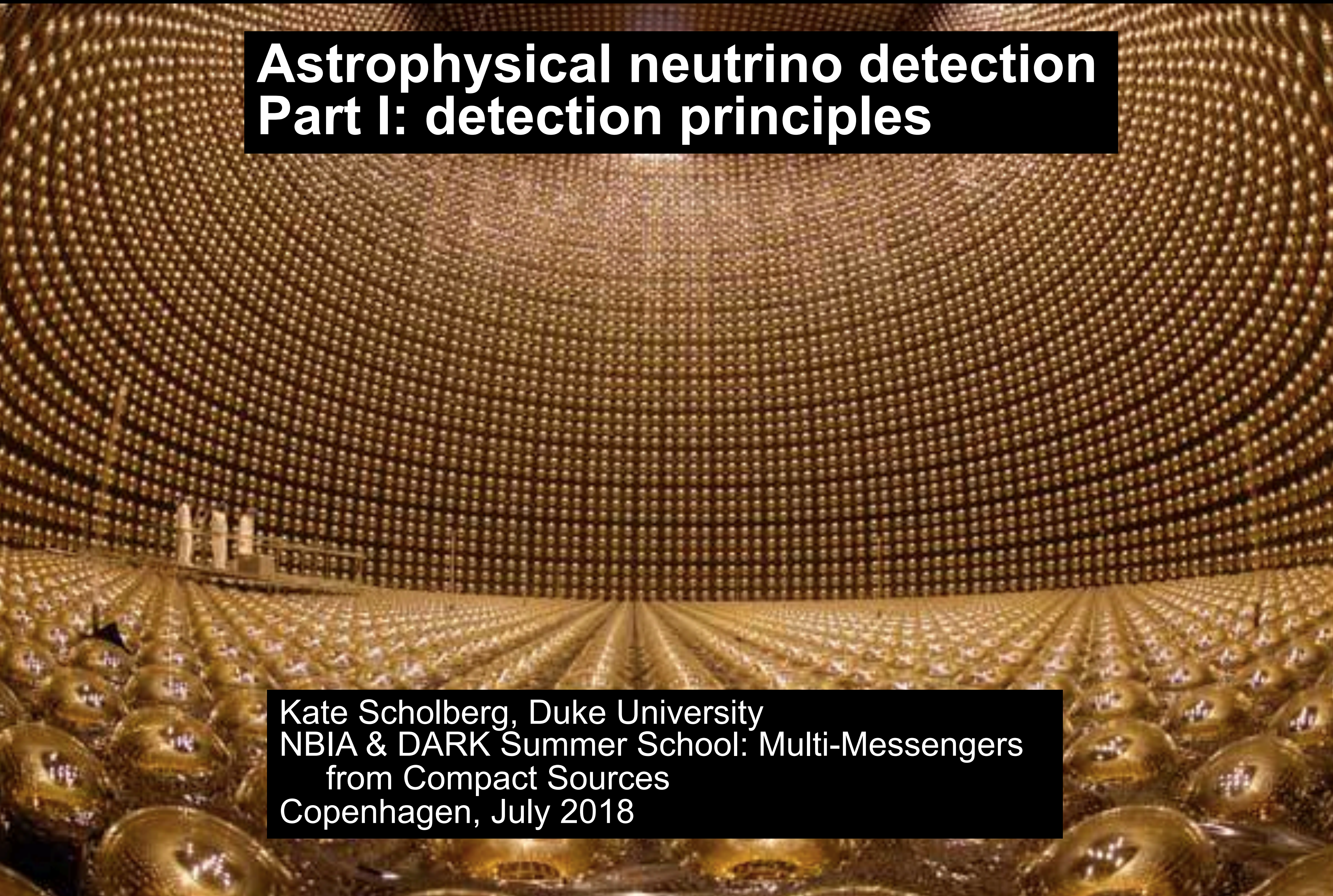
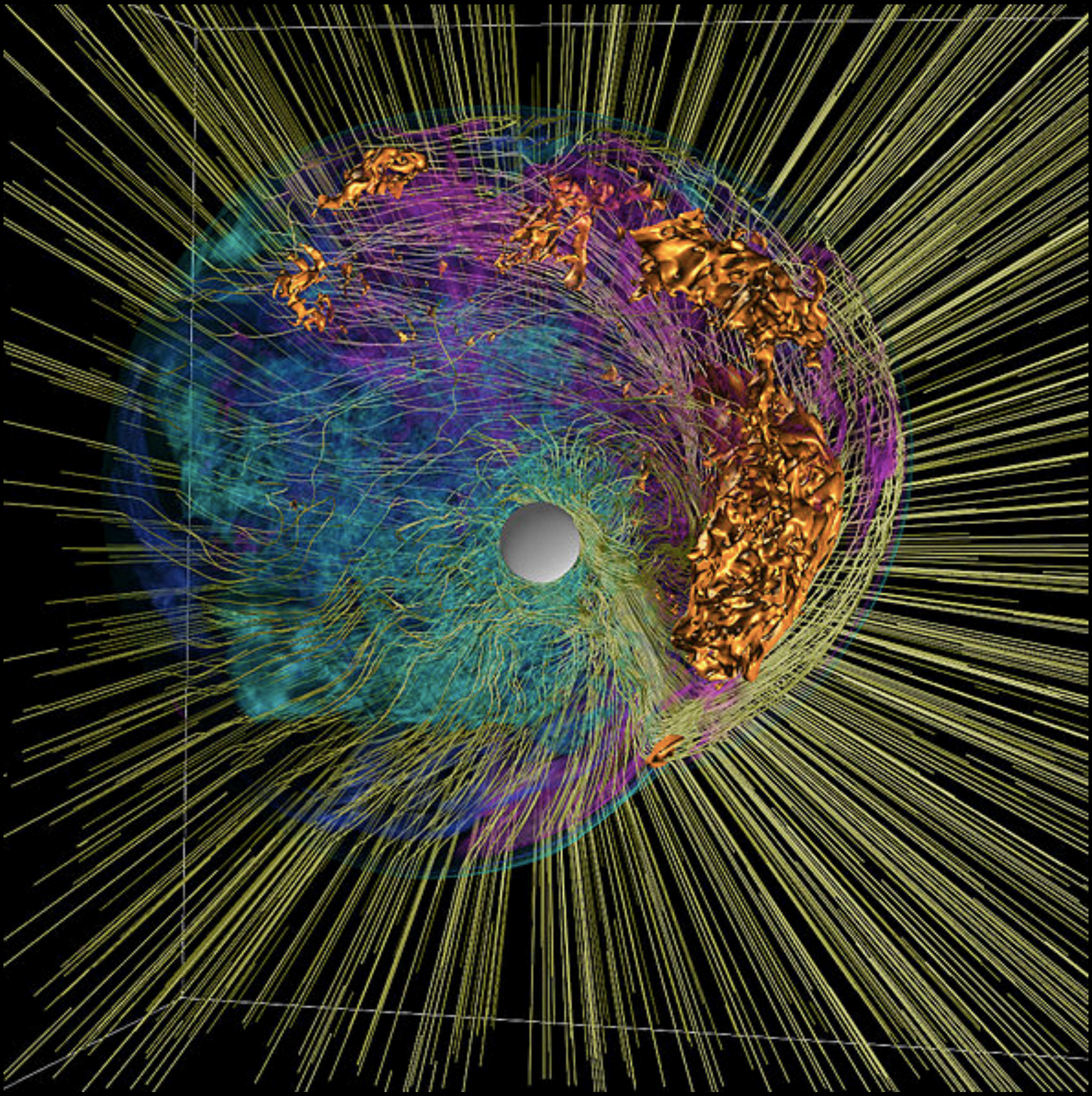


Astrophysical neutrino detection
Part I: detection principles

Kate Scholberg, Duke University
NBIA & DARK Summer School: Multi-Messengers from Compact Sources
Copenhagen, July 2018

Goal of these lectures



Describe detection techniques, capabilities and issues for astrophysical neutrino detectors over a range of energies (emphasis on core-collapse supernovae)

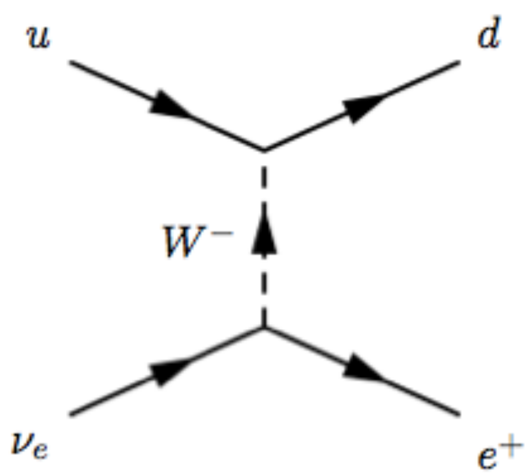
A. Mezzacappa

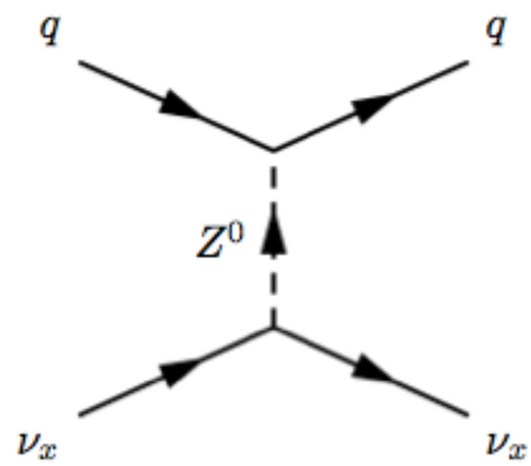
NEUTRINOS

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

neutral partners
to the charged leptons

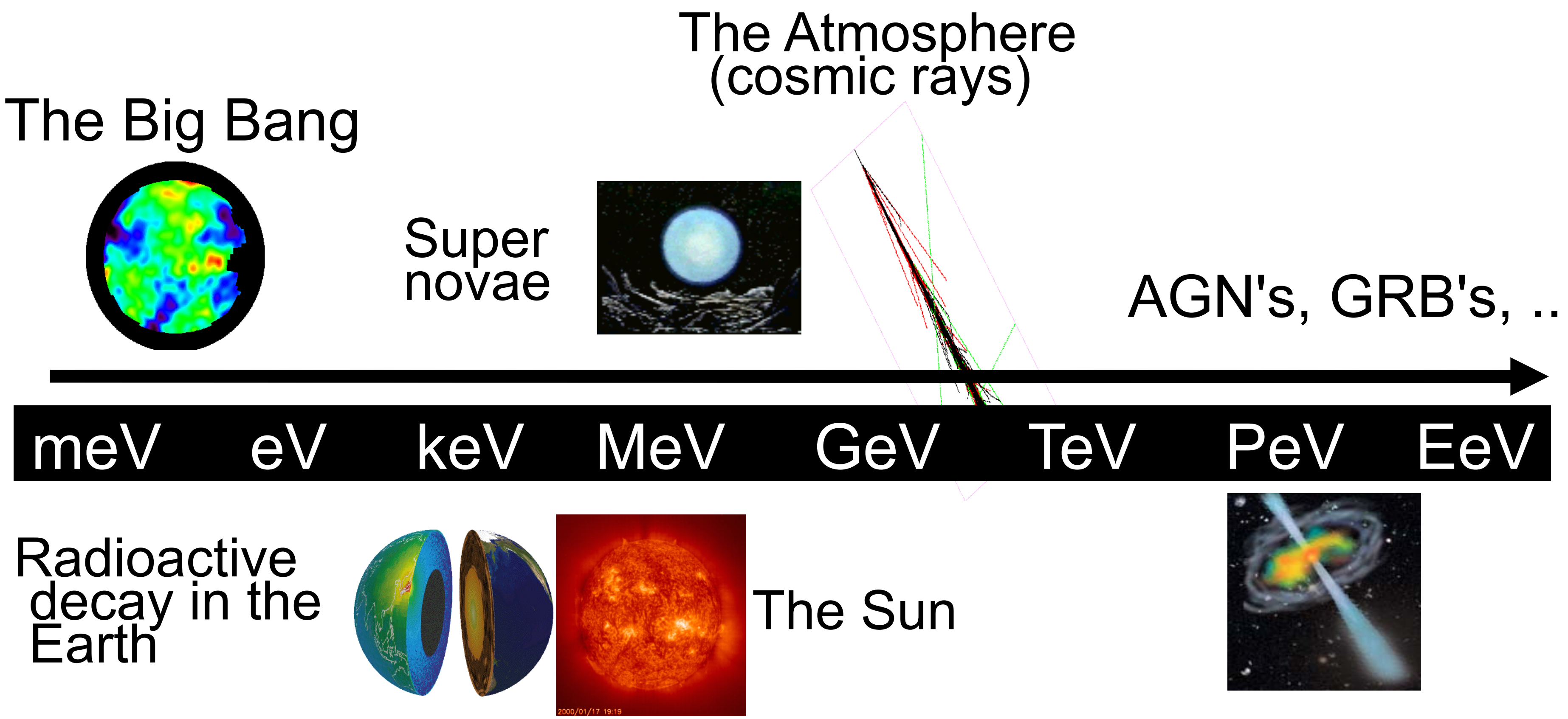
- Three flavors (families), neutrinos and antineutrinos
- Tiny masses (< 1 eV) and **oscillations** (flavor change)
- Interact *only* via *weak interaction* (& gravity)





Exchange of
W and Z bosons in
weak interactions

Sources of ‘wild’ neutrinos

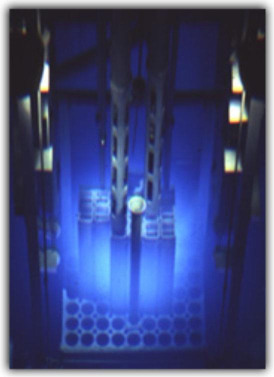


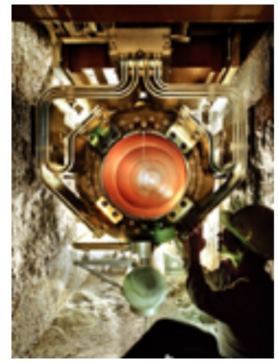
Sources of ‘tame’ neutrinos

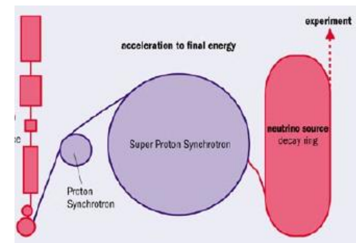
Proton accelerators

Beta beams

Nuclear reactors

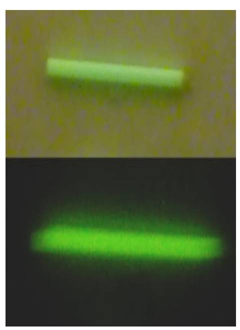


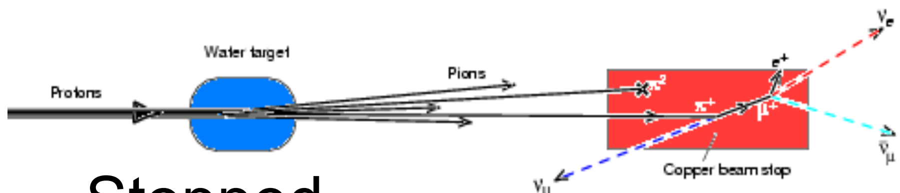




eV keV MeV GeV TeV

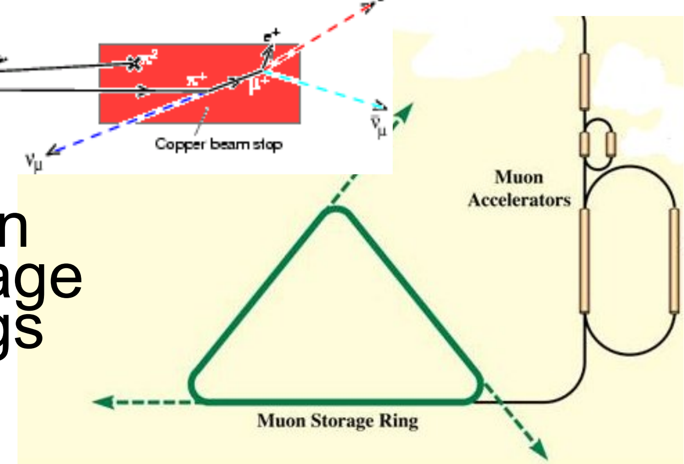
Artificial radioactive sources





Stopped pion sources

Muon storage rings



... common strategies, but we’ll focus on the “wild” ones...

Lecture Overview

- Neutrino interactions with matter
- General principles of particle detection
- Survey of neutrino detection techniques

- Specific astrophysical detectors,
  organized by energy range

- few to few tens of MeV:
  core-collapse supernova, solar

- few hundred MeV to TeV
  atmospheric ν's

- TeV to EeV +
  AGNs, GRBs, mergers, ...

Tue

as far
as we
get....

Fri

Lecture Overview

- Neutrino interactions with matter
- General principles of particle detection
- Survey of neutrino detection techniques

- Specific astrophysical detectors, organized by energy range

  - few to few tens of MeV:
    core-collapse supernova, solar

  - few hundred MeV to TeV
    atmospheric ν's

  - TeV to EeV +
    AGNs, GRBs, mergers, ...

