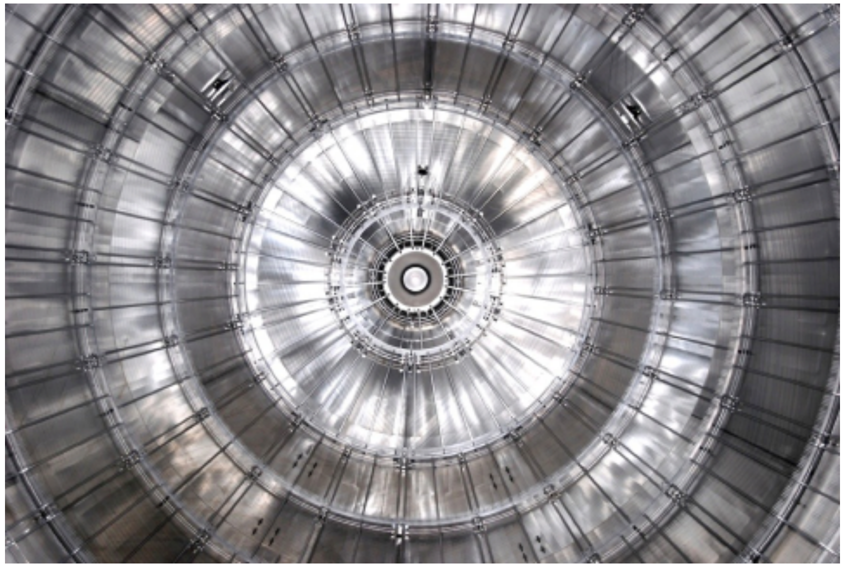
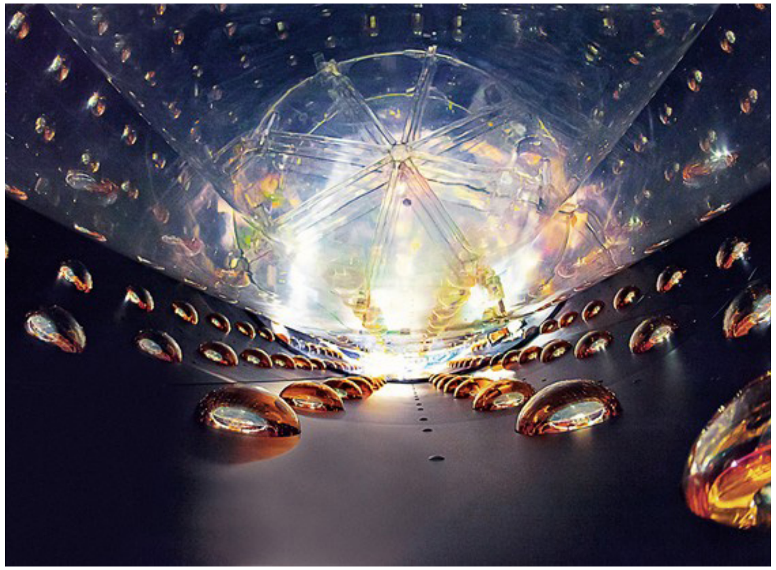
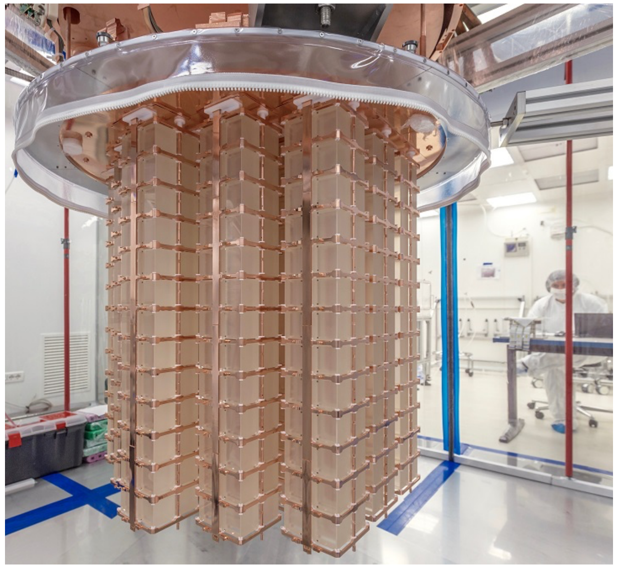
Introduction to Neutrino Physics and Neutrino Masses

Annual Retreat of RTG 2149 *"Strong and Weak Interactions — From Hadrons to Dark Matter"*
Marienheide, 25-28 Sept. 2017

KATHRIN VALERIUS, KIT Center Elementary Particle and Astroparticle Physics (KCETA)







What's on the menu today?

- Introduction & overview:

How do we know neutrinos exist?

How do they interact?

How do we know they have a mass?

What is their role in our Universe?

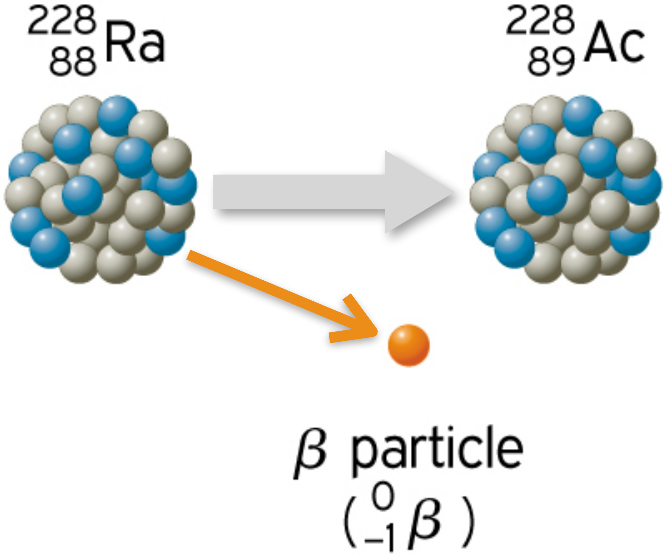
- Probing the neutrino mass with lab experiments
  - Search for neutrinoless double beta decay (0νββ)
  - Direct kinematical searches (^{3}H β-decay, ^{163}Ho EC)
- Summary & future prospects

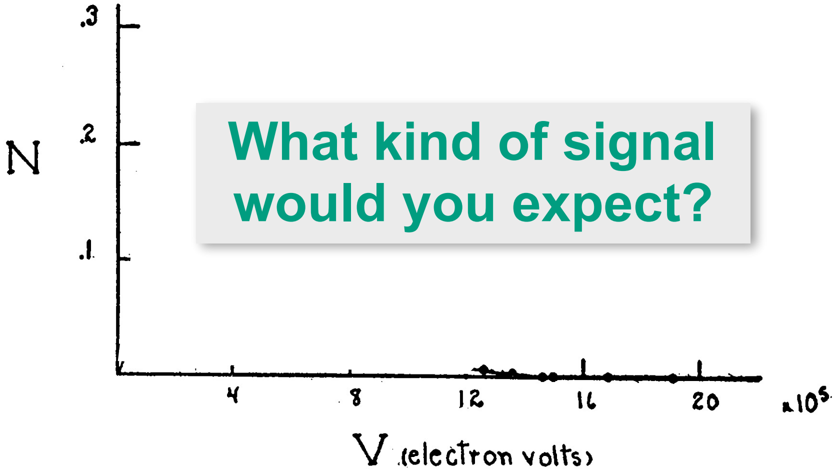
I. Discovery

= postulation & detection

of neutrinos

Imagine you were a physicist in the 1920s …

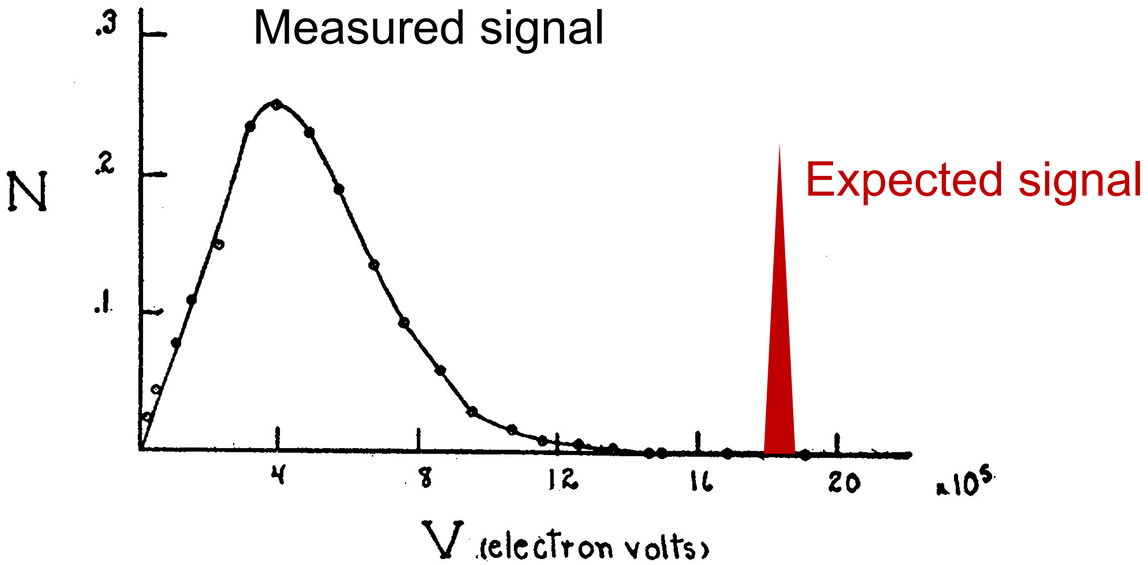




What kind of signal would you expect?

