selected topics in particle astrophysics

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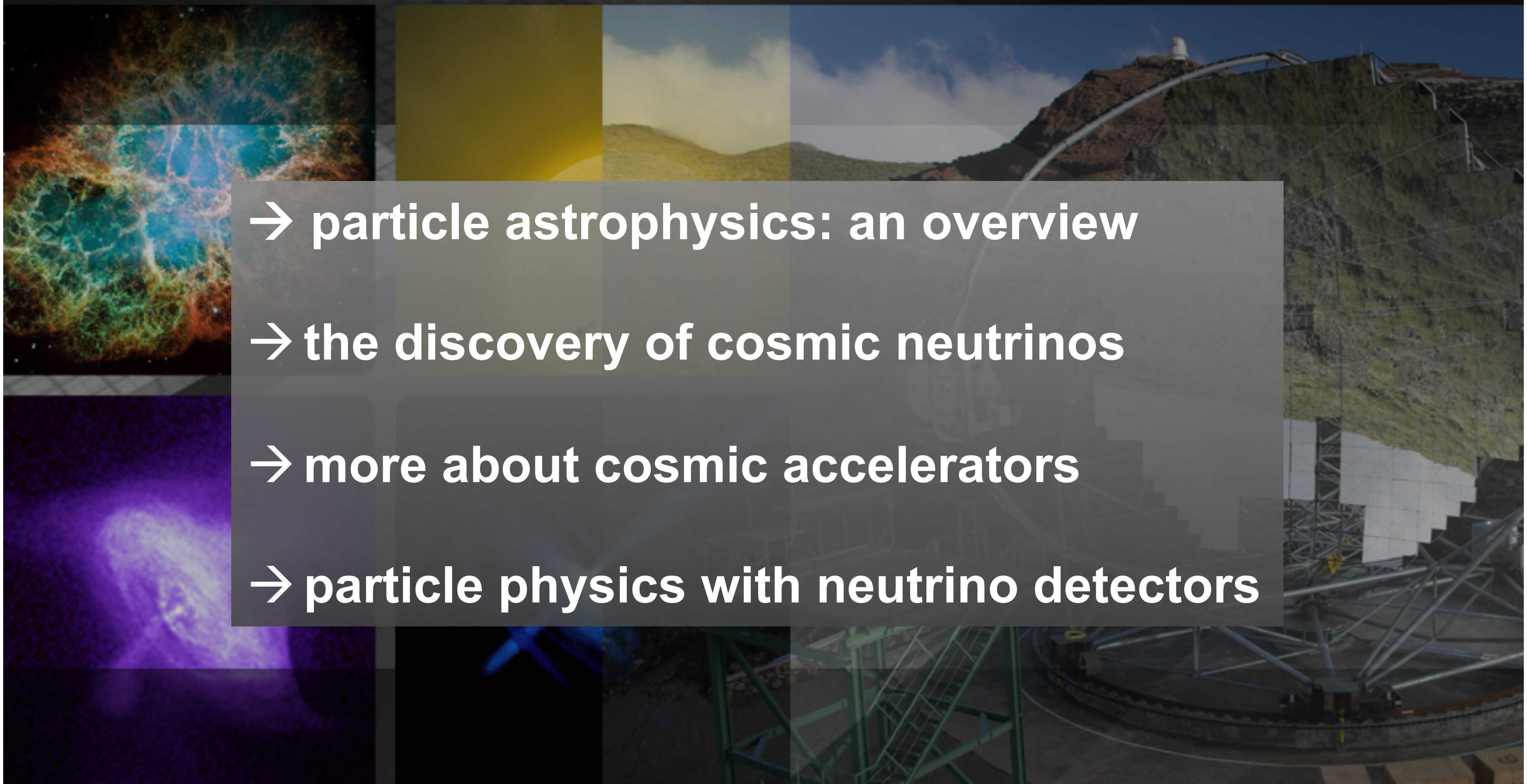
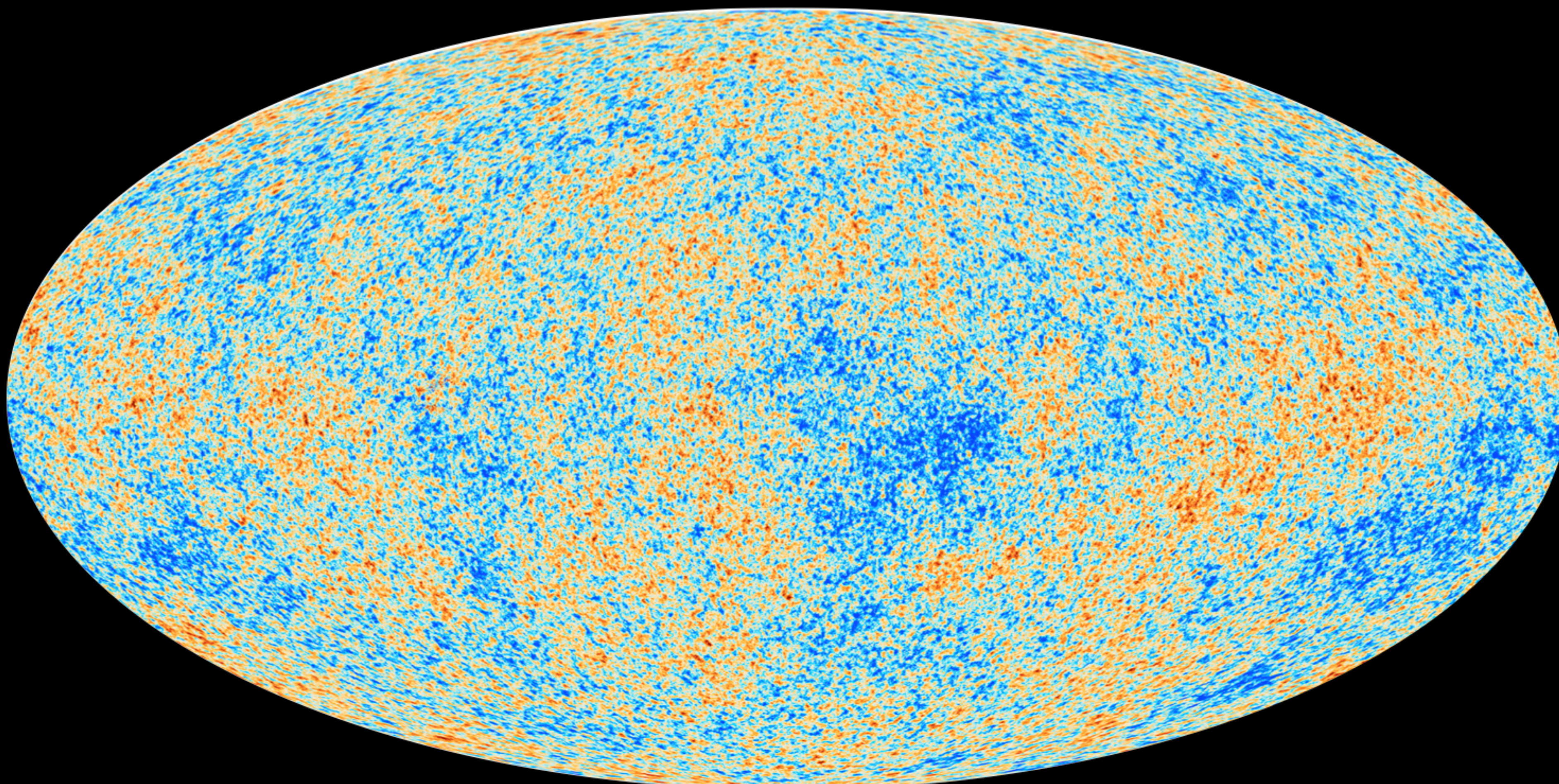


- → particle astrophysics: an overview
- → the discovery of cosmic neutrinos
- → more about cosmic accelerators
- → particle physics with neutrino detectors

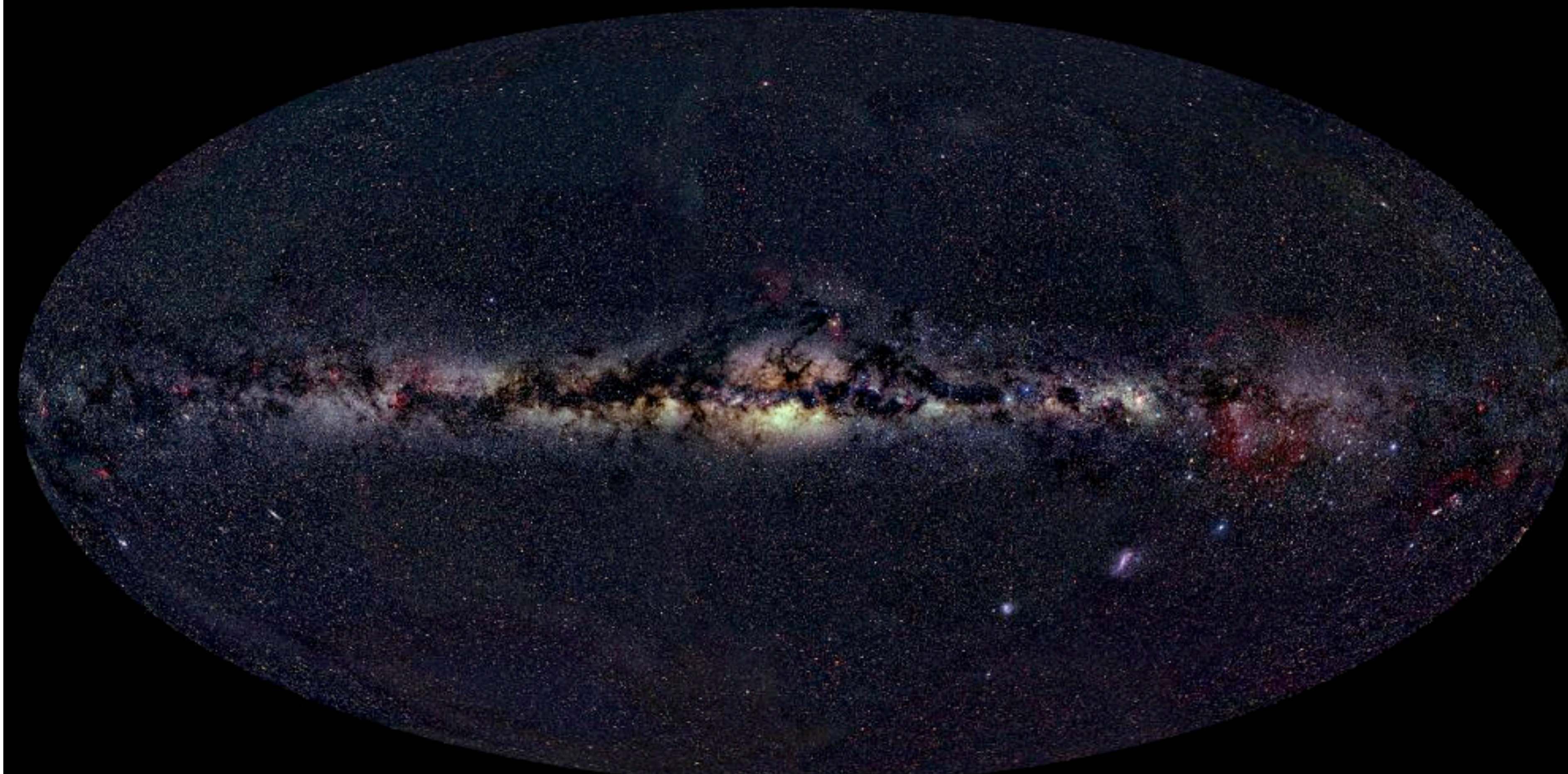
The real voyage is not to travel to new landscapes,
but to see with new eyes. . . Marcel Proust

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang



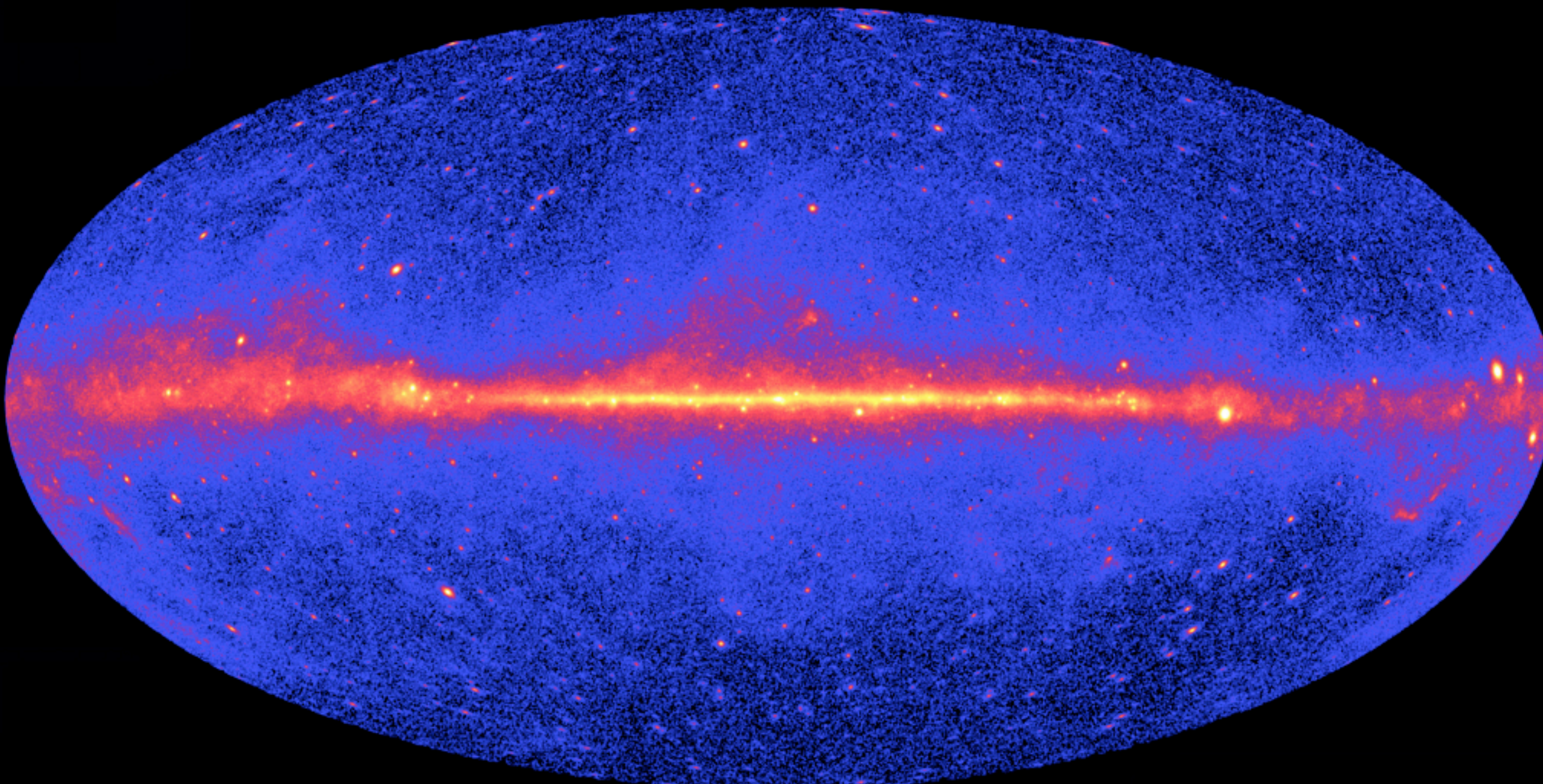
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m ⇔ energy = 1 eV

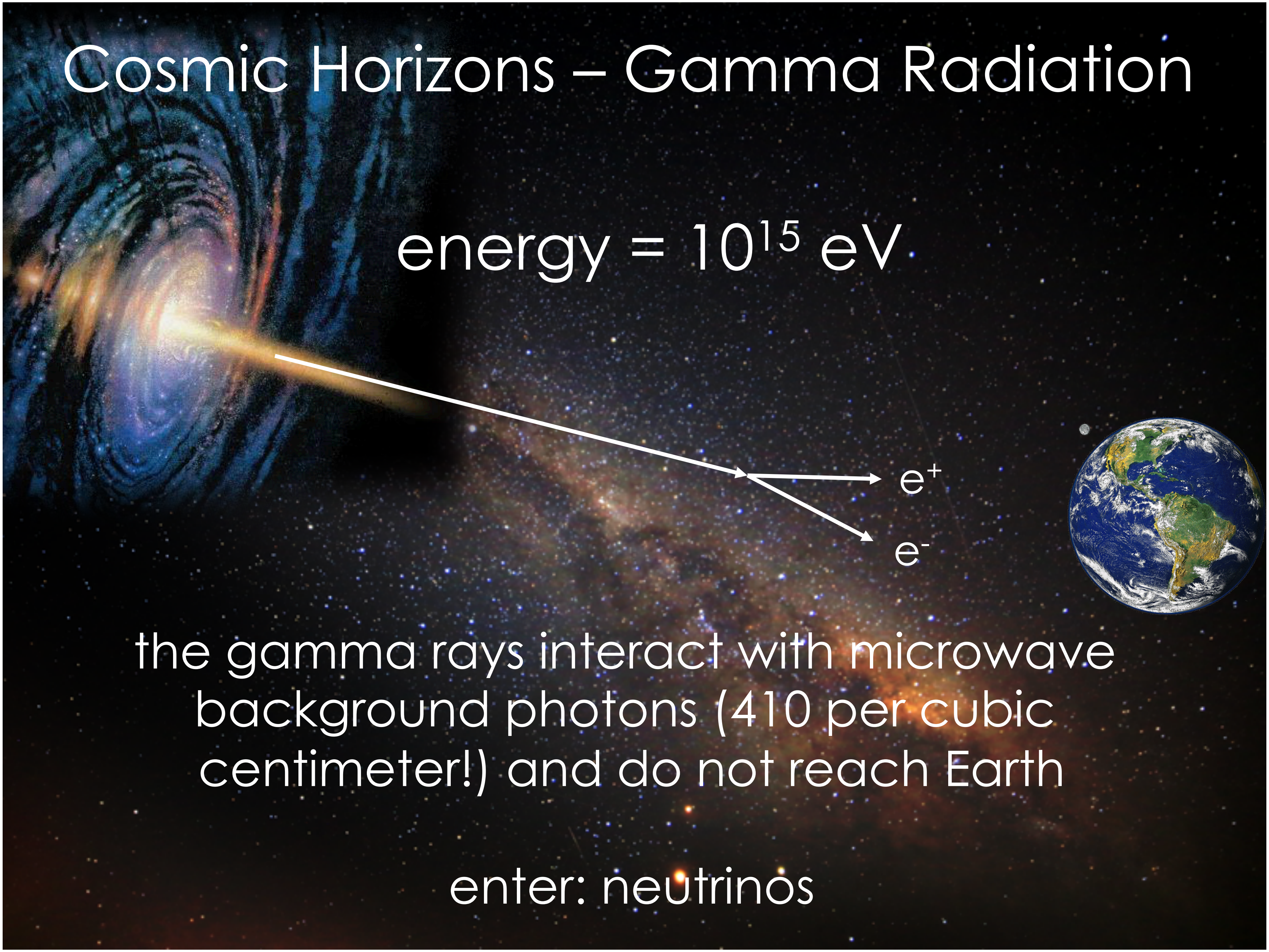
Cosmic Horizons – Gamma Radiation



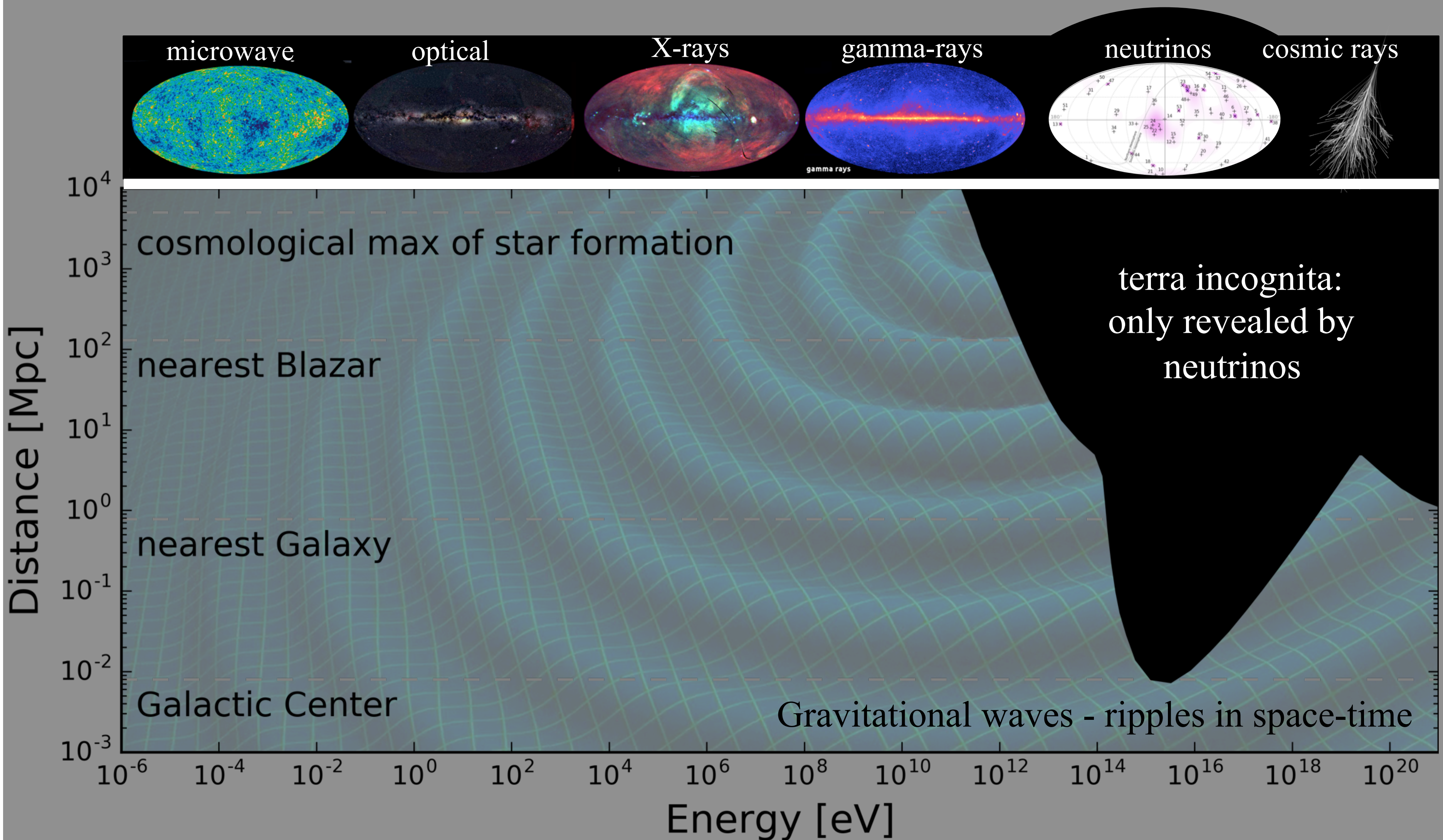
wavelength = 10^{-15} m ⇔ energy = 10^{9} eV

Cosmic Horizons – Gamma Radiation

energy = 10^{15} eV

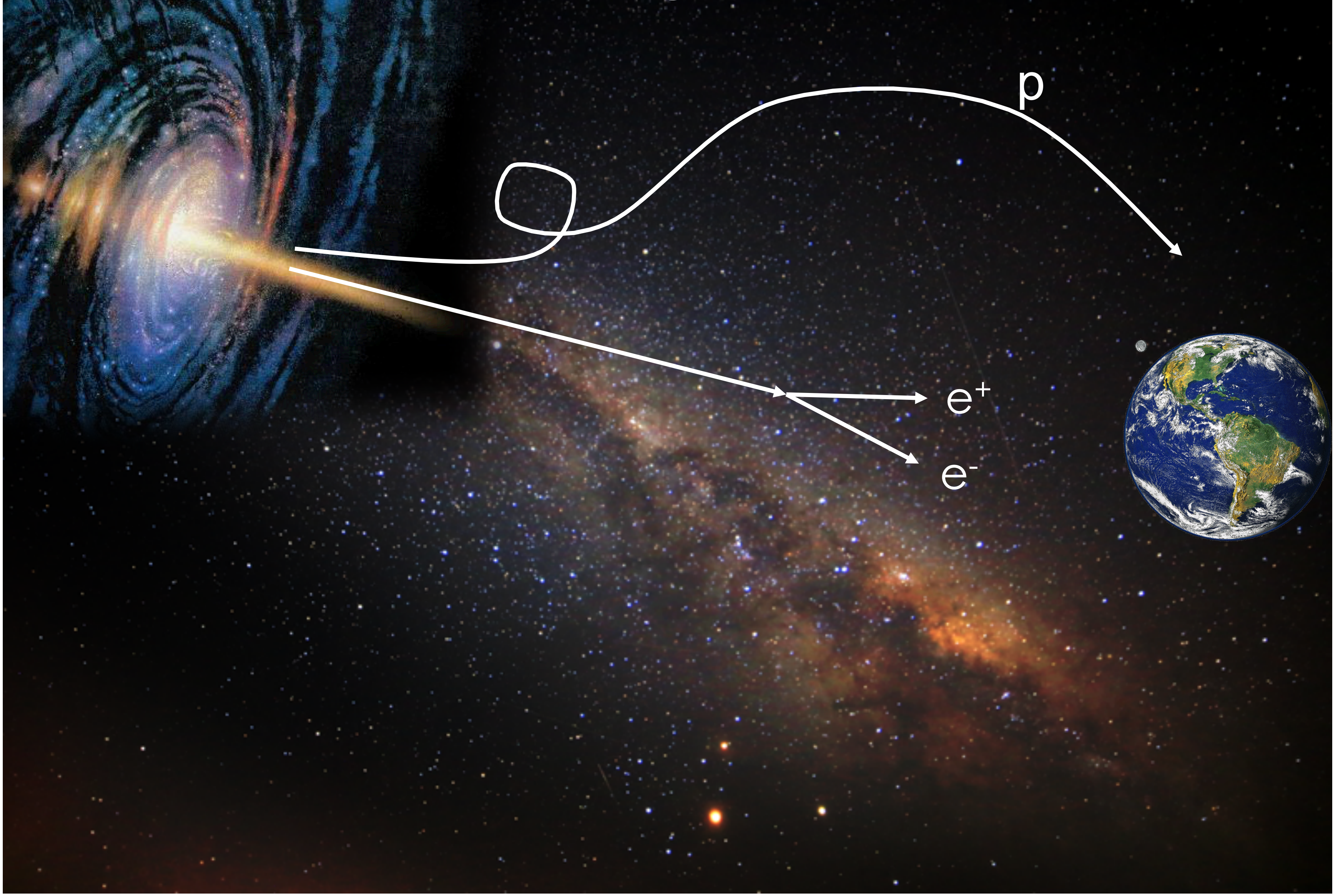

Cosmic Horizons – Gamma Radiation
energy = 10^15 eV
e+
e-
the gamma rays interact with microwave background photons (410 per cubic centimeter!) and do not reach Earth
enter: neutrinos

Multi-Messenger Astronomy

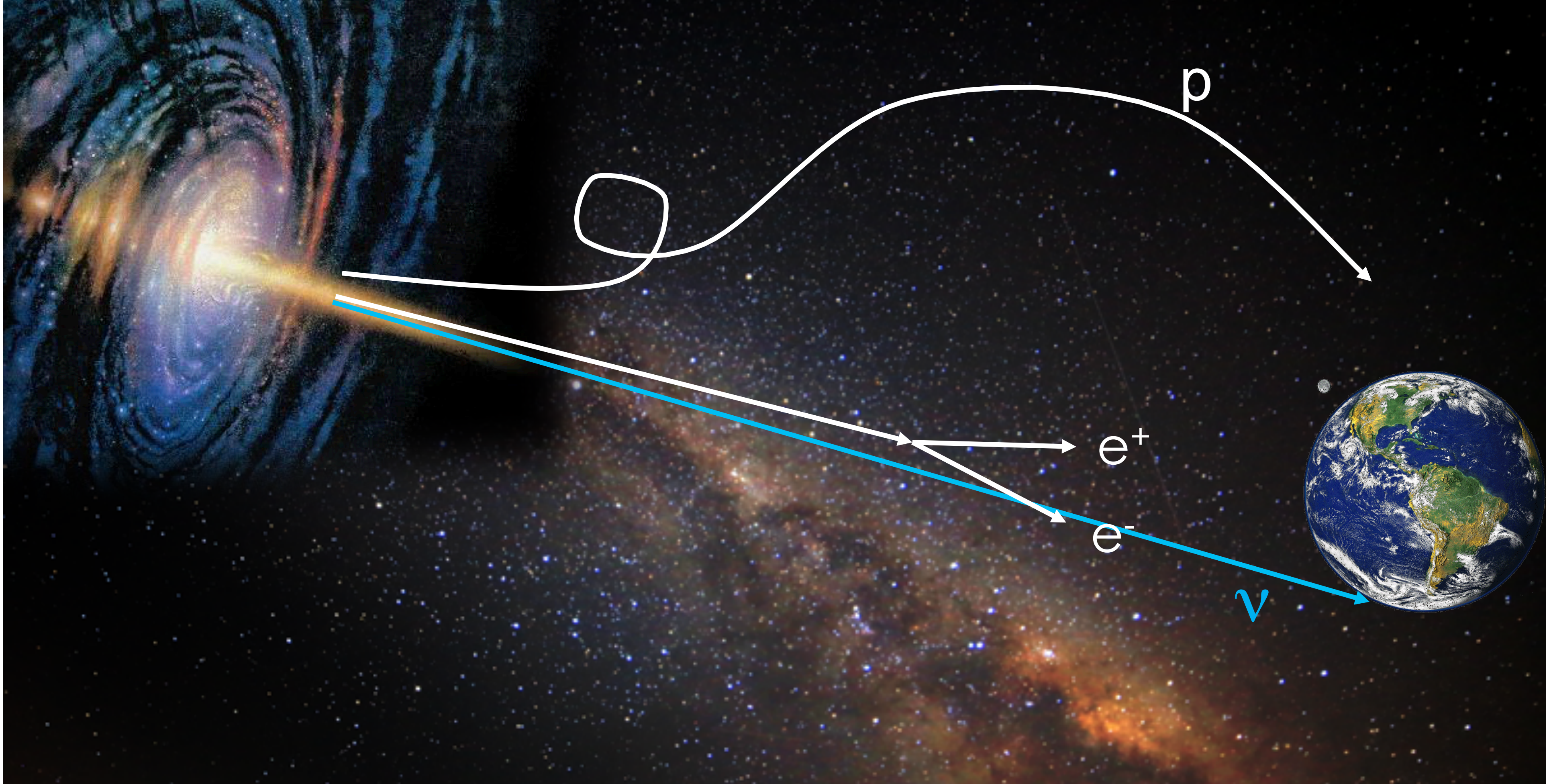


20% of the Universe is opaque to the EM spectrum

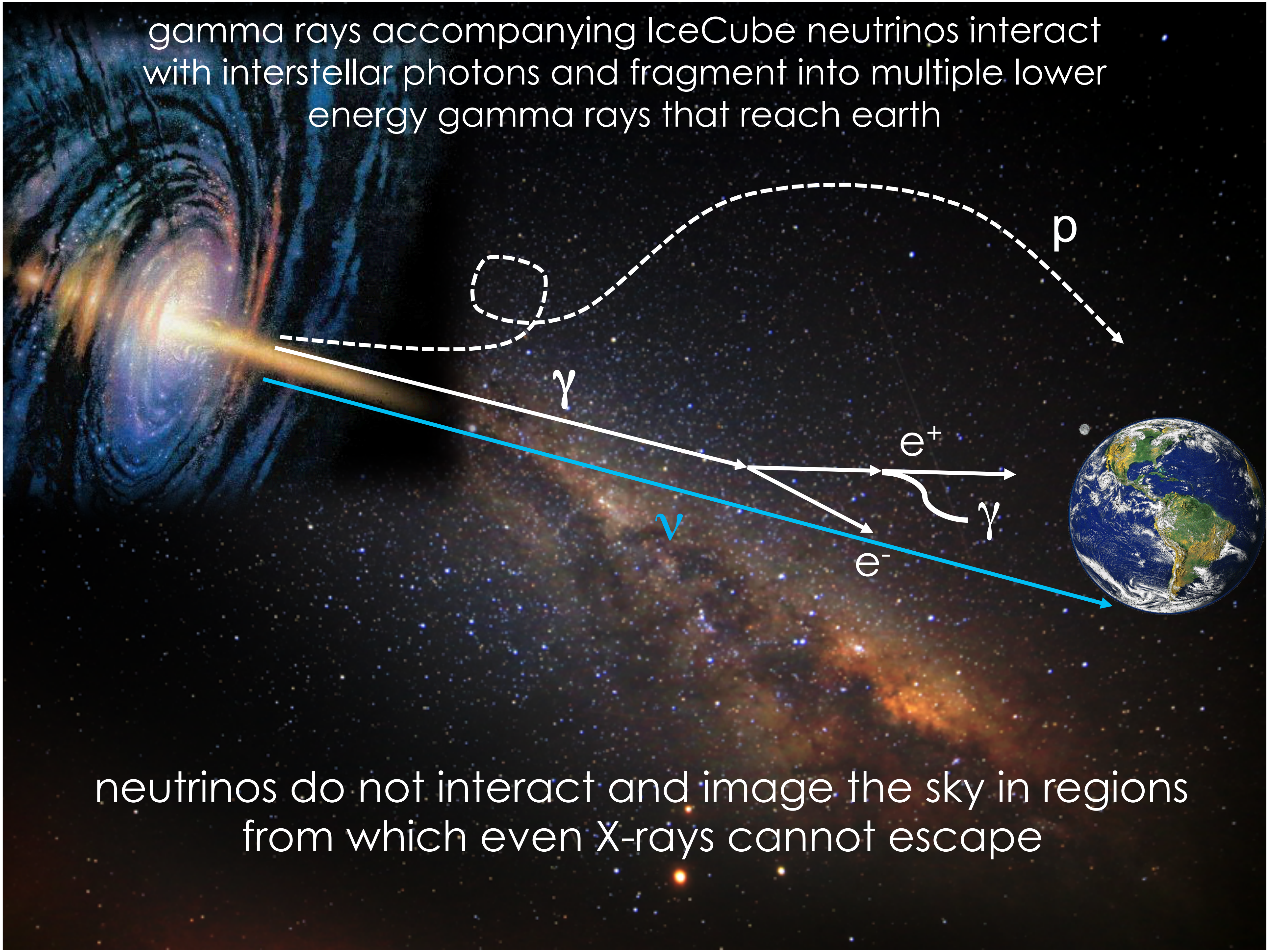
Cosmic Rays? Charged – Do not point

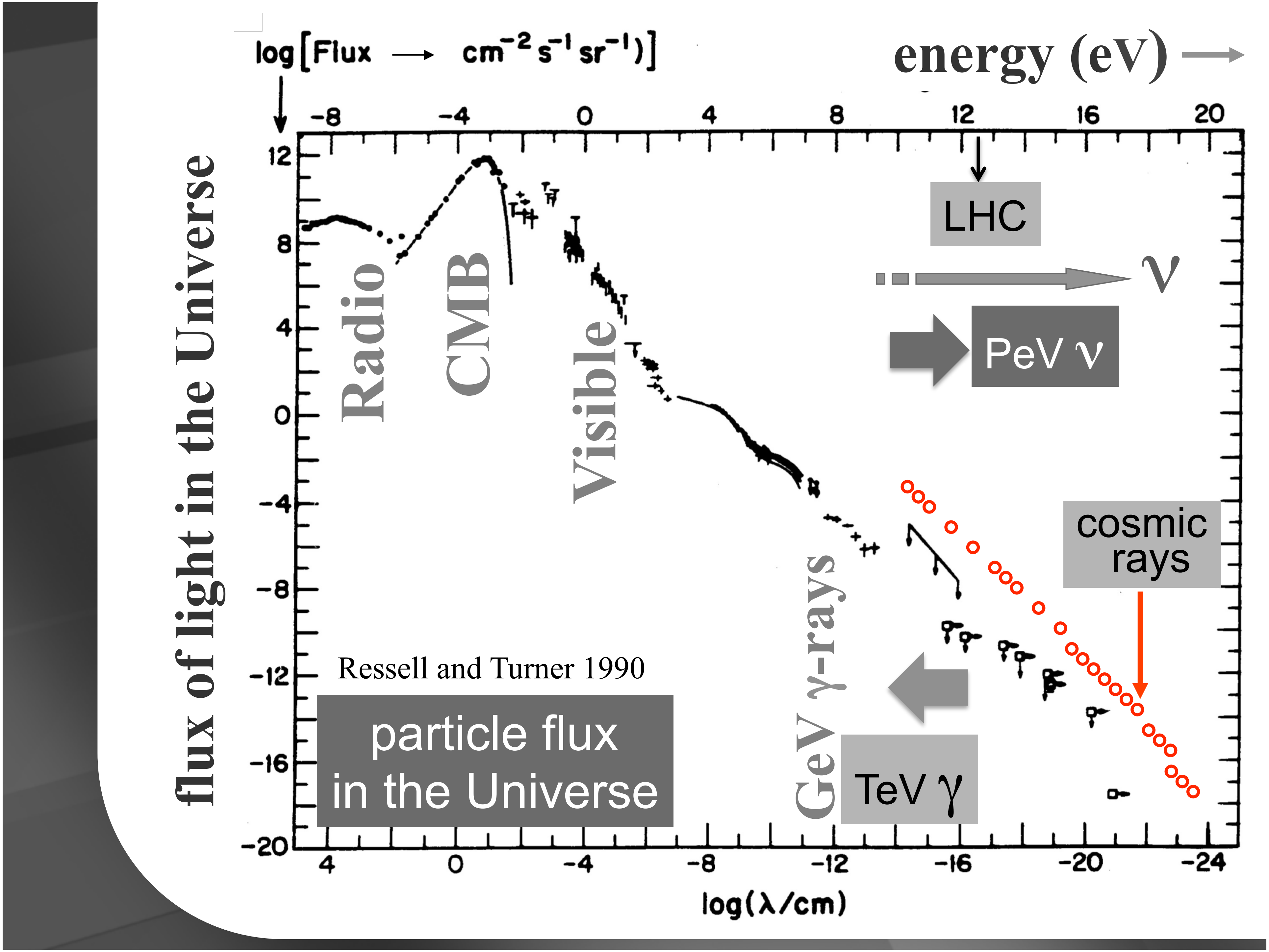


Neutrinos? Perfect Messenger



neutrinos do not interact and image the sky in regions from which even X-rays cannot escape

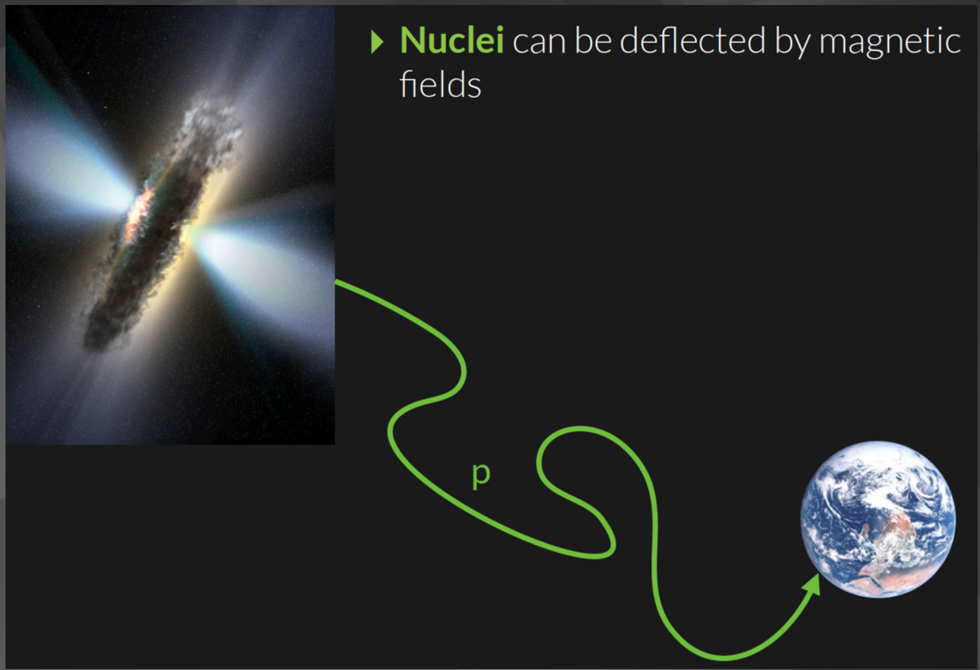

gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth
p
γ
e+
γ
ν
e-
neutrinos do not interact and image the sky in regions from which even X-rays cannot escape



log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV)
-8
-4
0
4
8
12
16
20
LHC
ν
PeV ν
Radio
CMB
Visible
GeV γ-rays
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe
flux of light in the Universe
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)

neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- … but difficult to detect



cosmic accelerators ?

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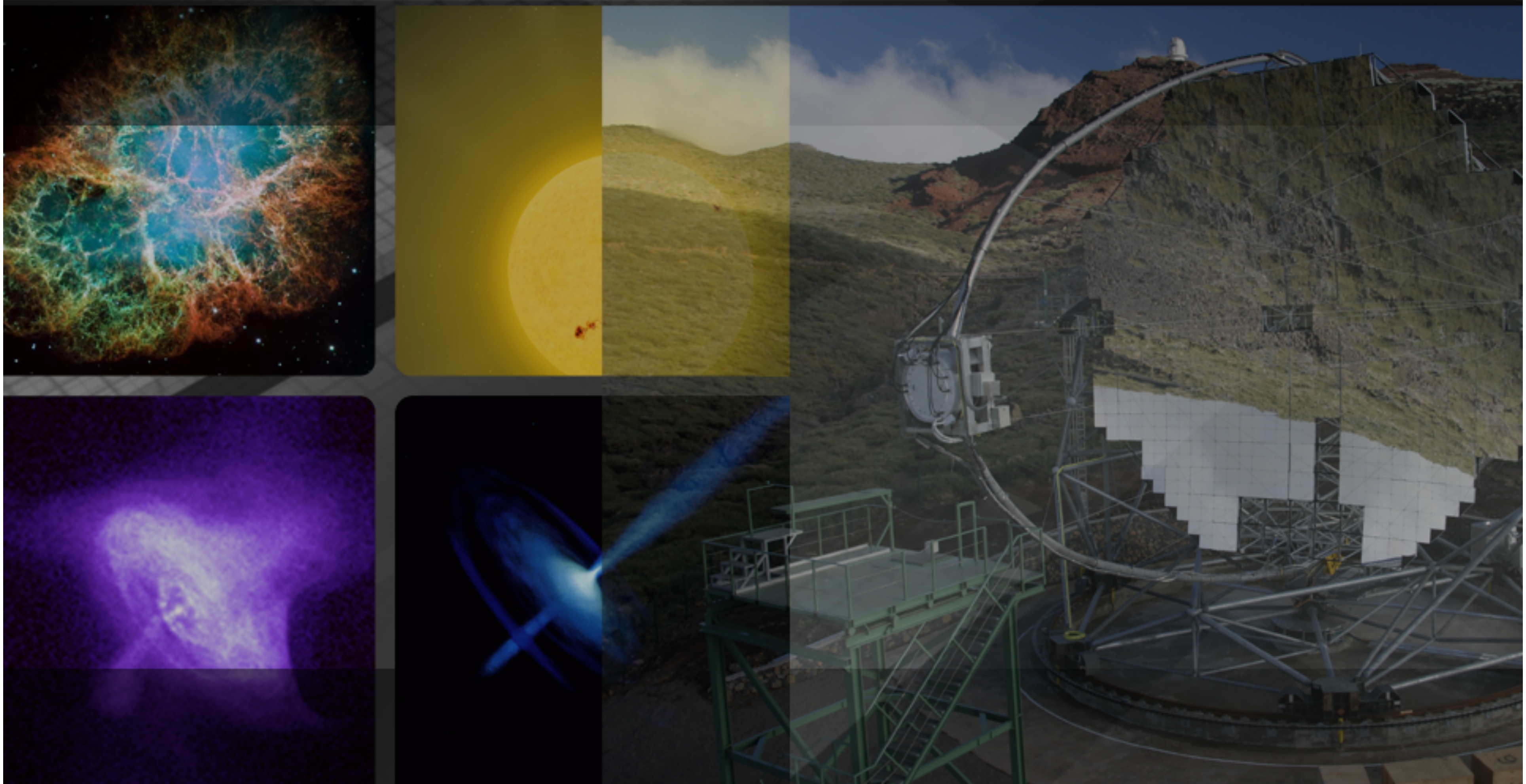


The real voyage is not to travel to new landscapes,
but to see with new eyes. . .

