Neutrino Properties & Phenomenological Consequences

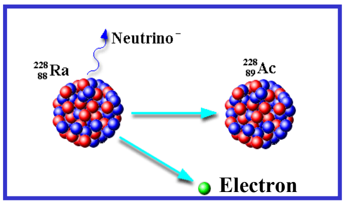
M. Lindner
MPI fuer Kernphysik
Heidelberg

Schule für Astroteilchenphysik 2006
Universität Erlangen-Nürnberg
October 4-12, 2006
Obertrubach-Bärnfels, Germany

The Birth of the Neutrino

W. Pauli

energy-momentum conservation:
→ postulate new particle
→ invisible, since Q=0
→ spin ½, ...



Letter to Tübingen

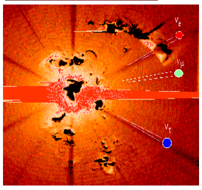
4th December 1930

Dear Radioactive Ladies and Gentlemen,

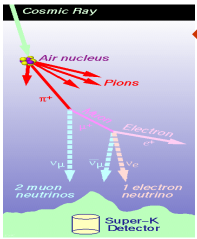
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

New Physics: Neutrino Sources

←Sun



←Cosmology



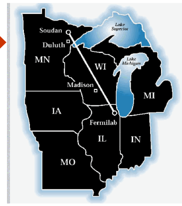
←Atmosphere

←Earth

Astronomy: →
Supernovae
GRBs
UHE ν's

Reactors→

Accelerators→



M. Lindner 3

The Standard Model

➔ **success of renormalizable gauge field theories**

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

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

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

$\mathcal{L}_{gauge} = -\frac{1}{2} Tr\,[G_{\mu\nu}G^{\mu\nu}] - \frac{1}{2} Tr\,[W_{\mu\nu}W^{\mu\nu}] - \frac{1}{4} B_{\mu\nu}B^{\mu\nu}$ (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 ⇔ SSB)

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

M. Lindner 4

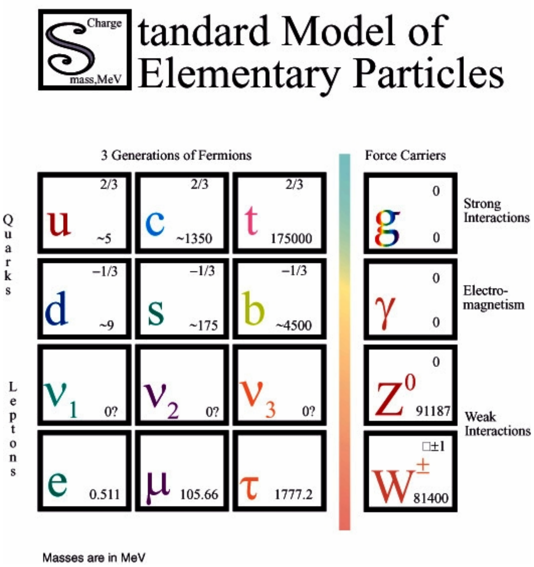
Chiral Fermion Fields in the SM

- Left-handed quarks and leptons: $L = (3_c$ or 1_c, 2_L, $Y = ...$, $Q = T_{3L} + Y/2)$
- Right-handed quarks and leptons: $r = (3_c$ or 1_c, 1_L, $Y = ...$, $Q = Y/2$

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

- SM does **not contain** right-handed neutrinos $r_\nu \equiv \nu_R$
- Right-handed neutrinos make the table more symmetric!
- Fermions: Most diverse and the least constrains
- Allowed are extra anomaly free combinations like extra generations, ν_R,....

M. Lindner 5



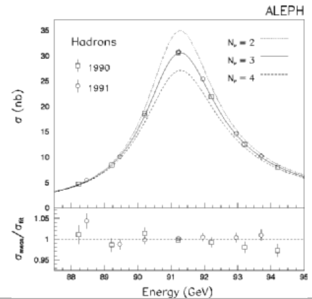
+Higgs particle $m_H \geq 115$ GeV

particles & parameters

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

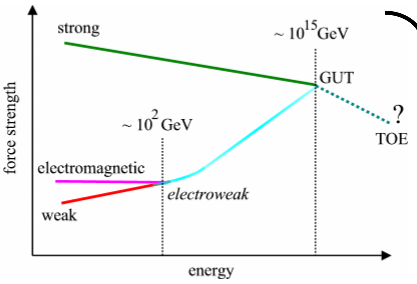
SM: 3 left-handed neutrinos

↔ Z line shape @ LEP



M. Lindner 6

Indications Beyond the SM



gauge bosons ➡

Higgs ➡ gauge hierarchy problem
$\delta m_H^2 \sim \Lambda^2$

quarks leptons ➡ 3 generations, fermion rep.
many parameters (m_i ,mixings)
unification into GUTs

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

experimental facts:
Dark Matter
Dark Energy
baryon asymmetry: $m_\nu > 0$
neutrino masses & mixings
➔ precision

SUSY ~TeV

astrophysics & cosmology

$\sim\Lambda_{GUT}$ +seesaw

M. Lindner 7

Physics Beyond the Standard Model

Dark Matter
Dark Energy
Baryon asymmetry
Neutrino masses & mixings

} new physics beyond Standard Model

- SM of particle physics works very well, but $m_\nu = 0$
- B and L (L_e, L_μ, L_τ) conservation
- indications for new physics connected to electro-weak symmetry breaking
  ⟷ SUSY, DSB, LR, extra dimensions, …
- the flavour problem

M. Lindner 8

Majorana Mass Terms

- **Charge conjugation for χ-ral fields Ψ=L+R** $R' = L^c \,;\quad L' = R^c$
- **Fermion mass terms ≃ m($\overline{L}$R+ $\overline{R}$L)**
- **ν mass terms ➔ Dirac *and* Majorana**

$$\left(\overline{\nu}_L, \quad \overline{\nu_R}^{\,c} \right) \begin{pmatrix} M_L & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

M. Lindner 9

Dirac & Majorana Neutrino Mass Terms

neutrino mass terms (Dirac & Majorana) $\left(\overline{\nu}_L, \quad \overline{\nu_R}^{\,c} \right) \begin{pmatrix} M_L & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$

- SM: $m_D=0$, $M_L=0$, $M_R=0$ ⇔ $m_\nu=0$
- BSM: all terms present ➔ general 6x6 mass matrix

- **„seesaw“ e.g.: $m_D \simeq$ leptons , $M_L= 0$, $M_R= 10^{16}$GeV**
  - diagonalization ➔ physical neutrinos:
    - 3 light (active) $\simeq m_D^2 / M_R$ AND 3 heavy (sterile) $\simeq M_R$
- **➔ lever arm for GUT-scale physics!**

Warning: This contains some assumptions:
- 3 ν_R ➔ N could be different from 3 ⇔ flavour representation
- Rank(M_R=3) ⇔ otherwise more light ν´s ⇔ sterile ν´s
- ordinary QFT
- type I seesaw, ...

M. Lindner 10

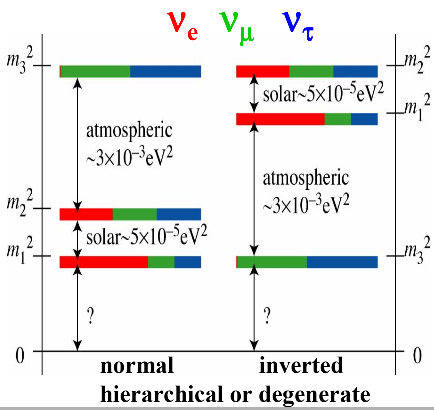
Parameters for 3 Light Neutrinos

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 or Majorana
➔ absolute mass scale: m_1
➔ mass ordering: sgn(Δm^2_{31})
➔ how small is θ_{13}, θ_{23} maximal?
➔ leptonic CP violation
➔ LSND ←→ sterile neutrino(s)
➔ L/E pattern of oscillations



M. Lindner 11

Four Methods of Mass Determination

- kinematical
- lepton number violation ←→ Majorana nature
- astrophysics & cosmology
- oscillations

Note: Here ~ theoretical perspective
➔ more (experimental) details: L. Baudis, G. Drexlin

M. Lindner 12

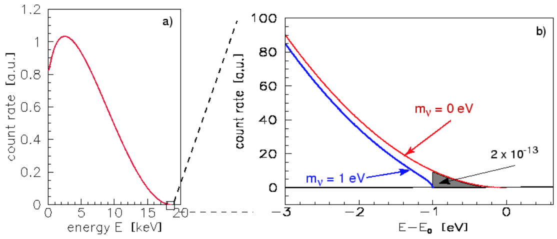
Kinematical Mass Determination

Relativistic kinematics:

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

Endpoint of decays:

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



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

Future: **KATRIN ➔ 0.25 eV** ➔ ? ⟷ **c.f. comological bounds**

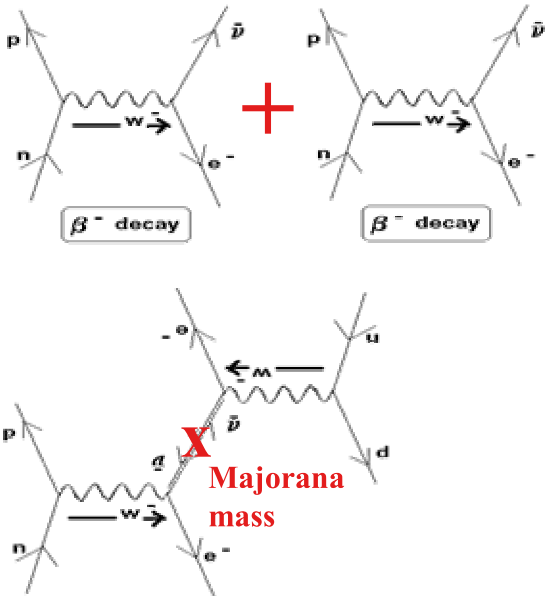
M. Lindner 13

Four Methods of Mass Determination

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

M. Lindner 14

Double Beta Decay

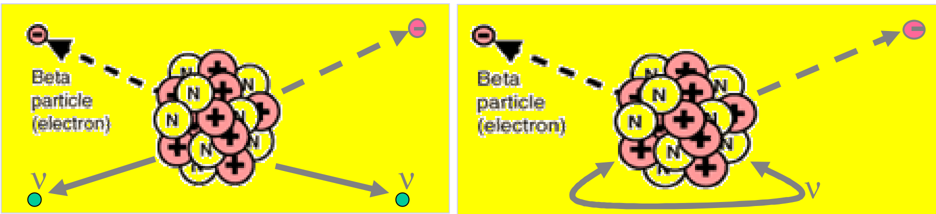


➔ 2 neutrinos plus 2 electrons

➔ no neutrinos just 2 electrons

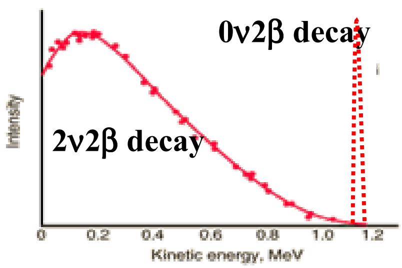
M. Lindner 15

Lepton Number Violation & 0ν2β Decay



2ν2β decay ^{76}Ge: τ=1.5 × 10^{21} y

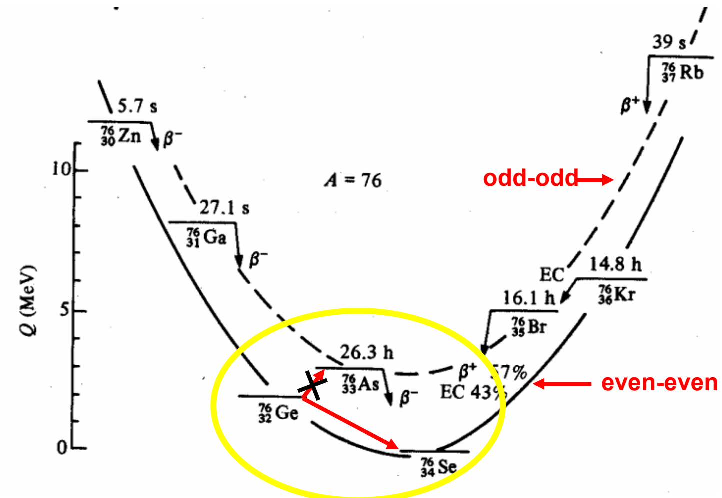
Majorana ν ➔ 0ν2β decay



0ν2β
⇕
Majorana neutrinos
⇕
lepton number violation

M. Lindner 16

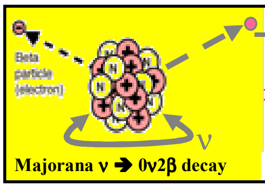
Double Beta Decay: Mass Parabolas

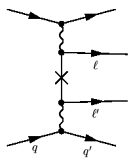


Ground states of even-even nuclei: 0^+
- **single beta decay of Ge76 kinematically forbidden**
- **double beta decay allowed**

