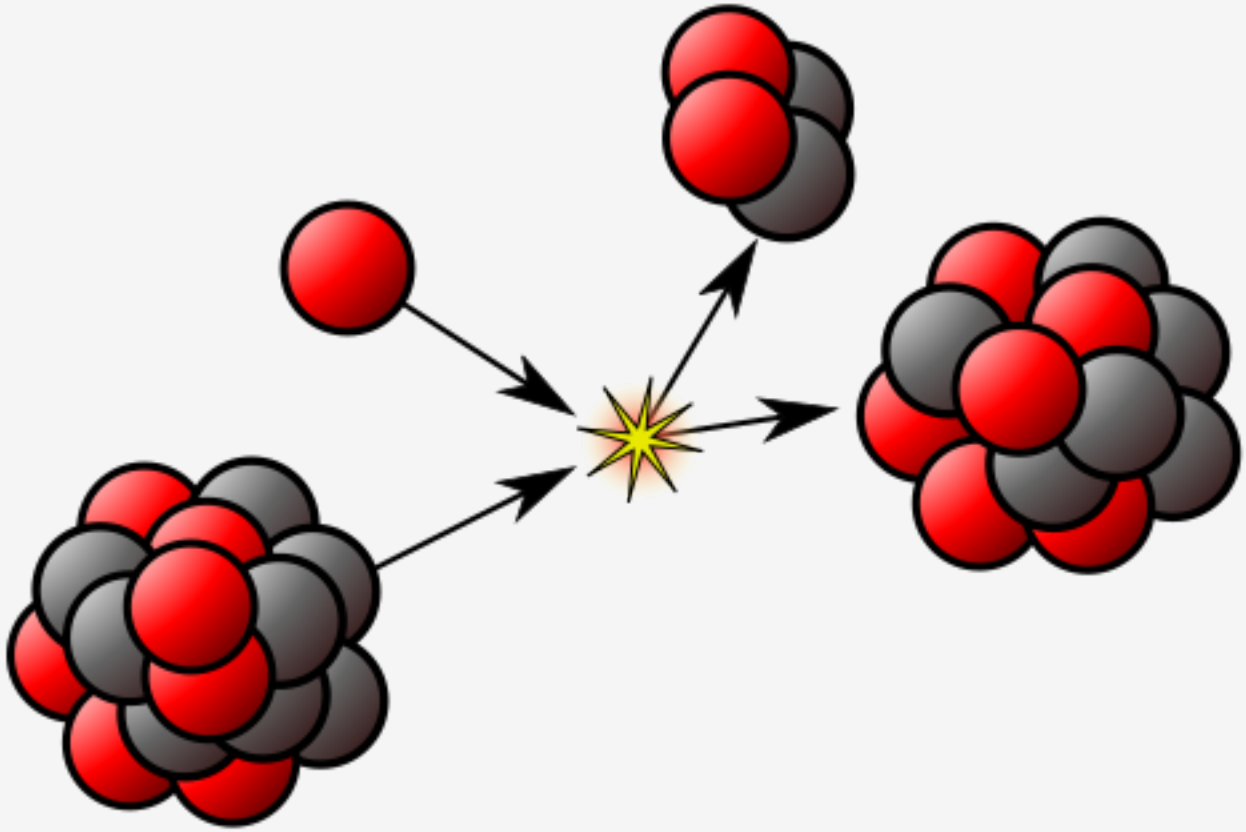
Nuclear Processes and Backgrounds



Kate Scholberg, Duke University
EDIT School
Fermilab, March 2018

This “nuclear processes and backgrounds” topic could mean a lot of things... I decided to pick a few relevant to some of my favorite physics topics

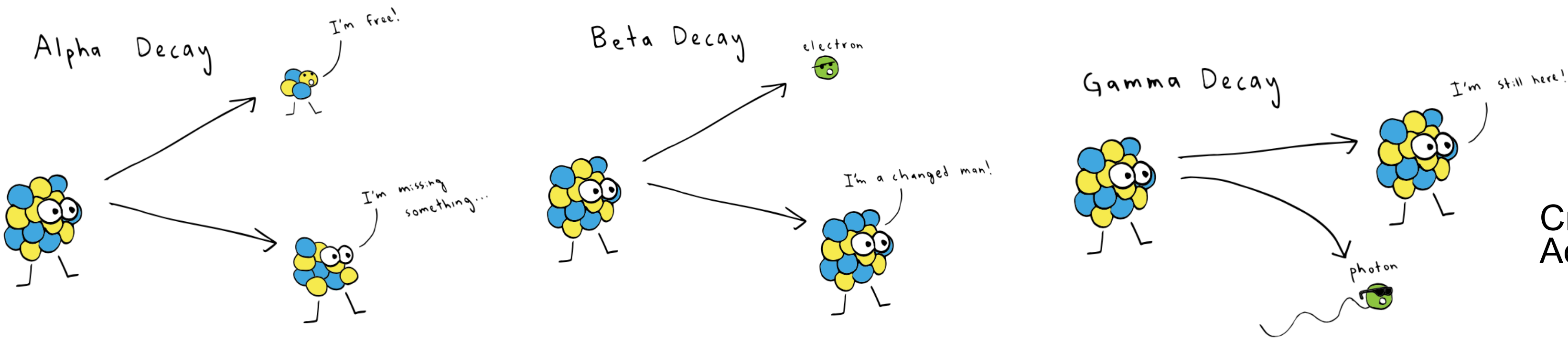
- **Part I:** **Energy loss of particles in matter**
  [generic material relevant
  for low-energy neutrino detection,
- but also many other situations
- ... some you have seen]

- **Part II:** Examples of signal and background for **low-energy neutrinos** in underground detectors
  - scintillator
  - water Cherenkov
  - liquid argon

“Nuclear Processes”

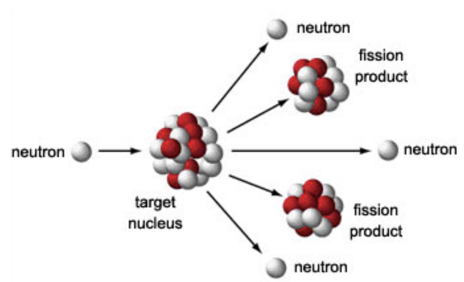
Could refer to almost anything involving nuclei...

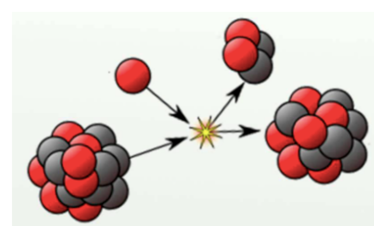
- Radioactive decay

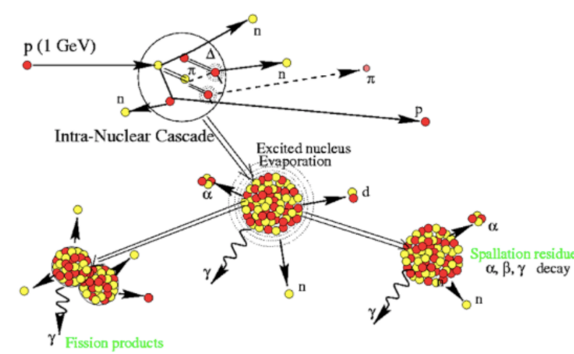


Credit: Khan Academy

- Fission
- Scattering
- Spallation

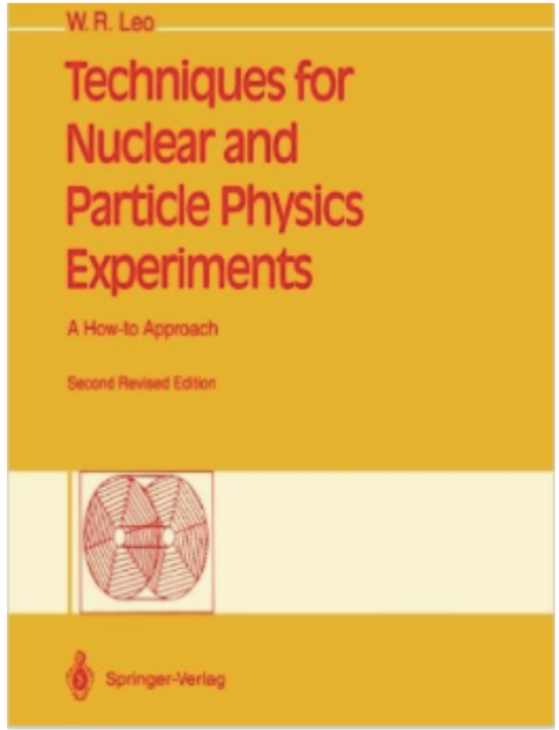






These could be your signal, or your background (or your calibration), possibly all in the same detector, depending on what you are trying to do...

References:



Essential for experimentalists!

2 *32. Passage of particles through matter*

32. PASSAGE OF PARTICLES THROUGH MATTER

Revised September 2013 by H. Bichsel (University of Washington), D.E. Groom (LBNL), and S.R. Klein (LBNL).

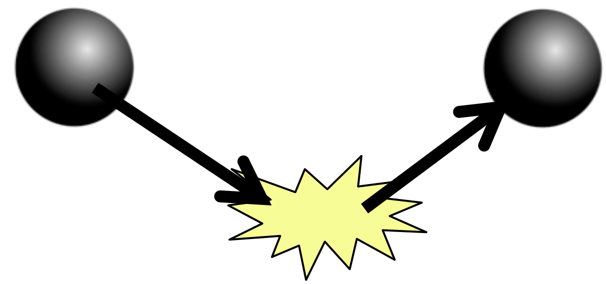
This review covers the interactions of photons and electrically charged particles in matter, concentrating on energies of interest for high-energy physics and astrophysics and processes of interest for particle detectors (ionization, Cherenkov radiation, transition radiation). Much of the focus is on particles heavier than electrons ($\pi^{\pm}$, p, etc.). Although the charge number z of the projectile is included in the equations, only $z = 1$ is discussed in detail. Muon radiative losses are discussed, as are photon/electron interactions at high to ultrahigh energies. Neutrons are not discussed. The notation and important numerical values are shown in Table 32.1.

PDG review (points to online databases)

Part I: Energy loss of particles in matter

Particles lose energy by interactions with atoms as they move through matter (and may also decay into other particles, or create new particles)

particles deposit energy and change direction

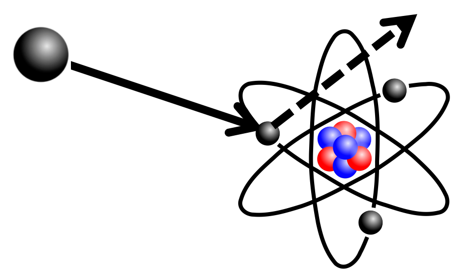


<table>
<tr><td rowspan="4">Common energy-loss processes</td><td colspan="2">Inelastic collisions w/ atomic electrons</td></tr>
<tr><td>Soft (excitations)</td><td>Hard (ionization, secondaries)</td></tr>
<tr><td colspan="2">Elastic scattering from nuclei</td></tr>
<tr><td colspan="2">Cherenkov radiation</td></tr>
<tr><td rowspan="2">Rare energy loss processes
(but still potentially important)</td><td colspan="2">Nuclear reactions</td></tr>
<tr><td colspan="2">Bremsstrahlung</td></tr>
</table>

First: **"Heavy"** (heavier than $e^{\pm}$) **charged particles**

$\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, α, ...

In "normal" cases,
most energy loss is from **inelastic collisions,**
e.g., ionization of atoms



"stopping power" $$\frac{dE}{dx}$$ as a function of projectile, material, energy, ... in basic approximation can be calculated w/ classical E&M (Jackson)

behaves statistically, but there are many collisions,
so fluctuations are typically small

The QM calc for relativistic particles:

"Bethe" or "Bethe-Bloch" equation

Mean rate of energy loss

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \rho$$

Symbol	Definition	Value or (usual) units
α	fine structure constant	
	$e^2/4\pi\epsilon_0\hbar c$	1/137.035 999 074(44)
M	incident particle mass	MeV/c^2
E	incident part. energy γMc^2	MeV
T	kinetic energy, $(\gamma-1)Mc^2$	MeV
W	energy transfer to an electron in a single collision	MeV
k	bremsstrahlung photon energy	MeV
m_ec^2	electron mass $\times\, c^2$	0.510 998 928(11) MeV
r_e	classical electron radius	
	$e^2/4\pi\epsilon_0 m_ec^2$	2.817 940 3267(27) fm
N_A	Avogadro's number	$6.022\,141\,29(27)\times10^{23}$ mol^{-1}
z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_ec^2$	0.307 075 MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	
$\hbar\omega_p$	plasma energy	$\sqrt{\rho\langle Z/A\rangle}\times 28.816$ eV
	$\sqrt{4\pi N_e r_e^3}\; m_ec^2/\alpha$	↳ ρ in g cm^{-3}
N_e	electron density	(units of r_e)$^{-3}$
w_j	weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
X_0	radiation length	g cm^{-2}
E_c	critical energy for electrons	MeV
$E_{\mu c}$	critical energy for muons	GeV
E_s	scale energy $\sqrt{4\pi/\alpha}\; m_ec^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

good to ~% in MeV-GeV range and intermediate Z materials

$$0.1 \lesssim \beta\gamma \lesssim 1000$$

The QM calc: **"Bethe" or "Bethe-Bloch" equation**

Mean rate of energy loss

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \rho$$

$\left\langle \frac{dE}{dx} \right\rangle \propto \rho$, the material density

PDG expression for "stopping power" is really

$$\frac{1}{\rho} \left\langle \frac{dE}{dx} \right\rangle \quad \mathrm{MeV\ cm^2/g}$$

I will drop the ρ, but in practice you need to remember to multiply by it

A few features of the Bethe-Bloch equation:

Mean rate of energy loss

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

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$m_e c^2$	electron mass $\times\, c^2$	$0.510\,998\,928(11)$ MeV
r_e	classical electron radius $e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,3267(27)$ fm
N_A	Avogadro's number	$6.022\,141\,29(27) \times 10^{23}\ \mathrm{mol}^{-1}$
z	charge number of incident particle	
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K	$4\pi N_A r_e^2 m_e c^2$	$0.307\,075\ \mathrm{MeV\ mol}^{-1}\ \mathrm{cm}^2$
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	
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E_s	scale energy $\sqrt{4\pi/\alpha}\ m_e c^2$	21.2052 MeV
R_M	Molière radius	$\mathrm{g\ cm}^{-2}$

$$W_{\max} = \frac{2m_e c^2\, \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

(basic kinematics)

Most quantities are basic physics constants, except:

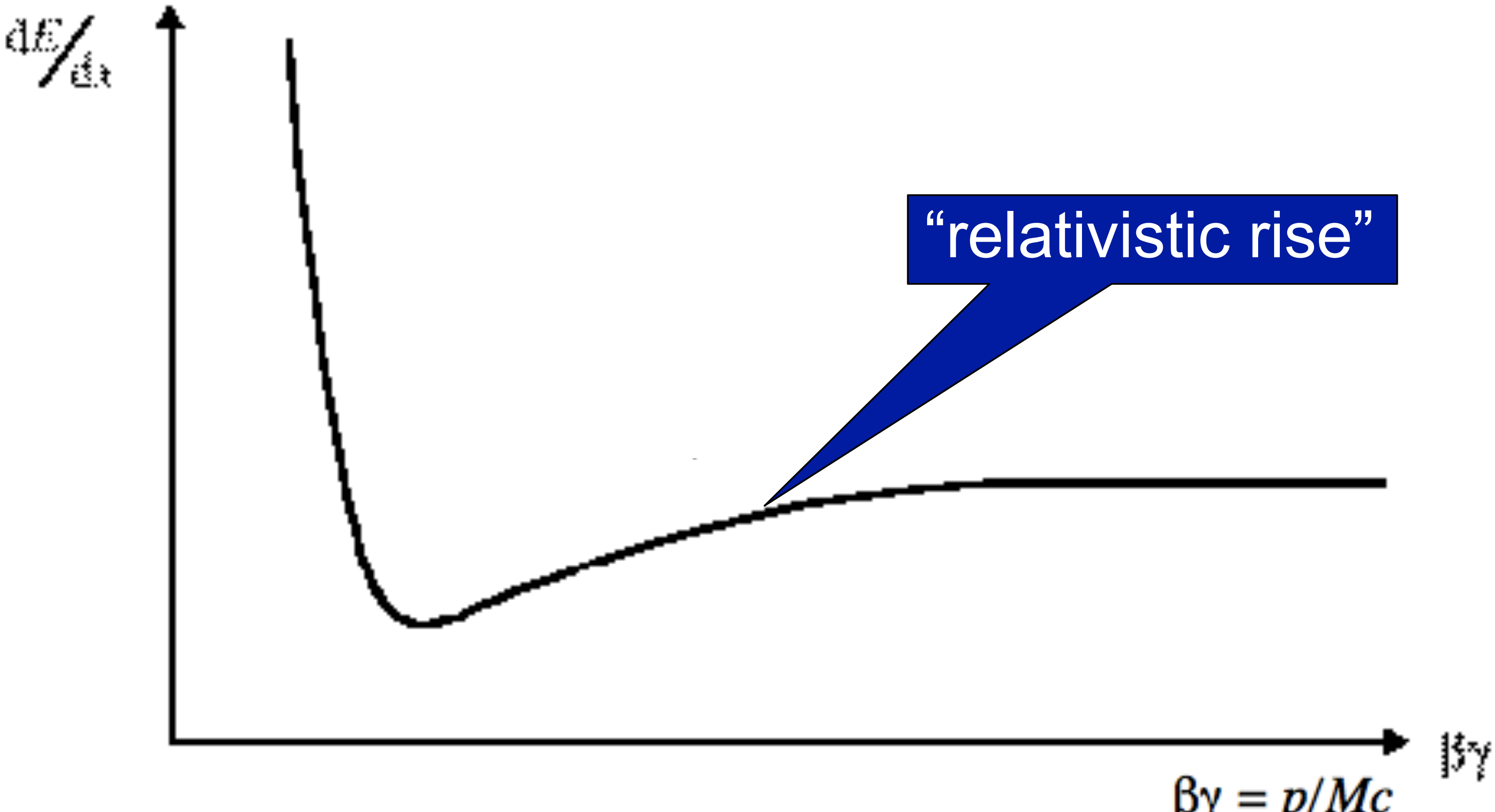
δ: "density correction" (~measured)

I: mean excitation energy (measured)

What this function looks like:

usually drawn log-log

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



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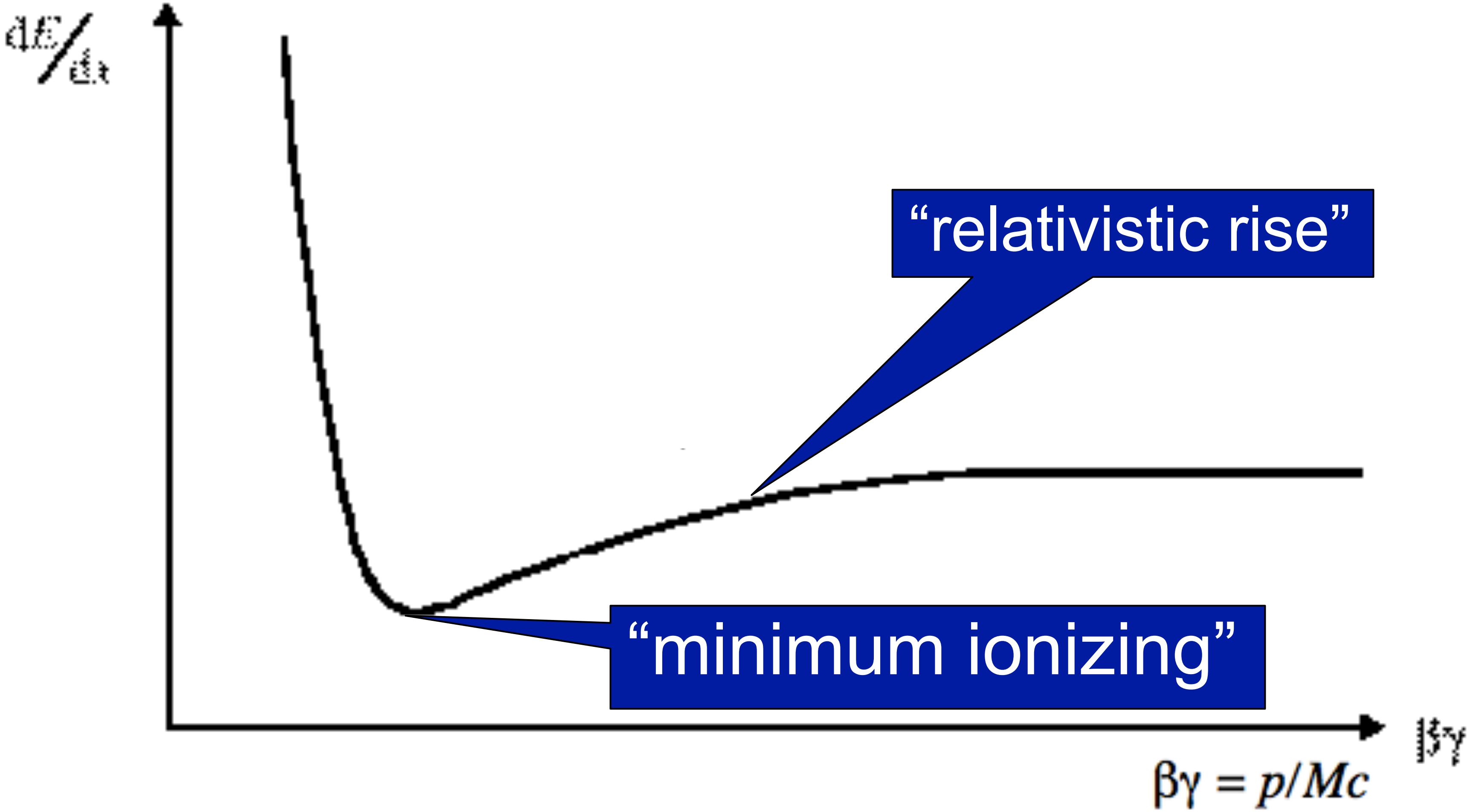
usually drawn log-log

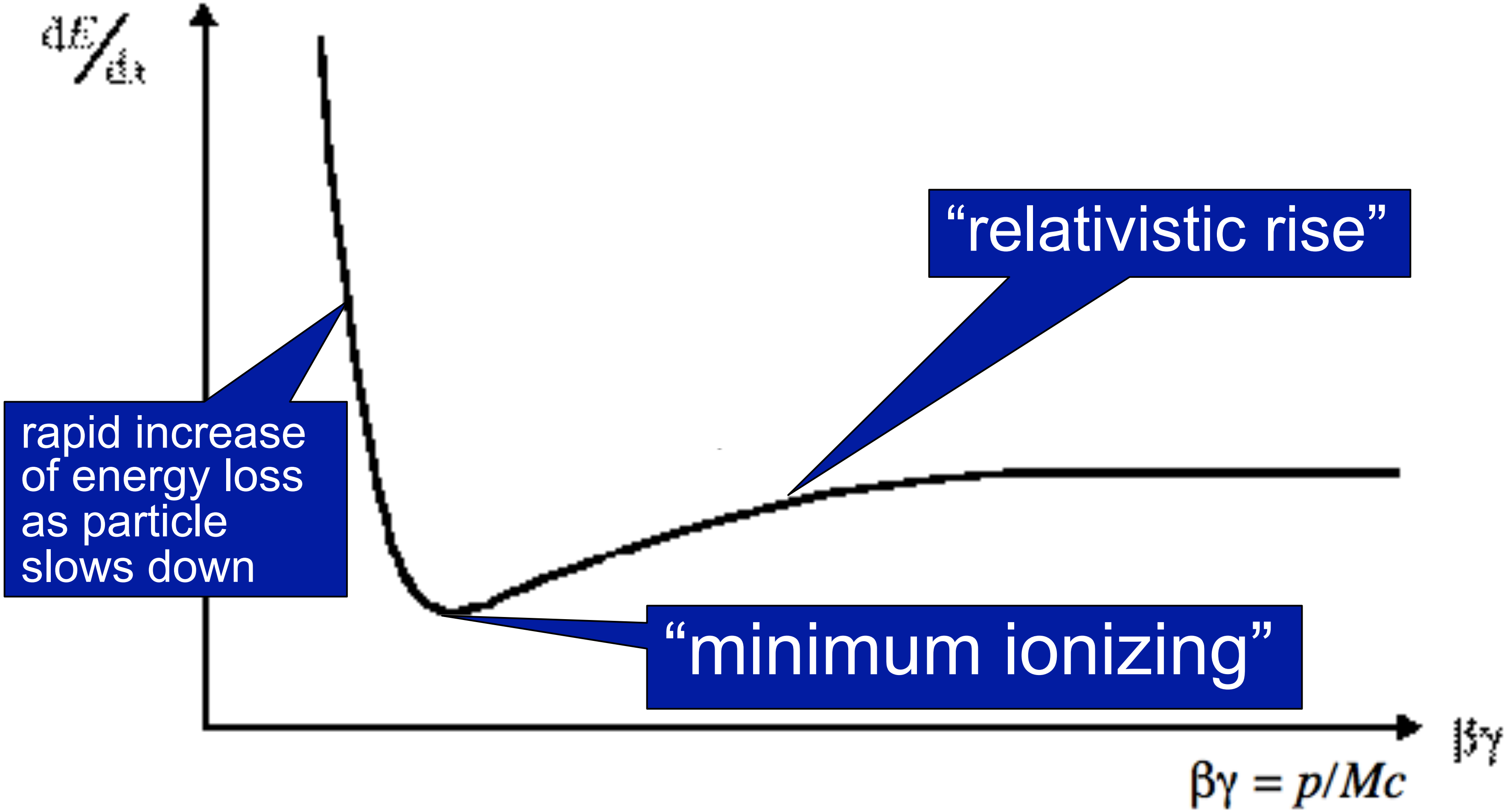
$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



What this function looks like:

usually drawn log-log

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



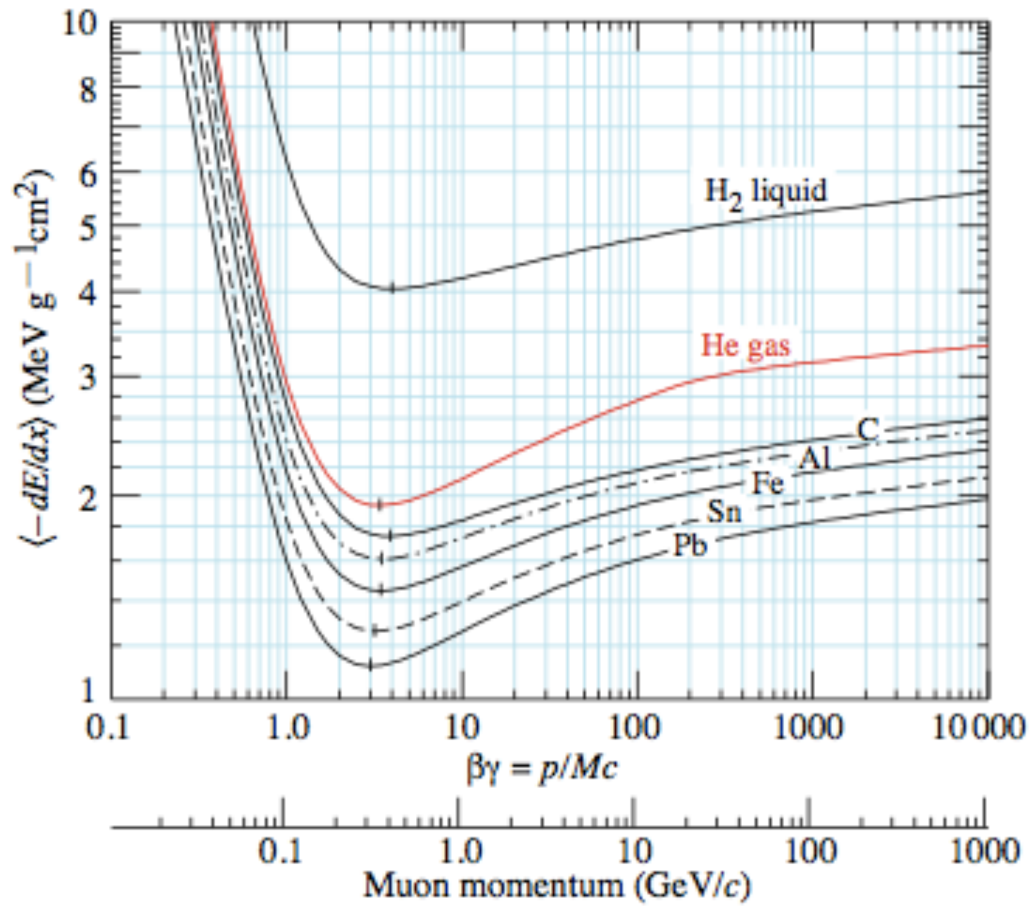
For different materials:

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{Z}{A}$$

of target material

(~0.5, so relatively weak dependence on target material)



For different incident particles:

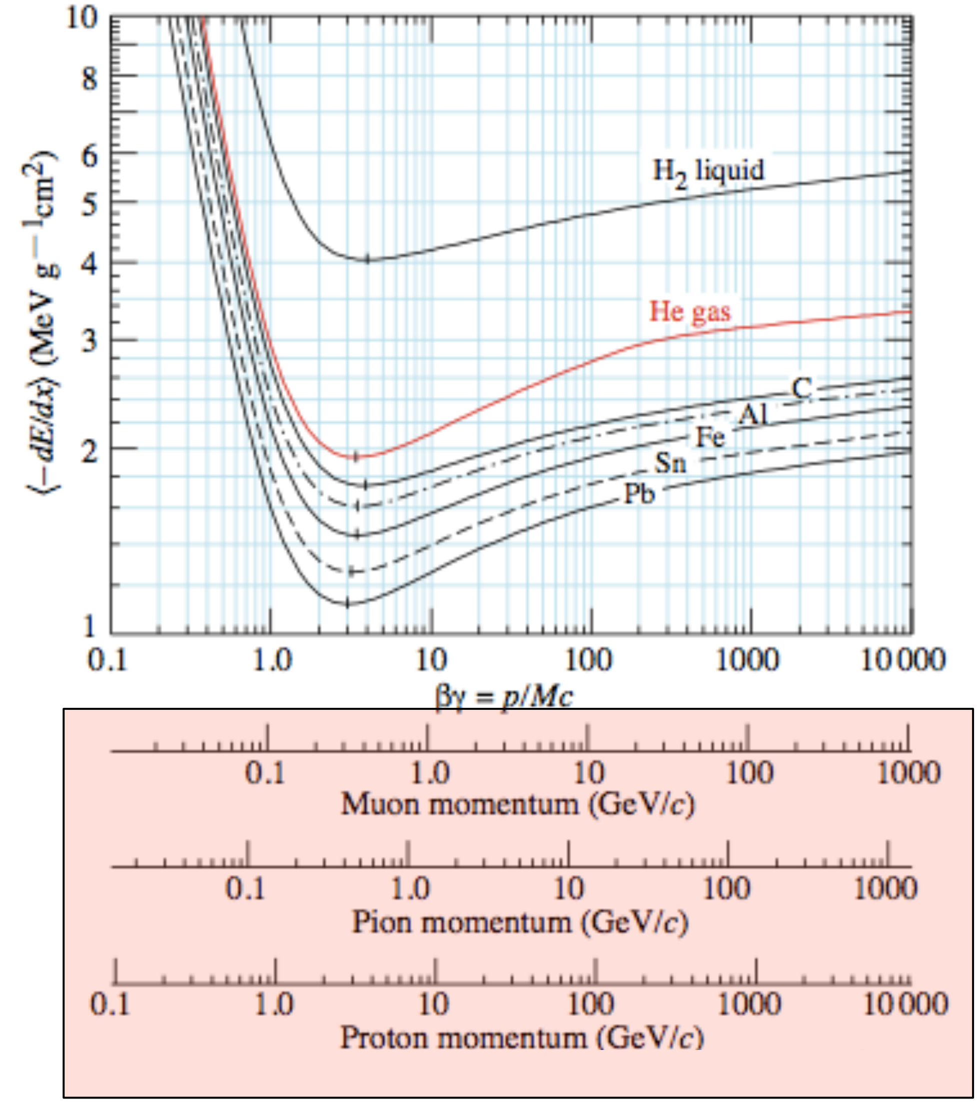
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$\left\langle \frac{dE}{dx} \right\rangle \propto z^2$$

and depends on βγ

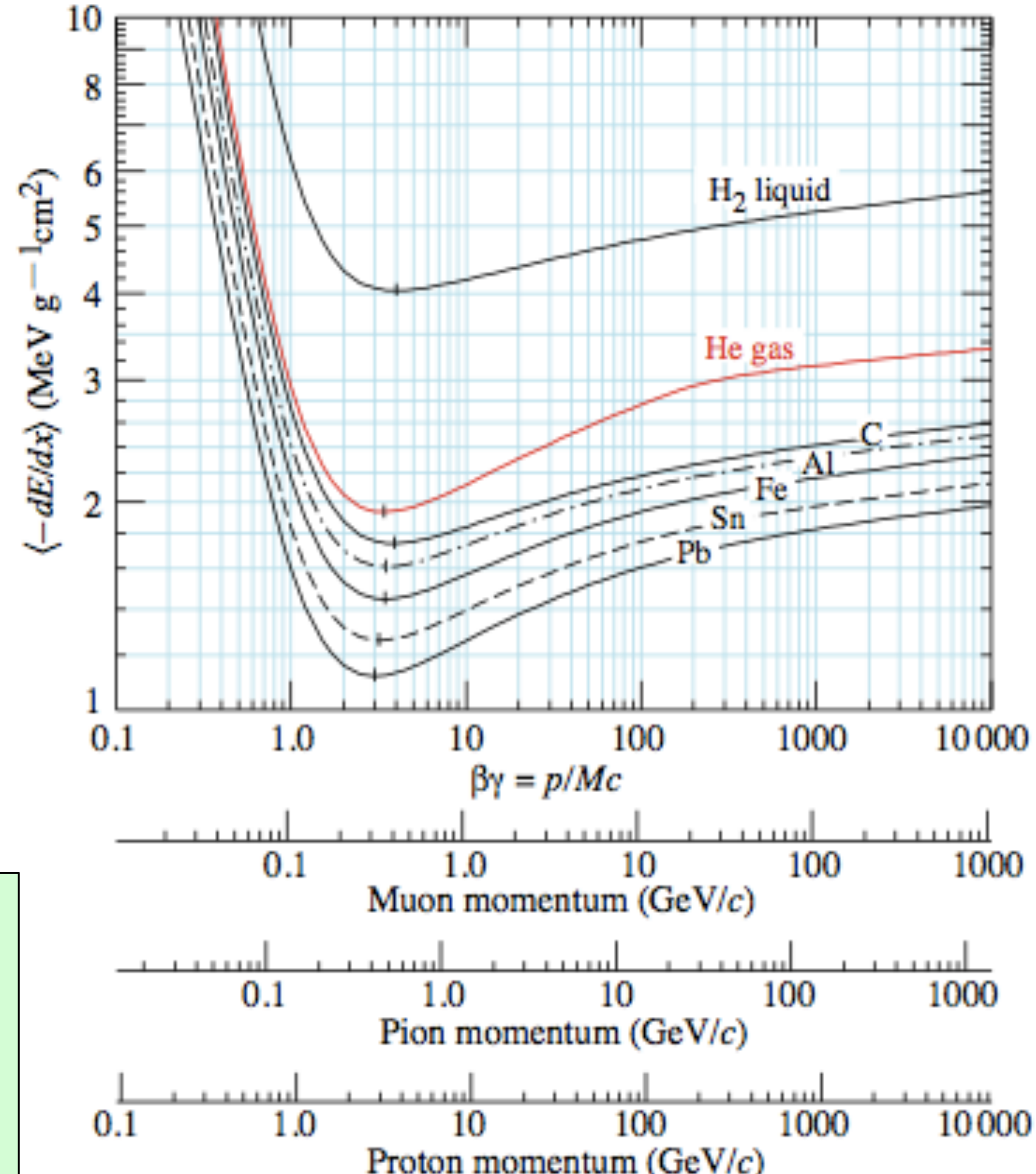
$\beta\gamma = p/Mc$

of incident particle



Terminology note:

minimum in
similar place for
given incident
particle $\beta\gamma$



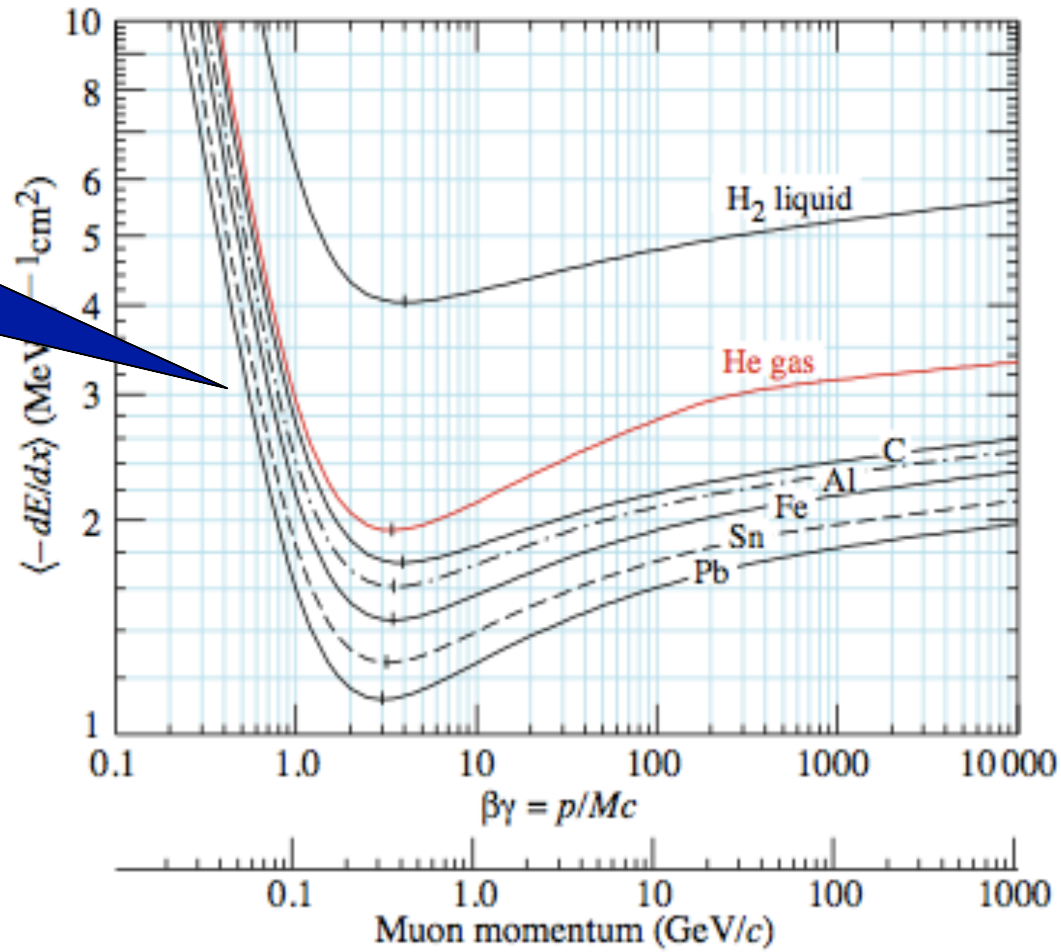
"mip": minimum ionizing particle

since relativistic rise
is slow, can often
estimate energy loss
using mip assumption

~2 MeV/cm
for μ in water

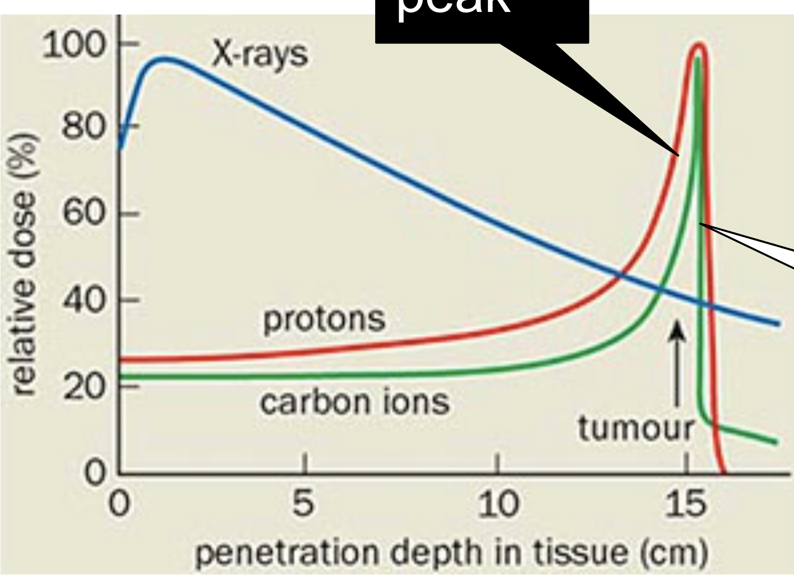
\begin{aside}

rapid increase of energy loss as particle slows down (BB breaks down)



Cute, and useful consequence:

“Bragg peak”



Energy mostly dumped at the end of the particle’s range... useful for killing tumors w/o damaging healthy tissue

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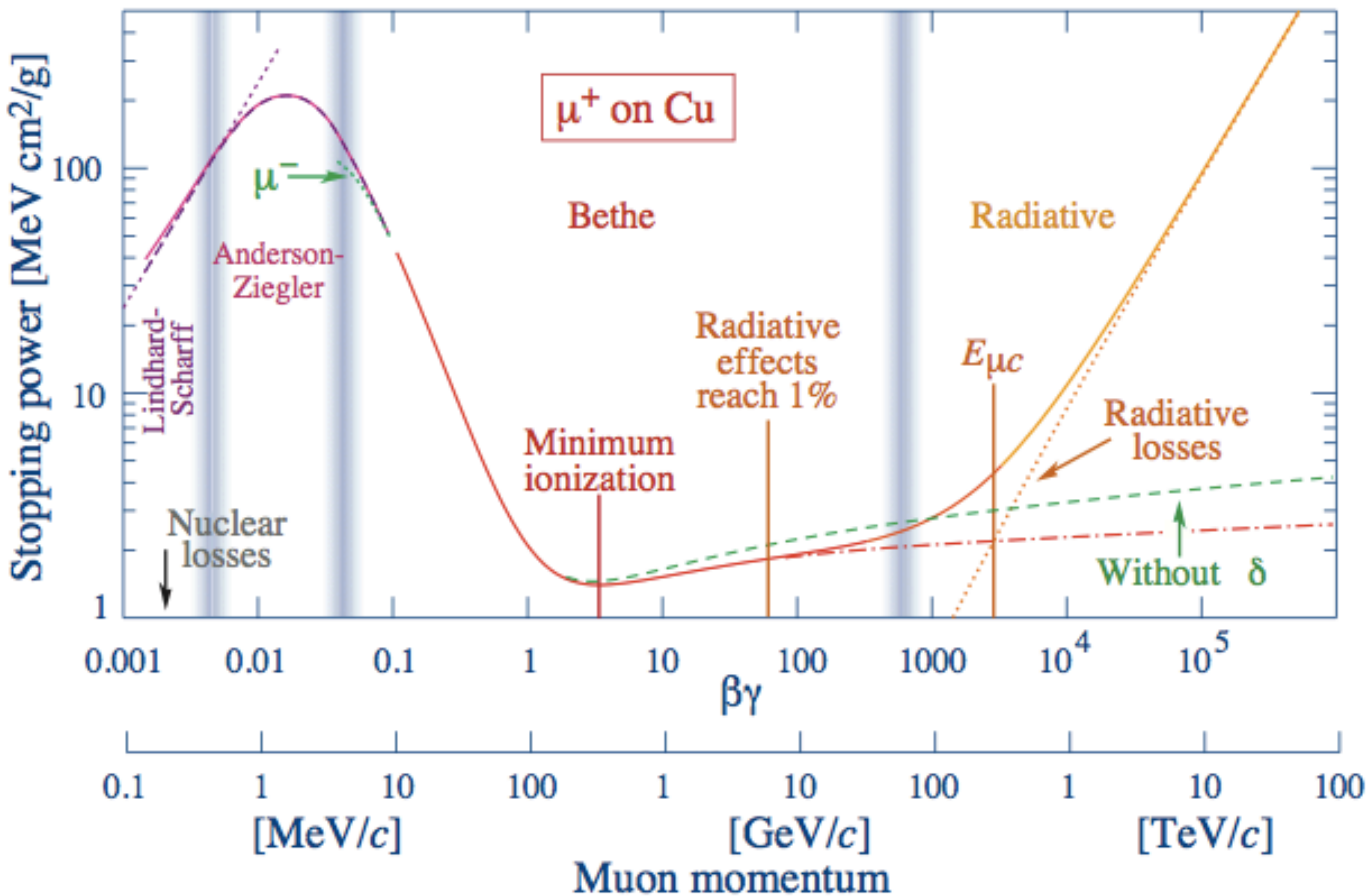
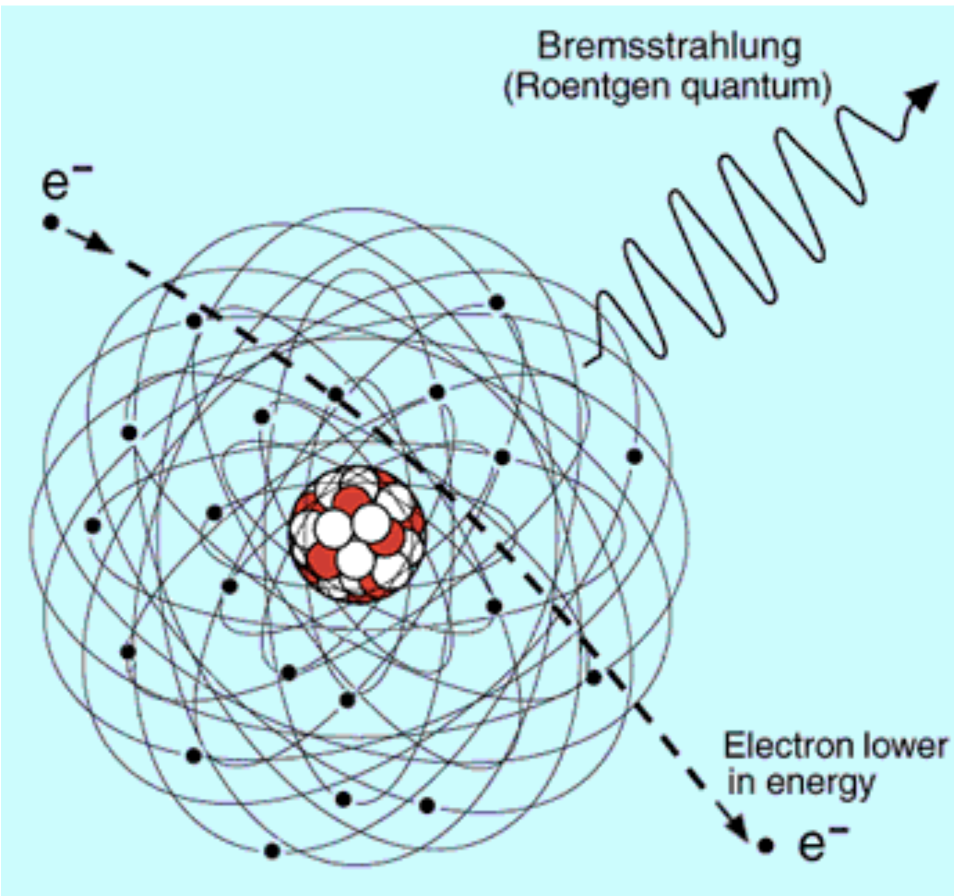
Be aware: Bethe-Bloch primarily valid for “intermediate” energies



This was for “heavy” particles
(i.e., heavier than atomic electrons)

Electrons (and positrons) act differently...



In addition to collisional energy loss, they are easily deflected (accelerated) and they **radiate photons (bremsstrahlung)**

$$\mathrm{prob} \propto \frac{1}{\mathrm{m}^2}$$

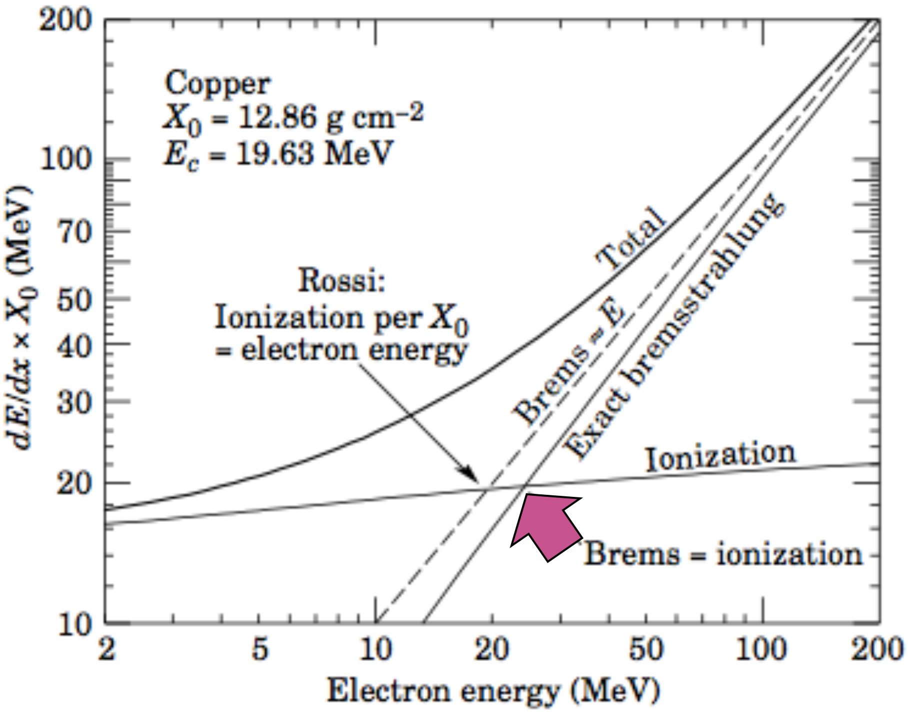
so brems from μ’s down by

$$m_e^2/m_\mu^2 = 0.511^2/106^2$$

$$\sim 4.5 \times 10^{-5}$$

$$\left(\frac{dE}{dx}\right)_{\rm tot} = \left(\frac{dE}{dx}\right)_{\rm rad} + \left(\frac{dE}{dx}\right)_{\rm coll}$$

At a few tens of MeV (depends on medium)
brem energy loss > ionization energy loss:
crossover is called the **CRITICAL ENERGY E_c**



Bethe-Heitler approximation

$$E_c \approx \frac{1600 m_e c^2}{Z}$$

Table 2.2. Critical energies of some materials

Material	Critical energy [MeV]
Pb	9.51
Al	51.0
Fe	27.4
Cu	24.8
Air (STP)	102
Lucite	100
Polystyrene	109
NaI	17.4
Anthracene	105
H_2O	92

Another commonly used quantity to characterize radiation of electrons/positrons: **RADIATION LENGTH, L_{rad}**

In the high-energy limit where radiation loss dominates

$$E = E_0 \exp\left(\frac{-x}{L_{\rm rad}}\right)$$

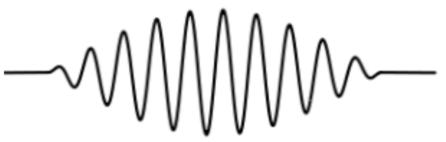
Table 2.3. Radiation lengths for various absorbers

Material	[gm/cm^2]	[cm]
Air	36.20	30050
H_2O	36.08	36.1
NaI	9.49	2.59
Polystyrene	43.80	42.9
Pb	6.37	0.56
Cu	12.86	1.43
Al	24.01	8.9
Fe	13.84	1.76
BGO	7.98	1.12
BaF_2	9.91	2.05
Scint.	43.8	42.4

Shorthand thinking:
L_{rad} is thickness for which you can expect to get an **electromagnetic shower** (more on this coming shortly)

Energy loss of photons in matter

In our context, this mostly means
x-rays and gamma rays

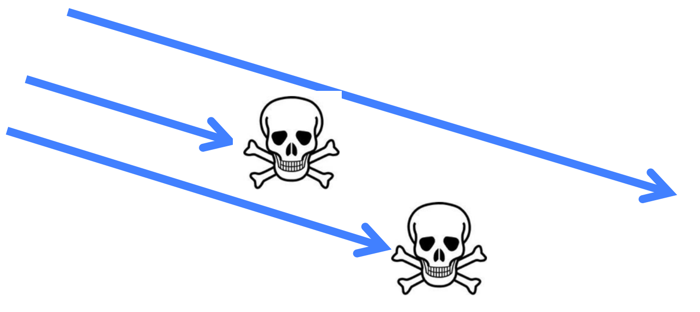


photons have no electric charge...
➔no Coulomb-induced collisions

4 electromagnetic energy loss mechanisms:

- photoelectric effect
- Compton scattering
- pair production
- (photonuclear effect)

most of these
destroy the photons rather than
change the energy (attenuation)

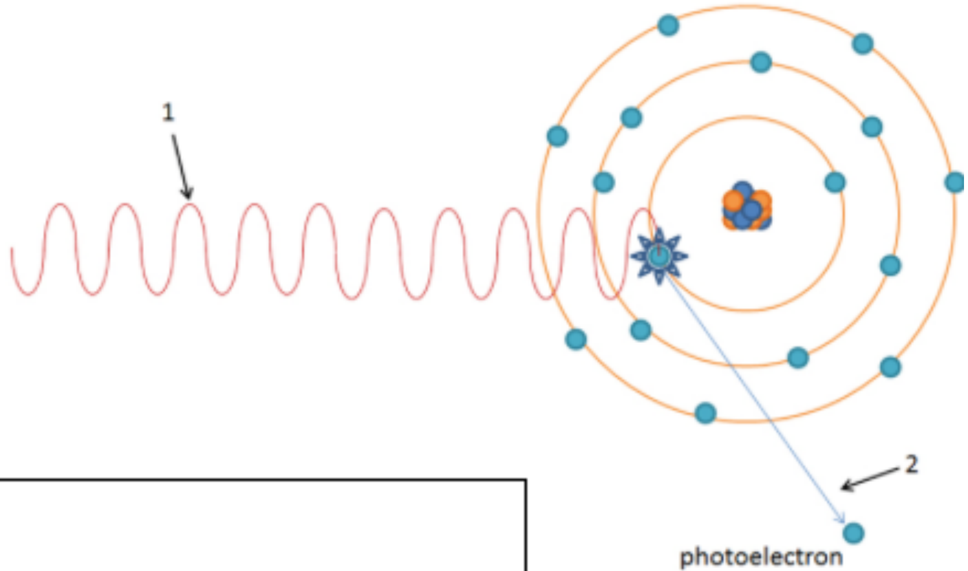


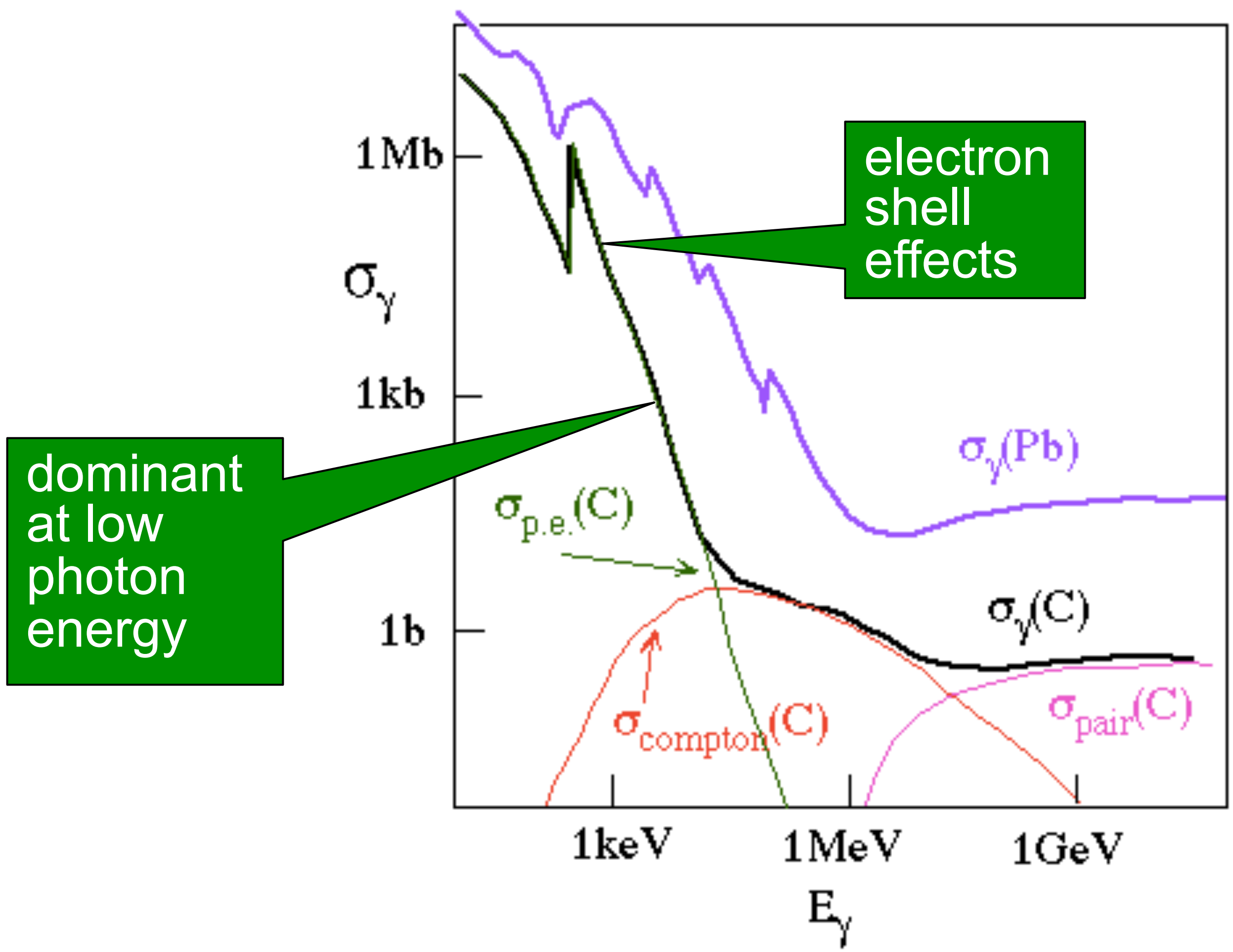
(Rayleigh scattering: scattering
off whole atoms; small at energies of
interest here)

Photoelectric Effect

Pop an electron
out of an atom
(photon is gone)

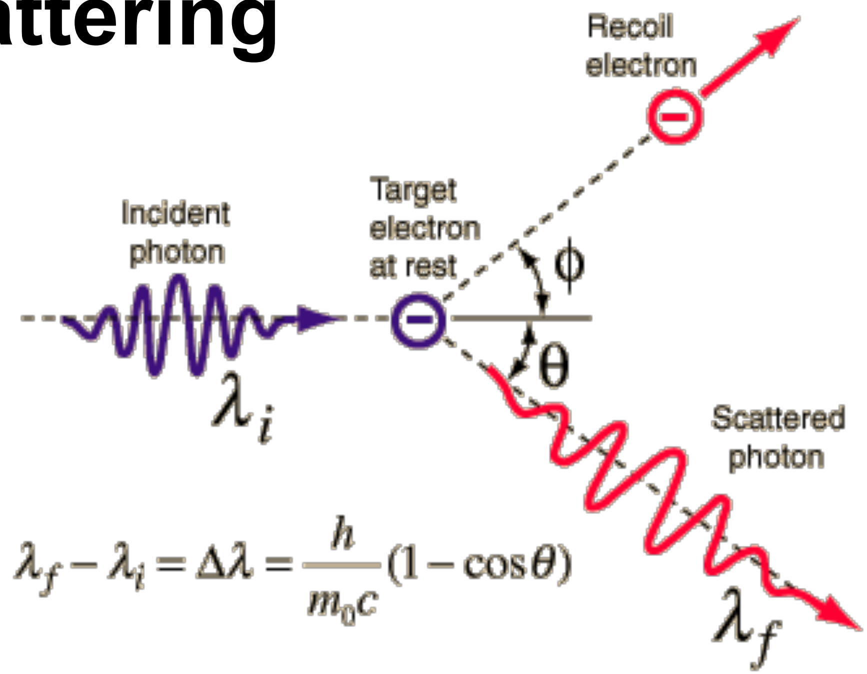
$$E_e = h\nu - \text{B.E.}$$



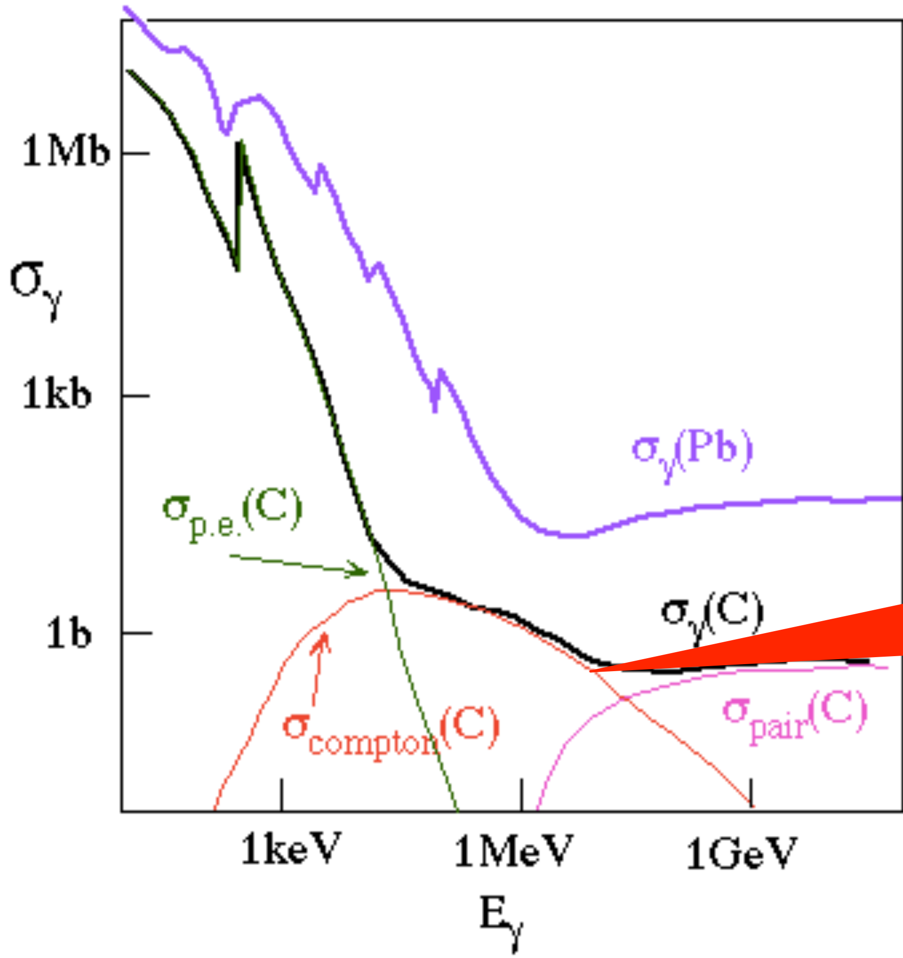


Compton Scattering

Kick an electron;
(the electron subsequently
 loses energy... γ keeps going)



$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

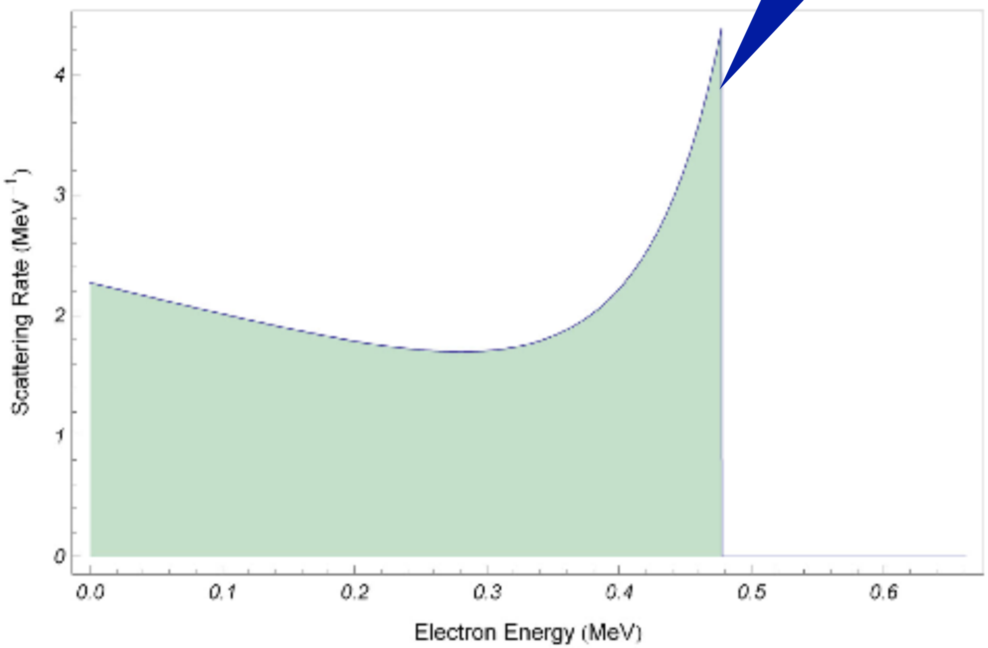


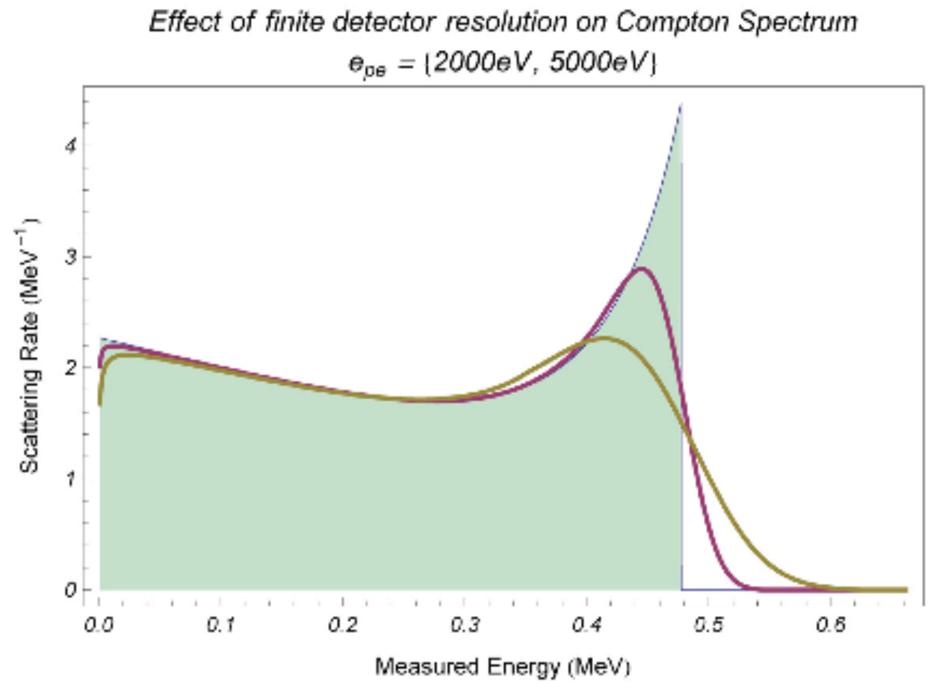
dominant
at
intermediate
photon
energy

Cross section calculated with Klein-Nishina formula (QED)

