WISCONSIN ICECUBE
PARTICLE ASTROPHYSICS CENTER

Neutrino Telescopes & the IceCube Observatory

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MCTP Mesoamerican Centre for Theoretical Physics
Centro Mesoamericano de Física Teórica

lectures outline

- **neutrino telescopes & the IceCube Observatory**
- observing the Universe
- neutrino observations
- cosmic ray observations
- astrophysics & interdisciplinary sciences

outline

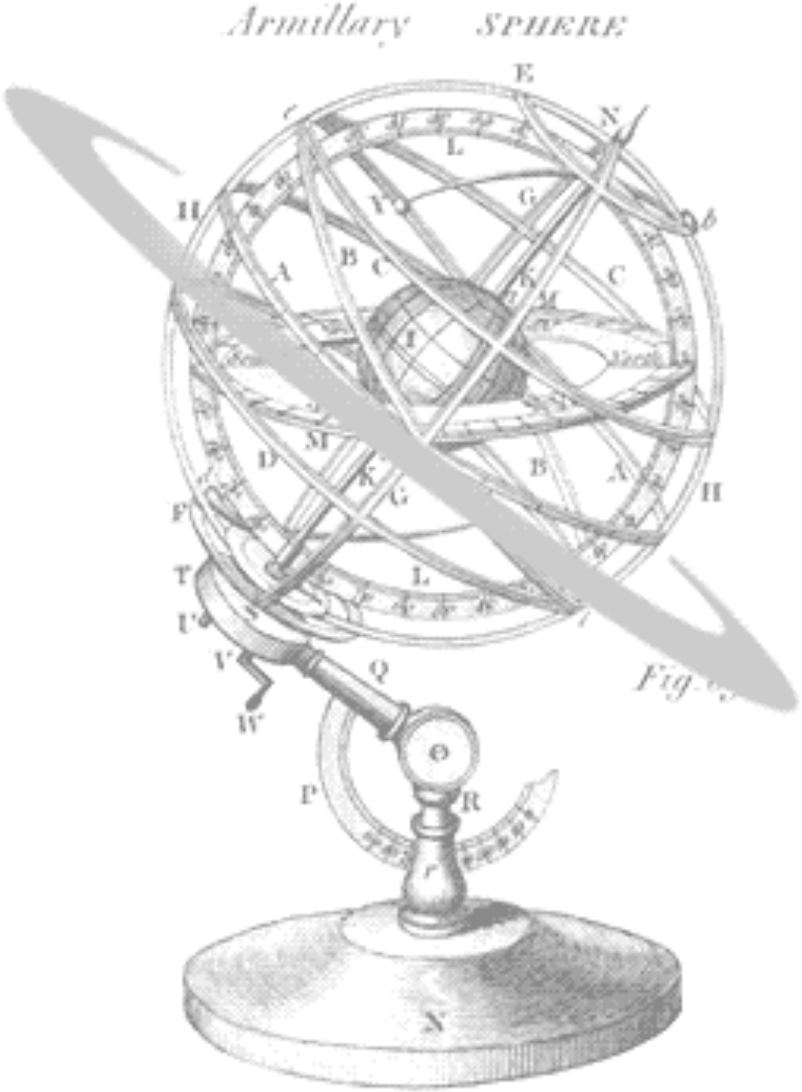
an introduction to the physics of IceCube

- observational astronomy
- cosmic rays and neutrinos
- detecting neutrinos
- detection techniques
- current experiments

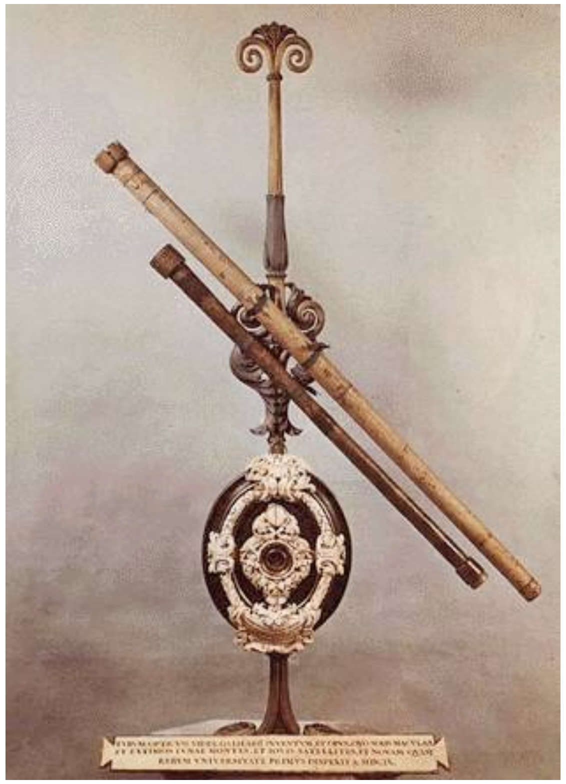
observational astronomy
the observation of the Universe

- **optical astronomy** started in 1610 when a spyglass was pointed to the sky

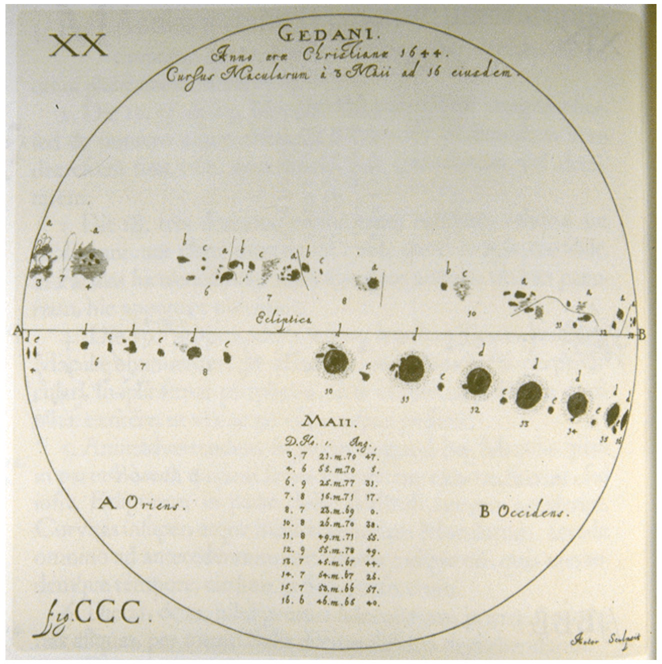

Galileo portrait in crayon by Leoni.



Telescope

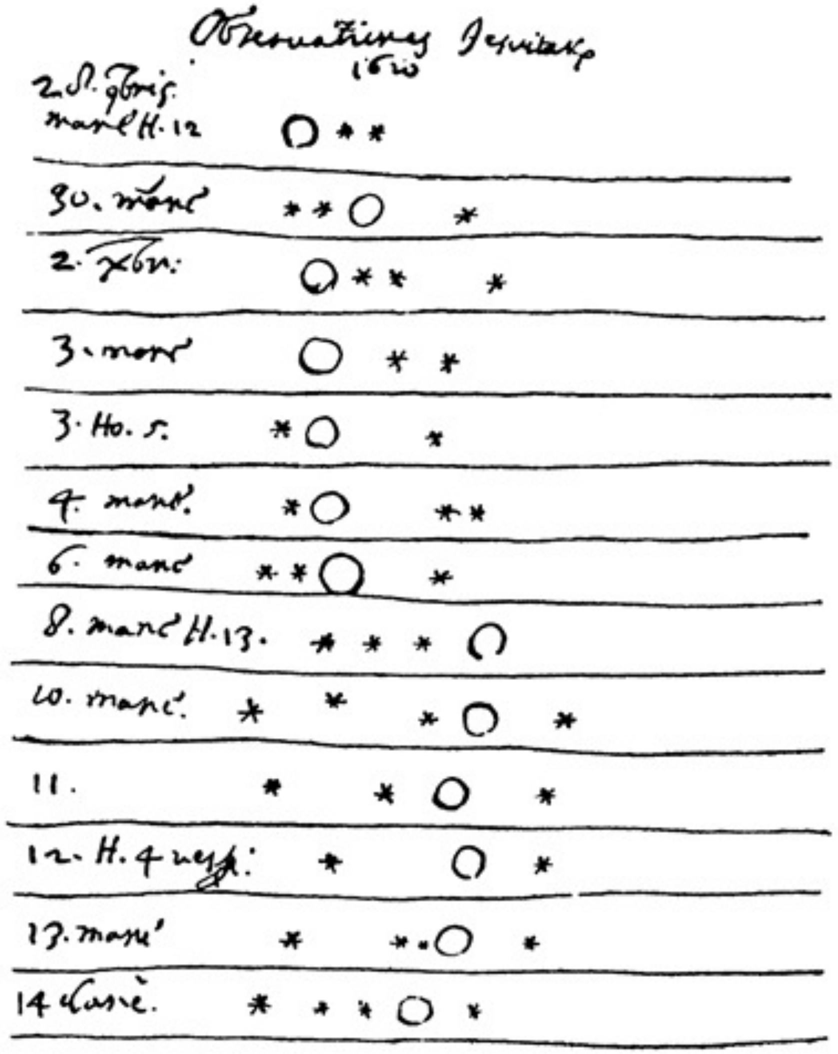


observational astronomy
optical astronomy

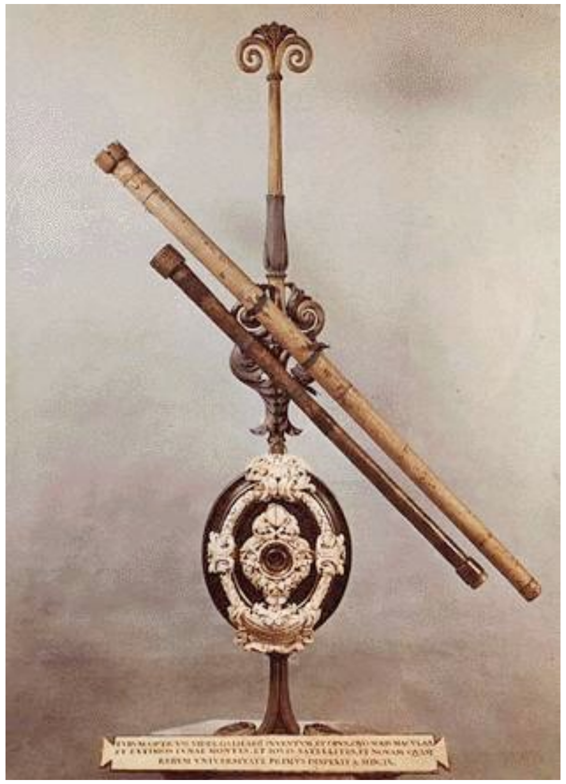


Sunspots

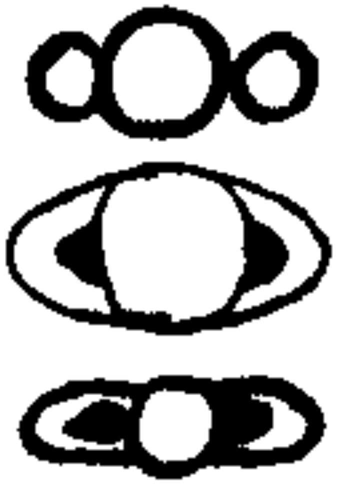
Jupiter's moons



Telescope

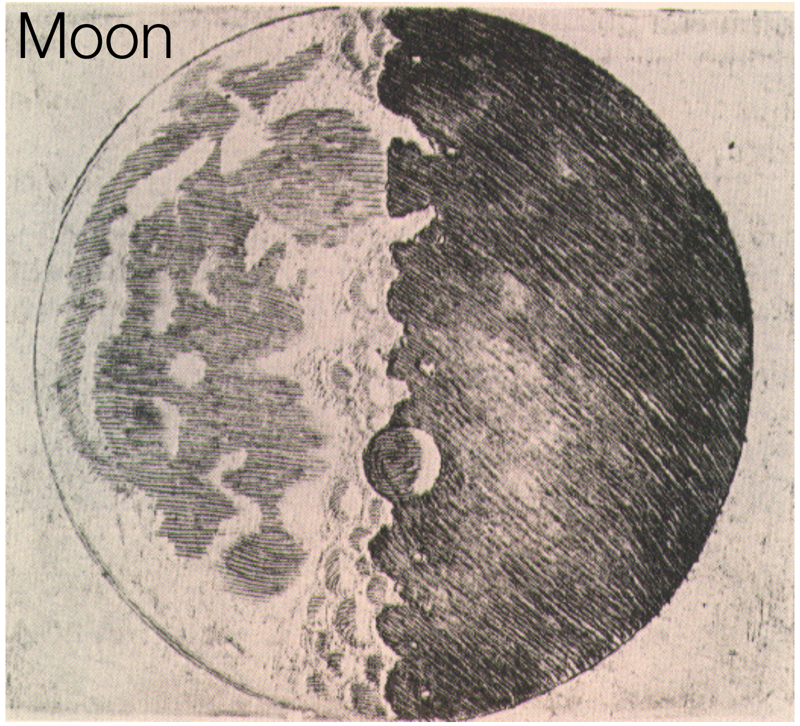


Saturn



These are sketches of three drawings Galileo made of Saturn through his primitive telescope. ("New Worlds," Couper & Henbest, p.86.)

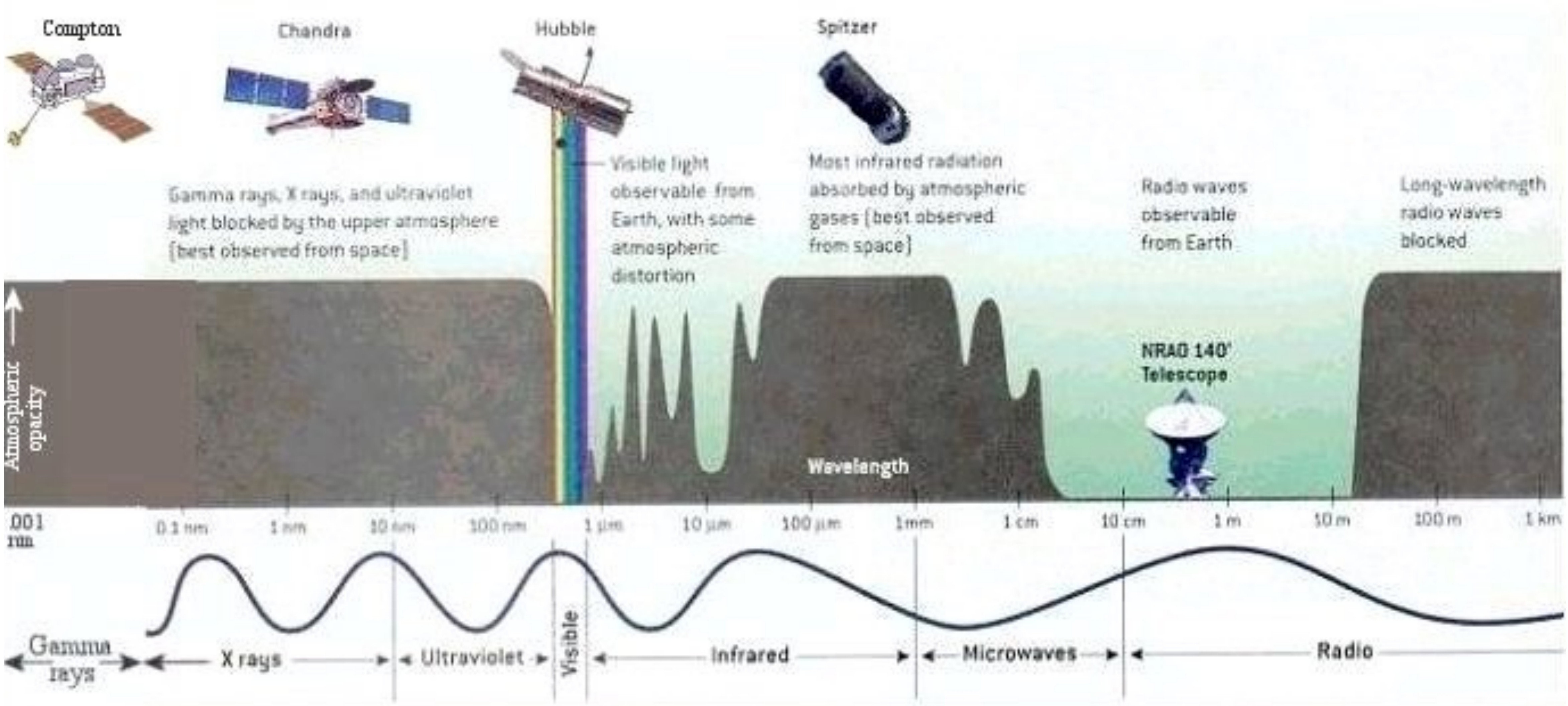
Moon



observational astronomy

beyond light: electromagnetic spectrum

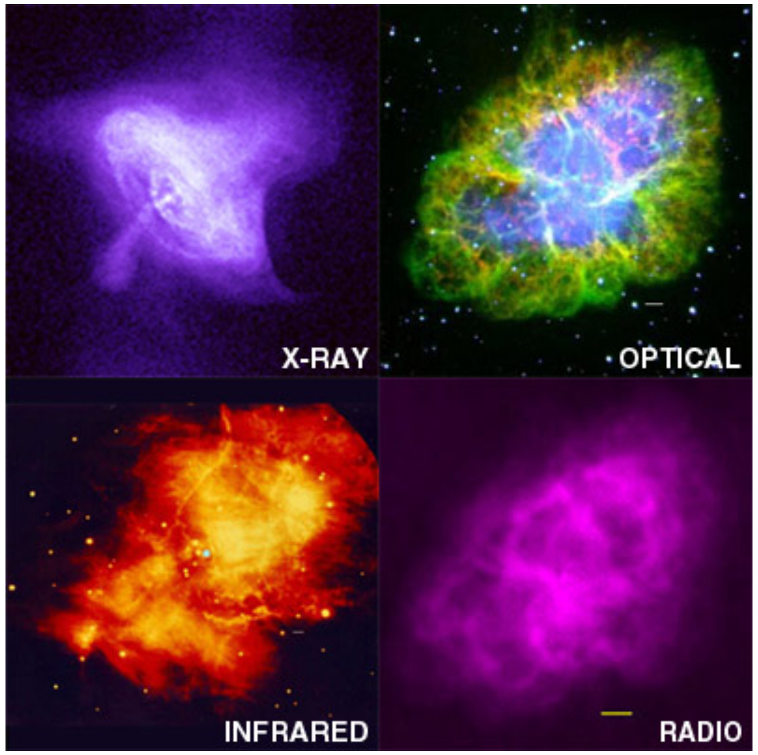
- **observational window** at the Earth’s surface of the electromagnetic radiation



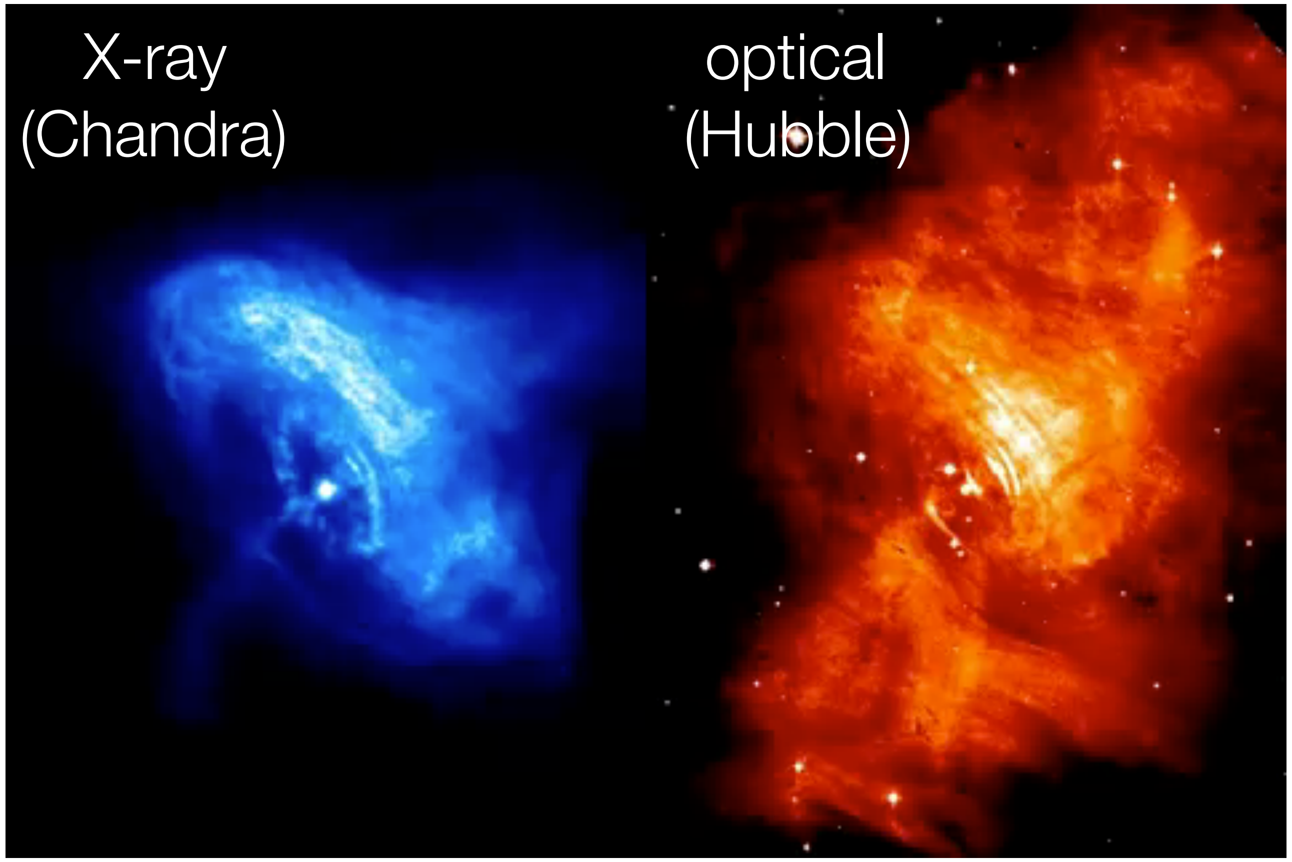
observational astronomy

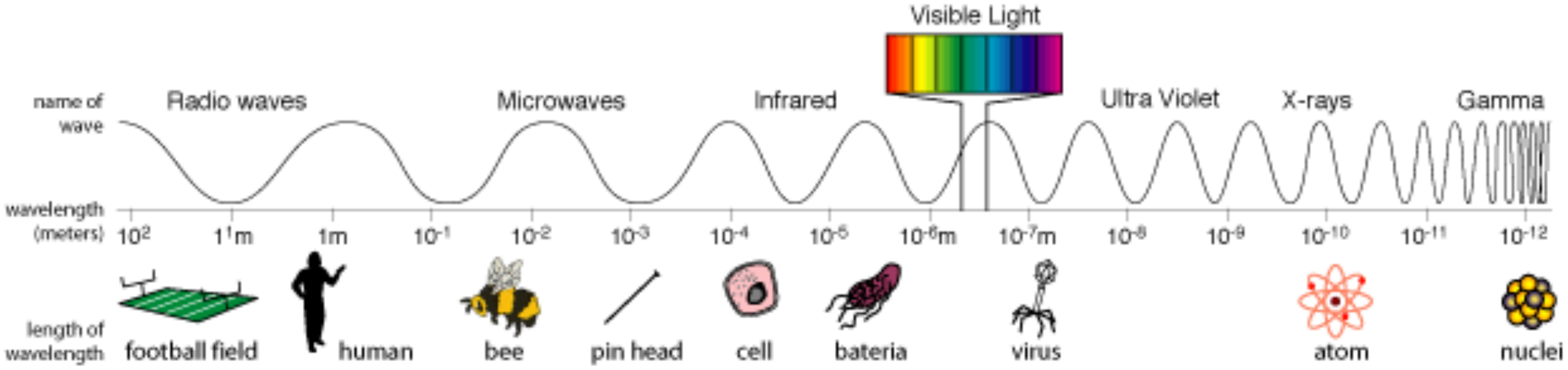
beyond light: electromagnetic spectrum

- visible light is only one **small portion** of the vast electromagnetic spectrum
- accelerated electrons swirling in magnetic fields



Crab Nebula





observational astronomy

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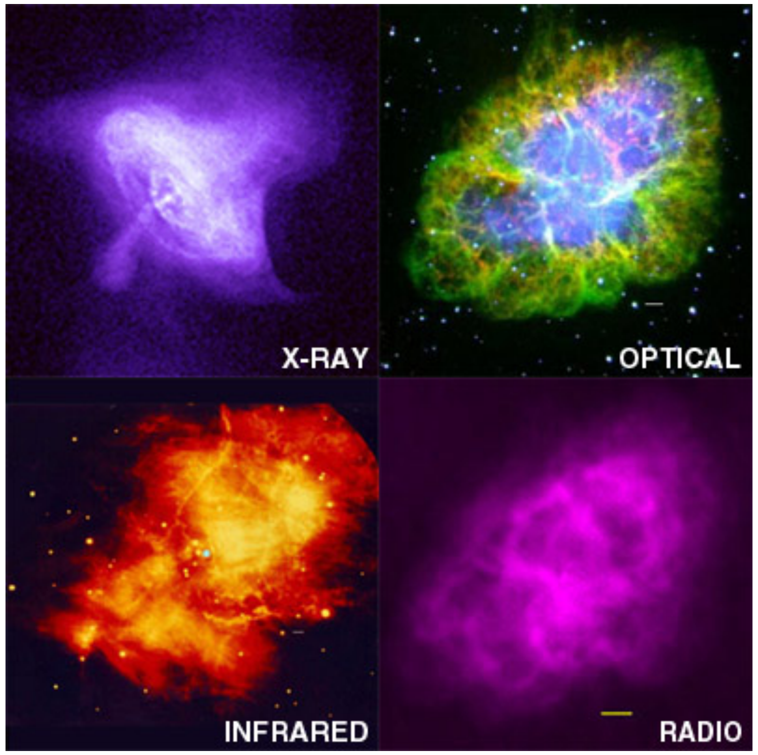

