Workshop Summary

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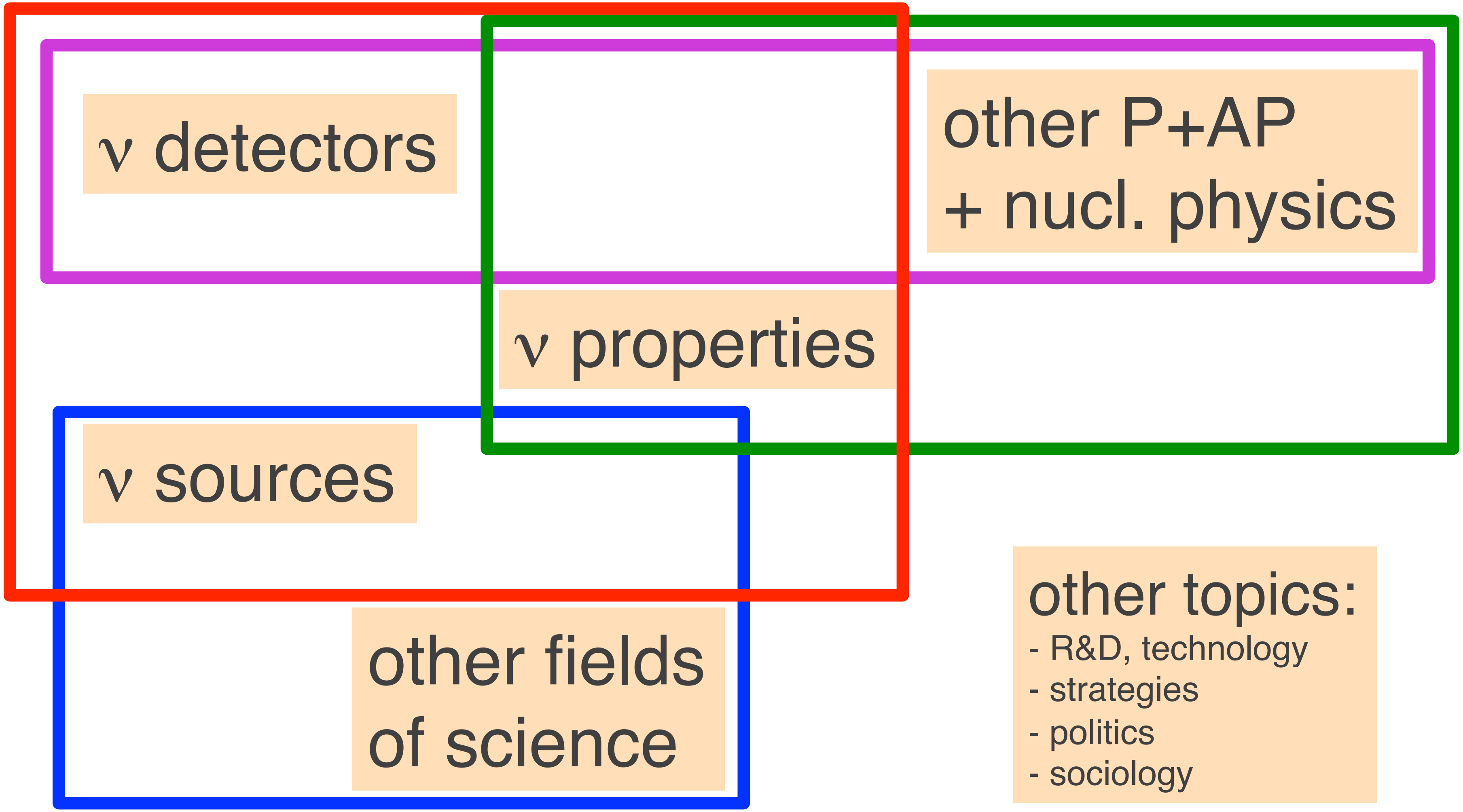
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
35th Course
Neutrino Physics: Present and Future
Erice-Sicily: September 16-24, 2013

Contents

We had O(60) interesting talks which covered many aspects…
number of slides 25-65(!) → O(2000) slides … many other things



ν detectors

other P+AP
+ nucl. physics

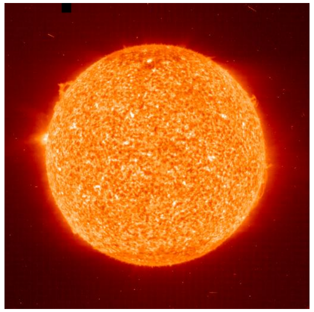
ν properties

ν sources

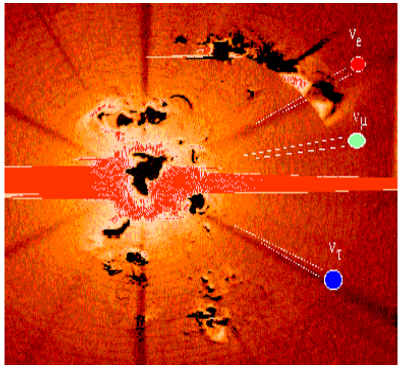
other fields
of science

other topics:
- R&D, technology
- strategies
- politics
- sociology

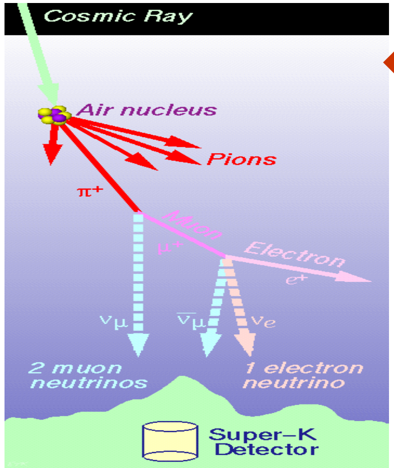
Sources & other Fields of Science



← **Sun**



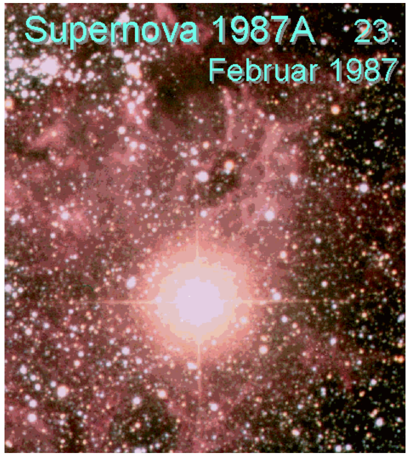
← **Cosmology**



← **Atmosphere**

← **Earth**

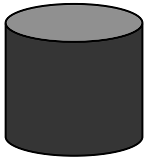
Astronomy: →
Supernovae
GRBs
UHE ν's



Reactors →

Accelerators →

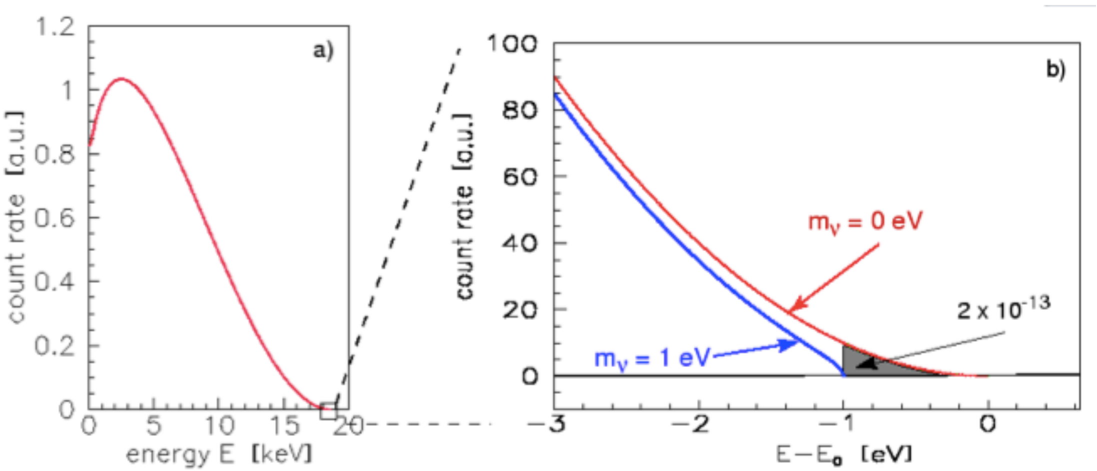
β-Sources →



Four Methods of ν-Parameter Determination

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

Kinematical Mass Determination



decays where:
- mass effect is enhanced
- clean kinematics

$$E^2 = p^2 + m^2; \;\; \sum p_i^\mu = \sum p_f^\mu$$

Endpoint of decays:

Tritium $\rightarrow He^3 + e^- + \overline{\nu}_e$

Bounds:

“Elektron-Neutrino”: $m < 2.2$ eV (Mainz, Troitsk)
“Muon-Neutrino”: $m < 170$ keV
“Tau-Neutrino”: $m < 15.5$ MeV

Sensitivity ⇔ degenerate ν-spectrum

⇒ **Oscillations:** $\Delta m_{ij}^2 \ll m_i^2 \Rightarrow$ $\boxed{\sum m_i^2 |U_{ei}|^2 < (2.2\ \text{eV})^2}$

robust towards new physics!

Weinheimer

Including electronic excited final states of excitation energy V_j with probability W_j

$$W_j = |\langle\Psi_0|\Psi_{f,j}\rangle|^2$$

⇒ **electronic final states are important**

Using $\varepsilon_j = E_0 - \boxed{V_j} - E$

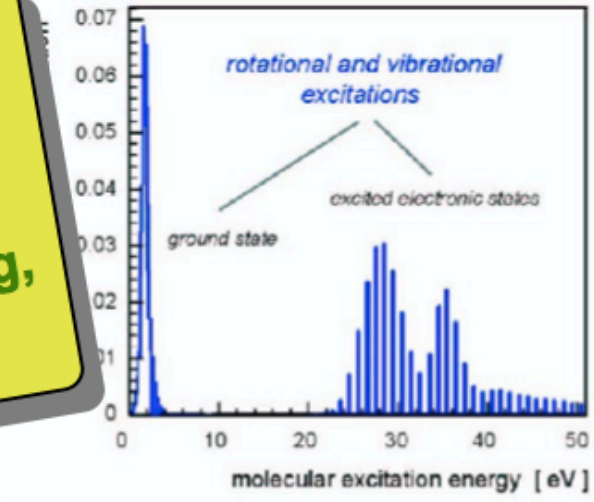
$$\frac{d^2N}{dt\,dE} = A\cdot F(E,Z+1)\cdot p\cdot(E+m)\cdot\sum_j \boxed{W_j}\,\varepsilon_j\cdot\sqrt{\varepsilon_j{}^2 - m^2(\nu_c)}\cdot\Theta(\varepsilon_j - m(\nu_c))$$

The electron spectrum coming out of a β-source is even more complicate due to inelastic scattering, backscattering. ...

Final states c

A. Saenz et al. P

N. Doss et al., P



Including neutrino mixing

$$\frac{d^2N}{dt\,dE} = A\cdot F(E,Z$$

$$\cdot\sum_j W_j\cdot\varepsilon_j\cdot\left(\sum_i \boxed{|U_{ci}|^2}\,\sqrt{\varepsilon_j{}^2 - \boxed{m^2(\nu_i)}}\cdot\Theta(\varepsilon_j - m(\nu_i))\right)$$

⇒ "Electron neutrino mass"

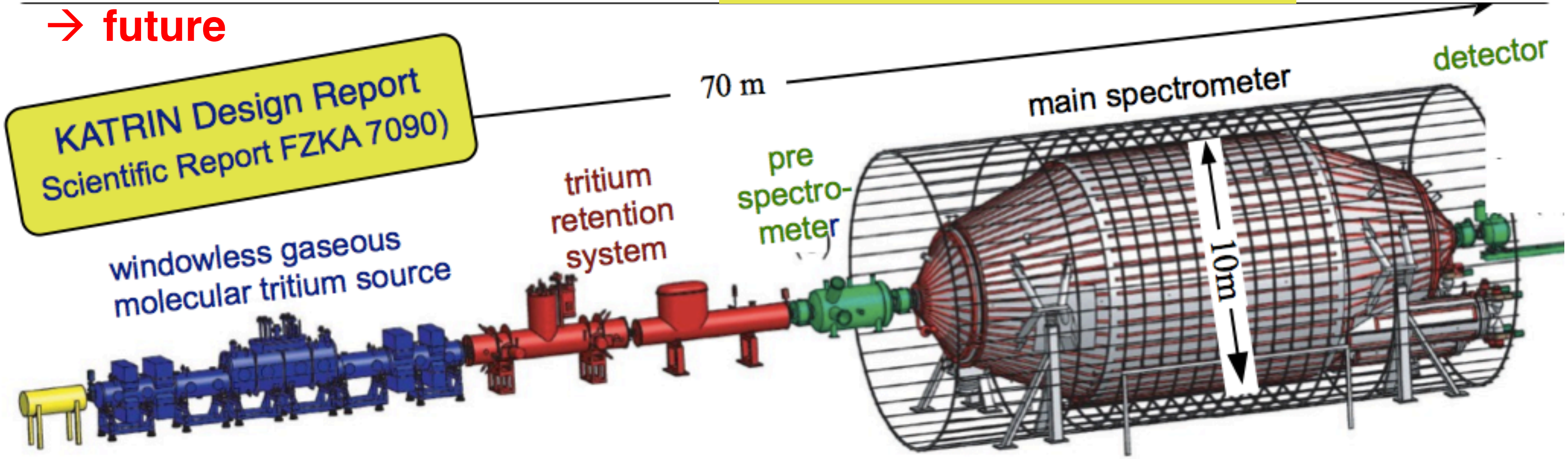
$$m^2(\nu_c) := \sum_i |U_{ci}|^2\cdot m^2(\nu_i)$$

⇒ **the different $m(\nu_i)$ are not important at present precision** now:

Mainz: $m(\nu) < 2.3$ eV (95% C.L.)

Troitsk: $m_\beta < 2.05$ eV, 95% CL

→ **future**



Weinheimer
Wandkowsky, Fischer
on-going work…
…challenging, but good progress →

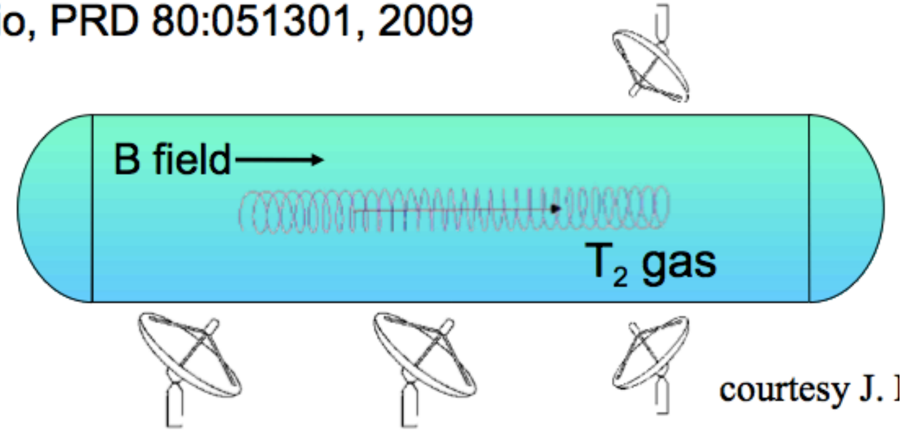
potential improvements:
TOF, … ←→…technological limits

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

discovery potential:
$m_\nu = 0.3$eV (3σ)
$m_\nu = 0.35$eV (5σ)

Other ideas:

B. Monreal and J. Formaggio, PRD 80:051301, 2009



courtesy J.

