Neutrino Physics – part2

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4. The Future of Neutrino Oscillations

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

Future Precision Oscillation Physics

Precise measurements ➔ 3f oscillation formulae

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

x Majorana-CP-phases

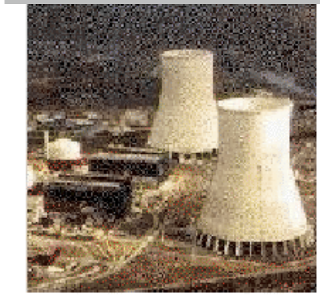
S_{13} ➔ 3 flavour effects
➔ CP phase δ

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

Complication: Matter effects ➔ effective parameters in matter
➔ expansion in small quantities θ_{13} and $a = \Delta m^2_{sol} / \Delta m^2_{atm}$

Burguet-Castell et al. , Akhmedov et al. …

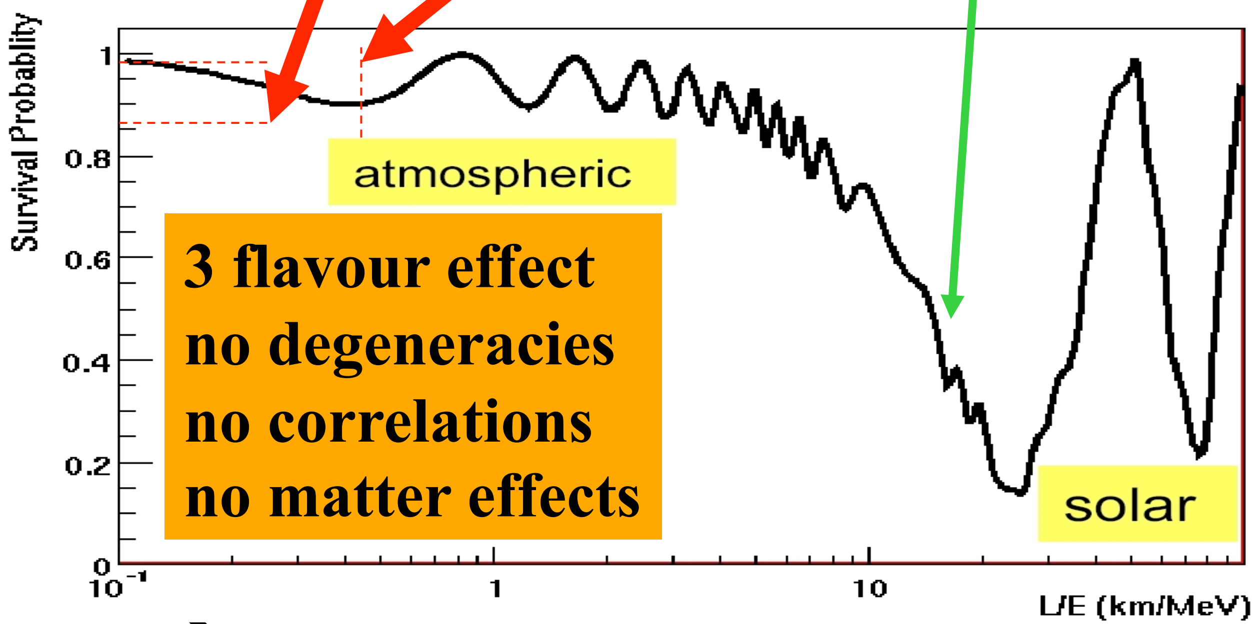
Future Precision with Reactor Experiments



$\overline{\nu}_e \Rightarrow$ **near detector** (170m) $\overline{\nu}_e \Rightarrow$ **far detector** (1700m)

identical detectors ➔ many errors cancel

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} - \left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$



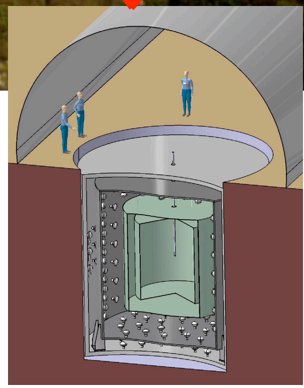
E=4MeV ➔ 2km 4km 40km 80km

- ➔ **Double Chooz**
- ➔ **Daya Bay**
- ➔ **Reno**
- ➔ **Angra**

clean & precise θ_{13} measurments

Double Chooz

Existing far detector hall

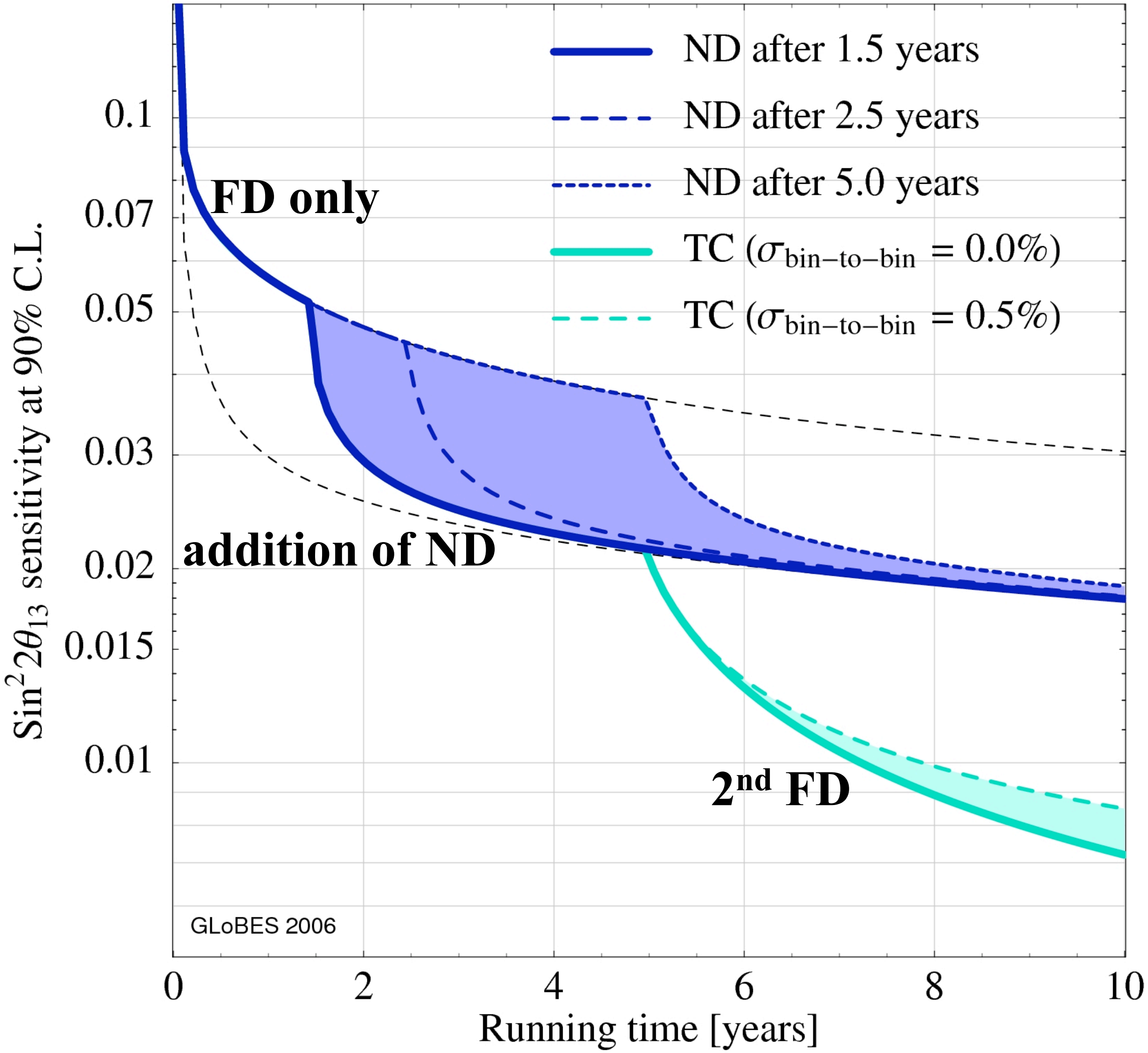


$\sin^2 2\theta_{13}$ sensitivity

Chooz (=now)	< 0.20
Double Chooz	< 0.02
Triple Chooz ?	< 0.007

➔ data taking 2009

Double Chooz and Triple Chooz

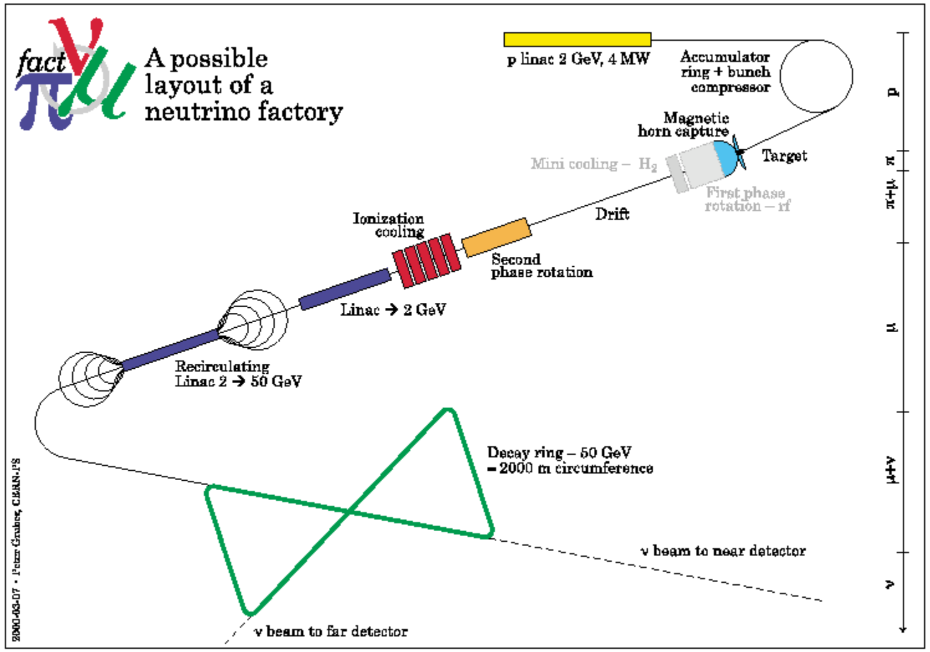


$\sin^2 2\theta_{13}$ sensitivity

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

A) conventional ν-beams from targets ➔ intense superbeams

B) neutrino factories



C) radioactive β-bemas

- Pure ν_e or $\overline{\nu}_e$ beam from radioactive decay, $\gamma \simeq 100$

Future 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

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

➔ correlations & degeneracies, matter effects

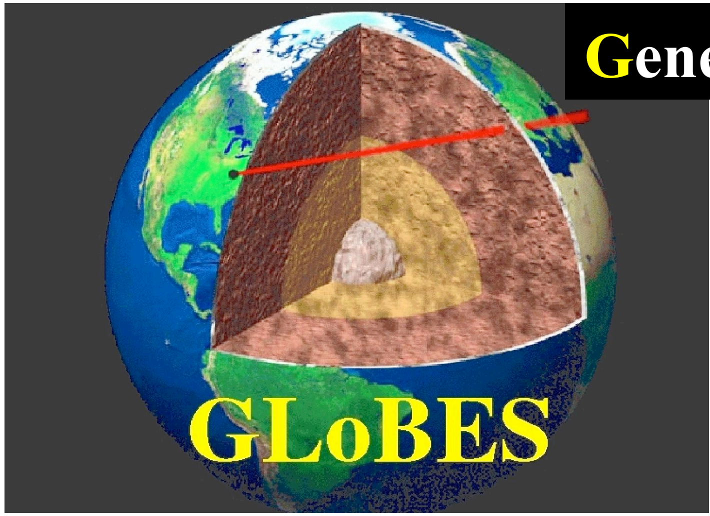
Simulation of Future Experiments

- 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 - 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)

