The Big Questions in Neutrino Physics

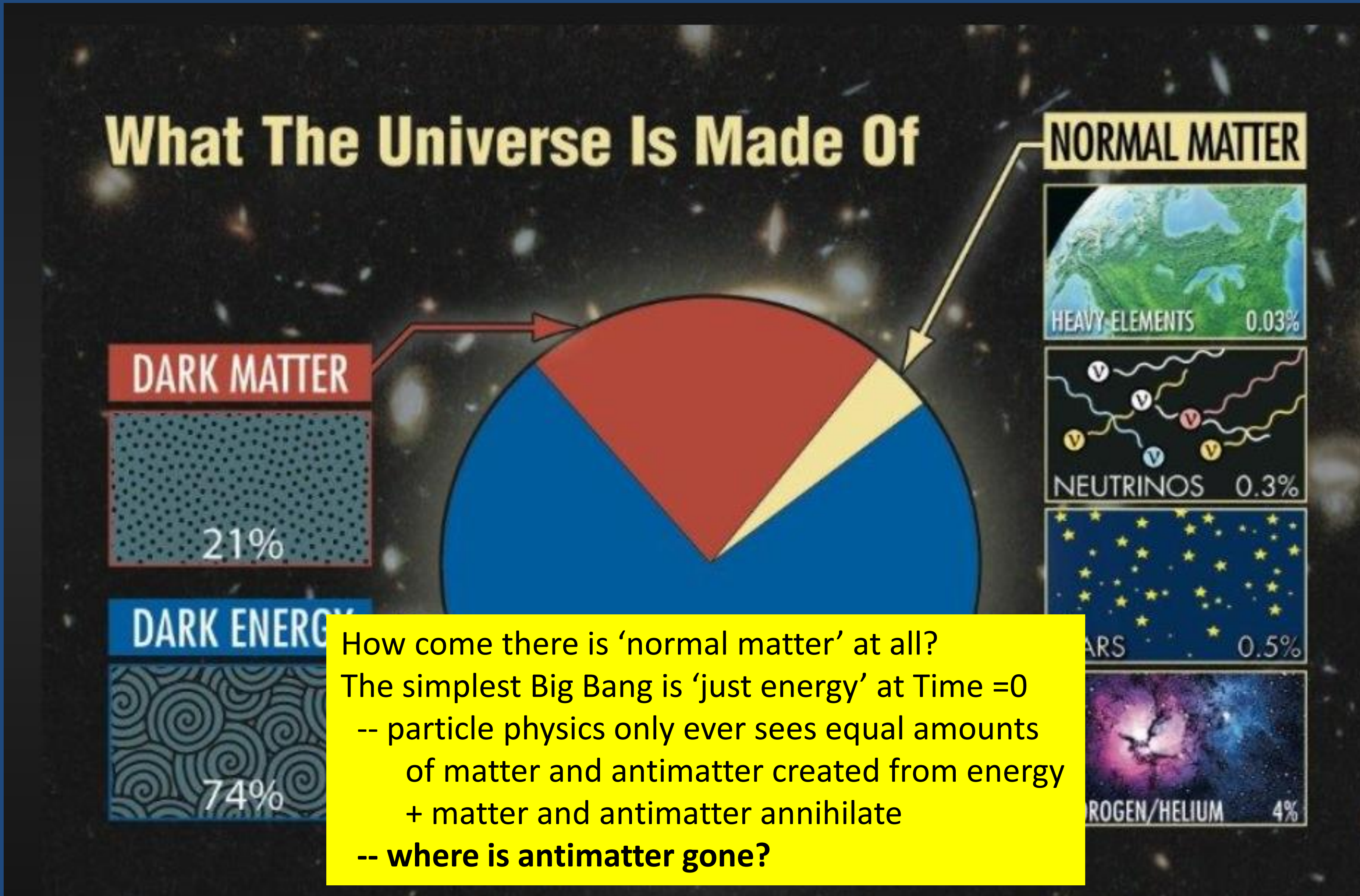
Alain Blondel Paris-Sorbonne and University of Geneva

The Big Questions in Neutrino Physics

The big questions of particle physics and neutrinos
-- How was the Universe born and how it works
-- Matter exists, but what happened to antimatter?
-- dark matter and dark energy
-- The Standard Model

Who are neutrinos?
-- neutral, left-handed, massive, mixing and oscillating (we know all that)

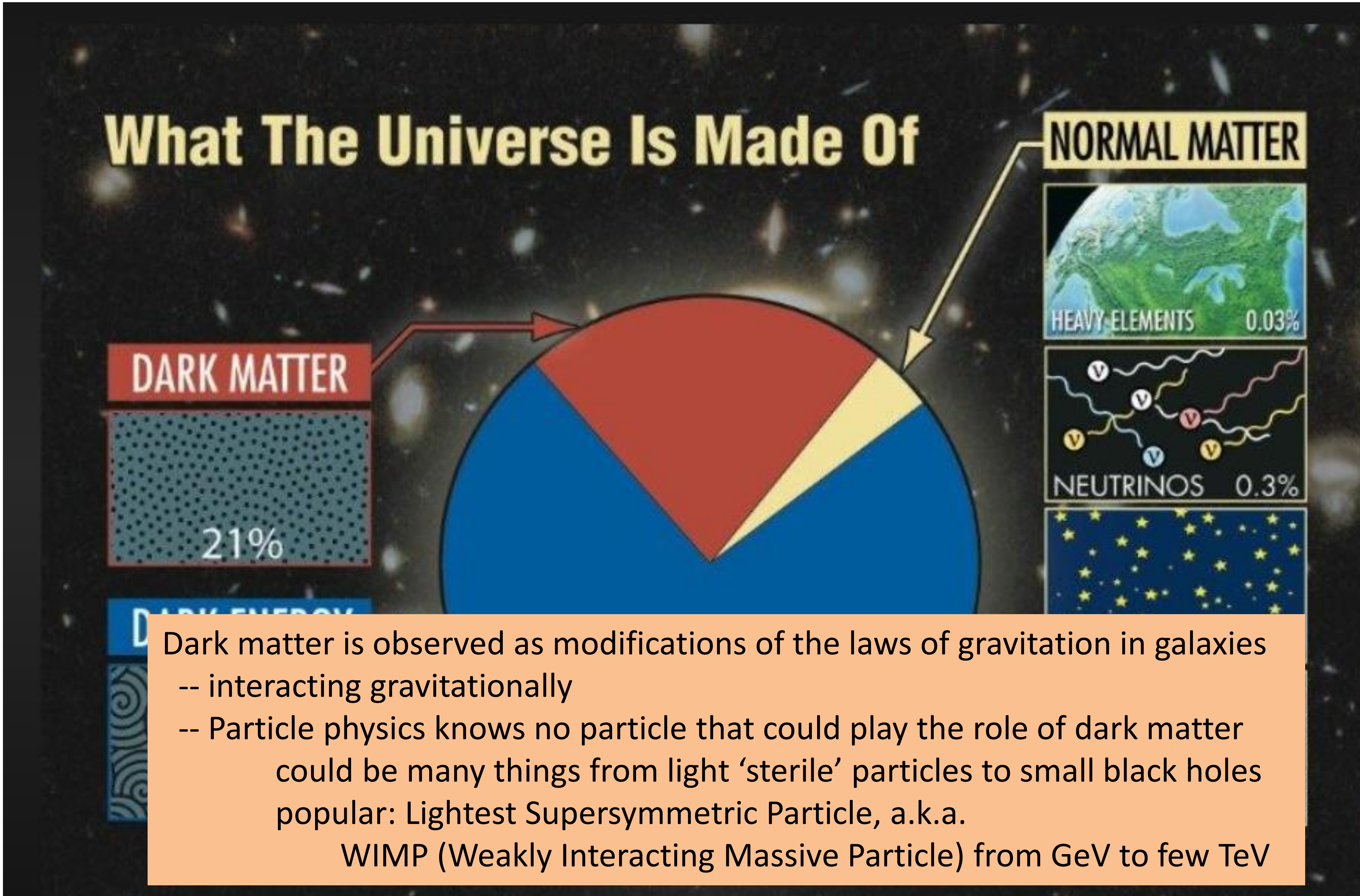
Neutrino questions and future
-- are neutrinos violating time-reversal (C.P or T) invariance
-- are neutrinos able to transform into antineutrinos
  -- fermion number conservation?
  -- The neutrino mass be explained in the Standard Model
-- how can we check all that?
  -- Neutrino mass measurements (in 0vββ and cosmology)
  -- Neutrino oscillations and CP violation future neutrino program
  -- How can we discover that neutrinos have a Majorana mass term?



How come there is ‘normal matter’ at all?

The simplest Big Bang is ‘just energy’ at Time =0

- -- particle physics only ever sees equal amounts of matter and antimatter created from energy
  + matter and antimatter annihilate
- **-- where is antimatter gone?**



Dark matter is observed as modifications of the laws of gravitation in galaxies

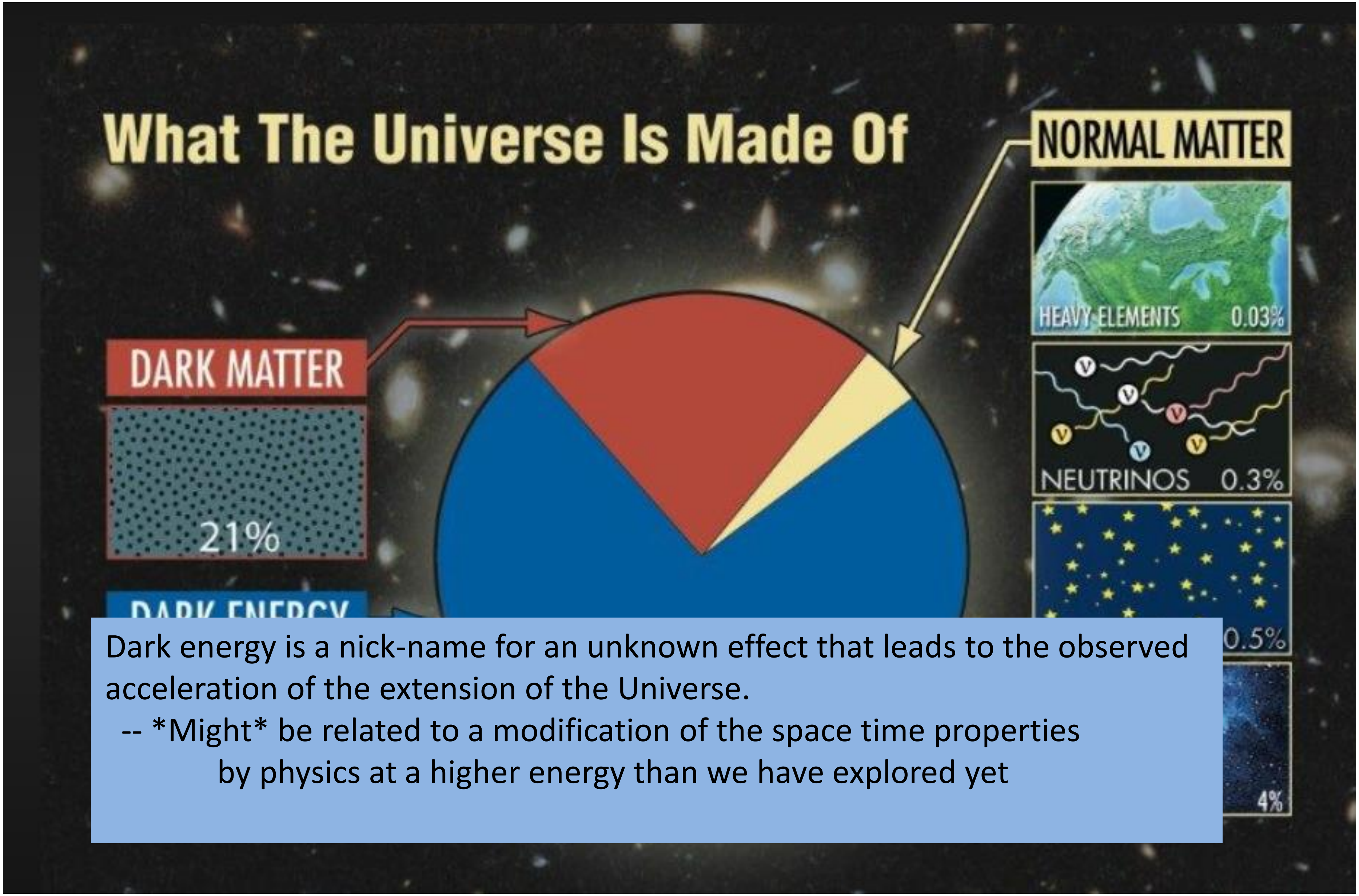
-- interacting gravitationally

-- Particle physics knows no particle that could play the role of dark matter

could be many things from light ‘sterile’ particles to small black holes

popular: Lightest Supersymmetric Particle, a.k.a.

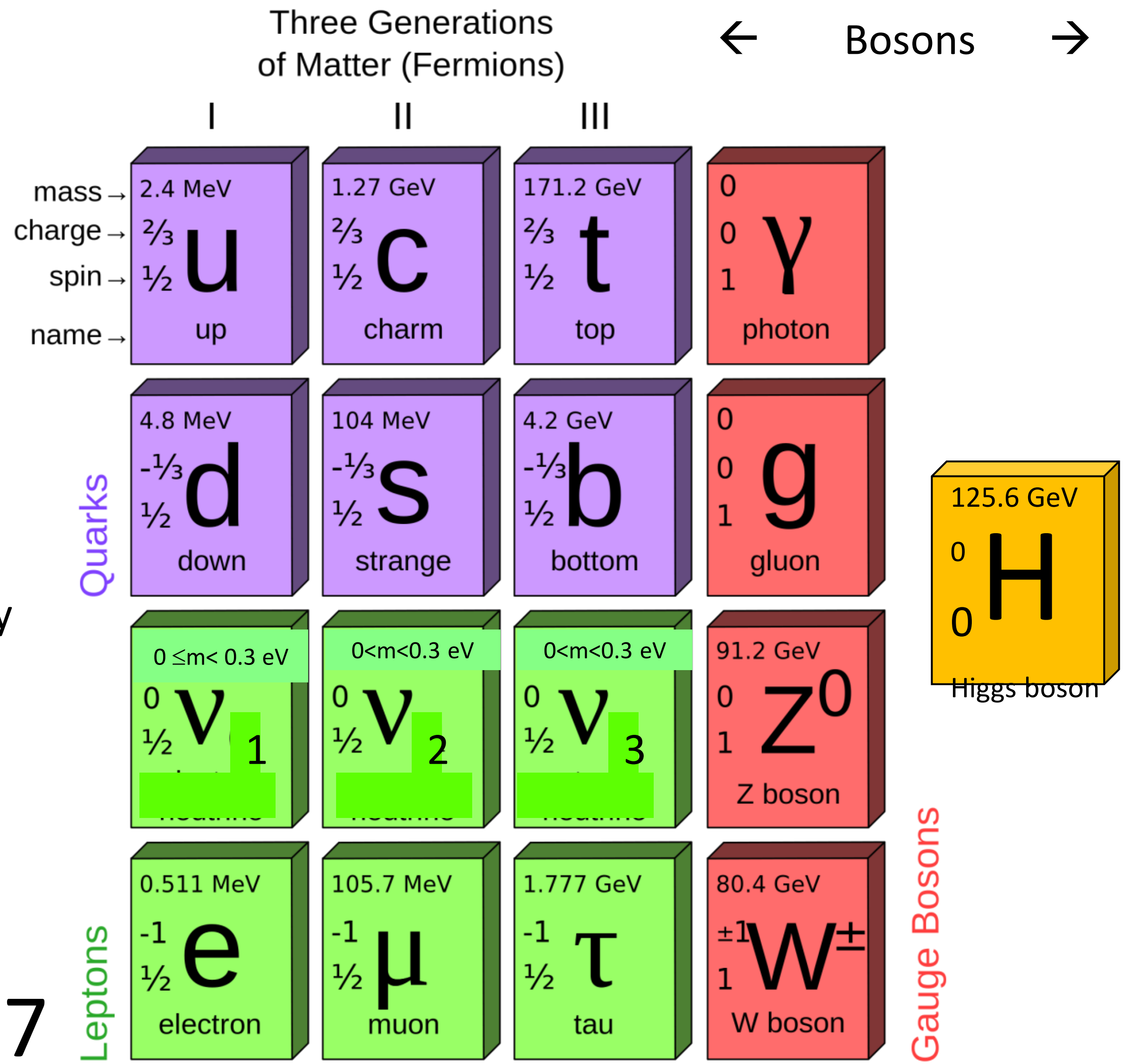
WIMP (Weakly Interacting Massive Particle) from GeV to few TeV



Dark energy is a nick-name for an unknown effect that leads to the observed acceleration of the extension of the Universe.

-- *Might* be related to a modification of the space time properties by physics at a higher energy than we have explored yet

Particle Physics: the STANDARD MODEL



2012

Each fermion
also appears as
Anti-fermion
with opposite
charge ans helicity

mass eigenstates!

1897

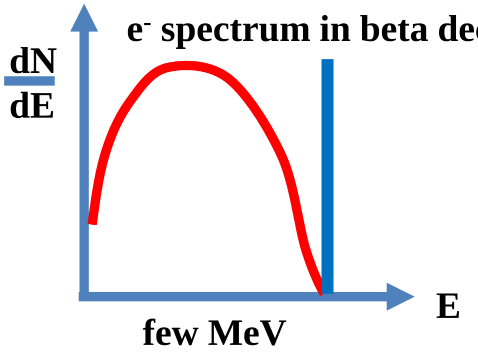
Number of fermions is ~conserved number of bosons as energy permits

Consider $^{6}He^{++} \rightarrow {}^{6}Li\ \bar{\nu}_e\ e^-$

Q=3.5078 MeV T/2 ≈ 0.8067 s

1930 Neutrinos: *the birth of the idea*

Pauli's letter of the 4th of December 1930



Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, 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 which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli

Wolfgang Pauli

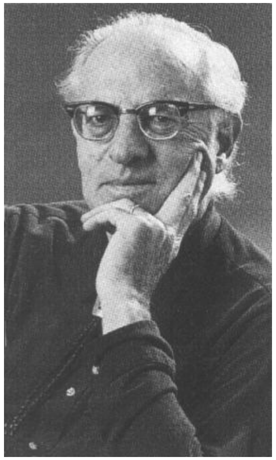
Neutrinos: *direct detection*

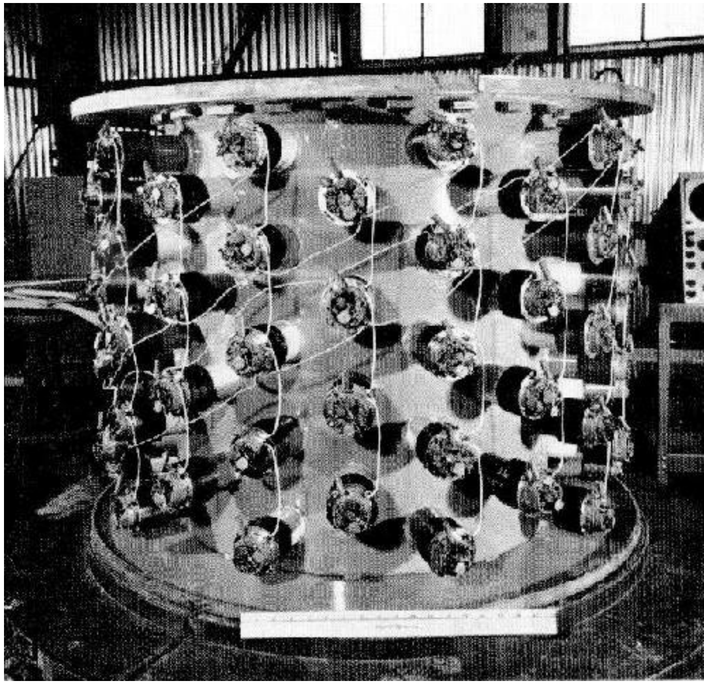
Reines and Cowan **1953**

The anti-neutrino coming from the nuclear reactor interacts with a proton of the target, giving a positron and a neutron.

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

The target is made of about 400 liters of water mixed with cadmium chloride





The positron annihilates with an electron of target and gives two simultaneous photons ($e^+ + e^- \rightarrow \gamma\gamma$) .

The neutron slows down before being eventually captured by a cadmium nucleus, that gives the emission of 2 photons about 15 microseconds after those of the positron.

All those 4 photons are detected and the 15 microseconds identify the "neutrino" interaction.

4-fold delayed coincidence

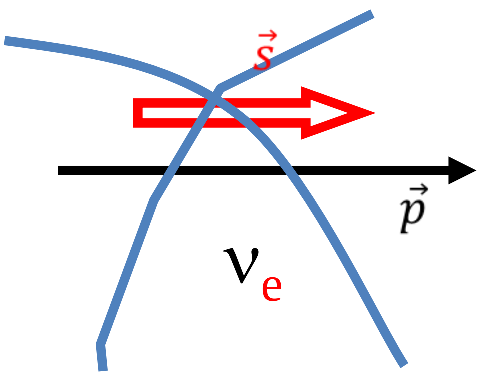
1956 Parity violation in Co beta decay: electron is left-handed (C.S. Wu et al)

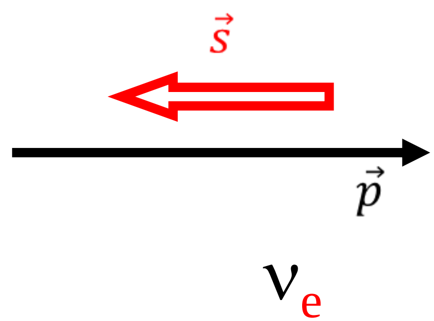
electrons with negative helicity } **interact with weak interaction**
positrons with positive helicity }

$$h = \frac{\vec{s}.\vec{p}}{|\vec{s}|.|\vec{p}|}$$

1957 Neutrino helicity measurement
M. Goldhaber et al Phys.Rev.109(1958)1015

(anti)neutrinos have <u>negative(positive) helicity</u>
(If massless this is the same as left-handed)



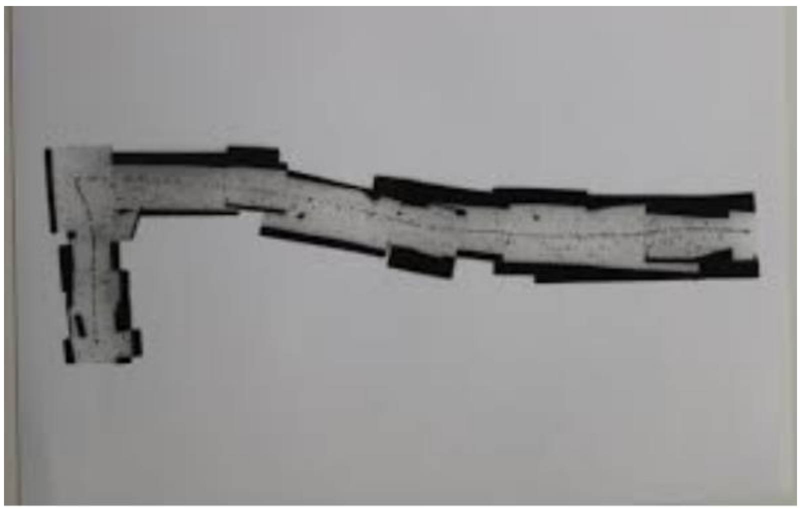


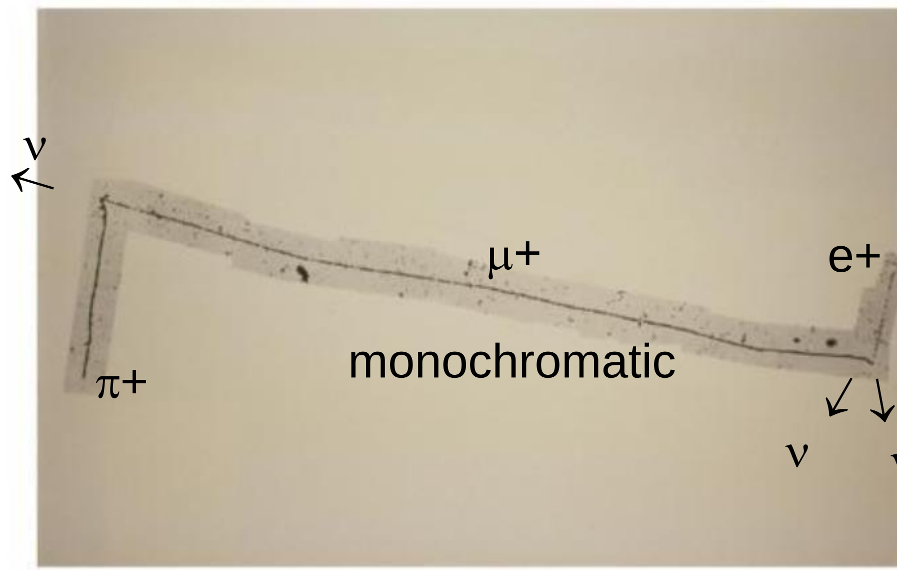
h= +1 , right-handed, not observed!

h= -1 , left-handed

Another neutrino was detected in 1947 with the discovery of the pion.
(Powell et al, 1947). Maybe it was the same neutrino than in beta decay?

These emulsions were made of photographic gel and stacked.
Placed in high altitude balloons at up to 10km altitude, they allowed the observation of strongly interacting particles which are otherwise stopped by the atmosphere.



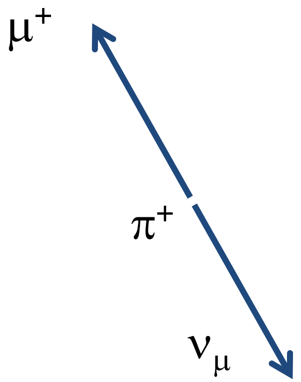


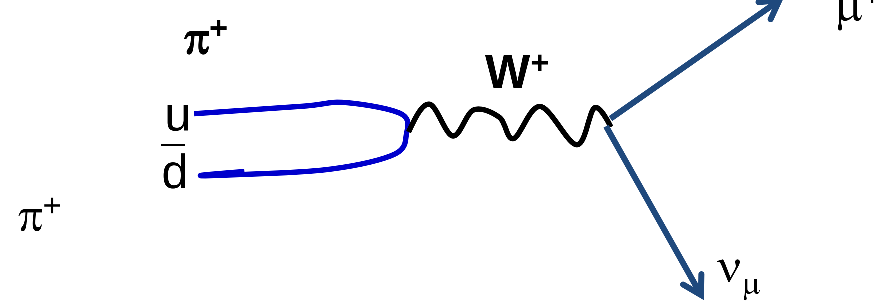
Emulsions played an important role in establishing the nature of the tau neutrino (**E531, 1986**) and detection of ν_τ interactions (DONUT and OPERA experiments)

Unrelated Preamble

Why do pions decay into $\pi^+ \to \mu^+ \nu_\mu$ much much more than into $\pi^+ \to e^+ \nu_e$?

Imagine the π decay at rest. (obviously the decay fraction is Lorentz invariant)



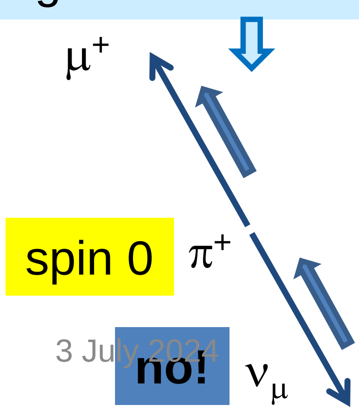


momenta are equal and opposite: $(P_{\mu,\nu})^2 = (m^2_\pi - m^2_\mu - m^2_\nu)/2\, m_\pi$

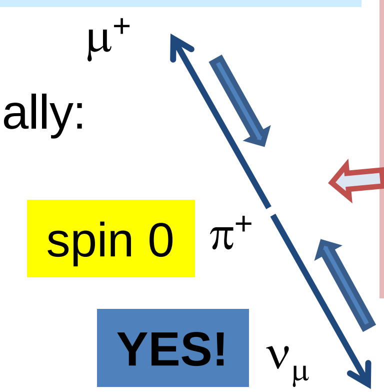
How are the spins? The μ^+ and ν_μ originate from weak interaction

➔ μ^+ and ν_μ are chirality left-handed … however the pion has spin 0

If helicity and chirality were identical
we would have violation of
angular momentum conservation!



really:



However they are not.

$|R\rangle, |L\rangle$ chirality states; $|+\rangle, |-\rangle$ helicity states

$|L\rangle = |-\rangle + m/E\ |+\rangle$

$|\bar{L}\rangle = |+\rangle + m/E\ |-\rangle$

thus the decay rate is proportional to

$||\langle \bar{L}|-\rangle||^2 = (m_\mu/E_\mu)^2$

Also multiply by the phase space factor
proportional to $(P\mu)^2 = (m^2_\pi - m^2_\mu - m^2_\nu)/2\, m_\pi$

However they are not.

$|R\rangle$, $|L\rangle$ chirality states; $|+\rangle$, $|-\rangle$ helicity states

$| L \rangle = | - \rangle \;+\; m/E \;|+\rangle$

$| \bar{L} \rangle = |+\rangle \;+\; m/E \;| - \rangle$

thus the decay rate is proportional to

$||\langle \bar{L}|-\rangle||^2 = (m_\mu / E_\mu)^2$

Also multiply by the phase space factor

proportional to $(P\mu)^2 = (m^2_\pi - m^2_\mu - m^2_\nu)/2\, m_\pi$

So we can derive the ratio $R_\pi = \dfrac{\pi \to e\nu}{\pi \to \mu\nu}$

$$R_\pi = (m_e/m_\mu)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2} \right)^2 = \quad 1.2351(2)\; 10^{-4} \text{ (theory)}$$

$$1.230(4)\; 10^{-4} \text{ (exp)}$$

It is very well established that the fermions that interact with the W are chirality (Lorentz invariant) left-handed

(one also calls the antiparticle Left-handed, although this corresponds to the opposite sign for the helicity)

1959 Ray Davis established that

(anti) neutrinos from reactors do not interact with chlorine to produce argon

reactor : n $\rightarrow$ p e^- ν_e or $\bar{\nu}_e$?

these ν_e **don't do** $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

they do this: $\bar{\nu}_e + p \rightarrow e^+ + n$

they are called anti-neutrinos!

