NOW 2008 - and Then

50 JAHRE
1958 2008
MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

M. Lindner

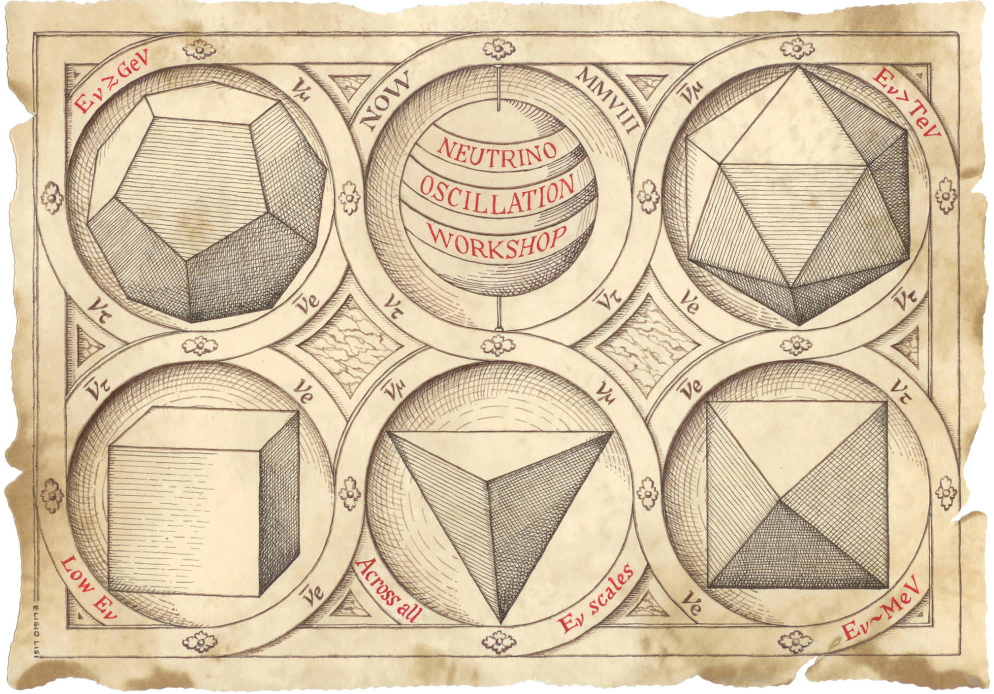
**Max-Planck-Institut
für Kernphysik, Heidelberg**

NOW 2008
Conca Specchiulla (Otranto, Italy), September 6-13, 2008

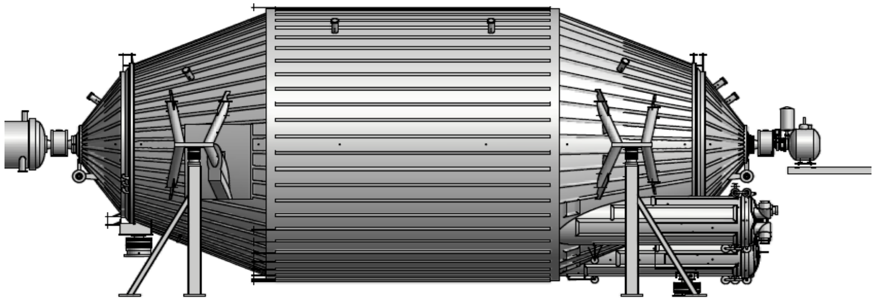
The Task

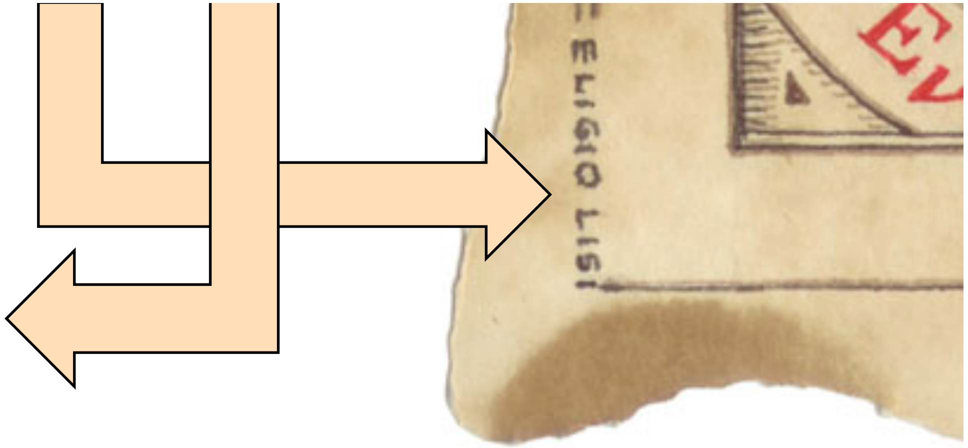
G. Fogli: The Ribbon

At this point it remains to interpret the role of the ribbon, which goes around the solids without interruption. (without a break) (uninterruptedly).

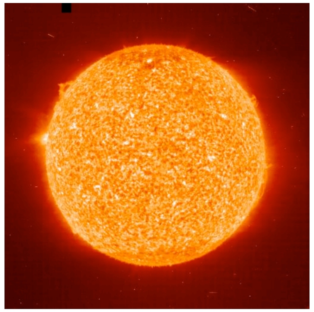


- relate the “Platonic solids"
- interprete connections
- the corners and cracks
- the larger picture

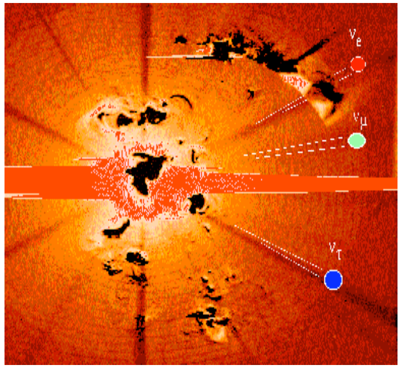




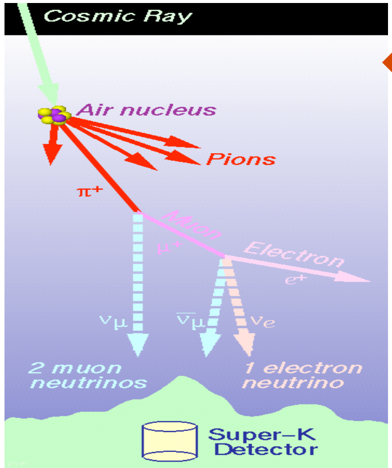
Neutrino Topics



←Sun



←Cosmology



←Atmosphere

←Earth

Astronomy: →

Supernovae

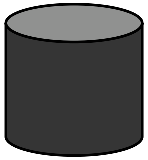
GRBs

UHE ν‘s

Reactors→

Accelerators→

β-Sources→



Four Methods of Mass Determination

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

ß-decay: energy spectrum

G. Drexlin

measurement of m(ν_e)
based on kinematics & energy conservation

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

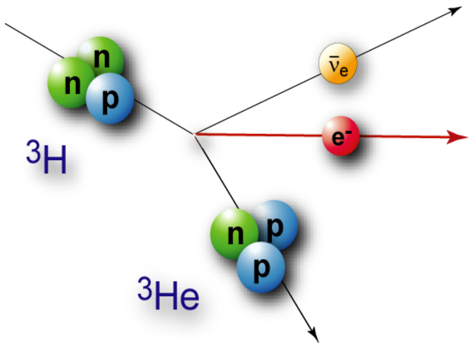
incoherent sum

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

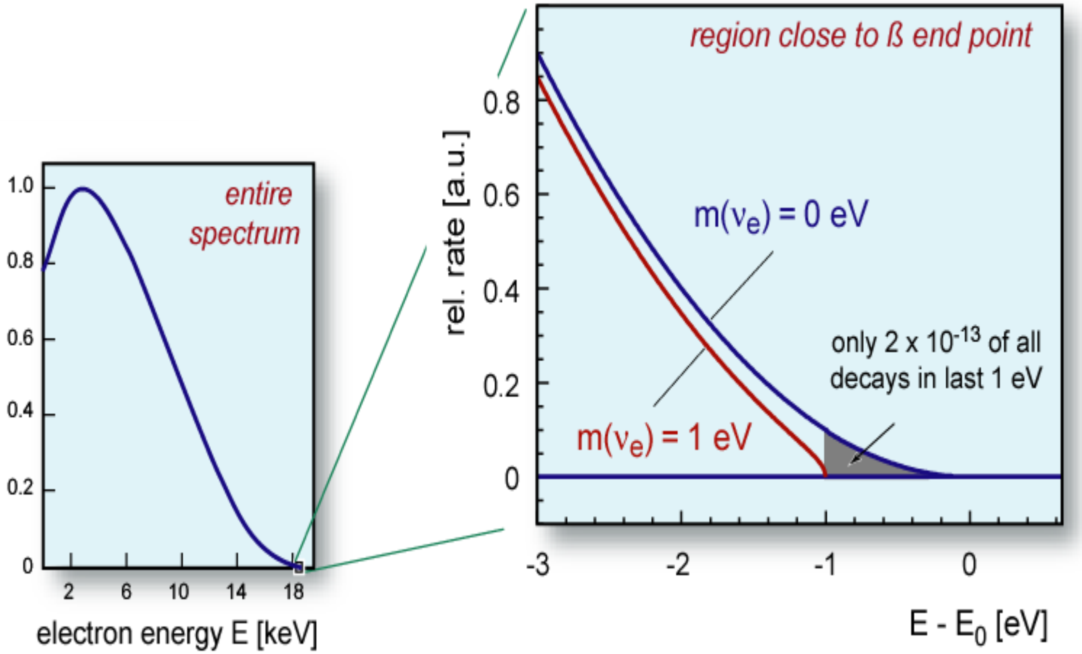
$$G_F^2 \frac{m_e^5}{2\pi^3} \cos^2\theta_C \, |M|^2$$

(ν− mass)^2

Fermi function



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



investigation of the kinematics of ß-decay:
➔ only model independent measurement of absolute ν mass scale
←➔ cosmology …

MARE: staged approach based on microcalorimeters ^{187}Re ß-decay
MARE-I ~300 detectors with m(ν) ~ 2 eV
MARE-II ~50.000 detectors with m(ν) ~ 0.2 eV
if successful R&D & if funded

KATRIN: designed as ´ultimate´ tritium ß-decay experiment
initial runs Q4/2010

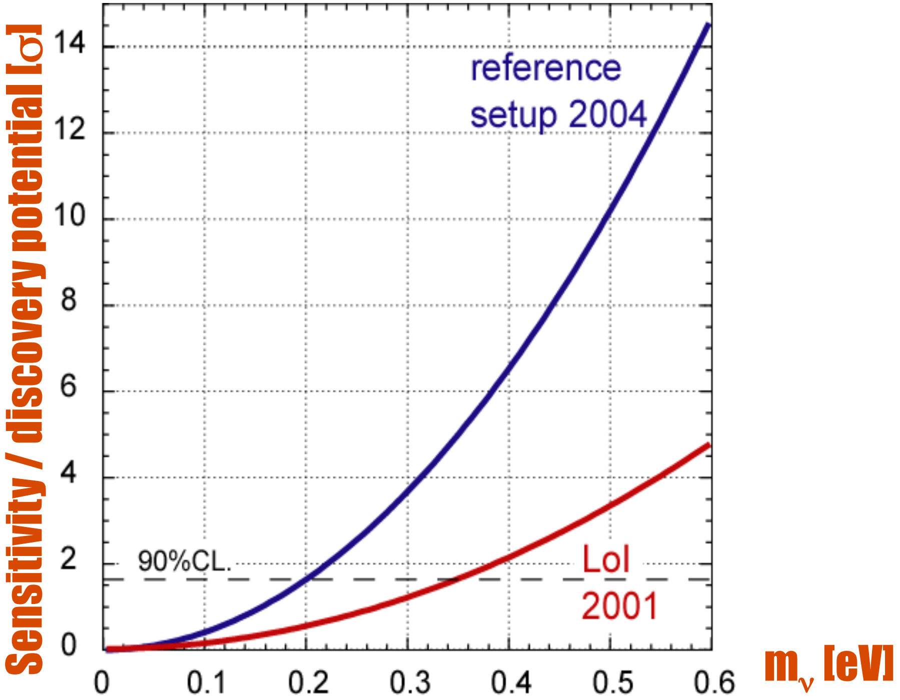
model-independent

status (Mainz, Troizk): $m_\nu < 2.3$ eV

potential: KATRIN, MARE-II

sensitivity (90% CL)
m(ν) < 200 meV

discovery potential
m(ν) = 350 meV (5σ)



Four Methods of Mass Determination

- kinematical
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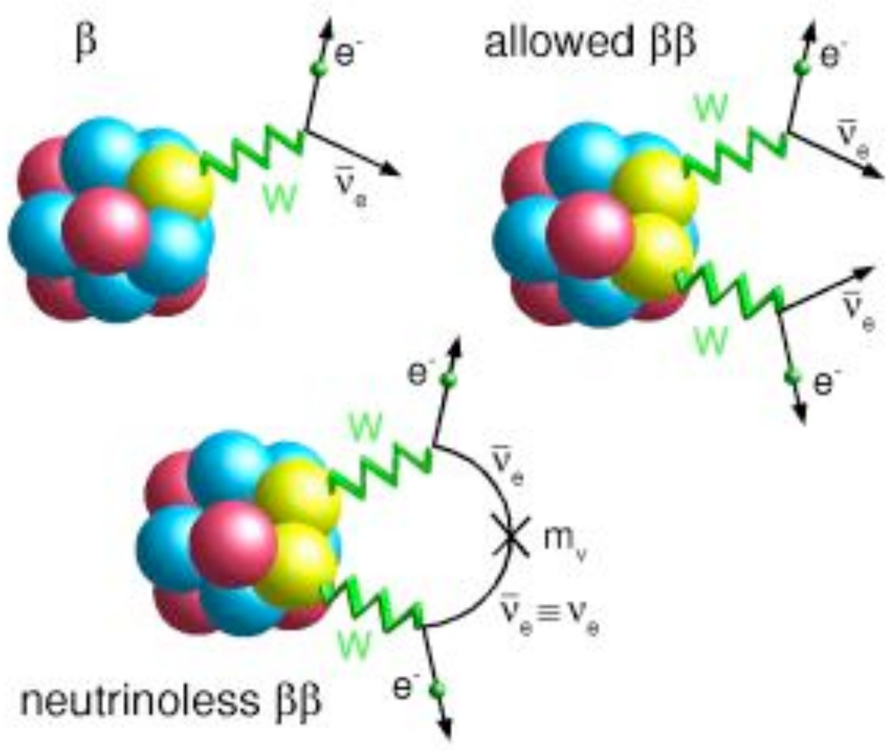
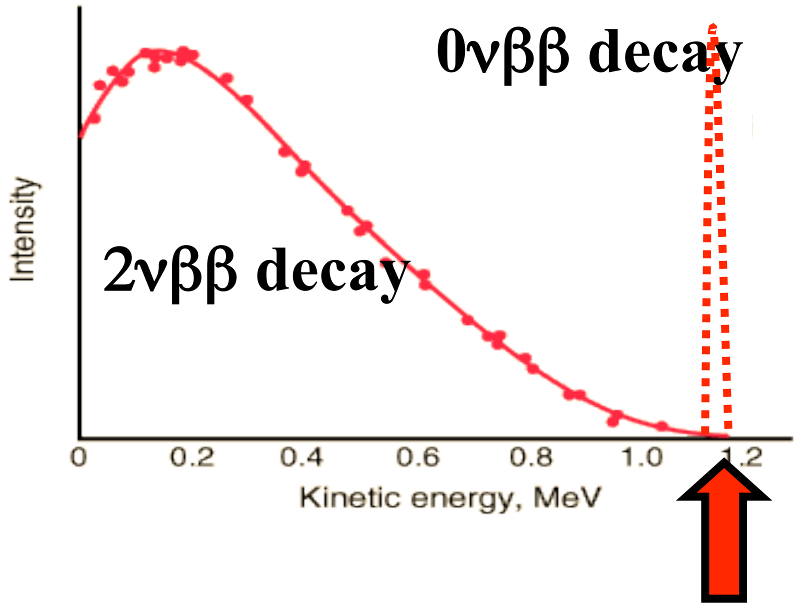
0νββ Decay Kinematics



