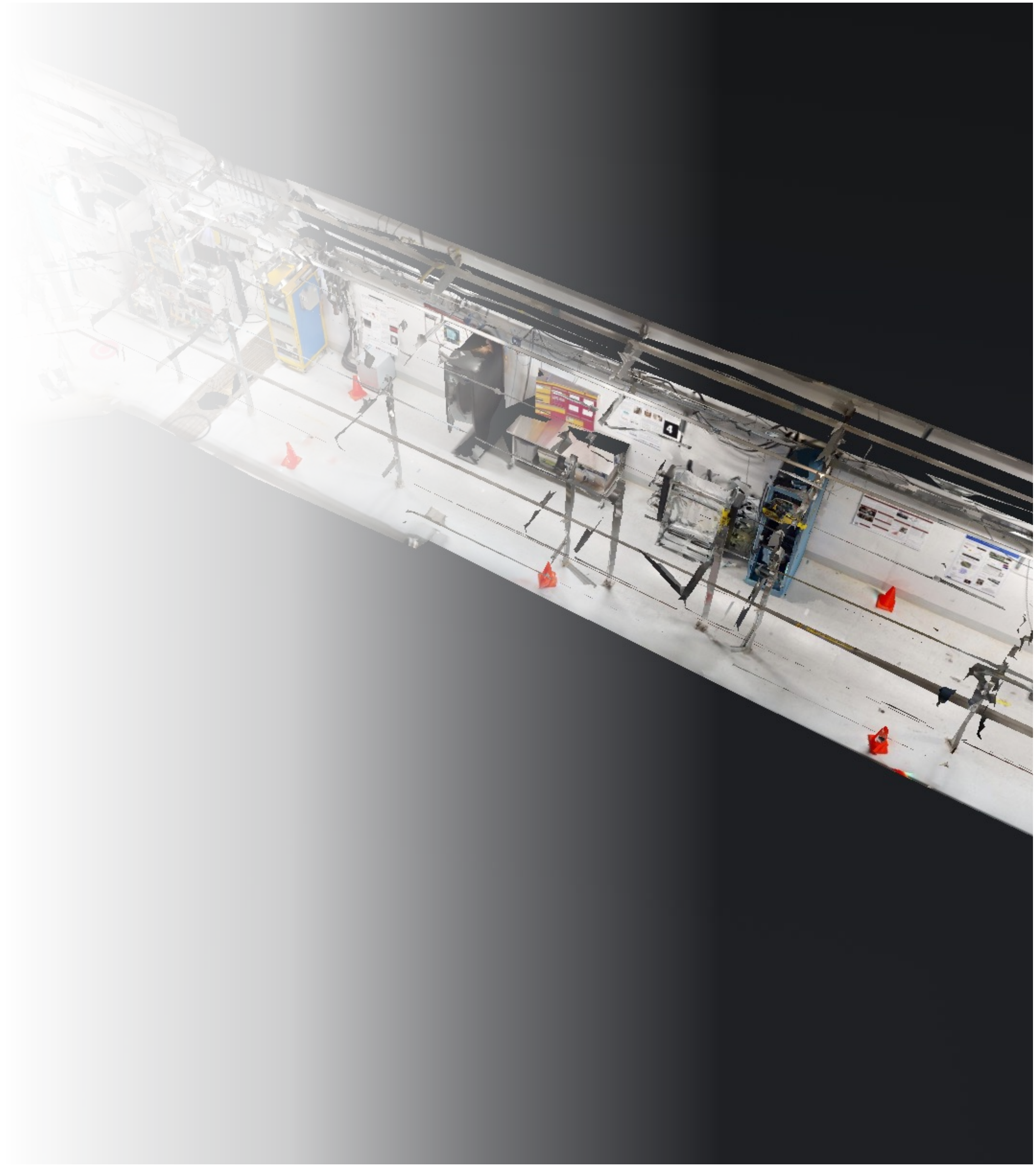
Neutrino Interactions

Kate Scholberg,
Duke University

MPA Summer School 2021:

Fundamental Interactions in Particle, Hadron and Nuclear Physics

September 2021



Outline of Lecture Topics

- Neutrino sources
- Neutrino interactions with matter
- Particle detection techniques

~Mon

- Physics with neutrinos in the ~1-100 MeV range
- Physics with stopped-pion neutrino sources

~Tue

- Physics in Neutrino Alley at the Spallation Neutron Source
- The COHERENT Experiment
- Future prospects

~Thu

- I may adjust as we go along...

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General overview

Specific example

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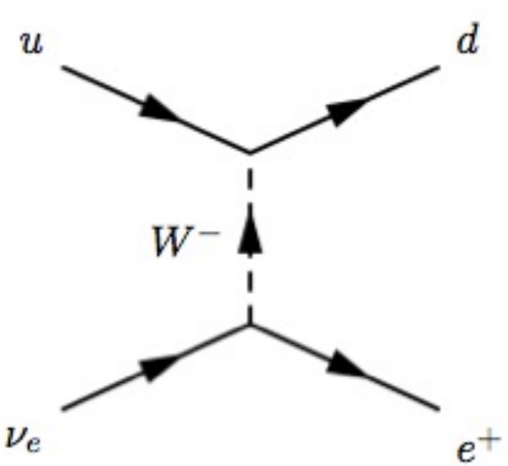
Specific example

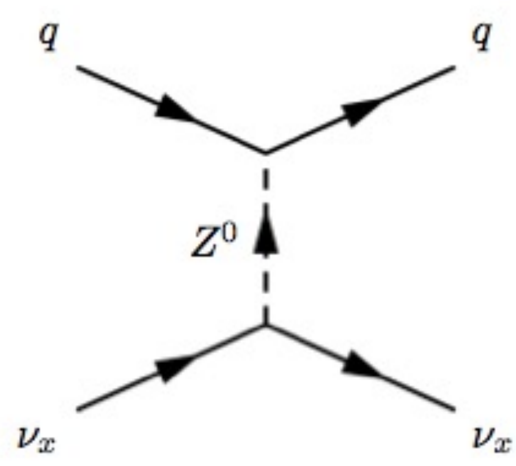
NEUTRINOS

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

neutral partners
to the charged leptons

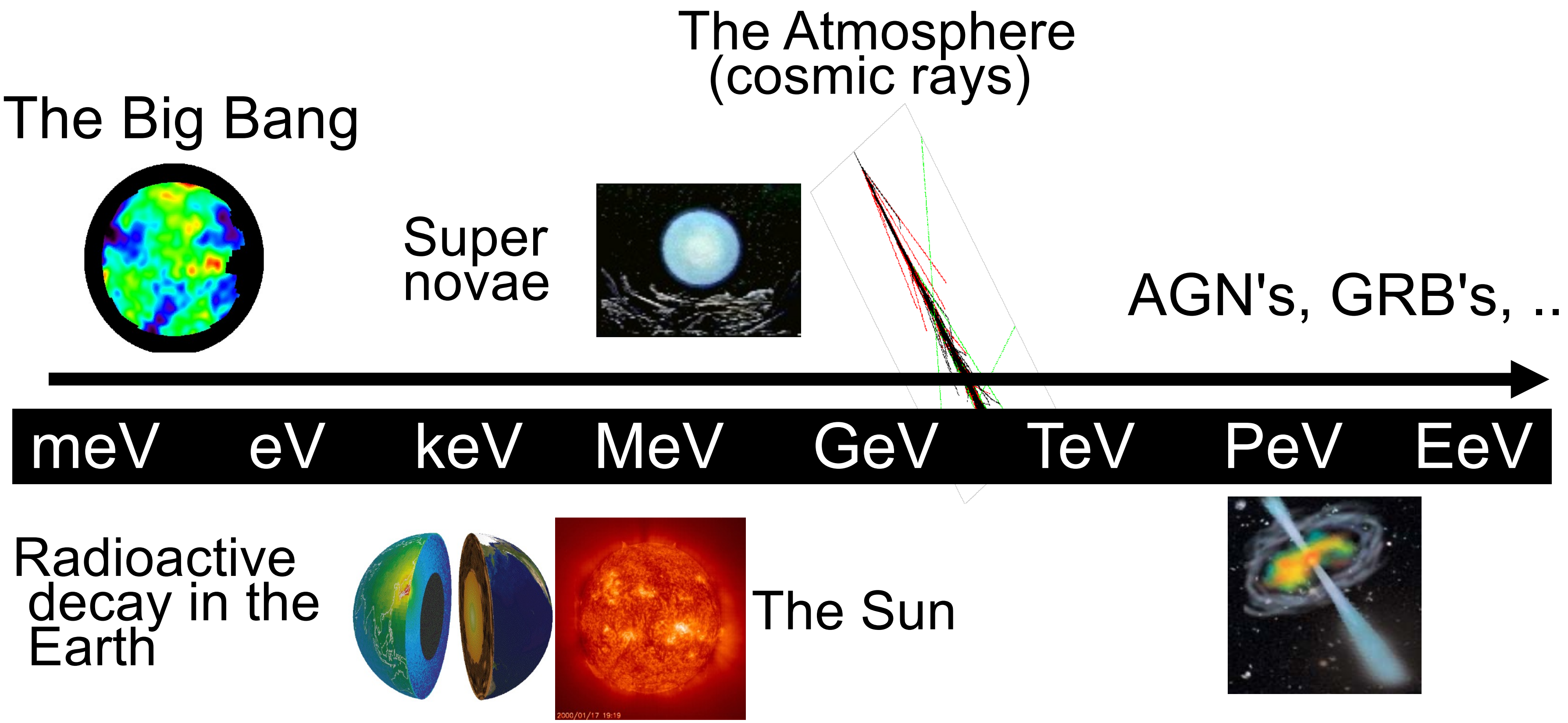
- Three flavors (families), neutrinos and antineutrinos
- Tiny masses (< 1 eV) and *oscillations* (flavor change)
- Interact *only* via *weak interaction* (& gravity)





