# Neutrino Experiment

2nd JENNIFER Summer School 2018
ICTP, Trieste

# Outline

Day 1: Detecting Neutrinos: the physics of detectors

Day 2: Principles behind different commonly used detectors

Day 3: Current neutrino experiments

# Outline

Day 1: Detecting Neutrinos: the physics of detectors

Day 2: Principles behind different commonly used detectors

Day 3: Current neutrino experiments

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Note: lecture can be flexible, especially for Day 3.

Please send me experiments or topics you might want to hear about -- especially if there are neutrino-related topics you might be interested to work on in graduate school

Provide questions/feedback at: https://tinyurl.com/jen2-nu-exp
Can leave your name or be anonymous

# My Goal

- Introduce you to the concepts that will allow you to evaluate neutrino experiment designs -- or design one yourself
- First hour each day will be introduction to concepts
- The last half hour -- break into groups and try a short activity
  - Day 1: given a physics topic, what is the signal (and backgrounds for detecting it), what is the appropriate detector type(s) and why?
  - Day 2: define how we can measure the signal from background
  - Day 3: estimate how well certain aspects of our experimental design has to perform to reach a given sensitivity
- Lot’s to cover on day 1,  however, so maybe start activity at beginning of day 2
- The point of the activities isn’t necessarily to get the right answer, but to provide a chance to apply the concepts and foster discussion (in the time allowed)

# Activity Example

- One the main experiments I work on: MicroBooNE
- **Physics**: investigate past anomalies which can be interpreted as signs of a new non-standard model neutrino
- **Signal (after day 1)**: measurement of an anomalous excess of electron neutrinos appearing in a beam of muon neutrinos. This means I have to find *electrons* in my detector coming from neutrino interactions. Use charge pattern to find electrons.
- **Background (after day 1)**: neutrino interactions that make photons which mimic electron neutrino events
- **Detector (after day 2)**: liquid argon TPC -- takes high-resolution pictures of showers which we can use to tell electrons from photons
- **Quantitative Exercise (after day 3)**: based on the number of electron neutrinos inherent in the beam, what's the efficiency I need to select electron neutrinos and reject NC using simple counting experiment statistics (Prof. Cowan will give you the stats. tools needed)

# Activity

- Don’t be afraid to impart your own background knowledge or apply some creativity -- maybe you’ll create a new experiment!
- For the quantification portion, might need to take some time in the evening to look up background information for estimates
- I am also preparing some tools to estimate rates where one can play around with cuts
- End of day 2 will cover those tools

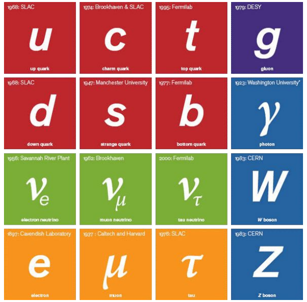
Day 1

# Detecting Neutrinos

# Why detect Neutrinos?

There is a lot we can learn about neutrinos themselves and through-them

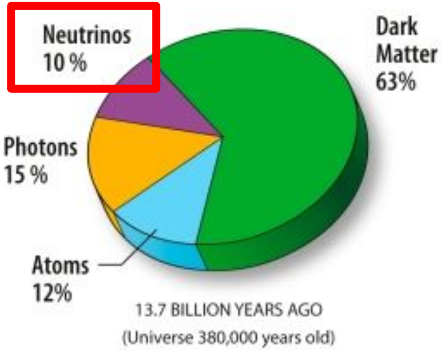
- How many are there really?
- How do they get their small mass?
- What is the value of the mass?




+ ??

Neutrinos provide an avenue to look for beyond-Standard Model neutrinos

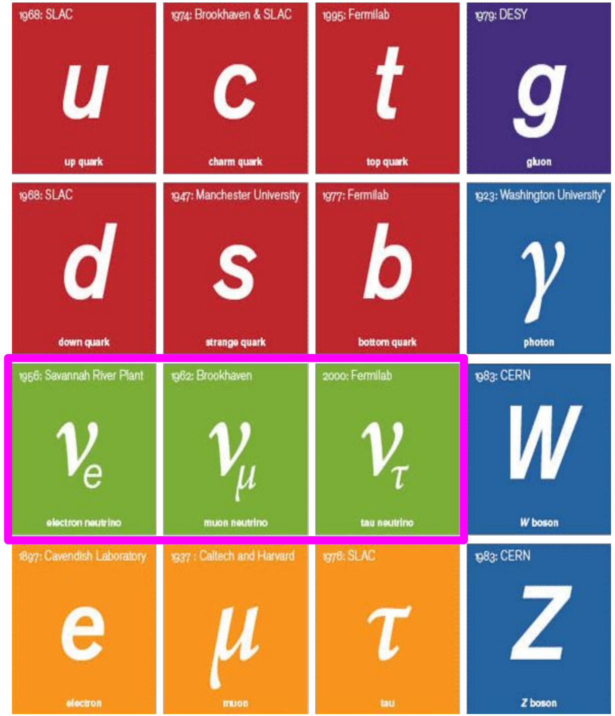
They are highly abundant in the universe and so play a role in the evolution of the universe -- exciting interplay between particle physics, cosmology, and astrophysics




Credit: NASA/WMAP

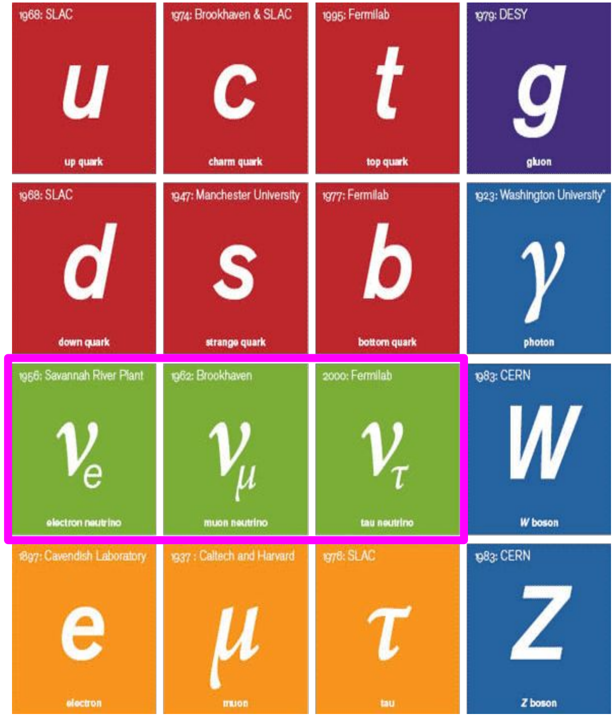
More details from Prof. Sala and Prof. Grossman

# What do we know about them?




- There are three “flavors”
- There have a very small, but non-zero mass
- The interact only via gravity and the weak interaction
- They have no electric charge

# What do we know about them?




- There are three “flavors”
- There have a very small, but non-zero mass
- The interact only via gravity and the **weak interaction**
- They have **no electric charge**

**These last two properties make observing neutrinos very challenging**
**-- but the physics makes it worth it!**

# Facts of life for the neutrino experimenter...

*Numerical example for typical accelerator-based experiment*

$$N_{\rm obs} = \left[\int \mathcal{F}(E_\nu)\sigma(E_\nu,\ldots)\epsilon(E_\nu,\ldots)dE_\nu d\ldots\right]\frac{M}{A\,m_N}T$$

| | | |
|---|---|---|
| $N_{obs}$ | : | number of neutrino events recorded |
| $\mathcal{F}$ | : | Flux of neutrinos ($\#/\mathrm{cm}^2/\mathrm{s}$) |
| $\sigma$ | : | neutrino cross section per nucleon $\simeq 0.7\frac{E_\nu}{[\mathrm{GeV}]}\times 10^{-38}\mathrm{cm}^2$ |
| $\epsilon$ | : | detection efficiency |
| $M$ | : | total detector mass |
| $A$ | : | effective atomic number of detector |
| $m_N$ | : | nucleon mass |
| $T$ | : | exposure time |

*typical "super-beam" flux at 1000 km*

*typical accelerator up time in one year*

$$N_{\rm obs} = \left[\frac{1}{\mathrm{cm}^2\mathrm{s}}\right]\left[0.7\times 10^{-38}\frac{E_\nu}{\mathrm{GeV}}\mathrm{cm}^2\right][\epsilon]\,[1\ \mathrm{GeV}]\left[\frac{M}{20\cdot 1.67\times 10^{-27}\ \mathrm{kg}}\right][2\times 10^7\ \mathrm{s}]$$

$$N_{\rm obs} = 4\times 10^{-6}\frac{E_\nu}{[\mathrm{GeV}]}\epsilon\frac{M}{\mathrm{kg}}$$

*need detector masses of $10^6$ kg = 1 kton to get in the game*

*work at high energies if you can*

*push this as high as you can*

*Challenge to the experimentalist: maximize efficiency and detector mass while minimizing cost*

Slide from M. Messier 2017 INSS

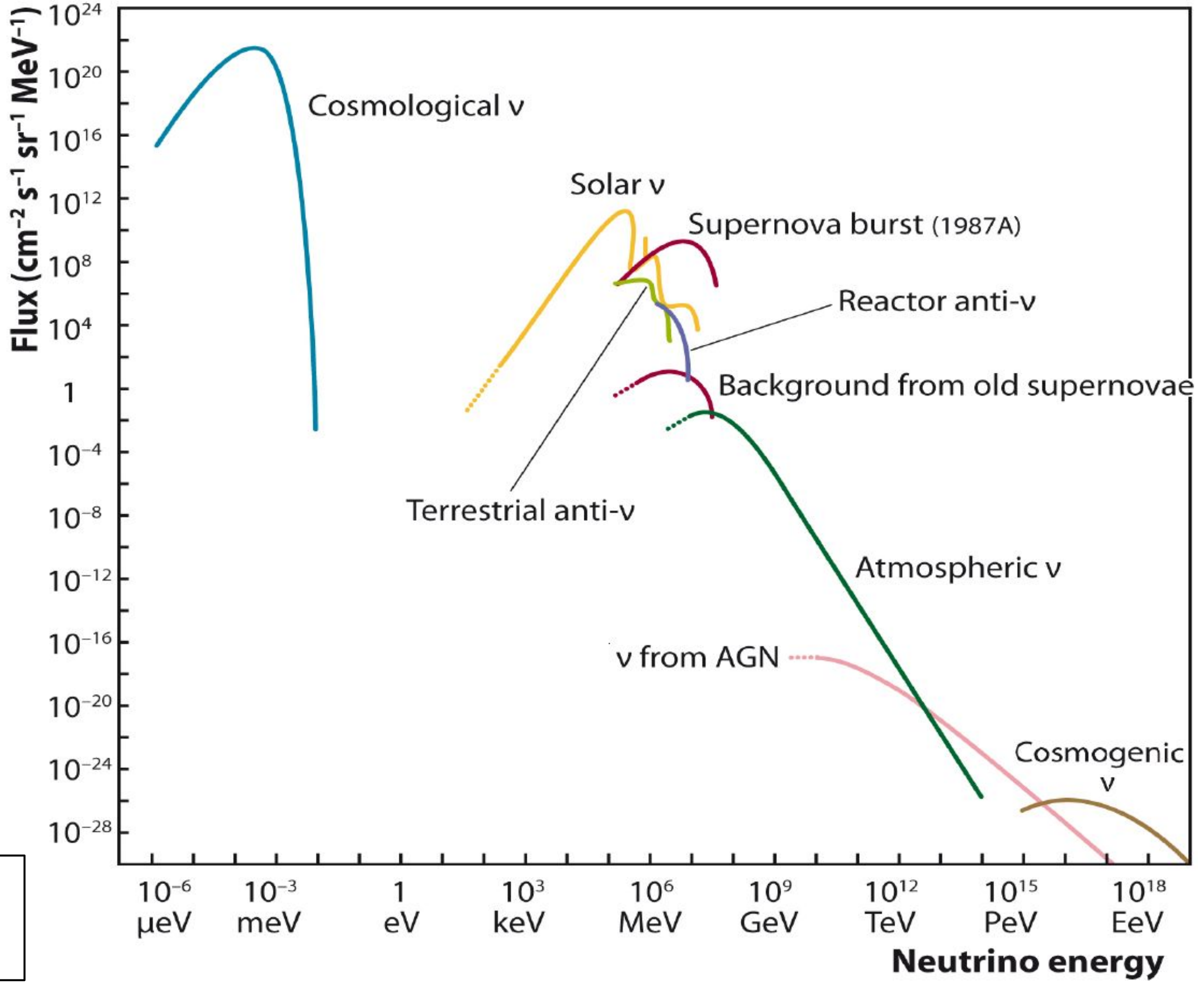


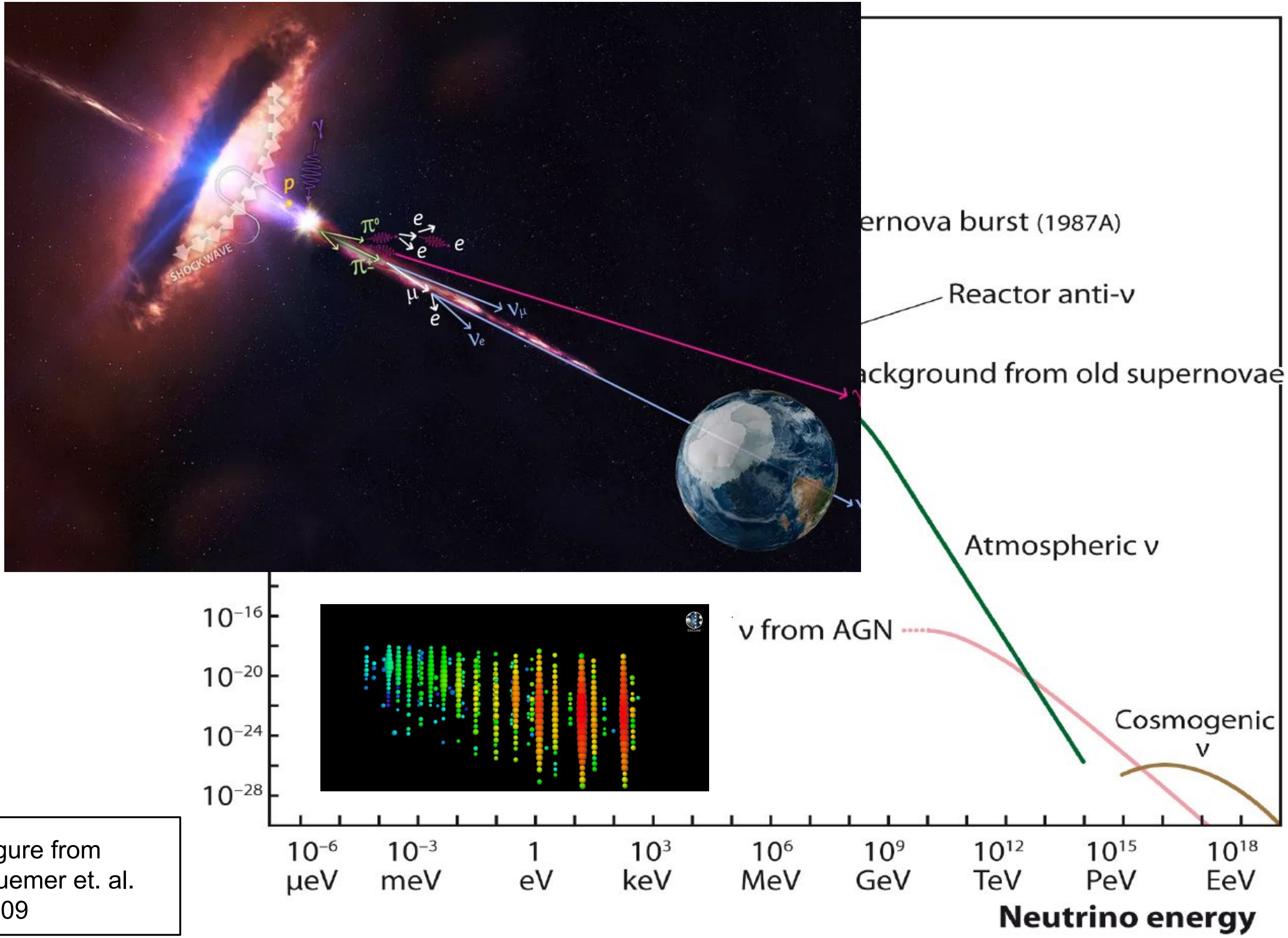

Figure from Bluemer et. al. 2009

But we still have options to make it work:

Neutrinos come from a wide array of sources at different energies and intensities

Trade off between intense sources and detector size

For activities, pay attention to energy ranges from sources




We've observed almost all of these!

