen and Jeff Hester (Arizona State University) and the Mt. Palomar Observatories (optical), 2MASS/UMass/IPAC- Caltech/NASA/NSF (infrared), and NRAO/AUI/NSF (radio)

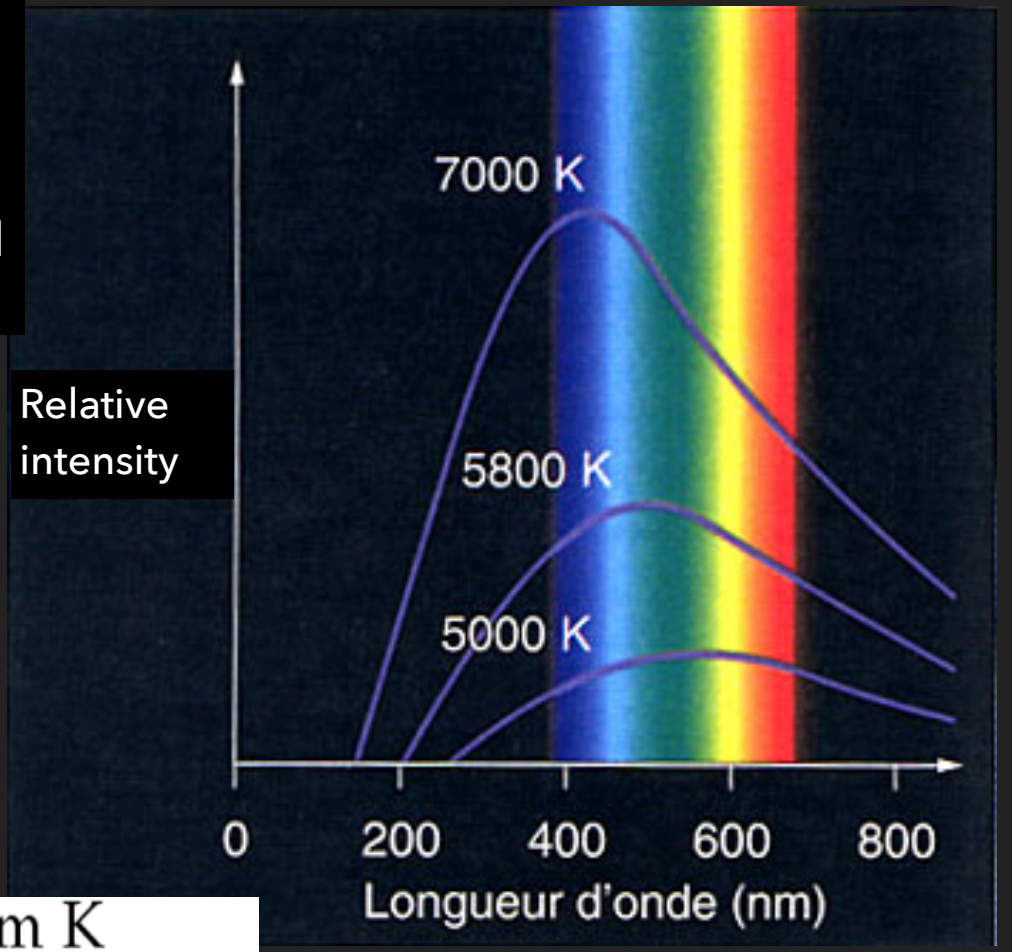
THE EXPLORATION OF THE NON-THERMAL UNIVERSE

Primary sources of thermal radiation in the cosmos are black body radiation emitted by stars and heated dust and thermally excited spectral line emissions of atoms in stars.
The black body is an ideal black, isolated and at a constant temperature body with
emission power per unit surface, solid angle and frequency (Planck function):

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

h = 6.62 x 10^{-34} J s (Planck constant)

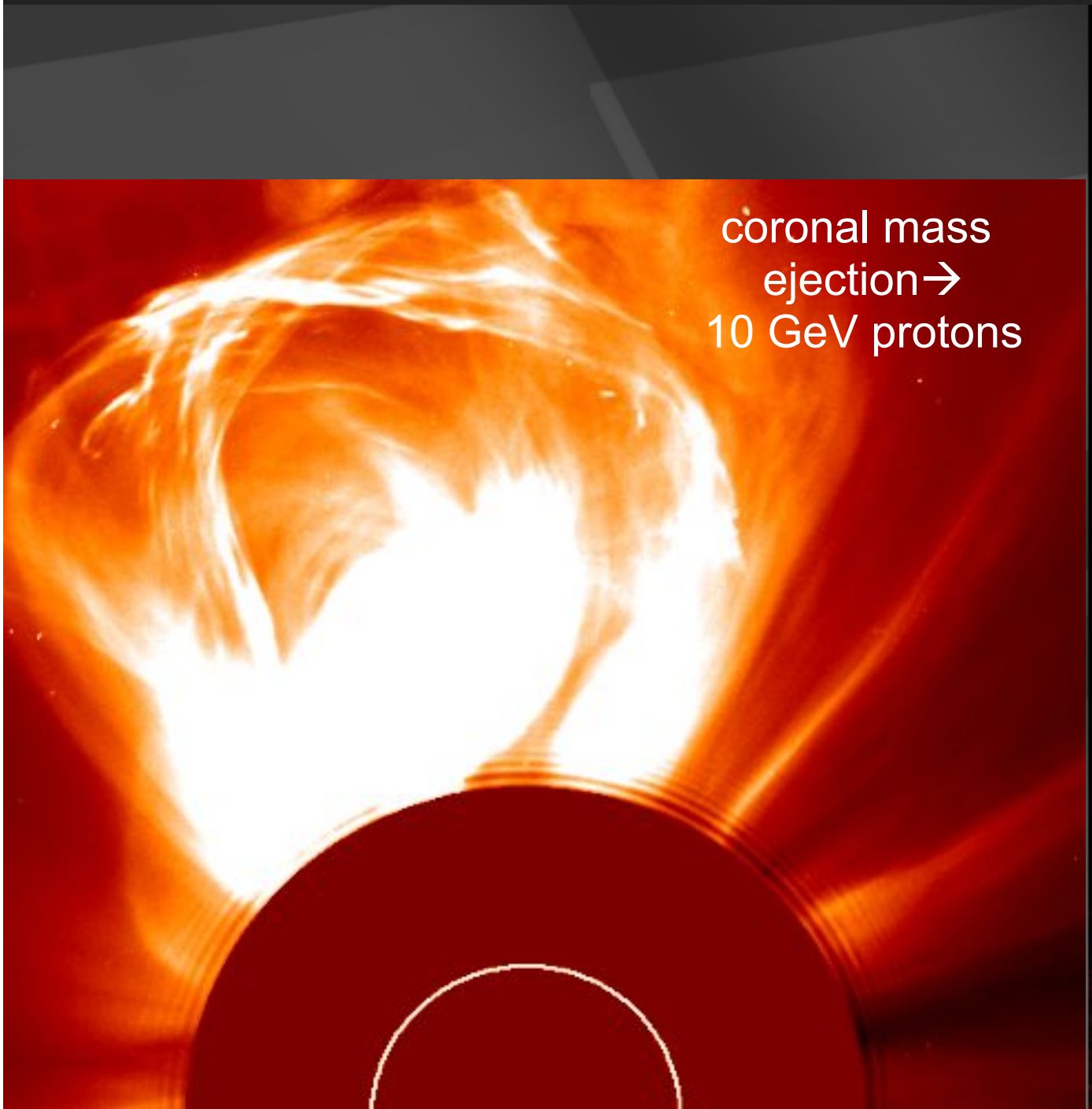
k = 1.38 x 10^{-23} J K-1 (Boltzmann constant)

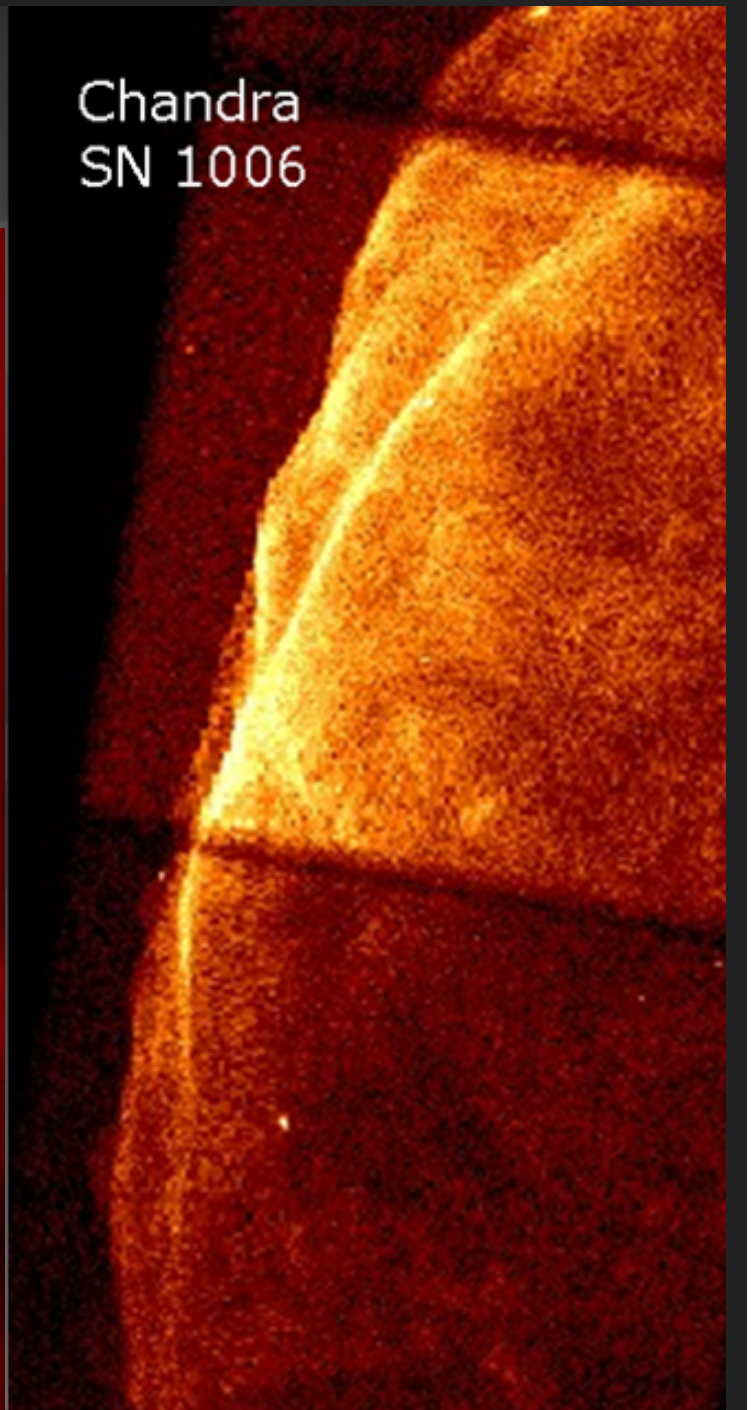


Wien's law $\lambda_{max} \times T = 2900 \quad \mu m\ K$

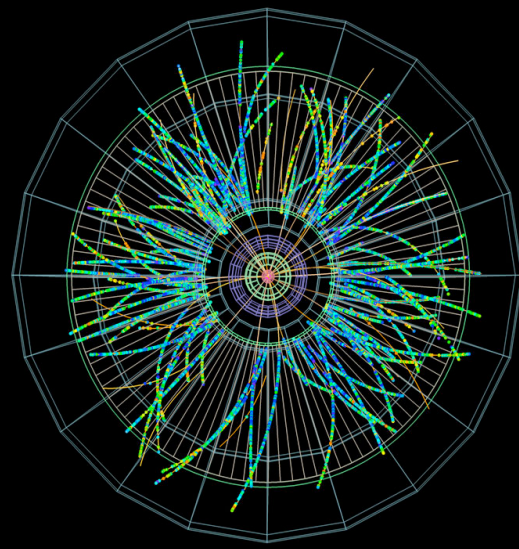
Sun	5500 K	0.5 μm	visible
Human being	310 K	9 μm	IR
Molecular cloud	15 K	200 μm	radio

THE NON-THERMAL ACCELERATORS



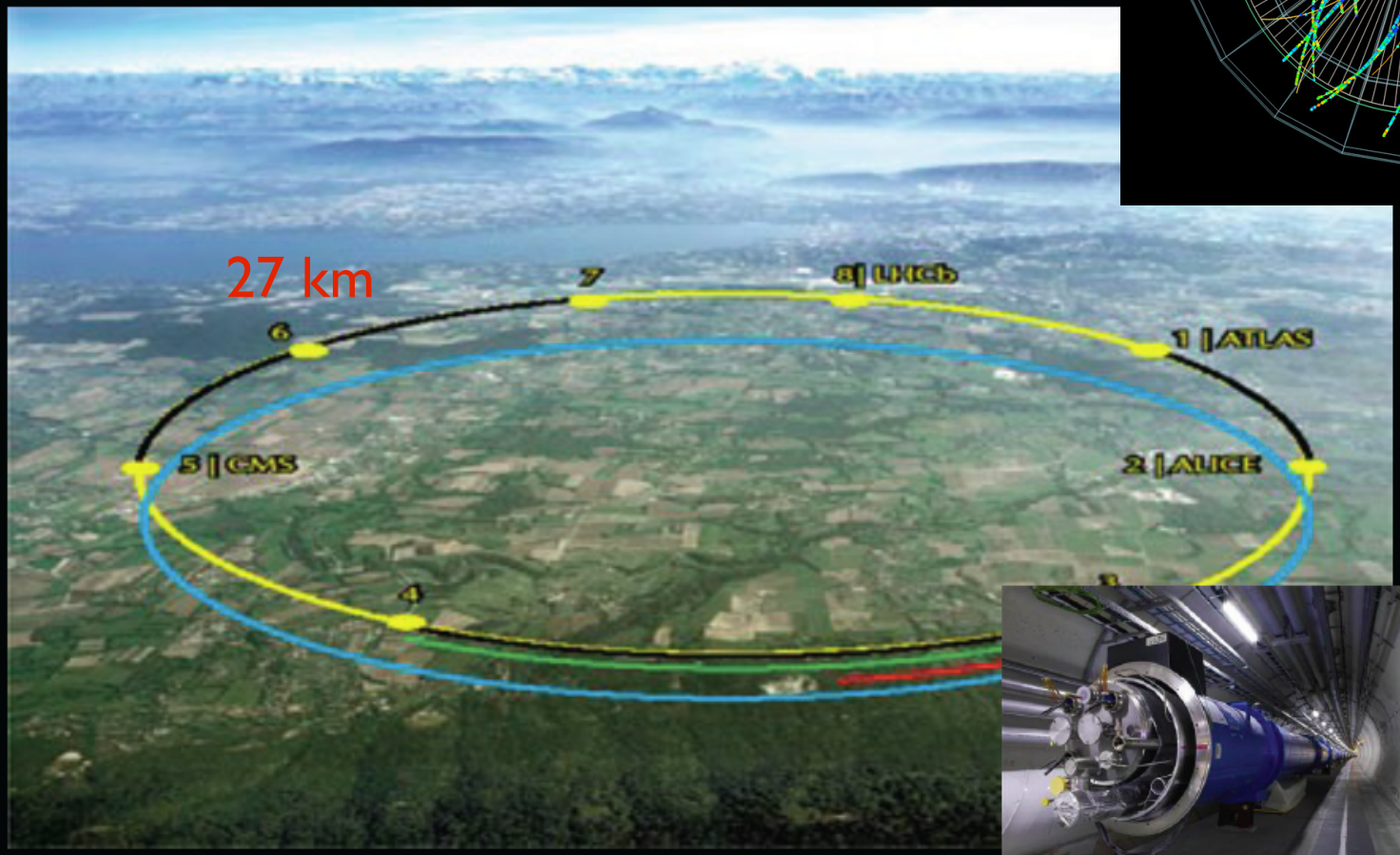


ACCELERATORS



Large Hadron Collider:

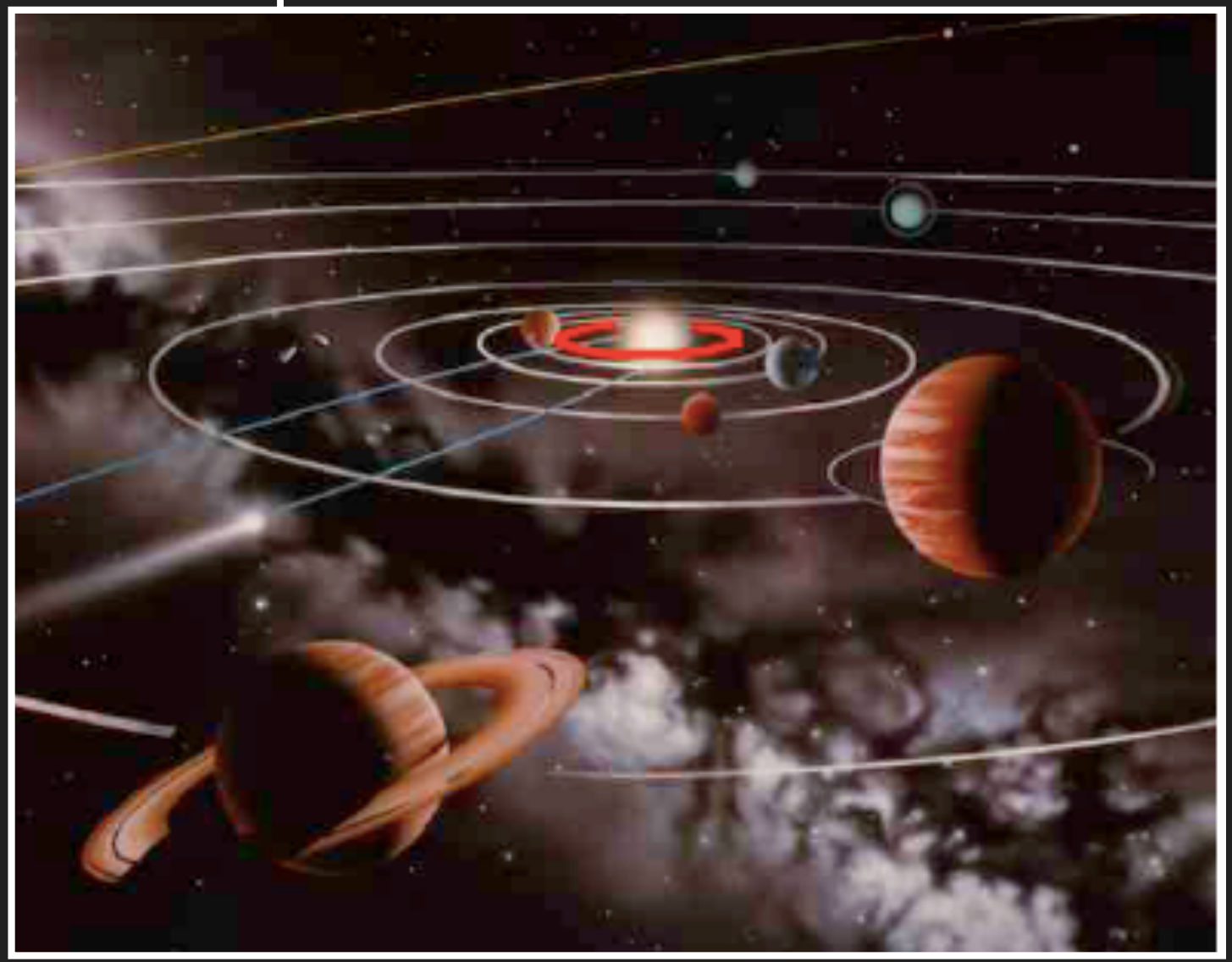
$E_{max} = c \cdot e \cdot B \cdot R = 7 \times 10^{12}$ eV



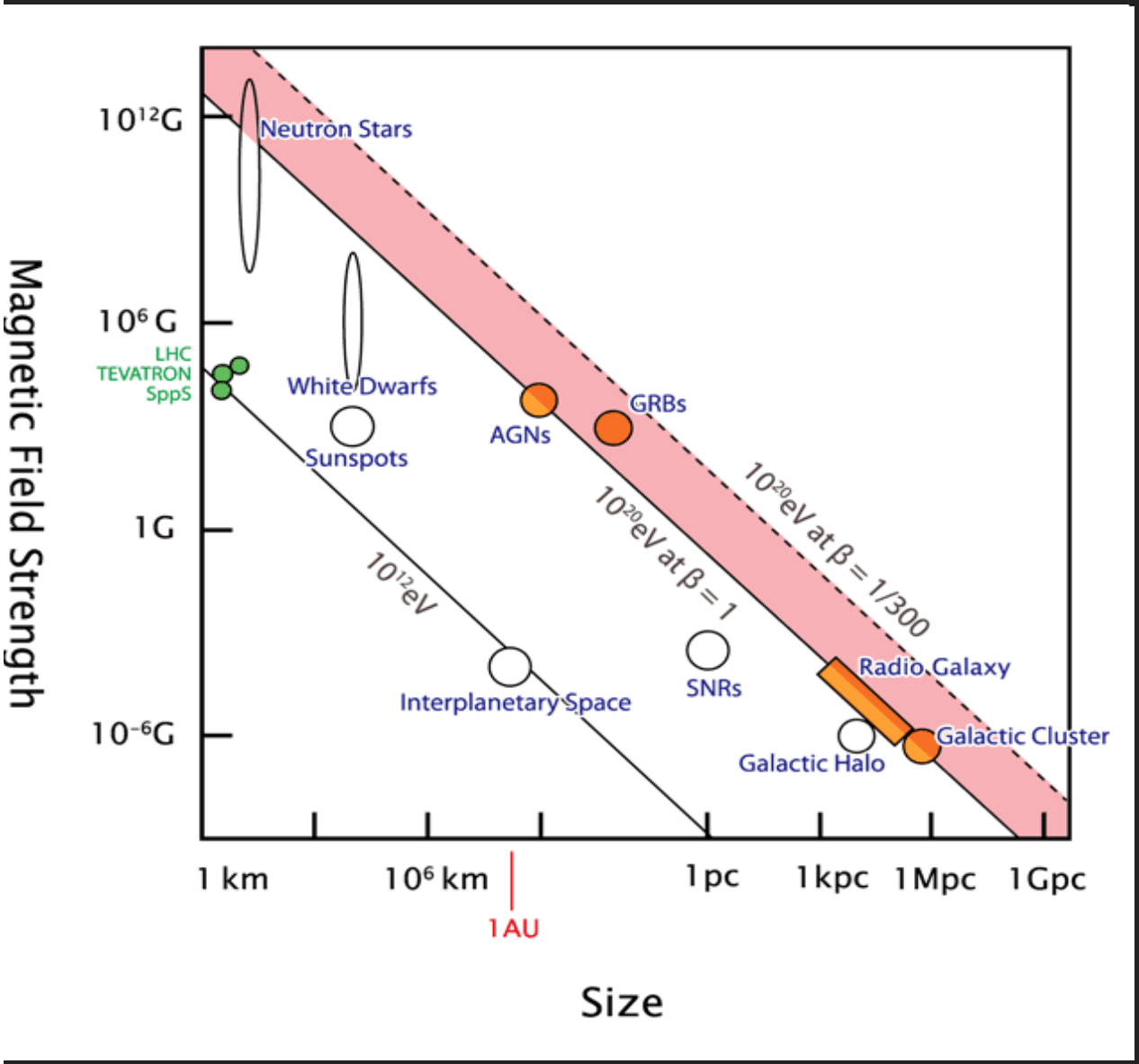
9593 superconducting magnets at -271.3 ◦C accelerate protons to collide in 4 points instrumented to analyse matter and its constituents in which it decomposes at these extreme conditions similar to 3×10^{-15} seconds after the Big Bang (~15 TeV correspond to abt. 10^{17} Kelvin)

COSMIC ACCELERATORS

An LHC with the radius of the Mercury orbit could accelerate protons to 10^{20} eV = 10^{7} x LHC!



MESSENGER ACCELERATION: THE HILLAS' PLOT



Lorentz force

$$F_L = qvB = m\frac{v^2}{R}$$

Imposing that the Larmour is equal to the accelerating region

R = R_{acc}

We find the maximum energy at which the charged relativistic particle with q = Ze can be accelerated

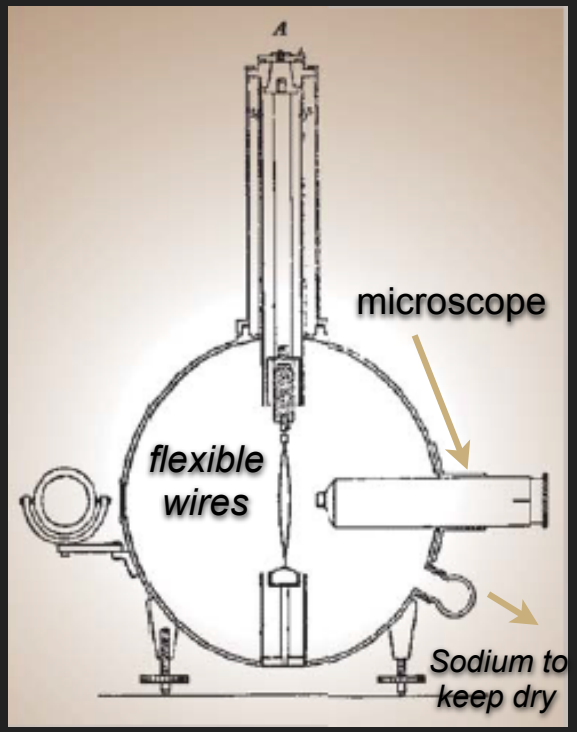
$$E_{\max} \simeq Z\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{R_{\mathrm{source}}}{\mathrm{kpc}}\right) \times 10^9\ \mathrm{GeV}$$

For jets with Lorentz factor Γ, $E_{max} \cong \Gamma$ ZBR (maximum energy depends on cosmic ray charge Z!!)

COSMIC RAY HISTORICAL HINTS

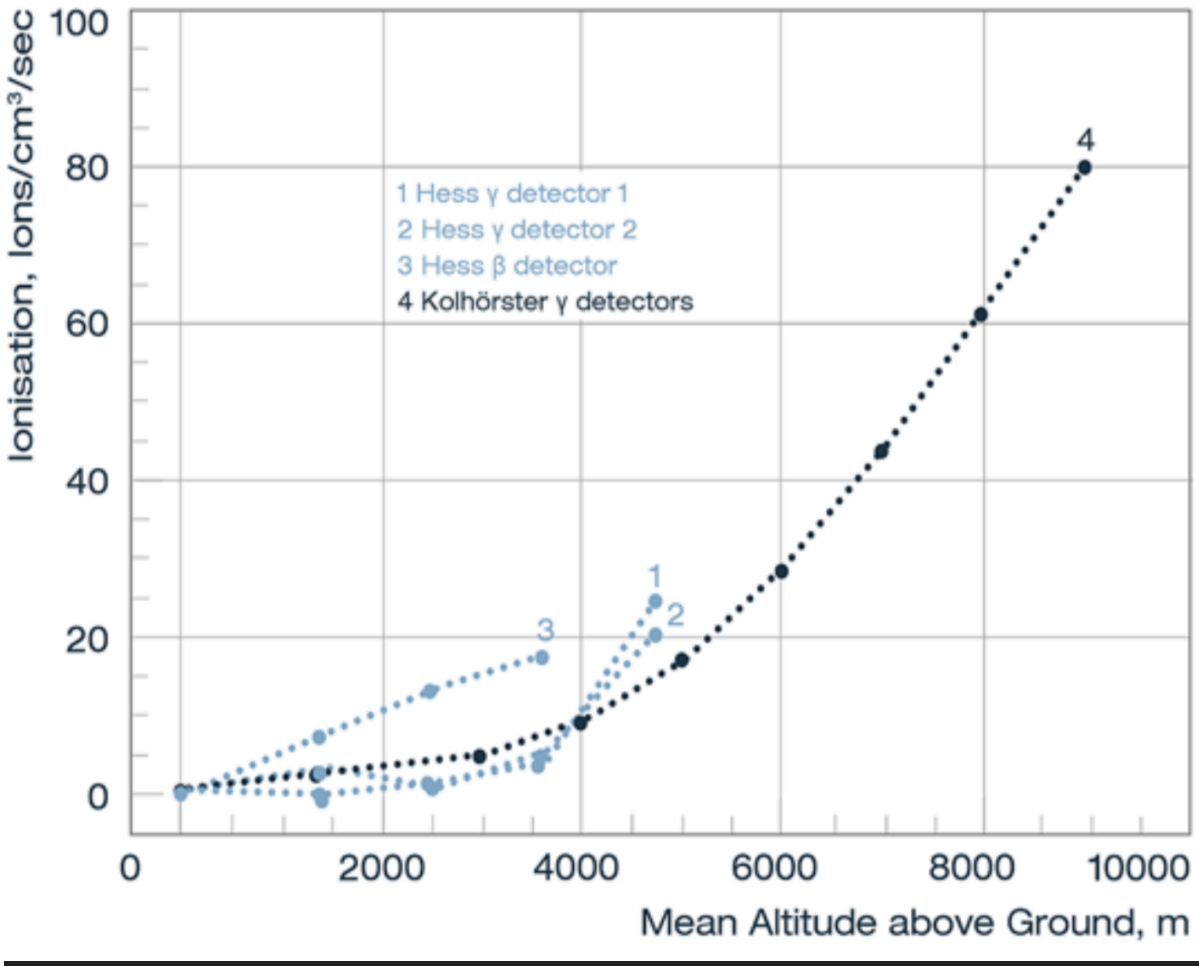
- A. Gockel (Swiss, 1909-1911): with a Wolf-type electroscope on 3 balloon flights discovers that the radiation discharging the electroscopes does not come from ground but increases with altitude.
- Wrong interpretation: gamma-rays from radioactive sources in the atmosphere
- V.F. Hess (1912, nobel prize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



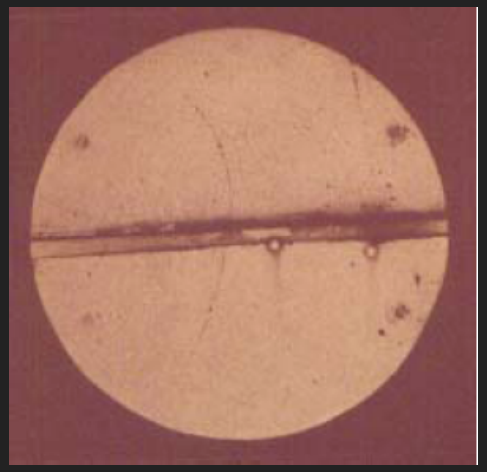
Nature (suppl) 121, 19, (1928)
Lecture at Leeds University

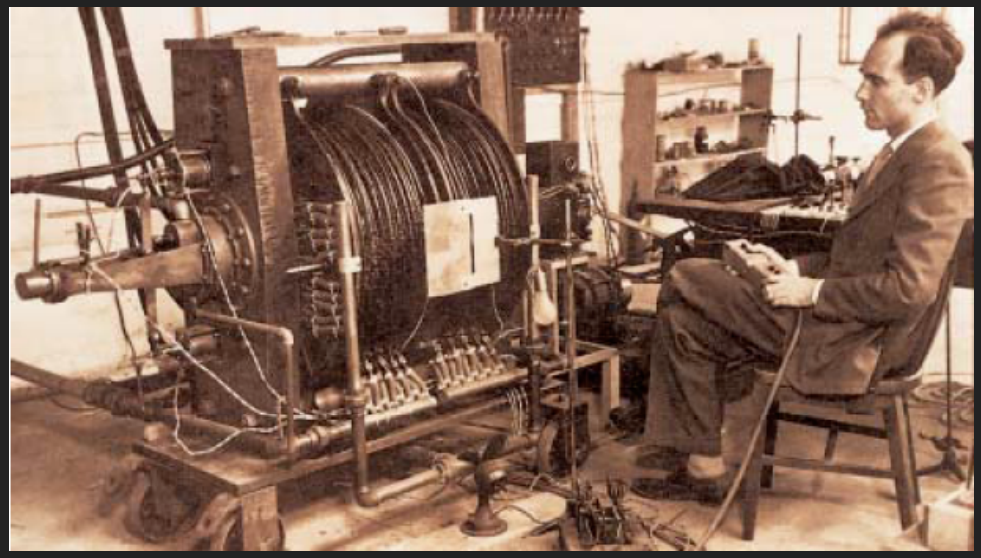
These facts, combined with the further observation made both before and at this time, that within the limits of our observational error the rays came in equally from all directions of the sky, and supplemented finally by the facts that the observed absorption coefficient and total cosmic ray ionisation 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. They recognised in it the anti-electron of the Dirac theory observing e^+e^- pair production.