Compton recoil energy distribution

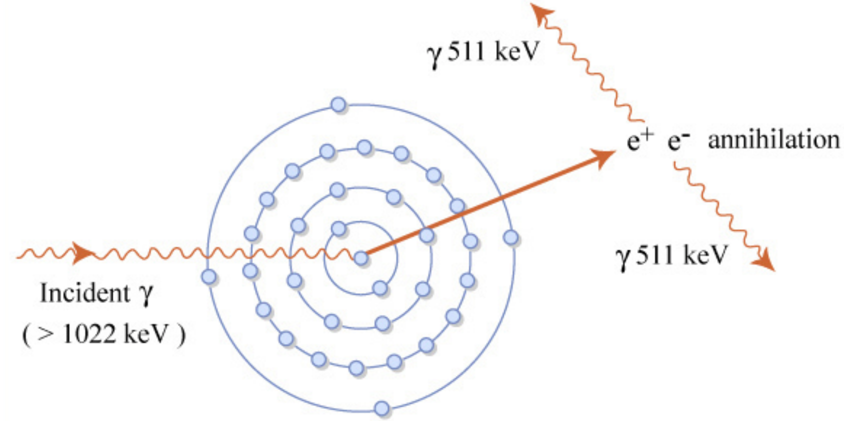
"Compton edge" for given γ energy

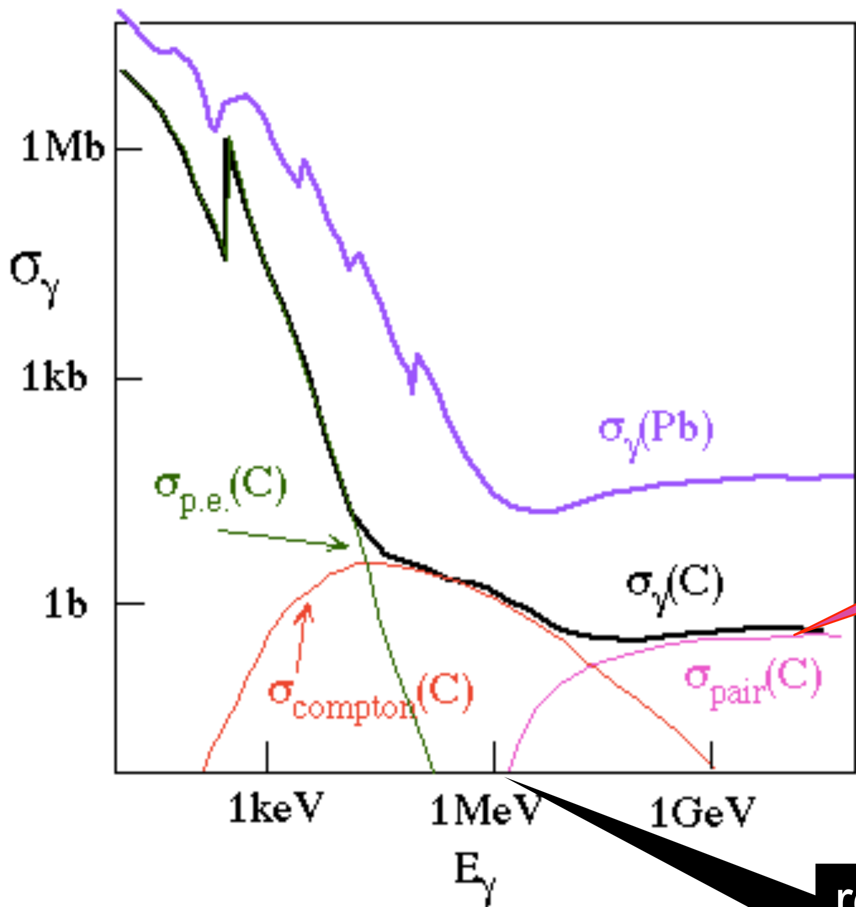




$$W_{\mathrm{max}} = h\nu\left(\frac{2\gamma}{1+2\gamma}\right) \qquad \gamma = \frac{h\nu}{m_e c^2}$$

Pair production

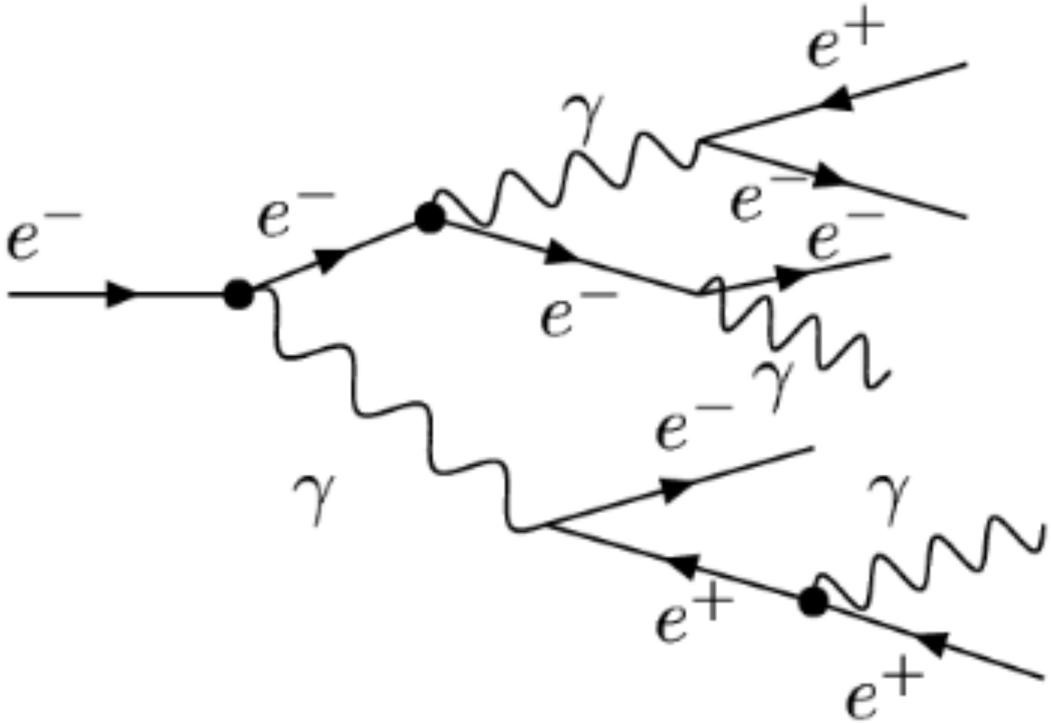




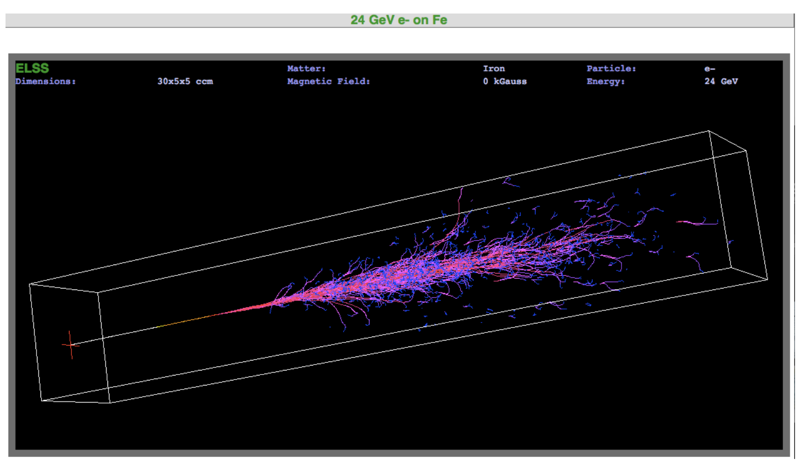
increases with energy and dominant at high energy

requires at least $2m_e$ of energy

Electromagnetic showers



An avalanche!
Can start with either a photon or $e^{\pm}$

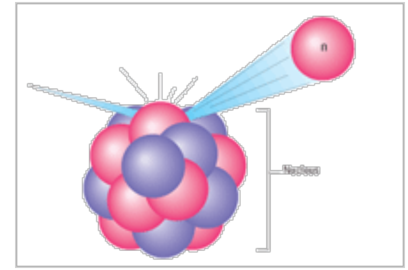


electron brems
➔ γ pair-produces
➔ $e^{\pm}$ brem
... until energies drop below pair-production threshold and/or E_c for electrons

Neutron energy loss

[later talk by Jeph Wang]

Neutrons interact via the strong force
short range force, so rare interactions
... neutrons are penetrating, and
will tend to ping around

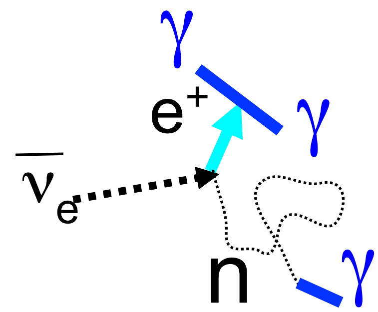


Mechanism	Reaction	Notes
Elastic scattering from nuclei	**A(n,n)A**	**Main mechanism of energy loss**
Inelastic scattering	$A(n,n')A^*$, A(n,2n')B,..	Deexcitation products or other secondaries
Radiative neutron capture	n+(Z,A) ➔ γ + (Z,A+1)	~ 1/v, so requires low energy
Other nuclear reactions	(n,p), (n, d), (n, α), etc.	Low energies required
Fission		Low energies required
Hadronic showers		High energy (>100 MeV)

There are specialized codes for simulating neutrons
(e.g., MCNPX, FLUKA... G4 has a bad rep, but is fine for many applications)

Neutron moderation and capture

Common for low-energy neutrino experiments, e.g. neutron from inverse beta decay



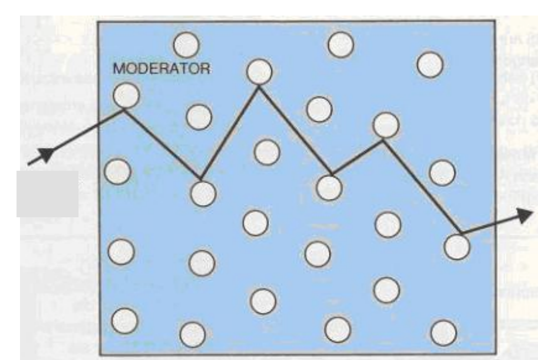
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

The neutron must thermalize (E~kT~1/40 eV) before capture
... "moderation" by multiple elastic scattering

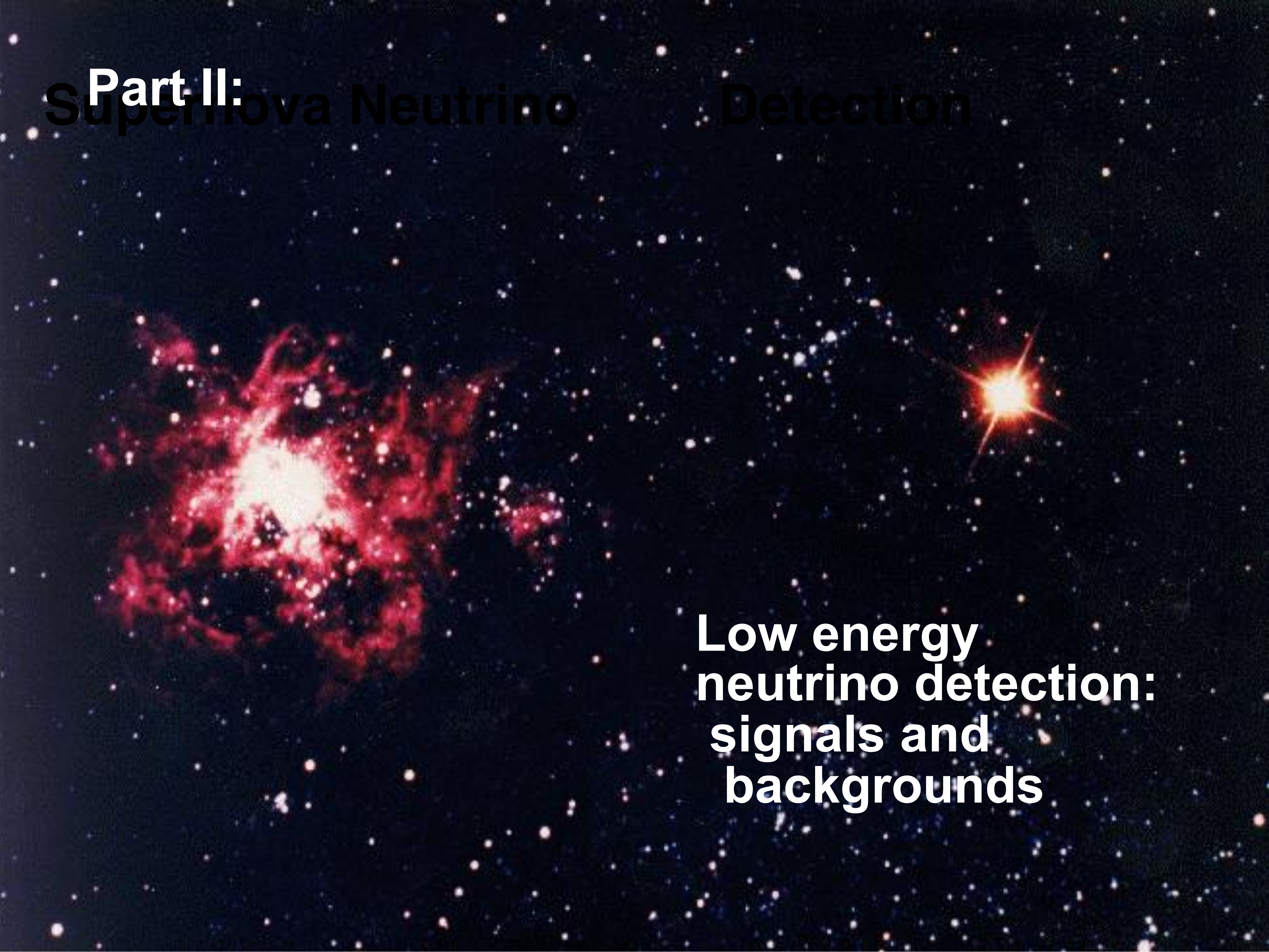
Elastic kinematics: $$\left(\frac{A-1}{A+1}\right)^2 E_0 < E < E_0$$

For small A , nucleus takes more energy away per scatter ➔ moderators made out of light materials (hydrogen, carbon...)

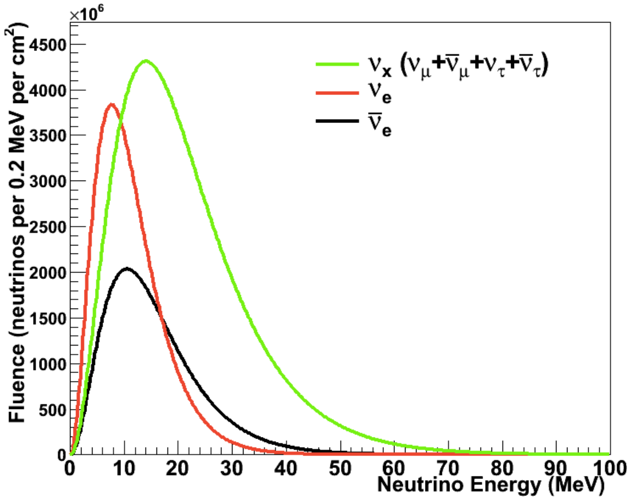


Summary of energy loss topics

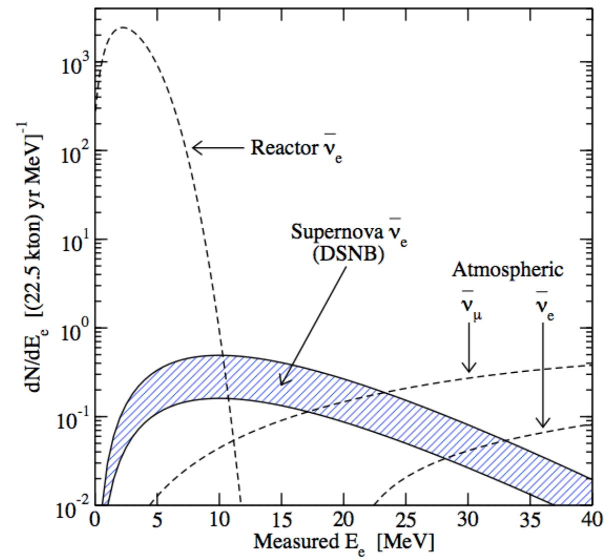
- charged particles
  - “heavy” (μ, π, p, ...): **Bethe-Bloch (ionization)**
  - e^+, e^-: **collisions + radiation**
    (know critical energy/radiation length)
- photons: **PE + Compton + pair production**
- neutrons: **elastic scattering** (+ radiative capture)


Part II:
Supernova Neutrino Detection
Low energy neutrino detection: signals and backgrounds

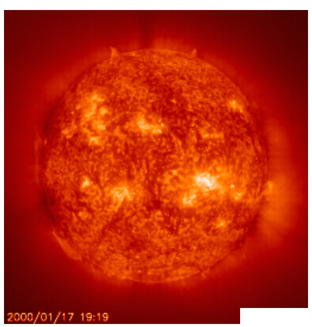
Neutrinos in the few to few tens of MeV range

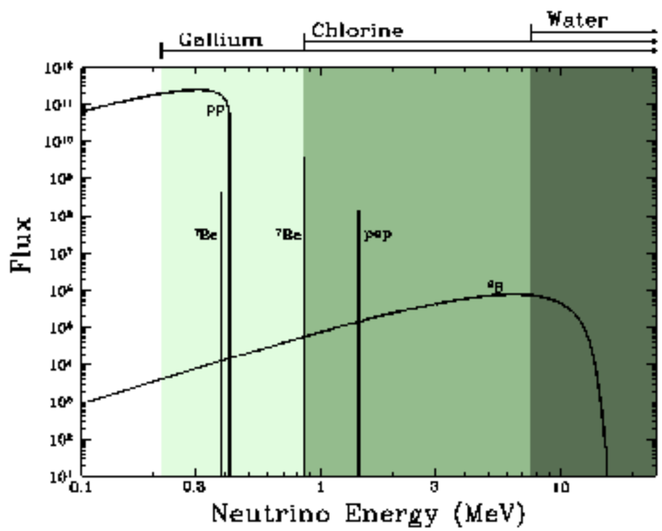


supernova neutrinos, burst & relic

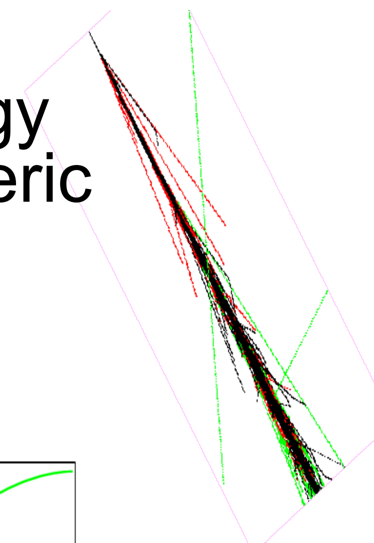


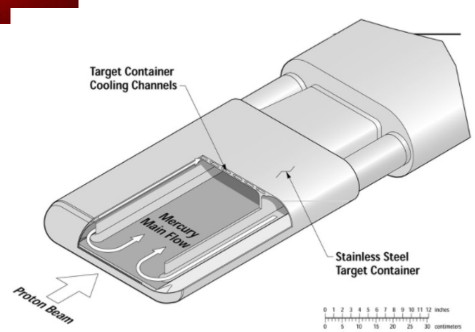
solar neutrinos



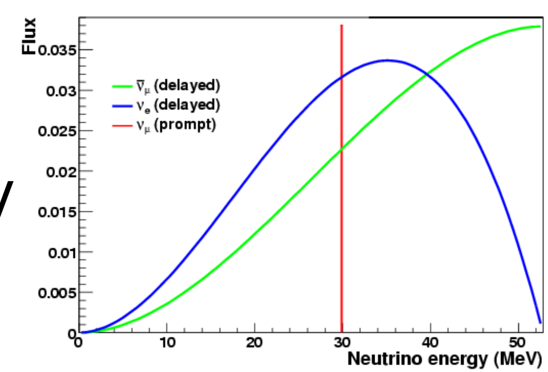


low energy atmospheric neutrinos





pion decay at rest



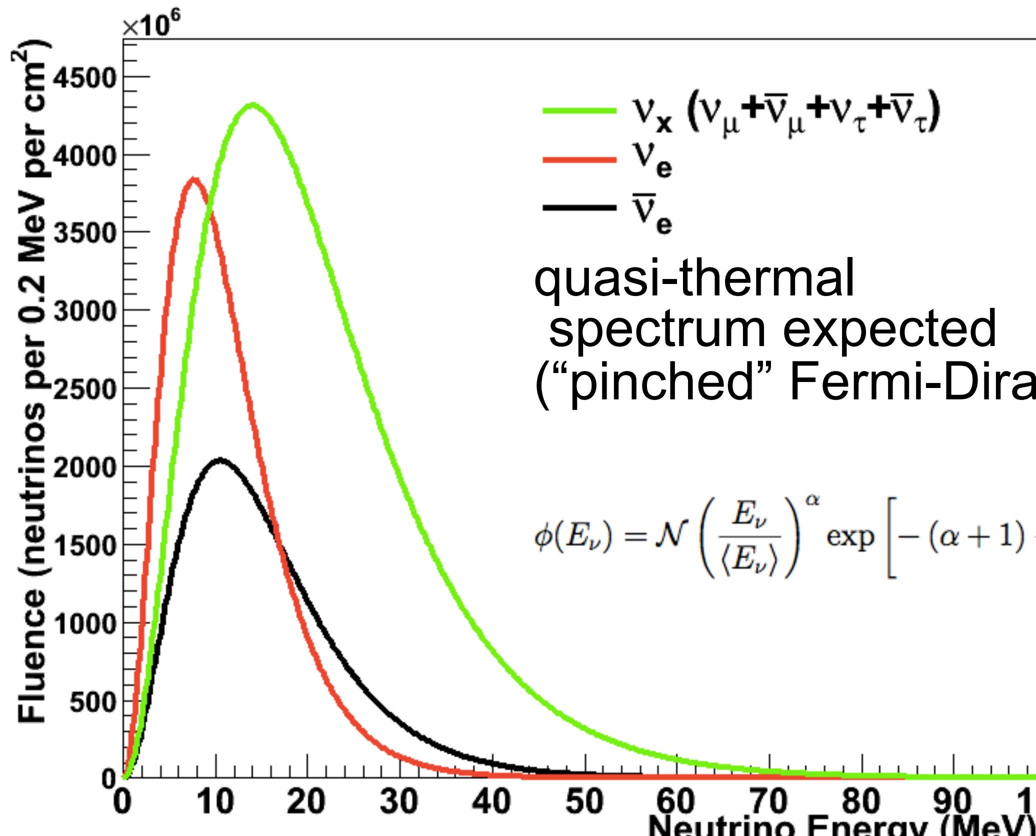
Example: neutrinos from core collapse

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with **~tens-of-MeV energies**

(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

Timescale: ***prompt*** after core collapse, overall **Δt~10's of seconds**



quasi-thermal spectrum expected ("pinched" Fermi-Dirac)

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

Information is in the ***energy, flavor, time*** structure of the supernova burst

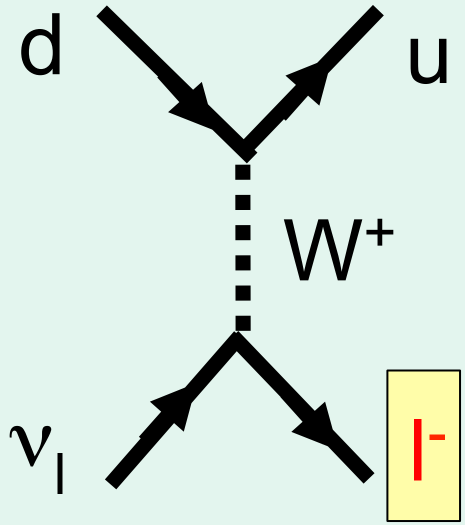
Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate << rate in burst; underground location usually excellent; surface detectors conceivably sensitive
Flavor sensitivity	Ability to **tag** flavor components
High up-time and longevity	Can't miss a ~1/30 year spectacle!

Note that many detectors have a “day job”...

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

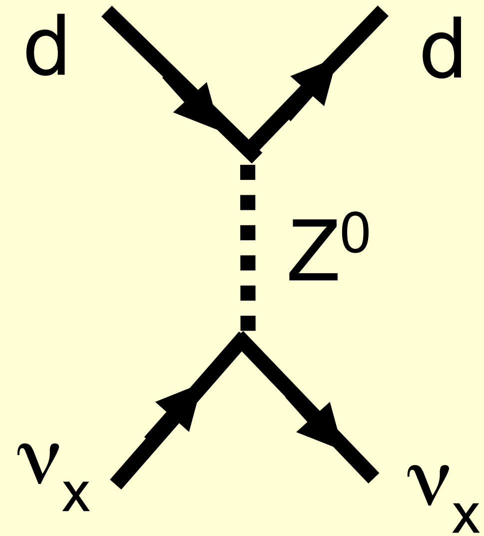


$\nu_l + N \rightarrow l^{\pm} + N'$

Produces lepton
with flavor corresponding
to neutrino flavor

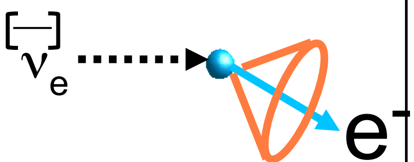
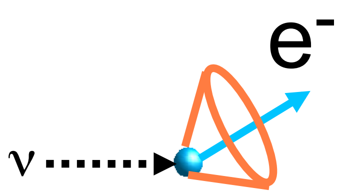
(must have enough energy
to make lepton)

Neutral Current (NC)



Flavor-blind

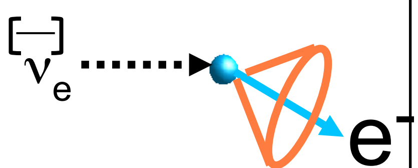
Supernova-relevant neutrino interactions

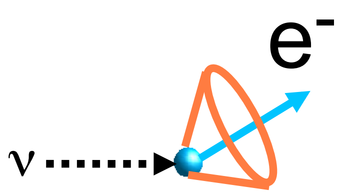
	Electrons		
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 		
Neutral current	 Useful for pointing		

Supernova-relevant neutrino interactions

<table>
<tr><th></th><th>Electrons</th><th>Protons</th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering

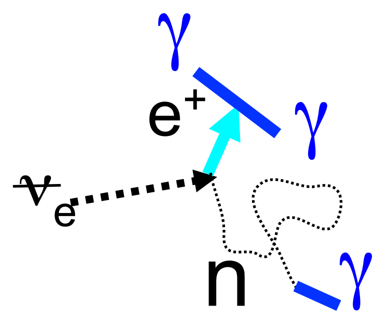
$\nu + e^- \rightarrow \nu + e^-$

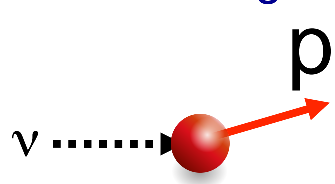




Useful for pointing</td><td>Inverse beta decay

$\bar{\nu}_e + p \rightarrow e^+ + n$


</td><td></td></tr>
<tr><td>Neutral current</td><td>Elastic scattering

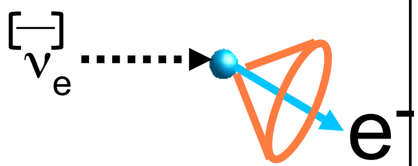


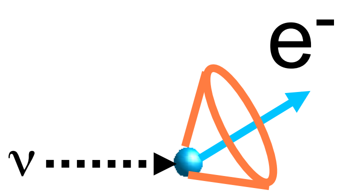
very low energy recoils</td><td></td></tr>
</table>

Supernova-relevant neutrino interactions

<table>
<tr><th></th><th>Electrons</th><th>Protons</th><th>Nuclei</th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering

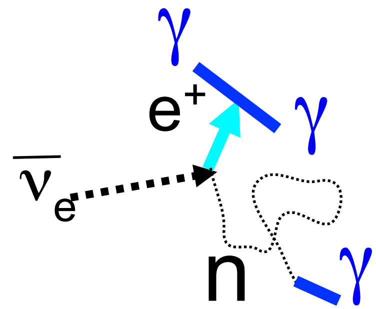
$\nu + e^- \rightarrow \nu + e^-$

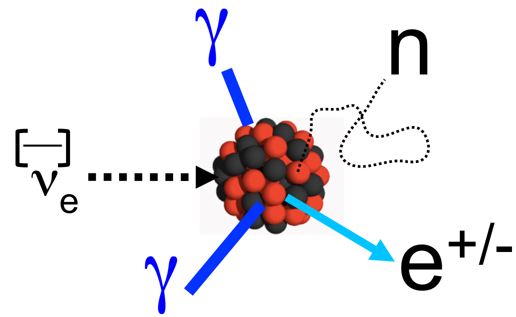




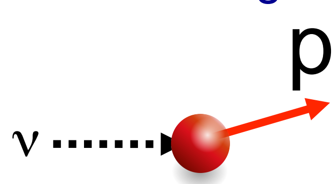
Useful for pointing</td><td>Inverse beta decay

$\bar{\nu}_e + p \rightarrow e^+ + n$

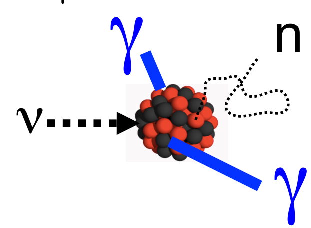
</td><td>$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$
$\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$



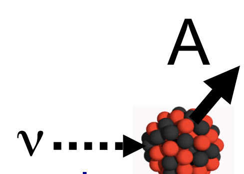
Various possible ejecta and deexcitation products</td></tr>
<tr><td>Neutral current</td><td>Elastic scattering



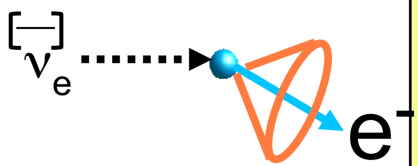
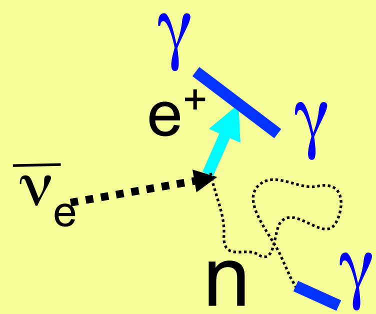
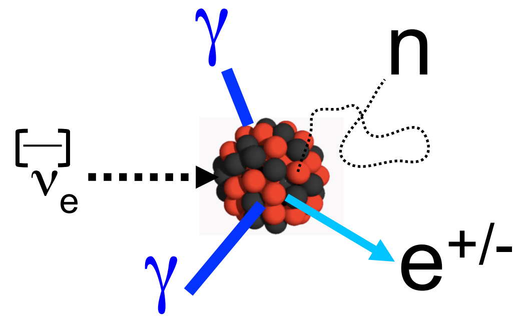
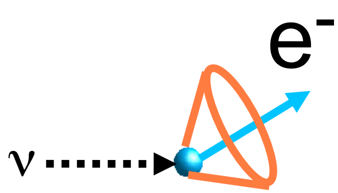
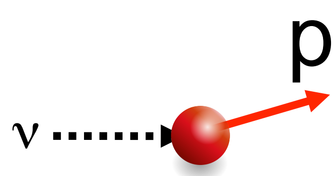
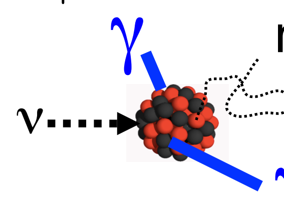
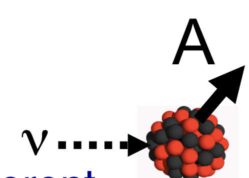
very low energy recoils</td><td>$\nu + A \rightarrow \nu + A^*$



$\nu + A \rightarrow \nu + A$

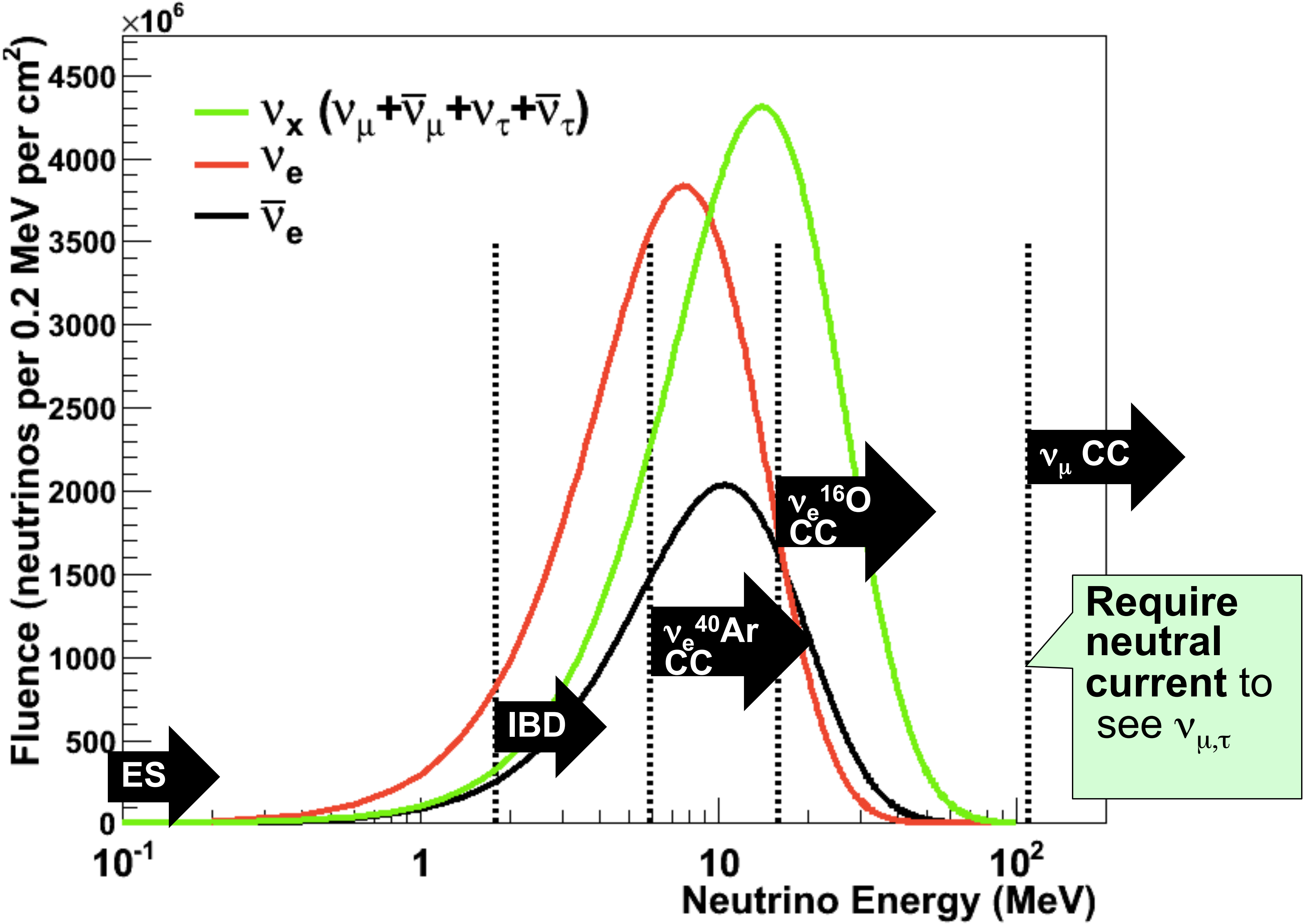

Coherent elastic (CEvNS)</td></tr>
</table>

Supernova-relevant neutrino interactions

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

IBD (electron *anti*neutrinos) dominates for current detectors

Neutrino interaction thresholds



Backgrounds

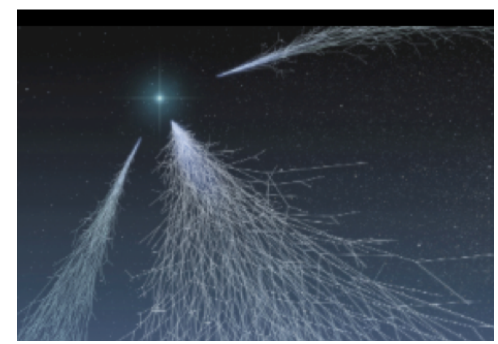
Same energy loss processes as the signal!