Marcel Proust

definitions

- flux $\left(particles\ per\ GeV\ per\ cm^2\ per\ s \right)$ $\frac{dN}{dE} = c\rho$
- luminosity $L = E^2 \frac{dN}{dE dt (d\Omega)}$
- density $\left(velocity \times \rho = total\ flux \right)$ $\rho = \frac{4\pi}{\mathrm{c}} \int \frac{dN}{dE} dE$
- energy density $\rho_E = \frac{4\pi}{\mathrm{c}} \int E \frac{dN}{dE} dE$
- mean free path $\lambda = \frac{1}{n_{tar}\sigma}$
- energy loss distance $R = \frac{E_f}{E_i} \lambda$

cosmic ray accelerators (preamble)

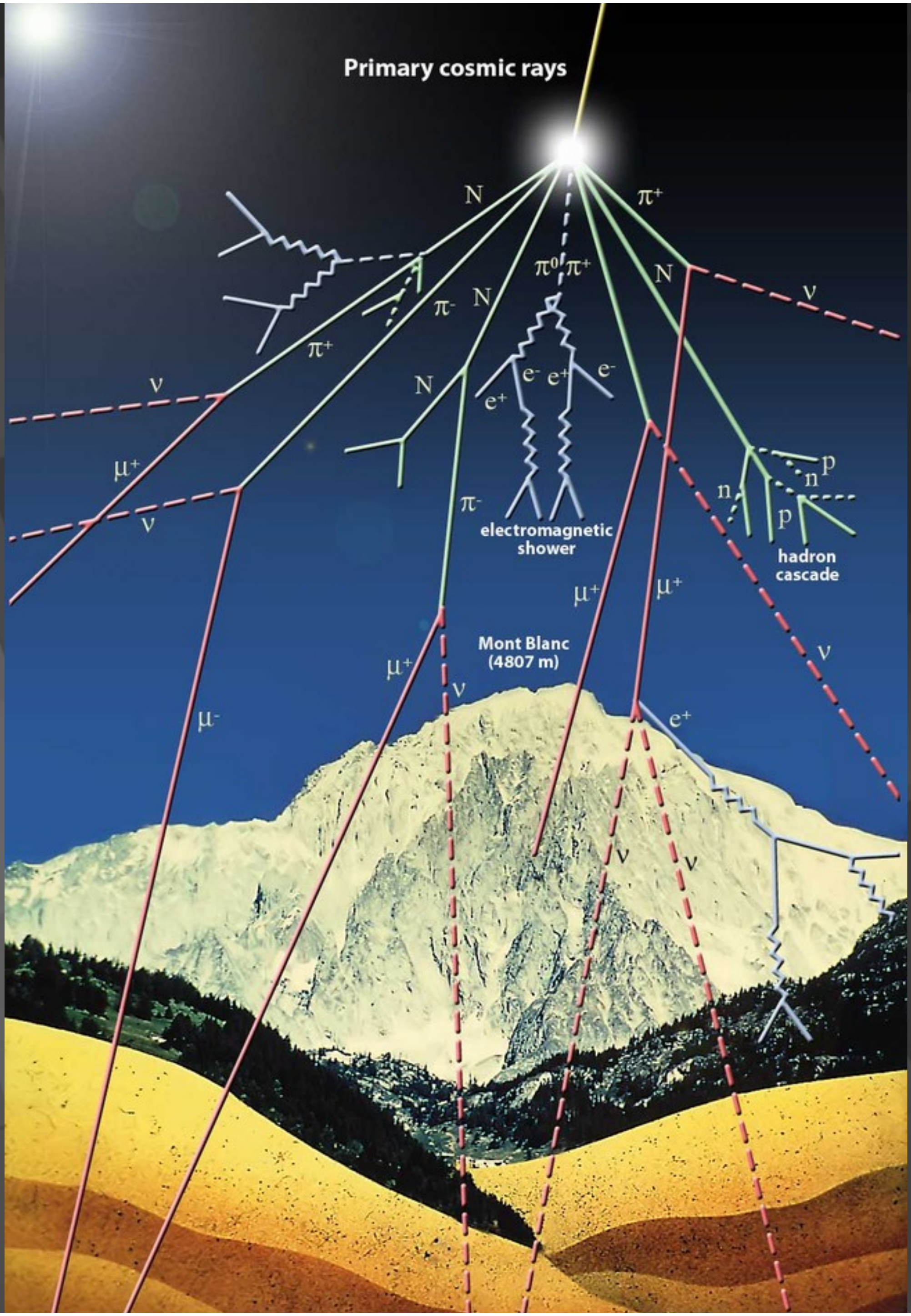
- best buy theory or why we believe that new astroparticle physics instrumentation will reveal the sources of the cosmic rays.

- cosmic rays, gamma rays and neutrinos
  → many 1000 km^2 air shower arrays
  → large arrays of ground-based gamma ray telescopes
  → kilometer-cube neutrino detectors

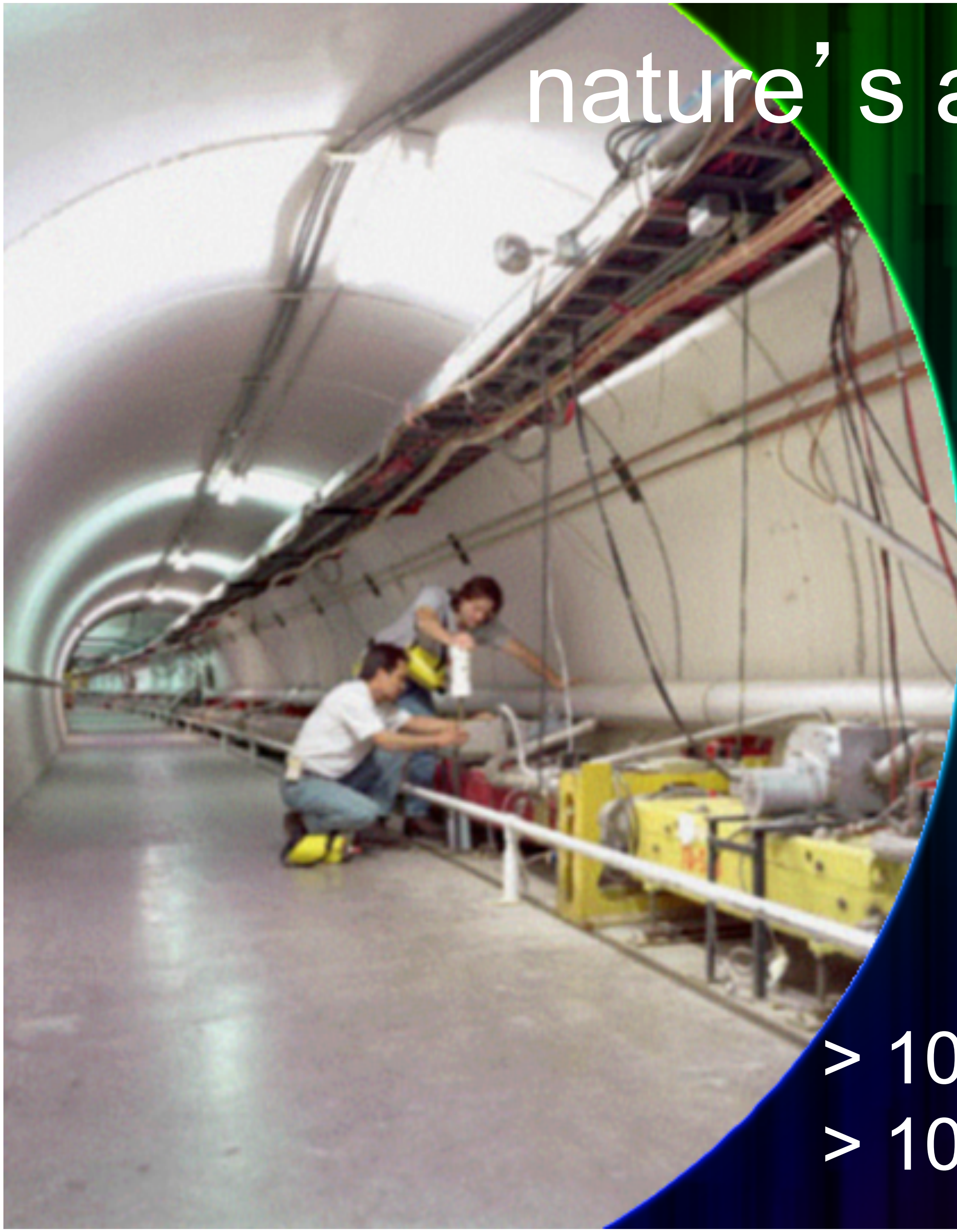
cosmic rays

Victor Hess
in 1912
discovers
radiation
from space

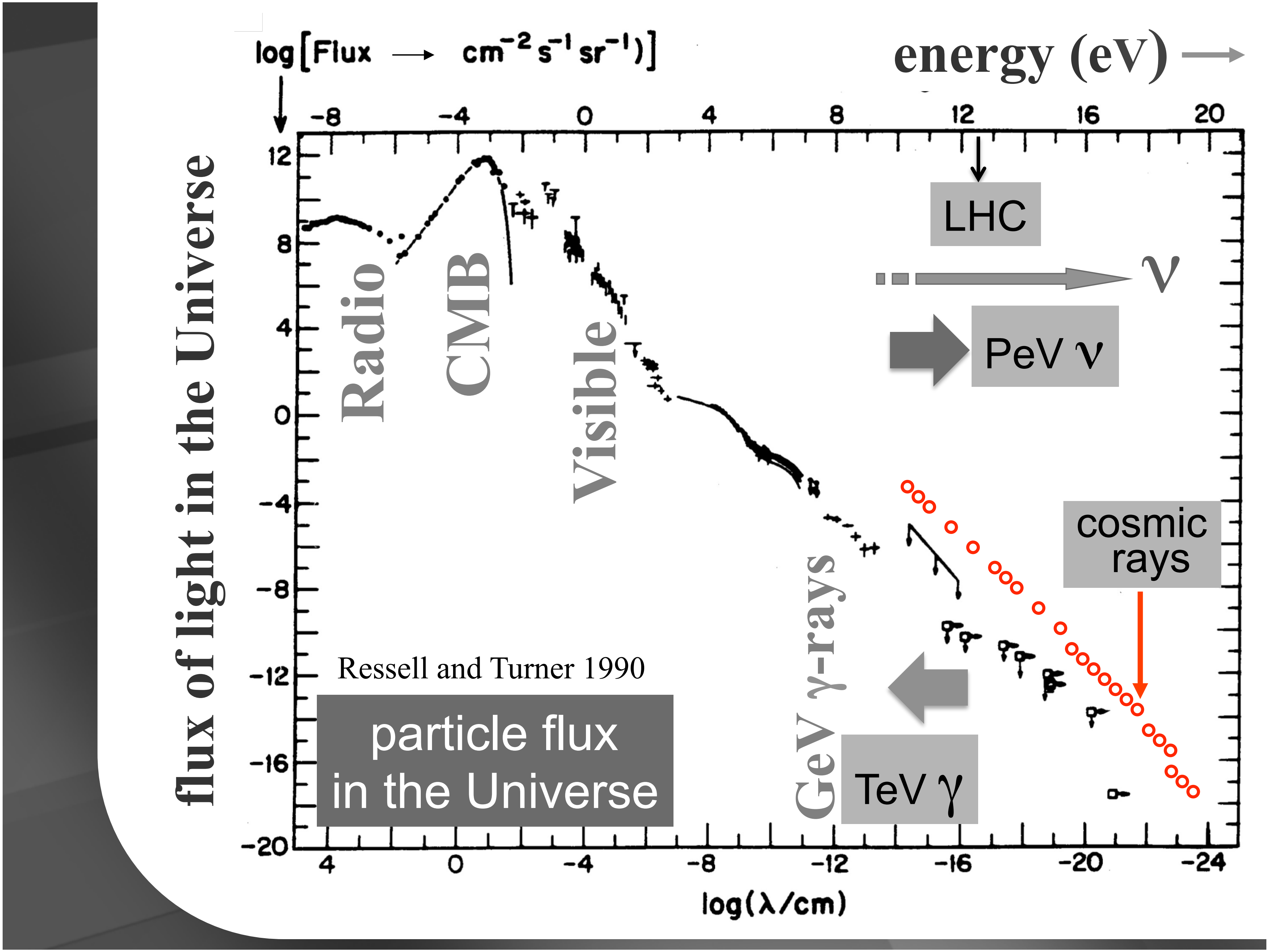
the oldest
puzzle
in astronomy



nature’s accelerators ?



> 10^8 TeV in the Universe
> 10^3 TeV in the Galaxy

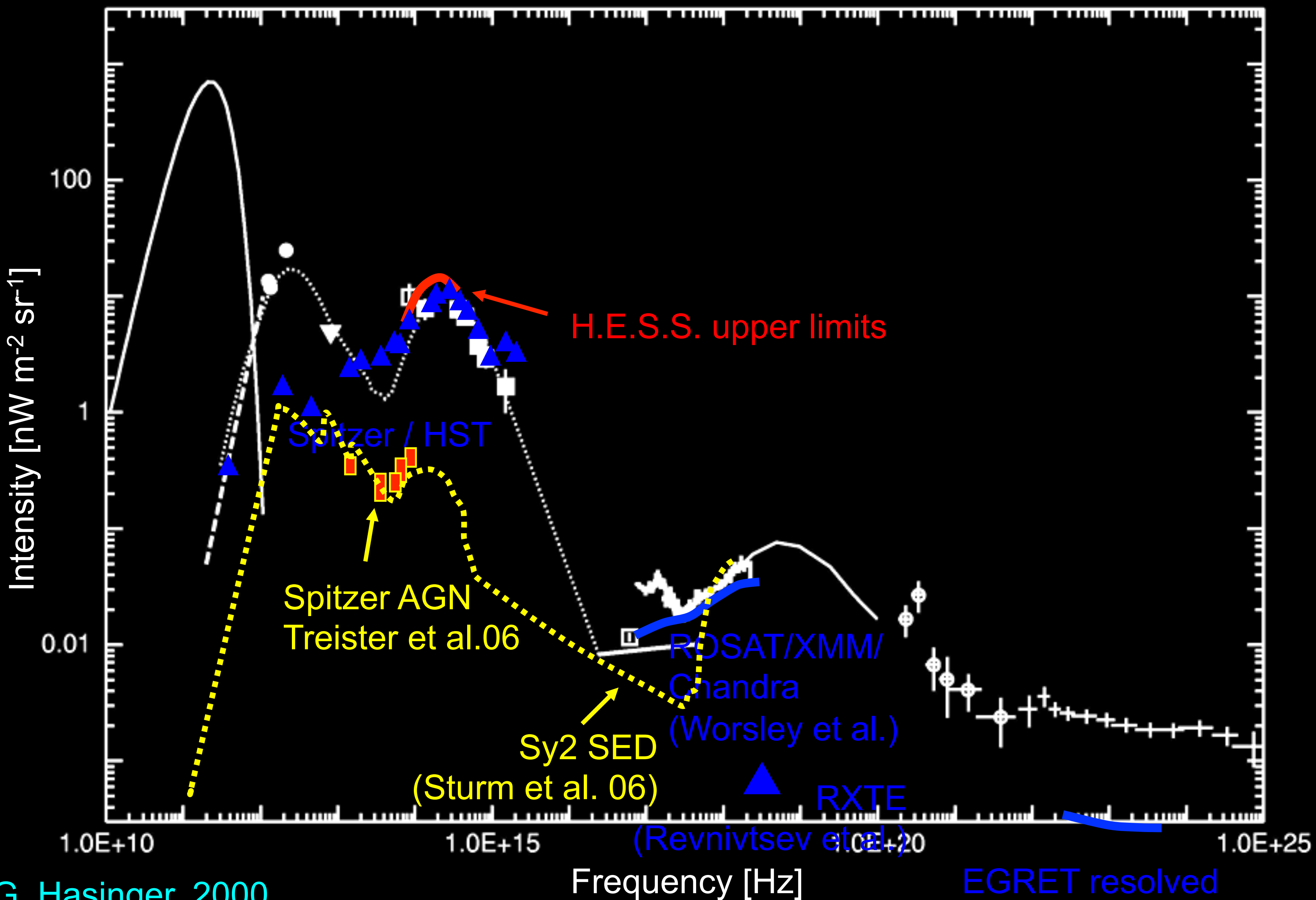


log[Flux → cm⁻²s⁻¹sr⁻¹)]
energy (eV)
-8 -4 0 4 8 12 16 20
12 8 4 0 -4 -8 -12 -16 -20
LHC
ν
PeV ν
Radio
CMB
Visible
cosmic rays
GeV γ-rays
TeV γ
flux of light in the Universe
Ressell and Turner 1990
particle flux in the Universe
4 0 -4 -8 -12 -16 -20 -24
log(λ/cm)

with 10^3 TeV energy, photons do not reach us from the edge of our galaxy because of their small mean free path in the microwave background

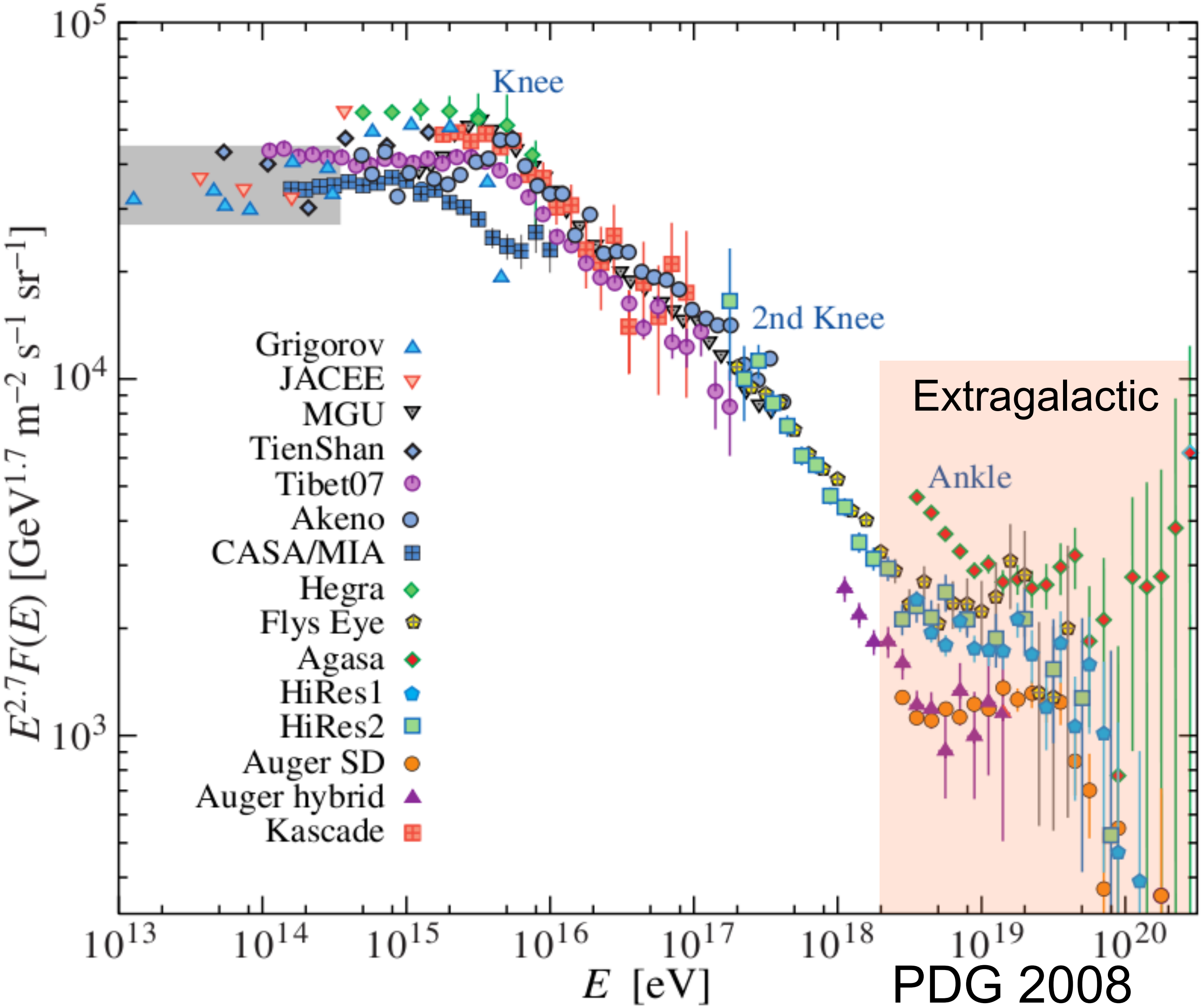
$$\gamma + \gamma_{CMB} \longrightarrow e^+ + e^-$$

Background Energy Distribution



G. Hasinger, 2000

cosmic rays

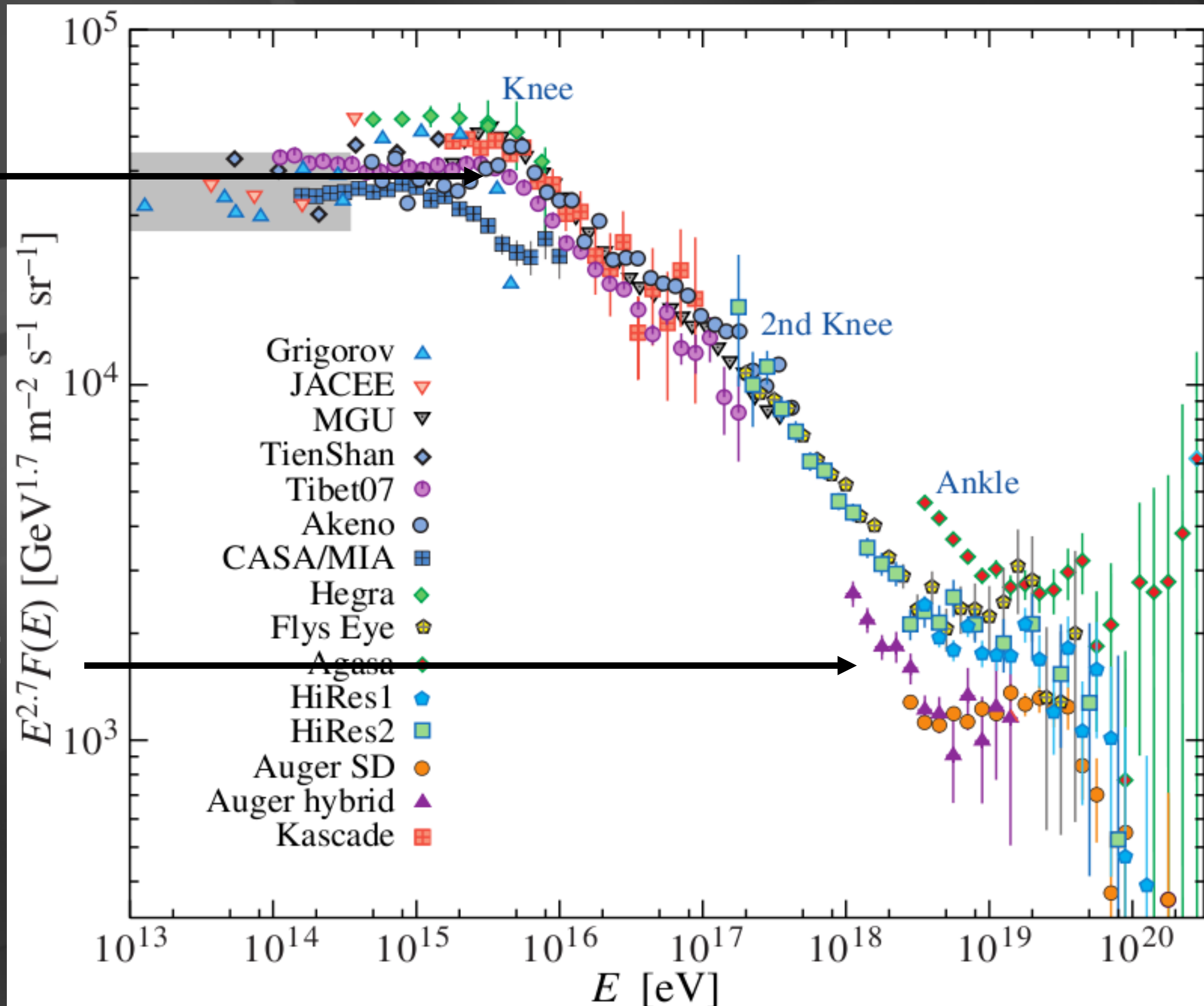


PDG 2008

… often wrong, but never in doubt …

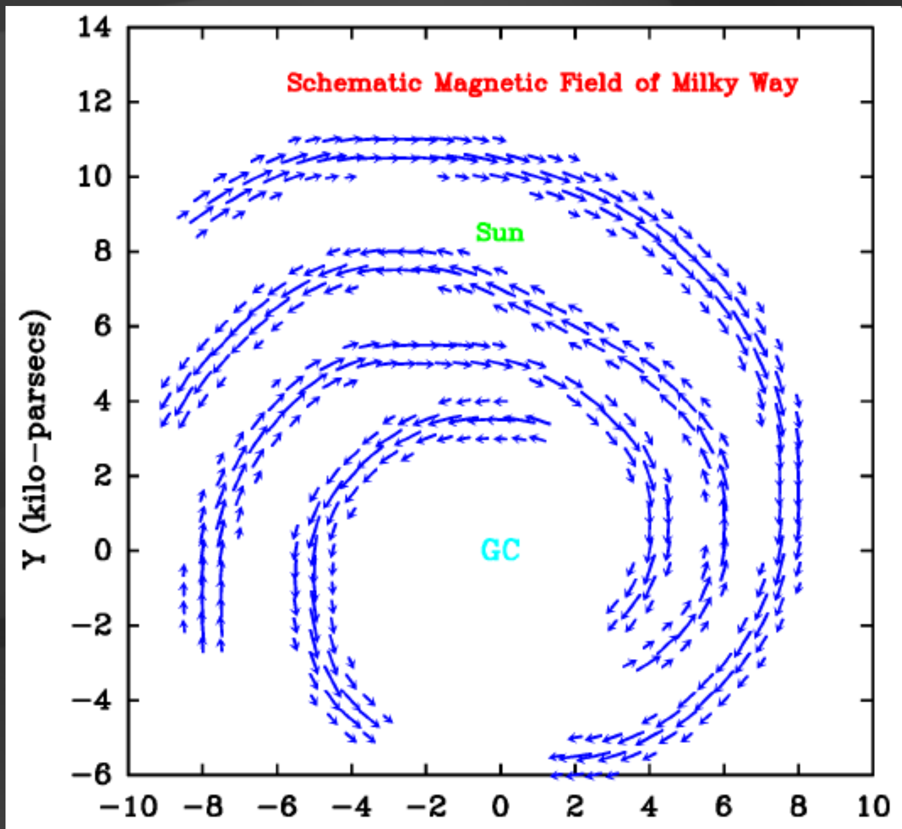
Galactic:
supernova
remnants?

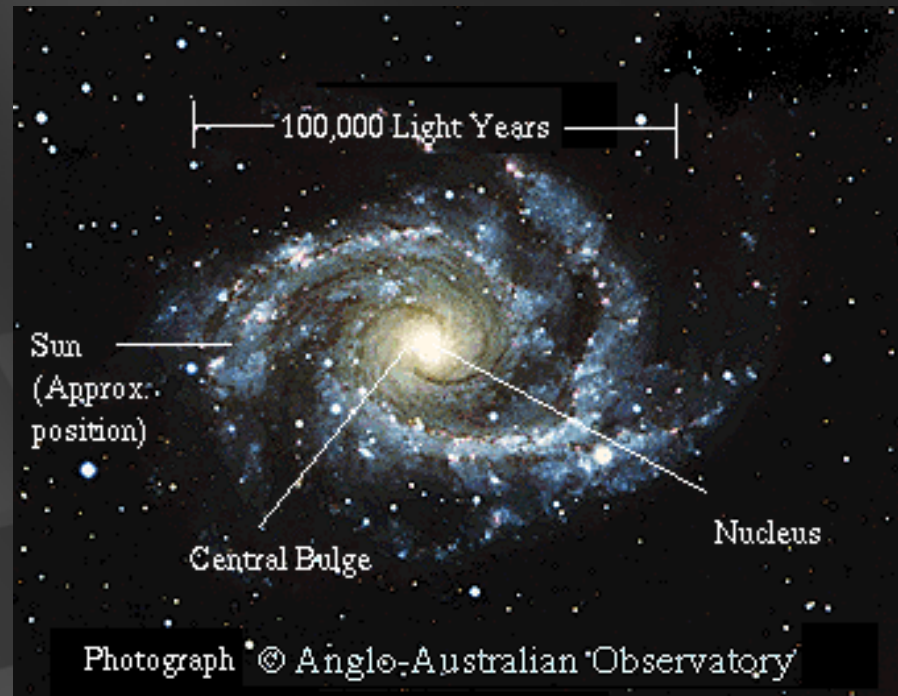
extragalactic:
gamma ray
bursts?

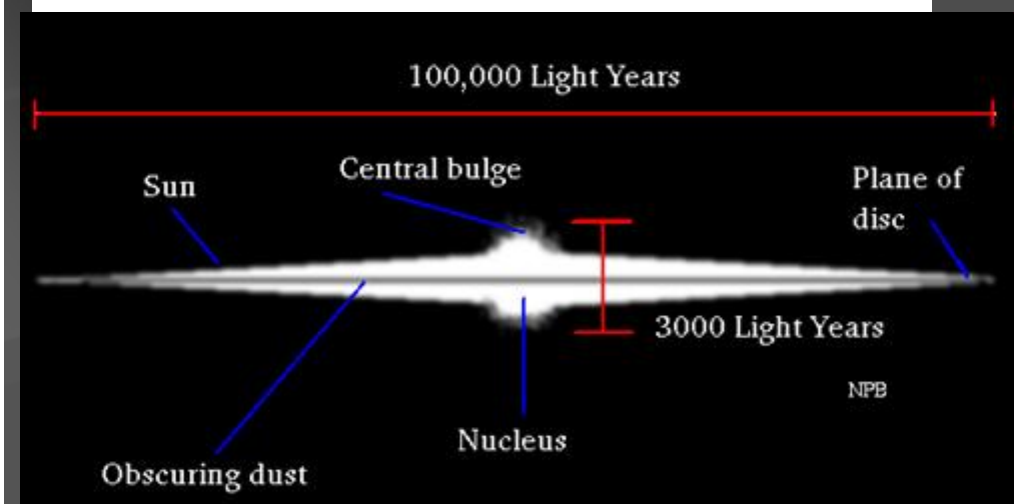


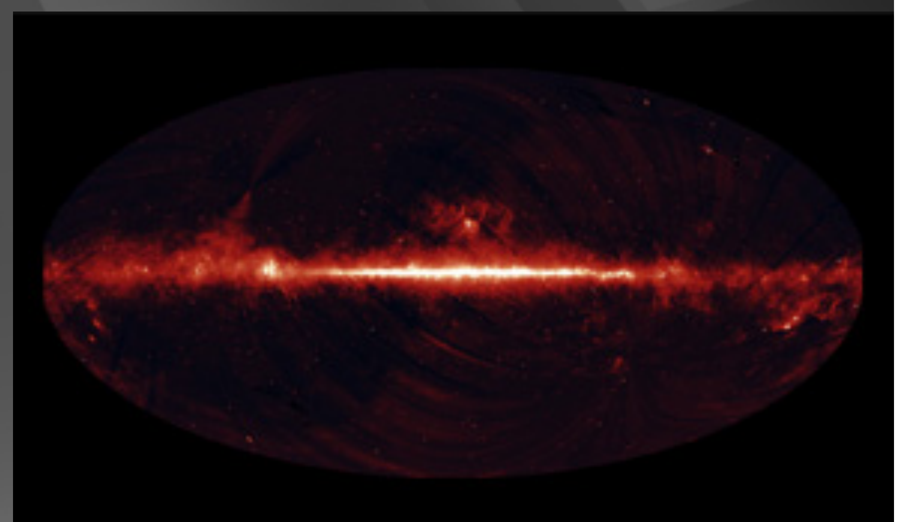
Galactic and extragalactic cosmic rays

- we live in a magnetic bottle filled with cosmic rays. The cosmic ray density is enhanced by magnetic trapping in an average field of a few μGauss.
- extragalactic space is filled over the Hubble radius with a much more tenuous gas produced over the entire history of the Universe.

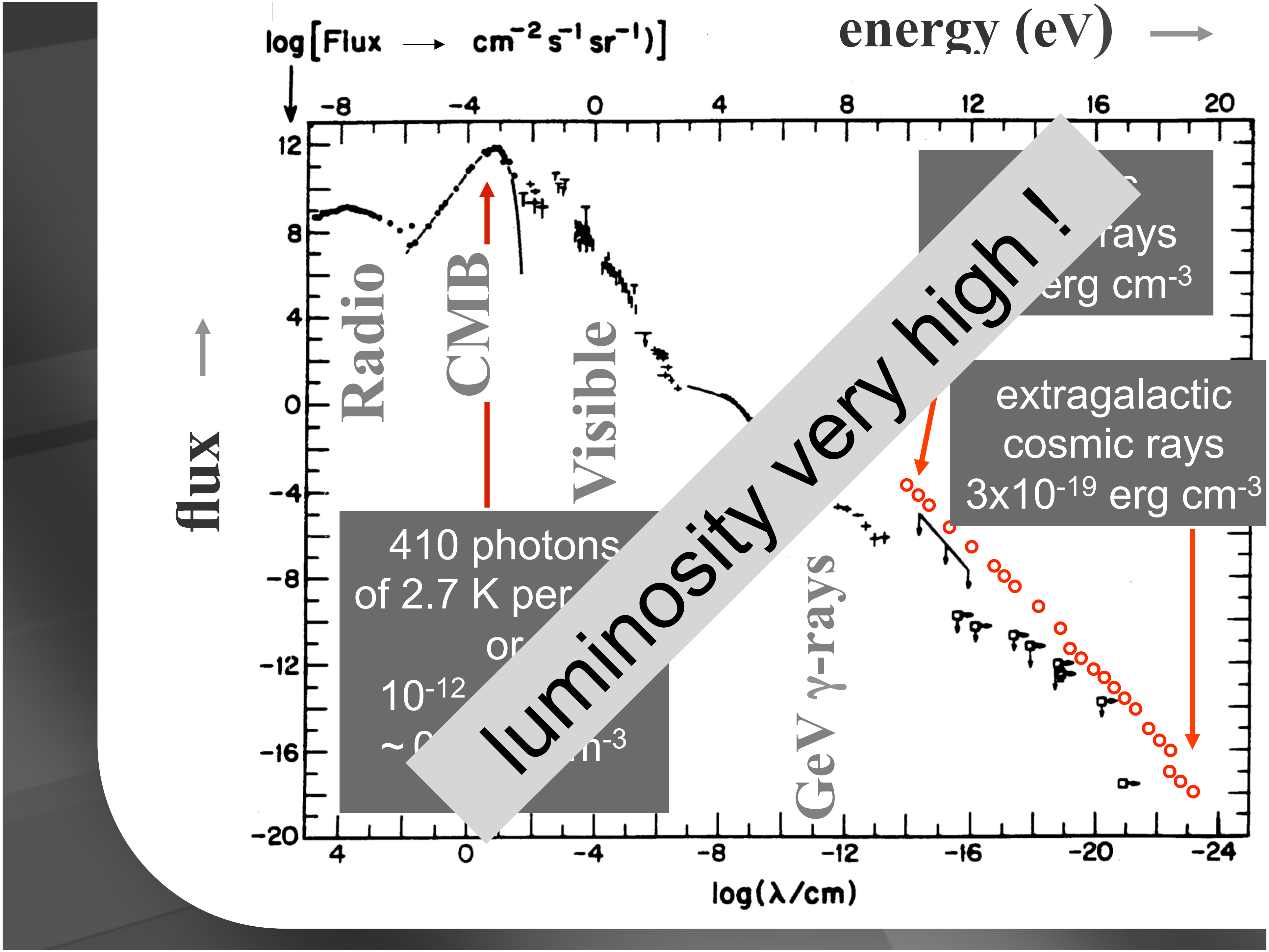

Schematic Magnetic Field of Milky Way
Sun
GC
Y (kilo−parsecs)
14
12
10
8
6
4
2
0
−2
−4
−6
−10
−8
−6
−4
−2
0
2
4
6
8
10


100,000 Light Years
Sun
(Approx.
position)
Central Bulge
Nucleus
Photograph © Anglo-Australian Observatory


100,000 Light Years
Sun
Central bulge
Plane of
disc
3000 Light Years
NPB
Nucleus
Obscuring dust



cosmic accelerators



log[Flux → cm-2 s-1 sr-1)]
energy (eV)
-8
-4
0
4
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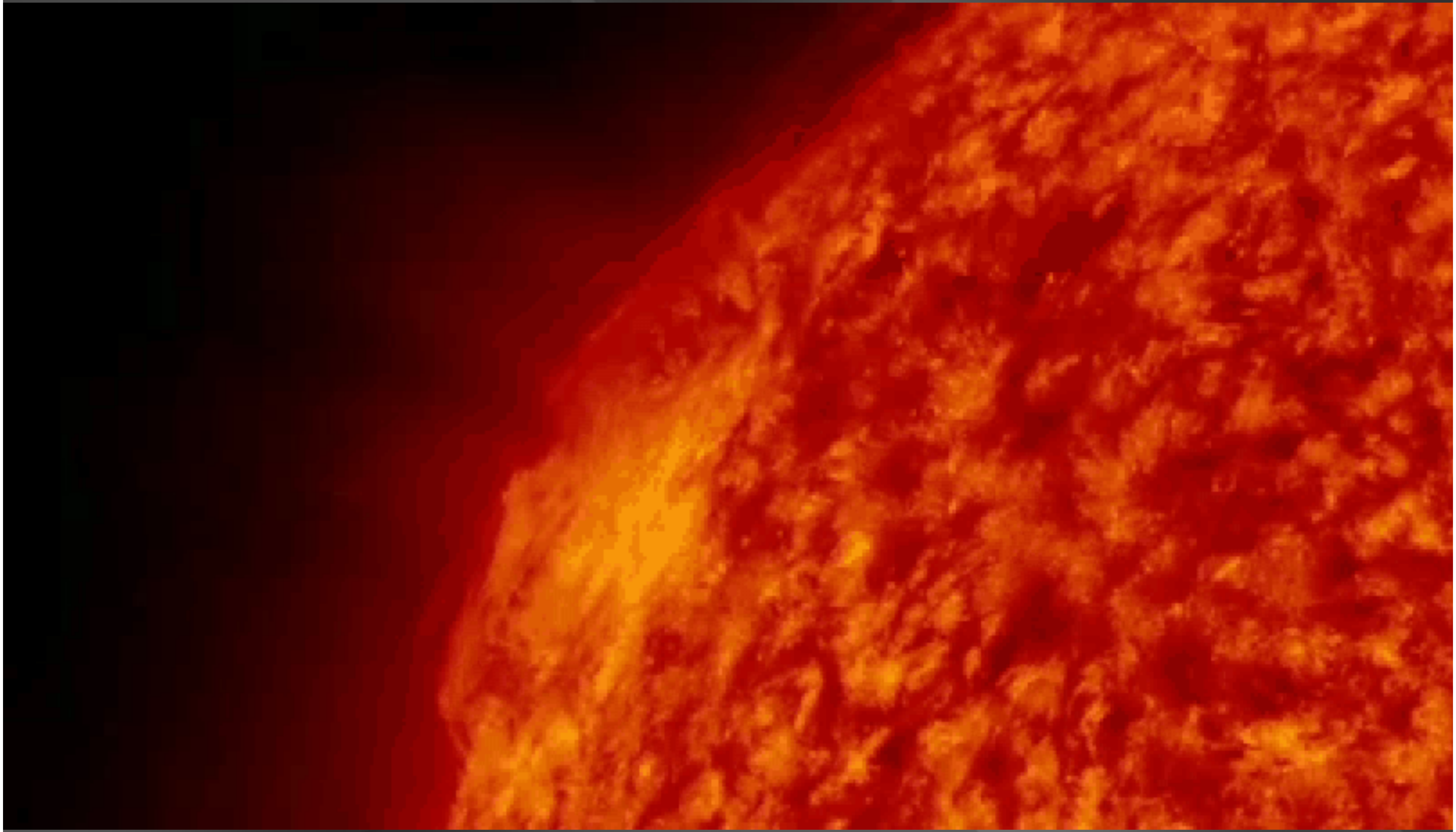
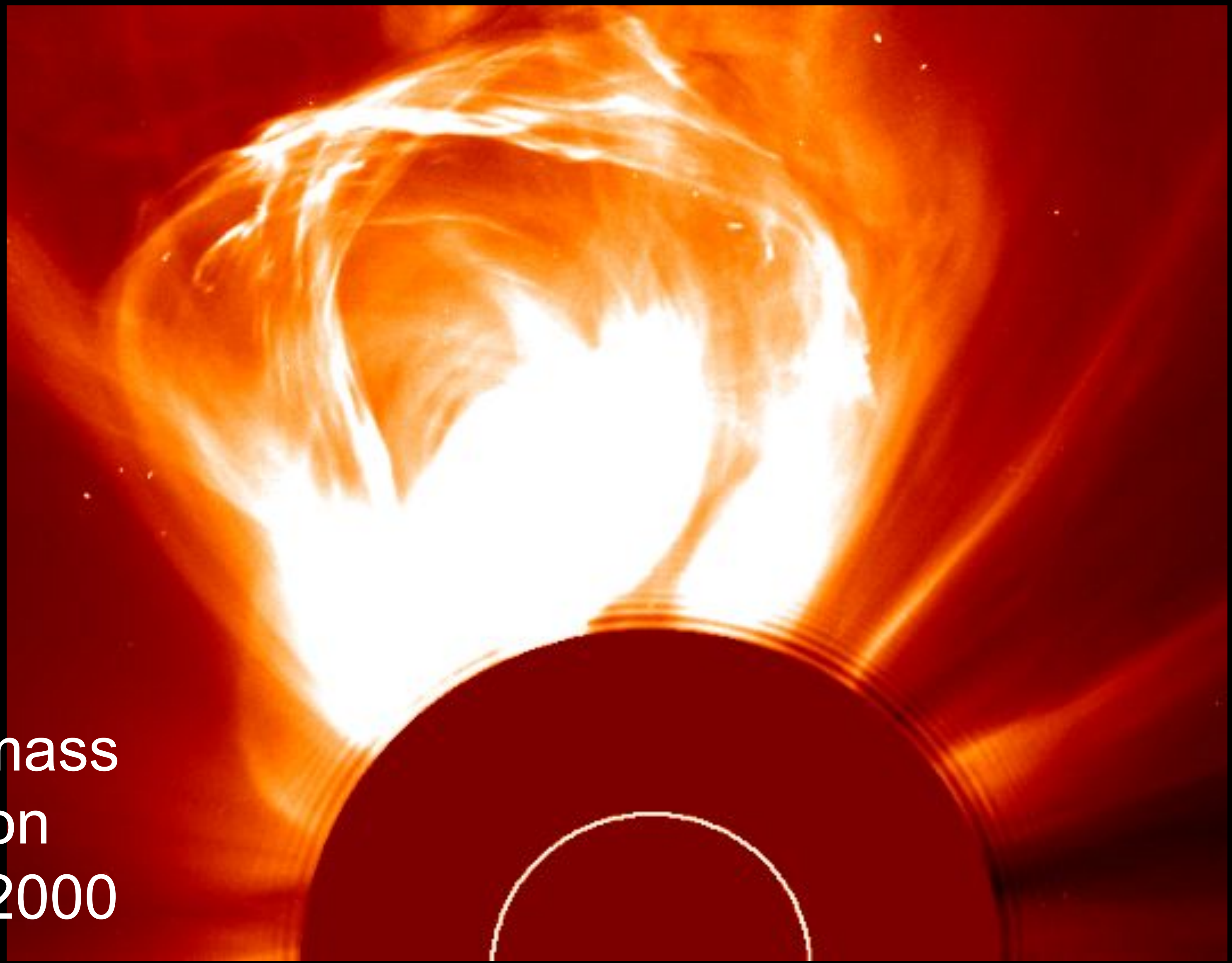
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)
flux
Radio
CMB
Visible
GeV γ-rays
410 photons
of 2.7 K per
or
10-12
~0
m-3
rays
erg cm-3
extragalactic
cosmic rays
3x10-19 erg cm-3
luminosity very high !

