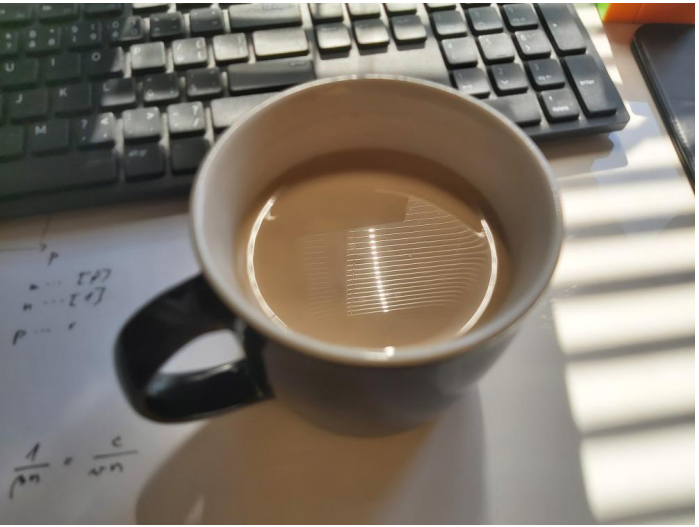
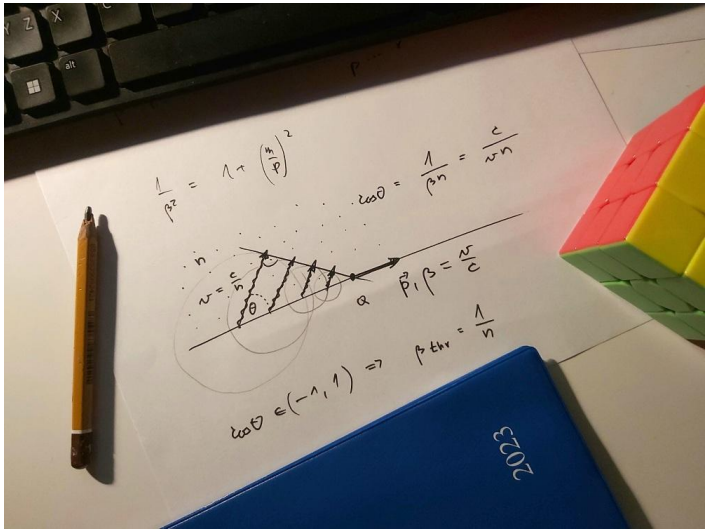
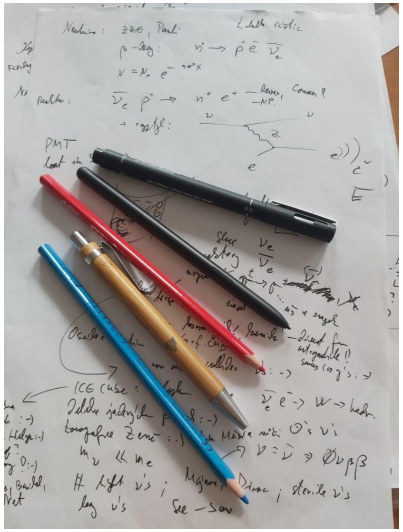




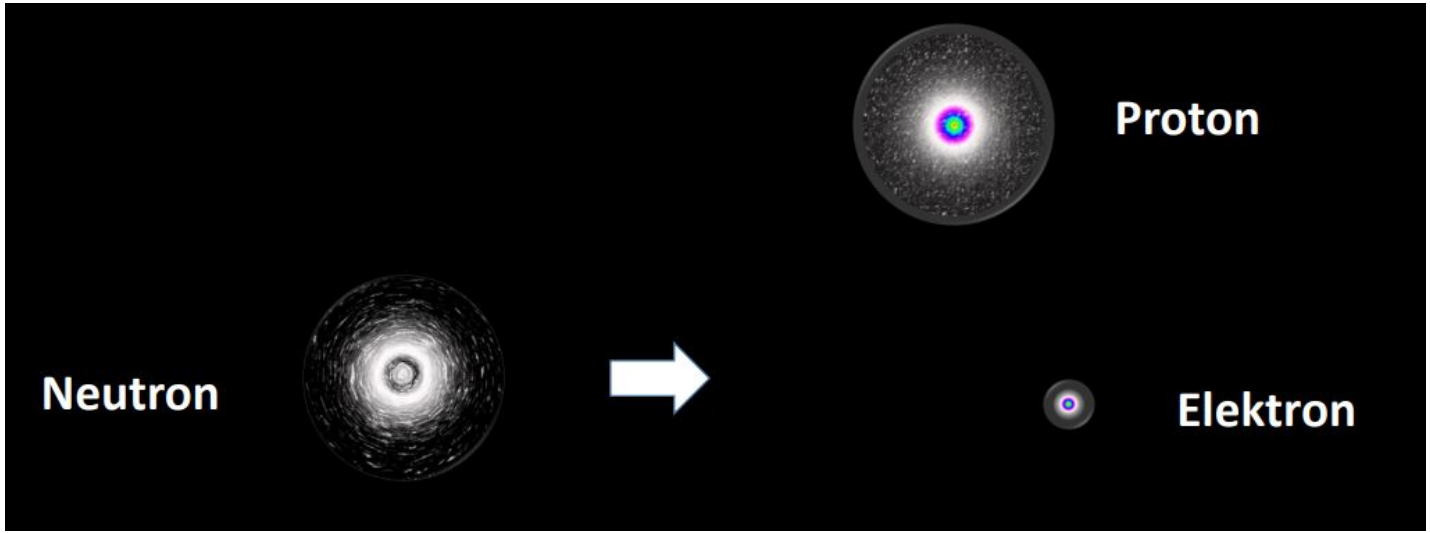


Jak se chytají neutrina

PALACKÝ UNIVERSITY OLOMOUC

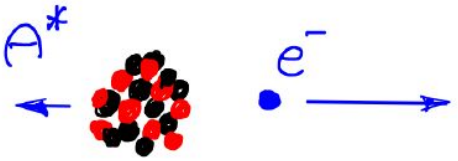
Mgr. Jiří Kvita, Ph.D.
Letní Škola Badatele 2023
Společná laboratoř optiky UP

Rozpad neutronu

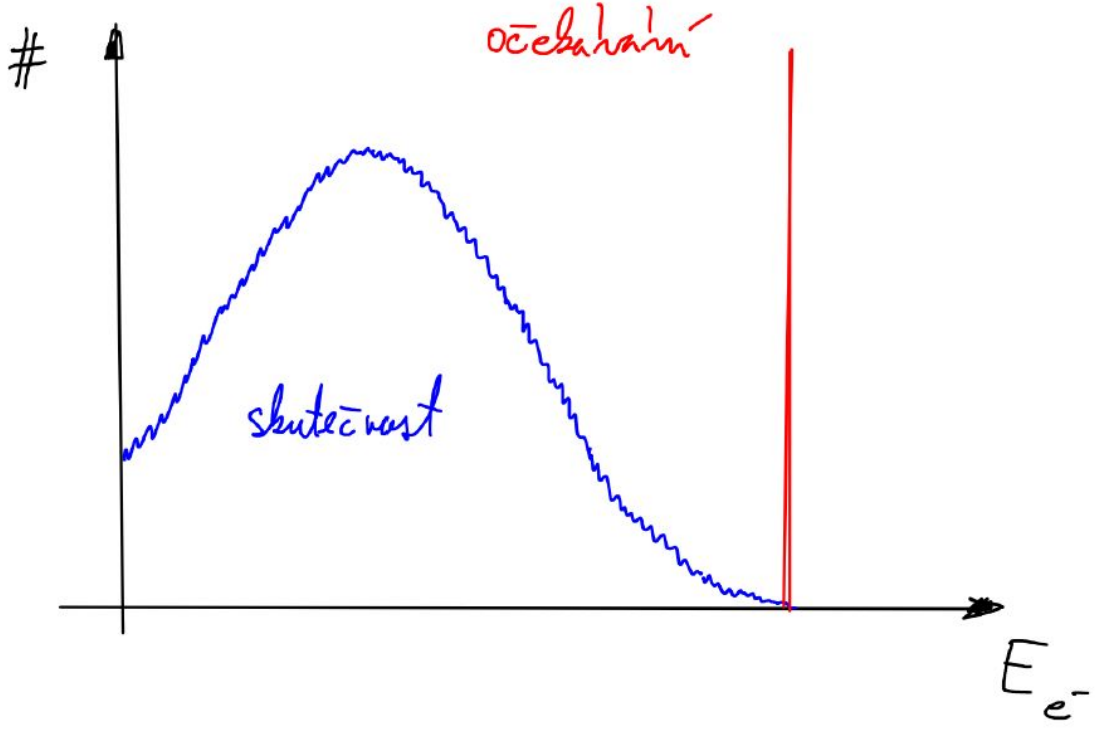


Beta rozpad

Beta rozpad



- Problém: pozorované spektrum energií elektronů z beta rozpady bylo široké, neodpovídalo očekávání jedné energie, kdyby šlo o dvojčásticovy rozpad $A \rightarrow A^{*}\, e^{-}$.
- Dáno zákonem zachování hybnosti a energie.



Neutrino – teoretické předpověď 1930

Wolfgang Pauli

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

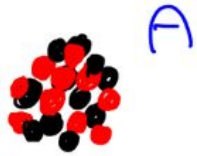
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

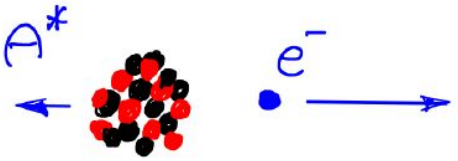
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und

Beta rozpad





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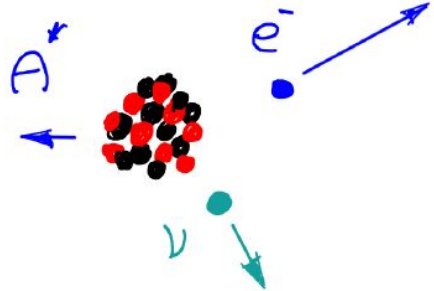
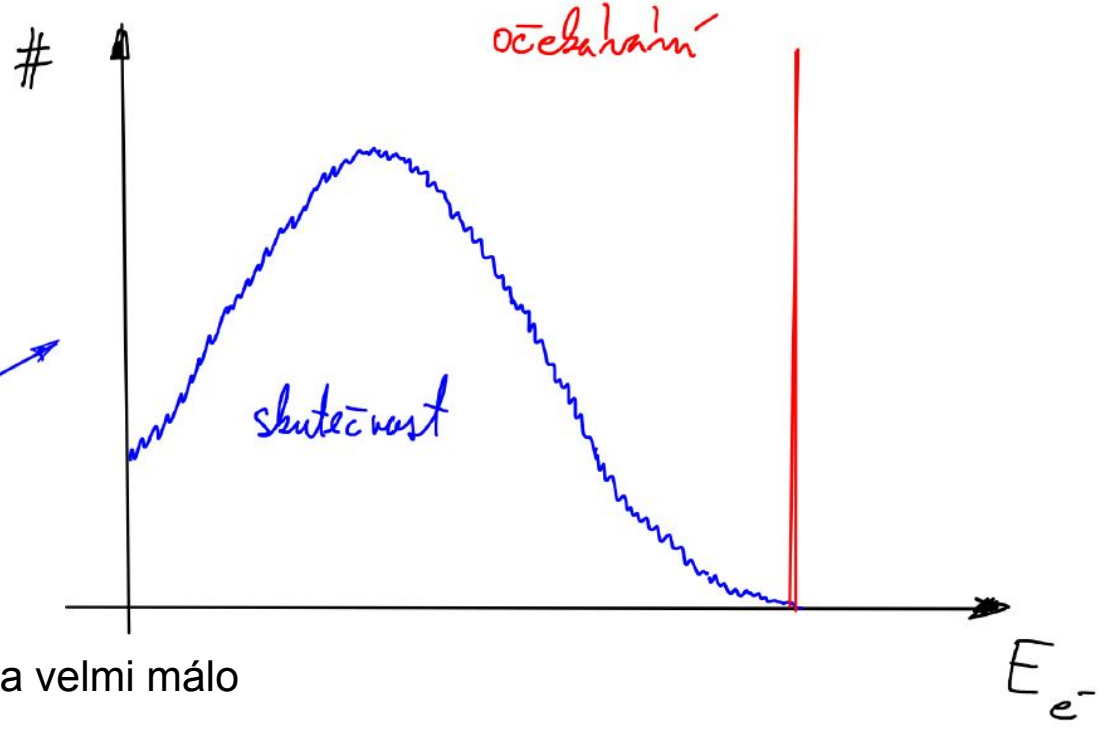
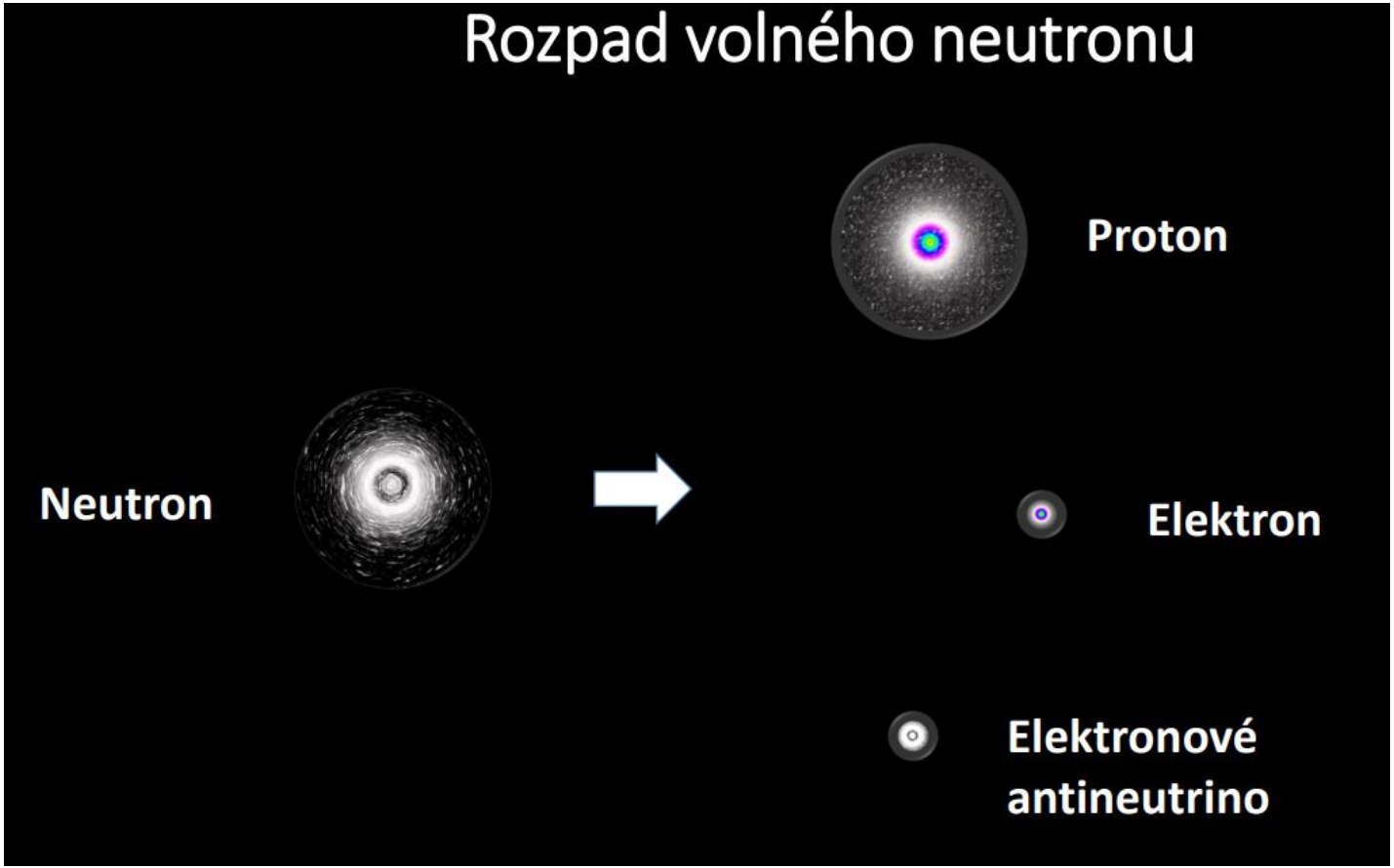




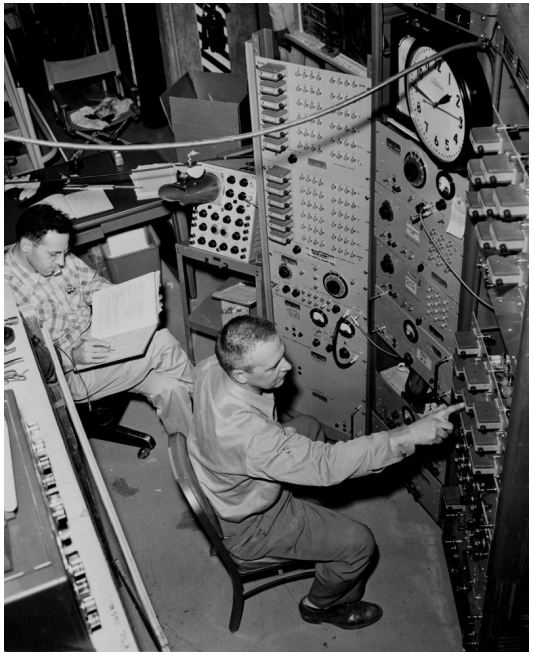
- Neutrino: neutrální, velmi lehká a velmi málo interagující částice.

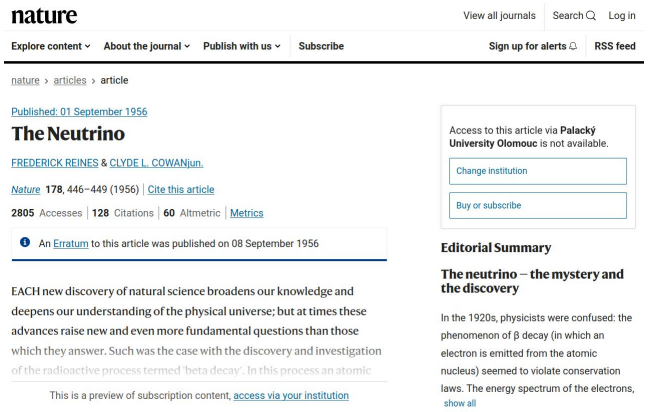
Beta rozpad


Rozpad volného neutronu
Proton
Neutron
Elektron
Elektronové
antineutrino

Objev neutrina :: 1956

- Reaktor Savannah river
- 5×10^{13} neutrin / s / cm^2
- Clyde Cowan, Frederic Reines.





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Published: 01 September 1956

The Neutrino

FREDERICK REINES & CLYDE L. COWANjun.

Nature **178**, 446–449 (1956) | Cite this article

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An Erratum to this article was published on 08 September 1956

EACH new discovery of natural science broadens our knowledge and deepens our understanding of the physical universe; but at times these advances raise new and even more fundamental questions than those which they answer. Such was the case with the discovery and investigation of the radioactive process termed 'beta decay'. In this process an atomic

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Editorial Summary

The neutrino – the mystery and the discovery

In the 1920s, physicists were confused: the phenomenon of β decay (in which an electron is emitted from the atomic nucleus) seemed to violate conservation laws. The energy spectrum of the electrons, show all

The Nobel Prize in Physics 1995

Photo from the Nobel Foundation archive.

