Neutrino interactions from 100 keV to 100 GeV:
natural/artificial fluxes and modeling
of neutrino cross sections

... A GUIDED TOUR OF NEUTRINOLAND

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This Lecture(s) were originally given at:

Cracow School of Theoretical Physics, XLIII Course, 2003

(extracted from PhD Course at Univ. of L'Aquila)

re-proposed at the

LArSoft Classes – FNAL, July 2013

and now at the

Neutrino Summer Student Lecture series – FNAL, July 2015

NB: some updates should necessarily be made to the material presented here,
however the main concepts are still valid ..
And these are what we will focus on.

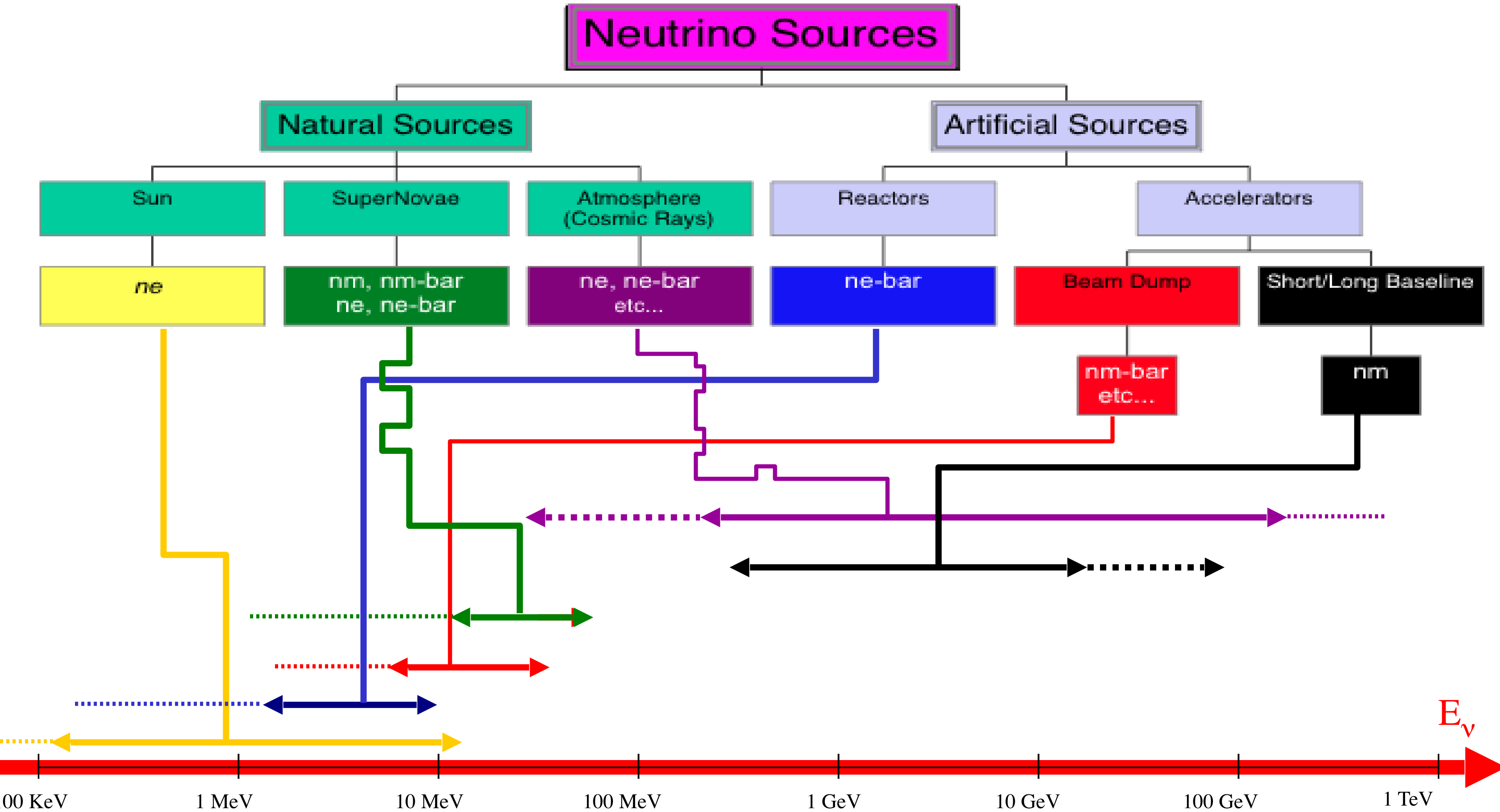
Outlook:

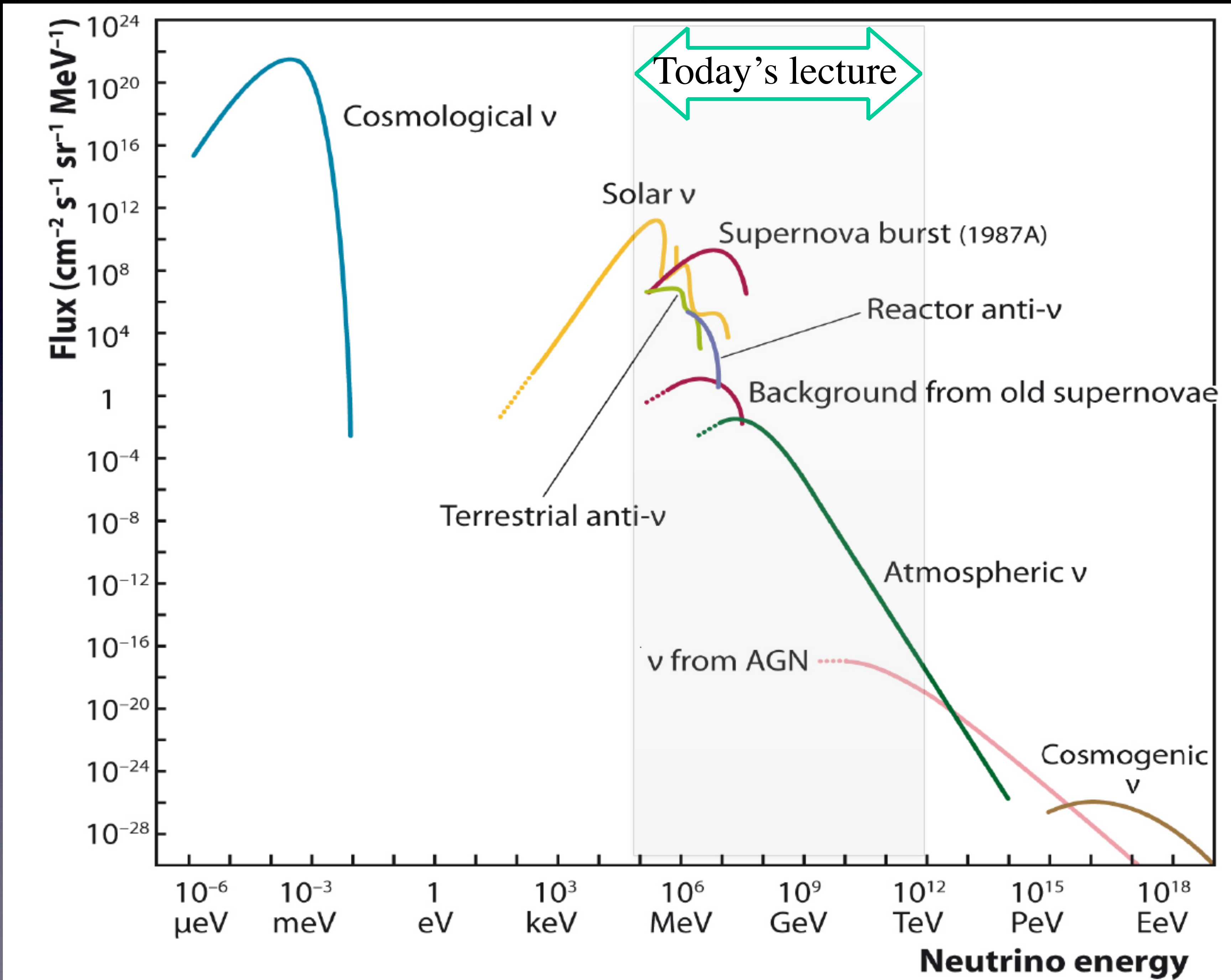
- What is NOT IN:
  - implications of neutrino non-zero mass

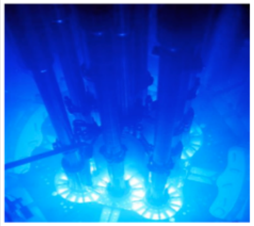
    (i.e. oscillations are almost not discussed … with a couple of exceptions…)
- What is IN:
  - Neutrino spectra of various origin
  - Neutrino cross-section
  - The available interaction targets (present, past and "future" experiments*)
- What we get
  - EXPECTED RATES CALCULATION

(*) .. many neutrino experiments are mentioned.

NeutrinoLand




Today's lecture
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy



Neutrinos from reactors.

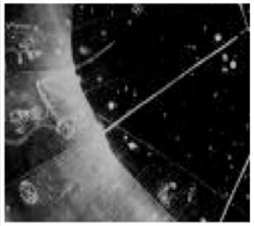
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)



Neutrinos from accelerators.

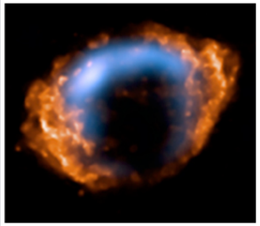
Created & detected (1960s)

Neutrinos from supernovae.

Detected (1980s)

Neutrinos from the Earth.

Detected (2000s)



Neutrinos from galactic sources.

~~Not yet (but close!)~~ Detected 2012

Neutrinos from the Big Bang.

Not even close...

J.A. Formaggio MIT

The extreme low energies:

The lowest energy neutrinos (below ~10 meV), are the so-called **relic neutrinos** or cosmic neutrino background (CνB). They are similar to the cosmic microwave background (CMB), but bring us information about an even older Universe, just two seconds after the Big Bang.
CνB are abundant: ~110 v's/cm^3 per flavor

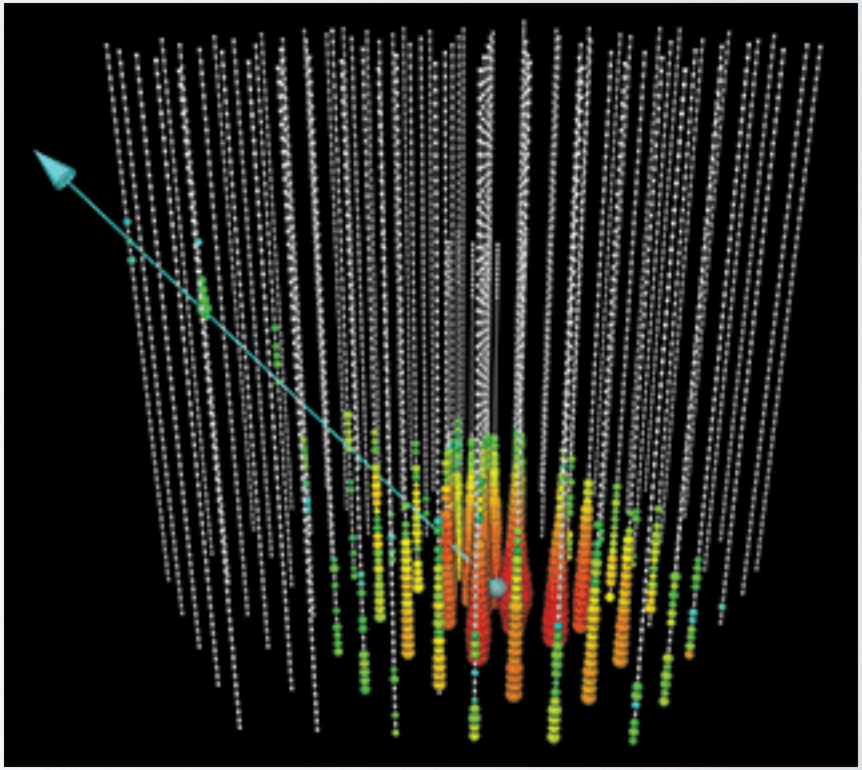
None of these low-energy neutrino fluxes have been detected so far.
An immediate direct detection does not appear to be feasible.
It will be an incredibly difficult challenge to reach detector sensitivity into this range of energies.

Proposed by Neutrino Capture Process: $^3H + \nu_e \rightarrow {}^3He^+ + e^-$
The process is energetically allowed even at zero momentum.
This threshold-less reaction allows for relic neutrino detection,
but the precise detection of e- is out of reach for now.

The extreme high energies:

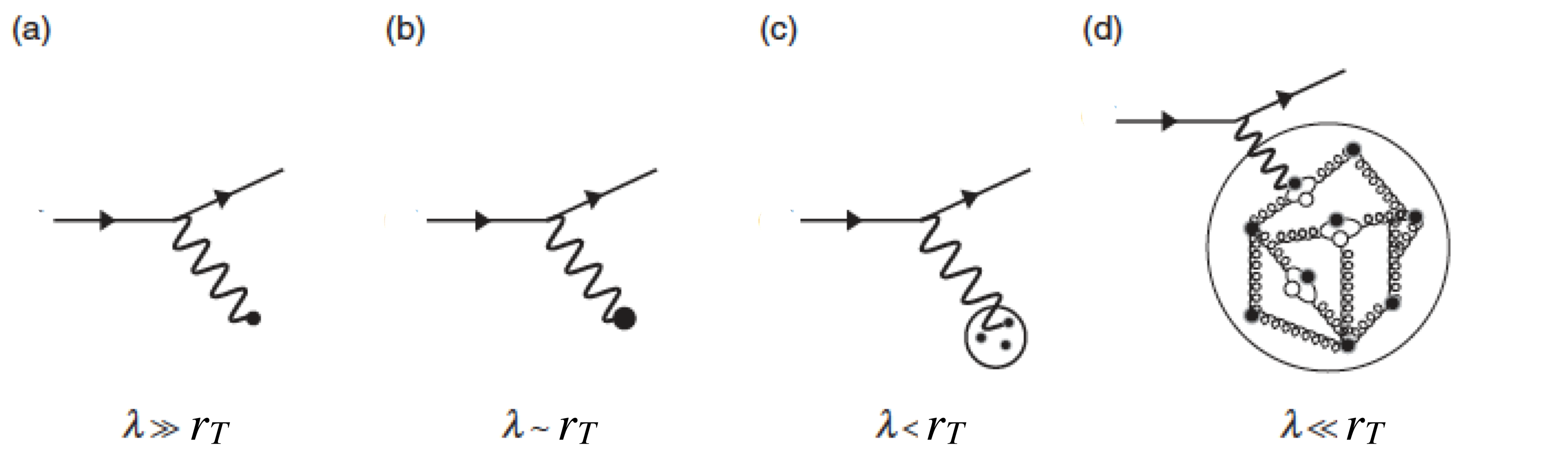
Extreme energies, in the **very high energy range** from a few TeVs to up to 10 PeVs, are reached by neutrinos that were created in or near the most extreme objects in our Universe, those powered by black holes and neutron stars.

When neutrinos are accelerated to energies above 10^{16} electronvolts, or 10 PeV, we cross another energy threshold, into the range of so-called **ultra-high-energy (UHE) neutrinos** or cosmogenic neutrinos.
They are produced by the interaction of ultra-high-energy cosmic rays (UHECR) with the cosmic microwave background radiation (CMB).
Neutrinos with energies around one PeV are predicted to interact while crossing the Earth at a rate of about one event per year per km^2, while those with energies around 100,000 PeV, or 10^{20} eV, would only interact at a rate of one event per century per km^2.



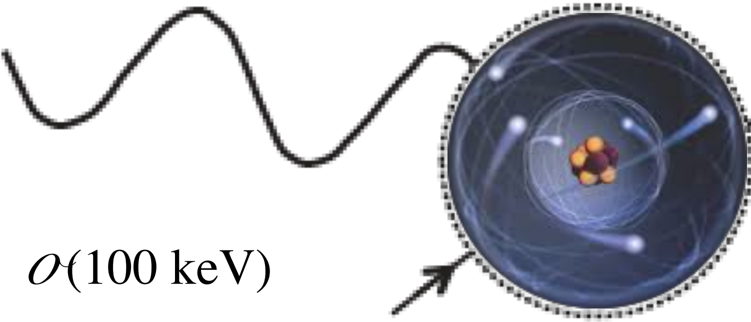
A 250 TeV neutrino interaction in IceCube.

