Neutrino Physics

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1. Introduction

The Birth of the Neutrino

W. Pauli

Before 1930: neutron → proton +e$^-$

2-body decay → monoenergetic spectrum expected

experiment: continuous β-decay spectrum

Pauli: energy-momentum conservation

→ postulate new particle

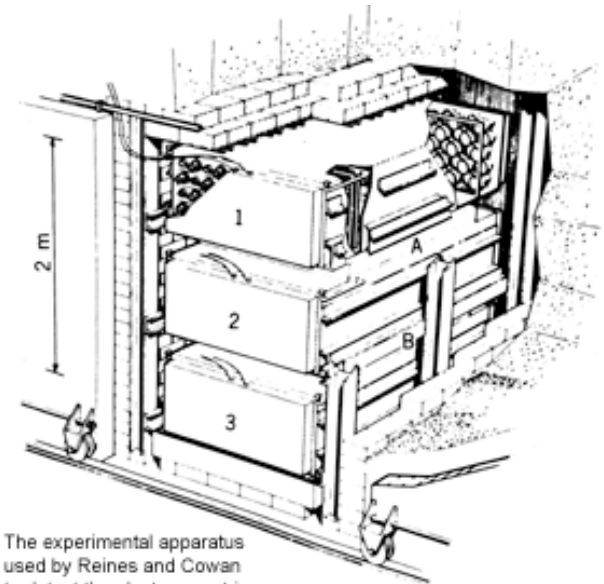
→ invisible, since Q=0

→ spin ½, ...

Letter to Tübingen Dec. 1930 …

… will never be detected

- Cowen & Reines 1954-56 project ``poltergeist“
  → detection of reactor neutrinos
  → Nobel price for F. Reines 1995



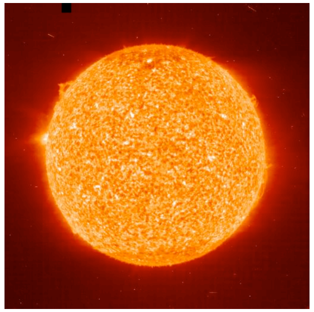
The experimental apparatus used by Reines and Cowan to detect the electron neutrino.


HERR AUGE
The "Eye" That First
Saw the Neutrino

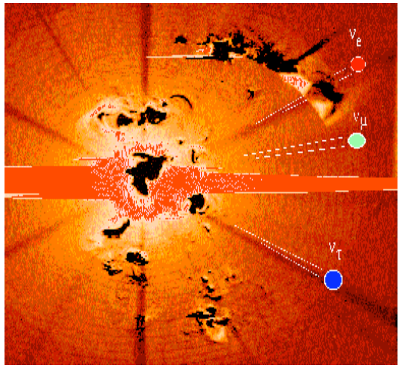

FIRST
OPERATION
NOV 10, 1953


"Herr
Augë"
1
ENTOMBED
MARCH
1953
HERR AUGE
The "Eye" That First

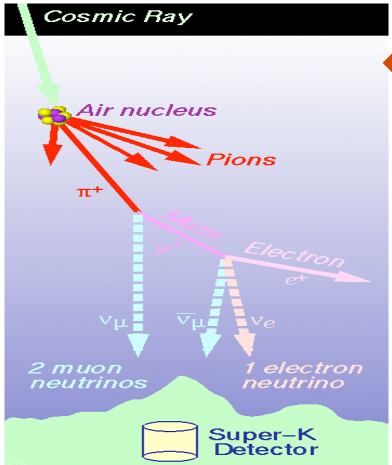
New Physics: Neutrino Sources



← Sun



← Cosmology



← Atmosphere

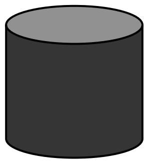
← Earth

Astronomy: →
Supernovae
GRBs
UHE ν's

Reactors →

Accelerators →

β-Sources →



The Standard Model

➔ **success of renormalizable gauge field theories**

QED $\Rightarrow$	QCD $\Rightarrow$	SM
$U(1)_{em} \Rightarrow$	$SU(3)_c \Rightarrow$	$SU(3)_c \times SU(2)_L \times U(1)_Y$

- Singlet with respect to all symmetries
- Renormalizability
- Anomaly free combinations of chiral fermions

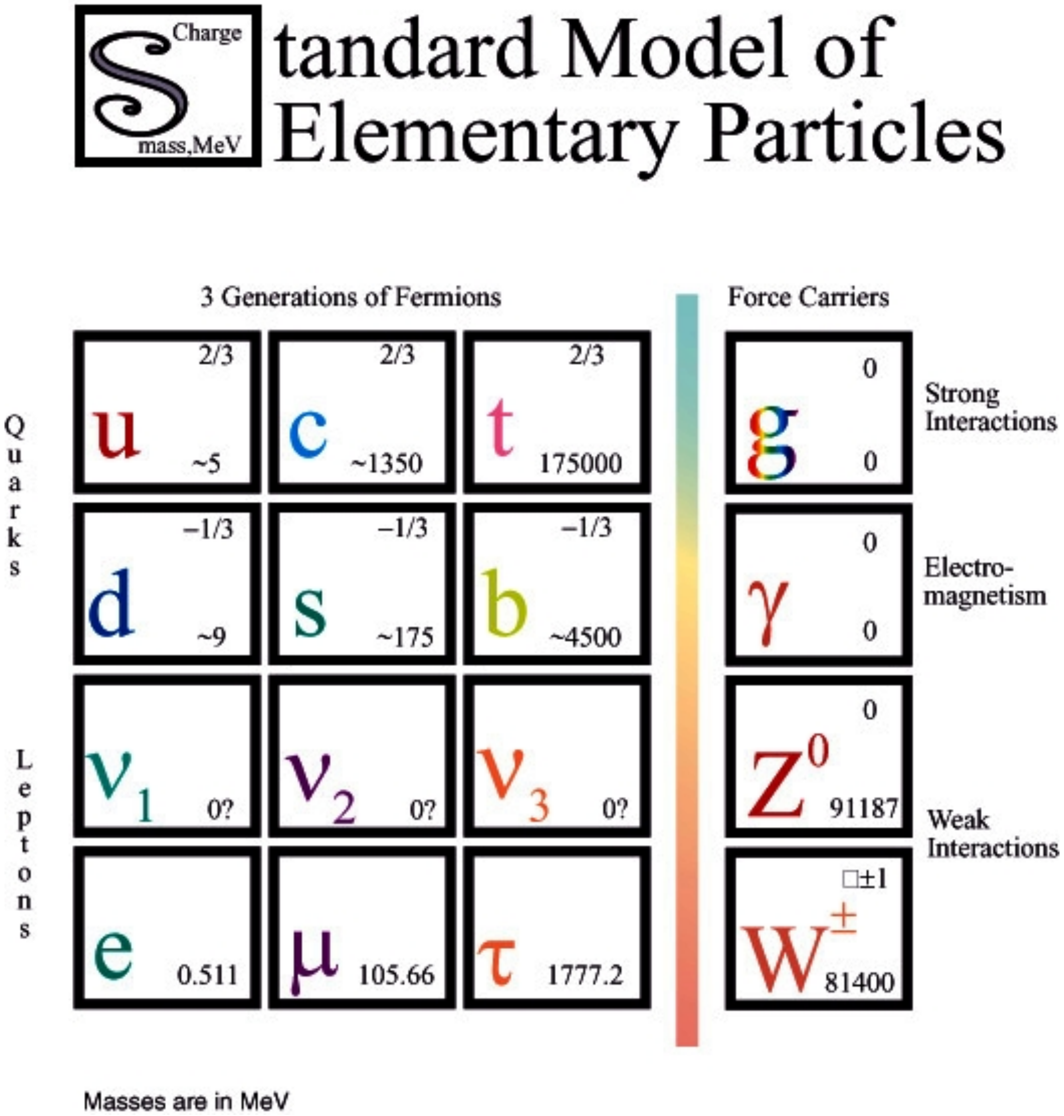
Many details fixed by Lagrangian: $\mathcal{L} = \mathcal{L}_{\textbf{gauge}} + \mathcal{L}_{\textbf{fermion}} + \mathcal{L}_{\textbf{Higgs}} + \mathcal{L}_{\textbf{Yukawa}}$

$$\mathcal{L}_{gauge} = -\tfrac{1}{2}Tr\left[G_{\mu\nu}G^{\mu\nu}\right] - \tfrac{1}{2}Tr\left[W_{\mu\nu}W^{\mu\nu}\right] - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$ (adjoint representations)

$$\mathcal{L}_{fermion} = \sum_L \overline{L}\, i\gamma^\mu D_\mu L + \sum_r \overline{r}\, i\gamma^\mu D_\mu r$$ (kinetic terms of all fermions)

$$\mathcal{L}_{Higgs} = |D\Phi|^2 - V(\Phi^+\Phi)$$ (Higgs potential $\Leftrightarrow$ SSB)

$$\mathcal{L}_{Yukawa} \simeq -g_Y \overline{L}\Phi r + h.c.$$ (fermion masses, CKM–mixing, fermion–Higgs interaction)



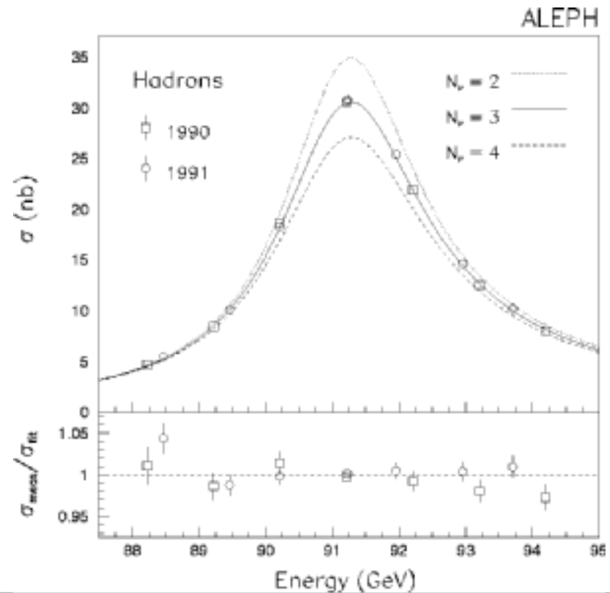
+Higgs particle $m_H \geq 115$ GeV

particles & parameters

gauge bosons	(3)
Higgs particle	(2)
quarks	(6+4)
charged leptons	(3)
strong CP problem	(1)
	total 19

SM: 3 left-handed neutrinos

⇔ Z line shape @ LEP



Problems of the Standard Model

- **The hierarchy problem**

  - how to stabilize m_H in an embedding?

  → SUSY, extra dimensions, composite, …

- **Strong CP problem**

  - why is CP-violation absent in strong sector

  → axions, …

- **Too many parameters in flavour sector**

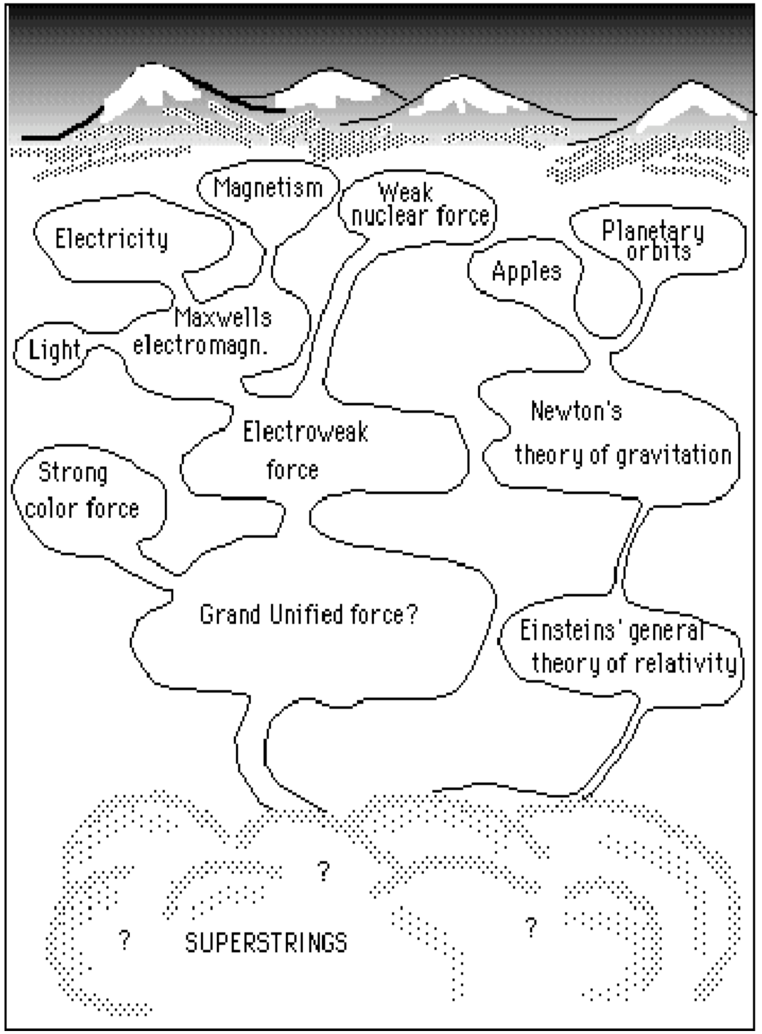
  → ? What are generations?

Physics Beyond the Standard Model

Theoretical arguments:

SM does not exist without cutoff
Higgs-doublett = only simplest extension
Gauge hierarchy problem
Why: 3 generations , fermion representations
Many parameters (9+? Masses, 4+? Mixings)
Charge quantisation, unification: GUTs, ...,
Gravitation, ...

2 directions: Sym. breaking & Flavour



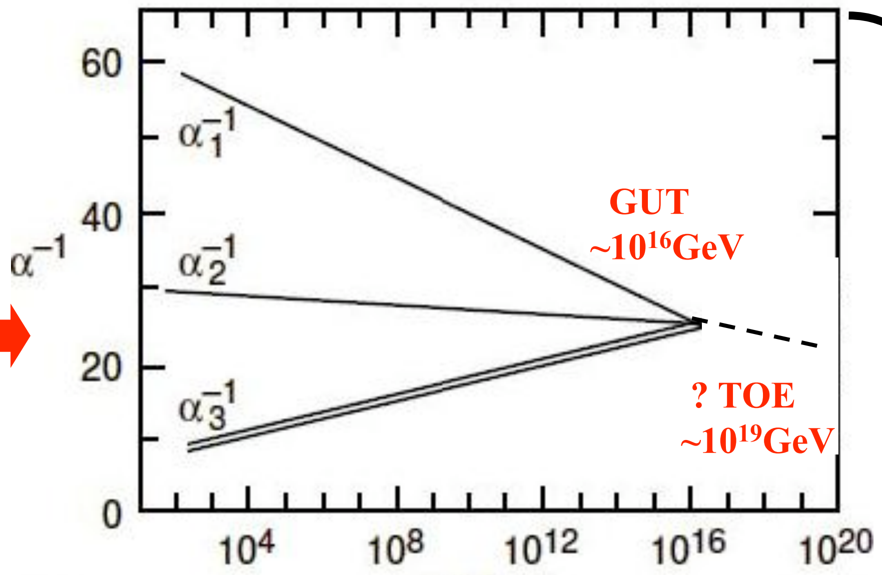
Experimental facts:

- Dark Matter & Dark Energy exist!
- Neutrino masses have been detected!
- Baryon asymetry of the universe ←→ $m_\nu > 0$

➔ physics beyond the standard model
➔ results ←→ implications for theory

Different Routes Beyond the SM

gauge bosons



Higgs

gauge hierarchy problem:

$\delta m_H^2 \sim \Lambda^2$

quarks leptons

flavour problem: 3 generations
many parameters (m_i, mixings)
unification into GUTs

$m_\nu = (m^D)^T M_R^{-1} m_D$

experimental facts:

Dark Matter
Dark Energy
neutrino masses & mixings
baryon asymetry ←→ $m_\nu > 0$
➔ indirect tests of VHE physics

SUSY
~TeV

astrophysics & cosmology

$\sim\Lambda_{GUT}$
+seesaw

2. Introducing Neutrino Masses & Mixings

Extending the Standard Model

➔ success of renormalizable gauge field theories in d=4

QED ➔	QCD ➔	SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$

➔ symmetry, renormalizability, no anomalies

➔ particle content (symmtery representations):

gauge sector – fixed by gauge group
scalar sector – must break EW symmetry, $SB \sim 2_L$
fermions – anomaly free combinations

➔ different levels of SM extension…

- add further SM representations
- extend the gauge symmetry
- add supersymmetry
- extend/modify basic concepts: quantum fields and/or space-time

Adding Neutrino Mass Terms

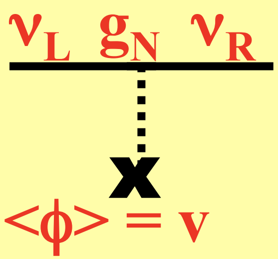
1) Postulate right handed neutrino fields → SM+

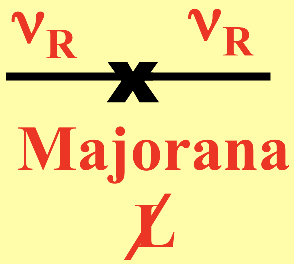
Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2

not part of SM !
makes table more symmetric
3 right handed neutrinos?
NEW: → 9 parameters
→ explicit fermion mass term
→ L number violation

Adding Neutrino Mass Terms

1) Simplest possibility: add 3 right handed neutrino fields





$$\rightarrow \begin{pmatrix} \overline{\nu}_L & \overline{\nu}_R^{\,c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons ➔ Dirac mass terms (including NMS mixing)

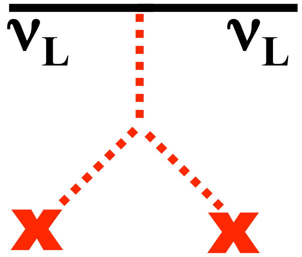
New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

6x6 block mass matrix
block diagonalization
M_R heavy ➔ 3 light ν's

NEW ingredients, 9 parameters ➔ SM+

Other Neutrino Mass Operators

2) new Higgs triplets Δ_L:

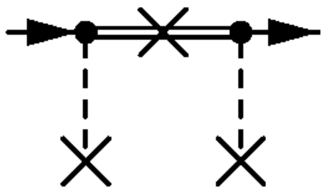


➔ **left-handed Majorana mass term:** ➔ $M_L \overline{L} L^c$

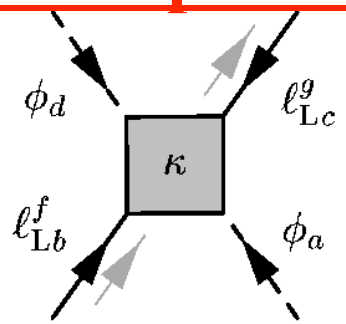
3) Both ν_R and new Higgs triplets Δ_L:

➔ see-saw type II $\quad m_\nu = M_L - m_D M_R^{-1} m_D^T$

4) Higher dimensional operators: d=5, …



$\Rightarrow$



$\Leftrightarrow \quad \mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$

➔ $M_L \overline{L} L^c$

5-N) …

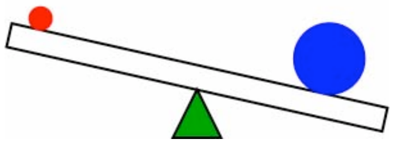
Suggestive Seesaw Features

QFT: natural value of mass operators ⇔ scale of symmetry

$m_D \sim$ electro-weak scale

$M_R \sim$ L violation scale ⇐?⇒ embedding (GUTs, …)

See-saw mechanism (type I)



$$m_\nu = m_D M_R^{-1} m_D^T \qquad m_h = M_R$$

Numerical hints:

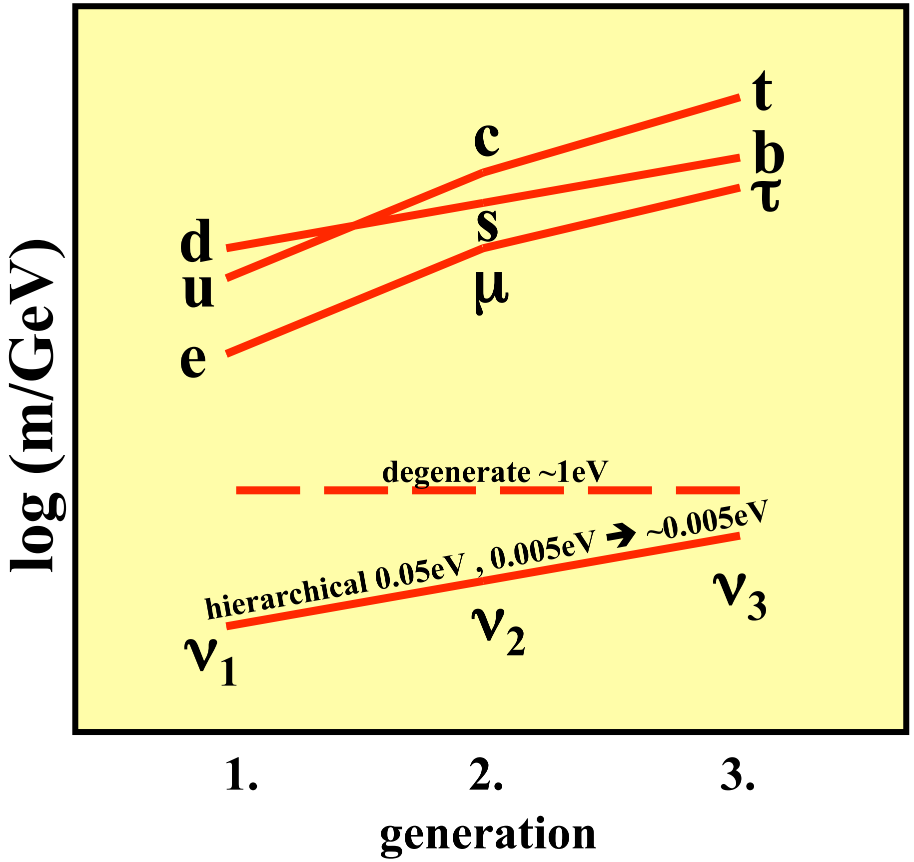
For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons ⇒ $M_R \sim 10^{11} - 10^{16}$GeV

⇒ν's are Majorana particles , m_ν probes ~ GUT scale physics!

⇒smallness of m_ν ⇔ high scale of $\not{L}$, symmetries of m_D ,M_R

2nd Look Questions

Quarks & charged leptons ➔ hierarchical masses ➔ neutrinos?



<u>Quarks and charged leptons:</u>

$m_D \sim H^n$; $n = 0,1,2$ ➔ $H \geq 20...200$

<u>Neutrinos:</u> $m_\nu \sim H^n$ ➔ $H \leq \sim 10$

<u>See-saw:</u>

$$m_\nu = -m_D^T \, M_R^{-1} \, m_D$$

	m_ν	m_D^T	M_R^{-1}	m_D
H	$\sim$10	$\geq$20	?	$\geq$20

- less hierarchy in m_D or correlated hierarchy in M_R ? ➔ theoretically connected!
- mixing patterns: not generically large, why almost maximal, θ_{13} small?

Other effective Operators Beyond the SM

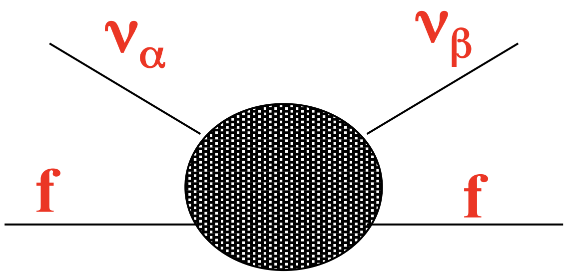
➔ effects beyond 3 flavours

➔ Non Standard Interactions = NSIs ➔ effective 4f opersators

$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

- integrating out heavy physics (c.f. G_F ⇔ M_W)

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$



Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow+Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli +Romanino, Bueno et al., Barranco+Miranda+Rashba, Kopp+ML+Ota, …

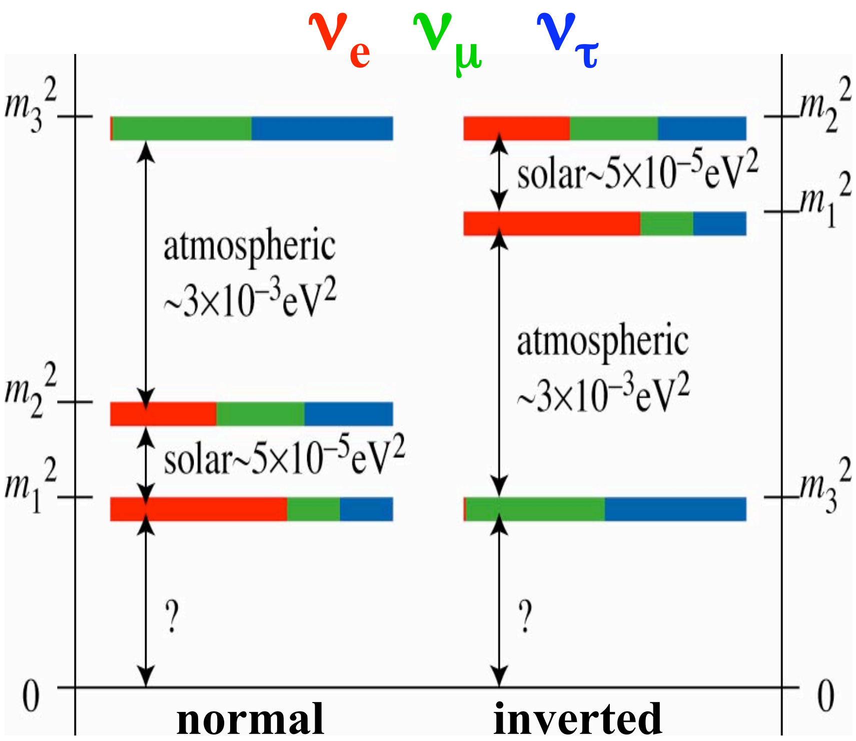
Parameters for 3 Light Neutrinos

mass & mixing parameters: m_1 , Δm^2_{21}, $|\Delta m^2_{31}|$, sign(Δm^2_{31})

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

questions:

- ➔ Dirac / Majorana
- ➔ mass scale: m_1
- ➔ mass ordering: sgn(Δm^2_{31})
- ➔ how small is θ_{13}, θ_{23} maximal?
- ➔ leptonic CP violation
- ➔ 3 flavour unitarity?
- ➔ why 3 generations, d=4, gauge group, …



hierarchical or degenerate

Overview of Neutrino Mass Determinations

neutrino mass scale

<23 eV

SN1987A

<2.2 eV

tritium endpoint
Mainz & Troitsk

<~0.2 eV

cosmology

< ~0.3 eV

$0\nu\beta\beta$ if
neutrino is
Majorana

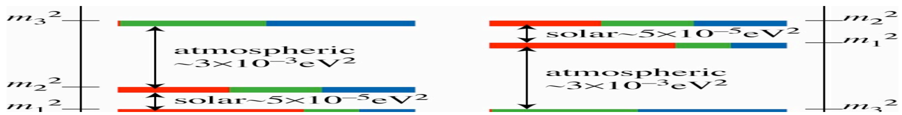
~ 0.2 eV

KATRIN

~ 0.05 eV

different types of masses / different systematics

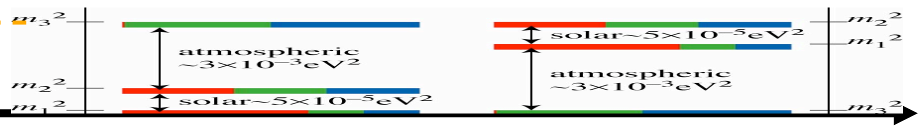
ν oscillations were observed
➔ finite mass splittings ➔ finite mass



~ degenerate

?

hierarchical



3. Neutrino Mass Determinations

Four Methods of Mass Determination

- **kinematical**
- **lepton number violation**
  ⟷ Majorana nature
- **astrophysics & cosmology**
- **oscillations**

Kinematical Mass Determination

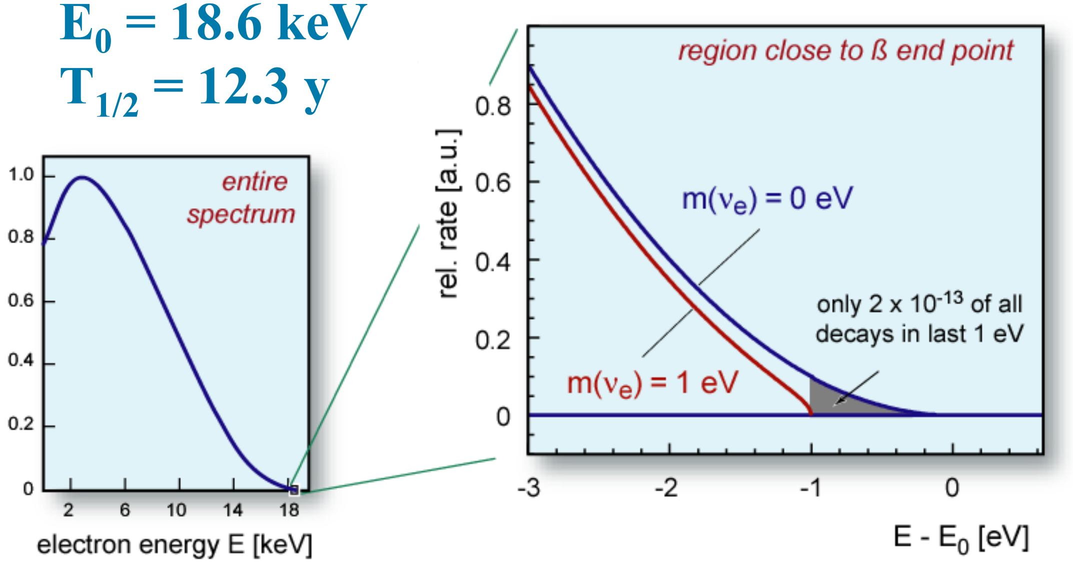
model independent neutrino mass from ß-decay kinematics

$$\boxed{\frac{\mathrm{d}\Gamma_i}{\mathrm{d}E} = C\,p\,(E+m_e)\,(E_0-E)\,\sqrt{(E_0-E)^2-m_i^2}\,F(E)\,\theta(E_0-E-m_i)}$$

$$C = G_F^2 \frac{m_e^5}{2\,\pi^3}\,\cos^2\theta_C\,|M|^2$$

experimental observable: m_ν^2

E_0 = 18.6 keV
$T_{1/2}$ = 12.3 y



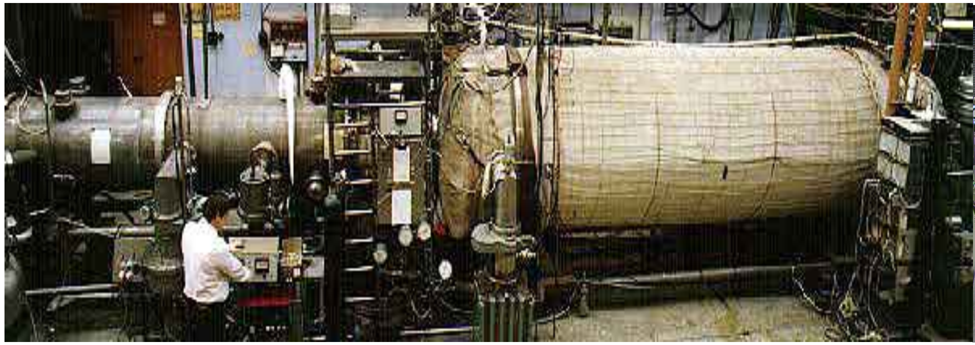
ß-source requirements :

- high ß-decay rate (short $t_{1/2}$)
- low ß-endpoint energy E_0
- superallowed ß-transition
- minimised inelastic scatters of ß's

ß-detection requirements :

- high energy resolution (< few eV)
- large solid angle ($\Delta\Omega \sim 2\pi$)
- low background

Status of kinematical Mass Determination



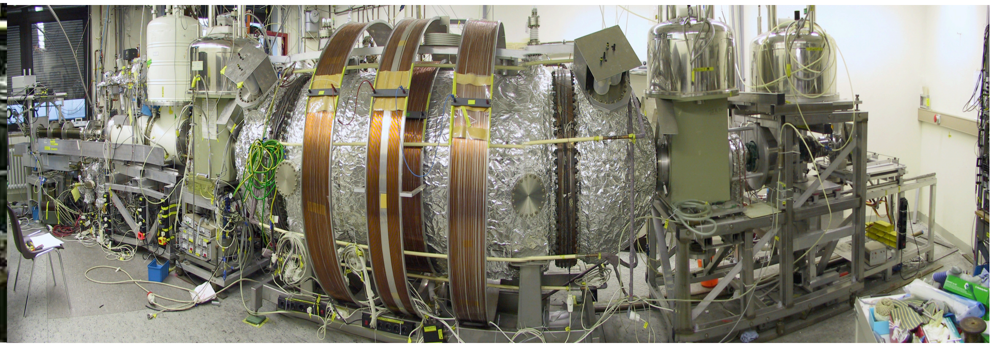
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0 \ eV^2$

$m_\nu \leq \quad 2.2 \ eV \ \ (95\% \ CL.)$



Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1 \ eV^2$

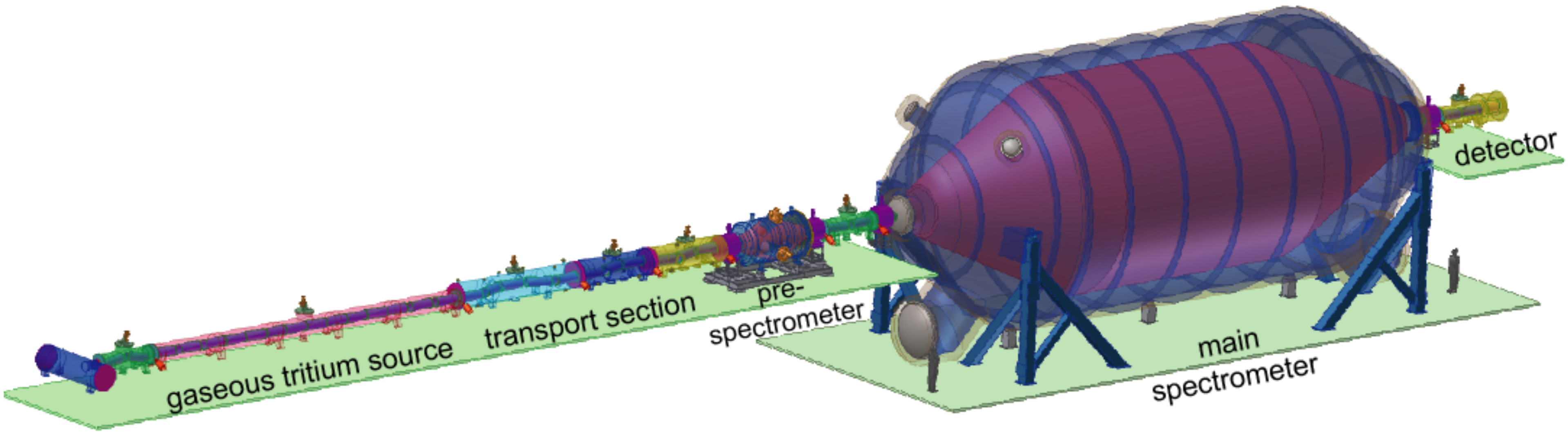
$m_\nu \leq \quad 2.2 \ eV \ \ (95\% \ CL.)$

both experiments have reached their intrinsic sensitivity limit

The Future

KATRIN - Karlsruhe Tritium Neutrino Experiment

direct n-mass measurement with sub-eV sensitivity



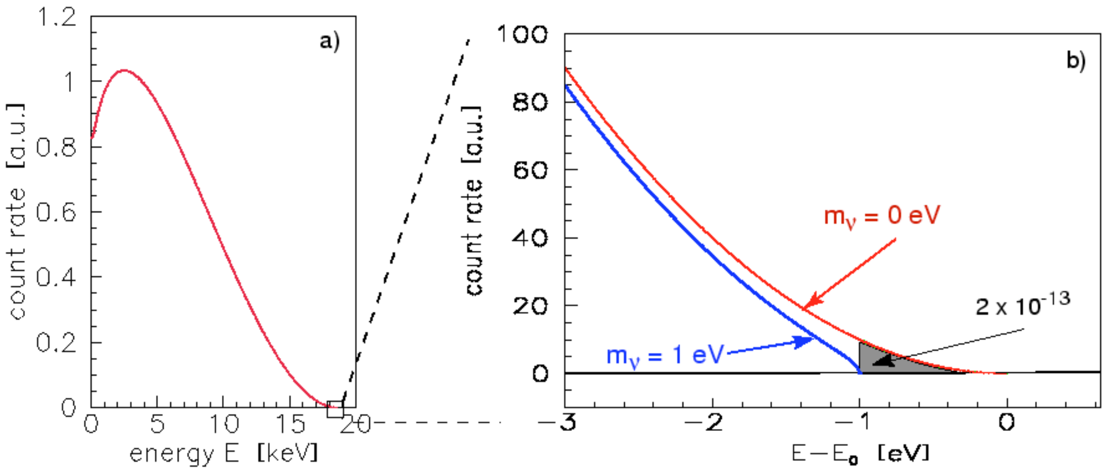
Kinematical Mass Determination

Relativistic kinematics:

$$E^2 = p^2 + m^2; \ \sum p_i^\mu = \sum p_f^\mu$$

Endpoint of decays:

Tritium $\longrightarrow He^3 + e^- + \overline{\nu}_e$



Bounds:

"Elektron-Neutrino": $m < 2.2$ eV (Mainz, Troitsk)
"Muon-Neutrino": $m < 170$ keV
"Tau-Neutrino": $m < 15.5$ MeV

Sensitivity $\Leftrightarrow$ **degenerate ν-spectrum**

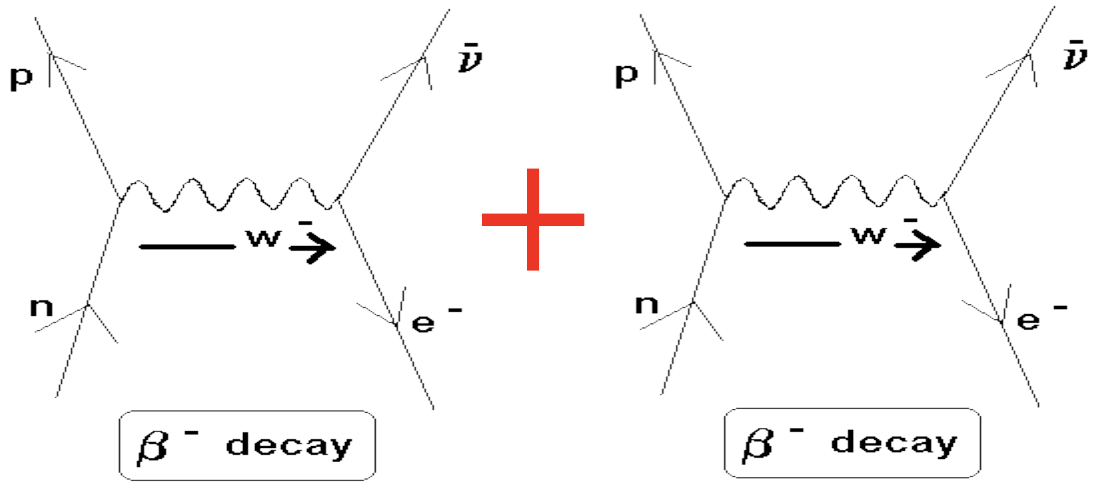
$\Rightarrow$ **Oscillations:** $\Delta m_{ij}^2 \ll m_i^2 \Rightarrow$ $\boxed{\sum m_i^2 |U_{ei}|^2 < (2.2 \text{ eV})^2}$

Future: **KATRIN → 0.20 eV** ↔ **c.f. comological bounds**

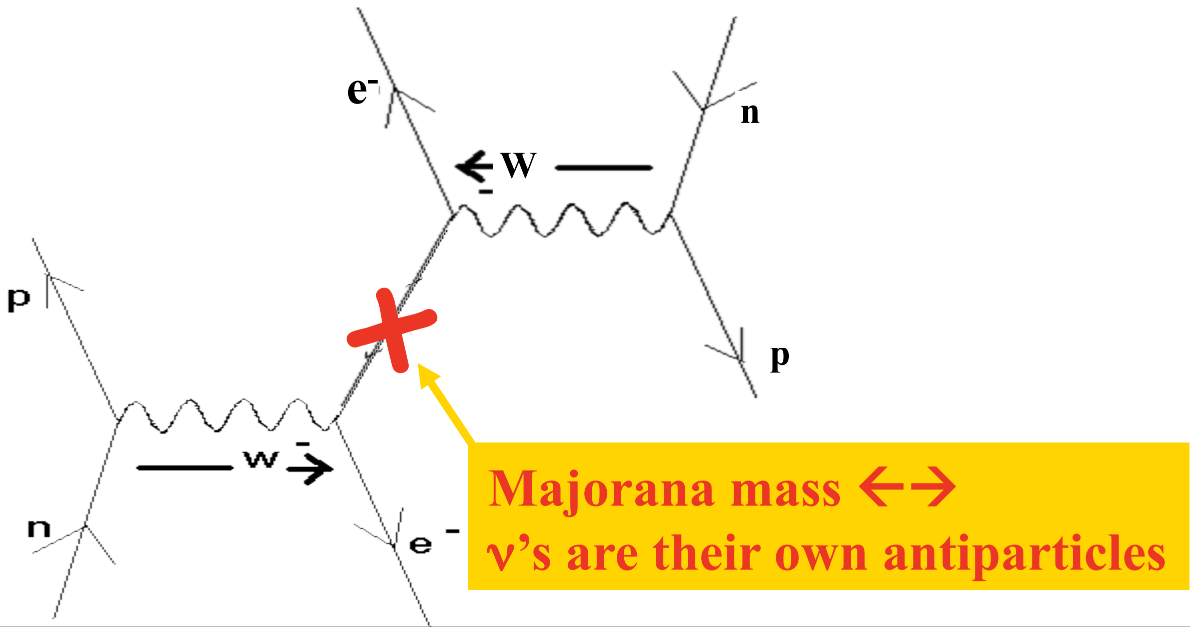
Four Methods of Mass Determination

- kinematical
- lepton number violation
  $\Leftarrow\!\Rightarrow$ Majorana nature
- astrophysics & cosmology
- oscillations

Double Beta Decay

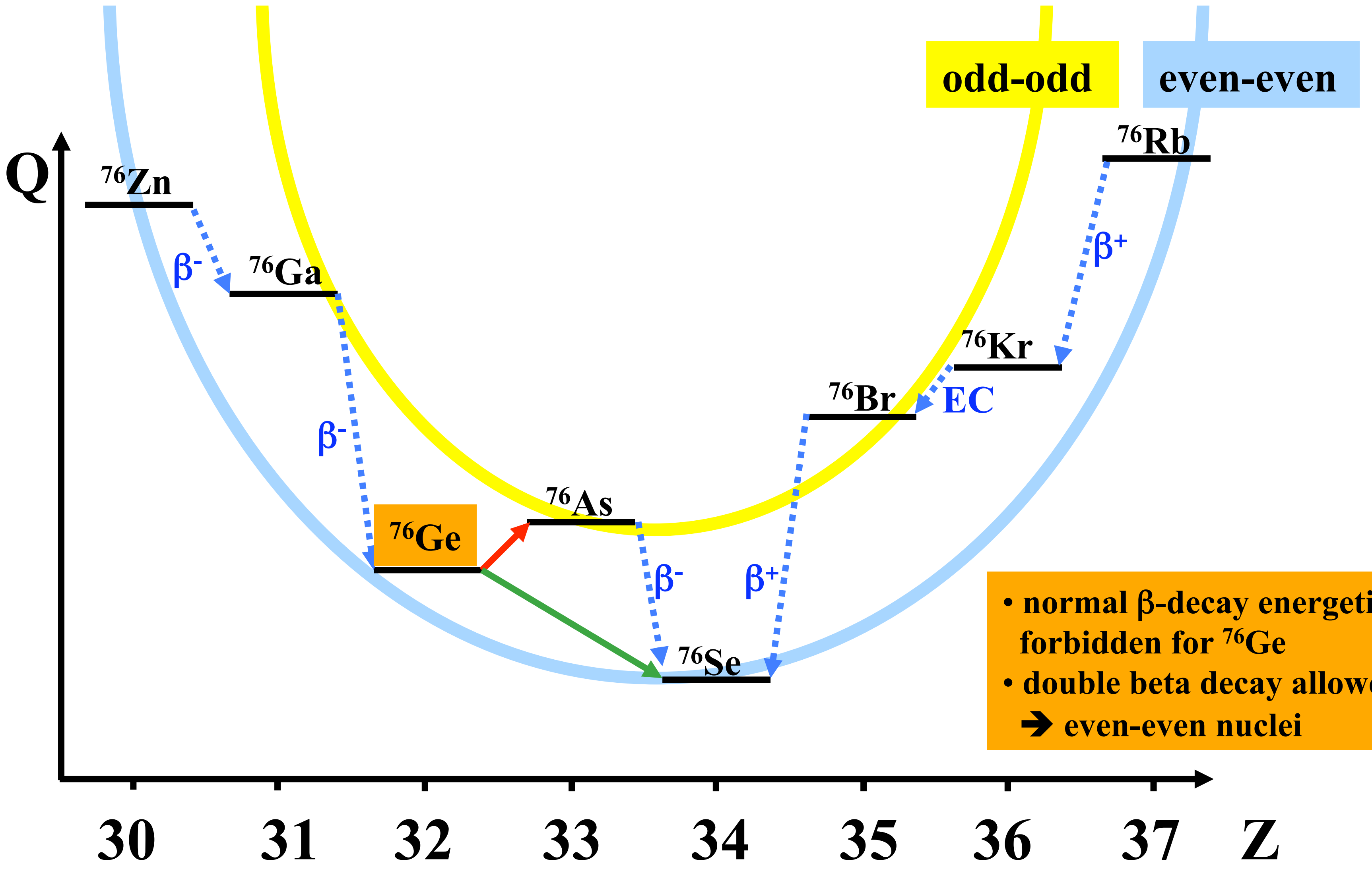


→ 2 neutrinos plus 2 electrons



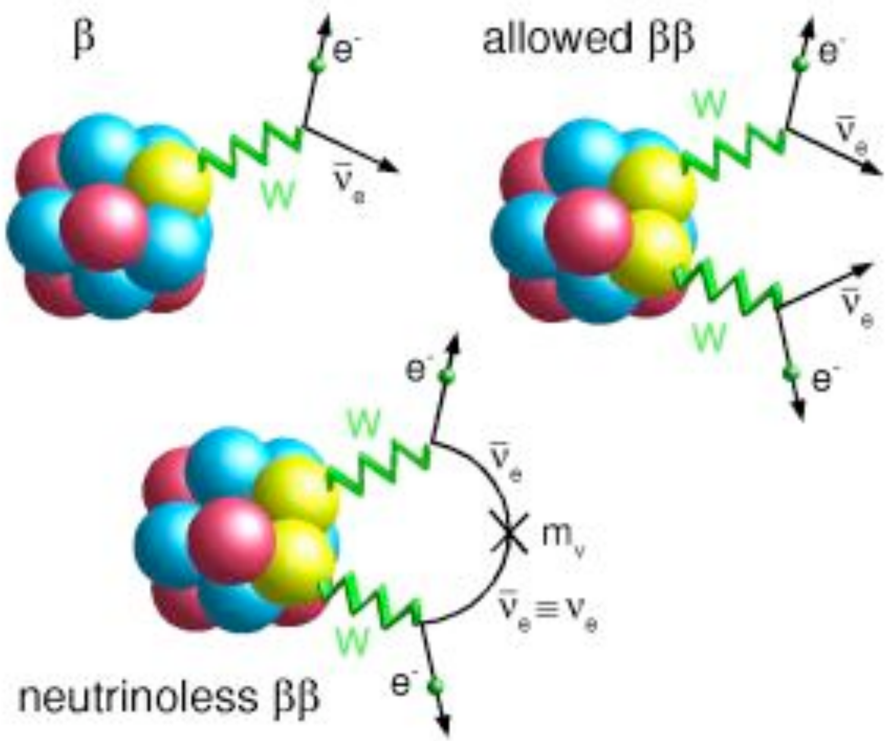
→no neutrinos just 2 electrons

Double Beta Decay: Mass Parabolas



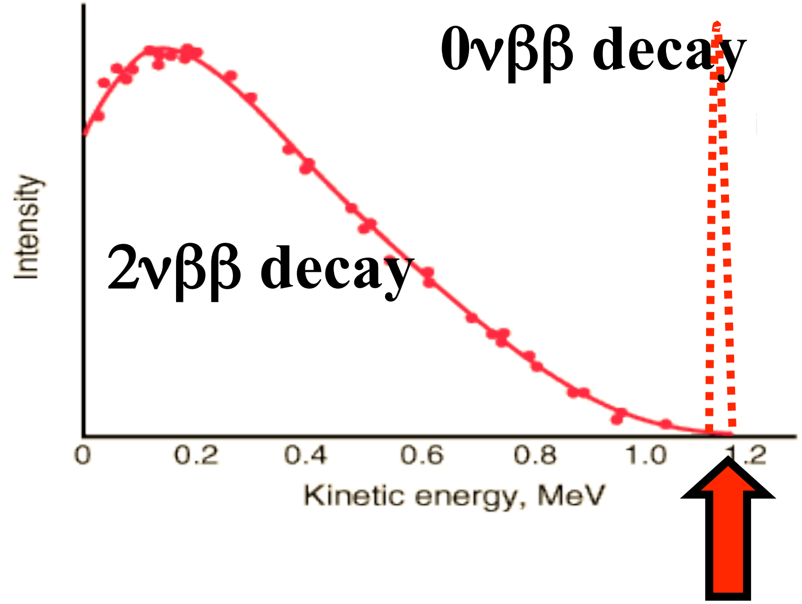
- normal β-decay energetically forbidden for ^{76}Ge
- double beta decay allowed
  ➔ even-even nuclei

$0\nu\beta\beta$ Decay Kinematics



$2\nu\beta\beta$ decay of ^{76}Ge observed:

$\tau = 1.5 \times 10^{21}$ y



Majorana ν ➔ $0\nu\beta\beta$ decay

- **signal at known Q-value**
- **$2\nu\beta\beta$ background (resulution)**
- **nuclear backgrounds**
  ➔ **use different nuclei**

warning:

other lepton number violating processes…

Relating Rates / Lifetimes to Neutrino Masses

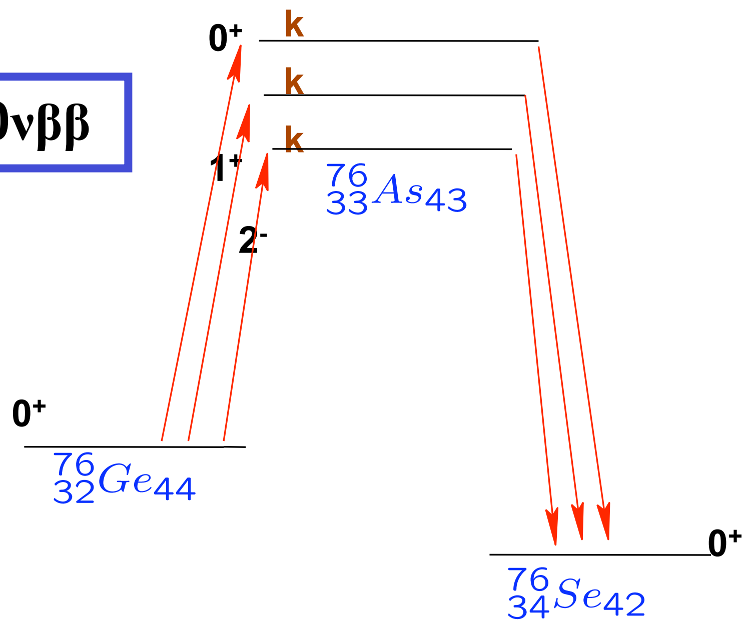
rate of $0\nu\beta\beta$ — phase space — nuclear matrix elements — effectiveMajorana neutrino mass

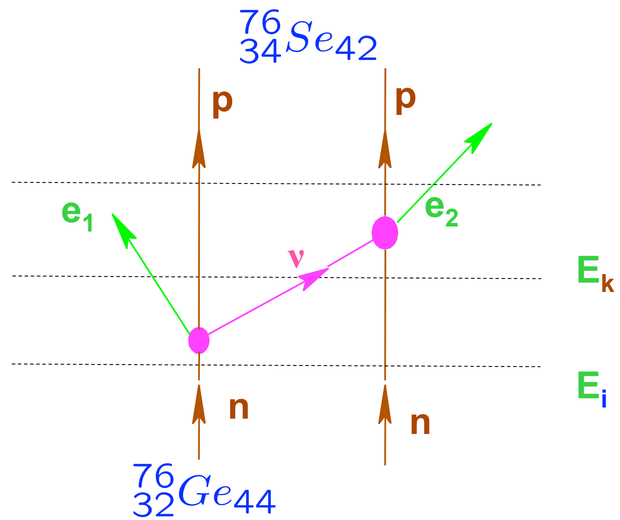
$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \,<m_{ee}>^2$$

nuclear matrix elements: Fäßler et al., …

➔ virtual excitations of intermediate states

$0\nu\beta\beta$





$$T = \Sigma_k \frac{< f|\hat{H}_W|k >< k|\hat{H}_W|i >}{E_i - E_k}$$

progress in TH errors ➔ reduced uncertainties

Decay Rates

2ν2β:

$$\left[T_{\frac{1}{2}}^{2\nu}\,(0^{+}\rightarrow 0^{+})\right]^{-1} = G^{2\nu}(E_0,Z)\left|M_{GT}^{2\nu}-\frac{g_V^2}{g_A^2}M_F^{2\nu}\right|^2$$

Phase space

nuclear matrix element

0ν2β:

(assuming that leading term is due to exchange of light Majorana-neutrino)

$$\left[T_{\frac{1}{2}}^{0\nu}(0^{+}\rightarrow 0^{+})\right]^{-1} = G^{0\nu}(E_0,Z)\left|M_{GT}^{0\nu}-\frac{g_V^2}{g_A^2}M_F^{0\nu}\right|^2 <m_\nu>^2$$

effective Majorana mass

Remark: 0ν2β also generated by SUSY, LR …..

Nuclear Matrix Elements

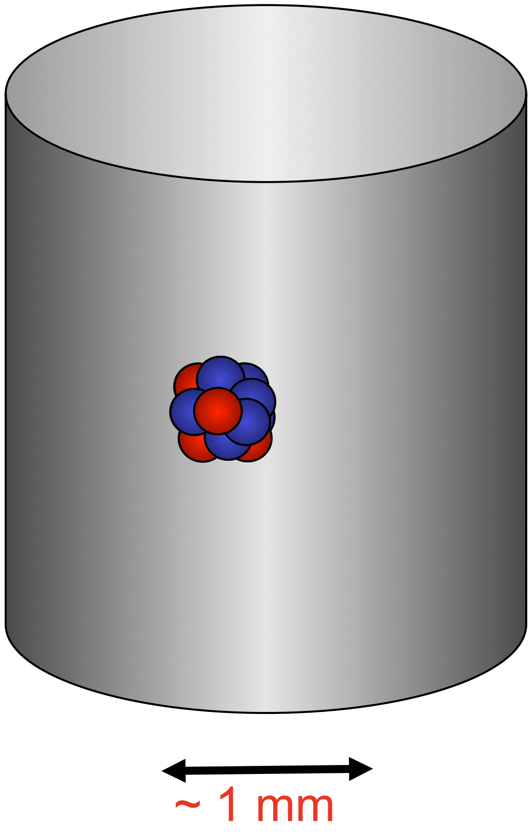
$0\nu2\beta$ half-lives in units of 10^{26} years for $<m_\nu>$=50 meV for nuclear matrix of different authors

Attention: systematically correleated calculations!

