NuFact 09 Perspectives

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NuFact09
11th International Workshop on Neutrino Factories, Superbeams and Beta Beams
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Neutrinos: A fascinating Story

W. Pauli

- continuous β-decay spectrum
- energy-momentum conservation

→ theory: a new particle

→ invisible, since Q=0, spin ½, ...

Dec. 1930: Letter to DPG @ Tübingen … will never be detected

- Cowen & Reines 1954-56

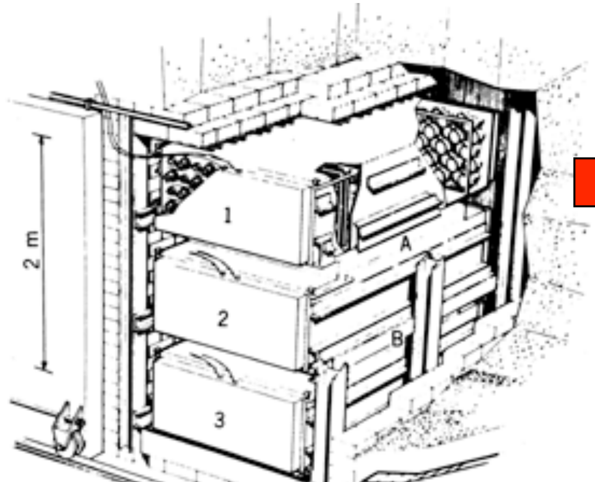
→ project ``poltergeist“

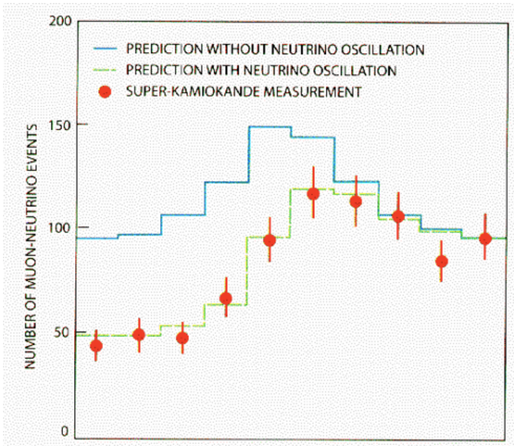
→ detection of reactor ν‘s

- neutrino beams, DIS,
- oscillations

→ masses and mixings

SM←→ BSM

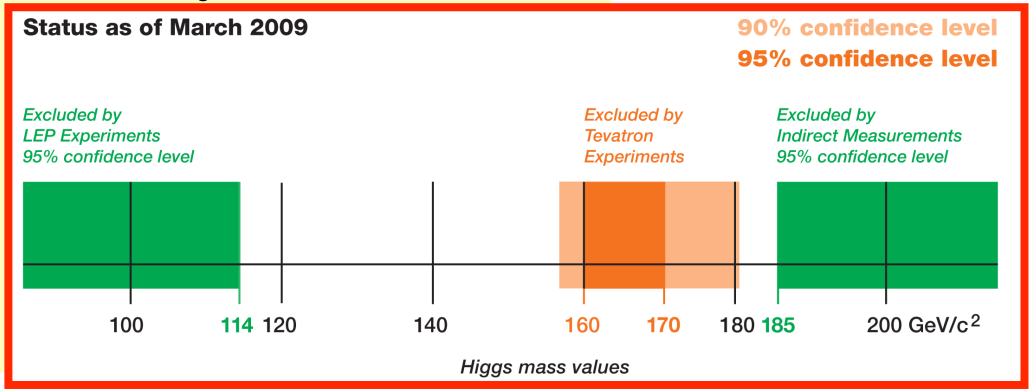




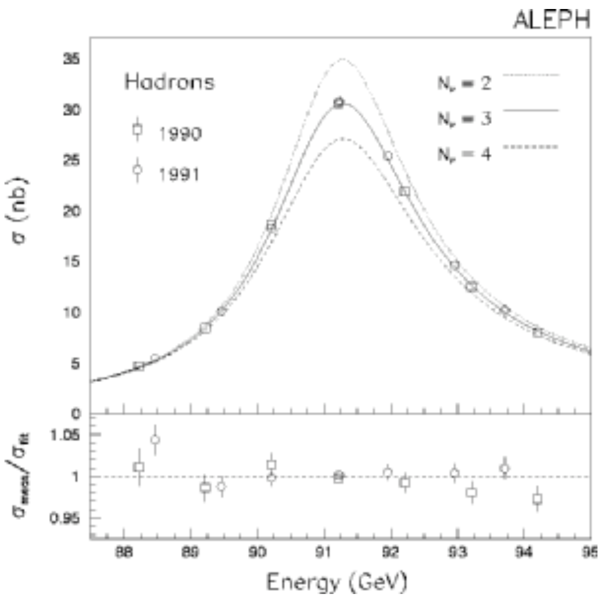
what next?
why?
what?

Success of the Standard Model

SM describes everything perfectly ... besides:
- missing Higgs particle ➔
- 3.7σ deviation in g-2
- no dark matter
- neutrinos are massless



SM: 3 neutrinos ⟷ Z line shape @ LEP



parameters of SM		add massive ν's
gauge bosons	3	
Higgs particle	2	fermions: 22
quarks (mass+mix)	6+4	
leptons	3	➔ +3+6
strong CP problem	1	
total	19	➔ 28

Physics Beyond the Standard Model

Theoretical arguments:

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

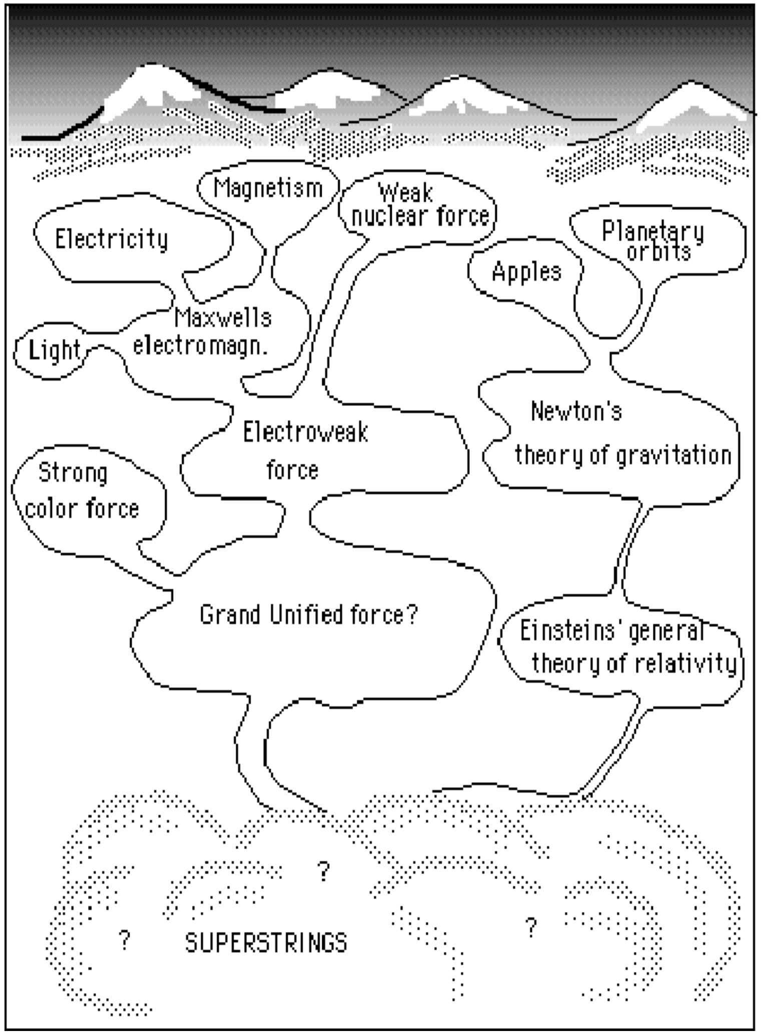
Two main directions:

- Symmetry breaking ←→ LHC
-Origin of generations/flavour ←→ ν's

Experimental facts:

- Dark Matter & Dark Energy exist
- g-2 deviates from SM
- Neutrino masses have been detected
- Baryon asymetry of the universe ←→ $m_\nu > 0$

unification



Extending the Standard Model

➔ success of renormalizable gauge field theories in d=4

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

➔ symmetry, renormalizability, no anomalies

➔ particle content (symmtery representations):

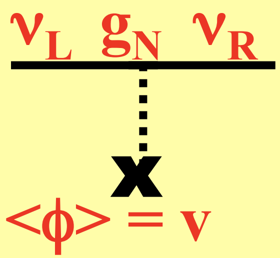
- gauge sector – fixed by gauge group
- scalar sector – must break EW symmetry, $SB \sim 2_L$
- fermions – anomaly free combinations (least understood sector!!!)

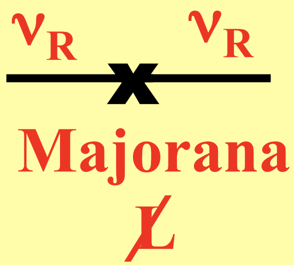
➔ different levels of SM extension… Pavel Fileviez Perez

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

Adding Neutrino Mass Terms

1) Simplest possibility: add 3 right handed neutrino fields





➔

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^{\mathbf{c}} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^{\mathbf{c}} \\ \nu_R \end{pmatrix}$$

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

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

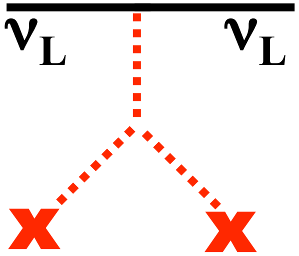
6x6 block mass matrix
block diagonalization
M_R heavy ➔ 3 light ν's

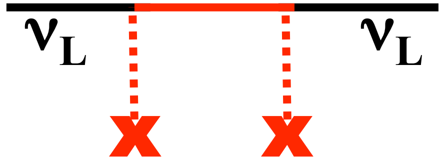
NEW ingredients, 9 parameters ➔ SM+

Note: Adding chiral fermion representations to SM non-trivial ⇔ radiative corrections S,T, …

Other Neutrino Mass Operators

2) new scalar or fermionic triplets:



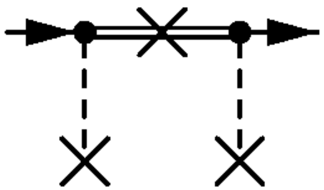


➔ left-handed Majorana mass term: ➔ $M_L \overline{L} L^c$

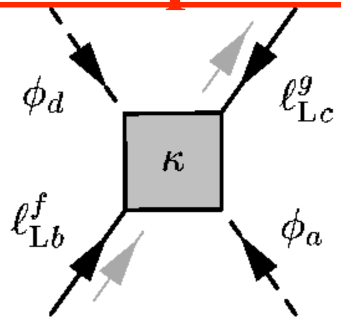
3) Both ν_R and new triplets:

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

4) Higher dimensional operators: d=5, …



$\Rightarrow$



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

➔ $M_L \overline{L} L^c$

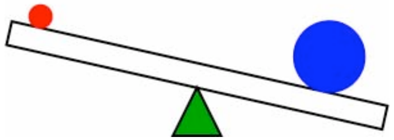
5-N) …

Suggestive Seesaw Features

QFT: natural value of mass operators ⇔ scale of symmetry

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

See-saw mechanism (type I)



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

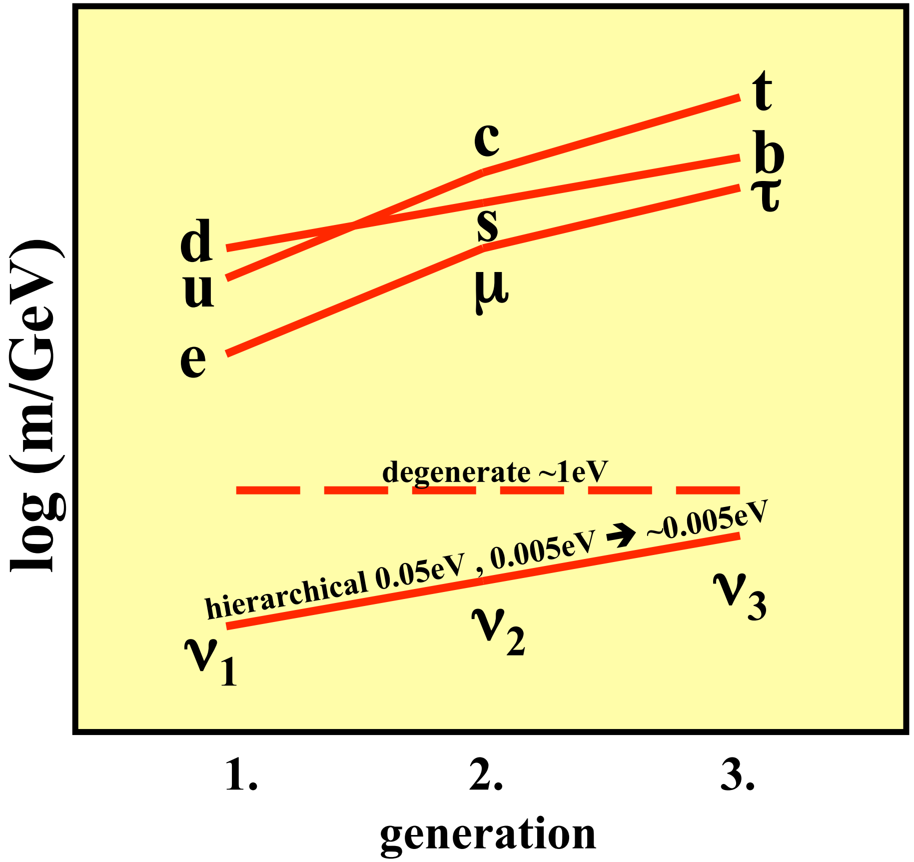
$m_h = M_R$

Numerical hints:

For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons ⇒ $M_R \sim 10^{11}$ - 10^{16}GeV
⇒ ν's are Majorana particles , m_ν probes ~ GUT scale physics!
⇒ smallness of m_ν ⇔ high scale of $\not{L}$, symmetries of m_D ,M_R

2nd Look Questions

Quarks & charged leptons ➔ hierarchical masses ➔ neutrinos?



