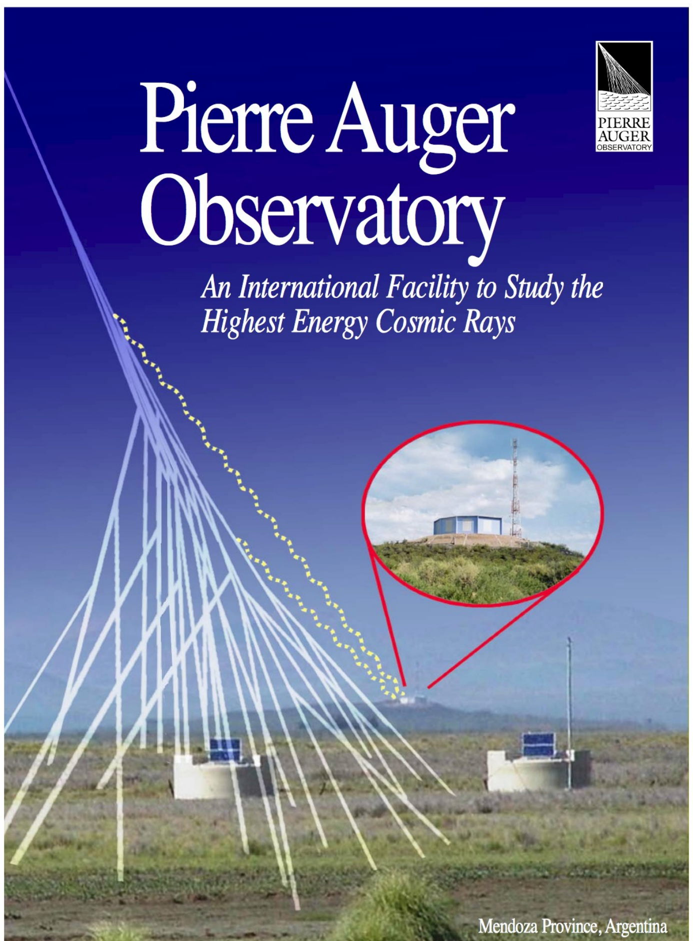
2011 BCVSPIN Advanced Study Institute in Particle Physics and Cosmology, Huê´, Vietnam, 25-30 July 2011

Ultra High Energy Cosmic Rays



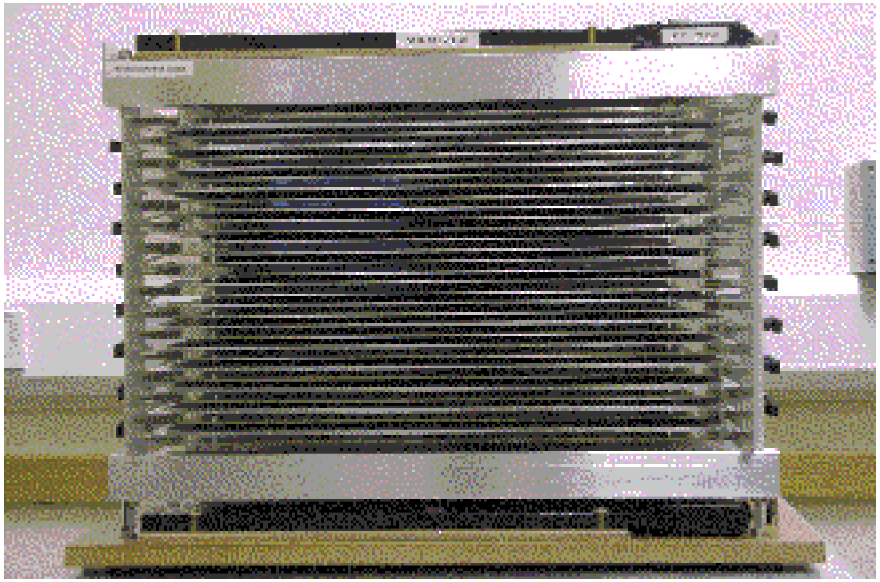
and_

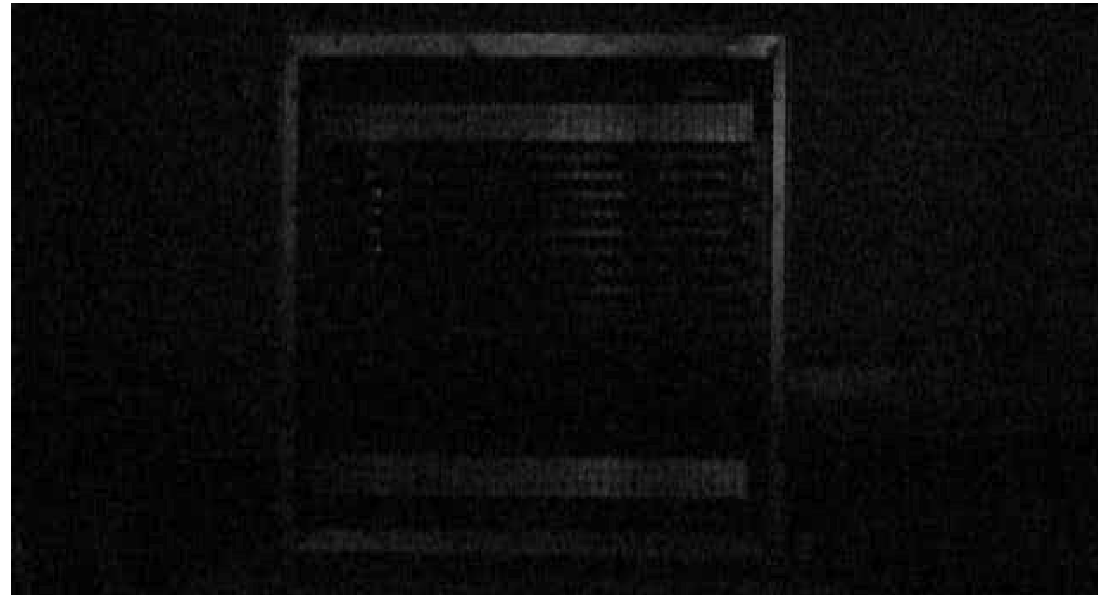
The Pierre Auger Observatory

Paolo Privitera

THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES

Cosmic Rays are always with us



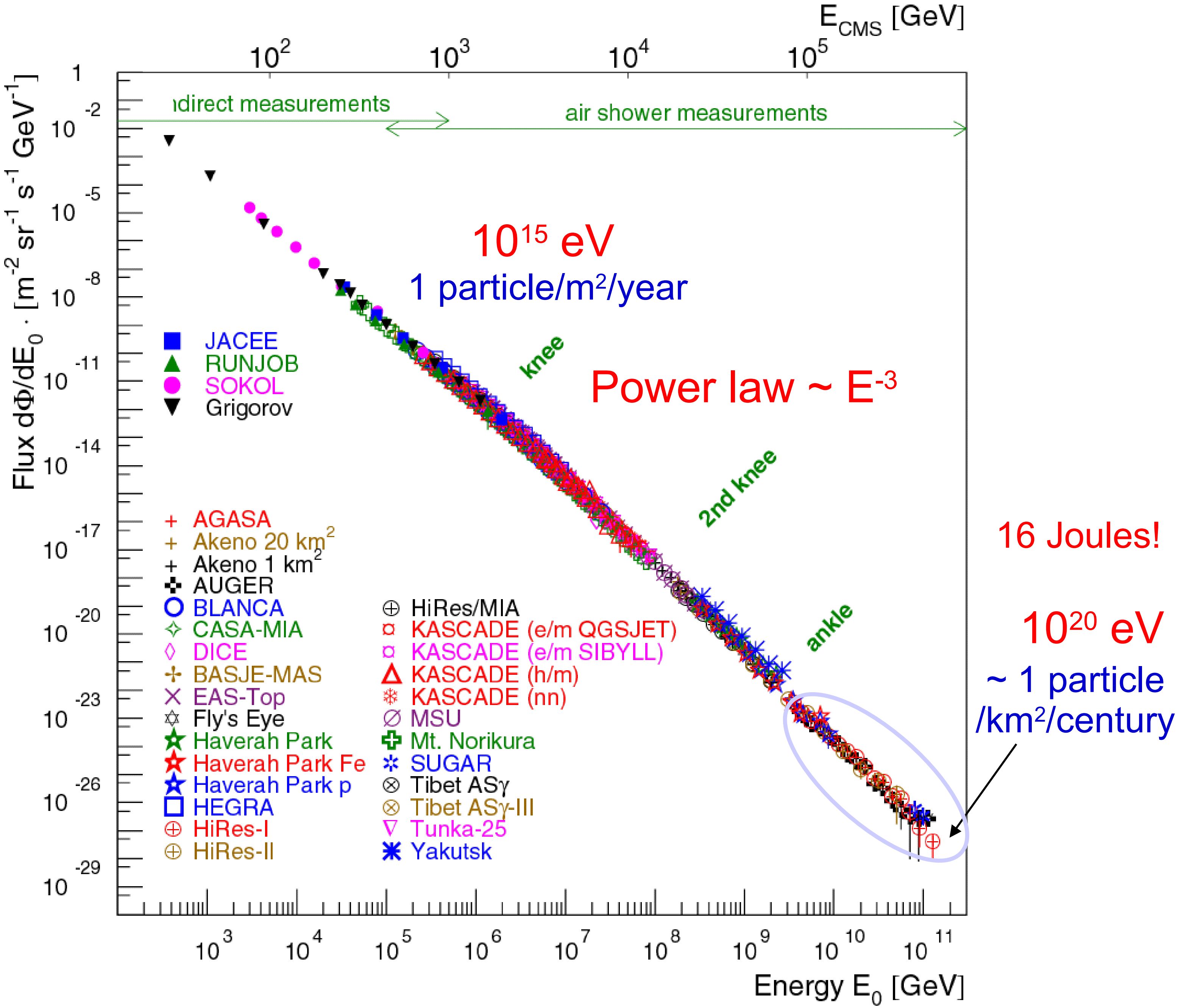


A particle detector: the Spark Chamber
(courtesy Universty of Birmingham)

Rate of cosmic rays at ground ≈ 1 / cm^2 / minute

Typical cosmic ray energy 1 GeV

Ultra High Energy Cosmic Rays



Amazing energies?

Ultra High Energy Cosmic Ray

10^{20} eV = 16 Joule !!!

Energy/mass = 10^{28} J/kg

Energy/size = 10^{31} J/cm^2

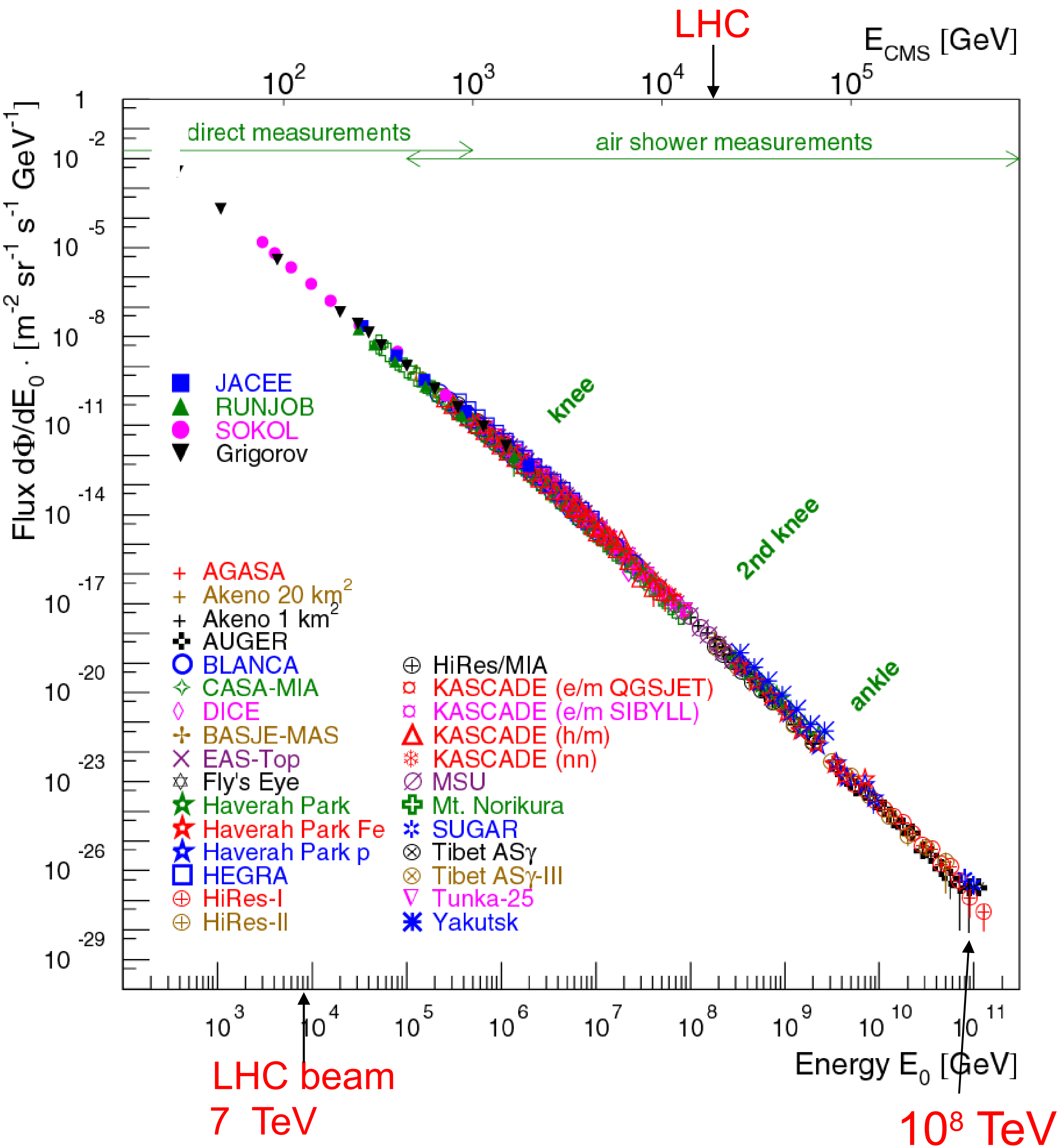
Sicilian cannolo:

300 Cal = 1.2 MJoule !!!

Energy/mass = 10^{7} J/kg

Energy/size = 10^{4} J/cm^2

UHECR vs LHC



$E_{CMS}(\text{UHECR}) \approx \sqrt{2\, m_p\, E_p}$

$= \sqrt{2\ 10^9\ 10^{20}} \approx\ 4.4\ 10^{14}$ eV

= **440 TeV**

E_{CMS} (LHC) = **14 TeV**

UHECR vs LHC

Proton pizza

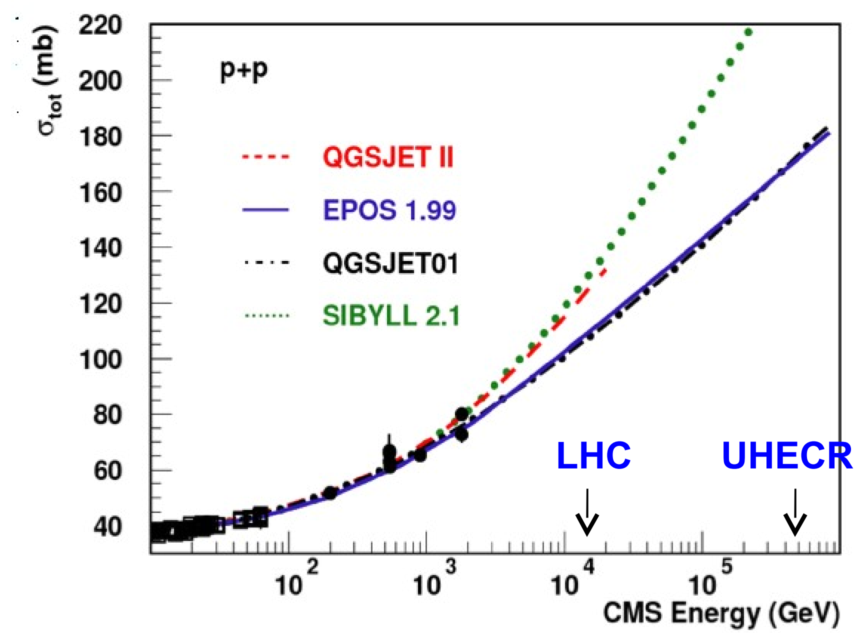
(Courtesy of F. Le Diberder)

Air pizza

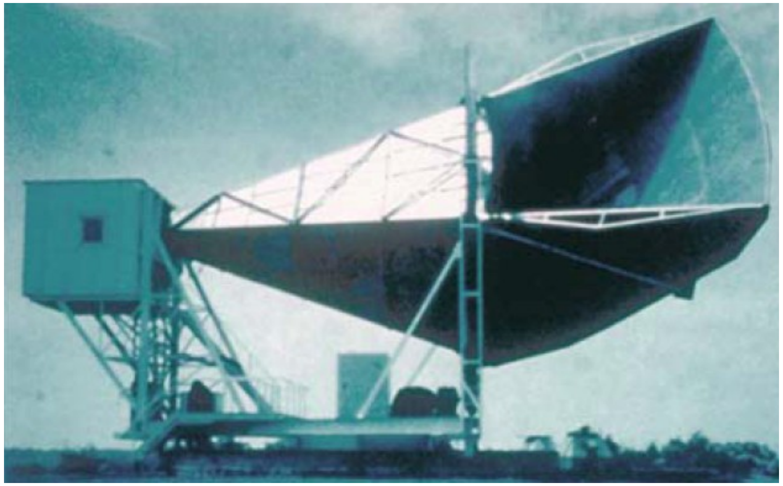
UHECR allow to explore “pizza-pizza” interactions (underlying events, minimum bias events) way above LHC energy.

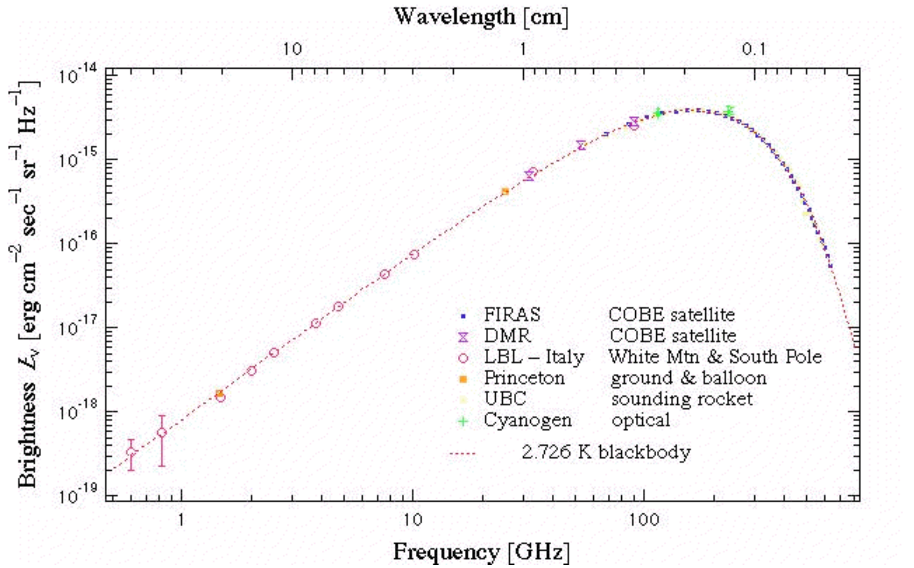
NOTE: too few events to study Higgs, supersimmetry, etc.

