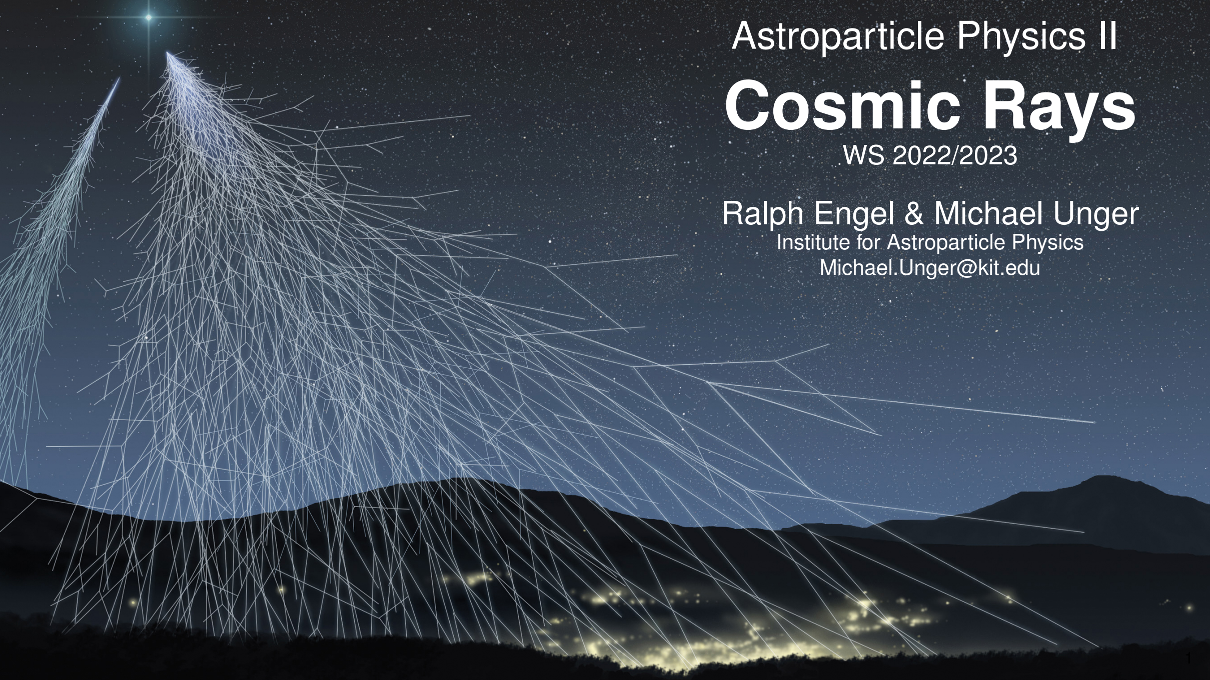

Astroparticle Physics II

Cosmic Rays

WS 2022/2023

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Institute for Astroparticle Physics
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General Remarks

- **lecture:** weekly, Tuesday 15:45 - 17:15 (HS 4)
- **tutorials:** five dates, Thursday 9:45 - 11:15 (Room 10/1)
- **ILIAS:** please register https://ilias.studium.kit.edu/goto.php?target=crs_1908844
- **office hours:** Monday, 10:30-11:30 (send me an email by Friday), zoom or CN 425/127
- **recommended background:** basic special relativity and particle physics

  Moderne Exp.phys. III (Physik VI, Teilchen und Hadronen)
- **related courses** (but not required as prerequisite for this course)
  - Astroteilchenphysik I: Dunkle Materie (winter)
  - Astroteilchenphysik II: Teilchen und Sterne (summer)
  - Astroteilchenphysik II: Kosmische Strahlung (winter)
  - Detektoren für Teilchen- und Astroteilchenphysik (winter)
  - Hauptseminar Astroteilchenphysik (winter & summer)

Credit Points

- 5 dates, 5 problem sets
  - return your solution via ILIAS
  - discuss solutions with Thomas
- 6 CPs for 50%
- 8 CPs for 75% (or 50% + essay or project)

Thomas Fitoussi

(thomas.fitoussi@kit.edu)

Dates of Lectures (L) and Exercises (E)

October

Su	Mo	Tu	We	Th	Fr	Sa
23	24	L	26	27	28	29
30	31					

November

Su	Mo	Tu	We	Th	Fr	Sa
		1	2	3	4	5
6	7	L	9	10	11	12
13	14	L	16	17	18	19
20	21	L	23	E	25	26
27	28	L	30			

