



Univerza v Ljubljani
Fakulteta za *matematiko in fiziko*



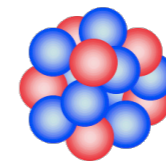
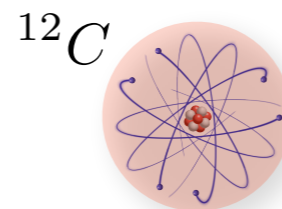
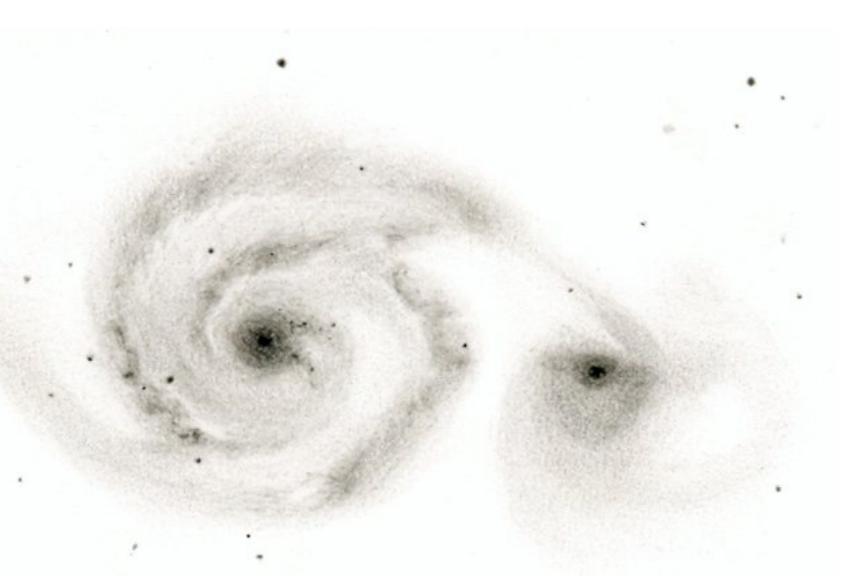
Nevtrini

Miha Nemevšek
(IJS & FMF)

CERN Slovenian Teacher Programme

CERN, 4. oktober 2023

Fizika delcev



?

... 10^{21} m

10^4 m

1 m

10^{-10} m

10^{-14} m

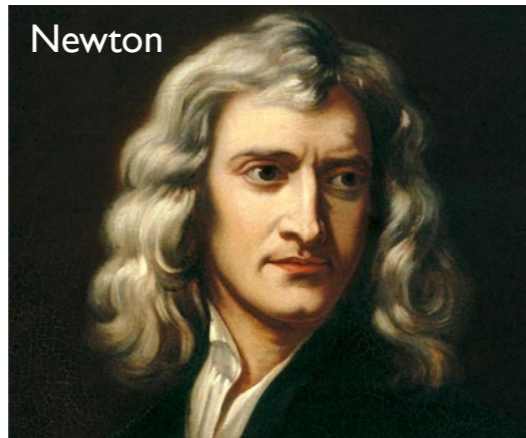
10^{-18} m

Teorija - Fizika delcev

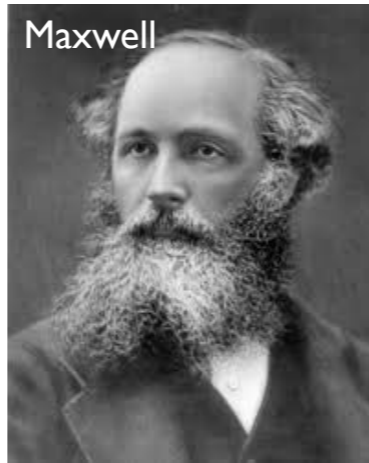
Radioaktivnost
elektron



Demokrit, ...



Newton



Maxwell

Planck, Einstein,...

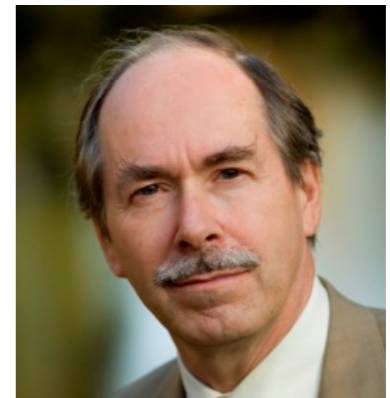
Bohr, Dirac, Pauli,
Fermi,...

Schwinger,
Feynman, ...

Weinberg



't Hooft



...veliko veliko drugih

Stari Grki,
Indija, Islam

Klasična
fizika

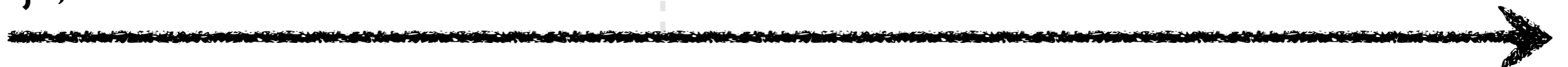
Moderna
fizika

Post-Moderna
fizika?

–500 let

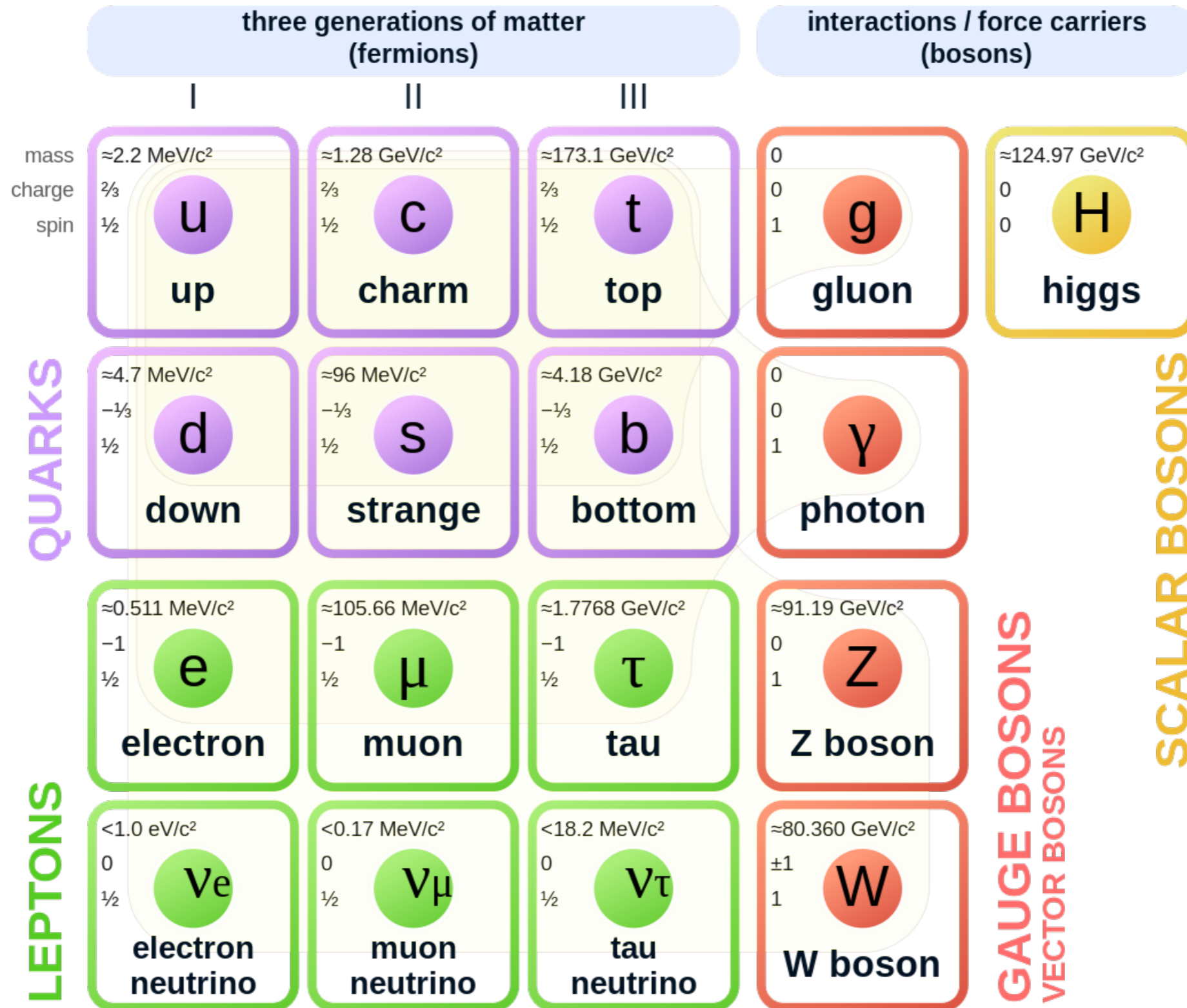
~ 1900

2012 →



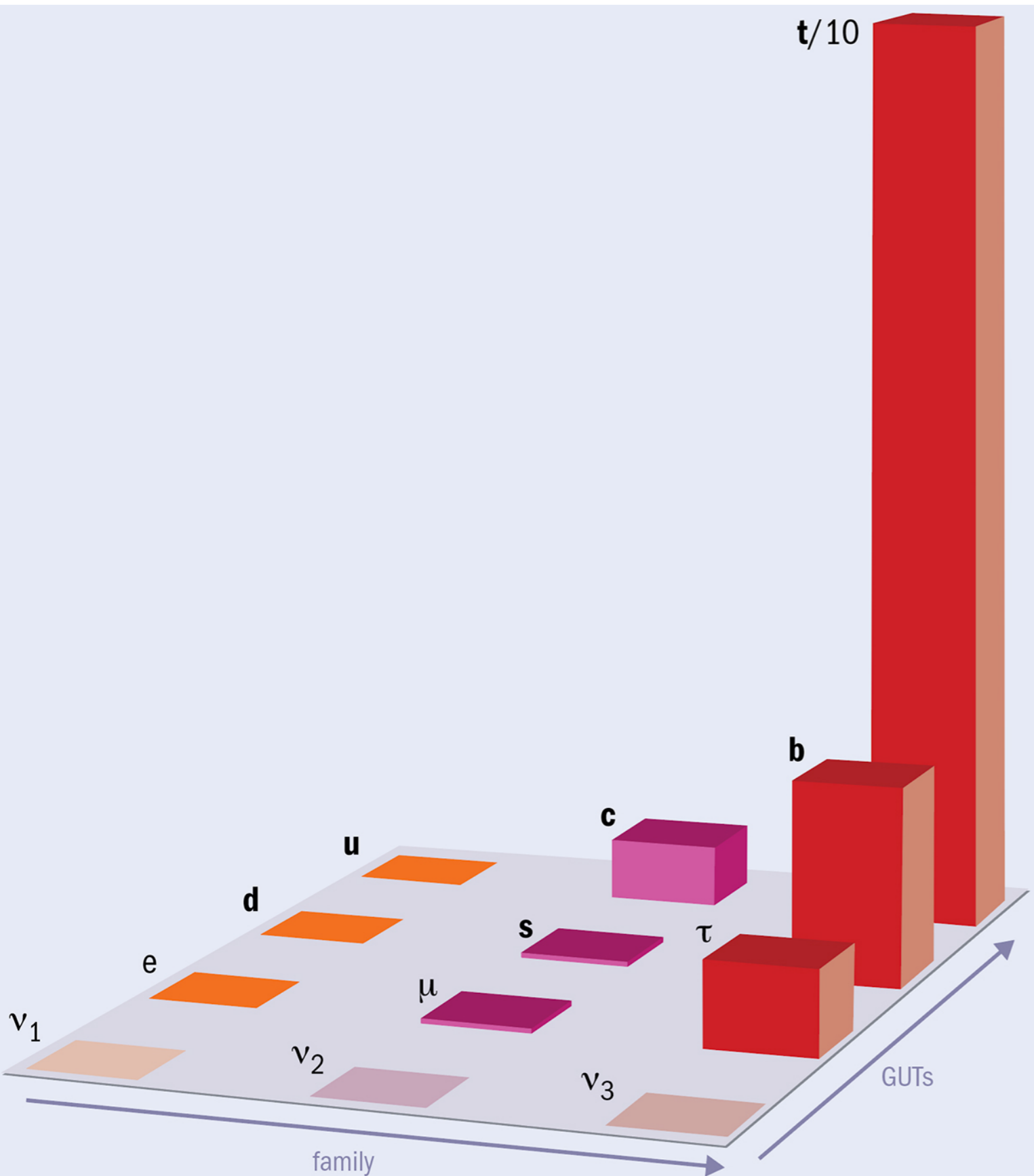
Teorija - Fizika delcev

Standard Model of Elementary Particles



Nevtrini!

Mase delcev



$$m_t c^2 = 174 \text{ GeV}$$

$$E = mc^2 = eU \text{ [eV]}$$

$$m_b c^2 = 4.5 \text{ GeV}$$

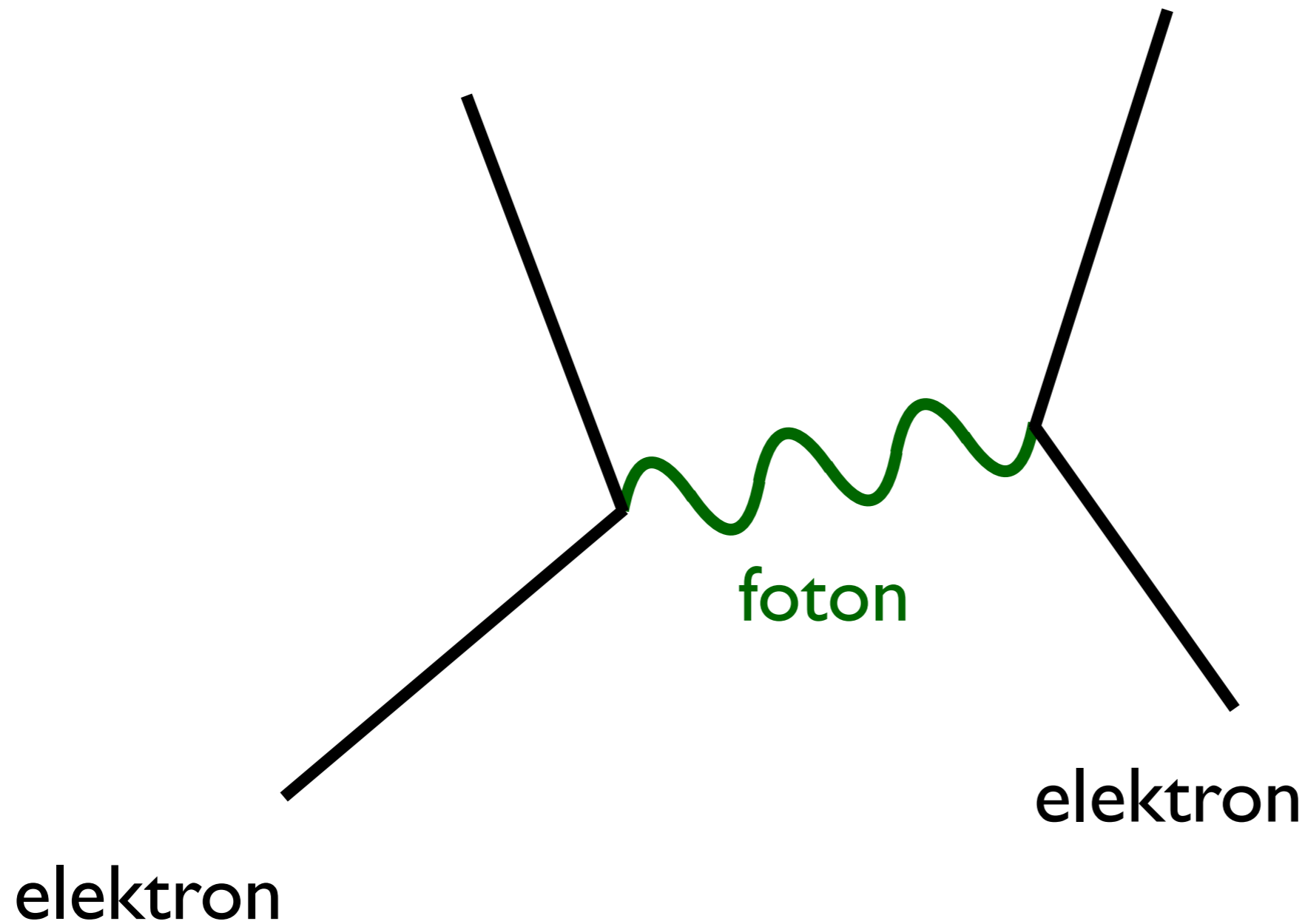
$$m_e c^2 = 0.5 \text{ MeV}$$

kinematika - magnetno polje

$$m_\nu c^2 \lesssim 0.1 \text{ eV}$$

oscilacije

Interakcija je izmenjava delcev

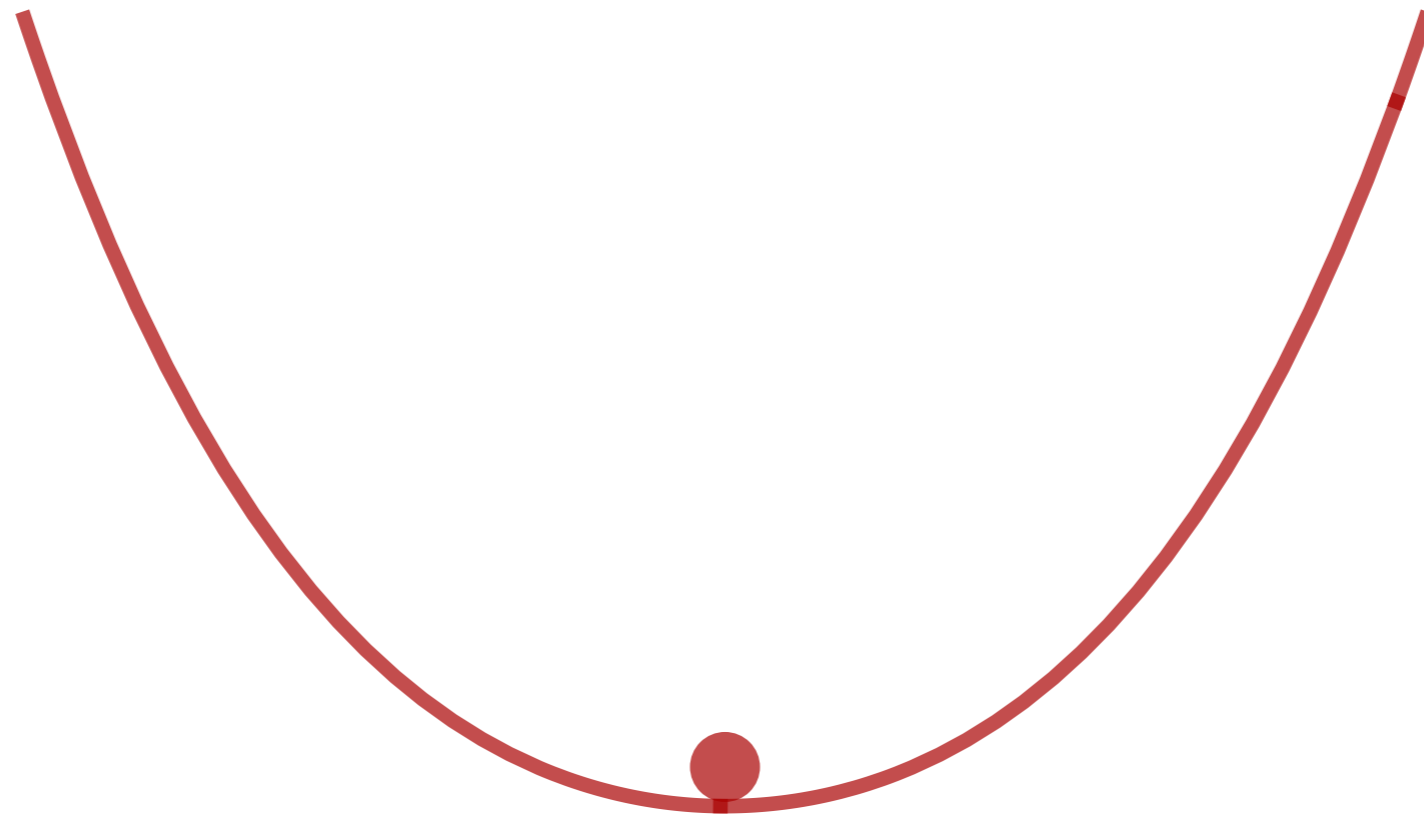


Brezmasni **prenašalec**,
neskončen doseg

Interakcija je simetrija



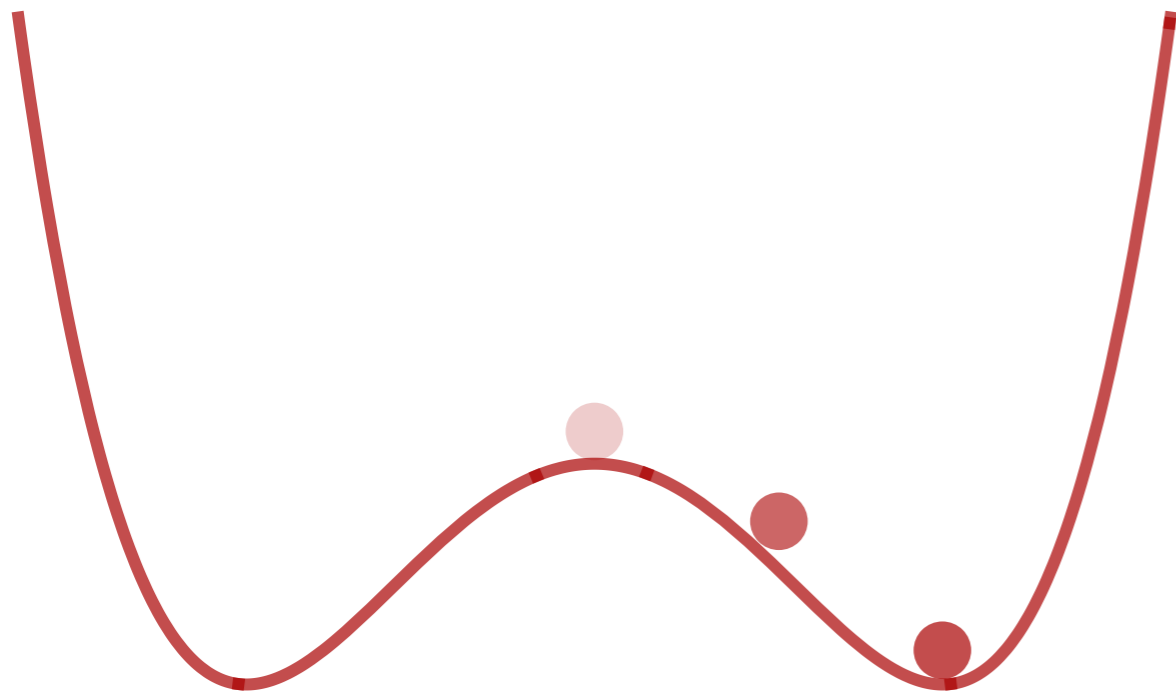
Interakcija je simetrija



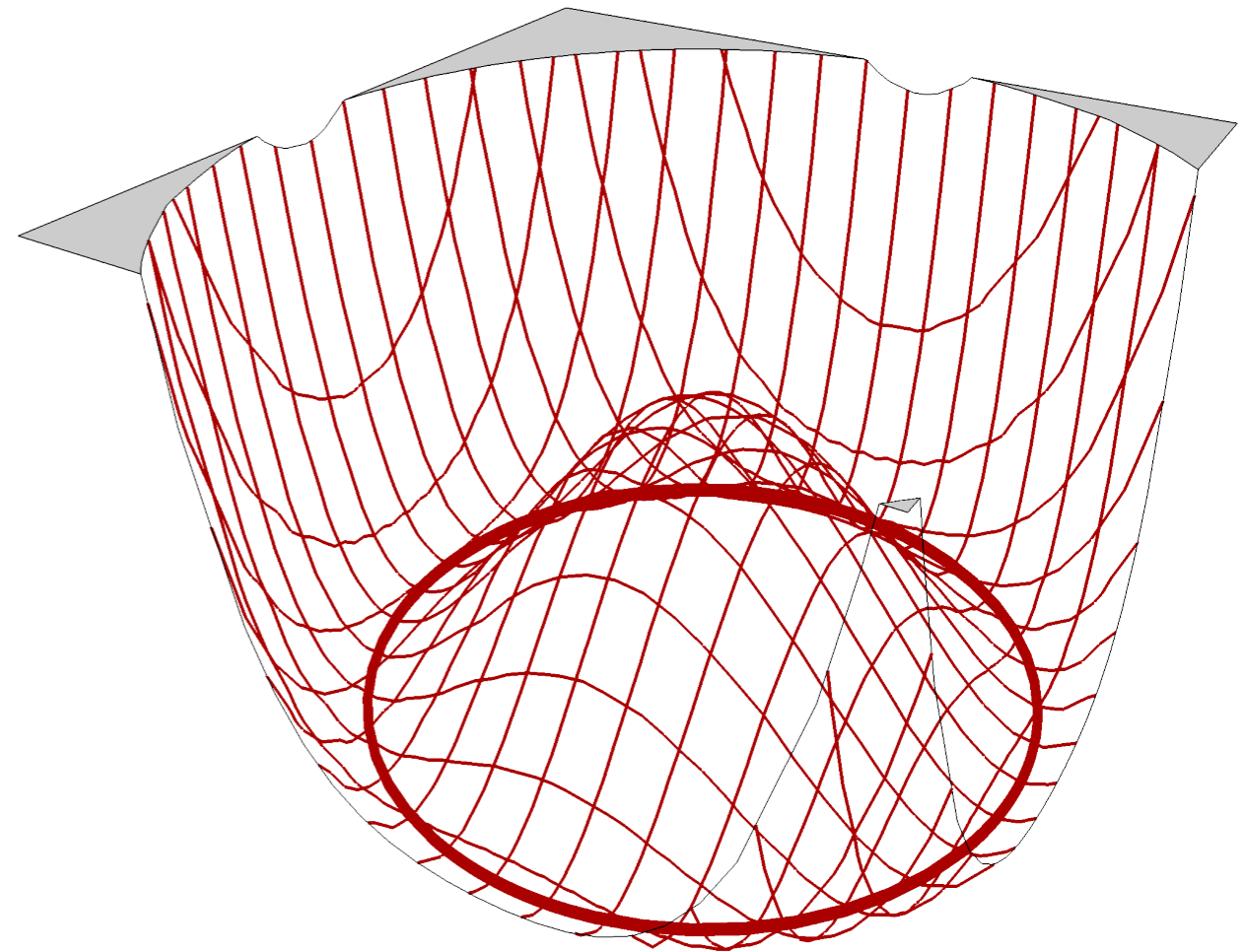
Simetrične rešitve,
osnovno stanje

Brezmasni **prenašalec**,
neskončen doseg

Interakcija je simetrija

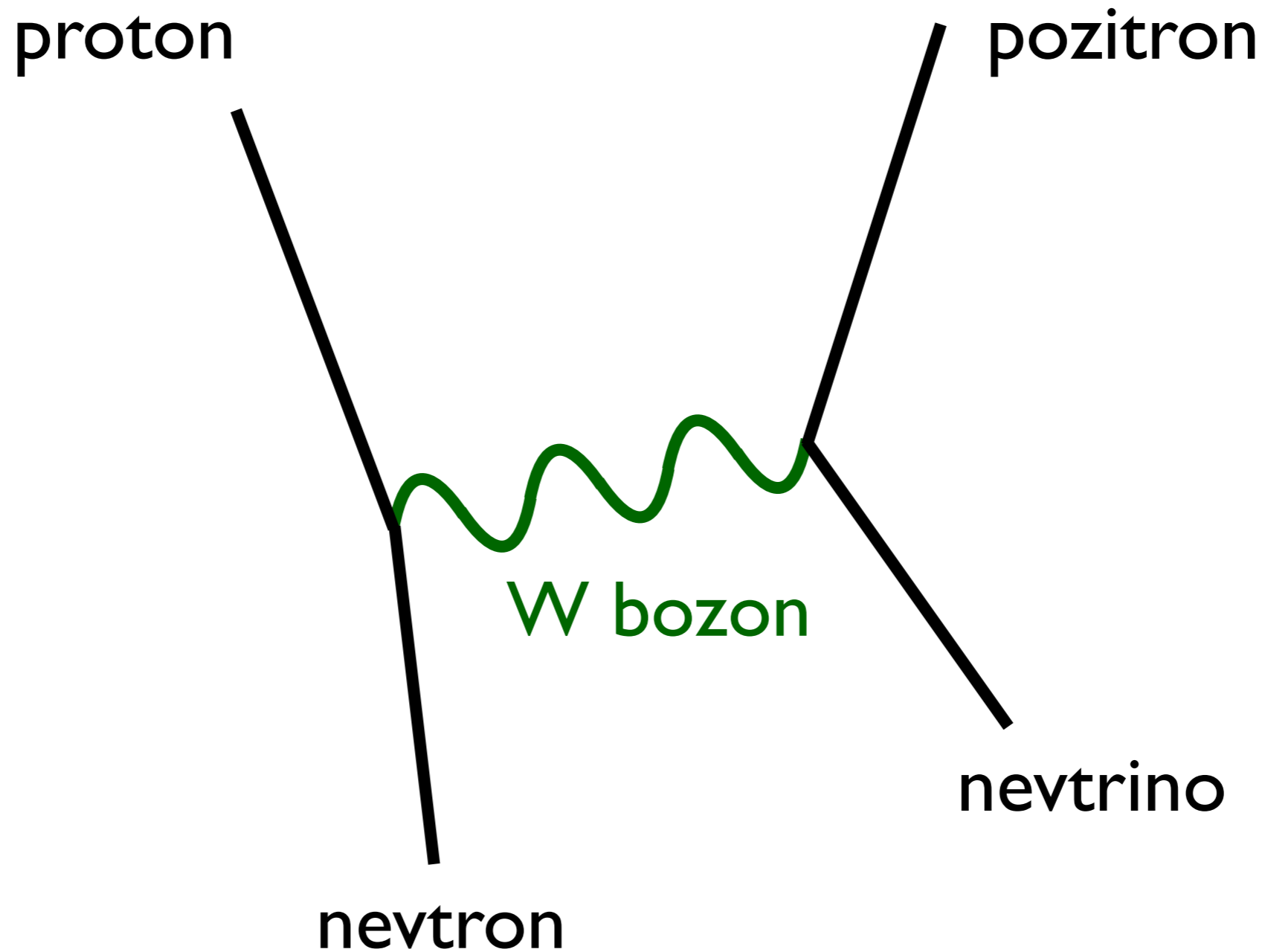


Asimetrične rešitve,
osnovno stanje

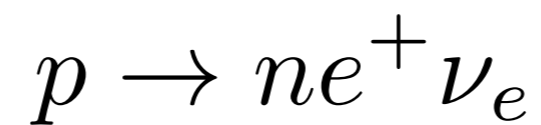


Masivni prenašalec,
končen doseg

Interakcija je simetrija



Beta razpad



Masivni prenašalec,
končen dosež

Odprta vprašanja - nova fizika?



