Interpretations of Precision Neutrino Measurements

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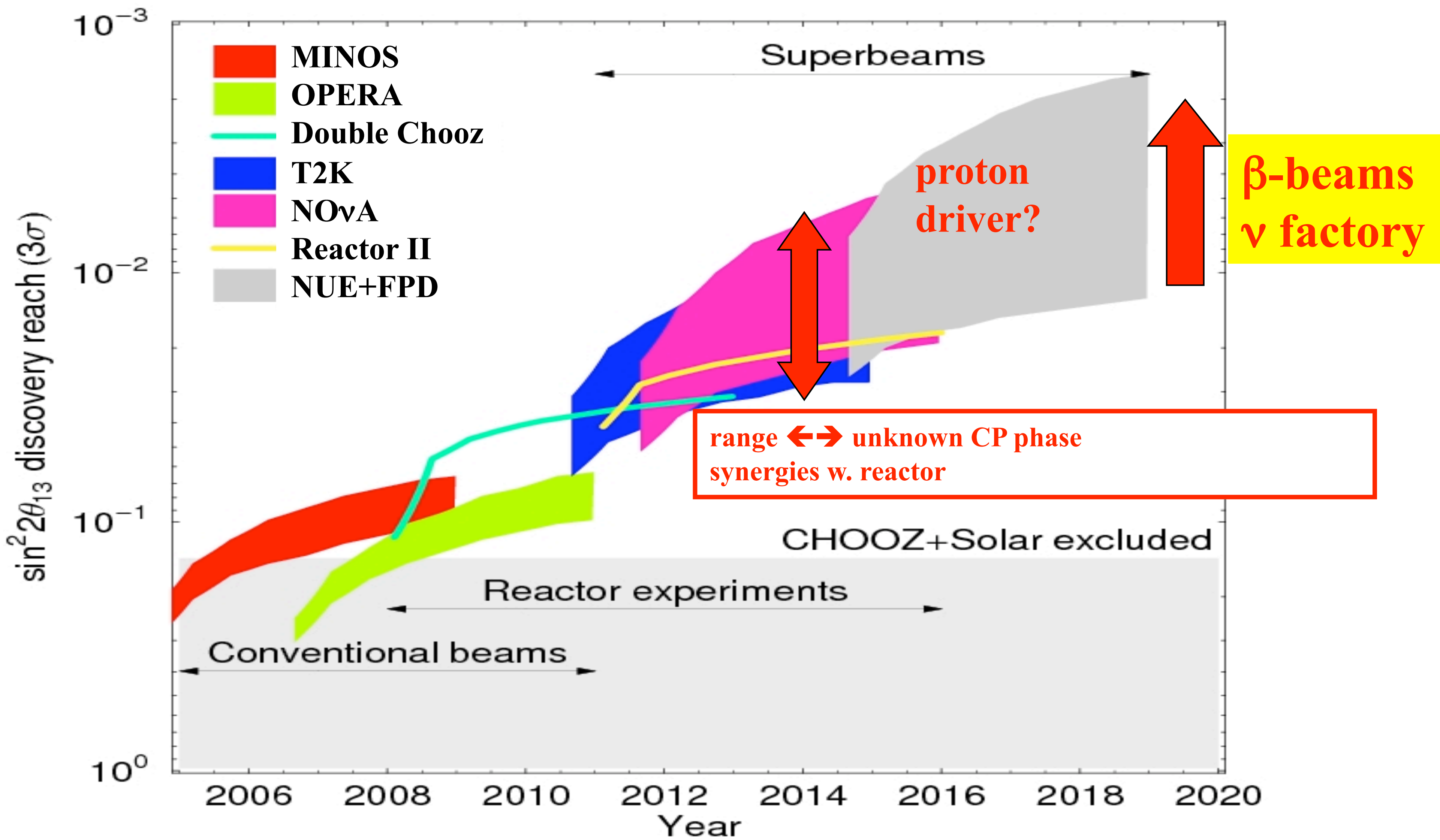
Future θ_{13} sensitivity

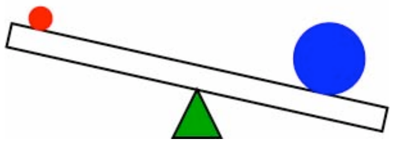


Suggestive Seesaw Features

QFT: natural value of mass operators ⇔ scale of symmetry

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

See-saw mechanism (type I)



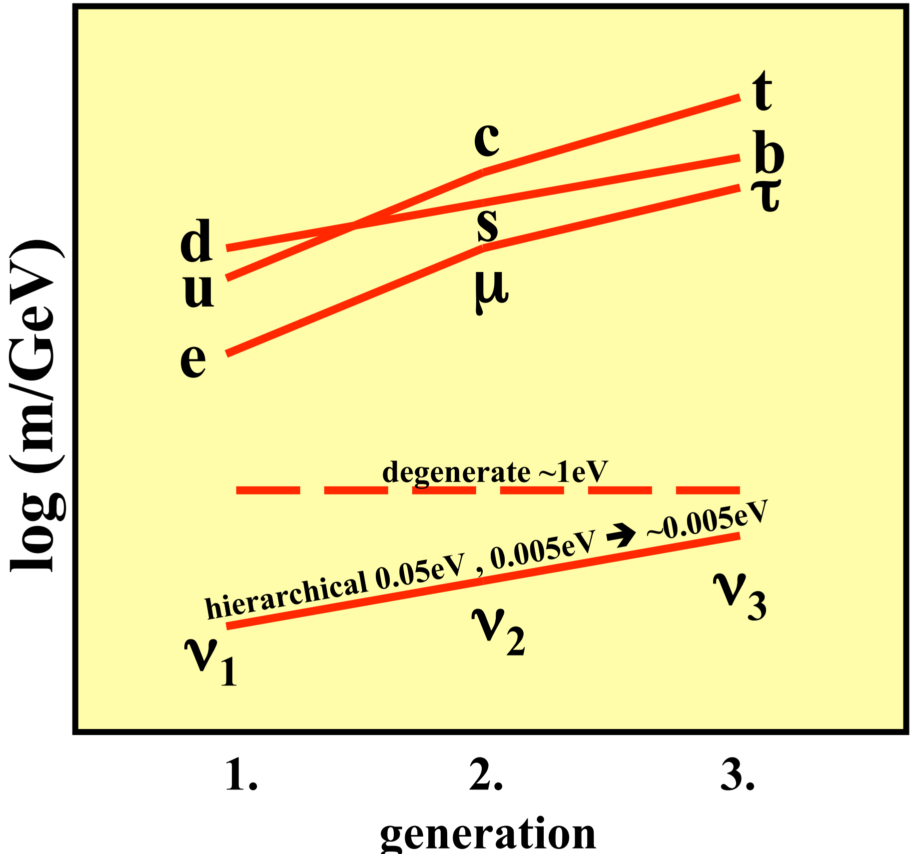
$$m_\nu = m_D M_R^{-1} m_D^T \qquad m_h = M_R$$

Numerical hints:

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

2nd Look Questions

Quarks & charged leptons ➔ hierarchical masses ➔ neutrinos?



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:

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

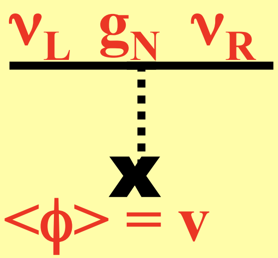
H	~10	≥20	?	≥20

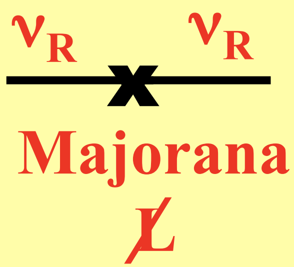
- **Less hierarchy in m_D or correlated hierarchy in M_R ? ➔ theoretically connected!**
- **Mixing patterns: not generically large, why almost maximal, θ_{13} small?**
- **Why 3 right handed neutrinos? what if M_R is singular? ...**

Adding Neutrino Mass Terms

SM: L=left-handed 2_L, $R=1_R$ ➔ no fermions masses ➔ Higgs

1) Simplest possibility: add 3 right handed neutrino fields





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

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

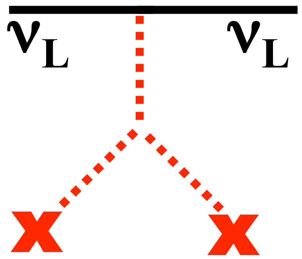
New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

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

NEW ingredients, 9 parameters ➔ SM+

Other Neutrino Mass Operators

2) new Higgs triplets Δ_L:

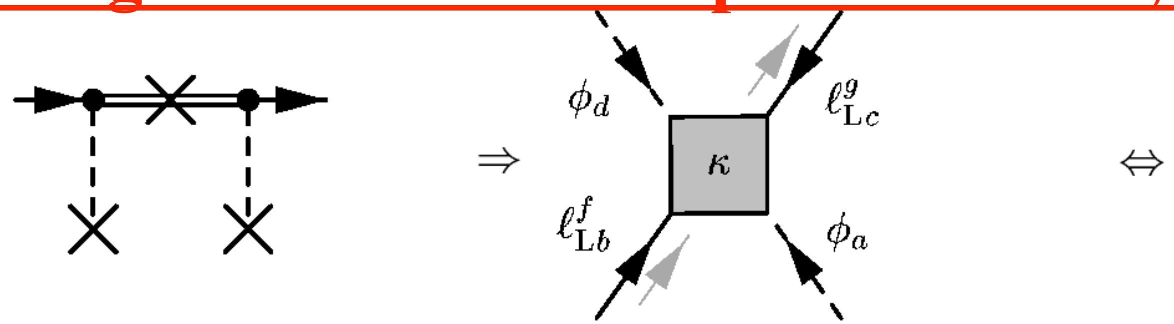


➔left-handed Majorana mass term: ➔ $M_L \overline{L} L^c$

3) Both ν_R and new Higgs triplets Δ_L:

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

4) Higher dimensional operators: d=5, …



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

➔ $M_L \overline{L} L^c$

5-N) …

Other effective Operators Beyond the SM

➔ higher d operators from integrating out some new physics
  ⇔ symmetries: L, flavour, GUTs, …

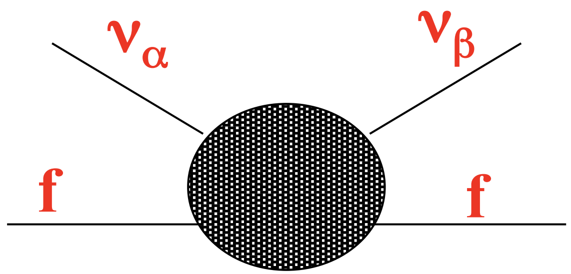
➔ effects beyond 3 flavours, L-violating operators, …