Introduce a <u>lepton number</u> which is

+1 for e^- and ν_e

and

-1 for e^+ and $\bar{\nu}_e$

which is (so far) observed to be conserved in weak/EM/Strong interactions

Neutrinos

the properties

1960

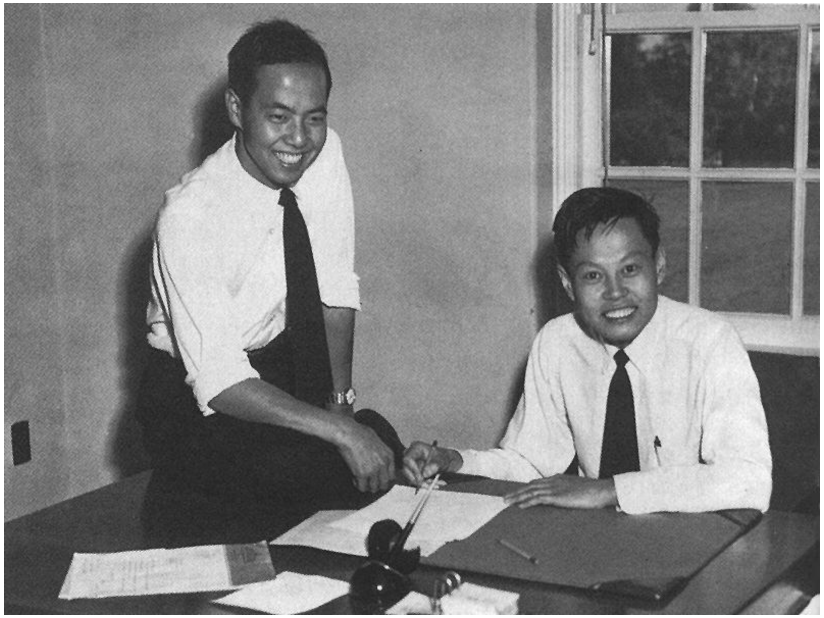
In 1960, Lee and Yang realized that if a reaction like

$$\mu^- \rightarrow e^- + \gamma$$

is not observed, this is because two types of neutrinos exist ν_μ and ν_e

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

otherwise $\mu^- \rightarrow e^- + \nu + \bar{\nu}$ has the same Quantum numbers as $\mu^- \rightarrow e^- + \gamma$



Lee and Yang

1962 discovery of the muon neutrino

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

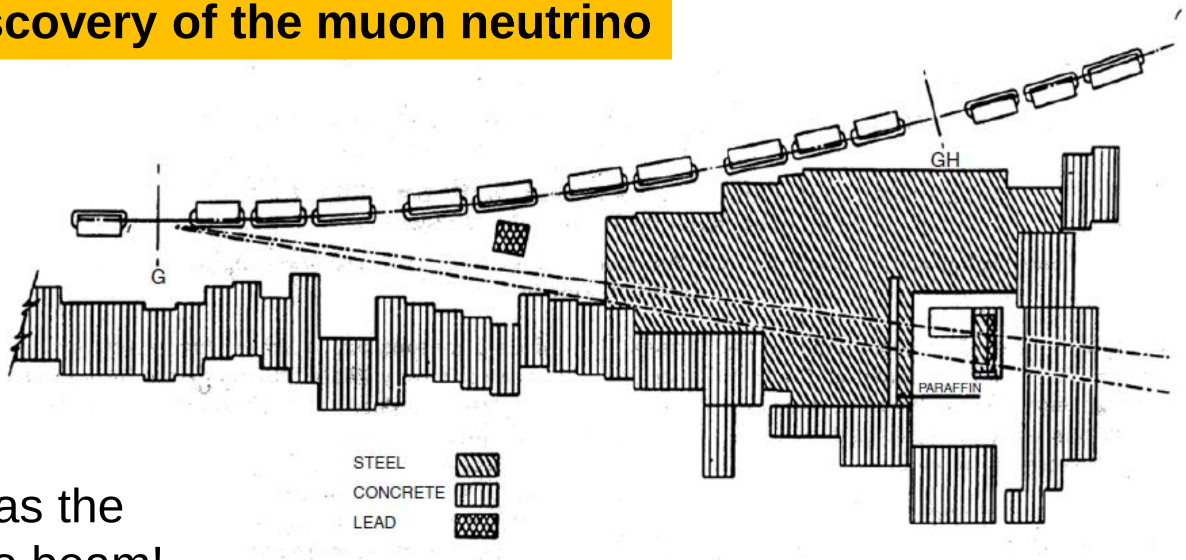
$$\pi^{\pm} \rightarrow \mu^{\pm} + (\nu/\bar{\nu}). \quad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

The question was not whether there was a neutrino produced in tau pion ys, but whether this neutrino was a new one!

1962 discovery of the muon neutrino



This also was the first neutrino beam!

Fig. 11. Plan view of the 2nd neutrino experiment.

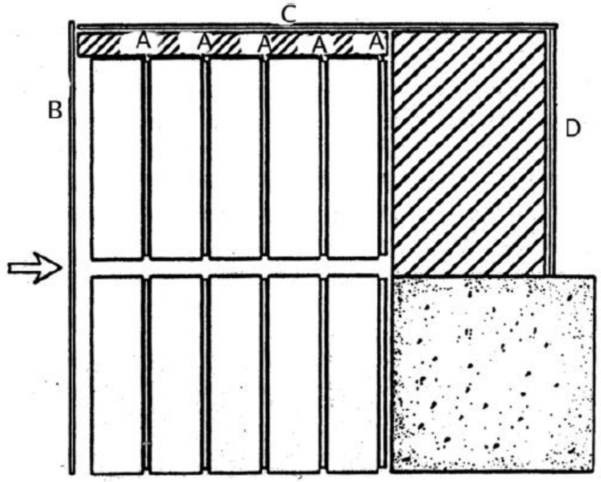


Fig. 12. Spark chamber and counter arrangement. A are triggering counters; B, C, and D are anticoincidence counters.

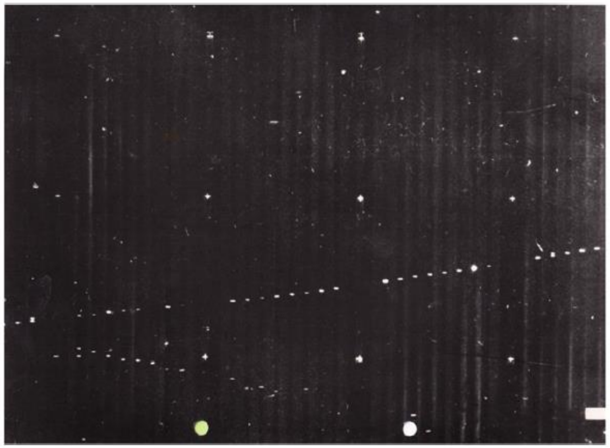


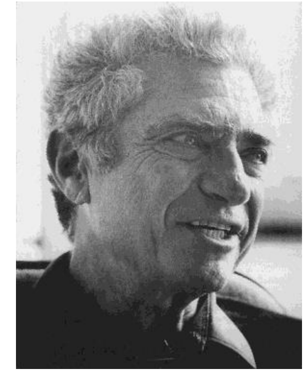
Fig. 14. Event with penetrating muon and hadron shower.

Two Neutrinos

1962

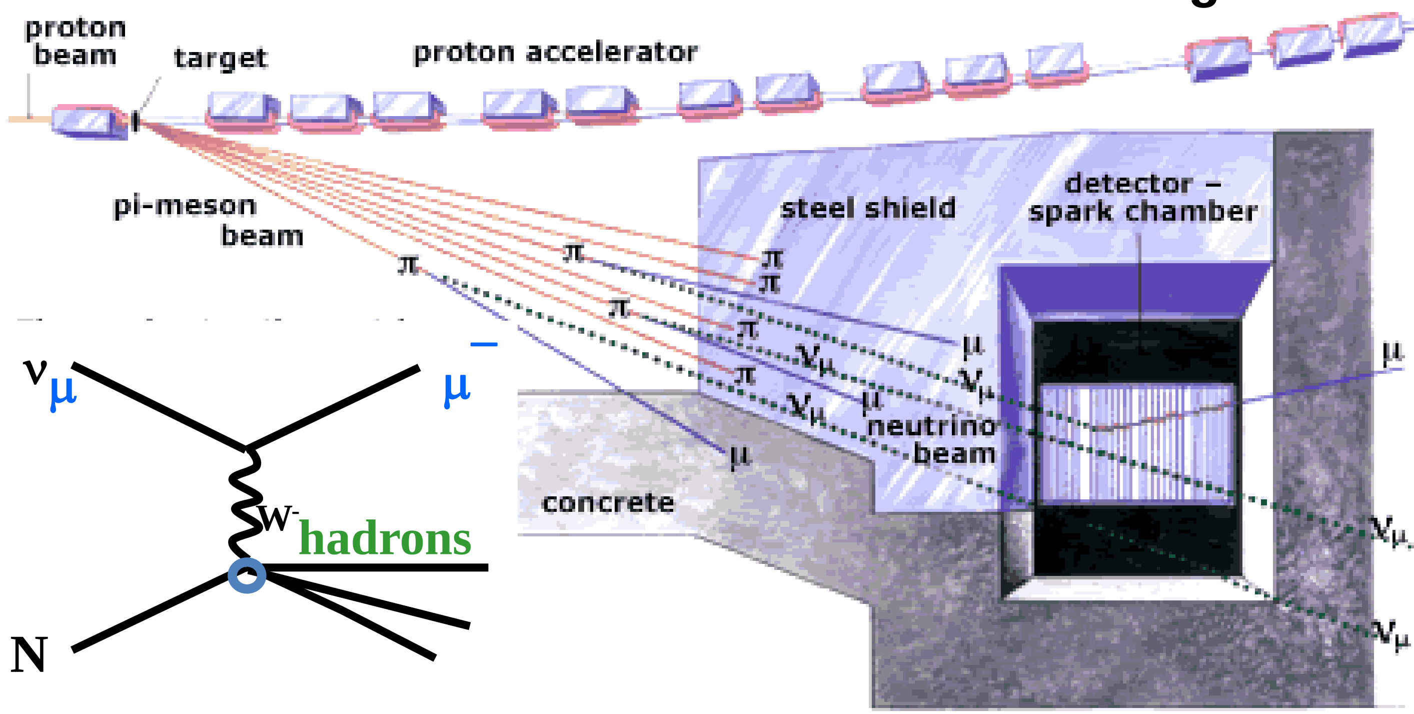
Schwartz

Lederman



Steinberger

AGS Proton Beam



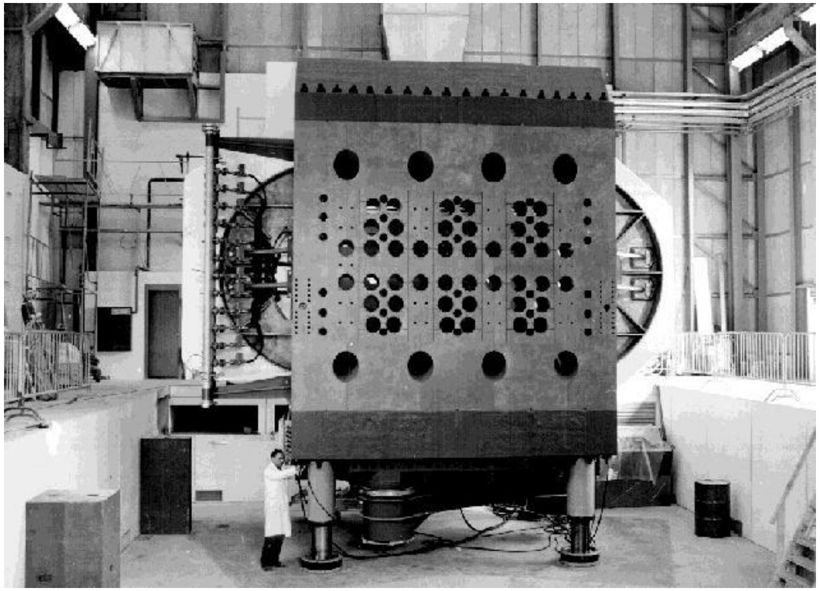
Neutrinos from π-decay only produce muons (not electrons)

when they interact in matter

SPARK CHAMBERS:
HeNe+ HV Al plates +scintillators

Neutrinos

the weak neutral current



Gargamelle Bubble Chamber
CERN

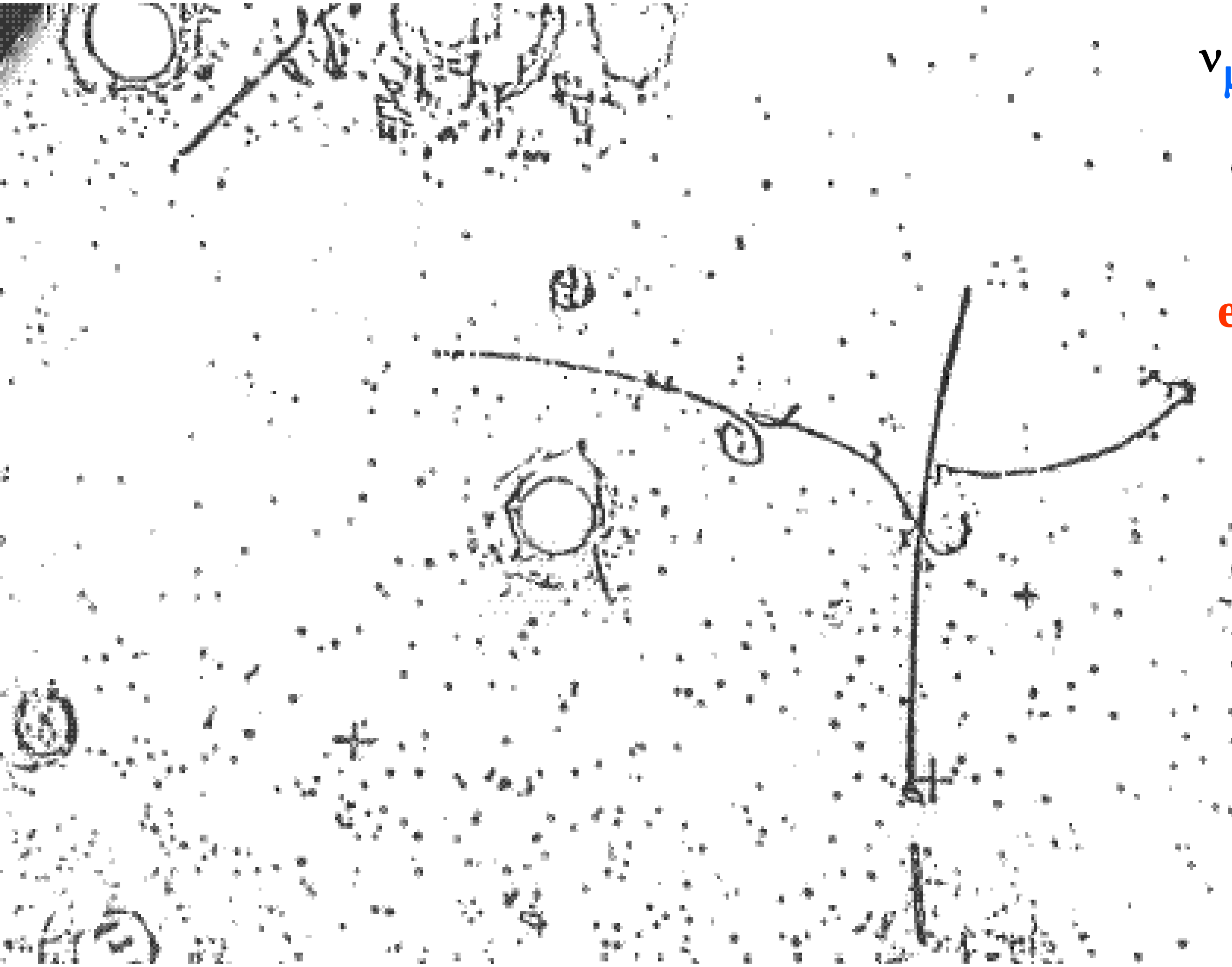
Discovery of weak neutral current

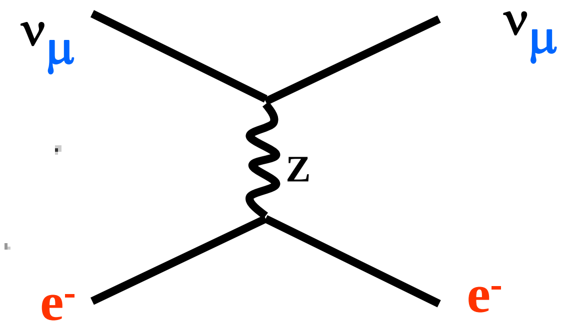
$\nu_\mu + e \rightarrow \nu_\mu + e$

$\nu_\mu + N \rightarrow \nu_\mu + X$ (no muon)

previous searches for neutral currents had been performed in particle decays (e.g. $K^0 \rightarrow \mu\mu$) leading to extremely stringent limits (10^{-7} or so)

early neutrino experiments had set their trigger on final state (charged) lepton!

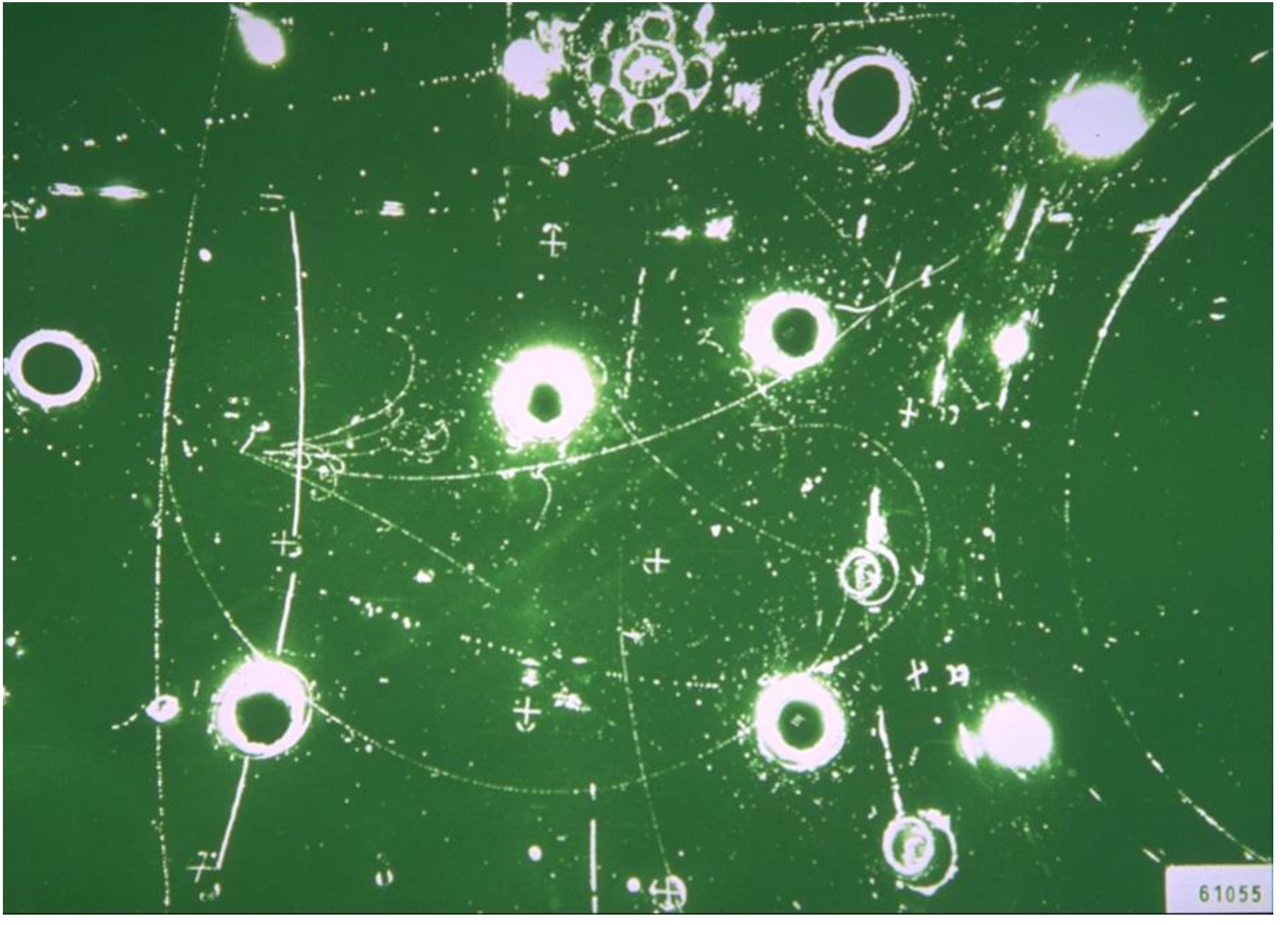




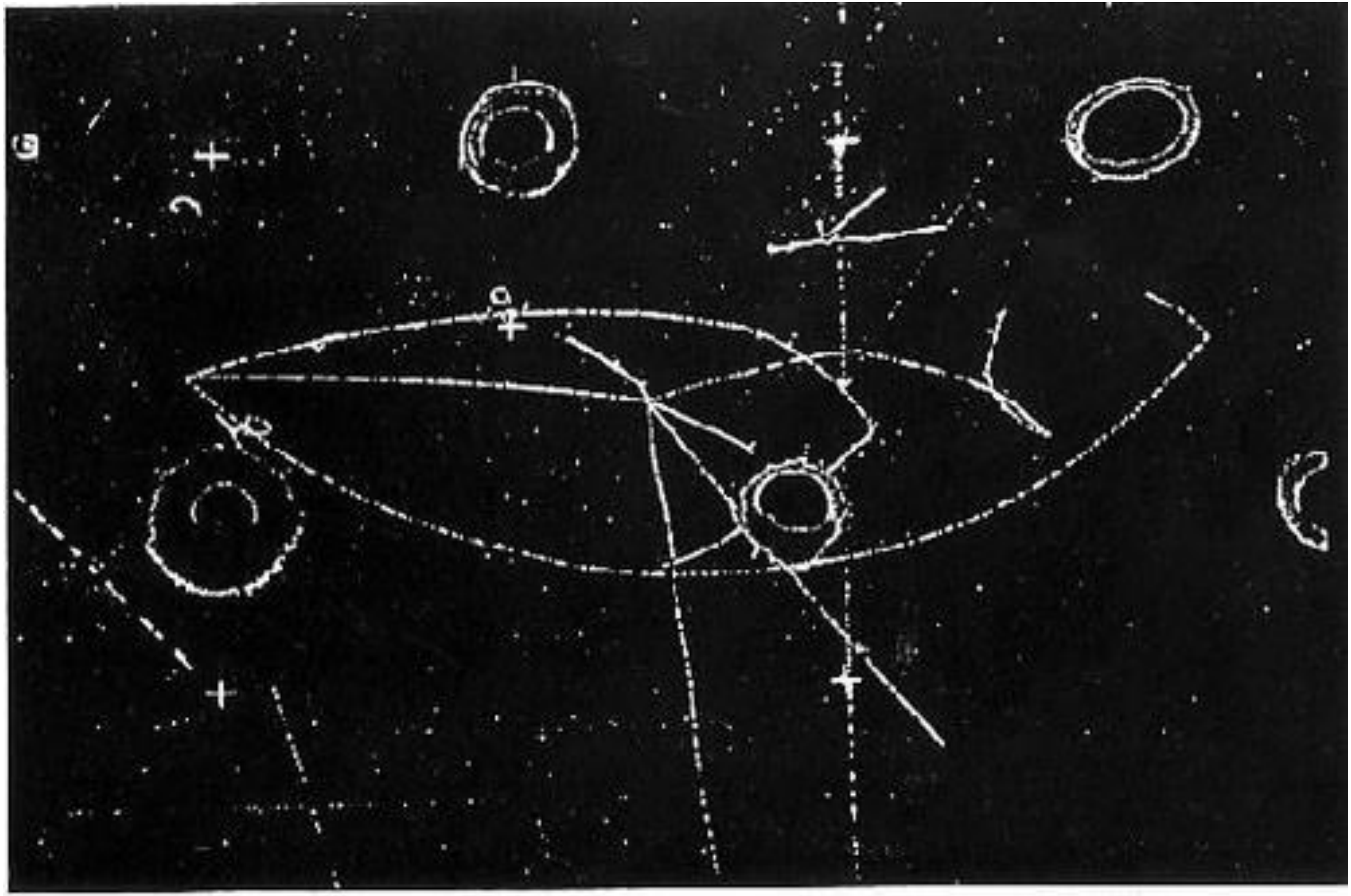
elastic scattering of neutrino off electron in the liquid

1973 Gargamelle

First manifestation of the Z boson experimental birth of the Standard model



Gargamelle Charged Current event

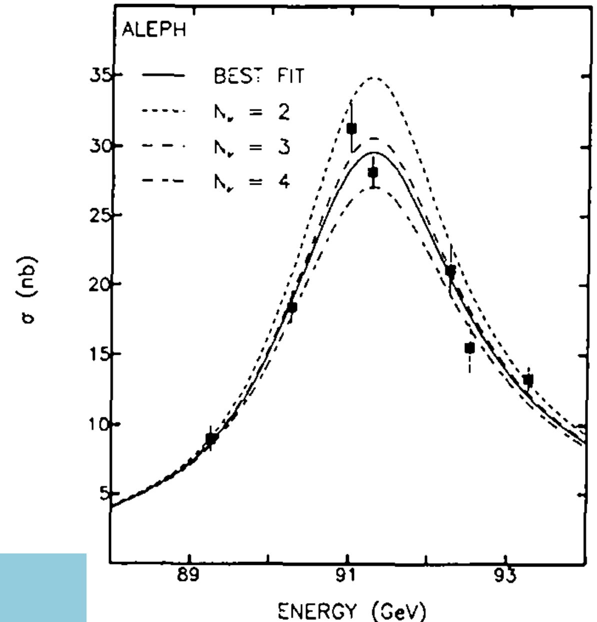


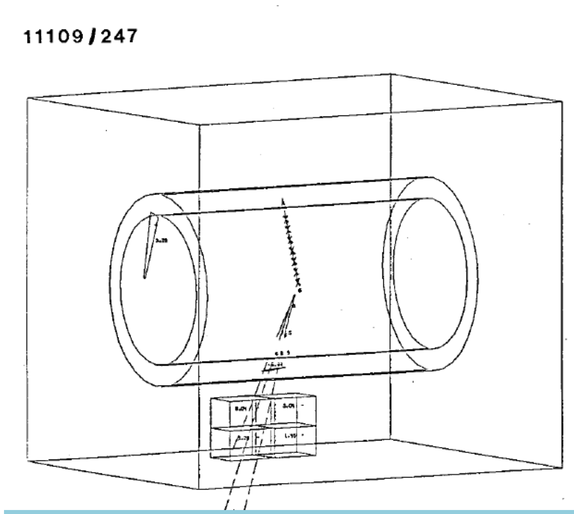
Gargamelle neutral current event (all particles are identified as hadrons)

The Third (and last) Family of (light) Neutrinos ν_τ

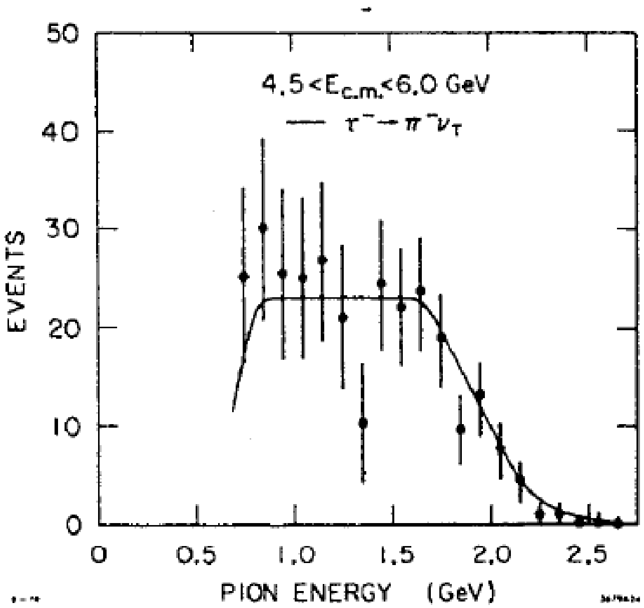
A.B. arXiv:1812.11362

LEP 1989 only 3 families!

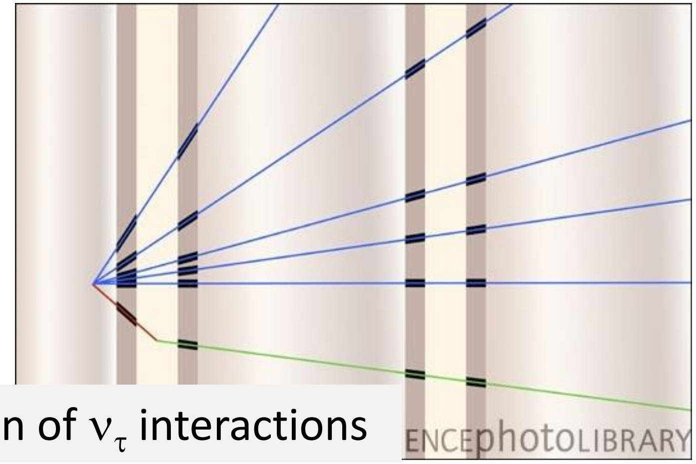




1985 UA1 $W \rightarrow \tau\nu_\tau \cong W \rightarrow e\nu_e$
1986 E531: no taus in $\nu_{\mu,e}$ beam



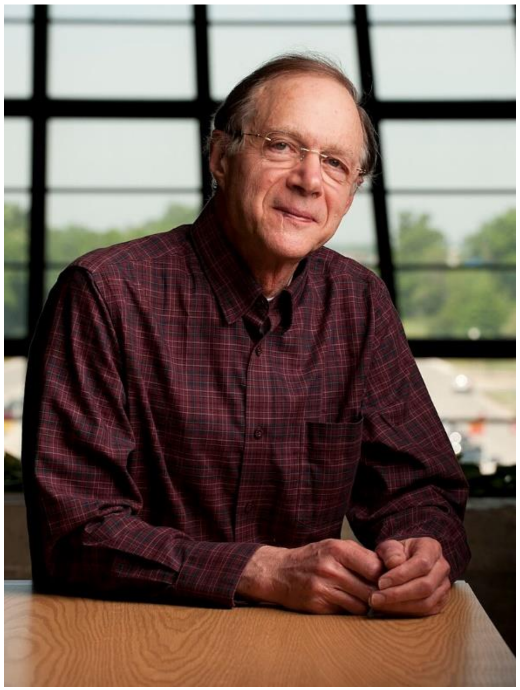
1977: Discovery in tau decays (e+e- collisions @SPEAR)
1982 Particle Data Group: "ν_τ established"



2000 observation of ν_τ interactions

W decay is precisely what we use to define the neutrino flavours.

Boris Kayser (1938-2024)
VIIth Pontecorvo School, 2017

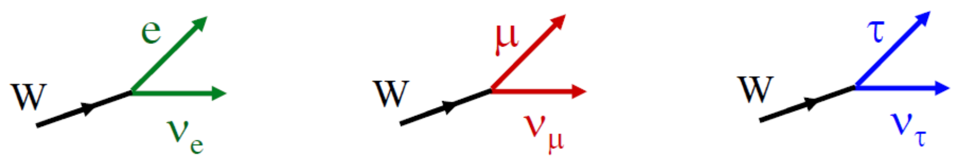


The Neutrino Flavors

There are three flavors of charged leptons: e , μ , τ

There are three known flavors of neutrinos: ν_e, ν_μ, ν_τ

We ***define*** the neutrinos of specific flavor, ν_e, ν_μ, ν_τ, by W boson decays:



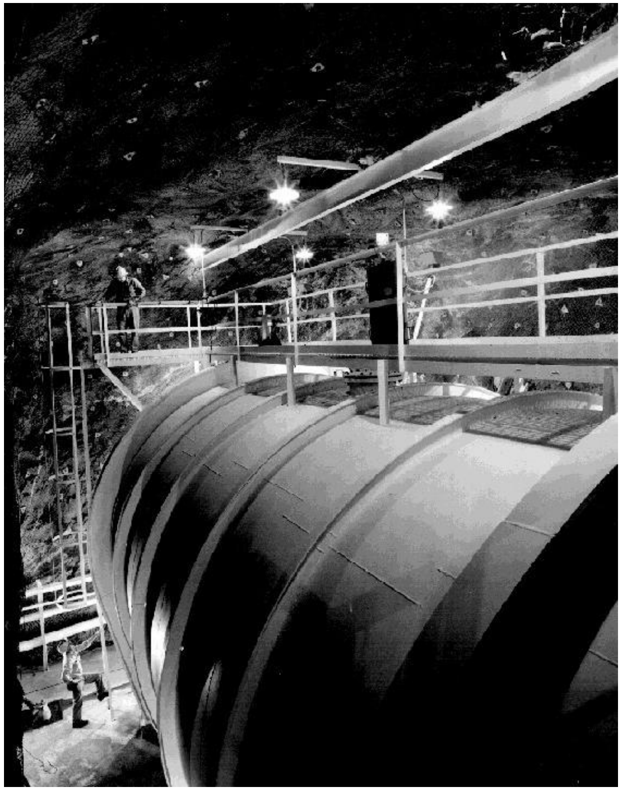
the existence of the three W decay modes with <u>similar branching</u> ratios (1985-1998) establishes the tau and its neutrino as a new sequential heavy lepton doublet

Neutrinos
astrophysical neutrinos

Ray Davis

since ~1968

Homestake Detector



Solar Neutrino Detection
600 tons of chlorine.