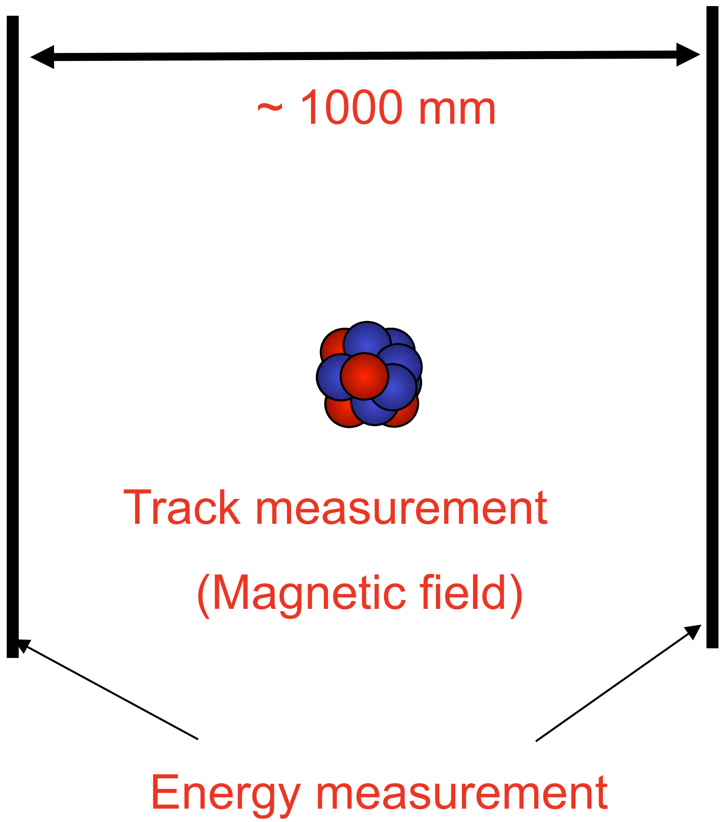
Nucleus	Haxton et al. Ref.: (20)	Caurier et al. (80)	Engel et al. (81)	Staudt et al. (82)	Faessler et al. (24, 83)	Pantis et al. (84)
^{48}Ca	12.7	35.3	-	-	-	10.0
^{76}Ge	6.8	70.8	56.0	9.3	12.8	14.4
^{82}Se	2.3	9.6	22.4	2.4	3.2	6.0
^{100}Mo	-	-	4.0	5.1	1.2	15.6
^{116}Cd	-	-	-	1.9	3.1	18.8
^{130}Te	0.6	23.2	2.8	2.0	3.6	3.4
^{136}Xe	-	48.4	13.2	8.8	21.2	7.2
^{150}Nd^{a})	-	-	-	0.1	0.2	-
^{160}Gd^{a})	-	-	-	3.4	-	-

How to measure $0\nu2\beta$ decay ?

Source = Detector



Source ≠ Detector



Heidelberg-Moscow Experiment @ LNGS

Technical parameters of the five enriched ^{76}Ge detectors

Detector number	Total mass (kg)	Active mass (kg)	Enrichment in ^{76}Ge(%)	PSA
No. 1	0.980	0.920	85.9 ± 1.3	No
No. 2	2.906	2.758	86.6 ± 2.5	Yes
No. 3	2.446	2.324	88.3 ± 2.6	Yes
No. 4	2.400	2.295	86.3 ± 1.3	Yes
No. 5	2.781	2.666	85.6 ± 1.3	Yes

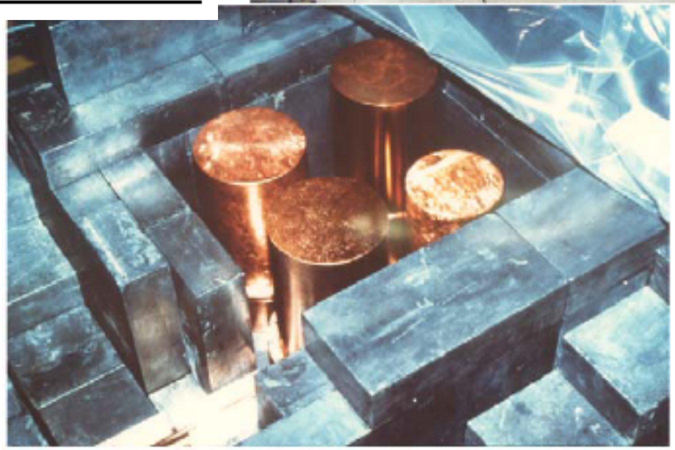


Fig. 1. The HEIDELBERG–MOSCOW ββ-experiment in the Gran Sasso (top), and four of the enriched detectors during installation (bottom left). The fifth detector was installed in an extra shielding using electrolytic copper as inner shield (bottom right).

Data acquisition and analysis of the ^{76}Ge double beta experiment in Gran Sasso 1990–2003

H.V. Klapdor-Kleingrothaus*[1], A. Dietz, I.V. Krivosheina[2], O. Chkvorets

NIM A 522 (2004)

Evidence by Part of HM

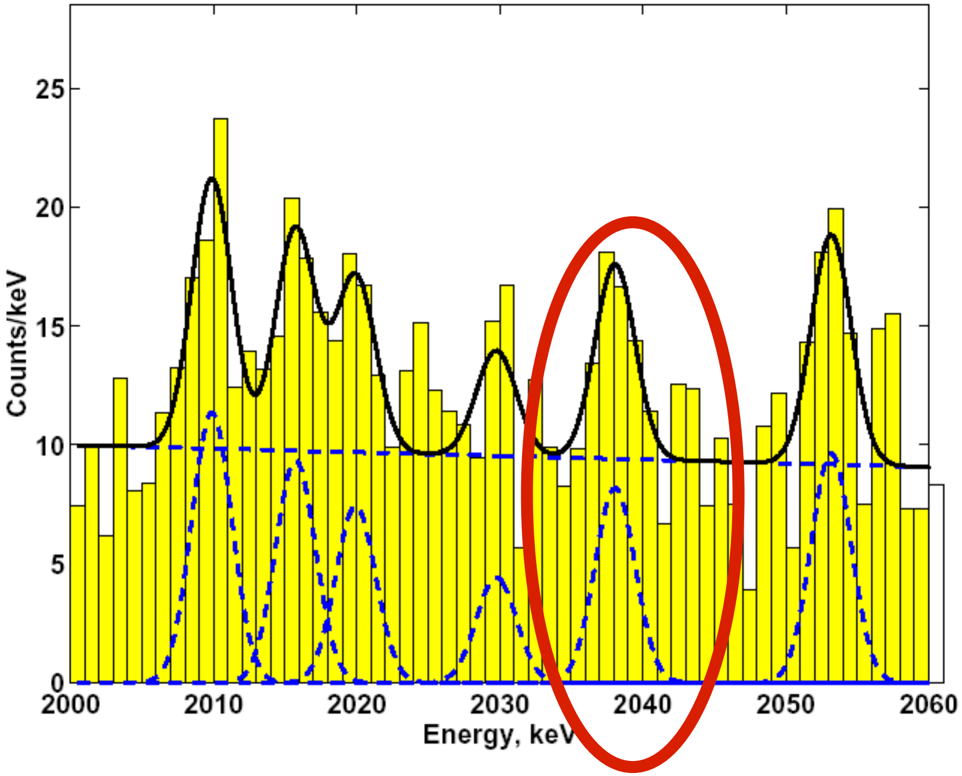


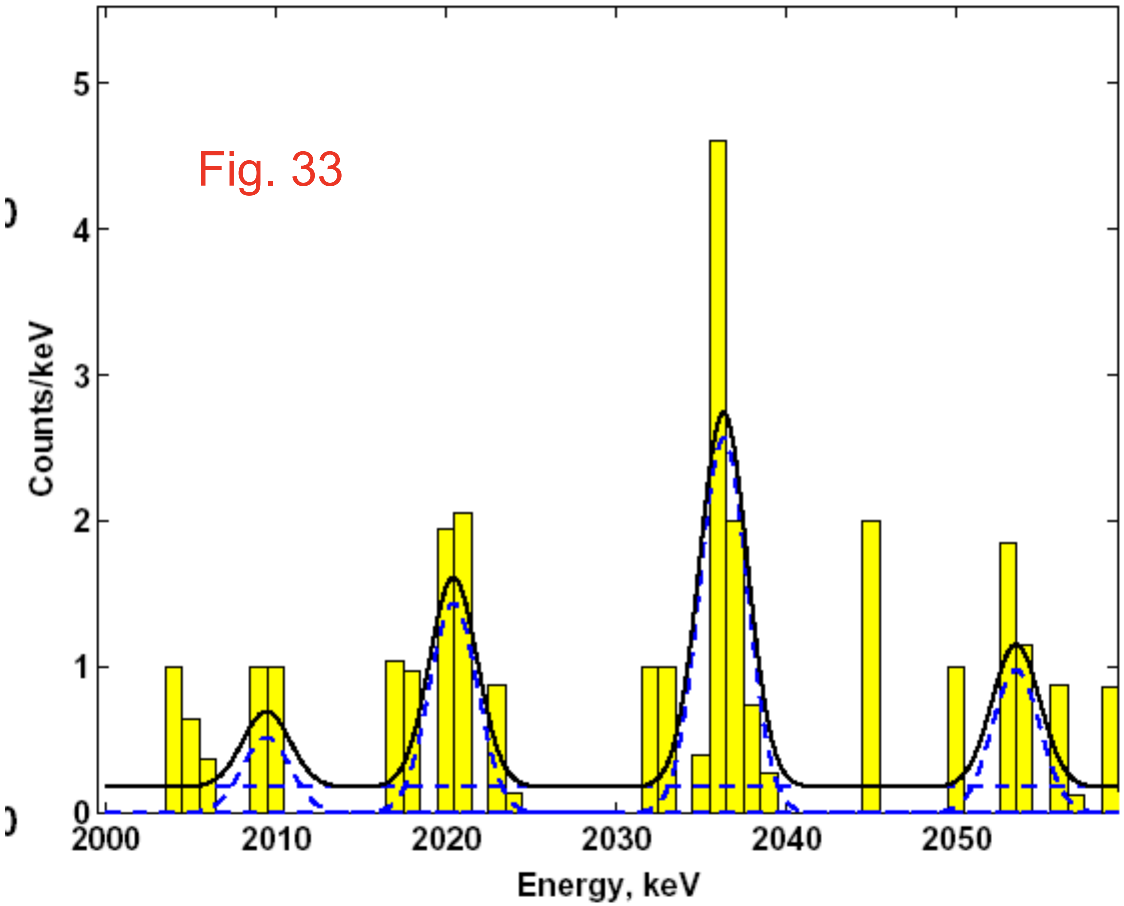
Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

- Nov 1990- May 2003
- 71.7 kg year
- Bgd 0.11 / kg y keV
- 28.75 ± 6.87 events (bgd:~60)
- 4.2 sigma evidence for $0\nu\beta\beta$

- 0.34-2.03 $\times 10^{25}$ y (3 sigma)
- Best fit 1.19 $\times 10^{25}$ y

- m_{ee} = 0.1-0.9 eV
- best fit 0.44 eV

SSE* Analysis: Strengthening the Evidence?



Other running Experiments

CUORICINO (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents):

Firenze, Gran Sasso, Insubria, LBNL, Leiden, Milano, Neuchatel, South Carolina, Zaragoza

Location: Gran Sasso Underground Laboratory

Source = detector, TeO_2 (40 kg) $\Rightarrow$ ^{130}Te (13 kg): Q = 2533±4 keV

$$\tau_{1/2} > 1.8\ 10^{24} \text{ at } 90\% \text{ C.L.} \quad (\langle m_\nu \rangle < [0.2 \div 1.1] \text{ eV})$$

NEMO3 (Neutrino Ettore Majorana Observatory):

CENBG Bordeaux, Charles Univ. Prague, FNSPE Prague, INEEL, IReS Strasbourg, ITEP Moscow, JINR Dubna, Jyvaskyla Univ., LAL Orsay, LPC Caen, LSCE Gif, Mount Holyoke College, Saga Univ, UCL London

Location: Frejus Underground Laboratory

Source ≠ detector $\Rightarrow$ study different nuclei; main target ^{100}Mo (6.9 kg): Q = 3034±6keV

Results ➔ so far mass limits weaker as HM ; O(0.7-5eV)

New Experiments

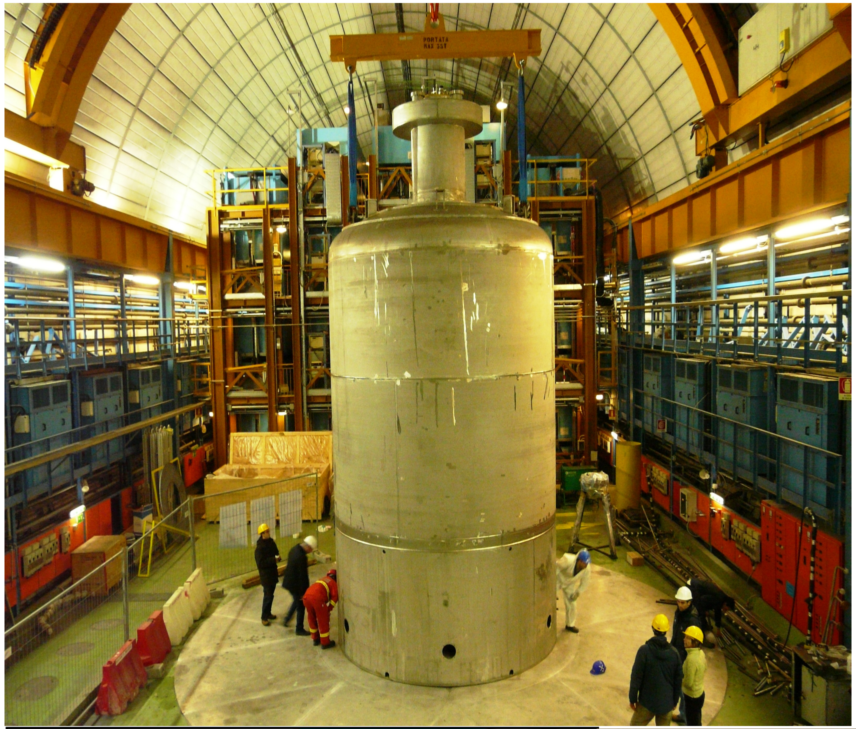
Advanced construcion:

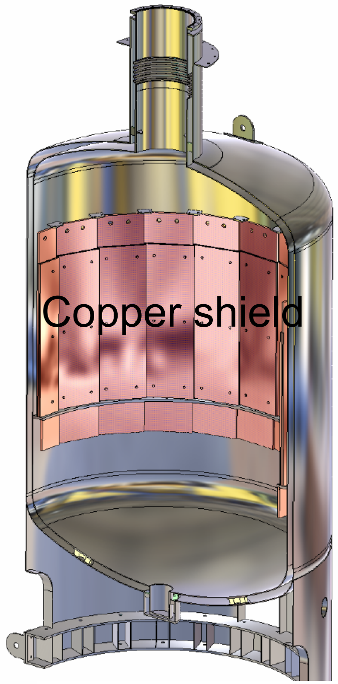
- CUORE (Te-130) ➔ 2010?
- GERDA (Ge-76) ➔ start 2009!

Under construction:

- Majorana
- EXO
- MOON
- Super-NEMO
- ...

GERDA Construction

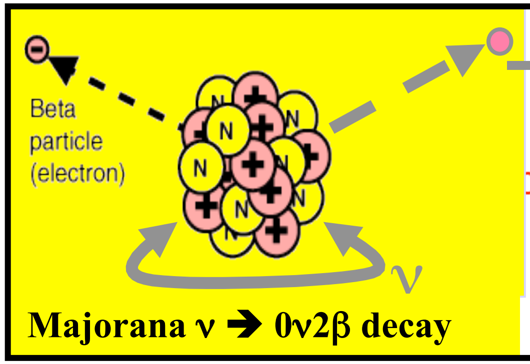


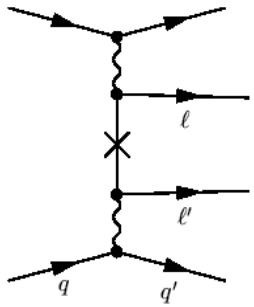


Vacuum-insulated double wall stainless steel cryostat

➔ **data taking 2009**

Neutrino-less Double β-Decay



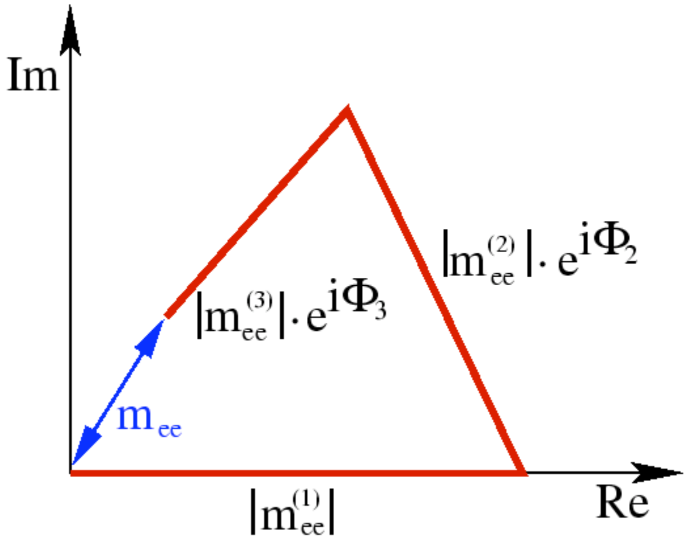


$$\propto |\langle m_{ee} \rangle| \;=\; |\textstyle\sum m_i U_{ei}^2| \;\; \underline{<} \; 0.35 \text{ eV ?}$$

