Neutrino Physics / 4

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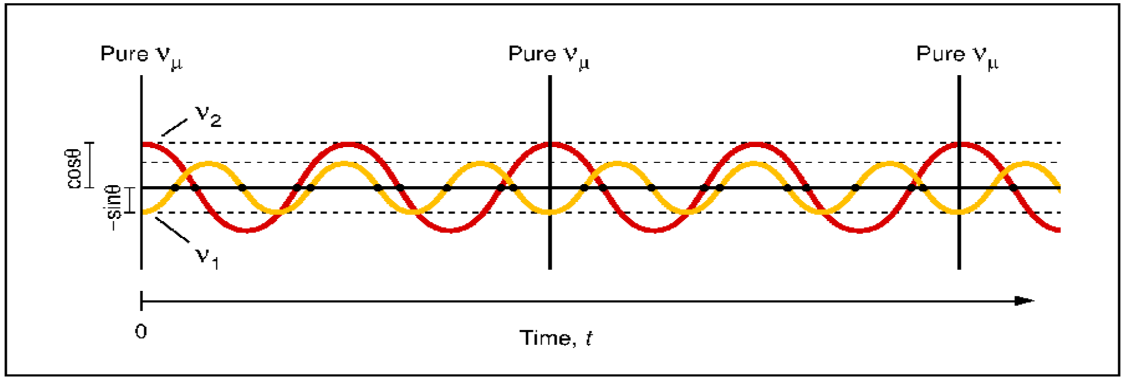
Two Neutrino Oscillations

2 Neutrinos: ν_e, ν_μ

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



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

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

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

simple QM derivation with assumptions:
- equal momentum?
- coherence, …

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, …

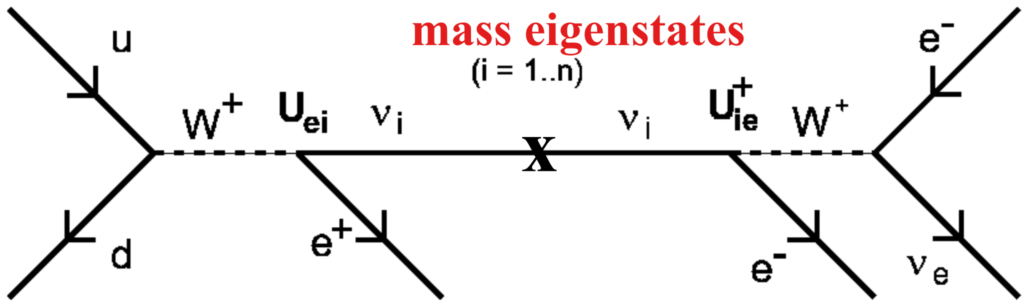
  ➔ Feynman diagram of neutrino oscillation:

  - 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

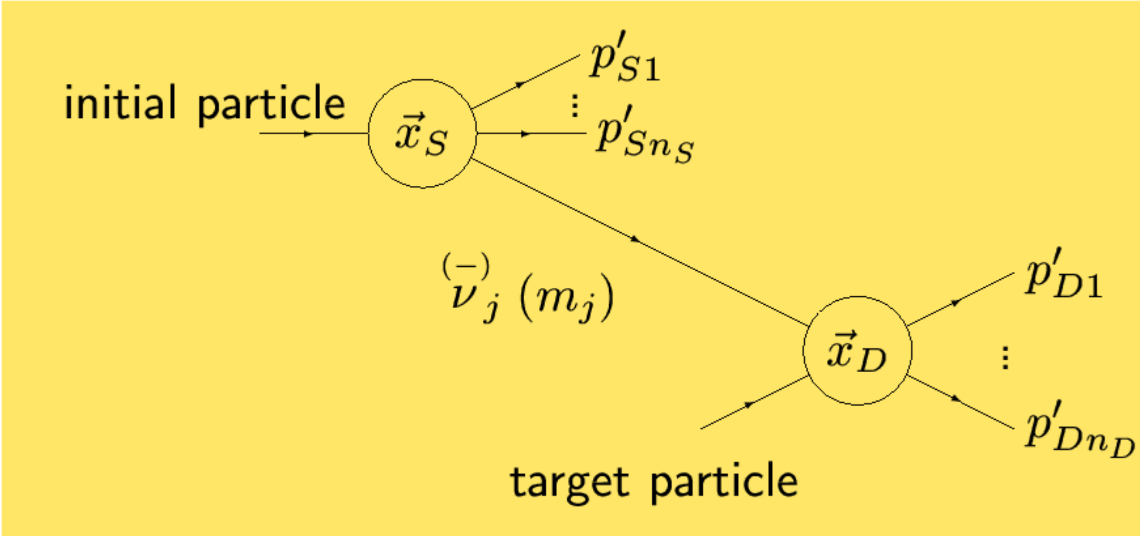
➔ $$\boxed{A_{ee} = \sum |U_{ei}|^2 e^{ip_i x} = \ldots}$$ +MSW

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)

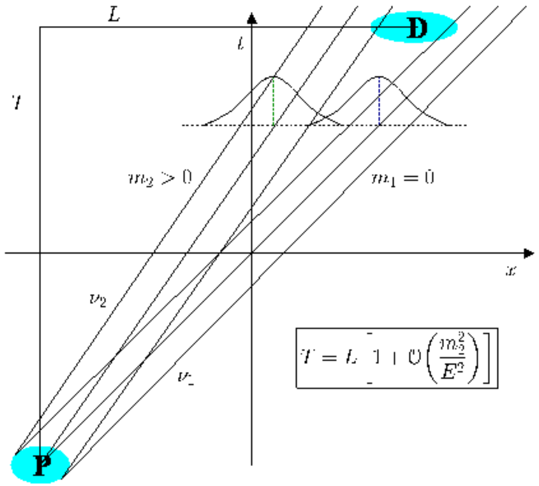
Localized Source and Detector:

- 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

$$\boxed{U_{MNS} = U \cdot \mathbf{diag}\,(\exp[\mathbf{i}\boldsymbol{\Phi}_1], \exp[\mathbf{i}\boldsymbol{\Phi}_2], \mathbf{1})}$$

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

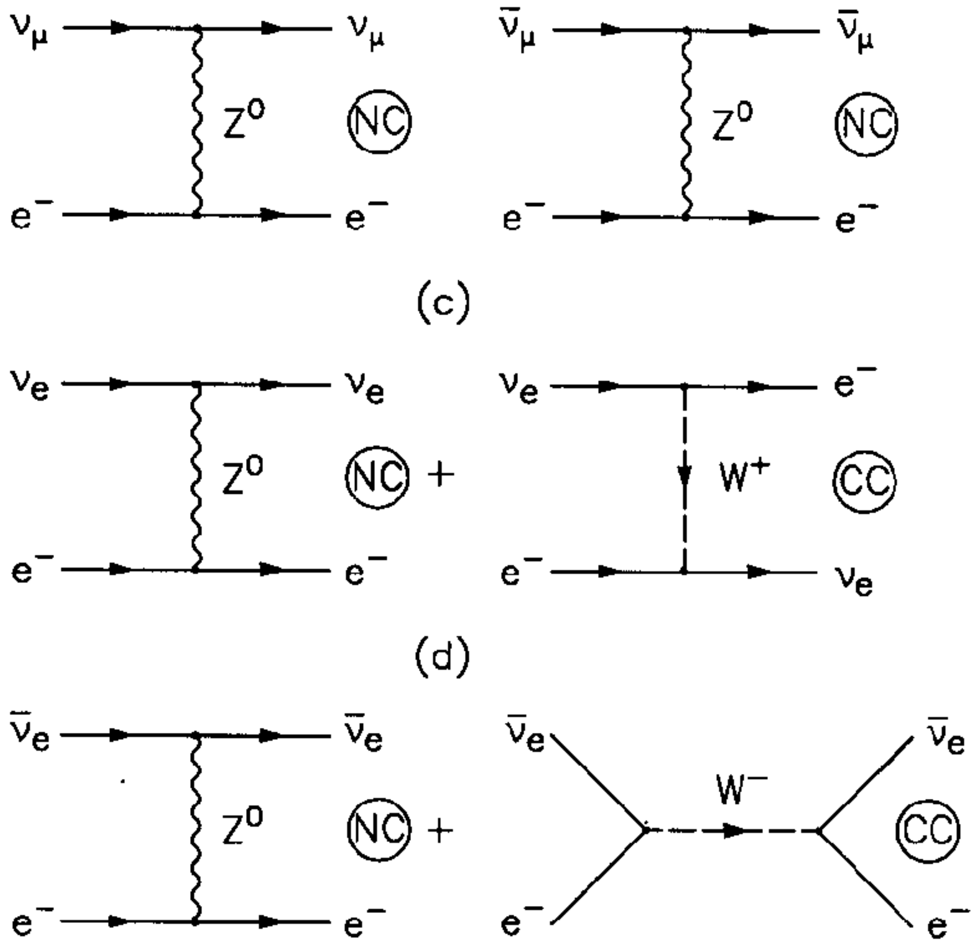
- Only U enters in neutrino oscillations: $\boxed{J_{ij}^{e_l e_m} := U_{li}U_{lj}^* U_{mi}^* U_{mj}}$
- All oscillation frequencies show up: $\boxed{\Delta_{ij} := \frac{\Delta m_{ij}^2 L}{4E} = \frac{(m_i^2 - m_j^2)L}{4E}}$

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

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

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

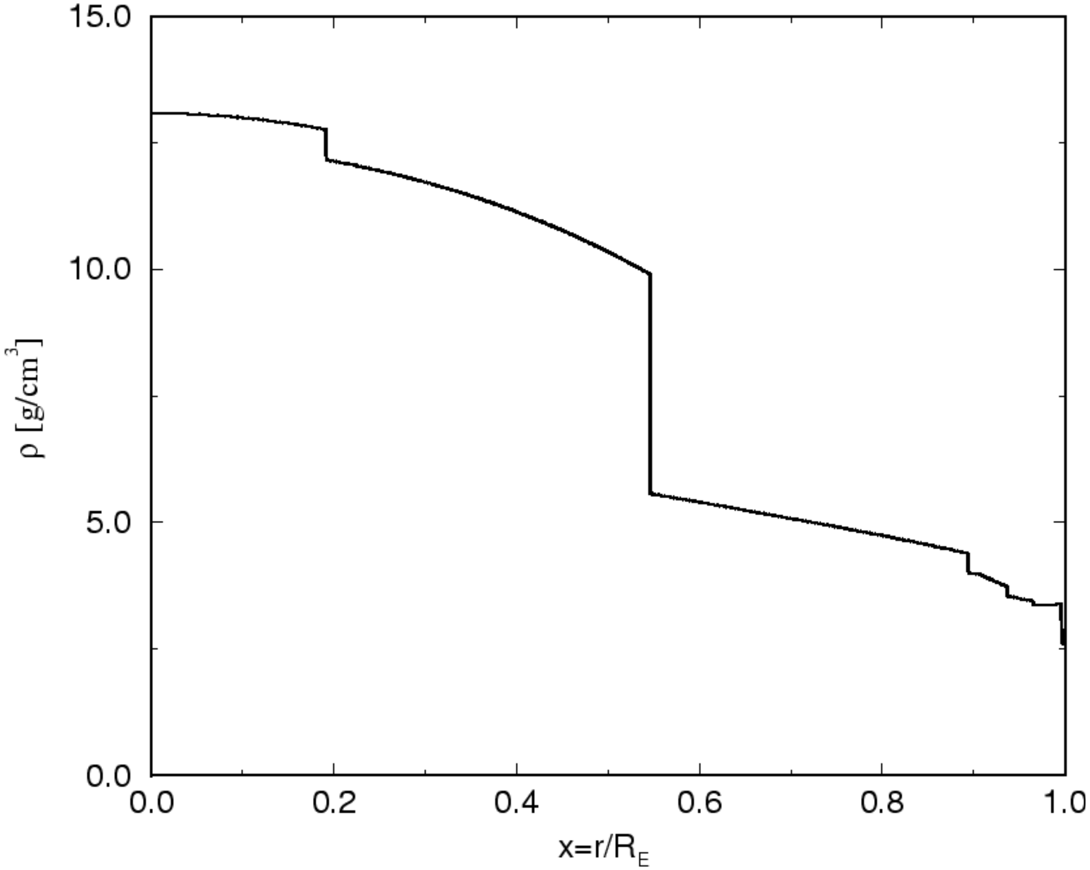
for beams
dominated by average density

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

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
$L \leq \mathcal{O}(10\,000 \text{ km})$ $\Leftrightarrow$ **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:

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

- $\mathbf{A} = \pm \frac{\mathbf{2\sqrt{2}G_F Y \rho E}}{\mathbf{m_n}} = 2V \cdot E$ $\quad \nu \oplus \text{matter} \quad$ and $\quad \overline{\nu} \oplus \text{anti} - \text{matter} \Rightarrow \quad$ “$+$”
- $Y = e^-$**/nucleon** ρ =**matter density** m_n =**nucleon mass**
- Overall phases drop out: $m_i \rightarrow m_i - m_1 \Rightarrow$ 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