Neutrino scattering over such extended range of energies provides a powerful tool for probing matter from its Atomic structure to the ultimate quark structure.
Recursive sequences of Elastic and Inelastic processes on nested “layers” of Targets take place at increasing energies of the Probe

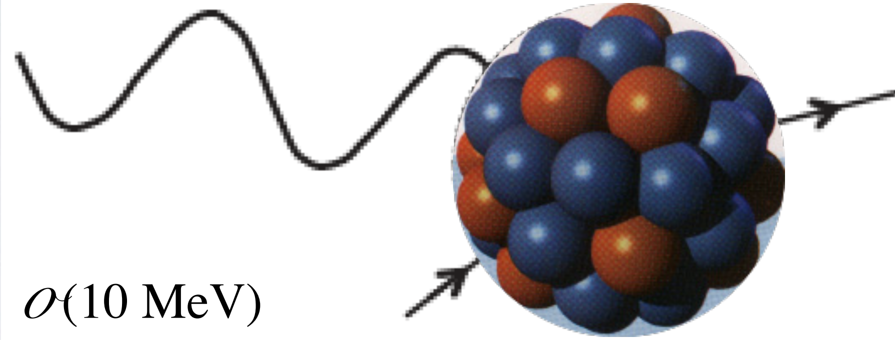


Reducing wavelength=increasing Momentum transfer => higher space resolution (probing more inside the target)

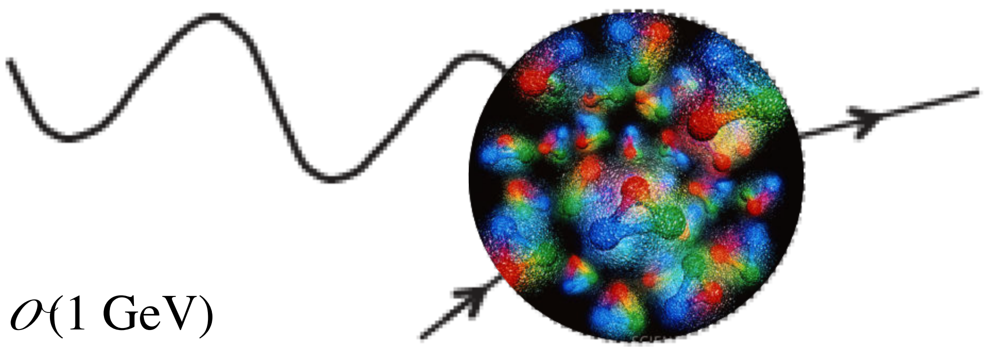
T= Atom (atomic electrons)



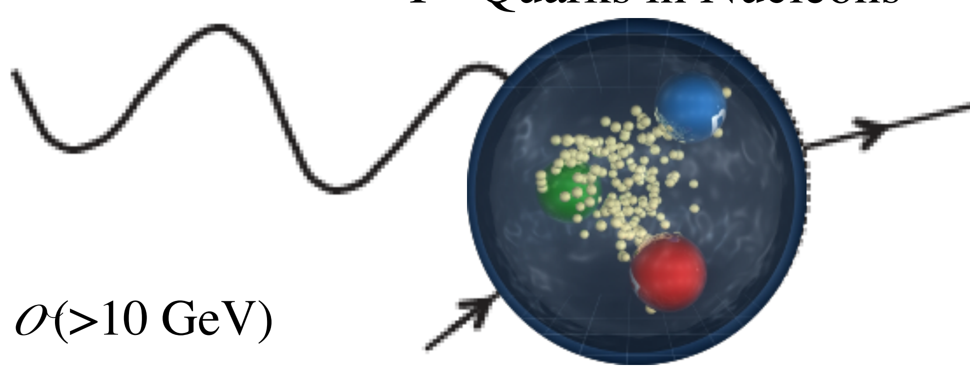
T= Nucleus



T= Nucleons (or clusters of Nucleons) in Nuclei



T= Quarks in Nucleons



Suggested reference:

From eV to EeV:
Neutrino Cross Sections Across Energy Scales
J.A. Formaggio, G.P. Zeller

NEUTRINO CROSS SECTION MEASUREMENTS
Data Particle Booklet by G.P. Zeller (Fermilab), Revised January 2014

As seen, most of the energy range covered by neutrino fluxes from various available sources has been explored by experimental searches for neutrino studies with large sensitive mass detectors.
The interaction rate is usually limited due to the very small neutrino interaction cross-section with matter, even though fluxes are typically very intense,

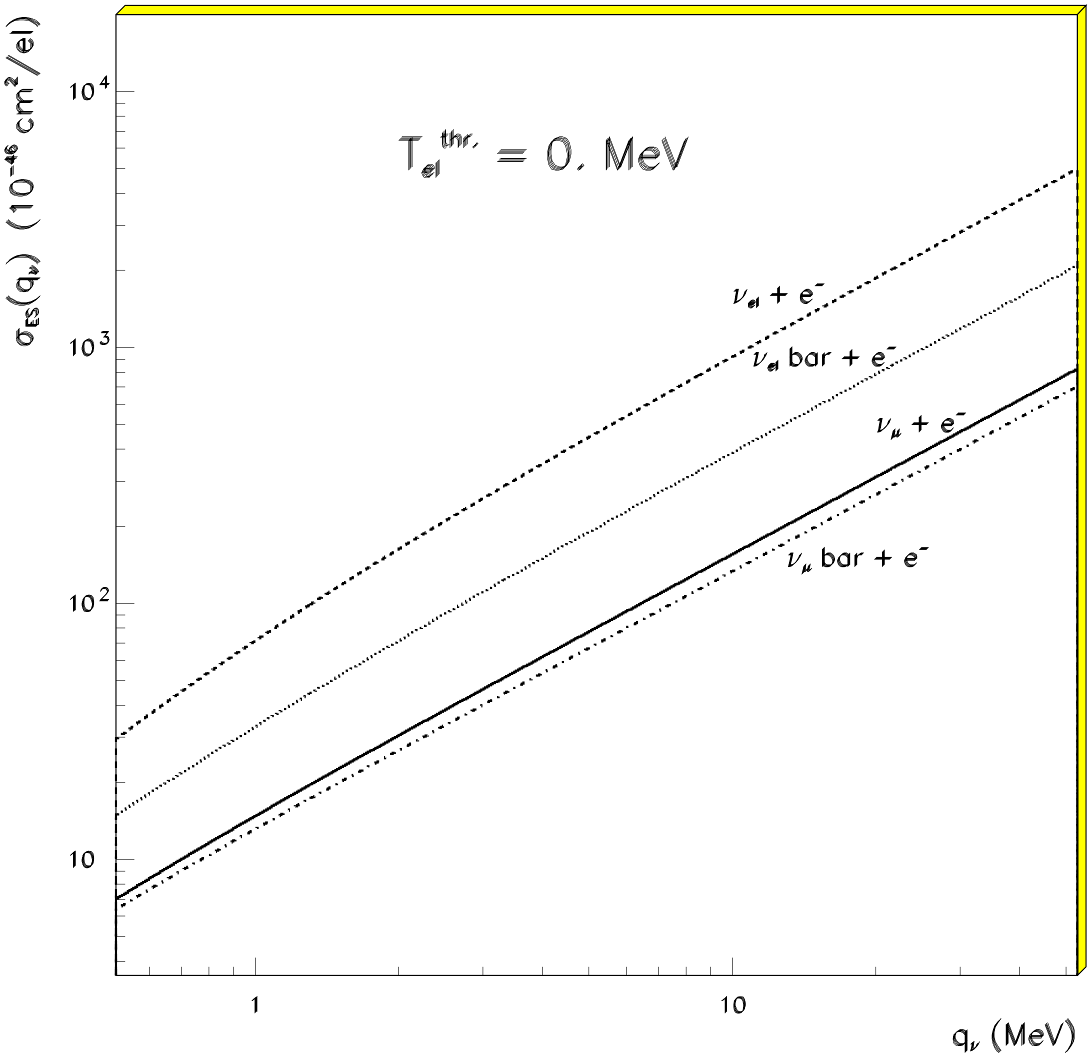
Different theoretical models for cross-section calculation have been developed for different energy sub-ranges and targets.

A significant reference quantity for easy evaluation of the expected event rate is the "SNU" ("Solar Neutrino Unit" - J. Bahcall). It represents the product of a calculated neutrino flux [cm^{-2} s^{-1}] ⊗ a theoretical cross section [cm^2]:

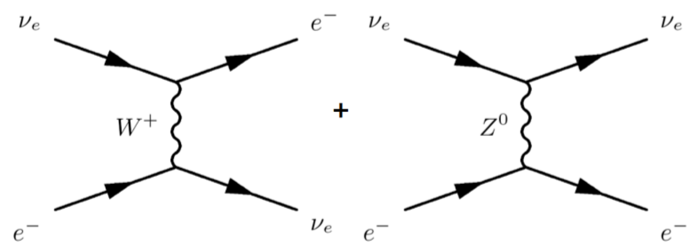
$$n \text{ SNU } [10^{-36} s^{-1}] = n \text{ of events per target per second}$$

For sake of comparison, we will compute the SNU calculation for all the neutrino sources listed above.

The Low Energy Range

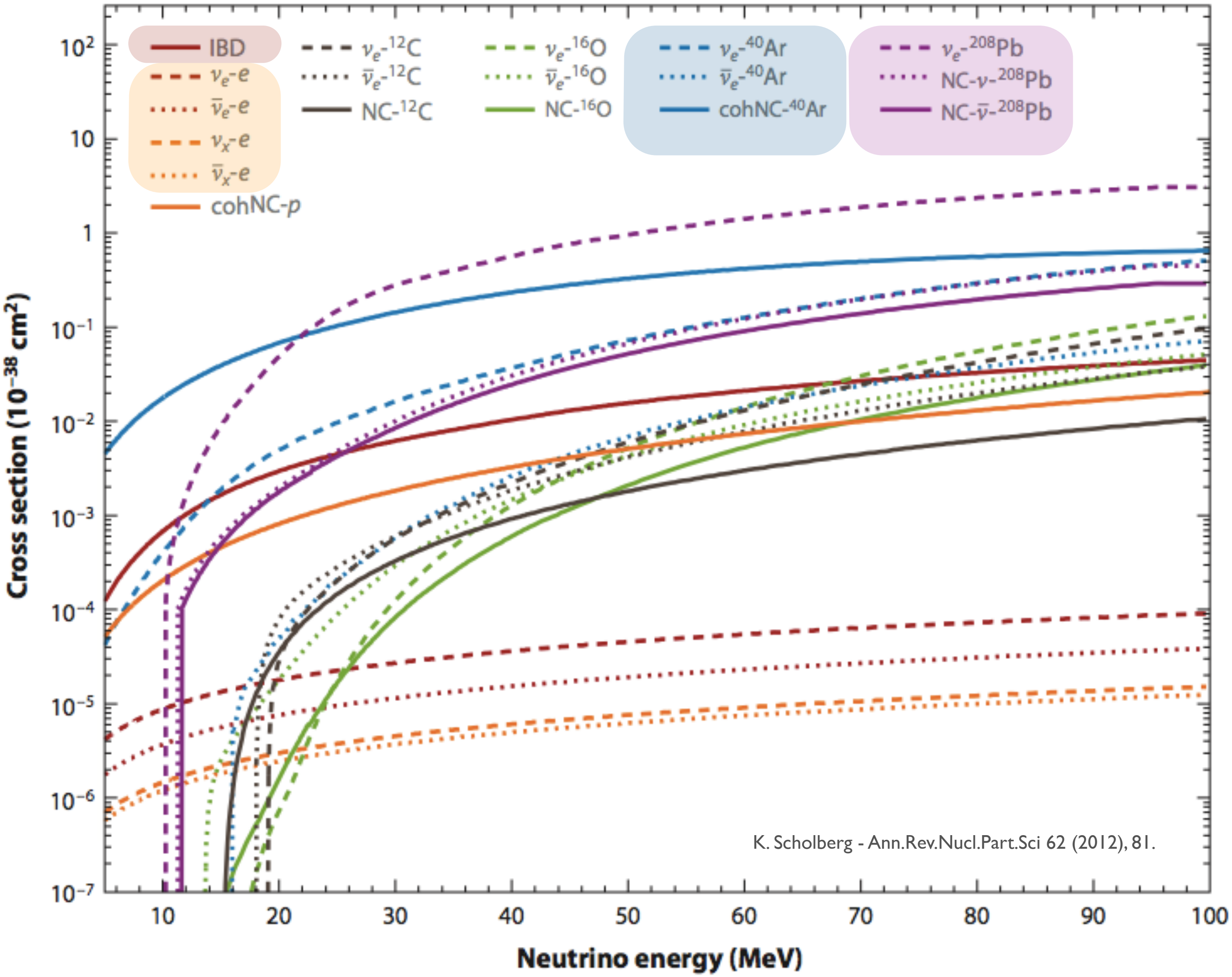


Elastic Scattering on Atomic Electrons is the only well-known process at $E_\nu > O(100$ KeV)



The coherent scattering on Nuclei (Ar) “potentially” provides much higher Xsect above ~1 MeV (to be confirmed experimentally)

Cross Section: O(1MeV) < E_ν < O(100 MeV)

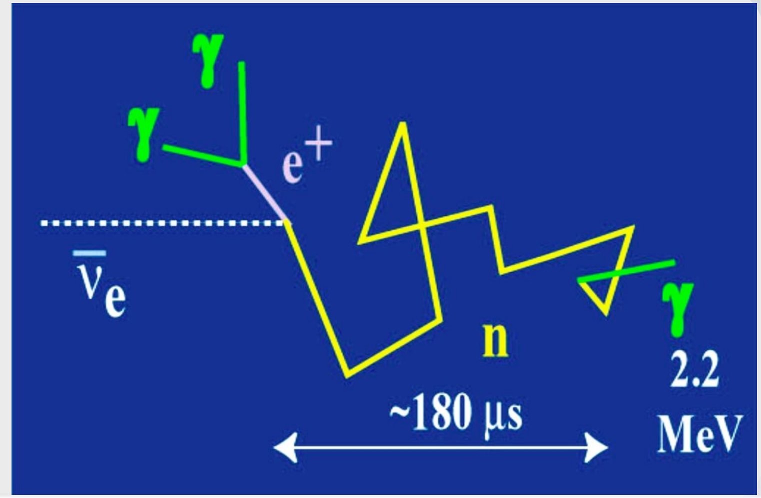


Neutrino interactions in the MeV range

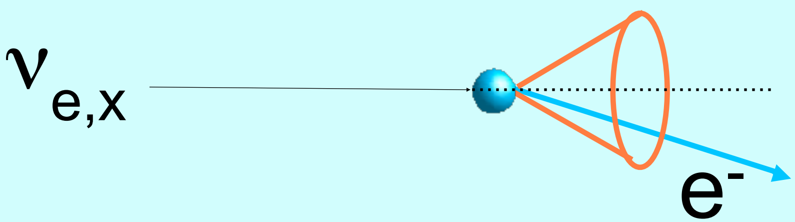
IBD - Inverse Beta Decay (CC)

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

In any detector with lots of free protons (e.g. water, liquid scintillator) this dominates



ES - Elastic Scattering on atomic electrons



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

(useful for pointing)

interactions on nuclei:

ABS - ν_e CC Absorption

NE - ν_x NC Nuclear Excitation

Coh - ν_x NC Coherent Scattering

$$\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$

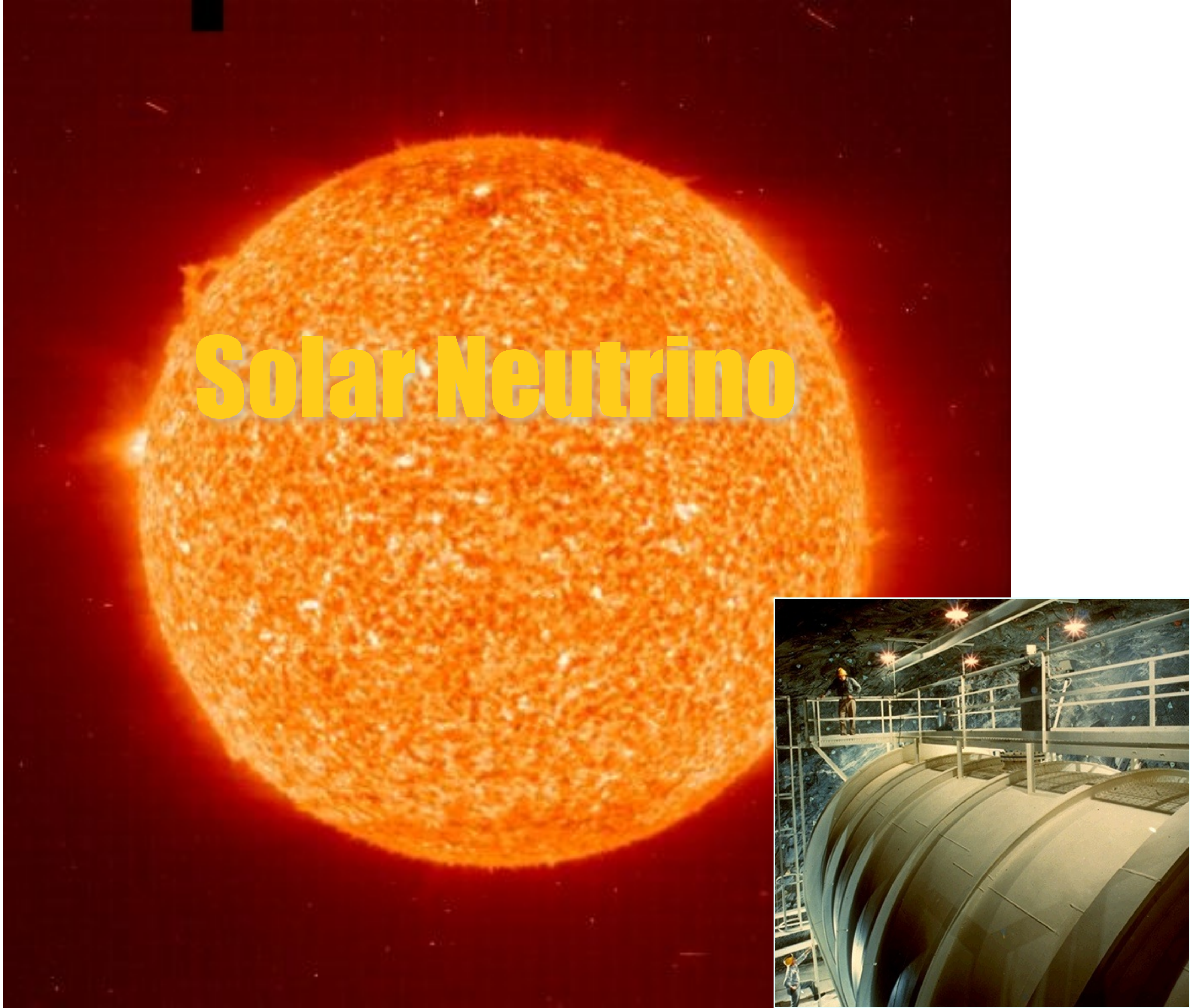
$$\bar{\nu}_e + (N, Z) \rightarrow (N+1, Z-1) + e^+$$