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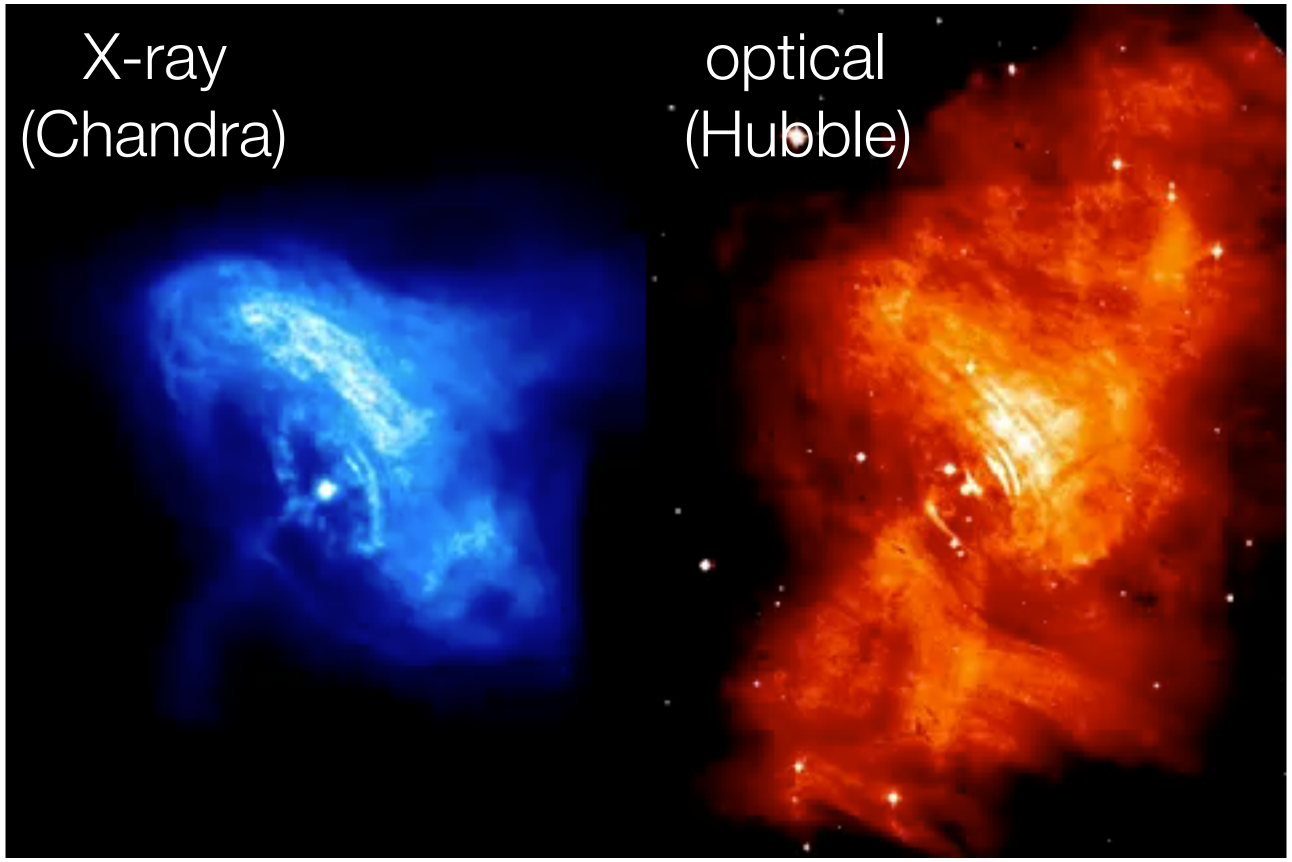
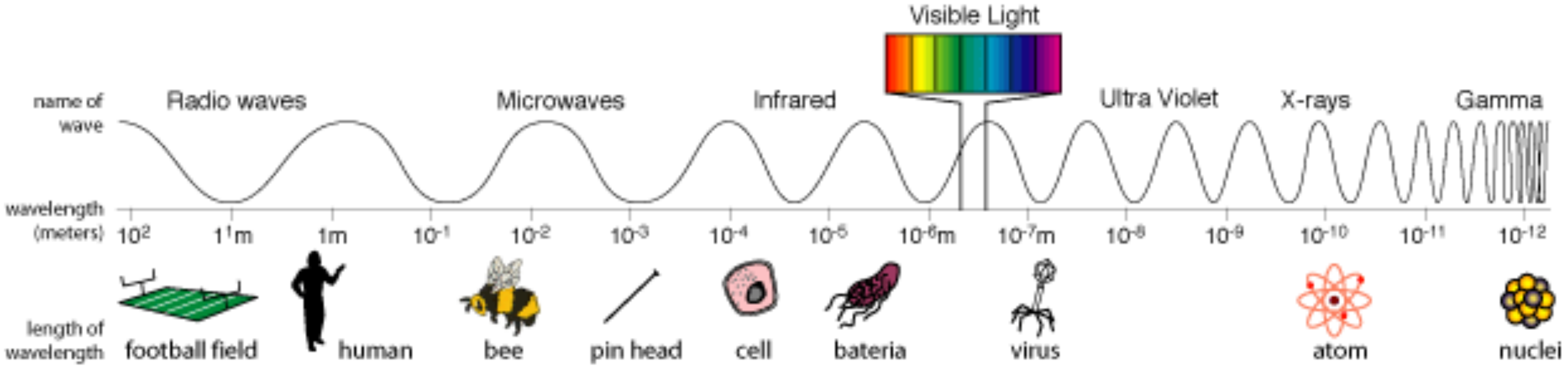
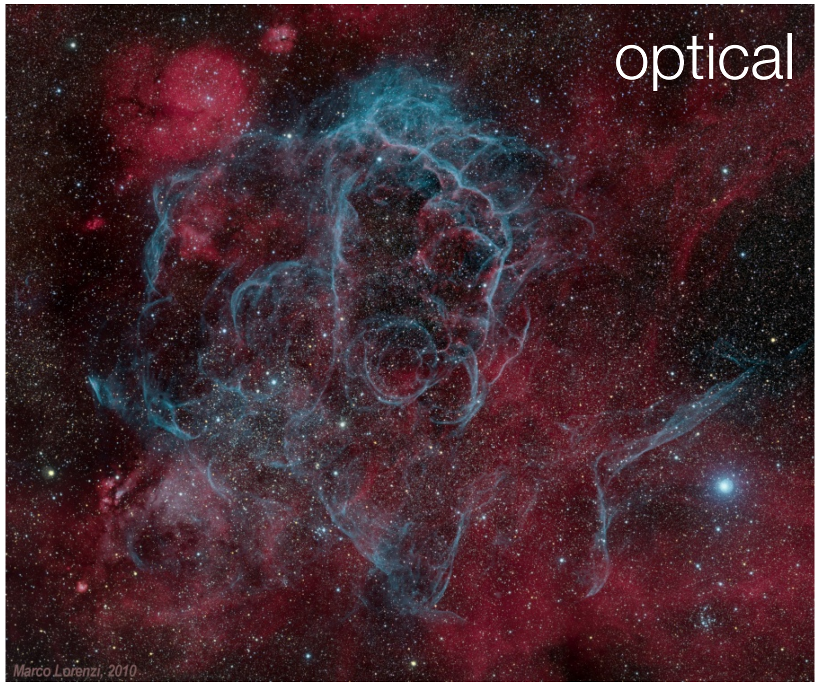


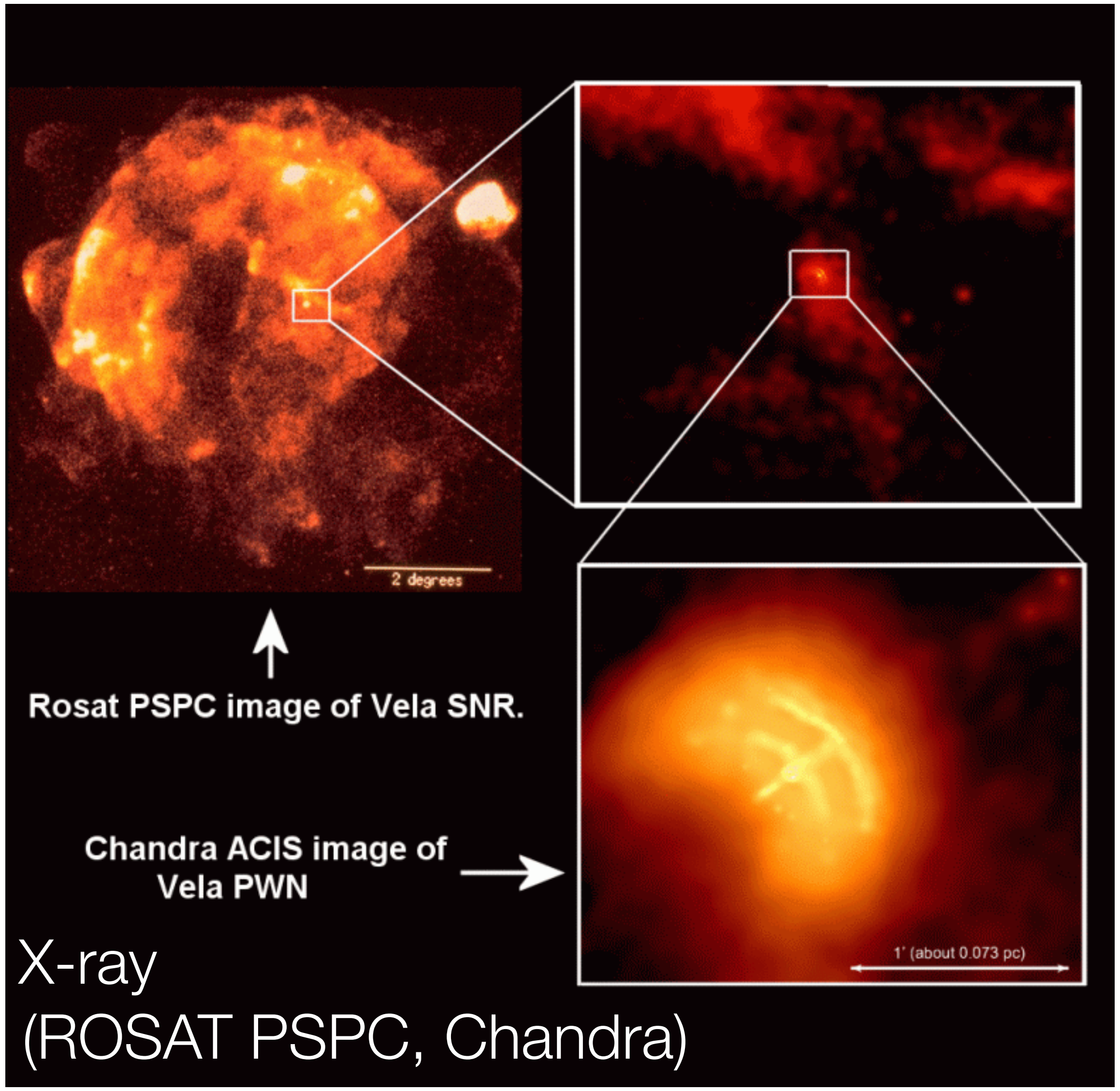


observational astronomy

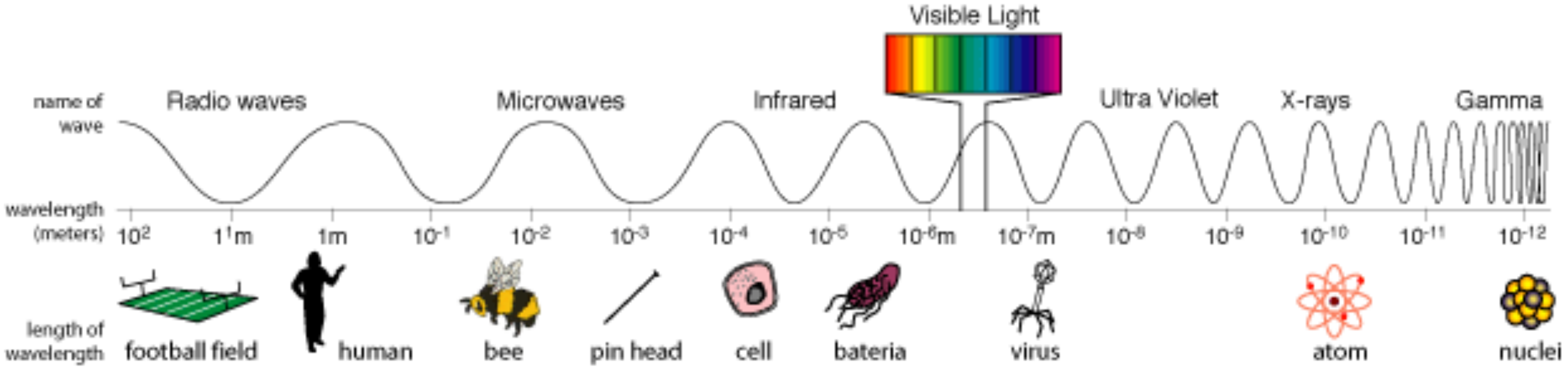
beyond light: electromagnetic spectrum

Vela Supernova Remnant

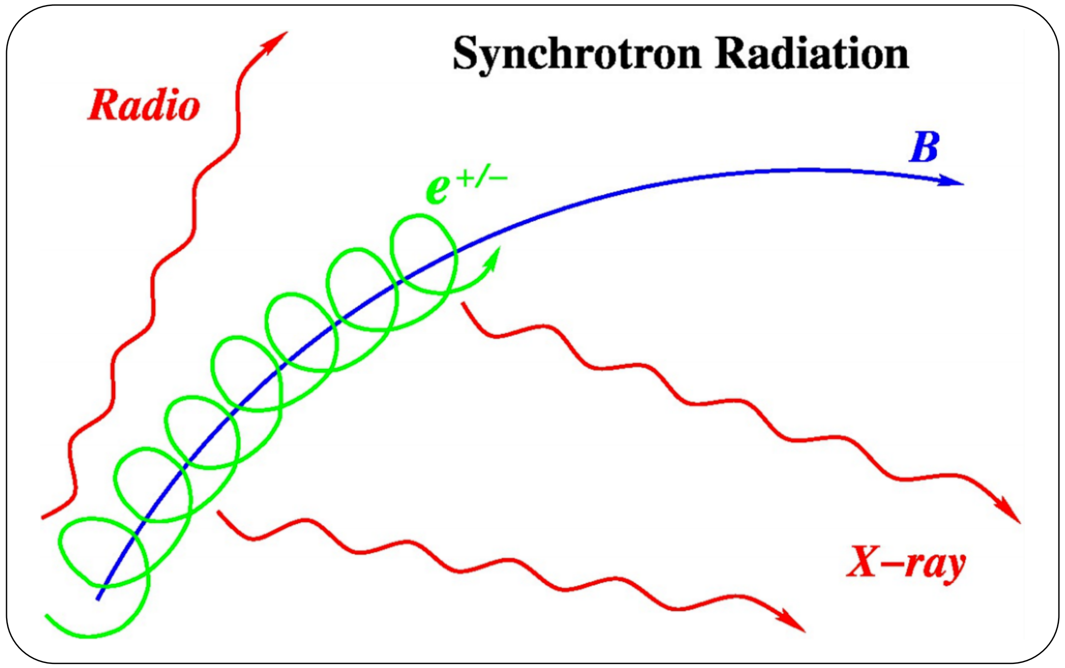




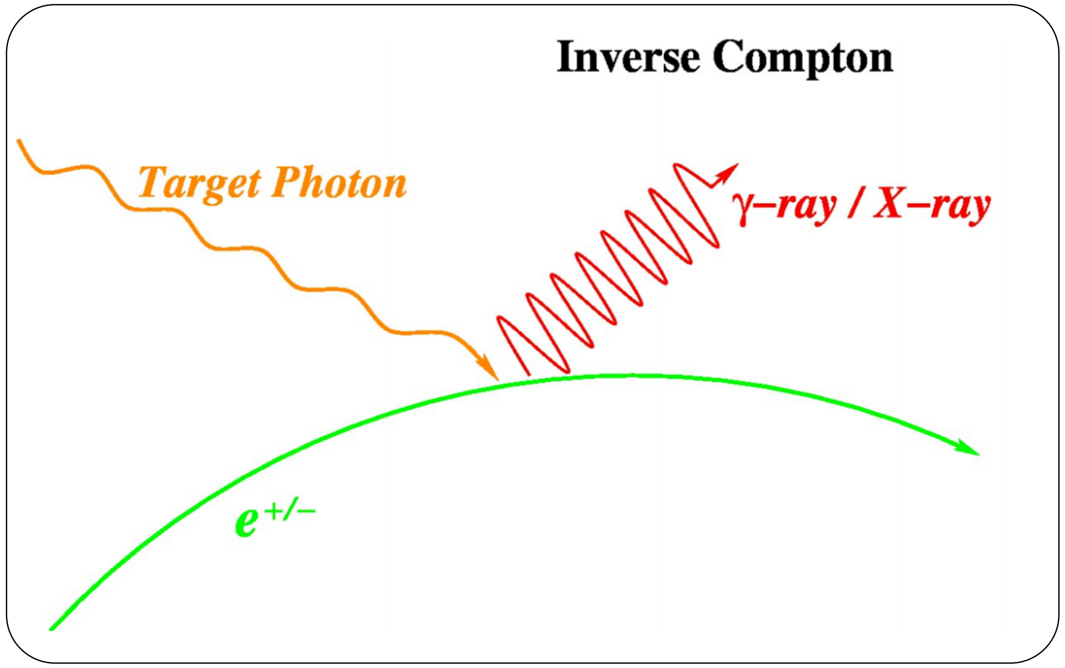
X-ray
(ROSAT PSPC, Chandra)



leptonic processes

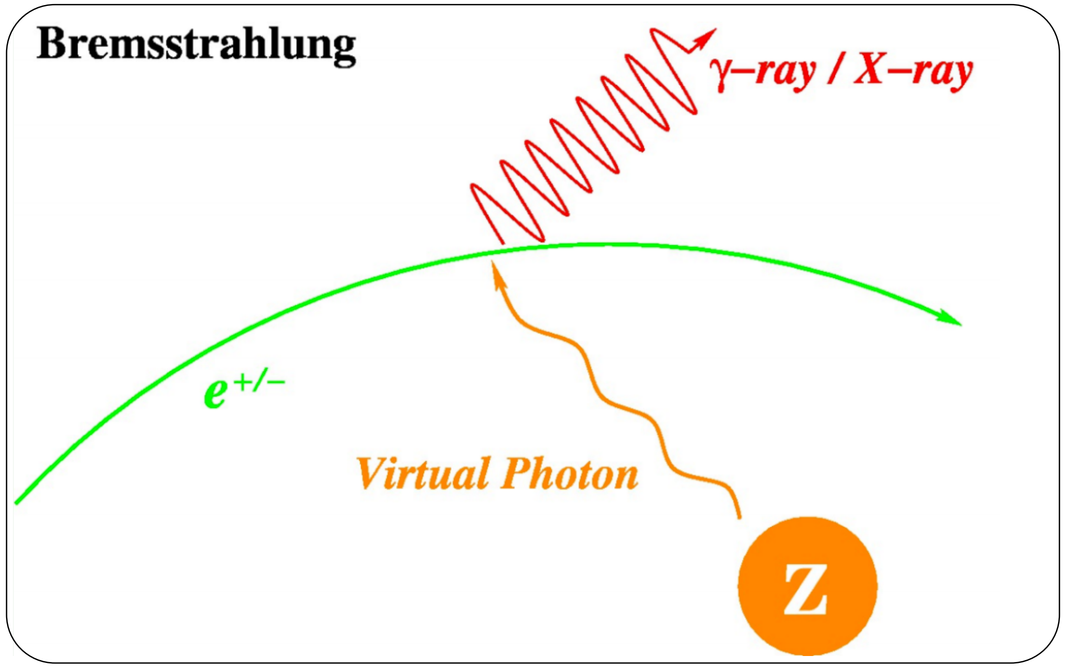


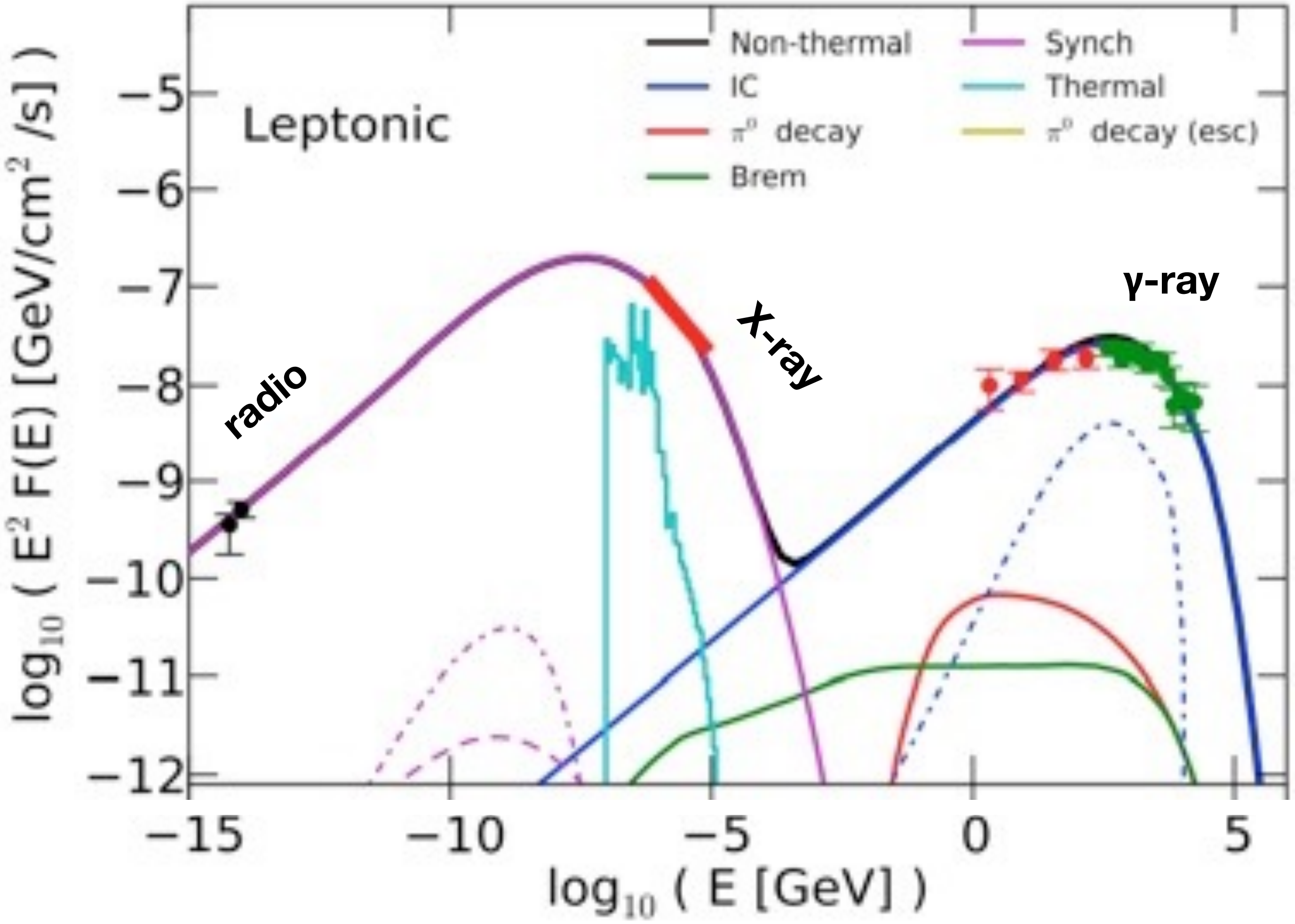
electrons interacting with magnetic fields



electrons interacting with photon fields

electrons interacting with matter





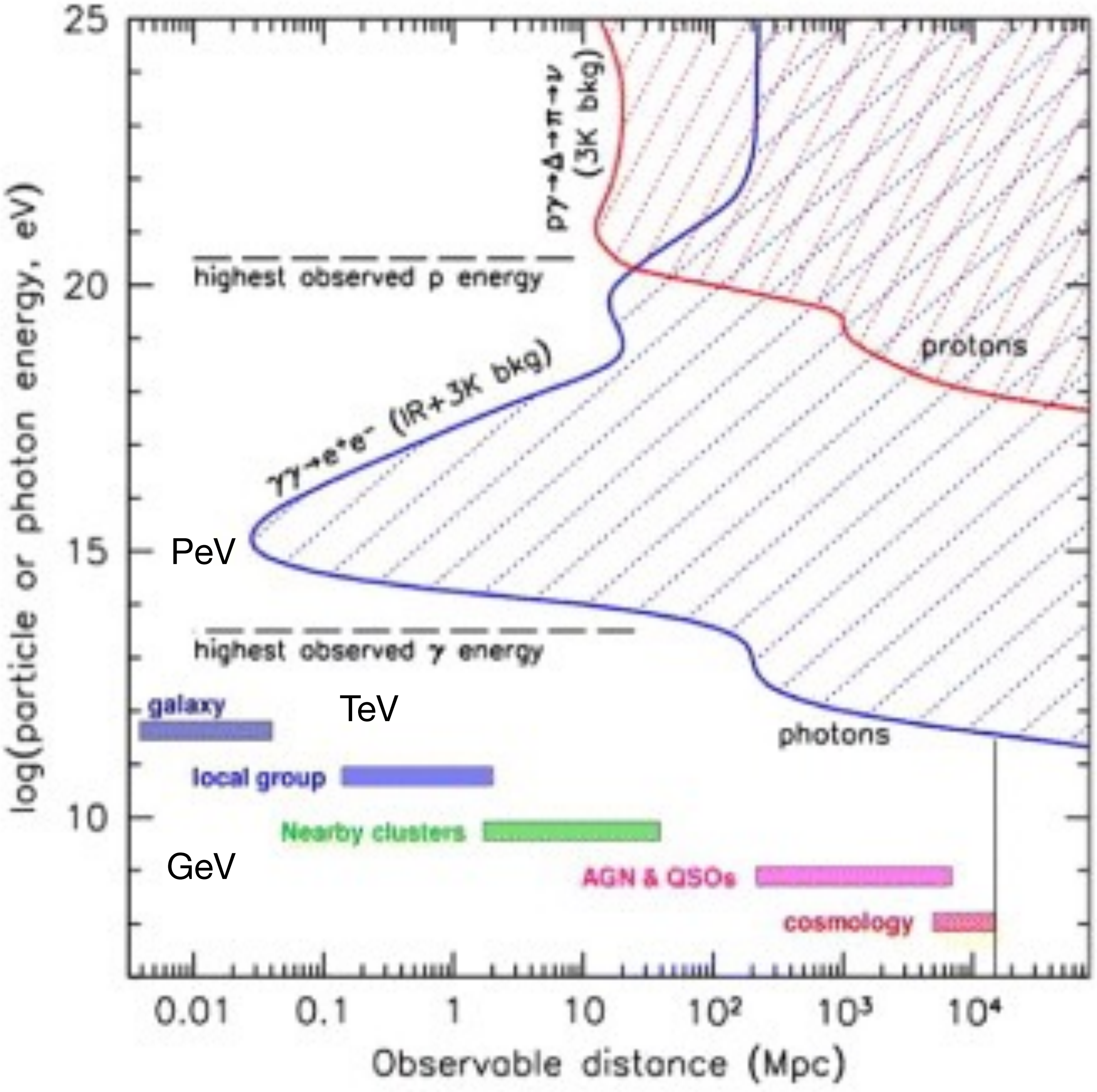
multi-wavelength spectrum of young SNR Vela Jr.

observational astronomy

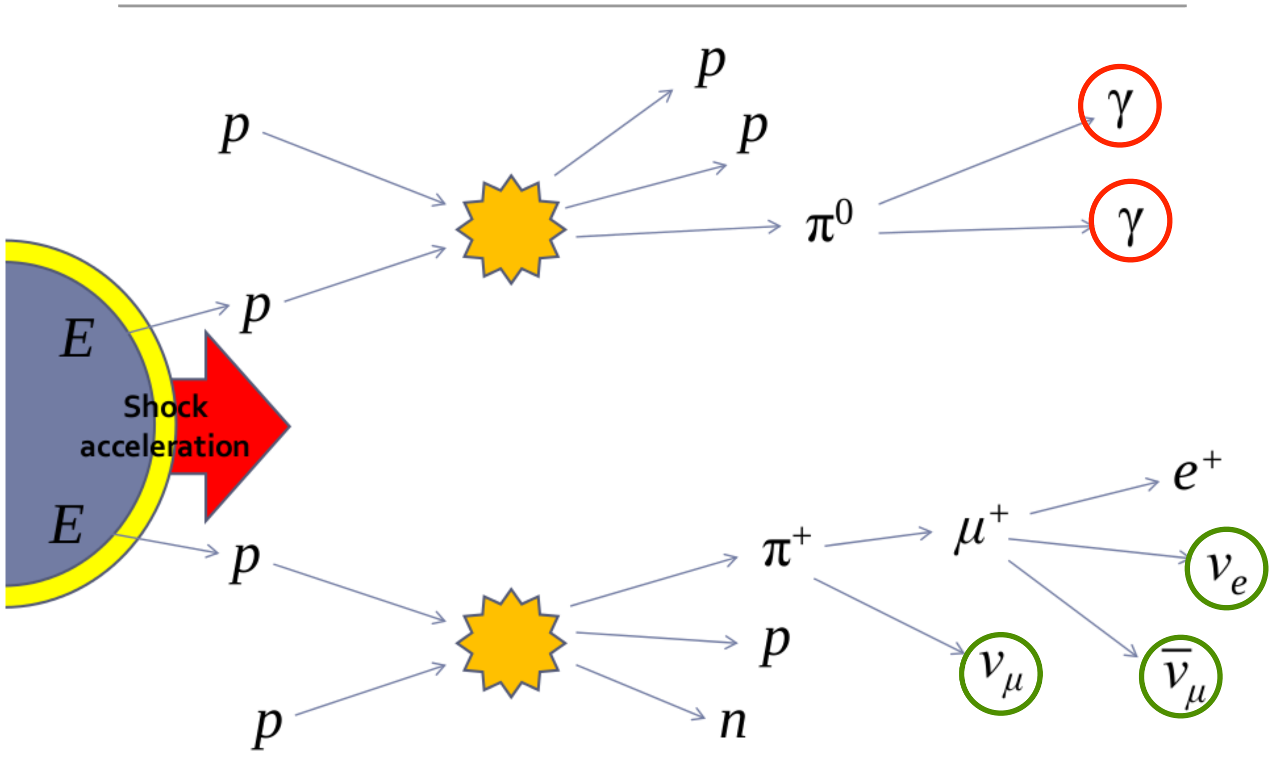
gamma rays & depth of observable Universe