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

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

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

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

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

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

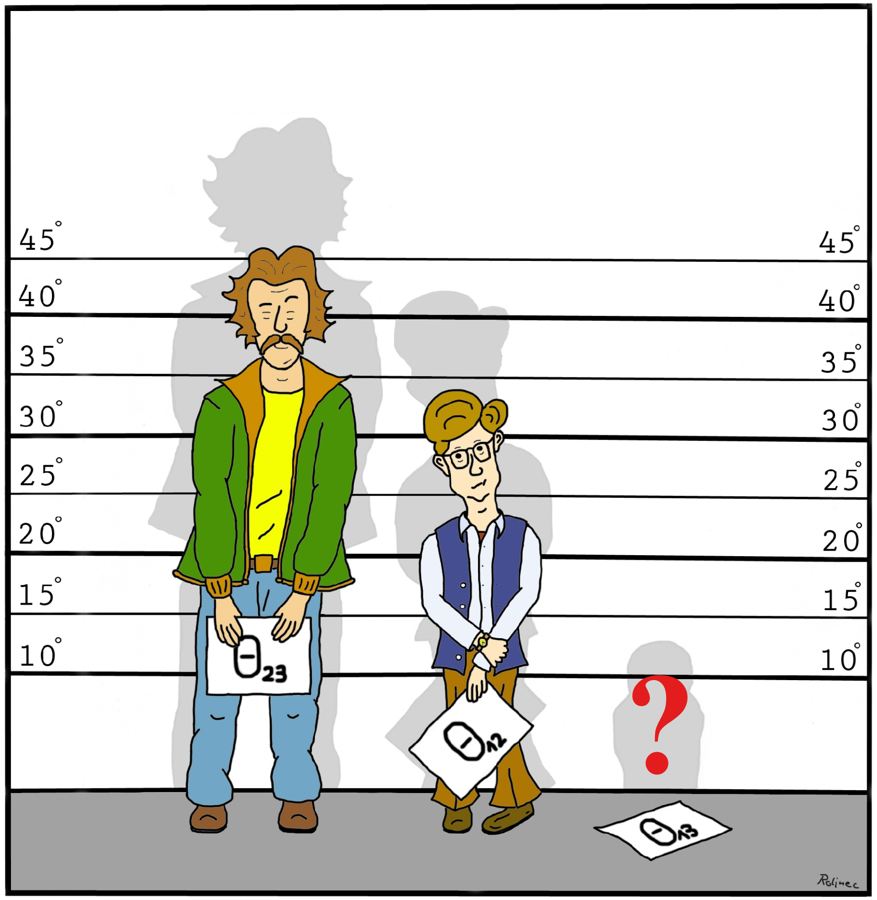
Cervera et al.
Freund, Huber, ML
Akhmedov, Johansson , ML, Ohlsson, Schwetz

5. The Value of Future Precision Experiments

1) Unique insight into various sources
   e.g. BOREXINO: Be flux, CNO, … ➔stellar evolution

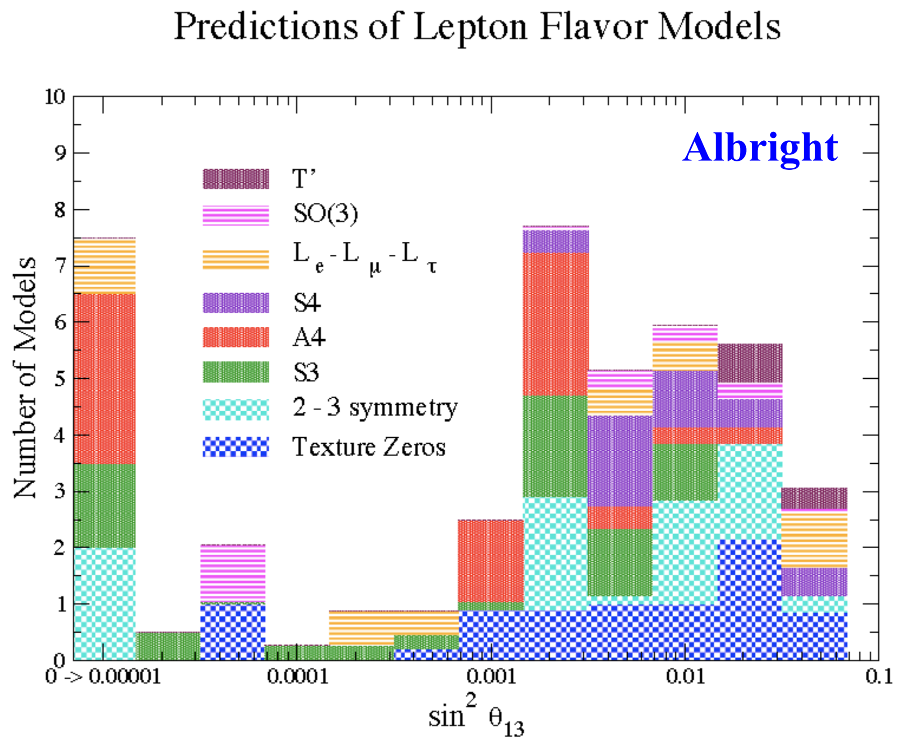
2) Information from lepton sector orthogonal to quarks
   ➔ free of hadronic uncertainties
   ➔ origin of flavour

θ_{13} – just one small Number?



… why care about θ_{13}

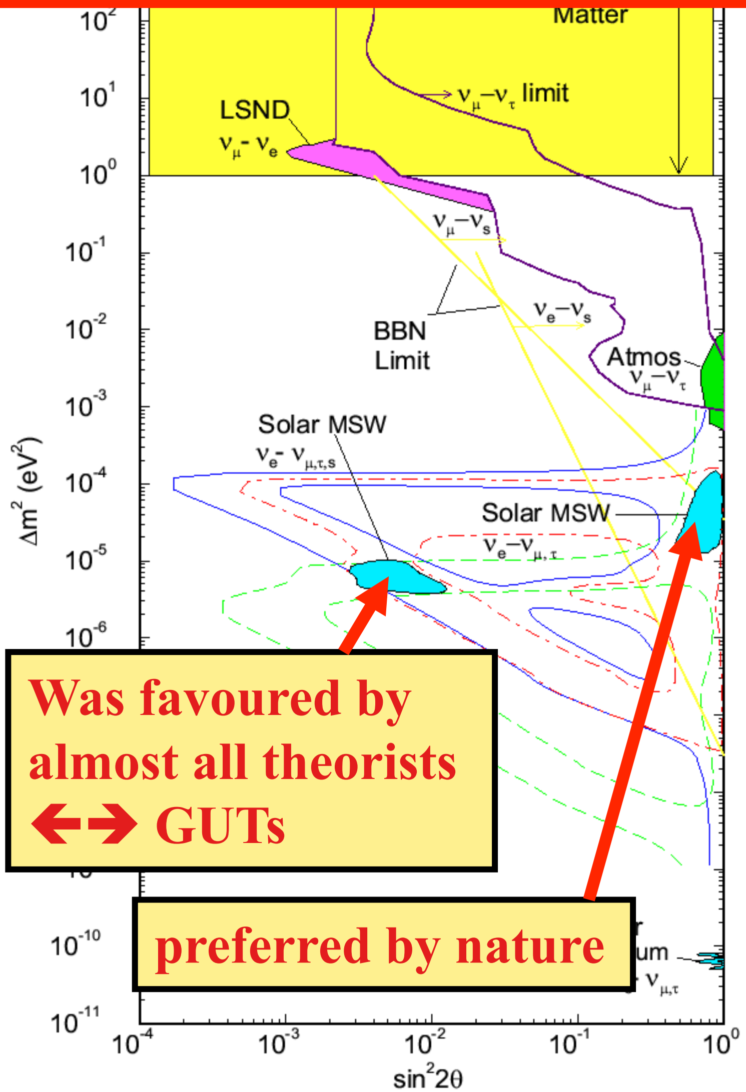
- **Good to know…**
- **Leptonic CP violation**
- **Theory models**



- **Is this enough? What else ???**

Learning about Flavour

History: Elimination of SMA



Was favoured by almost all theorists
⇔ GUTs

preferred by nature

Next: Smallness of θ_{13}, θ_{23} maximal

- models for masses & mixings
- input: known masses & mixings
  - ➔ distribution of θ_{13} predictions
  - ➔ θ_{13} expected close to ex. bound
  - ➔ well motivated experiments

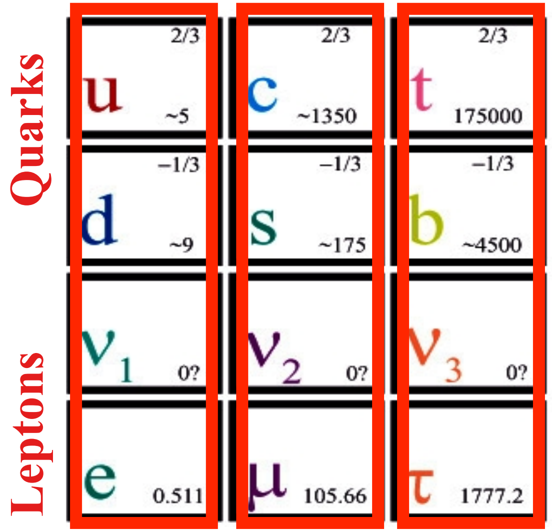
what if θ_{13} is very tiny?
or if θ_{23} is very close to maximal?

➔ numerical coincidence unlikely
➔ special reasons (symmetry, …)

➔ answered by coming precision

The larger Picture: GUTs

Gauge unification suggests that some GUT exists



1. 2. 3. generation

<u>**Requirements:**</u>

gauge unification

particle multiplets ⇔ ν_R

proton decay

…

E_6

$SU(5)\times U(1)$ — $SO(10)$ — $SU(3)_C \times SU(3)_L \times SU(3)_R$

$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$ — $SU(5)$

$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(3)_C \times SU(2)_L \times U(1)_Y$

many models…

GUT Expectations and Requirements

Quarks and leptons sit in the same multiplets

➔ one set of Yukawa couplings 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
➔ …

Sequential Dominance

$$m_D = \begin{pmatrix} . & . & . \\ . & a & b \\ . & c & d \end{pmatrix} \quad M_R = \begin{pmatrix} . & . & . \\ . & x & 0 \\ . & 0 & y \end{pmatrix}$$

$$\Rightarrow \quad m_\nu = -m_D \cdot M_R^{-1} \cdot m_D^T = \begin{pmatrix} . & . & . \\ . & \frac{a^2}{x} + \frac{b^2}{y} & \frac{ac}{x} + \frac{bd}{y} \\ . & \frac{ac}{x} + \frac{bd}{y} & \frac{c^2}{x} + \frac{d^2}{y} \end{pmatrix}$$

If one right-handed neutrino dominates, e.g. y >> x

- ➔ **small sub-determinant ~ $m_2 \cdot m_3$**
- ➔ **$m_2 \ll m_3$ (hierachy) and $\tan\theta_{23} \simeq a/c$ (large mixing)**

$$M_R = \begin{pmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{pmatrix} \Rightarrow$$

x<<y<<z

sequenatial dominance:

$m_1 \ll m_2 \ll m_3$ natural

naturally large mixings

S.F. King, …

Large Mixings and Type II See-Saw

Type II see-saw:
- rather natural
- interference of two terms

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

m_D and M_R may have small mixings and hierarchy

However: M_L can be numerically more important

Example: Break GUT → $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ → M_L from LR

→ large mixings natural for almost degenerate case $m_1 \sim m_2 \sim m_3$

→ type I see-saw would only be a correction

type I – type II interference → Rodejohann, ML

→ $M_L \simeq m_D M_R^{-1} m_D^T$ → interesting possibilities

→ dominance of one term + perturbation by 2nd term →

$U_{e3}=0$; maximal θ_{23} + small Perturbations

Leading structure from one type II term➔ perturbation by 2nd

Three simple, stable candidates for $U_{e3}=0$ and maximal θ_{23}

$$(A): \sqrt{\frac{\Delta m_A^2}{4}} \begin{pmatrix} 0 & 0 & 0 \\ \cdot & 1 & -1 \\ \cdot & \cdot & 1 \end{pmatrix} \qquad L_e \quad EV = \sqrt{\Delta m_A^2} \quad NH$$

$$(B): \sqrt{\frac{\Delta m_A^2}{2}} \begin{pmatrix} 0 & 1 & 1 \\ \cdot & 0 & 0 \\ \cdot & \cdot & 0 \end{pmatrix} \qquad L_e - L_\mu - L_\tau \quad EV = 0 \quad IH$$

$$(C): m_0 \begin{pmatrix} 1 & 0 & 0 \\ \cdot & 0 & 1 \\ \cdot & \cdot & 0 \end{pmatrix} \qquad L_\mu - L_\tau \quad EV = -m_0 \quad degenerate$$

Perturbation of the Leading Structure

e.g. 'democratic' perturbation:

$$m_\nu^I \simeq v_L\,\epsilon \begin{pmatrix} 1 & 1 & 1 \\ \cdot & 1 & 1 \\ \cdot & \cdot & 1 \end{pmatrix}$$

<u>e.g. as correction to case (A):</u>

➔ **naturally large $\theta_{12} = 1/3$ (tri-bimaximal mixing)**

➔ **finite $\theta_{13} \simeq$** $\sqrt{(\Delta m^2_{sol}/\Delta m^2_{atm})} \simeq 1/30$

➔ **corrections to θ_{23}-$\pi/4 \simeq$** $\sqrt{(\Delta m^2_{sol}/\Delta m^2_{atm})} \simeq 1/30$

Tri-bimaximal Mixing

- tri-bimaximal mixing works phenomenologically very well
- mass matrix can be written as a sum of three terms

$$m_\nu = \frac{m_1}{6}\begin{pmatrix} 4 & -2 & -2 \\ \cdot & 1 & 1 \\ \cdot & \cdot & 1 \end{pmatrix} + \frac{m_2}{3}\begin{pmatrix} 1 & 1 & 1 \\ \cdot & 1 & 1 \\ \cdot & \cdot & 1 \end{pmatrix} + \frac{m_3}{2}\begin{pmatrix} 0 & 0 & 0 \\ \cdot & 1 & -1 \\ \cdot & \cdot & 1 \end{pmatrix}$$

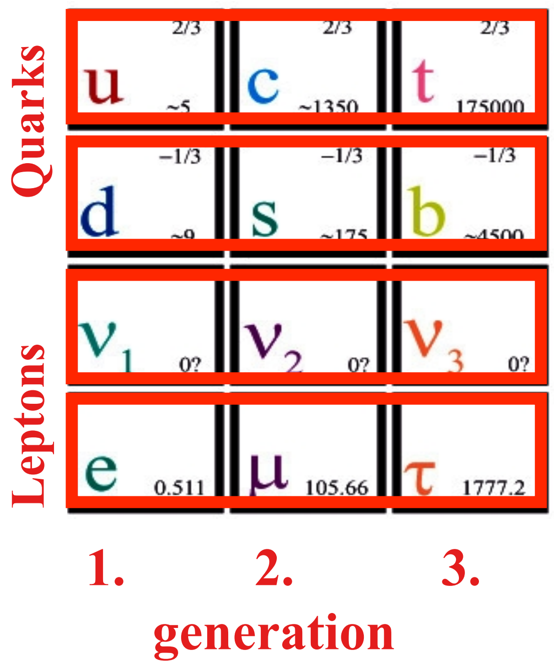
- phenomenologically very sucessful
- tempting to think of it as a consequence of three terms
- type II $\Leftrightarrow$ m_2, m_3
- third scale?