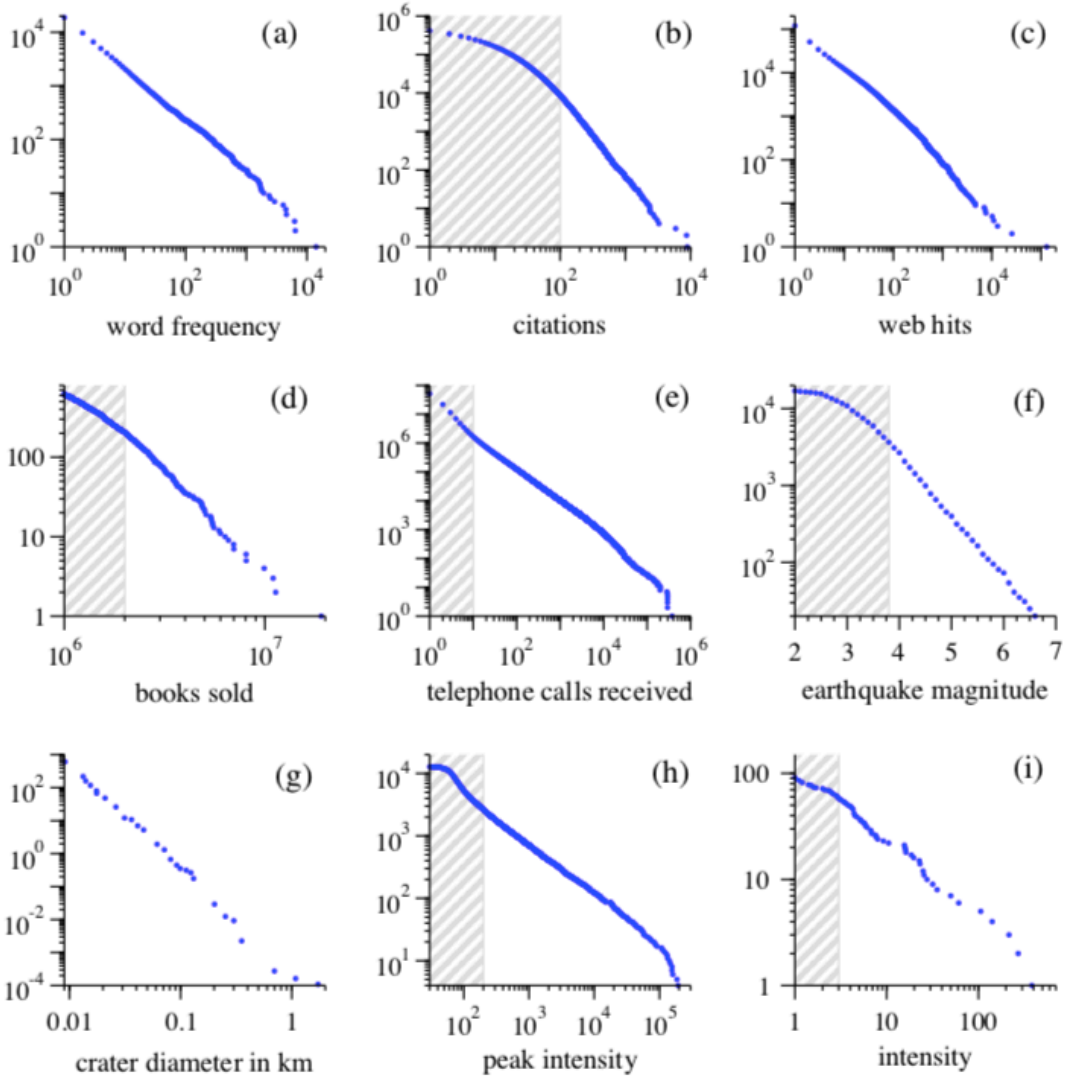


- Auger in the late 30's at the Jungfraujoch (3500 m a.s.l.) concluded that registered particles were secondaries generated in the atmosphere by primary CRs.

- C.F. Powell, G. Occhialini & C. Lattes (1947) observed the pion, predicted by Yukawa, in photographic emulsions. Powell : Nobel prize in 1950.

http://ifjungo.ch/jungfraujoch/

POWER LAWS IN NATURE



	quantity	minimum $x_{\min}$	exponent α
(a)	frequency of use of words	1	2.20(1)
(b)	number of citations to papers	100	3.04(2)
(c)	number of hits on web sites	1	2.40(1)
(d)	copies of books sold in the US	2 000 000	3.51(16)
(e)	telephone calls received	10	2.22(1)
(f)	magnitude of earthquakes	3.8	3.04(4)
(g)	diameter of moon craters	0.01	3.14(5)
(h)	intensity of solar flares	200	1.83(2)
(i)	intensity of wars	3	1.80(9)
(j)	net worth of Americans	$600m	2.09(4)
(k)	frequency of family names	10 000	1.94(1)
(l)	population of US cities	40 000	2.30(5)

https://arxiv.org/pdf/cond-mat/0412004.pdf

$$p(x) = Cx^{-\alpha},$$

(M. Newman cond-mat/0412004)

Power-laws with α < 1 do not occur in nature or the normalization would diverge.

$$1 = \int_{x_{\min}}^{\infty} p(x)\,\mathrm{d}x = C\int_{x_{\min}}^{\infty} x^{-\alpha}\,\mathrm{d}x = \frac{C}{1-\alpha}\left[x^{-\alpha+1}\right]_{x_{\min}}^{\infty}.$$

$$p(x) = \frac{\alpha-1}{x_{\min}}\left(\frac{x}{x_{\min}}\right)^{-\alpha}$$

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. Below the knee:

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

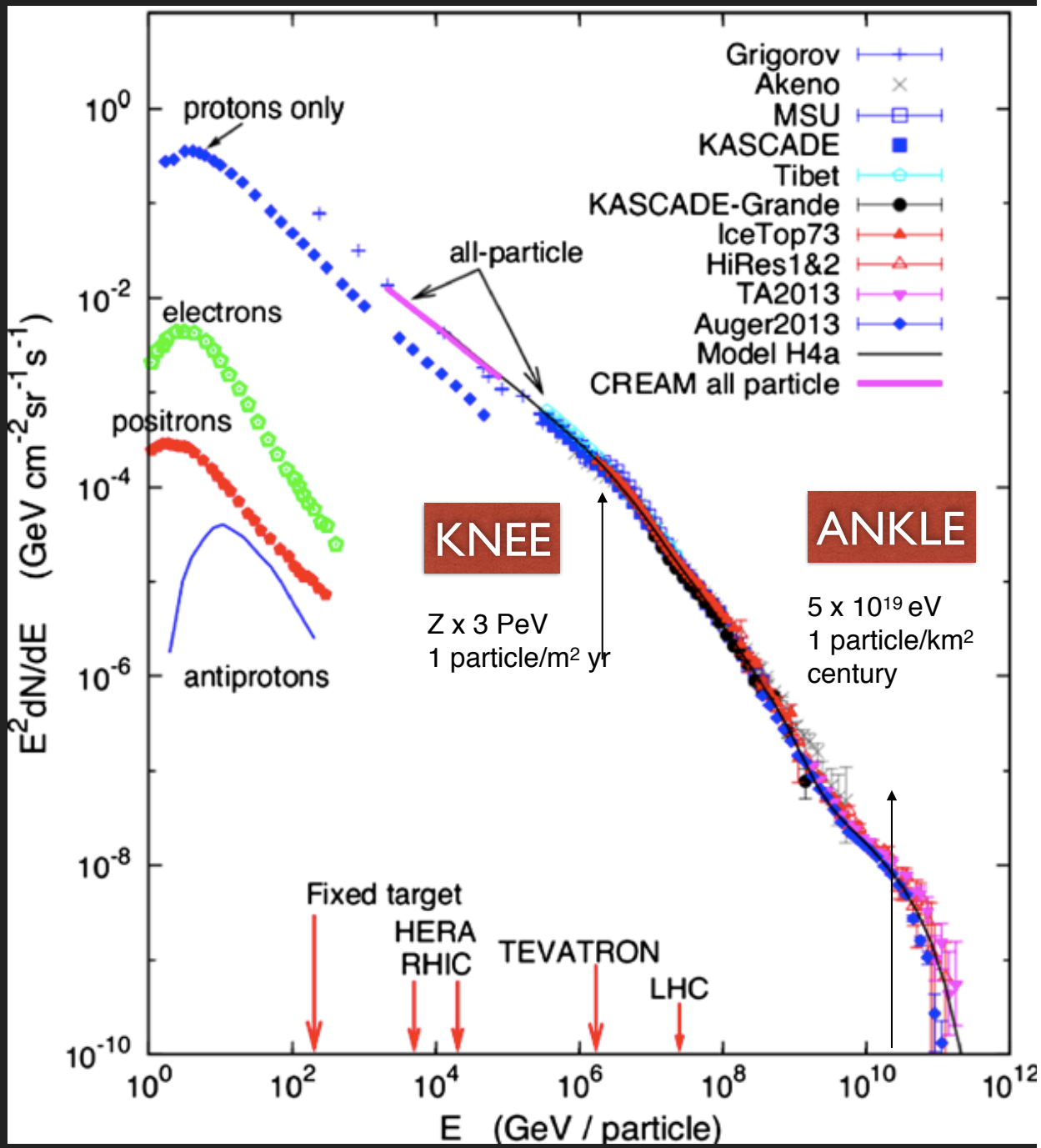
E_{knee} ~ Z x 3 PeV

E_{ankle} ~ 5 x 10^{19} eV

Notice: $$\log\left[\frac{dN}{dE}\right] = log[A] - \alpha \cdot log[E]$$

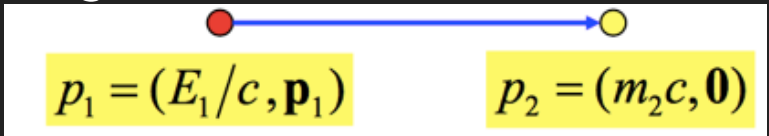
Since the spectrum is steep, we multiply by E^{β}:

$$\log\left[E^{\beta}\frac{dN}{dE}\right] = log[A] - (\alpha - \beta) \cdot log[E]$$



COSMIC RAY PHYSICS – LHC PHYSICS

- CR and fixed target nucleus 4-momentum:



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

- 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 $p^{2)}$):

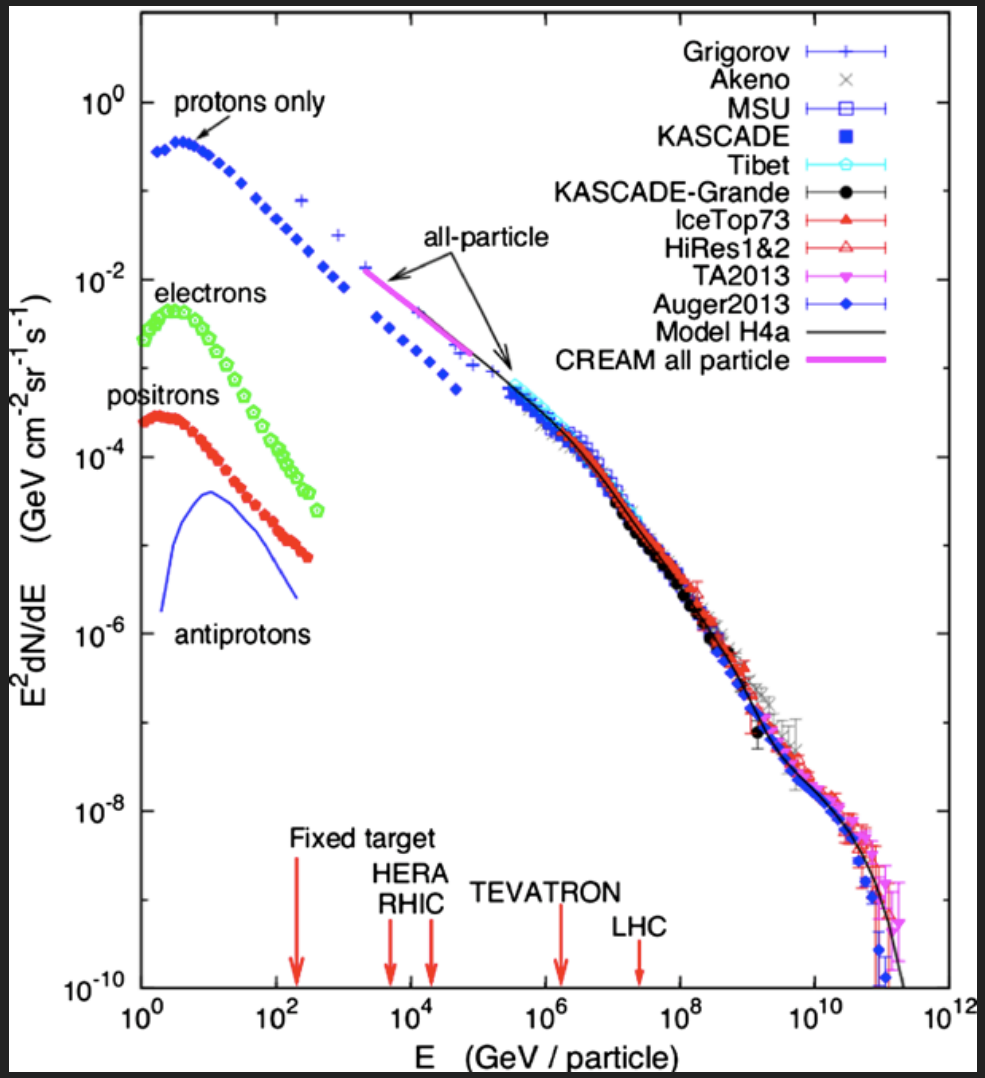
$$\mathbf{E_{CM}^2 = p^\mu p_\mu c^2 = (m_1^2 + m_2^2)c^4 + 2E_1 m_2 c^2}$$

- LHC and CR physics:

E_{CM} = 7TeV+7TeV
$E_1 = E_p >> m_2 = m_p$ ~1 GeV

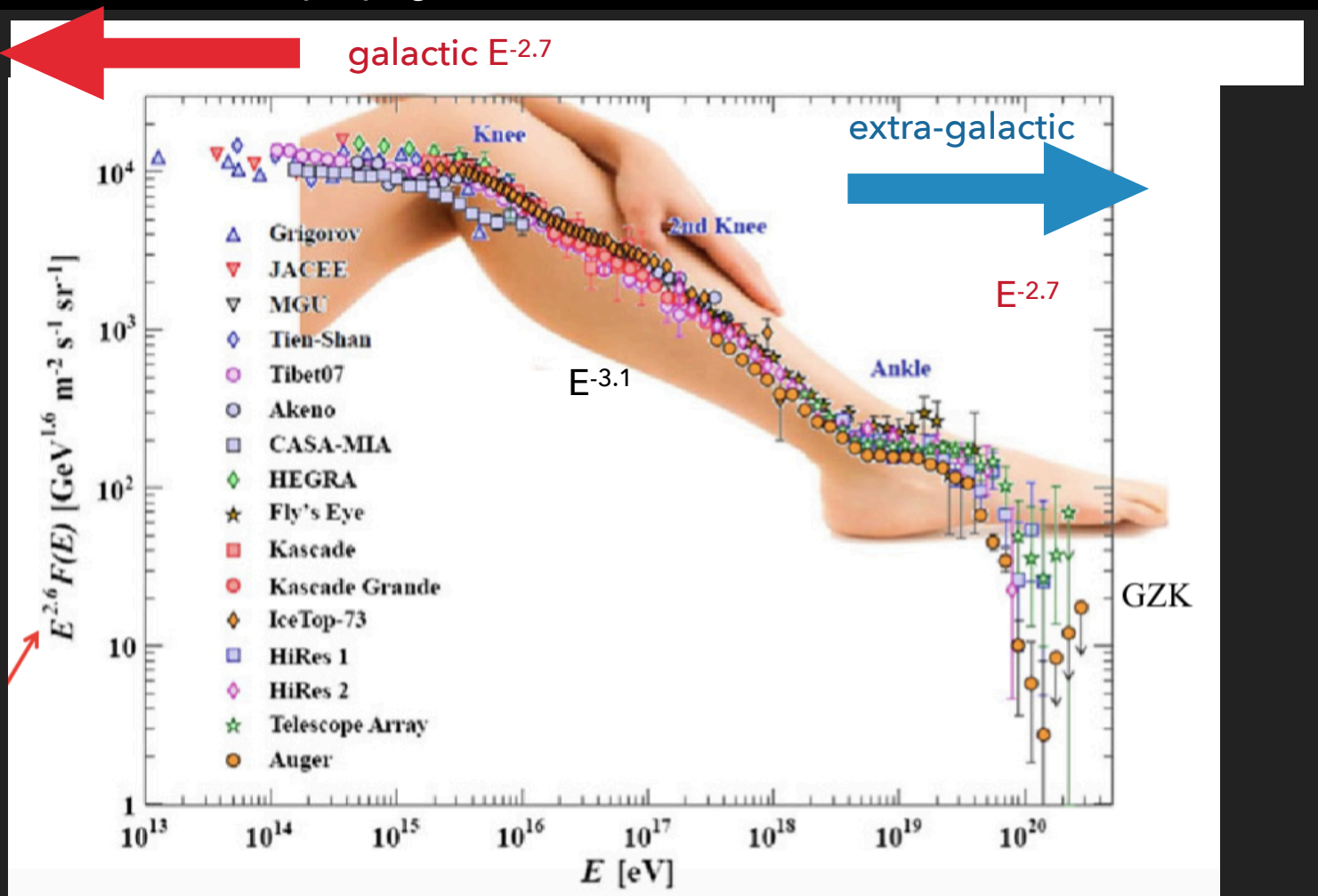
$$E_p \sim \frac{E_{CM}^2}{2m_2c^2} \sim \frac{(14\times 10^3)^2}{2} \sim 1\times 10^{17}\text{eV}$$

If you consider interactions on $<A_{Air}>$ ~14.5
0.6 x 10^{16} eV



THE SPECTRAL FEATURES

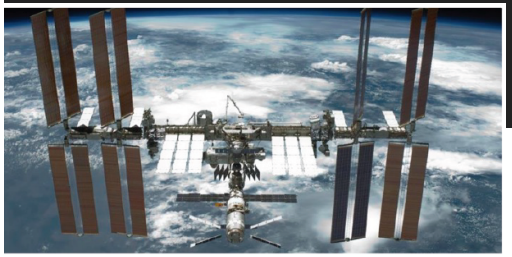
- The power law is explainable through acceleration processes in magnetic fields (Fermi acceleration). The diffuse shock acceleration predicts spectra of about E^{-2}
- The maximum energy at which a charged particle of charge Z can be accelerated in a shock wave is proportional to Z: Emax ~Z x 100 TeV
- The general consensus that acceleration is due to shock waves in supernova remnants (SNR) with diffusive propagation in the Galactic magnetic field. The changes of slope are connected to changes of sources and/or propagation features



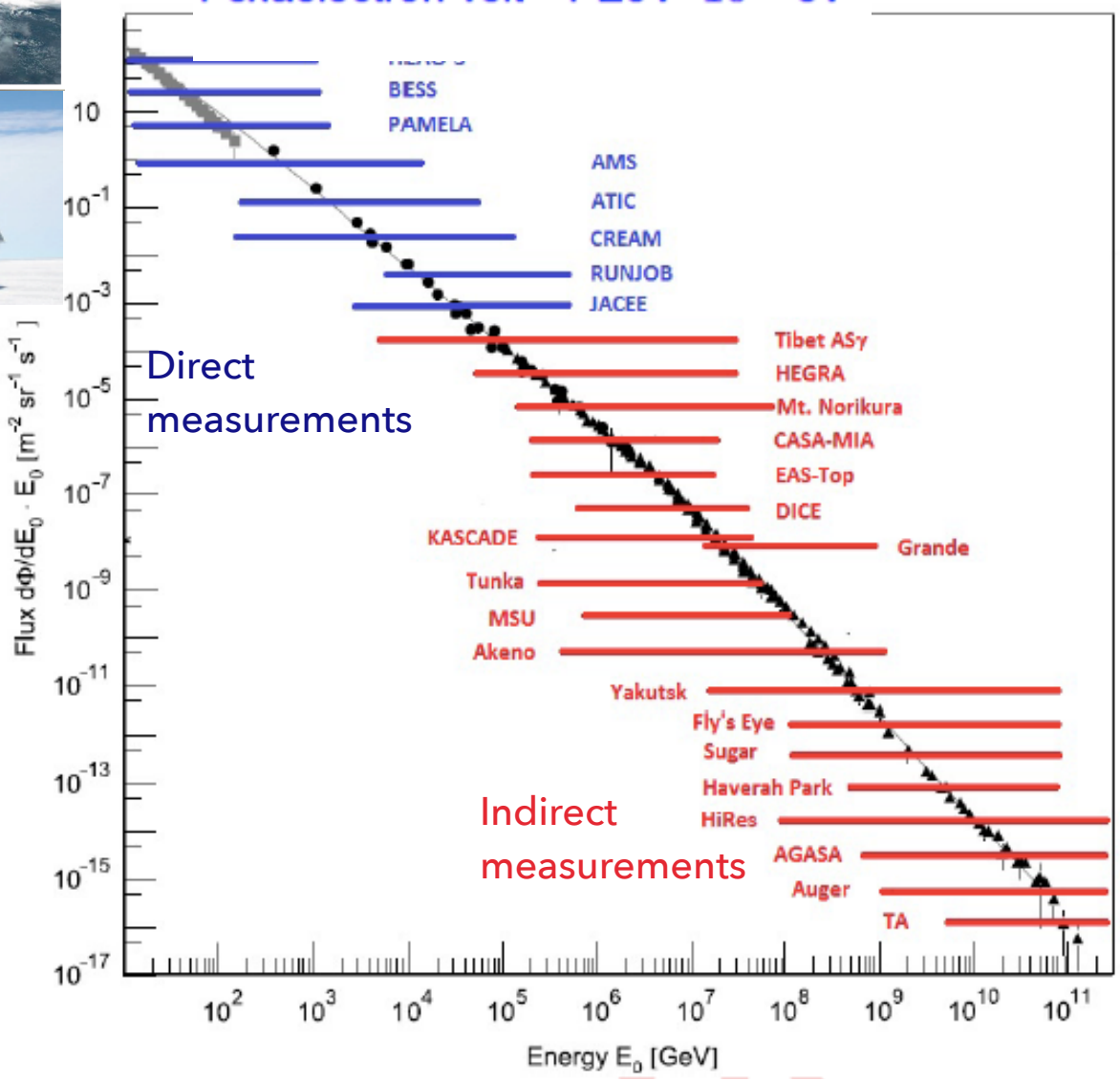
The end of the spectrum:

GZK cut-ff

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



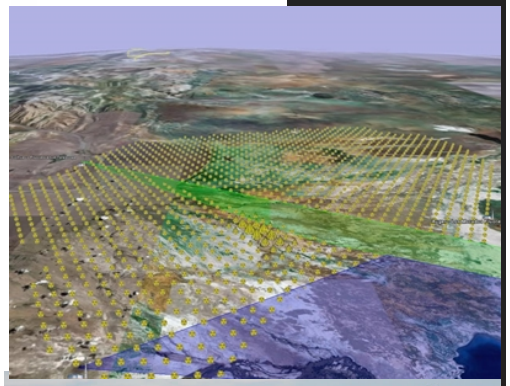
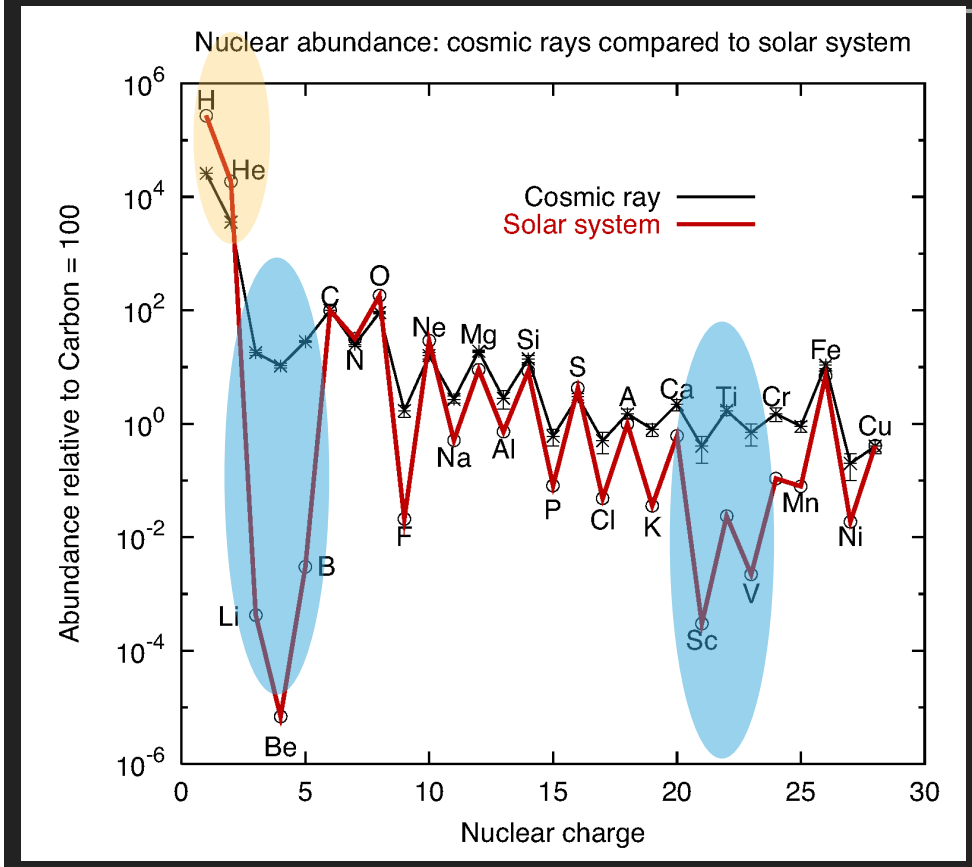
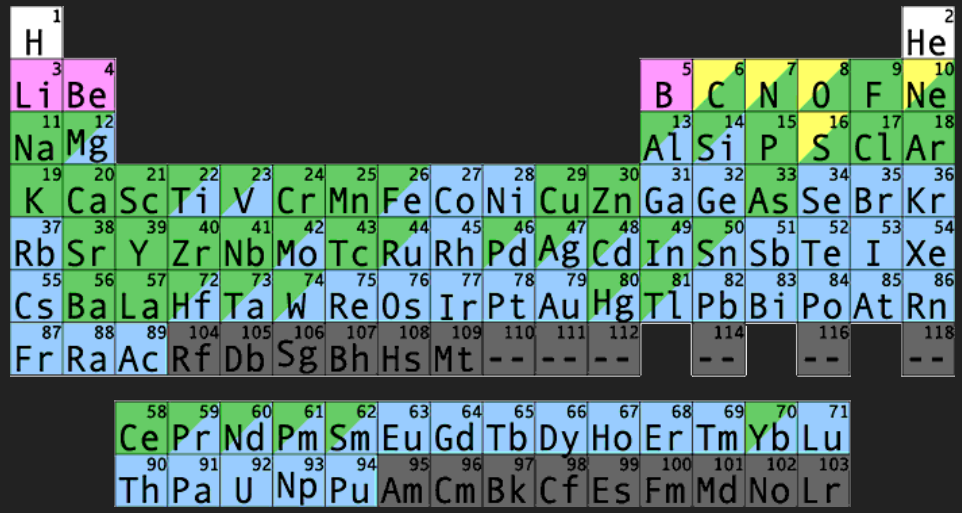


Figure from M. Spurio's book, Particles & Astrophysics

COSMIC RAY COMPOSITION BELOW THE KNEE

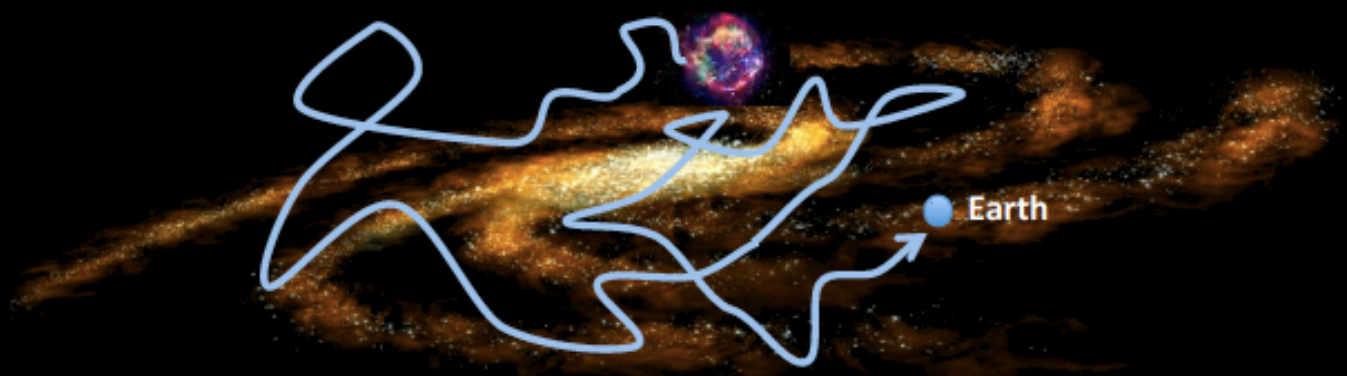




White - Big Bang
Pink - Cosmic Rays
Yellow - Small Stars
Green - Large Stars
Blue - Supernovae

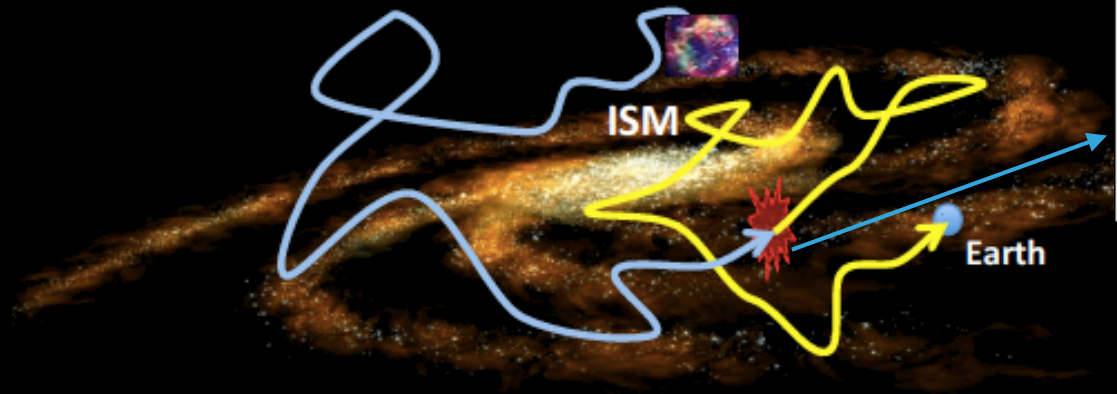
- All stable elements of the periodic table are found in galactic CRs
- The CRs composition is similar to the elements in the Sun indicating that they have stellar origin
- H, He directly accelerated in stars. Li, Be, B are secondary nuclei produced in the spallation of heavier elements (C and O). Also 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