the Sun constructs an accelerator

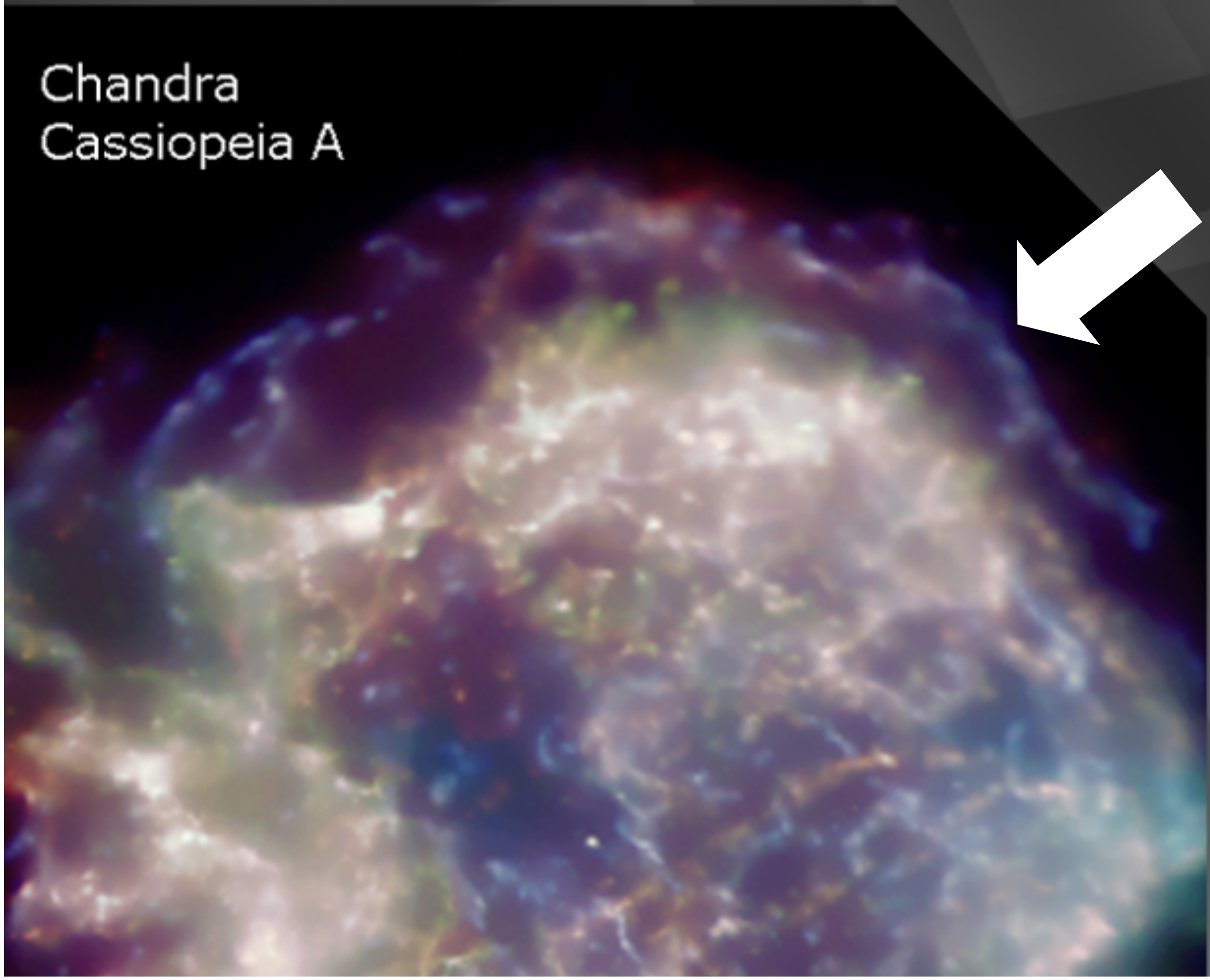


the sun constructs an accelerator



coronal mass
ejection
09 Mar 2000

large magnetic field in young supernova remnants

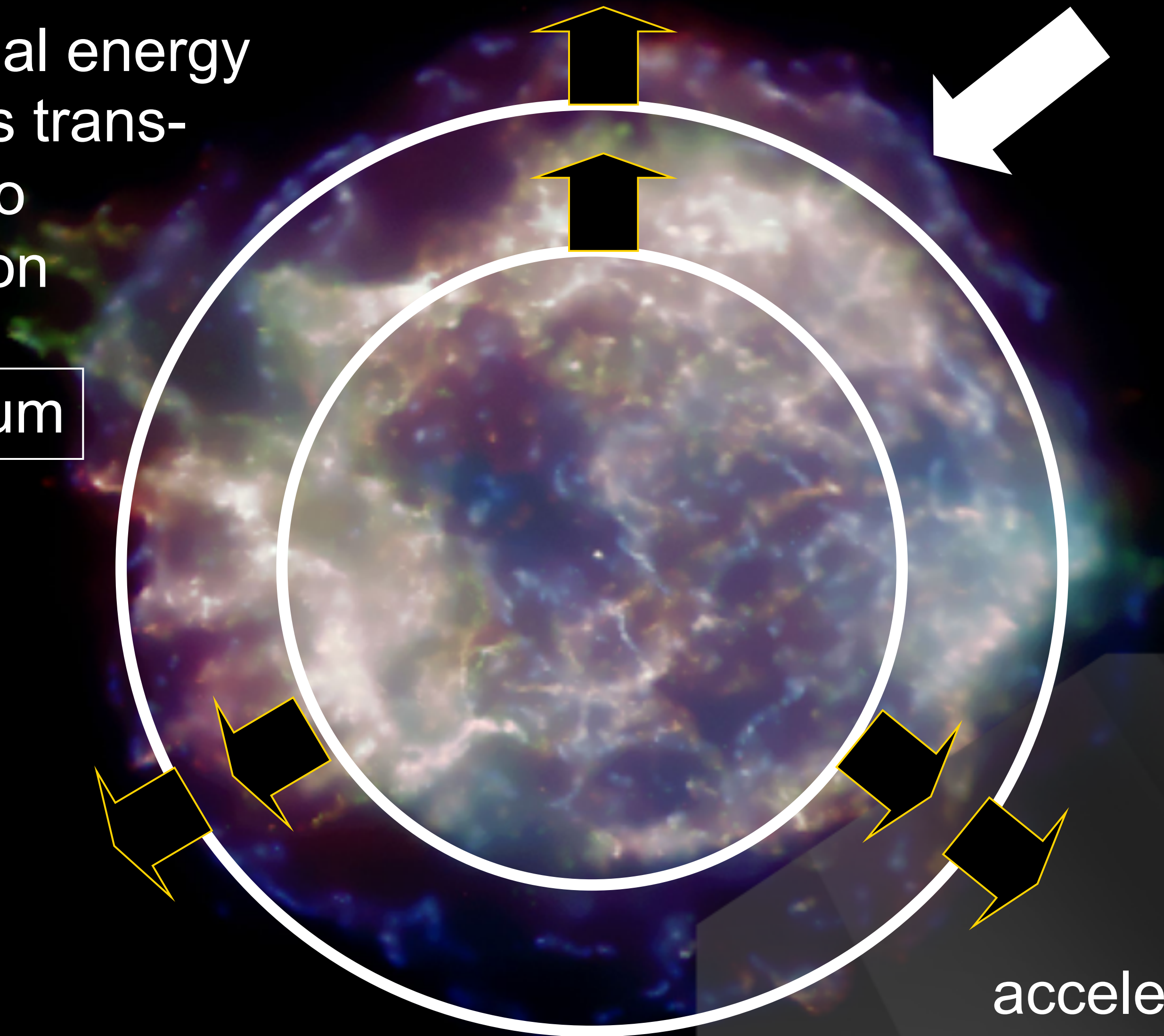


cassiopeia A supernova remnant in X-rays

gravitational energy released is transformed into acceleration

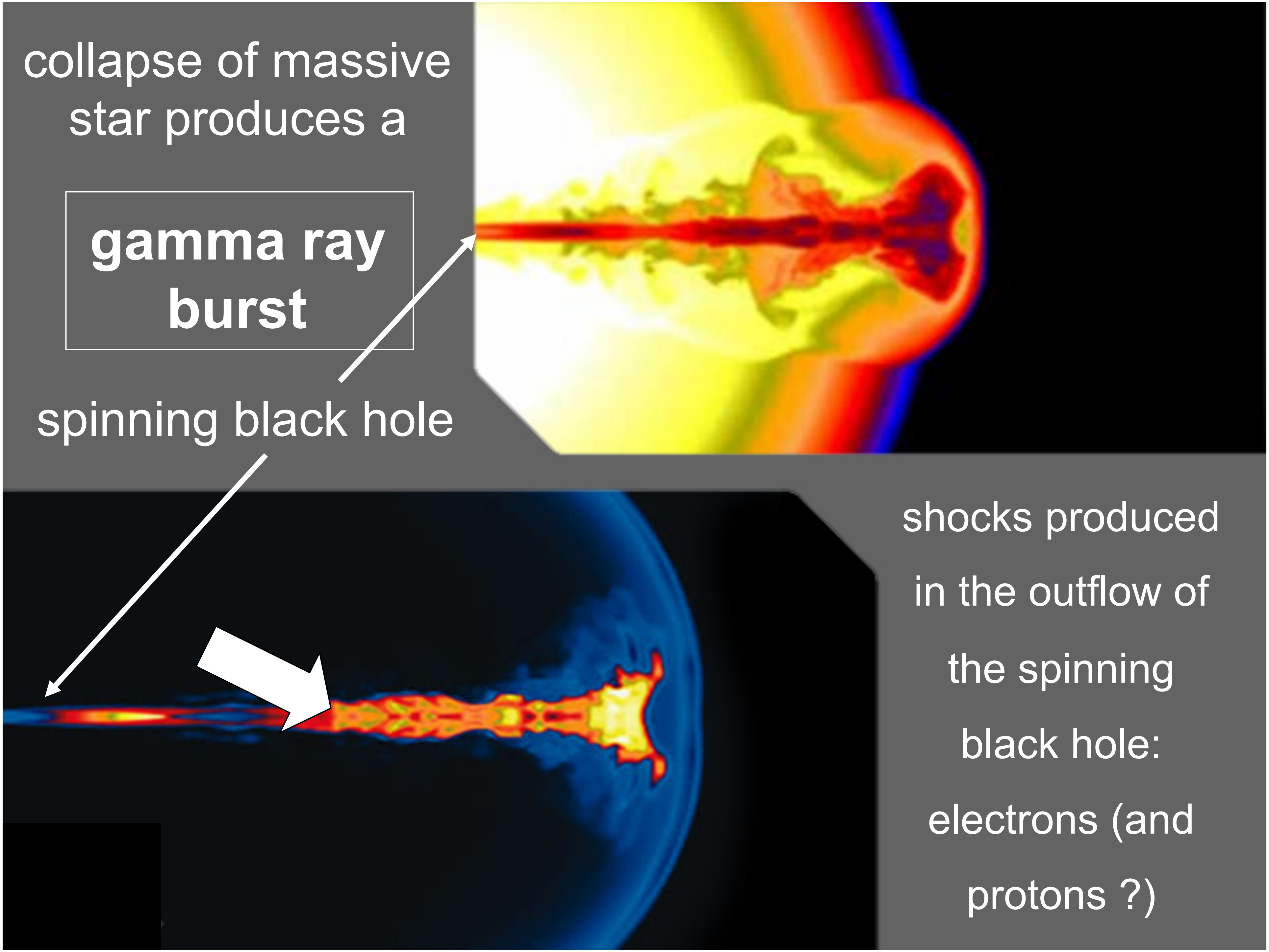
→

E^{-2} spectrum



acceleration when particles cross high B-fields and if the star collapses to a black hole …

→ happens in seconds not thousands of years
→ beamed not spherical
→ simulation not image


collapse of massive star produces a
gamma ray burst
spinning black hole
shocks produced in the outflow of the spinning black hole: electrons (and protons ?)

Hillas formula :

- accelerator must contain the particles

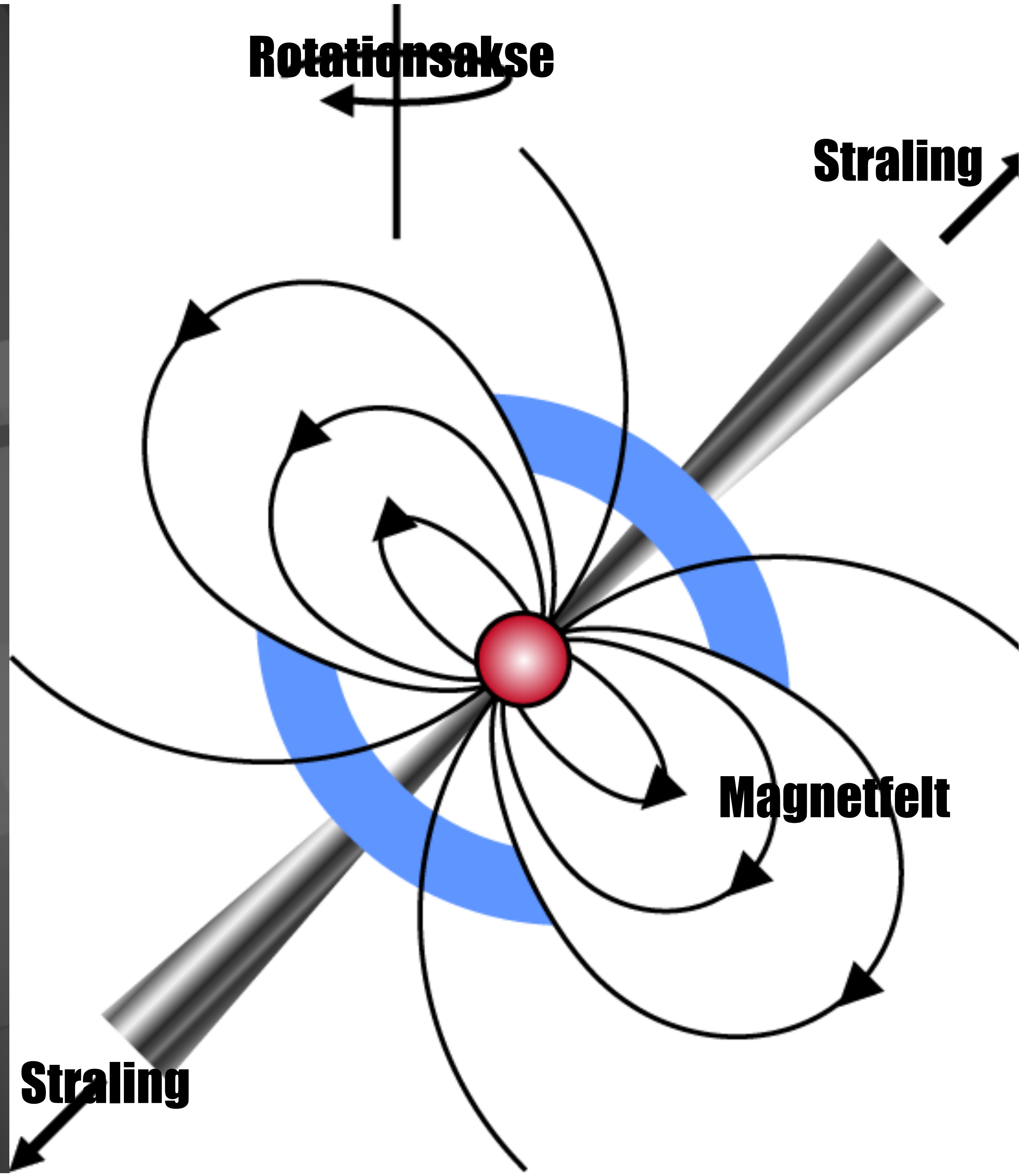
$$R_{gyro} \left(= \frac{E}{\mathrm{v}qB}\right) \le R$$

$$E \le \mathrm{v}\, qBR$$

- dimensional analysis, difficult to satisfy

pulsar

$$v \to \frac{2\pi R}{T}$$

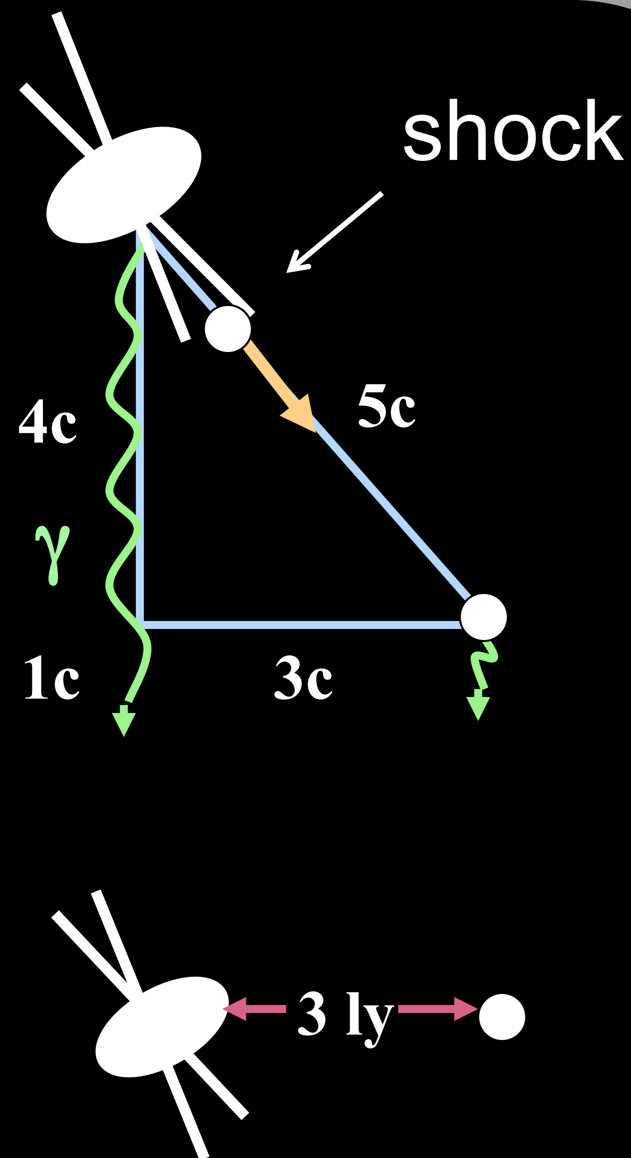


$$E(eV) = B(Tesla)\, R(m)\, \frac{2\pi R}{T}$$

	ms-pulsar	*Fermilab*
R	10 km	km
B	10^8 Tesla	Tesla
T^{-1}	10^3	10^5 (#rev/s)
E	10^7 TeV	10^{12} eV = 1 TeV !

still a very open problem…

superluminal motion: boosted accelerators



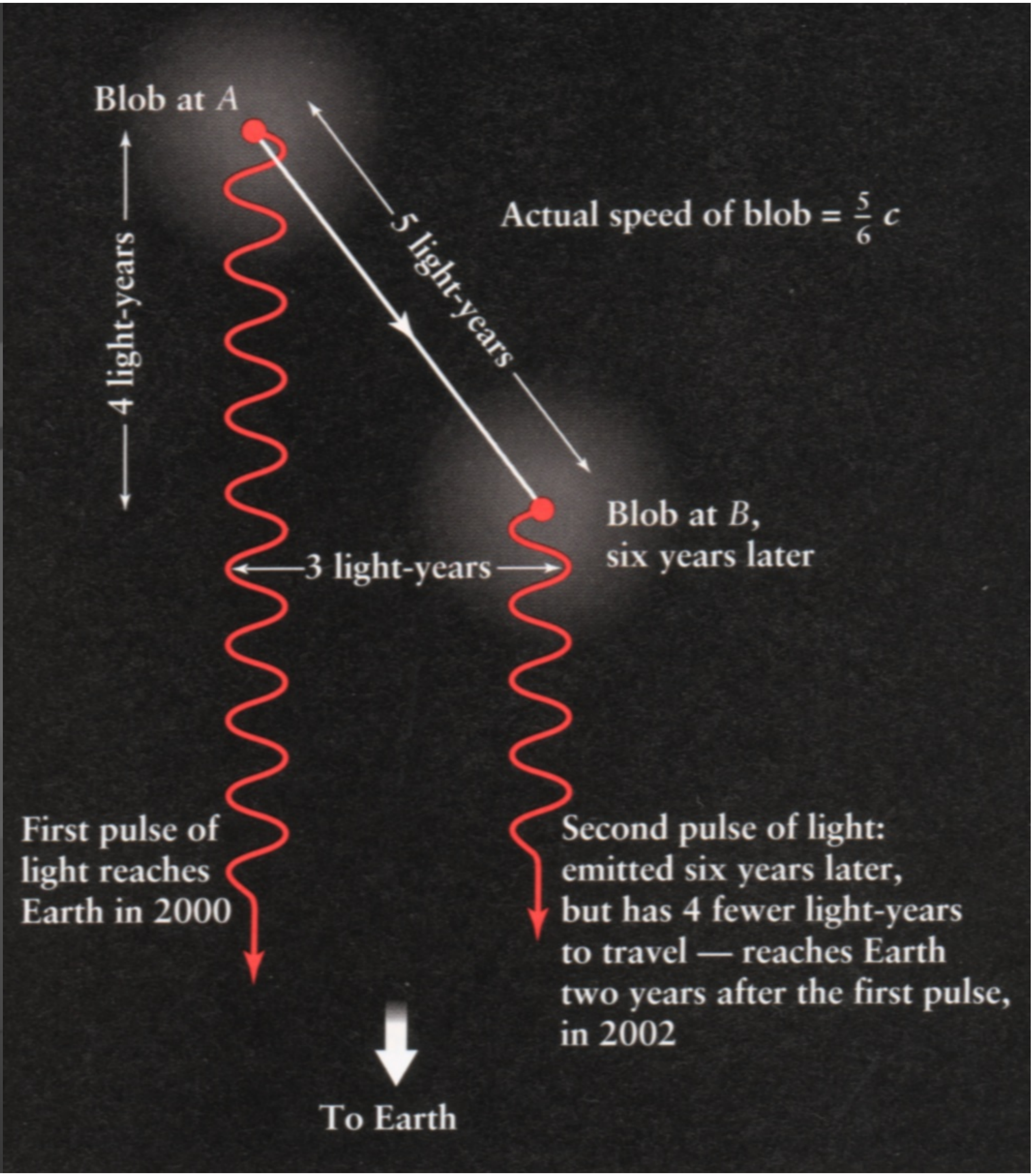
$$E_{obs} = \Gamma E'$$

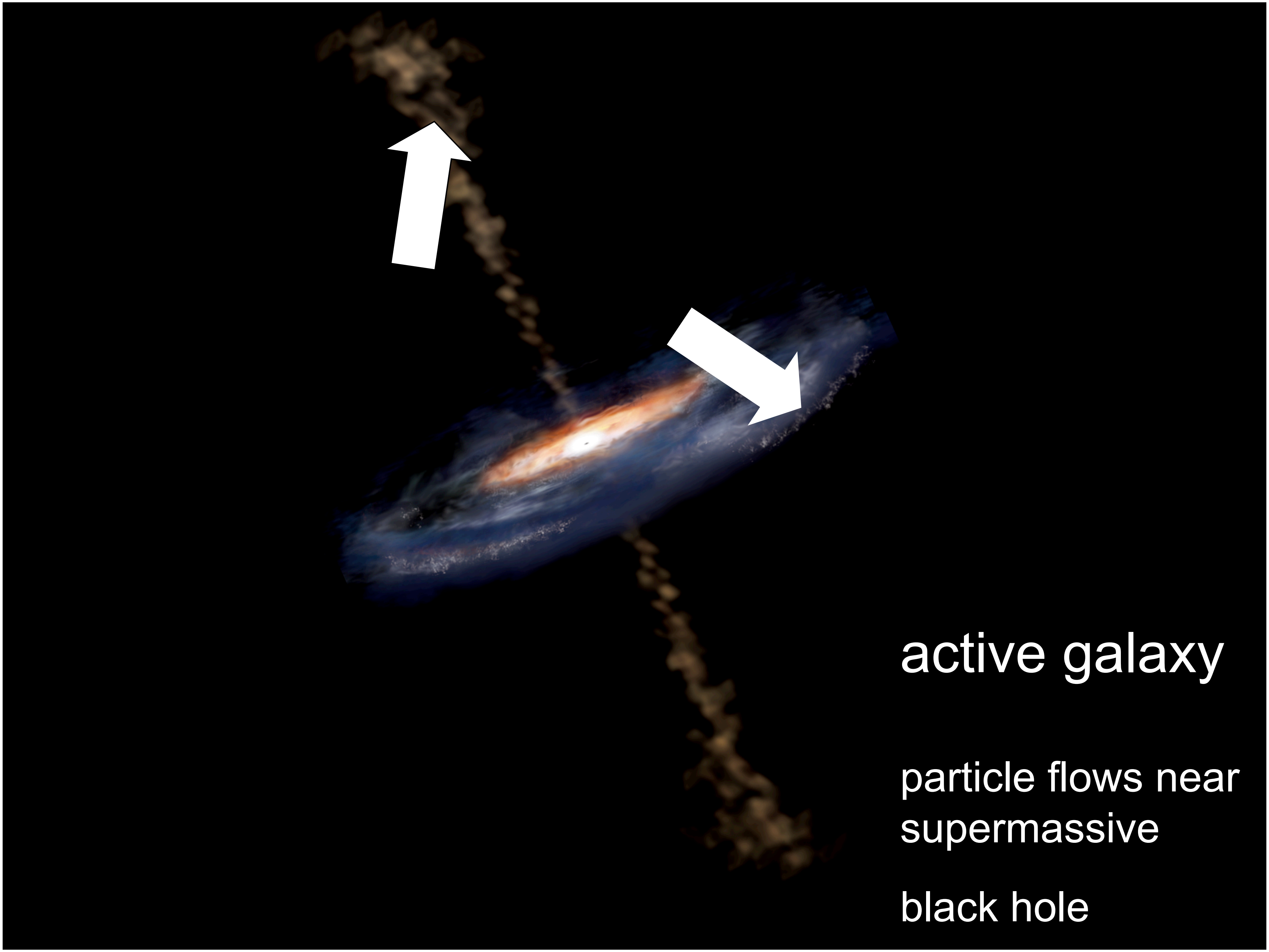
$$\Delta t_{obs} = \frac{1}{\Gamma} \Delta t'$$

- prime: accelerator frame
- observations Γ = a few - 1000

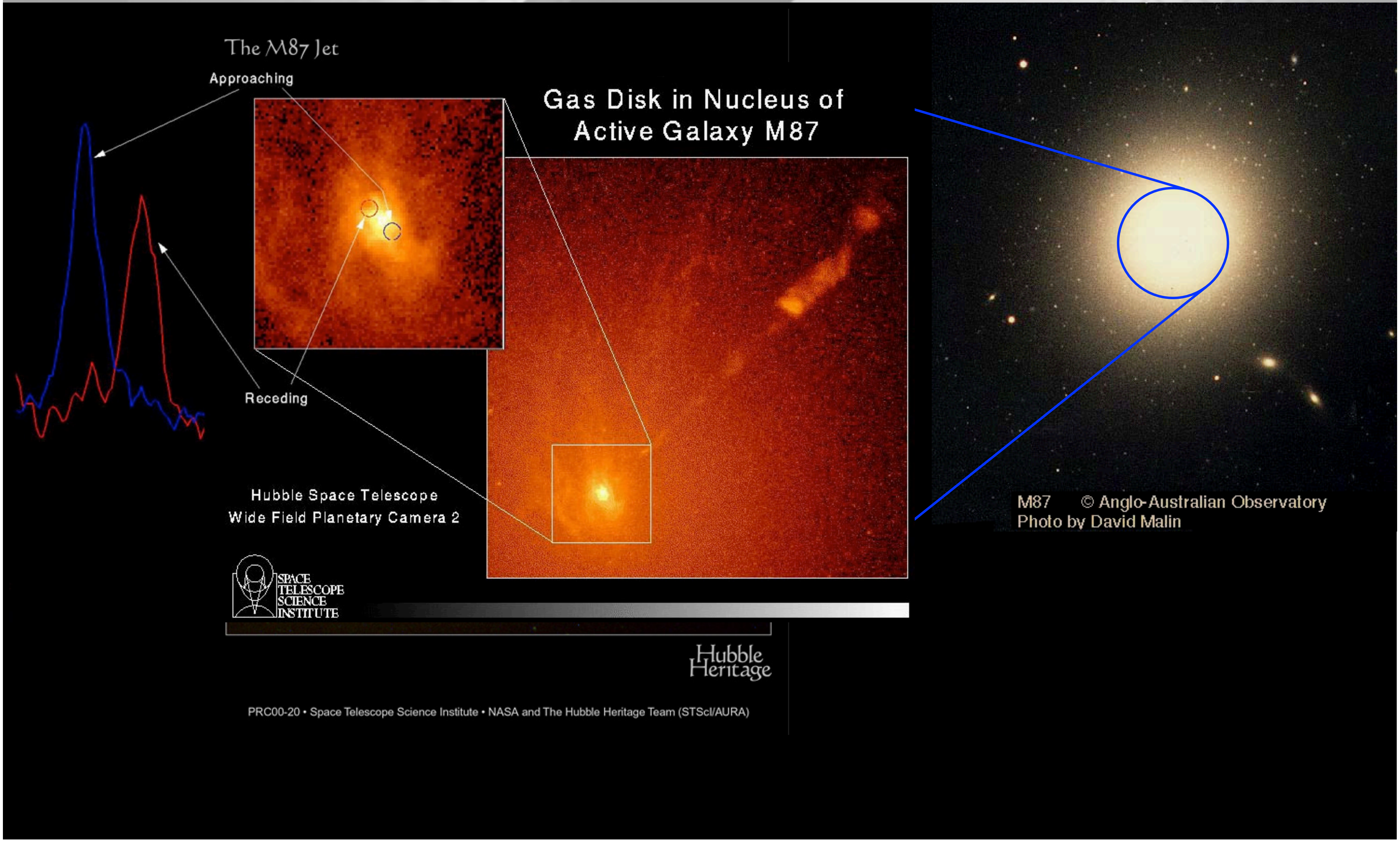
light from the blob arrives only 1 year after the light from the agn blob !

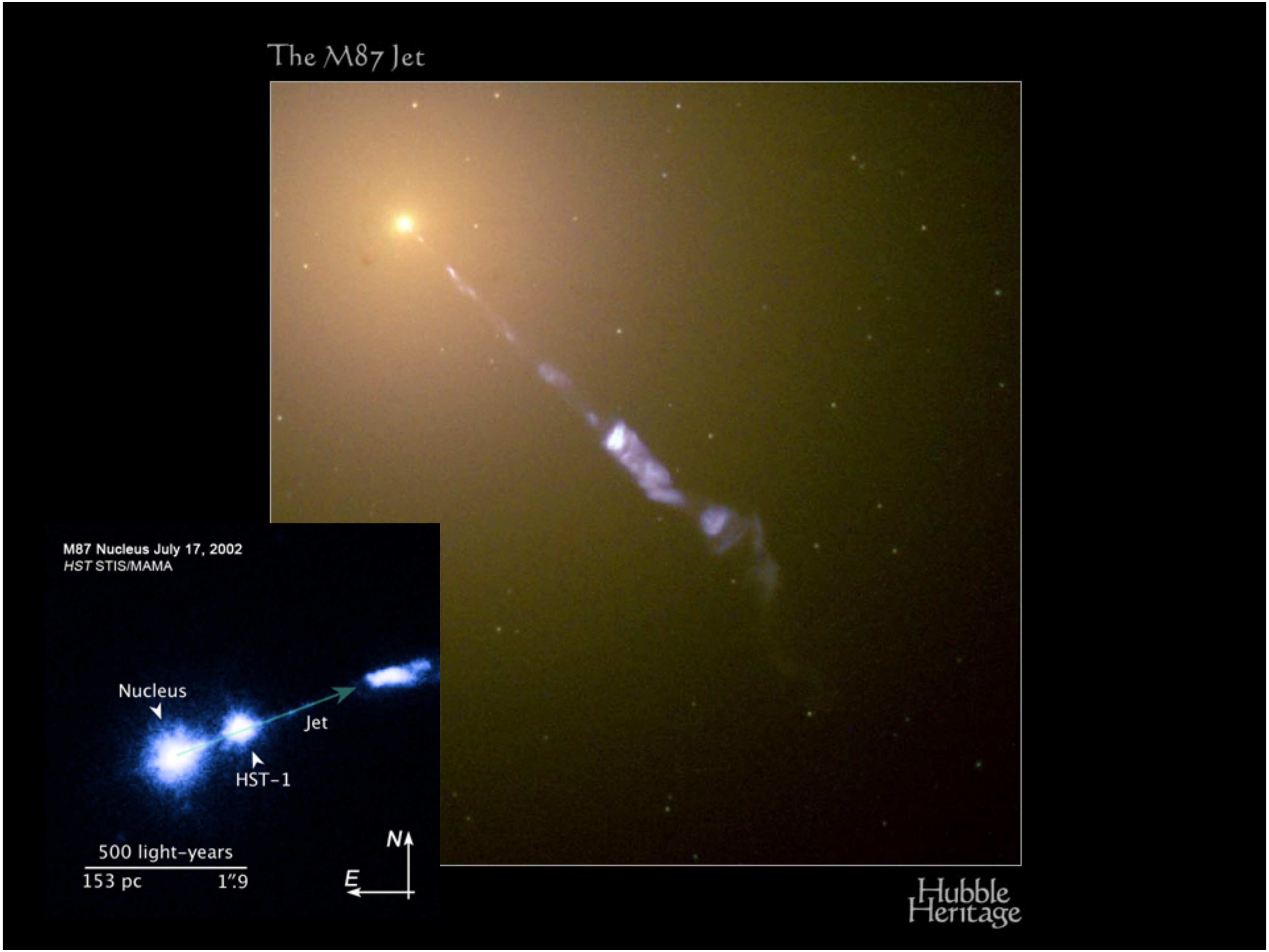
superluminal motion

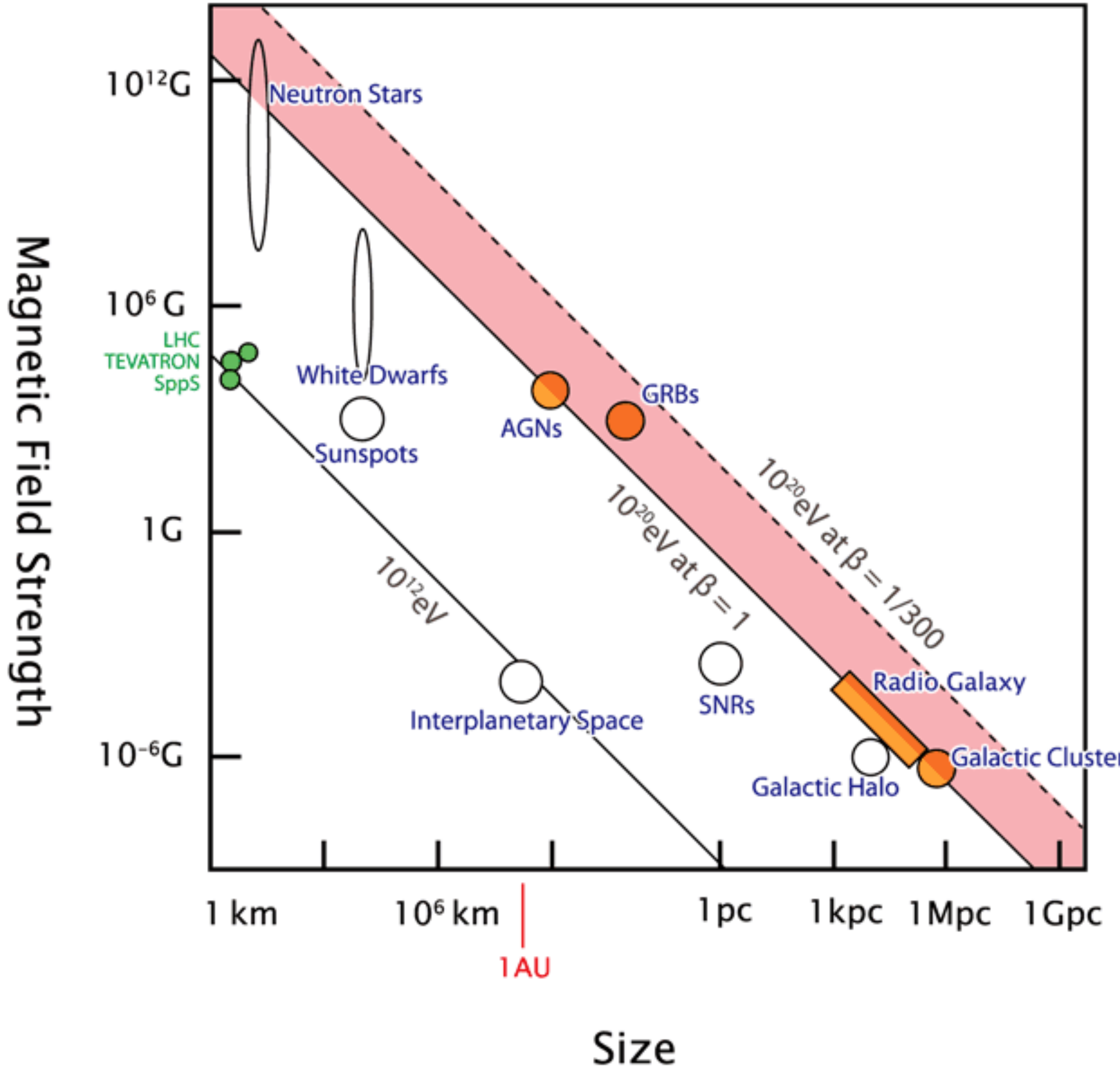



active galaxy
particle flows near
supermassive
black hole

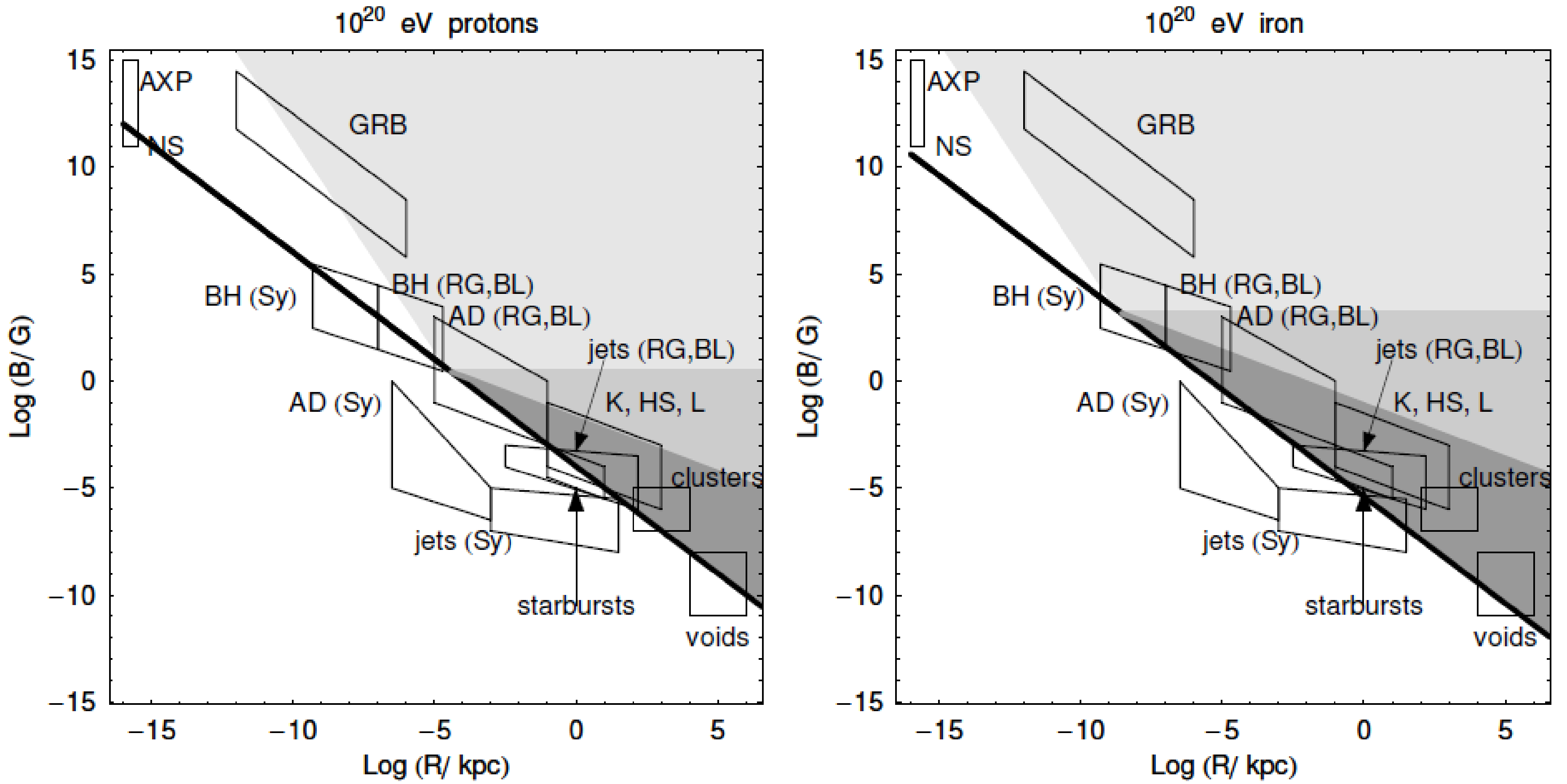
active galaxy M87




The M87 Jet
M87 Nucleus July 17, 2002
HST STIS/MAMA
Nucleus
Jet
HST-1
500 light-years
153 pc
1".9
N
E
Hubble Heritage