$$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$$

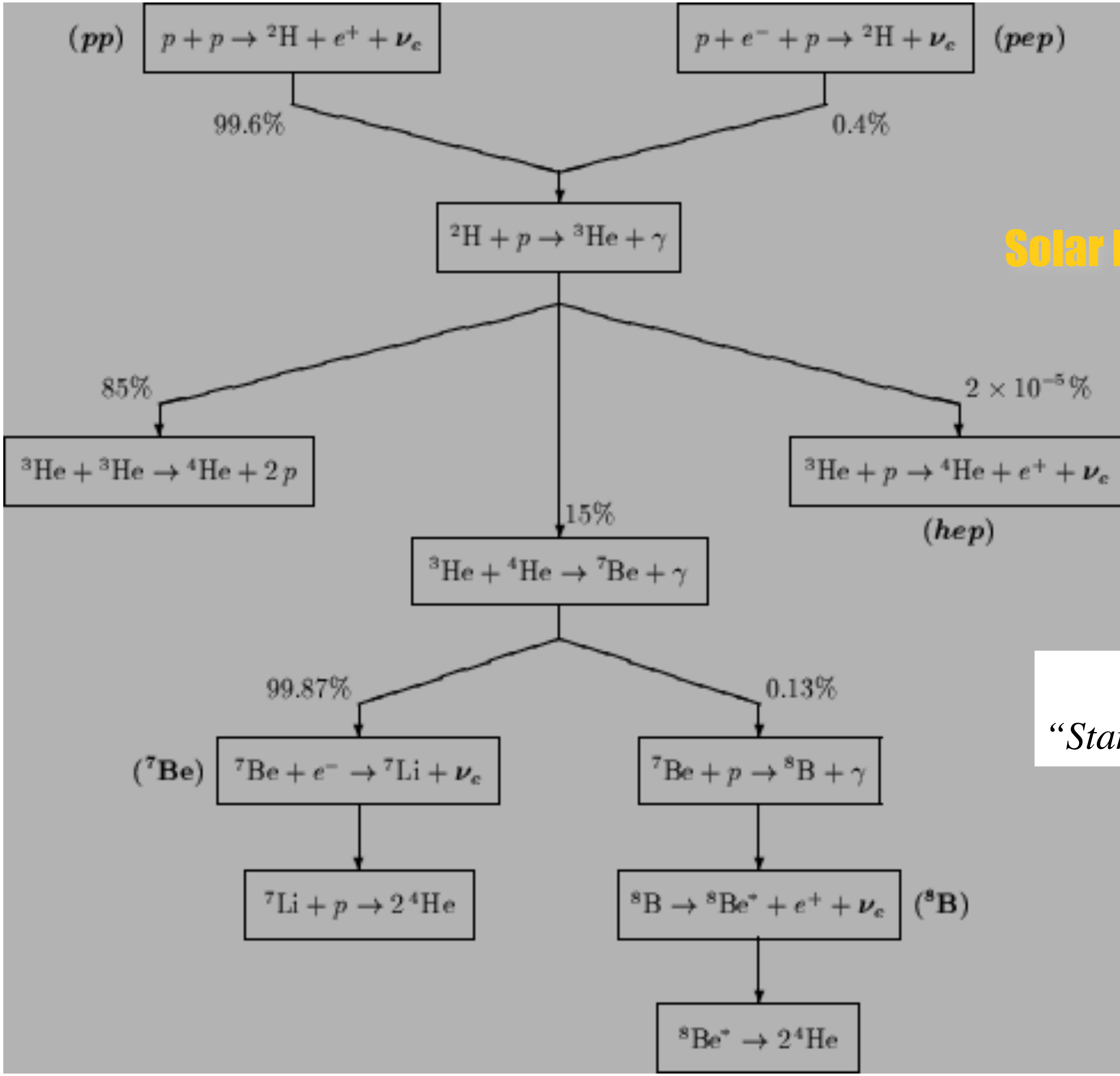
$$\hookrightarrow (A,Z) + \gamma$$

+ NC coherent scattering

Low Energy neutrinos

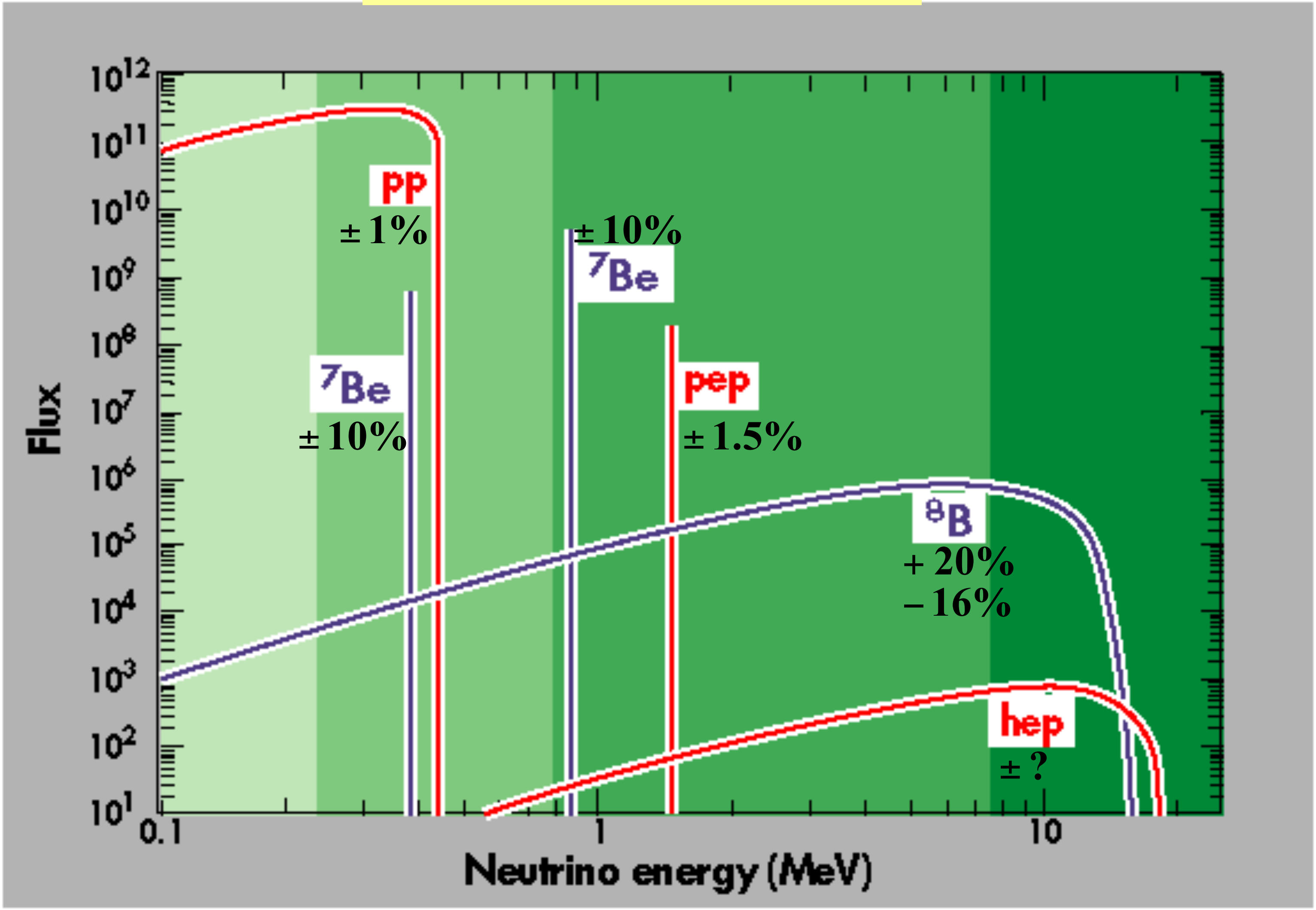


Solar Neutrino Flux



from the “Standard Solar Model”

The Solar Neutrino Spectrum



BP00: astro-ph/0010346

Flux Properties

Source	Flux $[10^{10}\ cm^{-2}\ s^{-1}]$	Energy Spectrum	Energy Mean Value [MeV]	Energy End Point [MeV]
pp	5.95	Cont.	0.2668	0.423
pep	0.014	line	1.445	1.445
hep	0.00000093	Cont.	9.628	18.778
^{7}Be	0.477	line	0.3855 0.8631	0.3855 0.8631
^{8}B	0.000505	Cont.	6.735	~ 15

"Low Energy" range

(1) Absorption Reactions (Inverse β decay)

$$\nu_e + A_Z \rightarrow e^- + A_{Z+1}$$

Absorption Reactions: the incoming ν is absorbed, an *electron* is created, and a *neutron* in the target Nucleus (*A*) is transformed into a *proton*. (with detection of *electron* and/or of A_{Z+1})

Dominant transitions are *ALLOWED* transitions:

Nuclear spin change $\Delta J = 0$ (Fermi Trans.), ± 1 (Gamow - Teller Trans.)

Nuclear parity (no change) $\Delta \pi = 0$

In particular, ***SUPER-ALLOWED* transitions**: $\Delta I = 0$ (Isotopic Analogue State Trans.)

Absorption Cross Section can be written in terms of *atomic and kinematic factors* times the *nuclear matrix element* (representing the n-p transformation):

$$\sigma = \sigma_o \times p_e W_e \; \mathrm{F}(Z, W_e)$$

$$\sigma_o = k \, |M_{i \rightarrow f}|^2$$

$$|M|^2 = \mathrm{B(F)} + \mathrm{B(GT)}$$

where

F : Fermi function

$\sigma_o[10^{-46} cm^2]$: transition matrix elemen

B(F) : Fermi Matrix Elements

B(GT) : Gamow - Teller Matrix Elements

B(F) and **B(GT)** ($\Rightarrow \sigma_o$) can be evaluated with **shell-model calculations** (high precision for B(F)) and compared with experimental data from half-life measurements of inverse nuclear processes (e.g. Electron Capture) by symmetry relations.

(*FORBIDDEN* reactions provide small corrections in the "Low energy" range)

- The emitted electron energy W_e is given by:

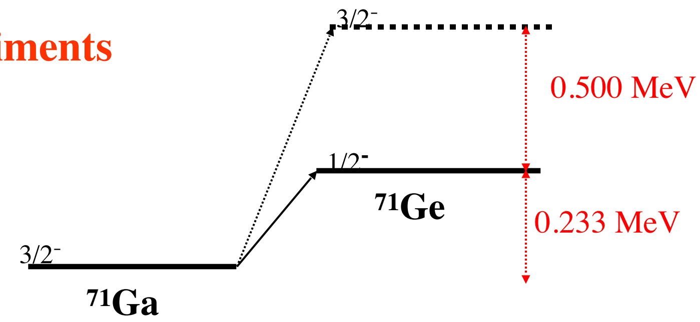
$$W_e = E_\nu - \Delta E_{nucl}$$

with ΔE_{nucl} being the nuclear mass difference

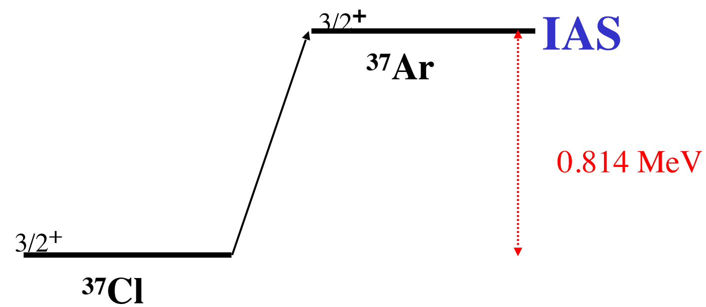
- The Fermi function $F(Z, W_e)$ takes into account corrections due to finite nuclear size and electron screening (important effect for high Z materials)

Target Nuclei in some present (past & "future") experiments

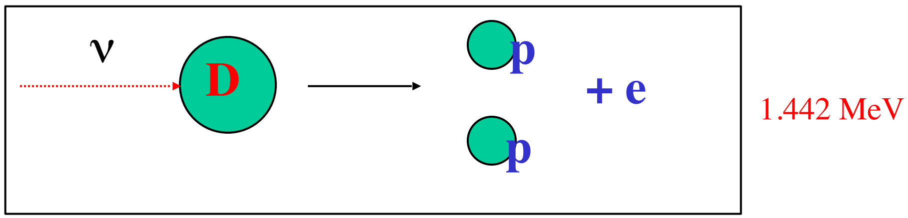
- **^{71}Ga** : *GALLEX/GNO* and *SAGE*



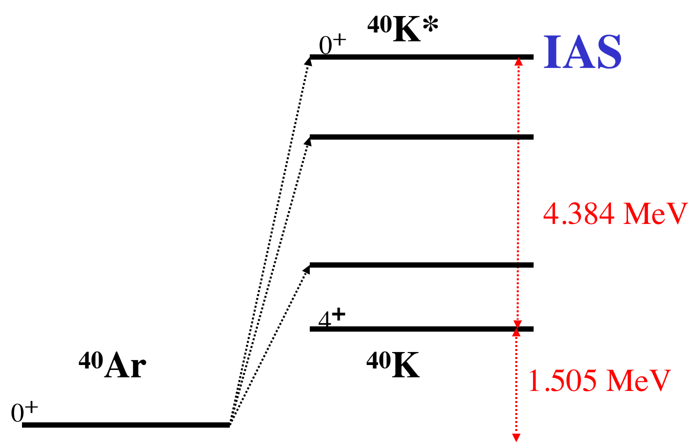
- **^{37}Cl** : *HOMESTAKE*



- **^{2}H$_{1}$** : *SNO*



- **^{40}Ar** : *DUNE*



Expected rates calculations

ν Absorption cross-section "averaged" over single flux component energy spectrum

$$\langle \sigma_f \rangle = \int_{E_\nu^{\min}}^{E_\nu^{\max}} \sigma(E_\nu)\, \lambda_f(E_\nu)\, dE_\nu \; ; \quad f = \mathrm{pp},\ {}^7\mathrm{Be},\ {}^8\mathrm{B},\ \ldots$$

$$\lambda_f = \text{normalized energy spectrum}$$

$$E_\nu^{\min} = \Delta E_{nucl} + m_e \left(+ E_{thr} \right)$$

$$SNU\left[10^{-36} s^{-1}\right] = \langle \sigma_f \rangle \left[10^{-46} cm^2\right] \times \Phi_f\left[10^{10} cm^2 s^{-1}\right]$$

$$N_{\mathrm{evt}} = SNU \times N_{\mathrm{targ}} \times \Delta \mathrm{t}\;; \qquad N_{\mathrm{targ}} = \frac{N_{Av}}{A}\left[g^{-1}\right] \times 10^6 \times M_{\mathrm{Det}}[t]$$

$$\left(\text{e.g.} \approx \frac{30\ \text{evt}}{\text{t}\cdot\text{yr}}\ \text{of Ga target}, \approx \frac{2\ \text{evt}}{\text{t}\cdot\text{yr}}\ \text{of Ar target}\right)$$

Δt: 1 yr = 3 x 10^7 s

Reference Numbers useful for Event Rate Calculations

Experiment	*Nuclear Target*	*Reaction*	σ_0 [10^{-46} cm^2]	ΔE_{nucl} [MeV] (no det. Thres.)		Flux Main Components	SNU [10^{-36} s^{-1}]
GALLEX/GNO SAGE	$^{71}Ga_{33}$	$\nu_e + ^{71}Ga \rightarrow e^- + ^{71}Ge$	8.611 ± 0.4% (GT)	0.2327		pp + ^{7}Be+^{8}B	128.0
HOMESTAKE	$^{37}Cl_{17}$	$\nu_e + ^{37}Cl \rightarrow e^- + ^{37}Ar$	1.725 (F)	0.814		^{8}B + ^{7}Be	7.6
SNO	$^2H_1$	$\nu_e + ^2H \rightarrow e^- + p + p$	(GT)	1.442		^{8}B	6.8
LArTPC	$^{40}Ar_{18}$	$\nu_e + ^{40}Ar \rightarrow e^- + ^{40}K^*$	148.58 (F) … 44.367 (GT_2) … 41.567 (GT_6) …	1.505 +	4.384 … 3.798 … 2.730	^{8}B	4.6 + 6.5