Flavour Unification

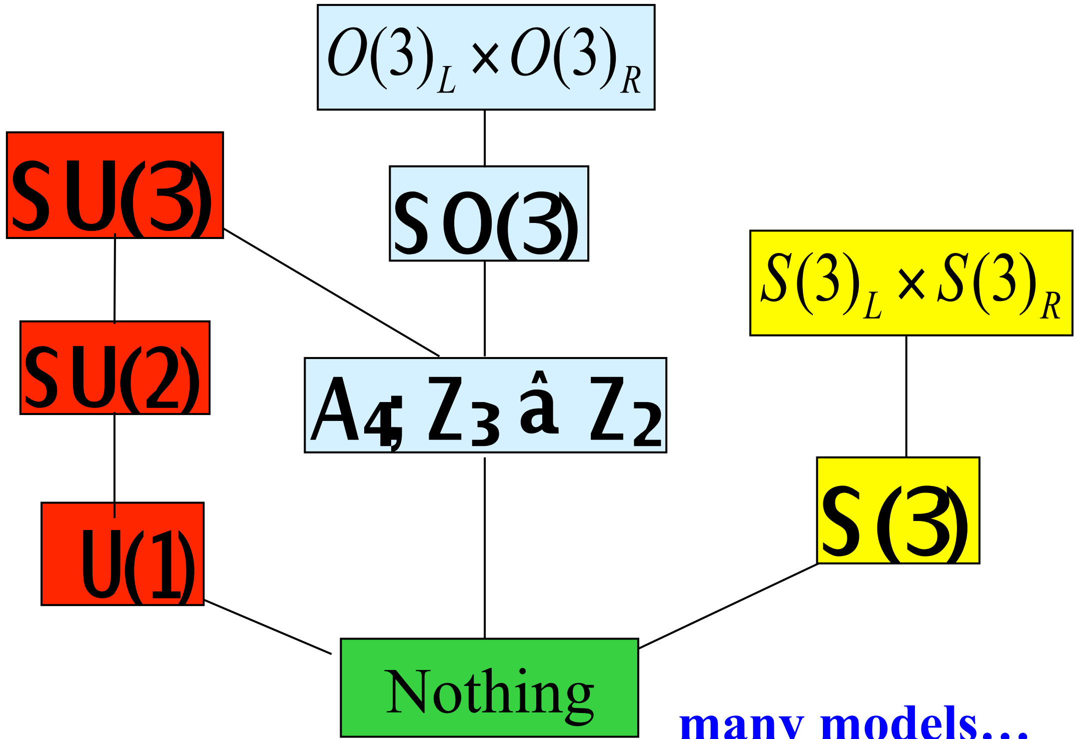
- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

➔ **symmetry** not texture zeros



Examples:

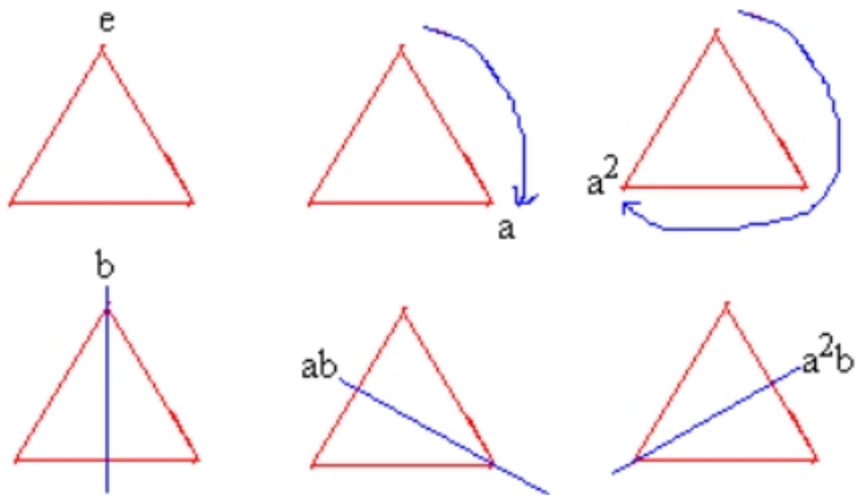


many models…

Discrete Flavour Symmetries

e.g. dihedral groups D_n

geometric origin of D_3:



phenomenologically promising example: D_5 Hagedorn, ML, Plentinger

task: search for mass terms which are for suitable Higges singlets under D_5

1) assign fermions to representations $L = \{L_1, L_2, L_3\}$

2) write down any possible mass term using arbitrary 'flavon' scalars
$\Leftrightarrow$ singlet under symmetry

D_5 Allowed Mass Terms

Dirac mass terms: $$\lambda_{ij} L_i^T (i\sigma_2) \phi L_j^c$$

Majorana mass terms: $$\lambda_{ij} L_i^T \Xi \phi L_j$$

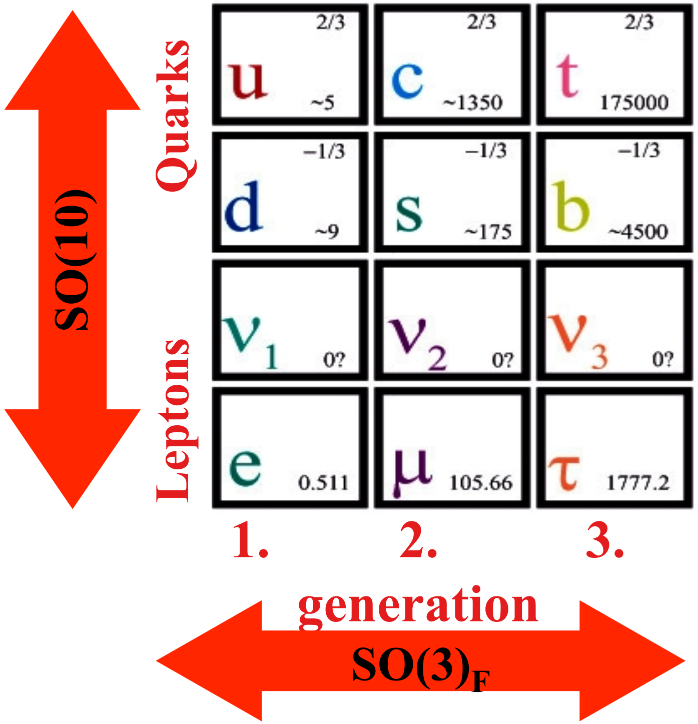
➔ **D5 symmetry induced mass matrices:**

Higgses ⇔ m_ν:
$\Phi_1 \sim 1_1$
$\Phi_2 \sim 1_2$
$\Psi_1 \sim 2_1$

L	L^C	Mass Matrix
$(1_2, 1_1, 1_1)$	$(2_1, 1_1)$	$\begin{pmatrix} \kappa_1\psi_2^1 & -\kappa_1\psi_1^1 & \kappa_4\phi^2 \\ \kappa_2\psi_2^1 & \kappa_2\psi_1^1 & \kappa_5\phi^1 \\ \kappa_3\psi_2^1 & \kappa_3\psi_1^1 & \kappa_6\phi^1 \end{pmatrix}$

➔ **check phenomenology** ➔ **OK + "predictions"**
PROBLEM: many sucessful symmetries

GUT ⊗ Flavour Unification



➔ GUT group ⊗ flavour group

<u>example:</u> $SO(10) \otimes SU(3)_F$

- SSB of $SU(3)_F$ between Λ_{GUT} and Λ_{Planck}
- all flavour Goldstone Bosons eaten
- discrete sub-groups survive ⟷ SSB
  e.g. Z2, S3, D5, A4
  ➔ structures in flavour space
  ➔ compare with data

GUT ⊗ flavour is rather restricted

⟷ small quark mixings *AND* large leptonic mixings ; quantum numbers

➔ only a few viable models; phenomenological success highly non-trivial

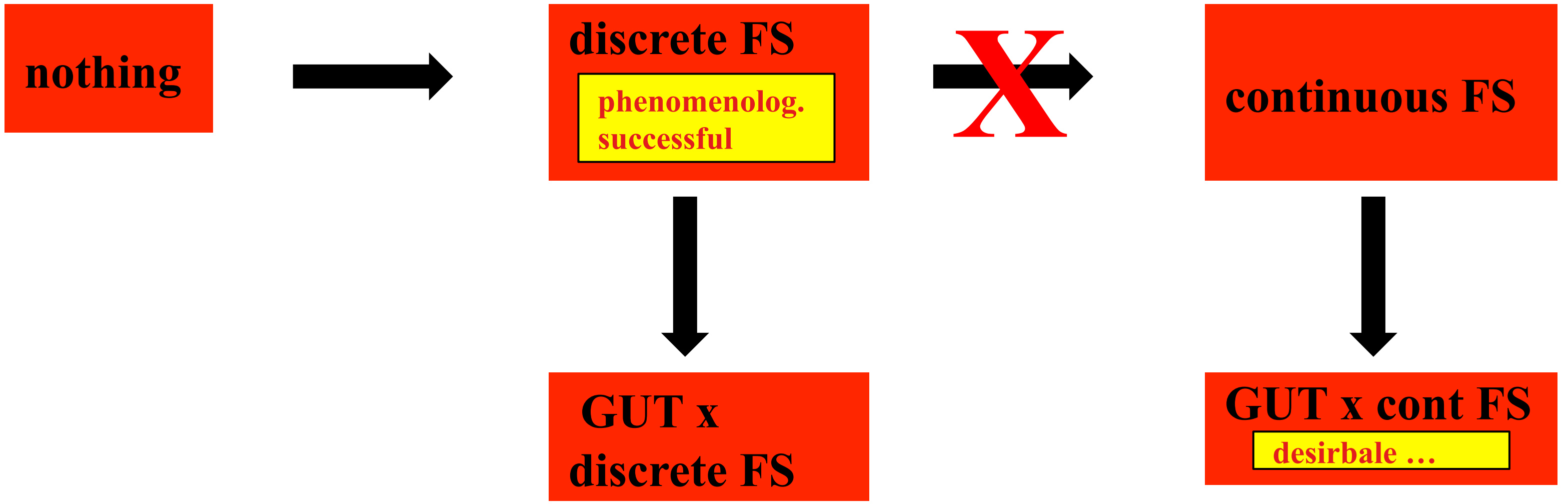
Adulpravitchai, Blum, ML:

no-go theorem: SU(2) or SU(3) + reasonably small representations ➔ only D'_2

➔ alternatives: e.g. discrete flavor sym. from T^2/Z_N orbifolds, … ???

➔ <u>aim: learn about the origin of flavour by future precision</u>

Flavour Symmetry Routes



Adulpravitchai, Blum, ML:

~ no-go theorem for embedding of discrete flavour symmetries:

- SU(2) or SU(3) + reasonably small representations ➔ only D'_2
- larger flavour groups ➔ larger representations ⇐⇒ new particles?

Alternative attitude concerning discrete flavour symmetries:

- other types of embedding of discrete flavour symmetries
  e.g. discrete flavor sym. from T^2/Z_N orbifolds, x-dra dimensions…
- direct embedding into continuous flavour symmetries

Renormalization Group Running

low energies:
- small masses
- large mixings

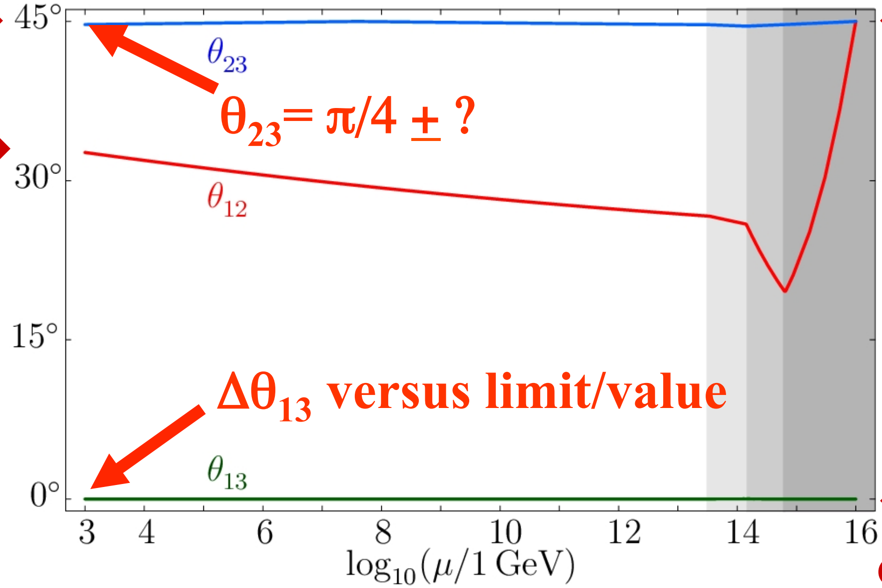
renormalization group running

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

atmospheric →

solar →

reactor →



← bi-maximal

← Small or even zero

MSSM example:
Antusch, Kersten, ML, Ratz

Guaranteed Results & Surprises?