Quarks and charged leptons:

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

Neutrinos: $m_\nu \sim H^n$ ➔ $H \leq \sim 10$

See-saw:

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

	m_ν	m_D^T	M_R^{-1}	m_D
H	~ 10	≥ 20	?	≥ 20

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

Other effective Operators Beyond the SM

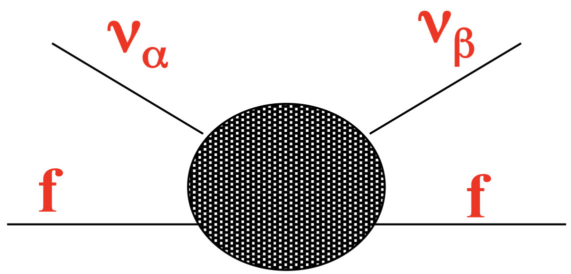
➔ **effects beyond 3 flavours**

➔ **Non Standard Interactions = NSIs** ➔ **effective 4f opersators**

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

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

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



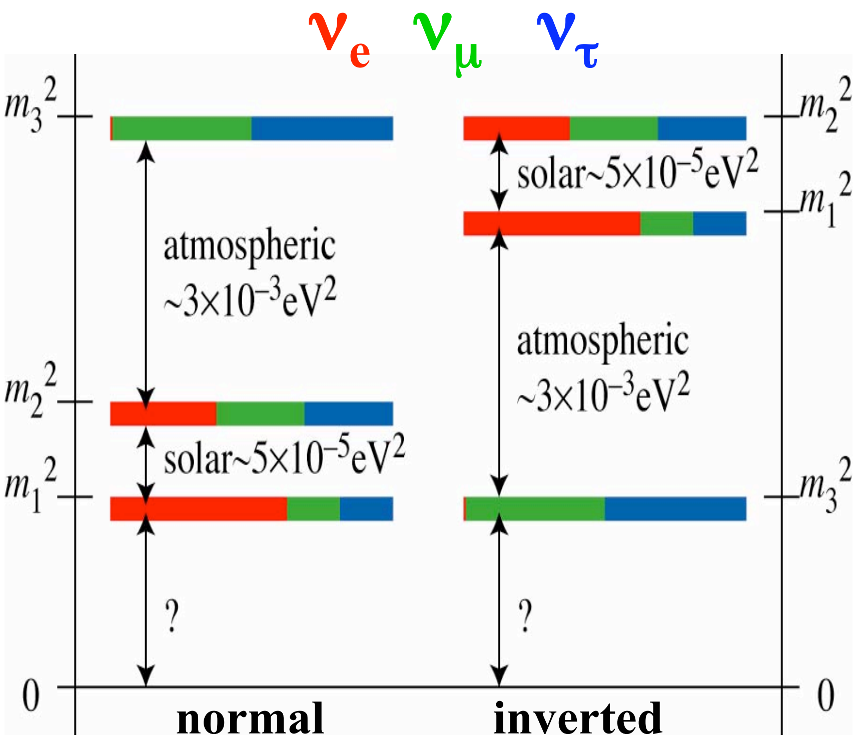
Parameters for 3 Light Neutrinos

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

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

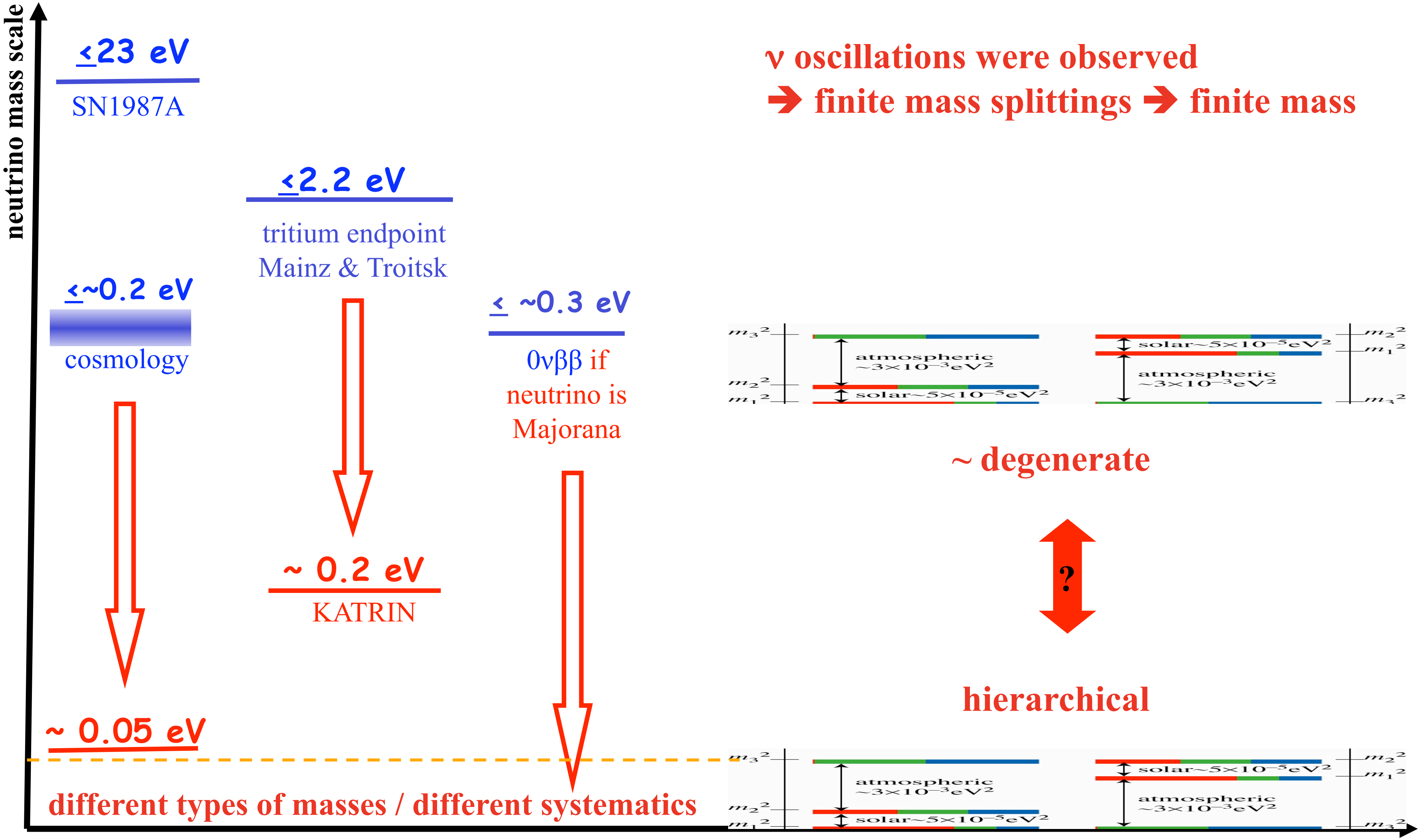
questions:

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



hierarchical or degenerate

Interplay of Neutrino Mass Determinations



Four Methods of Mass Determination

- kinematical
- lepton number violation
  ⇔ Majorana nature
- astrophysics & cosmology
- oscillations

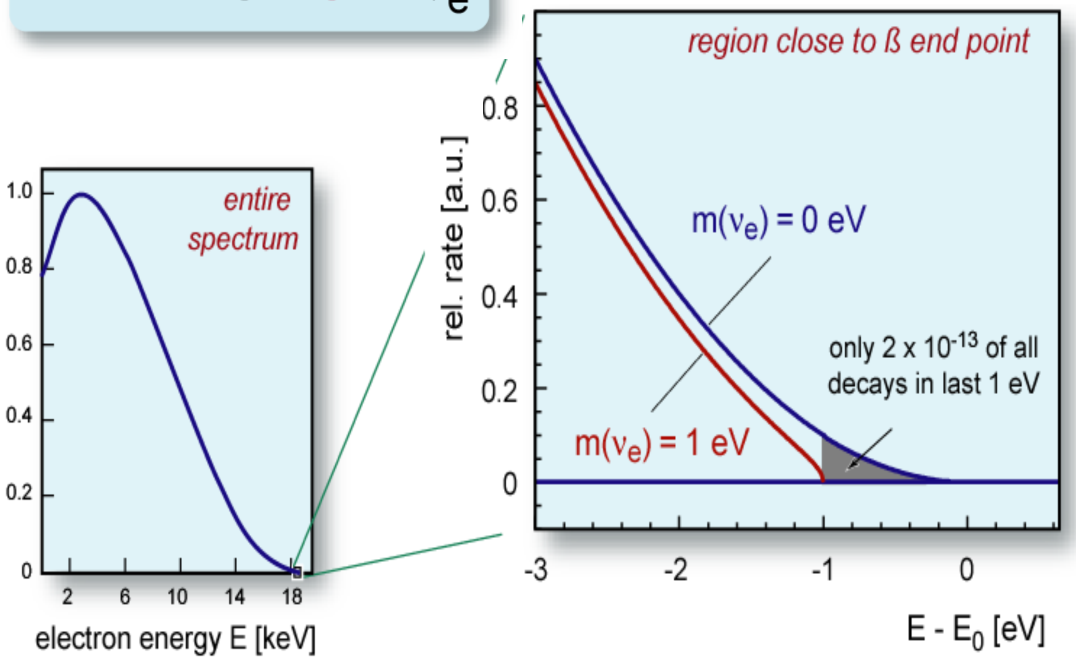
Beta Decay Energy Spectrum

m_ν from kinematics & energy conservation
➔ 'theoretically clean'

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

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

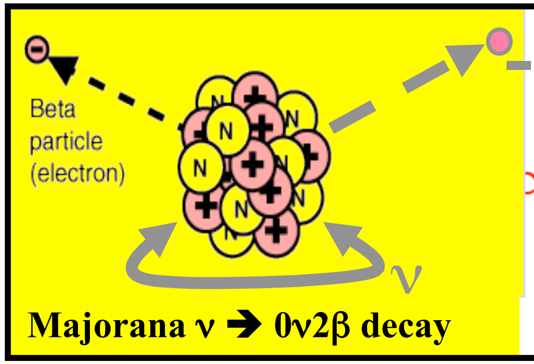
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

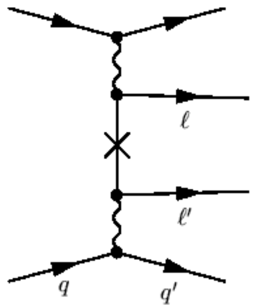


KATRIN aim

sensitivity:
$m_\nu < 0.2$eV (90%CL)

Neutrino-less Double β-Decay



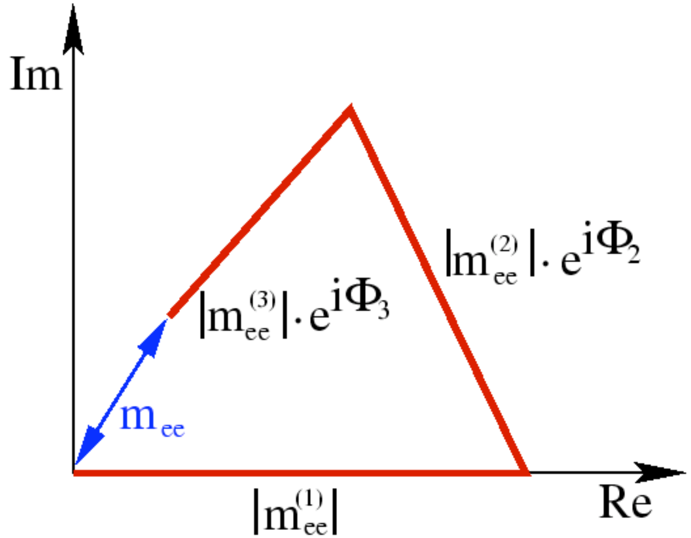


$$\propto |\langle m_{ee} \rangle| = |\sum m_i U_{ei}^2| \quad \leq 0.35 \text{ eV ?}$$

Heidelberg-Moscow experiment

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

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



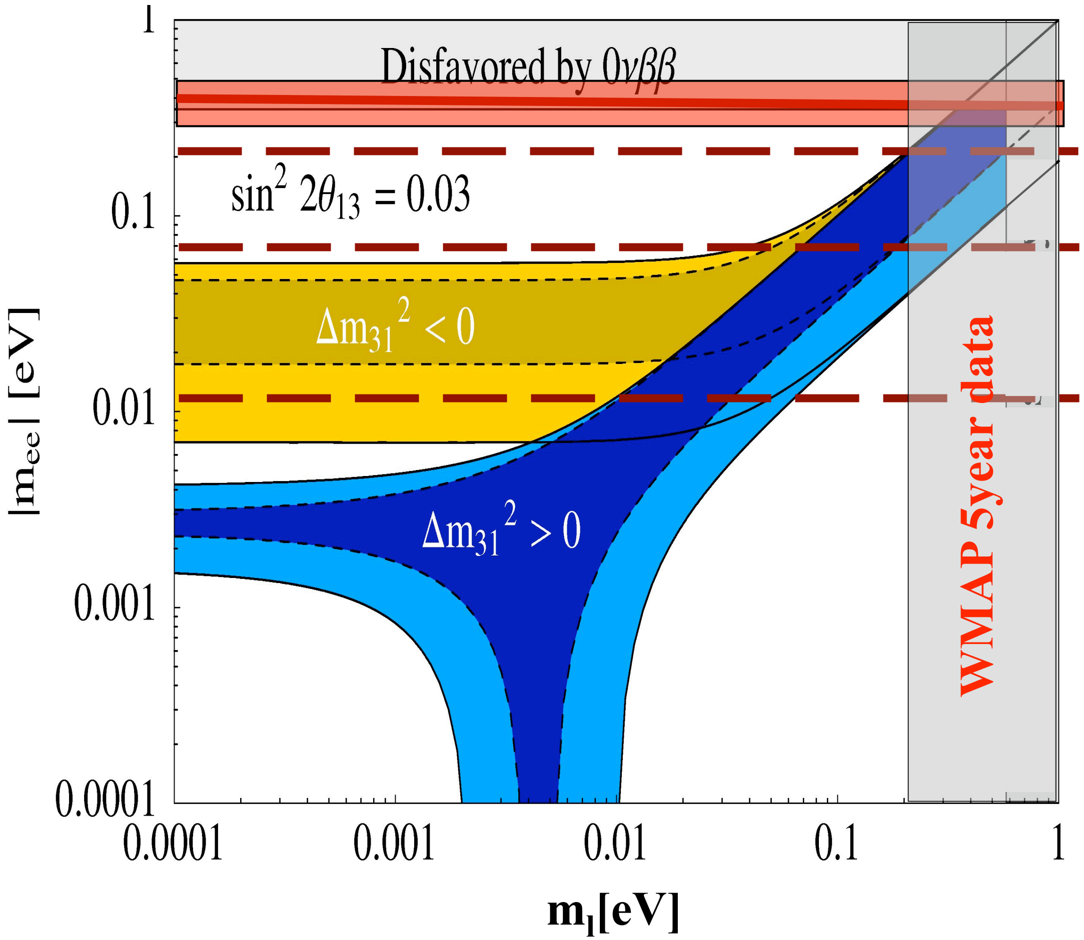
solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