Martin L. Perl

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Frederick Reines

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https://www.symmetrymagazine.org/article/neutrino-turns-60

https://en.wikipedia.org/wiki/Cowan%E2%80%93Reines_neutrino_experiment

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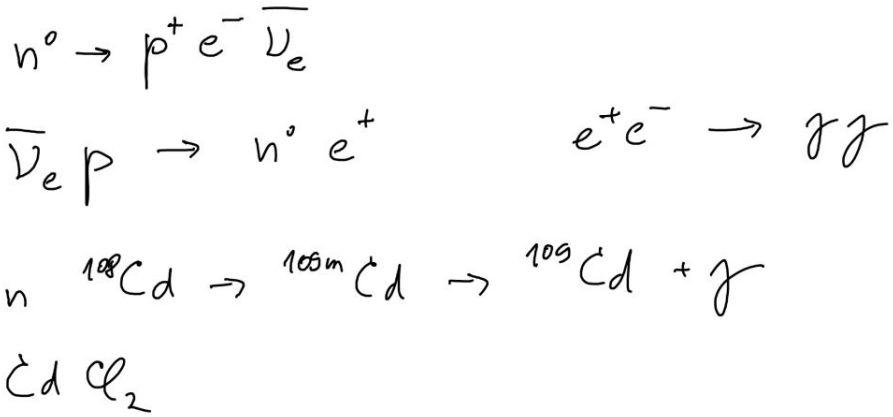

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The Nobel Prize in Physics

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Martin L. Perl

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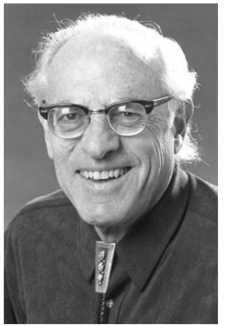

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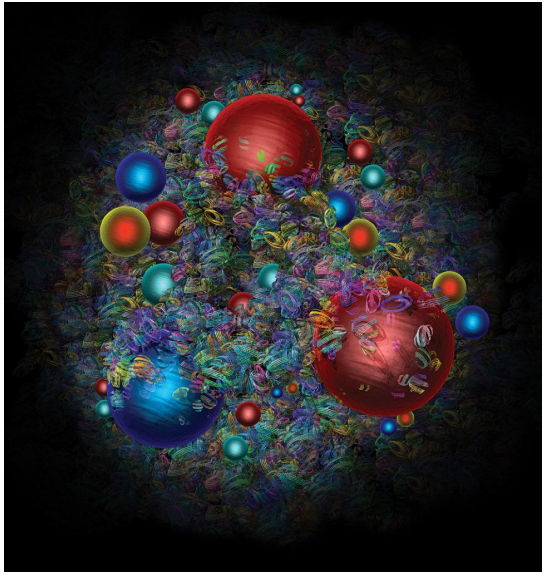
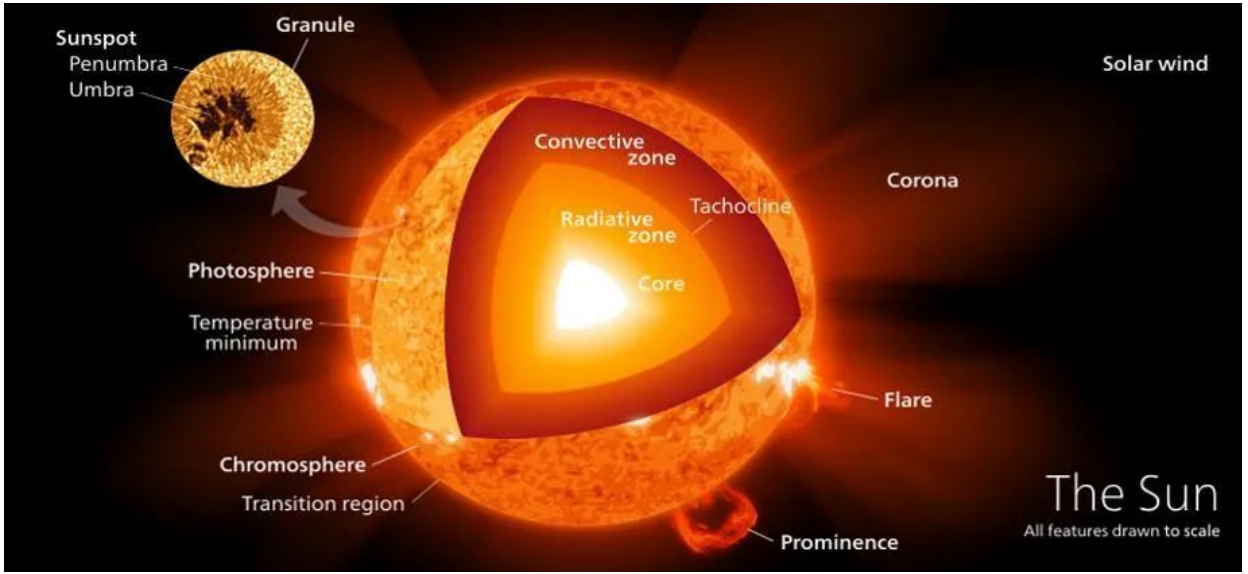
https://www.symmetrymagazine.org/article/neutrino-turns-60
https://en.wikipedia.org/wiki/Cowan%E2%80%93Reines_neutrino_experiment

Proton

- Nejjednodušší a nejčastější jádro atomu ve Vesmíru
- Stabilní
- Palivo hvězd, ve kterých vznikají těžší jádra a energie

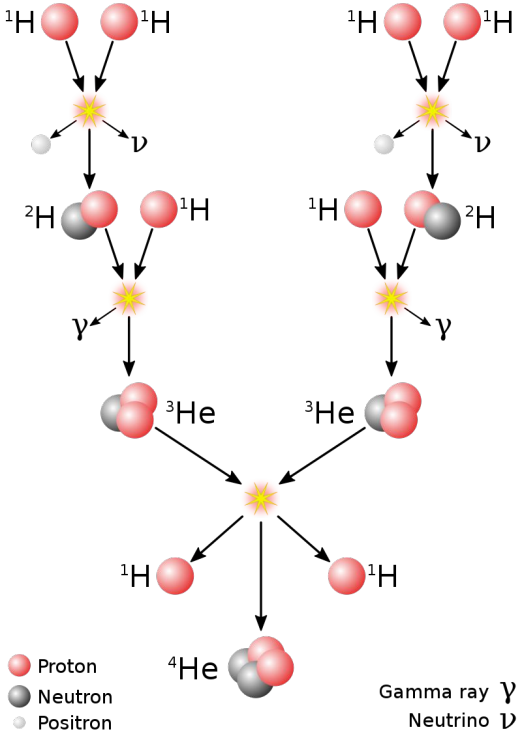
https://home.cern/news/news/physics/proton-century

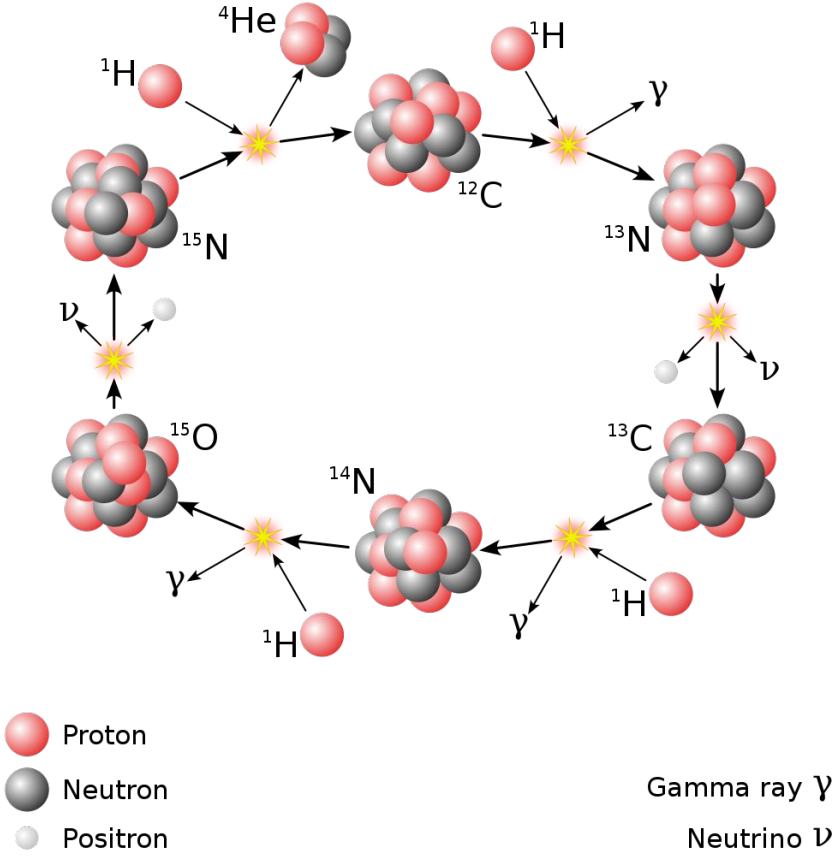




https://www.forbes.com/sites/startswithabang/2017/09/05/the-suns-energy-doesnt-come-from-fusing-hydrogen-into-helium-mostly/

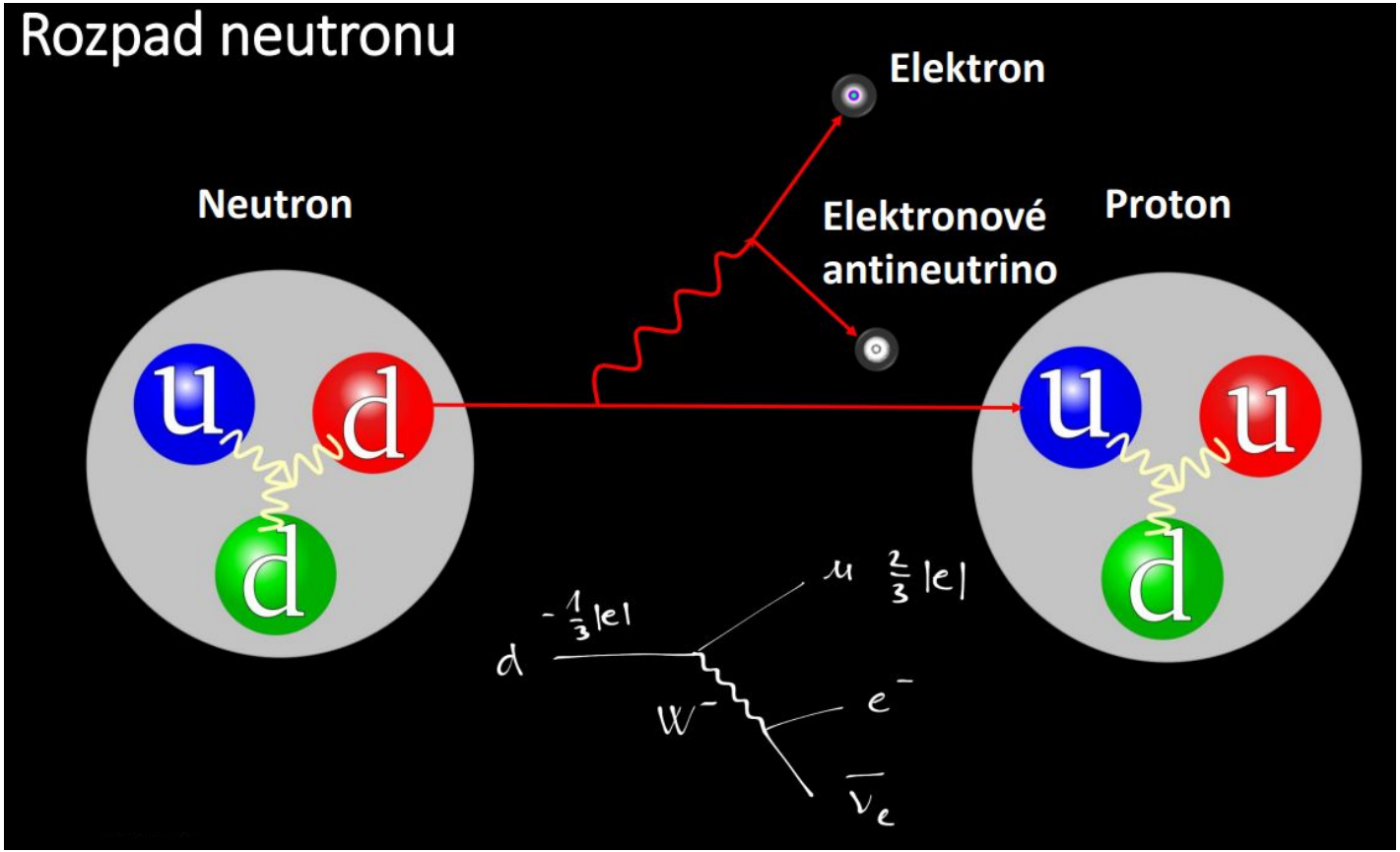
Neutrina ze Slunce: pp a CNO cyklus





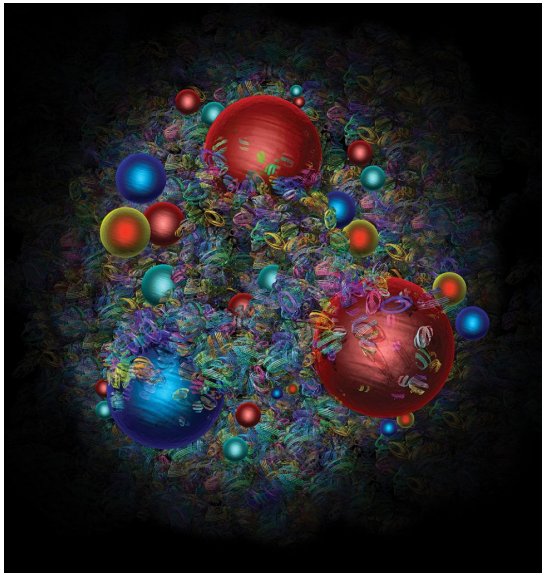
https://en.wikipedia.org/wiki/CNO_cycle

Neutrina z beta rozpadu



Rozpad protonu?

- Možný v některých teoriích za současný Standardní model mikrosvěta.
- Hledejme tedy!
- Kdyby byl pozorován, je to náznak nové fyziky!



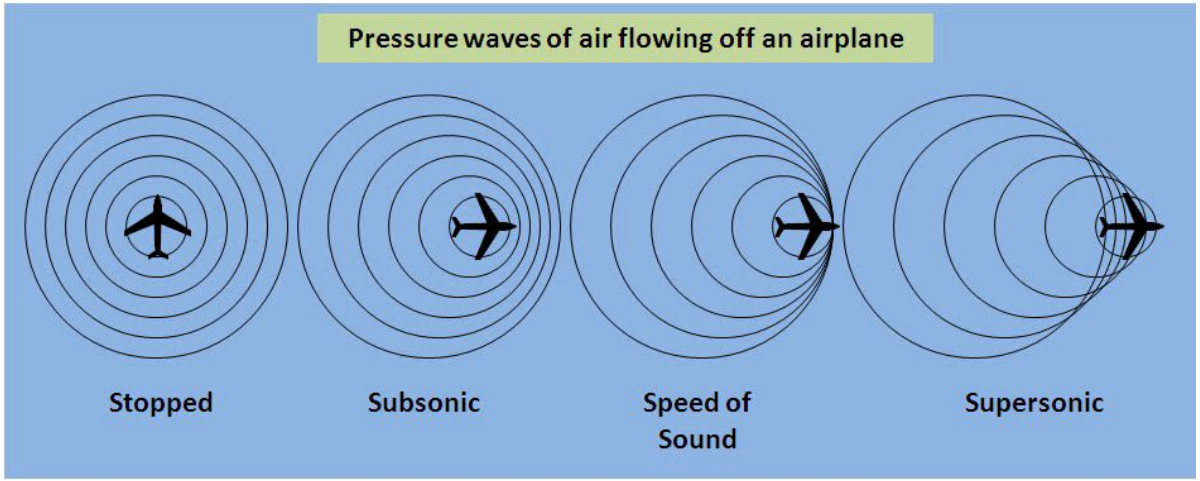
$p^+ \rightarrow e^+ \pi^0$ $\quad \pi^0 \rightarrow \gamma\gamma$

$p^+ \rightarrow \mu^+ \pi^0$ $\quad \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

$\pi^0 \rightarrow \gamma\gamma$

Odbočka: Rázová akustická vlna

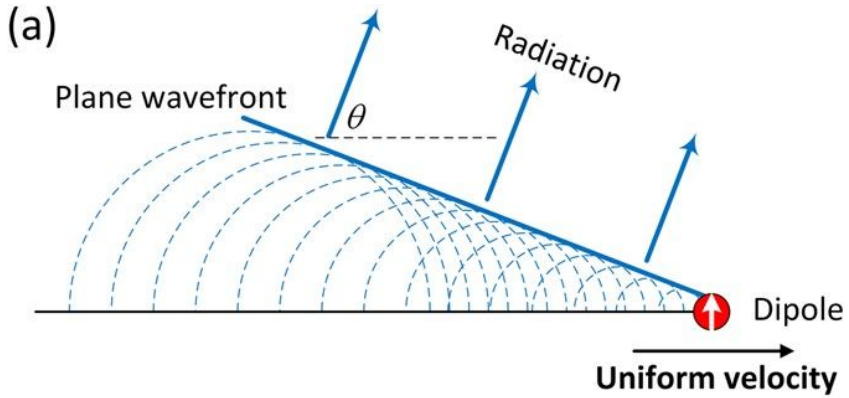
- Letadlo překračuje rychlost zvuku

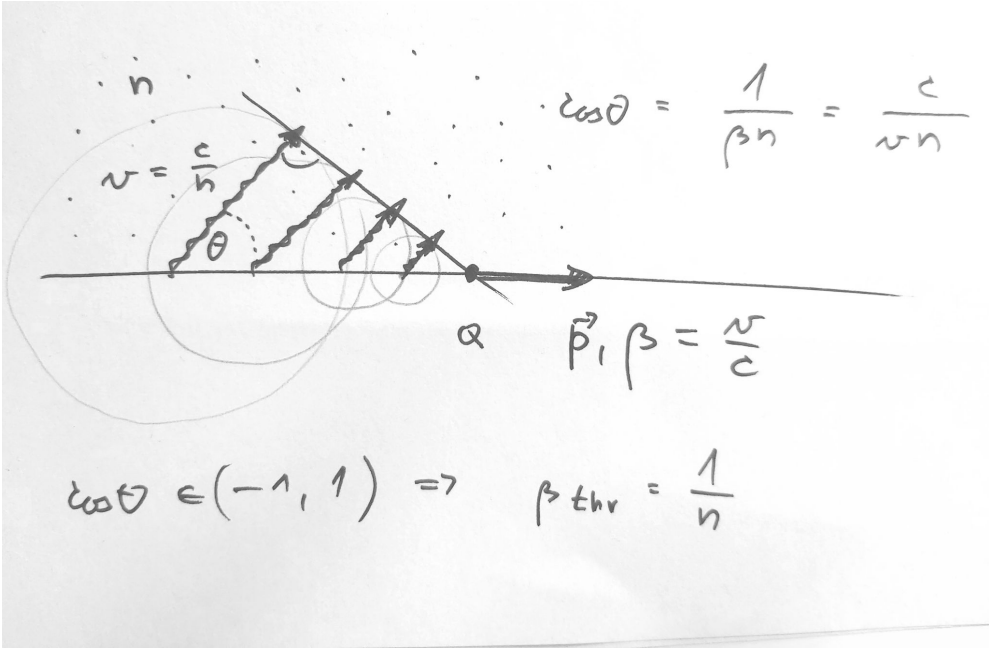


https://physics.stackexchange.com/questions/282353/how-does-particle-speed-affect-cherenkov-radiation
https://en.wikipedia.org/wiki/Sound_barrier