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…

NME's: Relating Lifetimes & Neutrino Masses

rate of 0νββ

phase space

nuclear matrix elements

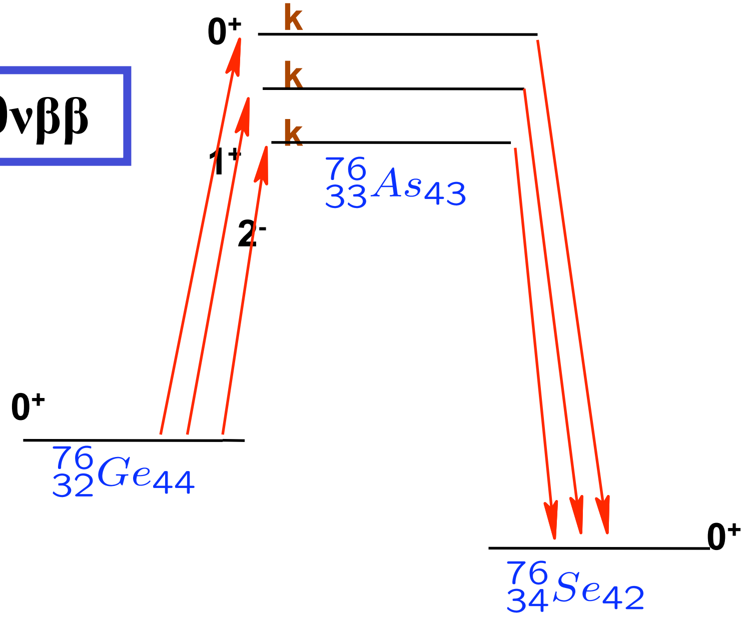
effectiveMajorana neutrino mass

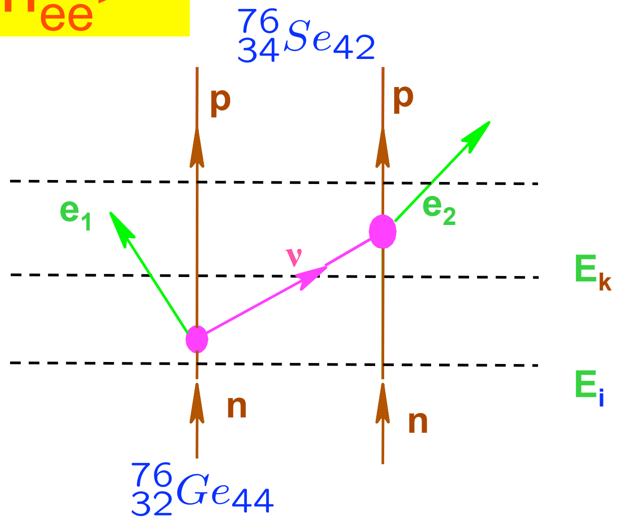
$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 \langle m_{ee}\rangle^2$$

nuclear matrix elements:

➔ virtual excitations of intermediate states

0νββ





A. Faessler, J. Suhonen, V.Rodin: good progress in TH errors

- ➔ QRPA & shell model
- ➔ reduced uncertainties
- ➔ what is a 1σ theory error?

A. Fässler

Summary: Neutrino Mass from 0νββ

Theory with R-QRPA and g_A =1.25

Exp. Klapdor et al. Mod. Phys. Lett. A21,1547(2006) ; ^{76}Ge

T(1/2; 0νββ) = (2.23 +0.44 -0.31) x 10^{25} years; 6σ

- <m(ν)> = 0.24 [eV] (exp+-0.02; theor+-0.01) [eV]
  Bonn CD, no short range correlations
- <m(ν)> = 0.22 [eV] (exp+-0.02;theor+-0.01) [eV]
  Bonn CD, Consistent Brückner Correlations
- <m(ν)> = 0.24 [eV] (exp+-0.02; theor+-0.01)
  Argonne, Consistent Brückner Correlations
- <m(ν)> = 0.30 [eV] (exp+-0.03;theor+-0.01) [eV]
  Bonn CD, Fermi Hypernetted Chain (Argonne in nuclei)
- <m(ν)> = 0.26 [eV] (exp+-0.02;thero+-0.01) Bonn CD, UCOM (AV18 in D)
- <m(ν)> = 0.31 [eV] (exp +-0.03;theor+-0.02) [eV] Bonn CD, Jastrow

0νββ Experiments

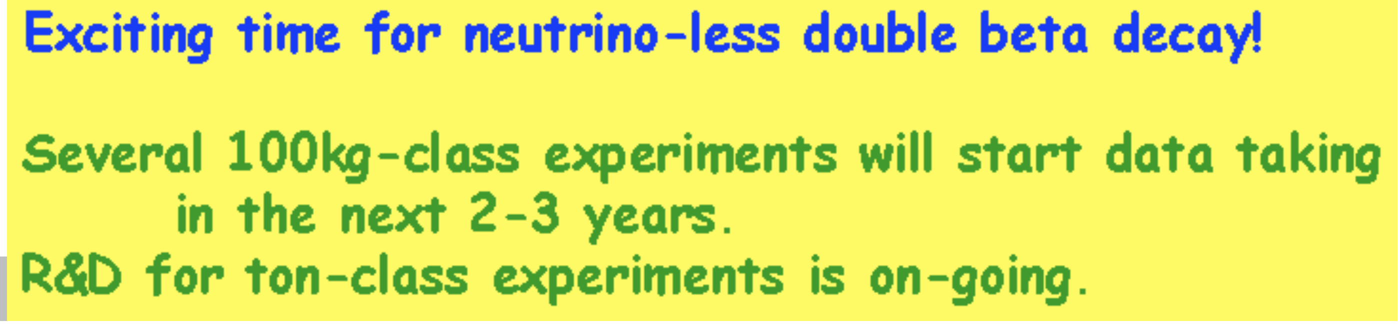
Future projects# (a broad brush, personal view)

Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	Majorana†	Eres, 2site tag, Cu shield	30+30kg	SUSEL
	Gerda†	Eres, 2site tag, LAr shield	18→40 kg	G Sasso
	MaGe/GeMa	See above	~1ton	DUSEL? G Sasso?
^{150}Nd	SNO+	Size/shielding	56 kg	SNOlab
^{150}Nd or ^{82}Se	SuperNEMO†	Tracking	100-200 kg	Canfranc Frejus
^{130}Te*	CUORE	E Res.	204 kg	G Sasso
^{136}Xe	EXO	Tracking	150 kg	WIPP
		Ba tag, Tracking	1-10ton	DUSEL?

➔ G. Gratta

$\geq$ 2 elements

see also talks by
J. Janisko (GERDA)
F. Bellini (CUORE)
L. Vala (SuperNEMO)
F. Sanchez (NEXT)
C. Jillings (SNO+)

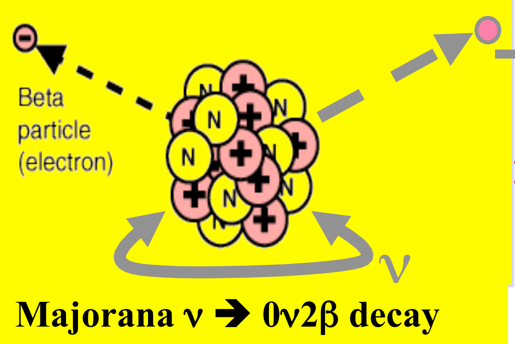


Exciting time for neutrino-less double beta decay!

Several 100kg-class experiments will start data taking in the next 2-3 years.

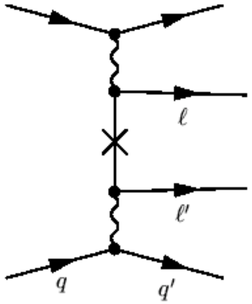
R&D for ton-class experiments is on-going.

Neutrino-less Double β-Decay



Majorana ν ➔ 0ν2β decay

$\propto$

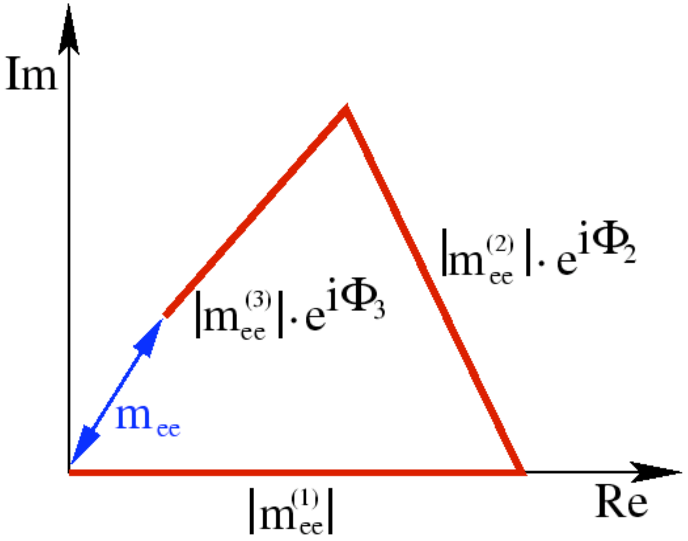


$\propto |\langle m_{ee} \rangle| = |\sum m_i U_{ei}^2|$ **$\leq$ 0.35 eV ?**

Heidelberg-Moscow experiment

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

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



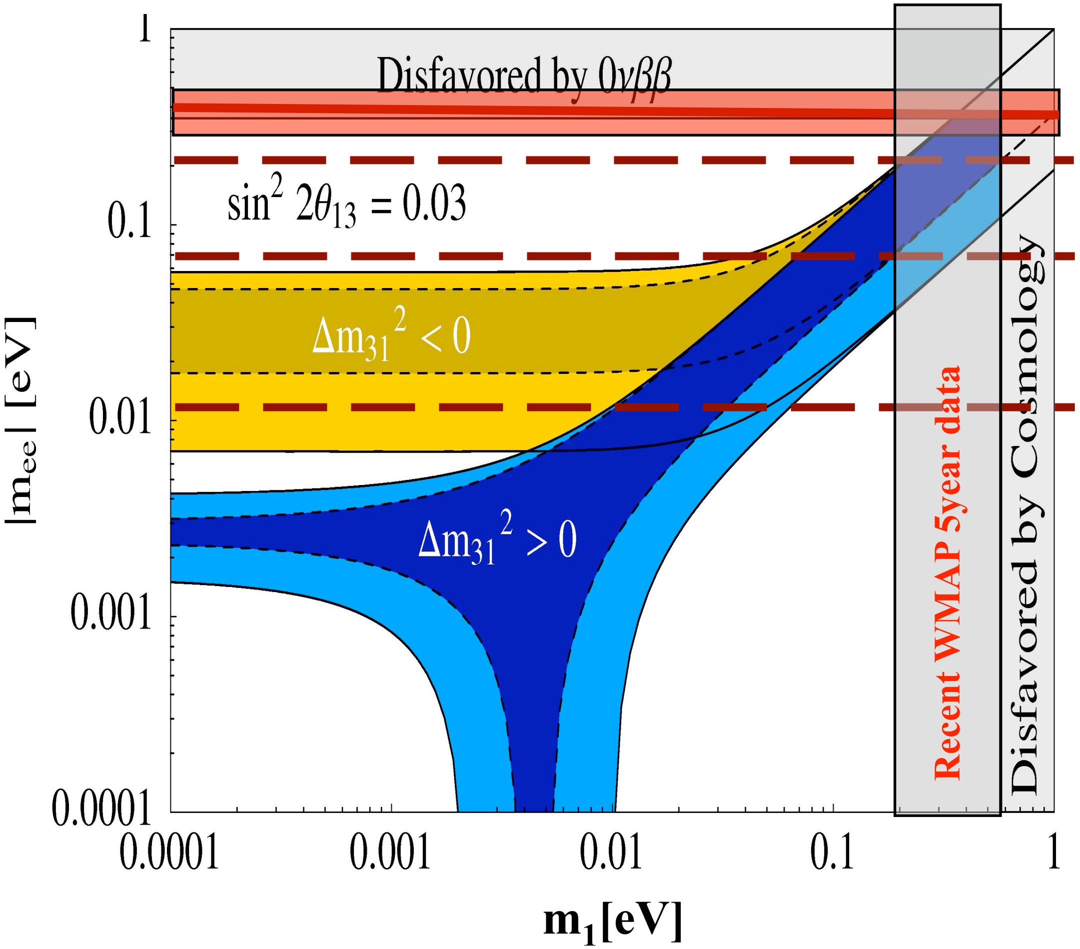
solar $\Rightarrow$ $|U_{e1}|^2, |U_{e2}|^2, \Delta m_{21}^2$ atmosph. $\Rightarrow$ $|\Delta m_{31}^2|$ CHOOZ $\Rightarrow$ $|U_{e3}|^2 < 0.05$

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

Claim of part of the original Heidelberg-Moscow experiment $\leftrightarrow$ cosmology ➔ ‚tension'

aims of new experiments:

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

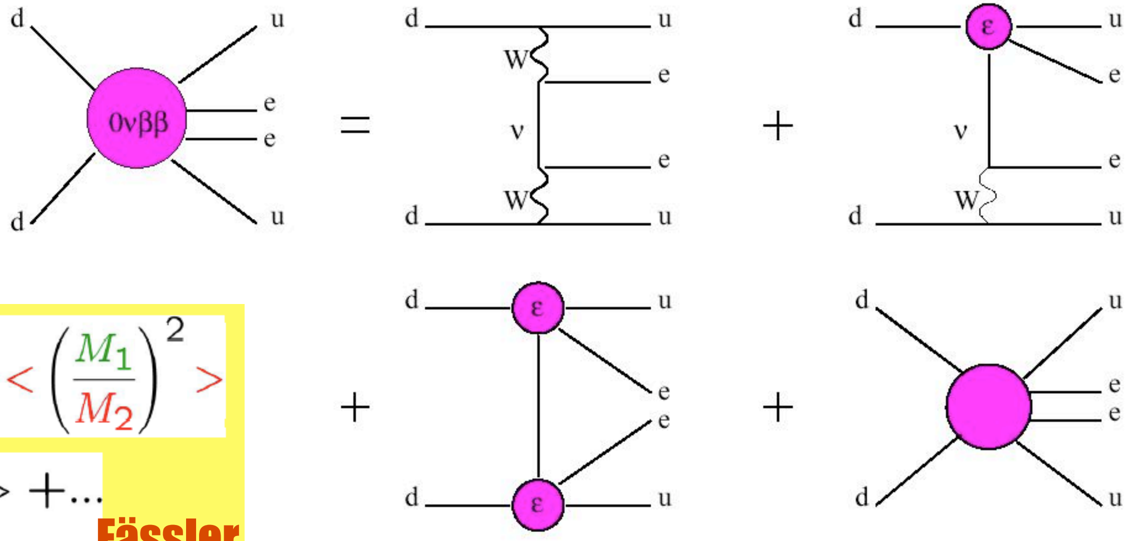


Comments:

- cosmology: limitation by systematical errors ➔ another factor ~5?
- 0νββ nuclear matrix elements ➔ unavoidable theory error in m_{ee}
- $\Delta m^2 > 0$ allows complete cancellation
- 0νββ from *other* new BSM lepton number violating operators

… this may not be the full story

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



$$T = M_m < m_\nu > + M_\theta < tg\vartheta > + M_{WR} < \left(\frac{M_1}{M_2}\right)^2 >$$

$$+ M_{SUSY}\lambda'^2_{111} + M_{VR} < \frac{m_p}{M_{VR}} > + \ldots$$

Fässler

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

➔ very promising interplay of neutrino mass determinations, cosmology, LHC, LVF experiments and theory
➔ see talks by A. de Gouvea, F. Cei, F. Joaquim, L. Merlo,