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:

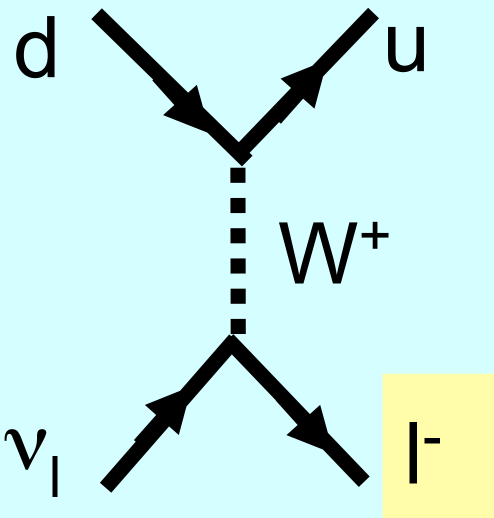
- flavor/CP state
- energy
- direction
- time of interaction
- position of interaction

plus pretty much always want:

- high statistics (mass,efficiency)
- low background

Neutrino interactions with matter

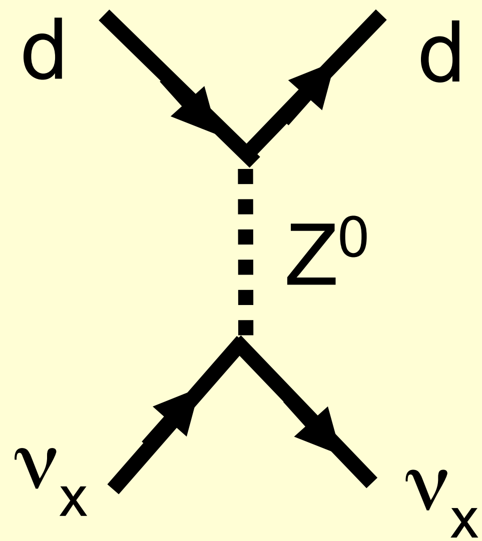
Charged Current (CC)



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

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

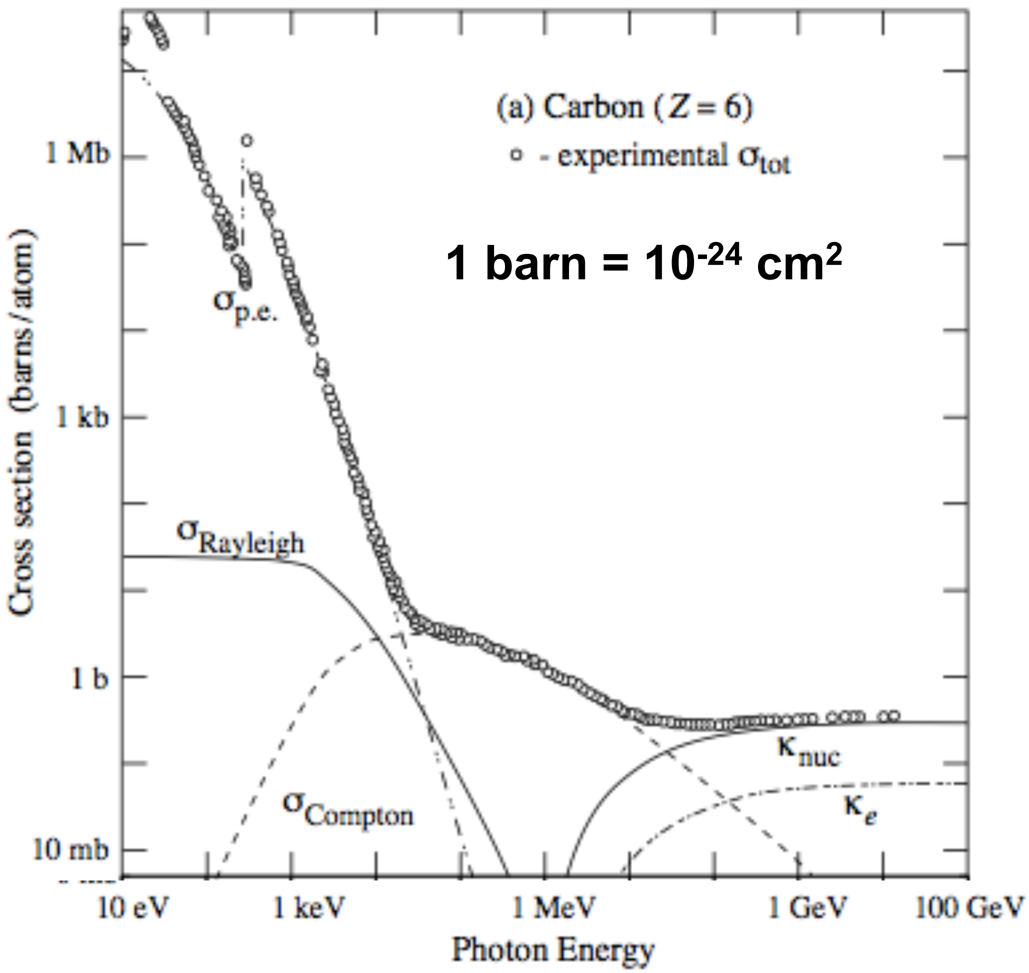
Neutral Current (NC)



Flavor-blind

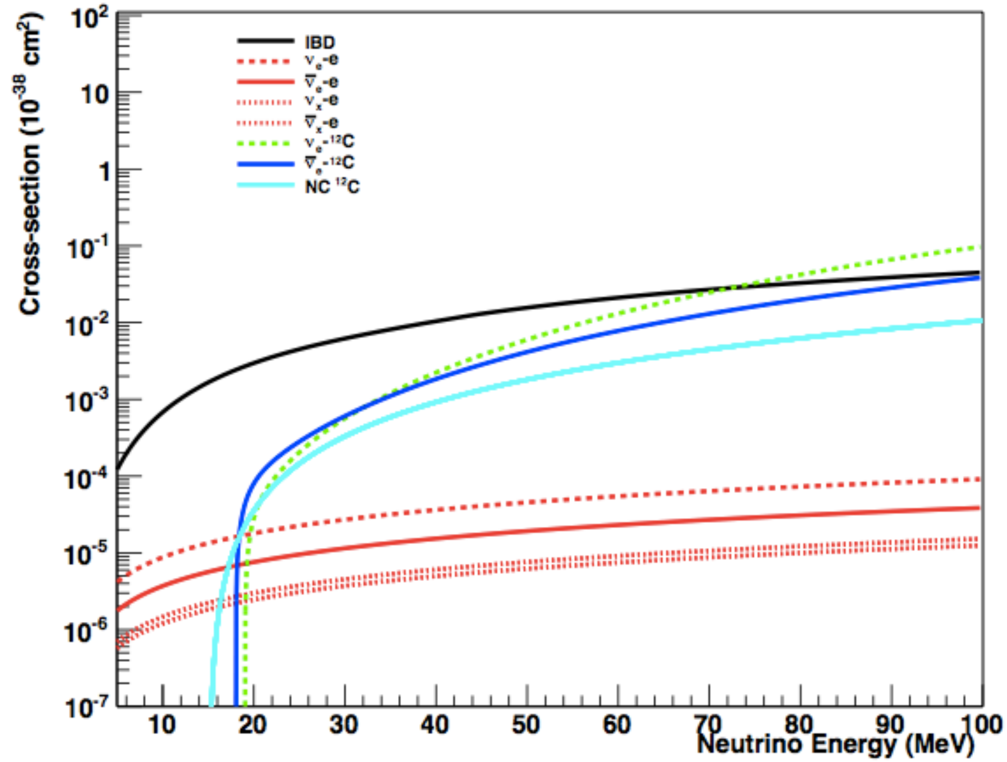
It's called the weak interaction for a reason

Photon-matter cross-sections



~10^{-24} cm^2

Neutrino-matter cross-sections



~10^{-40} cm^2

~16-17 orders of magnitude smaller

In 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!

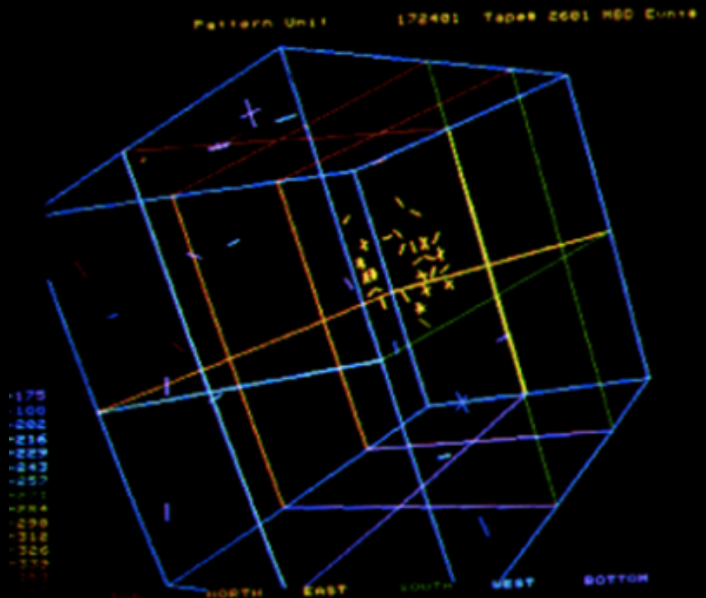
Jargon alert!

In particle physics,
an “event” is *not* this...

~10^{52-53} ergs

It’s an individual *recorded neutrino interaction*:

few times
10^{-5} ergs



e.g., “the IMB neutrino
detector saw 8 events
from 1987A”

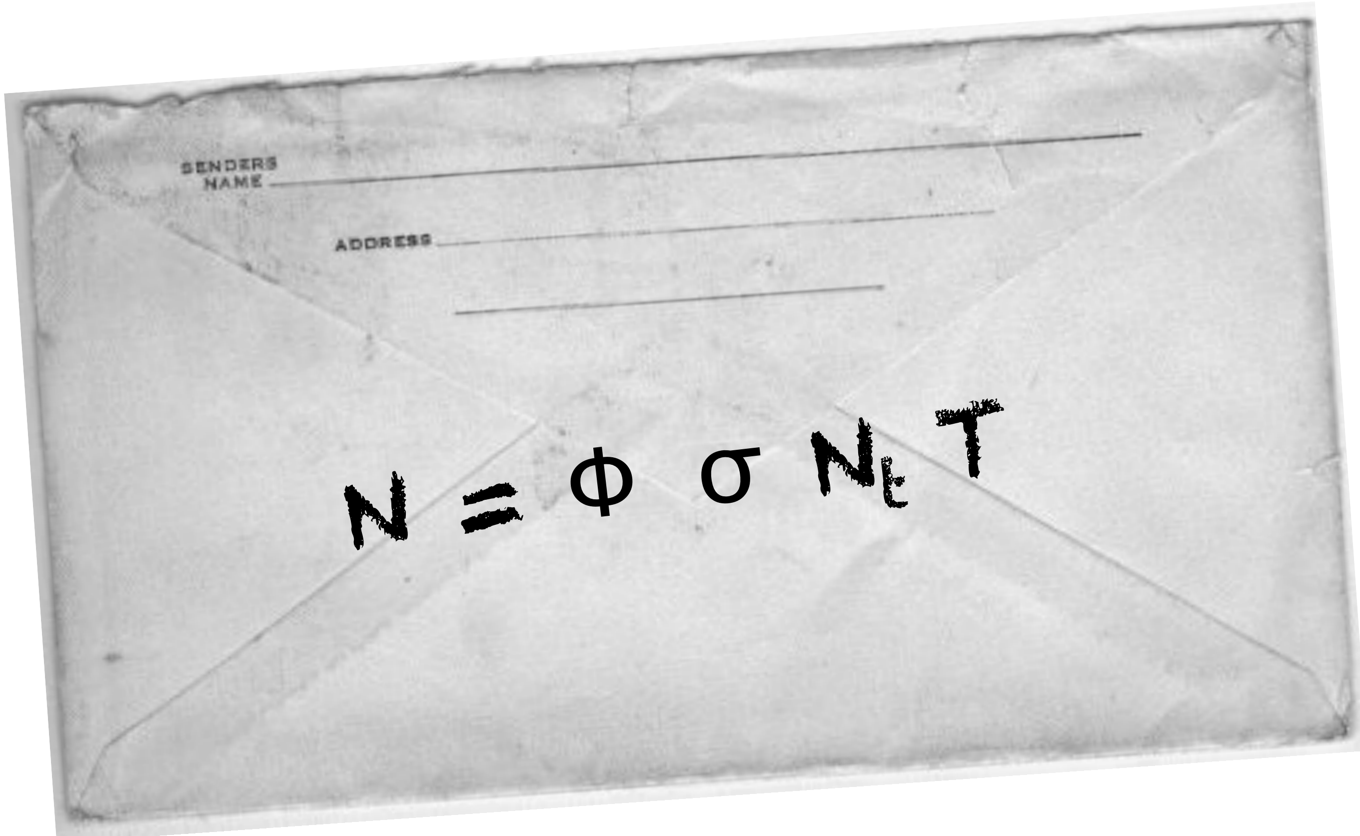
Interaction rates in a detector material

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

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

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

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

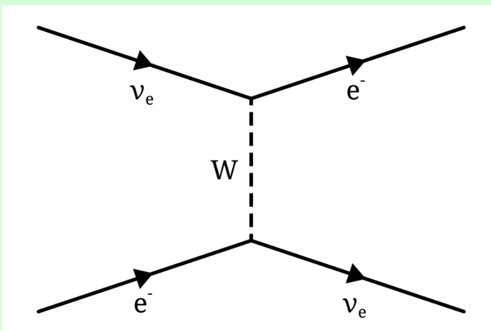


How many solar neutrinos will interact in your body during your lifetime?

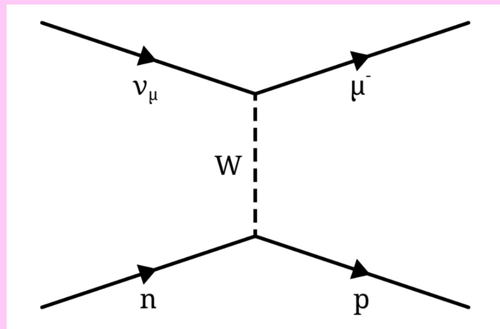
$\sigma \sim 5 \times 10^{-44}$ cm^2 (electron scattering cross-section above a few MeV)
$\phi \sim 2 \times 10^6$ cm^{-2}s^{-1} (flux above a few MeV, mostly from ^{8}B neutrinos)

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

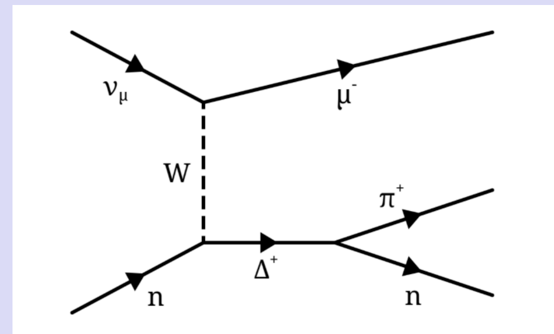
Common nomenclature for neutrino interactions



"Elastic"
same particles
in as out



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



"Inelastic"
energy converted
to new particles

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

Tool for predicting neutrino event rates

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

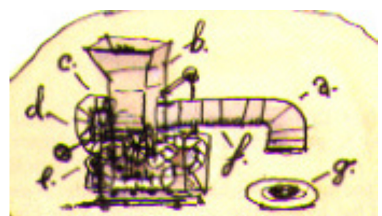
neutrino flux differential spectra w/physics

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

SNOwGLoBES



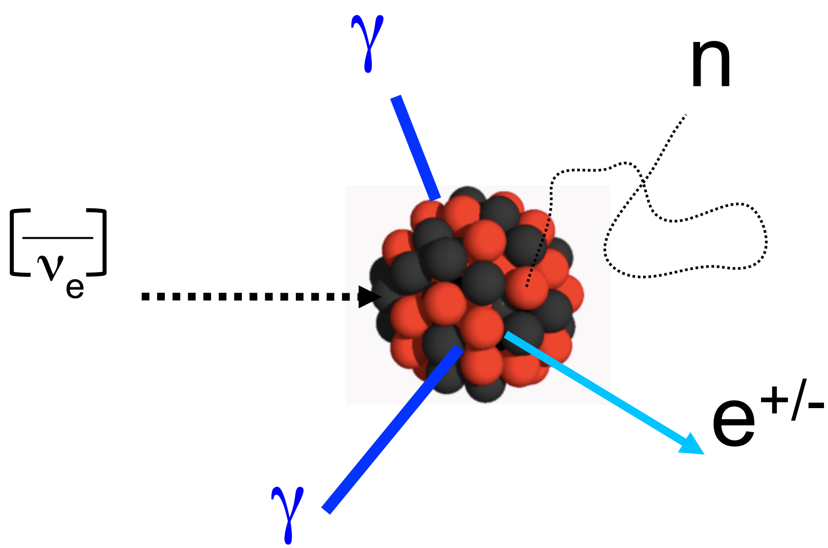
interaction rates, as a function of neutrino energy

'smeared' rates as a function of detected energy

what we see in a detector

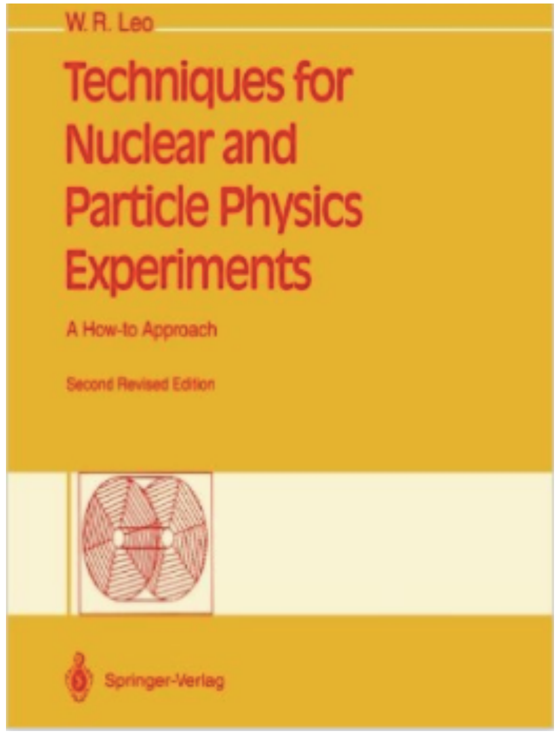
http://phy.duke.edu/~schol/snowglobes

First: **physics of electromagnetic- or strongly-interacting particle detection.**
with emphasis on cases common in ν experiments



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

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).