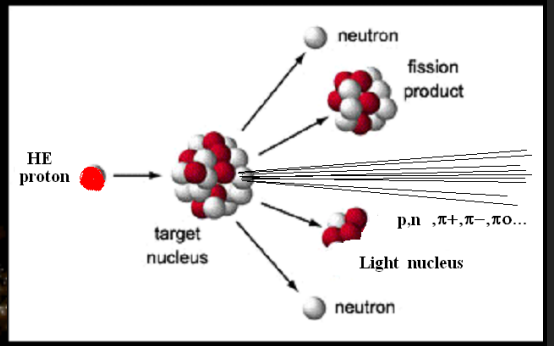
PRIMARY AND SECONDARY COSMIC RAYS



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

C, O, …, Fe + ISM → Li, Be, B + X

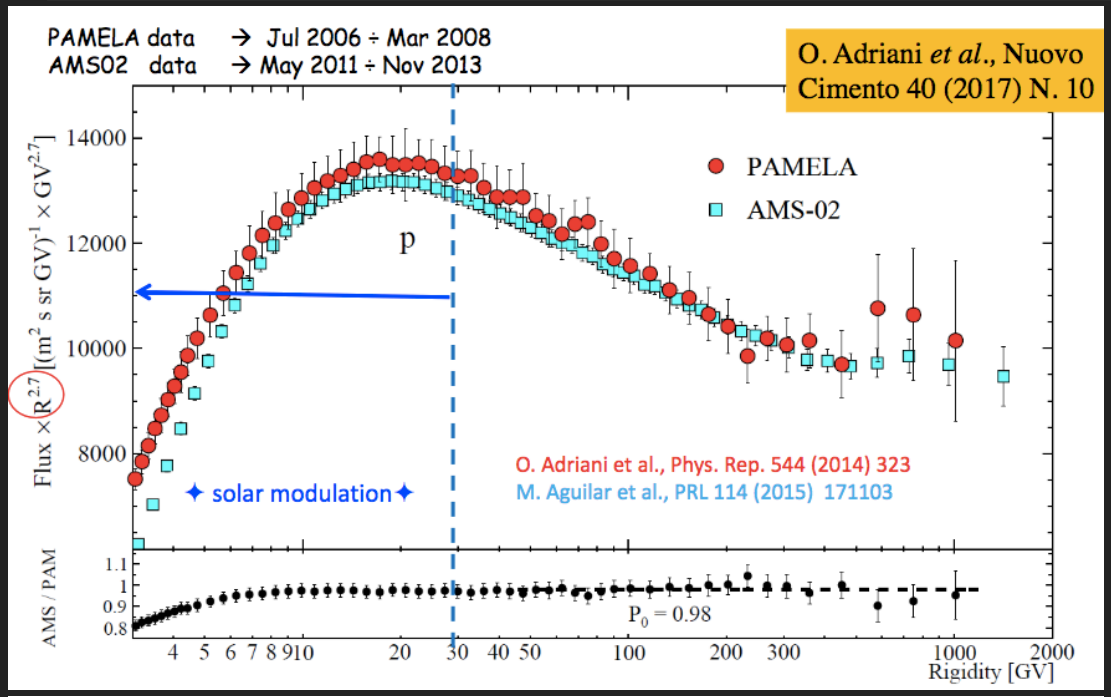


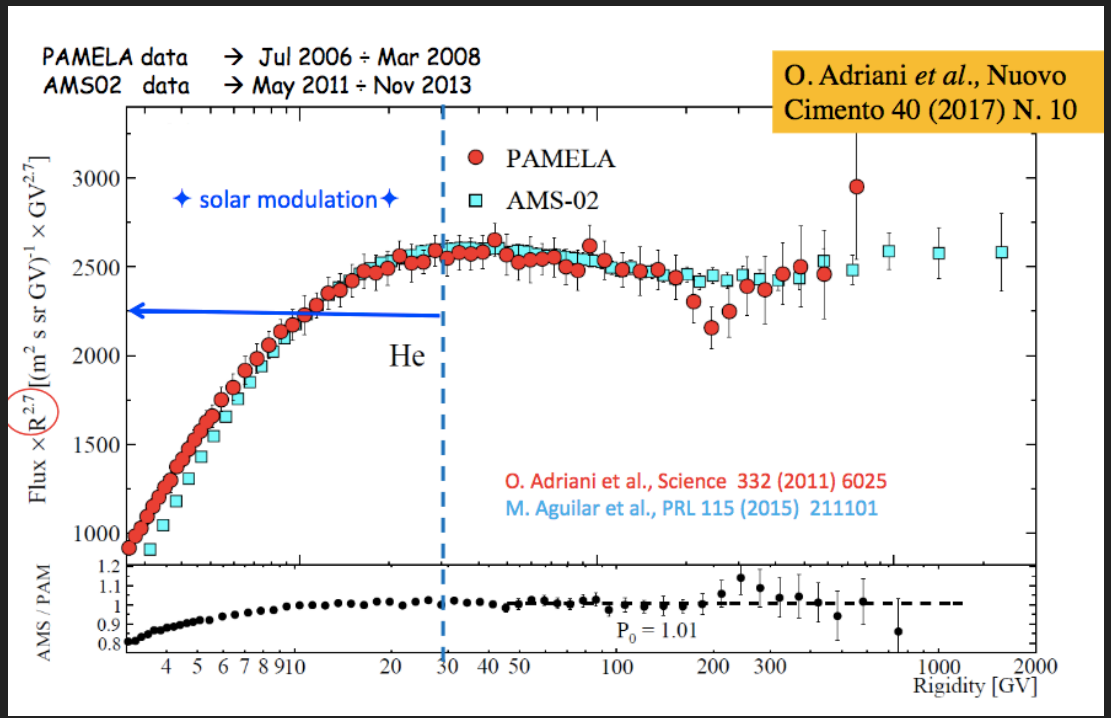


Spallation interaction

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

CURRENT BEST KNOWLEDGE OF COSMIC RAYS BELOW THE KNEE (GALACTIC)

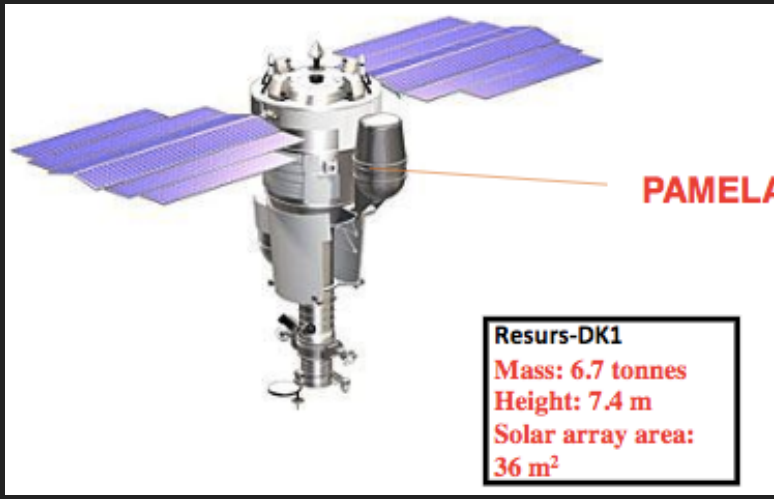




An unexpected kink at ~200 GV/n first detected by Pamela (Science 2011) and confirmed by AMS-02 in the proton and heavier nuclei spectra.

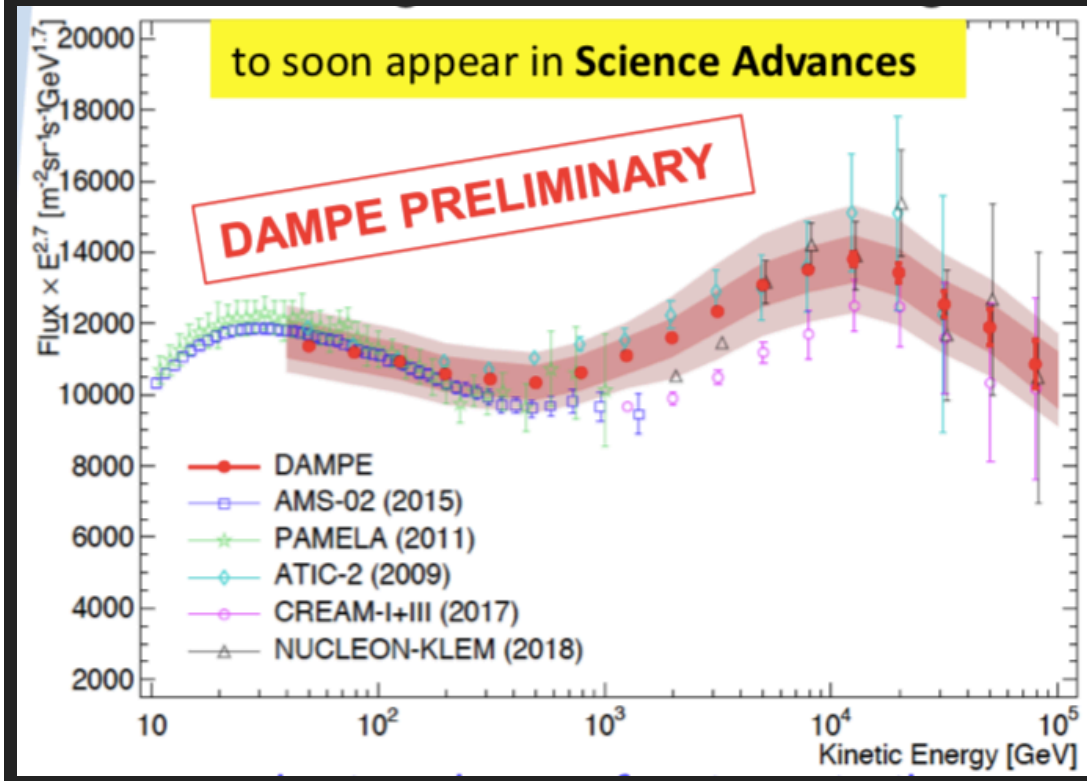
Could hint to young efficient accelerators or propagation effects (arXiv: 1704.05696).

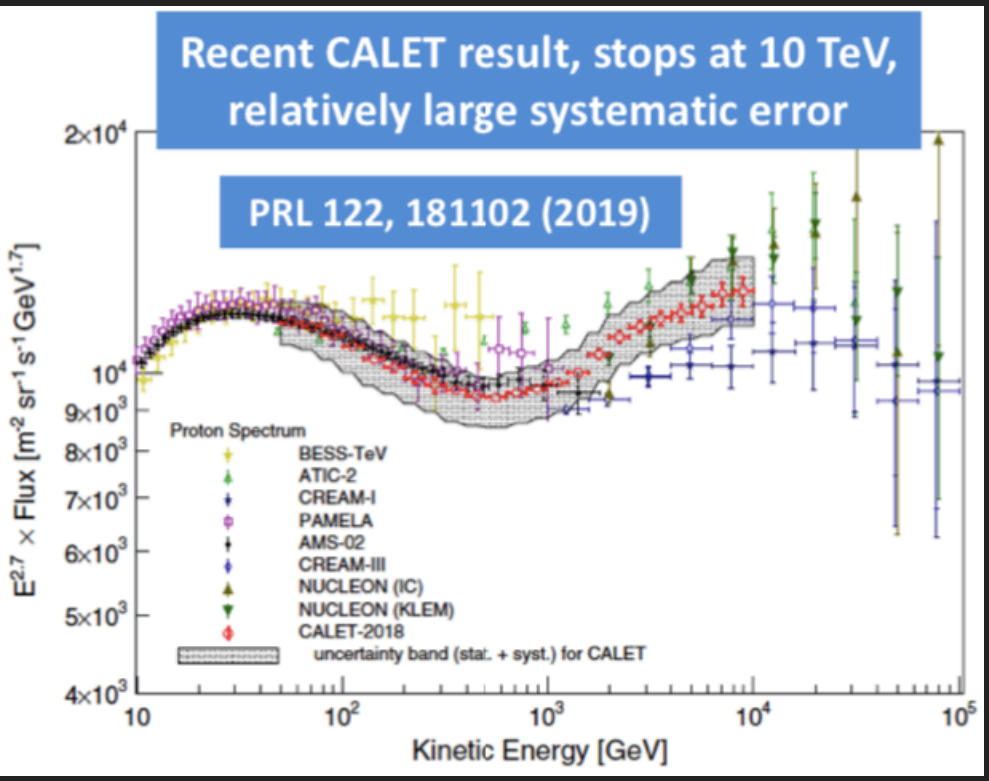
H and He have not parallel spectra. The knee region could be dominated by He not H.