➔ Non Standard Interactions = NSIs ➔ effective 4f opersators

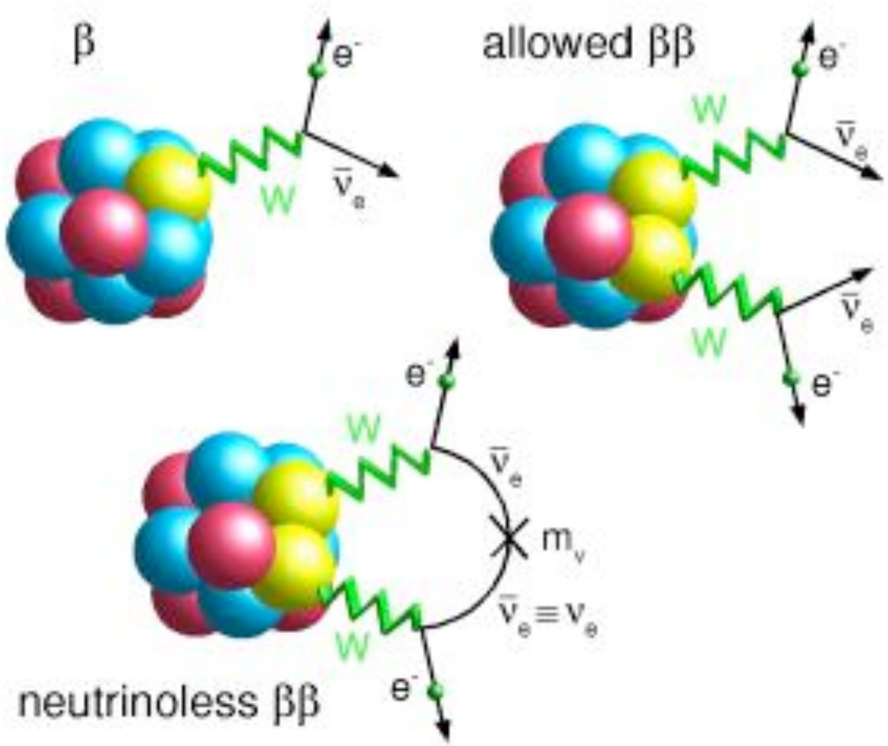
$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

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

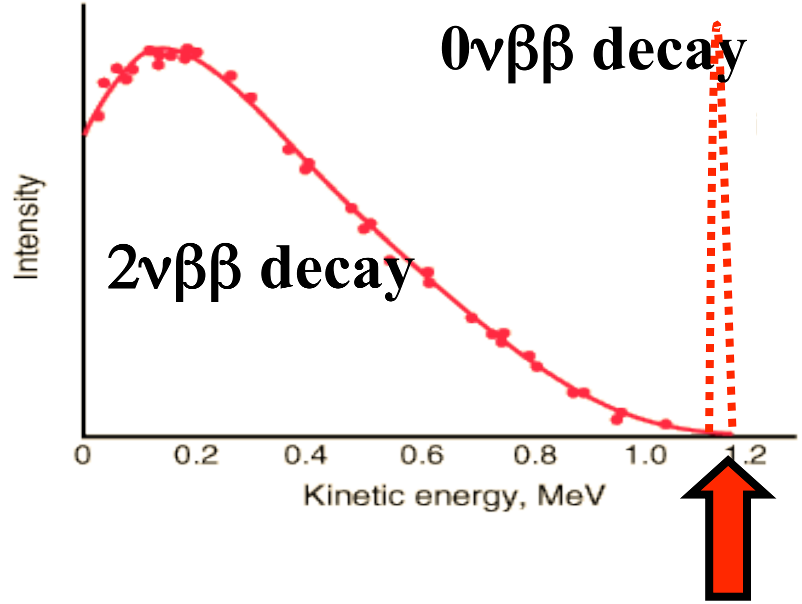
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$



Effects on 0νββ Decay



2νββ decay of [76]Ge observed:
$\tau = 1.5 \times 10^{21}$ y



Majorana ν ➔ 0νββ decay

- signal at known Q-value
- 2νββ background (resulution)
- nuclear backgrounds
  ➔ use different nuclei

warning:

other lepton number violating processes…

Relating Rates / Lifetimes to Neutrino Masses

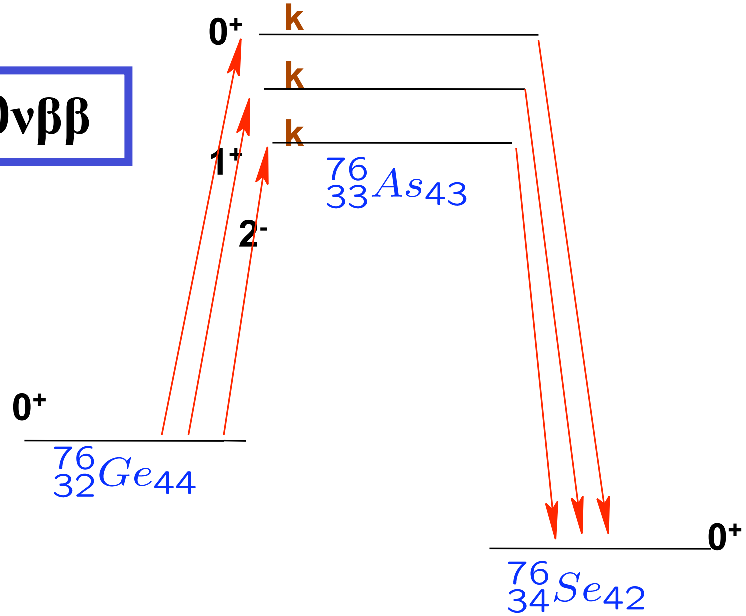
rate of 0νββ — phase space — nuclear matrix elements — effectiveMajorana neutrino mass

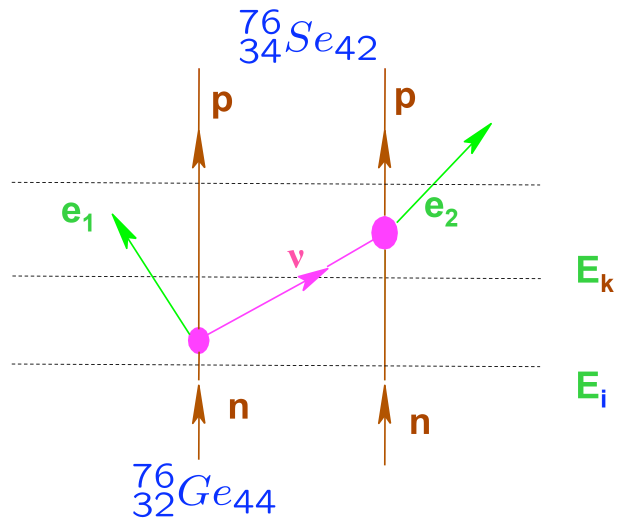
$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \, <m_{ee}>^2$$

nuclear matrix elements: Fäßler et al., …

➔ virtual excitations of intermediate states

0νββ

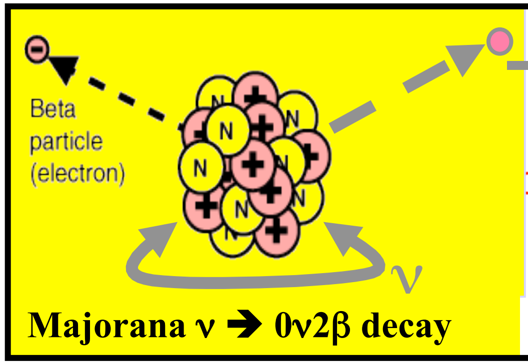




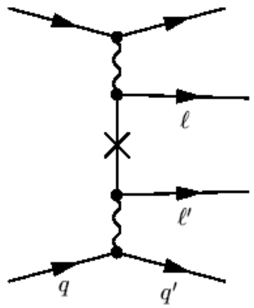
$$\boxed{T = \Sigma_k \frac{< f|\hat{H}_W|k >< k|\hat{H}_W|i >}{E_i - E_k}}$$

progress in TH errors ➔ reduced uncertainties

Neutrino-less Double β-Decay



$\propto$



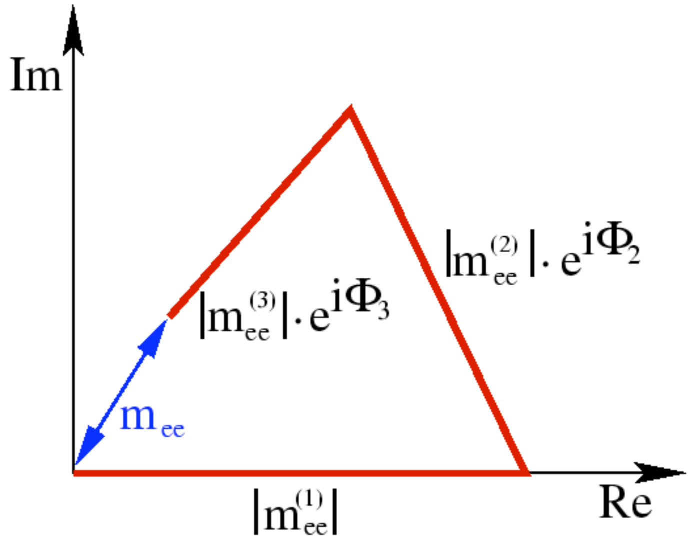
$\propto |\langle m_{ee} \rangle|$

$\leq$ 0.35 eV ?