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

A Powerful Simulation Tool



General Long Baseline Experiment Simulator

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

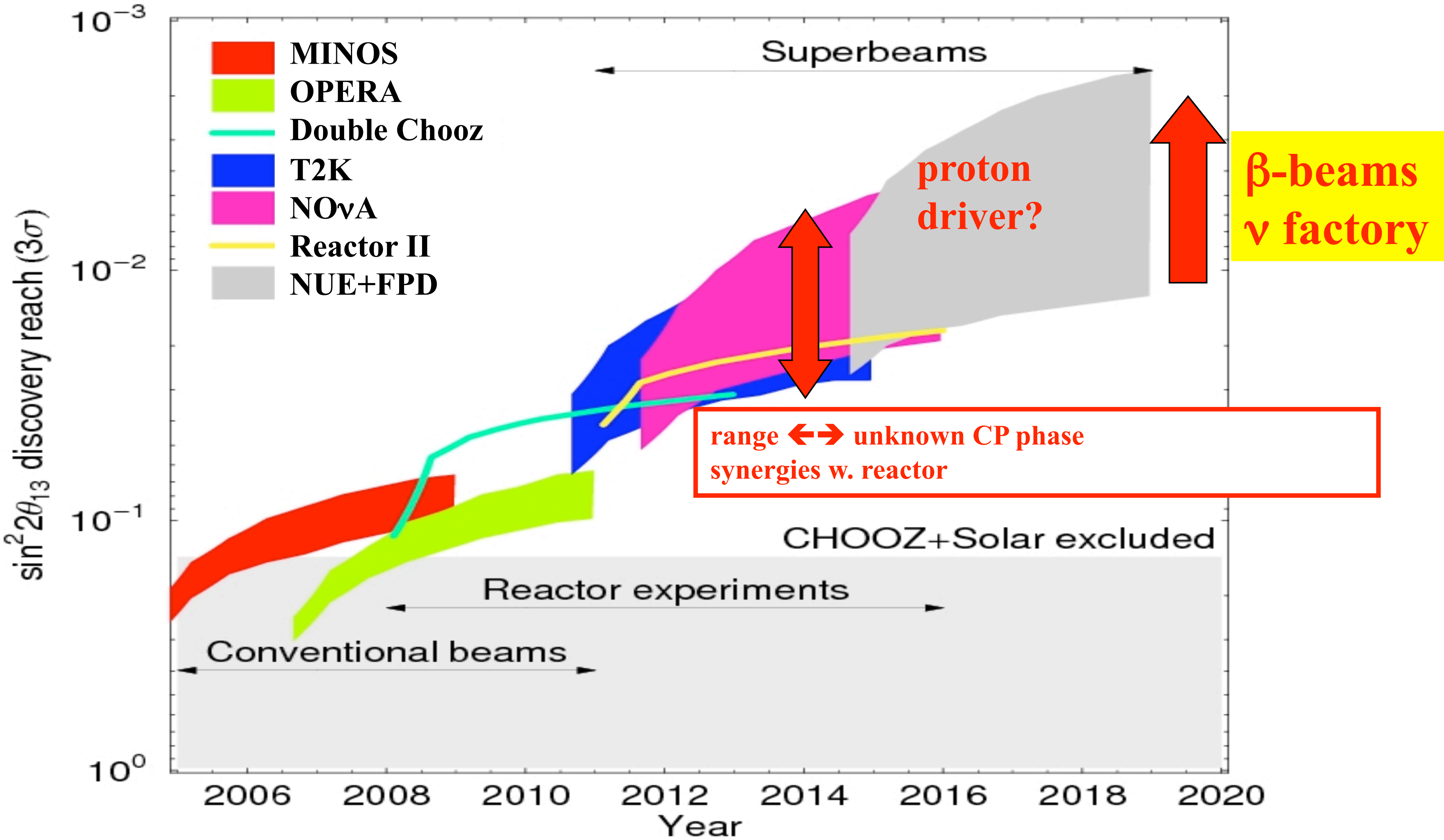
http://www.mpi-hd.mpg.de/~globes

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

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

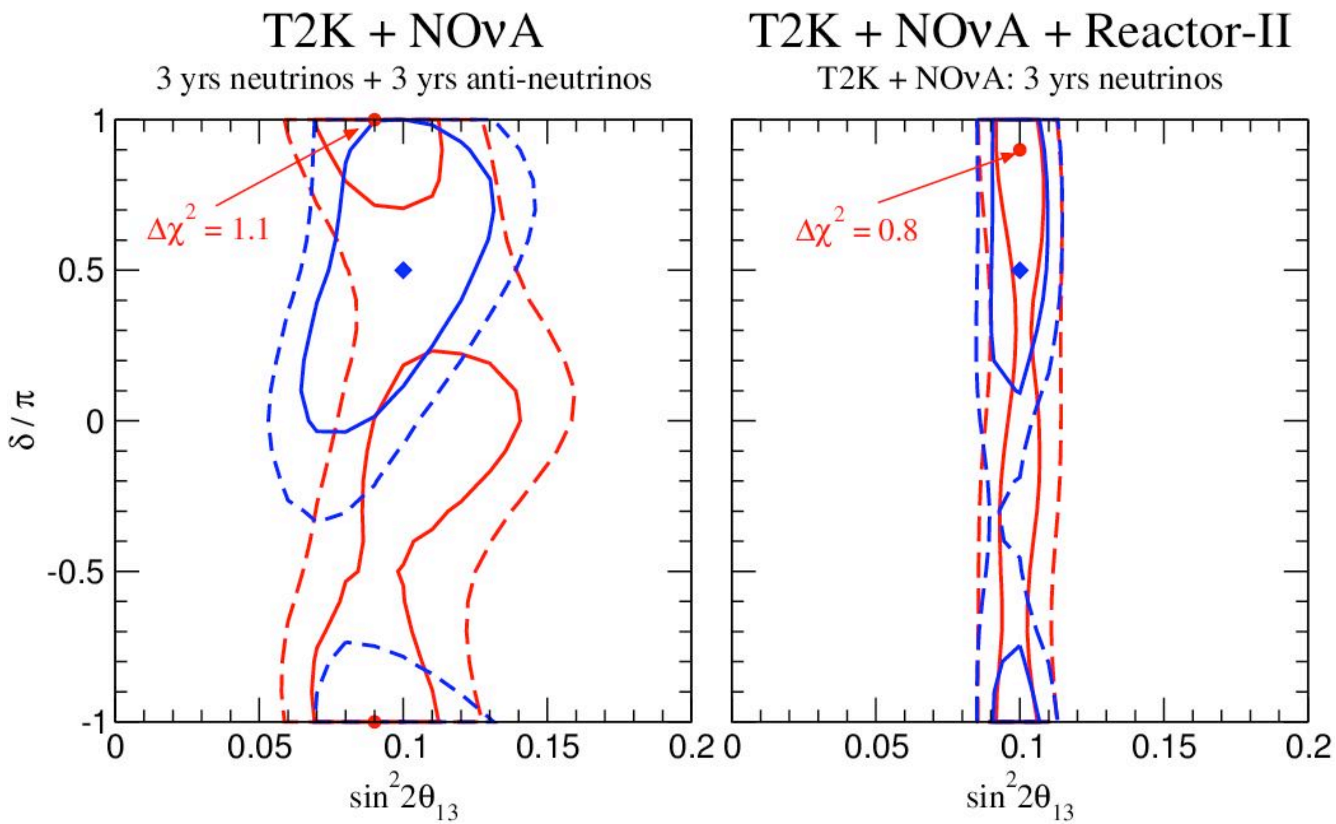
1) **AEDL (Abstract Experiment Definition Language)**
2) simulation of an experiment ➔ 3-ν oscillations; scan „true values"
3) analysis ➔ event distriutions, ..., sensitivities, ...

θ_{13} – Now and in the Future



Leptonic CP-Violation

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



$\Delta m^2 > 0$

$\Delta m^2 < 0$

—— 90%CL

····· 3σ

➔ **bounds or measurements of leptonic CP-violation**

➔ **harder for smaller $\sin^2 2\theta_{13}$**

➔ **β-beams or/and neutrino factory ➔ θ_{13} is a key parameter for road maps**

Further Implications of Precision

Precision allows to identify / exclude:

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

Provides also measurements / 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

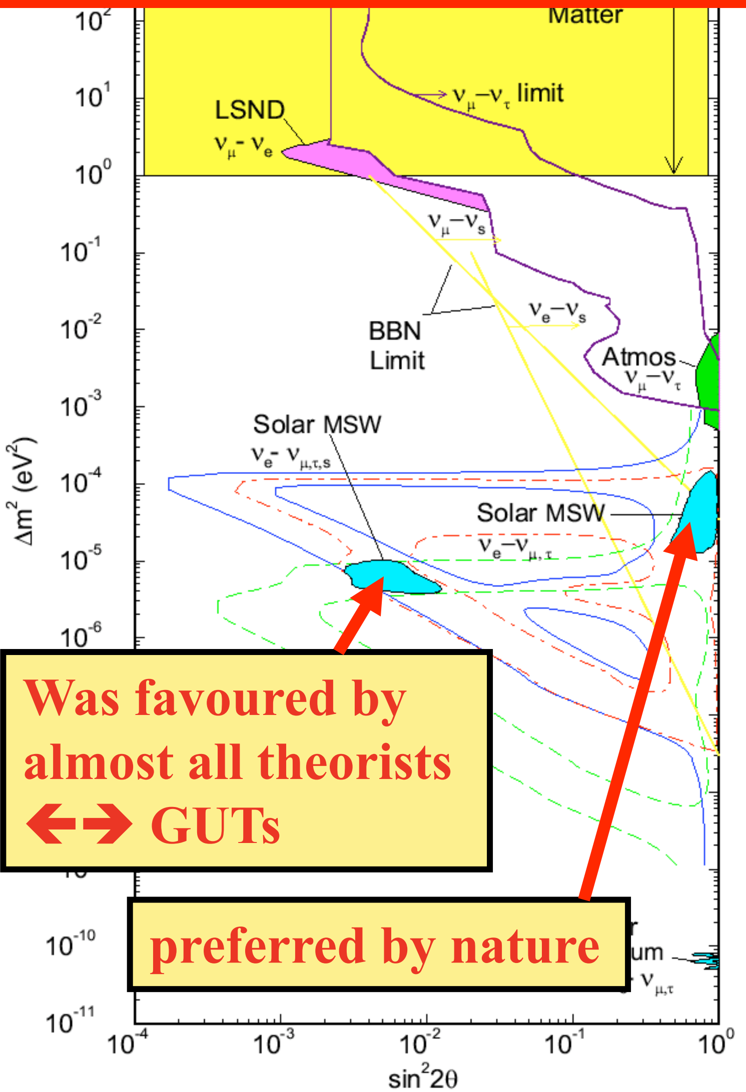
5. The Value of Future Precision Experiments

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

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?

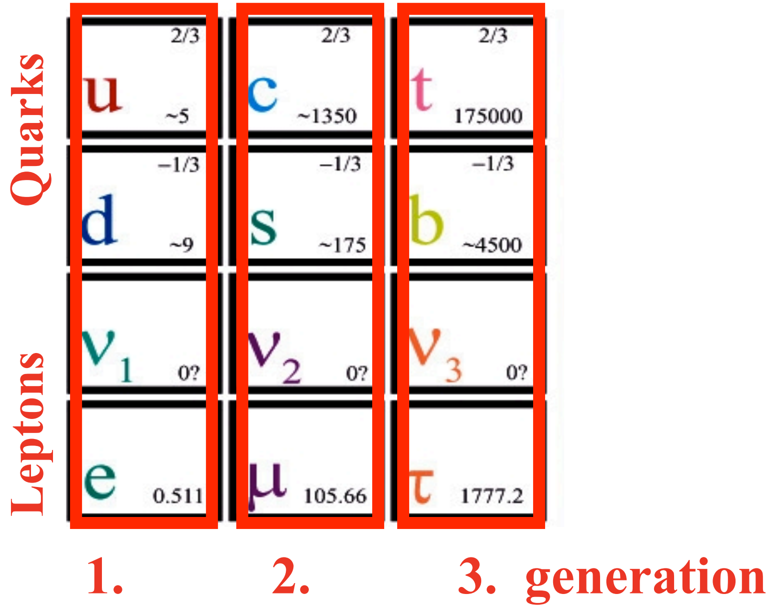
➔ numerical coincidence unlikely
➔ special reasons (symmetry, …)

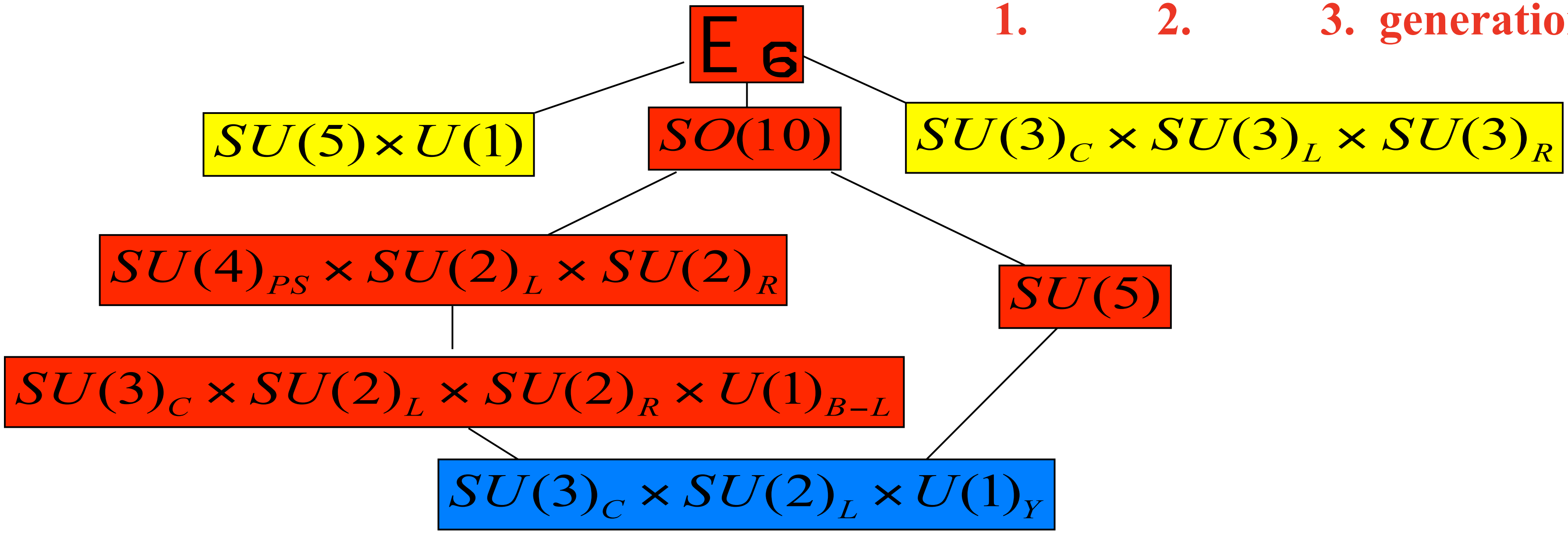
➔ answered by coming precision

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

Requirements:
gauge unification
particle multiplets ⇔ ν_R
proton decay
…





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 ~ $m_2 . m_3$

➔ $m_2 << m_3$ (hierachy) and tan $\theta_{23} \simeq a/c$ (large mixing)

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

x<<y<<z

sequenatial dominance:

$m_1 << m_2 << m_3$ natural

naturally large mixings

S.F. King, …

Large Mixings and See-Saw Type II

see-saw type II:
- 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 perturbation

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

Tri-bimaximal Mixing

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

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

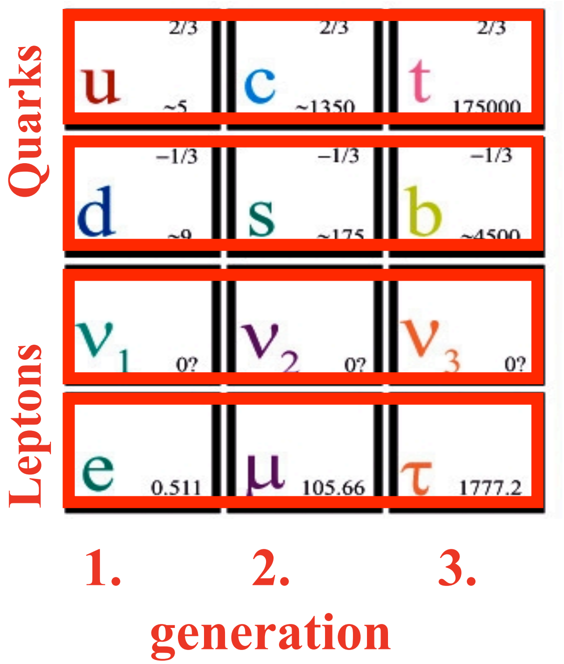
- phenomenologically very sucessful
- tempting to think of it as a consequence of three terms
- type II ⇔ m_2, m_3