- neutral particles
- point back to sources
- limited observable distance
- gamma rays absorbed in space

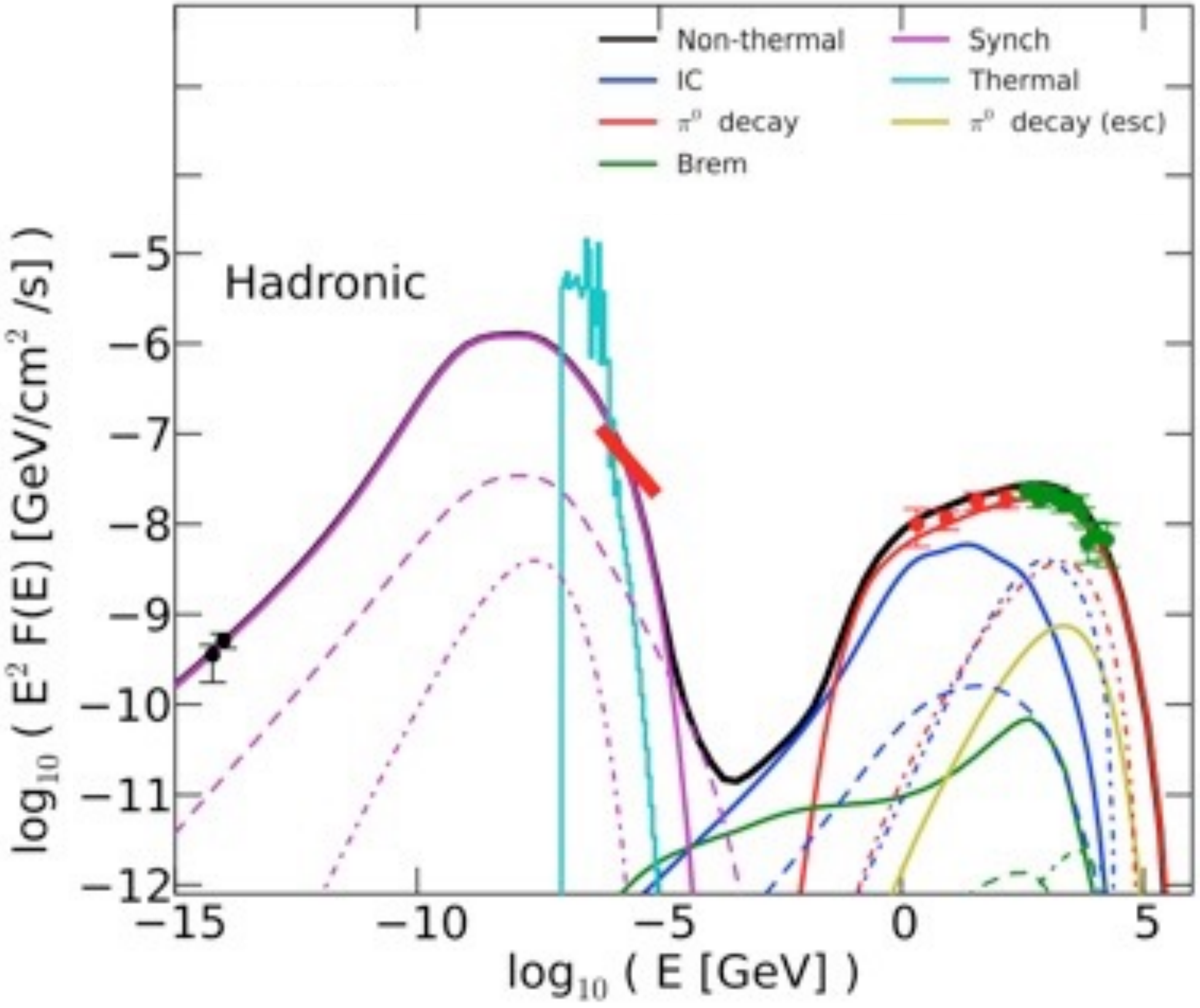
P. Gorham



hadronic processes



Greg Vance (UW-Madison REU)



multi-wavelength spectrum of young SNR Vela Jr.

- protons and atomic nuclei interacting with matter: **cosmic rays**
- **photon multi-wavelength** approach to pin-point sources of cosmic rays
- **gamma rays** & **neutrino** as cosmic messengers to probe into the origin of CRs

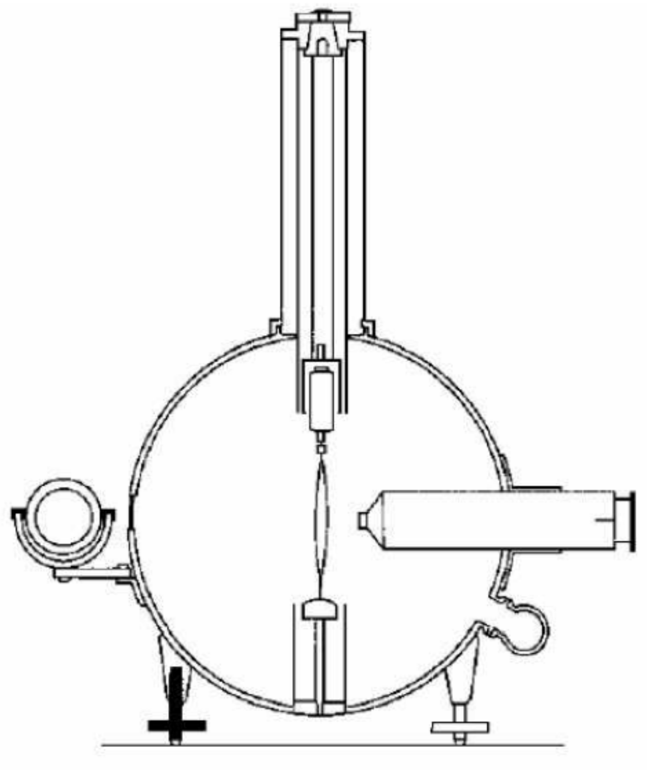
cosmic rays

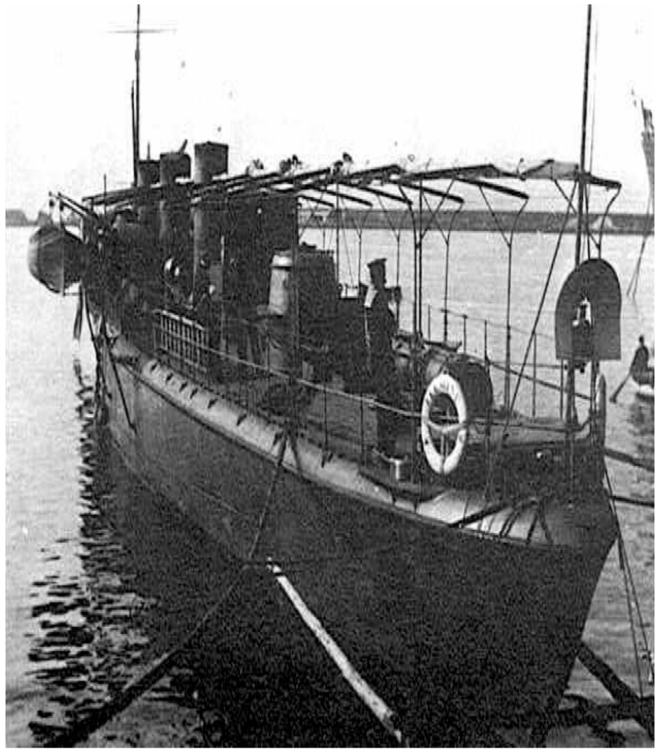
more than 100 years from their discovery

Theodor Wulf (1868-1946)

Domenico Pacini (1878-1934)

Victor Francis Hess (1883-1964)



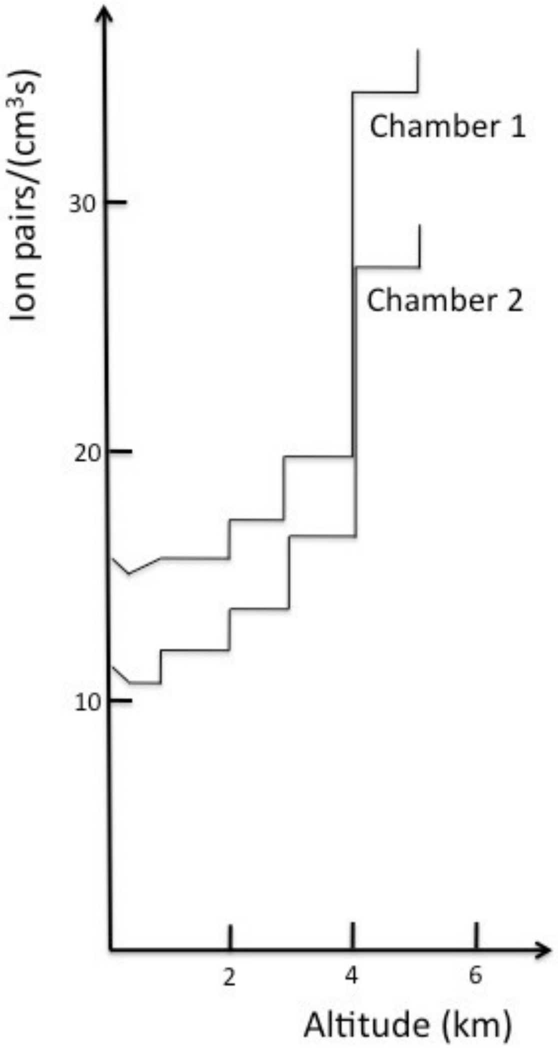


1910: radiation at the bottom and the top of Eiffel Tower. Lower decrease than expected

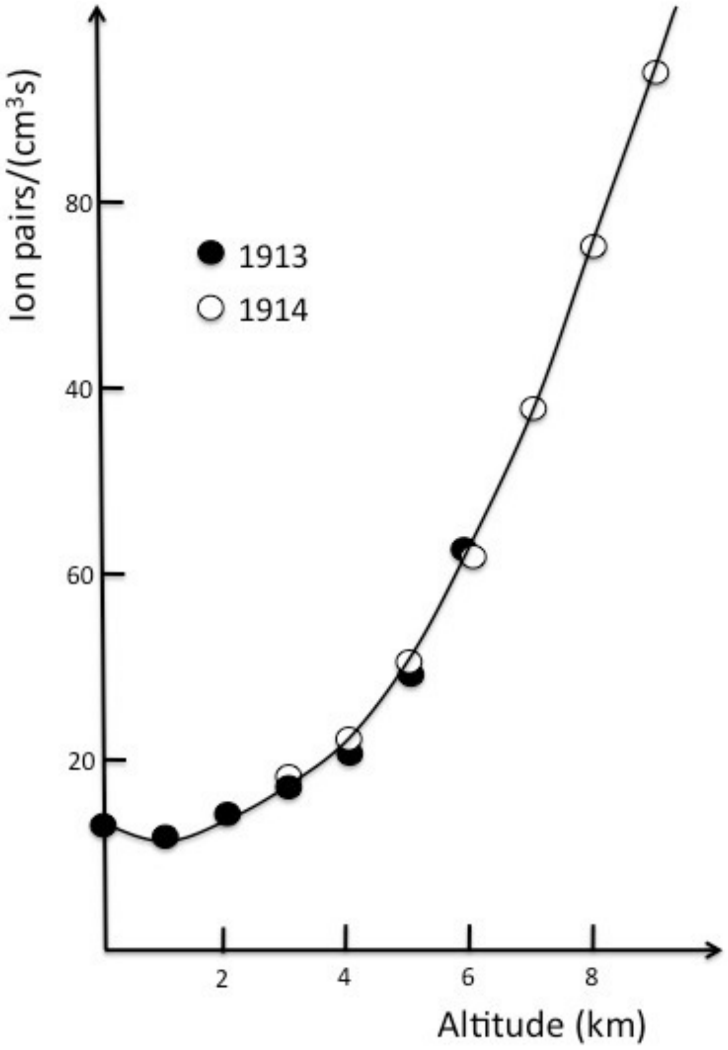
1910-11: radiation over and below sea surface. Decrease underwater. Seasonal variations.

1911-12: balloon measurements up to 5,300 meters. Radiation increased 4 times.

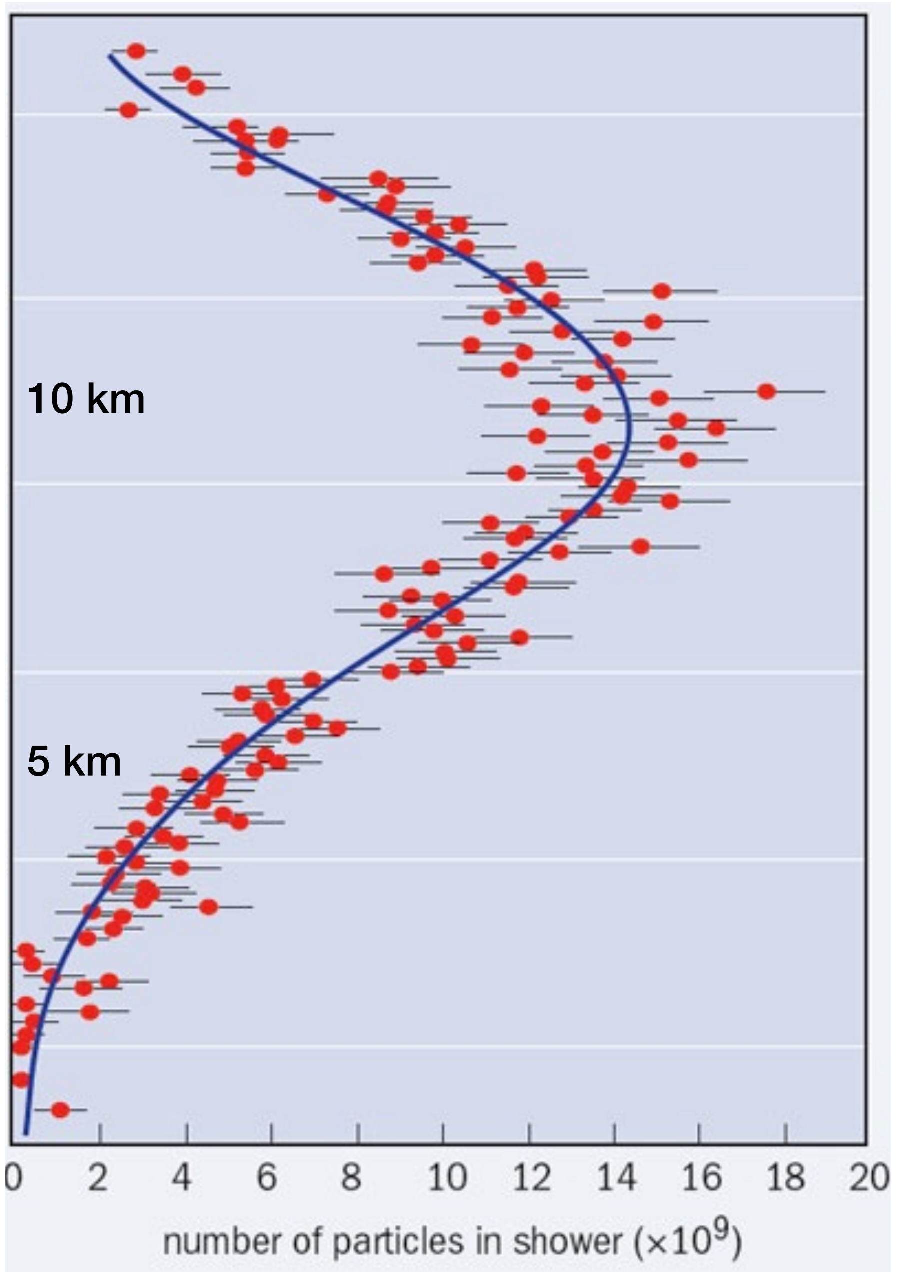
cosmic rays
bombarding Earth from space



Hess (1912)

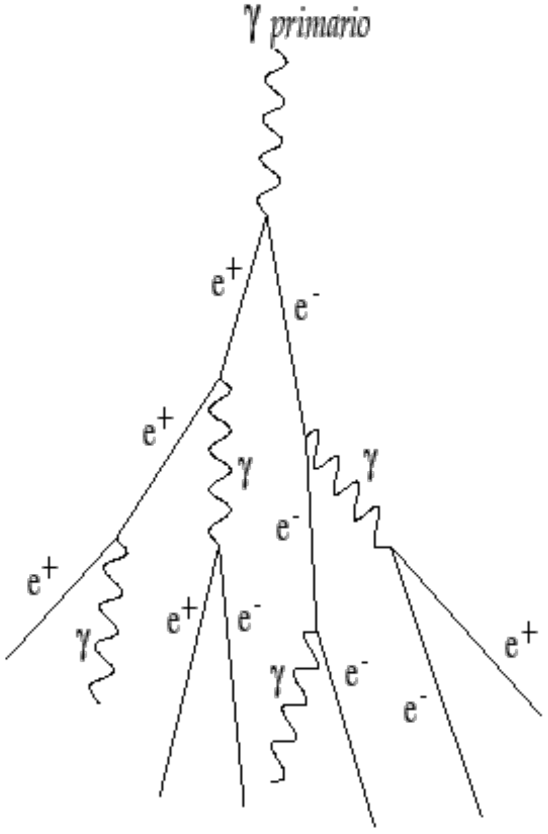


Kolhörster (1913-14)



history of cosmic ray physics

penetrating cosmic radiation



- the term **cosmic ray** was introduced by Millikan (1920s)

  who did an extensive measurement campaign
- Millikan proposed energetic photons (**gamma rays**) produced

  in interstellar space by hydrogen fusion into heavier nuclei
- gamma rays in the atmosphere *produce* electrons via **Compton scattering**
- latitude variation of cosmic ray flux by Clay (1927): **charged particles**
- Bothe & Kolhöster (1929) discovered penetrating charged particles: **not only electrons**
- Rossi (1930) predicted **east-west** effect from geomagnetic deflection: **positive charge**

charge of cosmic rays

east-west effect

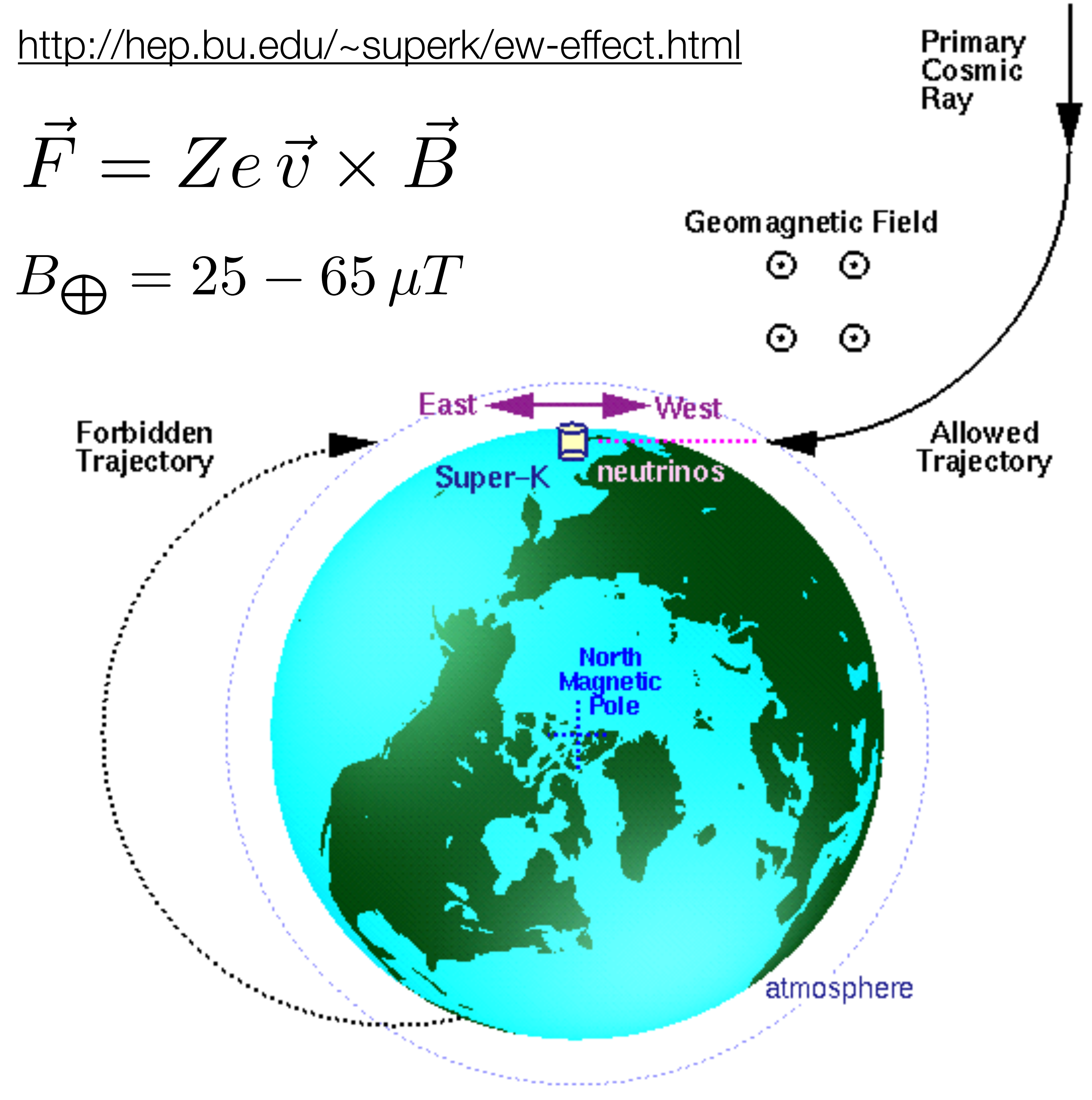
$$r_L \sim \frac{3.3\times 10^4}{Z}\,\frac{E(GeV)}{B(G)}\,m$$

- geomagnetic field effect

- higher cosmic ray flux from west indicate particles are predominantly positive

$$r_L = \frac{p_\perp}{ZeB}$$

- Earth shadow



http://hep.bu.edu/~superk/ew-effect.html

$$\vec{F} = Ze\,\vec{v}\times\vec{B}$$

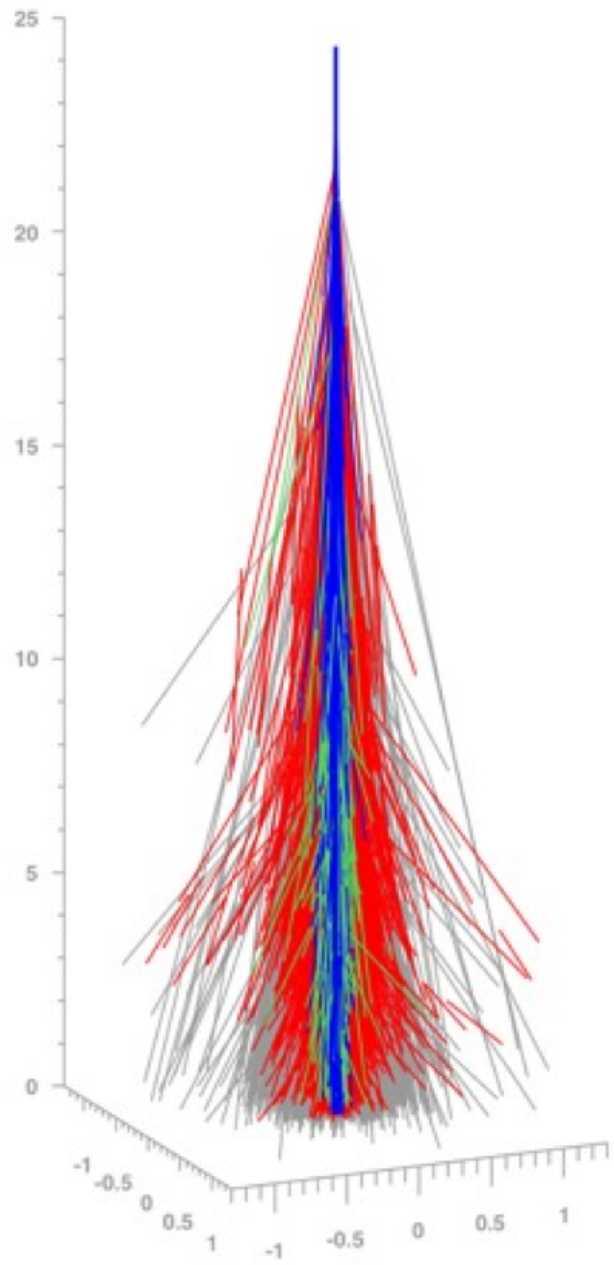
$$B_\oplus = 25 - 65\,\mu T$$

extensive air showers

penetrating cosmic radiation

- **atmospheric air showers** of particles are **extended**
  - while measuring “east-west” effect Rossi noticed coincident far apart signals
  - independently Auger (1937) concluded that primary CR interact in upper atmosphere initiating cascade of **secondary interactions** that reaches ground
- Bhabha & Heitler (1937) explained development of **soft** CR showers as sequence of **γ rays** and **e^-e^+ pairs**
- evidence of **hard** penetrating component of **hadronic** CR showers that can be detected underground

proton-induced shower of 10^{19} eV

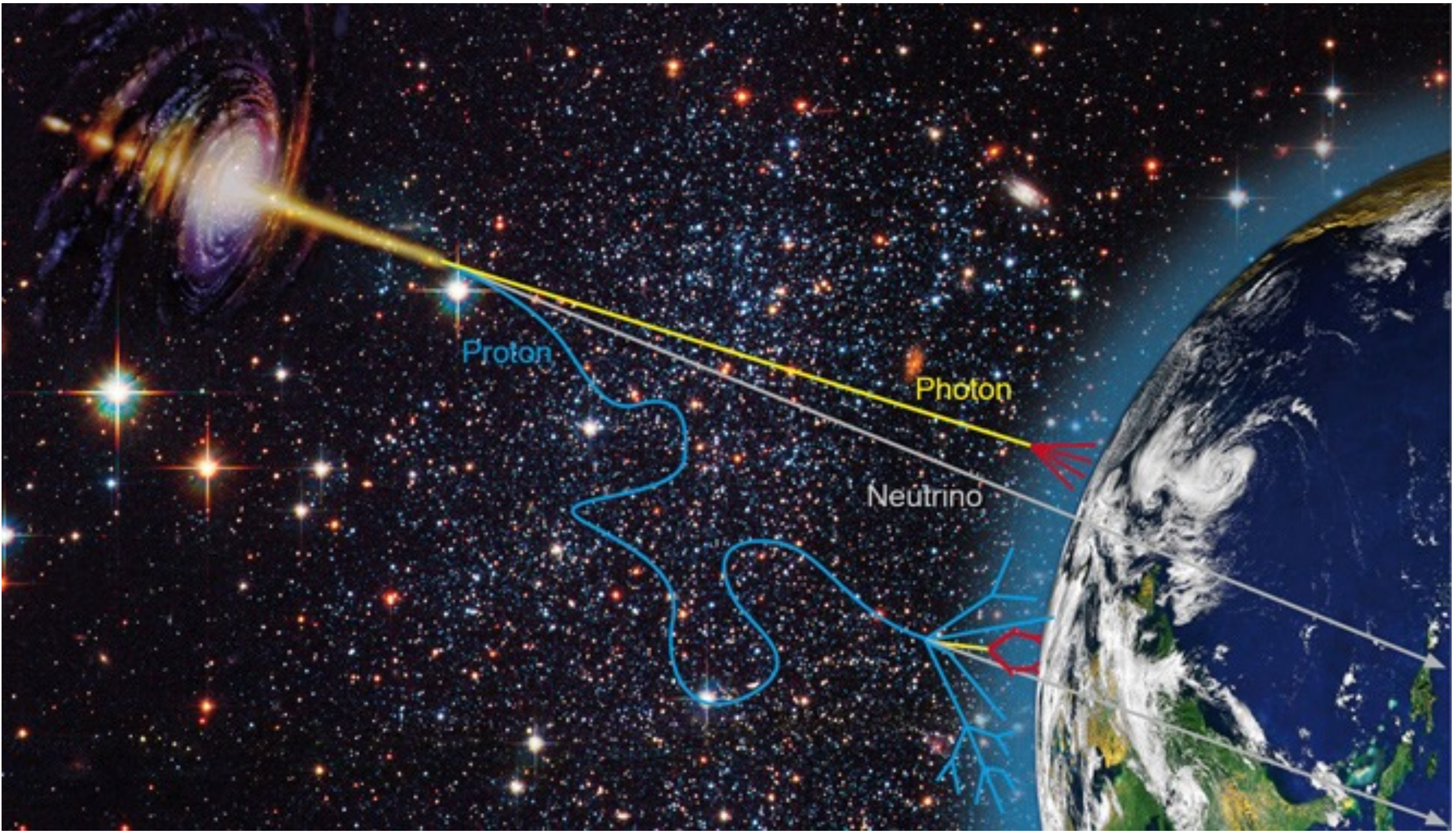


observational astronomy

the origin of the cosmic rays

- cosmic rays on Earth are ***shaped*** by propagation in magnetic fields
- photons & neutrinos can tell us about the **sources** of the cosmic rays
- neutrinos look **deeper** into the Universe because they are **harder** to see