M. Lindner **17**

Neutrino-less Double β-Decay



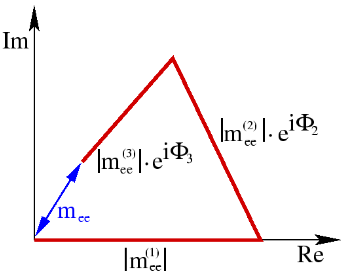


$\propto |\langle m_{ee} \rangle| = |\sum m_i U_{ei}^2|$ **$\leq$ 0.35 eV ?**

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 $\Rightarrow$ $|U_{e3}|^2 < 0.05$

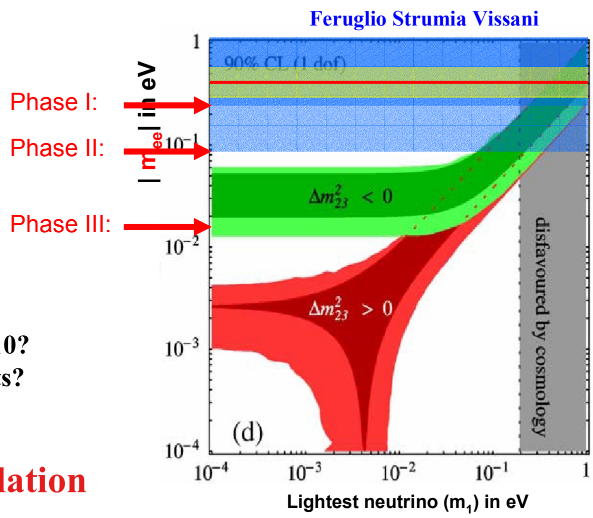
➔ **free parameters: m_1, sign(Δm^2_{31}), CP-phases Φ_2, Φ_3**

M. Lindner **18**

$m_1 \rightarrow$ small $\rightarrow$ m_{ee} =const. ~ $(\Delta m_{ij}^2)^{1/2}$ $\leftrightarrow$ sign(Δm^2_{31})
m_1 large $\rightarrow$ $m_{ee} \sim m_1$

cosmological bound on m_1
HM-claim $\rightarrow$ ‚tension'

new experiments:
CUORICINO, GERDA $\rightarrow$
CUORE, Majorana, …
aim: $(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV



Cosmology: syst. errors $\rightarrow$ X10?
$0\nu2\beta$ – nuclear matrix elements?
theory: LR, RPV-SUSY, ...

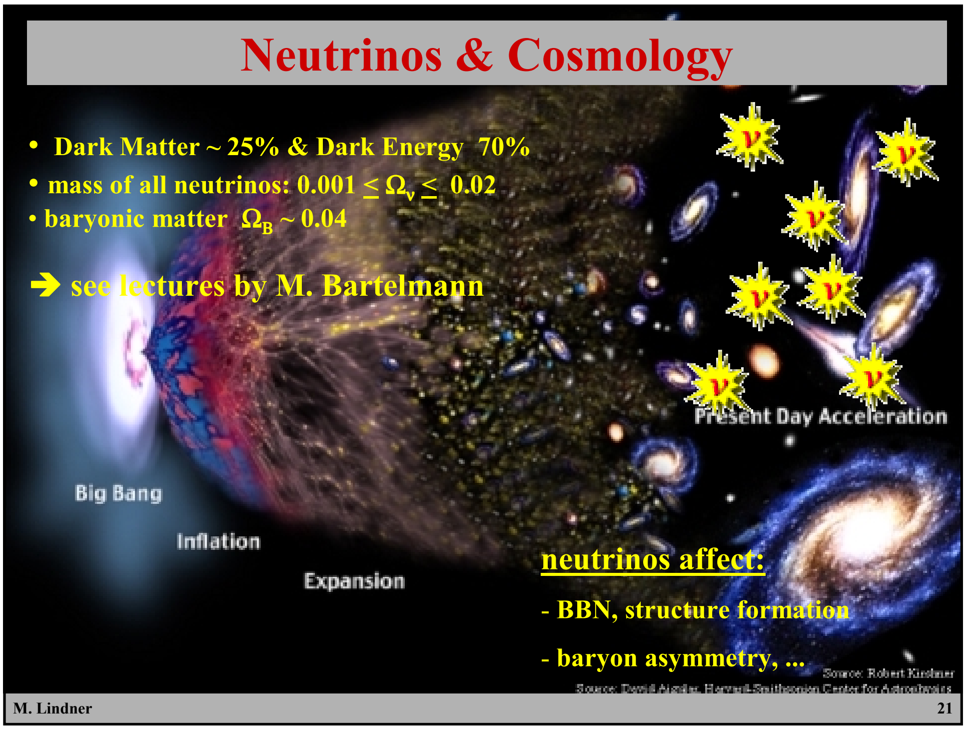
$\rightarrow$ lepton number violation

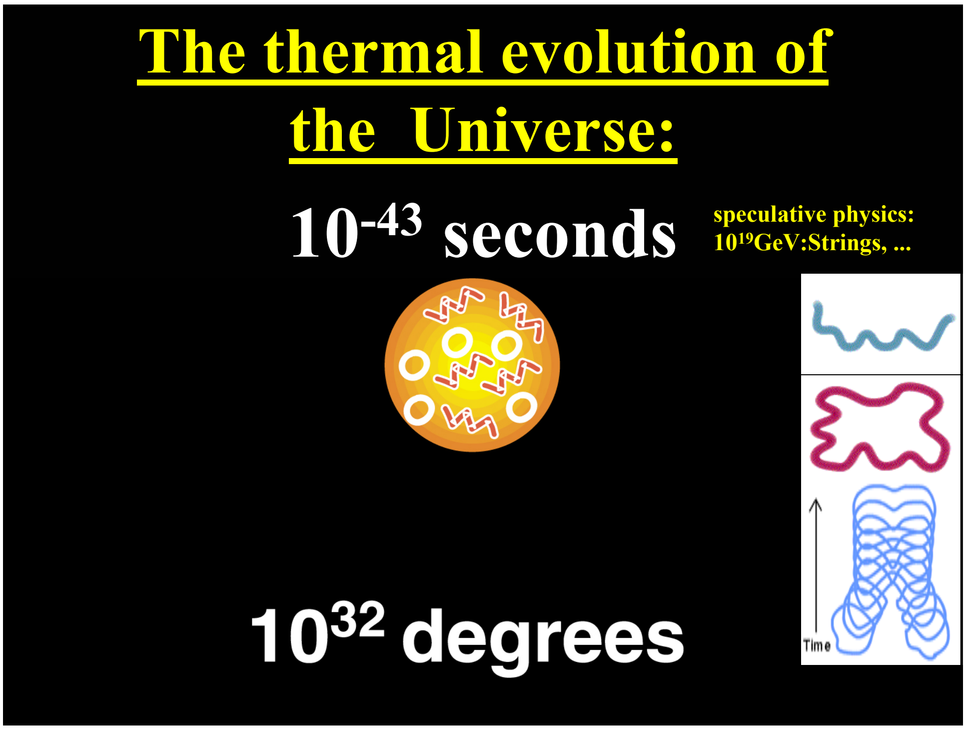
M. Lindner 19

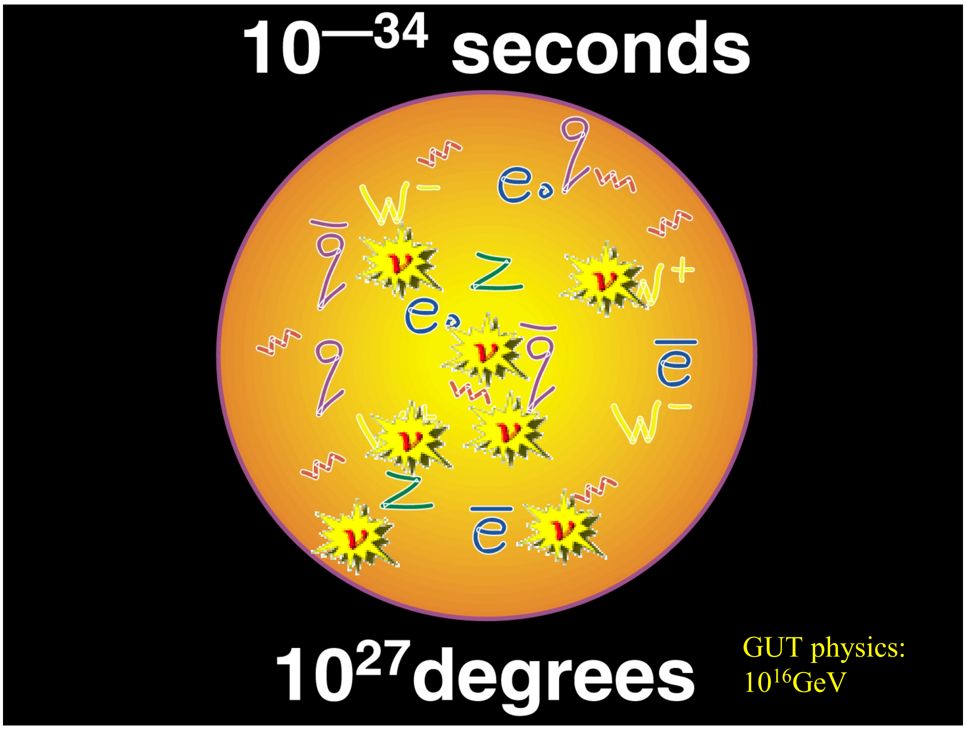
Four Methods of Mass Determination

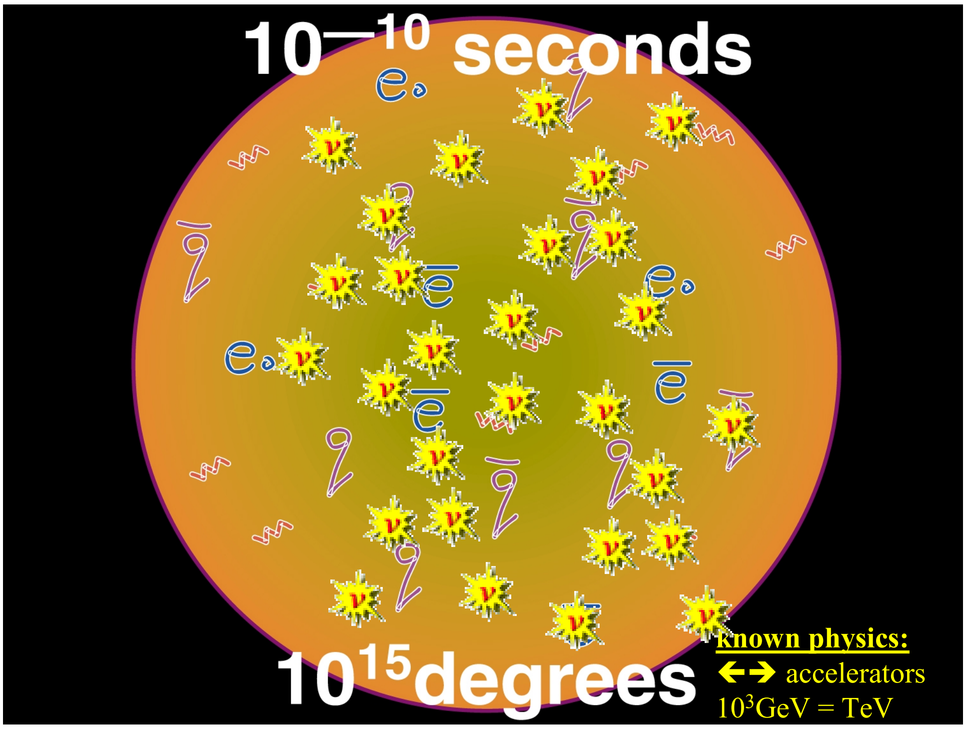
- kinematical
- lepton number violation
  $\leftrightarrow$ Majorana nature
- astrophysics & cosmology
- oscillations