Nevtrini

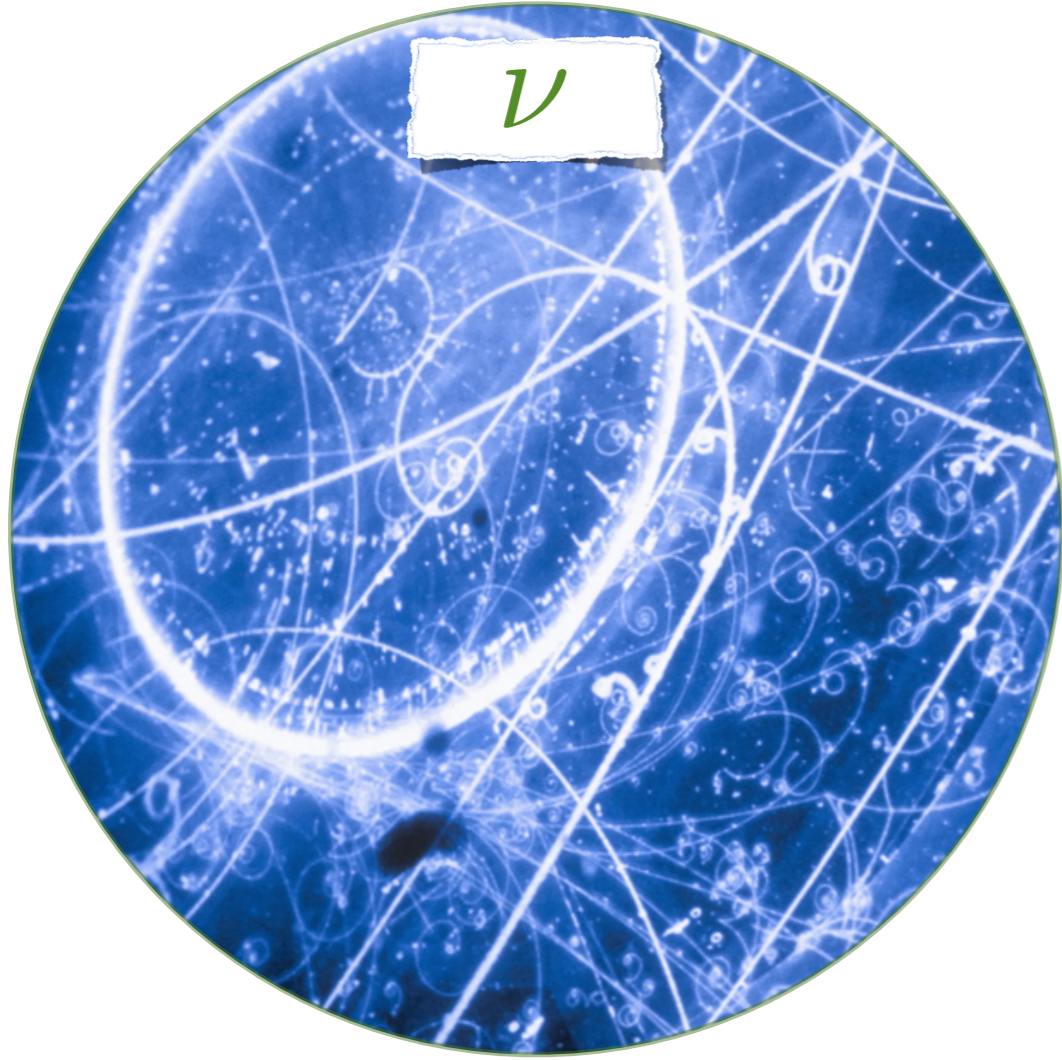


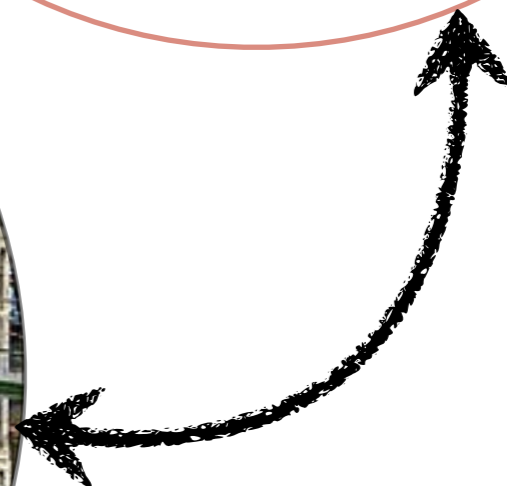
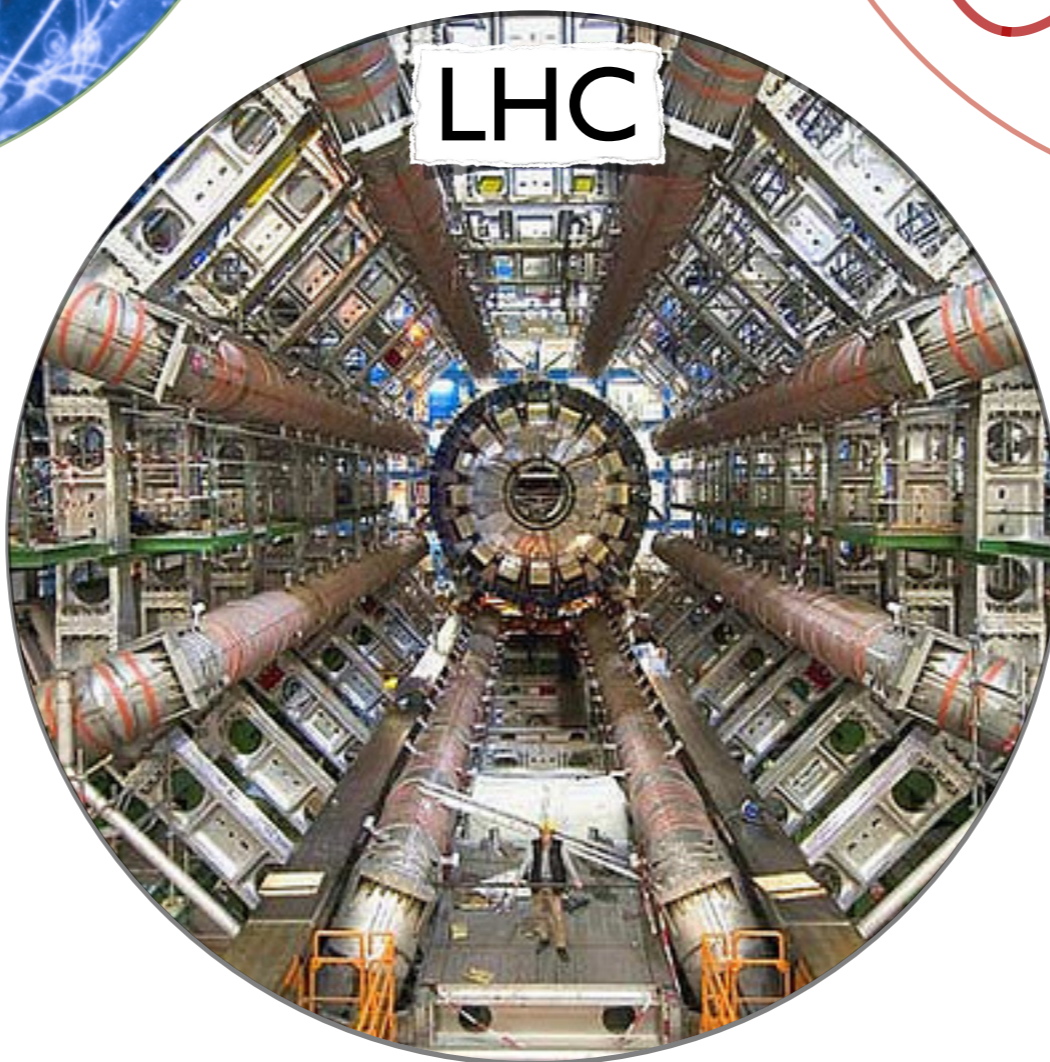
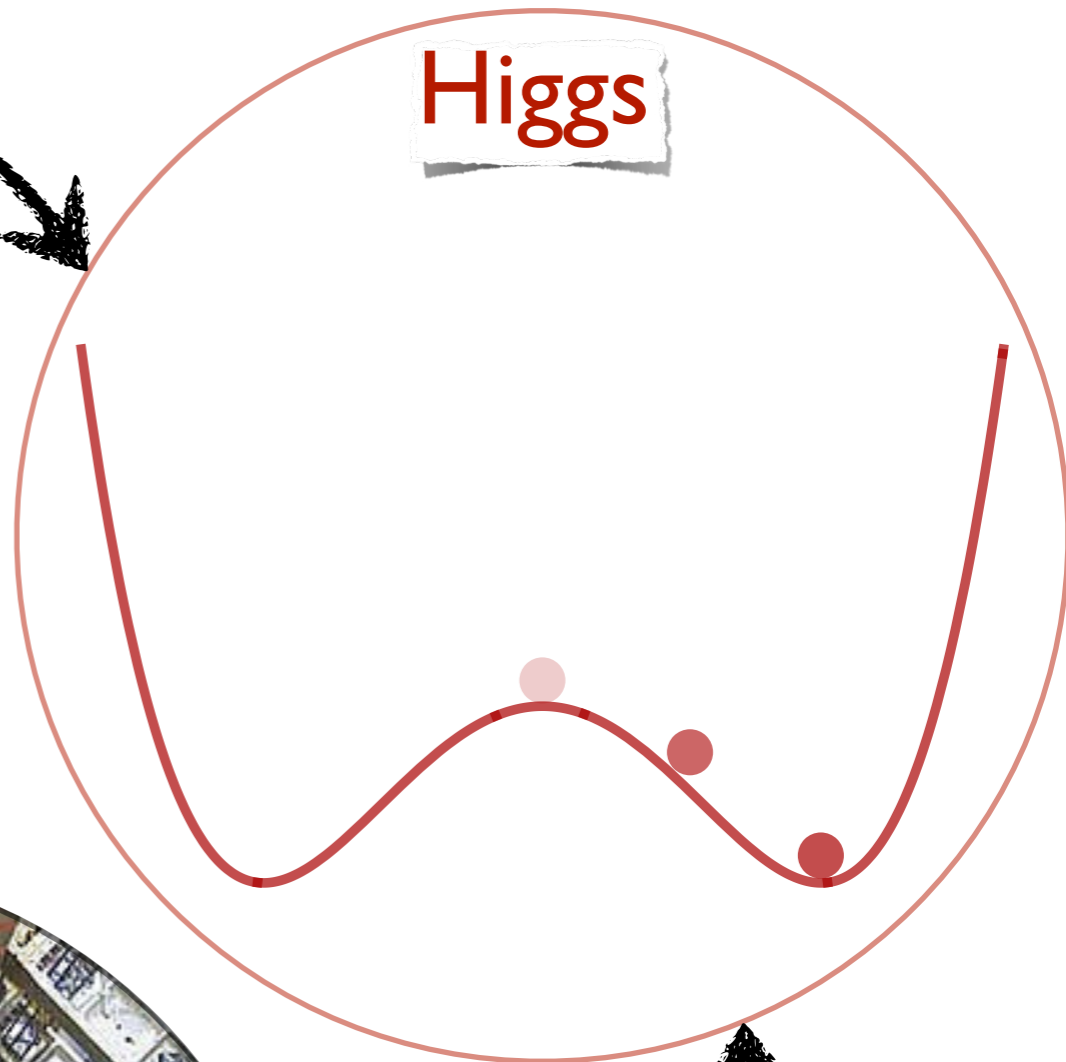
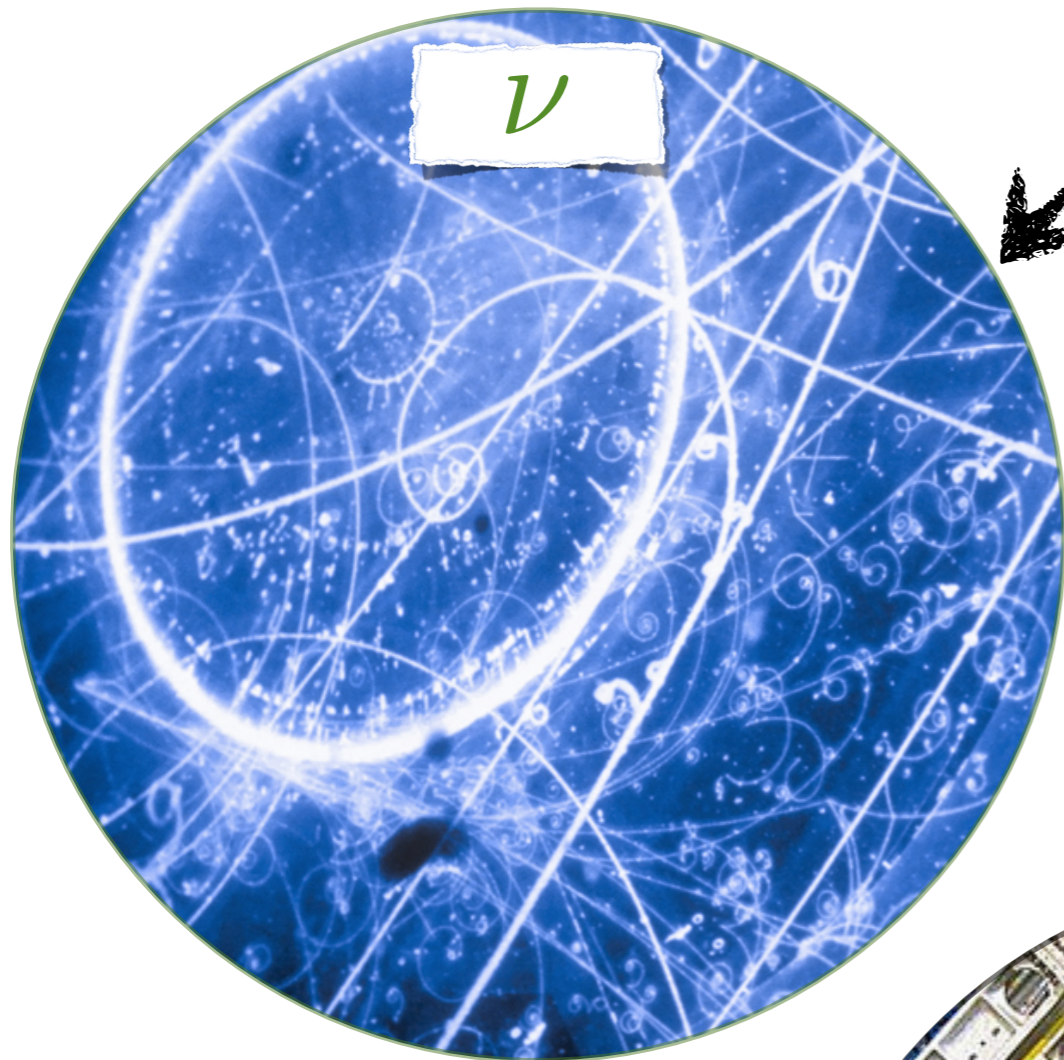
Temna
snov

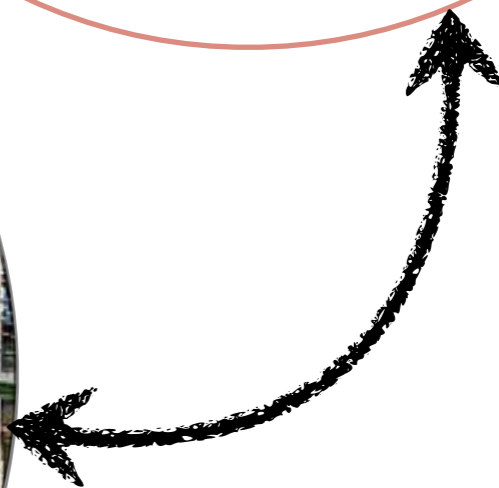
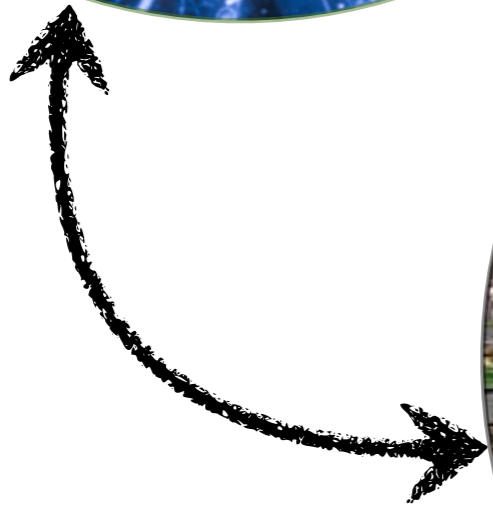
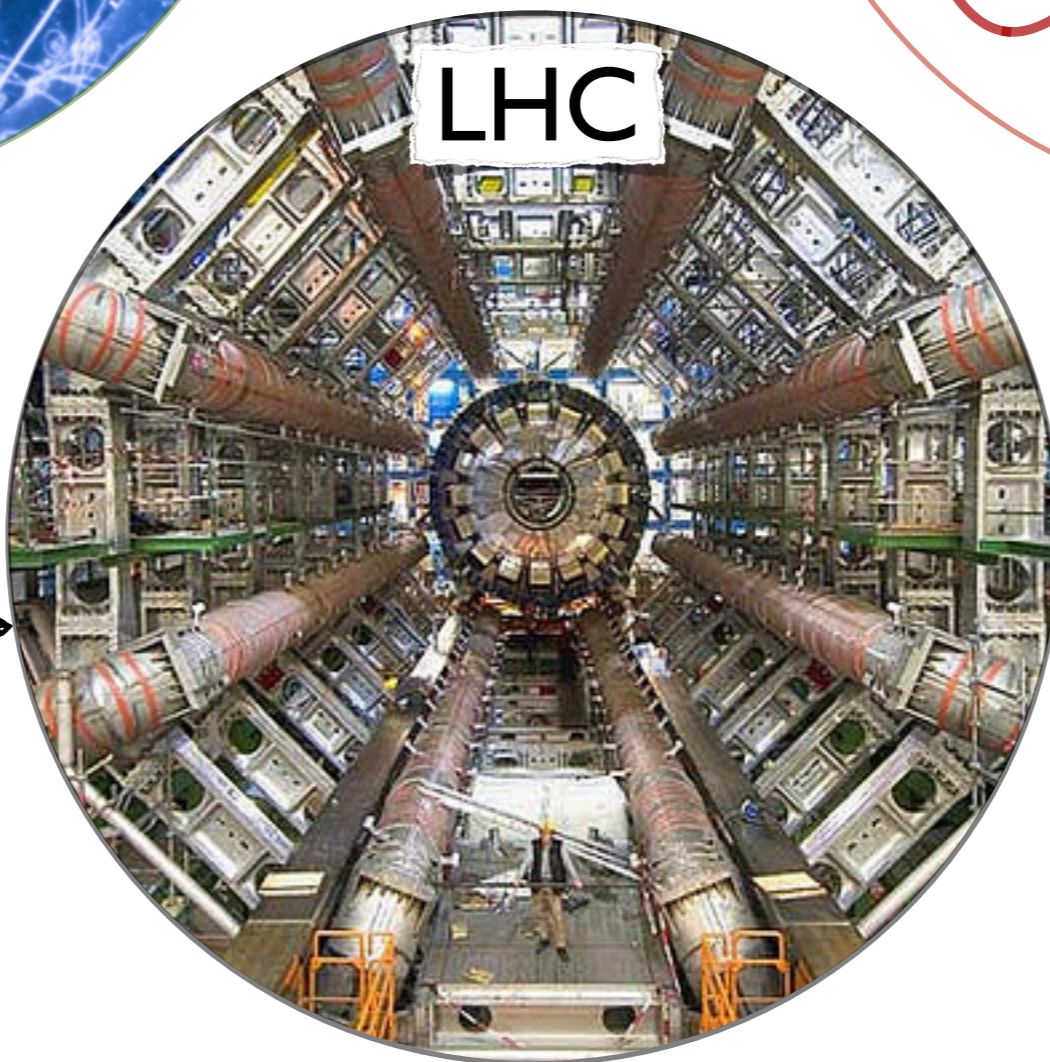
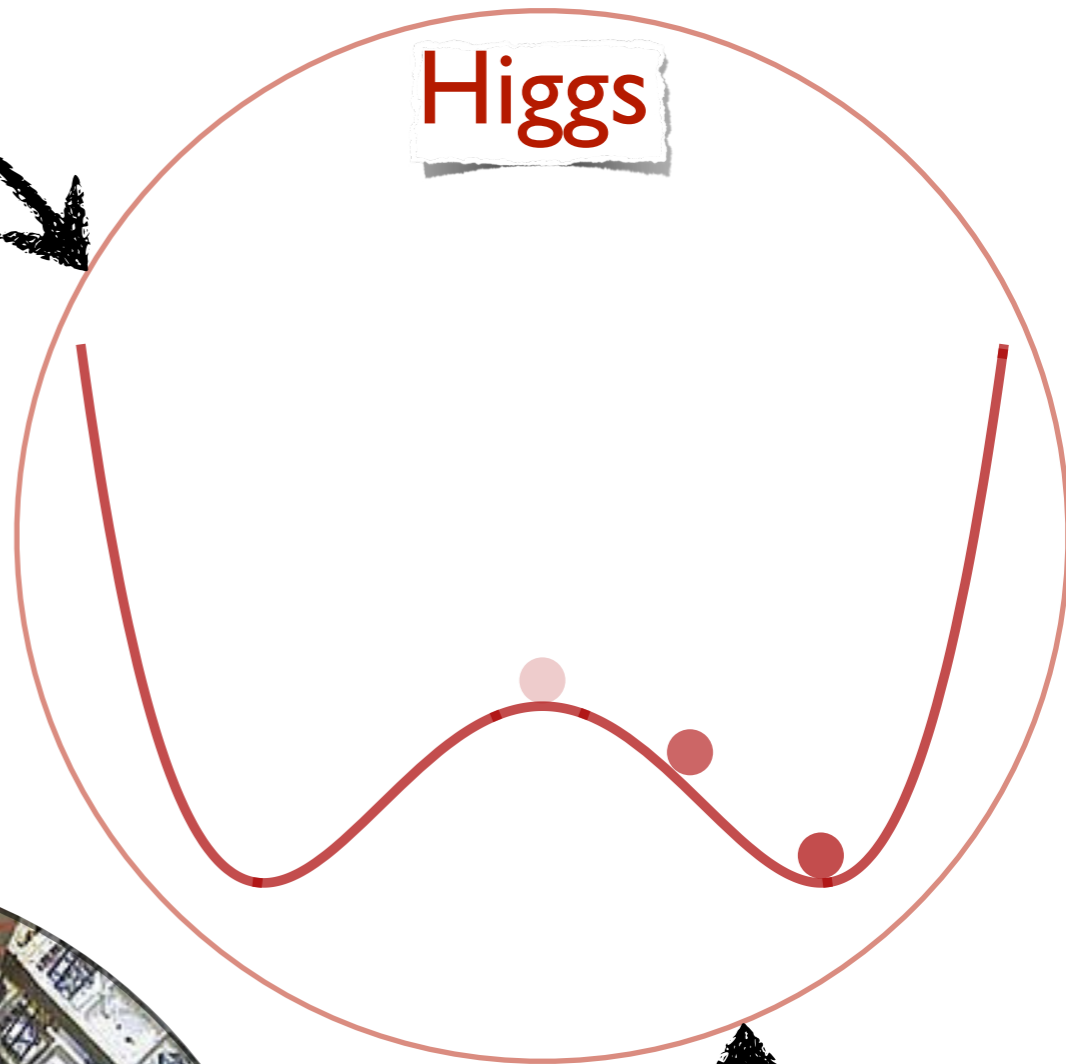
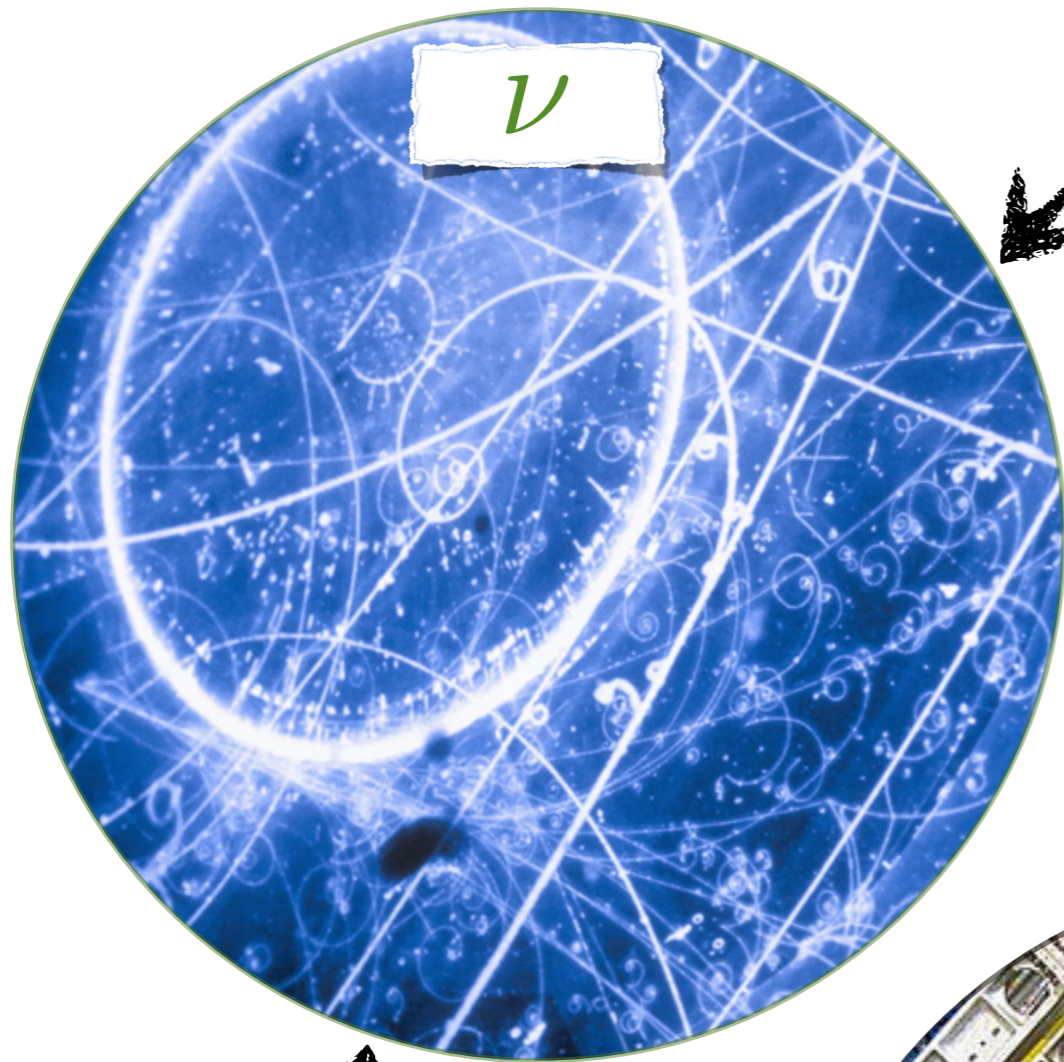


Snov >
anti-snov

ν

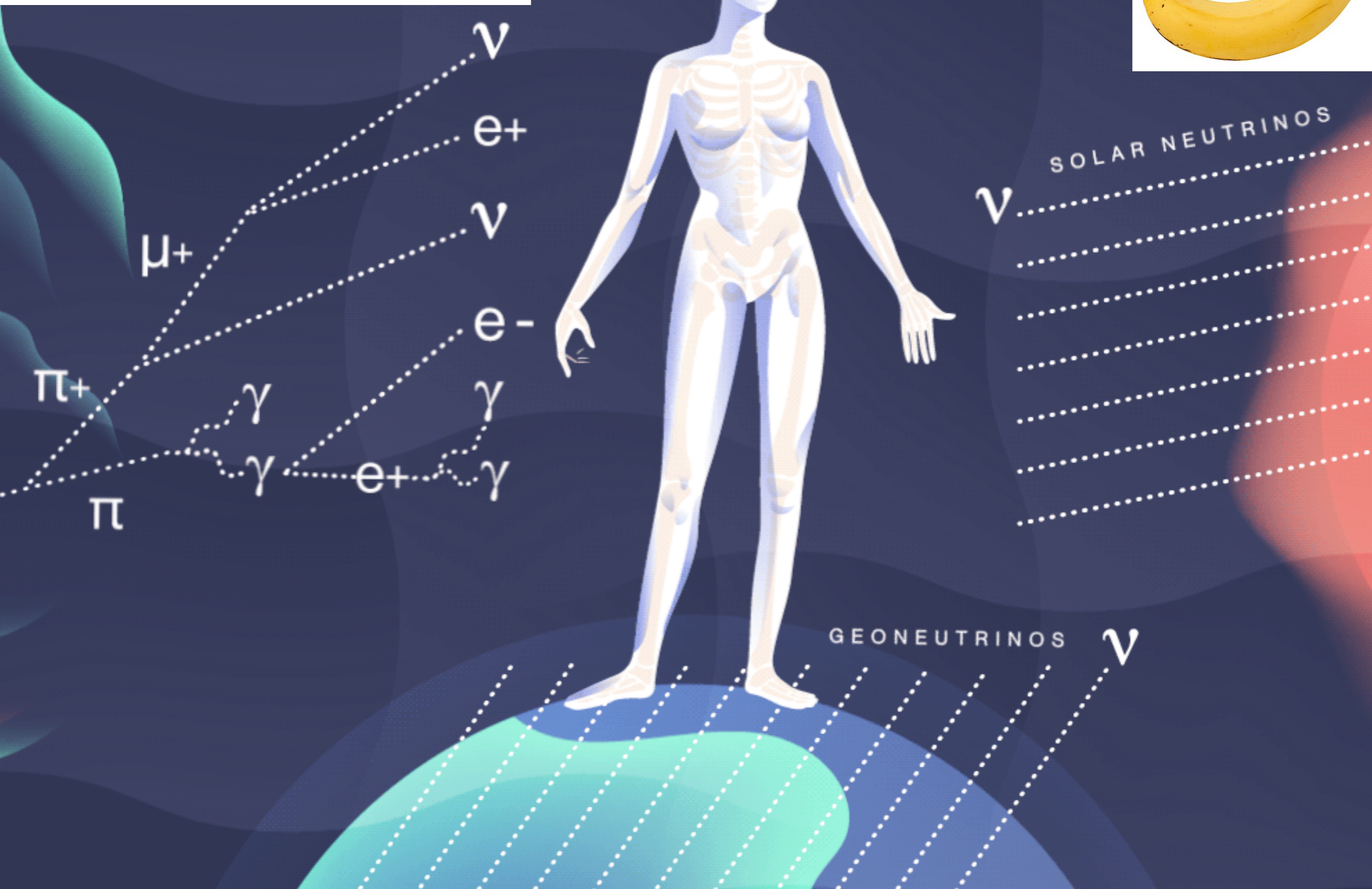
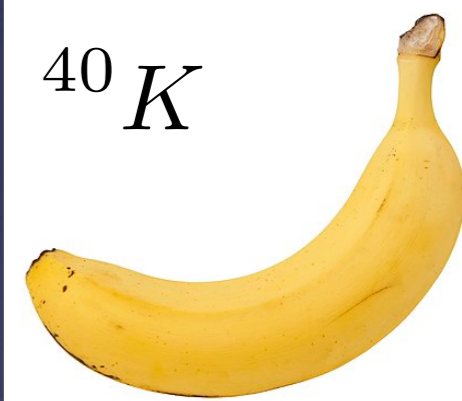






