Energy Loss

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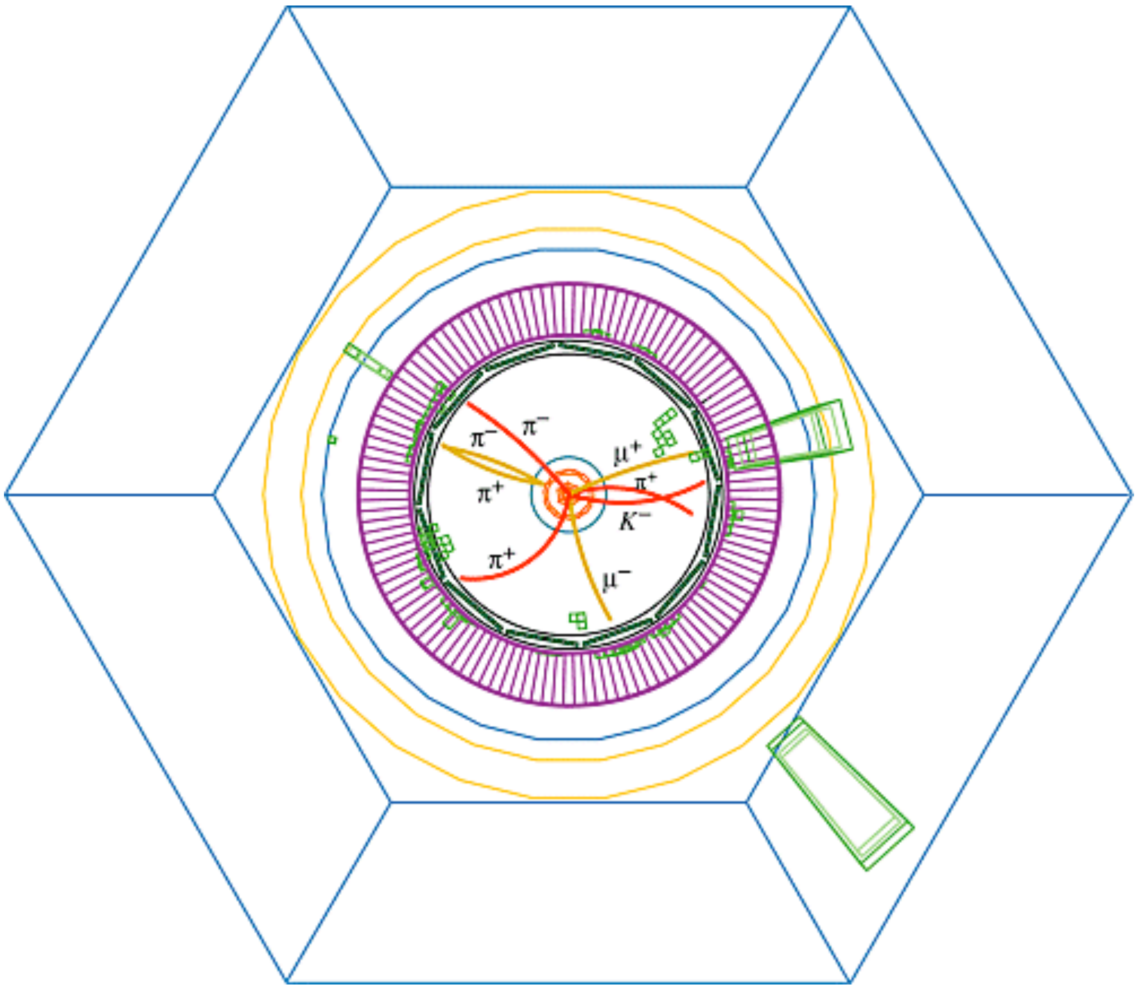
Outline

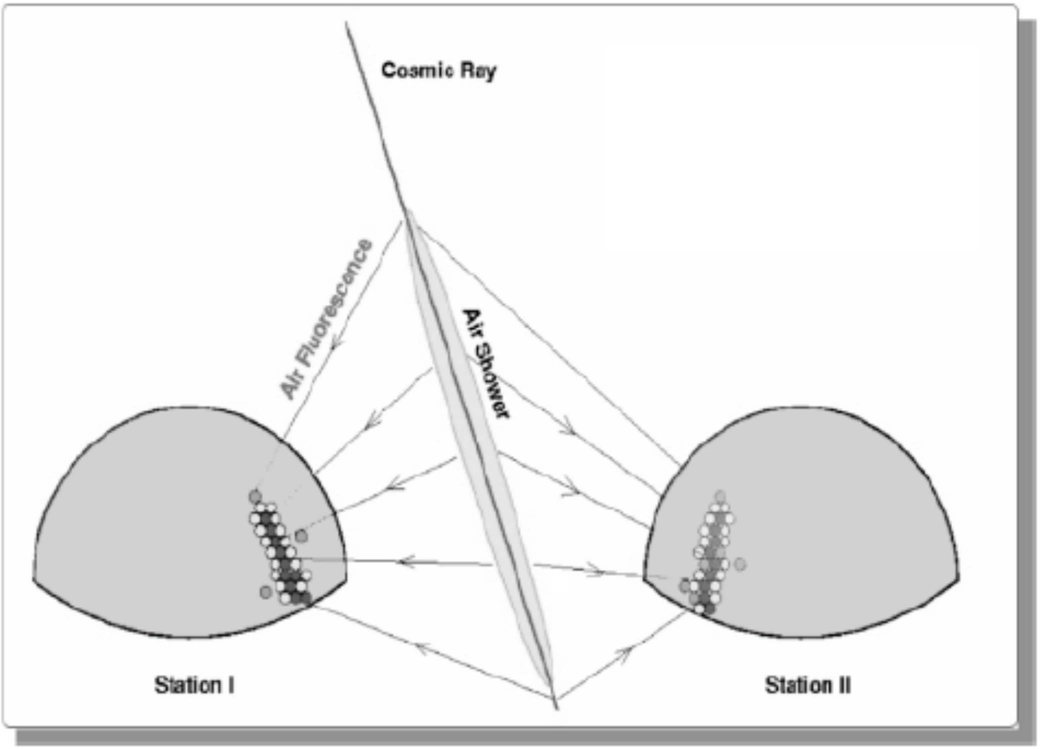
- Why study energy loss?
- Cases
  - Ionization, TPCs
  - Cerenkov, very high energy neutrinos
  - Transition, TRT, AMS/TRD
  - Nuclear Recoil, CDMS, CRESST
- Key numbers
- References

Why study energy loss?

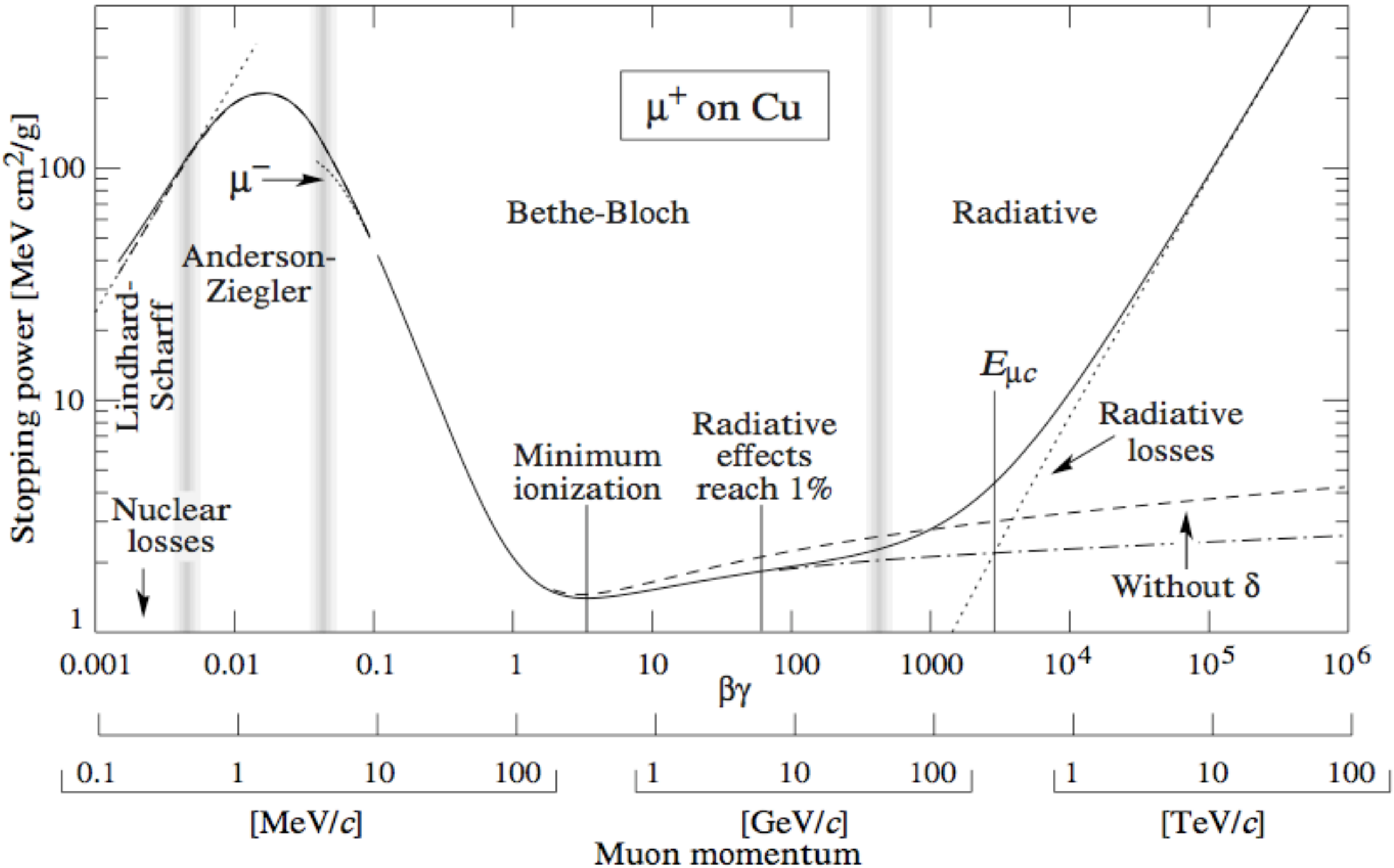


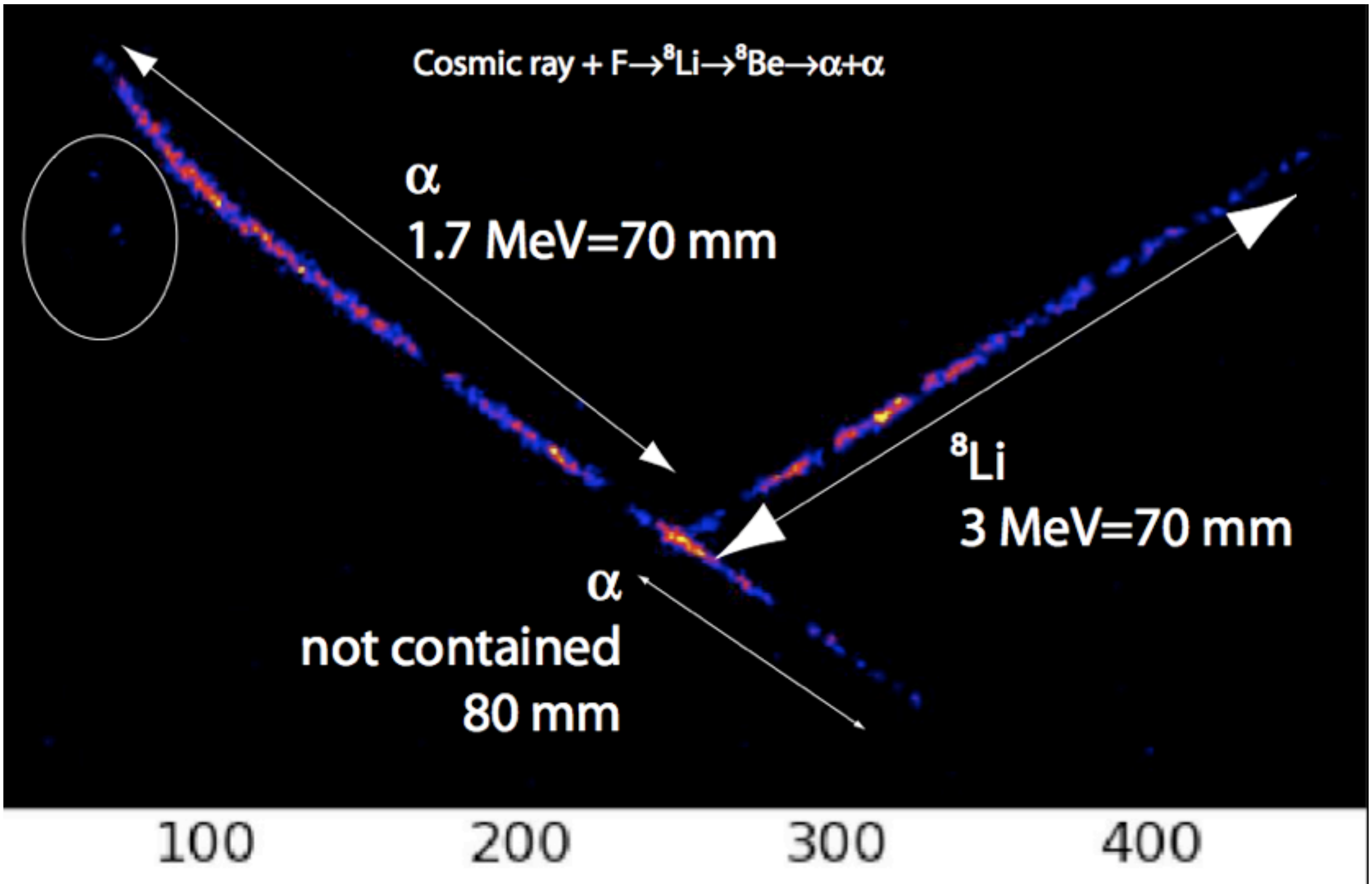
Even the very best detectors don't tell you what the particles are!

Why (cont.)?



Understanding energy loss mechanisms can lead to new experiments - Fly's Eye (later HiRES) relies only on fluorescence and clear air to detected the very highest energy particles.


μ+ on Cu
Stopping power [MeV cm2/g]
100
10
1
μ−
Bethe-Bloch
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Eμc
Radiative
losses
Minimum
ionization
Radiative
effects
reach 1%
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum


Cosmic ray + F→⁸Li→⁸Be→α+α
α
1.7 MeV=70 mm
⁸Li
3 MeV=70 mm
α
not contained
80 mm
100
200
300
400

Nomenclature

- N - number density
- Z - number protons
- A=N+Z
- m_N - nucleon mass
- m - electron mass
- ρ - mass density, radial coordinate
- T - deposited energy
- E - incident energy
- dx - medium thickness
- ε - dielectric constant
- θ - scattering angle in lab
- $\alpha = e^2/hc/2\pi = 1/137$
- ω - angular frequency

Single particle kinematics

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \Rightarrow m = \frac{p}{\gamma\beta c}$$

$$E = \gamma mc^2$$

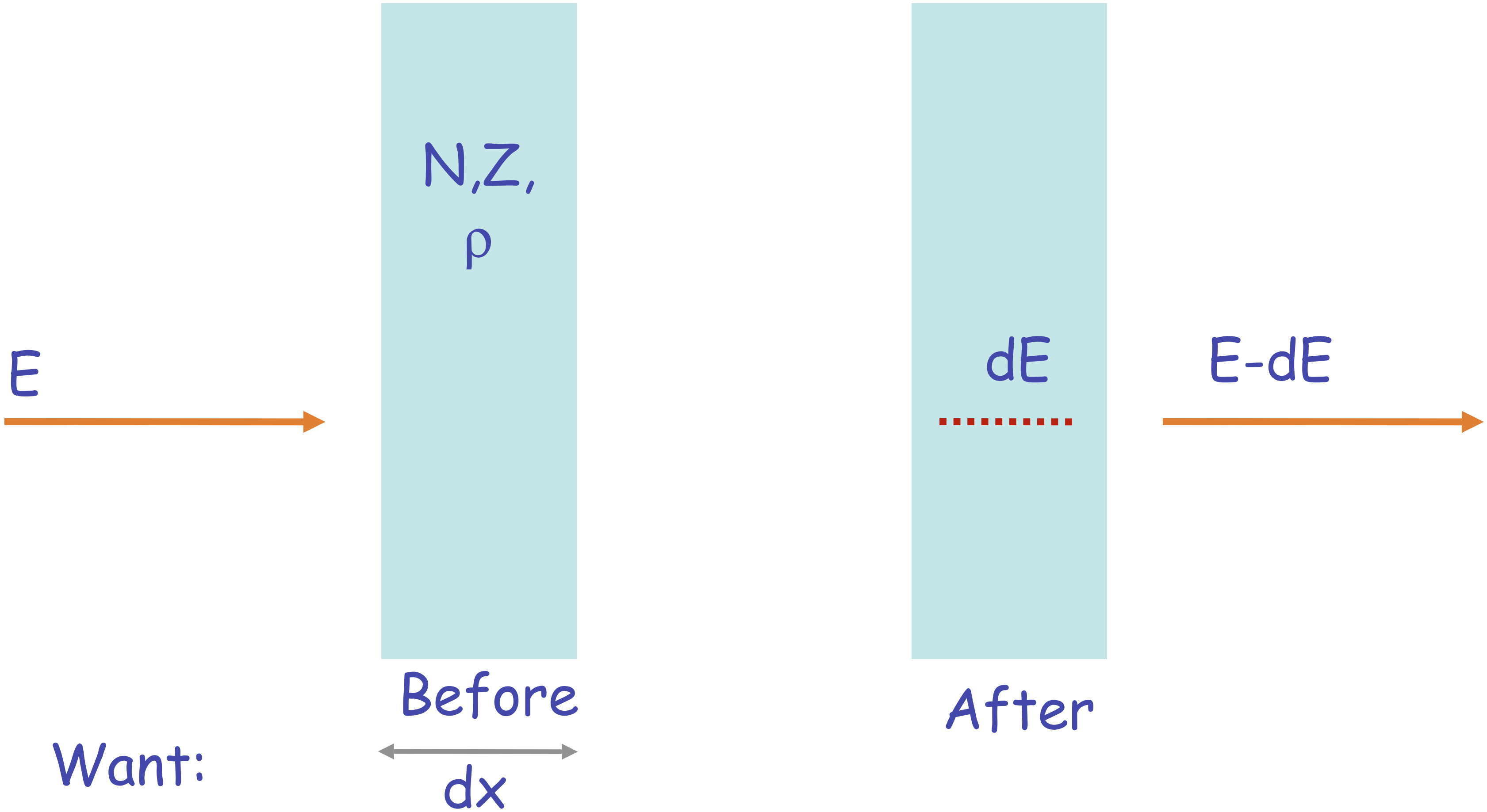
$$p = \gamma\beta mc$$

- Identifying a particle is (generally) the same as measuring it mass
- Need to measure two quantities to find m.