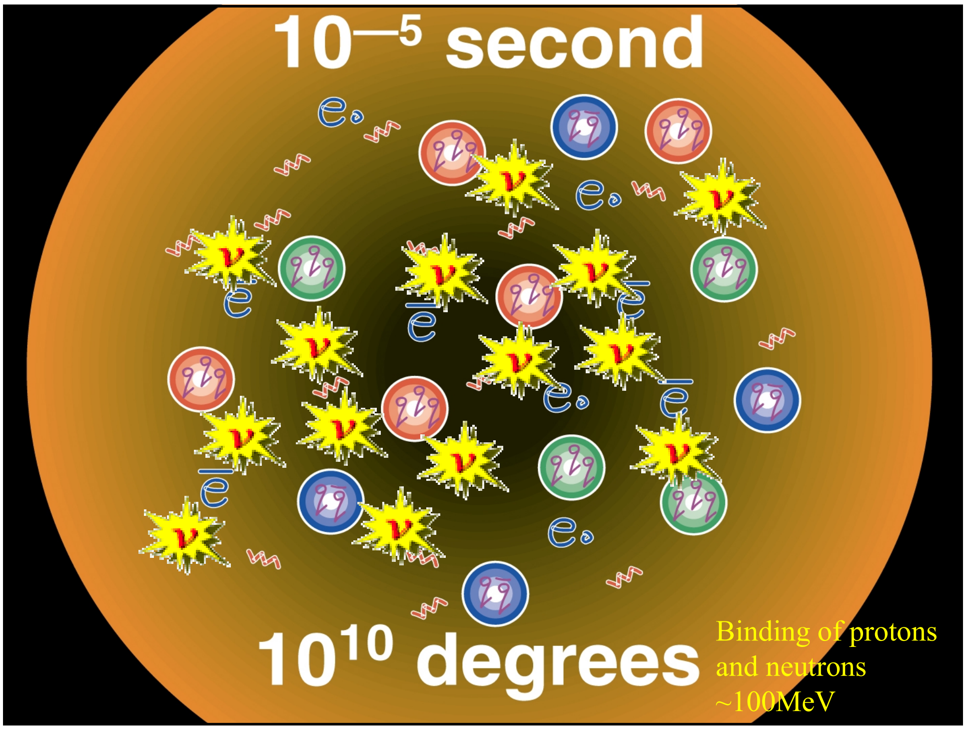
M. Lindner 20

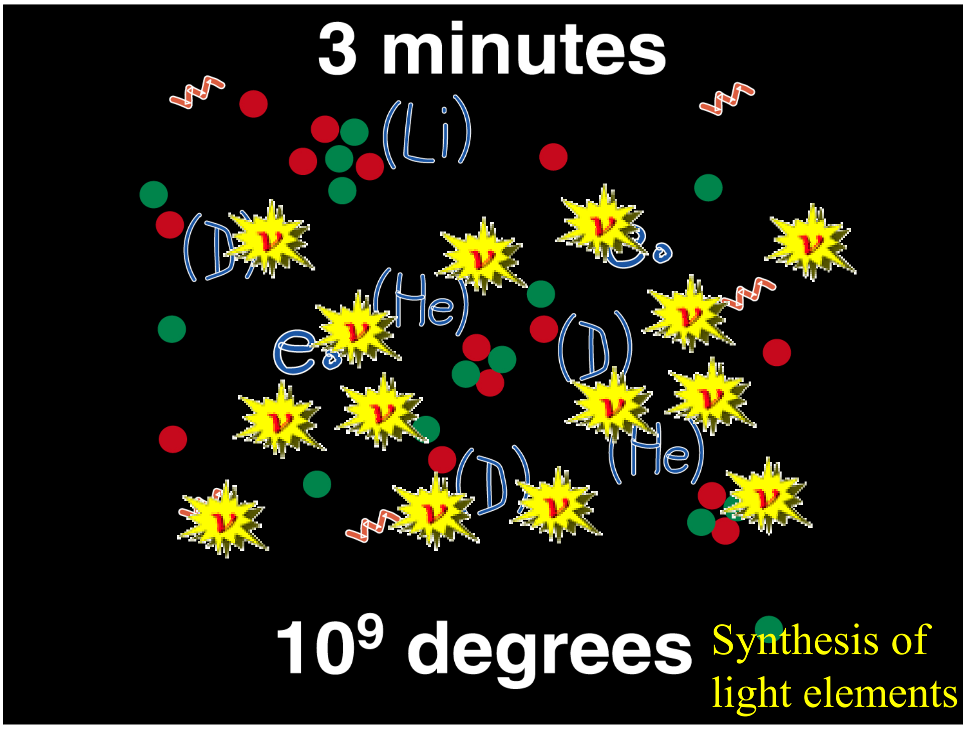

Neutrinos & Cosmology
• Dark Matter ~ 25% & Dark Energy 70%
• mass of all neutrinos: 0.001 ≤ Ω_ν ≤ 0.02
• baryonic matter Ω_B ~ 0.04
➔ see lectures by M. Bartelmann
Present Day Acceleration
Big Bang
Inflation
Expansion
neutrinos affect:
- BBN, structure formation
- baryon asymmetry, ...
Source: Robert Kirshner
Source: David Aguilar, Harvard-Smithsonian Center for Astrophysics
M. Lindner
21

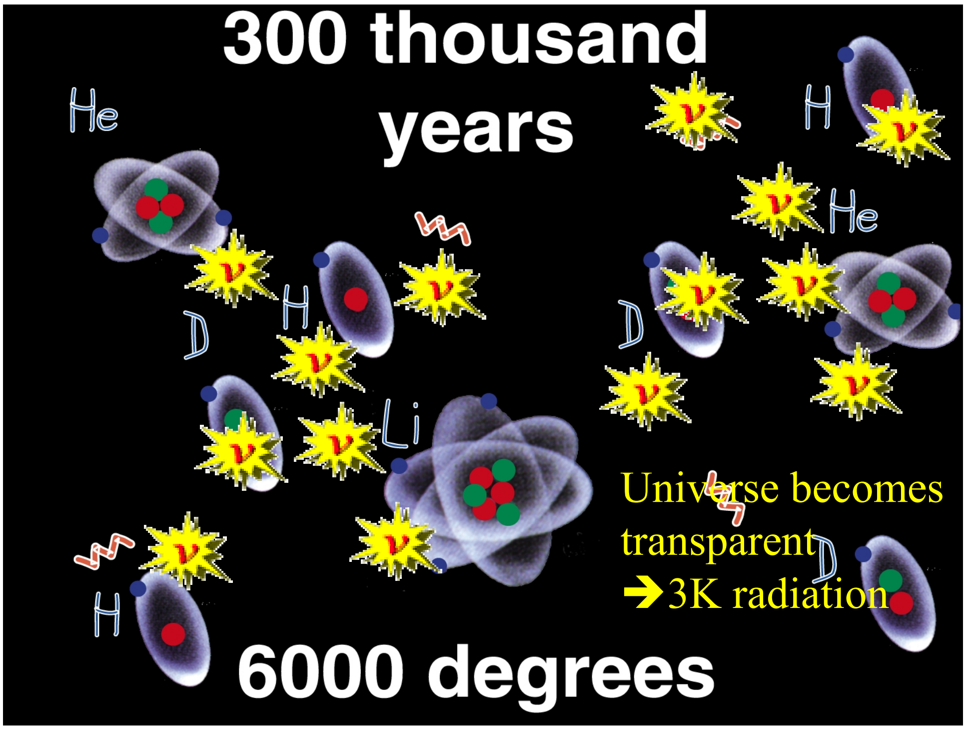

The thermal evolution of the Universe:
10^-43 seconds
speculative physics:
10^19GeV:Strings, ...
Time
10^32 degrees

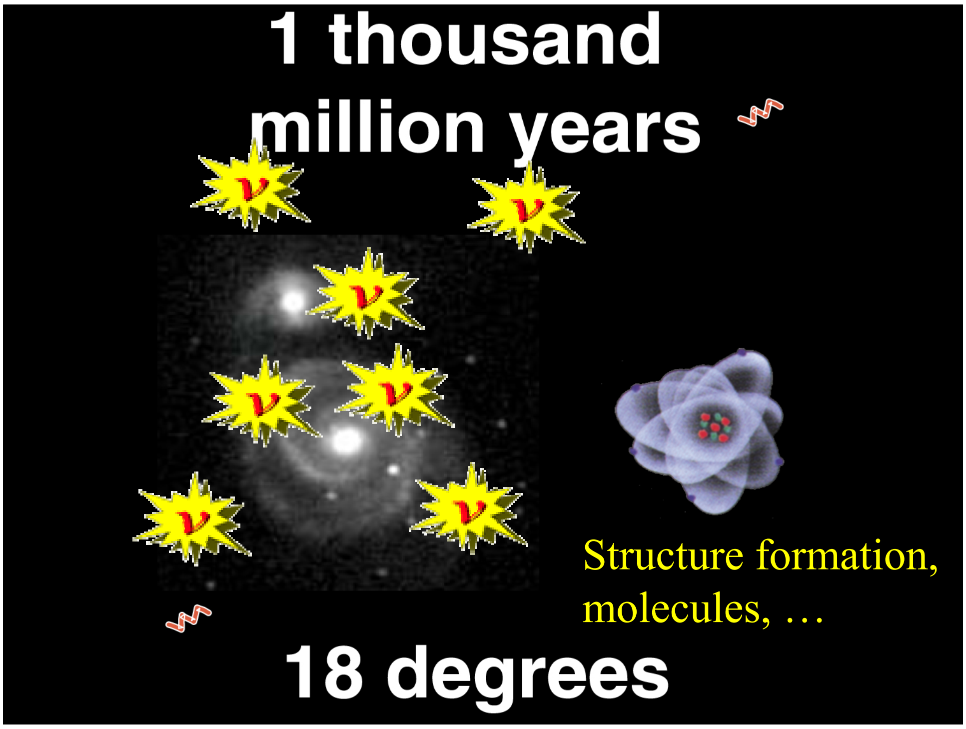

10—34 seconds
W−
e
Z
W+
e
W−
Z
e
10^27 degrees
GUT physics:
10^16 GeV

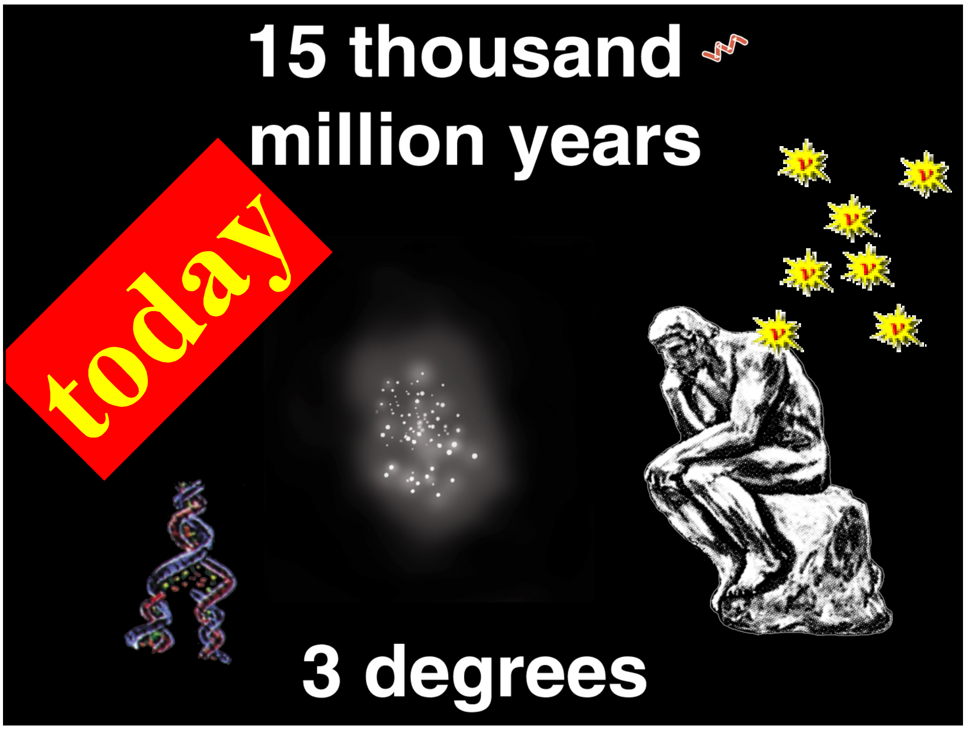

10—10 seconds
e
e
e
e
e
10^15 degrees
known physics:
↔ accelerators
10^3 GeV = TeV