- Detected neutrinos E> 1MeV

- fusion process in the sun

solar : $pp \rightarrow pn\ e^+\ \nu_e$ (then D gives He etc…)

these ν_e do $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

they are neutrinos

- The rate of neutrinos detected is **three** times less than predicted!

solar neutrino 'puzzle' since 1968-1975!

solution: 1) solar nuclear model is wrong or 2) neutrinos oscillate

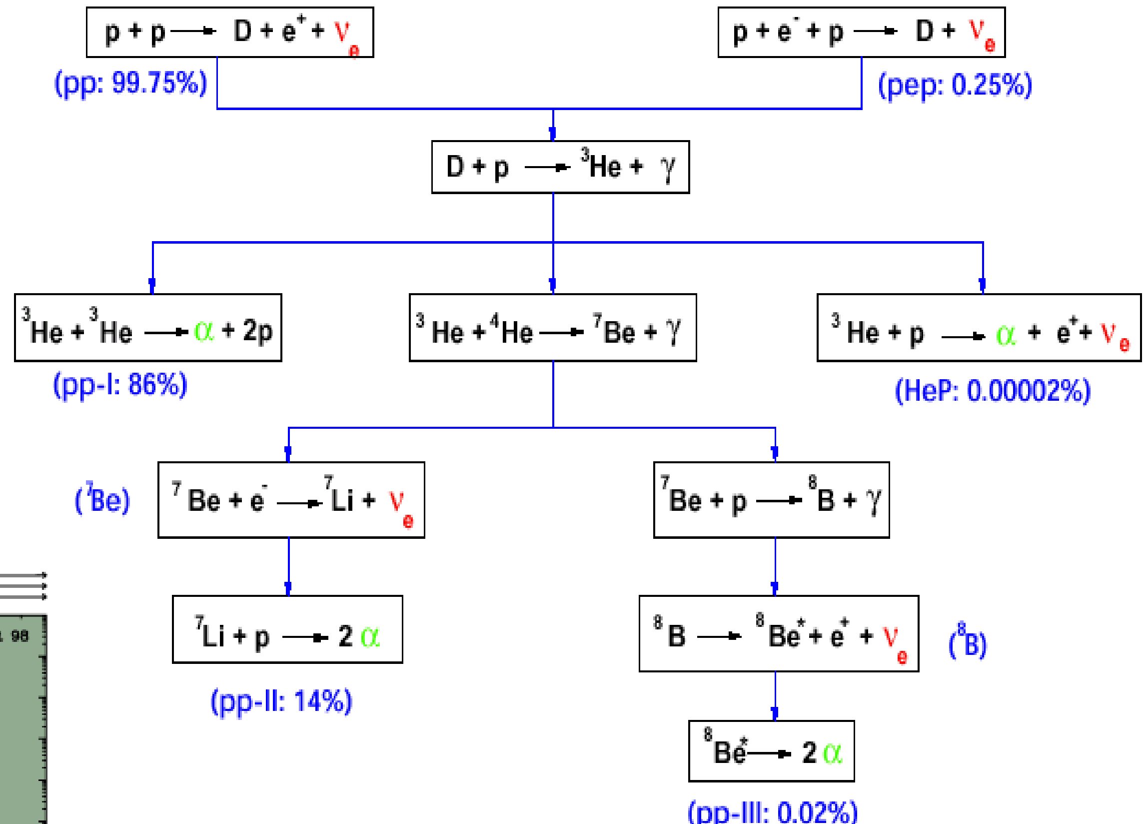
ν_e solar neutrinos

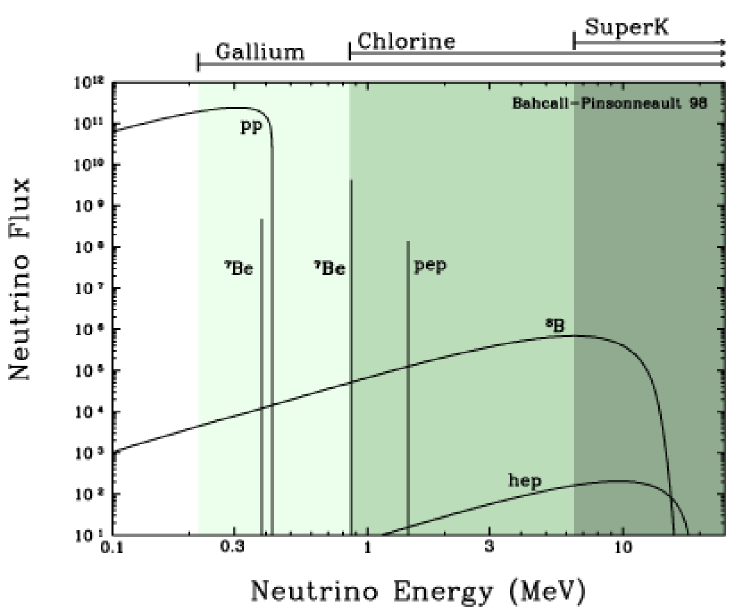
Sun = Fusion reactor

Only ν_e produced

Different reactions

Spectrum in energy





Counting experiments vs flux calculated by SSM

BUT …

The Pioneer: Chlorine Experiment

The interaction

$^{37}Cl(\nu_e,e)^{37}Ar$ (E_{thr} = 813 keV)

K_{shell} **EC** τ = **50.5** d

→ ^{37}Cl + 2.82 keV (*Auger* e^-, *X*)

ν Signal Composition: (BP04+N14 SSM+ ν osc)

pep+hep	0.15 SNU	(4.6%)
^{7}Be	0.65 SNU	(20.0%)
^{8}B	2.30 SNU	(71.0%)
CNO	0.13 SNU	(4.0%)
Tot	3.23 SNU ± 0.68 1σ	

Expected Signal (BP04 + N14)

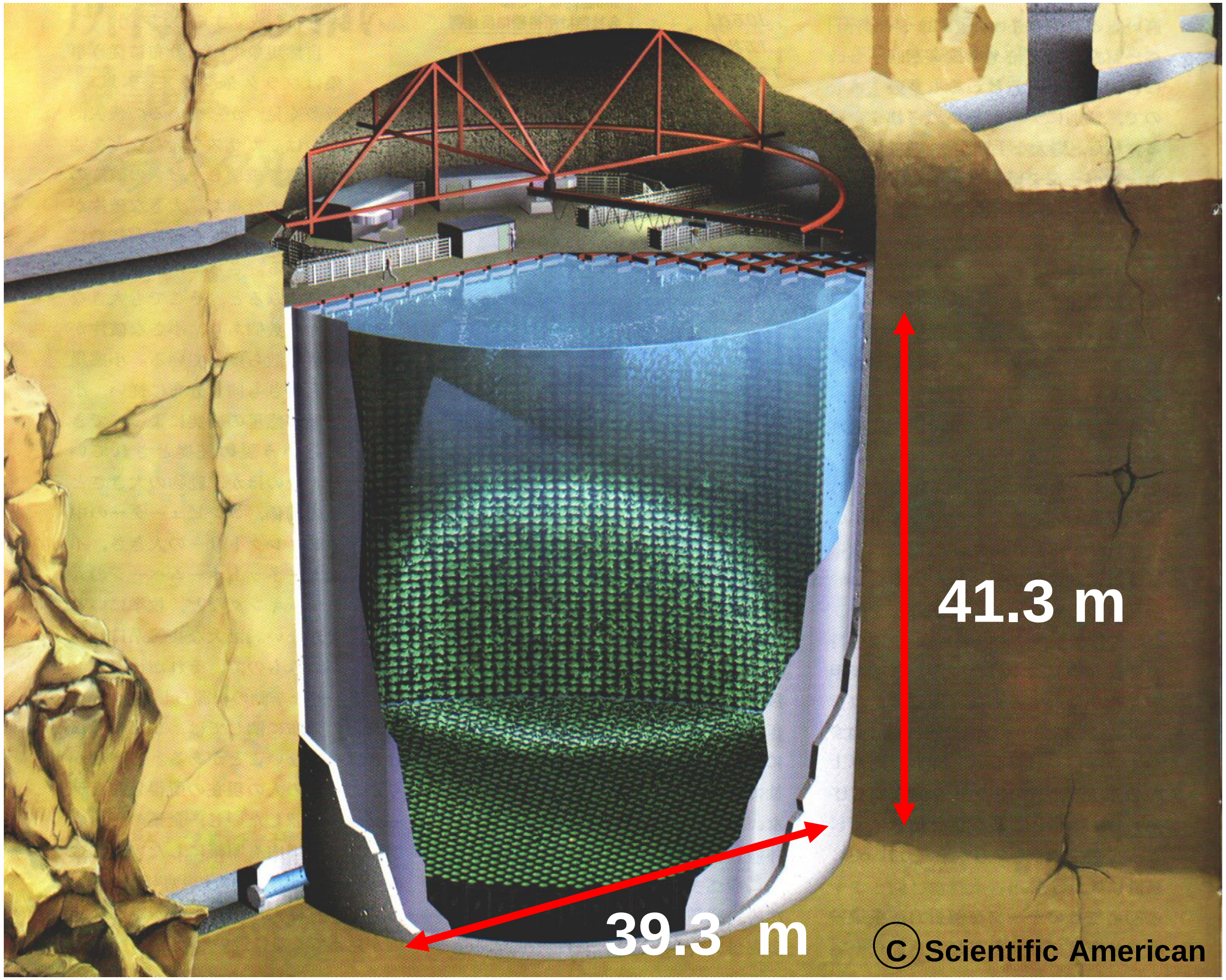
8.2 SNU $^{+1.8}_{-1.8}$ 1σ

S.N.U. = Solar Neutrino Unit
(electron-) neutrino flux producing 10^{-36} captures per target atom per second

Generalities on radiochemical experiments

	Data used for R determination	N runs	Average efficiency	Hot chem check	Source calib	R_{ex} [SNU] **expected (no osc)**
Chlorine (Homestake Mine); South Dakota USA	1970-1993	106	0.958 ± 0.007	^{36}Cl	No	2.55 ± 0.17 ± 0.18 6.6% 7% **2.6 ± 0.3** **8.5+-1.8**
GALLEX /GNO LNGS Italy	1991-2003	124		^{37}As	Yes twice ^{51}Cr source	69.3 ± 4.1 ± 3.6 5.9% 5% **131+-11**
SAGE Baksan Kabardino Balkaria	1990-ongoing	104		No	Yes ^{51}Cr ^{37}Ar	70.5 ± 4.8 ± 3.7 6.8% 5.2% **70.5 ± 6.0** **131+-11**

Super-K detector



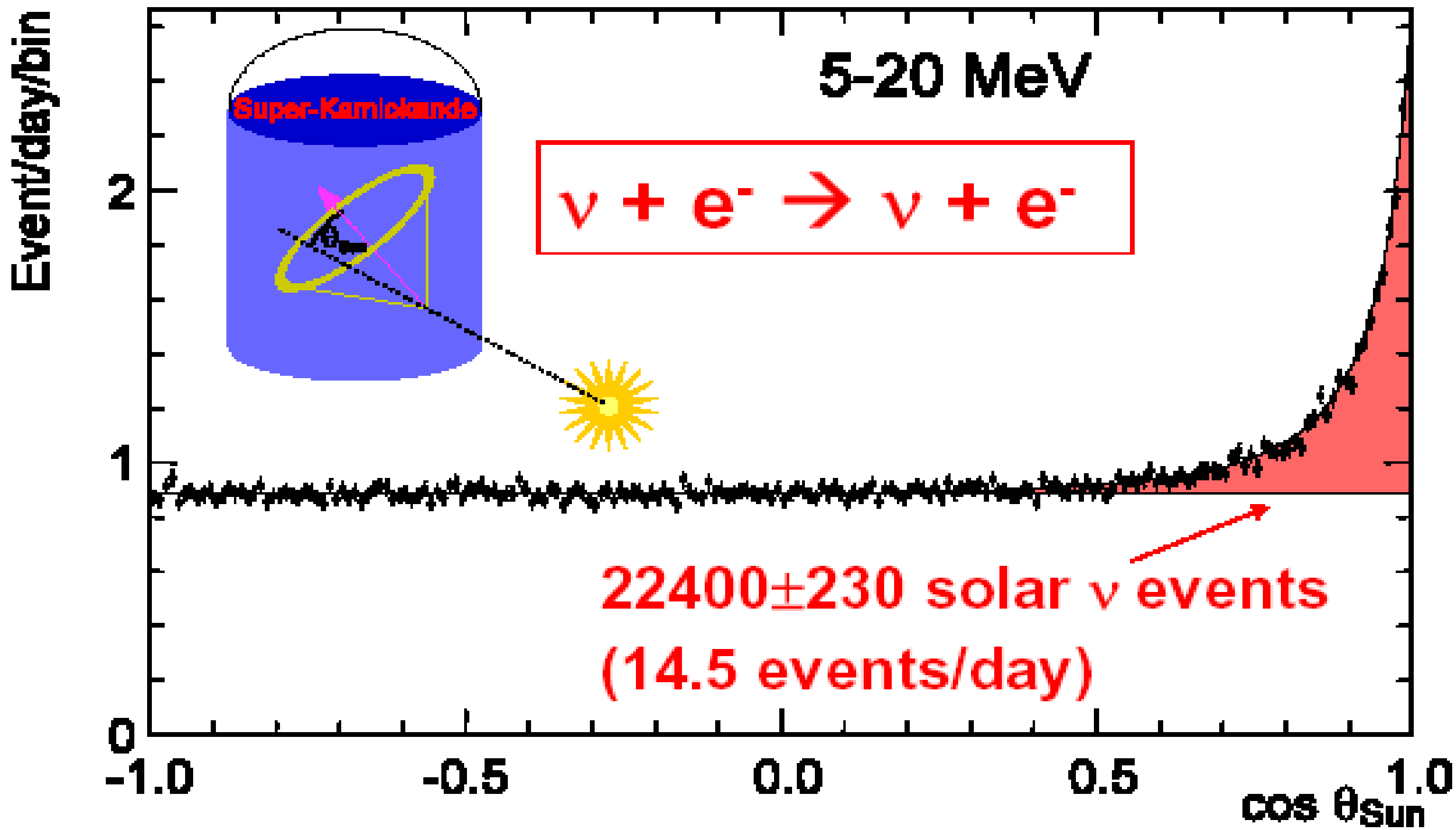
Water Cerenkov detector

50000 tons of pure light water

≈10000 PMTs

Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)



^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \ {}^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

Missing Solar Neutrinos

Only fraction of the expected flux is measured !

Possible explications:

wrong SSM

NO. Helio-seismology

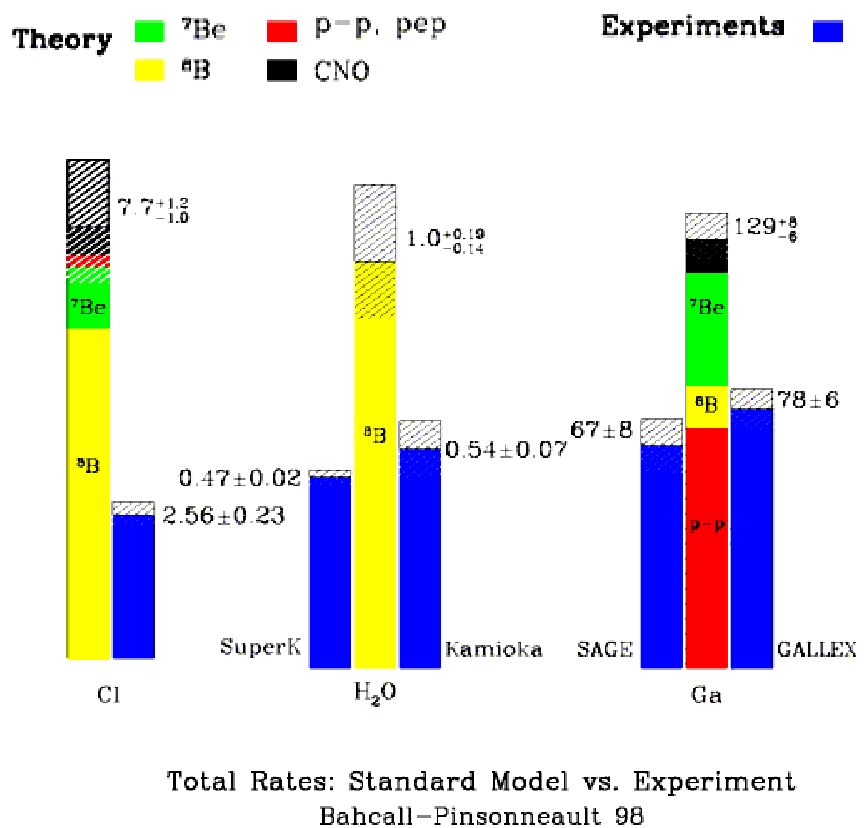
wrong experiments

NO. Agreement between different techniques

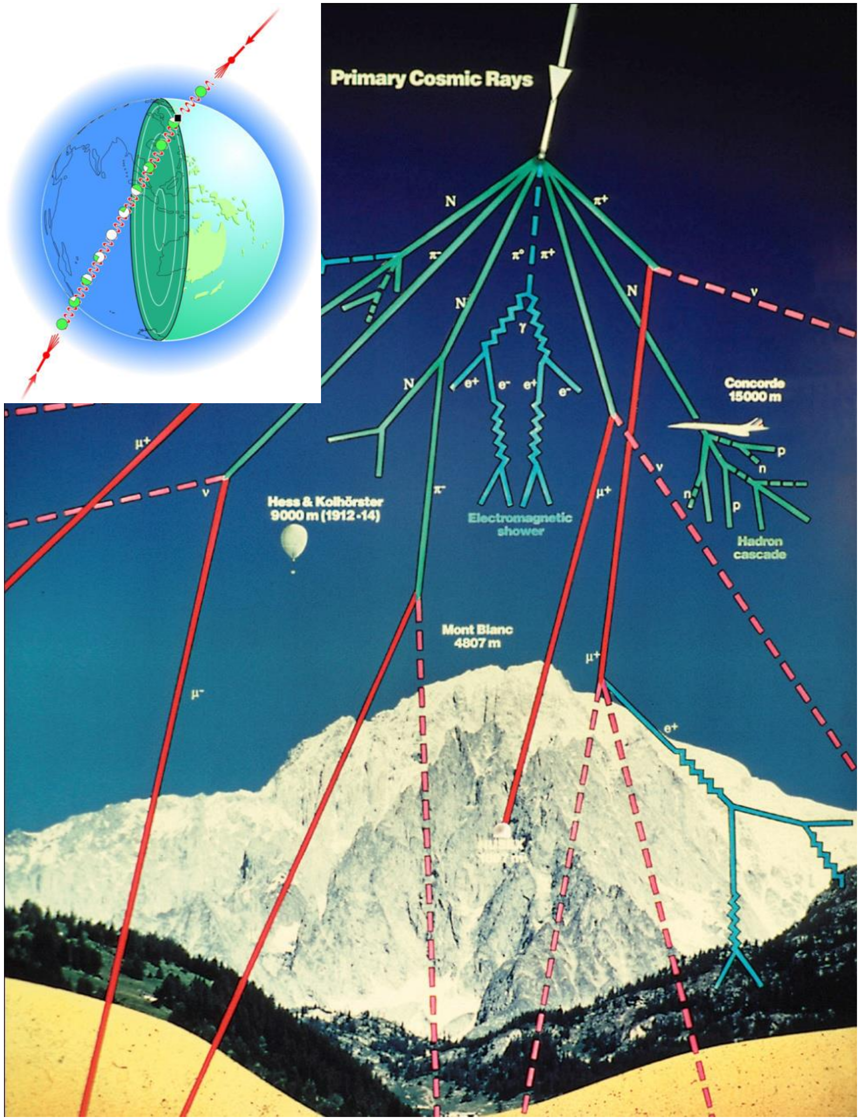
or

ν_e's go into something else

Oscillations?

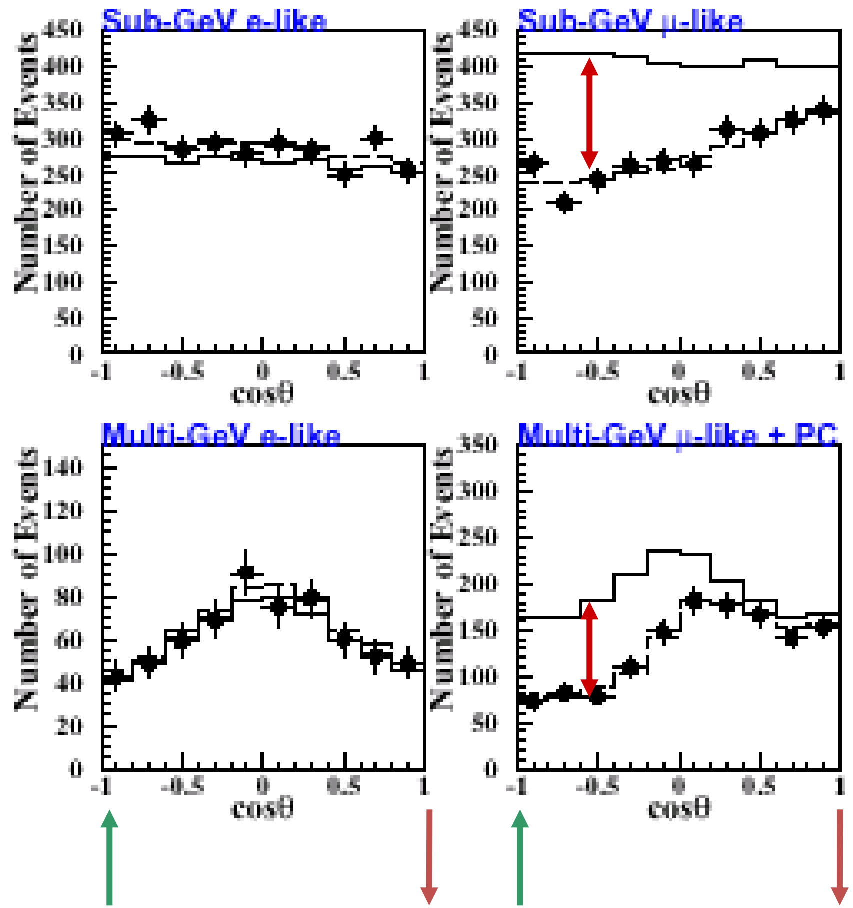


Atmospheric ν : up-down asymmetry



Super-K results

ν_e ν_μ

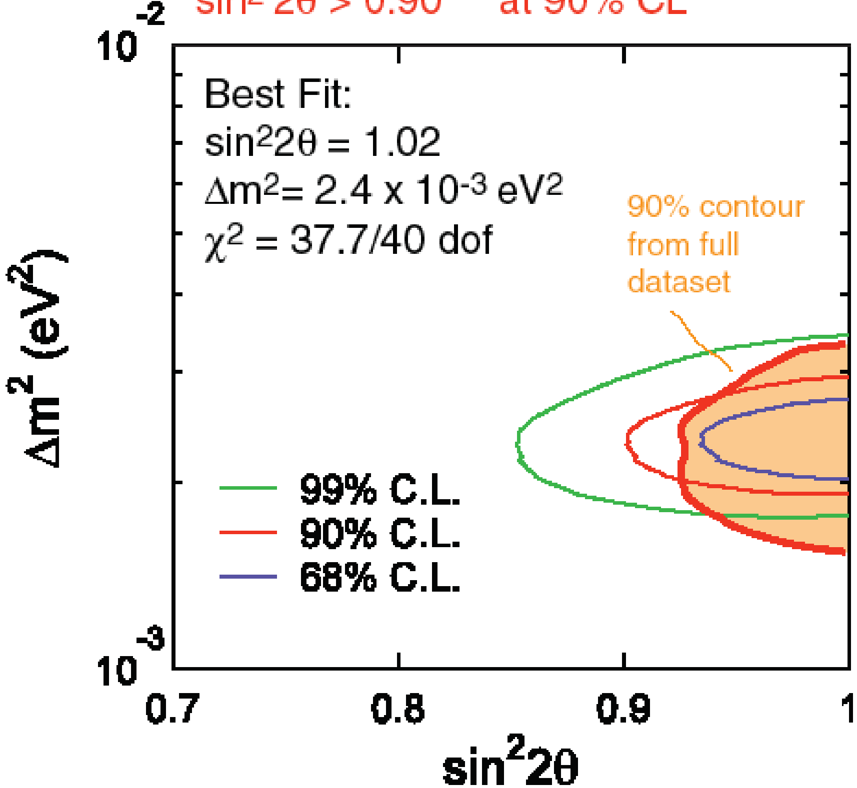


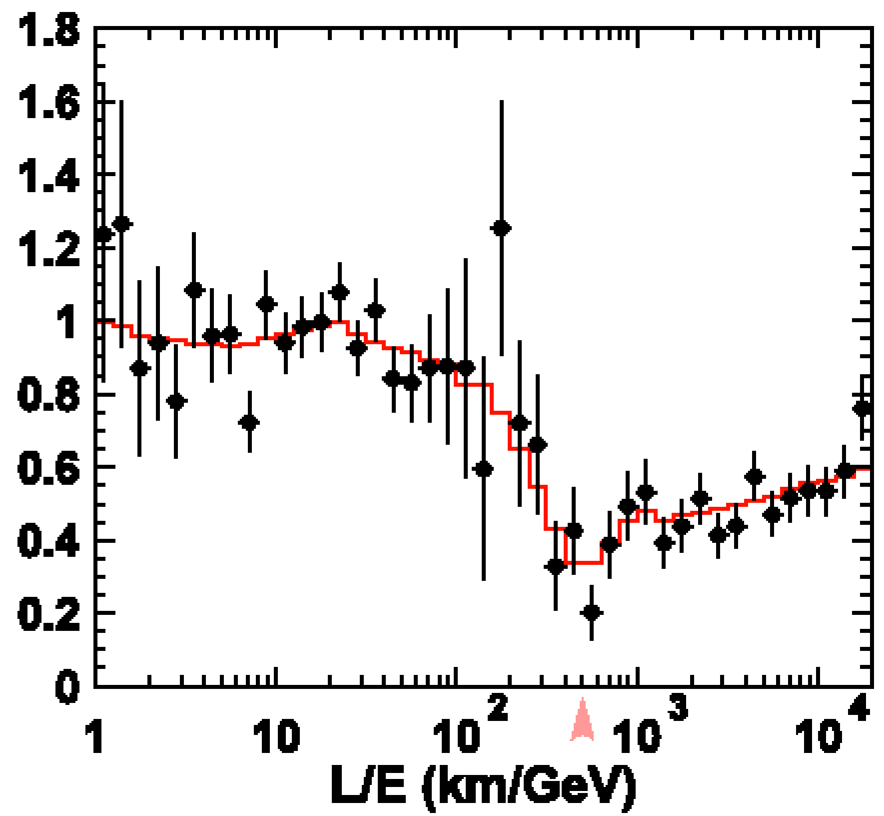
up down

Atmospheric Neutrinos

SuperKamiokande At

$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.0 \times 10^{-3}\ eV^2$
$\sin^2 2\theta > 0.90$ at 90% CL





Neutrino mass…

The simple fact that neutrinos transform during their flight from source to detector is a proof that they have mass.

Particle that has no mass cannot transform:

$\tau_{lab} = \gamma\, \tau_{particle} = E/m\, \tau_{particle}$ if $m \rightarrow 0 \Rightarrow \tau_{lab} \rightarrow \infty$!

neutrino definitions

the electron neutrino is present in association with an electron (e.g. beta decay)

the muon neutrino is present in association with a muon (pion decay)

the tau neutrino is present in association with a tau ($W \rightarrow \tau\nu$ decay)

these flavor-neutrinos are not (as we know now) quantum states of well defined mass (neutrino mixing)

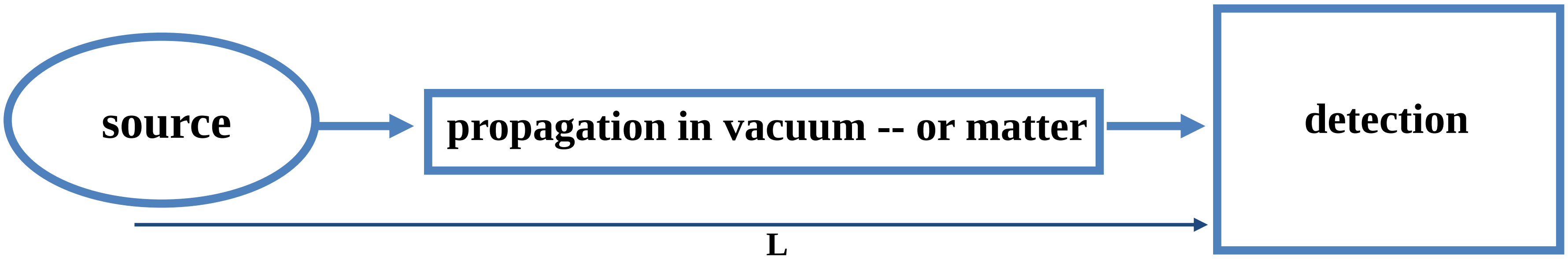
the mass-neutrino with the highest electron neutrino content is called ν_1

the mass-neutrino with the next-to-highest electron neutrino content is ν_2

the mass-neutrino with the smallest electron neutrino content is called ν_3

Neutrino Oscillations (Quantum Mechanics lesson 5)

since Pontecorvo)



weak interaction produces 'flavour' neutrinos

e.g. pion decay $\pi \rightarrow \mu\nu$

$|\nu_{\mu}> = \alpha\, |\nu_1> + \beta\, |\nu_2> + \gamma\, |\nu_3>$

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)> = \alpha\, |\nu_1> \exp(i E_1 t) + \beta\, |\nu_2> \exp(i E_2 t) + \gamma\, |\nu_3> \exp(i E_3 t)$$

t = proper time $\propto$ **L/E**

weak interaction: (CC)

$\nu_{\mu}\, N \rightarrow \mu^{-}\, X$

or $\nu_e\, N \rightarrow e^{-}\, X$

or $\nu_{\tau}\, N \rightarrow \tau^{-}\, X$

$$P(\nu_{\mu} \rightarrow \nu_e) = |<\nu_e|\nu(t)>|^2$$

α **is noted** $U_{1\mu}$

β **is noted** $U_{2\mu}$

γ **is noted** $U_{3\mu}$ **etc….**

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

Share this: 951

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

roupe
ersité de

Q | Terms

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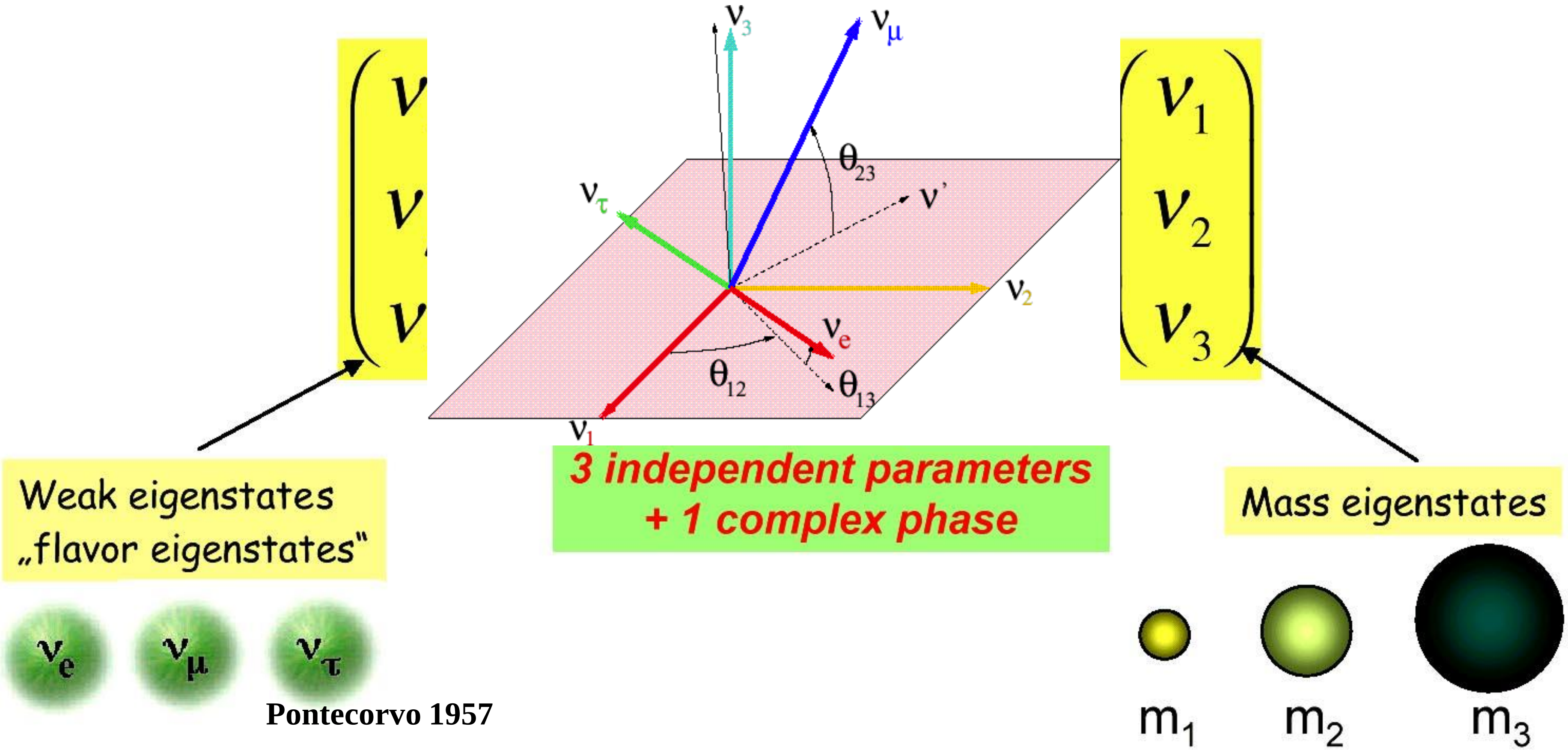
Lepton Sector Mixing

