An Overview of High Energy Astroparticle Physics

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Part 0: Preliminaries

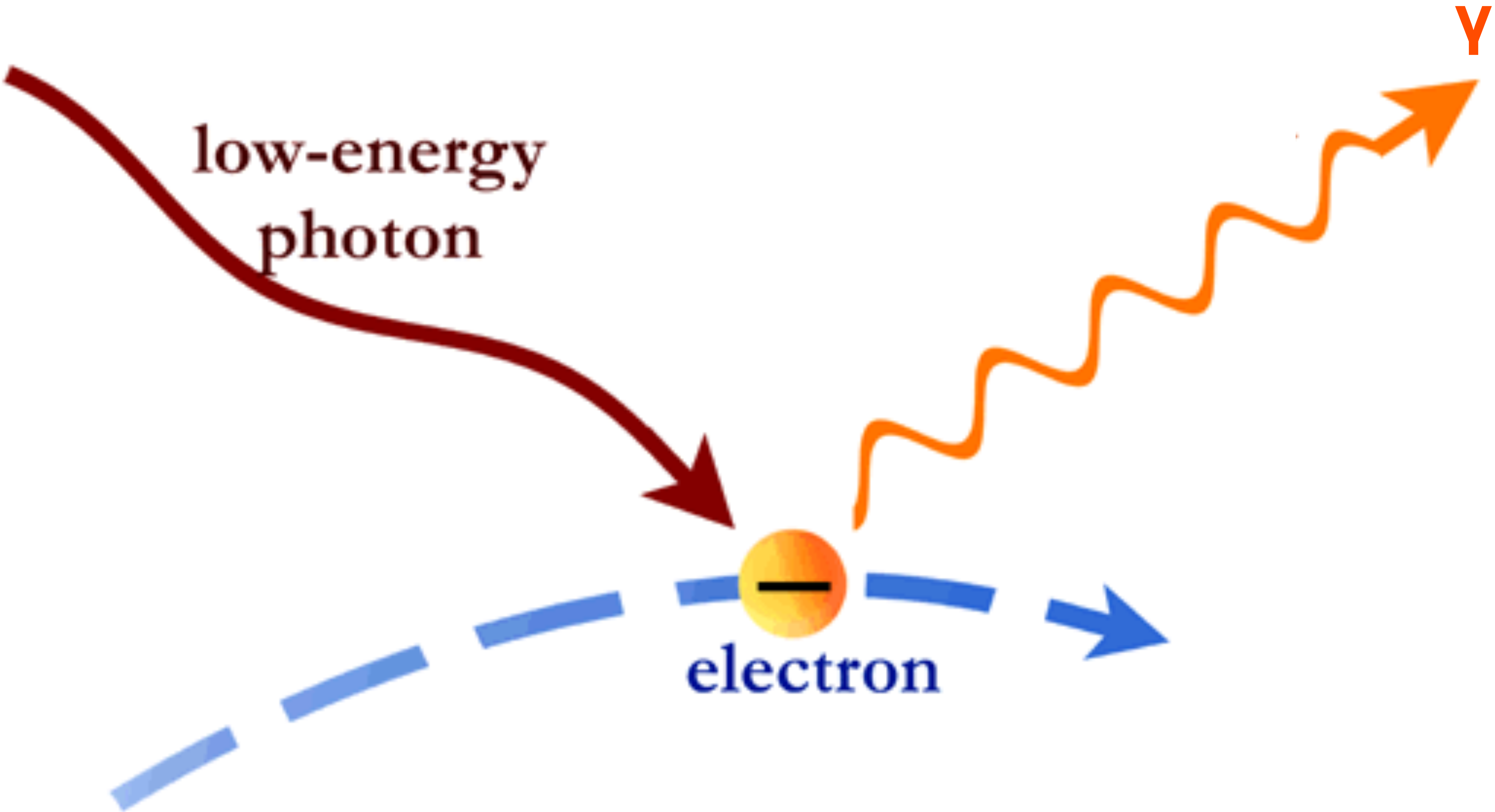
Energy Scales

unit	meaning	
eV		optical/UV regime; atomic transitions
keV	10^3 eV	X-ray regime
MeV	10^6 eV	"soft" γ-rays; nuclear line regime
GeV	10^9 eV	"high energy" γ-ray regime; the orbiting *Fermi*-LAT operates in the 100 MeV - 100 GeV range
TeV	10^{12} eV	"very high energy" γ-ray regime; ground-based imaging air Cherenkov telescopes (IACTs) operate in the 10 GeV - 100 TeV+ range; note: 1 TeV $\sim$ 1 erg
PeV	10^{15} eV	rough energy of cosmic ray "knee"; energy regime of astrophysical neutrinos detected by IceCube
EeV	10^{18} eV	regime of "ultra-high energy" cosmic rays
ZeV	10^{21} eV	approximate energy scale of highest energy cosmic ray ever recorded

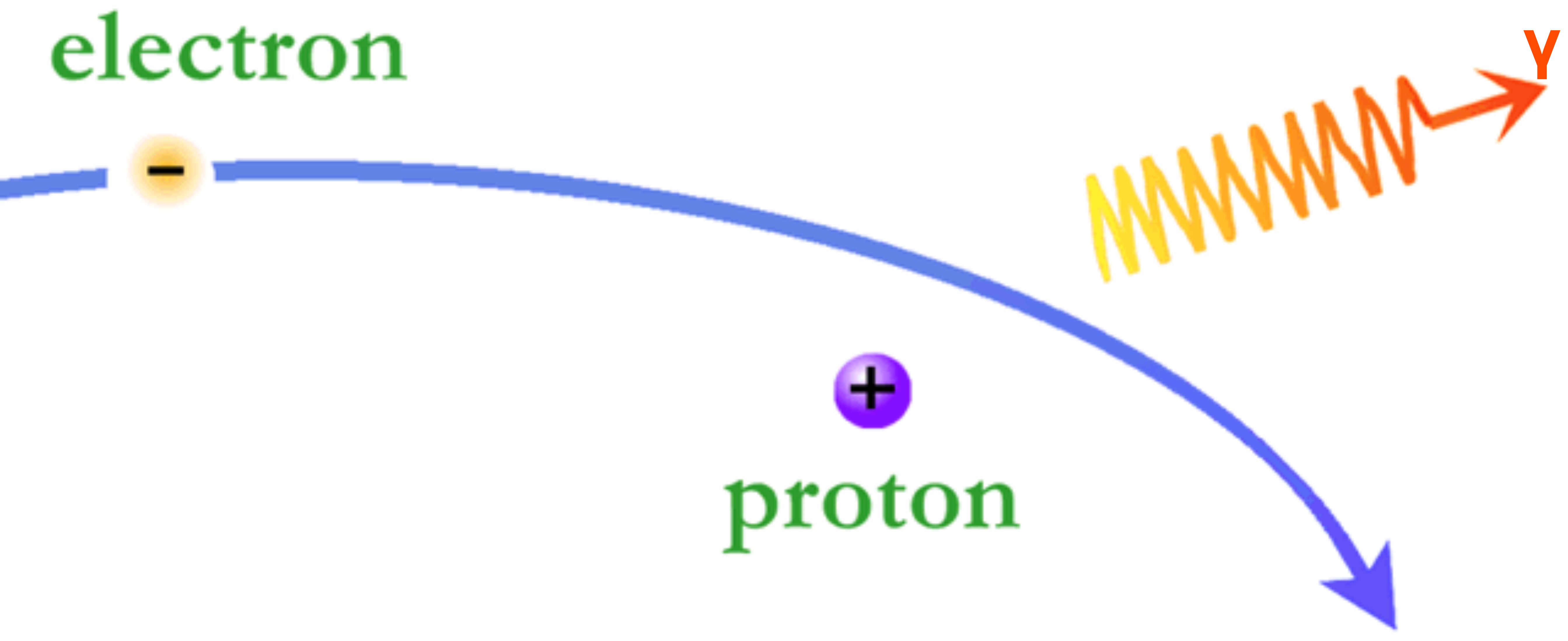
Continuum Emission Processes from Cosmic Rays

Synchrotron

Inverse Compton Scattering



Bremsstrahlung



‘Hadronic’ emission:

$pp \rightarrow$ stuff

$p\gamma \rightarrow$ stuff

‘Hadronic’ emission:

pp → stuff

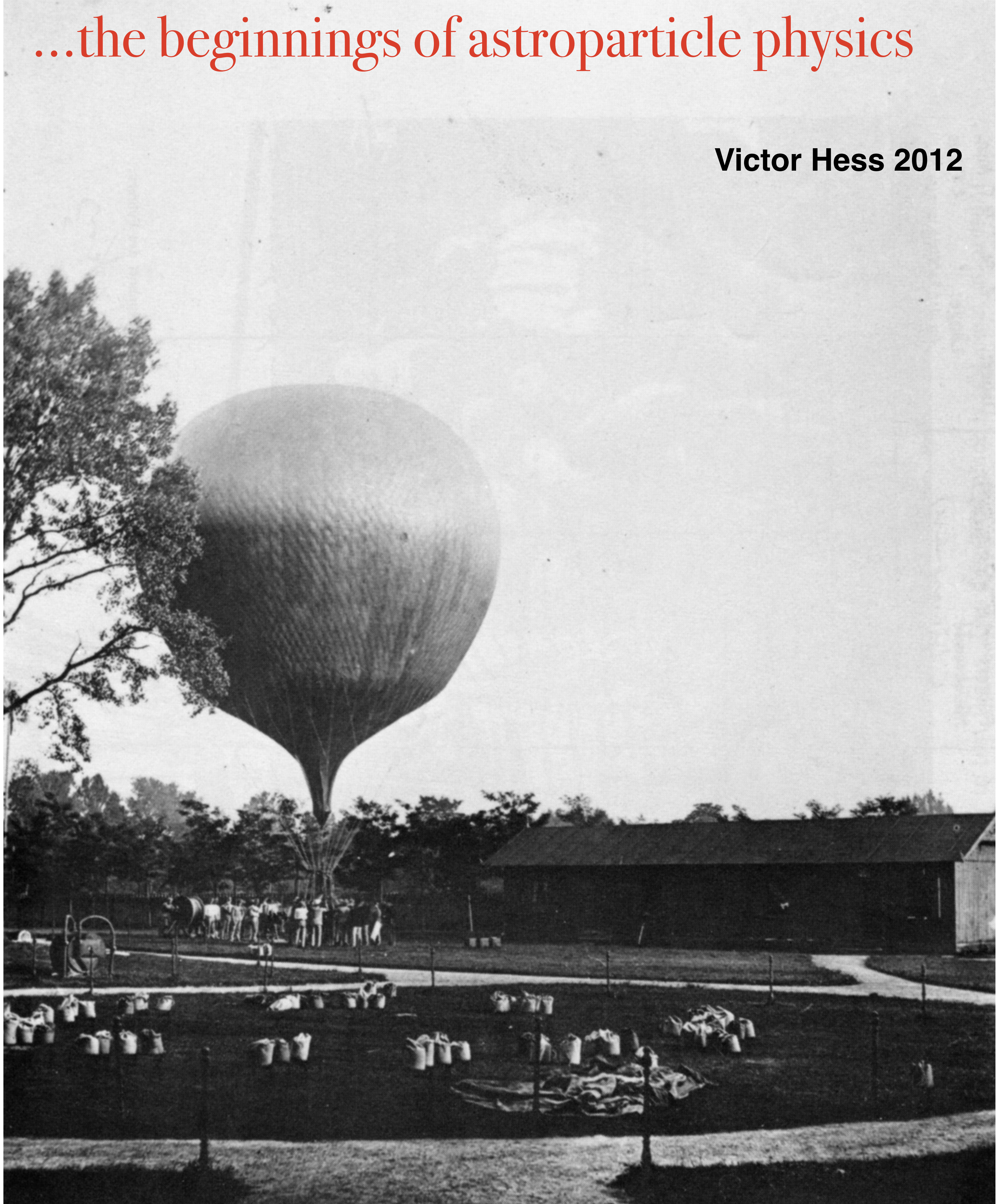
pγ → stuff

This will be discussed in the next lecture

Part I: Cosmic Rays:

What are they good for?