In a magnetic field:

$$p_\perp = \frac{0.3\text{GeV}}{\text{T}-\text{m}} B\rho$$

General Problem

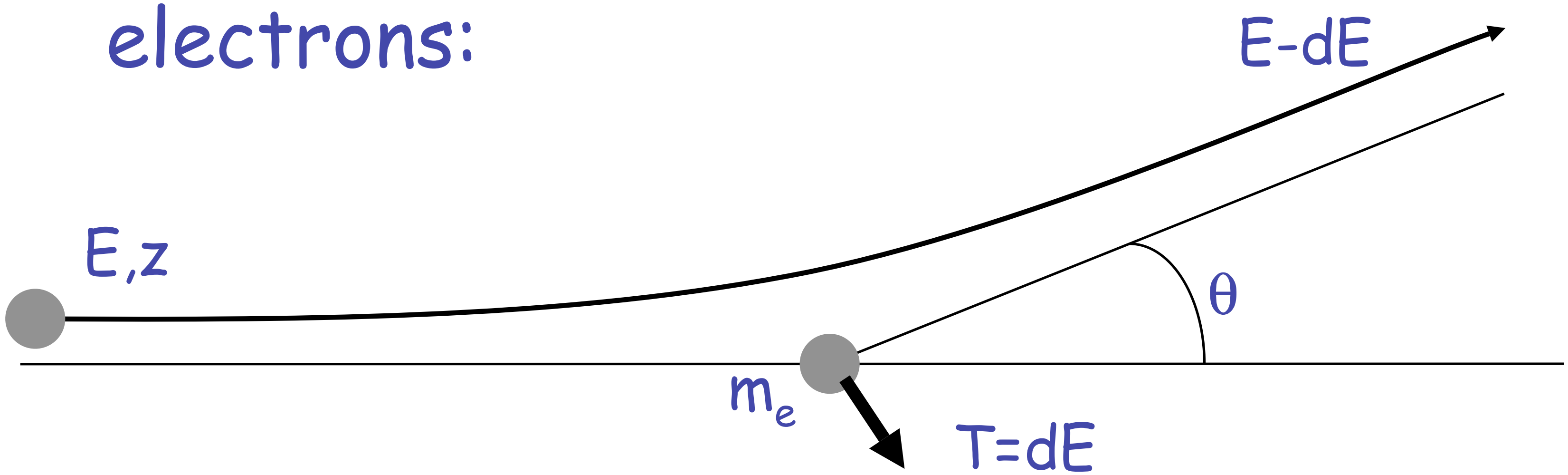


Want:

- dE/dx - particle
- Effect on medium - detection

1a. Ionization loss - adding single collisions

Simplest approach - treat as a series of Coulomb collisions with atomic electrons:



Rutherford:

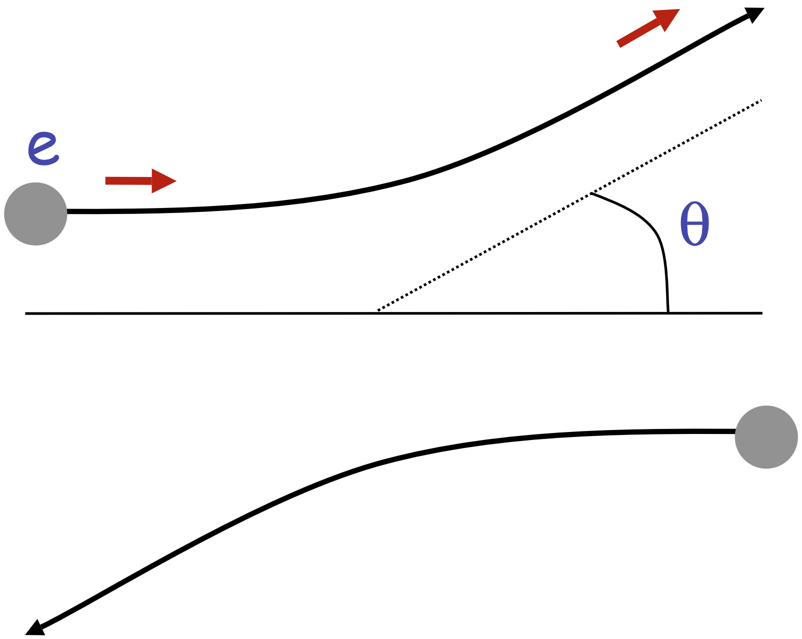
$$\frac{d\sigma}{d\Omega} = \frac{z^2 e^4}{4 p v \sin^4 \theta/2}$$

Kinematics

- Some trig: $$\sin^2\frac{\theta}{2} = \frac{1}{2}\left(1-\cos\theta\right)$$
- Momentum transfer: $$Q^2 = -(p-p')^2 = 4p^2\sin^2 \theta/_2 = 2mT$$
- Recoil kinetic energy: $$T = \frac{Q^2}{2m}$$
- Solid angle: $$d\Omega = 2\pi d\left(\cos\theta\right) = \frac{\pi}{2p^2}dQ^2$$

$$\frac{d\sigma}{dQ^2} = 4\pi\frac{z^2e^4}{\beta c Q^4} \Rightarrow \frac{d\sigma}{dT} = \frac{2\pi z^2 e^4}{mc^2\beta T^2}$$

A quantum correction for spin



- Spin of electron rotated through angle θ during collision
- Average over initial, sum over final states gives probability factor

$|A|^2=(1-\beta^2\sin^2\theta/2)$

$$\Rightarrow \frac{d\sigma}{dT} = \frac{2\pi z^2 e^4}{mc^2\beta^2 T^2}\left(1-\beta^2\frac{T}{T_{\max}}\right) \text{ and } T_{\max} = 2\gamma^2\beta^2 mc^2$$

Sum over many scatters…

- Sum over N scattering sites particle passes
- Minimum energy $\varepsilon \gg E_{binding}$

$$\frac{dE}{dx} = \int_{\varepsilon}^{T_{\max}} \left(N \frac{d\sigma}{dT} \right) T dT = 2\pi N Z \frac{e^4}{mc^2 \beta^2} \left[\ln\left(\frac{2\gamma^2 \beta^2 mc^2}{\varepsilon} \right) - \beta^2 \right]$$

Observations:

1. Goes like $1/\beta^2$ -> very large loss at low β
2. Goes like $\ln \gamma$ as $\beta \to 1$, but density effect
3. Independent of particle mass -> can measure β
4. Distant collisions (Bethe 1930), $\varepsilon \to h\langle\omega\rangle/2\pi$

- •Emulsion pictures of π–μ-e decays
- • μ all have same length -> two body π decay
- • μ track gets wider near end -> $1/\beta^2$ energy loss

Minimum ionizing

Leading factor $\frac{2\pi N Z e^4}{mc^2}$ gives charcteristic energy loss.

For most materials:

- $N=\rho/Am_N$
- $Z=A/2$

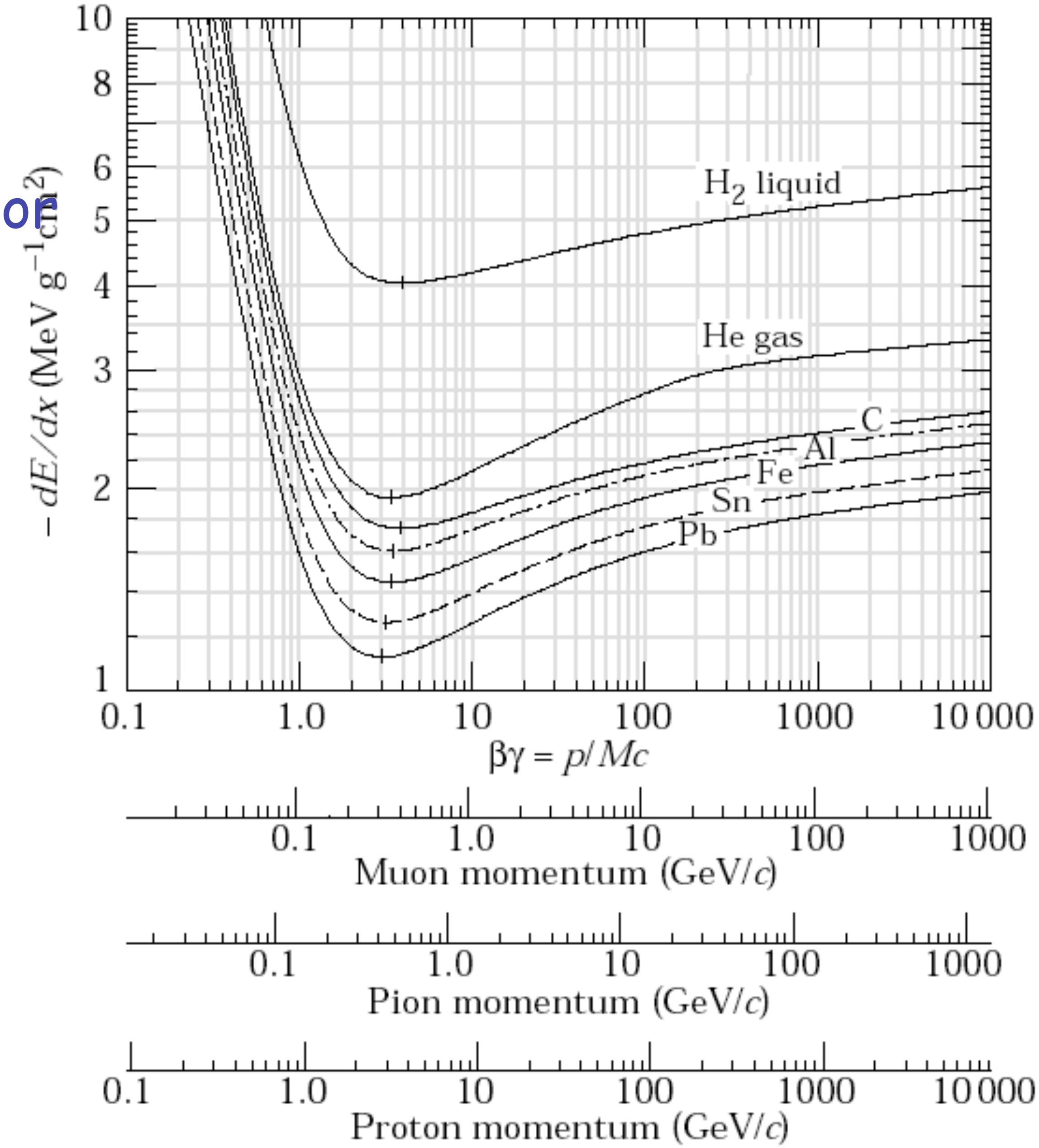
$$\frac{2\pi\alpha^2(\hbar c)^2}{mc^2}\frac{A}{2}\frac{\rho}{Am_N}\approx 0.08\frac{\text{MeV}}{\text{g/cm}^2}\rho$$

Minimum occurs at γ~4:

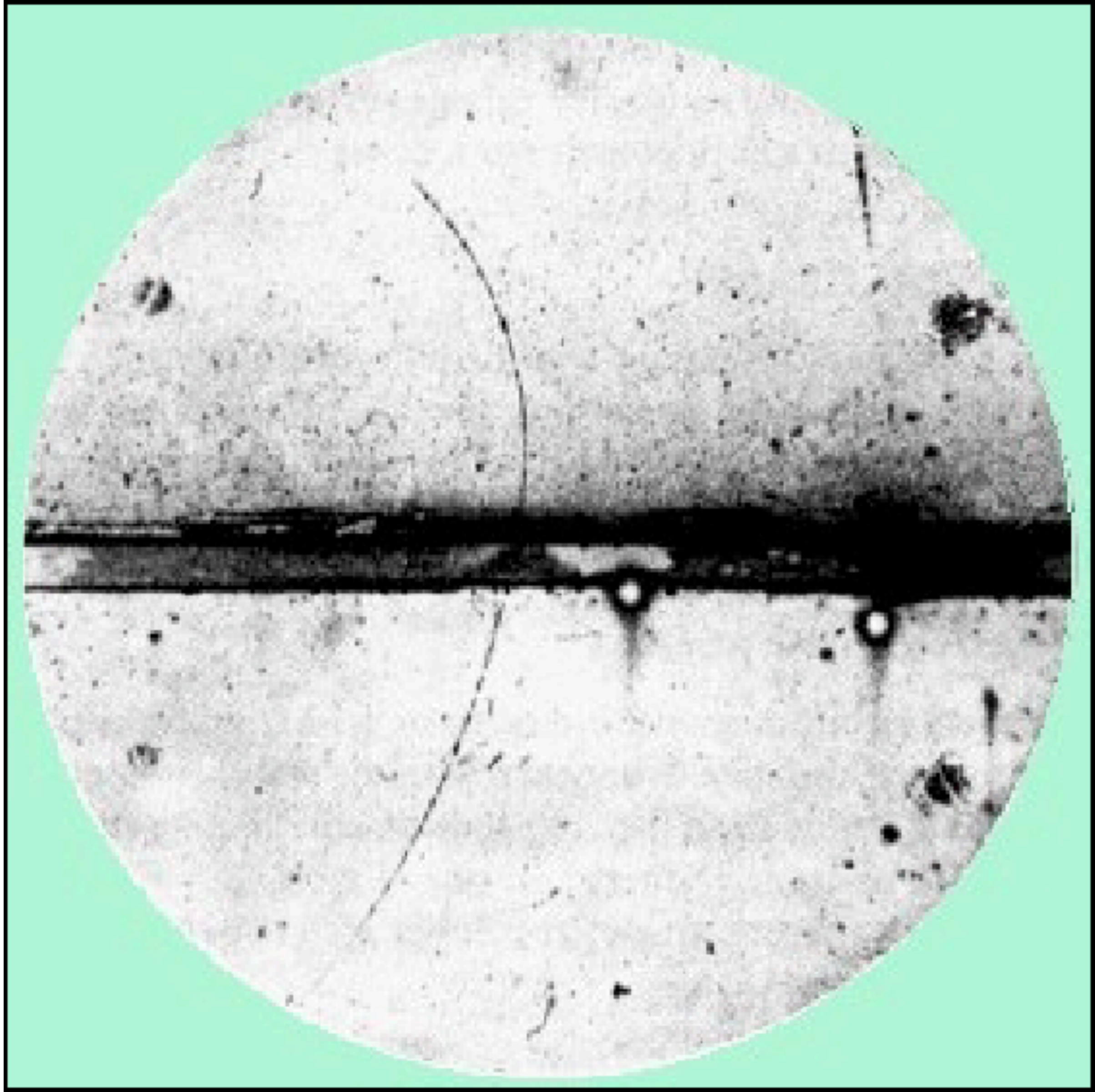
$$\left(\frac{dE}{dx}\right)_{\min}\approx 1.8\frac{\text{MeV}}{\text{g/cm}^2}$$

From PDG - dE/dx for various materials

- $(dE/dx)_{min}$=1-2MeV/g-cm^2
- Minimum occurs near E=4m



Discovery of positron in cloud chamber



Lead plate thickness = 6 mm

Magnetic field = 24000 gauss into picture

Dimensions: 17 x 17 x 3 cm

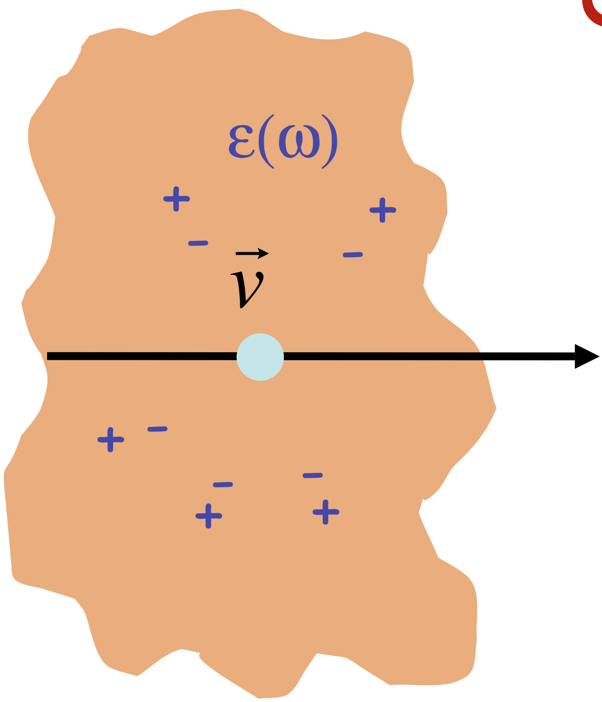
Change of curvature implies particle moving up, so charge is positive

Track density => $Z/\beta = 1$

$A\beta\gamma/Z = 0.07$ below plate, 0.02 above plate: so $A < 0.02$

For very low energy particles like these, mass and charge can be measured, showing them to be positrons.

1b. Single collision in dielectric



source terms:

$$\rho(\vec{x},t) = ze\delta(\vec{x}-\vec{v}t)$$

$$\vec{J}(\vec{x},t) = ze\vec{v}\delta(\vec{x}-\vec{v}t)$$

Solve for potentials with source terms:

$$\left(k^2 - \frac{\omega^2}{c^2}\varepsilon(\omega)\right)\Phi = \frac{4\pi}{\varepsilon(\omega)}\rho$$

$$\left(k^2 - \frac{\omega^2}{c^2}\varepsilon(\omega)\right)\vec{A} = \frac{4\pi}{c}\vec{J}$$

Calculation of energy loss

$$E_{\parallel} = -\frac{ize\omega}{v^2}\left(\frac{2}{\pi}\right)^{1/2}\left[\frac{1}{\varepsilon(\omega)} - \beta^2\right]K_o(\lambda b)$$

$$E_{\perp} = \frac{B_{\perp}}{\beta\varepsilon(\omega)} = \frac{ze}{v}\left(\frac{2}{\pi}\right)^{1/2} K_1(\lambda b)$$

$$\lambda^2 = \frac{\omega^2}{c^2}\left(1 - \beta^2\varepsilon(\omega)\right)$$

$$\Rightarrow \quad \Delta E = -\int_{-\infty}^{\infty} \vec{v} \bullet \vec{F} dt = -e\int_{-\infty}^{\infty} \vec{v} \bullet \vec{E} dt = -\frac{ca}{2} e \int_{-\infty}^{\infty} B_{\perp}(t) E_{\parallel}(t) dt$$

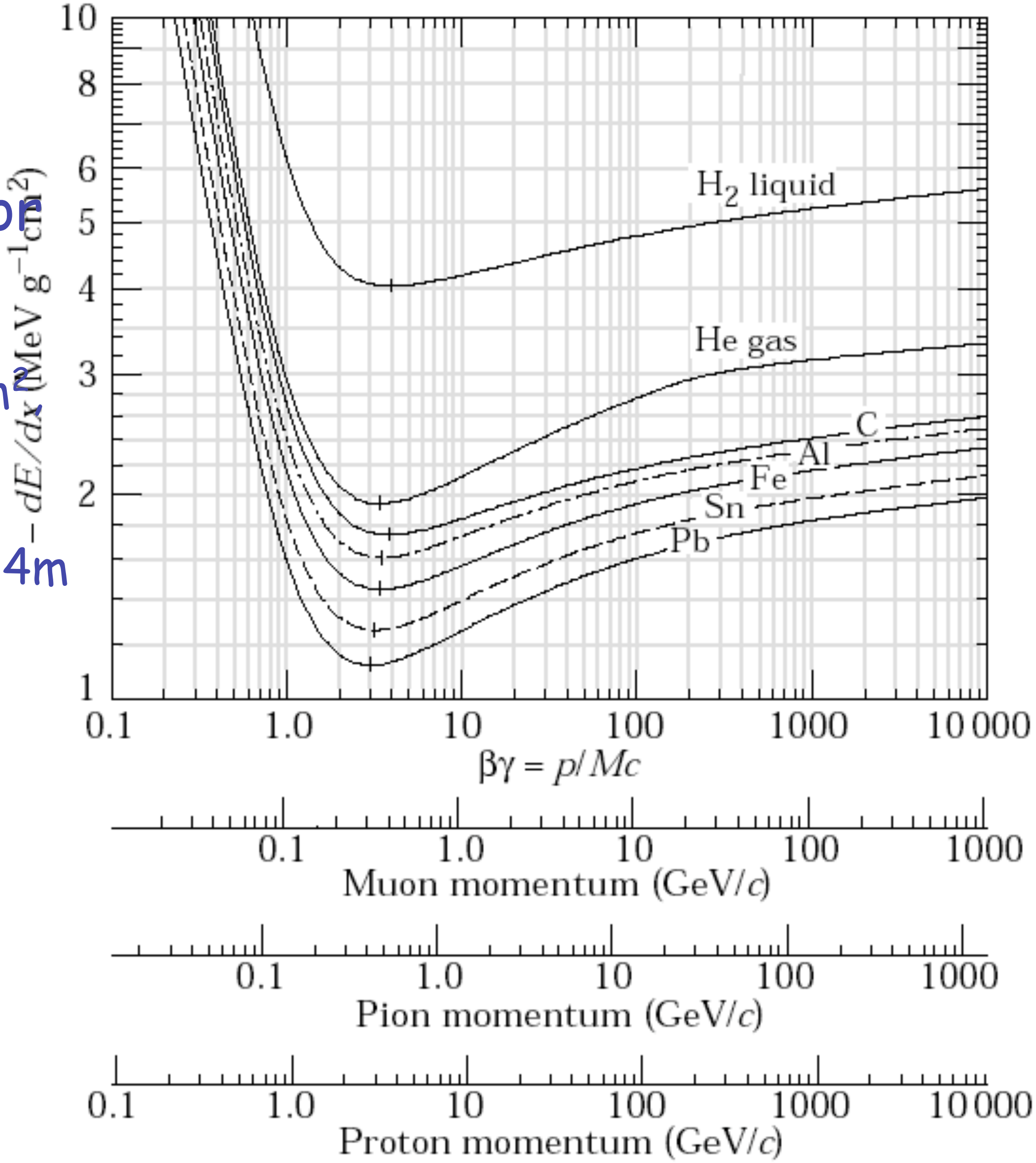
λ is a characteristic length if the fields