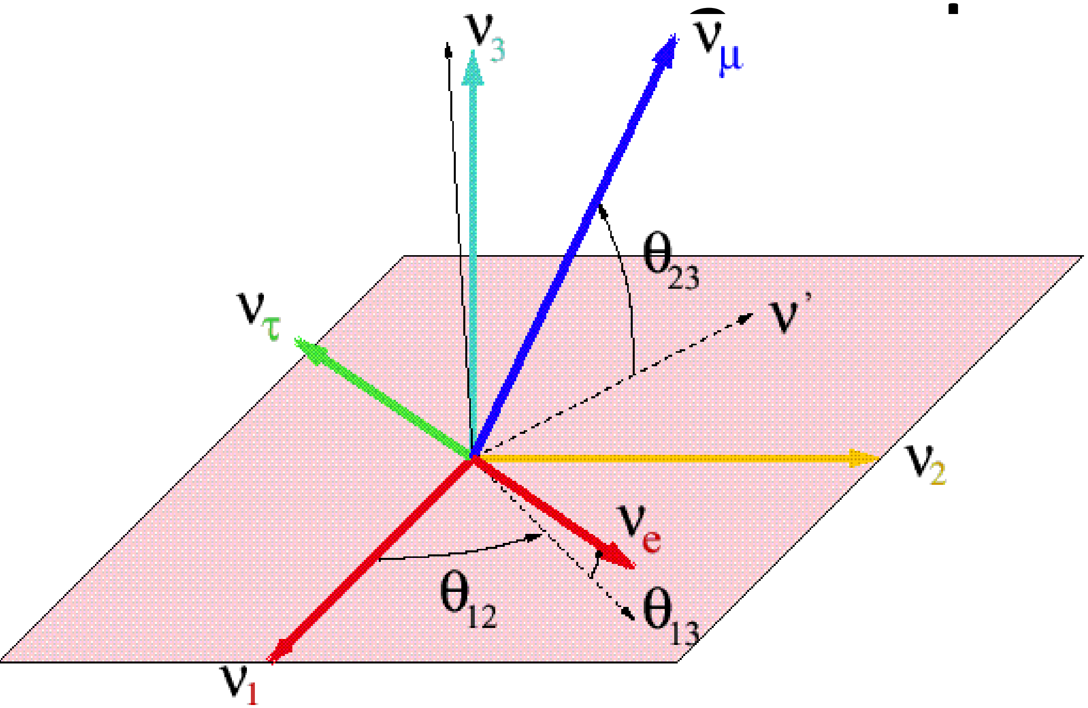
- If neutrinos are massive particles, then it is possible that the **mass eigenstates** and the **weak eigenstates** are not the same:

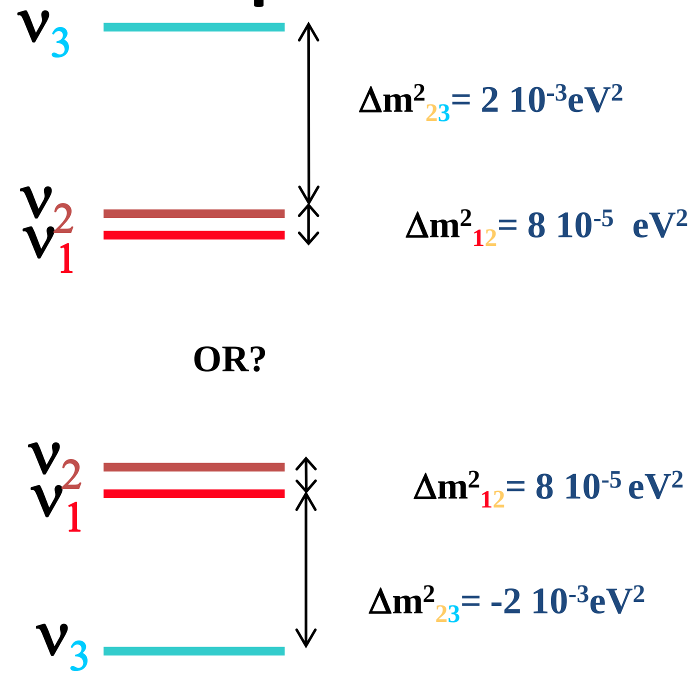


Pontecorvo 1957

The neutrino mixing matrix:

and a phase δ





$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known phase δ , sign of Δm^2_{23}

food for thought: (simple)

what result would one get if one measured the mass of a ν_e (in K-capture for instance)?

what result would one get if one measured the mass of a ν_μ (in pion decay) ?

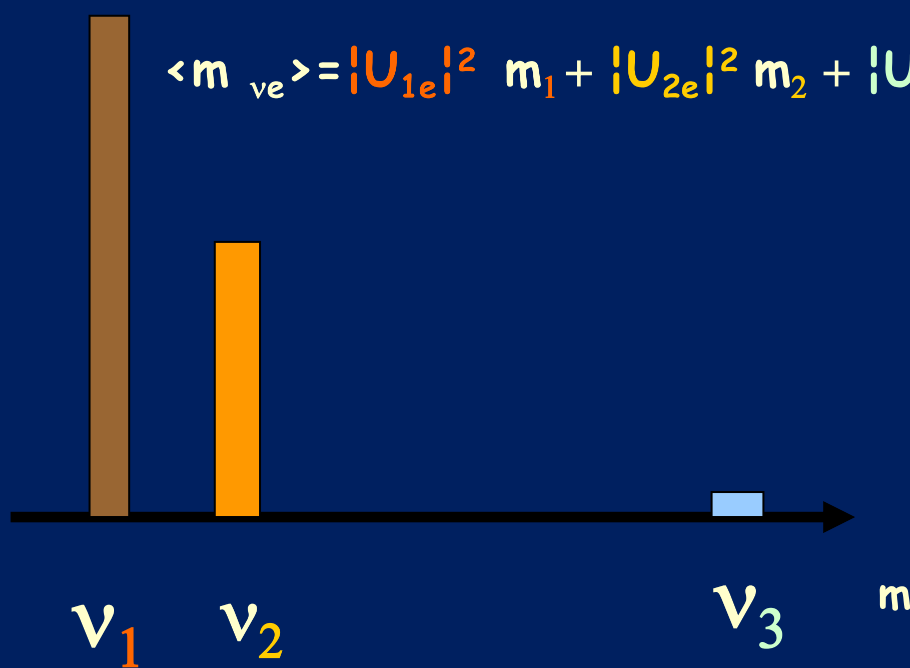
Is energy conserved when neutrinos oscillate?

ν_e

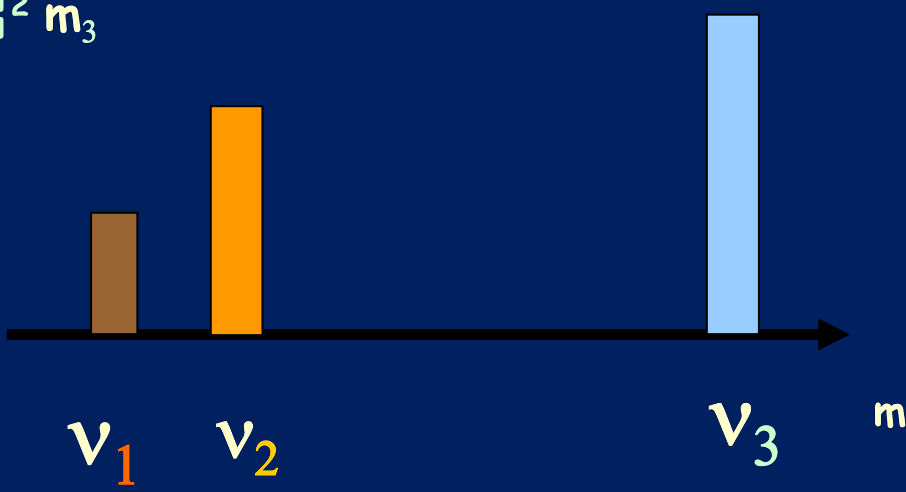
would measure a distribution with three values of mass with the following probabilities

$|U_{1e}|^2$ $|U_{2e}|^2$ $|U_{3e}|^2$

$$<m_{\nu e}> = |U_{1e}|^2 \, m_1 + |U_{2e}|^2 \, m_2 + |U_{3e}|^2 \, m_3$$



ν_μ



Is energy conserved when neutrinos oscillate?

Energy (i.e. mass) eigenstates propagate

$$|\nu(t)\rangle = U_{1e}|\nu_1\rangle \exp(i E_1 t) + U_{2e}|\nu_2\rangle \exp(i E_2 t) + U_{3e}|\nu_3\rangle \exp(i E_3 t)$$

$P(\nu_1) = |U_{1e}|^2$

$P(\nu_2) = |U_{2e}|^2$

$P(\nu_3) = |U_{3e}|^2$

are conserved during propagation

Why do neutrinos oscillate?

take $\pi \rightarrow \mu\nu$ decay $M=m_\pi$ $m_1= m_\mu$ $m_2=m_\nu$

muon momentum:

$$\frac{p}{c} = \frac{M^2 - m_1^2 - m_2^2}{2M}$$

variation of muon momentum upon neutrino mass and mass differences

$$\frac{\delta p_\mu}{c} = \left(\frac{p_\mu}{c}\right)_{m_\nu=0} - \left(\frac{p_\mu}{c}\right)_{m_\nu=m_0} \quad , \quad \frac{\delta' p_\mu}{c} = \left(\frac{p_\mu}{c}\right)_{m_\nu=m_0} - \left(\frac{p_\mu}{c}\right)_{m_\nu=m_0'}$$

$$\frac{\delta p_\mu}{c} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} - \frac{m_\pi^2 - m_\mu^2 - m_0^2}{2m_\pi} = \frac{m_0^2}{2m_\pi}$$

$$1.4 \times 10^{-14}\ \mathrm{MeV/c}$$

for $m_\nu = 2\mathrm{eV}/c^2$

$$\frac{\delta' p_\mu}{c} = \frac{m_\pi^2 - m_\mu^2 - m_0^2}{2m_\pi} - \frac{m_\pi^2 - m_\mu^2 - m_0'^{\,2}}{2m_\pi} = -\frac{\Delta m^2}{2m_\pi}$$

$$8.9 \times 10^{-18}\ \mathrm{MeV/c}$$

for $\Delta m^2_\nu = 2\ 10^{-3} (\mathrm{eV}/c^2)^2$

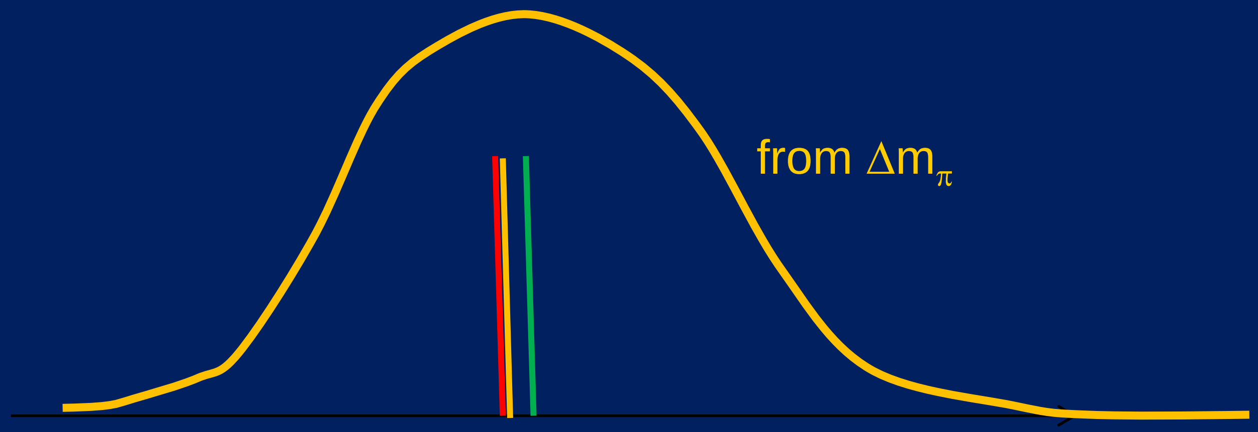
However we need to take into account the width of the pion since it decays with a life time of 26ns or $c\tau$=7.8m (hbar.c = 200 MeV.fm)

Δm_π = hbar/τ ~4 10^{-14} MeV/c^2 ➔ Δp_μ ~ 3 10^{-14} MeV/c

➔ the uncertainty due to the pion decay width is much larger than the difference in momentum between the neutrino mass eigenstates.

This is the same relationship that ensures that interference happens between light coming from different holes. (can't tell which hole the light went through)

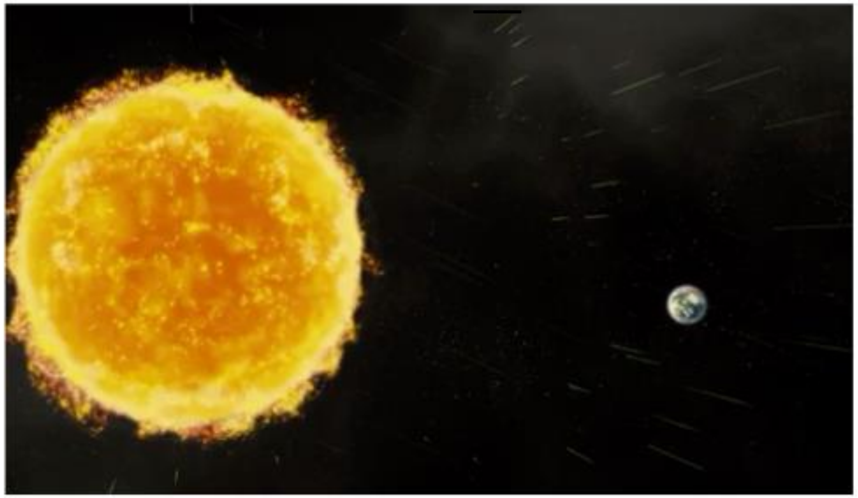
Neutrinos oscillate for the fundamental quantum reason that the width of the decaying parent makes it impossible to tell the neutrino mass by measuring its mass from kinematics.



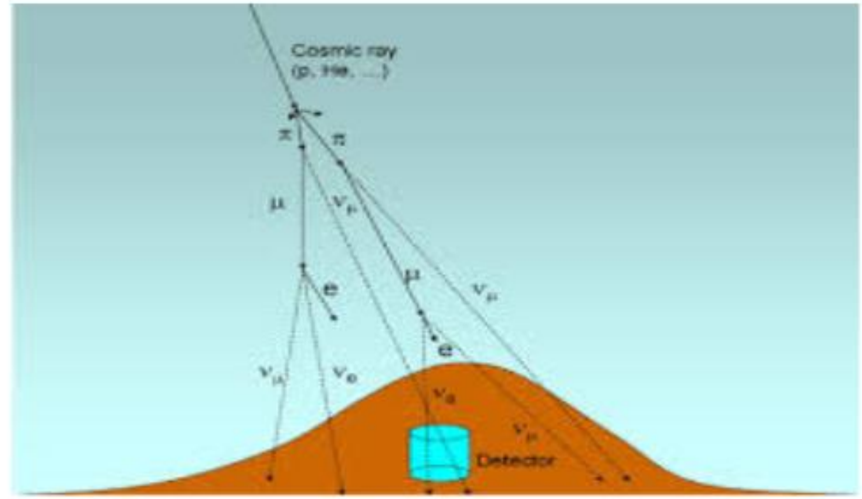
much amplified: the central value of $p_\mu(\nu 1)$, $p_\mu(\nu 2)$, $p_\mu(\nu 3)$ distribution

Neutrino oscillations

Solar sector: θ_{12}, θ_{13}, Δm^2_{21}

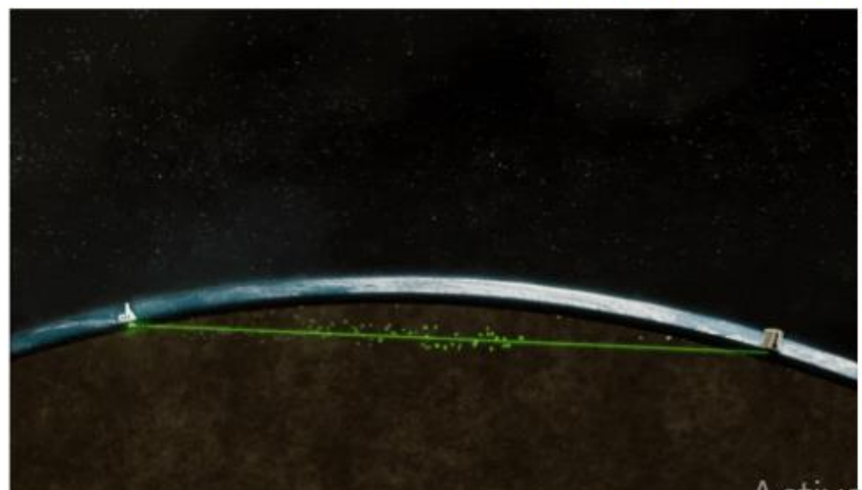


Atmospheric sector: $2\theta_{23}$, θ_{13}, $\pm\Delta m^2_{31}$, δ

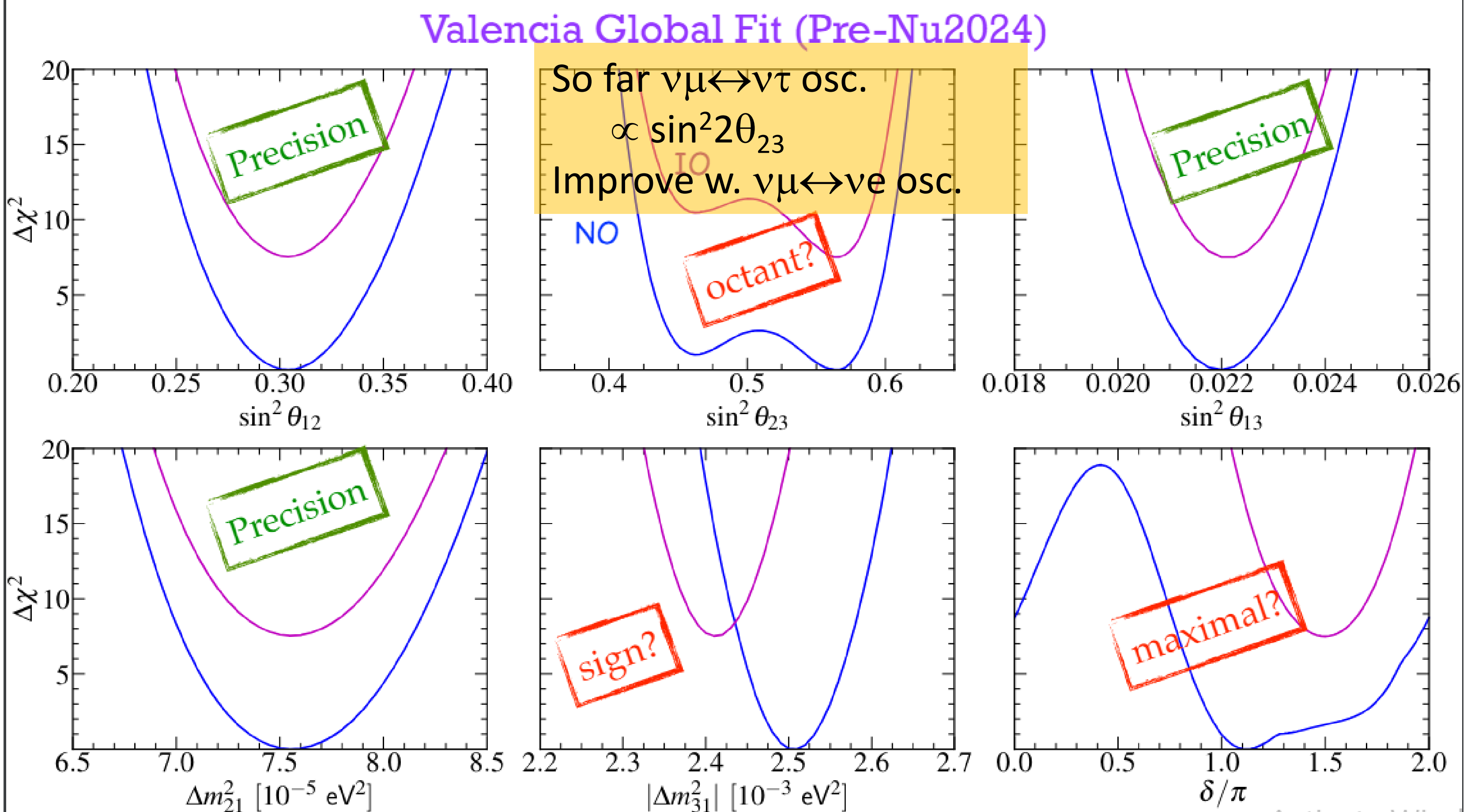


Reactor sector: θ_{13}, Δm^2_{31}

Accelerator sector: $2\theta_{23}$, θ_{13}, $\pm\Delta m^2_{31}$, δ



Global fit to ν oscillation parameters



SSM HZ model - MB22m

with SK atmospheric

$\Delta\chi^2$(IO-NO) = 7.5

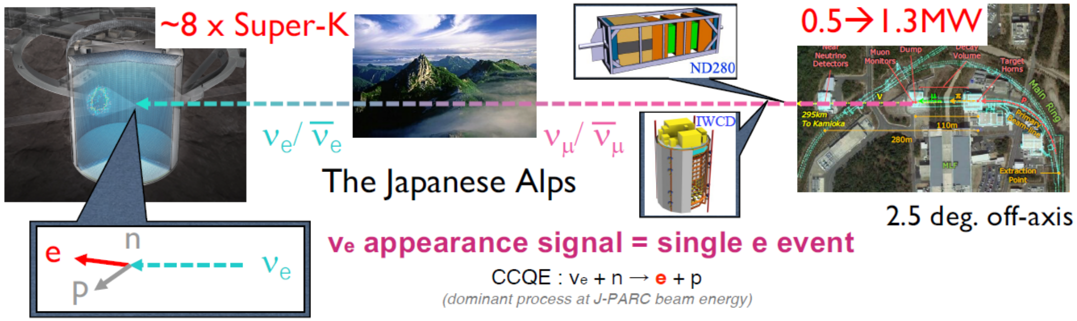
Activate Wind
Go to Settings to a

No conclusion yet concerning the mass ordering or the T (CP) violation! So wanted

HyperKamiokande water Cherenkov detector

T2K beam with upgrade to 1.3MW (presently 800KW running)
Upgraded near detector (angular coverage) and (later) new off axis WC
And a formidable 180kton fid. far detector (SK x 8) **beam in 2027/8**

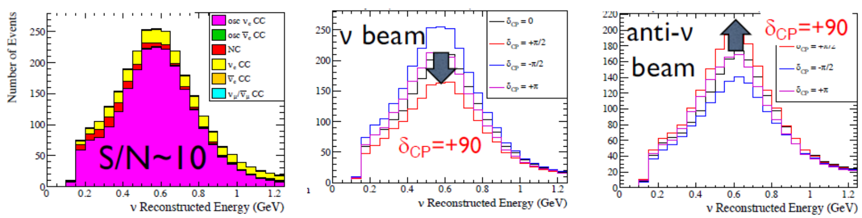
J-PARC off-axis ν_μ & $\overline{\nu}_\mu$ beam (~0.6 GeV, ~295 km)



ν_e appearance signal = single e event

CCQE : $\nu_e + n \rightarrow e + p$

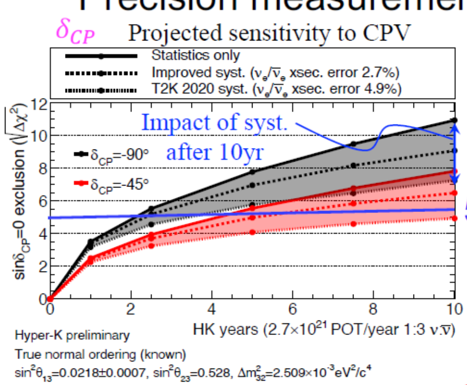
(dominant process at J-PARC beam energy)

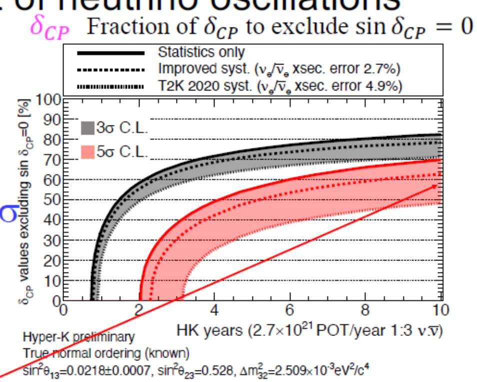


Relatively Small matter Effect & Large CPV Effect

HK 10 yr, 2.7×10^{22} POT 1:3 ν:$\overline{\nu}$, 1-ring e-like + 0 decay e, > 1000 events each

Precision measurement of neutrino oscillations





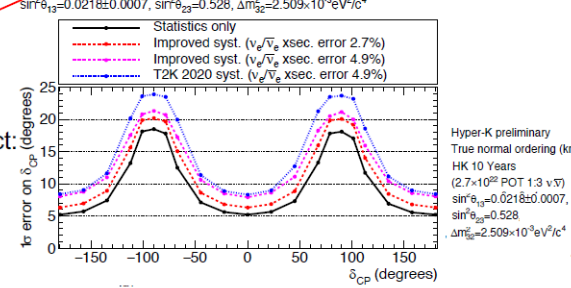
Discovery of CP violation at >5 σ for >60% of δ_{CP}

1σ resolution of δ_{CP} in 10 yrs

~20° for $\delta_{cp} = -90°$ / ~6° for $\delta_{cp} = 0°$

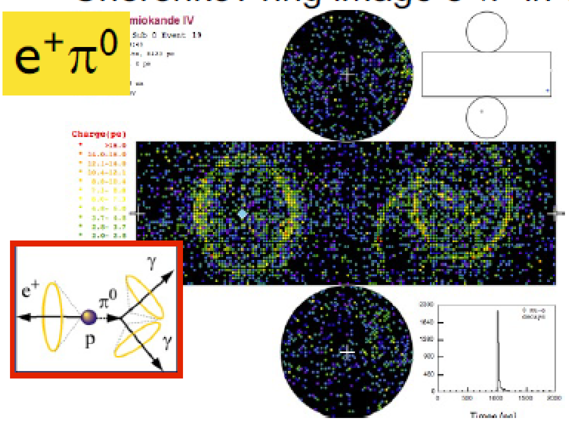
Reduction of systematic uncertainty has sizable impact:

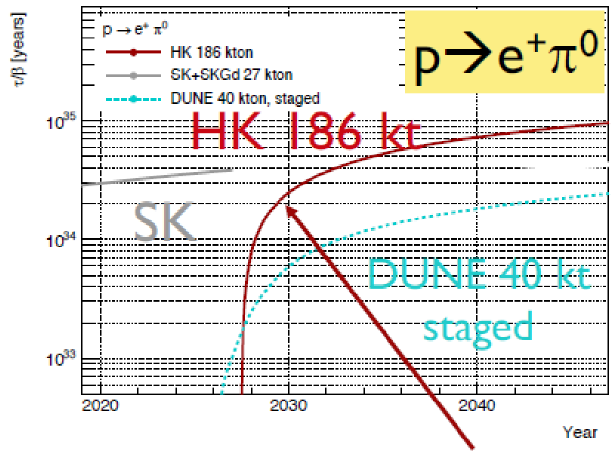
- Upgrade of ND280 + ~600 ton Intermediate Water Cherenkov detector (IWCD)
- Aim to suppress detector error below 1%

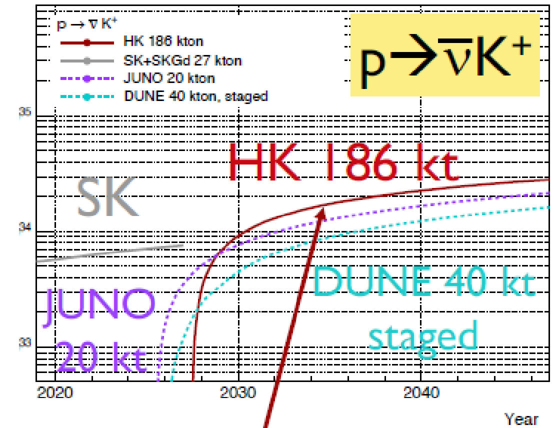


Proton decay searches (note: FV ~8 x Super-K)

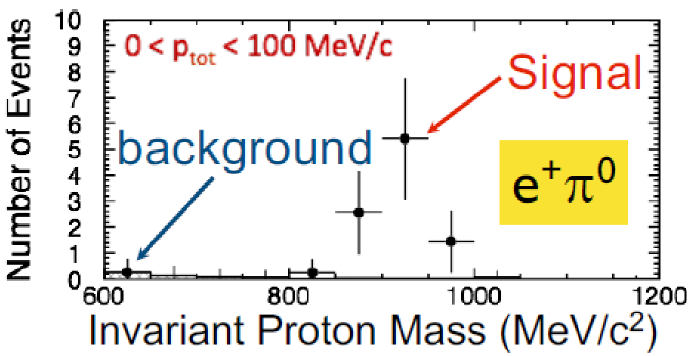
Cherenkov ring image $e^+\pi^0$ in SK







Hyper-K 10 years operation assuming Tproton=1.7×10^{34} years (~Super-K limit)



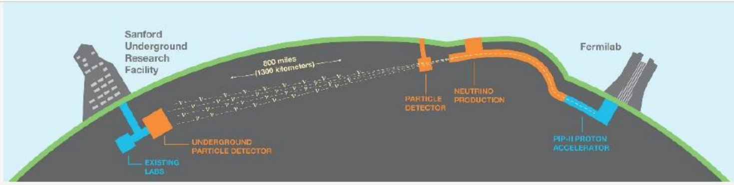
3σ discovery potential

HK 10 years

- $p\rightarrow e^+\pi^0$: ~6×10^{34} yrs
- $p\rightarrow \nu K^+$: ~2×10^{34} yrs
- …

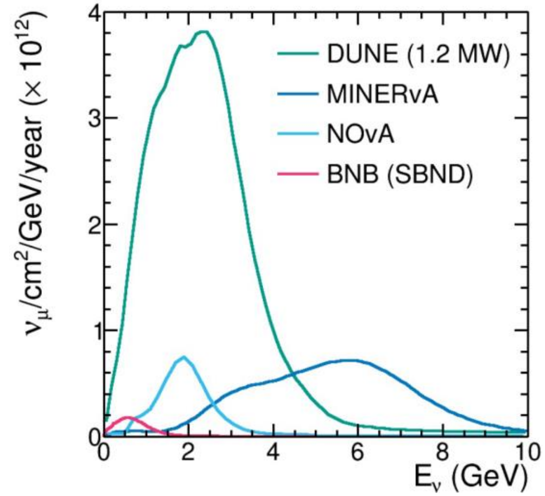
Hyper-K will play a leading role in the next-generation proton decay search