…the beginnings of astroparticle physics



Teshima 2004 Erice Summer School

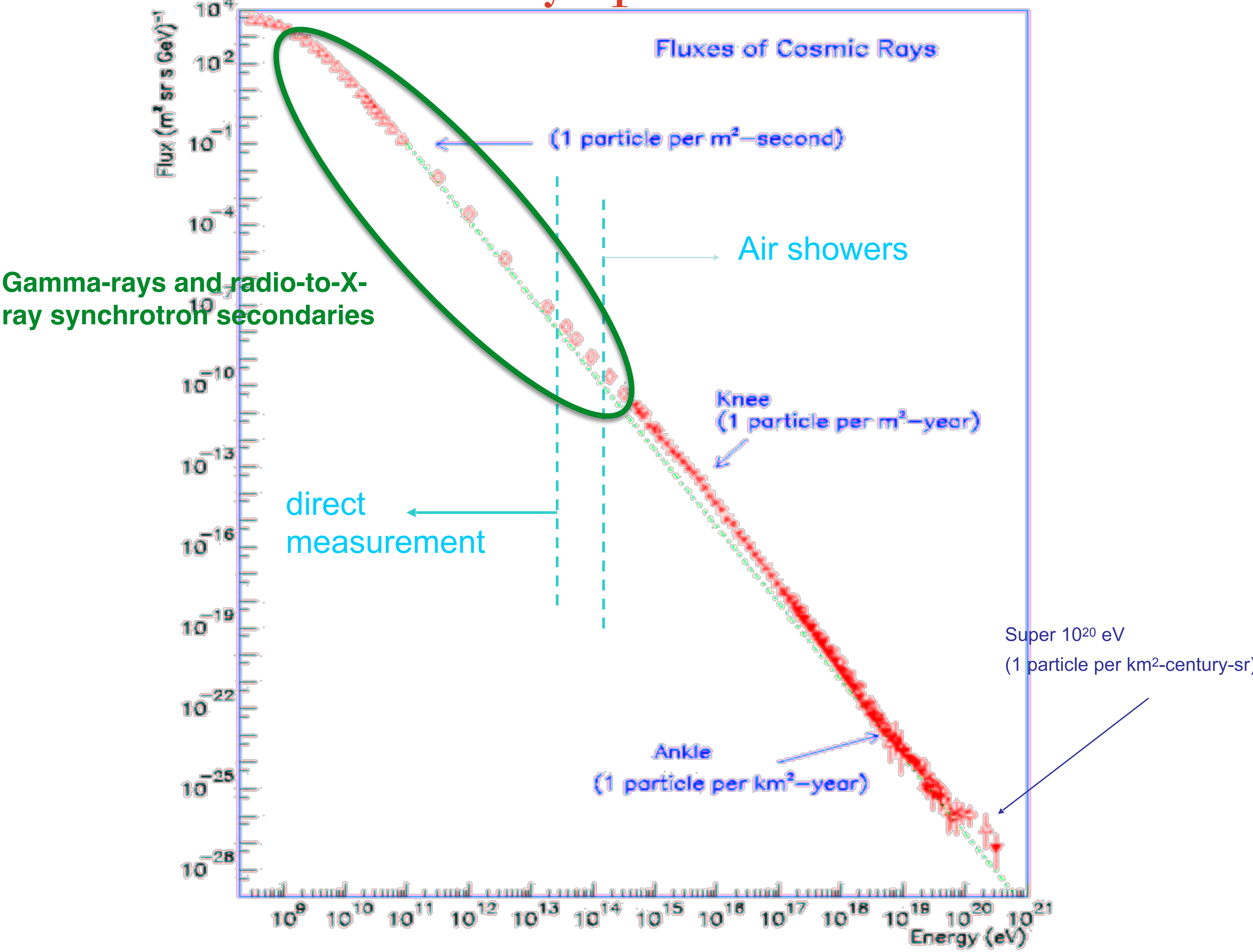
Victor Hess

- Hess ascended to a height of a few km in a balloon (without oxygen!) carrying a gold-leaf electroscope
- In light of the recently-detected phenomenon of radioactivity, he anticipated that as he moved further from terrestrial sources of radioactivity and the ionisation they produce, the charge on the electroscope would decline
- Instead, he found the opposite: the charge increased with altitude; there seemed to be a source of ionising 'radiation' coming from space
- …we are now stuck with the terminology of cosmic 'rays'

Cosmic Rays:
What are they good for?

- Q: What are they?
- A: non-thermal, charged particle populations; dominantly protons and heavier ions and electrons
- low energy CRs accelerated in the Sun
- Sun's magnetic activity affects flux we detect

The Cosmic Ray Spectrum at Earth



G. Sigl, http://www.iap.fr/users/sigl/homepage.html

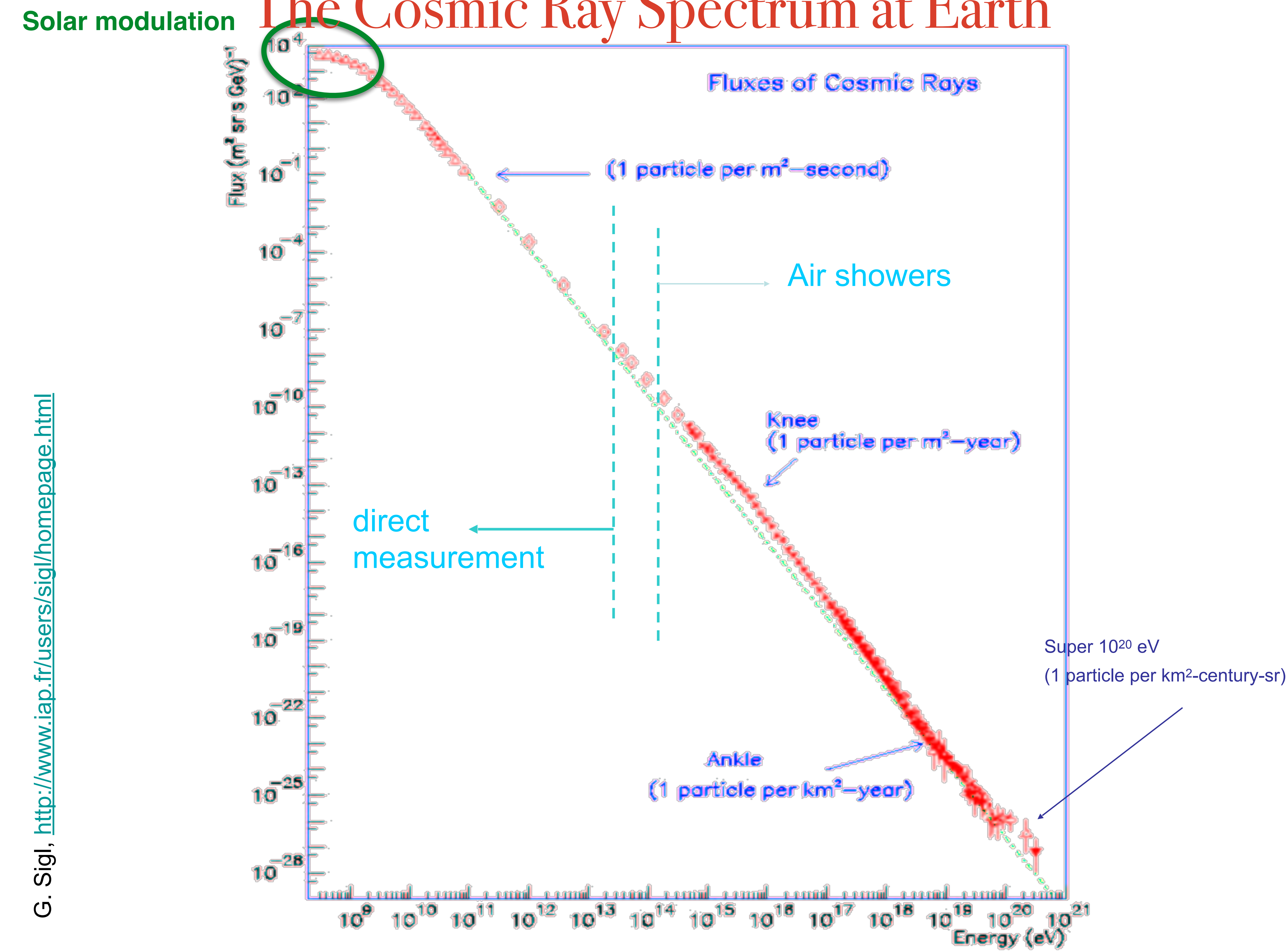
Cosmic Ray Spectrum: Features

- Almost featureless (slightly broken) POWER LAW $\sim E^{-2.7}$ over 10+ decades in energy / 33+ decades in flux
- Low energy turn-over: solar modulation
- Knee
- Ankle
- High energy turn-over: GZK "cut-off" (?)