Measurement of the p-p cross section, a fundamental quantity in particle physics



UHECR and Cosmology





Penzias and Wilson discovery of Cosmic Microwave Background (1965)

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

The Greisen-Zatsepin-Kusmin "cutoff"

A definite prediction:
strong suppression of the flux

The Greisen-Zatsepin-Kusmin "cut-off"

$$p + \gamma_{2.7^\circ K} \longrightarrow \begin{array}{l} p + \pi^0 \\ n + \pi^+ \end{array}$$

PION PHOTOPRODUCTION

$$s = m_p^2 + 2 E_p \varepsilon_\gamma (1 - \beta \cos\vartheta) \rightsquigarrow m_p^2 + 4 E_p \varepsilon_\gamma$$

$$\geq (m_p + m_\pi)^2 \quad \text{AT THRESHOLD}$$

$$\Rightarrow \quad E_p \geq \frac{m_\pi (m_\pi + 2 m_p)}{4 \varepsilon_\gamma} \simeq 7 \cdot 10^{19}\ \text{eV}$$

$\varepsilon_\gamma \sim 10^{-3}$ eV

INTERACTION LENGTH

$$L = (\sigma \rho_\gamma)^{-1} \simeq 6\ \text{Mpc}$$

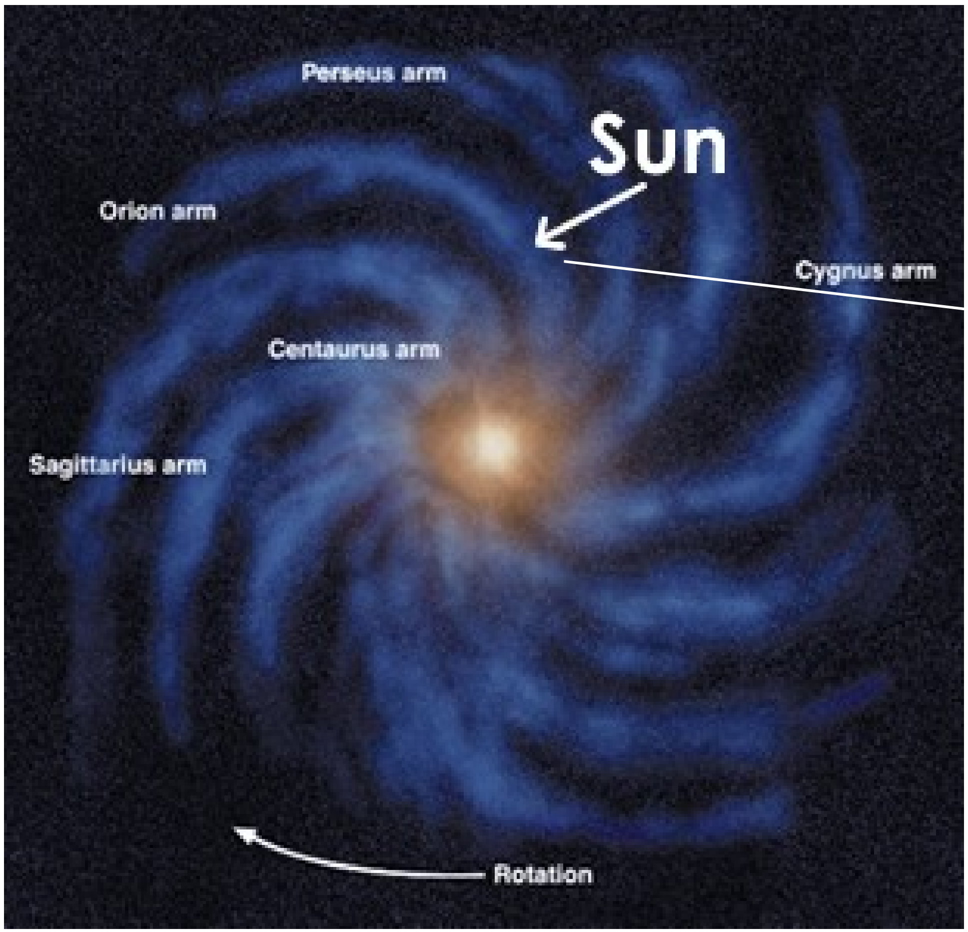
σ: 130 μb ρ_γ: $\frac{400}{cm^3}$

1 b = 10^{-24} cm^2

1 pc = 3.26 light years ≈ 10^{18} cm

Astronomical distances

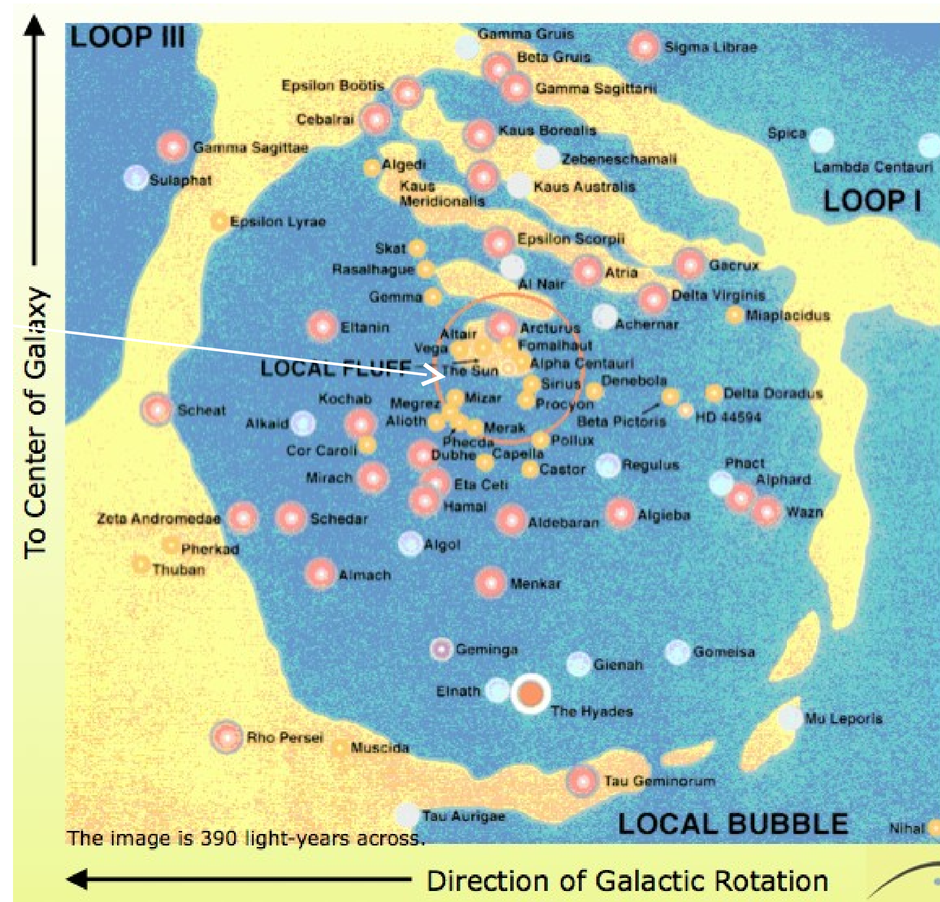
The Milky Way



30 kpc

Distance Sun to center of Milky way 8 kpc

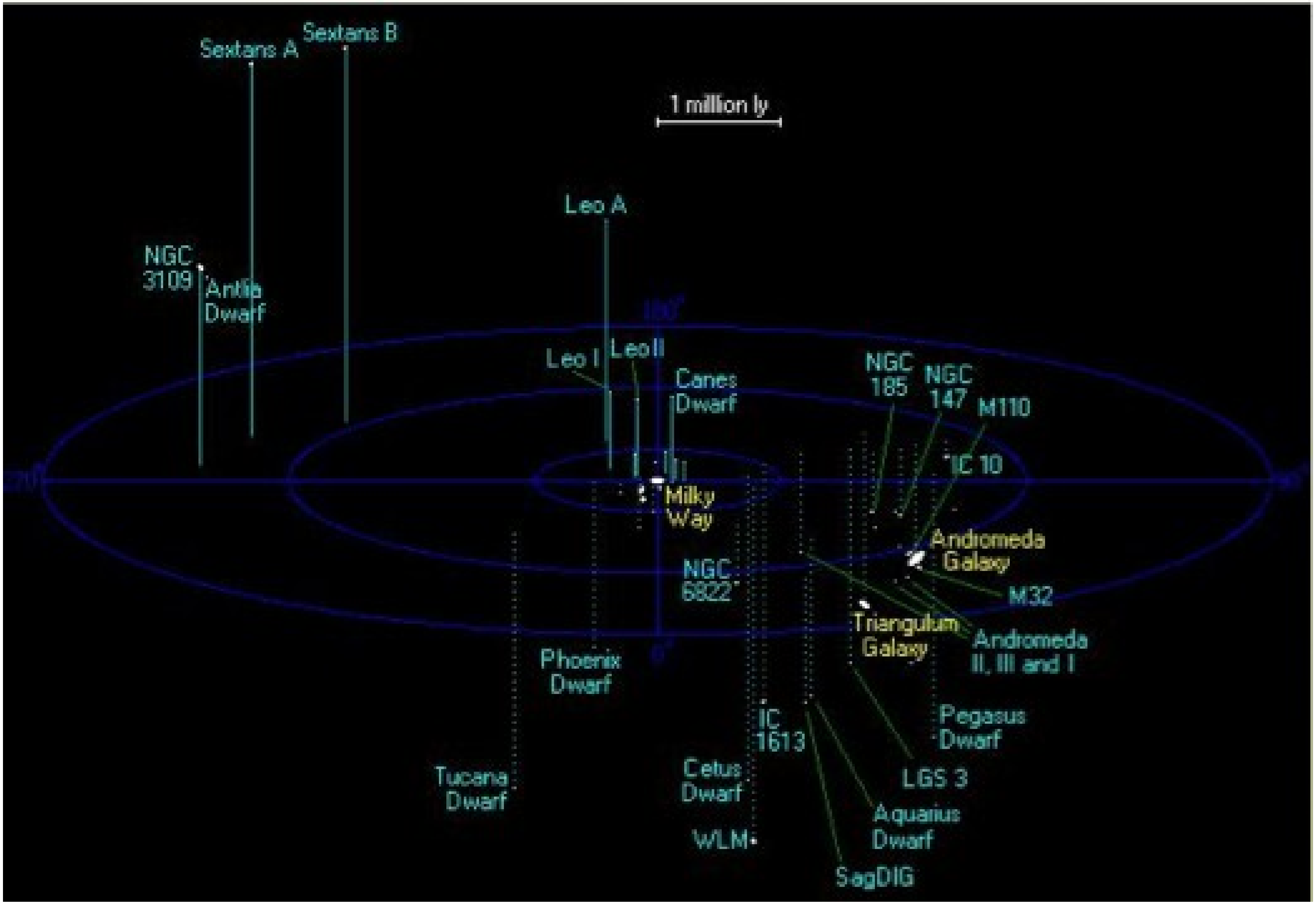
The Solar neighborhood



120 pc

Distance earth to Alpha Centauri 1.3 pc

Local group of galaxies



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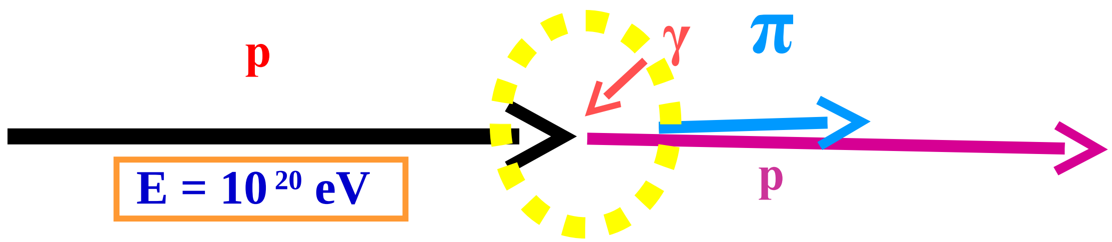
2 Mpc

The Greisen-Zatsepin-Kusmin "cut-off"

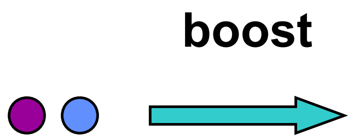


$$E_p \sim E_p' + E_\pi$$

$$E_p - E_p' = \Delta E_p = E_\pi$$

$$\frac{\Delta E_p}{E_p} = \frac{E_\pi}{E_p}$$

at threshold

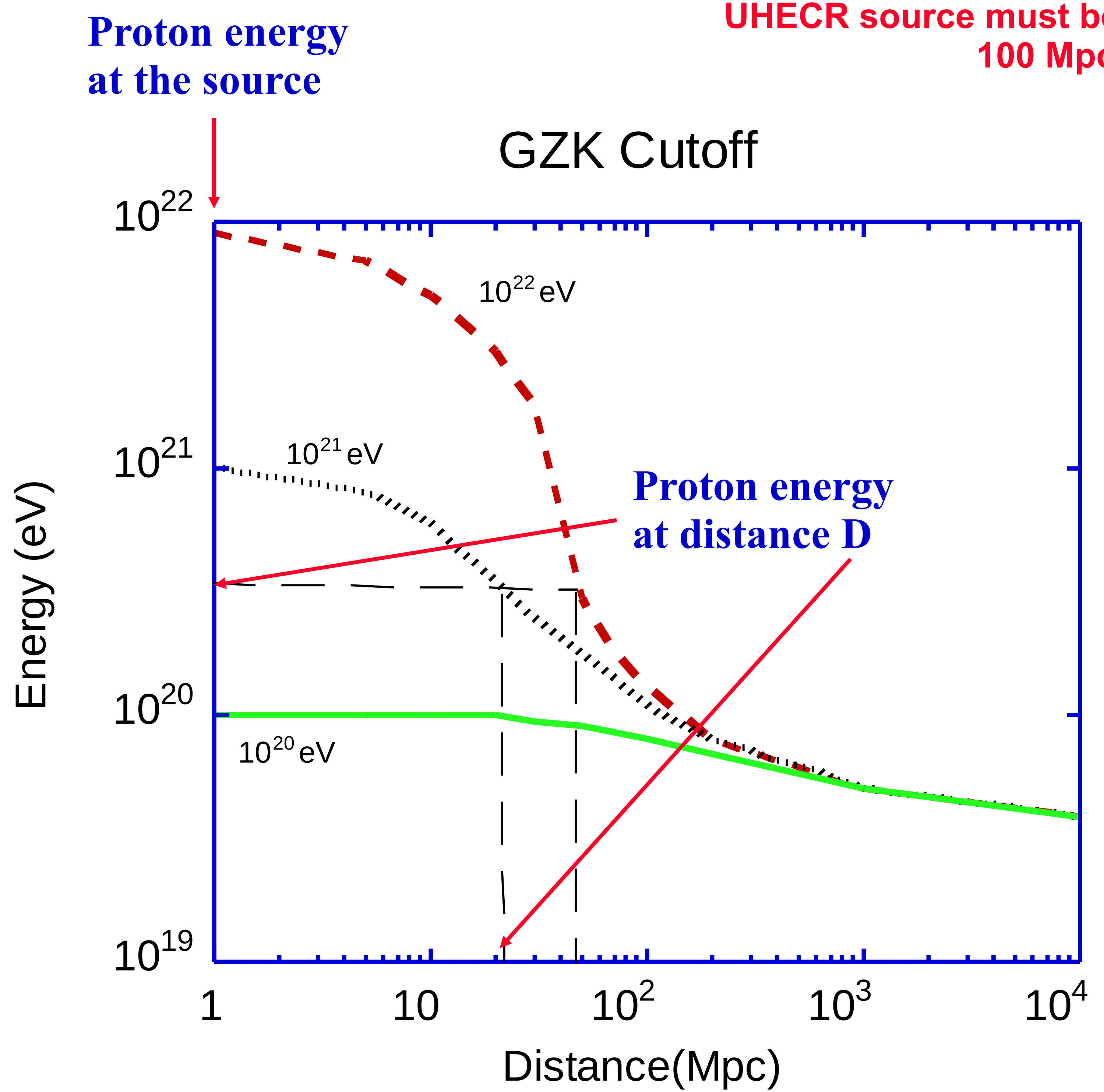


$$\gamma_{Lab} = E_p/(m_p + m_\pi)$$

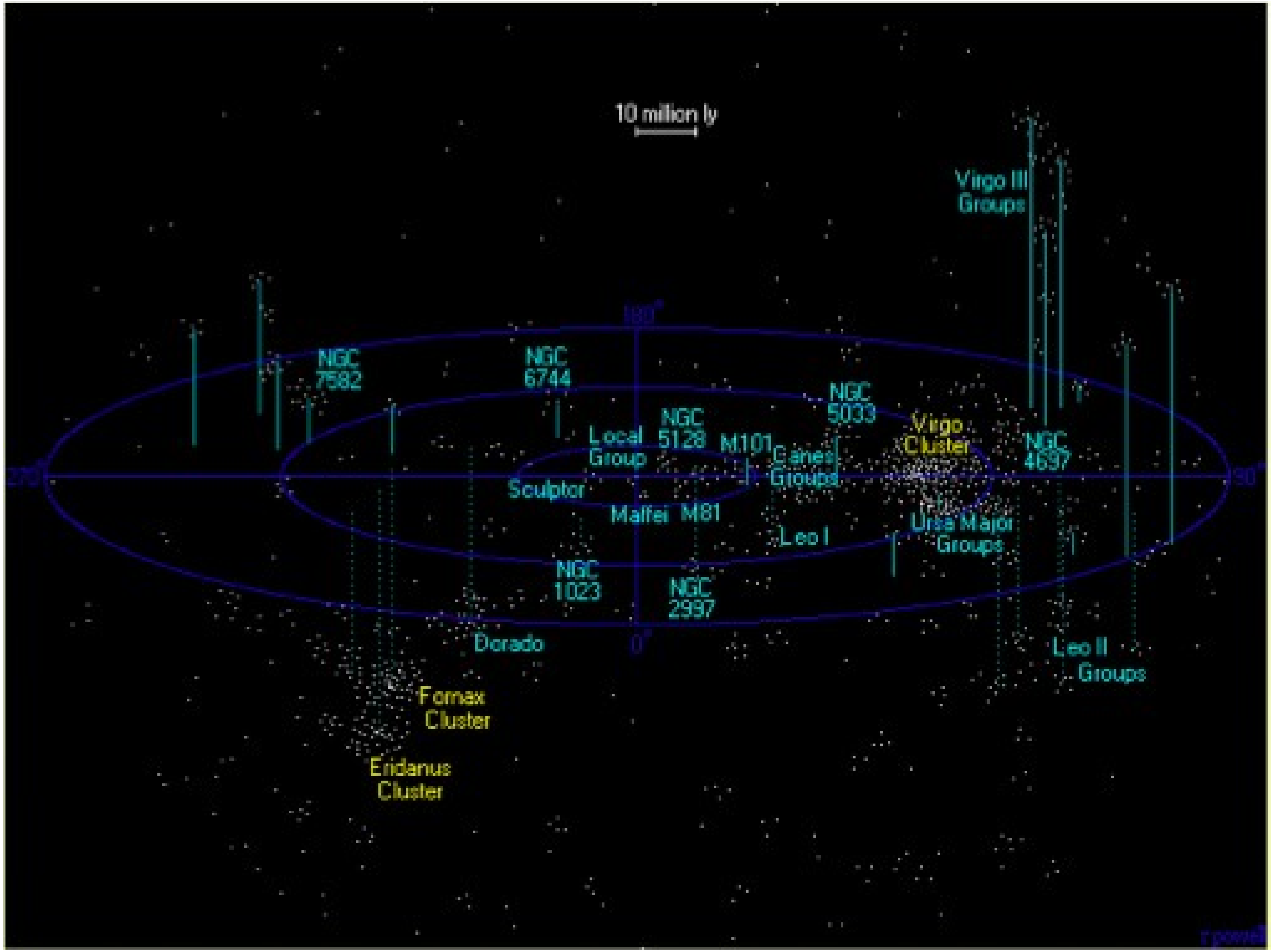
$$E_\pi = \gamma_{Lab}\, m_\pi = E_p\, m_\pi /(m_p + m_\pi)$$

$$\frac{\Delta E_p}{E_p} \sim \frac{m_\pi}{m_p + m_\pi} \sim 15\ \%$$

UHECR source must be closer than 50-100 Mpc!



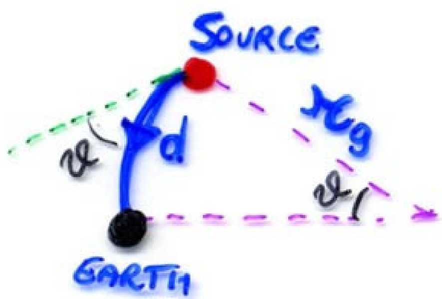
Local supercluster



40 Mpc

Can we find their origin?

✳ ARRIVAL DIRECTION



$$\vartheta \sim \frac{d}{r_g} \qquad r_g \sim \frac{E}{ZeB}$$

$$\Rightarrow \quad \vartheta_d \simeq 0{,}5^\circ \, Z \cdot \left(\frac{E}{10^{20}\,eV}\right)^{-1} \cdot \left(\frac{d}{1\,Mpc}\right) \cdot \left(\frac{B}{10^{-9}\,G}\right)$$

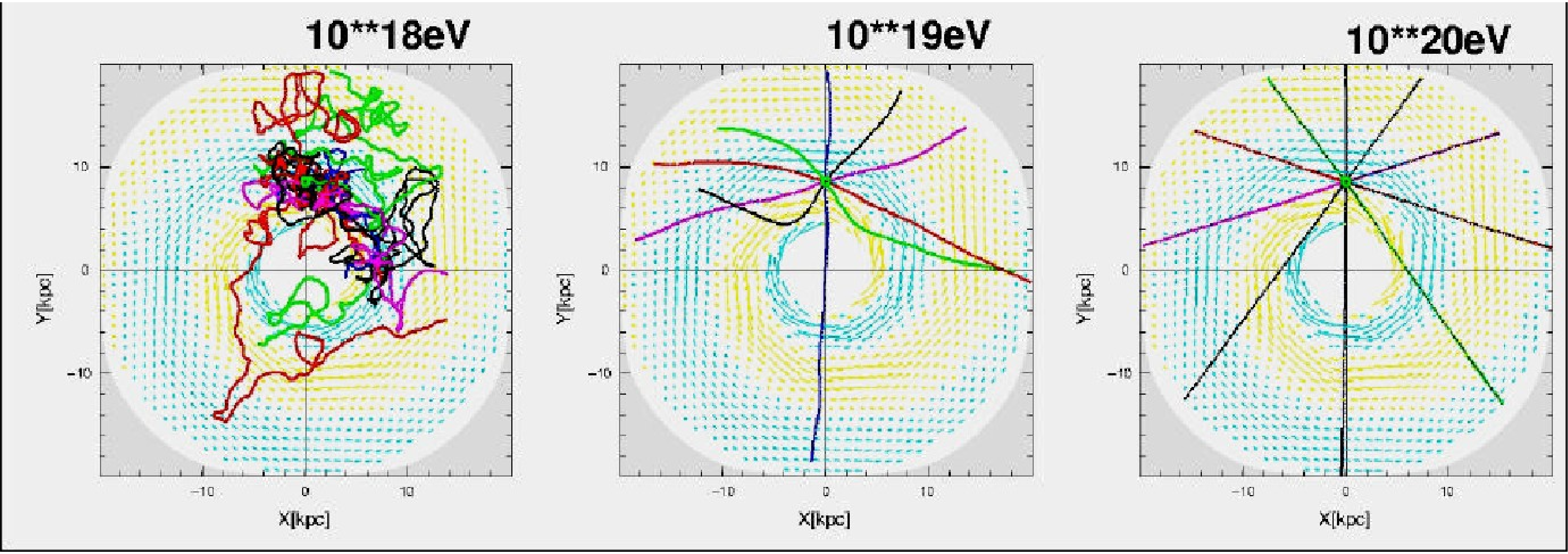
Ex: PROTON FROM THE GALACTIC CENTER

$E = 3 \cdot 10^{20}\,eV$, $d = 8{,}5\,Kpc$, $B = 2\,\mu G$

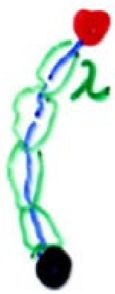
$\Rightarrow \quad \vartheta \sim 3^\circ$

- **Galactic magnetic fields:**

A 10^{20} eV proton is almost not deflected in the galactic magnetic field (μG



Can we find their origin?



$$\sigma_\vartheta(d) \simeq \sqrt{N}\,\vartheta_\lambda \simeq \sqrt{\frac{d}{\lambda}\cdot\frac{\lambda}{r_g}} \simeq \sqrt{d}\,\sqrt{\lambda}\,\frac{1}{r_g}$$