PROJECT-8

General idea:

cyclotron radiation detection

Cryobolometers: β-decay in absorber

MIBETA

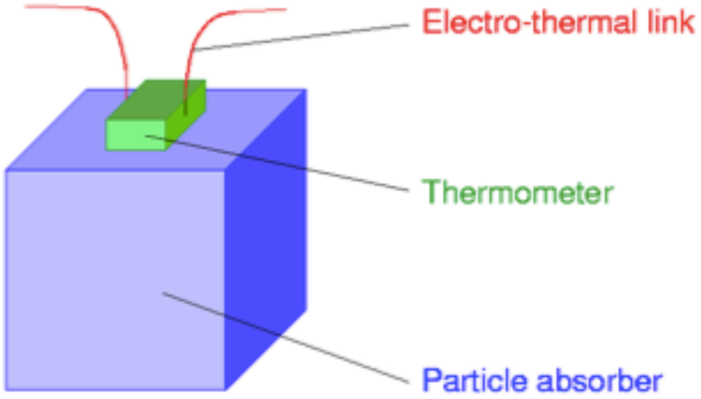
MANU

MARE-1

MARE-2

^{187}Re β-decay

advantages & challenges



$\Delta T = \Delta E / C$

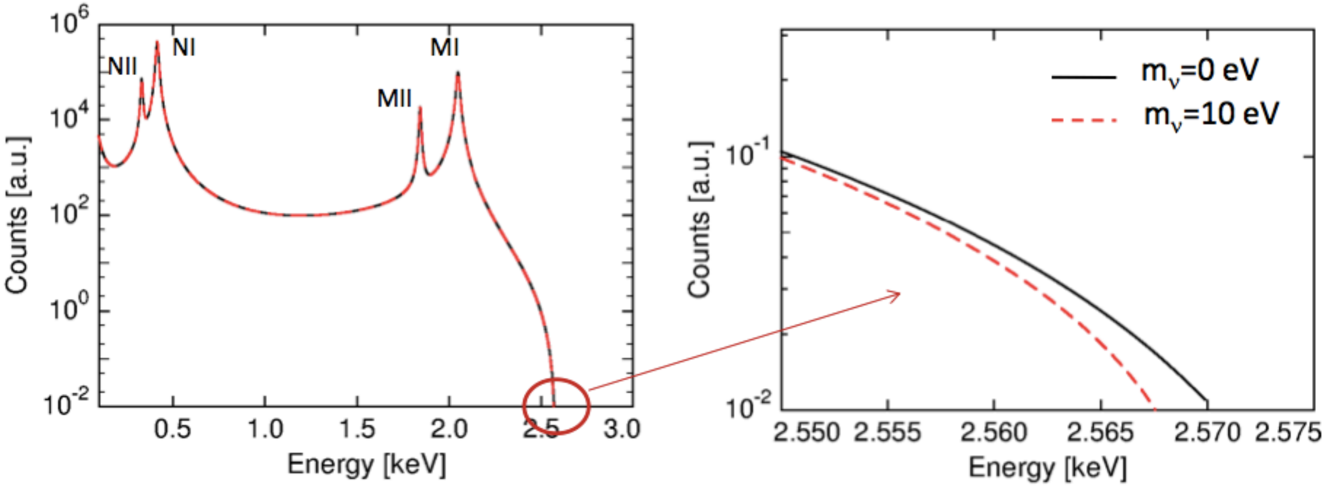
Debye:

$C \sim T^3$

ECHO:
Gestaldo ; Chung-On Ranitzsch

$$^{163}_{67}\mathrm{Ho}\rightarrow{}^{163}_{66}\mathrm{Dy}^{*}+\nu_{e}$$

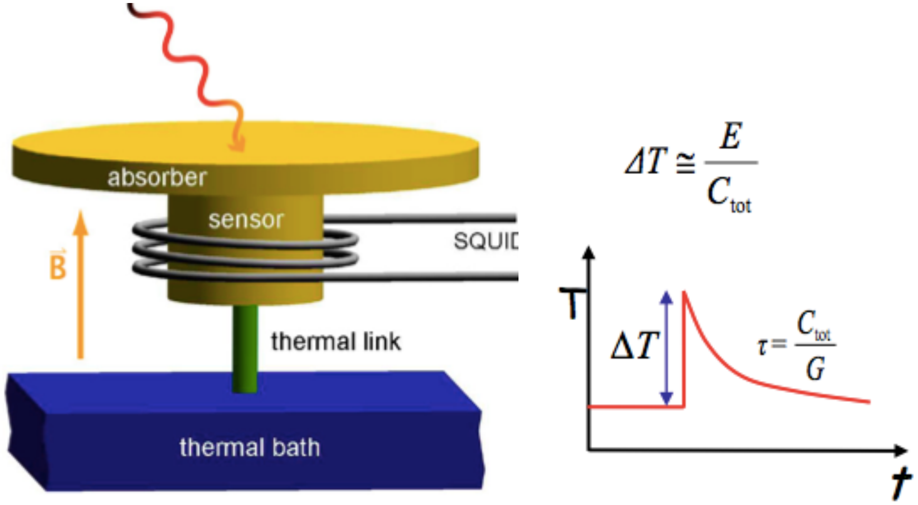
$$^{163}_{66}\mathrm{Dy}^{*}\rightarrow{}^{163}_{66}\mathrm{Dy}+E_{C}$$



Low temperature Metallic
Magnetic Calorimeters (MMC)