- **Precise angles, phases and masses!**
- **Potential for other physics!**
- **Unexpected effects?**

Other effective Operators Beyond the SM

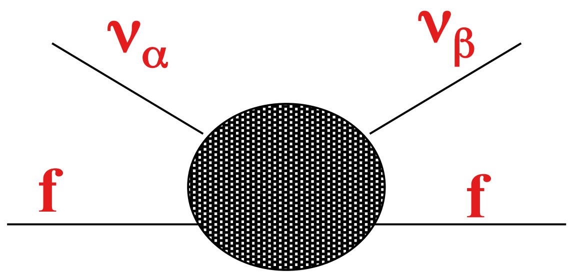
➔ effects beyond 3 flavours

➔ 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)

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



NSIs & Oscillations

Future precision oscillation experiments:

- must include **full 3 flavour oscillation probabilities**
- **matter effects**
- define **sensitivities on an event rate basis**

  ➔ **Simulations with GLoBES**

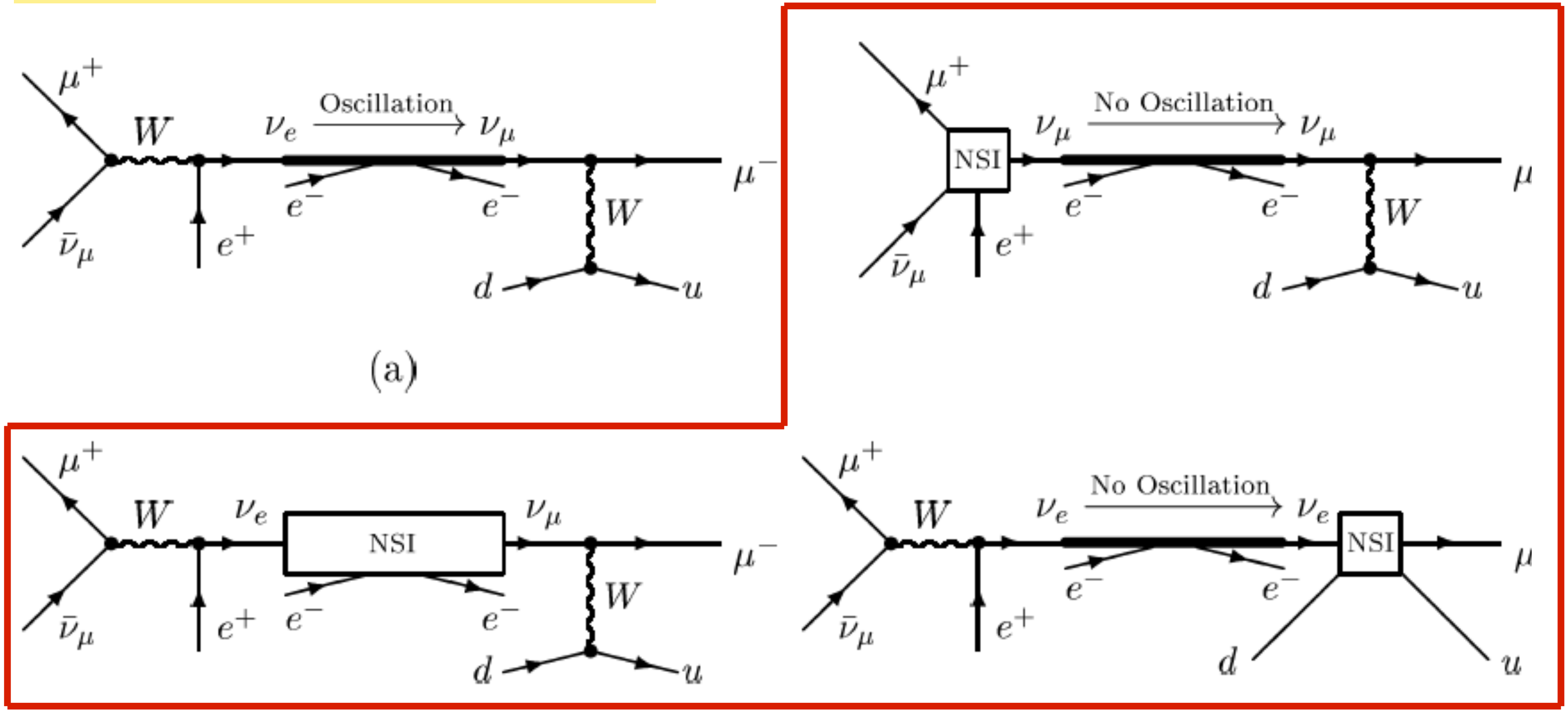
Source	⊗	Oscillation	⊗	Detector
- neutrino energy E - flux and spectrum - flavour composition - contamination - symmetric $\nu/\overline{\nu}$ operation		- oscillation channels - realistic baselines - MSW matter profile - degeneracies - correlations		- effective mass, material - threshold, resolution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

precision experiments might see new effects beyond oscillations ➔ NSIs!

NSIs interfere with Oscillations

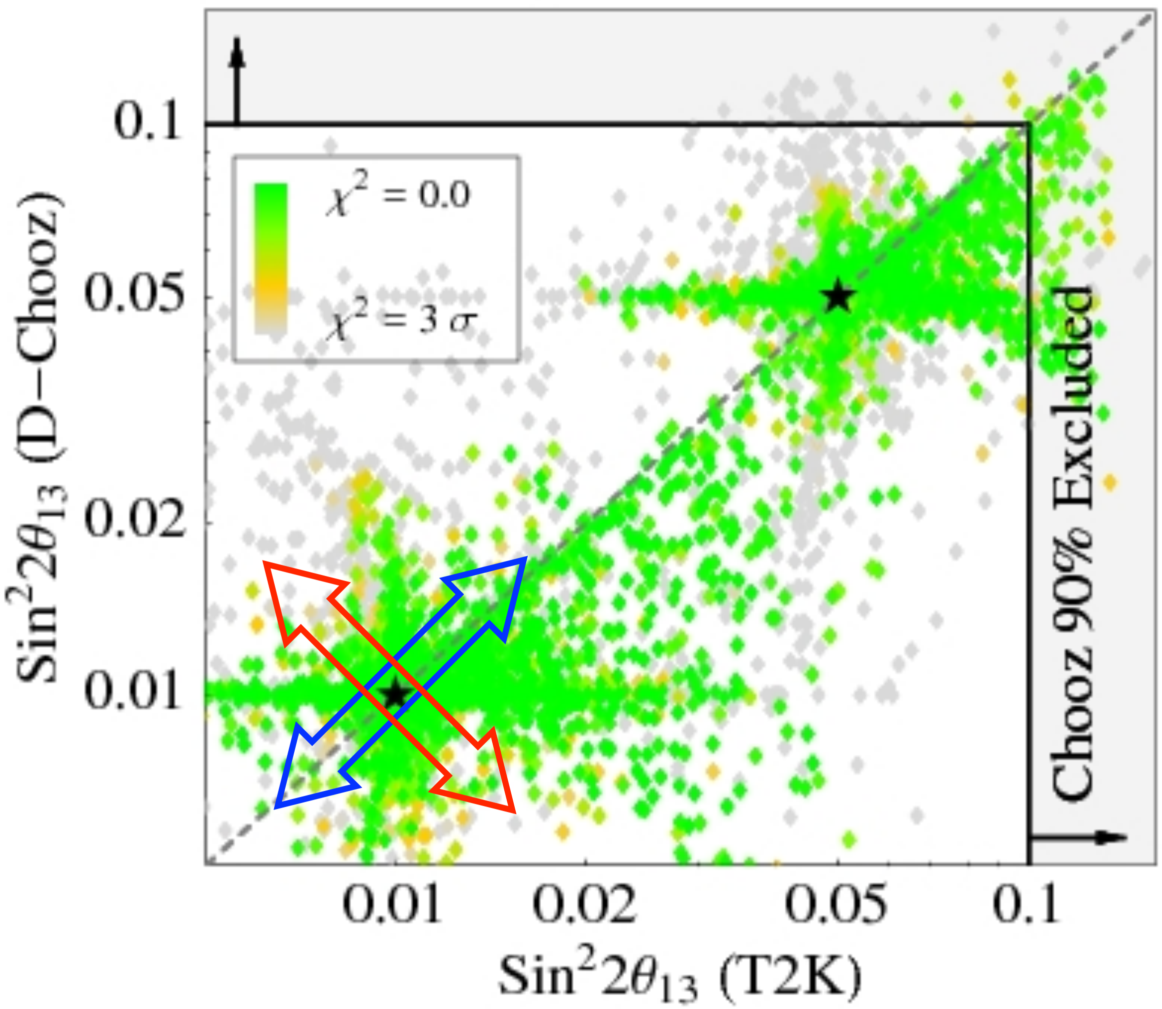
the "golden" oscillation channel

NSI contributions to the "golden" channel



note: interference in oscillations ~ε || FCNC effects ~ε^2

NSI: Offset and Mismatch in θ_{13}



Kopp, ML, Ota, Sato

<u>**redundant measurement of θ_{13}**</u>

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

<u>**scatter-plot:**</u>

- **ε values random**
- **below existing bounds**
- **random phases**

<u>**NSIs can lead to:**</u>

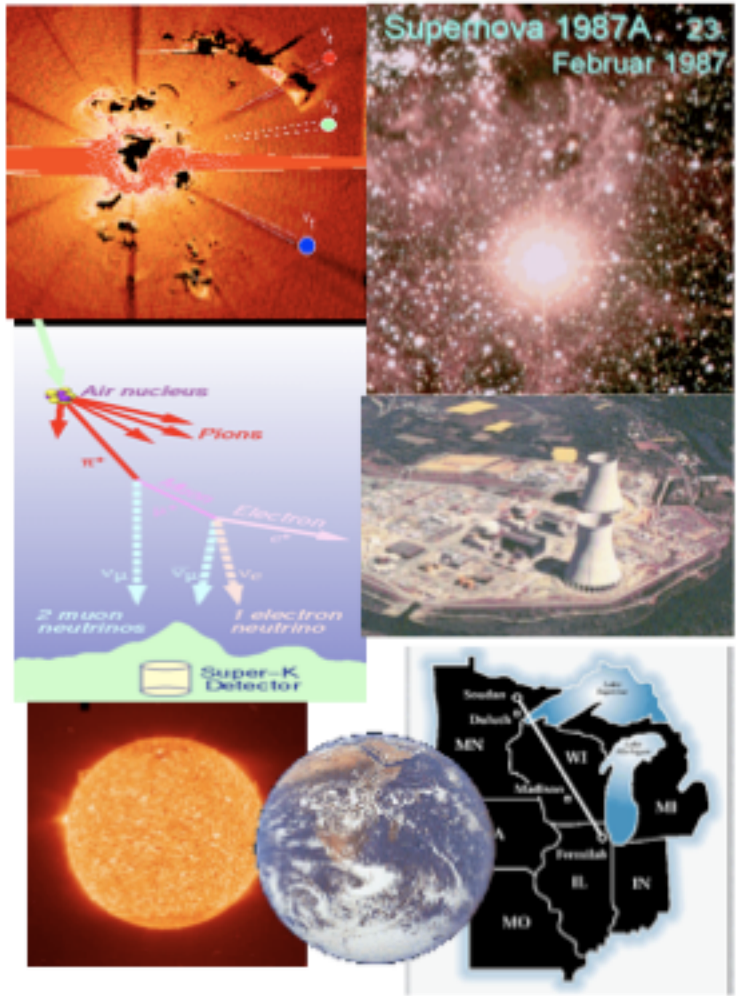
- **offset**
- **mismatch**

➔ **redundancy**

➔ **interesting potential**

6. Neutrino as Probes into Sources

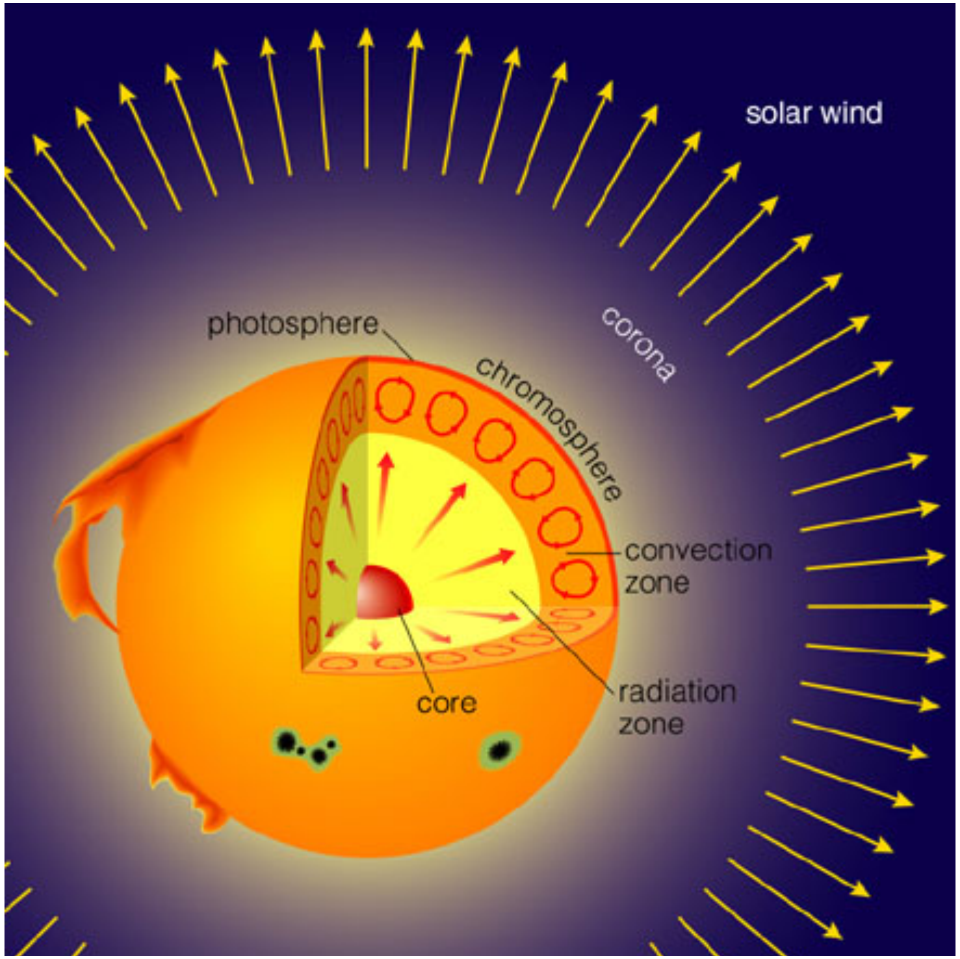
➔unique insights into sources!
⇔ connections to many fields