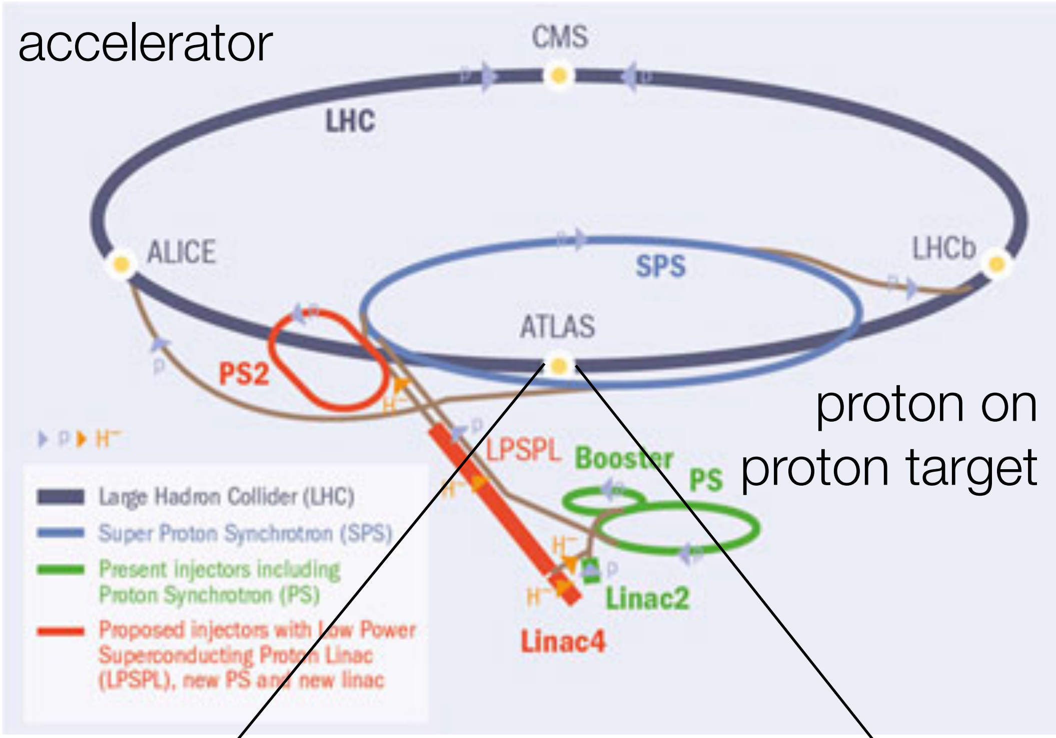
cosmic rays
remotely
at the source



cosmic rays
locally
on Earth

cosmic rays
a natural laboratory

accelerator

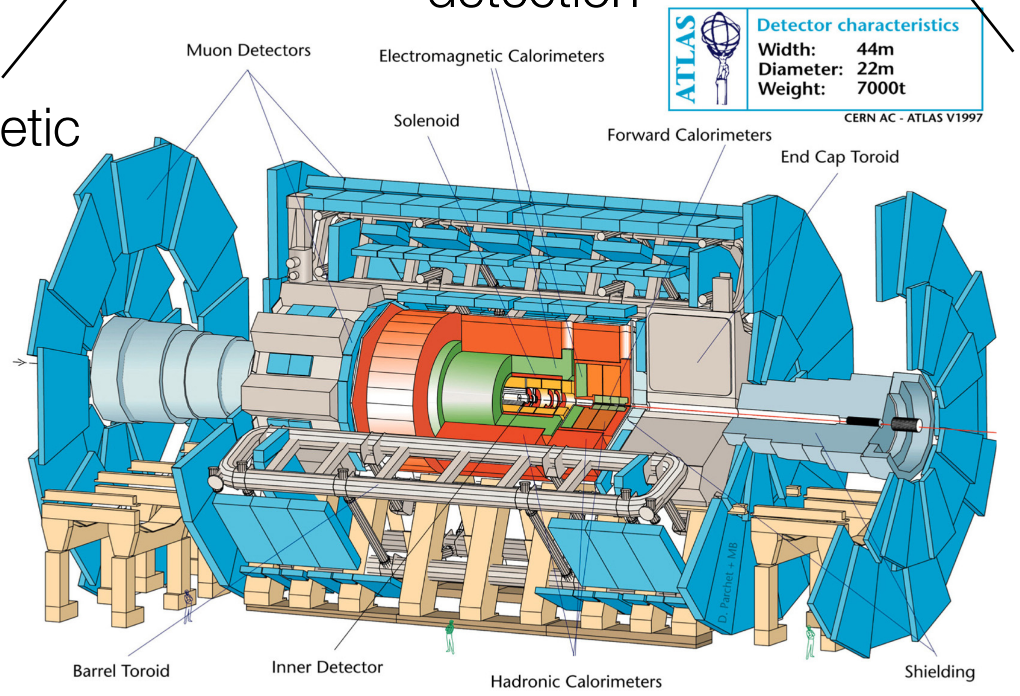


proton on proton target

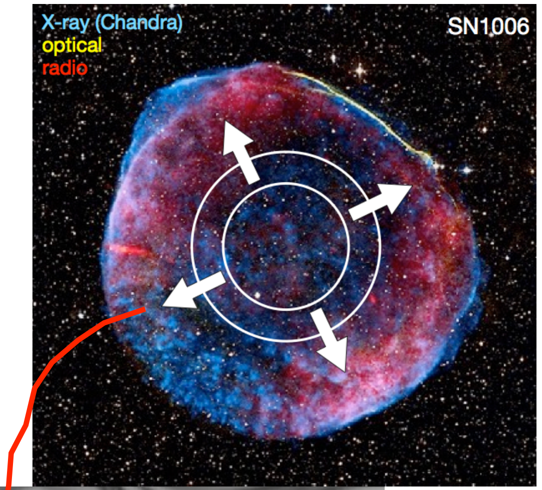
propagation

detection

magnetic fields



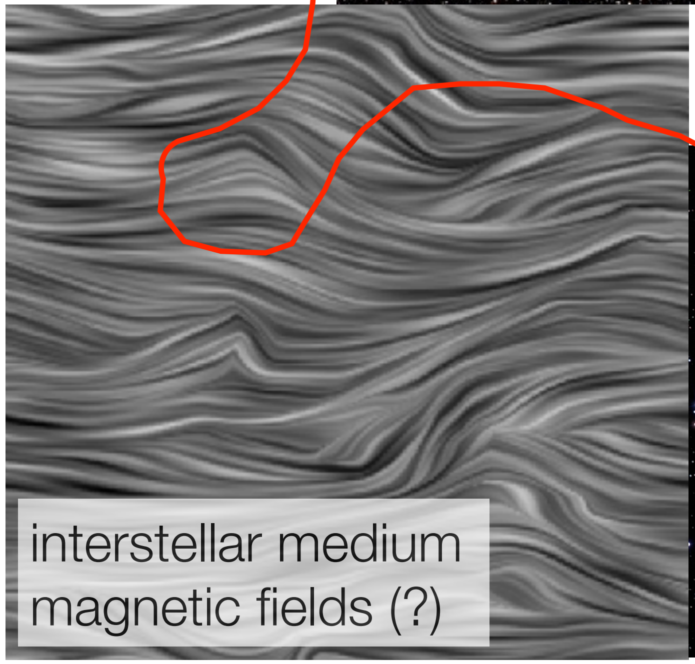
accelerator (?)



γ rays

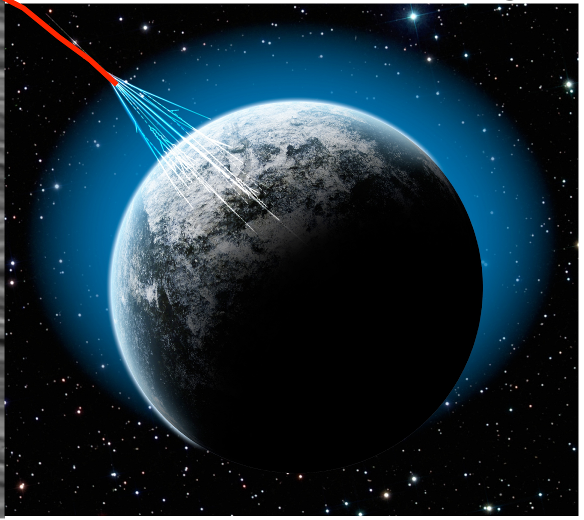
ν neutrinos

propagation

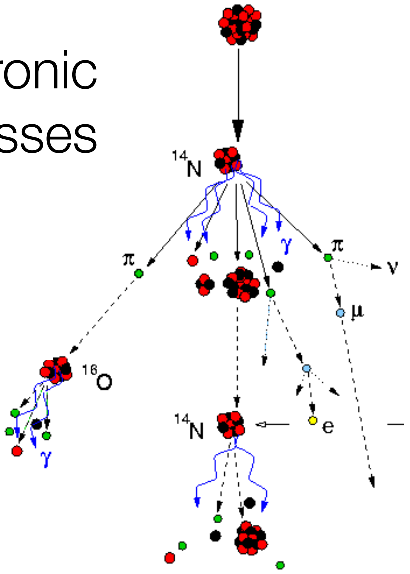


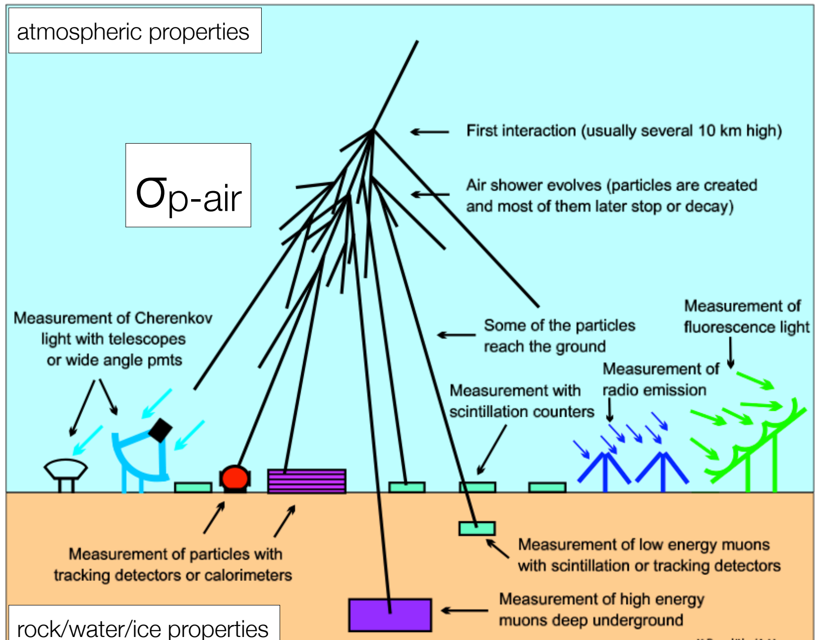
interstellar medium magnetic fields (?)

Earth atmosphere
dynamic target



nuclear & hadronic processes





atmospheric properties

$\sigma_{\text{p-air}}$

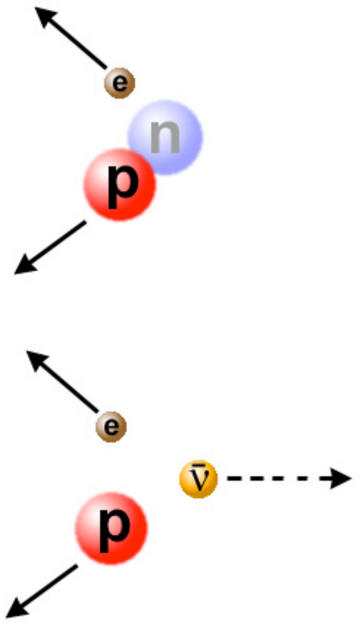
rock/water/ice properties

cosmic ray detection

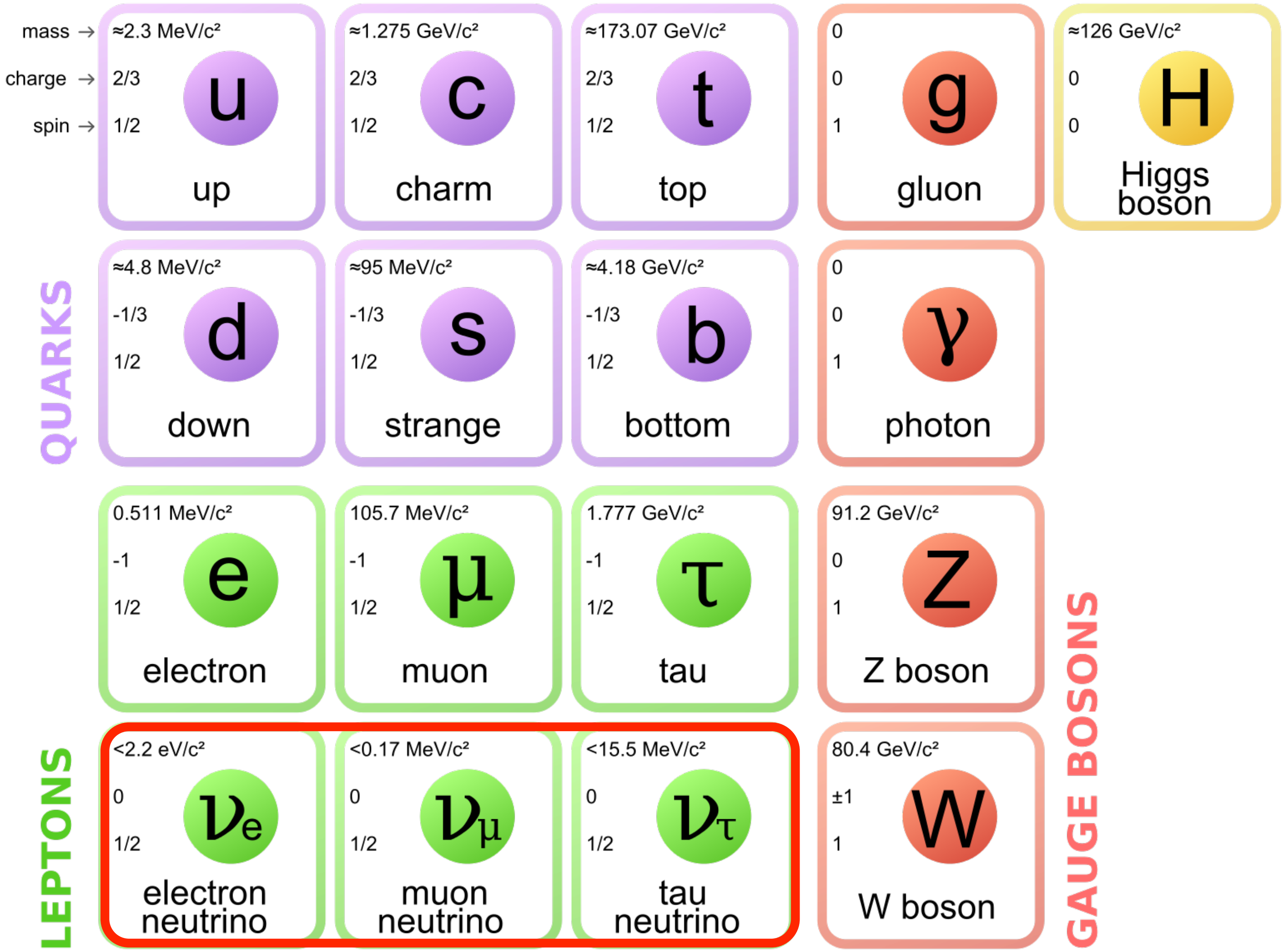
detecting neutrinos

neutrinos in particle physics

β decays



- in **standard model** they are neutral leptons with no electric charge
- they exist in three ***flavors***, one for each generation of particles
- in **radioactivity** processes
- in **weak** (short range) interactions
- **unknown mass** but …
- **oscillating** flavors …



mass → charge → spin →	$\approx$2.3 MeV/c^2 2/3 1/2 u up	$\approx$1.275 GeV/c^2 2/3 1/2 c charm	$\approx$173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	$\approx$126 GeV/c^2 0 0 H Higgs boson
QUARKS	$\approx$4.8 MeV/c^2 -1/3 1/2 d down	$\approx$95 MeV/c^2 -1/3 1/2 s strange	$\approx$4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

detecting neutrinos

neutrinos in particle physics

β decays

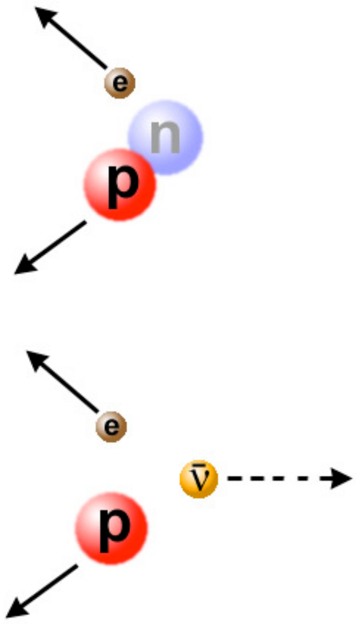


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Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

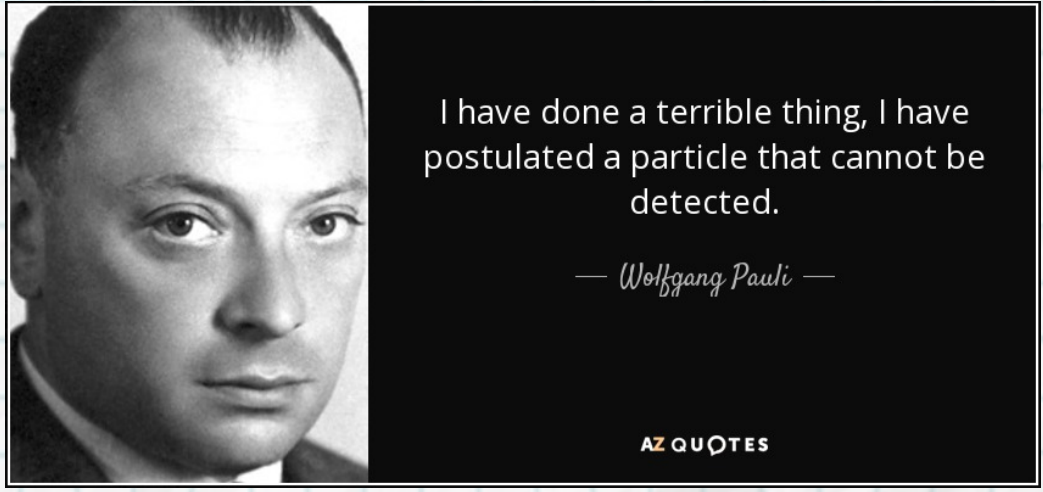
Prize share: 1/2

2015

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

detecting neutrinos

it's not easy to see neutrinos



I have done a terrible thing, I have postulated a particle that cannot be detected.

— *Wolfgang Pauli* —

- our body contains 20 mg of ^{40}K, which is β-radioactive. Thus we emit about 340 million neutrinos each day without knowing

- wherever we are on Earth, even underground, neutrinos **pass through** our body
    - ~50 billion neutrinos from Earth natural radioactivity (~ keV)
    - 10-100 billion neutrinos from nuclear plants all over the world (~ MeV)
    - 400,000 billion neutrinos/sec from the Sun (up to 10 MeV)

- … however, only one (or a few) neutrinos **interact** inside our body in a lifetime

detecting neutrinos

neutrino interaction cross sections

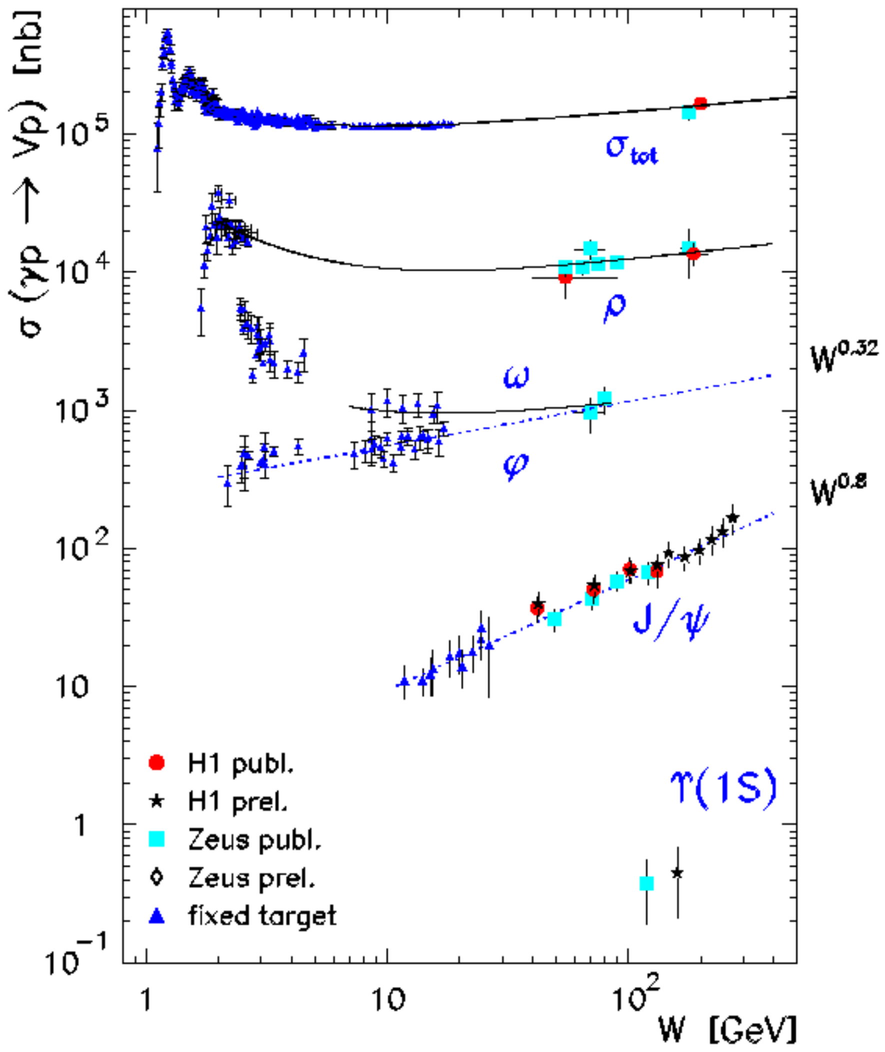
- ν-p interaction x-section << that of γ-p (@100 GeV)

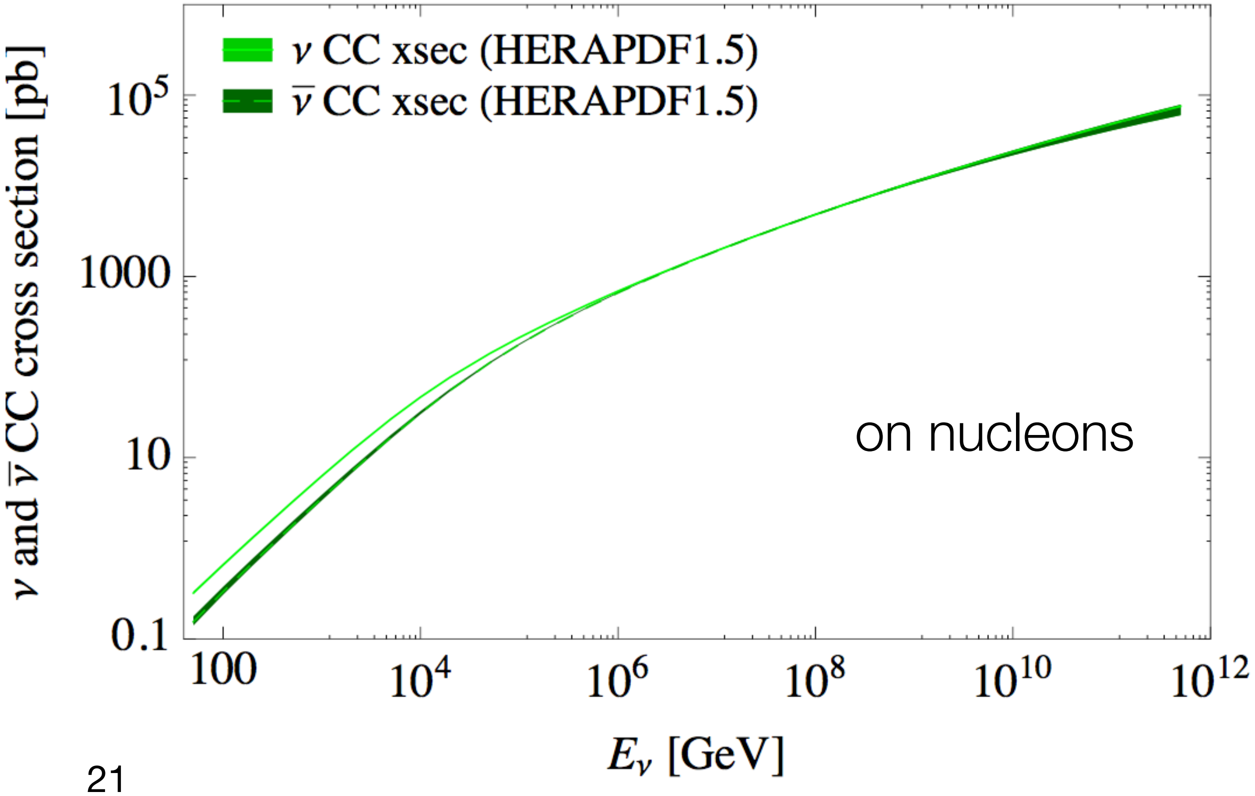
(1 barn = 10^{-24} cm^2)

1 nb = 10^{-9} b

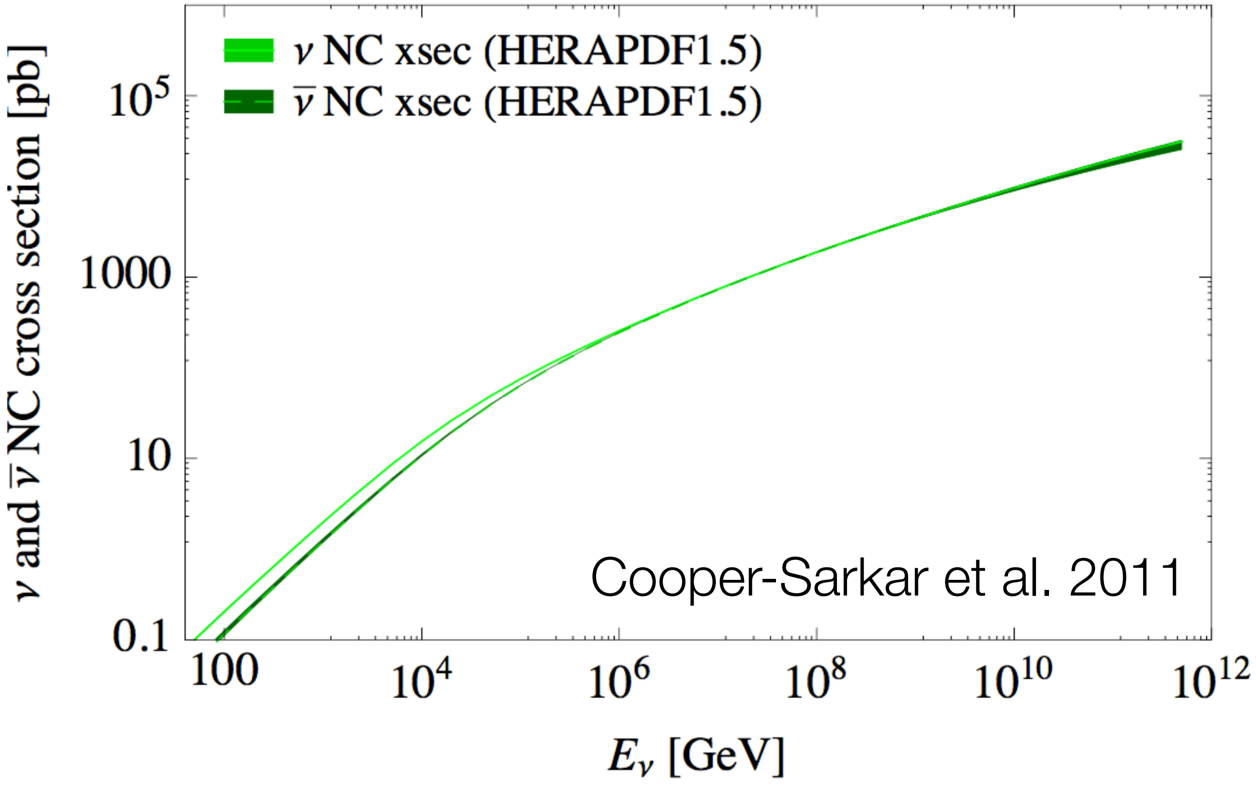
1 pb = 10^{-12} b

compare: γ+p x-section





on nucleons



Cooper-Sarkar et al. 2011

detecting neutrinos

neutrino interaction cross sections

It is an **effective area** that quantifies the intrinsic likelihood of a scattering event when an incident beam strikes a target object, made of discrete particles.