December

Su	Mo	Tu	We	Th	Fr	Sa
				1	2	3
4	5	6	7	E	9	10
11	12	L	14	L	16	17
18	19	L	21	22	23	24
25	26	27	28	29	30	31

January

Su	Mo	Tu	We	Th	Fr	Sa
1	2	3	4	5	6	7
8	9	L	11	E	13	14
15	16	L	18	19	20	21
22	23	L	25	E	27	28
29	30	L				

February

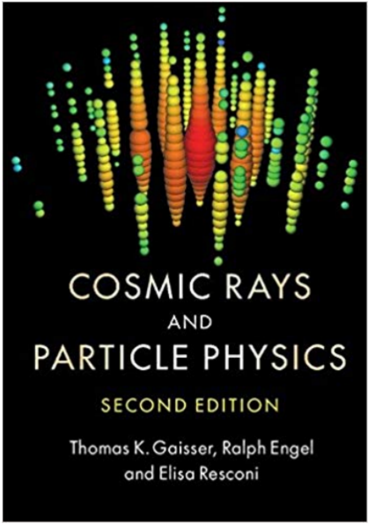
Su	Mo	Tu	We	Th	Fr	Sa
			1	2	3	4
5	6	L	8	E	10	11
12	13	L	15	16	17	18

L: Tuesday 15:45 - 17:15 (HS 4)

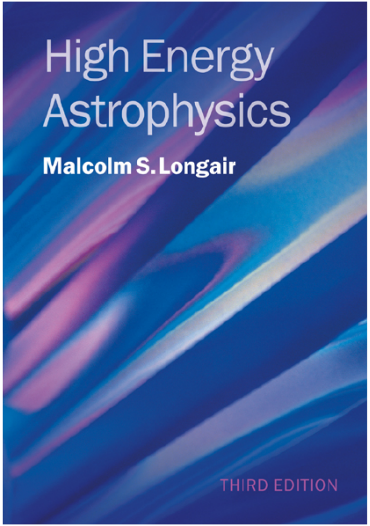
E: Thursday 9:45 - 11:15 (Room 10/1)

Text Books

main reference:



useful for ATPII CRs *and* ATPII γ/ν:



Preliminary Schedule

1	Nov 8	**Introduction**	units, history, composition, energy spectra, energy density
2	Nov 15	**Cosmic Rays in the Galaxy I**	Galaxy, direct detection, particle diffusion, nuclear fragmentation
3	Nov 22	**Cosmic Rays in the Galaxy II**	leaky box model, diffusion-advection equation, anti-particles
4	Nov 29	**Extragalactic Propagation**	photo-pion production, photo-nuclear interactions, magnetic fields
5	Dec 13	**Acceleration I**	first order Fermi acceleration, astrophysical shocks
6	Dec 20	**Acceleration II**	second order Fermi acceleration, diffuse shock acceleration, non-linearities
7	Jan 10	**Particles in the Atmosphere**	atmosphere, interactions, Z-factors, cascade equations, inclusive fluxes
8	Jan 17	**Extensive Air Showers I**	electromagnetic cascades, Heitler model
9	Jan 24	**Extensive Air Showers II**	hadronic air showers, Heitler-Matthews model, superposition model
10	Jan 31	**Air Shower Detection**	particle, fluorescence, Cherenkov and radio detectors
11	Feb 7	**Sources of Cosmic Rays I**	flux features, Peters cycle, anisotropy
12	Feb 14	**Sources of Cosmic Rays II**	Hillas criterion, Blanford criterion, SHDM, LIV

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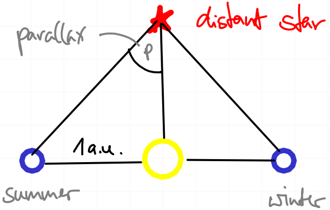
Some frequently-used non-SI units

Length:

- astronomical unit: $1\,\mathrm{AU} \approx 1.5 \cdot 10^{11}\,\mathrm{m}$
- light year: $1\,\mathrm{ly} = 9.46 \cdot 10^{15}\,\mathrm{m}$
- parsec: $1\,\mathrm{pc} = 3.26\,\mathrm{ly}$
- redshift: $z = \frac{\lambda_{obs} - \lambda_{emitted}}{\lambda_{emitted}}$

z	distance
0.01	≙ 40 Mpc
0.1	≙ 415 Mpc
1	≙ 4750 Mpc



$p = 1\,\mathrm{arcsec}$ $(1'' = 1^\circ/3600)$

$\Leftrightarrow d = 1\,\mathrm{pc}$

Mass:

- solar mass: $M_\odot = 1.99 \cdot 10^{30}\,\mathrm{kg}$
- $1\,\mathrm{GeV}/c^2 = 1.78 \cdot 10^{-27}\,\mathrm{kg}$

Energy:

- $1\,\mathrm{erg} = 10^{-7}\,\mathrm{J}$
- $1\,\mathrm{GeV} = 1.61 \cdot 10^{-10}\,\mathrm{J}$

X-rays: 100 eV – 100 keV

γ-rays: > 100 keV

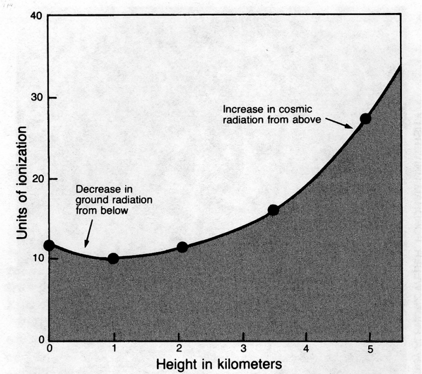
$\mathrm{TeV} = 10^{12}\,\mathrm{eV}$

$\mathrm{PeV} = 10^{15}\,\mathrm{eV}$

$\mathrm{EeV} = 10^{18}\,\mathrm{eV}$

Discovery of Cosmic Rays

Victor Hess baloon flights 1912 (Nobel prize 1936)

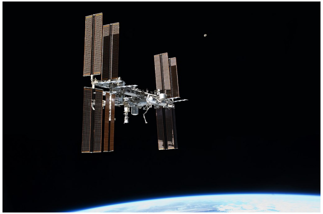


Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above". These cosmic rays contain the only modern samples of matter from outside our solar system which can be investigated directly.