PRELIMINARY PROTON RESULTS FROM DAMPE AND CALET

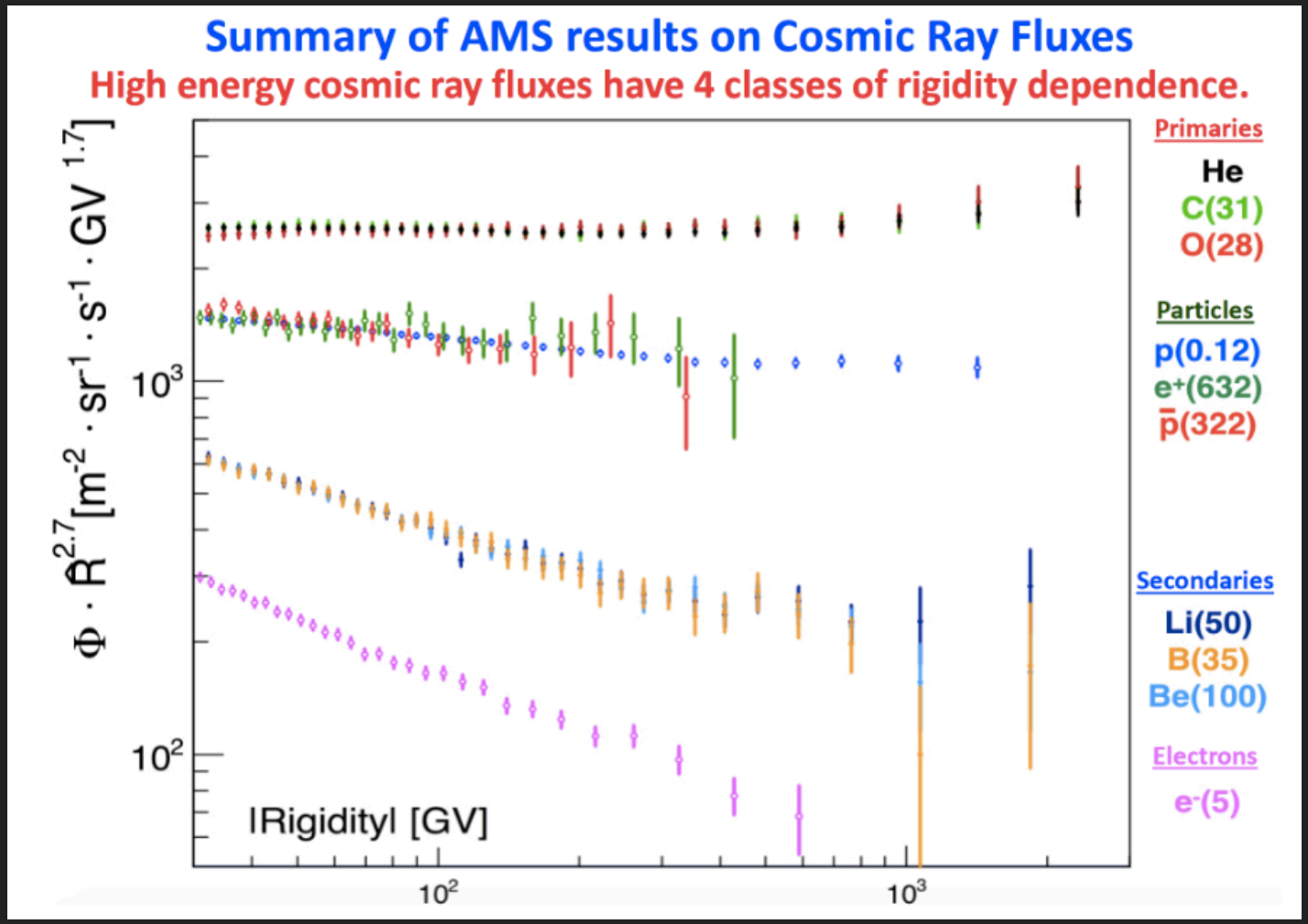
Launched in 2015





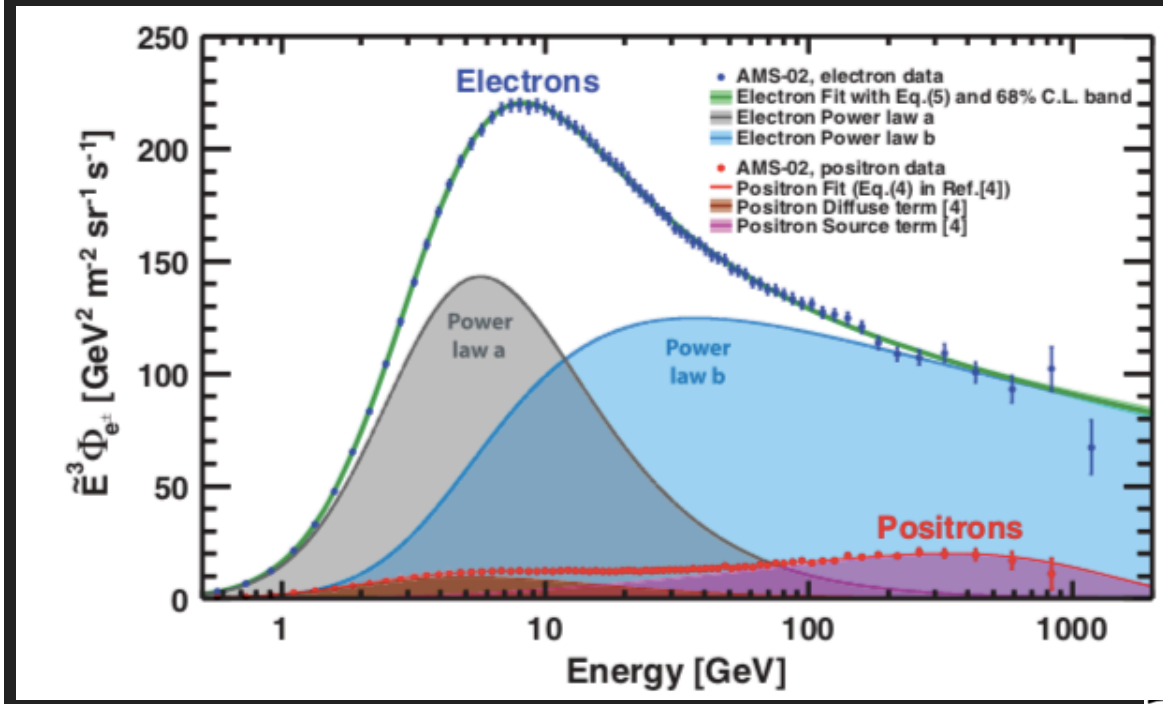
PROTONS AND ELECTRONS AND THEIR ANTIPARTICLES

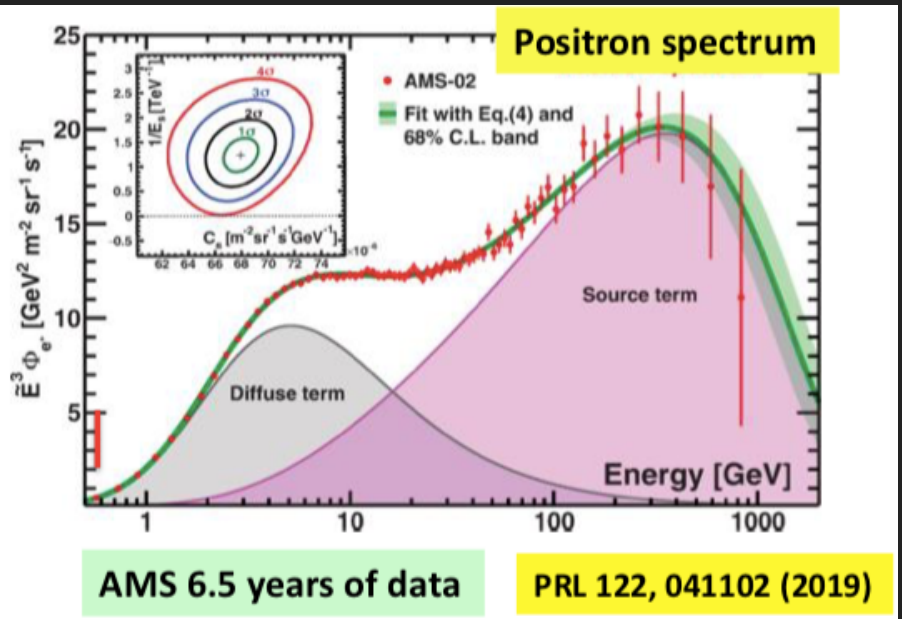
Unexpected result: the energy (rigidity) dependence of positrons (e^+, protons and anti-protons are similar) but electrons (e^-) are have a very different dependence. Is this a hint of Dark Matter?



PRL 122, 101101 (2019)

DARK MATTER HINTS IN ANTI-ELECTRONS/ELECTRON RATIO





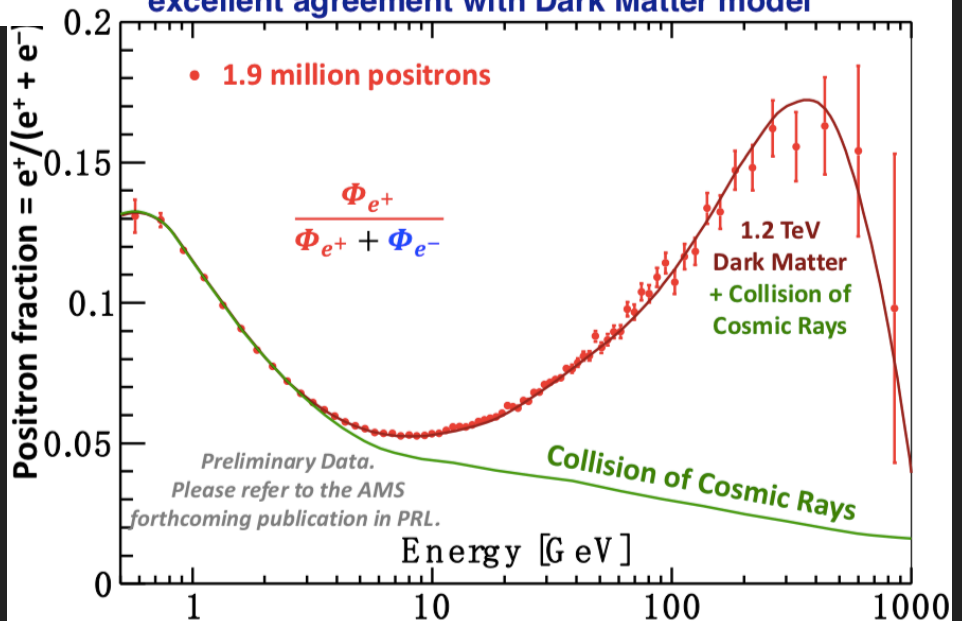
AMS 6.5 years of data

PRL 122, 041102 (2019)

High precision data will allow to discriminate the local source accelerator scenario from dark matter scenarios, but DM models are severely constrained. In 6.5 yr AMS published abut 2M of positrons and 28 M of electrons

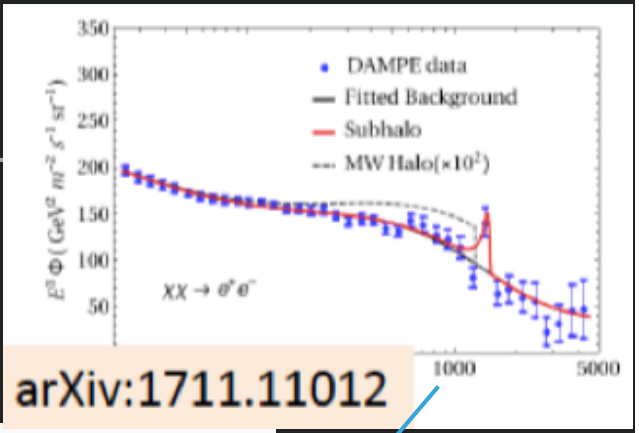
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.122.101101

Latest AMS Positron fraction results appears to be in excellent agreement with Dark Matter model

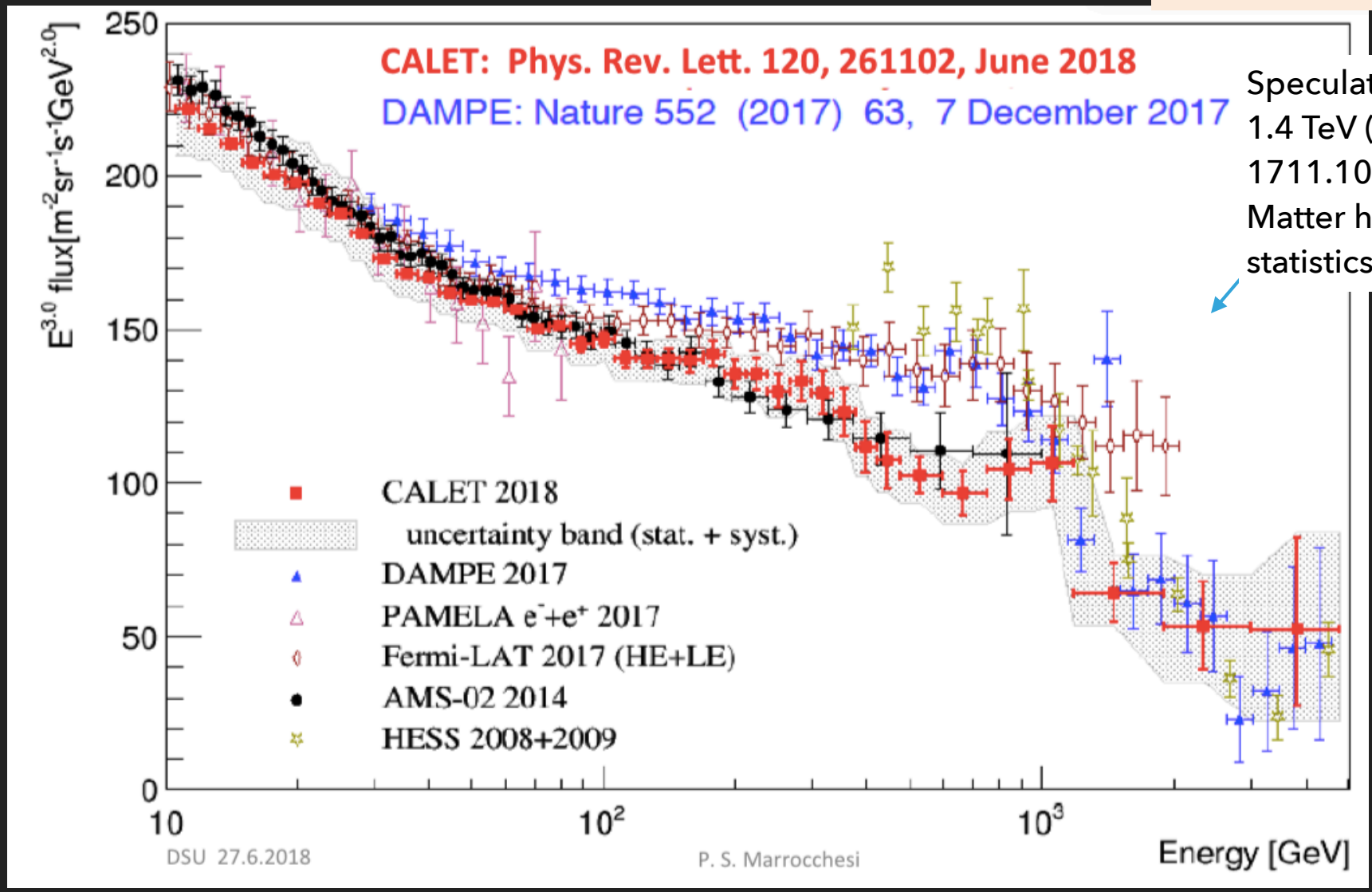


THE ELECTRON SPECTRUM

Energy scale still under study for DAMPE and CALET

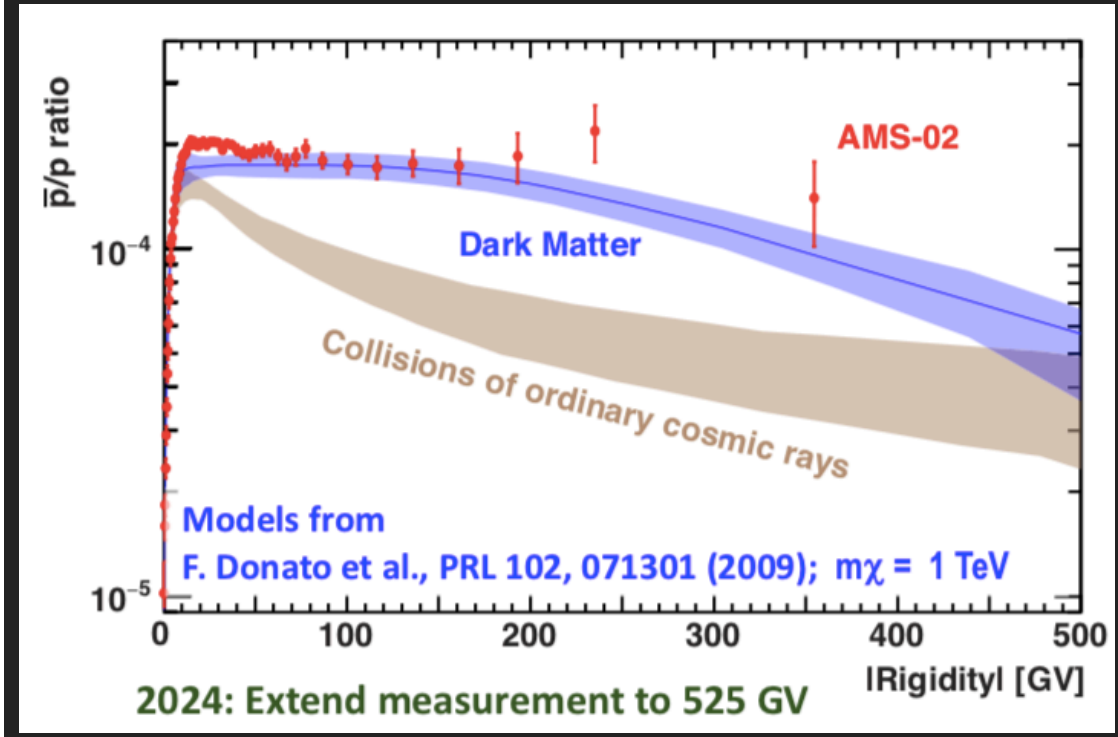


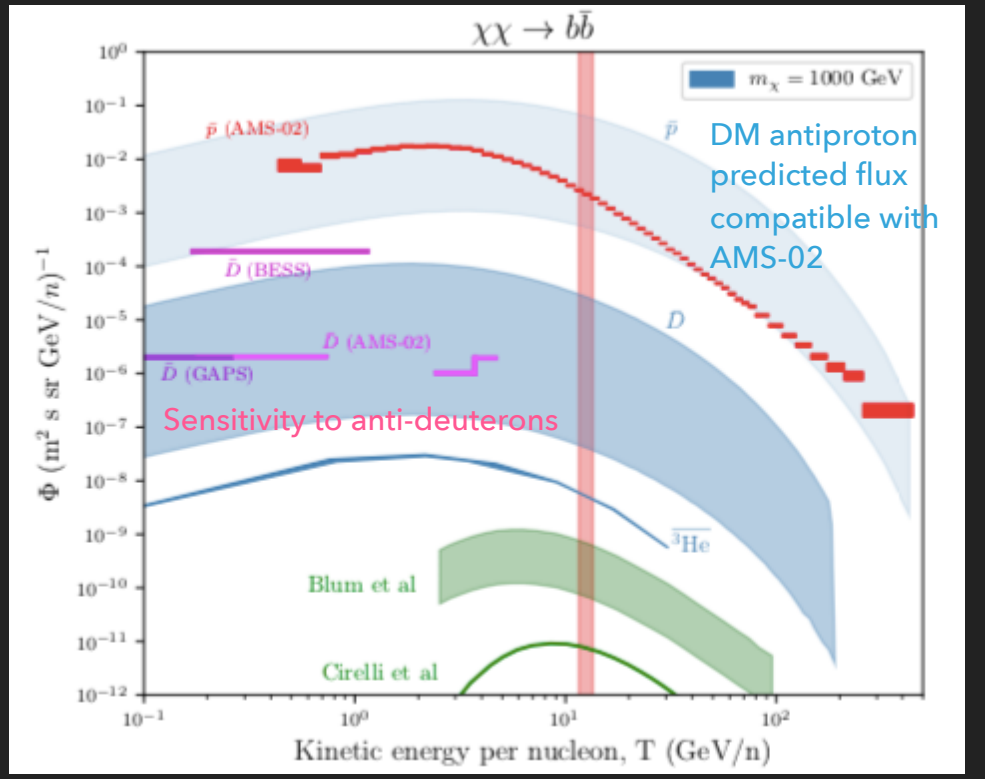
arXiv:1711.11012



Speculations on peak at 1.4 TeV (arXiv1711.11579, 1711.10995,...) as Dark Matter hint need better statistics