Heidelberg-Moscow experiment

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

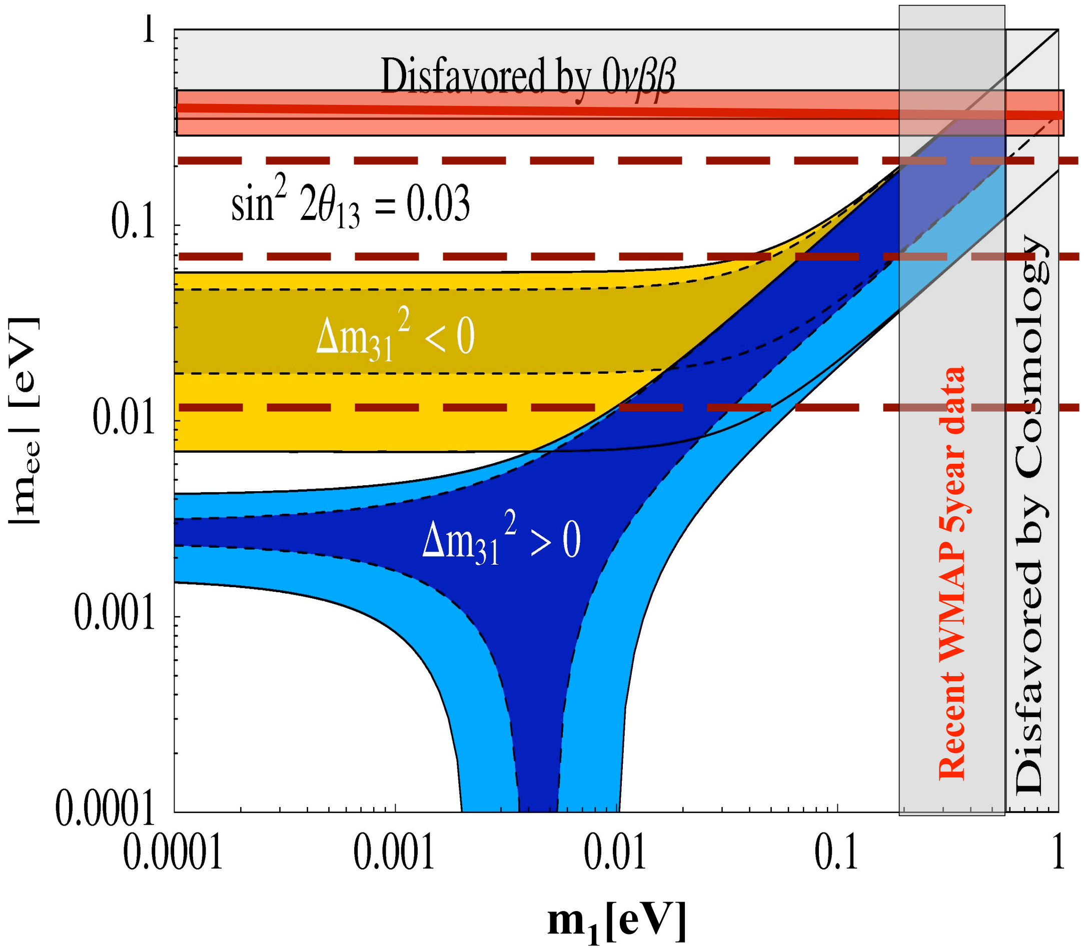
$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \end{aligned}$$



solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

➔ **free parameters: m_1, sign(Δm_{31}^2), CP-phases Φ_2, Φ_3**

Claim of part of the original Heidelberg-Moscow experiment ←→ cosmology → ‚tension‘



aims of new experiments:

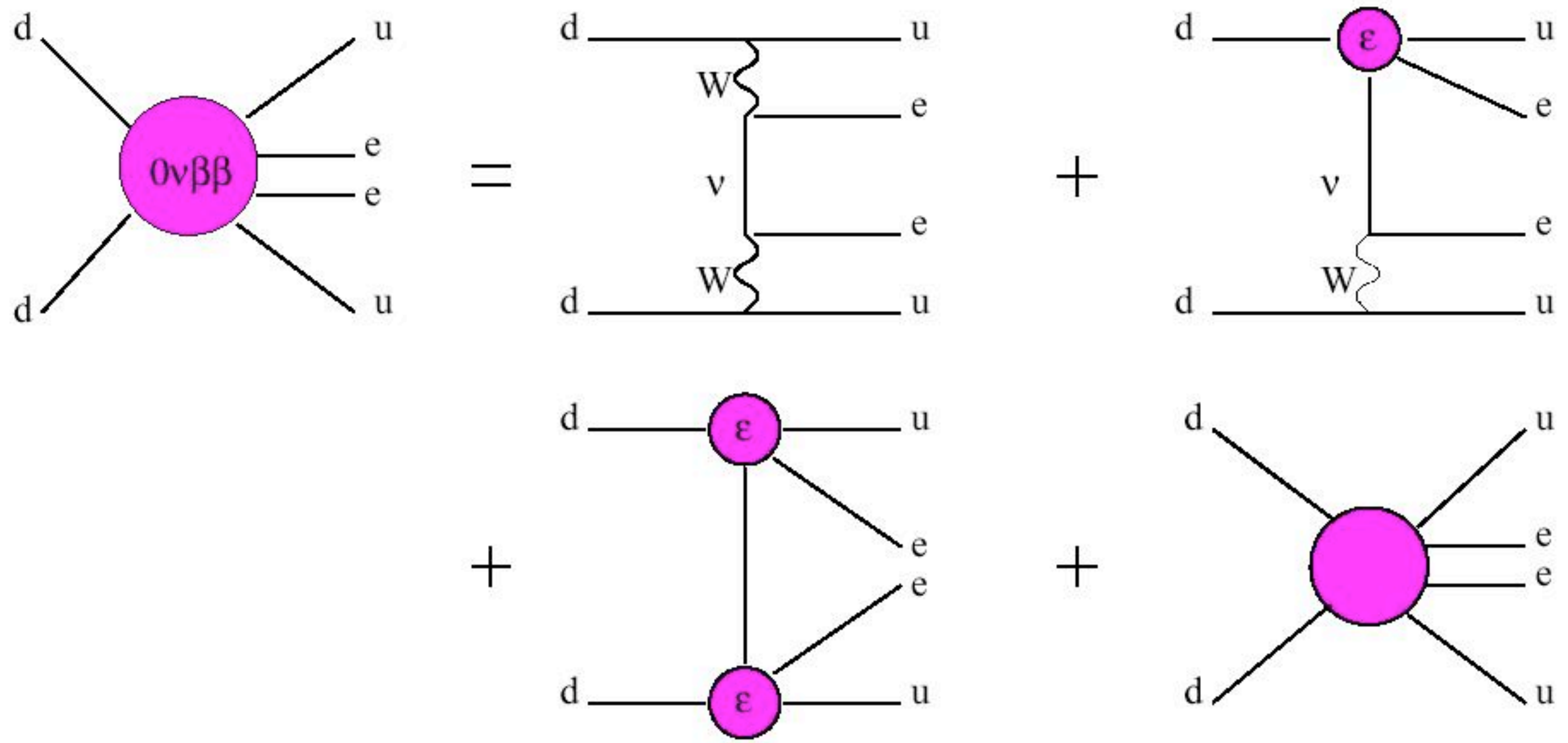
- test HM claim
- $(\Delta m_{31}^2)^{1/2} \simeq 0.05\text{eV} \pm$ errors
  - → reach 0.01eV
  - → CUORE
  - → GERDA phases I, II, (III)

Comments:

- cosmology: limitation by systematical errors → ~another factor 5?
- $0\nu\beta\beta$ nuclear matrix elements ~factor 1.3-2 theoretical uncertainty in m_{ee}
- $\Delta m^2 > 0$ allows complete cancellation → $0\nu\beta\beta$ signal not guaranteed
- $0\nu\beta\beta$ signal from *some other* new BSM lepton number violating operator

→ very promising interplay of neutrino mass determinations, cosmology, LHC, LVF experiments and theory

alternatives: LR, RPV-SUSY, …→ other $\not{L}$ operators ↔ NSI's



Schechter+Valle:

L violating operator → radiative mass generation → Majorana nature of ν's

However: This may only be a tiny correction to a much larger Dirac mass term

Lepton Flavour Violation

- **Majorana neutrino mass terms**
- **…**
- **R-parity violating supersymmetry**

Hall+Kosteleck+Rabi, Borzumati+Masiero, Hisano+Tobe, Casas+Ibarra, Antusch +Arganda+Herrero+Teixeira, Joaquim+Rossi, …

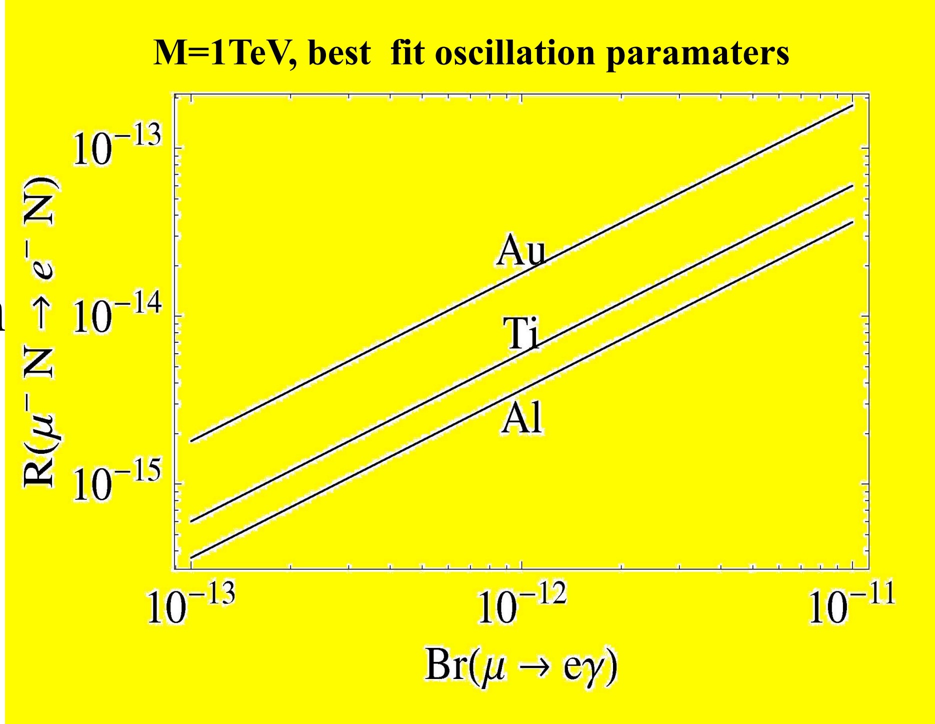
➔LFV and leptonic CP violation can even exist for m_ν➔0

➔ e.g. modifications of correlation between μ^- ➔ $e^- \gamma$ decay and nuclear μ^- ➔ e^- conversion

MEG: 10^{-13}

PRISM: 10^{-18}

➔interplay: ν's – LFV - LHC



Deppisch+Kosmas+Valle

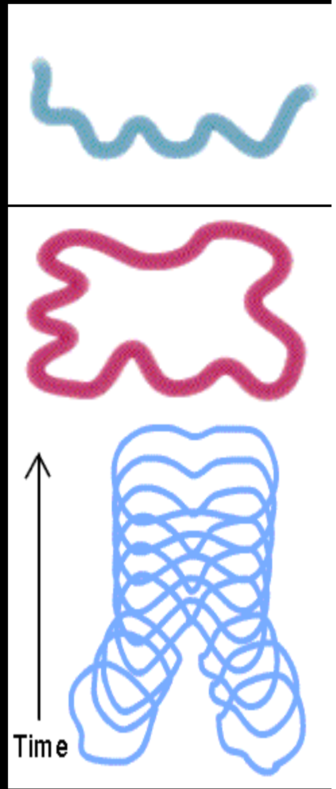
Four Methods of Mass Determination

- kinematical
- lepton number violation
  $\Leftrightarrow$ Majorana nature
- astrophysics & cosmology
- oscillations

The thermal evolution of the Universe:

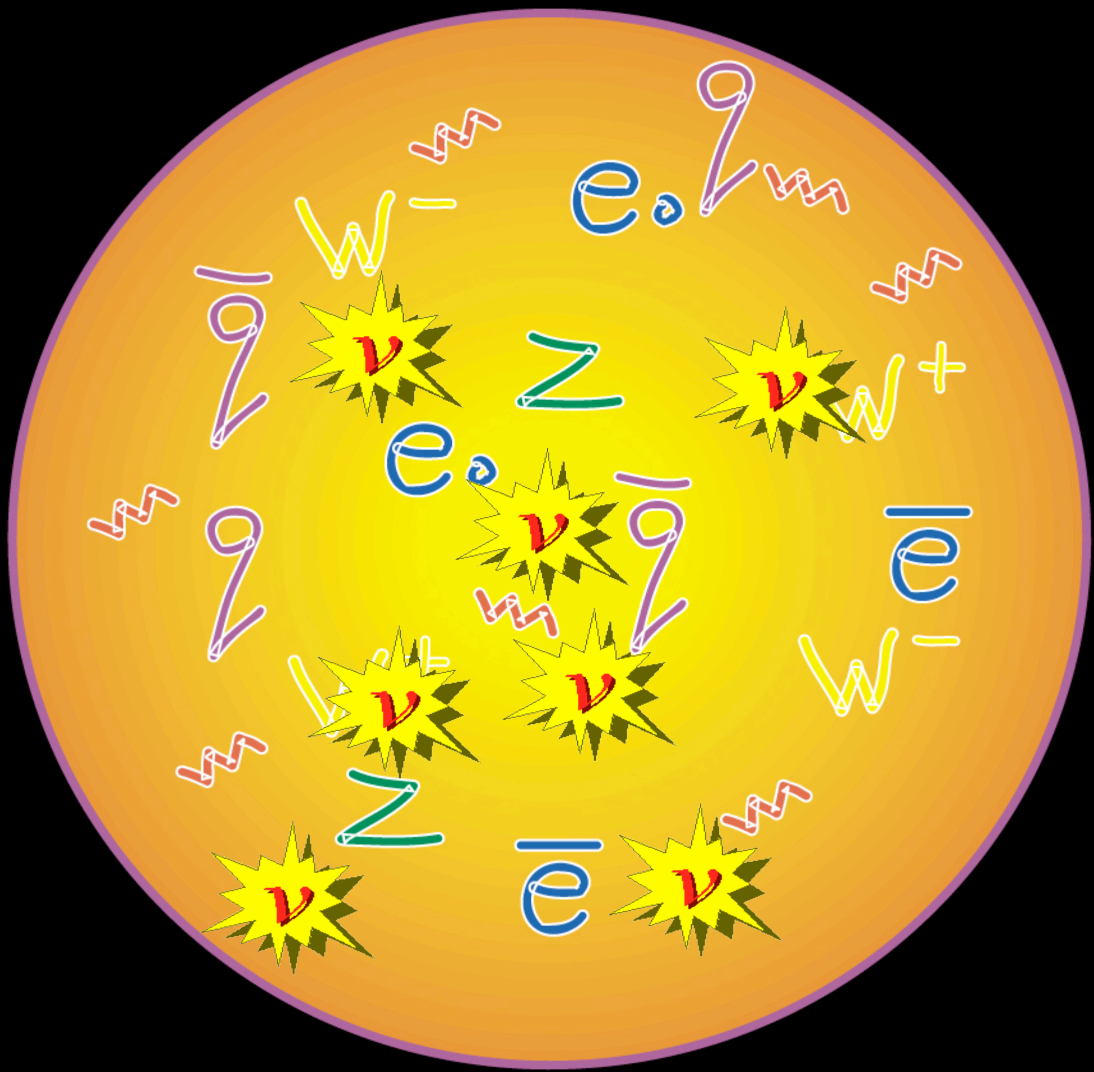
10^{-43} seconds

speculative physics:
10^{19}GeV:Strings, ...