competitive → $\geq 10^5$ detectors
feasible, promising, …challenging

←→ backgrounds

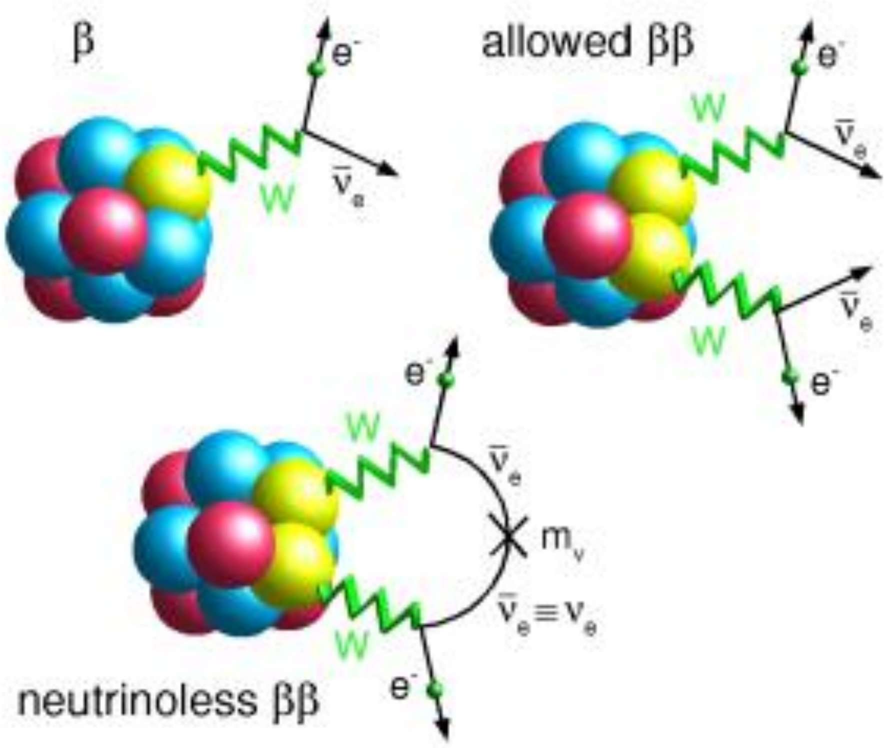


$$\Delta T \cong \frac{E}{C_{tot}}$$

Four Methods of Mass Determination

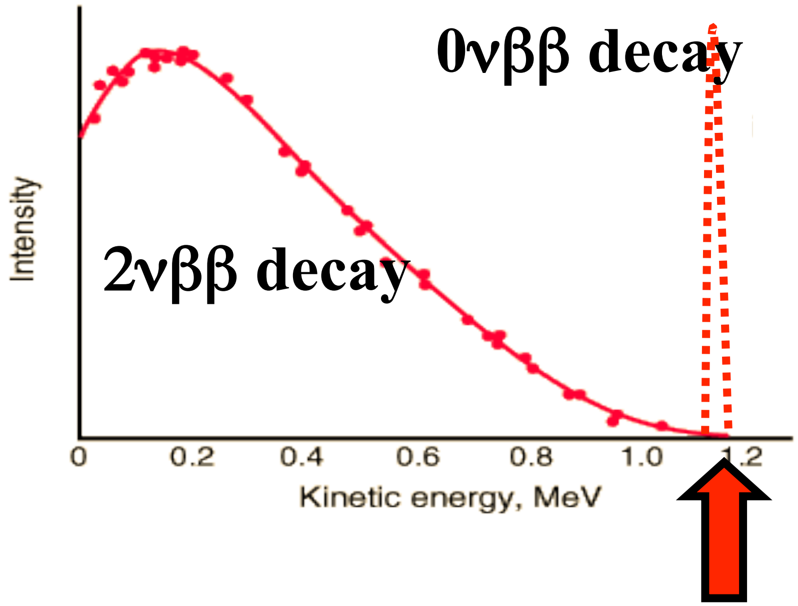
- kinematical
- lepton number violation
  ↔ Majorana nature
- astrophysics & cosmology
- oscillations

0νββ Decay Kinematics



2νββ decay of ^{76}Ge observed:

$\tau = 1.5 \times 10^{21}$ y



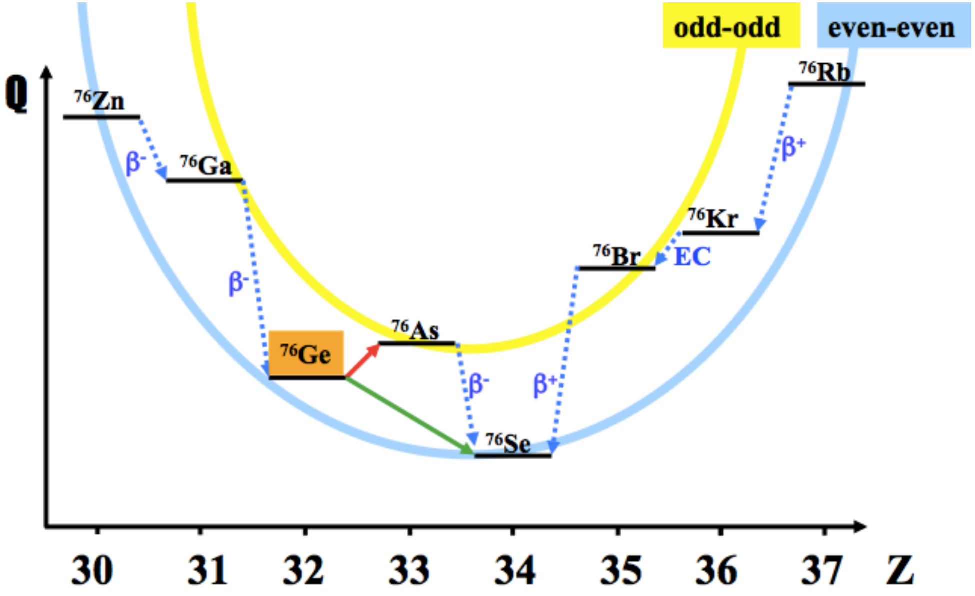
Majorana ν ➔ 0νββ decay

warning:

other lepton number violating processes…

- **signal at known Q-value**
- **backgrounds**
- **nuclear physics…**
  ➔ **use different nuclei**

0νββ Decay: Isotopes and Experiments



$Q_{\beta\beta}$

natural abundance

detector technology

NMEs …

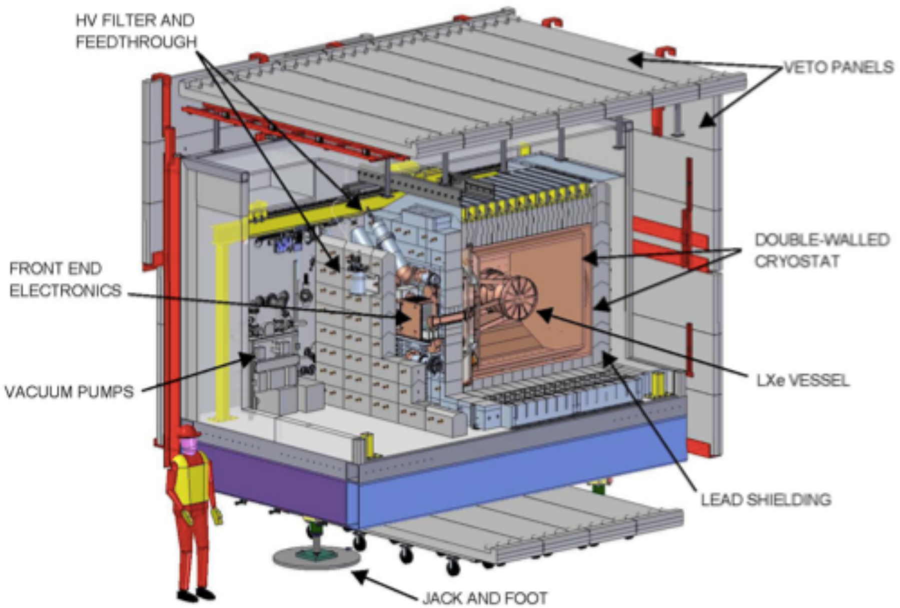
backgrounds

➔ we need 2 isotopes

$\beta\beta$-decay	$G^{0\nu}$ $[10^{-14}\,\mathrm{y}^{-1}]$	Q [keV]	nat. abund. [%]	experiments
$^{48}\mathrm{Ca} \to {}^{48}\mathrm{Ti}$	6.3	4273.7	0.187	CANDLES
$^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se}$	0.63	2039.1	7.8	GERDA, Majorana
$^{82}\mathrm{Se} \to {}^{82}\mathrm{Kr}$	2.7	2995.5	9.2	SuperNEMO, Lucifer
$^{100}\mathrm{Mo} \to {}^{100}\mathrm{Ru}$	4.4	3035.0	9.6	MOON, AMoRe
$^{116}\mathrm{Cd} \to {}^{116}\mathrm{Sn}$	4.6	2809	7.6	Cobra
$^{130}\mathrm{Te} \to {}^{130}\mathrm{Xe}$	4.1	2530.3	34.5	CUORE
$^{136}\mathrm{Xe} \to {}^{136}\mathrm{Ba}$	4.3	2461.9	8.9	EXO, KamLAND-Zen, NEXT, XMASS
$^{150}\mathrm{Nd} \to {}^{150}\mathrm{Sm}$	19.2	3367.3	5.6	SNO+, DCBA/MTD

0νββ Experimental Results: EXO

Piepke

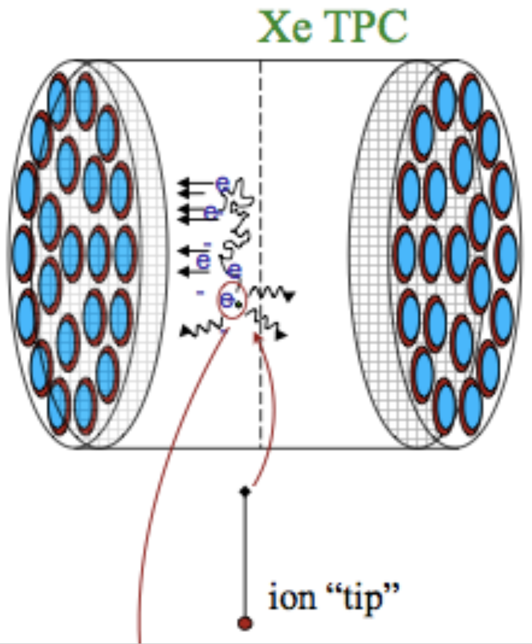


located @ WIPP, 1585 mwe
- Xe TPC
- use radio-pure materials
- calibration sources
- data taking since May 2011

detect the 2 electrons (ionization + scintillation in xenon detector)