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

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

aims of new experiments:

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

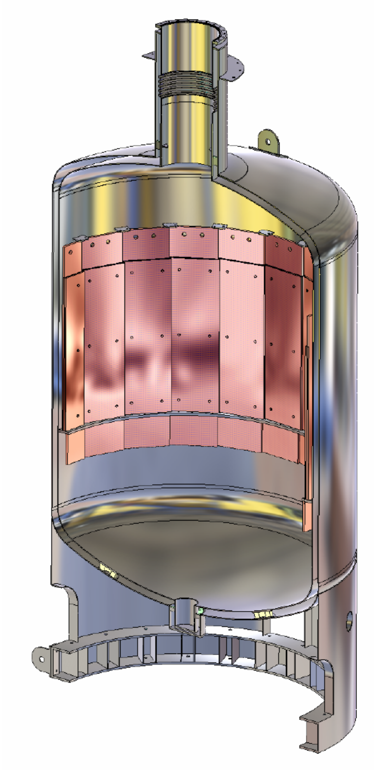


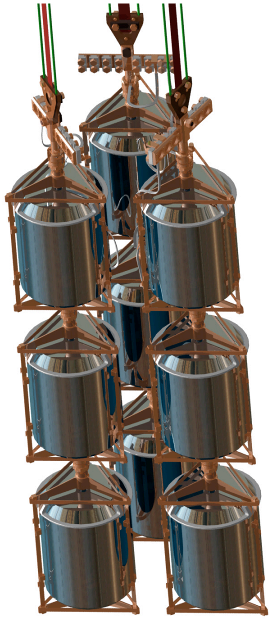
Comments:

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

➔ very promising interplay of cosmology, other mass determinations LHC, LVF and theoretical ideas

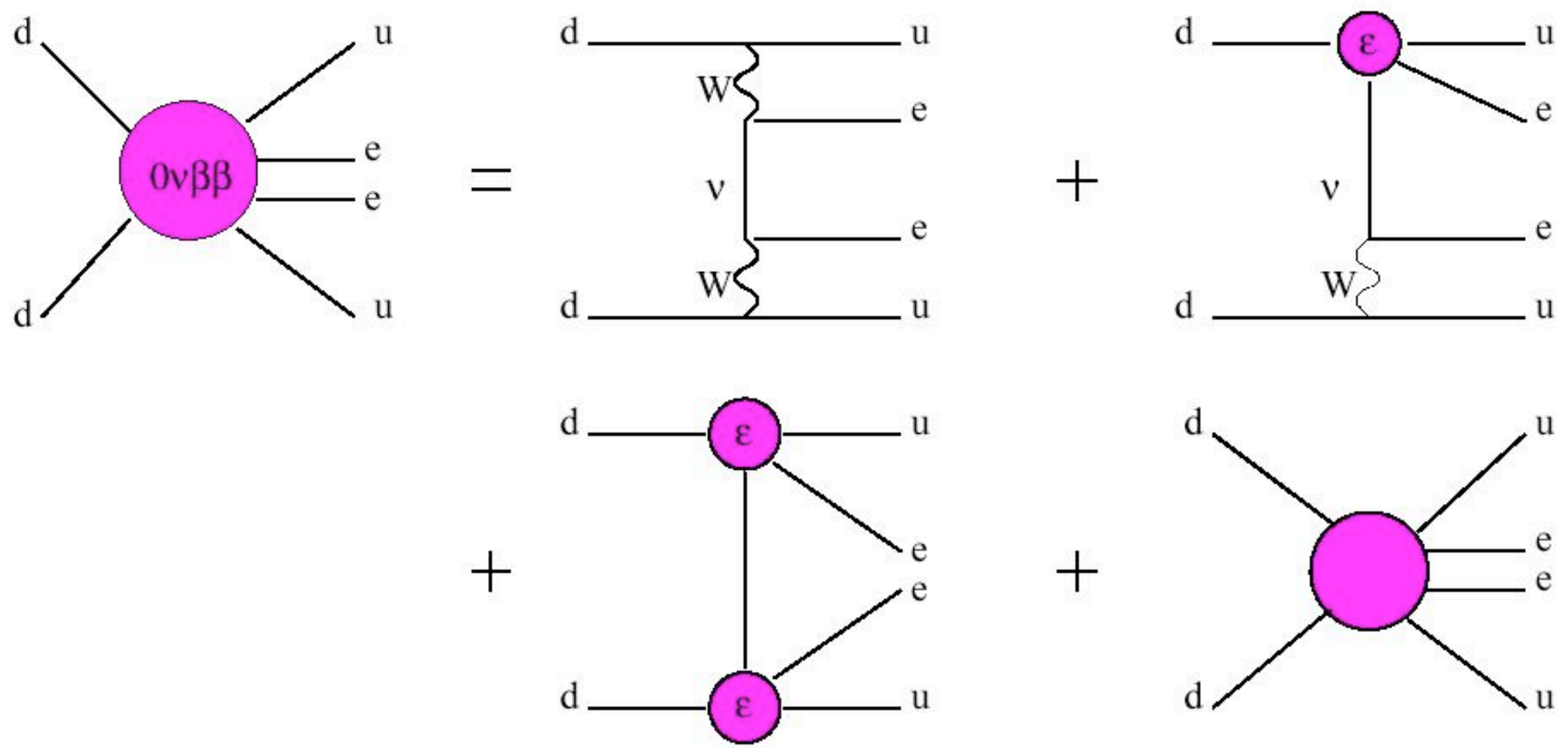
GERDA Construction





➔ **detector filling 2009**

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



Schechter+Valle:

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

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

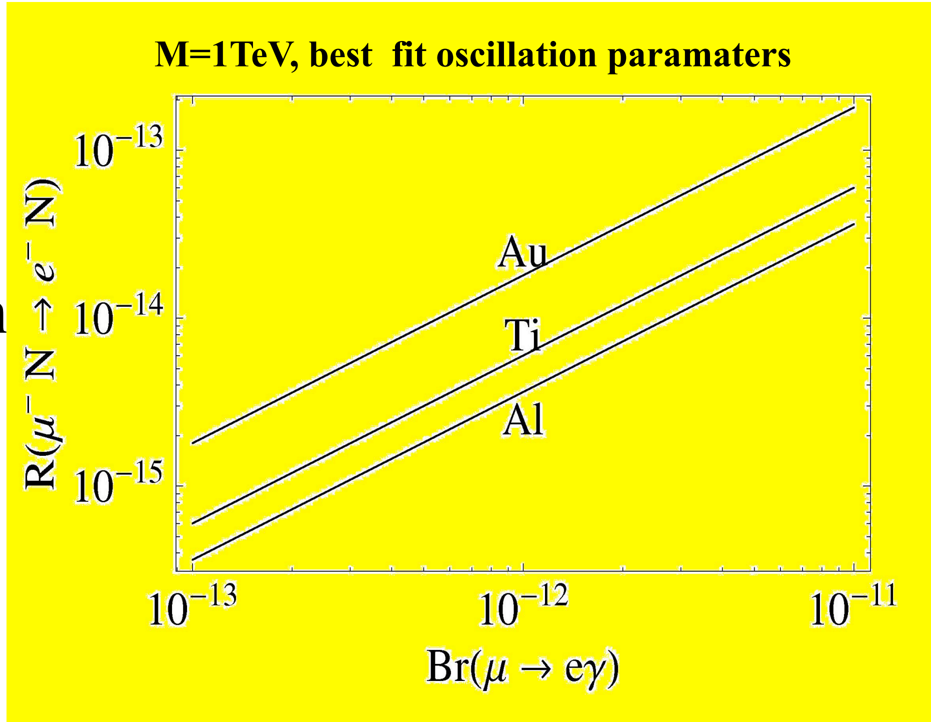
Lepton Flavour Violation

- **Majorana neutrino mass terms**
- **…**
- **R-parity violating supersymmetry**
  Hall+Kosteleck+Rabi, Borzumati+Masiero, Hisano+Tobe, Casas+Ibarra, Antusch +Arganda+Herrero+Teixeira, Joaquim+Rossi, …

➔LFV and leptonic CP violation can even exist for $m_\nu \rightarrow 0$

➔ e.g. modifications of correlation between $\mu^- \rightarrow e^- \gamma$ decay and nuclear $\mu^- \rightarrow e^-$ conversion
MEG: 10^{-13}
PRISM: 10^{-18}

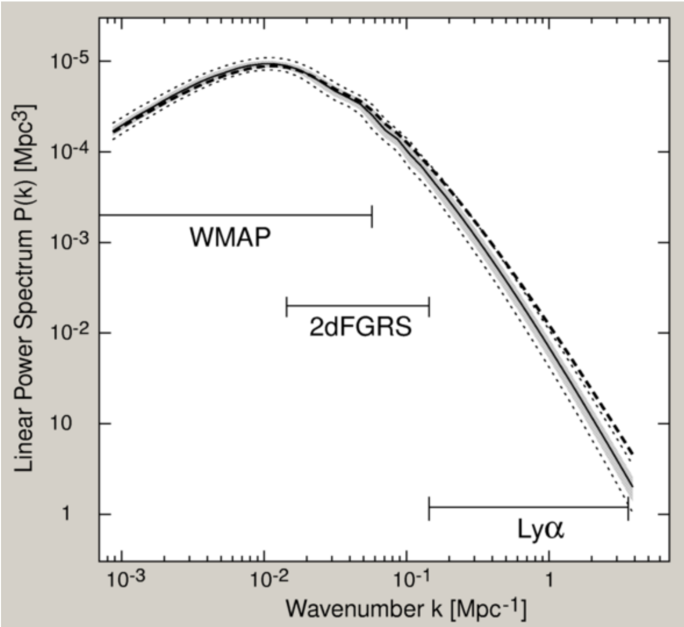
➔interplay: ν's – LFV – LHC in the coming years

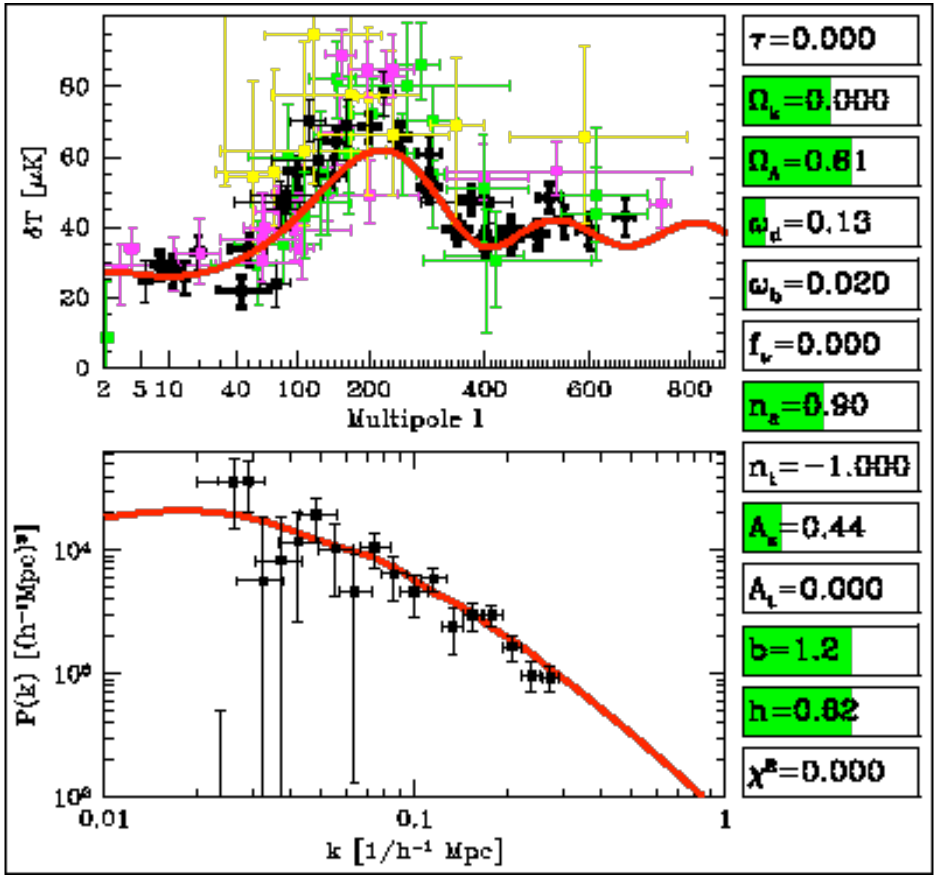


Deppisch+Kosmas+Valle

Cosmology and Neutrino Mass

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





- **WMAP+2dFGRS + Lyα+...**

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

⬅➔ levels of systematic errors

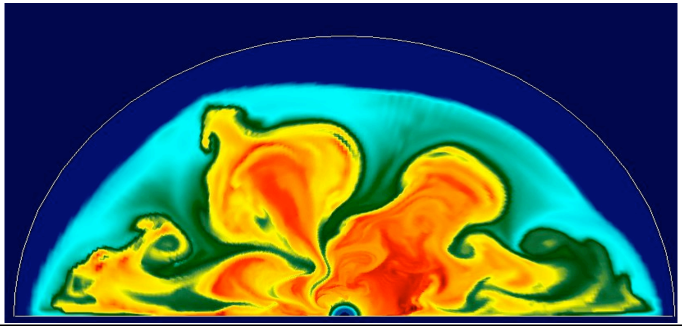
- **3 degenerate neutrinos, conservative approach**