A candidate neutrino from a blazer seen by the Ice Cube experiment just a few weeks ago

Saw coincidence of neutrino and increase EM from same source

Figure from Bluemer et. al. 2009

Aside 2: if you figure out how to observe and measure these, that would be a big deal

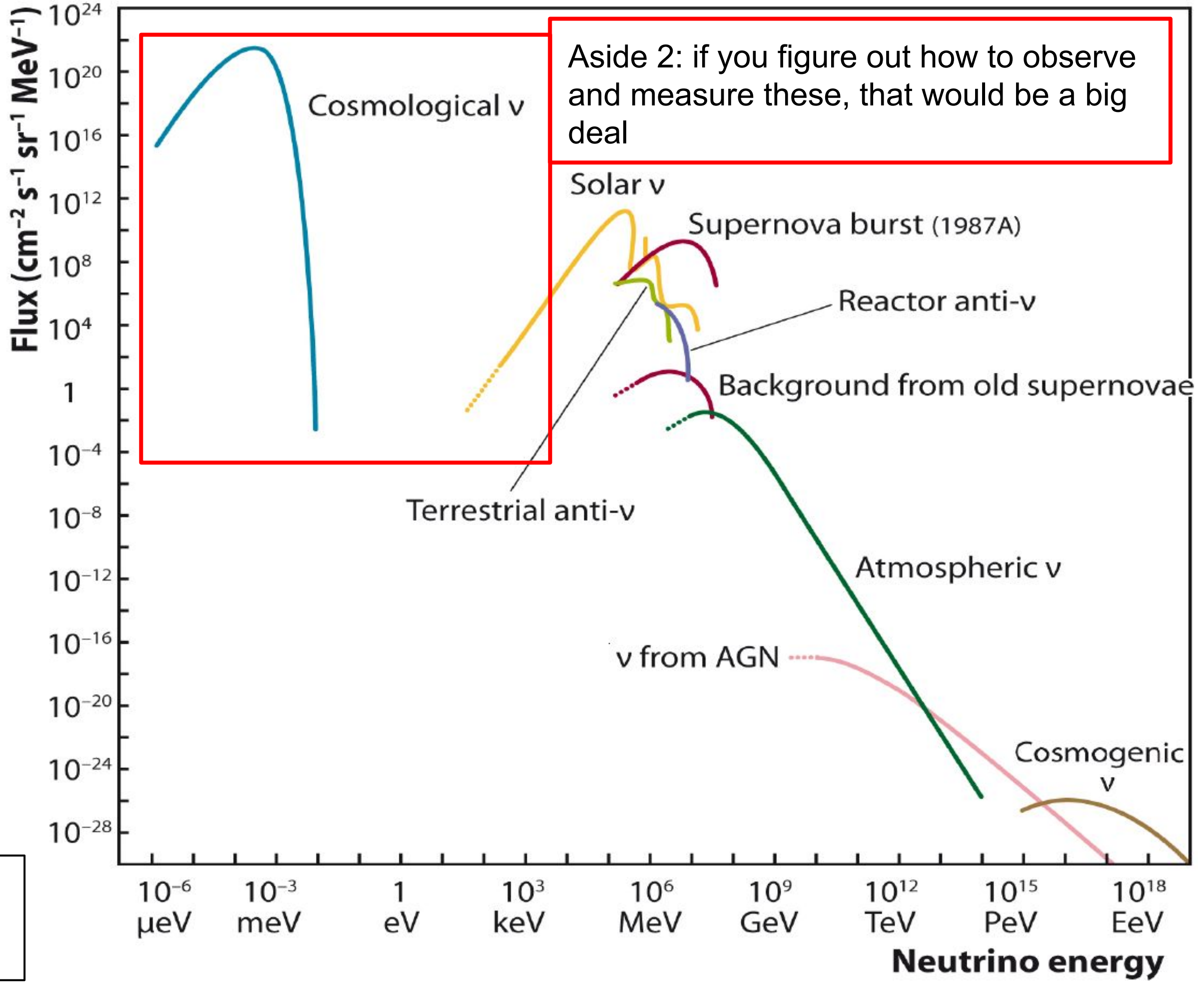
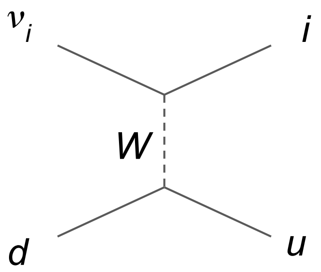



Figure from Bluemer et. al. 2009

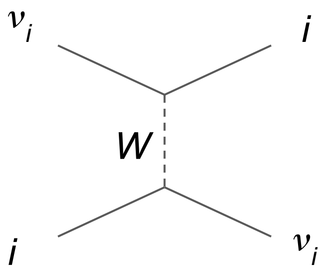
# Neutrino Interactions

Can divide (weak) interactions into two kinds: charged-current and neutral current

<u>Charge-current</u>

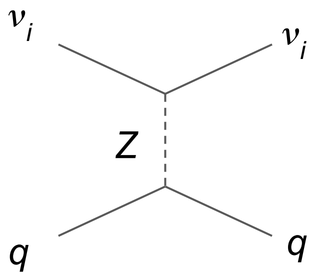



neutrino-quark

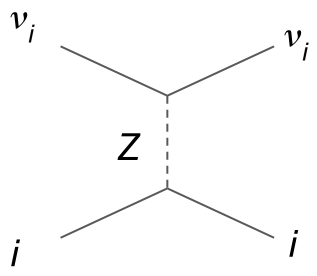



Neutrino-lepton
(often electron)

<u>Neutral-current</u>




neutrino-quark




Neutrino-lepton
(often electron)

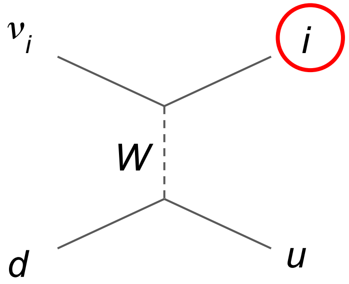
*i: flavors e,mu,tau*

*q: quark flavors*

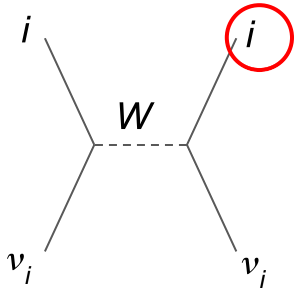
# Neutrino Interactions

1) One product of a neutrino interaction is a *lepton* gets created or gets a kick of momentum

<u>Charge-current</u>




neutrino-quark




Neutrino-lepton
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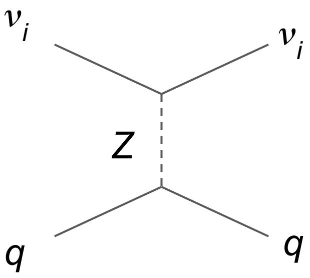
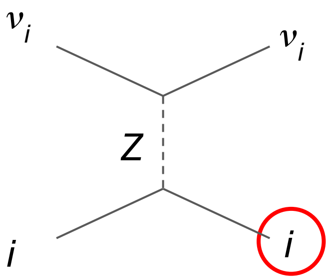
<u>Neutral-current</u>




neutrino-quark




Neutrino-lepton
(often electron)

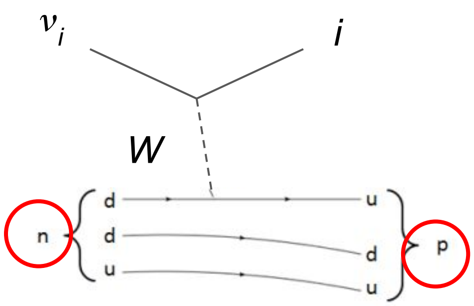
*i: leptons e,mu,tau*

*q: quarks*

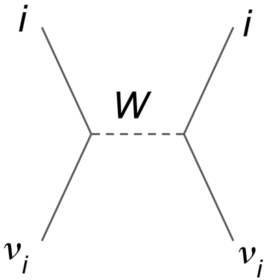
# Neutrino Interactions

2) We don't scatter or produce free quarks -- we hit <u>*nucleons, inside nuclei*</u>

<u>Charge-current</u>

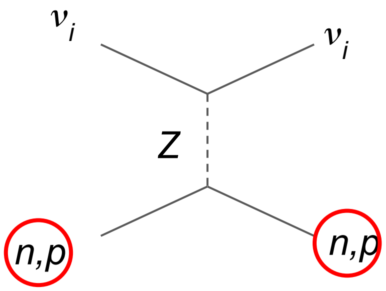



neutrino-nucleon

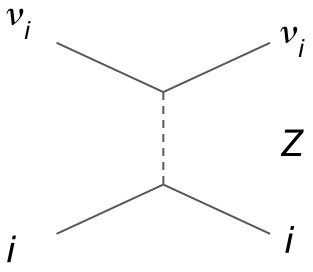



Neutrino-lepton
(often electron)

<u>Neutral-current</u>




neutrino-quark




Neutrino-lepton
(often electron)

*i: flavors e,mu,tau*

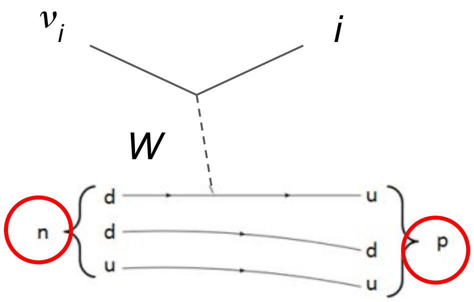
*q: quark flavors*

# Neutrino Interactions

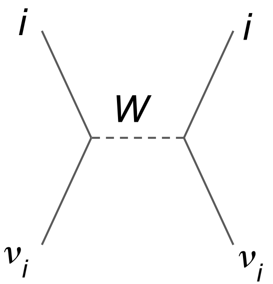
This means that we also can get produce hadrons (things made of quarks)

2) We don’t scatter or produce free quarks -- we hit *__nucleons, inside nuclei__*

__Charge-current__

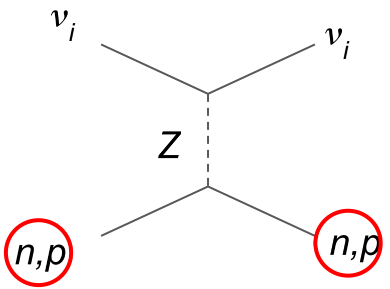



neutrino-nucleon

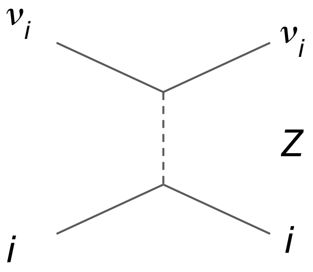



Neutrino-lepton (often electron)

__Neutral-current__




neutrino-quark

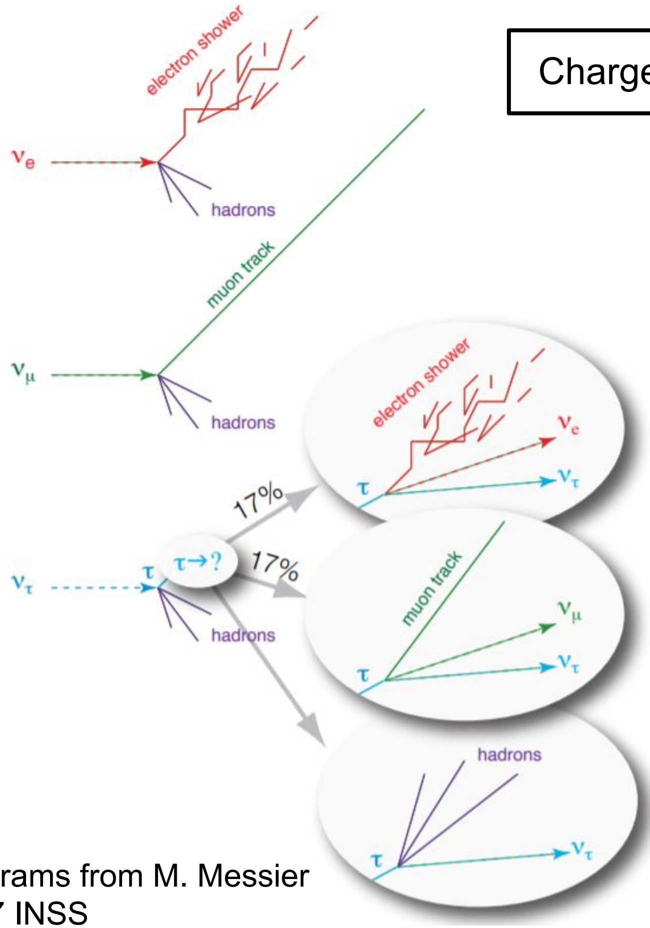



Neutrino-lepton (often electron)

*i: flavors e,mu,tau*

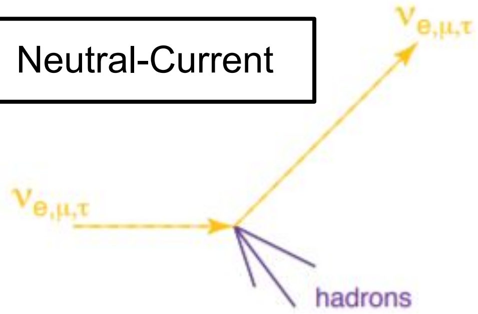
*q: quark flavors*

# Neutrino-Nucleus Interactions




Charged-Current

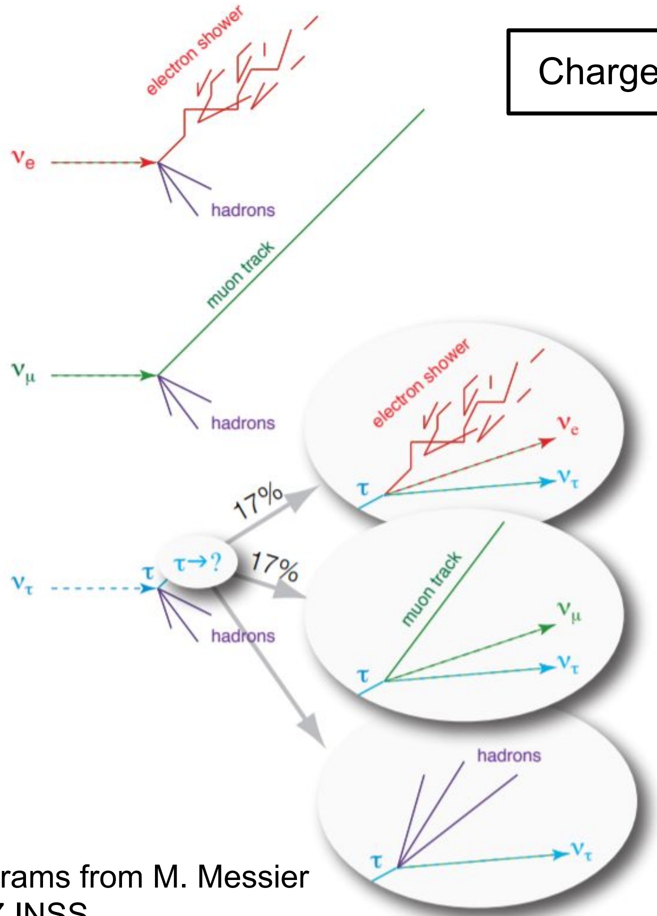
Neutral-Current




- For charged-current reactions, we can use the lepton to <u>*infer the flavor*</u> of the neutrino -- key for certain measurements
- Cartoons express the fact the different leptons can "look" different in the detector (more on this later)

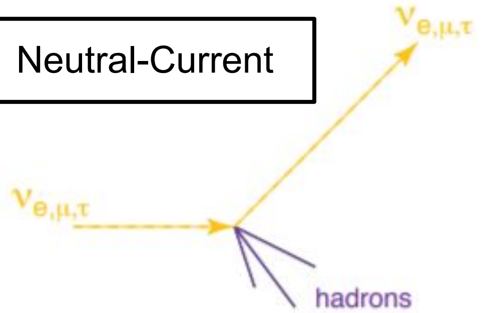
Diagrams from M. Messier 2017 INSS

# Neutrino-Nucleus Interactions




Charged-Current

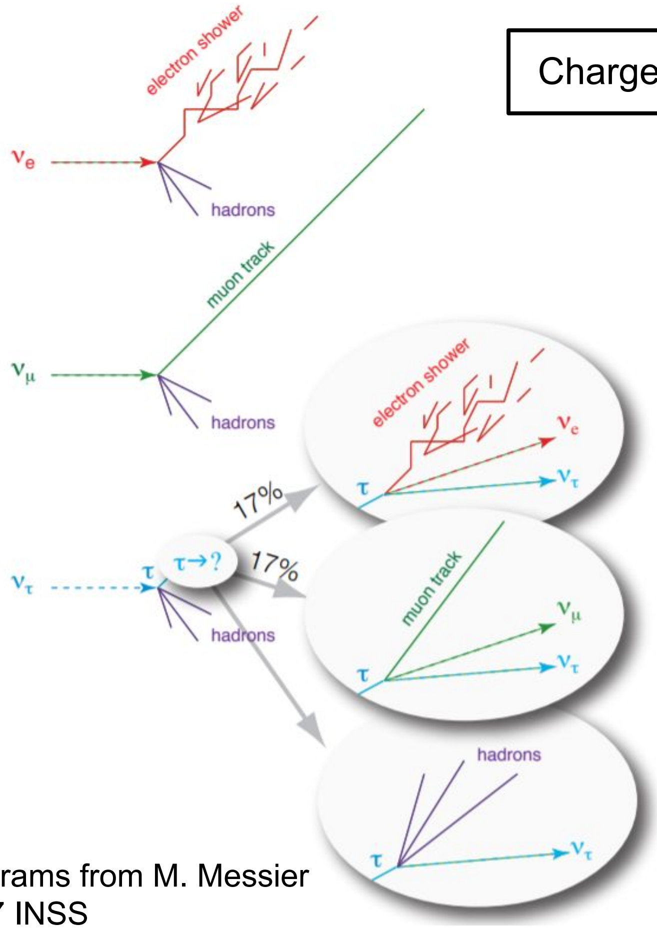
Neutral-Current




- Note: hitting the nucleus can produce hadrons which we can sometimes see
- Can be useful: the hadrons and lepton signals can help us infer the energy/momentum of the neutrino to some degree
- Not-as-useful: hadrons can “fake” or lepton signatures, causing us to misclassify interactions