Exchange of
W and Z bosons in
weak interactions

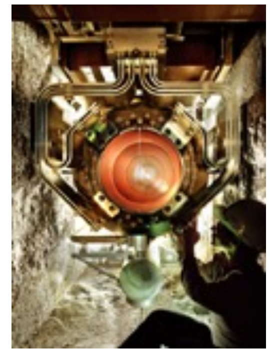
Sources of ‘wild’ neutrinos



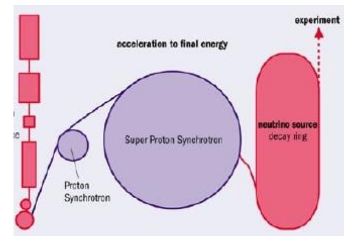
Sources of ‘tame’ neutrinos

Nuclear reactors

Proton accelerators

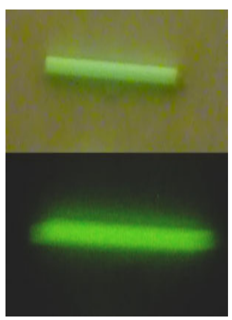


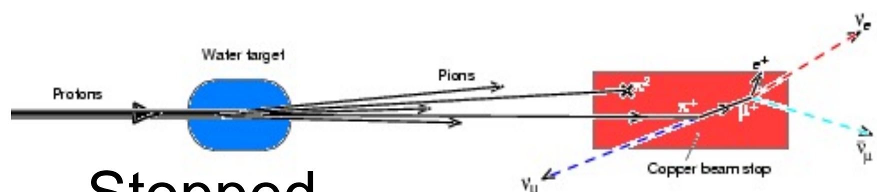
Beta beams



eV keV MeV GeV TeV

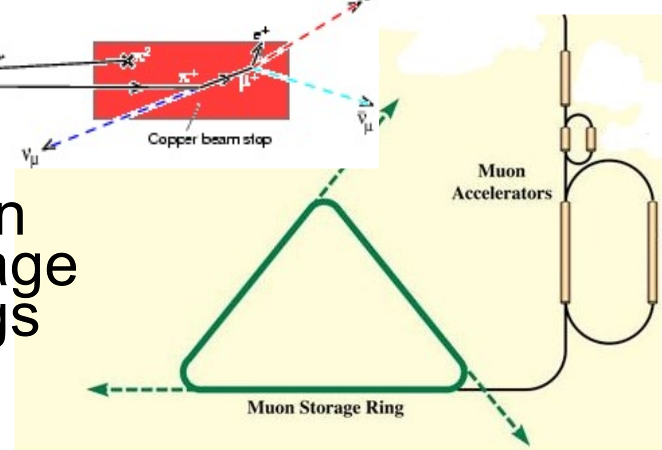
Artificial radioactive sources





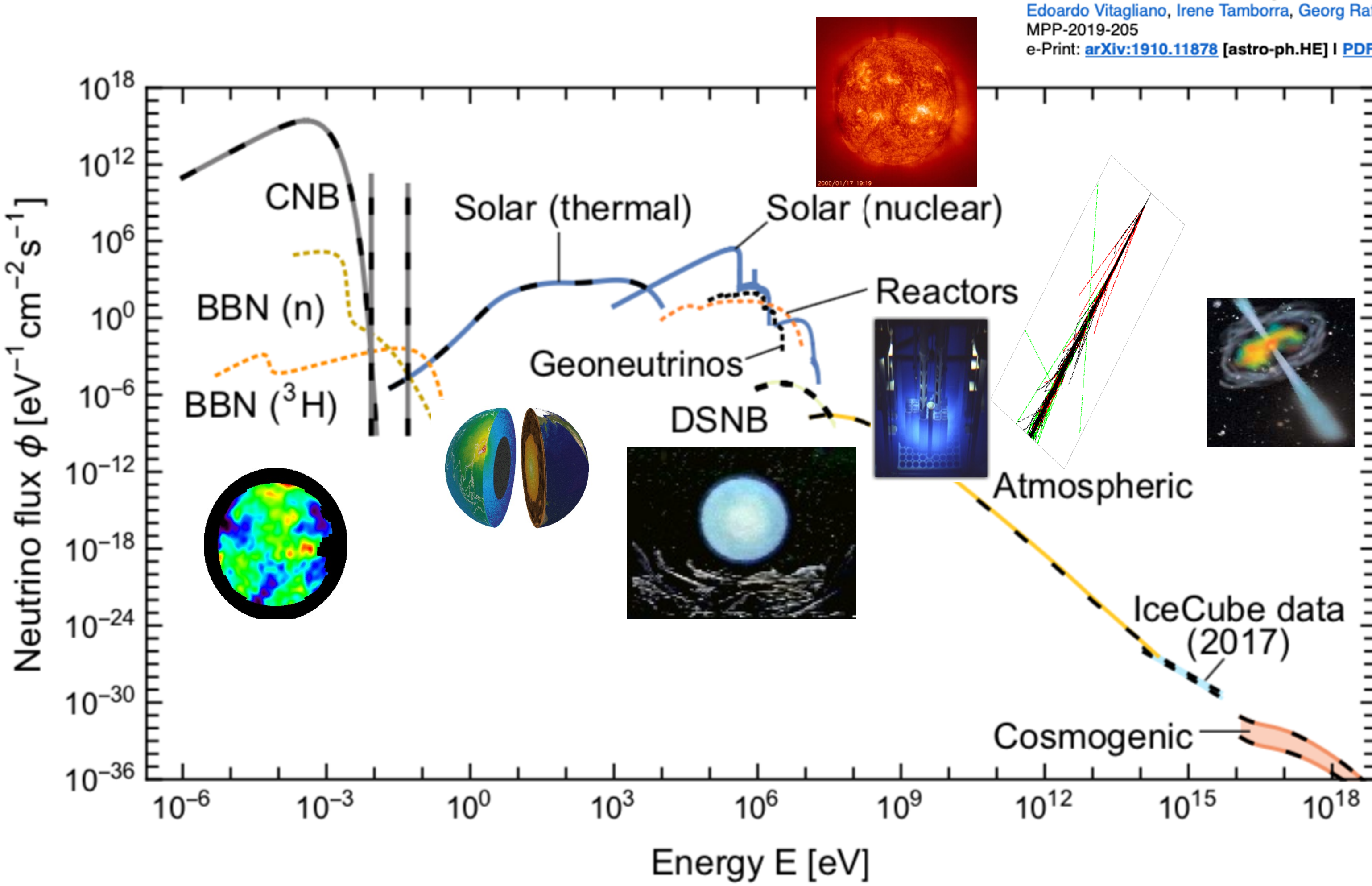
Stopped pion sources

Muon storage rings



Energy spectrum of neutrino sources

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] I PDF



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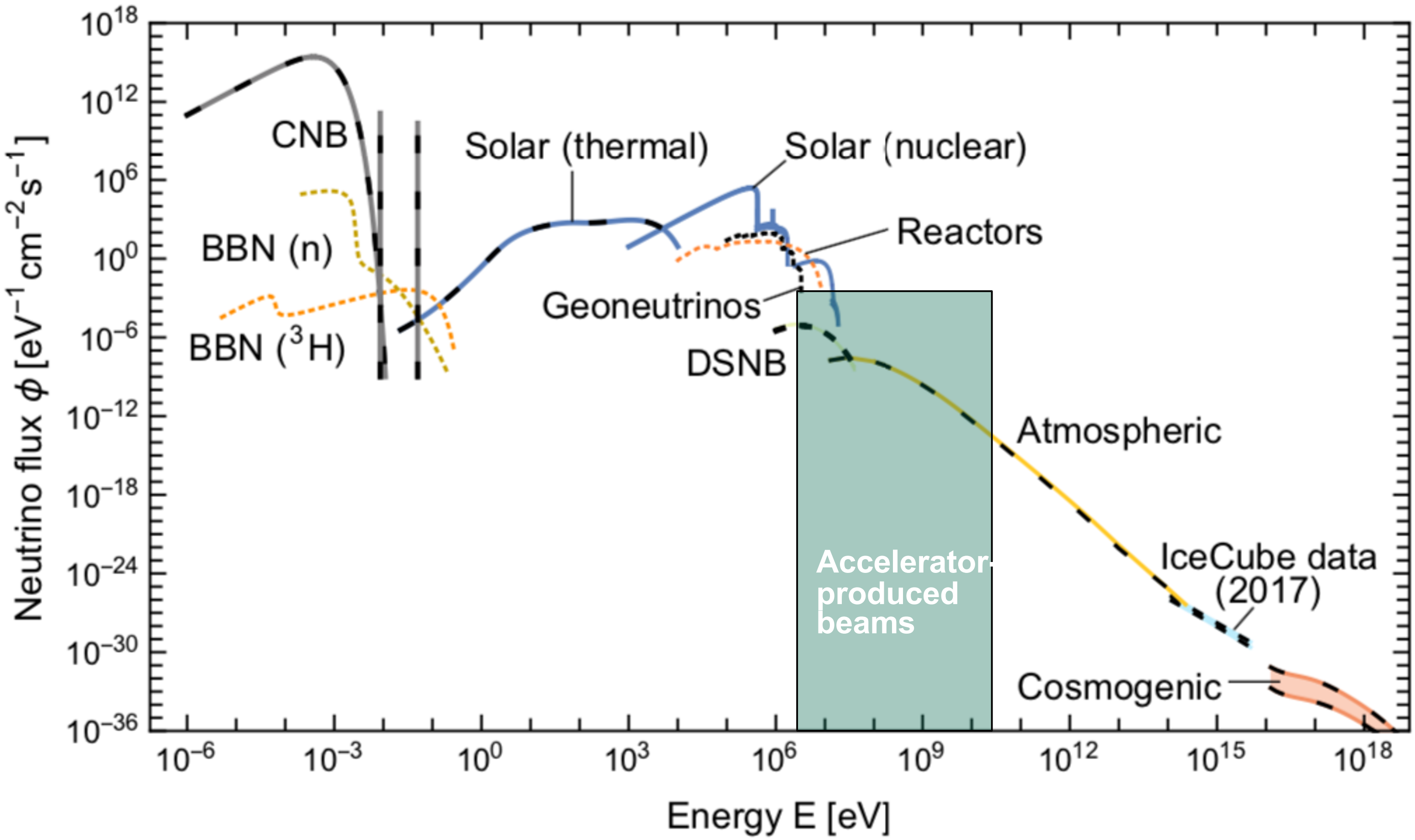

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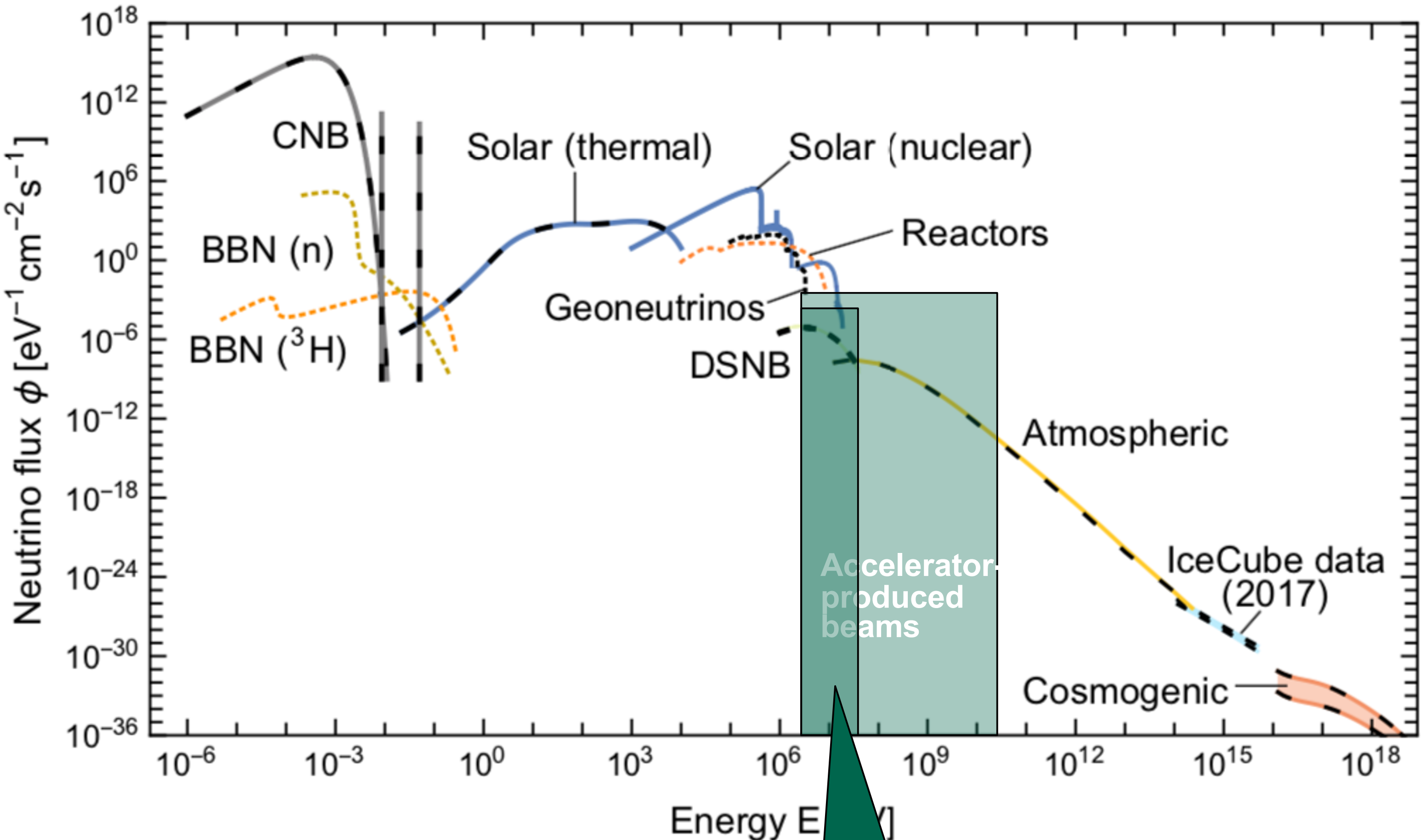

we're going to zoom in here eventually

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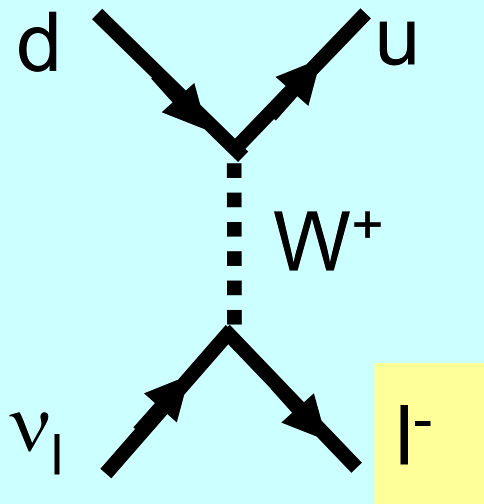
Neutrino interactions with matter