Heidelberg-Moscow experiment

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

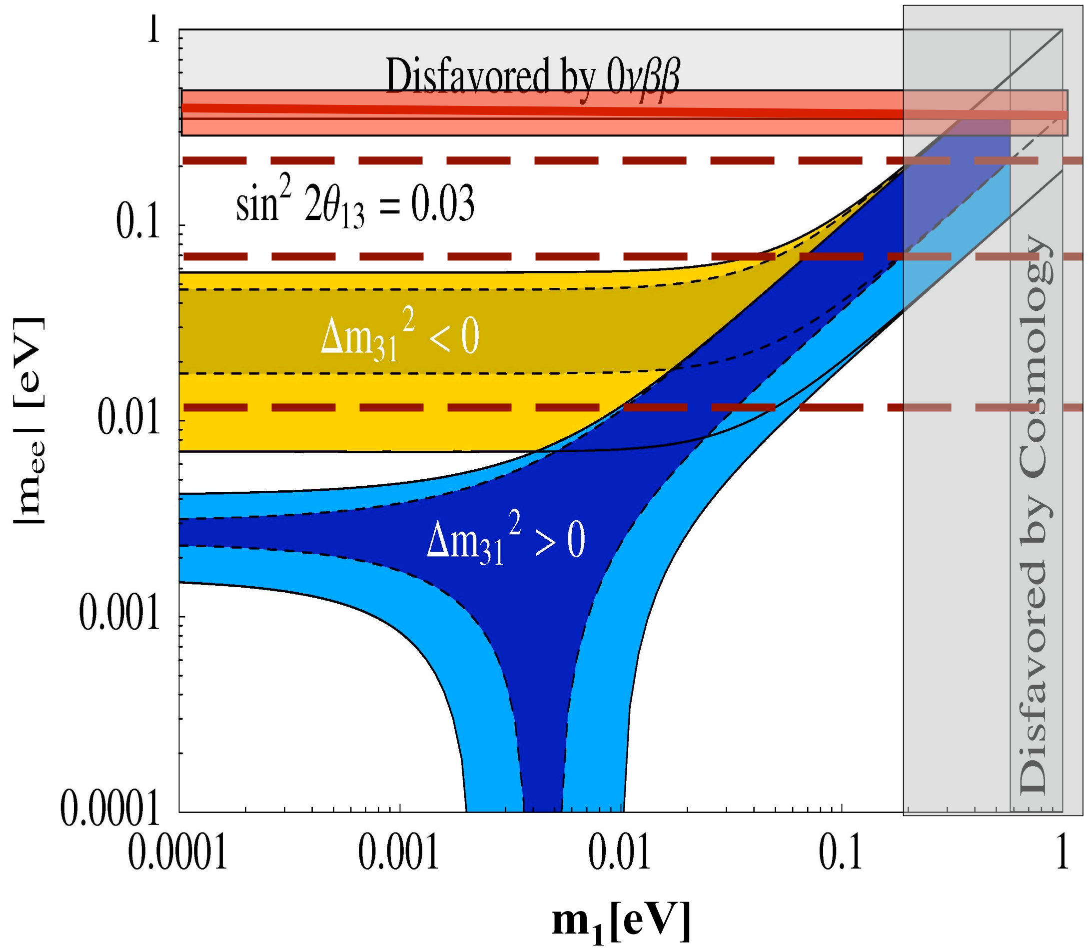
$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \end{aligned}$$



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**

Claim of part of the original Heidelberg-Moscow experiment ⟷ cosmology ➔ ‚tension'



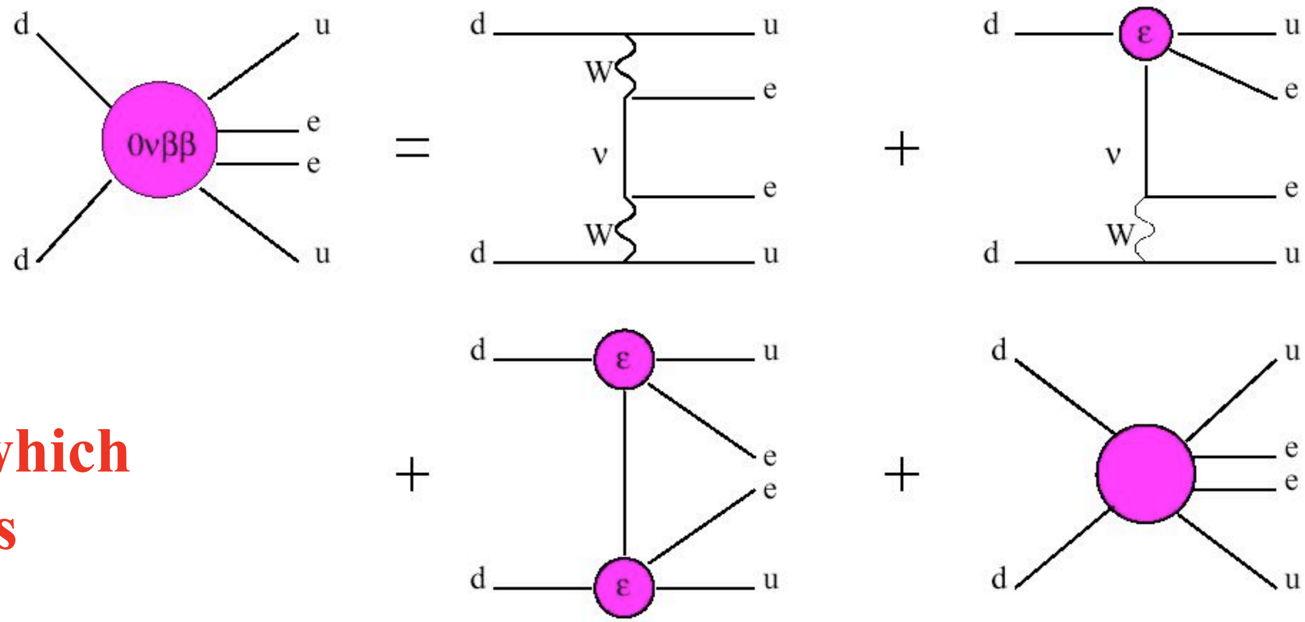
aims of new experiments:
- test HM claim
- $(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV $\pm$ errors
  - ➔ reach 0.01eV
  - ➔ CUORE
  - ➔ GERDA phases I, II, (III)

Comments:

- cosmology: limitation by systematical errors ➔ ~another factor 5?
- $0\nu\beta\beta$ nuclear matrix elements ~factor 1-2 theoretical uncertainty in m_{ee}
- $\Delta m^2 > 0$ allows complete cancellation ➔ $0\nu\beta\beta$ signal not guaranteed
- $0\nu\beta\beta$ signal from *some other* new BSM lepton number violating operator

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

… this may not be the full story



LR, RPV-SUSY, …
➔ other operators which violate L ⇔ NSI's

$$T = M_m < m_\nu > + M_\theta < tg\vartheta > + M_{WR} < \left(\frac{M_1}{M_2}\right)^2 >$$
$$+ M_{SUSY} \lambda'^2_{111} + M_{VR} < \frac{m_p}{M_{VR}} > + \ldots$$

Schechter+Valle: Any L violating operator ➔ radiative mass generation ➔ Majorana nature of ν's
However: This might be a tiny correction to a much larger Dirac mass

Lepton Flavour Violation

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

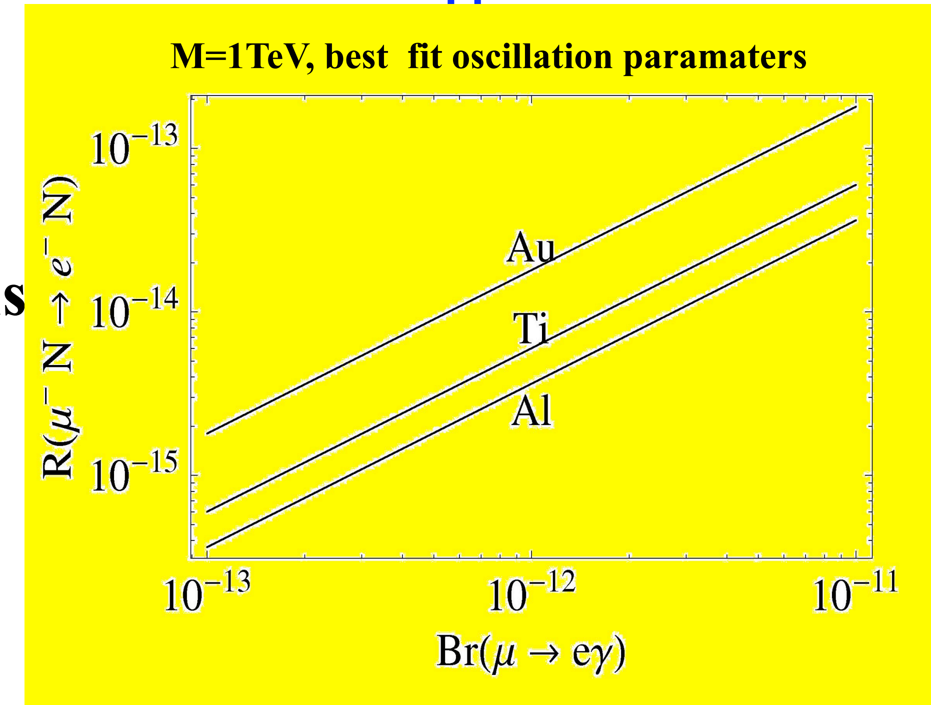
➔LFV and leptonic CP violation can even exist for m_ν➔0

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

MEG: 10^{-13}

PRISM: 10^{-18}

Deppisch+Kosmas+Valle



➔interplay ←➔ disentangeling:

ν's – LFV – LHC

e-capture decays, excited states, multiple $0\nu\beta\beta$ isotopes, angular distributions, ..., ➔ exciting options!

Effects on Precision Oscillation Physics

Precise measurements ➔ 3f oscillation formulae

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

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

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

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

Oscillations in QFT

- is ordinary QM sufficient to describe ν–oscillations?
- ν's are relativistic, 2nd quantized, …

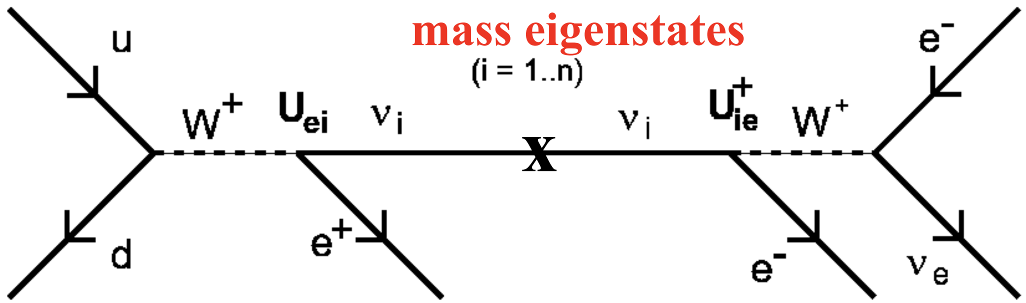
➔ **Feynman diagram of neutrino oscillation:**

- 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

Kinematics: Equal Energy or equal Momenta?