Radiologicals

- alpha, beta, gamma, fission
- intrinsic to your detector, or ambient

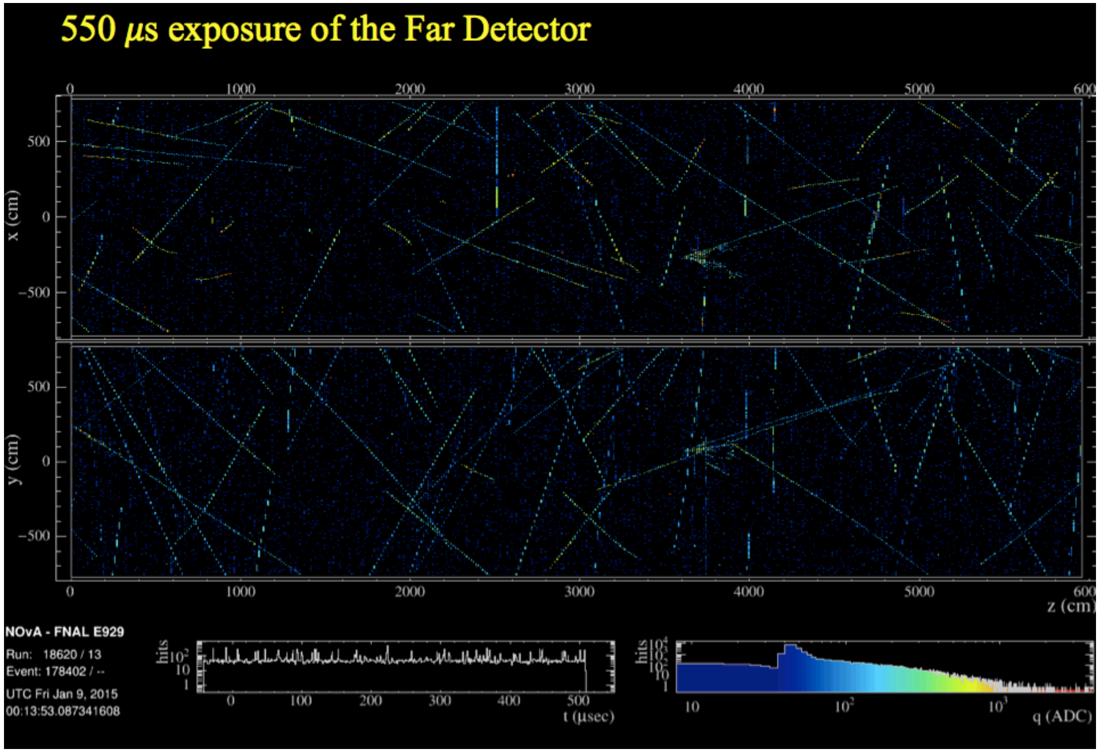
Cosmic rays and cosmogenics

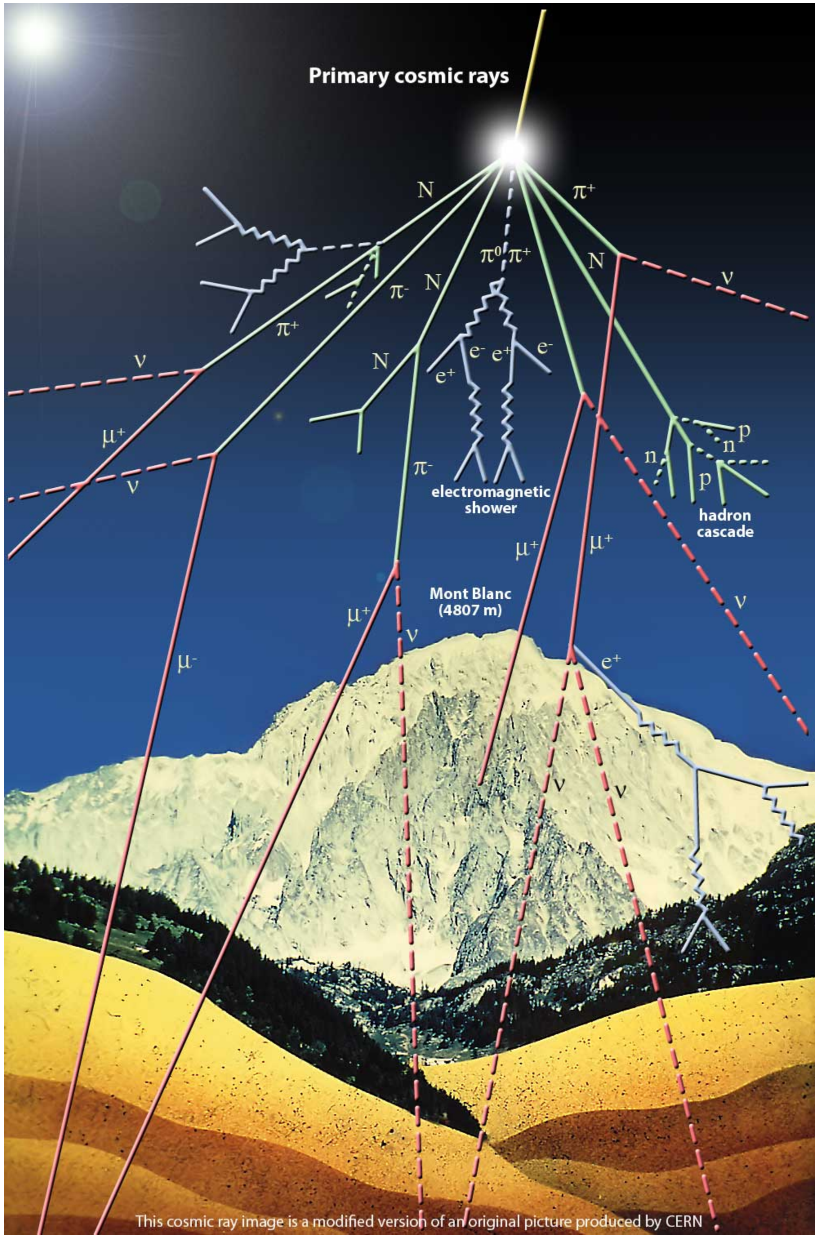
- showers (neutrons) near the surface, penetrating muons underground
- spallation products, activation



(Sometimes you can use your backgrounds for calibration!)

Cosmic rays

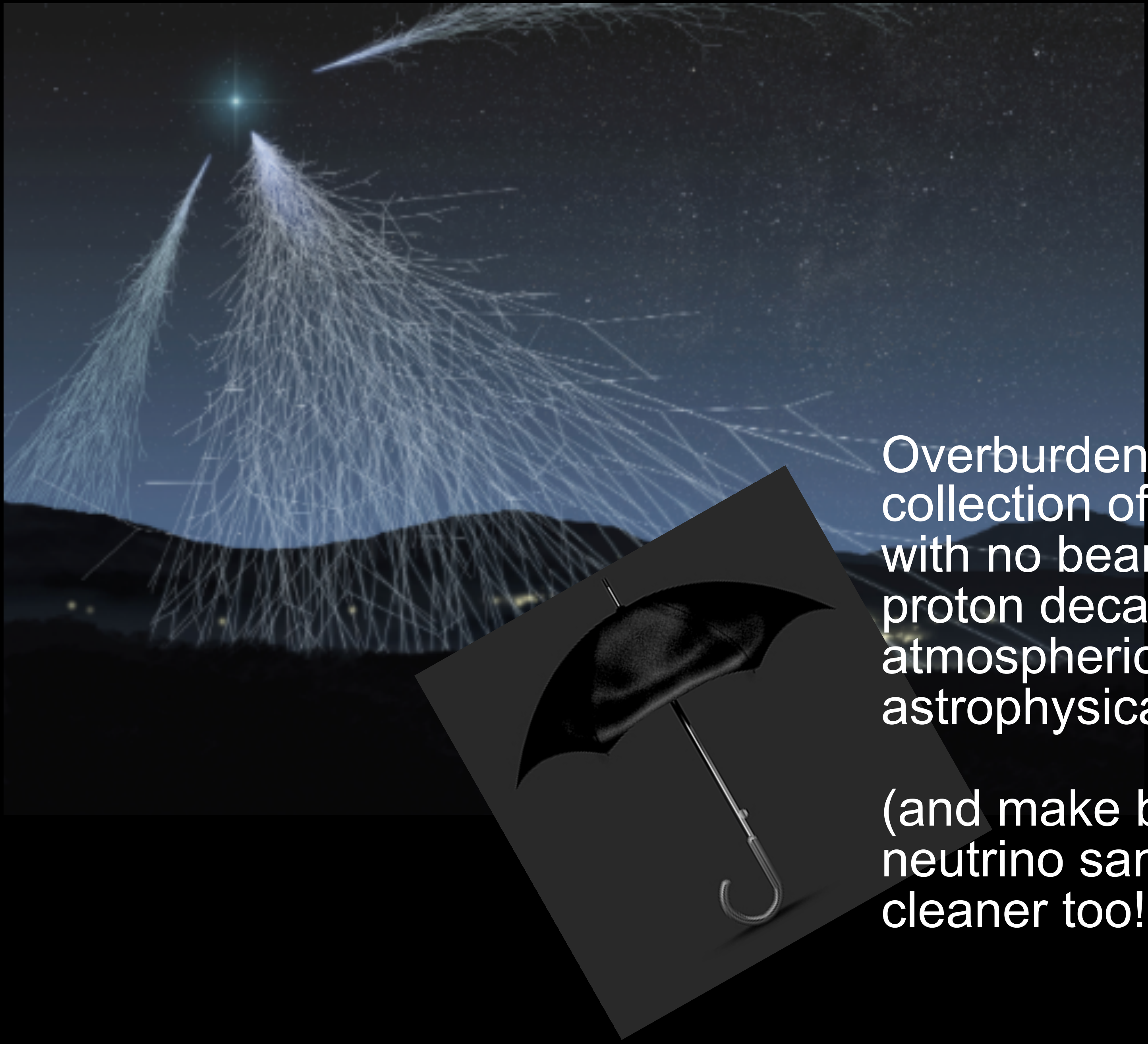




Beams are usually **pulsed..** so you know when the ν's arrive

"duty factor": pulse rate * pulse width
(fraction of time beam is on = rejection factor for CR bg)

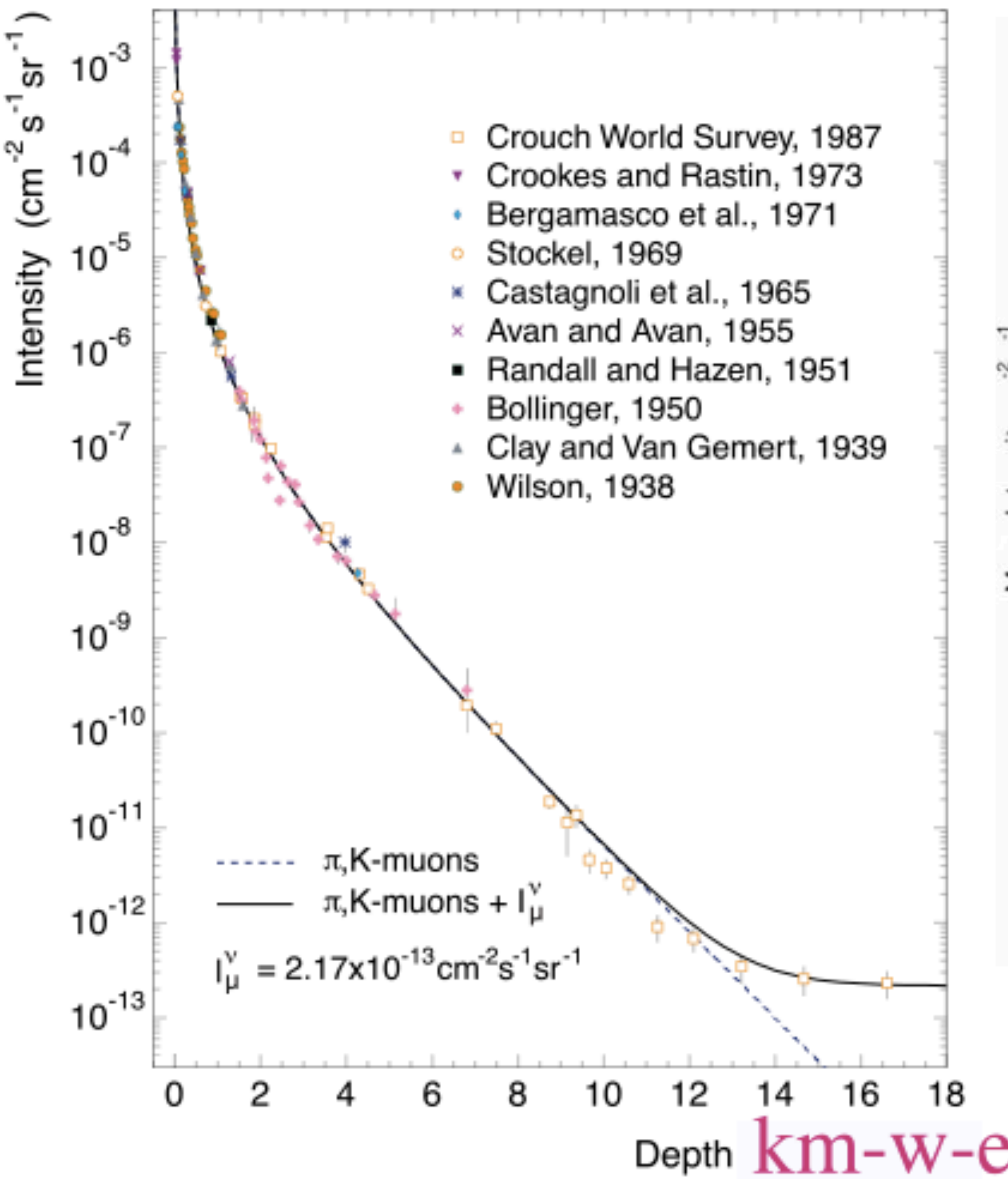
The weather is always fine underground

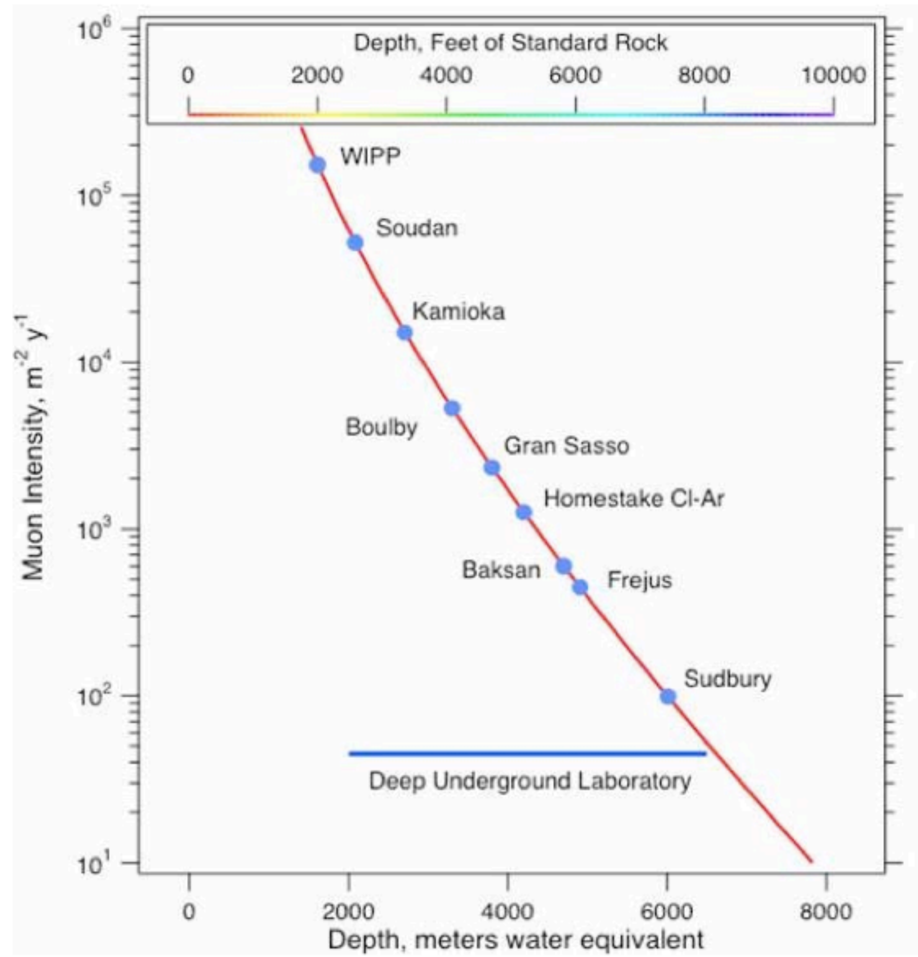


Overburden enables collection of neutrinos with no beam trigger: proton decay, atmospheric ν's, astrophysical ν's,...

(and make beam neutrino samples cleaner too!)

Muons are the penetrating particles



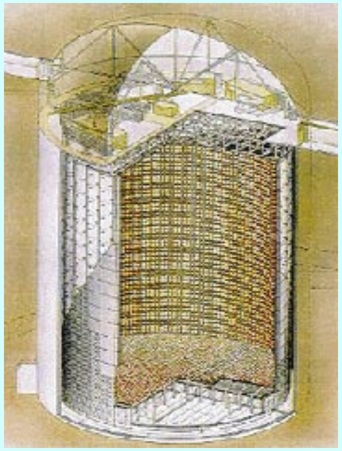


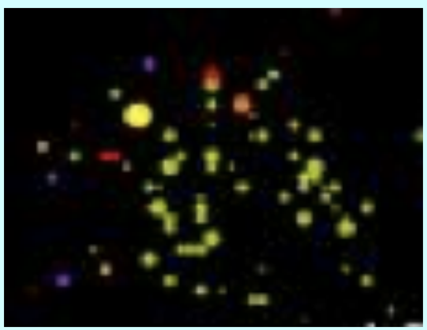
(Note: μ intensity decreases, but μ spectrum gets harder with depth)

mwe = “meters-water-equivalent” (scale by density)

Large (multi-kton) detector technologies for low energies

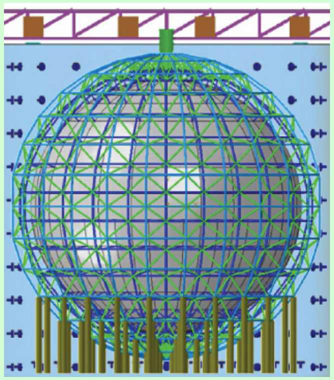
Water Cherenkov

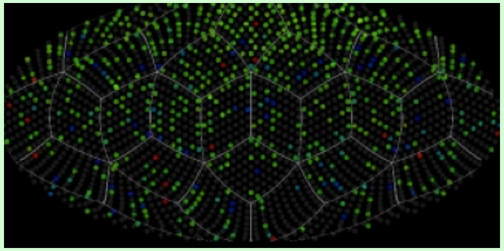




Cheap material, proven at very large scale

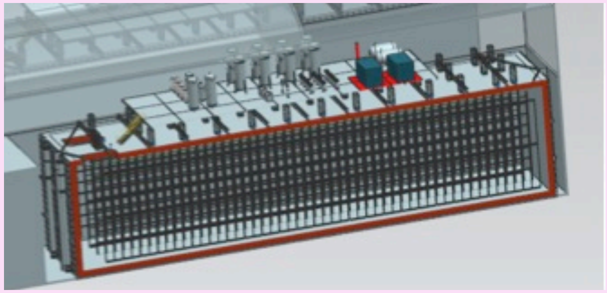
Liquid scintillator

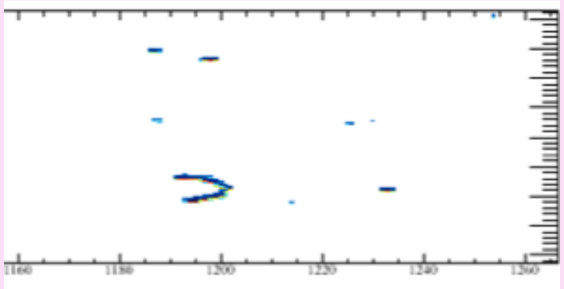




Low threshold, good energy resolution

Liquid Argon

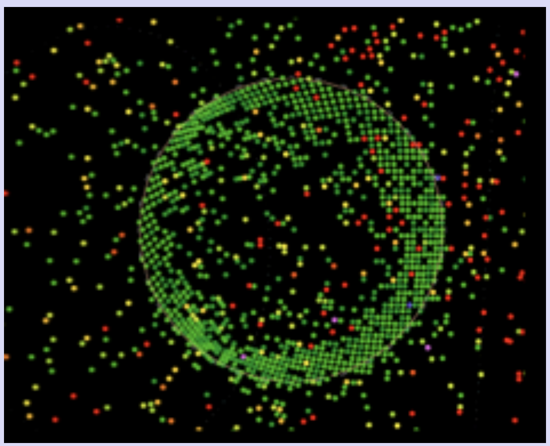


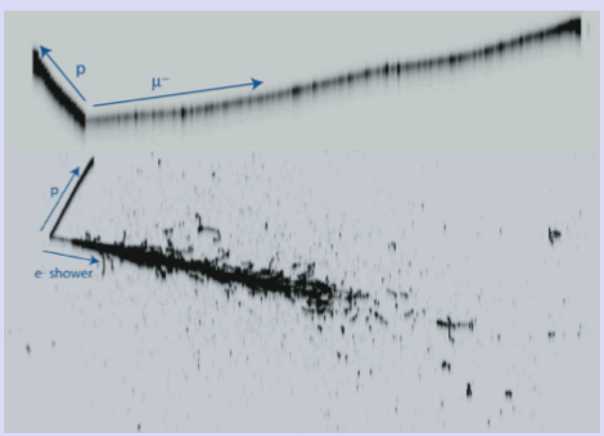


Good particle reconstruction

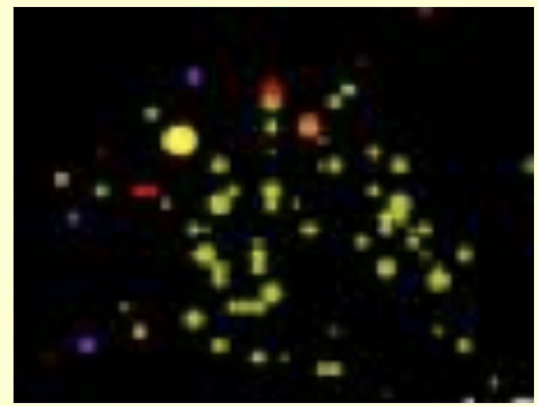
+ some other detector types for specific uses

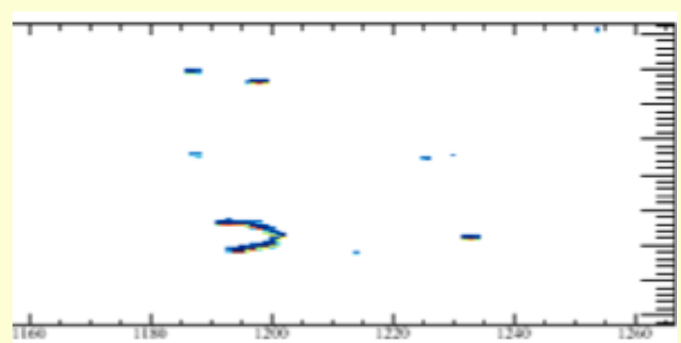
GeV-scale events: handsome and distinctive





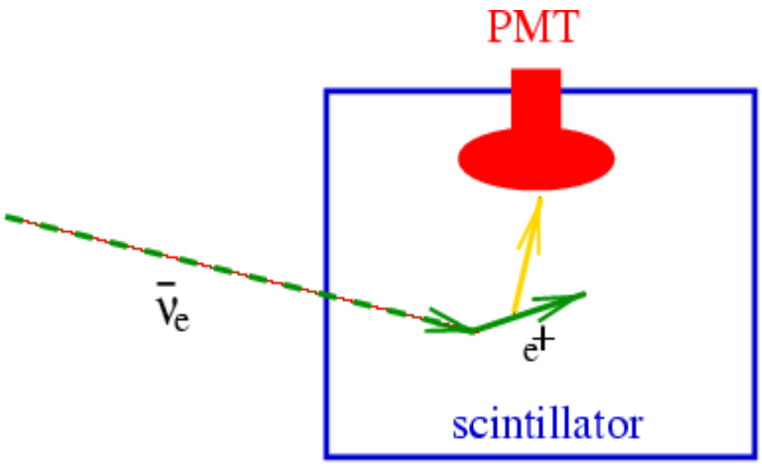
MeV-scale events: crummy little stubs





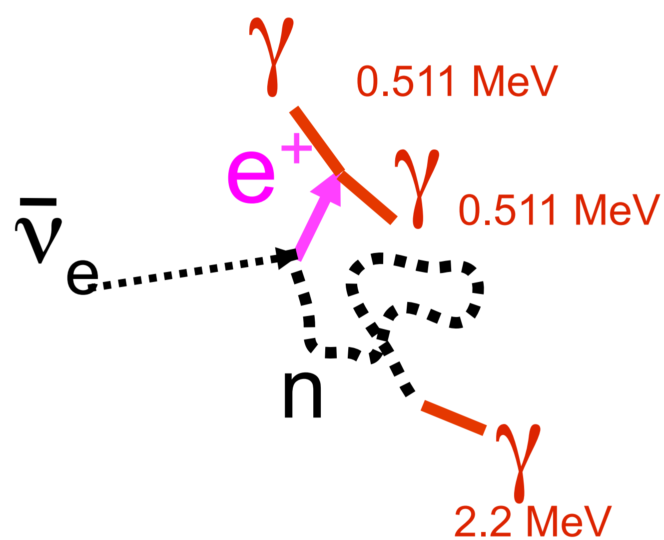
hungry for visible dE/dx!

Scintillation detectors



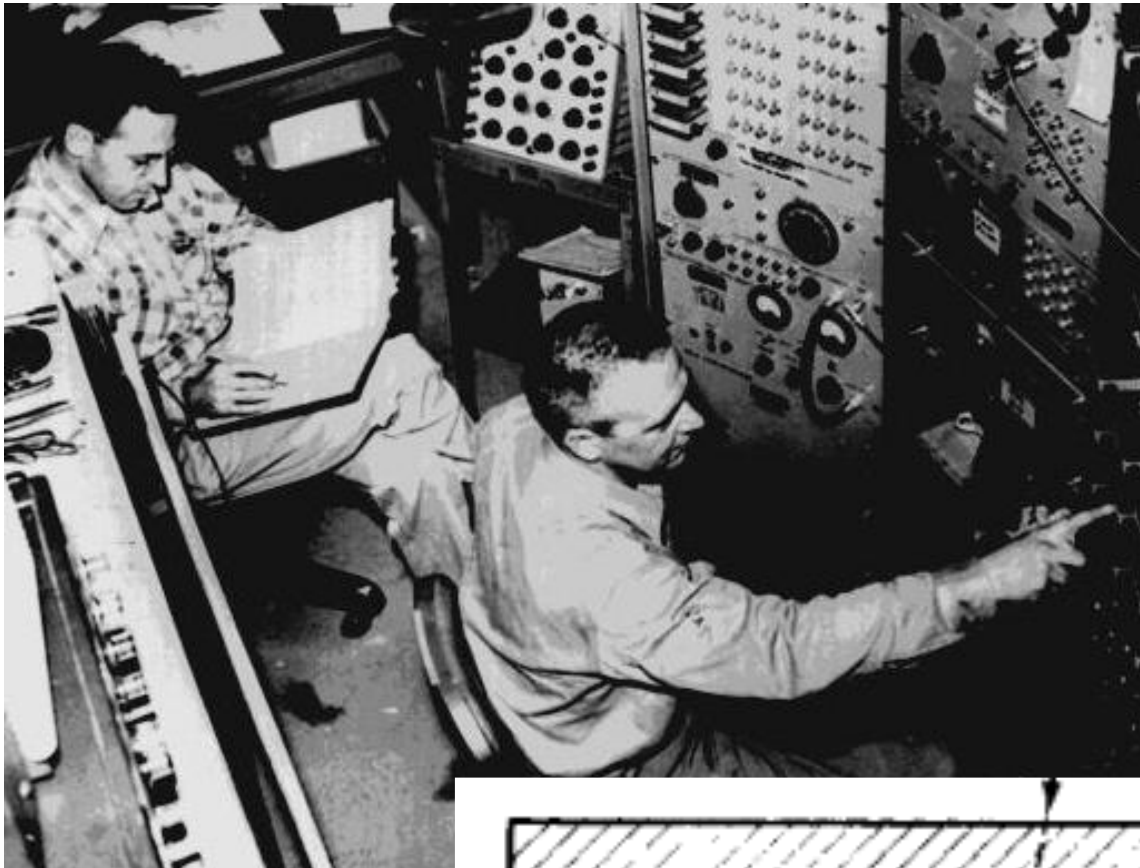
Liquid scintillator (C_nH_{2n}) volume surrounded by photomultipliers

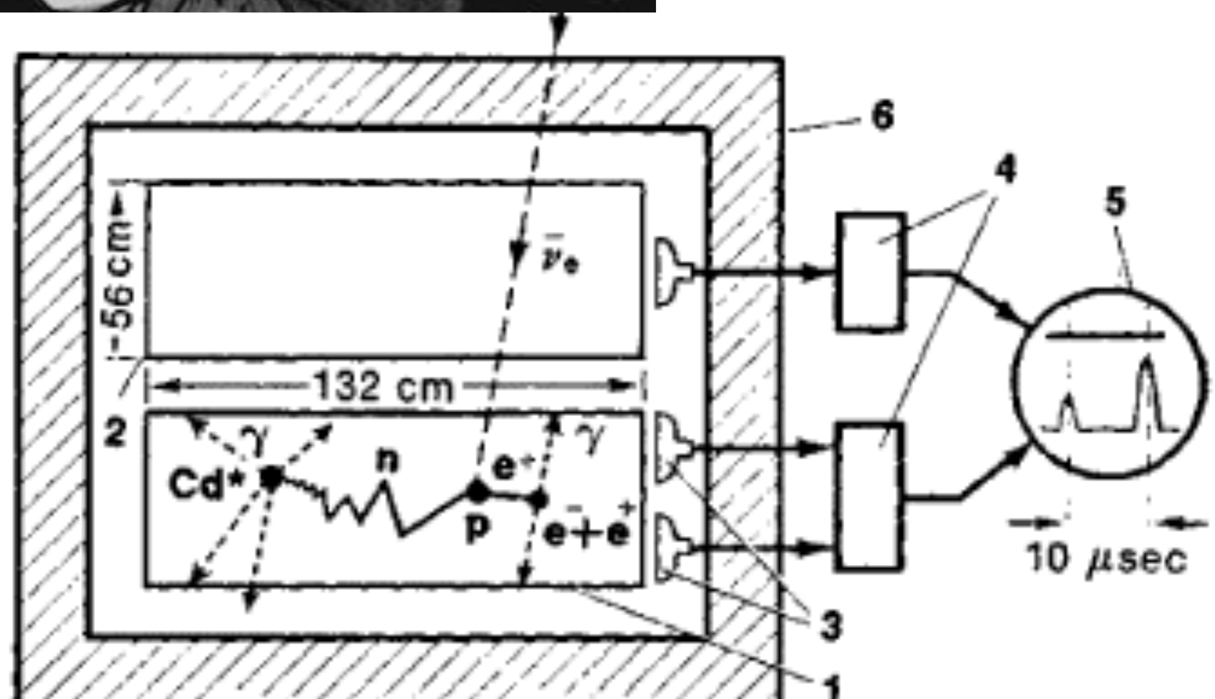
- **lots of photons:** few 100 pe/MeV
  ➔**low threshold** (<1 MeV), **good energy resolution** (3-8%/√E)
- little pointing capability (light is ~isotropic even if interaction were directional...)
- can also dope with Gd