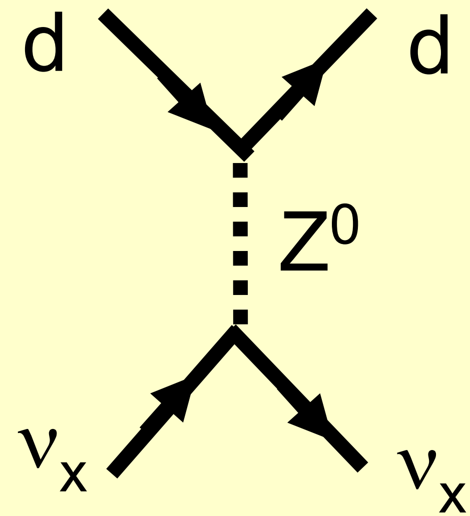
Charged Current (CC)



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

Produces lepton
with **flavor corresponding to neutrino flavor**
(must have enough energy
to make lepton)

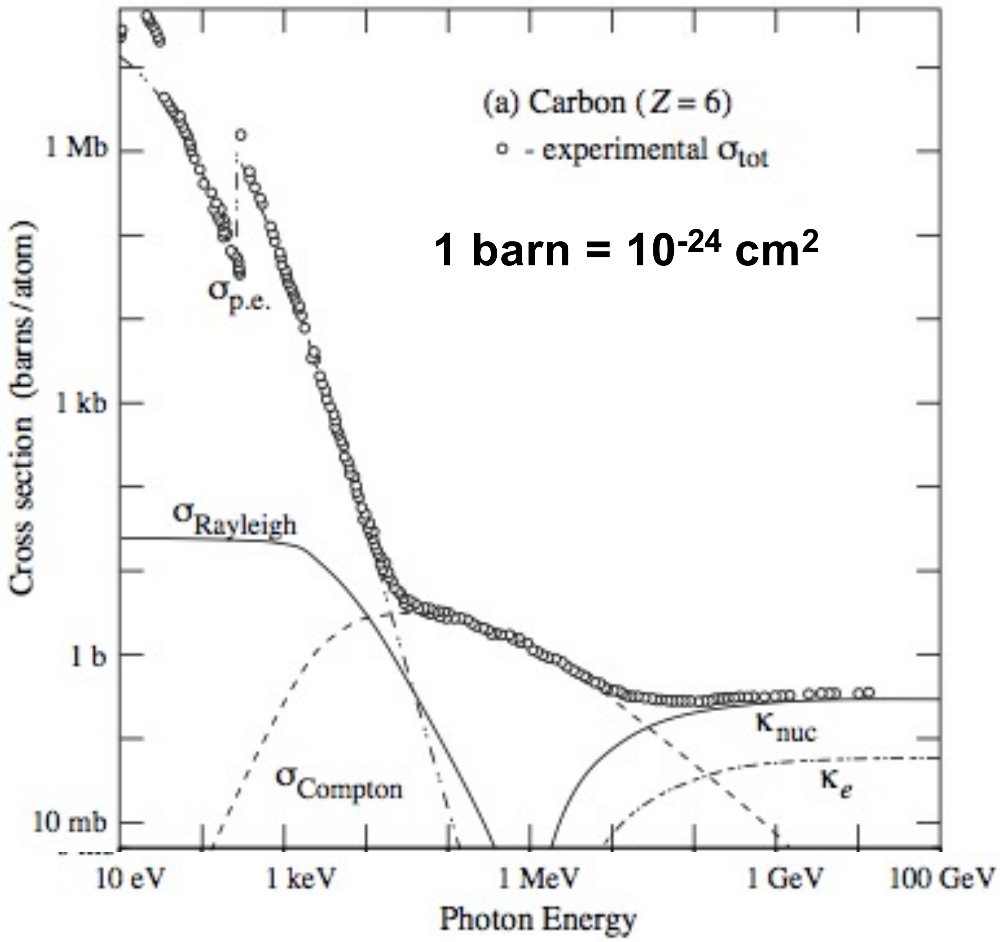
Neutral Current (NC



Flavor-blind

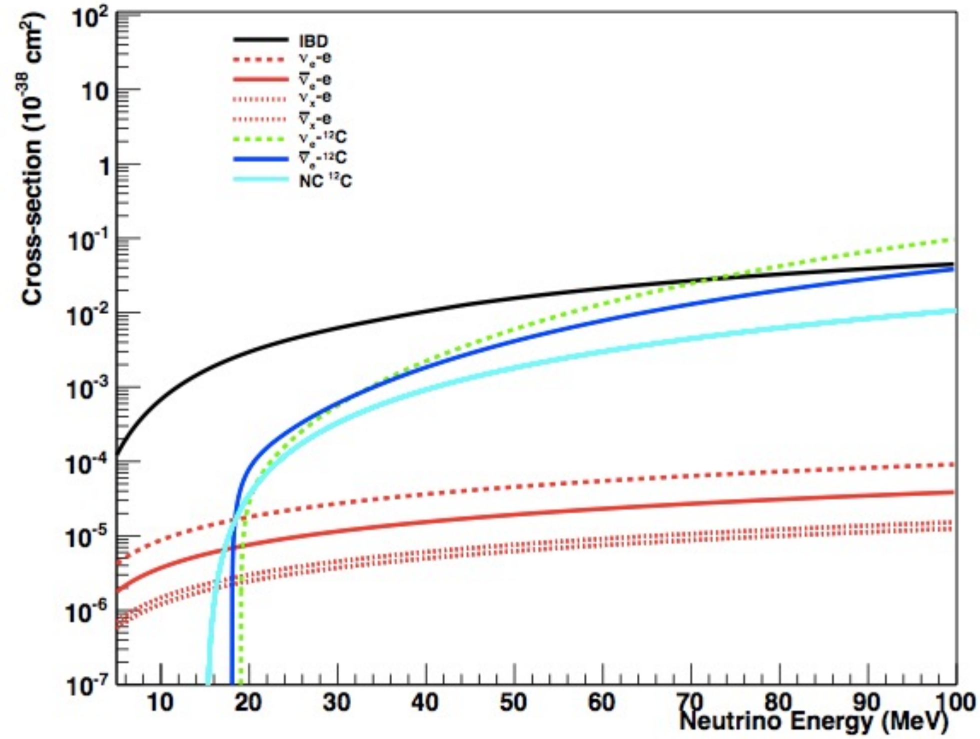
It’s called the weak interaction for a reason

Photon-matter cross-sections



~10^{-24} cm^2

Neutrino-matter cross-sections



~10^{-40} cm^2

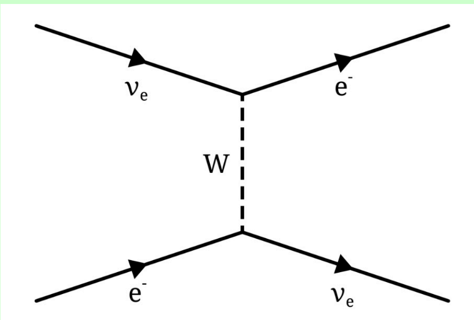
~16-17 orders of magnitude smaller

For astrophysics, the weakness of the interaction is both a blessing and a curse...

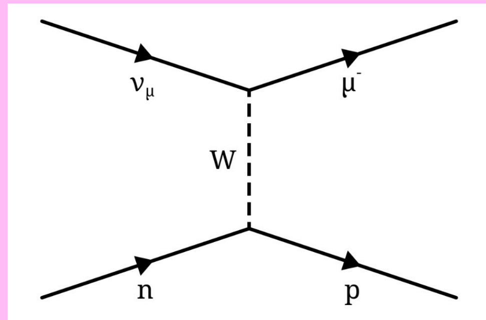
- neutrinos bring information from deep inside objects, from regions where photons are trapped

- but they require heroic efforts to detect!

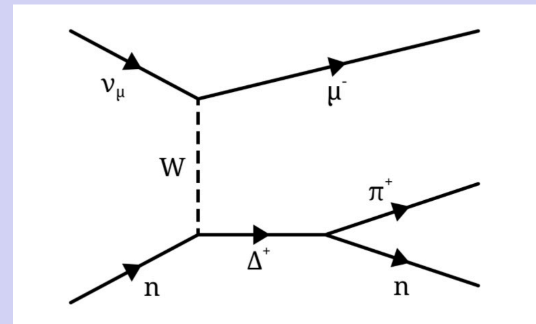
Common nomenclature for neutrino interactions



"Elastic"
same particles in as out



"Quasi-elastic"
different final-state particles but same number of particles

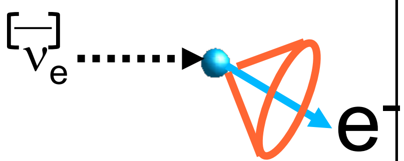


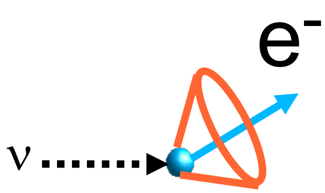
"Inelastic"
energy converted to new particles

Low-energy neutrino interactions

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

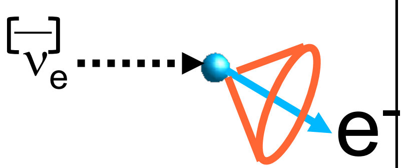
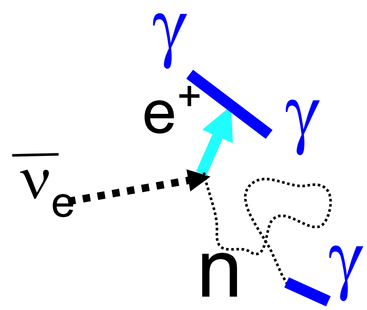
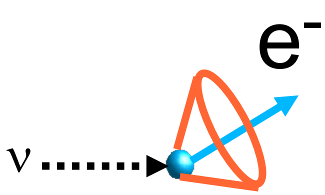
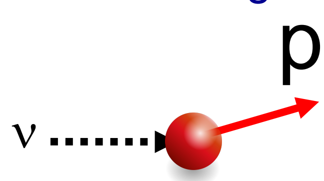
$\nu + e^- \to \nu + e^-$



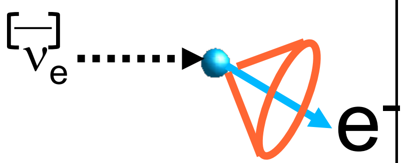
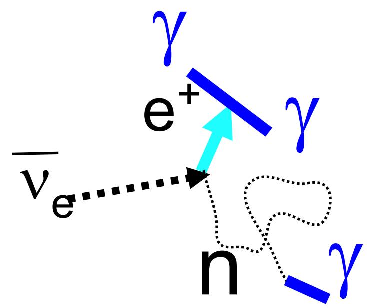
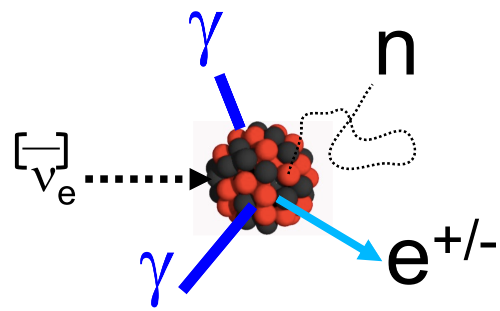
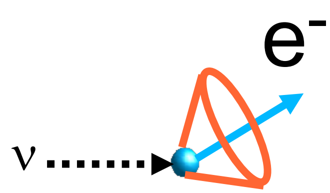
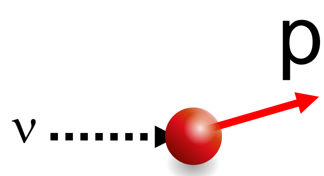
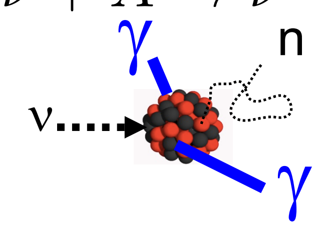
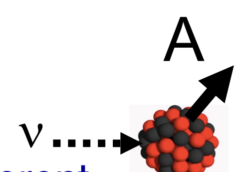


Useful
for pointing</td><td></td><td></td></tr>
<tr><td>Neutral current</td><td></td><td></td></tr>
</table>