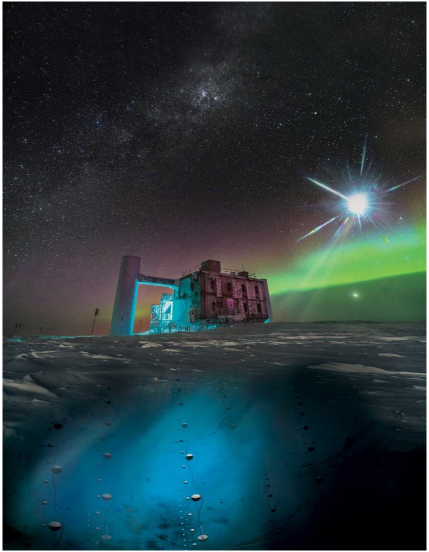
Modern Research

J. Cham&D. Whiteson "We have no idea"

AMS on ISS

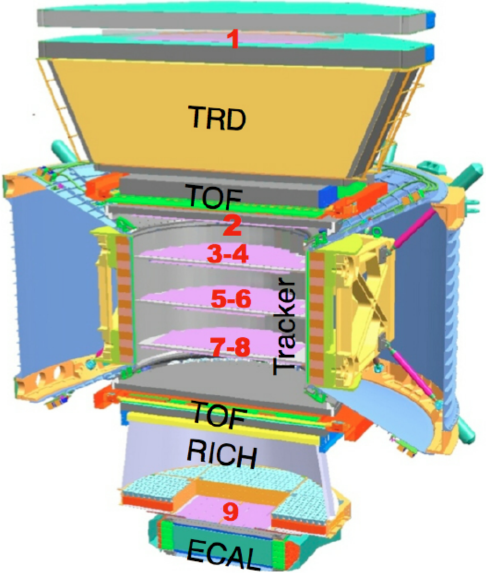


Pierre Auger Observatory, Argentina

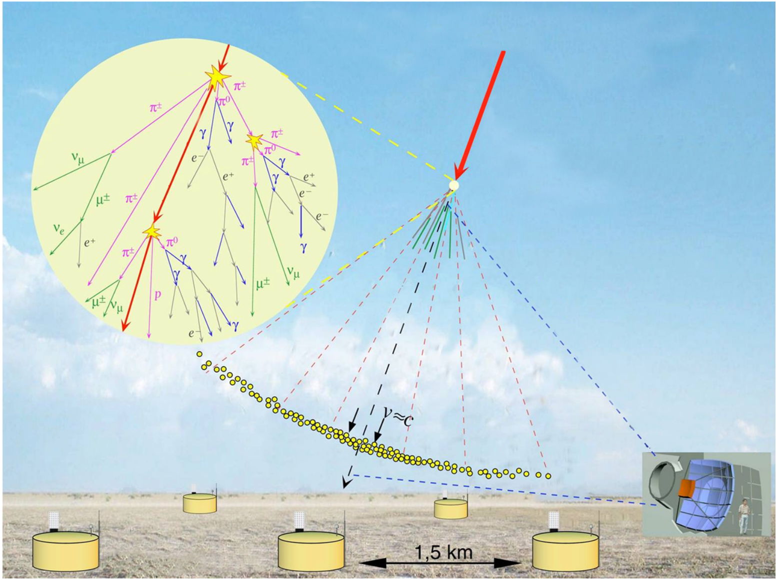


IceCube, Antarctica

Alpha Magnetic Spectrometer (5 m^2)



Pierre Auger Observatory (3000 km^2)



Low-Energy Mass Composition

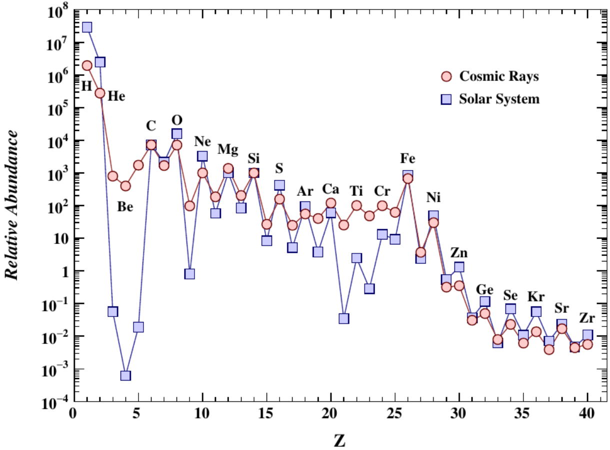
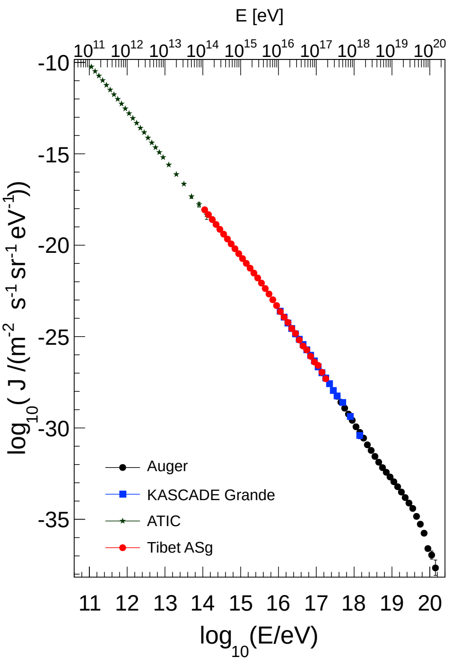
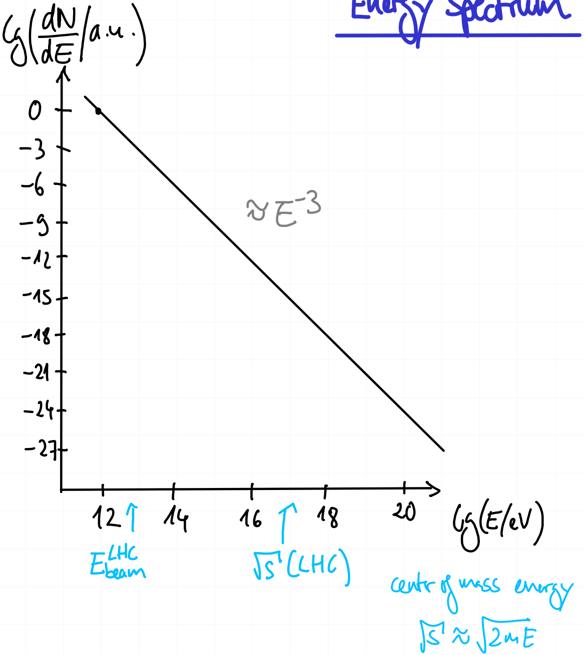


Figure 30.2: Cosmic ray elemental abundances compared to abundances in present-day solar system material. Abundances are normalised to Si=10^3. Cosmic ray abundances are from AMS-02 (H,He) [3,17], ACE/CRIS (Li-Ni) [18,19], and TIGER/SuperTIGER (Cu-Zr) [20,21]. Solar system abundances are from Table 6 of Ref. [22].