Flavour Unification

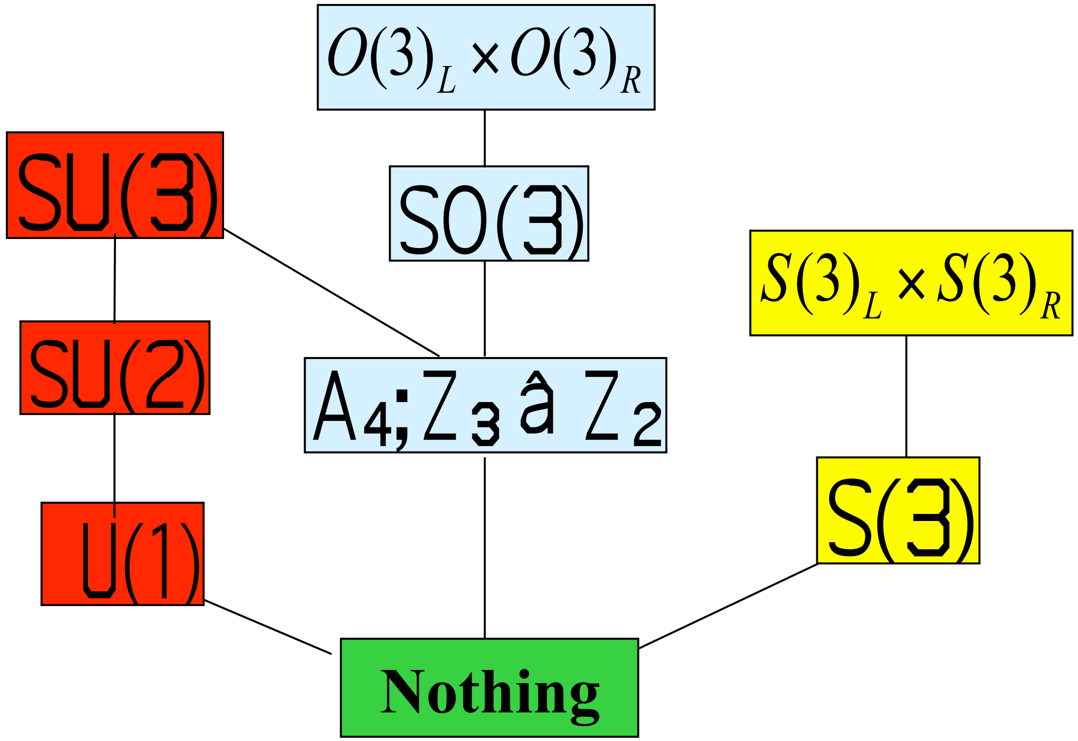
- so far **no understanding of flavour, 3 generations**
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

➔ **symmetry** not texture zeros



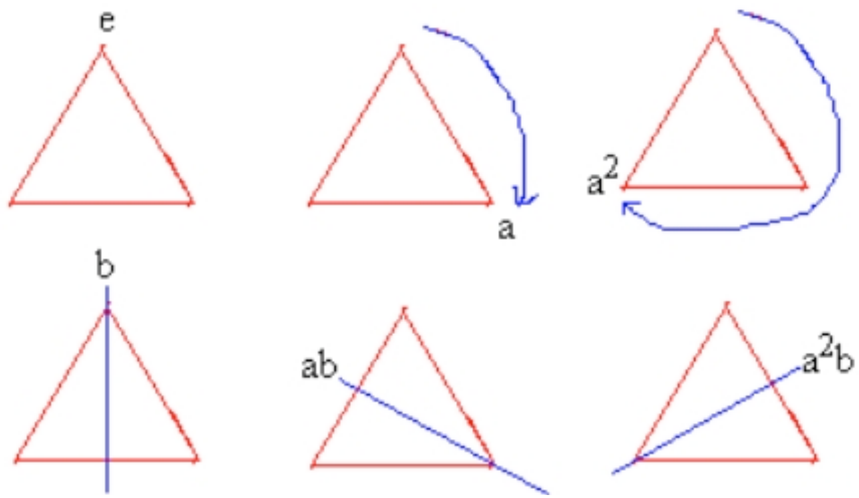
Examples:



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 scalars ⇔ 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:**

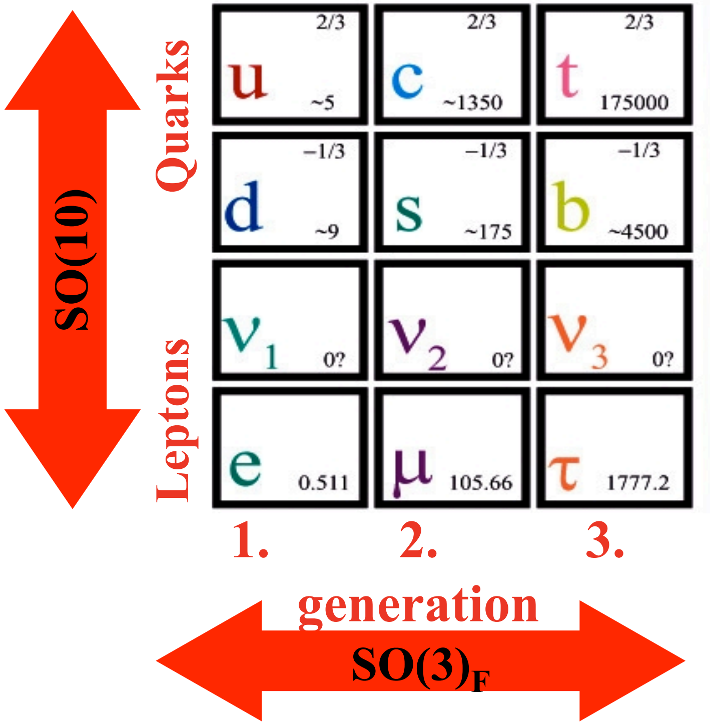
Higgses:
$\Phi_1 \sim 1_1$
$\Phi_2 \sim 1_2$
$\Psi_1 \sim 2_1$

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) ⊗ $SU(3)_F$

- 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

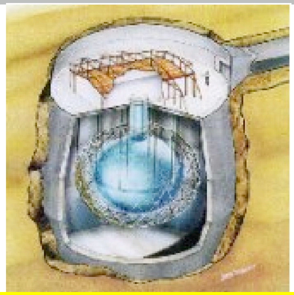
GUT ⊗ flavour is rather restricted

←→ small quark mixings *AND* large leptonic mixings ; quantum numbers

➔ so far only a few viable models
rather limited number of possibilities; phenomenological success non-trivial

➔ aim: <u>distinguish models further by future precision</u>

Renormalization Group Running

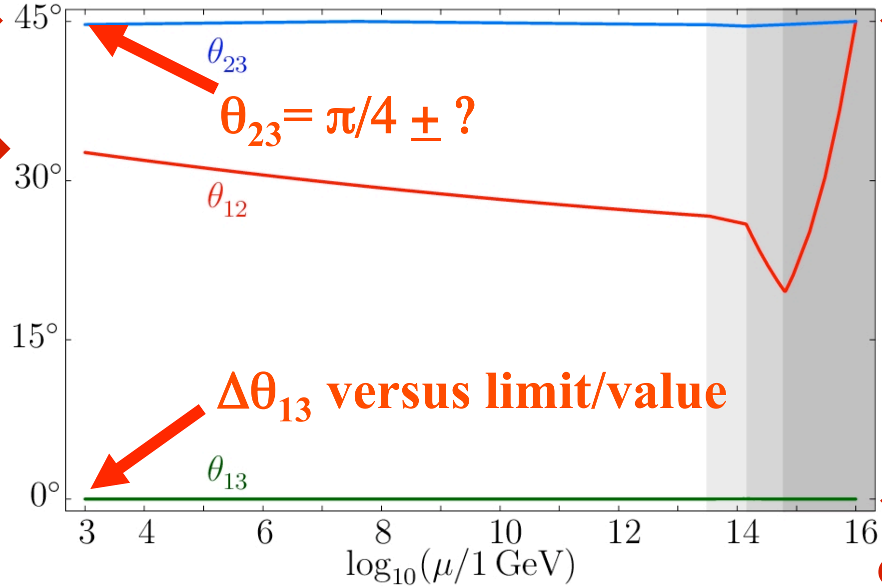


low energies:
- small masses
- large mixings

renormalization group running →

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

atmospheric →
solar →
reactor →



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

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

← 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

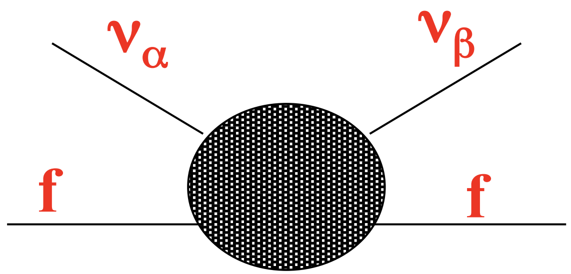
➔ **effects beyond 3 flavours**

➔ **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

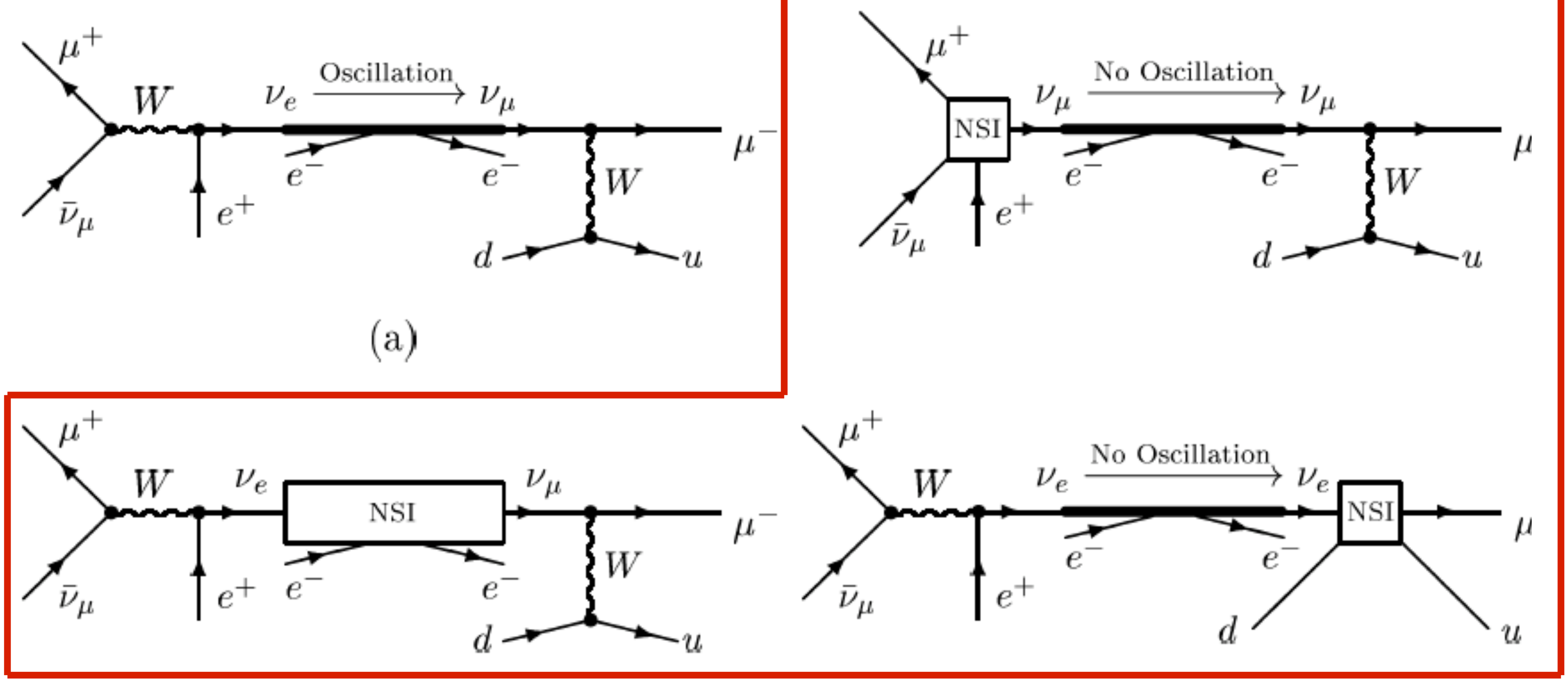
Source ⊗	Oscillation ⊗	Detector
- neutrino energy E	- oscillation channels	- effective mass, material
- flux and spectrum	- realistic baselines	- threshold, resolution
- flavour composition	- MSW matter profile	- particle ID (flavour, charge, event reconstruction, ...)
- contamination	- degeneracies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

precision experiments might see new effects beyond oscillations ➔ NSIs!