Solar Neutrinos: Learning About the Sun

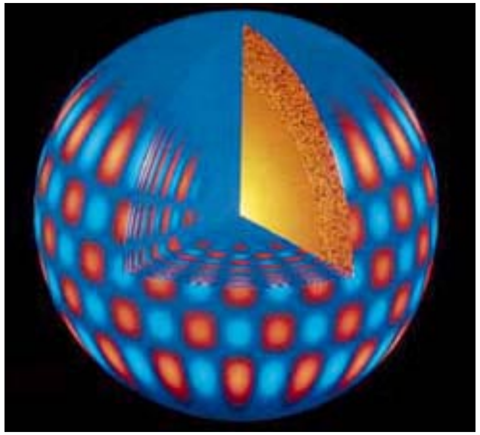
<u>Observables:</u>

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



<u>Topics:</u>

- **nuclear cross sections (at finite T ~ few MeV)**
- **solar dynamics**
- **helio-seismology**
- **variability**
- **composition**



Hydrogen Burning: Proton-Proton Chains

$p + p \rightarrow {}^2H + e^+ + \nu_e$
< 0.420 MeV

$p + e^- + p \rightarrow {}^2H + \nu_e$
1.442 MeV

100%

0.24%

${}^2H + p \rightarrow {}^3He + \gamma$

85%

15%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$
< 18.8 MeV

90%

10%

0.02%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$
0.862 MeV

${}^7Be + e^- \rightarrow {}^7Li^* + \nu_e$
0.384 MeV

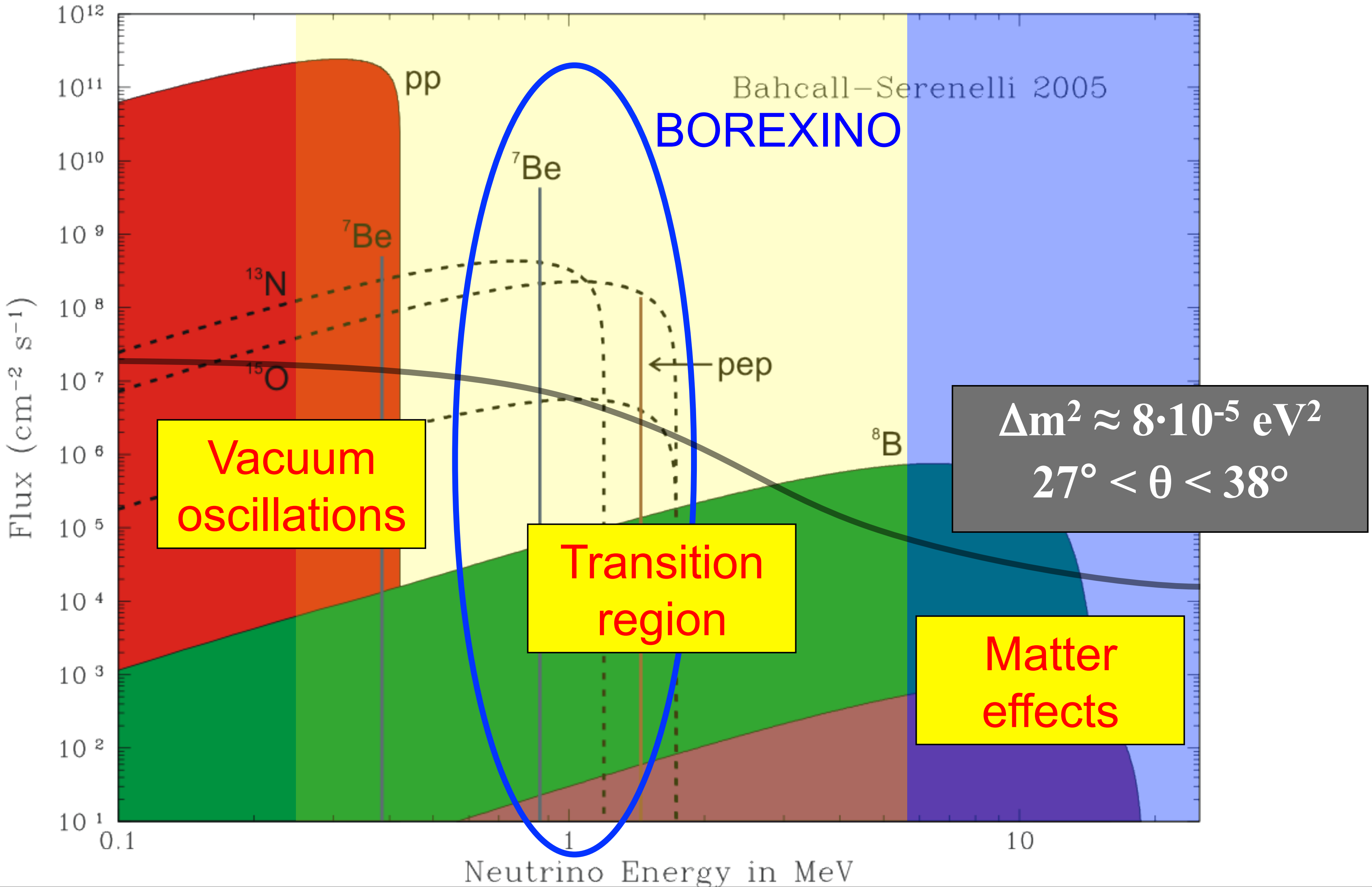
${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
< 15 MeV

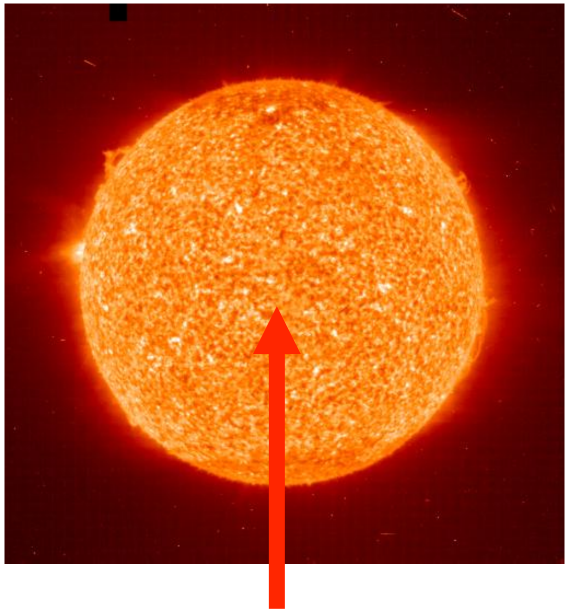
${}^8Be^* \rightarrow {}^4He + {}^4He$

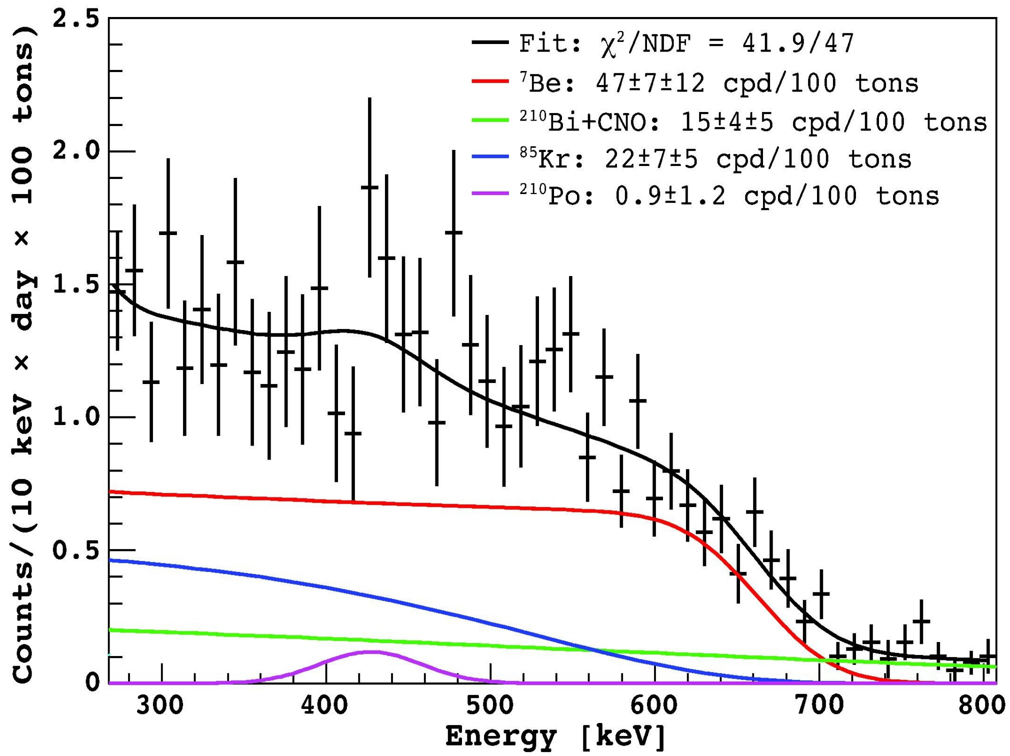
${}^7Li + p \rightarrow {}^4He + {}^4He$

Solar Neutrino Spectroscopy



Borexino tests the Sun





BOREXINO:

the sun in real time
photons ~10ky delay

47±7 events / day /100t
expected:
with oscillation 49±4
without 75±4

More to come:

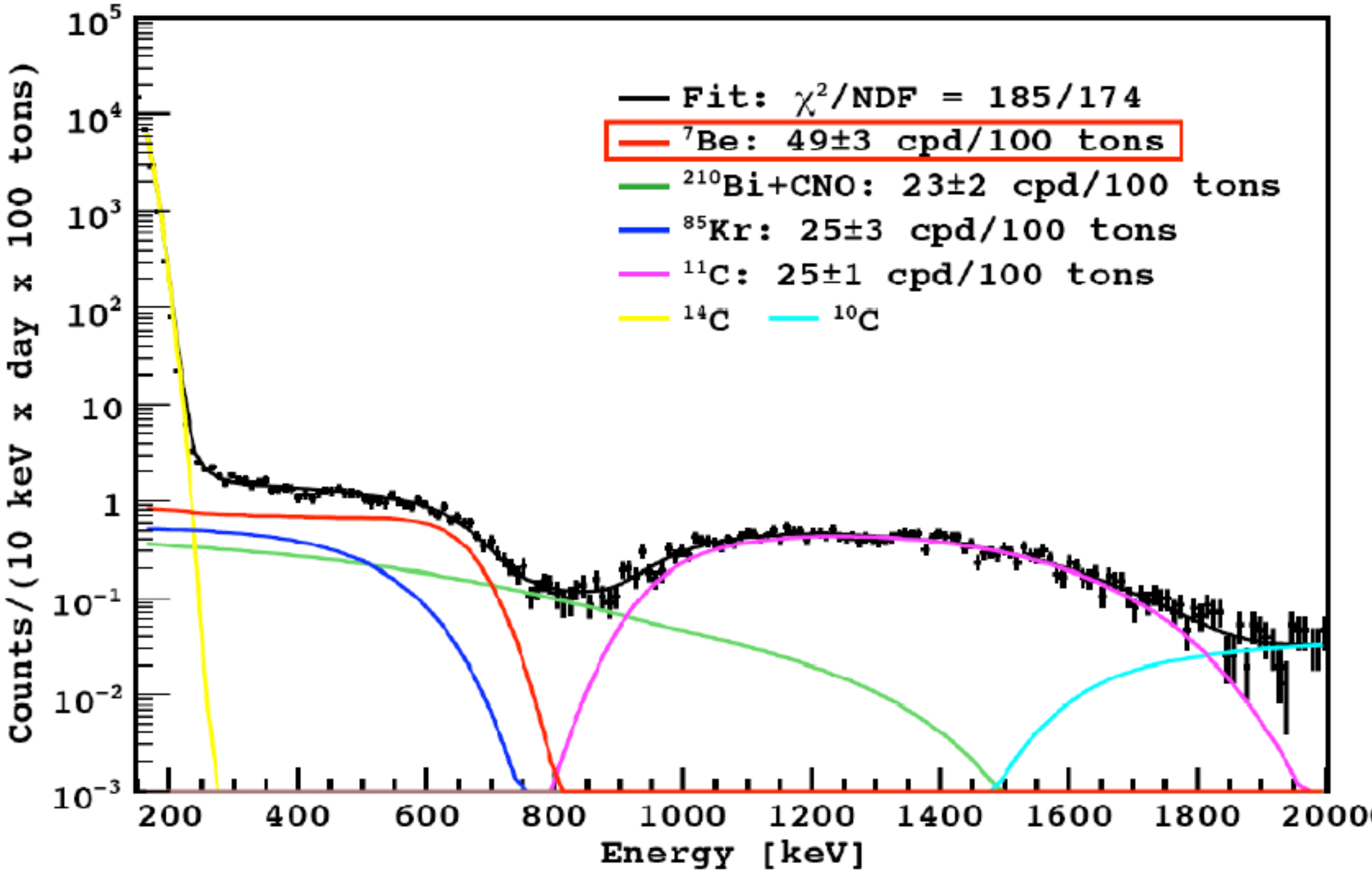
Improved statistics and reduced systematics