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^- \, (+\, 2\nu_e)$$

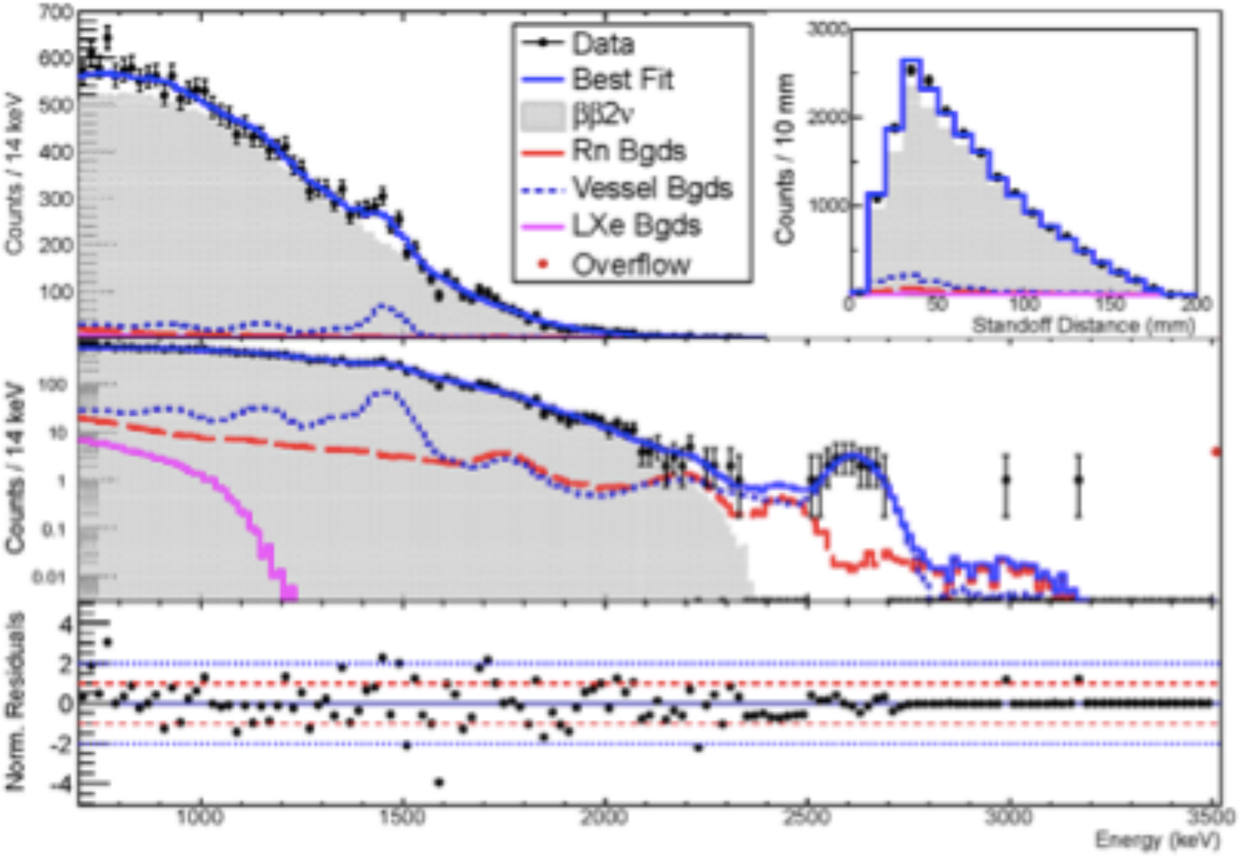
positively identify daughter via



χ^2 / ndf = 82.5 / 74.5

SS event set dominated by point-like β–events. Perform coupled MS and SS data fit to obtain:

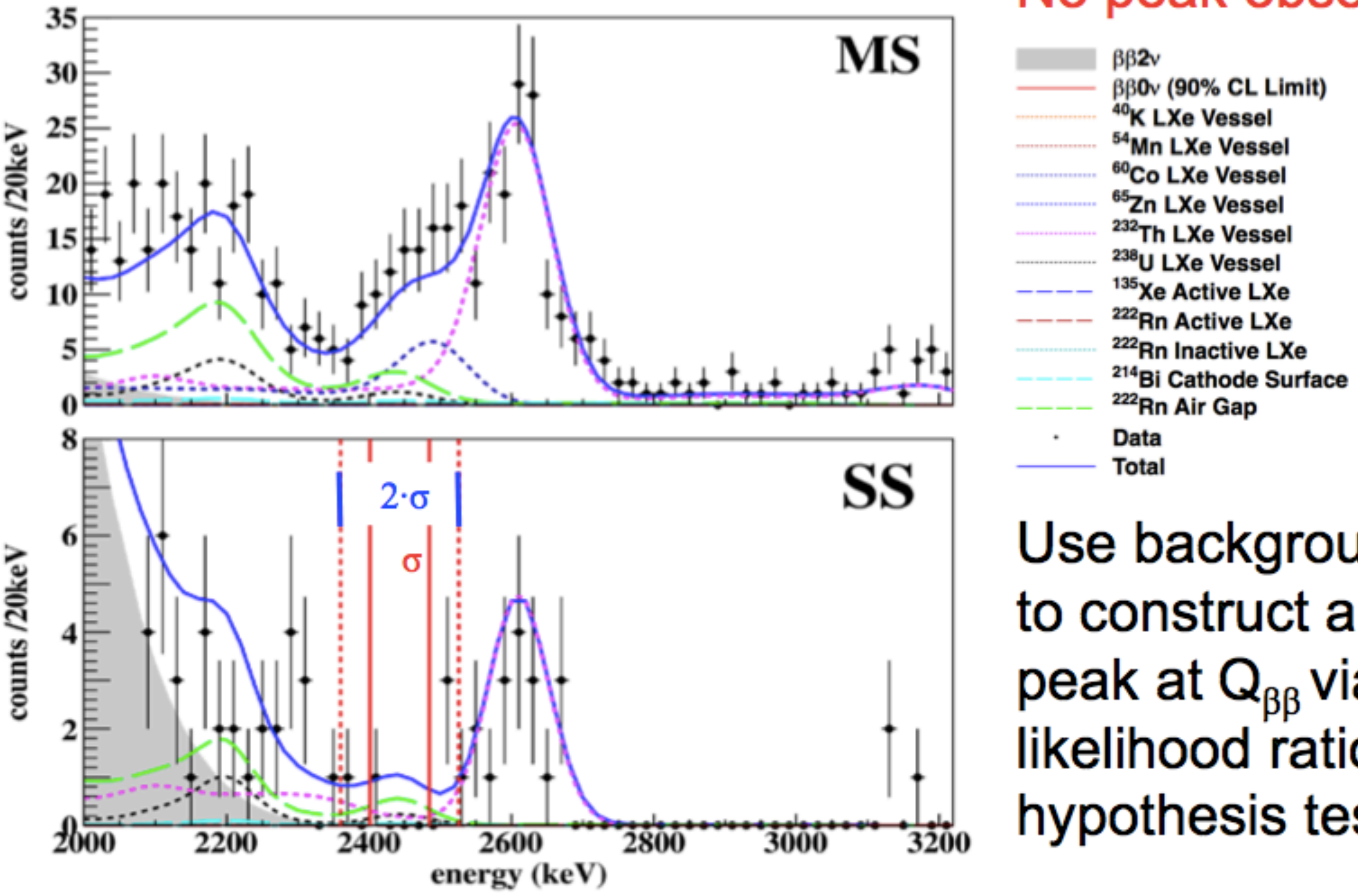
The longest and most precisely measured 2νββ–decay half life.



$$T_{1/2}^{2\nu\beta\beta} = \left(2.171 \pm 0.017^{stat} \pm 0.060^{syst}\right)\cdot 10^{21}\ \mathrm{yr}$$

Smallest and best known 2νββ–matrix element: 0.0217 0.0003 MeV^{-1}.

Low background data: around $Q_{\beta\beta}$



No peak observed at $Q_{\beta\beta}$.