Spallation/Confinement: Energy-dependence of 2ndary/primary CR nuclei

- Abundance ratio: $B/C \propto E^{-0.6}$
- Observed spectrum:
- $\phi(E) = dN/dE \propto E^{-2.7}$
- Interpretation:
- Propagation depends on E
- Confinement time: $\tau(E) \propto E^{-0.6}$…but why this exponent? Expect $\propto E^{-0.3}$ (for Kolmogorov spectrum of turbulence)
- Implication: Injection spectrum $Q(E) \propto E^{-2.1}$ …this is consonant with expectations for astrophysical **shock acceleration**

The Cosmic Ray Spectrum at Earth



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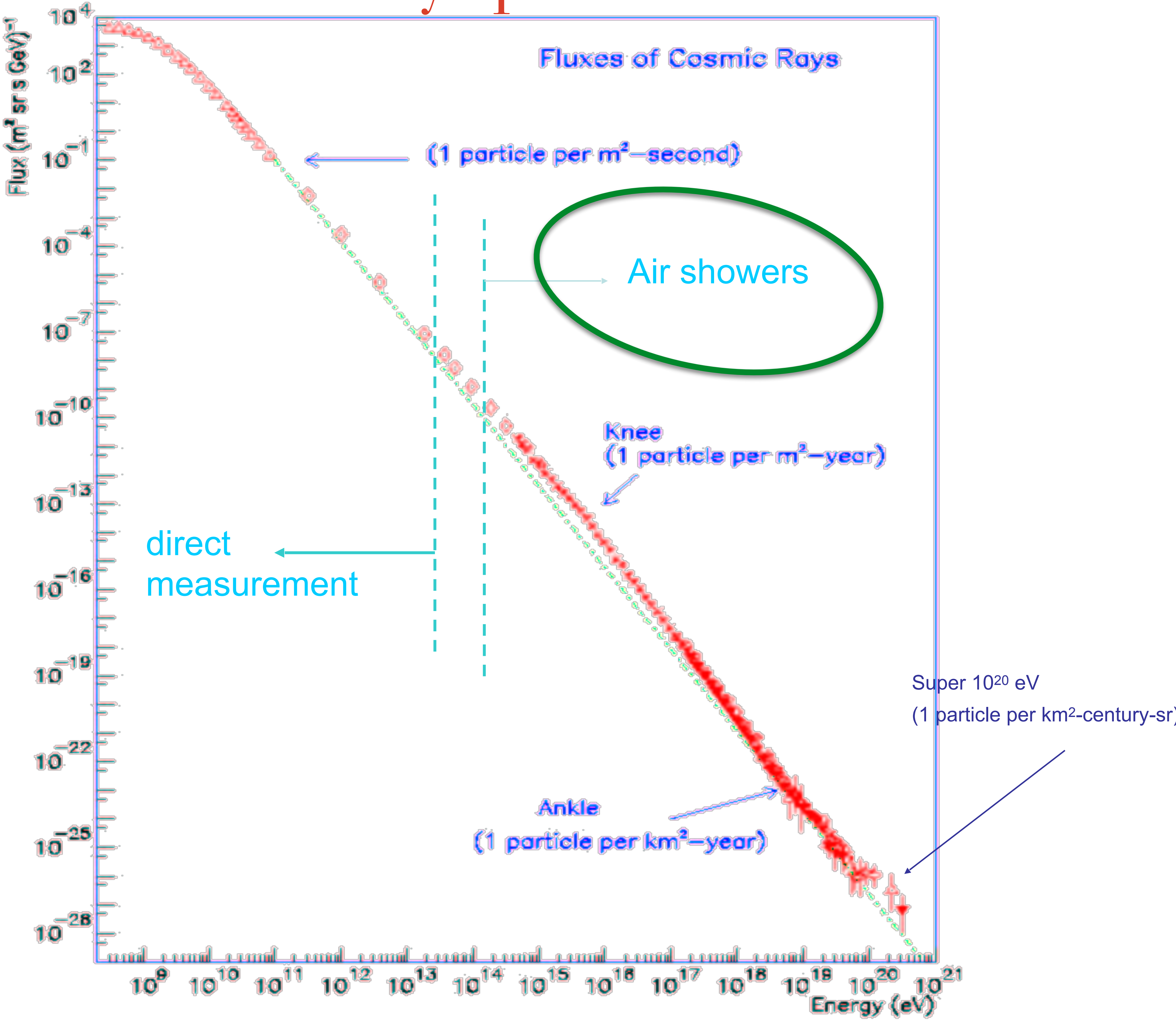
The Cosmic Ray Spectrum at Earth



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CR detection

- Above ~10^{14} eV, we cannot launch into space detectors with sufficiently large areas to detect the rapidly declining CR flux
- Instead we have to rely on detecting secondary and tertiary particles initiated in air showers by the collision of the primary cosmic ray high in this atmosphere

The Cosmic Ray Air Shower

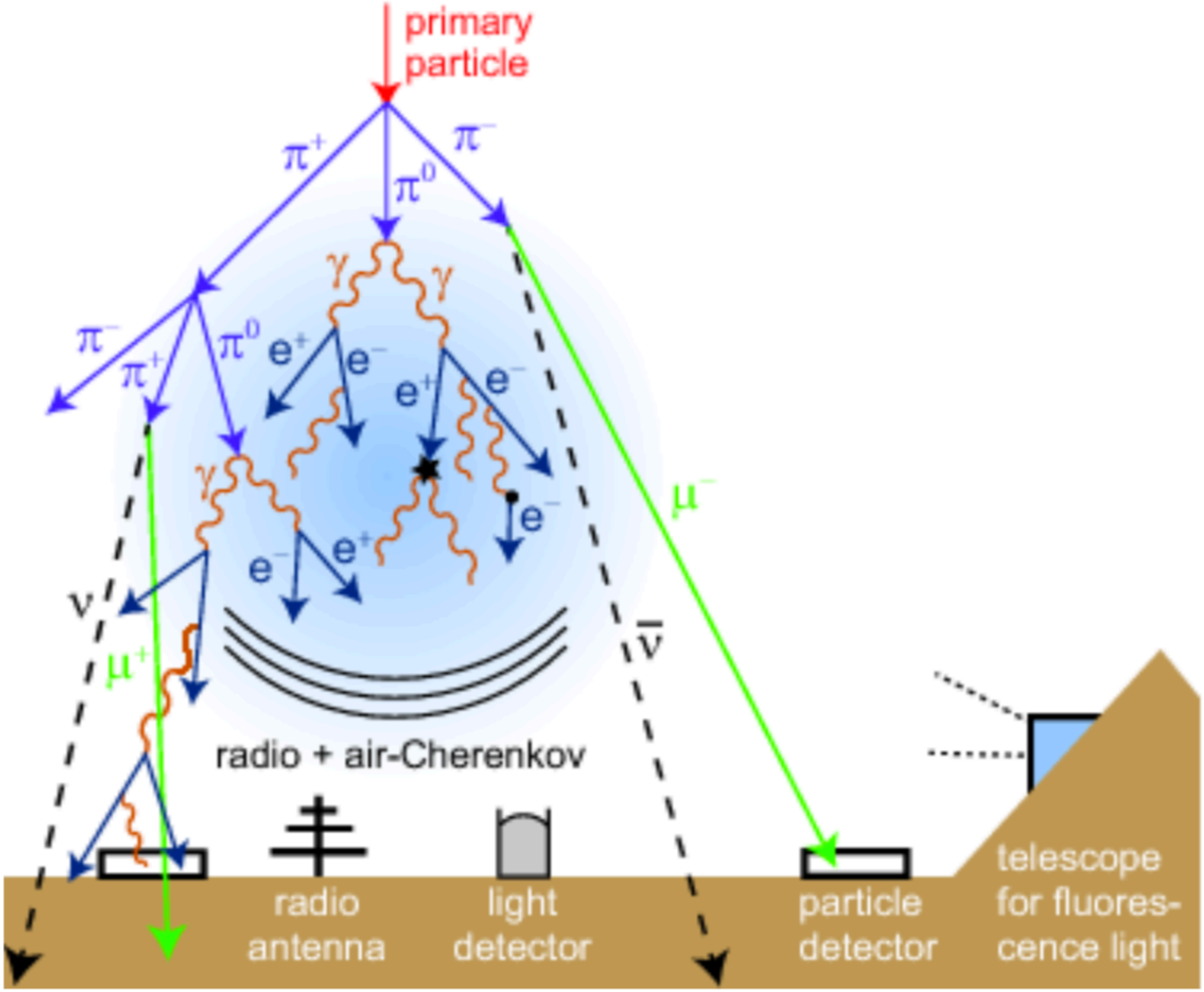
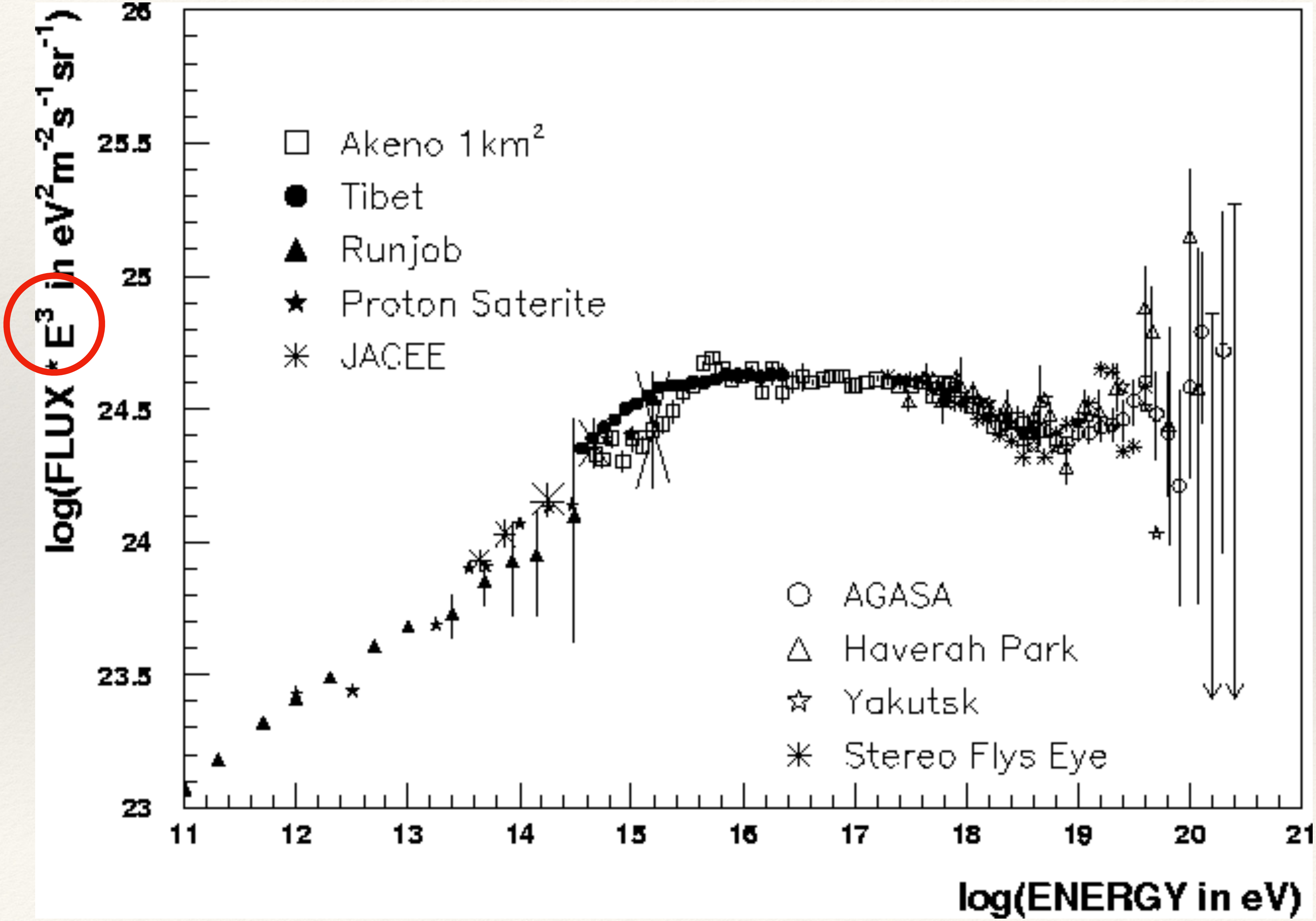
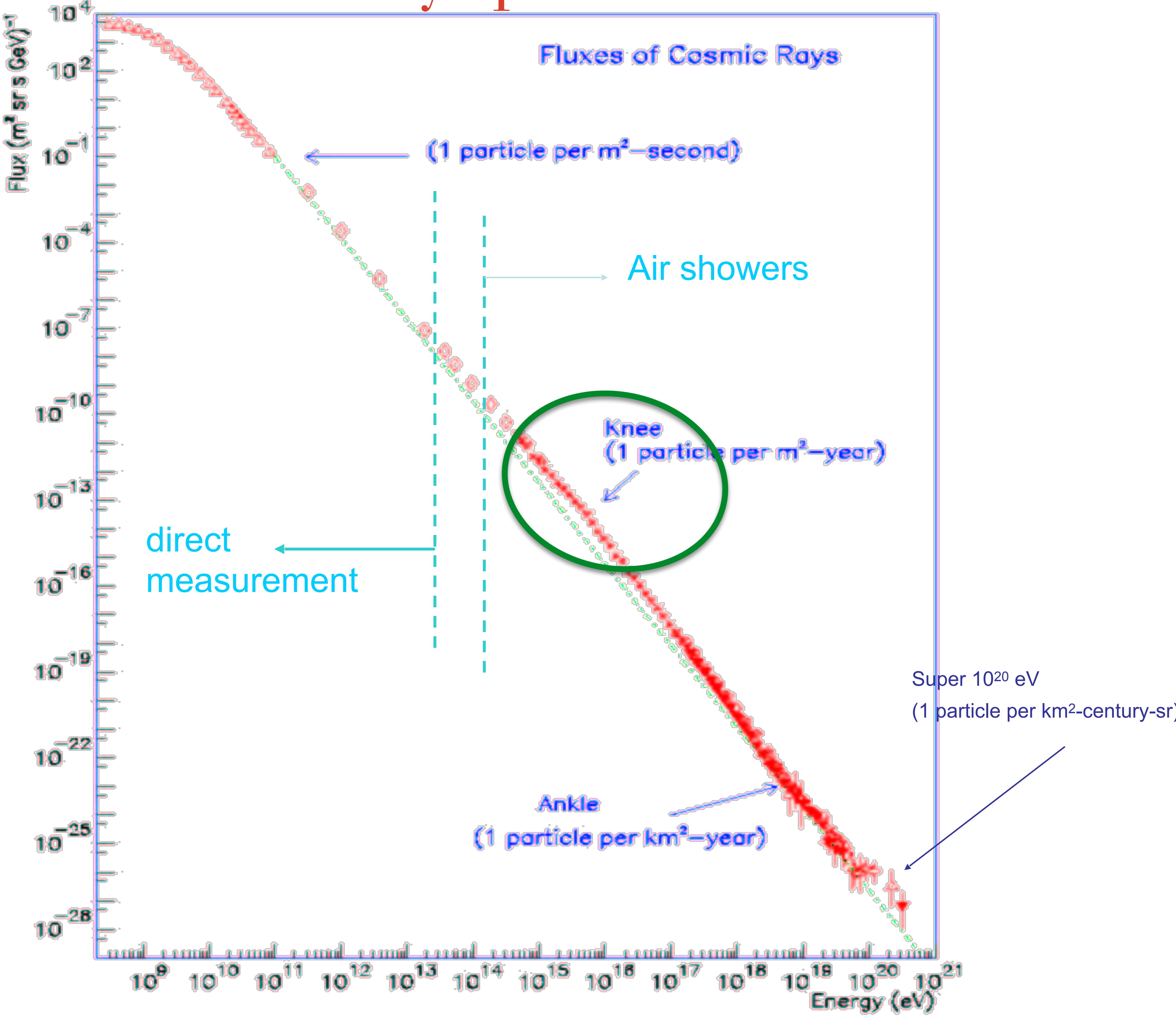