NSIs interfere with Oscillations

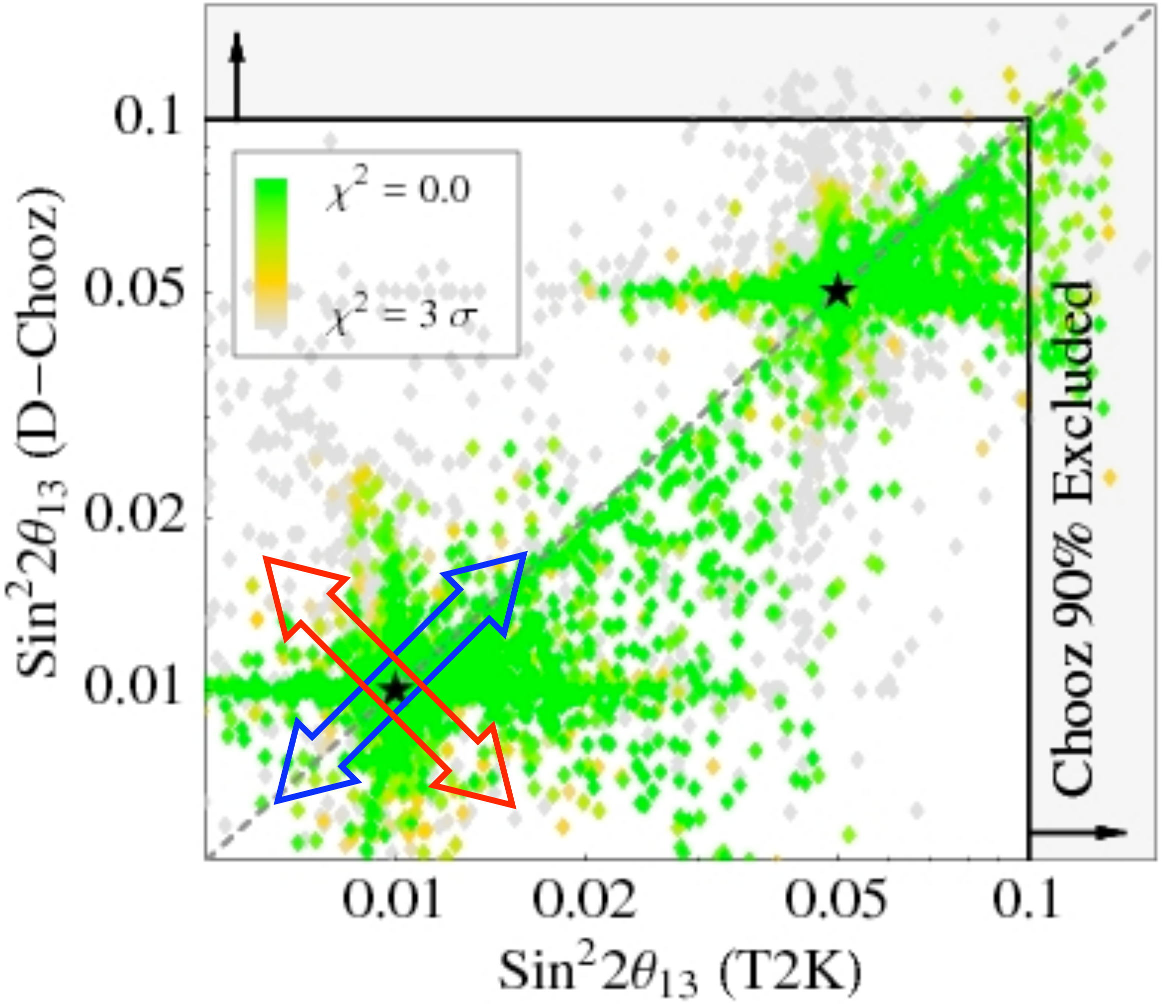
the "golden" oscillation channel

NSI contributions to the "golden" channel



note: **interference in oscillations $\sim\varepsilon$ |\ FCNC effects $\sim\varepsilon^2$**

NSI: Offset and Mismatch in θ_{13}



Kopp, ML, Ota, Sato

redundant measurement of θ_{13}

Double Chooz + T2K

*=assumed 'true' values of θ_{13}

scatter-plot:

- ε values random
- below existing bounds
- random phases

NSIs can lead to:

- offset
- mismatch

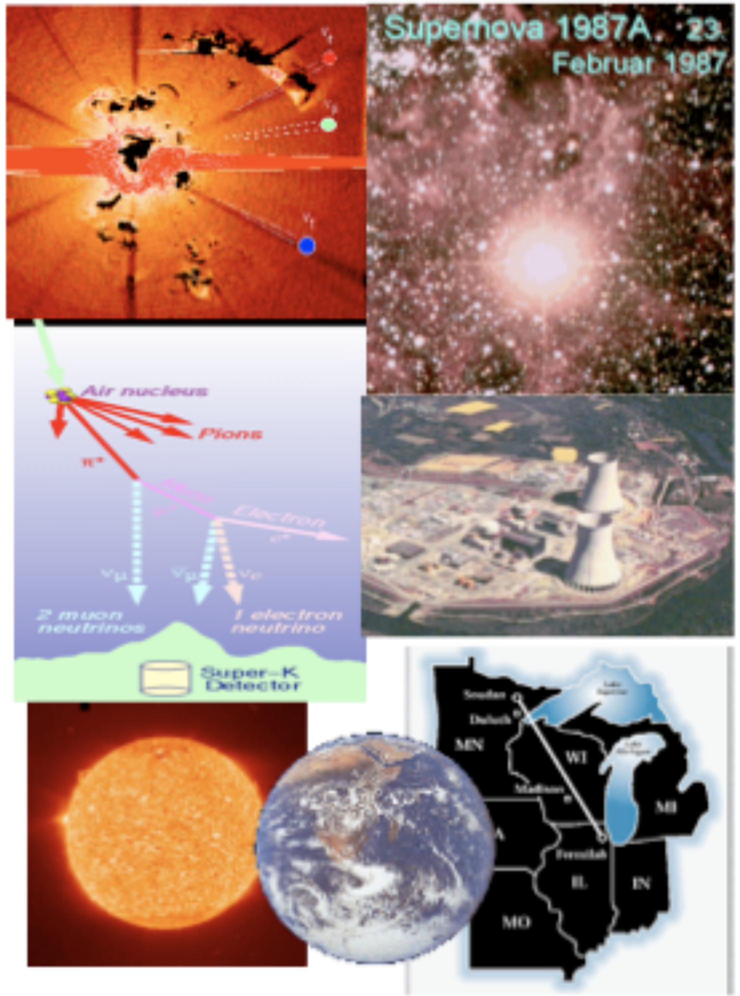
➔ redundancy

➔ interesting potential

6. Neutrino as Probes into Sources

➔unique insights into sources!

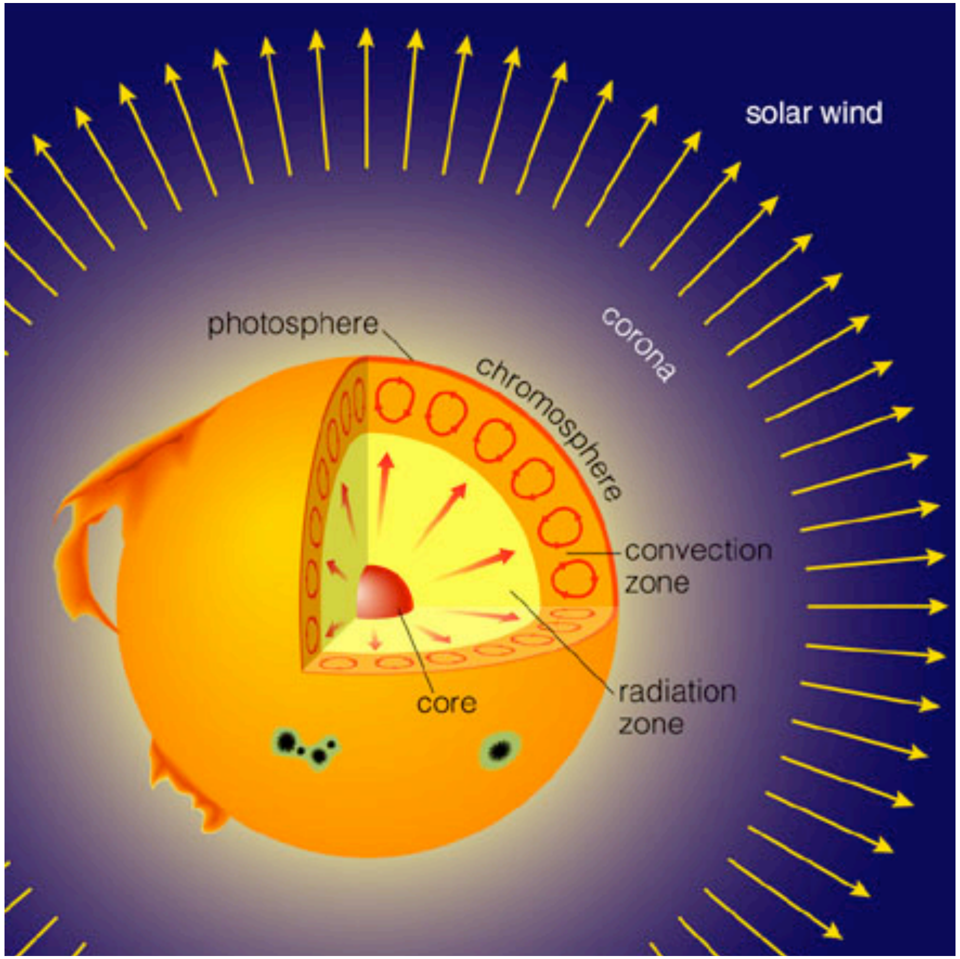
⇔ connections to many fields



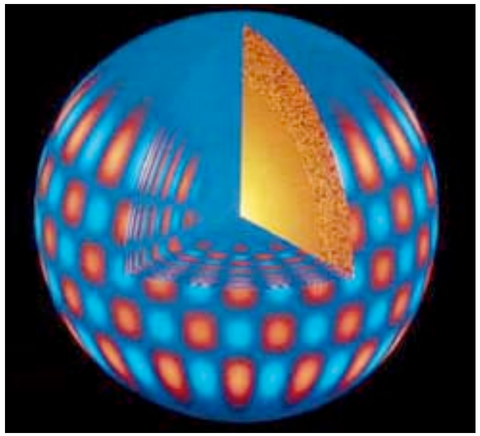
Solar Neutrinos: Learning About the Sun

Observables:

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



Topics:
- **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%

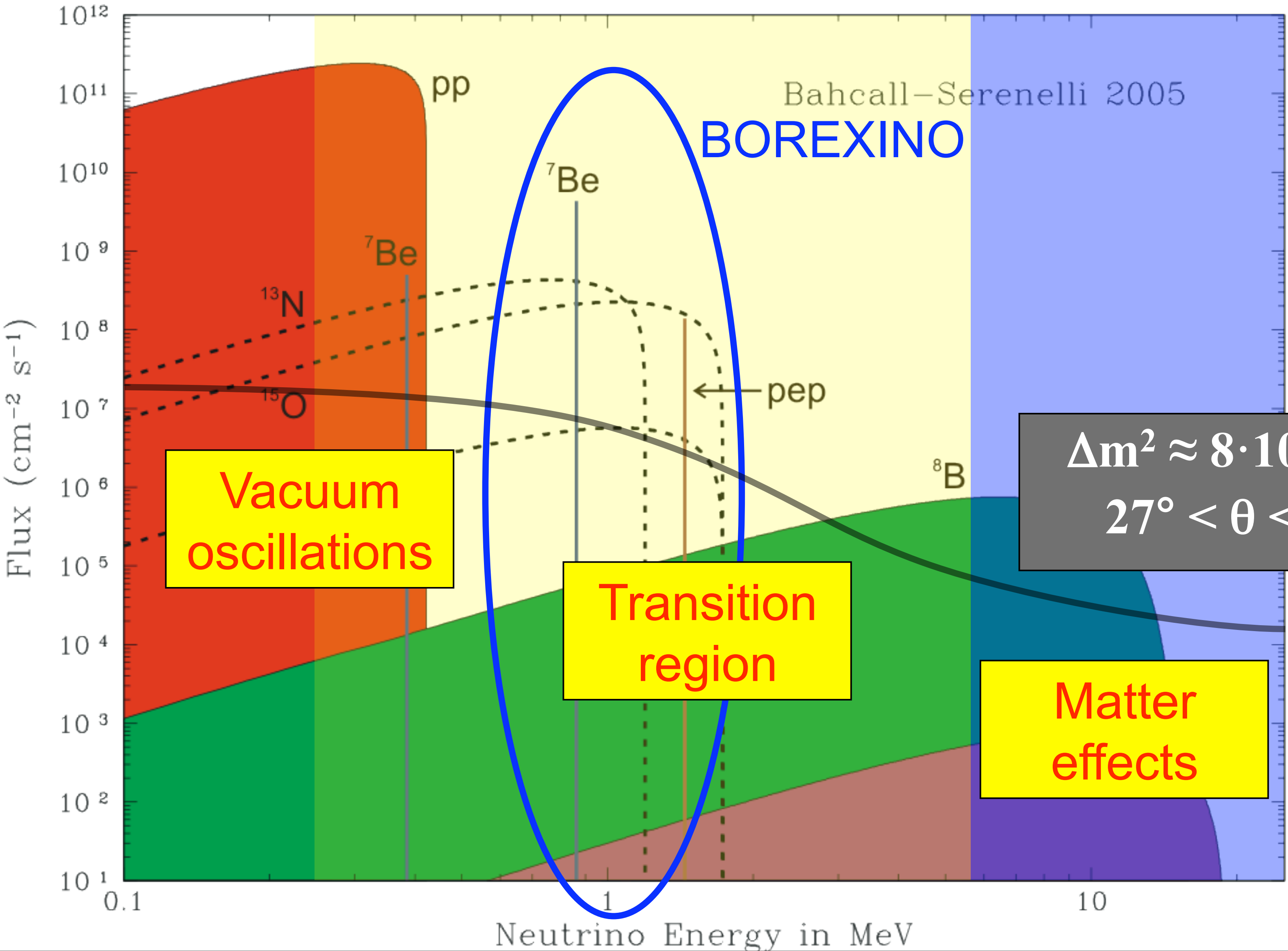
$$ {}^7Be + e^- \rightarrow {}^7Li + \nu_e $$
0.862 MeV

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

$$ {}^7Be + p \rightarrow {}^8B + \gamma $$
$$ {}^8B \rightarrow {}^8Be^* + e^+ + \nu_e $$
< 15 MeV
$$ {}^8Be^* \rightarrow {}^4He + {}^4He $$