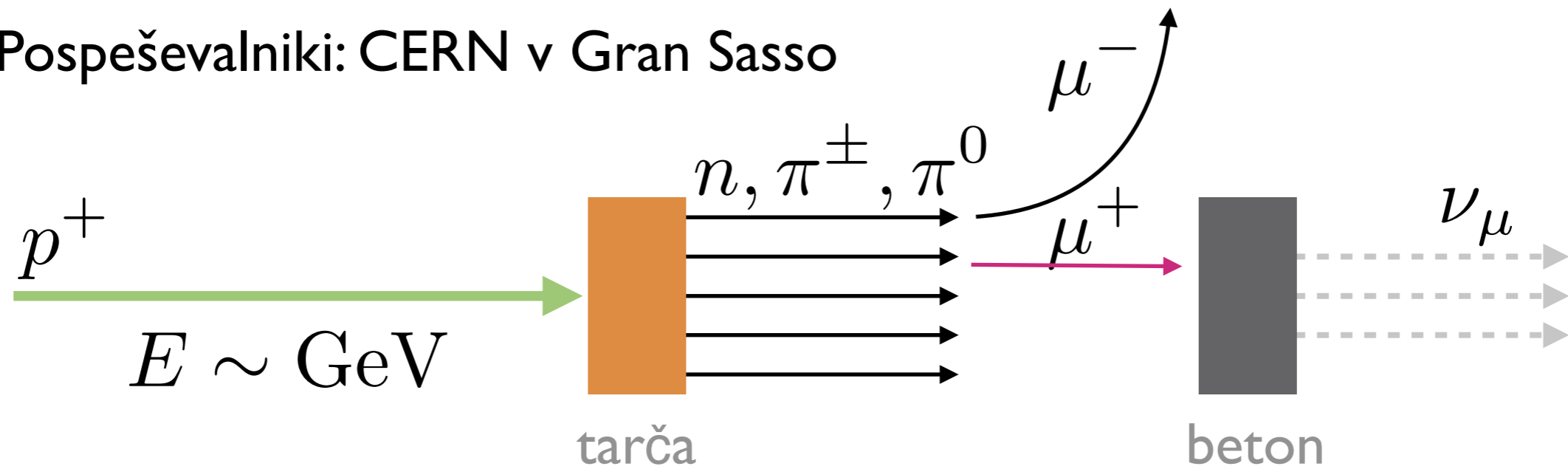
Nevtrino izvori v naravi

^{40}K

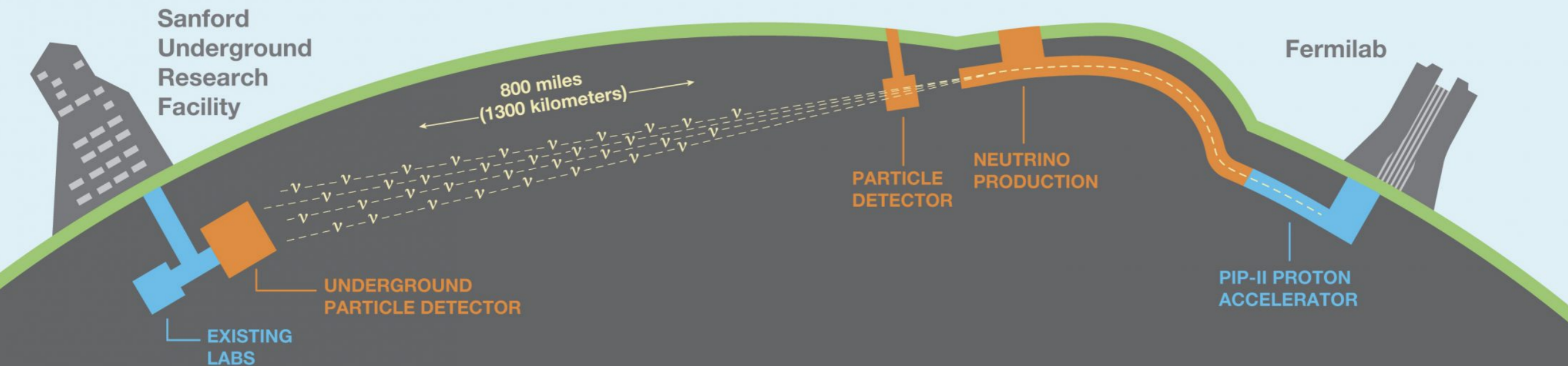


Nevtrino izvori v naravi

Pospeševalniki: CERN v Gran Sasso

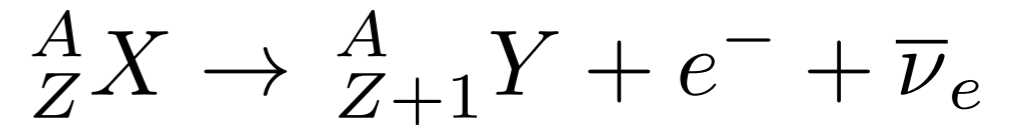


Fermilab v SURF



Nevtrino izvori v naravi

$$E_\nu \sim \text{MeV}$$



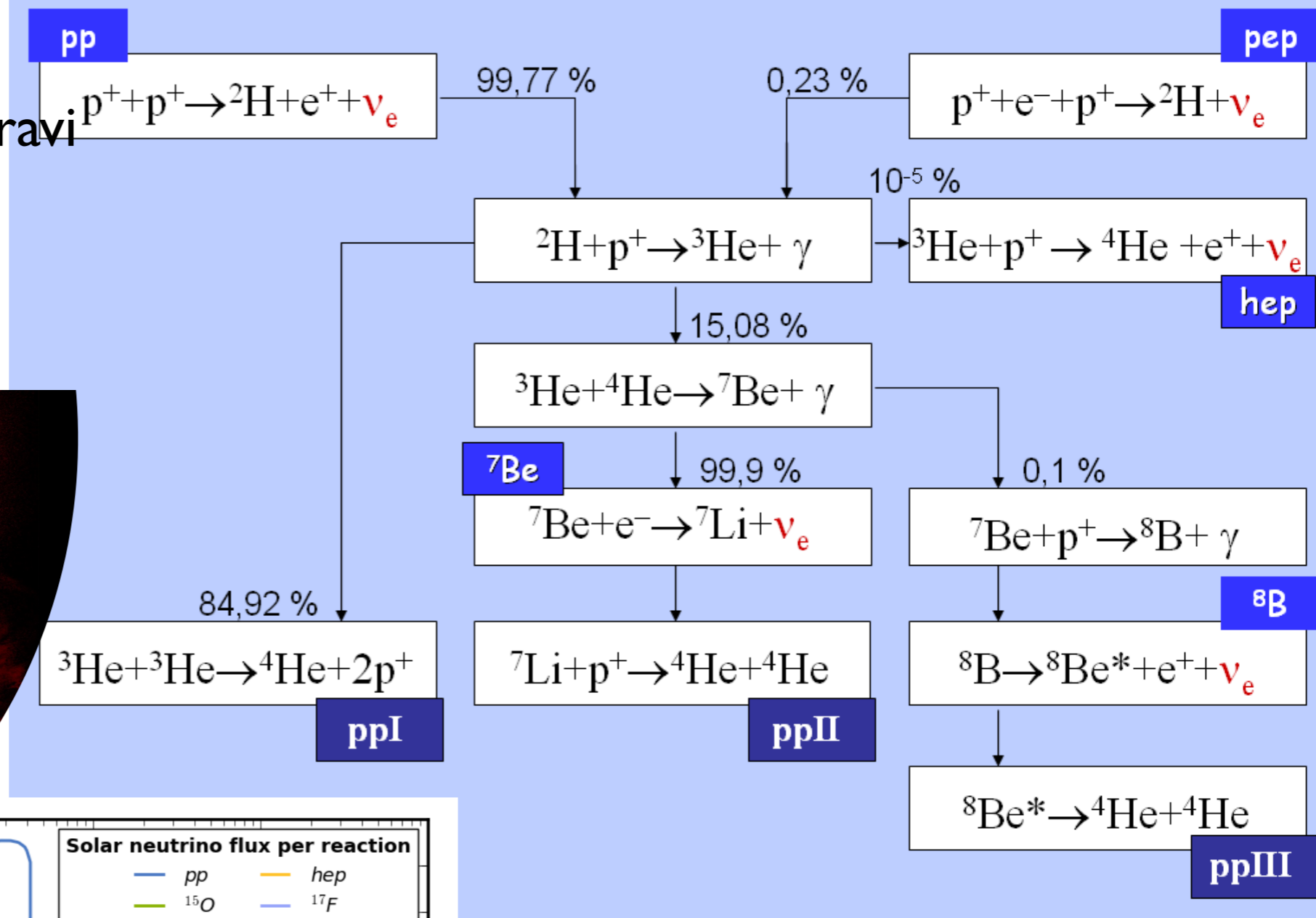
Daya Bay

$$\Phi_\nu \sim 10^{23} / \text{sec}$$



Nevtrino izvori v naravi

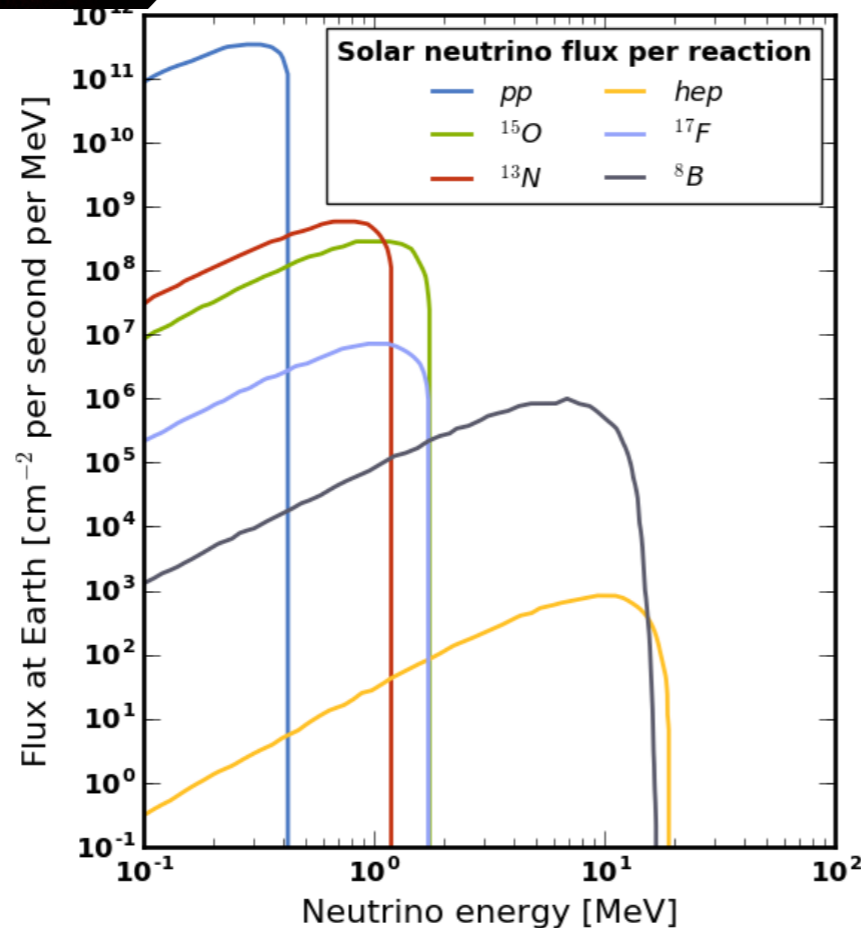
Sonce



Zlivanje jeder

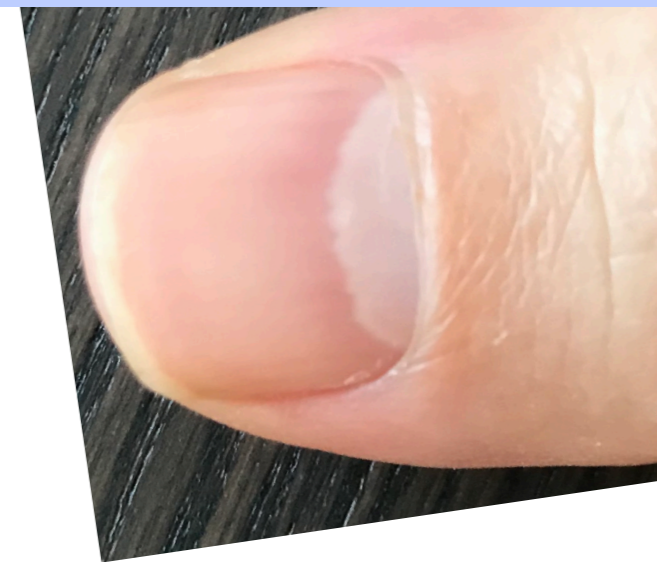
je izvor

nevtrinov



$$E_\nu \sim \text{MeV}$$

$$\Phi_\nu \sim 100 \text{ milijard/sec/cm}^2$$



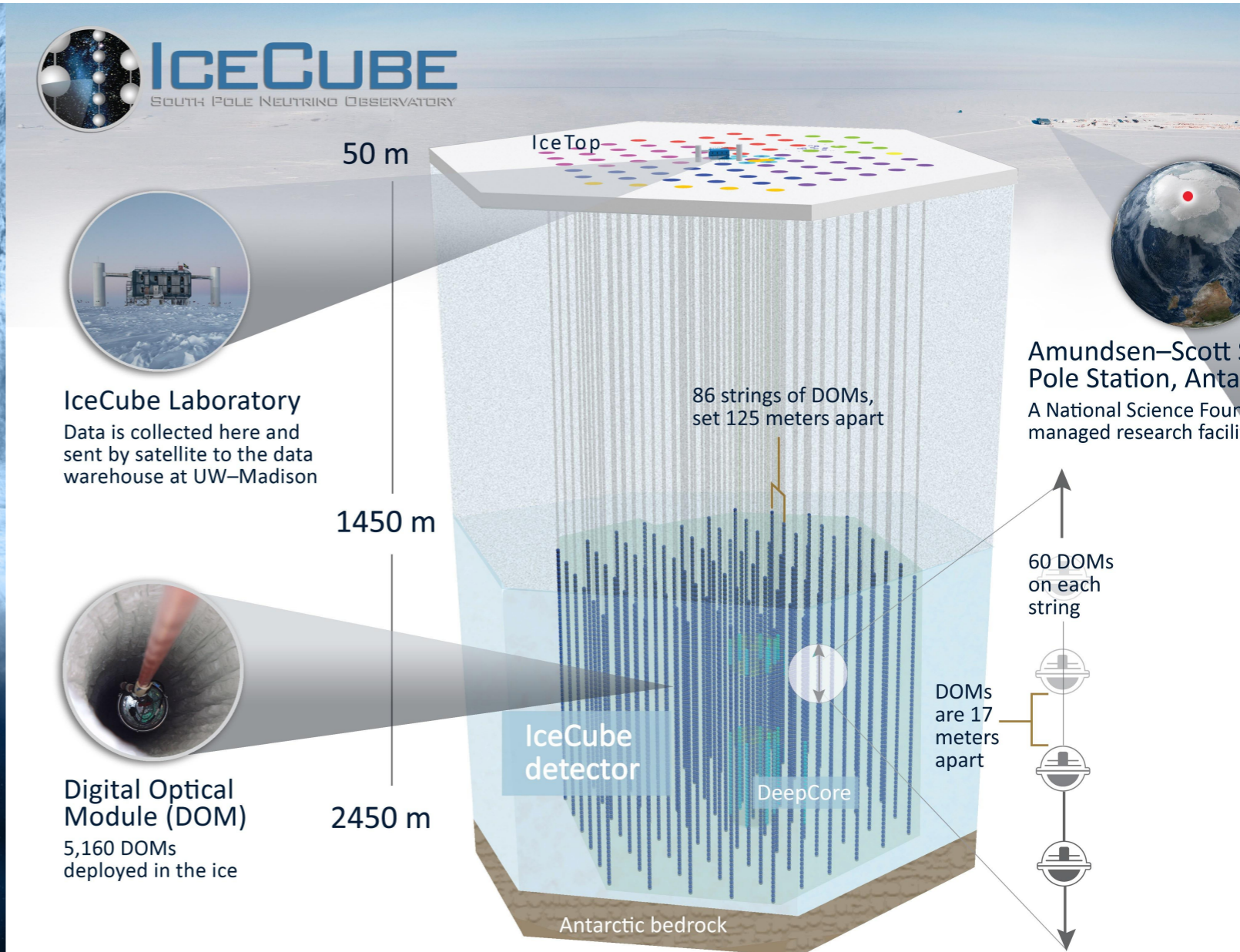
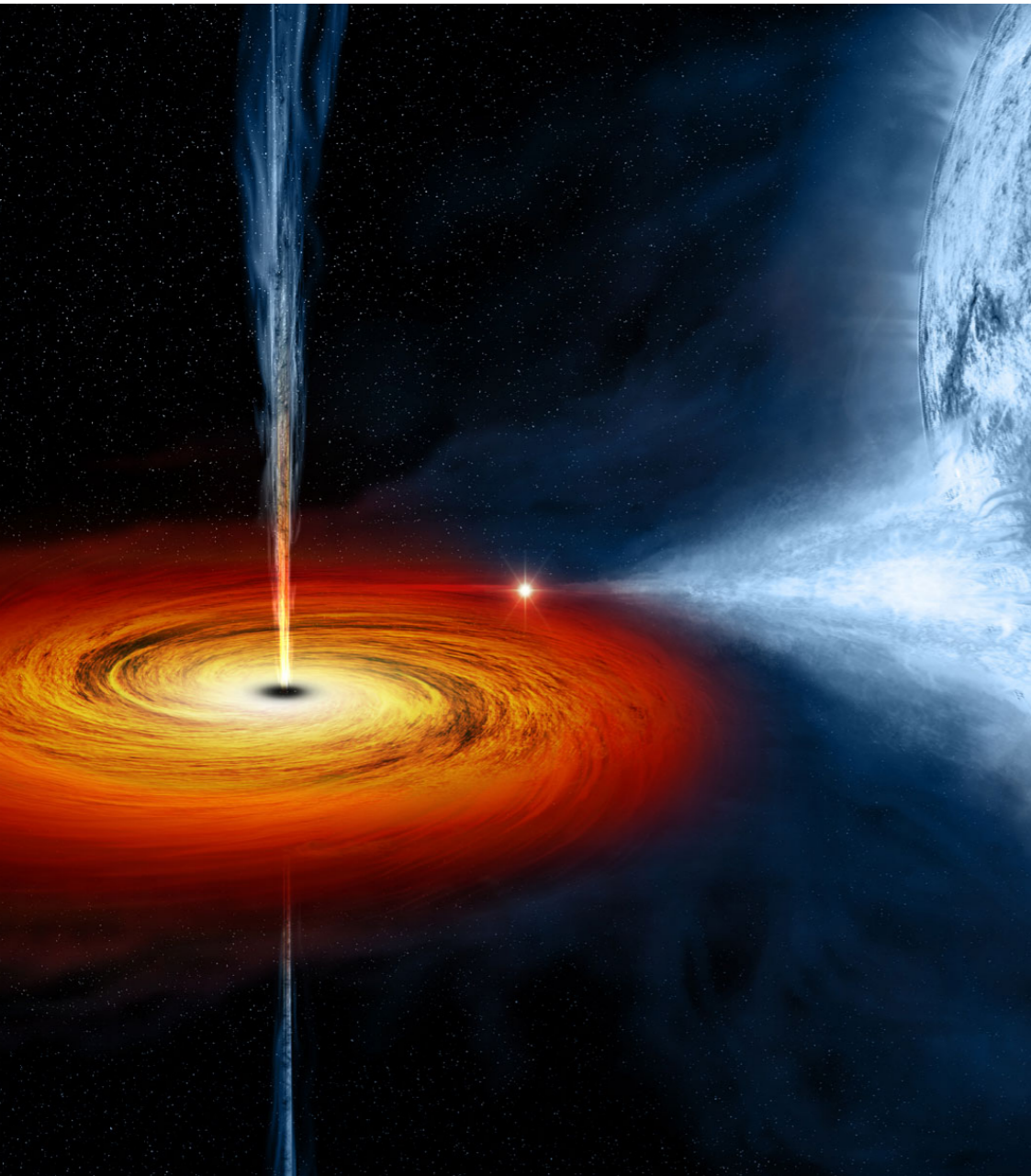
Nevtrino izvori v naravi

Zvezde/galaksije

$$E_\nu \lesssim \text{PeV}$$

Črne luknje, pulzarji, Supernove SNI 987

IceCube observatorij



Nevtrino izvori v naravi

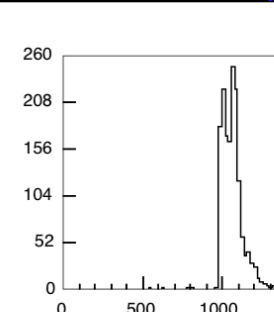
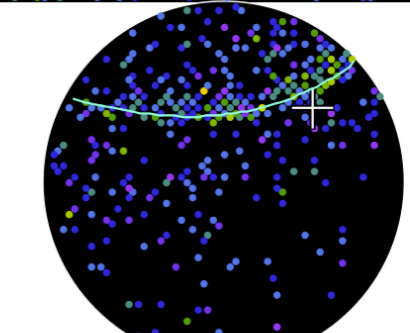
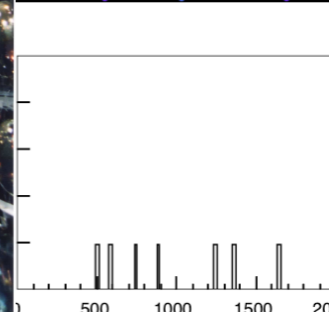
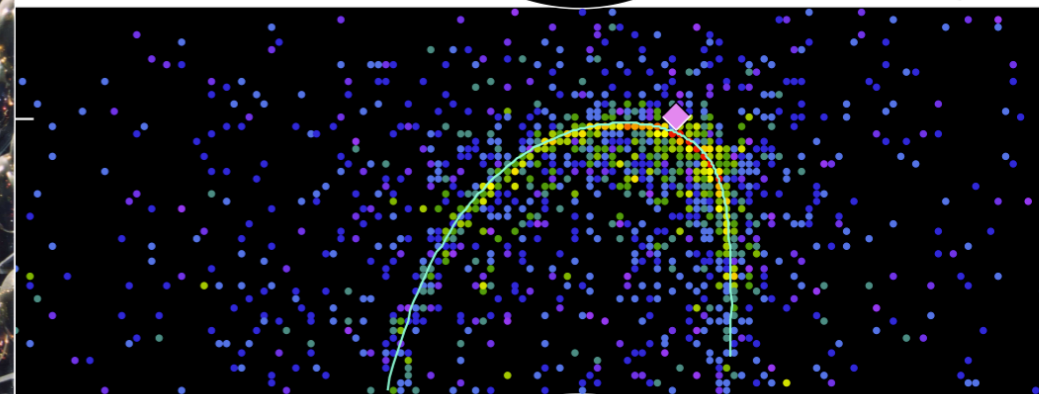
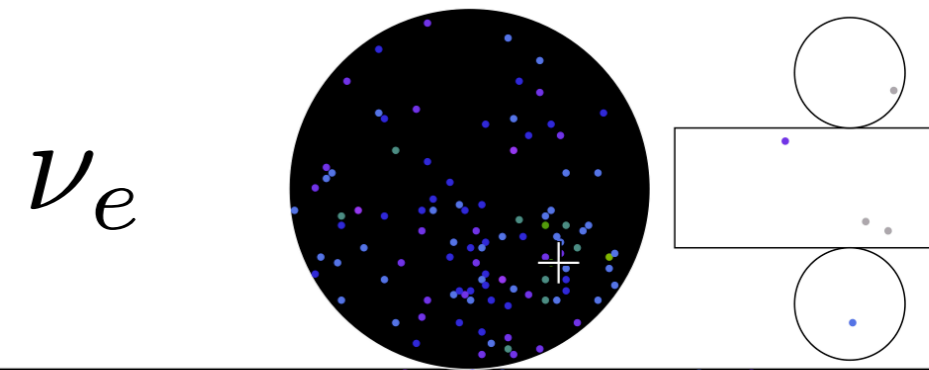
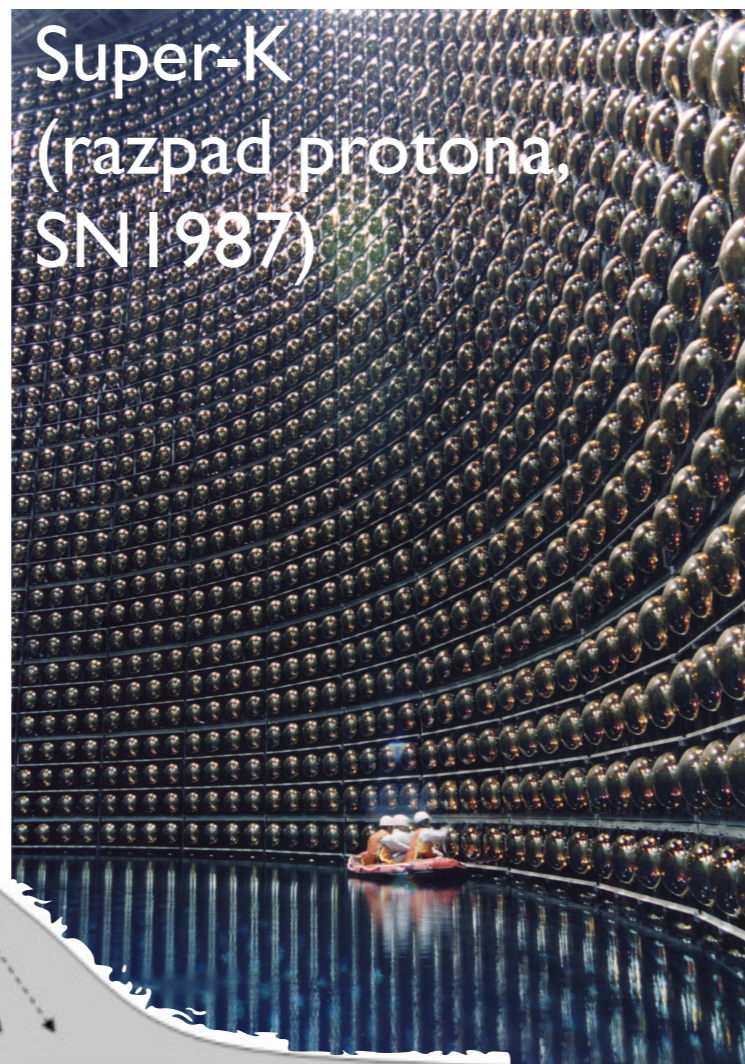
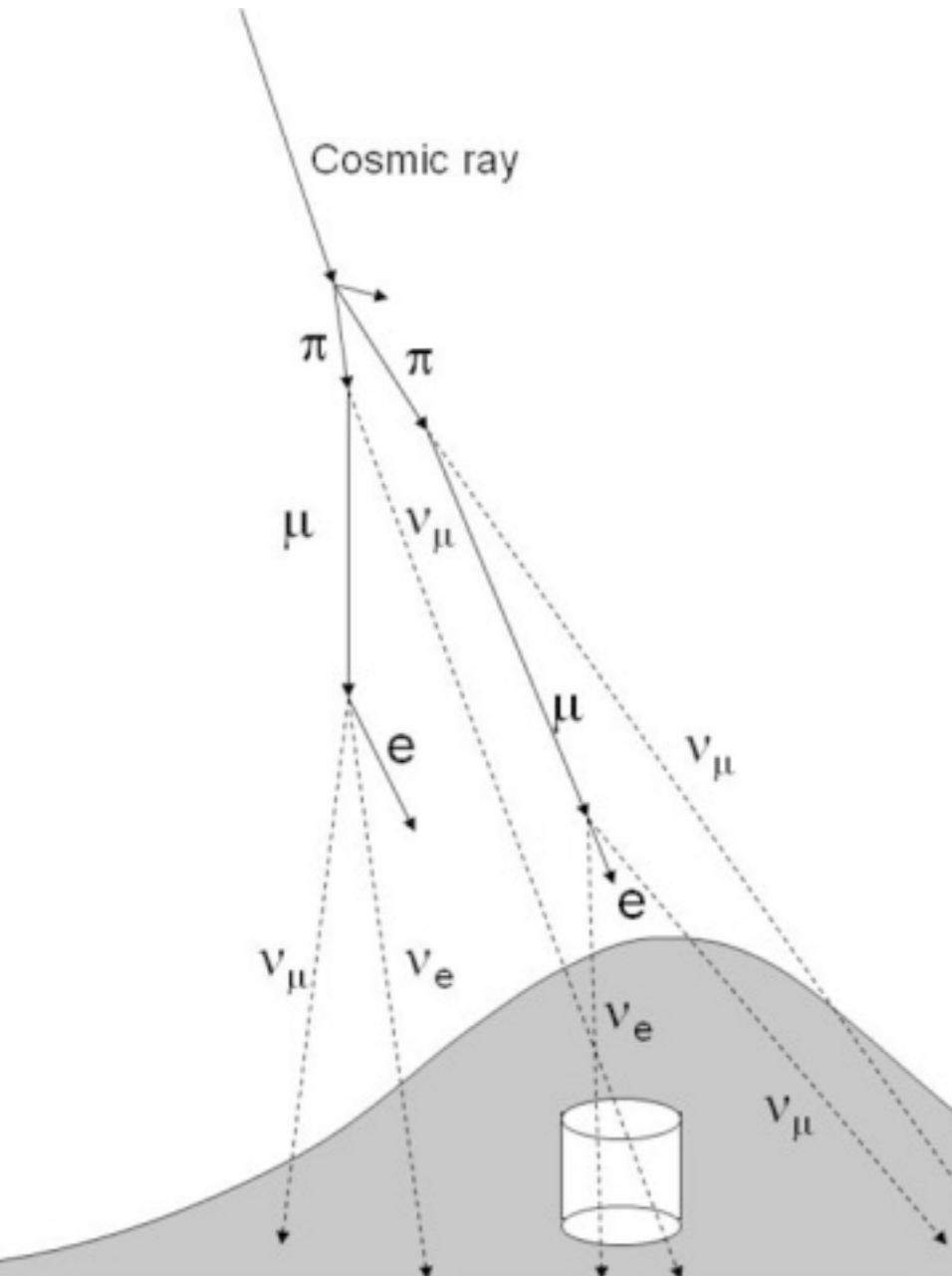


Atmosferski nevtrini

$$\frac{N_{\nu_\mu}}{N_{\nu_e}} \simeq \frac{2}{1} \quad \text{pričakovana vrednost}$$

$$E_\nu \in [10 \text{ MeV}, 100 \text{ TeV}]$$

p, n, lahka jedra

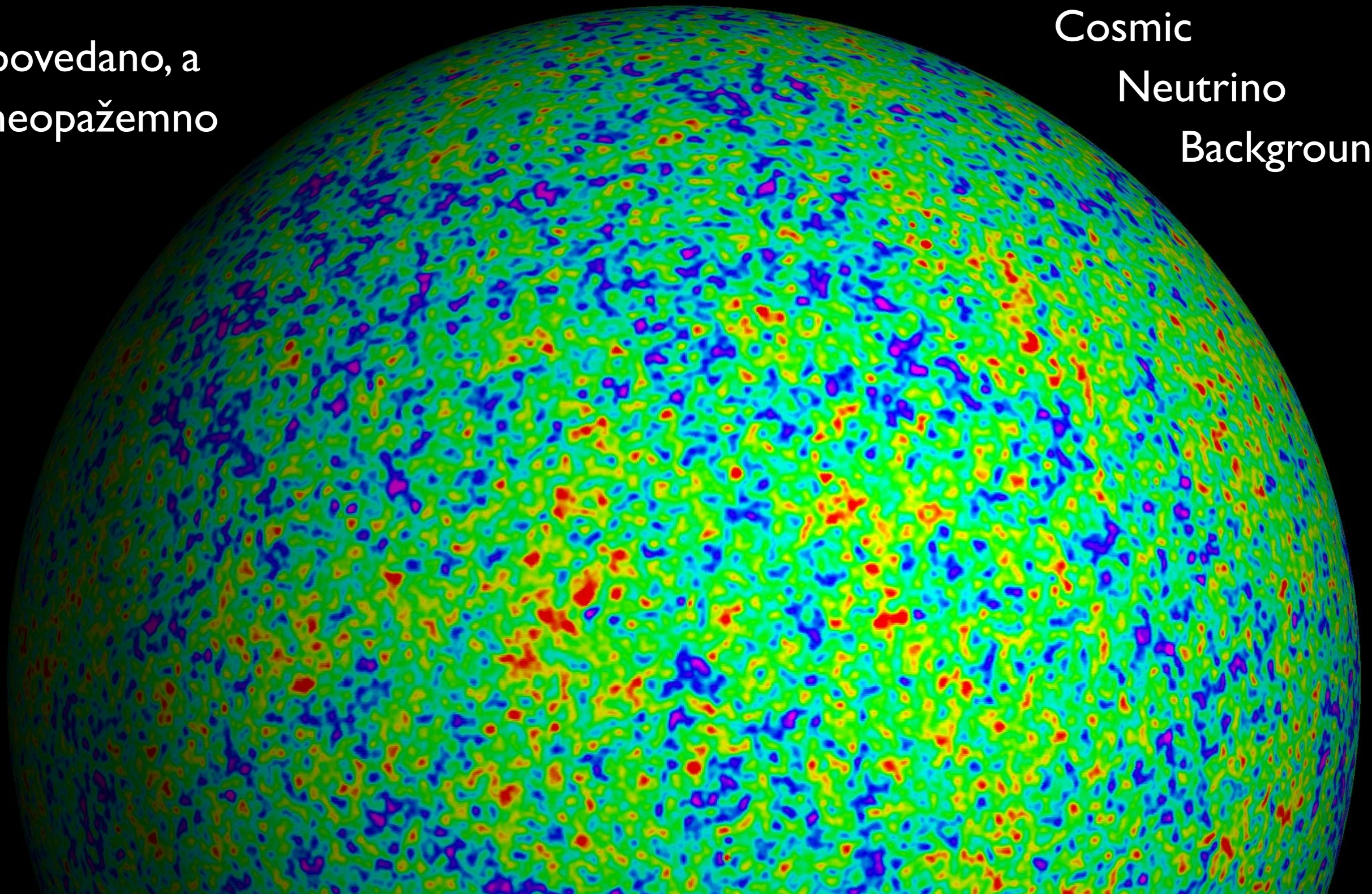


Nevtrino izvori v naravi

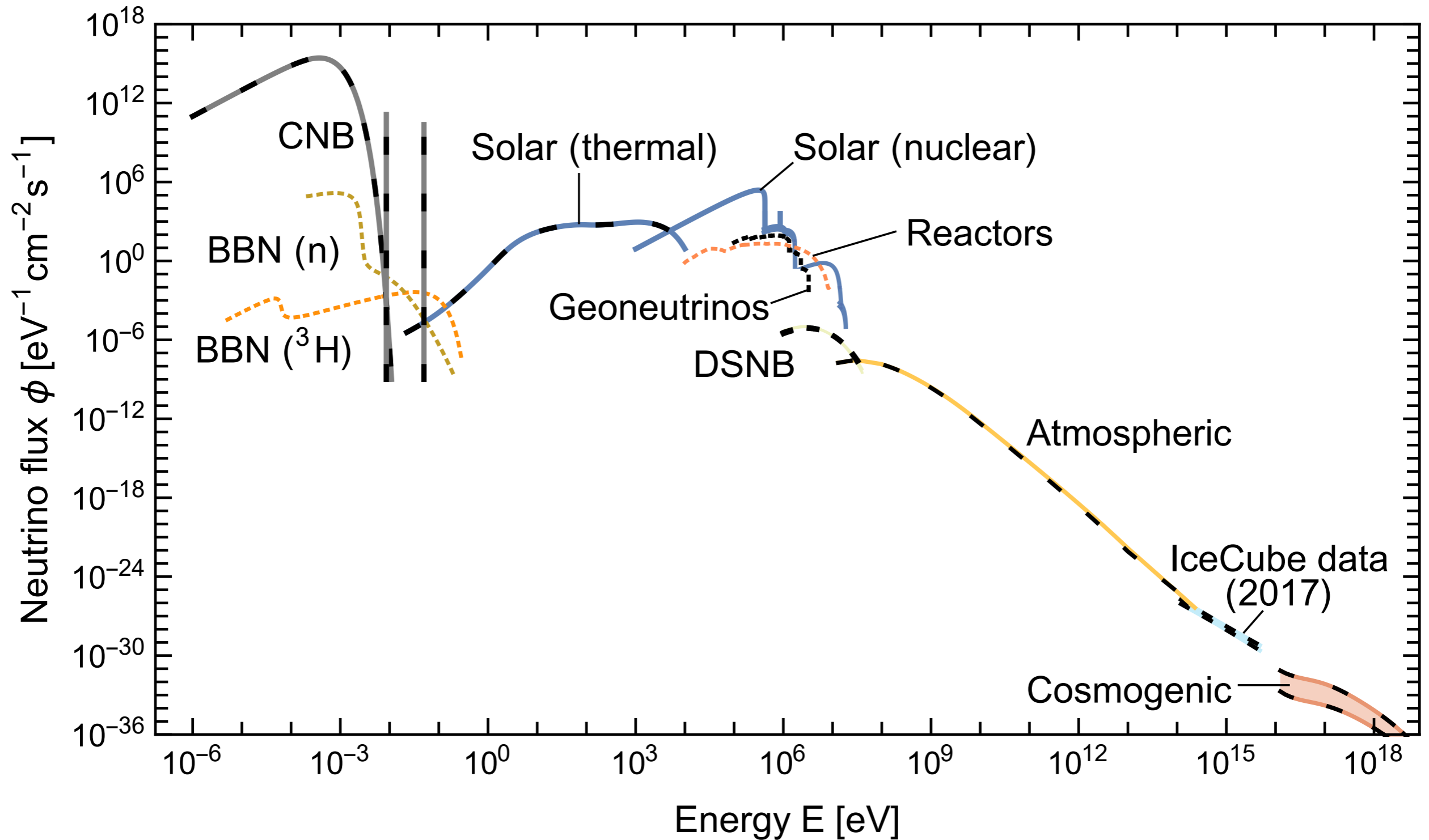
Celotno vesolje!