Figure 10: Schematic of cosmic ray extensive air shower with different detector technologies (credit: F. Schröder et al. 2017). Different techniques have advantages in different energy ranges.

E³-Weighted Cosmic Ray Spectrum



The Cosmic Ray Spectrum at Earth



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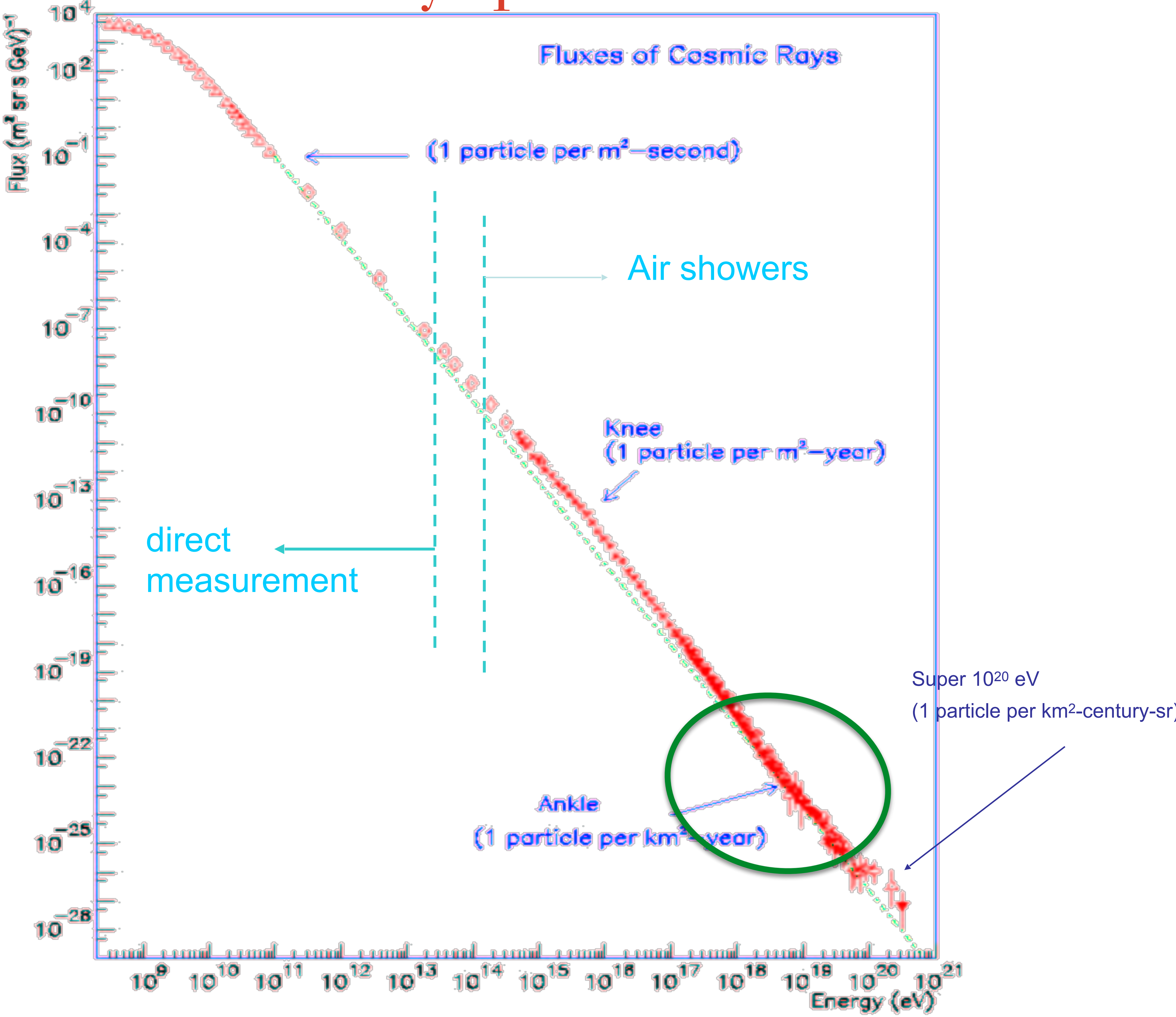
The Cosmic Ray Spectrum at Earth



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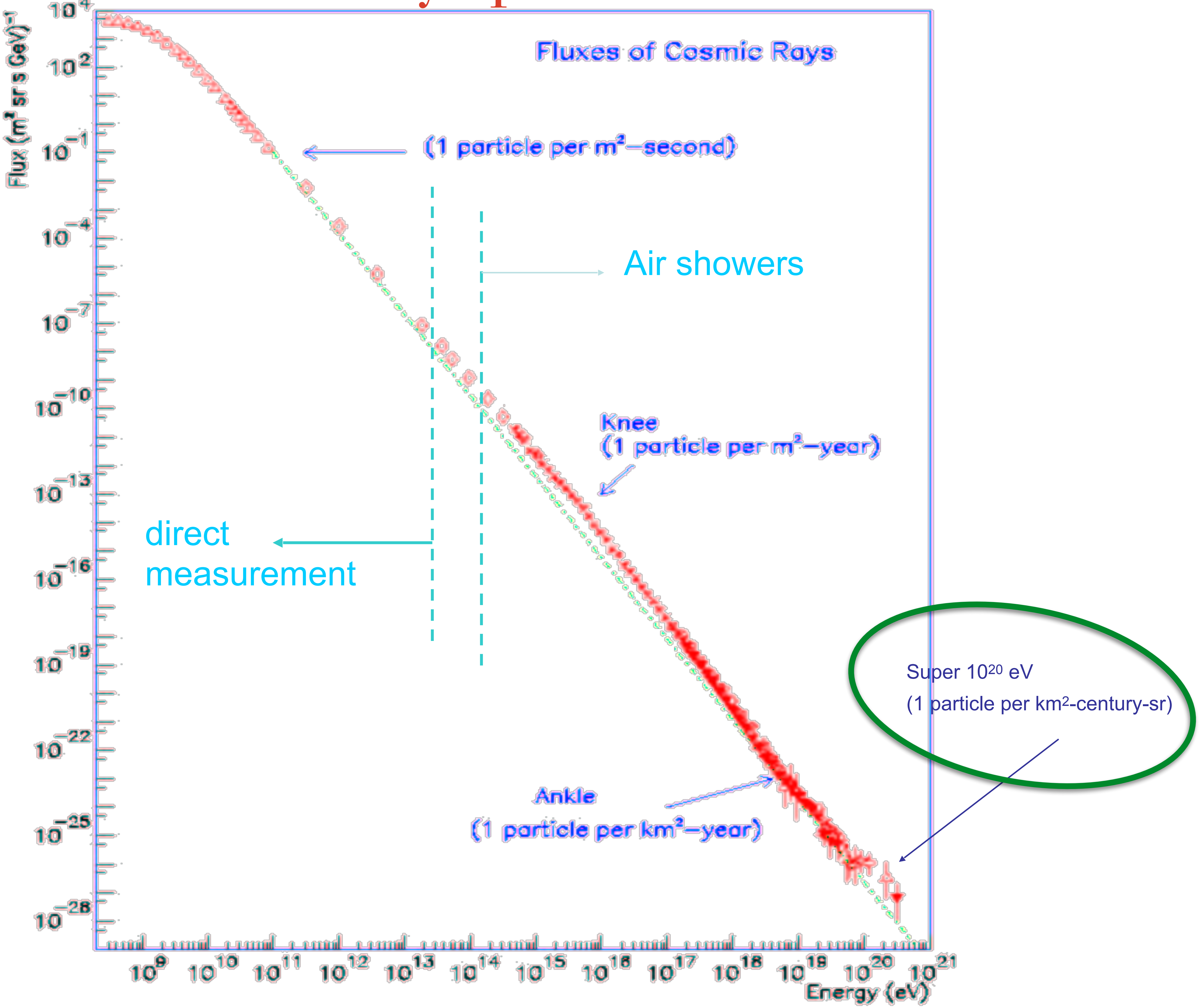
The Cosmic Ray Spectrum at Earth



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Why are CRs of astrophysical interest?