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

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

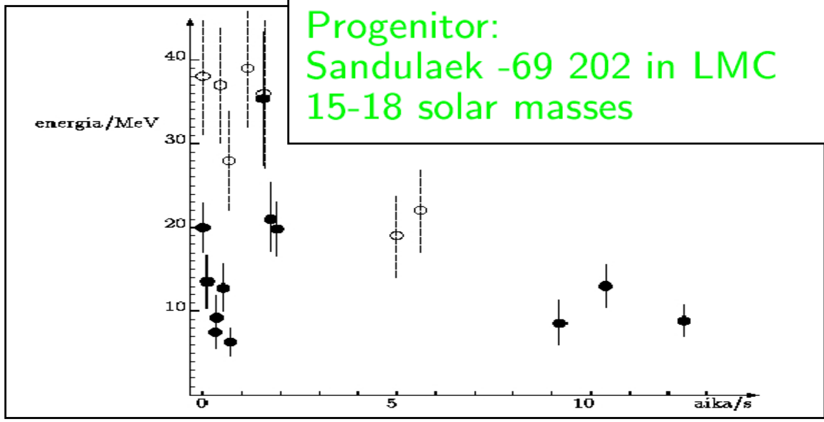
Supernova Neutrinos

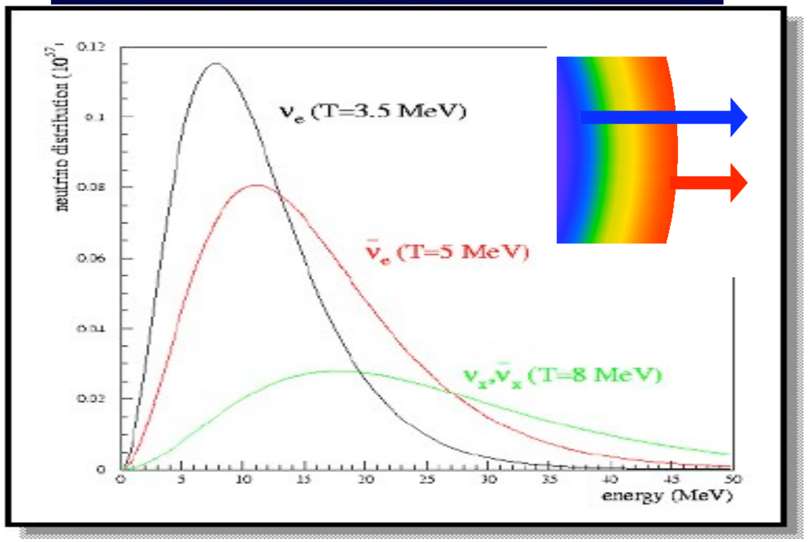
- Collaps of a typical star ➔ ~10^{57} ν's
- ~99% of the energy in ν's
- ν's essential for explosion
- 3d simulations do not explode
  (so far... 2d➔3d, ➔convection? ...)



SN1987A neutrino burst

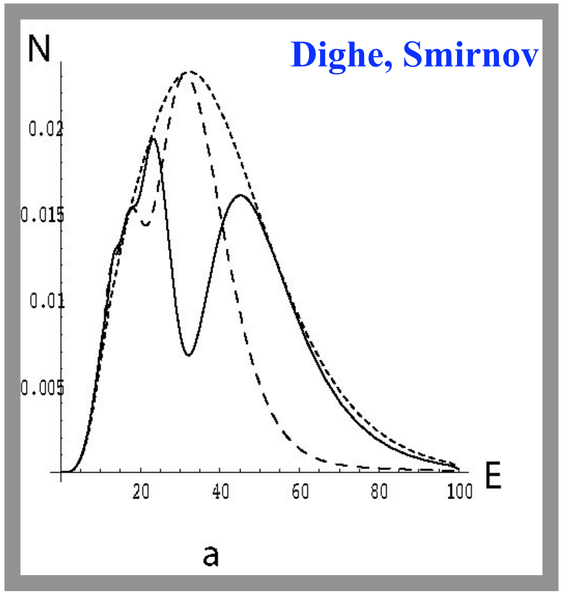
Progenitor:
Sandulaek -69 202 in LMC
15-18 solar masses





MSW: SN & Earth

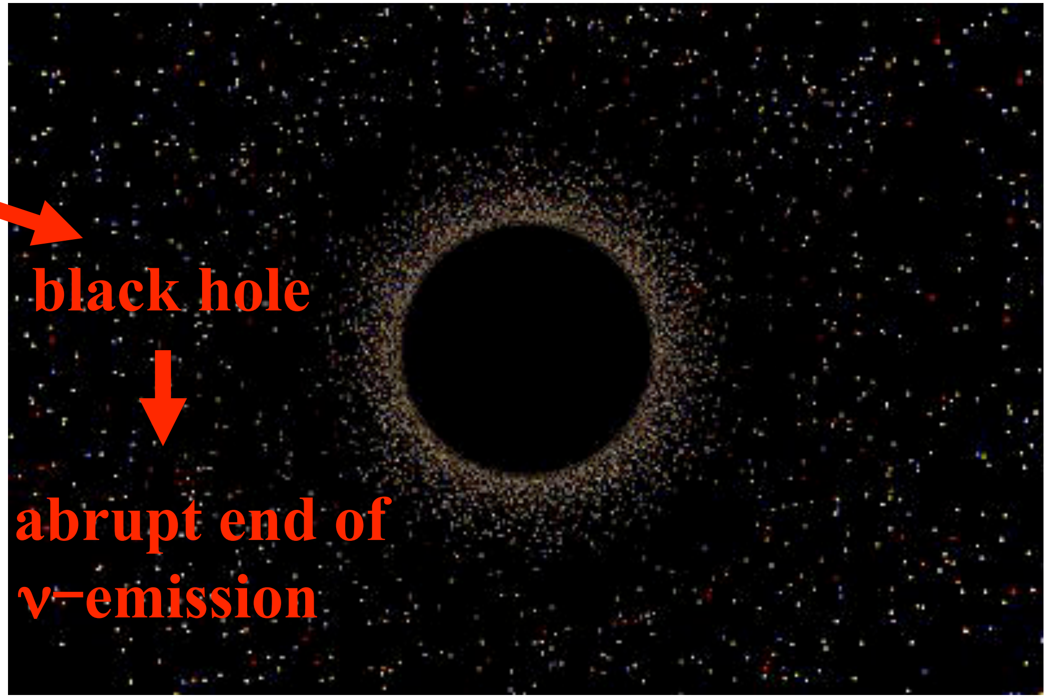
Very sensitive to finite θ_{13} and sgn(Δm^2)



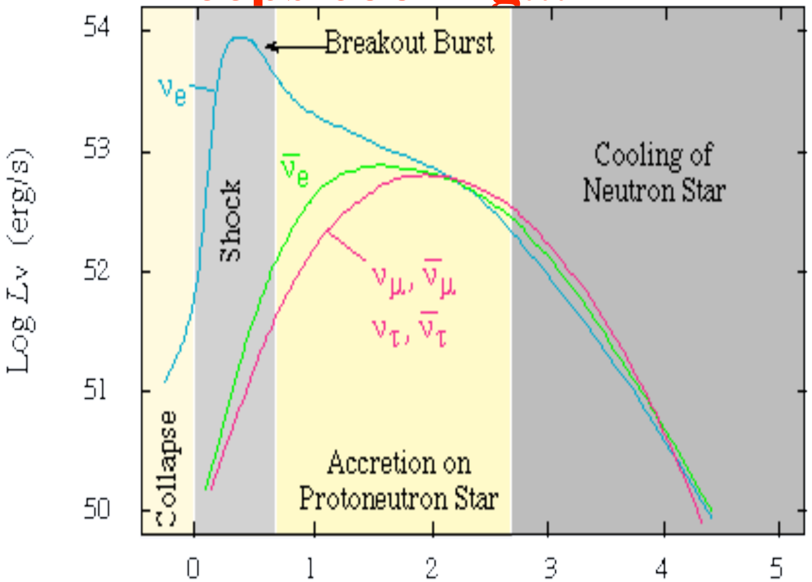
2 possibilities:

Supernova

neutron star or black hole



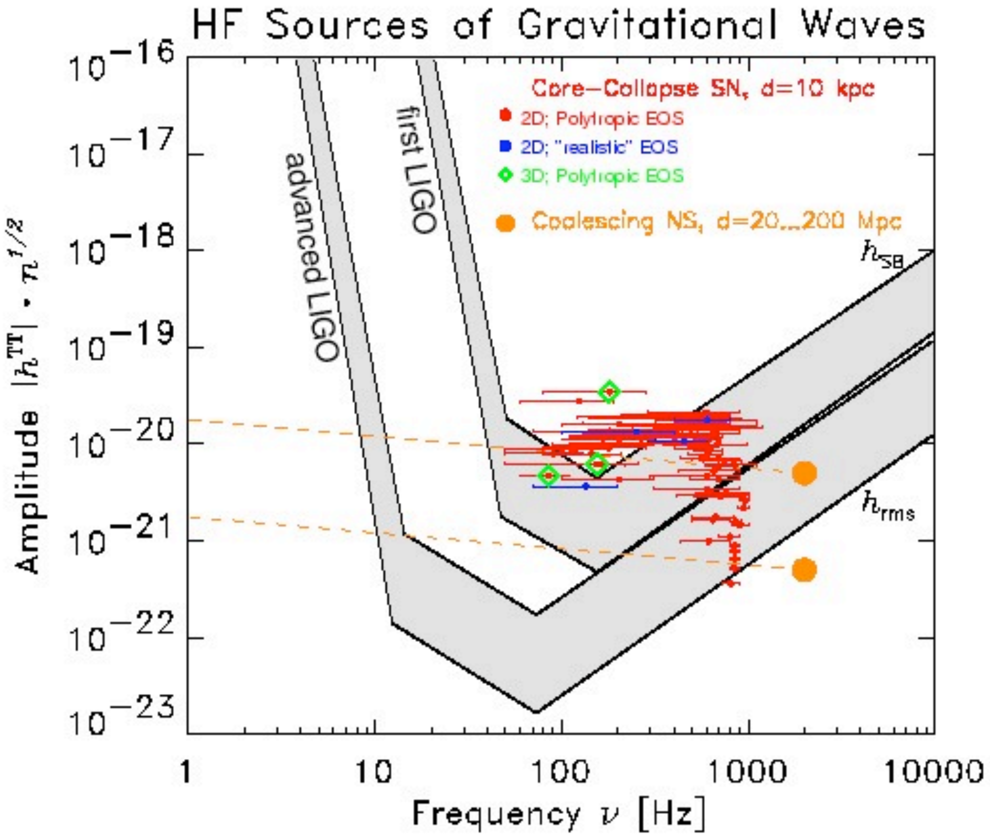
Keeps cooling...