Important Experimental Observable

Radio-chemical experiments (Ge, Cl target): ♥ rate

♣ time variation of the rate

Real-time experiments (D, Ar target): ♥ rate

♦ electron Energy Spectrum

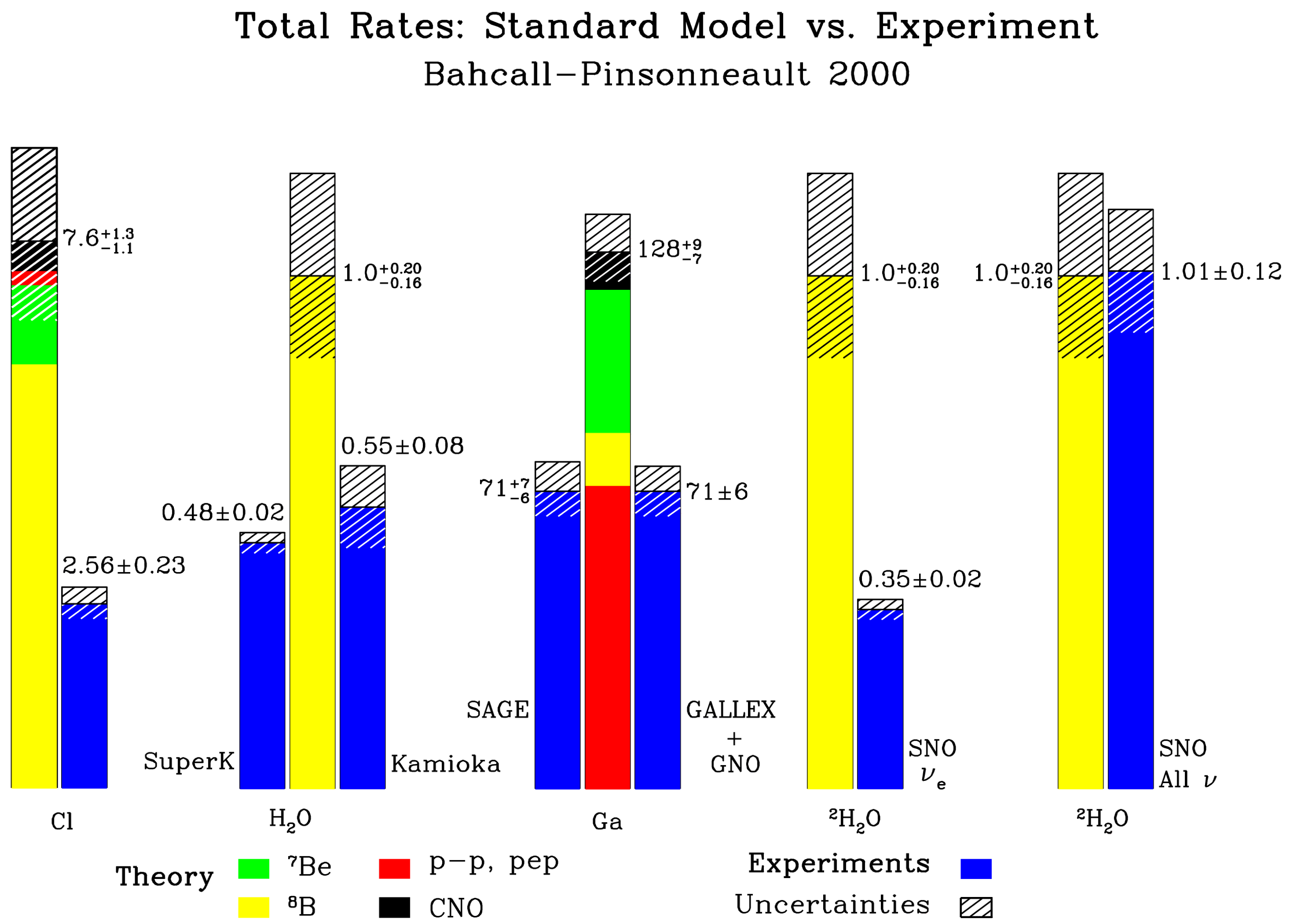
 (D target) - recoil proton Energy Spectrum

 (Ar target) - calorimetric measurement of de-excitation energy ($K^* \rightarrow K + \gamma$)

♦ electron Energy Spectrum:

$$\frac{d\sigma}{dW_e} = \sigma(E_\nu)\,\lambda_f(E_\nu) \quad ; \qquad E_\nu = W_e + \Delta E_{\rm nucl}\left(+E_{\rm thr}^{\rm Det}\right)$$

NB: spectrum distortion introduced by neutrino oscillation !!



7 Experiments; 40 years of activity!!!;

Reactor $\bar{\nu}_e$ are emitted in the same (“Low”) energy range of Solar-ν: the interaction cross-sections with matter are established by the theoretical models discussed in the Solar neutrino section

The average energy distribution for the energy released per fission with a thermal neutron in uranium-235

TABLE 6
Instantaneous Energy from Fission

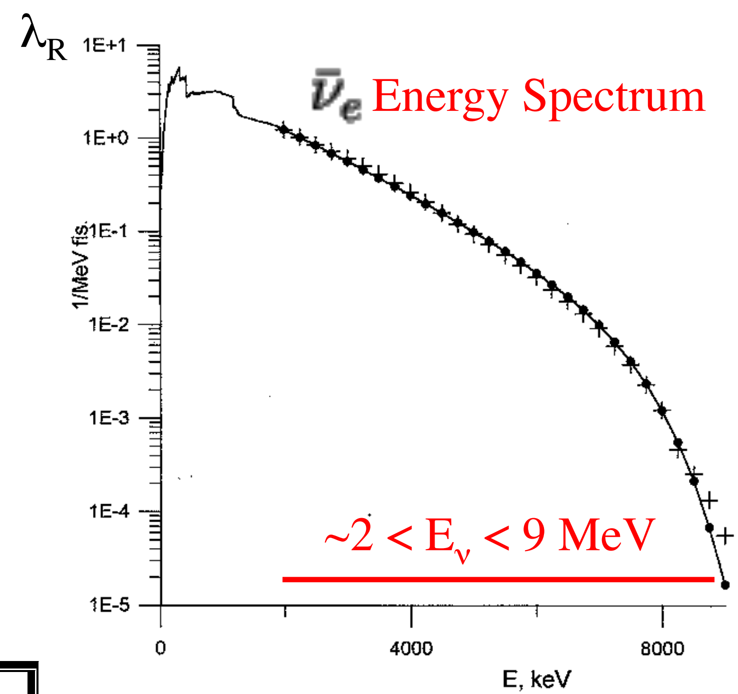
Kinetic Energy of Fission Products	167 Mev
Energy of Fission Neutrons	5 MeV
Instantaneous Gamma-ray Energy	5 MeV
Capture Gamma-ray Energy	10 MeV
Total Instantaneous Energy	187 MeV

TABLE 7
Delayed Energy from Fission

Beta Particles From Fission Products	7 Mev
Gamma-rays from Fission Products	6 MeV
Neutrinos	10 MeV
Total Delayed Energy	23 MeV

Source	Flux $[10^{10}\ cm^{-2}\ s^{-1}]$	Energy Spectrum	Energy Mean Value (E_ν>2MeV) [MeV]	Energy End Point [MeV]
^{235}U ^{239}Pu Fission	≈ 2000 d~30 m	Cont.	≈ 3	≈ 9

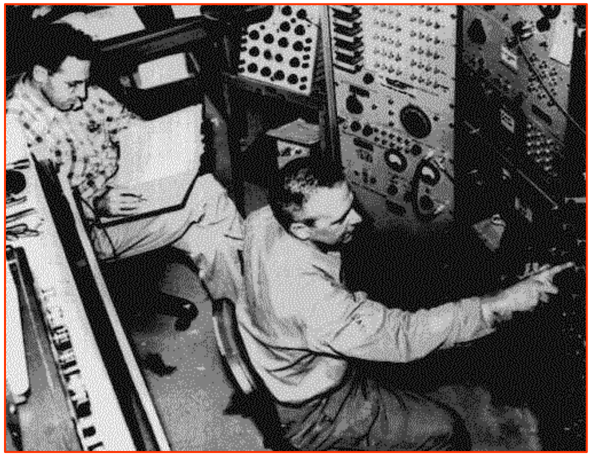
The tremendous anti-neutrino flux produced by nuclear reactors ($5\ 10^{20}\ \bar{\nu}_e$ per second for a 2800 MW reactor) led to the neutrino experimental discovery.



REACTOR ANTINEUTRINO ENERGY SPECTRUM
for the average contribution to the number of fission:
U235 - 58%, Pu239 - 30%, U238 - 7%, Pu241 - 5%

Curve and circles - Kurchatov Institute (measurement at reactor E > 2 MeV and calculation E < 2 MeV)
Crosses - STANDARD $\tilde{\nu}_e$ - spectrum (from electron spectra E > 2 MeV, 1 - day irradiation time)

The detection technique is generally very similar to that pioneered by Reines and Cowan experiment:
a large tank of liquid scintillator
(C_nH_{2n+2} hydrocarbon molecule rich in H, n >20)
doped with an element (Cd) adequate for neutron capture is exposed to the neutrino flux.



Anti-neutrinos interact with protons in the target through the inverse beta decay reaction:

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

The gold-plated reaction!!

leaving as signature a prompt light pulse corresponding to the positron annihilation followed by a delayed light pulse from the de-excitation after neutron capture.

The reaction has a threshold on neutrino energy:

$$E_{\bar{\nu}}^{\mathrm{Thr}} = (M_n - M_p) + m_e = 1.805\ MeV$$

- *Precise cross-section calculation*
- *Low threshold*
- *Unambiguous signature*
- *Target availability*

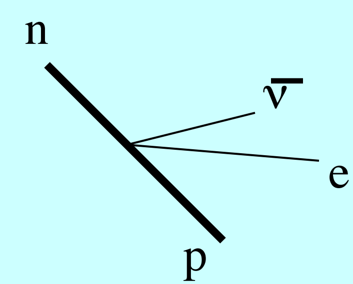
Cross Section

Fermi Theory:

In 1933 E. Fermi assumed that an electron and an antineutrino are produced in the process

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

and calculated the n-decay matrix element.



If the interaction responsible for the decay of the neutron is known, one can connect the cross section of the $\bar{\nu}_e$ process, at the small reactor energies, with the lifetime of the neutron.
Neglecting small corrections due to neutron recoil, the total cross section of the process $\bar{\nu}_e + p \rightarrow e^{+} + n$ is given by:

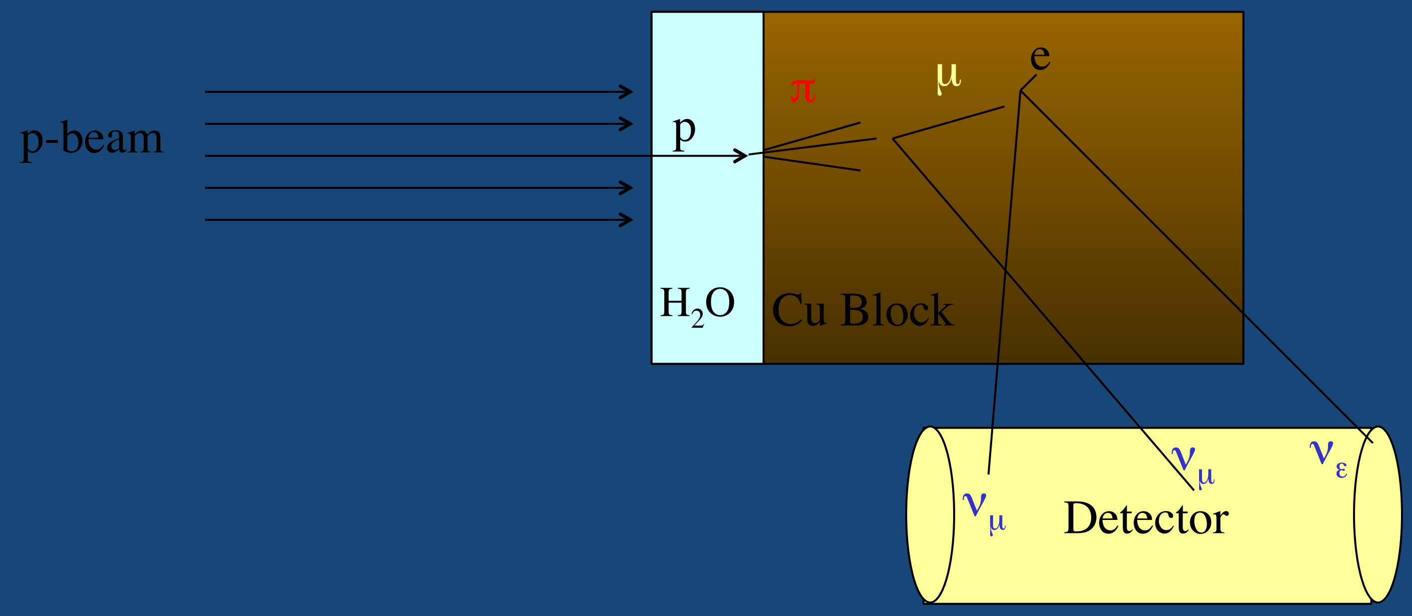
$$\sigma = \sigma_0 \times p_e W_e \; ; \quad \text{where } \sigma_0 \left[10^{-42} cm^2\right]: \text{ trans. matrix element}$$

$$\text{and } W_e = E_\nu - (M_n - M_p)$$

$$\langle \sigma_R \rangle = \int \sigma(E_\nu)\, \lambda_R(E_\nu)\, dE_\nu \approx 2 \times 10^{-45} cm^2 \qquad \text{averaged over Reactor } \nu\text{-flux}$$

$$"SNU" \left[10^{-36} s^{-1}\right] = \langle \sigma_R \rangle \times \Phi_R \approx 4 \times 10^4$$

$$\text{Evt. Rate : } \frac{N_{evt}}{h} \approx 3 - 4 \text{ for a detector Mass of } 0.2 \text{ t}$$

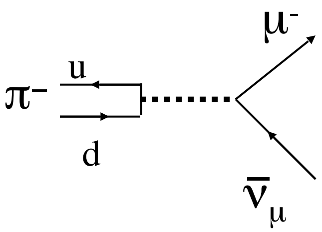


Meson decay neutrino

Neutrino fluxes from decay of **Pion** and **Muon** at rest ("beam dump neutrinos") have well defined energy spectra (and angular distributions). The neutrino energy range encompasses the solar & reactor range and extends up to about **50 MeV (the "Moderate Energy" range)**.

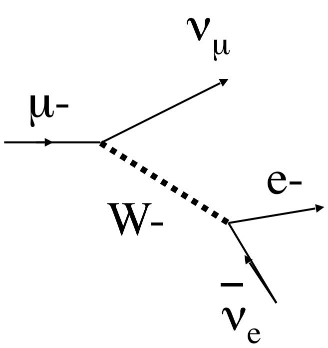
The interaction cross-sections with matter can be established by the theoretical models discussed in the Solar&Reactor neutrino sections…. but need some further deepening.