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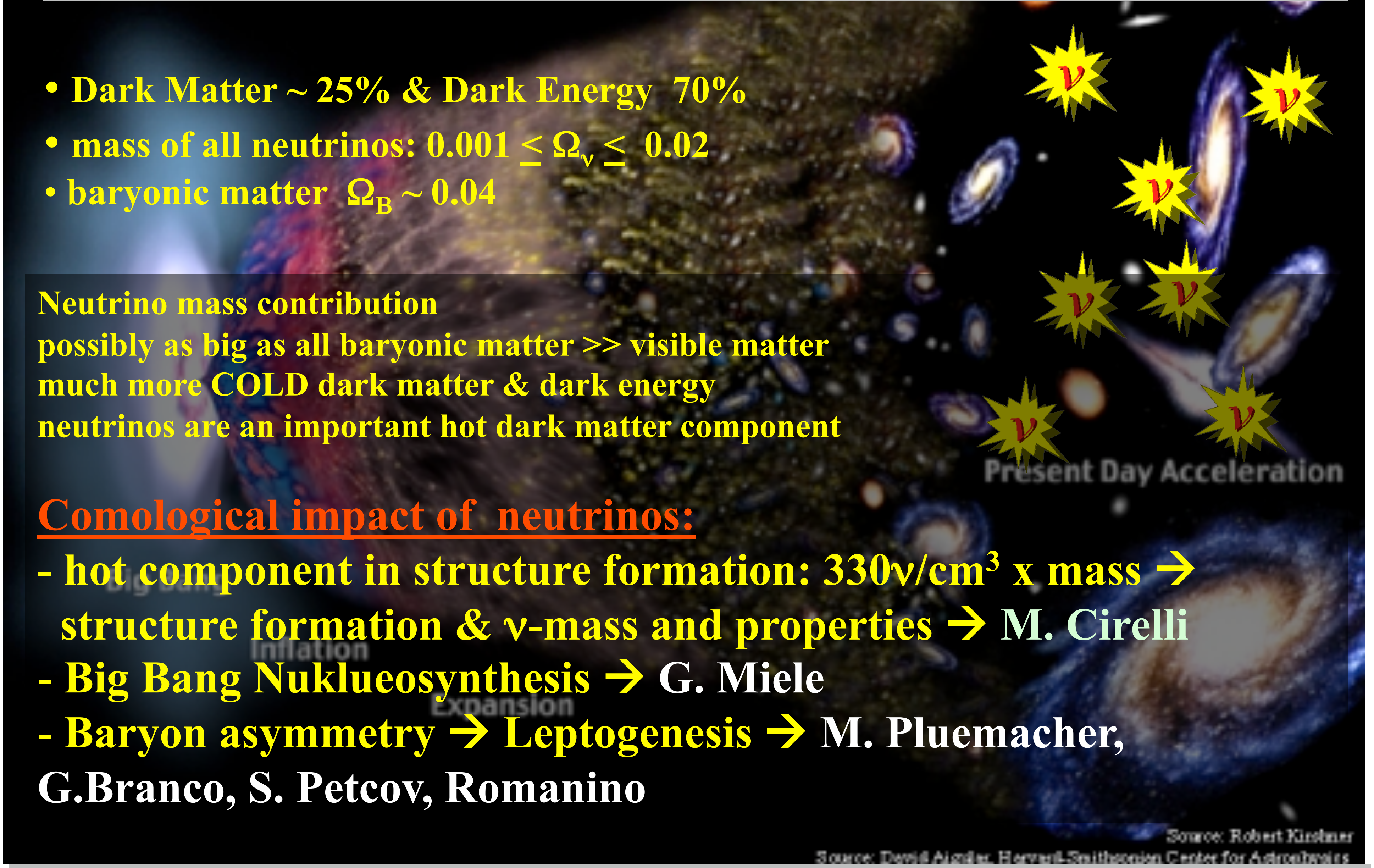
  ↔ Majorana nature
- cosmology & astrophysics
- oscillations

Neutrinos & Cosmology



- Dark Matter ~ 25% & Dark Energy 70%
- mass of all neutrinos: $0.001 \leq \Omega_\nu \leq 0.02$
- baryonic matter $\Omega_B \sim 0.04$

Neutrino mass contribution
possibly as big as all baryonic matter >> visible matter
much more COLD dark matter & dark energy
neutrinos are an important hot dark matter component

Comological impact of neutrinos:

- hot component in structure formation: $330\nu/\text{cm}^3$ x mass → structure formation & ν-mass and properties → M. Cirelli
- Big Bang Nuklueosynthesis → G. Miele
- Baryon asymmetry → Leptogenesis → M. Pluemacher, G.Branco, S. Petcov, Romanino

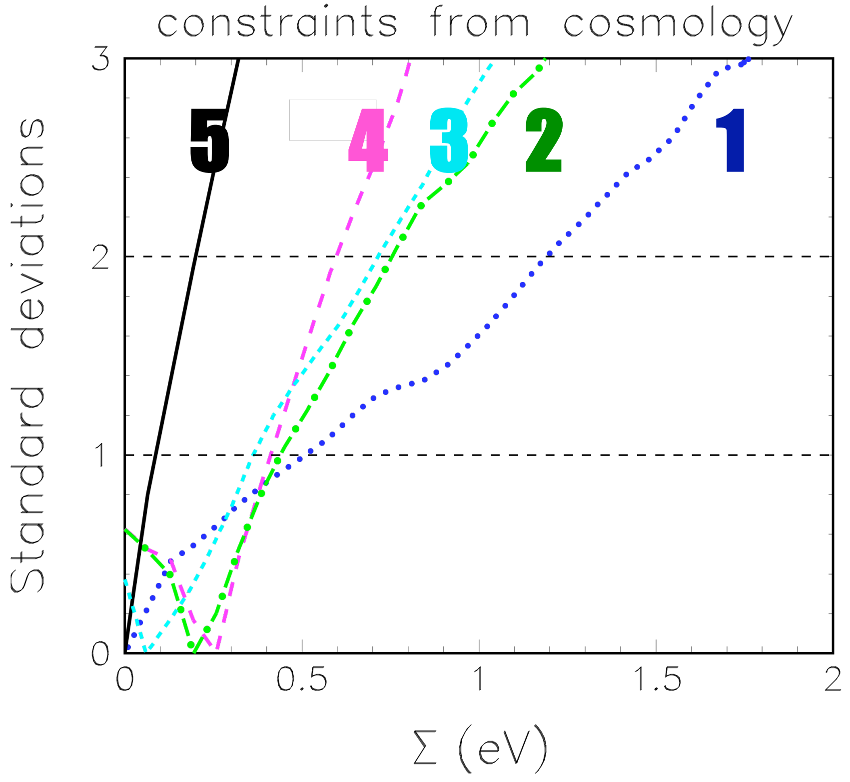
Source: Robert Kirshner
Source: David Aguilar, Harvard-Smithsonian Center for Astrophysics

Cosmological Neutrino Mass Limit(s)

Talk of A. Palazzo:

Fogli et al., Phys. ReV. D 78, 033010 (2008) [arXiv:0805.2517v3]

data set	*2σ limit*
1- CMB	**1.19 eV**
2- CMB + HST + SN-Ia	**0.75 eV**
3- CMB + LSS	**0.72 eV**
4- CMB +HST + SN + BAO	**0.60 eV**
5- CMB+ HST + SN + BAO + Ly-α	**0.19 eV**



- reliability of Lyα ?
- systematic limitations for increased precision?

Four Methods of Mass Determination

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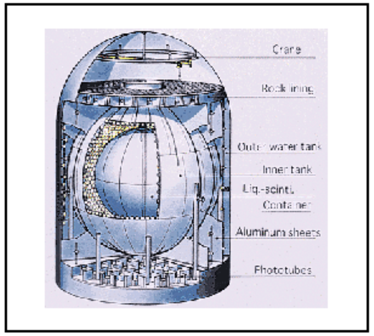
I. Shimizu: KamLAND results & update on solar / cleaning
G. Prioir: SNO phase III
J. Evans: Latest results from MINOS
Y. Kurimoto: SciBooNE
L. Scotto-Lavina: OPERA

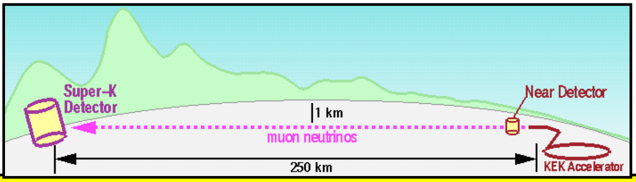
Status of Neutrino Oscillations



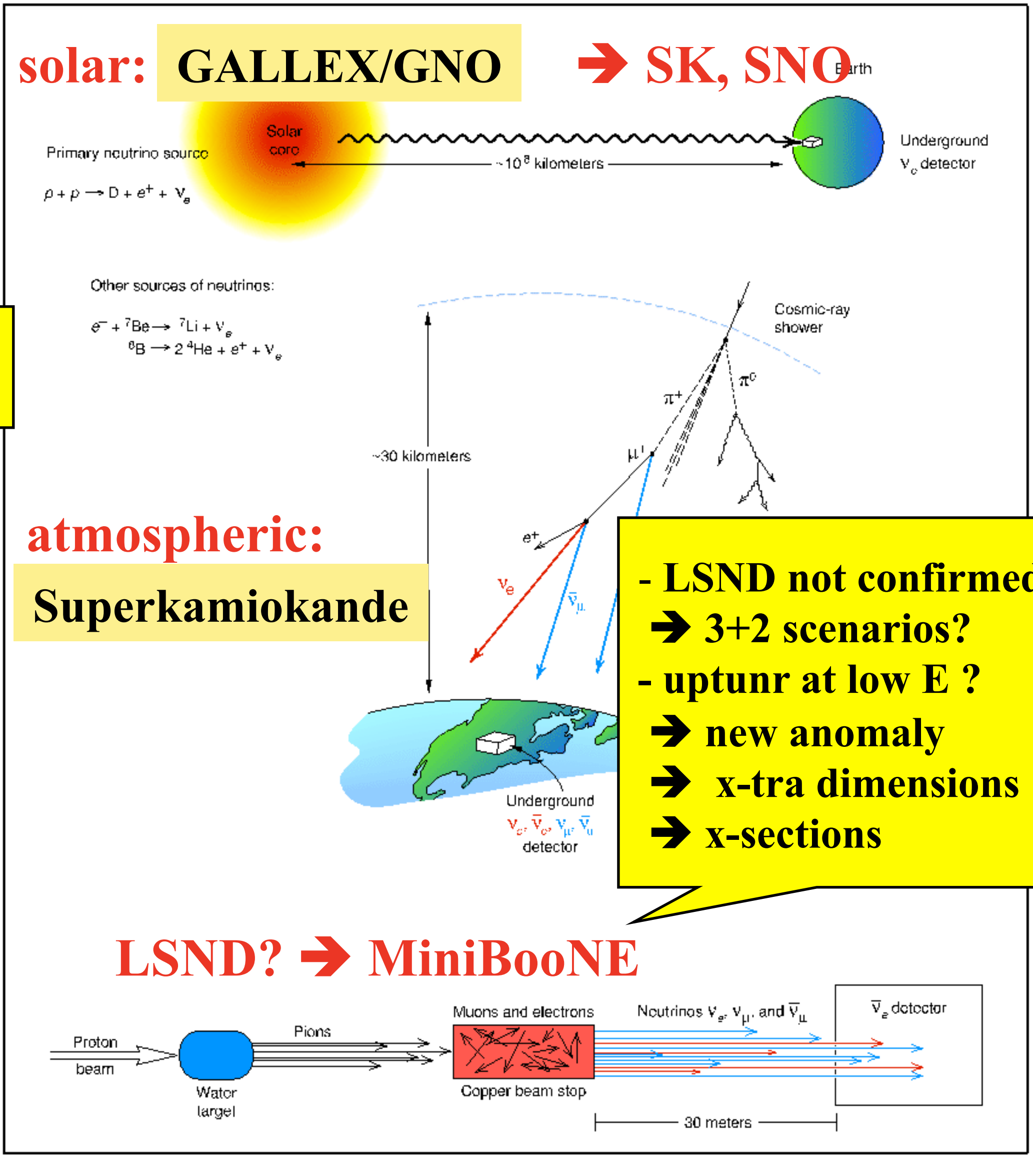
Reactors: KAMLAND

improved results

Beams: K2K ➔ MINOS
➔ OPERA



$\Delta m^2_{21} = (7.67 \pm 0.18) * 10^{-5}\ \mathrm{eV}^2$
$\sin^2\theta_{12} = 0.312 \pm 0.019$
$\Delta m^2_{31} = (2.39 \pm 0.1) * 10^{-3}\ \mathrm{eV}^2$
$\sin^2\theta_{23} = 0.466 + 0.073 - 0.058$
$\sin^2 2\theta_{13} < 0.11$ Chooz+global fit
sensitivity to L/E



solar: **GALLEX/GNO** ➔ SK, SNO

atmospheric: **Superkamiokande**

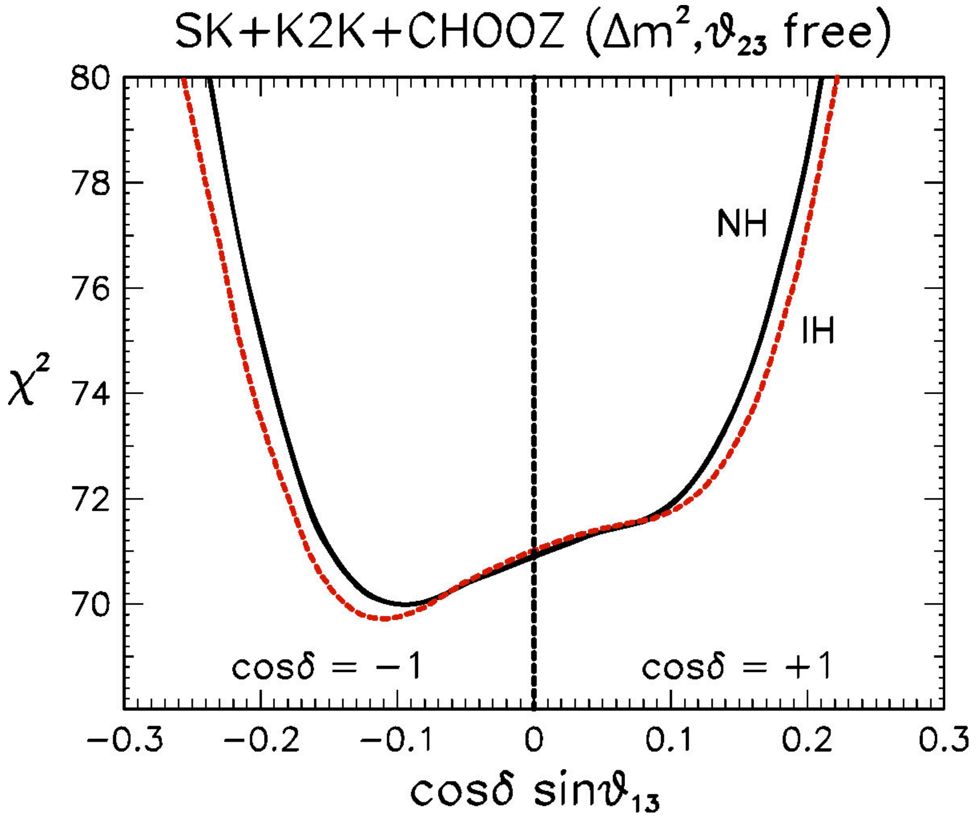
- LSND not confirmed !
  - ➔ 3+2 scenarios?
- uptunr at low E ?
  - ➔ new anomaly
  - ➔ x-tra dimensions
  - ➔ x-sections

LSND? ➔ MiniBooNE

Talk of A. Palazzo:

Fogli et al., Phys. ReV. D 78, 033010 (2008) [arXiv:0805.2517v3]

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81



Fogli et al. [arXiv:0806.2649]

Excess of sub-GeV e-like events and sub-leading 3f effects ←→ “solar” dm^2

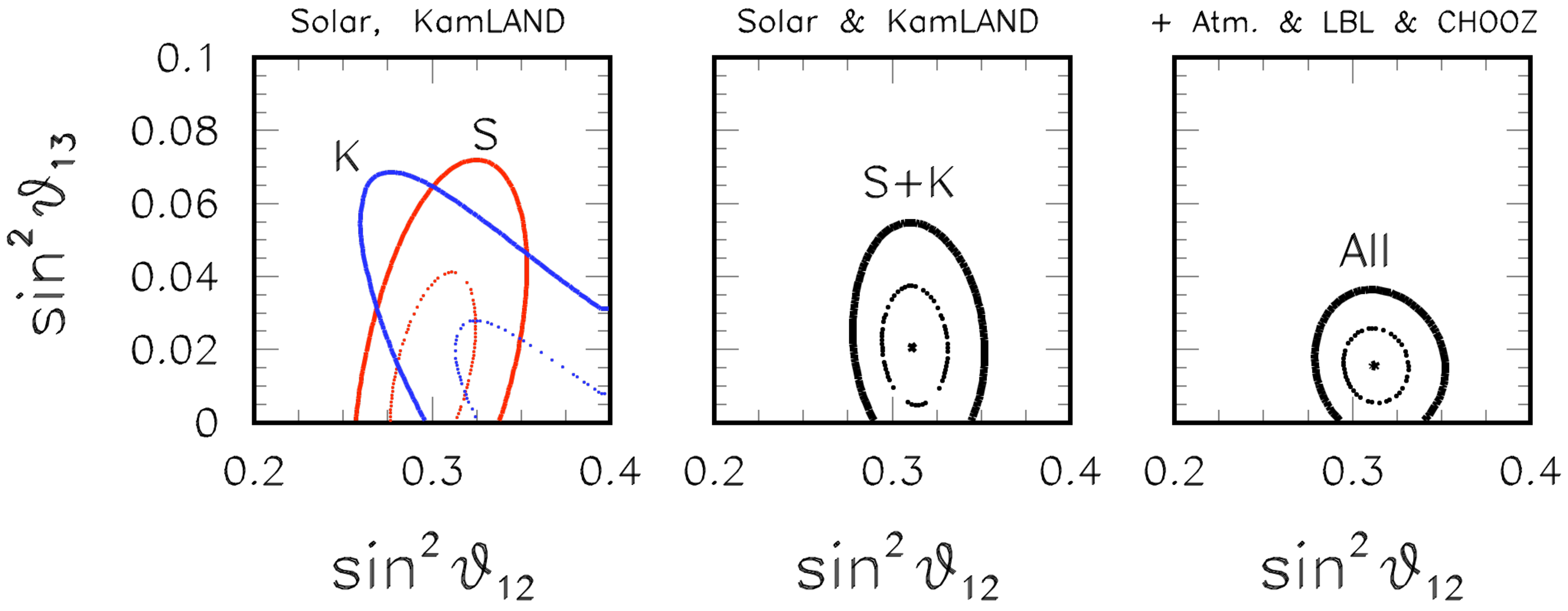
→ ~1σ preference for $\sin^2\theta_{13} > 0$

Effect also seen by other groups:
Schwetz et al.