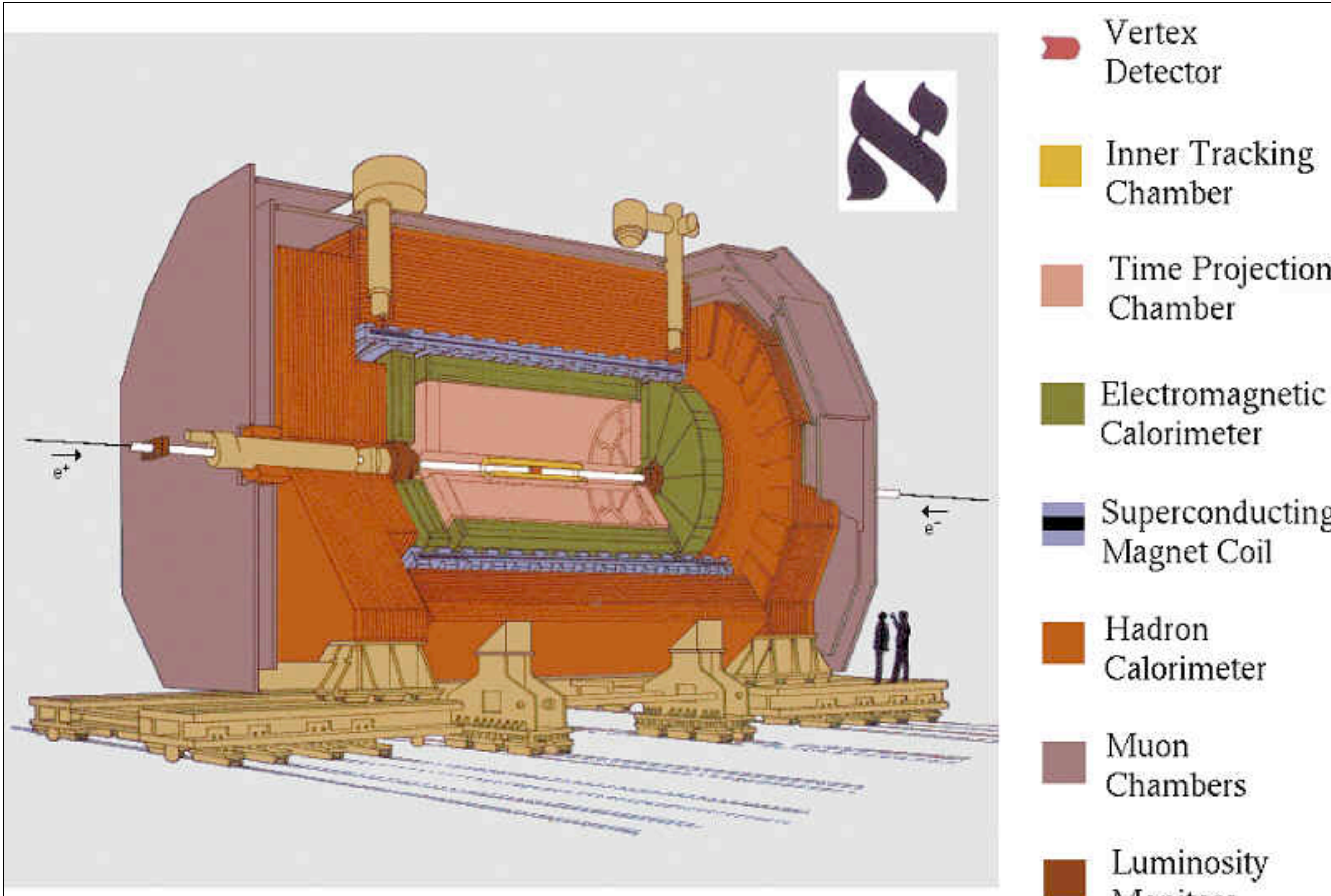
For $\beta \sim 1$ and $\lambda\beta << 1$ (near field region) $$\frac{dE}{dx} = \frac{(ze)^2\omega_p^2}{c^2}\ln\left(\frac{1.123c}{a\omega_p}\right)$$

Energy loss becomes independent of energy at $\beta \sim 1$

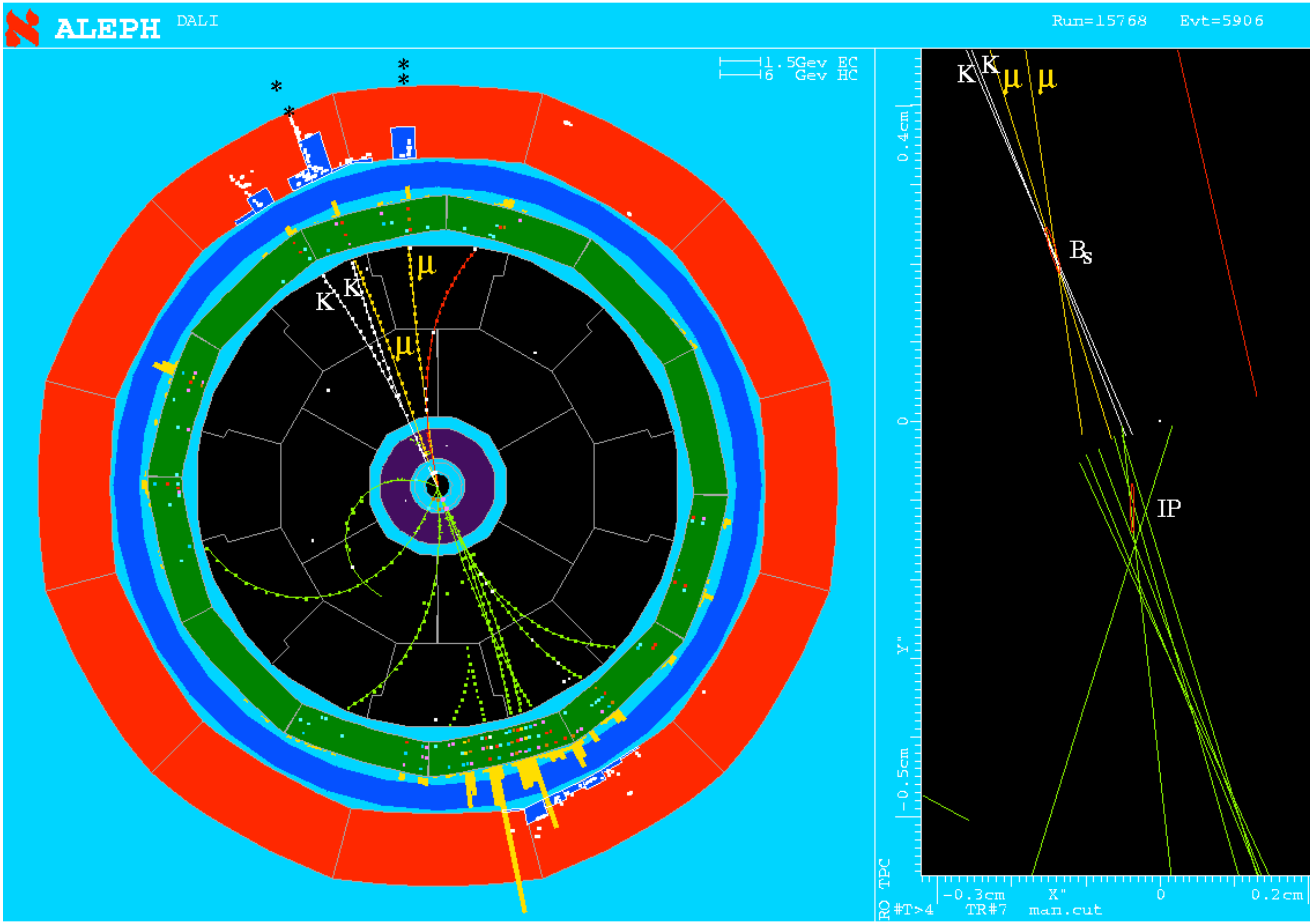
From PDG - dE/dx for various materials

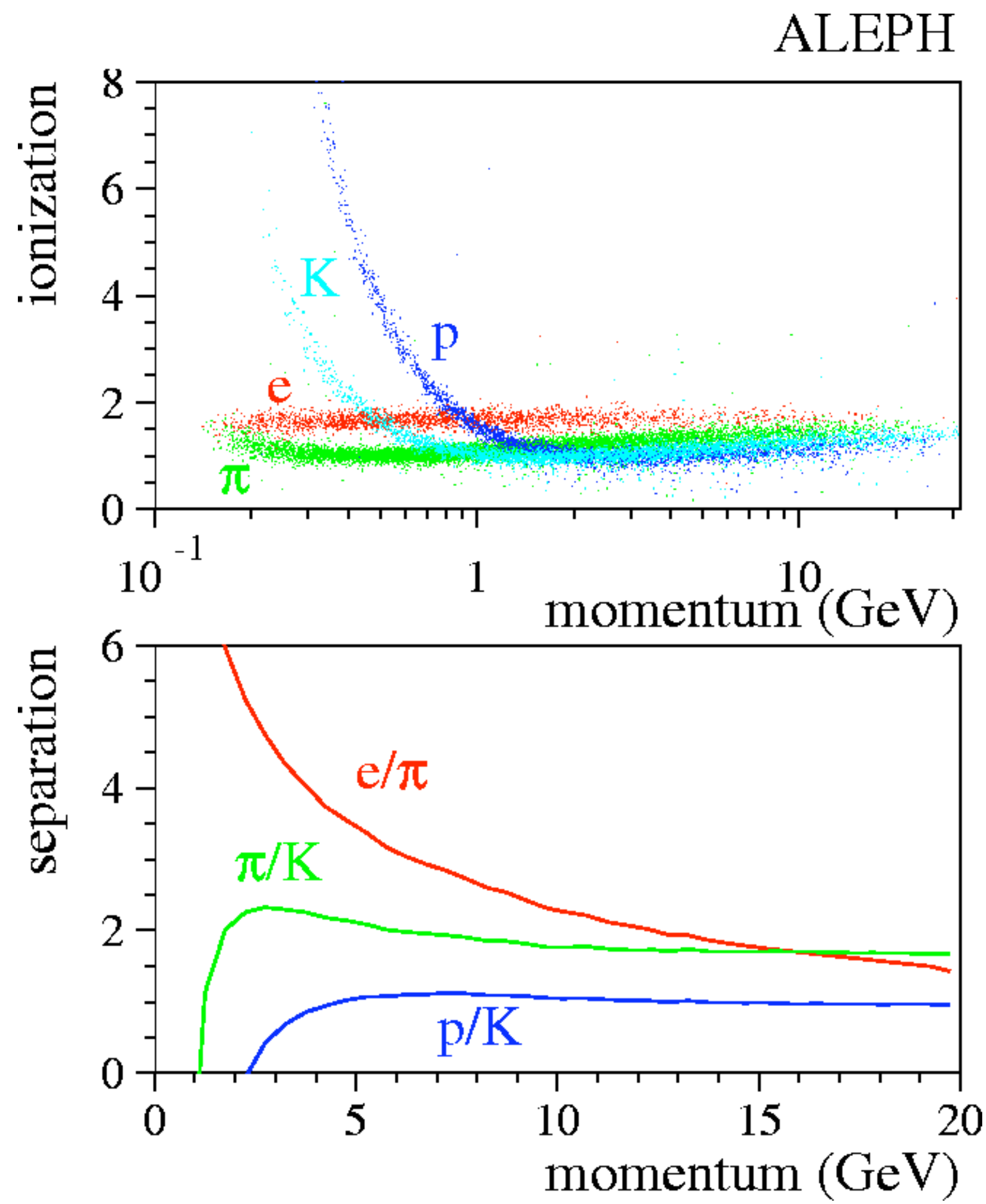
- $(dE/dx)_{min}$=1-2MeV/g-cm² depends on Z/A.
- Minimum occurs near E=4m
- "Relativistic rise" by 10-20% to γ=10,000





The ALEPH Detector


ALEPH
DALI
Run=15768 Evt=5906
1.5Gev EC
6 Gev HC
K
K
μ
μ
Bs
IP
0.4cm
0
-0.5cm
Y"
-0.3cm
X"
0
0.2cm
RO TPC
#T>4
TR#7
man.cut



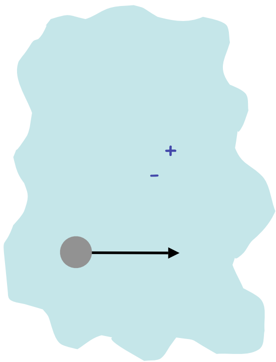
- Masses:
  - M_e=0.0005 GeV
  - M_π=0.14 GeV
  - M_K=0.49 GeV
  - M_p=0.938 GeV
- Thickness of bands due to statistical fluctuations in energy loss
- Separation up to ~10 GeV

Further topics

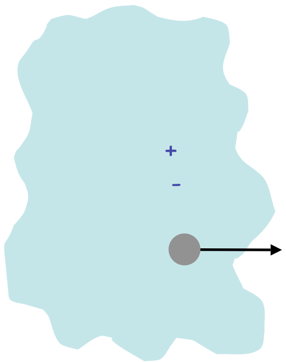
- High energy secondary electrons ("δ-rays")
- Radiation from collisions (bremstrahlung)
- Electromagnetic showers (cascade of pair production from initial e or γ.
- Hadronic showers

2. Cerenkov radiation - the radiation field in a homogeneous medium

- Energy lost in photons -> radiation field from charged particle
- Mechanism - polarization of medium changes as particle passes

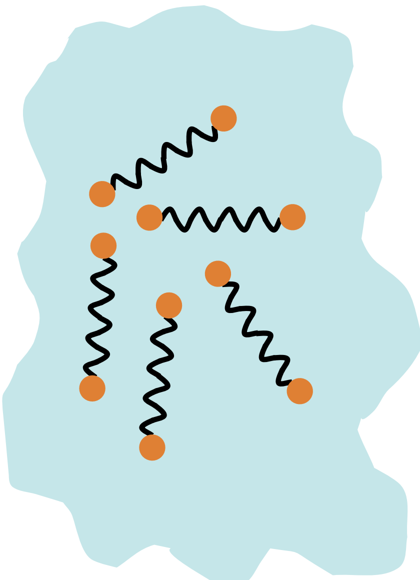


t_1



t_2

Picture of matter



View atoms in matter as "harmonically bound", which gives a simple expression for dielectric constant:

$$m\left(\ddot{\vec{x}} + \gamma\dot{\vec{x}} + \omega_o^2\vec{x}\right) = -e\vec{E} \Rightarrow$$

$$\vec{p} = -e\vec{x} = \frac{e}{m}\,\frac{\vec{E}}{\omega_o^2 - \omega^2 - i\omega\gamma} = \varepsilon(\omega)\vec{E} \Rightarrow$$

$$\varepsilon(\omega) = \varepsilon_o\left(1 + \frac{Ne^2}{m\varepsilon_o}\sum_i \frac{f_i}{\omega_o^2 - \omega^2 - i\omega\gamma}\right) \quad \text{and} \quad \sum_i f_i = Z$$

Plasma frequency: $\omega_p = \dfrac{NZe^2}{\varepsilon_o m}$ Oscillation frequency of a fully ionized plasma

Calculation of energy loss

$$E_{\parallel} = -\frac{ize\omega}{v^2}\left(\frac{2}{\pi}\right)^{1/2}\left[\frac{1}{\varepsilon(\omega)} - \beta^2\right]K_o(\lambda b)$$

$$E_{\perp} = \frac{B_{\perp}}{\beta\varepsilon(\omega)} = \frac{ze}{v}\left(\frac{2}{\pi}\right)^{1/2}K_1(\lambda b)$$

$$\lambda^2 = \frac{\omega^2}{c^2}\left(1 - \beta^2\varepsilon(\omega)\right)$$

$$\Rightarrow \quad \Delta E = -\int_{-\infty}^{\infty}\vec{v}\bullet\vec{F}dt = -e\int_{-\infty}^{\infty}\vec{v}\bullet\vec{E}dt = -\frac{ca}{2}e\int_{-\infty}^{\infty}B_{\perp}(t)E_{\parallel}(t)dt$$

λis a characteristic length if the fields

For β~1 and λβ<<1 (near field region) $\frac{dE}{dx} = \frac{(ze)^2\omega_p^2}{c^2}\ln\left(\frac{1.123c}{a\omega_p}\right)$

Energy loss becomes independent of energy at β~1

Fields (we have already done the work)

Cerenkov involves collisions far from the particle trajectory, $\lambda b \gg 1$, asymptotic form for K_o, K_1:

$$E_{\parallel} = i\frac{ze\omega}{c^2}\left[1 - \frac{1}{\beta^2\varepsilon(\omega)}\right]\frac{e^{-\lambda b}}{\sqrt{\lambda b}}$$

$$B_{\perp} = \frac{\beta ze}{v}\sqrt{\frac{\lambda}{b}}e^{-\lambda b}$$

$$E_{\perp} = \frac{ze}{v\varepsilon(\omega)}\sqrt{\frac{\lambda}{b}}e^{-\lambda b}$$

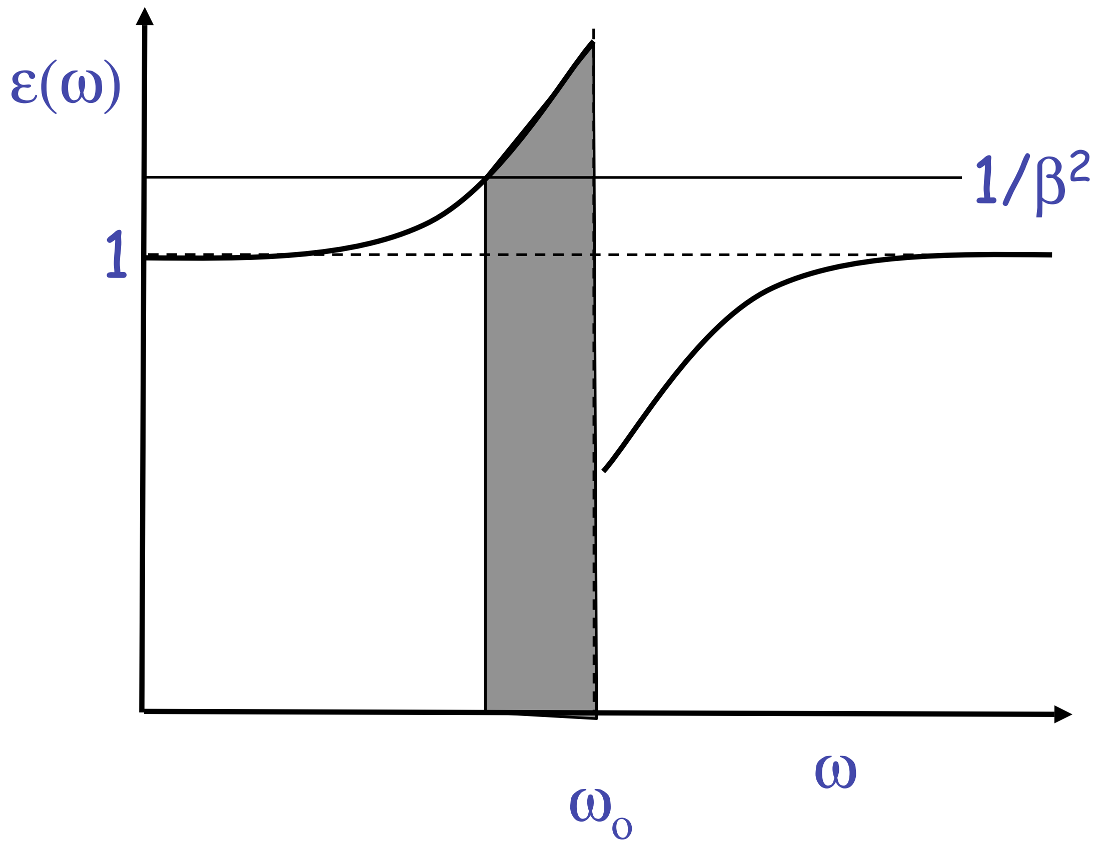
λ imaginary -> propagating fields

-> $\lambda^2=\omega^2/c^2(1-\beta^2\varepsilon(\omega))<0$ -> $\beta>1/\varepsilon(\omega)^{1/2}$