- Consider e.g. pion decay at rest: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- 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!**

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

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

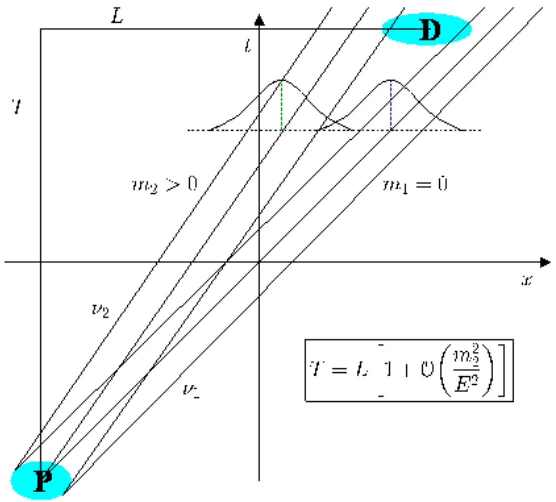
Localized Source and Detector:

- 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



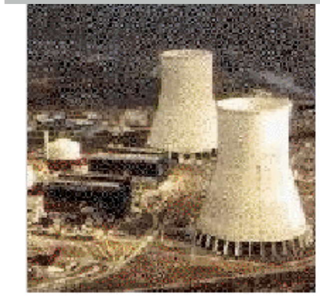
- separation of wave packets: $\boxed{\Delta x_{ij} = \frac{|\Delta m_{ij}^2| L}{2E^2}}$

- 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)

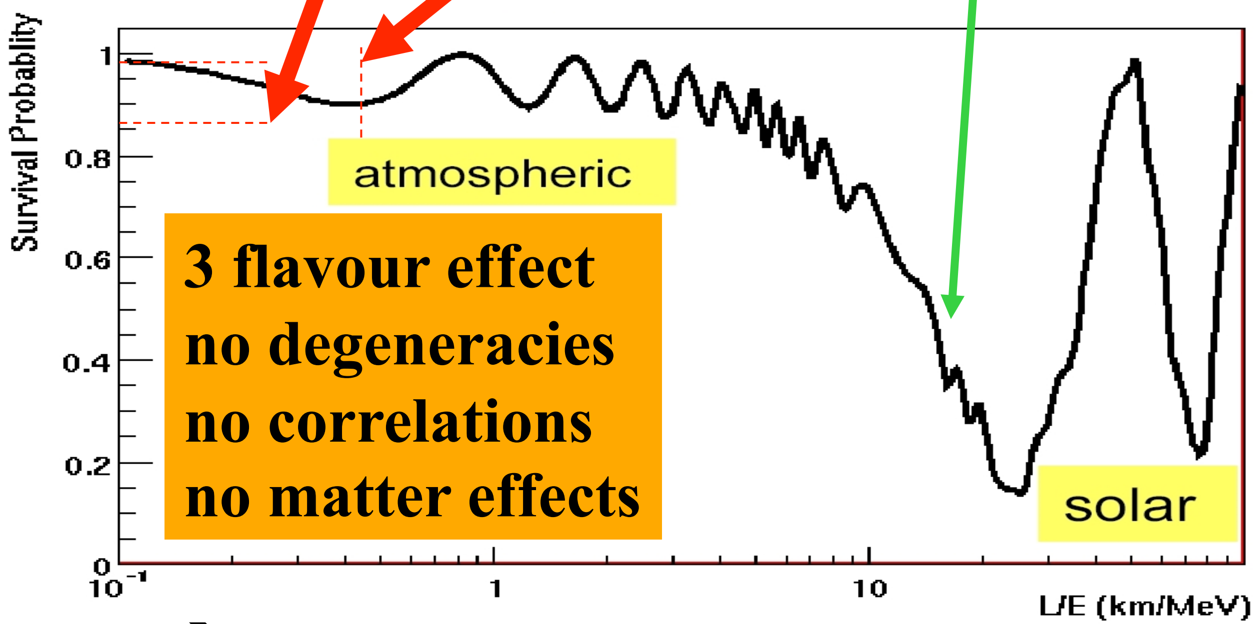
Future Precision with Reactor Experiments



$\overset{\bar{\nu}_e}{\Longrightarrow}$ **near detector** (170m) $\overset{\bar{\nu}_e}{\Longrightarrow}$ **far detector** (1700m)

identical detectors ➔ many errors cancel

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



3 flavour effect
no degeneracies
no correlations
no matter effects

E=4MeV ➔ 2km 4km 40km 80km

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

clean & precise θ_{13} measurments

NSIs & Neutrino Oscillations

Future precision oscillation 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!

➔ modifications of 3f oscillation formulae, different L/E

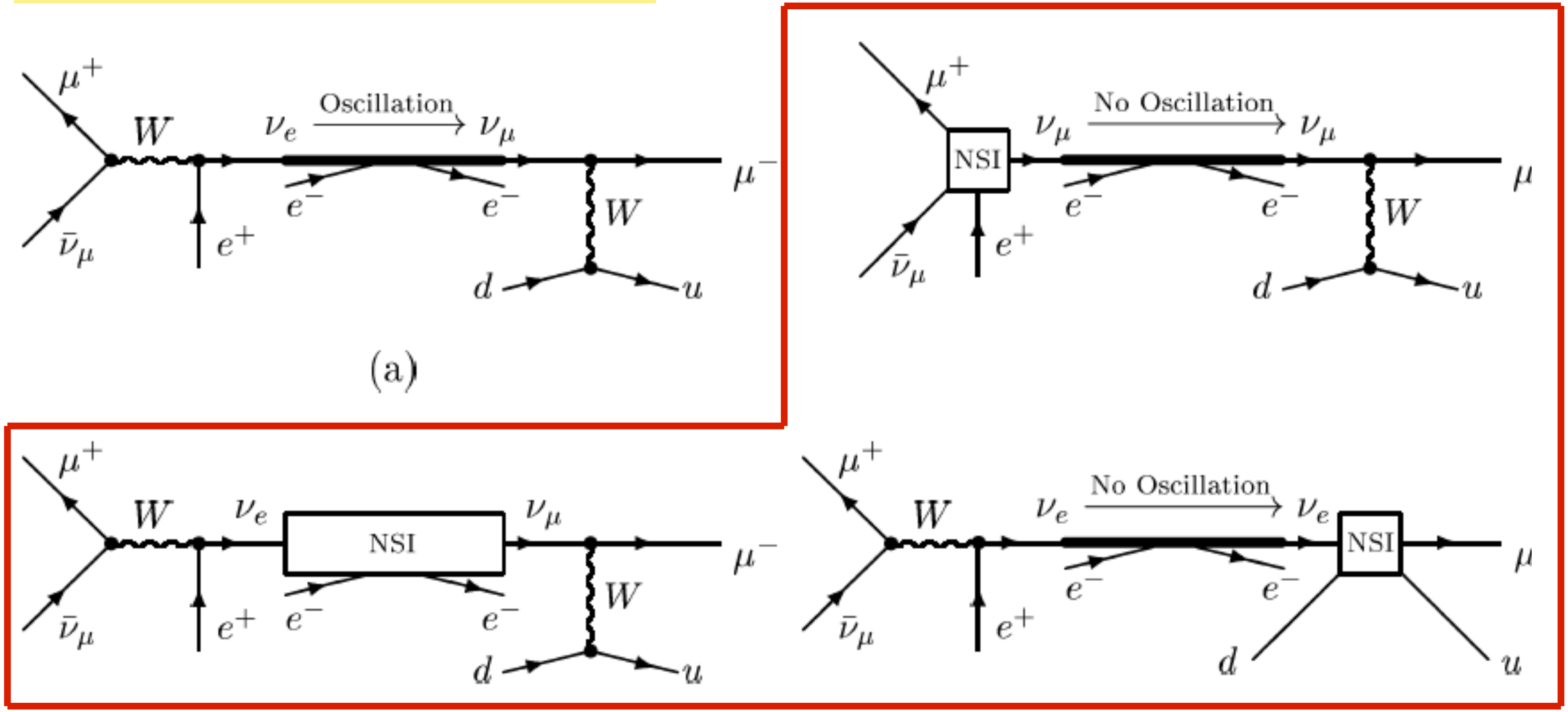
➔ small event rates: offset in oscillation parameters