- provide energy density / pressure equivalent to other ISM phases

  ⇒ help to support the scale height of the gaseous disk

- dominate heating and ionisation of H2

  ⇒ maintain temp of H2 and ensure it is coupled to magnetic fields

  ⇒ affects star formation

- probably help to launch galactic outflows
- mutagenic effect on terrestrial life

Aside: particles first discovered in/as comic rays:

- **Positron** – 1932 by Anderson (shared 1936 Nobel Prize with Victor Hess)
- **Muon** – 1936 by Anderson and Nedermeyer
- **Pion** – 1947 by Powell and co-workers (Nobel Prize 1950)
- **Kaon** – 1947 by Rochester and Butler
- CRs interaction are even today detected at centre-of-mass energies (up to ~PeV) many orders of magnitude higher than available in collider experiments (LHC: ~14 TeV)

Cosmic Rays:
What are they good for?

- Cosmic rays can be measured locally and their presence throughout the Galactic disk can be inferred from its gamma-ray emission
- Similarly, we know from gamma-ray observations that there are diffuse cosmic ray populations suffusing the disks of external galaxies (local group, nearby starbursts)

The Galactic Plane as seen by Fermi

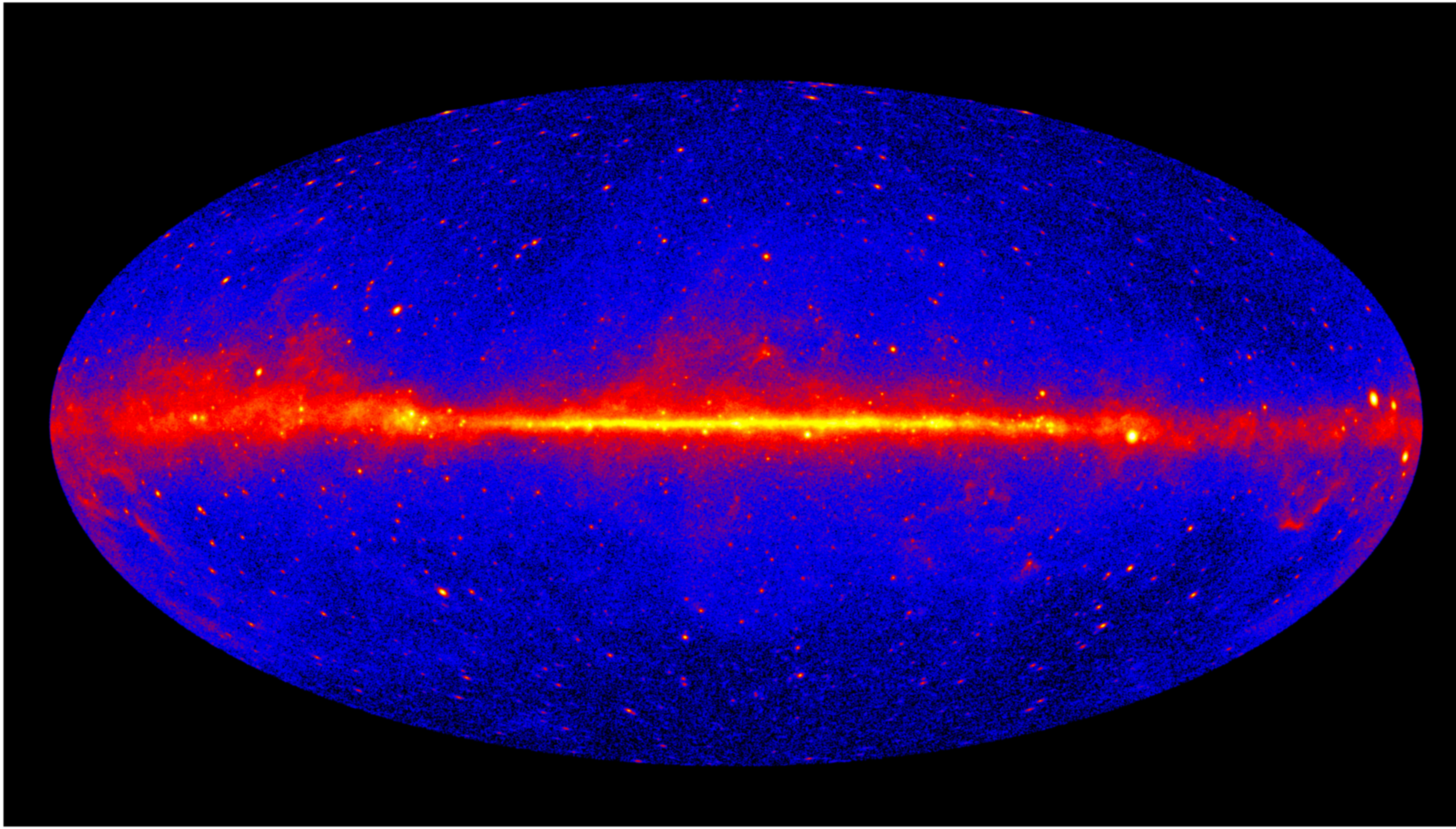


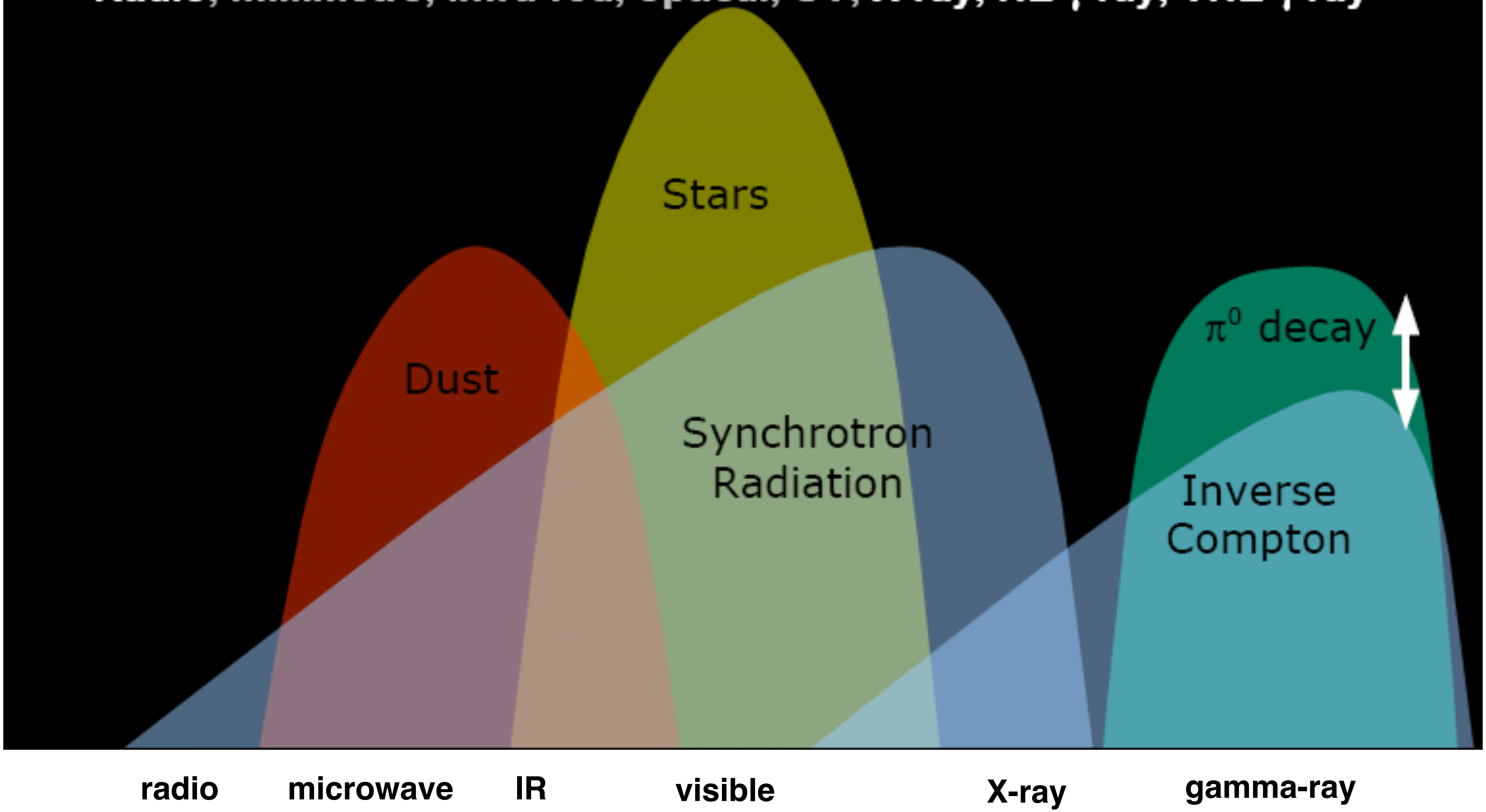
Figure 1: *Fermi*-LAT all sky image in Galactic co-ordinates. Credit: NASA/DoE.