Napovedano, a
še neopažemno

Cosmic
Neutrino
Background



Nevtrino izvori v naravi



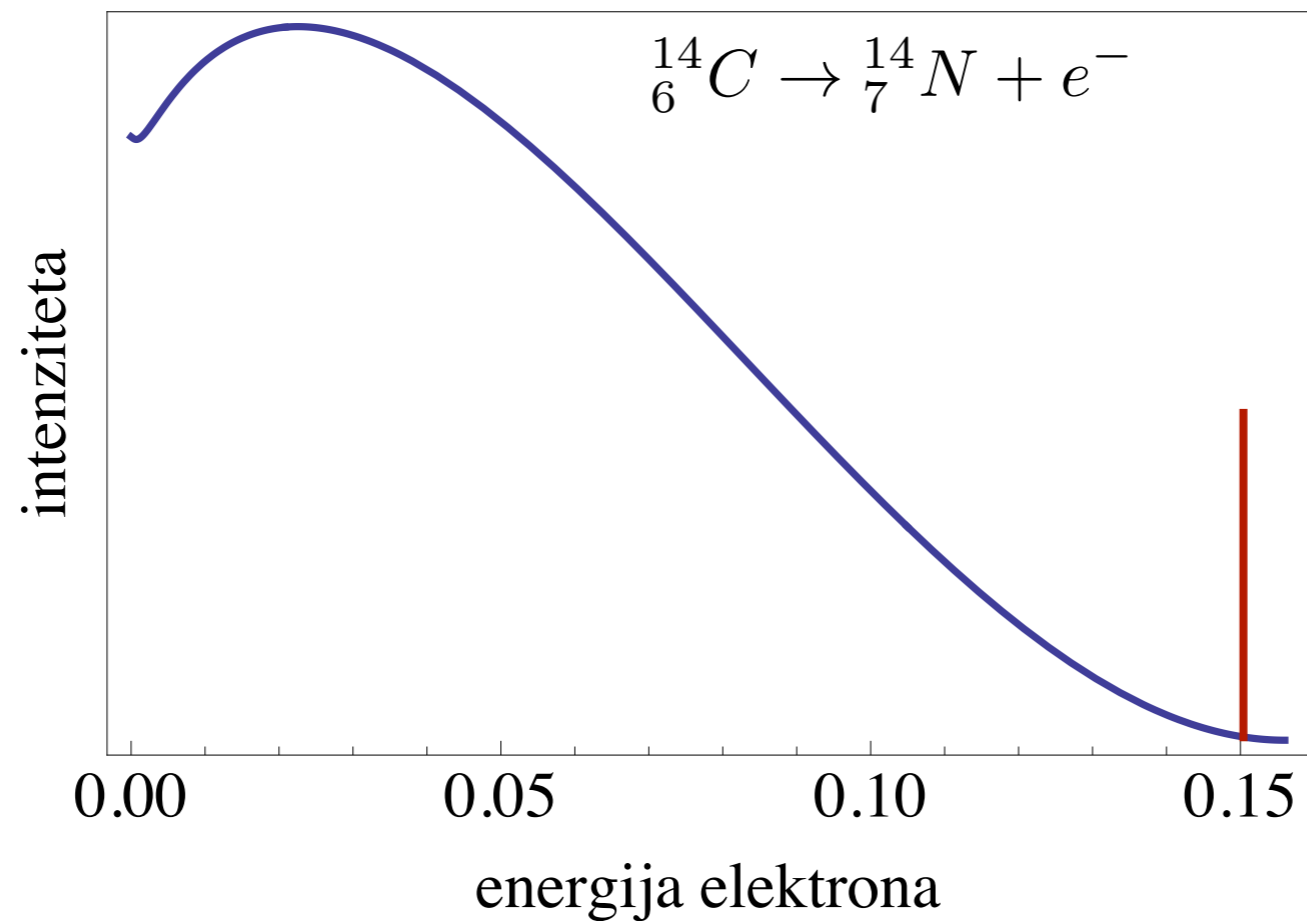
Poenoteni spekter nevtrinov

Nevtrino kratka zgodovina eksperimenta

1930 v zmedi glede beta razpada

1914 Chadwick, ...

se energija
ne ohranja?



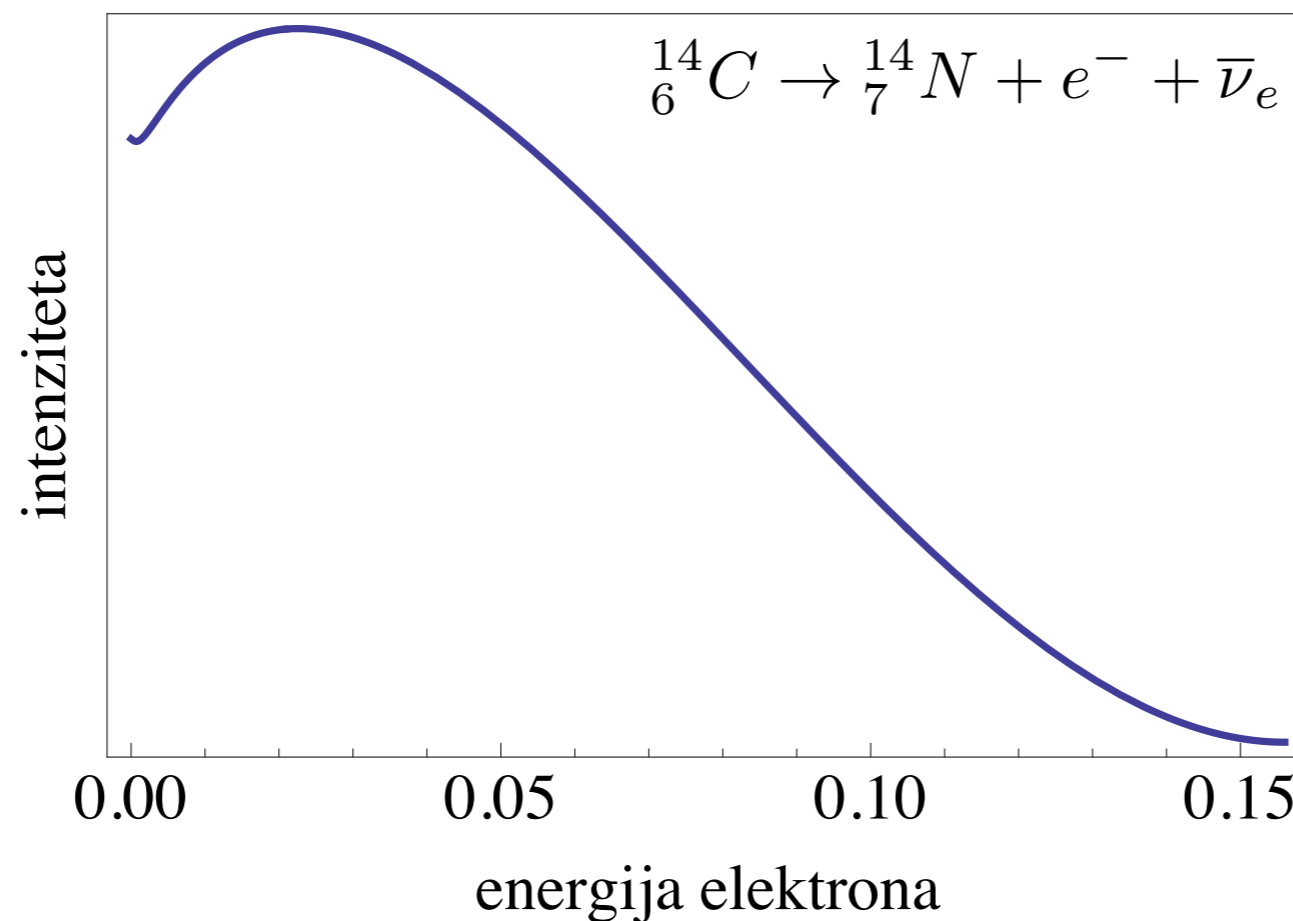
Nevtrino kratka zgodovina eksperimenta

1930 v zmedi glede beta razpada Pauli predlaga obstoj *nevtrona*

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,
Wie der Ueberbringer dieser Zeilen, den ich herzlichst



KATRIN
eksperiment

Nevtrino kratka zgodovina eksperimenta

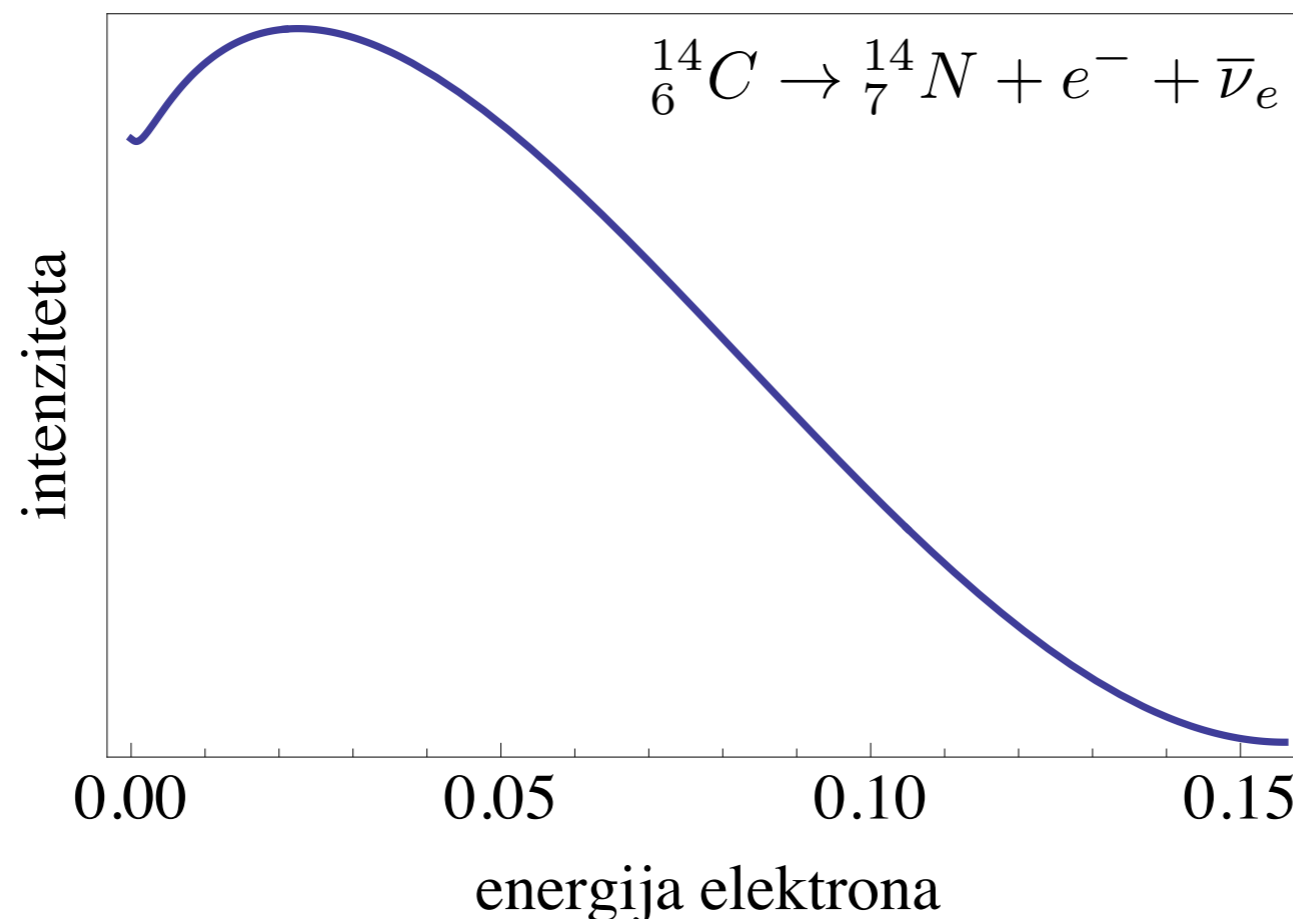
neutrino Fermi

1930 v zmedi glede beta razpada Pauli predlaga obstoj ~~neutrona~~

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,
Wie der Ueberbringer dieser Zeilen, den ich herzlichst



Nevtrino lastnosti

Nima naboja, nima sledi

$$Q(\nu) = 0$$

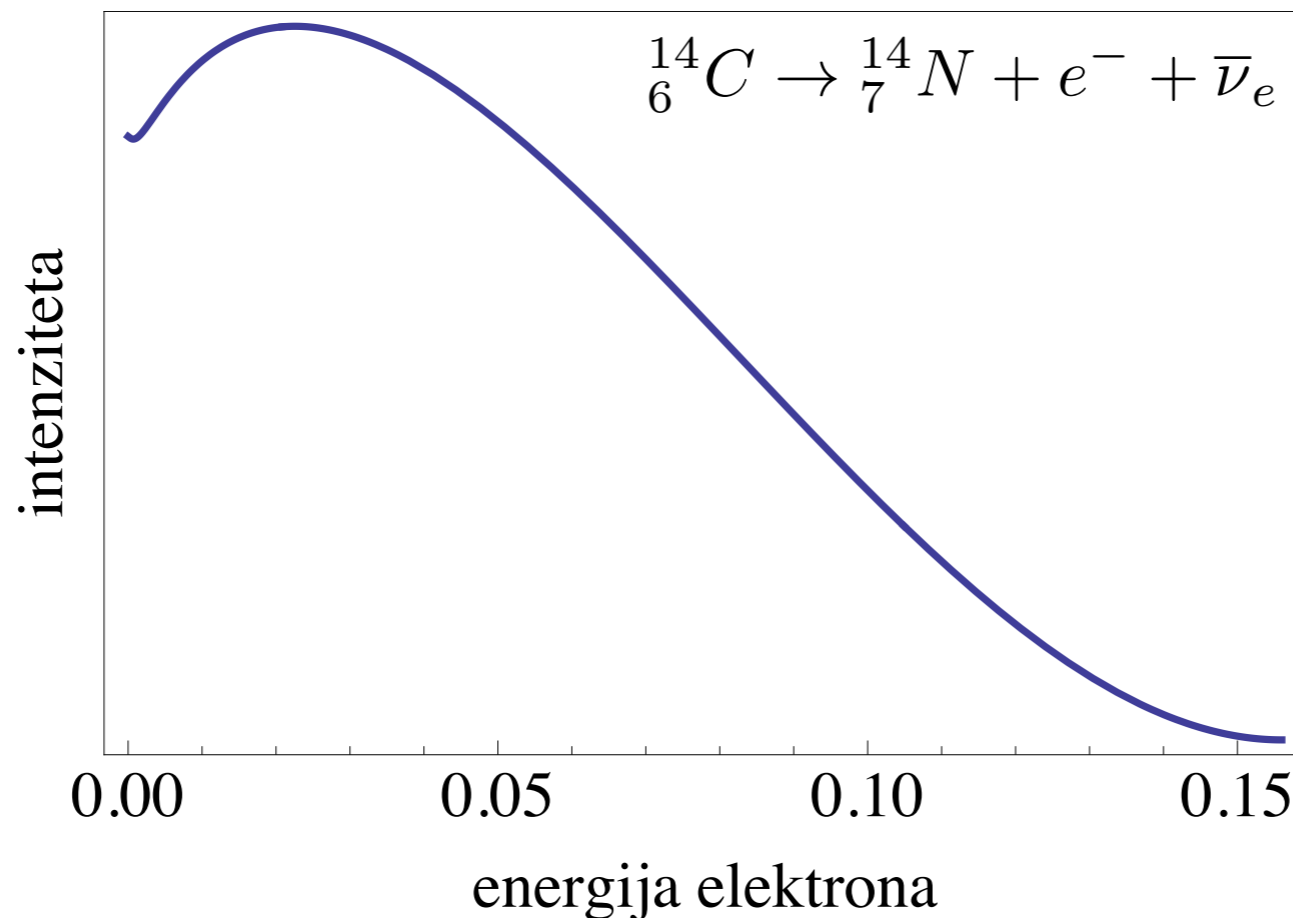
Biti mora 'lahek'

$$m_\nu \ll m_e$$

$$m_e c^2 = 511 \text{ keV}$$

Je fermion, kot elektron

$$s(\nu) = \frac{1}{2}$$



KATRIN
eksperiment

$$m_\nu c^2 < 0.8 \text{ eV}$$

Nevtrino kratka zgodovina eksperimenta

1930 v zmedi glede beta razpada Pauli predlaga obstoj *nevtrina* (*Baade stava*)

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

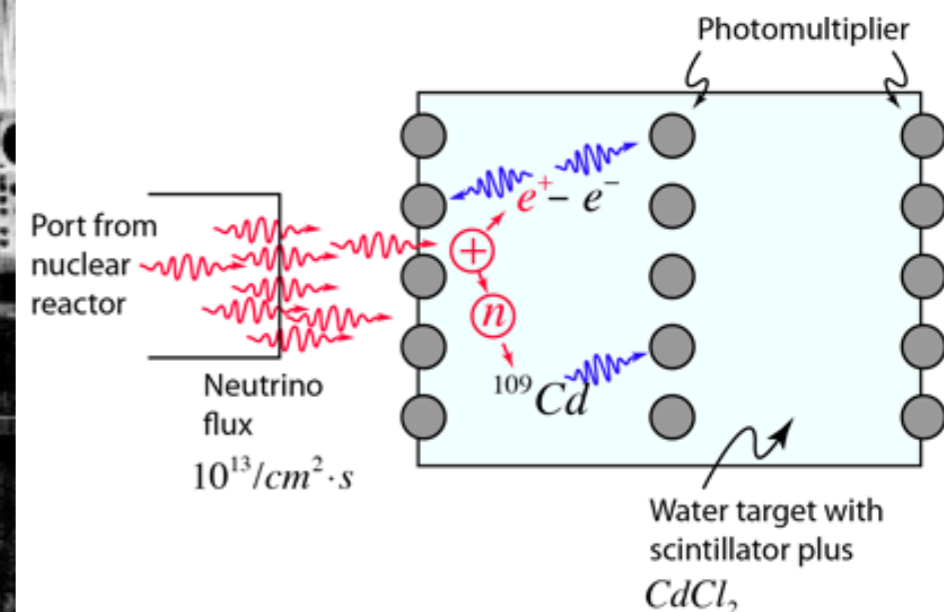
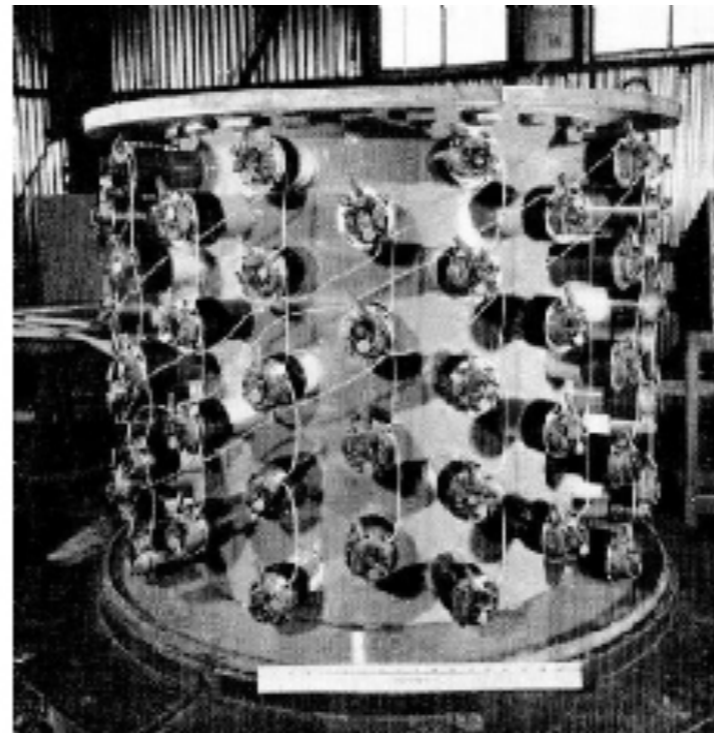
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,
Wie der Ueberbringer dieser Zeilen, den ich herzlichst

1956 Reines in Cowan izmerita reaktorske anti-nevtrine



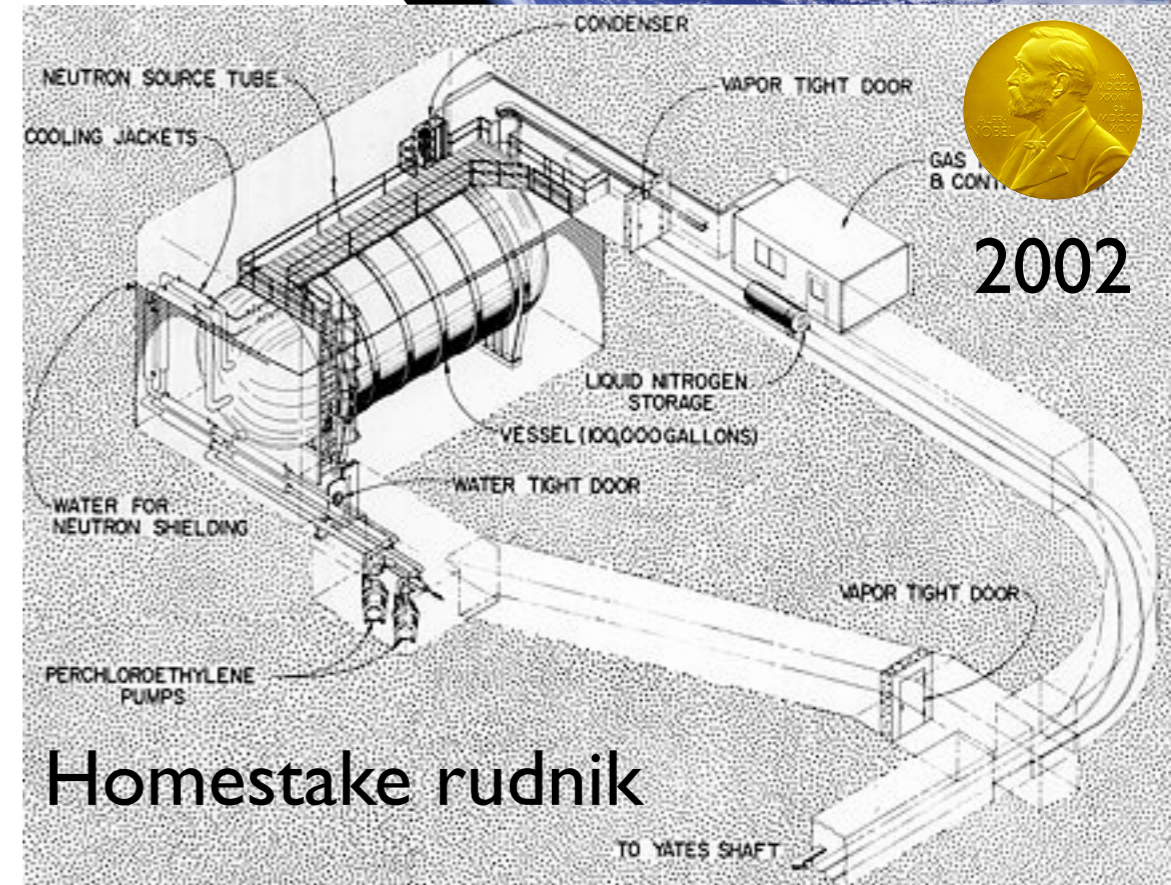
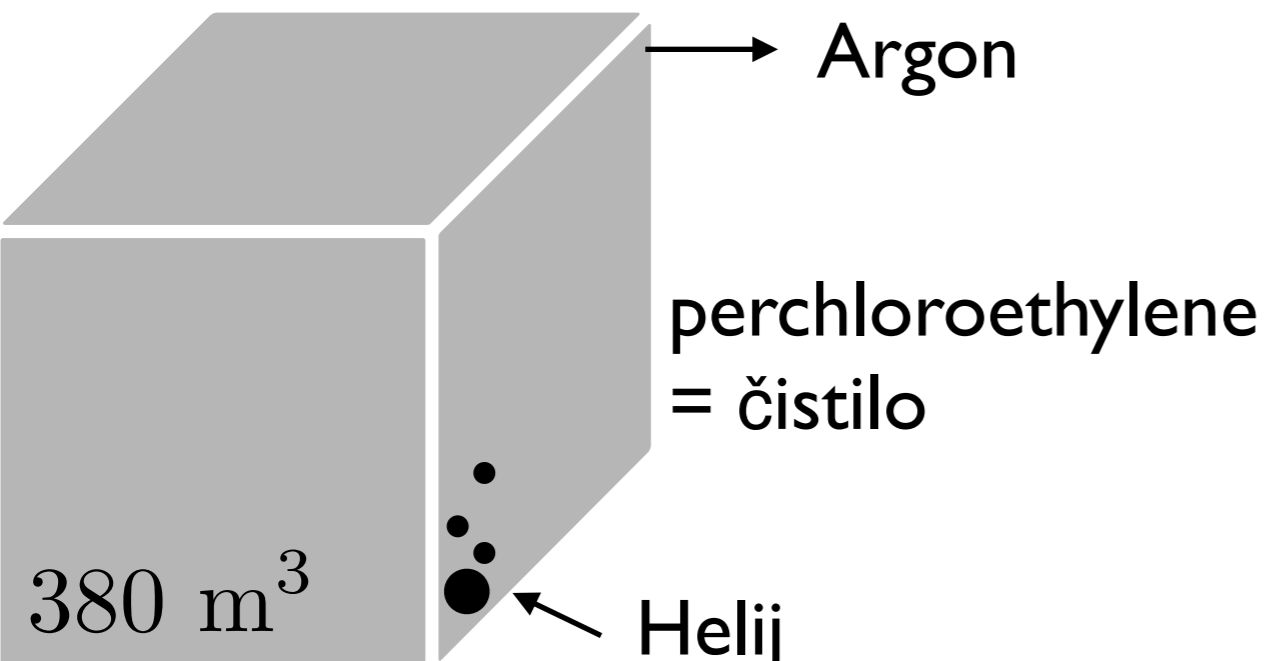
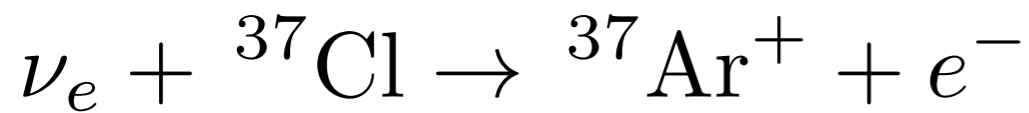
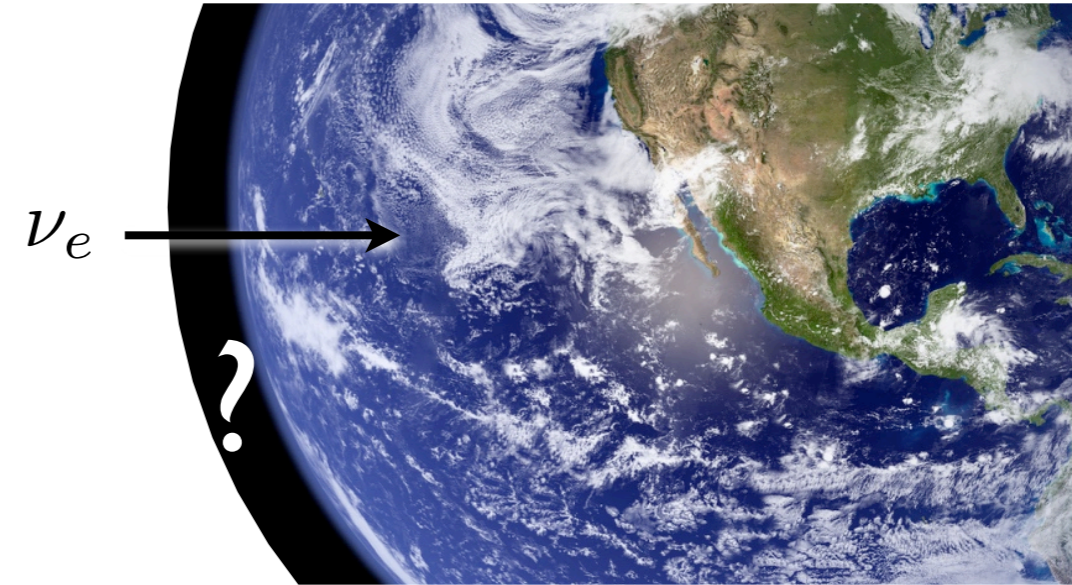
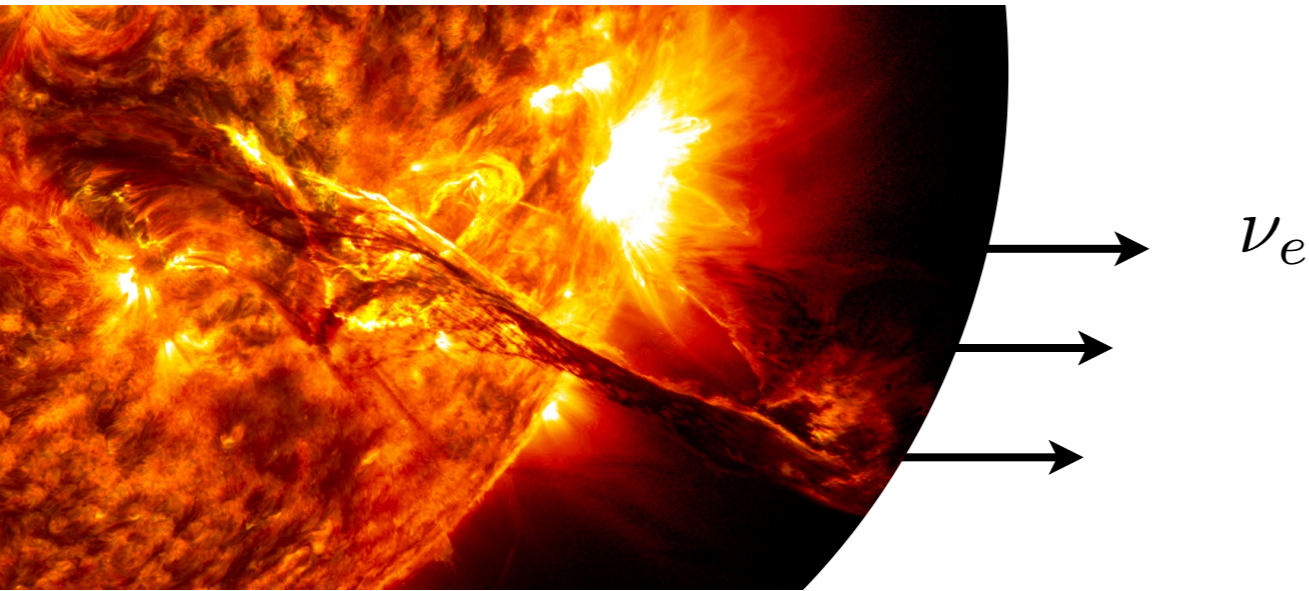
1995



Poltergeist eksperiment: 400 l mešanice vode in kadmijevega klorida (Cd).
Veliko nevtrinov redko interagira s protoni v tarči (2.8/uro).