Čerenkovovo záření

- Nabitá částice překračuje rychlost světla v hmotném prostředí
  - ideálně transparentní médium
- $v_{světla}$ = c / index lomu = c / n





https://www.nature.com/articles/s41598-017-08705-4

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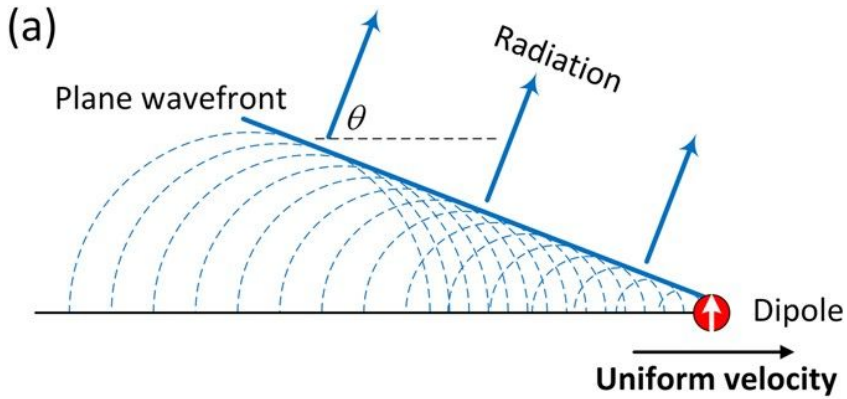
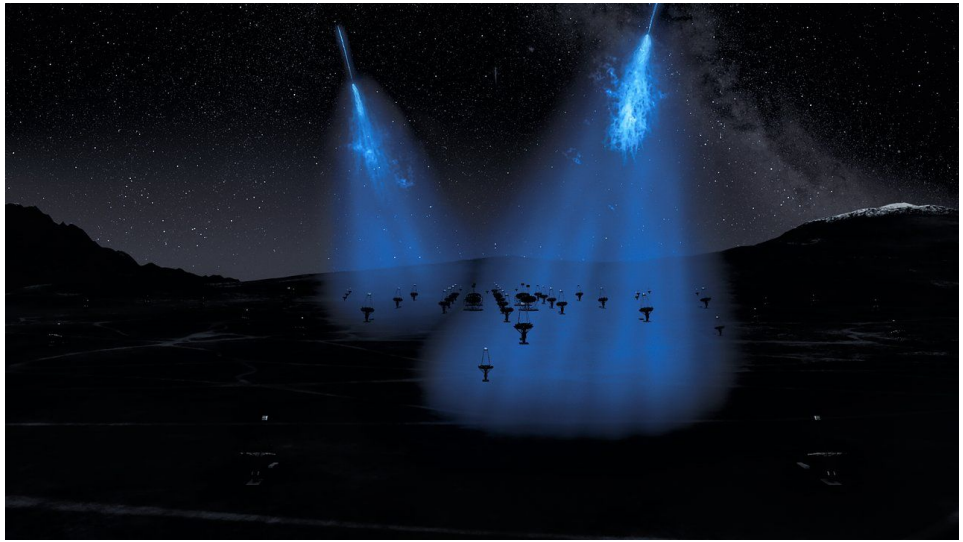
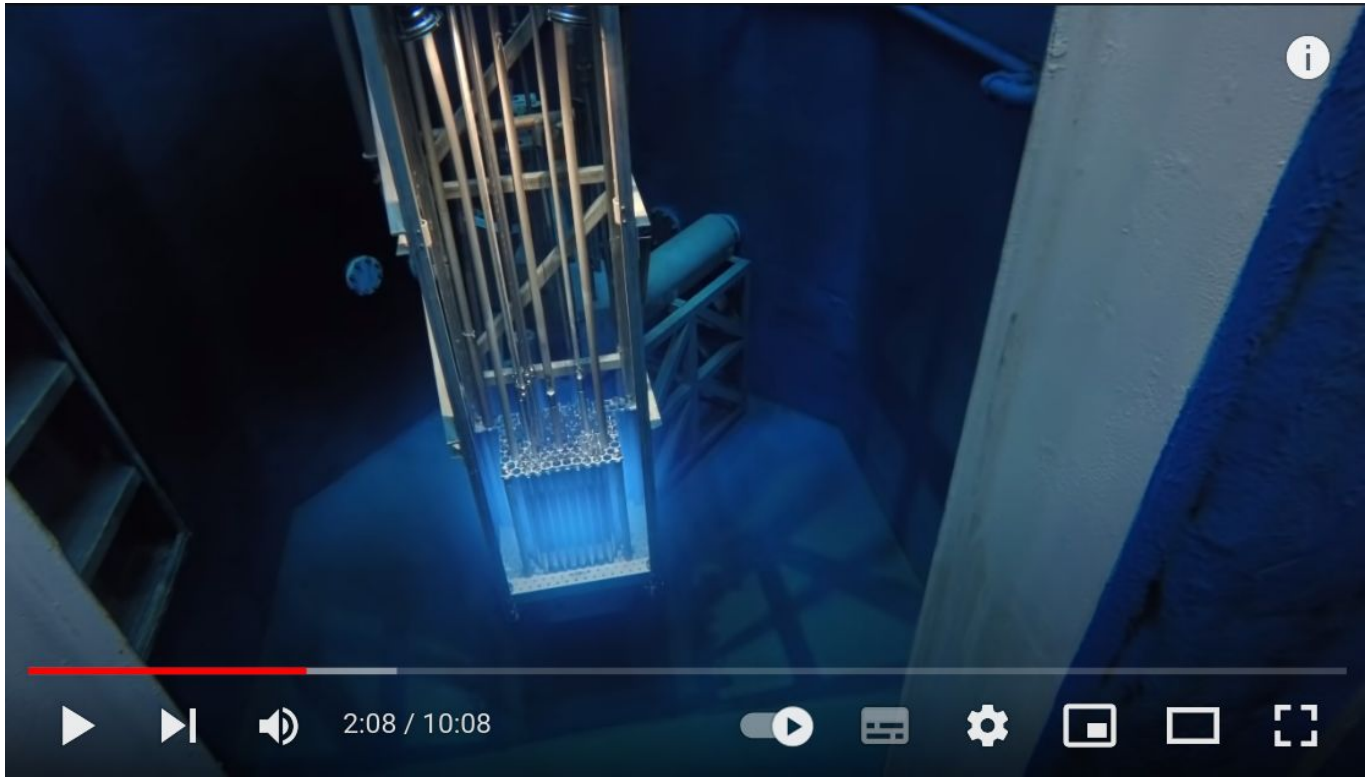


https://www.nature.com/articles/s41598-017-08705-4



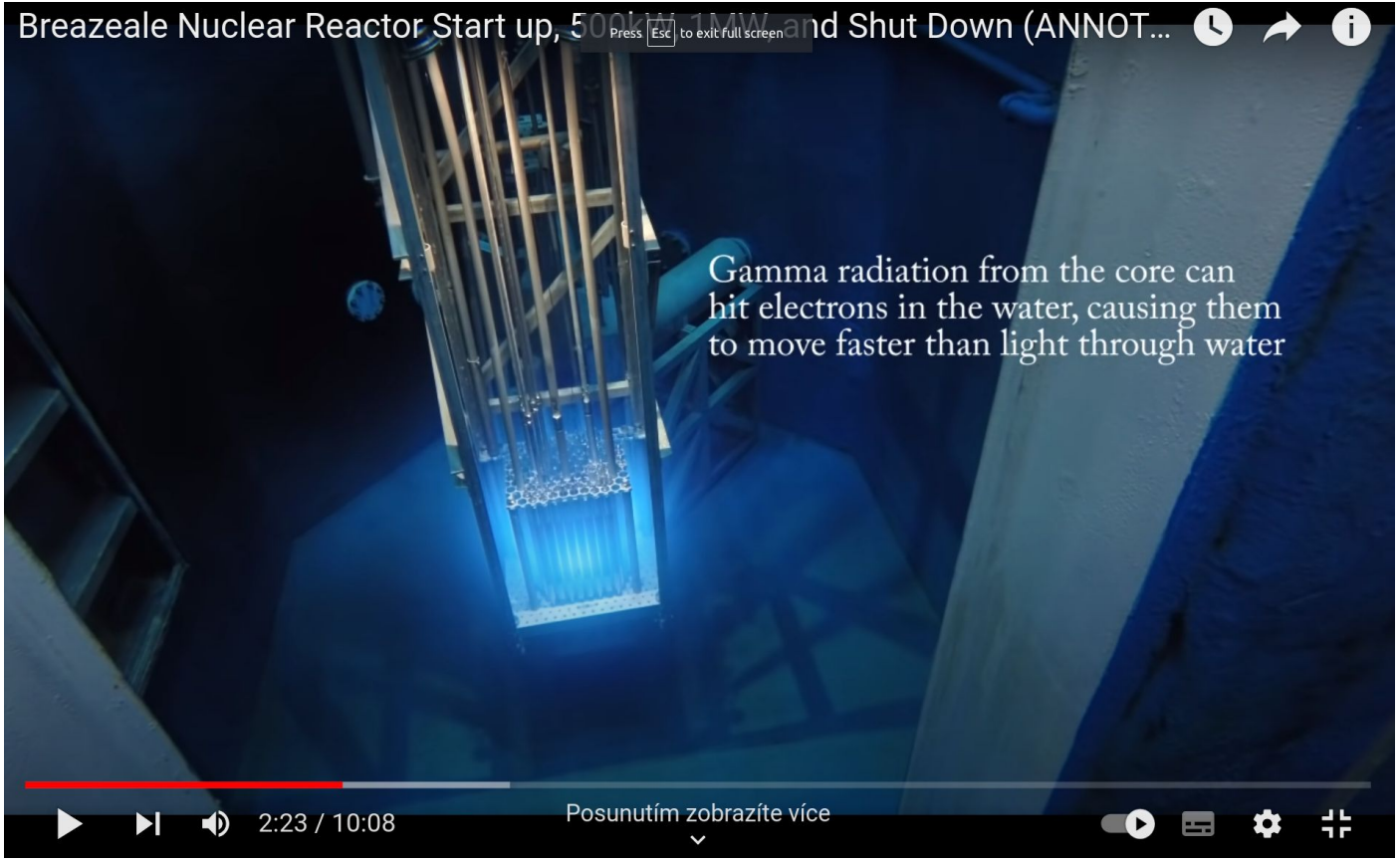
https://www.eso.org/public/czechrepublic/images/eso1841i/

Čerenkovovo záření



https://www.youtube.com/watch?v=uYrhWO_ZLYw&t=516s&ab_channel=AlexLandress

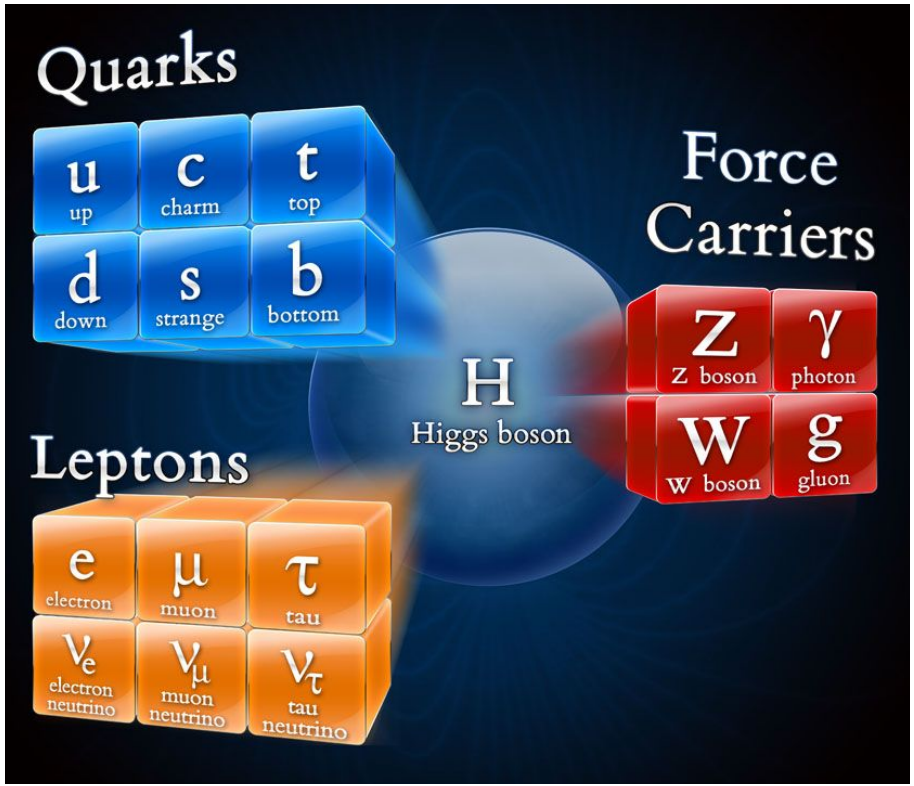
Čerenkovovo záření

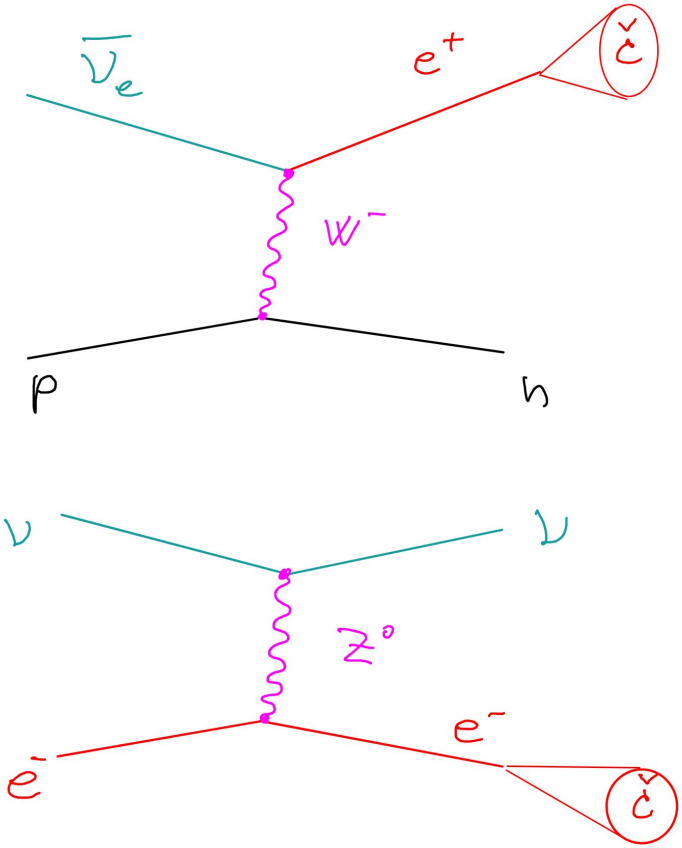


https://www.youtube.com/watch?v=uYrhWO_ZLYw&t=516s&ab_channel=AlexLandress

Interakce neutrin

- Měříme částice, které v interakcích vzniknou
- Druh neutrina je spjat s druhem nabitého leptonu





Experiment Kamiokande(-II) :: 3kt H_20

$p^+ \rightarrow e^+ \pi^0$

$p^+ \rightarrow \mu^+ \pi^0$

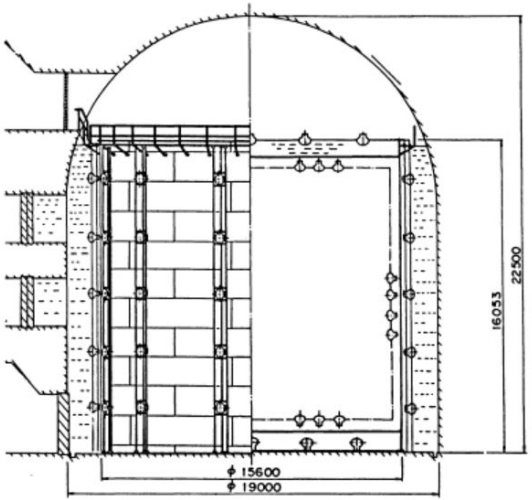
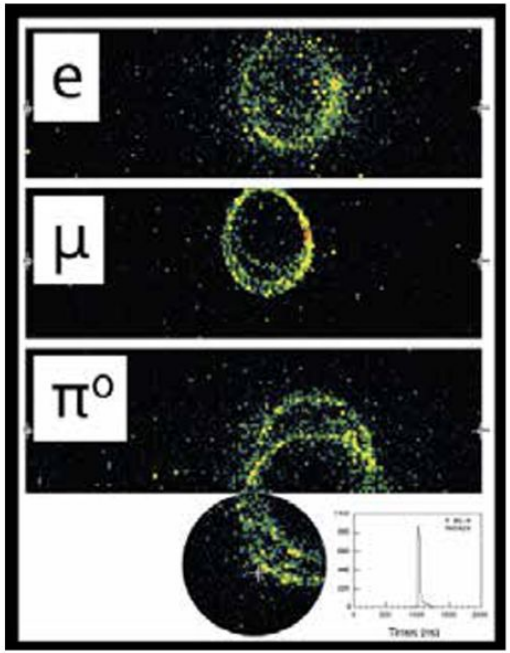


Figure 2: The detector of KAMIOKANDE -II. The dimensions are given in millimeters.



Neutrino identification

https://articles.adsabs.harvard.edu//full/1987ESOC...26..219K/0000220.000.html

SN1987A 24.2.1987 :: 170kly

SN1987A 24.2.1987 :: 170kly

SN1987A 24.2.1987 :: 170kly

https://en.wikipedia.org/wiki/SN_1987A

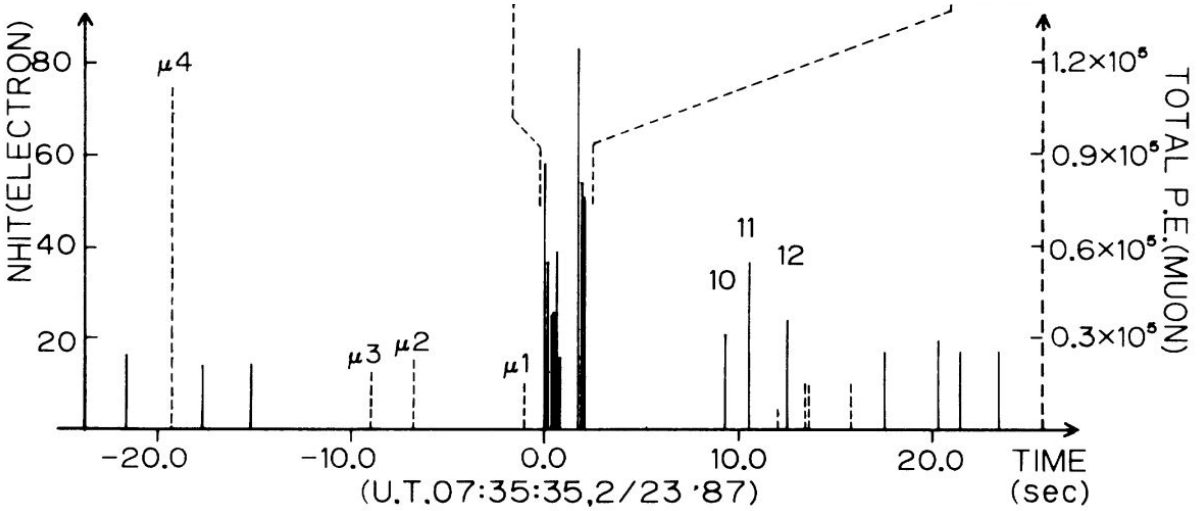
https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/324

Experiment Kamiokande(-II) :: 3kt H_20

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

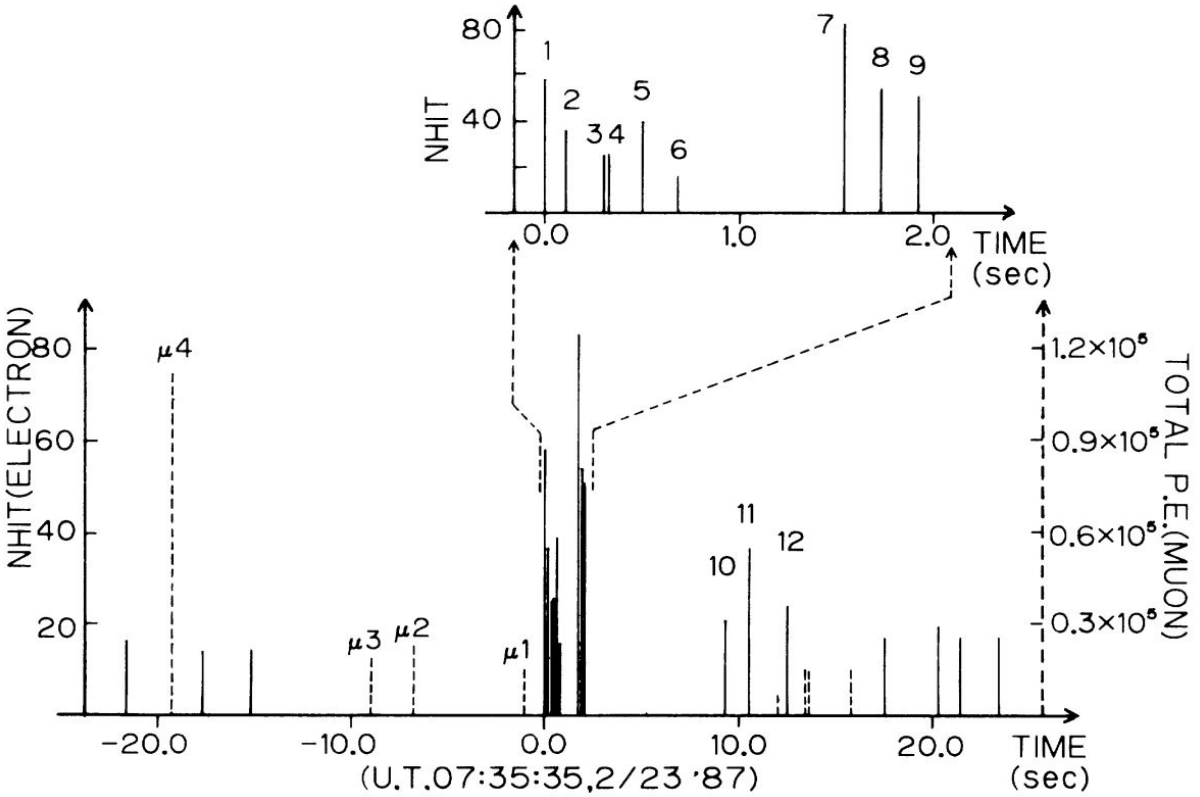
Observation of a Neutrino Burst from the Supernova SN1987A

K. Hirata,[a] T. Kajita,[a] M. Koshiba,[a,b] M. Nakahata,[b] Y. Oyama,[b]
N. Sato,[c] A. Suzuki,[b] M. Takita,[b] and Y. Totsuka[a,c]
University of Tokyo, Tokyo 113, Japan



Experiment Kamiokande(-II) :: 3kt H_20

- Počátky neutrinové astronomie! :-)



Experiment Kamiokande(-II) :: 3kt H_20

- Počátky neutrinové astronomie! :-)
- 1 Erg is a unit of energy equal to 10^{-7} Joules (100 nJ)

form volume distribution. Additional support is provided by the correlation in angle of the first two observed events with the direction to SN1987A. The event burst occurred roughly 18 h prior to the first optical sighting.[1] Correcting for energy-dependent detection efficiency, and assuming that nine of the twelve events are due to $\bar{\nu}_e p^+ \rightarrow e^+ n$, we obtain an integral flux of 1.0×10^{10} $\bar{\nu}_e$ cm^{-2} for the burst, where the $\bar{\nu}_e$ energy (the observed electron energy plus 1.3 MeV) is above 8.8 MeV. This, in turn, leads to the $\bar{\nu}_e$ output of SN1987A of 8×10^{52} ergs for an assumed average energy of 15 MeV.