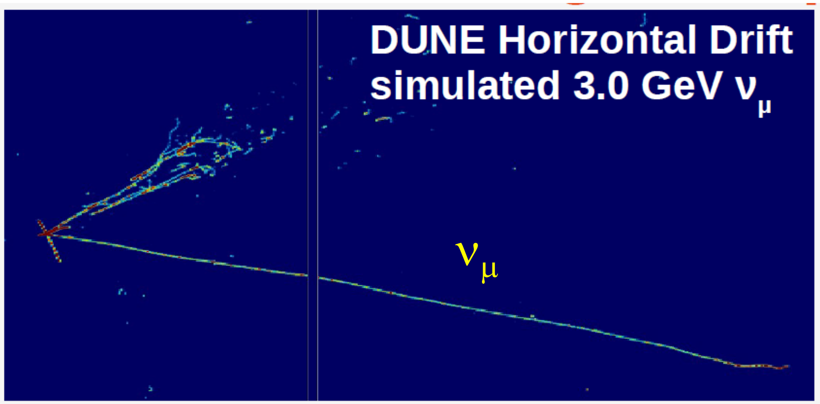
Activate Windows

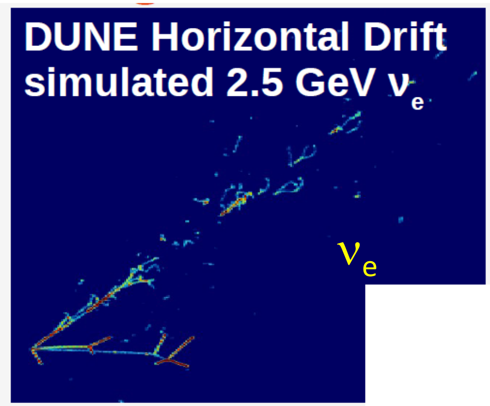


- Wideband (anti)neutrino beamline with >2MW intensity
- Underground, modular LArTPC Far Detector with ≥40 kt fiducial mass
- Movable LArTPC Near Detector with muon spectrometer and separate on-axis detector
- Global collaboration of >1400 scientists and engineers

5 DUNE - Neutrino24 - Chris Marshall



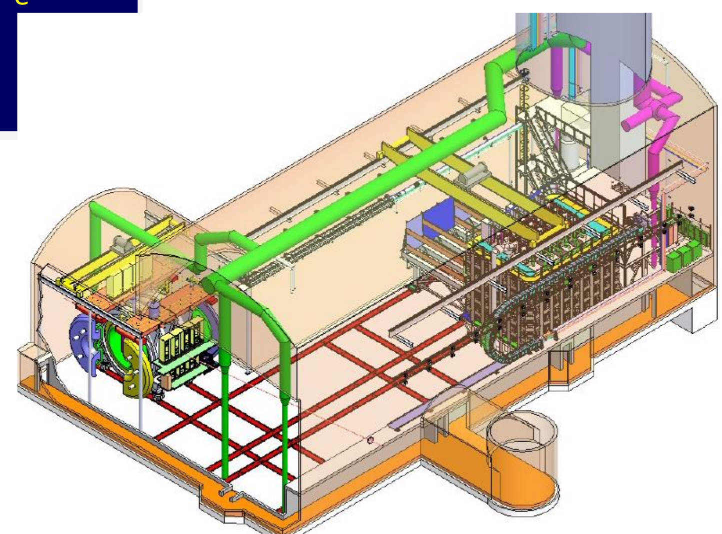


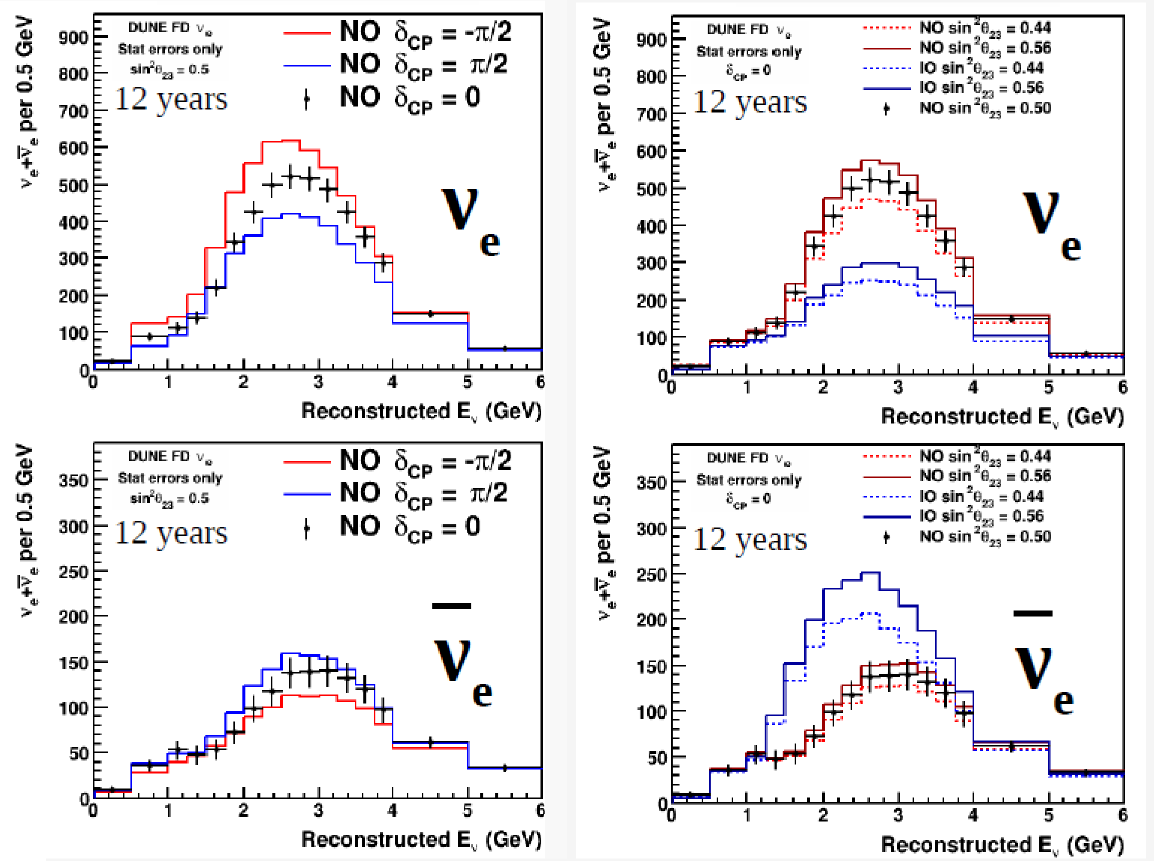


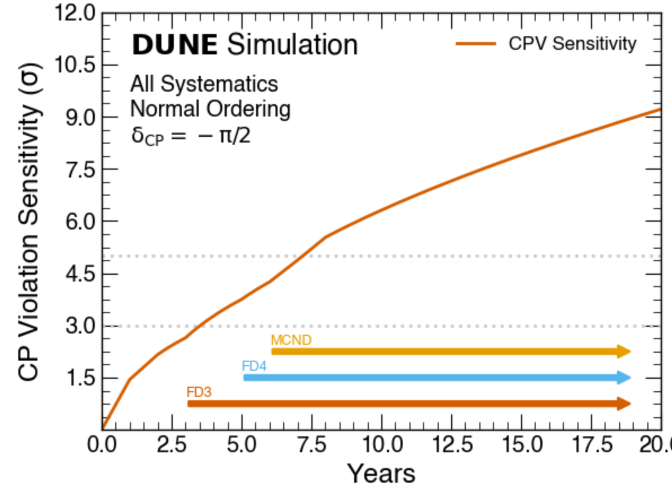
Near detector includes On and off axis var. angle Detectors.

Far site excavation is complete

- Building & Site Infrastructure work mid-2025
- Far Detector installation in 2026-27
- Physics in 2028/early 2029
- Beam physics with Near Detector + 2 far modules: 2031







Time 0 = 2031

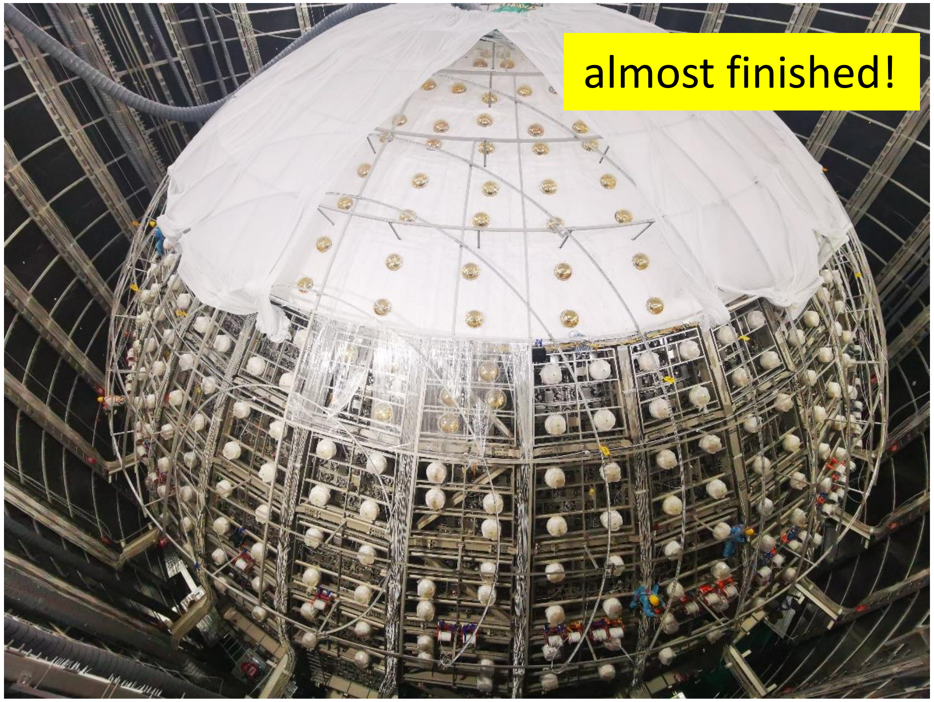
5sigma for δ_{CP}=-pi/2

After 8yrs w. 4 detectors

- If δ_{CP} ~ -π/2, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- If the mass ordering is normal, DUNE will measure a *much larger* enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape → additional handle on resolving degeneracies
- If new physics is present, there may be no combination of MO, δ_{CP}, and θ_{23} that fits data

JUNO : a high precision program

Proposed 2008 (PRD78:111103,2008; PRD79:073007,2009**)**
53km from 2 nuclear reactors. Far (JUNO) and near (JUNO-Tao) detectors
20 kton LS, 3% energy resolution, 700 m underground
Approved in 2013 Construction in 2015-2024 (2025 conferences!)



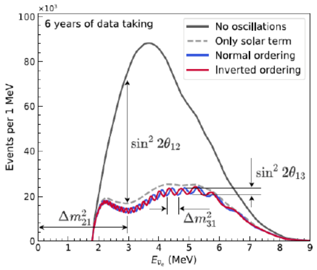
reactor (anti-neutrino)+
solar, supernova, atmospheric,
geo-neutrinos, proton decay,
exotic searches

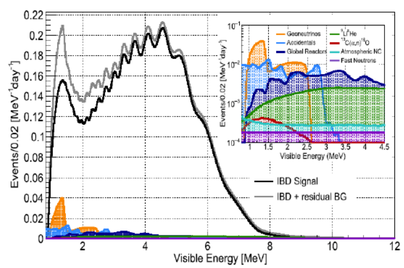
Precision Measurement of oscillation parameters

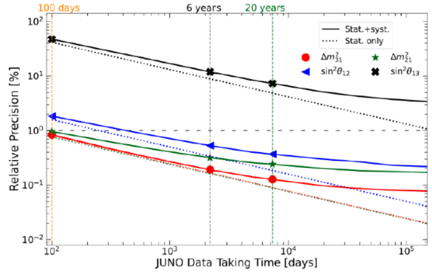
$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

ID#223, Precision Measurement

Chin. Phys. C46 (2022) 12, 123001







	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

$\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$, leading measurements in 100 days; precision <0.5% in 6 years

JUNO will make legacy measurements on solar sector and $\sin^2\theta_{13}$

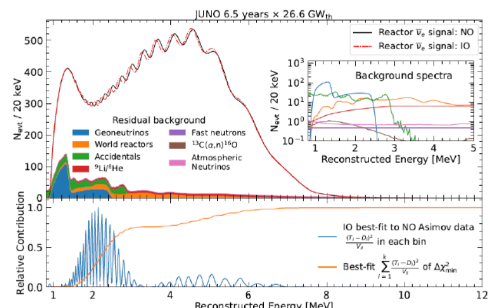
AND

determine the mass hierarchy from the phase of the oscillation!

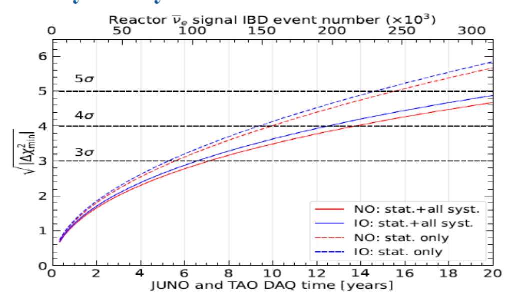
Neutrino Mass Ordering

ID#506, NMO sensitivity

ID#335, IBD selection



Sensitivity mostly from 1.5-3 MeV



arXiv:2405.18008 (2024)

	Design	Now
Thermal Power	36 GW$_{th}$	26.6 GW$_{th}$ (26%↓)
Signal rate	60 /day	47.1 /day (22%↓)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (11%↑)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (2%↑)
Shape uncertainty	1%	JUNO+TAO
3σ NMO sens. Exposure	<6 yrs × 35.8 GW$_{th}$	~6 yrs × 26.6 GW$_{th}$

- **JUNO NMO median sensitivity: 3σ (reactors only) @ ~6 yrs * 26.6 GW$_{th}$ exposure**
- **Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity (see next page→)**

Neutrino mass…

The simple fact that neutrinos transform during their flight from source to detector is a proof that they have mass.

Particle that has no mass cannot transform:

$\tau_{lab} = \gamma\, \tau_{particle} = E/m\, \tau_{particle}$ if $m \rightarrow 0 \Rightarrow \tau_{lab} \rightarrow \infty$!

Neutrino oscillations are sensitive to mass differences Δm_{ij}^2

$$P_\mu(|\nu_e(t)\rangle) = \sin^2 2\theta \sin^2(1.27\Delta m_{12}^2 L/E)$$

How can one detect the neutrino mass itself?

There are presently 4 different methods:

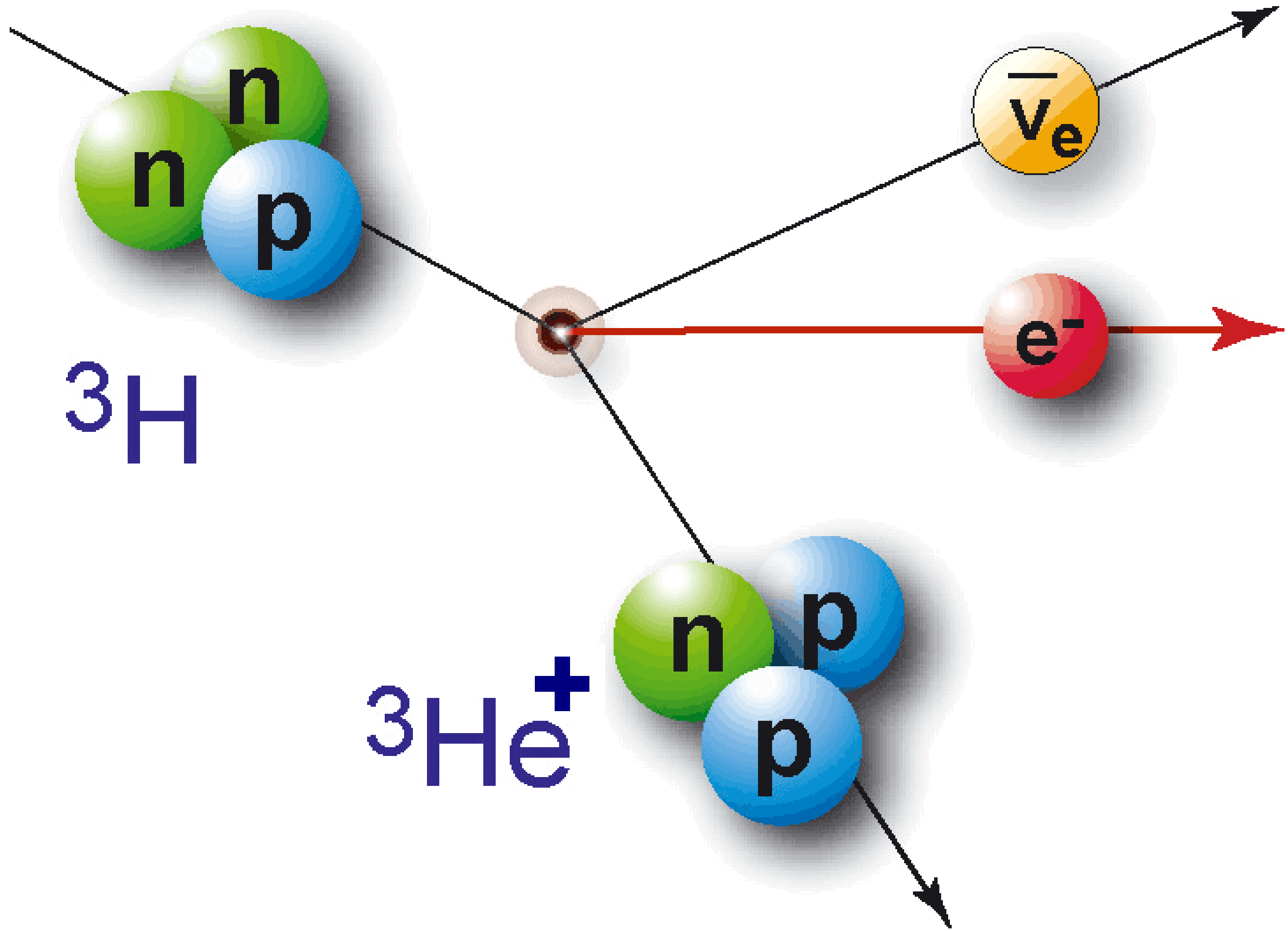
-- kinematic method (the most direct and most difficult)

-- effect of neutrino mass on the early universe

-- neutrinoless double beta decay

-- detect directly the heavy right-handed neutrinos

Electron antineutrino mass measurement in tritium β decay



What is measured

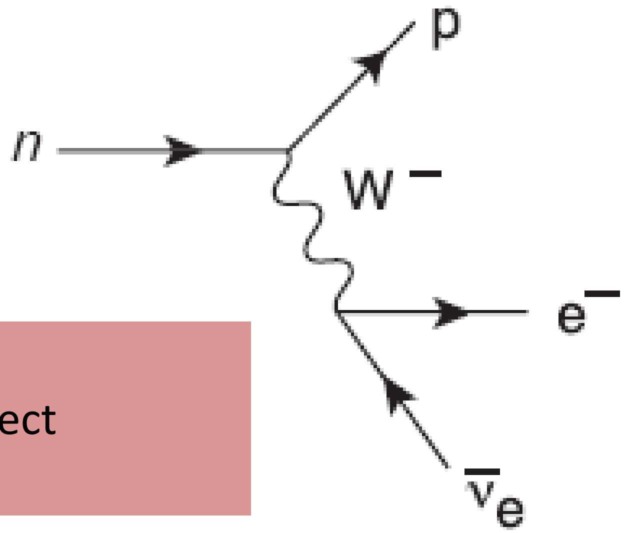
e- spectrum in β decay

$$(\mathrm{Z},\mathrm{A}) \rightarrow (\mathrm{Z}+1,\mathrm{A})^{+} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

The only variable measured is electrons kinetic energy

The goal of the measurement is to determine a value for the mass of the electron antineutrino

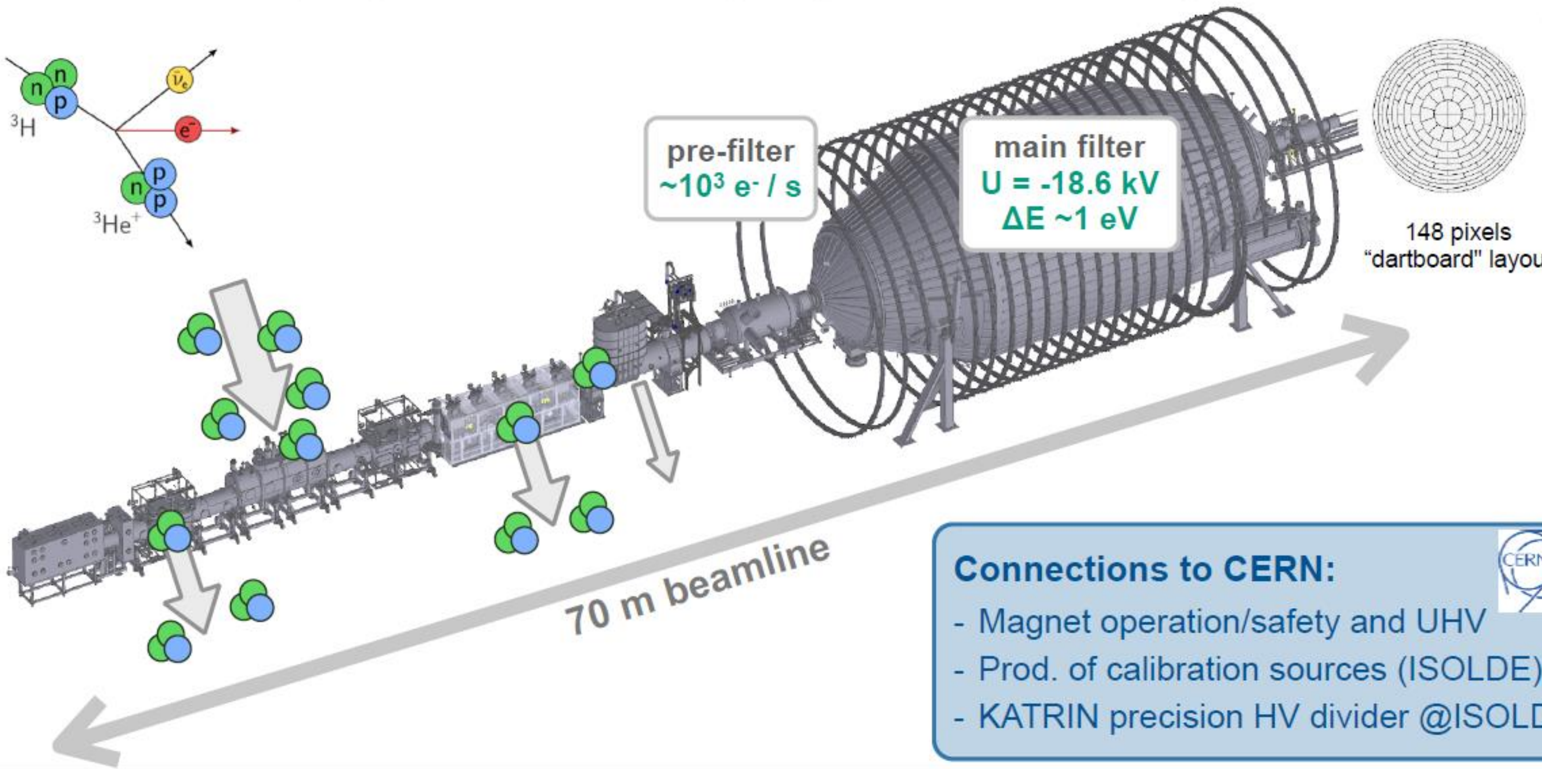
$$m^2(\nu_{\mathrm{e}}) = \sum_{\mathrm{i}} |U_{\mathrm{ei}}|^2 \cdot m^2(\nu_{\mathrm{i}})$$



Tritium is chosen for very small Q-value
➔small electron energy, relatively larger effect
Also practical questions e.g. lowest dE/dx

Working principle of KATRIN

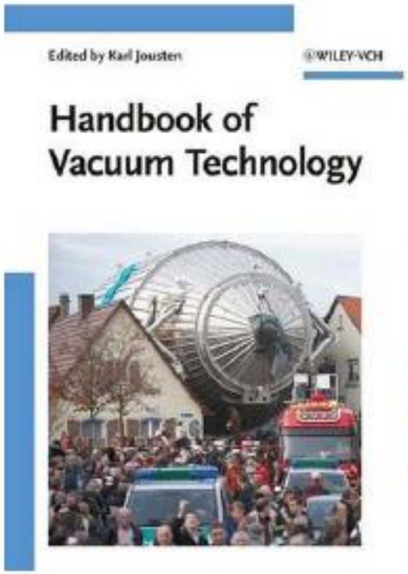
windowless gaseous T_2 source	tritium pumping & e^- transport	high-pass energy filters	counting detector
10^{11} e^- / s	T_2 flow reduction $>10^{14}$	MAC-E filter	< 1 e^- / s



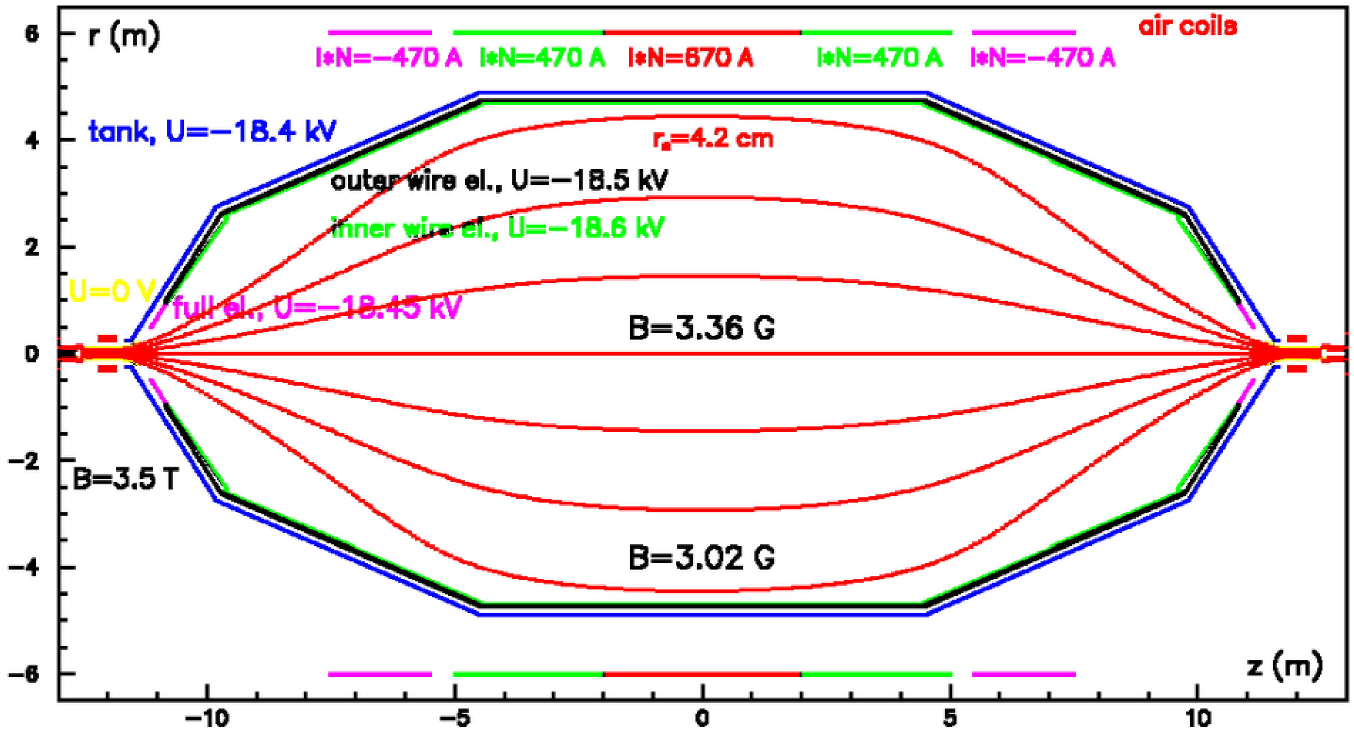
Connections to CERN:
- Magnet operation/safety and UHV
- Prod. of calibration sources (ISOLDE)
- KATRIN precision HV divider @ISOLDE

Physics run in 2019-2025!

spectrometer - transport



Oct. – Nov. 2006:
8800 km sea-going voyage from Deggendorf-FZK

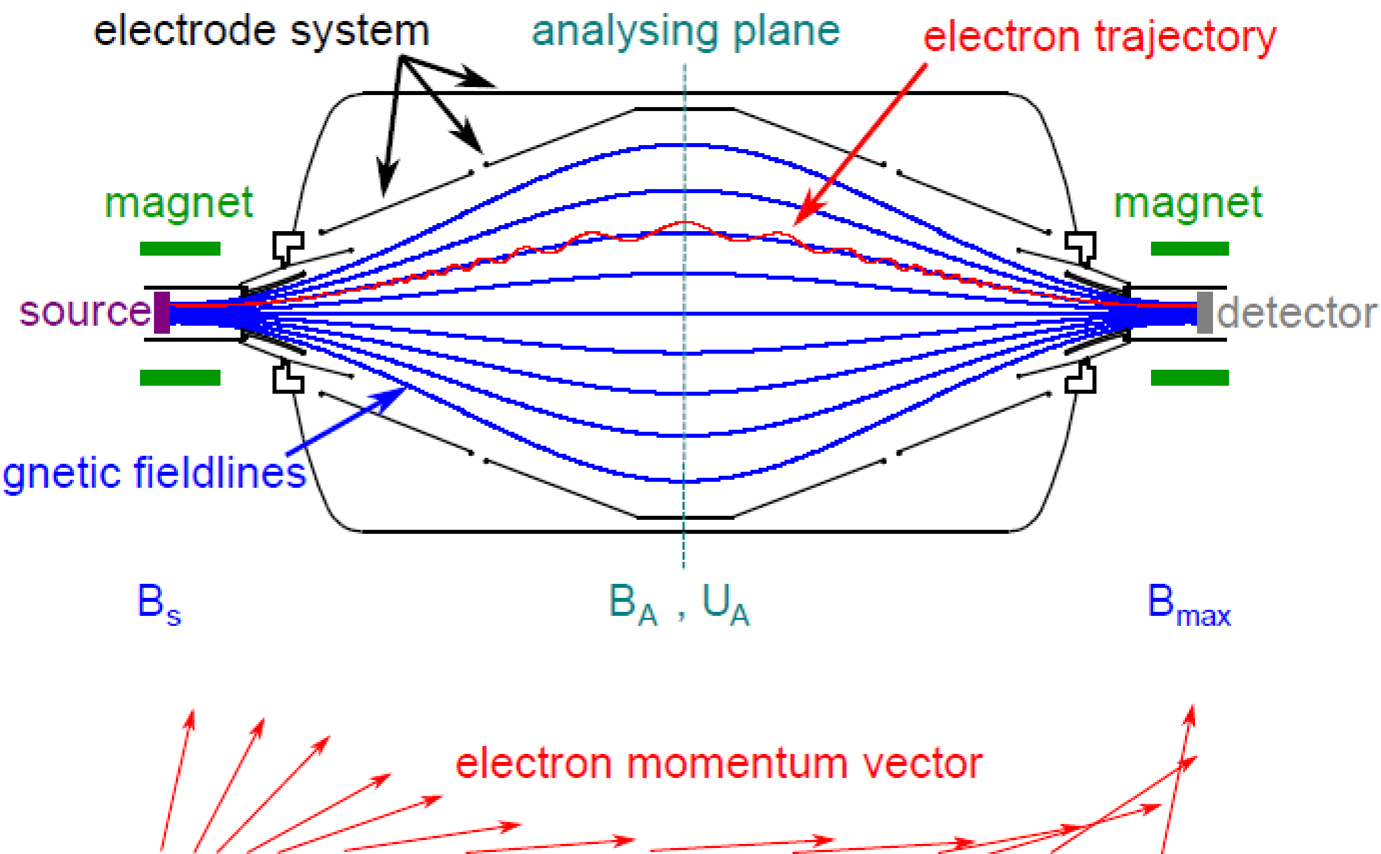


: Electromagnetic design of the KATRIN main spectrometer with two-layer wire electrodes

Take electrons of any momentum orientation in high B-field (B = 3.5 T)
and make the adiabatic transformation to longitudinal momentum
in very small B-field (B_{min} = 3.36 G) (1T = 10'000 G)
Conservation of angular momentum
L = P_T.R with R= P_T/0.3B ➔ L= $P_T^{\,2}$/0.3B =Cte ➔ P_T scales as 1/sqrt(B)

Magnetic Adiabatic Collimation & Electrostatic filter

- Align electrons along electrostatic field
- Select all signal electrons with $E > qU_A \left(1 + \frac{B_A}{B_{max}}\right)$



Preprint → https://www.katrin.kit.edu/130.php#Anker0

Conclusion and Outlook

New KATRIN release improves direct neutrino-mass bound by a factor of 2:

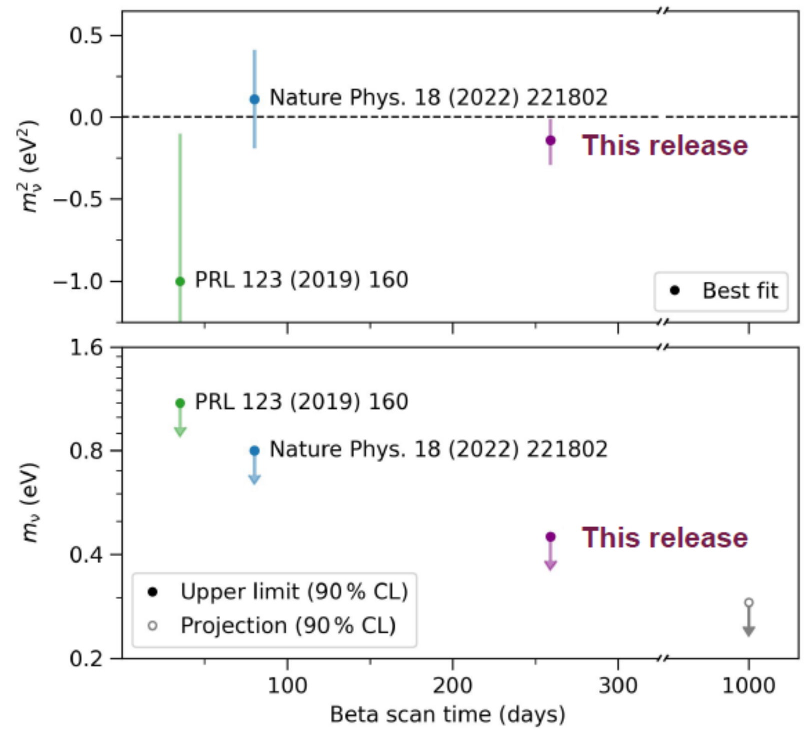
$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

Ongoing analysis:

- 70 % of total anticipated data recorded, improvements in systematics
- Several BSM physics searches: eV-sterile, exotic interactions, light bosons, relic ν… ⇒ stay tuned!