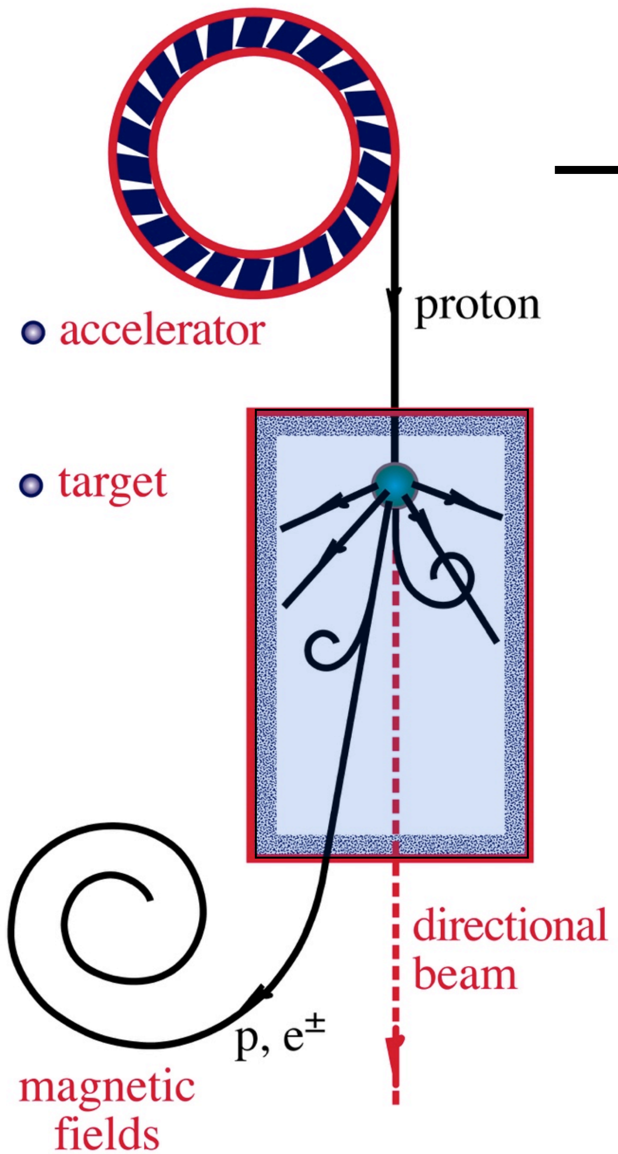
Magnetic Field Strength
10^{12}G
10^{6} G
1G
10^{-6}G
LHC
TEVATRON
SppS
Neutron Stars
White Dwarfs
Sunspots
AGNs
GRBs
10^{12}eV
10^{20}eV at β = 1
10^{20}eV at β = 1/300
Interplanetary Space
SNRs
Radio Galaxy
Galactic Halo
Galactic Cluster
1 km
10^{6} km
1AU
1pc
1kpc
1Mpc
1Gpc
Size



10^{20} eV protons
10^{20} eV iron
Log (B/ G)
Log (R/ kpc)
AXP
NS
GRB
BH (Sy)
BH (RG,BL)
AD (RG,BL)
jets (RG,BL)
AD (Sy)
K, HS, L
clusters
jets (Sy)
starbursts
voids

cosmic rays, gamma rays and neutrinos

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

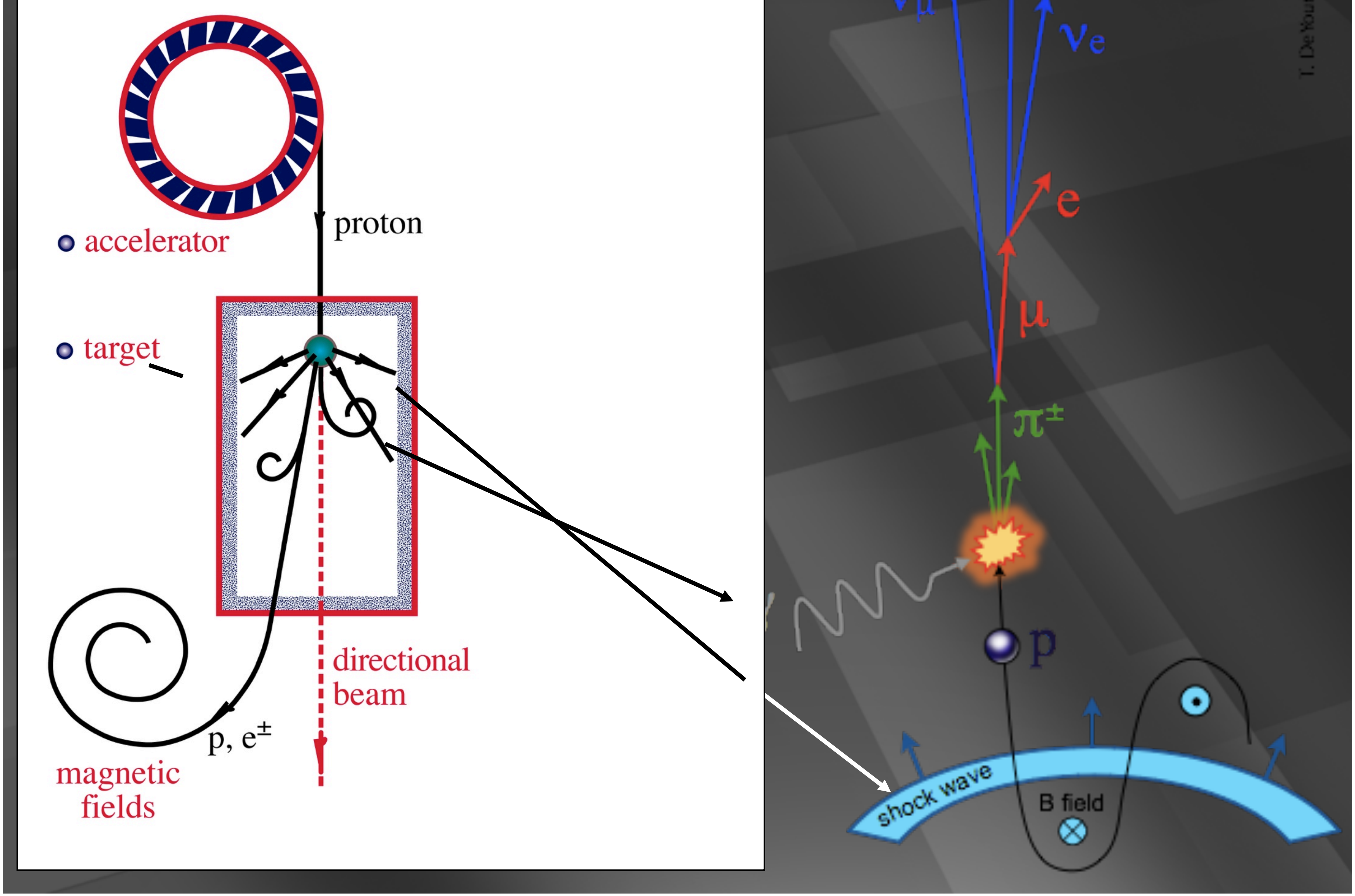
black hole
neutron star

radiation
and dust

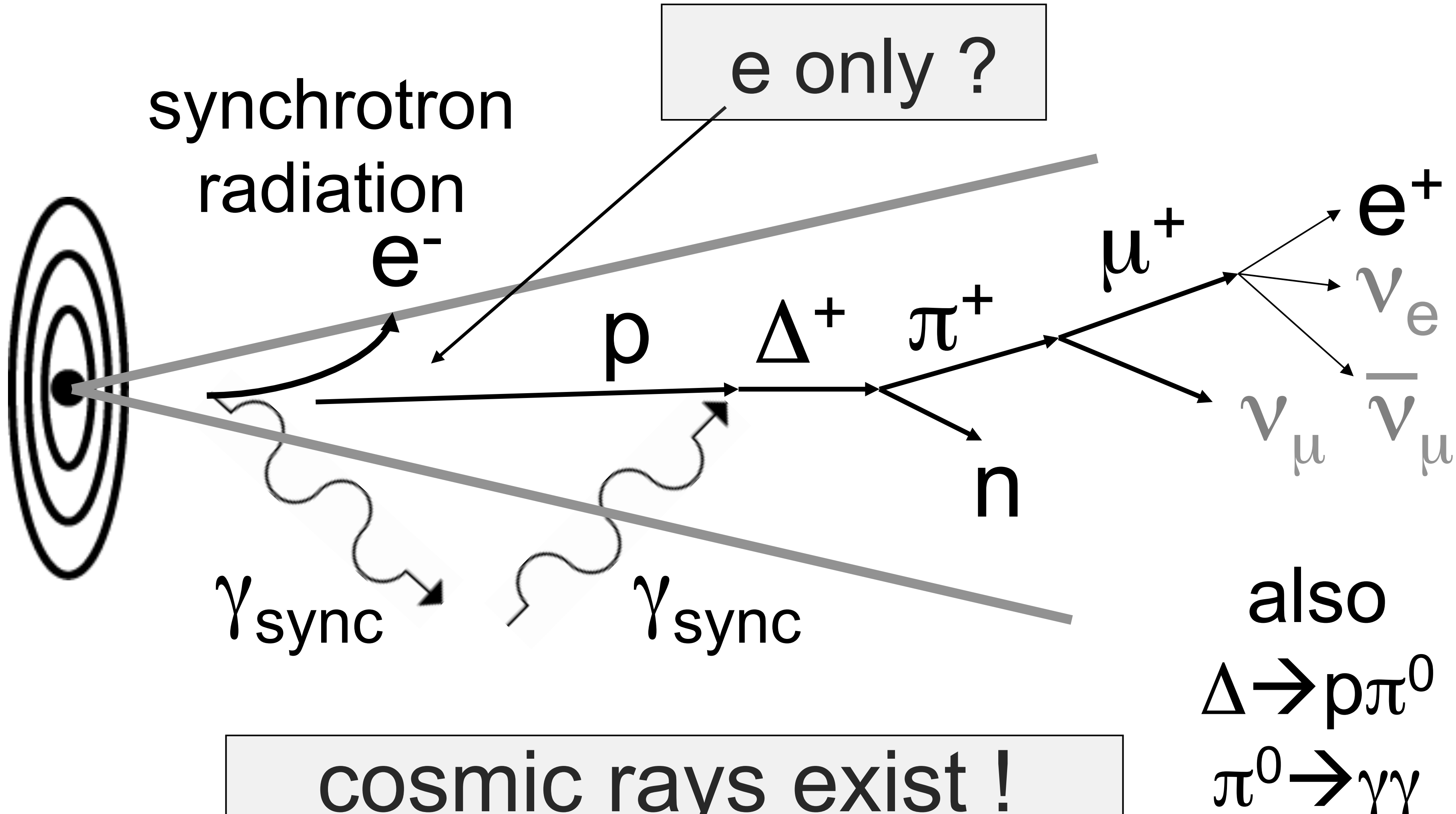
$p + \gamma \rightarrow n + \pi^{+}$
~ cosmic ray + neutrino

$\rightarrow p + \pi^{0}$
~ cosmic ray + gamma

NEUTRINO BEAMS: HEAVEN & EARTH

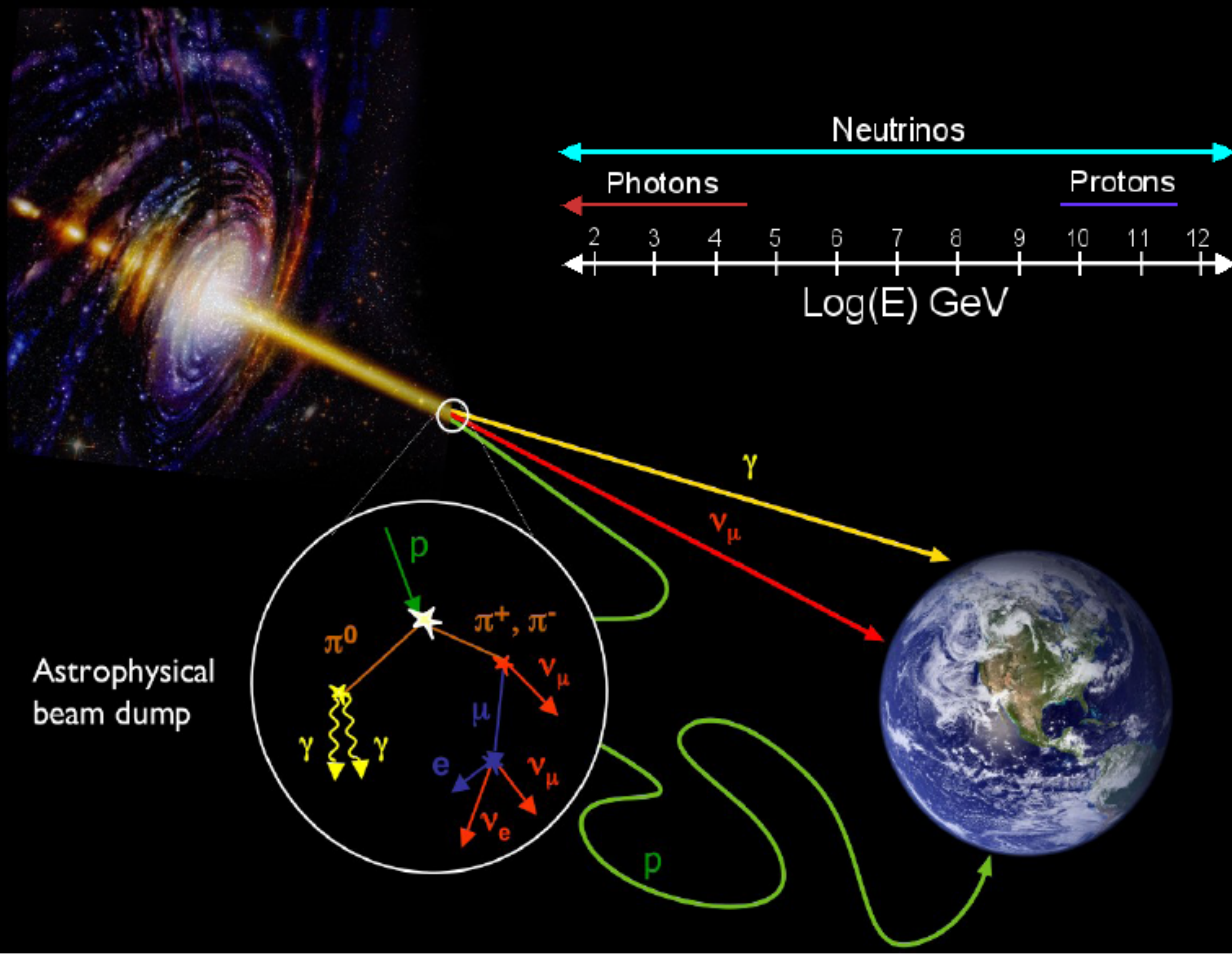


heavenly neutrino beam dump: photons: synchrotron versus $\pi^0 \to \gamma\gamma$



cosmic rays exist !

Astronomical Messengers



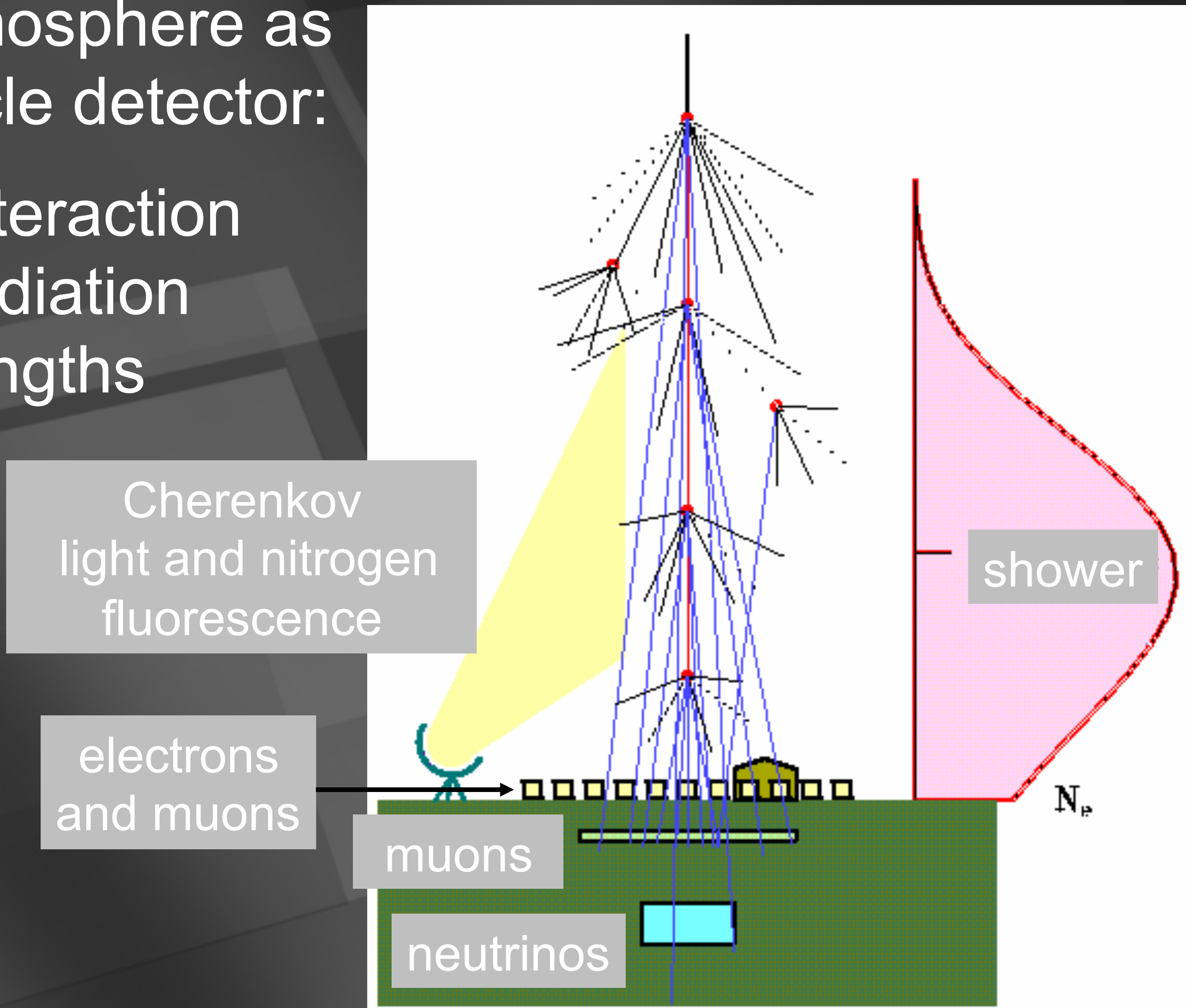
multi-messenger identification of cosmic ray sources

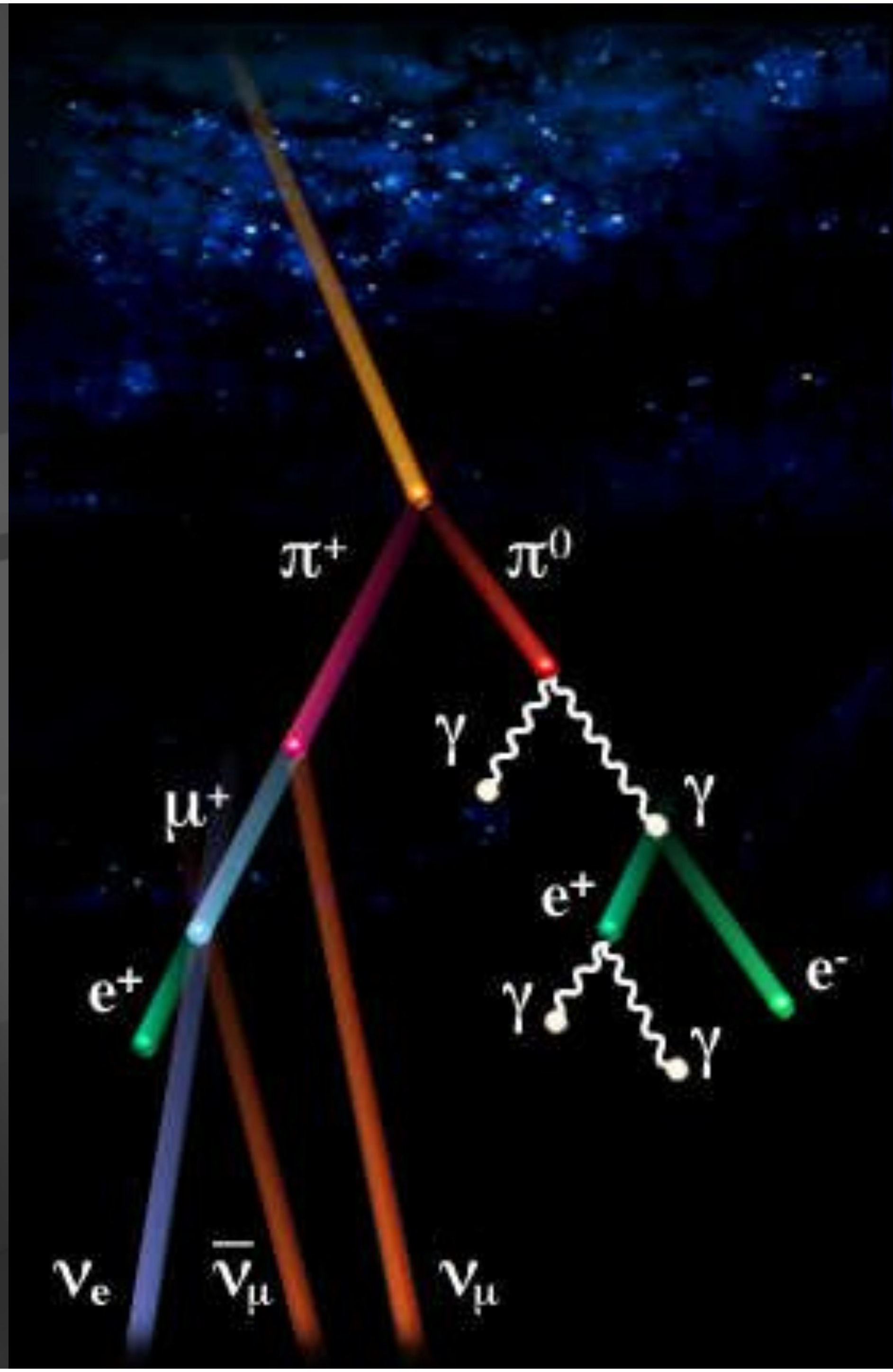
- **cosmic rays with little magnetic deflection** *(flux very low near 10^{20} eV)*
- **pions produced in interactions close to the source**

  → **TeV photons:** *difficult to disentangle from those produced by synchrotron radiation and inverse Compton scattering*

  → **neutrinos:** *difficult to detect (→ rationale for kilometer-scale detectors)* the atmosphere as a particle detector:

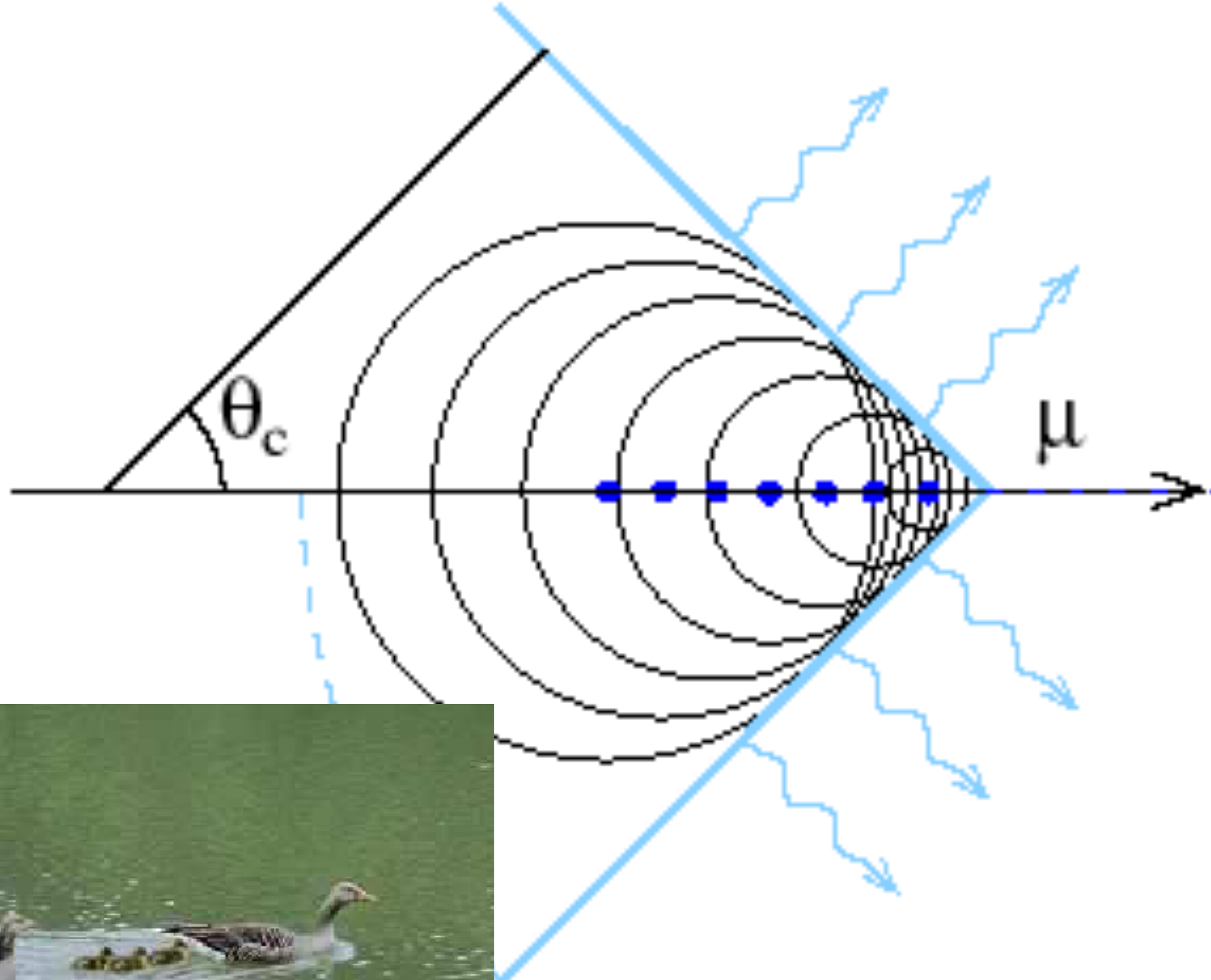
- 10 interaction
- 25 radiation lengths



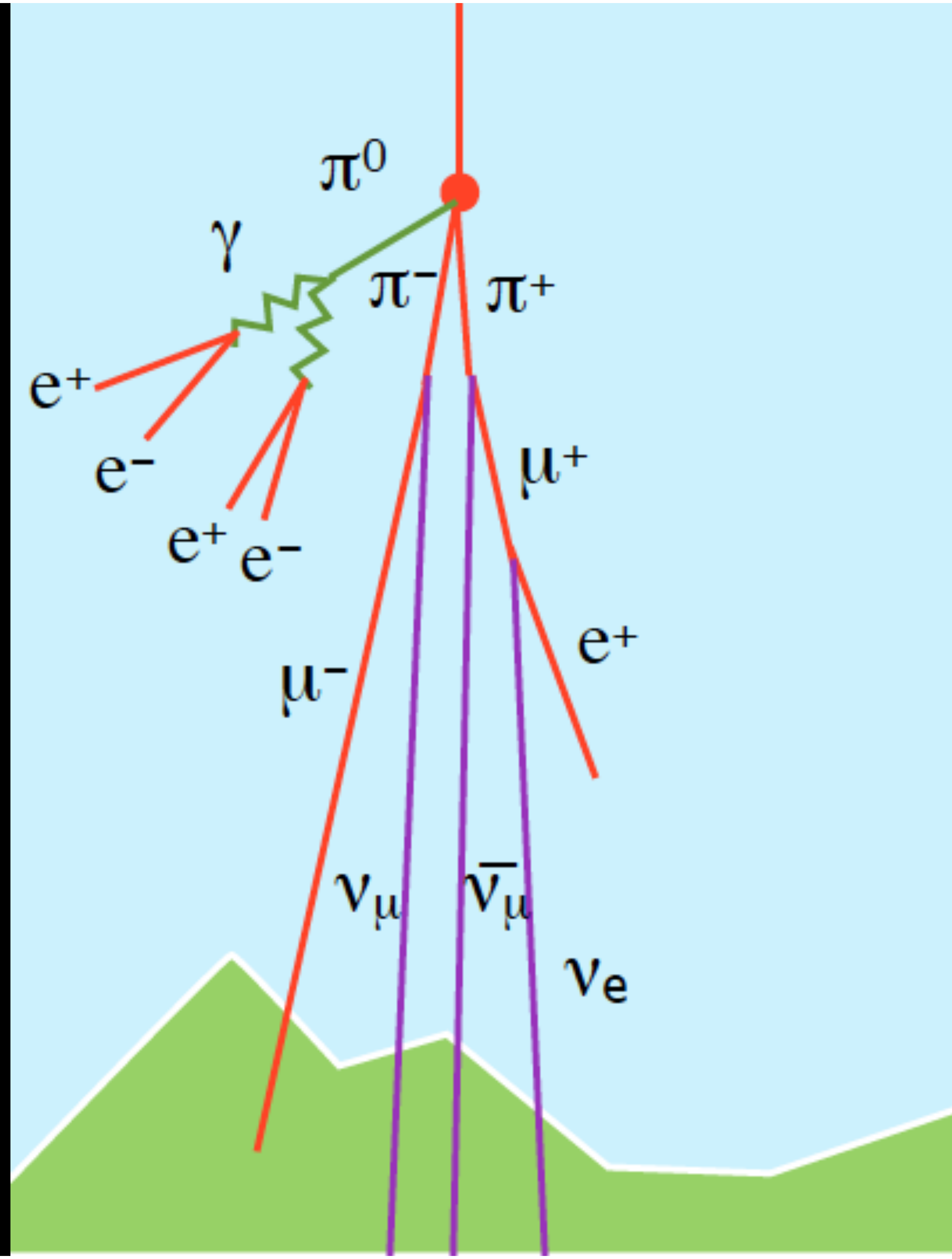


π+
π0
γ
γ
μ+
e+
e+
e-
γ
γ
νe
ν̄μ
νμ

Cherenkov radiation: particle’s speed exceeds the speed of light

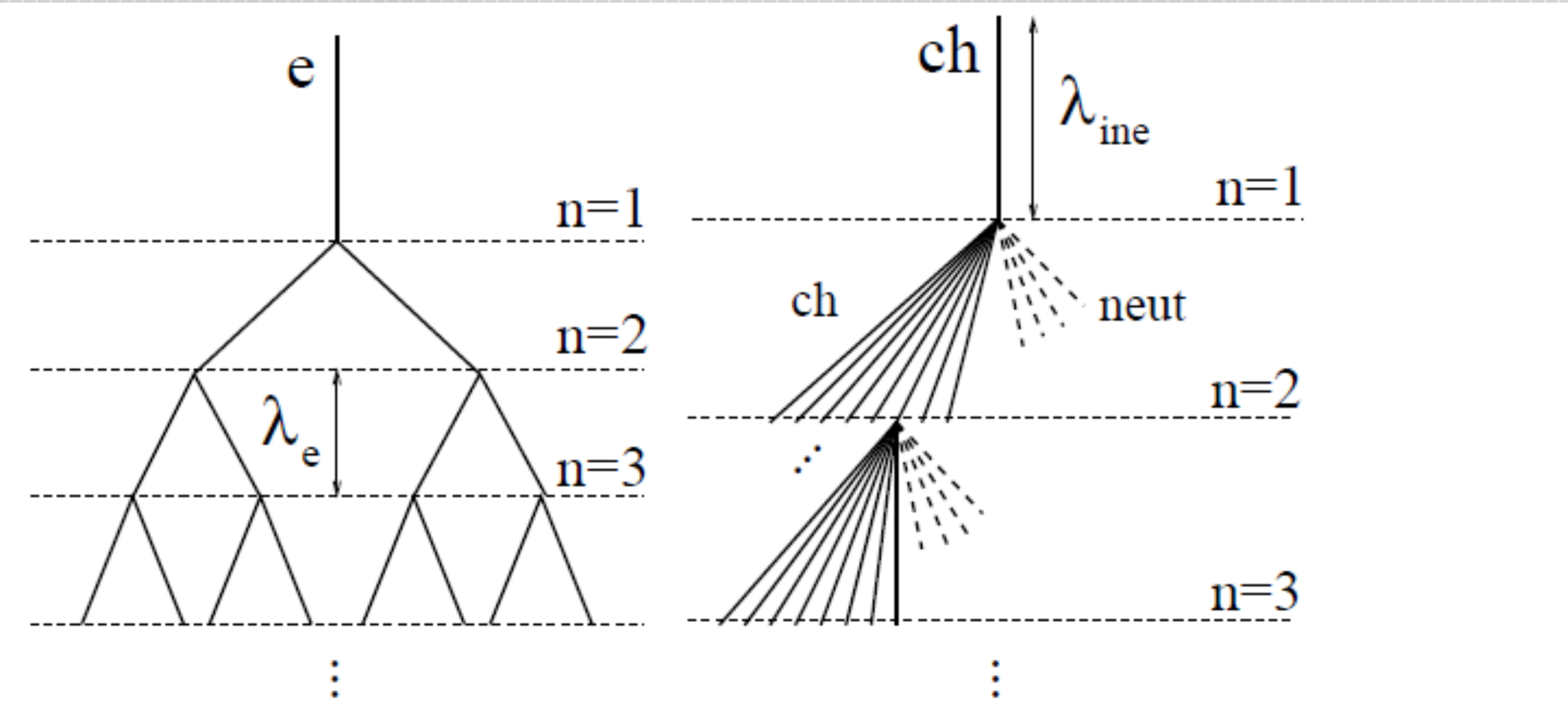


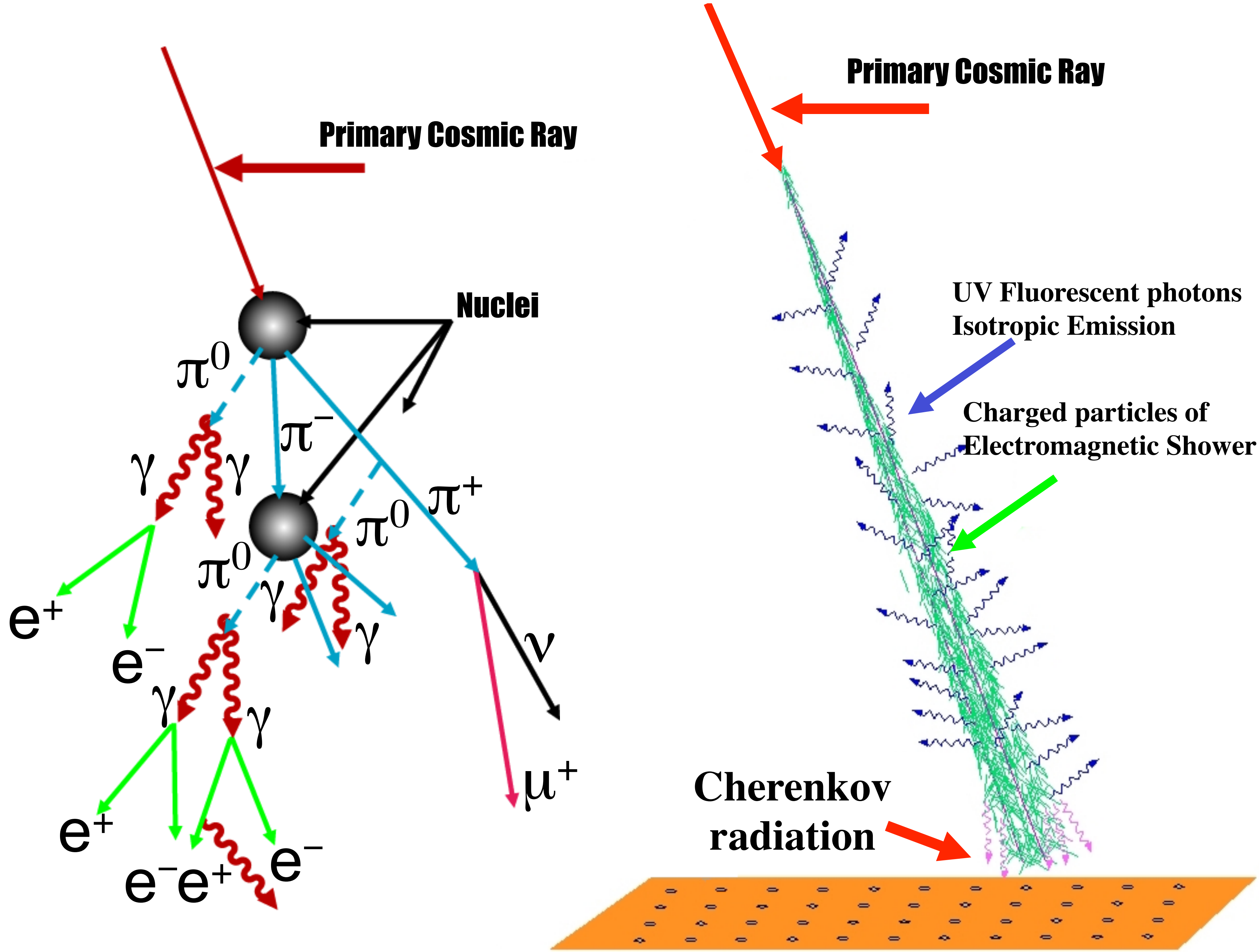
atmospheric muons
and
neutrinos

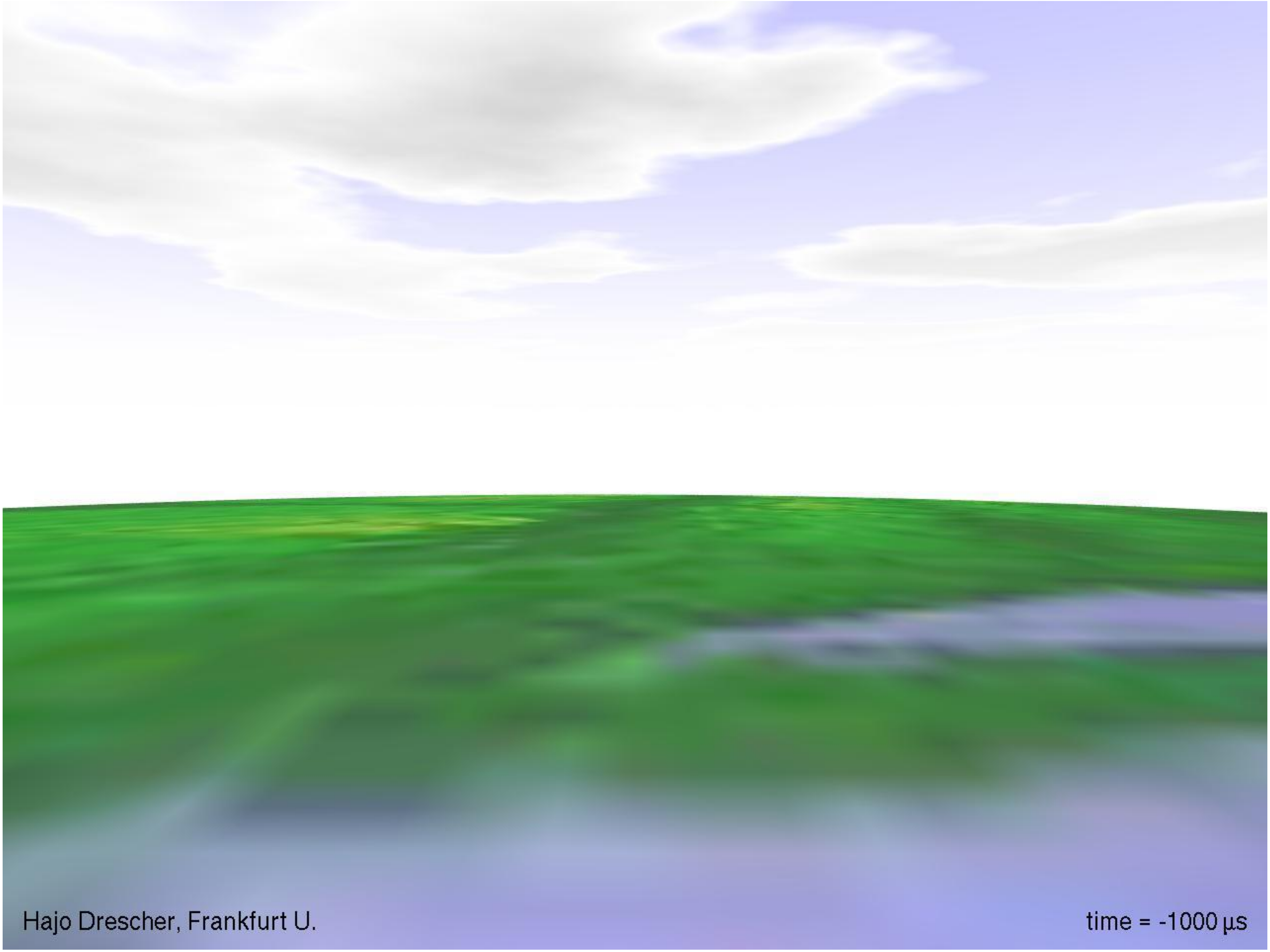


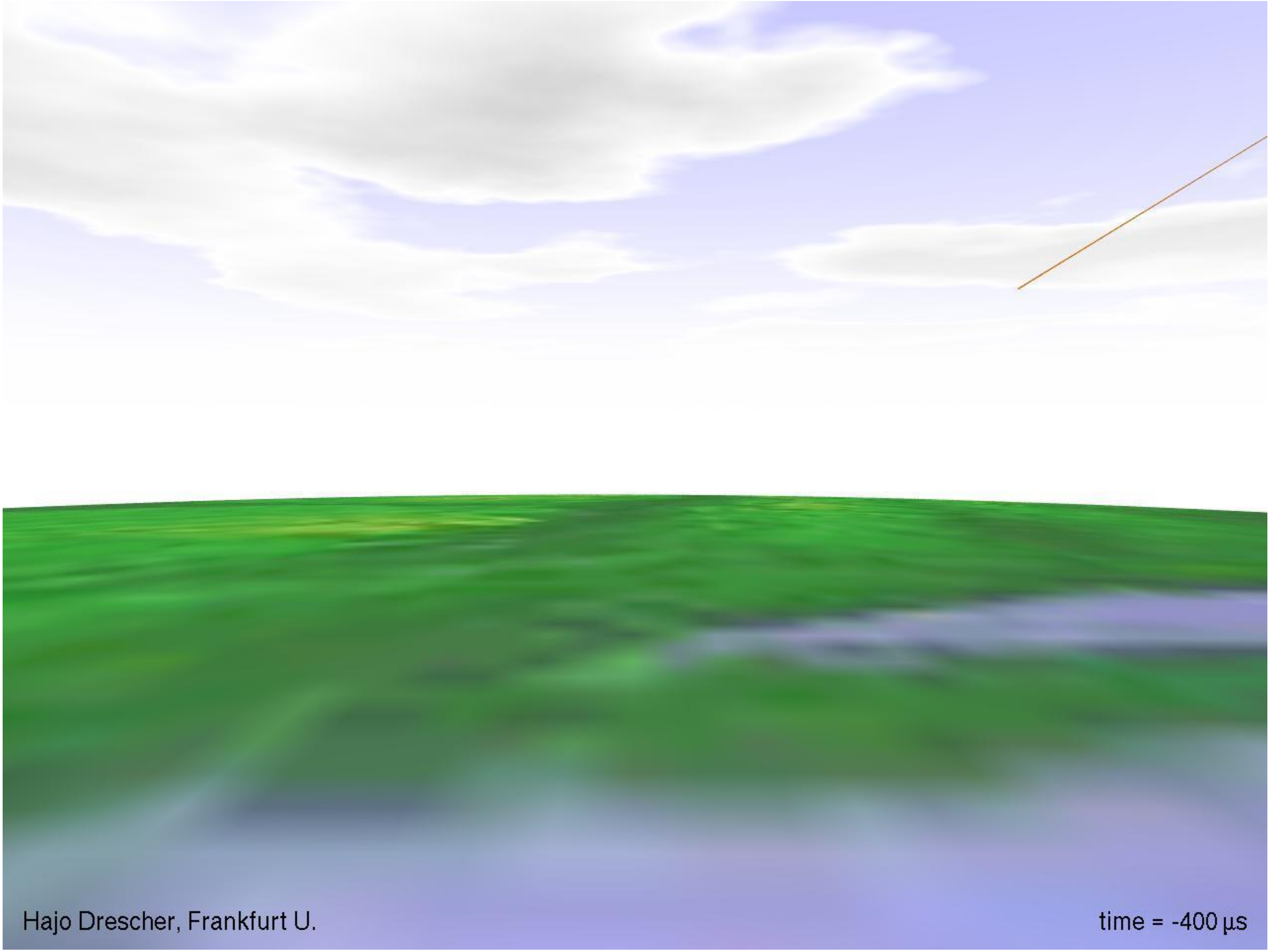
electromagnetic and hadronic showers

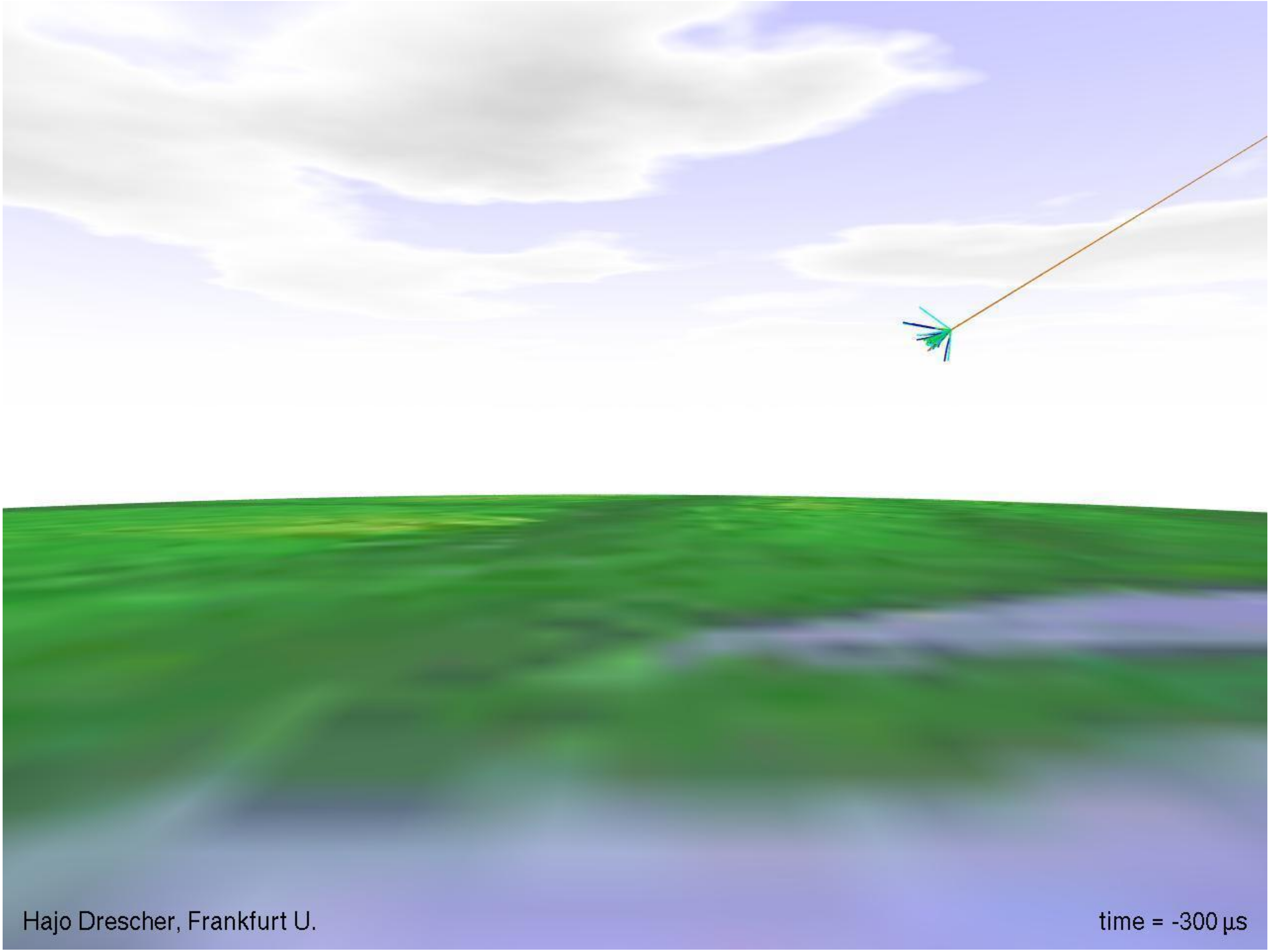
cross sections for γ + air → e^++e^- and e + air → γ+e are approximately equal