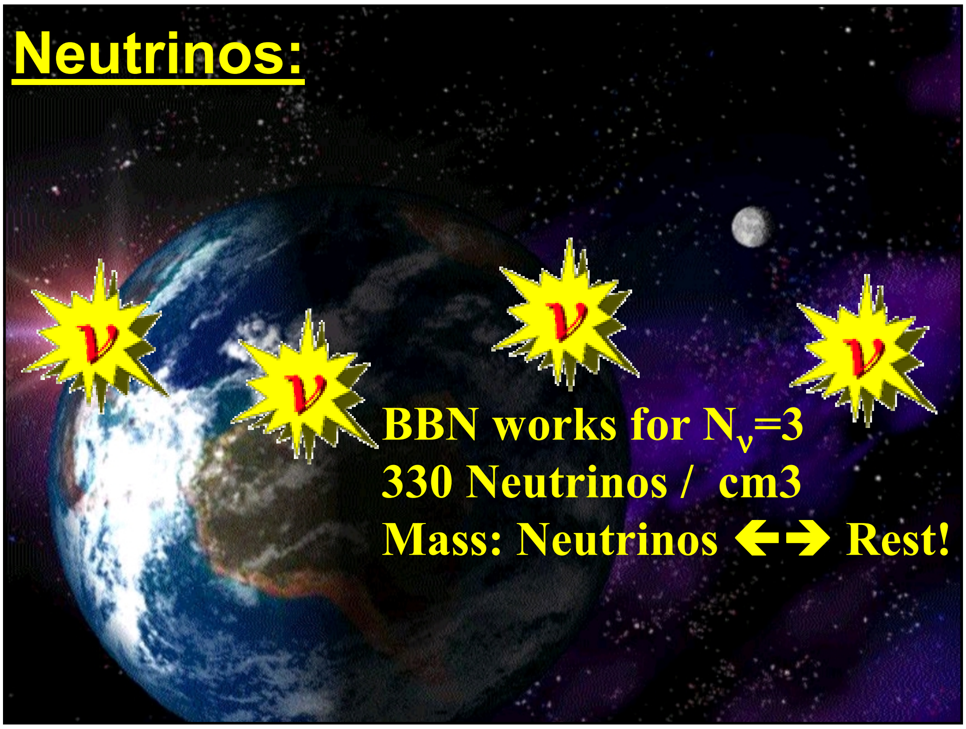

10⁻⁵ second
10¹⁰ degrees
Binding of protons
and neutrons
~100MeV


3 minutes
(Li)
(D)
(He)
(D)
(D)
(He)
10⁹ degrees
Synthesis of
light elements


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

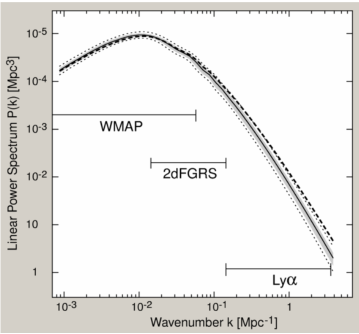

1 thousand million years
Structure formation, molecules, …
18 degrees

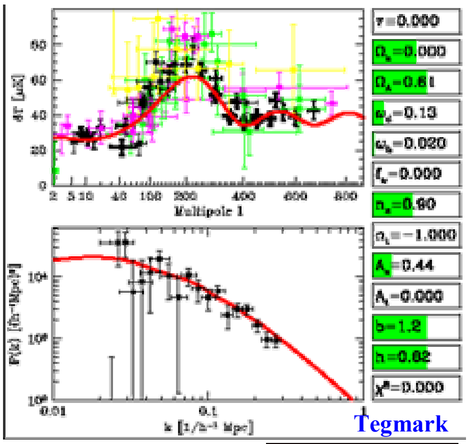

15 thousand million years
today
3 degrees


Neutrinos:
BBN works for N$_\nu$=3
330 Neutrinos / cm3
Mass: Neutrinos ←→ Rest!

Cosmology and Neutrino Mass

• ν's are hot dark matter ➔ smears structure formation on small scales





•WMAP+2dFGRS + Lyα

➔ mass bound: $\Sigma m_\nu < 0.7 \ldots 1.2$ eV

• 3 degenerate neutrinos

➔ $m_\nu < 0.4$ eV future improvements: ~factor 5-10 ?

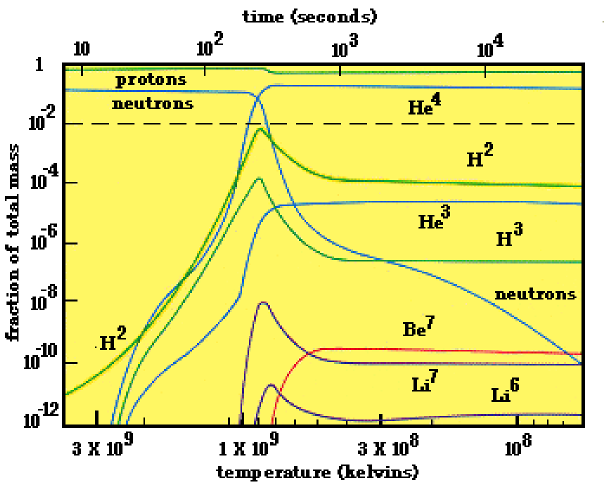
$f_\nu = \Omega_\nu / \Omega_{matter}$

• comparison with 0ν2β, LSND

• will be tested directly by KATRIN WMAP➔ PLANCK

M. Lindner 31

Big Bang Nucleosynthesis



BBN with N_ν=3 predicts light element abundances very nicely

➔ more neutrinos make things worse...

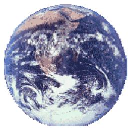
M. Lindner 32

Baryon Asymmetry & Neutrinos

theory — **observation**

X ⟷ symmetry ⟷ $\overline{X}$

particle — anti-particle

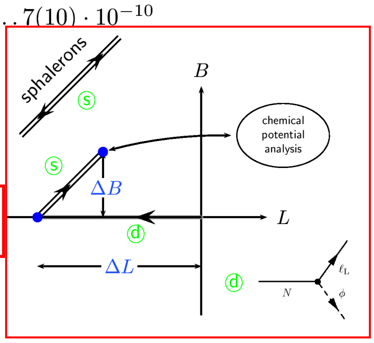


matter ⟷ baryon-asymmetry ⟷ **?** anti-matter

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**

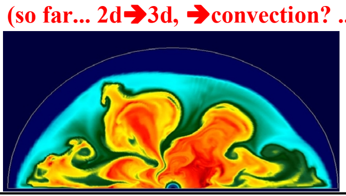


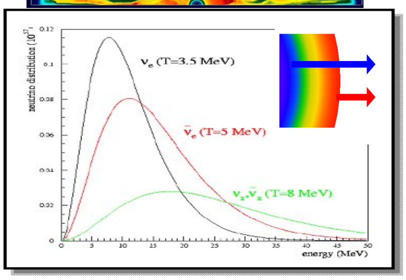
- **minimal leptogenesis works nicely**
- **different interesting variants ... a talk by itself**

M. Lindner 33

Supernova Neutrinos

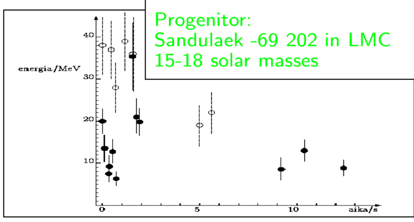
- **Collaps of a typical star ➔ ~10^{57} ν's**
- **~99% of the energy in ν's**
- **ν's essential for explosion**
- **3d simulations do not explode (so far... 2d➔3d, ➔convection? ...)**





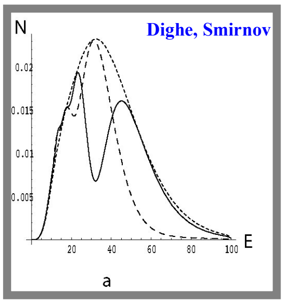
SN1987A neutrino burst

Progenitor:
Sandulaek -69 202 in LMC
15-18 solar masses



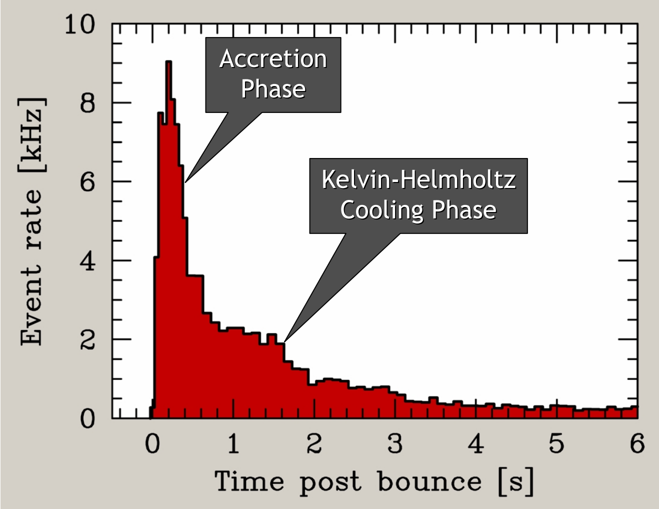
MSW: SN & Earth

sensitive to finite θ_{13} and sgn(Δm^2)



M. Lindner 34

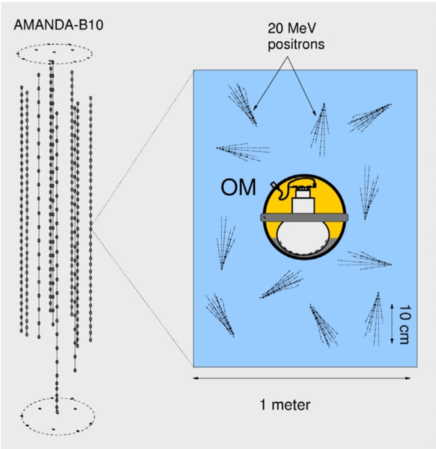
Simulated Supernova Signal at SK

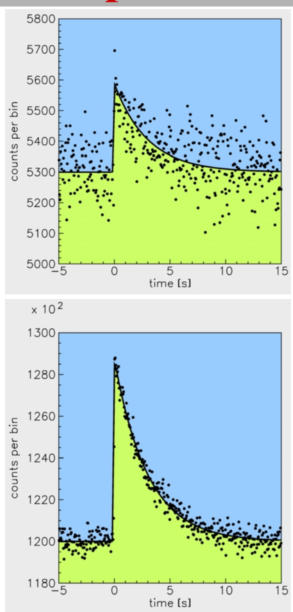


Simulation for Super-Kamiokande SN signal at 10 kpc
Totani, Sato, Dalhed & Wilson

M. Lindner 35

Amanda/IceCube as a Supernova Detector





SN @ 8.5 kpc Signal in Amanda

SN @ 8.5 kpc Signal in IceCube

Each optical module (OM) picks up Cherenkov light from its neighborhood
SN ➔ correlated "noise" between OMs

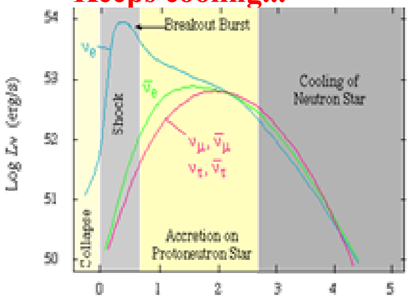
M. Lindner 36

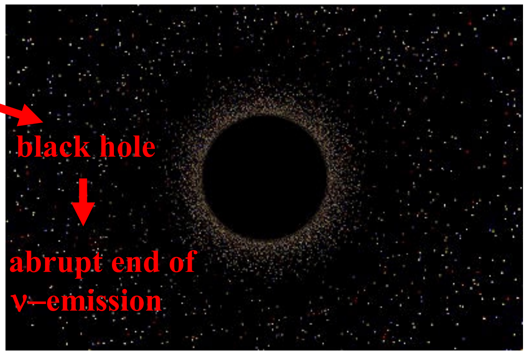
2 possibilities:

Supernova

neutron star or black hole

Keeps cooling...