A general point about non-thermal emission

- The non-thermal emission from astrophysical objects tends to hidden by the very bright thermal emission by stars and dust in the IR - optical - UV band
- …but if we go to higher or lower photon wavelengths outside these bands, non-thermal emission can become evident

Generic Galactic 'SED' (Spectral Energy Distribution)

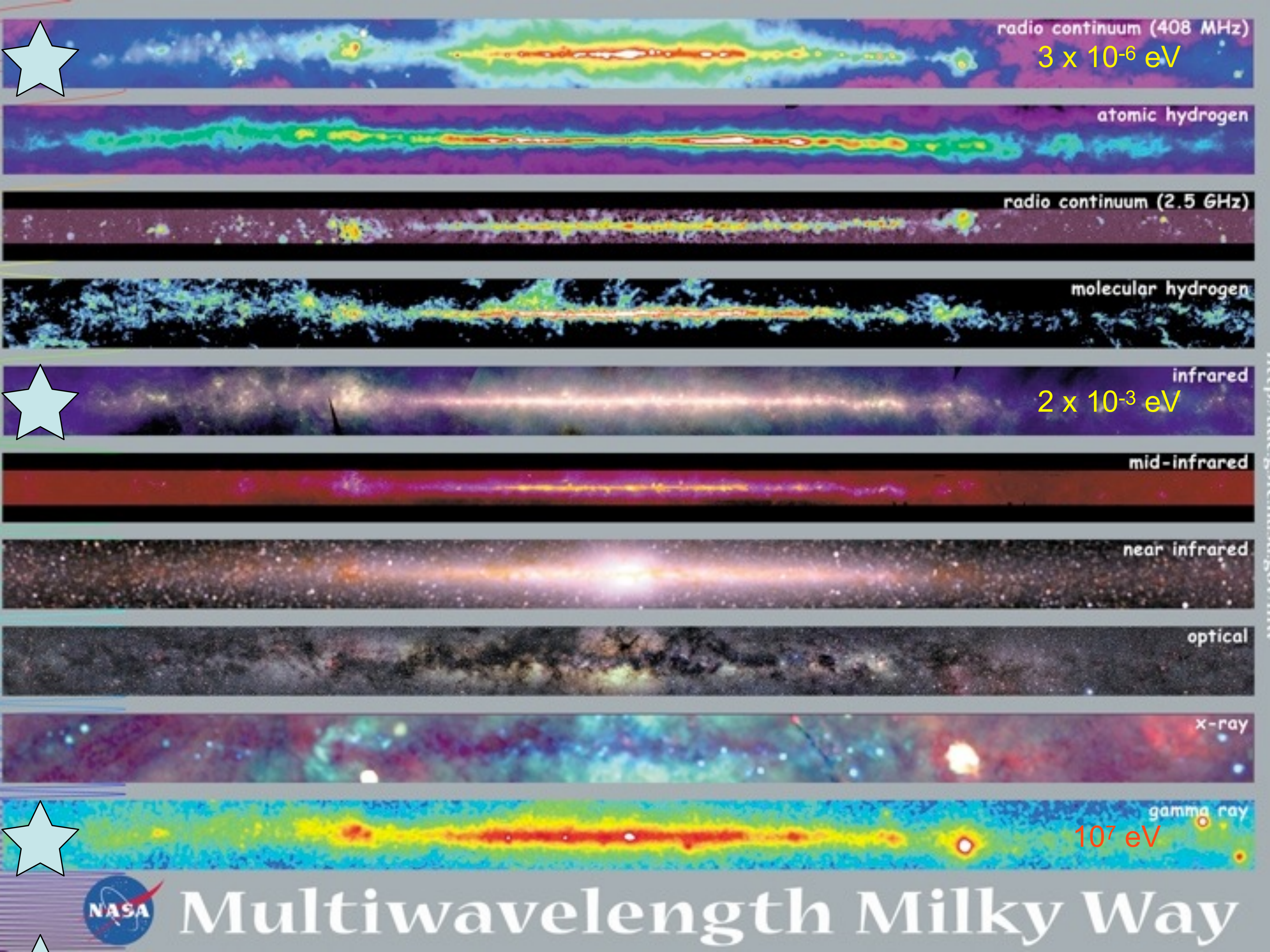
- Radio, millimetre, infra-red, optical, UV, X-ray, HE γ-ray, VHE γ-ray



http://www-zeuthen.desy.de/astro-workshop/vortraege/donnerstag/puehlhofer_zeuthen.pdf

Non-thermal emission

- Surprisingly, astrophysical photons with very different wavelengths can share the same morphology


radio continuum (408 MHz)
3 x 10-6 eV
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
2 x 10-3 eV
mid-infrared
near infrared
optical
x-ray
gamma ray
107 eV
NASA
Multiwavelength Milky Way

Non-thermal emission

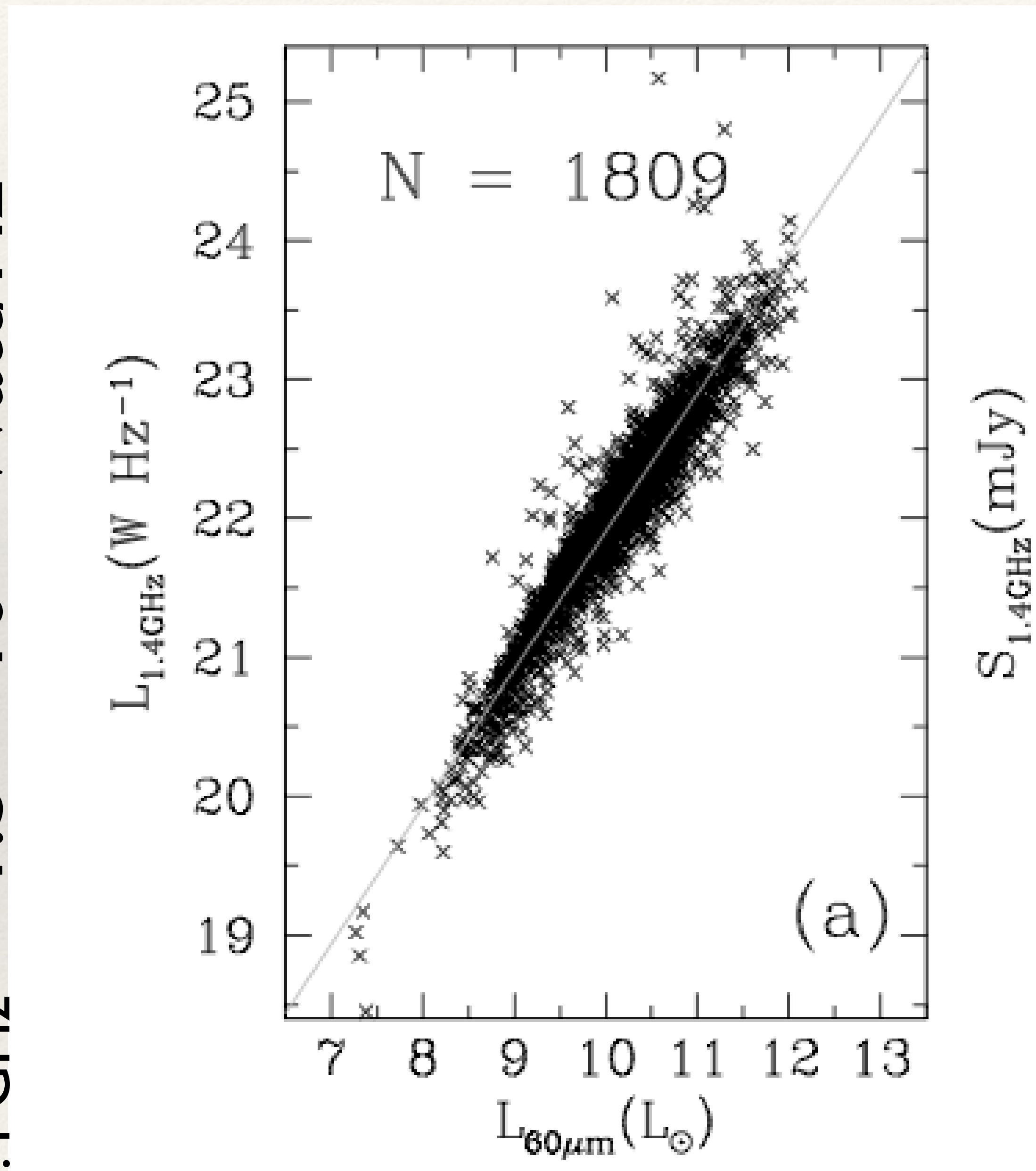
- Surprisingly, astrophysical photons with very different wavelengths can share the same morphology
- This reflects the fact that they are initiated by the same underlying population of cosmic rays

Non-thermal emission

- In addition, non-thermal emission (e.g., radio synchrotron) is sometimes spatially correlated with thermal emission (from, e.g., warm dust)
- …such is the case for the far-infrared—radio continuum correlation

‘Far Infrared-Radio Continuum Correlation’

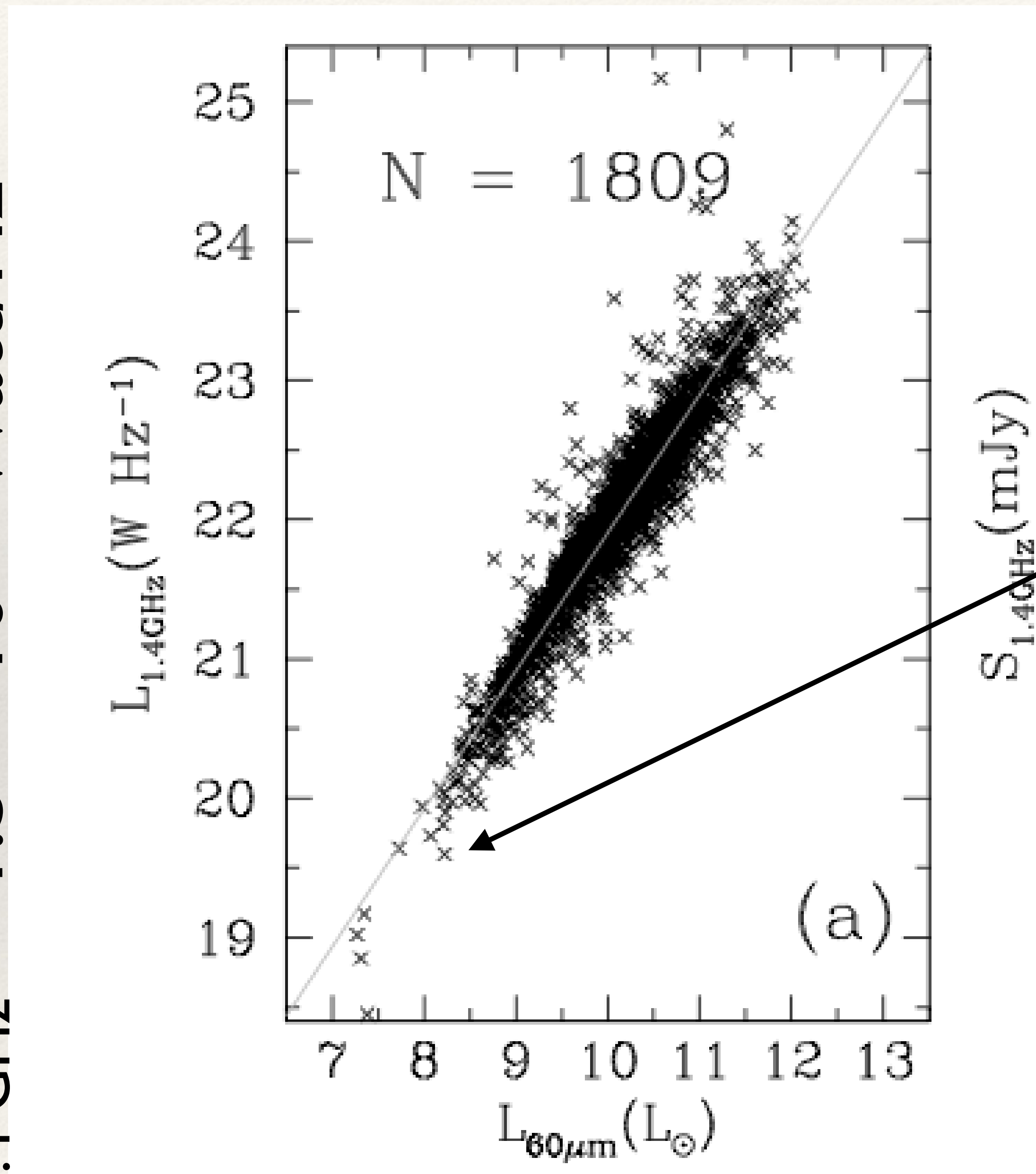
$L_{1.4\,GHz} = 1.5 \times 10^{20}$ Watt/Hz