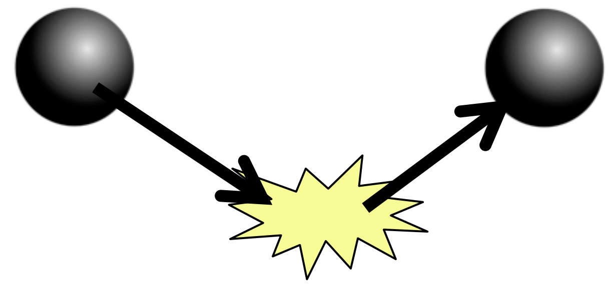
This review covers the interactions of photons and electrically charged particles in matter, concentrating on energies of interest for high-energy physics and astrophysics and processes of interest for particle detectors (ionization, Cherenkov radiation, transition radiation). Much of the focus is on 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)

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

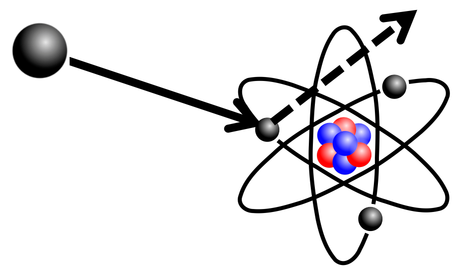


<table>
<tr><td rowspan="5">Common energy-loss processes</td><td colspan="2">Inelastic collisions w/ atomic electrons</td></tr>
<tr><td>Soft (excitations)</td><td>Hard (ionization, secondaries)</td></tr>
<tr><td colspan="2">Elastic scattering from nuclei</td></tr>
<tr><td colspan="2">Cherenkov radiation</td></tr>
<tr><td colspan="2"></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

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

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	$6.022\,141\,29(27)\times 10^{23}$ 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
	$\sqrt{4\pi N_e r_e^3}\ m_ec^2/\alpha$	$\hookrightarrow \rho$ 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}

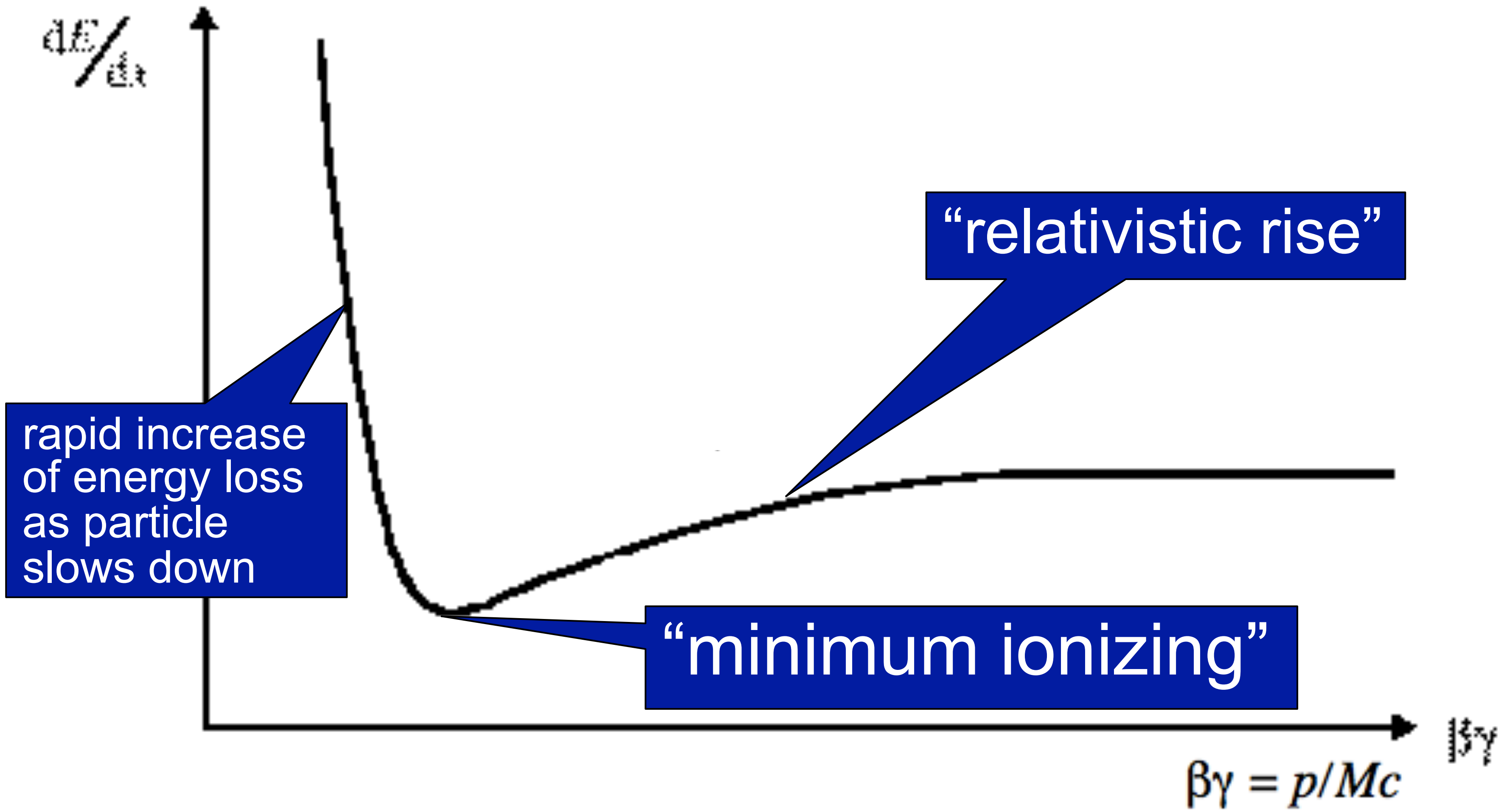
good to ~% in MeV-GeV range and intermediate Z materials

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

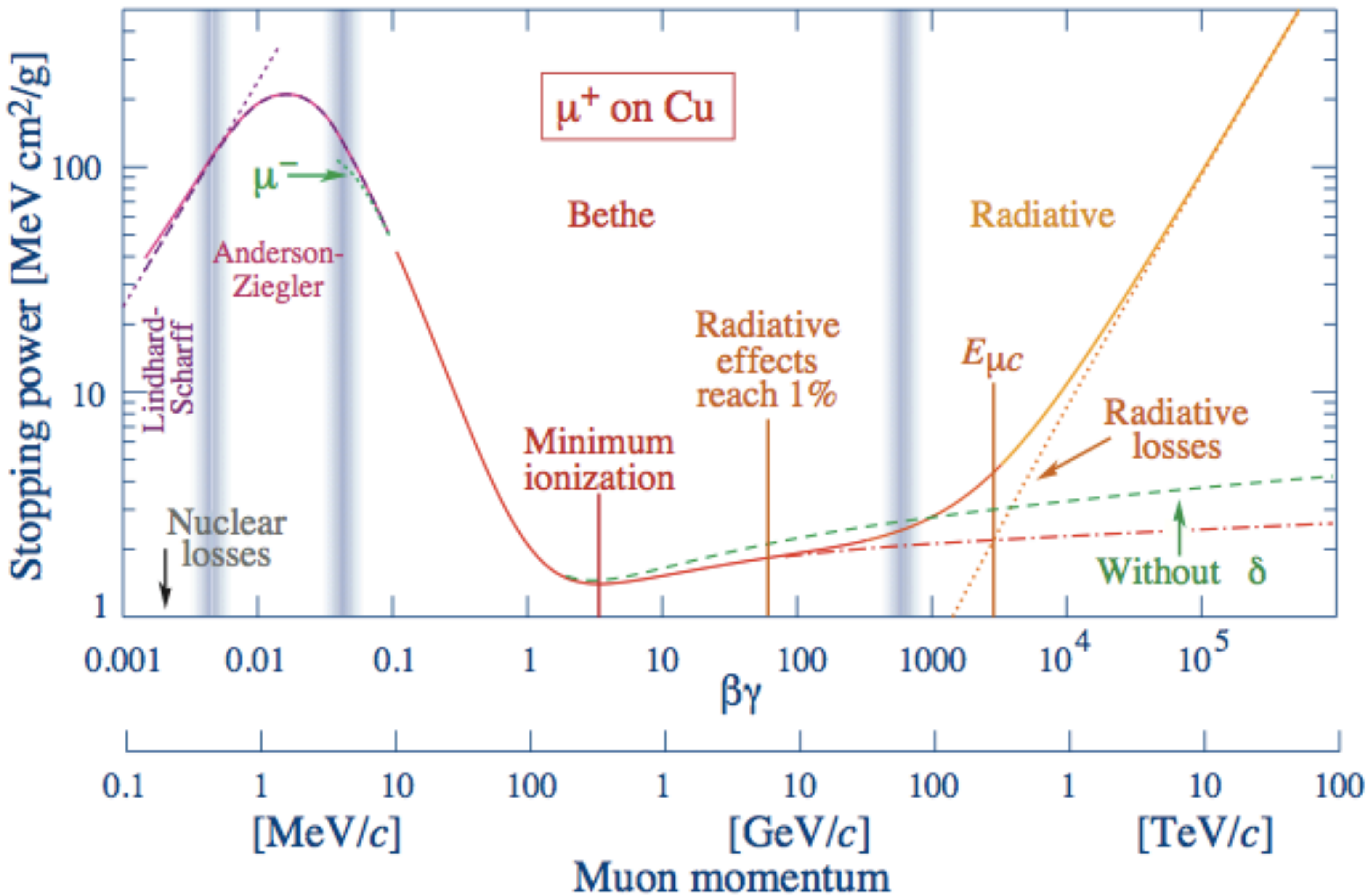
What this function looks like:

usually drawn log-log

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

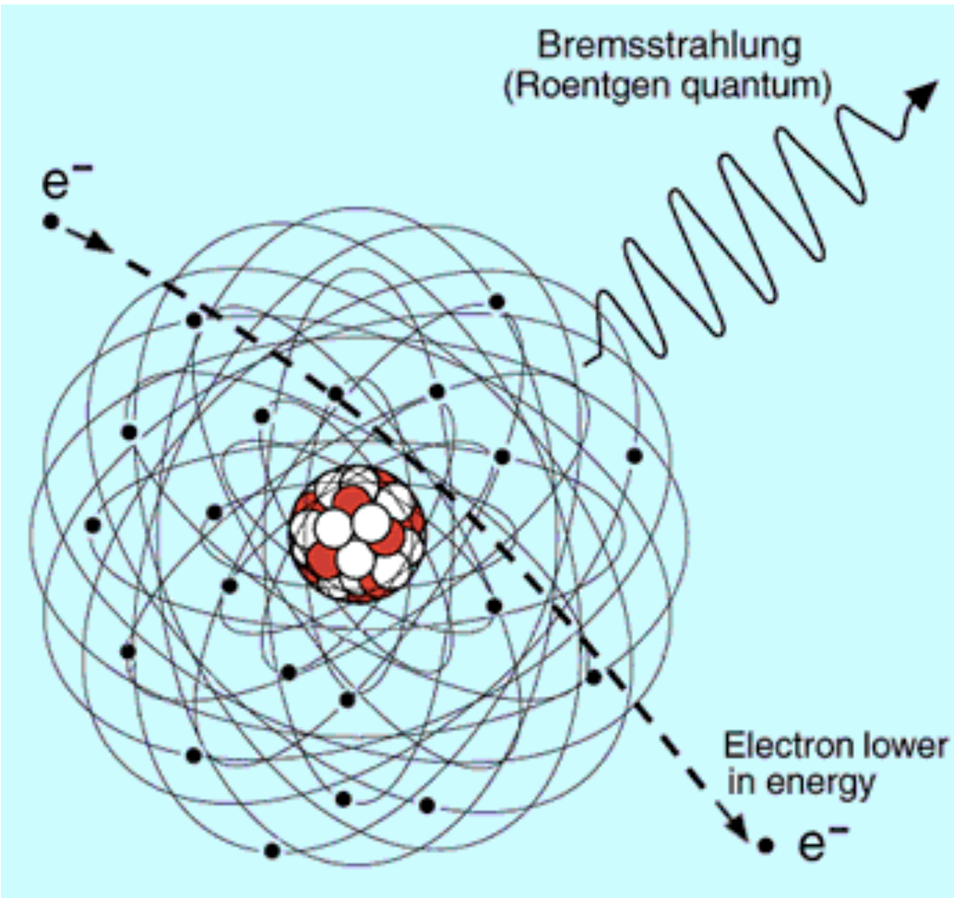


Be aware: Bethe-Bloch primarily valid for “intermediate” energies



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)**

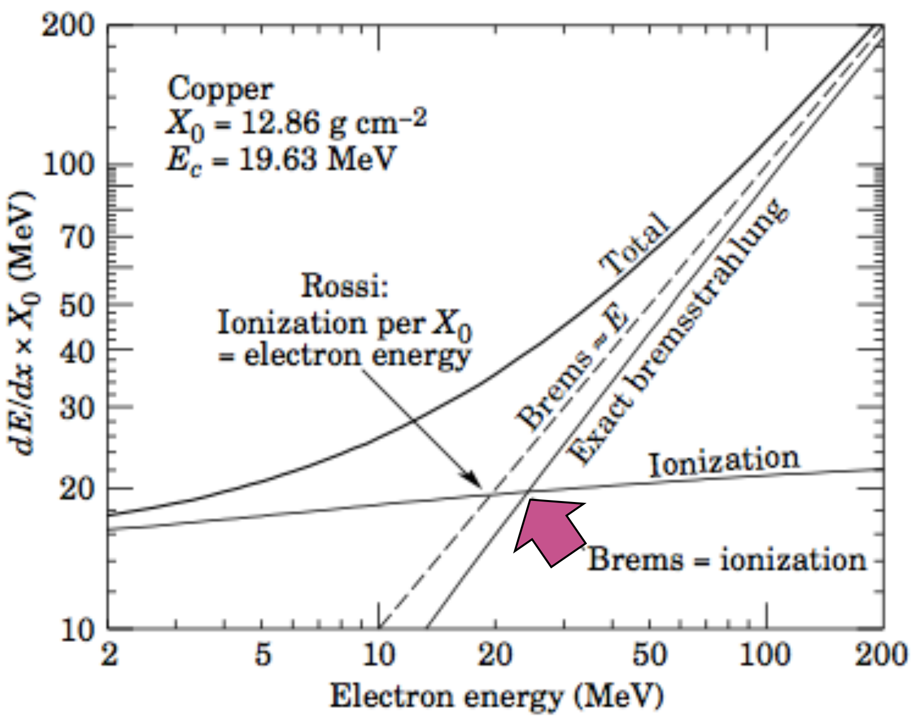
$$\text{prob} \propto \frac{1}{\text{m}^2}$$

so brems from μ’s down by

$$m_e^2/m_\mu^2 = 0.511^2/106^2$$
$$\sim 4.5 \times 10^{-5}$$

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

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

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

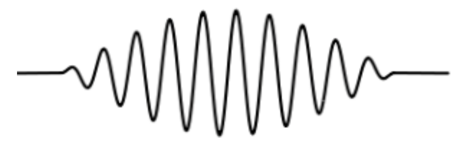
Table 2.3. Radiation lengths for various absorbers

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

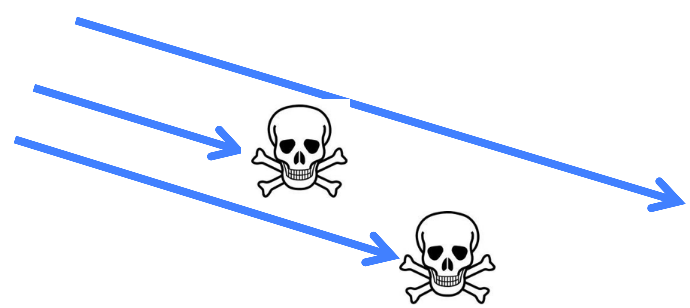


photons have no electric charge...
➔no Coulomb-induced collisions

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)

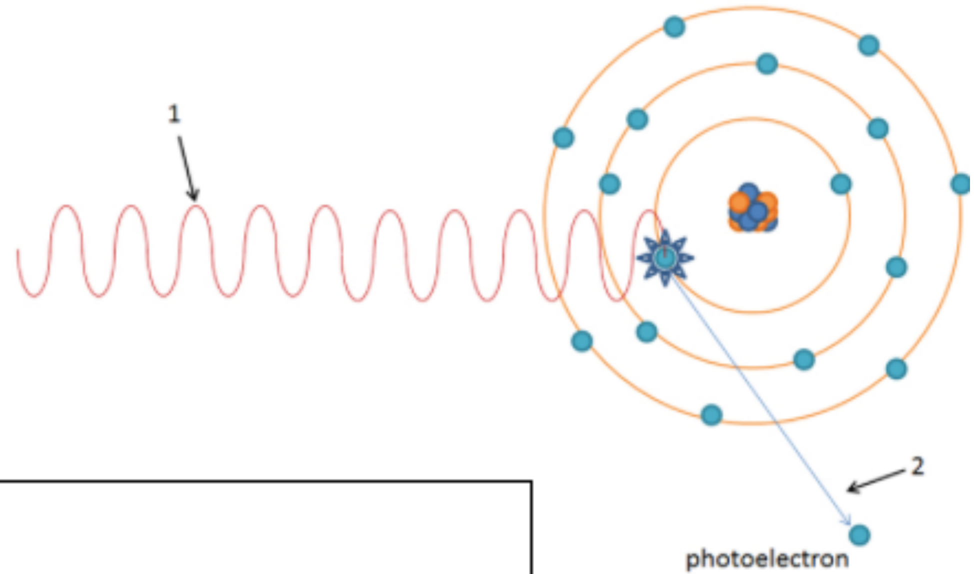


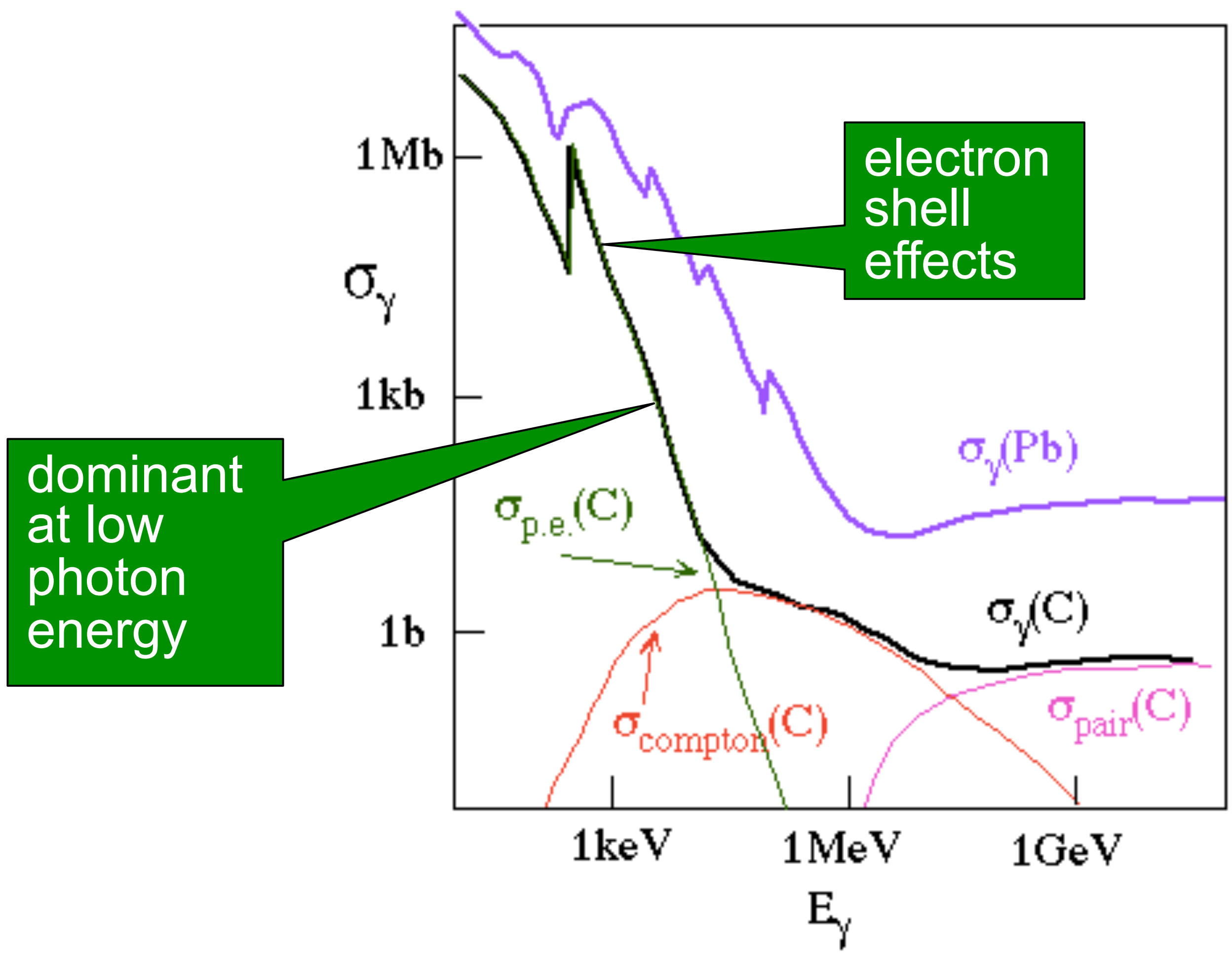
(Rayleigh scattering: scattering
off whole atoms; small at energies of
interest here)