This observation is the first direct observation in neutrino astronomy, and coincides remarkably well with the current model of supernova collapse and neutron-star formation.[6] In that model an aged, massive star, having exhausted its nuclear fuel, undergoes a supernova explosion. In supernovae of Type II almost all of the gravitational binding energy of the resultant neutron star, $\sim3\times10^{53}$ ergs, is radiated within a few seconds in the form of 10^{58} neutrinos of all flavors with average energy in the vicinity of 10–15 MeV.

Experiment Kamiokande(-II) :: 3kt H_20

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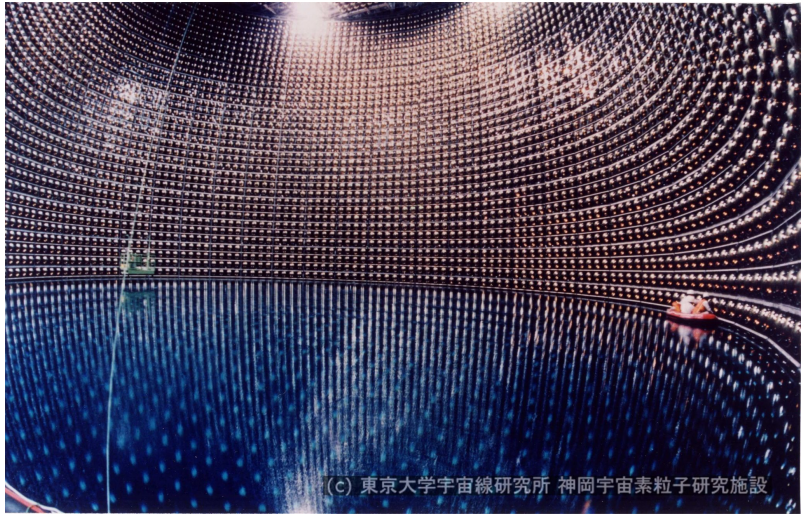
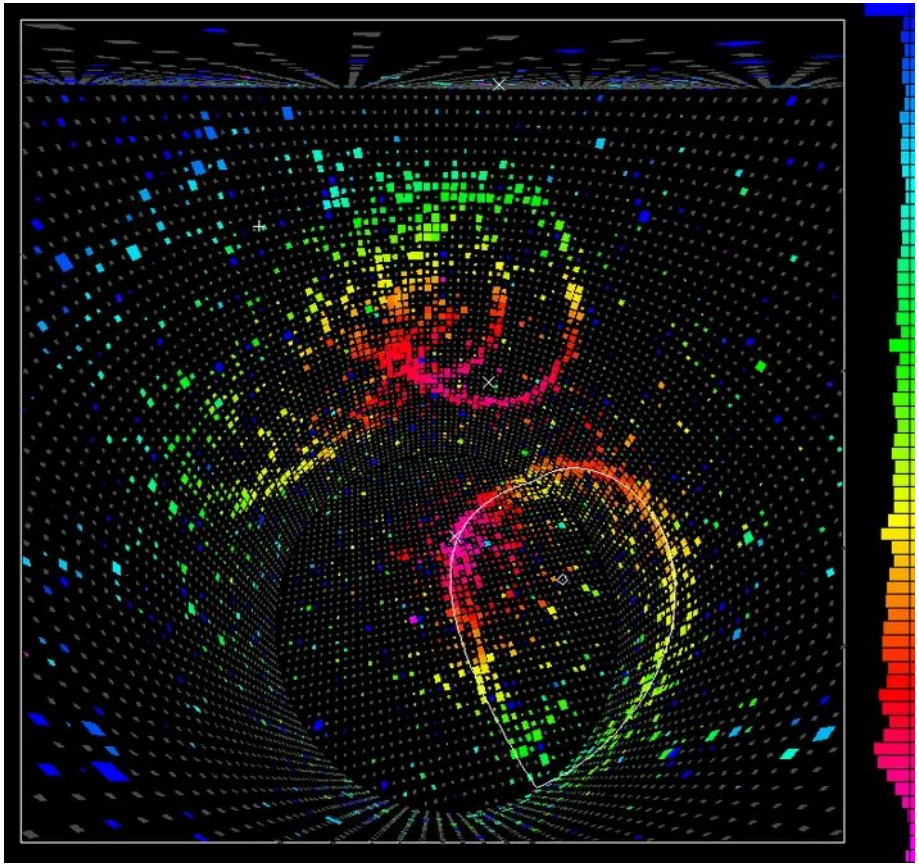
Super Kamiokande :: 50kt H_20
Kamioka Nucleon Decay Experiment

https://www-sk.icrr.u-tokyo.ac.jp/en/sk/about/history/

https://www-sk.icrr.u-tokyo.ac.jp/en/sk/experience/gallery/
https://www.forbes.com/sites/startswithabang/2018/12/05/is-there-really-a-fourth-neutrino-out-there-in-the-universe/





Fyzikální program: Oscilace neutrin

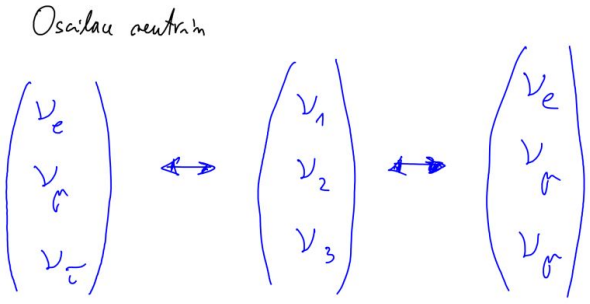
- Zde ilustrace na měření oscilací reaktorového experimentu Daya Bay a JUNO.

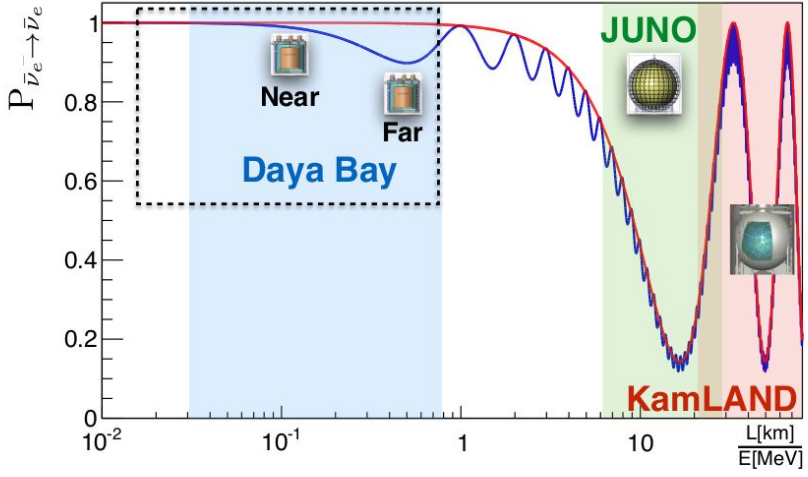
WW Looking at the flux of $\bar{\nu}_e$ as a function of distance and energy

WW Some $\bar{\nu}_e$'s disappear due to neutrino oscillation

Medium baseline | Short baseline

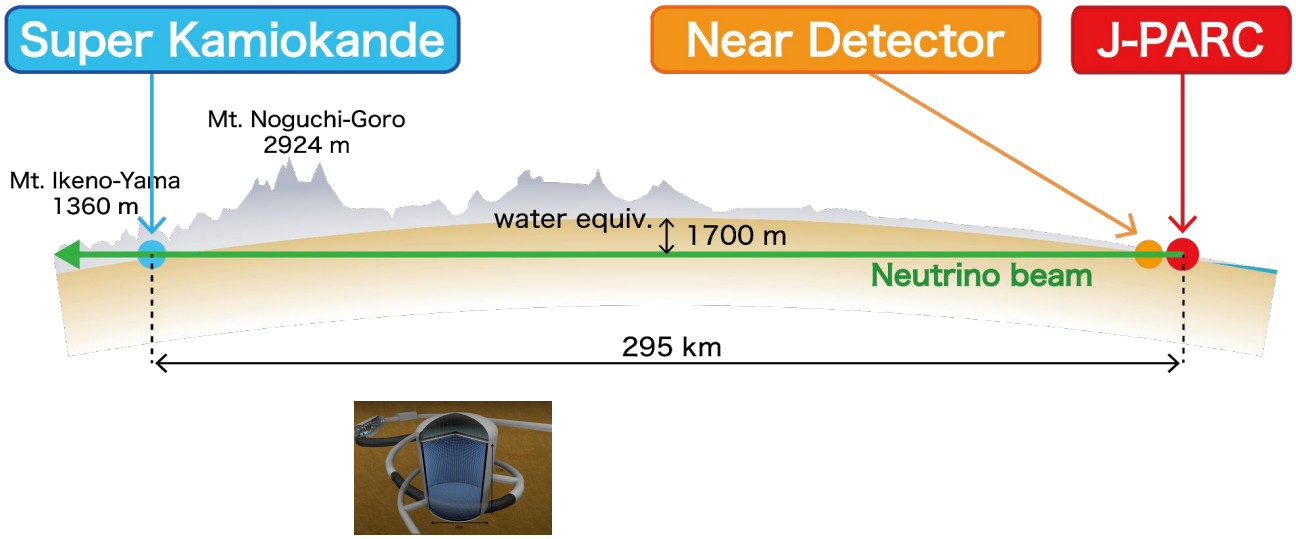
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E} - \sin^2 2\theta_{13} \left(\cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} \right)$$





Super Kamiokande a neutrina z urychlovačů

- Oscilace neutrin zkoumány i s uměle vytvořenými neutriny ze svazků částic na urychlovačích.



Super Kamiokande

https://www-sk.icrr.u-tokyo.ac.jp/en/sk/experience/gallery/
https://www.forbes.com/sites/startswithabang/2018/12/05/is-there-really-a-fourth-neutrino-out-there-in-the-universe/

The Nobel Prize in Physics 2002

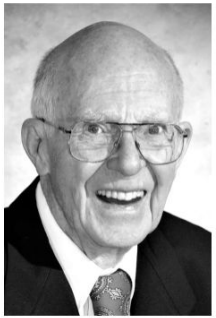


Photo from the Nobel Foundation archive.

Raymond Davis Jr.

Prize share: 1/4

Photo from the Nobel Foundation archive.

Masatoshi Koshiba

Prize share: 1/4

Photo from the Nobel Foundation archive.

Riccardo Giacconi

Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos" and the other half to Riccardo Giacconi "for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

The Nobel Prize in Physics 2015

© Nobel Media AB. Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud

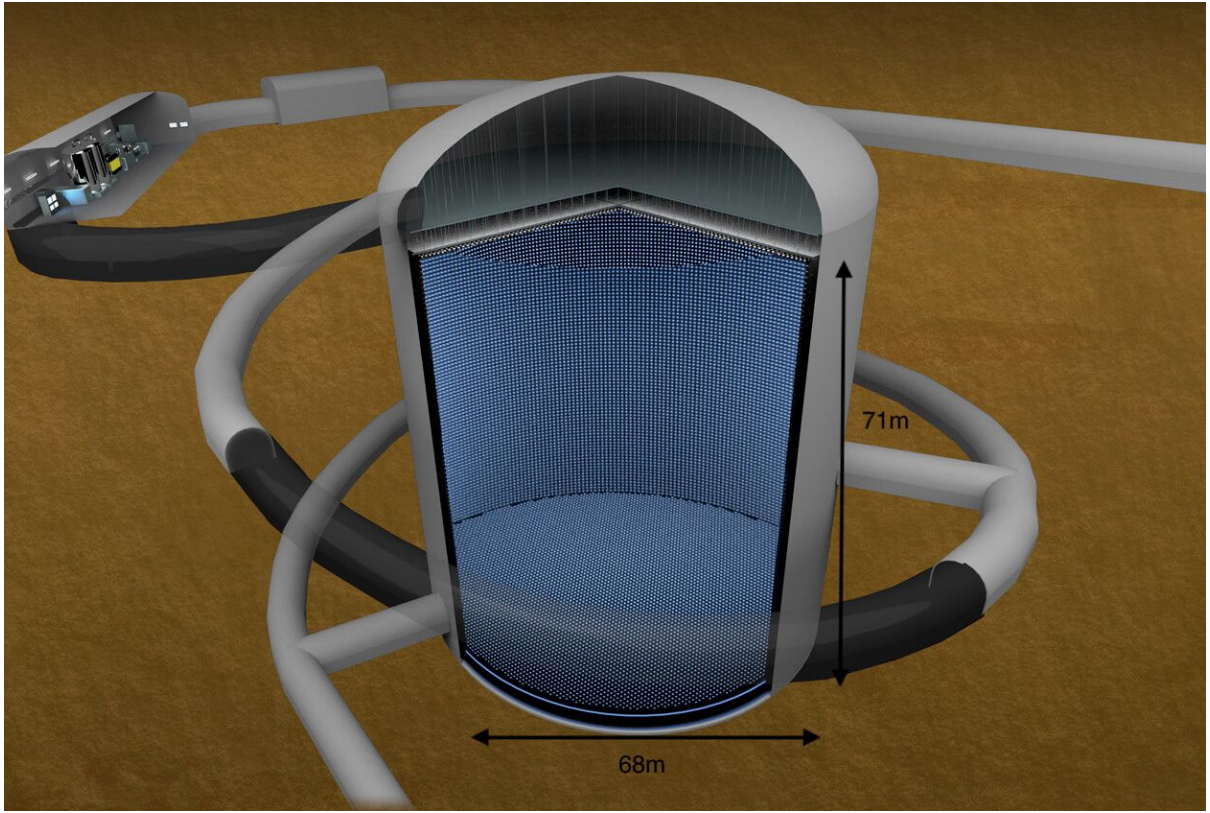
Arthur B. McDonald

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"

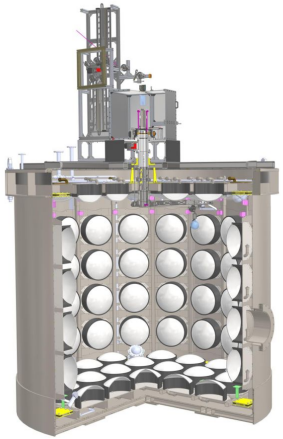
Hyper Kamiokande :: 250kt H_20

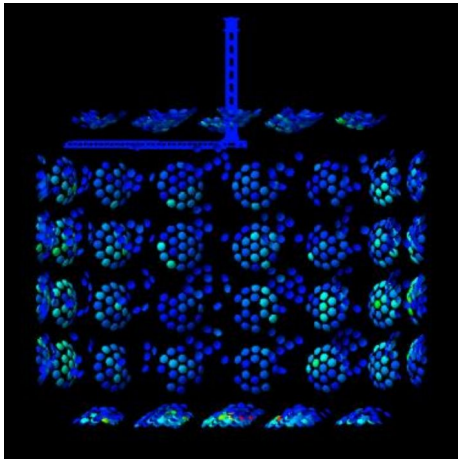
https://www-sk.icrr.u-tokyo.ac.jp/en/hk/about/detector/
https://www-sk.icrr.u-tokyo.ac.jp/en/hk/



YT :: Hyper-Kamiokande
https://www.youtube.com/watch?v=JFOE3D2z7LM&t=12s&ab_channel=Hyper-Kamiokande

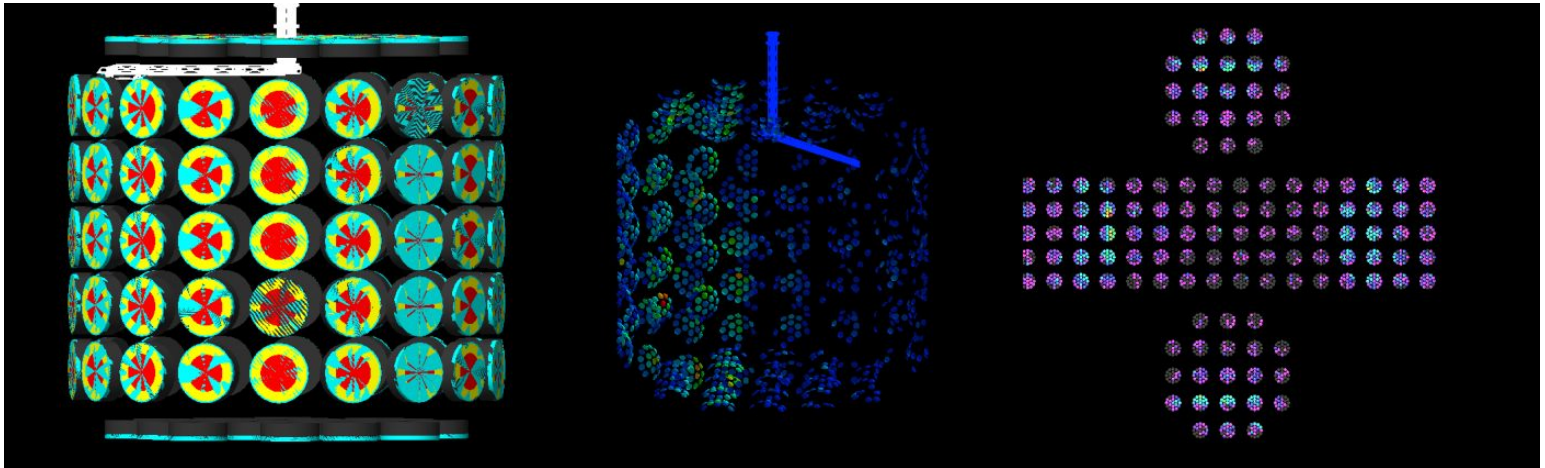
Water Cherenkov Test Experiment :: 50t H_2O @ CERN