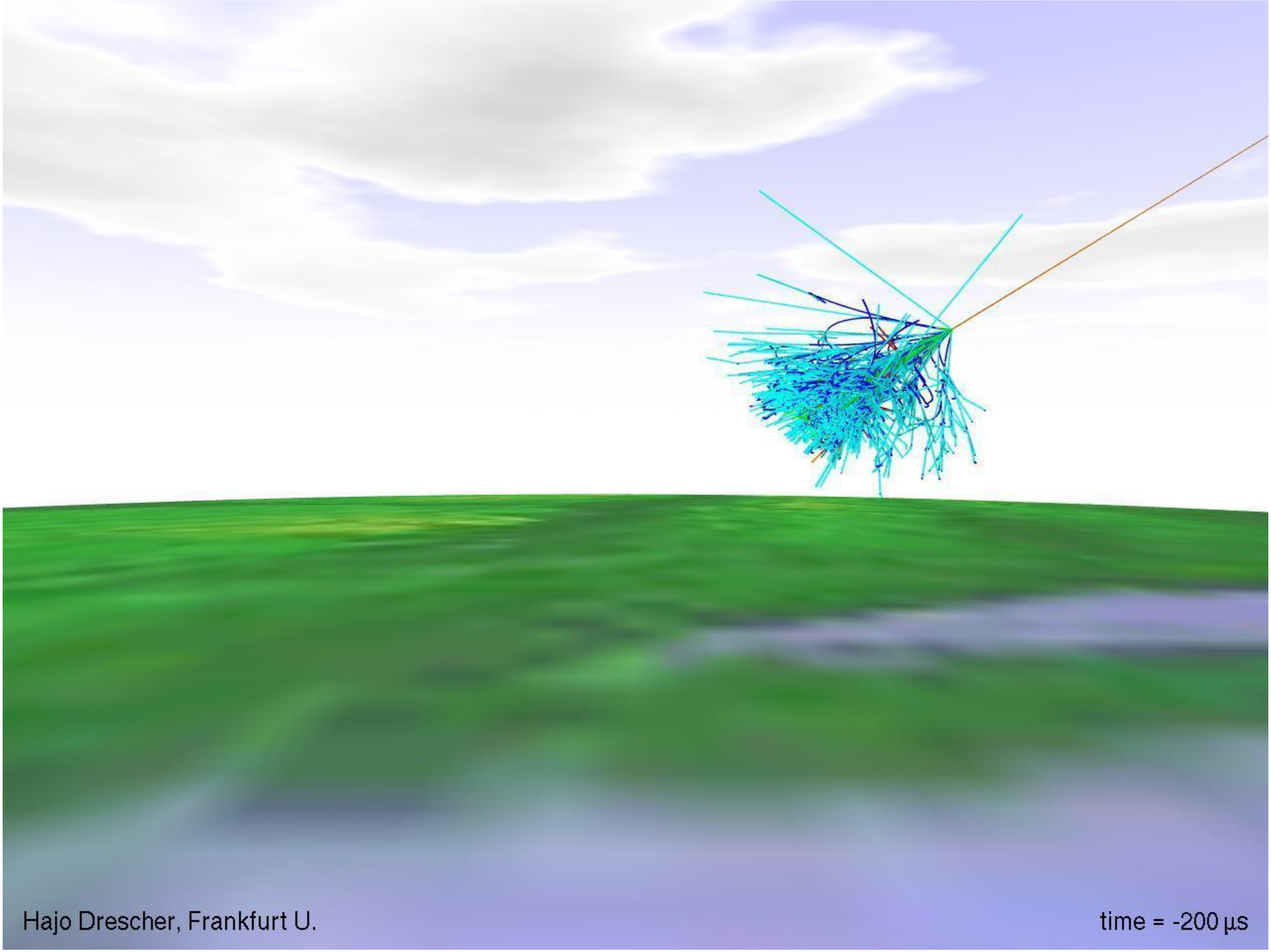


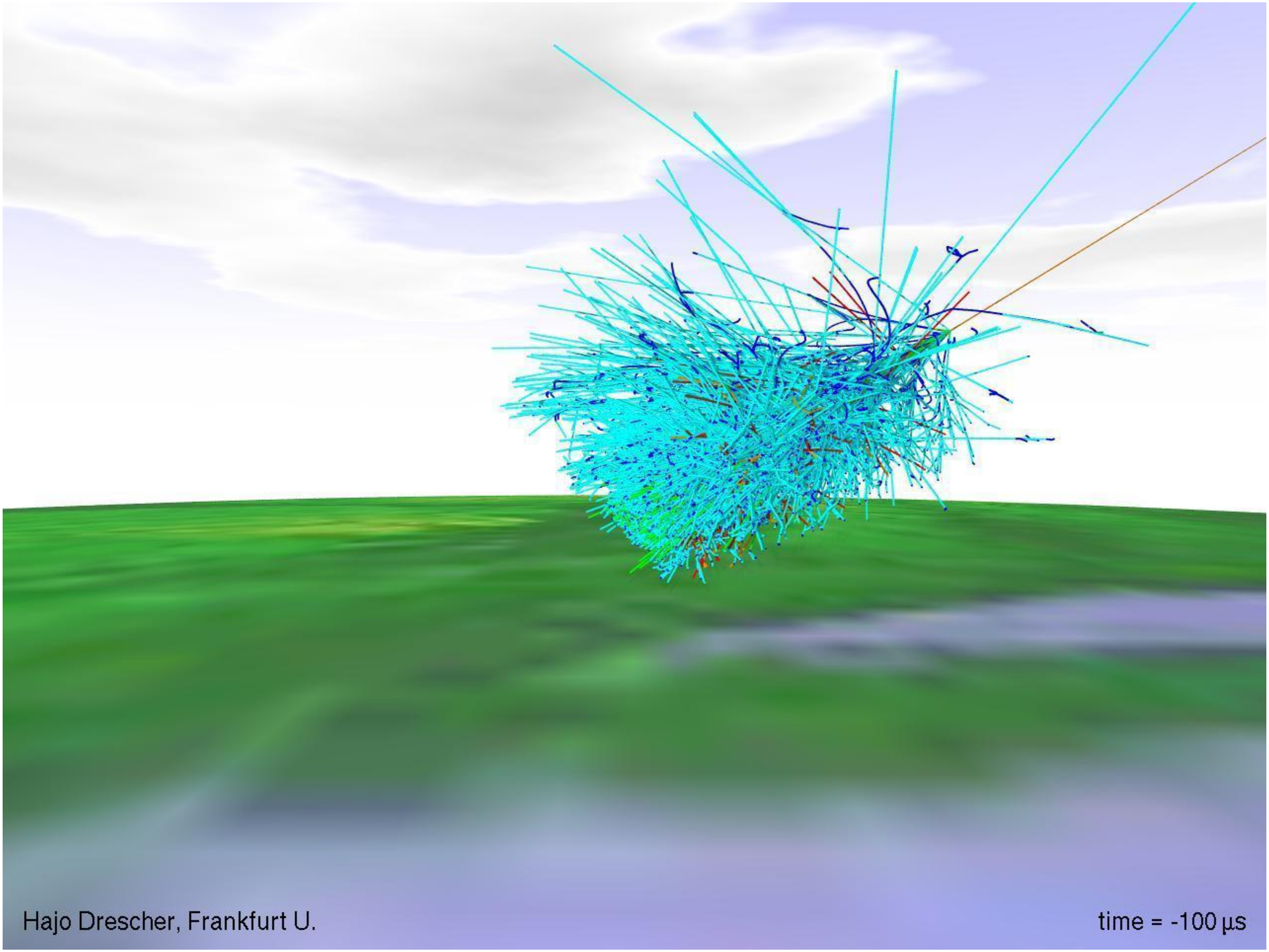

Primary Cosmic Ray
Nuclei
π0
π−
π+
π0
π0
γ
γ
γ
γ
γ
γ
γ
e+
e−
e+
e−e+
e−
ν
μ+
Primary Cosmic Ray
UV Fluorescent photons
Isotropic Emission
Charged particles of
Electromagnetic Shower
Cherenkov
radiation

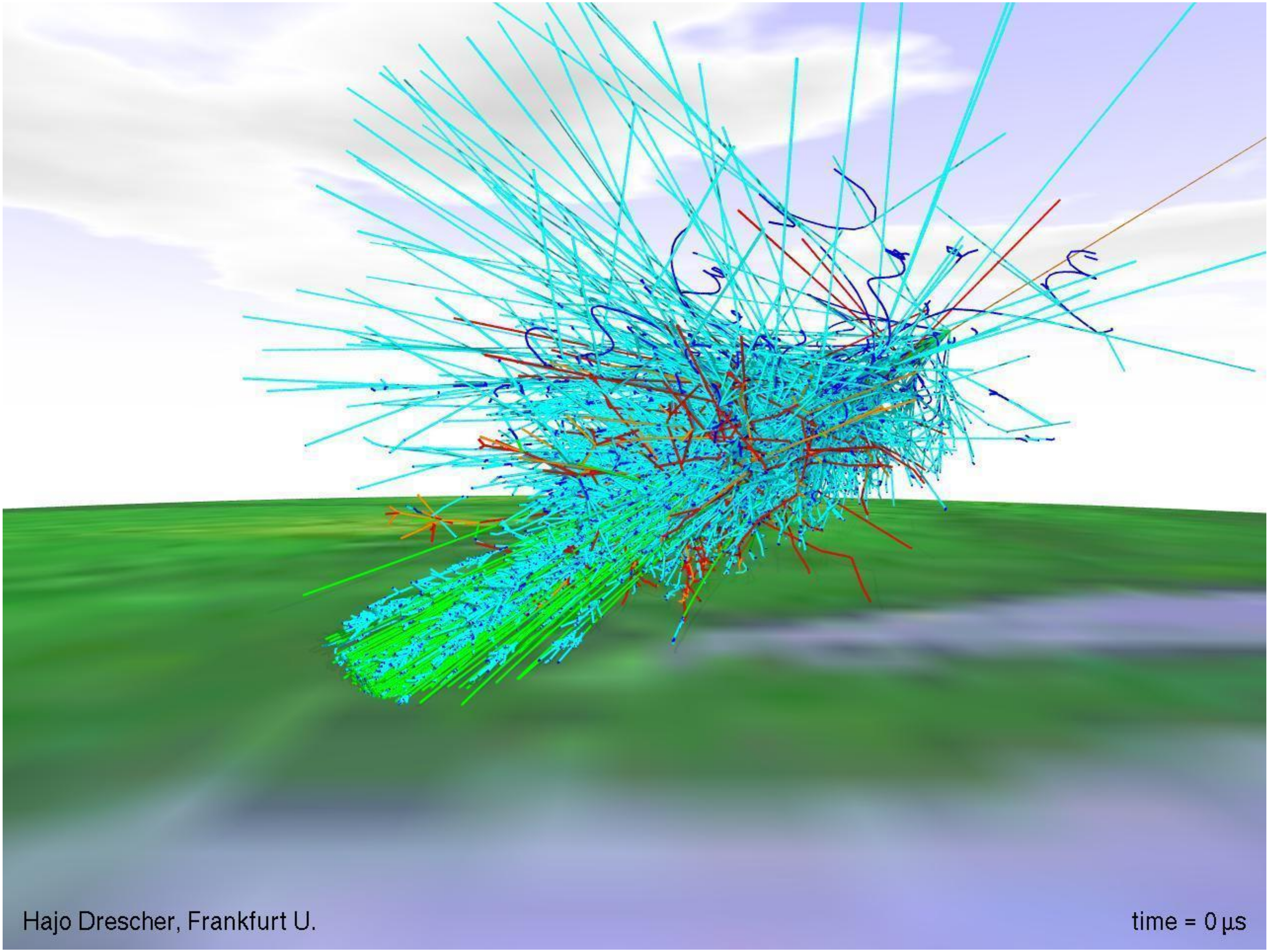

Hajo Drescher, Frankfurt U.
time = -1000 µs

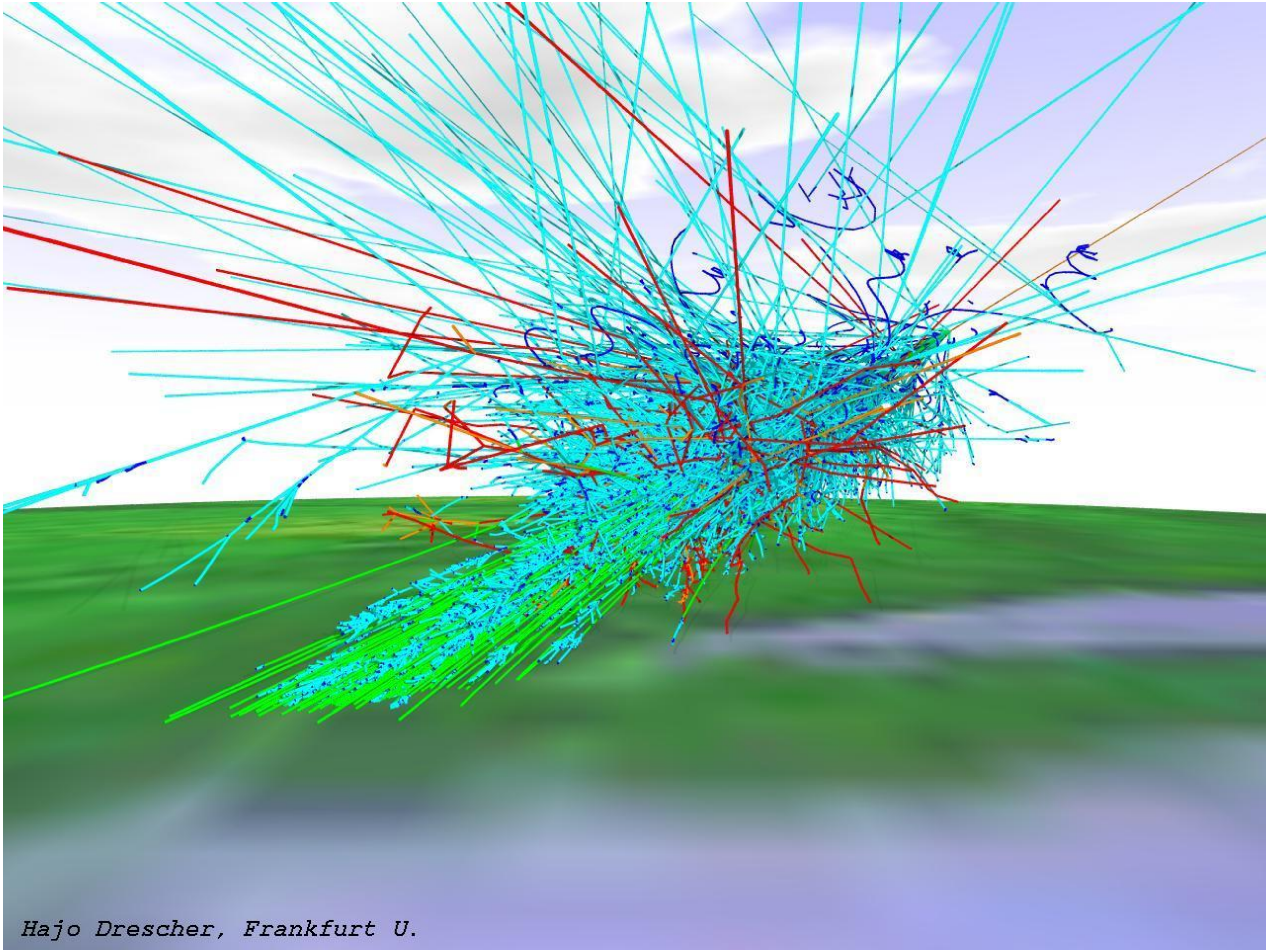

Hajo Drescher, Frankfurt U.
time = -400 µs

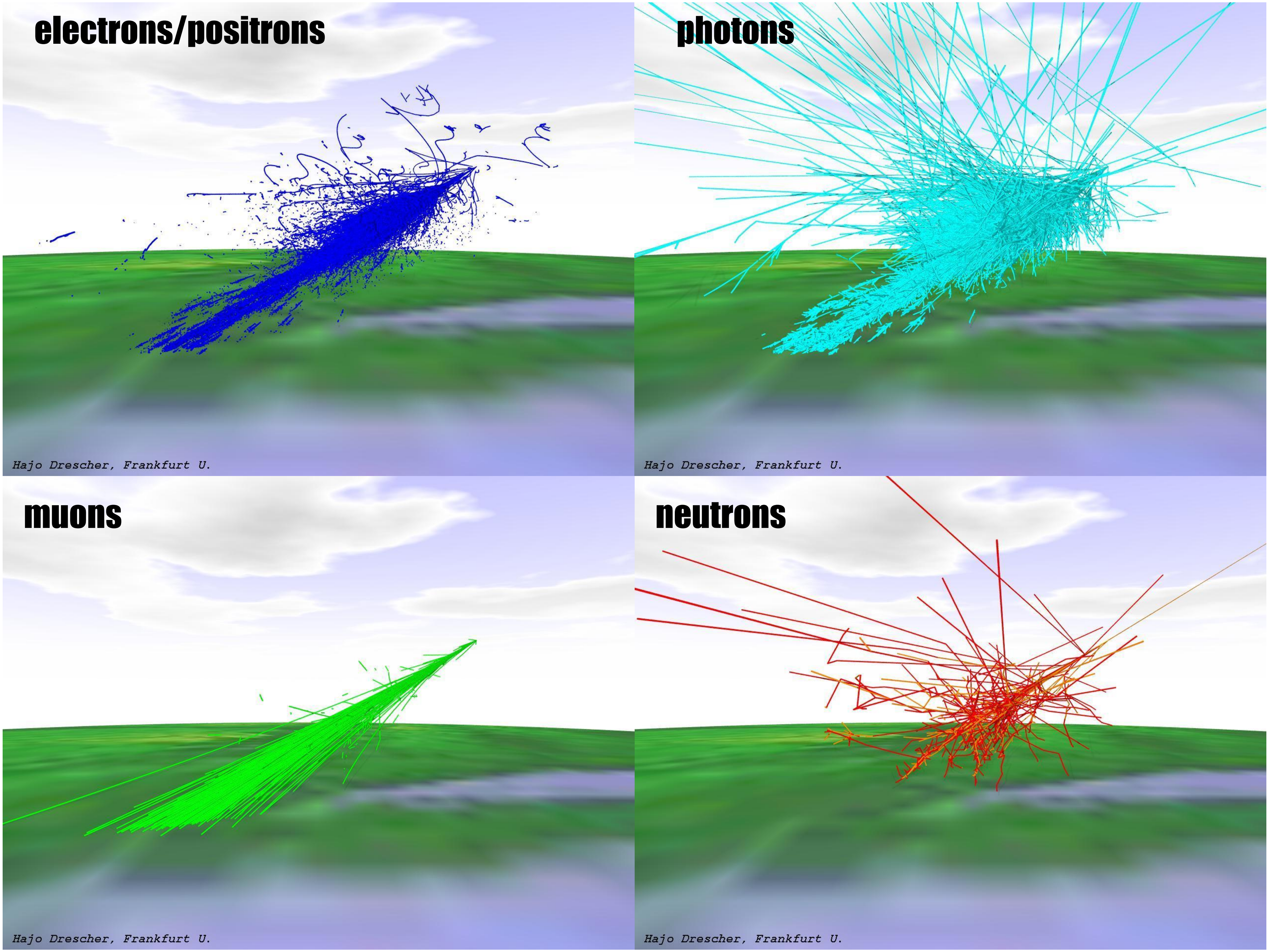

Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
time = -200 µs


Hajo Drescher, Frankfurt U.
time = -100 µs


Hajo Drescher, Frankfurt U.
time = 0 µs


Hajo Drescher, Frankfurt U.


electrons/positrons
Hajo Drescher, Frankfurt U.
photons
Hajo Drescher, Frankfurt U.
muons
Hajo Drescher, Frankfurt U.
neutrons
Hajo Drescher, Frankfurt U.

air showers

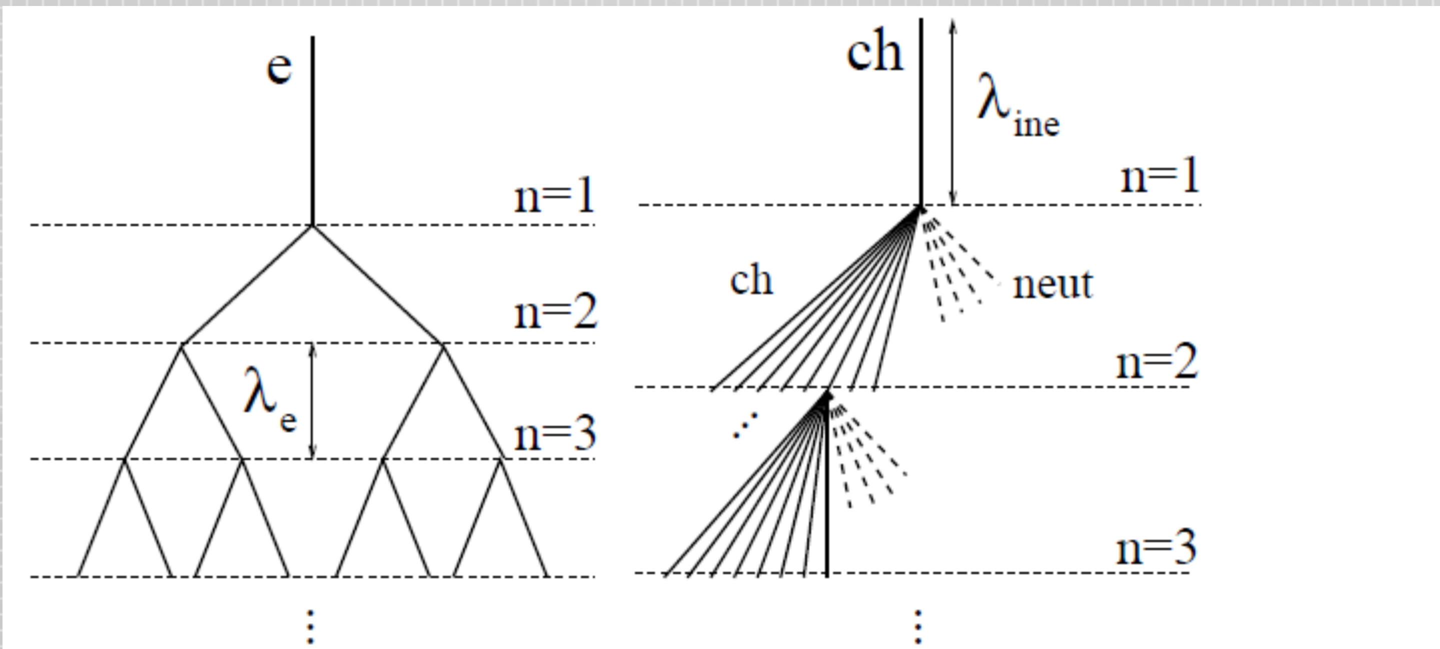
- the atmosphere is a detector with a total depth of 25 radiation length (λ_e) and 10 interaction length (λ_{ine}).

- an electromagnetic shower penetrates N radiation lengths until the particle energy is reduced to the critical energy of E_c~85 MeV where bremsstrahlung stops and the shower is absorbed in the atmosphere by e ionization. It is observed by the detection of electrons, positrons and (mostly) photons.

- a hadronic showers travels N' interaction lengths producing pions down to an energy ε_π where the pion interaction length is shorter than its decay length. At that point muon production stops.

electromagnetic showers

cross sections for γ + air → e^++e^- and e + air → γ+e are approximately equal



electromagnetic showers

$$number\ of\ particles\ n\ after\ N\ steps; \quad depth\ X = N\lambda_e$$

$$n(X) = 2^N = 2^{\frac{X}{\lambda_e}} \quad and \quad E(X) = \frac{E_i}{2^N} = \frac{E_i}{2^{\frac{X}{\lambda_e}}}$$

$$after\ complete\ development \quad N_{\max} = \lambda_e X_{\max}$$

$$E(X_{\max}) = E_c = \frac{E_i}{2^{\frac{X_{\max}}{\lambda_e}}} \quad \rightarrow \quad n_{\max} = 2^{N_{\max}} = 2^{\frac{X_{\max}}{\lambda_e}} = \frac{E_i}{E_c}$$

$$therefore$$

$$X_{\max} \approx \lambda_e \ln\frac{E_i}{E_c} \quad and \quad n_{\max} = \frac{E_i}{E_c}$$

hadronic showers

$$\lambda_e \quad \gamma \rightarrow e^+ + e^-$$

$$\lambda_{ine} \quad p \rightarrow n\left(\pi^0 + \pi^+ + \pi^-\right) \quad with \quad \pi^0 \rightarrow \gamma + \gamma \rightarrow em\,shower$$

$$\pi^{ch} \rightarrow \mu + \nu_\mu \rightarrow muons$$

$$E_{had} = \left(\frac{2}{3}\right)^N E_i \quad and \quad E_{em} = \left[1 - \left(\frac{2}{3}\right)^N\right] E_i$$

$$electromagnetic\ shower \rightarrow dictates\ total\,depth$$

$$X_{\max}^{em} = \lambda_{ine} + X_{\max}^{e} \approx \lambda_{ine} + \lambda_e \ln\left(\frac{E_i}{n\,E_c}\right)$$

$$hadronic\ shower: N\lambda_{ine}\ from\ E_i \rightarrow \varepsilon_\pi \approx 150\,GeV$$

$$\varepsilon_\pi = \frac{E_i}{n^N} \quad \rightarrow n_\mu = n_{ch}^N \equiv \left(\frac{E_i}{\varepsilon_\pi}\right)^\alpha \quad with\ \alpha = \frac{\ln n_{ch}}{\ln n} \approx 0.82 - 0.95$$

showers: nuclei

$$mass\ A\ with\ energy\ E \approx A\ showers\ with\ energy\ \frac{E}{A}$$

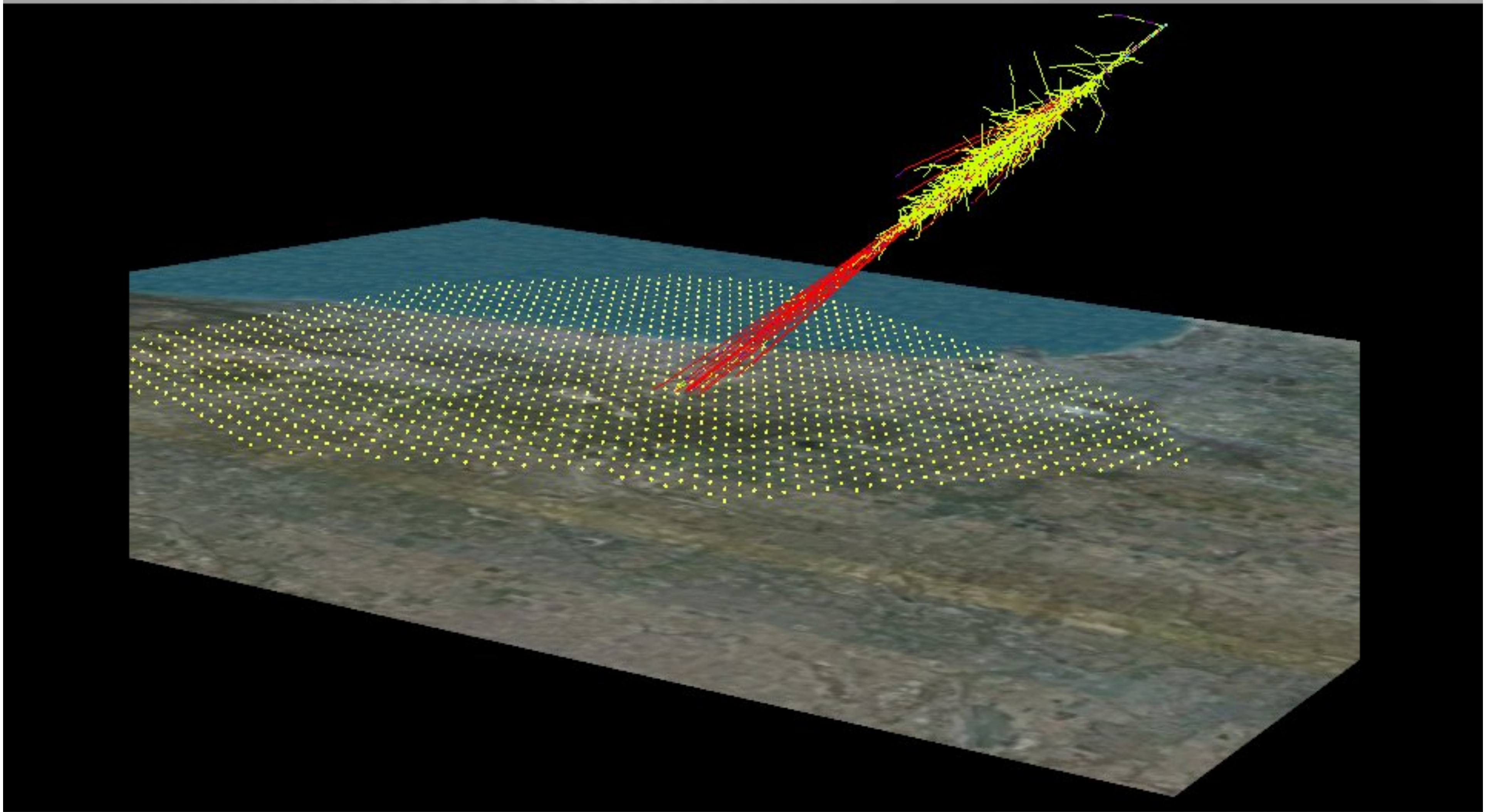
$$N_{\max}^{A} \approx A\frac{E_p}{E_c} = \frac{E_i}{E_c} = N_{\max} \quad and \quad X_{\max}^{A} \approx \frac{E_i}{A} X_{\max}$$

$$n_{\mu}^{A} \approx A\left(\frac{E_i / A}{\varepsilon_{\pi}}\right)^{\alpha} = A^{1-\alpha} n_{\mu}$$

progress through instrumentation

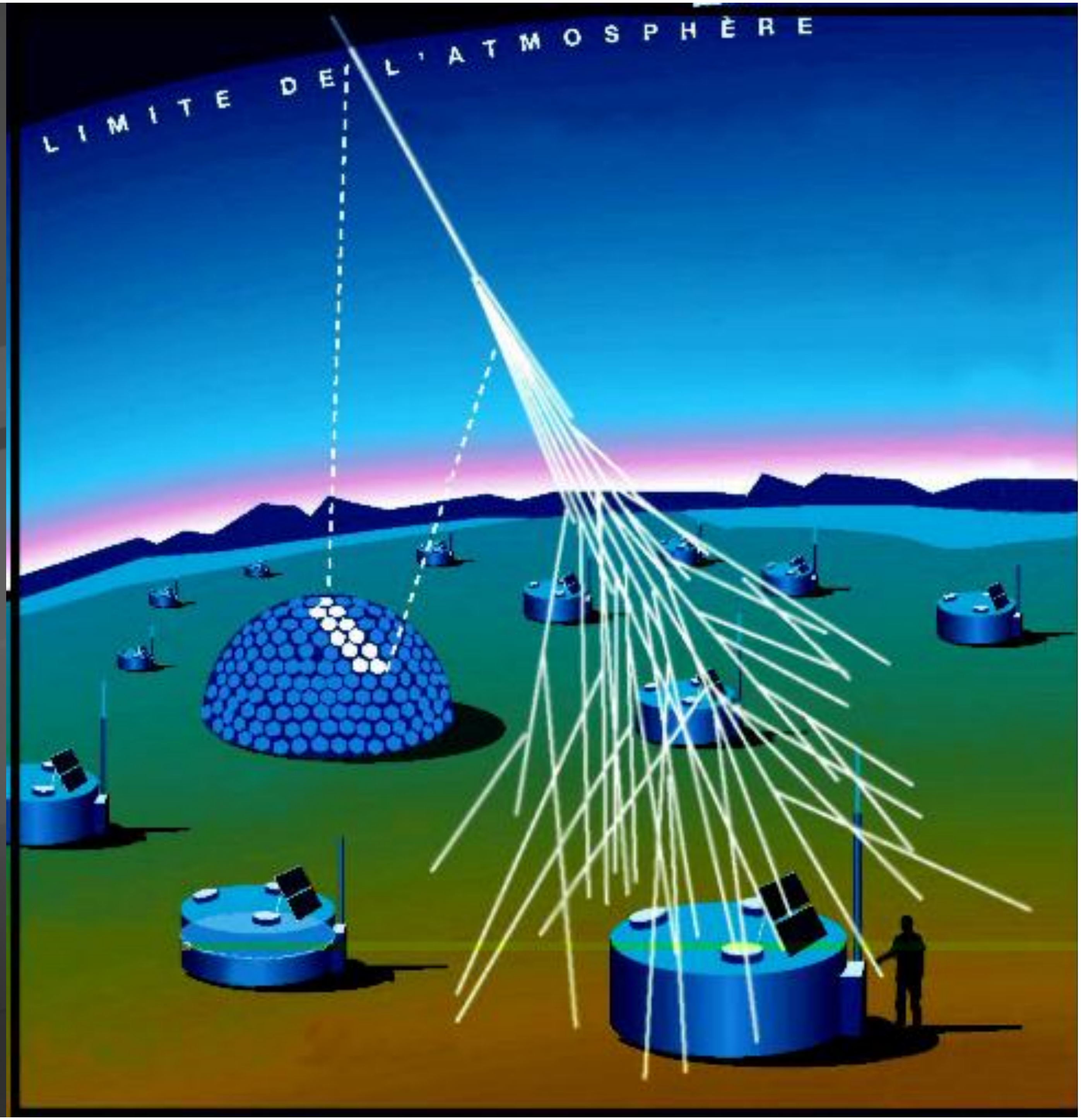
- Auger, Telescope Array …
- HESS, Magic, Veritas, Milagro, Tibet, Argo … HAWC
- IceCube and KM3NeT …

cosmic rays

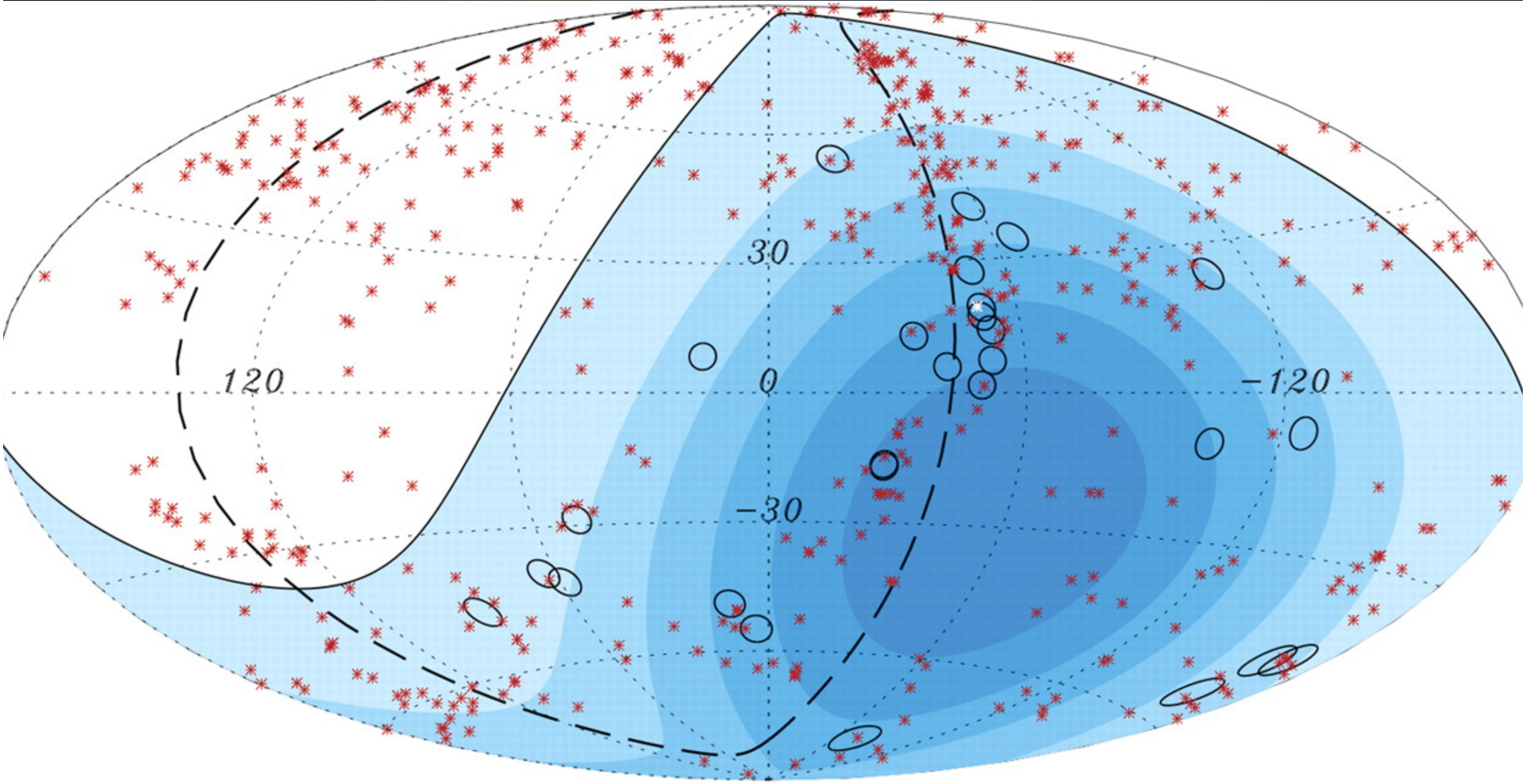


Auger ~ 3000 km^2 air shower array

Auger array



Auger : the sources revealed ?