Diagrams from M. Messier 2017 INSS

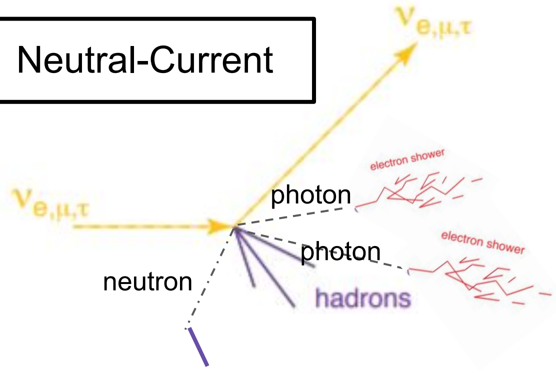
# Neutrino-Nucleus Interactions




Diagrams from M. Messier 2017 INSS

Charged-Current

Neutral-Current

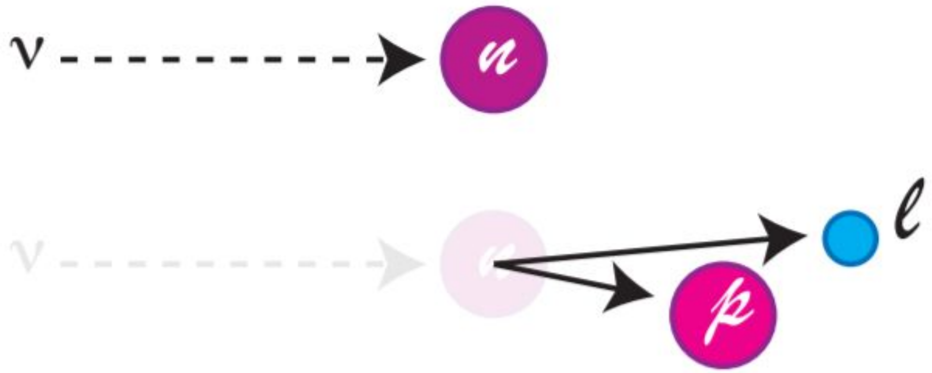



- Also, we can produce neutral particles, photons and neutrons, which eventually can make charged particles
- If you can ID when this happens, great!
- But often missed, causing uncertainty in quantities like the neutrino energy
- Can sometimes produce “fake” signals as well

# “Seeing” neutrinos

- Seeing neutrinos boils down to accurately ID’ing product particles and measuring their kinematics
- So we need to understand how these charged particles pass through matter and deposit energy
  - How much energy?
  - What are the signals they provide?
  - Is there some kind of pattern we can exploit?
- The details of above depends on the energy of the particles, i.e. the source of neutrinos, and also the detector type
- The “game” is to build a detector where the information you want is easy to pick out
  - Note: it’s not always the case you want to see everything -- there can be times where you choose a detector where some particles and interactions are not visible

# Production Thresholds




Only possible if neutrino has enough energy to

1) make the **lepton**
2) Kick the hadron out of the **nucleus**

$$l = e \quad m_e = 0.511 \text{ MeV} \quad P_{\text{thresh}} = 0.511 \text{ MeV}$$

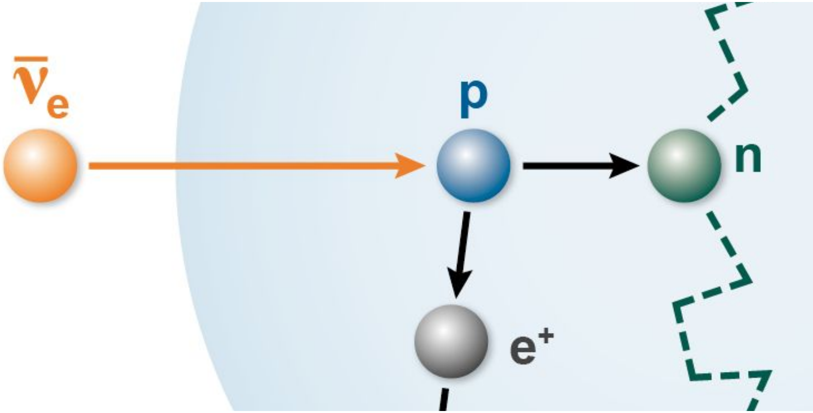
$$l = \mu \quad m_\mu = 106 \text{ MeV} \quad P_{\text{thresh}} = 112 \text{ MeV}$$

$$l = \tau \quad m_\tau = 1.78 \text{ GeV} \quad P_{\text{thresh}} = 3.47 \text{ GeV}$$

# Production Thresholds

For low-energy neutrinos (e.g. from the sun or nuclear reactors) we can still see interactions

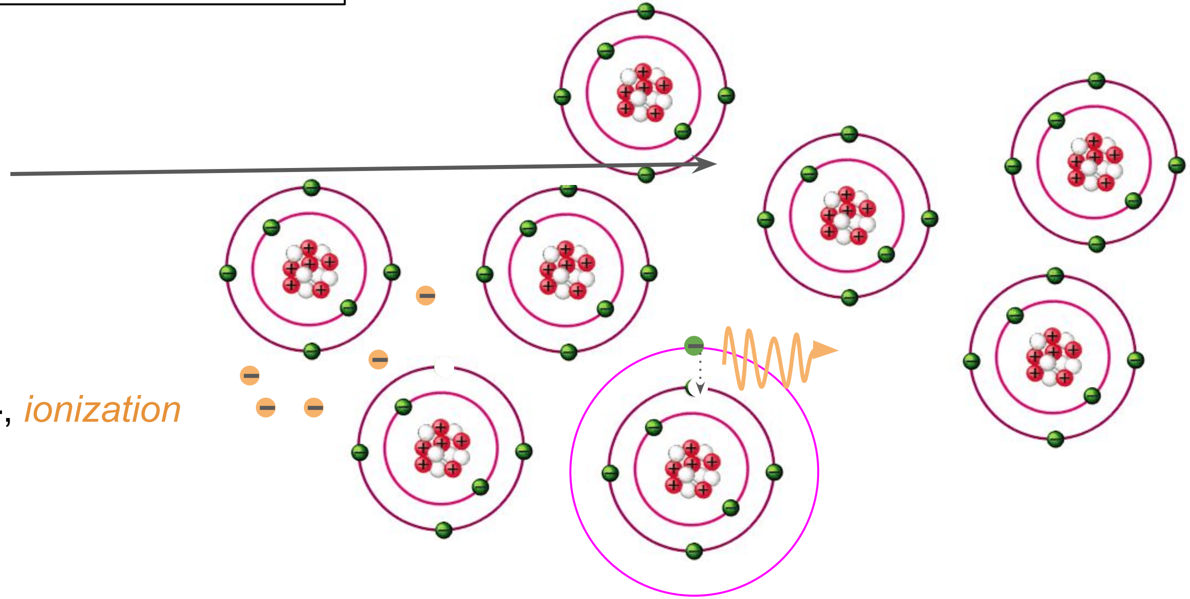
e.g. on free protons via inverse beta-decay



# Physics of charged particles in matter

Charged particles interact with detector medium via EM

*M,q,E*



Liberates e-, *ionization*

Excitation/de-excitation atoms/molecules produces light, *scintillation*

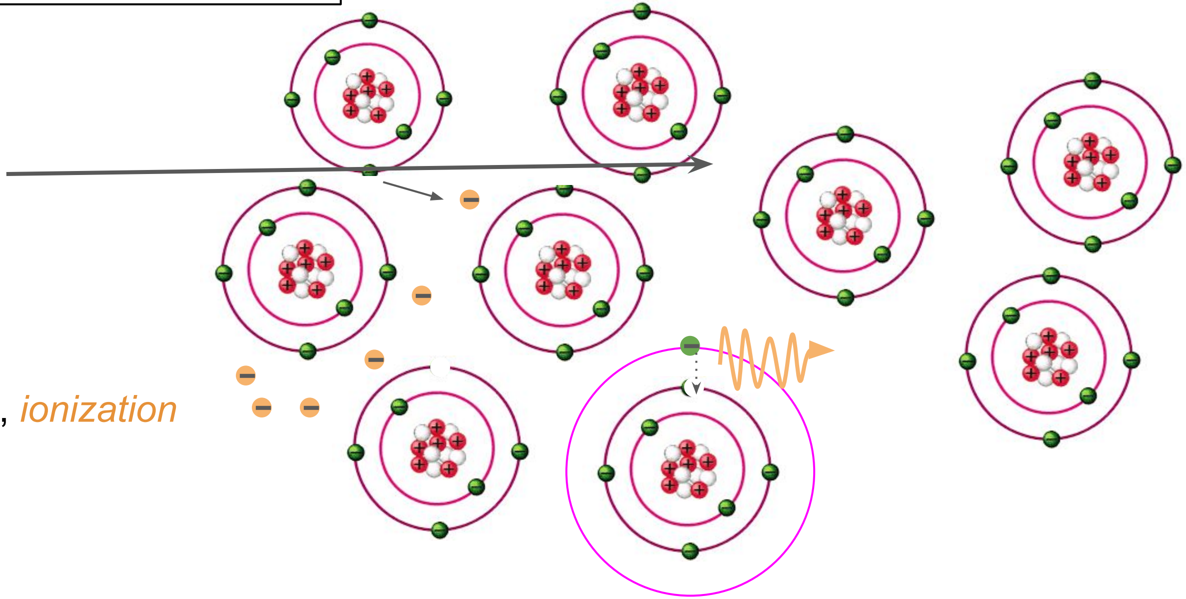
Cartoon adapted from C. Marinas JENNIFER ‘17

# Physics of charged particles in matter

Charged particles interact with detector medium via EM

Scattering w/ e-, *delta-ray*

*M,q,E*



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Cartoon adapted from C. Marinas
JENNIFER ‘17

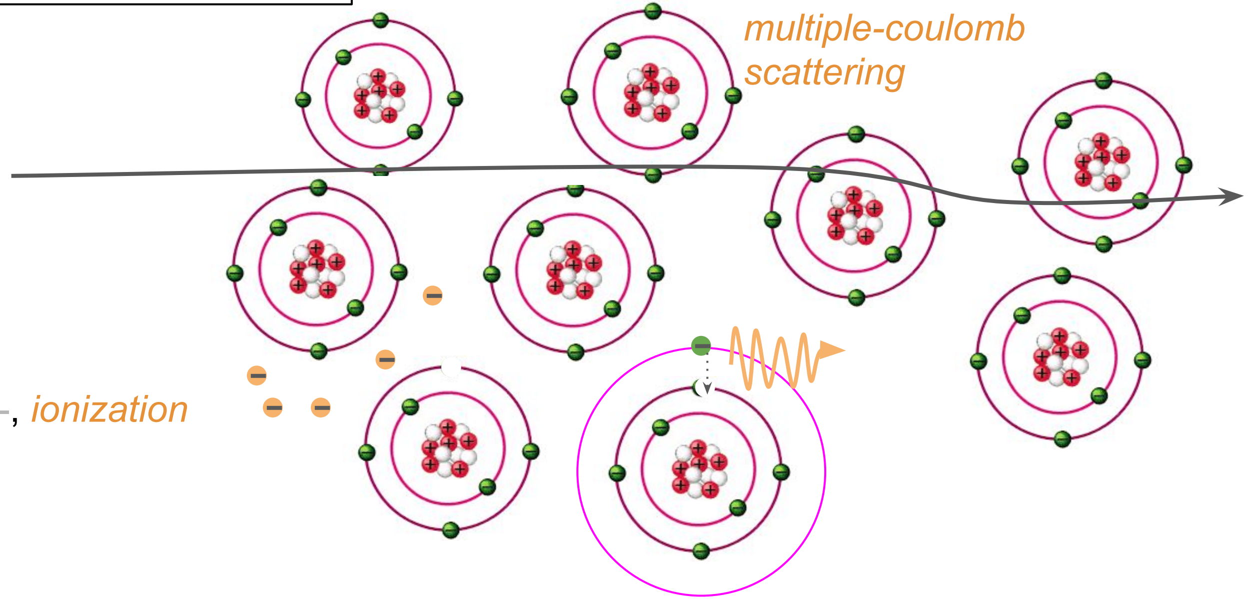
# Physics of charged particles in matter

Charged particles interact with detector medium via EM

Scattering w/ e-, *delta-ray*

Particle scattering with EM field of nucleus: *multiple-coulomb scattering*

*M,q,E*



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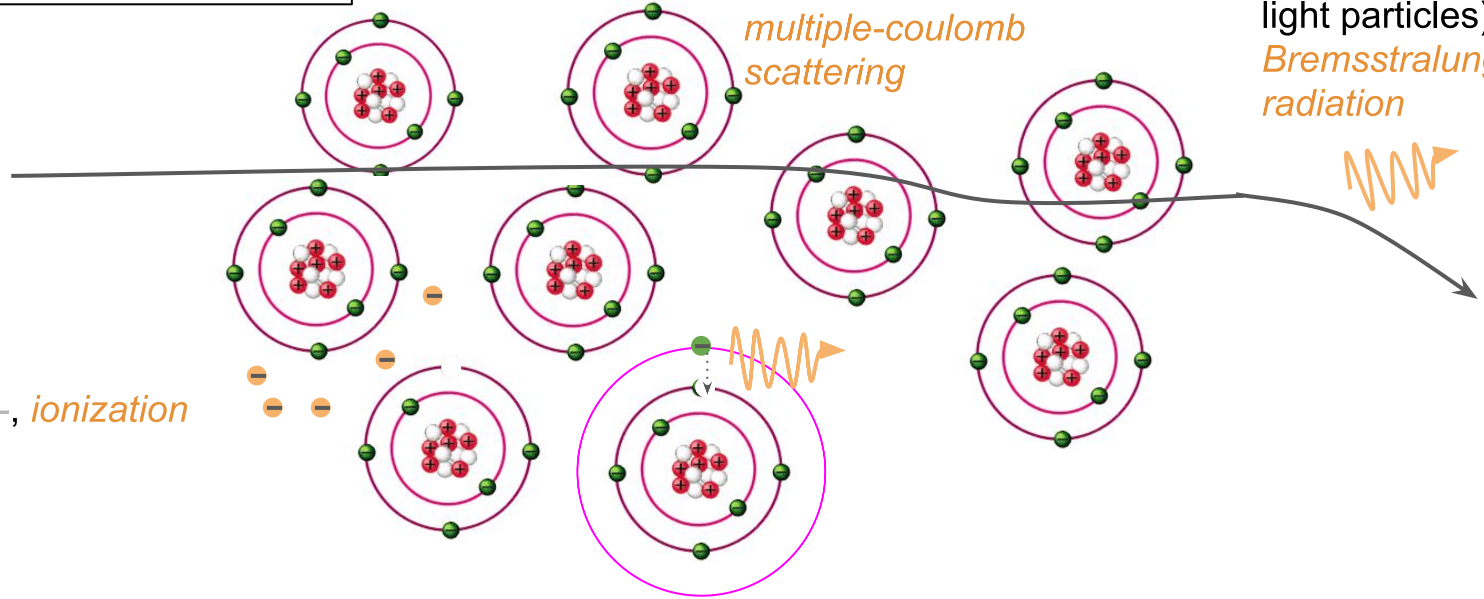

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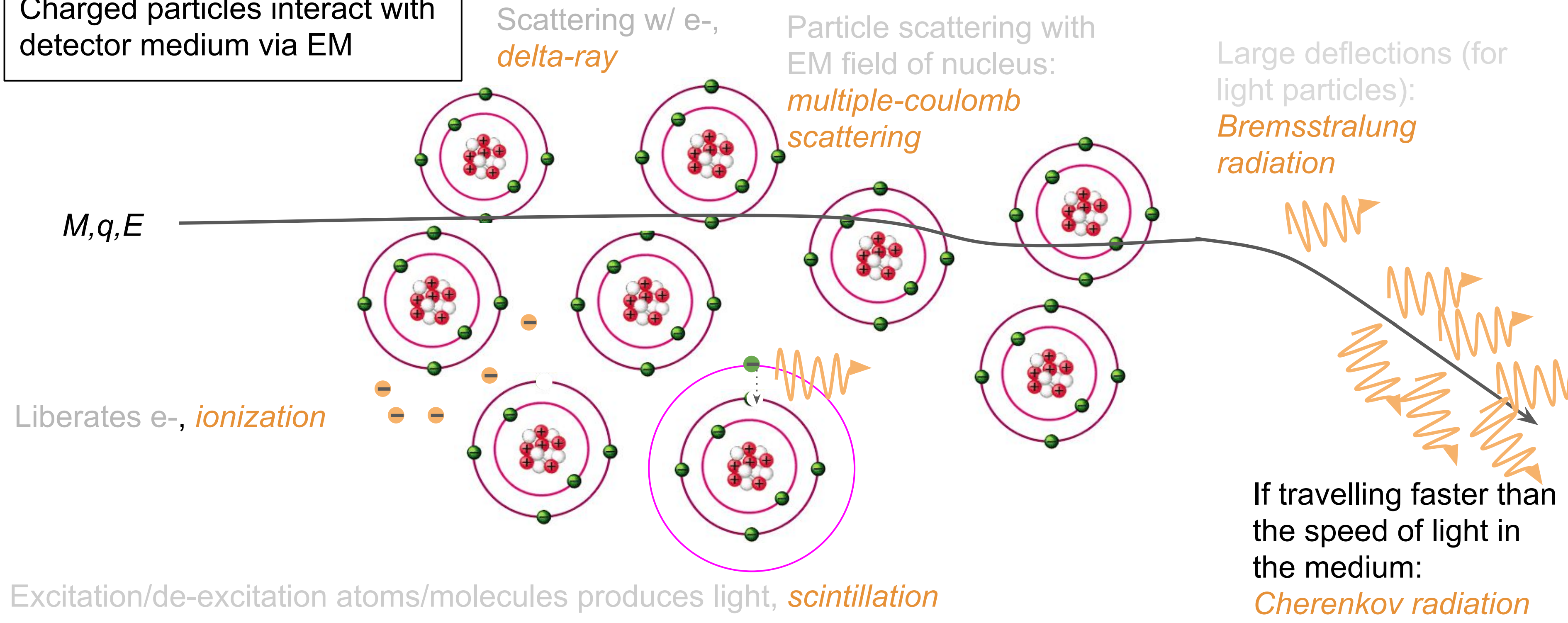
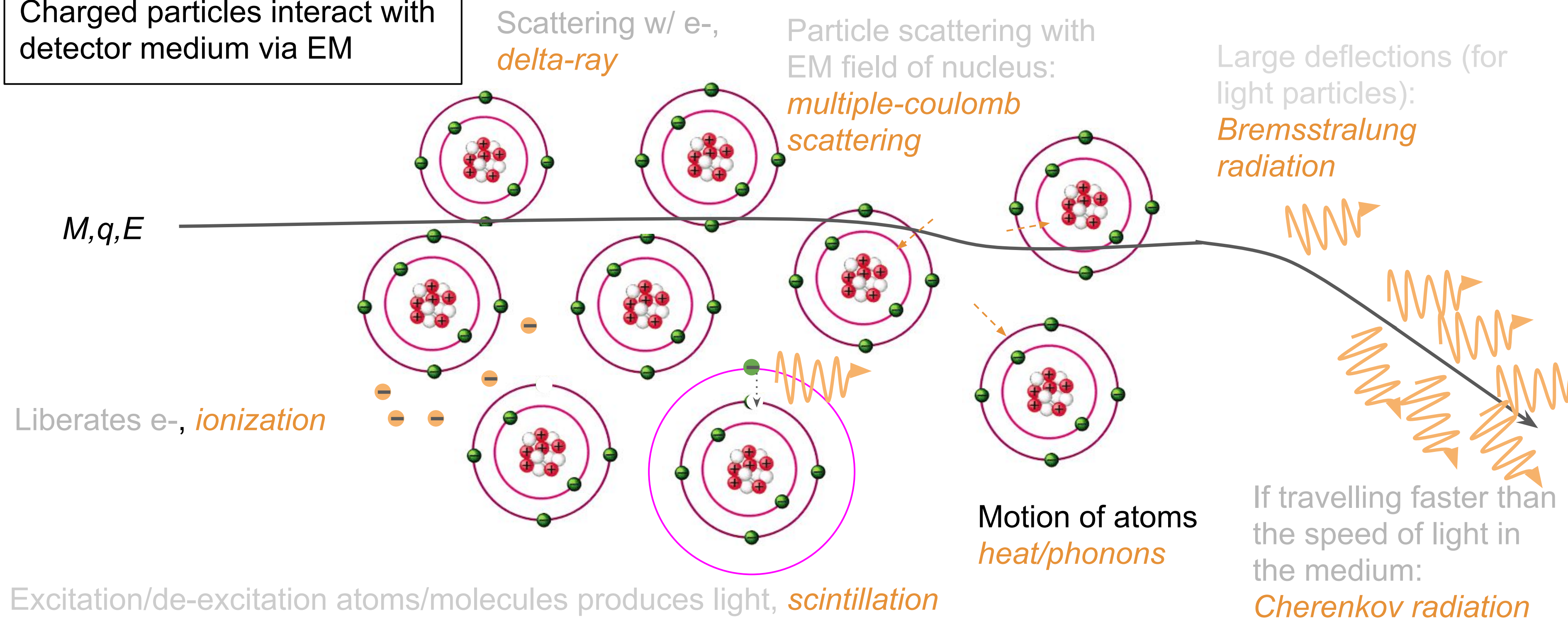