Use background model to construct a limit for peak at $Q_{\beta\beta}$ via a likelihood ratio hypothesis test.

←→ very good understanding of small (!) backgrounds

Profile likelihood analysis takes into account the peak shape of 0νββ signal. More sensitive than window analysis.

We get at 90% CL: $\boxed{T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}\ yr}$

The longest ^{136}Xe 0νββ-decay limit comes from the KamLAND-Zen experiment: $>1.9 \cdot 10^{25}$ yr.

EXO-200 result translates into a Majorana ν mass limit range:

$\boxed{\langle m \rangle_{\beta\beta} < 140 - 380 \text{ meV}}$ [Auger et al., PRL 109 (2012) 032505]

Outlook:

- Continue data taking
- Demonstrate the technology for a next generation experiment. → nEXO

Run 1 (5/2011-7/2011, 31.36 d, 63 kg (of 110 kg active) Xe, *charge read-out only*): first observation of $2\nu\beta\beta$–decay of ^{136}Xe

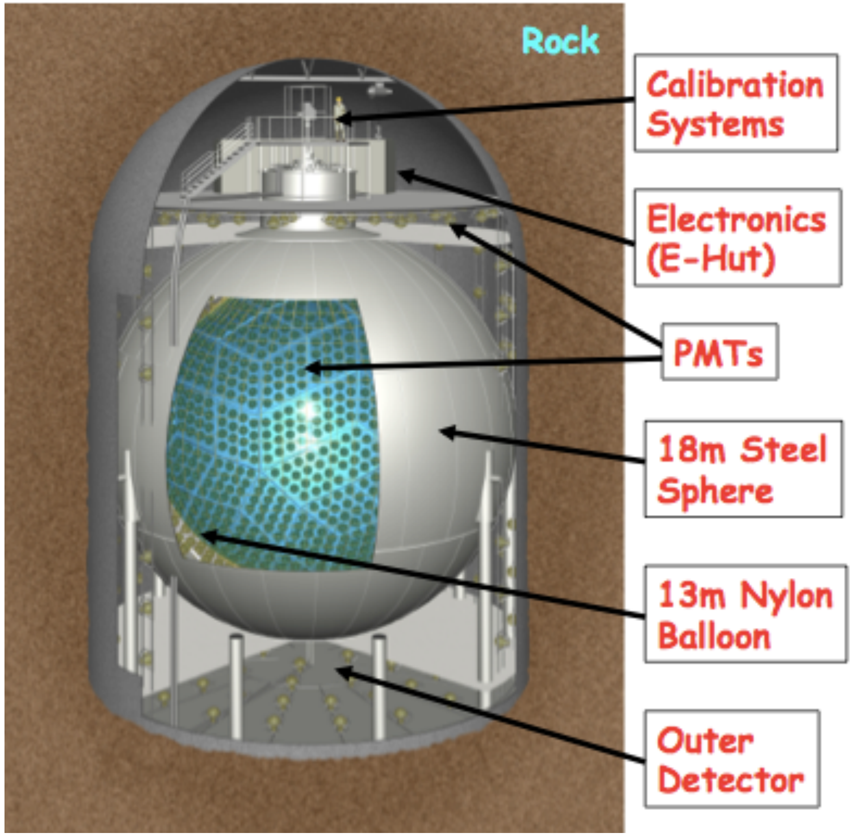
Run 2a (9/2011-4/2012, 120.69 d, 82.1 and 98.5 kg Xe): most accurate measurement of any $2\nu\beta\beta$–decay rate, one of most stringent limits on $0\nu\beta\beta$–decay (32.6 kg·yr) and Majorana neutrino mass, challenge of ^{76}Ge evidence.

Run 2 (9/2011-6/2013, 439.6 d, 97.7 kg Xe): 3.6 times exposure compared to 2012 data set. $0\nu\beta\beta$–analysis not finalized yet.

Run 3 (6/2013...): taking data

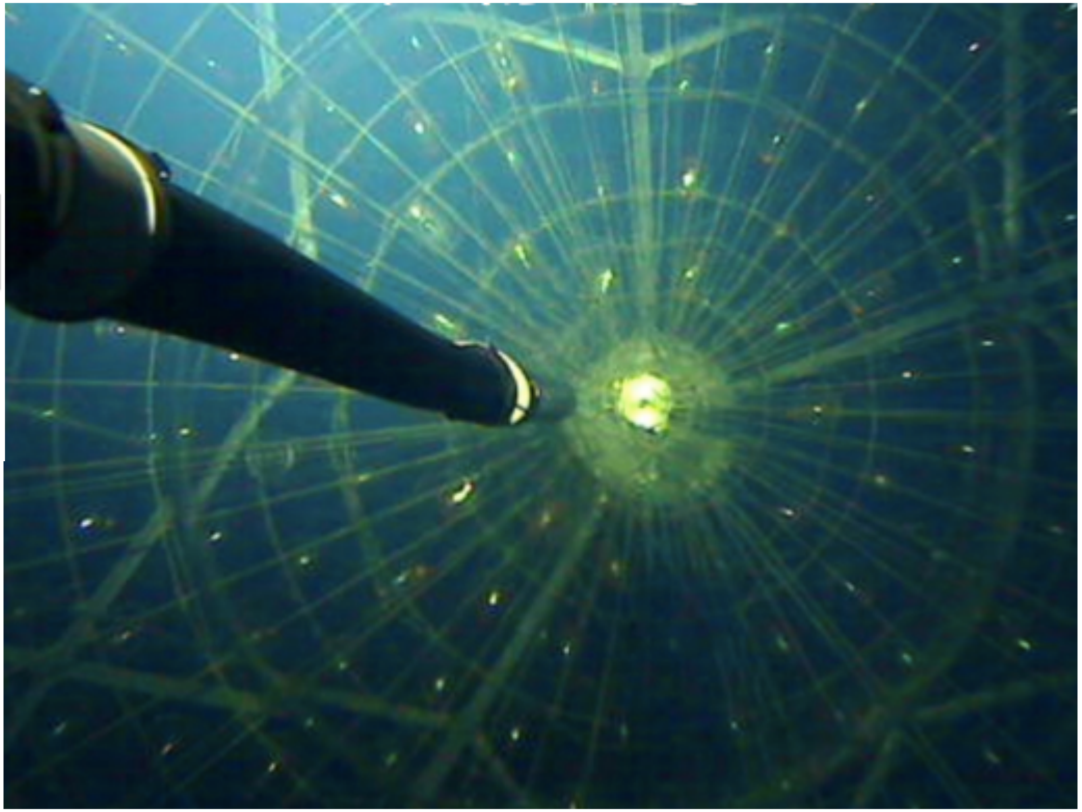
stay tuned…

0νββ Experimental Results: KamLAND-Zen



Berger

Xe loaded liquid scintillator



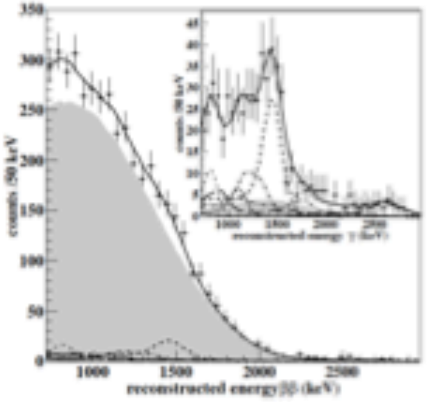
^{136}Xe 2νββ Half Life

First measured by EXO-200 (2011)

$T^{2\nu}_{1/2} = 2.11 \pm 0.04\ (\mathrm{stat}) \pm 0.21\ (\mathrm{syst}) \times 20^{21}$ yr

PRL 107, 212501 (2011)