Ongoing data taking through **2025** → **Σ 1000 days**

- target sensitivity below 0.3 eV

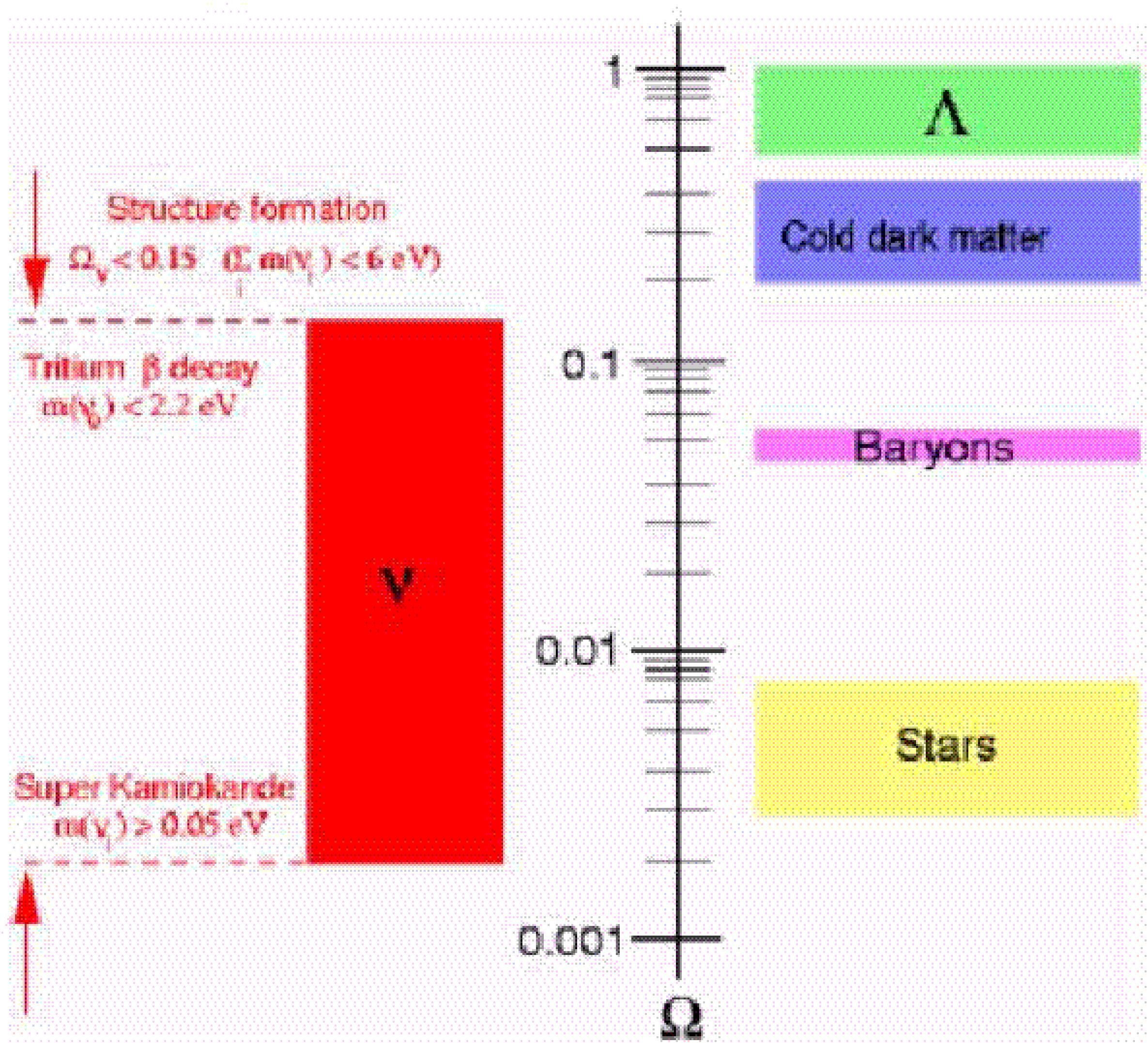


Alexey Lokhov, Neutrino 2024 agenda.infn.it/event/37867/

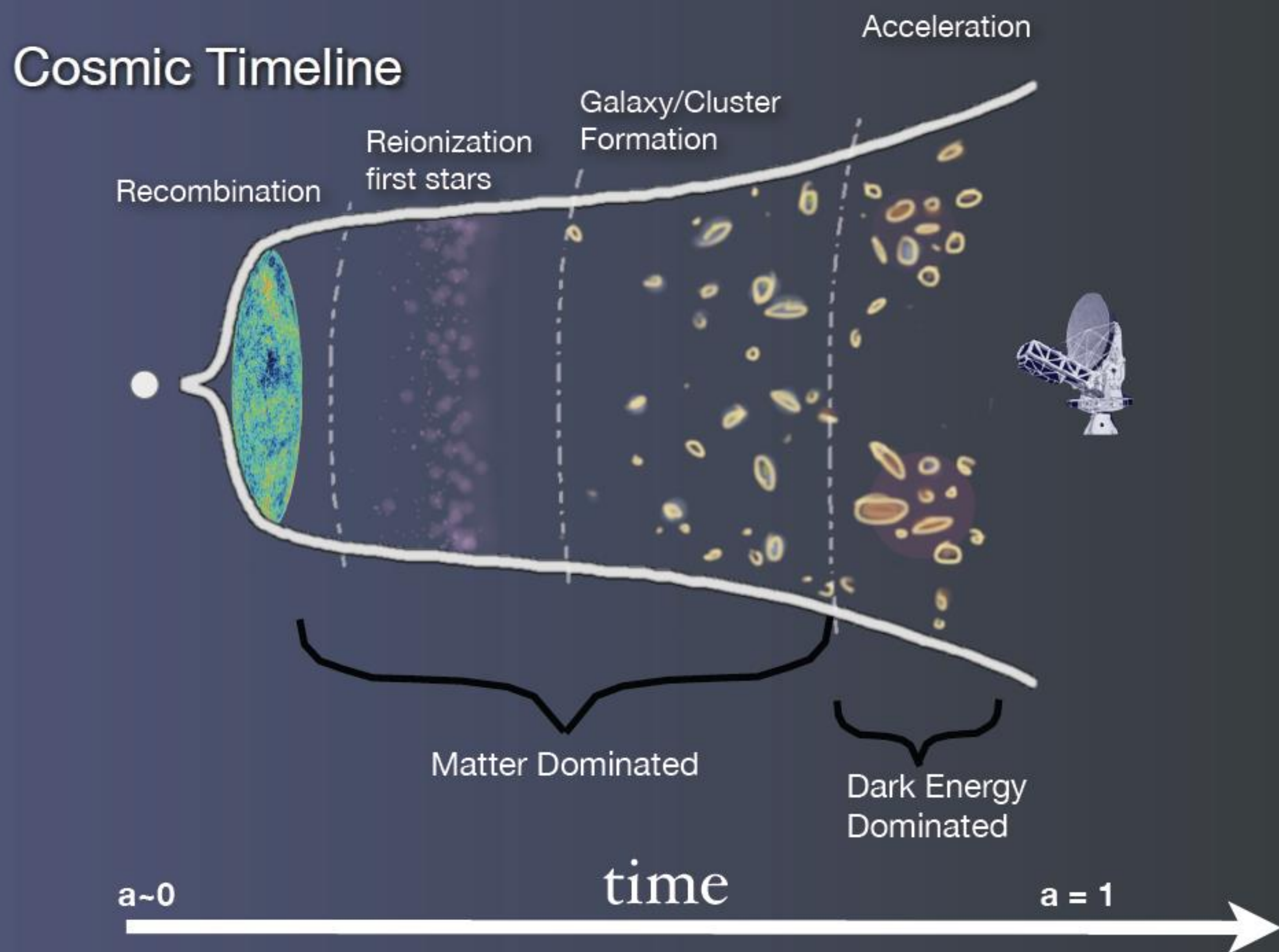
Δm^2=2.5 10^{-3} eV^2 ➔ m(heaviest) > 0.05 eV

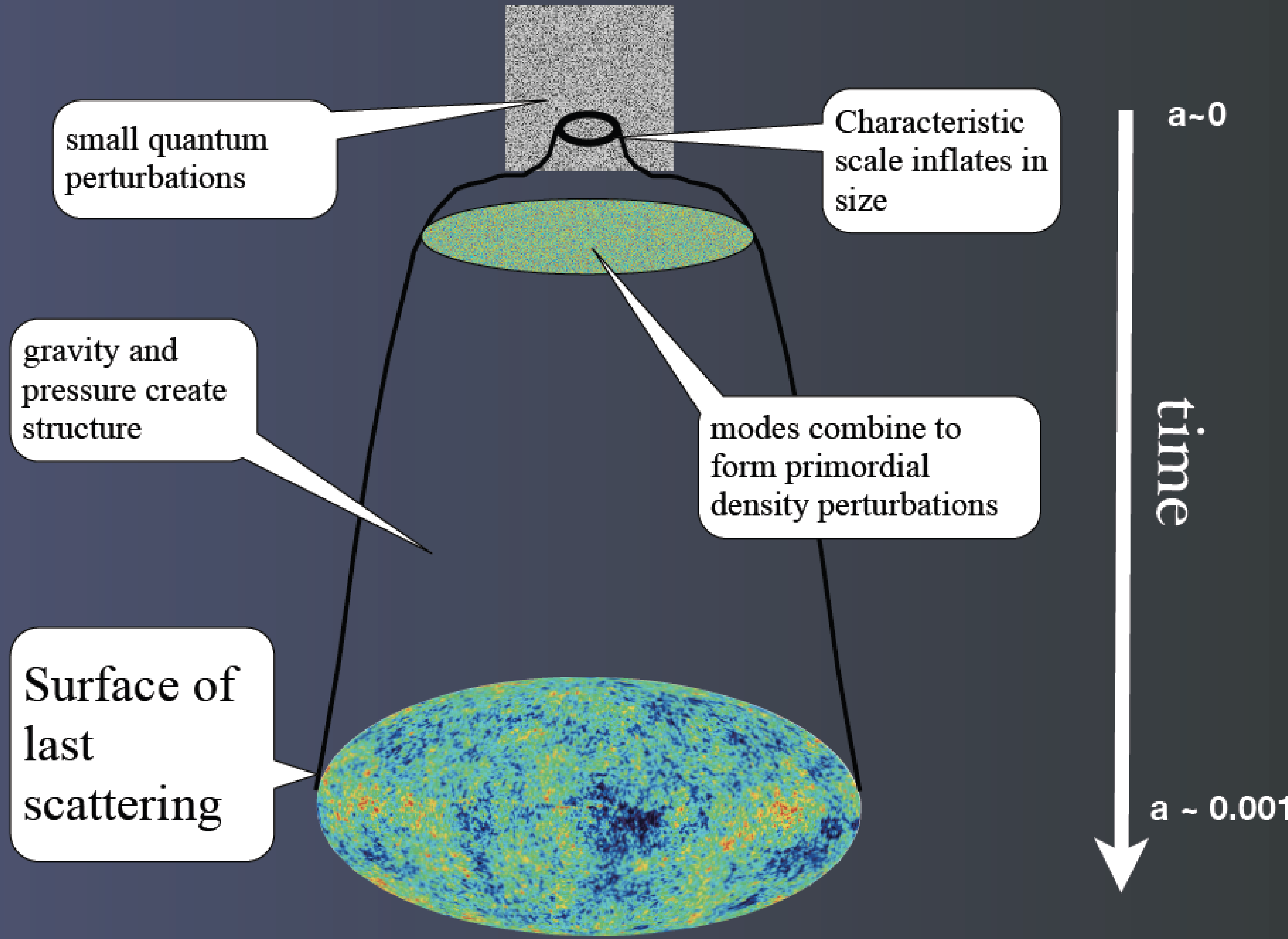
What IS the neutrino mass?????

Cosmology and neutrino mass



There is a long way to go to match direct measurements of neutrino masses with oscillation results and cosmological constraints


Cosmic Timeline
Acceleration
Galaxy/Cluster
Formation
Reionization
first stars
Recombination
Matter Dominated
Dark Energy
Dominated
time
a~0
a = 1



small quantum perturbations
Characteristic scale inflates in size
a~0
gravity and pressure create structure
modes combine to form primordial density perturbations
time
Surface of last scattering
a ~ 0.001

Direct exploration of the Big Bang -- Cosmology

measurements of the large scale structure of the universe
using a variety of techniques

-- Cosmic Microwave Background
-- observations of red shifts of distant galaxies with a variety of candles.
Big news in 2002 : Dark Energy or cosmological constant

→large scale structure in space, time and velocity
is determined by early universe fluctuations, thus by mechanisms of energy release
(neutrinos or other hot dark matter)

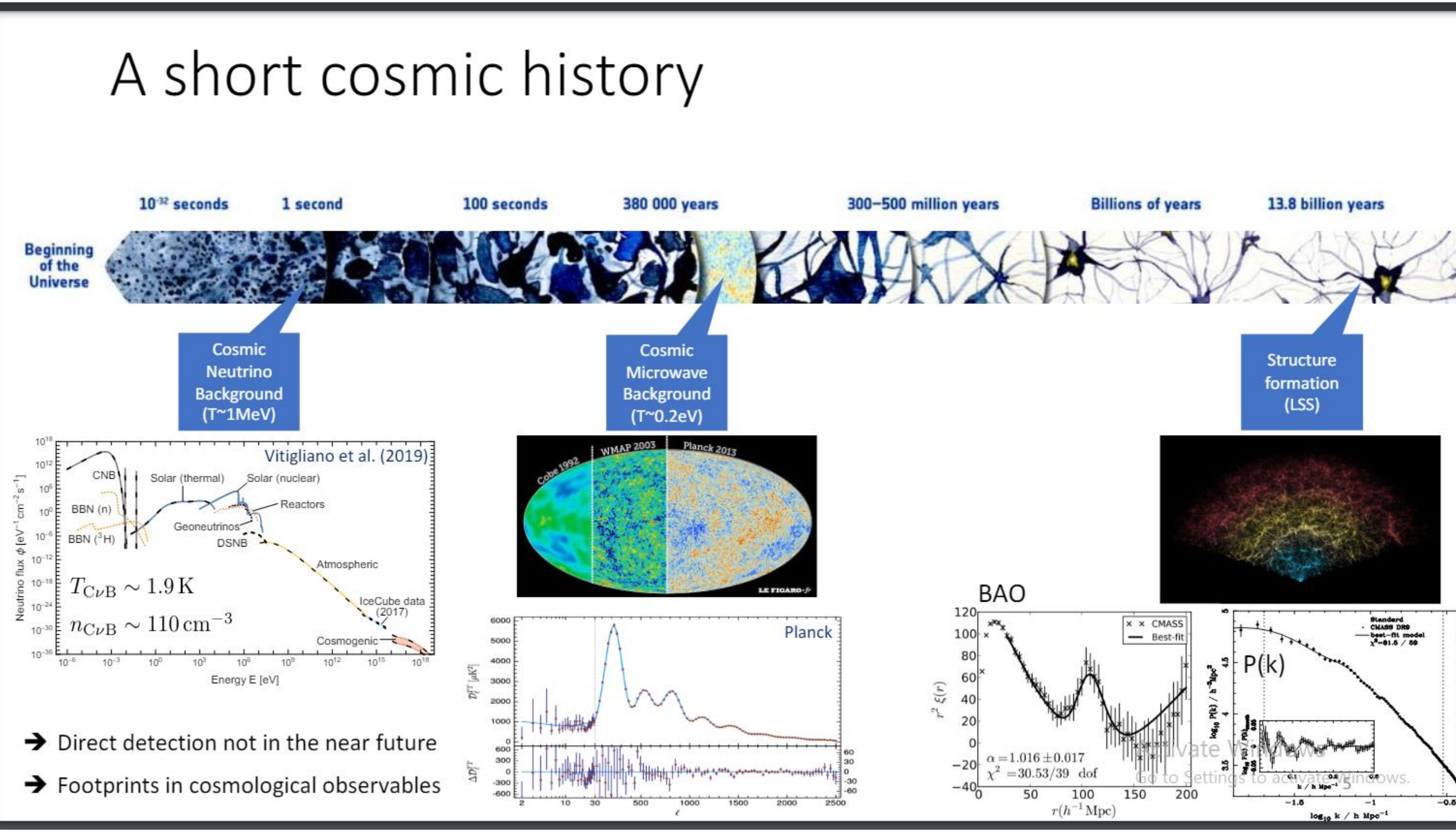
The early universe is sensitive to neutrinos which are carriers of fast, weakly interacting, kinetic energy.

Number of neutrino (or neutrino-like) degrees of freedom

controls the size of the effects

Mass of neutrinos

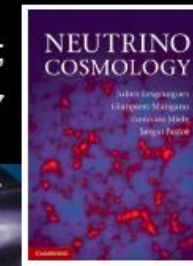
controls the velocity of neutrinos and the energy at which they stop being relevant

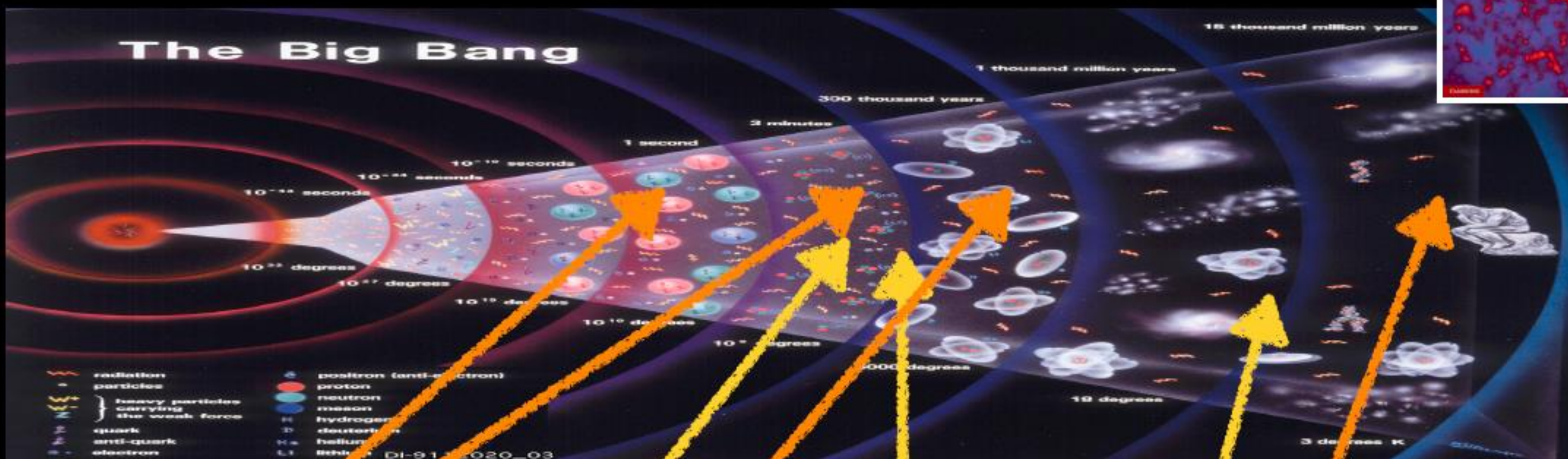


[Maria Archidiacono](#) NEUTRINO 2024

What neutrino effects are we testing?

JL & Pastor Pys. Rep. 2016; JL, Mangano, Miele, Pastor "Neutrino Cosmology" CUP;
Drewes et al. 1602.04816; PDG review: JL & Verde "Neutrinos in Cosmology"; Gerbino & Lattanzi 2017





relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

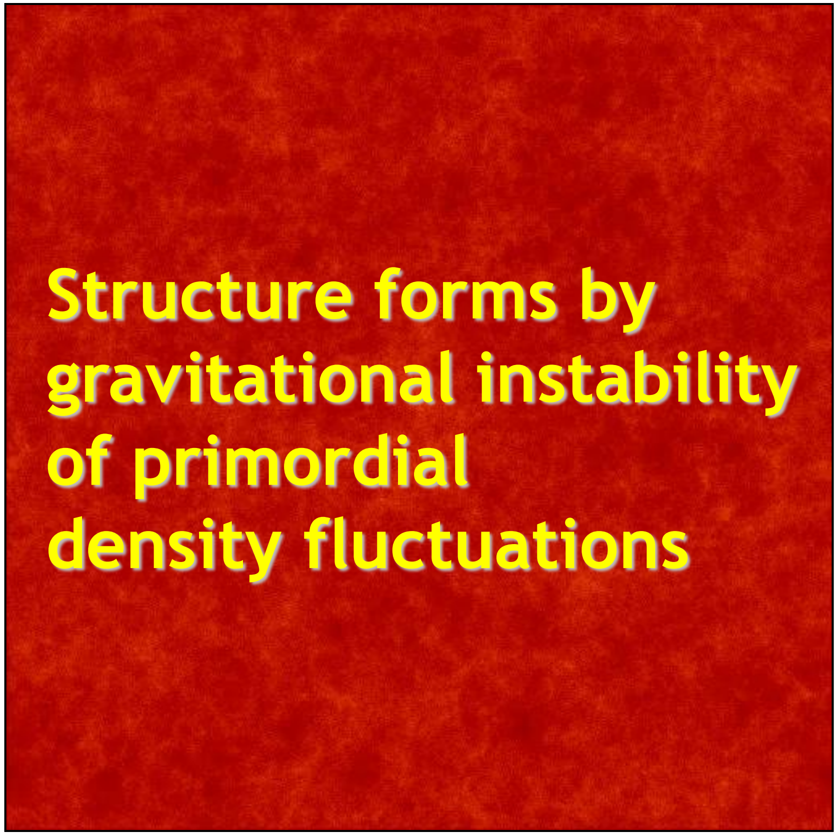
neutrino slow down early dark matter clustering

neutrino propagation and dispersion velocity

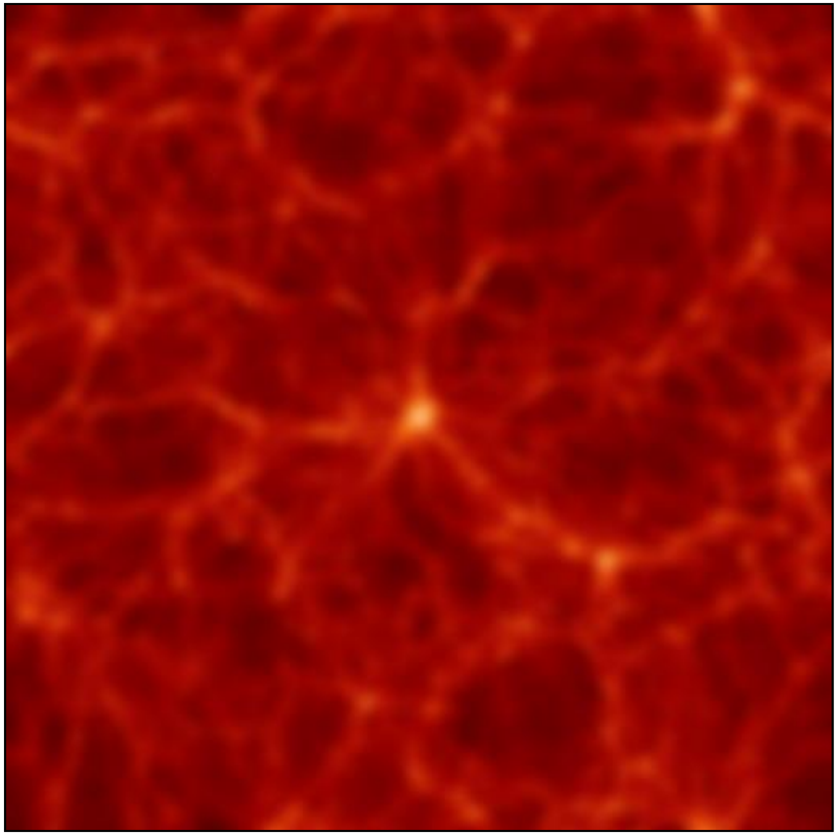
neutrino slow down late ordinary/dark matter clustering

Formation of Structure

Smooth → **Structured**



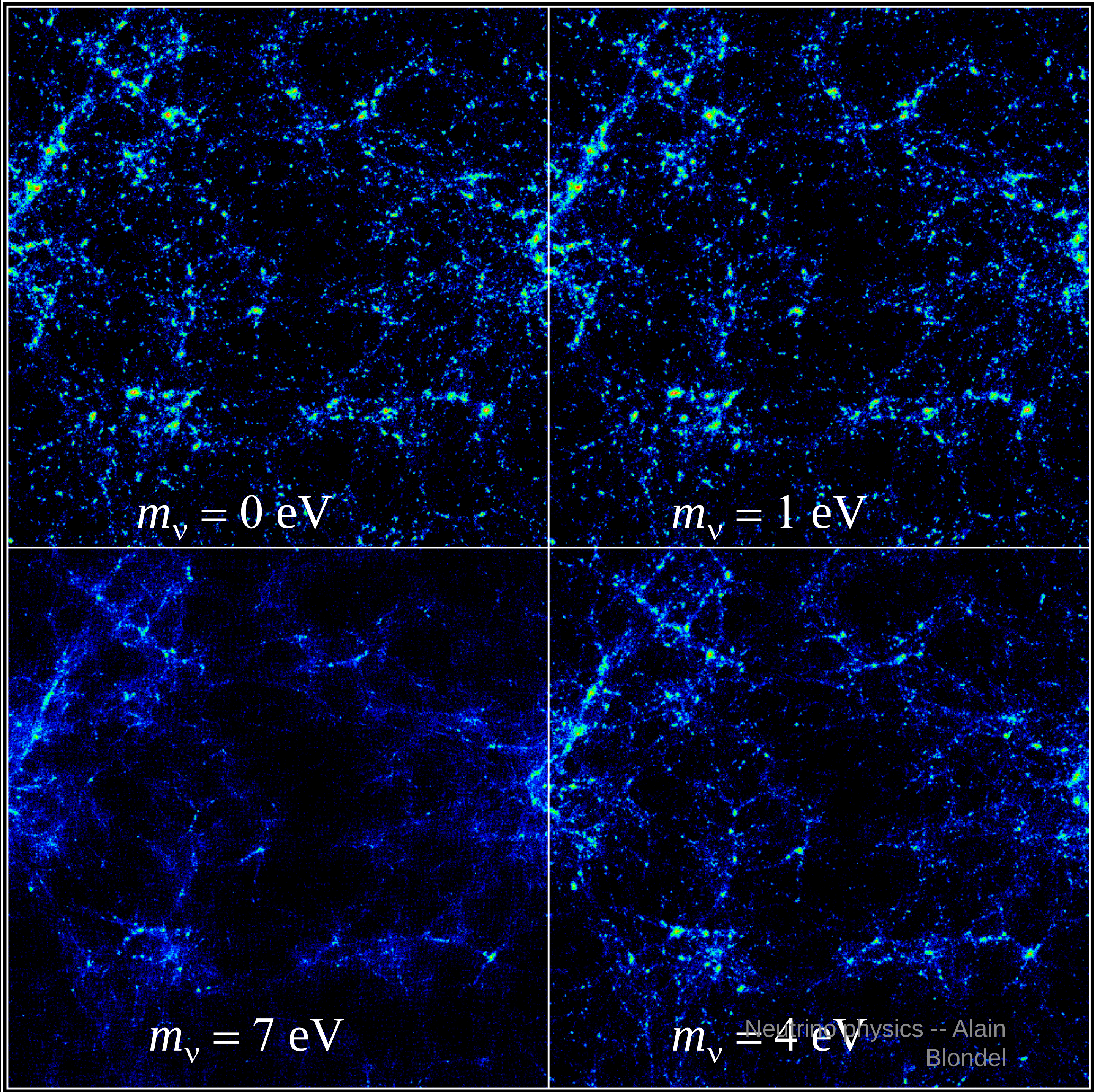
Structure forms by gravitational instability of primordial density fluctuations



A fraction of hot dark matter suppresses small-scale structure

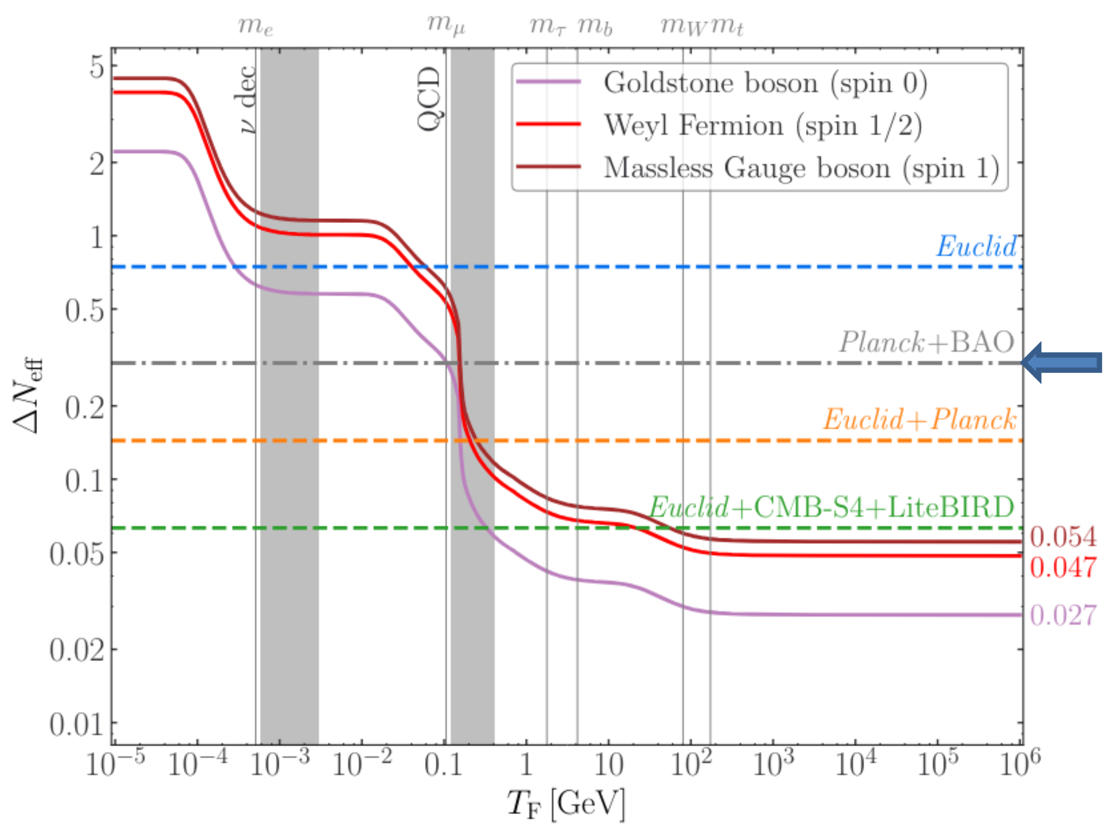
Halzen

adding hot neutrino dark matter erases small structure



Bounds on new light particles ($\Delta\ N_{eff}$)

$N_{eff} = N_{eff}^{SM}(=3.044) + \Delta\ N_{eff}$



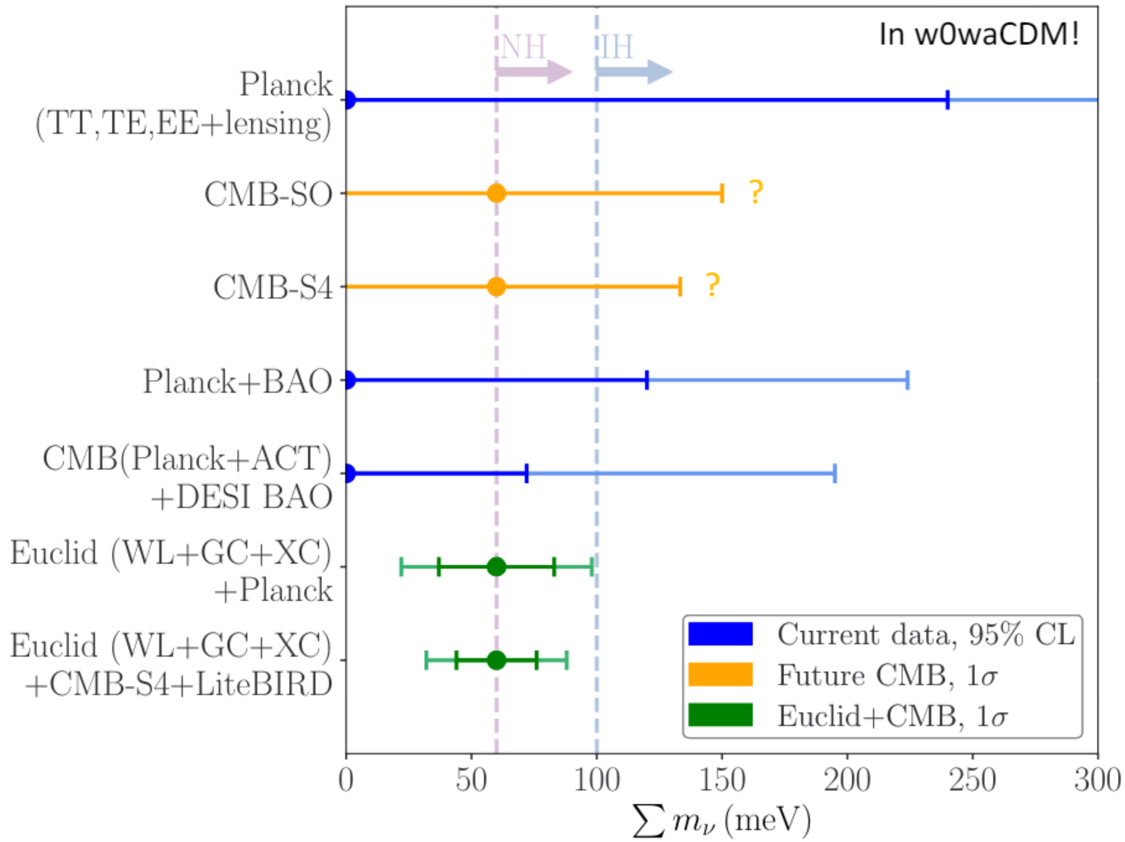
Present boundary
$N_{eff}=3.1\pm0.17$(95%CL)

Activate Windows
Go to Settings to activate Windows

Euclid Collaboration: Archidiacono et al. (2024)

This is valid for the eV scale sterile neutrinos
Sensitivity depends on mass with unclear upper value (eV?, keV, MeV?)