-> $v>c/n$

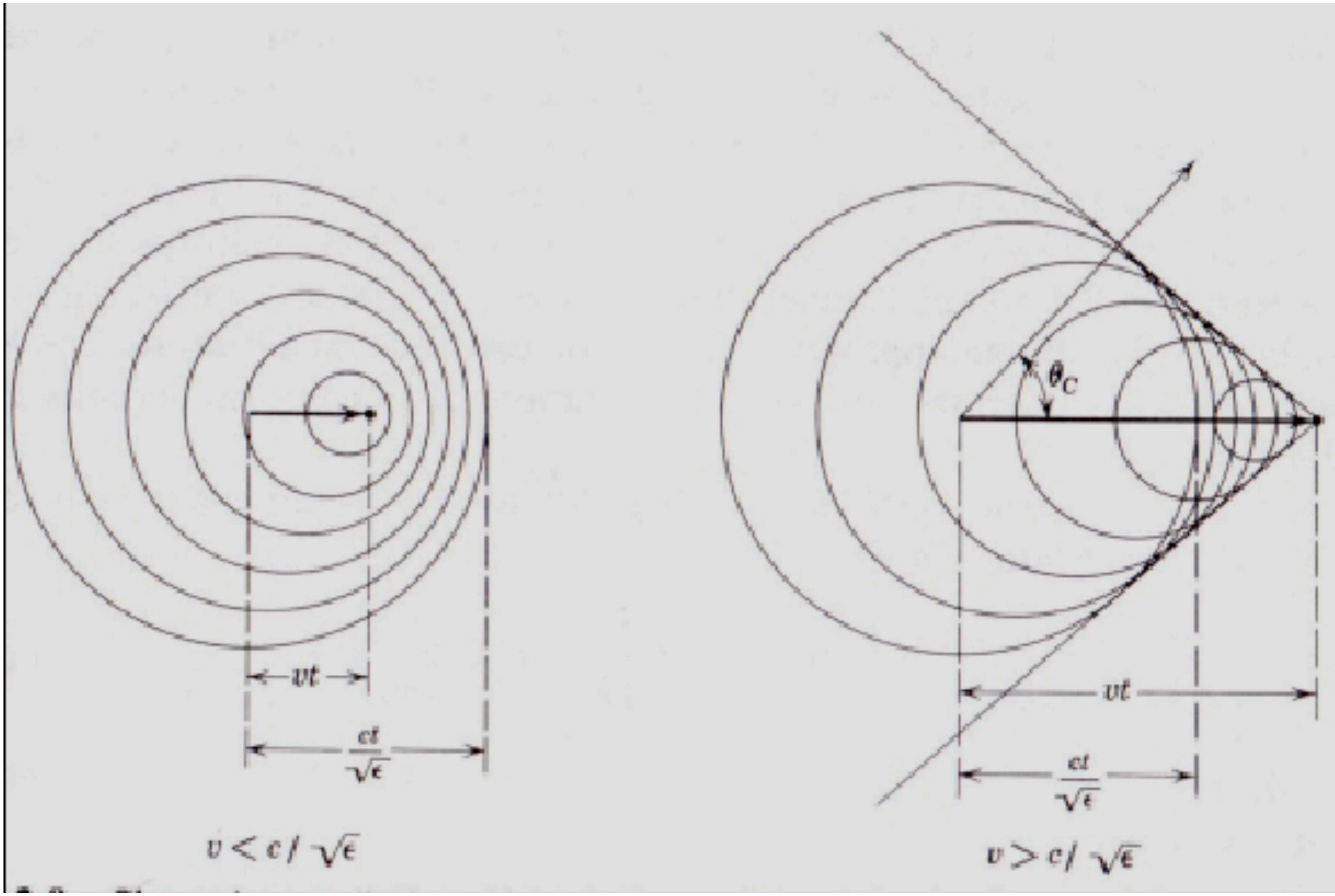
Radiation

Direction: $\tan\theta_c = -\frac{E_\parallel}{E_\perp} \Rightarrow \cos\theta_c = \frac{1}{\beta\sqrt{\varepsilon(\omega)}}$



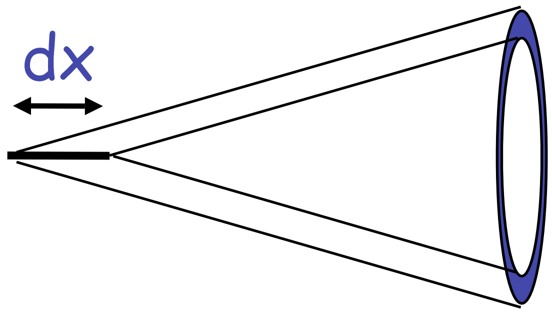
Cerenkov radiation occurs near atomic resonances -> radiation in optical at angle θ_c

The usual picture....



Intensity of Radiation

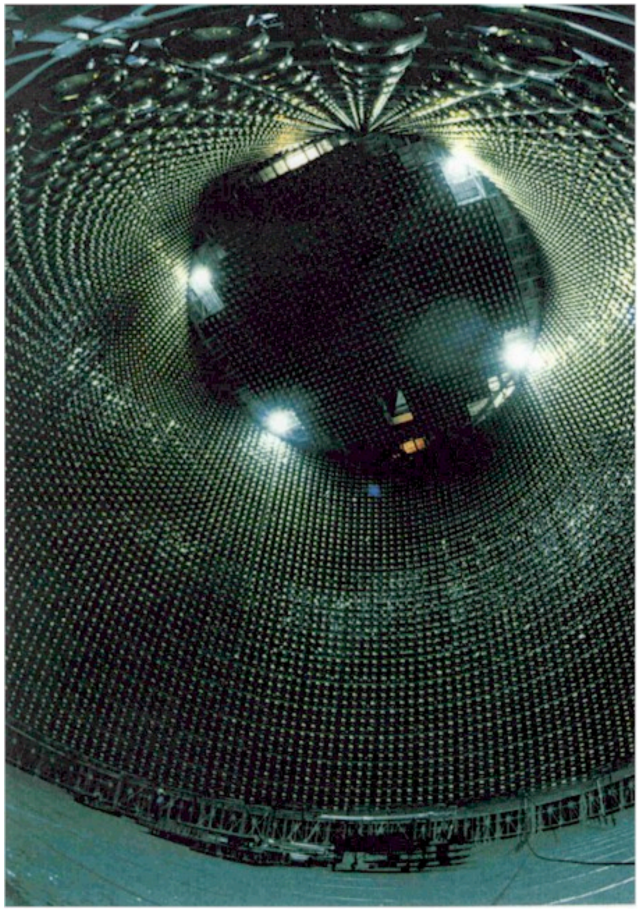
Photon flux into Cerenkov cone:



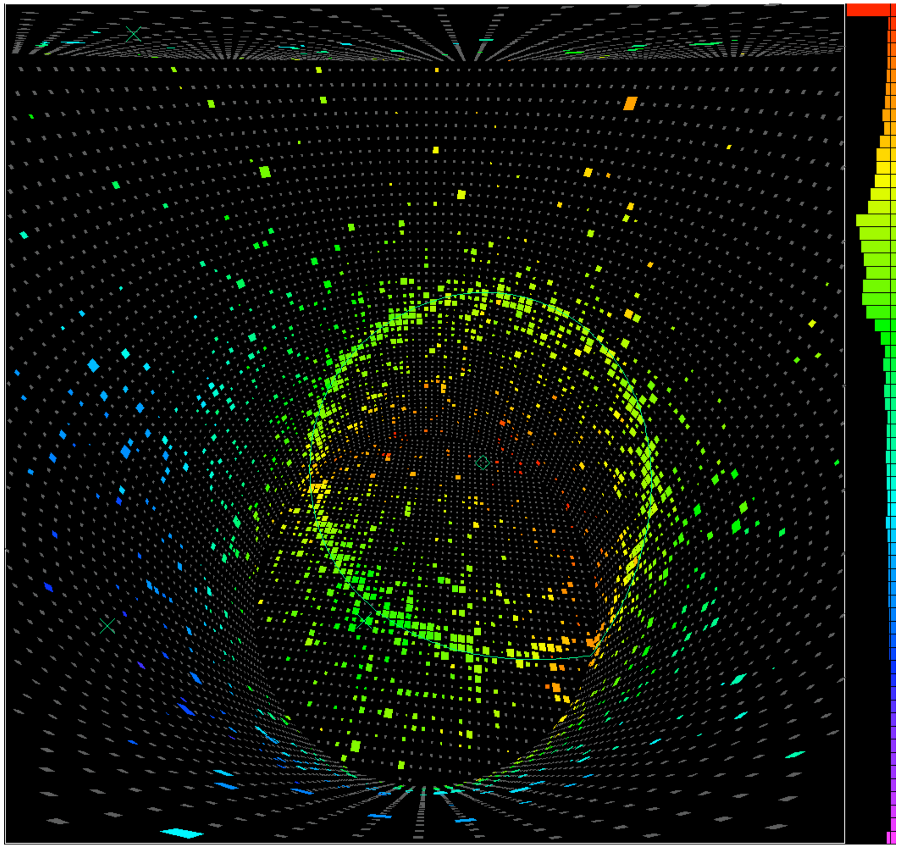
$$\frac{d^2N}{d\omega dx} = \int_{cone} \frac{\vec{S} \bullet d\vec{a}}{\hbar\omega} = \frac{c}{4\pi} \int_{cone} \frac{\left(\vec{E} \times \vec{B}\right) \bullet d\vec{a}}{\hbar\omega}$$

$$\frac{d^2N}{dE dx} = \frac{\alpha z^2}{\hbar c} \sin^2\theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$
$$\approx 370 \sin^2\theta_c(E) \text{ eV}^{-1}\text{cm}^{-1} \qquad (z = 1) \ ,$$

Integrate over PMT response: $dN_\gamma/dx = (90/\text{cm})\sin^2\theta_c$

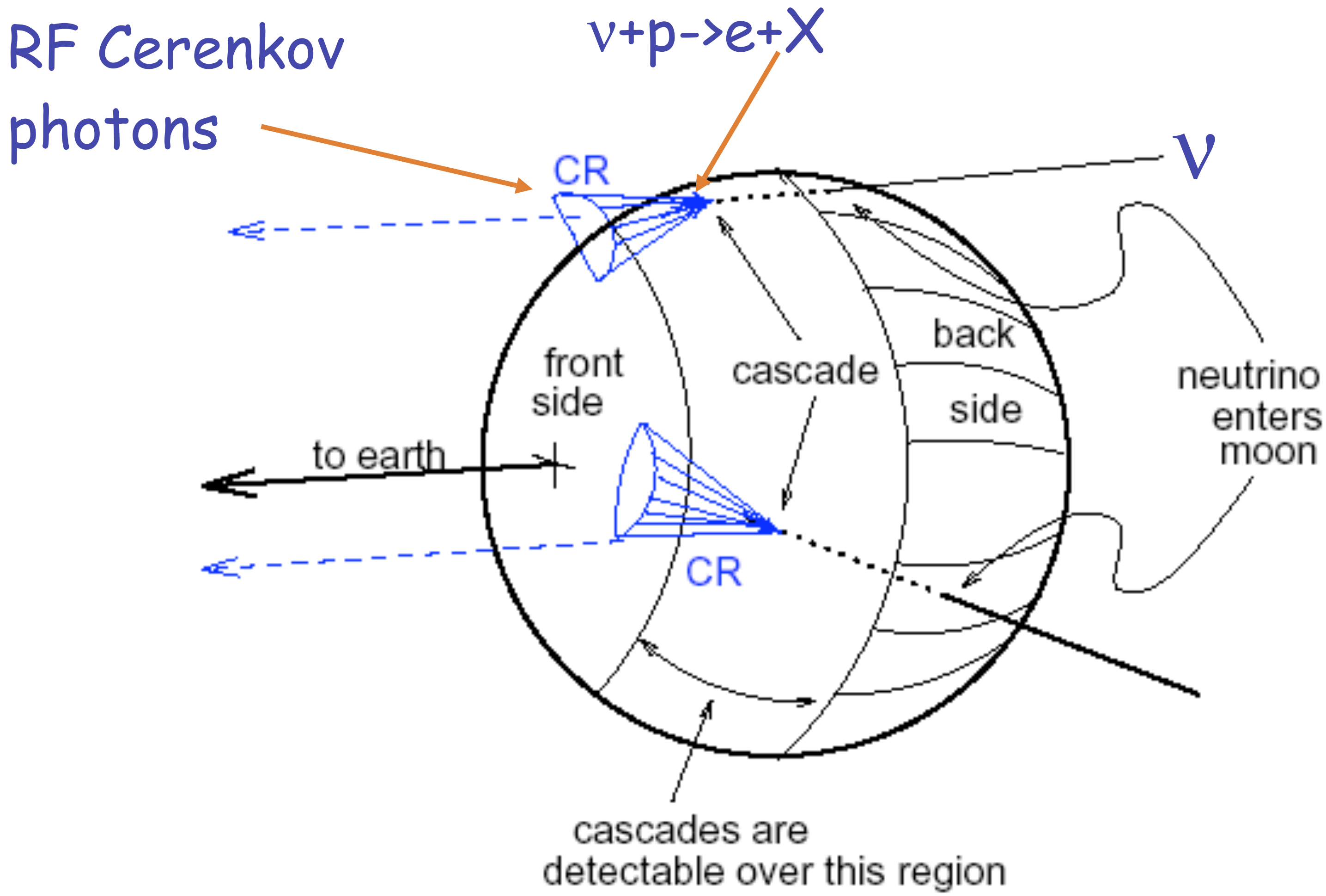


Superkamiokande - n_{water}=1.33



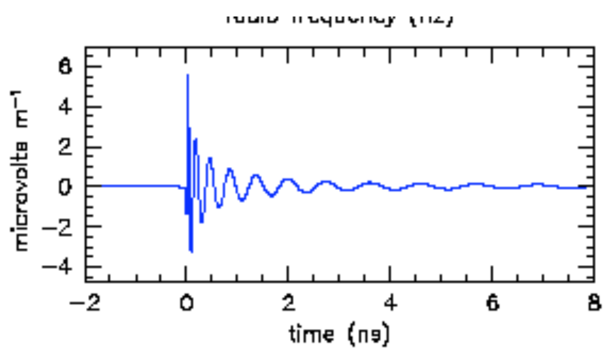
Single electron event

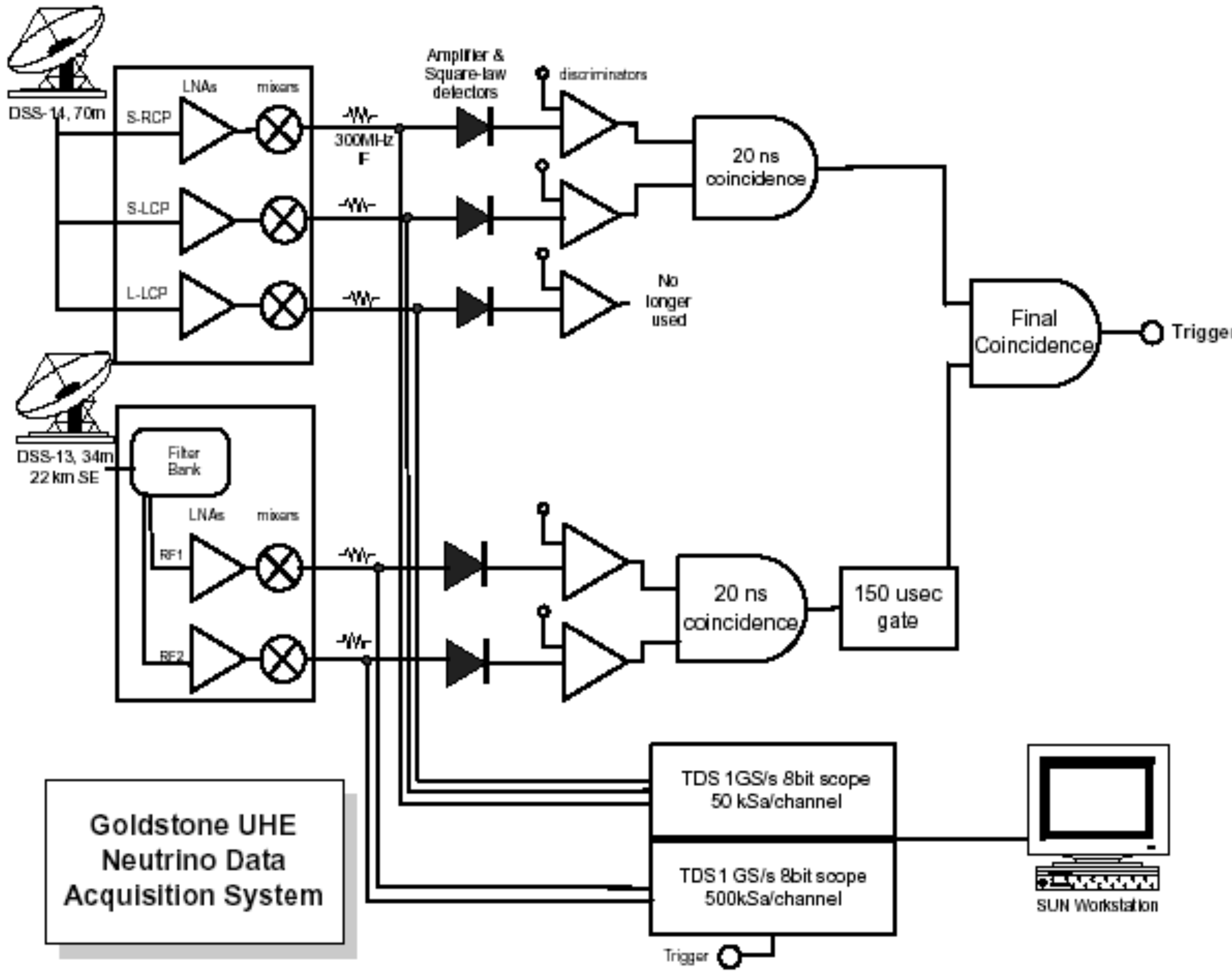
Very high energy neutrinos



Goldstone DSN receiver

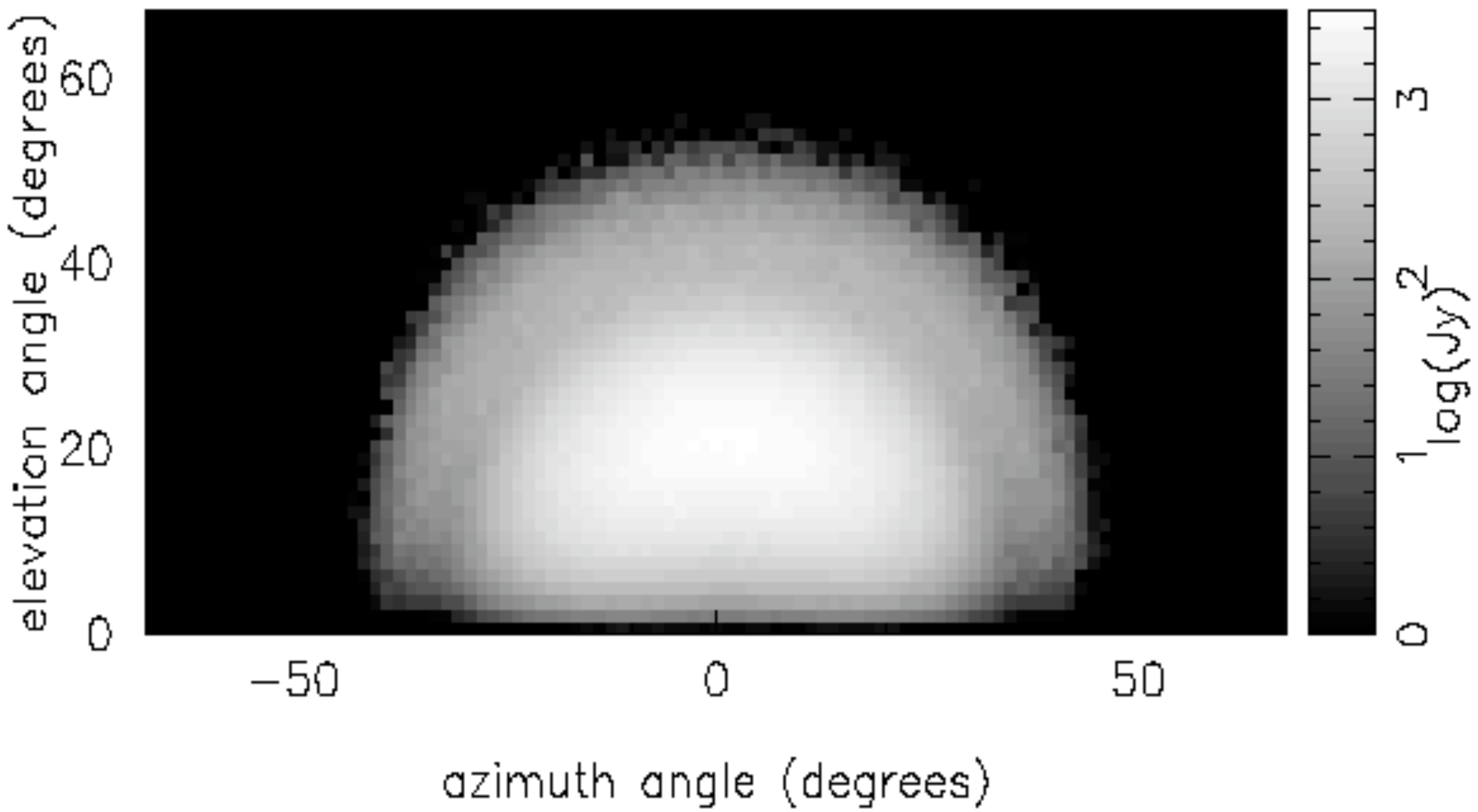
- Able to image the entire moon
- Power sensitivity - pW
- Large backgrounds - operate two dishes in coincidence
- Typical signal:





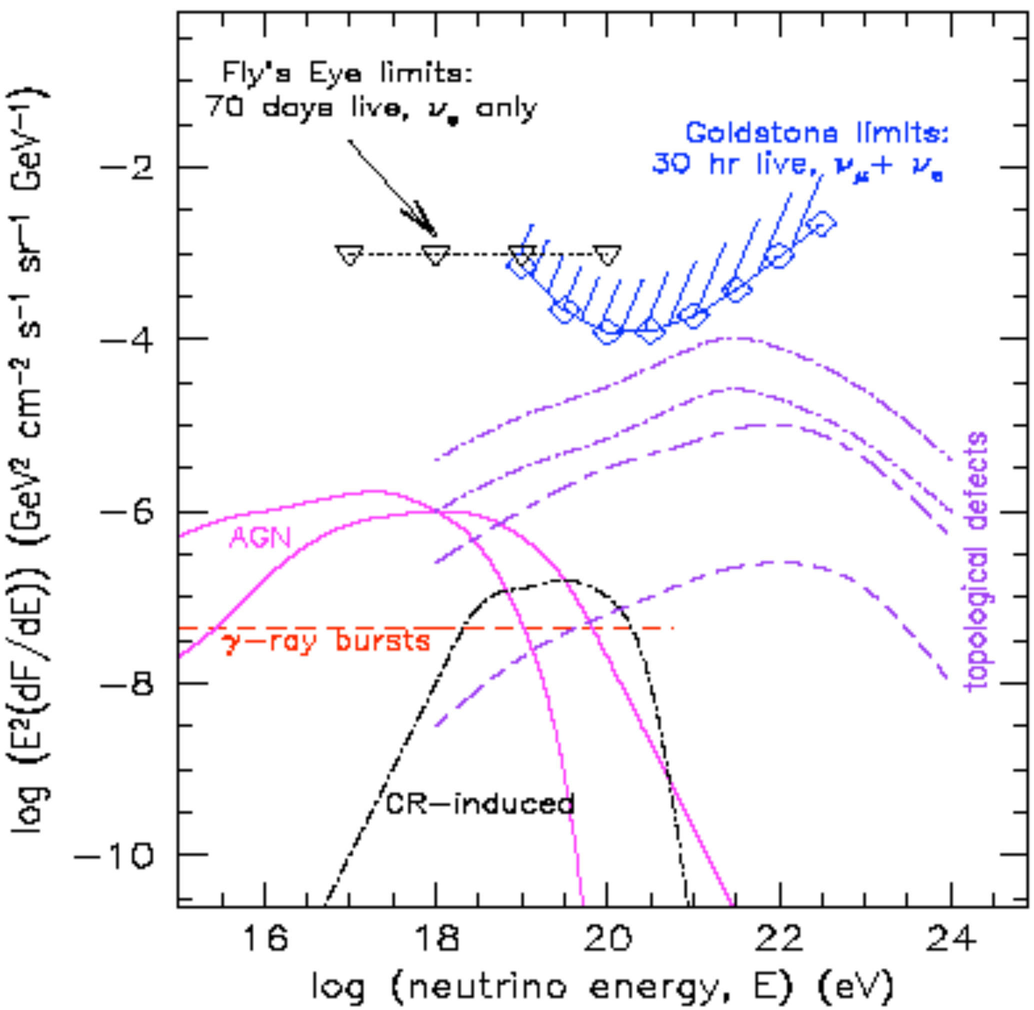
DSS-14, 70m
LNAs
mixers
S-RCP
S-LCP
L-LCP
300MHz
F
Amplifier &
Square-law
detectors
discriminators
20 ns
coincidence
No
longer
used
Final
Coincidence
Trigger
DSS-13, 34m
22 km SE
Filter
Bank
LNAs
mixers
RF1
RF2
20 ns
coincidence
150 usec
gate
TDS 1GS/s 8bit scope
50 kSa/channel
TDS 1 GS/s 8bit scope
500kSa/channel
Trigger
SUN Workstation
Goldstone UHE
Neutrino Data
Acquisition System

Moon imaged by RF Cerenkov from EHE neutrinos

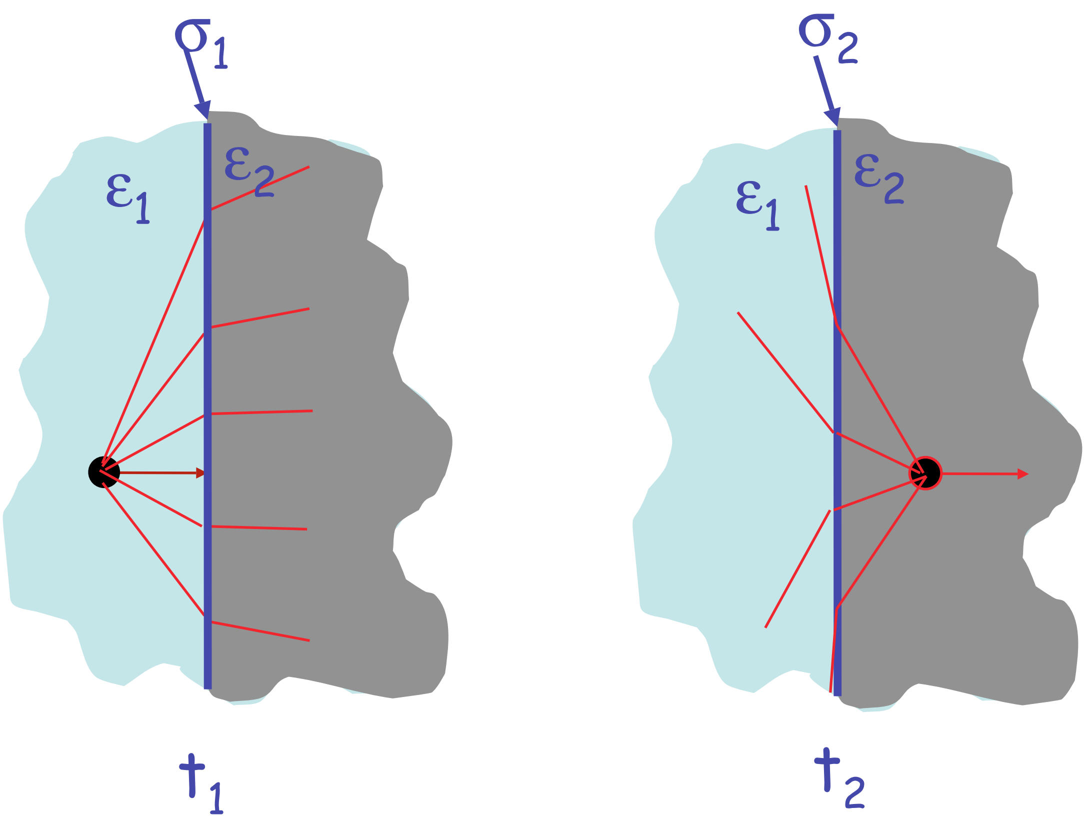


Results

30 h data - unique results within factor of 100 of models



3. Transition radiation - radiation field in a heterogeneous medium



Particle crossing interface causes coherent change in surface charge density -> radiation

Coherent radiation region

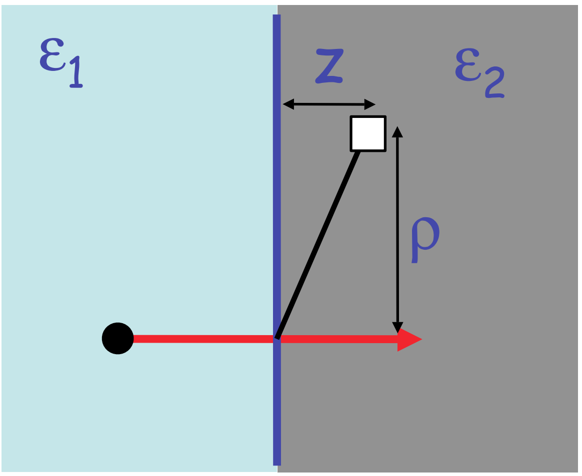
Fields of a moving point charge:

$$E_{\parallel} = \frac{qv\gamma t}{\left(\rho^2 + \gamma^2 v^2 t^2\right)^{3/2}} = \int E_{\parallel}(\omega)d\omega$$

$$E_{\perp} = \frac{q\gamma\rho}{\left(\rho^2 + \gamma^2 v^2 t^2\right)^{3/2}} = \int E_{\perp}(\omega)d\omega$$

$\Rightarrow$ Fields have radial range

$\rho_{max} \sim \gamma v/\omega$



For coherent radiation, phase factor

$$E \propto \exp\left(i\frac{\omega}{v}z\right)\exp\left(-i\frac{\omega}{v}n(\omega)\cos\theta z\right)$$

$$\times\exp\left(-i\frac{\omega}{v}n(\omega)\rho\sin\theta\cos\phi\right)$$

Total phase should be close to one.

Conditions for radiation

Two conditions for coherence:

1. $n(\omega)\gamma\beta\sin\theta \sim n(\omega)\gamma\theta < 1$ -> collinear, for γ large (~1000)
2. $(\omega/c)[1/\beta - n(\omega)\cos\theta]d(\omega) < 1$ -> $d_{max} \sim \gamma c/\omega_p \sim 10^{-6}$ m

Transition radiation:

Emitted at the interface

Propagates along with charged particle

Requires $\gamma > 1000$

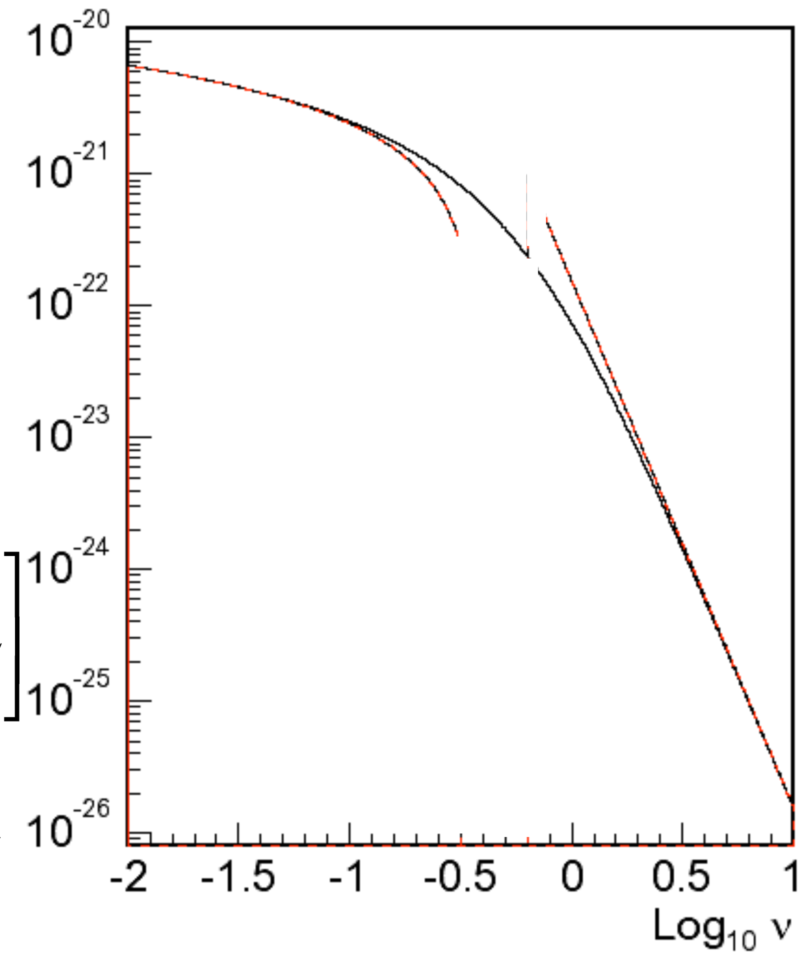
At typical collider energies, TR is a signal for electrons

Radiation spectrum

- Must compute fields, complicated!
- Dimensionless frequency:

$$\nu = \frac{\omega}{\gamma \omega_p}$$

- Peak around ν=1 -> 10 keV



$$\frac{dI}{d\nu} = \frac{z^2 e^2 \gamma \omega_p}{\pi c}\left[\left(1+2\nu^2\right)\ln\left(1+\frac{1}{\nu^2}\right)-2\right]$$

$$= \frac{z^2 e^2 \gamma \omega_p}{\pi c} 2\ln\left(\frac{1}{e\nu}\right) \quad \text{for} \quad \nu << 1$$

$$= \frac{z^2 e^2 \gamma \omega_p}{\pi c}\frac{1}{6\nu^4} \quad \text{for} \quad \nu >> 1$$

Total intensity

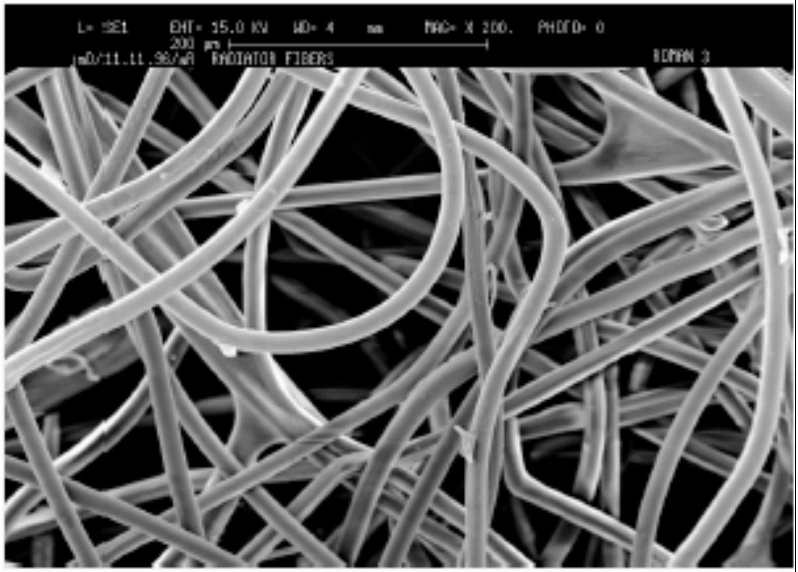
Total intensity:

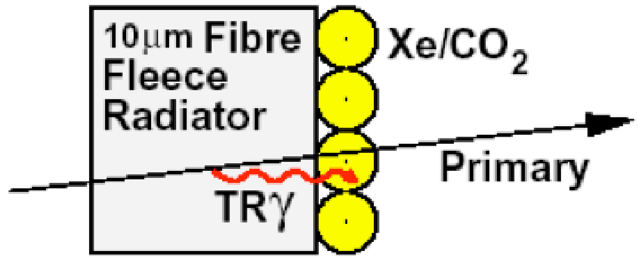
$$I = \frac{z^2 \alpha}{3} \gamma \hbar \omega_p$$

Only 10^{-3} photons per interface; need many interfaces ->

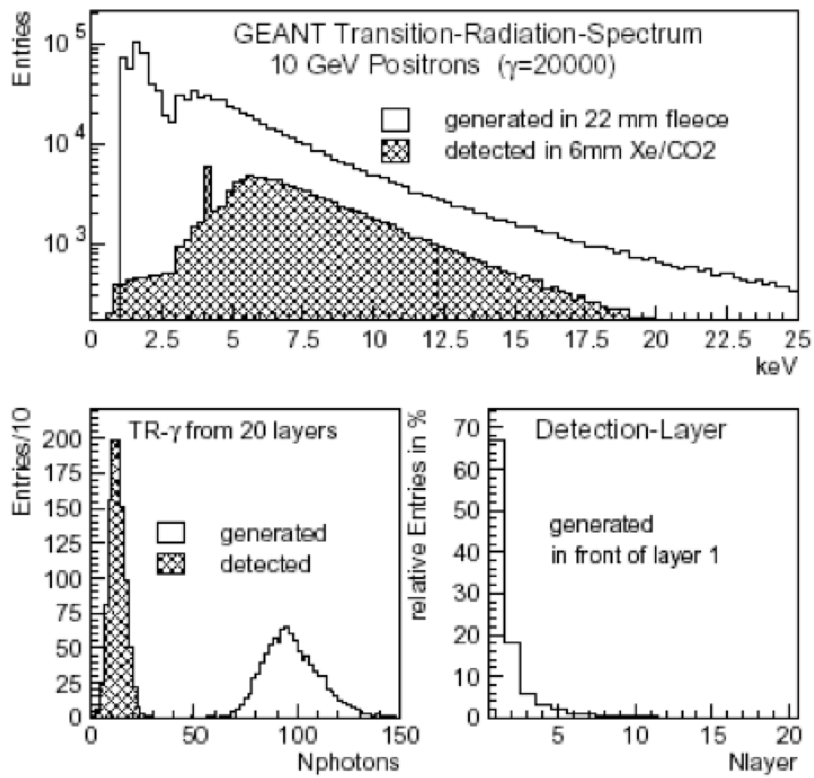
- Stack up foils
- Polypropylene fleece

Need to detect ~10 keV photons



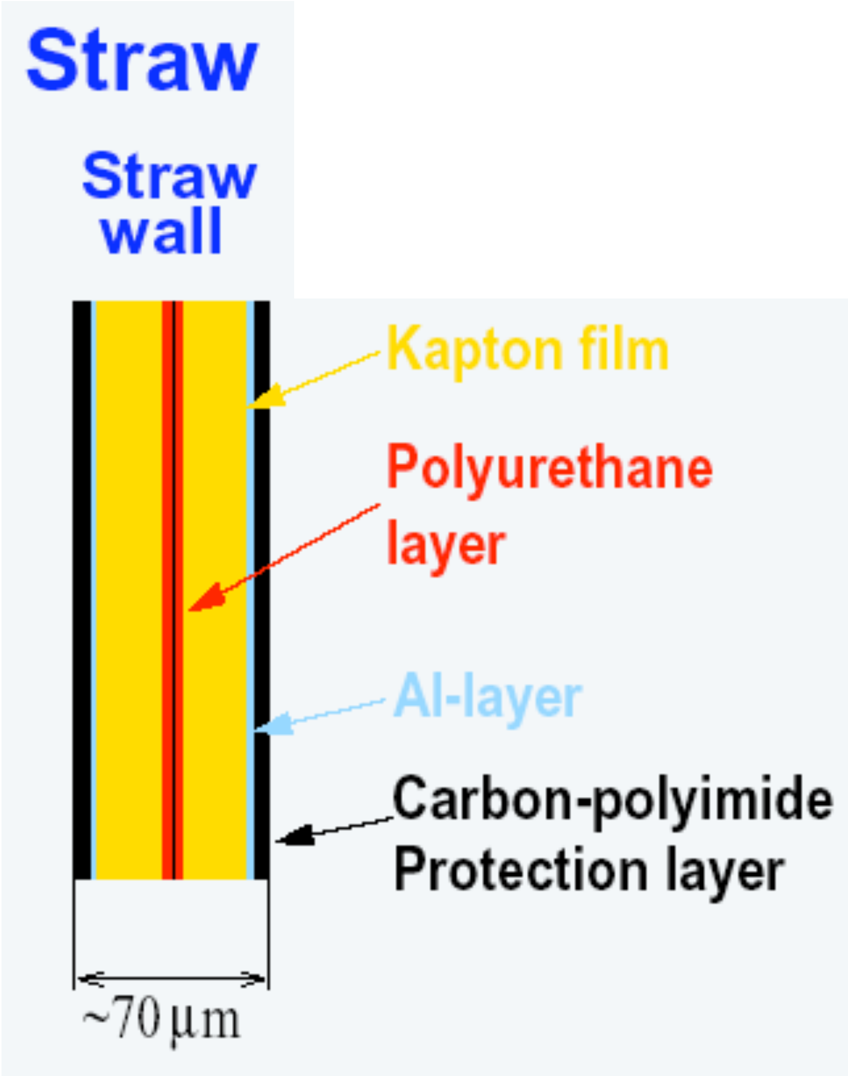


$$N_{Ph} \quad \mathcal{O} \quad \alpha_{em} \times N_{tr}$$
$$E_{Ph} \quad \sim \quad \gamma$$
$$\theta_{Ph} \quad \sim \quad 1/\gamma$$