DARK MATTER HINTS IN COSMIC RAYS? ANTI-PROTONS





Coogan & Profumo: arxiv:1705.09664

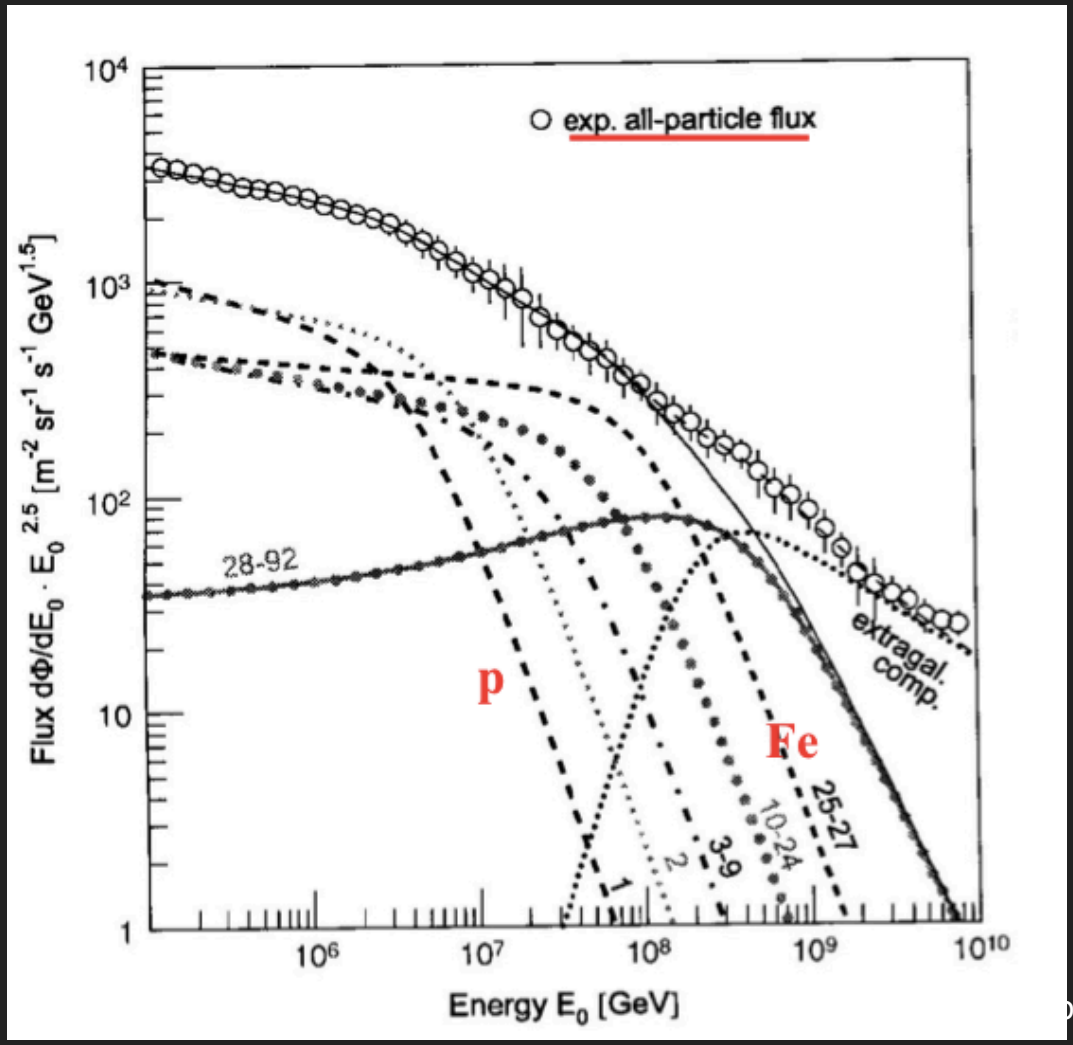
The pbar/p ratio not conclusive.

Better prediction for secondary production and discrimination of anti-heavier element flux is needed.

Great expectations for anti-nuclei given to lower secondary backgrounds.

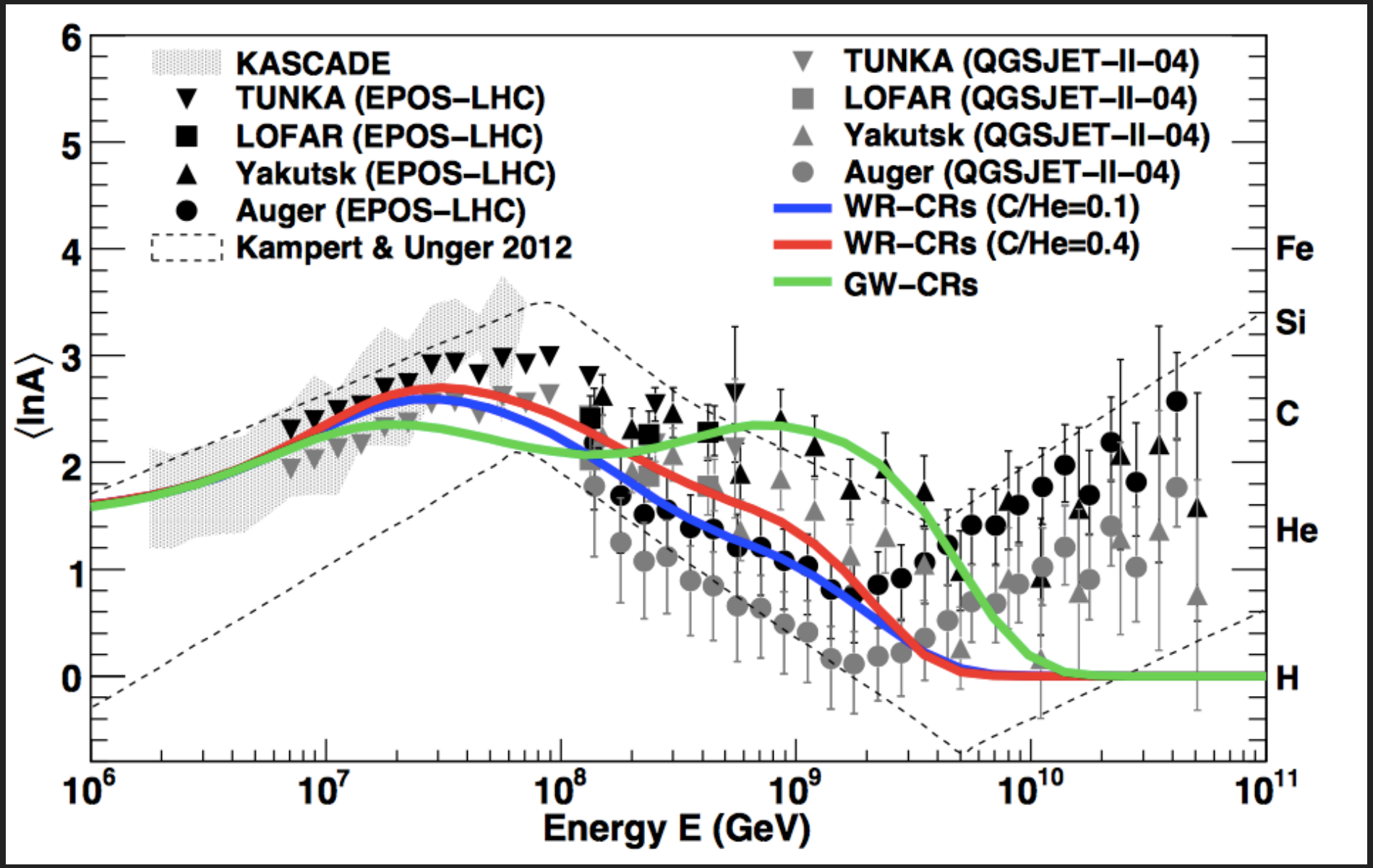
THE KNEE

- 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 and to the E_{max} in a shock 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}, …At some point there is the onset of an extragalactic component.