Weak Processes: leptonic decay



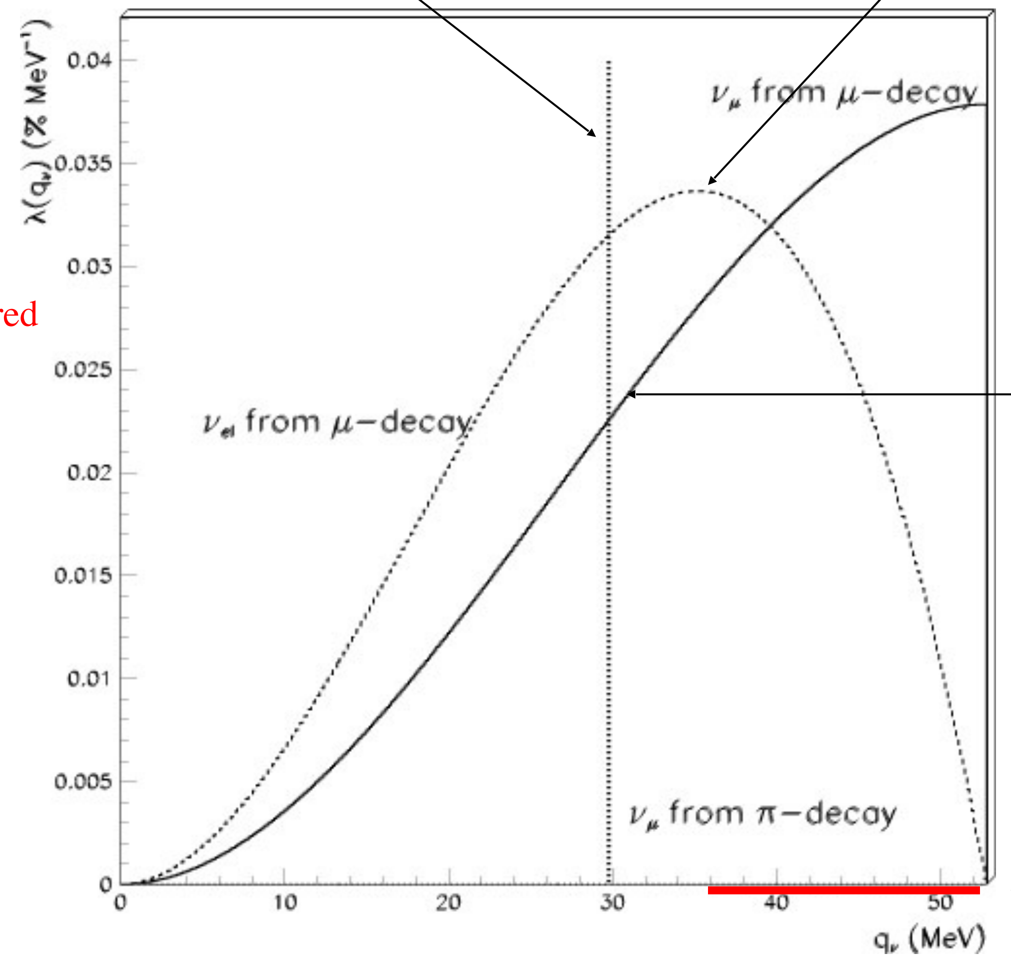
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu \quad ; \quad \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$



Dominant Channel:

- N(π^+) > N (π^-)
- π^- and μ^- are captured



Shape of the Neutrino Flux

Range of investigation

p-beam: (LAMPF) 800 MeV p-energy, 1 mA p-intensity (6×10^{15} pot/s)

Flux Properties

Source	Type	<Flux> @ detector $[10^6\ cm^{-2}\ s^{-1}]$	Energy Spectrum	Energy Mean Value [MeV]	Energy End Point [MeV]
$\pi^+ \to$	ν_μ	≈ 5.	Line	29.8	29.8
$\mu^+ \to$	$\bar{\nu}_\mu$	≈ 5.	Cont.	~ 45.	52.8 $\left(= \frac{m_\mu}{2}\right)$
$\mu^+ \to$	ν_e	≈ 5.	Cont.	~ 36.	52.8 $\left(= \frac{m_\mu}{2}\right)$
$\pi^- \to$	$\bar{\nu}_\mu$	≈ 2.5×10^{-3}	Line	29.8	29.8
$\mu^- \to$	ν_μ	≈ 2.5×10^{-3}	Cont.	~ 45.	52.8 $\left(= \frac{m_\mu}{2}\right)$
$\mu^- \to$	$\bar{\nu}_e$	≈ 2.5×10^{-3}	Cont.	~ 36.	52.8 $\left(= \frac{m_\mu}{2}\right)$

"Moderate Energy" range

In the $36 < E_\nu < 52.8$ MeV energy range, the $\bar{\nu}_e$ rate relative to $\bar{\nu}_\mu$ is even lower so that the observation of a significant $\bar{\nu}_e$ rate would be evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.

The signature for a $\bar{\nu}_e$ interaction in a liquid scintillator detector is the reaction:

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

followed by n + p $\longrightarrow$ d + γ (2.2 MeV)

… the same signature exploited with reactor neutrinos at lower ν energy.

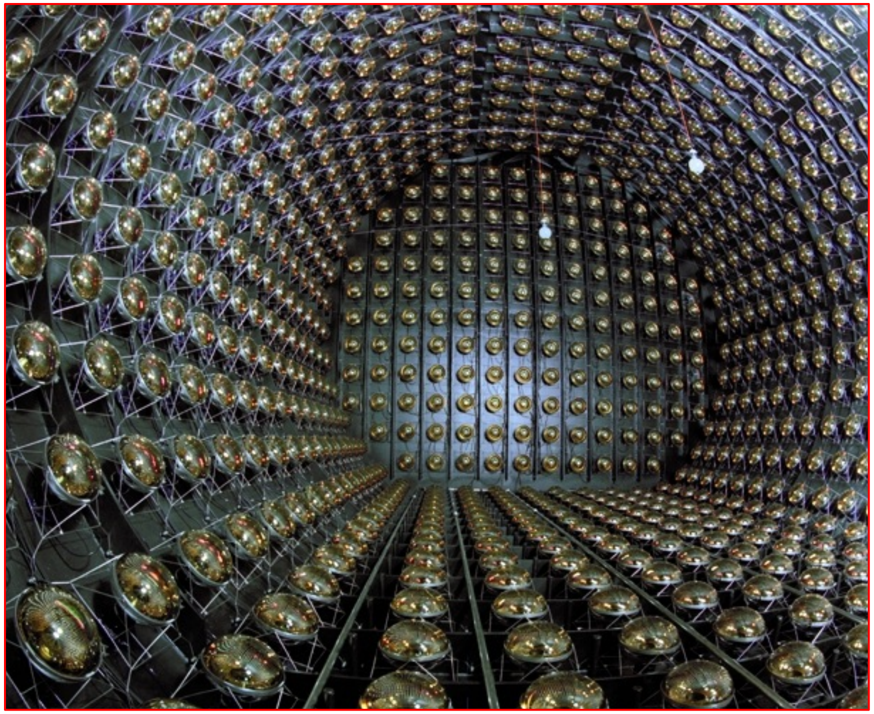
The reaction has a threshold on neutrino energy:

$$E_{\bar{\nu}}^{\mathrm{Thr}} = \left(M_n - M_p\right) + m_e = 1.805\ MeV$$

LSND Experiment

@ Los Alamos Meson Physic Facility:

- 200 m^3 of Liq.Scint. (ρ=0.85)



Cross Section (Fermi Theory):

See formulas from “Reactor Neutrino” section

$$\sigma = \sigma_0 \times p_e\, W_e \;; \quad \text{where } \sigma_0\left[10^{-42}\,cm^2\right]: \text{ trans. matrix element}$$

$$\text{and } W_e = E_\nu - (\mathrm{M_n} - \mathrm{M_p})$$

NB: σ increases ≈ quadratically with ν energy. Compared to the Reactor experiments, at the higher energies (>36 MeV) investigated at beam dump experiments, larger cross section compensate lower flux

(… but cross-section calculation with Fermi Theory not fully adequate).

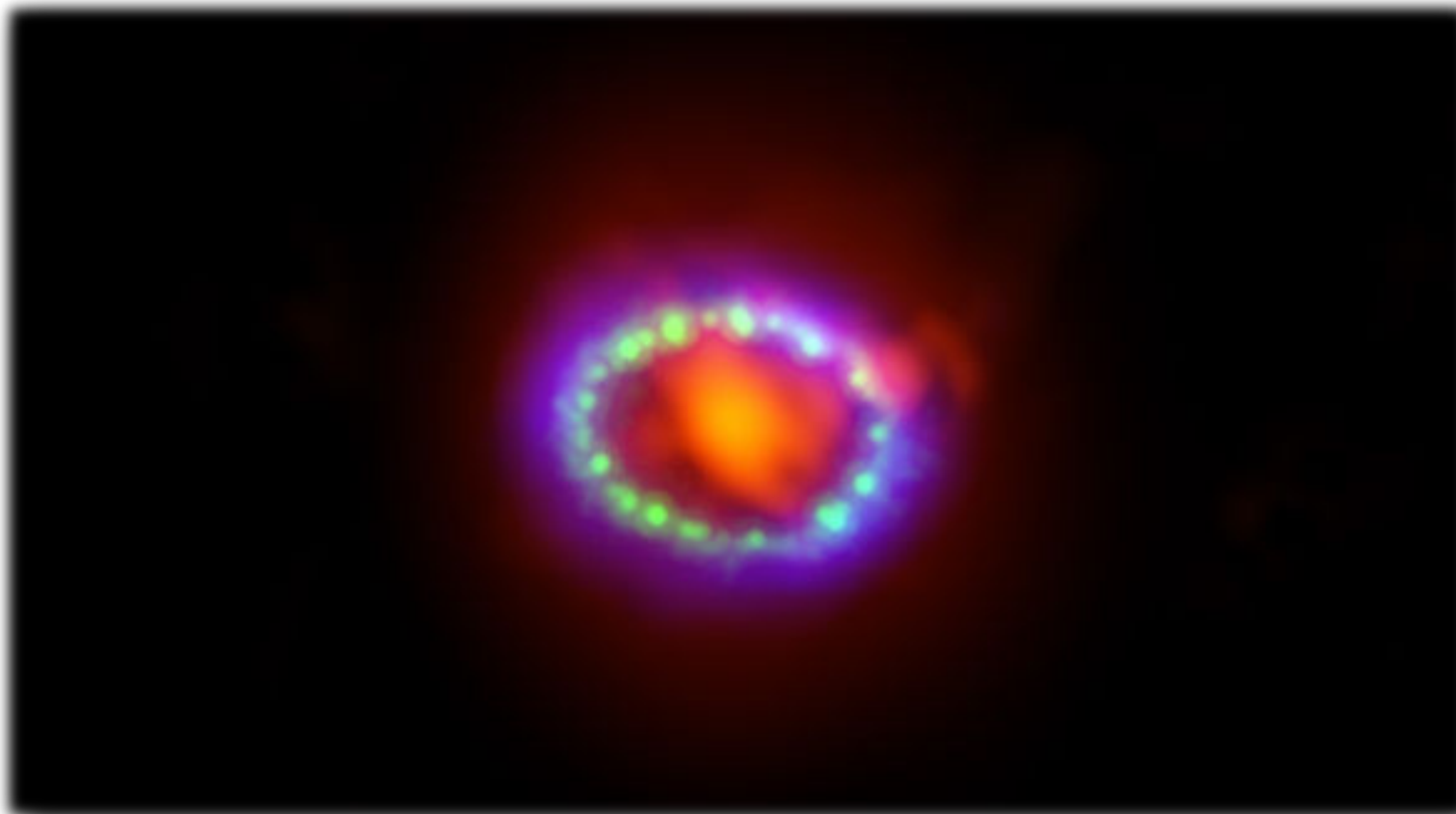
$$\langle \sigma_{\mathrm{BD}} \rangle = \int \sigma(E_\nu)\, \lambda_{\mathrm{R}}(E_\nu)\, dE_\nu \approx 4 \times 10^{-41} cm^2$$ averaged over BeamDump ν-flux

$$"SNU"\ \left[10^{-36} s^{-1}\right] = \langle \sigma_{\mathrm{BD}} \rangle \times \Phi_{\mathrm{BD}} \approx 0.1$$

$$\text{Evt. Rate}\ :\ \frac{N_{evt}}{yr} \approx 4-5 \quad (!!!)\ \text{for a detector Mass of 180 t}$$

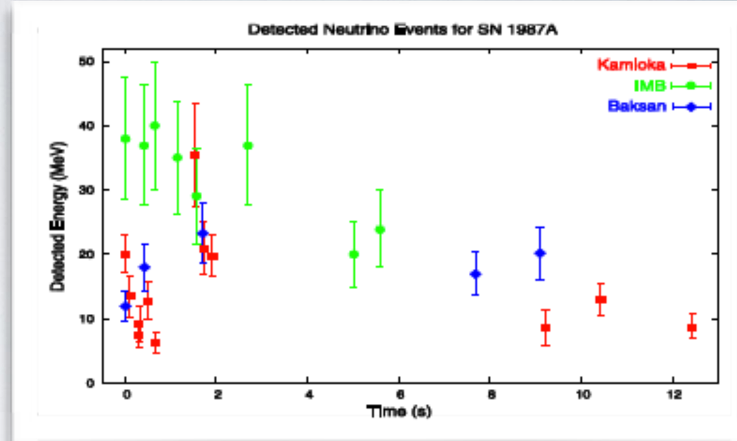
Hp. Sterile Neutrinos

The negligible $\bar{\nu}_e$ expected rate makes the search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation very effective due to the much larger $\bar{\nu}_\mu$ flux (22 events **have been detected !! by LSND).**



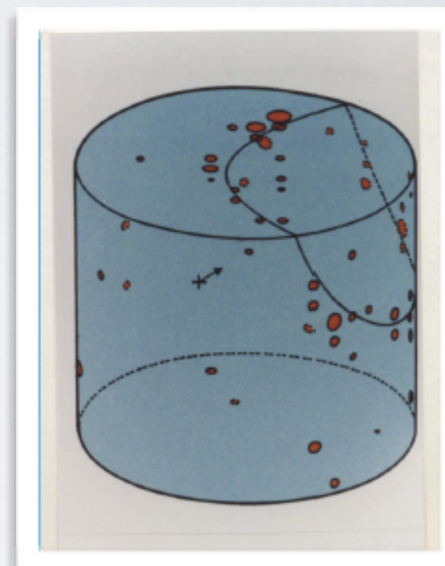
Supernova Neutrino

About 20 events were detected in 1987 by simultaneous observations of Kamiokande II, IMB, Baksan detectors from supernova, SN1987A, located in the Large Magellanic Cloud, at a distance D < 50 kpc.
Usually, all these events are attributed to IBD - inverse β-decay



The experimental detection of these events heralded extragalactic neutrino astronomy.

The rate of occurrence of core collapse supernovae for our galaxy ranges from ~1/(10 y) to ~1/(100 y).
In water or scintillator detectors one expects roughly 300 ν_e-events/kton, for a distance D =10 kpc - when our galaxy has a radius of ~15 kpc and we are located at 8.5 kpc from its center.

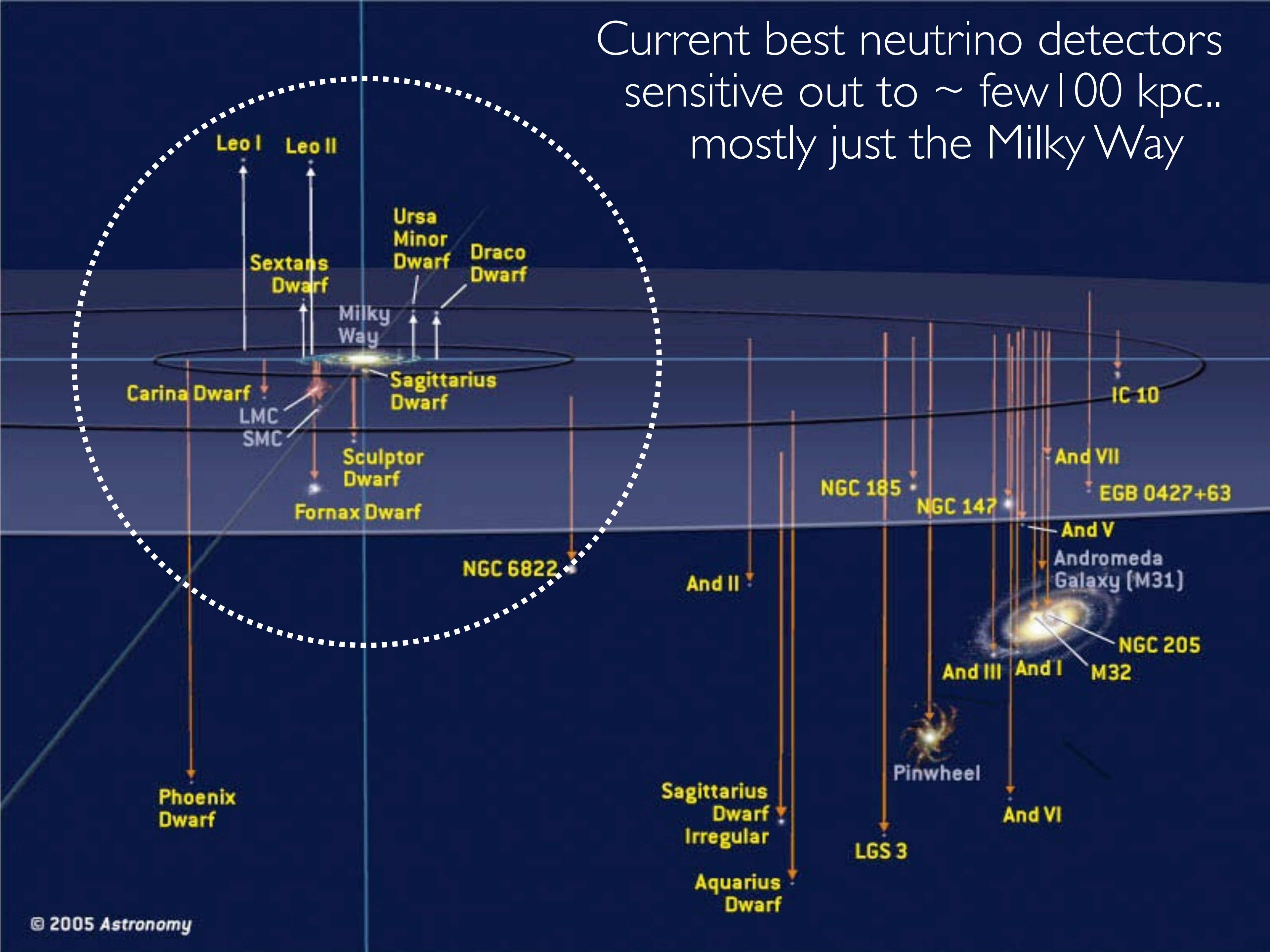


Many operating neutrino detectors like ***Super-Kamiokande, LVD, KamLAND, Baksan, AMANDA/IceCube, Borexino and Halo*** could be blessed by the next galactic supernova.

Other detectors like ***SNO+***, ***MicroBooNE*** will also be able to contribute to galactic supernovae monitoring in the near future.