(Kinetic energy of electron)

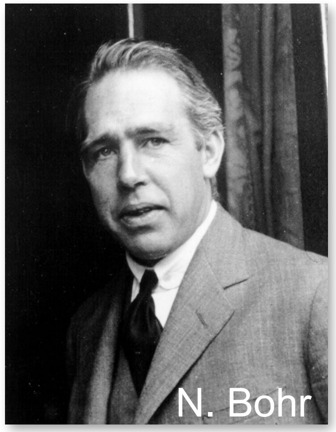
The problem of the beta-decay spectrum



(Kinetic energy of electron)

Perhaps energy is not conserved in nuclear decays?

KEEP
CALM
AND
STUDY
NUCLEAR
PHYSICS

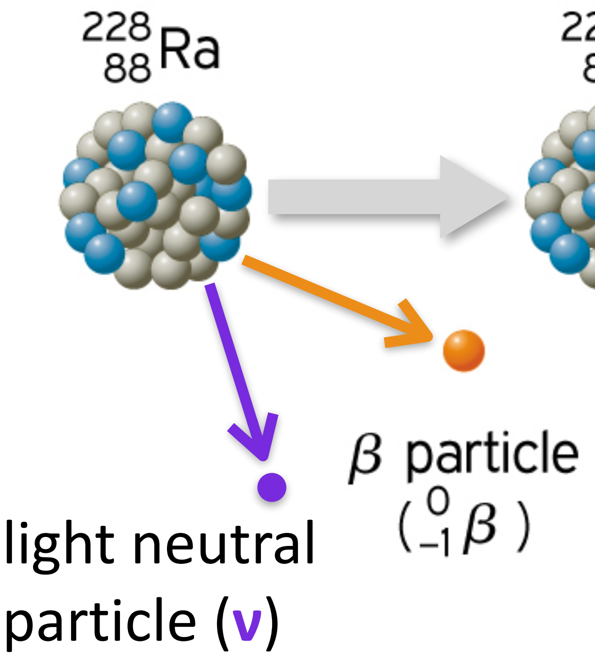

N. Bohr

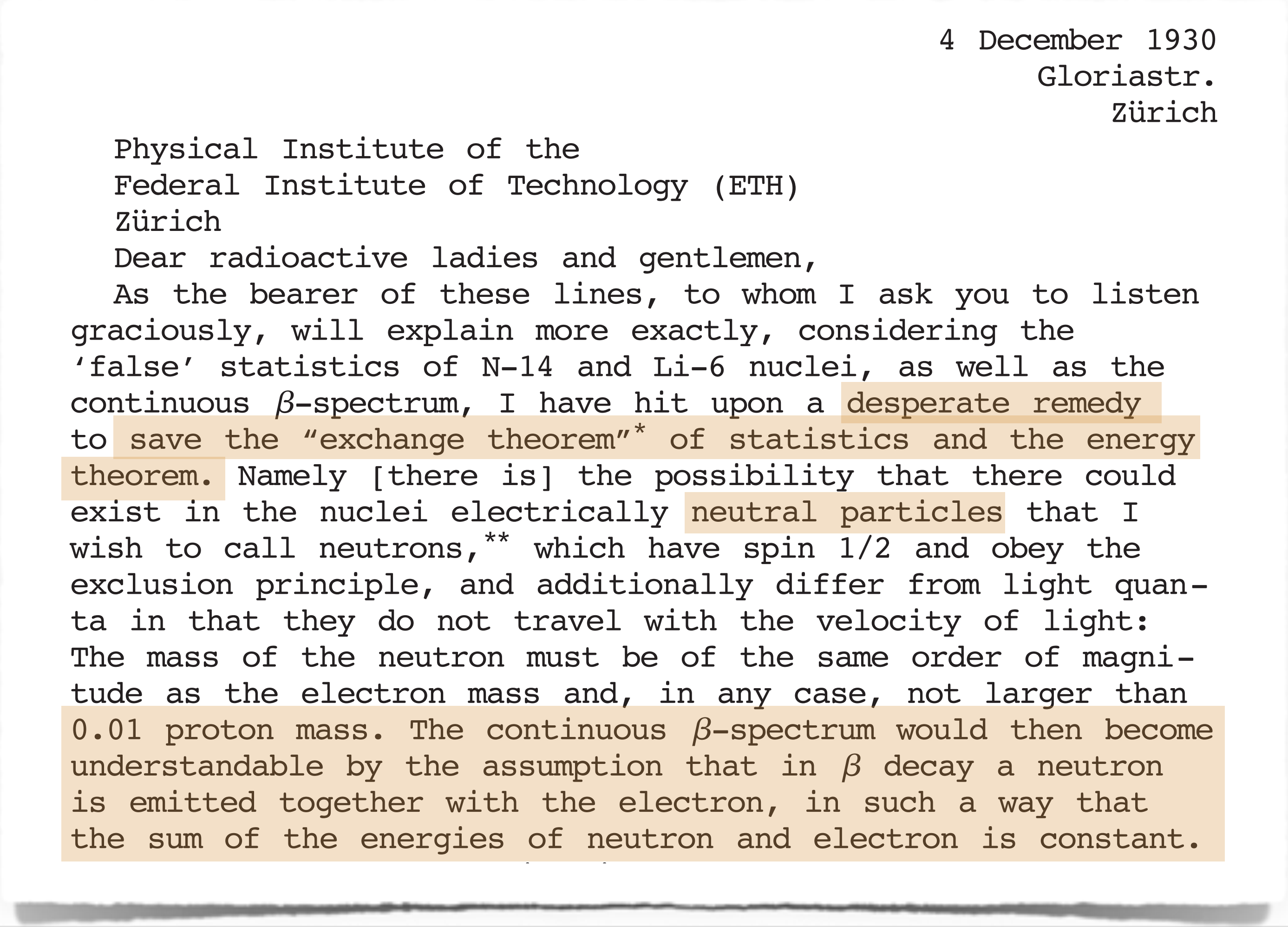

W. Pauli

Enter the neutrino

1930: Wolfgang Pauli's "desperate remedy" to solve the problem of apparent violation of energy & momentum conservation in β-decay

postulation of **new particle**: neutral, spin ½, weak interaction




4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

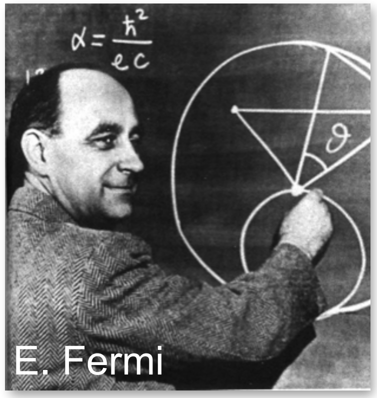
Dear radioactive ladies and gentlemen,

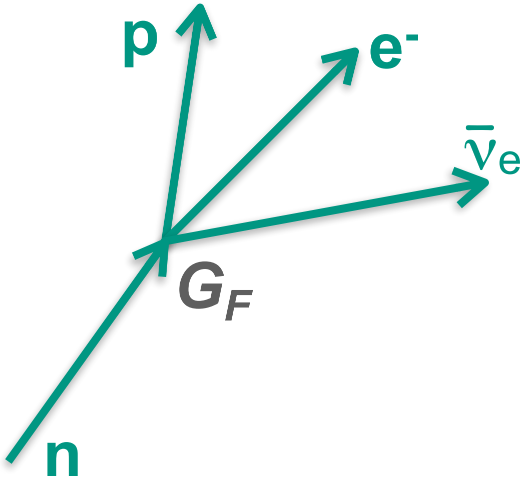
As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"* of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

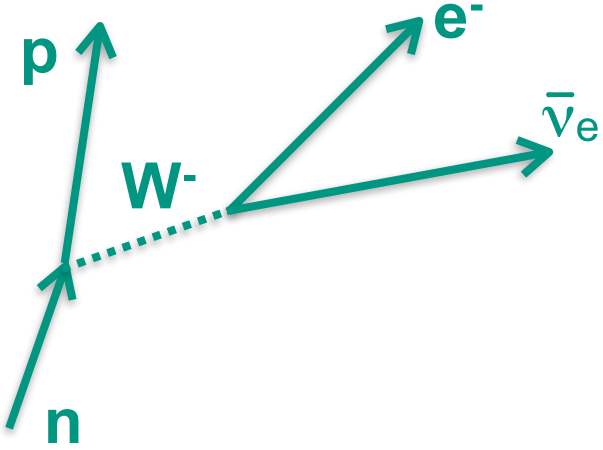
Enter the neutrino

1933/34: Enrico Fermi's seminal **theory of β-decay** as a 4-point interaction

➜ foundation of modern weak interaction framework



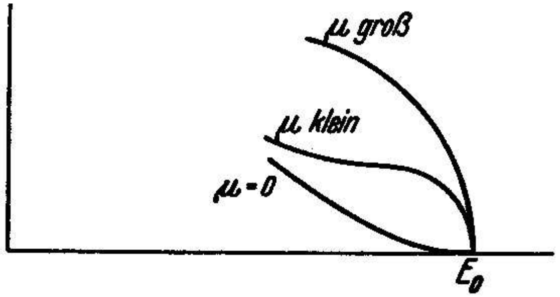




1933: Fermi 4-point interaction
contact of 2 vector currents
$\sigma \sim G_F^2 E^2$ grows without bound

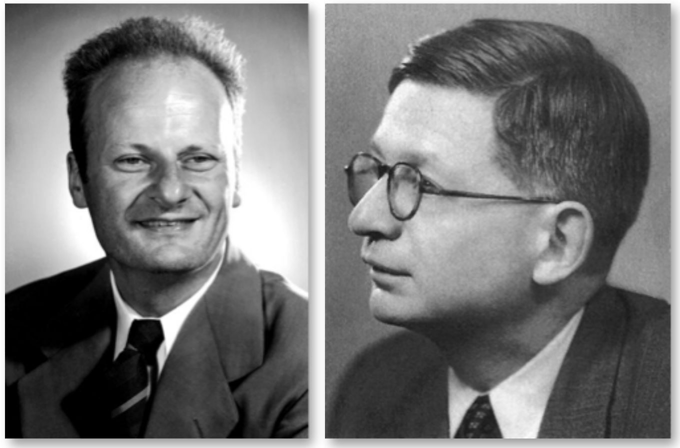
1938: boson mediation (Yukawa, Klein *et al.*)
mitigates divergence of σ at high energies
later: parity-violating currents, V-A structure

- Fermi changed the name to "neutrino"
- He also proposed a way to measure its rest mass:



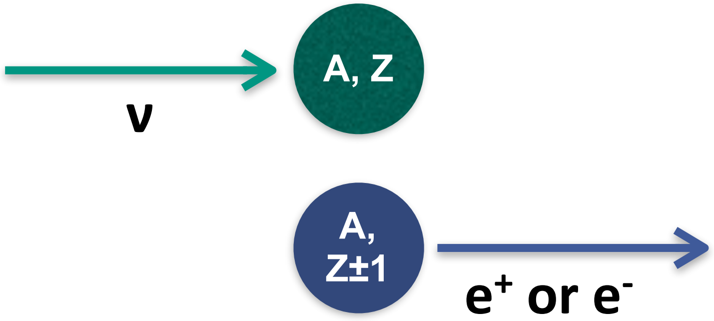
[E. Fermi, *Versuch einer Theorie der Betastrahlen*, Z. Phys. 88 (1934) 161]

Can neutrinos be detected?