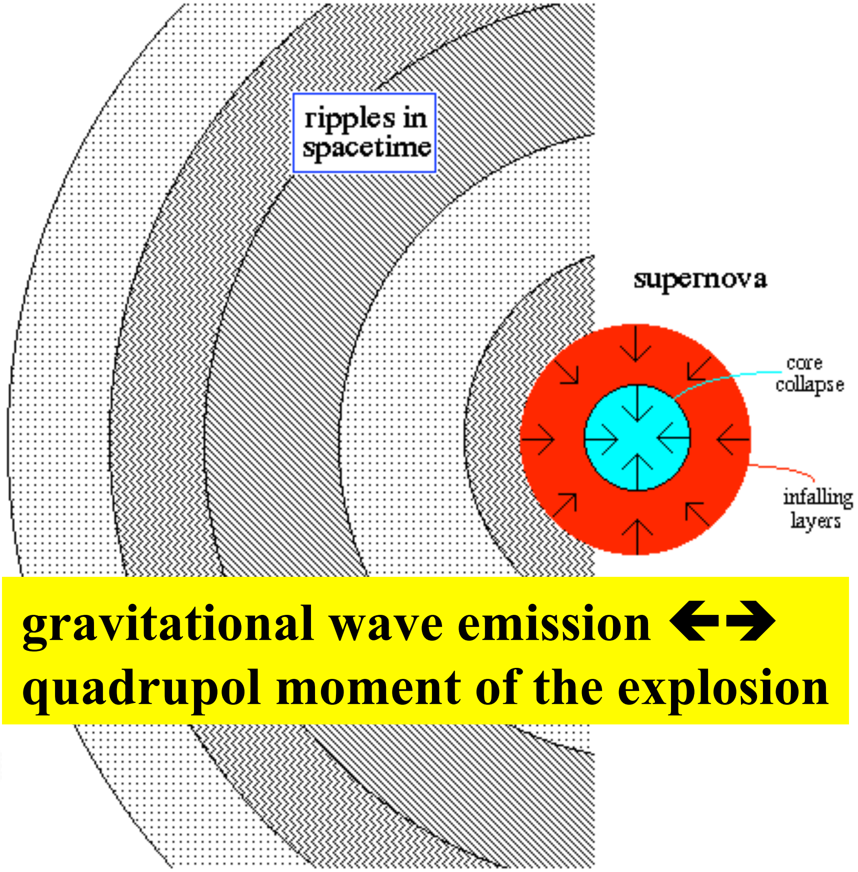


abrupt end of ν−emission

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

Supernovae & Gravitational Waves



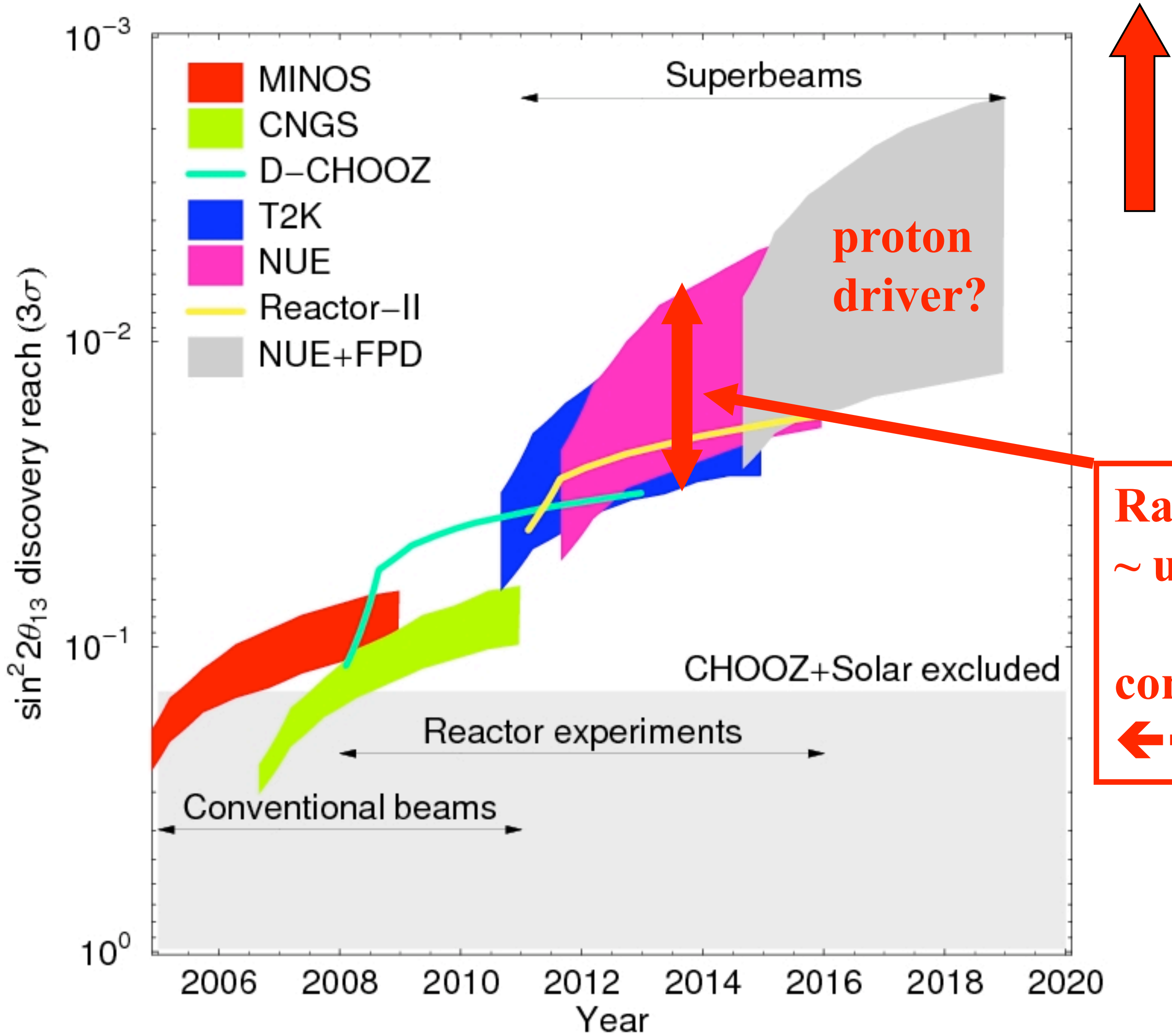


gravitational wave emission ←→ quadrupol moment of the explosion

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

Oscillations: θ_{13} Sensitivity Versus Time

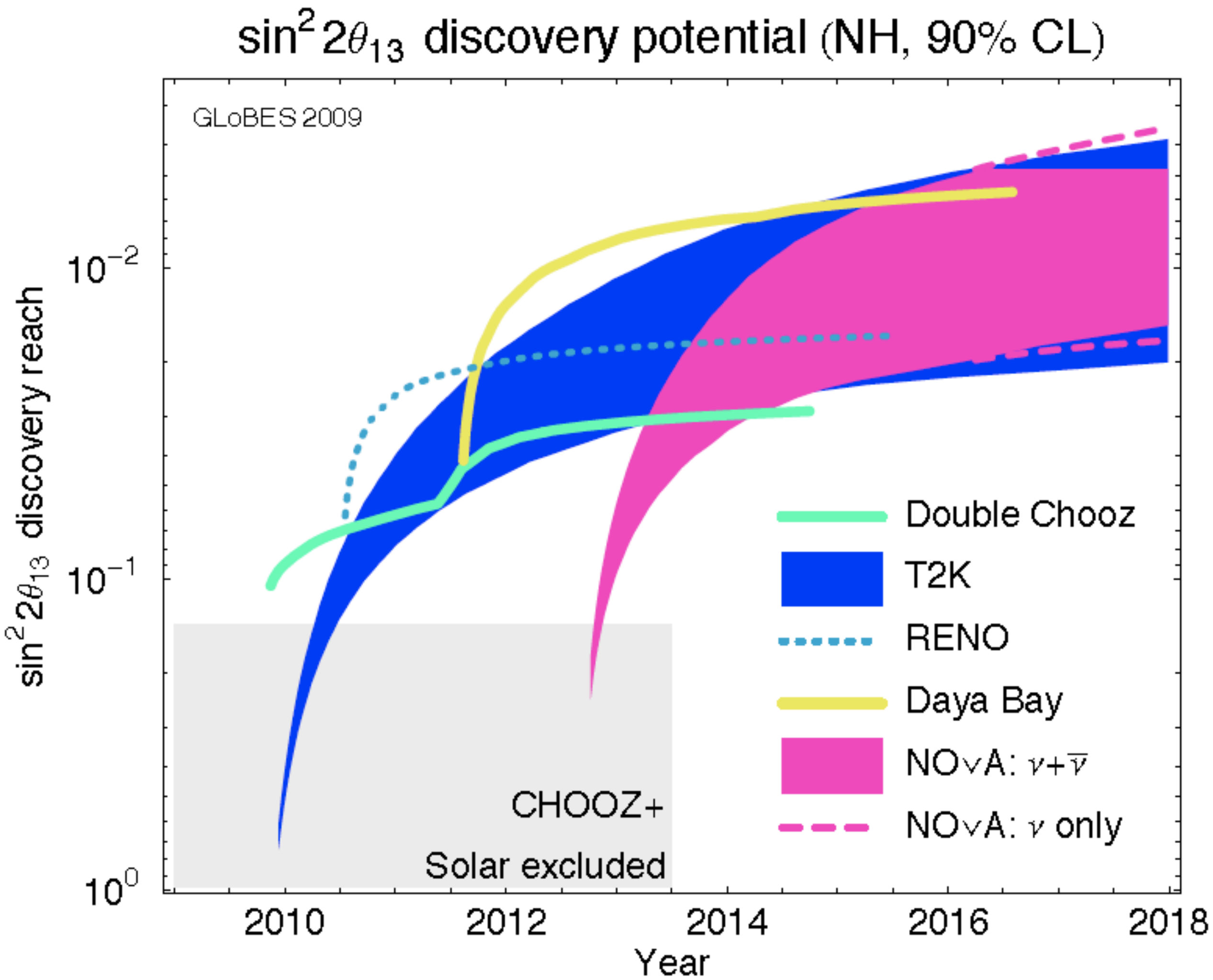


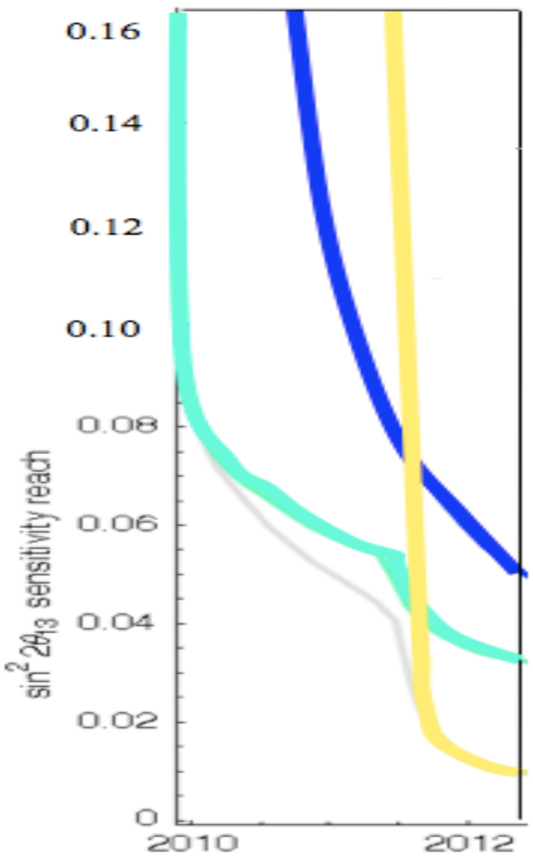
β-beams
neutrino factory

Range ↔
~ unknown CP phase

combination with reactor
↔ synergies

Update for next Generation

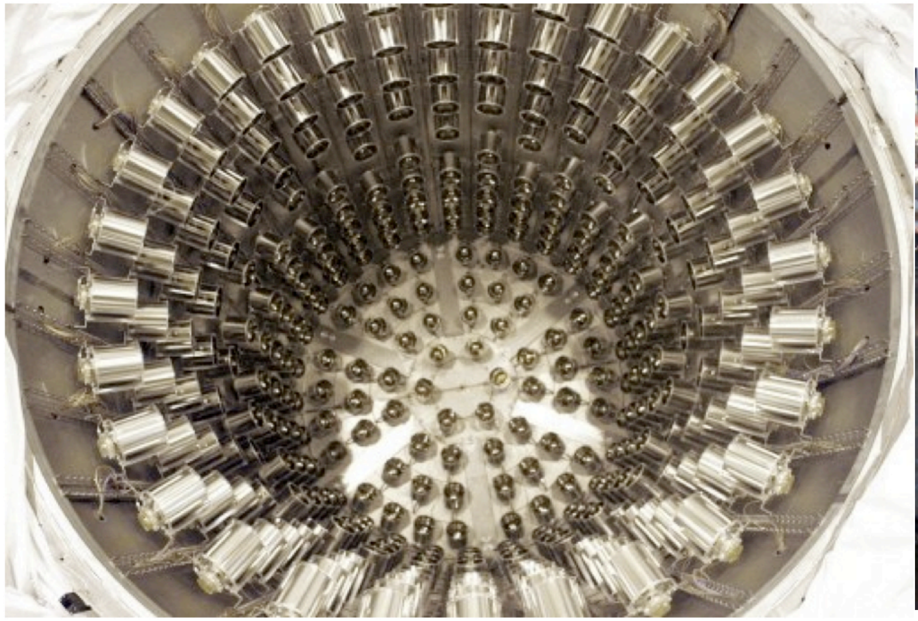




Huber, ML, Schwetz, Winter, arXiv:0907.1896

a linear scale – next years: significant improvements

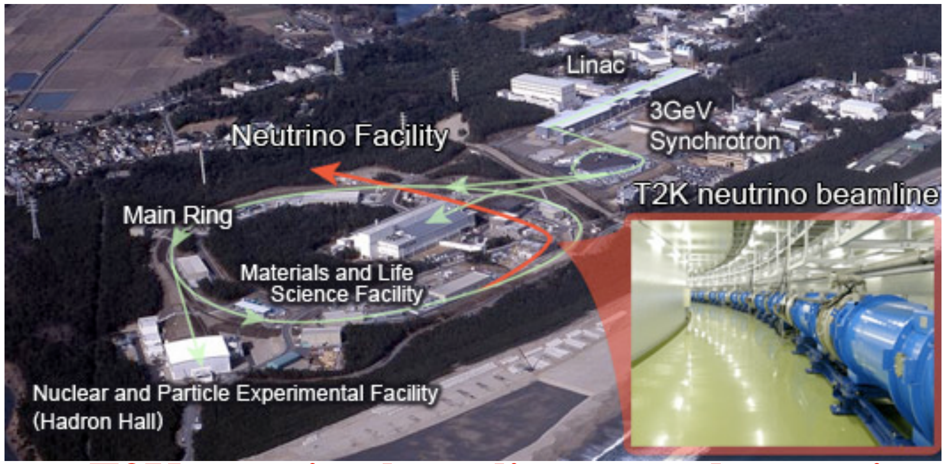
Things will move again soon…