Other gigantic detectors like ***Hyper-K, DUNE*** will hopefully join in the future, as well as ***also LENA, MEMPHYS***

Current best neutrino detectors sensitive out to ~ few100 kpc.. mostly just the Milky Way



SUPERNOVA NEUTRINOS

Reference ranges on SN neutrino energies averaged on time (starting at flash time, $t_0 = t_{fl}$) found comparing a number of numerical calculations are:

$$\langle E_{\nu_e} \rangle = 10\text{–}12\,\mathrm{MeV}, \quad \langle E_{\bar{\nu}_e} \rangle = 11\text{–}17\,\mathrm{MeV}, \quad \langle E_{\nu_x} \rangle = 15\text{–}25\,\mathrm{MeV}.$$

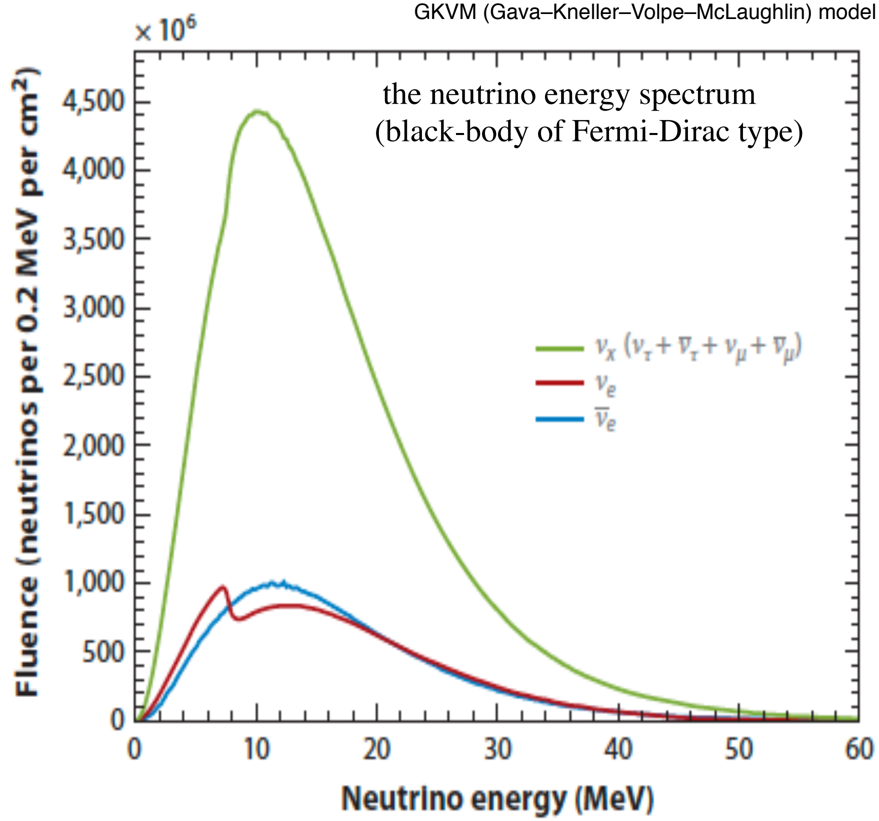
The reason for this hierarchy is that neutrinos that interact more -- $\boldsymbol{\nu}_e$ and anti-$\boldsymbol{\nu}_e$ -- undergo CC reactions, beside NC — i.e. decouple in more external regions of the star at lower temperature. In other words, each neutrino type has its own "neutrino-sphere" - ν_e's one being the outermost.

The approximate amount of the total energy ε_B carried away by the specific flavor is

$$\varepsilon_{\nu_e} = f_{\nu_e}\varepsilon_B \quad \text{with}: f_{\nu_e} = 10\text{–}30\%$$
$$\varepsilon_{\bar{\nu}_e} = f_{\bar{\nu}_e}\varepsilon_B \quad \text{with}: f_{\bar{\nu}_e} = 10\text{–}30\%$$
$$\varepsilon_{\nu_x} = f_{\nu_x}\varepsilon_B \quad \text{with}: f_{\nu_x} = 20\text{–}10\%$$

Modeling has steadily improved over the past few decades, with inclusion of more and more effects. There may be significant variations in the expected flux from supernova to supernova due to differences in the mass and composition of the progenitor, and possibly asymmetries, rotational effects, or magnetic field effects.

GKVM (Gava–Kneller–Volpe–McLaughlin) model



Summary of current supernova ν detectors

of events expected for 10kpc. Directionality

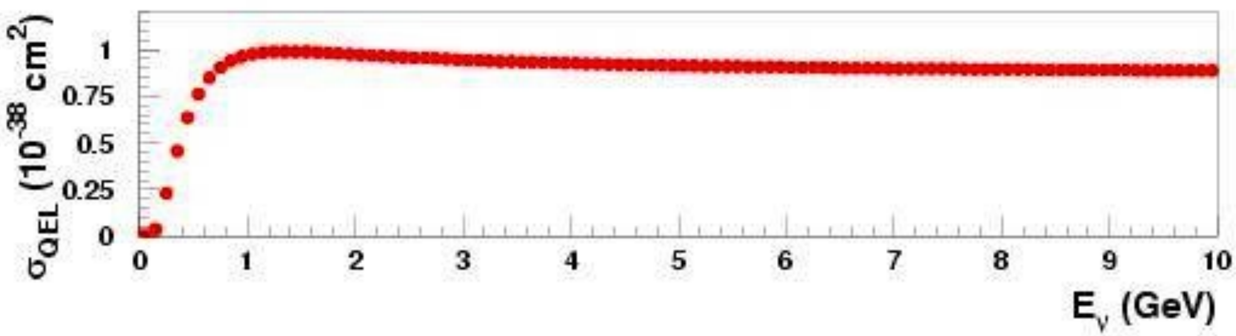
		Directionality
Baksan (1980-)	330 ton liquid scintillator ~100 $\overline{\nu}_e p \rightarrow e^+n$ events.	No
LVD (1992-)	1000 ton liquid scintillator. 840 counters 1.5m^3 each. 4 MeV thres., ~50% eff. for tagging decayed signal. ~300 $\overline{\nu}_e p \rightarrow e^+n$ events.	No
Super-K (1996-)	32,000 tons of water target. ~7300 $\overline{\nu}_e p \rightarrow e^+n$, ~300 $\nu e \rightarrow \nu e$ scattering events.	Yes
KamLAND (2002-)	1000 ton liquid scintillator, single volume. ~300 $\overline{\nu}_e p$, several 10 CC on ^{12}C, ~60 NC γ, ~300 $\nu p \rightarrow \nu p$	No
ICECUBE (2005-)	Gigaton ice target. By coherent increase of PMT single rates. High precision time structure measurement.	No
BOREXINO (2007-)	300 ton liquid scintillator, single volume. ~100 $\overline{\nu}_e p$, ~10 CC on ^{12}C, ~20 NC γ, ~100 $\nu p \rightarrow \nu p$	No
HALO (2010-)	SNO ^3He neutron detectors with 76 ton lead target. ~40 events expected.	No

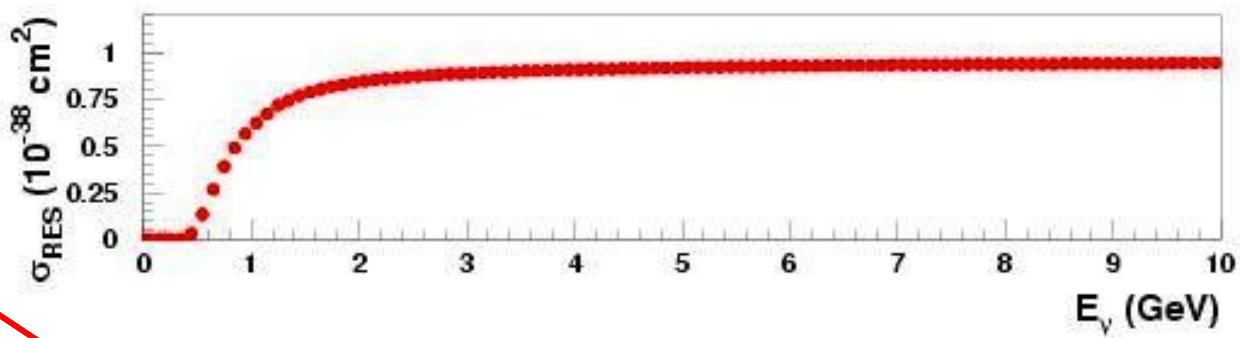
The Intermediate Energy Range

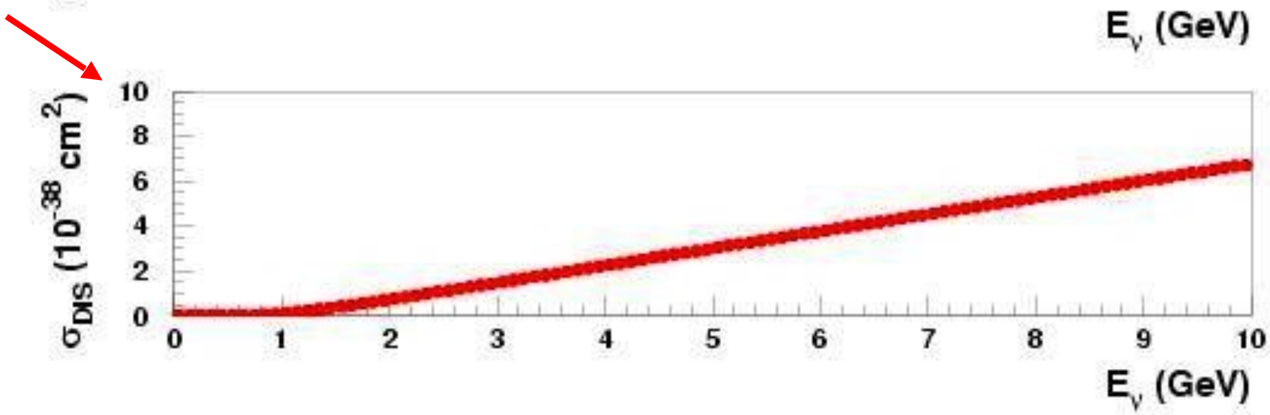
Cross Section

Neutrino Cross-Section in the "Intermediate" Energy range can be decomposed in:

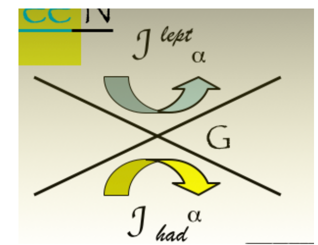
$$\sigma^{CC} = \sigma_{QEL} + \sigma_{RES} + \sigma_{DIS}$$



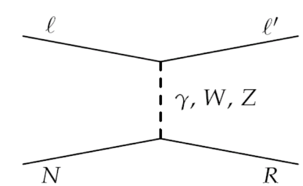




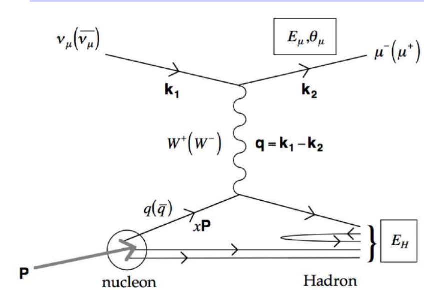
QEL cross section



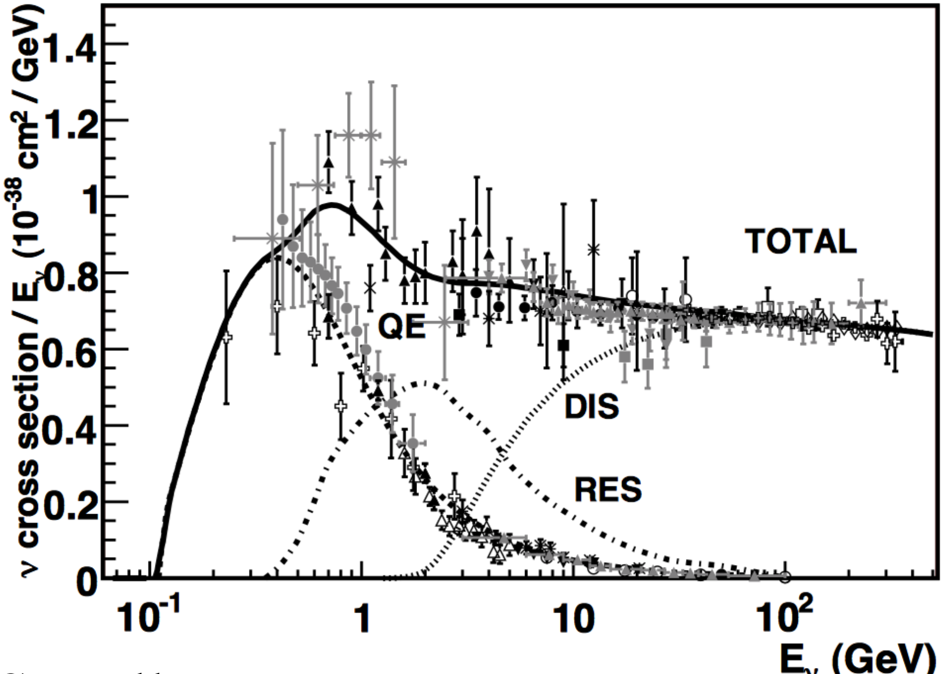
RES cross section



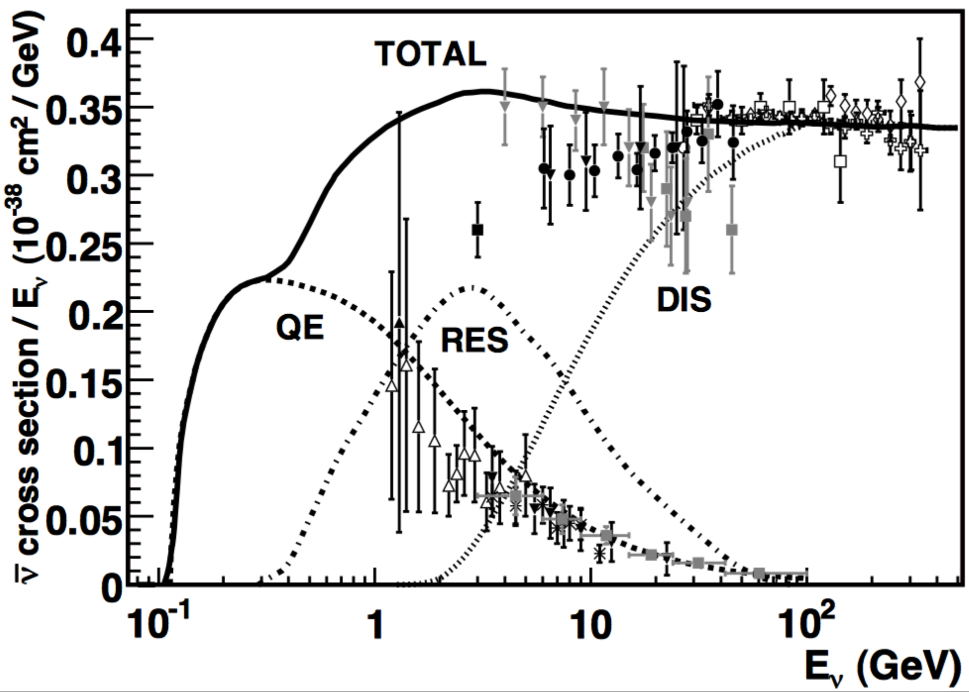
DIS cross section



The “XSECT battlefield”