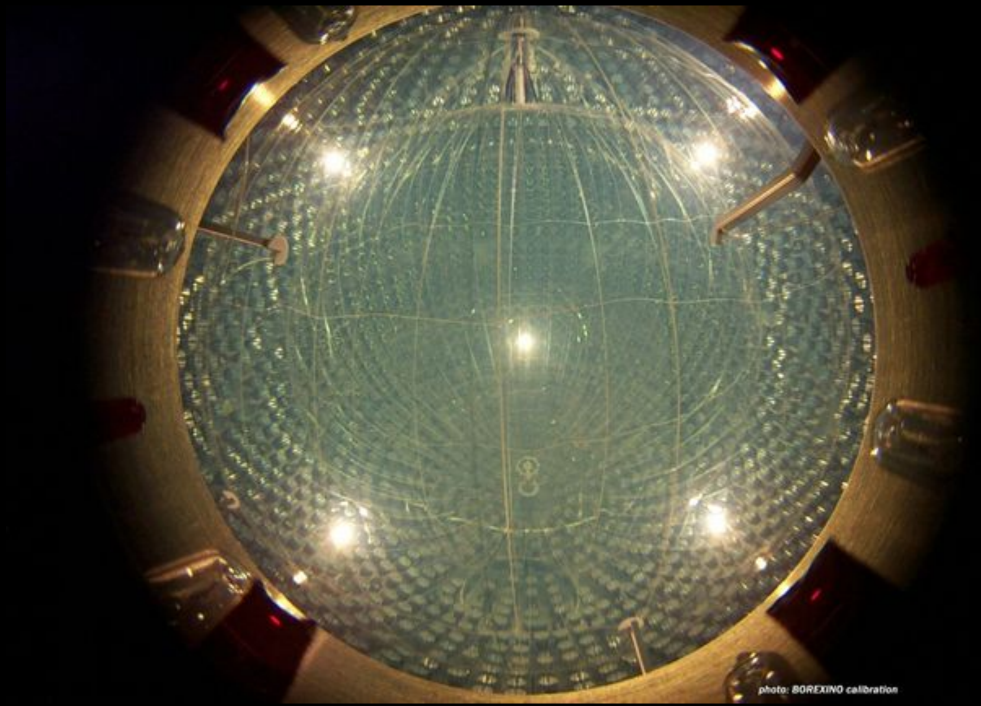
retrieve the energy of the n-capture and annihilation γ's

First neutrinos ever detected were from a nuclear reactor; Reines & Cowan, 1956





Large Underground Scintillation Detectors

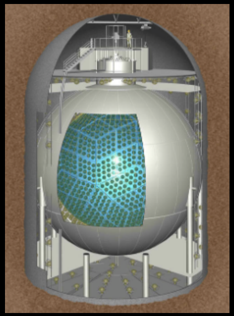
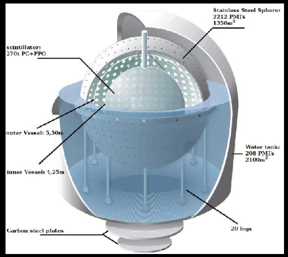
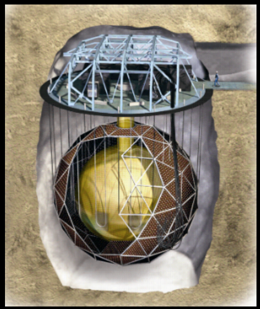
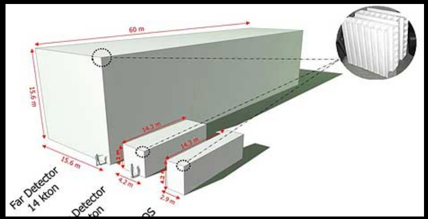


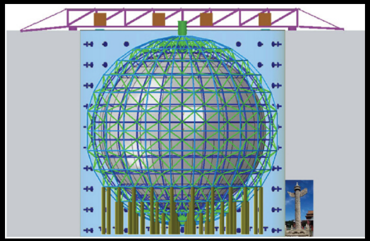
Liquid hydrocarbon (C_nH_{2n}) that emits (lots of) photons when charged particles lose energy in it

Will see supernova **electron antineutrinos**, with good energy resolution

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

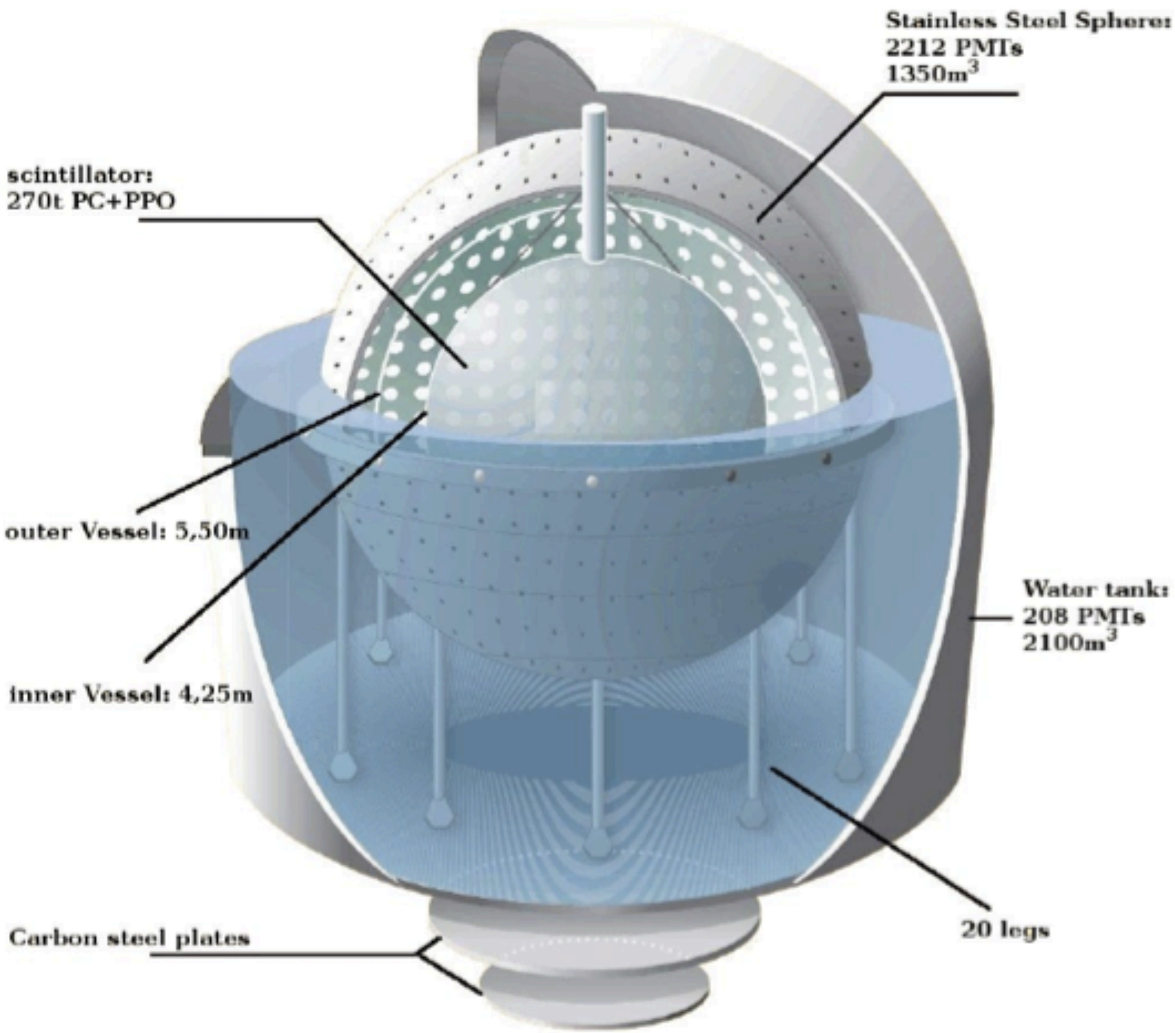
Many examples worldwide of current and future detectors



Example: Borexino Experiment

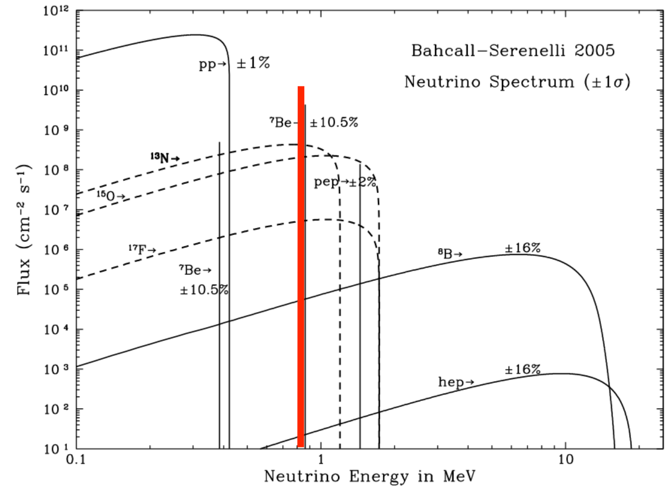
Gran Sasso, Italy

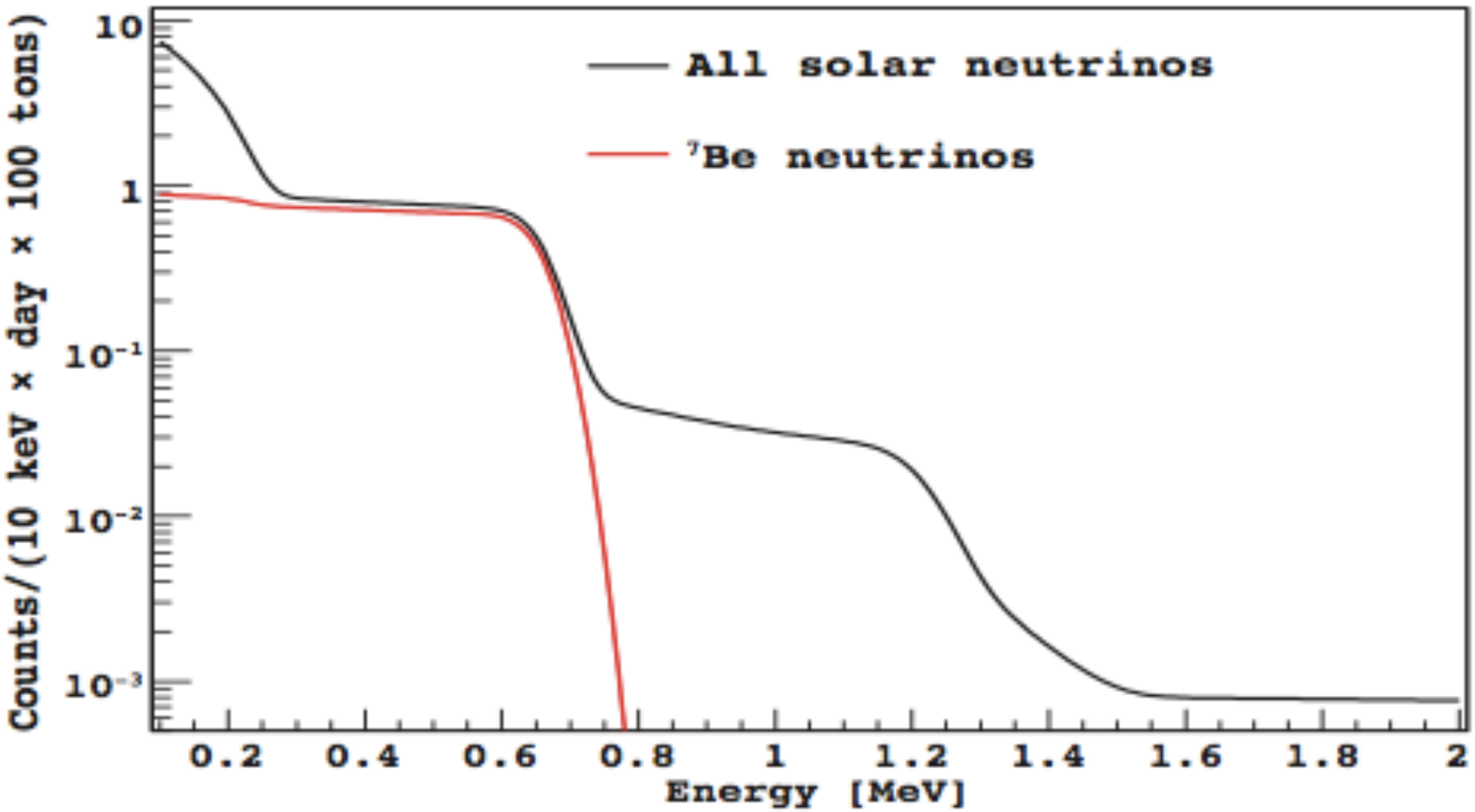


$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

- Scintillator (300 ton)
- Very low threshold (down to ~200 keV)
- Very low radioactivity
- Real time

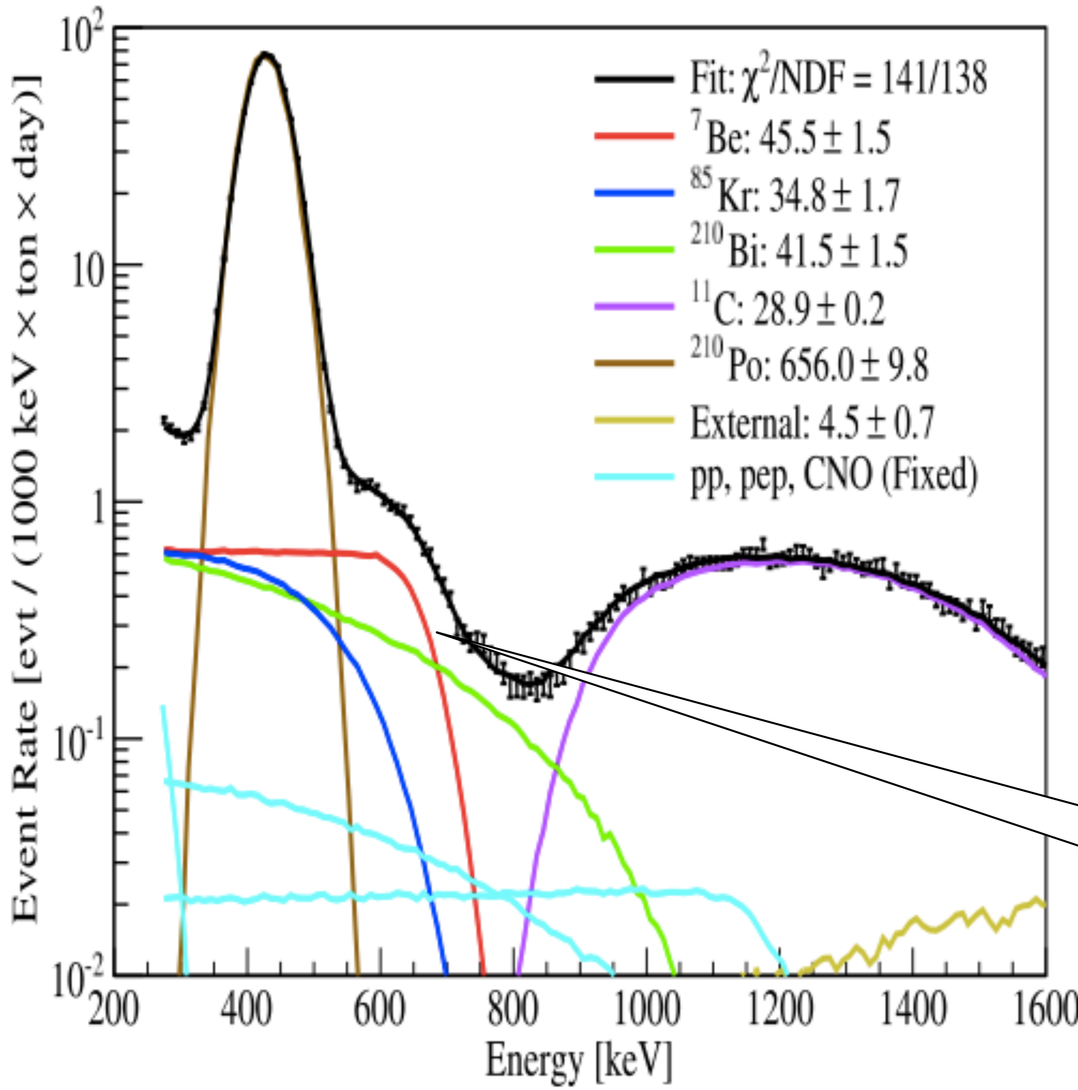
Go after recoil electrons from the ^{7}Be line





...

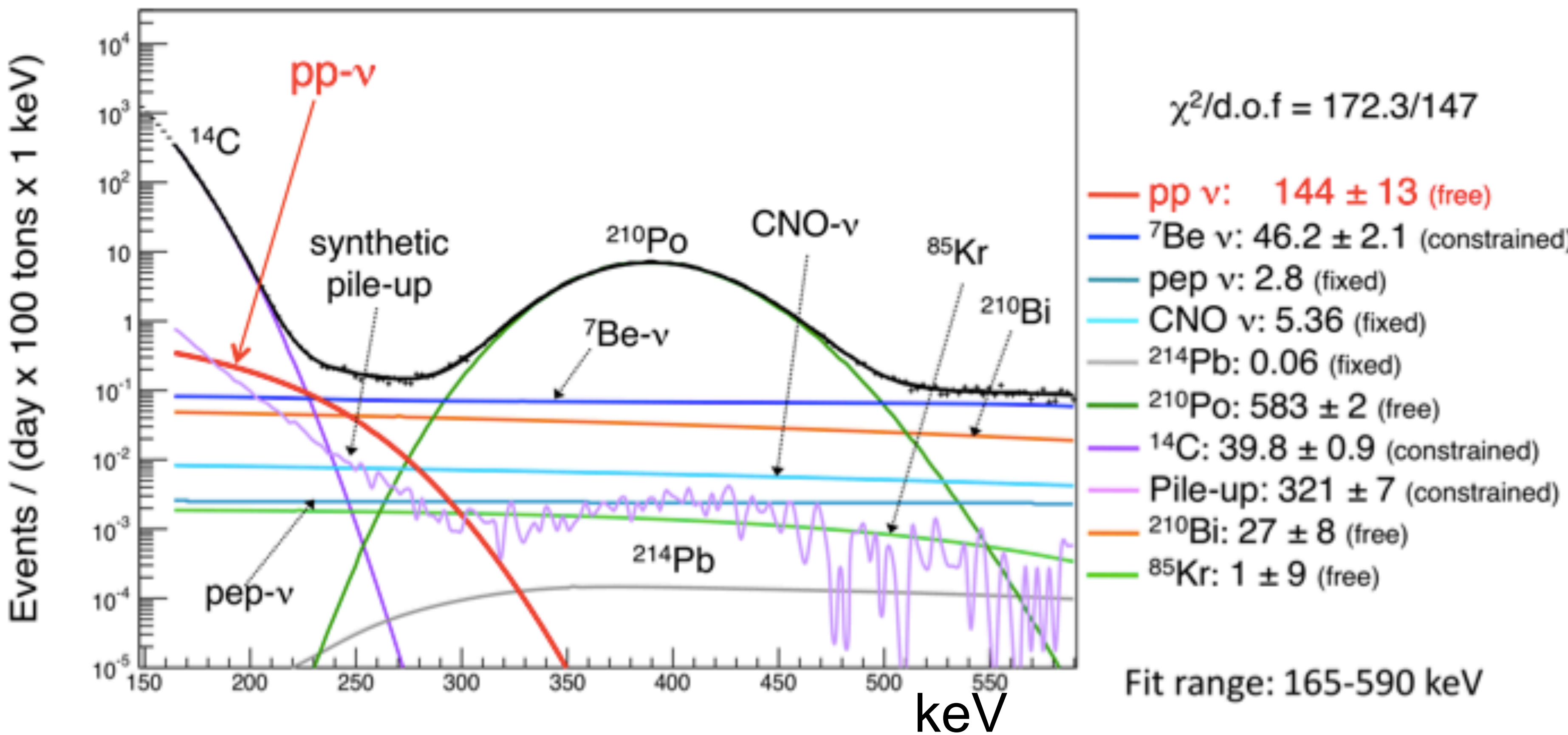
Heroic (and successful) struggle with radioactive (ambient & cosmogenic) backgrounds



it's all about the backgrounds

^{7}Be neutrinos identified

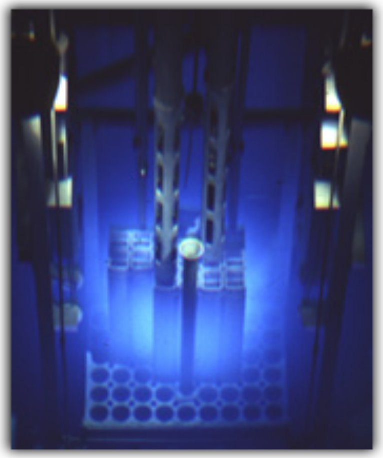
Even more heroic extraction of pp rates:



it's all about the backgrounds ...

Water Cherenkov Detectors

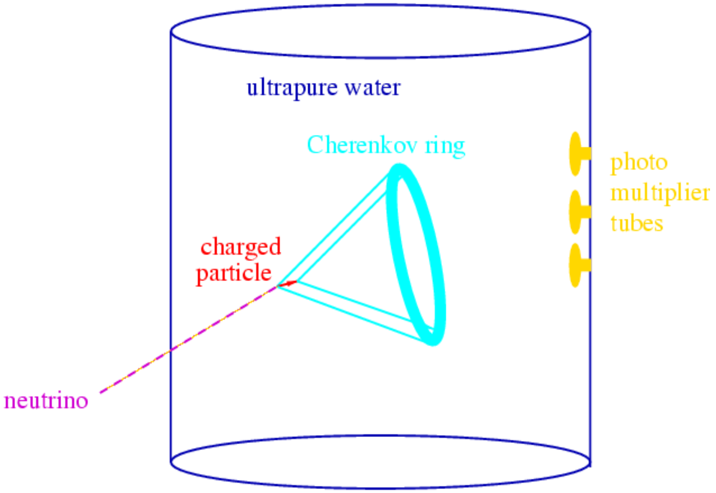
Charged particles produced in neutrino interactions emit Cherenkov radiation if $\beta > 1/n$



$$\cos\theta_C = \frac{1}{\beta n}$$

$\theta_C = 42^0$ for relativistic particle in water

No. of photons $\propto$ energy loss



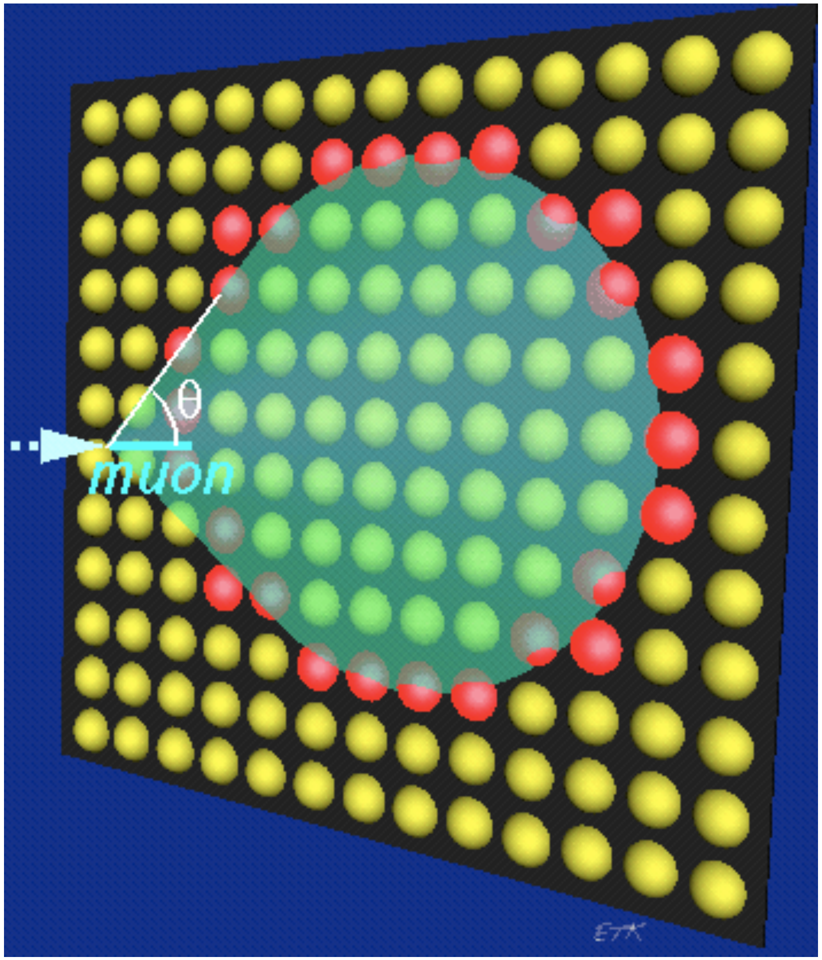
Thresholds (MeV)

$$E_{th} = \frac{m}{\sqrt{1 - 1/n^2}}$$

e	0.73 MeV
μ	150 MeV
π	200 MeV
p	1350 MeV

- **Low light yield**, but **directional signal** is helpful for reconstruction
- **Loss of heavy/low energy particles due to Cherenkov threshold**
- Possible enhancement with Gd for inverse beta decay tagging (more later)

Photomultiplier tubes (PMTs) detect single photons



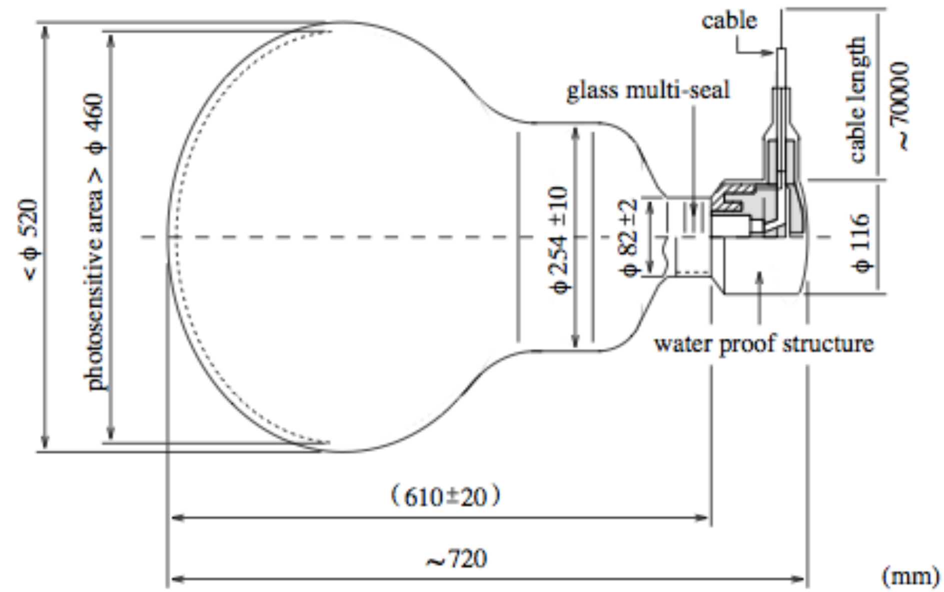


Fig. 7. Schematic view of a 50 cm PMT.

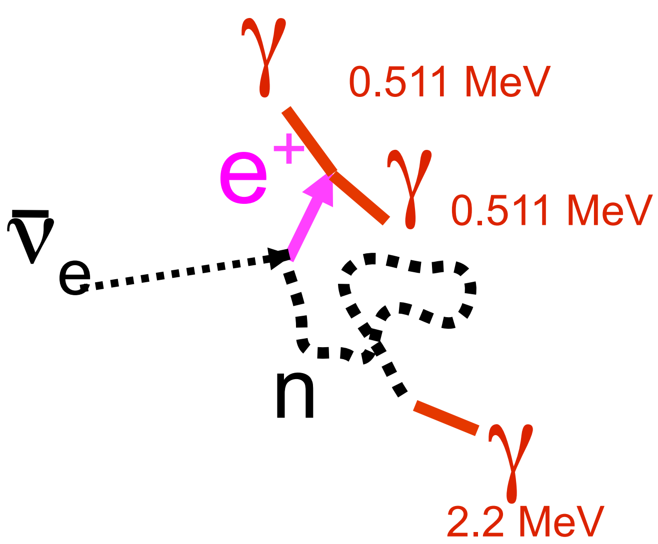
Photons → photoelectrons
→ amplified PMT pulses
→ digitize charge, time
→ reconstruct vertex, energy, direction

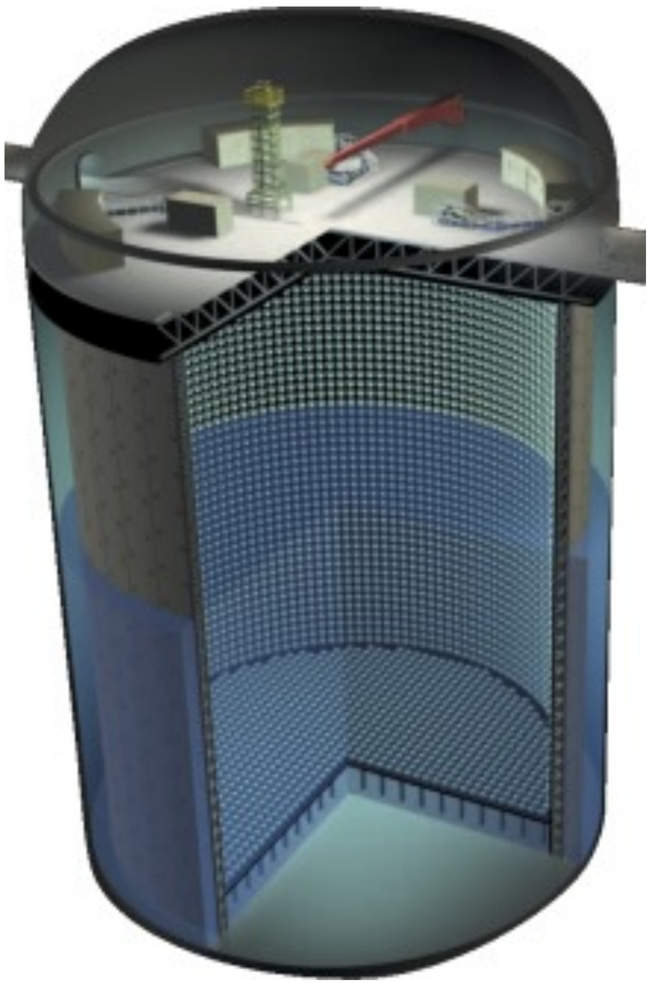
Water Cherenkov detectors for supernova neutrinos

Inverse Beta Decay (CC)

$\bar{\nu}_e + p \rightarrow e^+ + n$ dominates

E_{thr}=1.8 MeV





- See Cherenkov light from the positron (~positron is isotropic)
- Can't see 0.511 MeV γ's (why not?)
- Limited by photocoverage (SK: ~40% ➔ ~6 pe/MeV)

Neutron tagging in water Cherenkov detectors

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

➔ **detection of neutron tags event as *electron antineutrino***

- especially useful for DSNB (which has low signal/bg)
- also useful for disentangling flavor content of a burst
  (improves pointing, and physics extraction)

R. Tomas et al., PRD68 (2003) 093013
KS, J.Phys.Conf.Ser. 309 (2011) 012028; LBNE collab arXiv:1110.6249
R. Laha & J. Beacom, PRD89 (2014) 063007

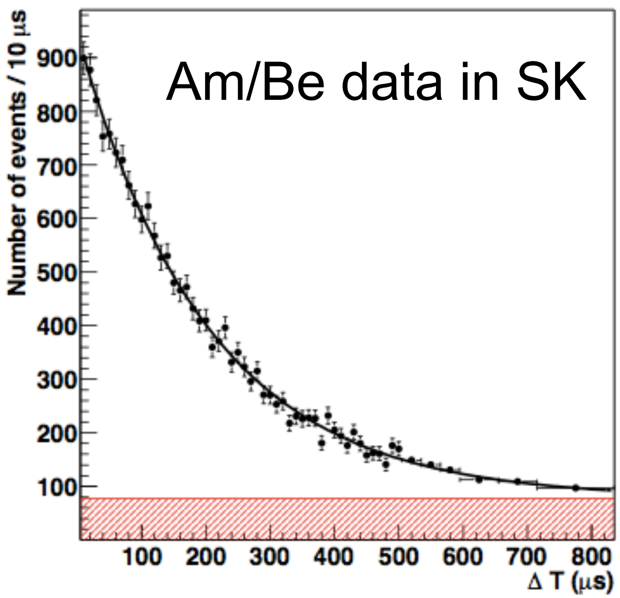
"Drug-free" neutron tagging

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

~200 μs thermalization & capture, observe Cherenkov radiation from γ Compton scatters

➔ with SK-IV electronics, ~18% n tagging efficiency

SK collaboration, arXiv:1311.3738;



Enhanced performance by doping!