1934: H. Bethe & R. Peierls calculate the neutrino interaction cross section

reversing the
β-decay process:



- **σ ~10^{-44} cm^2** at energies of a few MeV:
  penetrating power of ~10^{16} km in solid matter
  ➜ "absolutely impossible to observe (…) neutrinos from nuclear transformations"
- Fermi theory predicts $\sigma \sim (E_\nu)^2$
  ➜ even at cosmic-ray energies, detection deemed "highly improbable"

Conclusion: "no practically possible way of observing the neutrino"

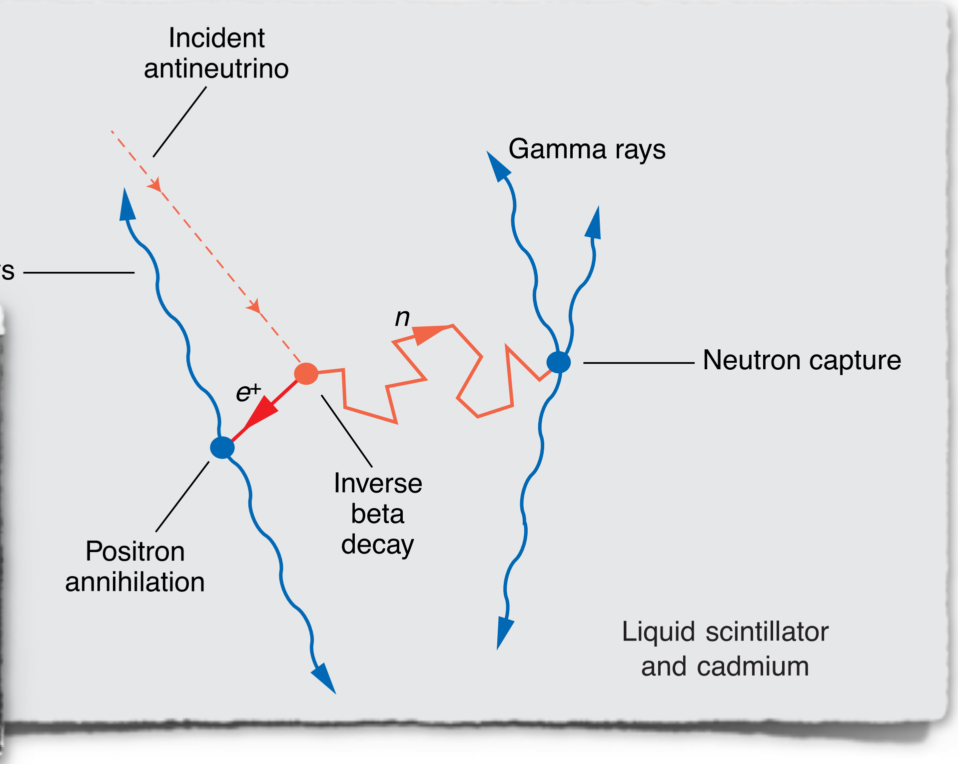
[H. Bethe and R. Peierls, *The "Neutrino"*, Nature 133 (1934) 532]

How to catch the neutrino?

1. proposed reaction

theory

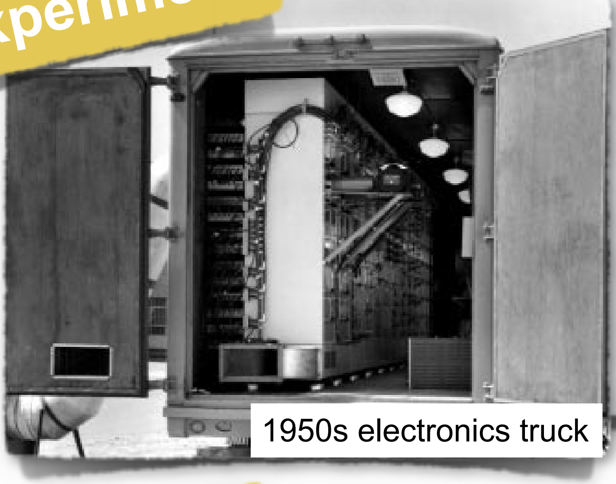
$\bar{\nu}_e + p \rightarrow n + e^+$
(inverse β-decay)



2. detection technique

experiment

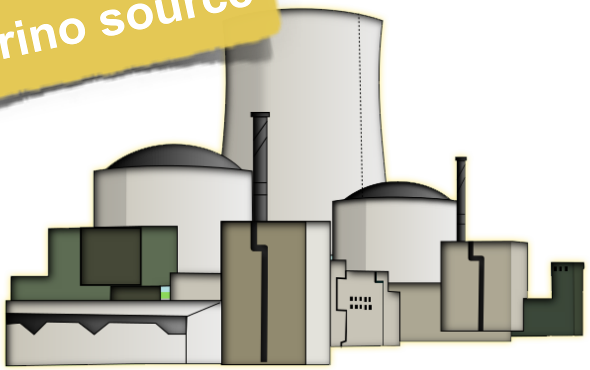
delayed coincidence of **e⁺** and **n** signals in liquid scintillator


1950s electronics truck

3. event statistics

neutrino source

β-decay of neutron-rich fission products in nuclear reactors



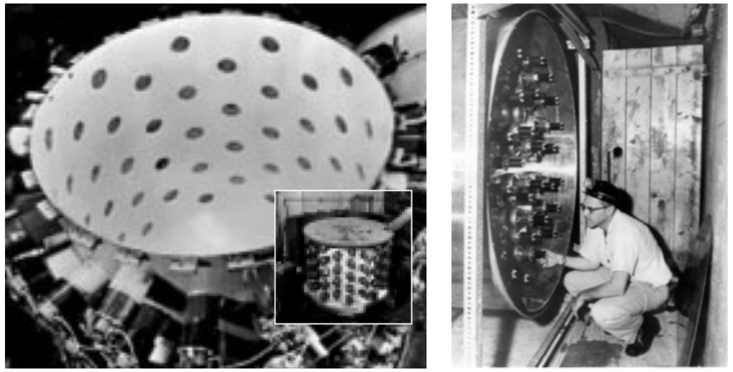
working principle of numerous neutrino experiments from the 1950s until today!

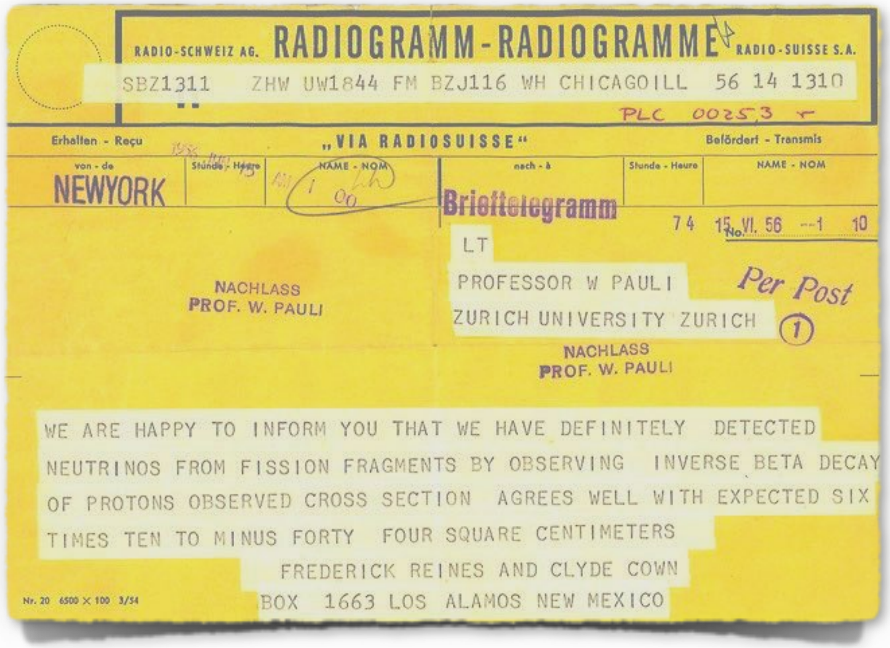
First detection of neutrinos

“Because everybody said you couldn’t do it”

— Fred Reines

Hanford 1954:
“Herr Auge”
300 ℓ liquid scintillator
with 90 PMTs





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PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