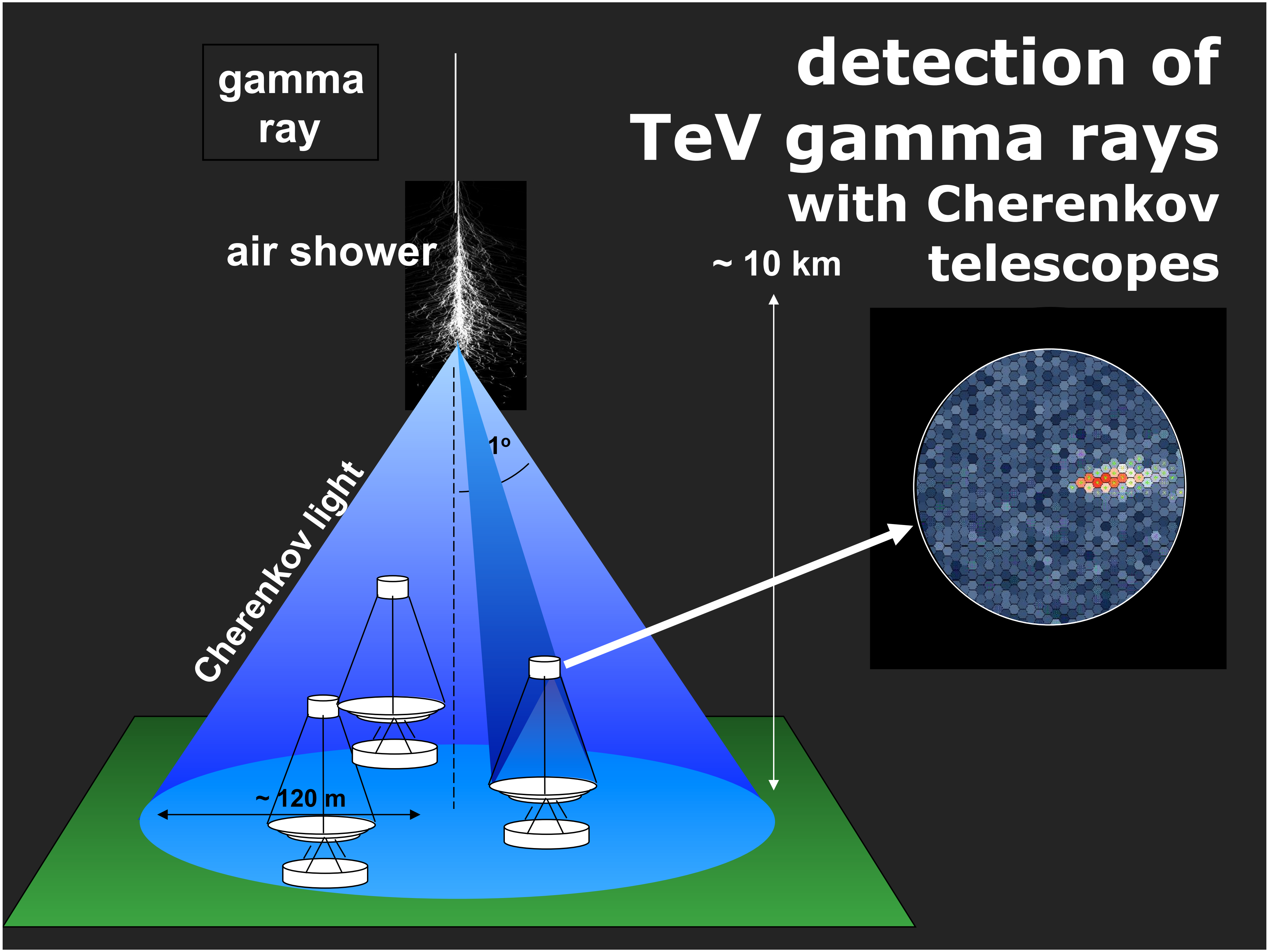
proton astronomy ?

pointing of cosmic rays :

$$\theta \cong \frac{d}{R_{gyro}} = \frac{dB}{E}$$

$$\frac{\vartheta}{0.1^\circ} \cong \frac{\left(\frac{d}{1\,Mpc}\right)\left(\frac{B}{10^{-9}\,Gauss}\right)}{\frac{E}{3\times10^{20}\,eV}}$$

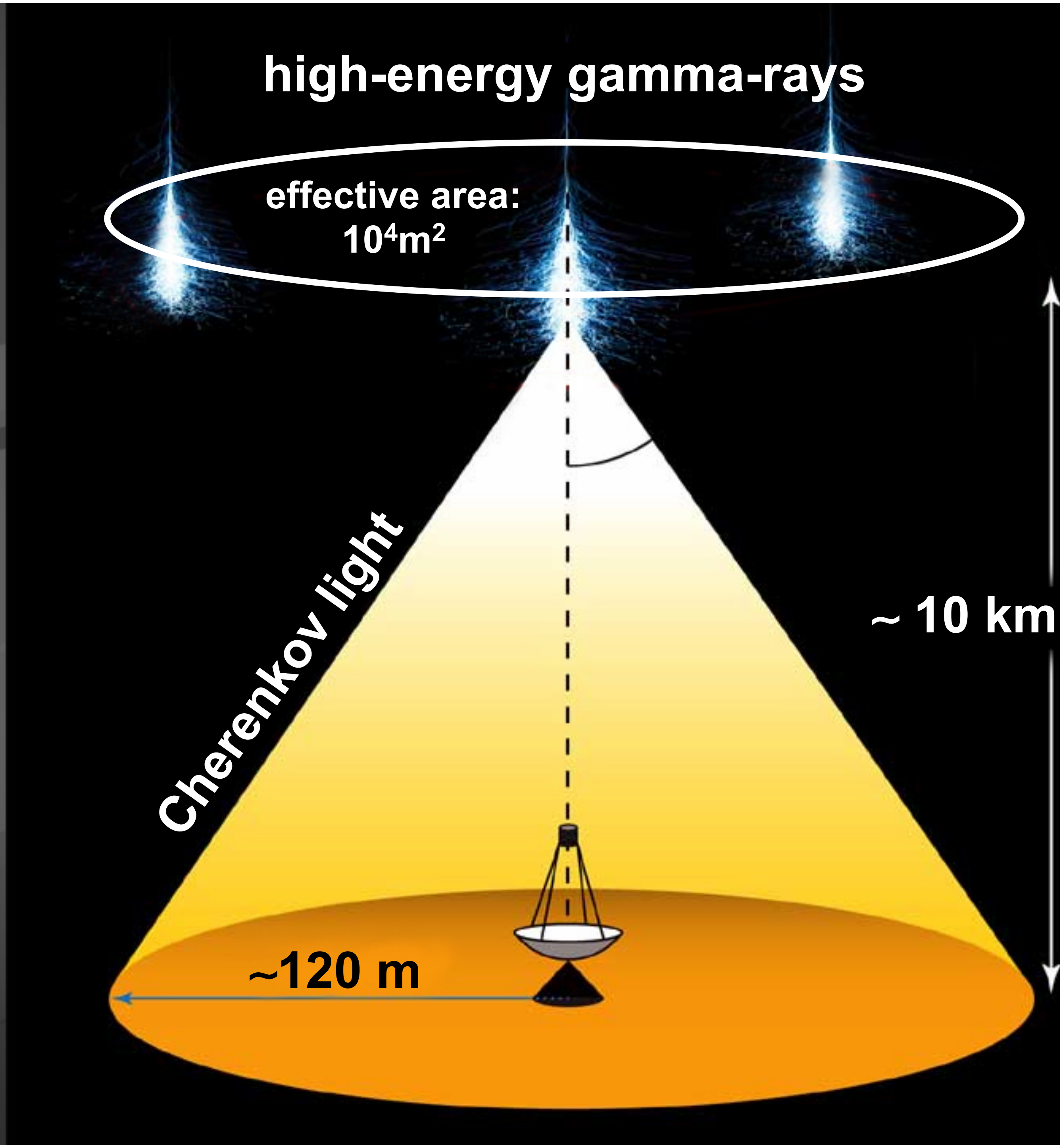
TeV gamma ray astronomy


detection of
TeV gamma rays
with Cherenkov
telescopes
gamma ray
air shower
~ 10 km
Cherenkov light
1°
~ 120 m

•a cosmic photon initiates an electromagnetic shower high in the atmosphere

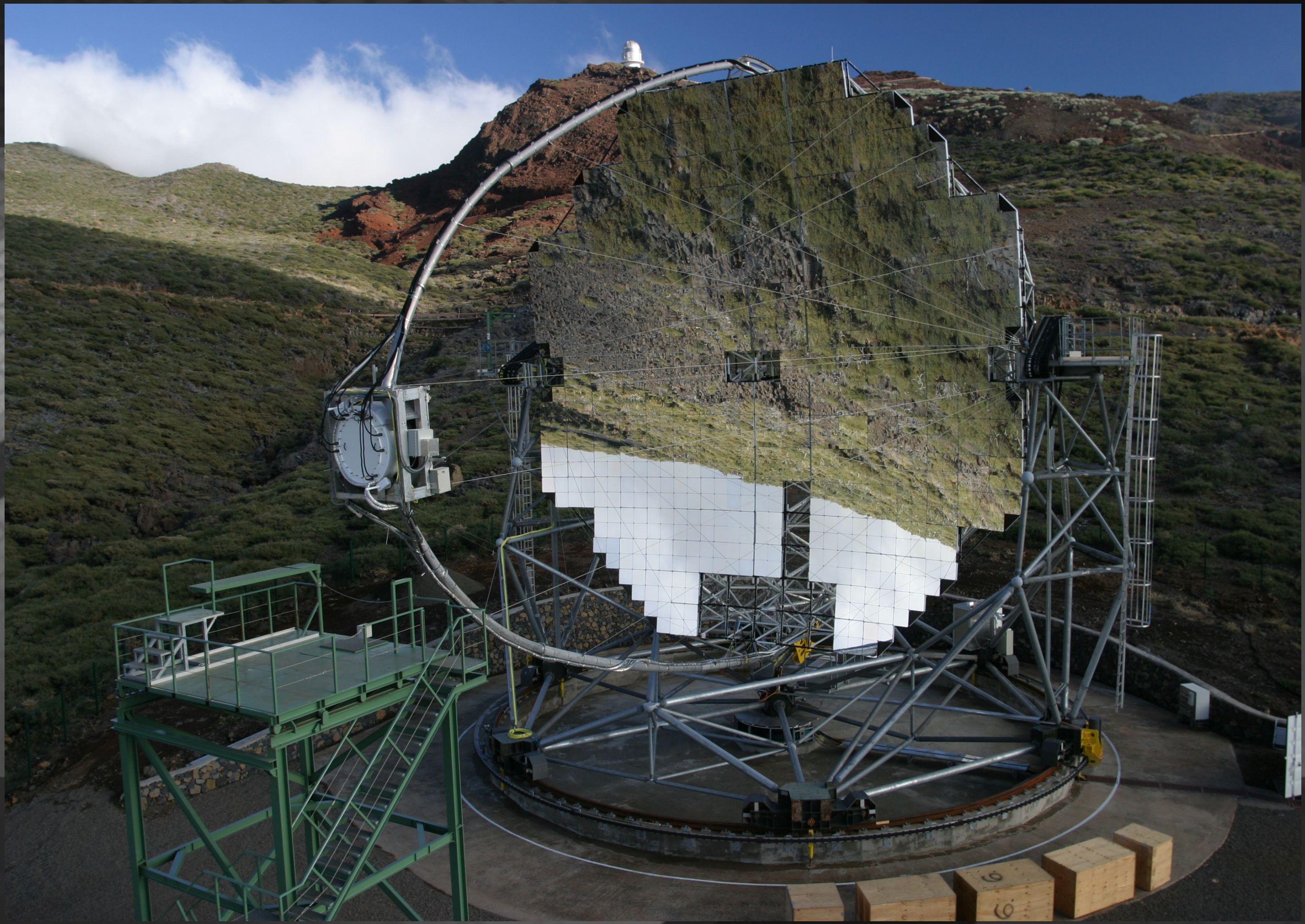
•the shower particles emit Cherenkov radiation

•this radiation is captured by mirrors read out by a cluster of photomultipliers



TeV gamma ray astronomy: the neutrino connection

MAGIC



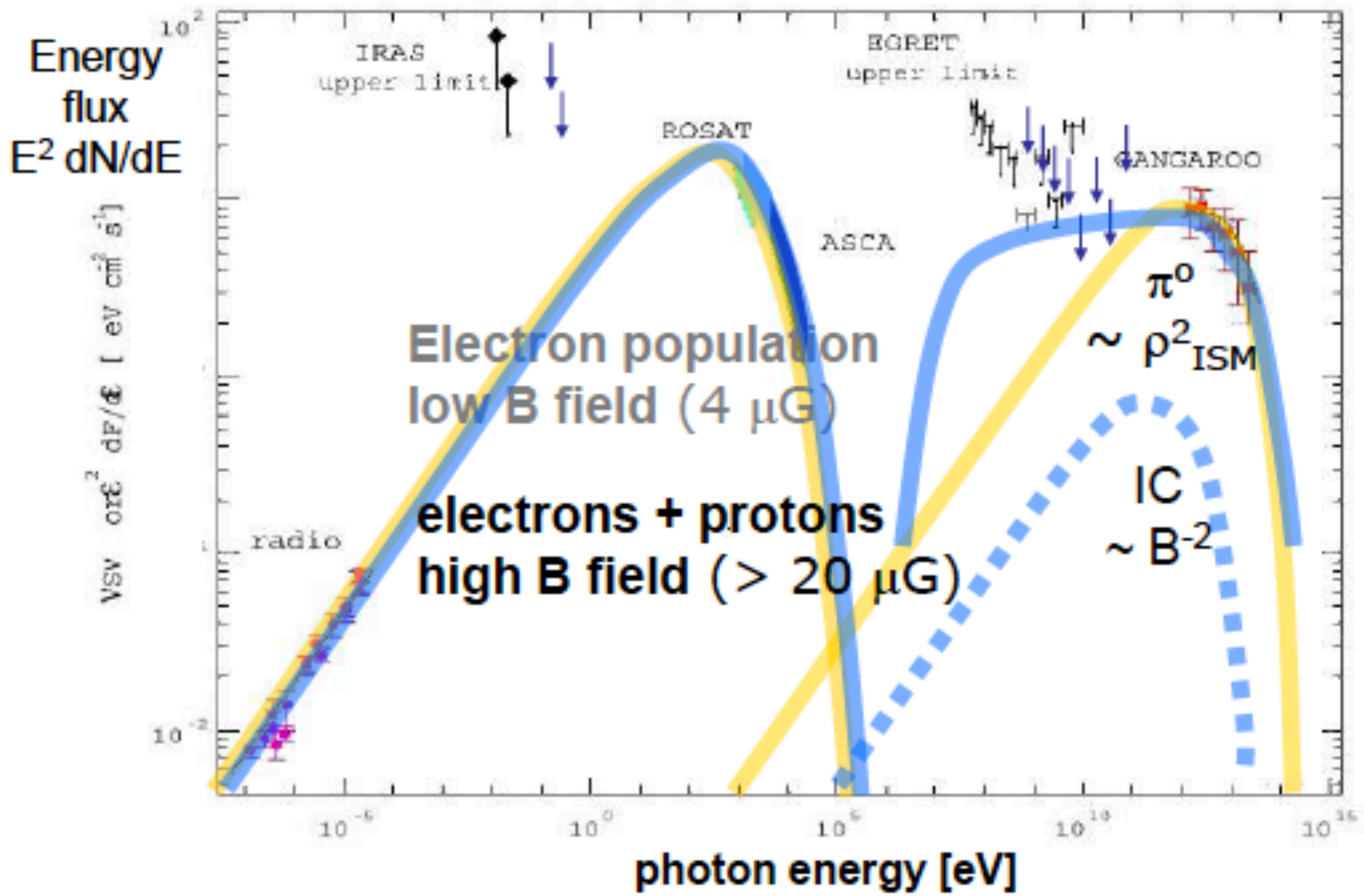
TeV γ survey instruments ~ 2-3 π

gamma rays are
muon-poor air showers

Tibet array and ARGO

Milagro

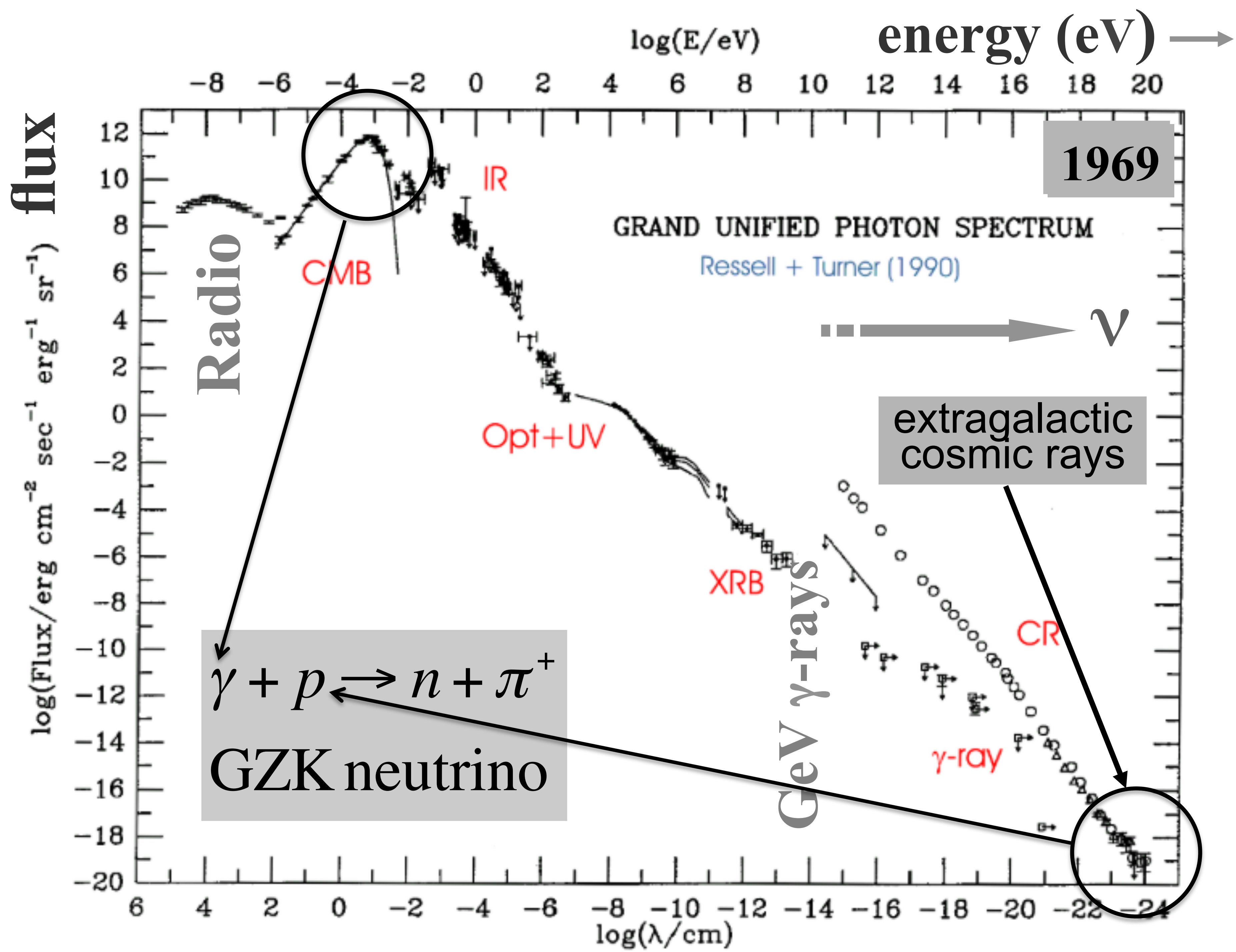
electromagnetic vs hadronic



high energy neutrino astronomy

neutrino astronomy

kilometer-scale detectors have the capability of detecting astrophysical neutrinos from cosmic sources with an energy density in neutrinos comparable to their energy density in the observed cosmic rays and TeV gamma rays



energy (eV)
log(E/eV)
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
log(λ/cm)
1969
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
γ-ray
CR
ν
extragalactic cosmic rays
$\gamma + p \rightarrow n + \pi^+$
GZK neutrino

cosmic rays interact with the microwave background

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

$400\ cm^{-3}$

$10^{-28}\ cm^{2}$

$$\lambda_{\text{int}} = \{n_{cmb}\sigma_{\gamma+p}\}^{-1} \sim 10\,Mpc$$

$$E_p \geq 5 \times 10^{7}\,TeV$$

cosmic rays interact with the microwave background

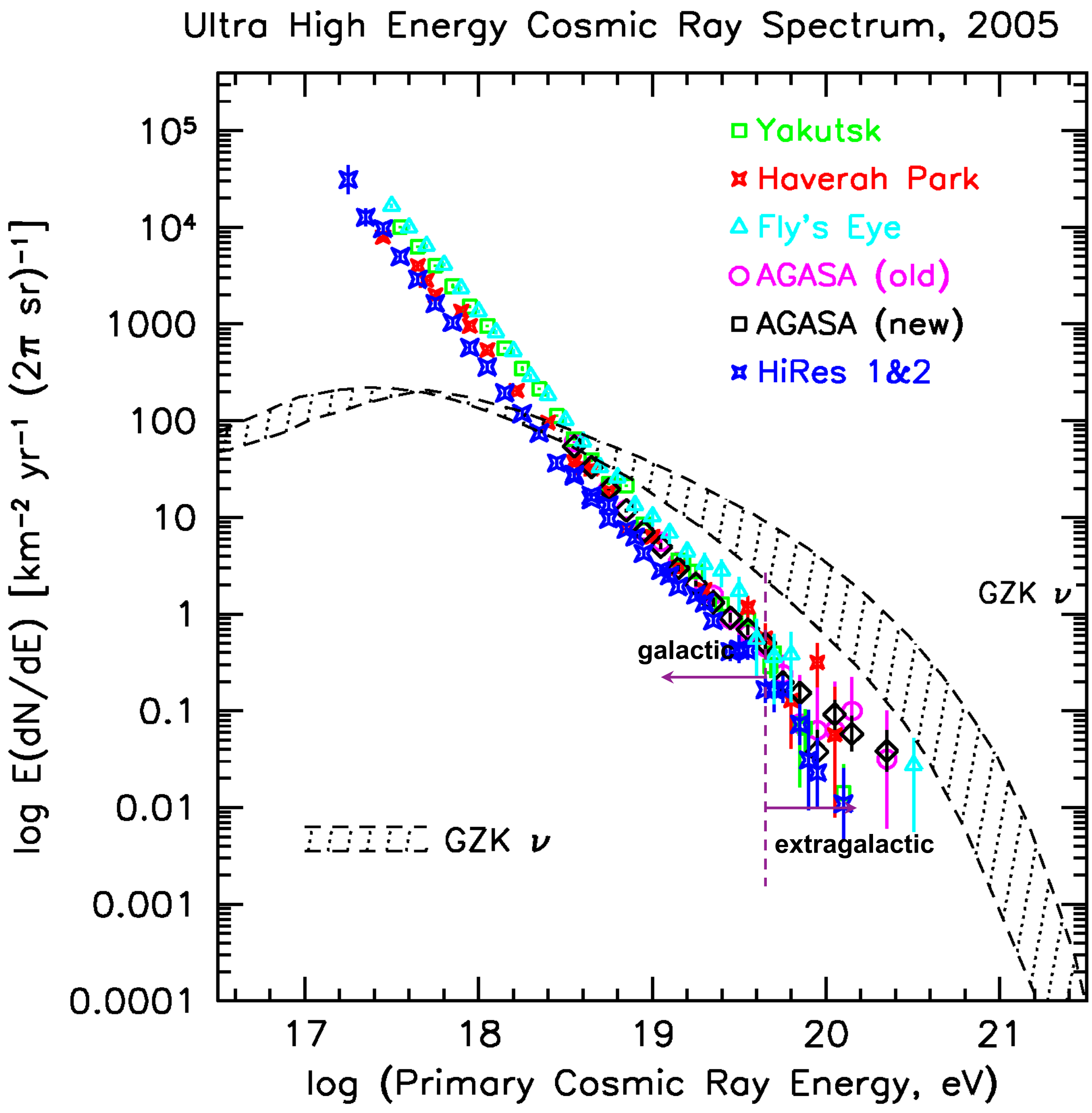
$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

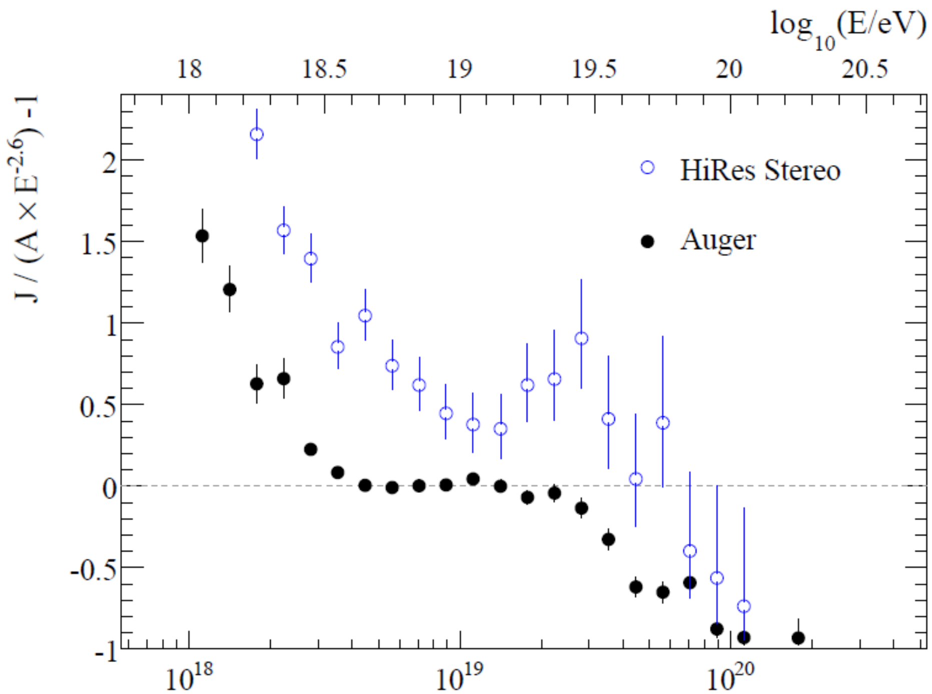
cosmic rays disappear, neutrinos with EeV (10^{18} eV) energy appear

$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year
...but it points at its source!

neutrinos from GZK interactions

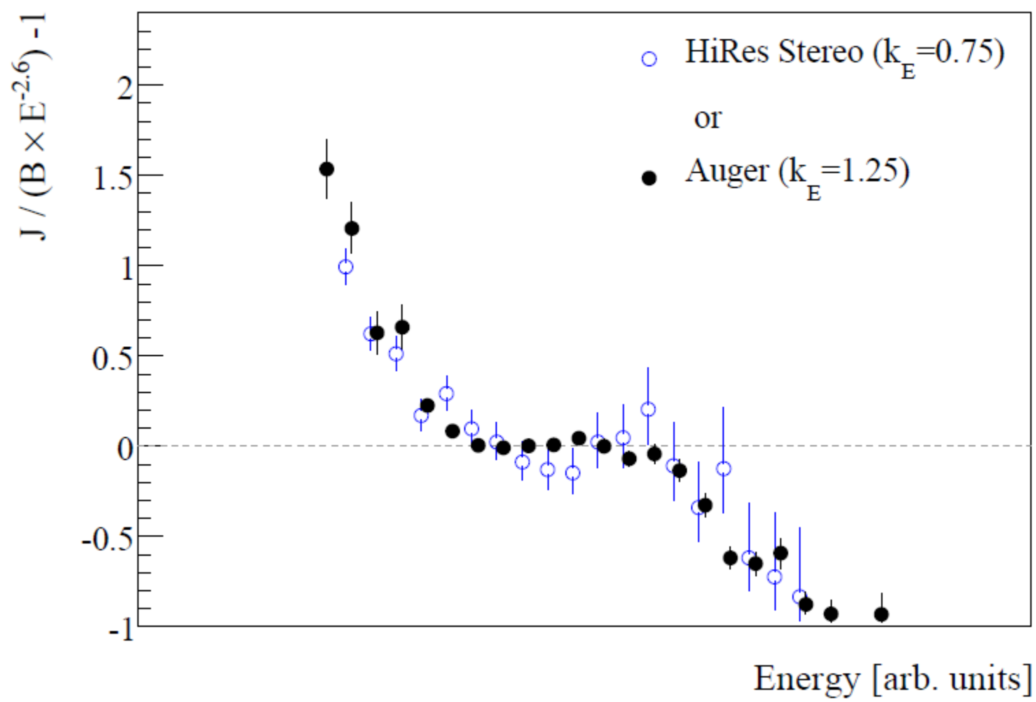


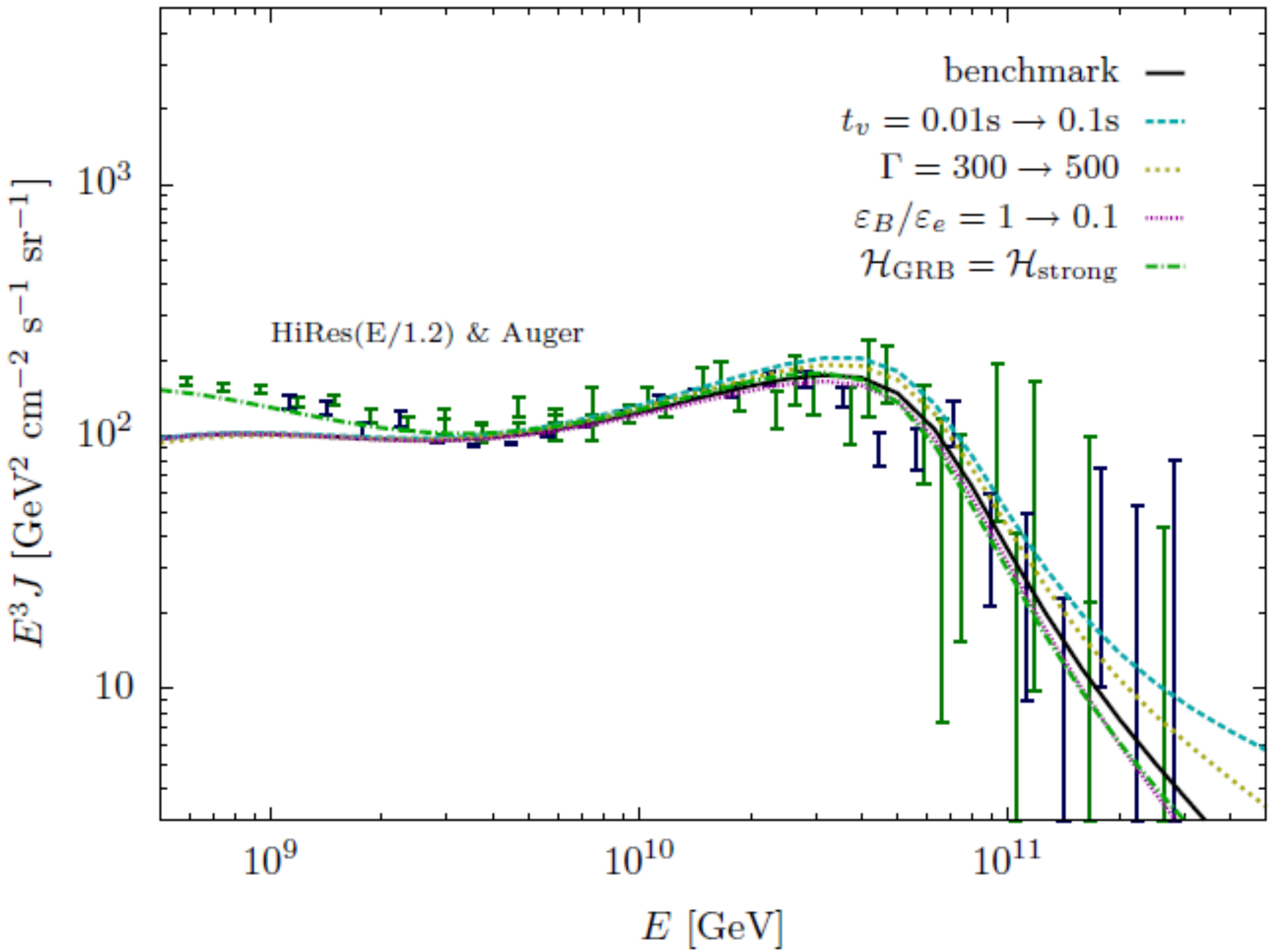


confirmed by Telescope Array

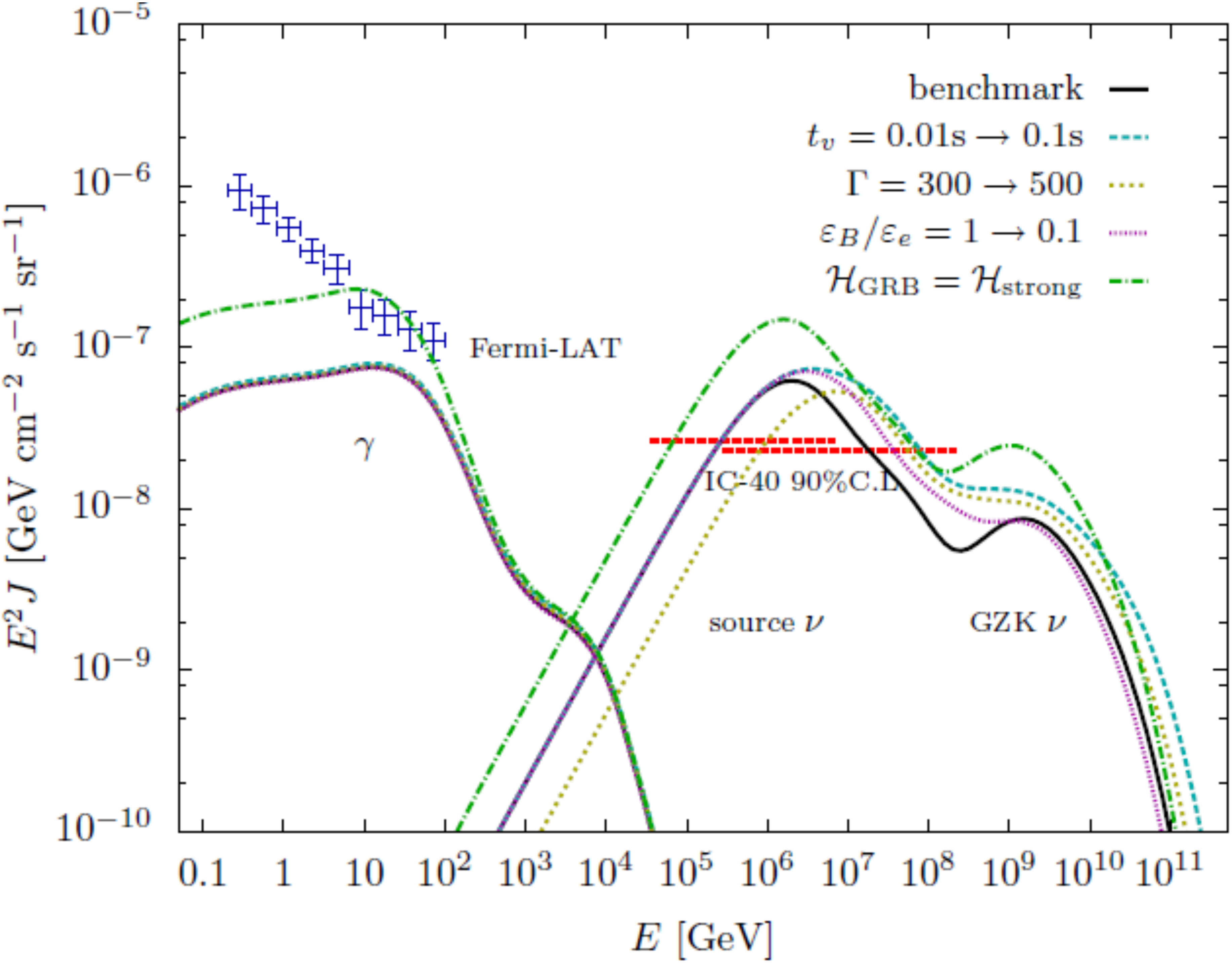
(Auger PRL **101** (2008) 61101, PLB (2010); HiRes APP **32** (2009) 53)

GZK absorption feature appears at the expected energy

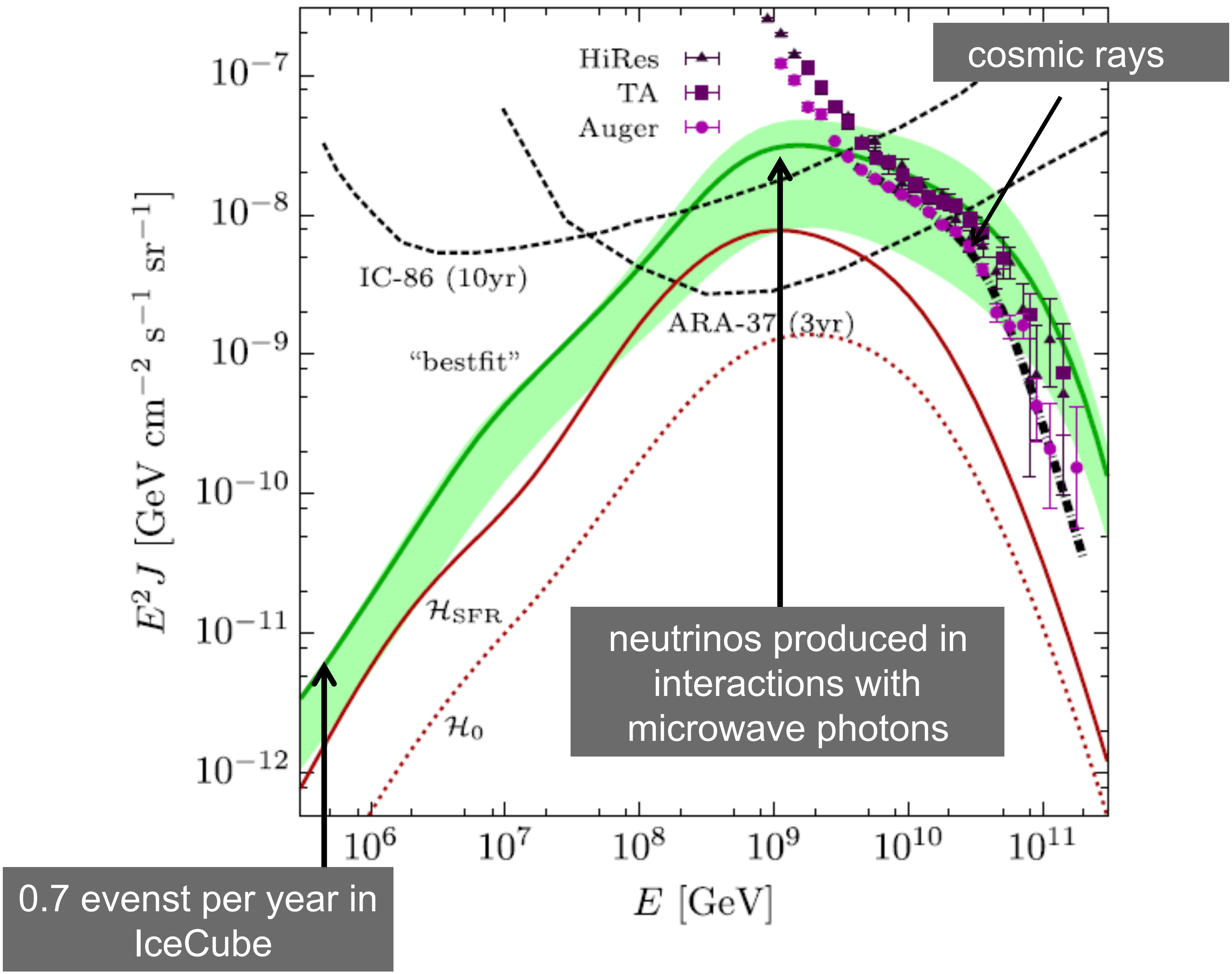




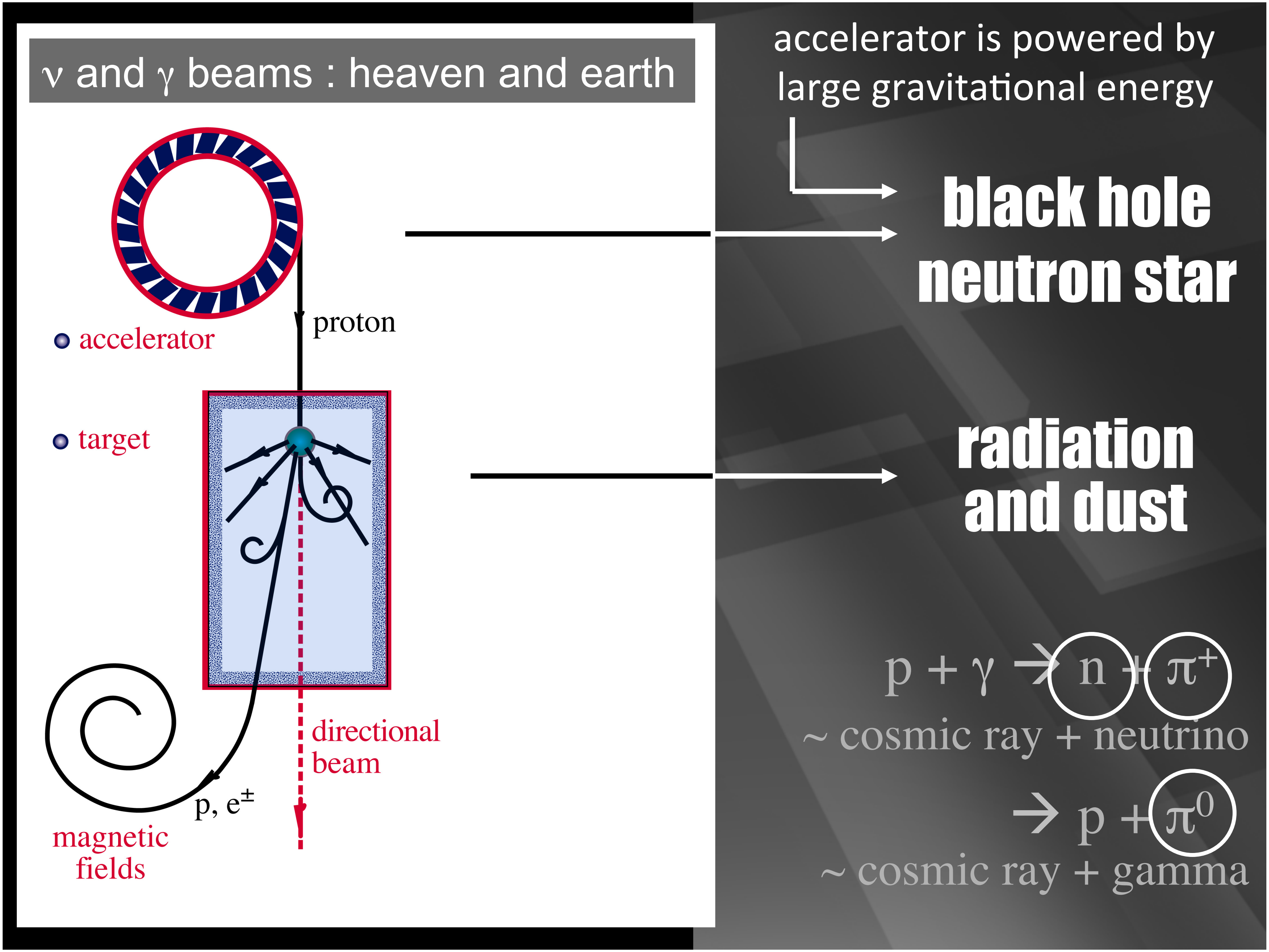
benchmark
$t_v = 0.01\text{s} \rightarrow 0.1\text{s}$
$\Gamma = 300 \rightarrow 500$
$\varepsilon_B/\varepsilon_e = 1 \rightarrow 0.1$
$\mathcal{H}_{\text{GRB}} = \mathcal{H}_{\text{strong}}$
HiRes(E/1.2) & Auger
$E^3 J$ [GeV^2 cm^{-2} s^{-1} sr^{-1}]
10^3
10^2
10
10^9
10^{10}
10^{11}
E [GeV]