Nevtrino kratka zgodovina eksperimenta

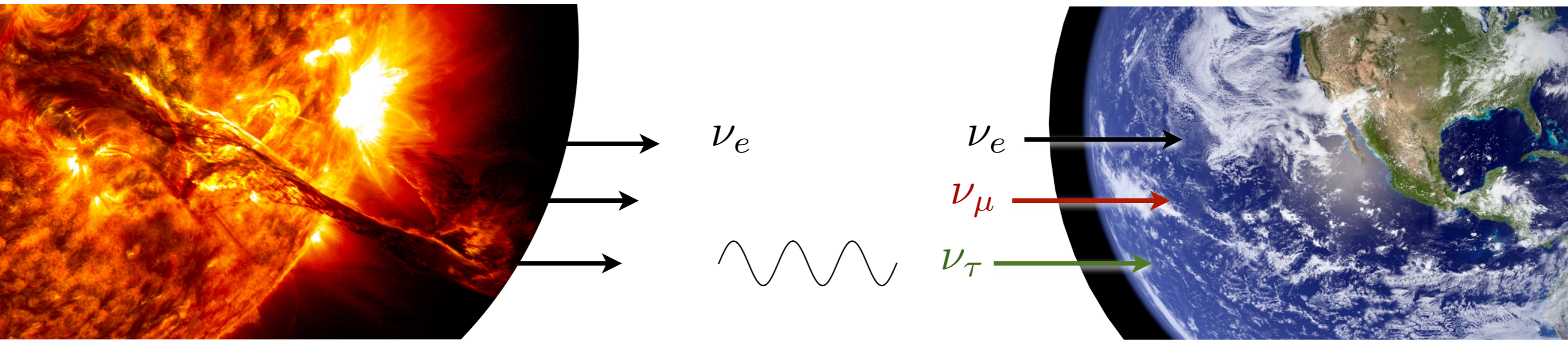
1960-1990 Bahcall napove, Davis izmeri 1/3 nevtrinov iz sonca



Homestake rudnik

Nevtrino kratka zgodovina eksperimenta

1960-1990 Bahcall napove, Davis izmeri 1/3 nevtrinov iz sonca



1957...- Pontecorvo predlaga
oscilacije nevtrinov z maso

Kvantno-mehanski proces

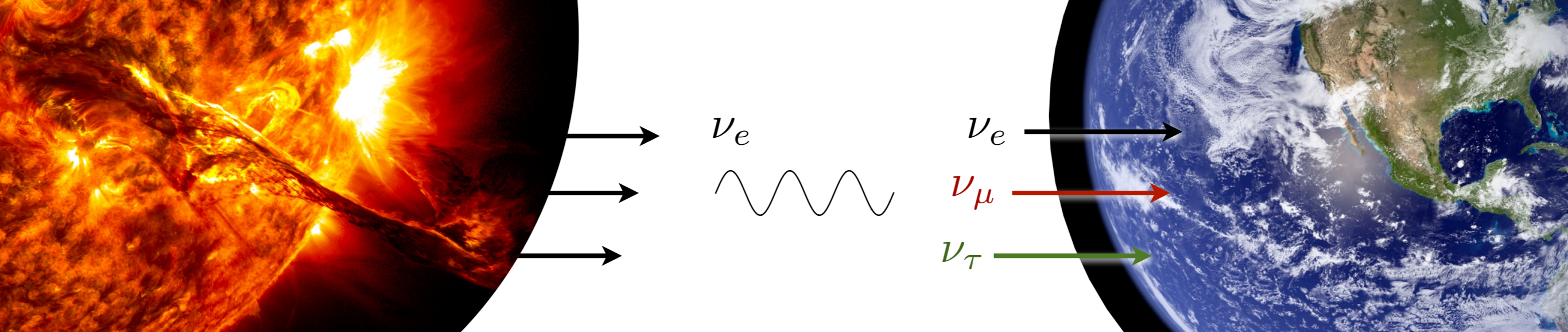
Interakcijska
baza

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

Masna baza

$$P(\nu_e \rightarrow \nu_\mu) \simeq \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Makroskopske
razdalje



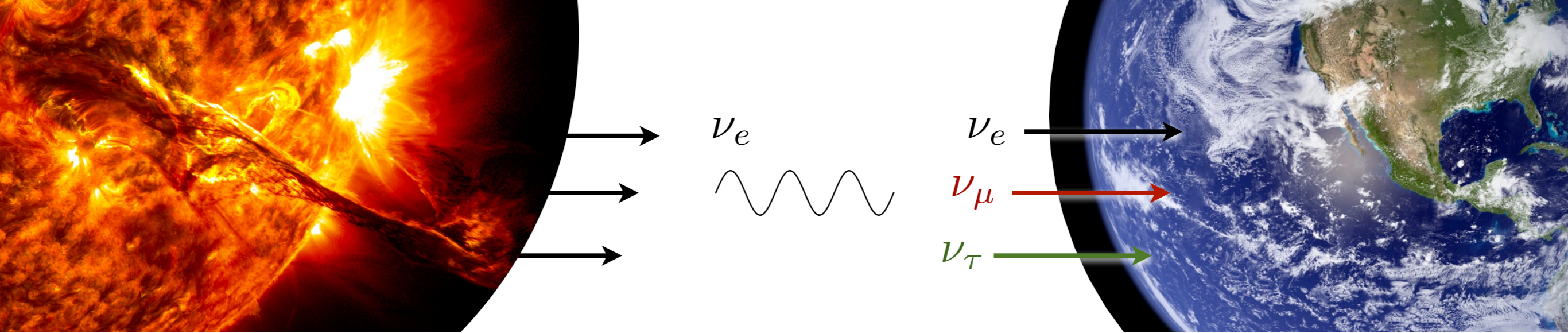
Nevtrinske oscilacije

1957 - Pontecorvo predlaga oscilacije nevtrino-antinevtrino

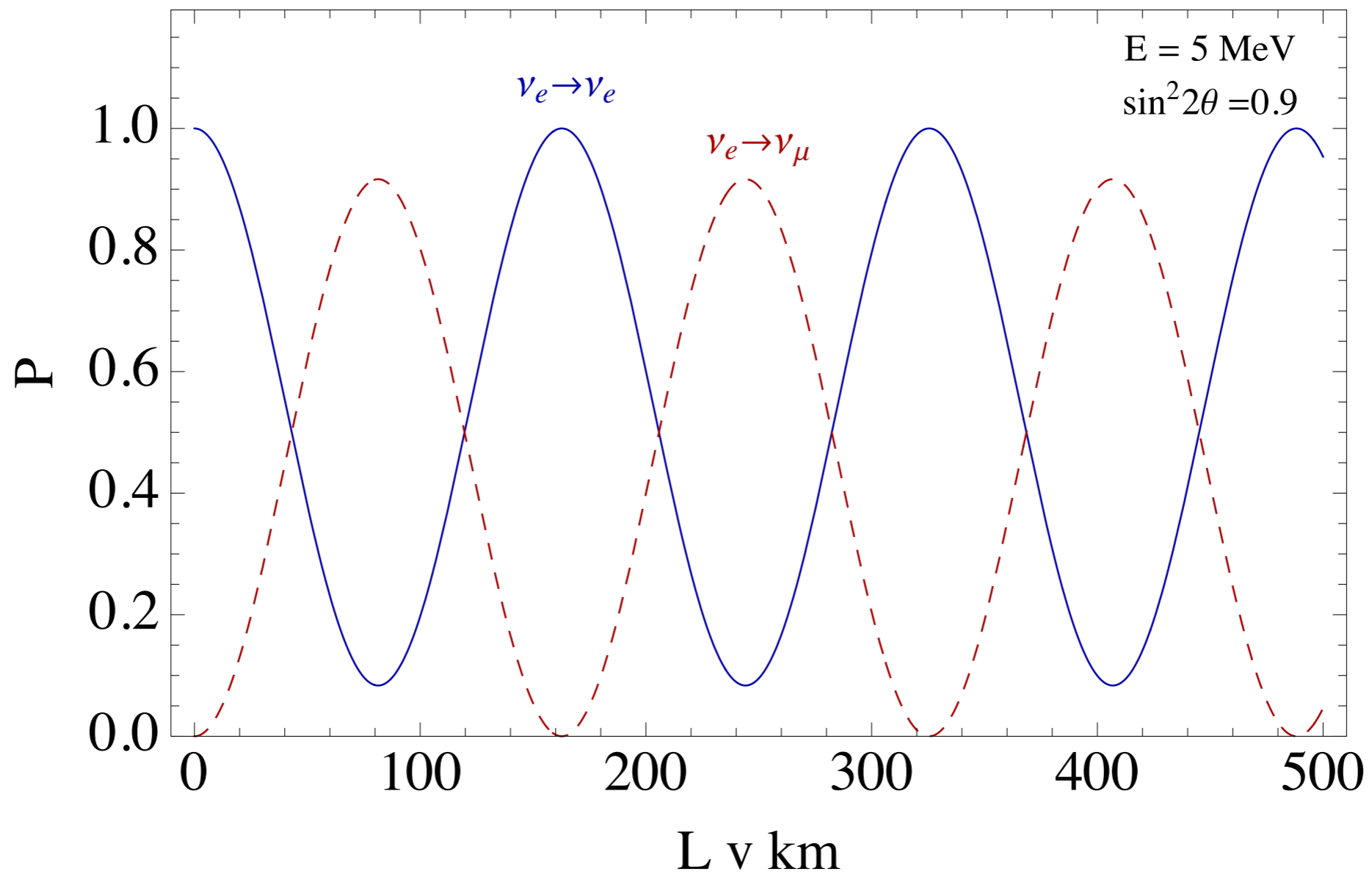
1962 - Maki, Nakagawa, Sakata; 1969 - Gribov, Pontecorvo

$$P(\nu_e \rightarrow \nu_\mu) \simeq \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$
$$m_\nu \neq 0$$

1978-1985 - Mikheyev, Smirnov, Wolfenstein: snov je pomembna

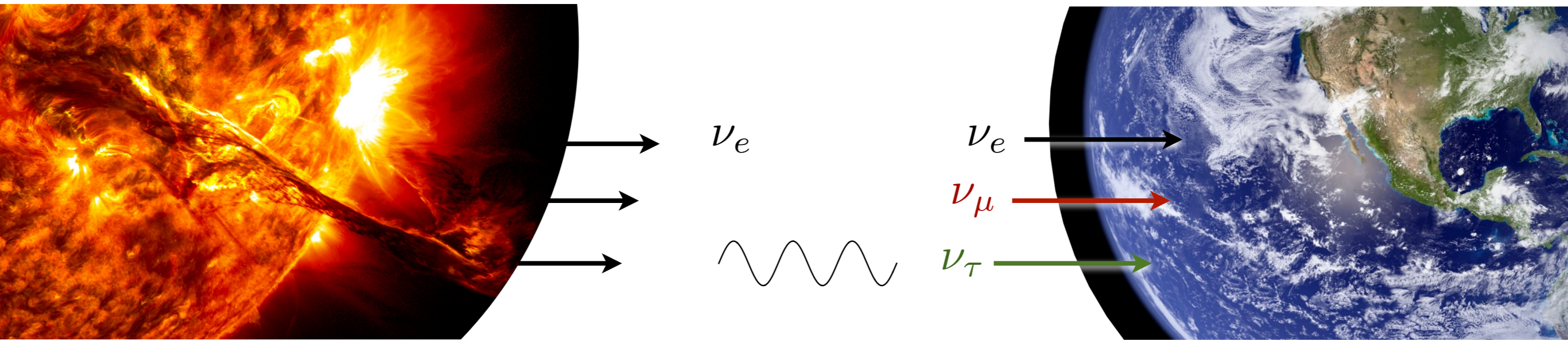


Nevtrinske oscilacije



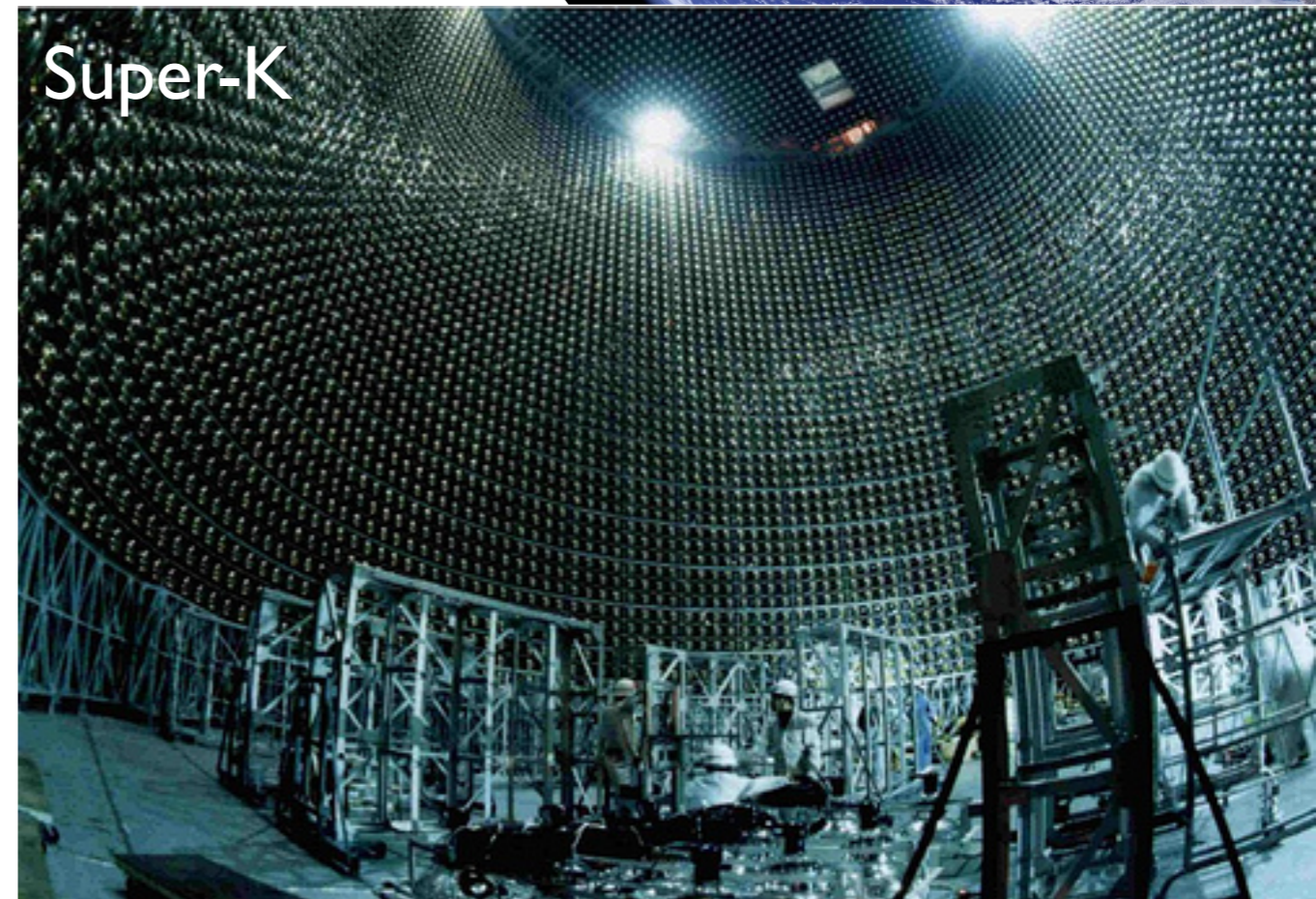
Nevtrino kratka zgodovina eksperimenta

1960-1990 Bahcall napove, Davis izmeri 1/3 nevtrinov iz sonca

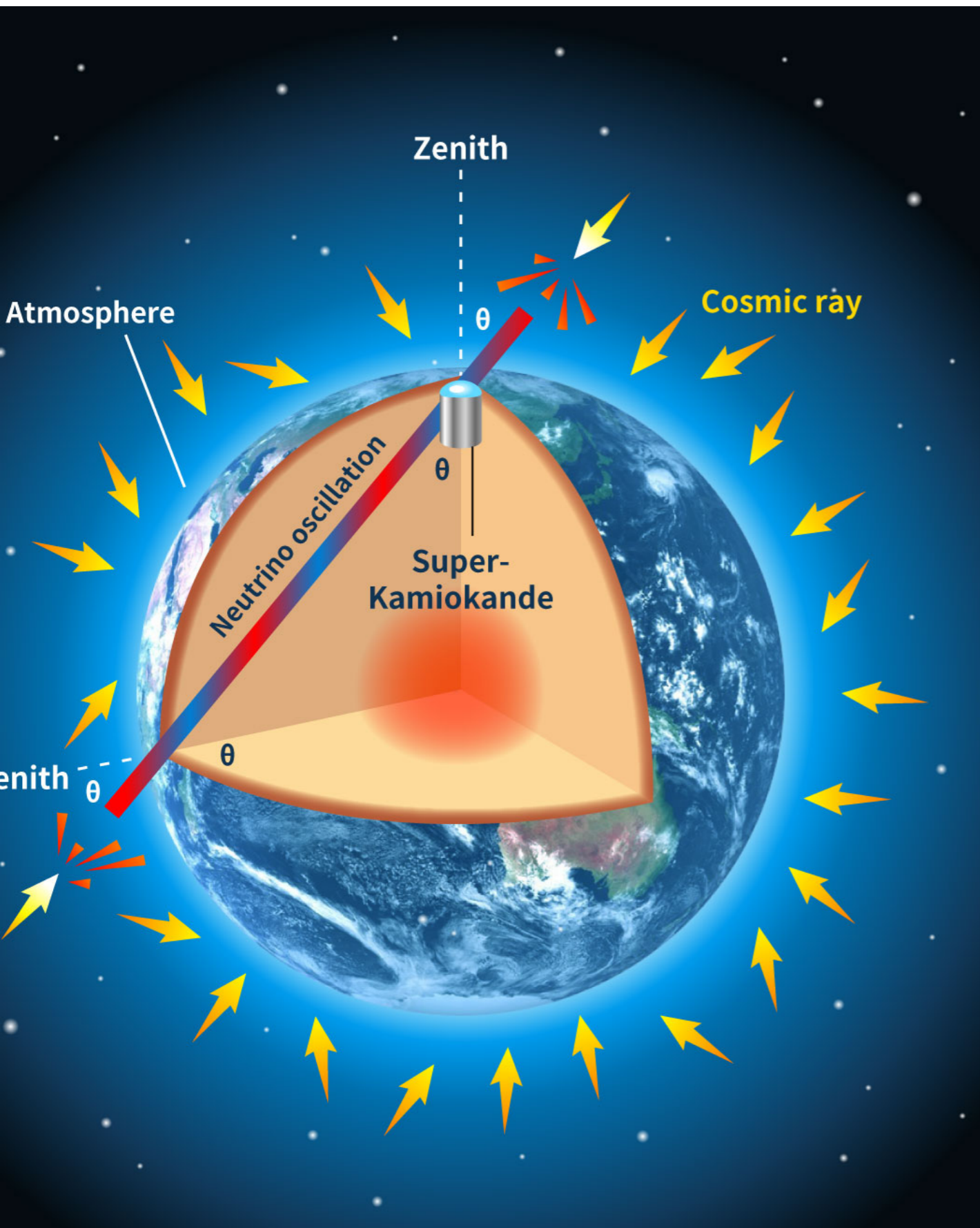


1957...- Pontecorvo predlaga
oscilacije nevtrinov z maso

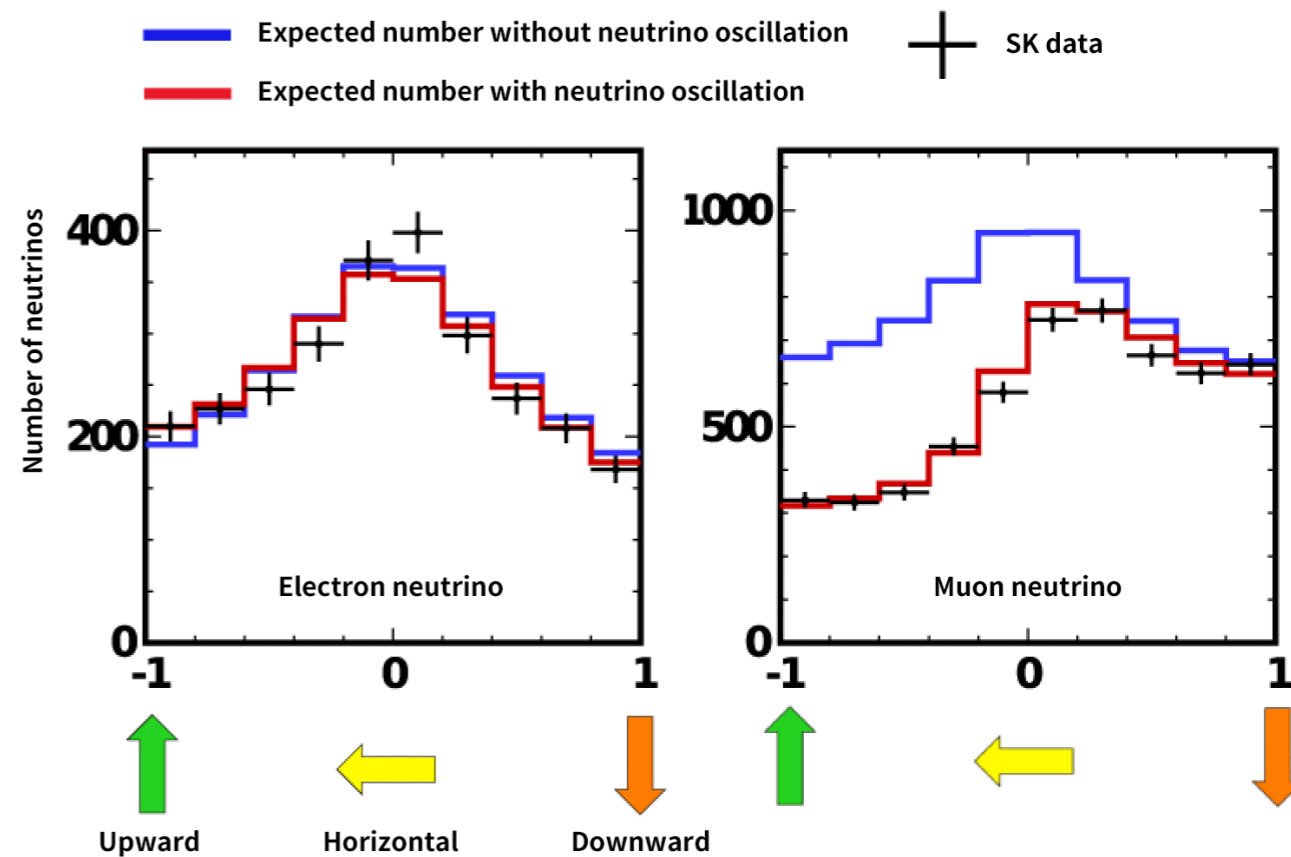
1998 Super-K izmeri atmosferske
oscilacije



1998 Super-K izmeri atmosfarske oscilacije



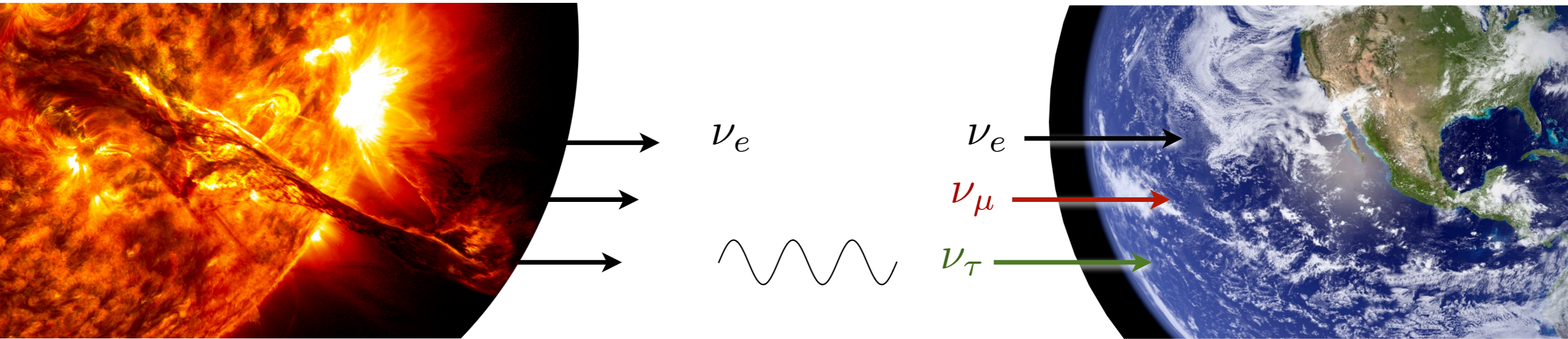
Nevtrini izotropni in prodorni, SK določi njihovo smer



Ločuje med elektroni, mioni in tau nevtrini; oscilacije v snovi

Nevtrino kratka zgodovina eksperimenta

1960-1990 Bahcall napove, Davis izmeri 1/3 nevtrinov iz sonca



1957...- Pontecorvo predlaga
oscilacije nevtrinov z maso

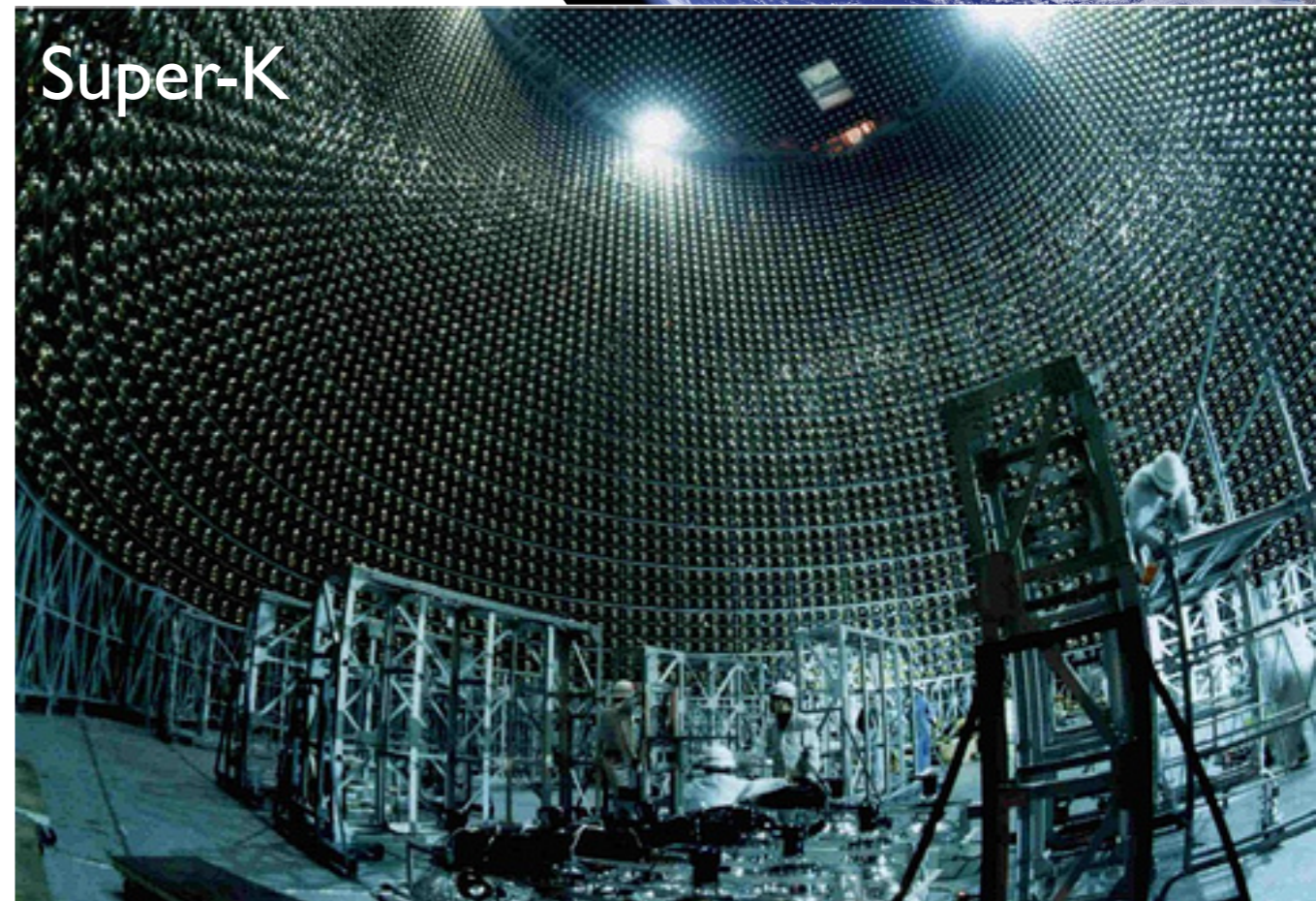
1998 Super-K izmeri atmosferske
oscilacije

2001 SNO potrди Davis-a

$$m_\nu \neq 0$$



2015



Nevtrino kaj vemo in česar ne

$$\begin{array}{l} \nu_e \longrightarrow \\ \nu_\mu \longrightarrow \\ \nu_\tau \longrightarrow \end{array} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{PMNS} Trije mešalni koti + CP faze

Razlike mas $\Delta m_{21}^2 = 7 \times 10^{-5} \text{ eV}^2$ $\Delta m_{32}^2 = 2 \times 10^{-3} \text{ eV}^2$

Mešalni koti $\theta_{12} = 34^\circ$, $\theta_{23} = 48^\circ$, $\theta_{13} = 8^\circ$



Masa najlažjega nevtrina in masna hierarhija (NH vs. IH)

CP faze

Ali so nevtrini Diracovi ali Majoranovi delci

Izvor mase nevtrinov

Izvor mase nevtrinov

Masa gradnikov snovi

1928 - Dirac postavi relativistično teorijo za elektron

$$m_D \bar{e}_L e_R$$

'31 napove *antimaterijo*

1932 - Anderson odkrije pozitron

Masa nevtrinov

1928 - Dirac postavi relativistično teorijo za elektron

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'31 napove *antimaterijo*

1932 - Anderson odkrije pozitron

1937 - Majorana najde enostavnejši opis za nevtrino

$$m_M \nu_L \nu_L$$

Nevtrino kratka zgodovina teorije

1933 Fermiju revija Nature *ne objavi* teorije beta razpada

Špekulativno

Nevtrino kratka zgodovina teorije

Špekulativno

1933 Fermiju revija Nature *ne objavi* teorije beta razpada

1937 Majorana za habilitacijo objavi teorijo 'realnih' fermionov



in izgine.

Nevtrino kratka zgodovina teorije

Špekulativno

1933 Fermiju revija Nature *ne objavi* teorije beta razpada

1937 Majorana za habilitacijo objavi teorijo 'realnih' fermionov

$$\nu = \bar{\nu}$$

in izgine.

1937 Racah & Furry: iskanje Majorana nevtrina...

...se nadaljuje še danes.

Masa nevtrinov

1928 - Dirac postavi relativistično teorijo za elektron

$$m_D \bar{e}_L e_R$$

'31 napove *antimaterijo*

1932 - Anderson odkrije pozitron

1937 - Majorana najde enostavnejši opis za nevtrino

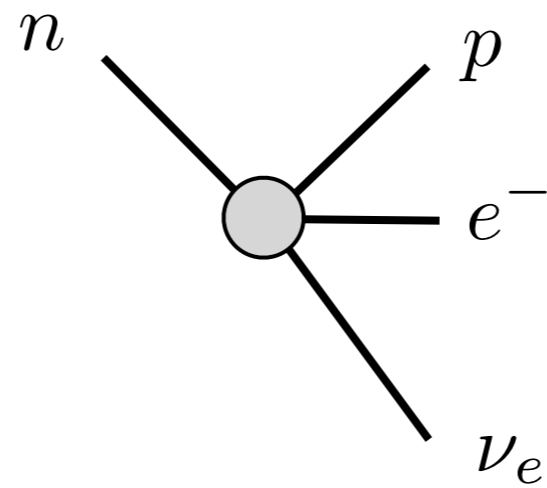
So nevtrini Diracovi ali Majoranovi delci?

Iskanje Majoranovih nevtrinov

~ jedrska fizika ~

Majorana nevtrino in jedrski procesi

'33 Fermi β razpad

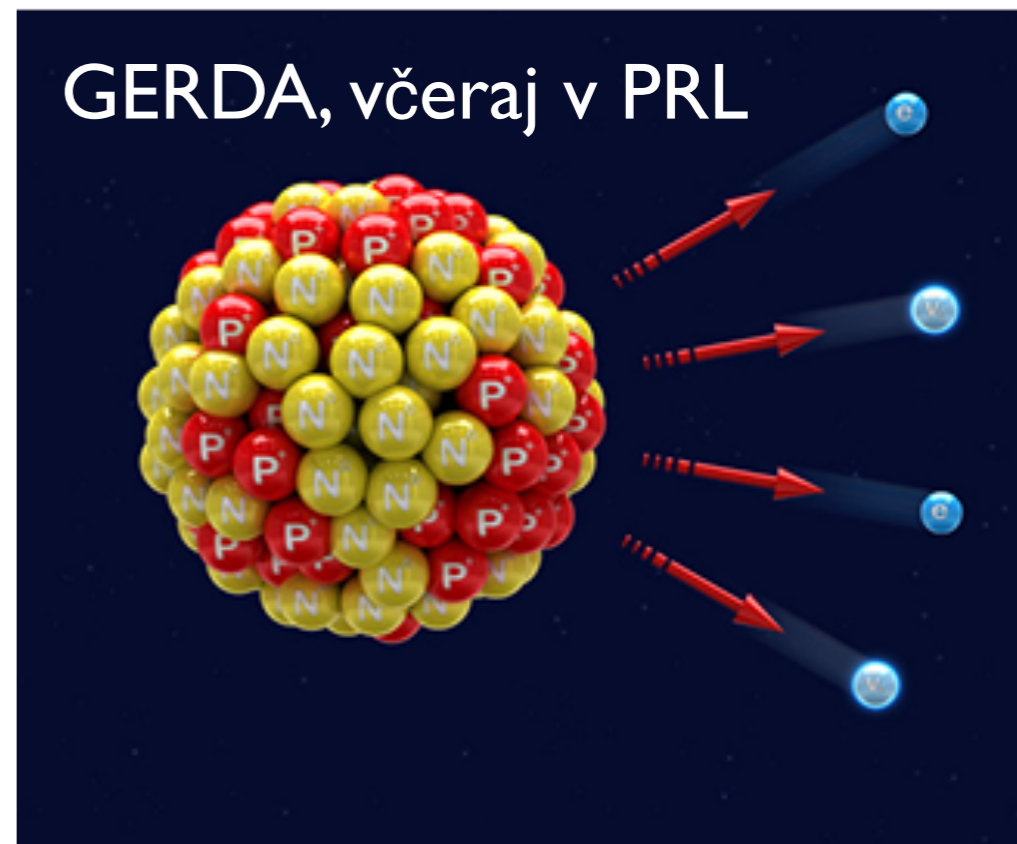
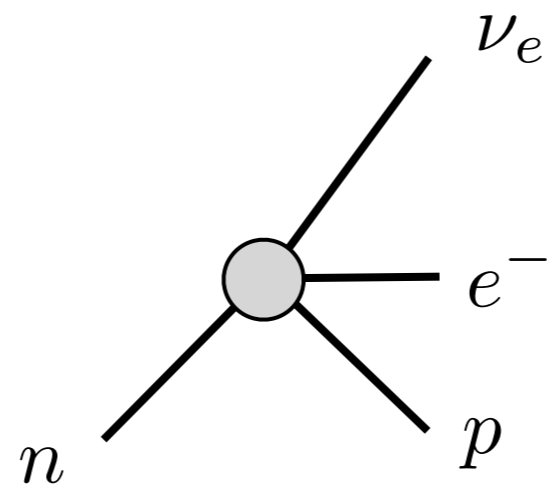
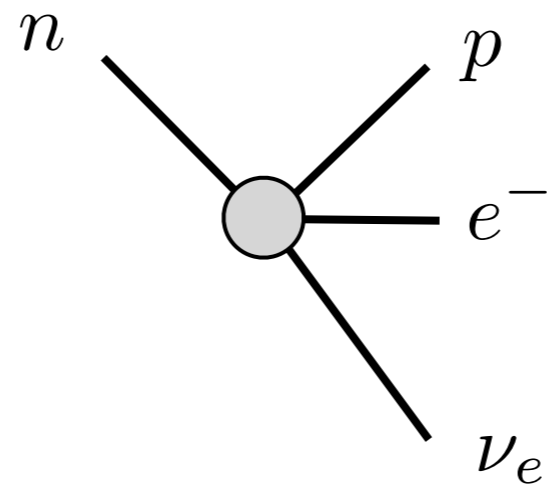