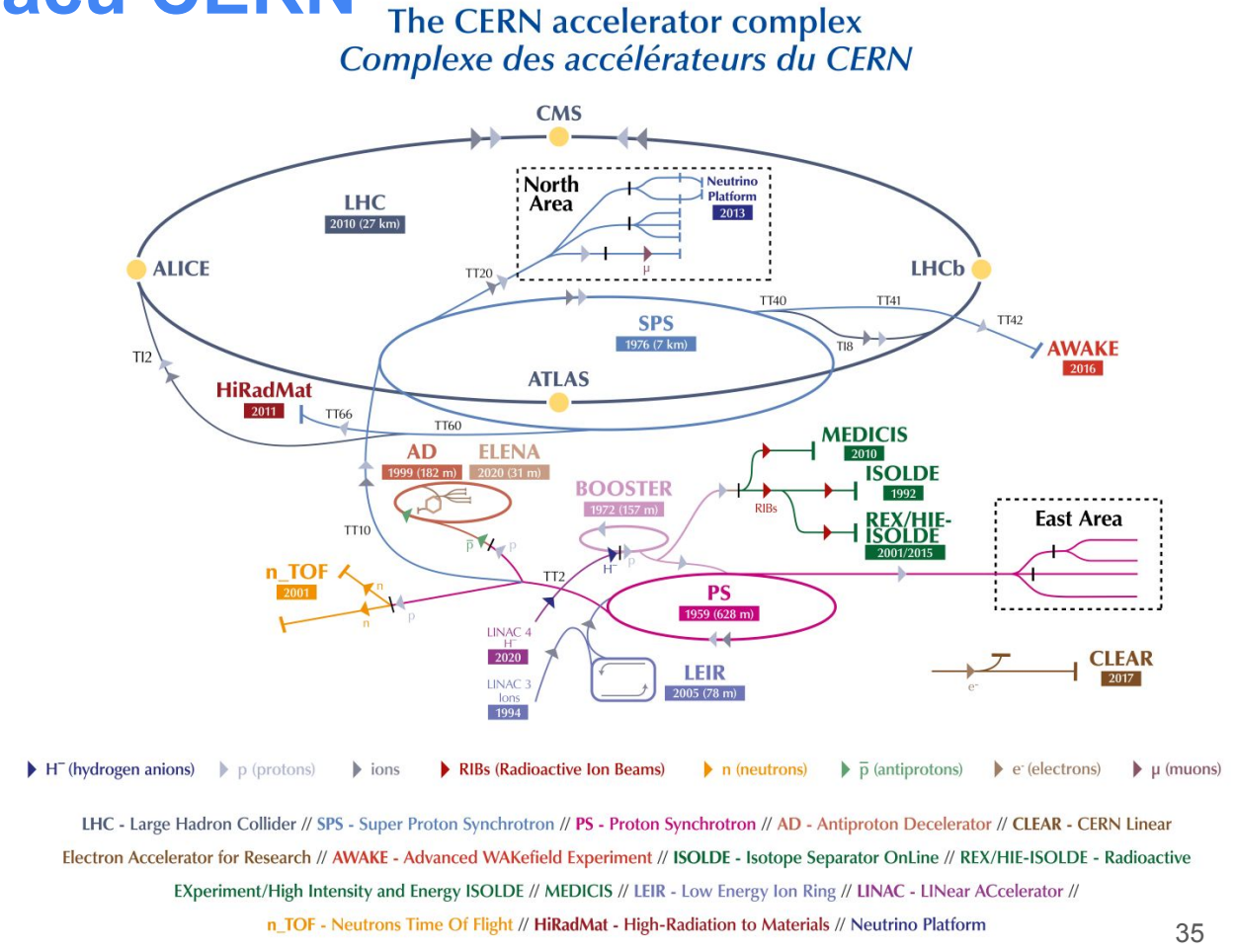


- Cíl: porozumět interakcím částic vznikajících v neutrinových reakcích.
- Pro kalibrace velkých neutrinových experimentů.

https://indico.cern.ch/event/855372/contributions/4452155/attachments/2304577/3921520/WCTE@CERN_NuFACT-2021-09-08_LAnthony.pdf

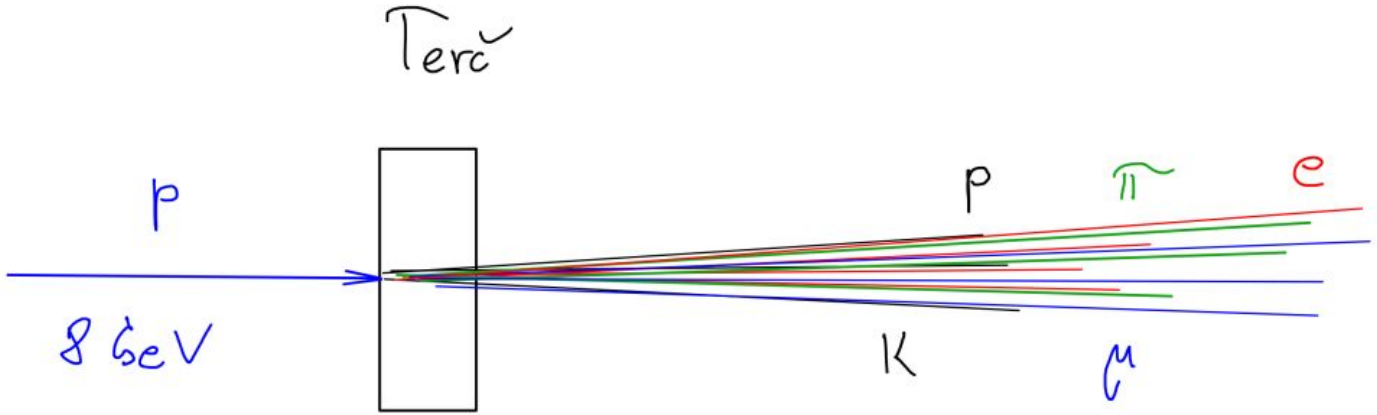


Komplex urychlovačů CERN



https://home.cern/science/accelerators/accelerator-complex

Složení svazku pro WCTE



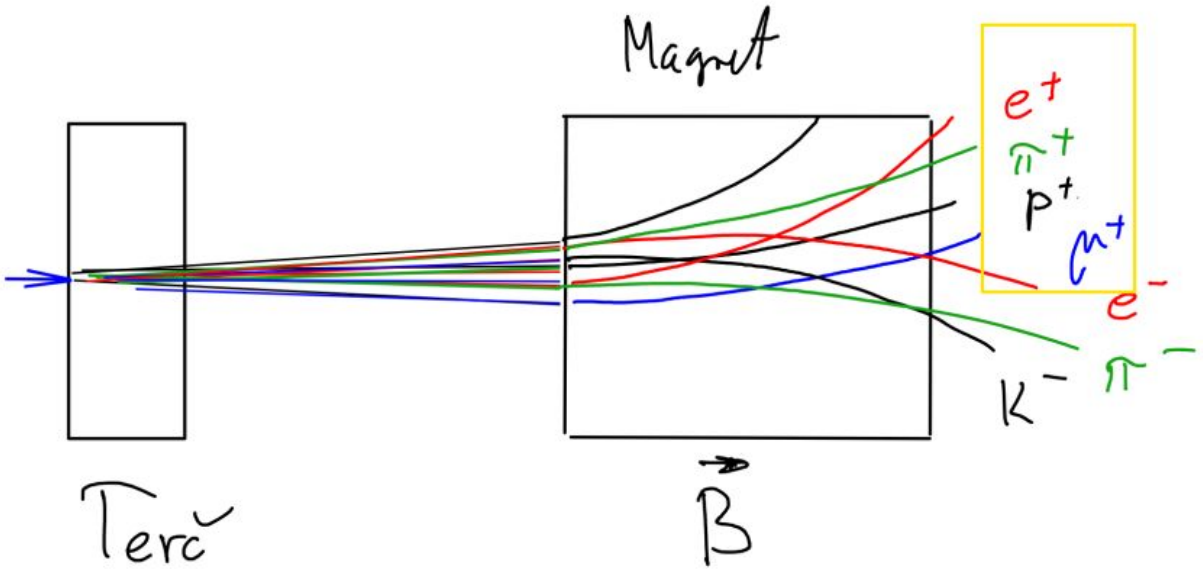
$|\vec{p}|$ 200 MeV ≃ 1 GeV

Složení svazku pro WCTE

$$p = m v \qquad \beta \equiv \frac{v}{c}$$

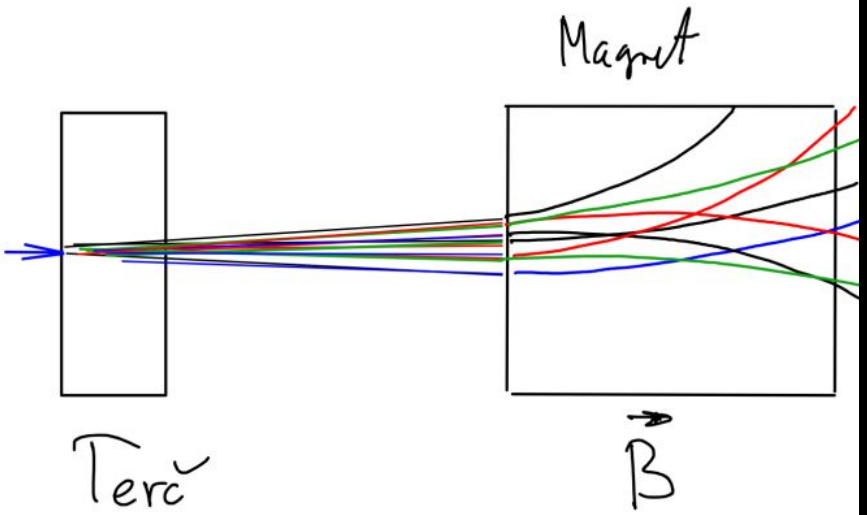
$$p = \gamma m v = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} m v$$

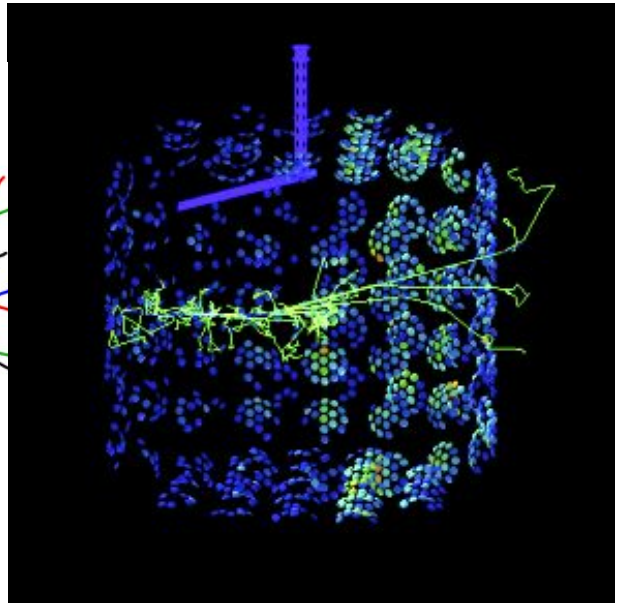
$$p = \beta \gamma mc = \frac{1}{\sqrt{1 - \beta^2}} \beta mc$$



Složení svazku pro WCTE

- Bude ale v sekundárním svazku dost pionů/mionů na kalibraci odezvy detektoru na tyto částice?
- Potřeba nejprve změřit složení svazku!
- Identifikace částic.





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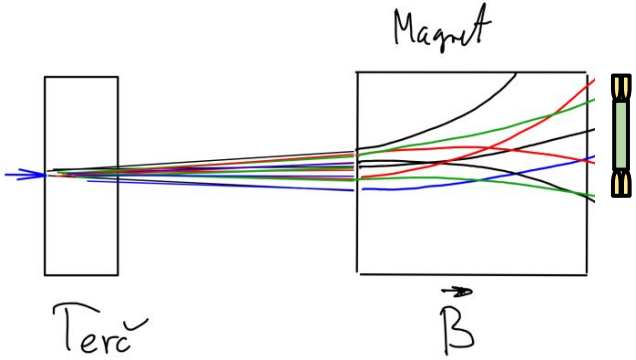
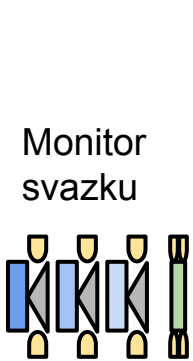
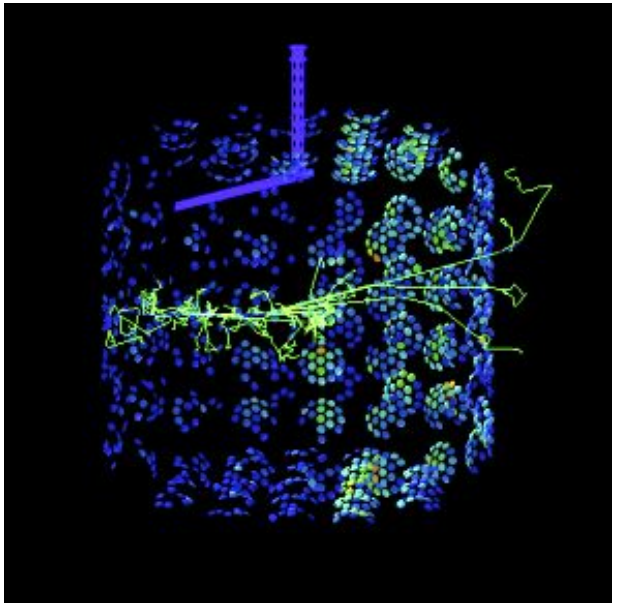
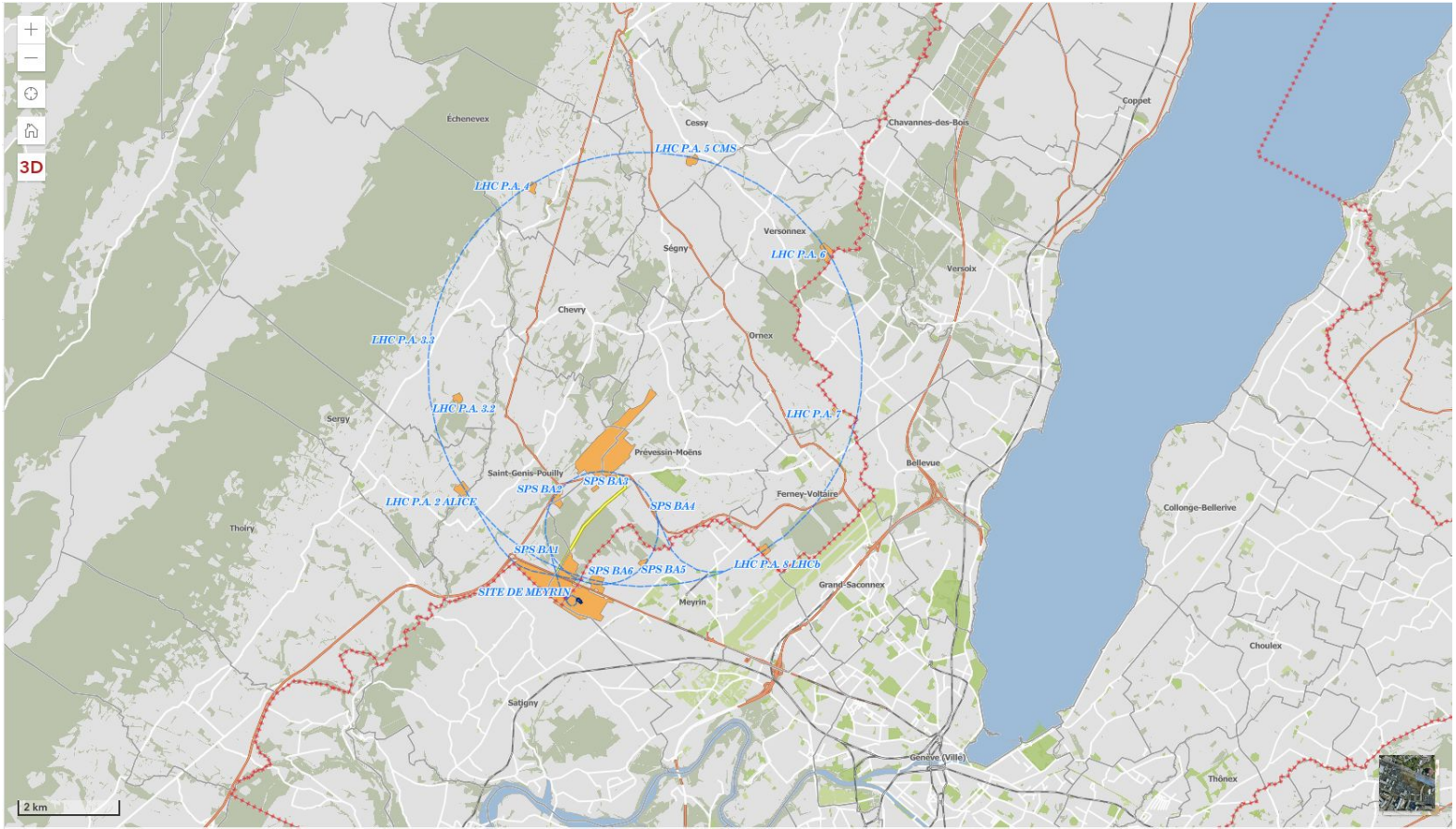


Monitor svazku





CERN :: https://maps.web.cern.ch/



CERN :: https://maps.web.cern.ch/

East Area 2022

- Building 157 at CERN's Meyrin site, large experimental hall housing also the CLOUD experiment, T8, T9 and T10 beam lines.

East Area

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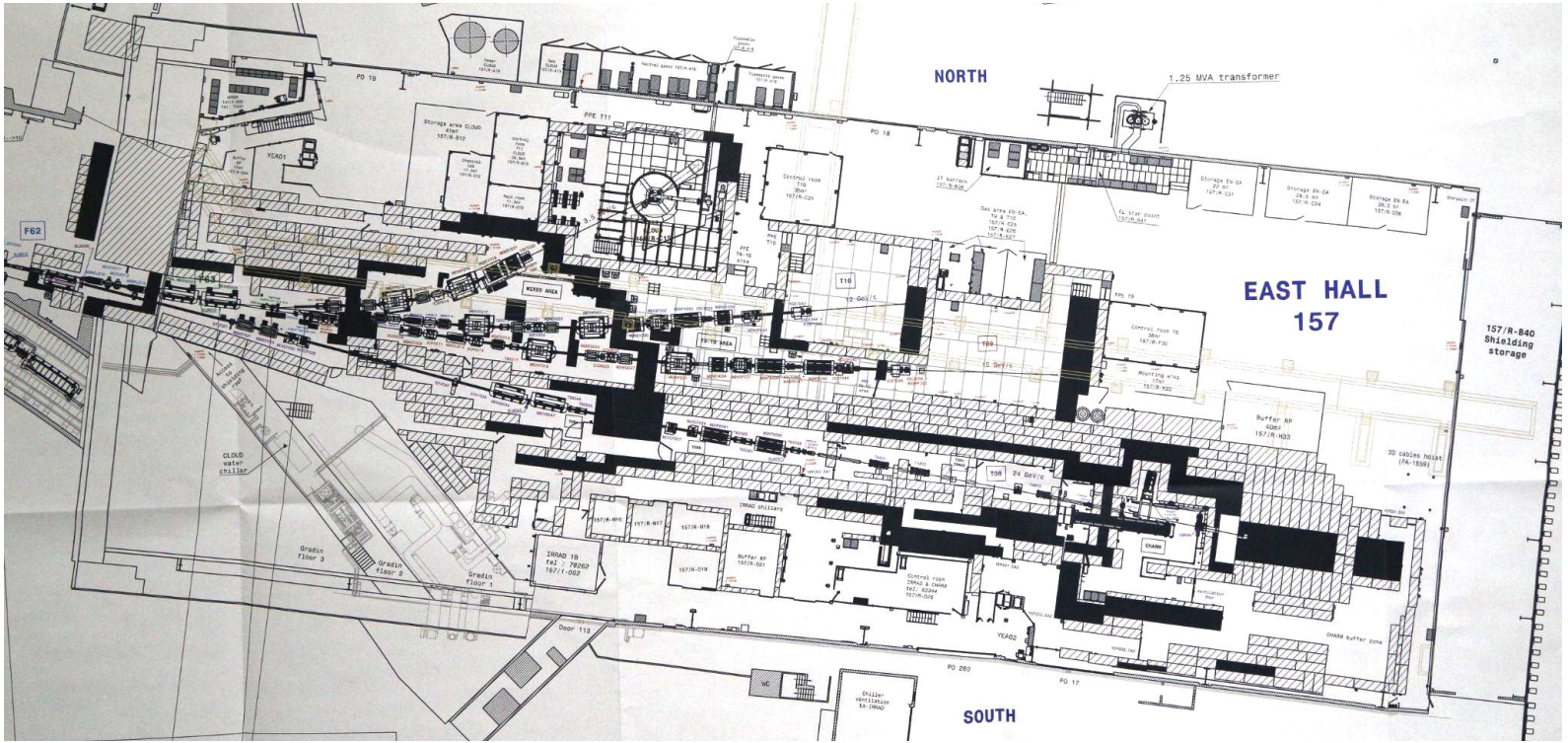