use gadolinium to capture neutrons

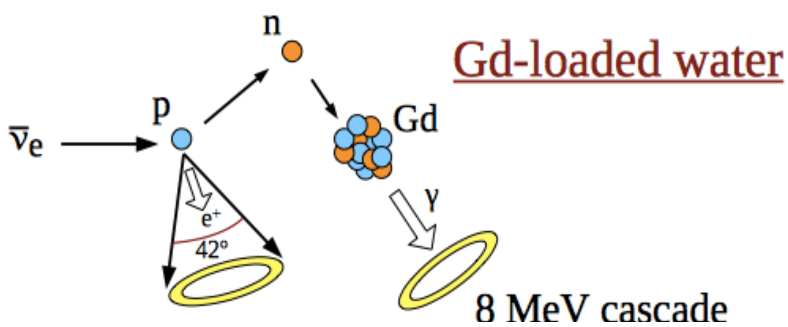
(common strategy for scintillator)

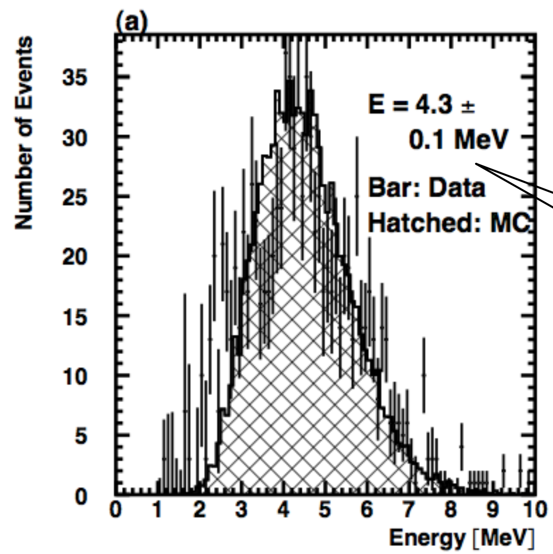
J. Beacom & M. Vagins, PRL 93 (2004) 171101

Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons

$n + Gd \rightarrow Gd^{*} \rightarrow Gd + \gamma$

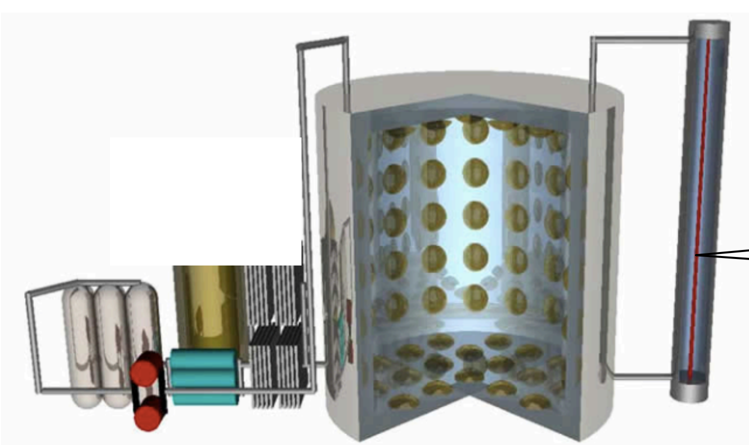
$$\sum E_{\gamma} = 8\ MeV$$





H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009)

About 4 MeV visible energy per capture; ~67% efficiency in SK

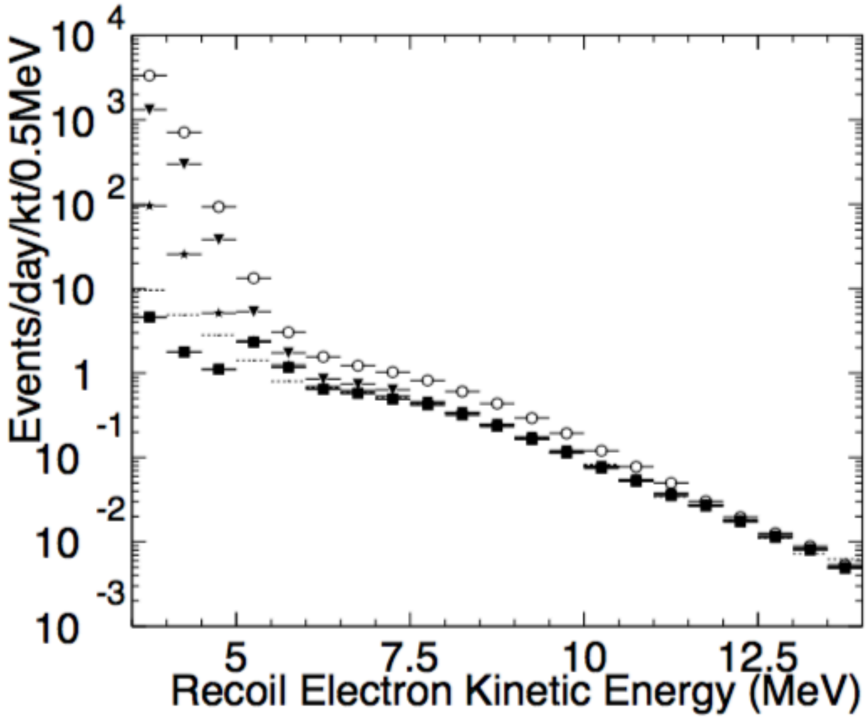


EGADS: test tank in the Kamioka mine for R&D

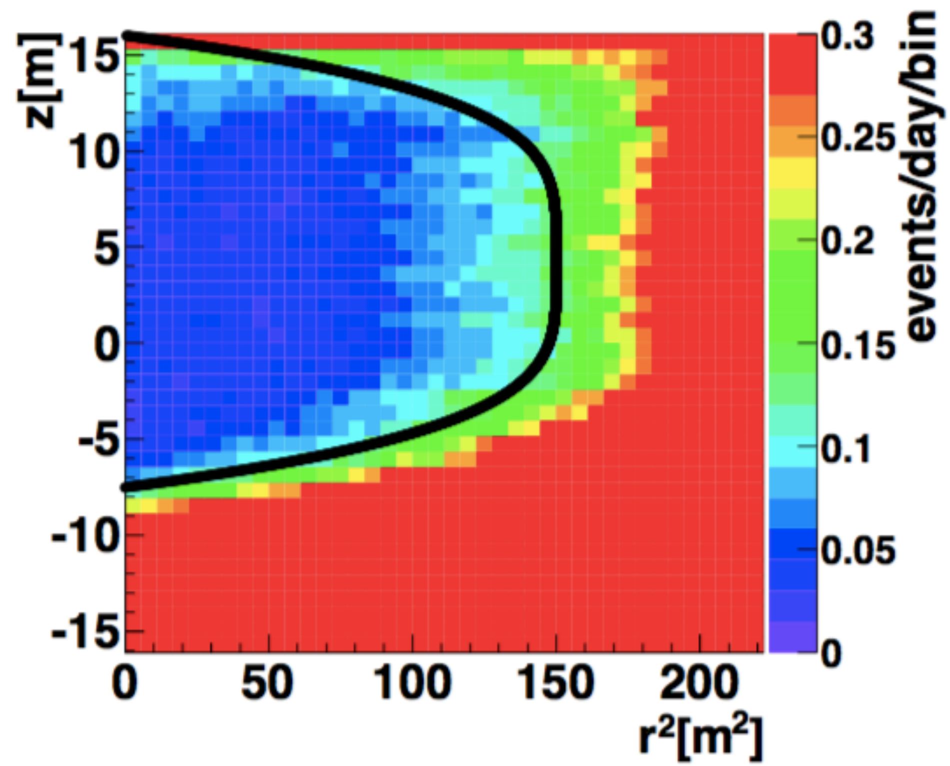
Going forward as **"SK-Gd"**

Low-energy backgrounds in Super-K

- radiologicals, some cosmogenics
- again, showing for solar sample

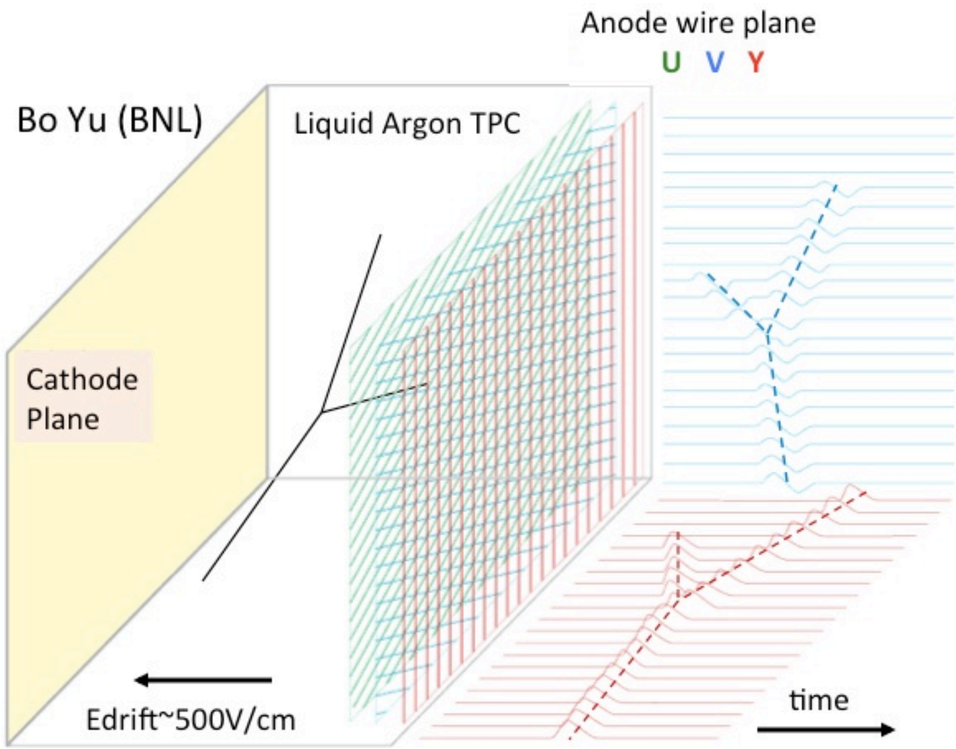


strongly threshold-dependent



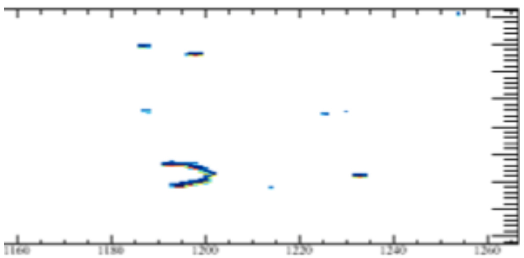
3.49-3.99 MeV bin
mostly radioactivity from wall

Liquid argon time projection chambers

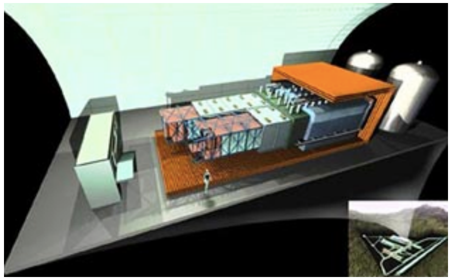


fine-grained trackers
sensitive to **electron neutrinos**
(as opposed to antineutrinos)

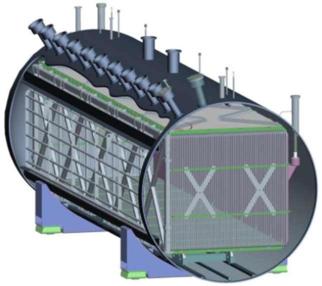
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



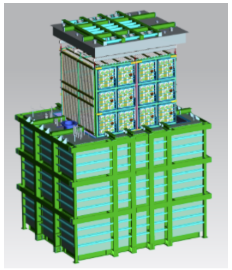
ICARUS
(Italy→USA)
0.6 kton



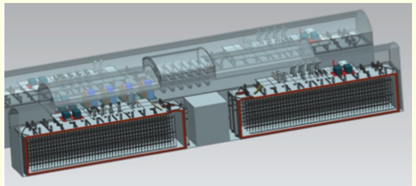
MicroBooNE
(USA)
0.2 kton



SBND
(USA)
0.112 kton

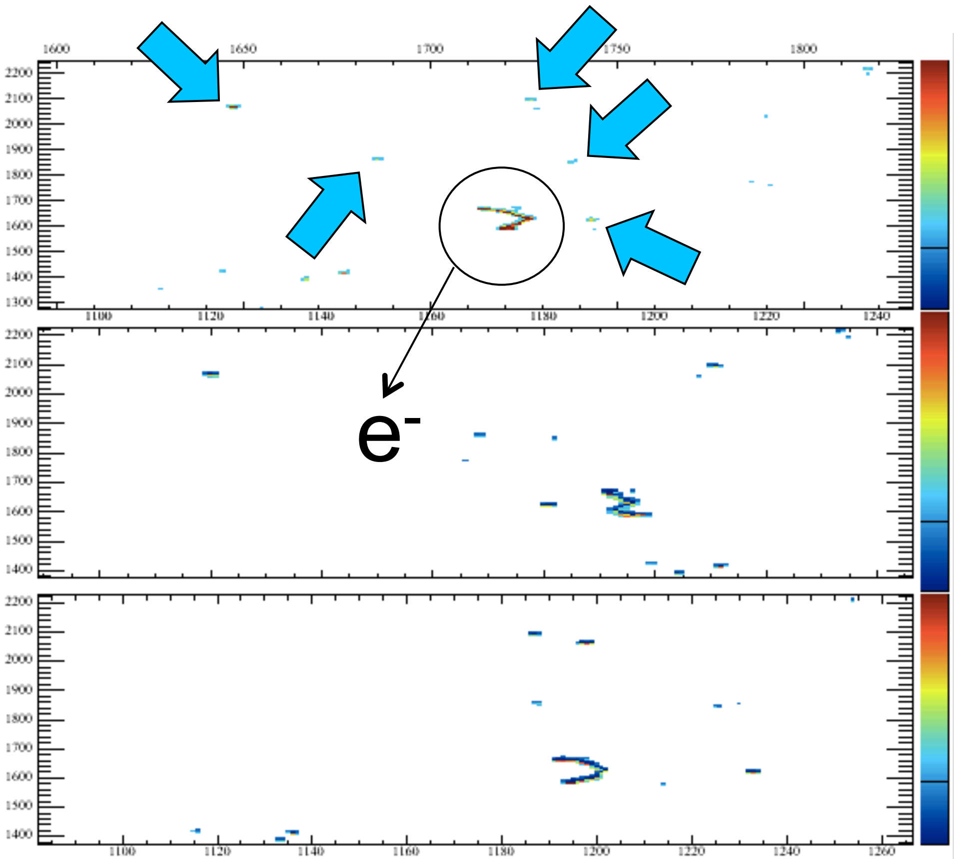


DUNE
(USA)
40 kton

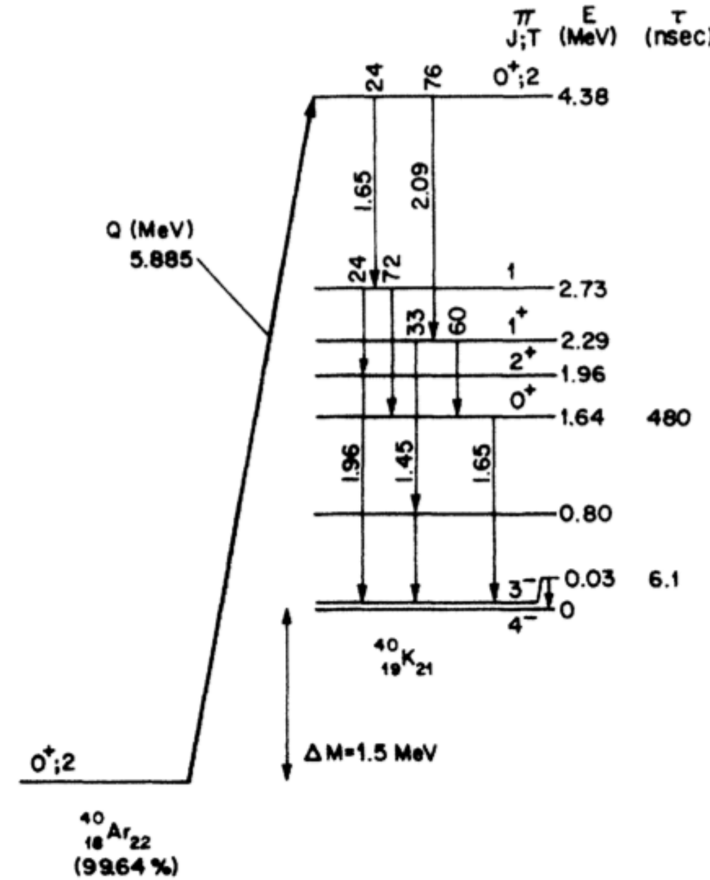


Can we tag ν_e CC interactions in argon using nuclear deexcitation γ's?

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



MicroBooNE geometry (LArSoft)



20 MeV ν_e , 14.1 MeV e^-, simple model based on R. Raghavan, PRD 34 (1986) 2088
Improved modeling based on ^{40}Ti (^{40}K mirror) β decay measurements in progress
Direct measurements (and theory) needed!

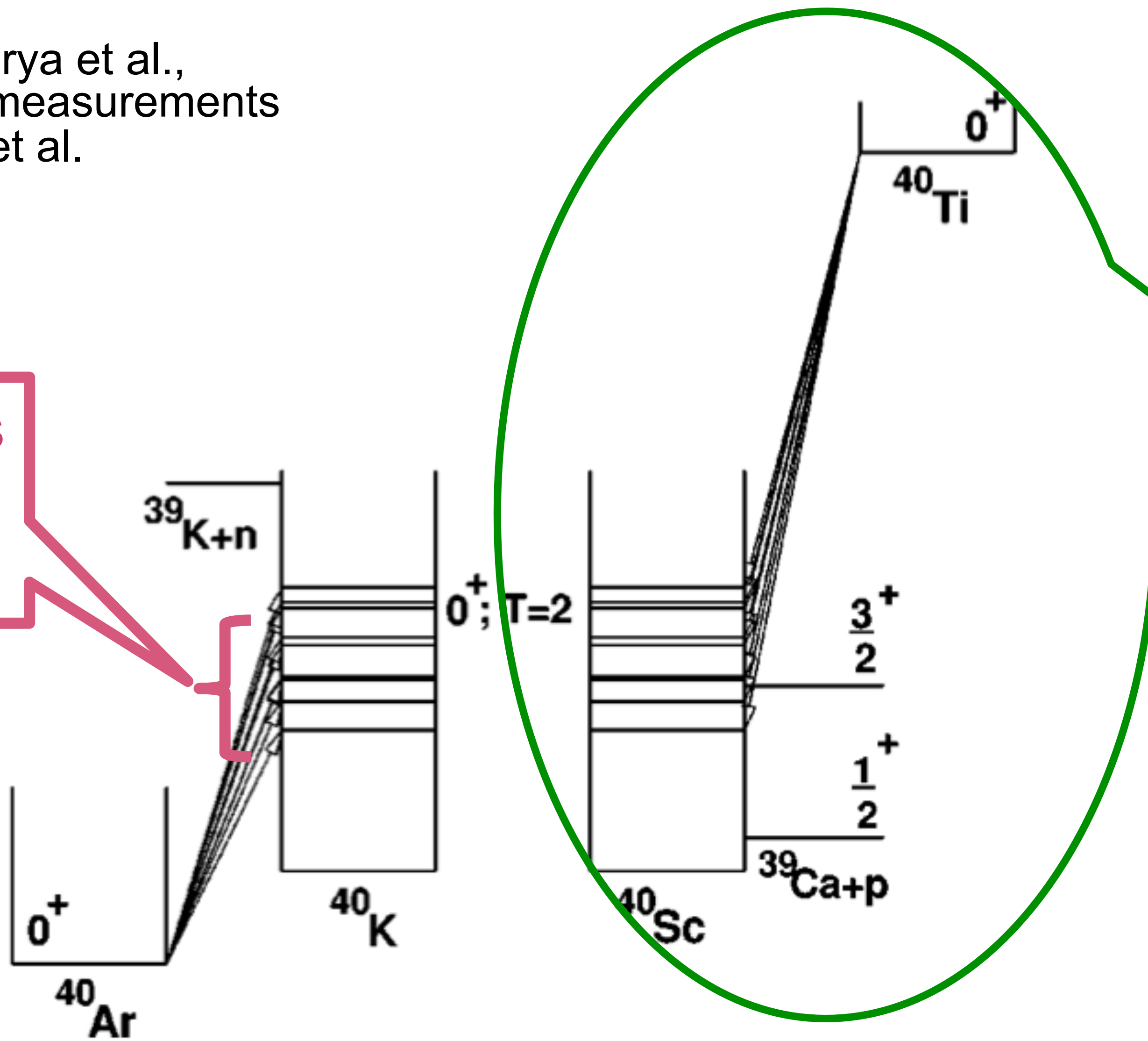
… in fact there can be transitions to intermediate states, adding to the cross section (and complicating the γ-tag)

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al.,
and newer measurements
by Trinder et al.

these states can be populated



measure relative strengths with βdk of ^{40}Ti to mirror nucleus

… in fact there can be transitions to intermediate states, adding to the cross section (and complicating the γ-tag)

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

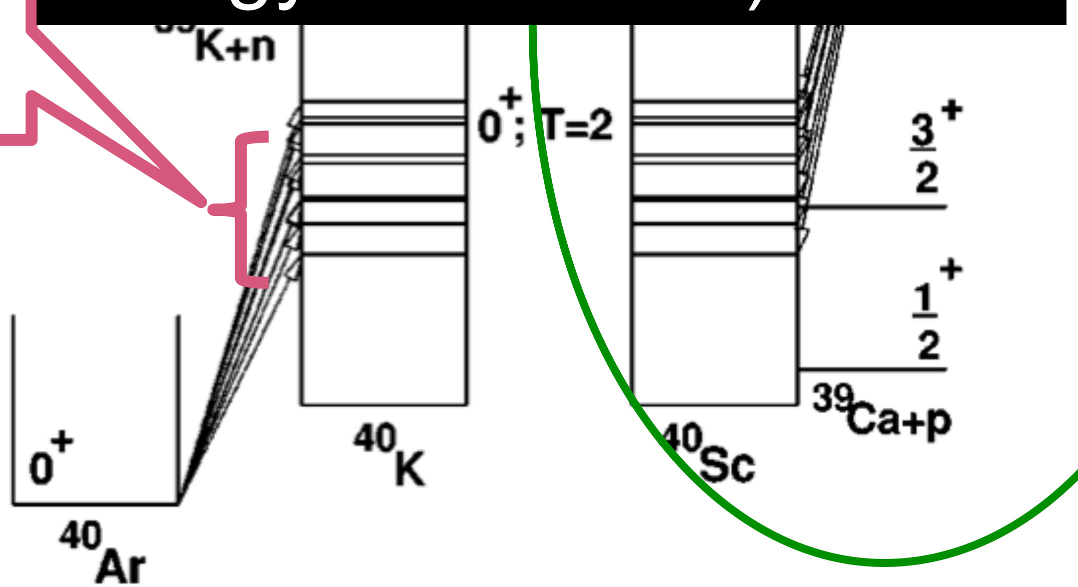
Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al.,
and newer me…
by Trinder et…

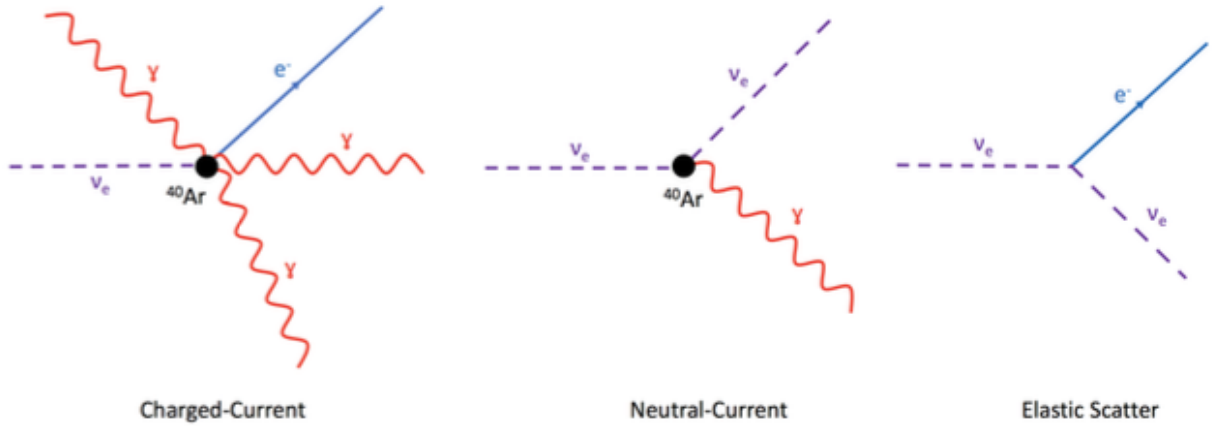
Nuclear physics of specific targets matters
@ ~10 MeV energies (nuclear energy-level scale)

these states can be populated

measure relative strengths with βdk of ^{40}Ti to mirror nucleus



How well can we *tag* interaction channels in argon?

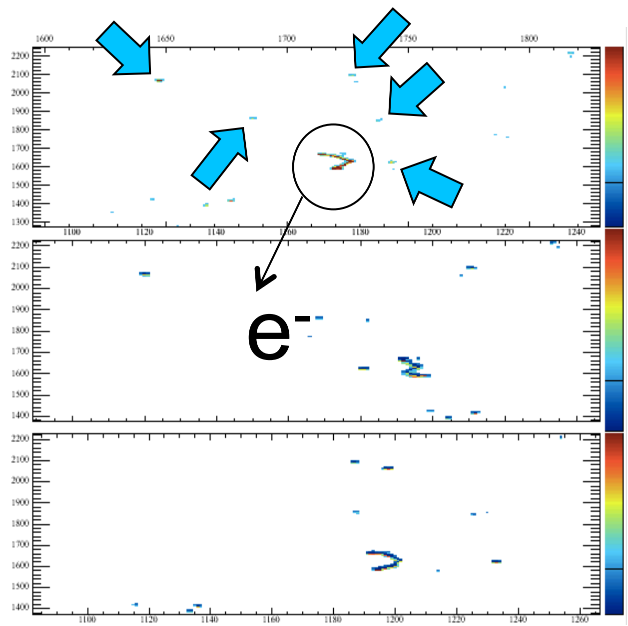


E. Conley

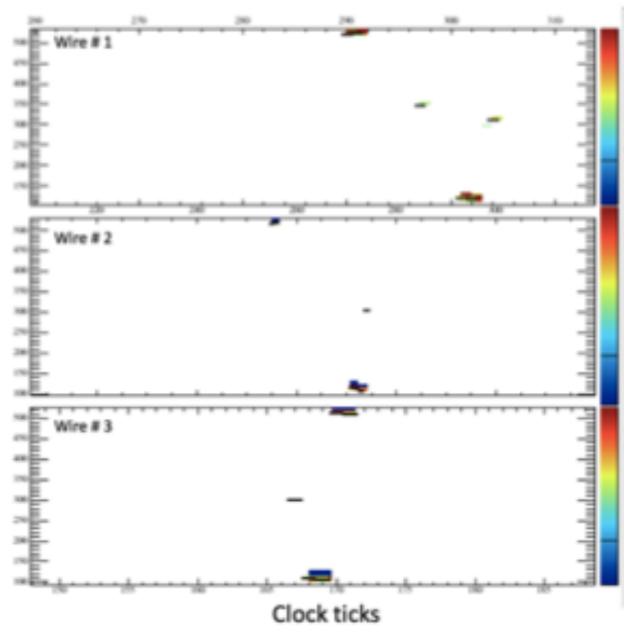
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

$\nu + {}^{40}\mathrm{Ar} \rightarrow \nu + {}^{40}\mathrm{Ar}^*$

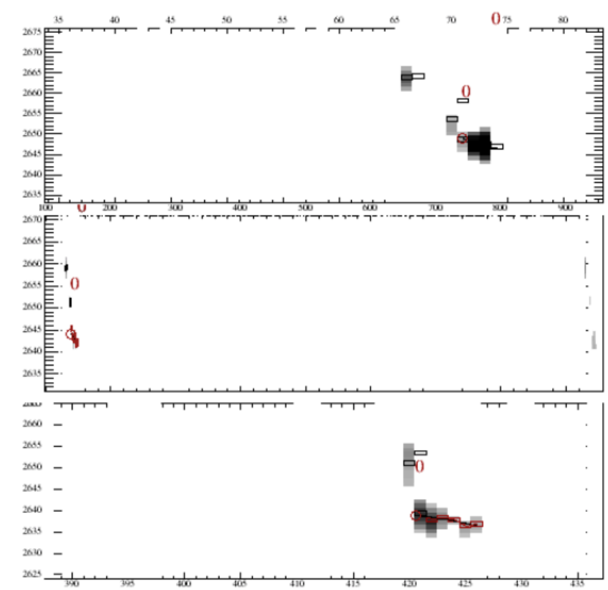
$\nu + e^- \rightarrow \nu + e^-$



track + deex γ blips
+ brem γ blips



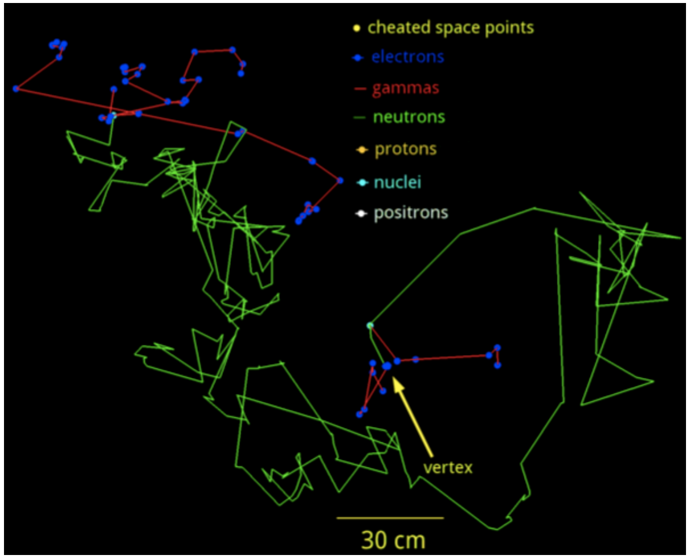
cloud of γ blips

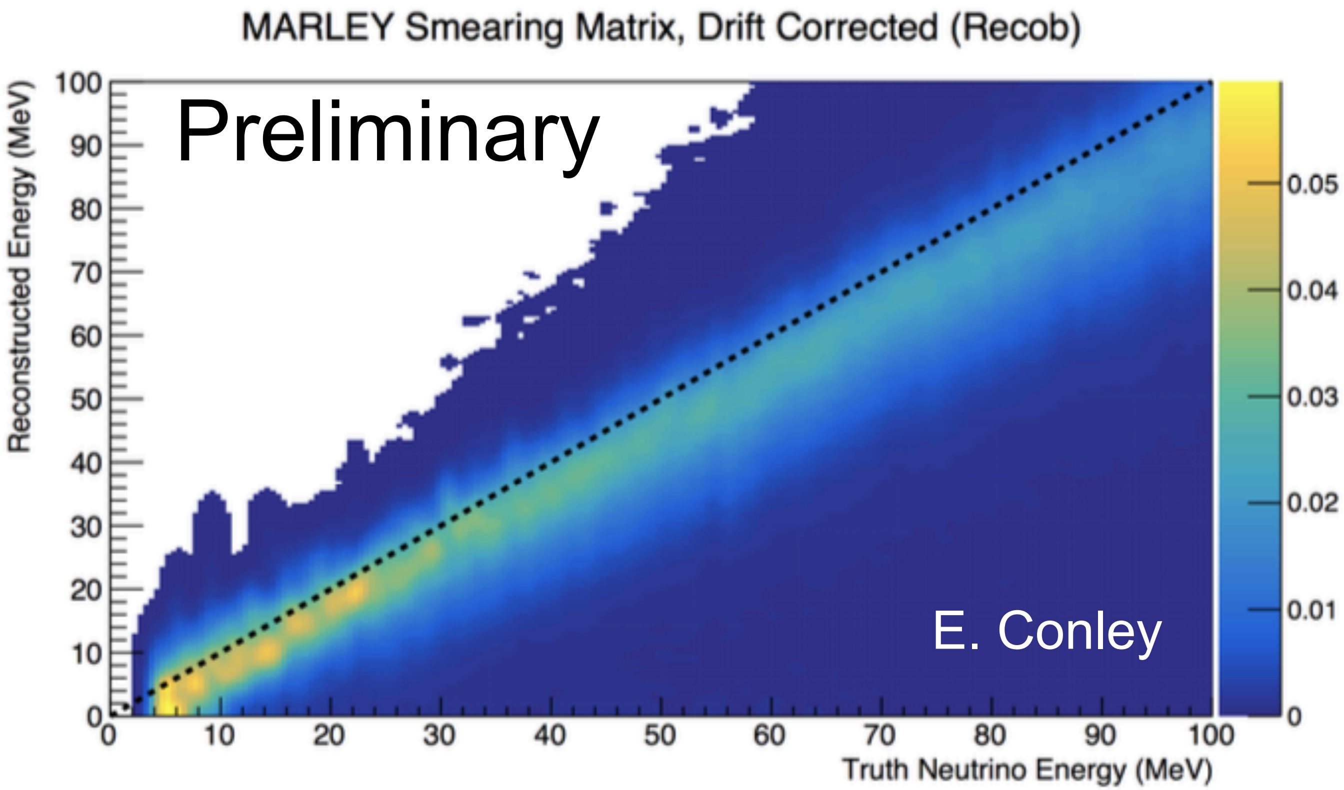


"clean" track

The final state can be complicated... some energy is lost

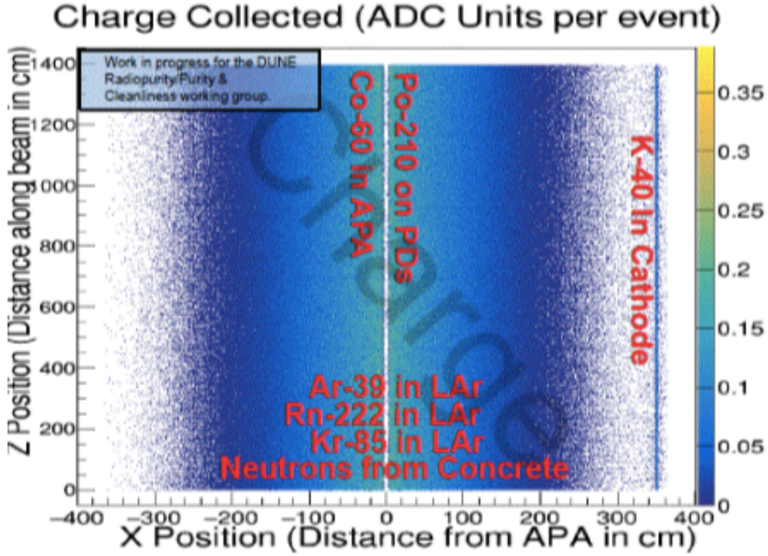
MARLEY sim
(S. Gardiner)