Per Post

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NACHLASS
PROF. W. PAULI

NACHLASS
PROF. W. PAULI

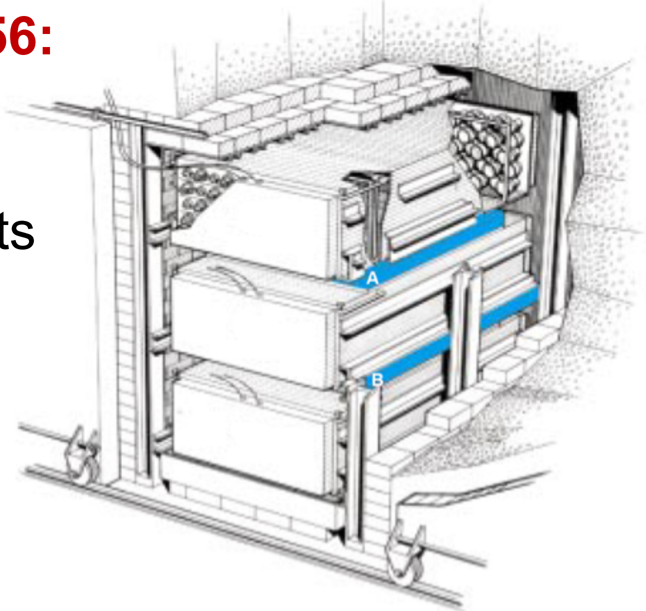
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

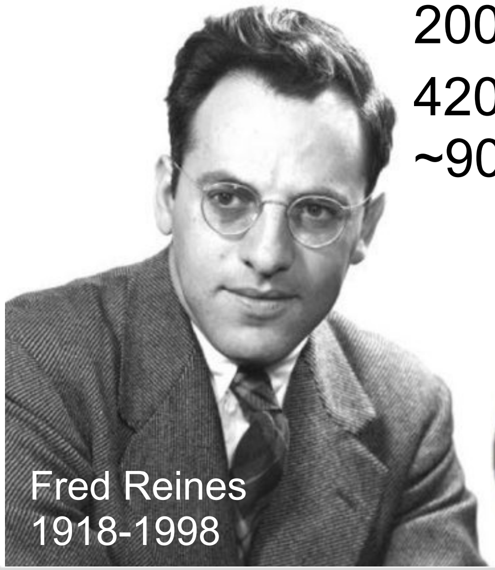
FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 X 100 3/54

Savannah River 1956:

200 ℓ H_2O-target
4200 ℓ scintillator
~900 h measurements





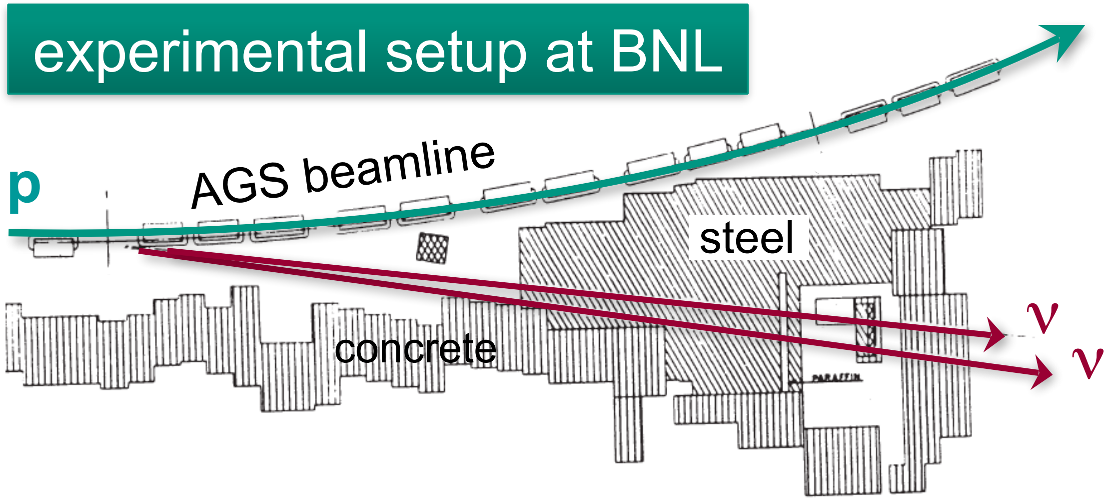
Fred Reines
1918-1998

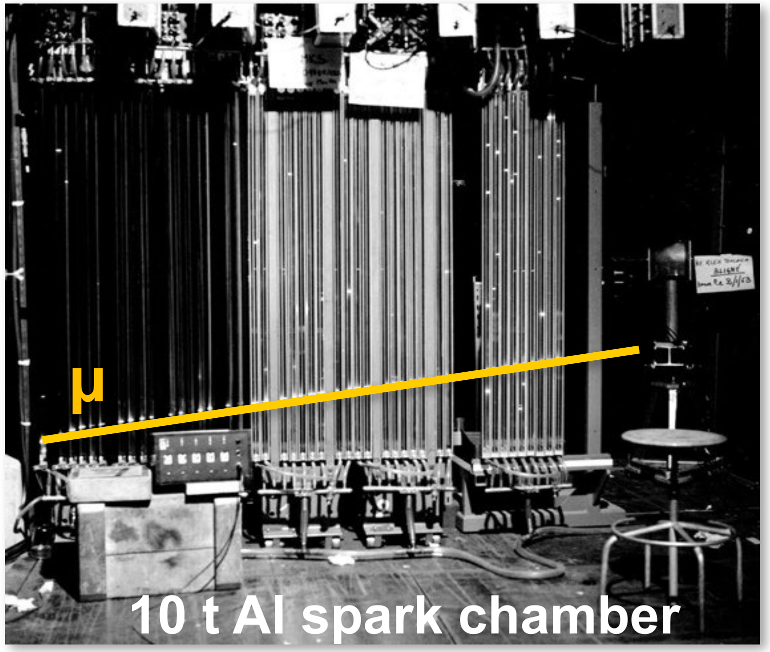
Nobel Prize
1995

AGS-experiment: the second neutrino ν_μ

1962: identity of neutrinos from pion decay $\pi^+ \rightarrow \mu^+ + \nu$ $\nu = \nu_\mu$ or ν_e ?

experimental setup at BNL

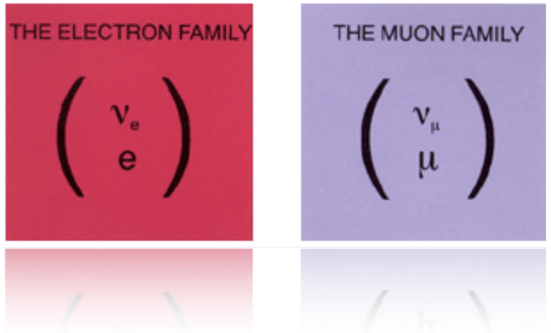




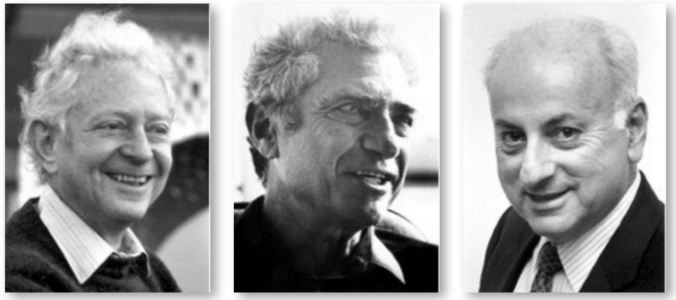
10 t Al spark chamber

- introduction of neutrino beam technology
- 10^{17} neutrinos produced
- 51 events observed: **muons**, not **electrons**!

  ➜ doublet structure of leptons:



Nobel Prize 1988



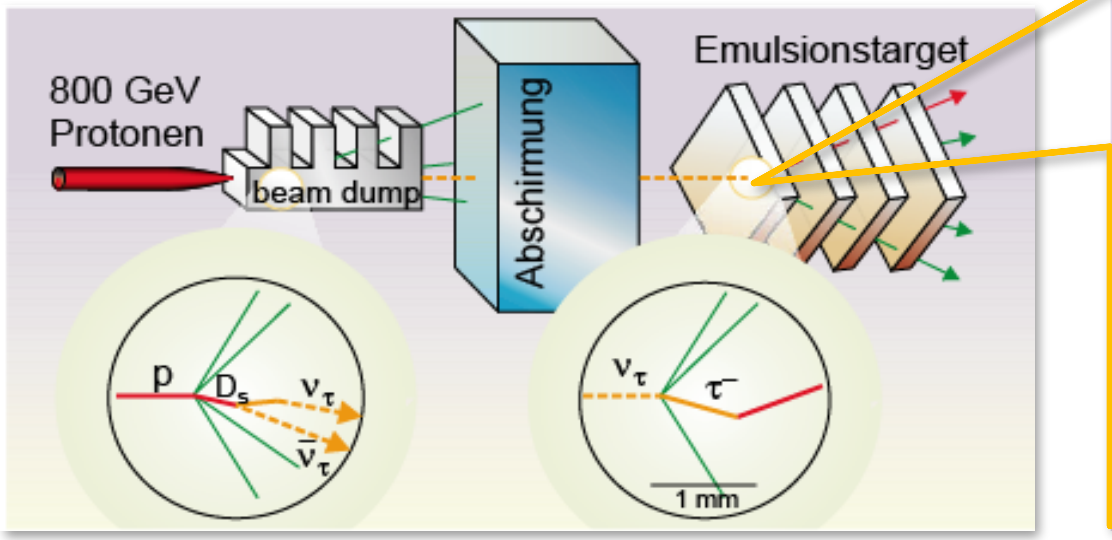
Leon M. Lederman Jack Steinberger Melvin Schwartz