➔ Non Standard Interactions = NSI's

NSIs interfere with Oscillations

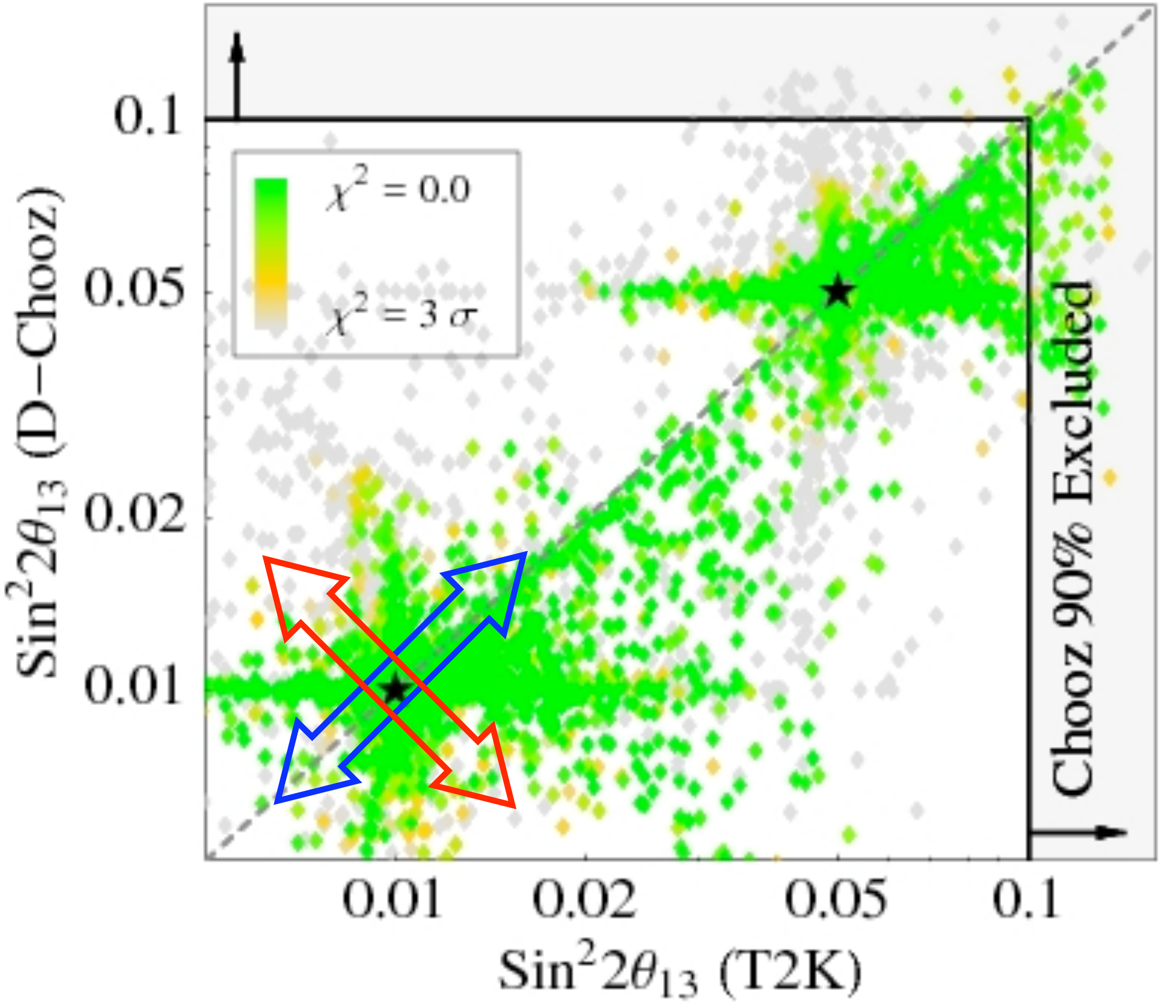
the “golden” oscillation channel

NSI contributions to the “golden” channel



<u>note:</u> interference in oscillations ~ε |\ FCNC effects ~ε²

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**

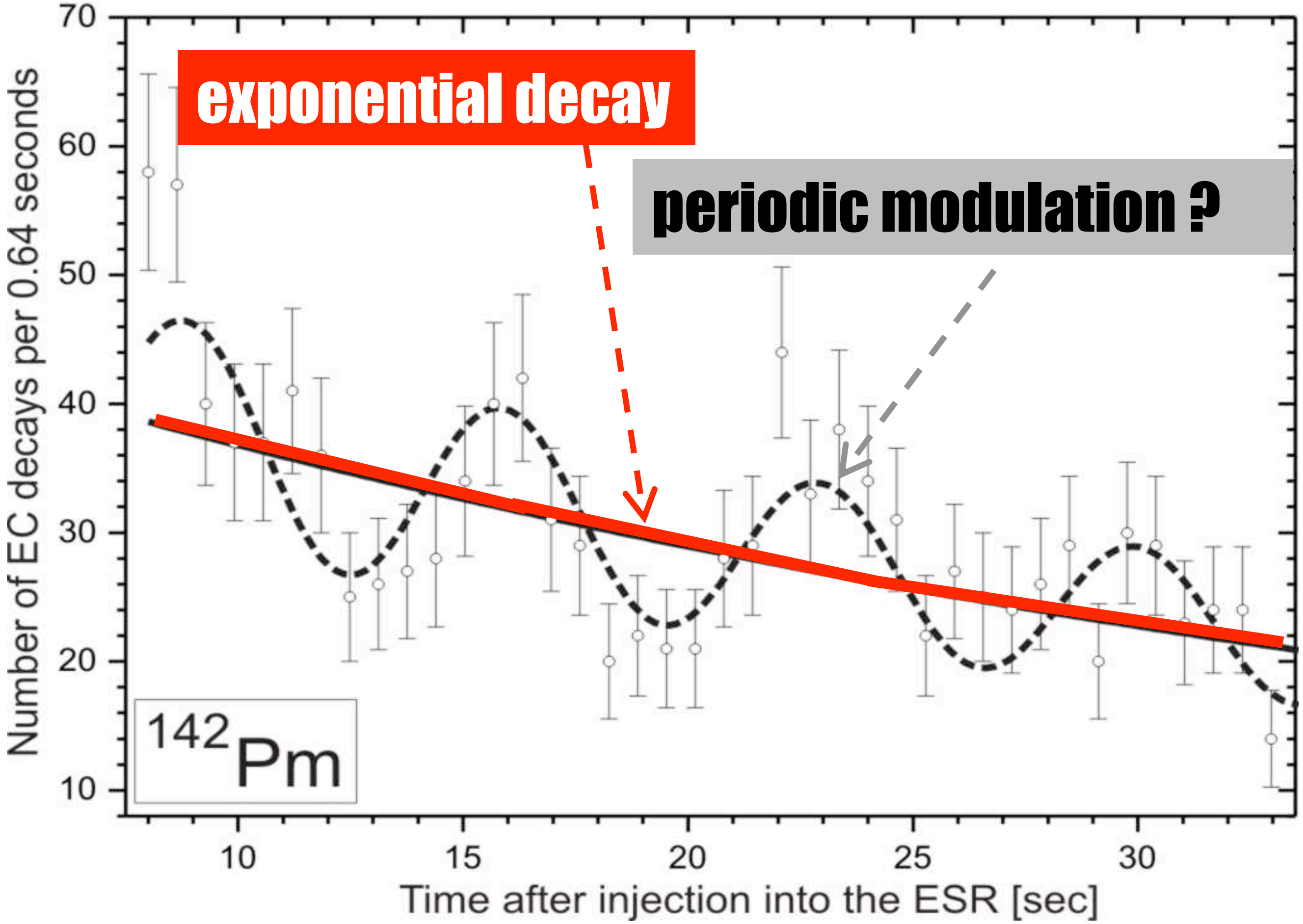
➔ **redundancy**

➔ **interesting potential**

➔ **optimization???**

Unexpected Effects: The GSI Anomaly

➔**Periodically modualted exponential β-decay law**
of highly charged, stored ions at GSI by the FRS/ESR Collaboration



3.5 σ

9.5 σ ???

Fit to 'Oscillations'

1) **exponential**

$$dN_{EC}(t)/dt = N_0 \exp\{-\lambda t\}\, \lambda_{EC}$$

$$\lambda = \lambda_{\beta^+} + \lambda_{EC} + \lambda_{loss}$$

2) **exponential plus periodic oscillation**

$$dN_{EC}(t)/dt = N_0 \exp\{-\lambda t\}\, \lambda_{EC}(t)$$

$$\lambda_{EC}(t) = \lambda_{EC}\,[1 + a\cos(\omega t + \varphi)]$$

Fit parameters of ^{140}Pr data					
Eq.	$N_0\lambda_{EC}$	λ	a	ω	χ^2/DoF
1	34.9(18)	0.00138(10)	-	-	107.2/73
2	35.4(18)	0.00147(10)	0.18(3)	0.89(1)	67.18/70
Fit parameters of ^{142}Pm data					
Eq.	$N_0\lambda_{EC}$	λ	a	ω	χ^2/DoF
1	46.8(40)	0.0240(42)	-	-	63.77/38
2	46.0(39)	0.0224(41)	0.23(4)	0.89(3)	31.82/35

T = 7.06 (8) s
φ = - 0.3 (3)

T = 7.10 (22) s
φ = - 1.3 (4)

Checks / Questions / Problems

Carefully checks:

- artefacts such as periodic coupling of the Schottky-noise to all sort of backgrounds excluded
- all EC decays are recorded; continuous information on the status of mother- and daughter ion during the whole observation time

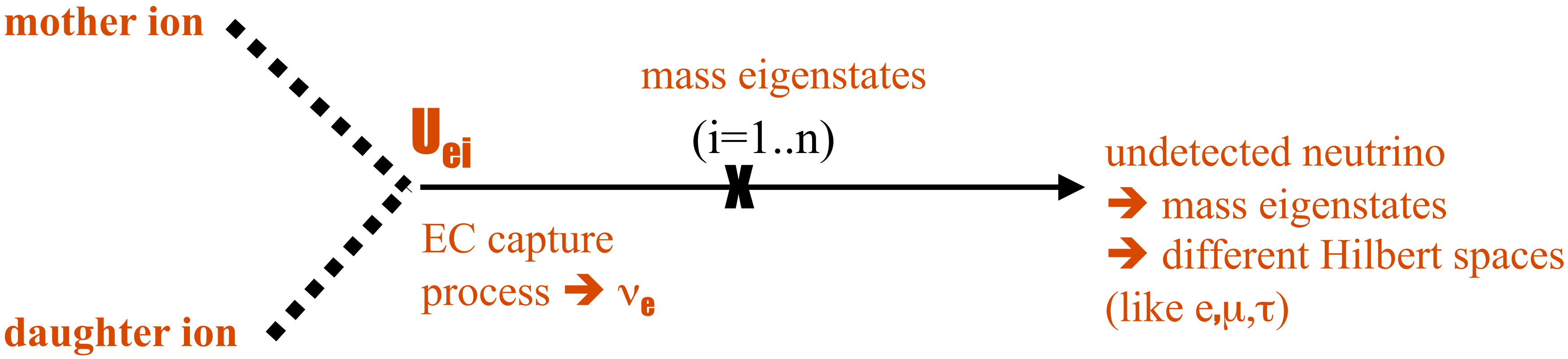
Questions / problems?

- 3.5σ ➔ could be a statistical fluctuation … but what if … 9.5σ ???
- a number of experimental issues…
- if this were due to neutrino mixing ➔

$$\boxed{\Delta m^2 \sim 2.2 \cdot 10^{-4}\ \mathrm{eV}^2} \quad \boxed{|m^{(2)} - m^{(1)}| \sim 8.4 \cdot 10^{-16}\ \mathrm{eV}}$$

➔ **disagrees with KamLAND**

The EC Process



Kinematics:

a) precise measurement of mother and daughter energies and momenta
   ➔ emitted mass eigenstate known ➔ one contribution
   ➔ no oscillation, but rate ~ $|U_{ei}|^2$ ➔ not realized here (& no oscillation)

b) finite kinematical resolution much less than neutrino masses

➔ all three mass eigenstates contribute incoherently

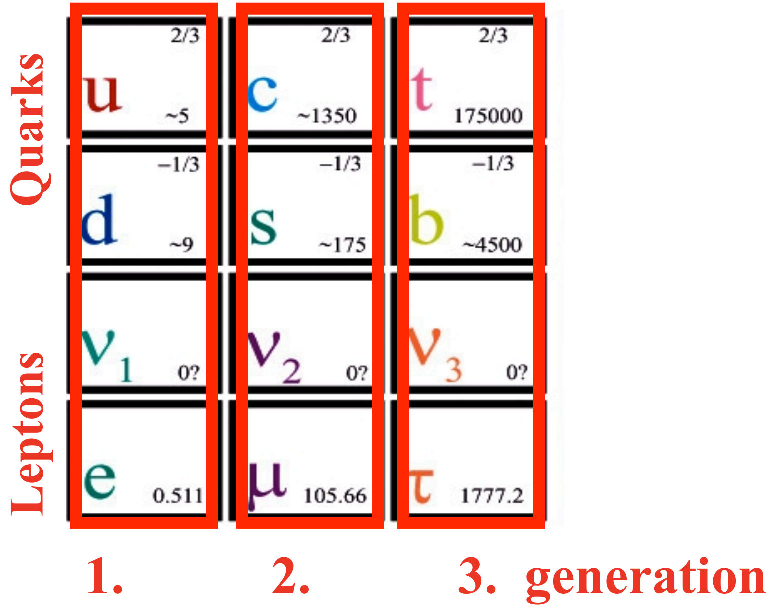
➔ $\propto \sum |U_{ei}|^2 = 1$ ➔ independent of flavour mixing