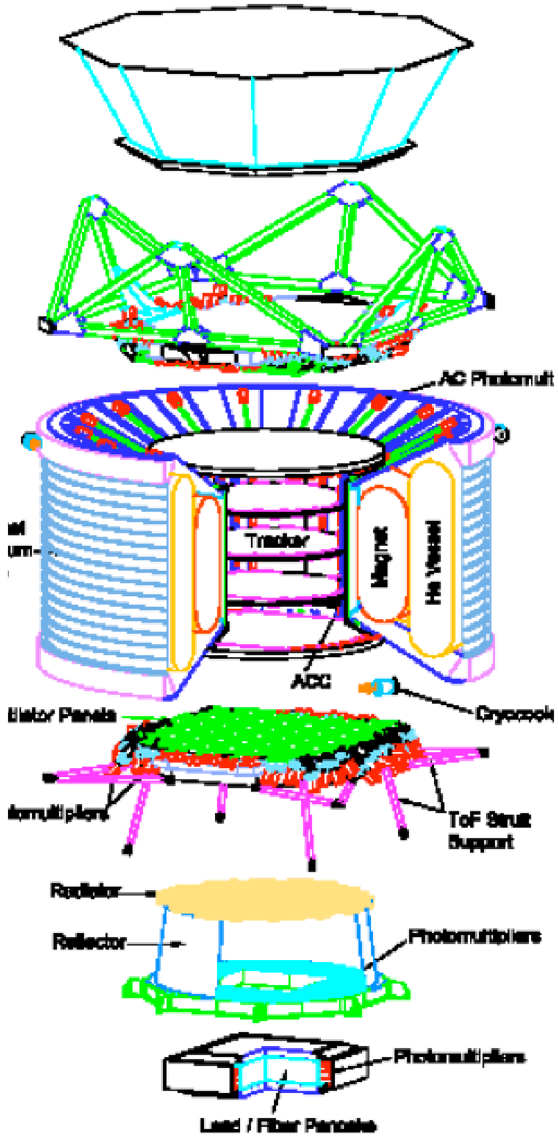


TR photon detection:

- Thin walls
- High Z absorber (Xe)
- Proportional amplification
- Timing for tracking, better discrimination



Large acceptance 0.5 m^2sr in orbit for 3 years



TRD Particle ID & 3D tracking
20 layers fleece + Xe/CO2
5248 channels 6mm straw-tubes

$p^+/e^+ < 10^{-2}$ (10 - 300 GeV)

TOF 1,2 Trigger $\sigma_t \approx 125$ps

Anticoincidence (Veto) counter

Silicon strip tracker
with internal laser alignment
6 m^2 in 3 double + 2 single xy layers
1σ charge separation up to 1TV

Superconducting Magnet (ETH)
B = 0.9T V = 0.6m^3

TOF 3,4 1.3m distance to TOF 1,2
$p^+/e^+ > 3\sigma$ below 2 GeV

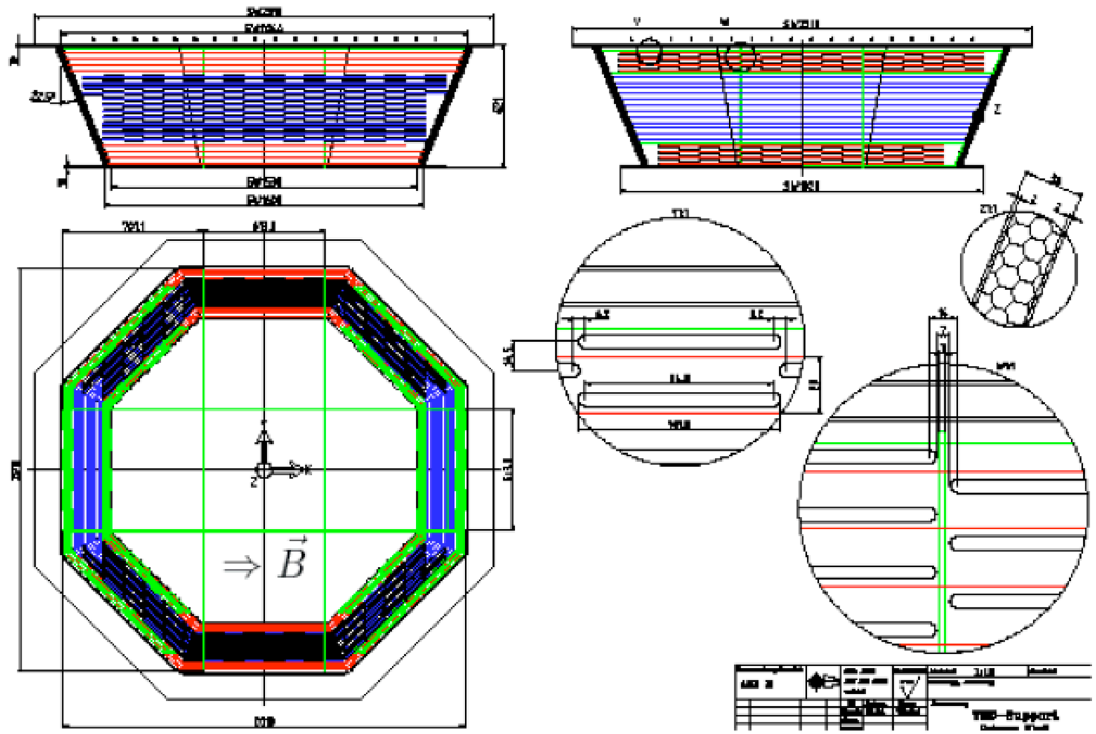
PFRICH AGL(+NaF) Radiator
for A$\leq$27 and Z$\leq$28
separation $> 3\sigma$ from 1-12 GeV

ECAL 3D sampling lead/scint.-fibre
with p-E matching and shower-shape

$p^+/e^+ < 10^{-4}$ (10 - 300 GeV)

TRD Octagon Construction

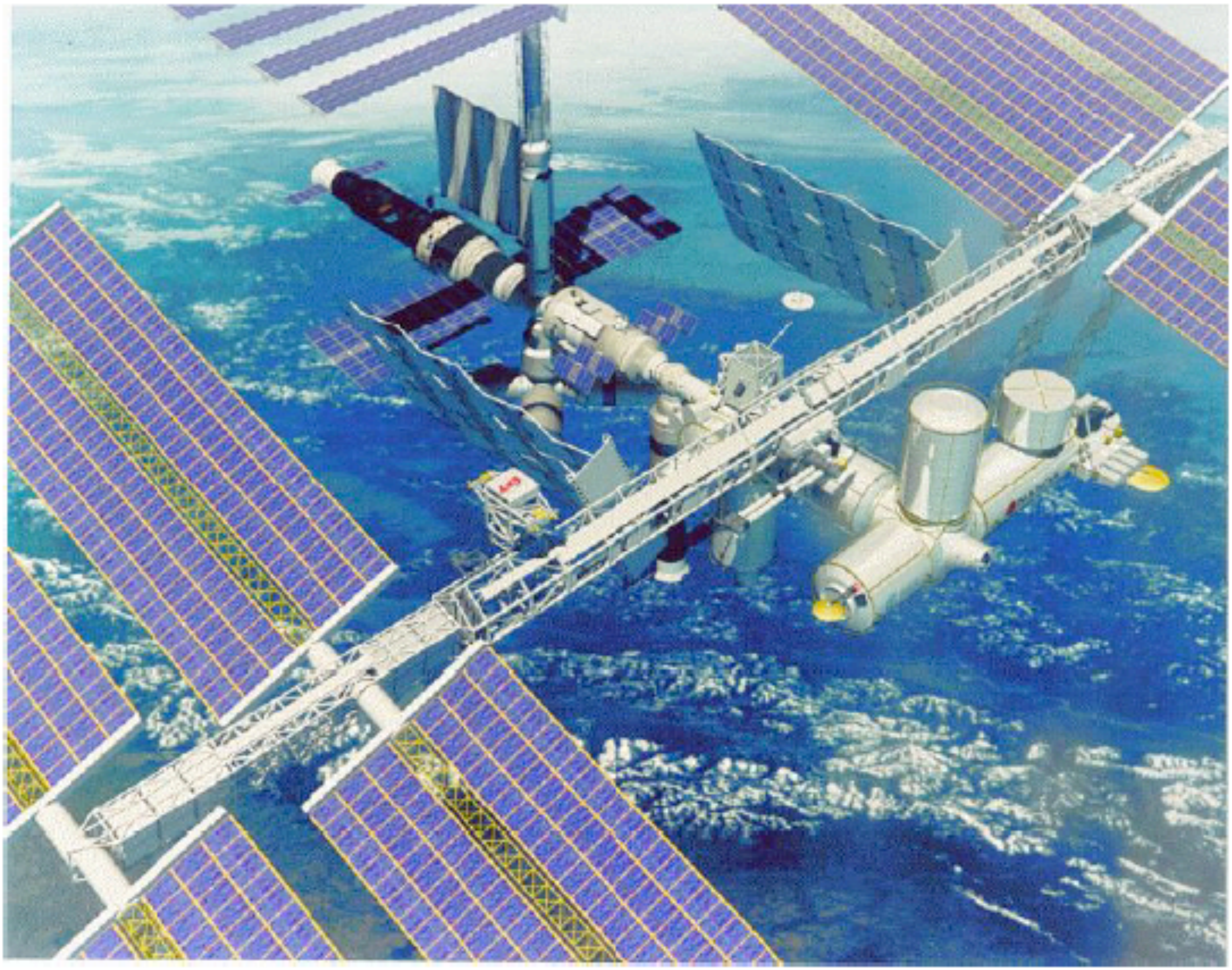
20 layers with 22mm radiator 6mm straw tube modules



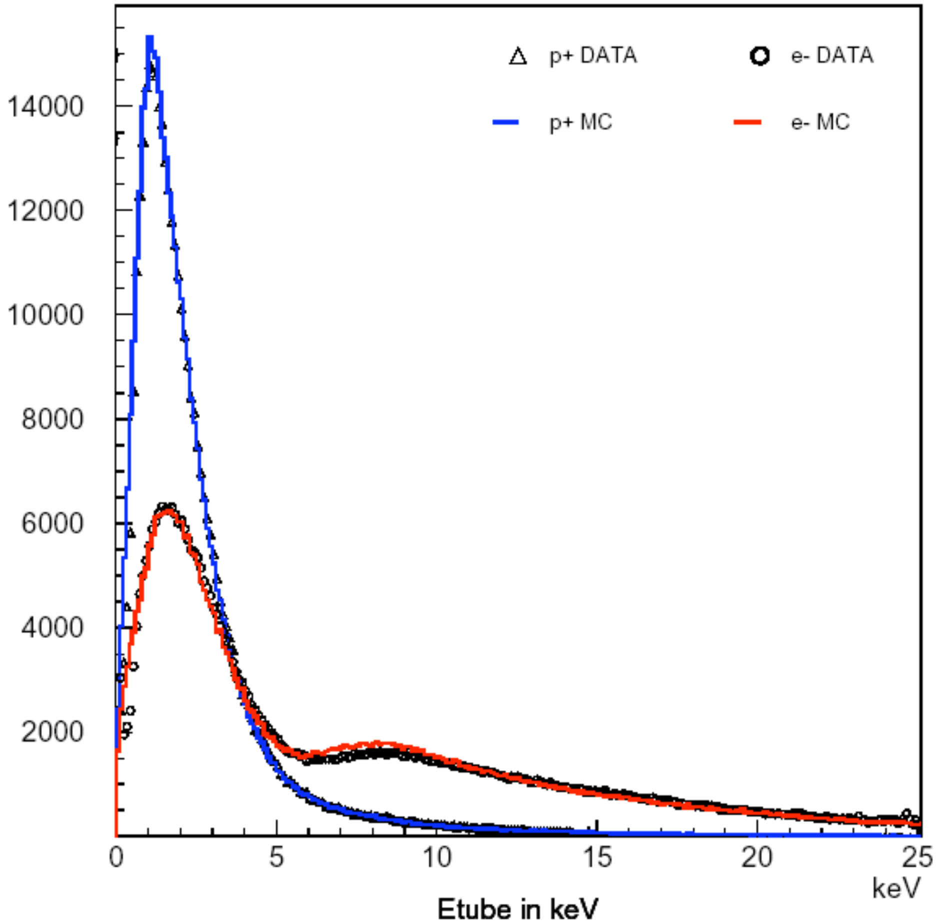
Upper/lower 4 layers measure in bending plane
Middle 12 layers measure in perpendicular plane

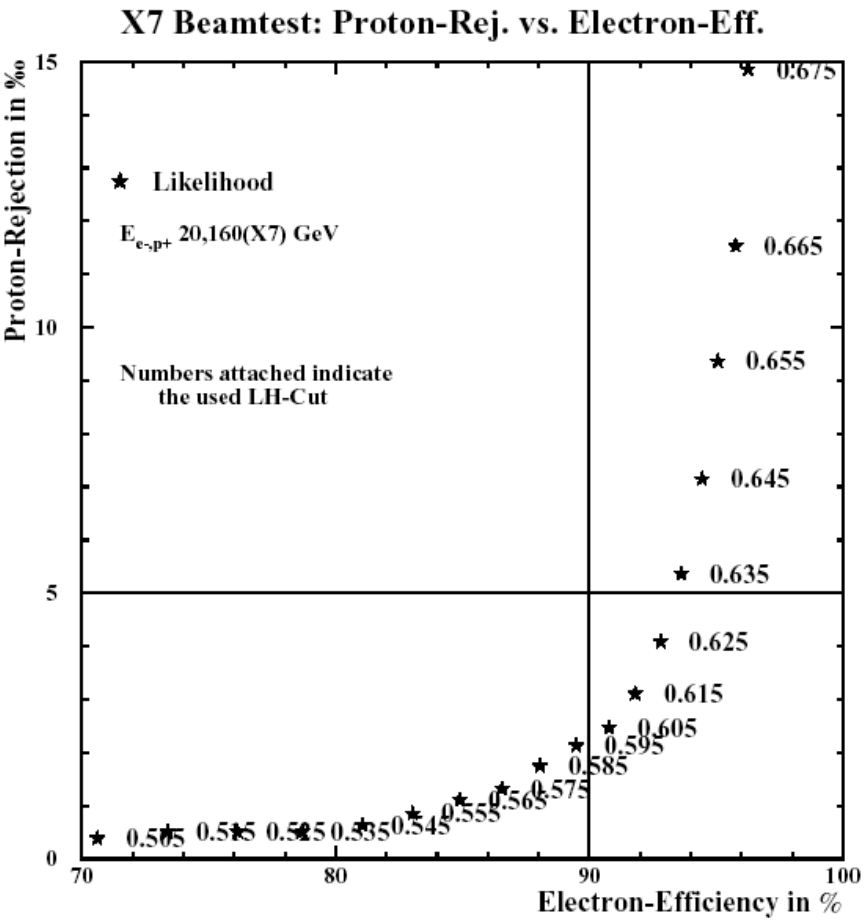
328 Modules, supported with 100 μm mech. accuracy

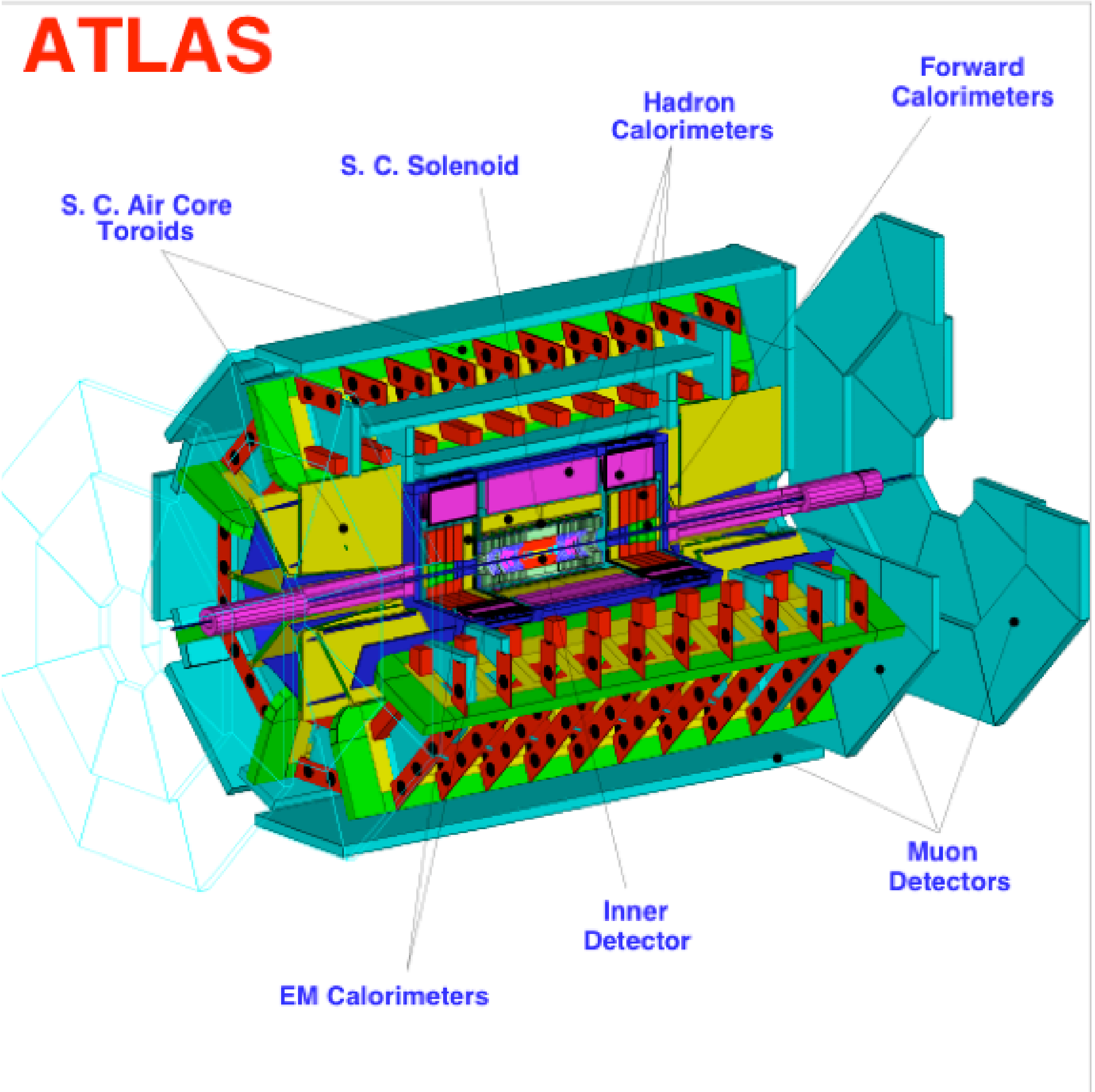
AMS - detect cosmic rays, must discriminate high energy e^+/p