Photoelectric Effect

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

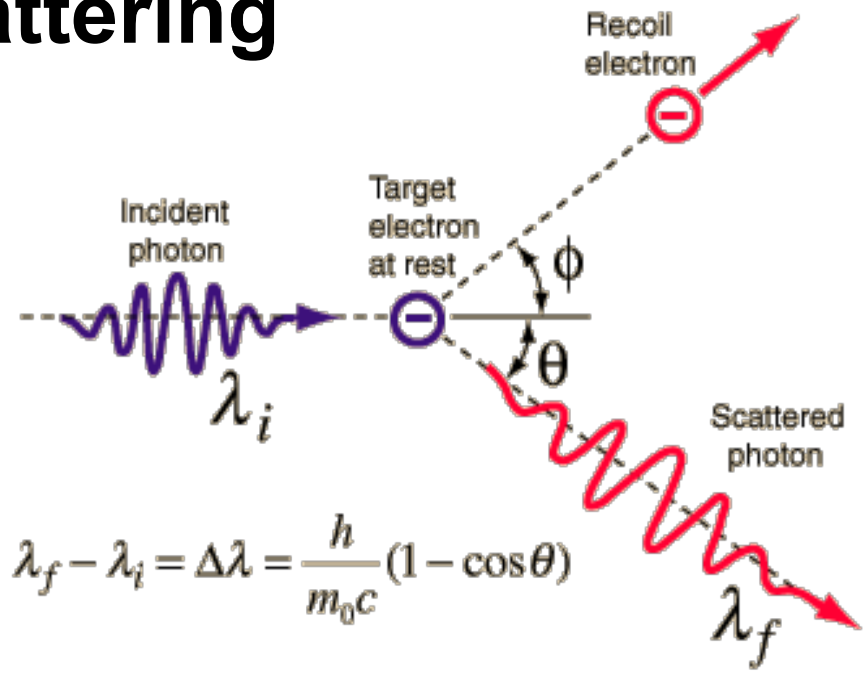
$$E_e = h\nu - \mathrm{B.E.}$$



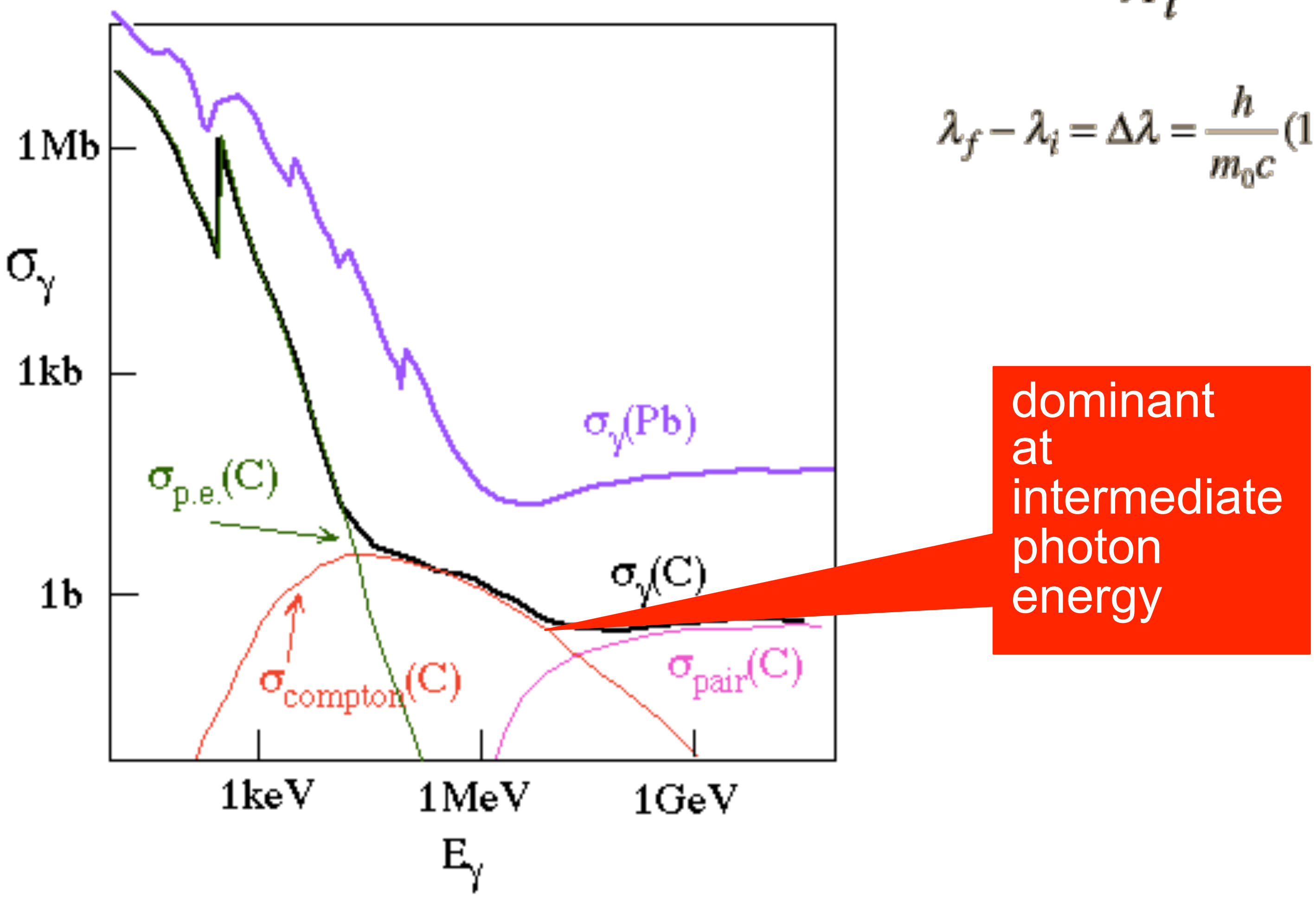


Compton Scattering

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



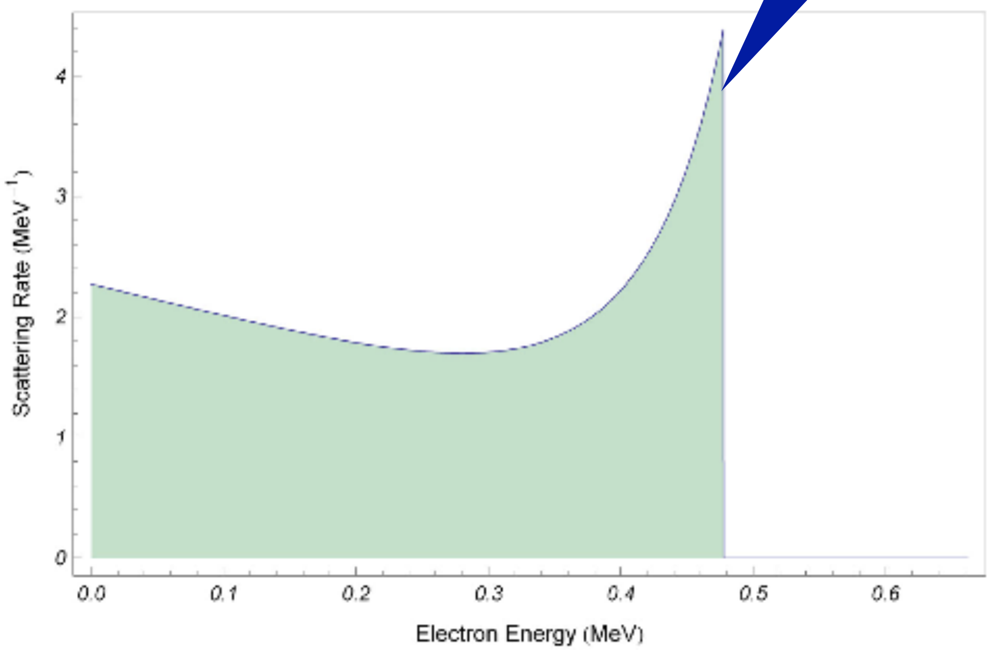
$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

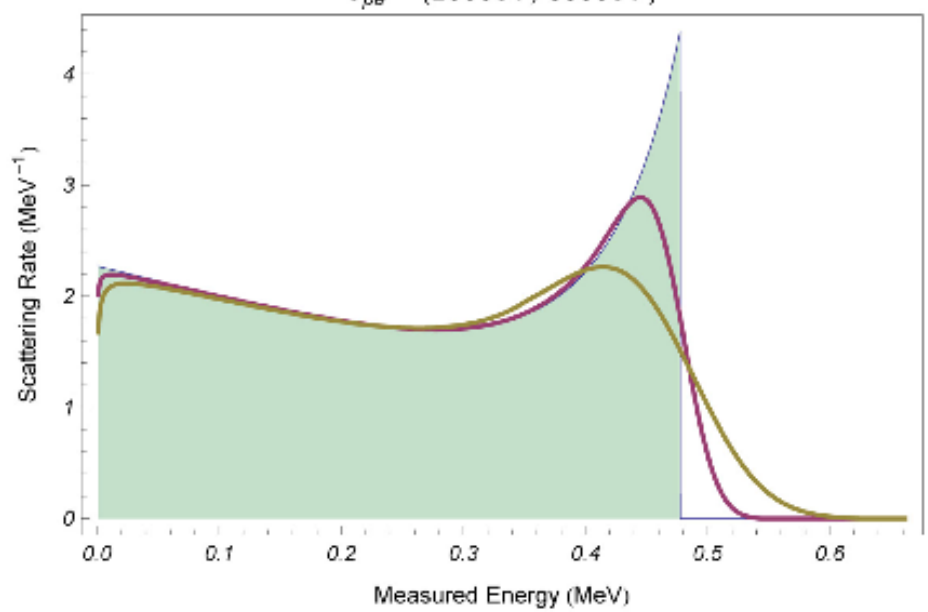


Cross section calculated with Klein-Nishina formula (QED)

Compton recoil energy distribution

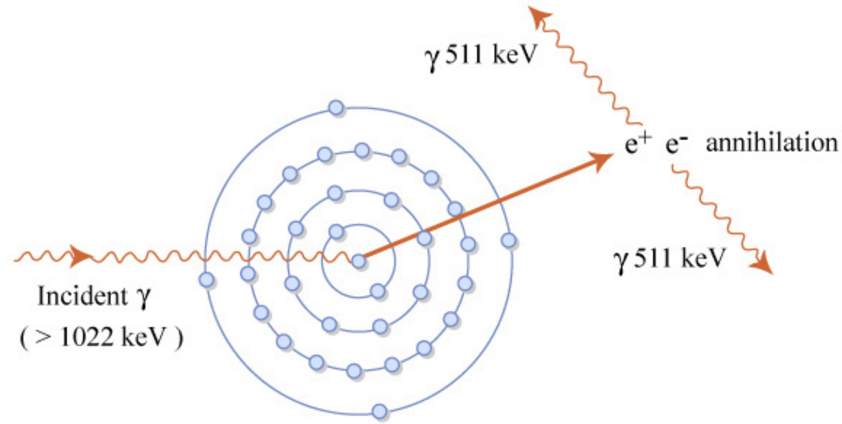
“Compton edge” for given γ energy

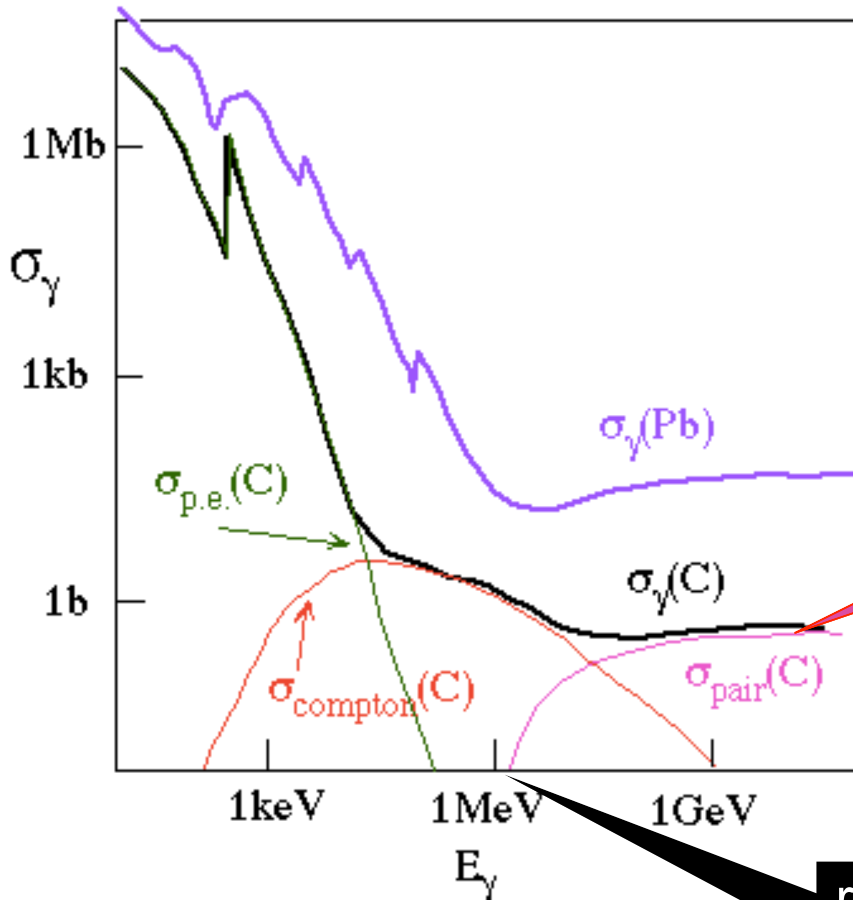




$$W_{\max} = h\nu\left(\frac{2\gamma}{1+2\gamma}\right) \qquad \gamma = \frac{h\nu}{m_e c^2}$$

Pair production

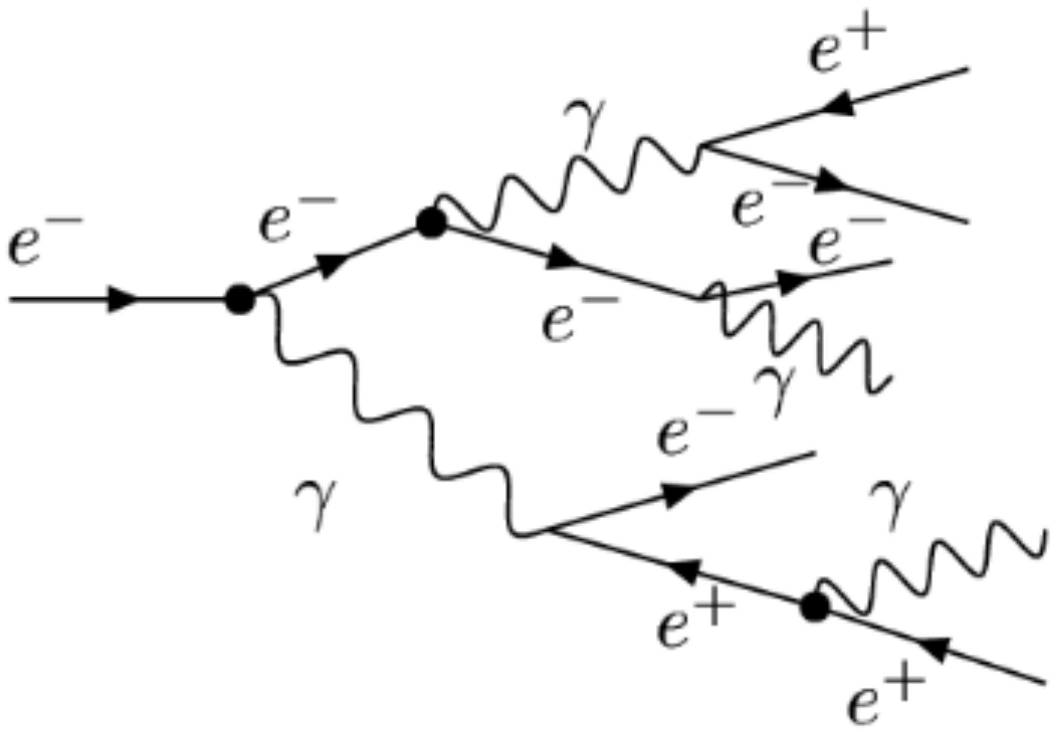


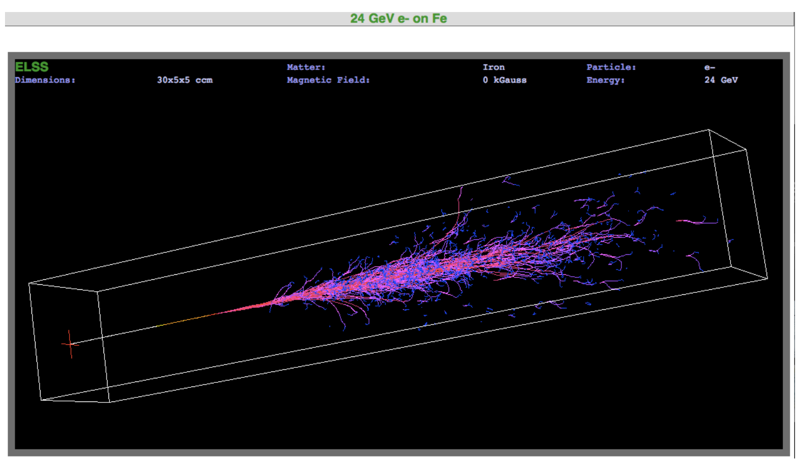


increases with energy and dominant at high energy

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

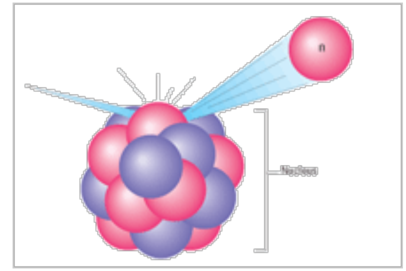
[later talk by Jeph Wang]

Neutrons interact via the strong force

short range force, so rare interactions

... neutrons are penetrating, and

will tend to ping around



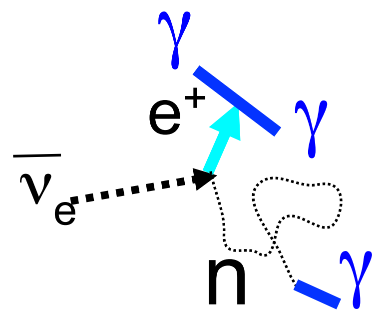
Mechanism	Reaction	Notes
Elastic scattering from nuclei	**A(n,n)A**	**Main mechanism of energy loss**
Inelastic scattering	A(n,n')A*, A(n,2n')B,..	Deexcitation products or other secondaries
Radiative neutron capture	n+(Z,A) ➔ γ + (Z,A+1)	~ 1/v, so requires low energy
Other nuclear reactions	(n,p), (n, 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



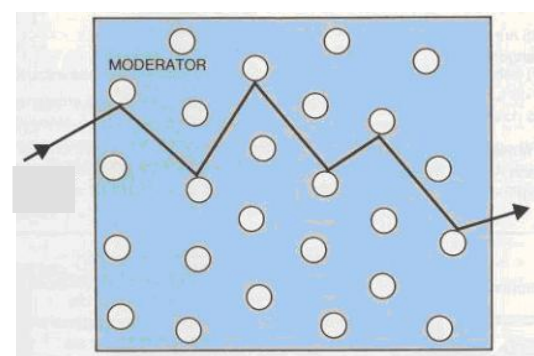
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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

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)