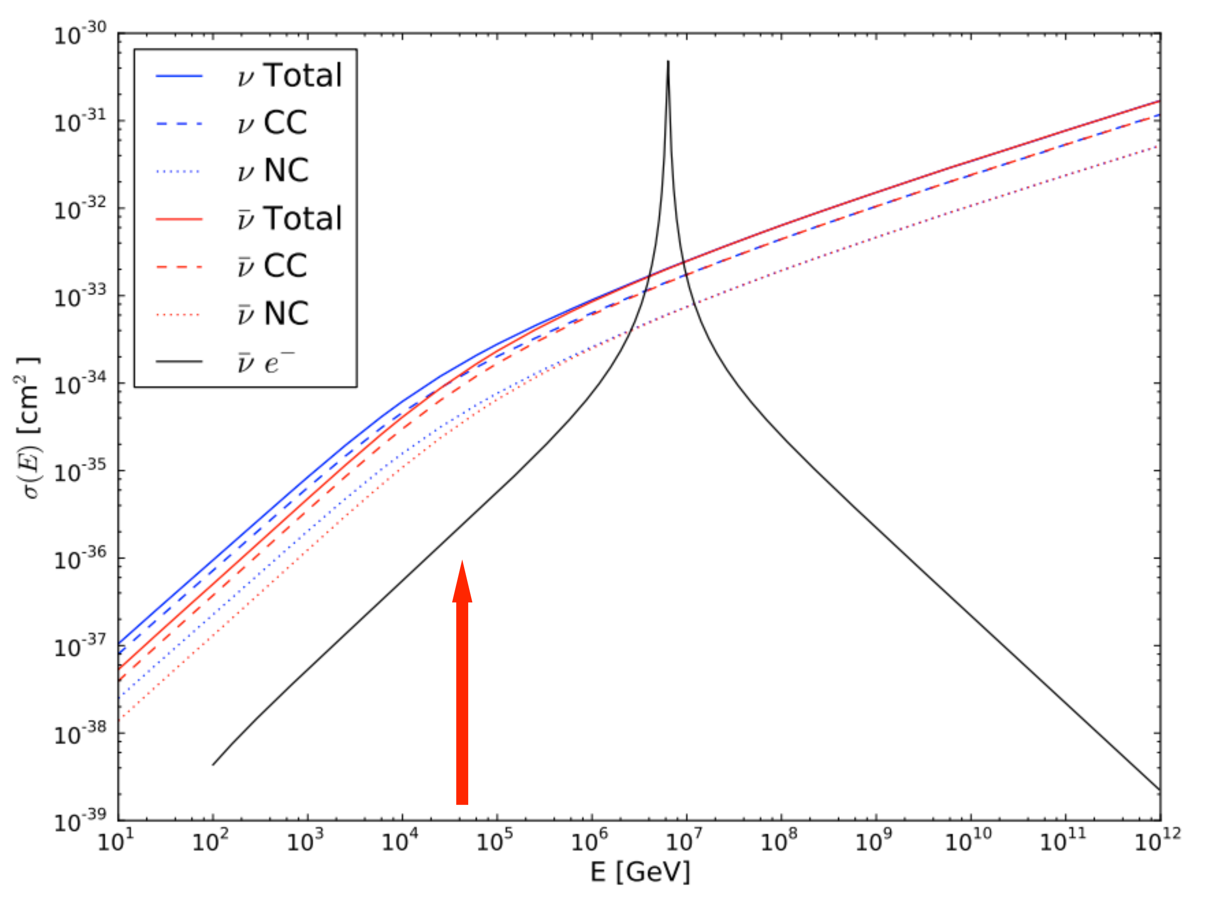
The cross section of a particle is the same as the cross section of a hard object, if the probabilities of hitting them with a ray are the same. [*Wikipedia*]

$$P_{int} = \sigma_{\nu N}\, N_A\, \rho\, L \qquad [cm^2\, nucl^{-1}][nucl\, g^{-1}][g\, cm^{-3}][cm]$$

$$L = \frac{P_{int}}{\sigma_{\nu N}\, N_A\, \rho} = \frac{1}{0.7 \times 10^{-38} \cdot E/GeV \cdot 6.022 \times 10^{23} \cdot \textcircled{5}}\,[cm]$$

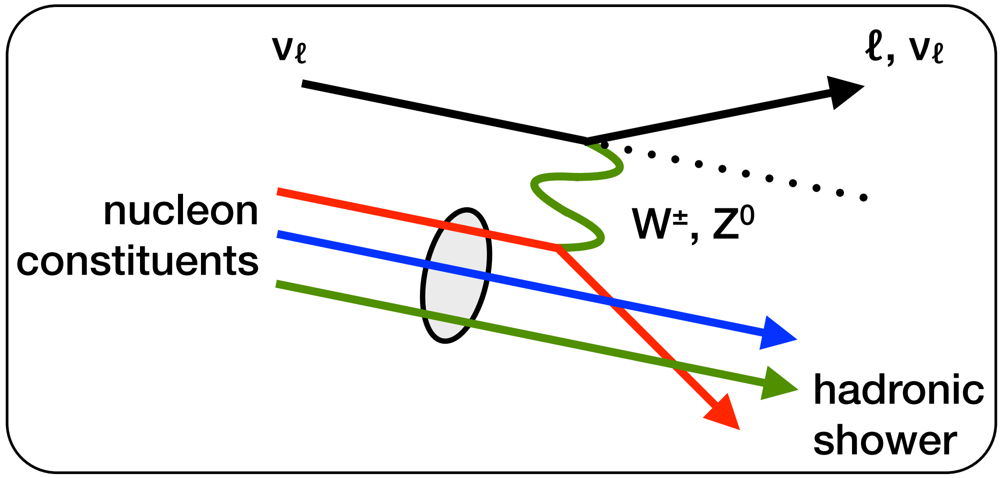
$$L = \frac{4.8 \times 10^{8}}{E/GeV}\,[km]$$

- @40 TeV L ~ Earth's size



detecting neutrinos

neutrino interactions with matter

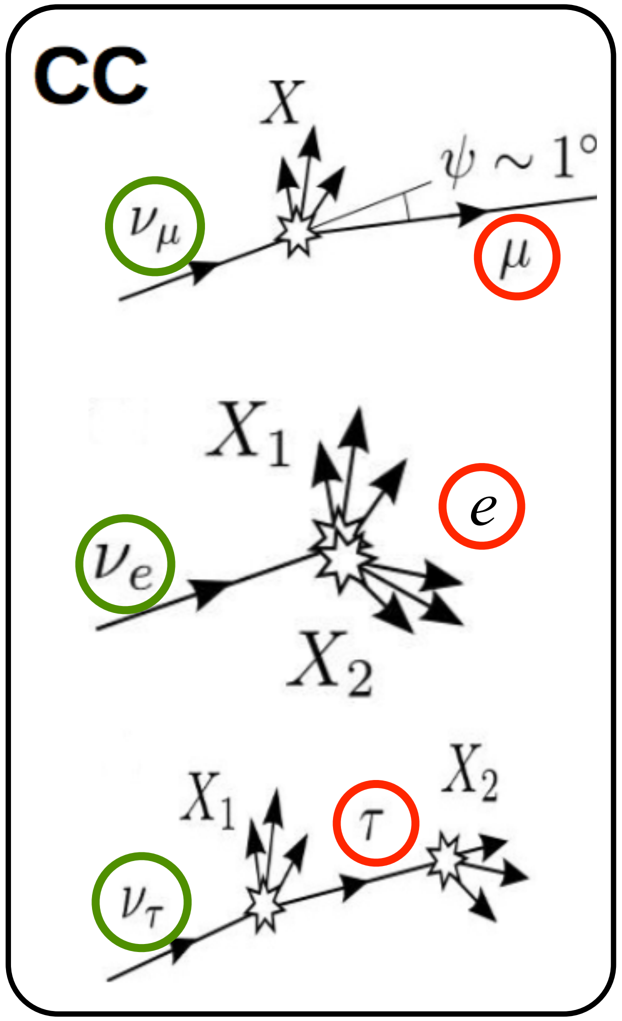


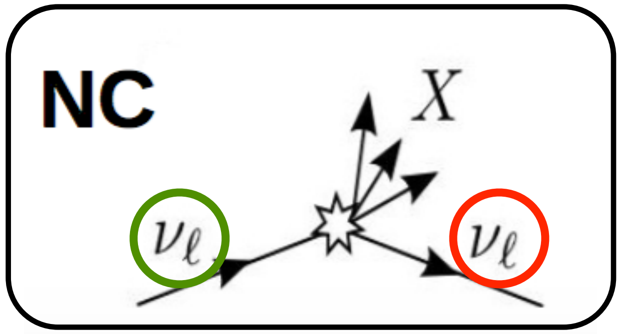
- neutrino interacts with quark constituents of nucleons
- they exchange Z^0 (**neutral**) or $W^\pm$ (**charged**) bosons

‣ **charged current** interaction

‣ **neutral current** interaction

‣ **indirect detection of neutrinos**





Lorentz covariance

and Mandelstam variables

- Lorentz covariance is a property of **spacetime** following from **special relativity**. Physics quantities do not change with reference system

- a physical quantity is Lorentz covariant if it transforms under Lorentz transformations

- in spacetime displacement is represented by 4-vector $X^{\mu} = (ct, x, y, z)$

- velocity by 4-vector

$$U^{\mu} = \frac{dX^{\mu}}{d\tau} = \gamma \left(c, \frac{dx}{dt}, \frac{dy}{dt}, \frac{dz}{dt} \right)$$

- momentum by 4-vector

$$P^{\mu} = m_0 U^{\mu} = \left(\frac{E}{c}, p_x, p_y, p_z \right)$$

- 4-momentum is conserved

Lorentz covariance

and Mandelstam variables

- Lorentz transformation preserve space-time interval

$$ds^2 = X^\mu X^\nu \eta_{\mu\nu} = c^2 dt^2 - dx^2 - dy^2 - dz^2$$

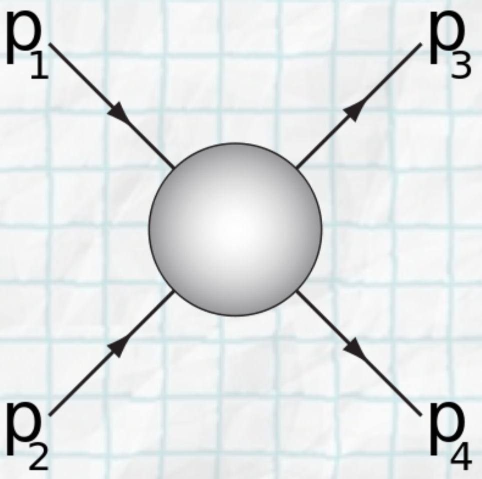
- proper time

$$d\tau^2 = \left(\frac{dt}{\gamma}\right)^2 = \frac{ds^2}{c^2}$$

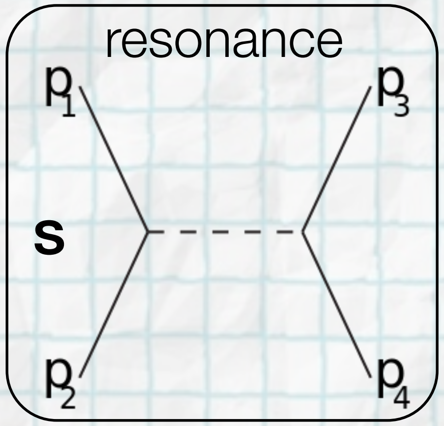
- rest mass (invariant mass)

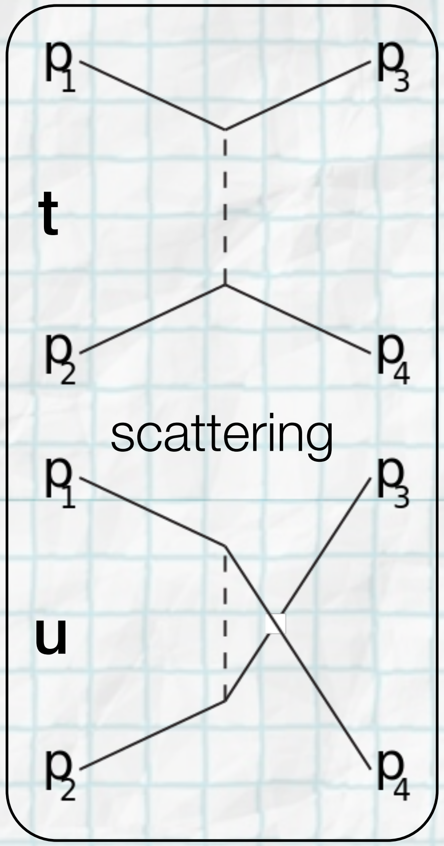
$$m_0^2 c^2 = P^\mu P^\nu \eta_{\mu\nu} = \frac{E^2}{c^2} - p_x^2 - p_y^2 - p_z^2$$

Mandelstam variables



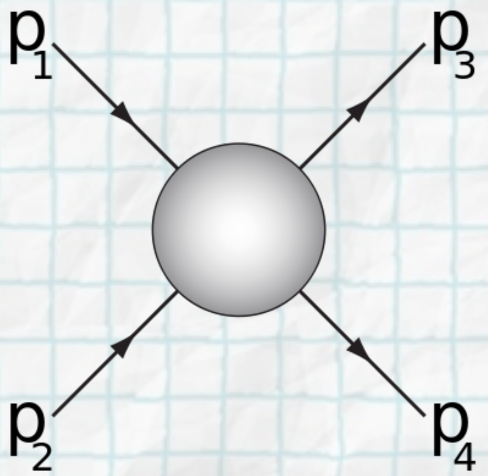
- numerical quantities encoding particles energy, momentum and angles in scattering processes in a Lorentz invariant formalism

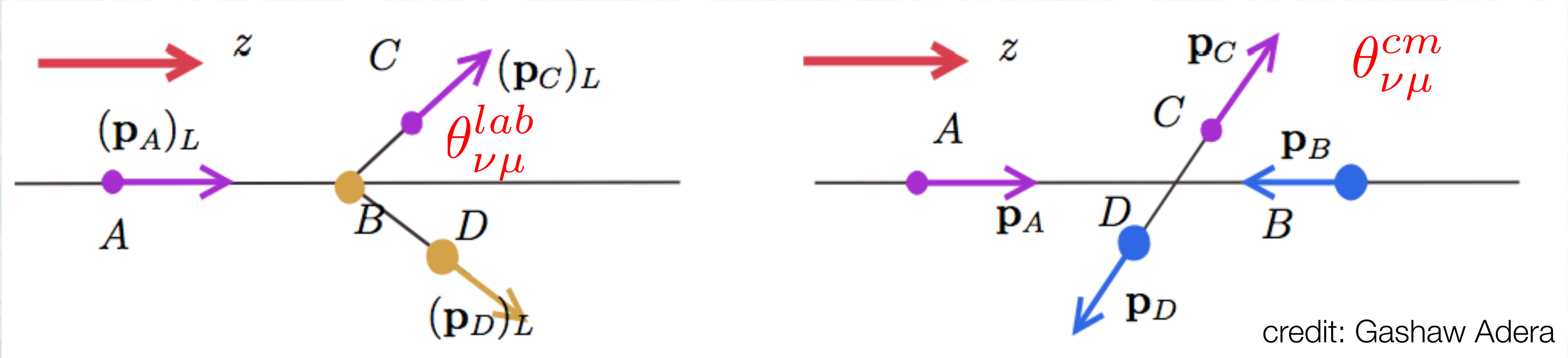




- s-process $$s = (P_1^\mu + P_2^\mu)^2 = (P_3^\mu + P_4^\mu)^2$$
  invariant mass
- t-process $$t = (P_1^\mu - P_3^\mu)^2 = (P_2^\mu - P_4^\mu)^2$$
  transferred 4-momentum
- u-process $$u = (P_1^\mu - P_4^\mu)^2 = (P_2^\mu - P_3^\mu)^2$$
  transferred 4-momentum

Mandelstam variables





credit: Gashaw Adera

- center of mass → lab

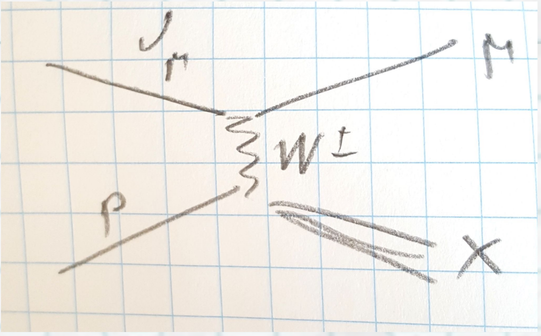
$$\boxed{E_{lab} = \frac{2E_{cm}^2 - (mc^2)^2}{mc^2}}$$

- scattering angle @ center of mass

$$\cos\theta_{\nu\mu}^{cm} = 1 + \frac{t}{2|\vec{p}|}$$

- scattering angle @ lab frame (E_ν > TeV)

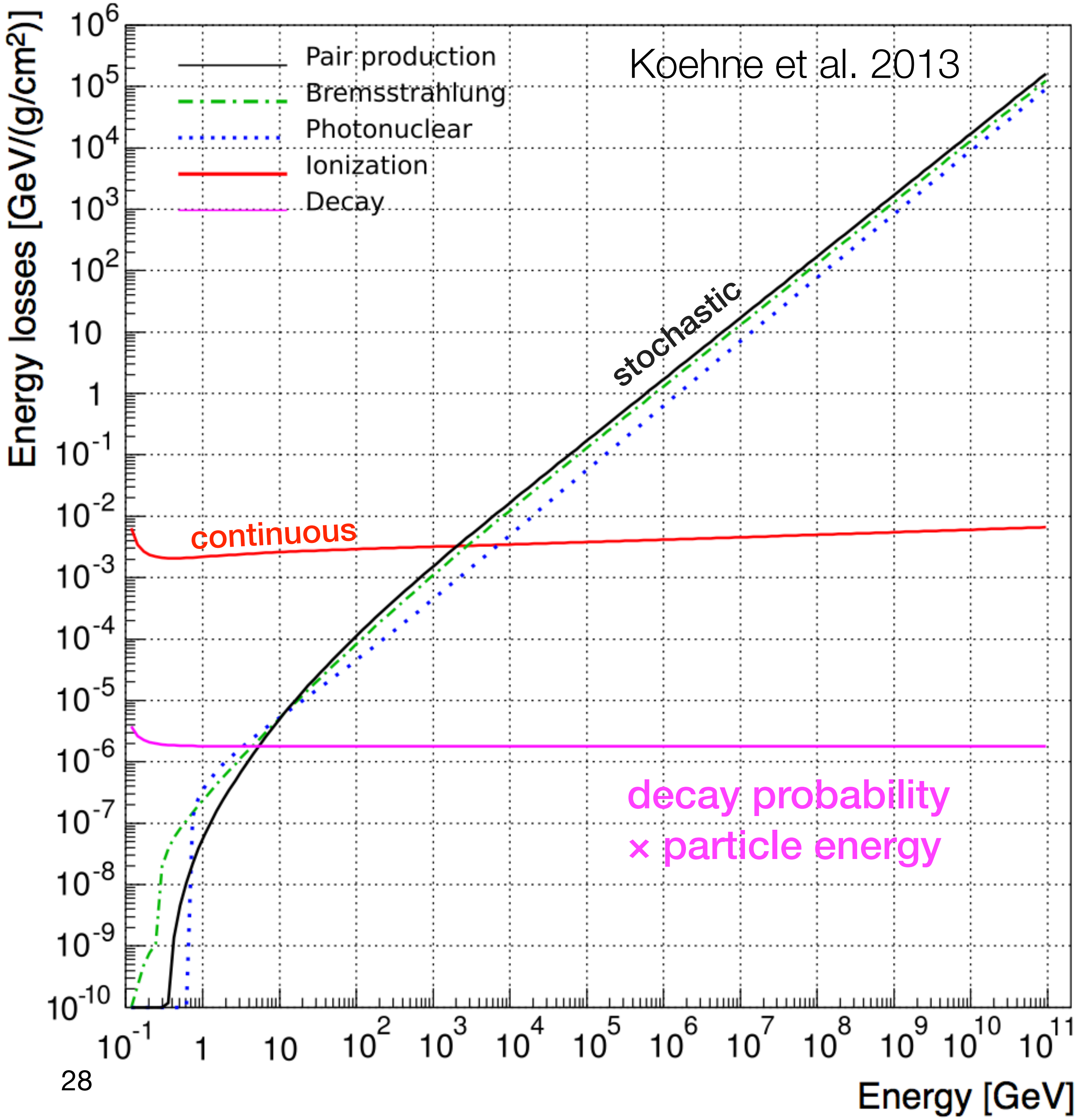
$$\boxed{\sqrt{\langle\theta_{\nu\mu}^2\rangle} \propto \sqrt{\frac{m_p}{E_\nu}}}$$

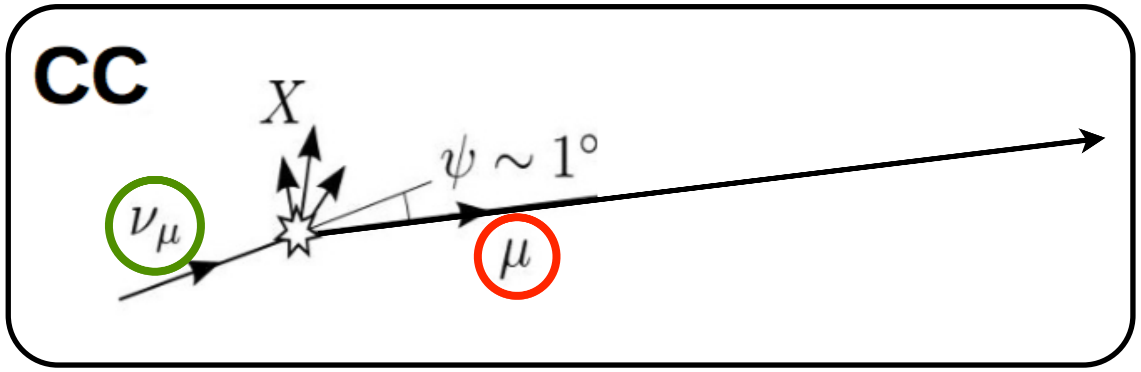


detecting neutrinos

detection of charged leptons

energy losses of muons in ice





- **indirect detection of ν_μ neutrinos**

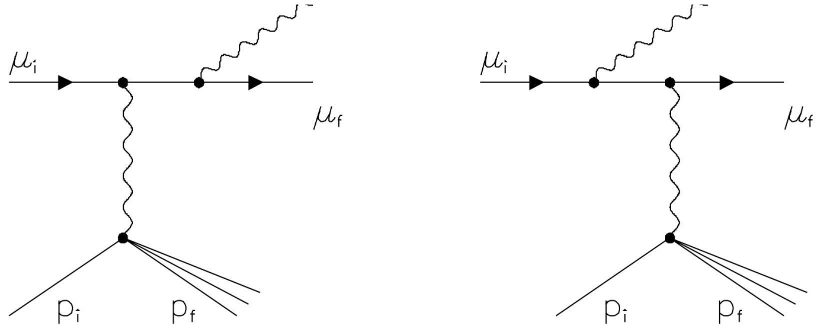
$$-\frac{dE_\mu}{dX} = a(E_\mu) + b(E_\mu)\, E_\mu$$

$$a = a_{ionization}$$

$$b = b_{brems} + b_{pair} + b_{nucl}$$

Koehne et al. 2013

muon energy losses
stochastic losses



bremsstrahlung

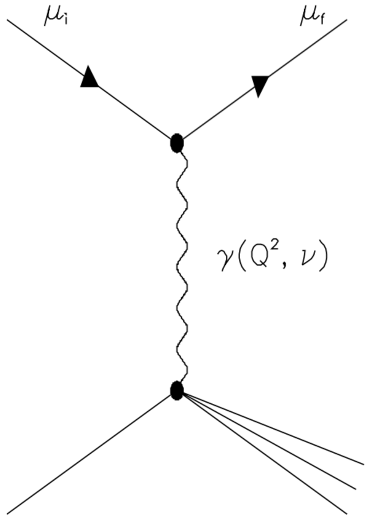
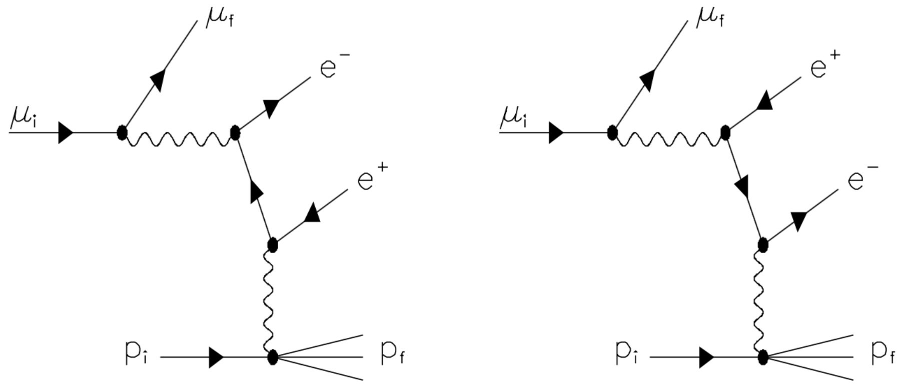
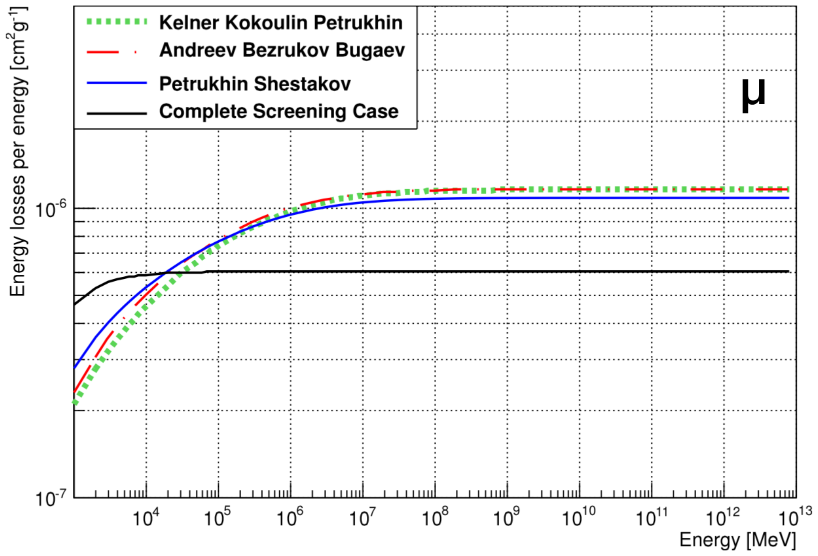
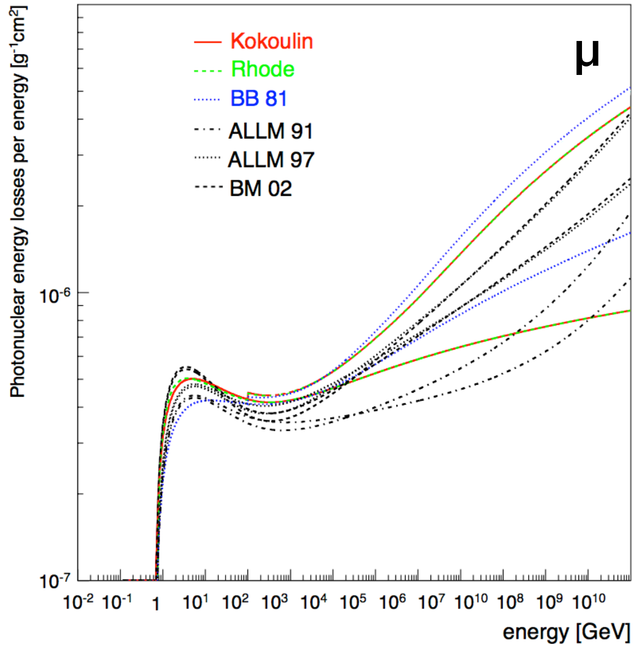