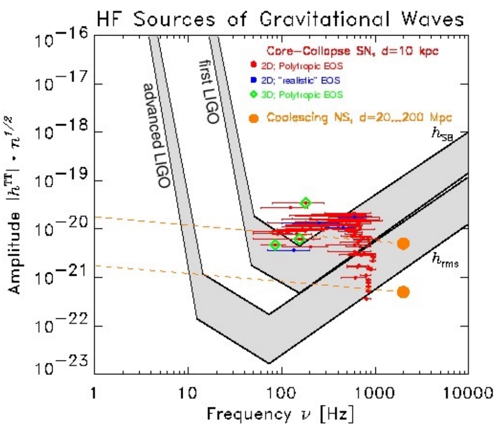


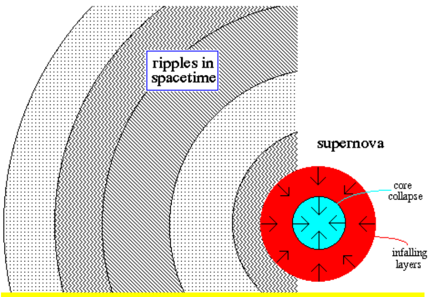


abrupt end of ν–emission

- impressive signal of a black hole in neutrino light
- neutrino masses ←→ edge of ν-signal

Supernovae & Gravitational Waves





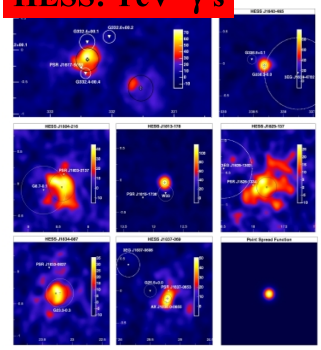
gravitational wave emission ←→ quadrupol moment of the explosion

Dimmelmeier, Font, Müller

- ➔ additional information about galactic SN
- ➔ **global fits:** optical + neutrinos + gravitational waves
- ➔ neutrino properties + SN explosion dynamics
- ➔ SN1987A: strongest constraints on large extra dimensions

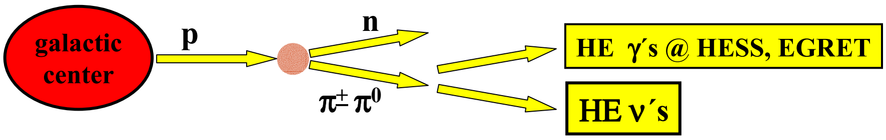
Neutrinos & TeV γ´s

HESS: TeV γ's



HESS and EGRET:
- TeV γ's from galactic center and galactic plane
- 8 sources observed
- some are at the position of known SN remnants
- others do not correlate to anything known?

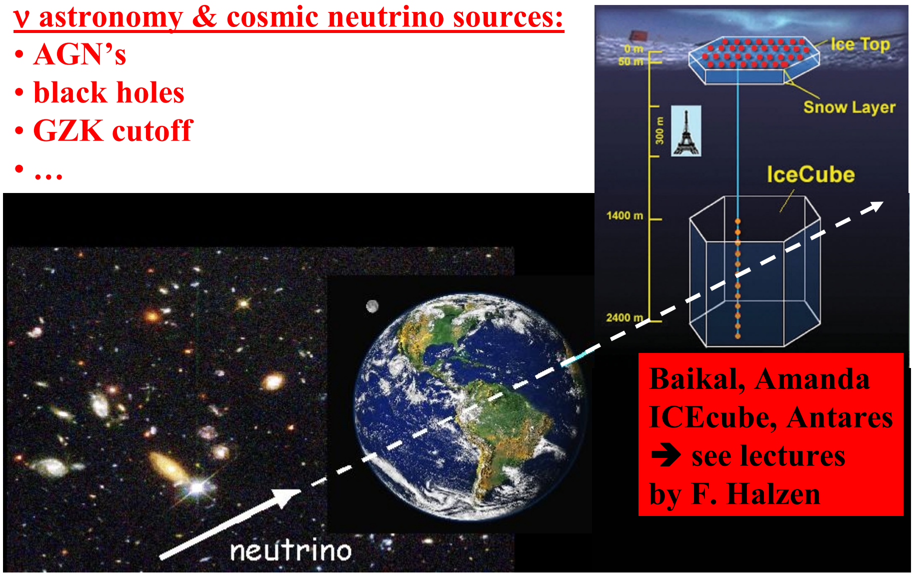
Plausible explanation:
-SN shock front acceleration
- γ´s from π^0 decay
  ➔ ν flux from GC
  ➔ ν signal @ km^3 detectors



M. Lindner 39

Neutrino Telescopes

ν astronomy & cosmic neutrino sources:
- AGN's
- black holes
- GZK cutoff
- …



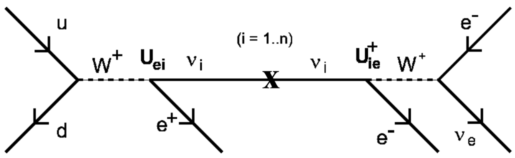
M. Lindner 40

Four Methods of Mass Determination

- kinematical
- lepton number violation
  ←→ Majorana nature
- astrophysics & cosmology
- oscillations

Neutrino Oscillations for N=2

Production
Propagation
Detection



$p + p \to d + \nu_e + e^+$ electron scattering

2 Flavours ν_e, ν_μ:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

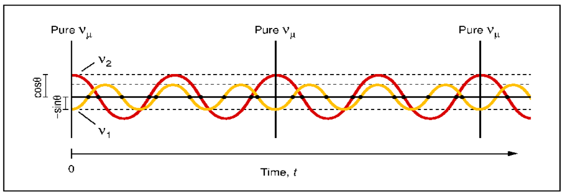
flavour states   mixing matrix · mass eigenstates

- Production as flavour eigenstate from W-exchange
- Detection via W-exchange ≡ projection on flavour state
- Propagation as mass eigenstate ⇒ use mixing matrix at vertex
- Is a simple QM treatment justified?

Neutrino Oscillations

2 Neutrinos: ν_e, ν_μ

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



$$|\nu_\mu(t)\rangle = -\sin\theta\;\exp[-\frac{iE_1 t}{\hbar}]\;|\nu_1\rangle + \cos\theta\;\exp[-\frac{iE_2 t}{\hbar}]\;|\nu_2\rangle$$

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

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

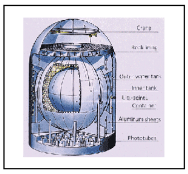
2ν-transition-probability:

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

ν_e, ν_μ, ν_τ ➔ 9 oscillation channels for neutrinos
$\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$ ➔ 9 channels for anti-neutrinos (assuming 3ν !)

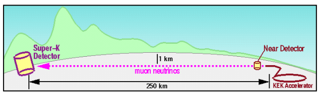
M. Lindner 43

Status of Neutrino Oscillation Signals

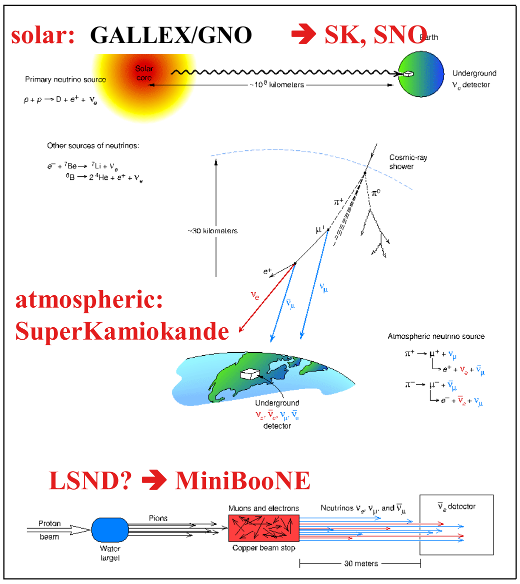


Reactors: KAMLAND

Beams: K2K, MINOS,
➔ OPERA

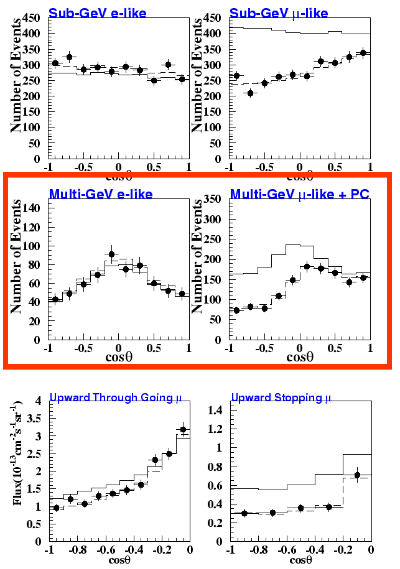


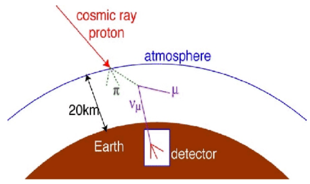
Δm^2_{21} = (8.2±0.3) * 10^{-5} eV^2
$\tan^2\theta_{12}$ = 0.39 ± 0.05
Δm^2_{31} = (2.5±0.6) * 10^{-3} eV^2
$\tan^2\theta_{23}$ = 1.0 ± 0.3
$\sin^2 2\theta_{13}$ < 0.16 Chooz



M. Lindner 44

Atmospheric Oscillations @SuperK





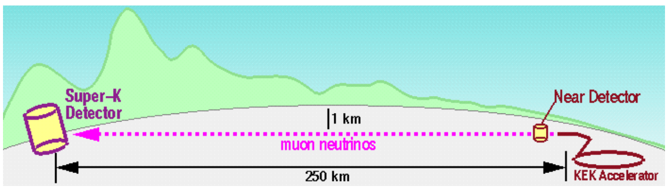
Oscillation fit (including K2K):

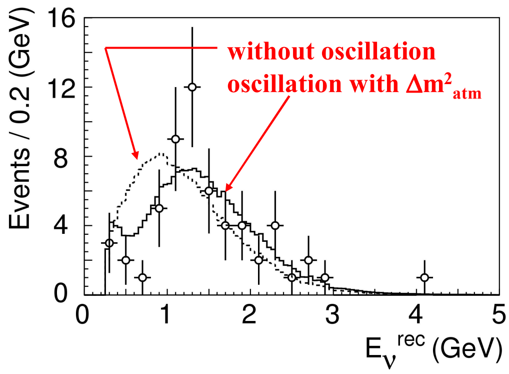
$|\Delta m^2_{31}| = (2.0 \pm 1.0) \cdot 10^{-3} \mathrm{eV}^2$
$\sin^2 2\theta_{23} \geq 0.85$

- 8σ signal for ν_μ disappearance
- NOT $\nu_\mu \to \nu_e$ (consistent with Chooz)
- $\Rightarrow$ $\nu_\mu \to \nu_\tau$ (some τ's seen)
- NOT $\nu_\mu \to \nu_s$ from NC/CC comparison
- L/E confirmed by K2K ($\simeq 2\sigma$)
- sensitivity for L/E-dependence of oscillations