Take-away points so far

- How to calculate neutrino event rates

$$R = \Phi \ \sigma \ N_t$$

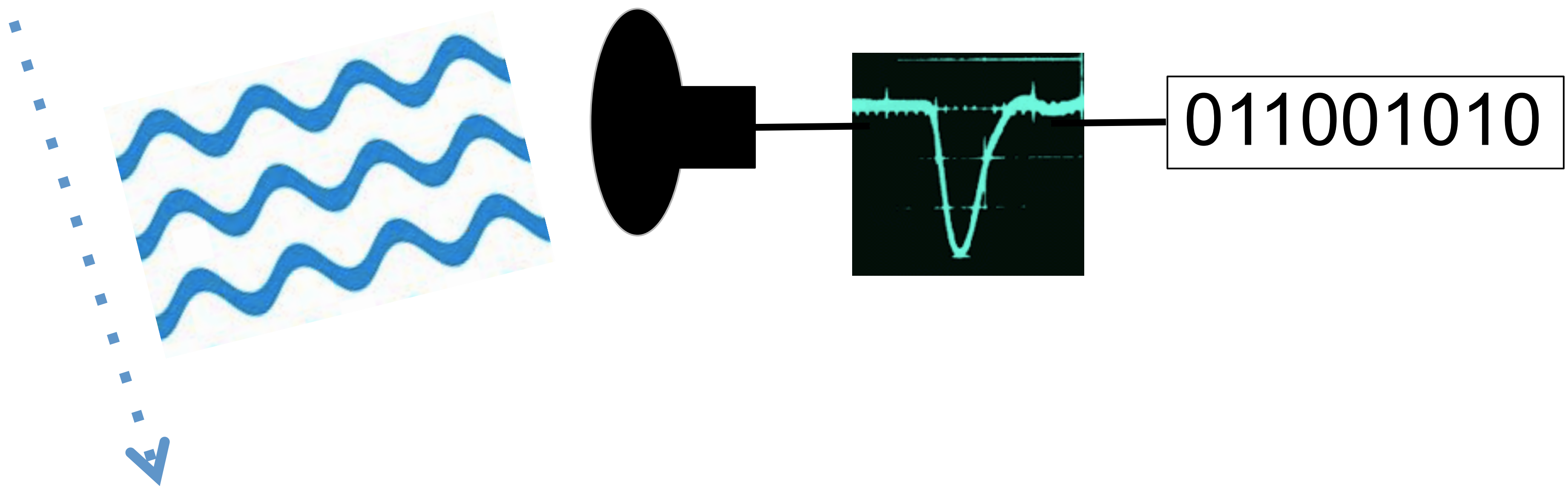
- How to estimate energy loss

<u>Most important effects</u>**:** (for ν experiments)

- 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)

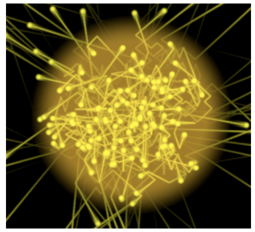
Detecting particles

... 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)

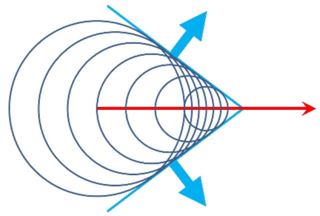


Common ways of gathering deposited energy for neutrino experiments

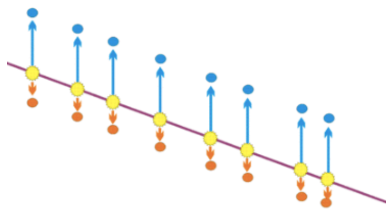
Scintillation light + photosensors



Cherenkov light + photosensors



Direct collection of ionization with electric field



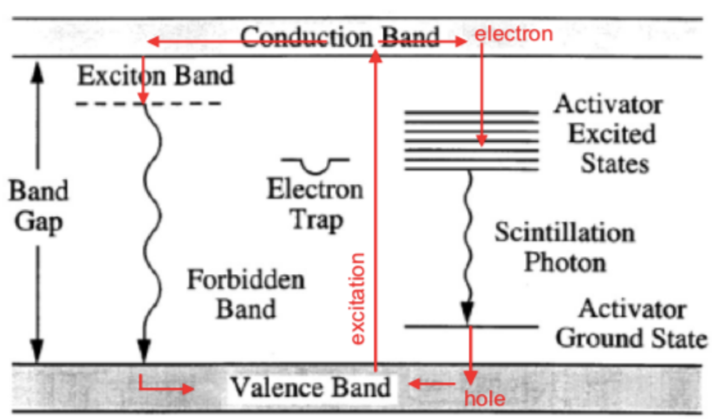
- Specific techniques vary by energy range and physics requirements
- Often more than one technique employed in a given detector

Scintillation for charged particle detection

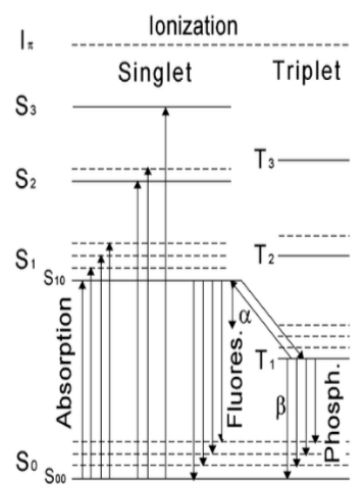
Particle energy loss excites energy levels in a material; photons (optical/UV) subsequently emitted at deexcitation

- No. of photons ∝ energy loss
- Isotropic emission

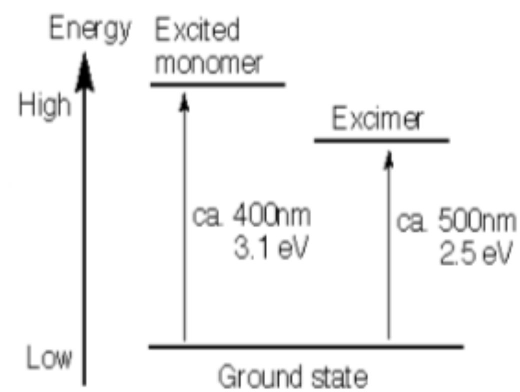
...somewhat different mechanisms for different types of scintillator



inorganic
(semiconductor, crystals)

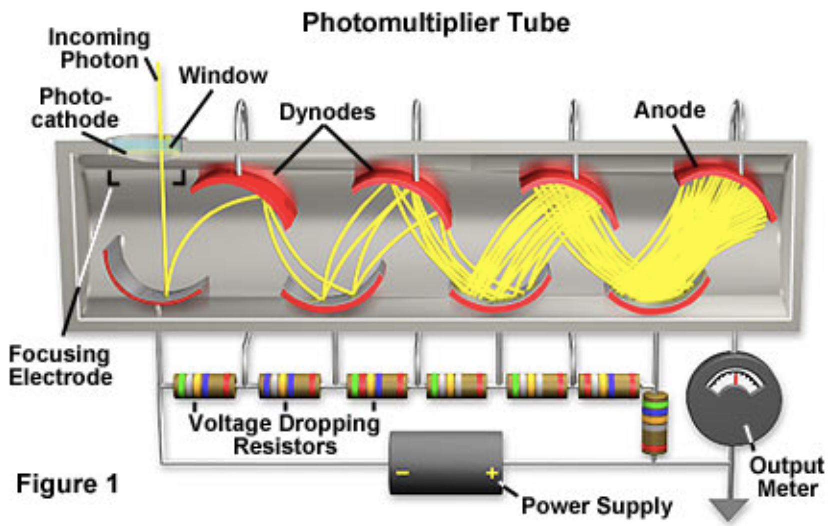


organic
(hydro carbons, liquid or solid)



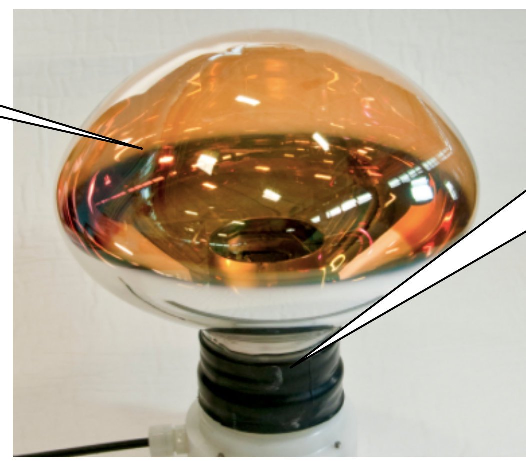
noble element
(liquid or gas)

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



general concept (... many variations)

photocathode

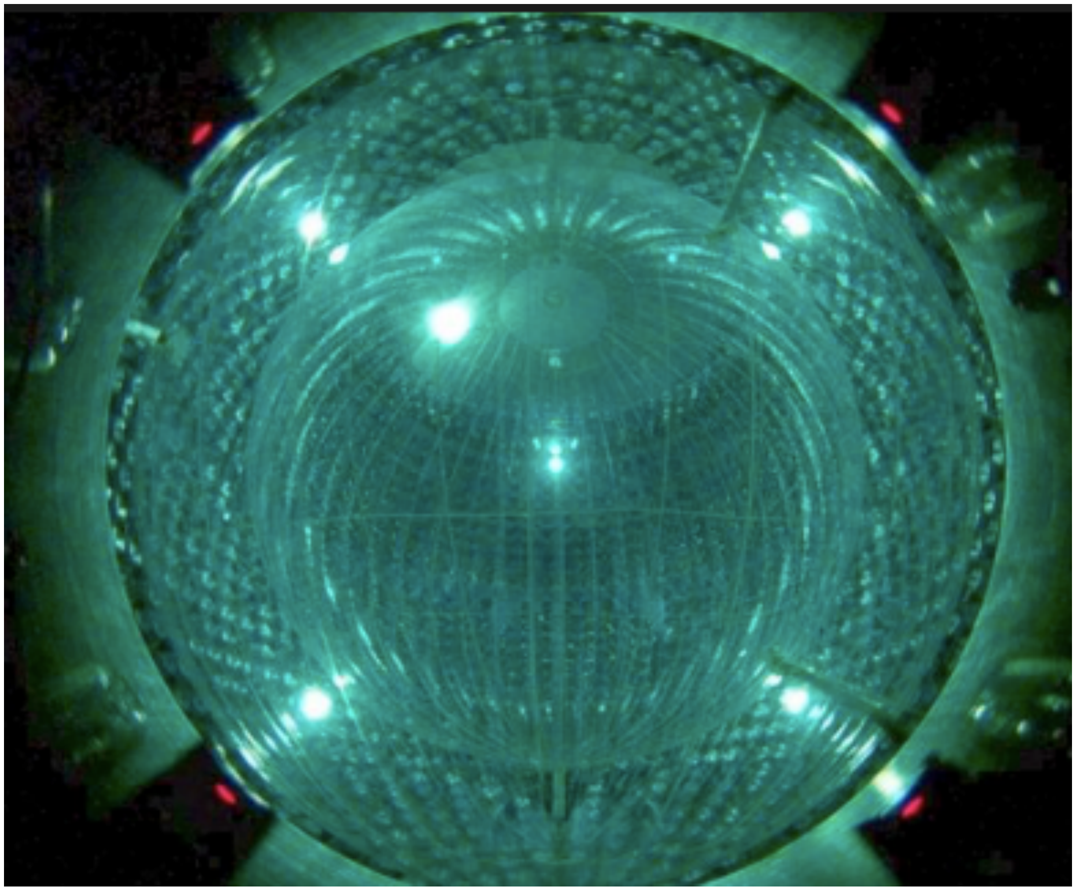


dynode chain

Common design for neutrino experiments maximizes photocoverage

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

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

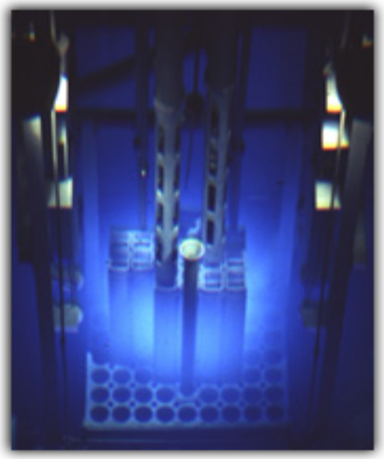


- most common is liquid hydrocarbon, $\sim C_nH_{2n}$
- often in form of homogeneous volume viewed by PMTs, but can also be segmented
- large light yield

[Also: noble liquid scintillates]

Cherenkov Radiation

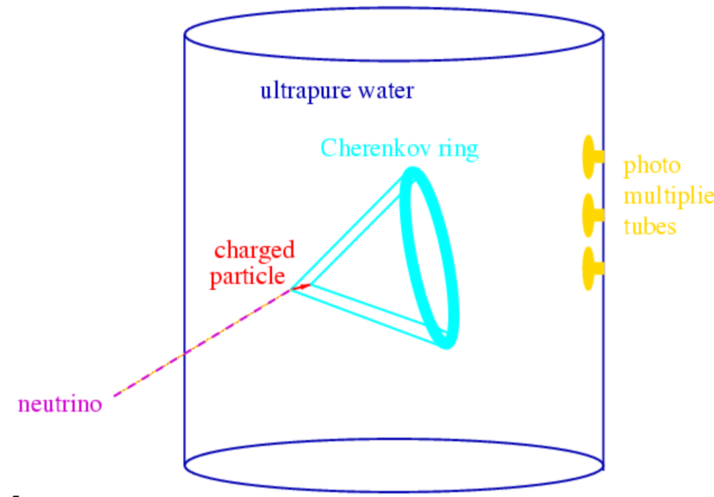
Charged particles emit Cherenkov radiation
in a medium if $\beta > 1/n$



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

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

No. of photons $\propto$ energy loss



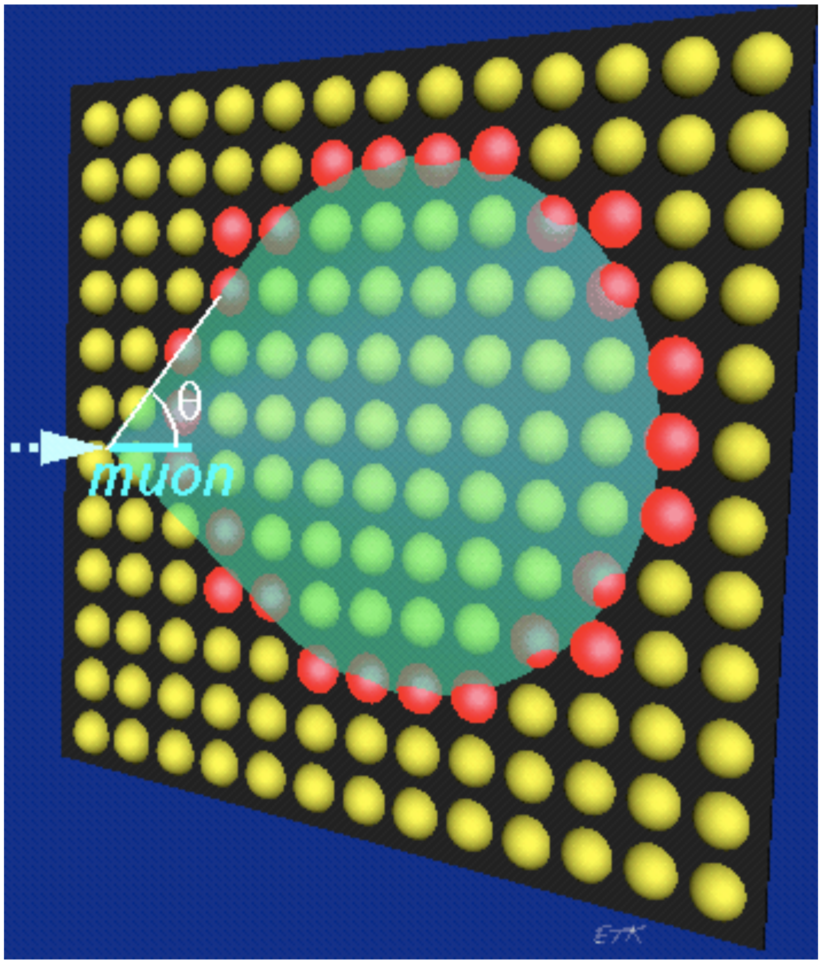
Thresholds (MeV)

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

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



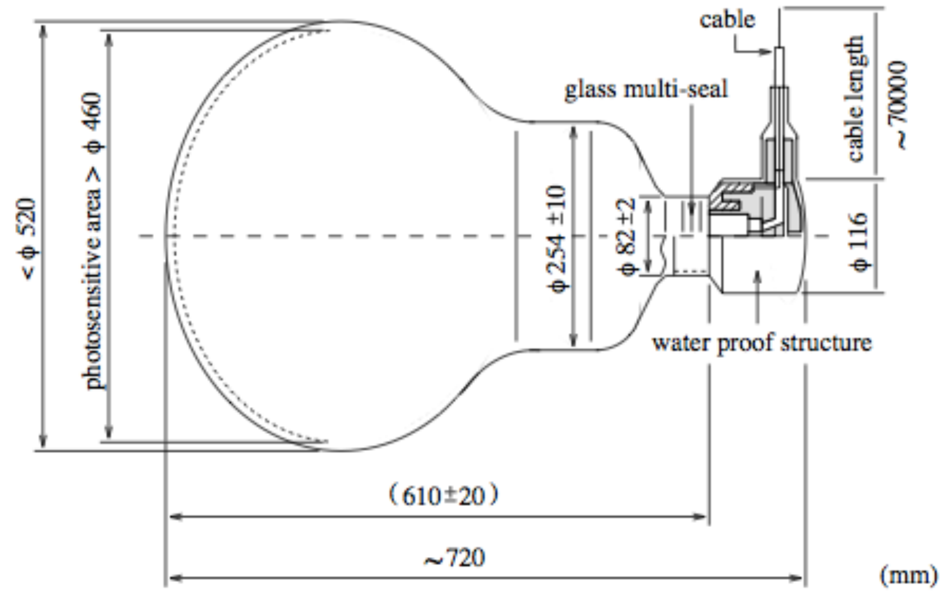
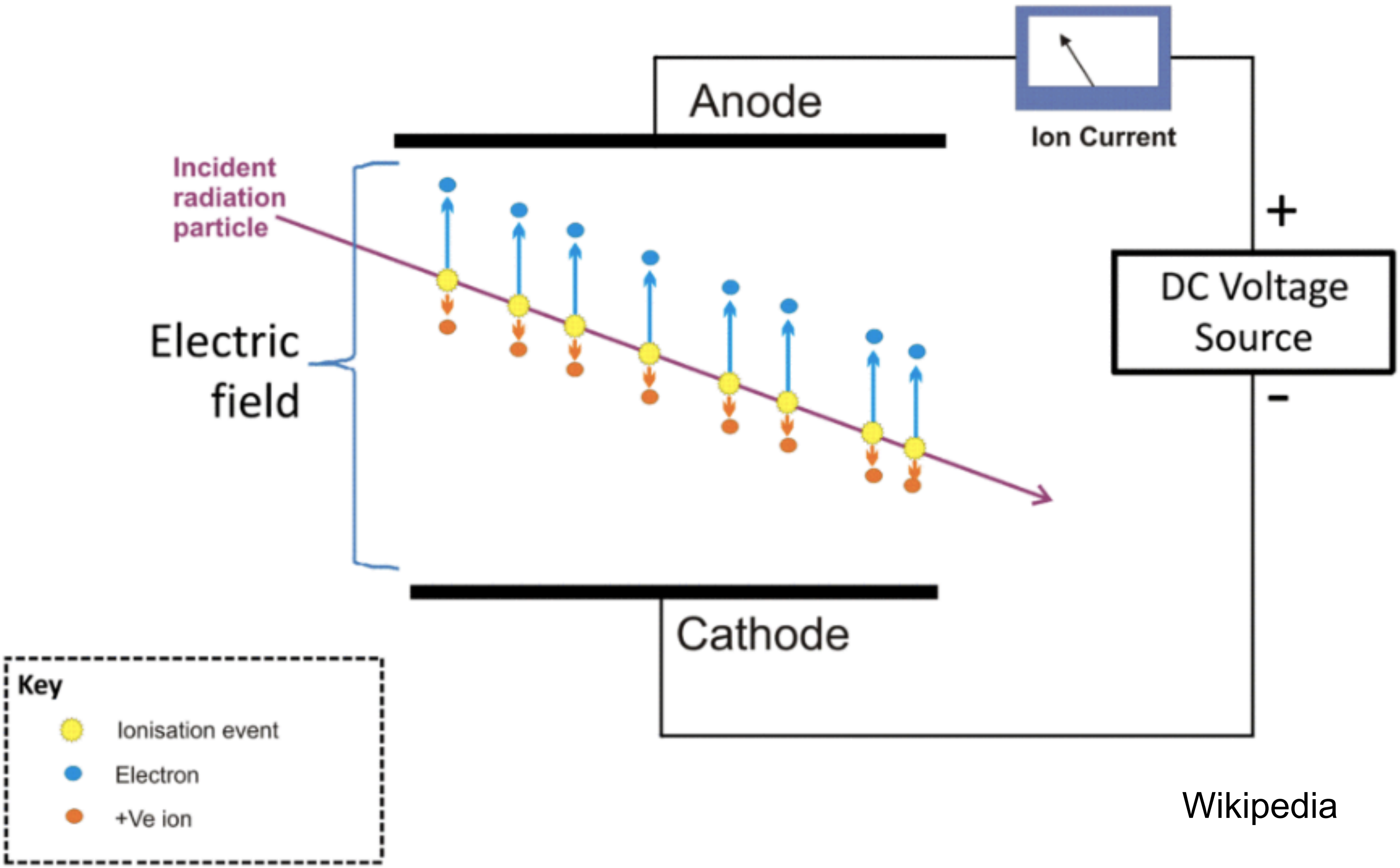


Fig. 7. Schematic view of a 50 cm PMT.