All-Nuclei Energy Spectrum



Energy Spectrum



- power law : $\frac{dN}{dE} \sim E^{-\gamma}$

  $\rightarrow \lg\left(\frac{dN}{dE}\right) \sim -\gamma \lg E$

- $\gamma \approx 3$

- particles with $E \gtrsim 10^{20.2}$ eV

  $\rightarrow 25 J!!$

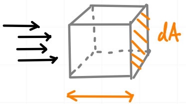
- tennis ball, $m = 50g$

  $v = \sqrt{2\frac{E}{m}} = 110$ km/h

Flux and Density

particle physics: particles with same energy and same direction

define flux: $$\phi = \frac{d^2N}{dt\,dA}$$

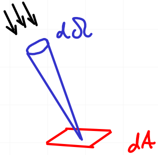


$$\frac{dN}{dV} = \frac{d^2N}{dl\,dA} = \frac{d^2N}{\beta c\,dt\,dA} = \frac{1}{\beta c}\phi \quad \Rightarrow \quad \frac{dN}{dV} = \frac{1}{\beta c}\phi$$

astrophysics: from all directions

$$\phi = \frac{d^4N}{dE\,dt\,dA\,d\Omega}$$

solid angle: $\int d\Omega = 4\pi$



$$\frac{d^2N}{dE\,dV} = \int \frac{1}{\beta c}\phi\,d\Omega \xrightarrow{\text{isotropic}} \frac{d^2N}{dE\,dV} = \frac{4\pi}{\beta c}\phi$$

Flux and Intensity

- Flux: J or $\phi = \dfrac{dN}{dt\, dA\, d\Omega\, dE}$ $\quad [s^{-1} cm^{-2} sr^{-1} eV^{-1}]$

- Intensity above E': $\quad I = \int_{E'}^{\infty} J(E)\, dE$

- Rate: $\quad R = \int I\, d\Omega \quad [s^{-1} cm^{-2}]$ $\quad$ (e.g. $R_{\mu}^{atm} = 200/s\cdot m^2$)

- power law: $\quad J = J_0 \left(\frac{E}{E_0}\right)^{-\gamma}$

$\rightarrow \quad I = \dfrac{J_0}{\gamma - 1} E' \left(\dfrac{E'}{E_0}\right)^{-\gamma+1}$

- Rate on horizontal area: $\quad (d\Omega = d\varphi \sin\theta\, d\theta = -d\varphi\, d\cos\theta)$

$$R = I \int_0^{\theta_c} d\Omega \cos\theta = I\, 2\pi \int_{\cos\theta_c}^{1} \cos\theta\, d\cos\theta = \pi I \sin^2\theta_c$$

(↳ $\cos\theta$: projection)

Example:

$E' = E_0 = 10^{20}\, eV$ (read from spectrum plot)

$\lg\left(J_0 / (m^{-2} s^{-1} sr^{-1} eV^{-1})\right) \sim -36.8$

$\gamma \sim 5.2$, $\quad \theta_c = \pi/2$

$\rightarrow$ $R \approx 1$ event per km^2 per 2000 years

Note:

- $I \sim \int \frac{dN}{dE} dE \sim E \frac{dN}{dE} = \frac{dN}{d\ln E}$ (power law; ~ particles per $\Delta \lg E$)

- $E^2 \frac{dN}{dE} = E \frac{dN}{d\ln E}$ ~ energy per $\Delta\lg E$

Area A, Aperture $\mathcal{A}$, Exposure $\mathcal{E}$ ($A \neq \mathcal{A}$!)