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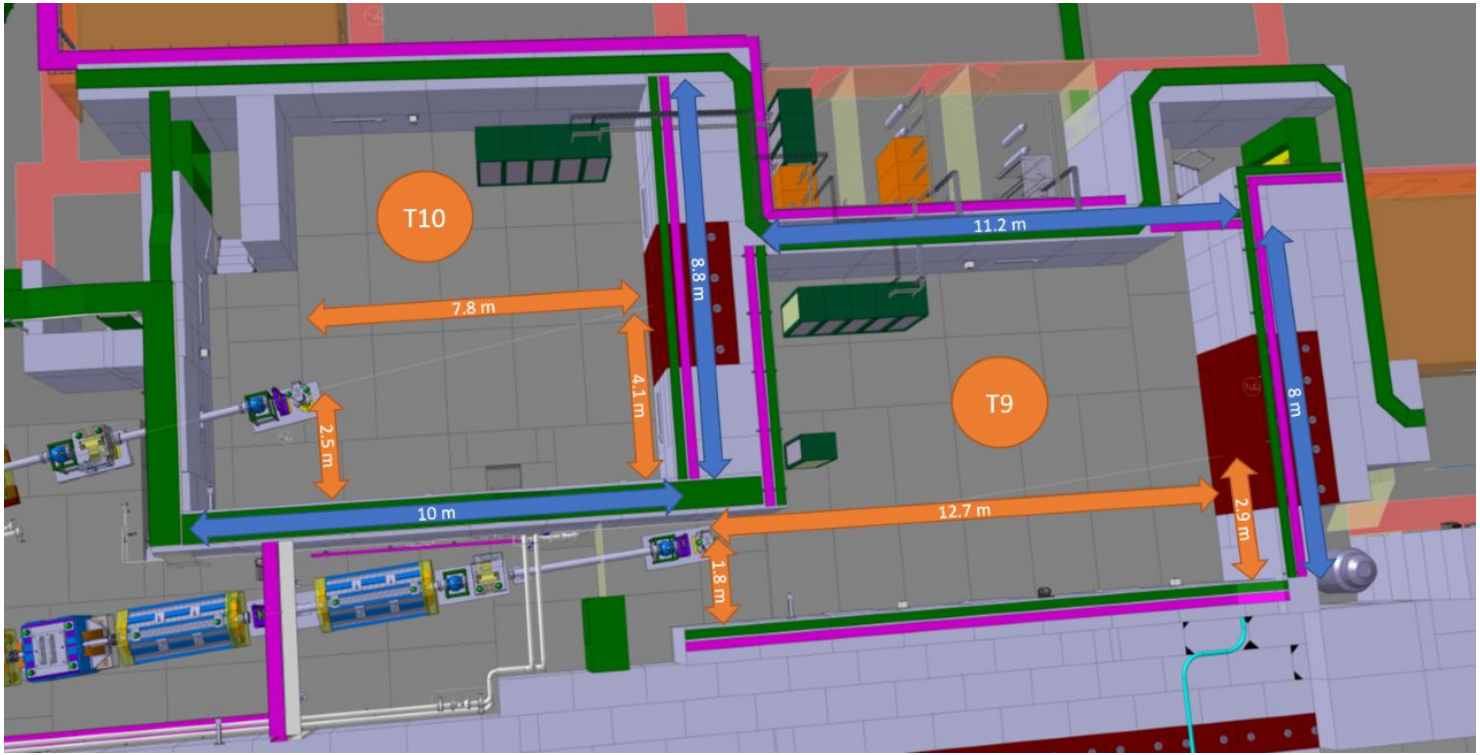

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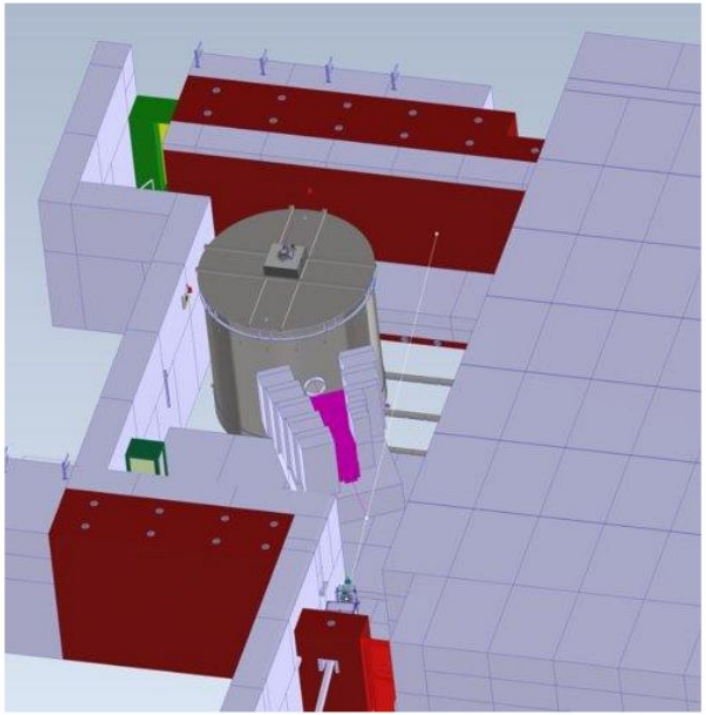

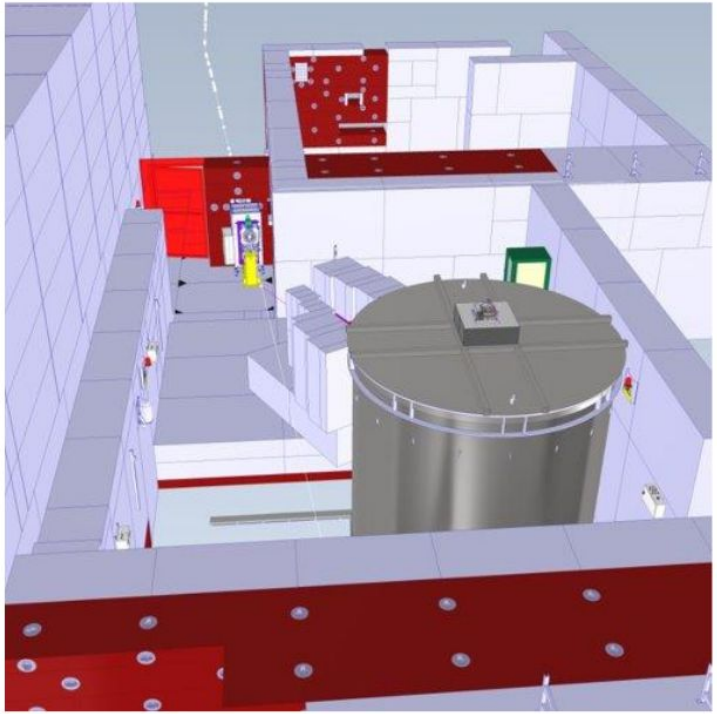

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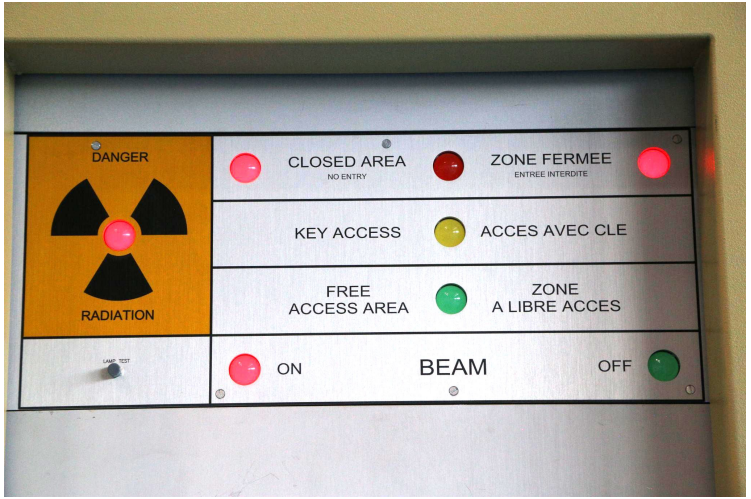
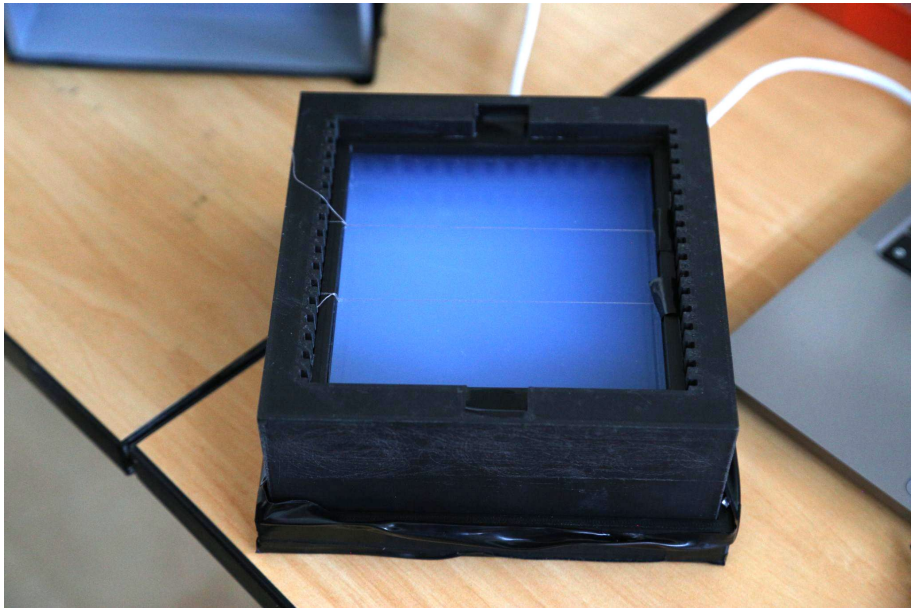


Installation :: Aerogel Cherenkovs

- Transparent aerogel produces Cherenkov radiation when a particle with velocity above the speed of light passes through.
- **World's Lightest Solid!**
  - https://www.youtube.com/watch?v=AeJ9q45PfD0&ab_channel=Veritasium
- Light is reflected by thin foil mirrors to PMT on both sides.

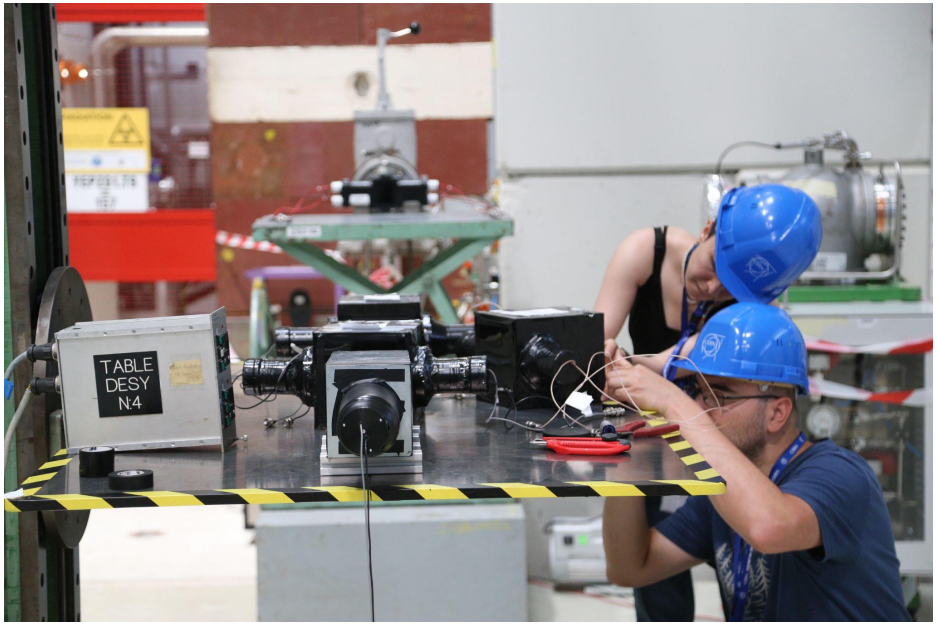


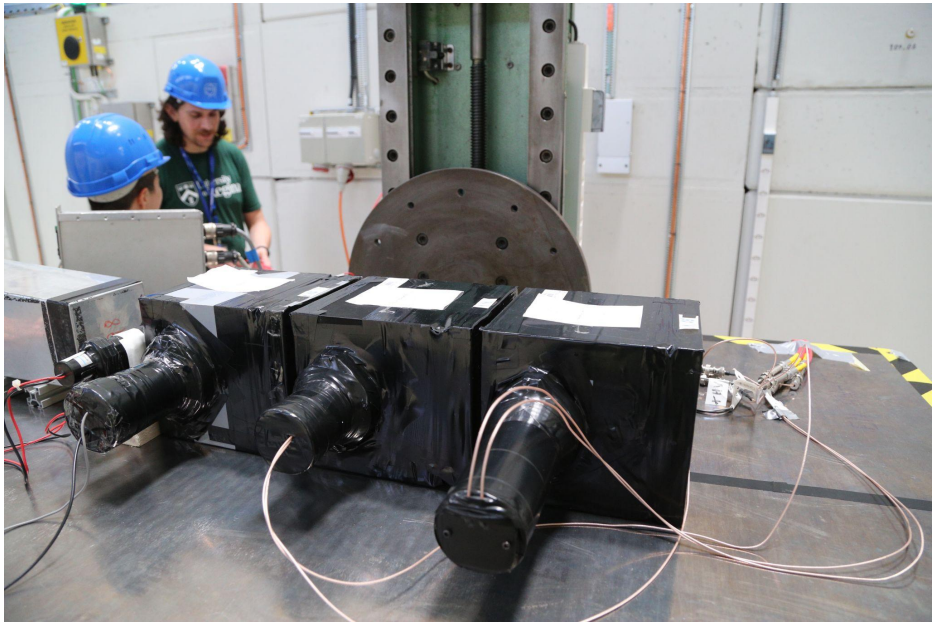
Aerogel

- **World's Lightest Solid!**
  - https://www.youtube.com/watch?v=AeJ9q45PfD0&ab_channel=Veritasium

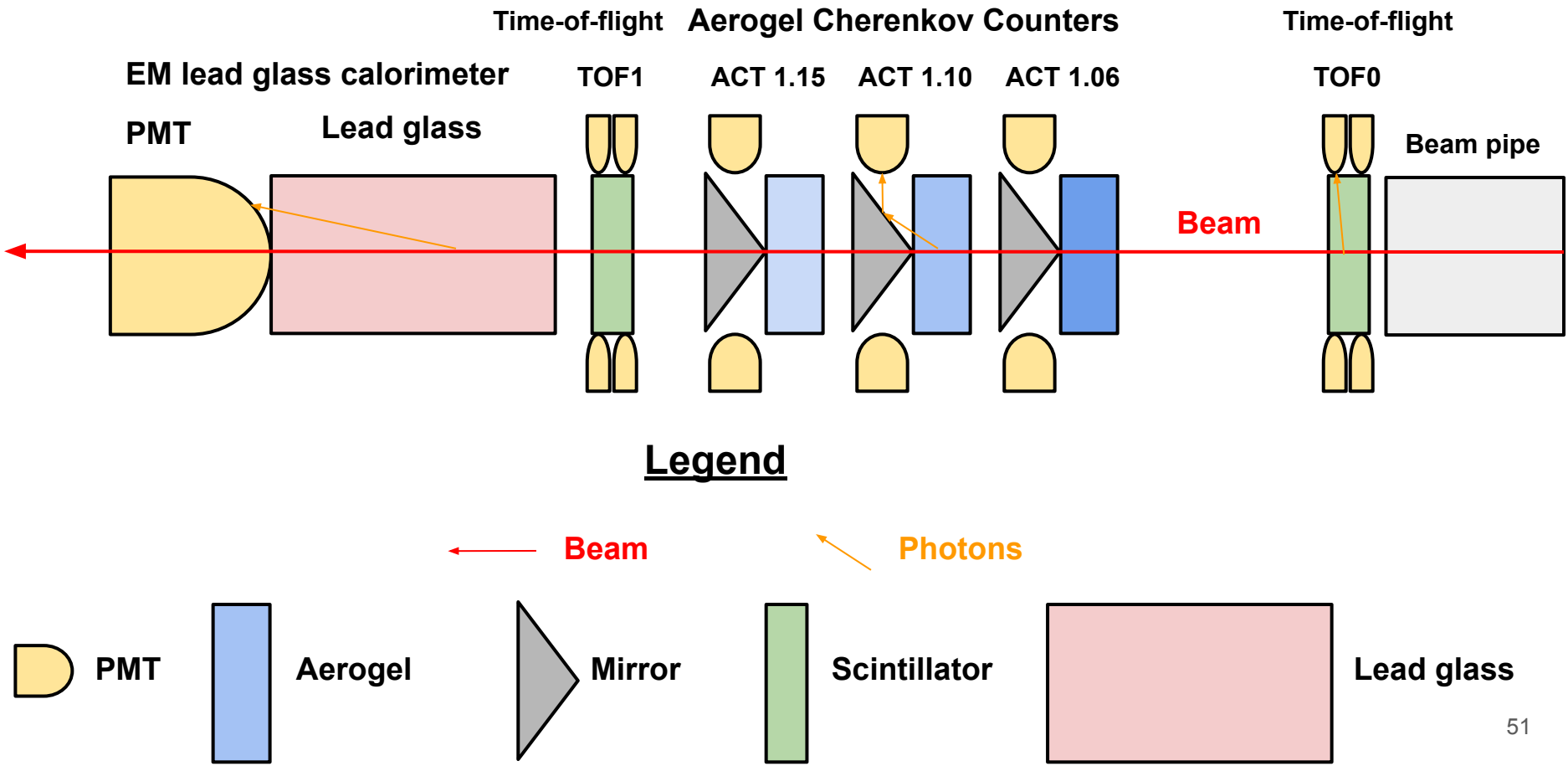
Installation :: Aerogel Cherenkovs

- Alignment enough to few mm from the indicated beam line.