Low-energy neutrino interactions

	Electrons	Protons	
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

Low-energy neutrino interactions

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

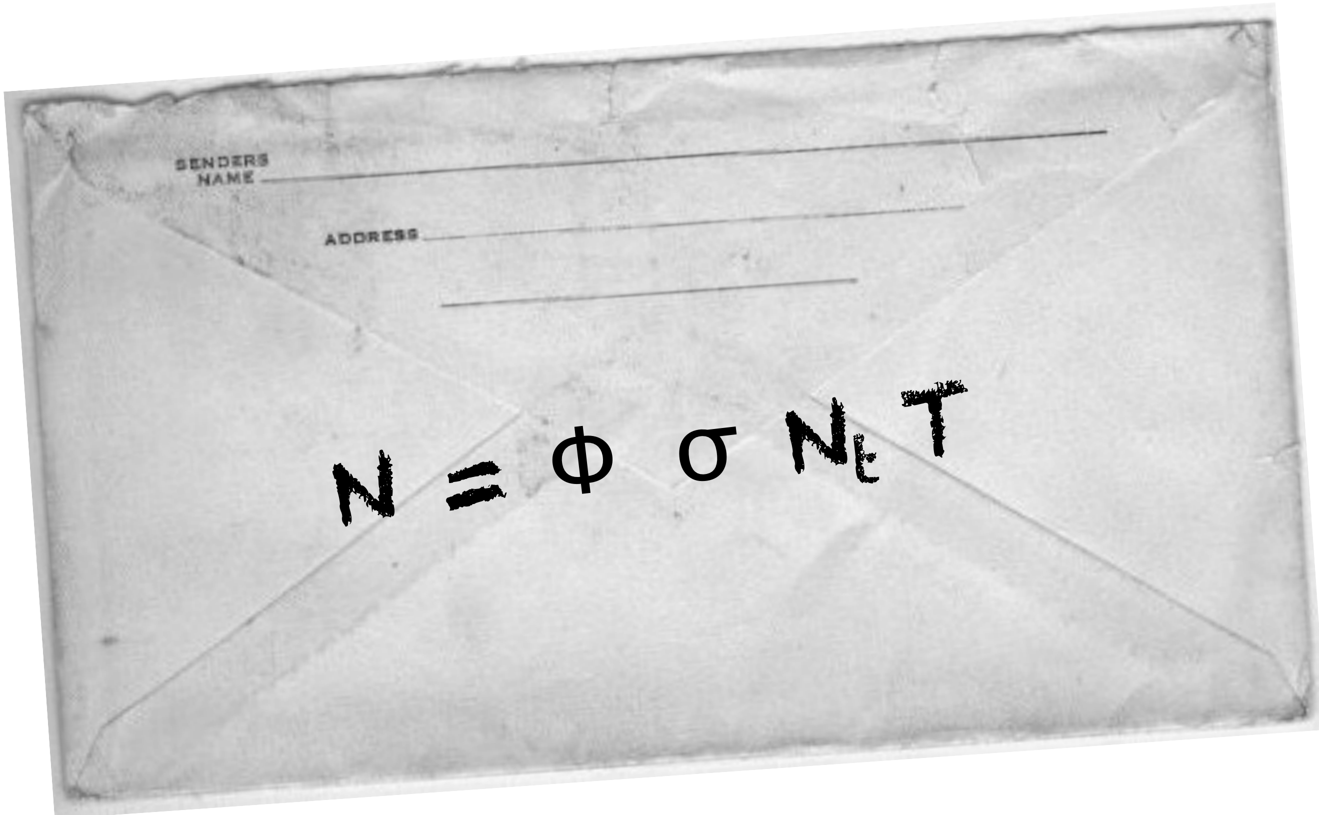
Interaction rates in a detector material

$$R = \overbrace{\boxed{\Phi}}^{\text{Flux}}\ \overbrace{\boxed{\sigma}}^{\text{Cross section}}\ \overbrace{\boxed{N_t}}^{\text{Number of targets}}$$

$$\propto \text{detector mass}, 1/D^2$$

(Note: fluxes, cross-sections are E_ν dependent)

In fact this may be the neutrino experimentalist's most useful back-of-the-envelope expression...



How many solar neutrinos will interact in your body during your lifetime?

$\sigma \sim 5 \times 10^{-44}$ cm^2 (electron scattering cross-section above a few MeV)
$\phi \sim 2 \times 10^6$ cm^{-2}s^{-1} (flux above a few MeV, mostly from ^{8}B neutrinos)

How many solar neutrinos interact in your body during your lifetime?

A. 10^-6

B. 10^-3

C. 10

D. 10^3

E. 10^6

What do we want from a neutrino detector?

depends on the source and the physics:

Geordi La Forge’s special visor that can see neutrinos

What do we want from a neutrino detector?

depends on the source and the physics:

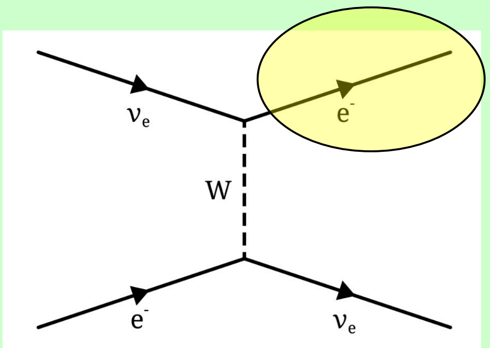
Geordi La Forge's special visor would tell us:

- flavor/CP state [nu vs antinu]
- energy
- direction
- time of interaction
- position of interaction

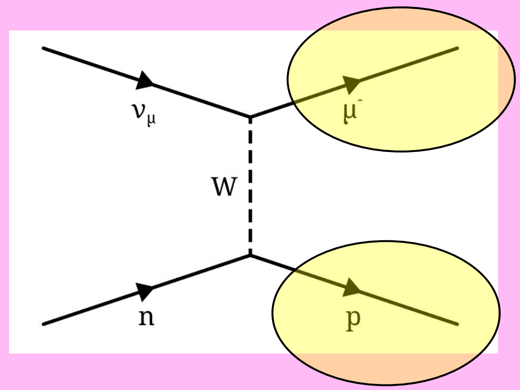
plus pretty much always want:

- high statistics (mass,efficiency)
- low background

What you actually ***detect*** is the
secondary(ies)... (and tertiaries...)
scattered particle, newly created particles,
ejected nuclei, showers...



"Elastic"
same particles in as out



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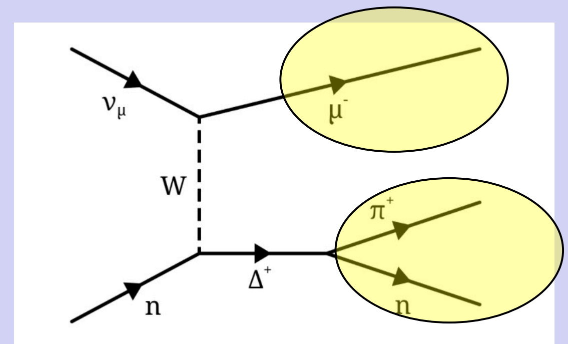


"Inelastic"
energy converted to new particles

Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$
can be categorized as:

A. charged-current elastic

B. charged-current quasi-elastic

C. charged-current inelastic

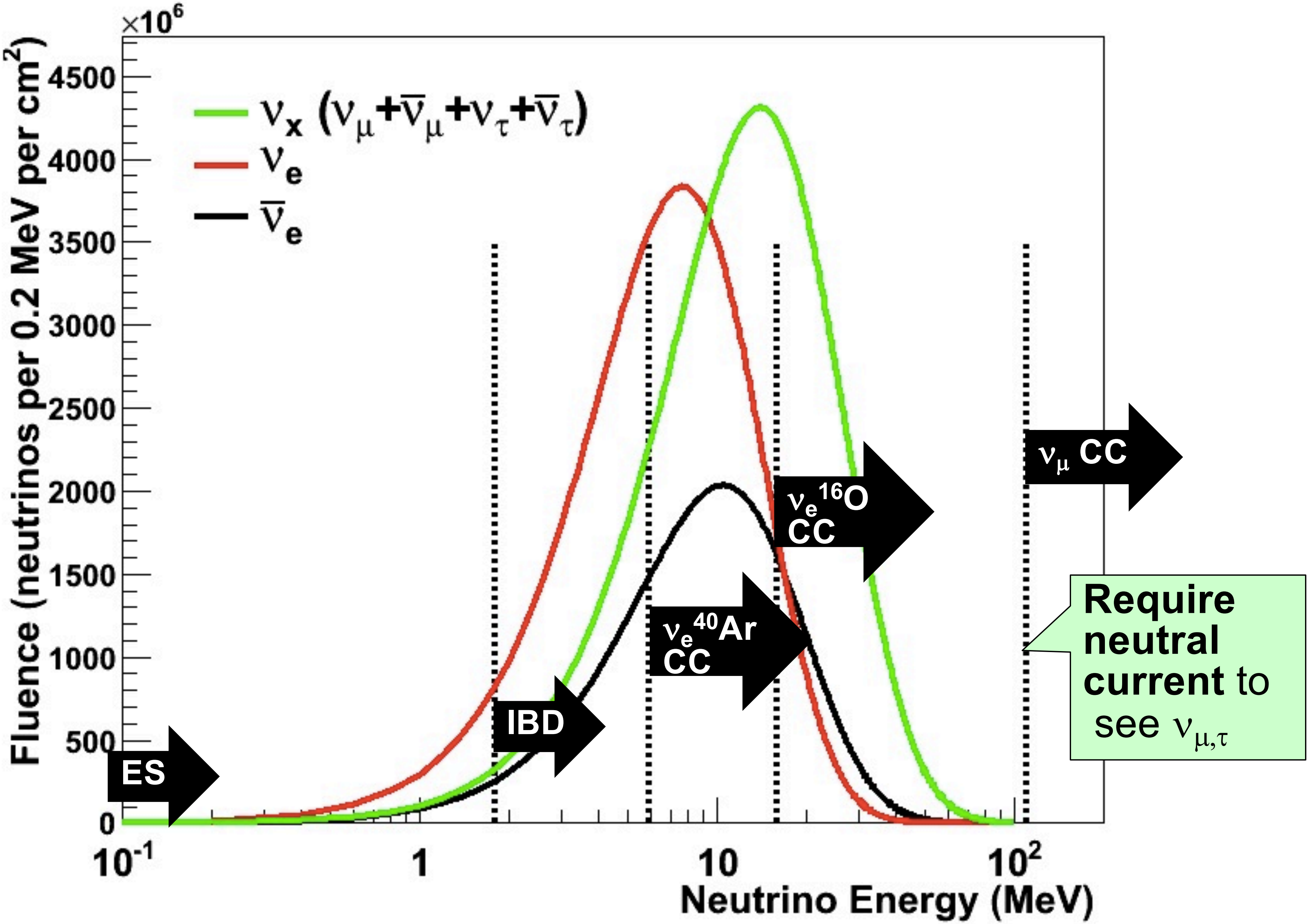
D. neutral-current elastic

E. neutral-current inelastic

Supernova neutrinos range up to about ~50 MeV, and arrive in a burst containing neutrinos and antineutrinos of all flavors

Why are only electron-flavor neutrinos visible via charged-current?