# Physics of charged particles in matter

Charged particles interact with detector medium via EM



# Physics of charged particles in matter

- A less clustered list
  - Ionization electrons
  - Scintillation
  - Scattering w/ electron
  - Multiple-coulomb scattering
  - Bremsstralung radiation
  - Cherenkov radiation
  - Heat
- What (combination) seen depends on mass, charge, energy of charged particle

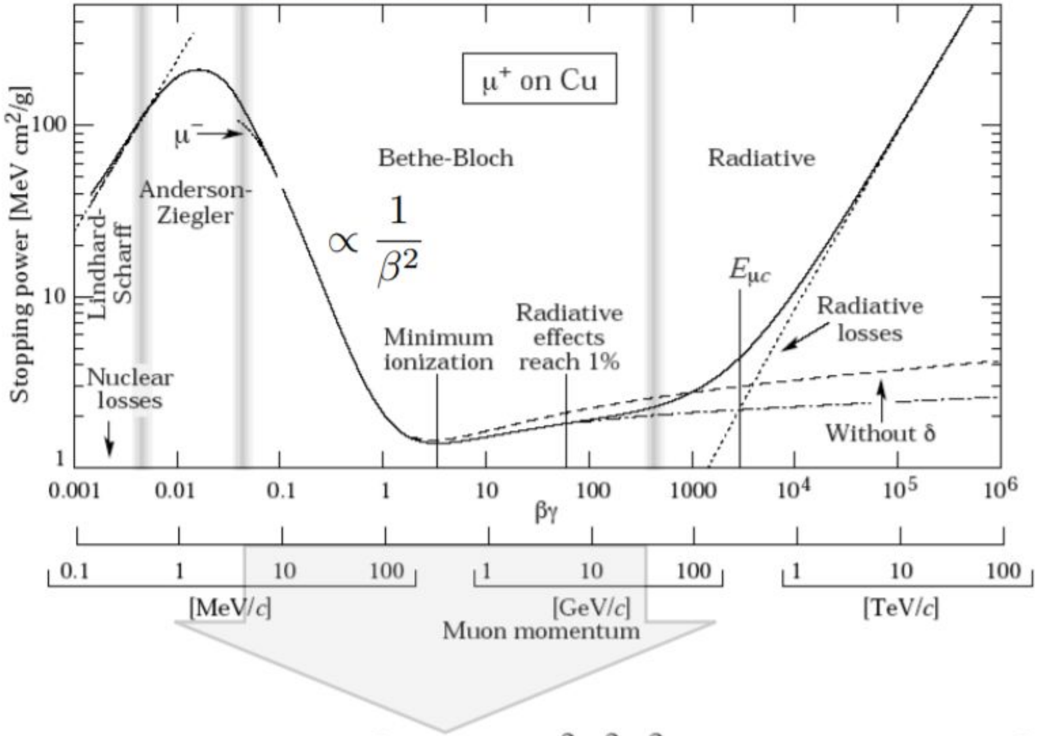
# Charge deposition in Matter

- Muons
- Electrons
- Hadrons
- Taus

# Muons

- Muons lose energy following the Bethe-Bloch equation

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)



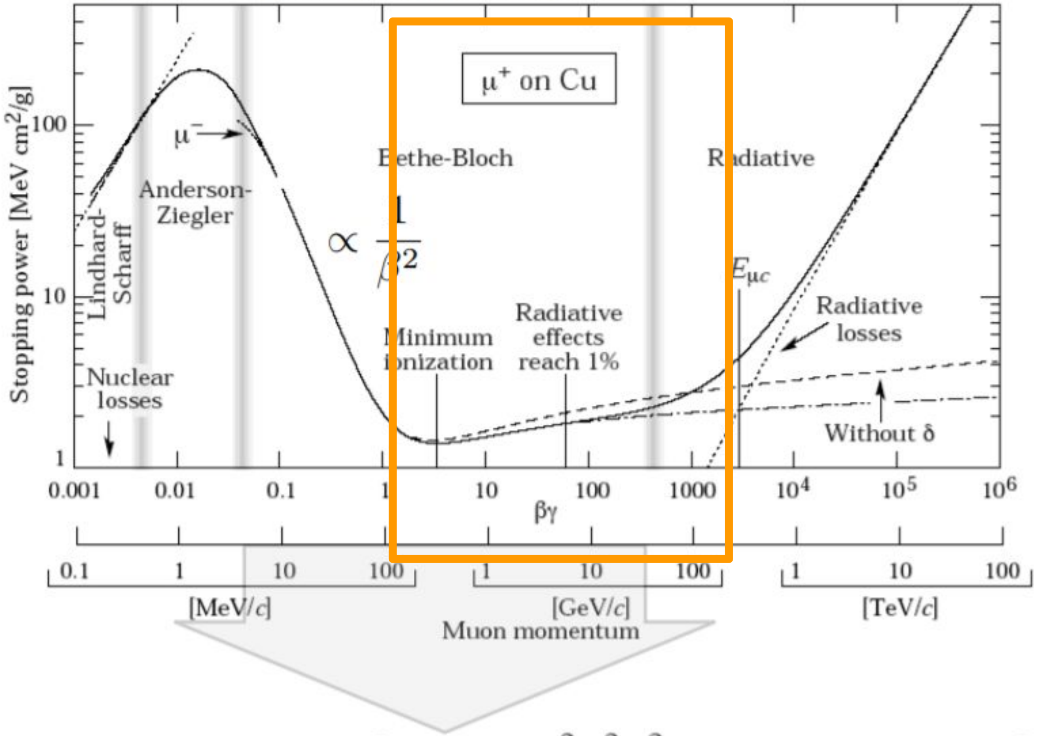

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Bethe-Bloch equation

# Muons

- Being relatively heavy, muons lose most of its energy via ionization over a large range of momentum [0.1, 100] GeV
- Fairly flat over this region
- Rule of thumb: 2 MeV/g/cm^3
- ***Often used as a way to calibrate ionization detected to energy deposited***
- ***Also implies that how far a muon travels into a detector (it's range) is a decent indication of its energy***

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

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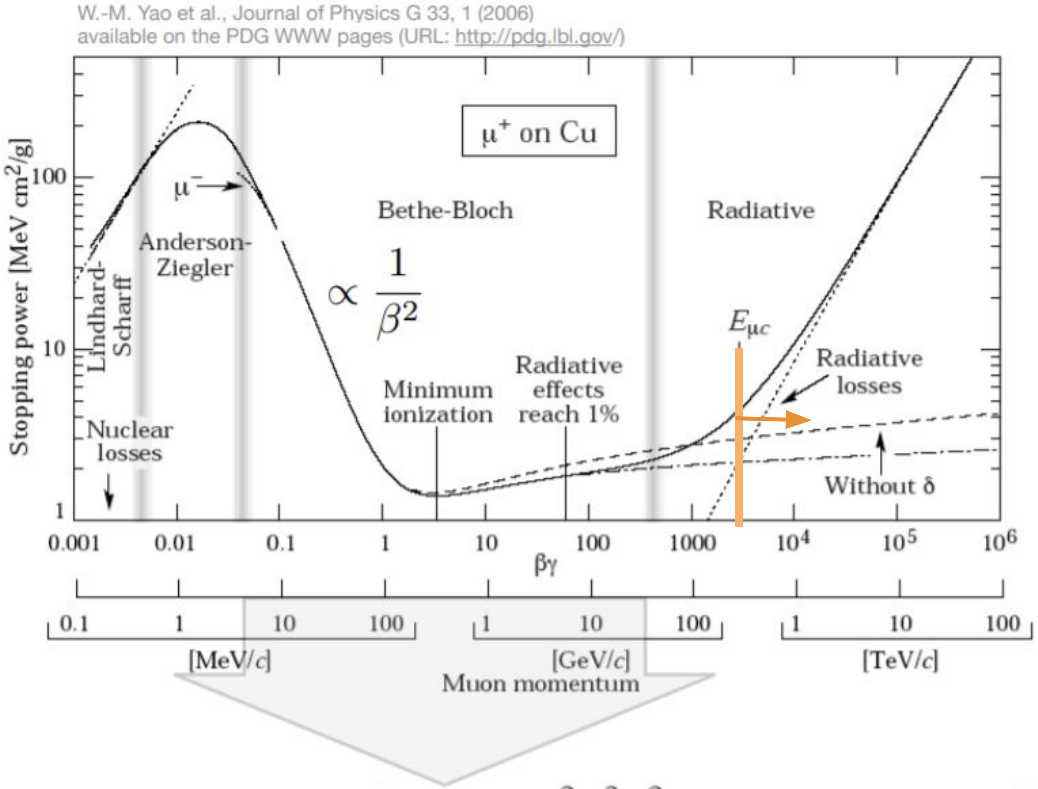
Bethe-Bloch equation

# Muons

- Note that above 100 GeV, radiative energy loss begins to dominate
- Where this point occurs is called the “critical point”




$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Bethe-Bloch equation

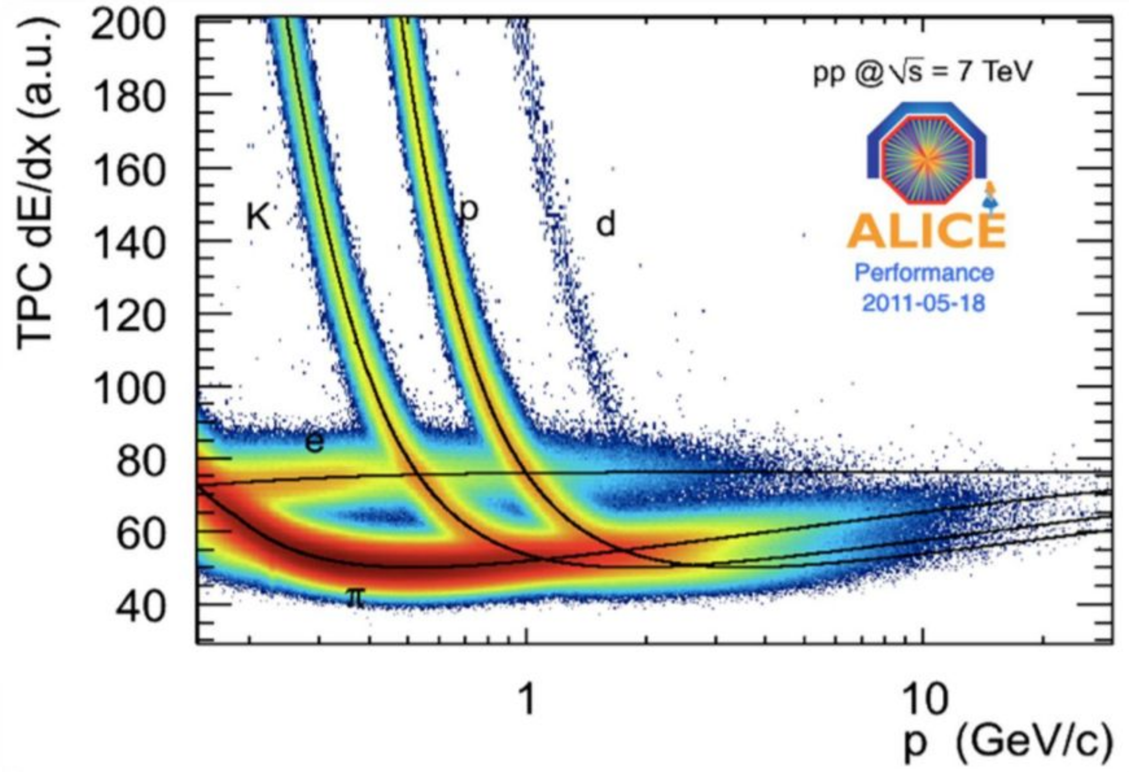
# Bethe-Bloch

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

- Actually, this description applies generically to heavy charged particles: muons, protons, pions
- dE/dx goes as $z^2$ : no fractionally charged particles -- a way to look for them
- dE/dx goes as $\gamma\beta$ ~ *p/m*
- Weakly dependent on material: *Z/A* changes slightly

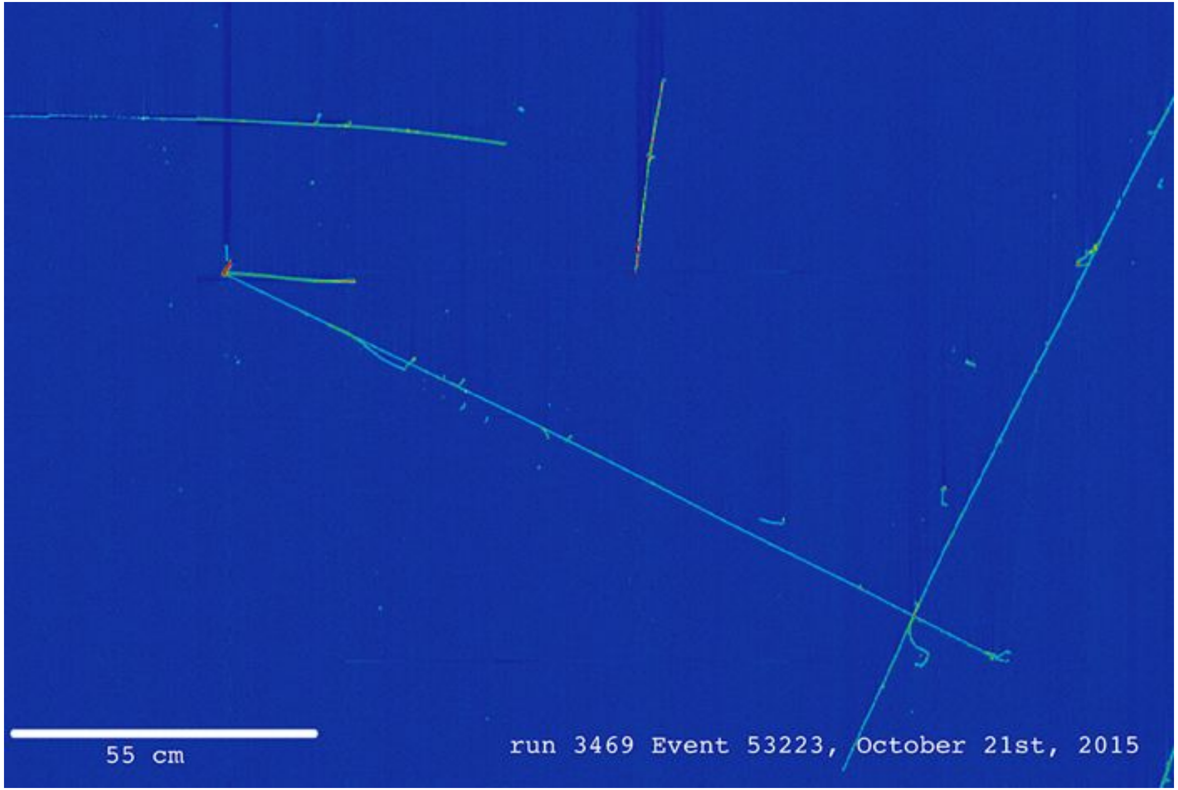
# Ionization

- dE/dx vs momentum
- If we plotted as p/m, curves would nearly be on top of one another