$L_{60\mu m} = 1.3 \times 10^8 L_\odot$

Yun et al. 2001 ApJ 554, 803 fig 5

‘Far Infrared-Radio Continuum Correlation’



$L_{1.4\,GHz} = 1.5 \times 10^{20}$ Watt/Hz

$L_{60\mu m} = 1.3 \times 10^{8}\, L_{\odot}$

Each point is an individual galaxy

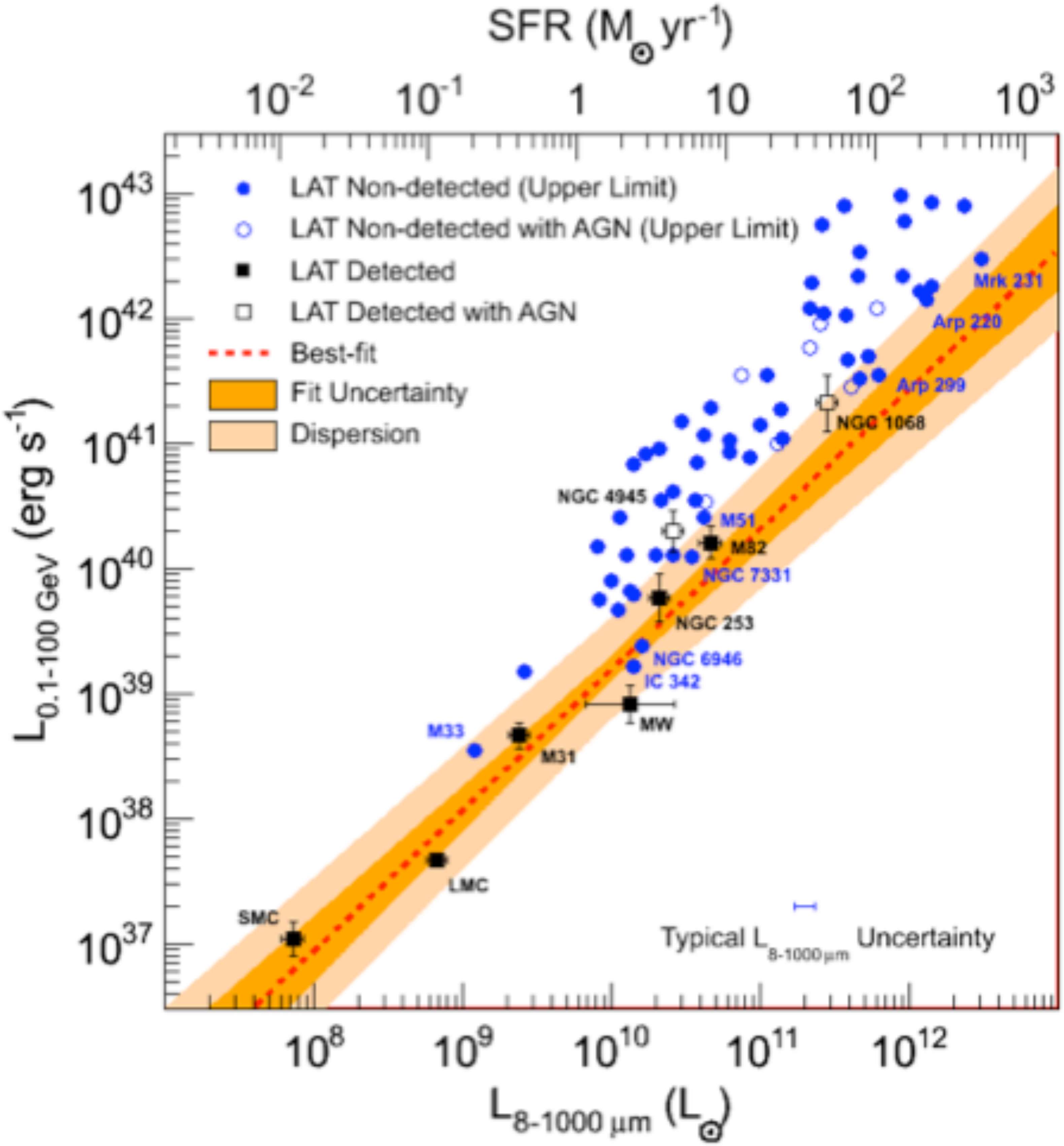
Yun et al. 2001 ApJ 554, 803 fig 5

Sidebar: origin of FIR-RC?

- correlation between FRC and RC ultimately tied back to massive star formation
- massive stars → UV → (dust) → IR
- massive stars → supernovae → SNRs → acceleration of CR e's → (B field) → synchrotron

FIR-γ-ray Correlation?

- SNR accelerate CR p's (and heavier ions)
  - there should exist a global scaling b/w FIR and gamma-ray emission from region (Thompson et al. 2007): $L_{GeV} \sim 10^{-5} L_{TIR}$ (assuming 10^{50} erg per SN in CRs)
  - Such a correlation is now becoming evident



Fermi collab

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

Cosmic Rays: What are they good for?

- Because CRs are charged, they respond to ISM magnetic fields

  ⇒ we cannot do CR astronomy (except maybe at highest energies)

- Scatter most strongly on magnetic field inhomogeneities of same scale as their *gyro radius*

  ⇒ CRs execute a random walk through turbulent ISM magnetic field structure

‘Gyroradius’ = ‘Larmor Radius’

$$r_{gyro} \simeq 1.1 \times 10^{-6}\ \mathrm{pc}\ \ (p_{perp}/\mathrm{GeV})\ \ (B/\mu\mathrm{G})\ \ 1/Z$$

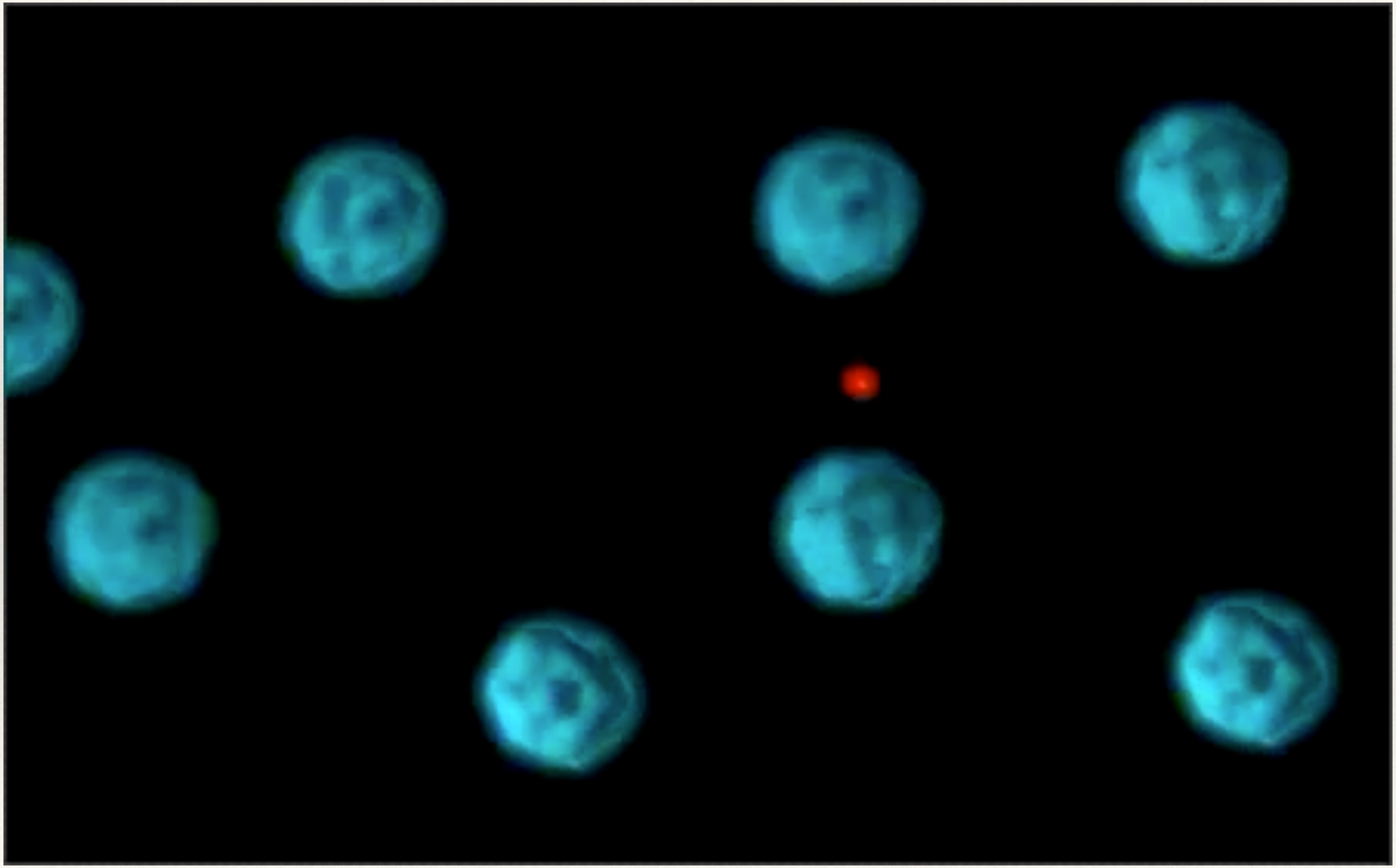
.

$$rigidity \equiv \frac{\mathrm{pc}}{\mathrm{Ze}} \approx \frac{\mathrm{E}}{\mathrm{Ze}}$$