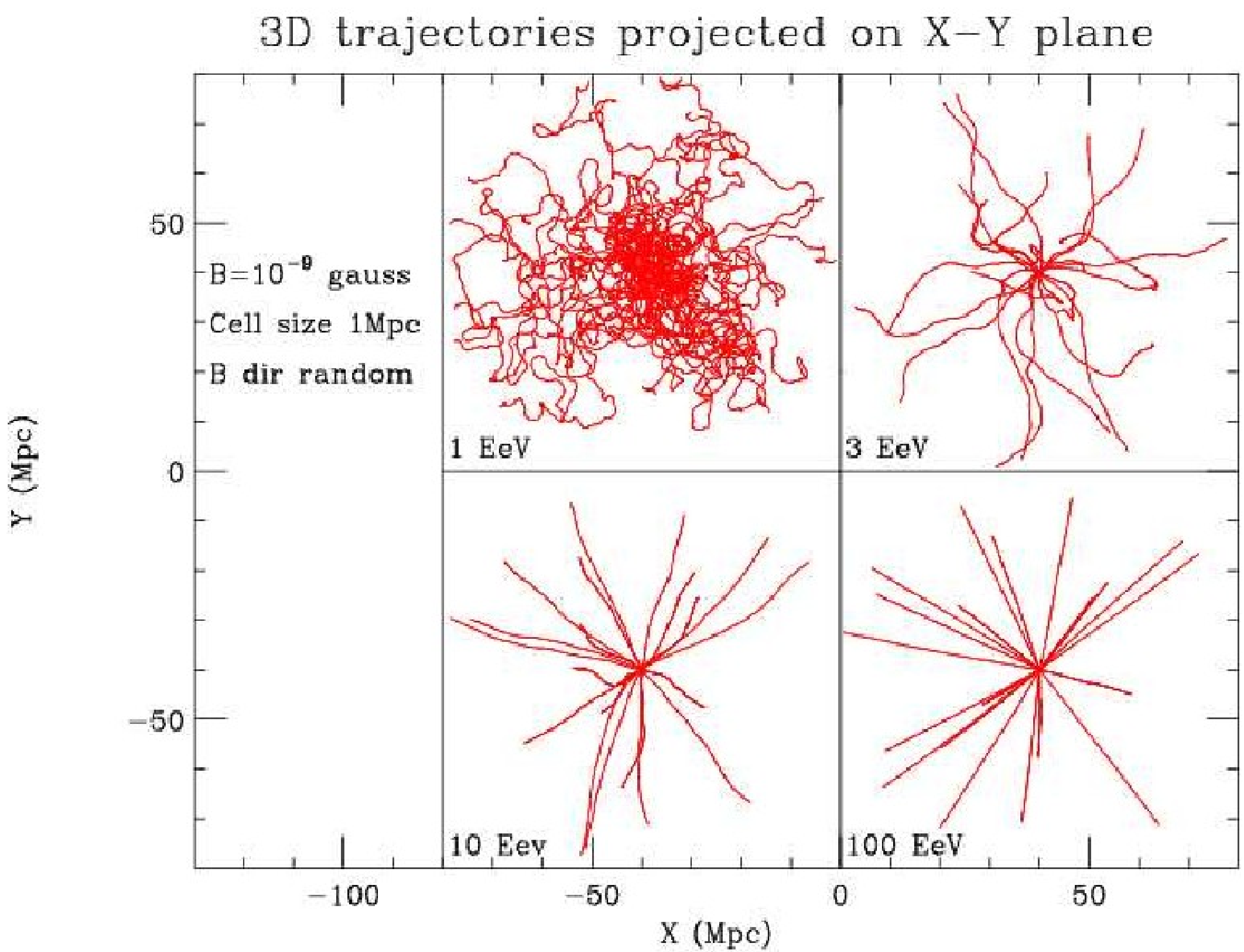
$$\simeq 0{,}8^\circ \cdot Z \cdot \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \cdot \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{\frac{1}{2}} \cdot \left(\frac{\lambda}{1\,\mathrm{Mpc}}\right)^{\frac{1}{2}} \cdot \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)$$

Ex: p, $d = 50\,\mathrm{Mpc}$

$\lambda = 1\,\mathrm{Mpc}$, $B = 1\,\mathrm{nG}$ $\Rightarrow$ $\sigma_\vartheta \sim 0{,}6^\circ$

- **Inter-Galactic magnetic fields:**

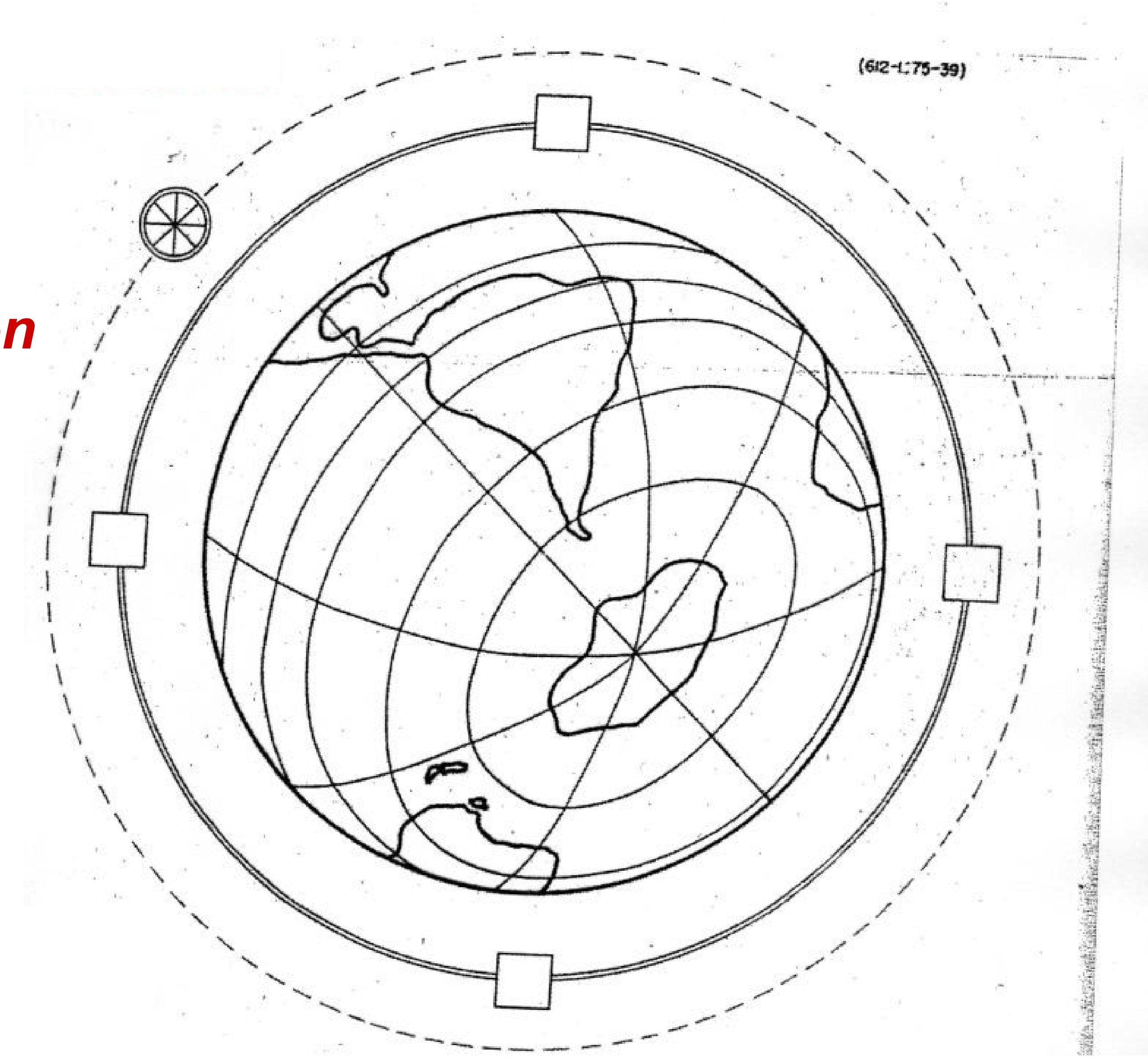
A 10^{20} eV proton is almost not deflected in the inter-galactic magnetic field (nG)



1 EeV = 10^{18} eV

10^{20} eV accelerator?

Fermi's
Globatron

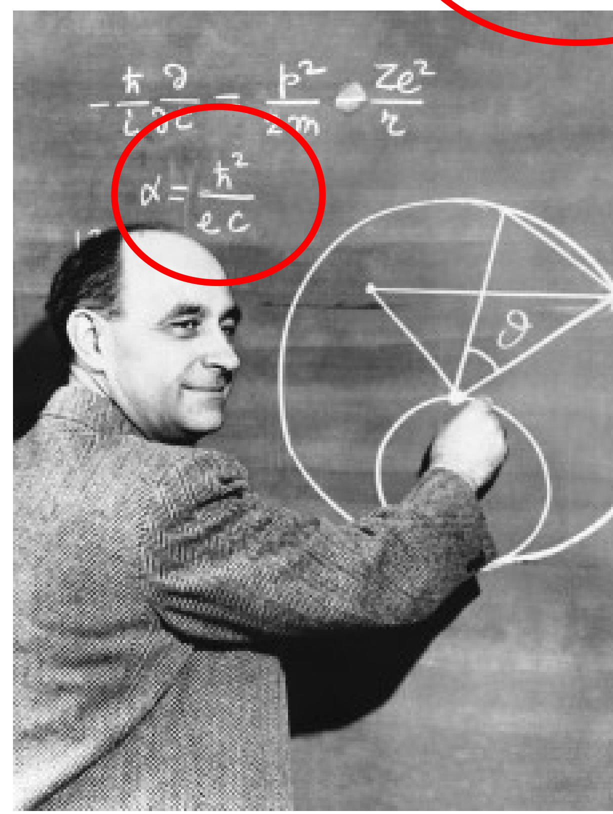


American Physical Society 1954

$5\ 10^{15}$ eV

Enrico Fermi
(1901 Rome – 1954 Chicago)

$$\alpha = \frac{e^2}{\hbar c} \; !$$

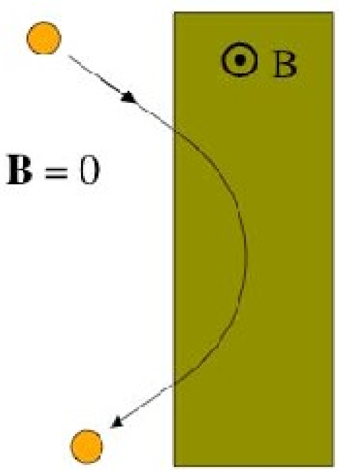


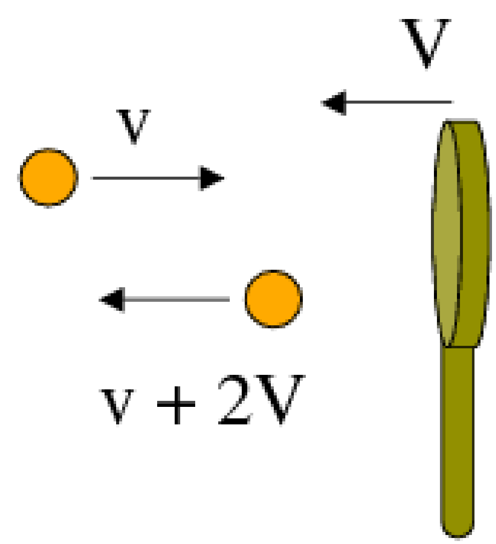
Chain reaction, the first atomic pile, theory of beta decay, Fermions, Fermilab, ….

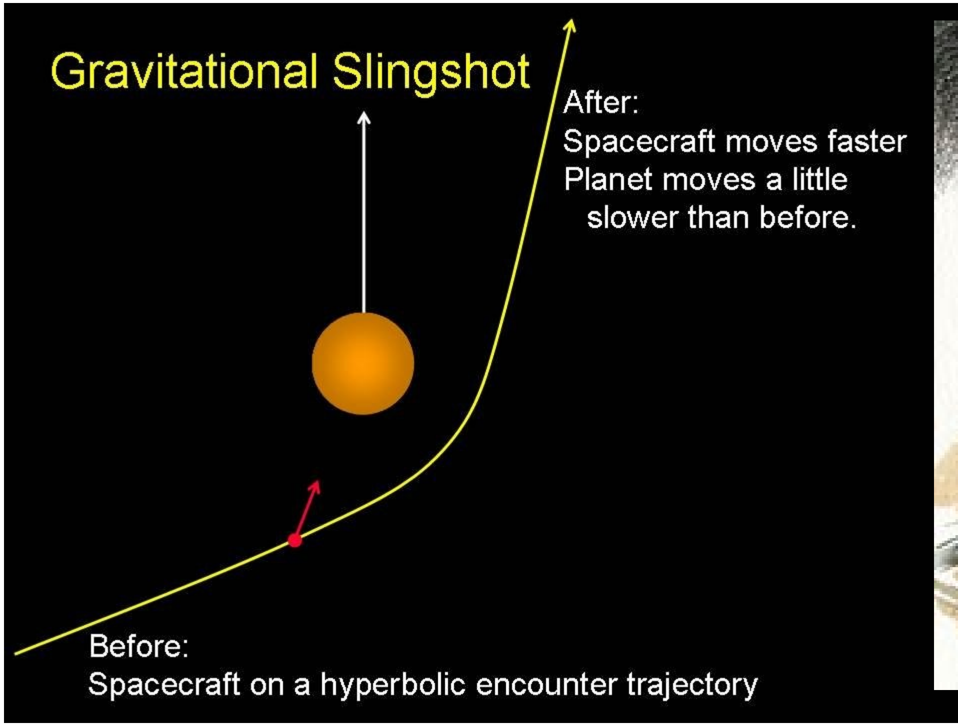
On the Origin of the Cosmic Radiation

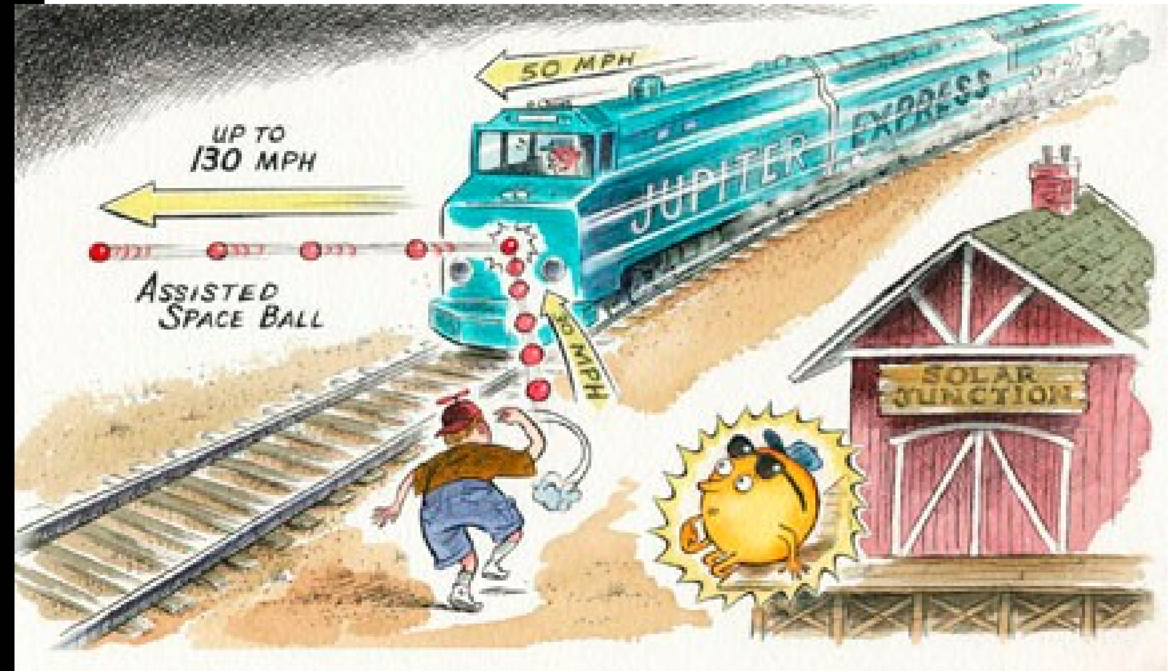
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

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.



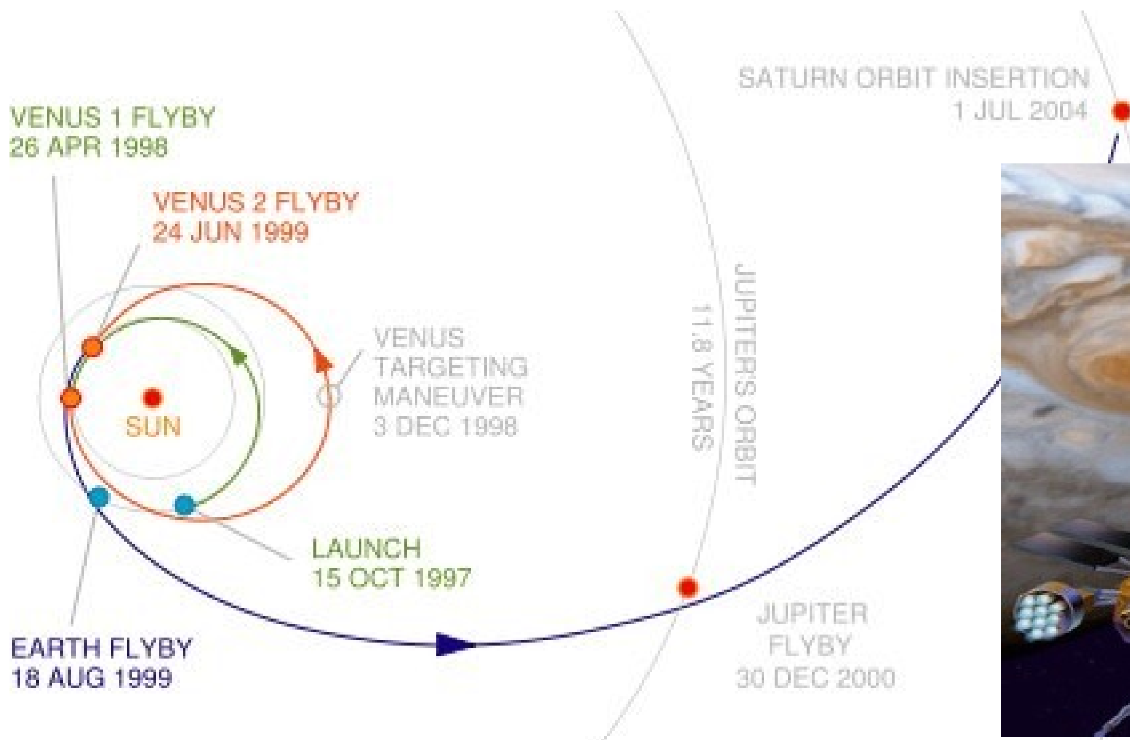


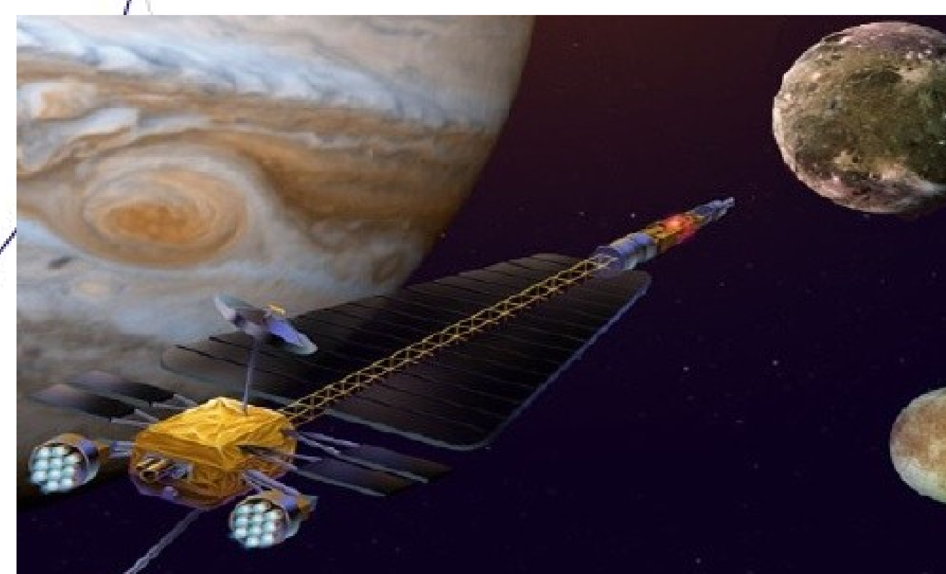




Gravity assist

Cassini





Fermi's notebook

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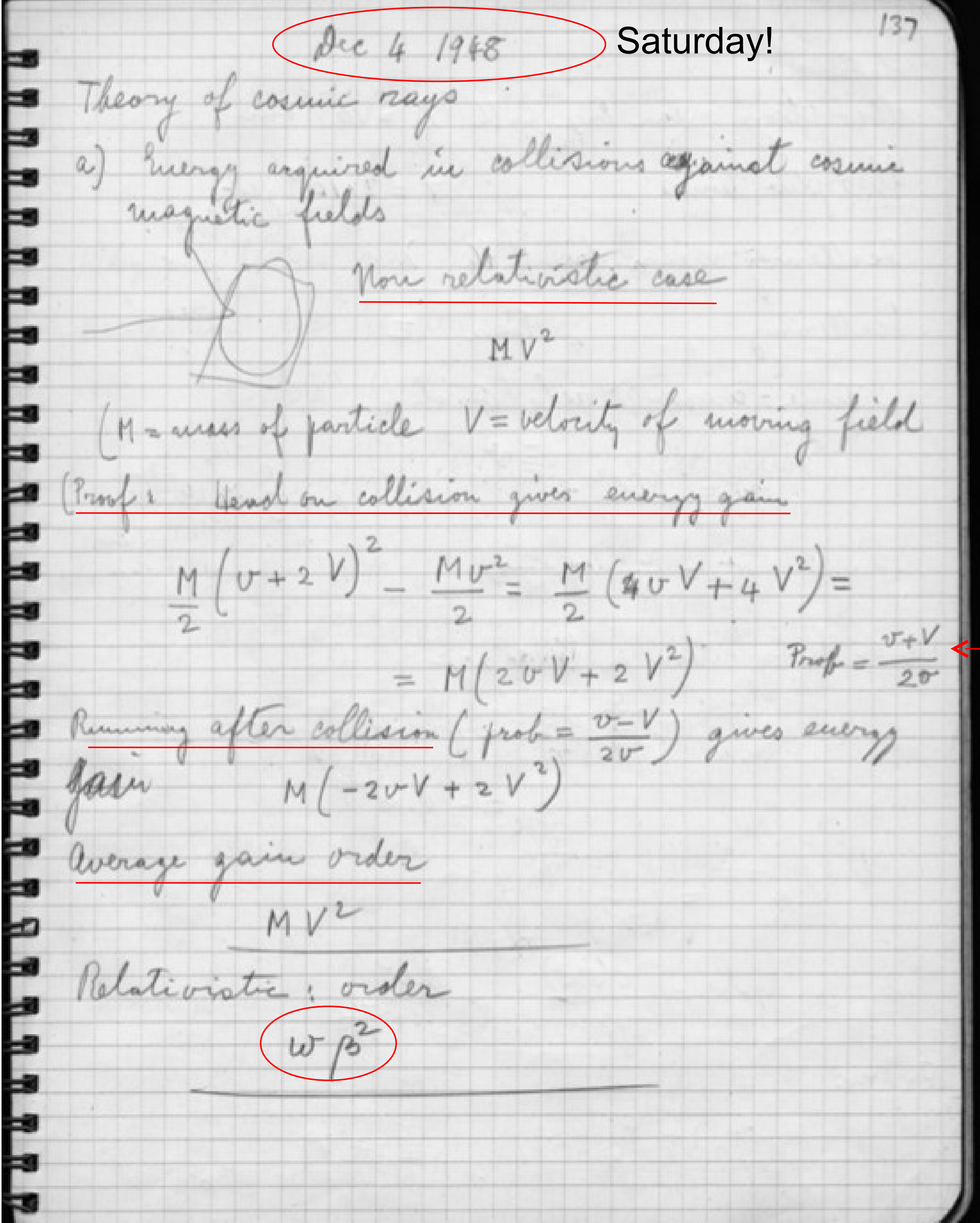

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Dec 4 1948 Saturday!

Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

$$MV^2$$

(M = mass of particle V = velocity of moving field

(Prob: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV+2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision $\left(\text{prob} = \frac{v-V}{2v}\right)$ gives energy gain

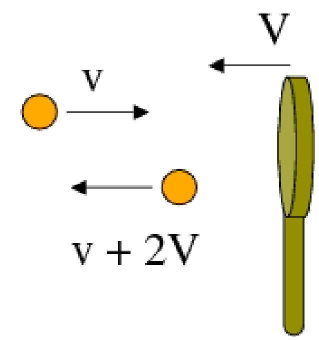
$$M(-2vV+2V^2)$$

Average gain order

$$MV^2$$

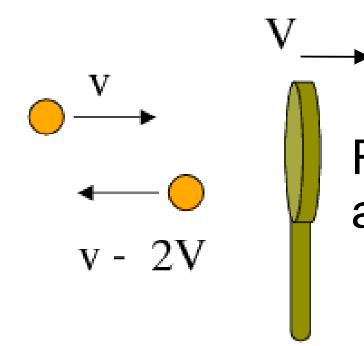
Relativistic: order

$$w\beta^2$$



Head-on collision

Frequency of collisions ≈ relative velocity



Running after collision

$$\beta = \frac{\text{Velocity of B field cloud}}{c}$$

Fermi’s notebook

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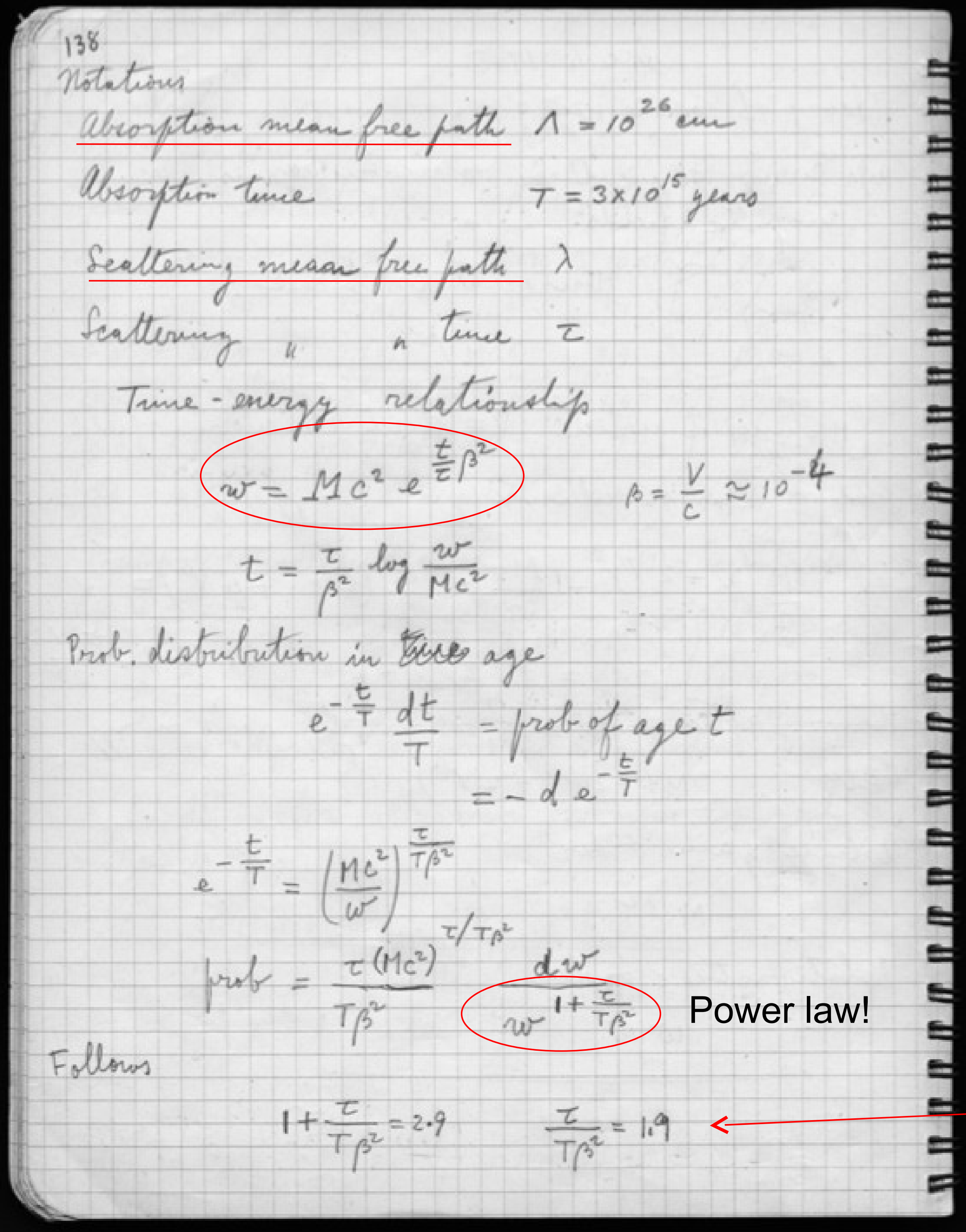
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Notations

Absorption mean free path $\Lambda = 10^{26}$ cm

Absorption time $T = 3\times10^{15}$ years

Scattering mean free path λ

Scattering " " time τ

Time-energy relationship

$$w = Mc^2 e^{\frac{t}{\tau}\beta^2} \qquad \beta = \frac{V}{c} \simeq 10^{-4}$$

$$t = \frac{\tau}{\beta^2}\log\frac{w}{Mc^2}$$

Prob. distribution in age

$$e^{-\frac{t}{T}}\frac{dt}{T} = \text{prob of age } t = -d\,e^{-\frac{t}{T}}$$

$$e^{-\frac{t}{T}} = \left(\frac{Mc^2}{w}\right)^{\frac{\tau}{T\beta^2}}$$

$$\text{prob} = \frac{\tau (Mc^2)^{\tau/T\beta^2}}{T\beta^2}\,\frac{dw}{w^{1+\frac{\tau}{T\beta^2}}}$$

Power law!

Follows

$$1+\frac{\tau}{T\beta^2} = 2.9 \qquad \frac{\tau}{T\beta^2} = 1.9$$

The measured spectral index gives information on absorption and scattering

Fermi's notebook

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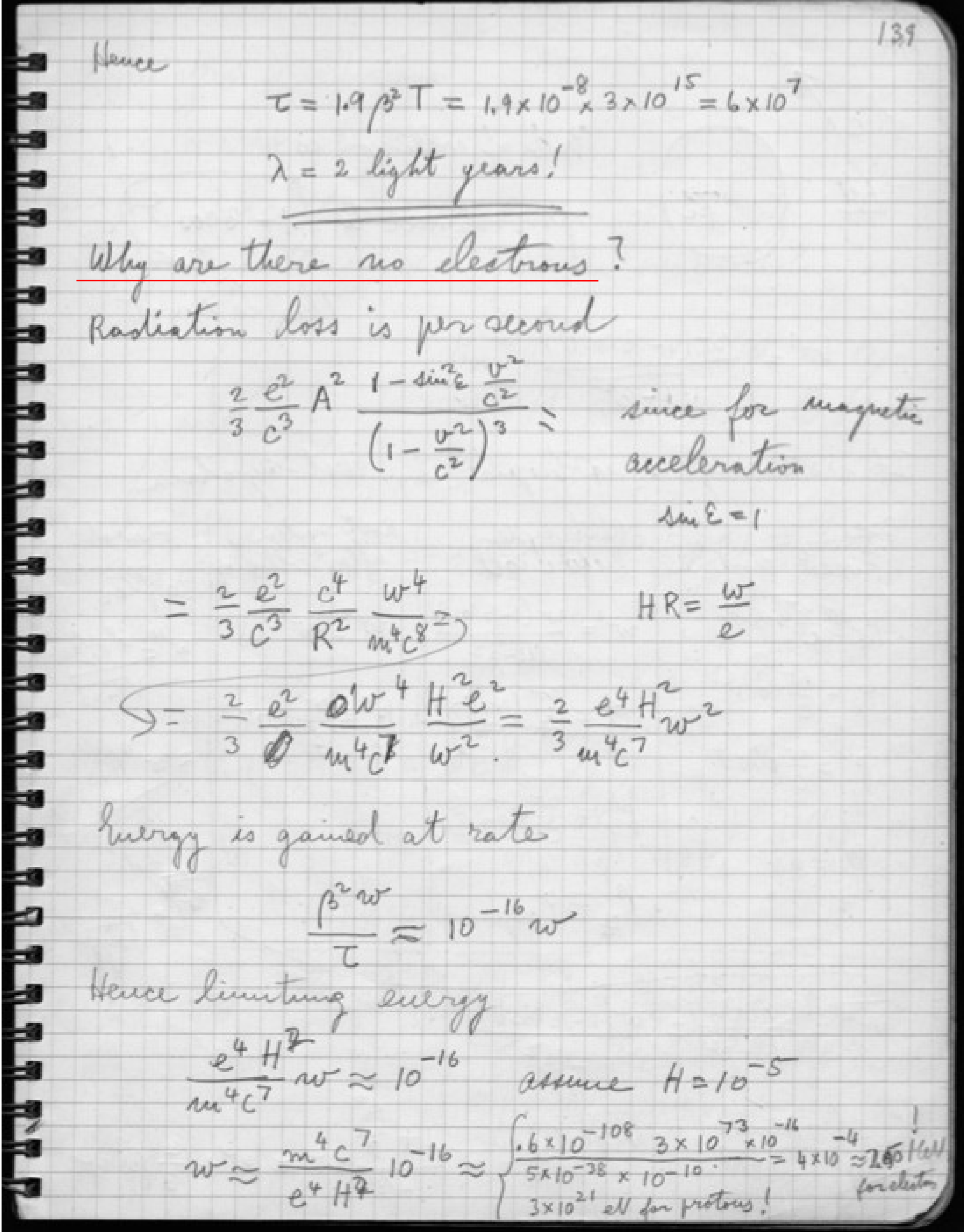

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Hence

$$\tau = 1.9\,\beta^2 T = 1.9\times10^{-8}\times3\times10^{15} = 6\times10^{7}$$

$\lambda = 2$ light years!

Why are there no electrons?

Radiation loss is per second

$$\frac{2}{3}\frac{e^2}{c^3}A^2\,\frac{1-\sin^2\varepsilon\,\frac{v^2}{c^2}}{\left(1-\frac{v^2}{c^2}\right)^3} \approx$$

since for magnetic acceleration $\sin\varepsilon = 1$

$$= \frac{2}{3}\frac{e^2}{c^3}\frac{c^4}{R^2}\frac{w^4}{m^4c^8} =$$

$$HR = \frac{w}{e}$$

$$= \frac{2}{3}\frac{e^2}{c}\frac{w^4}{m^4c^7}\frac{H^2e^2}{w^2} = \frac{2}{3}\frac{e^4H^2}{m^4c^7}w^2$$

Energy is gained at rate

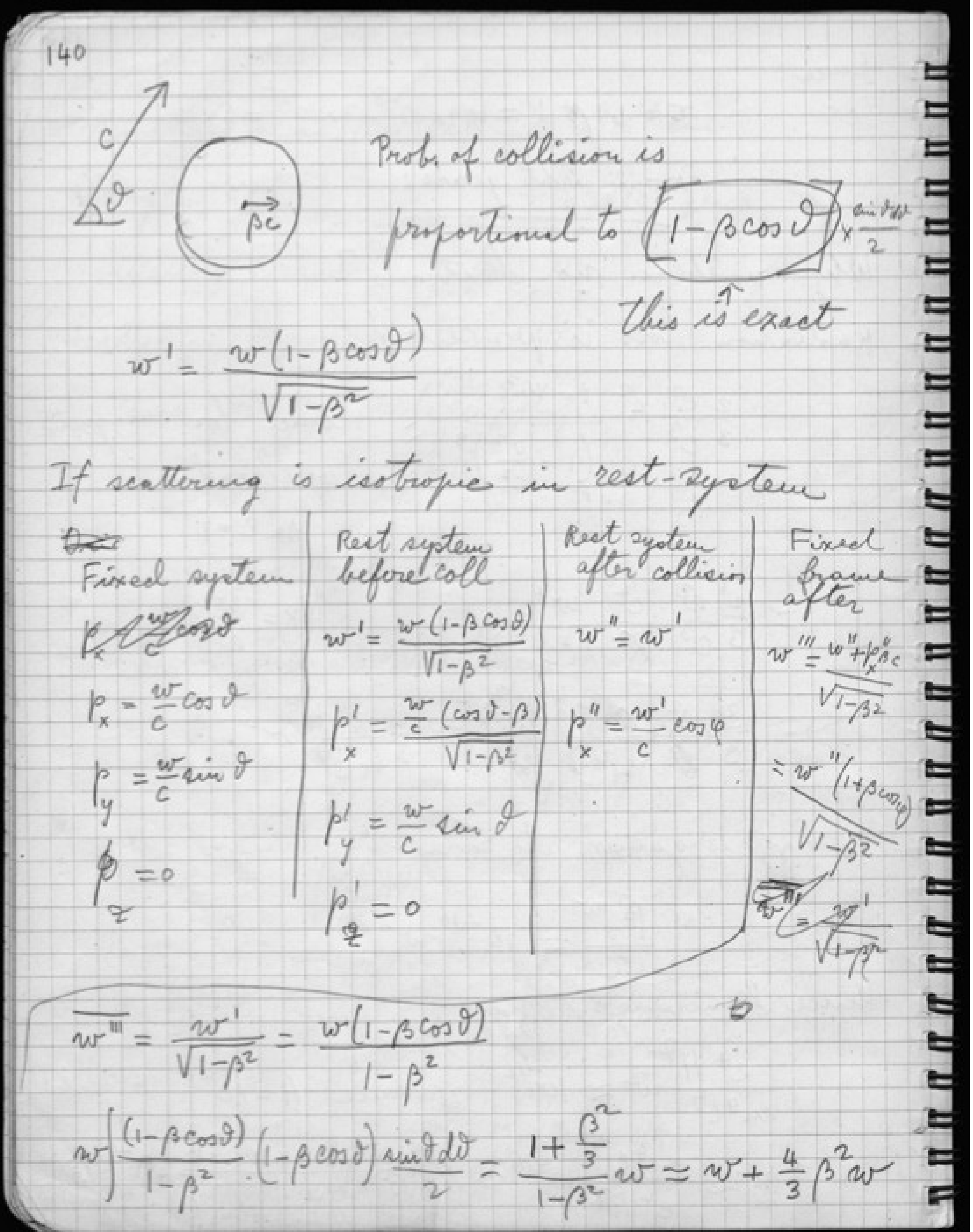
$$\frac{\beta^2 w}{\tau} \approx 10^{-16}\,w$$

Hence limiting energy

$$\frac{e^4H^2}{m^4c^7}\,w \approx 10^{-16}$$

assume $H = 10^{-5}$

$$w \approx \frac{m^4c^7}{e^4H^2}10^{-16} \approx \begin{cases}\frac{.6\times10^{-108}\;3\times10^{73}\times10^{-16}}{5\times10^{-38}\times10^{-10}} = 4\times10^{-4} \approx 250\text{ MeV! for electrons}\\ 3\times10^{21}\text{ eV for protons!}\end{cases}$$



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Prob. of collision is proportional to $(1-\beta\cos\vartheta) \times \frac{\sin\vartheta\, d\vartheta}{2}$

this is exact

$$w' = \frac{w(1-\beta\cos\vartheta)}{\sqrt{1-\beta^2}}$$

If scattering is isotropic in rest-system

Fixed system	Rest system before coll	Rest system after collision	Fixed frame after
$p_x = \frac{w}{c}\cos\vartheta$	$w' = \frac{w(1-\beta\cos\vartheta)}{\sqrt{1-\beta^2}}$	$w'' = w'$	$w''' = \frac{w'' + p''_x \beta c}{\sqrt{1-\beta^2}}$
$p_y = \frac{w}{c}\sin\vartheta$	$p'_x = \frac{\frac{w}{c}(\cos\vartheta - \beta)}{\sqrt{1-\beta^2}}$	$p''_x = \frac{w'}{c}\cos\varphi$	$= \frac{w''(1+\beta\cos\varphi)}{\sqrt{1-\beta^2}}$
$p_z = 0$	$p'_y = \frac{w}{c}\sin\vartheta$		$\overline{w'''} = \frac{w'}{\sqrt{1-\beta^2}}$
	$p'_z = 0$		

$$\overline{w'''} = \frac{w'}{\sqrt{1-\beta^2}} = \frac{w(1-\beta\cos\vartheta)}{1-\beta^2}$$

$$w\int \frac{(1-\beta\cos\vartheta)}{1-\beta^2}(1-\beta\cos\vartheta)\frac{\sin\vartheta\, d\vartheta}{2} = \frac{1+\frac{\beta^2}{3}}{1-\beta^2}w \simeq w + \frac{4}{3}\beta^2 w$$

Fermi’s notebook

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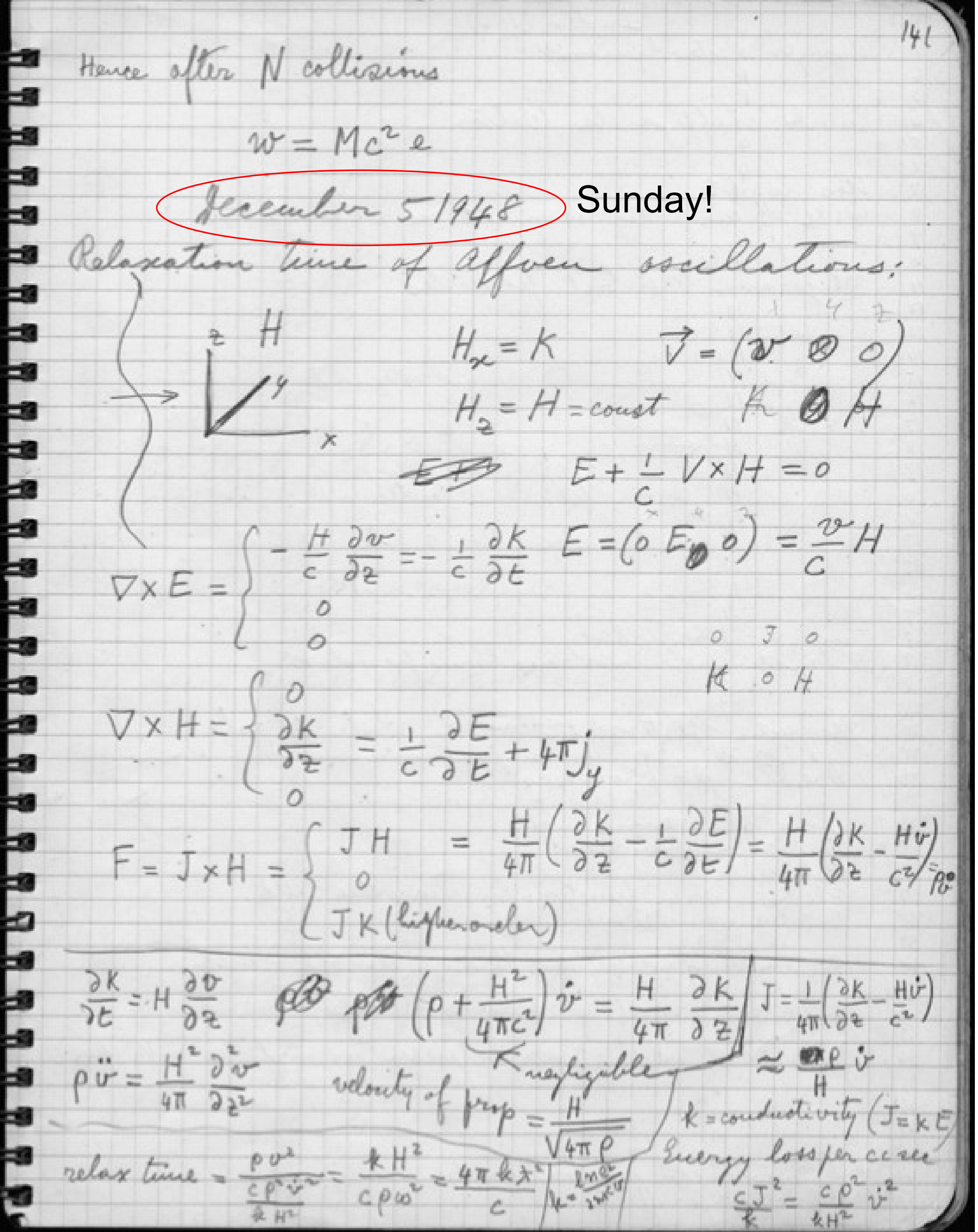
Relativistic calculation



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Hence after N collisions

$$w = Mc^2 e$$

December 5 1948

Sunday!