…

Combining solar and KamLAND

A. Palazzo:



~1.2σ preference for $\theta_{13} > 0$?how robust?

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

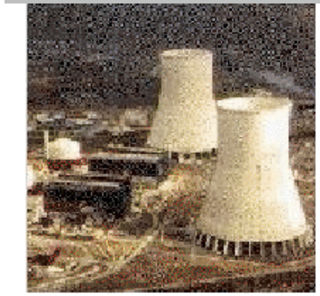
Aims: ➔ improved precision of the leading 2x2 oscillations
➔ detection of generic 3-neutrino effects: θ_{13}, CP violation

Complication: Matter effects ➔ effective parameters in matter

➔ expansion in small quantities θ_{13} and $\alpha = \Delta m^2_{sol} / \Delta m^2_{atm}$

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

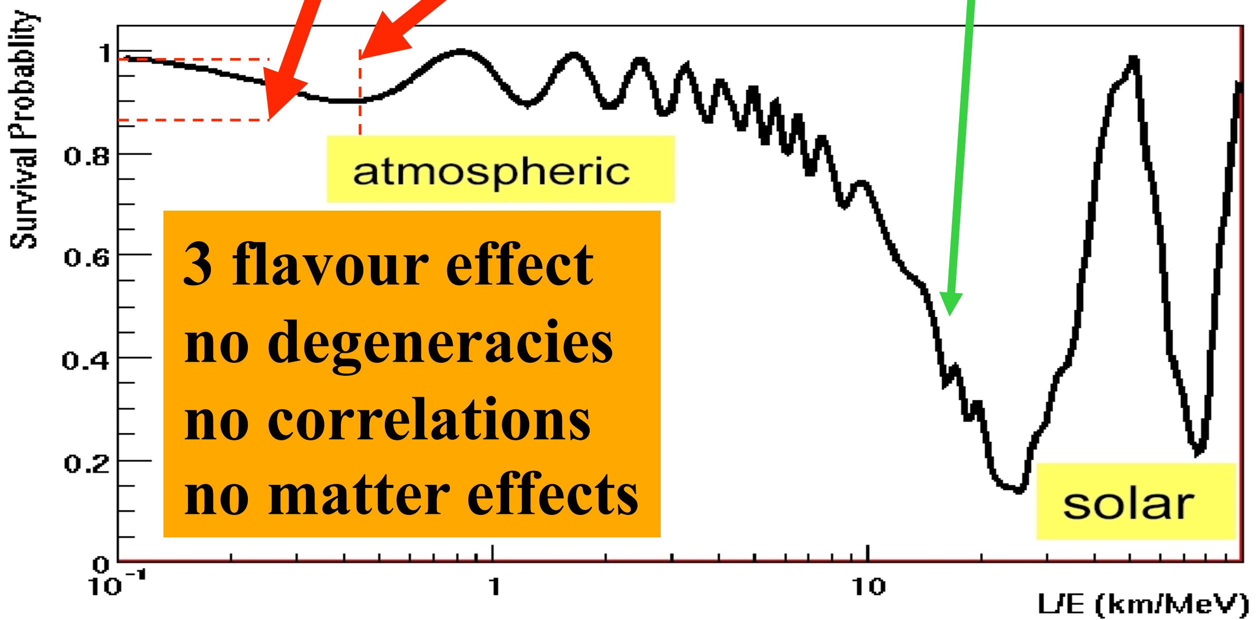
Future Precision with Reactor Experiments



$\overset{\overline{\nu}_e}{\Longrightarrow}$ **near detector** (170m) $\overset{\overline{\nu}_e}{\Longrightarrow}$ **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**
- ➔ **Angra**

clean & precise θ_{13} measurments

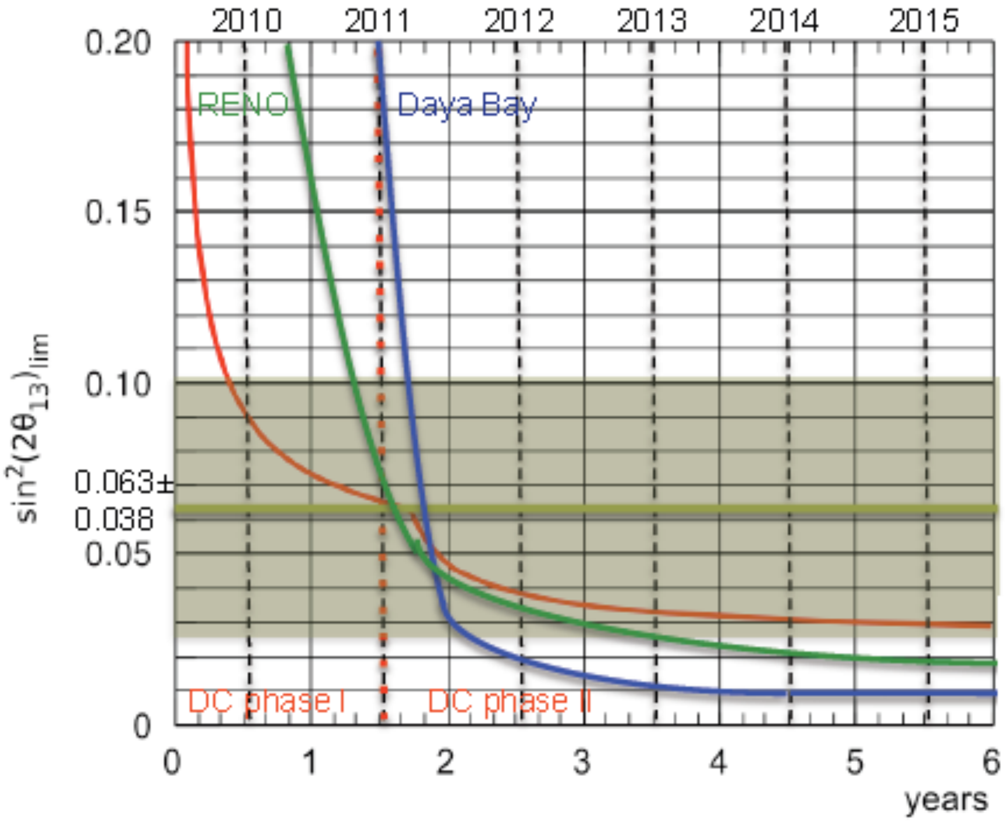
New Reactor Experiments

S. Peeters
(overview & Double Chooz)
Y. Oh (RENO)
D. Lhuillier (monitoring)

Experiments	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)
Double-CHOOZ	France	8.7	280/1050	60/300	10/10
RENO	Korea	16.4	290/1380	120/450	15/15
Daya Bay	China	11.6	360(500)/1985(1613)	260/910	40x2/80

- promising experiments
- precision is very demanding:
  → stable scintillator (c.f. Chooz!)
  → technological challenges
  → backgrounds
  → systematics
  → different optimism on schedules

→ comparison possible, but they depend on non-trivial assumptions…



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

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

↳ correlations & degeneracies, matter effects

overview by W. Winter

Channels of interest

- Disappearance for Δm_{31}^2, θ_{23}: ν_μ ⇨ ν_μ

  $1 - P_{\mu\mu} = \sin^2 2\theta_{23} \sin^2 \Delta_{31} + \text{h.o.t.}$ $\Delta_{31} = \Delta m_{31}^2 L/(4E)$

  NB: We expand in $\sin 2\theta_{13}$ and $\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2$ $(|\alpha| \sim 0.03)$

- Appearance for θ_{13}, CPV, MH:
  - Golden: ν_e ⇨ ν_μ (NF/BB) or ν_μ ⇨ ν_e (SB)

    (e.g., De Rujula, Gavela, Hernandez, 1999; Cervera et al, 2000)
  - Silver: ν_e ⇨ ν_τ (NF – low statistics!?)

    (Donini, Meloni, Migliozzi, 2002; Autiero et al, 2004)
  - Platinum: ν_μ ⇨ ν_e (NF: difficult!)

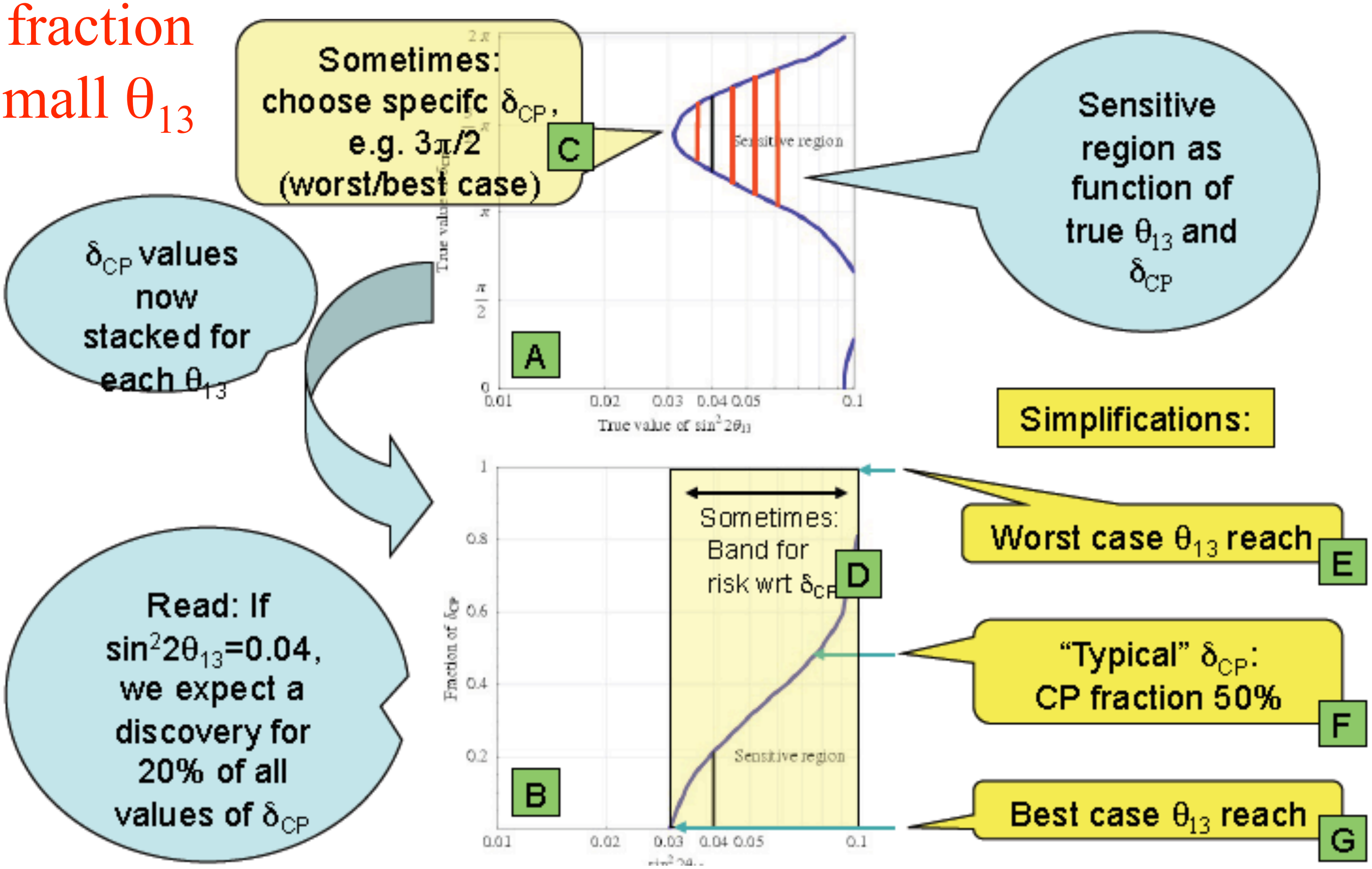
    (see e.g. ISS physics working group report)
- Other appearance: ν_μ ⇨ ν_τ (OPERA, NF?)
- Neutral currents for new physics

  (e.g., Barger, Geer, Whisnant, 2004; MINOS, 2008)

Resolving degeneracies: information beyond rates @ fixed L/E
➔ different L/E, different channels & beams, spectral info., …

Optimization:

- more than one quantity (θ_{13}, δ, θ_{ij}, hierarchy, BSM,…),
- definitions: CP fraction
- physics: large/small θ_{13}



Sometimes: choose specifc δ_{CP}, e.g. $3\pi/2$ (worst/best case)

Sensitive region as function of true θ_{13} and δ_{CP}

δ_{CP} values now stacked for each θ_{13}

Simplifications:

Read: If $\sin^2 2\theta_{13}=0.04$, we expect a discovery for 20% of all values of δ_{CP}

Sometimes: Band for risk wrt δ_{CP}

Worst case θ_{13} reach

"Typical" δ_{CP}: CP fraction 50%

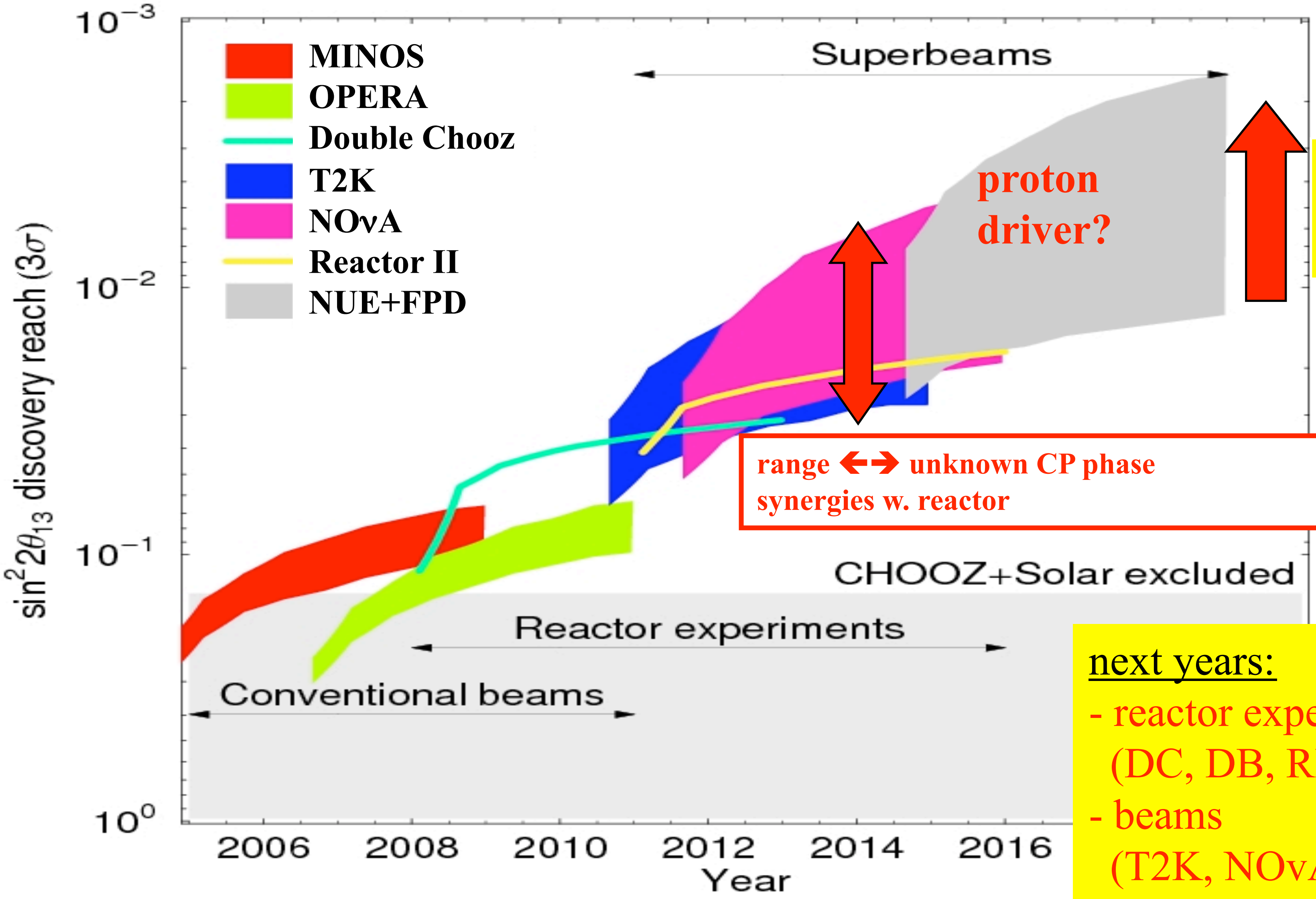
Best case θ_{13} reach

H. Kakuno (T2K → impressive progress)
M. Goodman (MINOS, NOνA & US perspective)
F. Ronga (LBL@ LNGS & EU perspective)
P. Sala (LNGS ν beam)
M. Mezzetto (beta beams)
S. Goswami (INO)
F. Dufour (T2KK)
A. Guglielmi (MODULAr)
T. Schwetz (future atmospheric ν's)
M. Bonesini (R&D towards a neutrino factory)
K. Long (International design study)