➔ 3.5% seasonal variation…

➔ CNO cycle

➔ geo-neutrinos, …

Borexino: 192 Days of Data

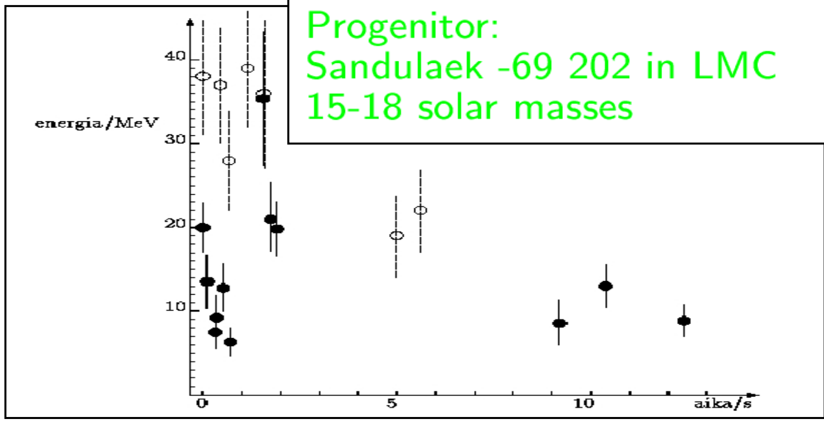


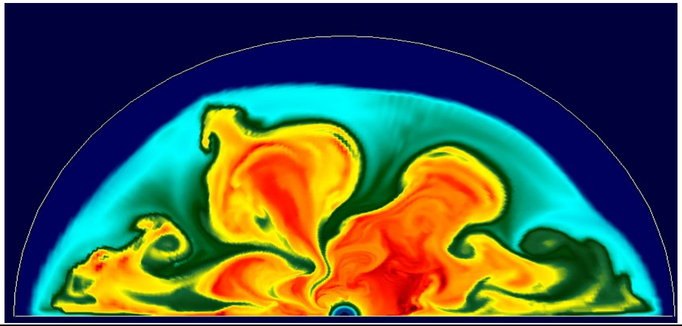
Supernova Neutrinos

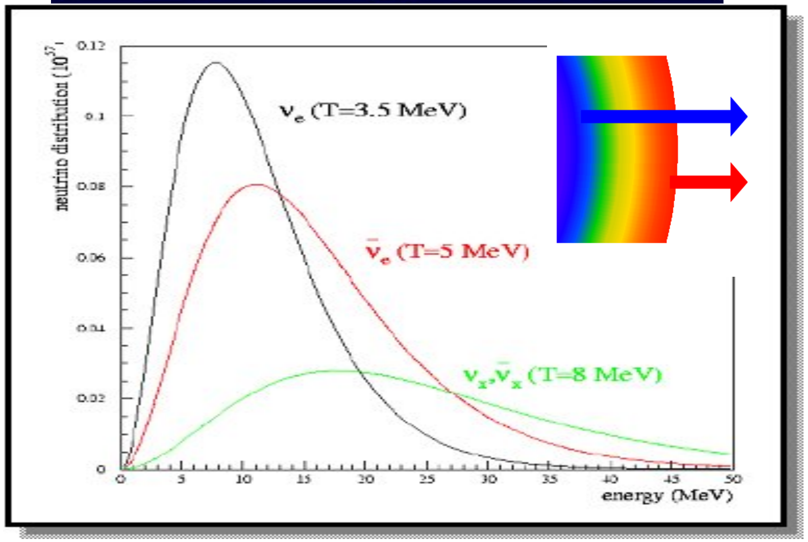
- Collaps of a typical star ➔ ~10^{57} ν's
- ~99% of the energy in ν's
- ν's essential for explosion
- 3d simulations do not explode
  (so far... 2d➔3d, ➔convection? ...)

SN1987A neutrino burst

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

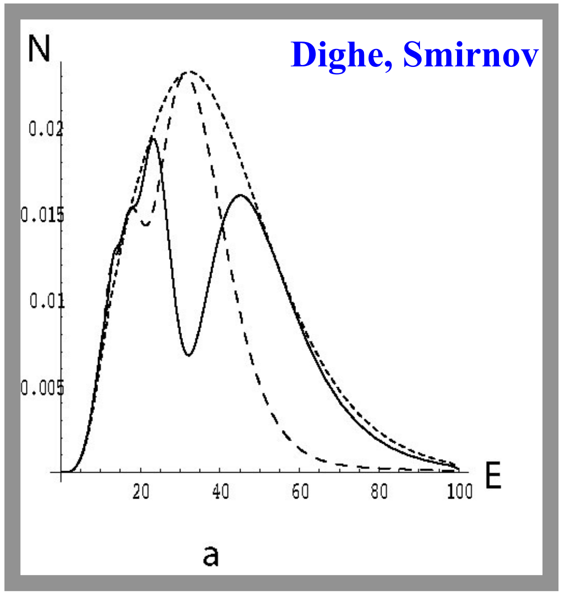




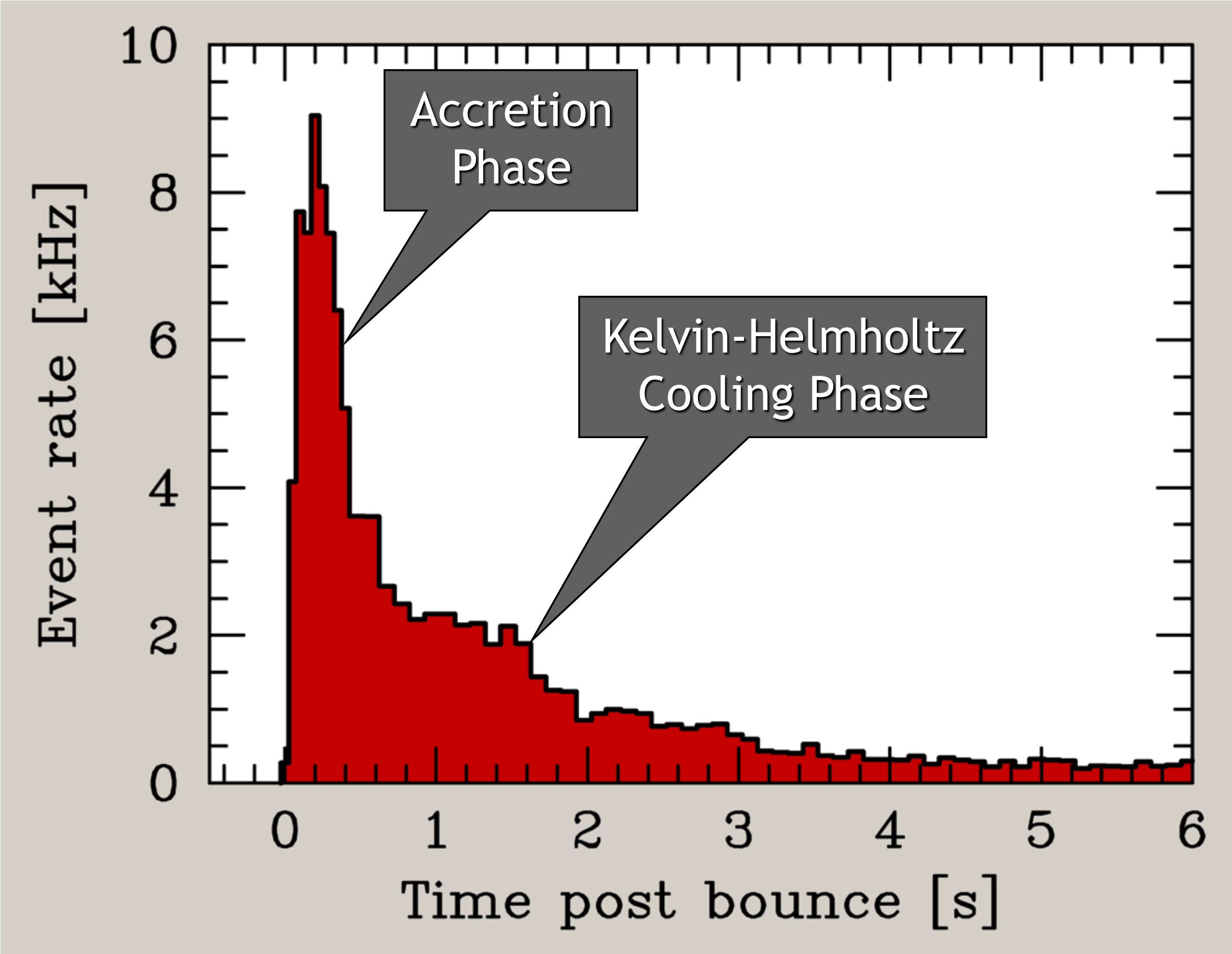


MSW: SN & Earth

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

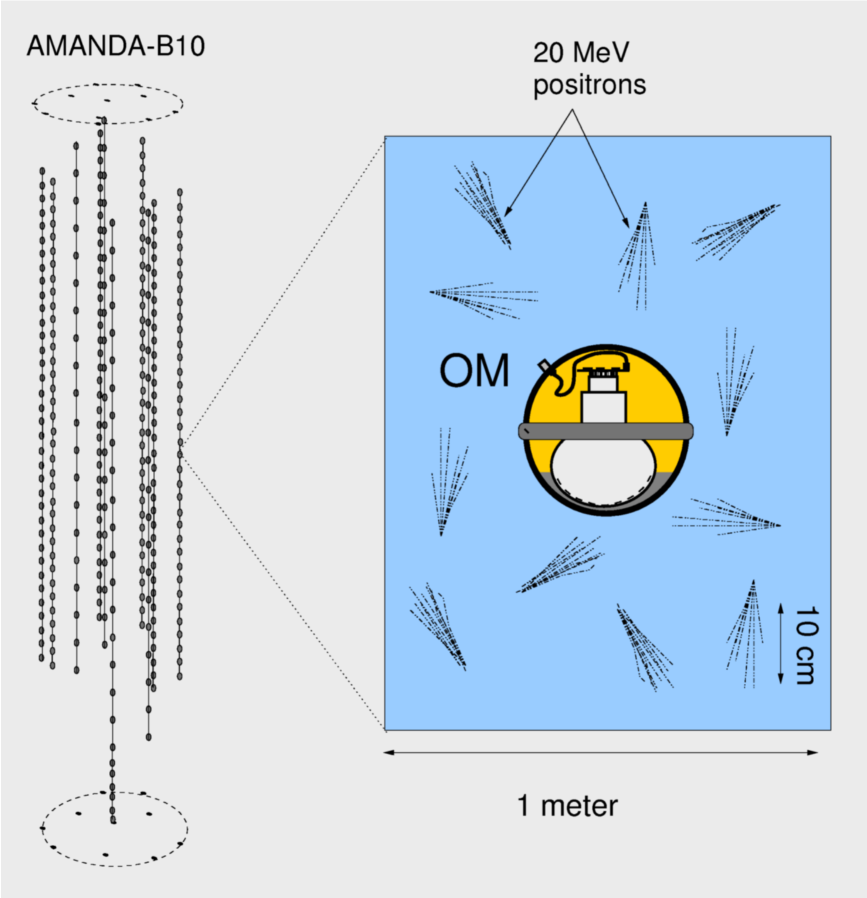


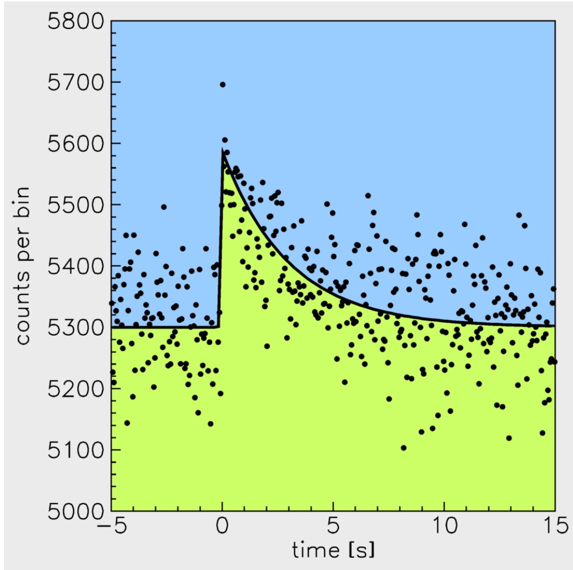
Simulated Supernova Signal at SK



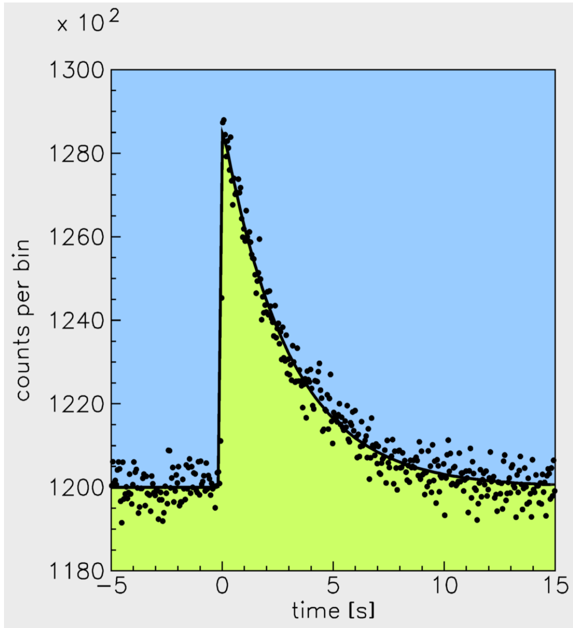
Simulation for Super-Kamiokande SN signal at 10 kpc
Totani, Sato, Dalhed & Wilson