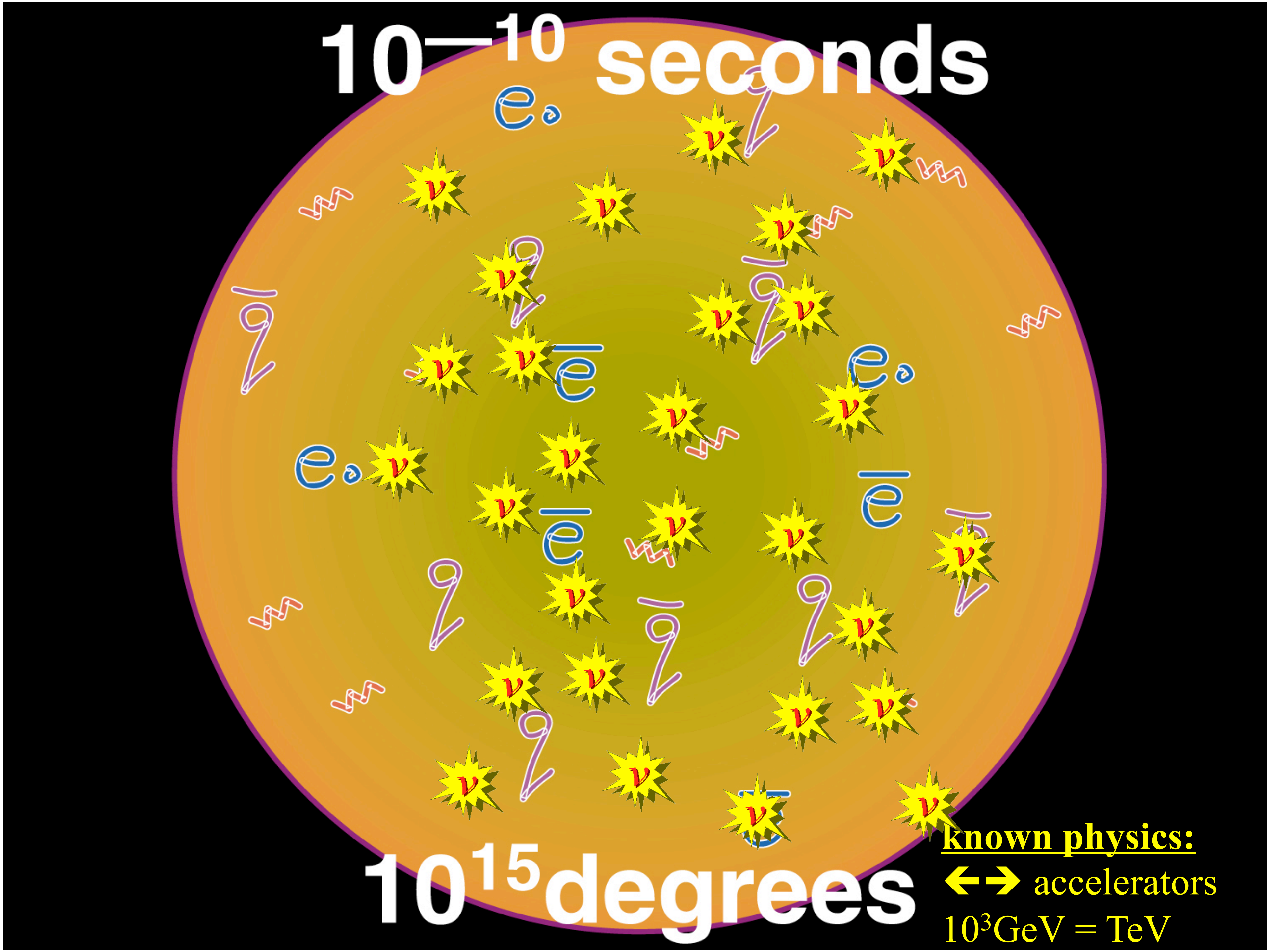
10^{32} degrees

10^{-34} seconds

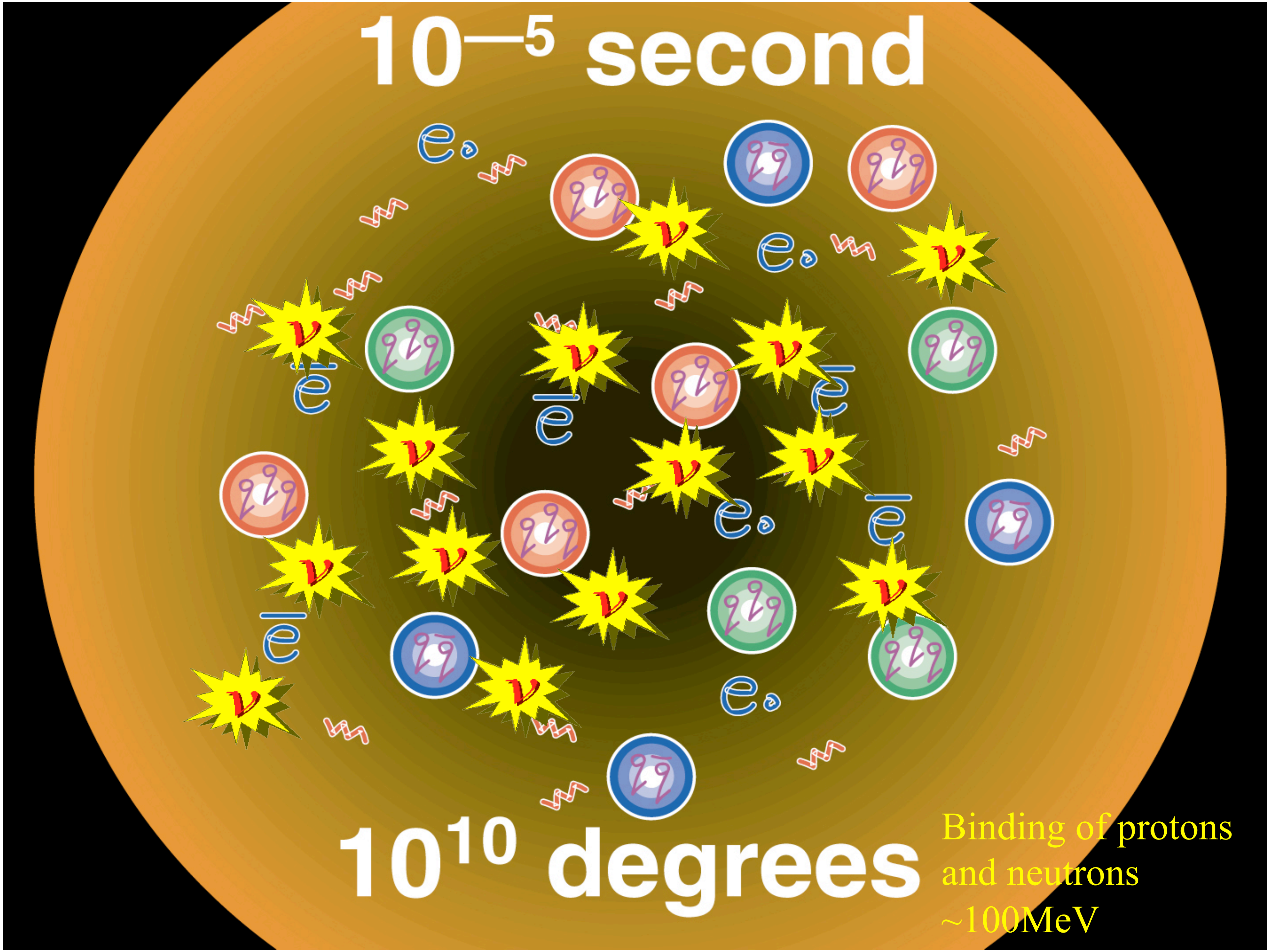


10^{27} degrees

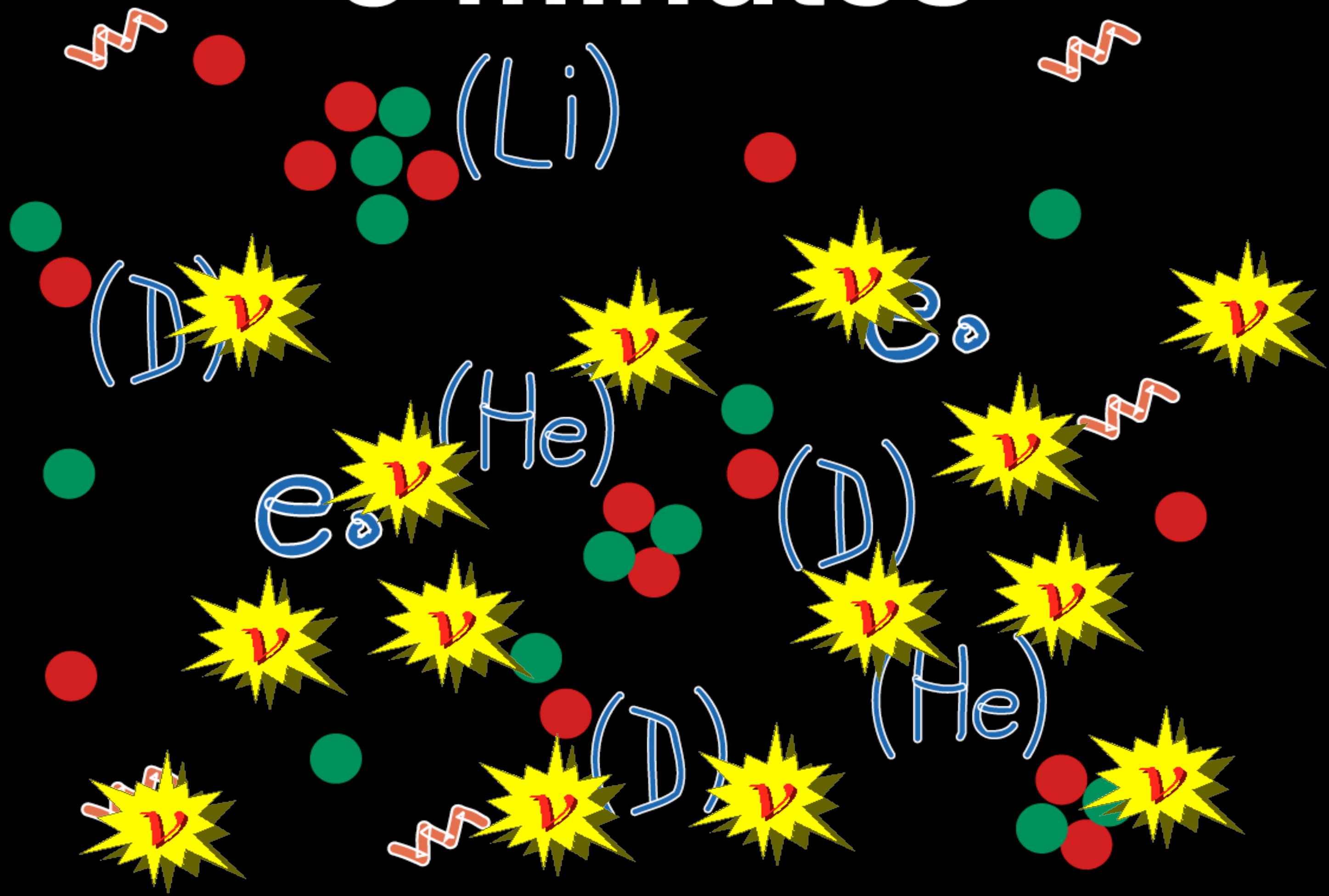
GUT physics:
10^{16}GeV



10—10 seconds
e
ν
q
1015degrees
known physics:
←→ accelerators
103GeV = TeV

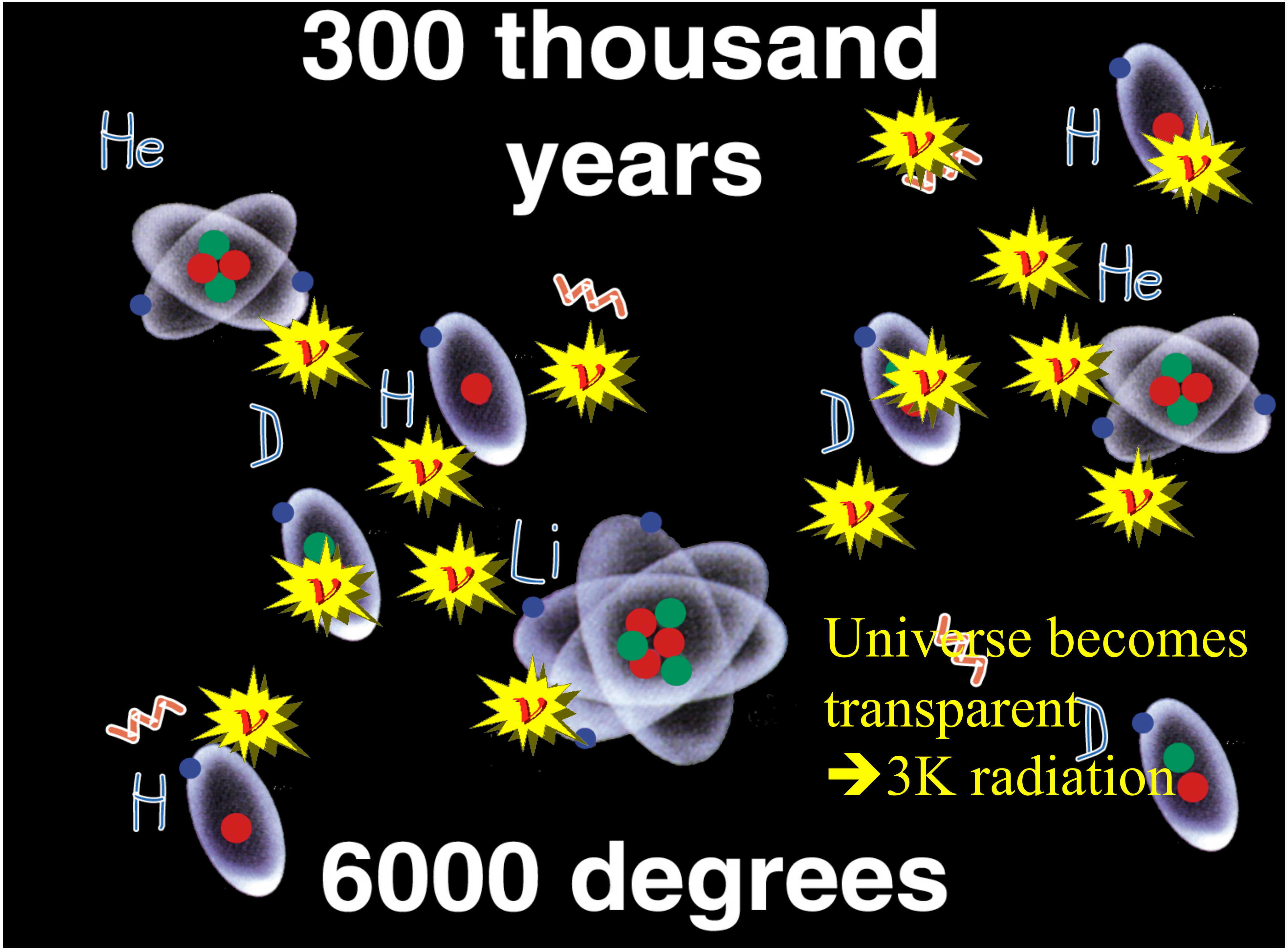

10^—5 second
10^10 degrees
Binding of protons
and neutrons
~100MeV

3 minutes

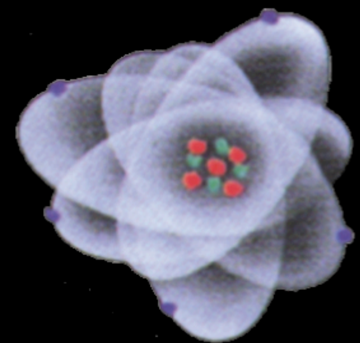


10^9 degrees

Synthesis of light elements


300 thousand years
He
H
He
D
H
D
Li
H
Universe becomes transparent
➔3K radiation
D
6000 degrees

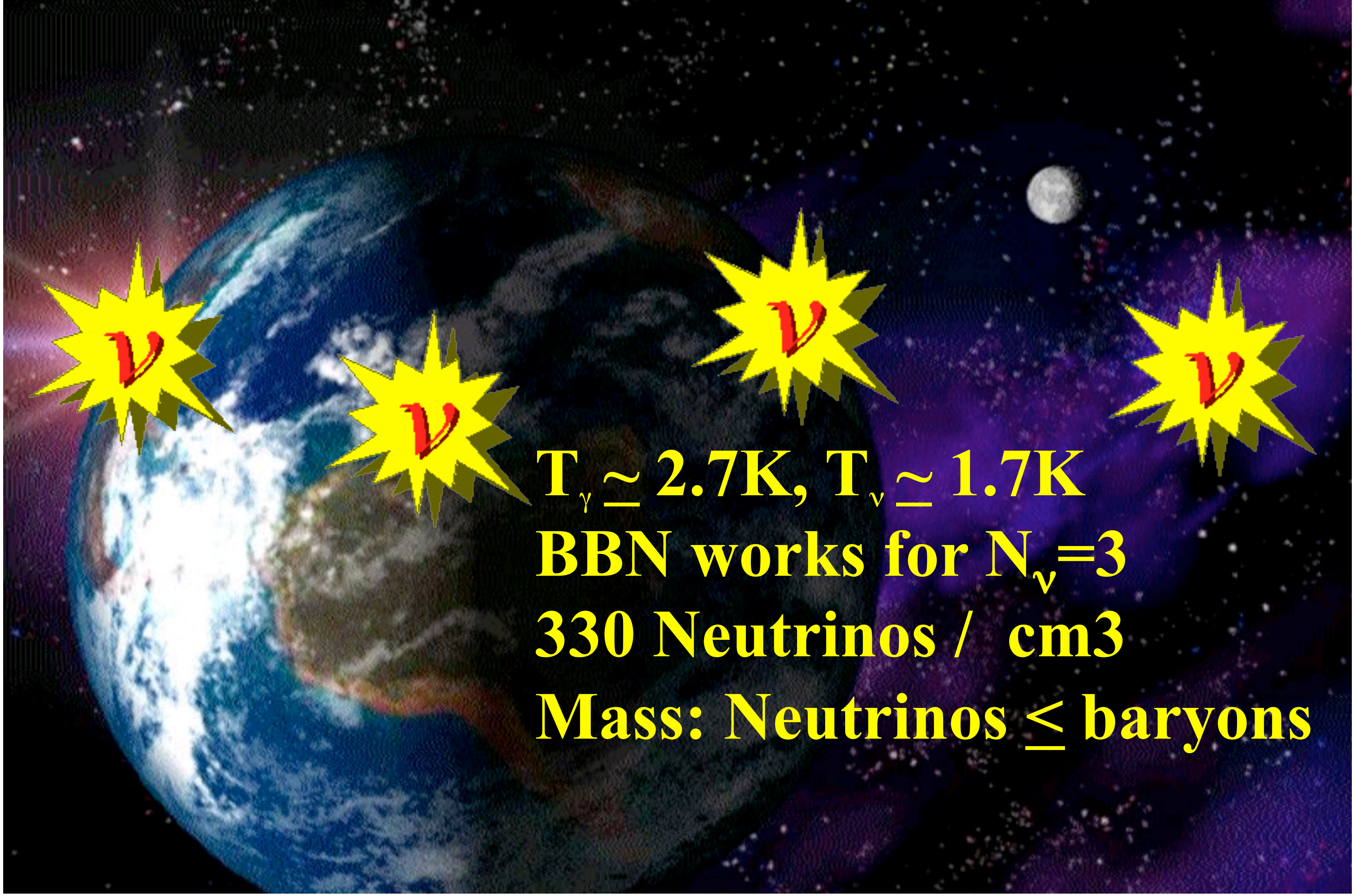
1 thousand million years



Structure formation, molecules, …

18 degrees

Today: 15 thousand million years



$T_\gamma \simeq 2.7K$, $T_\nu \simeq 1.7K$

BBN works for N_ν=3

330 Neutrinos / cm3

Mass: Neutrinos $\leq$ baryons

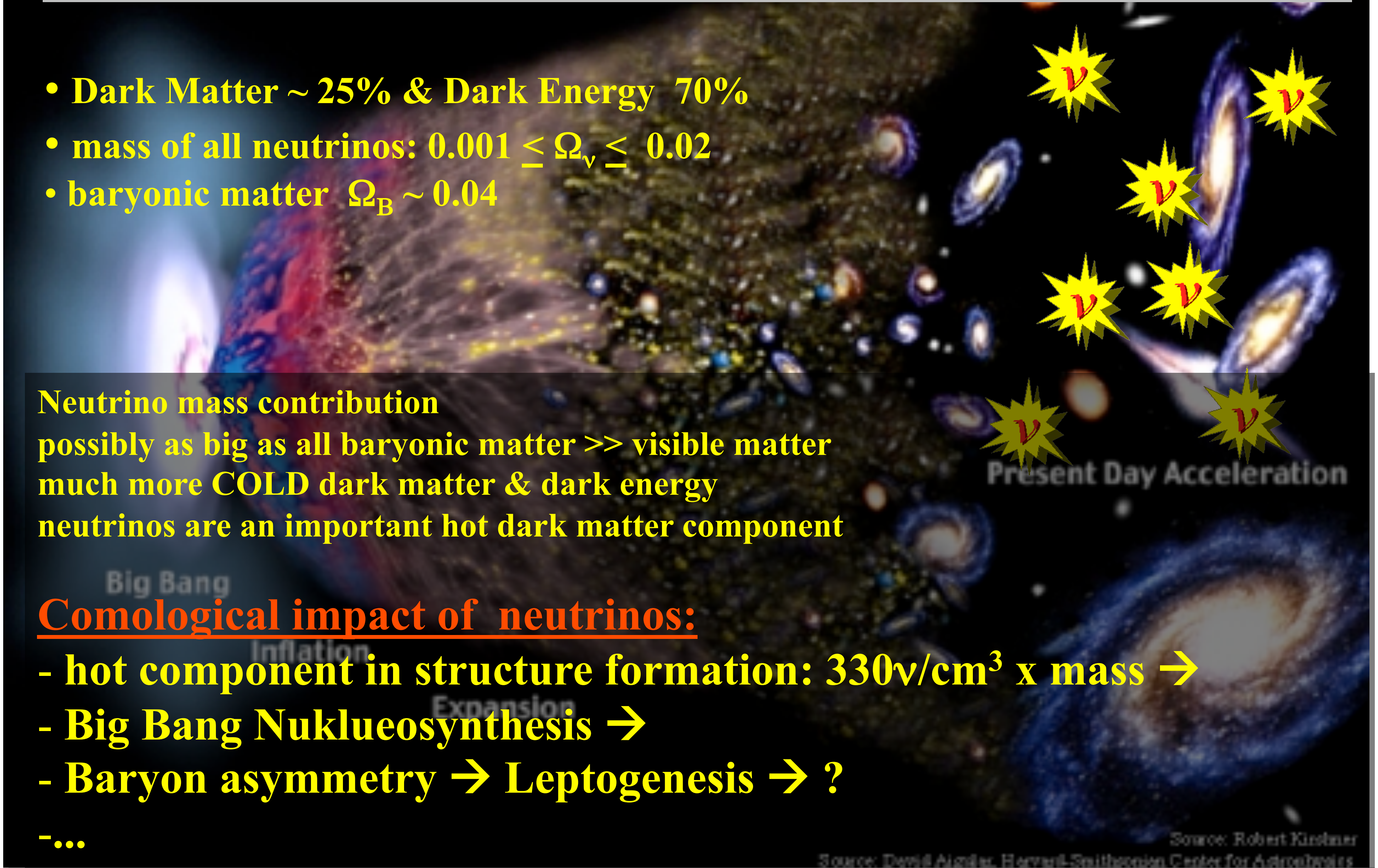
Neutrinos & Cosmology

- Dark Matter ~ 25% & Dark Energy 70%
- mass of all neutrinos: $0.001 \leq \Omega_\nu \leq 0.02$
- baryonic matter $\Omega_B \sim 0.04$