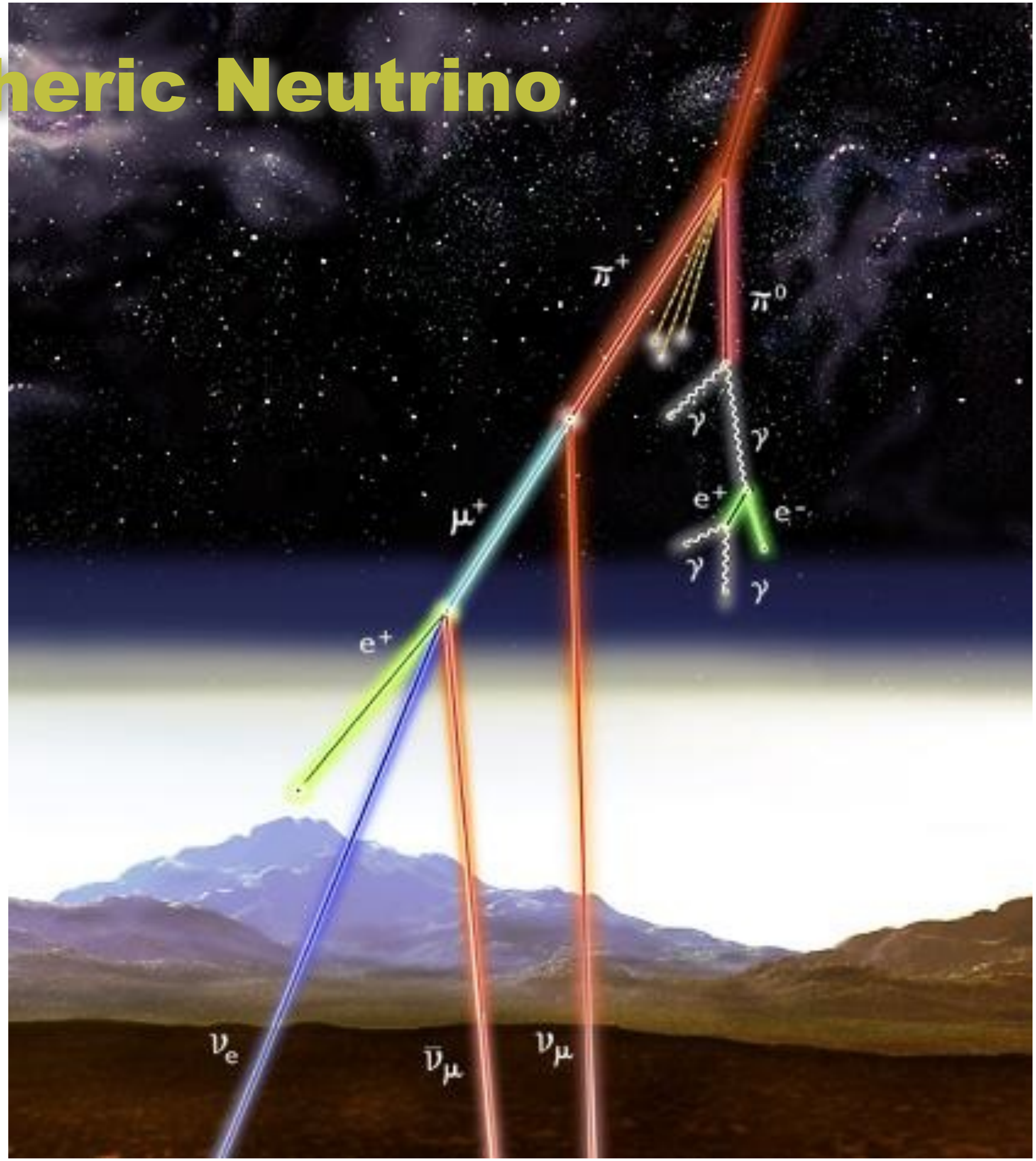
S. Zeller



σ/E plot

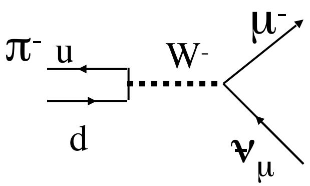
Atmospheric Neutrino

Intermediate Energy neutrinos



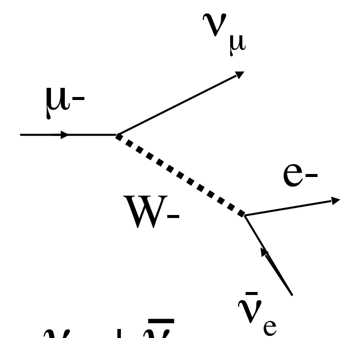
Cosmic Rays (p, A-nuclei) after entering the atmosphere collide with nuclei in the air
(NB: Primary C.R. Fluxes suffer large uncertainties and
Hadronic Interaction cross-section at extremely high energies are poorly known).

Pions and Kaons in the hadronic cascades decay in flight producing ν's and μ's.
Muons can in turn decay into ν's.



$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad ; \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

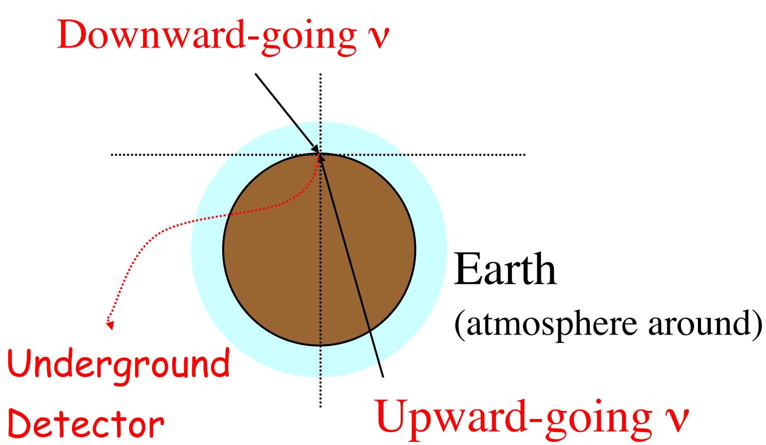
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad ; \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

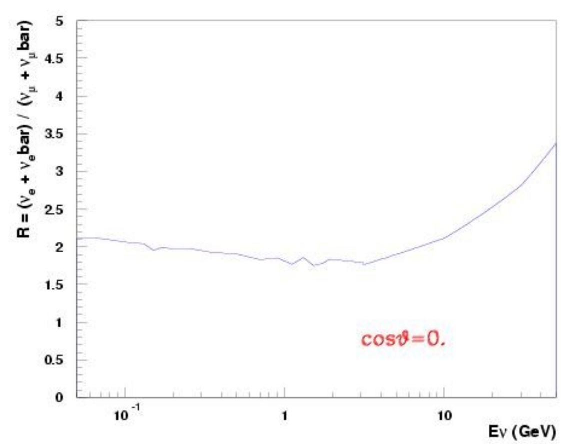


The ν-flavor Ratio at Earth surface is approximately constant

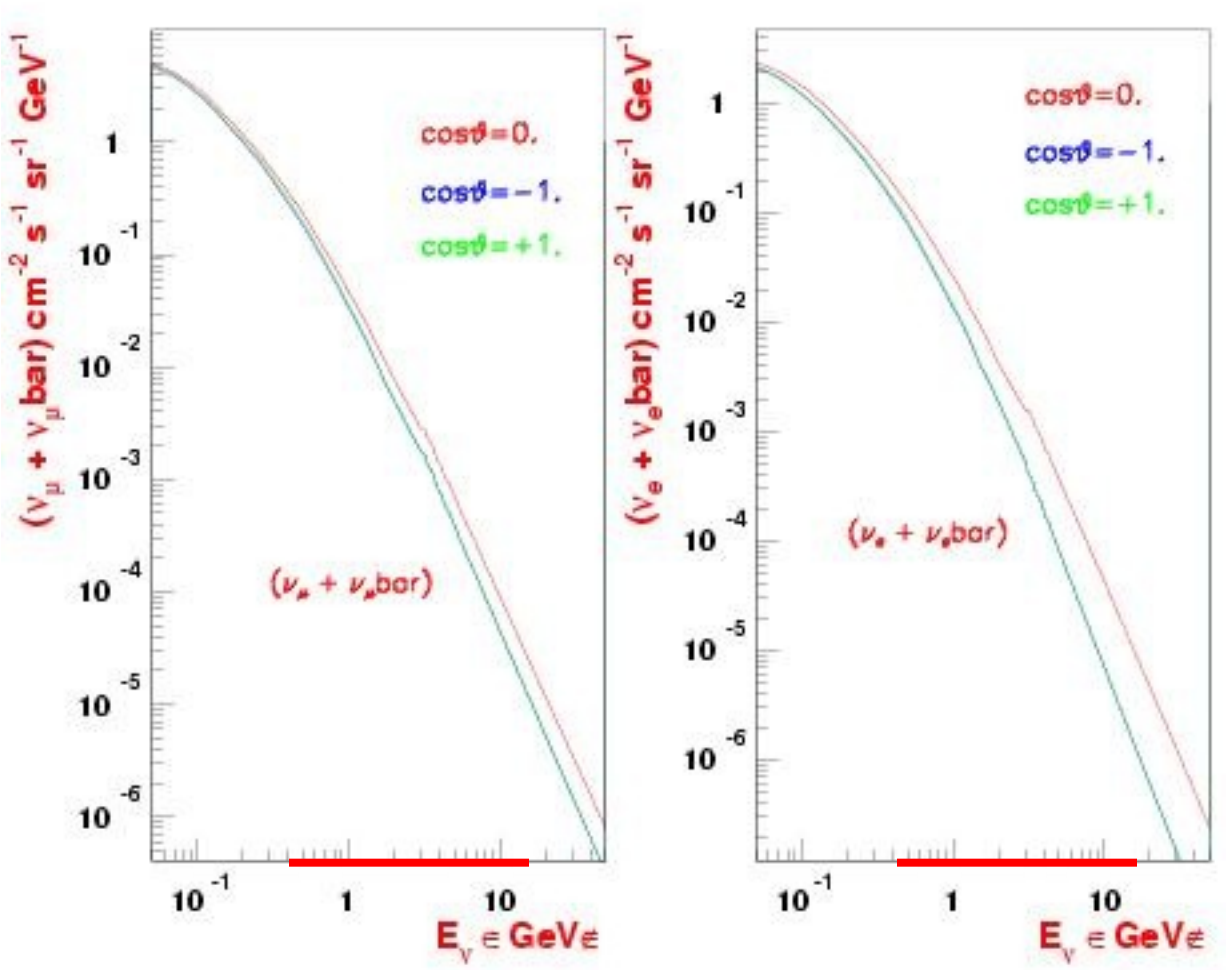
$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \cong 2$$

.. however for $E_\nu \approx 1$ GeV, the parent muon reaches the surface of the Earth before it decays ⇒ the e-neutrino fluxes decreases and **R becomes larger**





Precise calculation of the atmospheric ν-flux required a tremendous effort of many different groups (it took about 20 yr of re-iterated discussions and checks) [e.g. 1D vs 3D models]



The energy spectrum covers many orders of magnitude. The largest fraction is concentrated below 1 GeV.

The explored range w/ past experiments is:

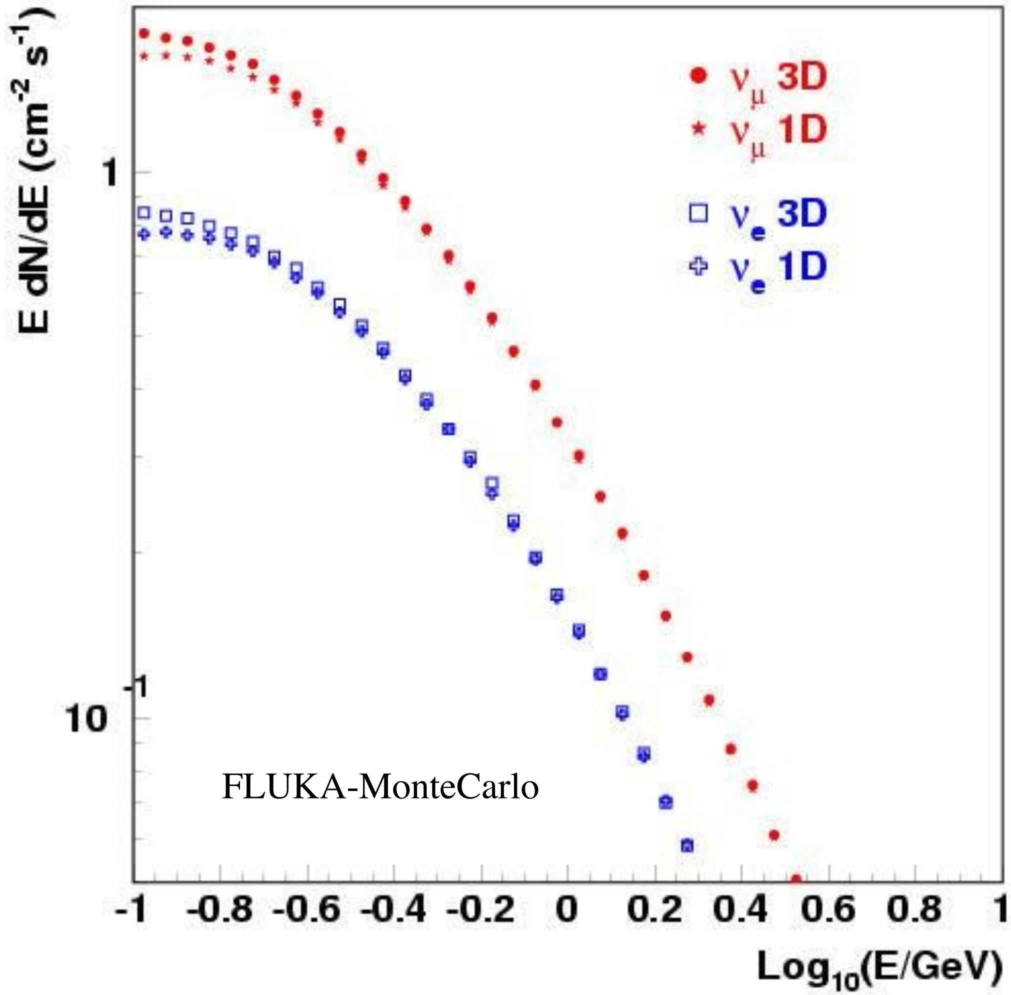
$\approx 400\ MeV \le E_\nu \le\ \approx 10\ GeV$

… but current experiment(s) now cover both the lower and the Higher part of the atm. energy ν-spectrum

The "Intermediate Energy" range

Differential ν-flux energy distributions at fixed zenith angles
(1D model - Bartol Group, Honda et al., Volkova)

Differential ν-flux distributions
(integrated over zenith angle)
from recent 3D model calculation
(FLUKA-MonteCarlo -
Battistoni, Ferrari, Lipari, Sala)



Source	Type	Flux @ detector [cm^{-2} s^{-1}]	Energy Spectrum	Energy **Mean Value** [GeV]
$\pi^{\pm}$; $\mu^{\pm} \rightarrow$	$\nu_\mu + \overline{\nu}_\mu$	≈ 2.	Cont.	0.1
$\mu^{\pm} \rightarrow$	$\nu_e + \overline{\nu}_e$	≈ 1.	Cont.	0.1

Cross Section

In the "Intermediate Energy" range (100 MeV <E_ν<2-3 GeV) the ν-projectile "sees" the nucleon N - possibly bound inside the Nucleus A_Z (above this energies - in the Deep Inelastic Region - the quark structure inside the nucleon starts to be "visible").

Neutrino Cross-Section in the "Intermediate" Energy range can be decomposed according to the final state multiplicity:

$$\sigma_\nu^{CC} = \sigma_{QEL} + \sigma_{RES} + \sigma_{DIS}$$

where :

$$\sigma_{QEL}\left(\nu_l + n \to l^- + p\right) \text{ and } \sigma_{QEL}\left(\bar{\nu}_l + p \to l^+ + n\right)$$

$$\sigma_{RES}\left(\nu_l + N \to l^- + \Delta \to l^- + N' + 1\pi^{\pm,0}\right) \text{ and } \sigma_{RES}\left(\bar{\nu}_l + N \to l^+ + \Delta \to l^+ + N' + 1\pi^{\pm,0}\right)$$

$$\sigma_{DIS}\left(\nu_l + N \to l^- + N' + X\left[\mathrm{n}\pi^{\pm,0}\right]\right) \text{ and } \sigma_{DIS}\left(\bar{\nu}_l + N \to l^+ + N' + X\left[\mathrm{n}\pi^{\pm,0}\right]\right)$$

$$l = e, \mu, \tau \qquad N = p, n$$

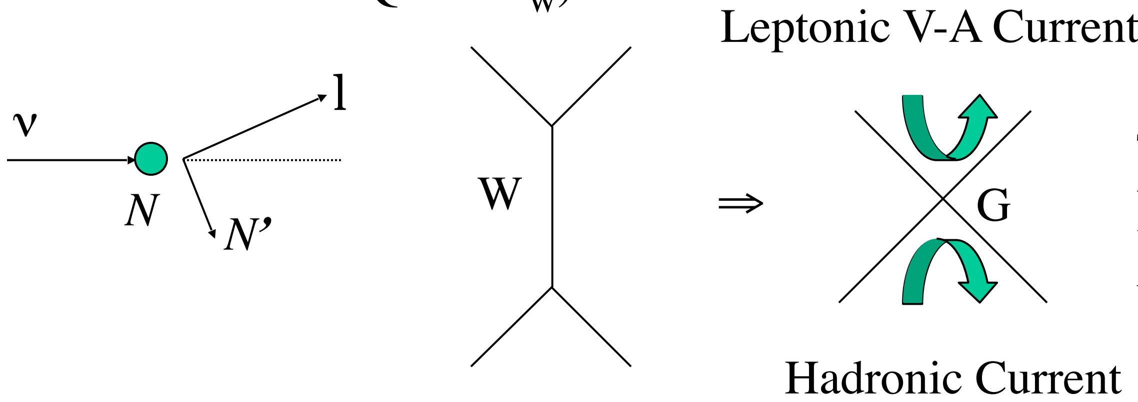
NC reaction are obtained replacing $l \Rightarrow \nu_l$

For atmospheric neutrinos

- QEL ("quasi-elastic" scattering) channel is dominant (65% of the rate)
- RES ("resonance excitation" production) channel is sub-dominant (30%)
- DIS (Deep Inelastic Scattering) is almost negligible (5%)

⇒ only QEL will be discussed in details

Dynamics of QEL interaction is described by "current-current" Lagrangian (valid in the limit of $Q^2 << M^2_W$)



The Hadronic Current is defined through the Vector (F_V^1,F_V^2) and Axial (F_A^1) Weak Form Factors of the Nucleon

The Weak f.f. (dipole form) are defined with a free parameter (M_V and M_A) to be fixed by experimental fits (or by non-perturbative QCD, but results are controversial !!).
The large error (≈15%) on M_A introduce a large uncertainty on the QEL cross section
New precise data to establish correct Cross section estimate

=> e.g. ArgoNeuT/LArTPC experiment at FNAL – 2009-10

From Q.F. Theory:

$$d\sigma = \frac{1}{(2\pi)^2}\ \delta^4\left(P_f - P_i\right)\ \frac{1}{2E_\nu\ 2m_N}\ \left|M_{fi}\left(F_V^1, F_V^2, F_A^1\right)\right|^2\ \frac{d\vec{p}_l}{2E_l}\ \frac{d\vec{p}_{N'}}{2E_{N'}}$$

where :

$$M_{fi} = \frac{G}{\sqrt{2}}\left[\bar{u}_l\ \gamma^\mu(1-\gamma_5)\ u_\nu\right]\left[\cos\theta_c\ \ \bar{u}_p\ \Gamma_\mu\ u_n\right]$$

Γ_μ function of the Nucleon Weak Form Factors

After integration over final state kinematics:

$$\sigma_{QEL}\left(E_\nu\right)\left[10^{-38}cm^2\right]$$

CC-QEL thresholds:

ν_e : $E_\nu^{thr} = 0.$

ν_μ : $E_\nu^{thr} = 110.\ MeV$

ν_τ : $E_\nu^{thr} = 3.45\ GeV$

In atmospheric ν experiments however nucleon targets are bound in Nuclei A_Z

Therefore QEL interactions are:

$$\nu_l + A_Z \rightarrow l^- + p + (A-1)_Z \quad \text{and} \quad \bar{\nu}_l + A_Z \rightarrow l^+ + n + (A-1)_{Z-1}$$

This introduces some constraints on both initial and final state kinematics due to Nuclear Effects (i.e. cross-section is reduced):

- *Fermi Motion of the nucleon N in A_Z*
- *Binding Energy of the Nucleus*
- *Pauli blocking*

Different types of nuclear target (O, Fe, Ar,…) introduce second order corrections to the QEL cross section (and additional uncertainty).