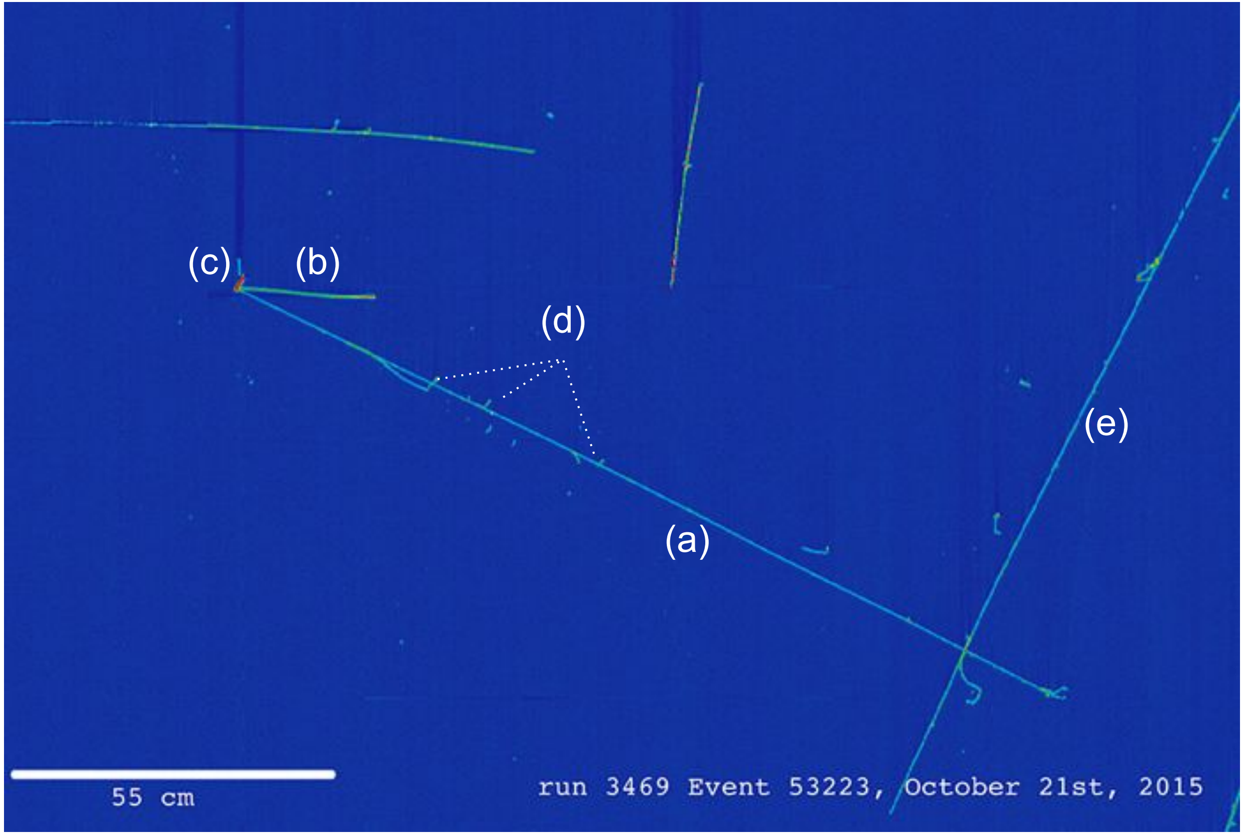
# Example of Ionization Tracks in a LArTPC

- Real neutrino interaction in data
- (I'll get to how the detector that made this image works)
- For now, just to demonstrate ionization tracks of different particles



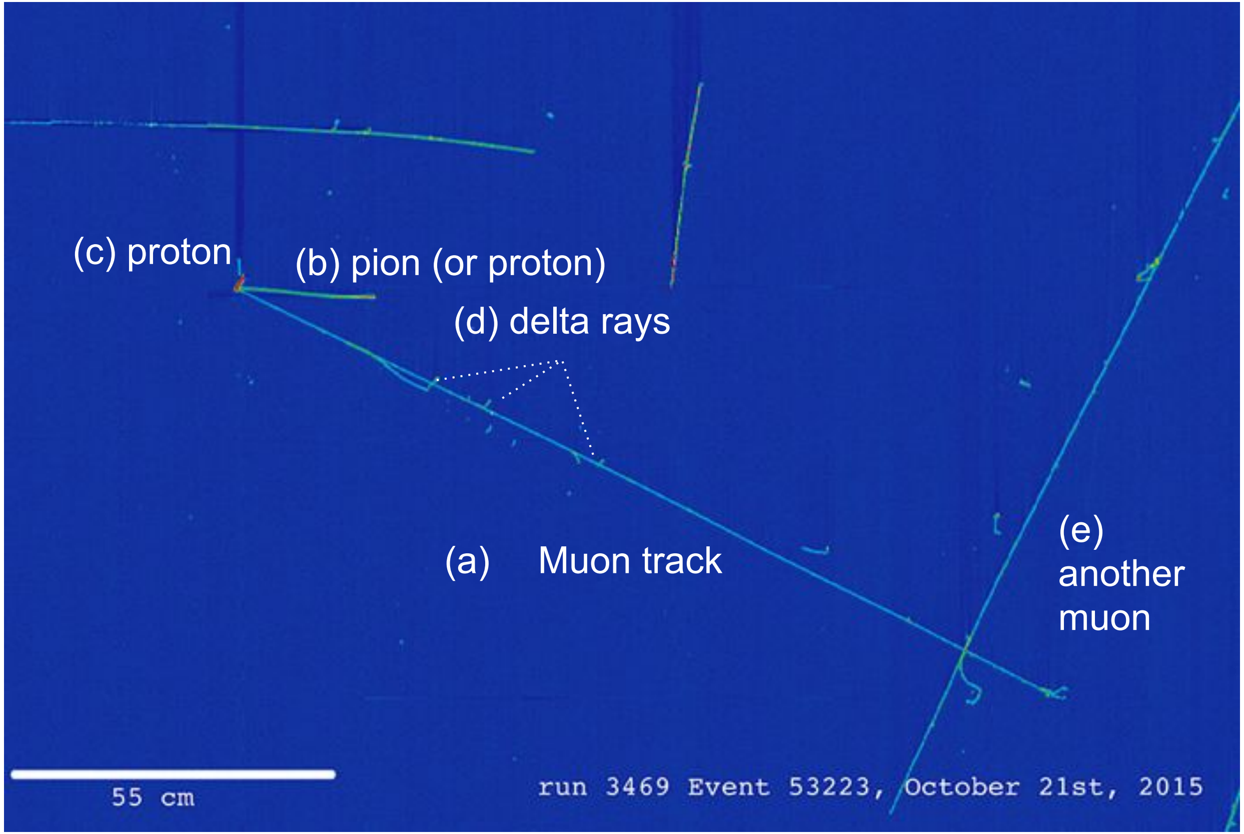
# Example of Ionization Tracks in a LArTPC

- Can we use what we know to identify some features/particles in this image?



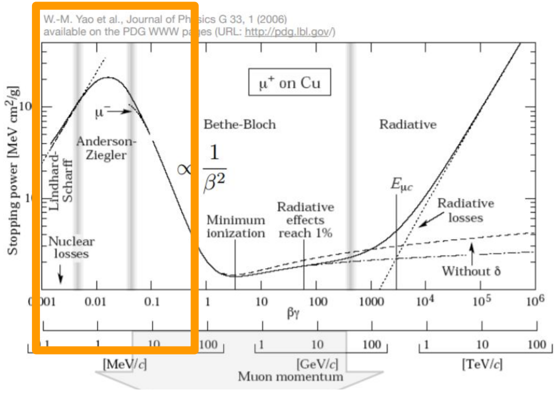
# Example of Ionization Tracks in a LArTPC

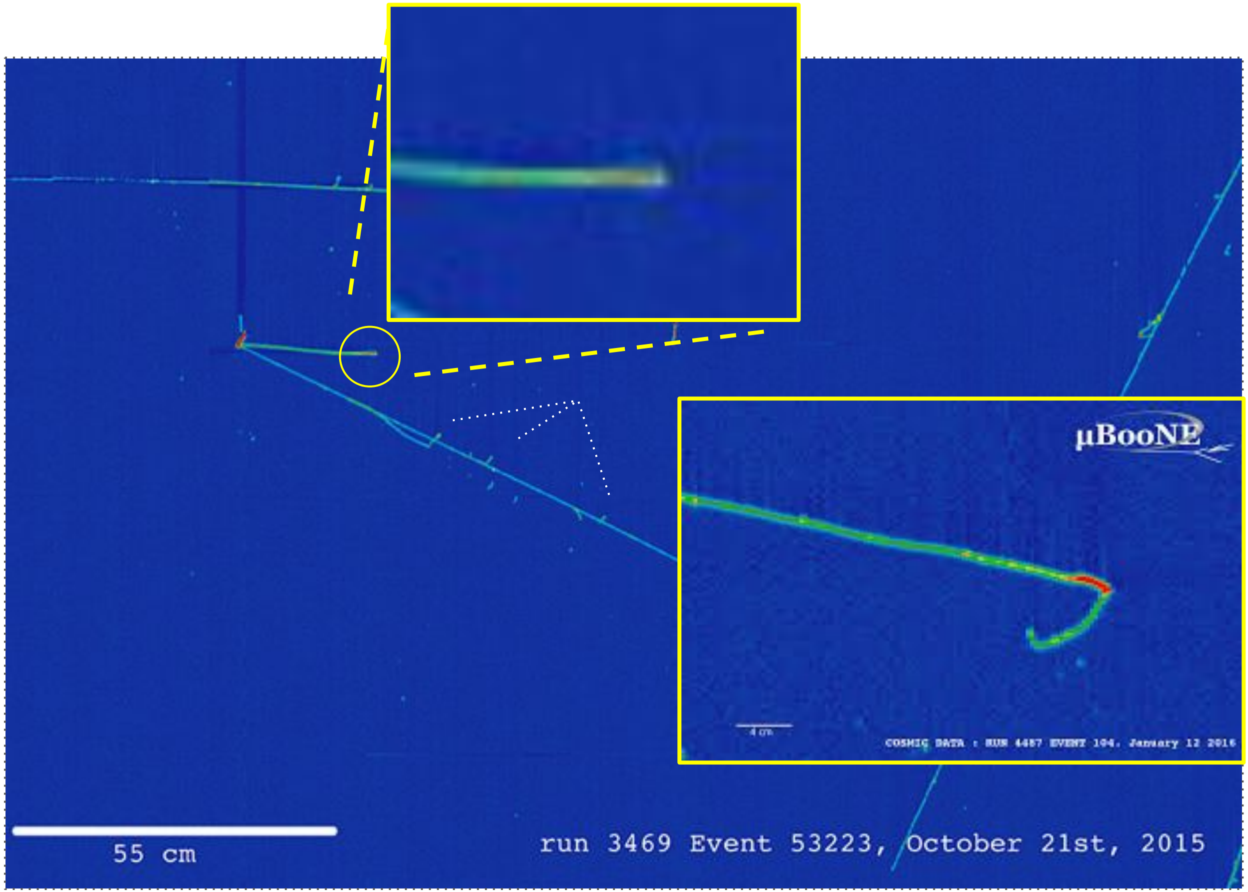
- What I think
- Note, though each particle type deposits a different amount, it is fairly uniform for most of the track
- Exception is at the end



# Example of Ionization Tracks in a LArTPC

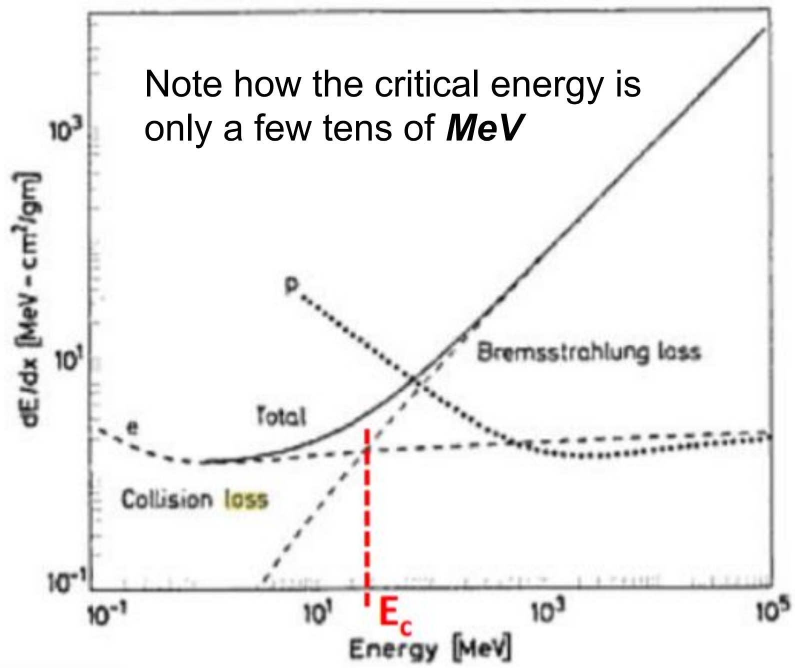
- At ends of track, heavy particles deposit much more energy
- This is known as the Bragg peak
- Up-turn also a handle for particle ID

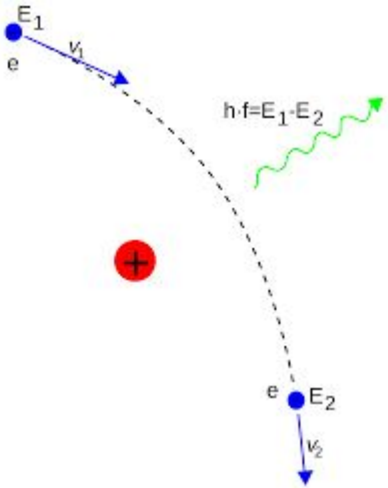


# Electrons

- Electrons are light, and so they are almost always at energies where radiative energy losses occur

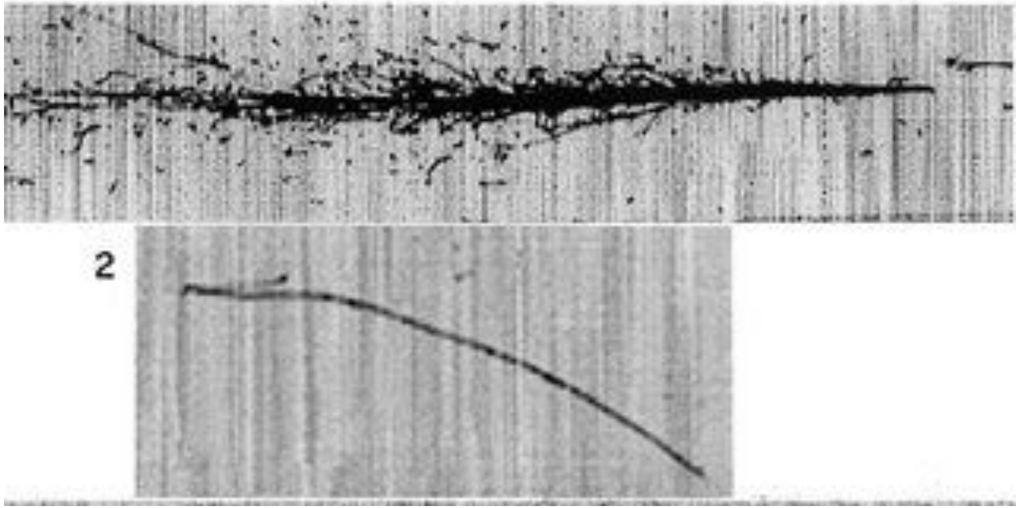


# Electrons

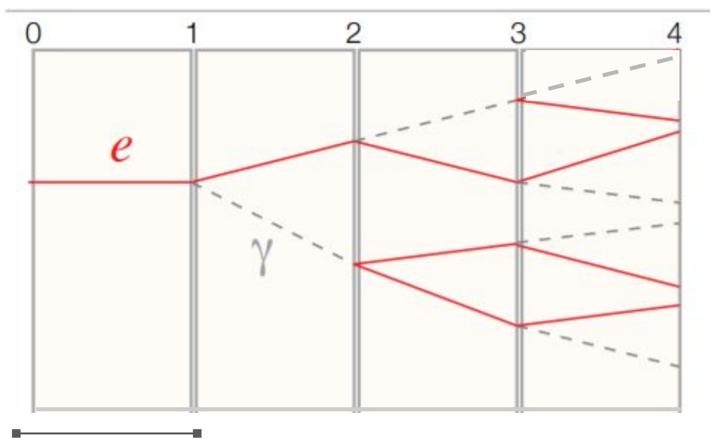
- Because they are constantly radiating, electrons instigate an ***electromagnetic shower*** inside a detector
- Another example from a LArTPC neutrino detector, but from Italian-led ICARUS -- the first of such detectors

Electron shower




Muon track for comparison

# Electronmagentic showers



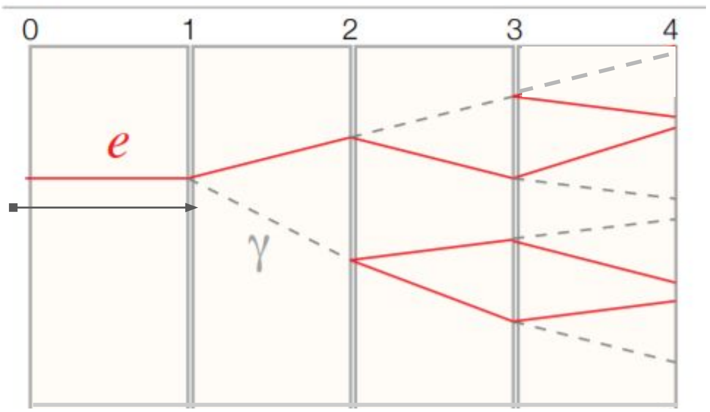

Interaction length

Simple model of shower

Consider evolution as a function of some characteristic interaction length.