-> 5x larger than 2002 DAMA limit

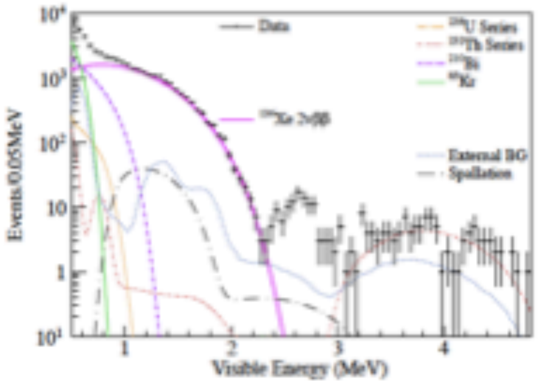


KamLAND-Zen (2012)

$T^{2\nu}_{1/2} = 2.38 \pm 0.02\ (\mathrm{stat}) \pm 0.14\ (\mathrm{syst}) \times 20^{21}$ yr

Phys.Rev.C 85, 045504 (2012)

-> Consistent with EXO-200 result



Current results:

KamLAND: $T^{2\nu}_{1/2} = 2.30 \pm 0.02\ (\mathrm{stat}) \pm 0.12\ (\mathrm{syst}) \times 20^{21}$ yr

Phys.Rev.C 86, 021601 (2012)

EXO-200: $T^{2\nu}_{1/2} = 2.172 \pm 0.017\ (\mathrm{stat}) \pm 0.060\ (\mathrm{syst}) \times 20^{21}$ yr

arXiv:1306.6106 (June 25, 2013)

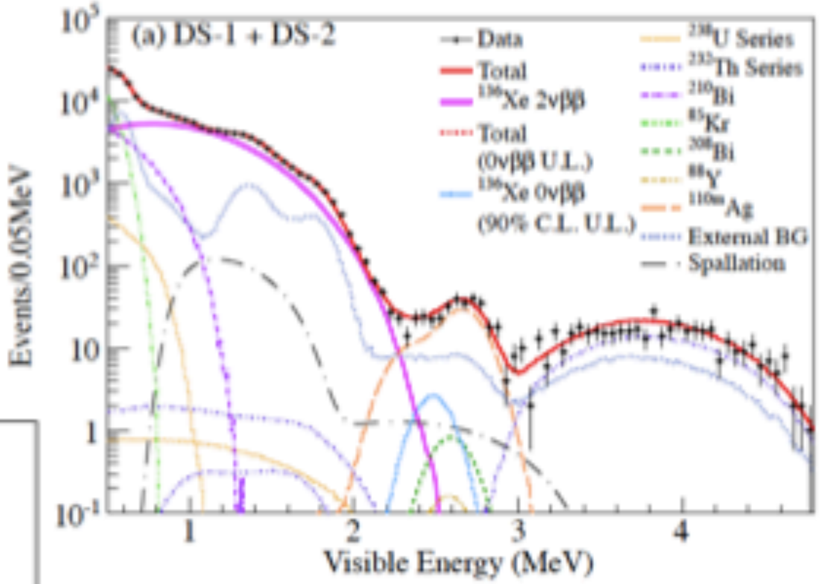
^{136}Xe 0νββ Results

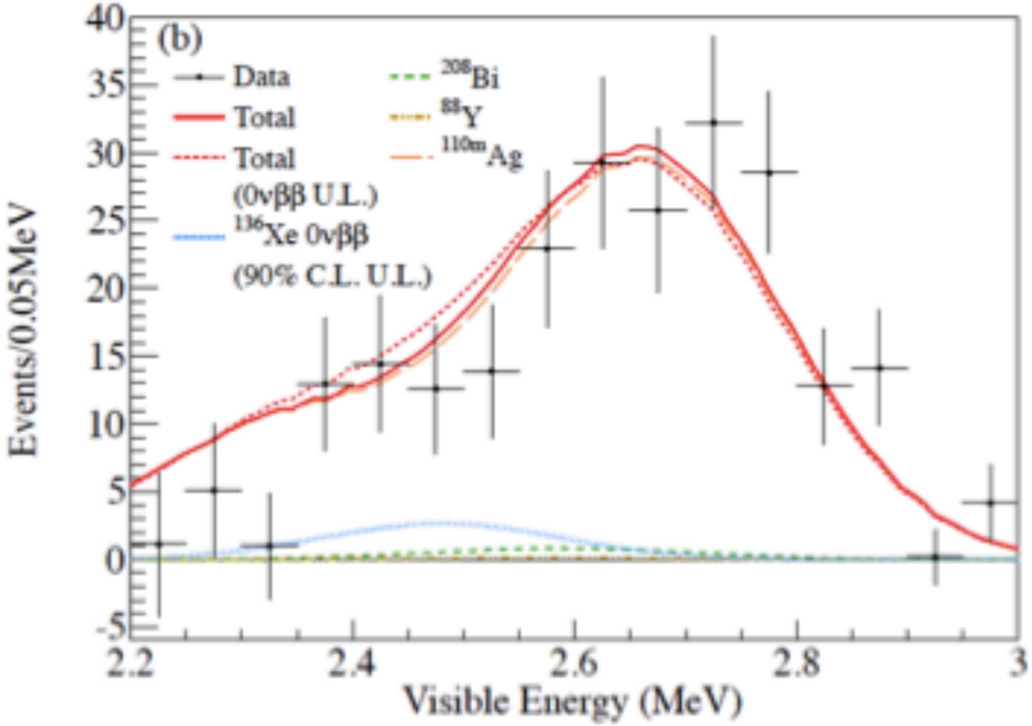
Full Phase I data: 213.4 days

90% CL: $T_{1/2}$ (^{136}Xe 0νββ) > 1.9 x 10^{25} yr

PRL 110, 062502 (2013)

Note: Sensitivity: 1.0 x 10^{25} yr





Comparison with ^{76}Ge claim

Comparisons between isotopes are complicated
by nuclear matrix element (NME) uncertainties

Plot $T_{1/2}$ (^{76}Ge) vs. $T_{1/2}$ (^{136}Xe):

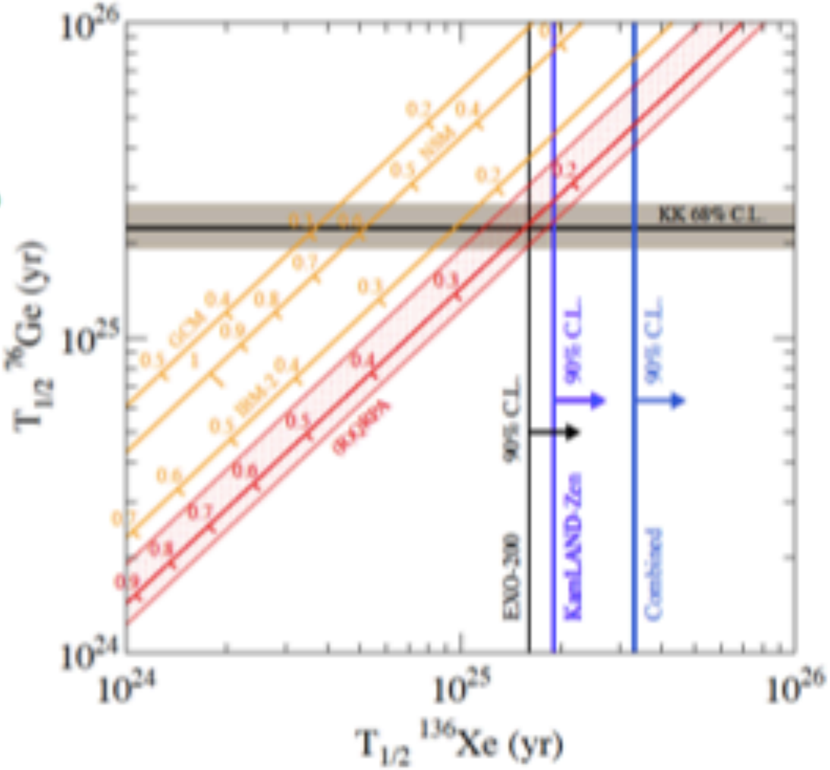
NME models are diagonal lines, marked by $\langle m_{\beta\beta} \rangle$ in eV