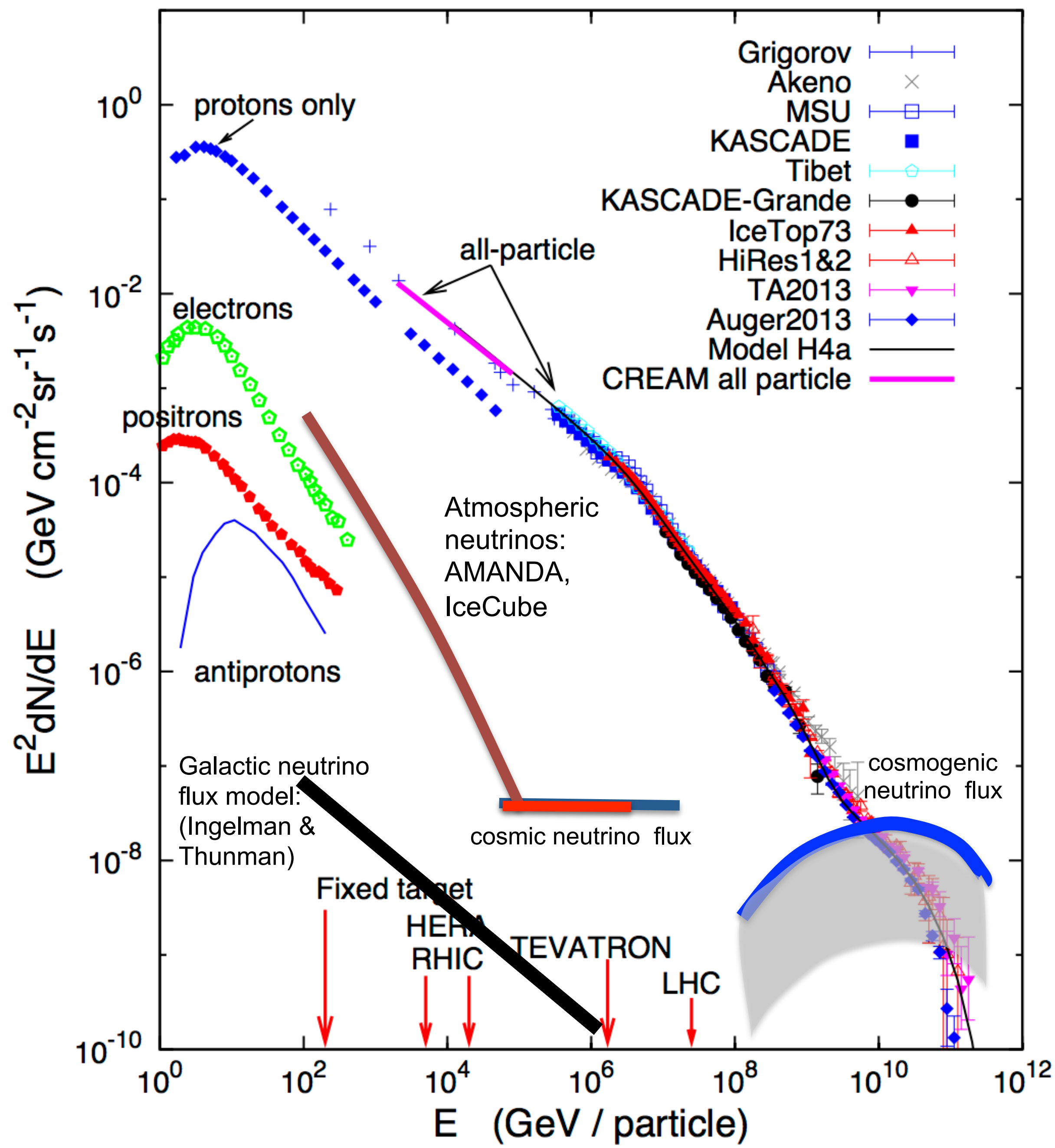
benchmark
$t_v = 0.01s \to 0.1s$
$\Gamma = 300 \to 500$
$\varepsilon_B/\varepsilon_e = 1 \to 0.1$
$\mathcal{H}_{GRB} = \mathcal{H}_{strong}$
Fermi-LAT
γ
IC-40 90%C.L.
source ν
GZK ν
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}



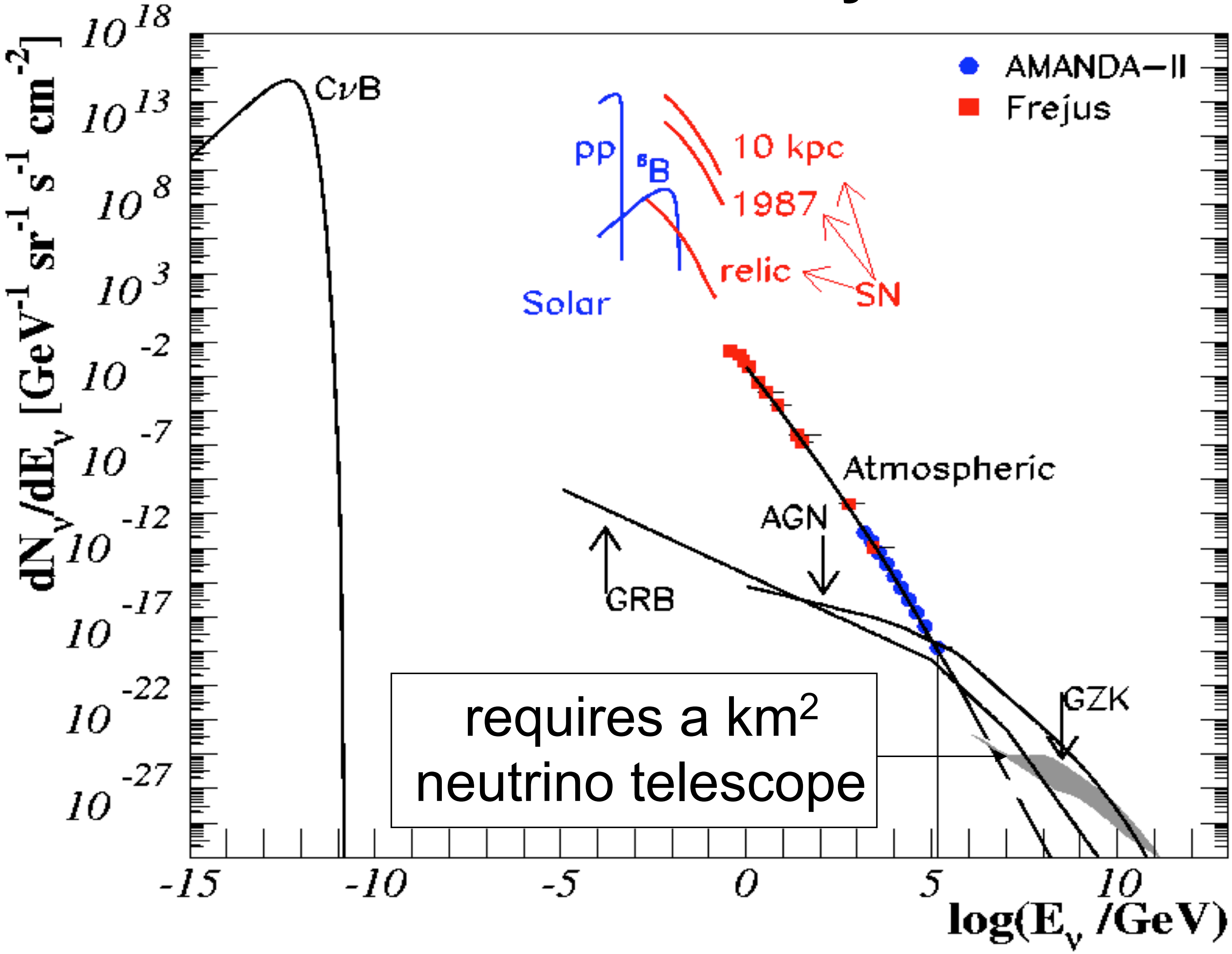
cosmic rays
HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\rm SFR}$
$\mathcal{H}_0$
neutrinos produced in interactions with microwave photons
0.7 evenst per year in IceCube
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^6
10^7
10^8
10^9
10^{10}
10^{11}


ν and γ beams : heaven and earth
accelerator
target
proton
directional beam
p, e±
magnetic fields
accelerator is powered by large gravitational energy
black hole
neutron star
radiation and dust
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma

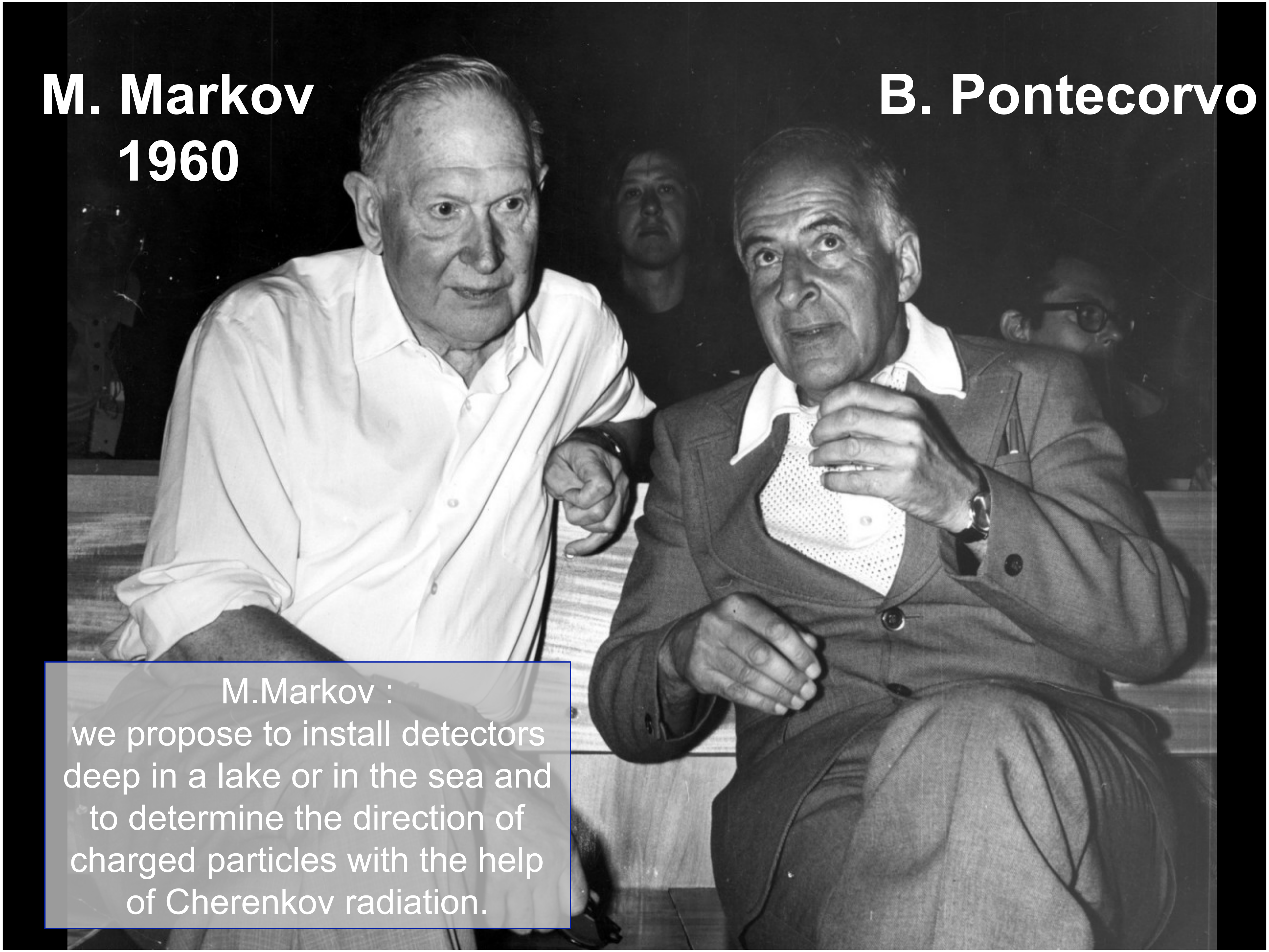
Energies and rates of the cosmic-ray particles

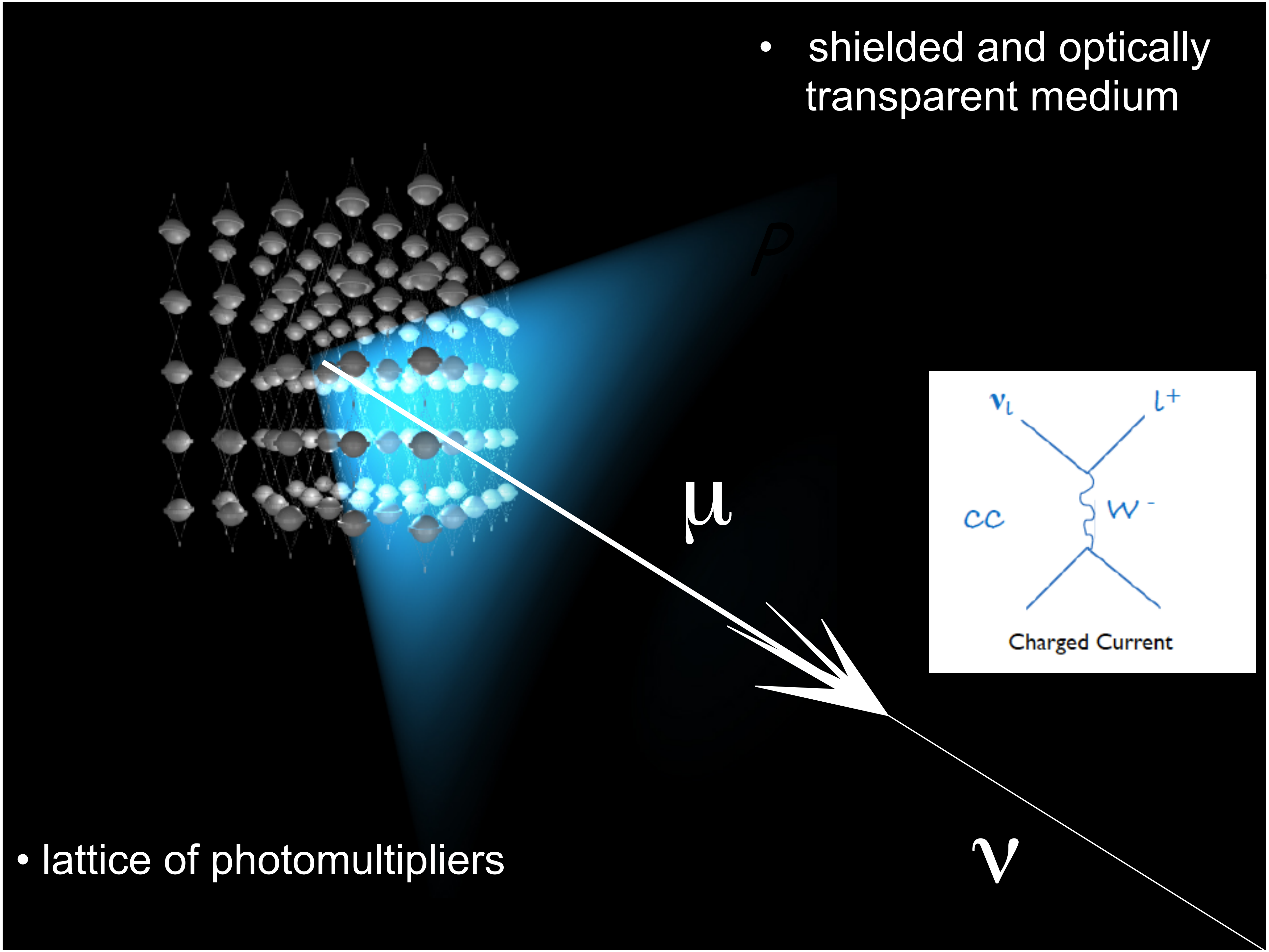


neutrino sky



requires a km^2 neutrino telescope

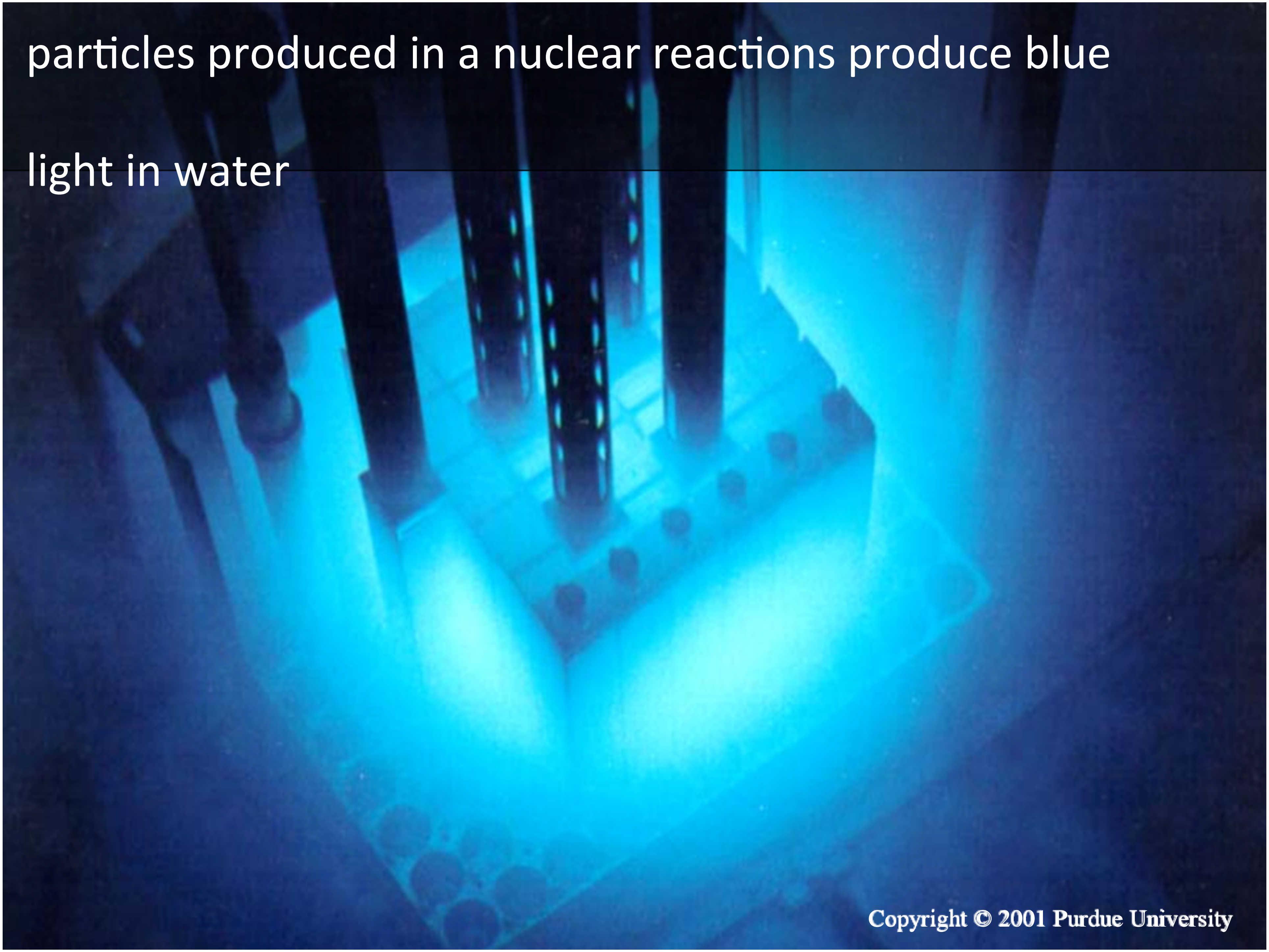

M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.


• shielded and optically transparent medium
μ
ν
• lattice of photomultipliers
ν_l
l+
cc
W-
Charged Current

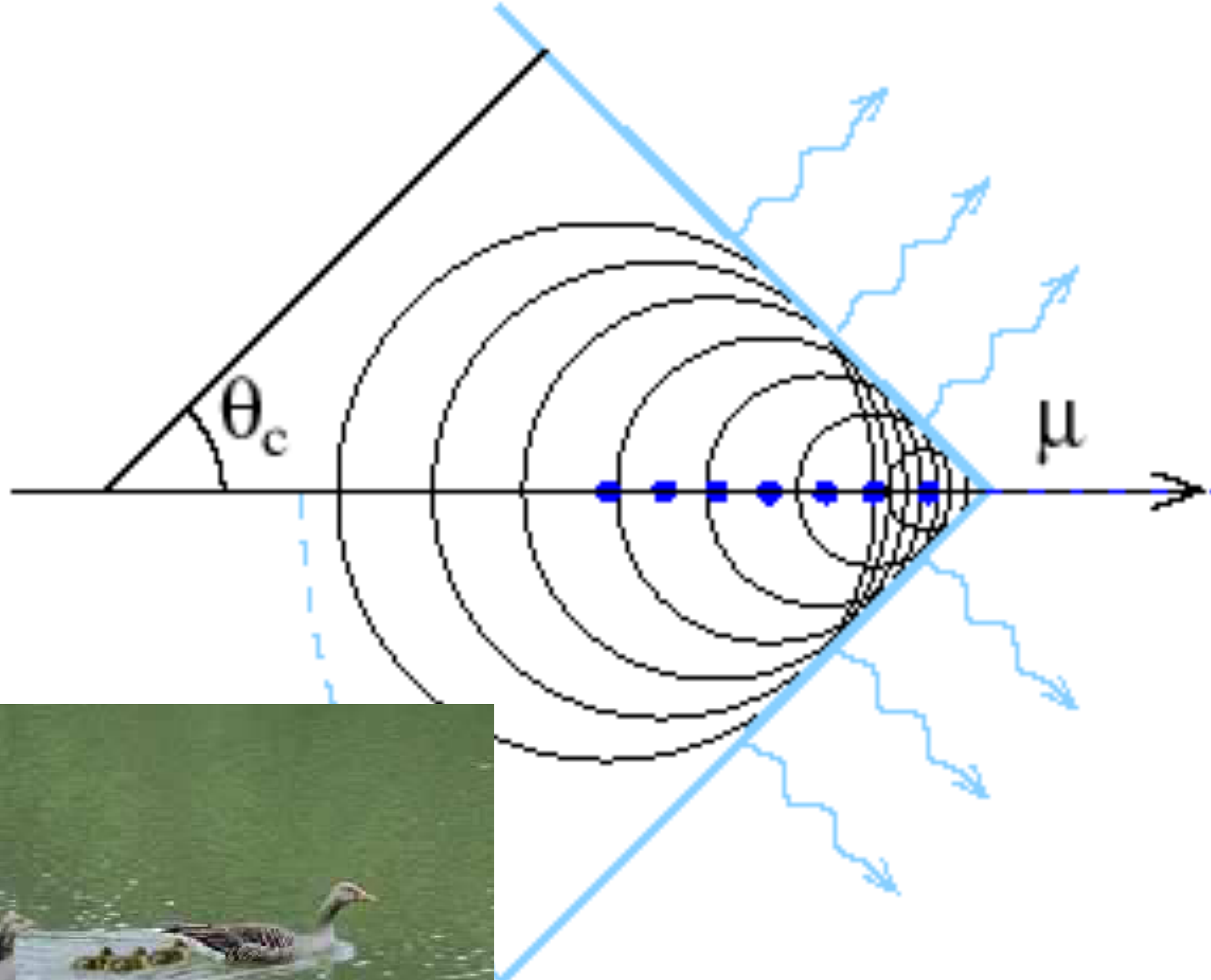
neutrinos

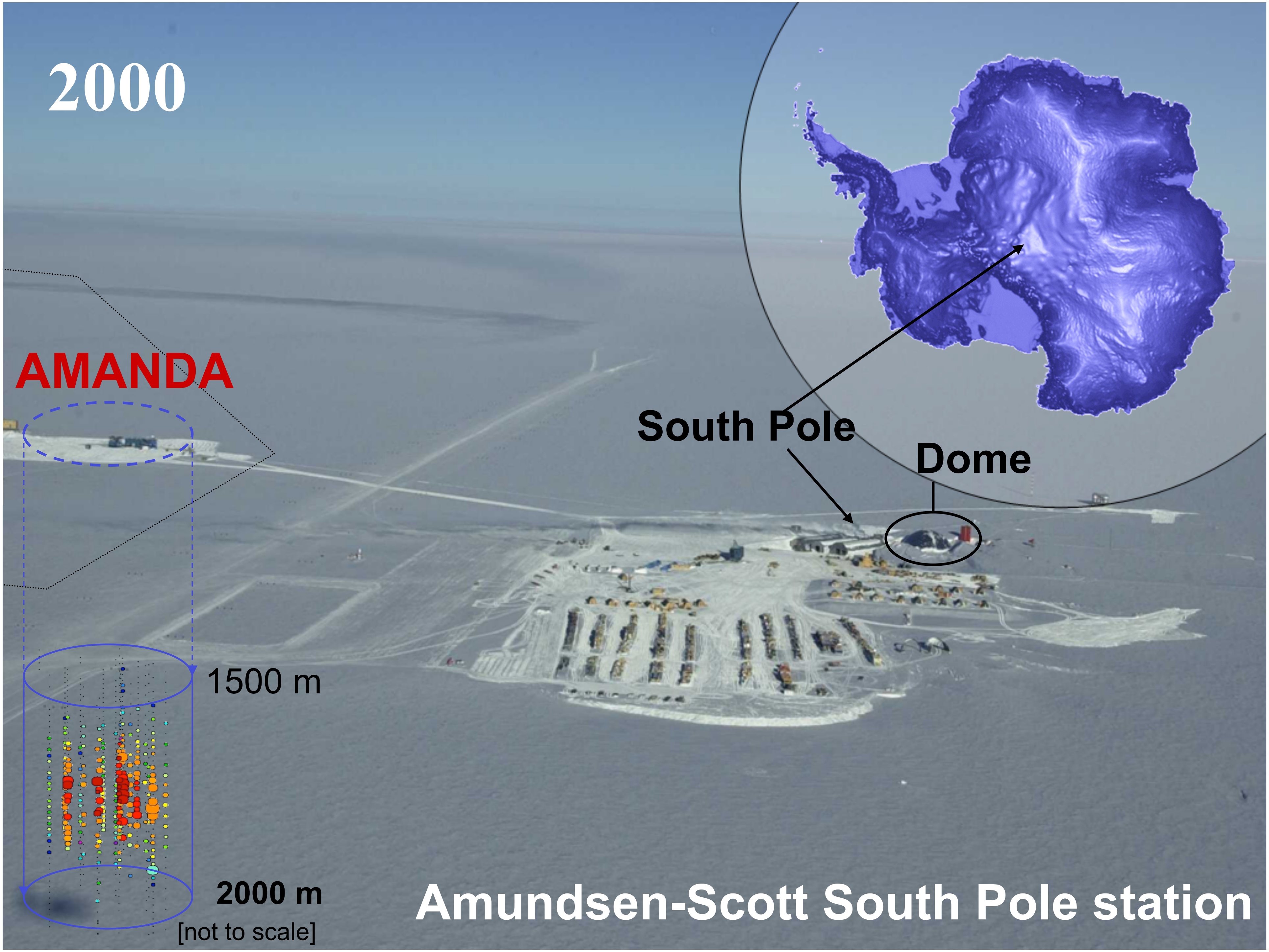
photomultiplier tube

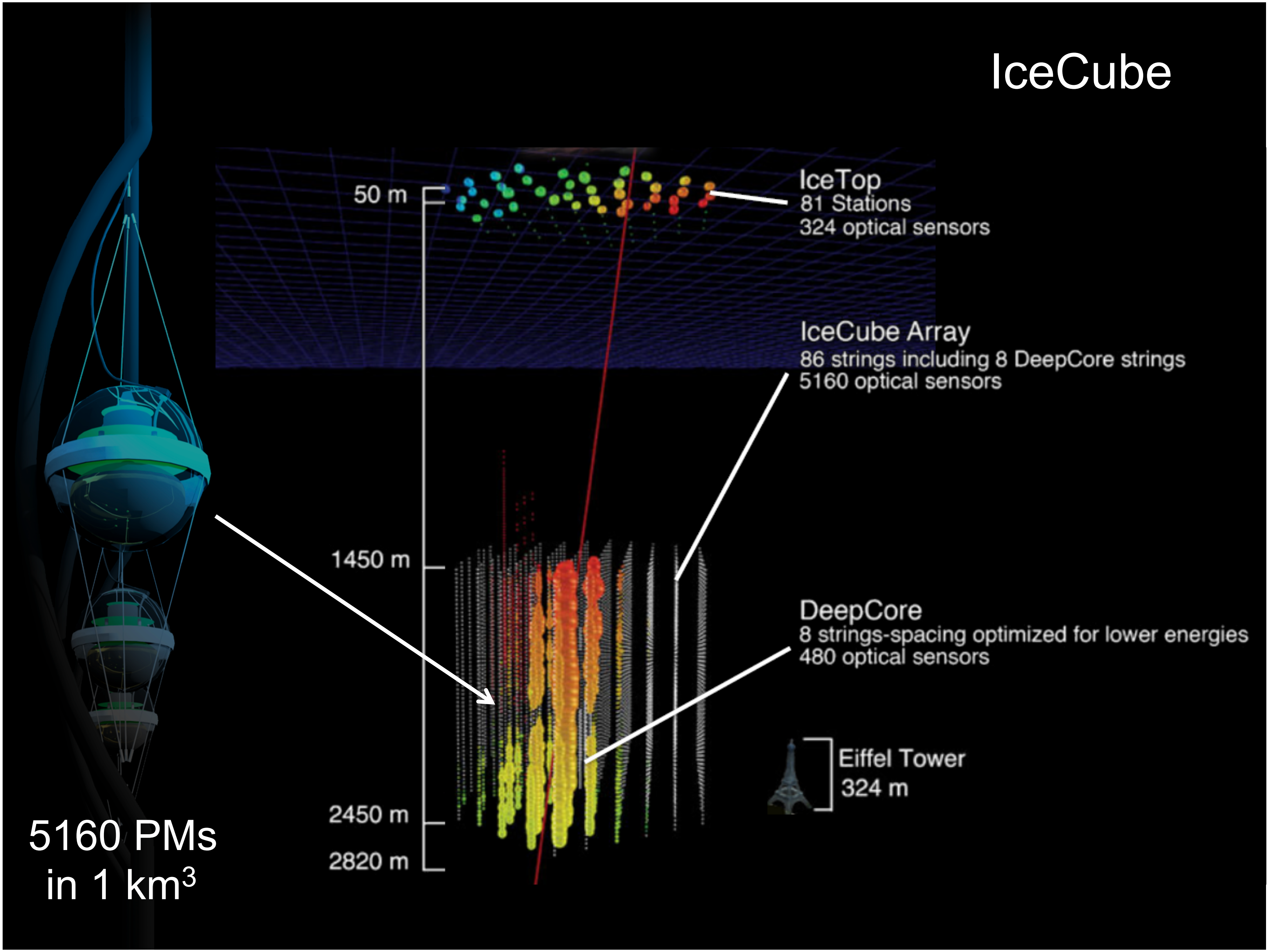
particles produced in a nuclear reactions produce blue light in water

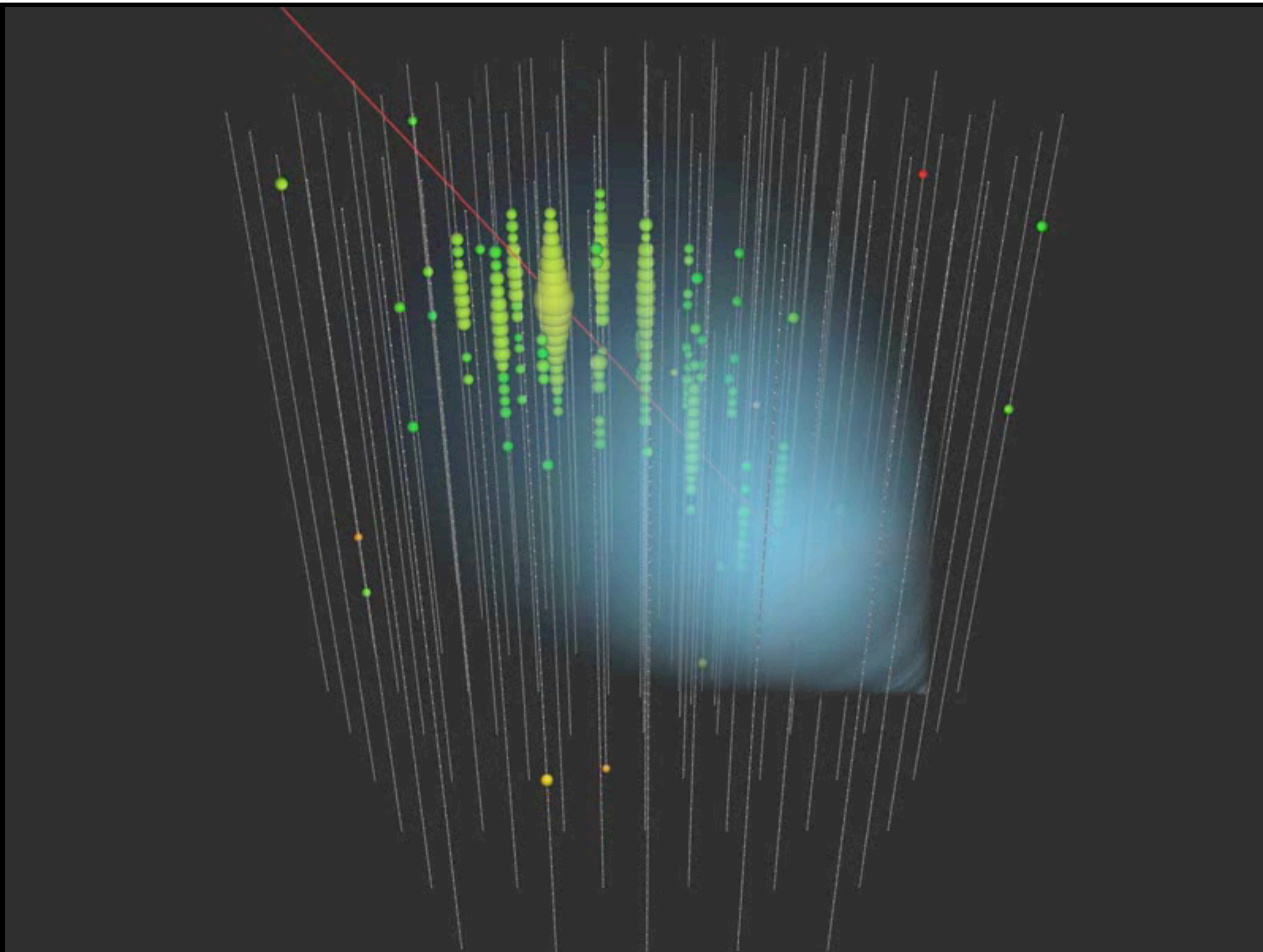


cherenkov radiation: particle's speed exceeds the speed of light



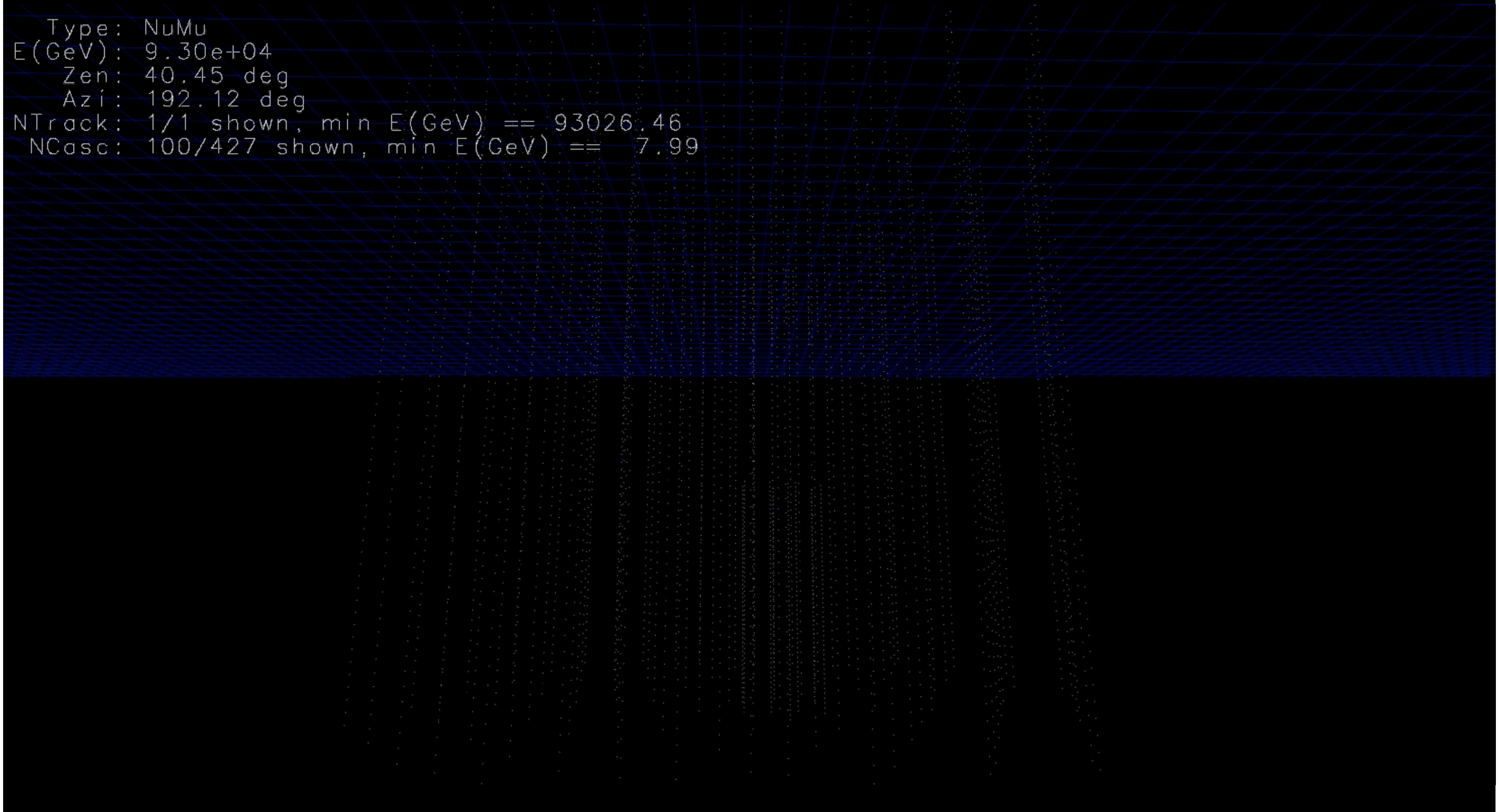

2000
AMANDA
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station


IceCube
50 m
1450 m
2450 m
2820 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
5160 PMs
in 1 km3

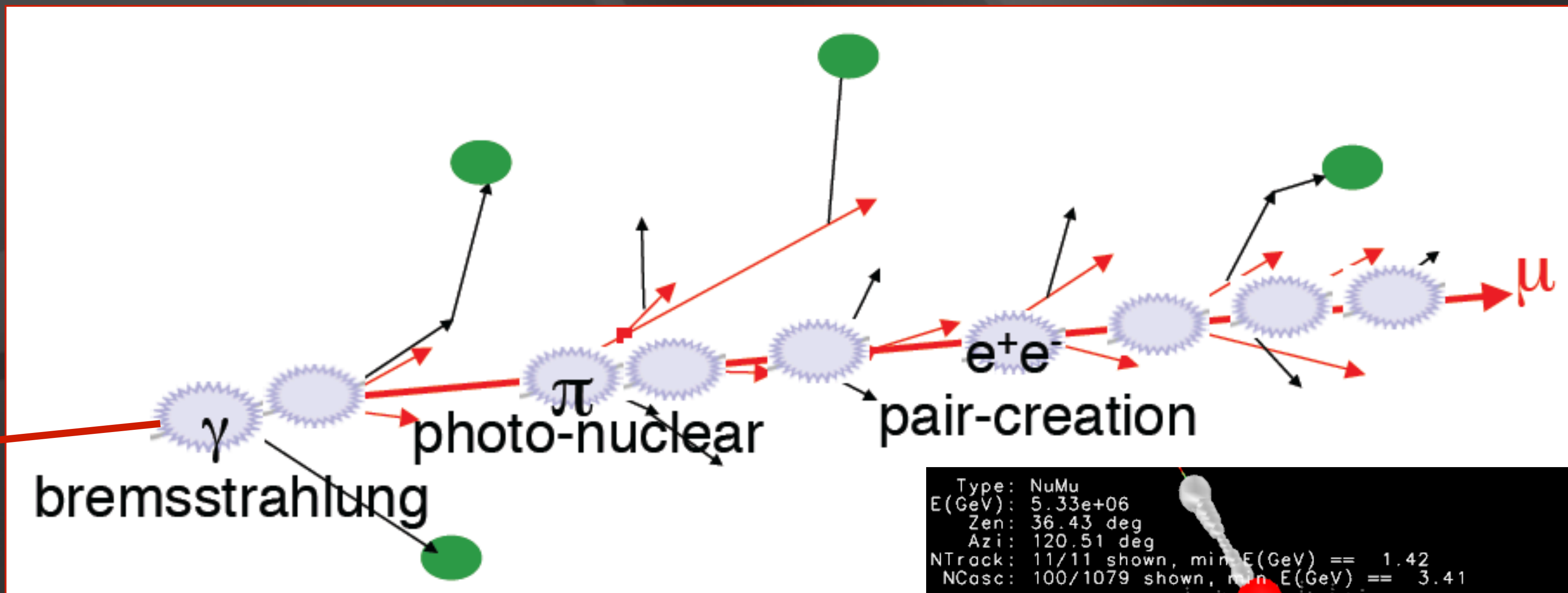


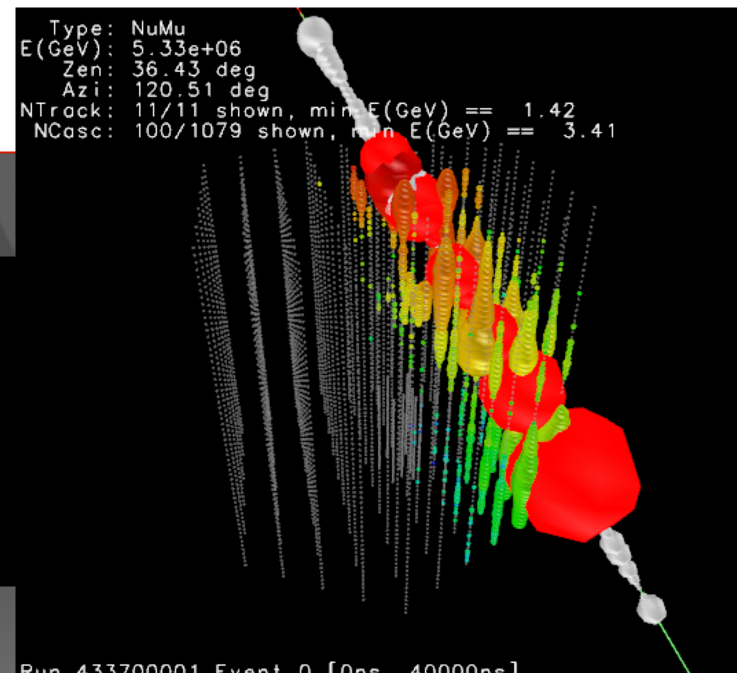
muon track: color is time; number of photons is energy