Amanda/IceCube as a Supernova Detector





SN @ 8.5 kpc Signal in Amanda



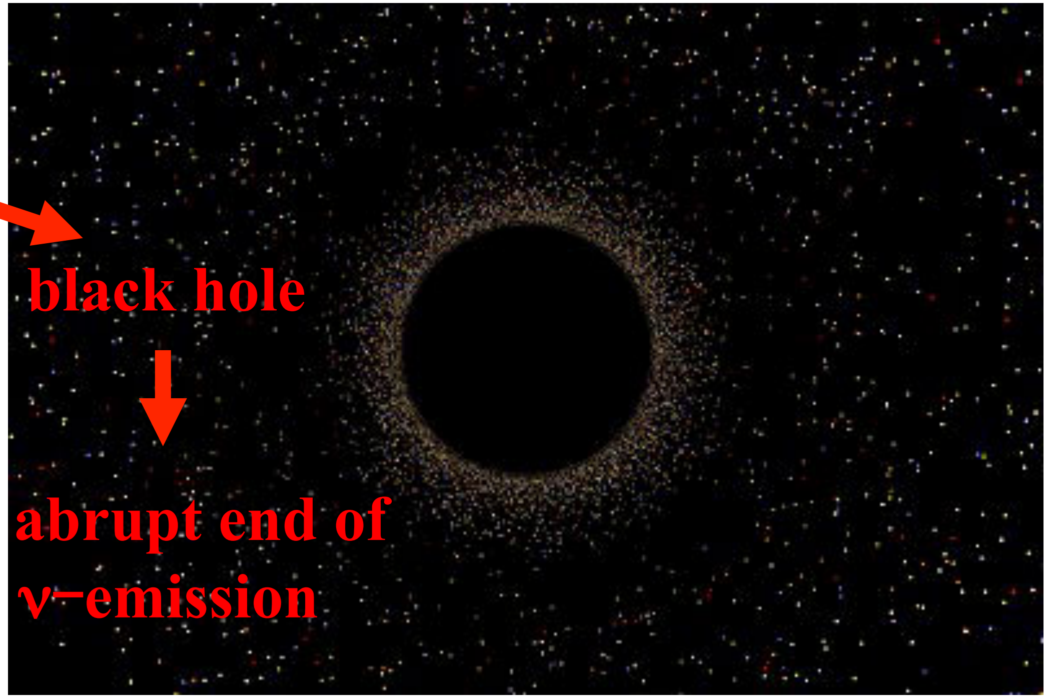
SN @ 8.5 kpc Signal in IceCube

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

2 possibilities:

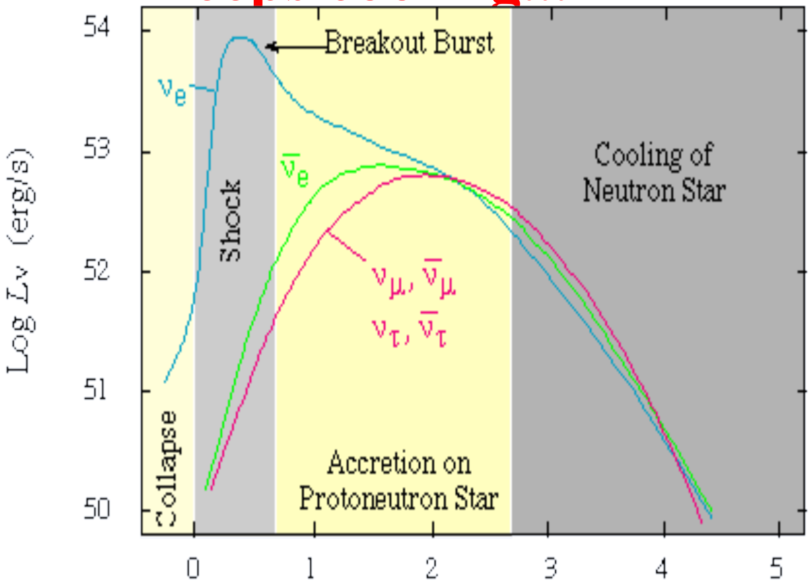
Supernova

neutron star or black hole



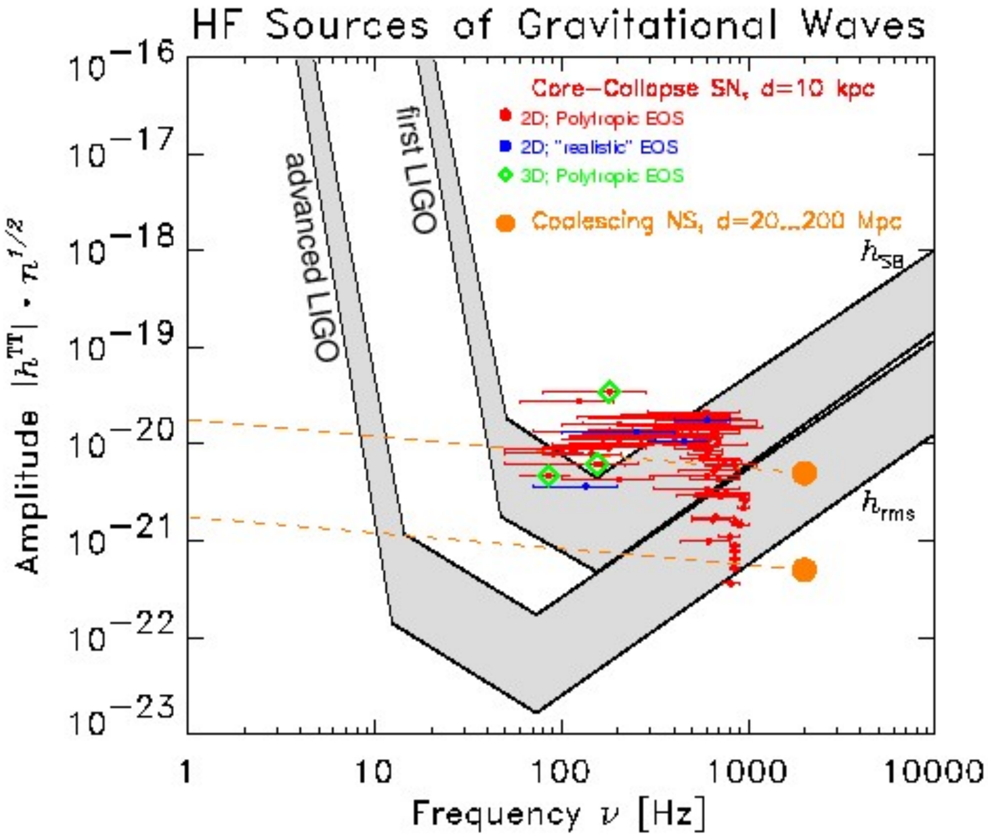
abrupt end of ν−emission

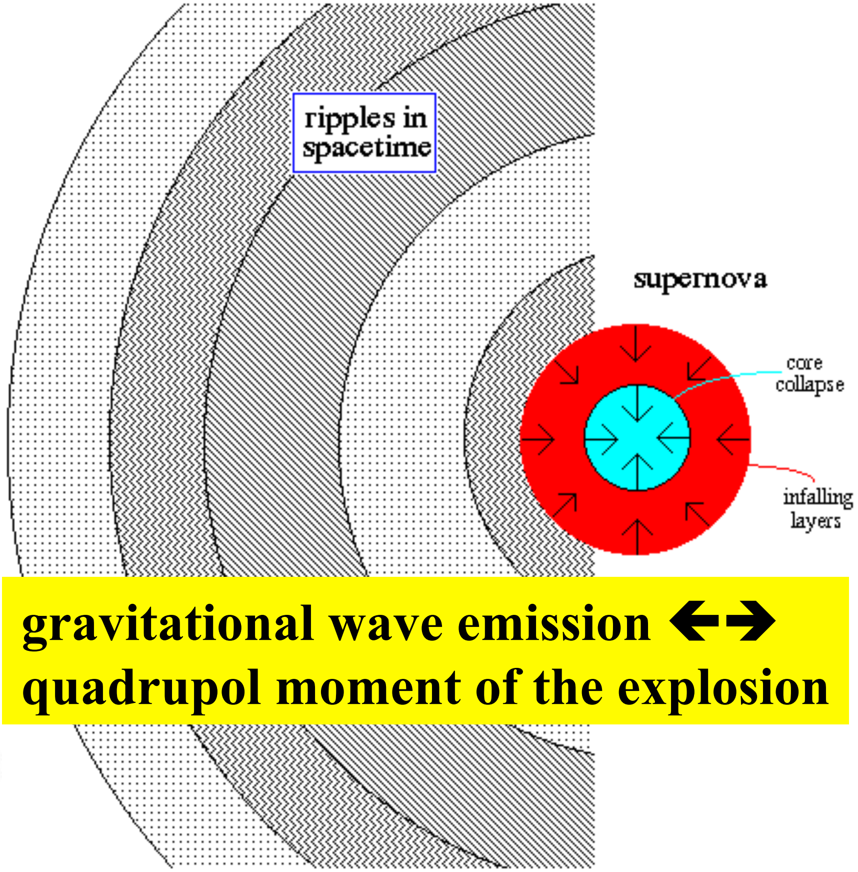
Keeps cooling...