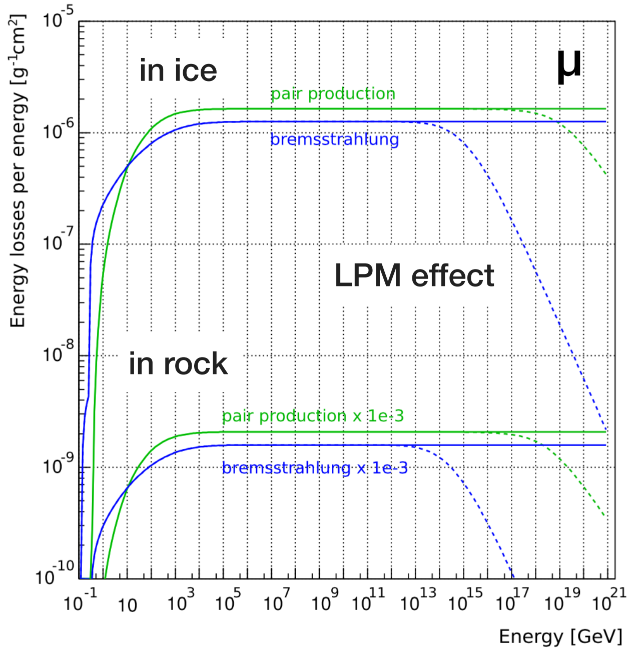
photo-nuclear interactions



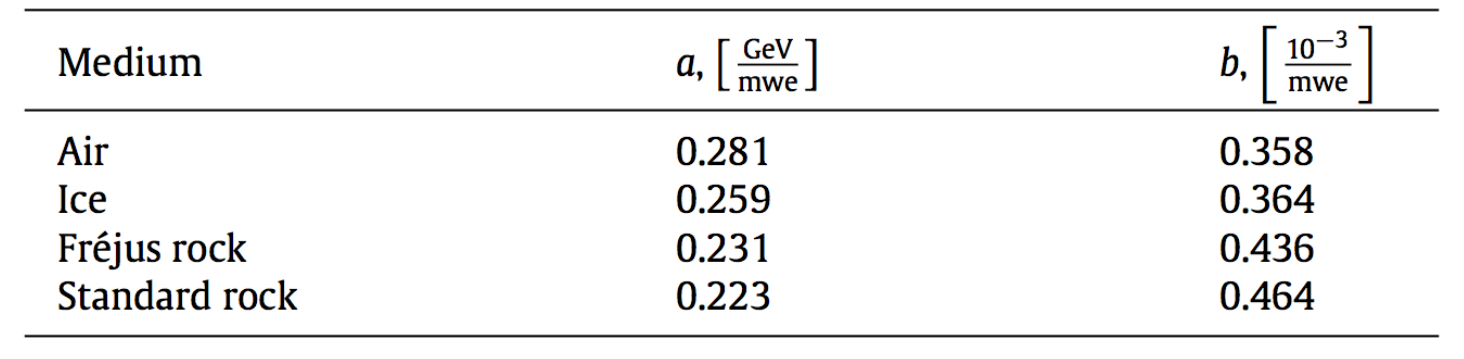
e-pair production







muon range



Medium	$a,\left[\frac{\text{GeV}}{\text{mwe}}\right]$	$b,\left[\frac{10^{-3}}{\text{mwe}}\right]$
Air	0.281	0.358
Ice	0.259	0.364
Fréjus rock	0.231	0.436
Standard rock	0.223	0.464

$$-\frac{dE_\mu}{dX} = a(E_\mu) + b(E_\mu)\,E_\mu$$

$$a(E_\mu) \propto log(E_\mu)$$

$$b(E_\mu) \sim const$$

- meter per water equivalent (mwe) = **depth × density of material**
- ρ_{water} = 1 g/cm^3 → **1 m of water ≡ 1 mwe = 100 g/cm^2**

- minimum muon energy @ given depth

$$E_\mu = \left(E_\mu^i + \frac{a}{b}\right) e^{-bX} - \frac{a}{b}$$

$$E_\mu^{min} = \frac{a}{b}\left(e^{bX} - 1\right)$$

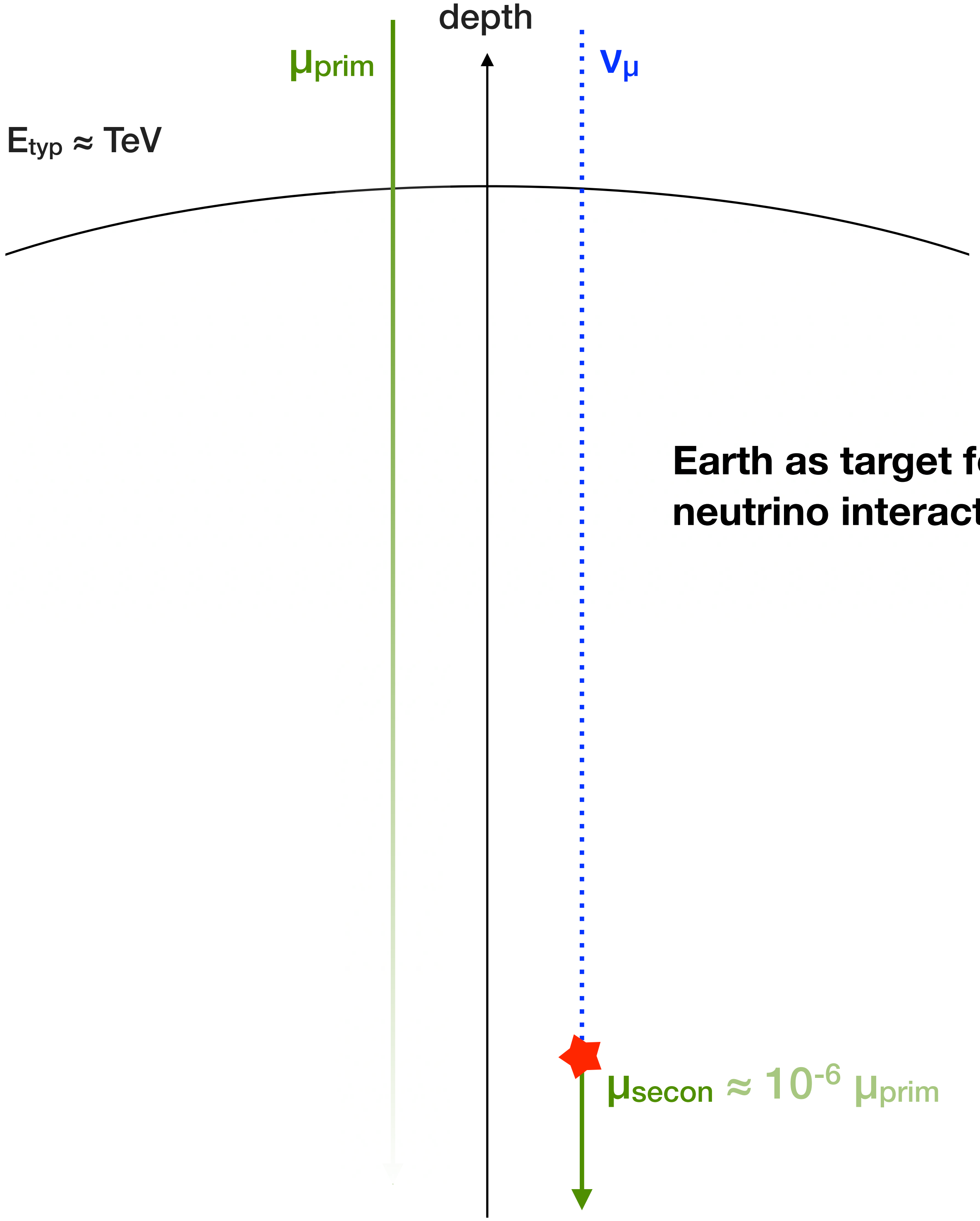
- muon range @ given energy

$$R_\mu = \frac{1}{b}\ln\left(1 + \frac{b}{a}E_\mu^i\right)$$

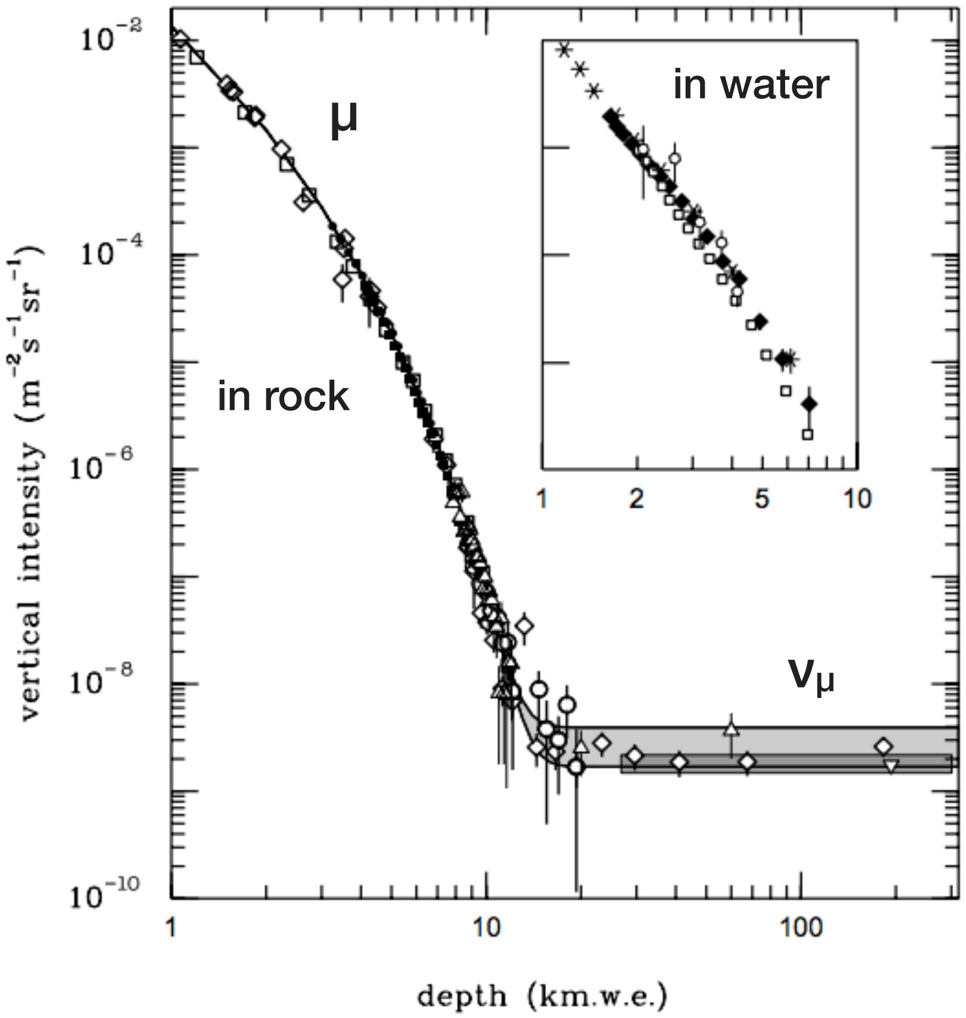
$$L_\mu = \frac{R_\mu}{\rho}$$

detecting neutrinos

detection of charged leptons



Earth as target for neutrino interactions

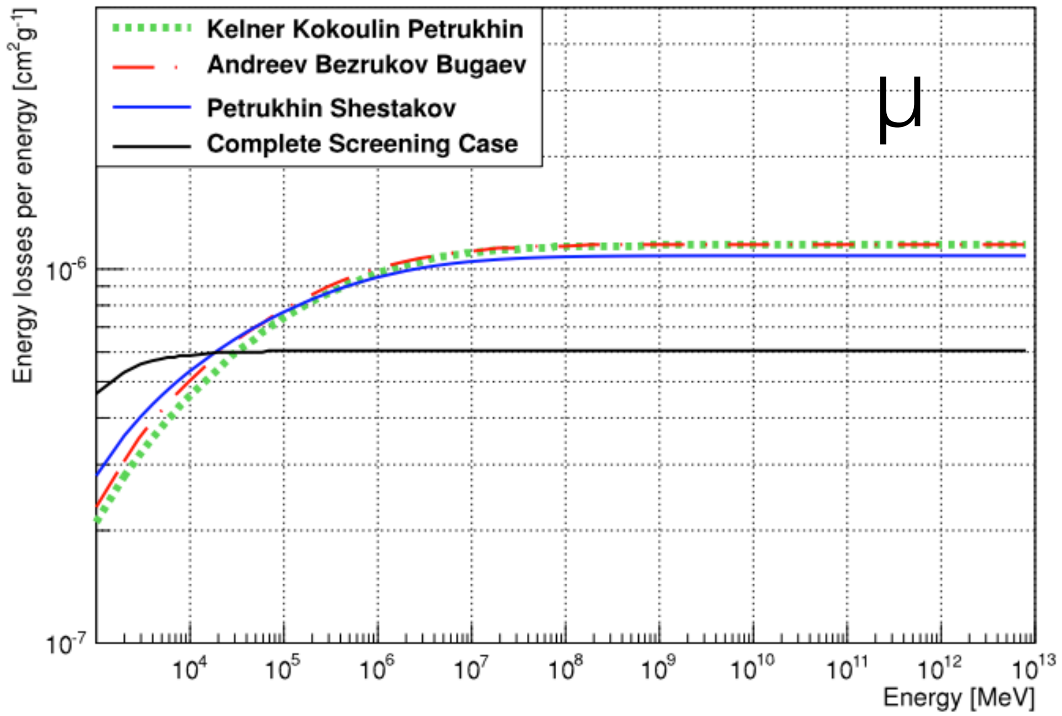


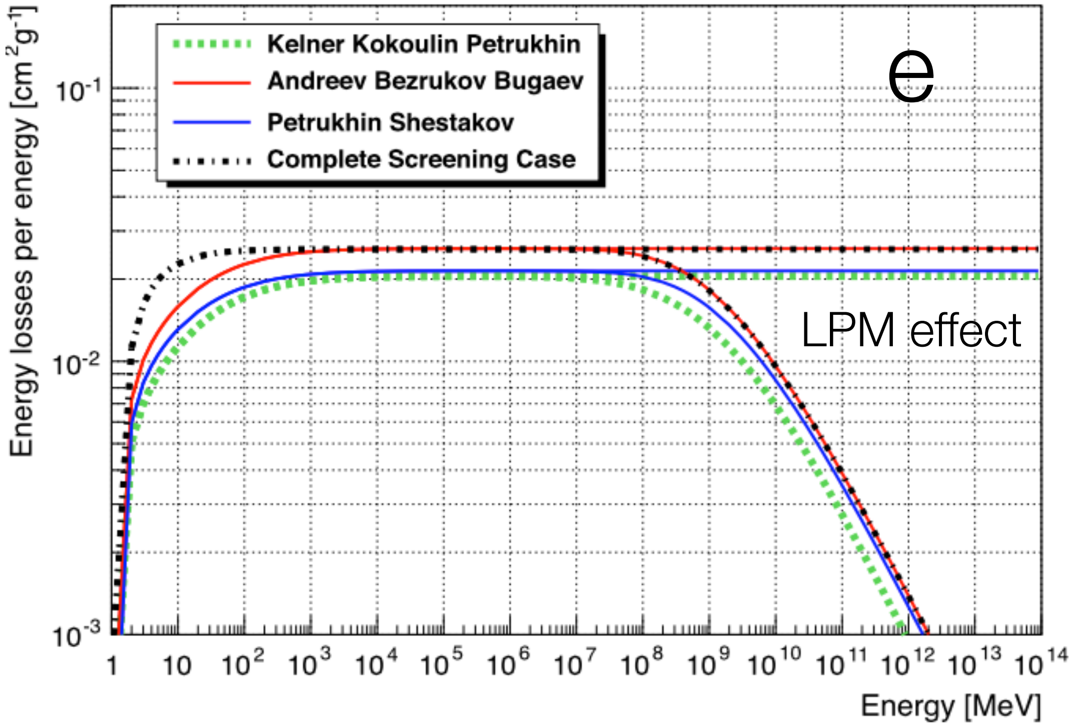
(from PDG)

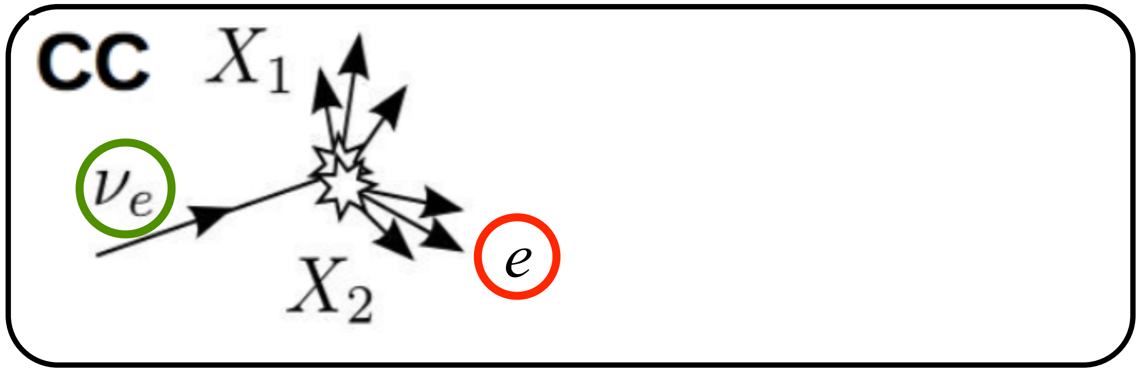
Figure 27.7: Vertical muon intensity vs depth (1 km.w.e. = 10^5 g cm^{-2}of standard rock). The experimental data are from: ◊: the compilations of Crouch [67], □: Baksan [72], ○: LVD [73], ●: MACRO [74], ■: Frejus [75], and △: SNO [76]. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons. Darker shading shows the muon flux measured by the SuperKamiokande experiment. The inset shows the vertical intensity curve for water and ice published in Refs. [68–71].

detecting neutrinos

detection of charged leptons





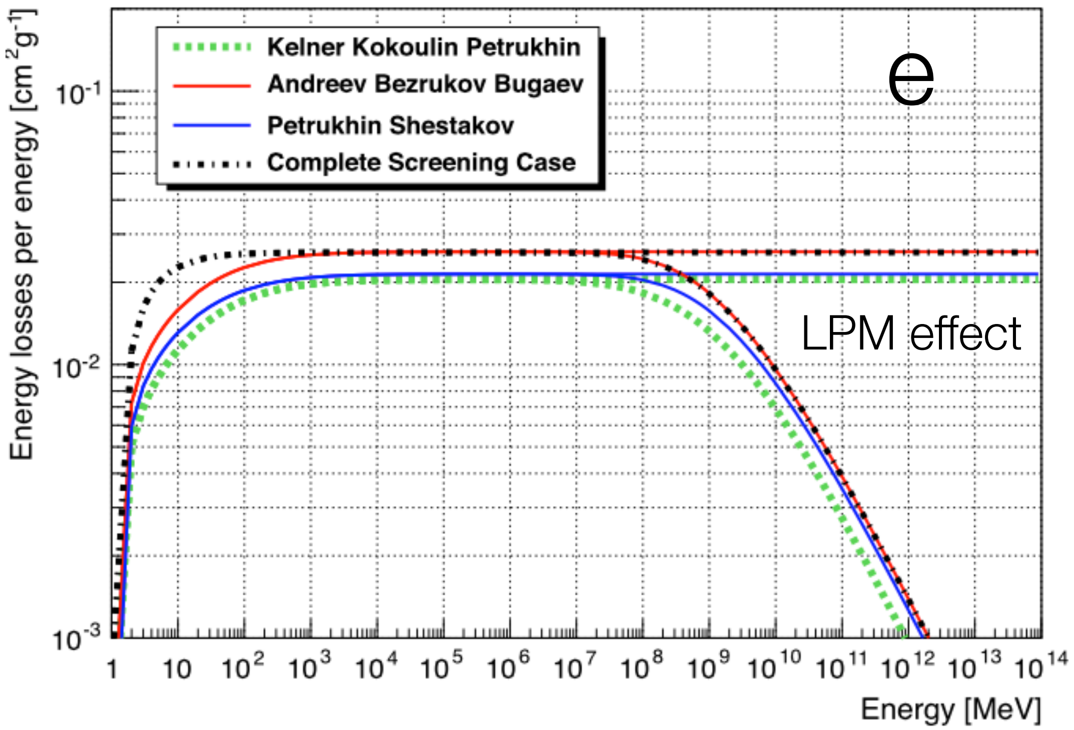


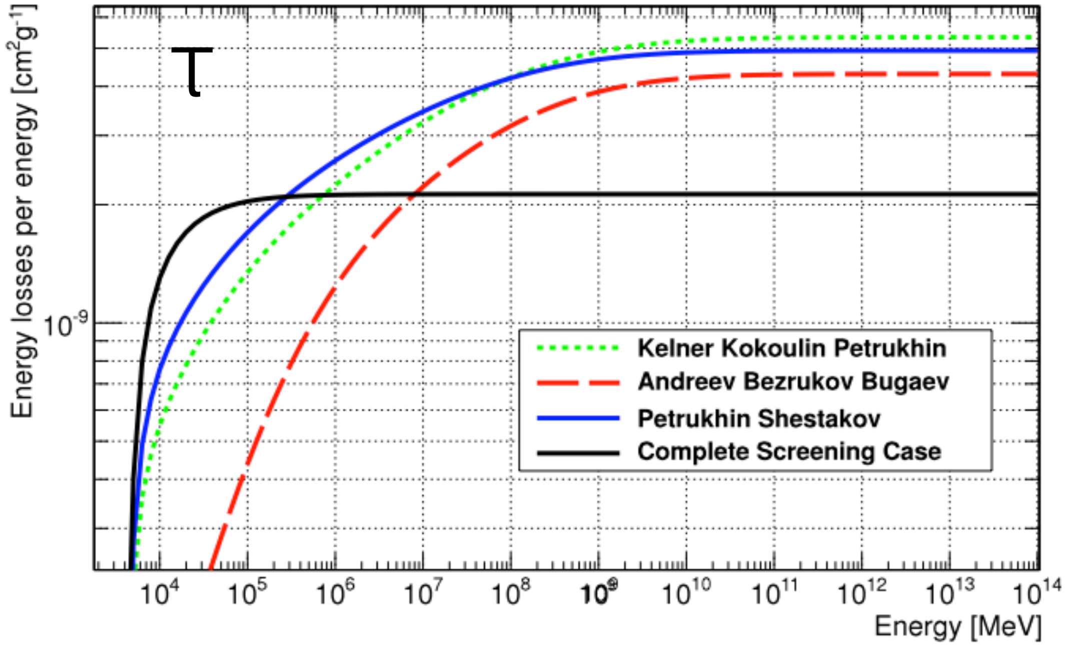
‣ **indirect detection of ν_e neutrinos**

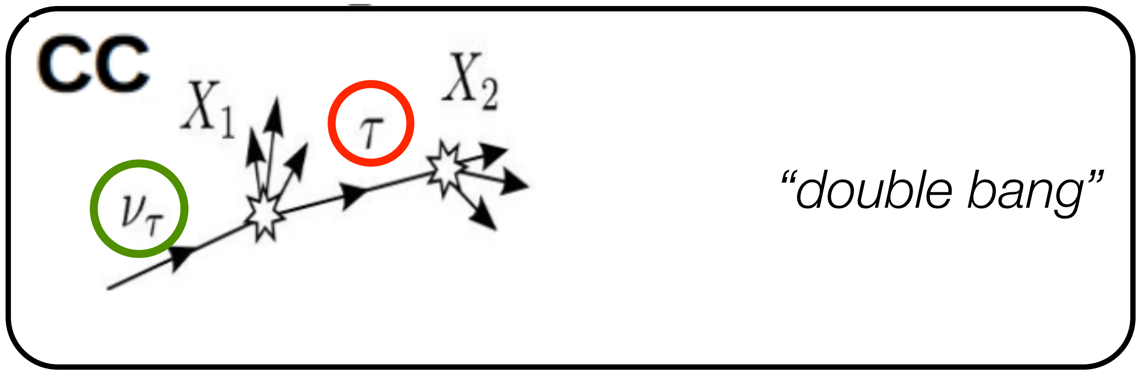
- **electrons** loose energy **faster** than **muons**
- track length ~ 10 meters

detecting neutrinos

detection of charged leptons







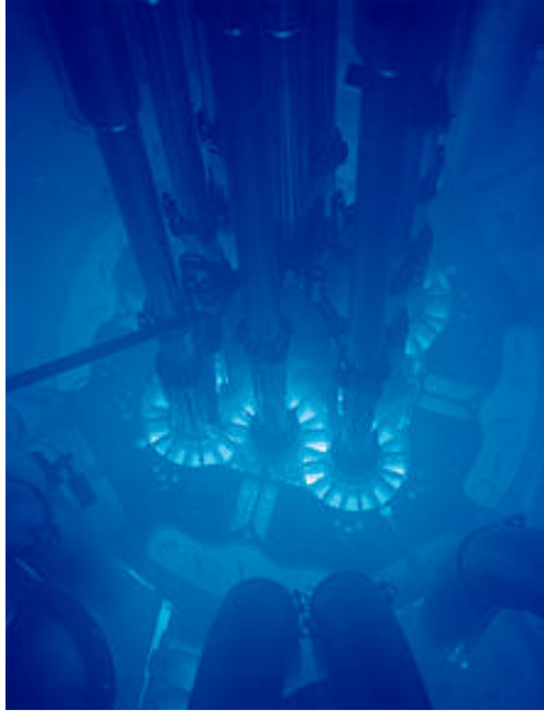
▸ **indirect detection of ν_τ neutrinos**