Relaxation time of Alfven oscillations:

$H_x = K \qquad \vec{V} = (v \;\; 0 \;\; 0)$

$H_z = H = \text{const} \qquad K \;\; 0 \;\; H$

$$E + \frac{1}{c} V \times H = 0$$

$$E = (0 \;\; E_y \;\; 0) = \frac{v}{c} H$$

$$\nabla \times E = \begin{cases} -\frac{H}{c}\frac{\partial v}{\partial z} = -\frac{1}{c}\frac{\partial K}{\partial t} \\ 0 \\ 0 \end{cases}$$

$0 \;\; J \;\; 0$

$K \;\; 0 \;\; H$

$$\nabla \times H = \begin{cases} 0 \\ \frac{\partial K}{\partial z} = \frac{1}{c}\frac{\partial E}{\partial t} + 4\pi j_y \\ 0 \end{cases}$$

$$F = J \times H = \begin{cases} JH = \frac{H}{4\pi}\left(\frac{\partial K}{\partial z} - \frac{1}{c}\frac{\partial E}{\partial t}\right) = \frac{H}{4\pi}\left(\frac{\partial K}{\partial z} - \frac{H\dot{v}}{c^2}\right) = \rho \dot{v} \\ 0 \\ JK \text{ (higher order)} \end{cases}$$

$$\frac{\partial K}{\partial t} = H \frac{\partial v}{\partial z} \qquad \left(\rho + \frac{H^2}{4\pi c^2}\right)\dot{v} = \frac{H}{4\pi}\frac{\partial K}{\partial z} \qquad J = \frac{1}{4\pi}\left(\frac{\partial K}{\partial z} - \frac{H\dot{v}}{c^2}\right) \approx \frac{[illegible]\,\rho \dot{v}}{H}$$

$\frac{H^2}{4\pi c^2}$ negligible

$$\rho \ddot{v} = \frac{H^2}{4\pi}\frac{\partial^2 v}{\partial z^2}$$

velocity of prop $= \frac{H}{\sqrt{4\pi\rho}}$

k = conductivity ($J = kE$)

Energy loss per cc sec

$$\frac{cJ^2}{k} = \frac{c\rho^2}{kH^2}\dot{v}^2$$

relax time $= \frac{\rho v^2}{\frac{c\rho^2 \dot{v}^2}{kH^2}} = \frac{kH^2}{c\rho\omega^2} = \frac{4\pi k \lambda^2}{c}$ $\quad k = [illegible]$

Fermi's notebook

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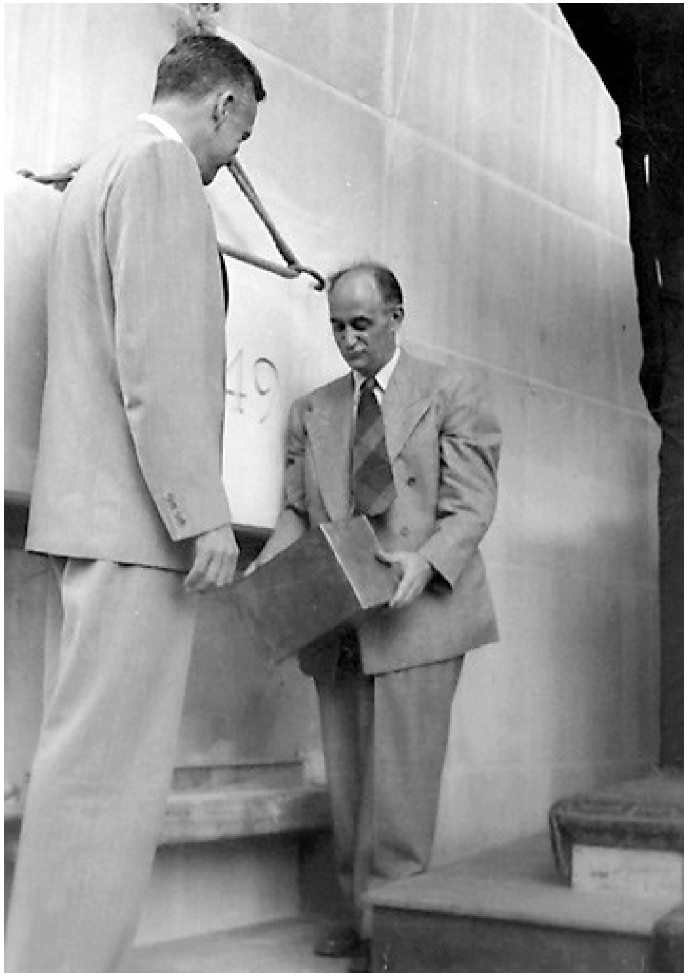
Fermi's time capsule



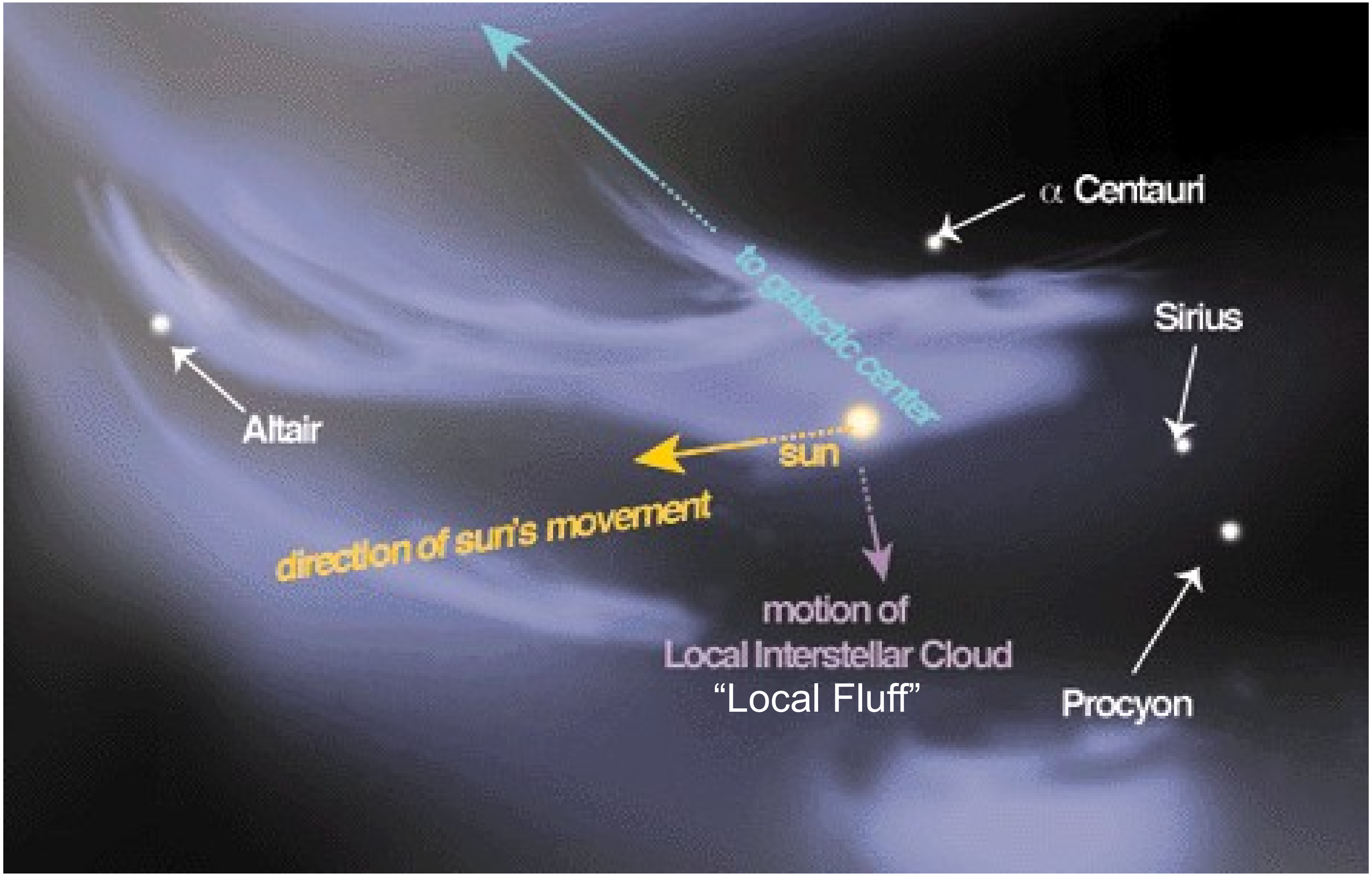
Opened June 2, 2011

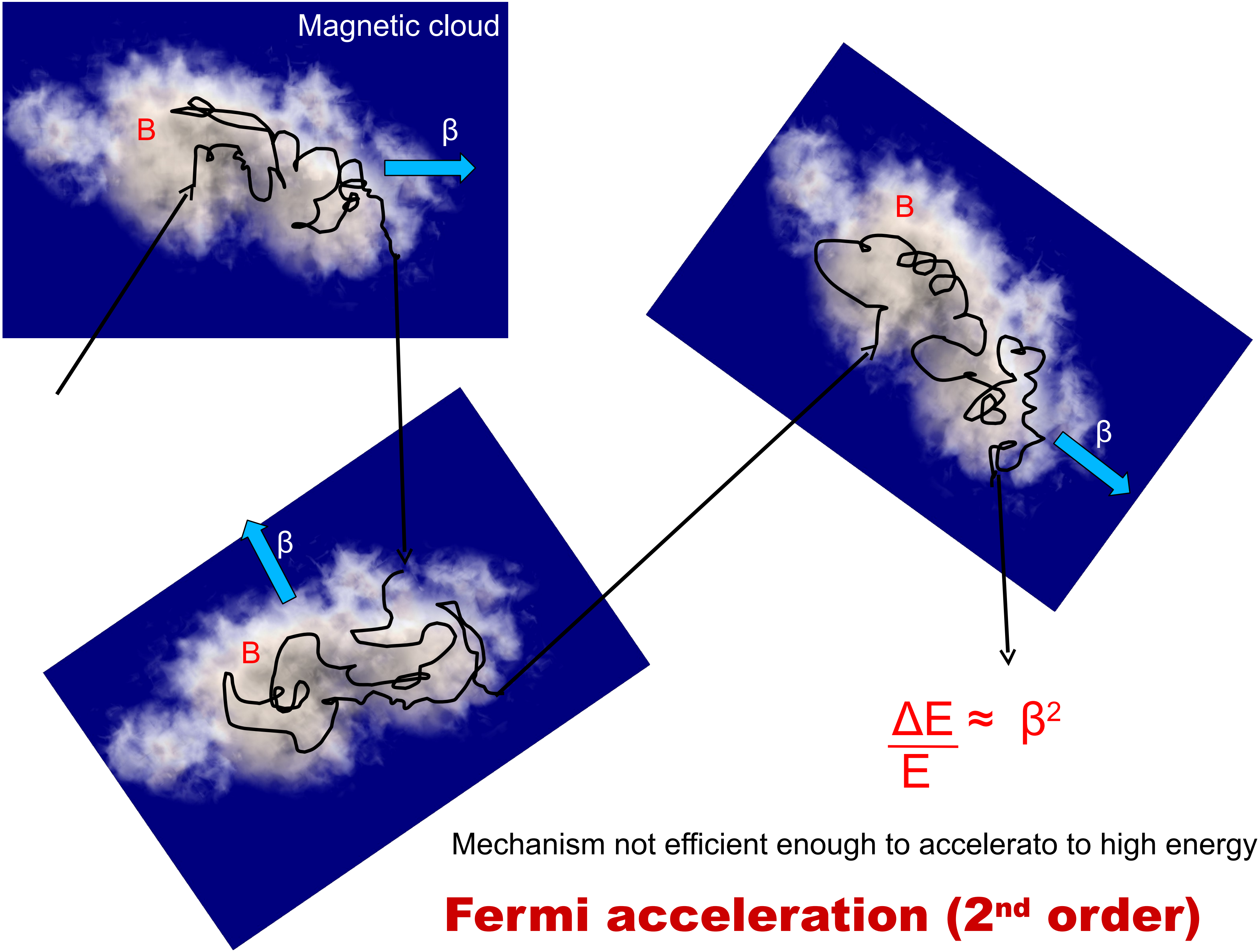
The time capsule contained these items:

- University of Chicago directory.
- University of Chicago announcements, May 25, 1948.
- Architect's sketch of the Research Institutes building.
- Booklet titled "The New Frontier of Industry — Atomic Research."
- Booklet titled "The Institute for Nuclear Studies, The Institute for the Study of Metals, The Institute of Radiobiology and Biophysics."
- Road map, train and airline timetables.
- List of postdoctoral fellows, Institute of Radiobiology and Biophysics, 1948-1949.

Also found with the time capsule was a 1927 buffalo nickel.

Magnetic Clouds



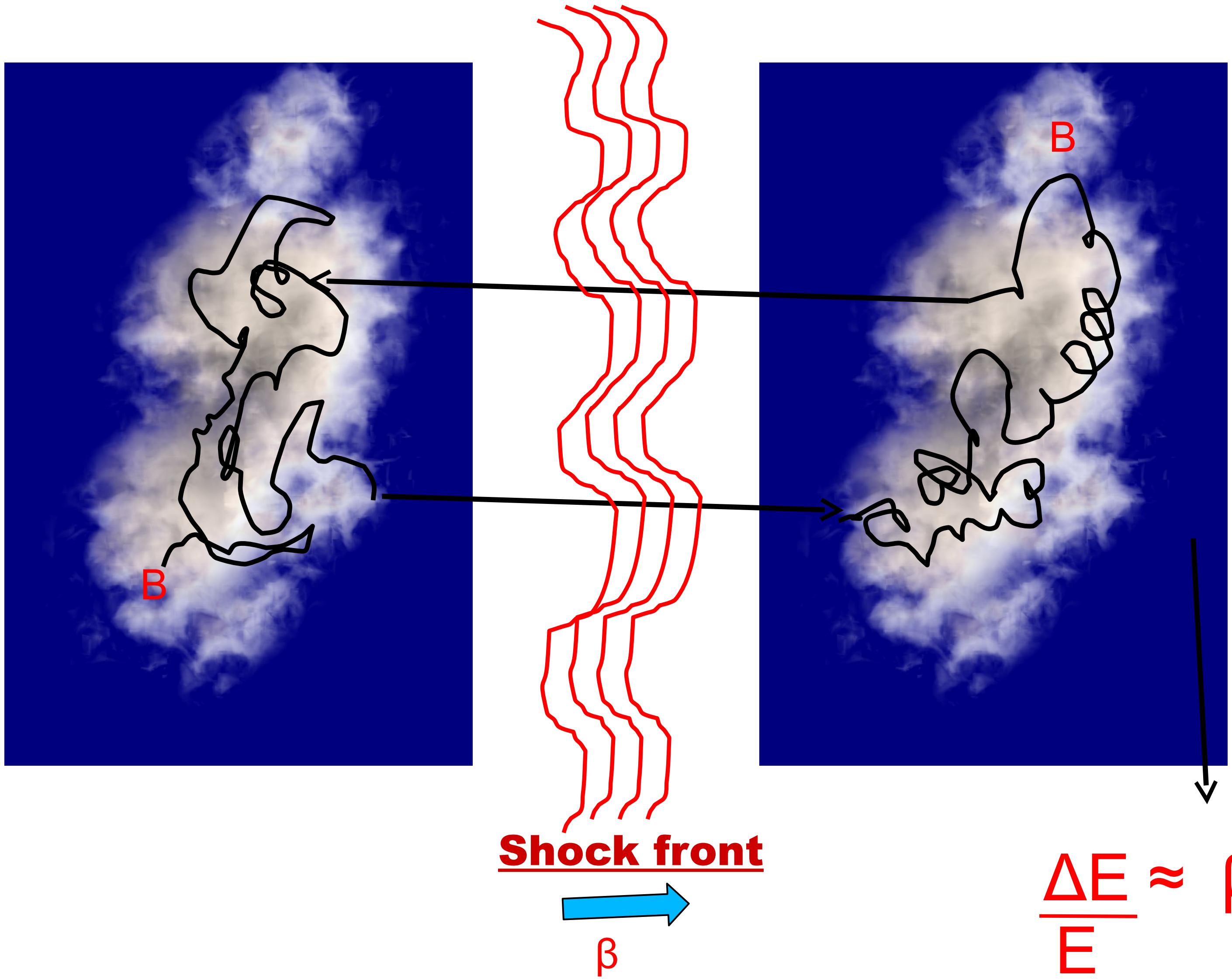


$$\frac{\Delta E}{E} \approx \beta^2$$

Mechanism not efficient enough to accelerato to high energy

Fermi acceleration (2nd order)

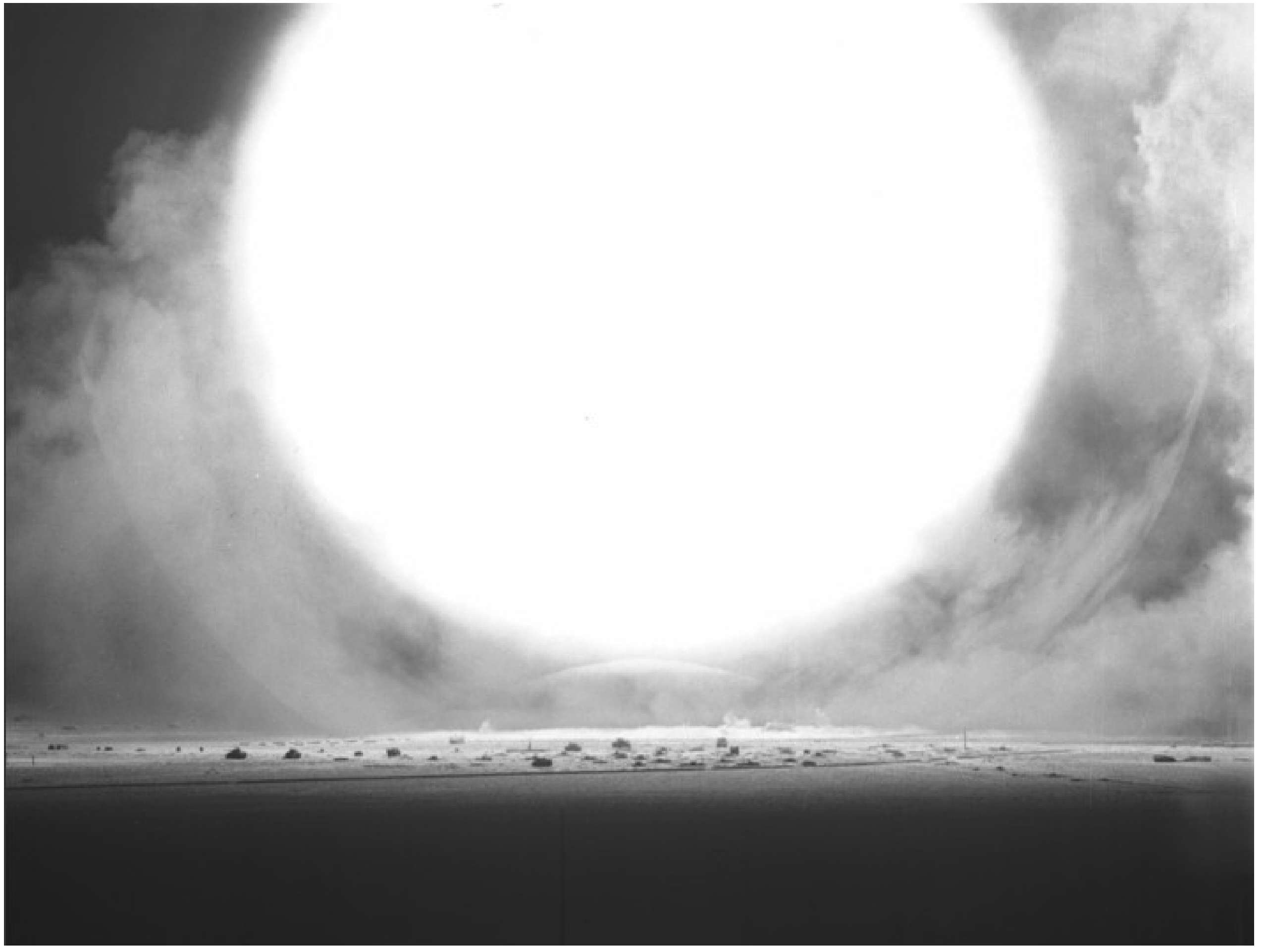
Fermi acceleration (1st order)



$$\frac{\Delta E}{E} \approx \beta$$

The cosmic ray moves back and forth between shocked and unshocked medium

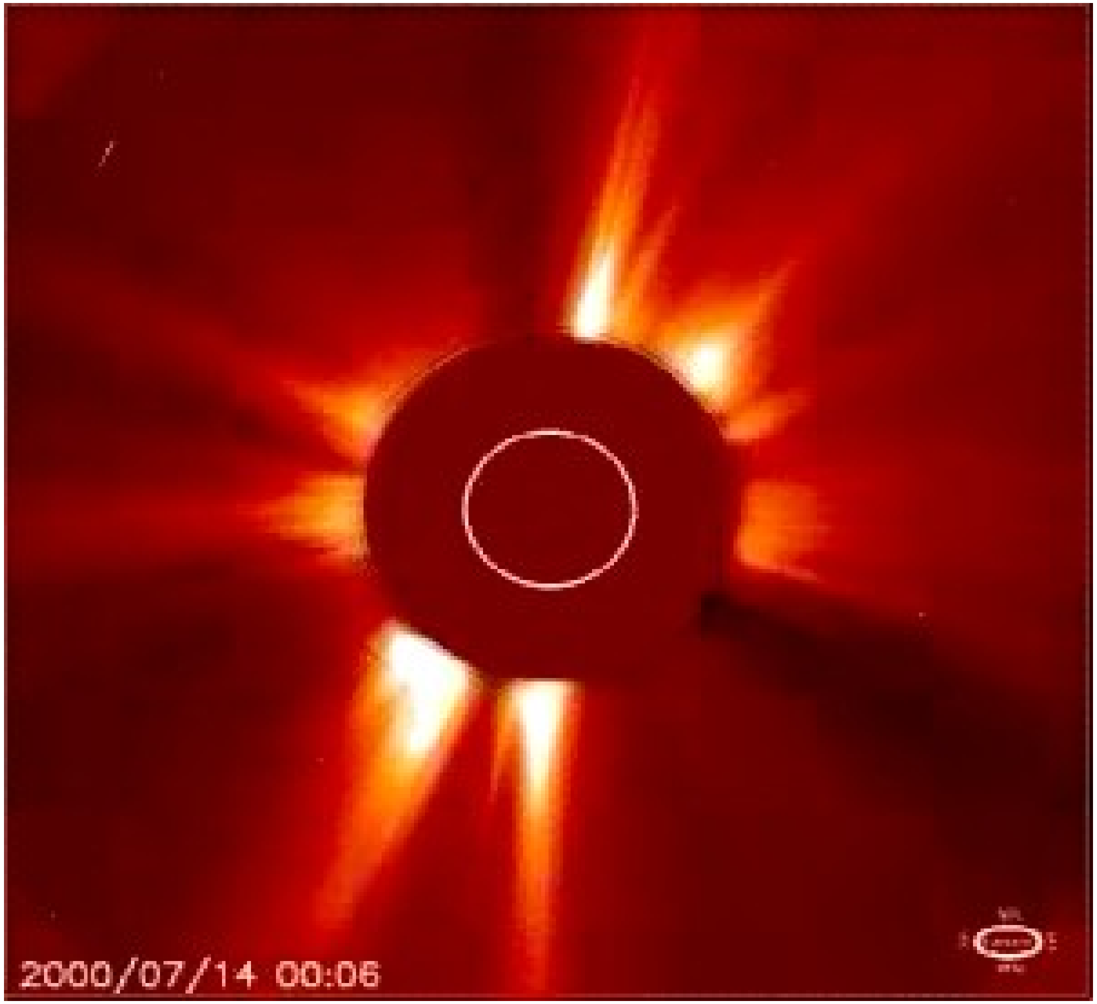
Shocks!