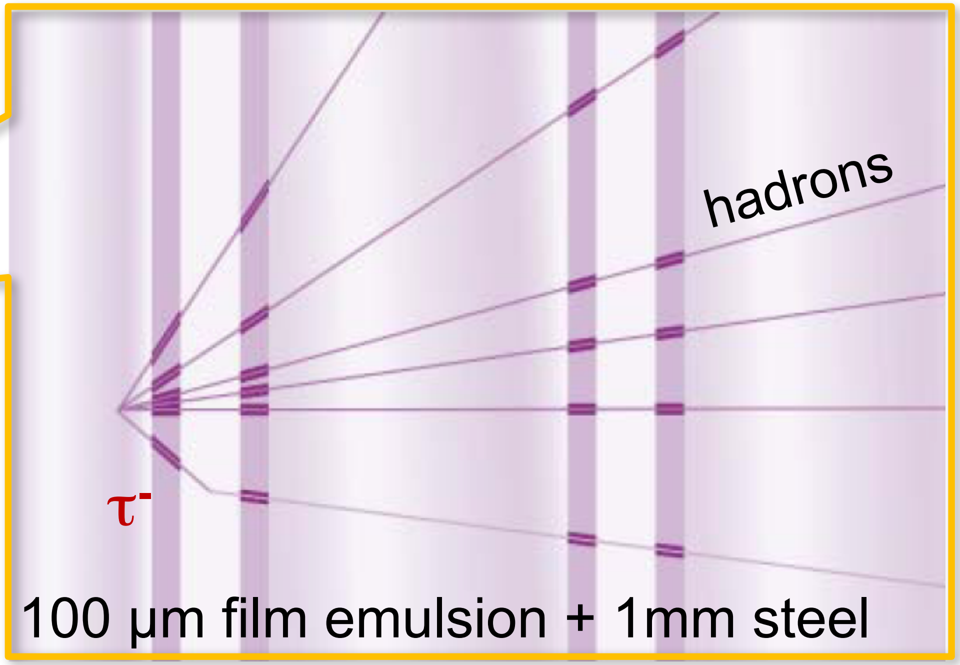
The DONUT experiment: the third neutrino ν_τ

2000: Direct **O**bservation of **NU T**au (DONUT)
proton beam on tungsten target produces D_s-mesons $(c\bar{s})$

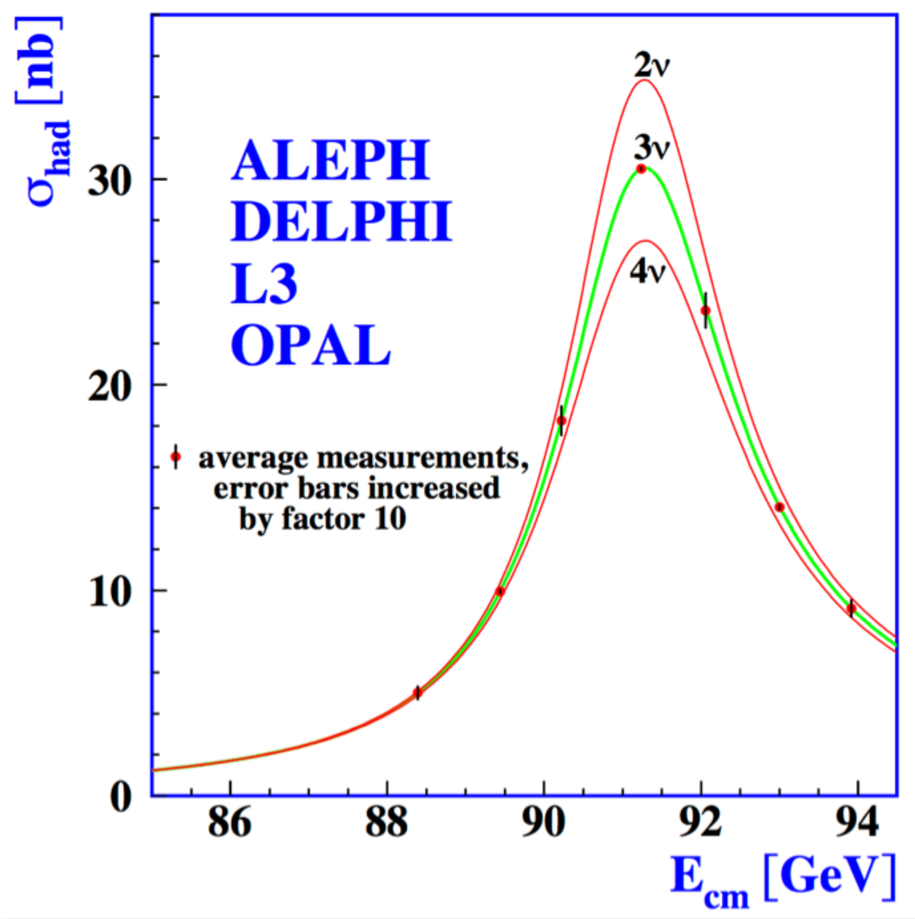
Results: 4 events identified with topology of a ν_τ : **τ-kink**
τ life time: $\tau = 3 \times 10^{-13}$ s, range $c\tau$ = few mm

DONUT experiment at Fermilab



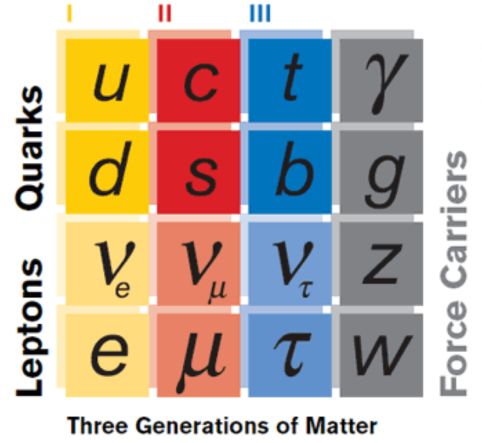


Are these all neutrino families?



Precision Z^0 parameters at e^+e^- colliders

- Total Z^0 width: Γ_{tot} = 2495(2) MeV
- Visible modes:
  e, μ, τ, and u, d, s, c, b pairs
- Invisible modes: Γ_{inv} = 499(2) MeV
- ν partial width, $Z^0 \rightarrow \nu_\alpha + \bar{\nu}_\alpha$:
  Γ_ν = 167.1 MeV
- N_ν = 2.99



➜ No room for extra neutrino with SM couplings up to $m = M_Z/2$

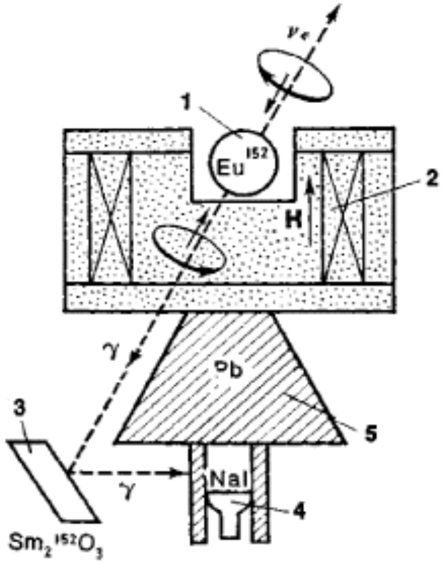
➜ Still room for new ideas, e.g. sterile neutrino states at eV … keV … GeV scales!

II. Neutrino interactions*

Remember what we've learned since the first detection of neutrinos:

Parity violation in weak int.
Wu *et al.*, 1956

Helicity of neutrinos
Goldhaber *et al.*, 1957



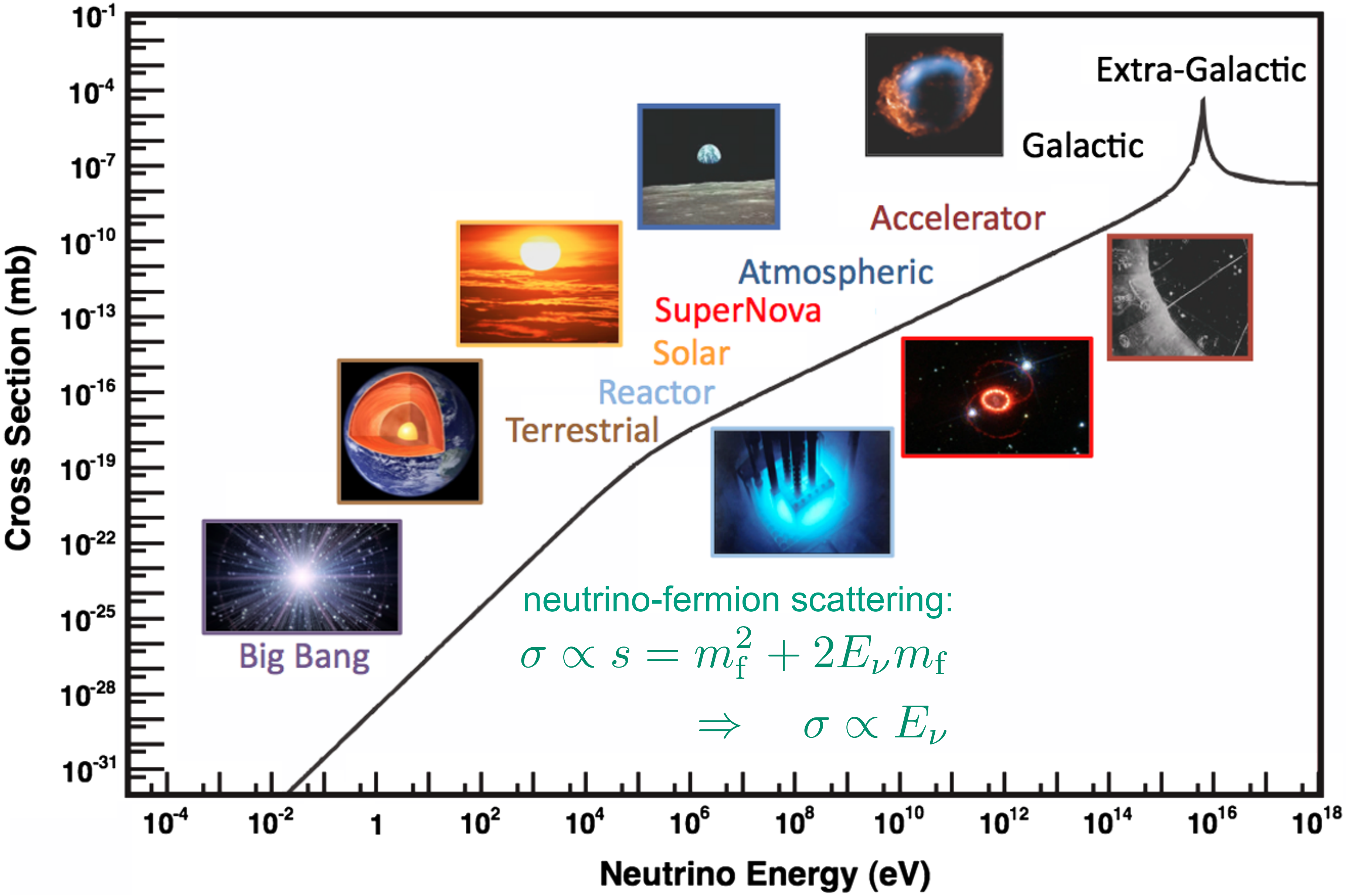
Existence of neutral currents
Gargamelle, CERN, ca. 1973