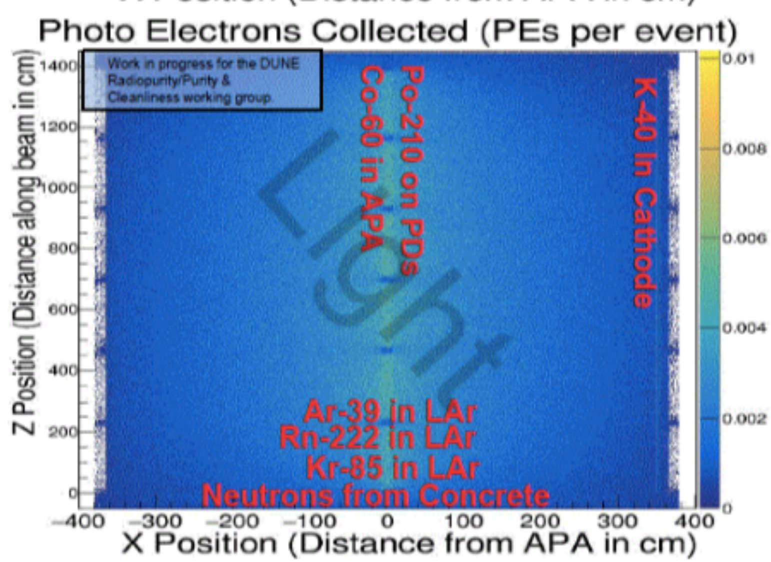


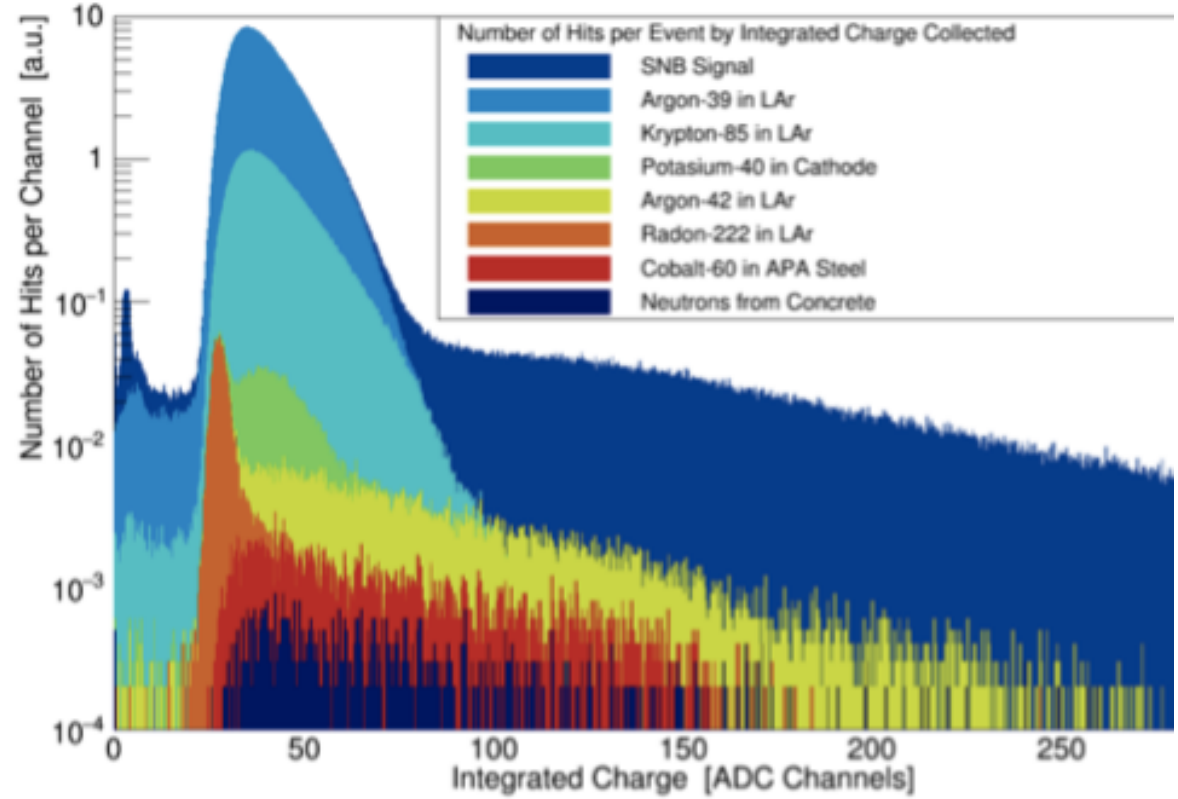


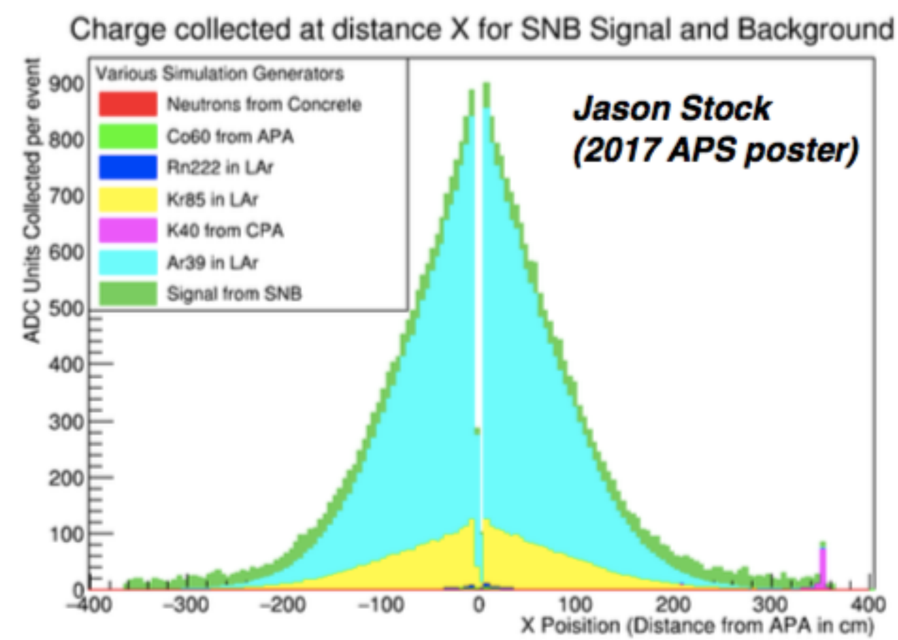
Modeling is improving, but still need nuclear theory help !

Radiologicals in DUNE









J. Reichenbacher, J. Stock

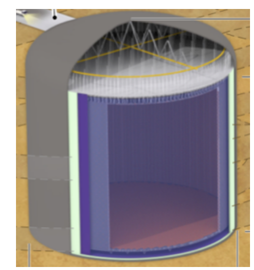
Summary of Part II

At low energy (<100 MeV):

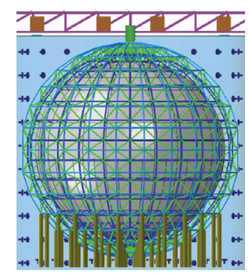
- Still want **energy** (quantity/resolution)**, angular resolution**
- Still want **flavor tagging**... but
  can only distinguish ν_e vs $\bar{\nu}_e$ vs ν_x
- Interactions w/ nuclei poorly understood;
  details of nuclear physics matter
- Background is critical... must be deep & clean

it's all about the backgrounds ...

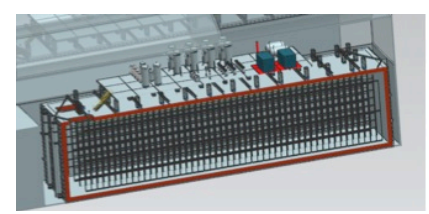
Water: cheap, proven, directional,
OK reconstruction, but low light yield,
hard to go <few MeV, neutron tagging w/Gd



Scintillator: proven, non-directional,
good light yield ➔energy resolution,
low threshold, neutron tagging



LArTPC: good reconstruction,
directional, still work to be done on tagging!

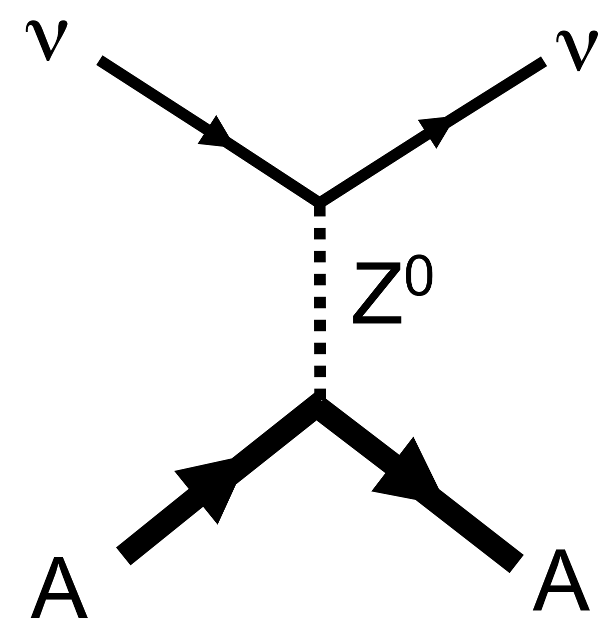


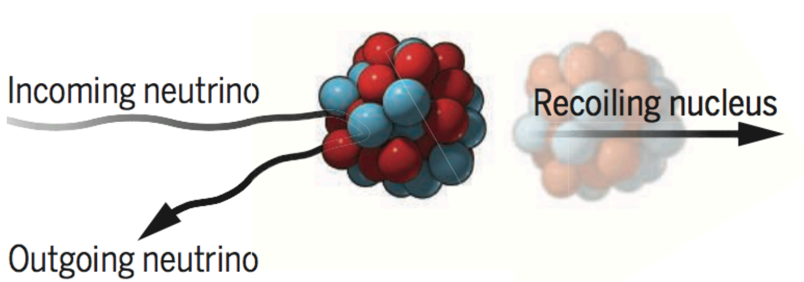
Extras/backups

Coherent elastic neutrino-nucleus scattering (CEvNS)

$\nu + A \rightarrow \nu + A$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV





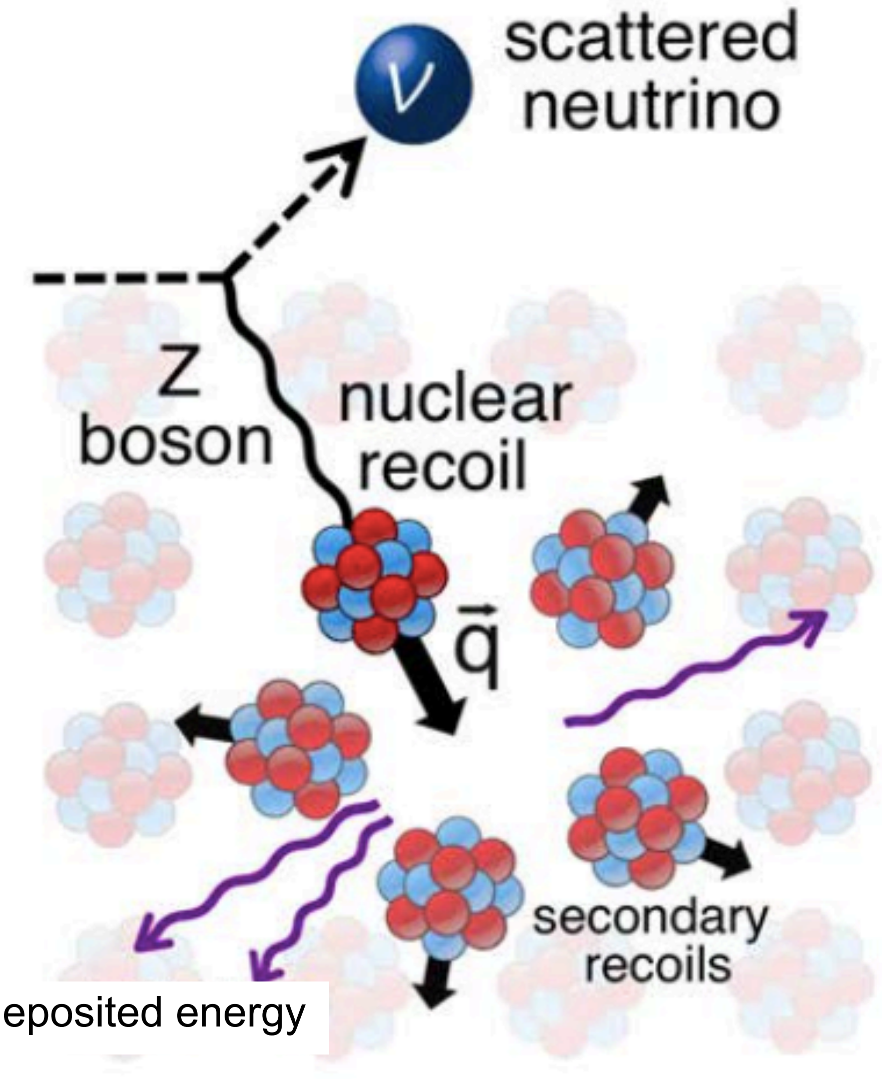
Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

Image: J. Link *Science* Perspectives

The only experimental signature of CEvNS:

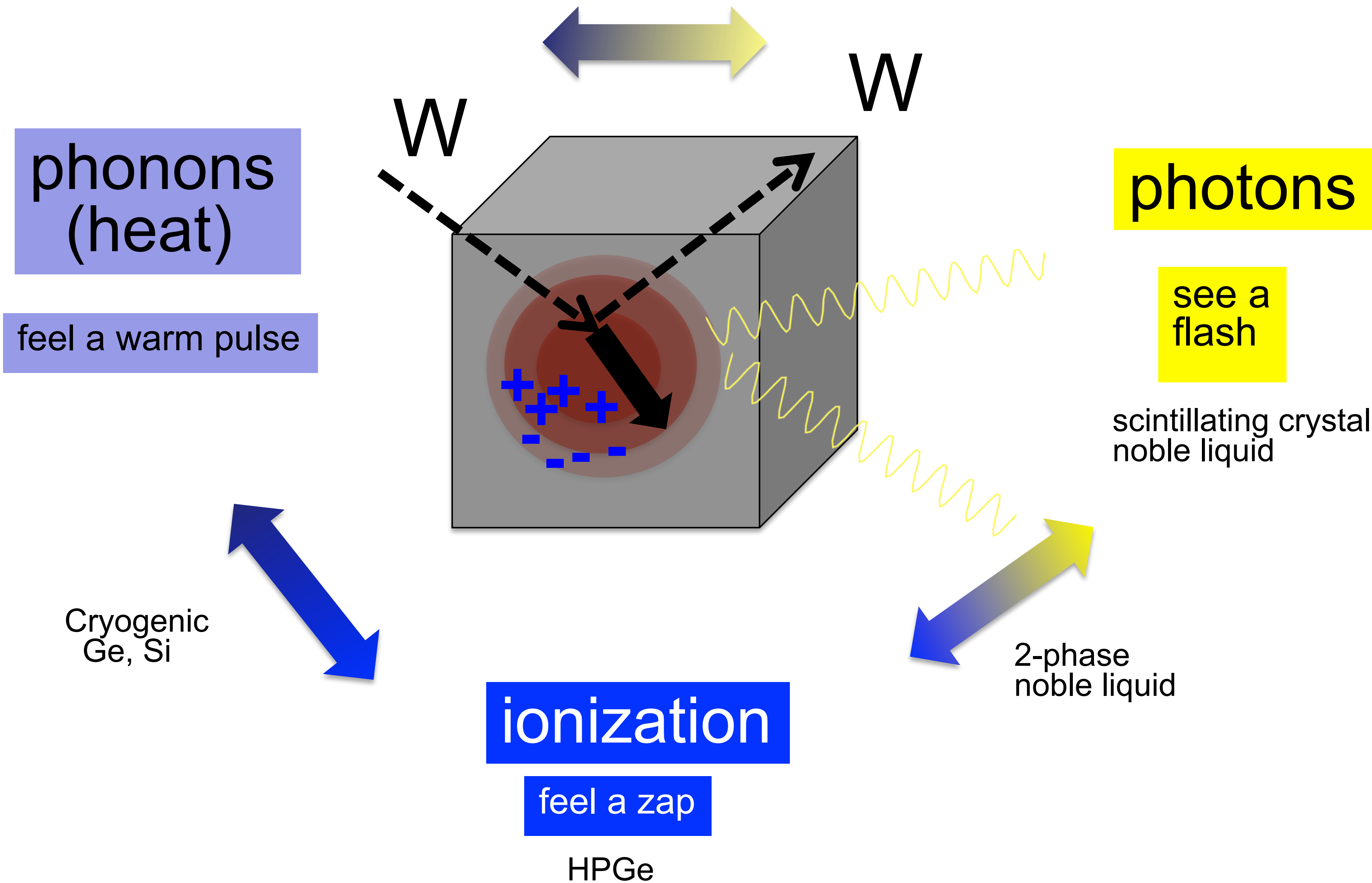
tiny energy deposited by nuclear recoils in the target material



➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

Now, ***detecting*** the tiny kick of the neutrino...

This is just like the tiny thump of a WIMP;
we benefit from the last few decades of low-energy nuclear recoil detectors

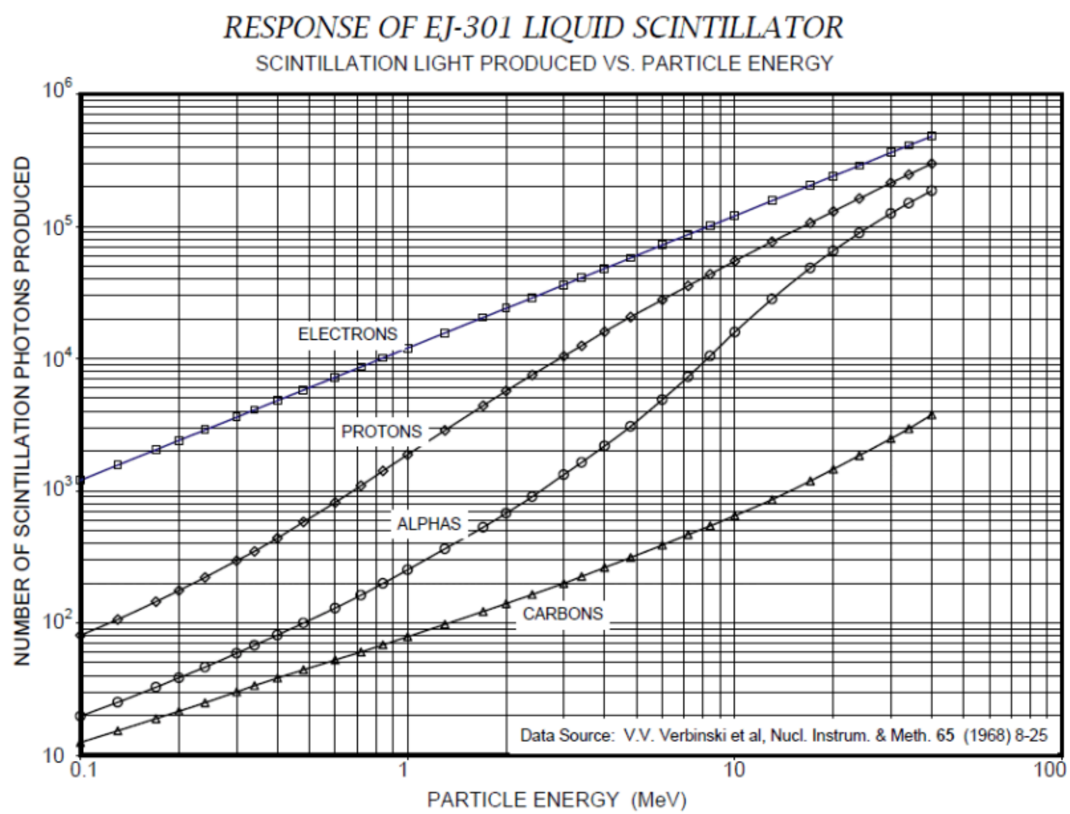


http://dmrc.snu.ac.kr/english/intro/intro1.html

"Quenching Factors" (QF)

Fraction of deposited energy that is detectable in a given channel; usually specified with respect to electron energy loss

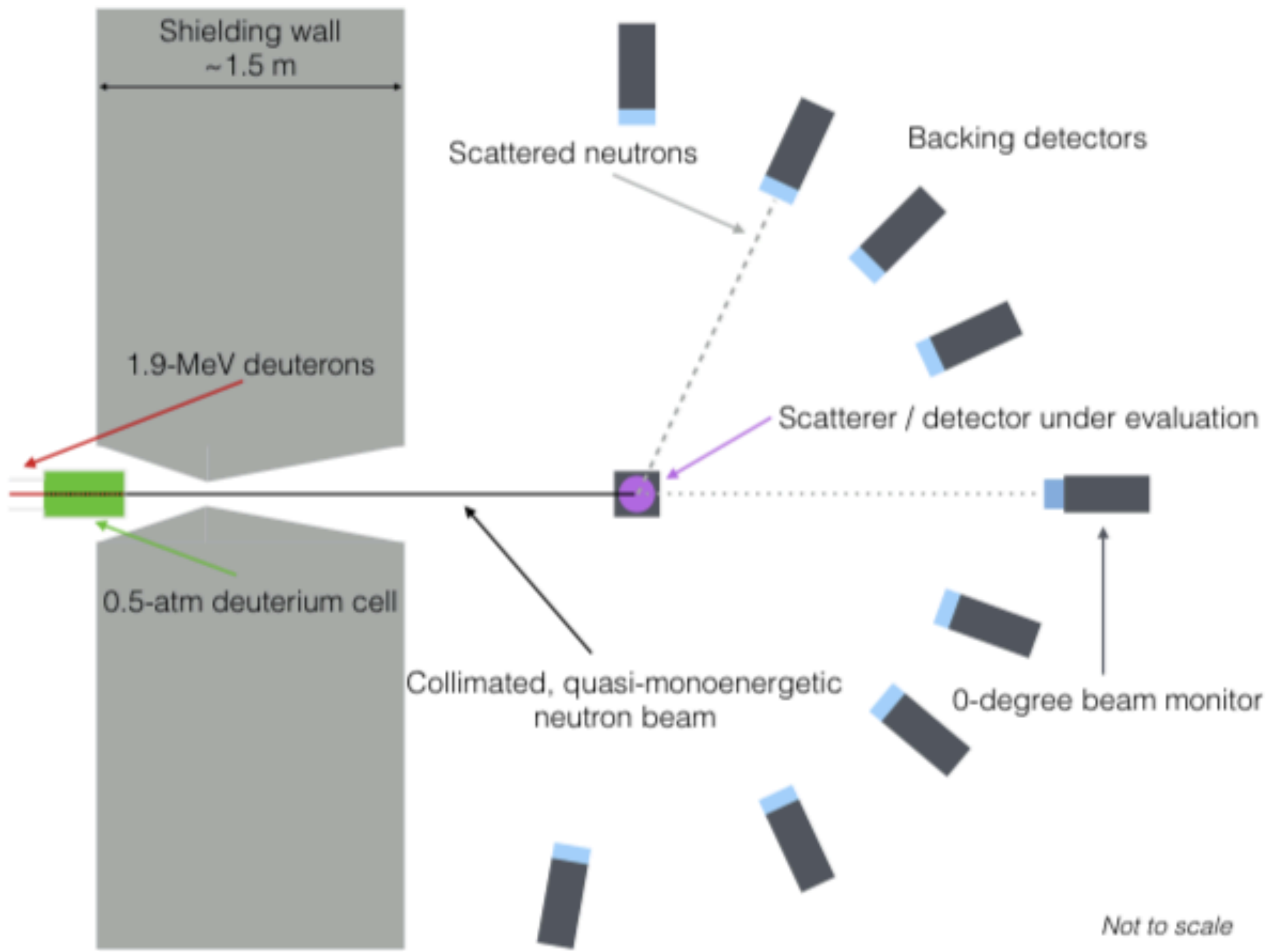
Observable nuclear recoil energy loss tends to be **"quenched"** with respect to electron energy loss



Nuclear recoil energy: **keVr**
"Electron-equivalent energy": **keVee**

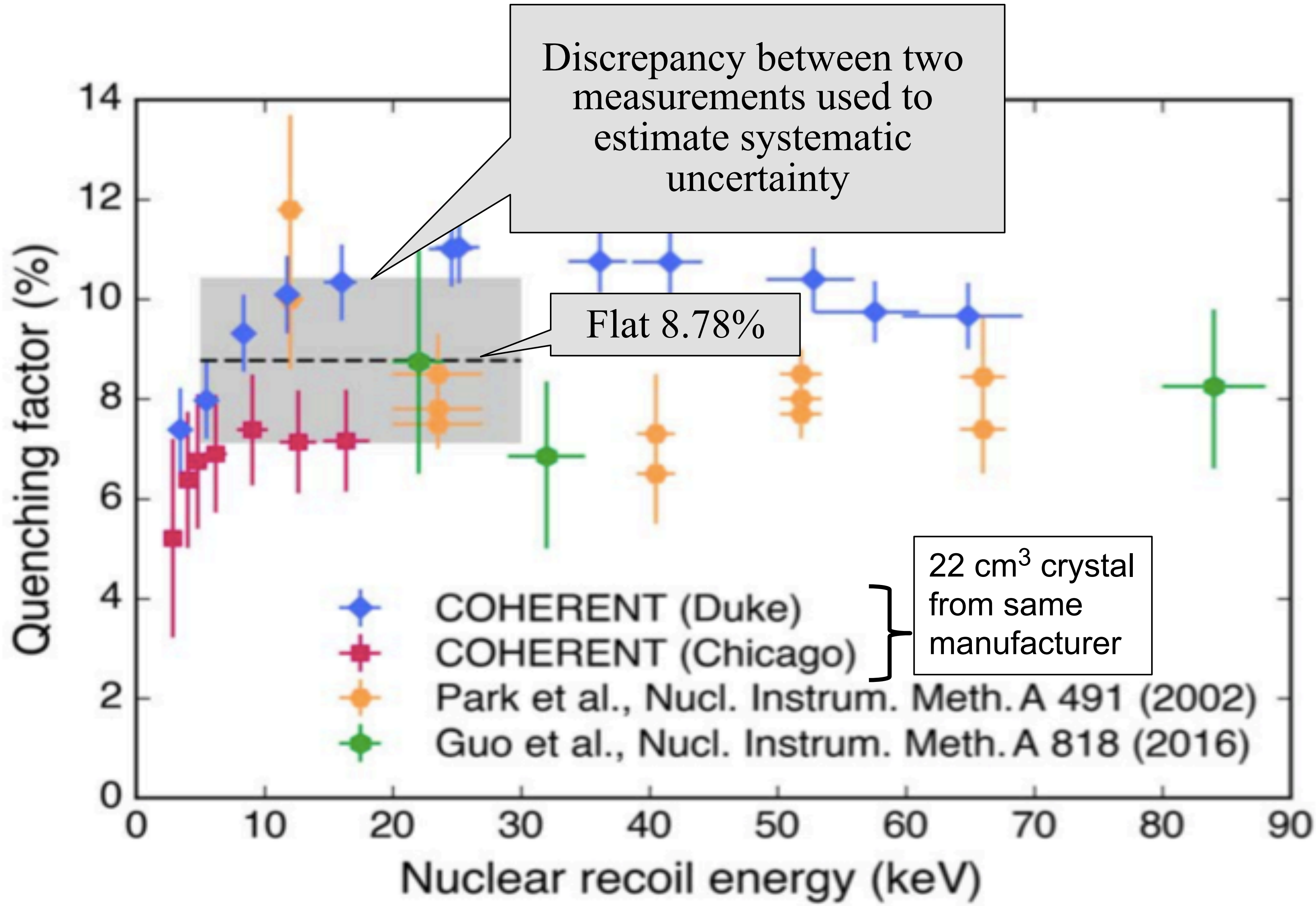
"Quenching Factors" (QF)

Understanding of quenching factors is critical for interpretation of data... need to be measured target by target



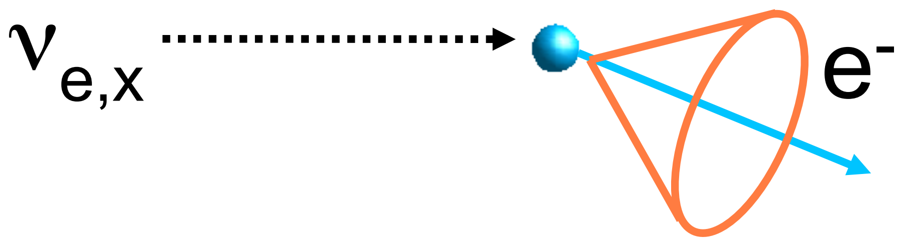
G. Rich thesis

CsI quenching factor measurements w/ neutrons



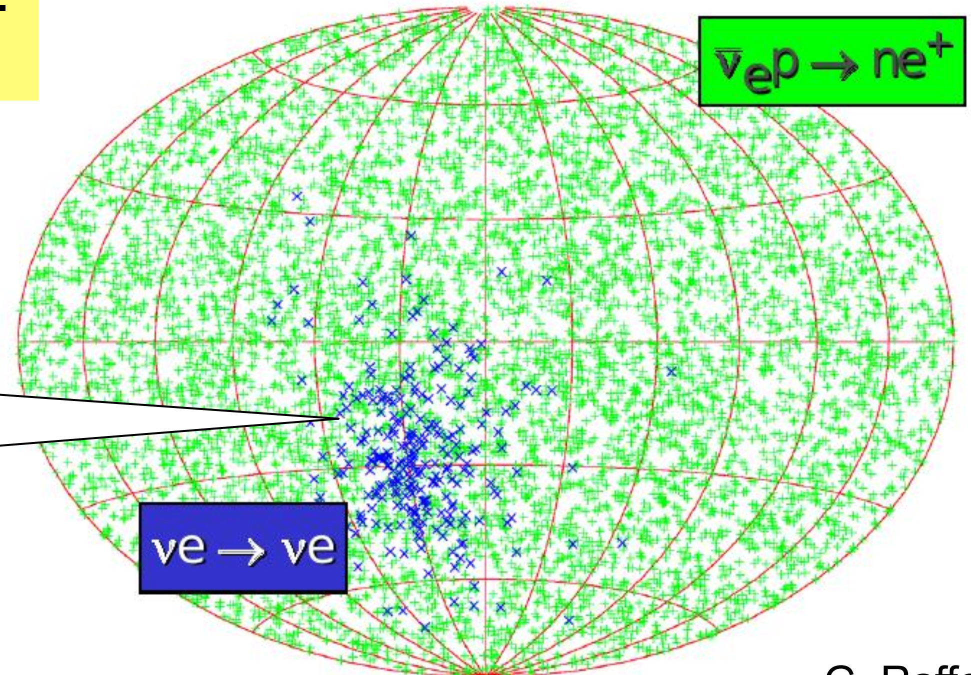
13.348 pe/keVee * 0.0878 keVee/keVr = **1.2 pe/keVr**

ee light yield — QF



$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Pointing from neutrino-electron elastic scattering

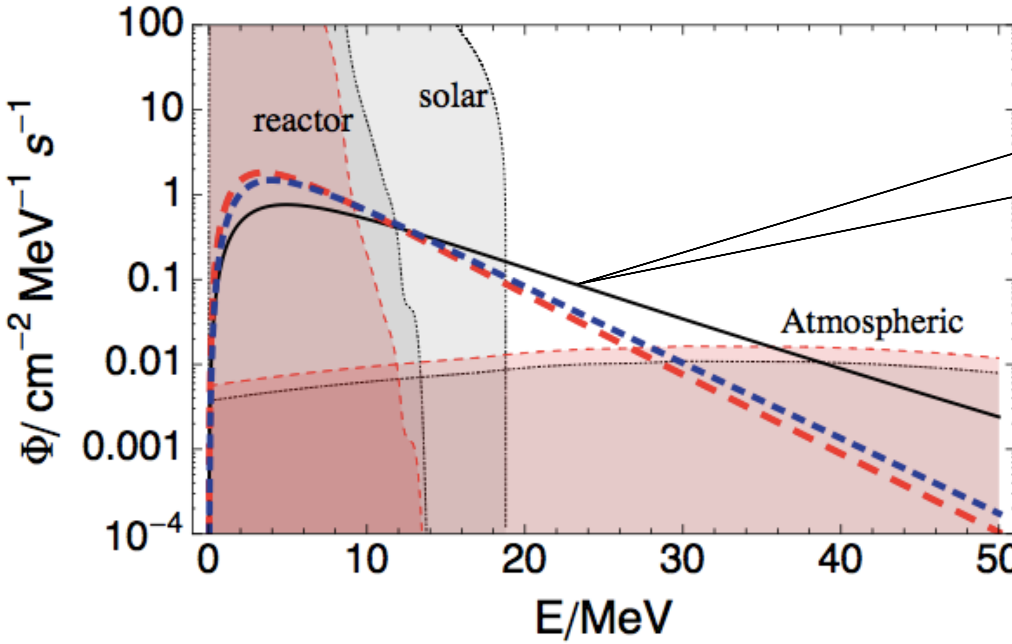


G. Raffelt

$$\delta(\theta) \sim \frac{30^\circ}{\sqrt{N}}$$

degraded by isotropic IBD

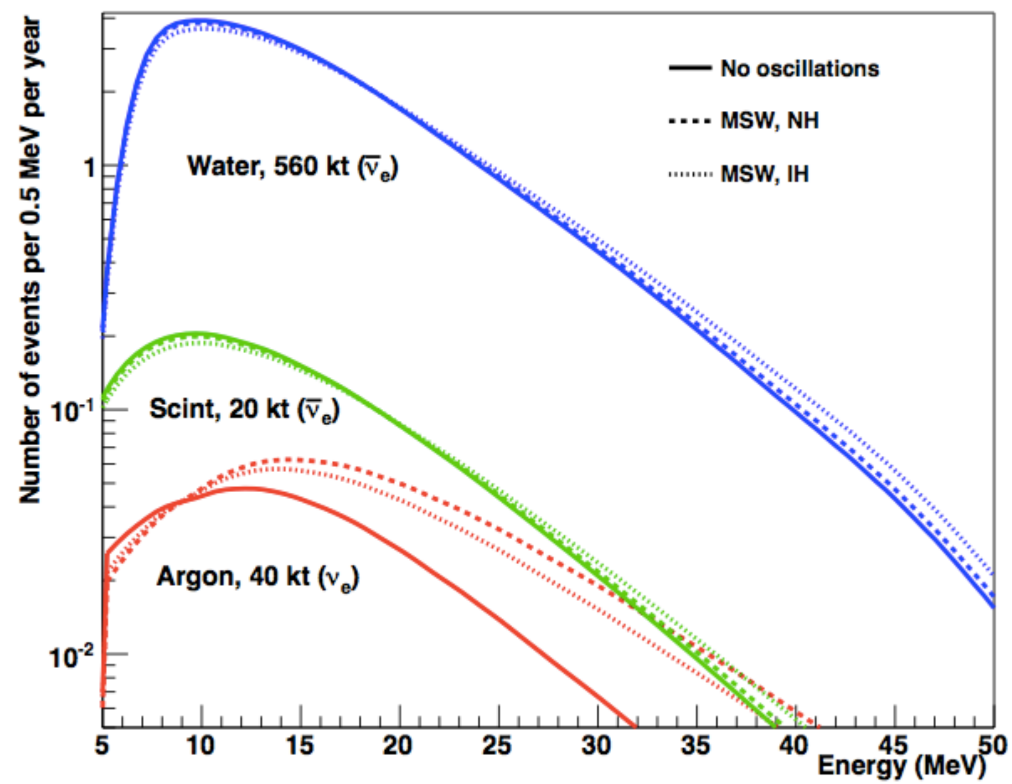
And going even farther out: we are awash in a sea of ***'relic'* or diffuse SN ν's (DSNB)**, from ancient SNae ...