From M. Messier
2017 INSS

# Electronmagentic showers




Simple model of shower

Consider evolution as a function of some characteristic interaction length.

After traveling that distance, electron radiates (e.g. via Bremsstralung) and produces a photon.

Photon also travels for some characteristic distance

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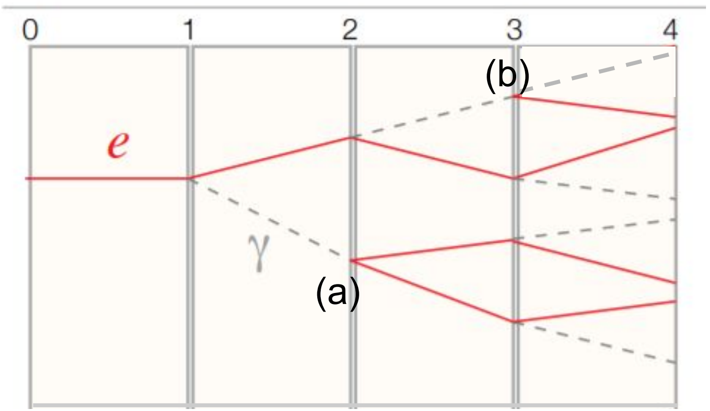
# Electronmagentic showers




<u>Simple model of shower</u>

Consider evolution as a function of some characteristic interaction length

After traveling that distance, electron radiates (e.g. via Bremsstralung) and produces a photon.

Photon also travels for some characteristic distance

Photons can (a) pair produce (into e+/e-) or (b) compton scatter

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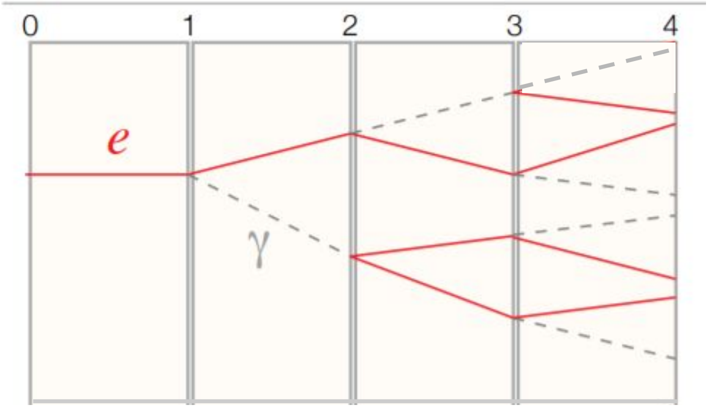
# Electronmagentic showers




<u>Simple model of shower</u>

Consider evolution as a function of some characteristic interaction length

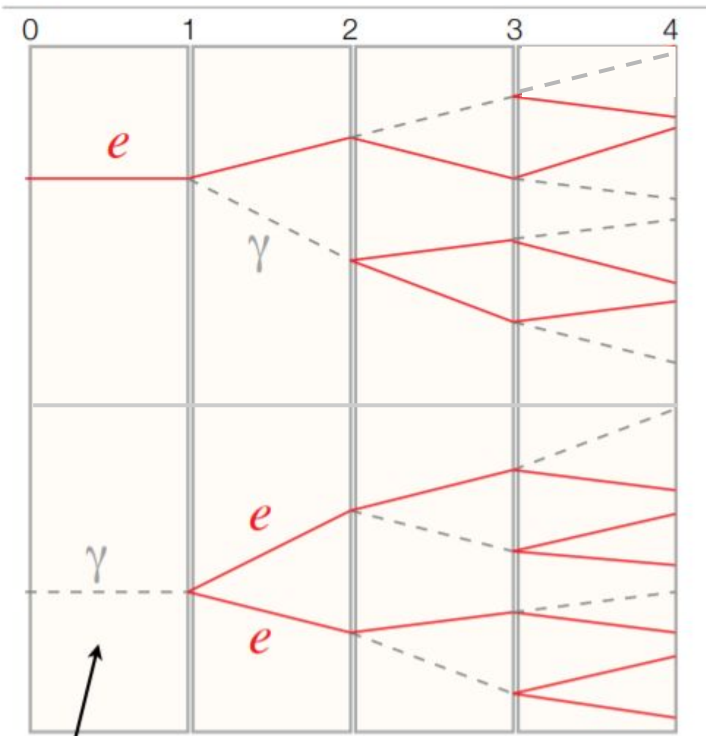
After traveling that distance, electron radiates (e.g. via Bremsstralung) and produces a photon.

Photon also travels for some characteristic distance

Photons can (a) pair produce (into e+/e-) or (b) compton scatter

Progresses until electron energy drops below the critical energy: no long radiate and simply ionize until out of energy

# Electronmagentic showers

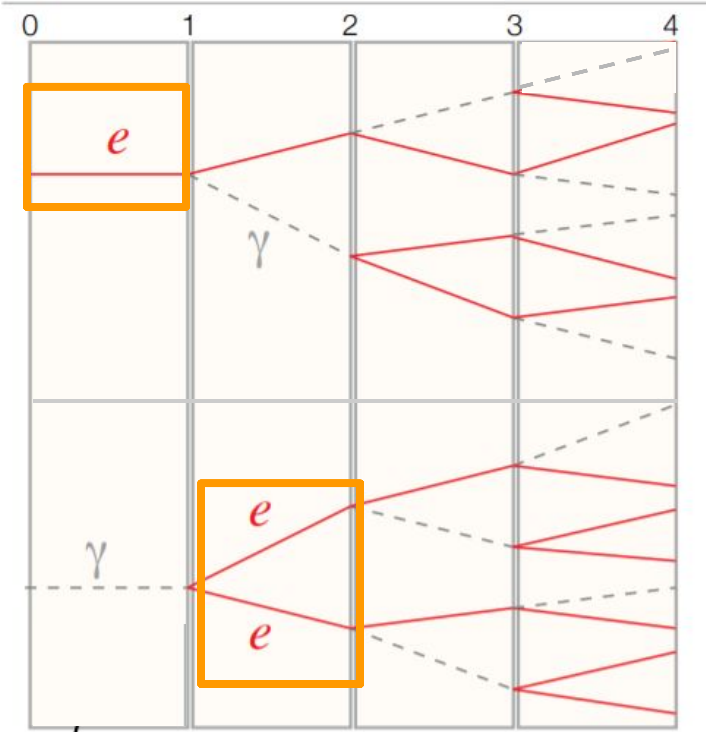



Early part of photon shower not visible until photon converts/scatters for the first time

Note that photons can also start the cascade

This will create a similar object as seen in the ionization pattern -- and so photons are often backgrounds for electrons

# Electronmagentic showers

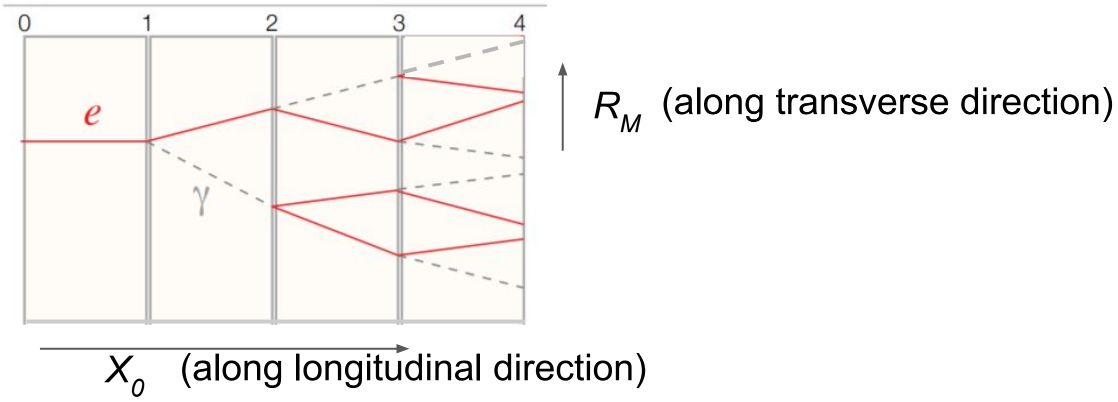



But … note that for photon shower, visible charge wil be higher higher

Shower starts with e+/e- pair instead of single electron

If you can measure this early difference, you can pick electron showers from photon showers

# Characterizing Showers




- **Radiation length**, $X_0$, of a material in cm (or g/cm^3 if density divided out) defined as

  Distance over which electron loses 1/e of its energy via radiation and is roughly

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})}\left[\frac{\mathrm{g}}{\mathrm{cm}^2}\right]$$

- **Moliere radius**, $R_M$, is the transverse distance for the same energy loss

$$R_{\mathrm{M}} = \frac{21.2\ \mathrm{MeV}}{E_C} X_0 = 0.0265(Z+1.2)X_0$$

# Characterizing Showers

| | Radiation length | | Moliere radius | |
|---|---|---|---|---|
| | $g/cm^2$ | cm | $g/cm^2$ | cm |
| liquid $H_2$ | 61.28 | 866 | 3.57 | 50.49 |
| liquid Ar | 19.55 | 14.0 | 9.95 | 7.12 |
| C | 42.70 | 18.8 | 8.15 | 3.59 |
| Fe | 13.84 | 1.76 | 10.71 | 1.36 |
| Air | 36.66 | 30420 | 7.62 | 6322 |
| $H_2O$ | 37.08 | 36.1 | 8.31 | 8.32 |
| $SiO_2$ | 27.05 | 12.3 | 8.61 | 3.91 |
| Polystyrene scintillator | 43.72 | 42.4 | 8.50 | 8.25 |
| Liquid scintillator | 51.07 | 43.9 | 8.93 | 7.68 |

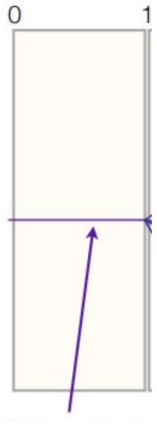
Radiation lengths and Moliere radii for common neutrino detector medium

Sets the scale of your detector

If you built a detector out of a box of liquid argon, what should its dimensions be?

# Hadron Showers

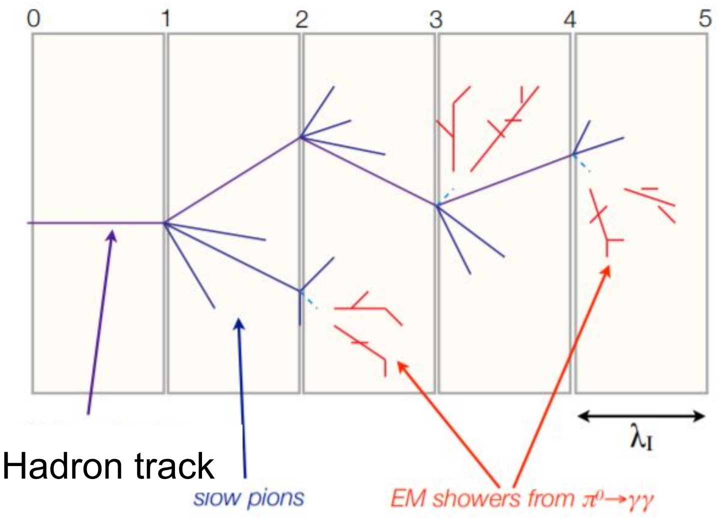
- Previously we saw hadrons (protons, pions) ionized in a similar fashion to muons




Hadron track

# Hadron Showers

- But hadrons, made of quarks, will *also interact via the strong force*
- This means they can lose energy by a cascade of interactions that create particles, i.e. a shower
- Use analogous model and characterization as electron shower




Whether a hadron interacts or ionizes depends on how much energy it has left

Stops when particles no longer have energy to radiate

# Hadron vs. EM Showers

- Angle of photon emission for bremsstrahlung is $\approx m_e/E$
- Hadronic processes typically produce particles with $P_T \sim= 300$ MeV/c
- For 1 GeV:
  - $\theta_{EM} \approx 0.5$ mrad
  - $\theta_{Had} \approx 300$ mrad

➡*EM showers are compact in the transverse direction compared to hadron showers which tend to be more diffuse in the transverse direction*

- Example at right shows 15 GeV e and π in glass (Z~=11).

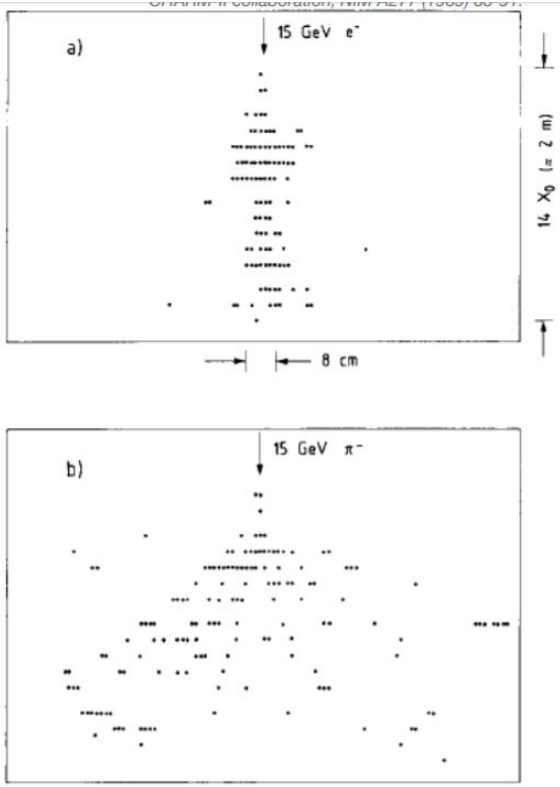



Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.

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2017 INSS

# Hadron vs. EM Showers

## *...Adding interaction length to our table*

| | Radiation length | | Moliere radius | | Interaction length | |
|---|---|---|---|---|---|---|
| | $g/cm^2$ | cm | $g/cm^2$ | cm | $g/cm^2$ | cm |
| liquid $H_2$ | 61.28 | 866 | 3.57 | 50.49 | 50.8 | 717.5 |
| liquid Ar | 19.55 | 14.0 | 9.95 | 7.12 | 117.2 | 84.0 |
| C | 42.70 | 18.8 | 8.15 | 3.59 | 86.3 | 38.1 |
| Fe | 13.84 | 1.76 | 10.71 | 1.36 | 131.9 | 16.8 |
| Air | 36.66 | 30420 | 7.62 | 6322 | 90.0 | 69600 |
| $H_2O$ | 37.08 | 36.1 | 8.31 | 8.32 | 83.6 | 83.6 |
| $SiO_2$ | 27.05 | 12.3 | 8.61 | 3.91 | 97.4 | 44.3 |
| Polystyrene scintillator | 43.72 | 42.4 | 8.50 | 8.25 | 81.9 | 79.4 |
| Liquid scintillator | 51.07 | 43.9 | 8.93 | 7.68 | 81.9 | 95.2 |

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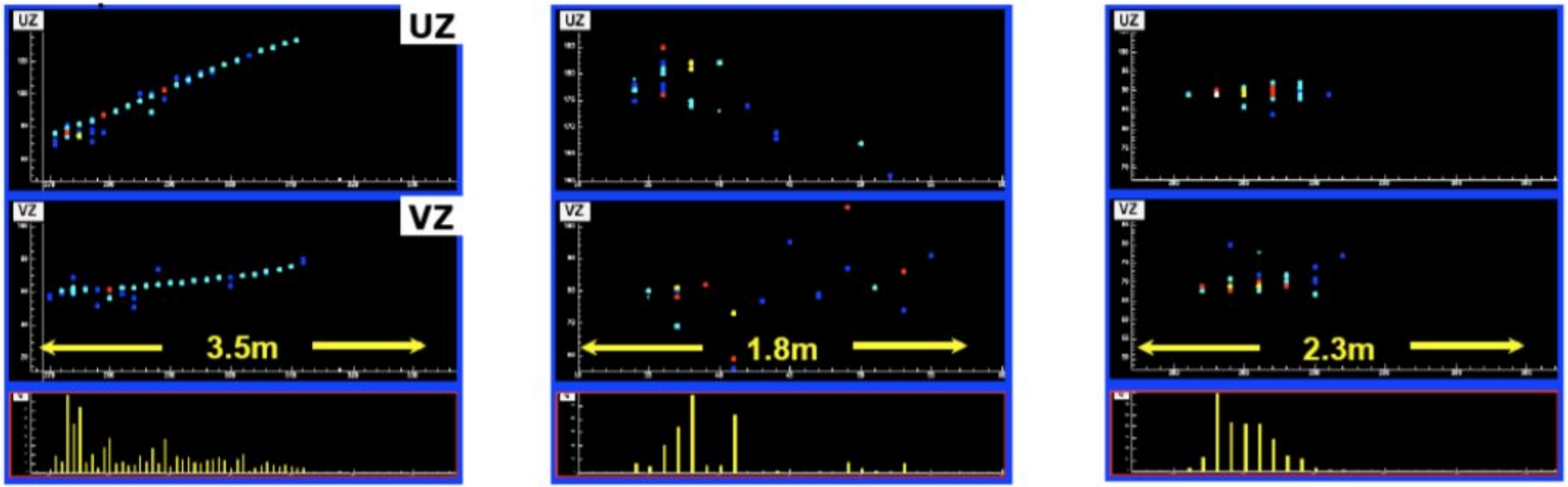
# Can you classify these events from the MINOS experiment?

$$X_0 = 1.8 \text{ cm}$$

$$\lambda_I = 17 \text{ cm}$$




I'll talk about MINOS and detectors like this tomorrow
But for now, showing 3D charge deposited as a function of position, projected into two planes