Double Chooz far detector

Daya Bay components

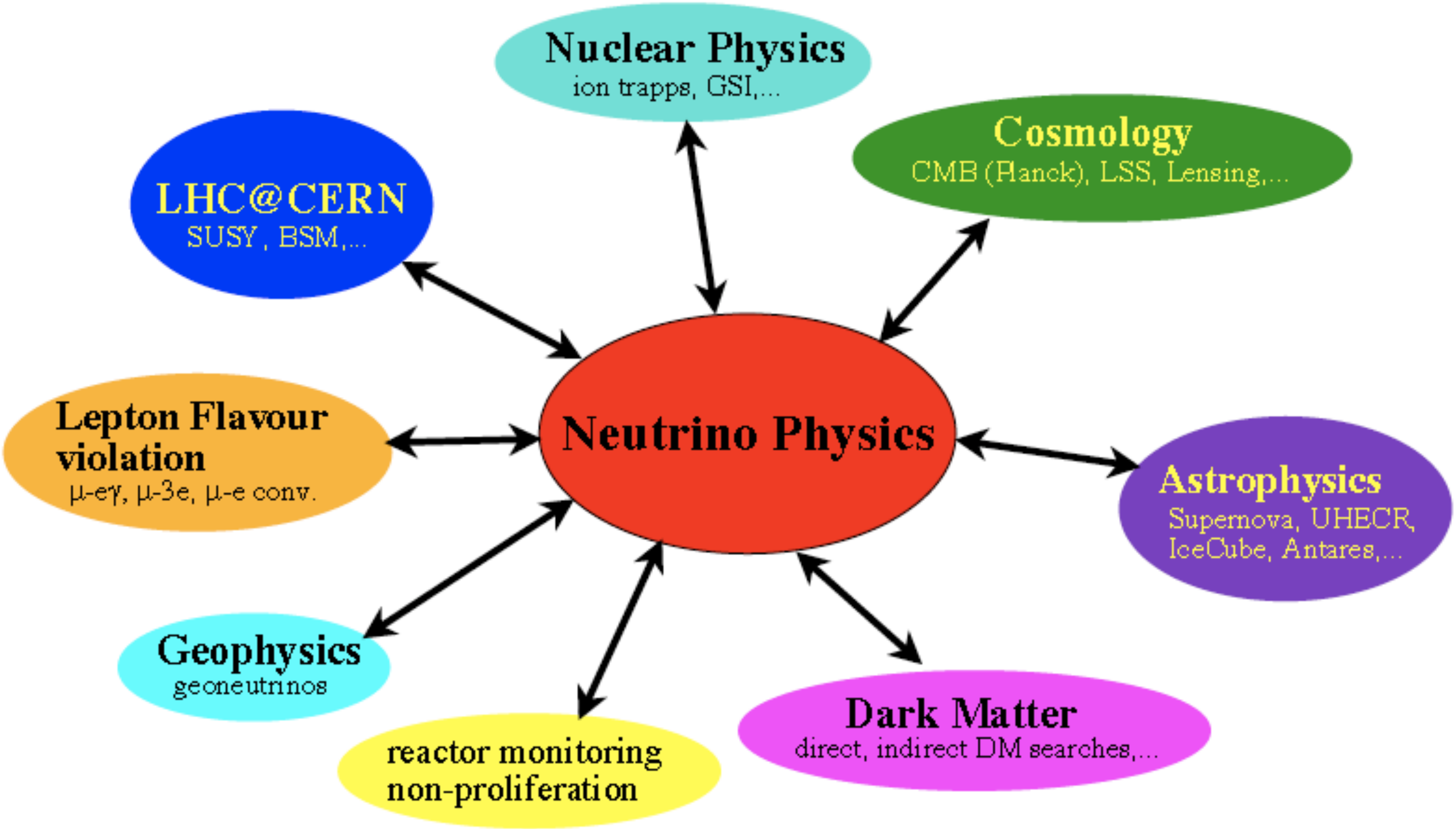
+ NOvA ground breaking



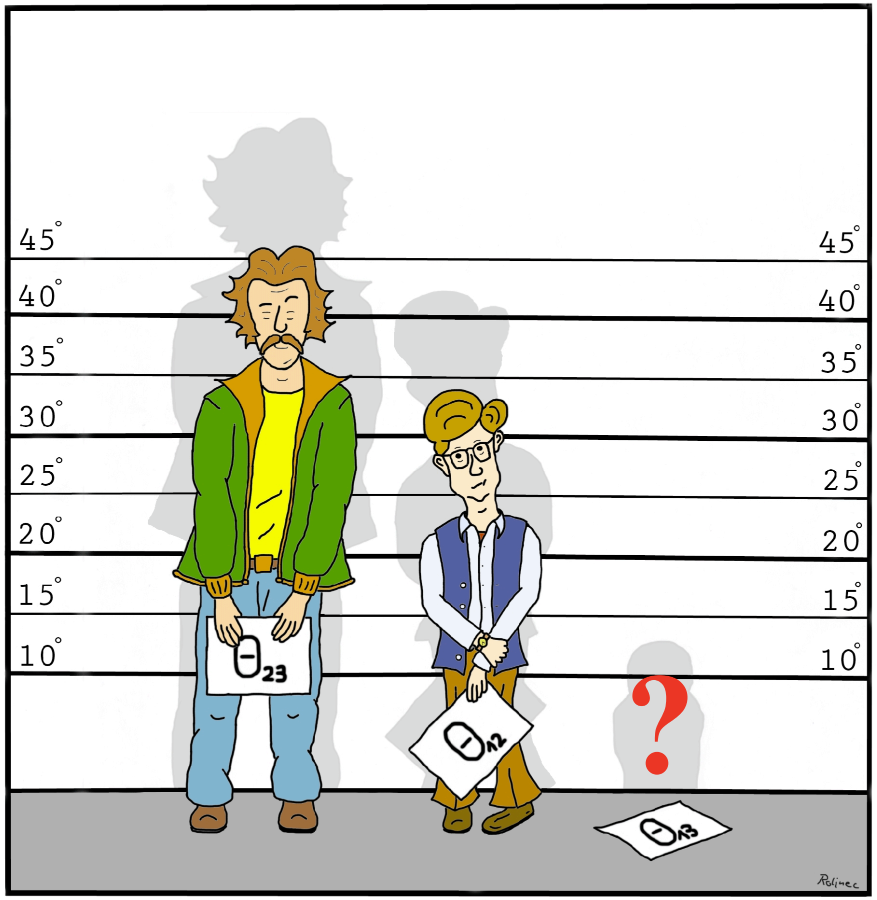
T2K neutrino beamline started operation

→very promising, especially if hints for finite $\sin^2\theta_{13}$ are correct…

Many Connections to other Fields

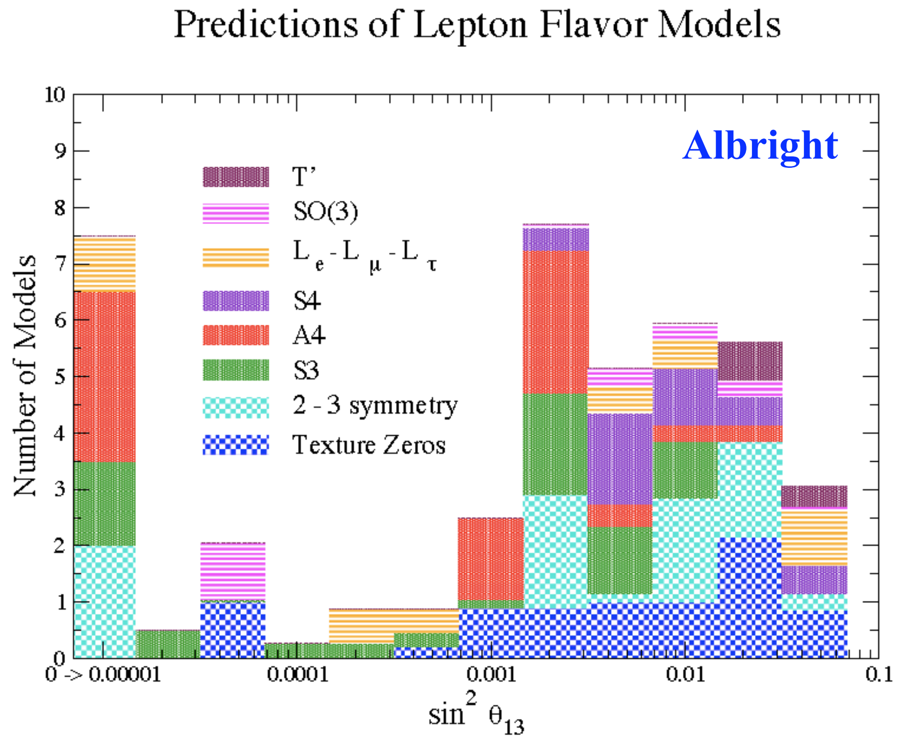


θ_{13} – just one small Number?



… why care about θ_{13}

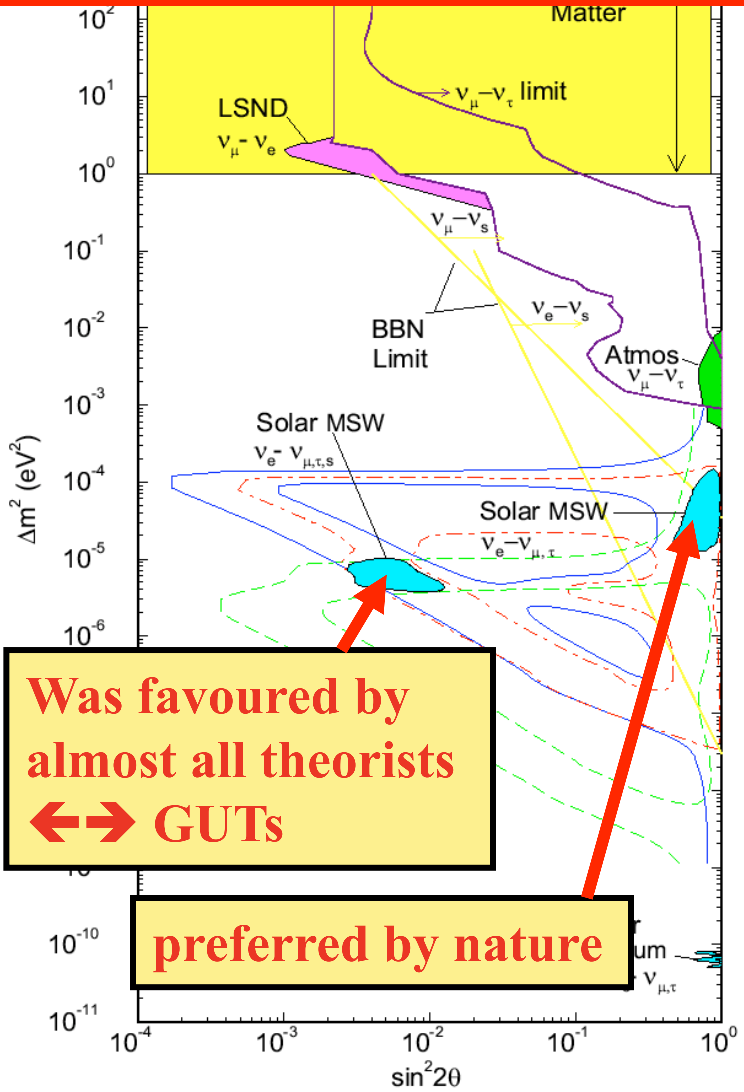
- Good to know…
- Leptonic CP violation
- Theory models



- Is this enough? What else ???

Learning about Flavour

History: Elimination of SMA



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?

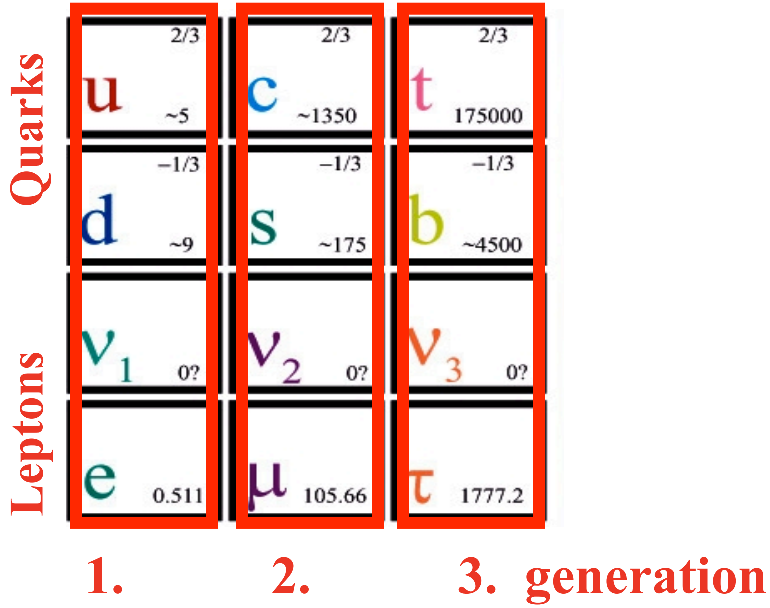
➔ numerical coincidence unlikely
➔ special reasons (symmetry, …)