Window with low ν bg, 20-40 MeV

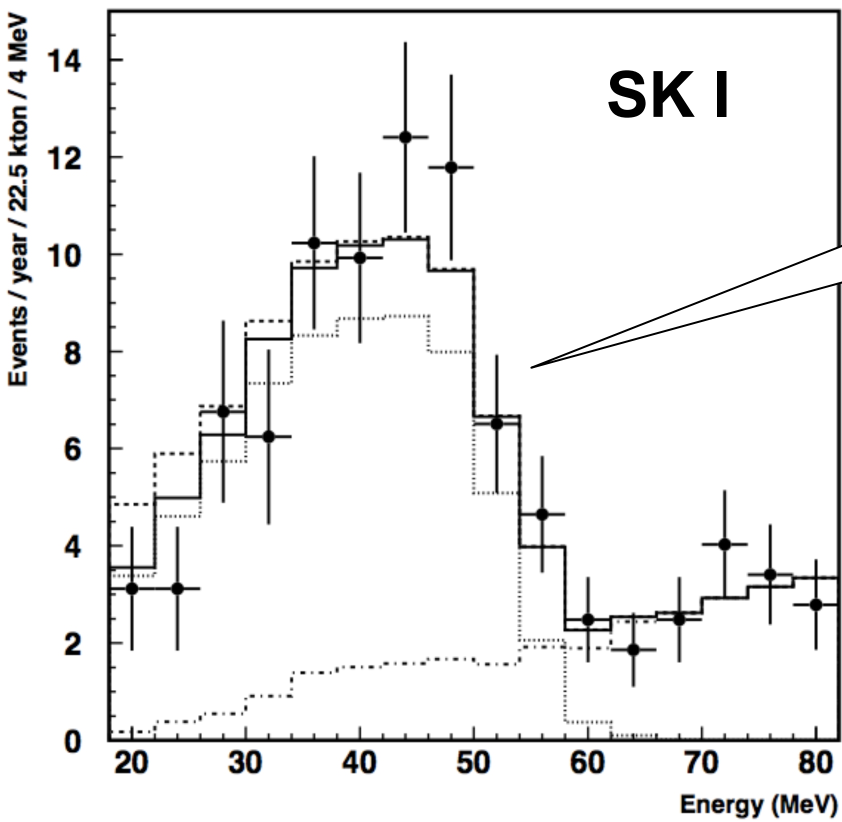
~few events per year in SK

Difficulty is tagging for decent signal/bg (no burst, coincidences w/ optical SNae...)



it's all about the backgrounds

In water: $\bar{\nu}_e + p \rightarrow e^+ + n$



Michel electrons from decays of sub-Cherenkov threshold muons

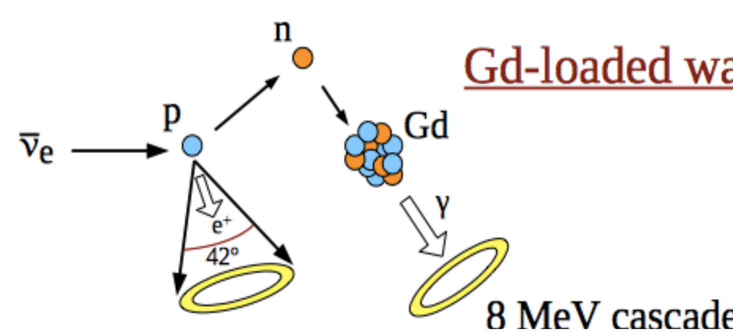
- Worst background is from decaying 'invisible muons' from atmospheric neutrinos → ***reduce by tagging electron antineutrinos with Gd***

LAr? Electron flavor, but low rate... bg unknown

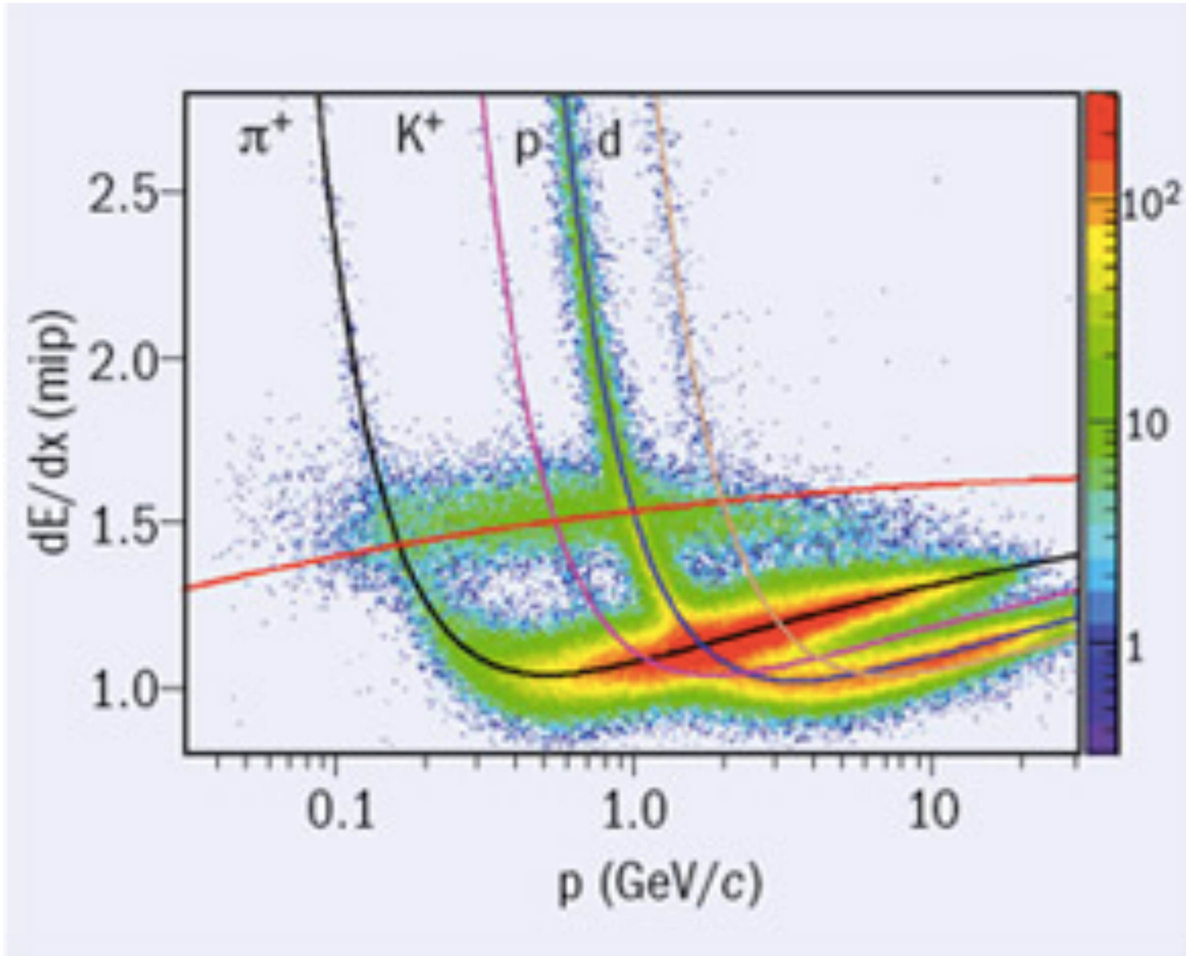
Scintillator?

Good IBD tagging, but NC bg...

Gd-loaded water



Particle ID using dE/dx



A common technique: if you know p and dE/dx, you can determine the particle type

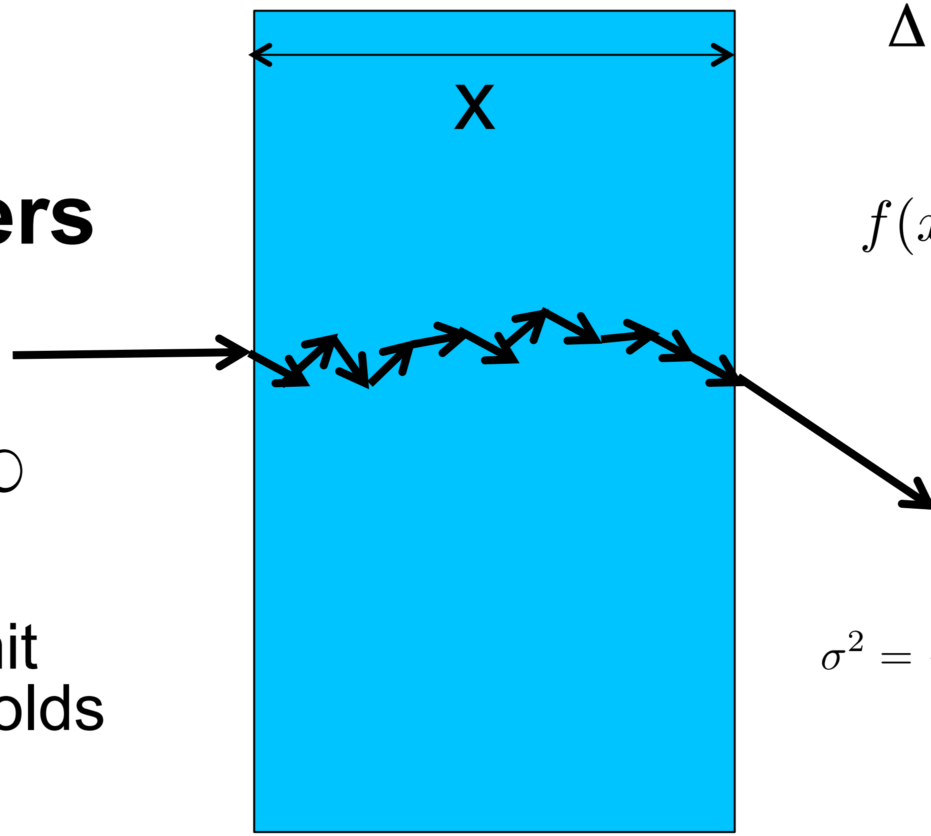
This was mean energy loss...
what about **distribution** of energy loss?

Depends on thickness of absorber...
no. of collision events N determines fluctuation behavior

Thick absorbers

$$N \to \infty$$

Central limit theorem holds



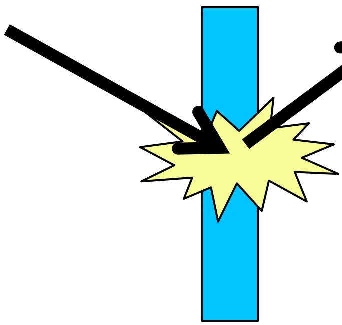
Δ: energy loss

$$f(x, \Delta) \propto \exp\left(\frac{-(\Delta - \bar{\Delta})^2}{2\sigma^2}\right)$$

$$\sigma^2 = \frac{(1 - \frac{1}{2}\beta^2)}{1 - \beta^2} 4\pi N_a r_e^2 (m_e c^2)^2 \rho \frac{Z}{A} x [\mathrm{MeV}^2]$$

“Thin” absorbers

Central limit theorem does not apply...
single collisions can matter

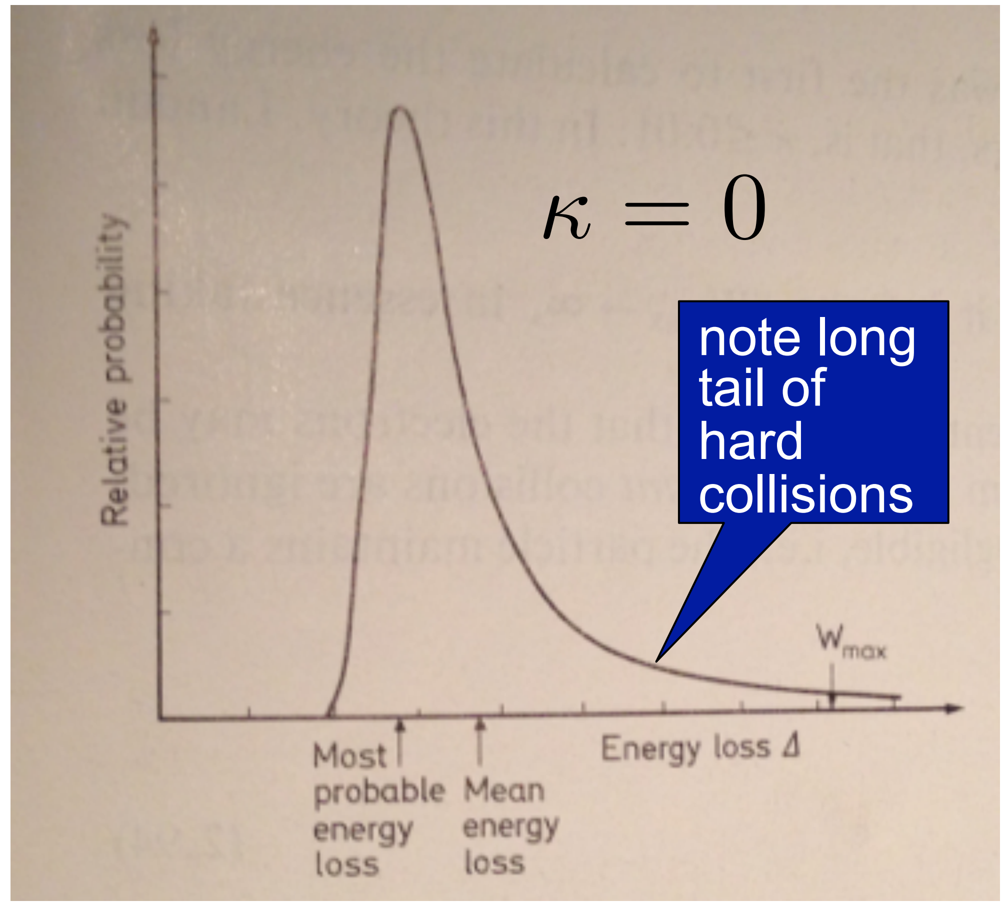


$$\kappa = \bar{\Delta}/W_{\mathrm{max}}$$

determines the behavior;
thin absorber corresponds to

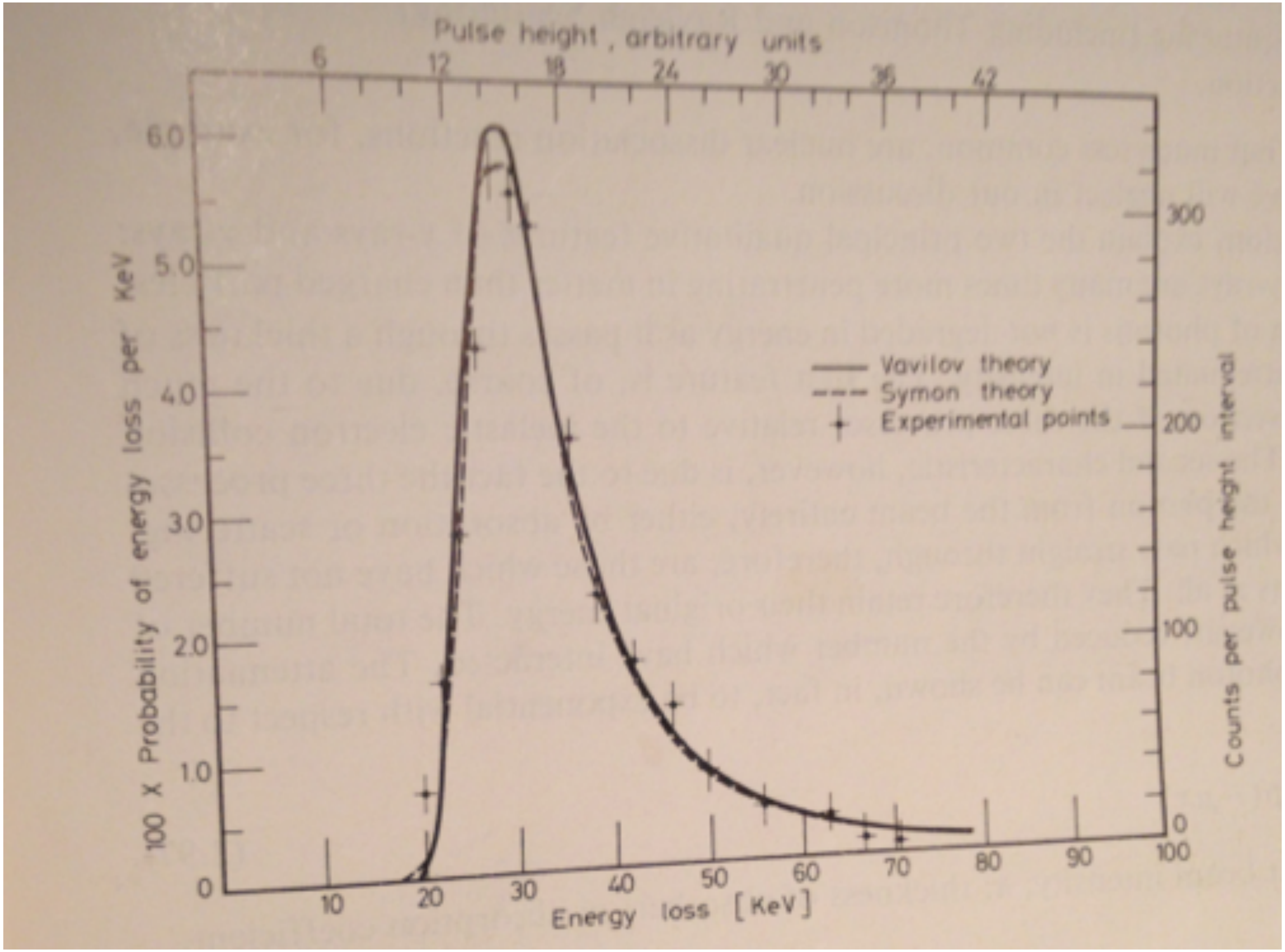
$$\kappa < 10$$

Landau distribution

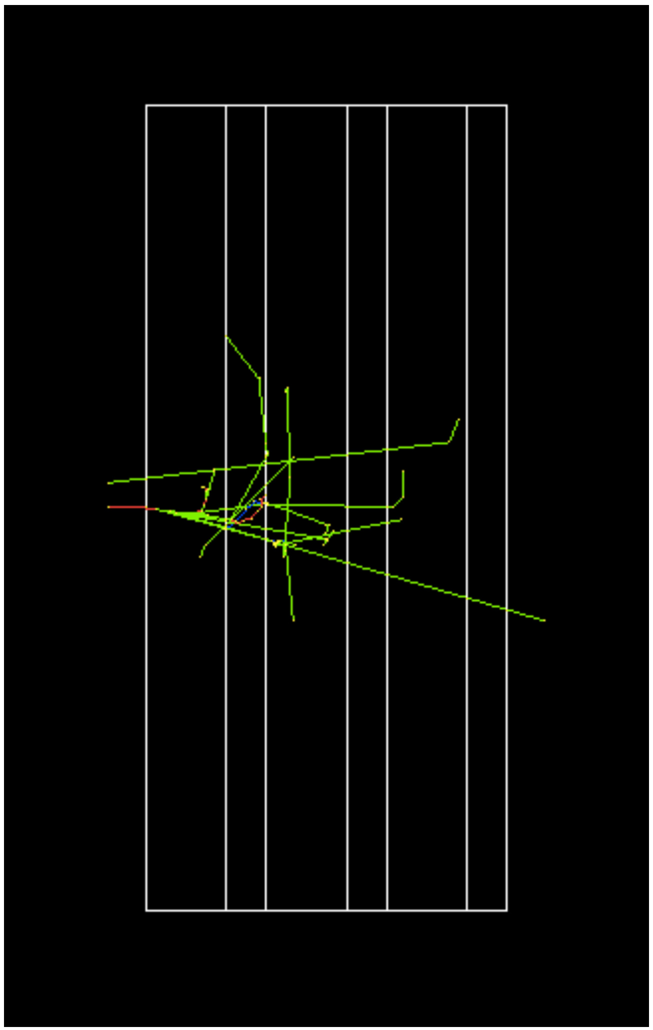


$$\Delta_{\mathrm{most\ probable}} < \bar{\Delta}$$

Vavilov/Symon distributions
are refinements to the Landau
(function of κ)



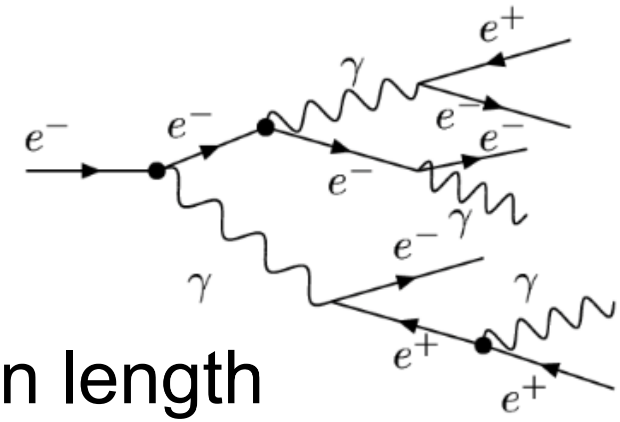
What about very thick absorbers?
... complicated, particle slows down...
➔ **in practice, use a Monte Carlo code**



- **Geant4** is the standard open-source detector simulation code
- Can specify desired materials, geometry, incident particles, physics processes
- May need tweaks for specialized applications

Electromagnetic shower size estimate

(in radiation lengths)



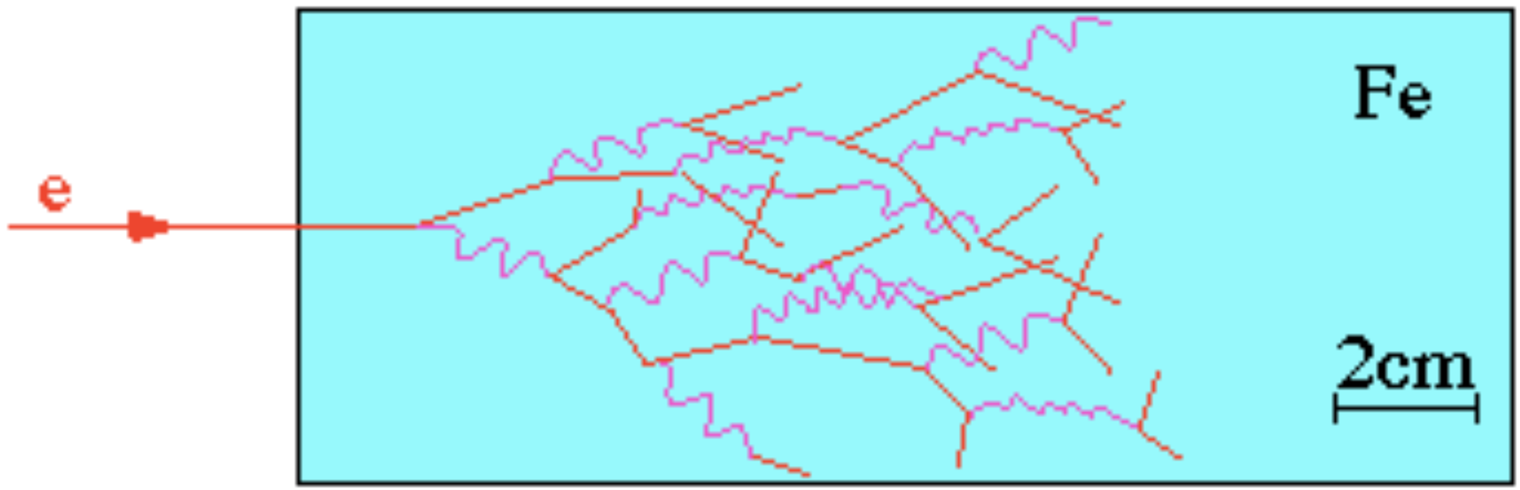
- Start with energy E_0
- Photon will convert after ~1 radiation length
  ➔ $E_0/2$ for each of e^+, e^-
- Divide energy per particle again by 2 after another radiation length
- After t radiation lengths,

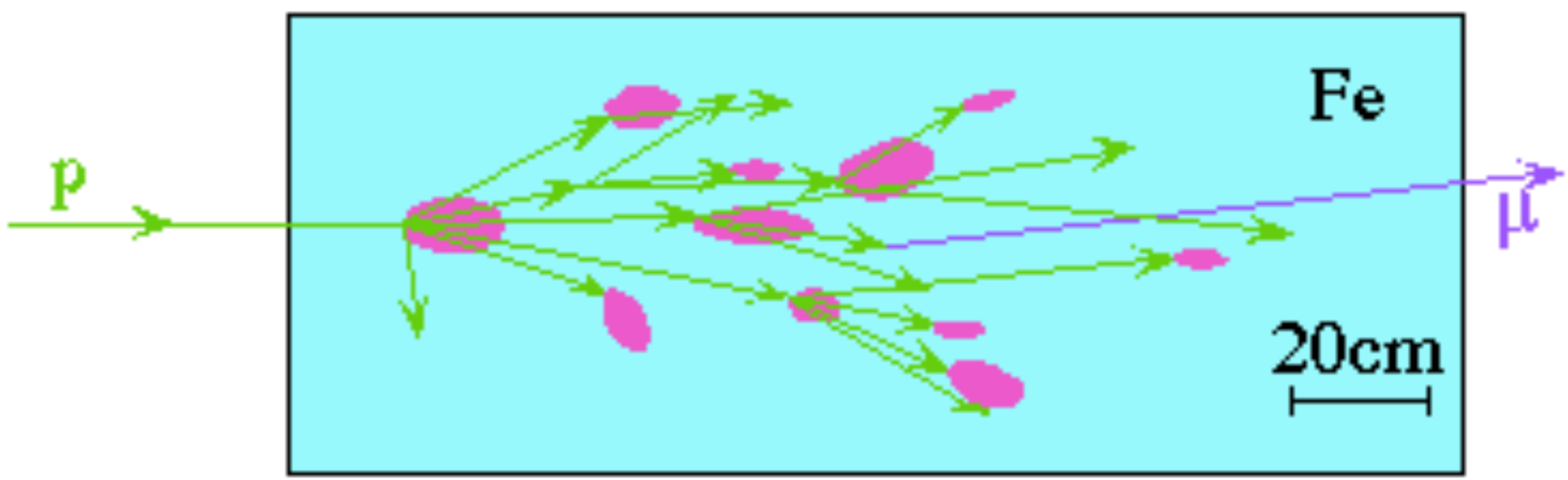
$N \sim 2^t$ so $E \sim E_0/2^t$ for each particle

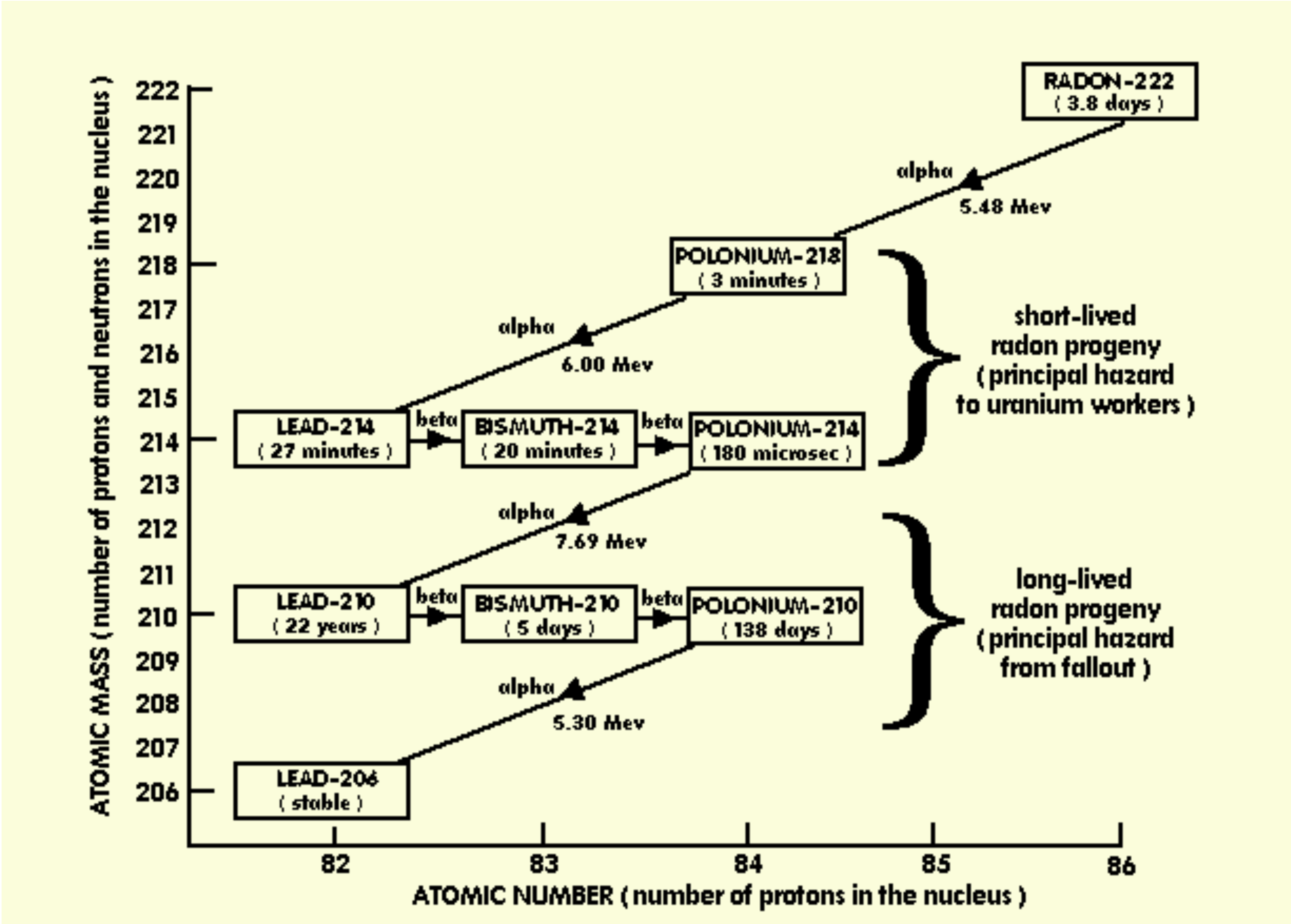
$$E(t_{\max}) = E_0/2^{t_{\max}} = E_c$$

➔ $$t_{\max} = \frac{\ln(E_0/E_c)}{\ln 2}$$

Hadronic showers also relevant for
high energies (initiated by protons, neutrons,..)






RADON-222
(3.8 days)
alpha
5.48 Mev
POLONIUM-218
(3 minutes)
alpha
6.00 Mev
LEAD-214
(27 minutes)
beta
BISMUTH-214
(20 minutes)
beta
POLONIUM-214
(180 microsec)
alpha
7.69 Mev
LEAD-210
(22 years)
beta
BISMUTH-210
(5 days)
beta
POLONIUM-210
(138 days)
alpha
5.30 Mev
LEAD-206
(stable)
short-lived
radon progeny
(principal hazard
to uranium workers)
long-lived
radon progeny
(principal hazard
from fallout)
ATOMIC MASS (number of protons and neutrons in the nucleus)
222
221
220
219
218
217
216
215
214
213
212
211
210
209
208
207
206
82
83
84
85
86
ATOMIC NUMBER (number of protons in the nucleus)