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

Ionization charge collection

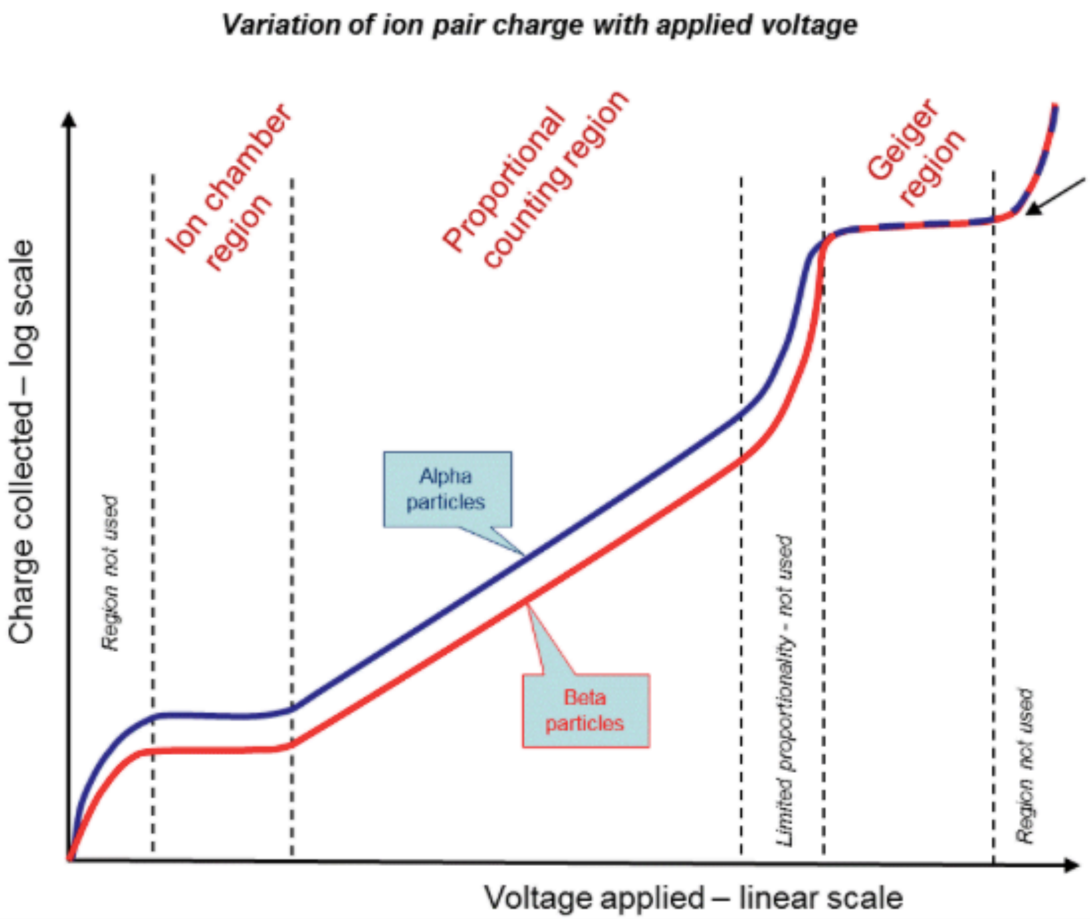
Basic concept: apply an electric field and gather charge* to form an observable pulse

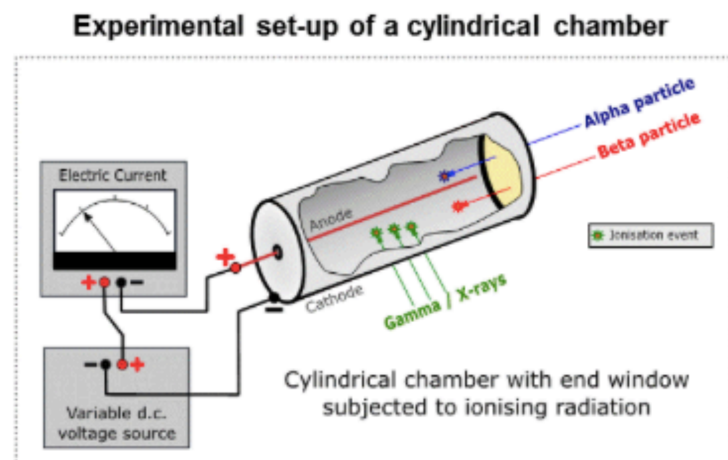


Wikipedia

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

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

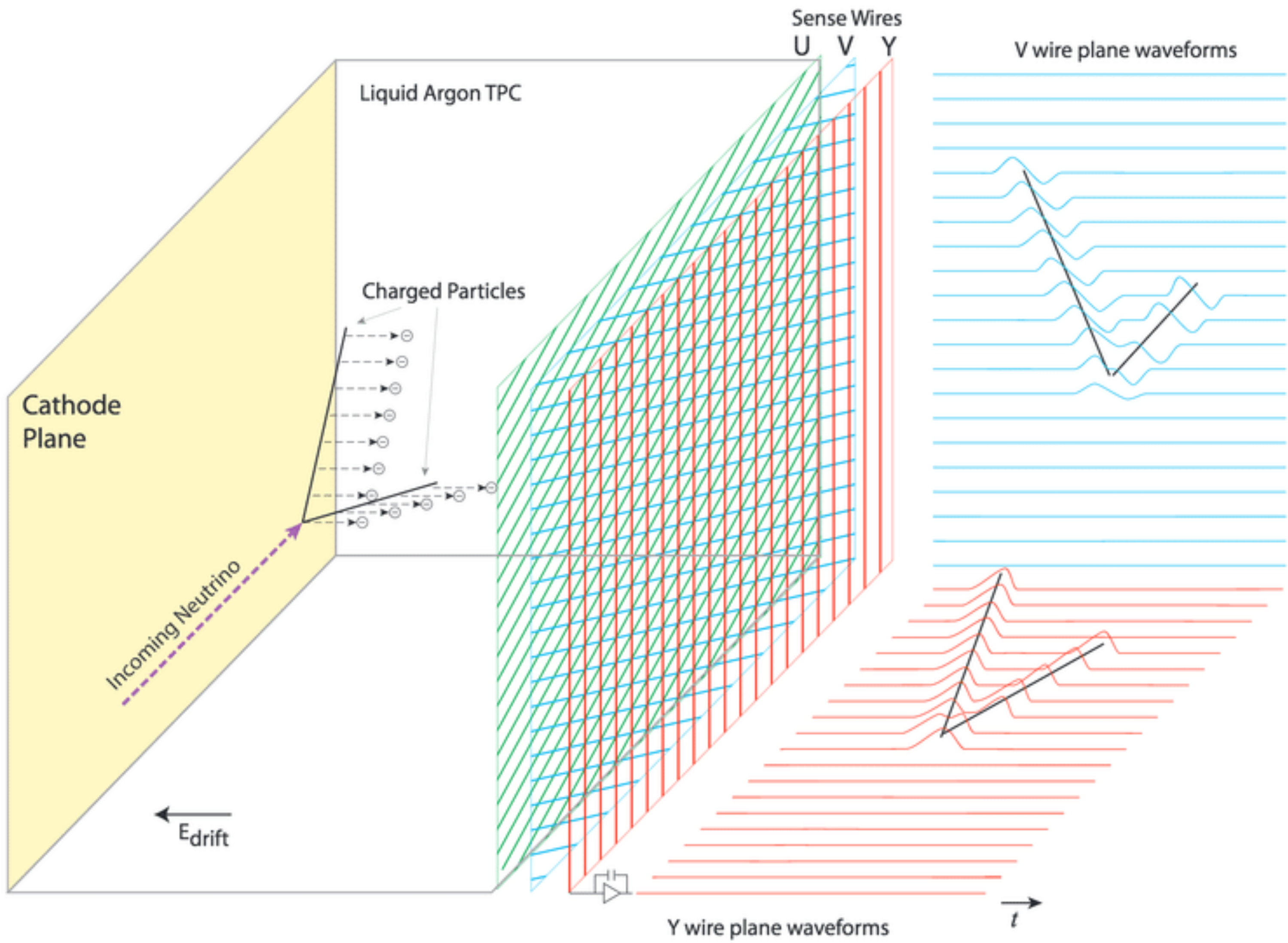




Low-penetrating radiation enters via an end window, but high-penetrating radiation can also enter via the cylinder side wall.

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

Time projection chambers



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

Lecture Overview

- Neutrino interactions with matter
- General principles of particle detection
- Survey of neutrino detection techniques

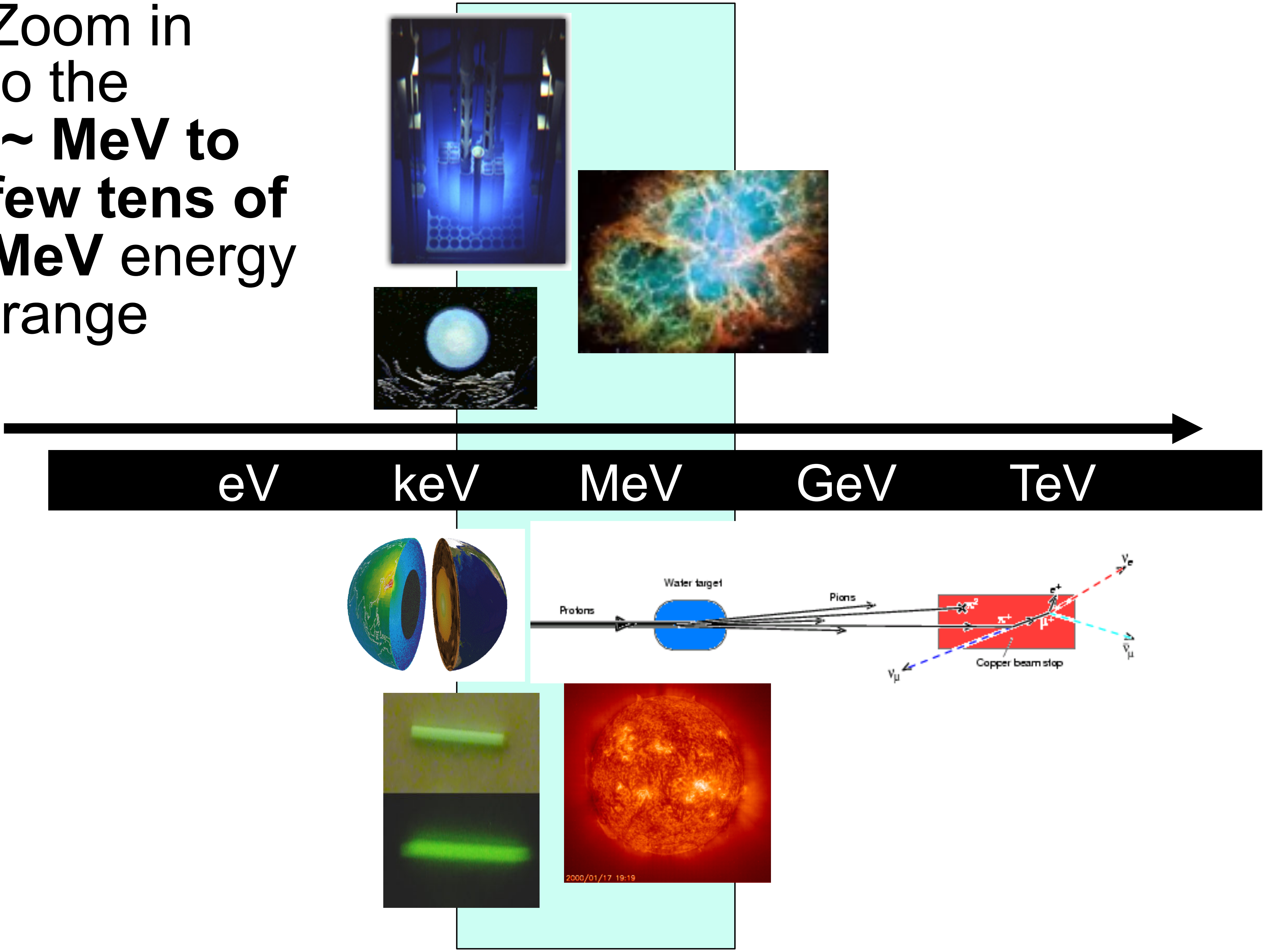
- Specific astrophysical detectors,
  organized by energy range

- few to few tens of MeV:
  core-collapse supernova, solar

- few hundred MeV to TeV
  atmospheric ν's

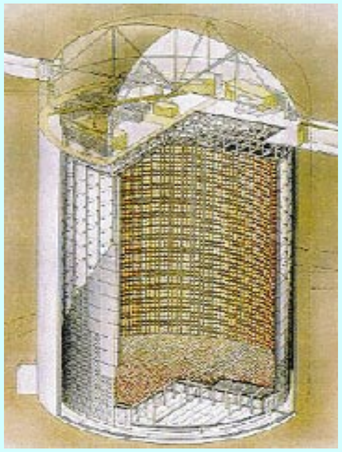
- TeV to EeV +
  AGNs, GRBs, mergers, ...

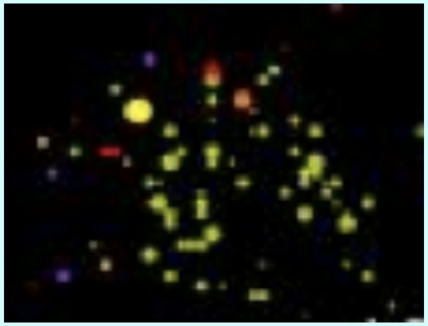
Zoom in to the **~ MeV to few tens of MeV** energy range



Large (multi-kton) detector technologies for low energies

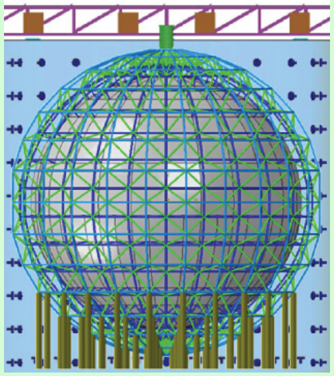
Water Cherenkov

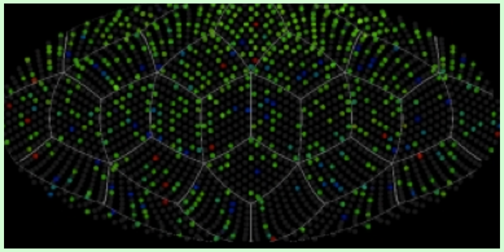




Cheap material, proven at very large scale

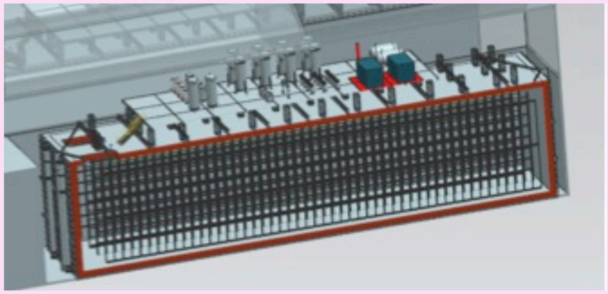
Liquid scintillator

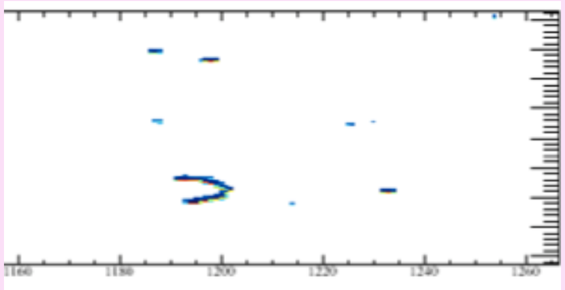




Low threshold, good energy resolution

Liquid Argon





Good particle reconstruction

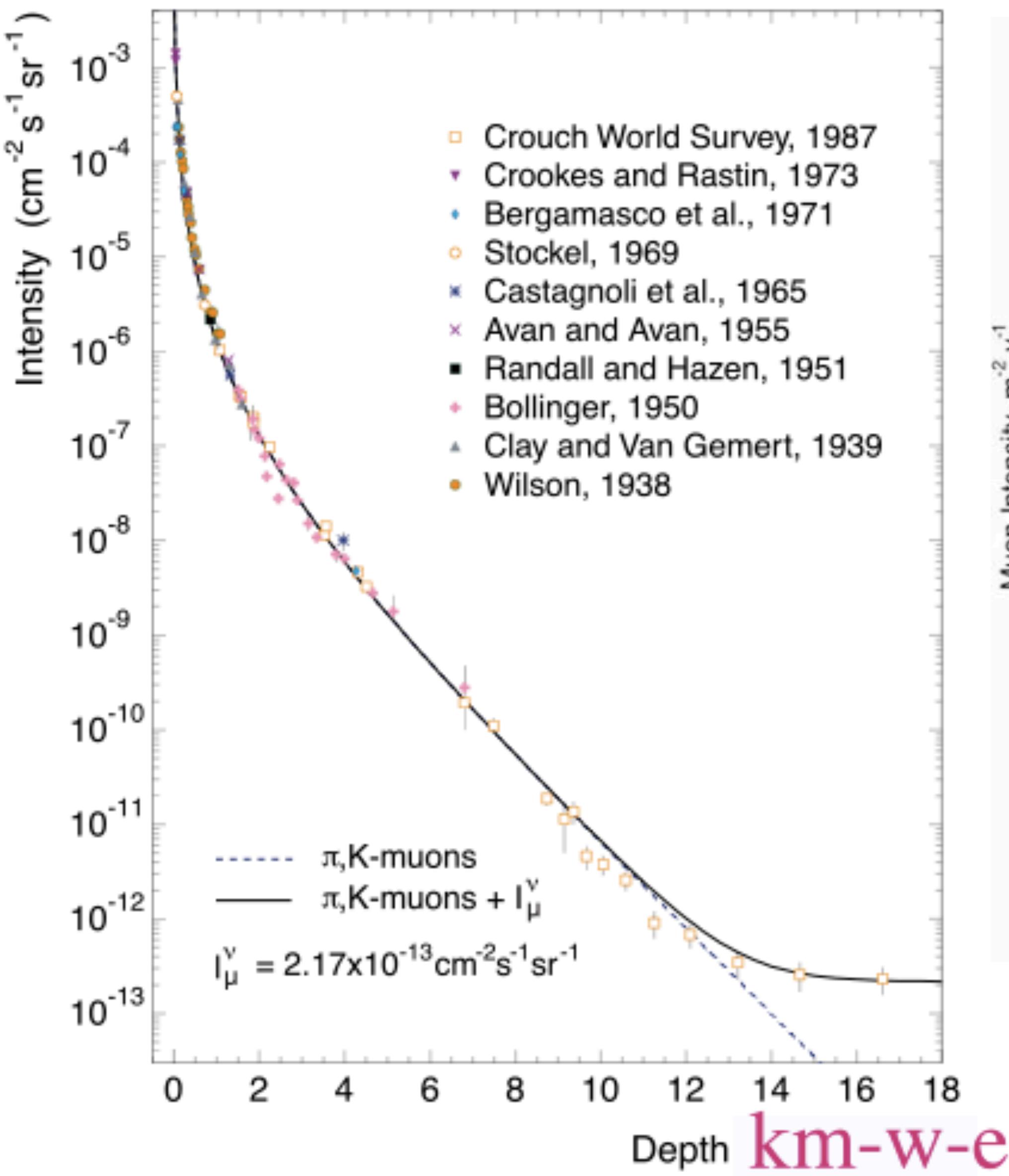
+ some other detector types for specific uses