- $A(E) = \iint \epsilon(x,y,E)\, dx\, dy$; ϵ: efficiency (note $\epsilon \neq \mathcal{E}$, efficiency $\neq$ exposure)

→ count rate for point source: $\phi\ [m^{-2} s^{-1} eV^{-1}]$: $\dot{N} = \int \phi(E)\, A(E)\, dE$

- $\mathcal{A}(E) = \iiint \mathcal{E}(x, y, \theta, \phi)\, d\vec{S}\, d\vec{\Omega}$

→ isotropic flux $J\ [m^{-2} s^{-1} sr^{-1} eV^{-1}]$: $\dot{N} = \int J(E)\, \mathcal{A}(E)\, dE$

- flat detector : $\mathcal{A} = S \pi \sin^2 \theta_{max}$

  e.g. Pierre Auger Obs.: $\theta_{max} = 80°$, $A = 3000\ km^2$ → $\boxed{\mathcal{A} \sim 9000\ km^2\, sr}$

- exposure : $\mathcal{E} = T \times \mathcal{A}$ T: measurement time

$$N = \int J(E)\, \mathcal{E}(E)\, dE$$

Cosmic-Ray Energy Density

Energy density of Galactic cosmic rays: $u_{CR} \sim 1\,\mathrm{eV/cm^3}$

- Galactic energy production needed $Q_{CR} = u_{CR} \cdot V / \tau_{esc}$
  $= 10^{41}\,\mathrm{erg/s}$

15 kpc, 200 pc

$V \approx \pi R^2 \cdot 2H$ → cylindrical approx. of galaxy

$\tau_{esc} \approx 1.5 \cdot 10^7$ years → see 3rd lecture

- SNRs: 2-3 / century, 10^{51} erg/SN $\quad Q_{SN} \approx 10^{42}\,\mathrm{erg/s}$

  supernova remnants

  $\Rightarrow Q_{CR} = 0.1\, Q_{SN}$!

compare:

light: $0.25\,\mathrm{eV/cm^3}$

magnetic field: $0.25\,\mathrm{eV/cm^3}$

CMB: $0.3\,\mathrm{eV/cm^3}$ ($\approx 400\,\gamma/\mathrm{cm^3}$)

$$\left(u = \int_0^\infty E \frac{d^2N}{dE\,dV} dE = \frac{4\pi}{\beta c} \int_0^\infty E \phi \cdot dE \right)$$

ultra-high energies ($E > 5 \cdot 10^{18}\,\mathrm{eV}$): $u_{UHE} \approx 6 \cdot 10^{53}\,\mathrm{erg/Mpc^3}$

energy loss time: $t_{loss} \approx 1\,\mathrm{Gpc}/c$ → see 4th lecture

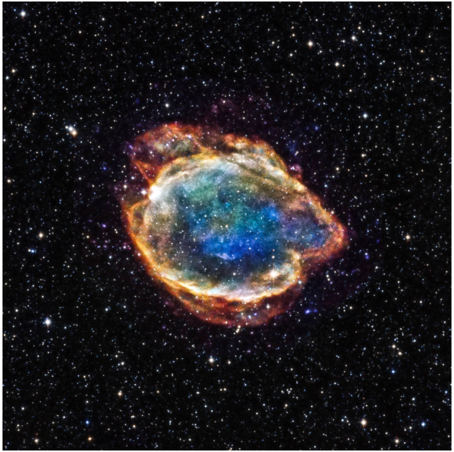
⇒ source luminosity density

$$\mathcal{L} \sim u/t = 2 \cdot 10^{44}\,\mathrm{erg/Mpc^3/yr}$$

⇒ Candidates for cosmic-ray accelerators: Supernovae ($\lesssim 10^{17}\,\mathrm{eV}$) and jetted AGN or starburst galaxies ($\gtrsim 10^{18}\,\mathrm{eV}$)

Source Candidates

Necessary criterion: energy requirement (more criteria will discussed in forthcoming lectures)