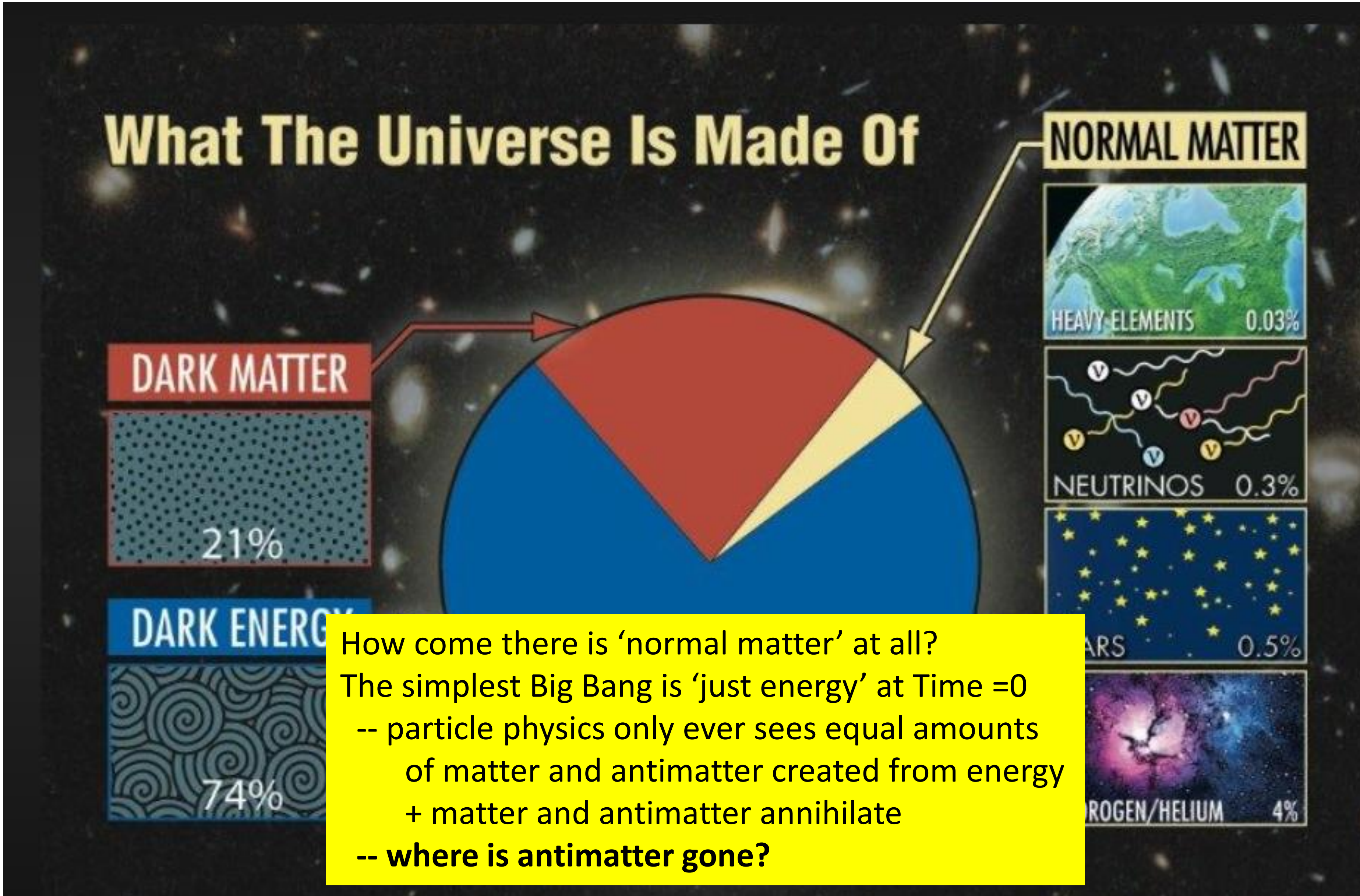
Neutrino mass constraints: the future



Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2.

Activate Windows
Go to Settings to activate Windows.

Cosmology (CMB, Large scale structure) sensitive to light neutrino masses
But model-dependence is strong.
➔knowledge of neutrinos would open new exploration power from cosmology!

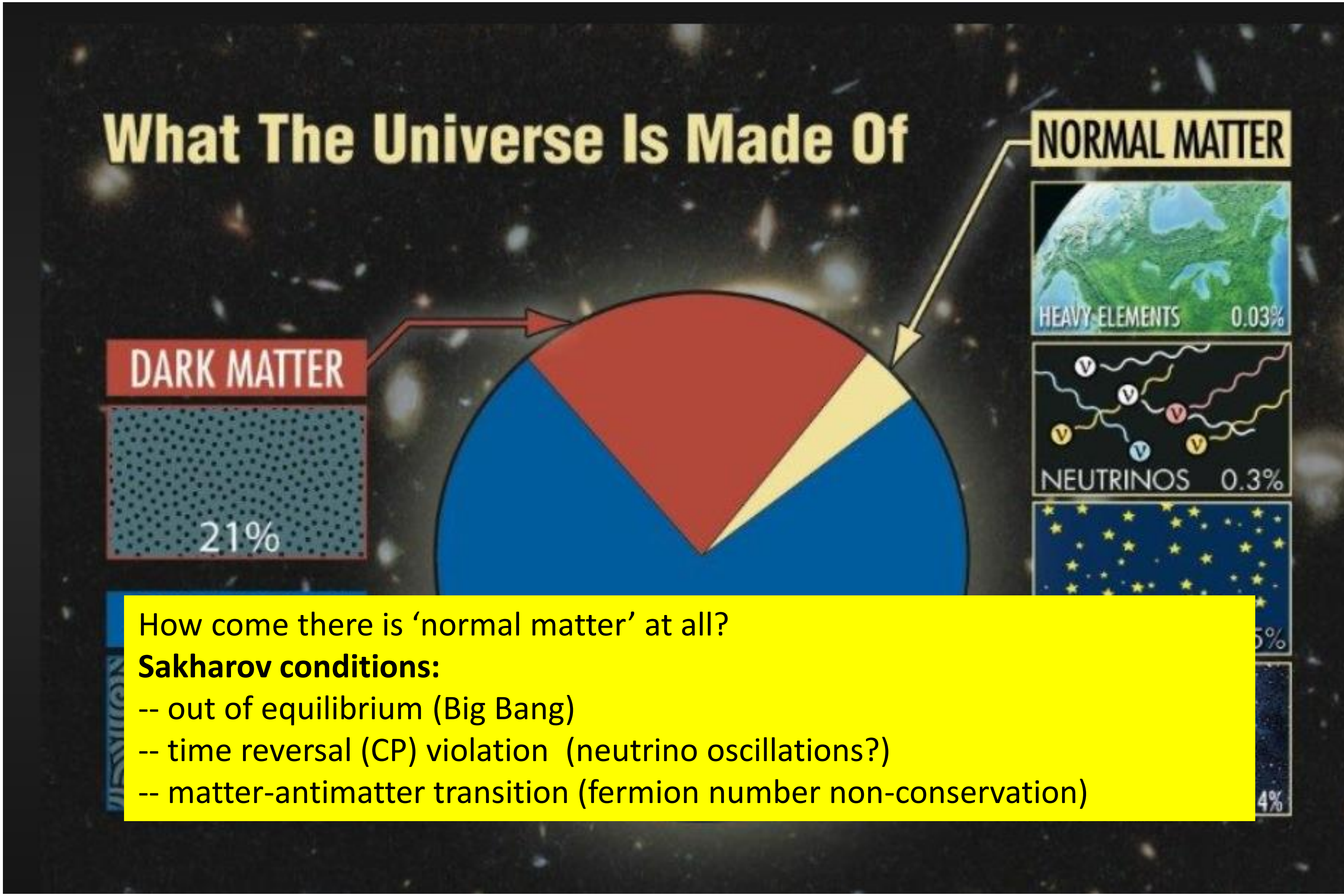


How come there is ‘normal matter’ at all?

The simplest Big Bang is ‘just energy’ at Time =0

-- particle physics only ever sees equal amounts
of matter and antimatter created from energy
+ matter and antimatter annihilate

-- where is antimatter gone?



How come there is ‘normal matter’ at all?

Sakharov conditions:

-- out of equilibrium (Big Bang)

-- time reversal (CP) violation (neutrino oscillations?)

-- matter-antimatter transition (fermion number non-conservation)

Neutrinos have mass and mix

This is NOT the conventional Standard Model

why cant we just add masses to neutrinos?

Fermion number conservation

Is *not* in itself a law or a symmetry of the Standard Model

For charged fermions (e/mu/tau and the quarks) it is not possible to transform a fermion into an antifermion **because of charge conservation**

For neutrinos, which are neutral, the SM assumes they are massless.
neutrino is left-handed (identical if massless to negative helicity)
and the antineutrino has positive helicity
neutrino <-> antineutrino transition is forbidden by **angular momentum conservation**

This results in practice in <u>apparent, accidental, conservation of fermion number</u>

The existence of massive neutrinos allows for spin flip and thus in principle a neutrino-antineutrino transition
since a left-handed field (EW eigenstate) has a component of the opposite helicity (EW state $\neq$ physical state)
$\nu_L \approx \nu_- + \nu_+ \, m/E$ (mass is what allows to flip the helicity)

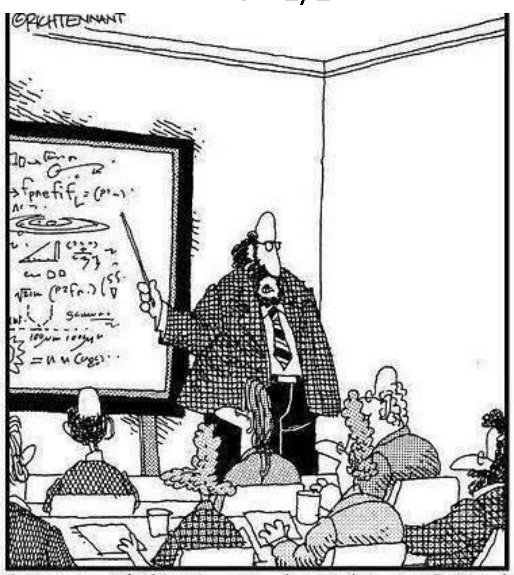
for allowed masses of light neutrinos this is tiny: for m_ν =50 meV and P^*_π =30 MeV ➔ $(m/E)^2 = 10^{-18}$

This can be observed in neutrino less double beta decay
or by searching directly for the right-handed neutrinos

my SM training in 1976

NEUTRINO MASSES

	I = 1/2	I = 0	
Electroweak eigenstates	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
		$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0



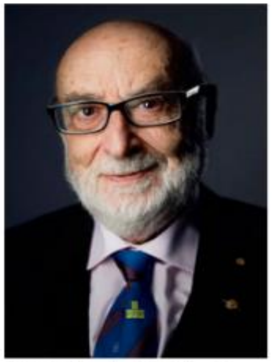
"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –
Also called 'sterile'

NB unlike for ν_L, nothing distinguishes the particle and antiparticle of ν_R which is a singlet (no 'charge')
→ naturally a Majorana particle

The Nobel Prize in Physics 2013



© Nobel Media AB. Photo: A. Mahmoud

François Englert

Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The Nobel Prize in Physics 2015

Takaaki Kajita, Arthur B. McDonald

Share this: 951

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

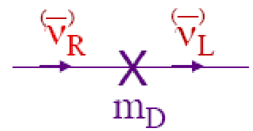
It is all about mass!

Neutrino masses occur via processes which are intimately related to the Higgs boson
what are the couplings of the H(125) to neutrinos?

Let us follow the steps of the Standard Model to construct a minimal neutrino mass model

Adding neutrino masses to the Standard model 'simply' by adding a Dirac mass
➔ right-handed neutrino

$m_D \overline{\nu_L} \nu_R$

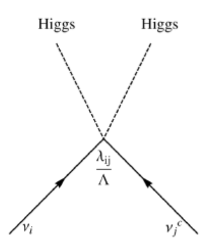


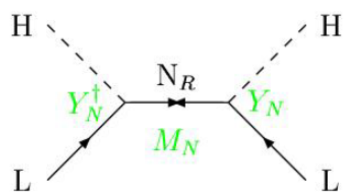
B. Kayser 1989

m_D is the Higgs **Yukawa coupling** (like everybody else). Then the right handed neutrinos are sterile, (**except** that they couple to both the Higgs boson and gravitation).
Things become more interesting: **a Majorana mass term** arises (So-called **Weinberg Operator**) using the Higgs boson and the neutrino Yukawa coupling:

Majorana mass term is extremely interesting as this is the **particle-to-antiparticle transition** that we want
in order to explain
the Baryon asymmetry of the Universe
(+ CP violation in e.g. neutrinos)

Origin of neutrino mass:





$M_R \overline{\nu_R^c} \nu_R$

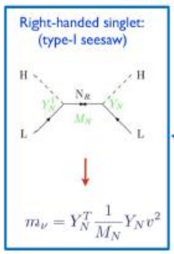
\+ restores SU(2) symmetry!

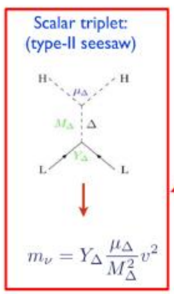
Pilar Hernandez, Silvia Pascoli
Granada 2019-05

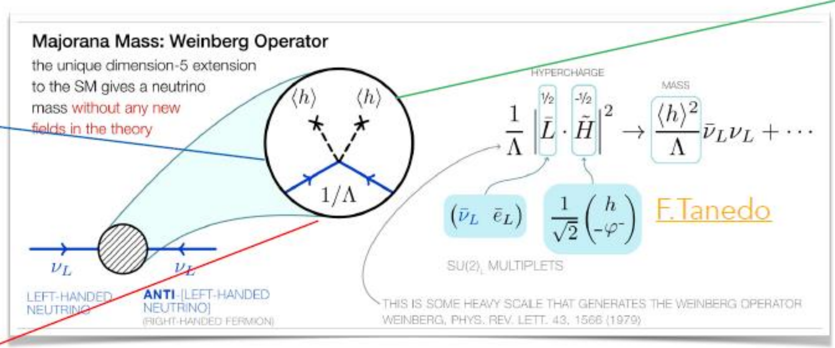
Seesaw Model

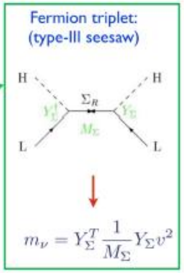
The minimal neutrino Standard Model
is type I see-saw (just complete with RH ν's)

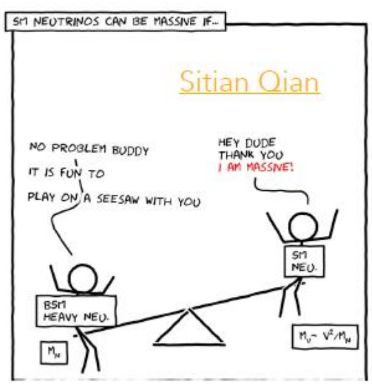
- Opening the black box of Weinberg Operator requires a "**seesaw**"
  - Only three different kinds of realization at Born-level are allowed











- Heavier BSM particles lead to lighter SM neutrinos

Having two mass terms per family , neutrinos undergo level splitting ➔ Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\,m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \frac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \frac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\,m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

I_{weak}=	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
	½	0	½	0

4 states of equal masses

Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

I_{weak}=	ν_L	$\bar{\nu}_R$
	½	½

2 states of equal masses

All have I=1/2 (active)

$M_R > m_D \neq 0$ see-saw

Dirac + Majorana

m ↑

dominantly:

I_{weak}=	ν	N	$\bar{\nu}$	N
	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

Manifestations of right handed neutrinos

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$$\nu = \nu_L \cos\theta - N^c_R \sin\theta$$

$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

what is produced in W, Z decays is:

$$\nu_L = \nu \cos\theta + N \sin\theta$$

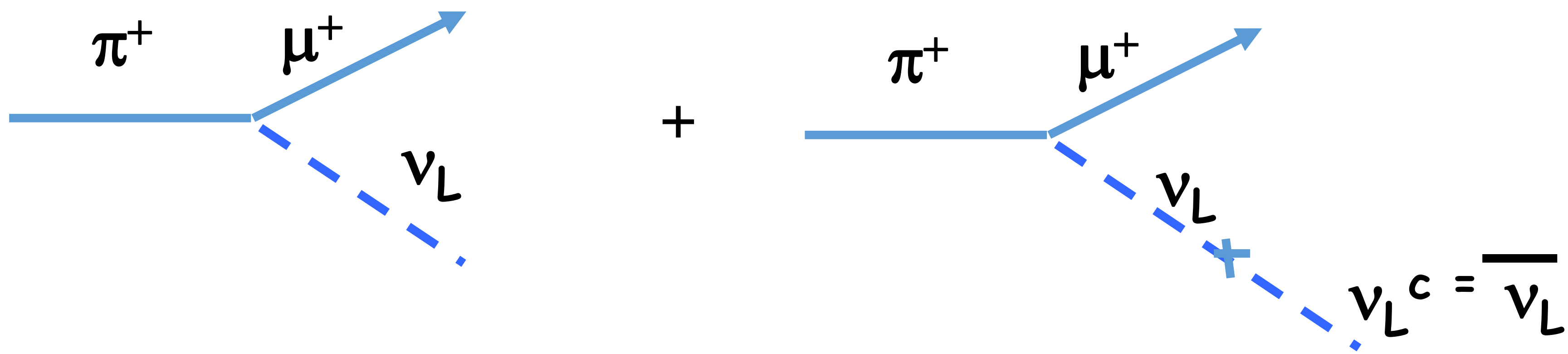
ν = light mass eigenstate
N = heavy mass eigenstate HNL
$\neq \nu_L$, active neutrino
which couples to weak inter.
and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences
-- observation of neutrinoless double beta decay
-- if very light (eV) , possible effect on neutrino oscillations ('eV sterile neutrino' (LSND/miniBooNE/reactor anomalies etc... but ruled out since PLANCK mission MINOS/ICECUBE/DAYABAY/microBooNE. Search still ongoing in broader region)

-- if in 5-100 keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$, KATRIN
-- possibly measurable effects at High Energy
→ If N is heavy it will decay in the detector → spectacular
→ Higgs, Z, W visible exotic decays $H \to \nu_i \bar{N}_i$ and $Z \to \nu_i \bar{N}_i$, $W \to l_i \bar{N}_i$
→ also in K, charm and b decays via $W^* \to l_i^\pm \bar{N}$, $N \to l_j^\pm$
with any of six sign and lepton flavour combination
→ violation of unitarity and lepton universality in Z, W or τ decays
→ PMNS matrix unitarity violation and deficit in Z «invisible» width
-- etc... etc...

-- Couplings are very small ($|U|^2 = m_\nu / m_N$) for one family. For three families they can be somewhat larger
but most interesting region is near the one-family see-saw limit

Pion decay with massive neutrinos



1

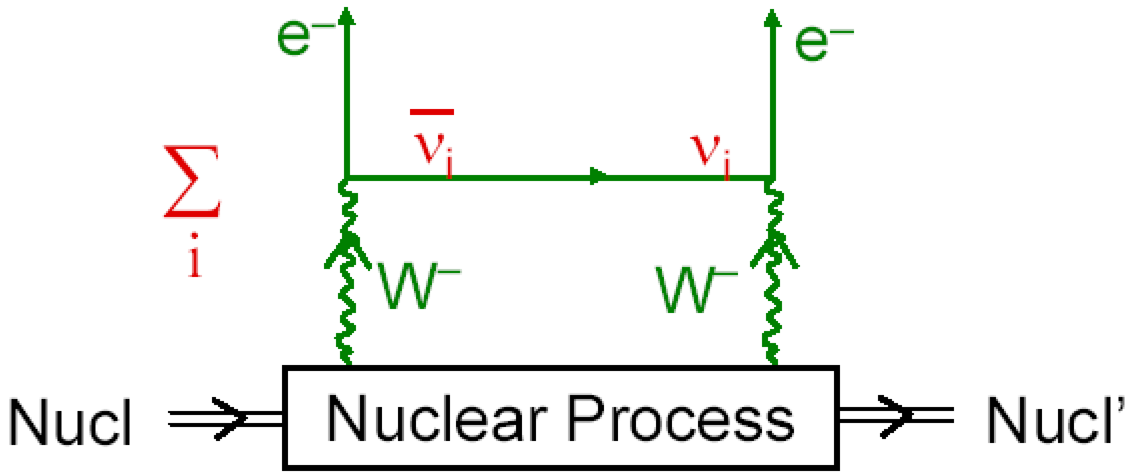
$(m_\nu / E)^2$

<u>in case of pure Dirac:</u>
transition to sterile right handed neutrinos
<u>in case of pure Majorana:</u>
transition to anti-neutrino
<u>in case of see-saw:</u>
if possible, transition to heavy RH neutrino

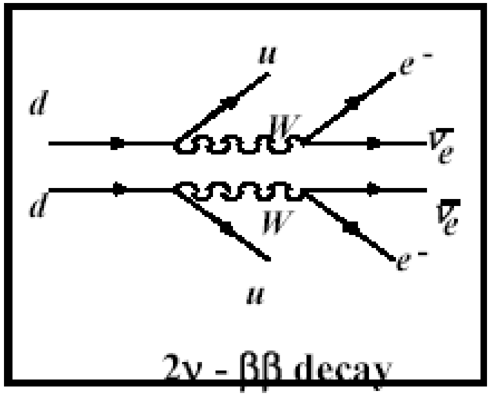
$(.05/30\ 10^6)^2 = 10^{-18}$

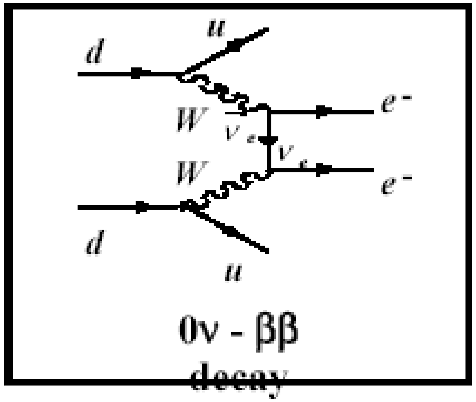
no problem

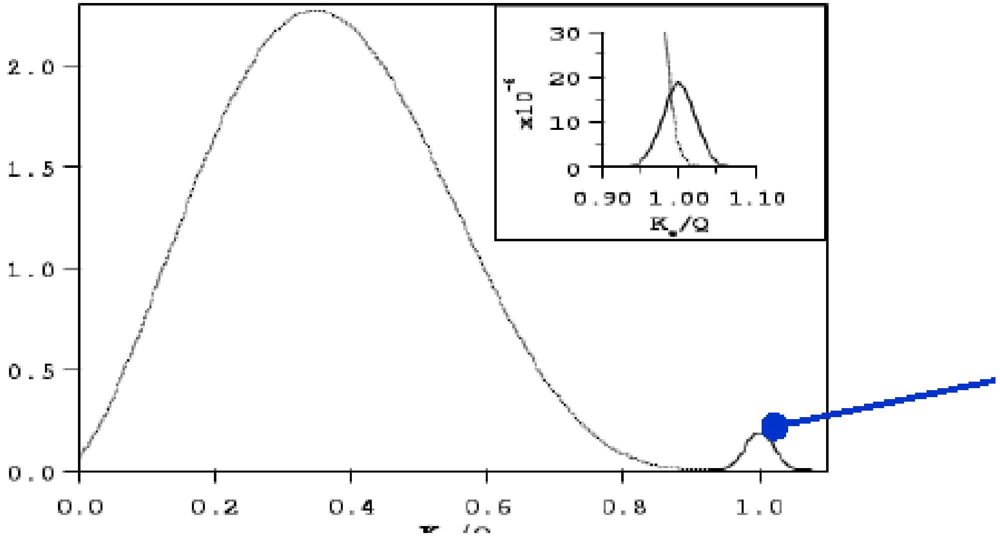
The Idea That Can Work — Neutrinoless Double Beta Decay [0νββ]



By avoiding competition, this process can cope with the small neutrino masses.

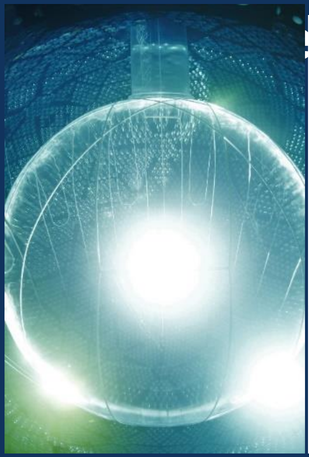
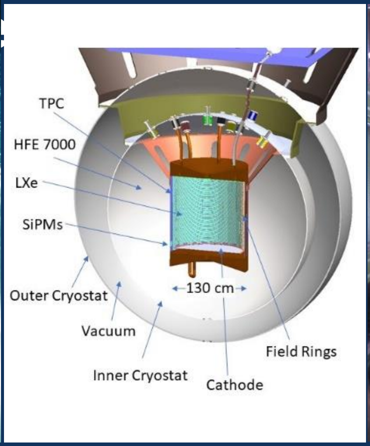


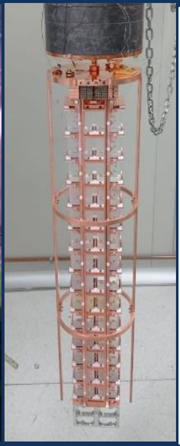
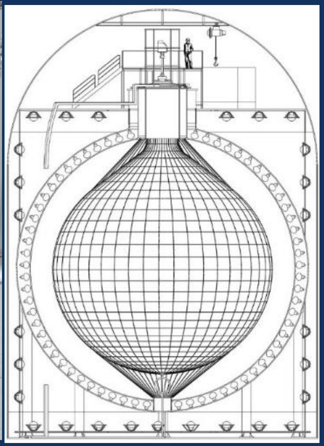




Two neutrino ββ decay has been detected in ten nuclei also into exited states

Neutrino-less Double Beta

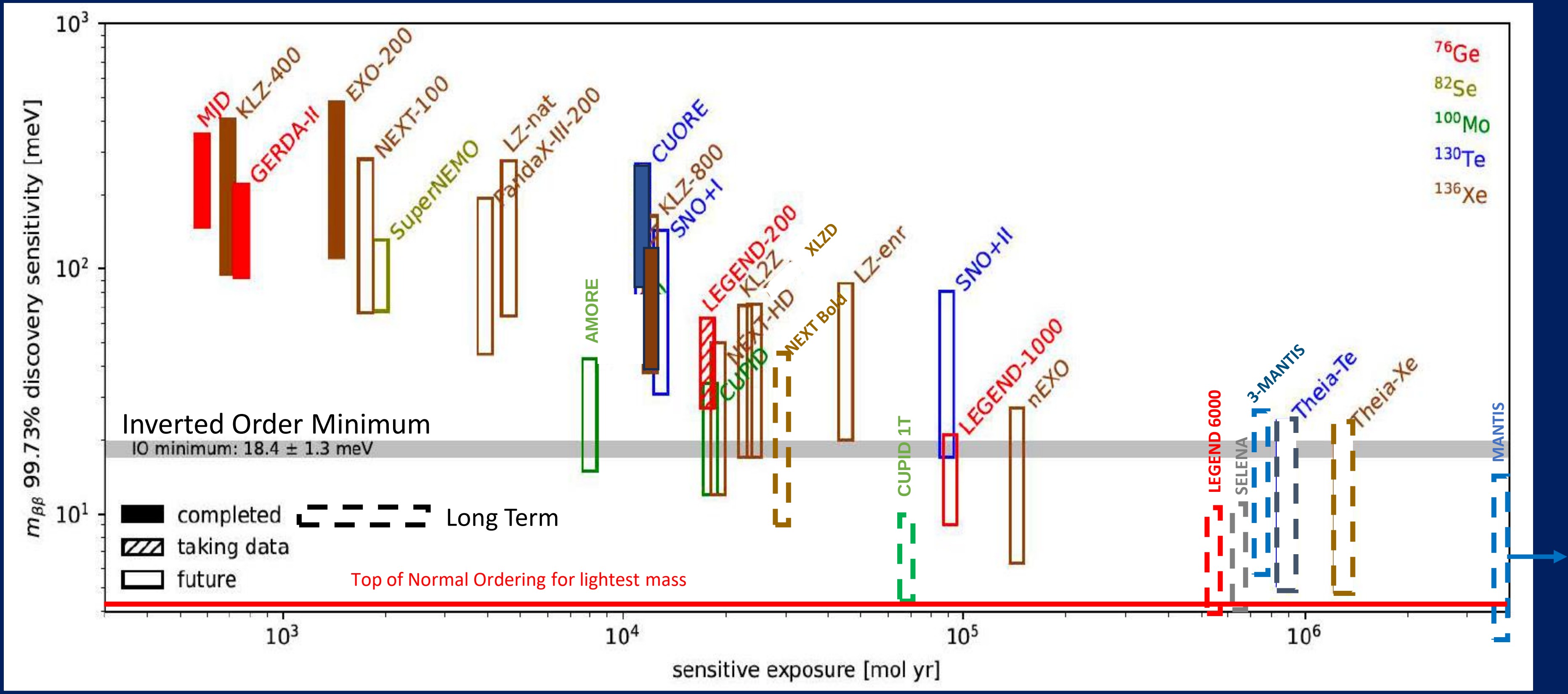




SNO+ (Te) | nEXO (Xe) | LEGEND (Ge) | CUPID (Mo) | KAM-ZEN (Xe)

- There are a number of experiments in operation and others in development with several different isotopes. This will be an advantage in the advent of a discovery

- Detailed nuclear theory calculations are needed to interpret these measurements and are an important part of the field.
- There is a question of quenching of g_A that could reduce the sensitivity of these experiments to effective neutrino mass by a factor of 2 to 4.