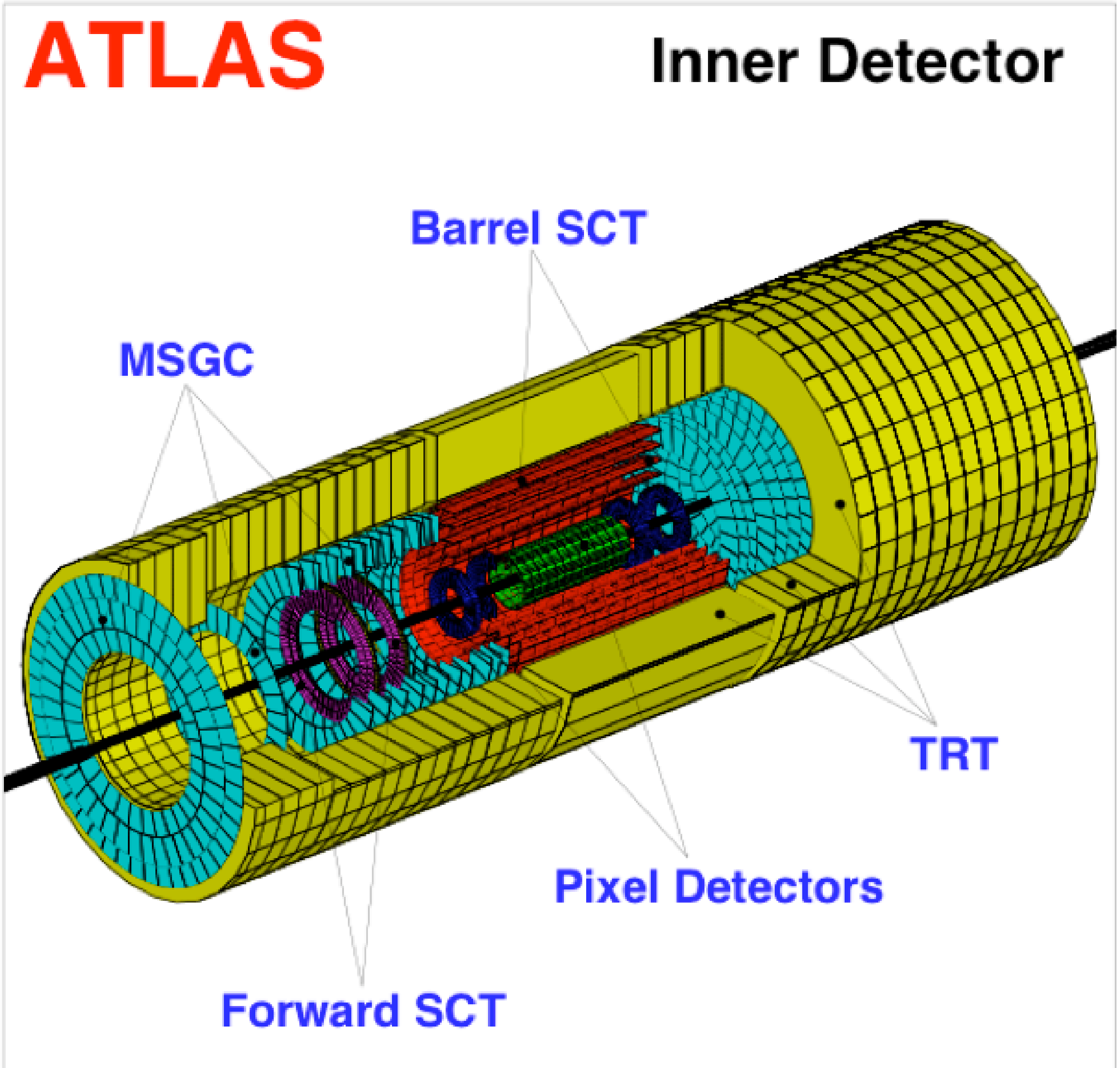


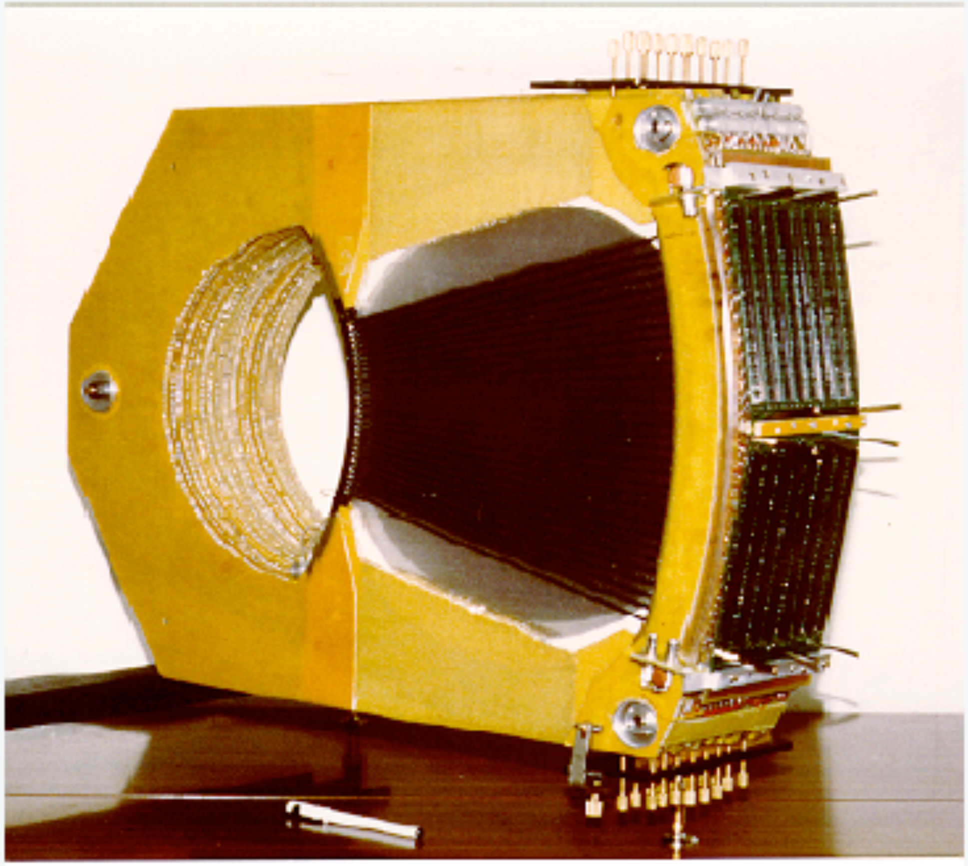
20 GeV Tube Spectra






ATLAS
Forward Calorimeters
Hadron Calorimeters
S. C. Solenoid
S. C. Air Core Toroids
Muon Detectors
Inner Detector
EM Calorimeters

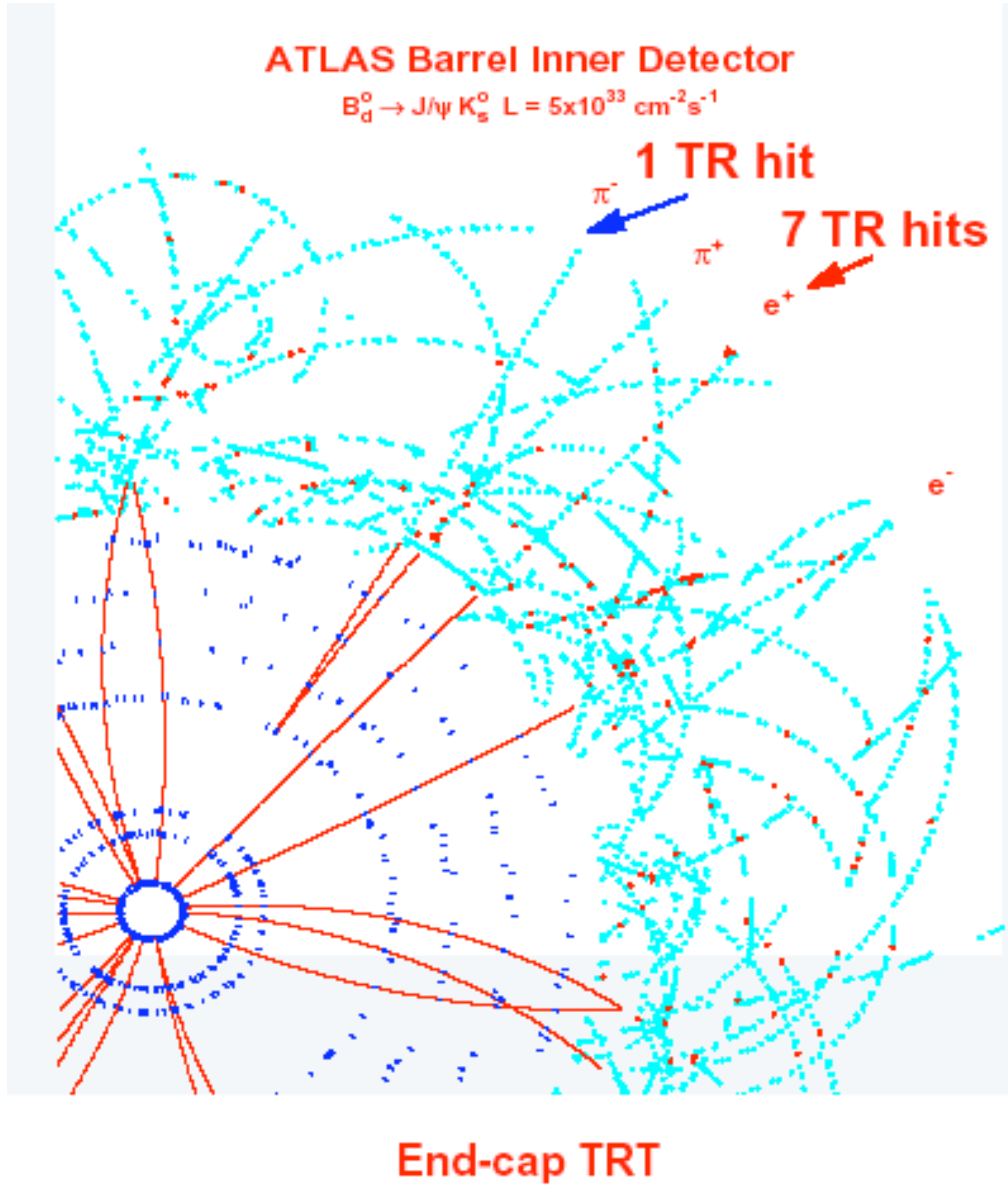

ATLAS
Inner Detector
Barrel SCT
MSGC
TRT
Pixel Detectors
Forward SCT



30^o sector prototype of the end-cap TRT at η~1.4

5 blocks, straws in total	2560
Wire offset	< 300 μm (97%)
Radiation length:	10% X_0
Wire-positioning accuracy:	50 μm
Number of crossed straws:	35-40

Simulated LHC event for B decays

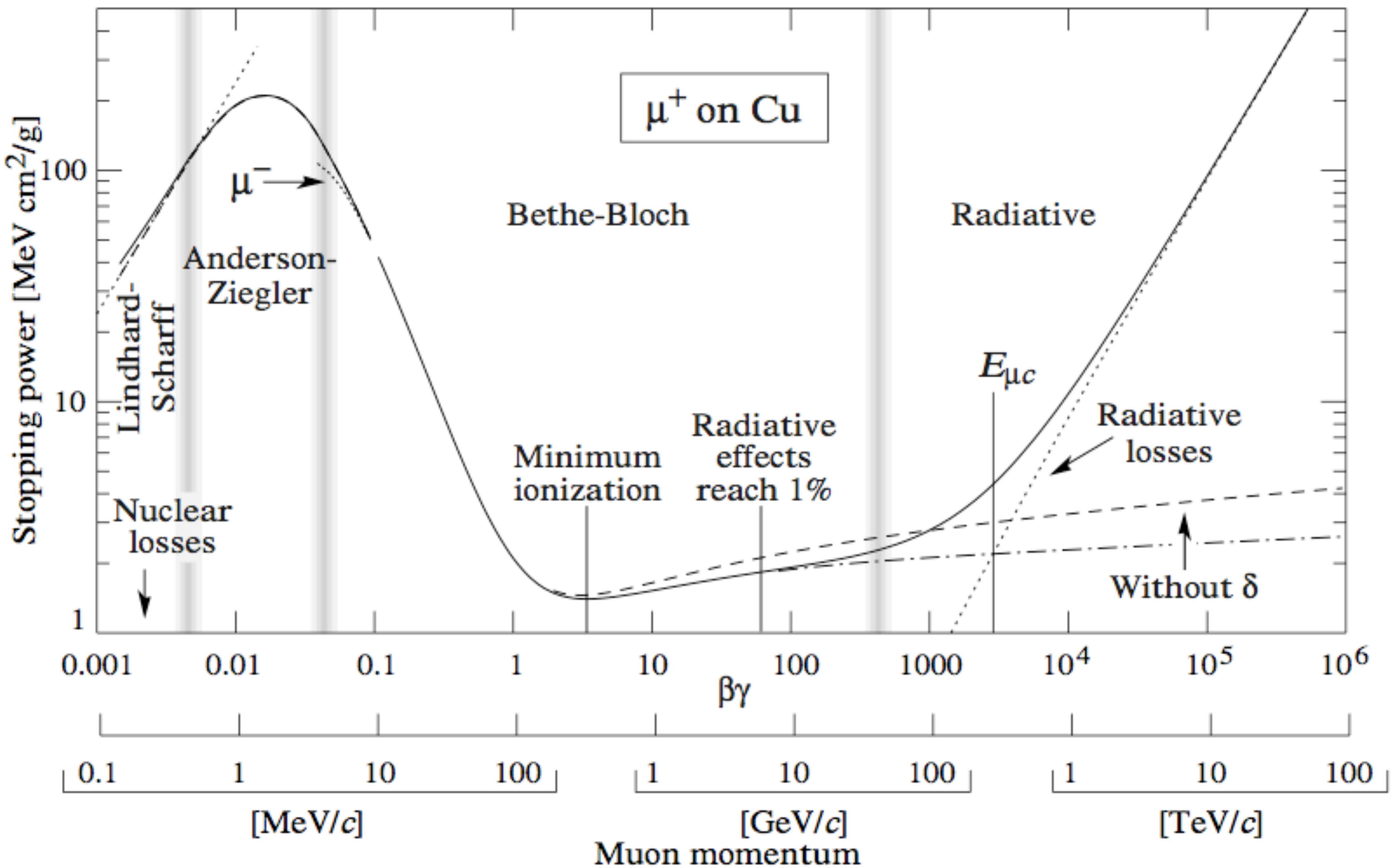


4. Nuclear recoil - single collisions in a lattice

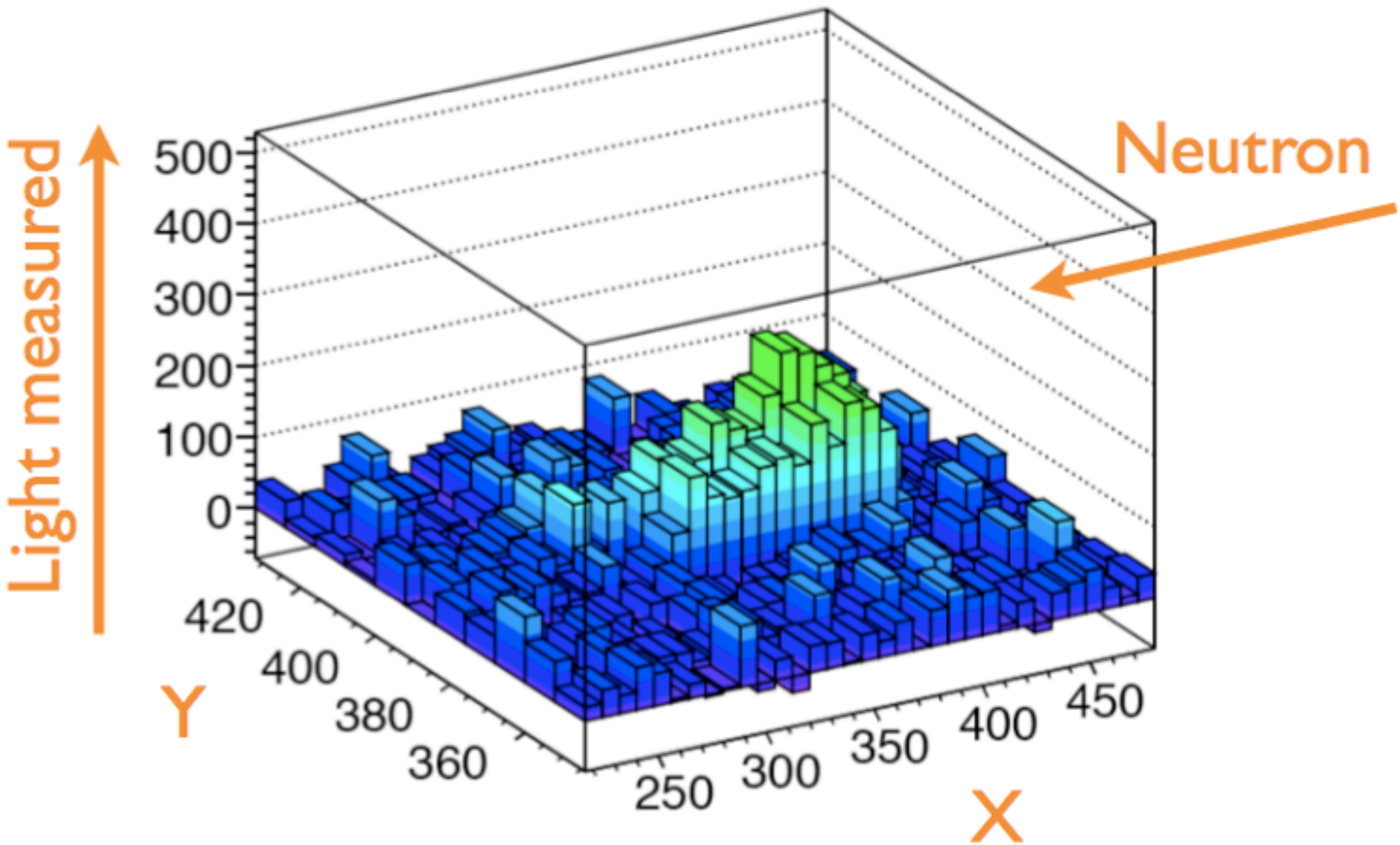
- Galactic dynamics -> dark matter ρ=0.3GeV/cm^3, v=270 km/s (β=0.0008)
- m_{DM}=10-1000 GeV (accelerator limits)
- May weakly interact via neutral current:
  - λ=h/p~20-2000 fm -> coherently interacts with all nucleons (mostly neutrons):

$$\frac{d\sigma}{dT} = \frac{G_F^2 A m_N c^2}{8\pi v^2} N^2 \underbrace{\exp\left(-\frac{A m_N 2TR^2}{3\hbar^2}\right)}_{\text{Coherence factor}}$$

For elastic scattering off a nucleus



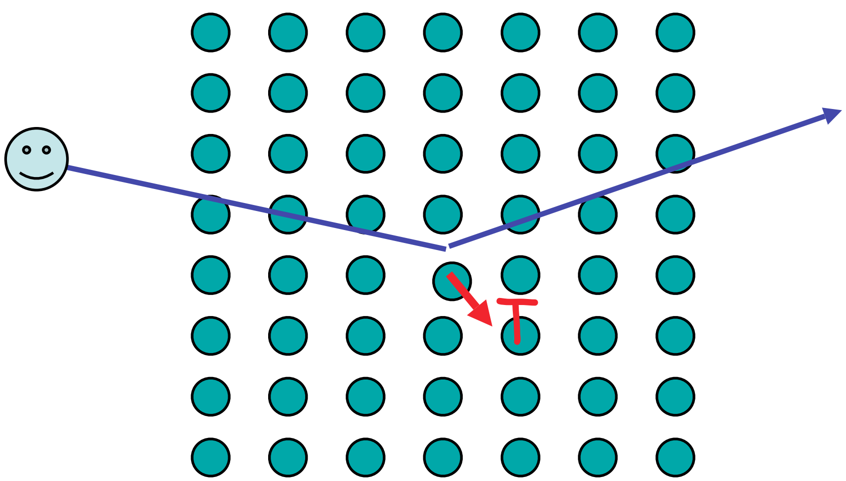
μ+ on Cu
Stopping power [MeV cm2/g]
μ−
Bethe-Bloch
Radiative
Anderson-Ziegler
Lindhard-Scharff
Eμc
Radiative losses
Minimum ionization
Radiative effects reach 1%
Nuclear losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum


Light measured
500
400
300
200
100
0
Neutron
420
400
380
360
Y
250
300
350
400
450
X

Detection

Must detect single interaction with a nucleus, T~5 keV

-> use nucleus in a semiconductor crystal lattice

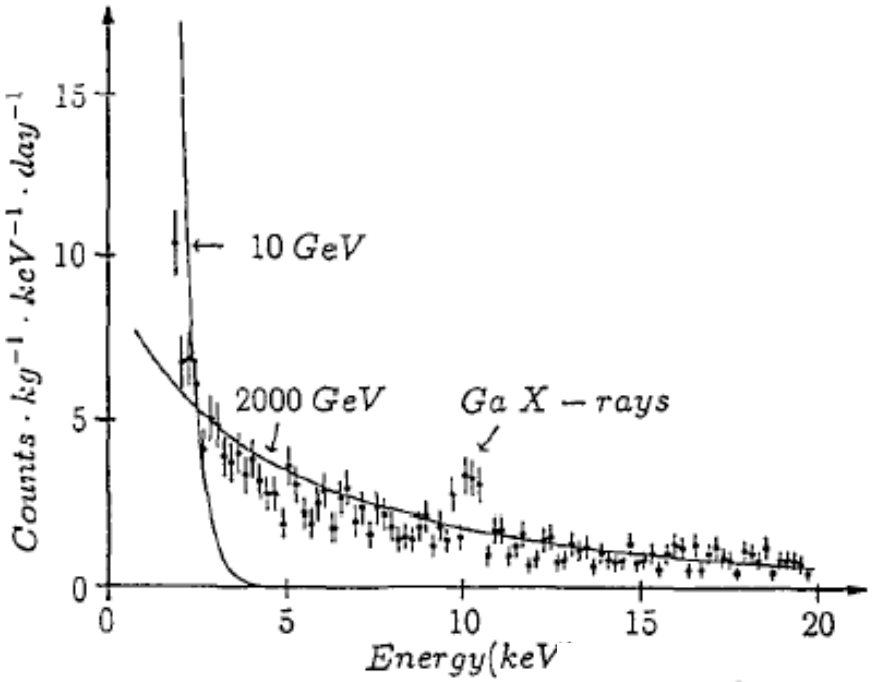


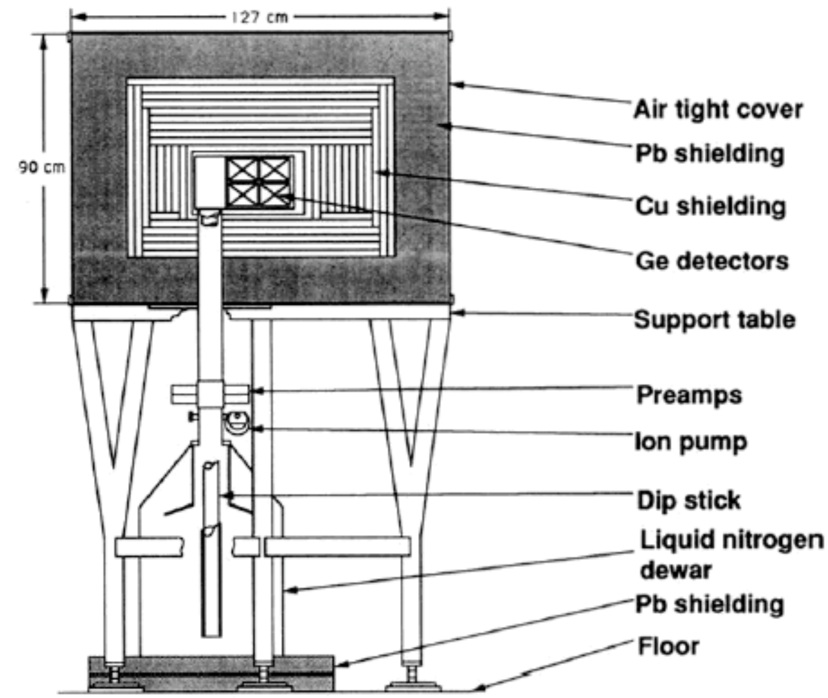
Energy loss at T~5 keV:

•1/3 ionization (conduction electrons)

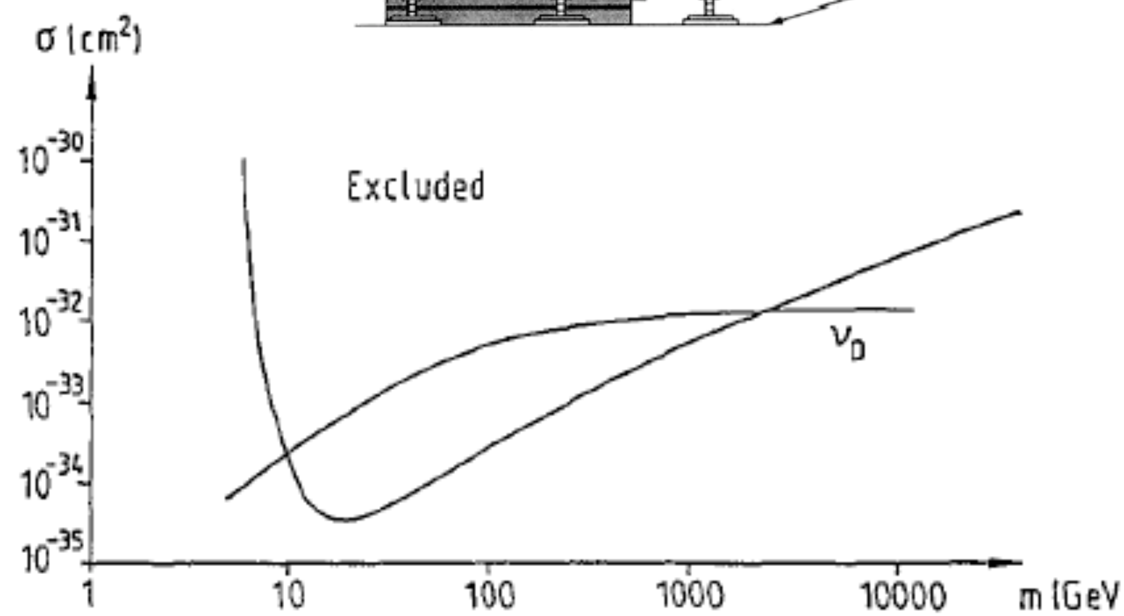
•2/3 phonons (lattice vibrations)

Major background: γ rays -> ionization only



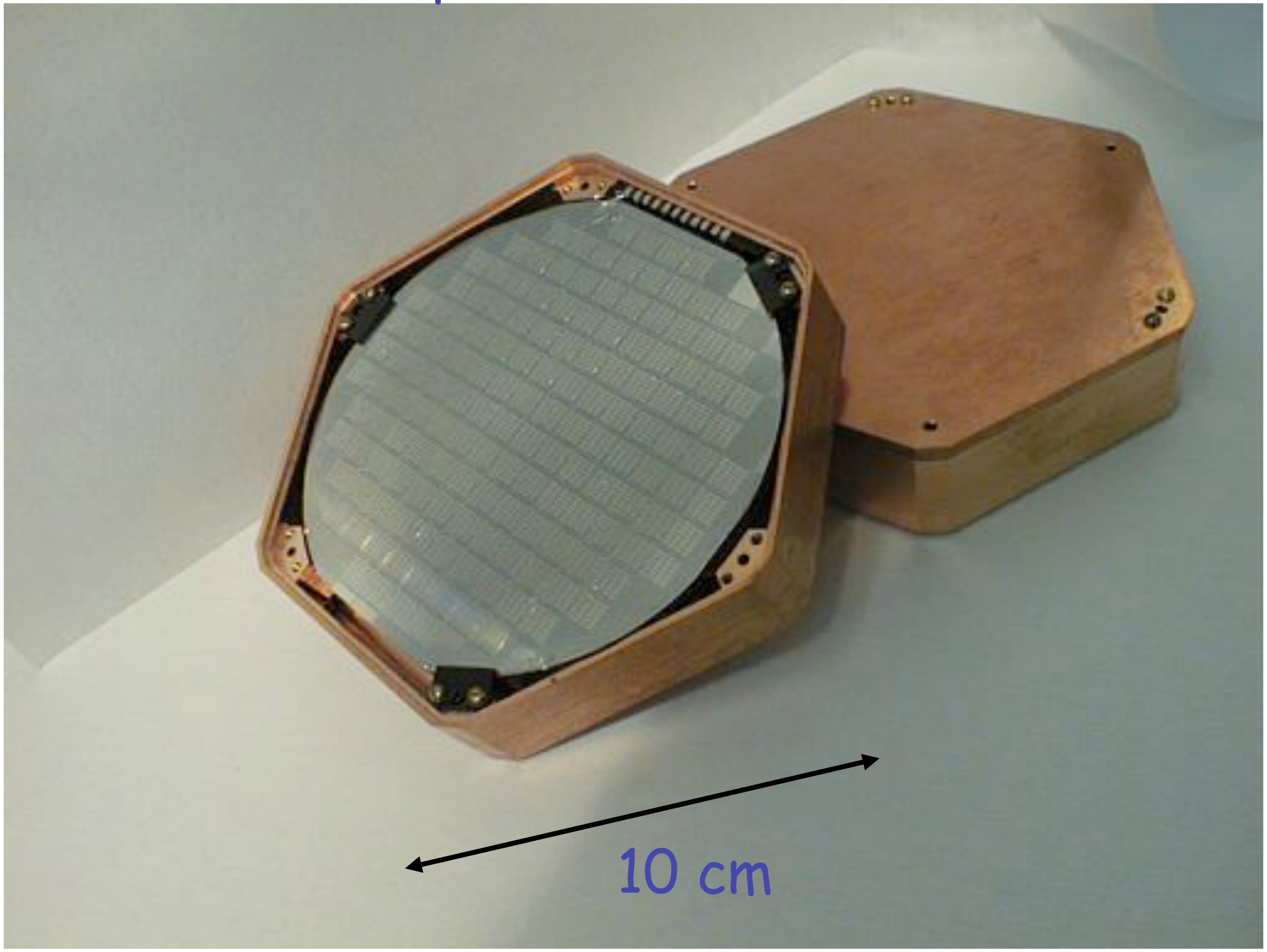


Early attempts: lower threshold on ββ decay experiments, detect ionization only



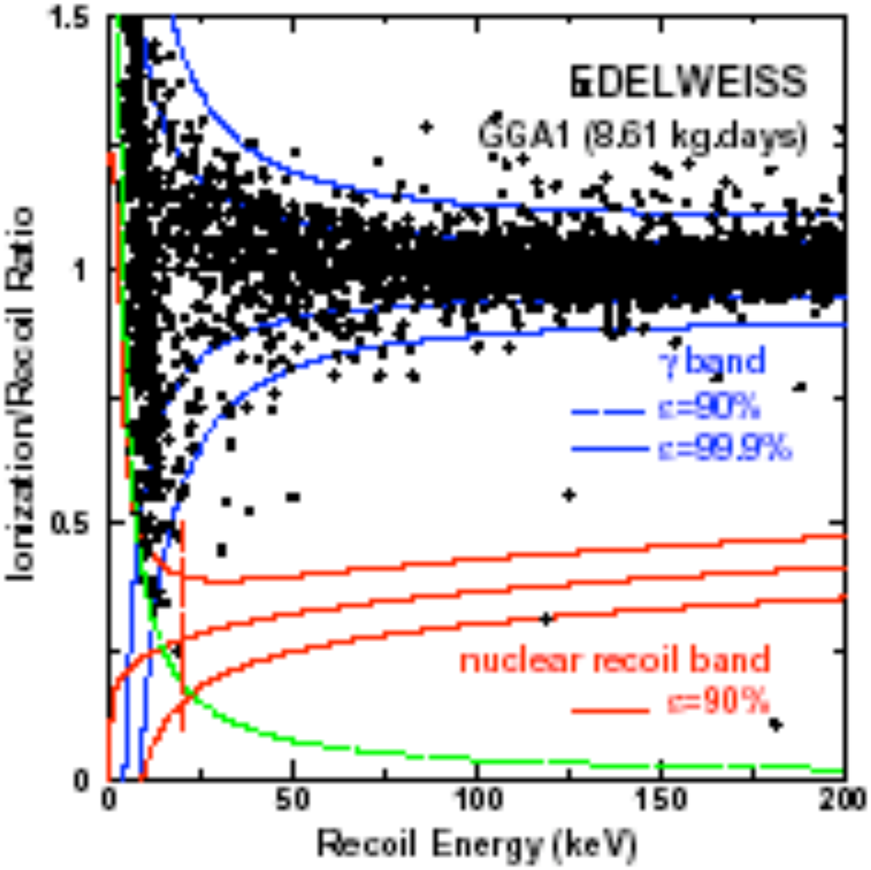
CDMS ZIP detector

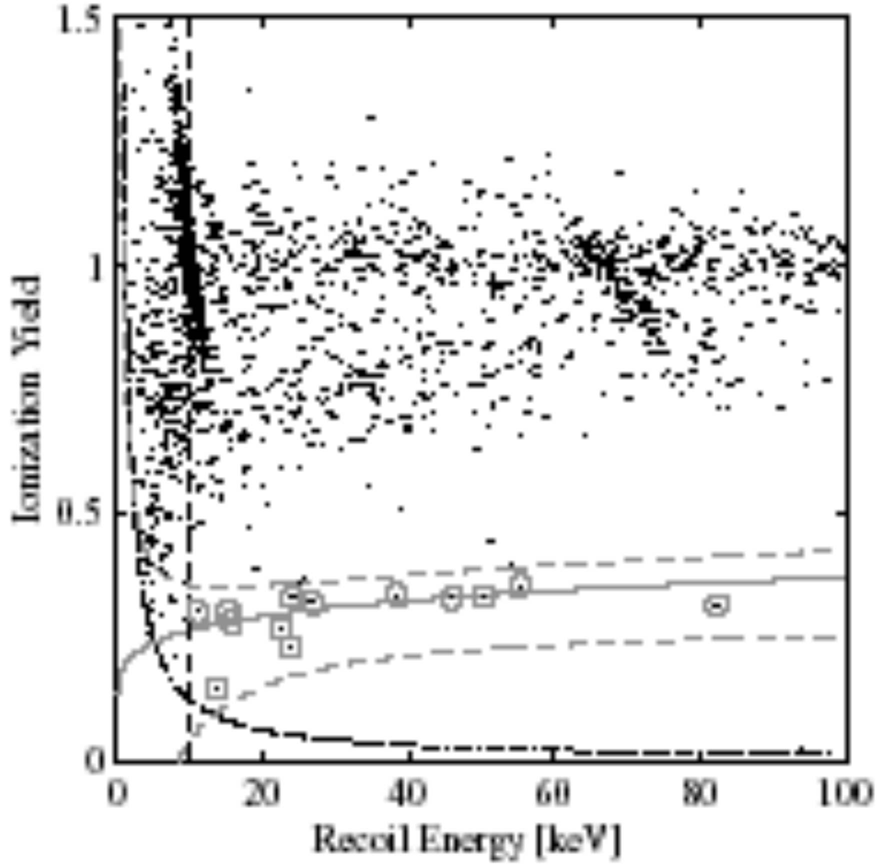
- One side collected ionization elections
- Other side covered with s.c. phonon detections

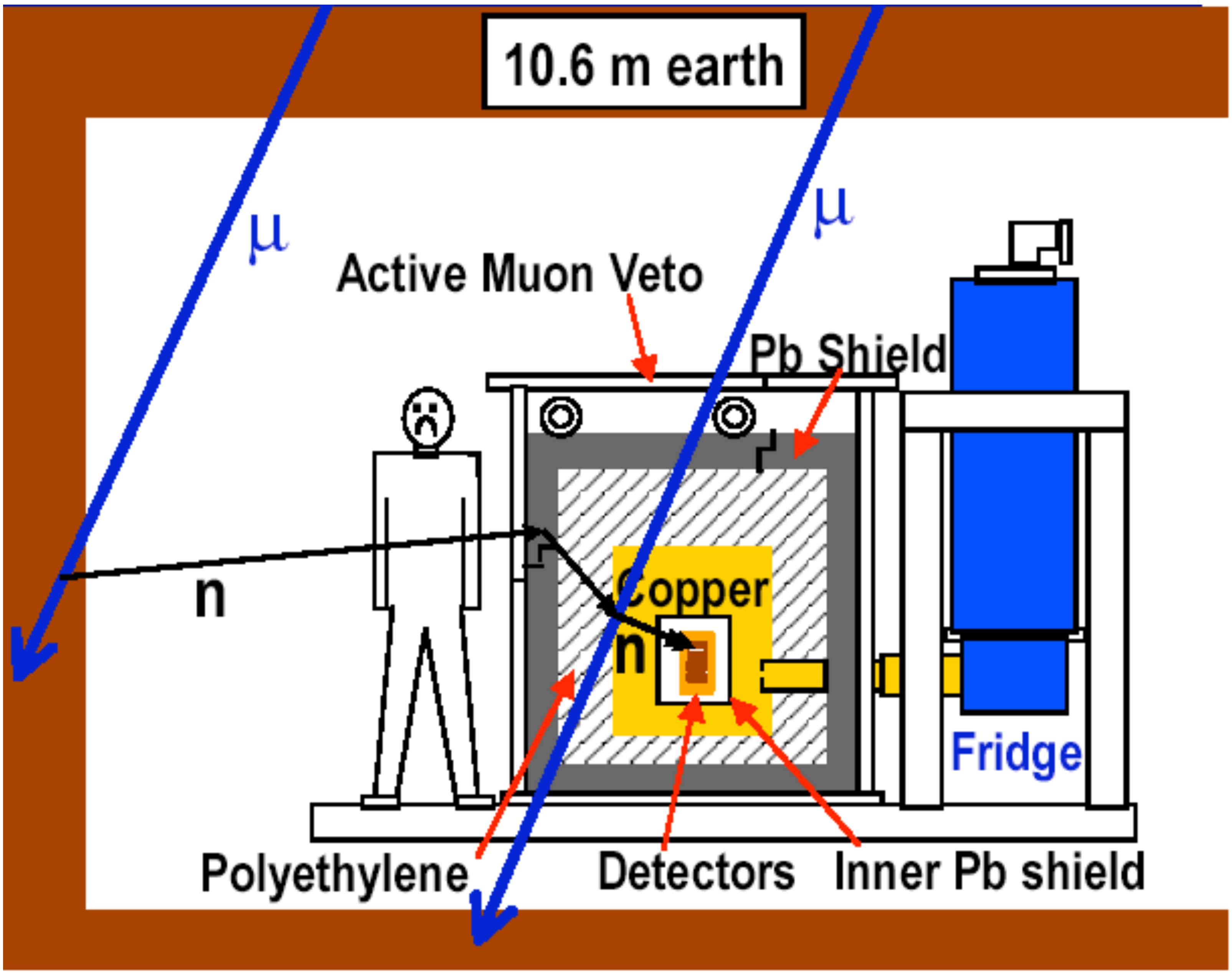


Rejection of γ backgrounds

Sensitivity improvement by 10,000,000!
(in twenty years..._






10.6 m earth
μ
μ
Active Muon Veto
Pb Shield
n
Copper
n
Fridge
Polyethylene
Detectors
Inner Pb shield

Numbers

- $(dE/dx)_{min}$=1.8 MeV/g/cm^2, γ~4
- 30 eV/ion dense matter, ~0.1 eV/e-h pair in semiconductor, 100eV/photon in scintillator
- Cerenkov: $\cos\theta_c = 1/\beta n$, $N_\gamma = (90/\text{cm})\sin^2\theta$
- TR: 10^{-3} photons/interface, 10 keV
- Nuclear recoil: T~5 keV, 1/3 ionization, 2/3 phonons, all ionization for photons

References

- “Classical Electrodynamics”, J.D. Jackson (esp. ch. 13)
- “Radiation Detection and Measurement”, G.F. Knoll
- “Experimental Methods in High Energy Physics”, T. Ferbel
- “High Energy Physics”, Rossi (buy used)
- Particle Properties Data Book, http://pdg.lbnl.gov
- Original papers by Bethe, Fermi, Bloch, Ginzberg, Cerenkov, Landau, …