Majorana nevtrino in jedrski procesi

1935 - Maria Goeppert Mayer predlaga dvojni β razpad

2β razpad

$$\tau_{2\beta}^{\text{Gee}} = 2 \times 10^{21} \text{ let}$$



Majorana nevtrino in jedrski procesi

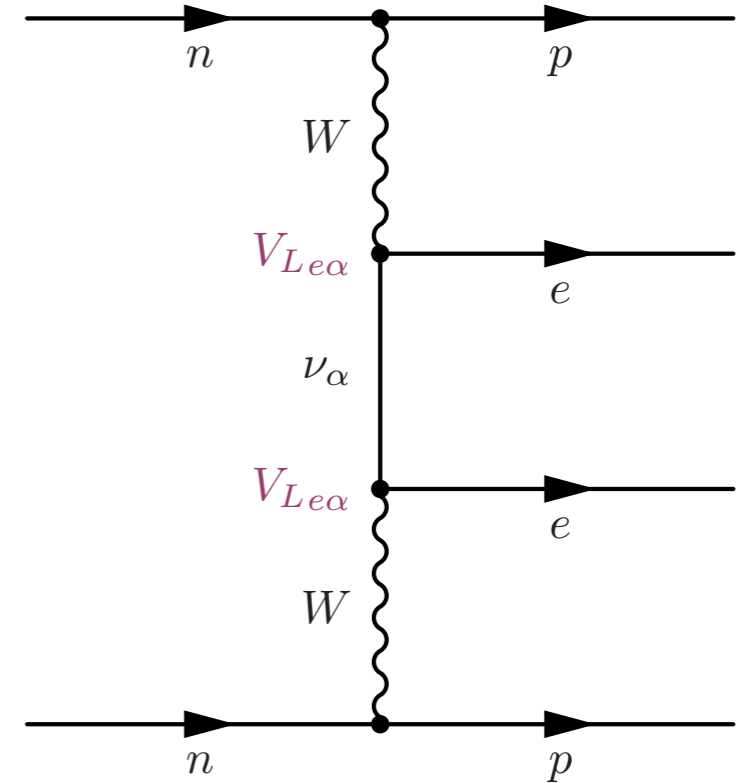
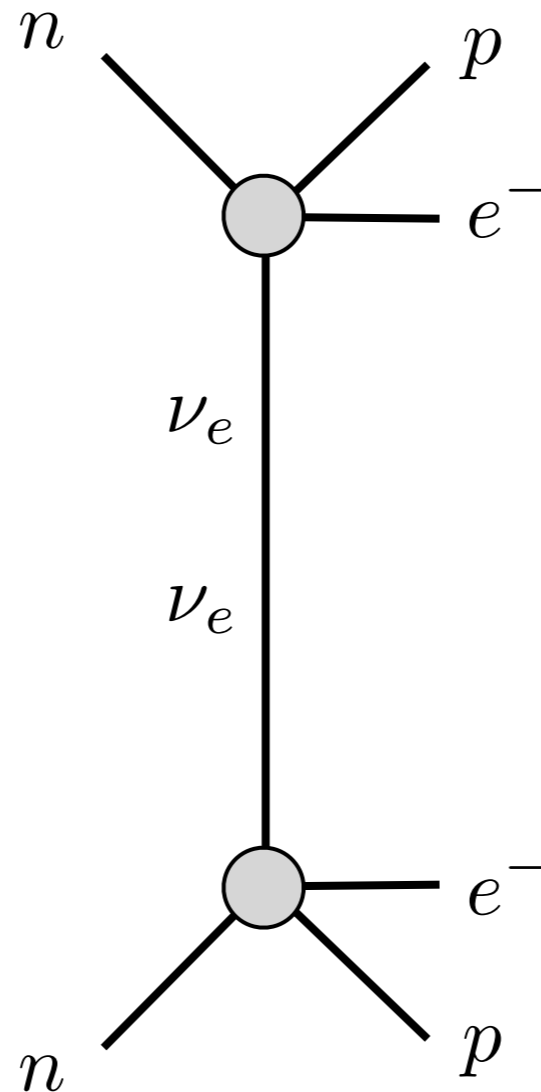
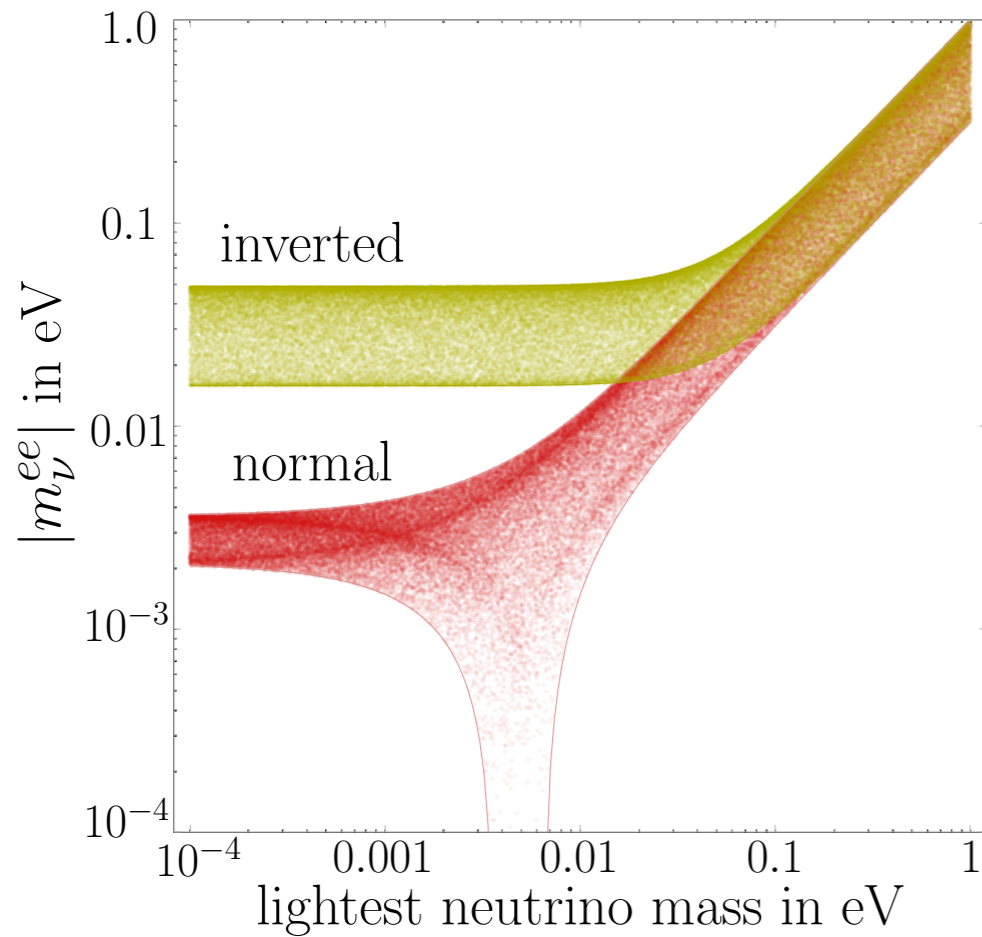
$\mathcal{O}(10)$ eksperimentov

Gerda



Majorana nevtrino in jedrski procesi

1937 - Racah in Furry predlagata breznevtrinski 2β razpad

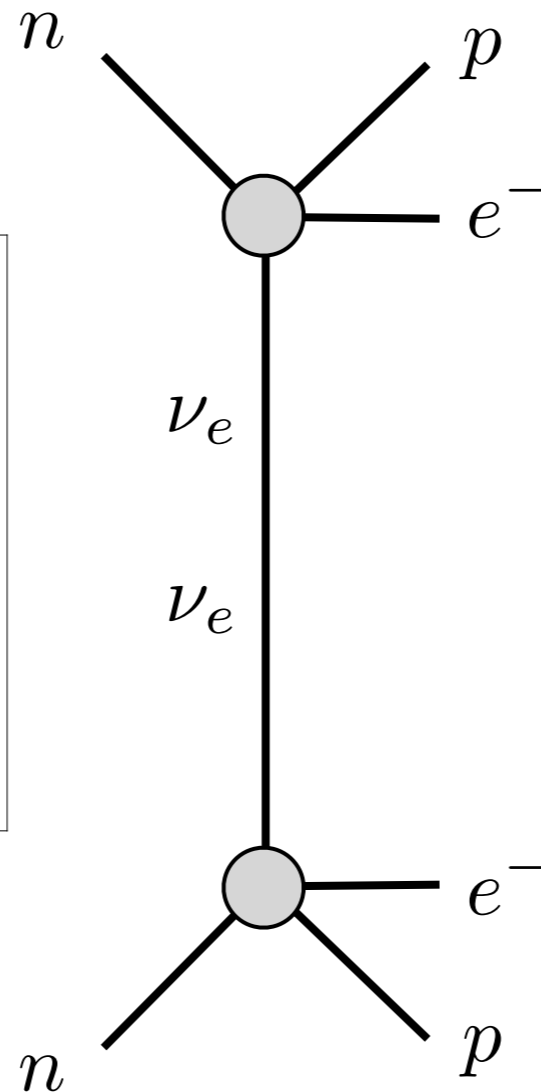
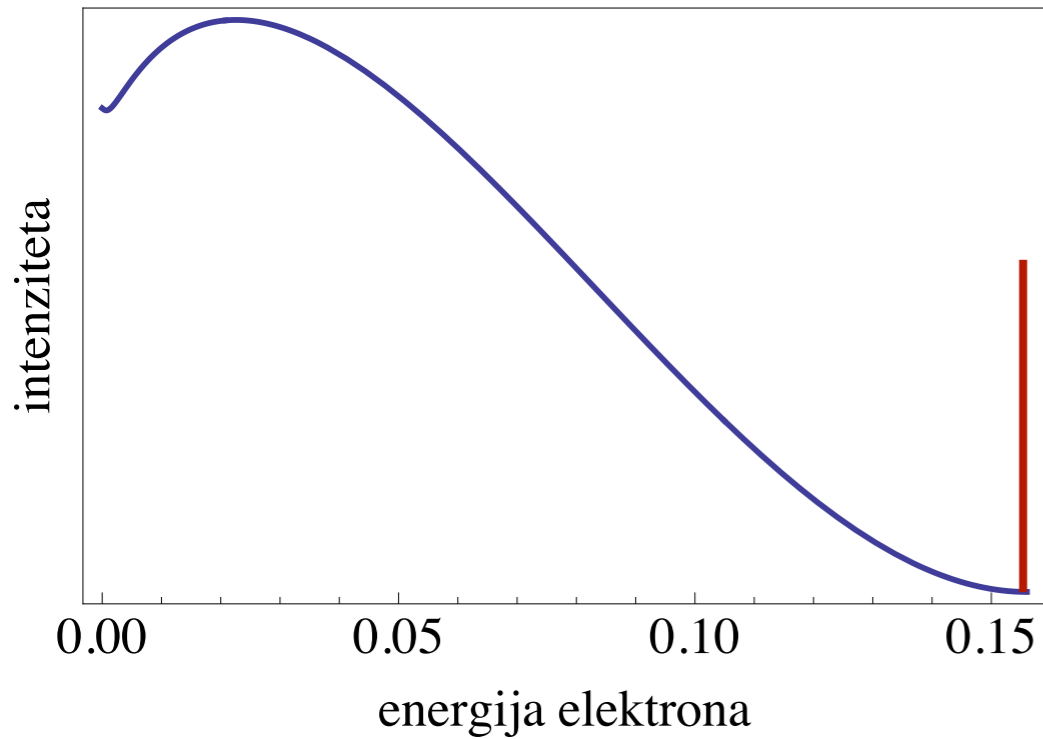


v modernem jeziku

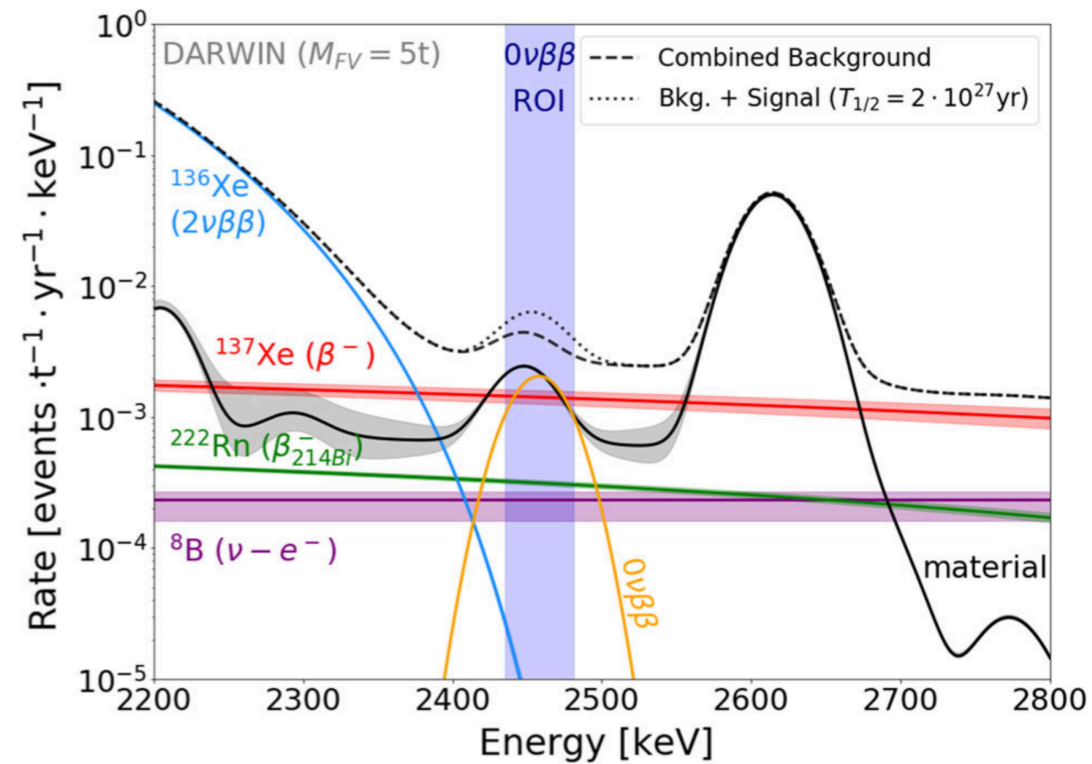
$$\Gamma \propto \left| \sum_i U_{ei}^2 m_{\nu_i} \right|^2$$

Majorana nevtrino in jedrski procesi

1937 - Racah in Furry predlagata breznevtrinski 2β razpad



zlomitev
leptonskega
števila

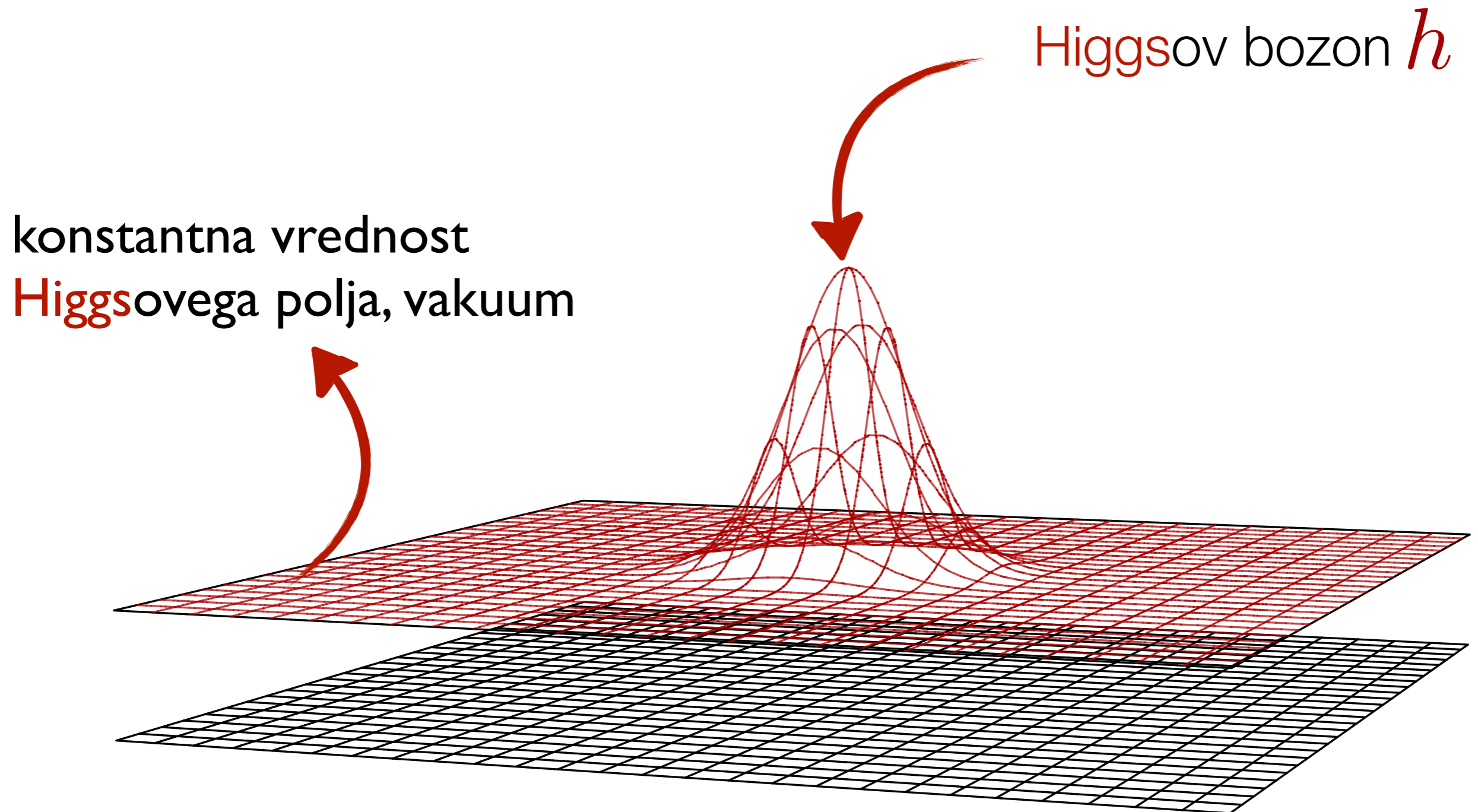


$$\tau_{0\nu 2\beta}^{\text{Ge}} > 10^{25} \text{ let}$$

Izvor mase nevtrinov

~ teoretična slika ~

Higgsov mehanizem



Higgsov mehanizem in izvor mase

Masivni gradniki snovi

Masivni prenašalci,
kratek doseg sile

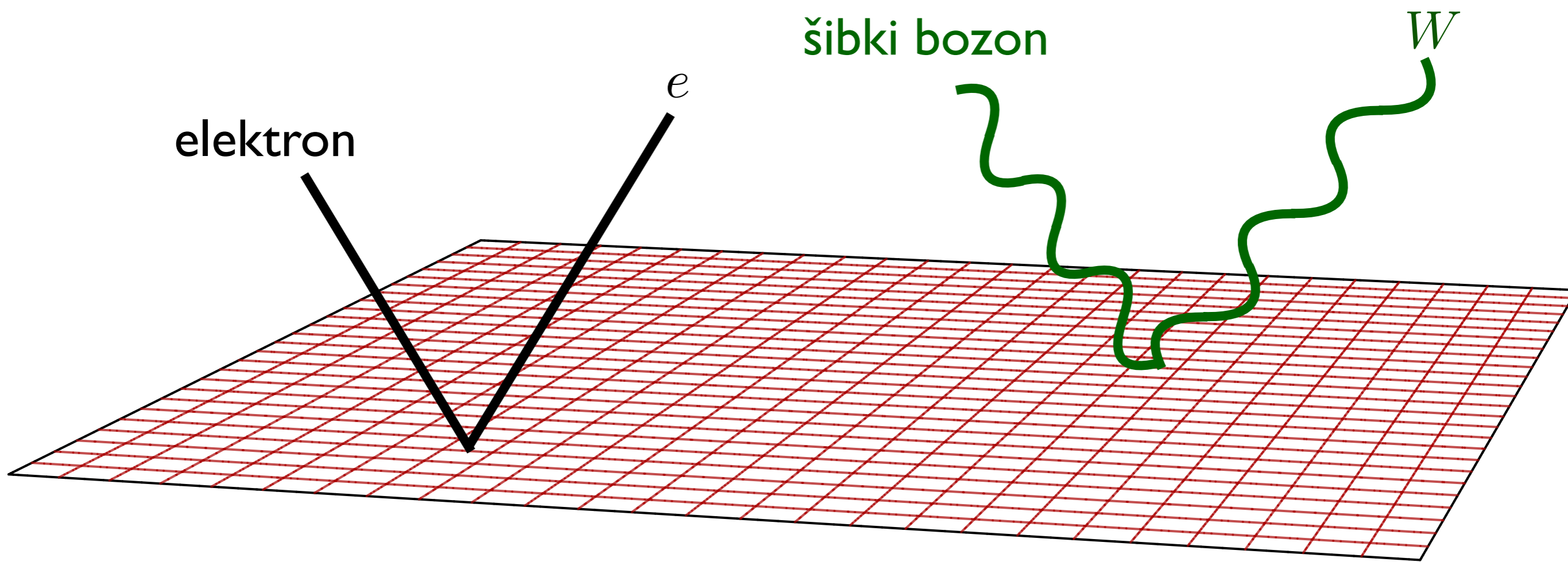
elektron

e

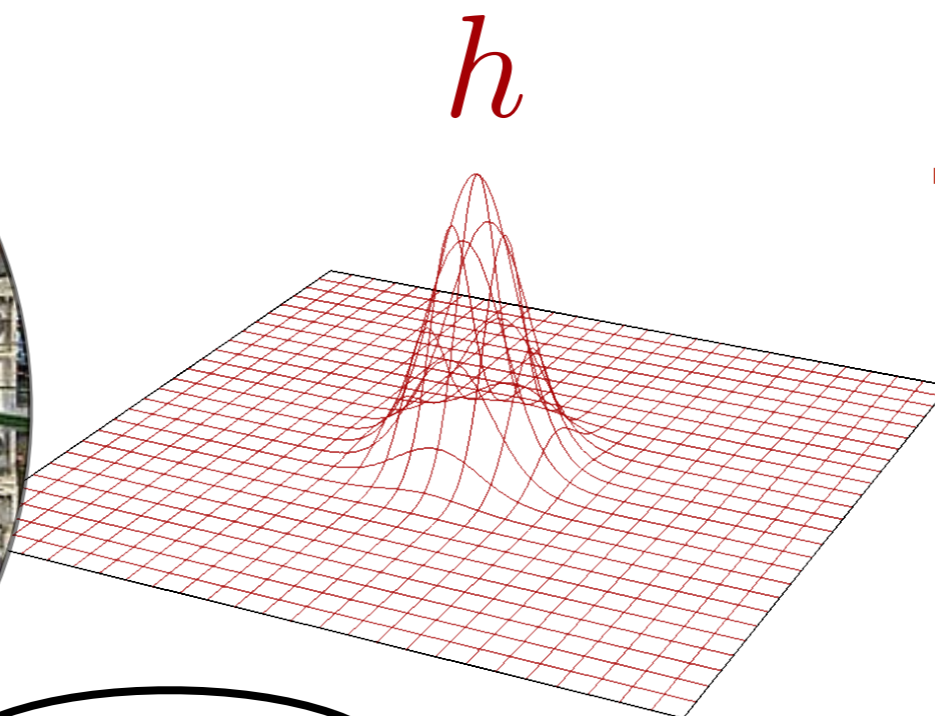
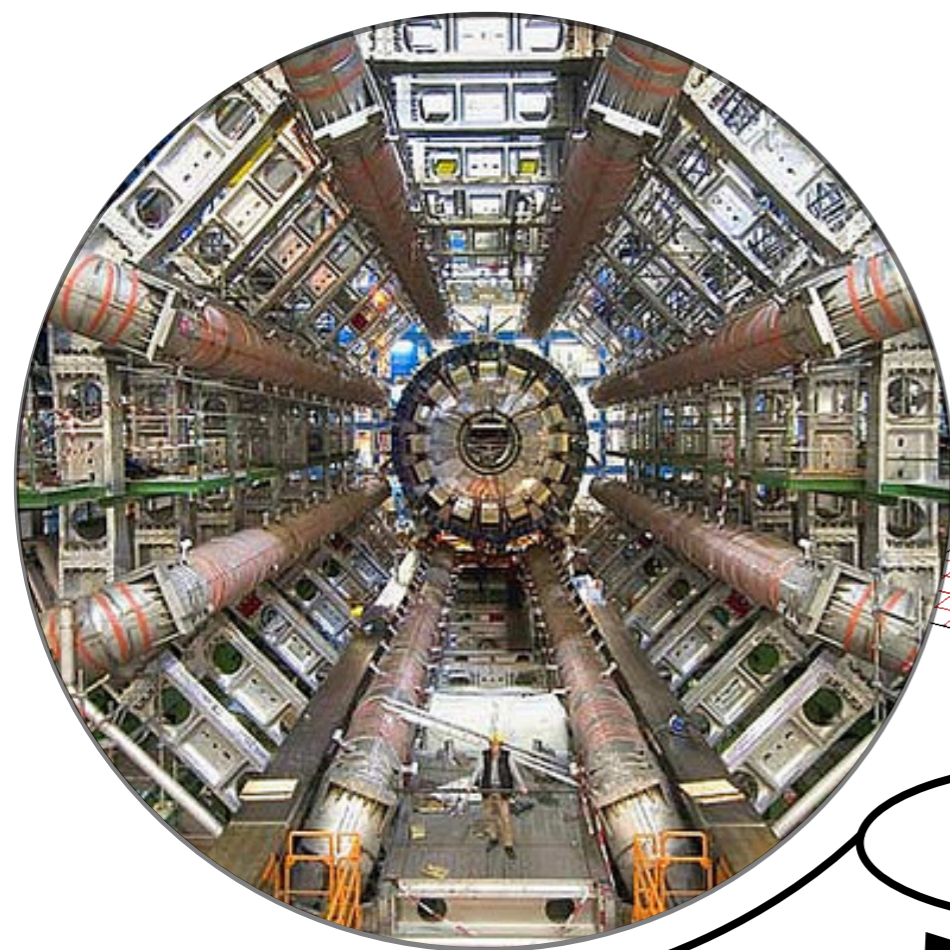
šibki bozon