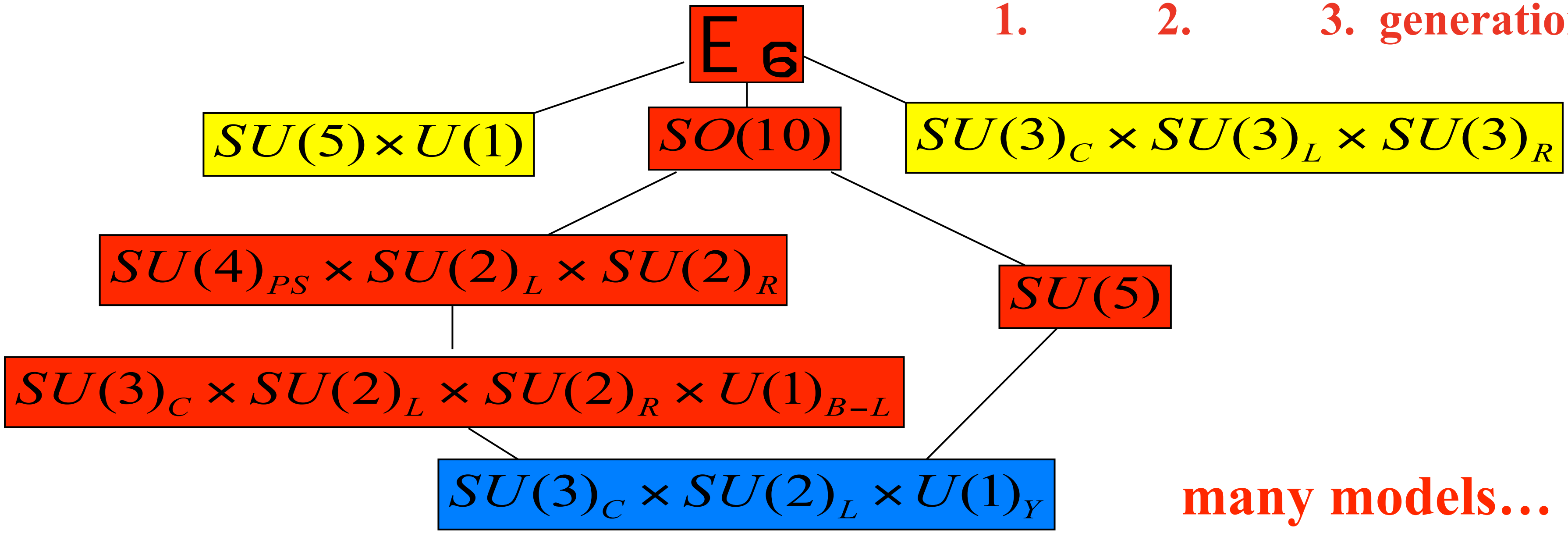
➔ no periodic modulation of decays due to neutrino mixing

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

Requirements:
gauge unification
particle multiplets ⇔ ν_R
proton decay
…





many models…

GUT Expectations and Requirements

<u>Quarks and leptons sit in the same multiplets</u>

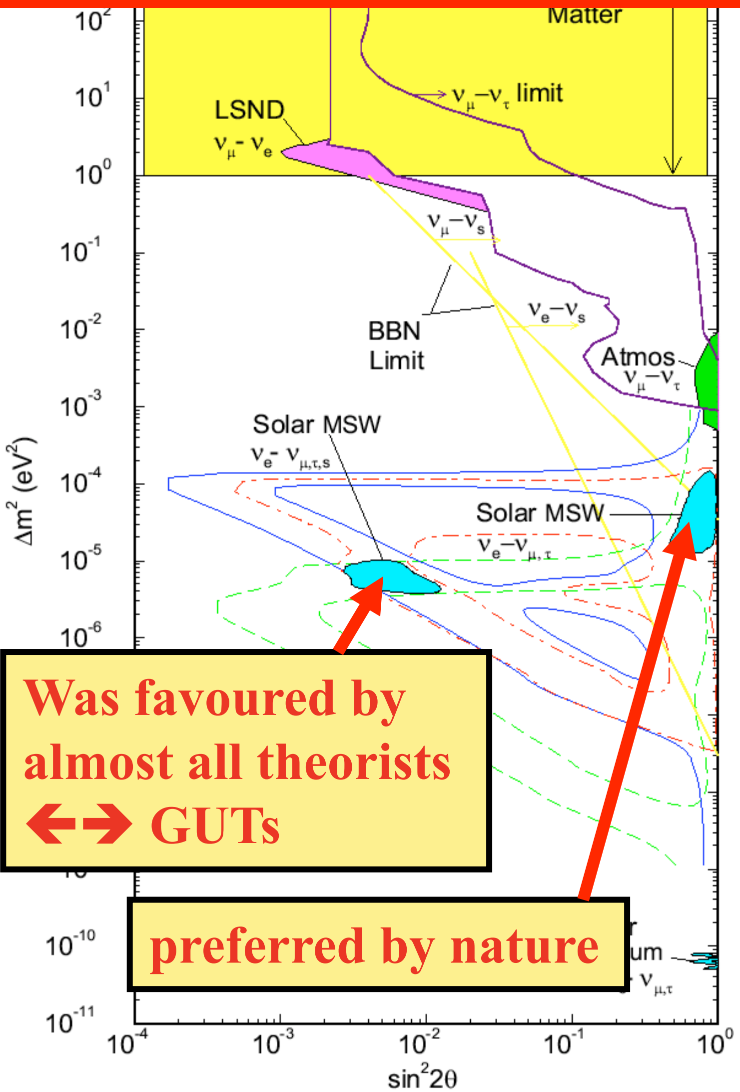
➔ one set of Yukawa couplings for given GUT multiplet
➔ ~ tension: small quark mixings ⇔ large leptonic mixings
➔ this was in fact the reason for the `prediction' of small mixing angles (SMA) – ruled out by data

<u>Mechanisms to post-dict large mixings:</u>

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

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, …)

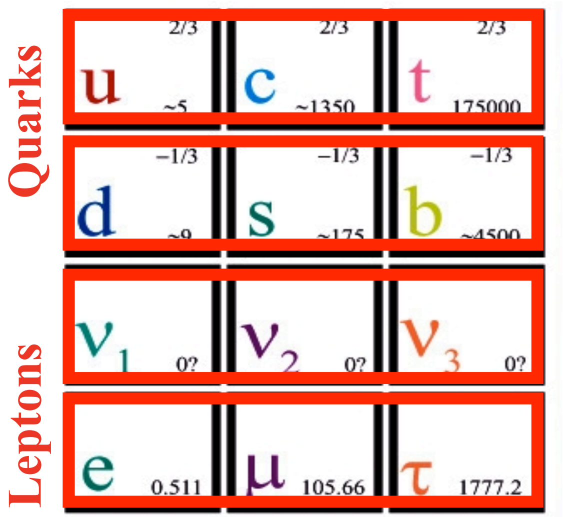
➔ answered by coming precision

Flavour Unification

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

➔ flavour symmetries (finite number for limited rank)

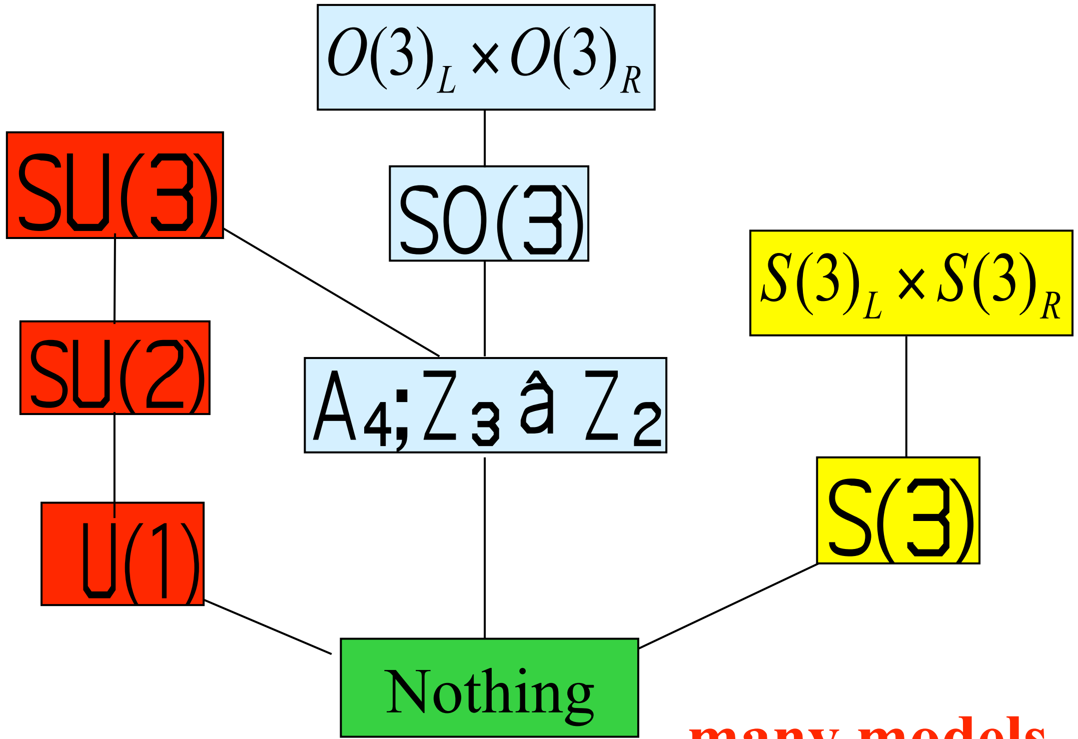
➔ **symmetries** not texture zeros



1. 2. 3.