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

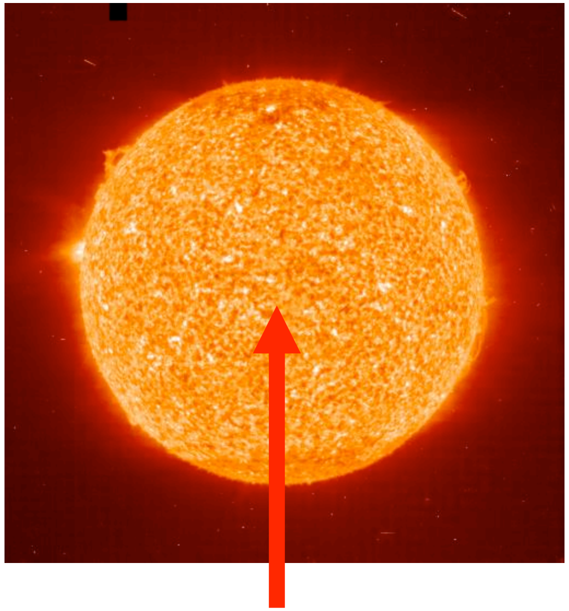
Solar Neutrino Spectroscopy



$\Delta m^2 \approx 8 \cdot 10^{-5}\ eV^2$

$27° < \theta < 38°$

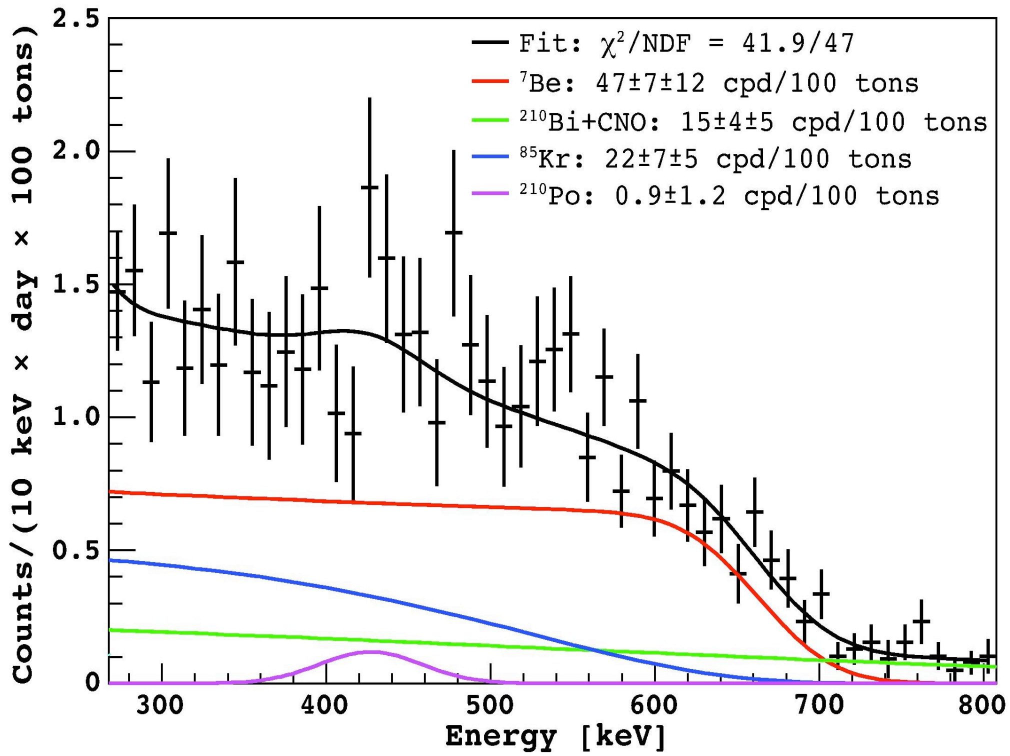
Borexino tests the Sun



BOREXINO:

the sun in real time
photons ~10ky delay

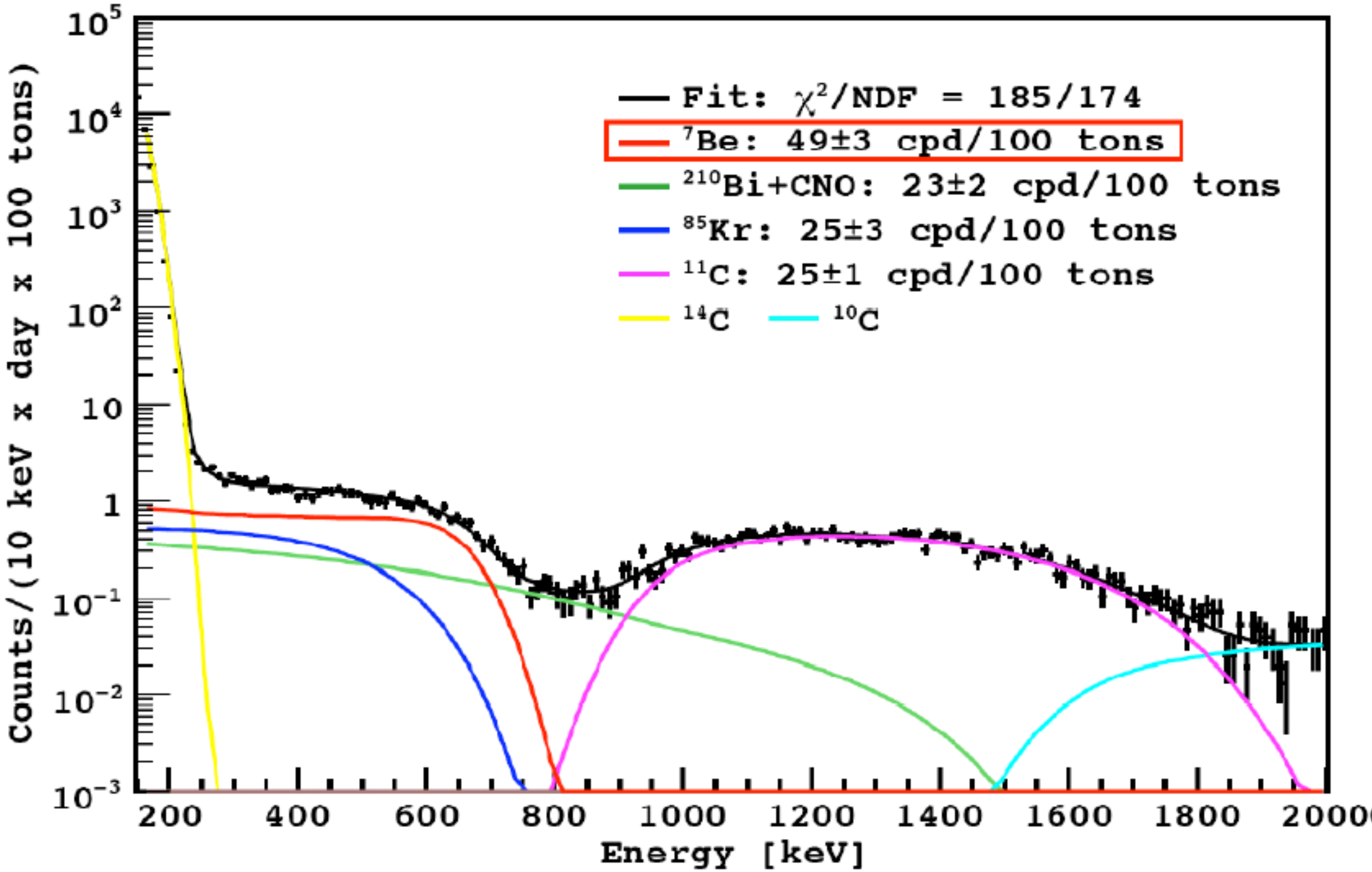
47±7 events / day /100t
expected:
with oscillation 49±4
without 75±4



More to come:

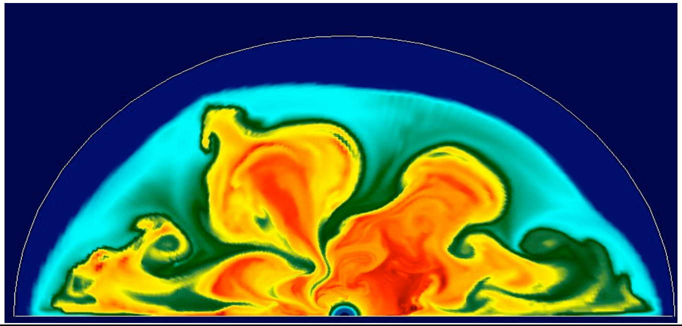
Improved statistics and reduced systematics
➔ 3.5% seasonal variation…
➔ CNO cycle
➔ geo-neutrinos, …

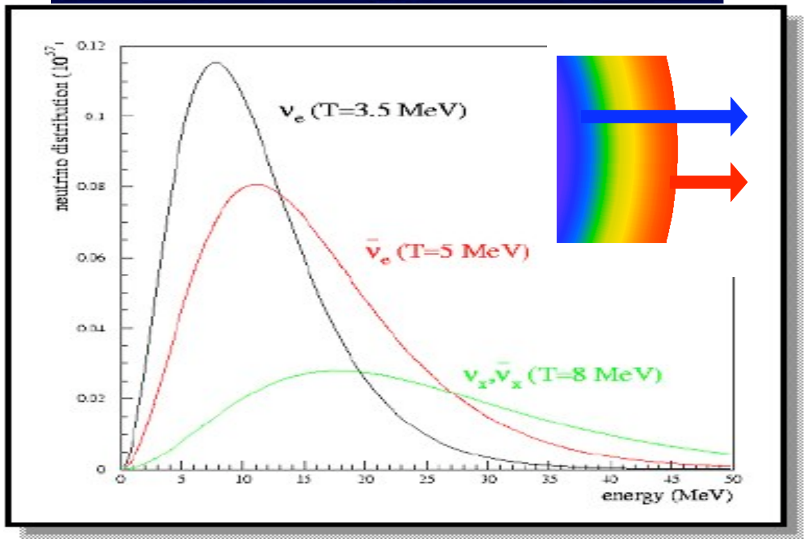
Borexino: 192 Days of Data



Supernova Neutrinos

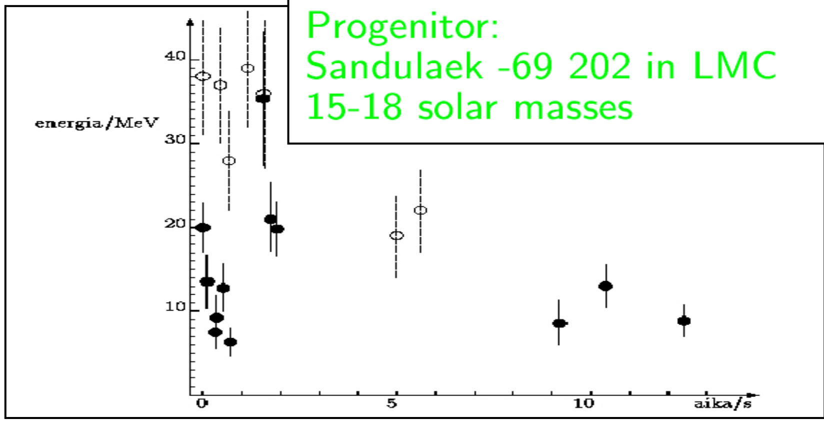
- Collaps of a typical star ➔ ~10^{57} ν's
- ~99% of the energy in ν's
- ν's essential for explosion
- 3d simulations do not explode
  (so far... 2d➔3d, ➔convection? ...)