W

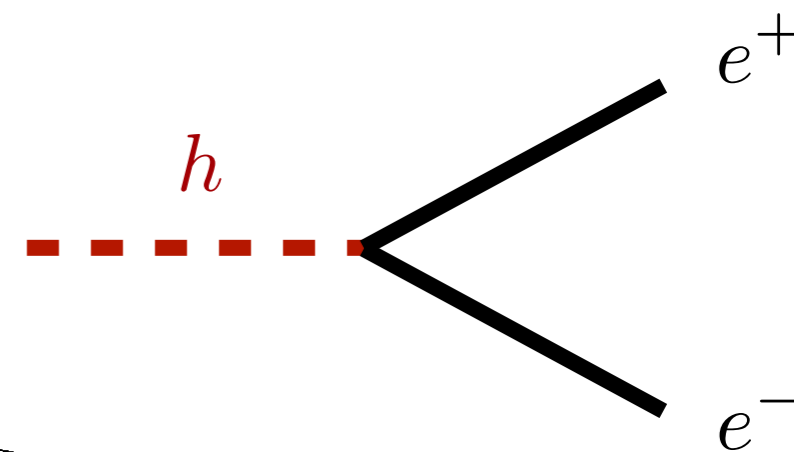
Večja sklopitev, težji delec



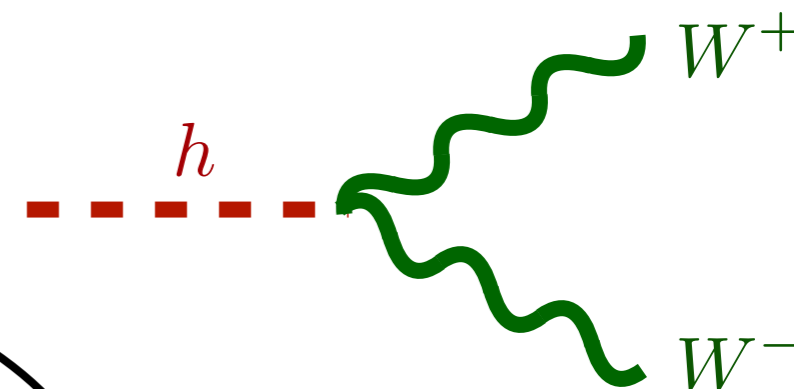
Higgsov mehanizem: testiranje



gradniki



prenašalci



p

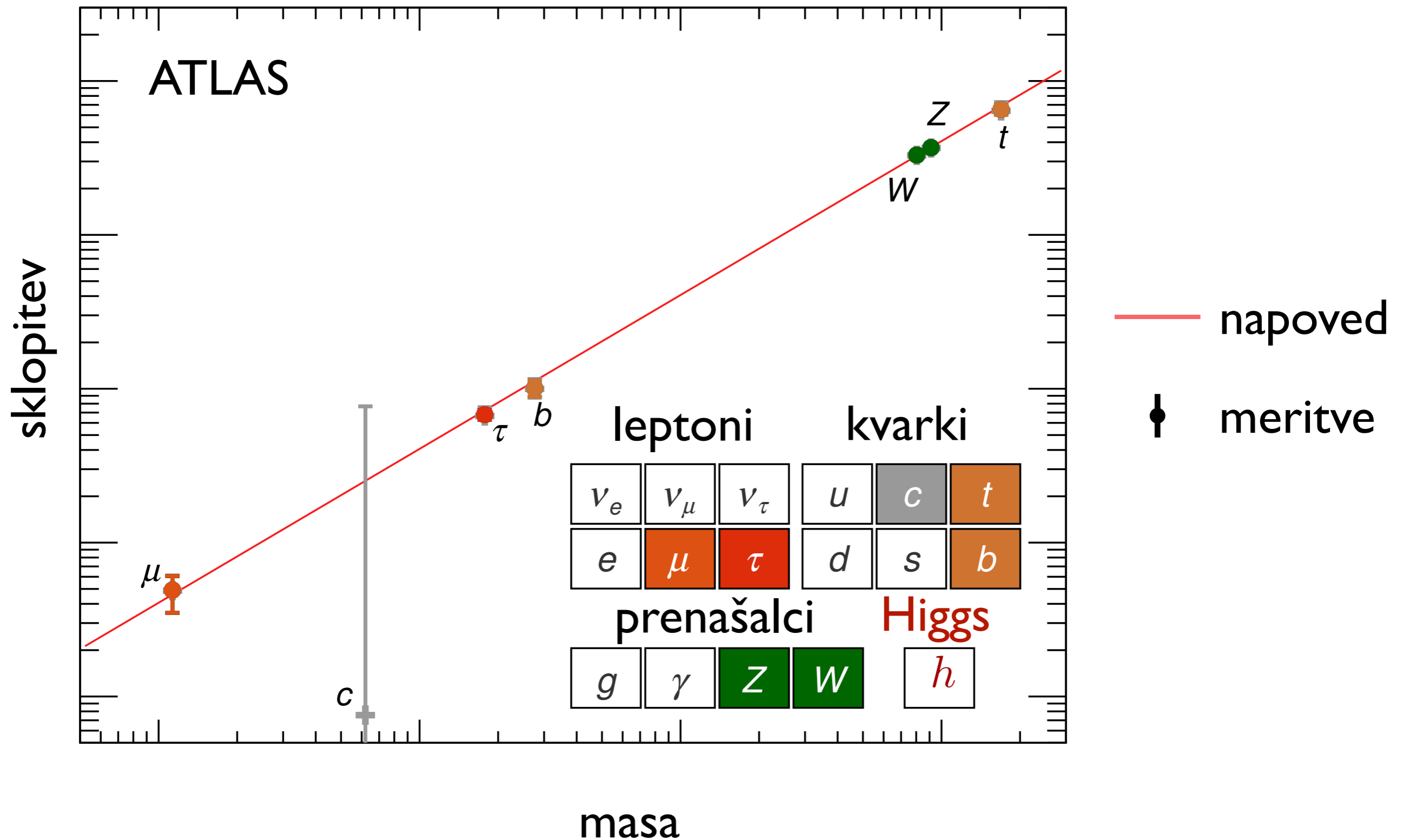
ATLAS

p

CMS

Večja sklopitev, bolj pogost razpad

Higgsov mehanizem: potrditev izvora mase

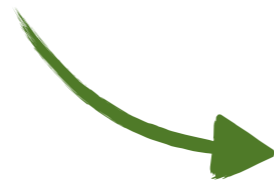


Nevtrino kratko nadaljevanje zgodovine teorije

1967 Weinbergov asimetrični model napove **Higgsove** sklopitve
in

$$m_\nu = 0$$

V skladu z (nekaterimi) teorijami poenotenja

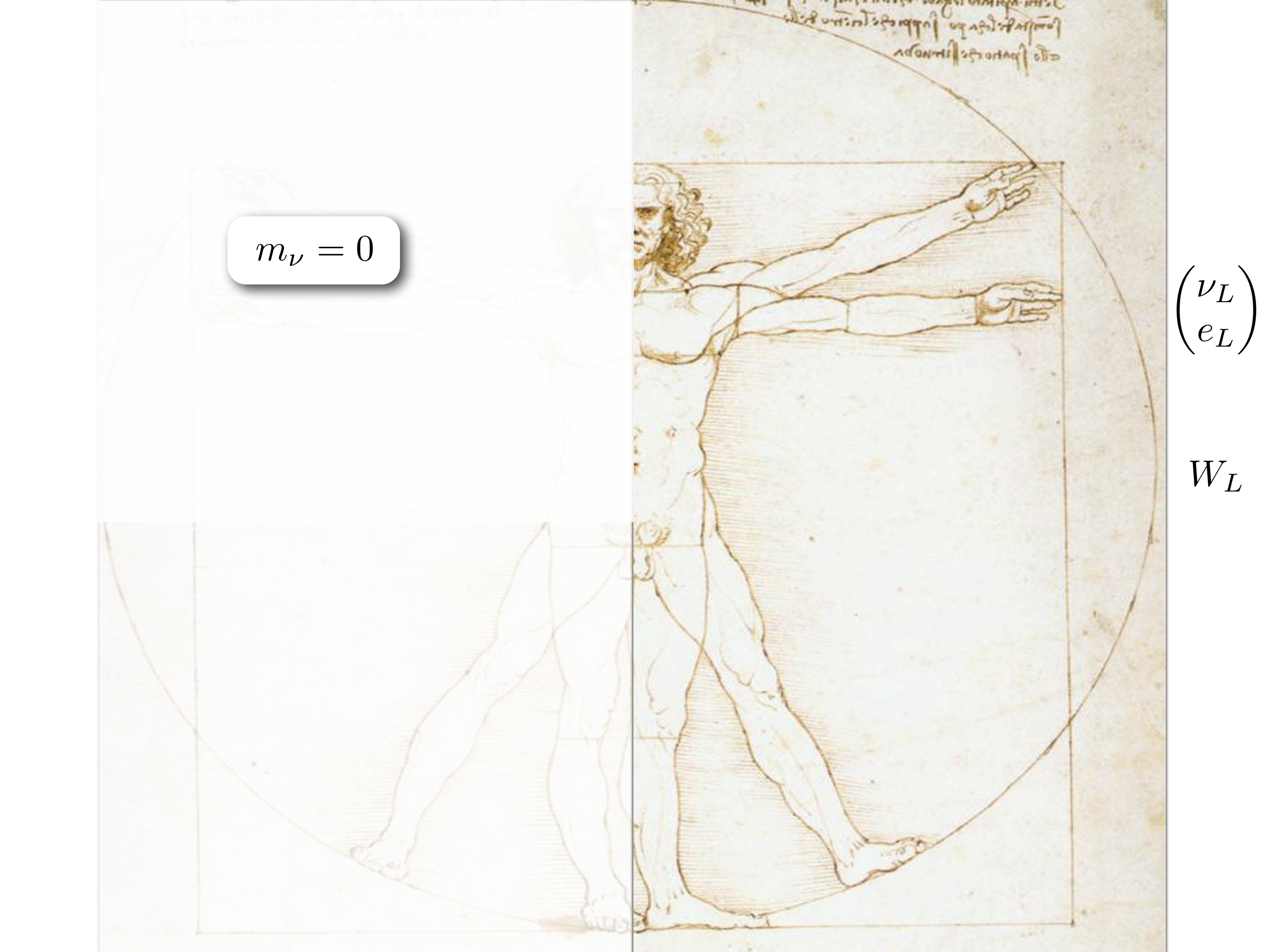


pedsodek proti Davis & Bahcall



$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

W_L


$$m_\nu = 0$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

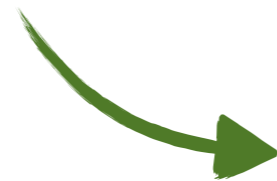
$$W_L$$

Nevtrino kratko nadaljevanje zgodovine teorije

1967 Weinberg napove **Higgs** sklopitve in

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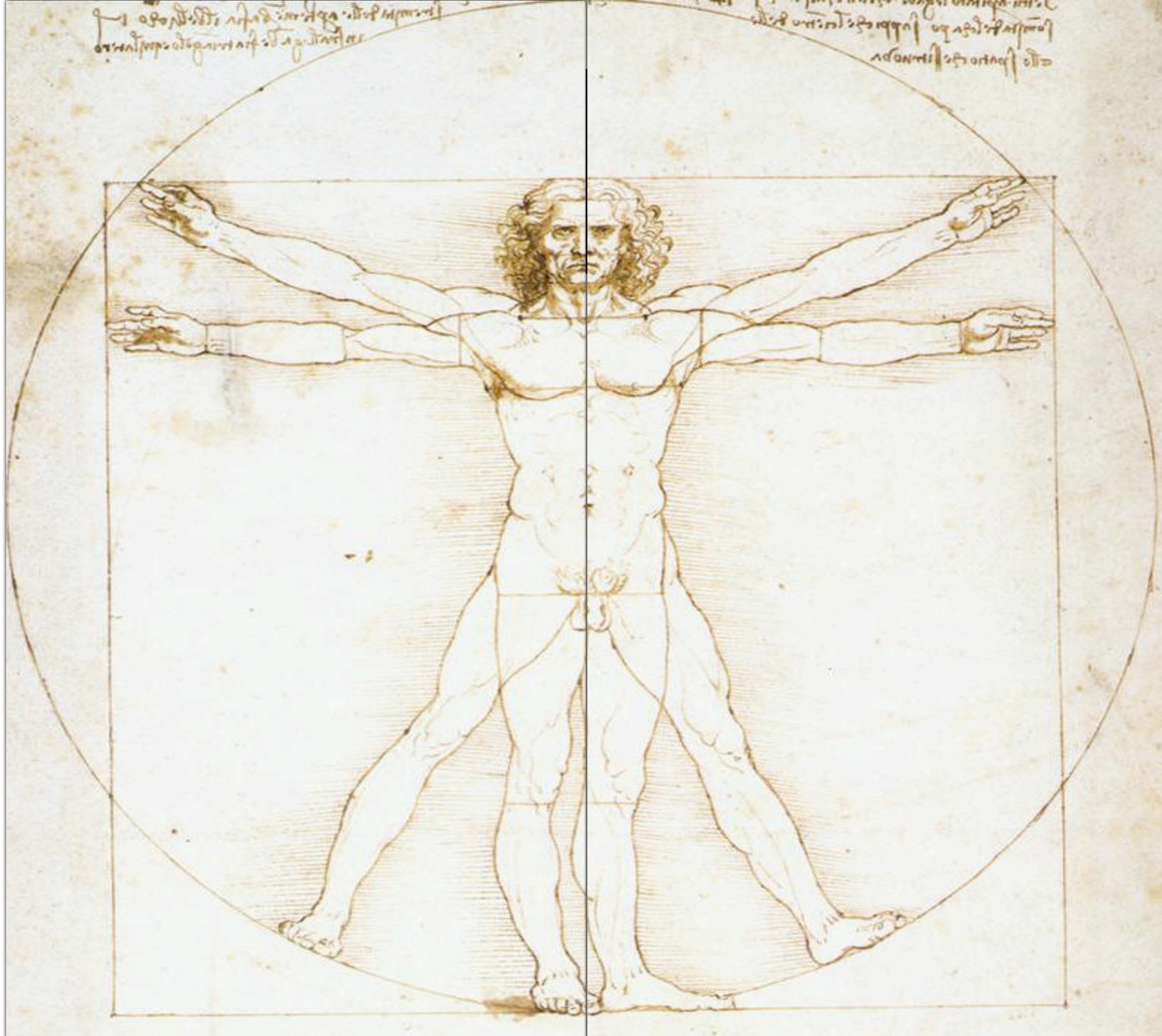
1974 Pati in Salam predlagata Levo-Desno simetrijo

1975 Senjanović in Mohapatra jo spontano zlomita

1979 Gugalnični mehanizem in majhne mase nevtrinov

$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$

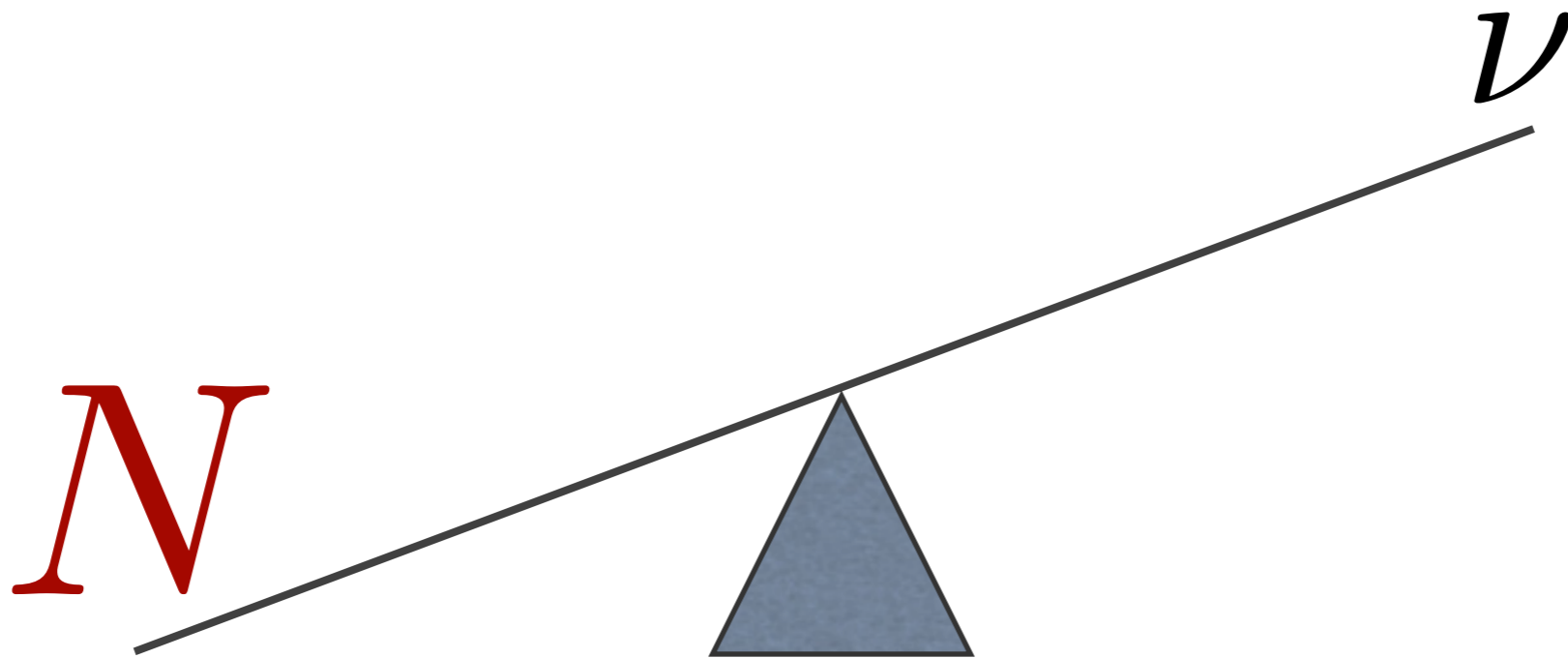
W_R



$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

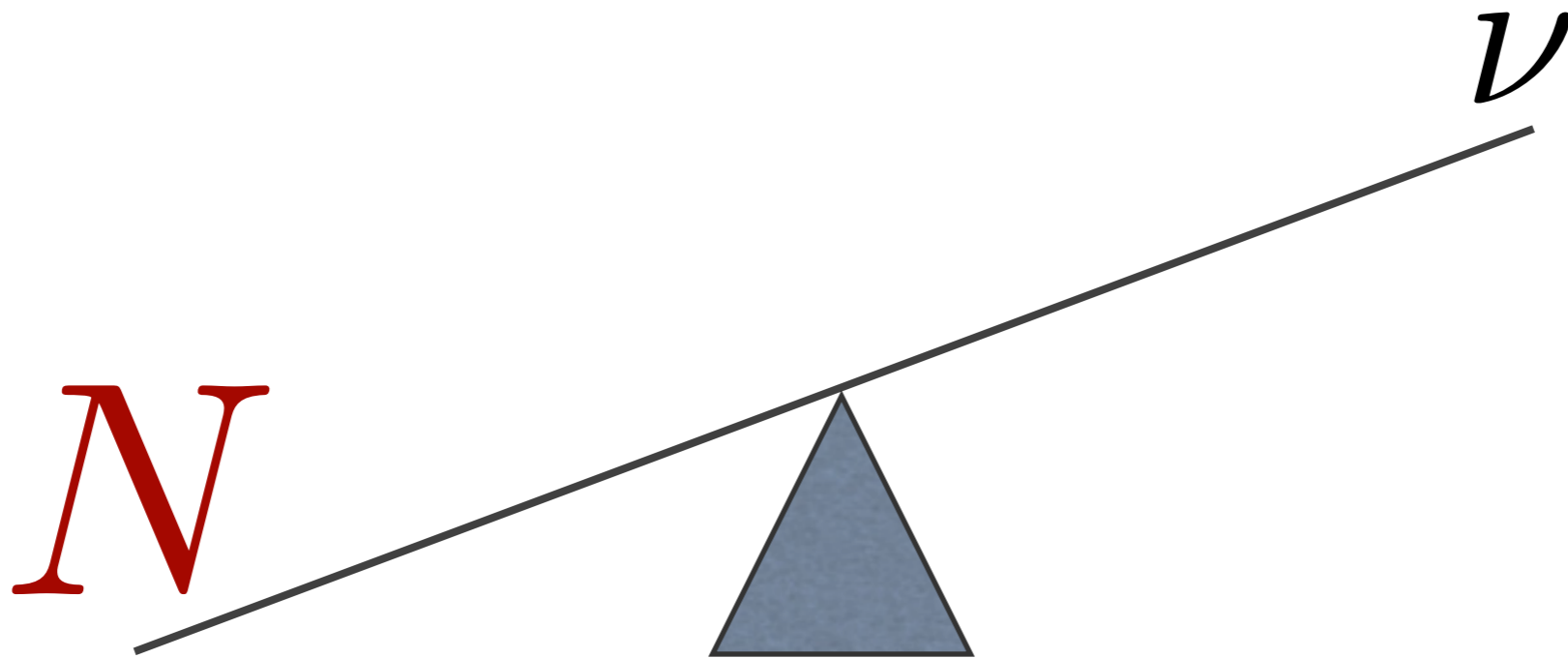
W_L

Majorana nevtrino in gugalnični mehanizem



$$m_\nu \propto \frac{v^2}{m_N}$$

Majorana nevtrino in gugalnični mehanizem



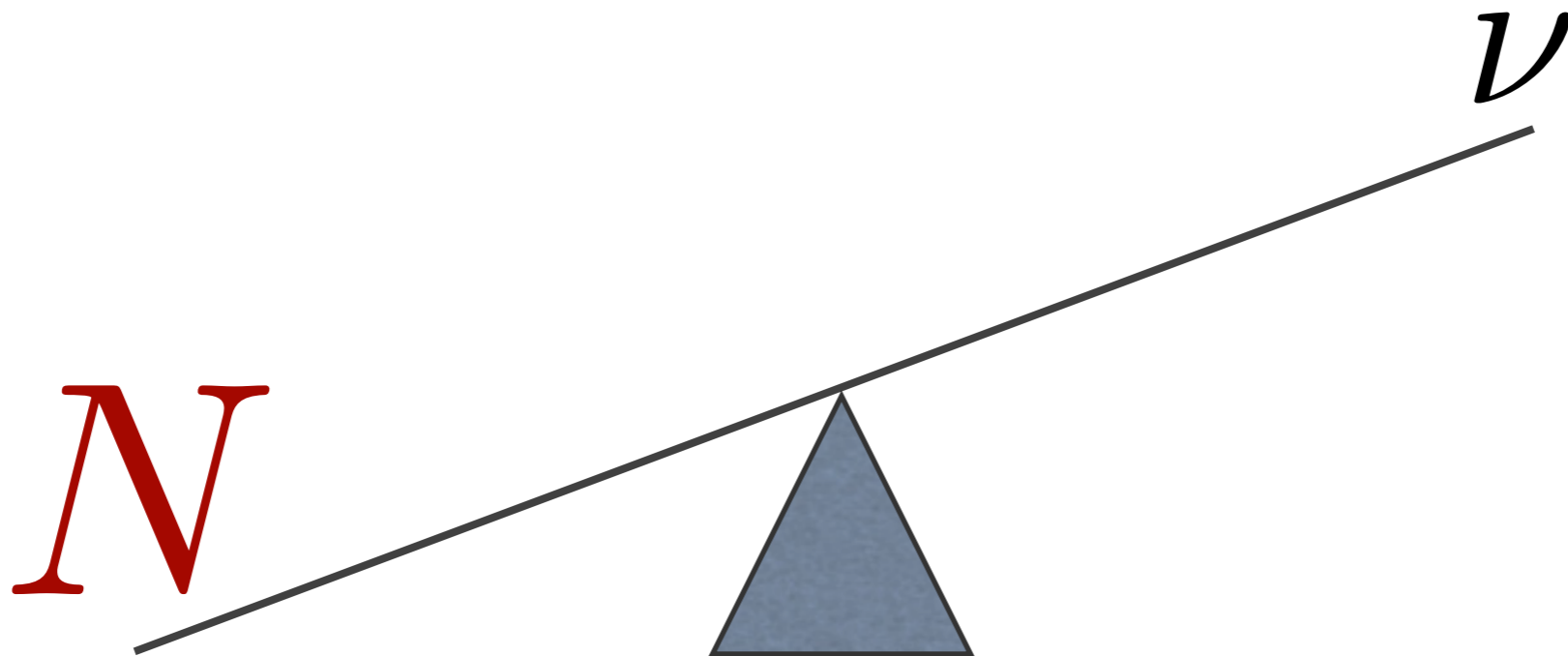
nevtrinske oscilacije

$0\nu 2\beta$

β spekter ?

kozmozologija

Majorana nevtrino in gugalnični mehanizem



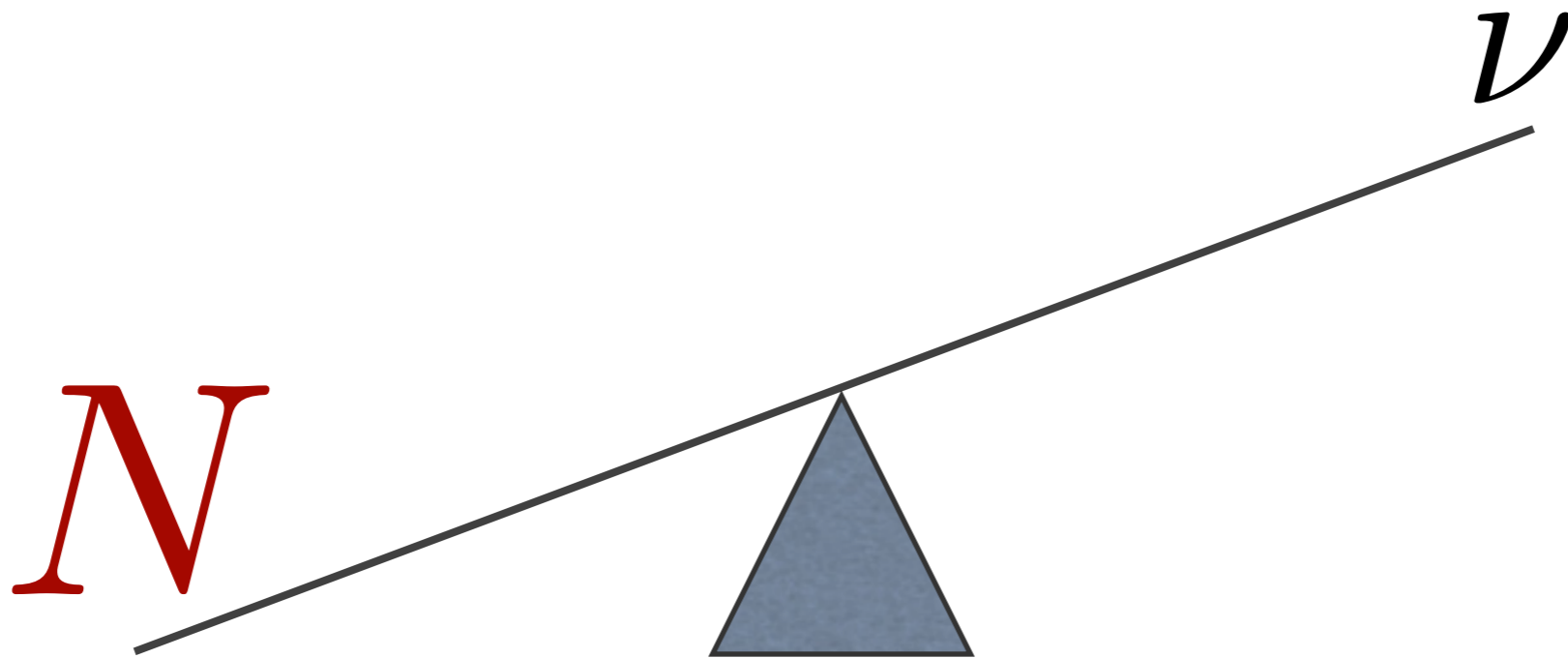
LHC in Higgs

redki razpadi

$0\nu 2\beta$?

temna snov

Majorana nevtrino in gugalnični mehanizem



LHC in Higgs

redki razpadi

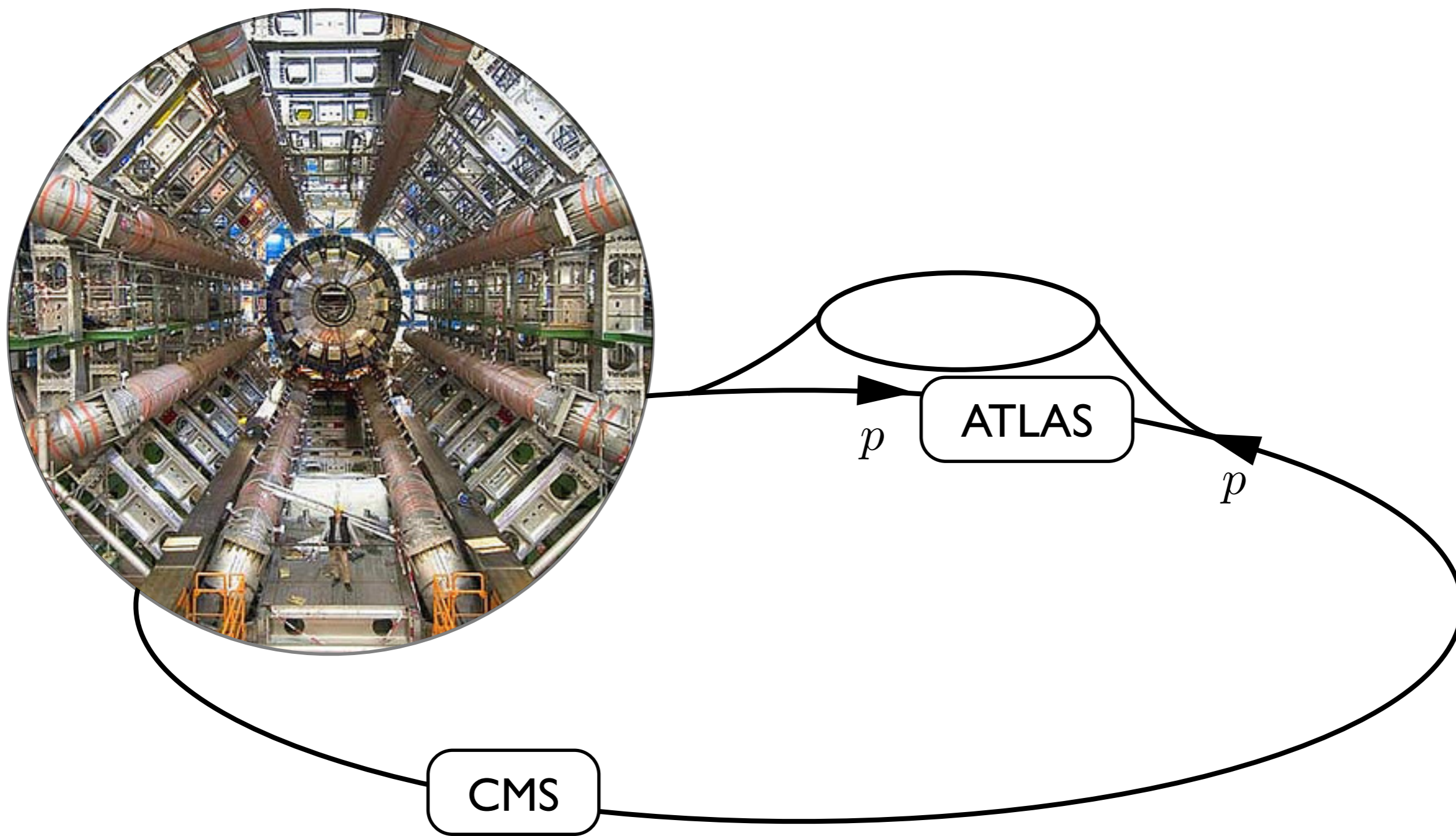
$0\nu 2\beta$?