Several theoretical models are available to describe nucleonic states inside Nuclei. The easiest (i.e. the most commonly used) is the "modified- Fermi Gas Model":

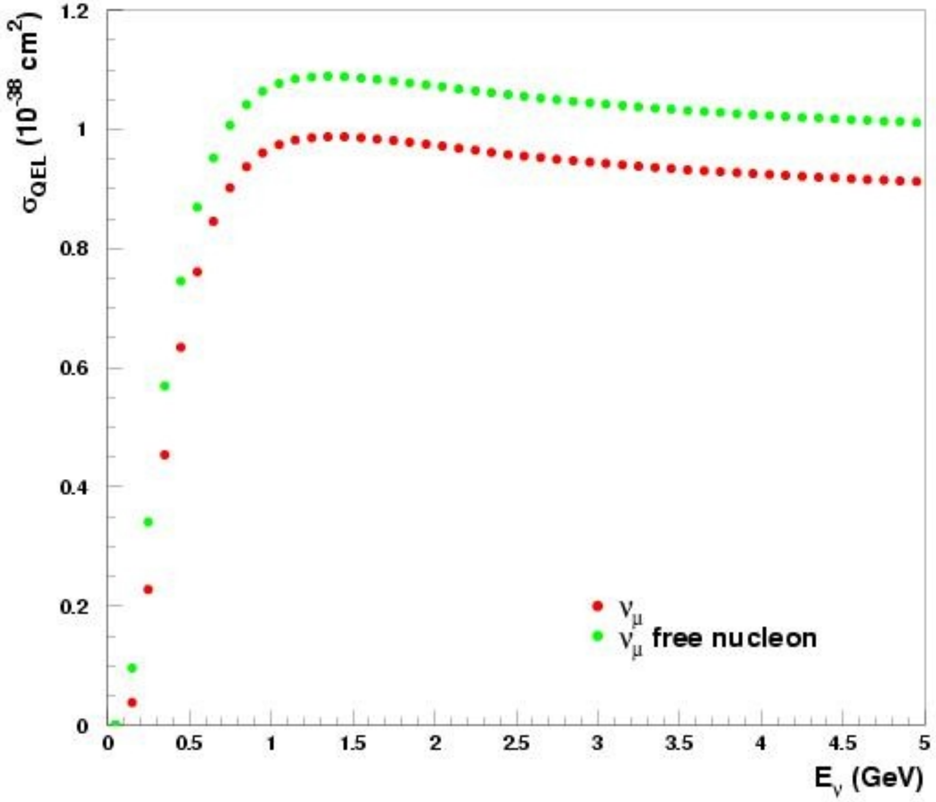
- incoherent impulse approximation (hit nucleon off-shell + spectator (A-1) on-shell)
- Fermi momentum distribution flat up to k_F, and modified with high momentum tail (*N*-*N* correlation)

Best suited techniques for cross-section calculation are MonteCarlo calculations (a big effort was produced by the "neutrino community" to reach a common framework to define cross sections => GENIE MC

… and new dedicated measurements are under way (ArgoNeuT/MINERvA/…).

Difference between QEL cross Section for ν_μ scattering on free nucleon *(n)* or bound nucleon in A_Z Nuclei

Cross section plots



Atmospheric neutrino event rate in present/future experiments

Nuclear targets in use in present experiments:

- O (Oxygen in H_2O) ⇐ SupeKamiokande (Kamiokande and IMB)
- Fe ⇐ SOUDAN/MINOS
- Ar ⇐ LArTPC (ICARUS/LBNE)
- [O(50%) + Si(30%) + … (Rock) ⇐ MACRO in high en range]

For the event rate calculation, Z/A ratio is more important than differences from nuclear effects (k_F, E_B).

$$\langle \sigma_{\rm Atm} \rangle = \int \sigma^{CC}_{QEL}(E_\nu)\, \lambda_{\rm Atm}(E_\nu, \cos\theta_Z)\, dE_\nu\, d\cos\theta_Z \approx 1.2 \times 10^{-38} cm^2$$

$$"SNU"\ \left[10^{-36} s^{-1}\right] = \langle \sigma_{\rm Atm} \rangle \times \Phi_{\rm Atm} \approx 0.033$$

$$\text{Evt. Rate}\ :\ \frac{N_{evt}}{yr} \approx 300$$

for a detector Mass of 1 kt (!!!);

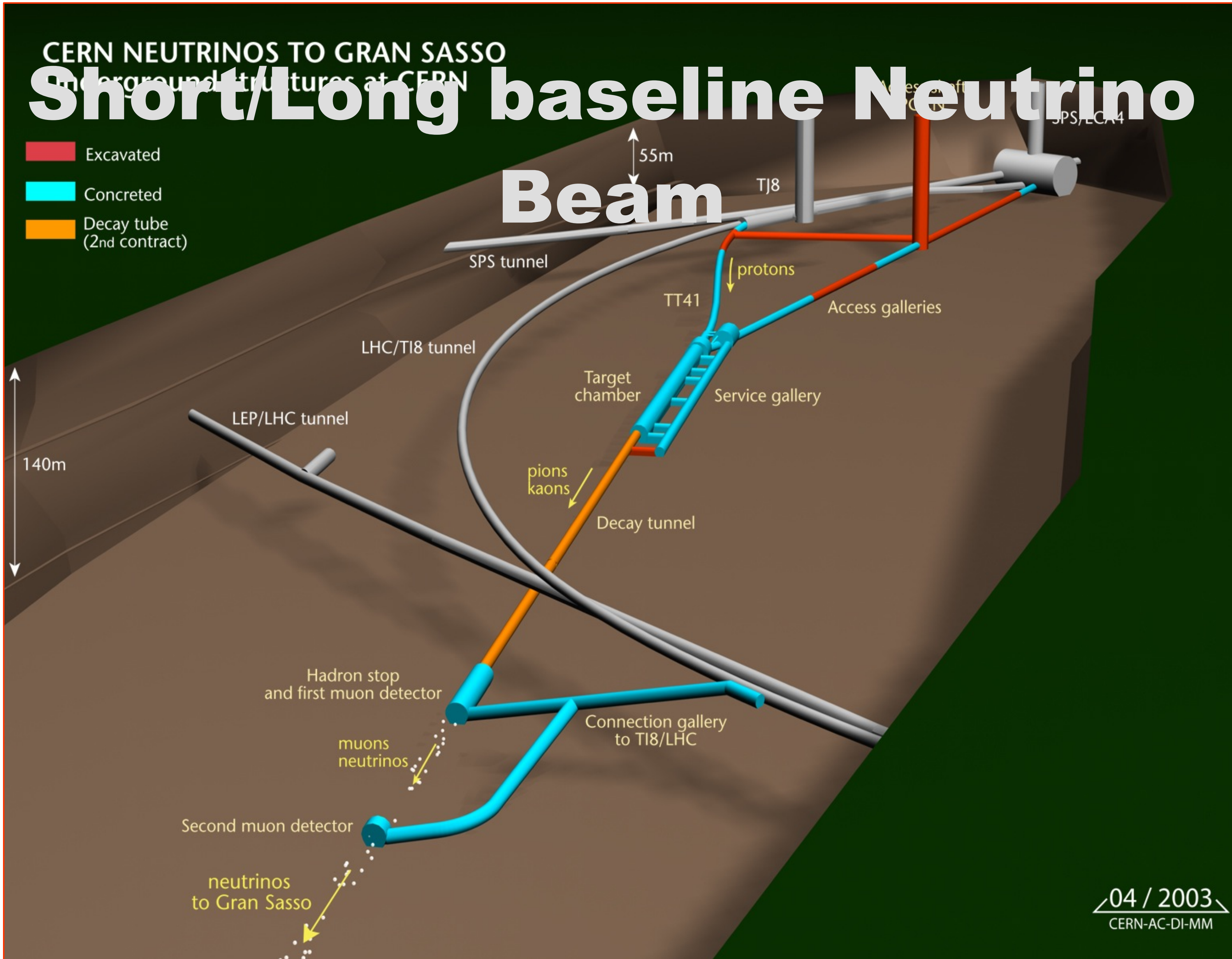
$\varepsilon_{\rm Det} = 1,\ E^{thr}_{\rm Det} = 0.$ (ideal case)

Summing up contributions of QEL (CC only) reactions from $\nu_\mu(47\%),\ \bar{\nu}_\mu(15\%),\ \nu_e(30\%),\ \bar{\nu}(8\%)$

Oscillation (50% suppression of ν_μ rate) effect ARE NOT included!!

Short/Long baseline Neutrino Beam

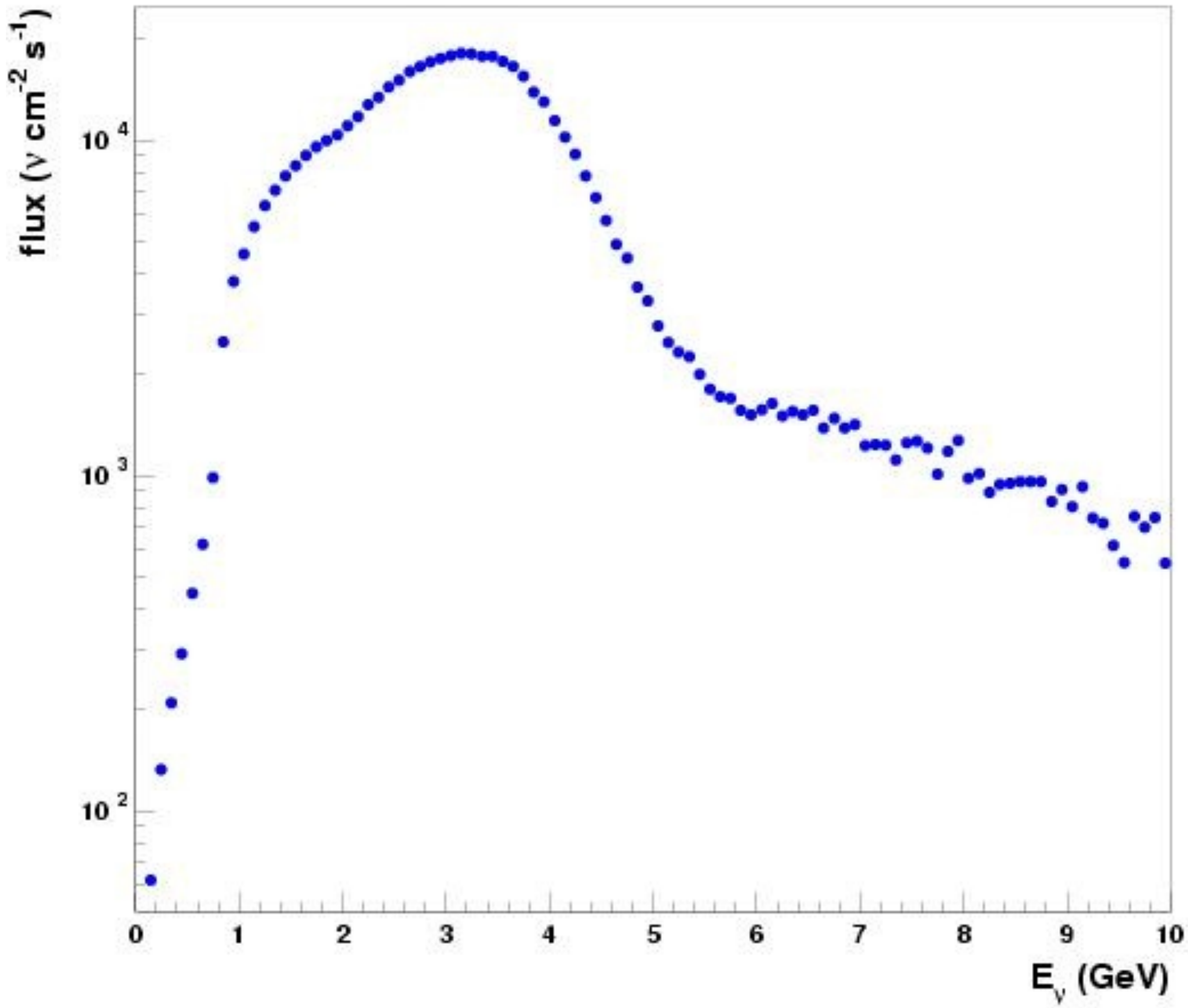
High Energy neutrinos



Best controlled fluxes of artificial neutrinos can be generated from beams of accelerated protons: after hitting a dense material target, secondary pions (after the target) are focused in a long tunnel where decay-in-flight occurs.
A collimated, high energy ν_μ beam is thus generated, pointing to the target (the experiment sensitive mass) located at near or far distance (short/long baseline).

Many neutrino beams have been built (FERMILAB, CERN, Russia, Japan, ..) in a >40 yrs long history.
We use as an example the NuMI long baseline beam at FERMILAB

	NuMI Beam Characteristics
p beam energy	120 GeV
P beam cycle	1.87 s
p beam intensity	4×10^{13} PoT/cycle
proton on Target (PoT)	3.8×10^{20} PoT/yr
π decay tunnel	670 m



NuMI Beam Flux
“Low Energy Option”

	"Low Neutrino Energy Option"
ν_μ fluence	1.6×10^{13} ν/cm^2
Average ν_μ Flux	5×10^5 ν/ cm^2s
Energy Mean Value	≈ 3 GeV

NB: “Low Energy Option” corresponds to the “High-Intermediate” range in NeutrinoLand

Huge unprecedented Rate at the near station

$$\langle \sigma_{\text{Beam}} \rangle = \int \sigma_{DIS}^{CC}(E_\nu)\, \lambda_{\text{Beam}}(E_\nu)\, dE_\nu \approx 2.2 \times 10^{-38} cm^2$$

$$"SNU"\ \left[10^{-36} s^{-1}\right] = \left\langle \sigma_{Beam}^{DIS} \right\rangle \times \Phi_{Beam}^{NuMI} \approx 1.14 \times 10^4$$

$$\text{Evt. Rate}: \frac{N_{evt}}{yr} \approx 8.5 \times 10^7$$ for a detector Mass of 1 kt (!!!);

$$\varepsilon_{\text{Det}} = 1,\ E_{\text{Det}}^{thr} = 0.$$ (ideal case)

With the "High Energy option" of NuMI Beam a much larger rate can be obtained (… but it is less attractive for present oscillation studies).

Obviously the Flux at far distance (730 Km) is MUCH smaller due to the divergence of the neutrino beam.

Summary

Source	SNU [10^{-36} s^{-1}]
Solar – pp (Ge absorption channel)	128
Solar – 8B (Ar absorption channel)	11.1
Solar – 8B (elastic *e*-channel)	1
Reactor (reaction of free *p*)	4 x 10^4
Beam Dump (reaction of free *p*)	0.1
Atmospheric (quasi-elastic on $\mathcal{N}$)	0.033
Long Baseline Beam (Deep Inelastic)	1.14 x 10^4

- Guided tour of NeutrinoLand
- Artificial/Natural ν sources
- Cross-section from various model calculations
- ν interaction counting rate
- New physics beyond Standard Model? YES (ν oscillations is now a well established effect ⇒ $m_\nu \neq 0$)
- New generation experiments are now in preparation … but a very accurate control of cross-section (and fluxes) is a mandatory request.
- … we still need to further probe standard neutrino properties!!! from both the experimental and the theoretical sides