Neutrino interaction thresholds



Event spectrum as a function of observed energy E’, for a realistic detector

$$\text{flux} \otimes \text{xscn} \otimes \text{interaction products} \otimes \text{detector response}$$

$$\frac{dn}{dE'} = N \int_0^\infty \int_0^\infty dE\, d\hat{E}\, \overbrace{\Phi(E)}^{\text{Flux}} \overbrace{\sigma(E)}^{\text{Cross section}} \underbrace{k(E-\hat{E})}_{\text{Interaction products (physics)}} \underbrace{T(\hat{E}) V(\hat{E}-E')}_{\text{Detector response (detector simulation)}}$$

E’: observed energy
k: observed energy for given neutrino energy
T: detector efficiency
V: detector resolution

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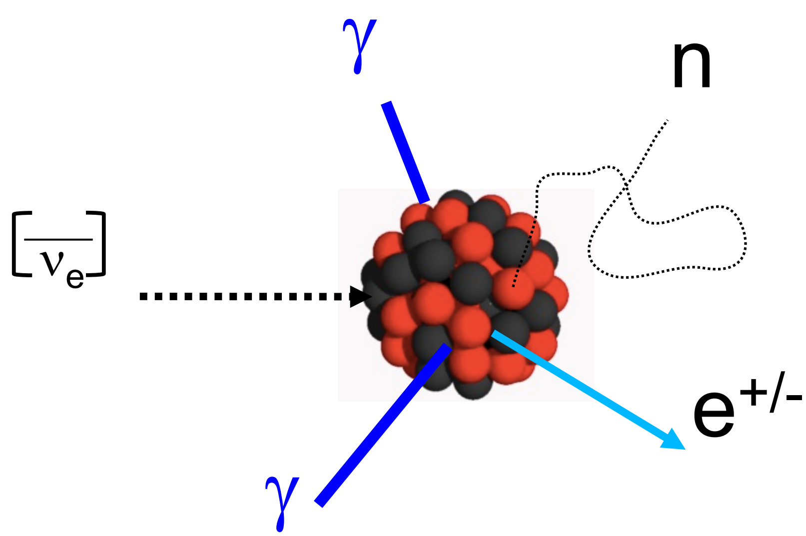
Specific example

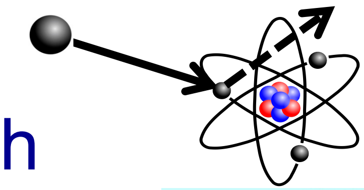
Neutrino detection physics
is actually **physics of electromagnetic-
or strongly-interacting particle detection**

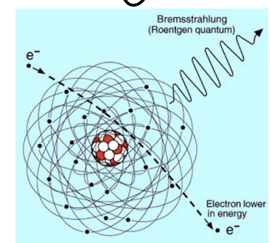


- charged particles
  - "heavy" (μ, π, p, ...)
  - e^+, e^-
- photons
- neutrons

<u>Particle energy loss</u> (most important for ν expts)

- **charged particles**
  - "heavy" (μ, π, p, ...): Bethe-Bloch (ionization)
  - e^+, e^-: collisions + radiation (bremsstrahlung)





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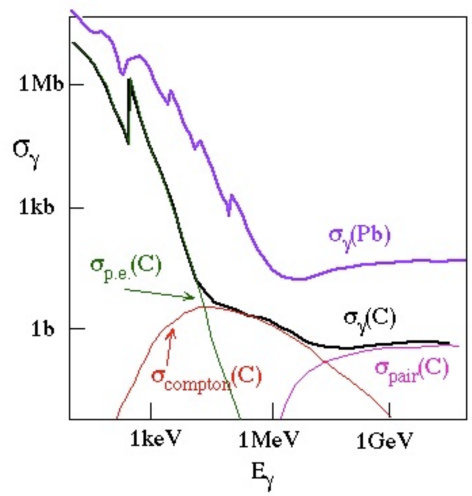
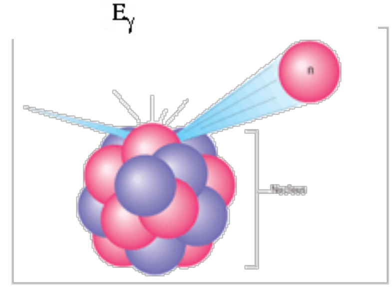
- **photons:** photoelectric + Compton scattering + pair production

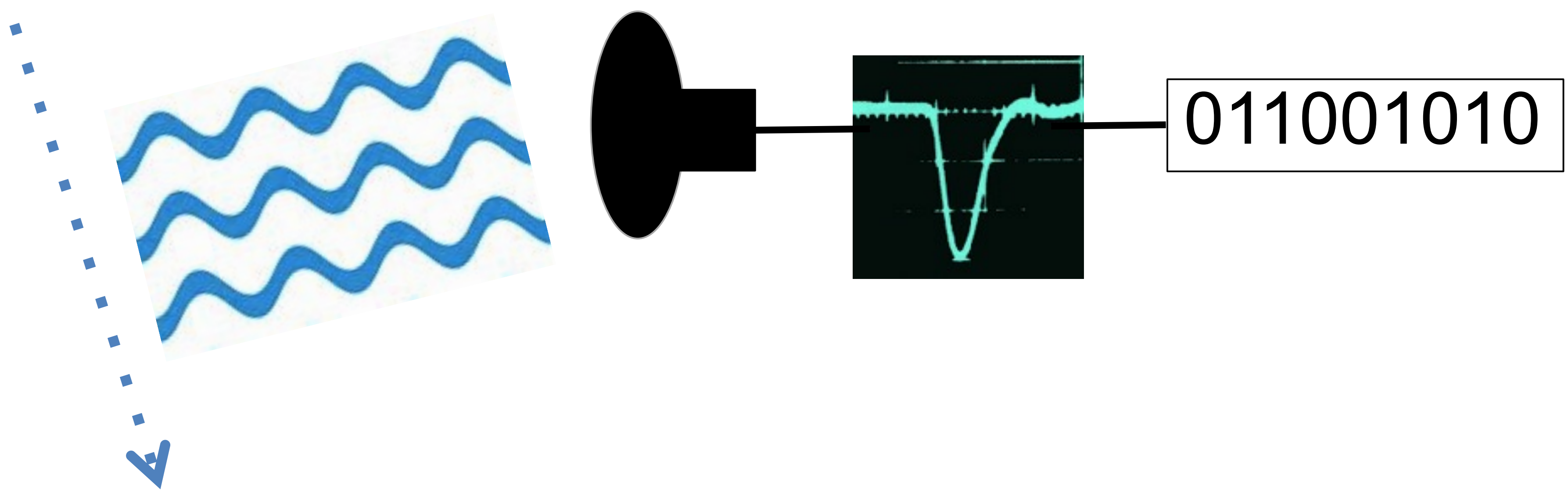


- **neutrons:** elastic scattering (+ radiative capture)



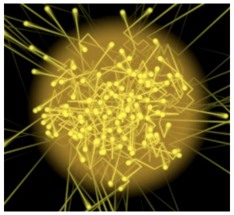
Detecting particles

... energy loss is coupled in some way into an electrical signal, which is digitized, and from which one reconstructs original neutrino information (energy, direction, flavor, position)

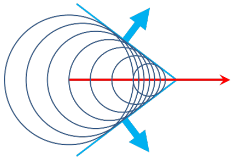


"Classic" ways of gathering deposited energy for neutrino experiments

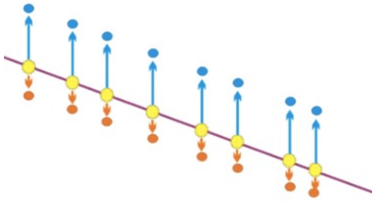
Scintillation light + photosensors



Cherenkov light + photosensors



Direct collection of ionization with electric field



Heat, phonons (low energy signals)

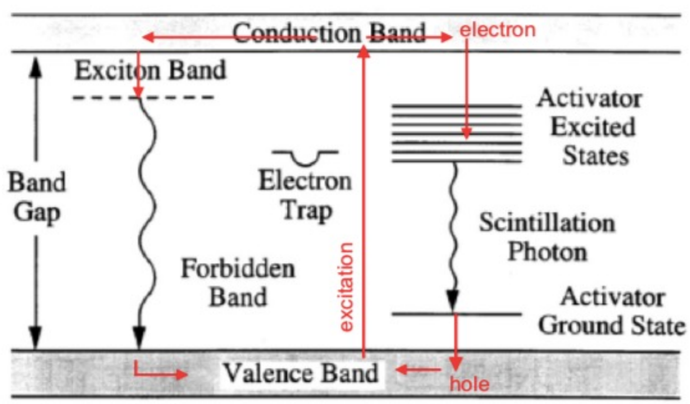
- Specific techniques vary by energy range and physics requirements
- Often more than one technique employed in a given detector

Scintillation for charged particle detection

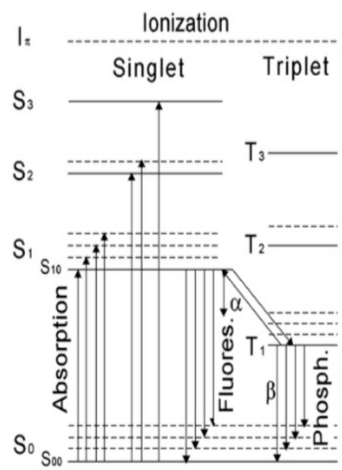
Particle energy loss excites energy levels in a material; photons (optical/UV) subsequently emitted at deexcitation

- No. of photons $\propto$ energy loss
- Isotropic emission

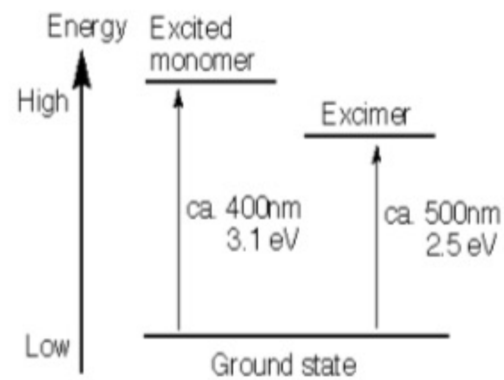
...somewhat different mechanisms for different types of scintillator



inorganic
(semiconductor, crystals)

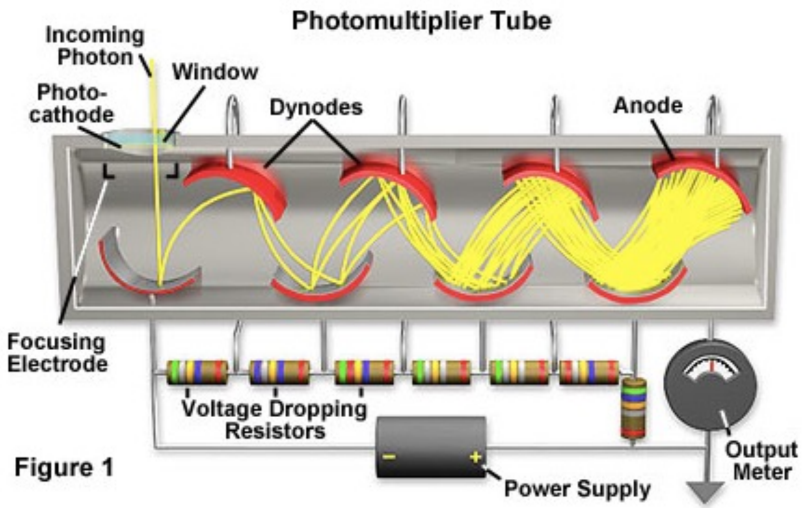


organic
(hydro carbons, liquid or solid)



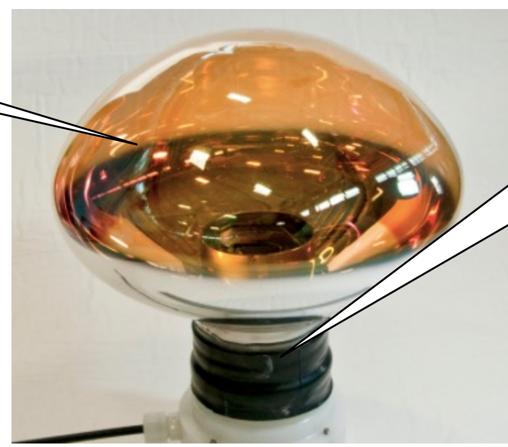
noble element
(liquid or gas)

In most cases, single photons are amplified into observable pulses by **photomultiplier tubes** (PMTs)



general concept
(...other ways to amplify
... SiPMs,
LAPPDs etc.)