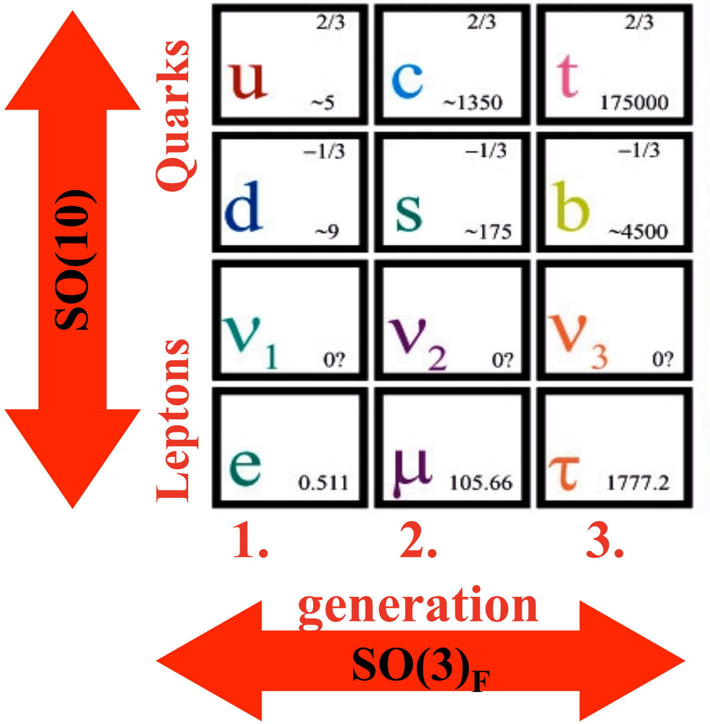
generation

Examples:



many models…

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

➔ 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>

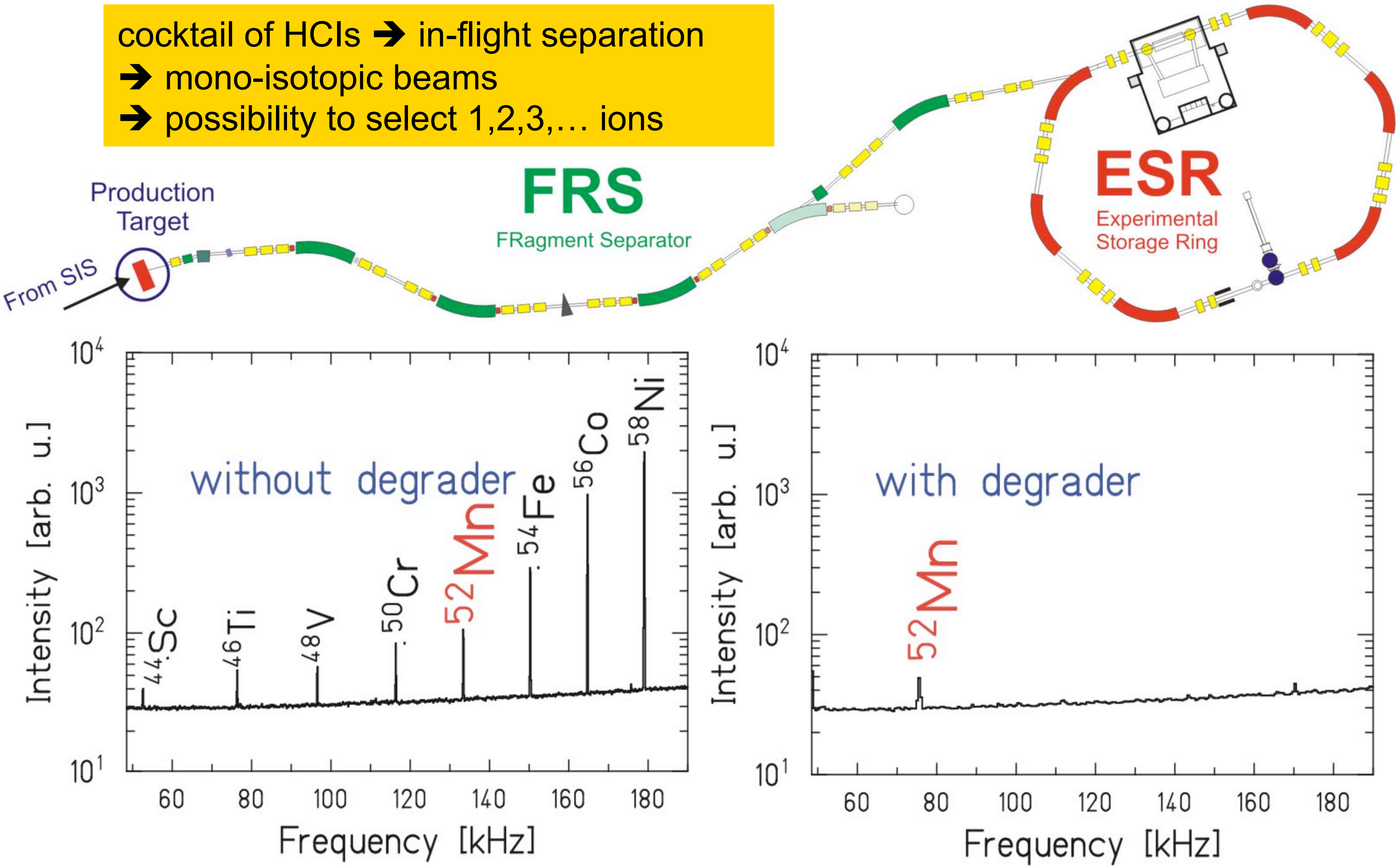
Concluding Remarks

- Neutrino physics will enter a precision phase
- Various possibilities and potential for surprises
- Unification path
  - GUTs … many options
  - flavour symmetries … many options
  - GUT ⊗ flavour unification … rather restricted
    ➔ will this allow a glimpse on the origin of flavour?
- Bottom-up approach
  - d>4 operators ➔ modifications of the standard picture
  ➔ 0nbb decay ←➔ L-violation
  ➔ oscillations and other flavour transitions
- Use QFT to get correct QM limits ←➔ experiments test correctness of QFT

BACKUP

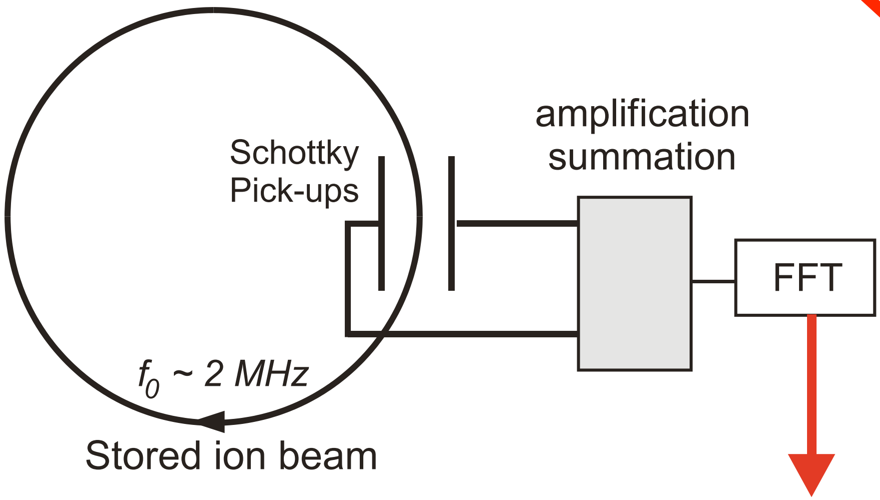
Production and Selection of exotic Nuclei

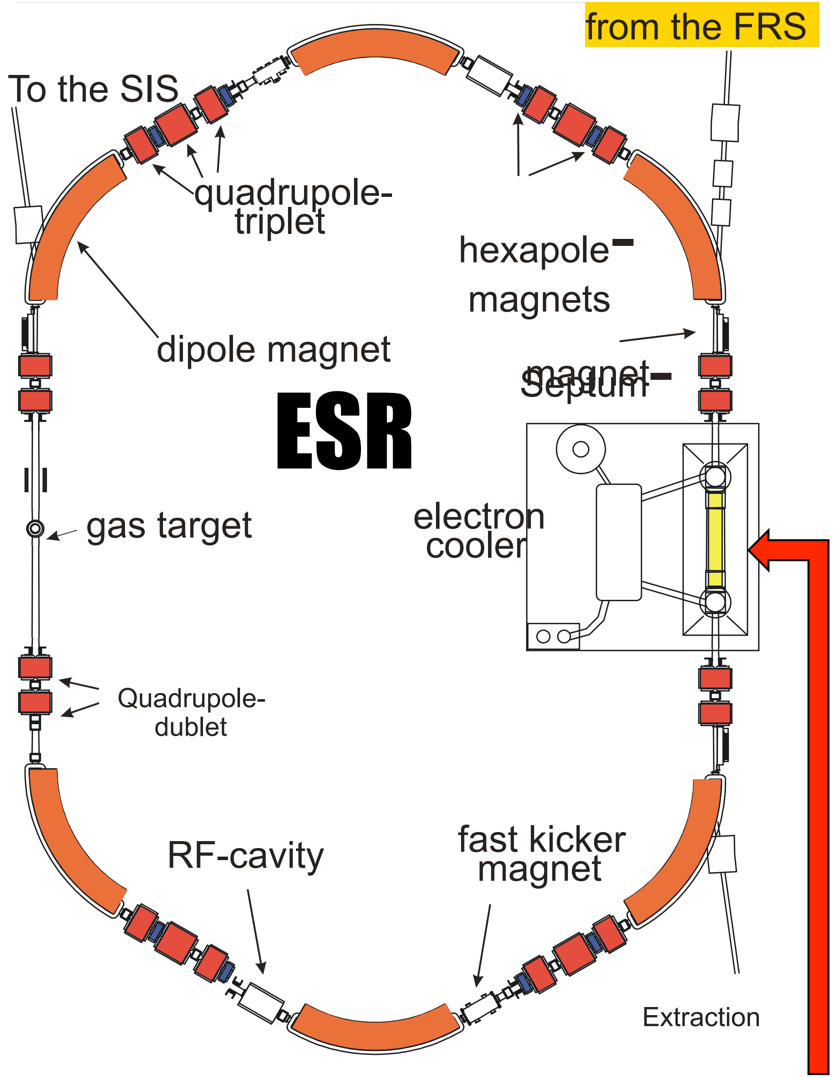
cocktail of HCIs ➔ in-flight separation
➔ mono-isotopic beams
➔ possibility to select 1,2,3,… ions