1) **build and exploit approved projects (T2K, …, reactor)**
2) **be aware of technological, physics (ν, LHC, LFV) and political uncertainties / problems**
   → **now: get R&D for new beams, detectors done …!**
   → **aim at decisions depending on results in a few years from now (2012?)**

see e.g. LAGUNA – talk by L. Oberauer

θ_{13} – Now and in the Future



proton
driver?

range ↔ unknown CP phase
synergies w. reactor

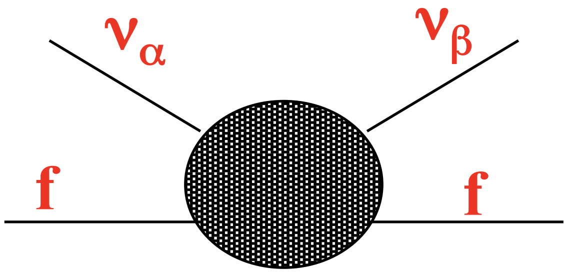
β-beams
ν factory

<u>next years:</u>

- reactor experiments
  (DC, DB, RENO)
- beams
  (T2K, NOνA?)

New Physics, NSIs & ν-Oscillations

See talks by
T. Rashba and T. Ota



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

Future precision oscillation experiments:

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 migh see new effects beyond oscillations!

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

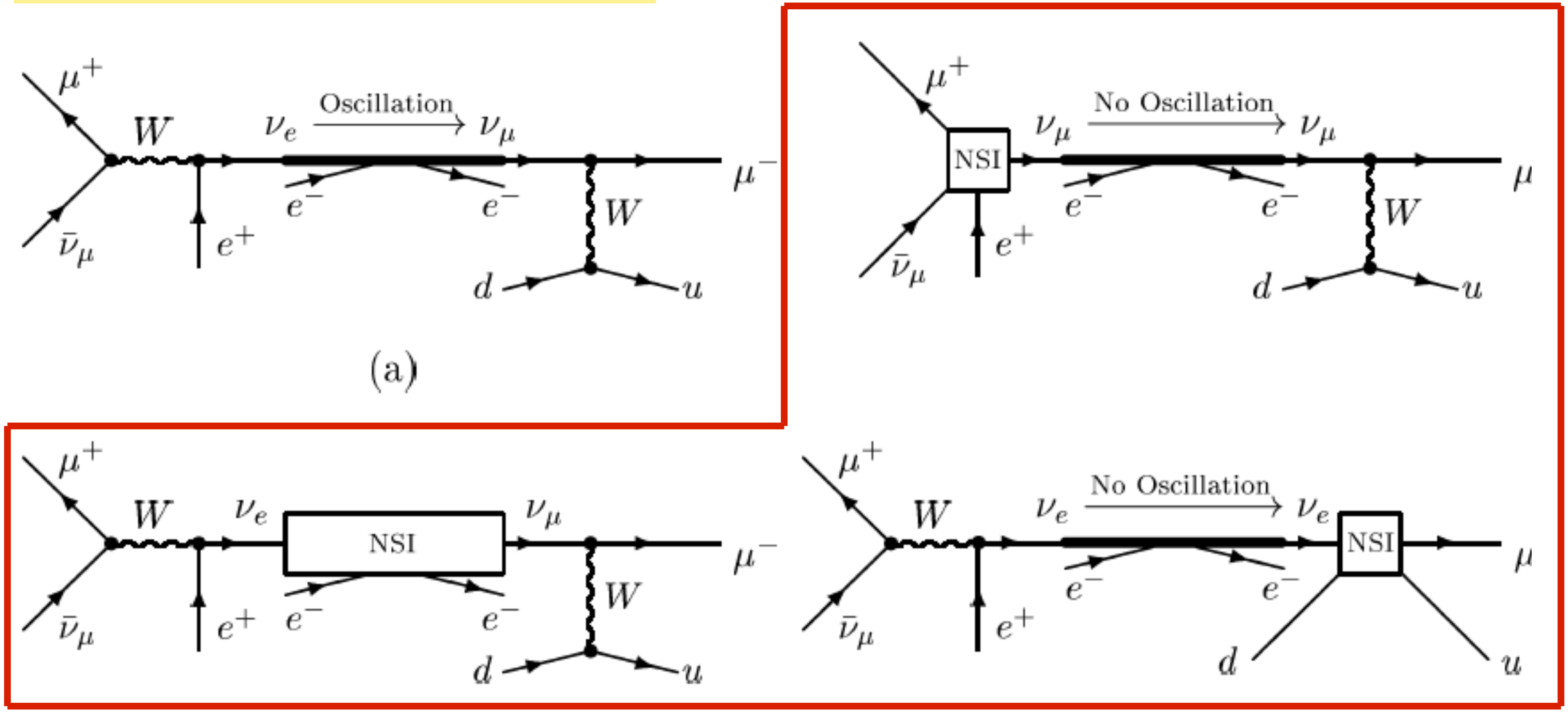
➔ small event rates: offset in oscillation parameters

➔ Non Standard Interactions = NSI's

NSIs interfere with Oscillations

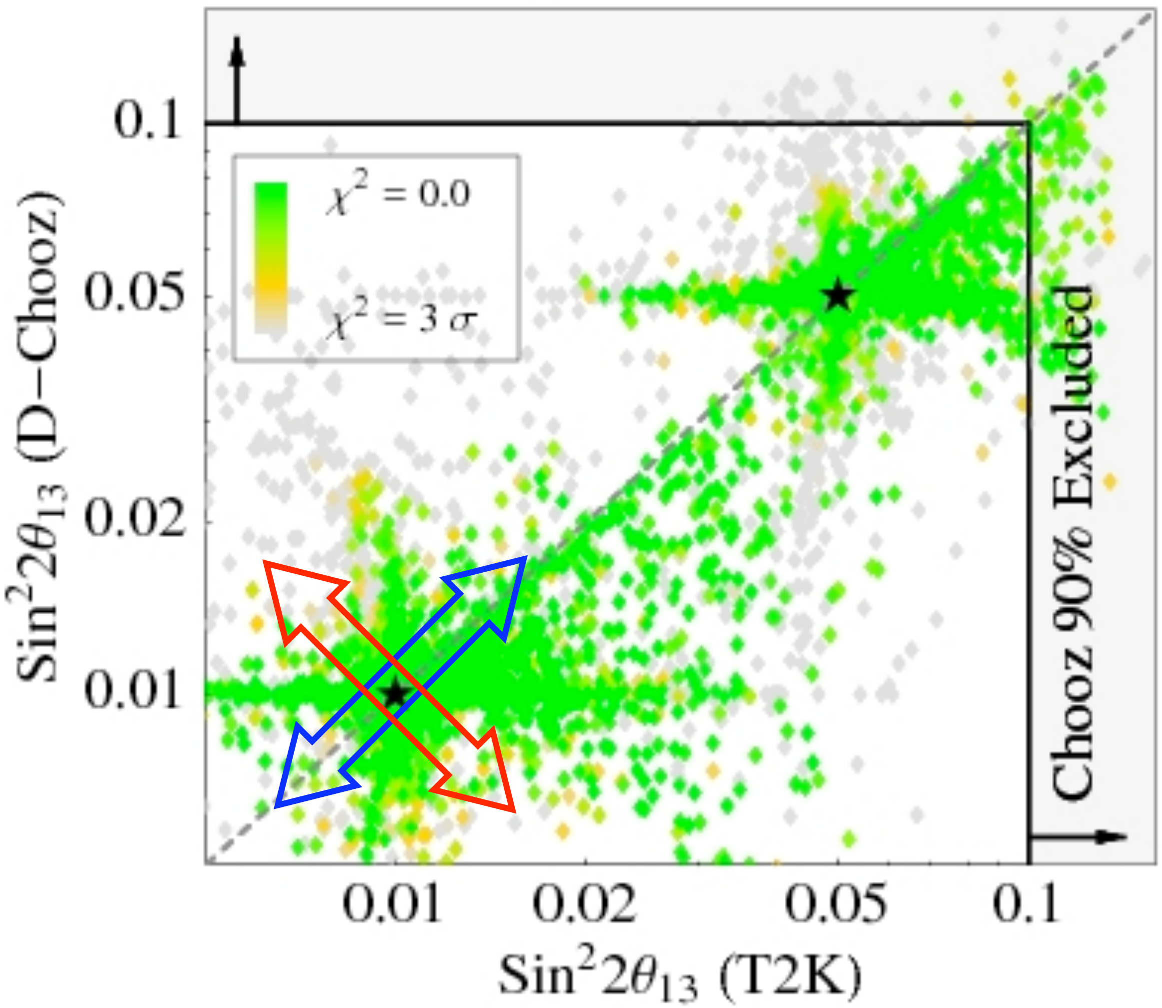
the “golden” oscillation channel

NSI contributions to the “golden” channel



<u>note:</u> interference in oscillations $\sim\varepsilon$ ⇔ 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**

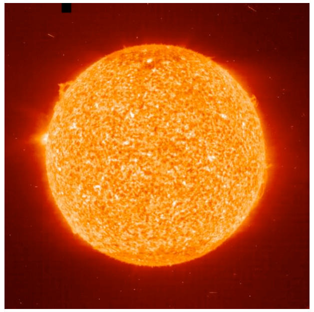
NSIs can lead to:

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

➔ redundancy

➔ interesting potential

New Physics: Neutrino Sources



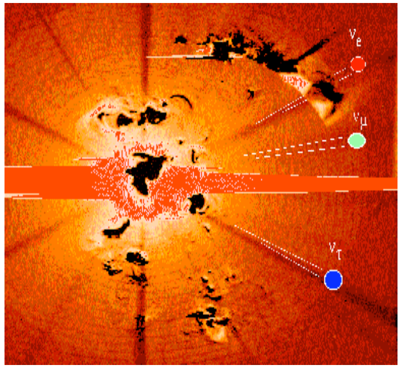
←Sun

Astronomy: →

Supernovae

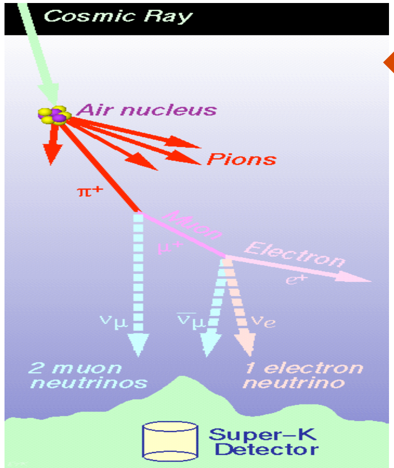
GRBs

UHE ν's



←Cosmology

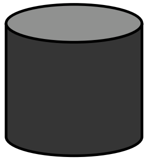
Reactors→



←Atmosphere

Accelerators→

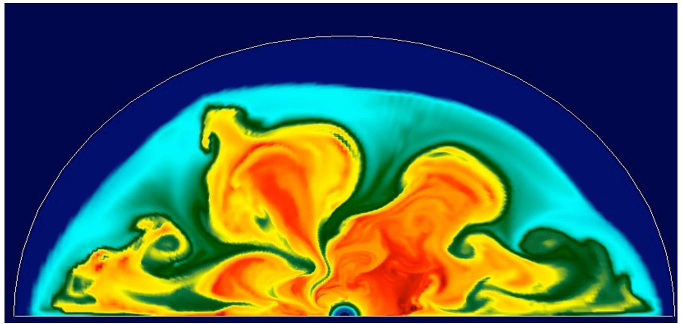
β-Sources→

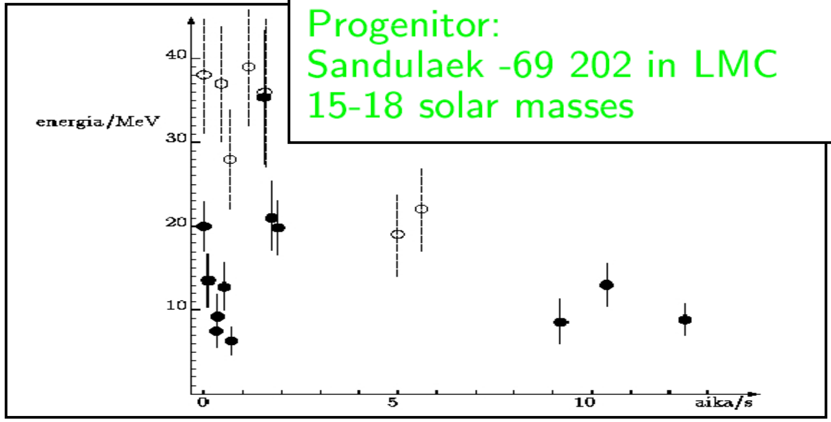


←Earth

Supernova Neutrinos

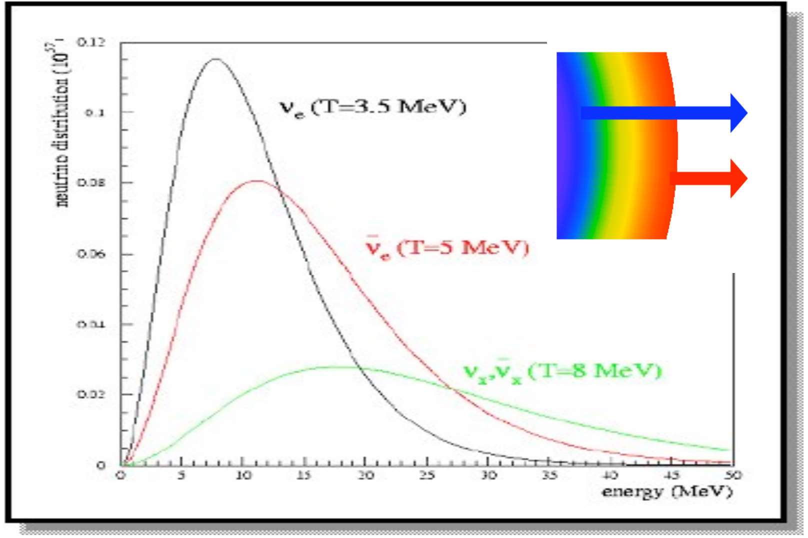
- Collaps of a typical star ➔ ~10^{57} ν‘s
- ~99% of the energy in ν‘s
- ν‘s essential for explosion
- 3d simulations do not explode (so far... 2d➔3d, ➔convection? ...)