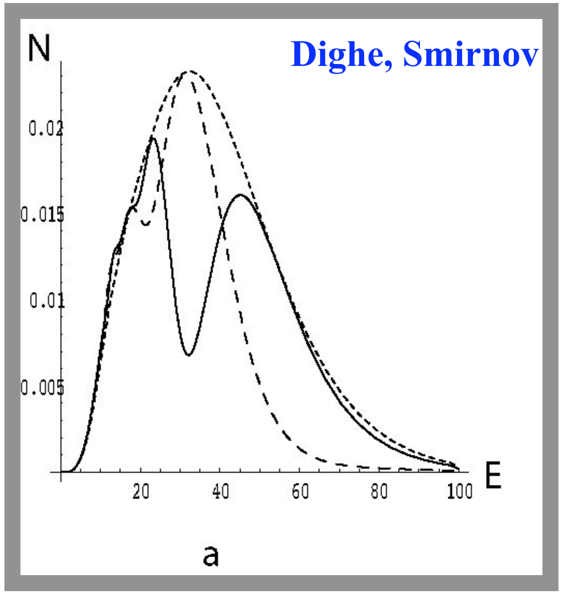
SN1987A neutrino burst

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

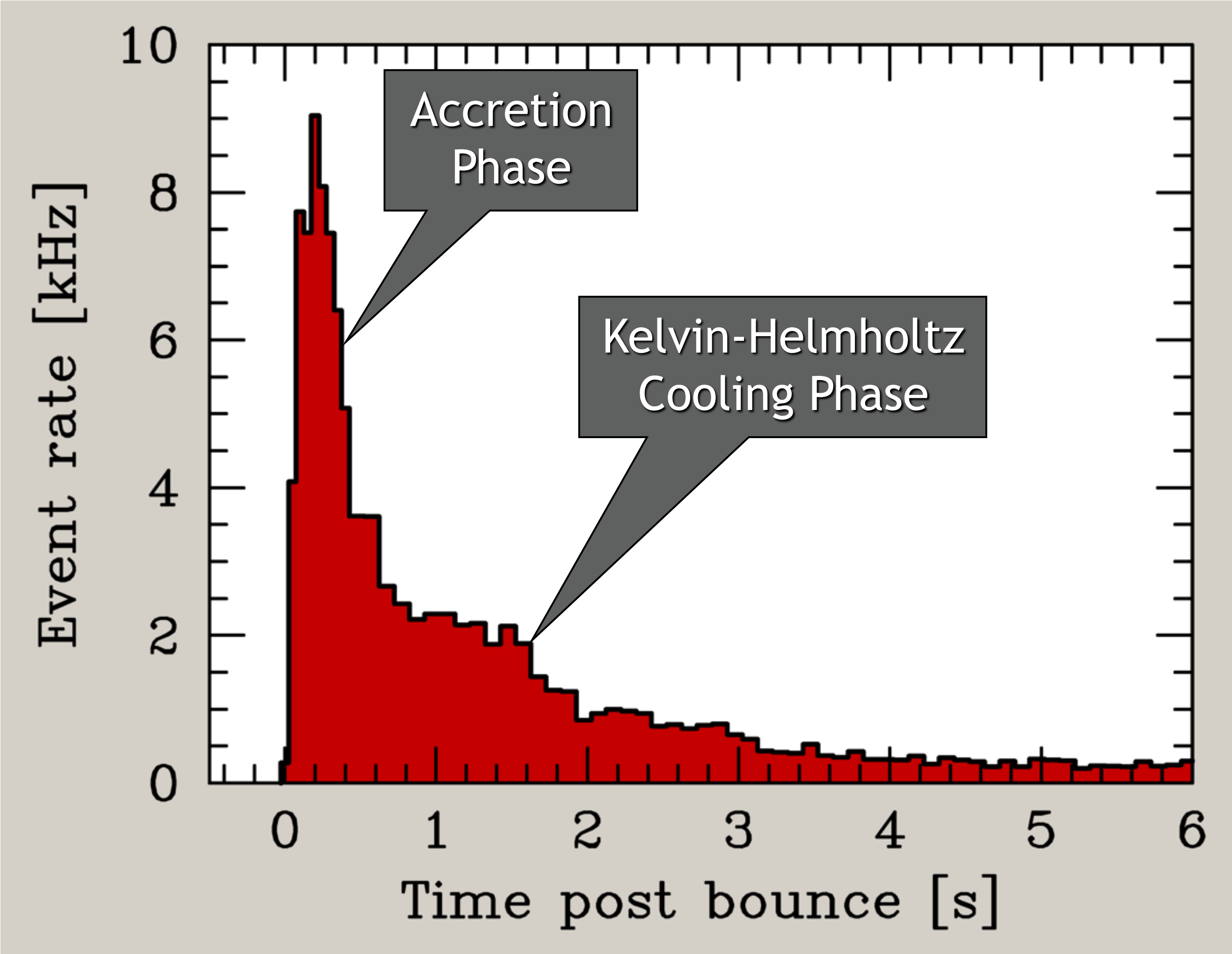


MSW: SN & Earth

sensitive to finite θ_{13} and $\mathrm{sgn}(\Delta m^2)$

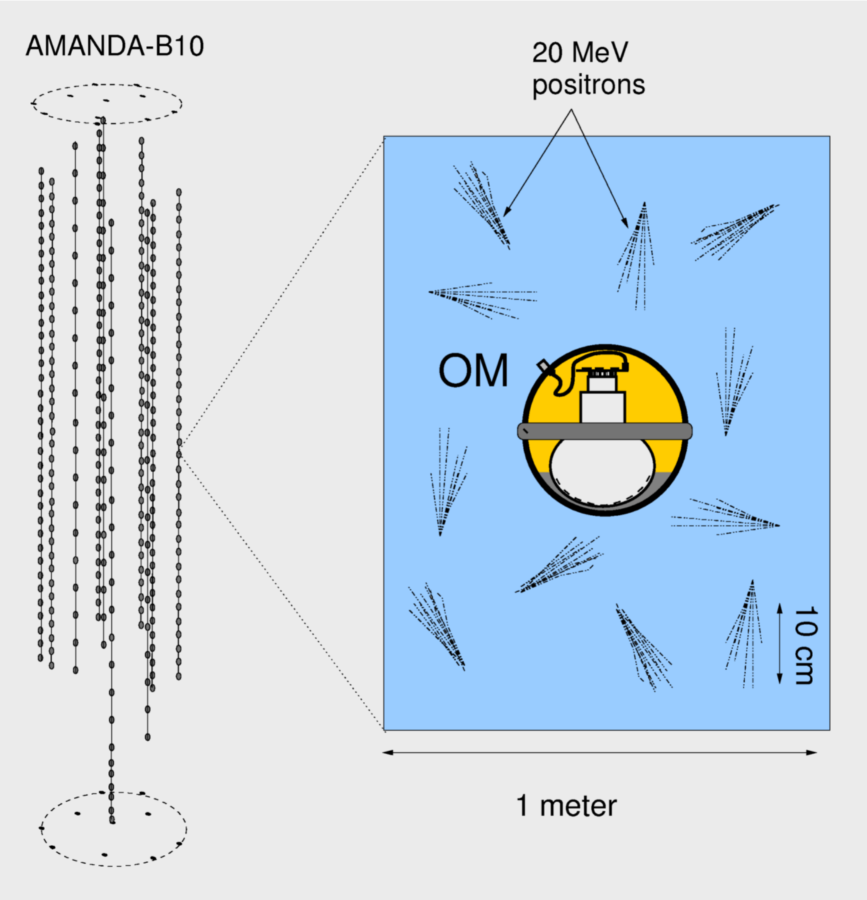


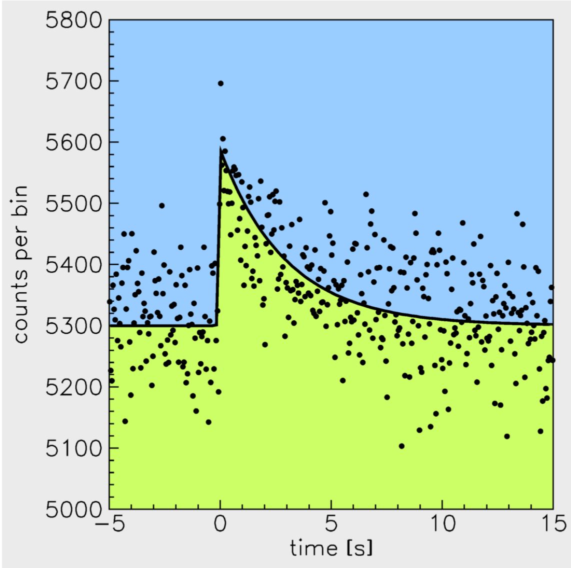
Simulated Supernova Signal at SK



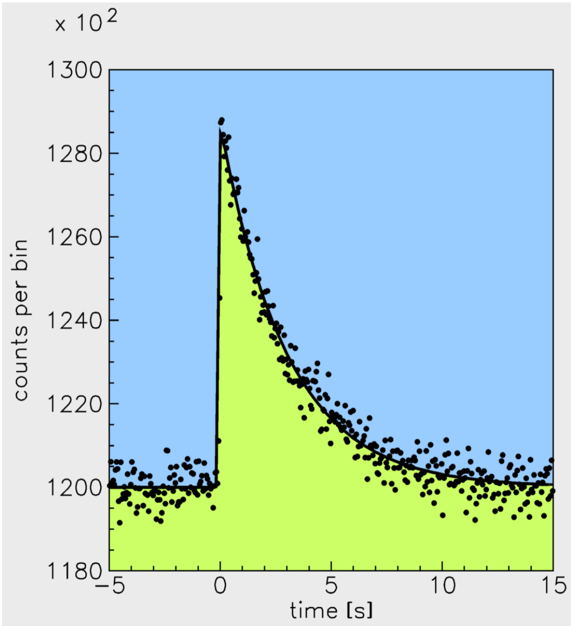
Simulation for Super-Kamiokande SN signal at 10 kpc
Totani, Sato, Dalhed & Wilson

Amanda/IceCube as a Supernova Detector





SN @ 8.5 kpc Signal in Amanda



SN @ 8.5 kpc Signal in IceCube

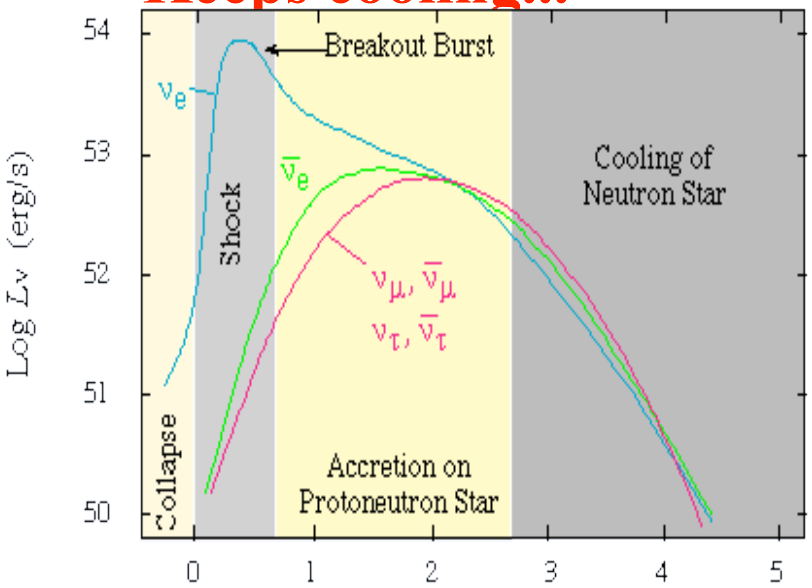
Each optical module (OM) picks up Cherenkov light from its neighborhood
SN ➔ correlated “noise” between OMs

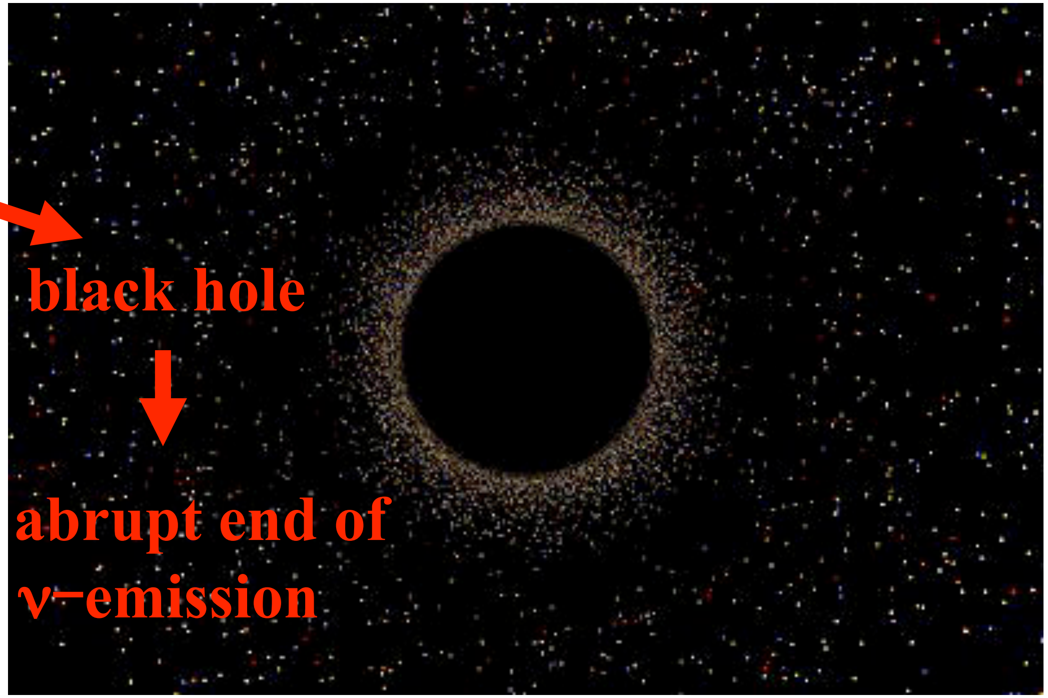
2 possibilities:

Supernova

neutron star or black hole

Keeps cooling...

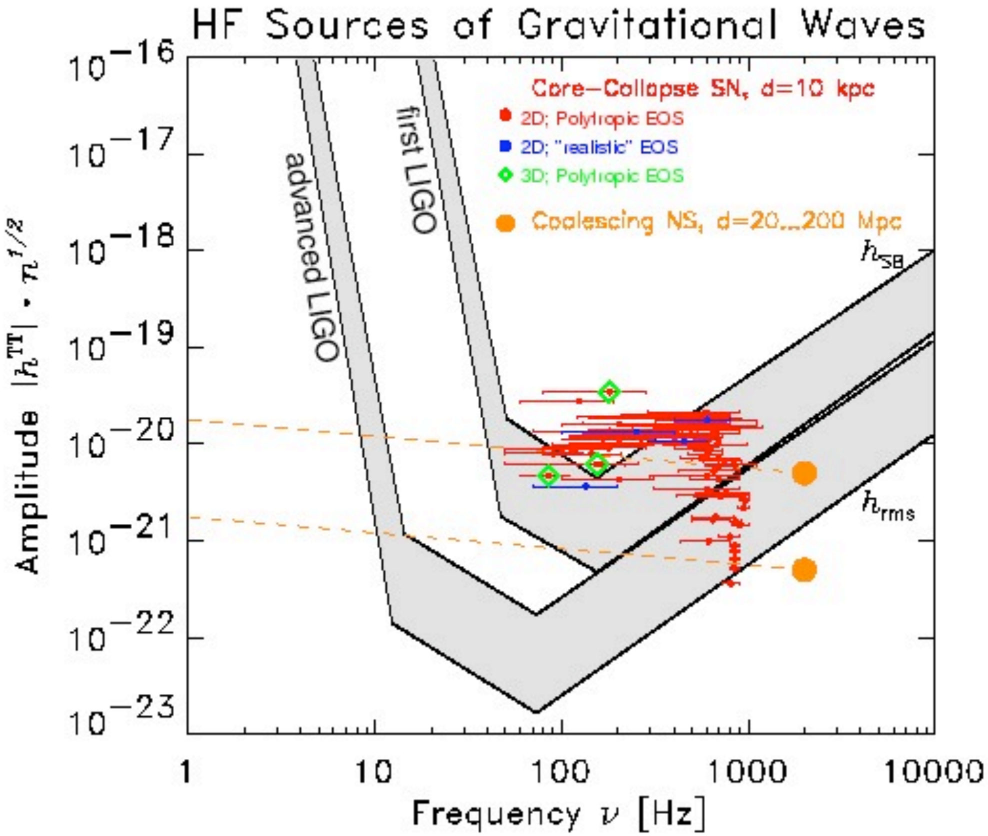


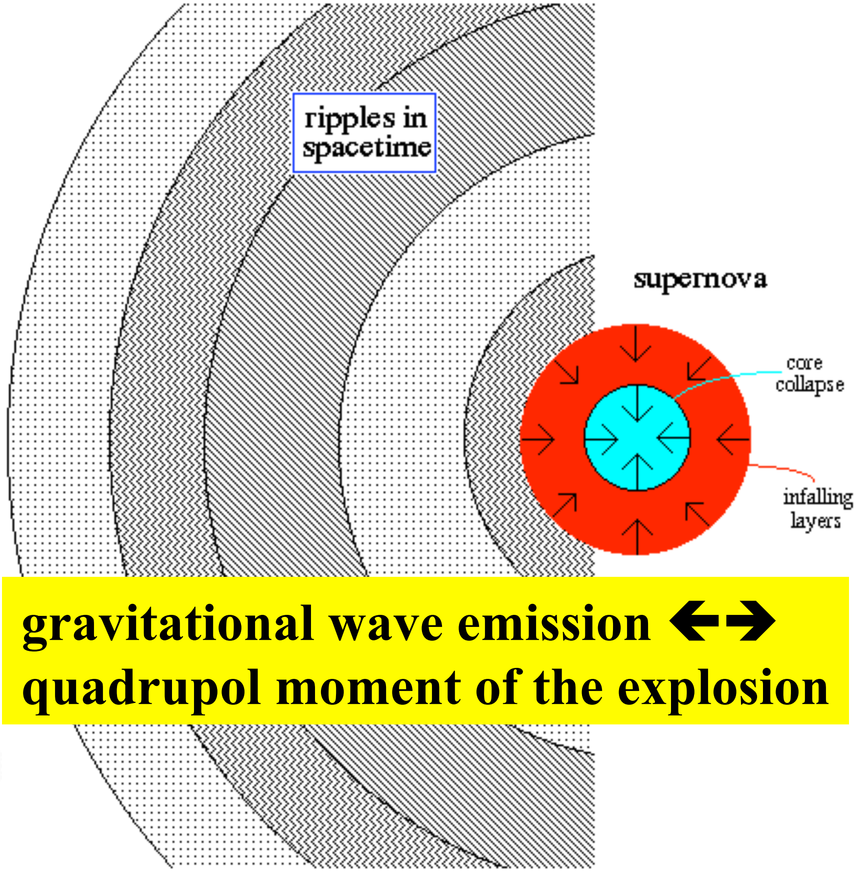


abrupt end of ν-emission

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

Supernovae & Gravitational Waves





Dimmelmeier, Font, Müller

→ additional information about galactic SN

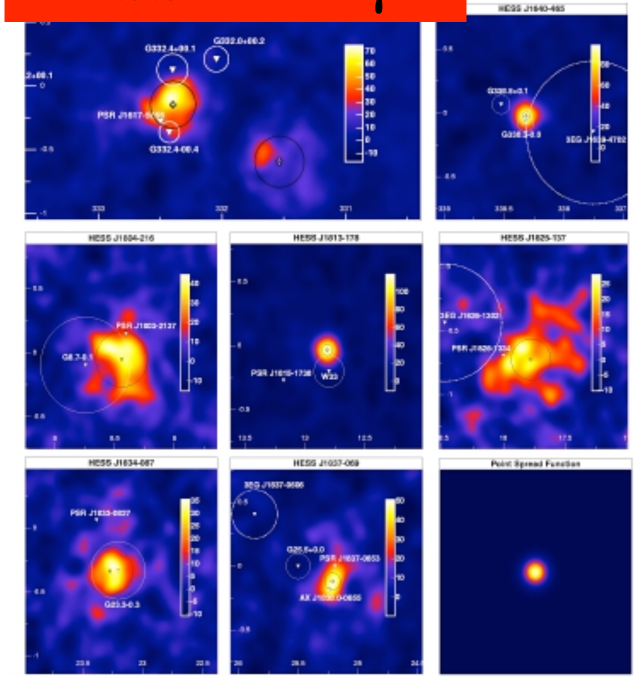
→ **global fits:** optical + neutrinos + gravitational waves

→ 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?