M. Lindner 45

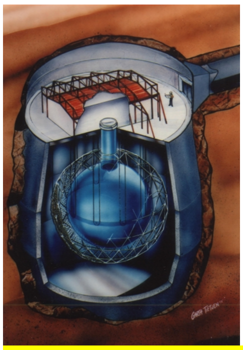
K2K confirms atmospheric Δm²

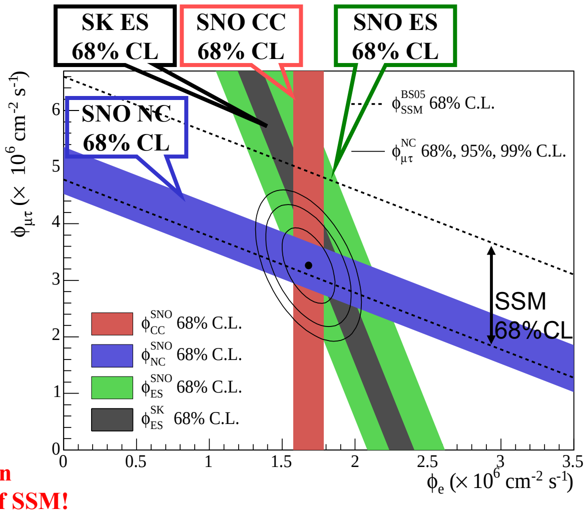




M. Lindner 46

Solar ν´s: NC, CC, ES Rates from SNO





$\Phi_{CC} = \Phi_e$

$\Phi_{ES} = \Phi_e + 1/6\ \Phi_{\mu\tau}$

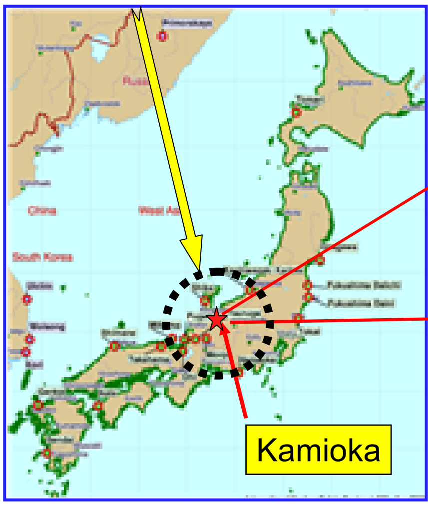
$\Phi_{CC} = \Phi_e + \Phi_\mu + \Phi_\tau$

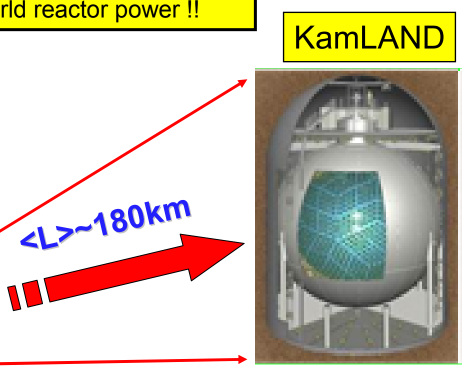
Clear proof of flavour conversion
Independent of SSM ⇐⇒ test of SSM!
No conversion and conversion to sterile ν's excluded by many sigma
≃ no L/E dependence

M. Lindner 47

KamLAND tests solar Oscillations

26 power reactors are located in narrow band at L~180km from KamLAND, producing 80GW$_{th}$, 7% of World reactor power !!

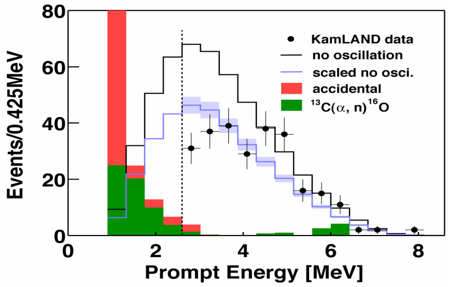




Contribution from overseas
Korea 2.46%
Other countries 0.7%

M. Lindner 48

Testing Solar L/E with KamLAND

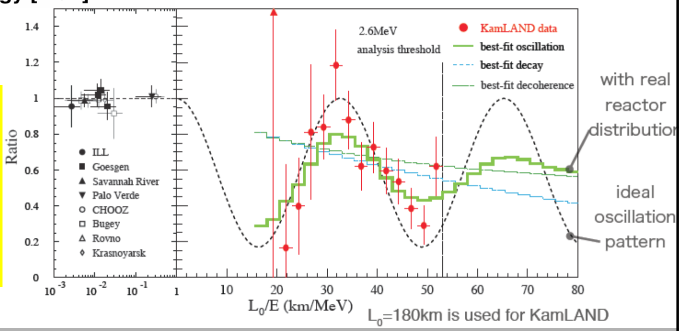


rate plus shape ➔
oscillations at 99.999995% CL

Best fit: $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$
$\tan^2\theta = 0.46$

improved tests of L/E:

- Super Kamiokande
- KamLAND
- MINOS
- …



M. Lindner 49

Coming Improvements

MINOS, OPERA: improved oscillation parameters
MiniBOONE ←→ LSND
L/E of oscillations ←→ oscillation/decay/decoherence
KATRIN: absolute neutrino mass
Better $0\nu2\beta$ limits / signals
…

But why do we need precision measurements?

M. Lindner 50

The Future of Neutrino Oscillations

➔ precision neutrino physics

➔ very valuable to exclude / constrain / test models of flavour (discrete symmetries, …)

The Future of Oscillation Physics

<u>Δm^2 and θ_{ij} regions</u> ➔ improved oscillation experiments
➔ controlled sources & detectors

➔ long baseline experiments with neutrino beams
➔ reactor experiments with identical near & far detector

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

x Majorana-CP-phases

θ_{23} — S_{13} ➔ 3 flavour effects ➔ CP phase δ — θ_{12} — matter effects

Aims: ➔ improved precision of the leading 2x2 oscillations
➔ detection of generic 3-neutrino effects: θ_{13}, CP violation

➔ **precision neutrino physics**

Analytic Approximations

- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31}$; $V = \sqrt{2} G_F n_e$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta + 2\,\alpha\,\cos^2\theta_{13}\cos^2\theta_{12}\sin^2 2\theta_{23}\Delta\cos\Delta$$

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

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

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

M. Lindner 53

Simulation of Future Experiments

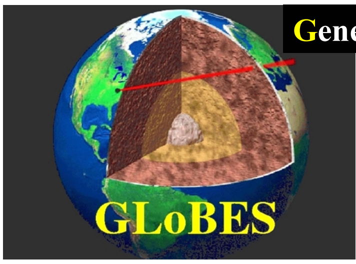
- **select a setup (beam, detector, baseline, ...)**
- **take „most realistic“ parameters ←→ best guess!**
- **simulate all relevant aspects as good as possible**

Source ⊗	Oscillation ⊗	Detector
- neutrino energy E	- oscillation channels	- effective mass, material
- flux and spectrum	- realistic baselines	- threshold, resolution
- flavour composition	- MSW matter profile	- particle ID (flavour, charge, event reconstruction, ...)
- contamination	- degeneracies	- backgrounds
- symmetric $\nu/\overline{\nu}$ operation	- correlations	- x-sections (at low E)

- **determine the potential: „true“ ←→ fitted parameters**
- **compare only realistic simulations (<u>all relevant</u> effects, errors & uncertainties)**

M. Lindner 54

A Powerful Simulation Tool



General Long Baseline Experiment Simulator

Comp. Phys. Comm. 167 (2005) 195, hep-ph/0407333

http://www.ph.tum.de/~globes

P. Huber, ML, W. Winter
M. Freund, M. Rolinec

- **C-based simulation software (GPL = free)**
- **extensive documentation & examples**
- **3 phase approach:**

1) AEDL (**Abstract Experiment Definition Language**)
2) simulation of an experiment ➔ 3-ν oscillations; scan „true values"
3) analysis ➔ event distriutions, ..., sensitivities, ...

M. Lindner 55

Precison with New Neutrino Beams

- **conventional beams, superbeams**
  ➔ **MINOS, CNGS, T2K, NOνA, T2H,…**
- **β-beams**
  ➔ **pure ν_e and $\bar{\nu}_e$ beams from radioactive decays; $\gamma \simeq 100$**
- **neutrino factories**
  ➔ **clean neutrino beams from decay of stored μ's**

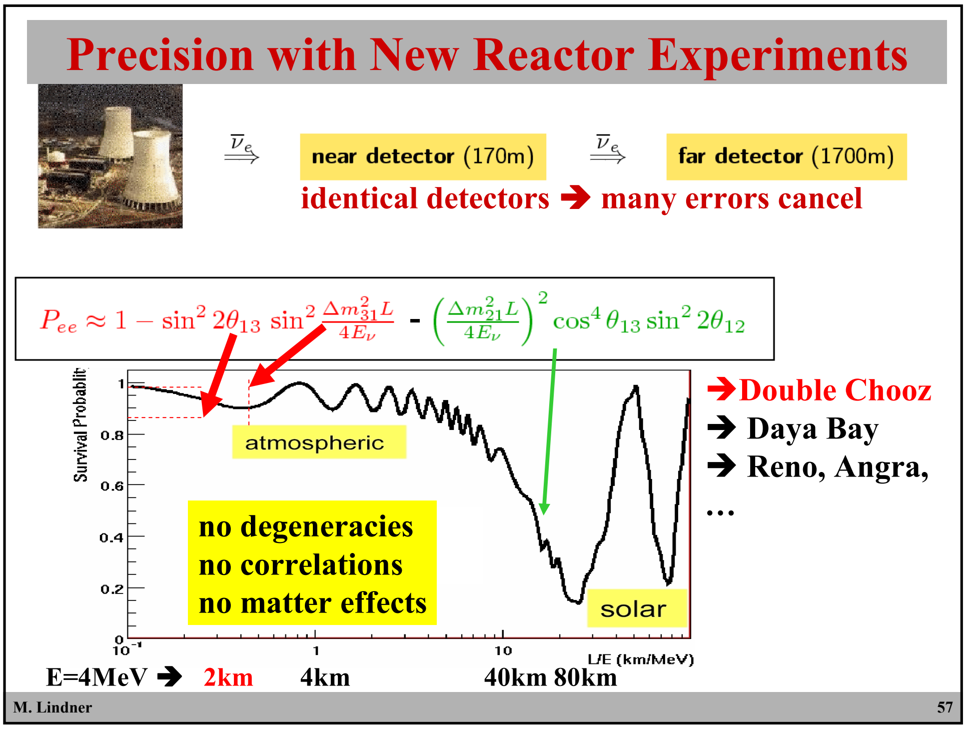
$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm\ & \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}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

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

➔ **$(\sin^2\theta_{13})_{eff}$ *or* correlations & degeneracies**

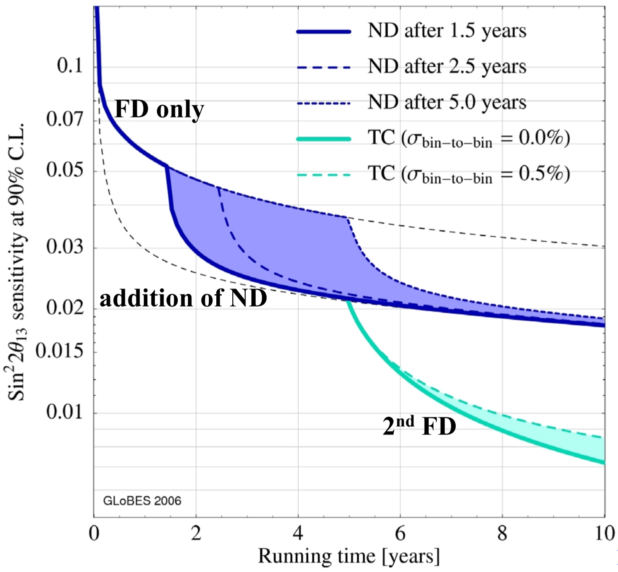
M. Lindner 56

M. Lindner: Schule für Astroteilchenphysik, Obertrubach-Bärnfels, October 4-12, 2006


Precision with New Reactor Experiments
near detector (170m)
far detector (1700m)
identical detectors ➔ many errors cancel
$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} - \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$
Survival Probabilit
atmospheric
no degeneracies
no correlations
no matter effects
solar
L/E (km/MeV)
➔Double Chooz
➔ Daya Bay
➔ Reno, Angra,
…
E=4MeV ➔ 2km 4km 40km 80km
M. Lindner
57


Double Chooz
existing far detector hall
… + another
existing big hall!
M. Lindner
58