Neutrino mass contribution
possibly as big as all baryonic matter >> visible matter
much more COLD dark matter & dark energy
neutrinos are an important hot dark matter component

Comological impact of neutrinos:

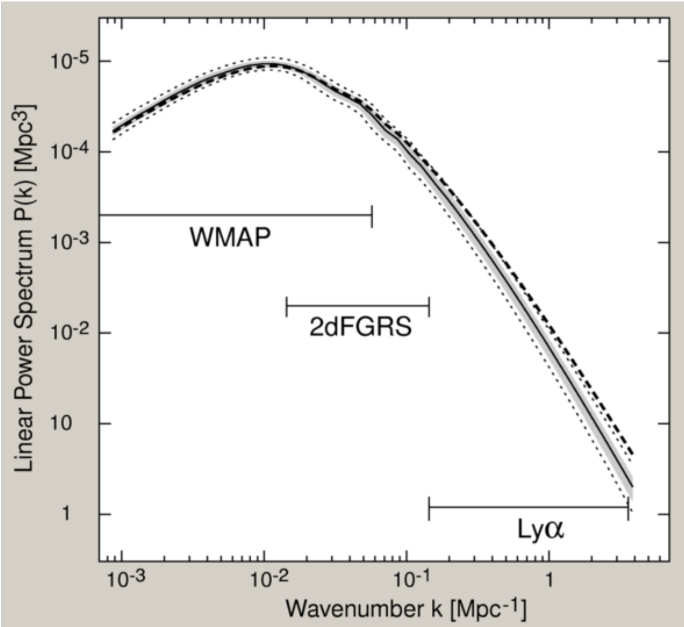
- hot component in structure formation: $330\nu/cm^3$ x mass →
- Big Bang Nuklueosynthesis →
- Baryon asymmetry → Leptogenesis → ?
-...

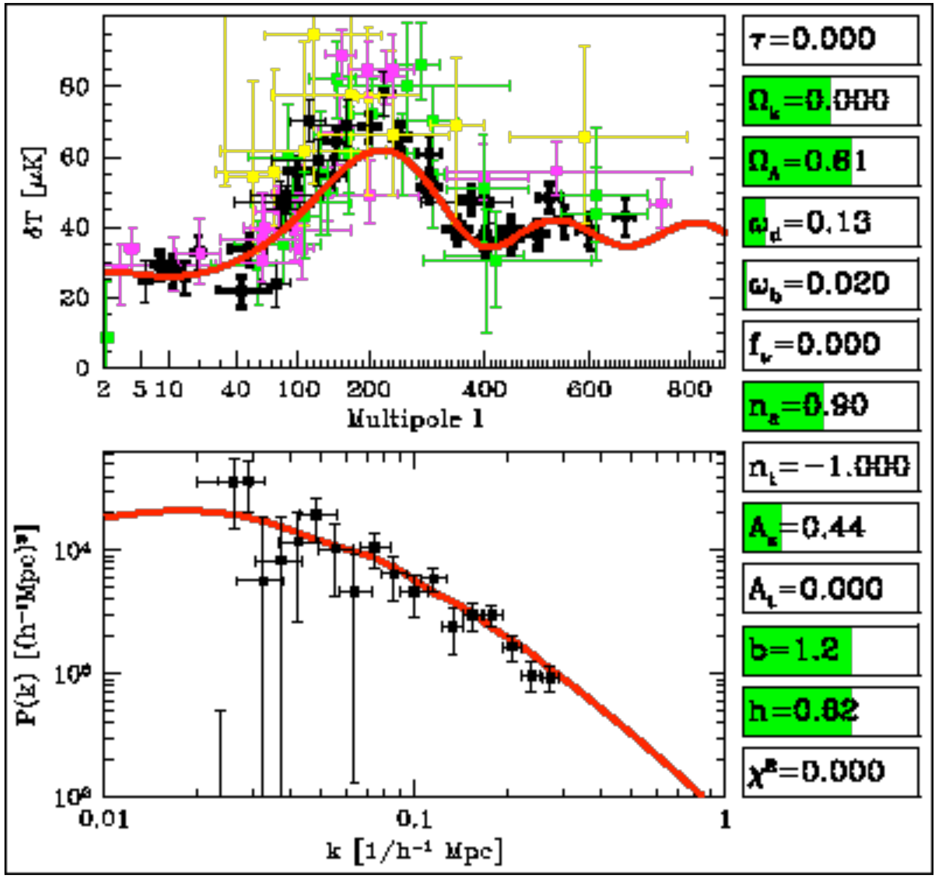


Cosmology and Neutrino Mass

- ν's hot dark matter ➔ smears structure @ small scales

Tegmark





- WMAP+2dFGRS + Lyα+...

bound: $\Sigma m_\nu < 0.17 - 1.2$ eV

⇔ levels of systematic errors

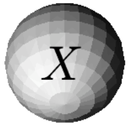
$f_\nu = \Omega_\nu / \Omega_{matter}$

- 3 degenerate neutrinos, conservative approach

➔ $m_\nu < 0.25$ eV future improvements: ~factor 5-10 ?

Baryon Asymmetry & Neutrinos

theory

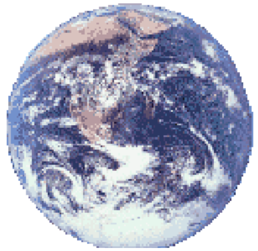


↔ symmetry

particle

anti-particle

observation



↔ baryon-asymmetry

?

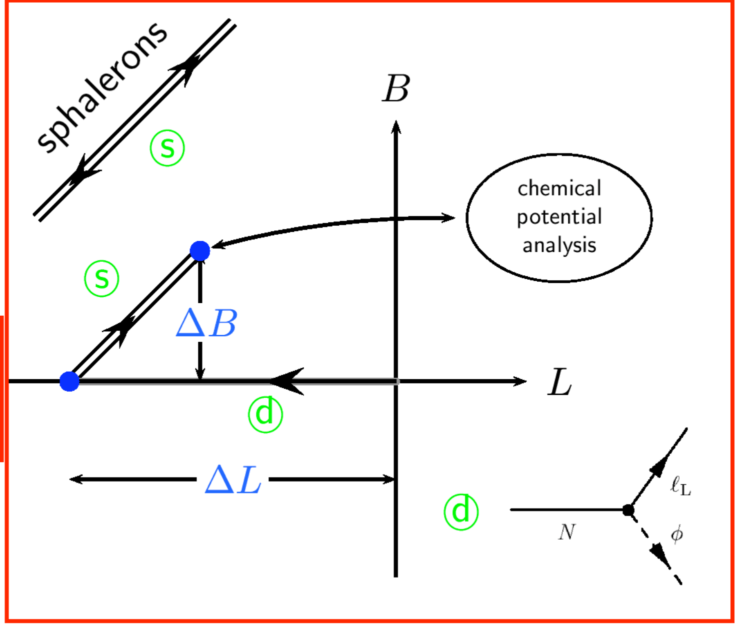
matter

anti-matter

measured baryon asymmetry: $\eta = \frac{n_B}{n_\gamma} = 4(3) \cdot 10^{-10} \ldots 7(10) \cdot 10^{-10}$

Necessary: Sakharov conditions:
- B-violating processes ↔ sphalerons
- C- and CP-violation ↔ contained in model
- departure from thermal equilibrium ↔ $\Gamma < H$

natural explanation of baryon asymmetry by **leptogenesis**



- **minimal leptogenesis works nicely**
- **different interesting variants ... a talk by itself**

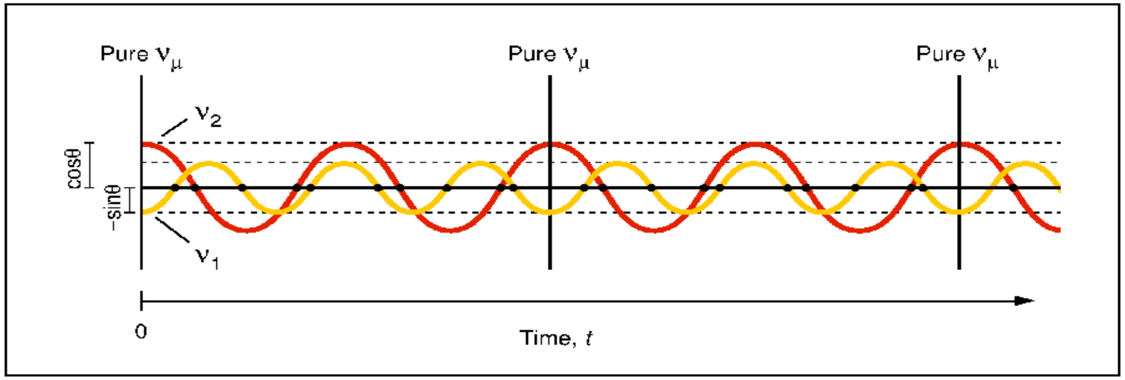
Four Methods of Mass Determination

- kinematical
- lepton number violation
  $\Leftrightarrow$ Majorana nature
- astrophysics & cosmology
- oscillations

Two Neutrino Oscillations

2 Neutrinos: ν_e,ν_μ

$$|\nu_e(0)\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_\mu(0)\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$



$$|\nu_\mu(t)\rangle = -\sin\theta\ \exp[-\frac{iE_1t}{\hbar}]\ |\nu_1\rangle + \cos\theta\ \exp[-\frac{iE_2t}{\hbar}]\ |\nu_2\rangle$$

$$E_i = \sqrt{p_i^2+m_i^2} \quad \xrightarrow{p_i=p\gg m_i} \quad \simeq p + \frac{m_i^2}{2p} \quad \simeq p + \frac{m_i^2}{2E}$$

$$L = c\cdot t \qquad \Delta m^2 = m_2^2 - m_1^2 \Rightarrow \quad E_2 - E_1 = \frac{\Delta m^2}{2E}$$

2ν-transition-probability:

$$\boxed{P(\nu_\mu \to \nu_e) = |\langle\nu_\mu(t)|\nu_e(0)\rangle|^2 = \sin^2 2\theta\cdot\sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

ν_e , ν_μ , ν_τ ➔ 9 oscillation channels for neutrinos

ν_e , ν_μ , ν_τ ➔ 9 channels for anti-neutrinos (assuming 3ν !)

Oscillations in QFT

- **is ordinary QM sufficient to describe ν−oscillations?**
- **ν's are relativistic, 2nd quantization, …**

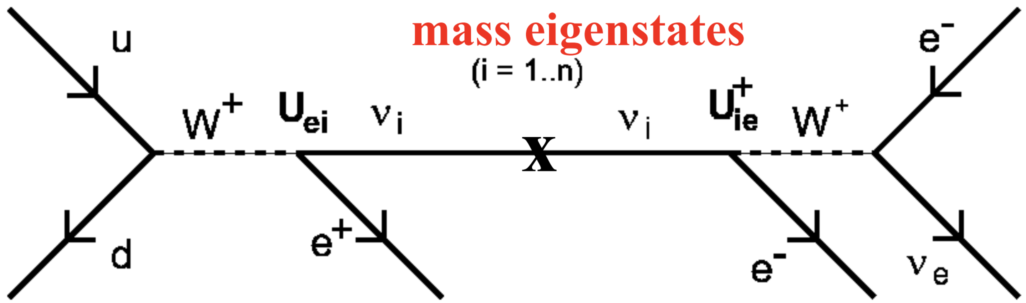
➔ Feynman diagram of neutrino oscillation:

- energy momentum properties, quantum numbers

➔ QM limit, coherence, kinematics, …

- e.g. observation of solar neutrinos in ν_e channel

Production
Propagation
Detection



$p + p \to d + \nu_e + e^+$
solar fusion process ➔ ν_e

electron scattering
➔ projection on ν_e

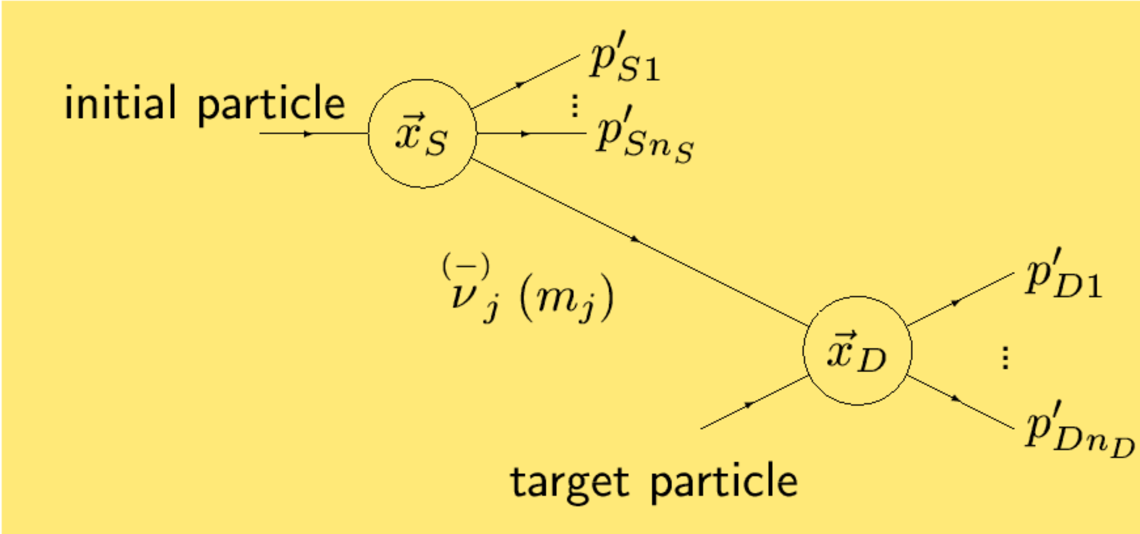
➔ $$\boxed{A_{ee} = \sum |U_{ei}|^2 e^{ip_i x} = \ldots}$$ **+MSW**

Neutrino Oscillations in QFT

QFT description of a neutrino produced in a decay at rest:

- localized source and detector
- $L = |\vec{x}_D - \vec{x}_S|$
- initial particle at rest
- target particle at rest

... DIF similar



Transition probability from Feynman diagram:

$$\boxed{\left\langle P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \right\rangle_{\mathcal{P}} \propto \int dP_S \int_{\mathcal{P}} \frac{d^3 p_{D1}}{2E_{D1}} \cdots \frac{d^3 p_{Dn_D}}{2E_{Dn_D}} \left| \mathcal{A}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \right|^2}$$

$\Rightarrow$ **leads to neutrino oscillation + avoids confusion ...**

Kinematics: Equal Energy or equal Momenta?