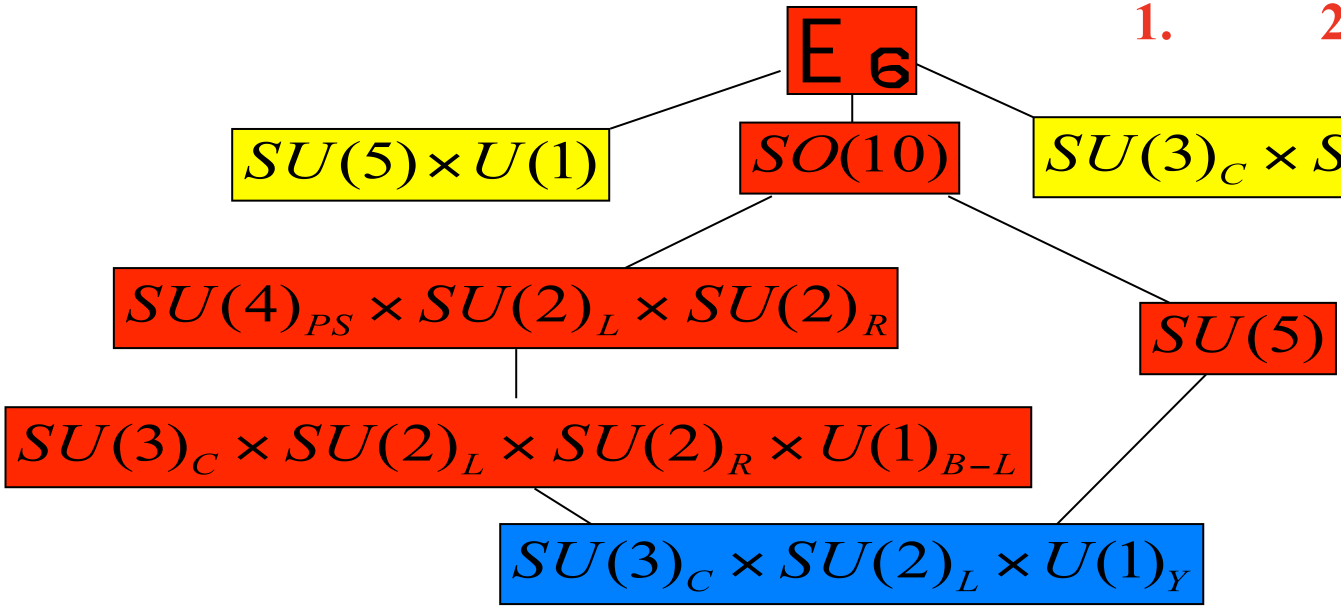
➔ addressed by coming precision

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

<ins>**Requirements:**</ins>
gauge unification
particle multiplets ⇔ ν_R
proton decay
…





many models…

GUT Expectations and Requirements

Quarks and leptons sit in the same multiplets

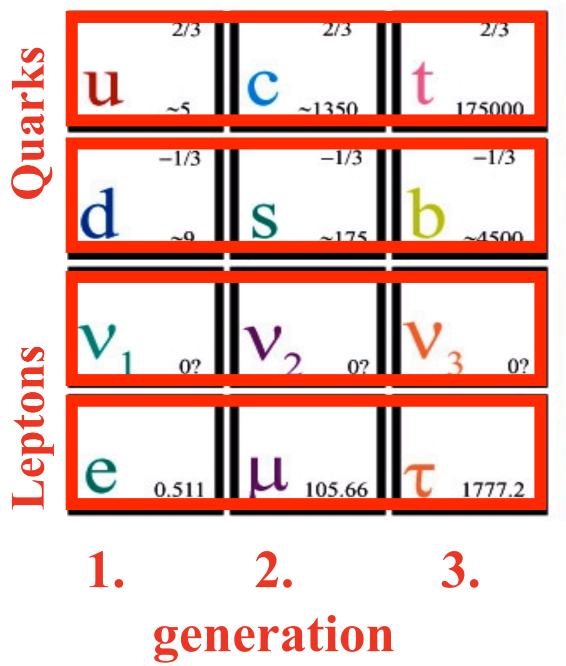
➔ one set of Yukawa couplings for given GUT multiplet
➔ ~ tension: small quark mixings ⇔ large leptonic mixings
➔ this was in fact the reason for the `prediction' of small mixing angles (SMA) – ruled out by data

Mechanisms to post-dict large mixings:

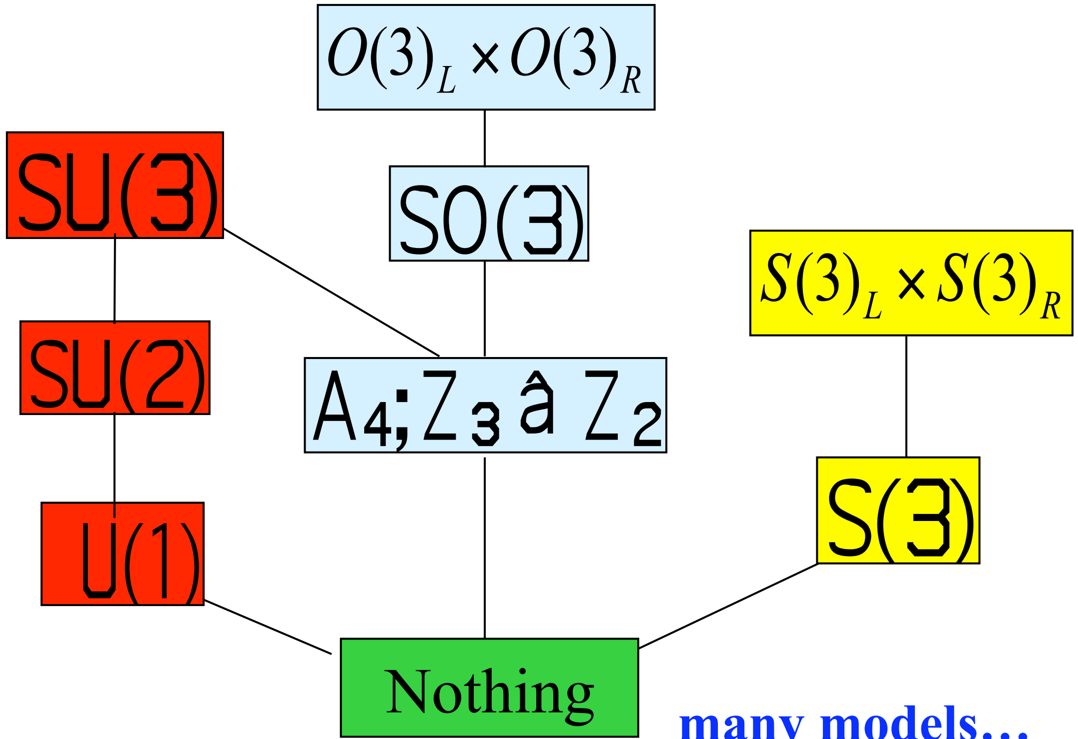
➔ sequential dominance
➔ type II see-saw
➔ Dirac screening
➔ …

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

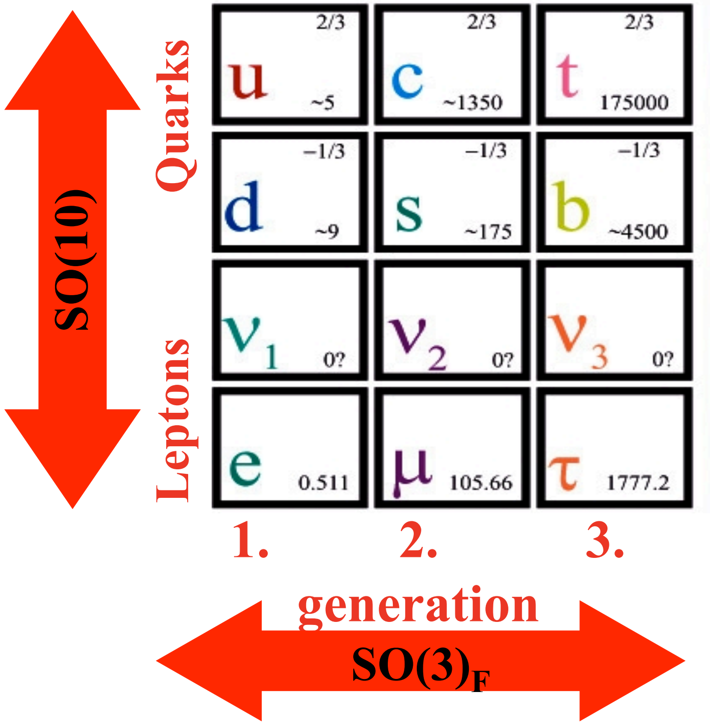


Examples:



many models…

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

➔ 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>

Neutrinos = Potential for Surprises

… many untested assumptions: Majorana, 3 ν's, mass mechanism

➔ there may be more surprises

- **light sterile neutrinos ←➔ good theoretical reasons, keV DM**
- **… ➔ example: How NSI's can fool us in precision experiments:**

Source	$\otimes$	Oscillation	$\otimes$	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 migh see
new effects beyond oscillations!

NSI Operators

- **Good reasons for physics beyond the SM+ (with ν's)**
  ➔ **expect effects beyond 3 flavours in many models**
  ➔ **effective 4f interactions**

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

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

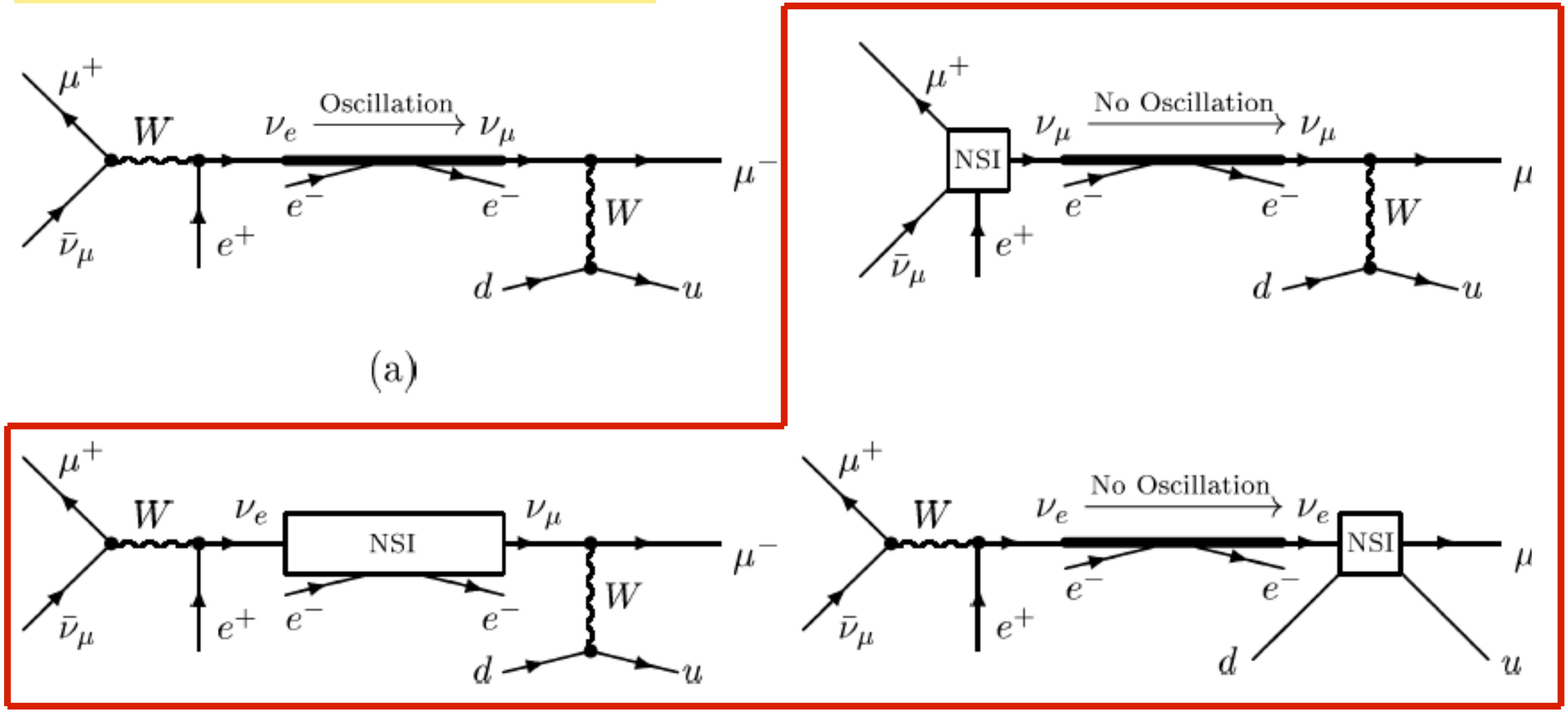
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

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

NSIs interfere with Oscillations

the "golden" oscillation channel

NSI contributions to the "golden" channel



<u>note:</u> interference in oscillations ~ε |\ FCNC effects ~ε^2

Physics Potential with NSIs included

Simulations

- full osciallation framework with NSIs included

➔ 4 possibilities for flavour transition:

- Oscillation
- NSI operator at source
- NSI operator at detector
- NSI effects in propagation

} no L/E dependence (NSI operator at source, NSI operator at detector, NSI effects in propagation)

Important: sensitivity limit from few events (small statistics)

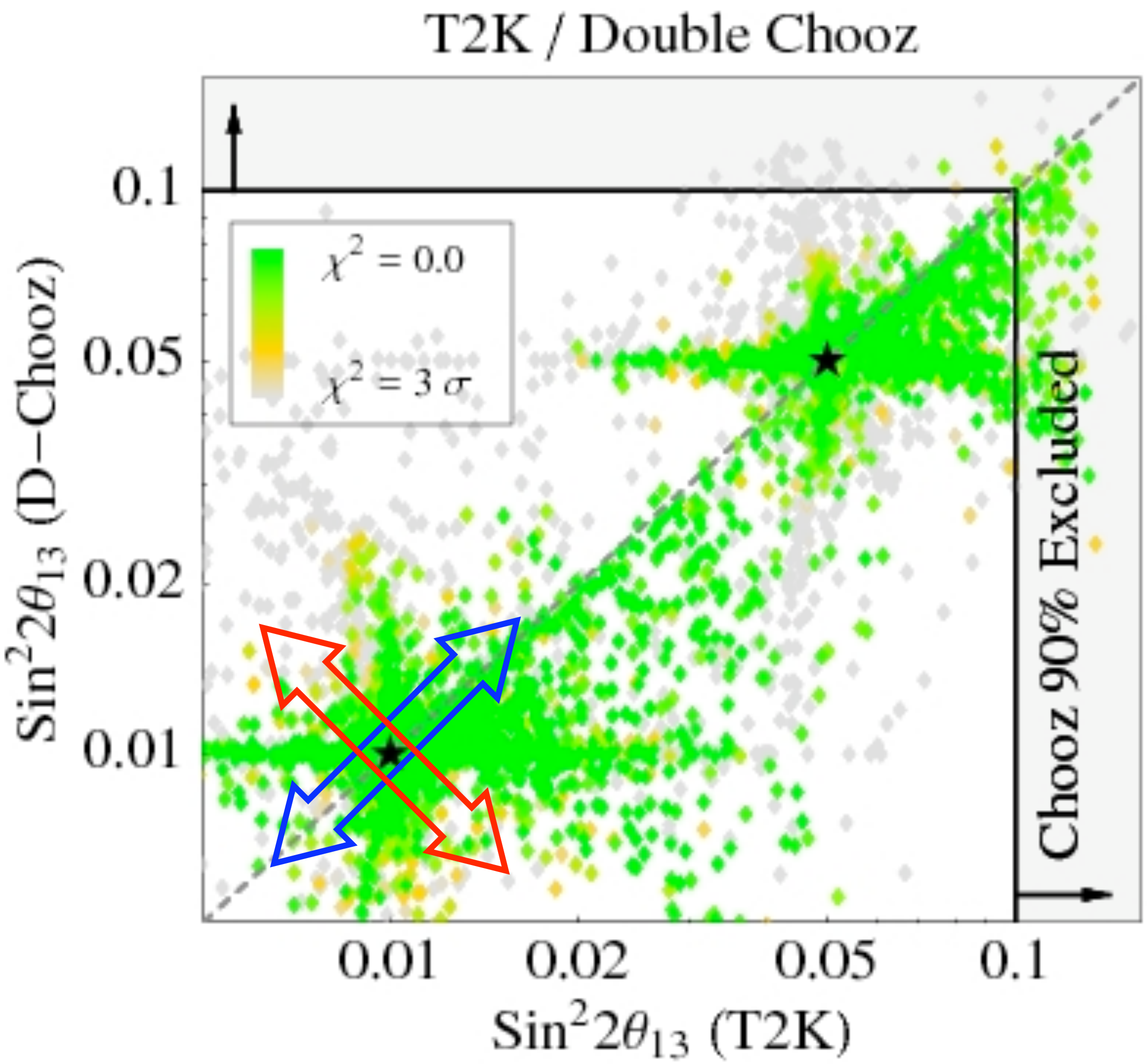
➔ no capability to distinguish different L/E dependence