photocathode

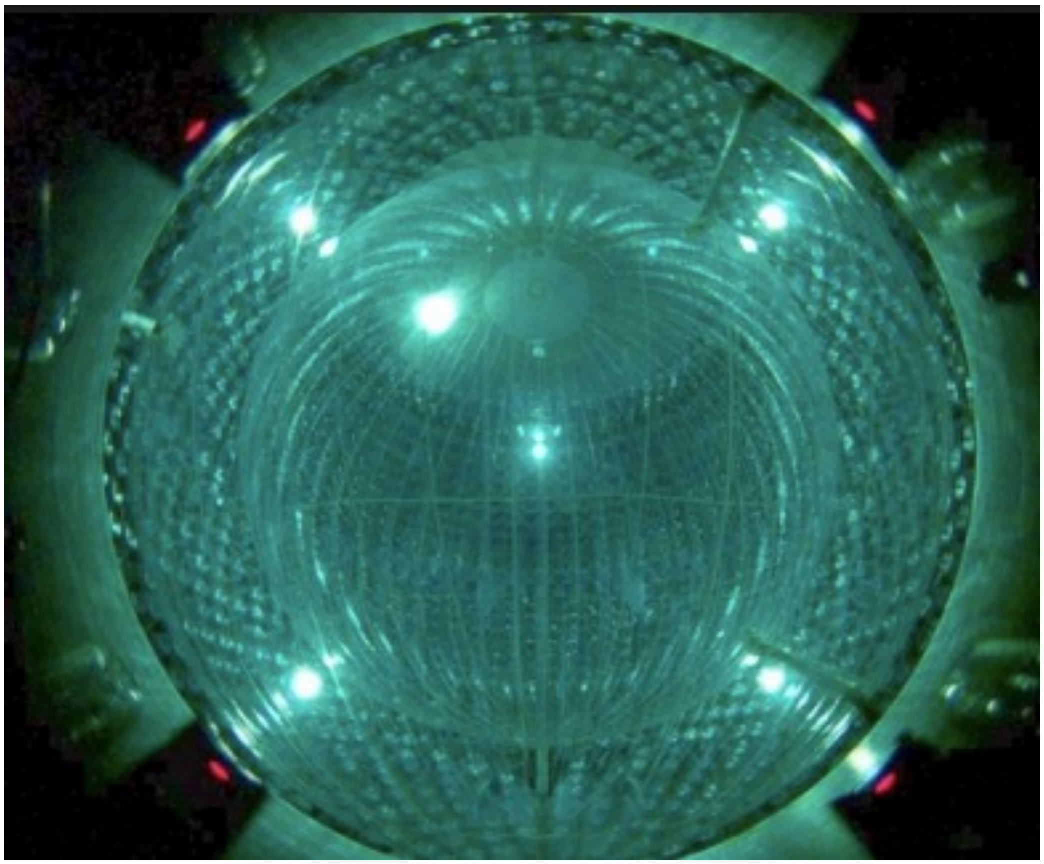


dynode chain

Common design for neutrino experiments maximizes photocoverage

Note: photodetector improvement is an area of active R&D

Many neutrino experiments need to be large, and hence, made of relatively inexpensive material



- most common is liquid hydrocarbon, ~C_nH_{2n}
- often in form of homogeneous volume viewed by PMTs, but can also be segmented
- large light yield

[Also: noble liquids scintillate]

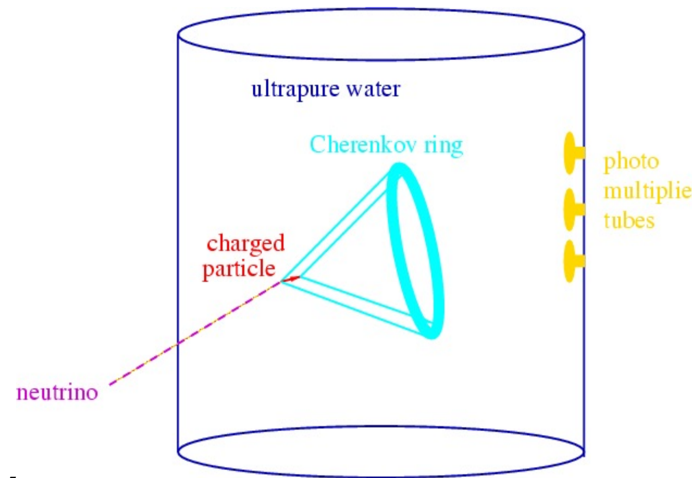
Cherenkov Radiation

Charged particles emit Cherenkov radiation in a medium 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



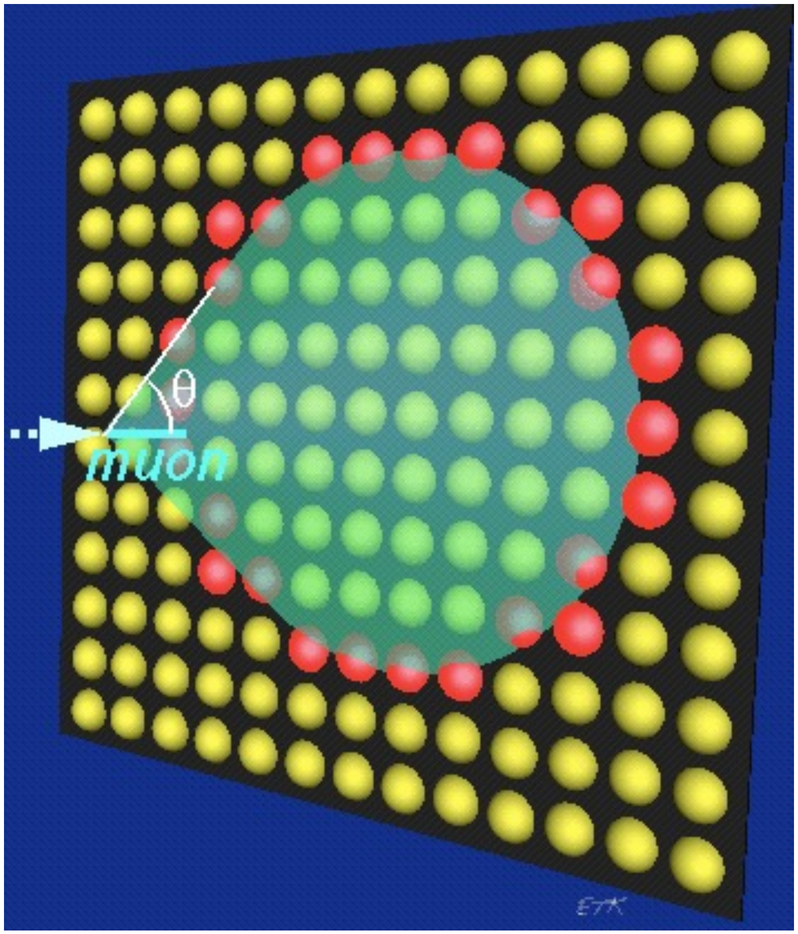
Thresholds (MeV)

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

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

Photomultiplier tubes (PMTs) detect single photons



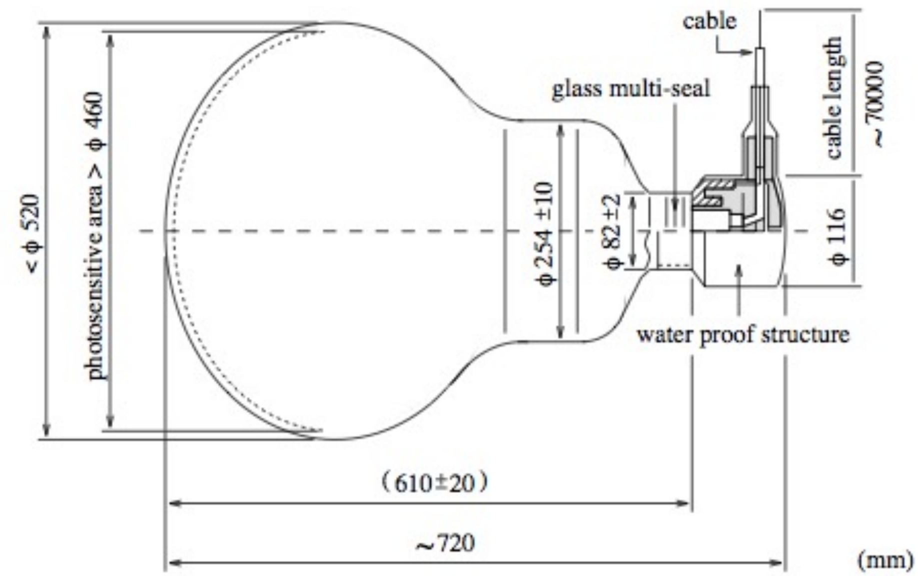
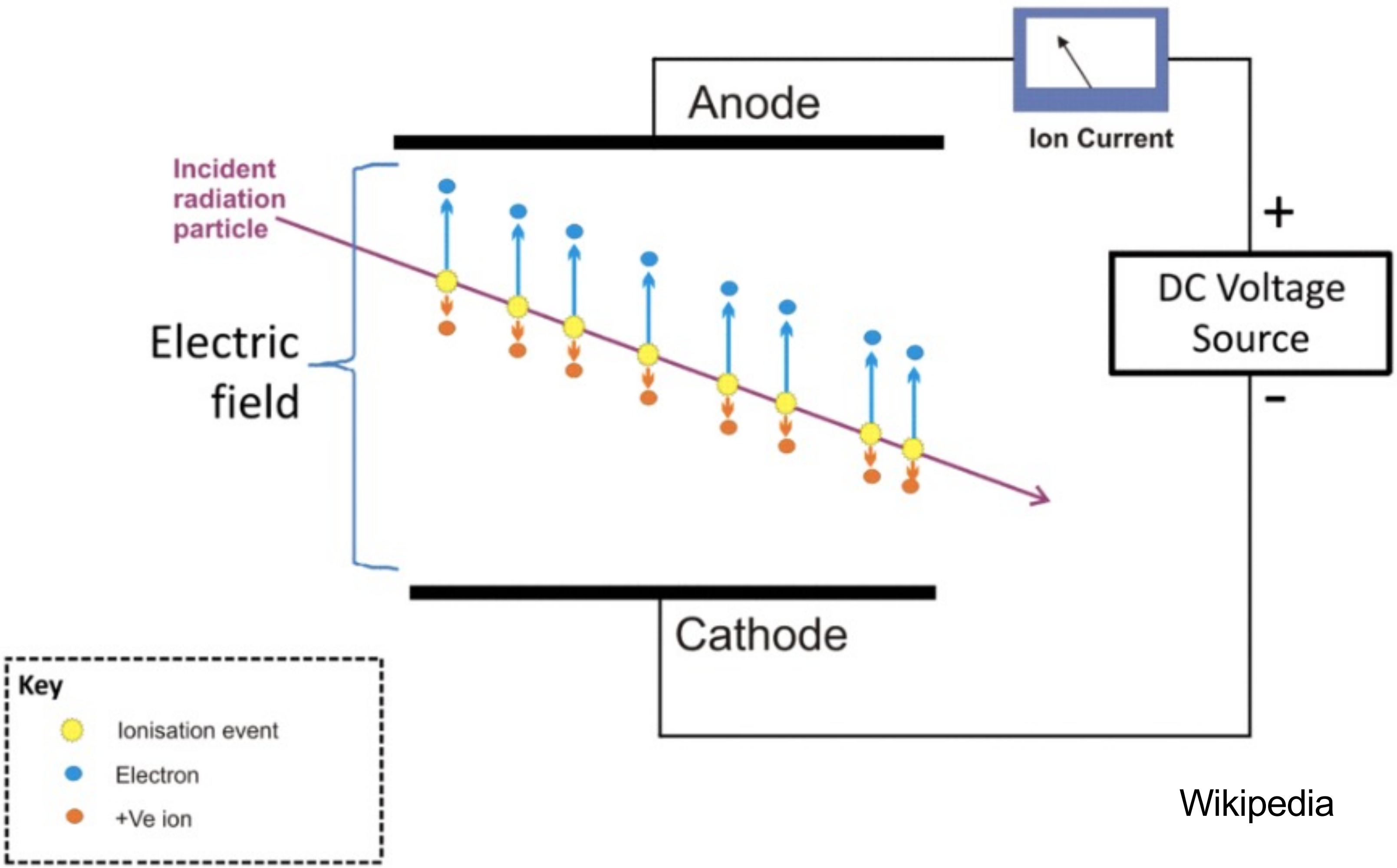


Fig. 7. Schematic view of a 50 cm PMT.