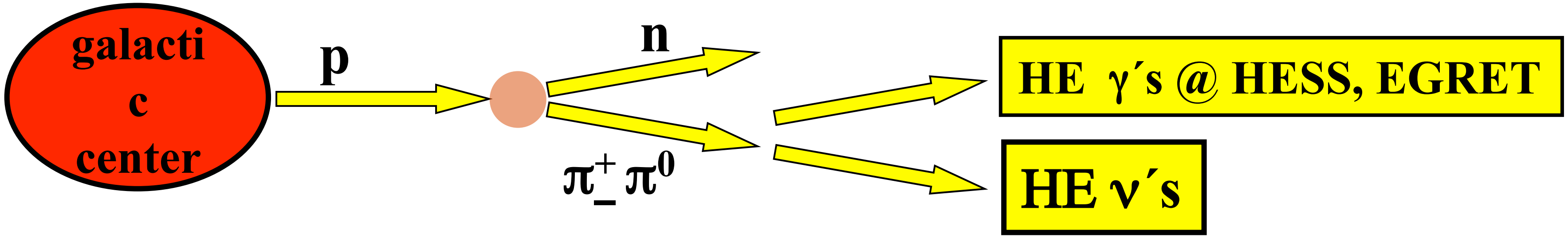
Plausible explanation:

-SN shock front acceleration

- γ´s from π^0 decay

➔ ν flux from GC

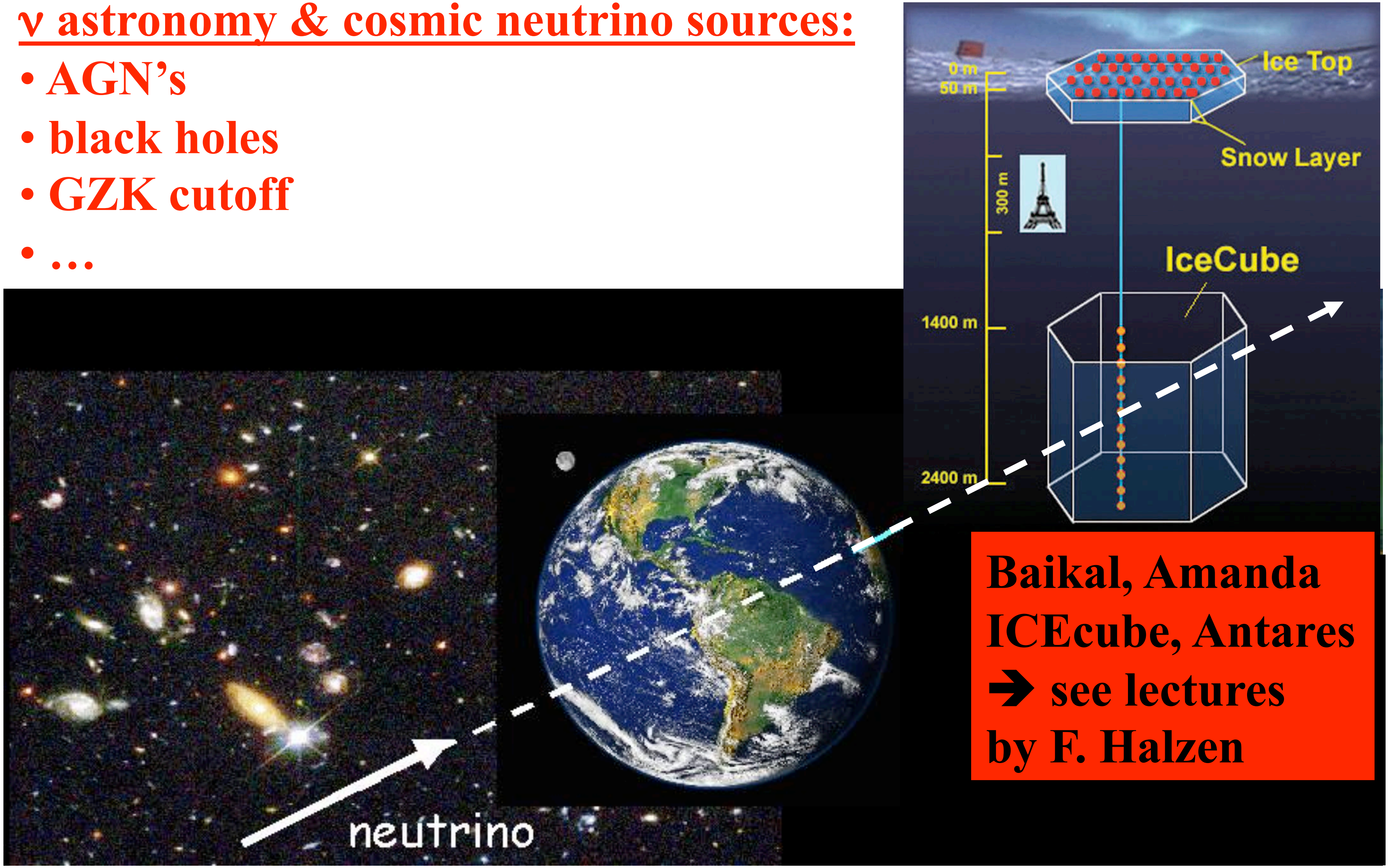
➔ ν signal @ km^3 detectors



Neutrino Telescopes

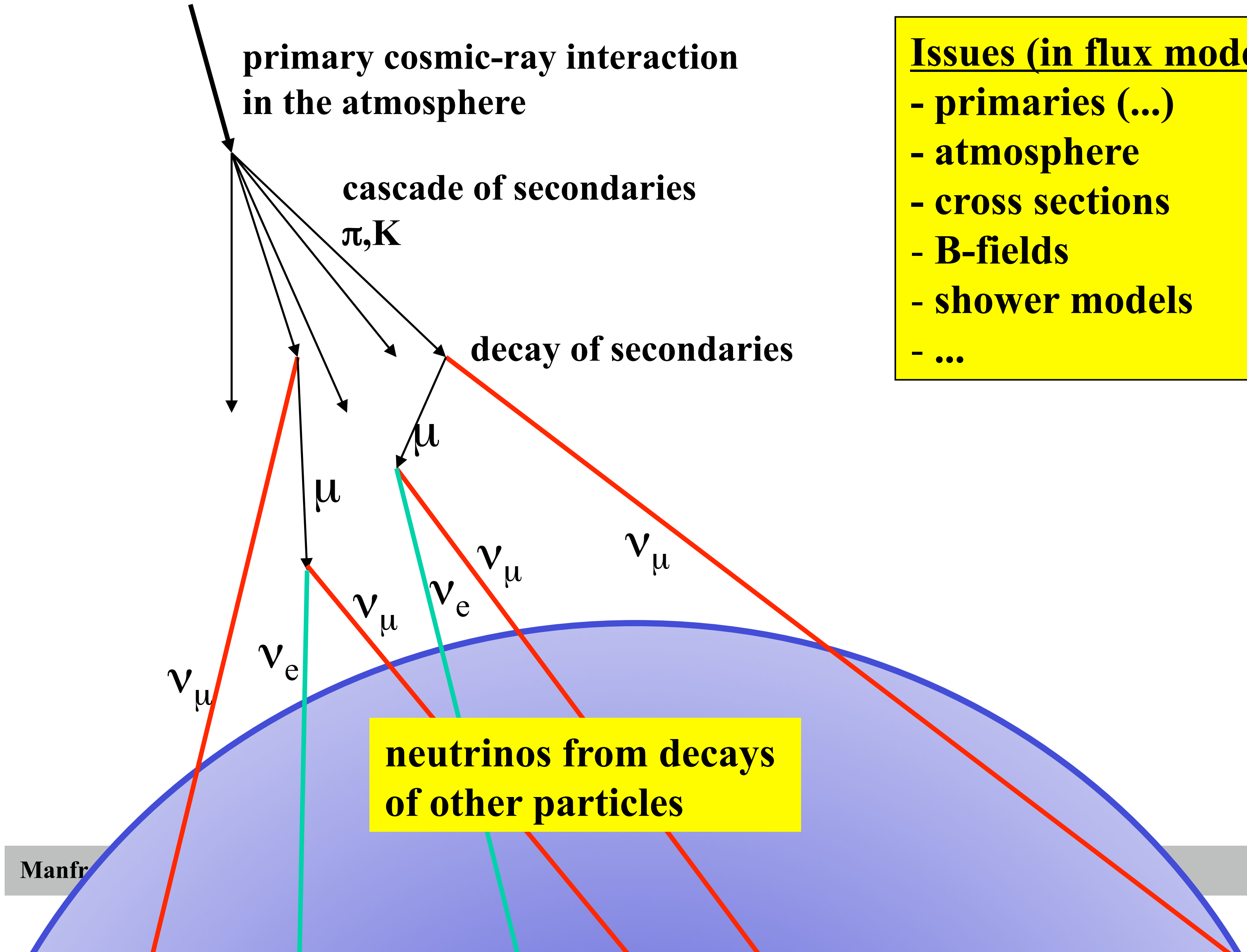
ν astronomy & cosmic neutrino sources:

- AGN's
- black holes
- GZK cutoff
- …



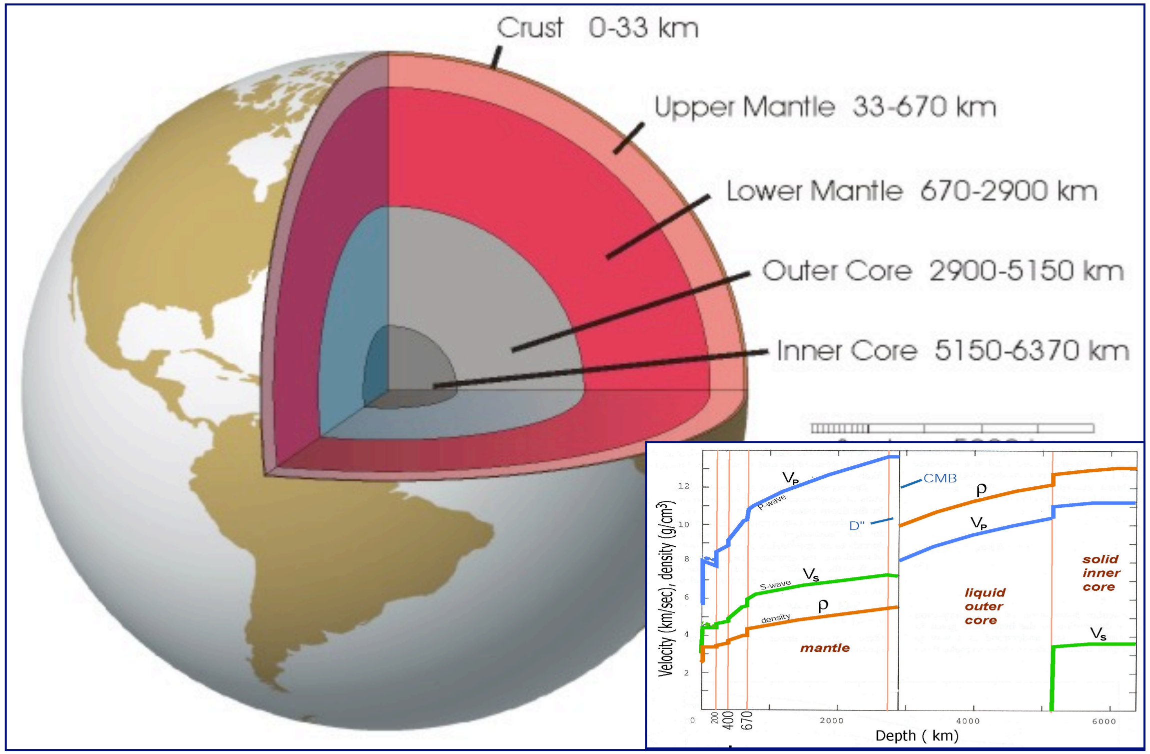
Baikal, Amanda
ICEcube, Antares
➔ see lectures
by F. Halzen