Double Chooz and Triple Chooz



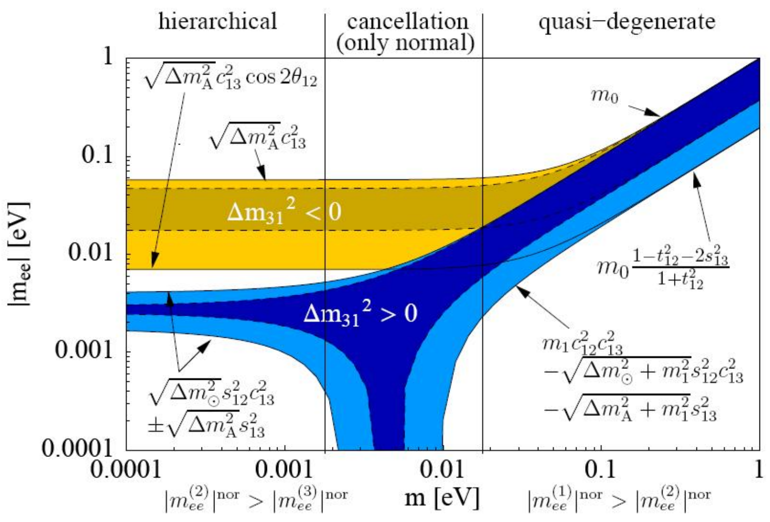
$\sin^2 2\theta_{13}$ sensitivity

Chooz limit < 0.20
Double Chooz < 0.02
Triple Chooz ? < 0.008

Huber, Kopp, ML, Rolinec, Winter

M. Lindner 59

Impact of $\sin^2\theta_{13}$ on $0\nu2\beta$ Mass Plot



M. Lindner 60

Double Chooz and 0ν2β

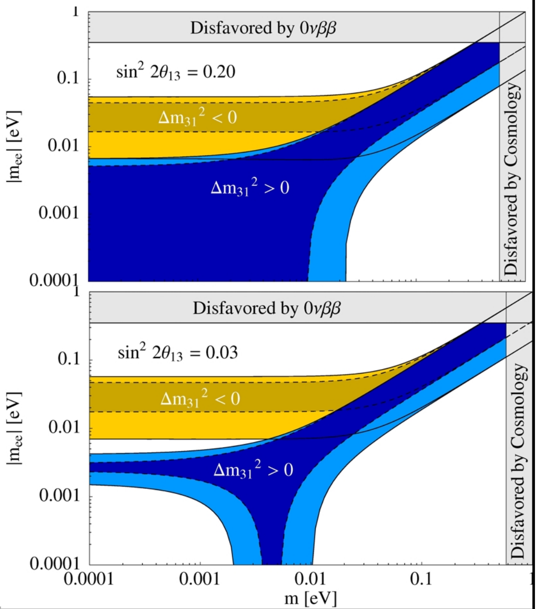
- m_{ee} versus m_1

  for $\sin^2 2\theta_{13} = 0.2$

  for $\sin^2 2\theta_{13} = 0.03$

  ➔ Double Chooz

Bilenky, Pascoli, Petcov
Klapdor, Päs, Smirnov
…
ML,Merle, Rodejohann



M. Lindner 61

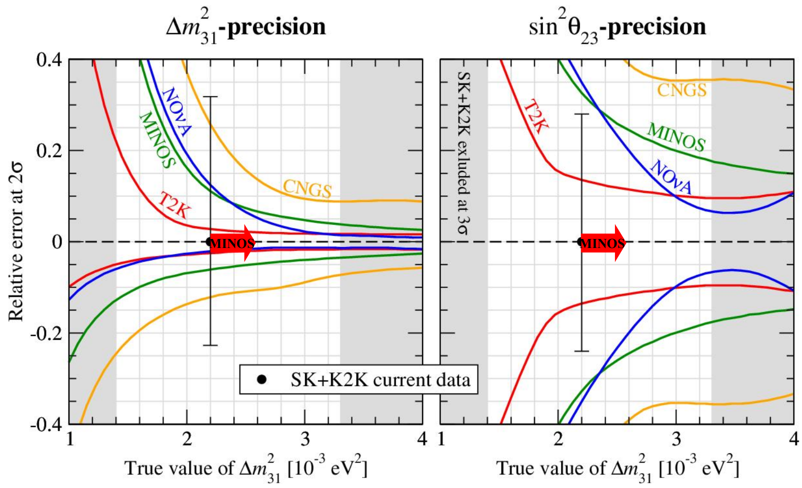
Future Long Baseline Experiments

K2K	analysis	establish atmospheric oscillations with beam
MINOS OPERA	running almost running	expected precision: 8% for Δm^2_{13} , 25% for $\sin^2\theta_{23}$, θ_{13} ?
T2K	construction	4% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$, ➔ θ_{13}
NOνA	pre-approved	3% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$ (combined with T2K) , ➔ θ_{13} , ➔ δ ? , ➔ sgn(Δm^2_{13})
T2KK, T2H, …	R&D	⬇
β-beams	R&D	precision neutrino physics
neutrino factory	R&D	
...muon collider	...	

- every stage is a necessary prerequisite for the next
- continuous line of improvements for beams, detectors, physics

M. Lindner 62

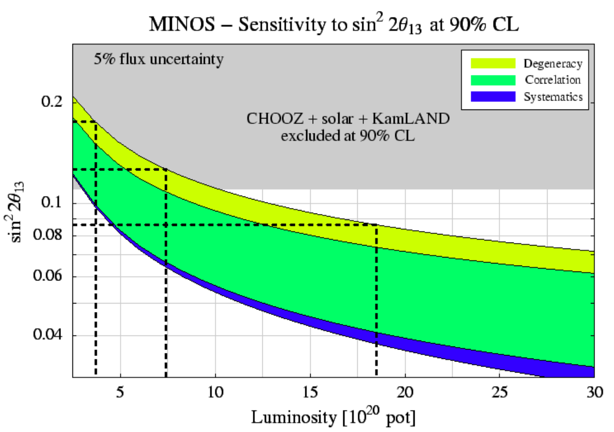
Improvement of Δm^2_{31} and $\sin^2\theta_{23}$



Huber, ML, Rolinec, Schwetz, Winter

M. Lindner 63

θ_{13} in the Coming LBL Generation



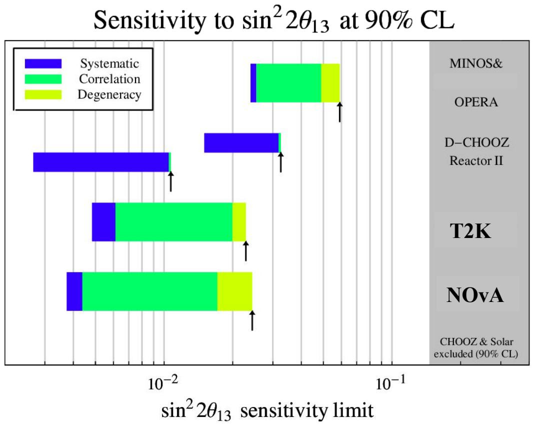
MINOS sensitivity as a funtion of time:

- MINOS: $3.7 \cdot 10^{20}$ pot/y
- 1,2,5 years

➔ **modest improvements**
➔ **other objectives**

M. Lindner 64

θ_{13} Sensitivity in the Next Generation



coming long baseline experiments

1 reactor +2 detectors

next generation long baseline experiments

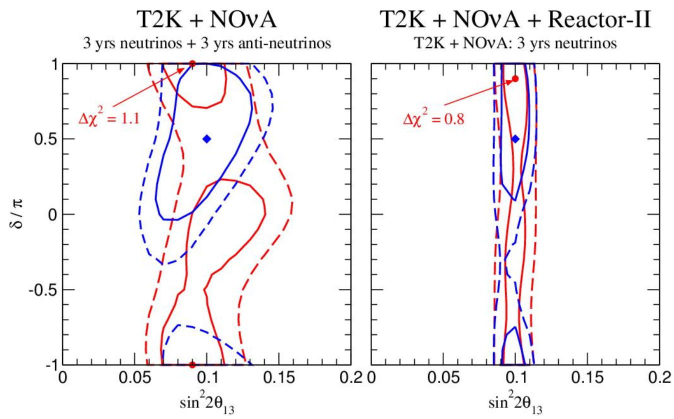
Compare:
- 5 years each
- 5% flux uncertainty

- one order of magnitude improvement for θ_{13}
- synergies between reactor and accelerator experiments
  - reactor anti-neutrinos ⇒ only neutrino beams (x-section)
  - reactor: uncorrelated θ_{13} ⇒ combine with beams & resolve correlations
- synergy between beams ⇒ NOνA at larges baseline ⇒ matter effects

M. Lindner 65

Leptonic CP Violation – Best Case

assume: $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2$ ➔combine: T2K+NOνA+Reactor



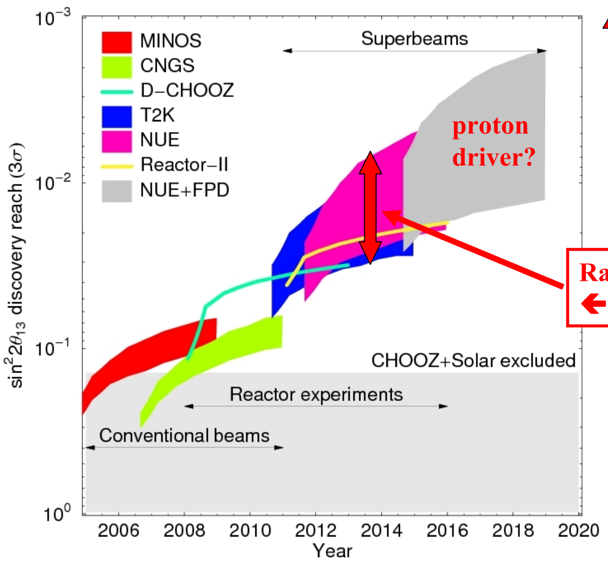
$\Delta m^2 > 0$
$\Delta m^2 < 0$
90%CL
3σ

➔ limits or measurement of leptonic CP violation
(… and sgn(Δm^2) for sizable $\sin^2 2\theta_{13}$)

Huber, ML, Rolinec, Schwetz, Winter

M. Lindner 66

Sensitivity Versus Time

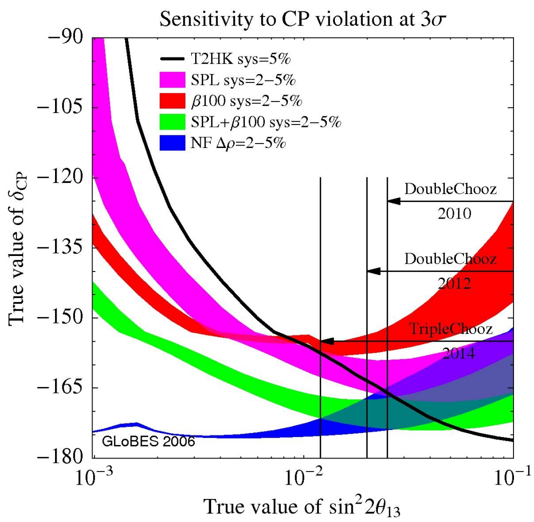


β-beams neutrino factory

Range ↔ ~unknown CP phase

M. Lindner 67

The Importance of θ_{13} for Road Maps



Huber, ML, Rolinec, Winter

→result of reactor experiments crutial for future steps

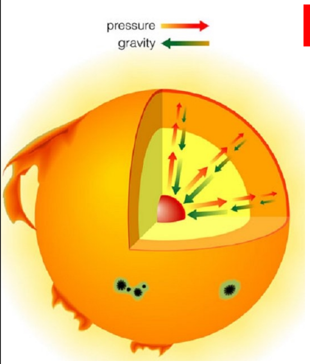
→unexpected results crutial for future steps (MiniBooNE, …)

M. Lindner 68

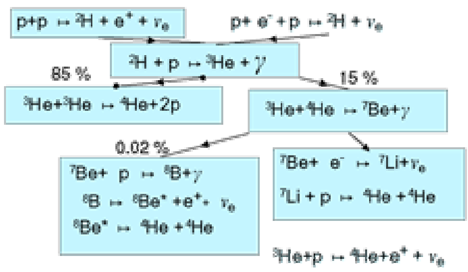
The Value of Future Precision Experiments

Solar Neutrinos: Learning About the Sun

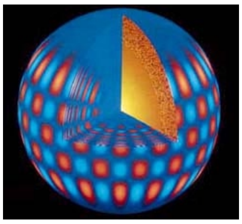
Observables:
- **optical** (total energy, surface dynamics, sun-spots, historical records, B, ...)
- **neutrinos** (rates, spectrum, ...)