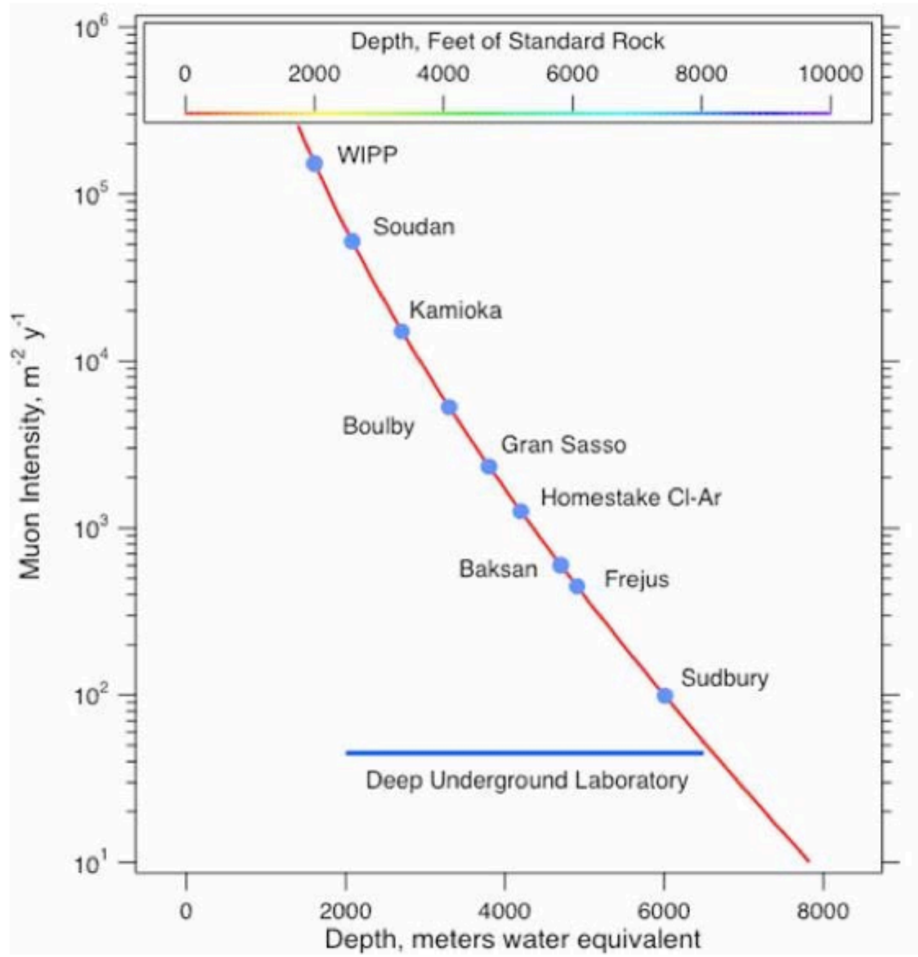
The weather is always fine underground

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

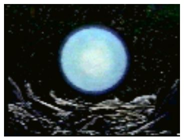




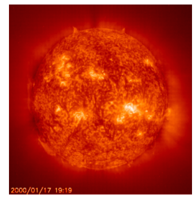
(Note: μ intensity decreases, but μ spectrum gets harder with depth)

mwe = "meters-water-equivalent" (scale by density)

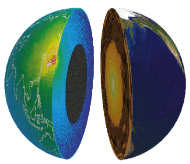
Physics/astrophysics of interest in this energy range (few to few tens of MeV)



Supernova neutrinos: burst and "relic"



Solar neutrinos



Geoneutrinos

Reactor neutrinos

Radioactive sources

Stopped-pion neutrinos

today

Major emphasis on supernova neutrinos

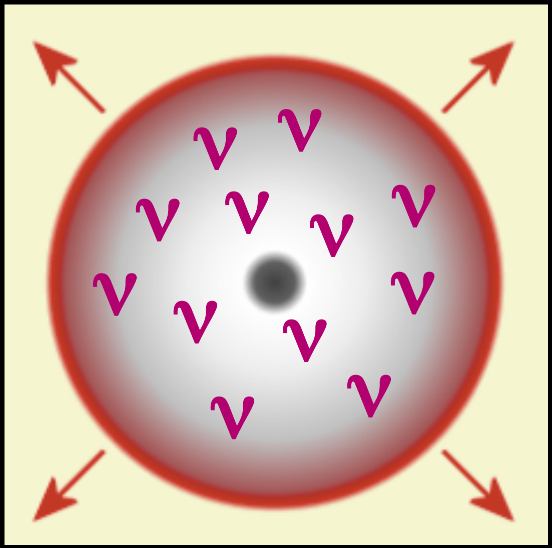
Neutrinos from core collapse

Just as gravitational potential energy turns into kinetic (and thermal) energy when an object falls,

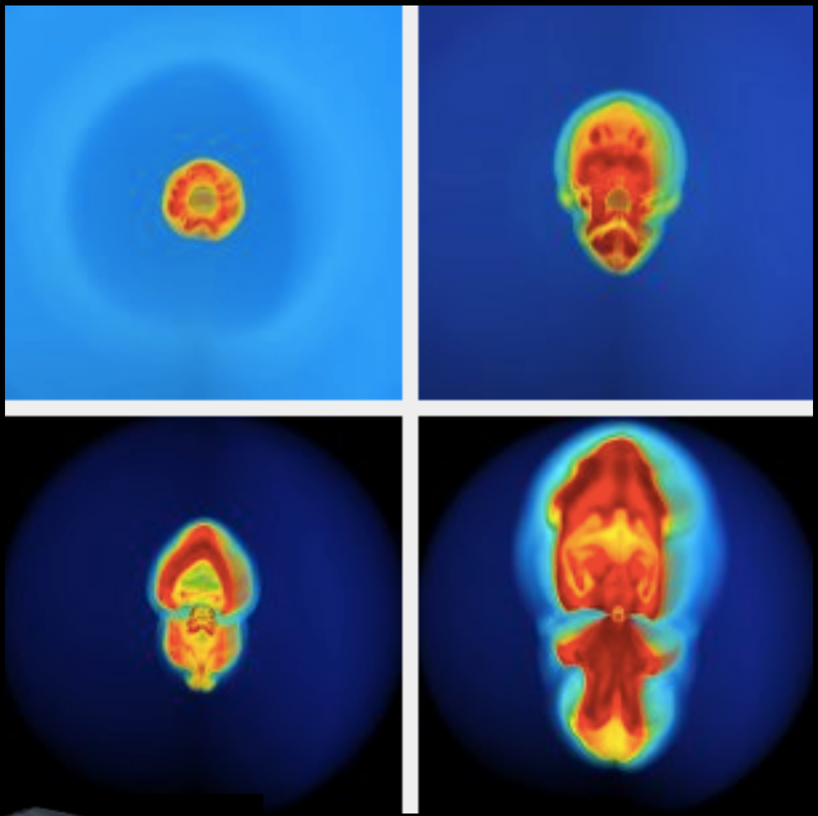
.... as the star falls inward, the gravitational energy *must go somewhere*...

The energy *can* escape via neutrinos, thanks to the weakness of the neutrino interactions

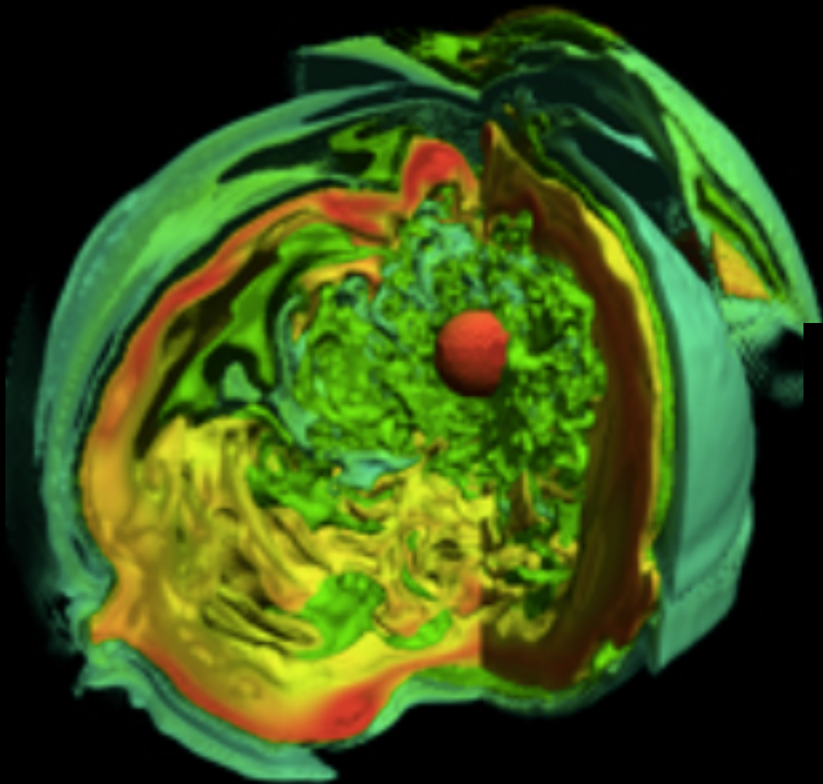
~99% of the vast binding energy of the proto-neutron star is shed within ~10 seconds in the form of *neutrinos and antineutrinos of all flavors*



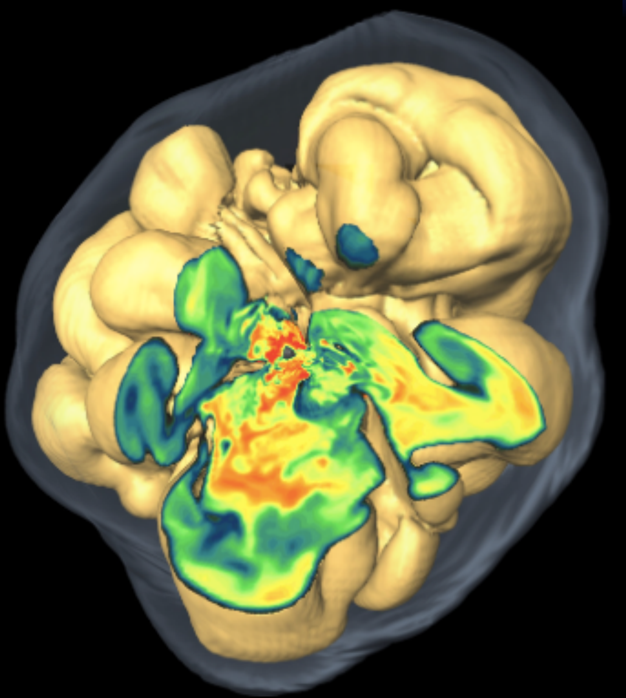
The core-collapse supernova explosion is still not well understood... numerical study ongoing



Marek & Janka



Blondin, Mezzacappa, DeMarino

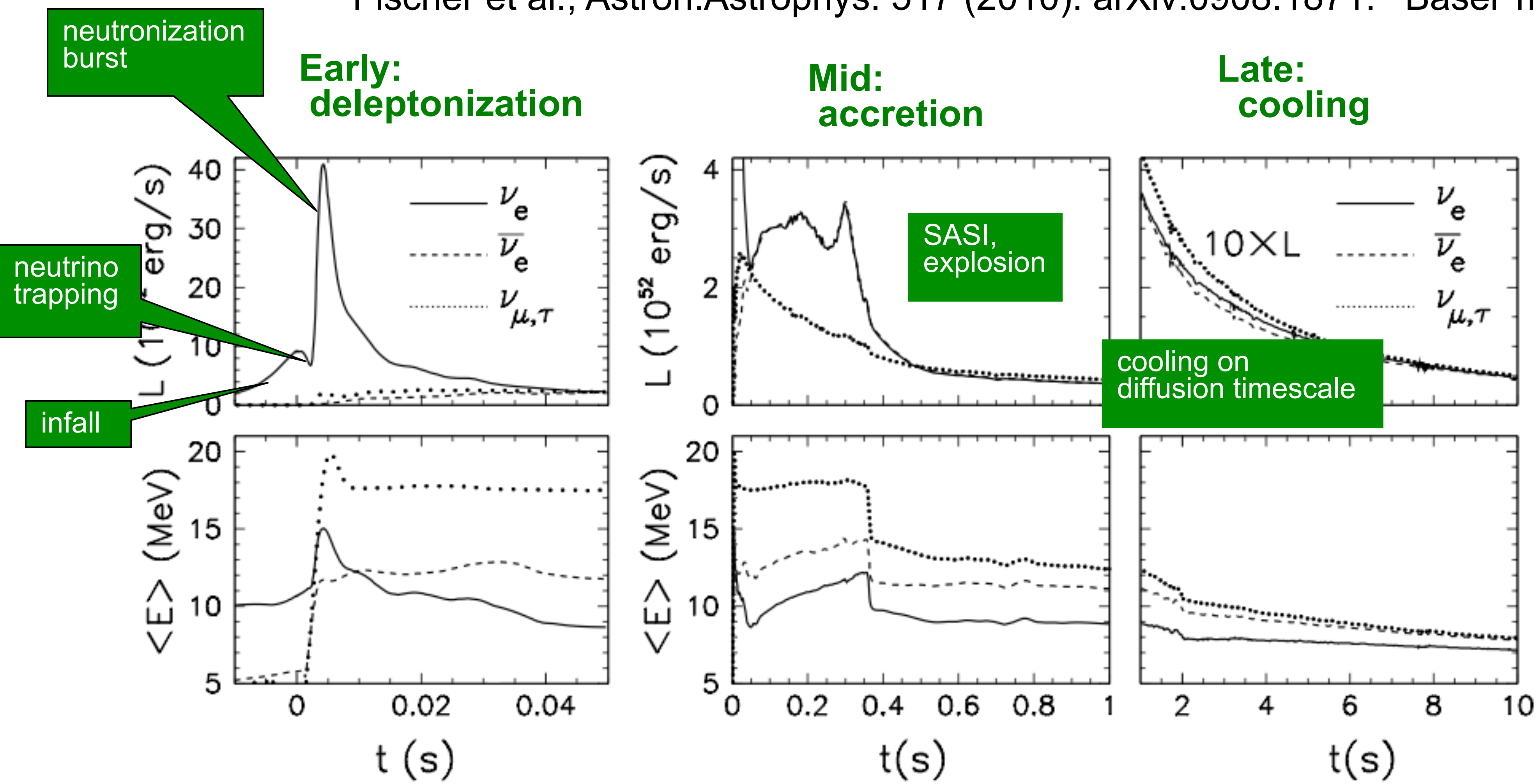


Neutrinos are intimately involved

Expected neutrino luminosity and average energy vs time

Vast information in the *flavor-energy-time profile*

Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: ‘Basel’ model



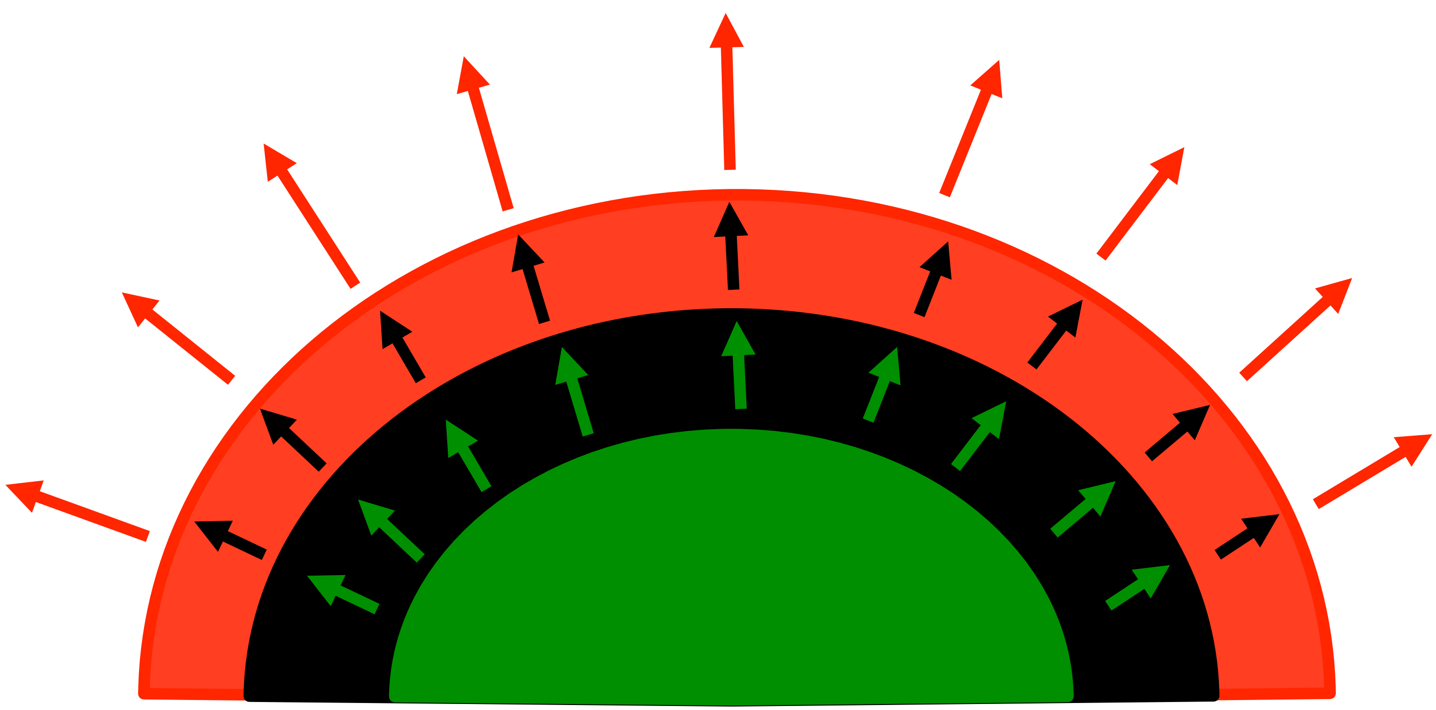
Generic feature:
(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Nominal expected flavor-energy hierarchy