- **electrons** loose energy **faster** than **muons**
- track length ~10 m

- **taus** loose energy **slower** than **muons**
- **BUT** lifetime 10^7 times **shorter**
- track length >100 m @ energy > 1 PeV

detecting neutrinos in transparent media

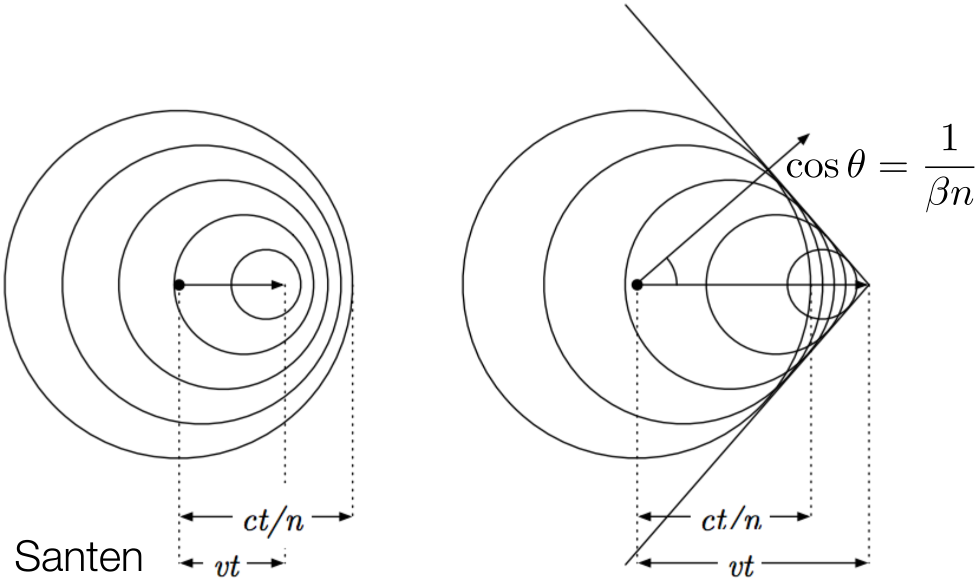
Cherenkov Effect



- electromagnetic radiation emitted when a charged particle passes through a **dielectric** medium at a speed greater than the phase velocity of light in that medium ($v > c/n_{\mathrm{medium}}$)

- atoms near the particle become polarized and emit coherent radiation when returning to equilibrium

$$\frac{dN^2}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$



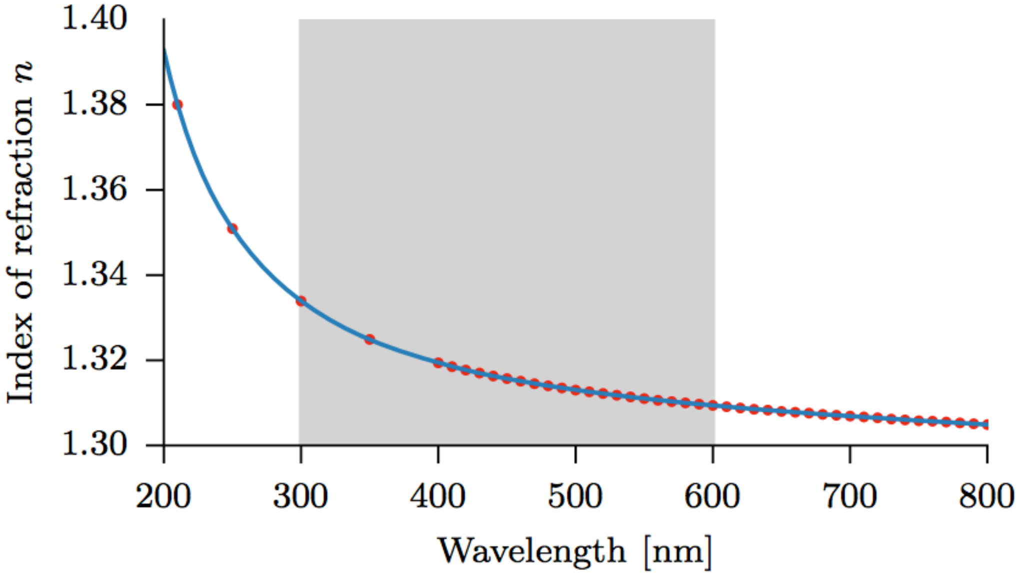
credit: J. van Santen

detecting neutrinos in transparent media

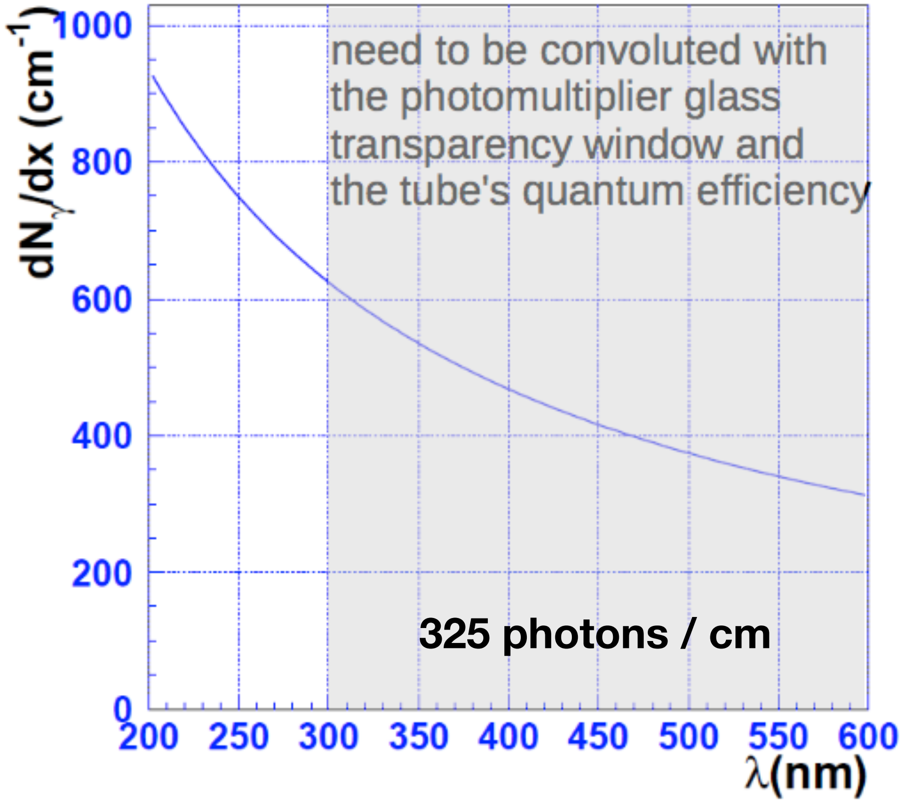
Cherenkov Effect

$$\frac{dN^2}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

credit: J. van Santen



$$\frac{dN}{dx} = 2\pi\alpha\sin^2\theta\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

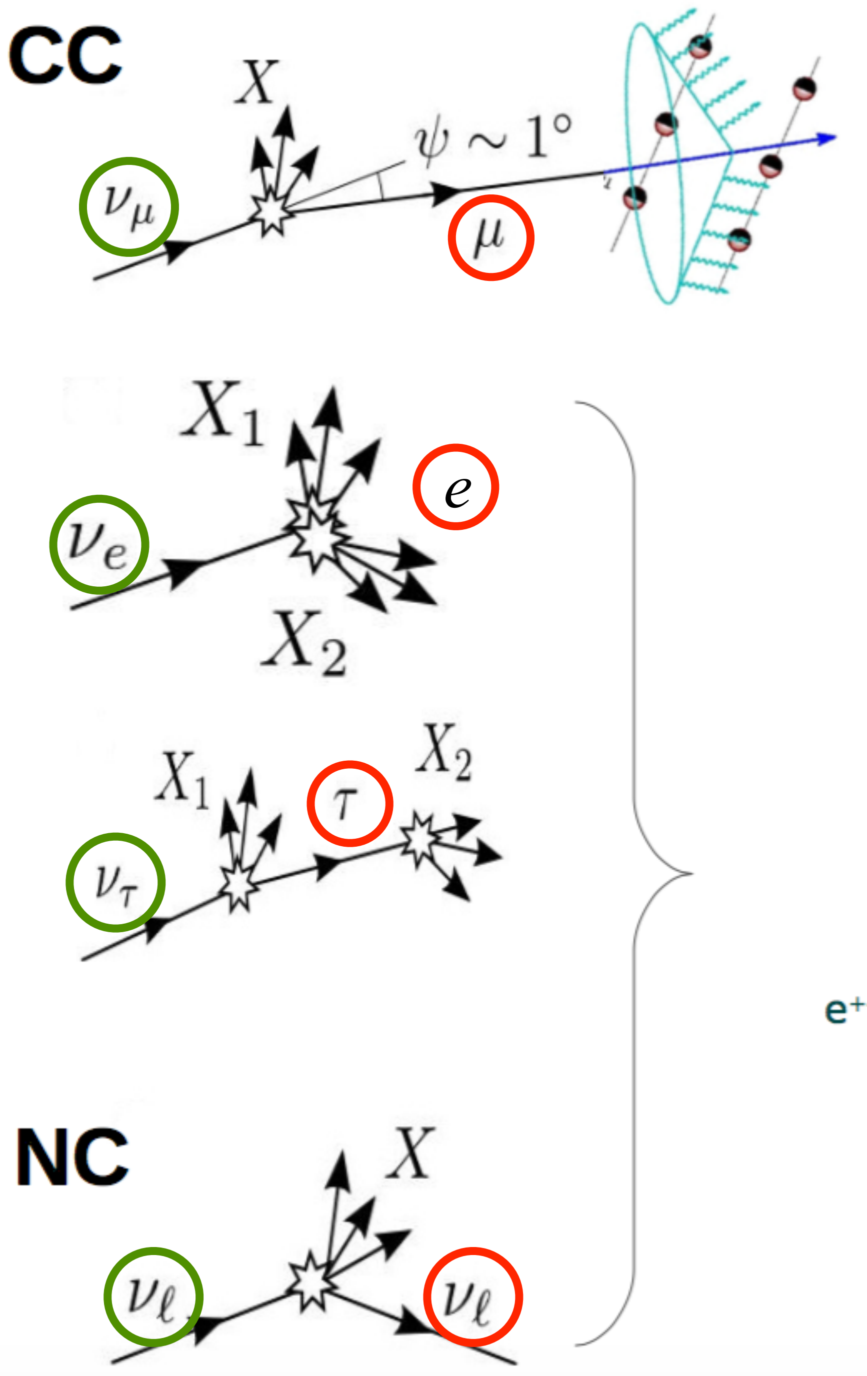


need to be convoluted with the photomultiplier glass transparency window and the tube's quantum efficiency

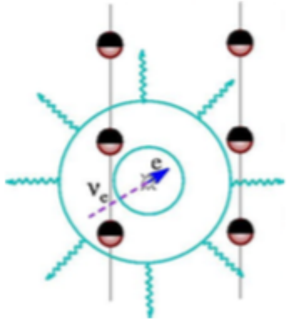
325 photons / cm

detection technique
Cherenkov radiation

photon scattering
in the transparent medium

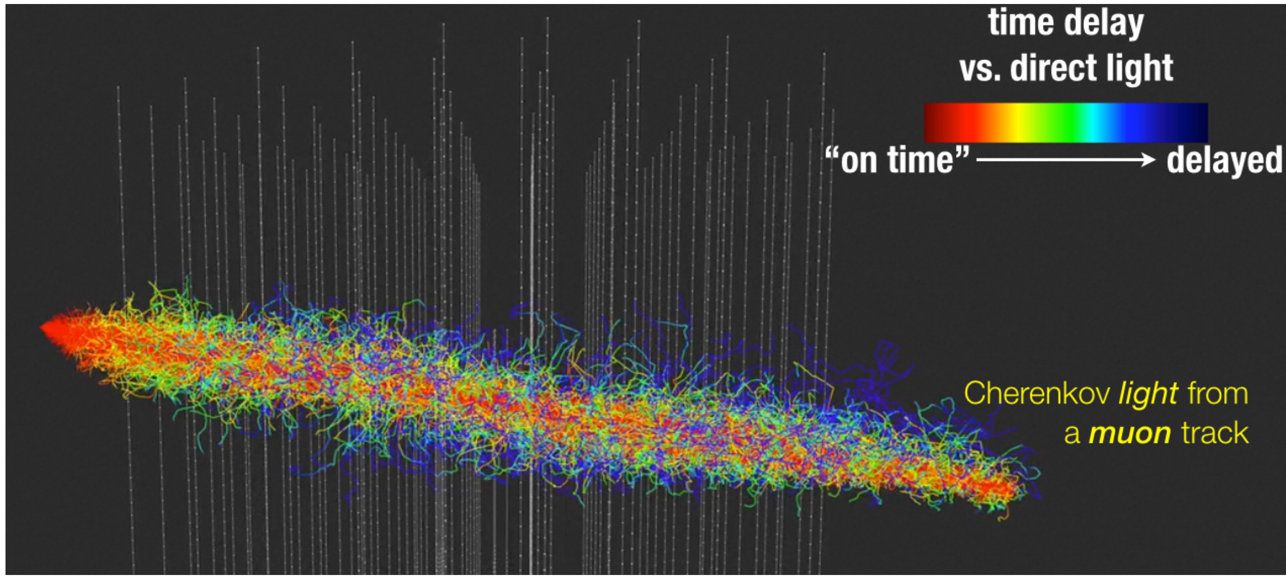


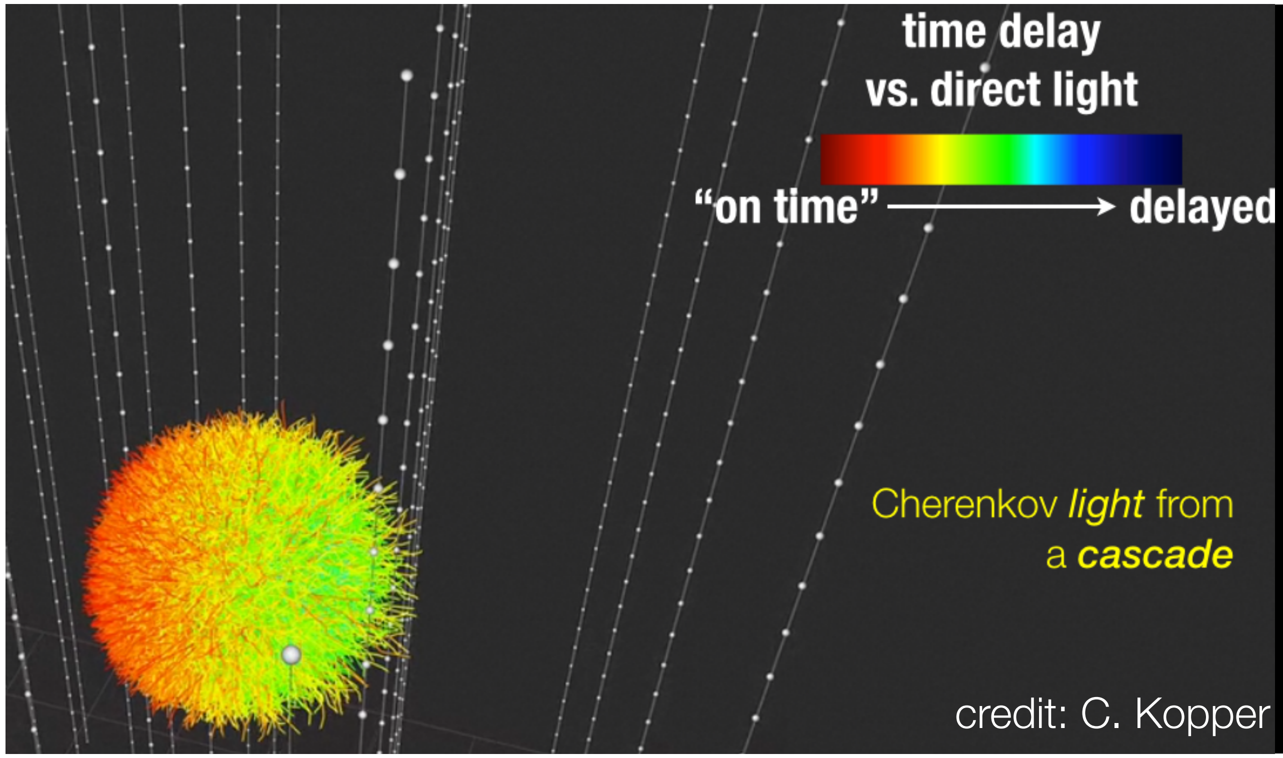
μ tracks >100m @ E>100 GeV



e^{+-} :electromagnetic shower

τ^{+-} : hadronic shower

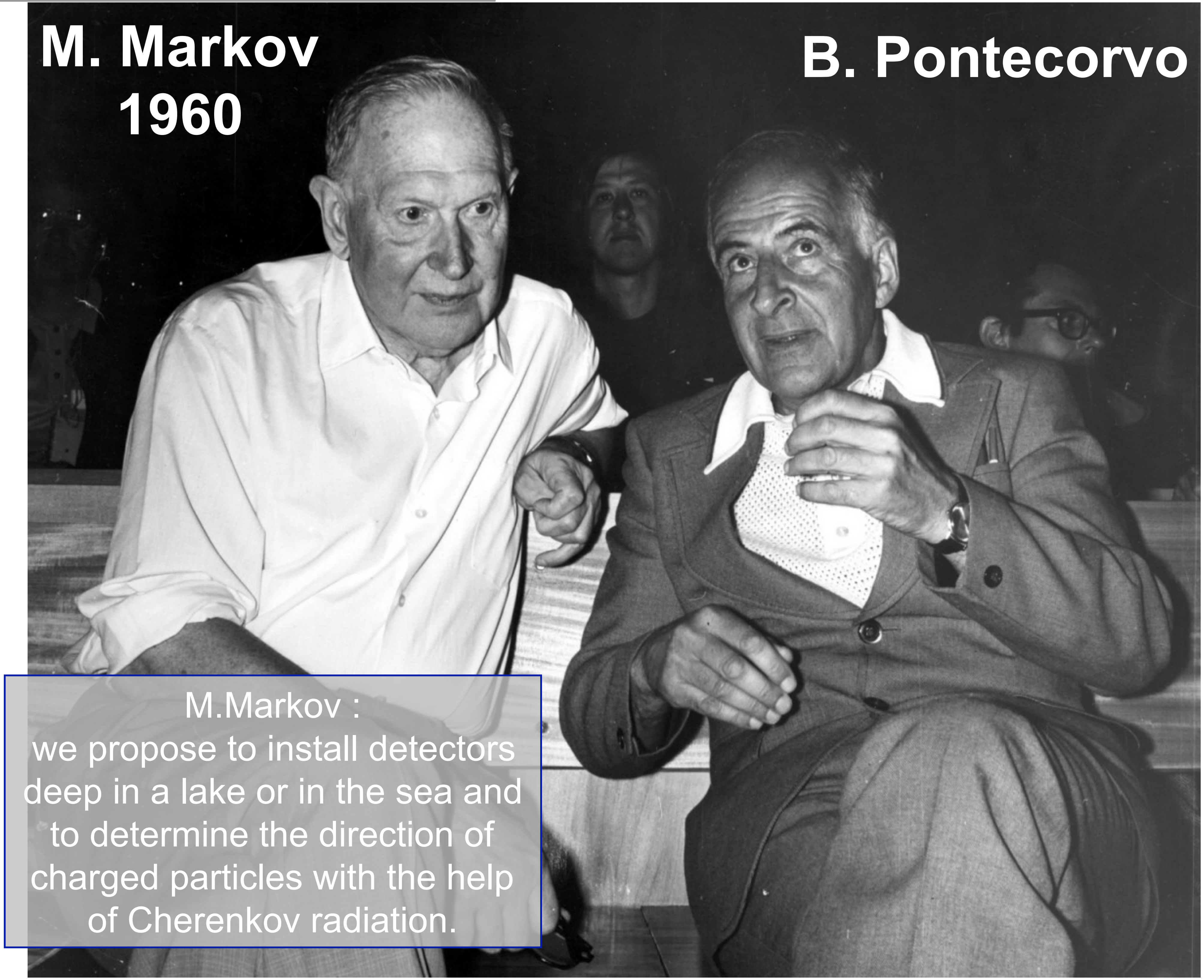




credit: C. Kopper

neutrino telescopes

proposal



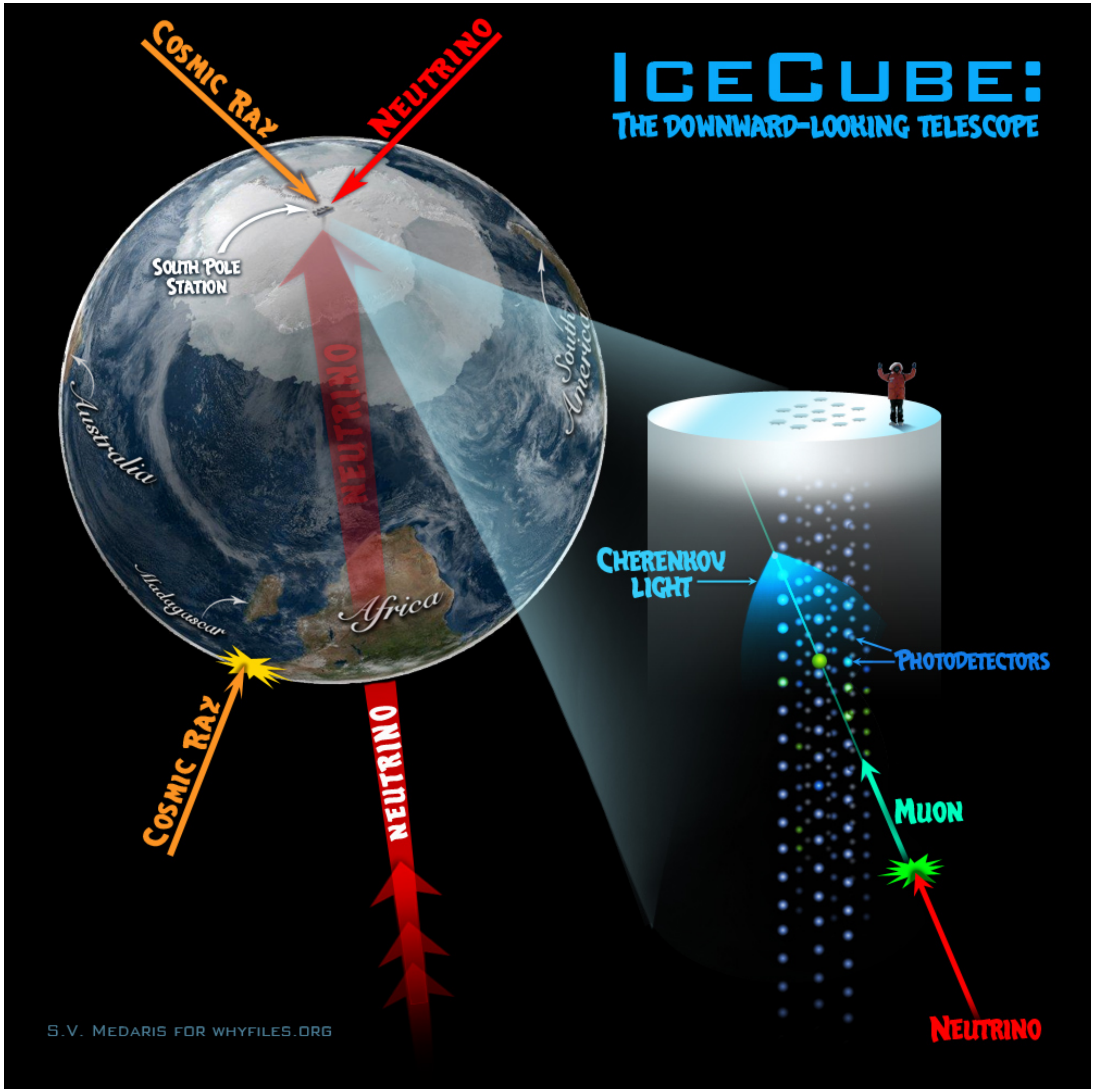
M. Markov
1960

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.