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

Ionization charge collection

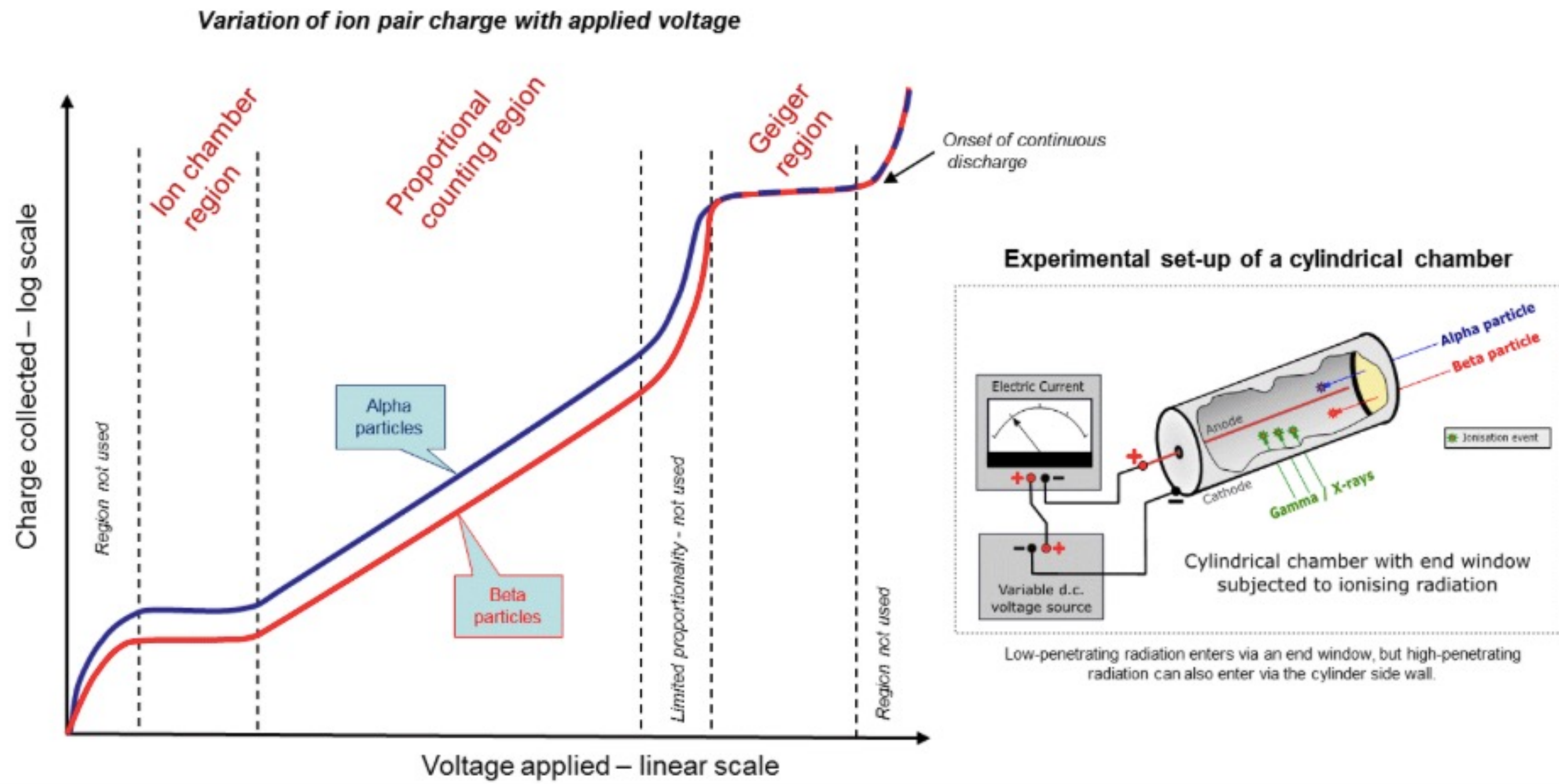
Basic concept: apply an electric field and gather charge*
to form an observable pulse



Wikipedia

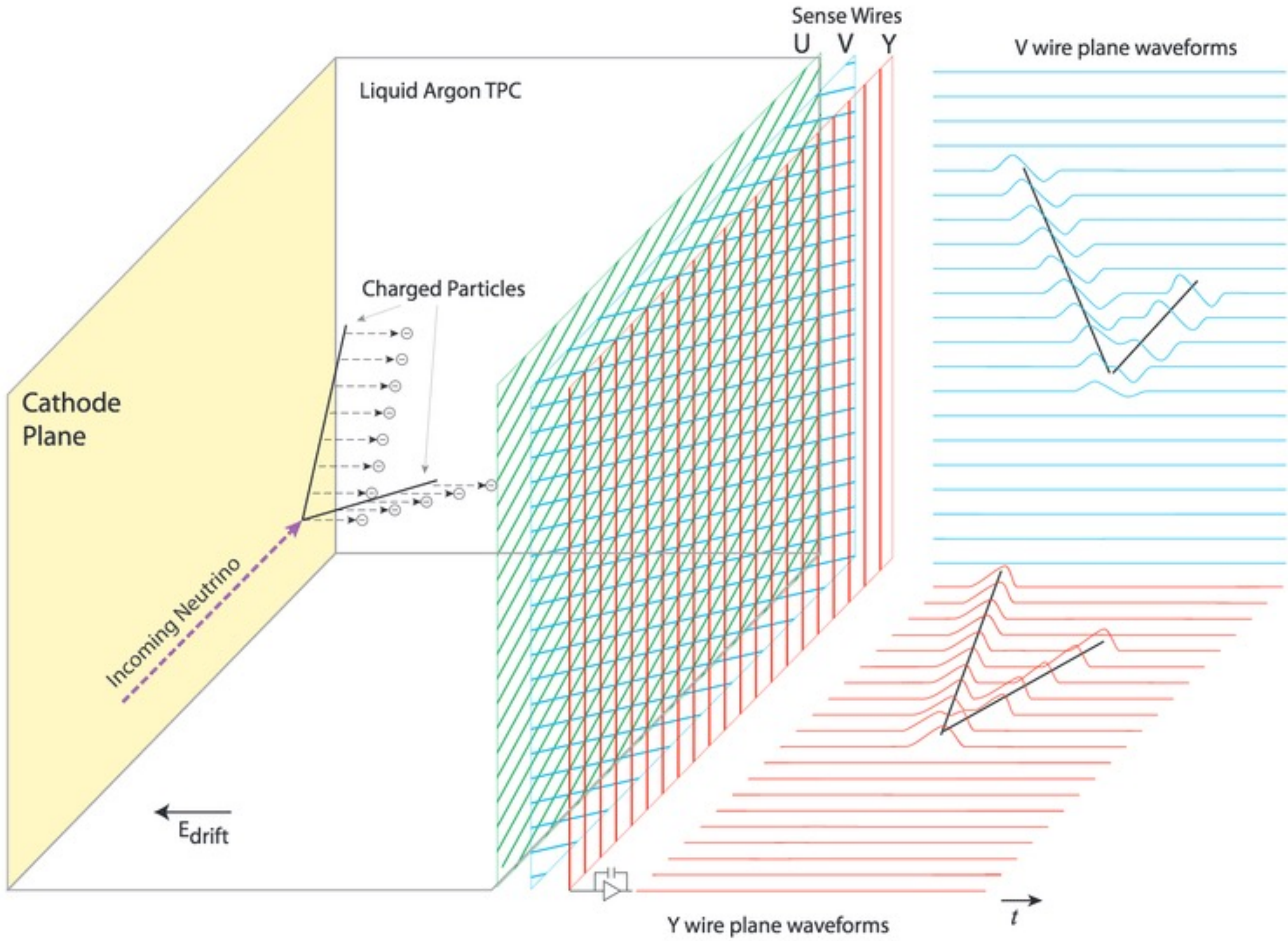
*generally electron charge, since electrons
are more mobile than ions

Technique used for wire chambers which can be arranged as fine-grained trackers



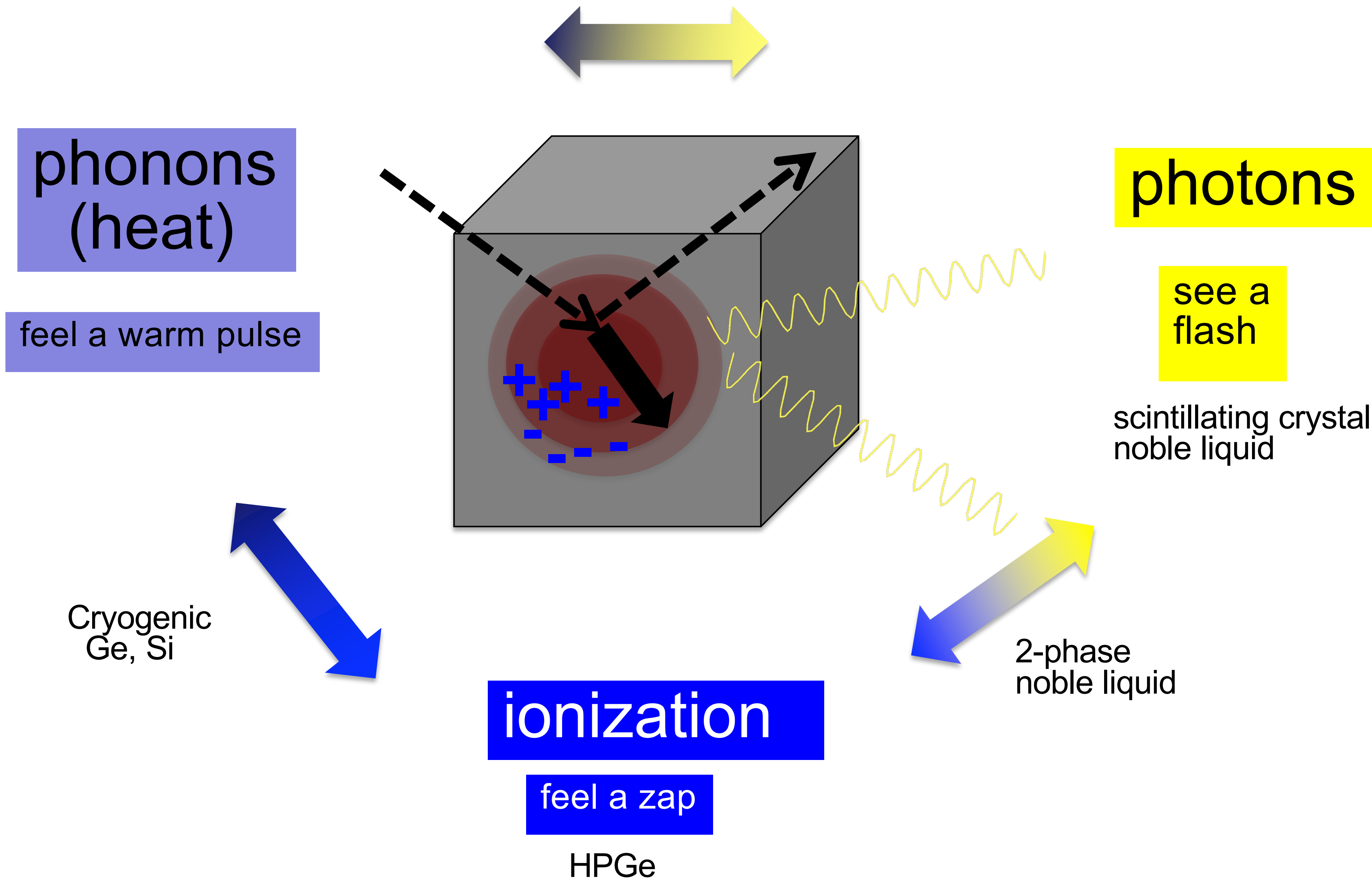
...used in a great variety of configurations, but not so much for very large detectors...

Time projection chambers



Get **3D** charged-particle track reconstruction

Low-energy nuclear recoil detection strategies



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

Backgrounds

Same energy loss processes as the signal!