Shock produced by object moving faster than sound in the medium

Shock acceleration of cosmic rays by the sun

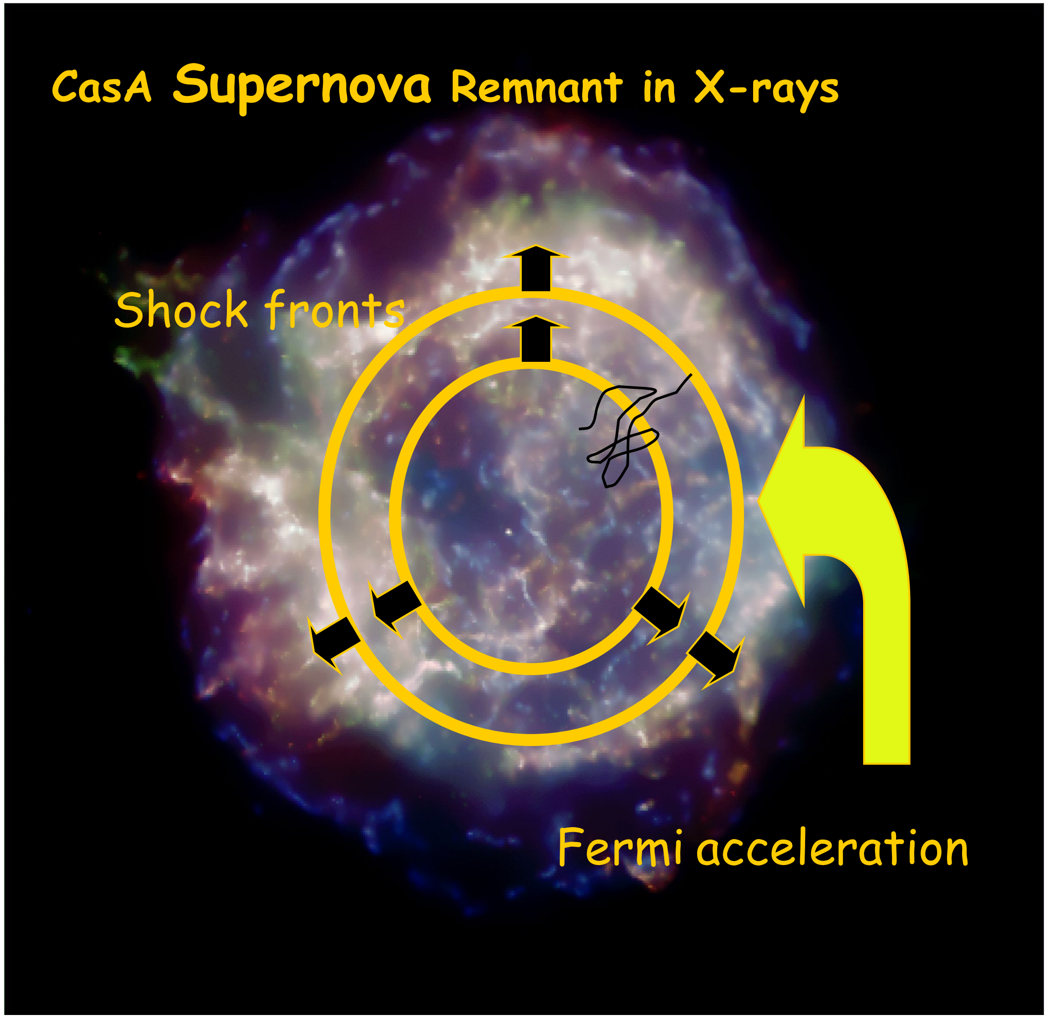
Coronal mass ejection: billions of tons of matter at millions of km / hour



SOHO (SOlar and Heliospheric Observatory) spacecraft

Shock acceleration in SNR

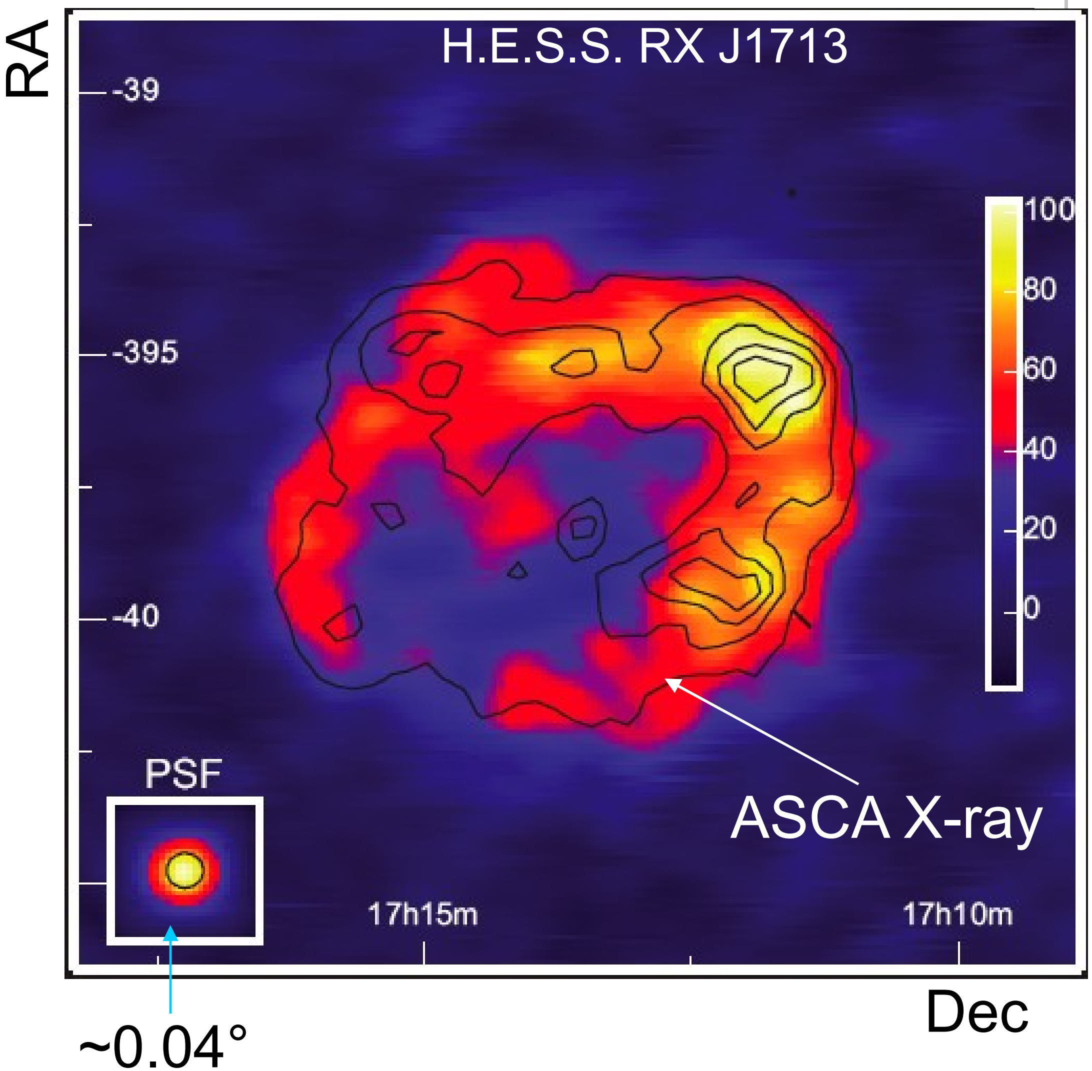
Popular model for high energy cosmic rays (up to 10^{15} eV)



$\beta \approx 0.01$ SNR expands for ≈ 1000 years

TeV Gamma Rays from SNR

Distance from earth 1 kpc
Shell radius = 10 pc



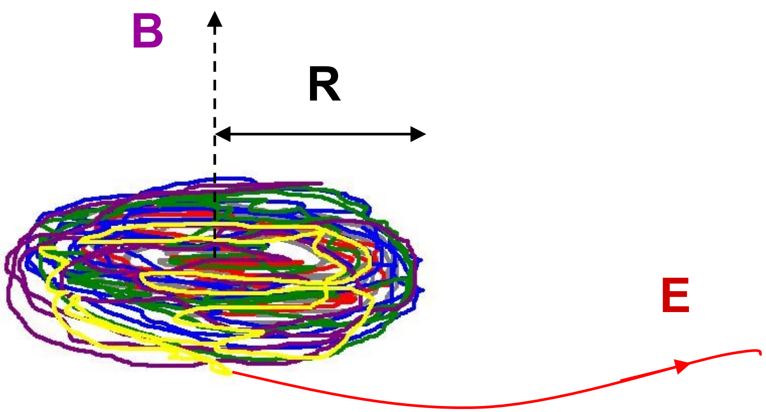
High-energy particle acceleration in the shell of a supernova remnant

NATURE | VOL 432 | 4 NOVEMBER 2004 |

HESS in Namibia

Atmospheric Cherenkov Telescope

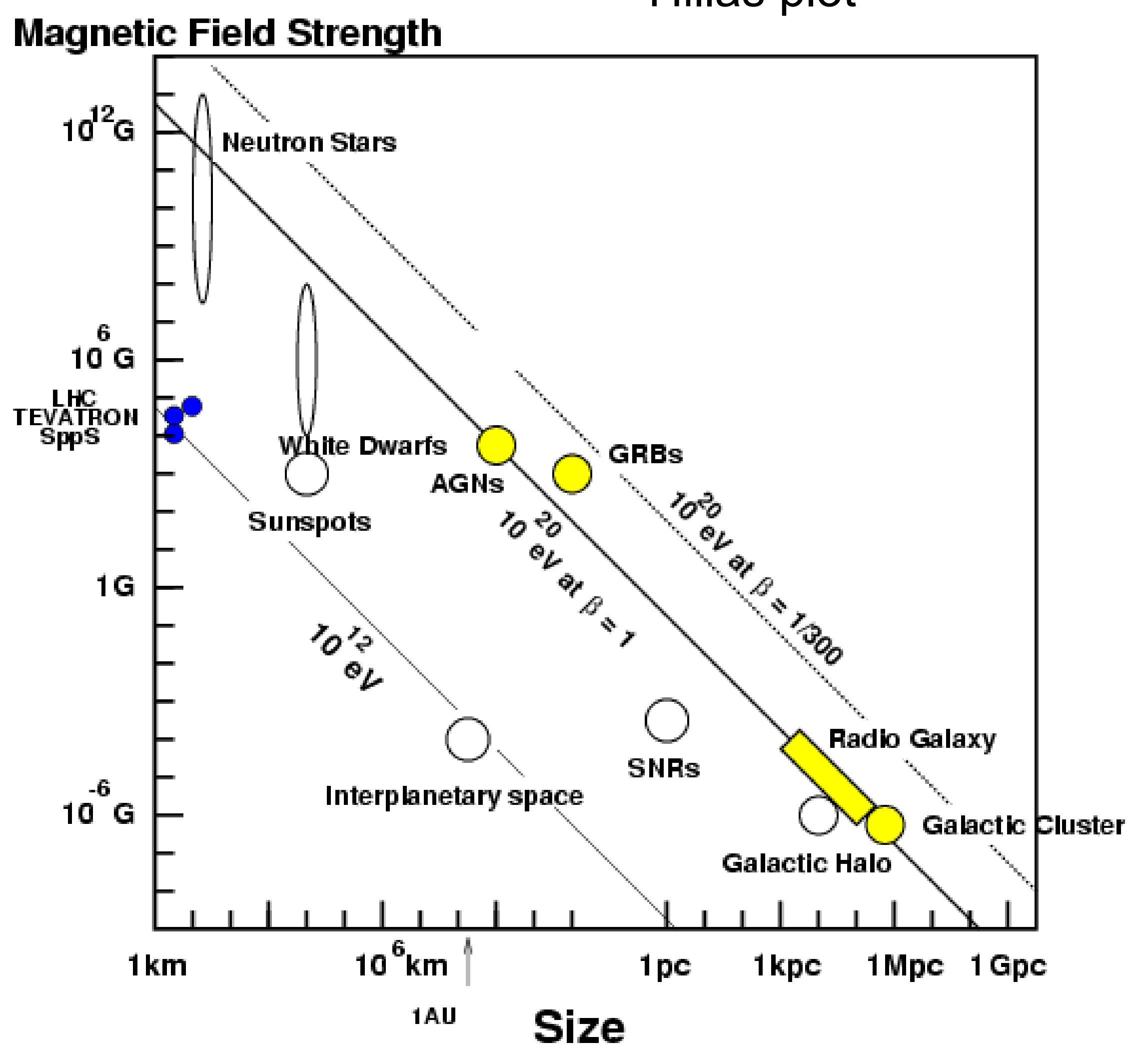
10^{20} eV accelerator?



$E \sim z \beta B R$

Particles must be confined by the magnetic field till they escape the accelerating region

Hillas plot

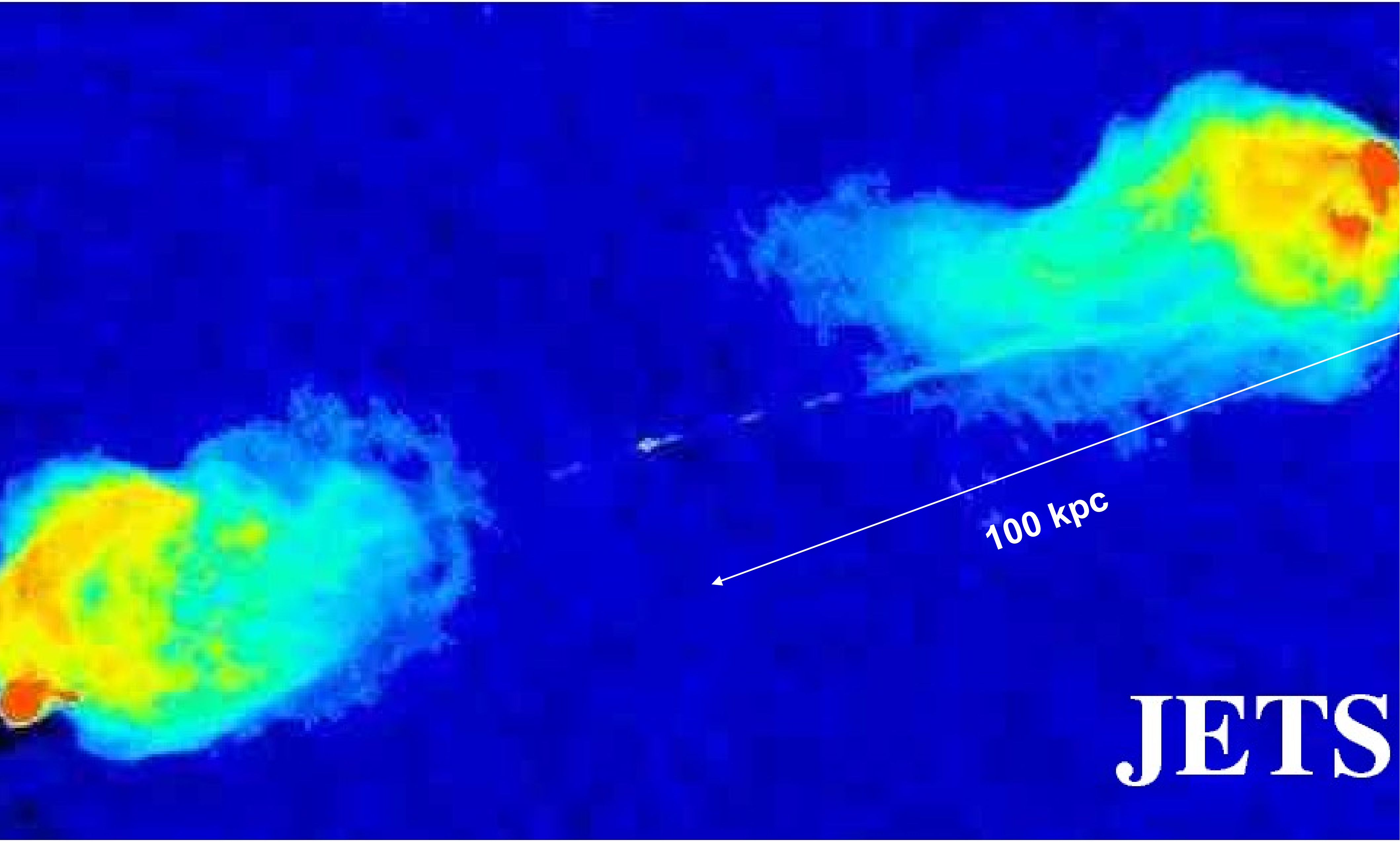


Astrophysical shocks

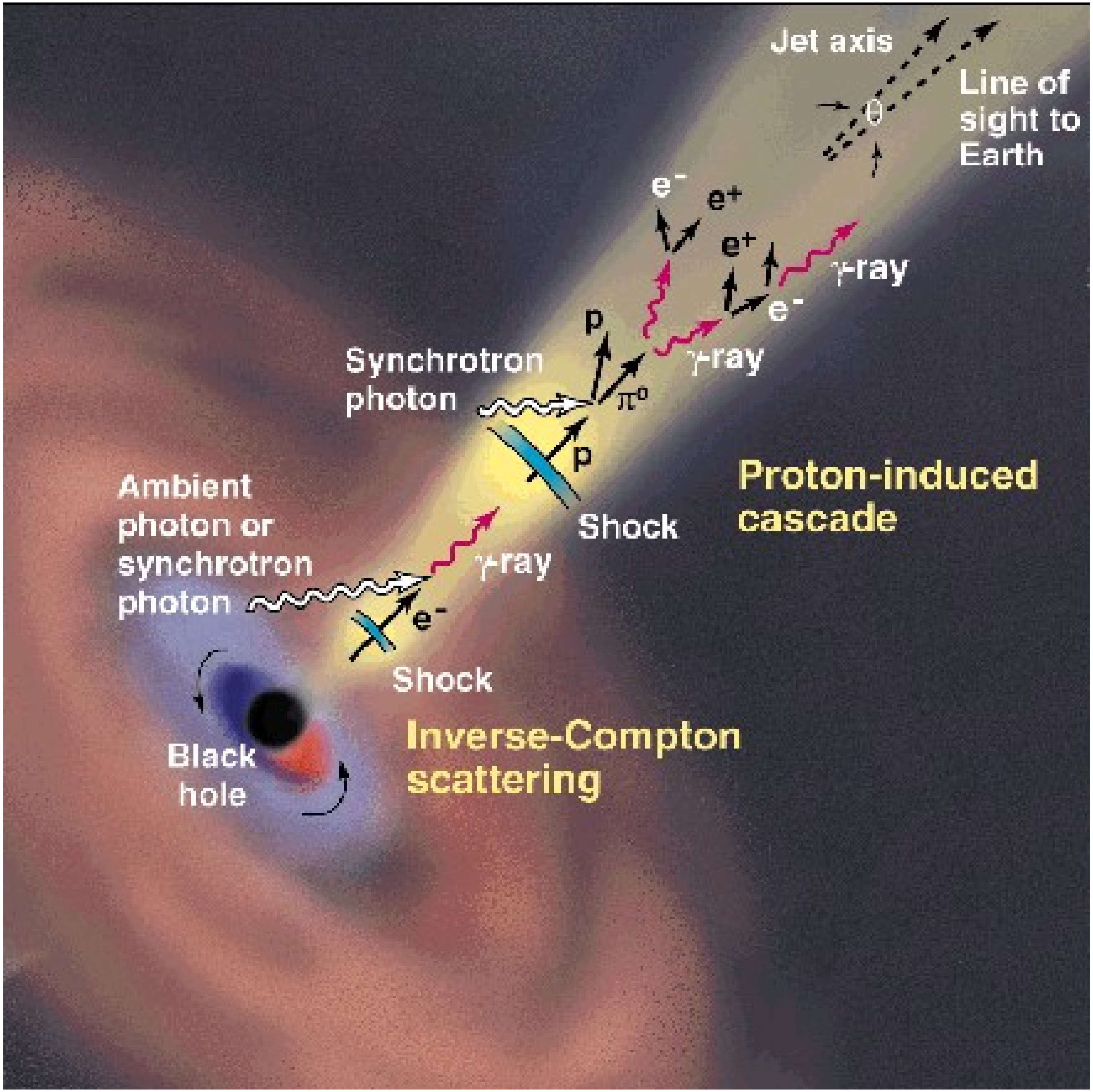
- Active galactic nuclei produce jets with internal shocks and huge shocks at the end (hot spots)

CYGNUS-A

FR-II z = 0.0565 ≈ 200 Mpc

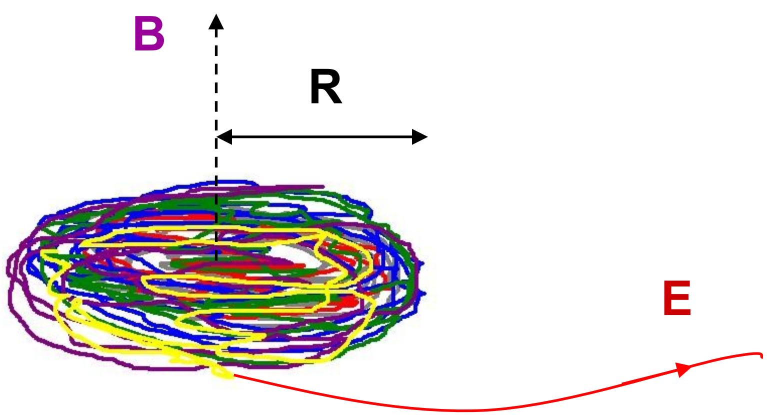


VLA radio image



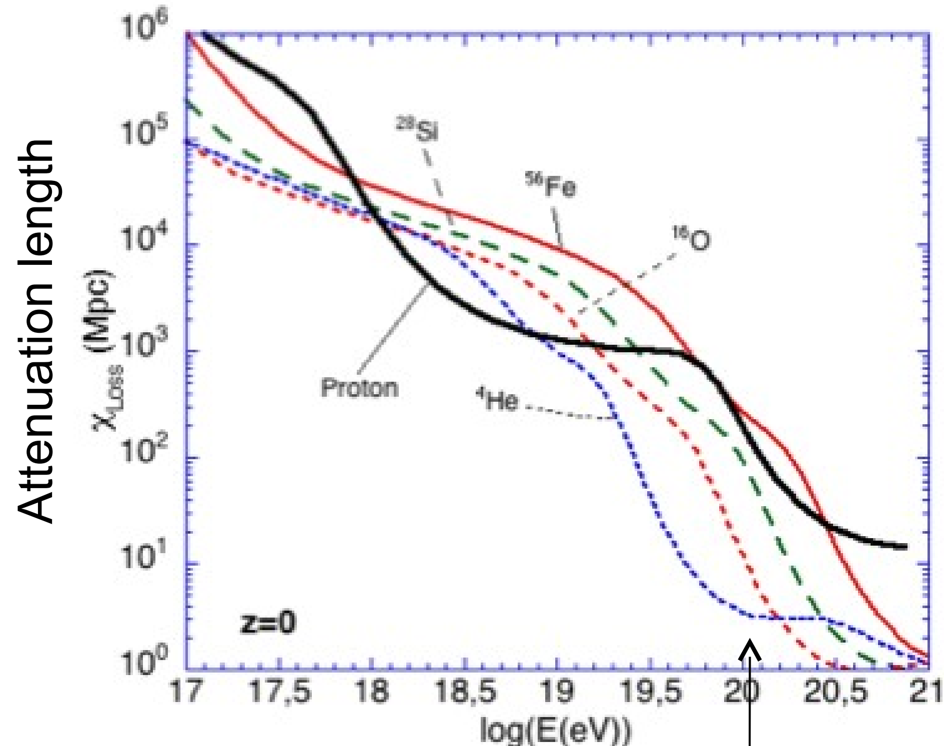
Active Galactic Nuclei

Proton vs heavy nuclei



$$E \sim z\,\beta\,B\,R$$

For the same magnetic field strength and accelerating region size, nuclei can reach energy Z times larger than a proton (example: Z = 26 for Iron) but……



Nuclei loose rapidly their energy through photodisintegration processes. Iron still ok.

$$\vartheta_d \simeq 0{,}5^\circ \cdot Z \cdot \left(\frac{E}{10^{20}\,eV}\right)^{-1} \cdot \left(\frac{d}{1\,Mpc}\right) \cdot \left(\frac{B}{10^{-9}\,G}\right)$$

If UHECR are heavy nuclei, their directions will be scrambled and they will not point back to the source!