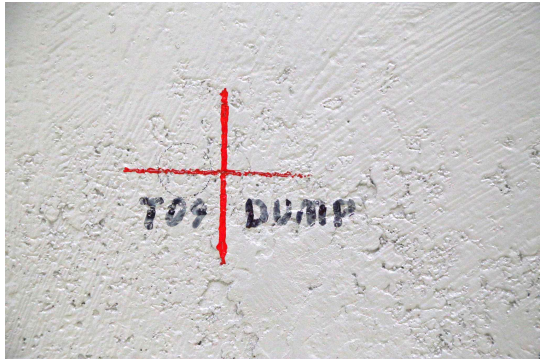


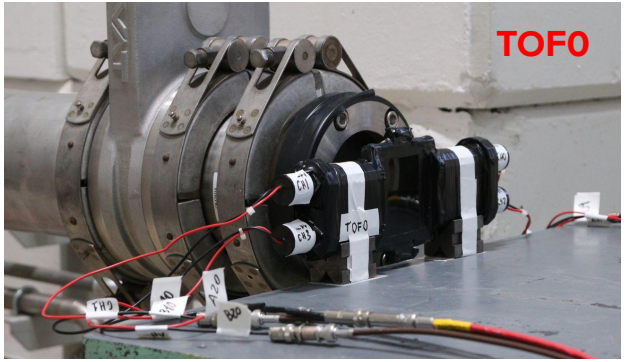


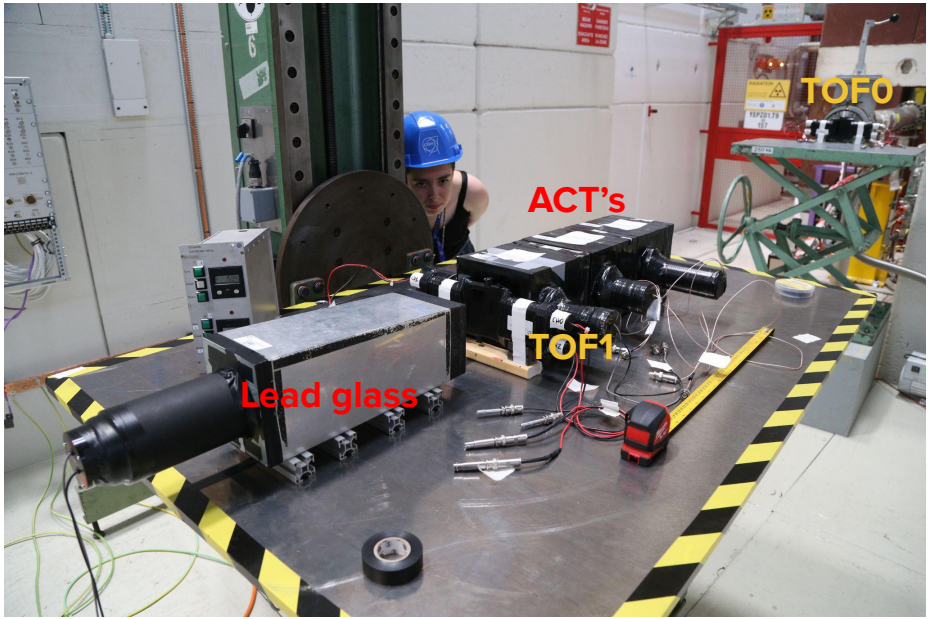
Setup overview

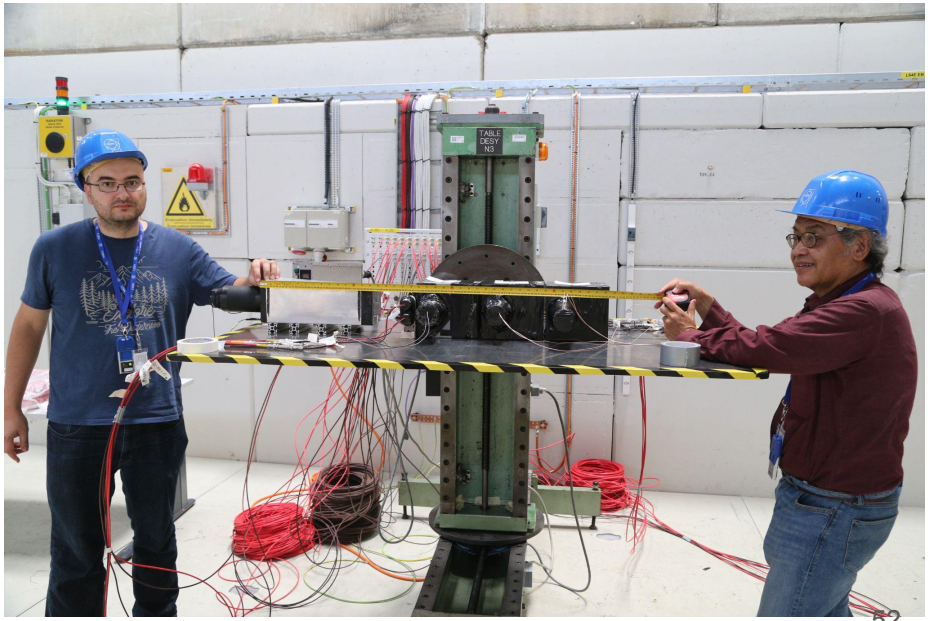


Real Experiment







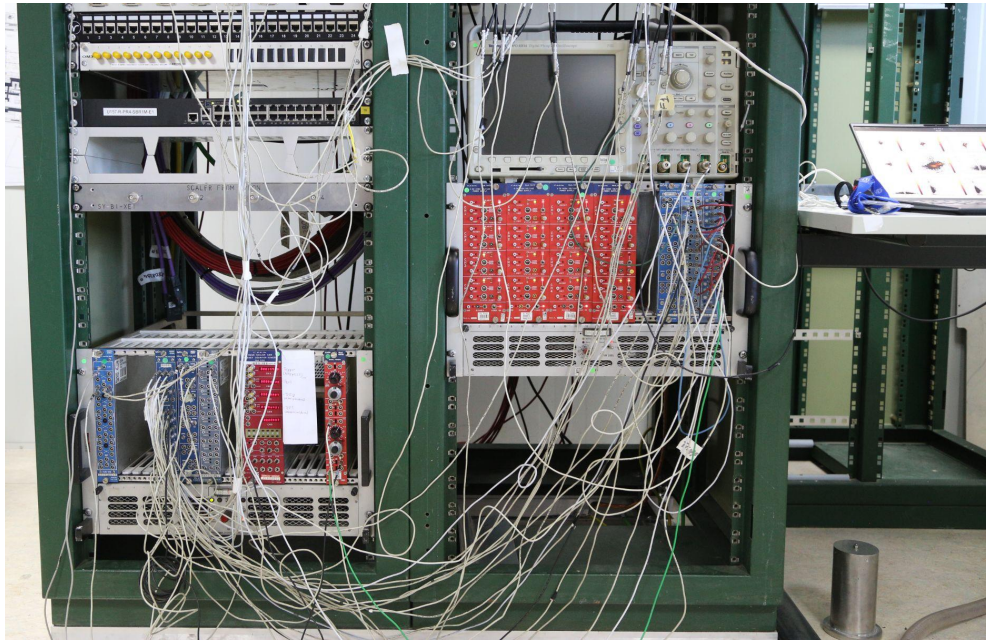


T9 Control Room

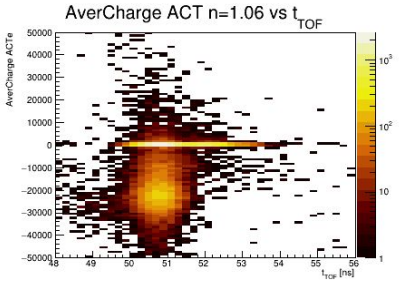
- Incoming spill sound;)
  - https://jointlab.upol.cz/kvita/TB_T9_beep.wav

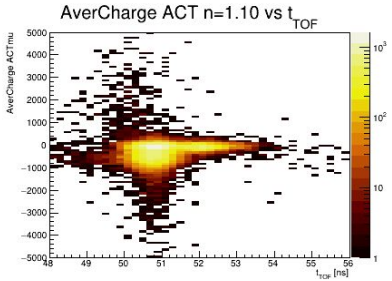
Readout setup

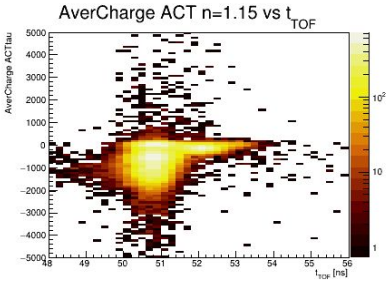
- High Voltage cables (HV)
- Readout cables to trigger/veto unit and to two 8-channel CAEN digitizers.
- 15 PMTs read out, one channel read out simultaneously by the two 8-channel digitizers, for time synchronization verification.

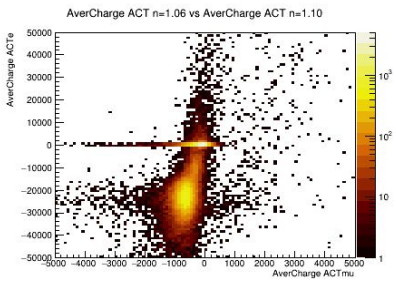


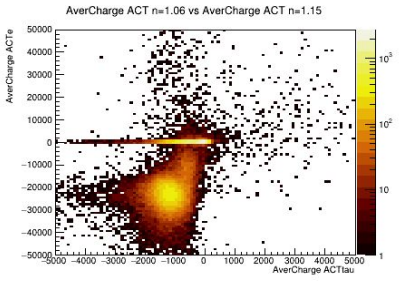
Channels correlations

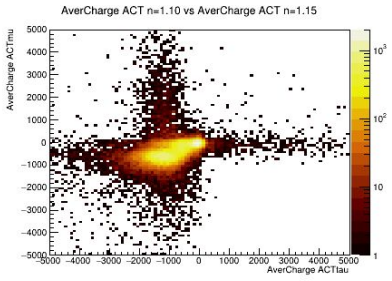
- 

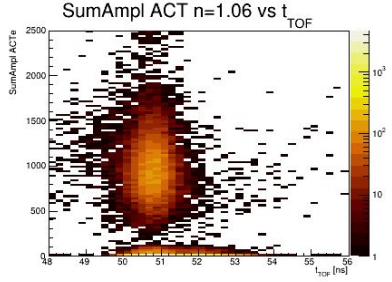


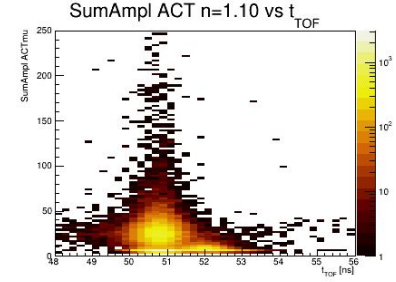


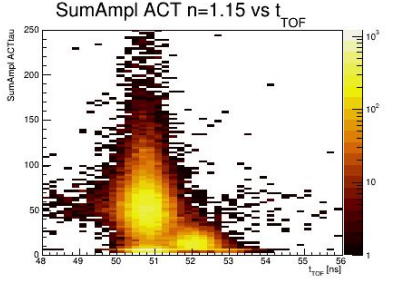


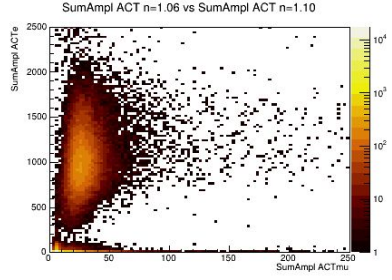


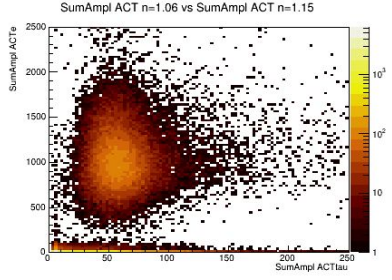


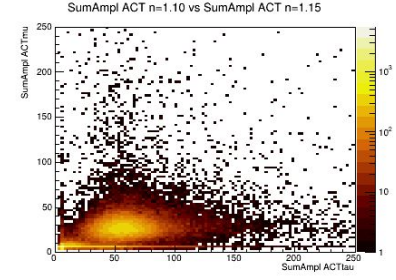






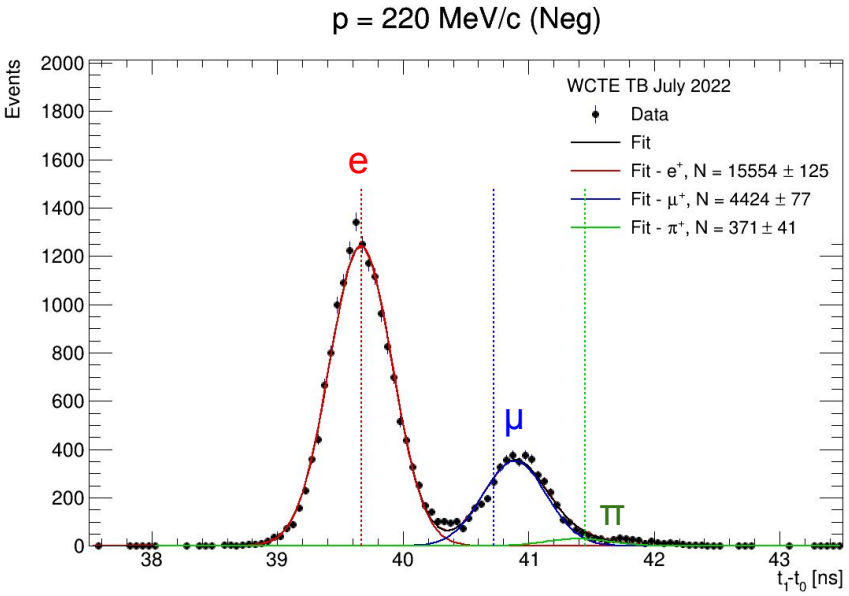


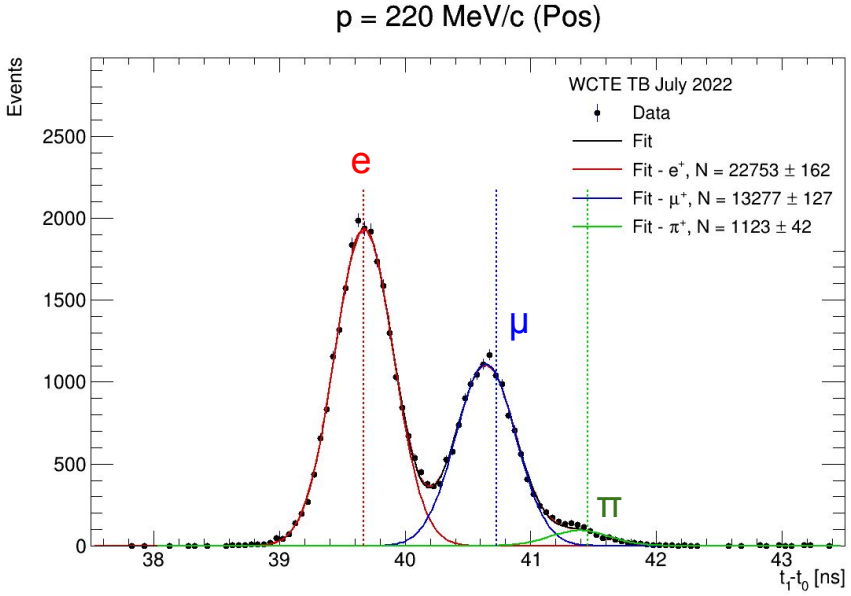




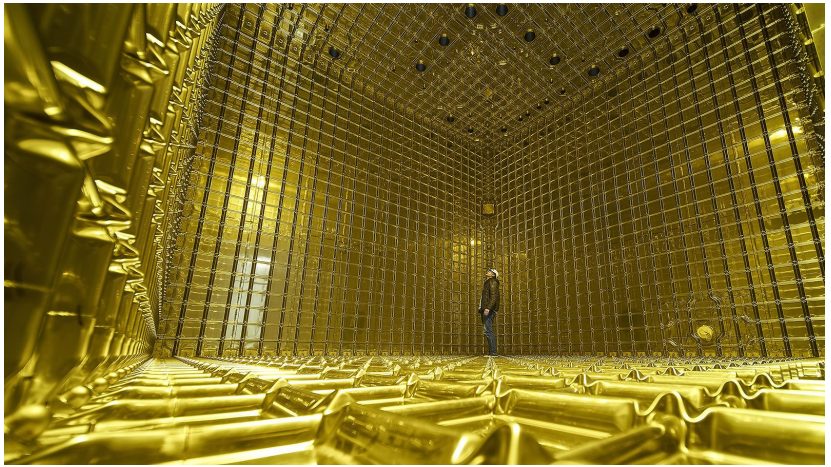
Results – Example TOF distributions

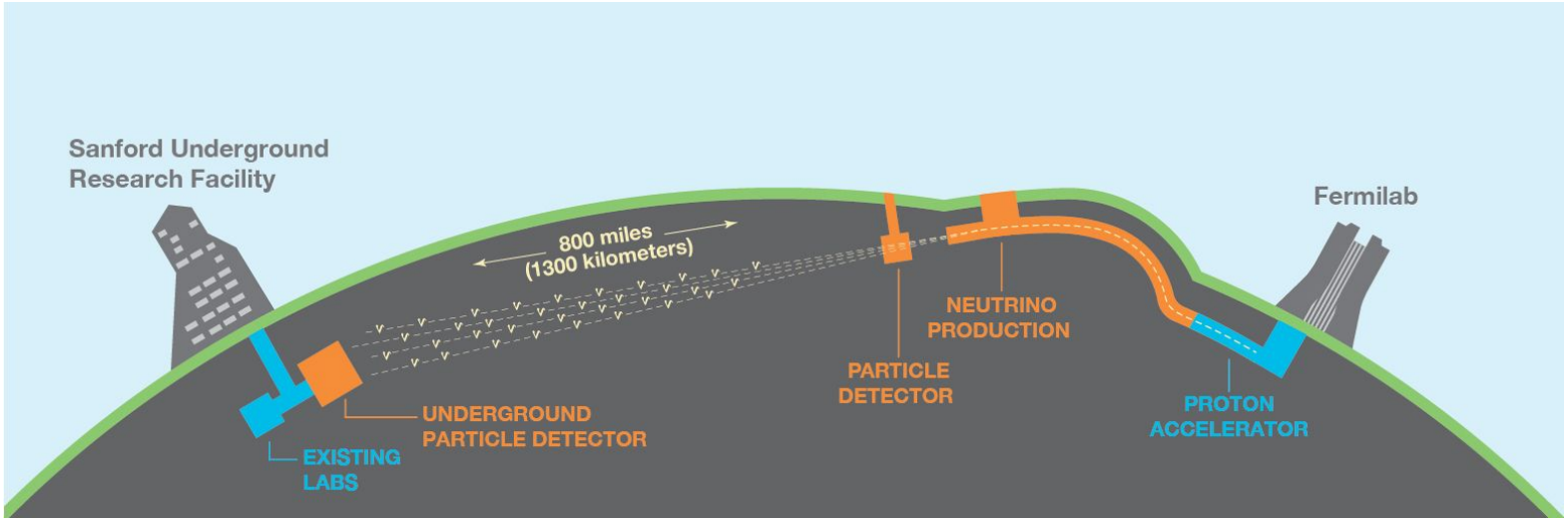
- Theoretical vertical lines for the μ and π TOF shifts after the fitted e peak.
- TOF peak positions: a possible beam bias between Pos and Neg momenta?



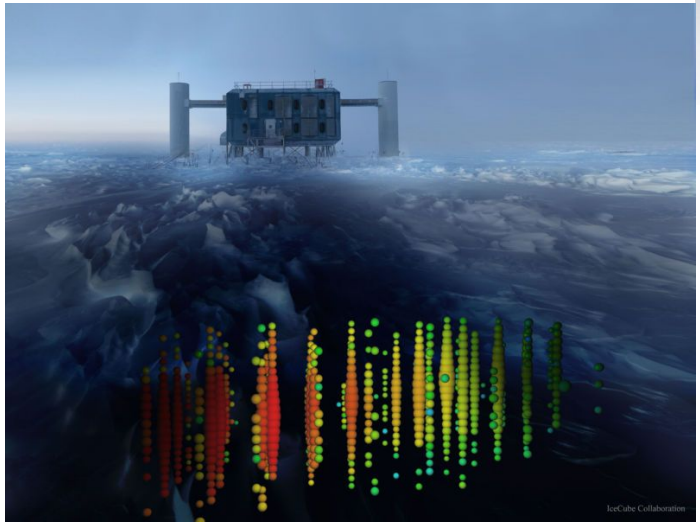


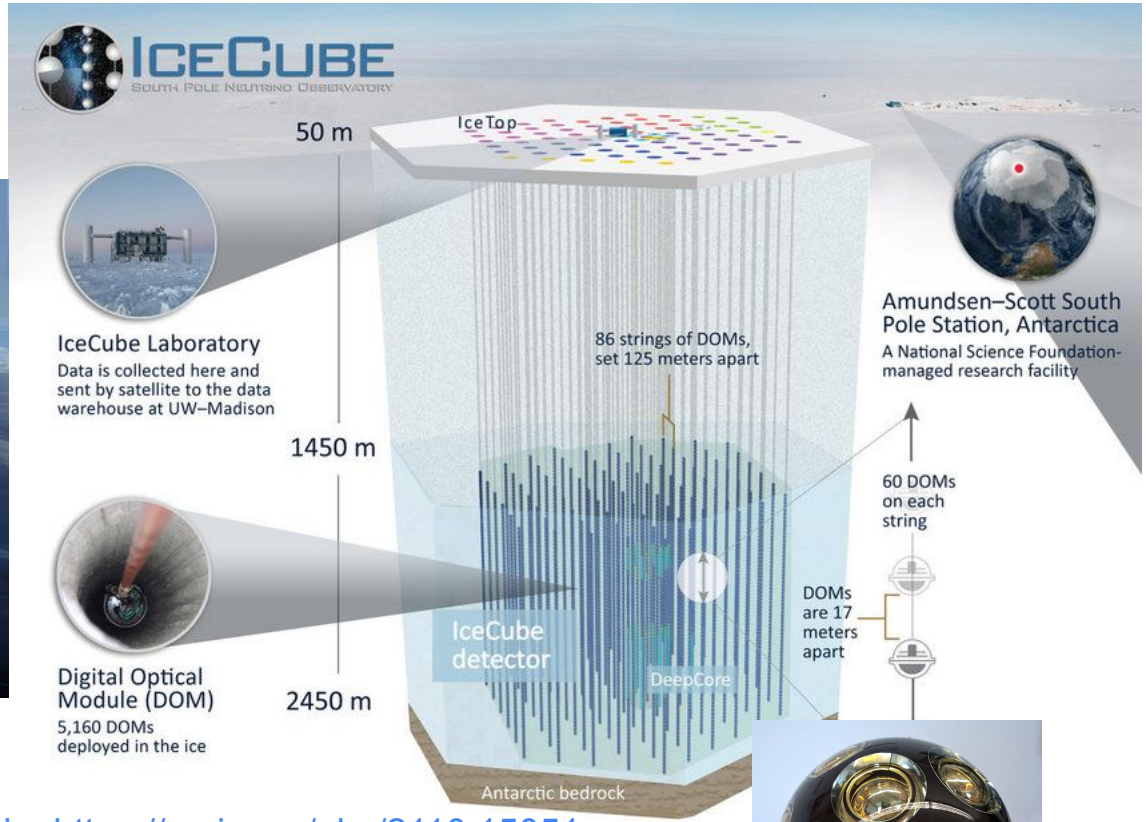
DUNE, ProtoDUNE
a neutrina z urychlovače ve americké laboratoři FERMILAB