➔ potential misinterpretation of NSI flavour transition effects

Potential consequences:

- offsets in parameter determinations
- conflicting analyses

NSI: Offset and Mismatch in θ_{13}



Redundant measurements:

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

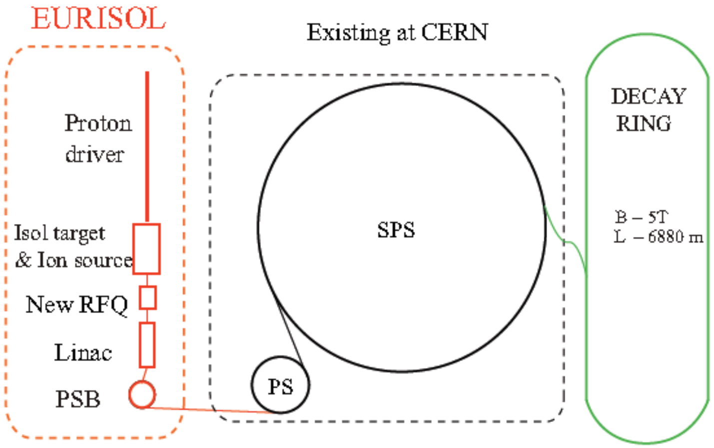
➔ interesting potential

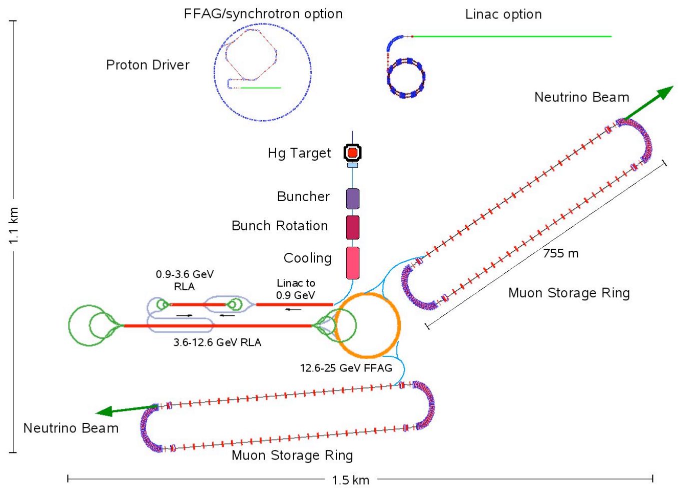
'natural magnitude' …more natural for NuFact

Where do we stand?

Enormous Progress made

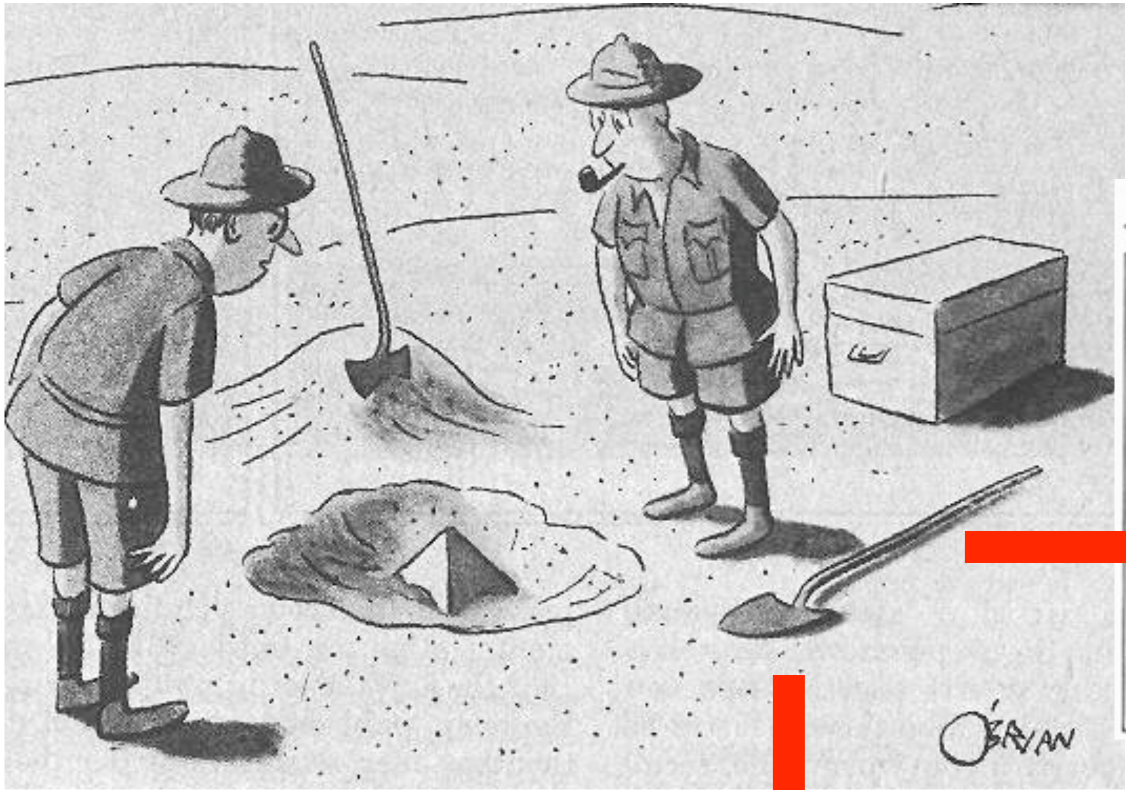
- **Experimental side:**
  - **super beams…**
  - **beta beams…**
  - **project X…**
  - **neutrino factory…**
    …low and high energy
  - **muon collider…**
  - **…**
- **Important detector R&D …**
- **Development of better beams …**

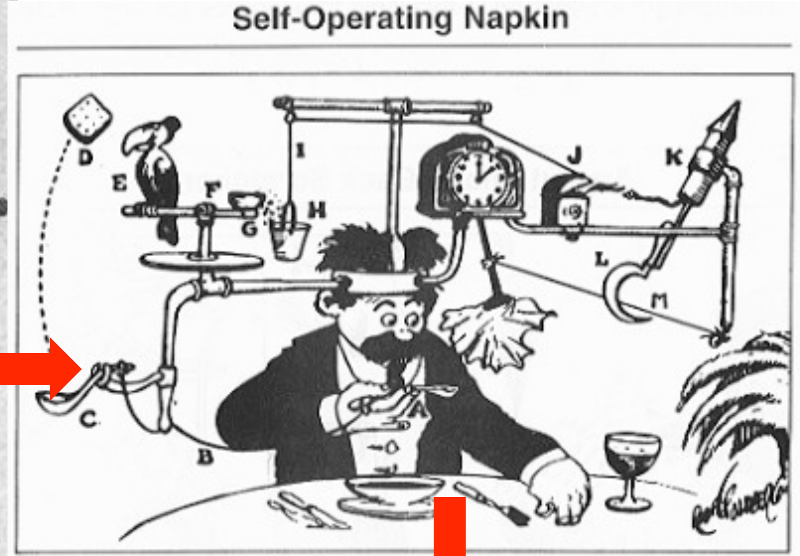


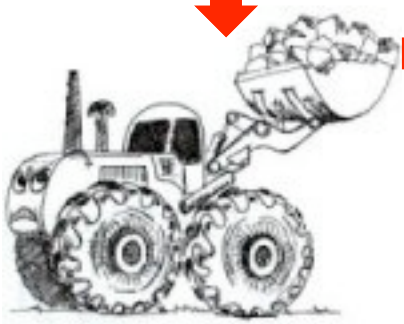


➔ crutial: timely R&D towards future options

Which Experimental Direction?







Progress continued

Phenomenology:

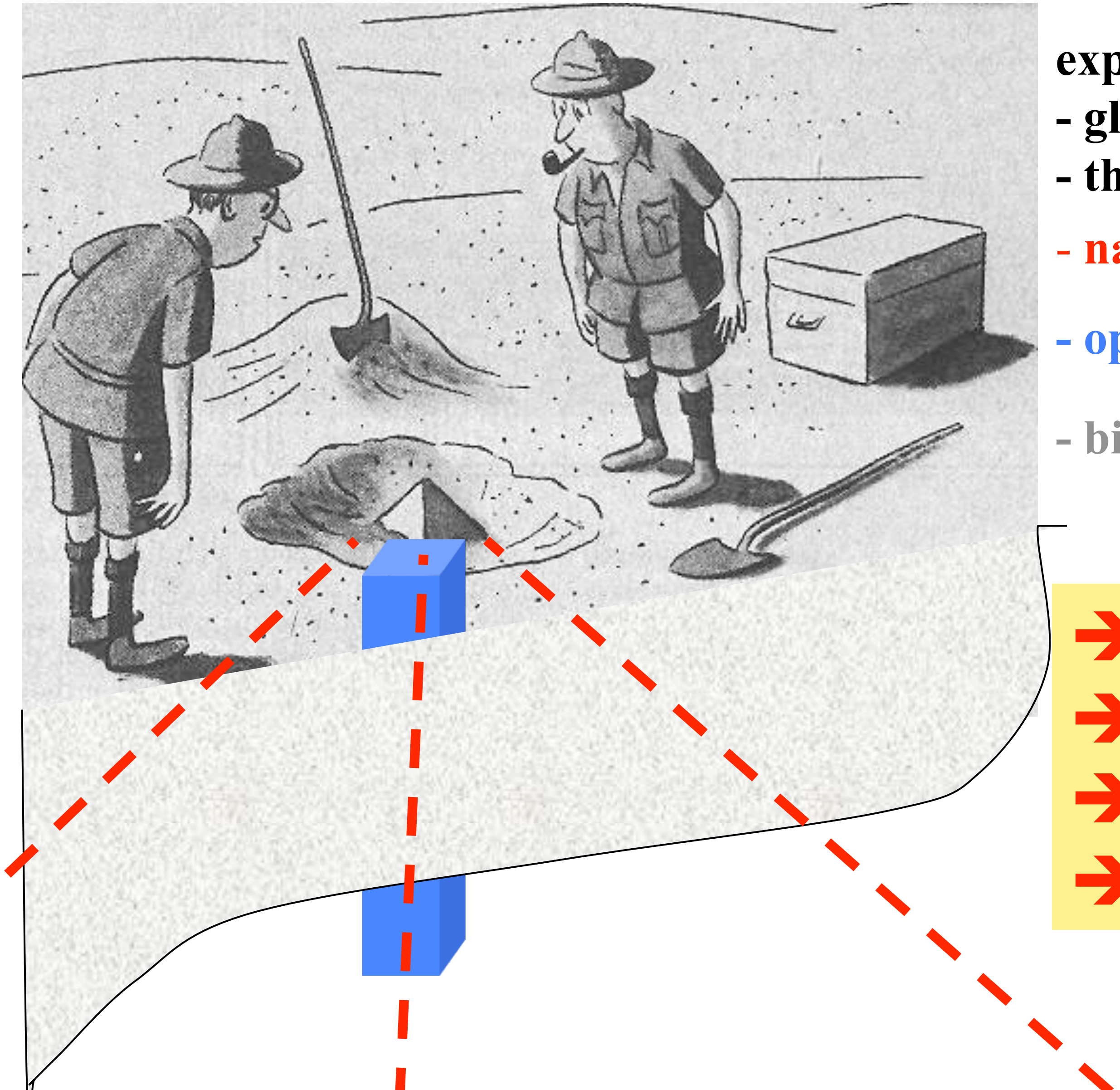
- interesting new ideas for improved / combined measurements
  ➔ which are realistic (backgrounds, technological requirements)?
- improved theoretical understanding (SN, QFT, …)
- new analytical and numerical tools
- further improvements of GLoBES

Theory:

- many interesting ideas, concepts, developments (new symmetries, x-tra dim., new particles …)
- models of masses and mixings
- … the unexpected…

➔ progress requires future precison !

Development of Theory



experimental facts ➔
- global fits
- theoretical ideas
- naturalness
- options/speculations
- big surprises?

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

Questions & Conclusions

- $$$$: Will there be enough funds for all R&D…?
- People: Will the community be large enough?
- Time: When could facility X,Y,Z fit in / be ready?
- New ideas: Maybe there exist other easier ways to measure neutrino properties…?

Conclusions:

- Double Chooz, Daya Bay, RENO, Gerda, Cuore, KATRIN, T2K, NOνA and others …are coming
- R&D towards future machines is crutial…
  ⇔ 2012 -2013 should be important

➔ future ν facilities are part of an exciting decade ahead!

Thanks to all!