Radiologicals

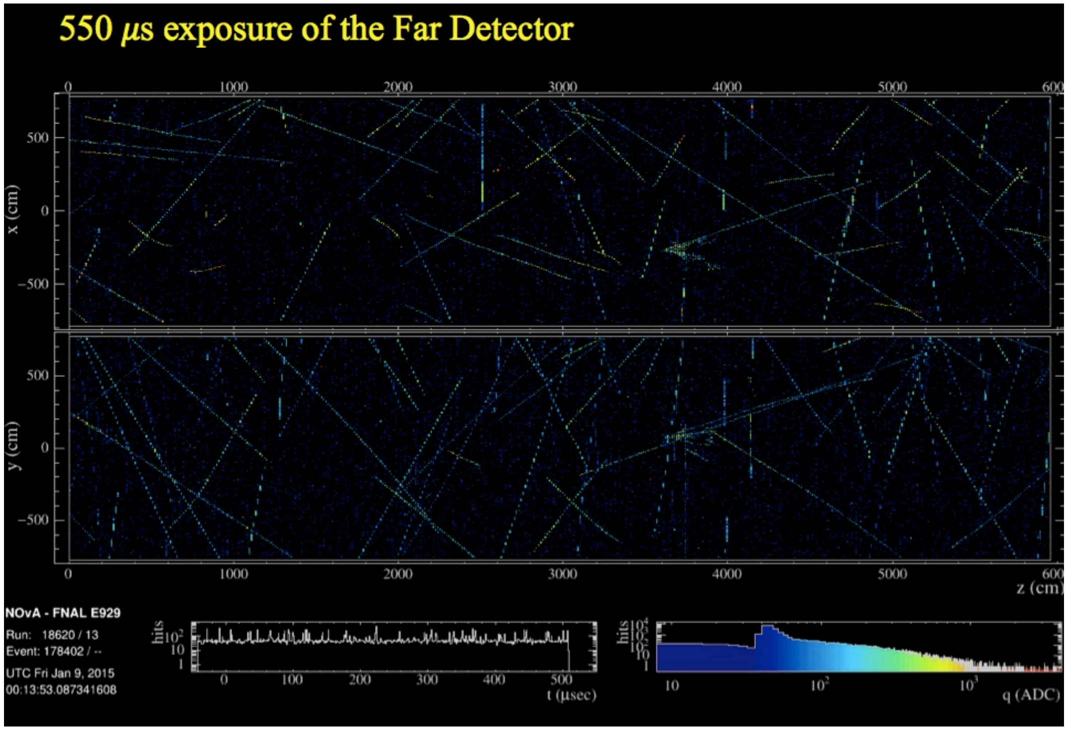
- alpha, beta, gamma, fission
- intrinsic to your detector, or ambient

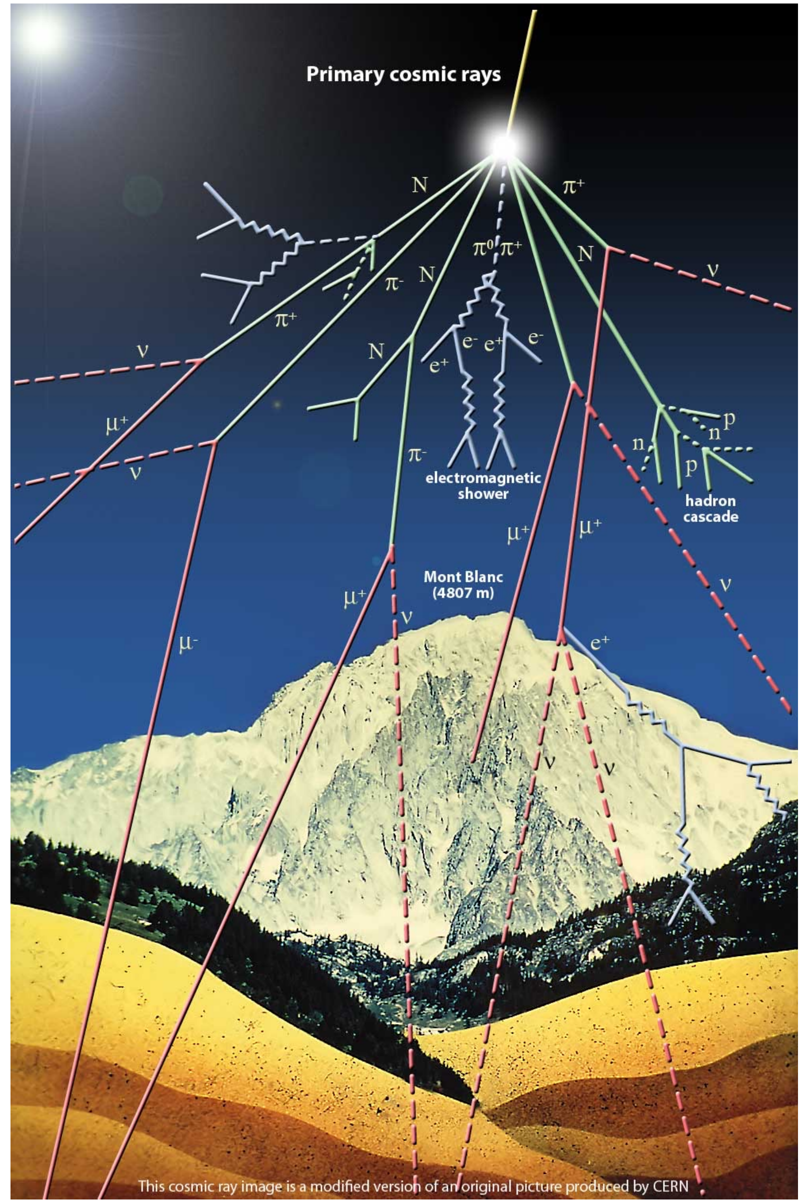
Cosmic rays and cosmogenics

- 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

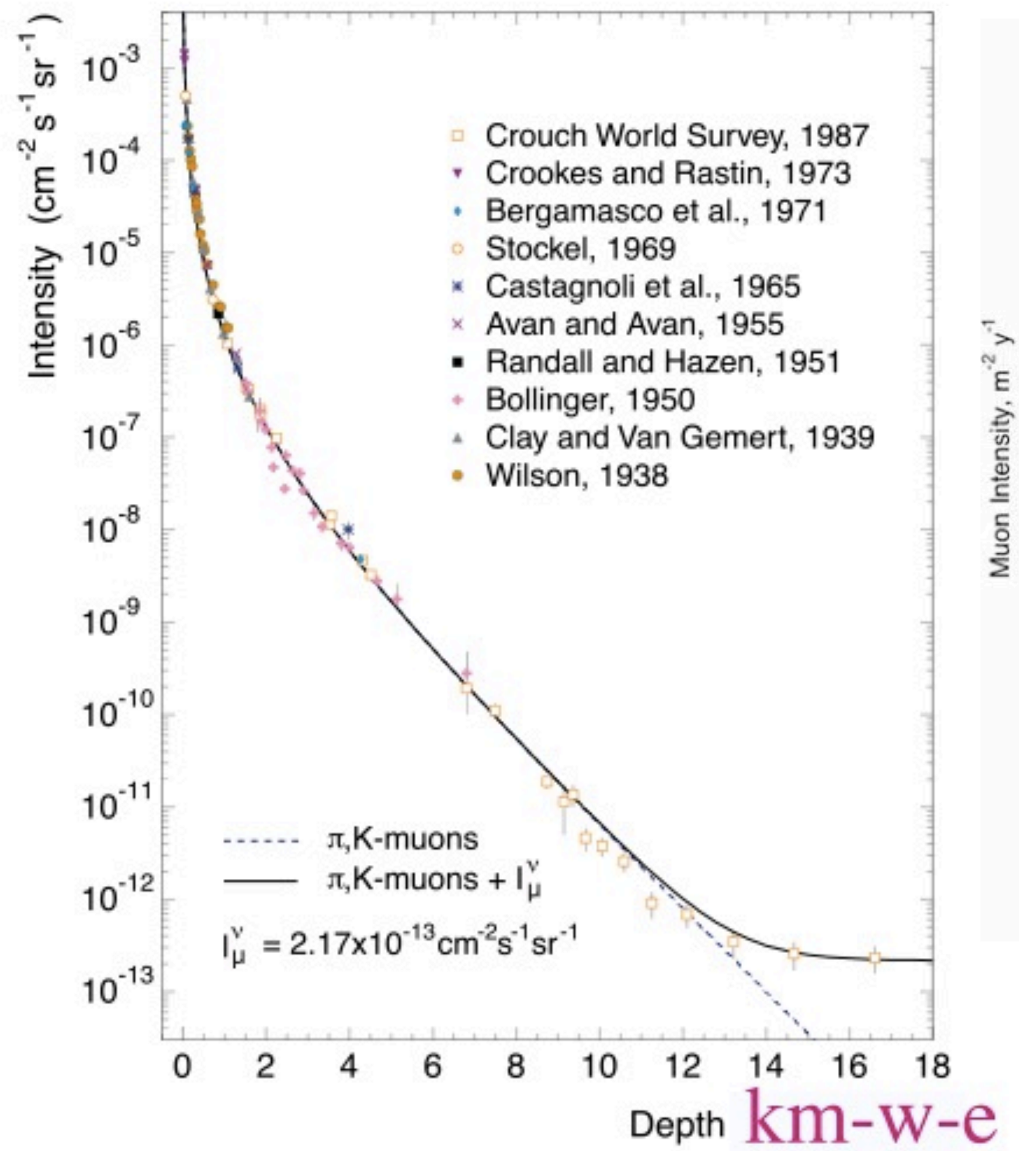
"duty factor": pulse rate * pulse width
(fraction of time beam is on = rejection factor for CR bg)

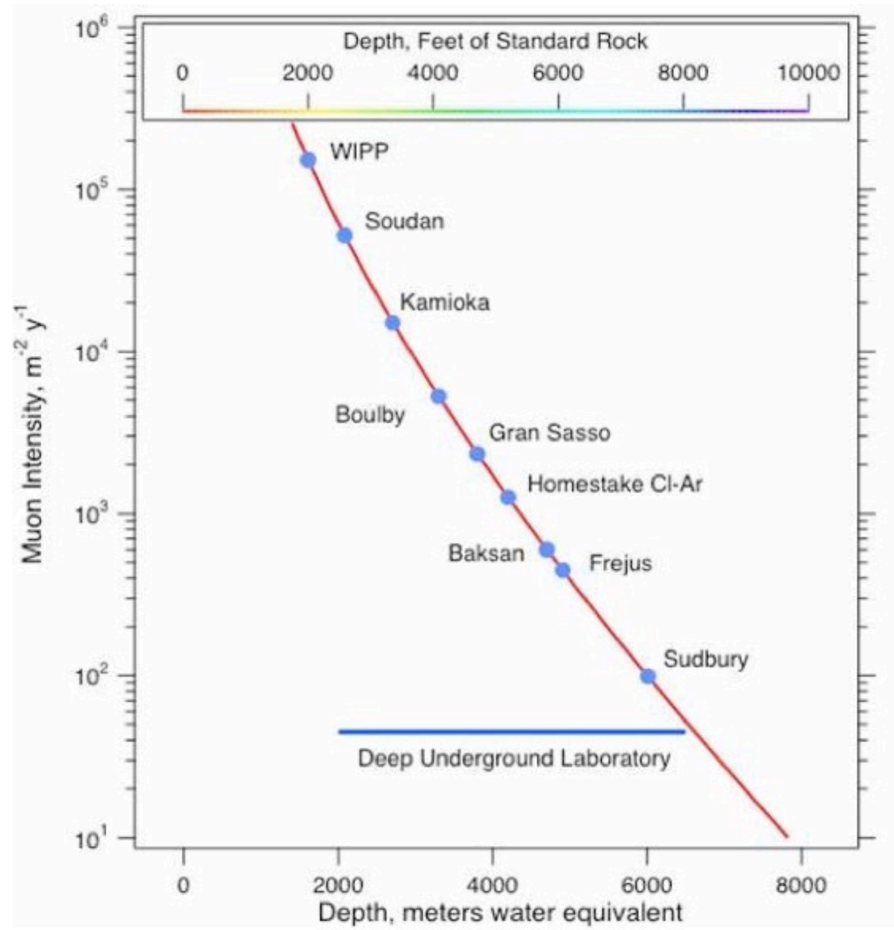
The weather is always fine underground

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)

How many muons per sec through your hand on the surface of the Earth?

A. 10^5

B. 1

C. 10^{-5}

How many muons per sec through Super-K (40 m high, 17 m radius) at ~2300 mwe?

A. 10^5

B. 1

C. 10^{-5}

Take-away points so far

- Neutrino sources:
  - natural and artificial sources over many orders of magnitude in energy

- Neutrino interactions:
  - CC, NC; elastic, QE, inelastic
  - How to calculate neutrino event rates $R = \Phi \; \sigma \; N_t$

- Neutrino detection:
  - Neutrinos are observed via secondaries/tertiaries
  - Particle energy loss
    - 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)
  - Many techniques in use for neutrinos:
    - scintillation, Cherenkov, ionization, phonons/heat
  - In practice, it's all about the backgrounds!

Outline of Lecture Topics

General overview

Specific example

- Neutrino sources
- Neutrino interactions with matter
- Particle detection techniques

- Physics with neutrinos in the ~1-100 MeV range
- Physics with stopped-pion neutrino sources

- Physics in Neutrino Alley at the Spallation Neutron Source
- The COHERENT Experiment
- Future prospects

~Mon

~Tue

~Thu