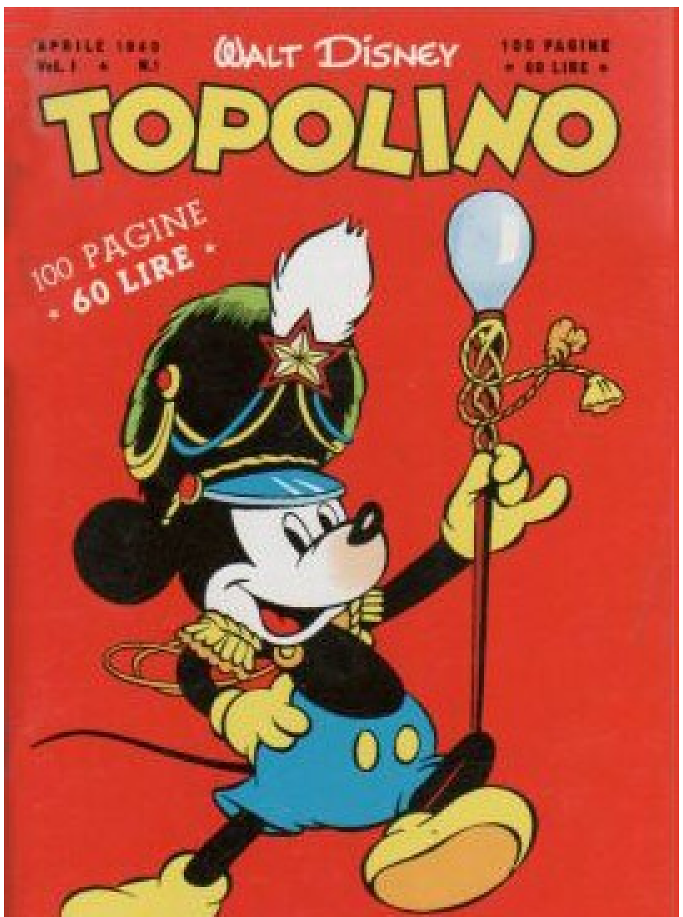
Physics (well) beyond the SM?

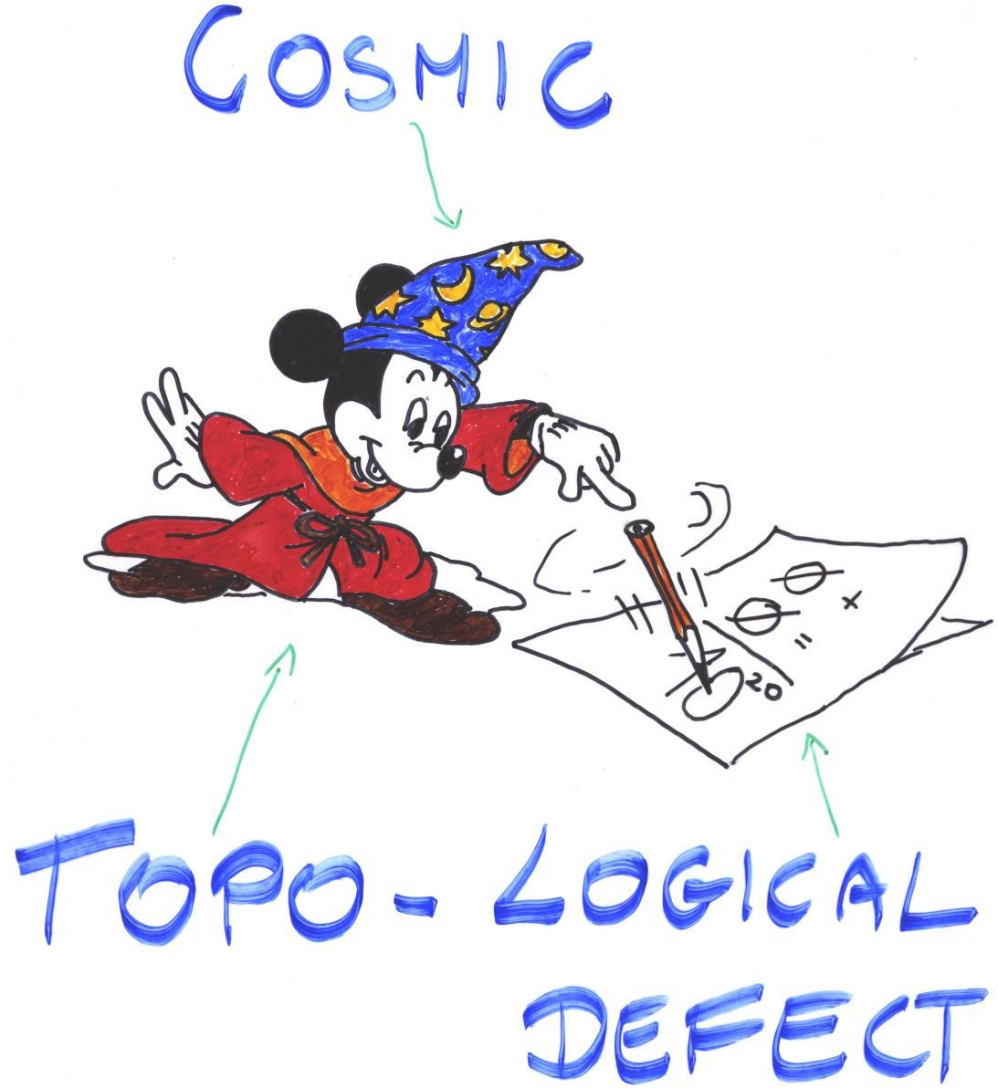
A few articles titles…..

- Microscopic black hole detection in UHECR
- Lorentz invariance violation …..
- Instant preheating mechanism and UHECR.
- Flipped Cryptons and the UHECRs.
- Super-heavy X particle decay …..
- Strongly interacting neutrinos ……
- Electroweak instantons as a solution …….
- Quantum-gravity phenomenology ……
- Superheavy dark matter……..
- Long-lived neutralino ……
- Cosmic Rays and Large Extra Dimensions
- UHECR from relic topological defects.
- Are UHECR a signal for supersymmetry?.

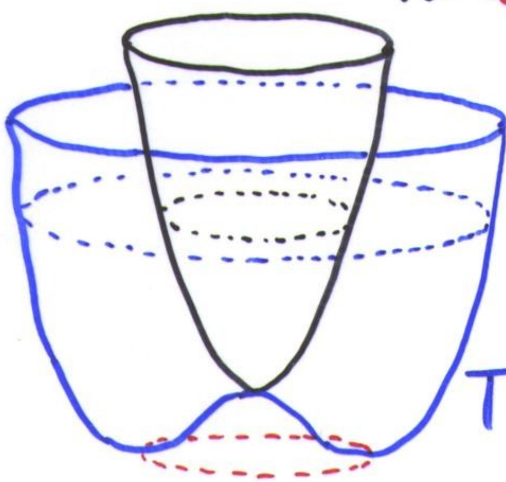
………

………


WALT DISNEY
100 PAGINE
60 LIRE
TOPOLINO
100 PAGINE
60 LIRE


COSMIC
TOPO - LOGICAL
DEFECT

SYMMETRY BREAKING PHASE TRANSITIONS IN EARLY UNIVERSE



Ex: $\mathcal{L}(\phi) = \frac{1}{2}(\partial_\mu \phi)^2 - V_T(\phi)$

- $T \to 0 \quad V_0 = \frac{1}{4}\lambda\left(|\phi|^2 - \eta^2\right)^2$
- $T > T_c \quad V \sim T^2 \phi^2$

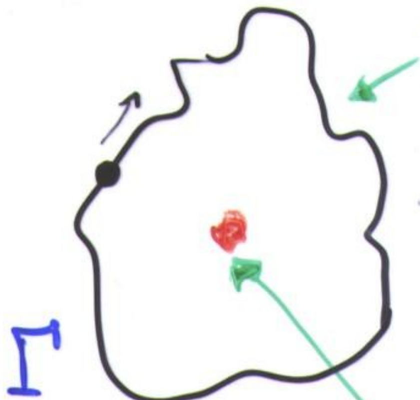
$T_c \sim m_{GUT} \sim 10^{25}\ eV$

$T > T_c$: VACUUM SYMMETRIC UNDER PHASE ROTATIONS

$T < T_c$: A GIVEN VACUUM STATE NO LONGER INVARIANT UNDER PHASE ROTATIONS → "SPONTANEOUS" SYMM. BREAKING

$\langle \phi \rangle = \eta(T)\, e^{i\alpha}$

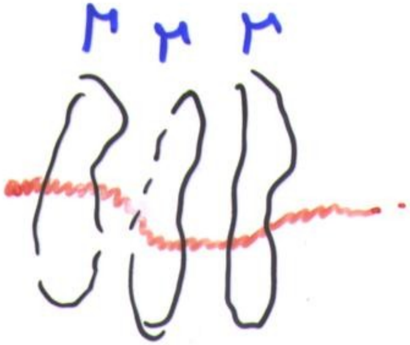
IN AN EARLY UNIVERSE PHASE TRANSITION, WE EXPECT THAT PHASES IN WIDELY SEPARATED REGIONS WILL BE UNCORRELATED



TAKE A CLOSED CURVE IN A PLANE OF PHYSICAL SPACE

MOVING AROUND Γ THE FIELD Φ CAN CHANGE ITS PHASE. ONCE BACK TO THE STARTING POINT $\alpha(1) = \alpha(0) + m\,2\pi$

IF $m \neq 0 \Longrightarrow$ THERE IS A REGION IN THE INTERIOR OF Γ WHERE $\langle \Phi \rangle = 0$

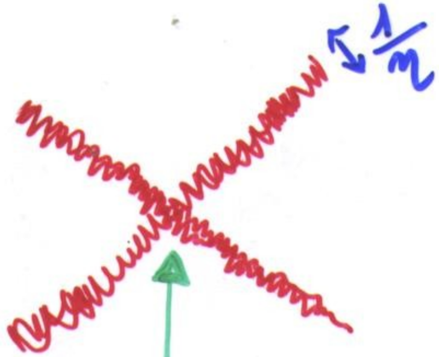


A COSMIC STRING!

$V_{T=0} \neq \emptyset$! THERE IS ENERGY (MASS) TRAPPED IN THERE

$m_X \sim \eta \sim T_c$

$(\mu \sim 10^{22}\ \text{gms/cm}\ !!)$

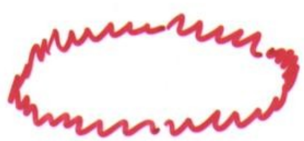


$$\mu \sim \eta^2$$

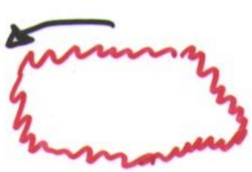
ENERGY PER UNIT LENGTH

$$\text{ENERGY RELEASE} \sim \mu \cdot \frac{1}{\eta} \sim \eta \sim m_X$$

INTERSECTION REGION $\sim 1/\eta$, THE PHASE BECOMES UNDEFINED AND THE ENERGY CONTAINED IN THE OVERLAPPING REGION IS RELEASED IN THE FORM OF X PARTICLES

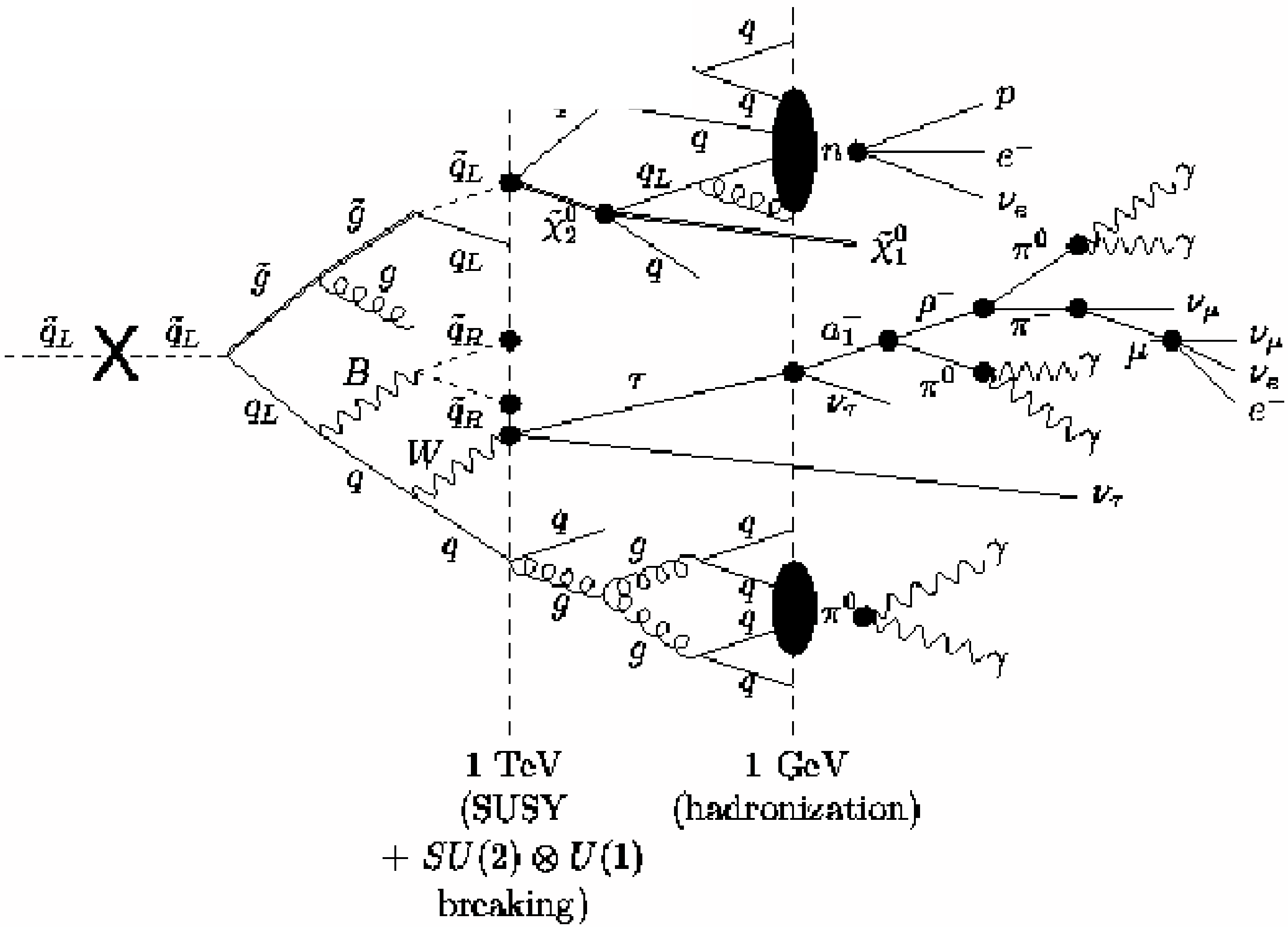


OSCILLATES EMITTING GRAVITATIONAL RADIATION TILL RADIUS $\sim 1/\eta$ AND THEN COLLAPSES



SUPERCONDUCTING STRING LOOPS. CARRY PERSISTENT ELECTRIC CURRENTS (CHARGED HIGGS, FERMIONS) SHRINKING THE CURRENT BECOMES $> I_{CRIT.}$ AND CHARGED CARRIERS ARE EJECTED

X-particle decay cascade



Schematic MSSM "jet" for an initial squark with a virtuality $Q \simeq M_X$. The full circles indicate decays of massive particles, in distinction to fragmentation vertices. The two vertical dashed lines separate different epochs of the evolution of the cascade: at virtuality $Q > m_{SUSY}$, all MSSM particles can be produced in fragmentation processes. Particles with mass of order m_{SUSY} decay at the first vertical line. For $m_{SUSY} < Q < 1$ GeV light QCD degrees of freedom still contribute to the perturbative evolution of the cascade. At the second vertical line, all partons hadronize, and unstable hadrons and leptons decay.
(from M. Drees, e-print hep-ph/0210142)

Particles at the end of the cascade:

predominantly photons

Neutrinos

Few protons

No nuclei

UHECR photons signature for New Physics

The UHECR 3-piece puzzle

1) The Greisen -Zatsepin-Kusmin cutoff:

Pion photoproduction (on CMB radiation)

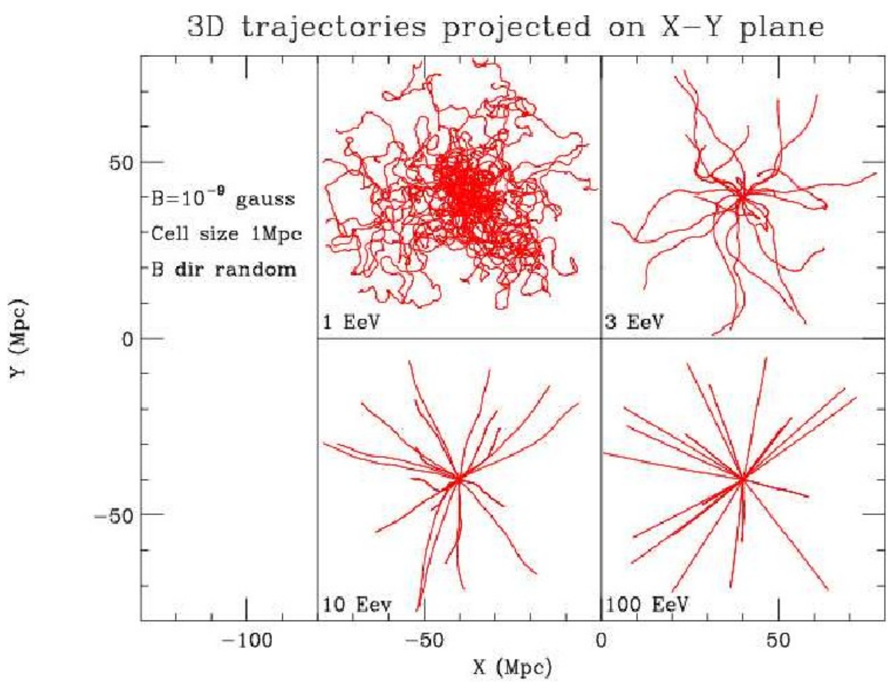
$p + \gamma_{2.7\,K} \rightarrow N + \pi$ **for** $E_p > 5\ 10^{19}$ **eV**

END TO THE COSMIC-RAY SPECTRUM?

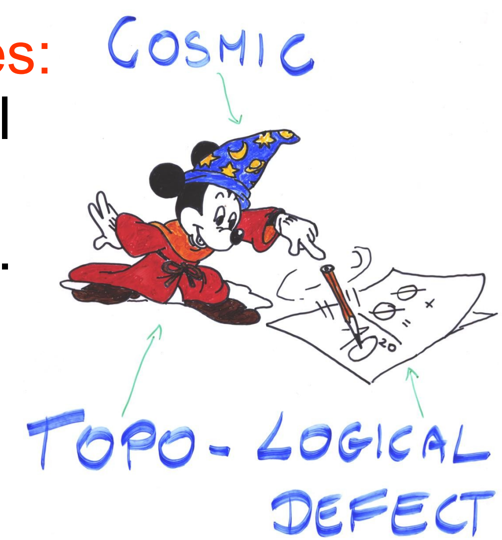
Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

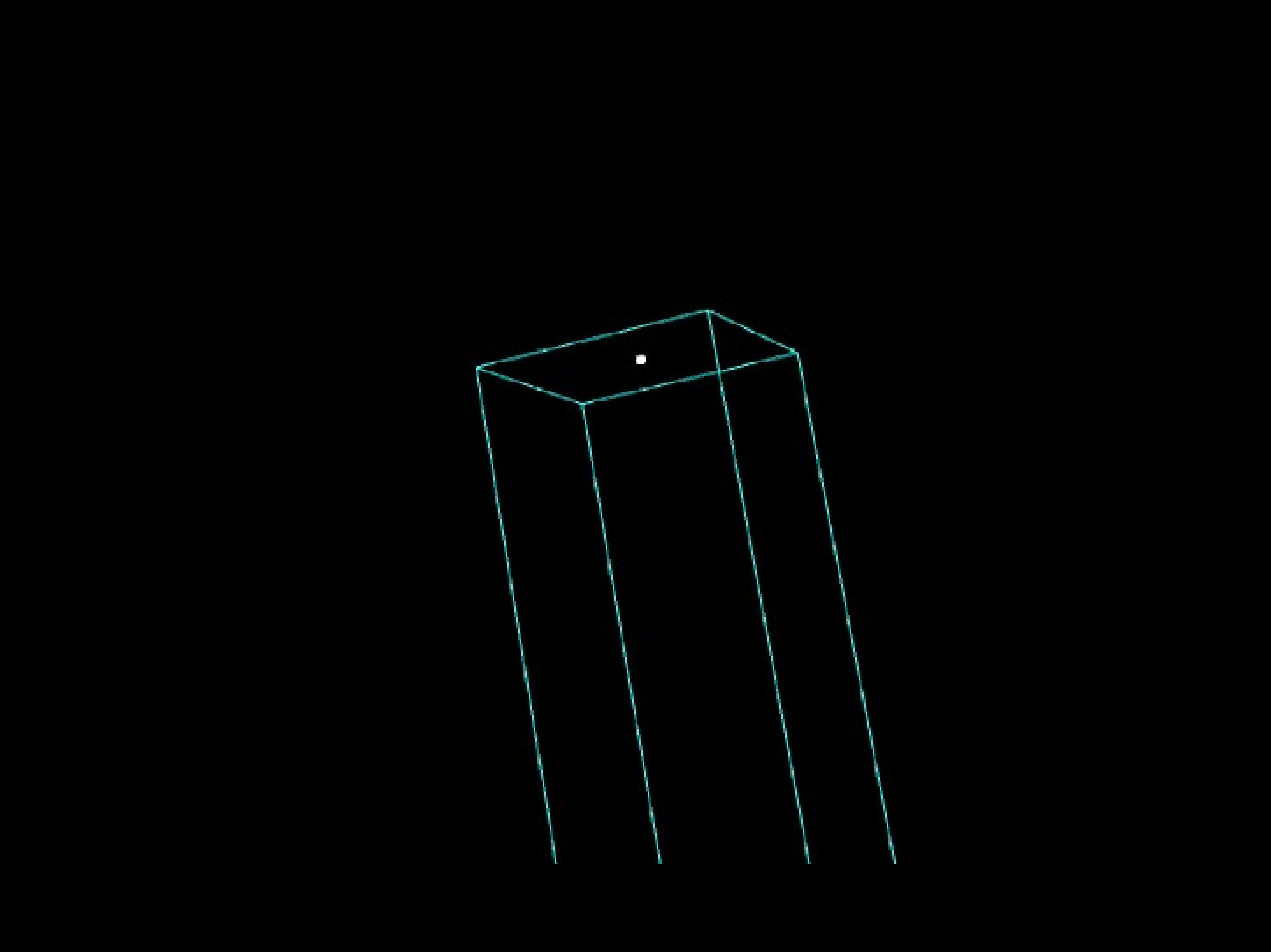


2) The UHECR sources:
Close-by astrophysical accelerators?
<100 Mpc due to GZK.
New Physics?