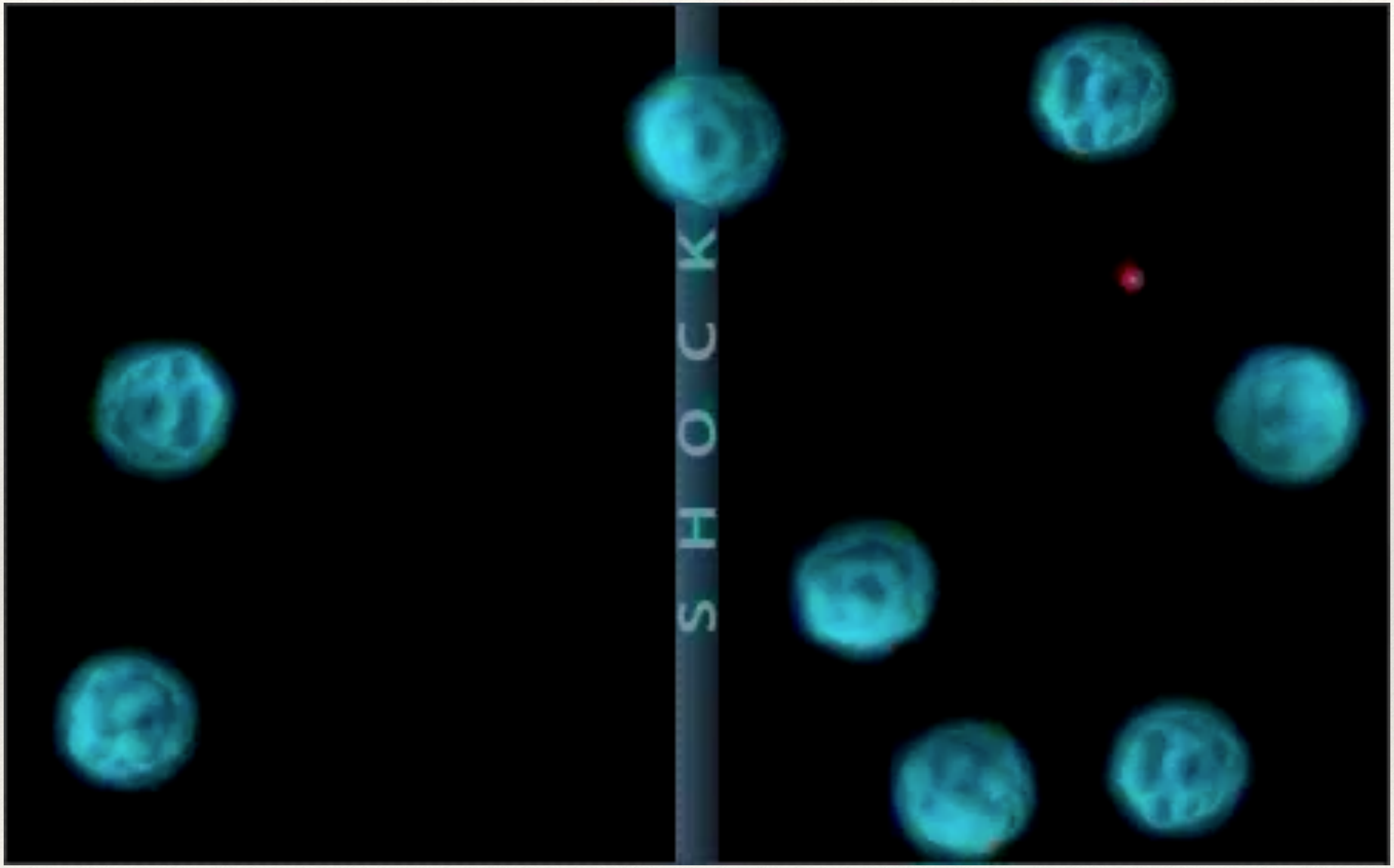
Cosmic Rays:
What are they good for?

- Q: Where do they come from?
- A: accelerated in astrophysical shocks (1st order Fermi acceleration in converging flows), primarily shocks from SN explosions (also stellar winds, etc, also 2nd order acceleration on ISM turbulence)
- Here 1st order ('Fermi-I') means that the acceleration rate is $\propto v/c$ and 2nd order ('Fermi-II') means that the rate is $\propto (v/c)^2$ where v is a characteristic velocity
- Thus 1st order Fermi acceleration is usually much faster than 2nd order

Fermi-II (slow)



Fermi-I (fast)



Cosmic Rays:

- Energetic match to power available from SNe
- $L_{CR} \sim 10^{-3} L_{light}$
- Q: why energy density in different ISM components ~the same?:

  $u_{CR} \sim u_{ISRF} \sim u_{turb} \sim u_{therm} \sim 1$ eV cm^{-3}

- A: because long CR escape/energy loss times, $>10^7$ years
- $u_{CR} \sim L_{CR}\, t/V_{CR}$
- $t_{CR} \sim \mathrm{Min}[t_{esc}, t_{loss}]$
- $t_{esc} \sim 0.1\, t_{loss}$ in MW
- $L_{CR} \sim SFR/(100\, M_{Sun}/CCSN) \times 0.1$

  $\sim 3 \times 10^{40}$ erg/s

Cosmic Rays:

- $V_{CR} \sim 2\,\mathrm{Pi}$ 2 kpc $(8\,\mathrm{kpc})^2 \sim 2\; 10^{67}\,\mathrm{cm}^3$
- $u_{CR} \sim L_{CR}\, t / V_{CR}$

  $\sim 3\; 10^{40}\,\mathrm{erg/s}\;\; 3\; 10^{7}\,\mathrm{year} / (2\; 10^{67}\,\mathrm{cm}^3)$

  $\sim 1.5\,\mathrm{eV\,cm}^{-3}$

Cosmic Rays:

- CR transport in Gal disk = random walk
- CRs effectively diffuse with λ_{CR}~pc scattering length
- As CRs scatter on B field they exchange momentum with the B field

  ⇒ they exert an effective pressure to the gas into which the B field is "frozen in"

Cosmic Rays:

- Can make sense of the analogue of an "Eddington limit" in CRs (Socrates et al. 2008)
- Momentum flux imparted by CRs, $\dot{P}_{CR}$, can be significantly enhanced because of the large effective optical depth they experience
- $\dot{P}_{CR} \sim \tau_{CR}\, L_{CR}$; τ_{CR} : cosmic ray optical depth
- $\tau_{CR} \sim R/\lambda_{CR} \sim 1000\ \mathrm{pc}/1\ \mathrm{pc} \sim 10^3$;

[λ_{CR} : N.B. CR mean free path $\lambda_{CR} \gg r_{gyro}$]

$\Rightarrow \dot{P}_{CR} \sim 10^3 \times 10^{-3}\, L_{light} \sim L_{light}$

Cosmic Rays:

- Can make sense of the analogue of a… (Socrates et al. 2008)
- Momentum flux impar… …icantly enhanced because of the lar… …y experience
- $\dot{P}_{CR} \sim \tau_{C}$… …al depth
- … 10^3 ;

[λ_{CR} : N.B. CR mean free path $\lambda_{CR} \gg r_{gyro}$]

… $10^3 \times 10^{-3} L_{light} \sim L_{light}$

Momentum feedback from CRs can be as important as that from radiation because CRs do NOT free stream

Cosmic Rays:

- CRs effectively behave as a relativistic fluid with adiabatic index $\gamma = 4/3$
- adiabatic losses are smaller than for non-rel fluid in an expanding outflow

  $\Rightarrow$ CRs become progressively more important the more a wind expands

Where do UHE CRs come from?
'Hillas Criterion'

- in any accelerator where the cosmic rays are magnetically confined by a field of characteristic amplitude B, their gyro- radius has to be smaller than the size of the system L:
- i.e., $r_{gyro} < L \Rightarrow E < Z\, e\, c\, B\, L$ (very generous upper limit)
- More realistically: $c \rightarrow v$, where v is a characteristic velocity
- $E < Z\, e\, \mathbf{v}\, B\, L$

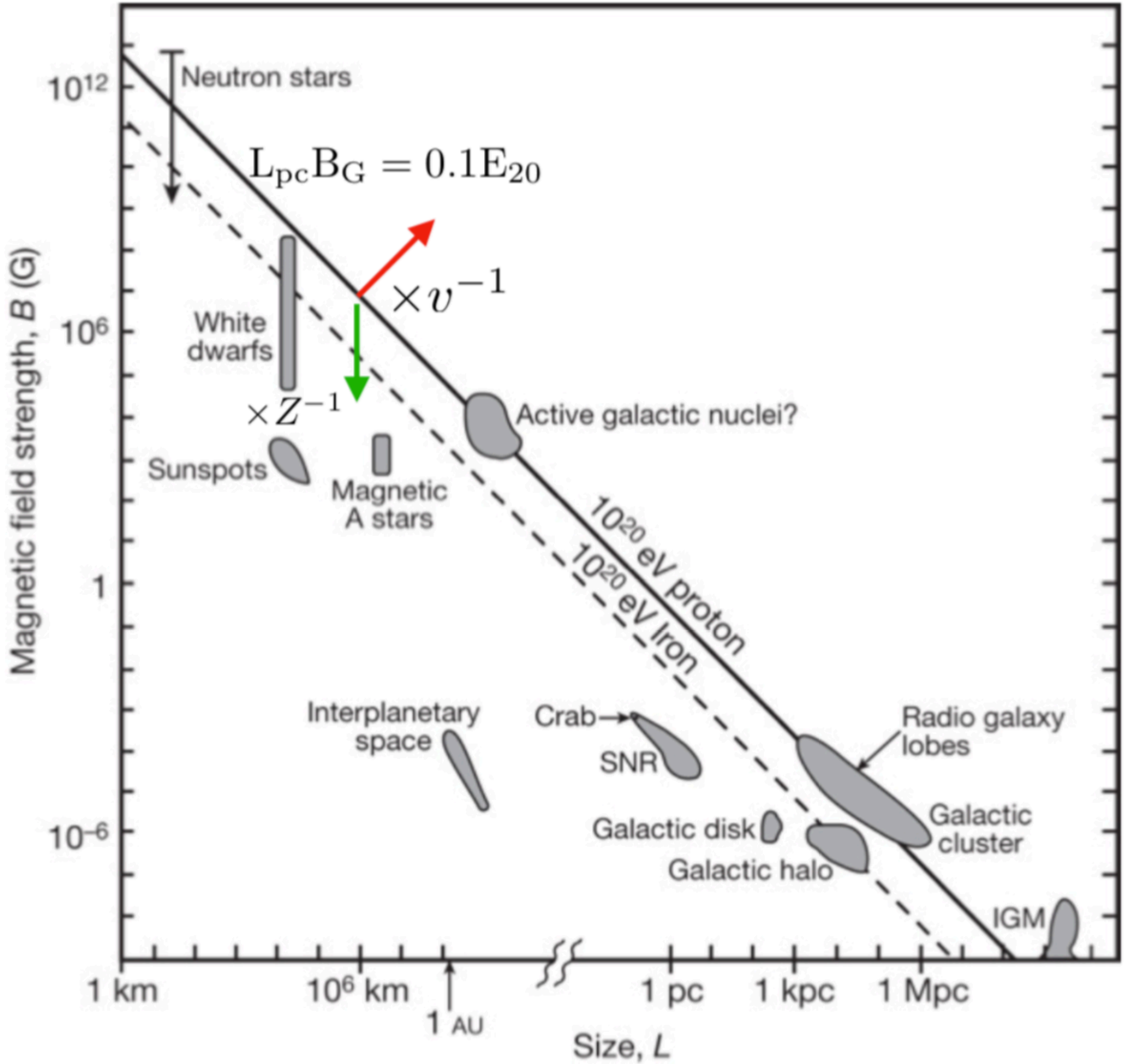


Figure 3: Hillas plot showing the maximum energy achievable in various astrophysical source of given characteristic size and magnetic field amplitude (credit: F. Aharonian).