- Consider e.g. pion decay at rest: $\pi^+ \to \mu^+ + \nu_\mu$
- Neutrino energy and momentum determined by energy-momentum conservation

$$p_k^2 = \frac{m_\pi^2}{4}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2 - \frac{m_k^2}{2}\left(1+\frac{m_\mu^2}{m_\pi^2}\right) + \frac{m_k^4}{4\,m_\pi^2}$$

$$E_k^2 = \frac{m_\pi^2}{4}\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2 + \frac{m_k^2}{2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right) + \frac{m_k^4}{4\,m_\pi^2}$$

- **For $E \gg m$:** $\boxed{p_k \simeq E - \xi\,\frac{m_k^2}{2E}\,, \qquad E_k \simeq E + (1-\xi)\,\frac{m_k^2}{2E}}$

with $E = \frac{m_\pi}{2}\left(1-\frac{m_\mu^2}{m_\pi^2}\right) \simeq 30\,\mathrm{MeV}\,, \qquad \xi = \frac{1}{2}\left(1+\frac{m_\mu^2}{m_\pi^2}\right) \simeq 0.8$

$\Rightarrow$ **neither equal energy nor equal momentum!**

$$e^{ipx} \Rightarrow \boxed{p_\mu \cdot x^\mu = p_k L - E_k T = -\frac{m_k^2 L}{2E}} \text{ for } L = T$$

$\Rightarrow$ ξ drops out of the oscillation formulae $\Leftrightarrow$ naive treatment correct

- Shown for π-decay, but valid in general (DIF, N-body, ..., different ξ)

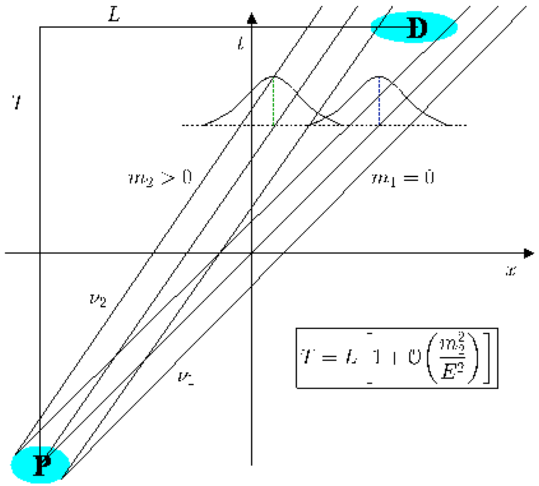
Localized Source and Detector:

- Feynman rules for particles of given momentum ($\simeq$ on-shell)
  $\Rightarrow$ this corresponds to an infinitely extended (non-localized) plane wave

- Localized source (wave packet) and detector in space-time $(\Delta x_S, \Delta t_S)$, $(\Delta x_D, \Delta t_D)$:

  $\Rightarrow$ Source: Fourier superposition of momenta with $\sigma_S^2 \simeq min(\Delta x_S^2, \Delta t_S^2)$
  $\Rightarrow$ Detector: projection on a superposition of momenta with $\sigma_D^2 \simeq min(\Delta x_D^2, \Delta t_D^2)$

- Different masses and momenta $\Rightarrow$ dispersion $\Rightarrow$ loss of coherence



- separation of wave packets: $\boxed{\Delta x_{ij} = \frac{|\Delta m_{ij}^2| L}{2E^2}}$

- coherence condition: $\Delta x_{ij} < \sigma := \sqrt{\sigma_S^2 + \sigma_D^2}$

- coherence length: $L < \frac{2E^2\sigma}{|\Delta m_{ij}^2|}$

- Oscillations from QFT $\Rightarrow$ $P_{\nu_\alpha \to \nu_\beta}(L,T) = \left|\sum_k U_{\alpha k}^* \, e^{ip_k L - iE_k T} \, U_{\beta k}\right|^2$
- Very interesting QM effects (σ, decay)

General 3x3 neutrino mixing matrix:

has (up to) 3 angles + 1 Dirac-phase +2 Majorana-phases: θ_{12}, θ_{23}, θ_{13}, δ, Φ_1, Φ_2

$$\boxed{U_{MNS} = U \cdot \mathbf{diag}\,(\exp[\mathbf{i\Phi_1}], \exp[\mathbf{i\Phi_2}], \mathbf{1})}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- Only U enters in neutrino oscillations: $\boxed{J_{ij}^{e_l e_m} := U_{li}U_{lj}^* U_{mi}^* U_{mj}}$
- All oscillation frequencies show up: $\boxed{\Delta_{ij} := \frac{\Delta m_{ij}^2 L}{4E} = \frac{(m_i^2 - m_j^2)L}{4E}}$

$$P(\nu_{e_l} \to \nu_{e_m}) = \delta_{lm} \underbrace{- 4\sum_{i>j} \mathrm{Re} J_{ij}^{e_l e_m} \sin^2 \Delta_{ij}}_{P_{CP}} \underbrace{-2 \sum_{i>j} \mathrm{Im} J_{ij}^{e_l e_m} \sin 2\Delta_{ij}}_{P_{\not{CP}}}$$

$\Rightarrow$ **Leptonic CP violation, genuine 3 flavour and matter effects**

Neutrinos: $P(\nu_{e_l} \to \nu_{e_m}) = P_{CP} + P_{\not{C}\not{P}}$
Antineutrinos: $P(\overline{\nu}_{e_l} \to \overline{\nu}_{e_m}) = P_{CP} - P_{\not{C}\not{P}}$

$\Rightarrow$ projecting out CP Asymmetries:

$$\mathbf{a}^{\mathrm{CP}} := \frac{\mathbf{P}(\nu_{\mathrm{e_l}} \to \nu_{\mathrm{e_m}}) - \mathbf{P}(\overline{\nu}_{\mathrm{e_l}} \to \overline{\nu}_{\mathrm{e_m}})}{\mathbf{P}(\nu_{\mathrm{e_l}} \to \nu_{\mathrm{e_m}}) + \mathbf{P}(\overline{\nu}_{\mathrm{e_l}} \to \overline{\nu}_{\mathrm{e_m}})} = \frac{P_{\not{C}\not{P}}}{P_{CP}}$$

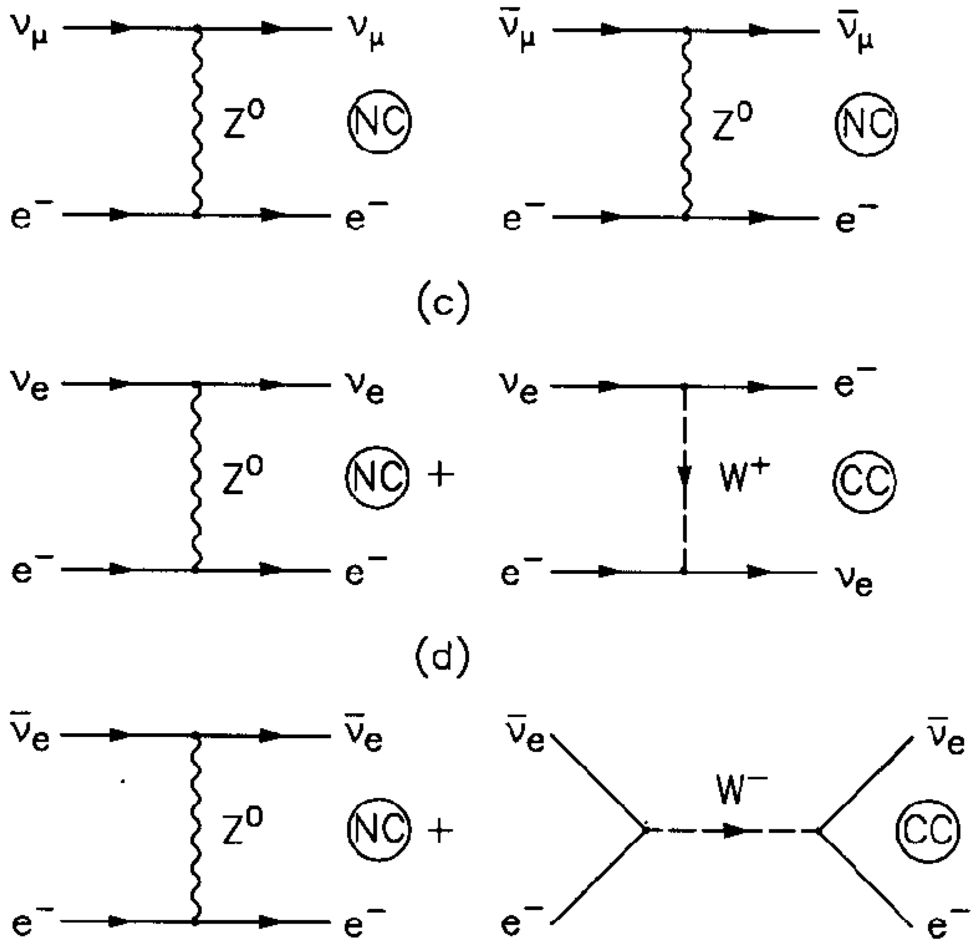
... in practise not very useful:

- different systemytics for ν and $\overline{\nu}$
- different statistics
- only one type of neutrinos

$\Rightarrow$ global fits with masses, mixings and CP parameters

Matter Effects and MSW Resonance

Mikheyev-Smirnov-Wolfenstein: coherent forward scattering



$\mathcal{L}_{NC}$ = flavour universal

$\mathcal{L}_{CC} = \sqrt{2}G_F n_e \quad \Leftrightarrow \quad$ only ν_e

MSW-resonance energy(Δm^2_{31})

Earth: $\mathbf{E_{res}} \simeq \mathbf{10}$ GeV

for beams
dominated by average density

$$\rho = \rho_{\text{average}} + \delta\rho$$

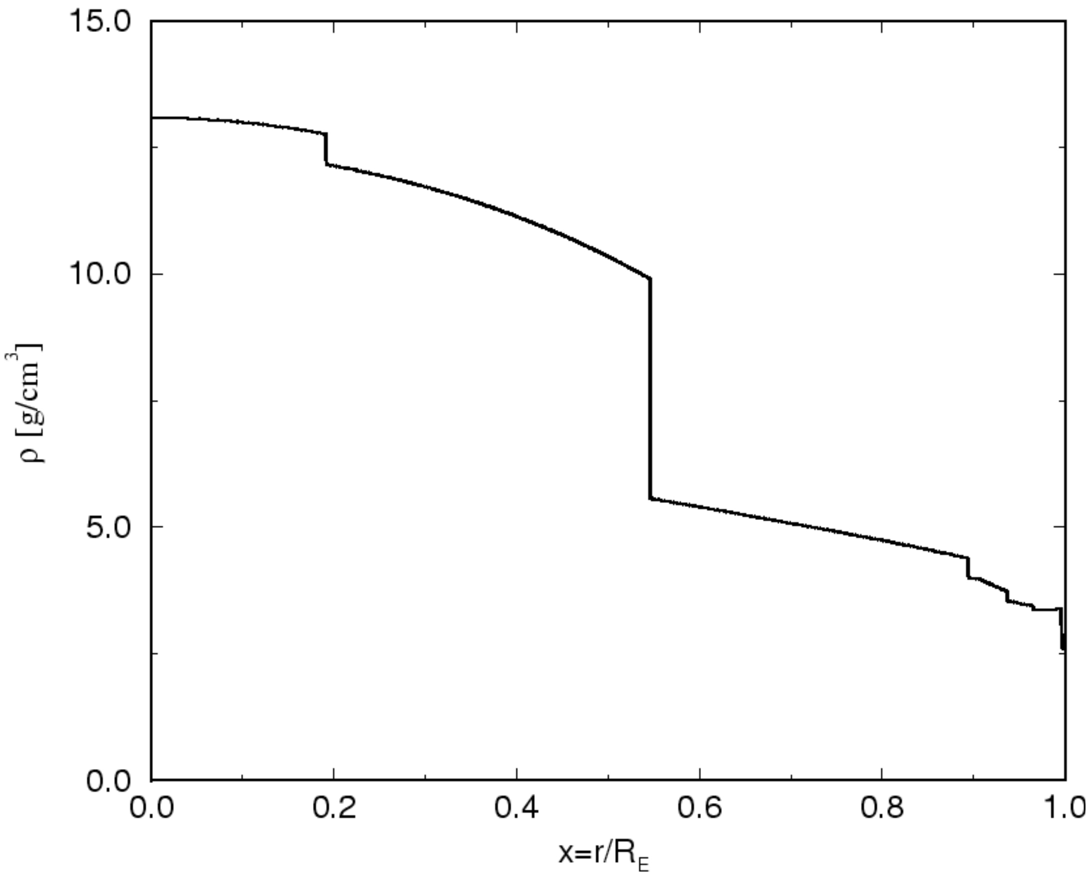
Baseline & MSW Matter Effect

Beams in Earth Matter:

$\Rightarrow$ electron density profile
as function of radius **Stacy**
density errors **Geller & Hara**

Large $L \Rightarrow$ steep angles

$L =$ 2800 km $\Leftrightarrow$ 13^o
$L =$ 7300 km $\Leftrightarrow$ 35^o
$L =$ 12750 km $\Leftrightarrow$ 90^o
$L \leq \mathcal{O}(10\,000\ \mathrm{km})$ $\Leftrightarrow$ **mantle**



- $E_{resonance} \simeq 10 - 15$ GeV, matter effects grow with distance L
- Average density profile uncertainties decrease with L $\Rightarrow$ $\simeq 5\%$ error

Hamiltonian for 3 Neutrino Oscillations in Flavour Basis:

$$\mathbf{H} = H_0 + \delta\mathbf{H}_{CC} + \delta\mathbf{H}_{NC} = \frac{1}{2E}\mathbf{U}\begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}\mathbf{U^T} + \frac{1}{2E}\begin{pmatrix} \mathbf{A}+\mathbf{A'} & 0 & 0 \\ 0 & \mathbf{A'} & 0 \\ 0 & 0 & \mathbf{A'} \end{pmatrix}$$

- $\mathbf{A} = \pm\frac{\mathbf{2\sqrt{2}G_F Y \rho E}}{\mathbf{m_n}} = 2V \cdot E$ $\nu \oplus \mathrm{matter}$ and $\overline{\nu} \oplus \mathrm{anti-matter} \Rightarrow$ "+"
- $Y = e^-$/**nucleon** ρ =**matter density** m_n =**nucleon mass**
- Overall phases drop out: $m_i \to m_i - m_1 \Rightarrow$ m_1 and A' can be eliminated

$$\mathbf{H'} = \frac{1}{2E}\mathbf{U}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}\mathbf{U^T} + \frac{1}{2E}\begin{pmatrix} \mathbf{A} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- In good approximation $\Delta m^2_{12} \simeq 0$
- $\mathbf{U}$ can be written as a sequence of rotations: $\mathbf{U} = R_{23} R_{13} R_{12}$

$$\mathbf{H}'' = \frac{1}{2E}\mathbf{R_{23}}\mathbf{R_{13}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \mathbf{R_{13}^{-1}}\mathbf{R_{23}^{-1}} + \frac{1}{2E}\mathbf{R_{23}} \begin{pmatrix} \mathbf{A} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \mathbf{R_{23}^{-1}}$$

$$= \frac{1}{2E}\mathbf{R_{23}} \left[\mathbf{R_{13}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} \mathbf{R_{13}^{-1}} + \begin{pmatrix} \mathbf{A} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \mathbf{R_{23}^{-1}}$$

$$= \frac{1}{2E}\mathbf{R_{23}} \left[\begin{pmatrix} \bullet & 0 & \bullet \\ 0 & 0 & 0 \\ \bullet & 0 & \bullet \end{pmatrix} + \begin{pmatrix} \mathbf{A} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right] \mathbf{R_{23}^{-1}}$$

$$= \frac{1}{2E}\mathbf{R_{23}} \left[\mathbf{R}'_{\mathbf{13}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Delta (m^2_{31})' \end{pmatrix} (\mathbf{R}'_{\mathbf{13}})^{-1} \right] \mathbf{R_{23}^{-1}}$$

$\Rightarrow$ re-insert R_{12} $\Rightarrow$ U' $\Rightarrow$ parameter mapping in 1-3 subspace

- **Different** mappings for **neutrinos** and **antineutrinos**
- 1-3 sub-space mapping like in 2 neutrino case
- Relevant quantitiy $\boxed{C_\pm^2 = \left(\frac{A}{\Delta m_{31}^2} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}$
- MSW resonance condition for $\theta_{13} \simeq 0$: $\quad \Delta m_{31}^2 = A = 2VE = \pm \frac{2\sqrt{2} G_F Y \rho E}{m_n}$
- Effective parameters in matter:

$$
\begin{aligned}
\sin^2 2\theta_{13}' &= \frac{\sin^2 2\theta_{13}}{C_\pm^2} \\
\Delta m_{31,m}^2 &= \Delta m^2 C_\pm \\
\Delta m_{32,m}^2 &= \frac{\Delta m^2 \; (C_\pm + 1) + A}{2} \\
\Delta m_{21,m}^2 &= \frac{\Delta m^2 \; (C_\pm - 1) - A}{2}
\end{aligned}
$$

- Corrections due to
  - $\Delta m_{12}^2 \neq 0$
  - non-constant matter profiles $\Rightarrow$ solve Schrödinger equation

Analytic Approximations

$\Delta = \Delta m^2_{31}\ L/4E$
$\alpha = \Delta m^2_{21} / \Delta m^2_{31} \sim 1/30$
A = matter potential

P($\nu_e \to \nu_\mu$) =

$$\approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2}$$

$$\pm \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

➔ analytic discussion / full simulations
➔ degeneracies, correlations ➔ $(\sin^2 2\theta_{13})_{eff}$

Cervera et al.
Freund, Huber, ML
Akhmedov, Johansson , ML, Ohlsson, Schwetz

Degeneracies, Correlations, ...

Fixed L/E ➔ probabilities invarinat under transformations:

- $\theta_{23} \rightarrow \pi/2 - \theta_{23}$ **Fogli, Lisi**
$P(\nu_e \rightarrow \nu_\mu)$ not really invariant ➔ compensation by small parameter off-sets

- $\Delta m^2 \rightarrow -\Delta m^2$ **compensated by offset in δ** **Minakata, Nunokawa**

- $P(\nu_e \rightarrow \nu_\mu)$**=const. ➔** $\delta - \theta_{13}$ **manifolds** **Koike, Ota, Sato & Burguet-Castell et al.**

- **➔ 8-fold degeneracy** **Barger, Marfatia, Whisnant**

- **parameter extraction suffers from correlations & degeneracies**
- **how to break degeneracies & correlations?**

The magic Baseline

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \quad \approx \quad & \sin^2 2\theta_{13} \sin^2 \theta_{23} \, \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm \quad & \sin \delta_{\rm CP} \ \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+ \quad & \cos \delta_{\rm CP} \alpha \sin 2\theta_{12} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+ \quad & \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

- All terms besides the first vanish for $\sin(\hat{A}\Delta) = 0$
- Condition for uncorrelated sensitivity to θ_{13} $\boxed{\hat{A}\Delta = \pi}$

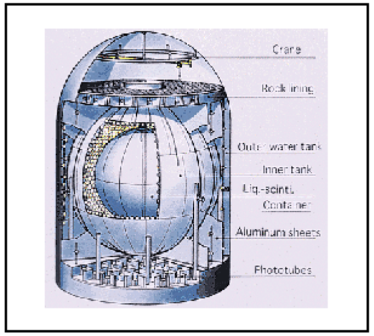
$\Rightarrow$ inserting $\hat{A} = A/\Delta m^2_{31}$, $A = 2VE$, $\Delta = \Delta m^2_{31} L/4E$ one finds

$$L_{magic} = \frac{2\pi}{\sqrt{2} G_F n_e} = 7630 \text{ km} \cdot \frac{\rho}{4.3 g/cm^3}$$

Huber, Winter

- Note that this is not the MSW resonance condition

Status of Neutrino Oscillations

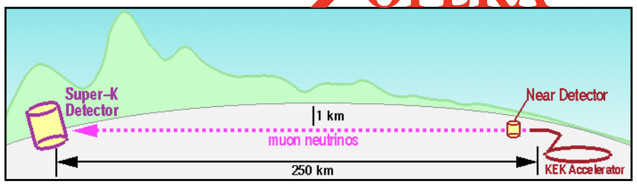


Reactors: KAMLAND

improved result

Beams: K2K ➔ MINOS

➔ OPERA



$\Delta m^2_{21} = (7.9 \pm 0.3) * 10^{-5}\ \mathrm{eV}^2$

$\tan^2\theta_{12} = 0.39 \pm 0.05$

$\Delta m^2_{31} = (2.4 \pm 0.3) * 10^{-3}\ \mathrm{eV}^2$

$\tan^2\theta_{23} = 1.0 \pm 0.3$

$\sin^2 2\theta_{13} < 0.16$ Chooz

solar: GALLEX/GNO ➔ SK, SNO

atmospheric: Superkamiokande

LSND? ➔ MiniBooNE

- LSND not confirmed !
  - ➔ 3+2 scenarios?
  - ➔ new anomaly
- upturn at low E ?