93 TeV muon: # photons ~ energy

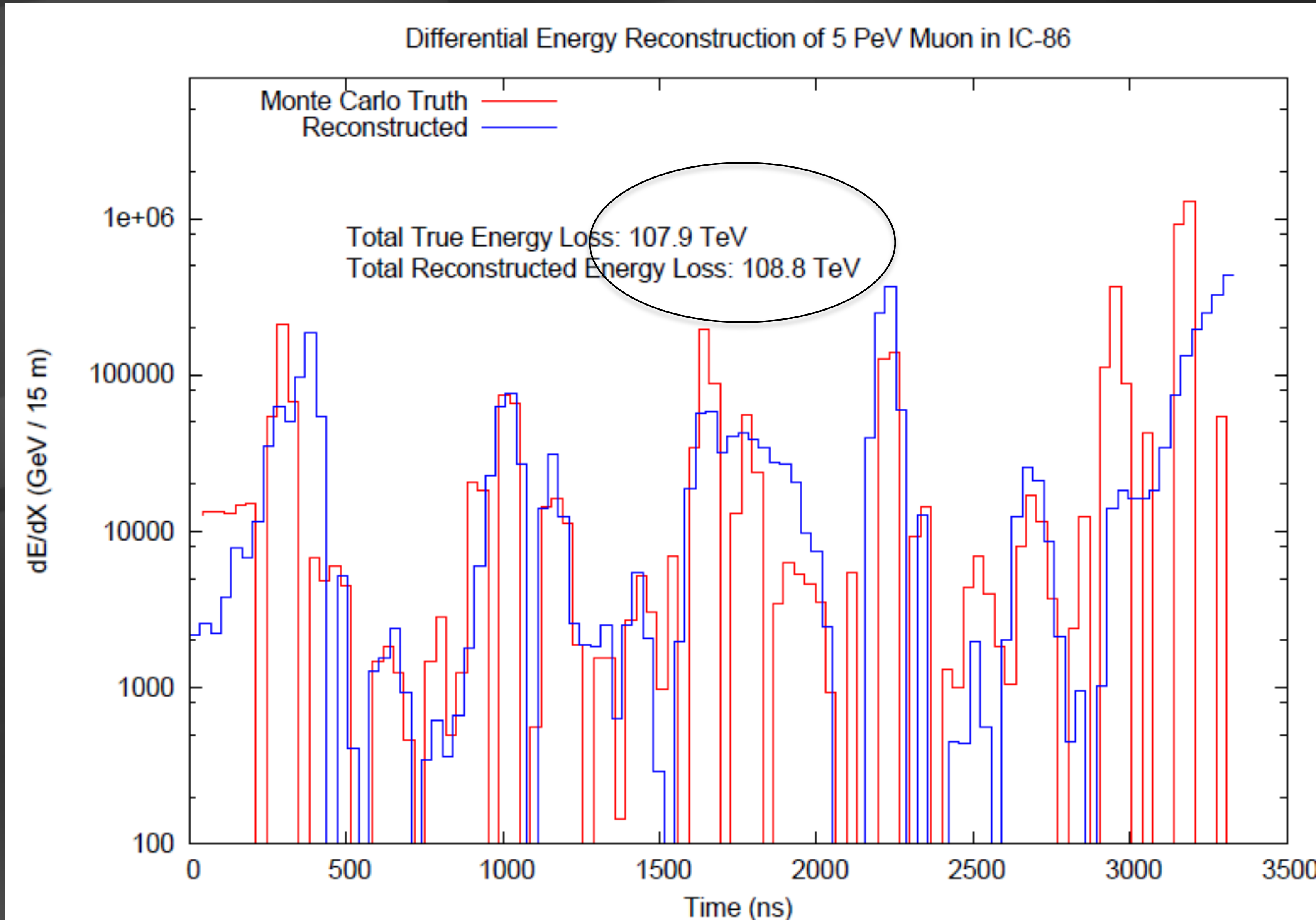


energy measurement (> 1 TeV)



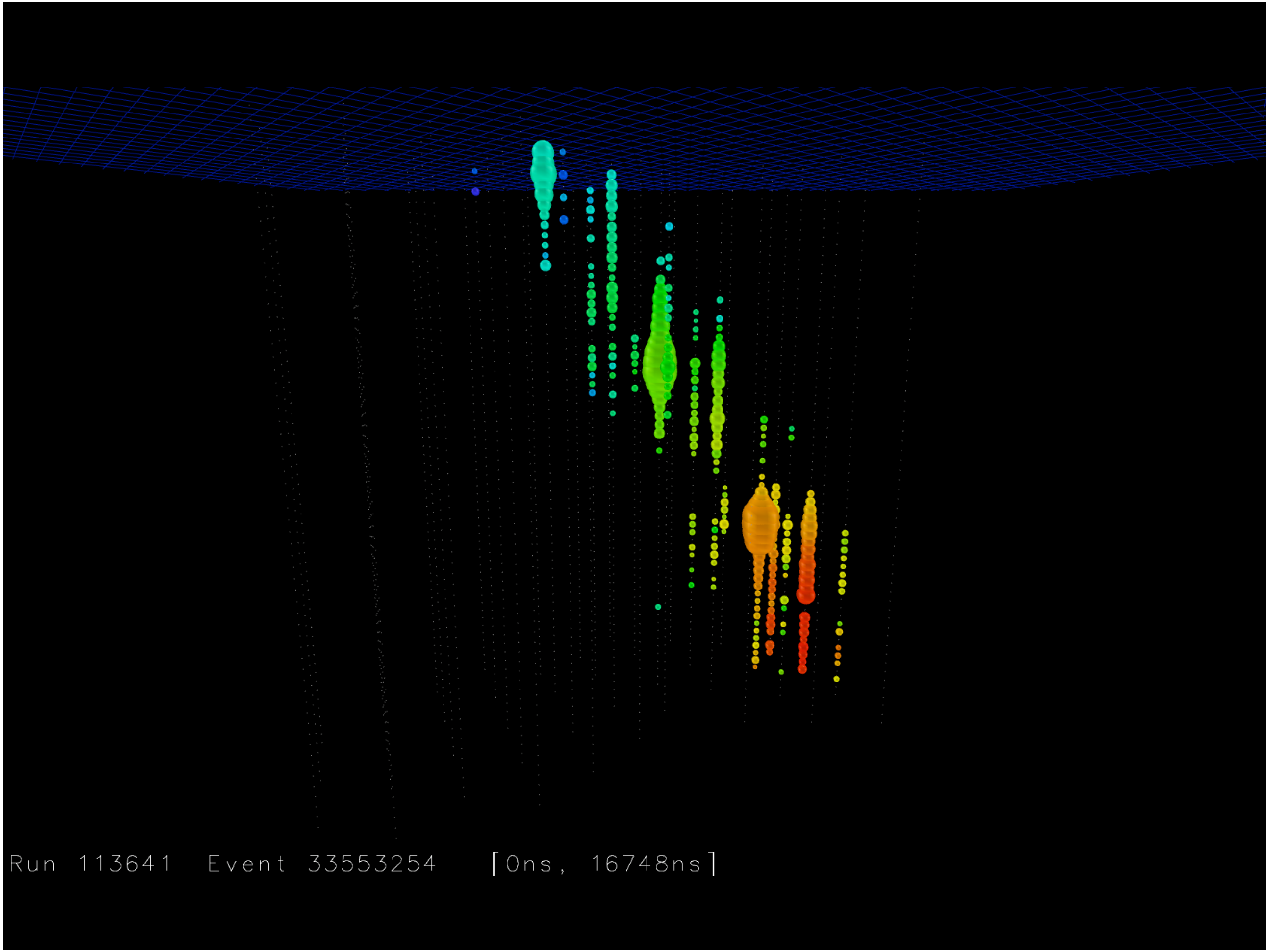


convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



1.1 km

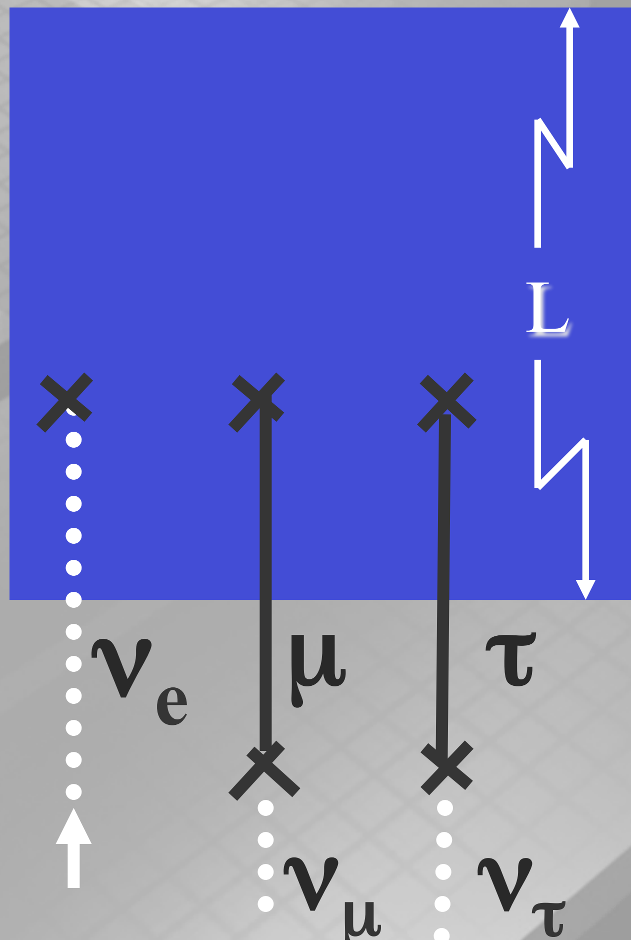
improving angular and energy resolution


Run 113641 Event 33553254 [0ns, 16748ns]

neutrino detection probability

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



neutrino detected

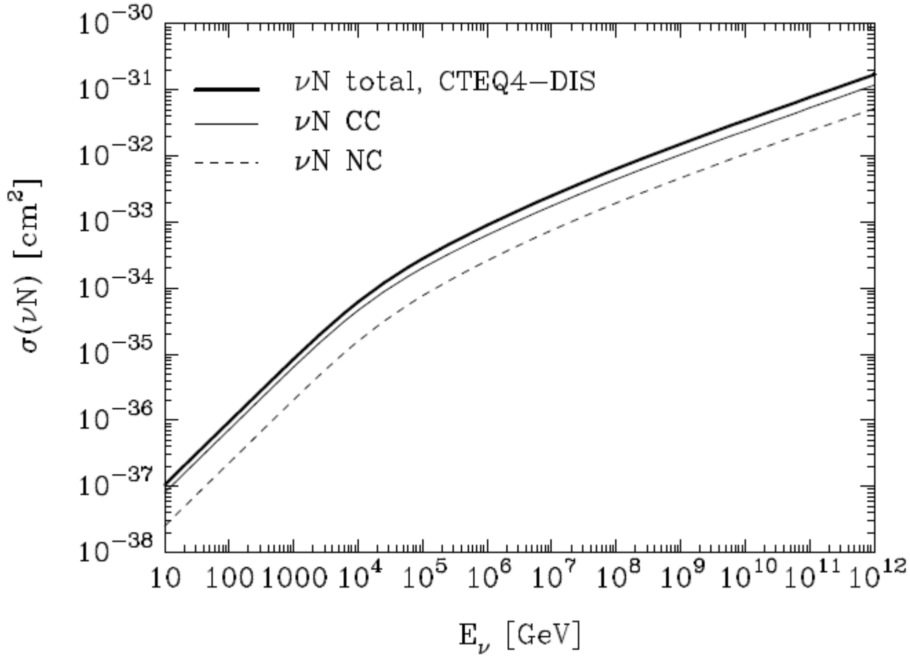
$$1 - e^{-\frac{L}{\lambda_\nu}}$$

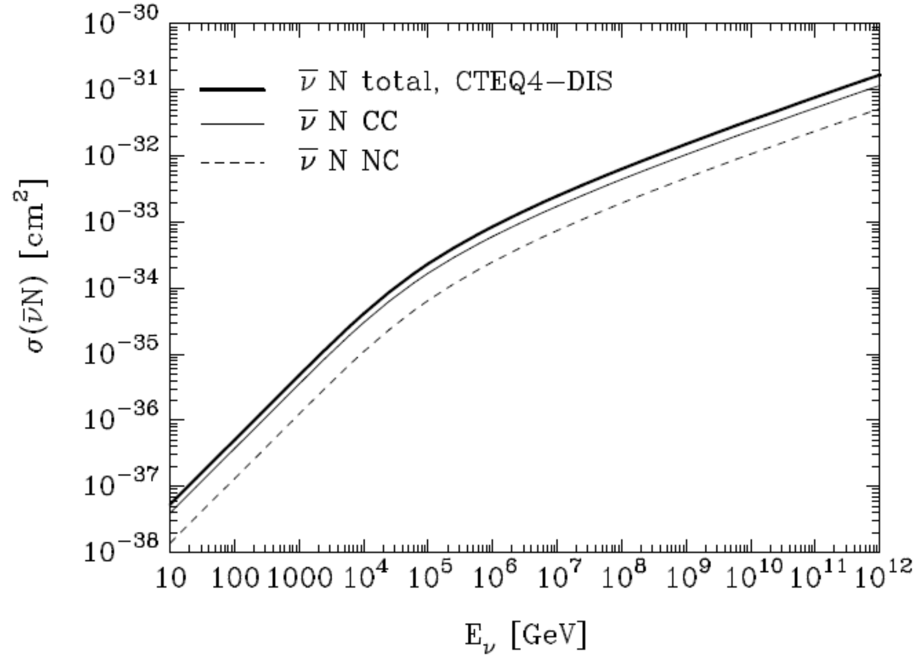
$$\cong \frac{L}{\lambda_\nu}$$

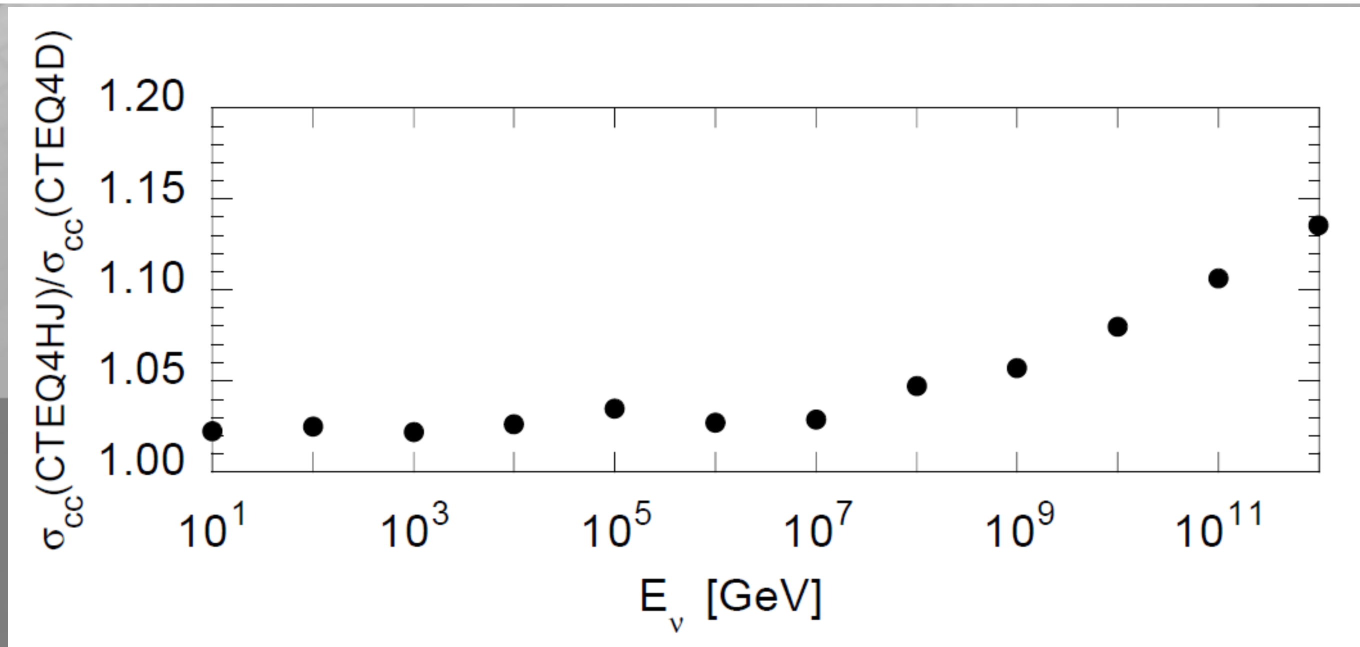
$$for \;\; \nu_\mu \quad L \rightarrow R_\mu\left[E_\mu = (1-y)E_\nu\right]$$

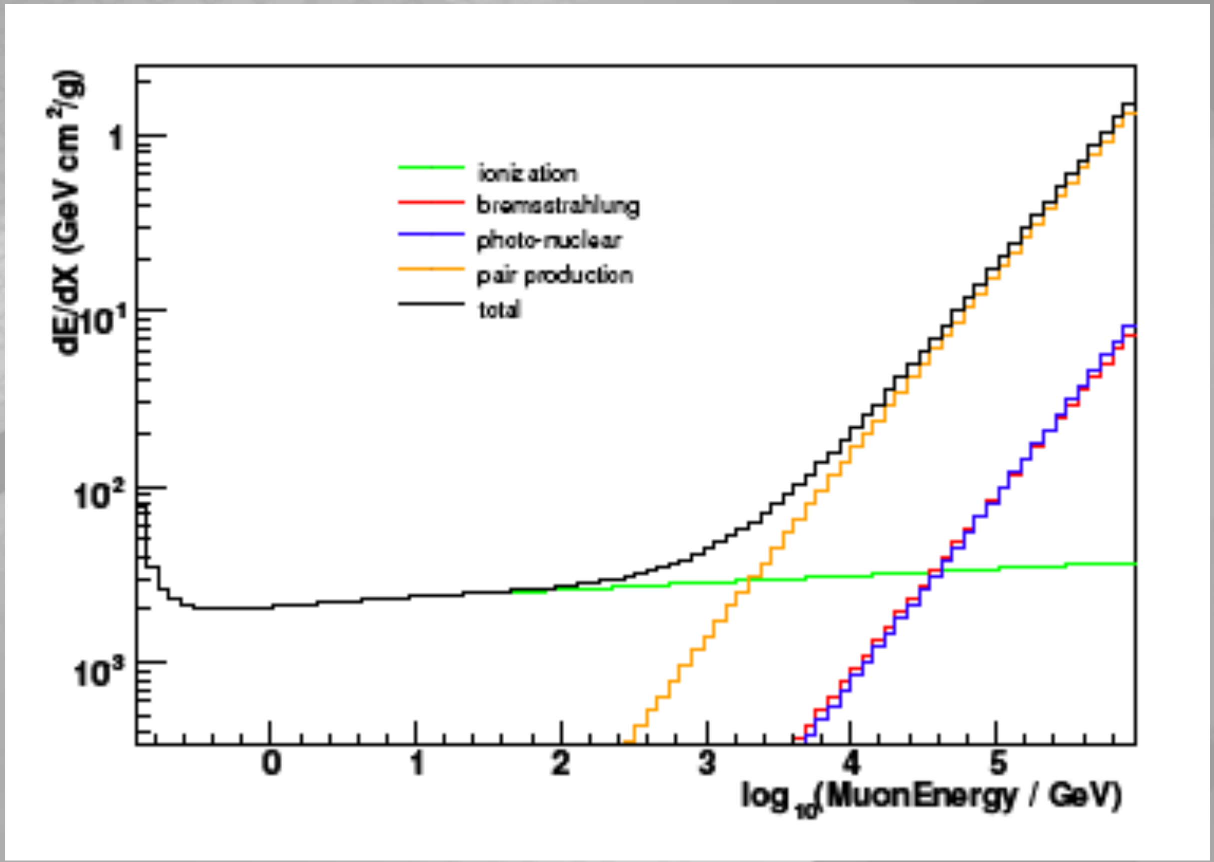
$$for \;\; \nu_\tau \quad L \rightarrow \left(E_\tau / m_\tau\right) c\tau_\tau$$

$$P_{\mathrm{det}} = n\sigma_\nu L$$

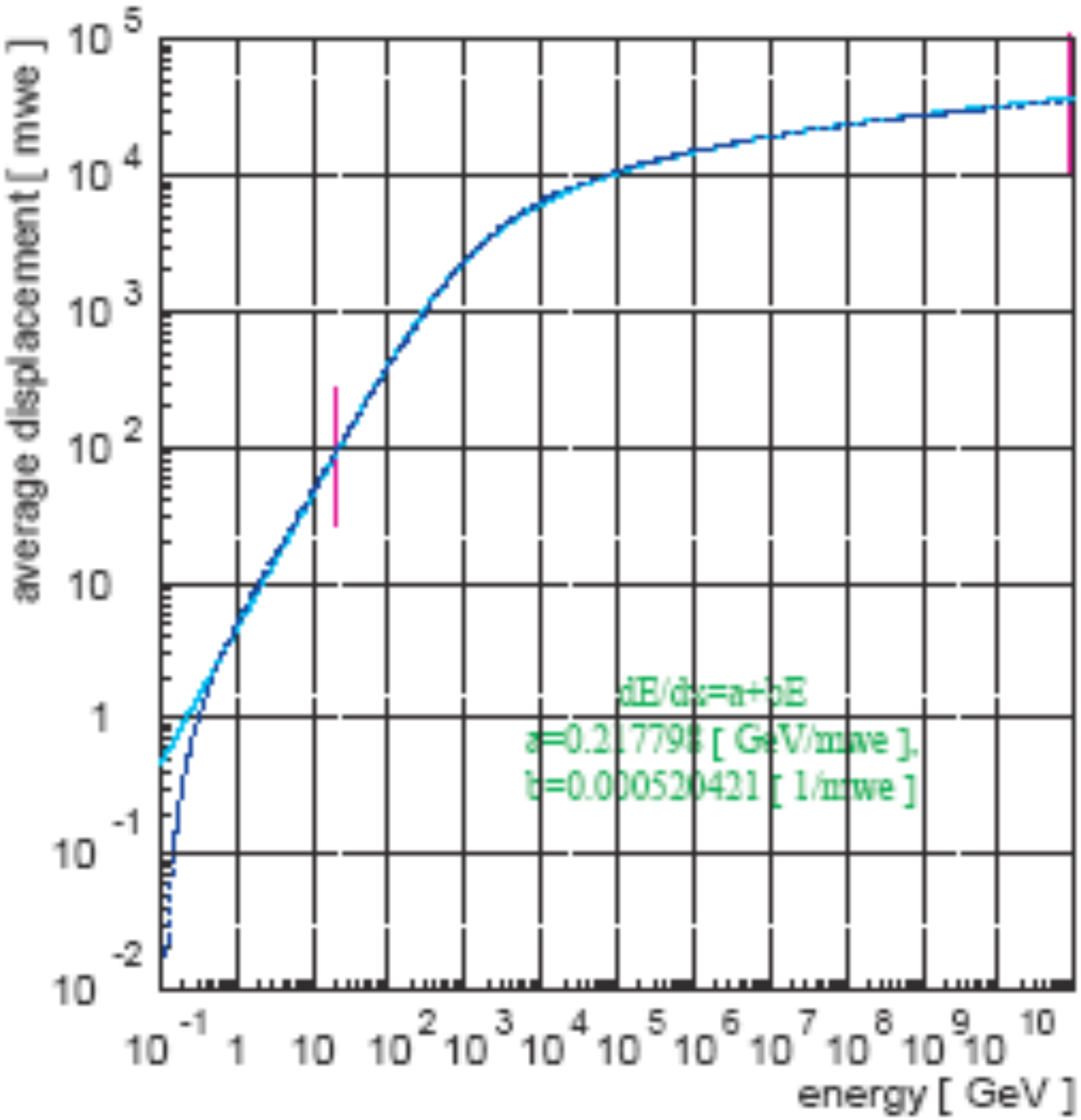

νN total, CTEQ4−DIS
νN CC
νN NC
σ(νN) [cm²]
E_ν [GeV]


ν̄ N total, CTEQ4−DIS
ν̄ N CC
ν̄ N NC
σ(ν̄N) [cm²]
E_ν [GeV]

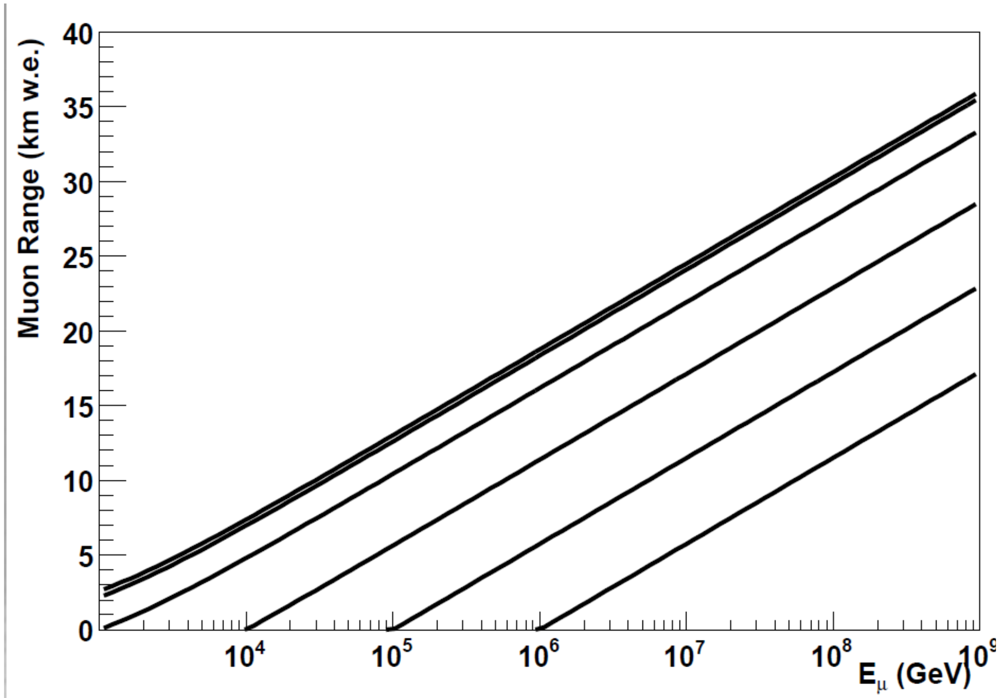

σ_cc(CTEQ4HJ)/σ_cc(CTEQ4D)
E_ν [GeV]


dE/dX (GeV cm^2/g)
1
10^-1
10^-2
10^-3
0
1
2
3
4
5
log_10(MuonEnergy / GeV)
ionization
bremsstrahlung
photo-nuclear
pair production
total

muon range

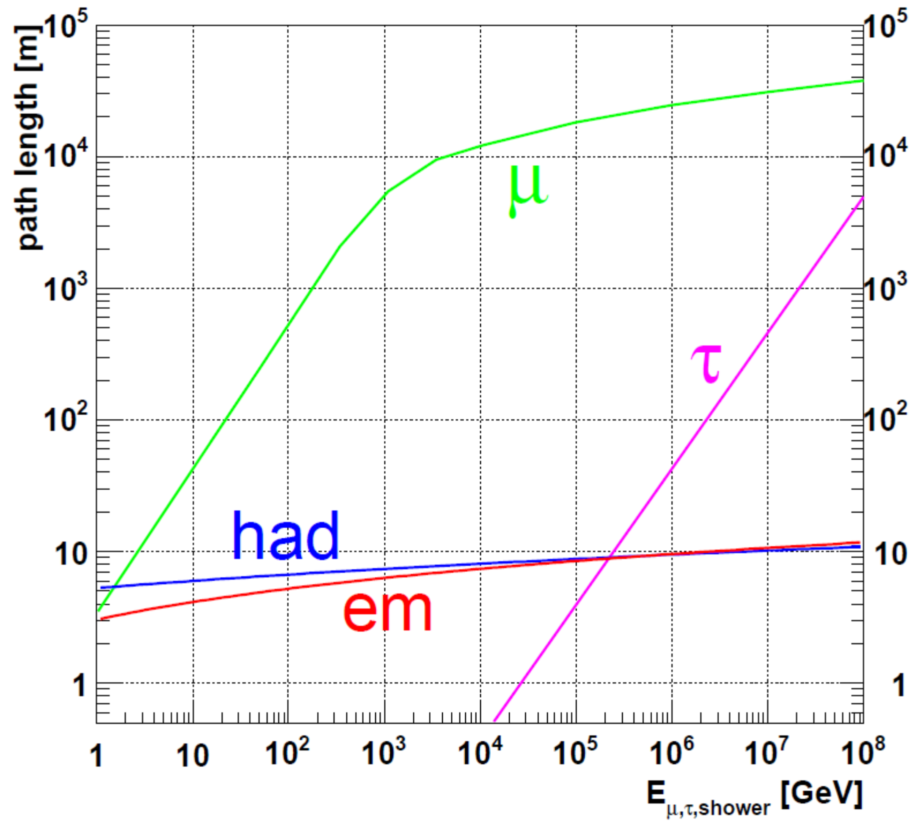


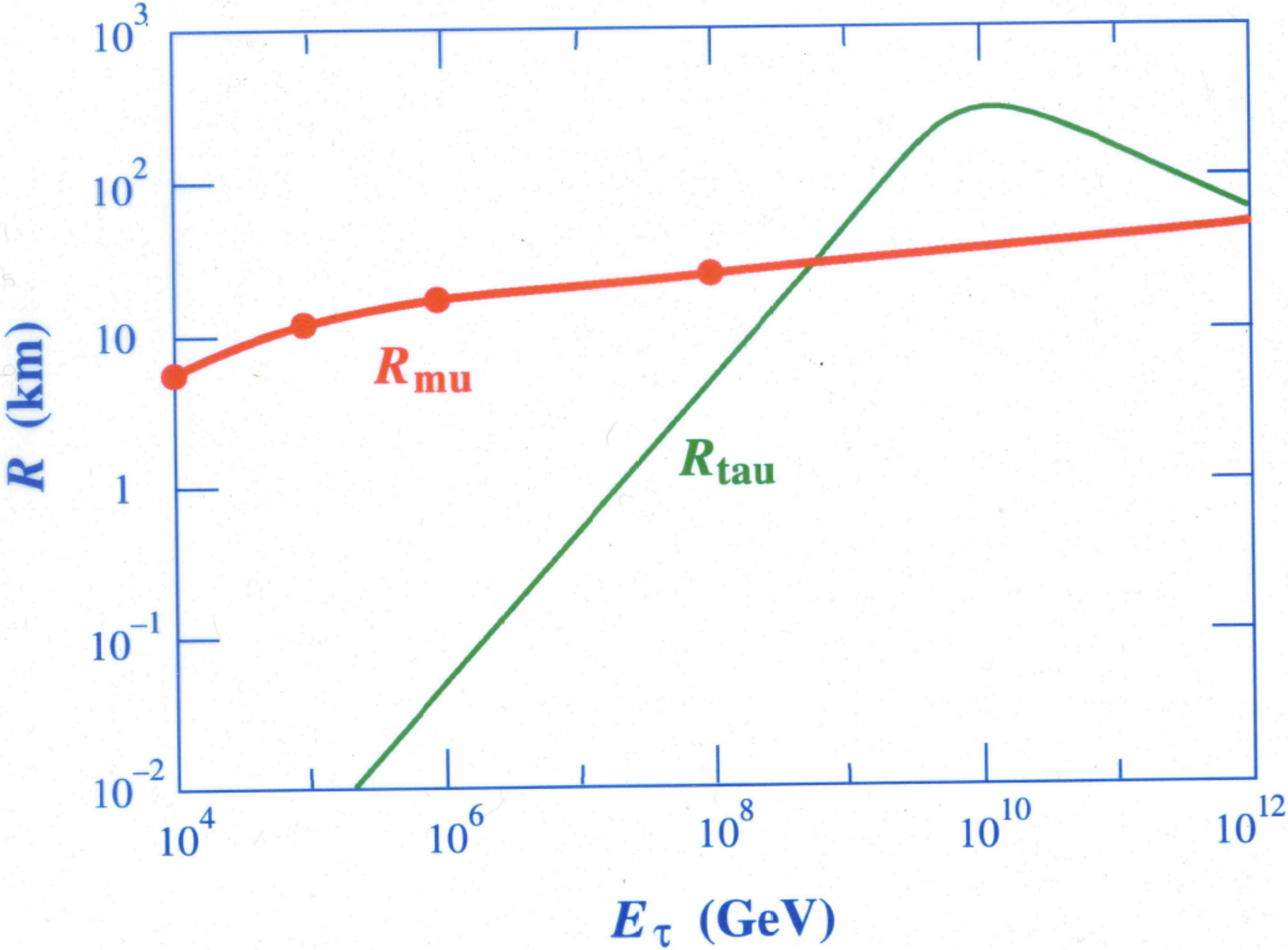
average displacement [mwe]
energy [GeV]
dE/dx=a+bE
a=0.217798 [GeV/mwe],
b=0.000520421 [1/mwe]



← muon range versus energy for detector threshold 1-10^6 GeV

pathlength versus energy →





10^3
10^2
10
1
10^{-1}
10^{-2}
R (km)
R_{mu}
R_{tau}
10^4
10^6
10^8
10^{10}
10^{12}
E_τ (GeV)

neutrino and muon area

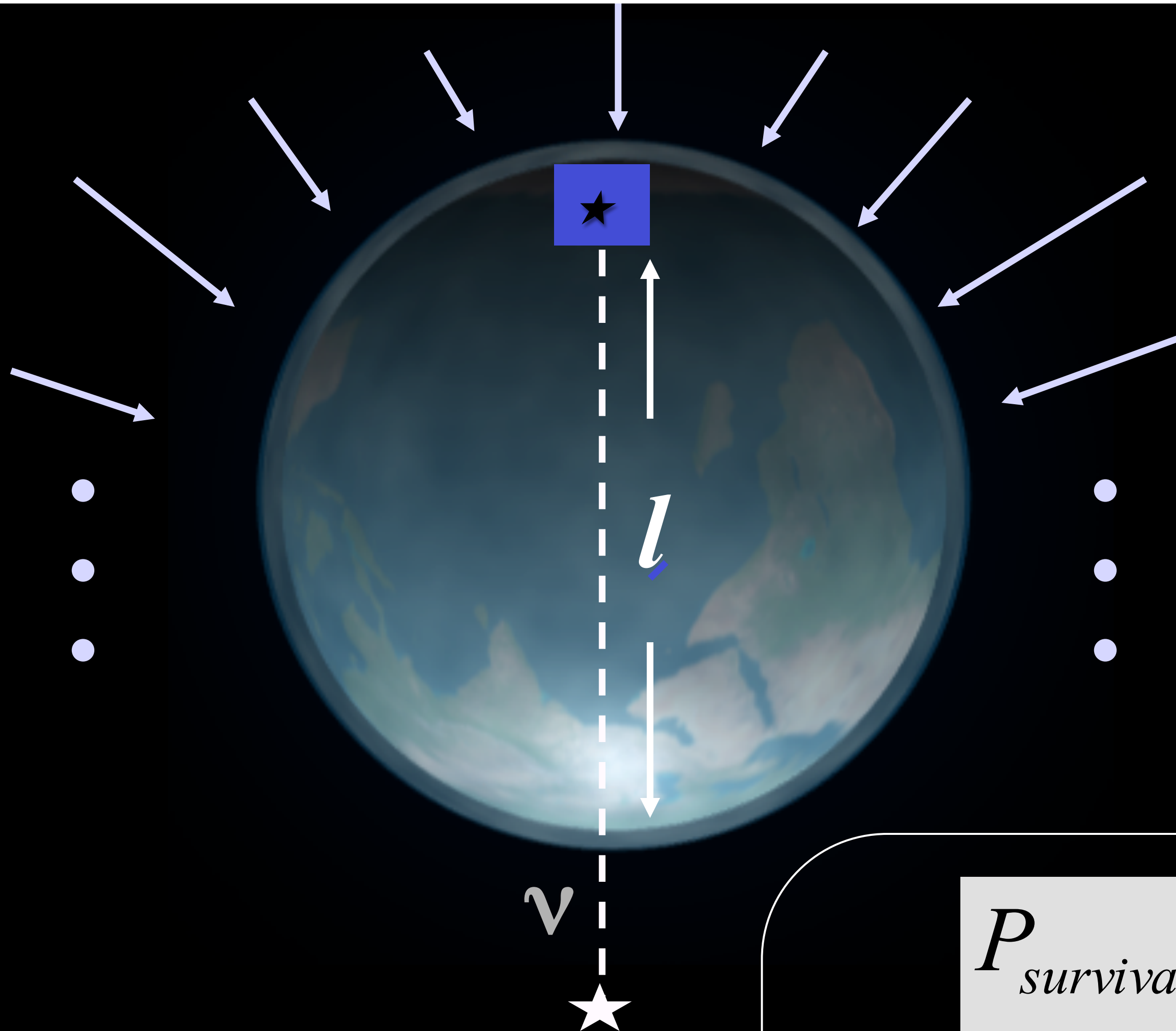
$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu \to \mu} \times \Phi_\nu$$

$$P_{\nu \to \mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_\nu = P_{\nu \to \mu} \; A_\mu$$

the earth as a cosmic ray muon filter



$$P_{survival} = \exp - \left(l / \lambda_\nu \right)$$

$$\lambda_\nu^{-1} = n \sigma_\nu \left(E_\nu \right)$$

$$n = \rho N_A$$

a neutrino of 70 TeV has an interaction length equal to the diameter of the earth

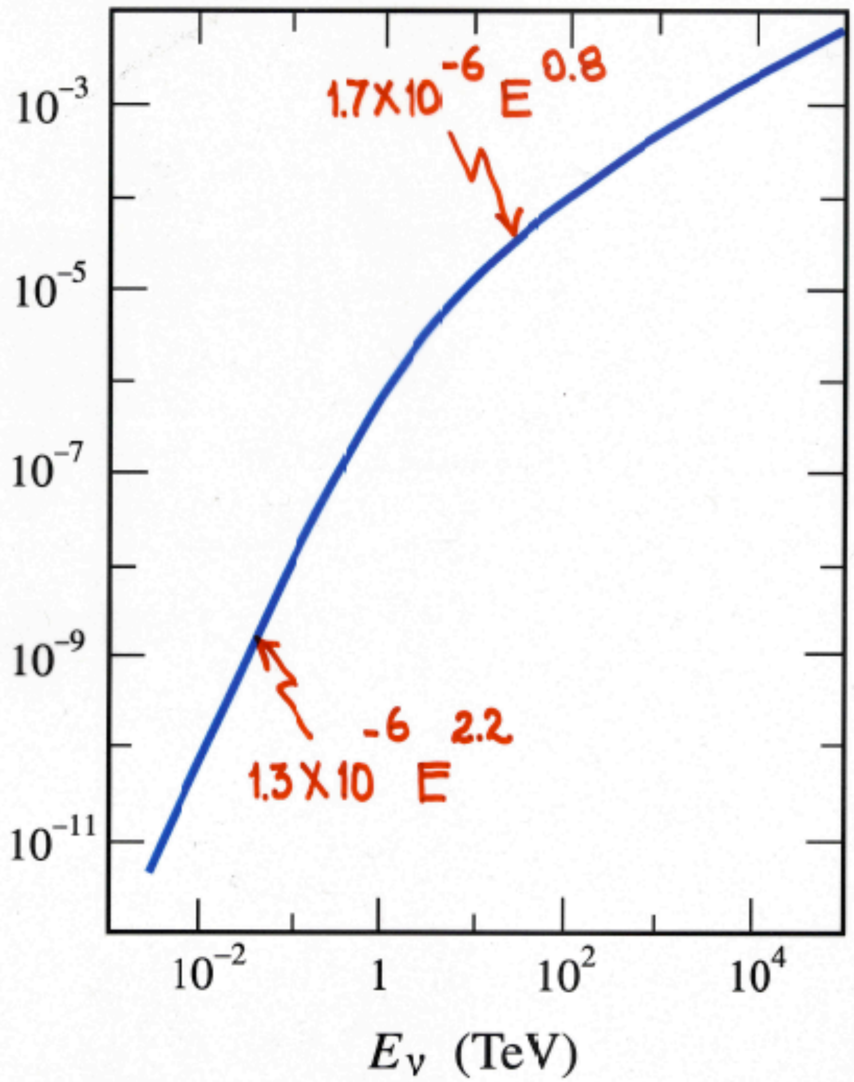
neutrino and muon area

$$events = A_\nu \times \Phi_\nu$$
$$= A_\mu \times P_{\nu\rightarrow\mu} \times \Phi_\nu$$

$$P_{\nu\rightarrow\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_\nu \rightarrow A_\nu = P_{\nu\rightarrow\mu} \; P_{survival} \; A_\mu$$

- $P_{\nu \to \mu} = \text{density} \cdot \sigma_\nu(E) \cdot R_\mu(E)$



- $N_{events} = \text{AREA} \int \frac{dN_\mu}{dE} P_{\nu \to \mu} \, dE$

effective telescope area at 100 TeV

$$area \times P_{\mu\rightarrow\nu} (= \frac{\lambda_\mu}{\lambda_\nu} = nR_\mu\sigma_\nu \cong 10^{-6}\ E_{TeV})$$

- AMANDA ~ ANTARES ~ 1 m^2
- IceCube 22 strings 30 m^2
- IceCube 80 strings 100 m^2