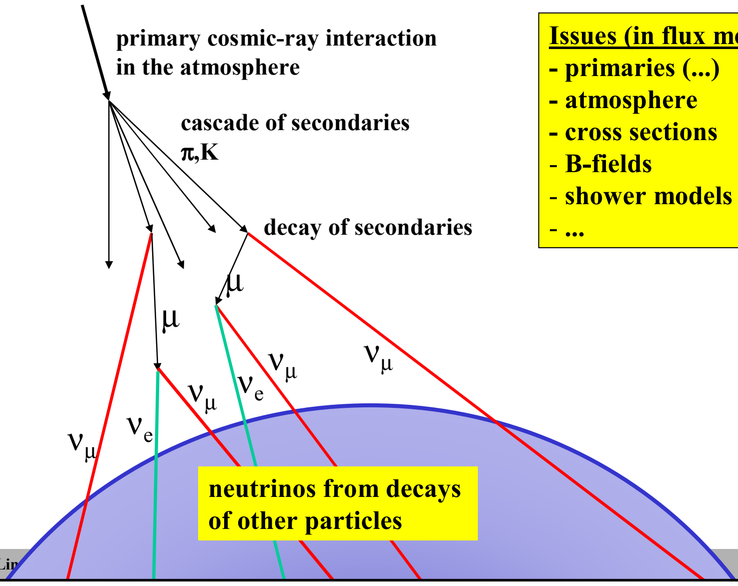
BOREXINO



Topics:
- **nuclear cross sections**
- **solar dynamics**
- **helio-seismology**
- **variability**
- **composition**



Learning from Atmospheric Neutrinos



Issues (in flux models):
- primaries (...)
- atmosphere
- cross sections
- B-fields
- shower models
- ...

M. Lin… 71

Learning about…

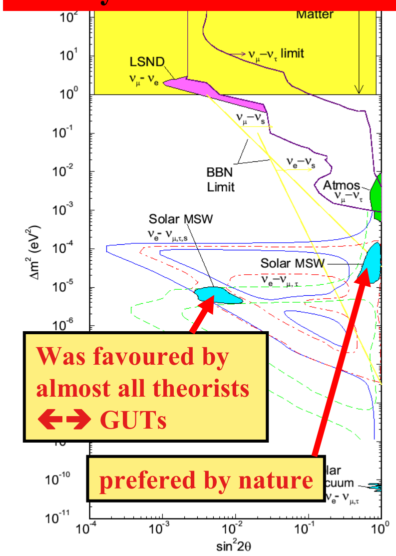
- Geo neutrinos ➔ Earth
- Reactor neutrinos ➔ nuclear physics
- Neutrino beams ➔ accelerator physics
- Supernova neutrinos ➔ element formation, …
- UHE neutrinos ➔ sources
- …
- Flavour:

  ➔ unique information
  ➔ very precise: no hadronic uncertainties
  ➔ different from quarks ⇐⇒ see-saw
  ➔ tests models / ideas about flavour

M. Lindner 72

Learning about Flavour

History: Elimination of SMA



Was favoured by almost all theorists ←→ GUTs

prefered by nature

Next: Smallness of θ_{13}

- models for masses & mixings
- input: known masses & mixings
  - → distribution of θ_{13} „predictions“
  - → θ_{13} often close to experimental bounds

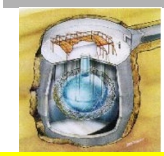
What if $\sin^2 2\theta_{13} < 0.01$?

question: why is θ_{13} so small ?
→ numerical coincidence
→ symmetry

←→ precision!

M. Lindner 73

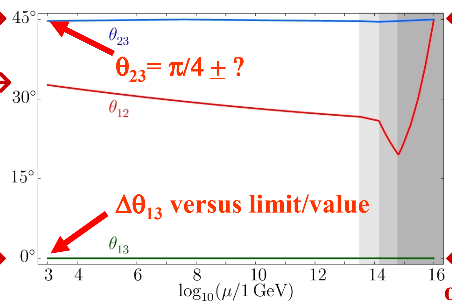
Renormalization Group Running



low energies:
- small masses
- large mixings

renormalization group running →

high energies:
- mass models
- flavour-symmetries
- GUT-models, ...



atmospheric → ; solar → ; reactor →

← bi-maximal

$\theta_{23} = \pi/4 \pm$?

$\Delta\theta_{13}$ versus limit/value

← Small or even zero

MSSM example:
Antusch, Kersten, **ML**, Ratz

M. Lindner 74

Further Implications of Precision

Precision allows to identify / exclude:

- **special angles: θ_{13}= 0°, θ_{23}= 45°, ... ⇔ discrete f. symmetries?**
- **special relations: θ_{12}+ θ_C = 45° ? ⇔ quark-lepton relation?**
- **quantum corrections ⇔ renormalization group evolution**

Provides also measurements or tests of:

- **MSW effect (coherent forward scattering and matter profiles)**
- **cross sections**
- **3 neutrino unitarity ⇔ sterile neutrinos with small mixings**
- **neutrino decay (admixture…)**
- **decoherence**
- **NSI**
- **MVN, ...**

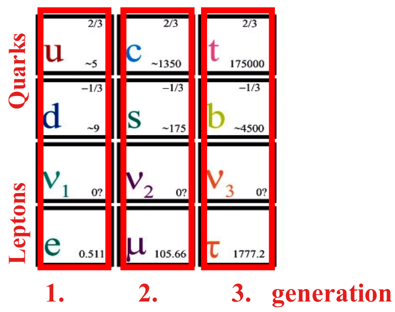
→ various synergies with LHC and LFV

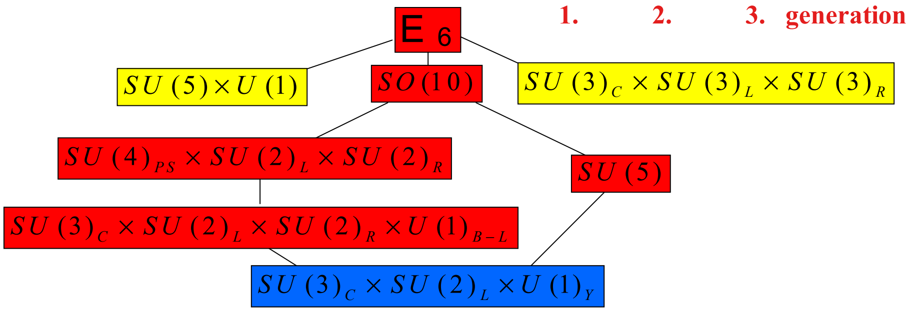
M. Lindner 75

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

Requirements:
gauge unification
particle multiplets ⇔ ν_R
proton decay
…





M. Lindner 76

GUT Expectations and Requirements

Quarks and leptons sit in the same multiplets

➔ one set of Yukawa coupling for given GUT multiplet
➔ ~ tension: small quark mixings ⟷ large leptonic mixings
➔ this was in fact the reason for the `prediction' of small mixing angles (SMA) – ruled out by data

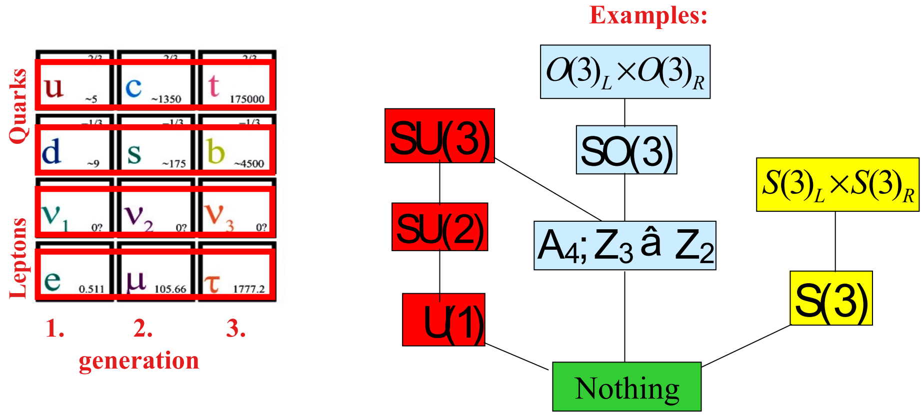
Mechanisms to post-dict large mixings:

➔ sequential dominance
➔ type II see-saw
➔ Dirac screening
➔ …

Flavour Unification

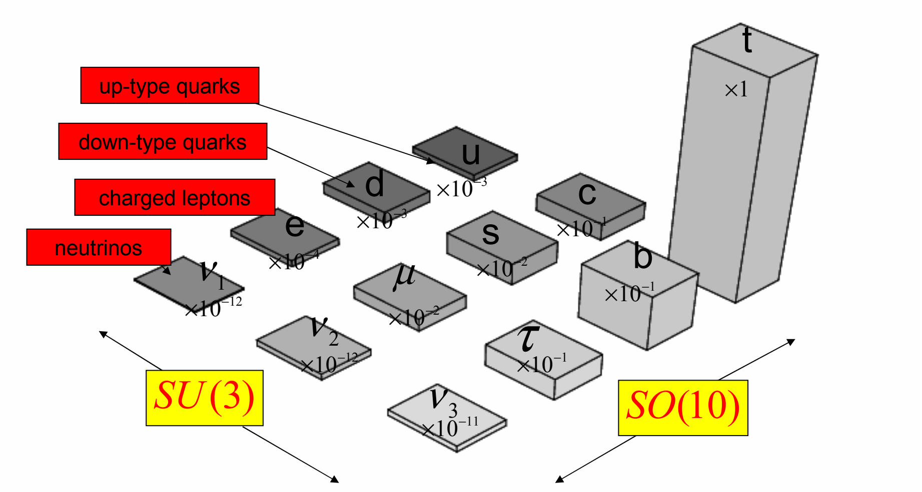
- so far no understanding of flavour, 3 generations
- apparent regularities in quark and lepton parameters

➔ flavour symmetries
➔ not texture zeros



GUT *and* Flavour Unification

Example: SO(10) x SU(3)



M. Lindner 79

GUT ⊗ Flavour Unification

- So far **no understanding of flavour, 3 generations**
- **Regularities in quark and lepton parameters**
- **Hints for unification**

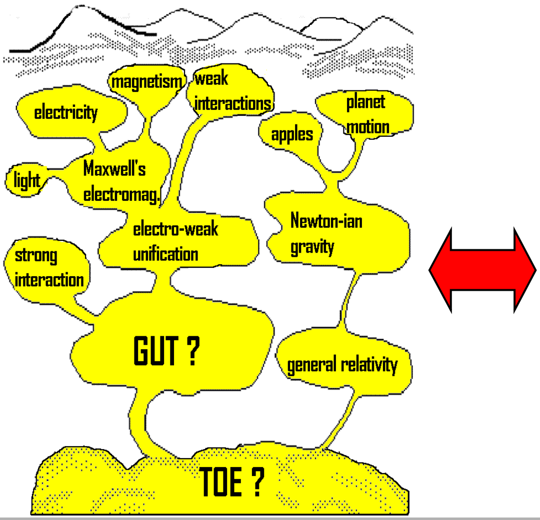
➔ GUT group ⊗ continuous, gauged flavour group

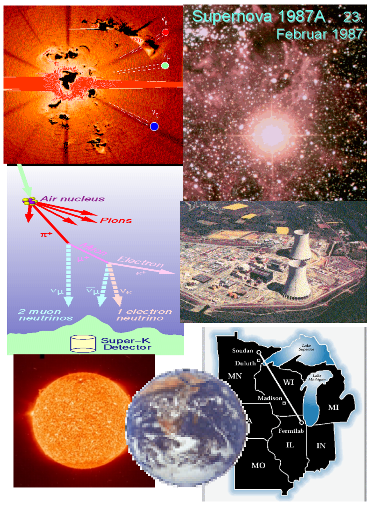
- **for example SO(10) ⊗ $SU(3)_{flavour}$**
- **Generations are 3_F**
- **SSB of $SU(3)_{flavour}$ between Λ_{GUT} and Λ_{Planck}**
  - **➔ all flavour Goldstone Bosons eaten**
  - **➔ discrete (ungauged) sub-group survives ←➔ SSB potential**
  - **➔ e.g. Z2, S3, D5, A4, ...**
  - **➔ structures in flavour space**

M. Lindner 80

Conclusions

Neutrinos probe new physics in many ways!





M. Lindner 81