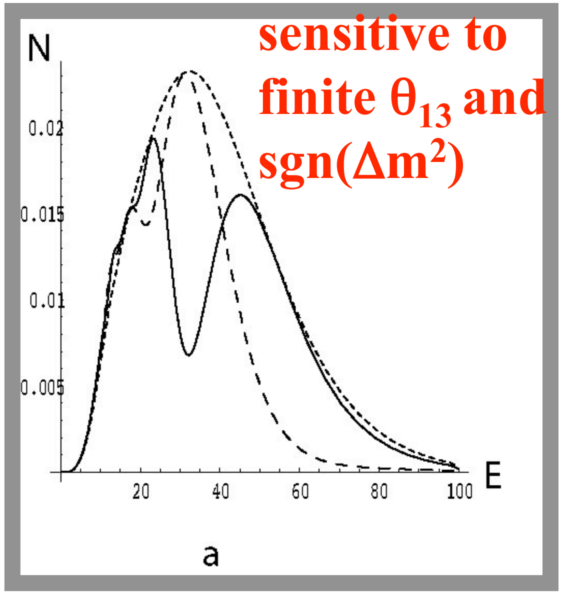
SN1987A neutrino burst

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



MSW: SN & Earth
non-linearity, ...

G. Sigl
C. Cardall
B. Dasgupta
A. Esteban

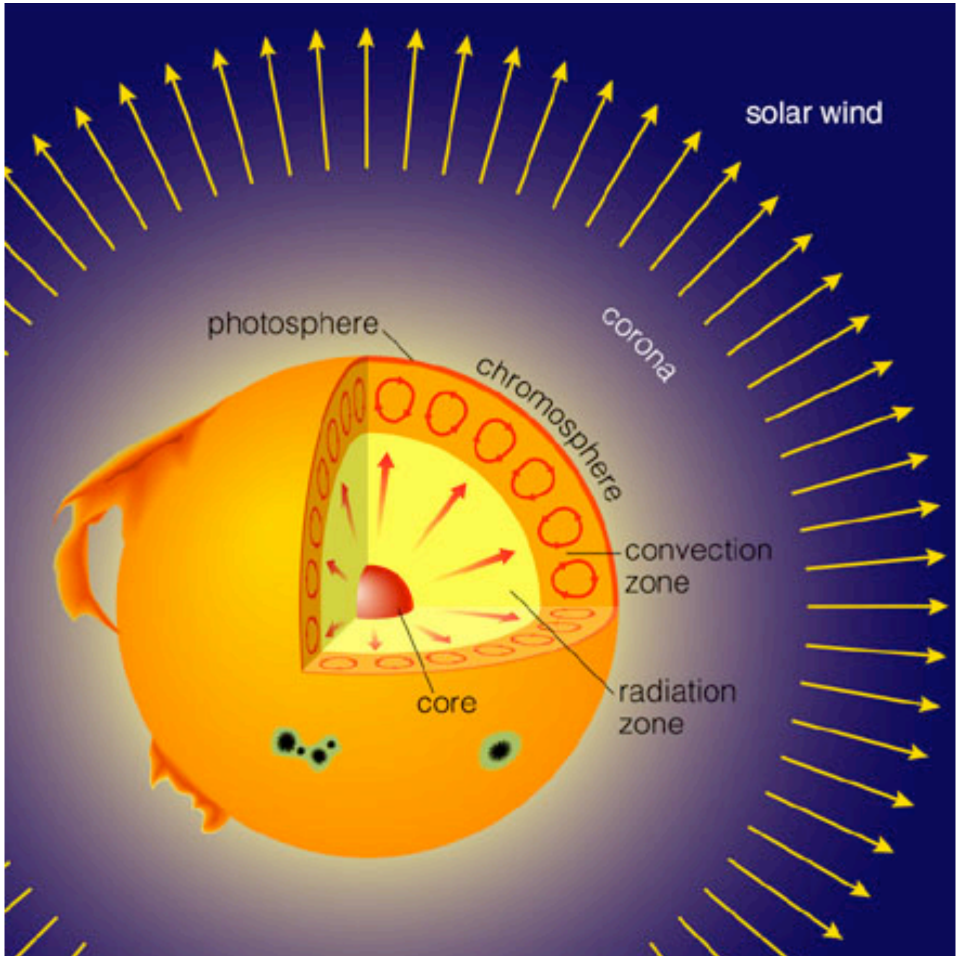


sensitive to finite θ_{13} and $\mathrm{sgn}(\Delta m^2)$

Solar Neutrinos: Learning About the Sun

Observables:

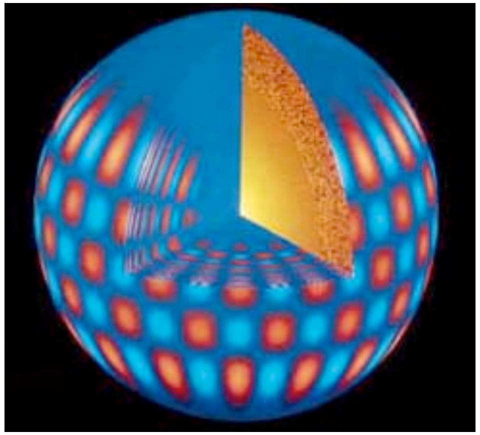
- **optical** (total energy, surface dynamics, sun-spots, historical records, B, ...)
- **neutrinos** (rates, spectrum, ...)



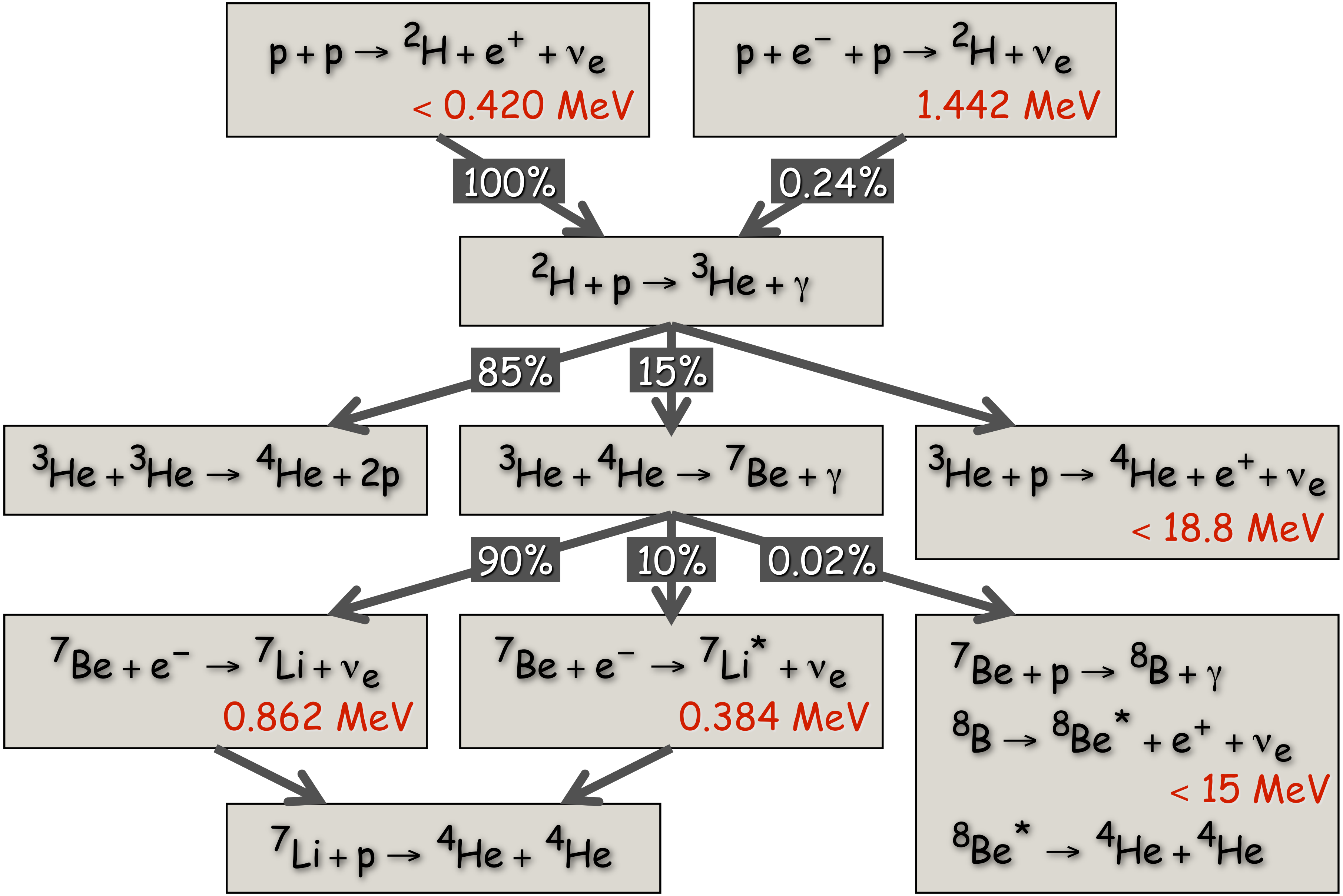
Topics:

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

➔ **recent debate about metallicitiy**



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

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

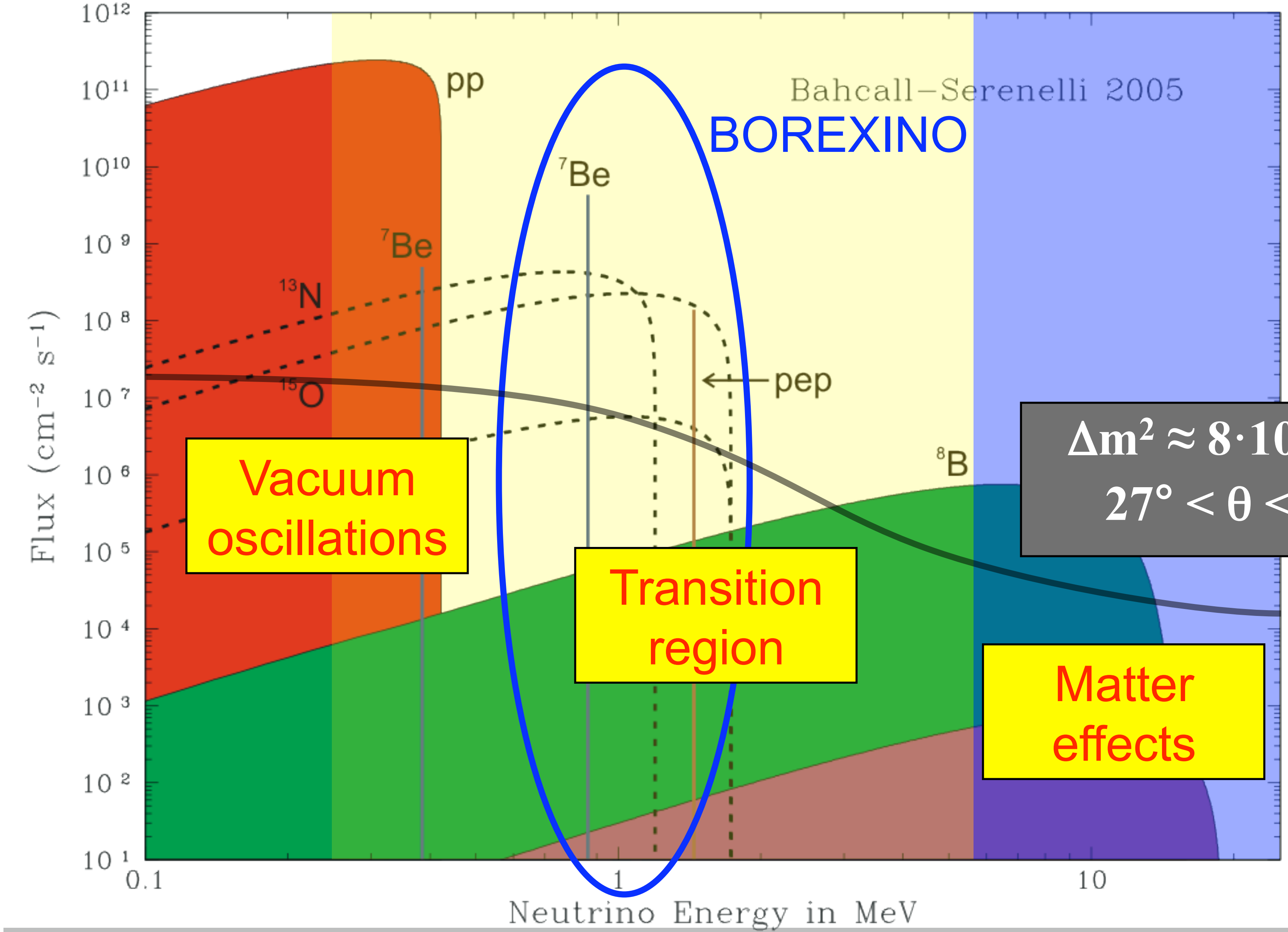
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

< 15 MeV

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

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

Solar Neutrino Spectroscopy



Vacuum oscillations

Transition region

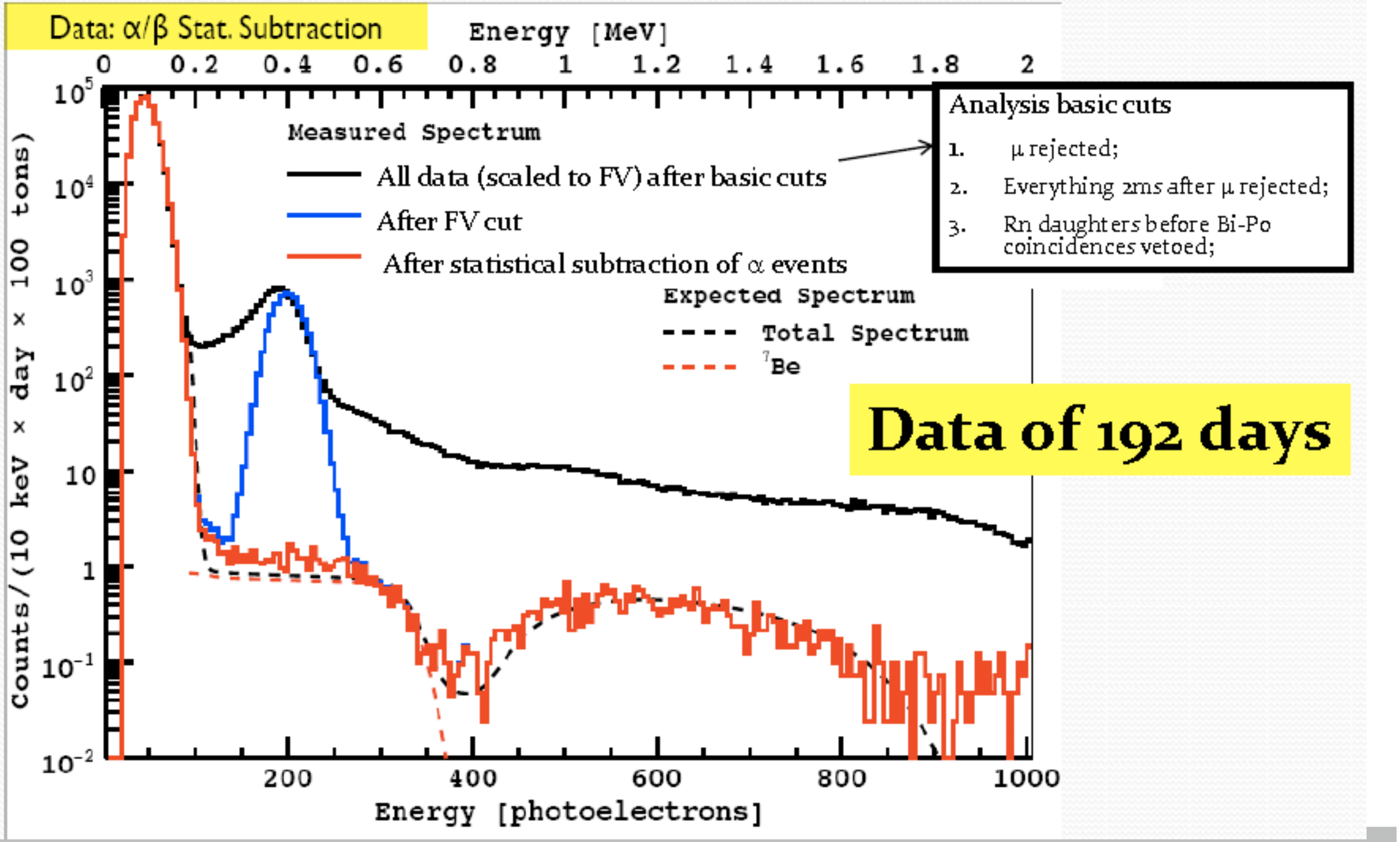
Matter effects

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

$27° < \theta < 38°$

Borexino Results

talks by L. Ludhova and D. Franco

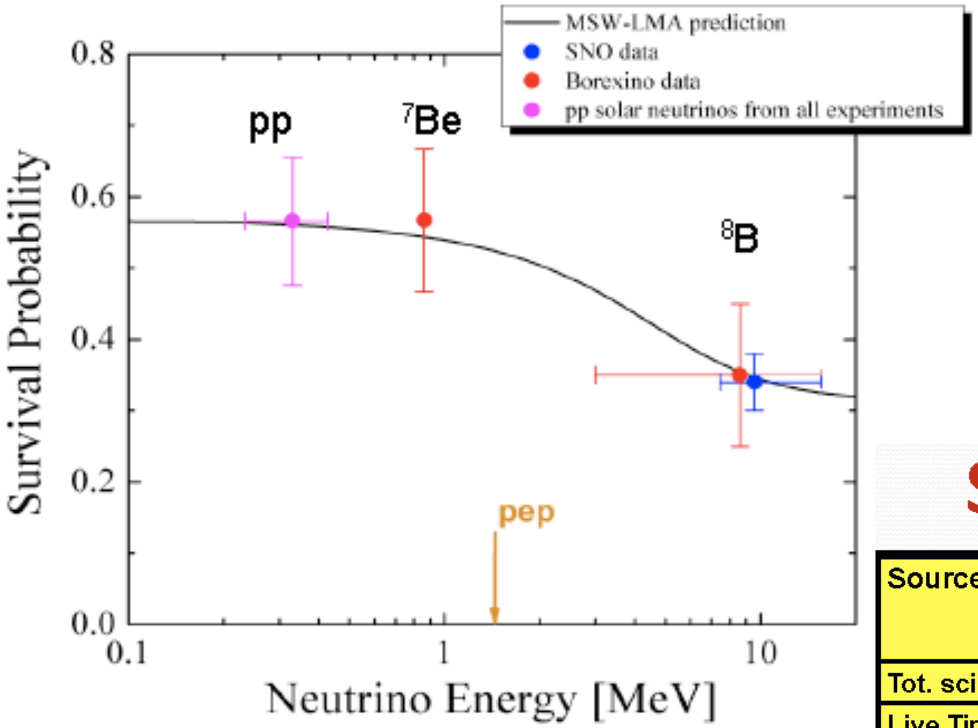


Analysis basic cuts

1. μ rejected;
2. Everything 2ms after μ rejected;
3. Rn daughters before Bi-Po coincidences vetoed;