$$\nu_\mu + N \to \nu_\mu + X$$

***) status update: summer 2017**

Energy dependence of the cross section

Example: elastic scattering $\bar{\nu}_e e^- \longrightarrow \bar{\nu}_e e^-$



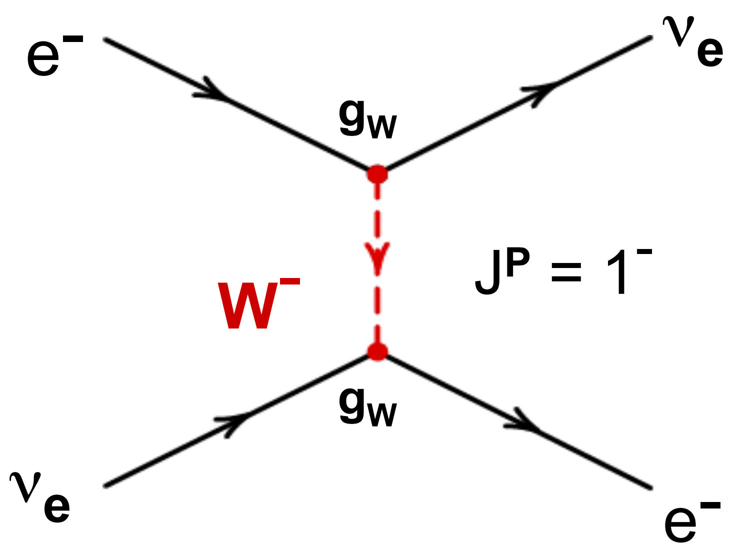
neutrino-fermion scattering:

$$\sigma \propto s = m_\mathrm{f}^2 + 2E_\nu m_\mathrm{f}$$

$$\Rightarrow \quad \sigma \propto E_\nu$$

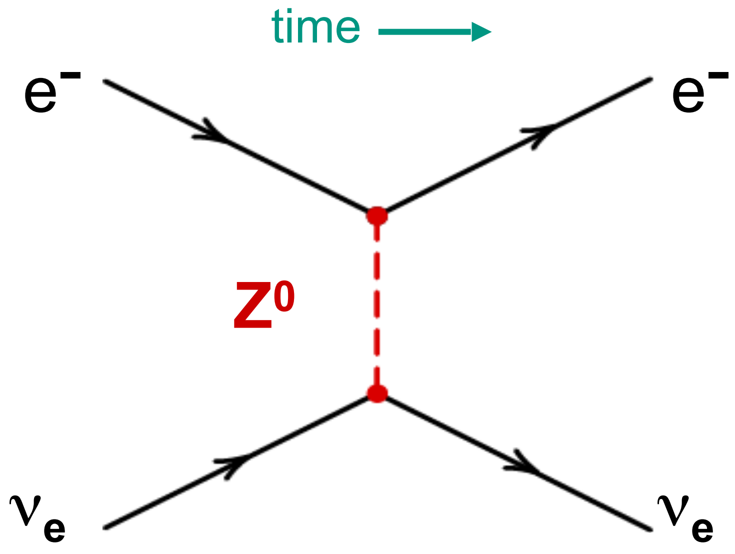
Intermediate vector bosons: CC & NC

Example: neutrino-electron scattering: $\sigma(\nu_e e \rightarrow \nu_e e) = \pi^{-1} \cdot G_F^2 \cdot s$



charged currents (CC)

- charge transfer via exchange of charged **W⁺ / W⁻** bosons (M = 80.4 GeV)
- induces transitions in in the electroweak isospin doublet (u ⇔ d´) (e^- ⇔ ν_e)

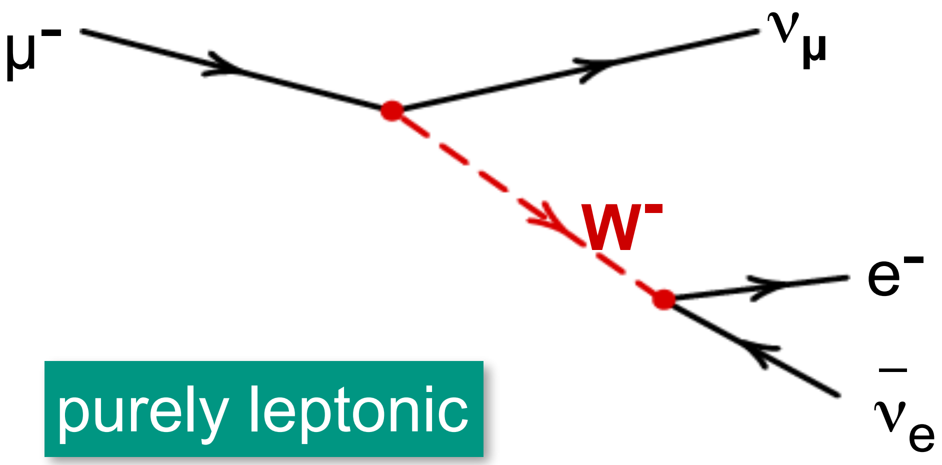


neutral currents (NC)

- no charge transfer, exchange of the neutral **Z⁰** bosons (M = 91.2 GeV)
- flavour universality of the NC: identical coupling ν_e, ν_μ, ν_τ with Z^0

Leptonic & semi-leptonic reactions

Reactions of the weak interaction in astroparticle physics:



purely leptonic

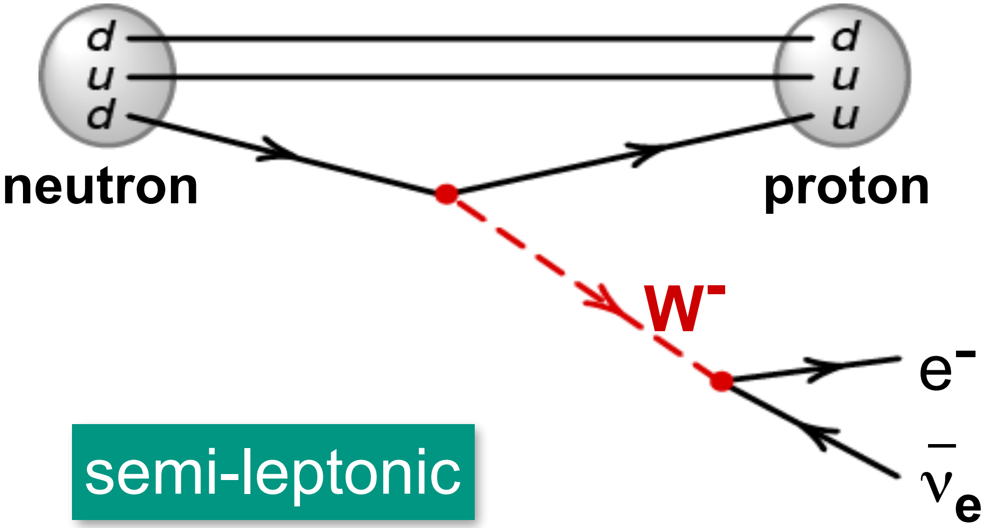
β-decay of muons

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$\tau = 2.2\ \mu s$

atmospheric/accelerator ν



semi-leptonic

β-decay of neutrons

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

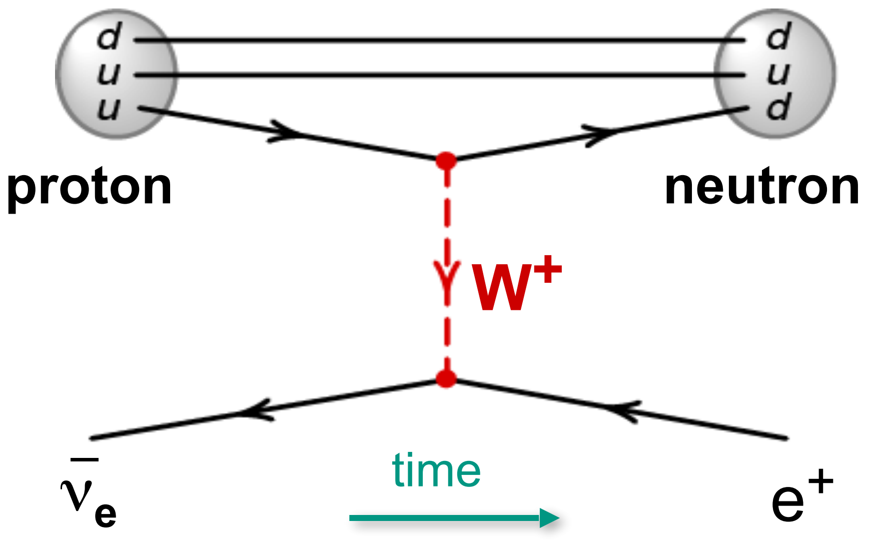
$\tau \approx 900\ s$

$d' \rightarrow u$: quark flavour transition

reactor neutrinos from β-decays

Semi-leptonic reactions

Other important semileptonic CC-reactions in astroparticle physics:

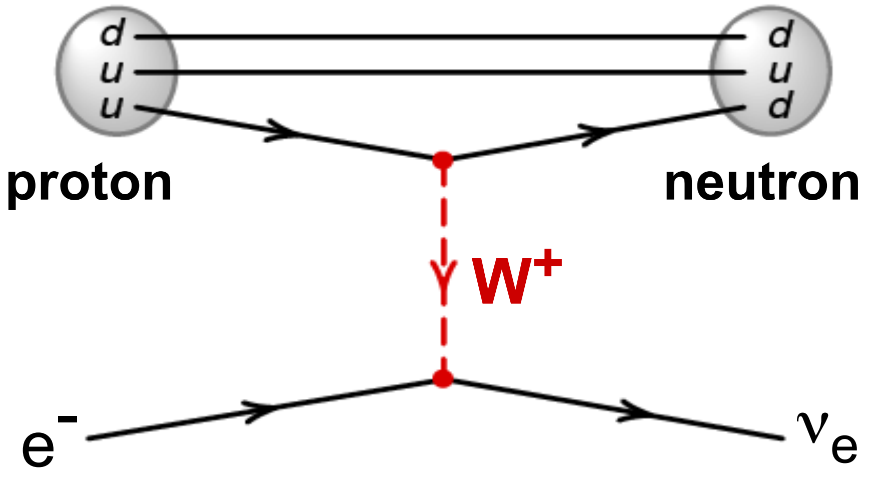


inverse β-decay

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

“classical” detection reaction:

- oscillation experiments at reactors, spallation sources & accelerators
- SN explosions, BBN, geoneutrinos, …



electron capture

$e^- + p \rightarrow n + \nu_e$

on free p and
on p in nuclei

- SNIIa: neutronisation / core-collapse
  radioactive decay (^{56}Ni, ^{56}Co)
- BBN: thermodynamical equilibrium

Science

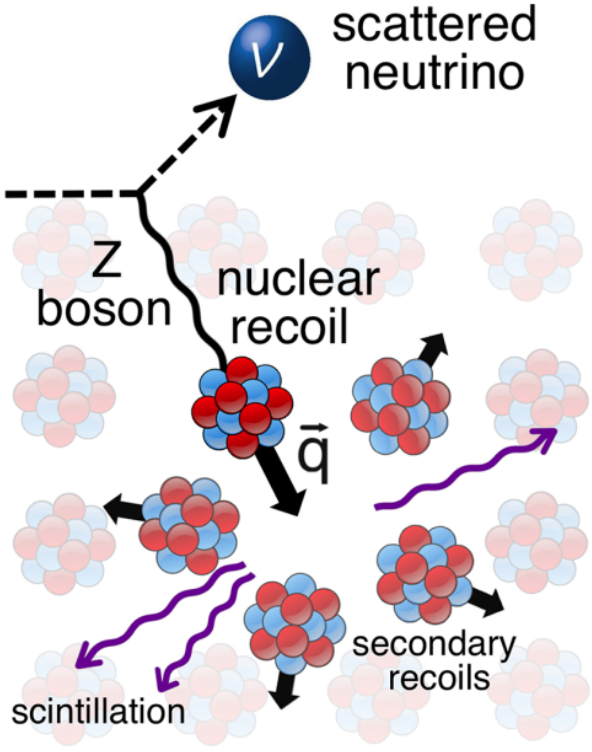
COHERENT Collaboration, 3 Aug 2017

REPORTS

Cite as: D. Akimov *et al.*, *Science*
10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

- At low momentum transfer ($qR_{nuc} < 1$) long-wavelength *Z* boson can probe ***entire*** nucleus
- Proposed by Freedman *et al.*, PRD 9 (1974) 1389



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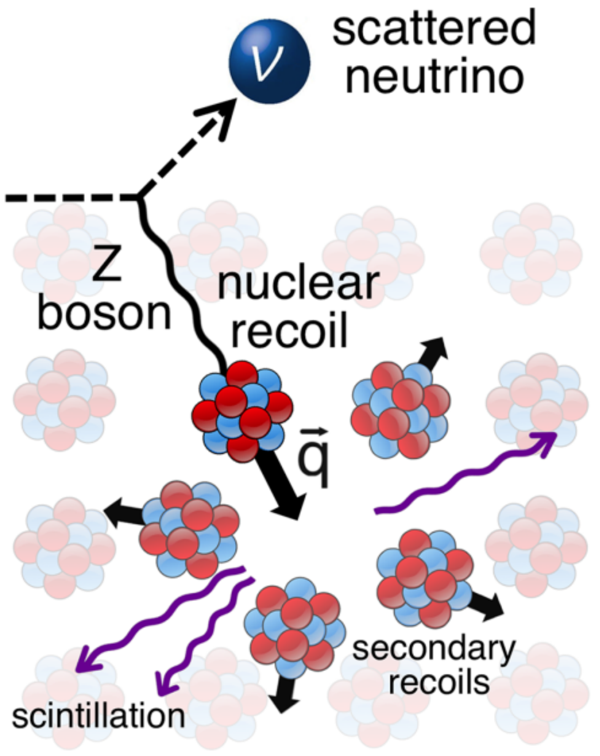
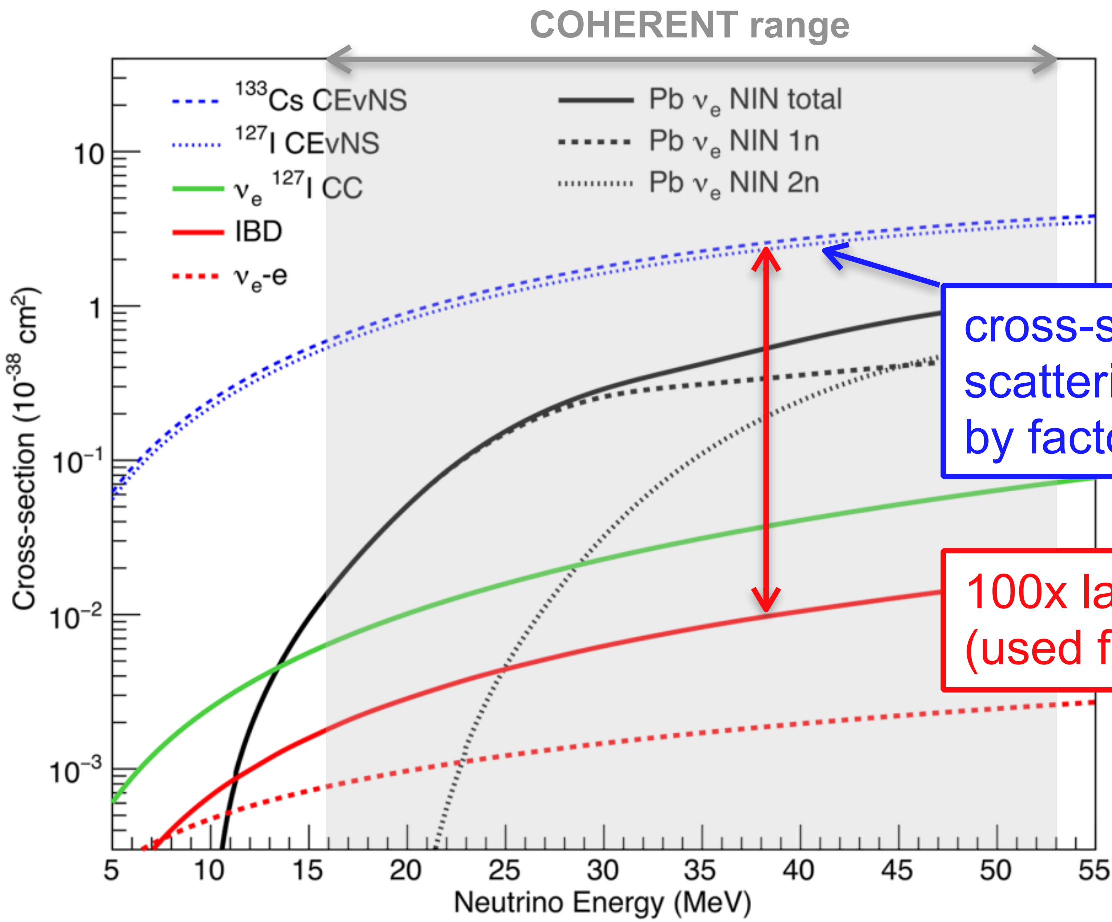