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

Supernovae & Gravitational Waves



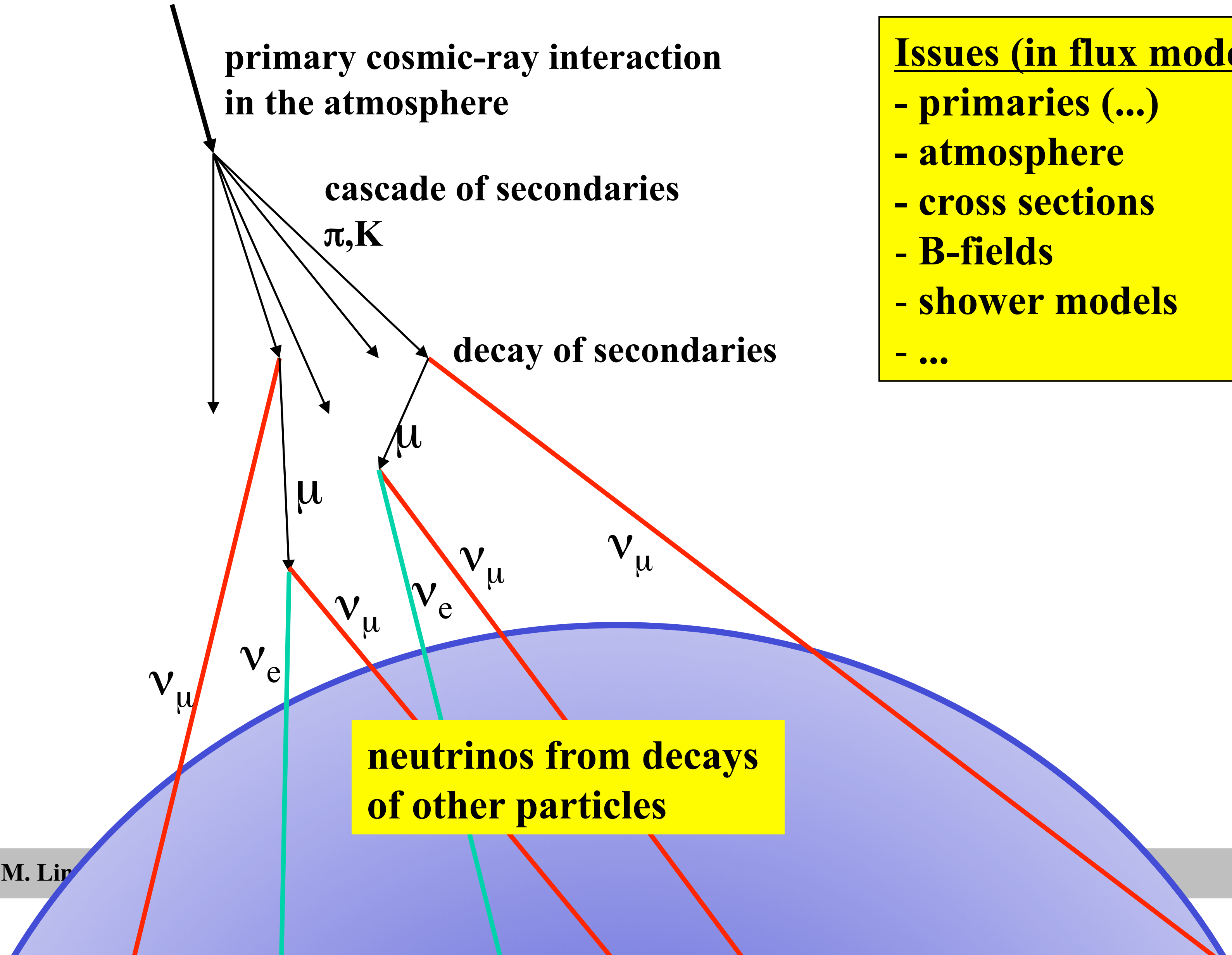


gravitational wave emission ←→ quadrupol moment of the explosion

Dimmelmeier, Font, Müller

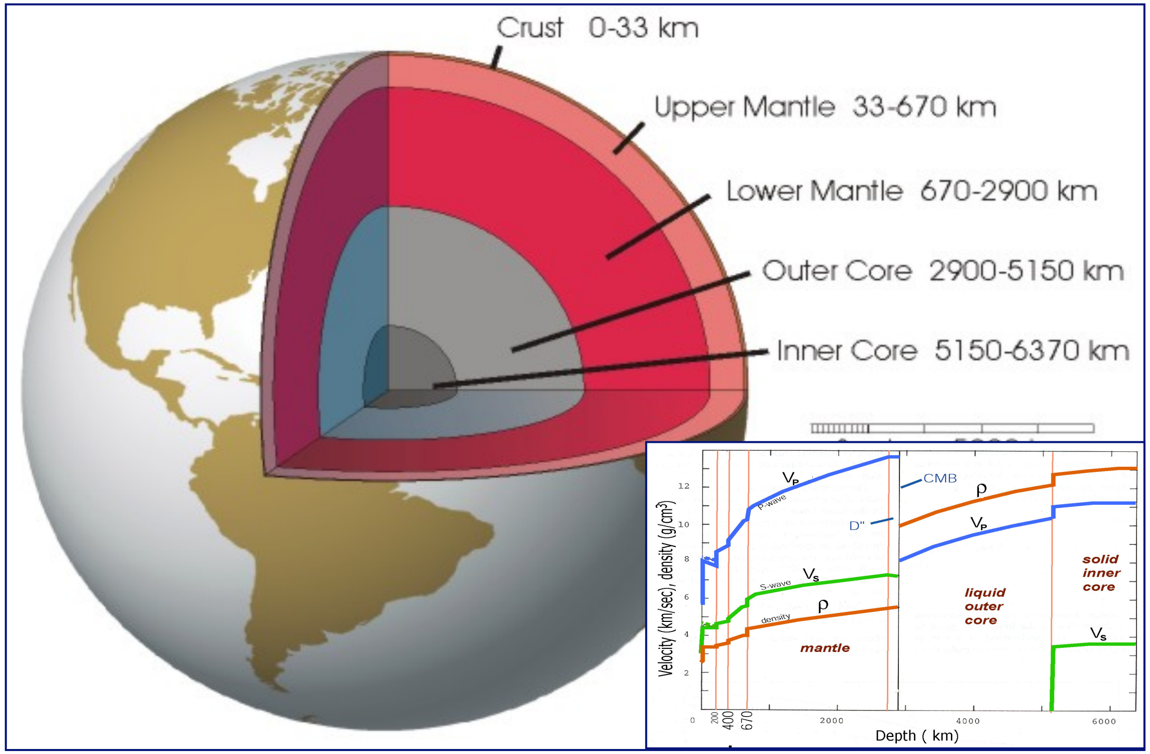
- ➔ additional information about galactic SN
- ➔ **global fits:** optical + neutrinos + gravitational waves
- ➔ neutrino properties + SN explosion dynamics
- ➔ SN1987A: strongest constraints on large extra dimensions

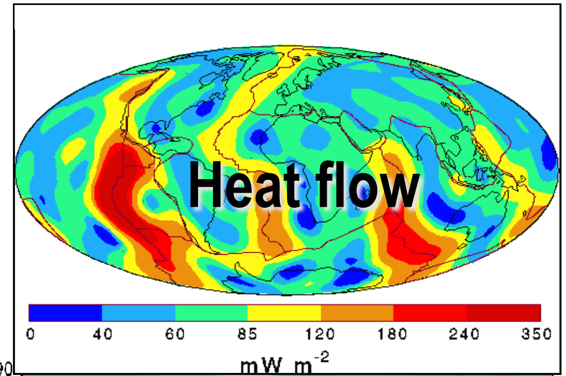
Learning from Atmospheric Neutrinos

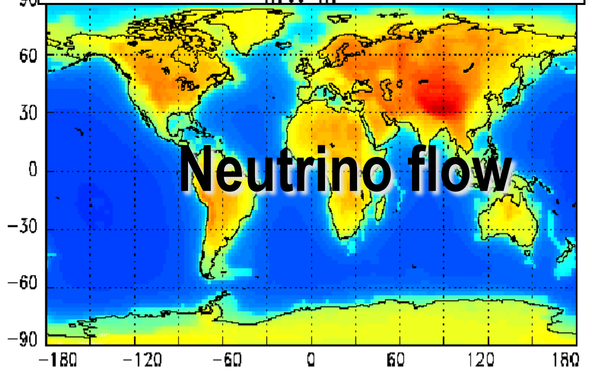


Issues (in flux models):
- primaries (...)
- atmosphere
- cross sections
- B-fields
- shower models
- ...

Geo Neutrinos as Probes of the Earth

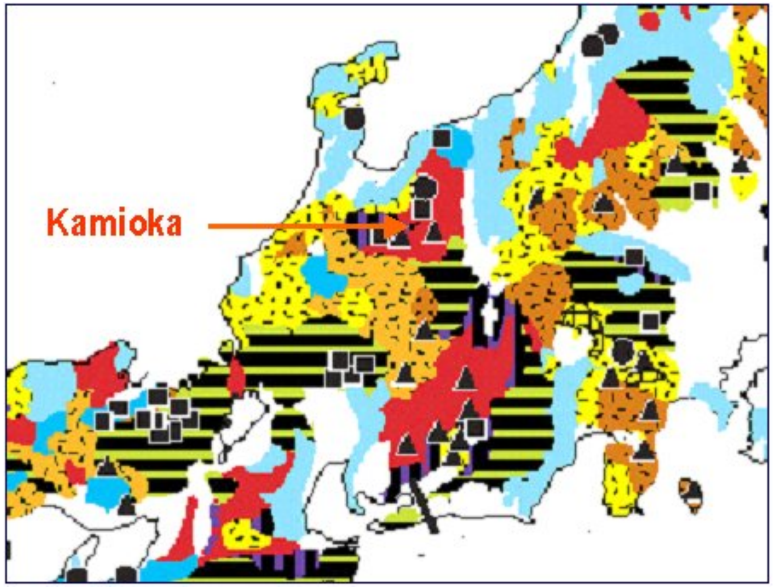


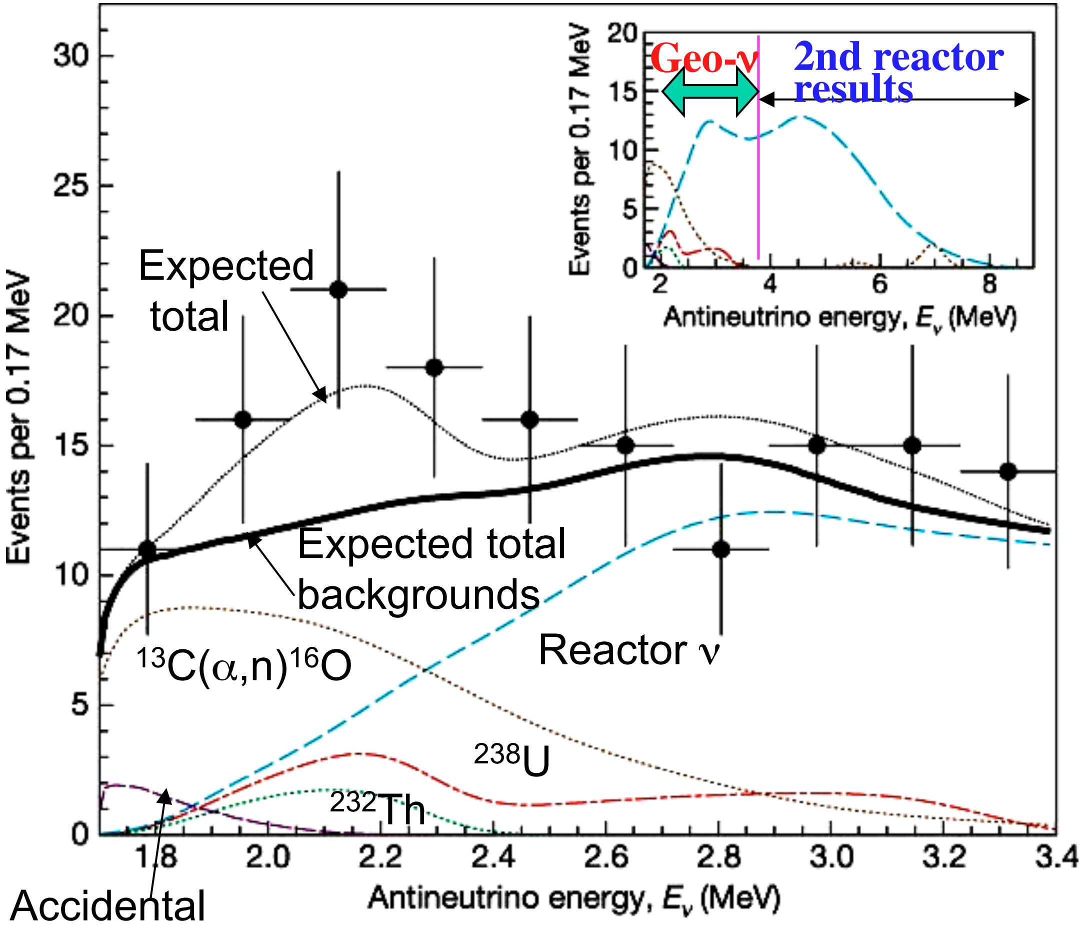




- radiogenic part of terrestrial heat flow ~80 mW/m^2 ➔ total: ~40 TW
- test geochemical model of the Earth, the Bulk Silicate Earth
- test unorthodox ideas of Earth's interior (K @ core, giant reactor)

Geo-Neutrino Observation at KamLAND

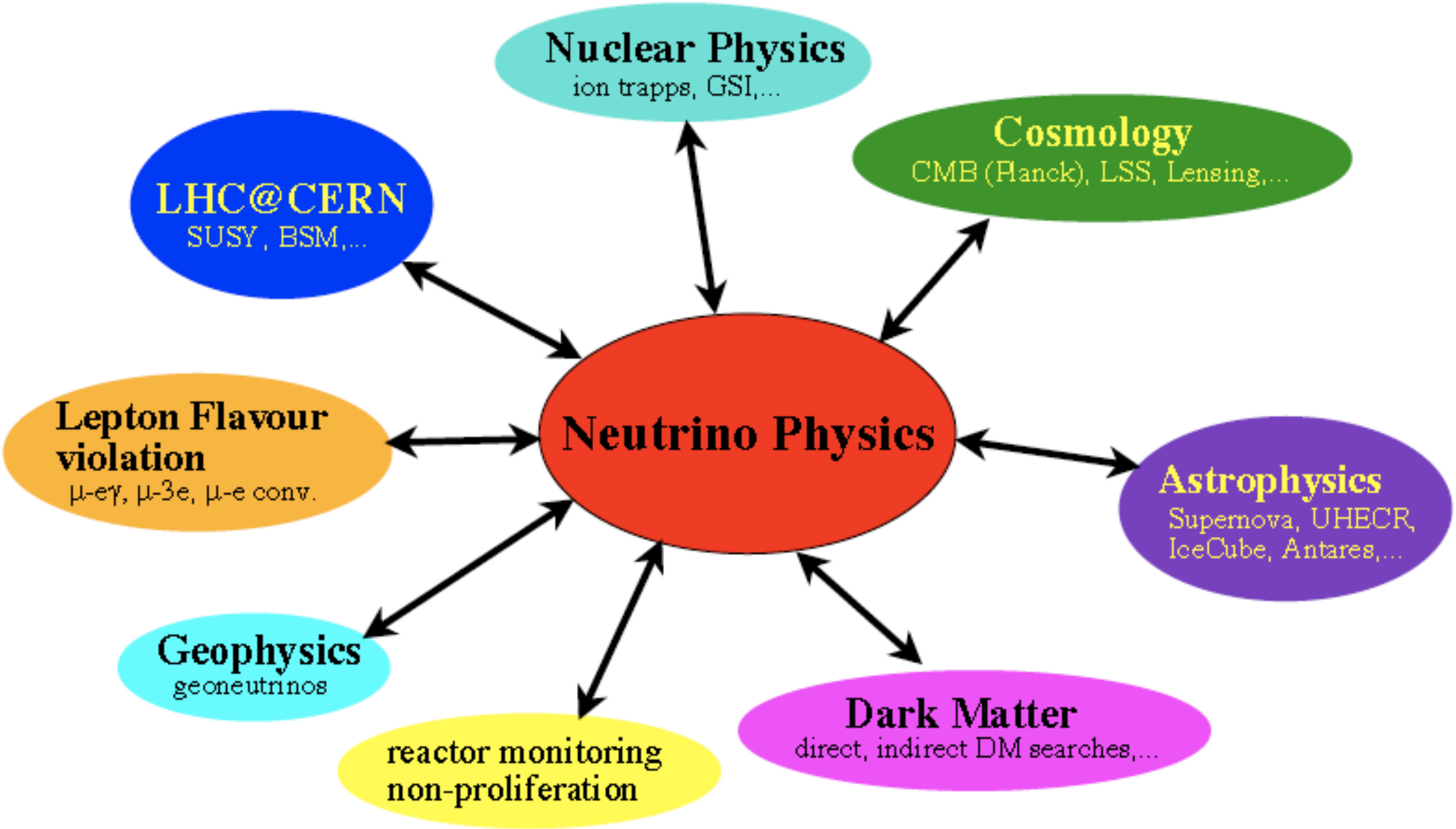




Observed $\bar{\nu}_e$ candidates 152 events
Expected total backgrounds 127±13

U+Th geo-ν candidates: 25^{+19}_{-18}
BSE model expectation: 19

Many Connections to other Fields



Neutrinos probe new physics in many ways!