Schottky-Noise Detection

Schottky pick-ups:
individual ions
⇔ noise





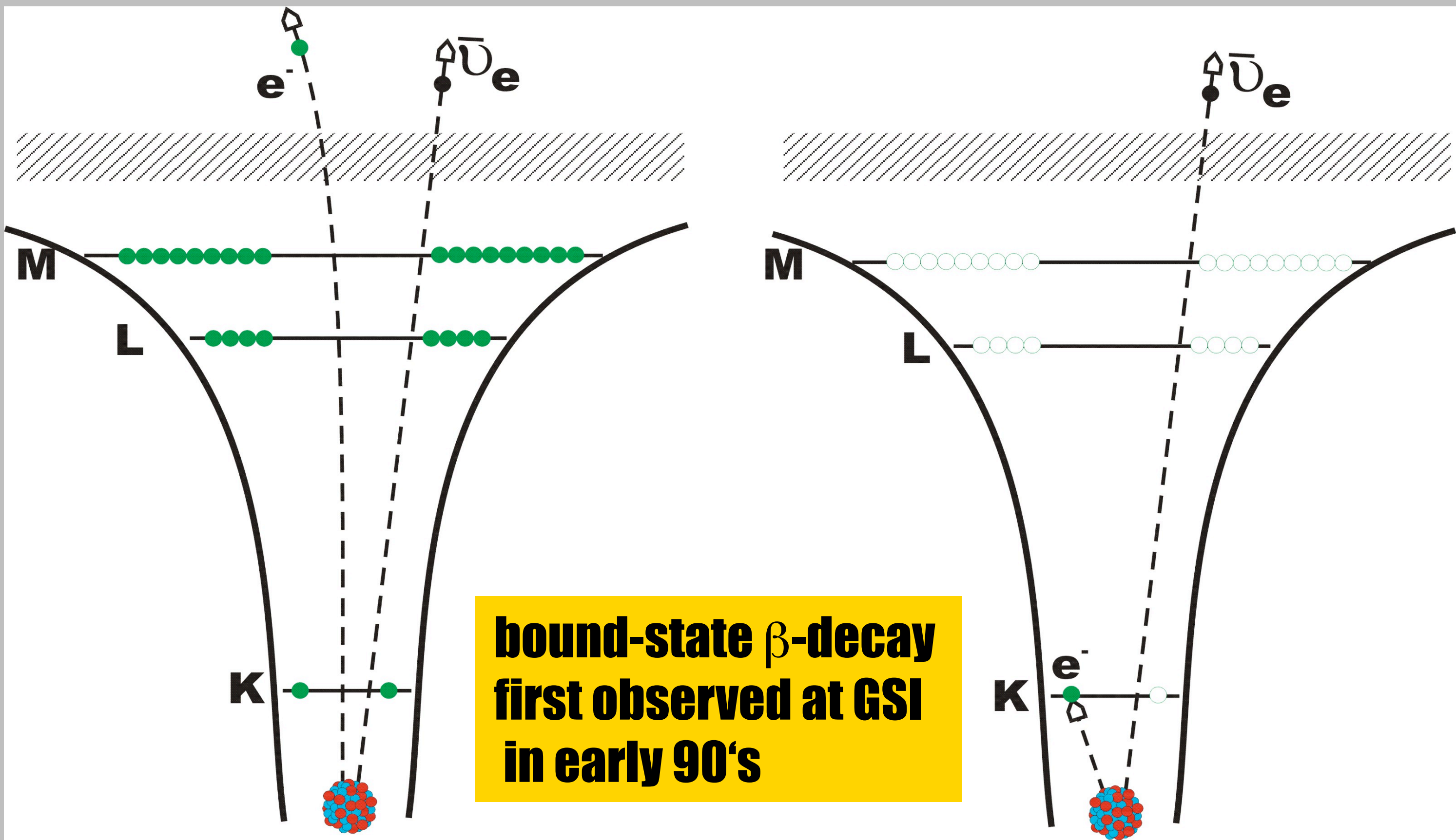
cooling ($\Delta v/v \rightarrow 0$) ➔

continious digitization of FFT output
and data storage for
1,2,3, … stored ions

Cooling (stochastic & electron)

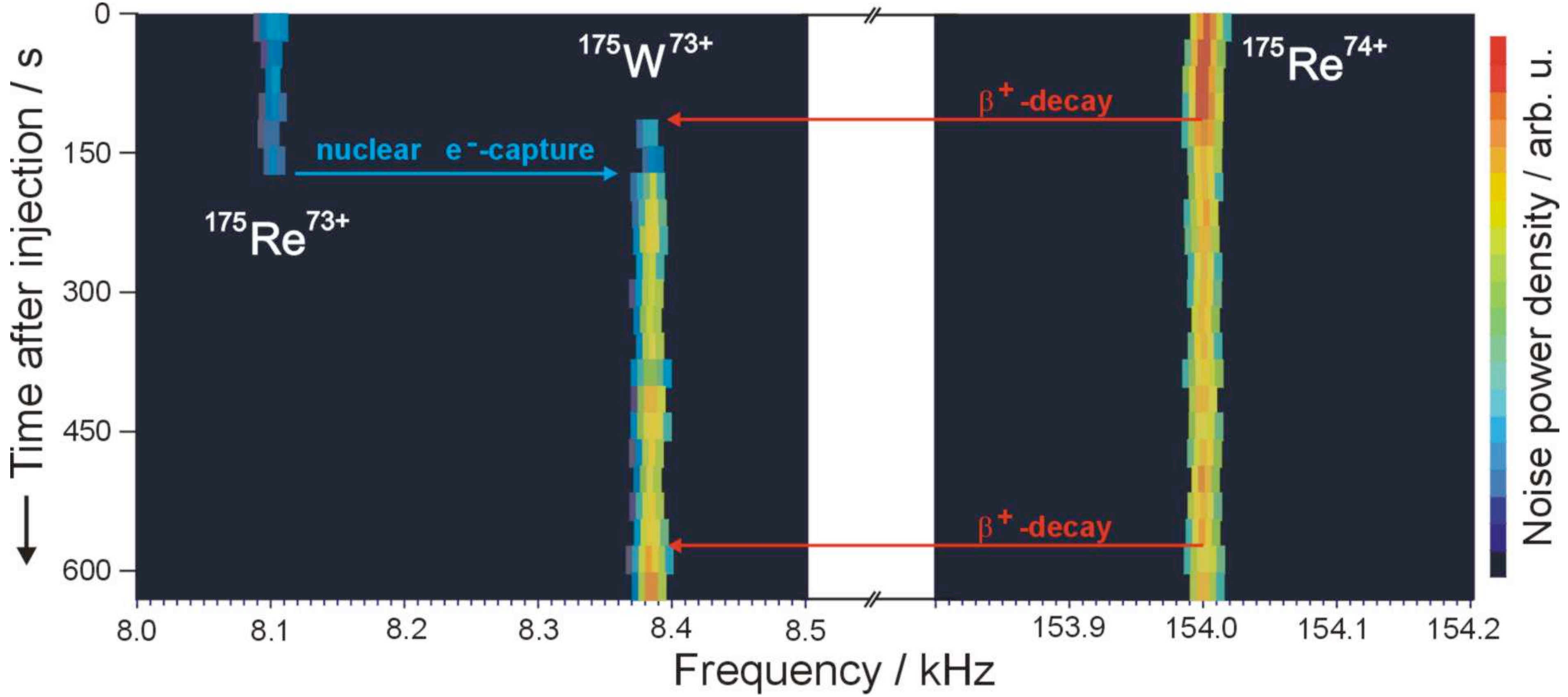
Observation of Decays of stored Ions

a) normal β-decay ➔ different charge ➔ different M/q
b) bound state β-decay by electon capture
➔ same q, slightly different M' (binding energy, n-emission)



bound-state β-decay first observed at GSI in early 90's

Examples for Decay of Single Ions

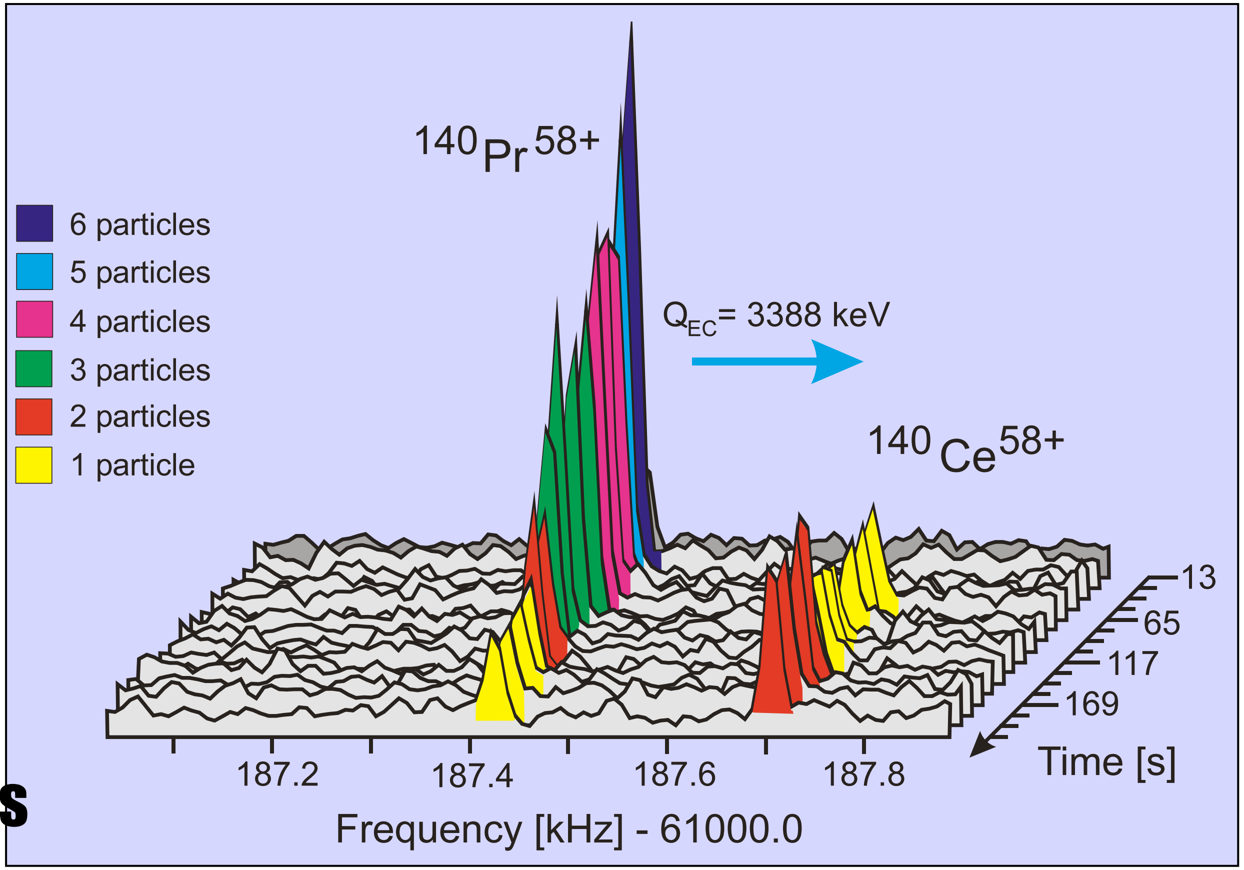


- ordinary β-decay and EC clearly separable
- for few ions: intensity allows to see individual decays

Spectroscopy of individual Particles

- sensitive to single ions
- well-defined
  - creation time t_0
  - charge states
- two-body β-decay
  → monochromatic ν_e

- observation of changes in peak intensities of mother and daughter ions



- investigation of a selected decay branch, e.g. pure EC decay
- time-dependence of the detection efficiency is excluded