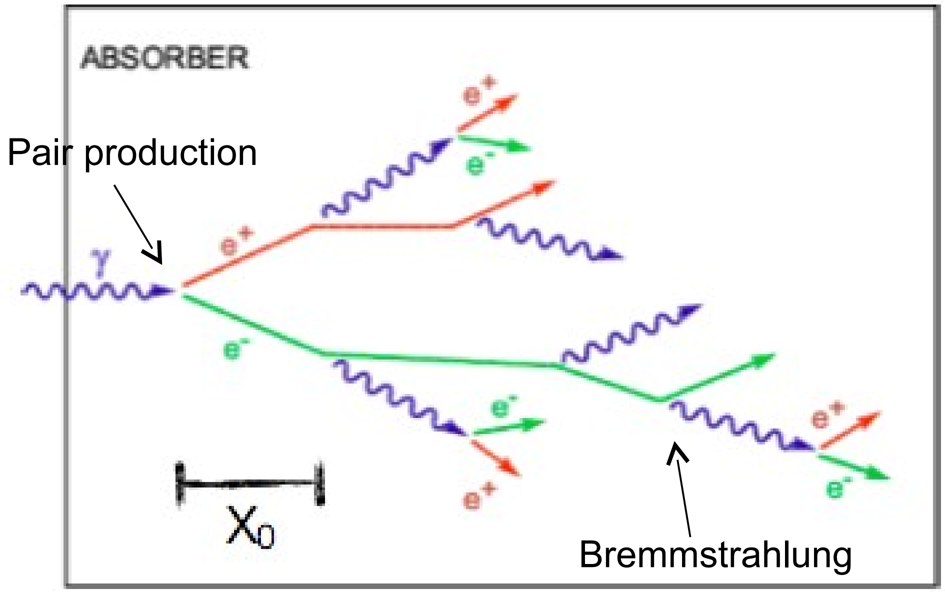


3) The UHECR composition:
protons? Heavier nuclei
(deviation in magnetic fields)

Only by understanding all of the three pieces we will unveil the true nature of UHECRs



Electromagnetic Showers



After ≈ one X_0 (radiation length) the electromagnetic particle (photon or $e^{\pm}$) interacts

X_0 in cm or (multiplying length by density of absorber) in g/cm^2

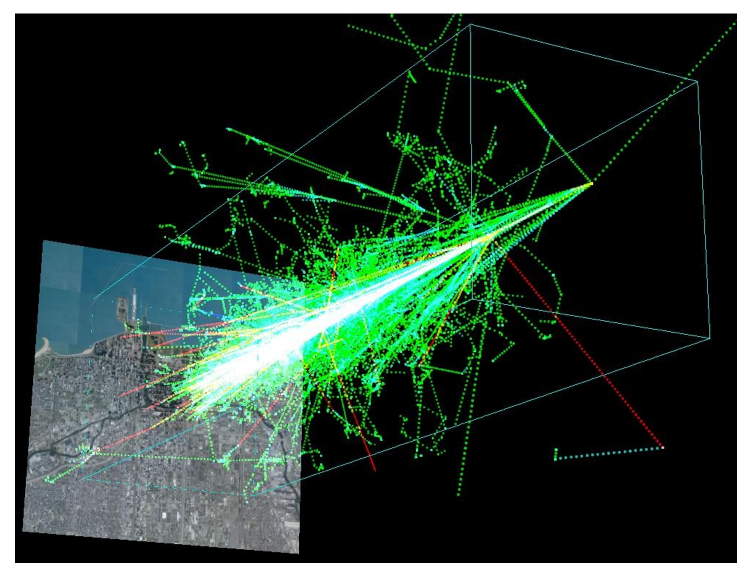
Examples:

X_0(Pb) = 6.4 g/cm^2 = 0.56 cm

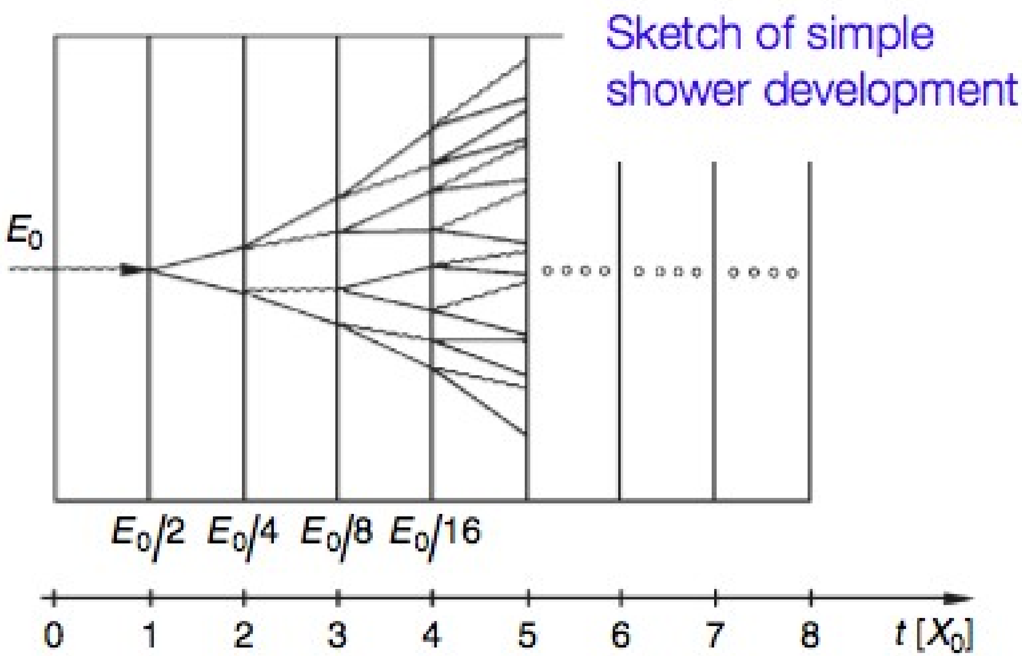
X_0(air) = 37 g/cm^2 = 300 m !

X_0(Pb) = 6.4 g/cm^2 = 0.56 cm

X_0(air) = 37 g/cm^2 = 300 m !



Heitler model of shower development



Assume that each time energy is divided equally between the two particles produced in the interaction

The shower will stop growing when the particle energy goes below a critical energy E_c (when energy loss by ionization overcome photon production by Bremmstrahlung)

N(t) 2 4 8 16 ………………… 2^t

The energy per particle after t radiation length is $E = E_0/2^t$

The maximum of the shower t_{max} is reached when the particles' energy is = to E_c

$$E_c = E_0/2^{t_{max}}$$

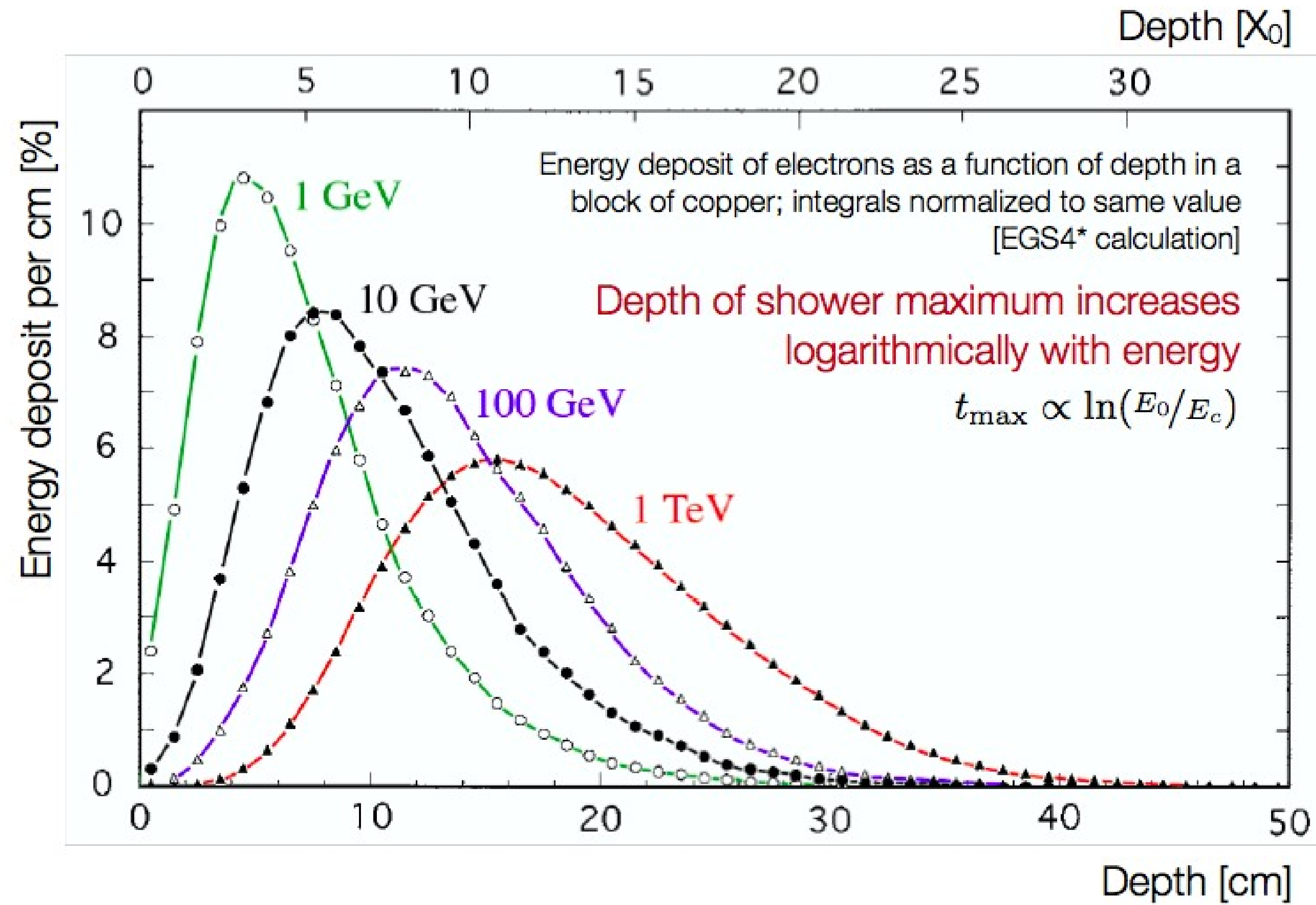
$$t_{max} = \log_2 (E_0/E_c)$$

$$N_{max} = 2^{t_{max}} = E_0/E_c$$

shower max increases logarithmically with E

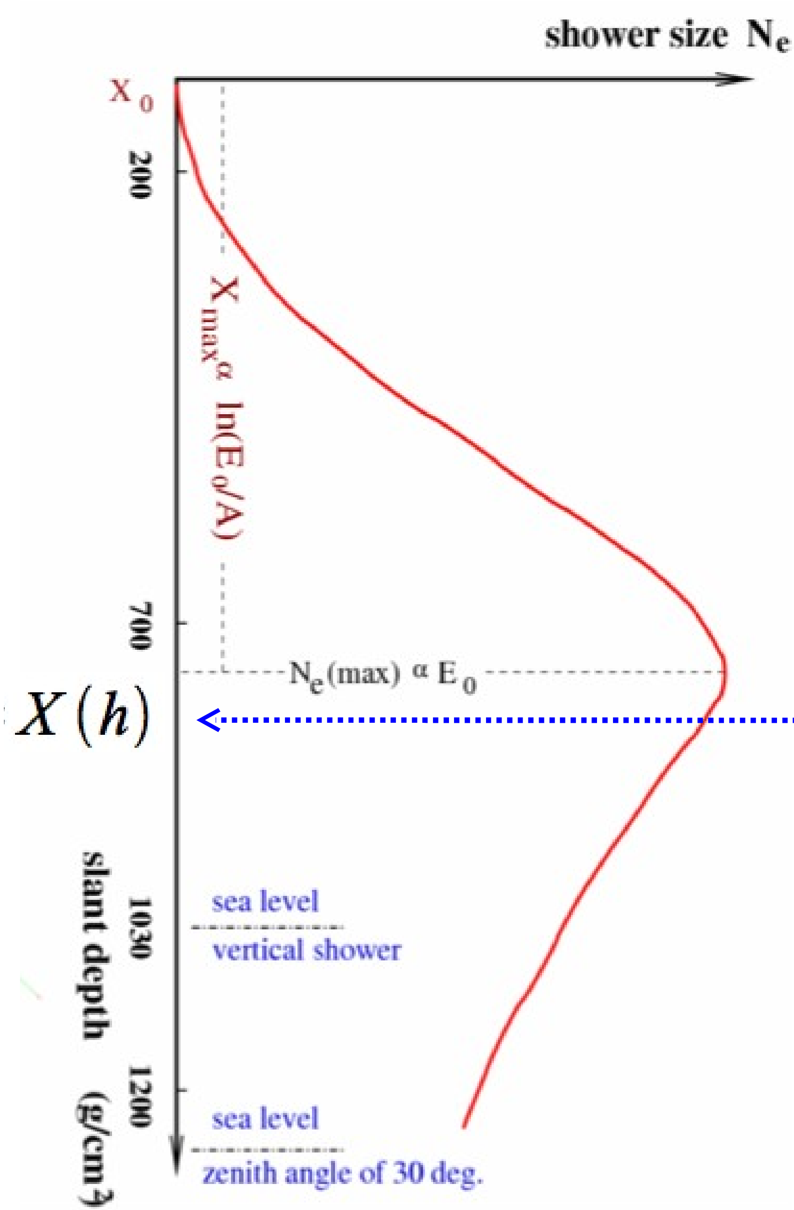
n. of particles at the max is proportional to E

Shower development



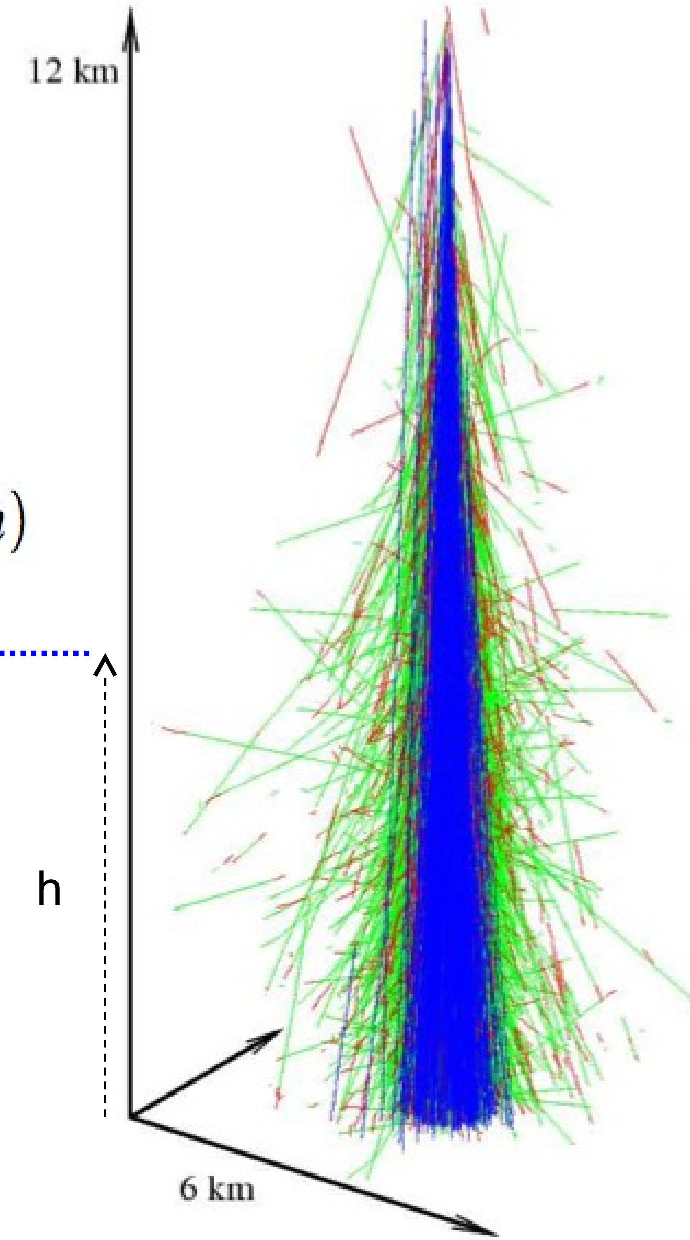
Fundamental for particle physics calorimetry: imagine if t_{max} would increase linearly with energy ……

Atmosphere as a "calorimeter"



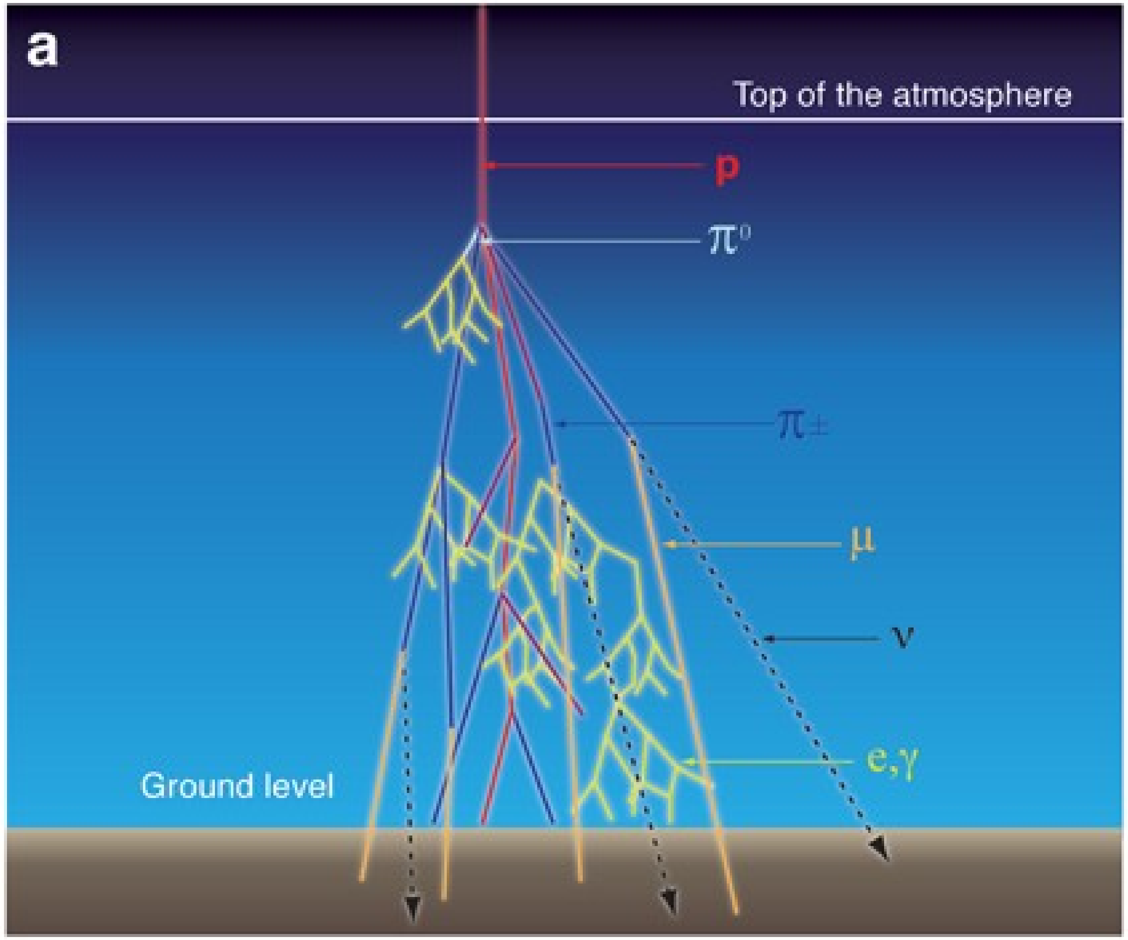
Air density

$$\int_h^{\infty} \rho(l)\, dl = X(h)$$



Air depth ≈ 25 X_0 for a vertical shower

Hadronic Showers



- Shower particles mainly $e^{\pm}$ and photons

($\pi^{\pm}$ interacts or decay, $\pi^0 \to \gamma\gamma$)

- ≈ 90% of the primary cosmic ray energy is converted to ionization energy

- ≈ 10^{11} particles in a 10^{19} eV shower!

At ground mainly $e^{\pm}$ and photons, muons, neutrinos

Let's detect UHECR showers!