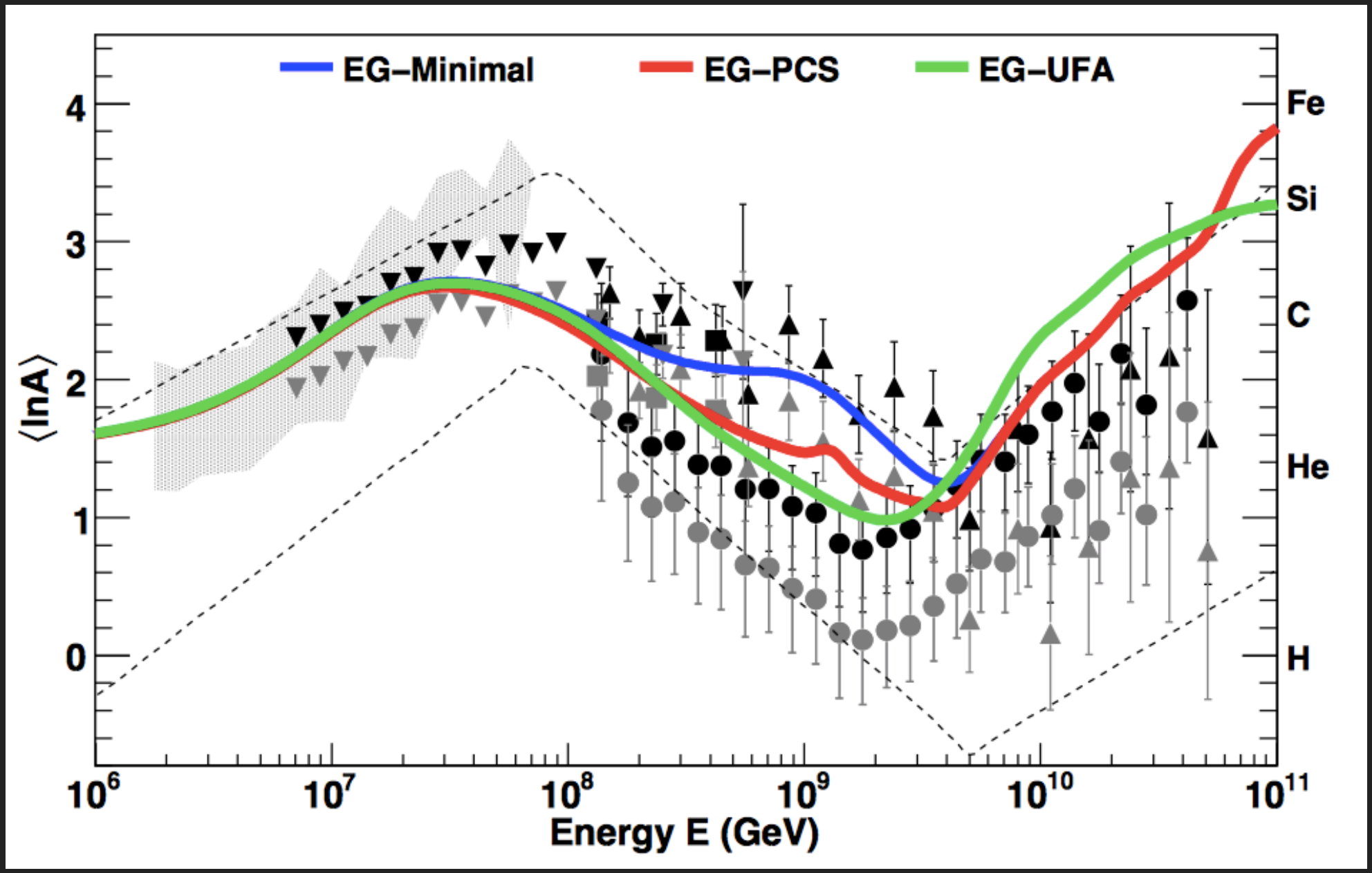
https://arxiv.org/pdf/1303.3565v1.pdf

COMPOSITION OF COSMIC RAYS WITH GALACTIC CR MODELS

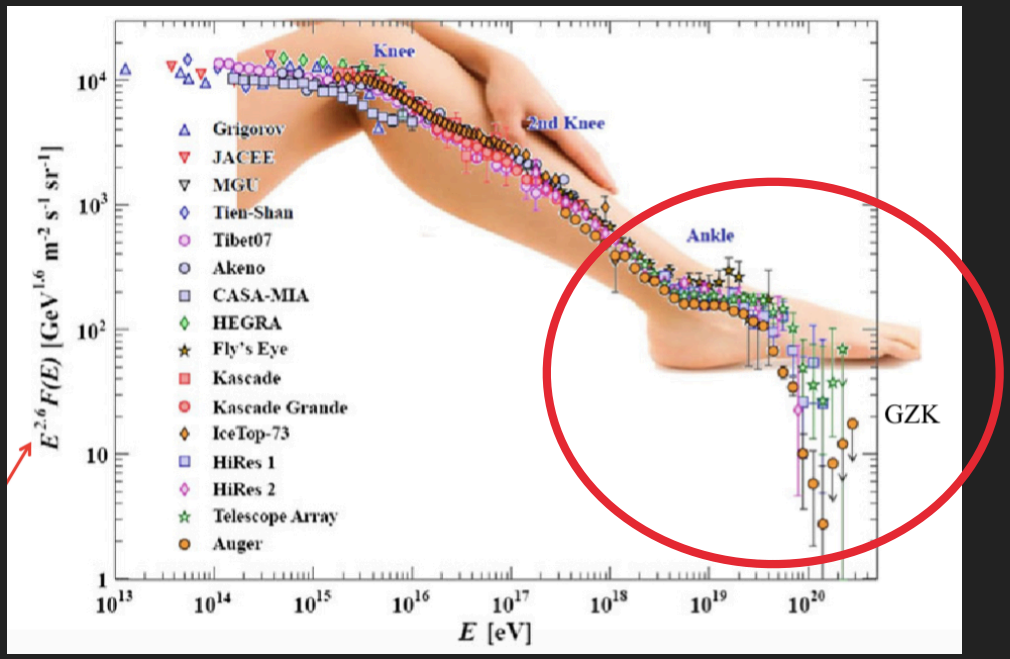


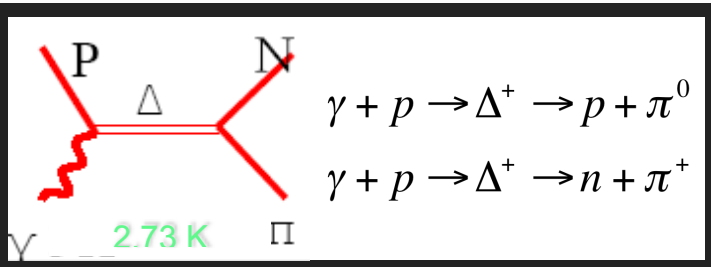
https://arxiv.org/pdf/1605.03111.pdf

. . . AND INCLUDING EXTRA-GALACTIC COMPONENTS



CURRENT STATUS OF UHECR SPECTRUM: THE ANKLE



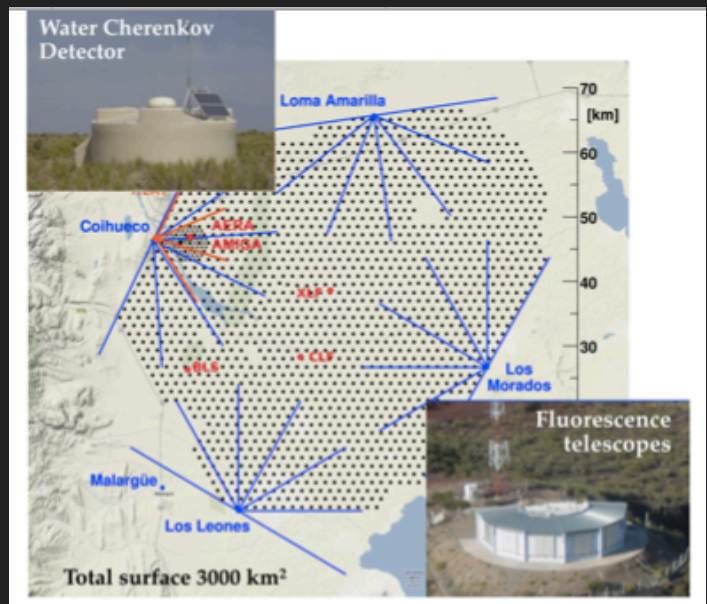


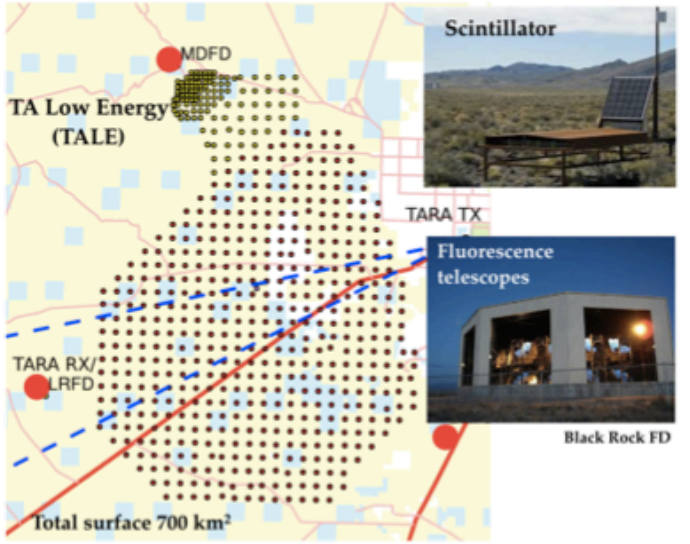
$$\gamma + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

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

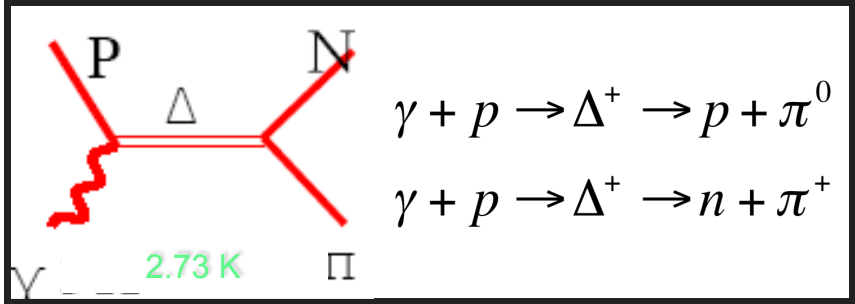
The end of the spectrum of CRs could be due to GZK cutoff and/or effect of sources exhausting their energy. The GZK cut-off is due to proton interactions. The threshold for production of delta resonance is around 5 x 10^{19} eV.

Shower sampling and fluorescence techniques in Pierre Auger (3000 km2!) and Telescope Array





THE ANKLE REGION: THE GZK CUT-OFF

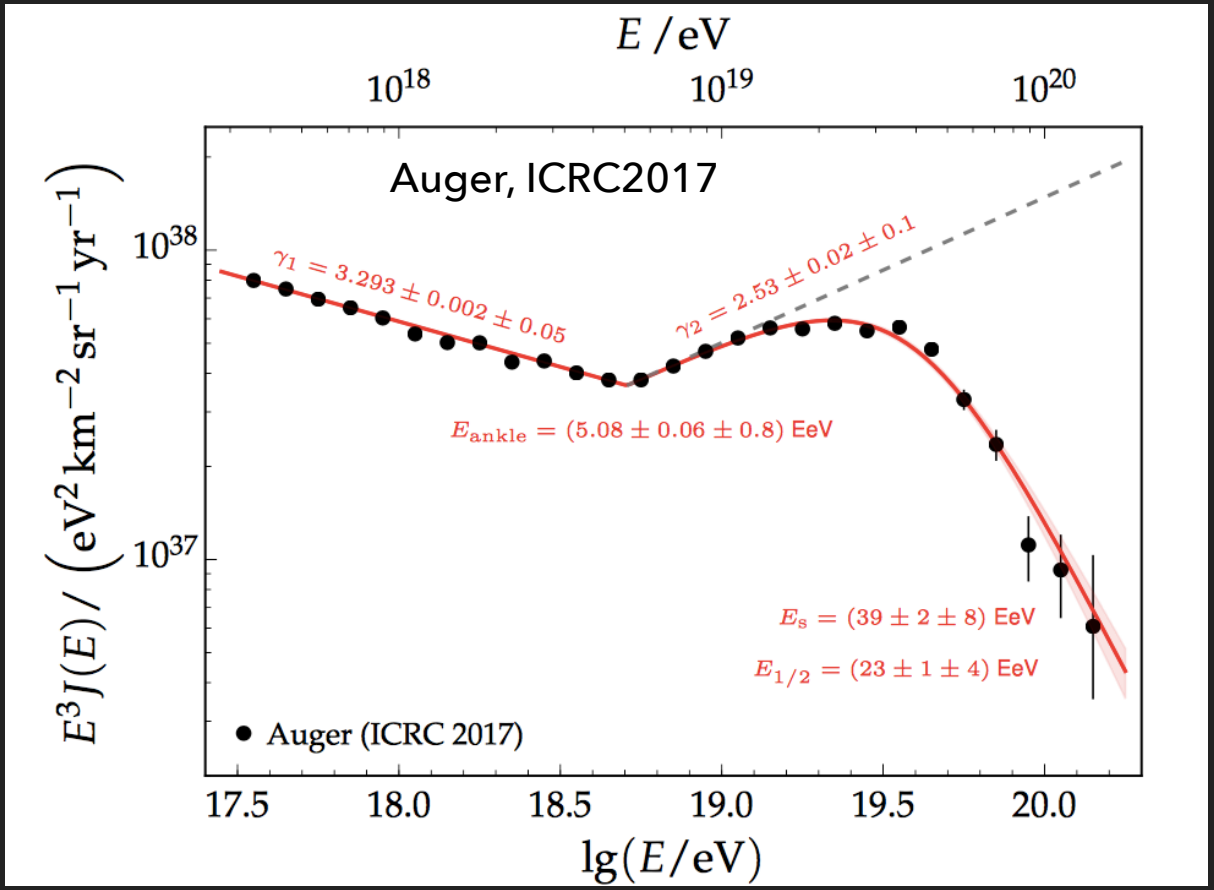


$$\gamma + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

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

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.

MAGNETIC FIELD DEFLECTIONS OF UHECRS

If UHECR are not protons then astronomy with them will be not easy due to larger magnetic deflections.

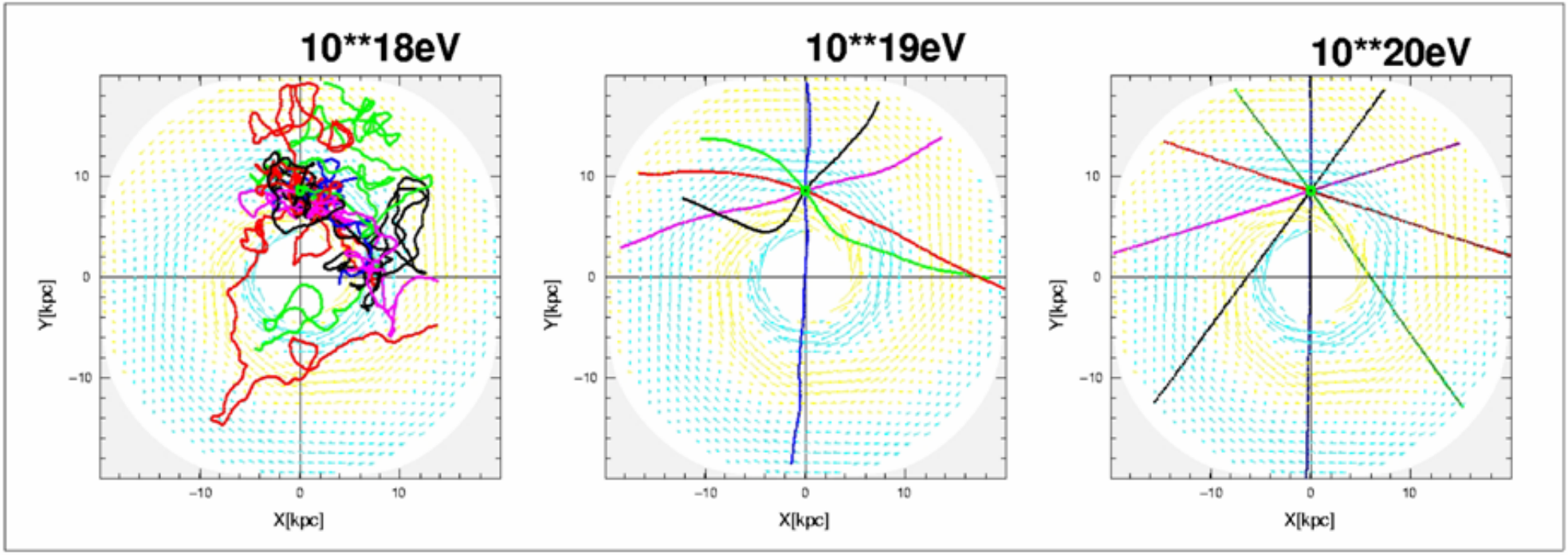
$$qvB = \frac{mv^2}{r_L} \rightarrow r_L = \frac{p}{ZeB}$$

$$R \equiv r_L Bc = \frac{pc}{Ze}$$

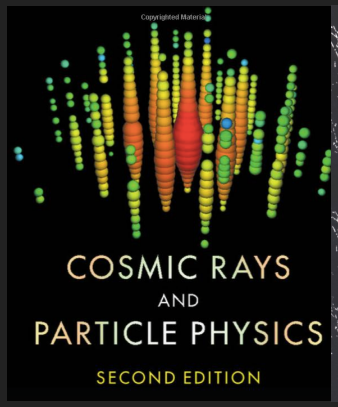
$$(10^{12}\,eV) = 10^{15}\,cm = 3\times10^{-4}\,pc$$

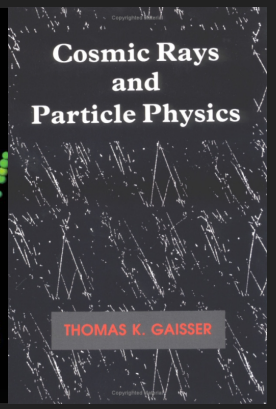
$$r = (10^{15}\,eV) = 10^{18}\,cm = 3\times10^{-1}\,pc$$

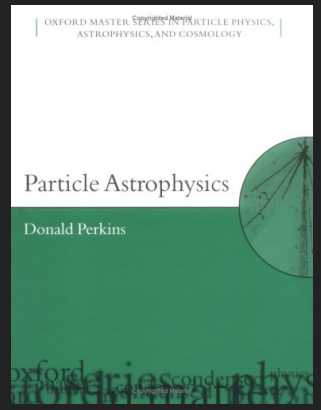
$$(10^{18}\,eV) \quad = 10^{21}\,cm = 300\,pc$$

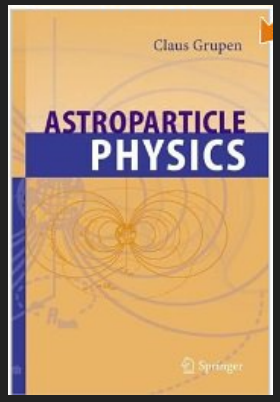


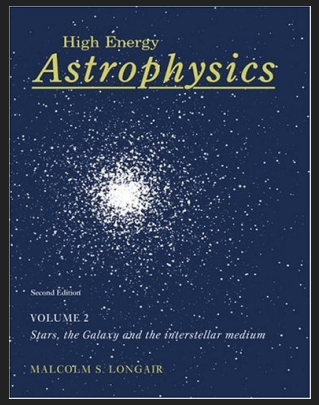
SOME REFERENCE TEXTBOOK

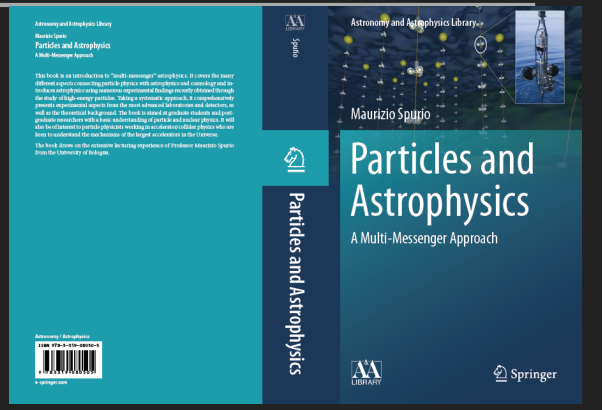




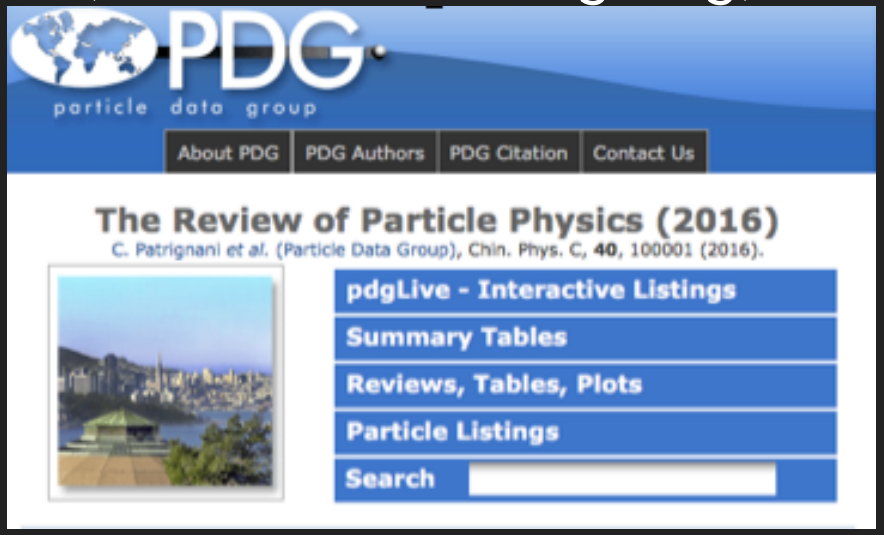








- T.K. Gaisser et al. Cosmic Rays and Particle Physics (also online cambridge.org)
- D. Perkins, Particle Astrophysics
- C. Grupen, Astroparticle Physics
- M.S. Longair, High Energy Astrophysics
- Rosswog & Brüggen, High Energy Astrophysics
- M. Spurio, Particle Astrophysics



- Data Particle Book: http://pdg.lbl.gov
- L. Bergstrom & A. Goobar, Cosmology and Particle Astrophysics
- De Angelis & M. Pimenta, Introduction to Particle and Astroparticle Physics

ONLINE MATERIAL

https://inspirehep.net

- **Cosmic Rays:**

  http://web.mit.edu/redingtn/www/netadv/Xcosmicray.html; Amato et al, Cosmic Ray Transport Review https://arxiv.org/pdf/1704.05696.pdf; 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; Ahlers and Halzen, https://inspirehep.net/record/1675301, https://www.worldscientific.com/doi/abs/10.1142/9789813226098_0009,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