Fewer interactions
w/ proto-nstar
$\Rightarrow$ deeper ν-sphere
$\Rightarrow$ hotter ν's

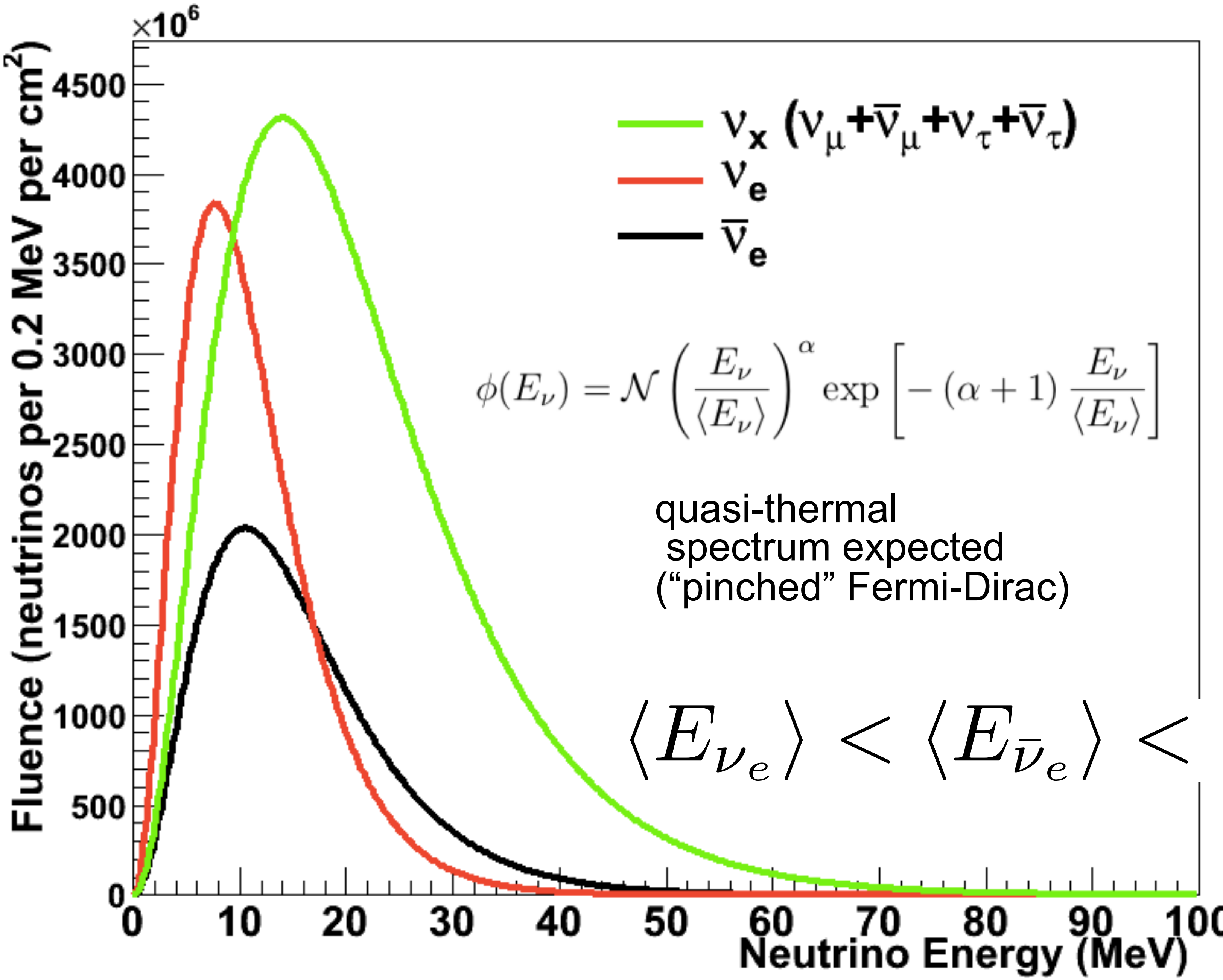
$\langle E_{\nu_e} \rangle \sim$ 12 MeV
$\langle E_{\bar{\nu}_e} \rangle \sim$ 15 MeV
$\langle E_{\overset{(-)}{\nu}_{\mu,\tau}} \rangle \sim$ 18 MeV



May or may not be robust...

Neutrino flavor oscillations (governed by fundamental neutrino parameters) will modify the spectra

Neutrino spectrum from core collapse

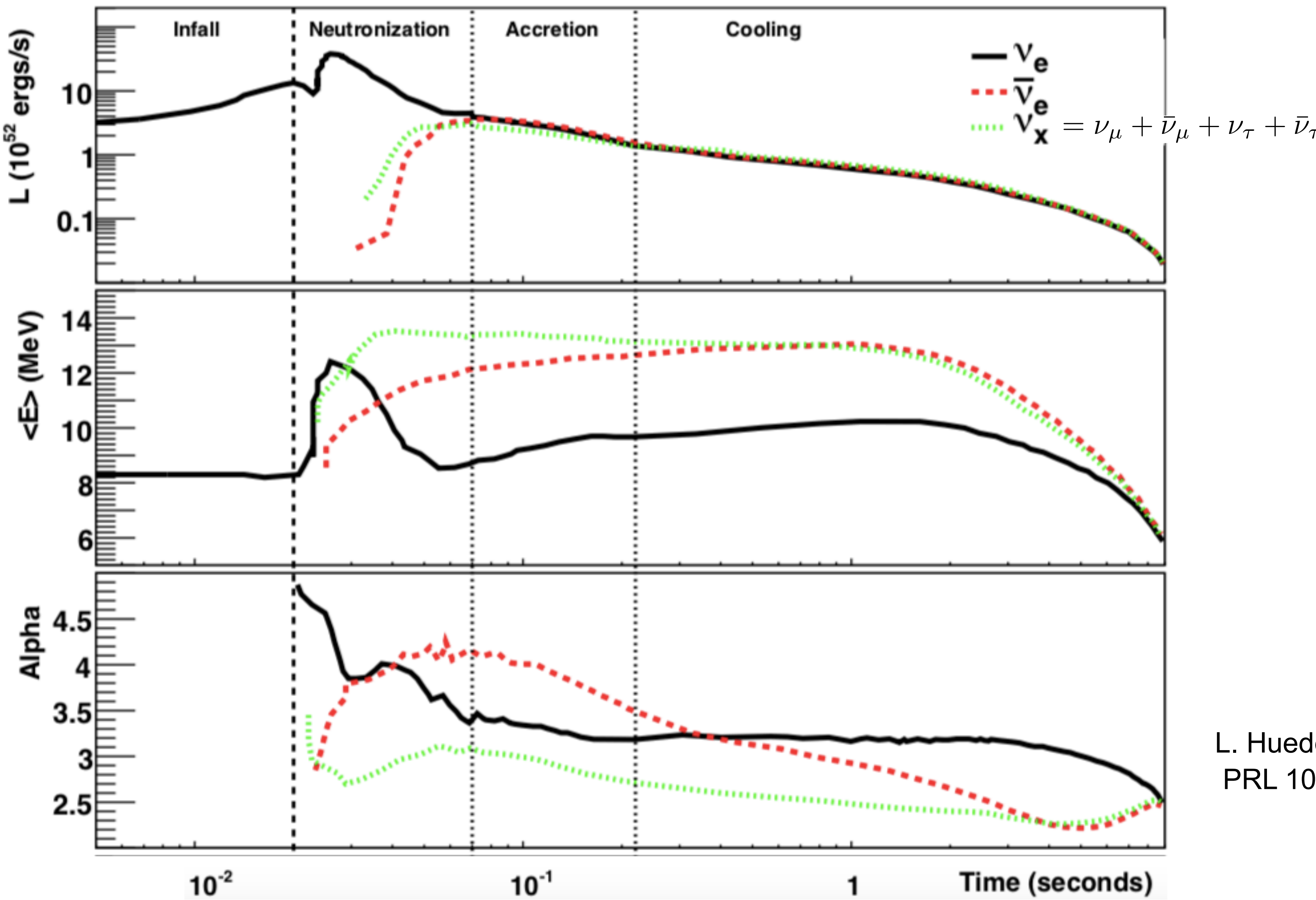


$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

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

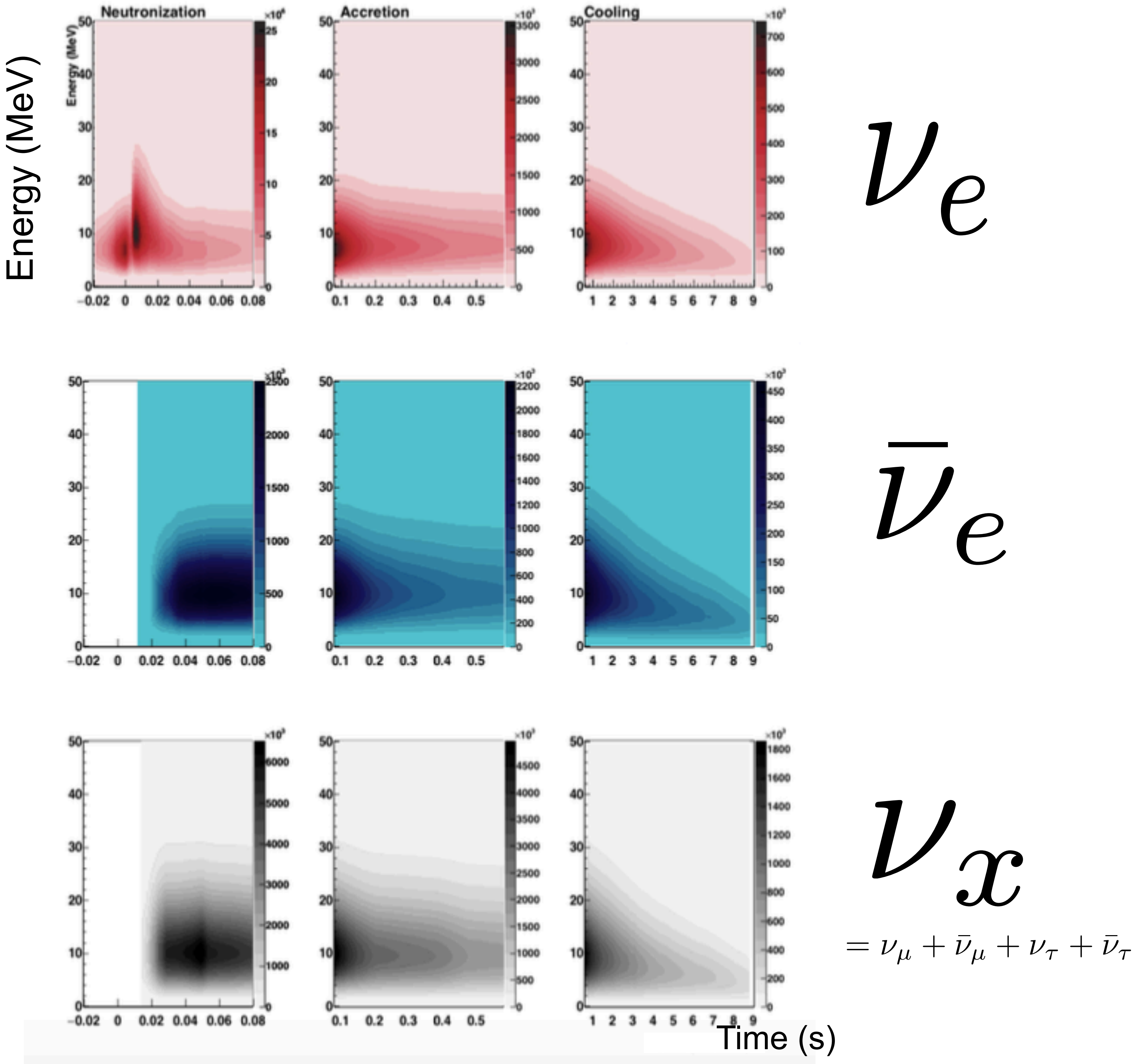
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Describe the flux by parameters vs time



L. Huedepohl et al.,
PRL 104 251101

Fluxes as a function of time and energy

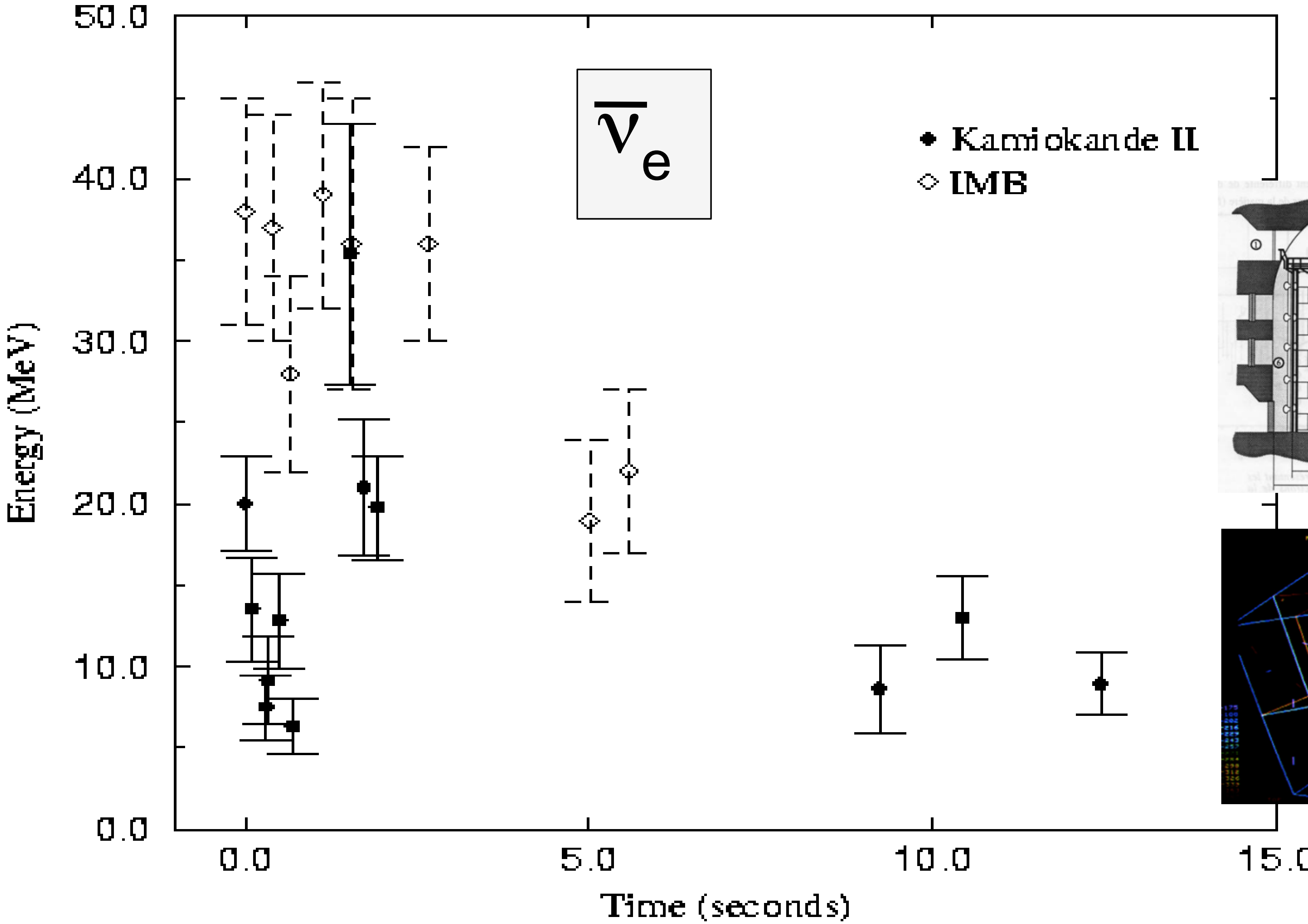


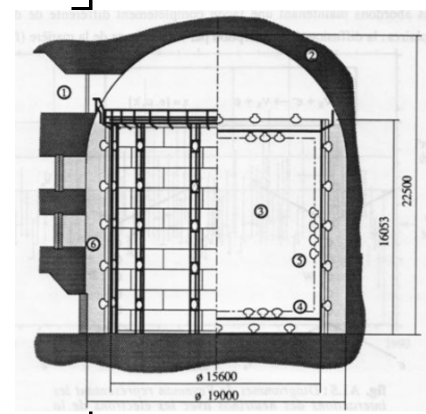
Supernova 1987A
in the Large Magellanic Cloud (55 kpc away)

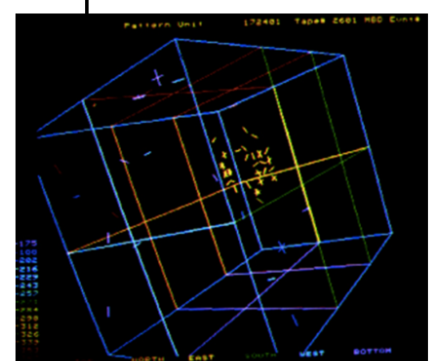
~two dozen neutrino interactions observed!

SN1987A in LMC

ν's seen ~2.5 hours before first light







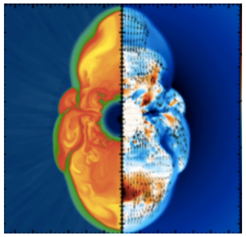
Confirmed baseline model... but still many questions

My colleagues singing Happy Birthday to a supernova

Image: Hank Sobel

What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS

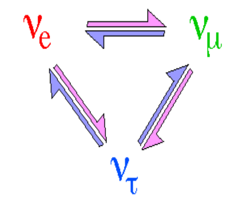


explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from photon (GW) observations

from flavor, energy, time structure of burst

input from neutrino experiments



NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass hierarchy)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

+ EARLY ALERT