Data of 192 days

Survival probability after Borexino



First simultaneous measurement in both vacuum-dominated and matter-enhanced regions

Assuming high-Z SSM (BPS 07) the ^{8}B rate measurement corresponds to

P_{ee} (^{8}Be) = 035   0.10 @ 8.6 MeV mean energy

Systematic uncertainties

Source	Syst.error (1σ)
Tot. scint. mass	0.2%
Live Time	0.1%
Efficiency of Cuts	0.3%
Detector Resp.Function	6%
Fiducial Mass	6%
TOT	8.5%

$49 \pm 3_{stat} \pm 4_{sys}$ cpd/100 tons

	Expected rate (cpd/100 t)
No oscillation	75 ± 4
BPS07(GS98) HighZ	48 ± 4
BPS07(AGS05) LowZ	44 ± 4

No-oscillation hypothesis rejected at 4σ level

Neutrino magnetic moment

SM with $m_\nu = 0$: $\mu_\nu = 0$

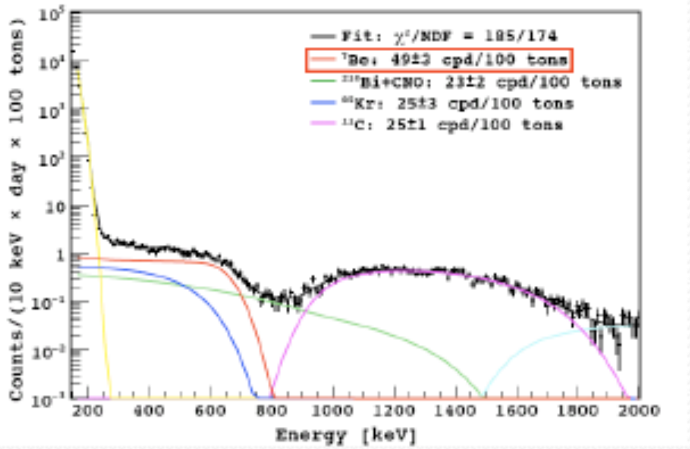
$$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2 + \left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

T – kinetic energy of scattered e
E_ν – neutrino energy

SM with $m_\nu > 0$: $\mu_\nu > 0$, additional EM term influencing the cross section and thus the spectral shape

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T} - \frac{T}{E_\nu}\right)$$

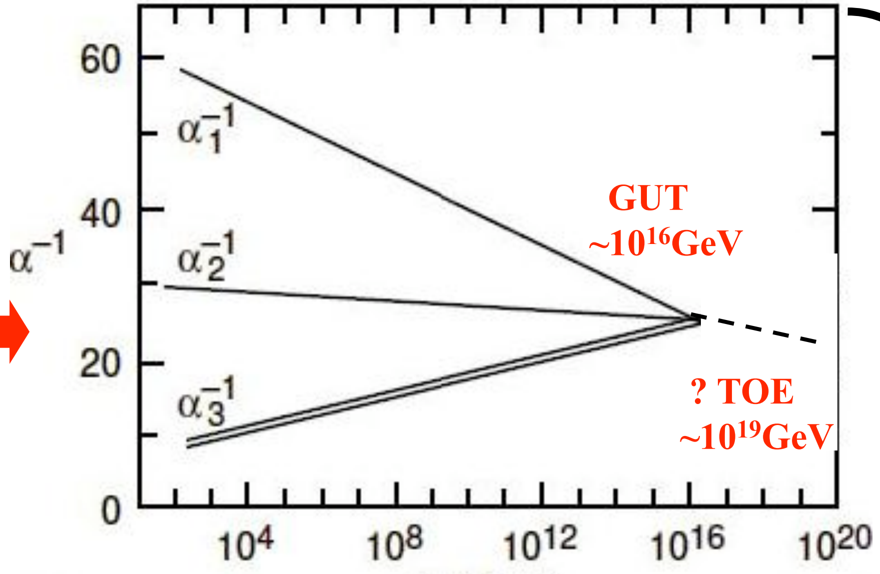
Sensitivity enhanced @ low energies



Estimate8	Method	90% C.L. 10^{-11} μ_B
SuperK	^{8}B above 5 MeV	< 11
Montanino *et al.*	^{7}Be (Borexino data)	< 8.4
GEMMA	Reactor anti-ν	< 5.8
Borexino	**^{7}Be**	**< 5.4**

Currently the best experimental limit!

Theory: Different Routes Beyond the SM



gauge bosons →

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

quarks leptons →

flavour problem: 3 generations
many parameters (m_i ,mixings)
unification into GUTs

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

experimental facts:

Dark Matter
Dark Energy
neutrino masses & mixings
baryon asymetry ←→ $m_\nu > 0$
➔ indirect tests of VHE physics

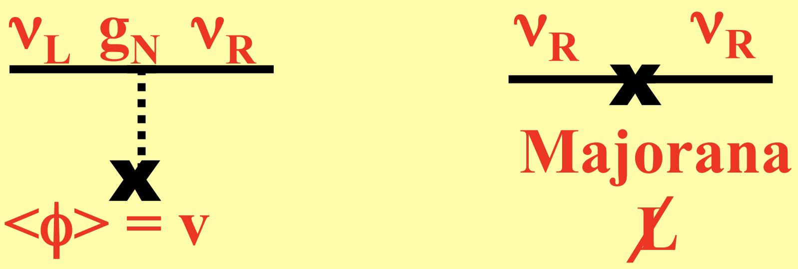
SUSY ~TeV

~Λ_{GUT} +seesaw

astrophysics & cosmology

Adding Neutrino Mass Terms

1) Simplest possibility: add 3 right handed neutrino fields



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

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

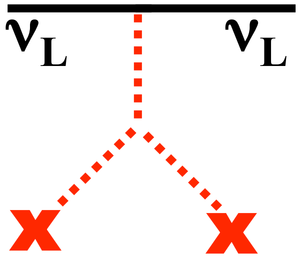
New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

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:

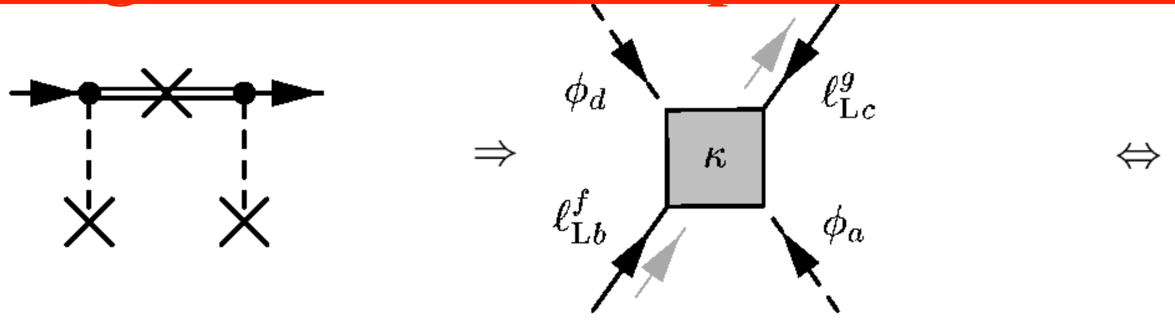
→ $M_L \overline{L} L^c$

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

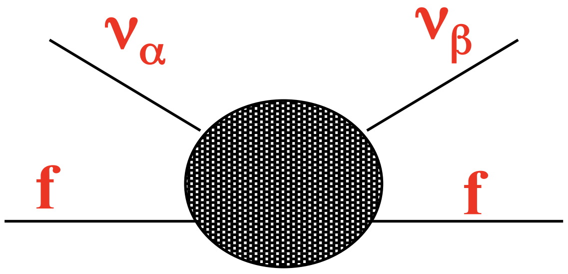
➔ effects beyond 3 flavours

➔ 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)

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



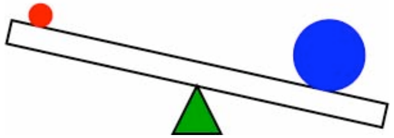
Suggestive Seesaw Features

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:

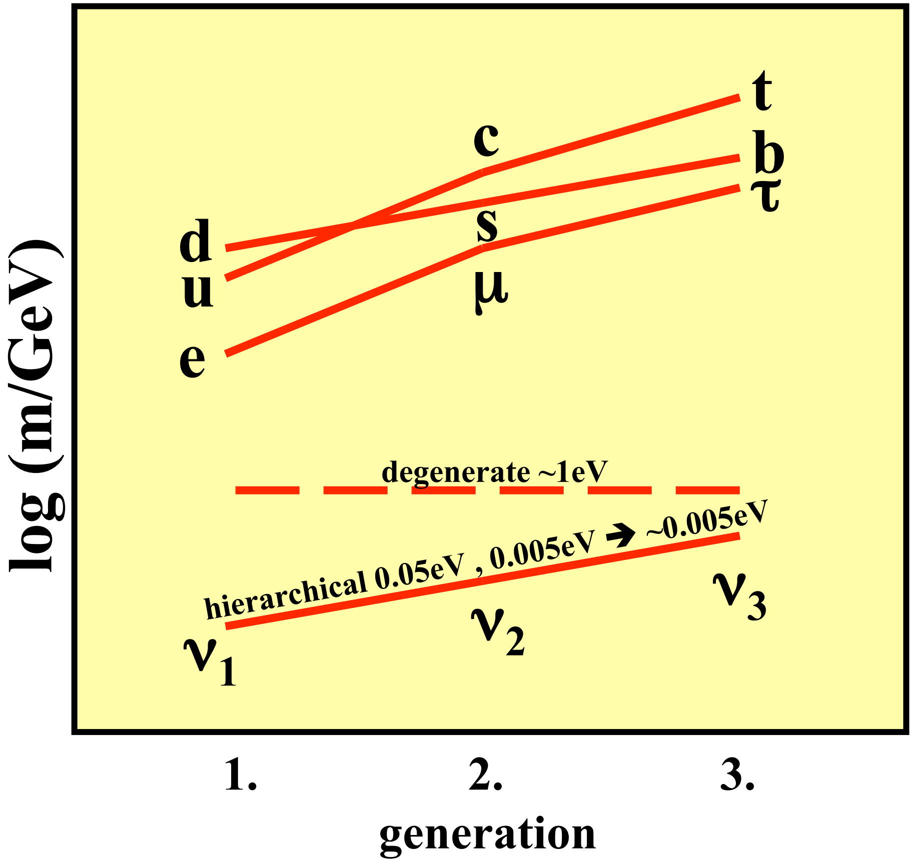
For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim$ leptons → $M_R \sim 10^{11} - 10^{16}$GeV

→ 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:

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

$$\updownarrow \qquad \updownarrow \qquad \updownarrow \qquad \updownarrow$$

H $\quad \simeq 10 \quad \geq 20 \quad ? \quad \geq 20$

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

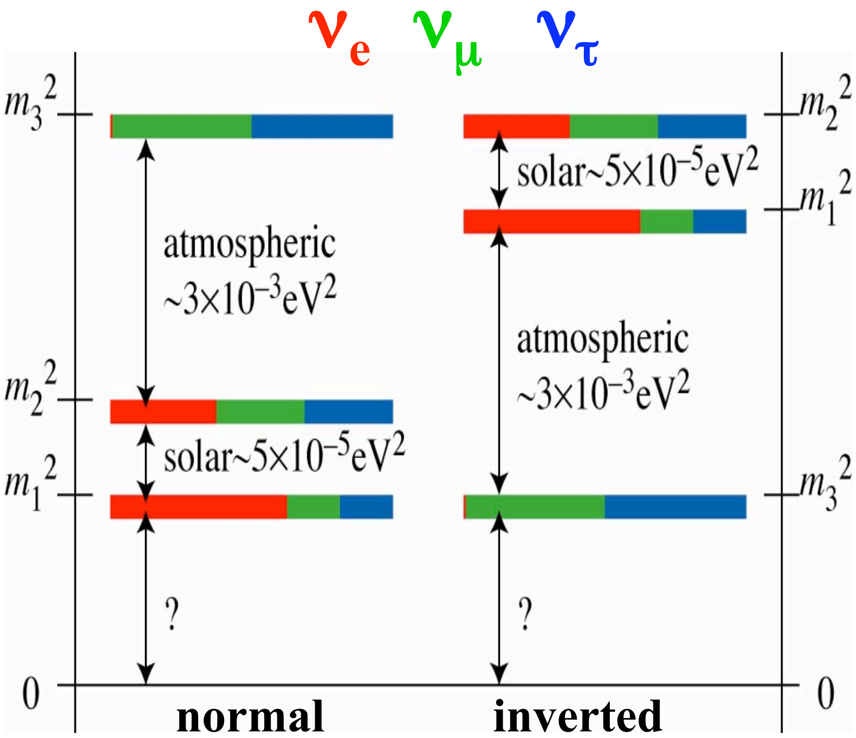
Parameters for 3 Light Neutrinos

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

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

questions:

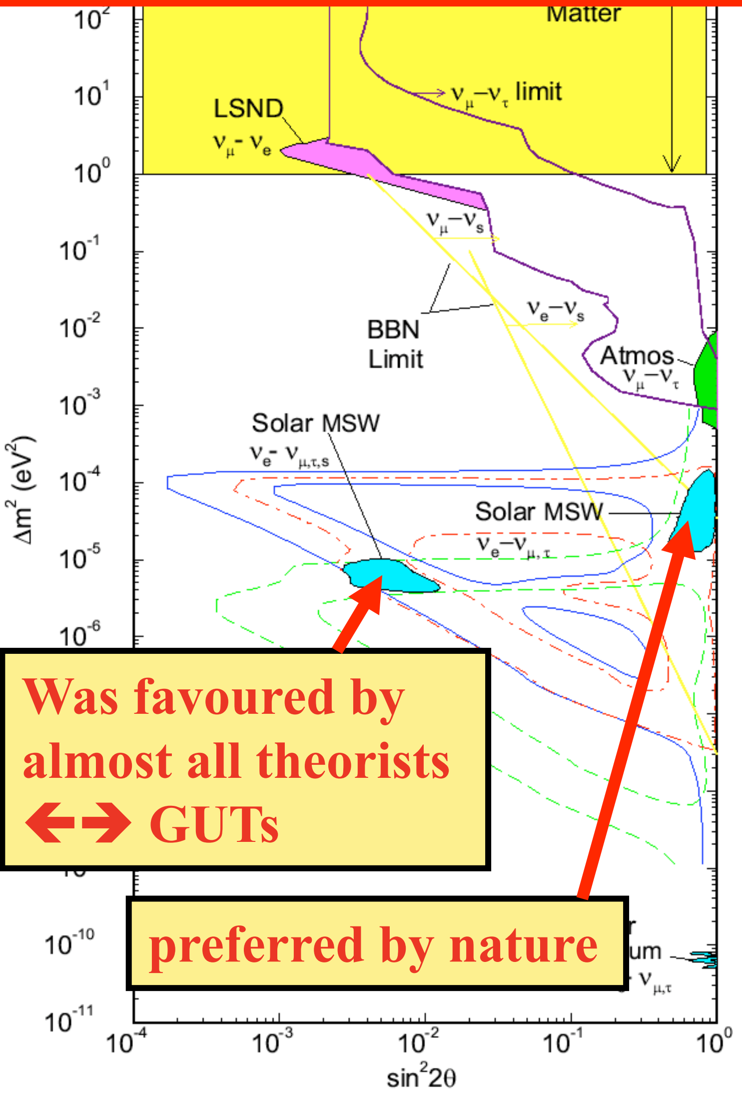
- ➔ Dirac / Majorana
- ➔ mass scale: m_1
- ➔ mass ordering: $\mathrm{sgn}(\Delta m^2_{31})$
- ➔ how small is θ_{13}, θ_{23} maximal?
- ➔ leptonic CP violation
- ➔ 3 flavour unitarity?
- ➔ why 3 generations, d=4, gauge group, …



hierarchical or degenerate

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

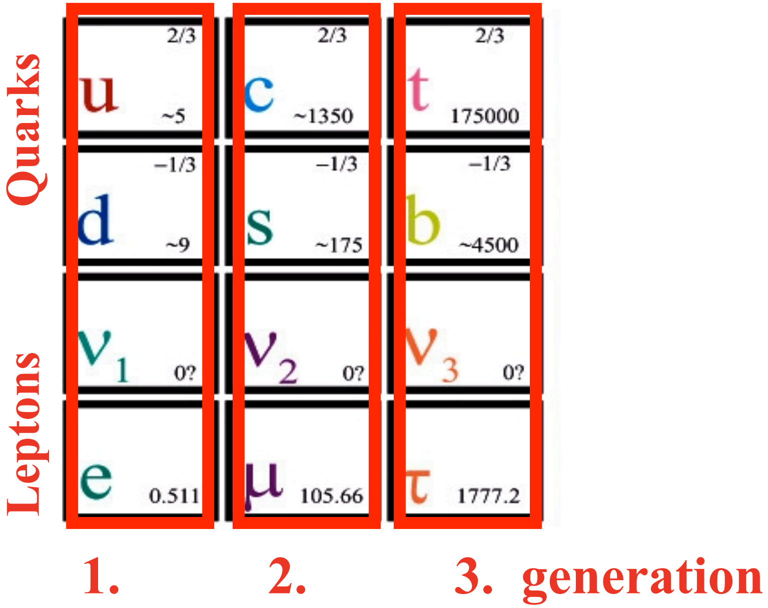
what if θ_{13} is very tiny?
or if θ_{23} is very close to maximal?

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

➔ answered by coming precision

The larger Picture: GUTs

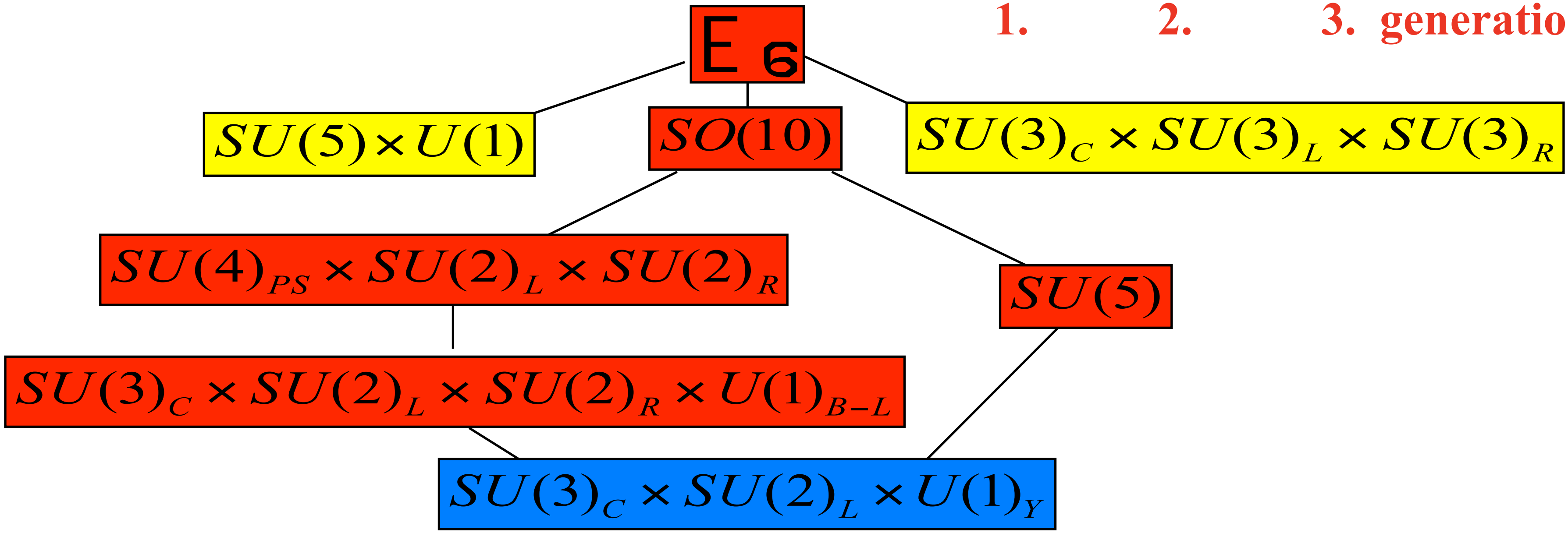
Gauge unification suggests that some GUT exists



	1.	2.	3. generation
Quarks	u 2/3 ~5	c 2/3 ~1350	t 2/3 175000
Quarks	d −1/3 ~9	s −1/3 ~175	b −1/3 ~4500
Leptons	ν_1 0?	ν_2 0?	ν_3 0?
Leptons	e 0.511	μ 105.66	τ 1777.2

Requirements:

gauge unification
particle multiplets ←→ ν_R
proton decay
…



E_6

$SU(5)\times U(1)$

$SO(10)$

$SU(3)_C\times SU(3)_L\times SU(3)_R$

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

$SU(5)$

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

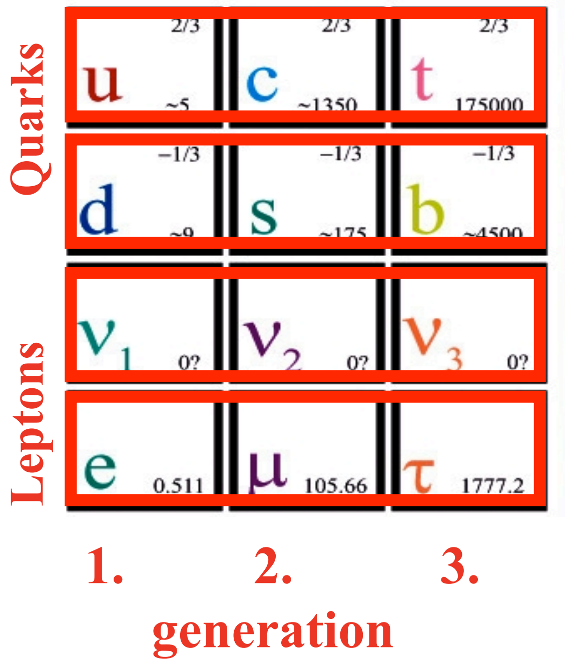
$SU(3)_C\times SU(2)_L\times U(1)_Y$

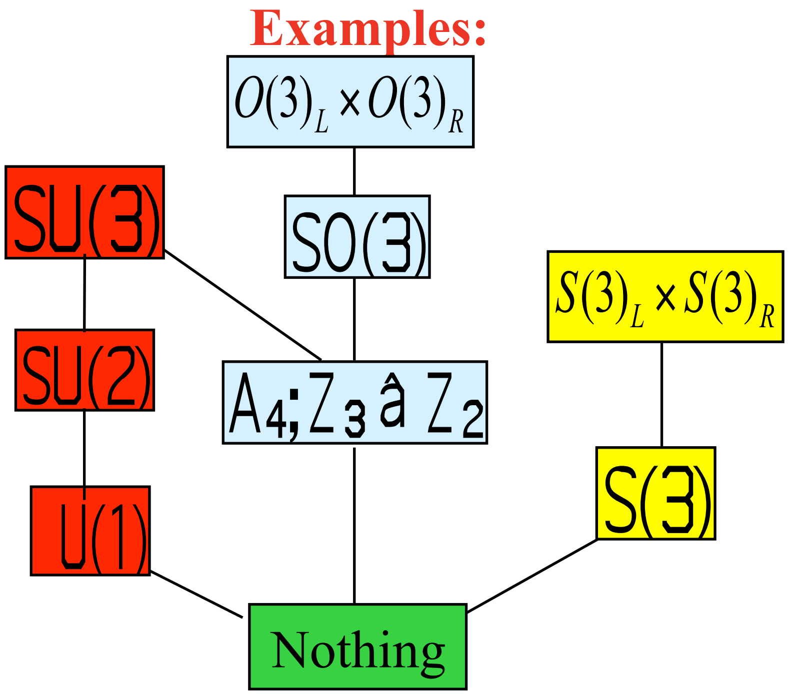
Flavour Unification

- 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





See talks by:

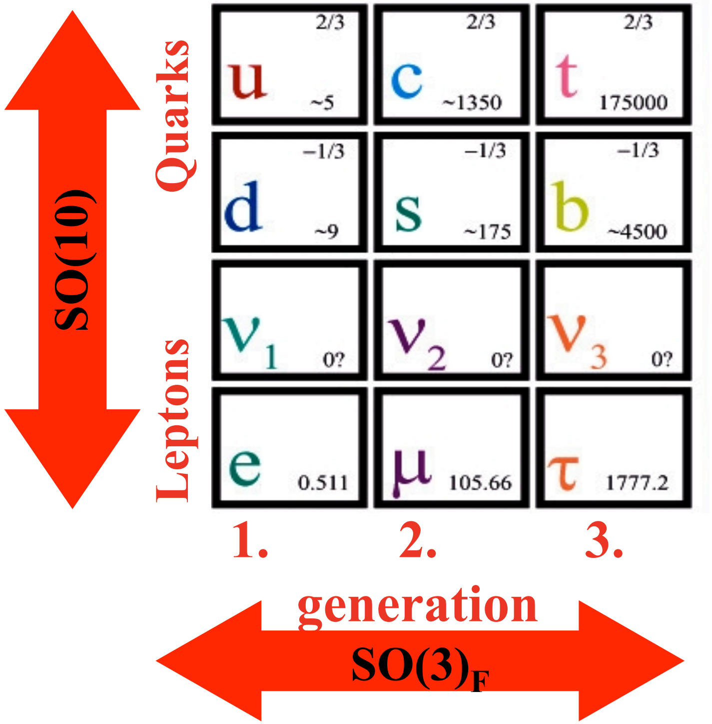
M.-C. Chen

A. Romanino

W. Rodejohann

L. Merlo

GUT x Flavour Unification



➔ GUT group x flavour group

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

- 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 x flavour is rather restricted

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

➔ so far only a few viable models (without supersymmetry)
rather limited number of possibilities; phenomenological success non-trivial

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

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 scattering
- cross sections (G. Co)
- 3 neutrino unitarity & sterile neutrinos (D. Meloni)
- neutrino decay (admixture…)
- Geophysics via oscillograms (E. Akhmedov)
- electromagnetic properties (A. Studenikin)
- NSI (T. Ota, T. Rashba, M. Cirelli)
- MaVaN scenarios (M. Lattanzi), unparticles (R. Zukanovich)

→ synergies with LHC and LFV (A. de Gouvea, F. Joaquium)

Guessing the Future

Status quo: neutrino revolution ➔ consolidation

- check and improve knowledge ←→ potential for surprises
- slowdown due to larger / more complex experiments
  ➔ dinosaurs & mutations
  ➔ scale known technologies (with required R&D)
  ➔ look for new ideas
    - GSI anomaly → not due to ν-mixing (C. Giunti) (if real…)
    - Moessbauer neutrinos (S. Parke) (very difficult but…)
    - relic neutrino detection (A. Cocco)
    - ν-masses from cosmological 21cm observation (J. Pritchard)

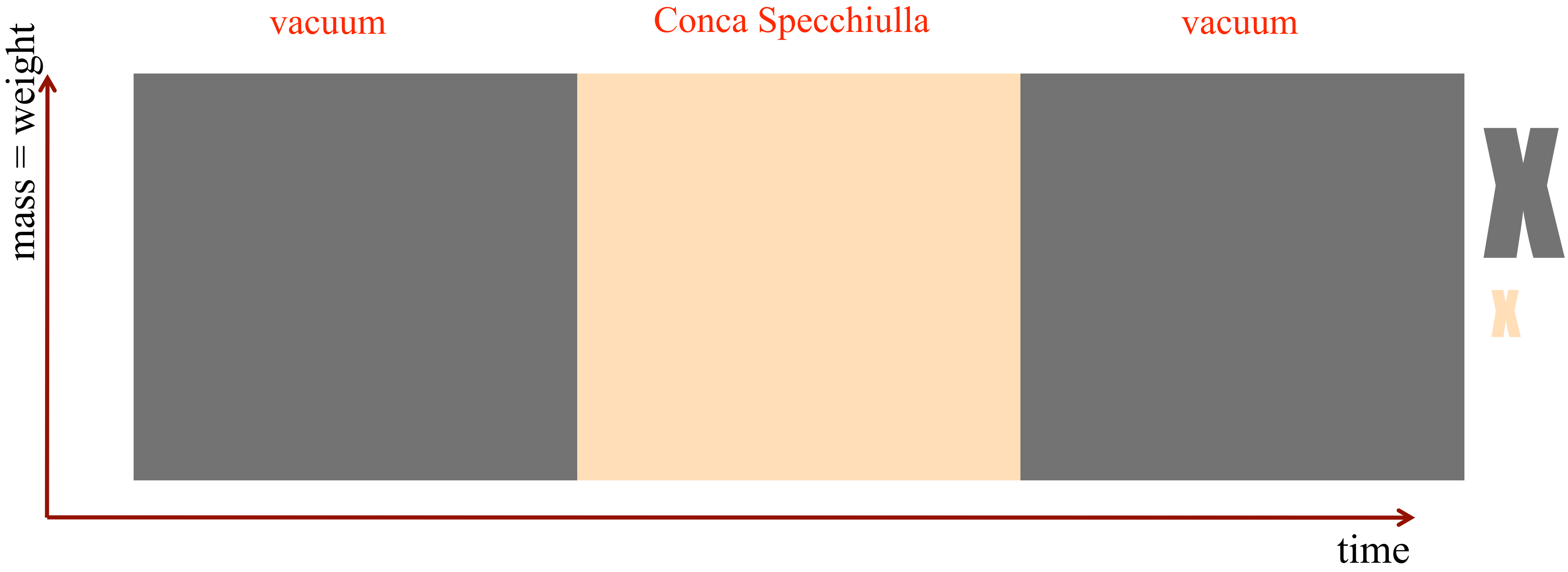
- additional promising areas: LHC, LFV, astroparticle/cosmology
  ➔ interesting by themselves & important theoretical interplay

Other Topics (apoligies)

- Neutrino telescopes (T. Montaruli, U. Katz, J.L. Bazo, E. Presani)
- Geoneutrinos (S. Dye)
- CMB in the light of Planck (P. de Bernardis)
- Dark Matter (N. Fornengo, F. Cafagna)
- HECR and UHECR (V. Berezinsky, L.Nellen, F. Villante, N. Busca, J. Matthews, E. Carmona, P. Serpico, R. Tomas, K.H. Kampert, D. Allard, N. Giglietto)
- Axions (A. Mirizzi)

The N.O.W. Effect

(invented by G. Fogli; assumes only an average physicist “X”)



- effect was seen in all runs (2000, 2004, 2006, evidence in 2008)
- high statistics ➔ 6.3 sigma effect
- safe (no black holes or other damages) ➔ can (should be) be repeated

Thanks to

- Gianluigi Fogli
- Eligio Lisi and all other co-organizers
- session convenors
- E. Forini for his nice special talk
- hotel & staff

We look forward to NOW 2010!