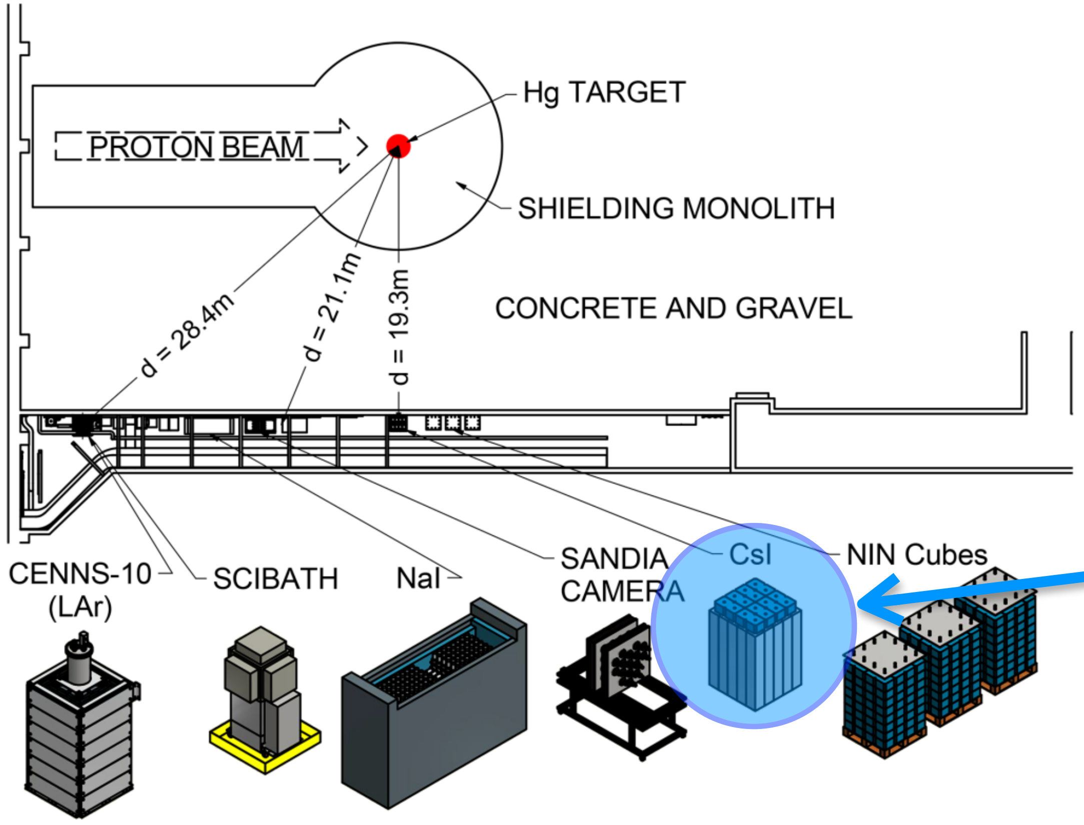


cross-sec. for coherent scattering boosted by factor **(#neutrons)^2**

100x larger than IBD (used for ν discovery)

The COHERENT experiment

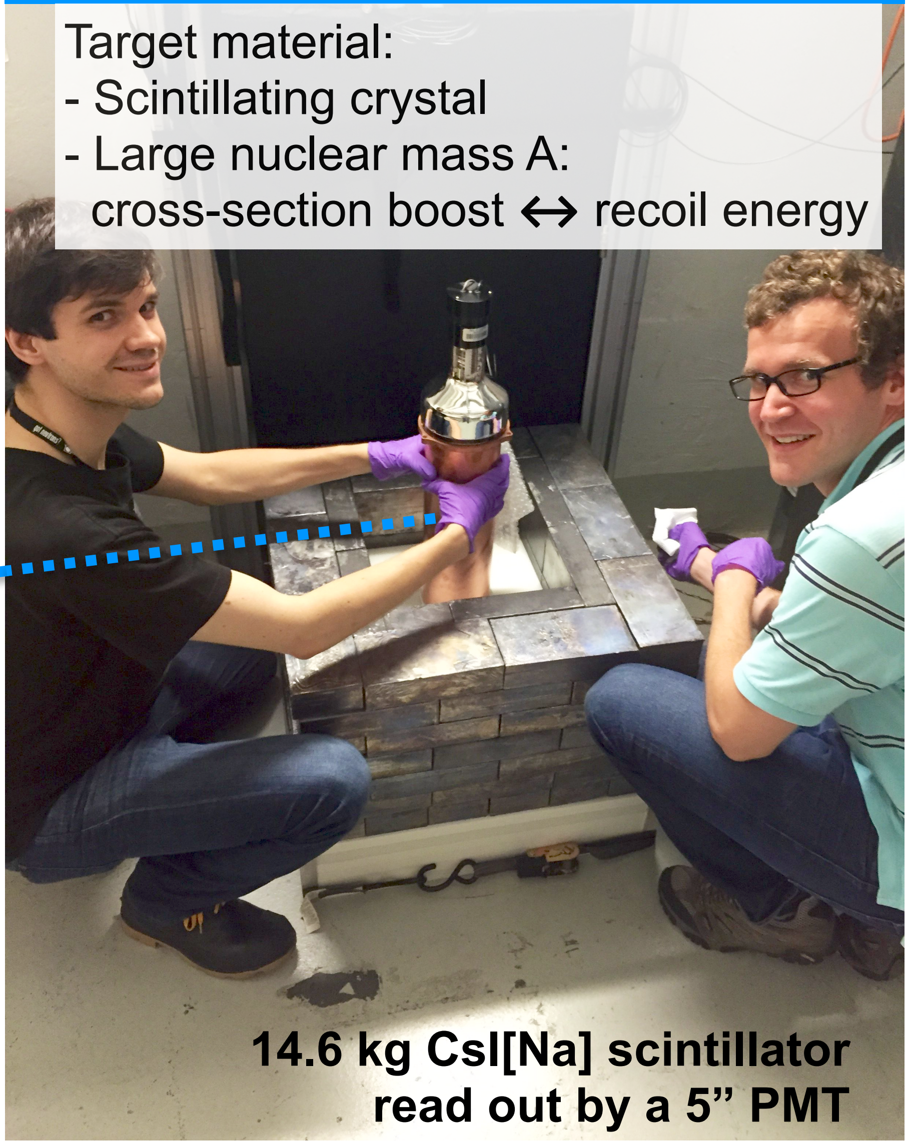
“Neutrino Alley” at the Spallation Neutron Source (SNS)



- Pulsed neutron beam (f = 60 Hz, Δt = 1 μs)
- Neutrino flux ~10^{11} ν / cm^2 / s
- Neutrino energies up to ~50 MeV

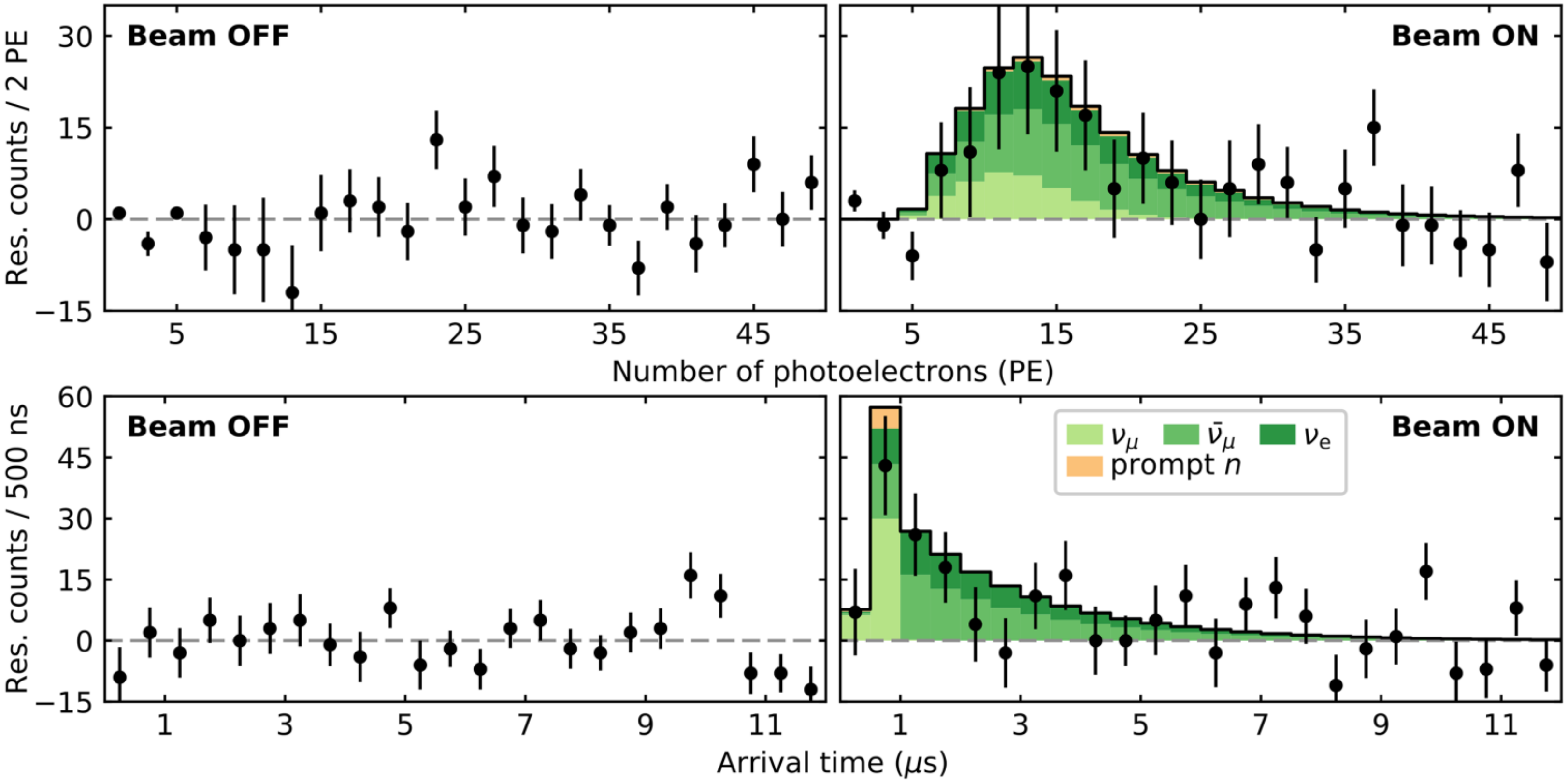
A neutrino detector the size of a milk can!

Target material:
- Scintillating crystal
- Large nuclear mass A:
  cross-section boost ↔ recoil energy



14.6 kg CsI[Na] scintillator read out by a 5” PMT

First COHERENT results



Time & energy distributions match SM expectation

Observed:
134 ± 22 events
Predicted:
173 ± 48 events

Many more experiments under way!

- **6.7σ detection** of Coherent Elastic ν Nucleus scattering (CEνNS)
- Implications for ν detectors (minimization)
- Constrains non-standard interactions between neutrinos and quarks (new mediators)
- Prospects for sterile ν search, ν magnetic moment, nuclear structure, …

[Akimov *et al.*, Science 10.1126/science.aao0990 (2017)]