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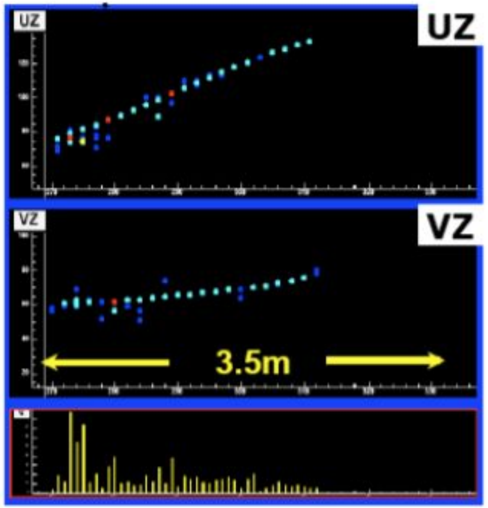
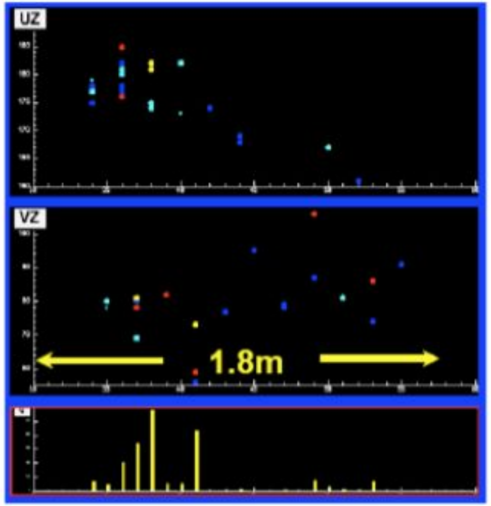
# Can you classify these events from the MINOS experiment?

$$X_0 = 1.8 \text{ cm}$$

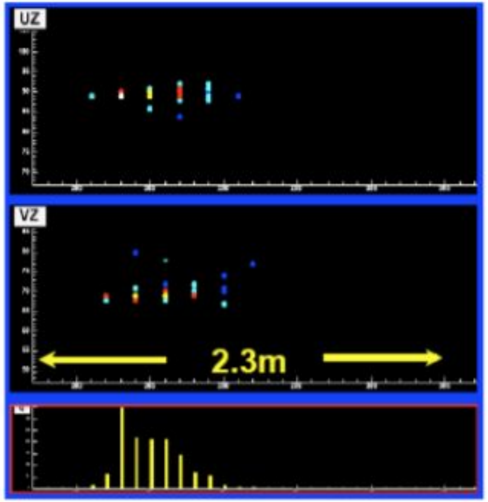
$$\lambda_I = 17 \text{ cm}$$

Muon + small amount of
hadronic energy near vertex
numu-CC interaction




Diffuse, wide pattern of
hadronic shower
NC interaction




Narrow shower pattern
nue-CC interaction

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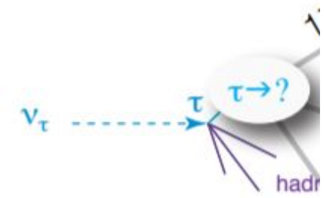
# Tau lepton

Lepton like muon and electron
Mass of 1776 GeV

Any guesses as to what kind of pattern it will make?

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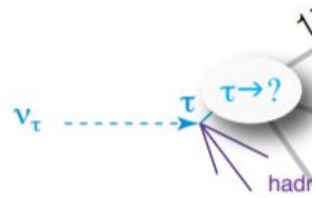
# Tau lepton

Lepton like muon and electron
Mass of 1776 GeV

Any guesses as to what kind of pattern it will make?

Hints: is it stable? What will it decay into?

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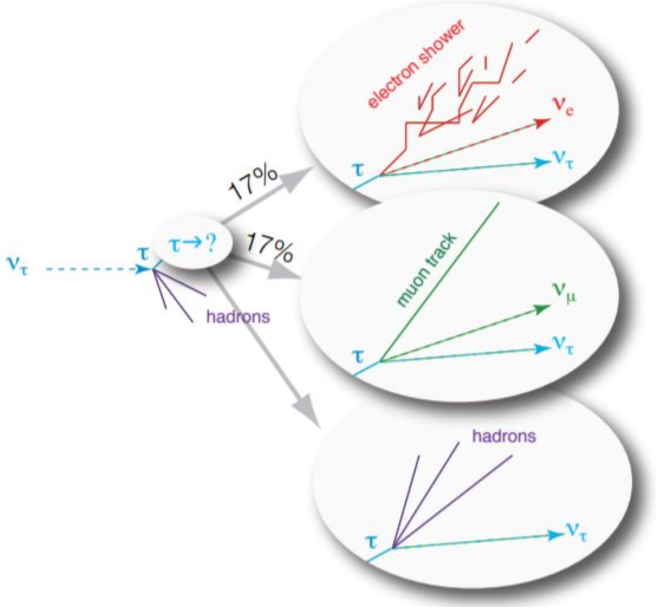
# Tau lepton

Not stable, so will decay into electrons and muons

Also, it can make hadrons

Going to get either EM, track, or hadron shower




But stable for a short amount of time, **291 fs**, so will leave a track of a few mm before decay occurs

Difficult, but it is possible to detect observer this -- at times referred to as a “double-bang” signature

From M. Messier
2017 INSS

# Recap

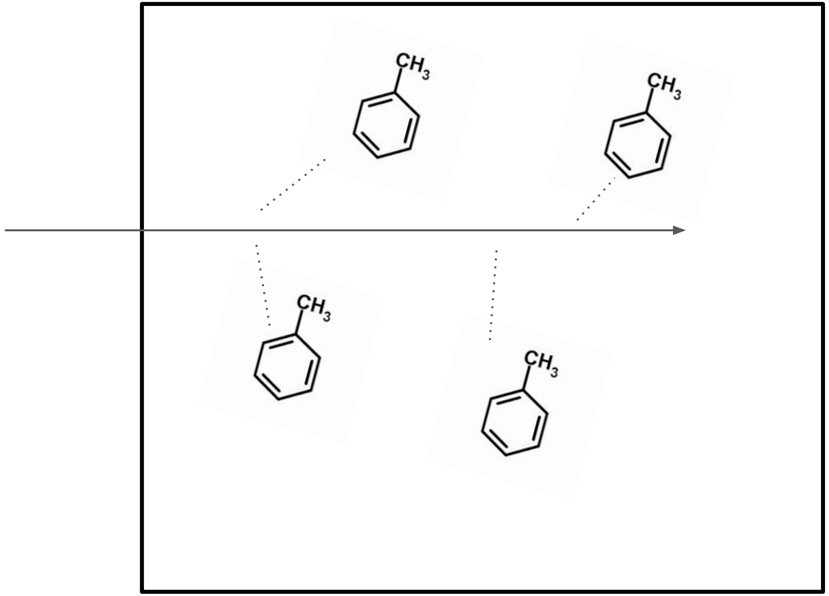
- Covered charge patterns deposited by various particles
- If particle below it’s critical energy, will just leave a fairly uniform track until the end (Bragg peak)
- If above critical energy, will produce EM shower
- For hadrons, if energy such that particle can travel beyond interaction length, will produce hadronic shower

| Electrons | Muons | Hadrons | Taus |
|---|---|---|---|
| EM shower (narrow) | Tracks only | Low energy: tracks<br><br>Higher energy: hadronic showers (wide) | Can either decay into muon track, EM shower, or hadronic shower<br><br>Can try to find tau decay vertex |

# Back to the signal list

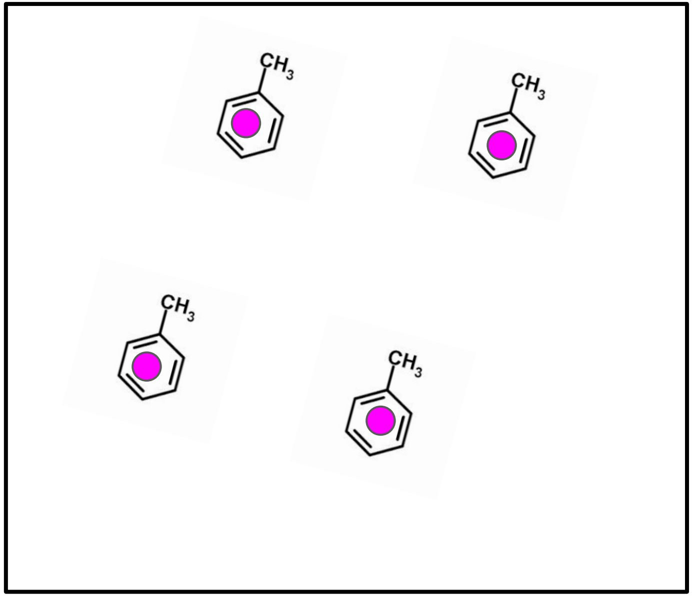
- A less clustered list
  - Ionization electrons ✓
  - Scintillation
  - Scattering w/ electron (delta-rays) ✓
  - Multiple-coulomb scattering
  - Bremsstralung radiation ✓
  - Cherenkov radiation
  - Heat
- What (combination) seen depends on mass, charge, energy of charged particle

# Scintillation




Particle as it travels in the medium interacts via EM with atoms and molecules -- same interaction as ionization

# Scintillation

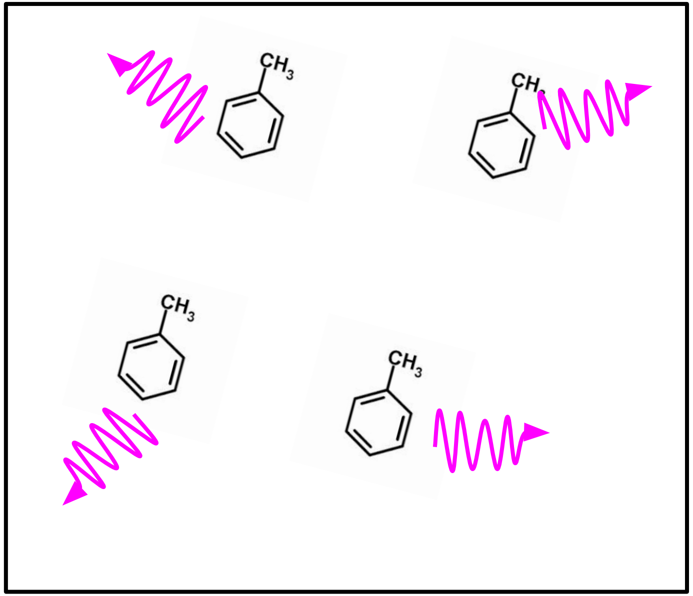



In the case of ionization, charge particle liberated charge

But we can also excite atoms/molecules, i.e. kick an electron into an unoccupied orbital

I have toluene in this diagram -- often use liquid solvents composed of compounds with benzene rings -- those orbitals can be excited

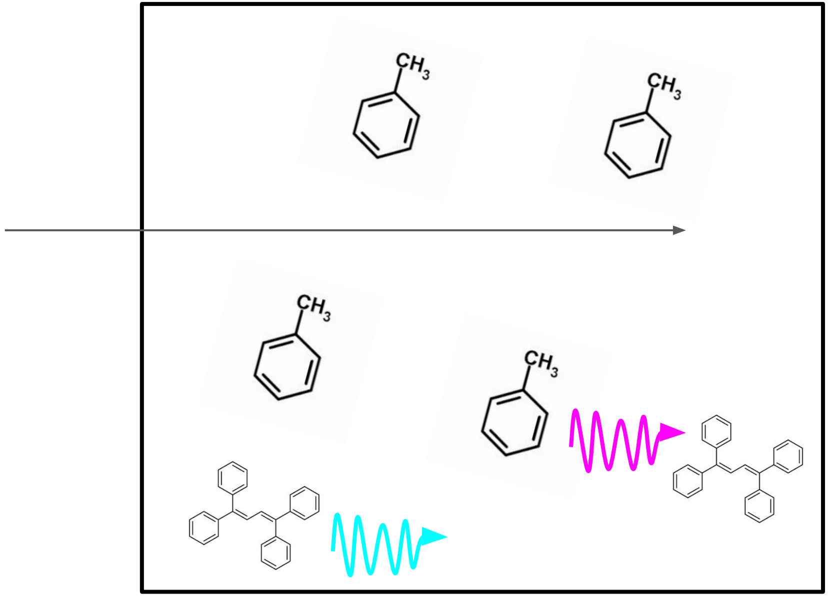
# Scintillation




After some time, the molecules will dexcite and emit a photon in the UV-vis spectrum

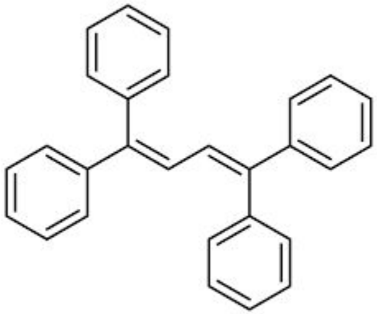
Example: toluene emits in the near UV

# Scintillation




UV light not easy to detect with common photo detectors -- not very efficient

So scintillators often provide a second compound as a solute that absorbs UV light and turns it into color easier to see (green-blue)



Example here is Tetraphenyl butadiene, an example of a "wavelength shifter"

Often have chains of benzene rings -- these lower the energy of the molecular orbitals

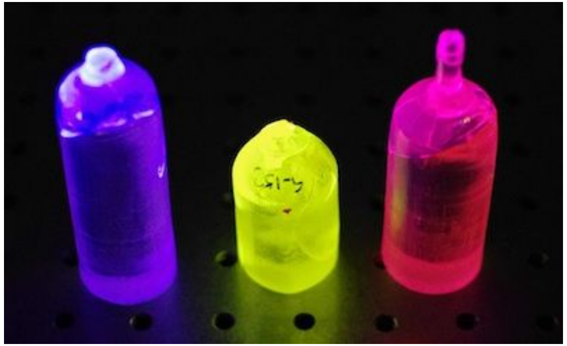
# Scintillators

Scintillators can be very bright

10k photons per MeV of deposited energy

Detectors can observe single photons (though with ~30-50% efficiency typically)

Compare that to ionization. Need some minimum cloud of charge for electronics to detector.



MicroBooNE threshold to find a hit of charge is around 10s of MeV

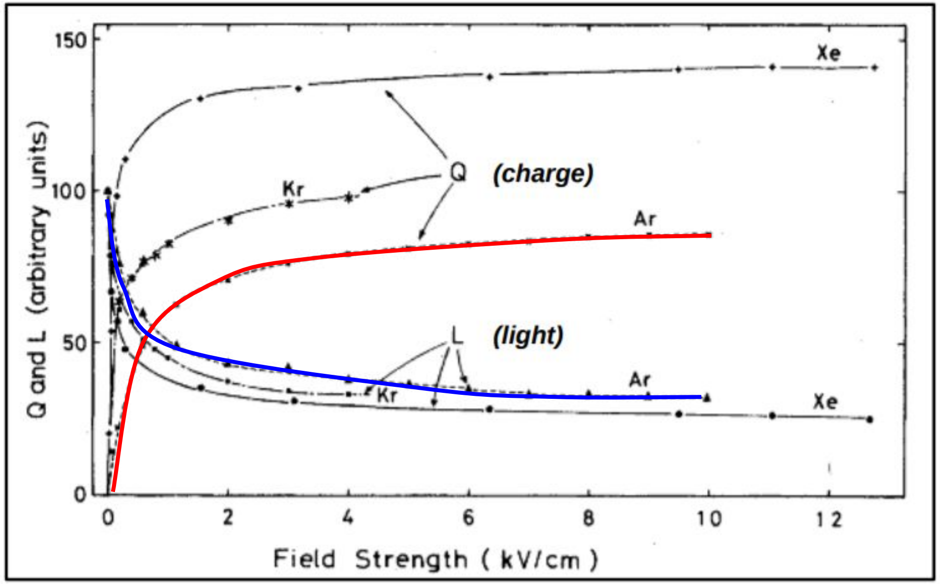
Scintillation light especially useful for low energy interactions

Note: I described organic liquid scintillators -- but there are also plastic and inorganic crystal scintillators as well. Instead of molecular orbitals, creating exiton states that turn into photons

# Scintillation vs. Ionization

- Both processes involve electrons in an atom or molecule to be excited, either into excited orbital (scintillation) or free (ionization)
- In fact, these processes compete: electron can either be liberated or used to make light

Light or Charge versus electron field across a liquid argon detector



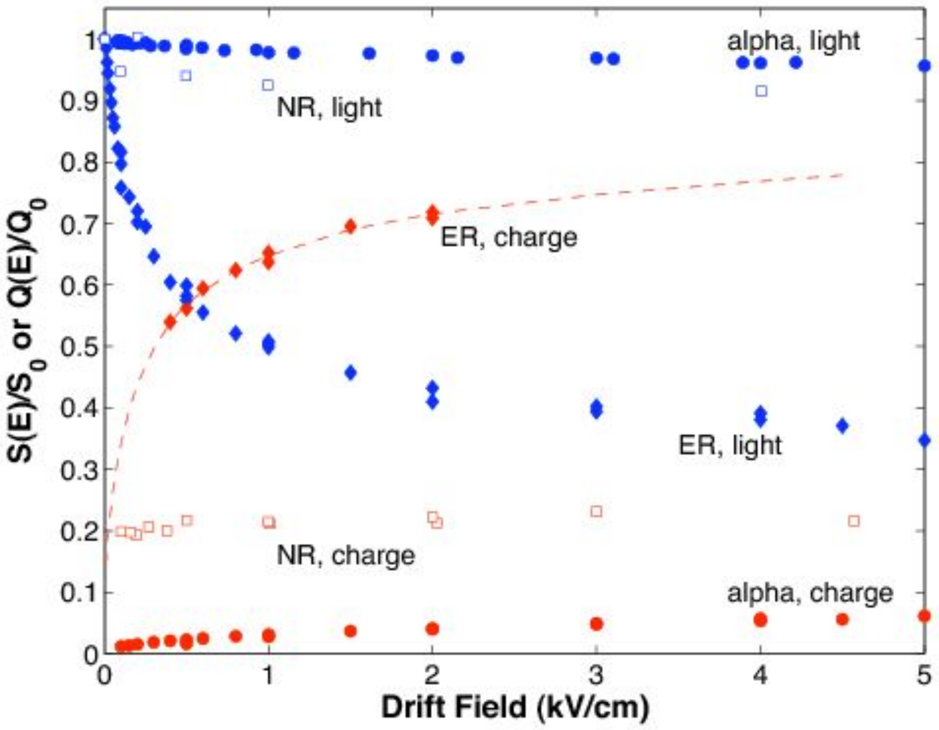

Electric field pulls away electrons

So less around to make light

But more to collect by charge-sensitive instruments

# Scintillation vs. Ionization

- Similar data, but now looking at different particles
- Different ratios of charge and light versus field!
- Again, earlier we know different particles traveling through the detector produce different amount of ionization per unit length
- That different charge density creates differences in the scintillation signal that allows us to distinguish different particles! -- more on that tomorrow.