neutrino telescopes

Earth as interaction target & ice as detection material



S.V. MEDARIS FOR WHYFILES.ORG

detection unit

photomultiplier tube

on photo-cathode

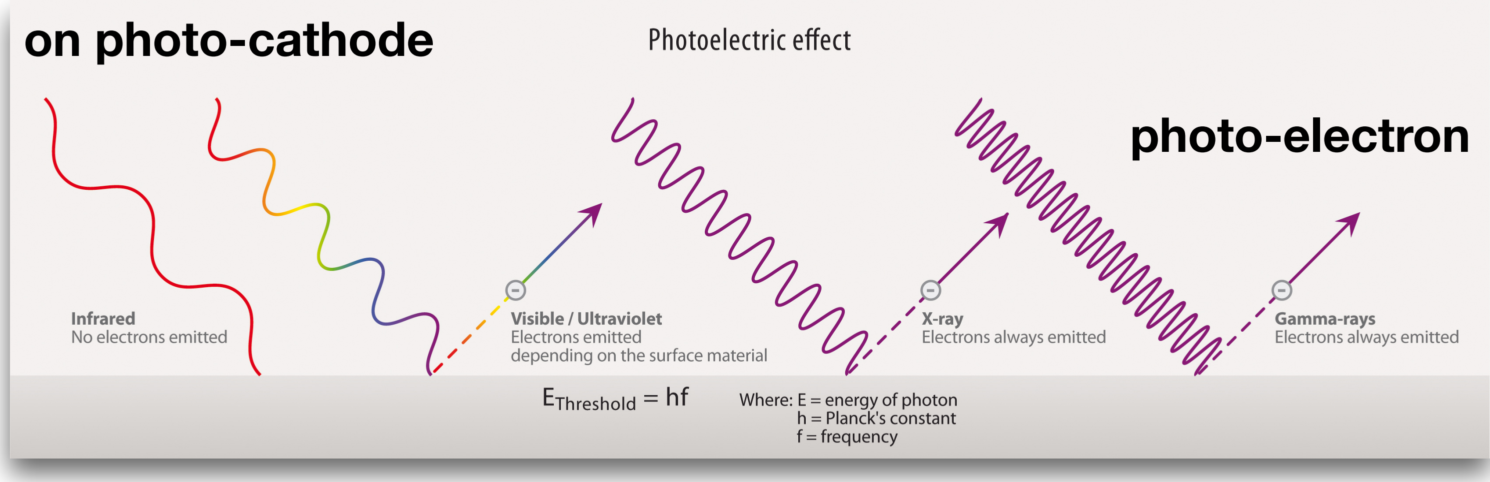
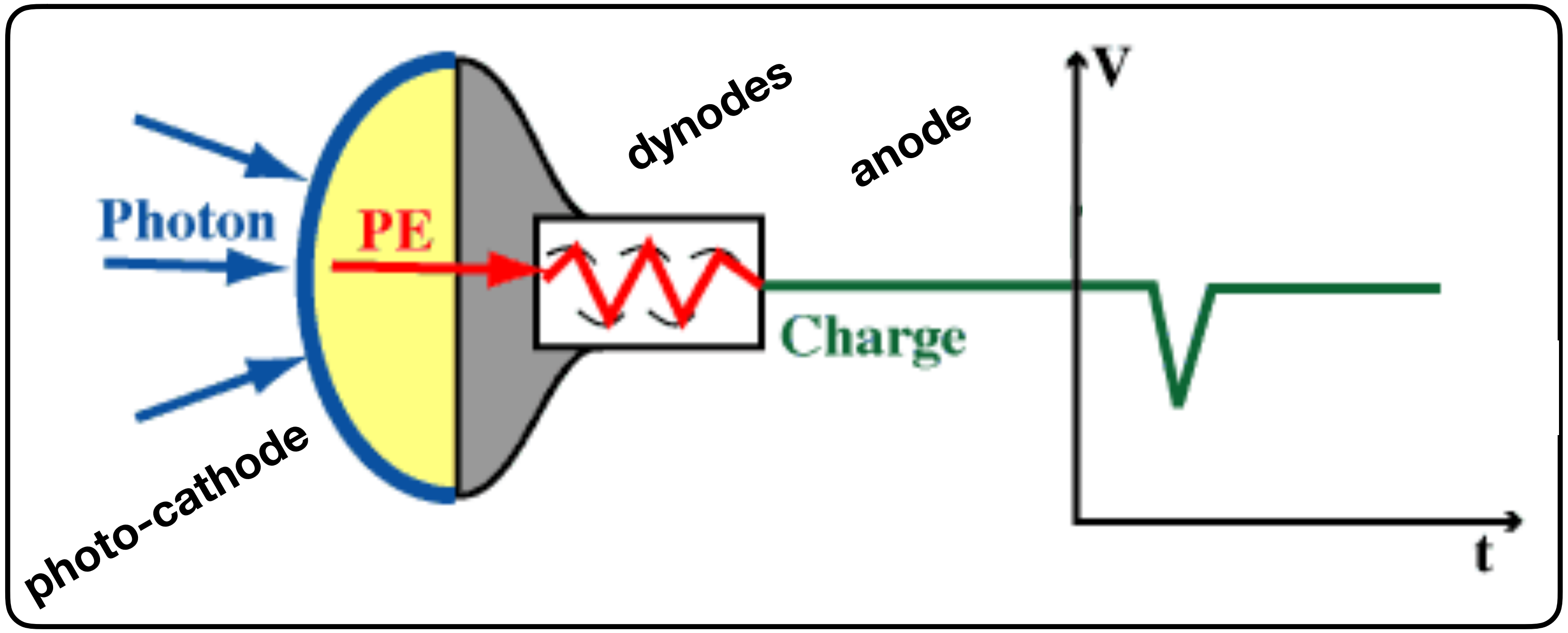
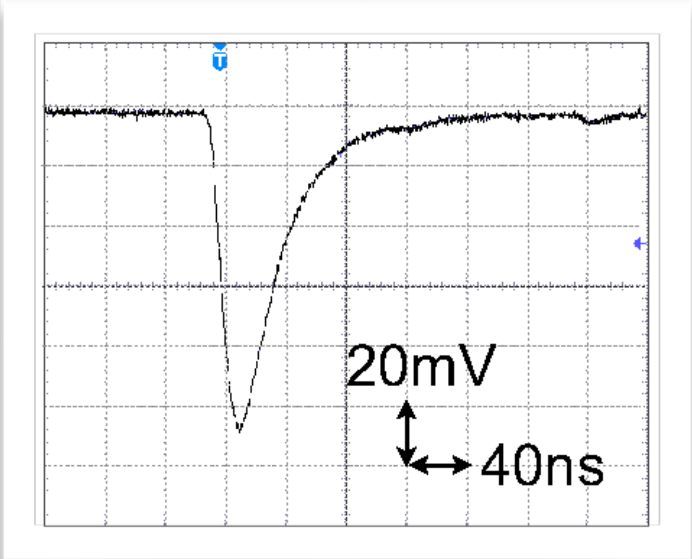


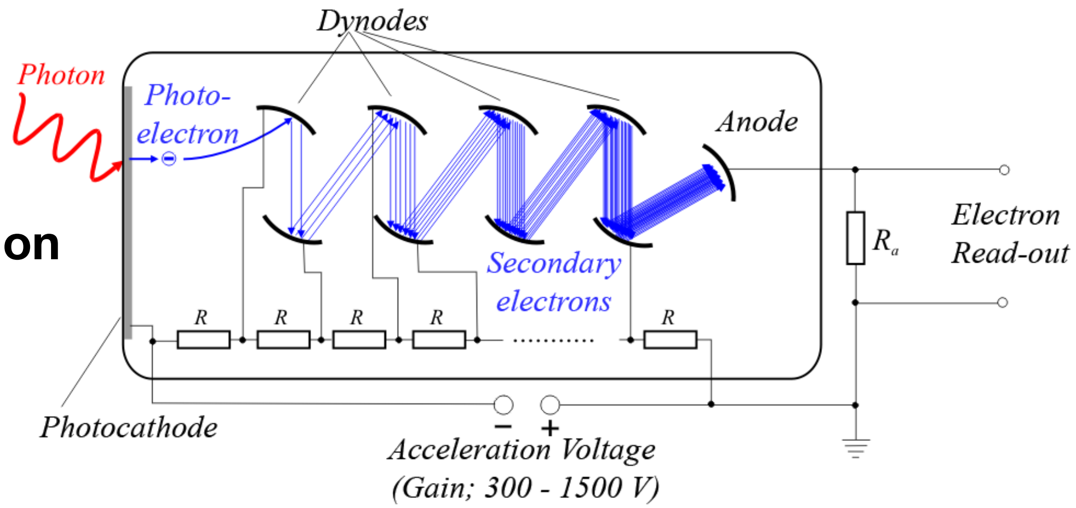
photo-electron



single photo-electron pulse



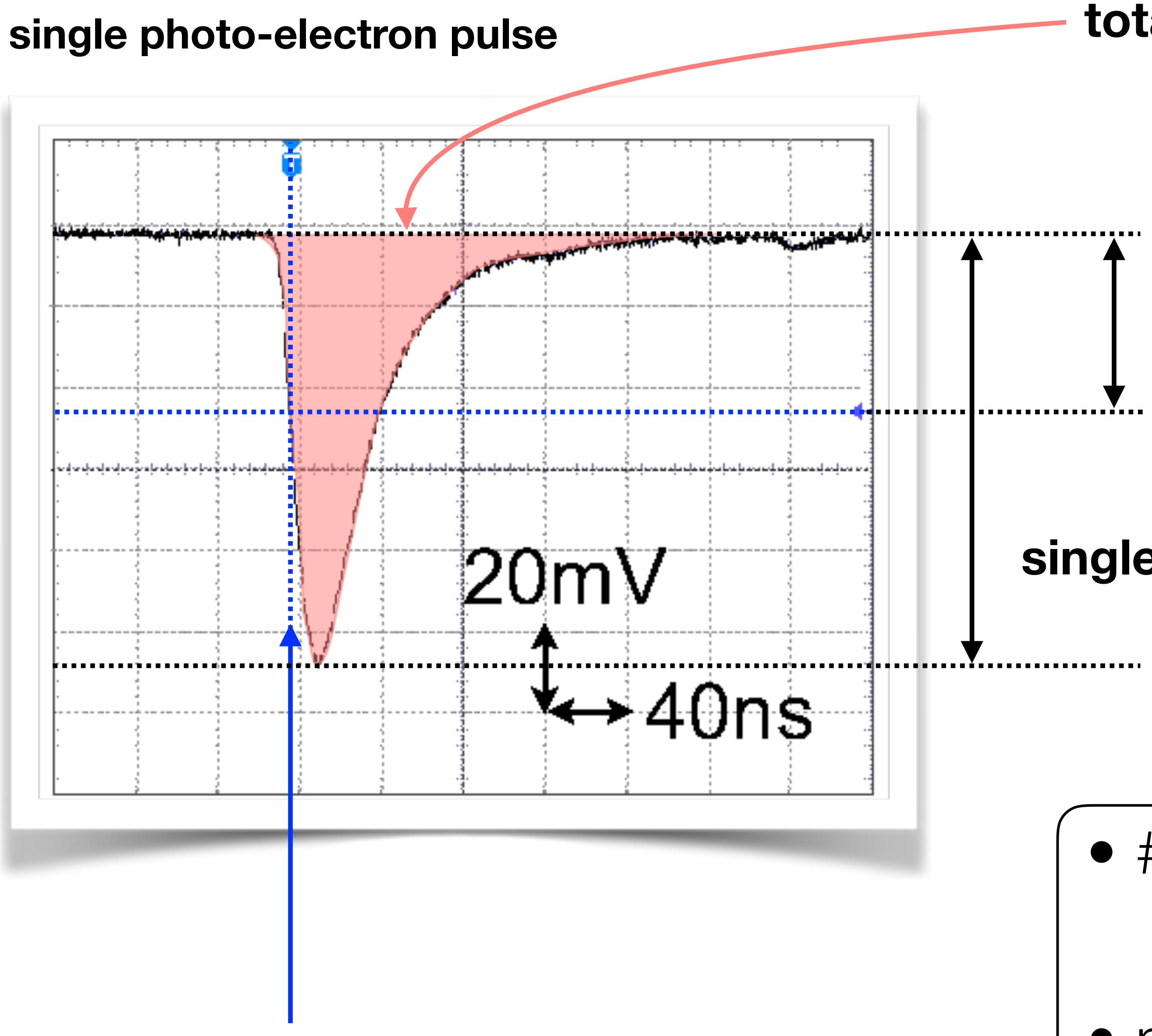
secondary electron emission for signal amplification



detection technique

photomultiplier tube

single photo-electron pulse



total charge ∝ #photon-electrons

threshold (1/4 photo-electron)

single photo-electron peak height

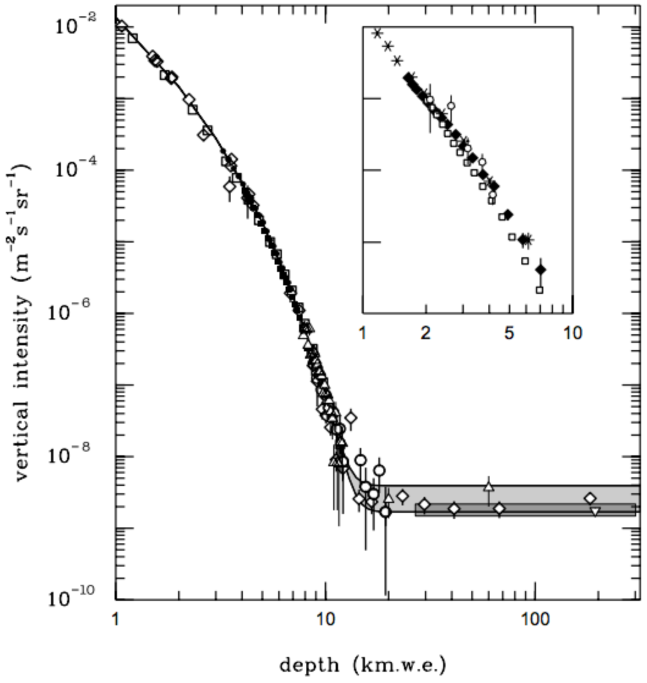
time stamp

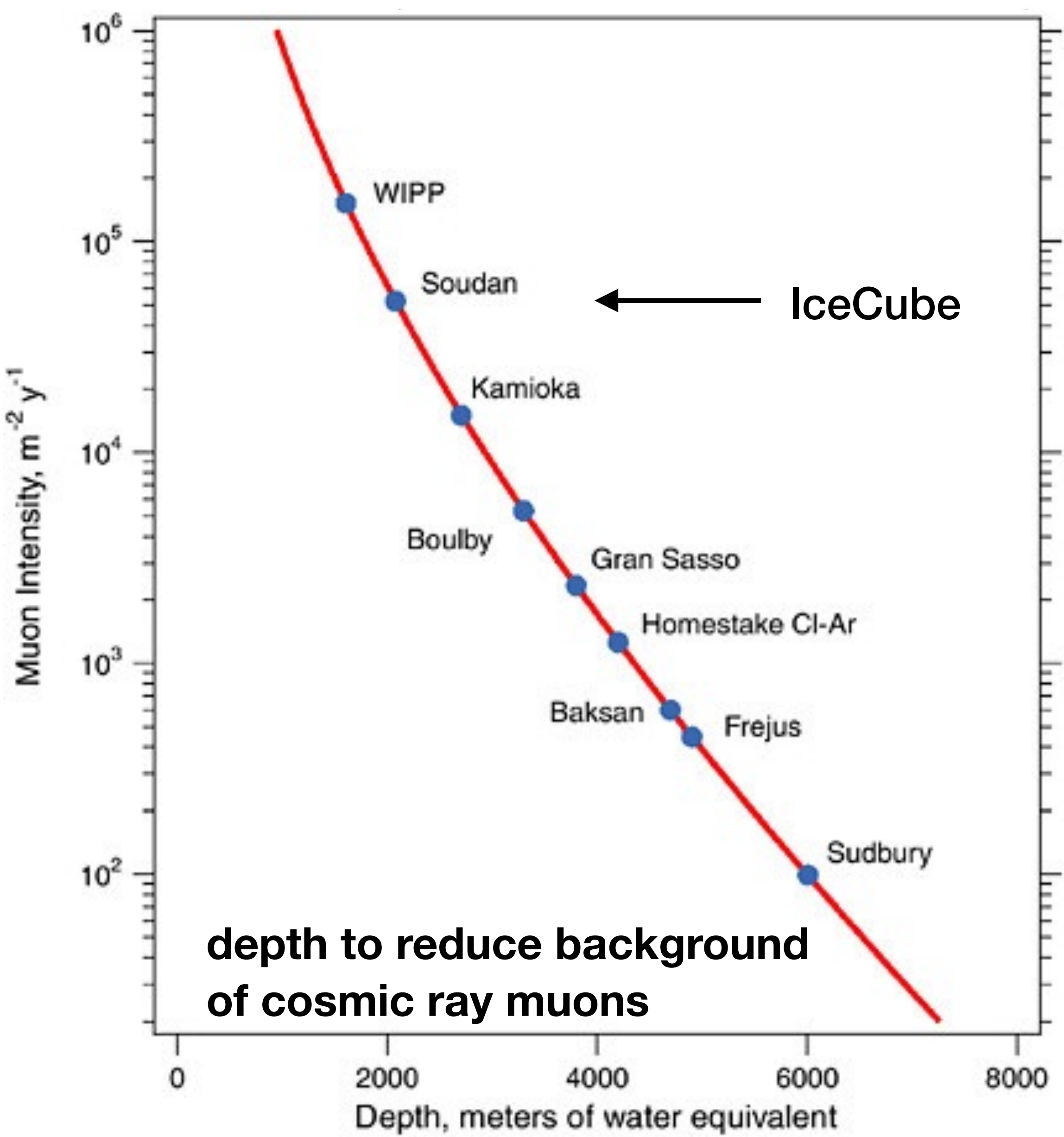
- #photo-electron = energy deposited × ε_{eff}
- measure **time** and **deposited energy**
- physics processes **shapes waveform**

detection technique

location, size and *photo-cathode area*

- **location** - under overburden to reduce background of cosmic ray muons
- **size** - increasing with neutrino energy. The largest experiments in transparent media.
- ***photo-cathode area*** - dense optical sensors in small detectors or coarse optical sensors in very large detectors. Influences **event reconstruction** and **flavor separation**.



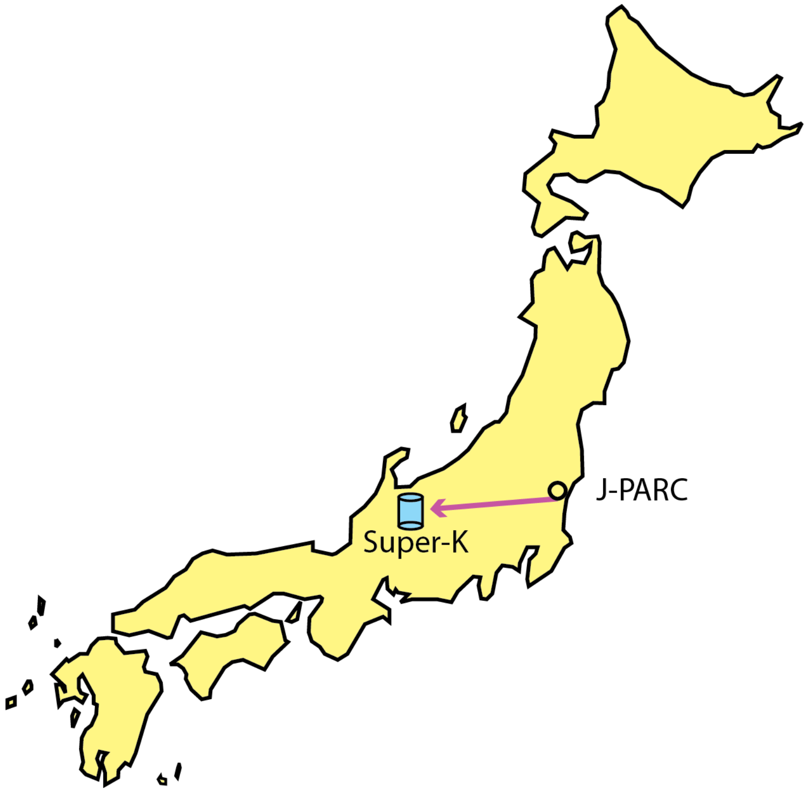


IceCube

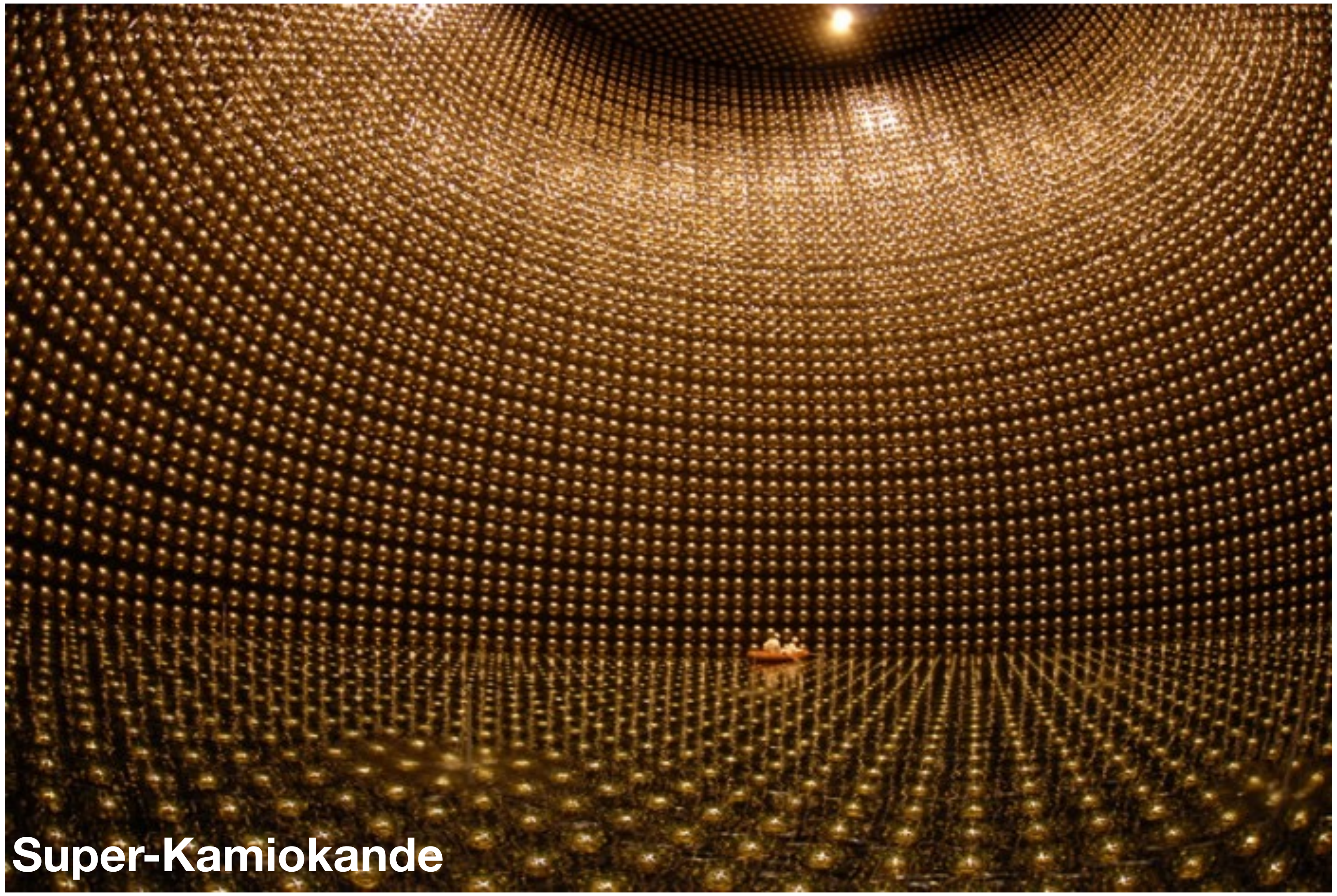
depth to reduce background of cosmic ray muons

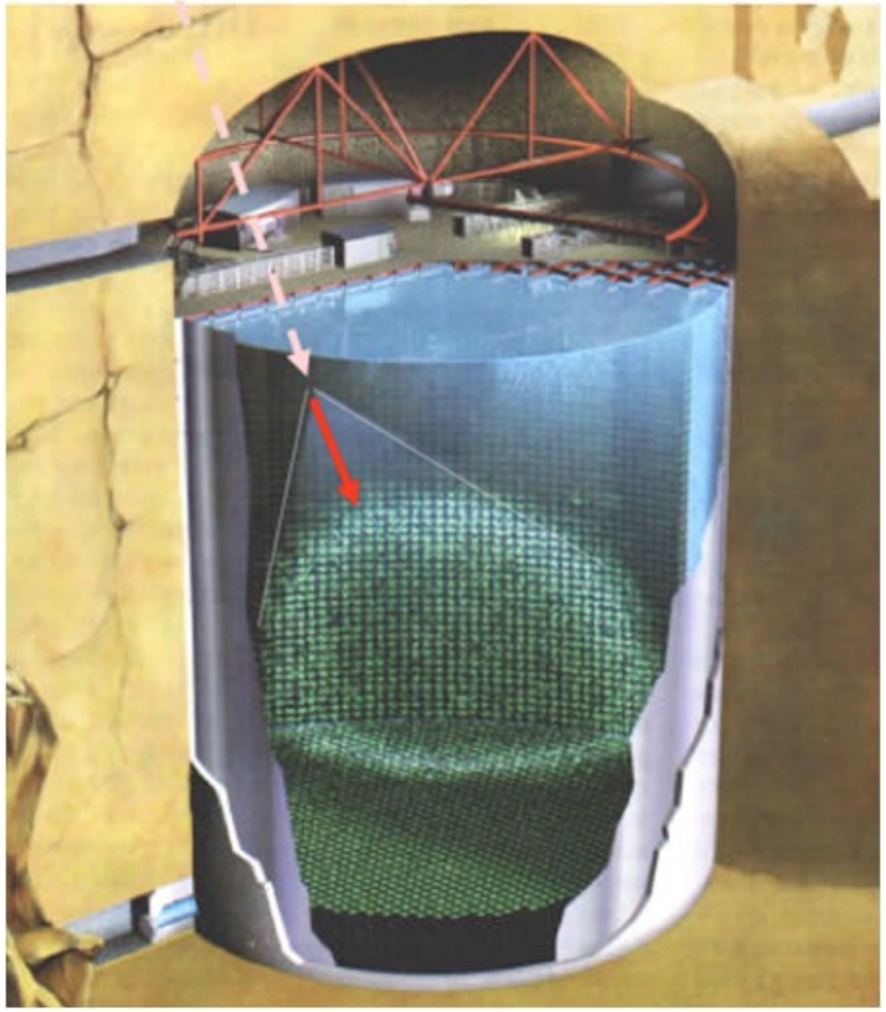
neutrino telescopes

location, size and *photo-cathode area*



- ***photo-cathode area*** - densely instrumented large volume experiments
  ~40^3 m^3 ~ 0.06 km^3

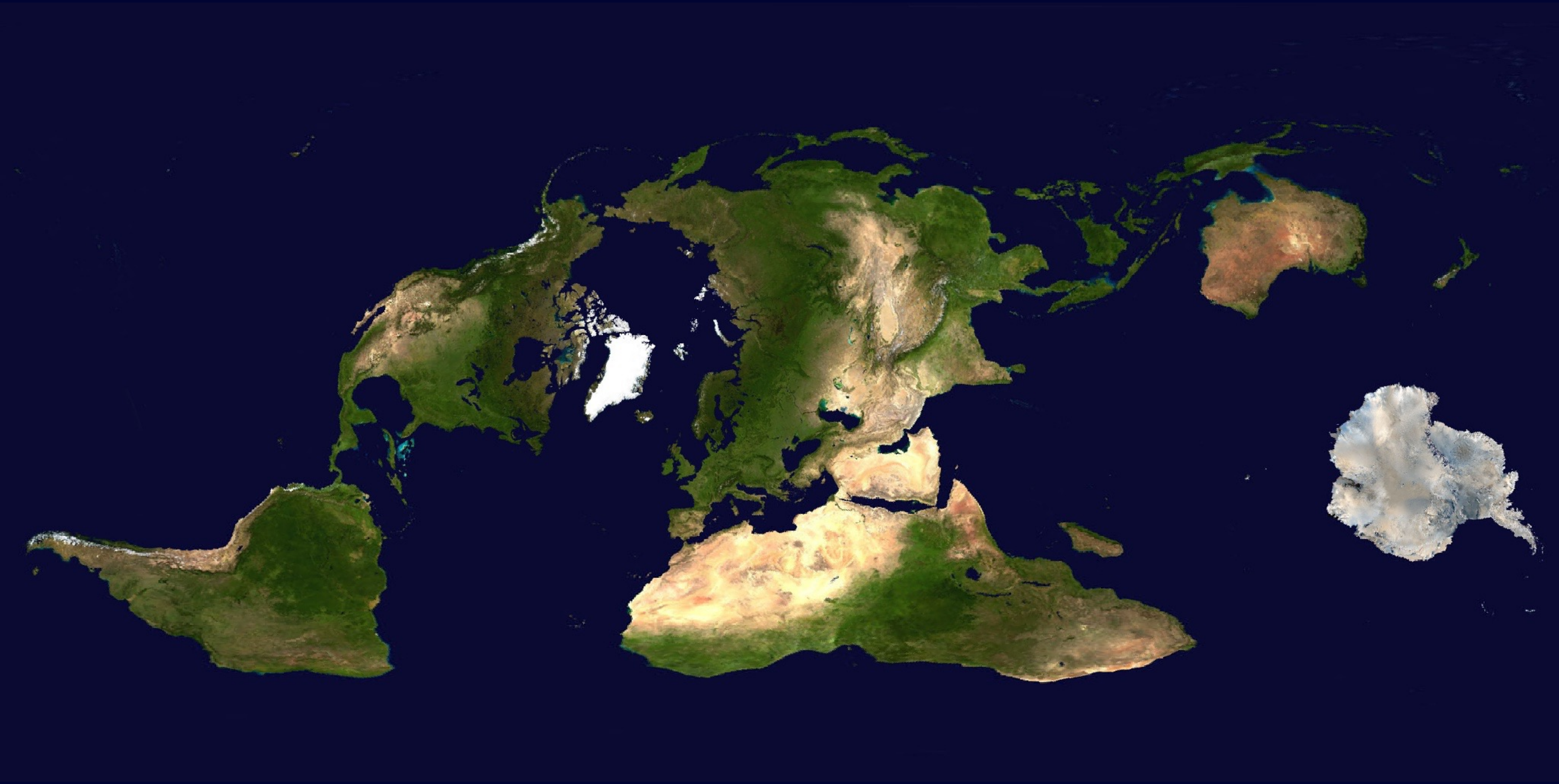




neutrino telescopes

large under-water/ice experiments

~ km^3 … and more



neutrino telescopes

large under-water/ice experiments

~ km^3 … and more

THANK YOU

NEXT:

- ICECUBE NEUTRINO TELESCOPE
- ACCELERATION MECHANISMS
- THE NEUTRINO MESSENGER