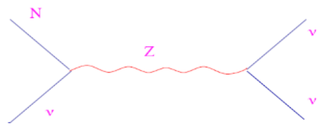
Summary plot from NSAC LRP White Paper (Augmented) (Values provided by experiments)
(Assuming that process is mediated by low mass neutrinos and g_A is not quensched)

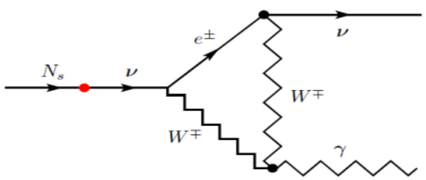


From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN):
Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451

Direct Search Processes (I)

m_N Below m_e:
$N \rightarrow 3\nu$; $N \rightarrow \nu\gamma$ w $E_\gamma = m_N/2$

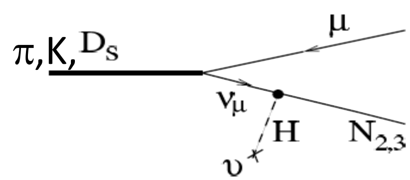


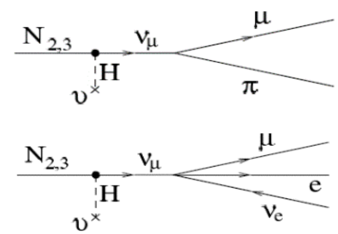


$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\,\text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

Long life, **dark matter candidate**
→Search for gamma emission line (such as 3.5 keV line)
Drewes et al; arXiv:1602.04816v1

Meson decay (π,K,D and neutrino beams) examples:





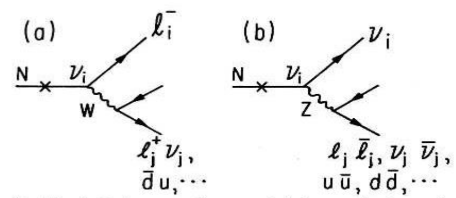


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

$$L \approx \frac{3}{|U|^2\,(m_{\nu_m}(\text{GeV}/c^2))^6} \times \frac{P_\nu}{45\,GeV/c}$$

Decay via W gives at least two charged particles, and amounts to ~60% of decays.
Searches for long lived decays in neutrino beams PS191, NuTeV, CHARM; SHIP and DUNE

Experiment	PS191	NuTeV	CHARM	SHiP
Proton energy (GeV)	19.2	800	400	400
Protons on target ($\cdot 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1 (He)	1 (He)	1 (air)	10^{-6} (air)
Distance to target (m)	128	1400	480	80-90
Off beam axis (mrad)	40	0	10	0

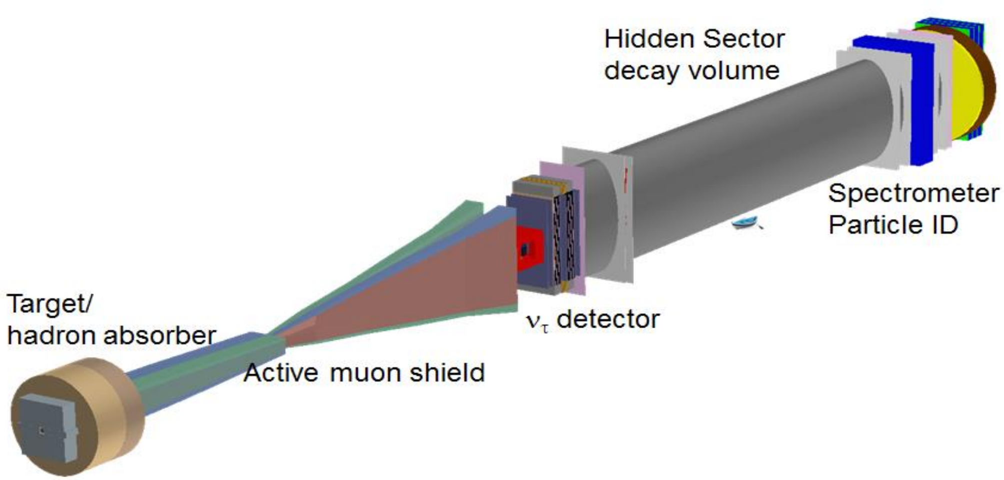
Next generation heavy neutrino search experiment SHIP

-- focuses on neutrinos from charm to cover 0.5 – 2 GeV region

-- uses beam dump to reduce background from neutrino interactions from pions and Kaons and bring the detector as close as possible to source.

-- increase of beam intensity and decay volume

status: proposal, physics report and technical report exist. R&D phase approved at CERN

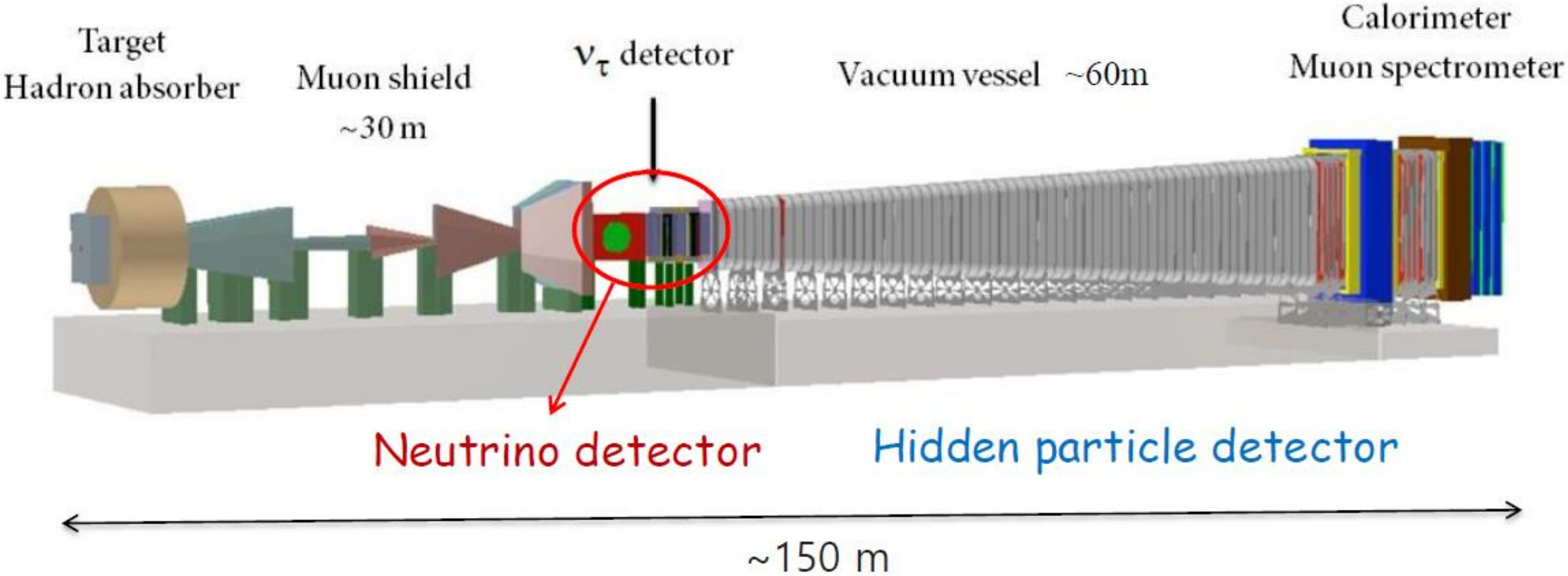


arXiv:1504.04855
arXiv:1504.04956

SHiP Detector

Active muon shield
deflect muons from 2ry meson decay
~ 35m long, 1.7 T magnet

PID
Energy measure

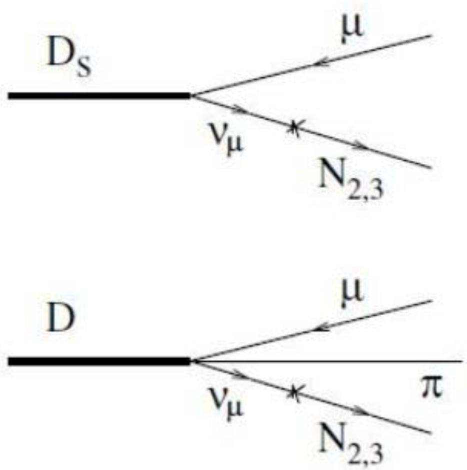


Hadron absorber
eliminate
2ry mesons
~ 5m Fe

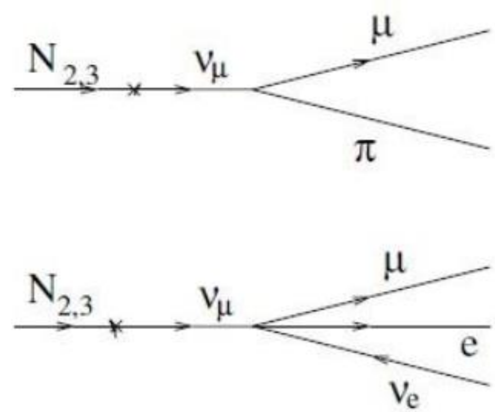
Nuclear Emulsion
Tau-neutrino physics
LDM search

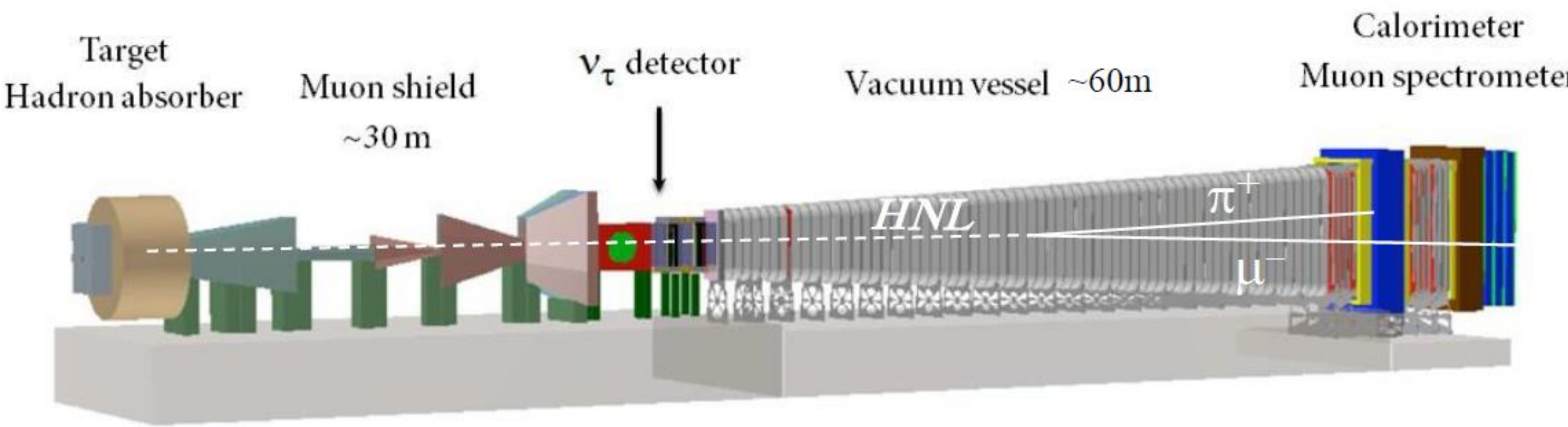
Vacuum decay vessel
~60 m long evacuated decay vessel surrounded by liquid scintillator veto system

HNL production



HNL decay





Neutrino detector

Hidden particle detector

HNL sensitivity

Cosmologically interesting region at low couplings

- **$m_{HNL} < m_b$**

  SHiP will have much better sensitivity than LHCb or Belle2

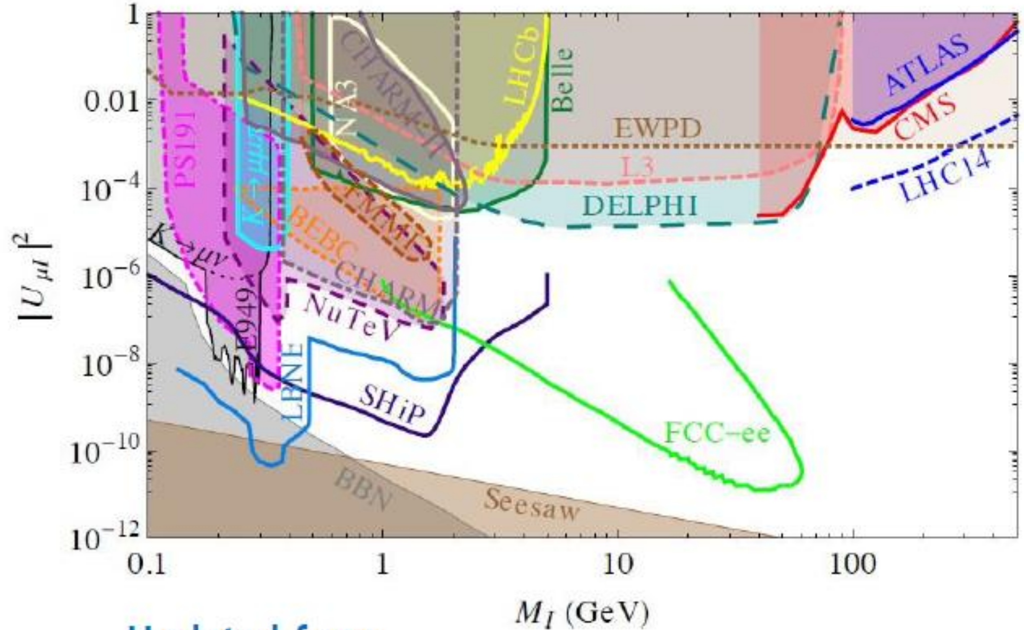
- **$m_b < m_{HNL} < m_Z$**

  FCC-ee, improvements expected from ATLAS/CMS

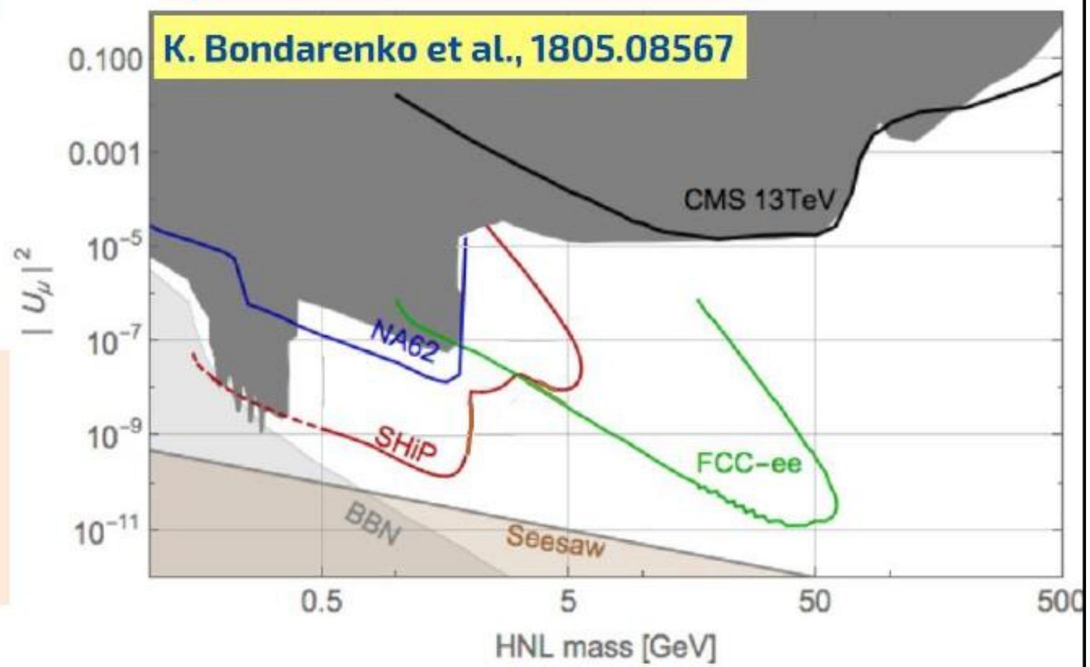
- **$m_{HNL} > m_Z$**

  targeted by ATLAS/CMS at HL-LHC

At **m_{HNL} = 1 GeV** and **$U^2 = 10^{-8}$** (50 x lower than present limit), SHiP will see more than **1,000** fully reconstructed events.



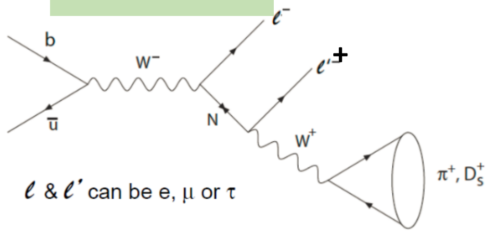
Updated from K. Bondarenko et al., 1805.08567



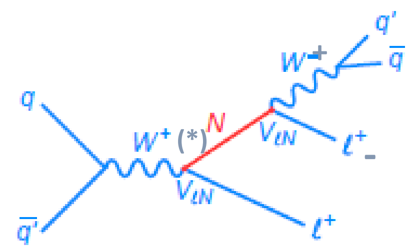
Processes (II)

Search for heavy right-handed neutrinos in F.T. or collider experiments.

B factories



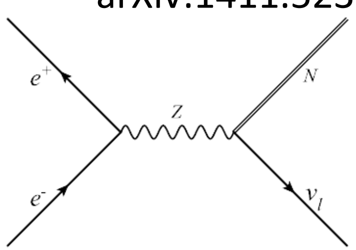
Hadron colliders



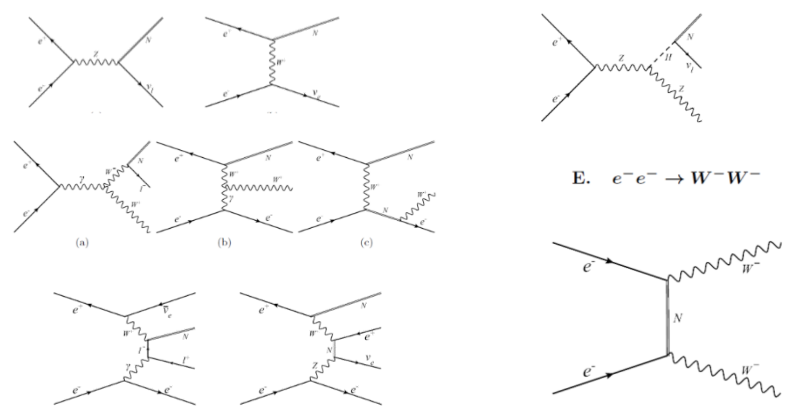
or $l^{\pm}\nu$

Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)



Recent heavy neutrino analyses at the LHC

- Probing heavy Majorana neutrinos & Weinberg operator via pp→$\mu^{\pm}\mu^{\pm}jj$
  - EXO-21-003
- Search for type-III seesaw heavy leptons
  - arXiv:2202.02039 ATLAS EXPERIMENT, arXiv:2202.08676
- Heavy Composite Majorana Neutrino
  - EXO-20-011
- Left-Right Symmetry model
  - JHEP 04 (2022) 047, EXO-20-006
- Long-lived heavy neutral leptons with displaced vertices
  - arXiv:2204.11988 ATLAS EXPERIMENT, arXiv:2201.05578

Heavy Neutral Leptons -- recent litterature

The Present and Future Status of Heavy Neutral Leptons

Asli M. Abdullahi, Pablo Barham Alzas, Brian Batell, Alexey Boyarsky, Saneli Carbajal, Animesh Chatterjee, Jose I. Crespo-Anadon, Frank F. Deppisch, Albert De Roeck, Marco Drewes, Alberto Martin Gago, Rebeca Gonzalez Suarez, Evgueni Goudzovski, Athanasios Hatzikoutelis, Marco Hufnagel, Philip Ilten, Alexander Izmaylov, Kevin J. Kelly, Juraj Klaric, Joachim Kopp, Suchita Kulkarni, Mathieu Lamoureux, Gaia Lanfranchi, Jacobo Lopez-Pavon, Oleksii Mikulenko, Michael Mooney, Miha Nemevsek, Maksym Ovchynnikov, Silvia Pascoli, Ryan Plestid, Mohamed Rashad Darwish, Federico Leo Redi, Oleg Ruchayskiy, Richard Ruiz, Mikhail Shaposhnikov, Ian M. Shoemaker, Robert Shrock, Alex Sousa, Nick Van Remortel, Vsevolod Syvolap, Volodymyr Takhistov, Jean-Loup Tastet, Inar Timiryasov, Aaron C. Vincent, Jaehoon Yu

777 references!

The existence of non-zero neutrino masses points to the likely existence of multiple SM neutral fermions. When such states are heavy enough that they cannot be produced in oscillations, they are referred to as Heavy Neutral Leptons (HNLs). In this white paper we discuss the present experimental status of HNLs including colliders, beta decay, accelerators, as well as astrophysical and cosmological impacts. We discuss the importance of continuing to search for HNLs, and its potential impact on our understanding on key fundamental questions, and additionally we outline the future prospects for next-generation future experiments or upcoming accelerator run scenarios.

Comments: 82 pages, 34 figures. Contribution to Snowmass 2021
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2203.08039 **[hep-ph]**
(or arXiv:2203.08039v1 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2203.08039

High Energy Physics - Experiment

[Submitted on 10 Mar 2022 (v1), last revised 11 Mar 2022 (this version, v2)]

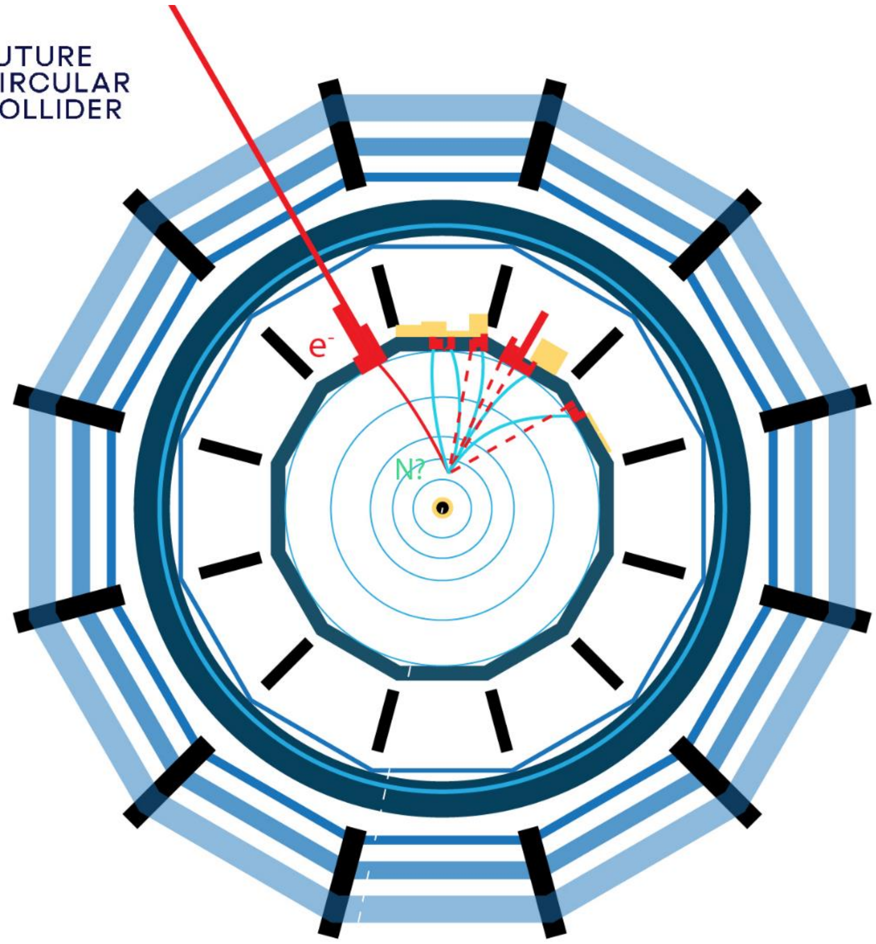
Searches for Long-Lived Particles at the Future FCC-ee

J. Alimena, P. Azzi, M. Bauer, A. Blondel, M. Drewes, R. Gonzalez Suarez, J. Klaric, S. Kulkarni, M. Neubert, C. Rizzi, R. Ruiz, L. Rygaard, A. Sfyrla, T. Sharma, A. Thamm, C. B. Verhaaren

The electron-positron stage of the Future Circular Collider, FCC-ee, is a frontier factory for Higgs, top, electroweak, and flavour physics. It is designed to operate in a 100 km circular tunnel built at CERN, and will serve as the first step towards $\geq$ 100 TeV proton-proton collisions. In addition to an essential and unique Higgs program, it offers powerful opportunities to discover direct or indirect evidence of physics beyond the Standard Model. Direct searches for long-lived particles at FCC-ee could be particularly fertile in the high-luminosity Z run, where 5×10^{12} Z bosons are anticipated to be produced for the configuration with two interaction points. The high statistics of Higgs bosons, W bosons and top quarks in very clean experimental conditions could offer additional opportunities at other collision energies. Three physics cases producing long-lived signatures at FCC-ee are highlighted and studied in this paper: heavy neutral leptons (HNLs), axion-like particles (ALPs), and exotic decays of the Higgs boson. These searches motivate out-of-the-box optimization of experimental conditions and analysis techniques, that could lead to improvements in other physics searches.

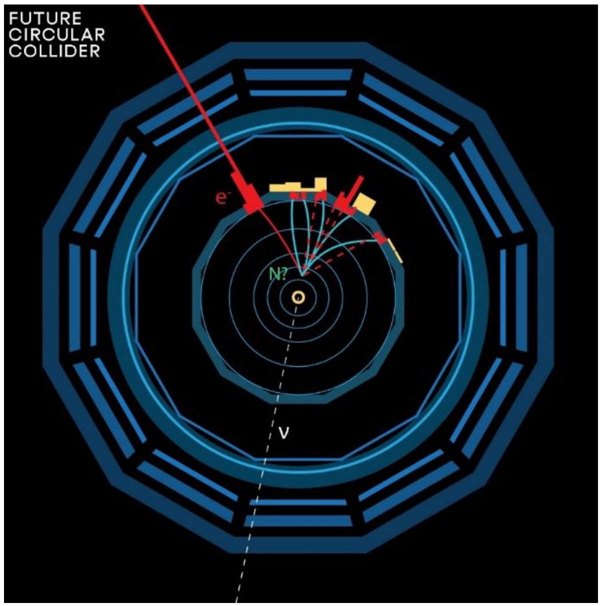
Comments: Contribution to Snowmass 2021
Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)
Cite as: arXiv:2203.05502 **[hep-ex]**
(or arXiv:2203.05502v2 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2203.05502

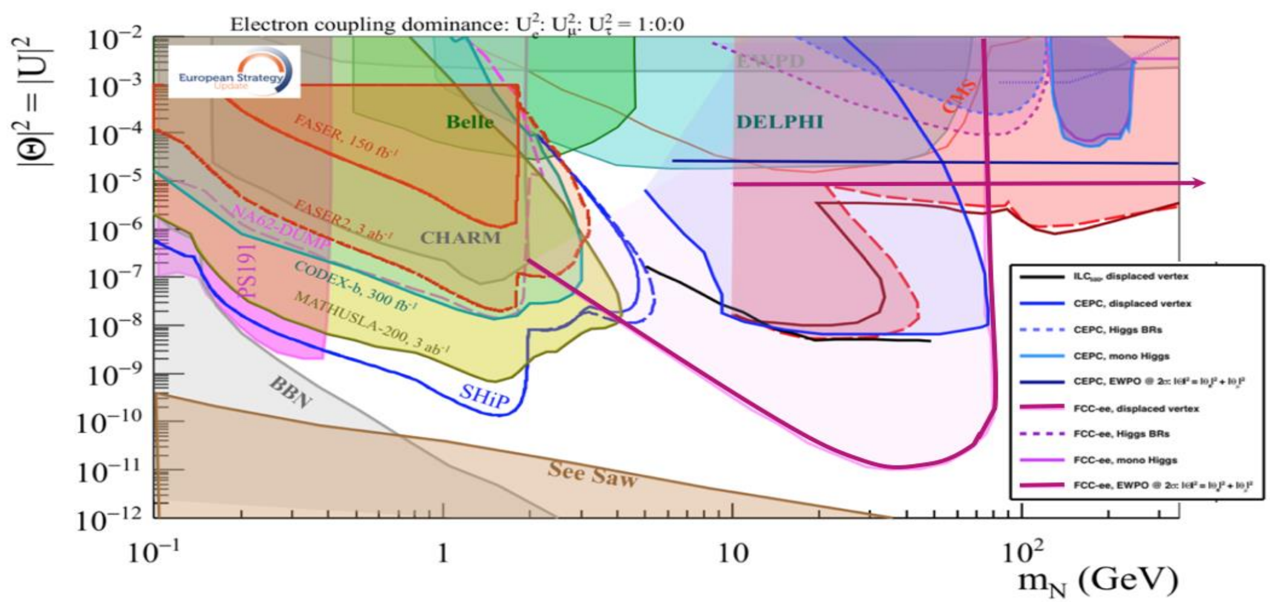
Heavy Neutral Leptons at the Z factory



courtesy
Panos Charitos

This picture from the briefing book is relevant to Neutrino, Dark sectors and High Energy Frontiers.
FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos
How close can we get to the 'see-saw limit'?

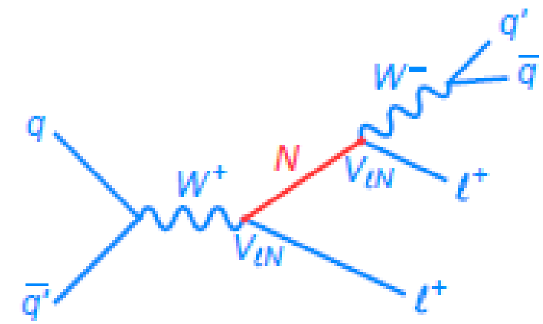




-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z),
-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

FCC-hh

We have seen that the Z factory offers a clean method
for detection of Heavy Right-Handed neutrinos
Ws are less abundant at the lepton colliders



At the 100 TeV pp W is the dominant particle,
Expect 10^{13} real W's.

There is a lot of /pile-up/backgrounds/lifetime/trigger issues which need to be investigated.
BUT.... in the regime of long lived HNLs the simultaneous presence of
-- the initial lepton from W decays
-- the detached vertex with kinematically constrained decay
allows for a significant background reduction.

But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

VERY interesting...

Conclusions

Neutrinos, at this moment in time, provide beautiful and intriguing mysteries
-- is time reversal violated in neutrino oscillations
-- is there a matter-antimatter transition in neutrinos
-- do right-handed neutrinos exist?
-- is the origin of neutrino masses the same (SM Higgs coupling) as that of the other fermions?

The answer to which have great chances to provide the explanation of the very existence of our 'matter' Universe

The solution of these mysteries requires an all-fronts program of research involving
-- theoretical understanding and calculations
-- neutrino beam experiments (but for how long?)
-- nuclear physics experiments ($0\nu\beta\beta$)
-- fixed target experiments (e.g. SHIP at CERN)
-- collider experiments (see you tomorrow ;-) !
-- you invent it!