temna snov

Iskanje Majoranovih nevtrinov

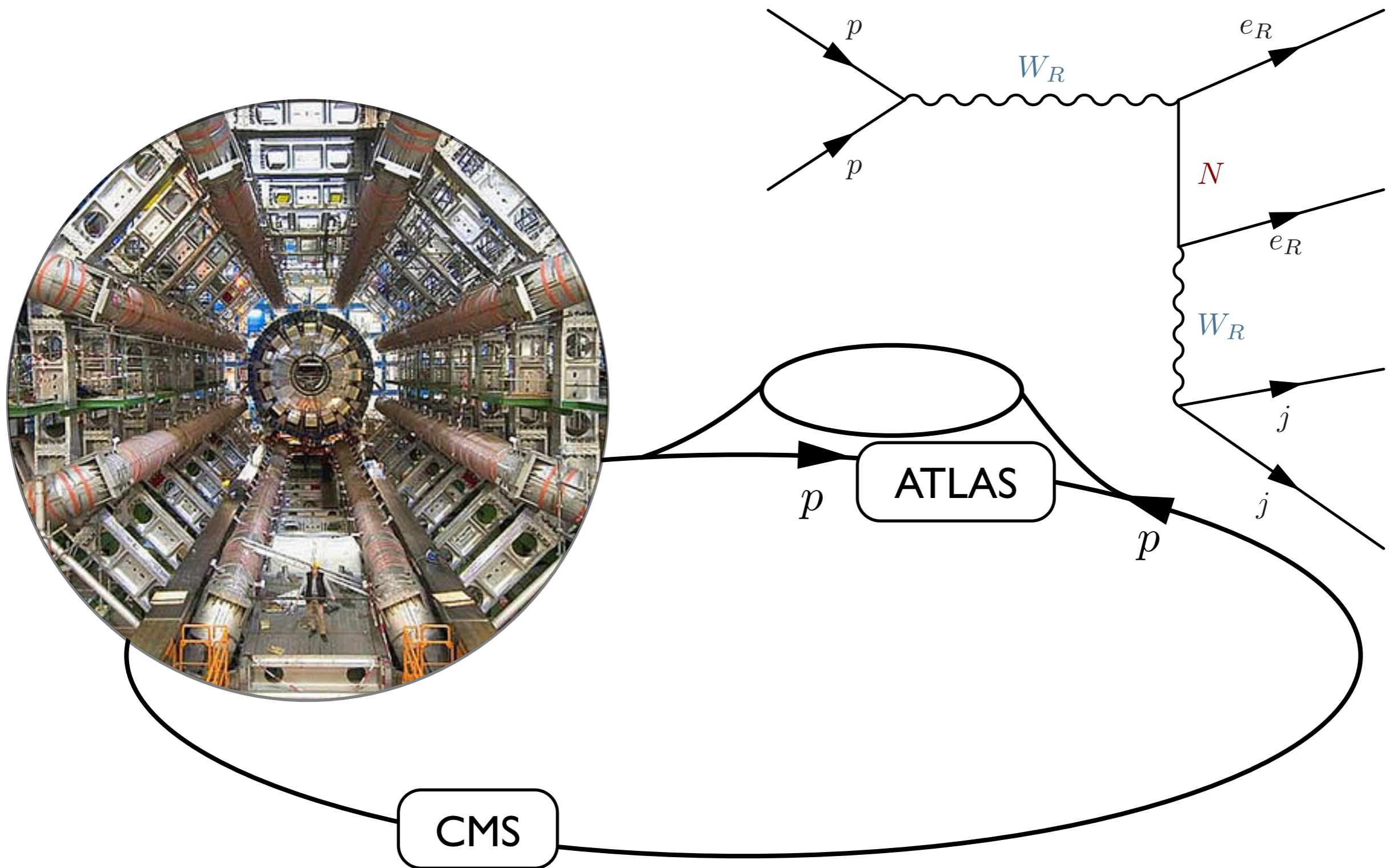
~trkalniki~

Majorana neutrino in LHC



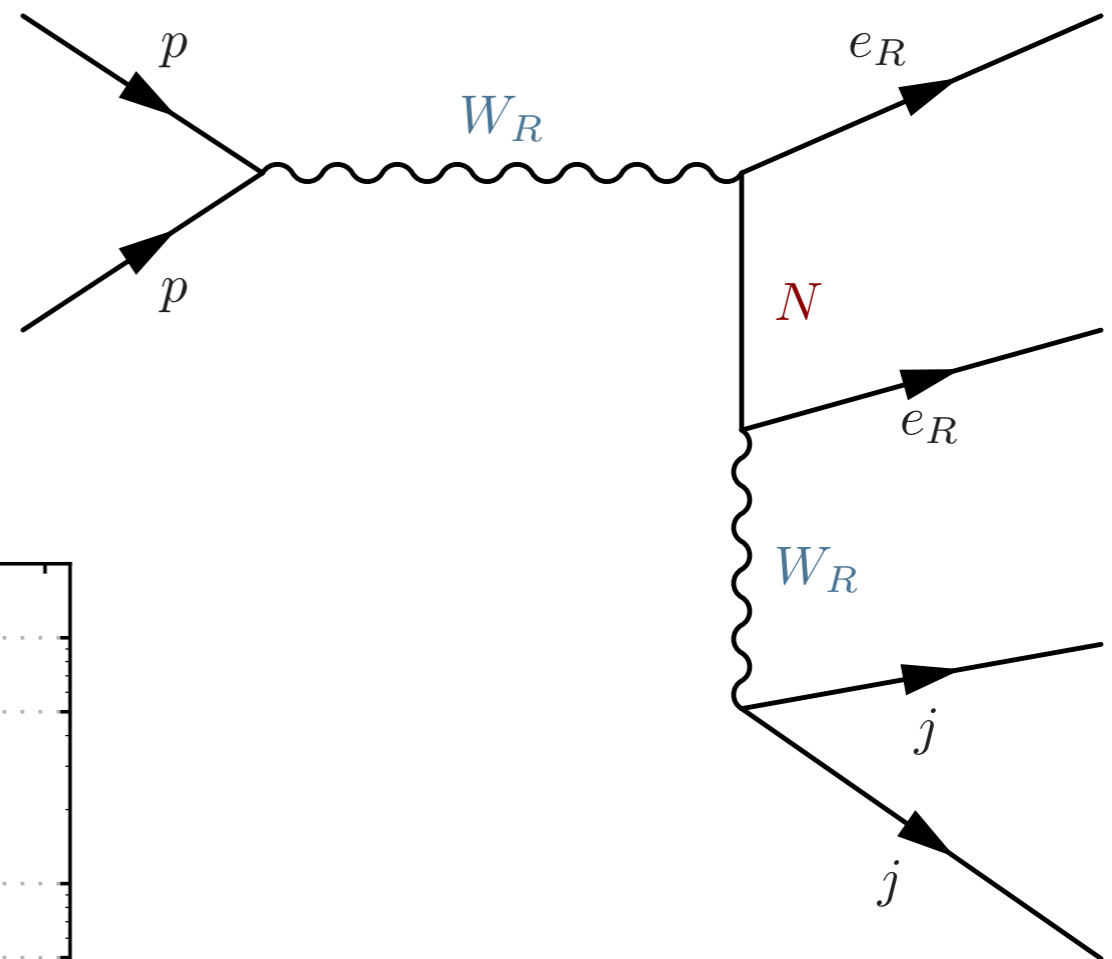
Majorana nevtrino in LHC

1983 Keung in Senjanović: N na trkalniku

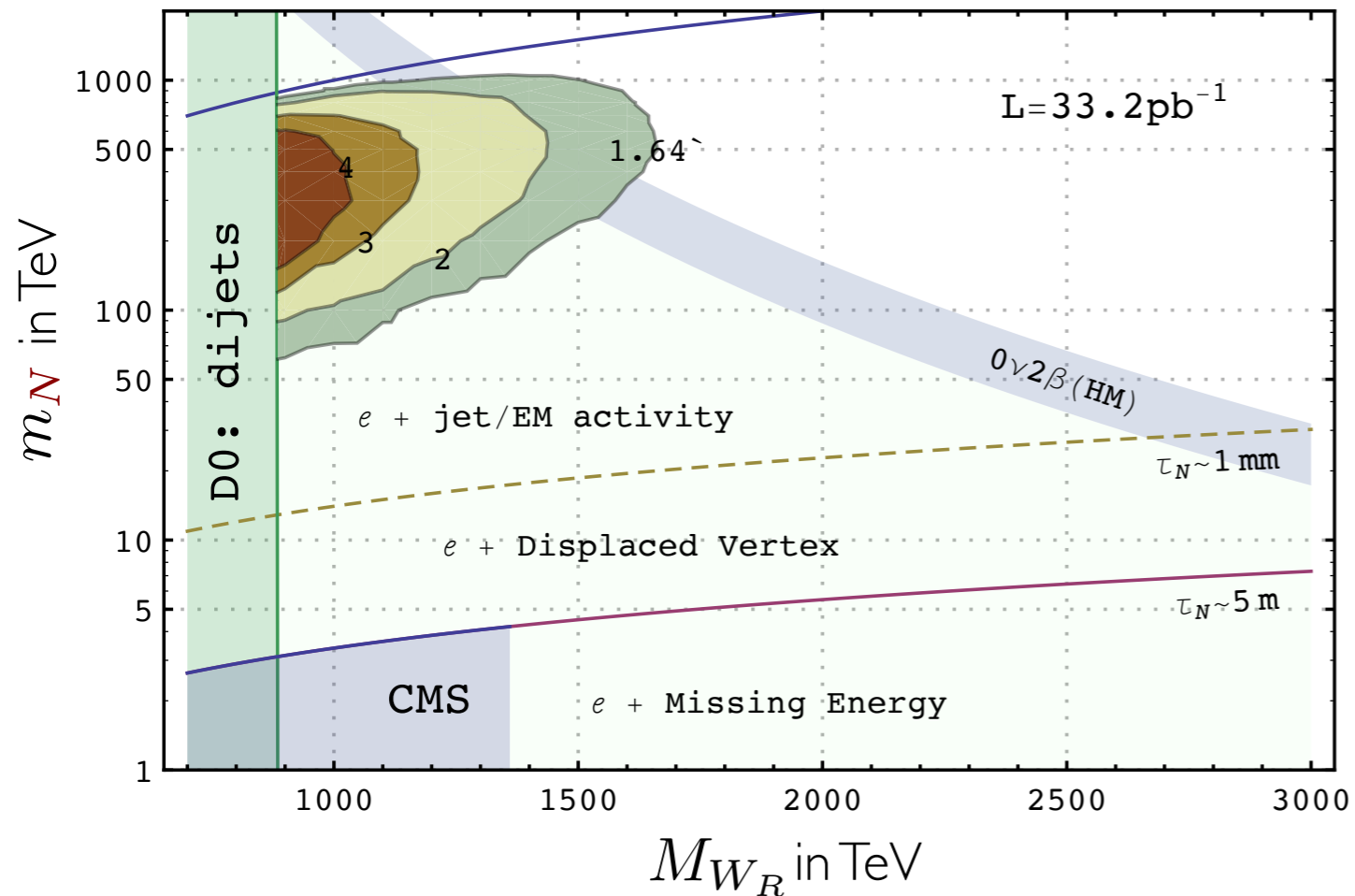


Majorana nevtrino in LHC

1983 Keung in Senjanović: N na trkalniku



MN, Nesti, Senjanović, Zhang '11

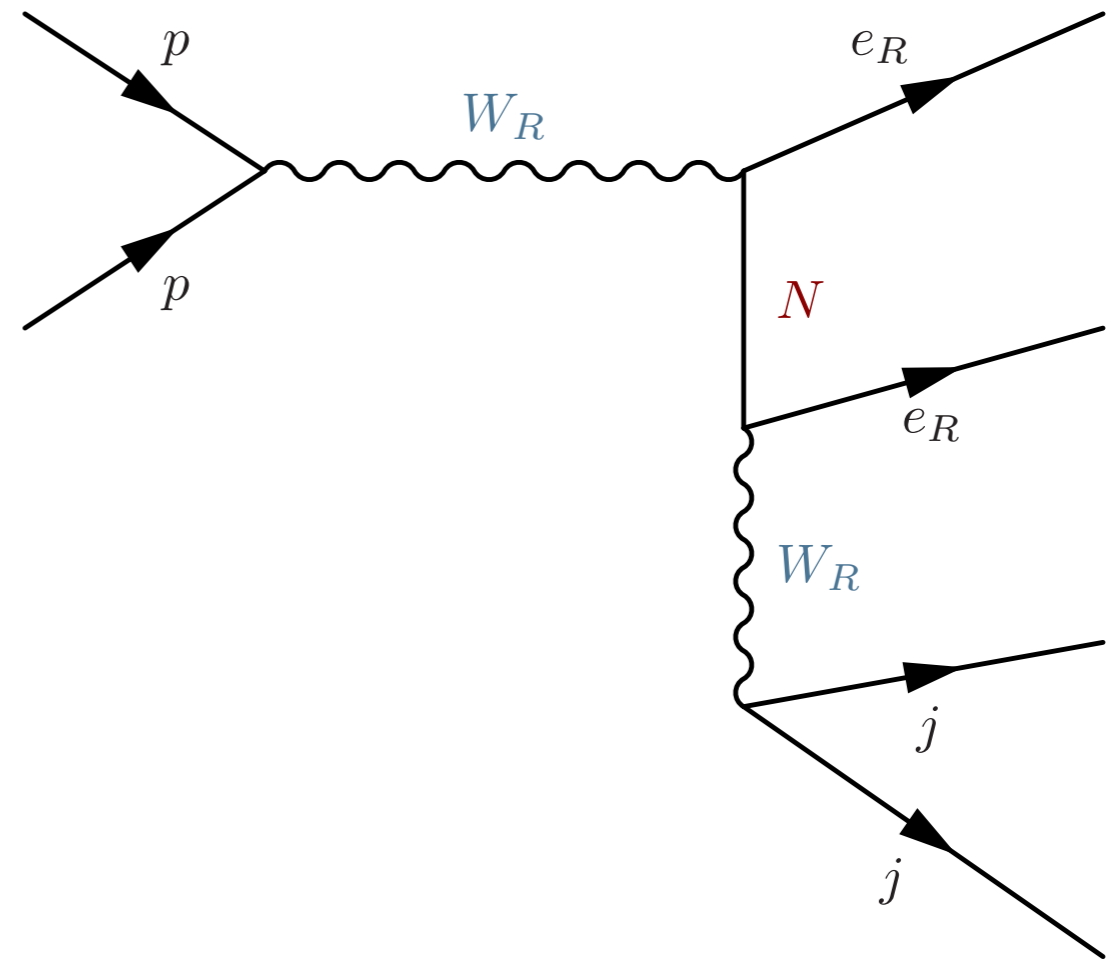
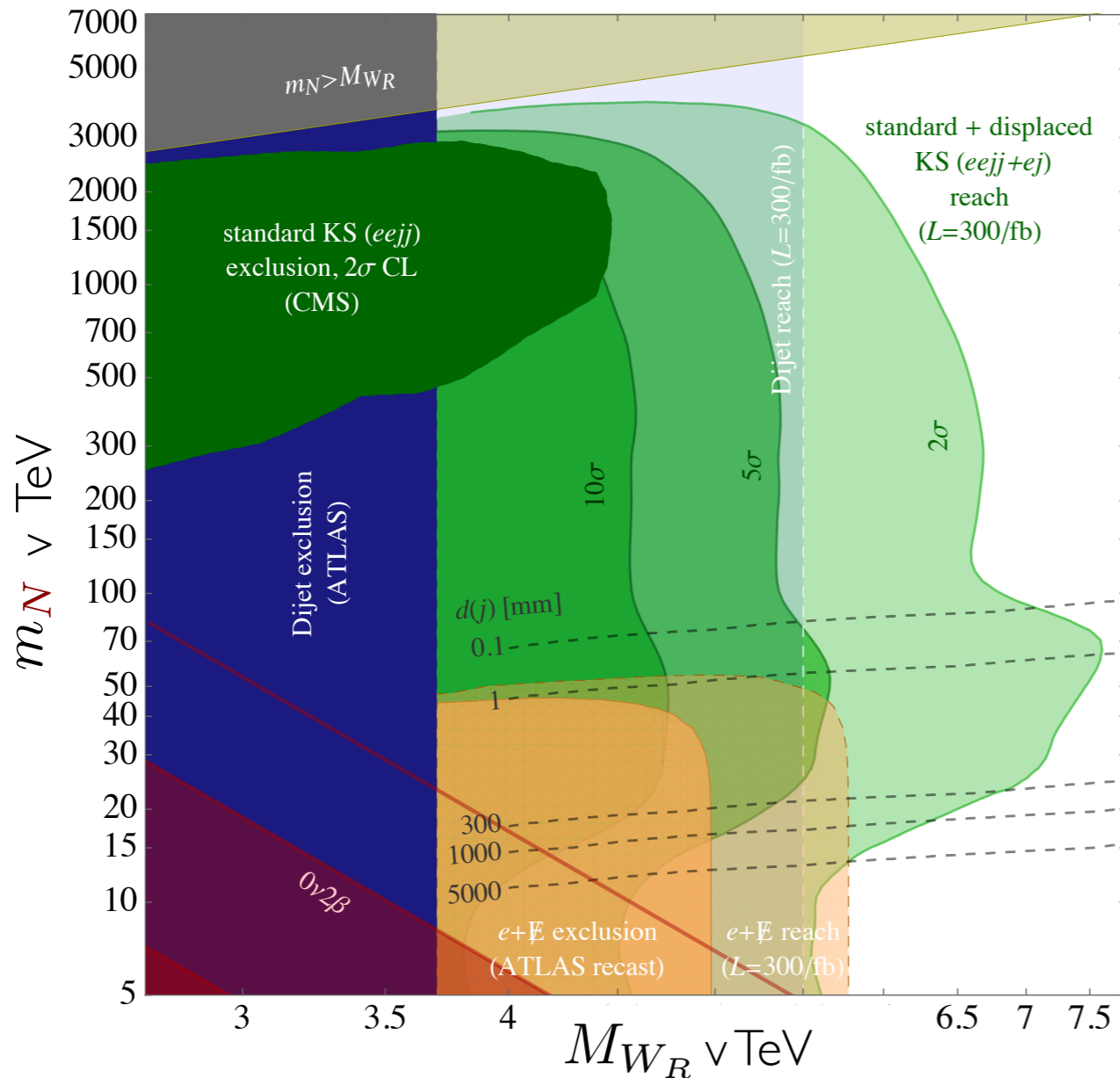


2011 Prva analiza za LHC

Majorana nevtrino in LHC

1983 Keung in Senjanović: N na trkalniku

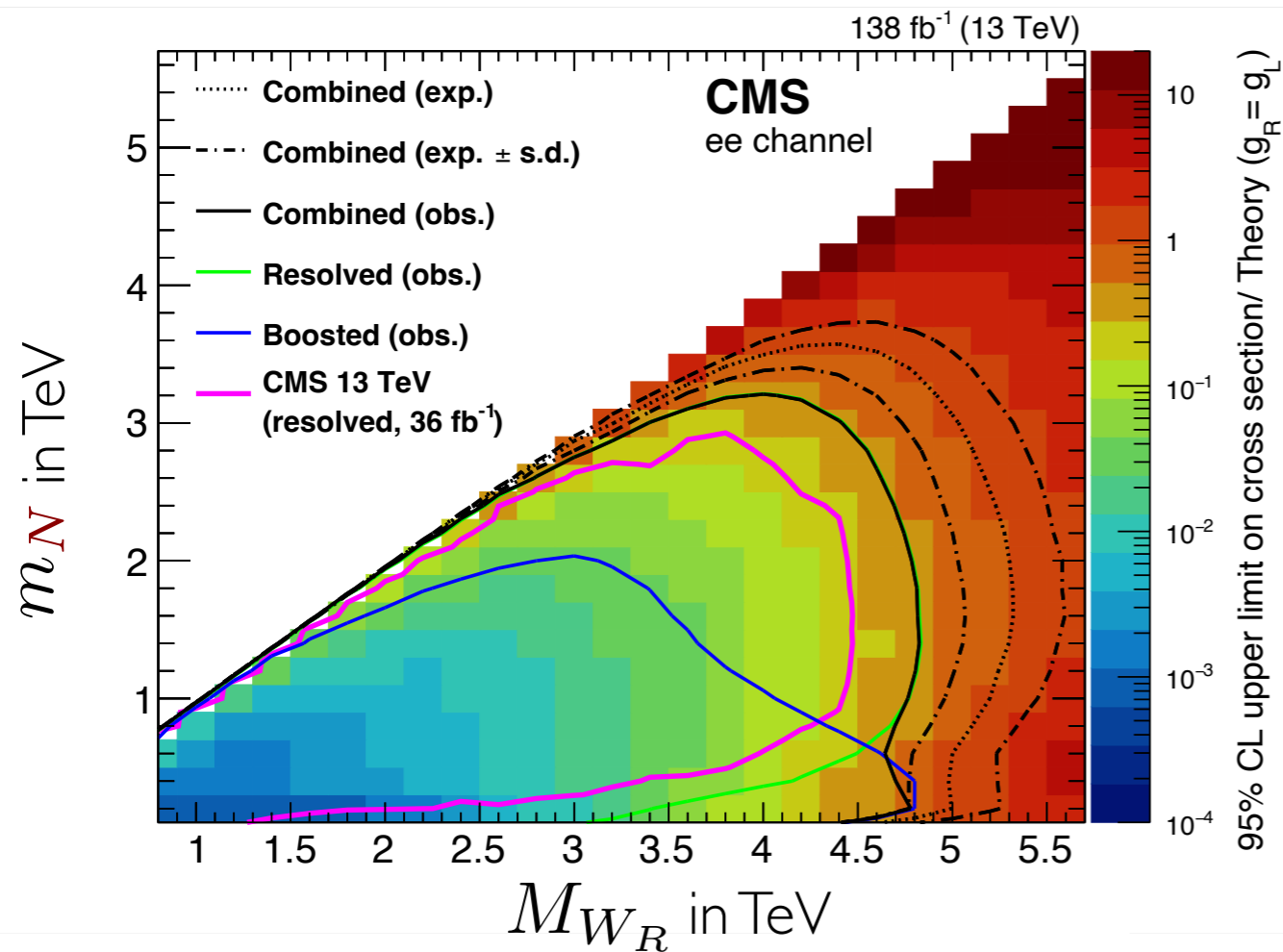
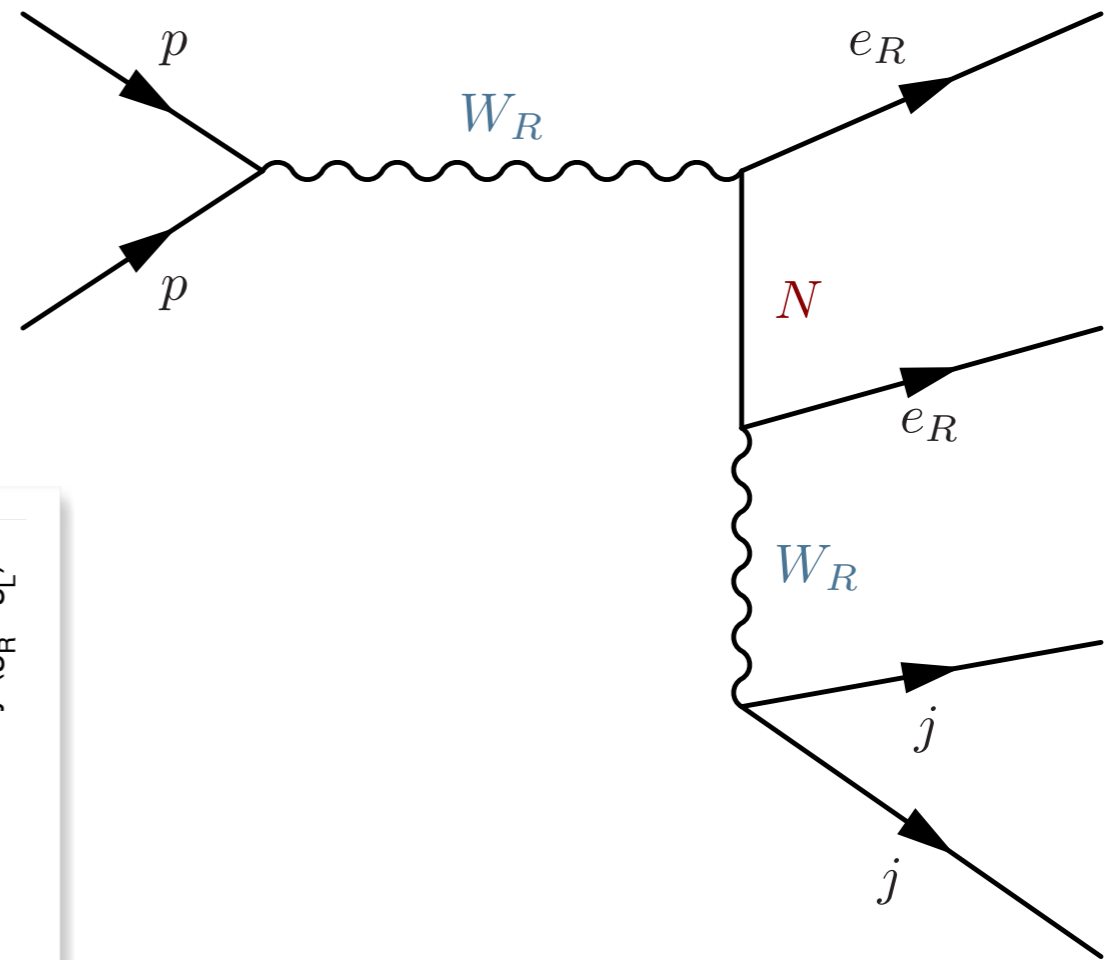
MN, Nesti, Popara '18



2018 Napredna analiza za LHC

Majorana nevtrino in LHC

1983 Keung in Senjanović: N na trkalniku

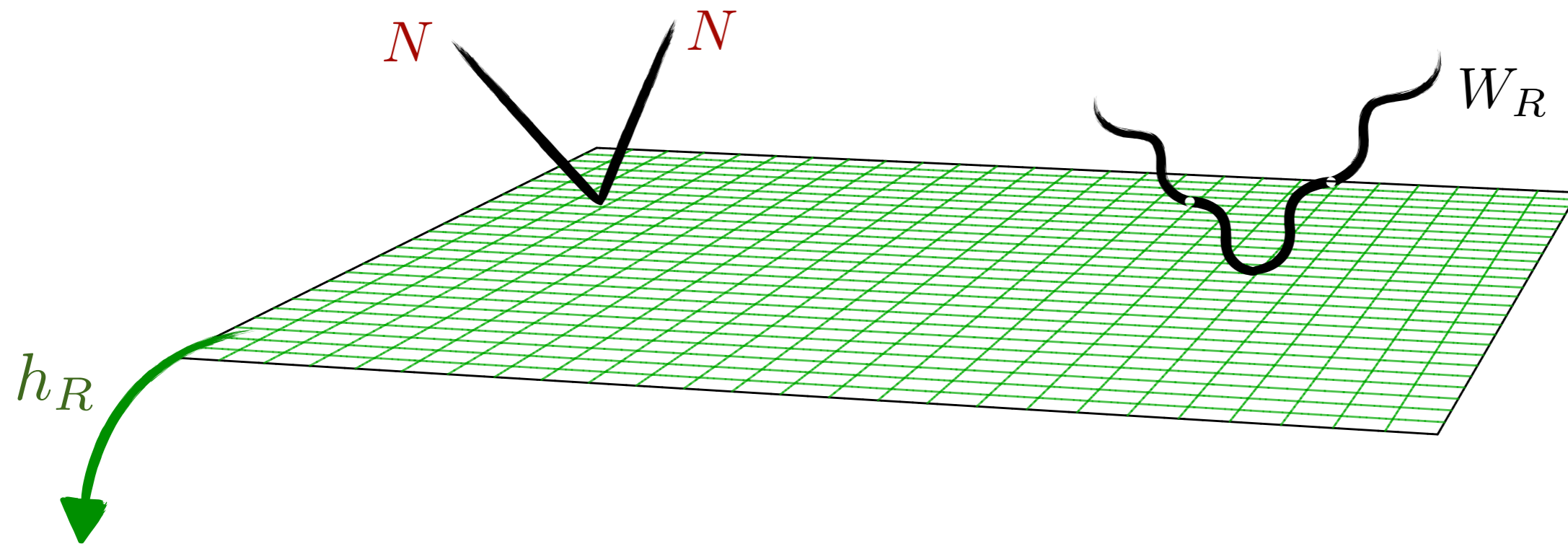


2014-2023 Zanimivi rezultati iz LHC

Prvi signal nove fizike?

Izvor mase N

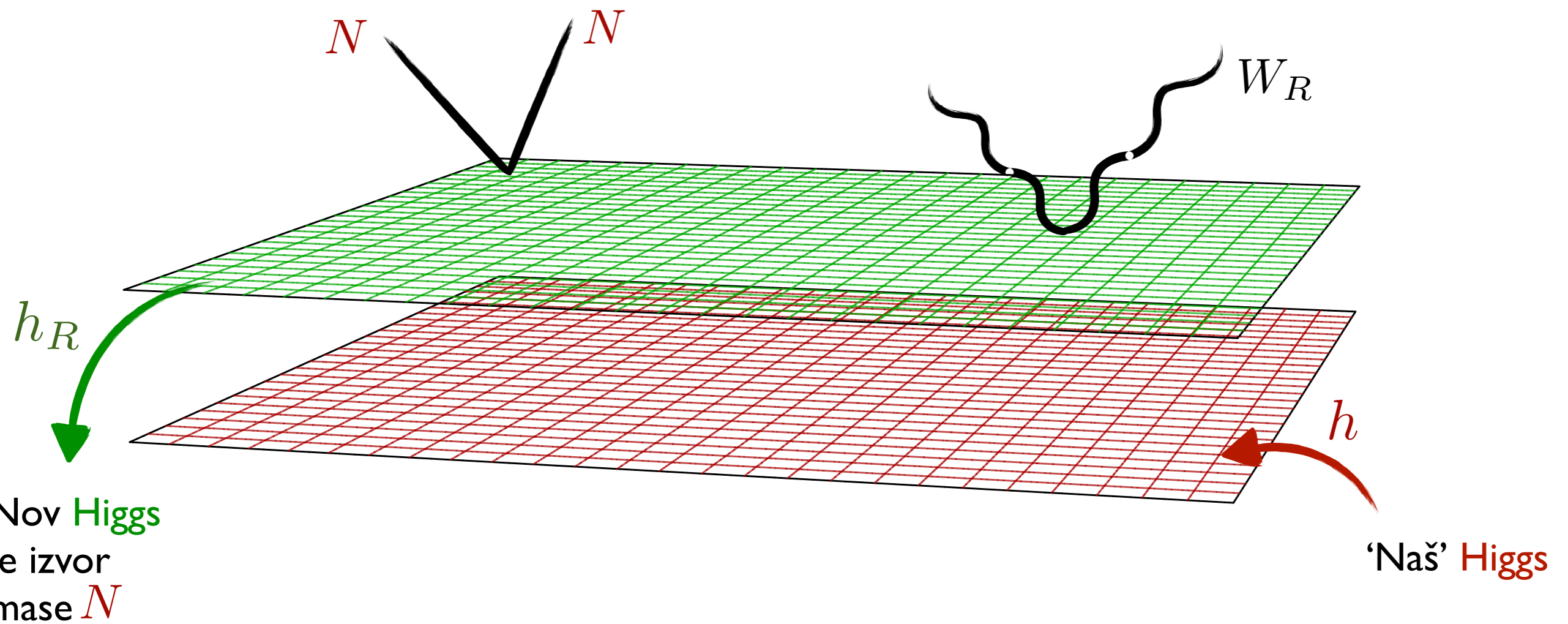
1979 Minkowski ter Mohapatra in Senjanović



Nov Higgs
je izvor
mase N

Izvor mase N

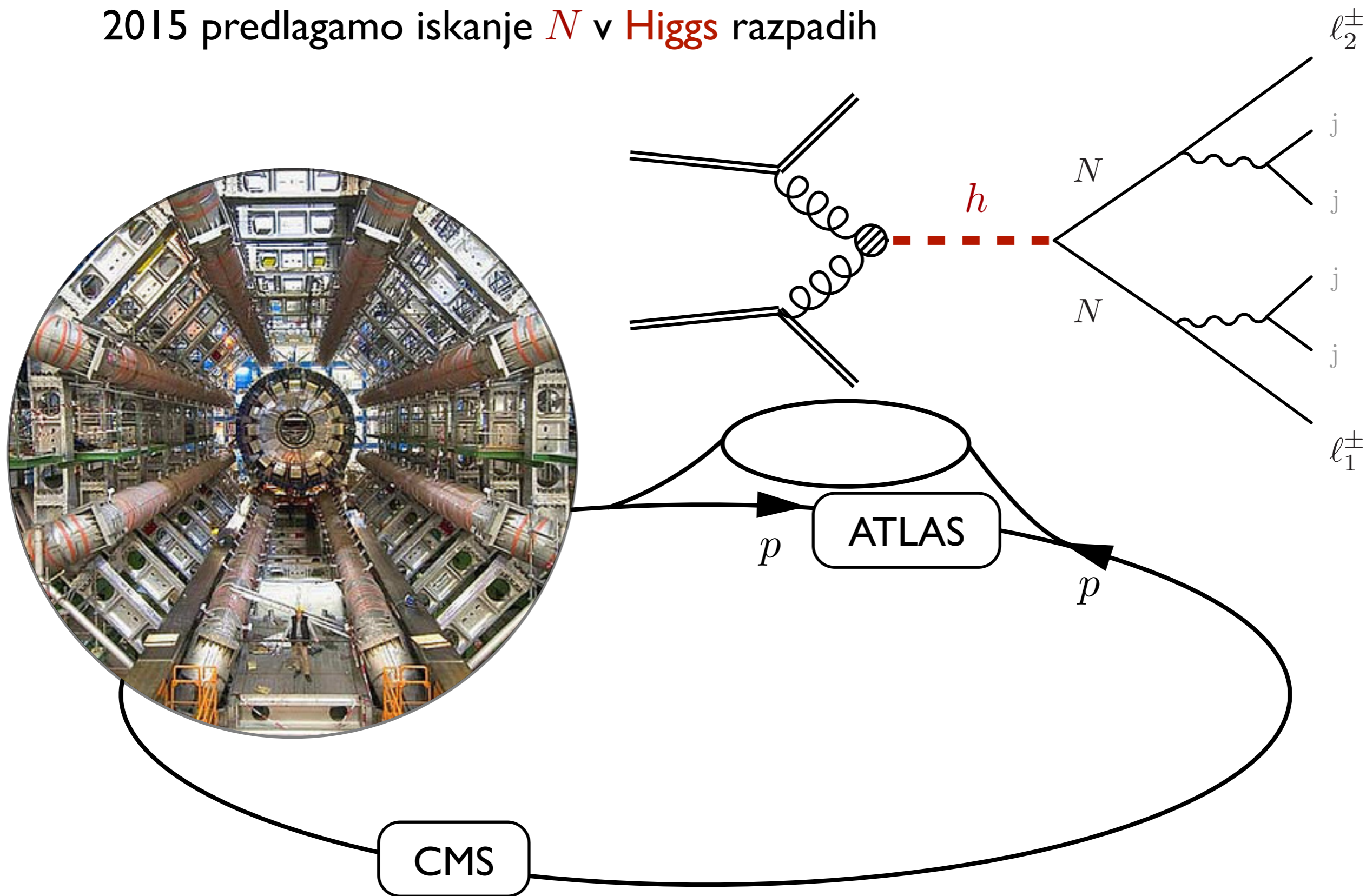
1979 Minkowski ter Mohapatra in Senjanović



h_R in h se lahko pogovarjata...

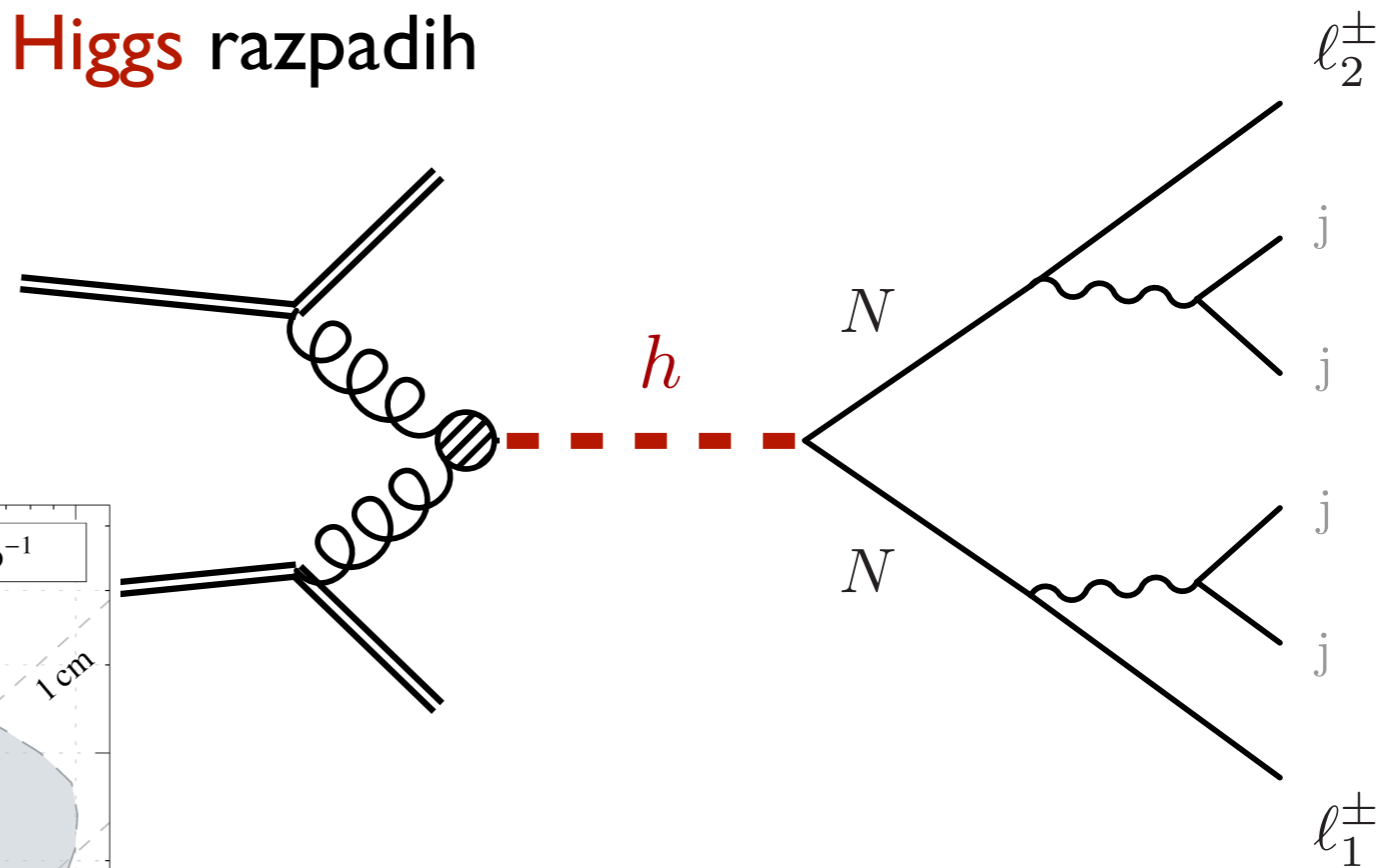
Izvor mase N na LHC

2015 predlagamo iskanje N v Higgs razpadih

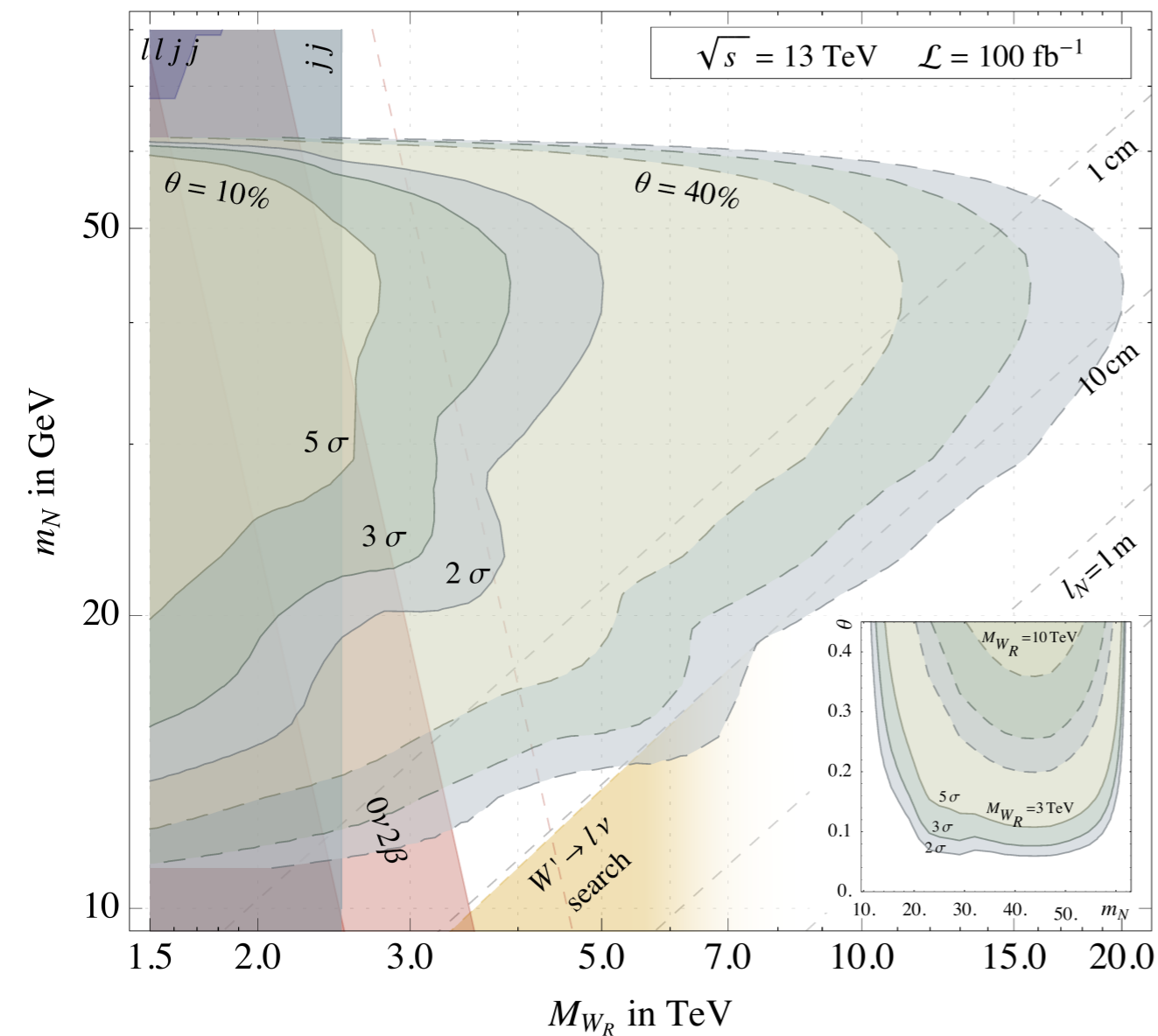


Izvor mase N na LHC

2015 predlagamo iskanje N v Higgs razpadih



Maiezza, MN, Nesti '15



Iskanje v teku

ATLAS skupina na IJS



Univerza v Ljubljani
Fakulteta za *matematiko in fiziko*



Hvala