IceCUBE





Francis Halzen

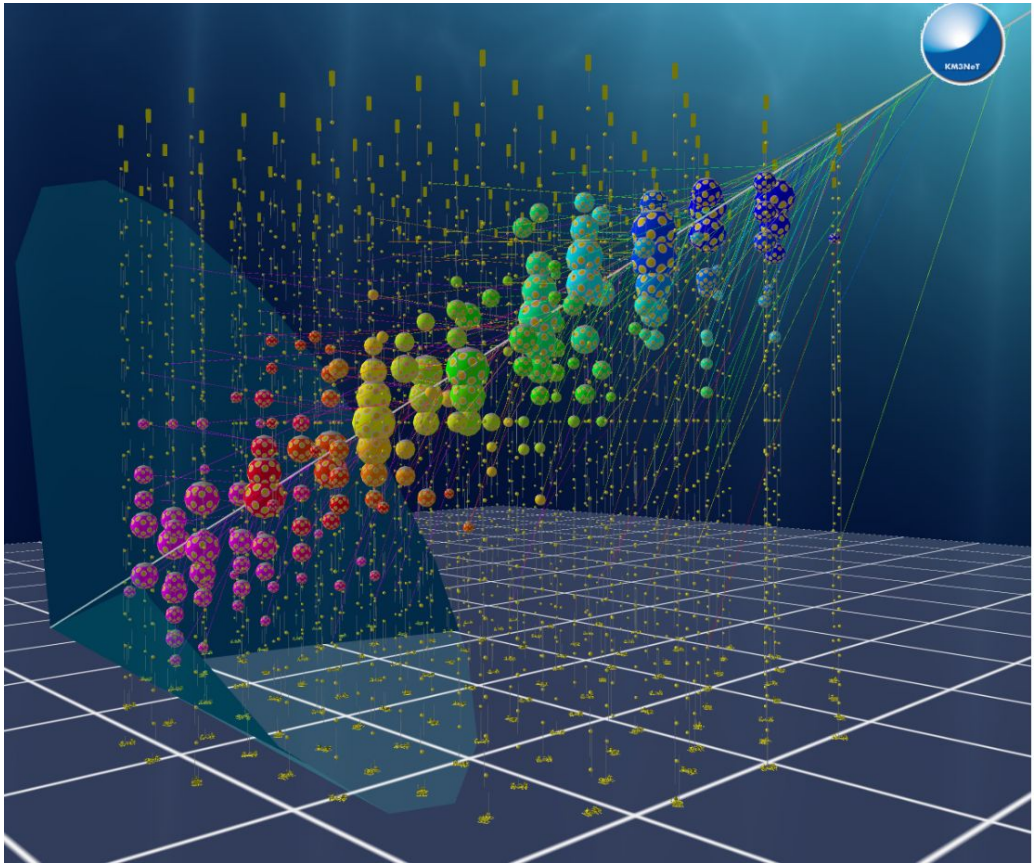
http://jointlab.upol.cz/kvita/idpacs2022.html :: https://arxiv.org/abs/2110.15051

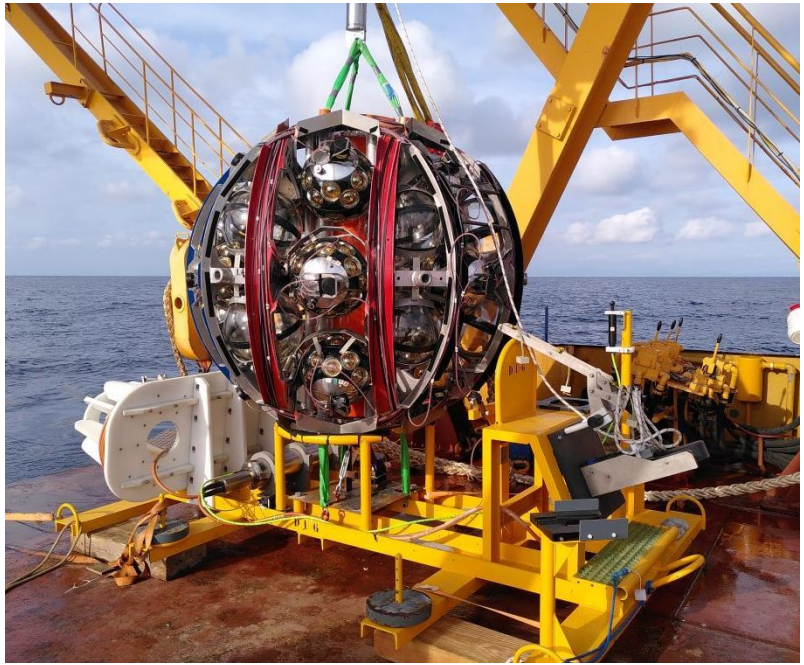
https://www.nature.com/articles/s41586-021-03256-1

https://sciencesprings.wordpress.com/tag/u-wisconsin-icecube-collaboration/

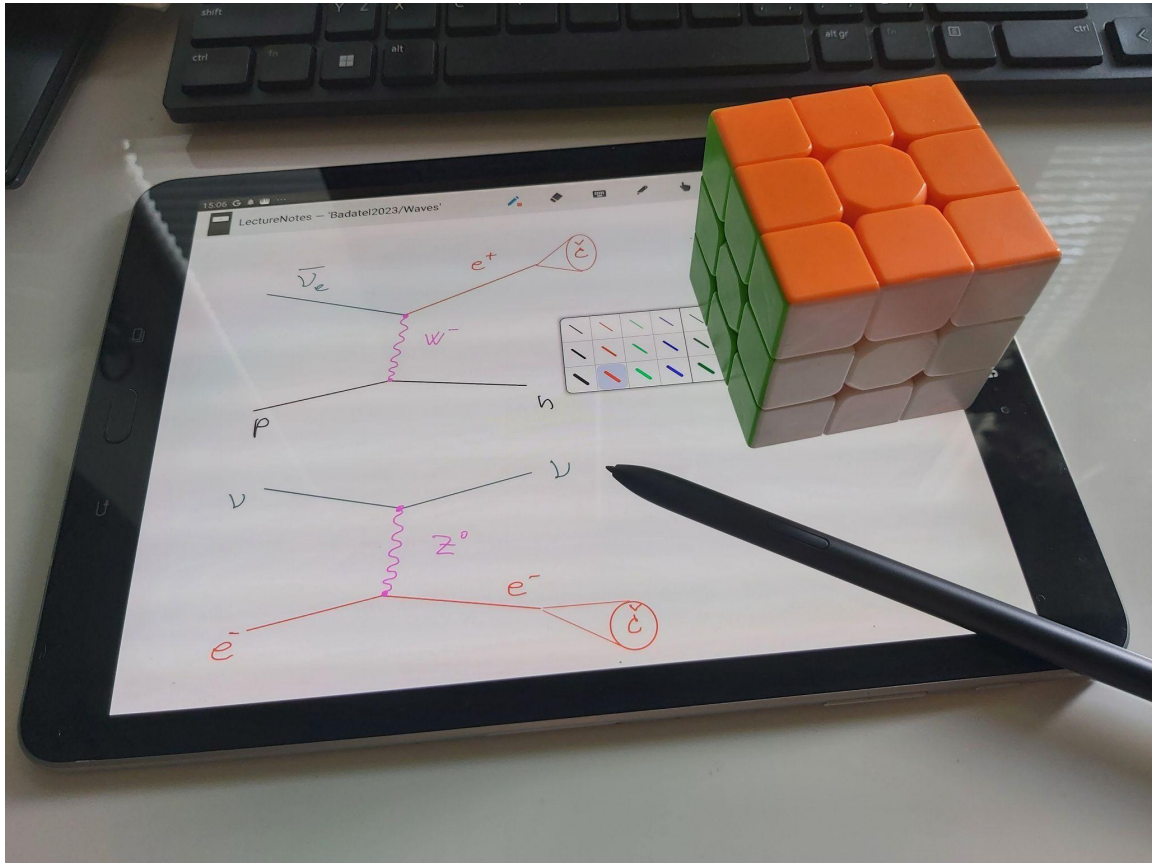
https://www.researchgate.net/figure/Prototypes-of-an-mDOM-left-and-an-D-Egg-right-for-the-IceCube-Upgrade_fig8_351199668

KM3NeT



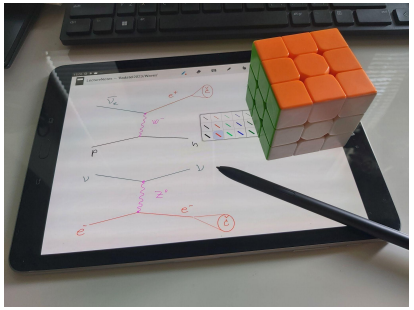


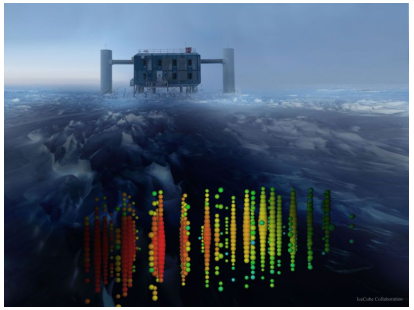
Conclusions

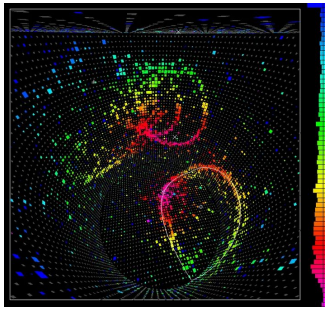


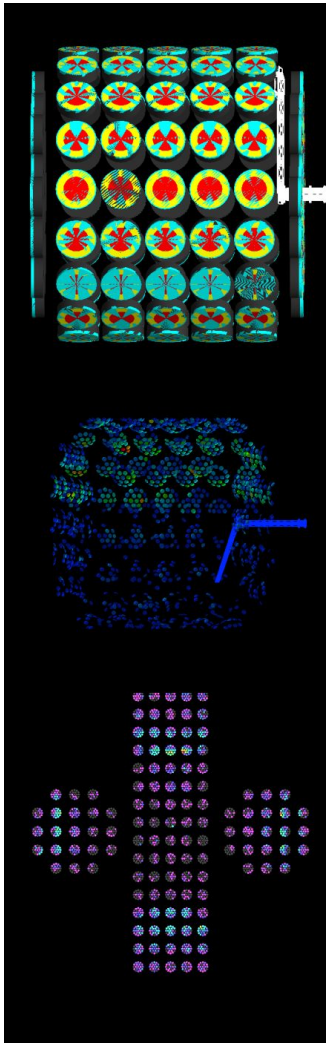
Conclusions

- Čerenkovovo záření
  - rozpad protonu, detekce neutrin, identifikace částic.
- Neutrinos not dead!
- Nejlehčí hmotné částice v mikrosvětě
- Nejméně interagující.
- Neutrina
  - ze Slunce
  - z atmosféry (z kosmického záření)
  - Astrofyzikální, kosmologická
  - Urychlovačová, reaktorová, geofyzikální…
- Studium oscilací neutrin a (narušení) symetrie mezi částicemi a antičásticemi.
- Neutrinová astronomie
  - nejen čekání na další supernovu:)









Backup

Neutrina:)

Original - Photocopie of PLC 0393

Abschrift/15.12.30 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Wolfgang Pauli

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gez. W. Pauli

http://library.cern/archives/history_CERN/historical_images/month-88-years-ago

Neutrina:)

COSMIC GALL

Every second, hundreds of billions of these neutrinos pass through each square inch of our bodies, coming from above during the day and from below at night, when the sun is shining on the other side of the earth!

—From "An Explanatory Statement on Elementary Particle Physics," by M. A. Ruderman and A. H. Rosenfeld, in American Scientist.

Neutrinos, they are very small.
  They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
  To them, through which they simply pass,
Like dustmaids down a drafty hall
  Or photons through a sheet of glass.
  They snub the most exquisite gas,
Ignore the most substantial wall,
  Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
  And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
  Down through our heads into the grass.
At night, they enter at Nepal
  And pierce the lover and his lass
From underneath the bed - you call
  It wonderful; I call it crass.

— *John Updike*

Wolfgang Pauli

https://twitter.com/mcnees/status/1334877571079671810

Neutrina:)

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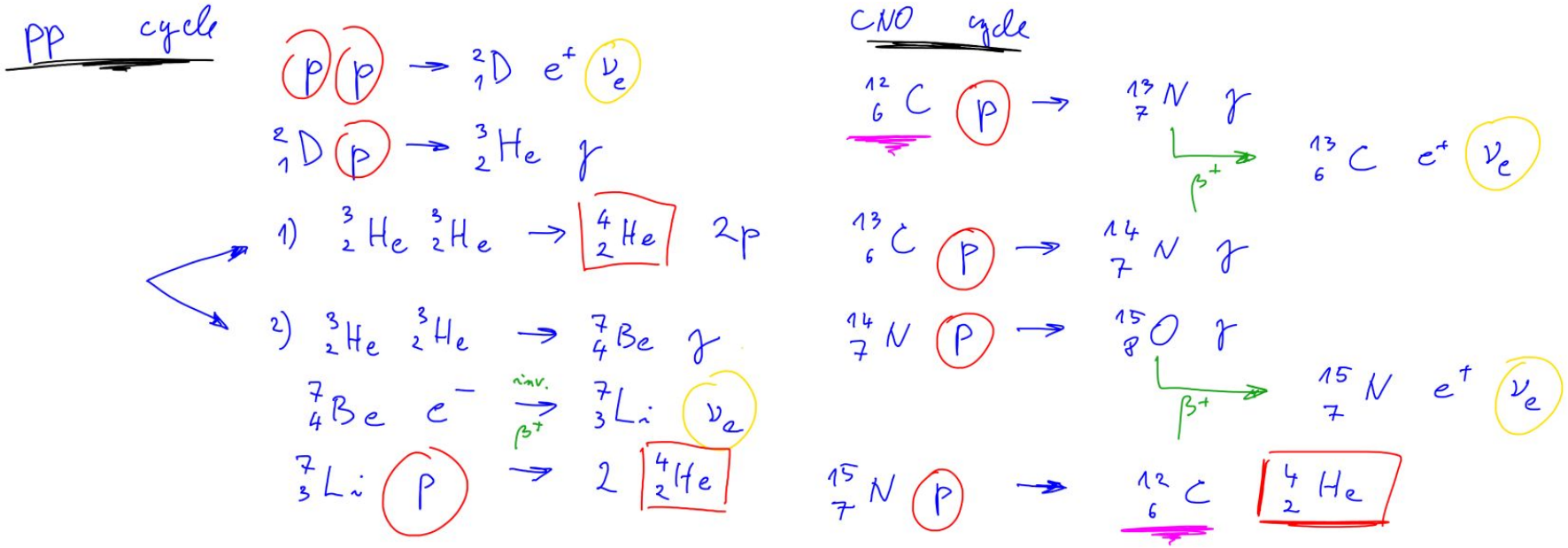
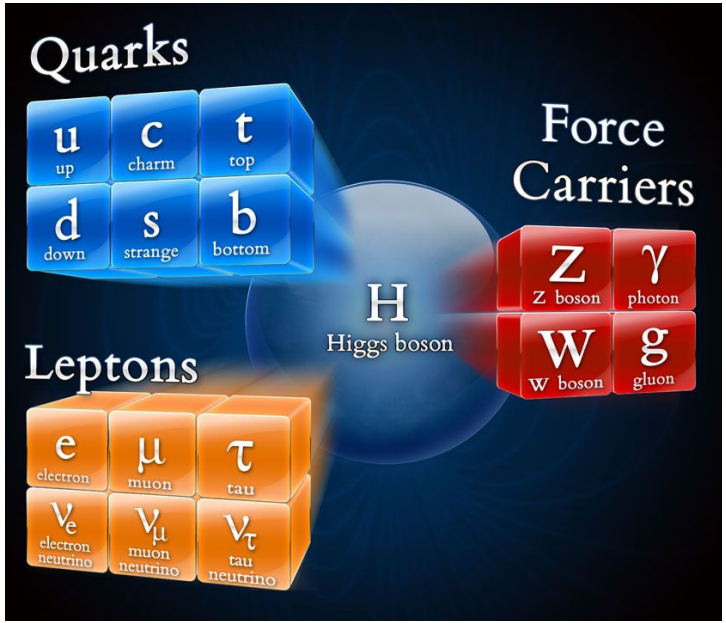
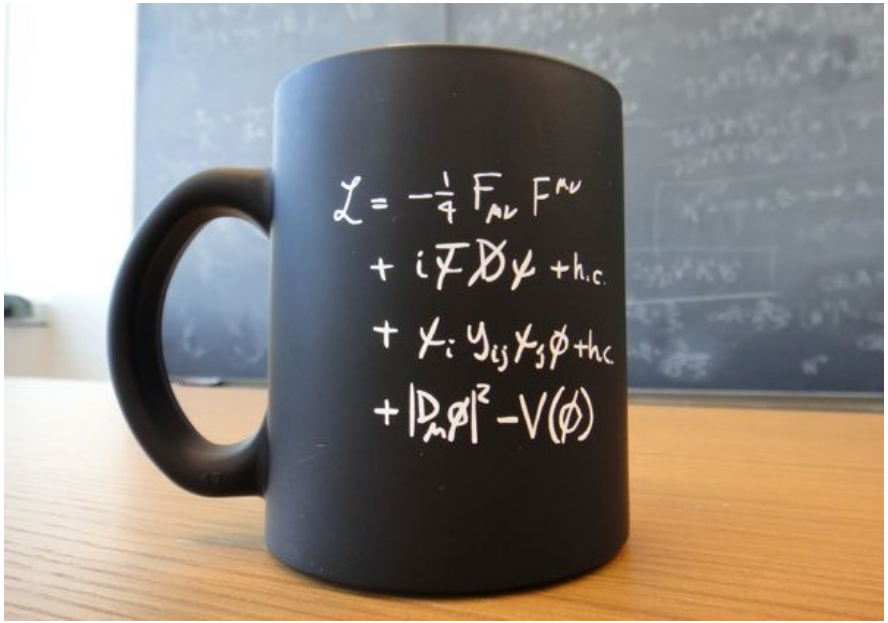
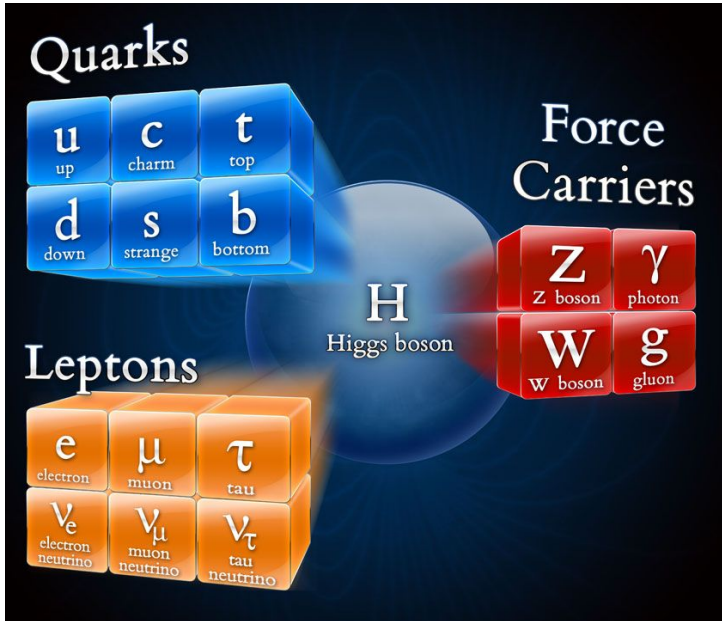

pp cycle
p p → ²₁D e⁺ νe
²₁D p → ³₂He γ
1) ³₂He ³₂He → ⁴₂He 2p
2) ³₂He ³₂He → ⁷₄Be γ
⁷₄Be e⁻ → ⁷₃Li νe
inv. β⁺
⁷₃Li p → 2 ⁴₂He
CNO cycle
¹²₆C p → ¹³₇N γ
β⁺
¹³₆C e⁺ νe
¹³₆C p → ¹⁴₇N γ
¹⁴₇N p → ¹⁵₈O γ
β⁺
¹⁵₇N e⁺ νe
¹⁵₇N p → ¹²₆C ⁴₂He

Neutrina:)


Quarks
u up
c charm
t top
d down
s strange
b bottom
Leptons
e electron
μ muon
τ tau
νe electron neutrino
νμ muon neutrino
ντ tau neutrino
H Higgs boson
Force Carriers
Z Z boson
γ photon
W W boson
g gluon


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Neutrina:)



$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\bar{\nu}_\kappa - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\bar{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) + \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).$$