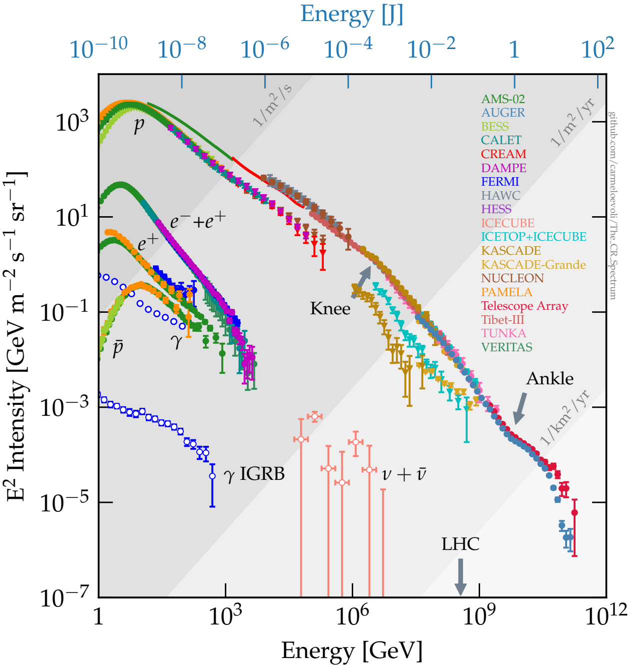


supernova remnant

jetted AGN

supernova: star explosion, AGN: active galactic nucleus

Energy Spectrum



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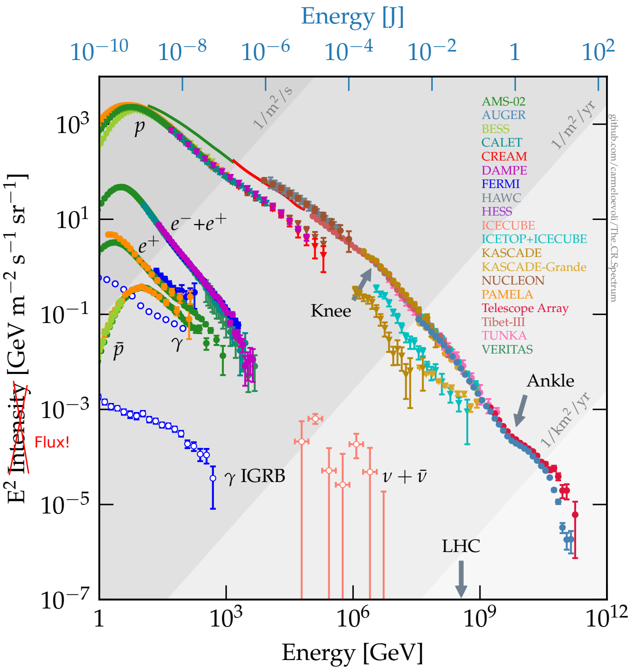

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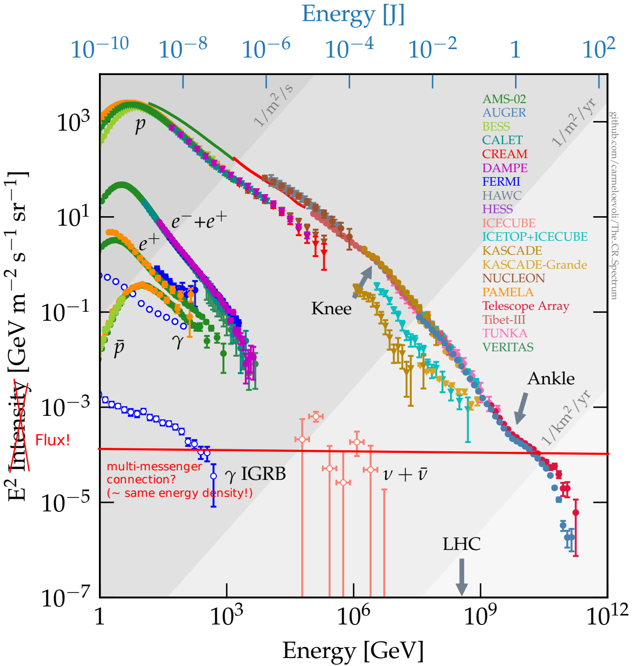

Summary: Cosmic Ray Overview

cosmic-ray facts:

- charged particles
- nuclear composition: similar solar, but secondary Li/Be/B, sub-Fe
- messengers of high energy universe
- energy spectrum: approximately power-law spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-\gamma}$
- microscopic particles with macroscopic energies
- astrophysical accelerators (by far more powerful than human-made ones)
- Galactic cosmic rays from supernova remnants?

key concepts:

- relation of flux and density
- aperture and exposure of detector
- cosmic-ray energy density
  $\rightarrow$ constraint on astrophysical accelerators!
  $\rightarrow$ multi-messenger connection (CR-ν-γ) or coincidence?