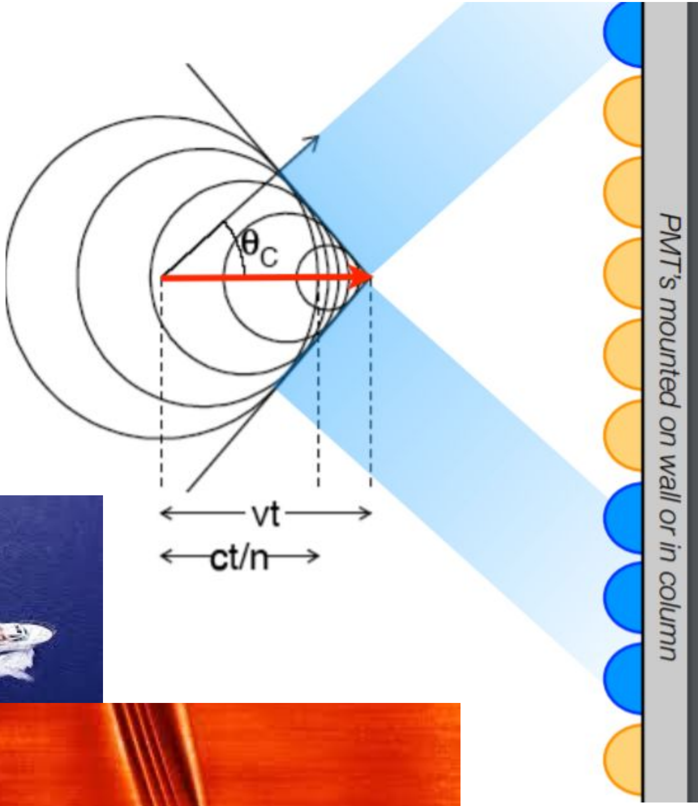


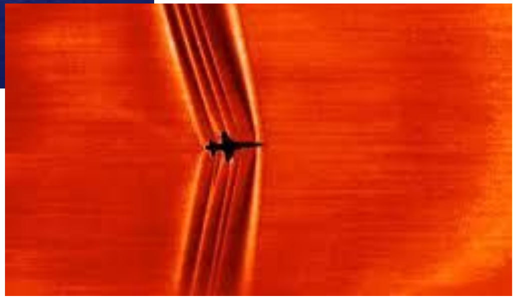
# Cherenkov Radiation

- Radiation that occurs when particl traveling faster than the speed of light in the medium
- Means there is an energy threshold for each particle
- Creates a shockwave of EM radiation -- directly analogous to shockwaves in air or wakes in water
- Broad spectrum: favors UV/blue
- Often photon sensors on walls, leaves a ring light pattern

**Thresholds (MeV)**

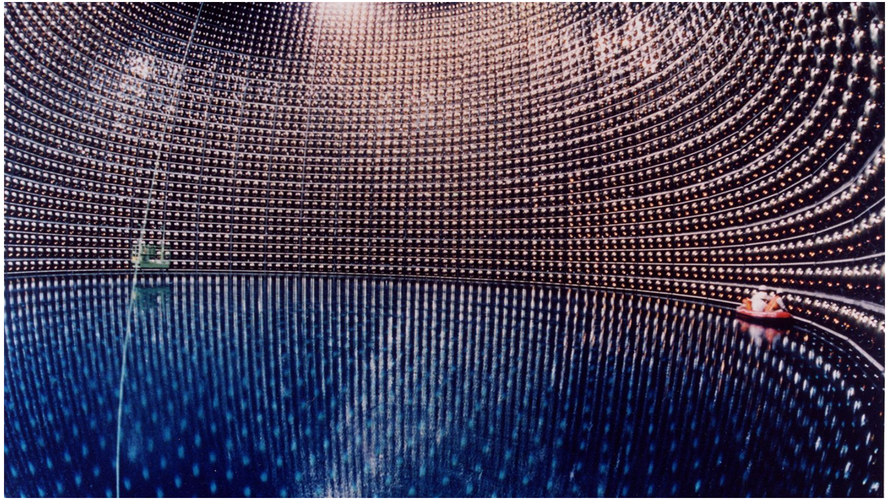
| | |
|---|---|
| e | 0.73 |
| μ | 150 |
| π | 200 |
| p | 1350 |

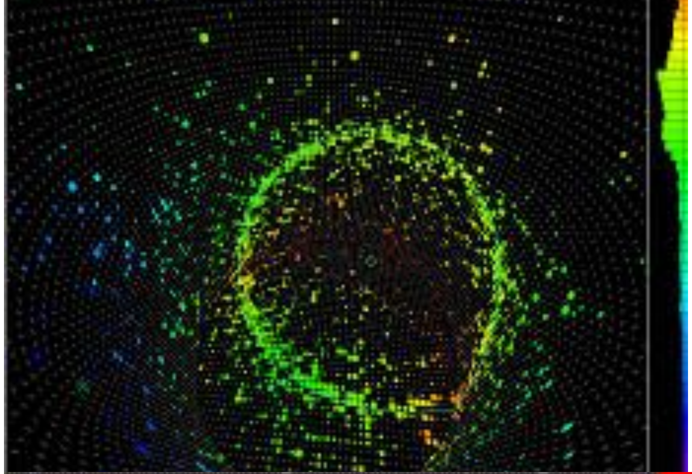


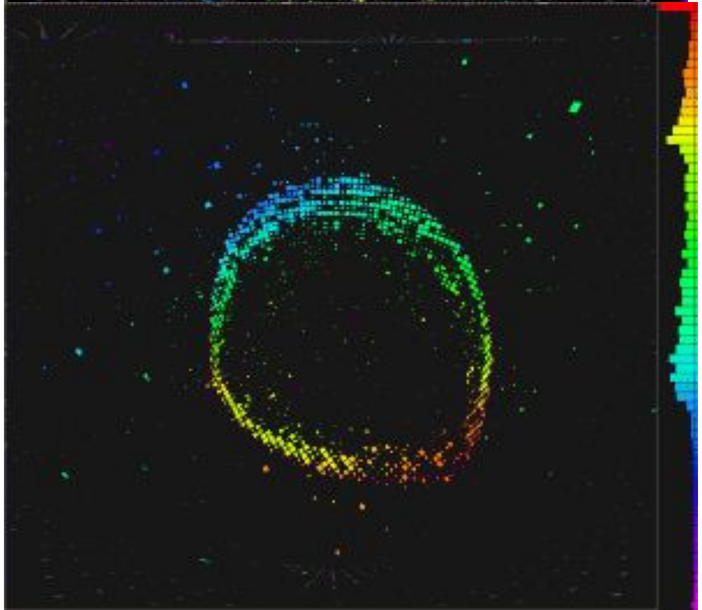



# Cherenkov Radiation

- Often photon sensors on walls, leaves a ring light pattern
- Here two examples from the Super-Kamiokande detector

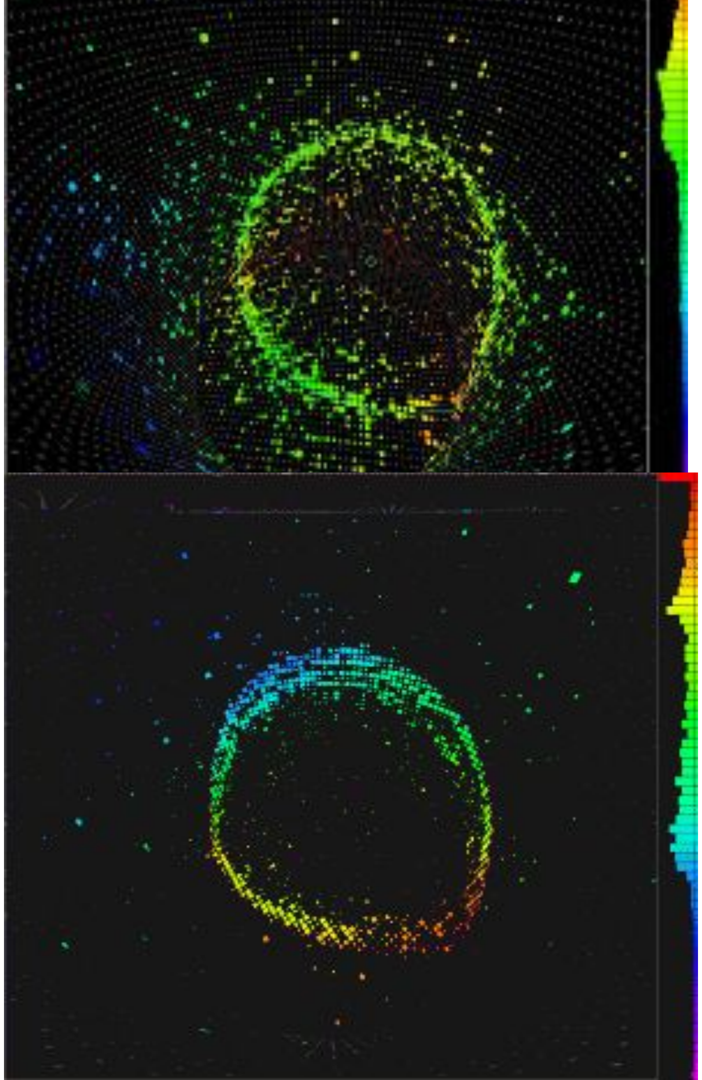






# Cherenkov Radiation

- One of these is from an electron
- Another is from a muon
- Thinking about how the pattern of ionization was different for electron and muon, can we reason which is which?



# Recap: signals from light

- Charged particles traveling through the detector can make scintillation light and Cherenkov light
- Both have particle ID capabilities!

| Scintillation light | Cherenkov light |
| --- | --- |
| Isotropic<br>10k photons per MeV | Directional<br>100s of photons per MeV |
| PID through light pulse shape | Ring shape provides PID |

# Summary

- We’ve covered the common signals to observe neutrino interactions
  - Ionization electrons ✓
  - Scintillation ✓
  - Scattering w/ electron (delta-rays) ✓
  - Multiple-coulomb scattering
  - Bremsstralung radiation ✓
  - Cherenkov radiation ✓
  - Heat
- Tomorrow: cover the types of detectors used
- But we already know enough to define possible strategies for looking for different physics signals

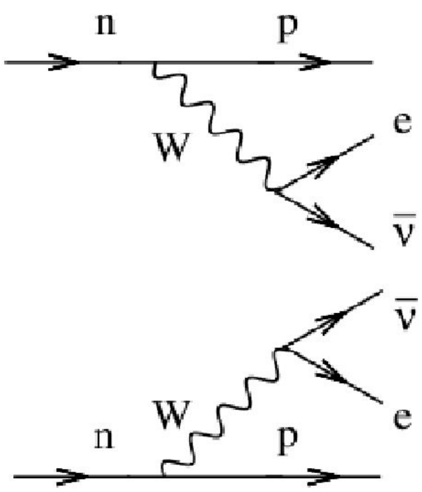
# Activity

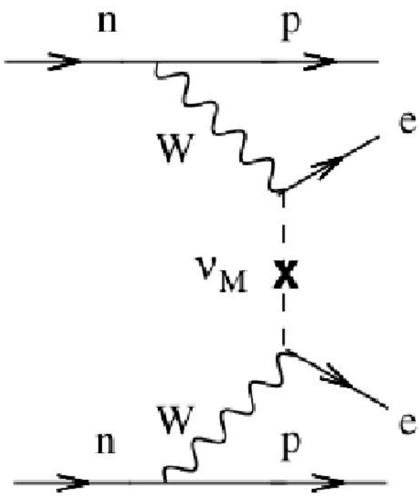
# Activity

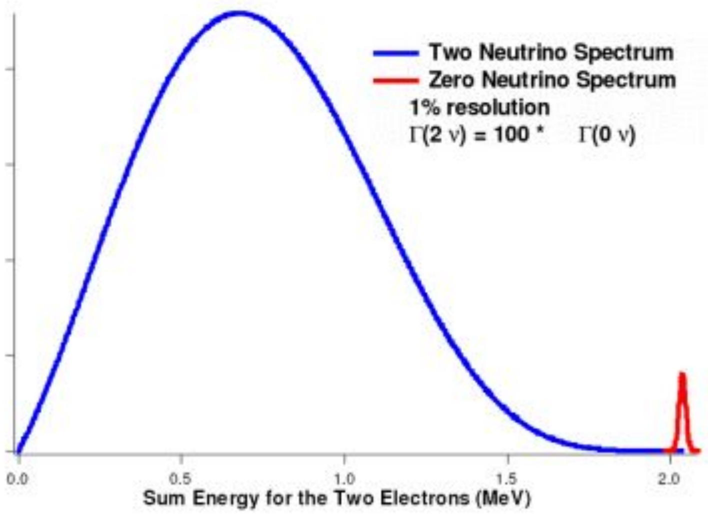
- Form into groups
- Pick a physics topic
  - Measuring neutrinoless double beta decay
  - Looking for sterile neutrinos
  - Measure delta-CP
  - Measuring one of the oscillation mixing angles
  - Looking for indirect signs of dark matter
- There are a couple of different strategies to make the measurement
- Come up with one or two ways to measure the signal and why it would work
  - This means, picking a ***source of neutrinos*** and a ***signal type***
- Also, think about one type of detector that won't work -- and why?
- We'll go around at the end and discuss. Volunteer someone in group to outline what the detector signal seems promising and why? What are the drawbacks for that choice?

# Signals

- Neutrino-less double beta-decay
- A process that would indicate that the neutrino is it’s own anti-particle
- Signal: two electrons back-to-back



# Signals

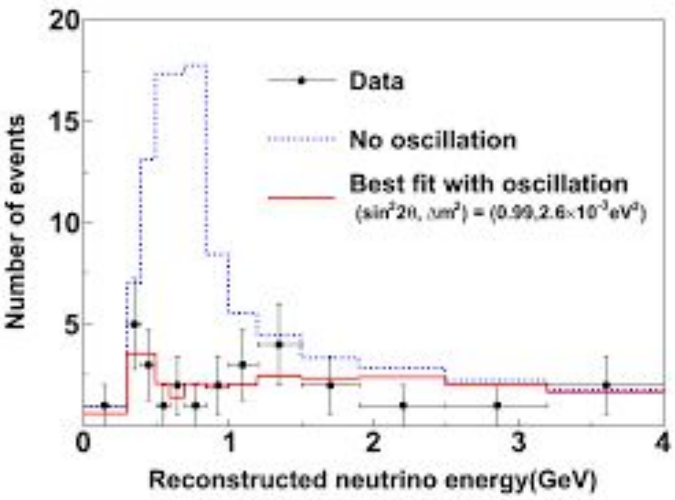
- Do neutrinos violate CP-symmetry?
- Compare rate of process called neutrino-oscillations for neutrino and anti-neutrinos
- Compare: numu turning into nue and numu-bar into nue-bar

# Signals

- Is there an additional neutrino?
- Signal: neutrinos in one flavor can turn into another flavor (i.e. oscillate) for energies and over distances not consistent with the three standard model neutrinos
- Measurement: observe that the number of electron neutrinos in a majority muon neutrino beam (100:1) are more than expecte
- Alternative: neutrinos coming from a source seem to disappear, i.e. they turn into a flavor where they cannot be seen

# Signals

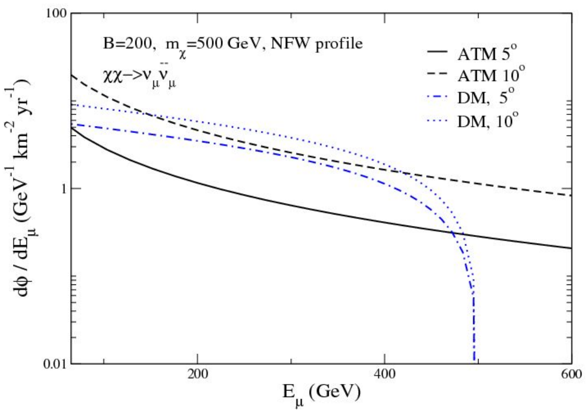
- Precision measurement of neutrino oscillation parameters
- Signal: neutrinos in one flavor can turn into another flavor (i.e. oscillate) with a very specific L/E depenence
- Measurement: observe the right pattern of oscillations for values of L and E




Numu spectrum with and without oscillations from an experiment called T2K

# Signals

- Detect neutrinos coming from dark matter annihilation
- Signal: neutrinos coming from a region of relatively high gravitational mass such as the sun, the core of the earth, or the center of the milky way galaxy
- Dark matter masses of interest range from 1-10 GeV to 1-10 TeVs
- Start with a dark matter decay product is a pair of neutrinos



Things to consider when picking a source

-- energy
-- given energy, what products can I produce? (production threshold)
-- do I have the right flavor of neutrinos I need?

# Sources for neutrino detectors