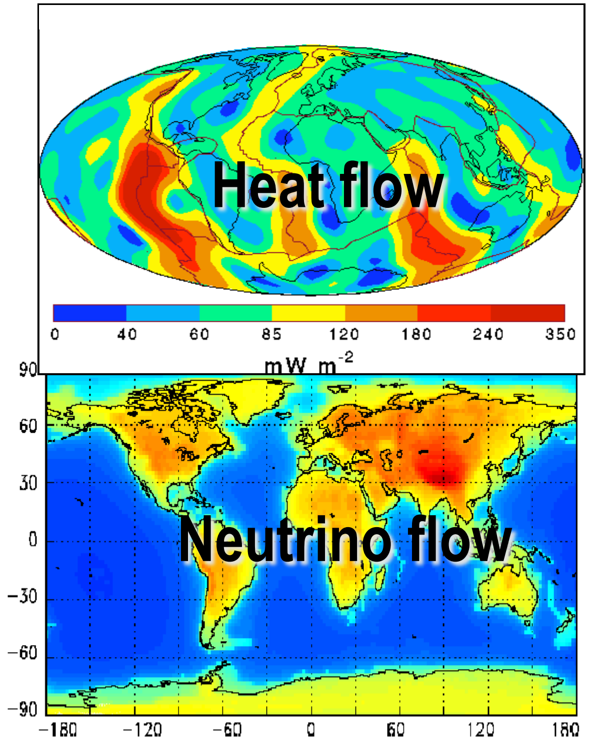
Learning from Atmospheric Neutrinos



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

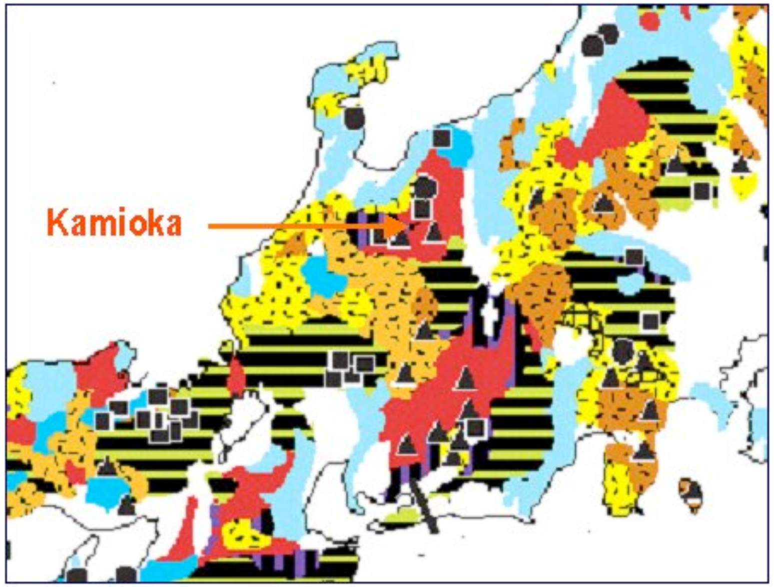
Geo Neutrinos as Probes of the Earth

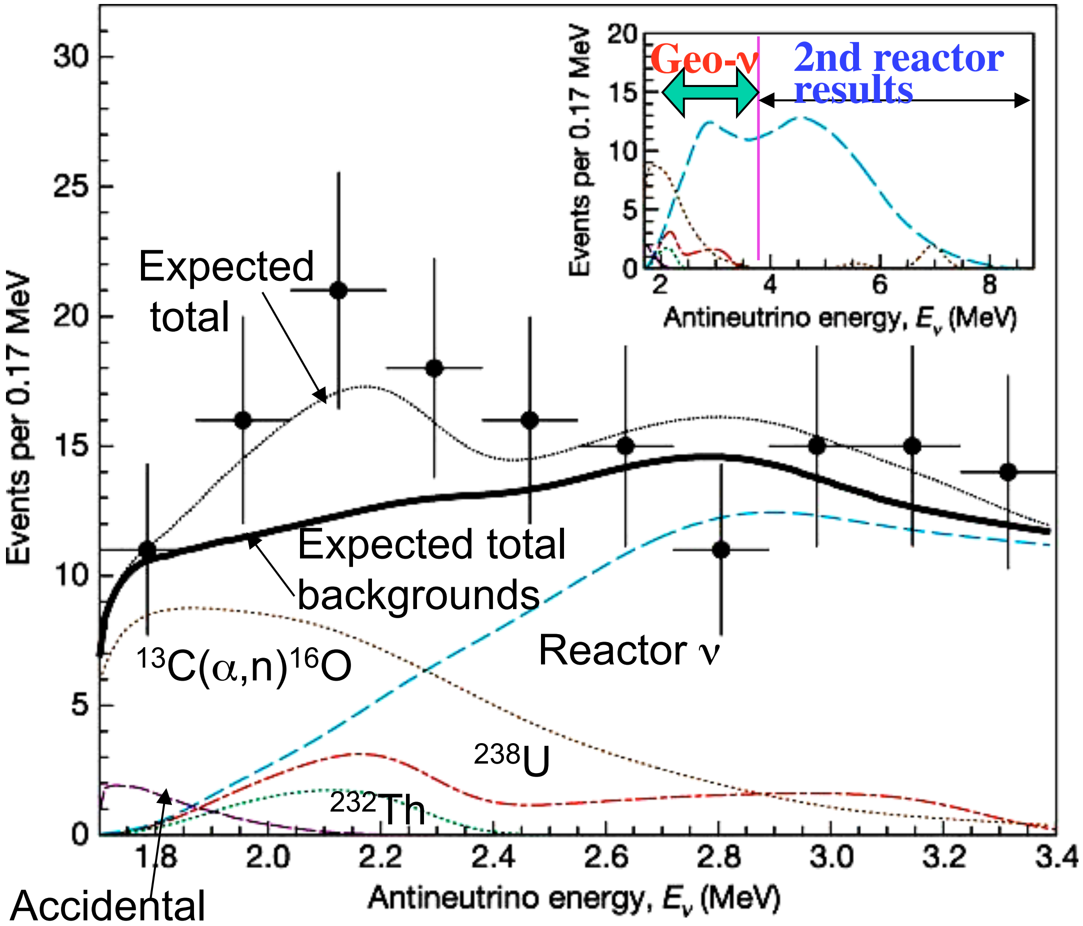




- radiogenic part of terrestrial heat flow ~80 mW/m² ➔ total: ~40 TW
- test geochemical model of the Earth, the Bulk Silicate Earth
- test unorthodox ideas of Earth's interior (K @ core, giant reactor)

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

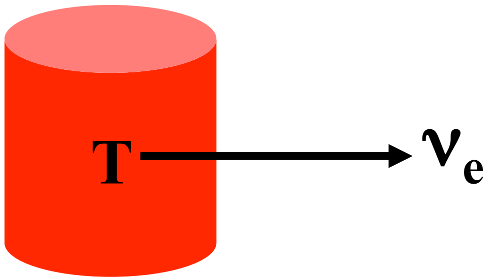
7. New Ideas / Challanges

- Strong beta source in TPC
- Neutrinos and atom traps
- Detecting cosmological neutrinos
- GSI oscillations ???
- Mößbauer neutrinos
- …

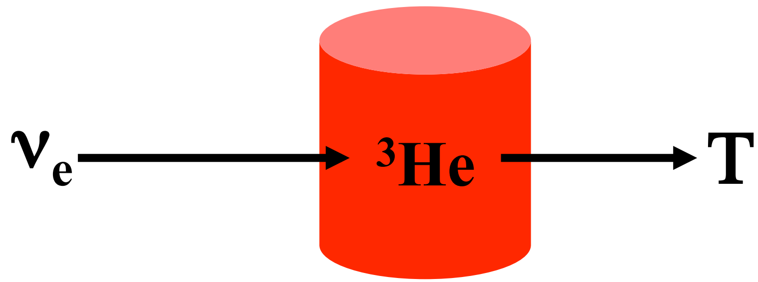
Mößbauer Neutrinos

$T \xrightarrow{\text{EC-process}} {}^3He + \nu_e$ ➔ monochromatic neutrinos

T recoil



Tritium in Nb lattice
➔ recoil-less emission

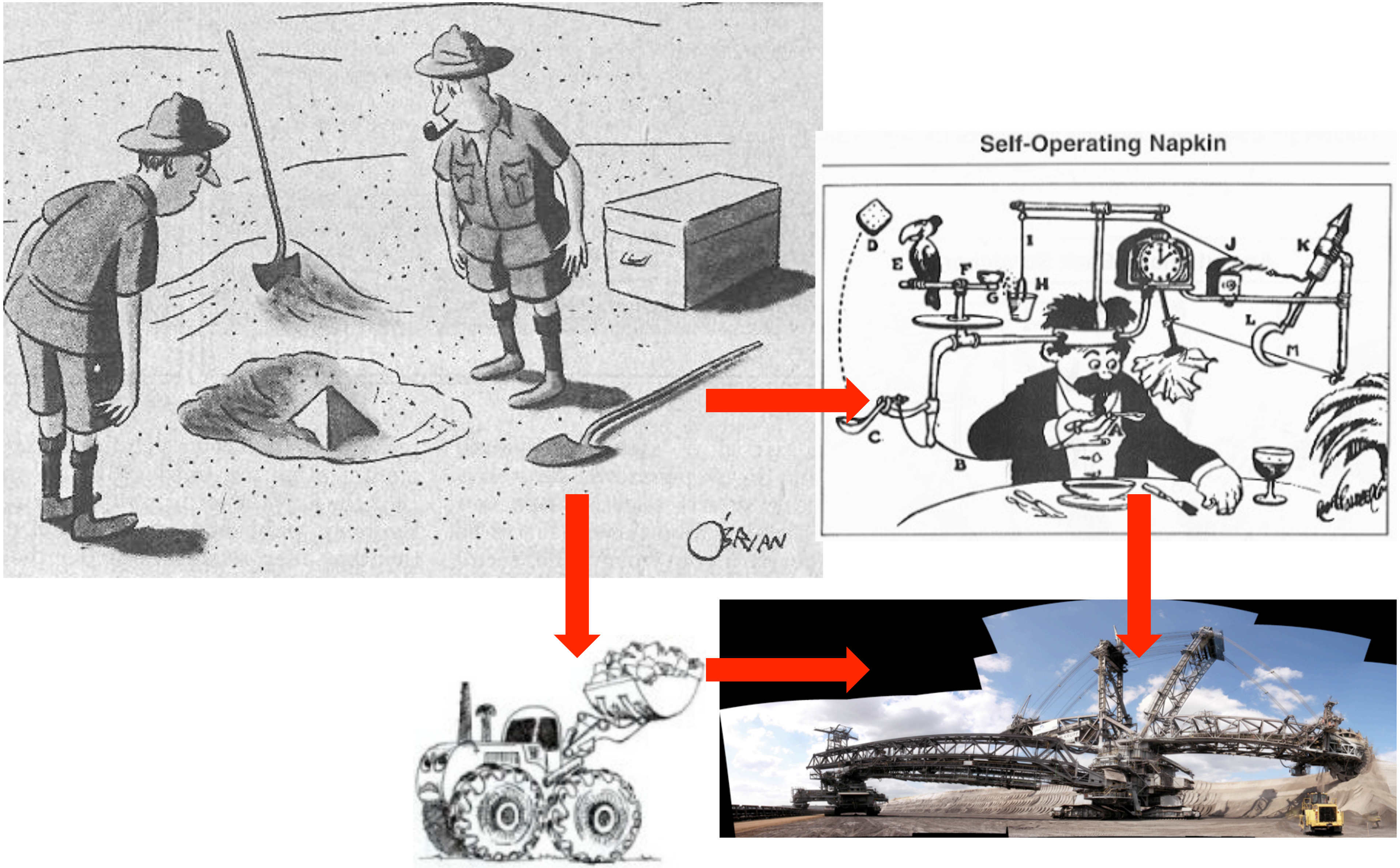


3He in lattice
➔ Tritium-production

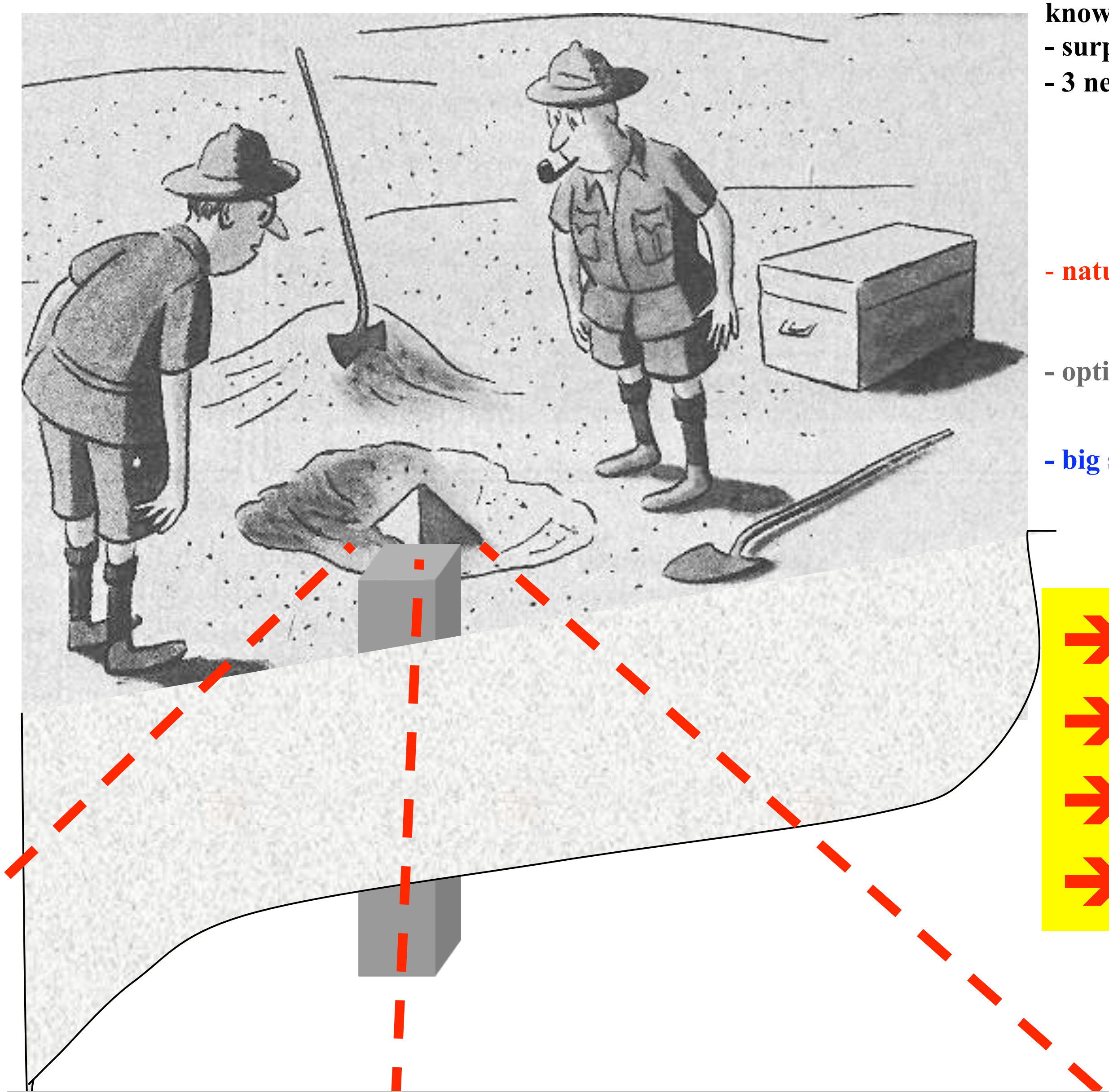
Questions:

1) **Oscillations ➔ YES, but not as simple as usual**
2) **Feasability ➔ ??? , not now, future?**

Development of Future Experiments



Development of Theory



known facts:
- surprising!
- 3 neutrino global fits

- naturalness???

- options/speculations

- big surprises?

→ all legitimate
→ no 'probability'
→ very promising
→ experiment will tell

Neutrinos probe new physics in many ways!