KamLAND-Zen: $T_{1/2}$ (^{136}Xe) > 1.9 x 10^{25} yr

EXO-200: $T_{1/2}$ (^{136}Xe) > 1.6 x 10^{25} yr

Combined: $T_{1/2}$ (^{136}Xe) > 3.4 x 10^{25} yr

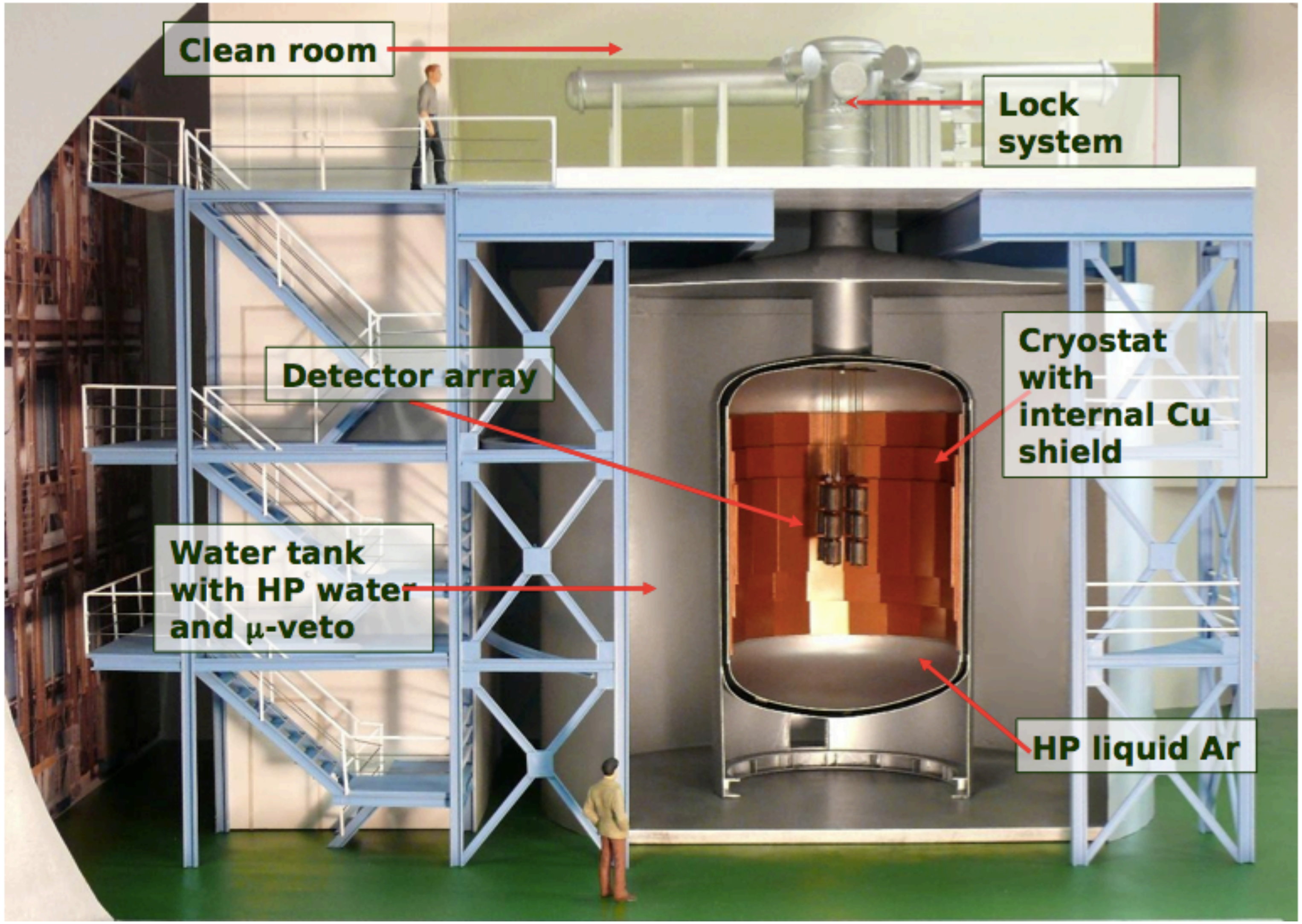
(Sensitivity: 1.6 x 10^{25} yr)



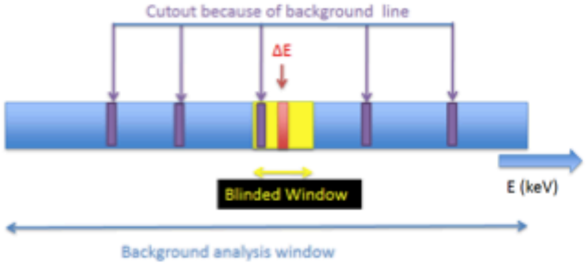
-> Incompatible with KK 2006 claim
at 97.5% CL

$0\nu\beta\beta$ Experimental Results: GERDA

Grabmayr

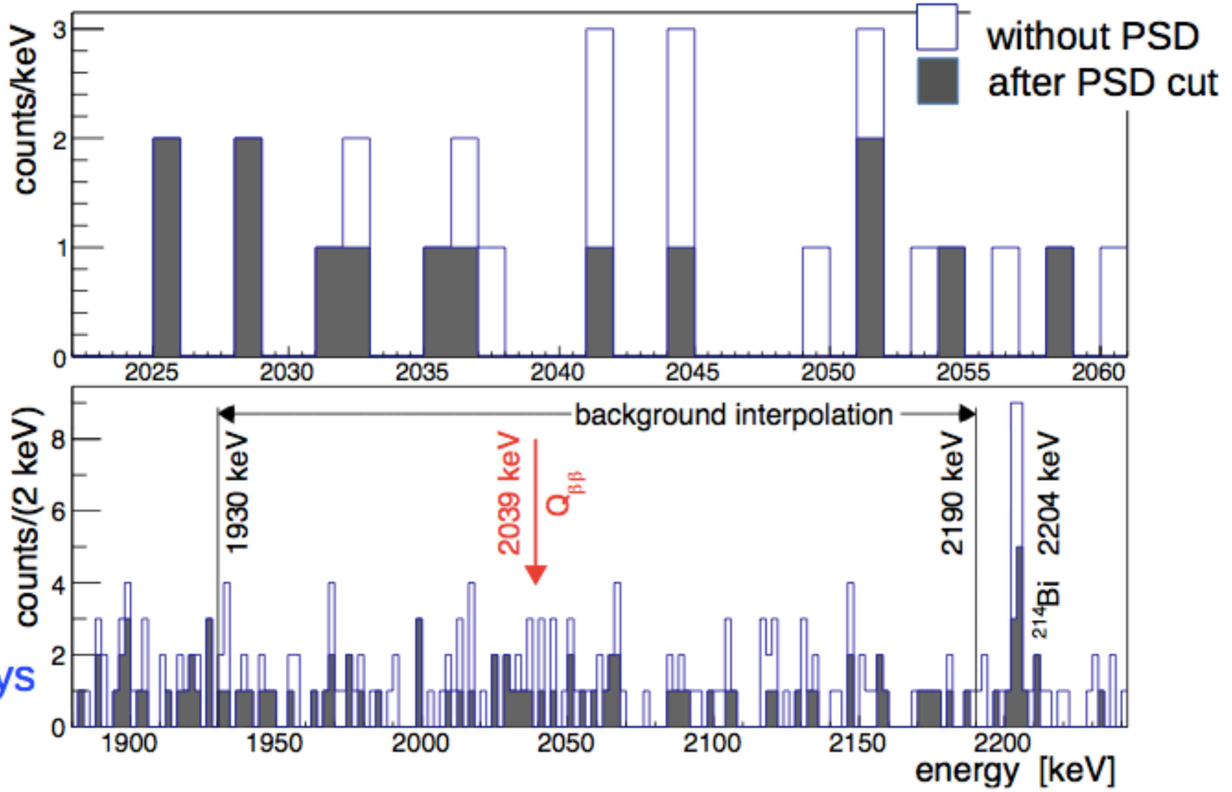


unblinding



calibration & stability
data sets defined
background model
PSD parameters fixed
analysis methods defined

whole collaboration during 4 days
unblinding of final ±5 keV

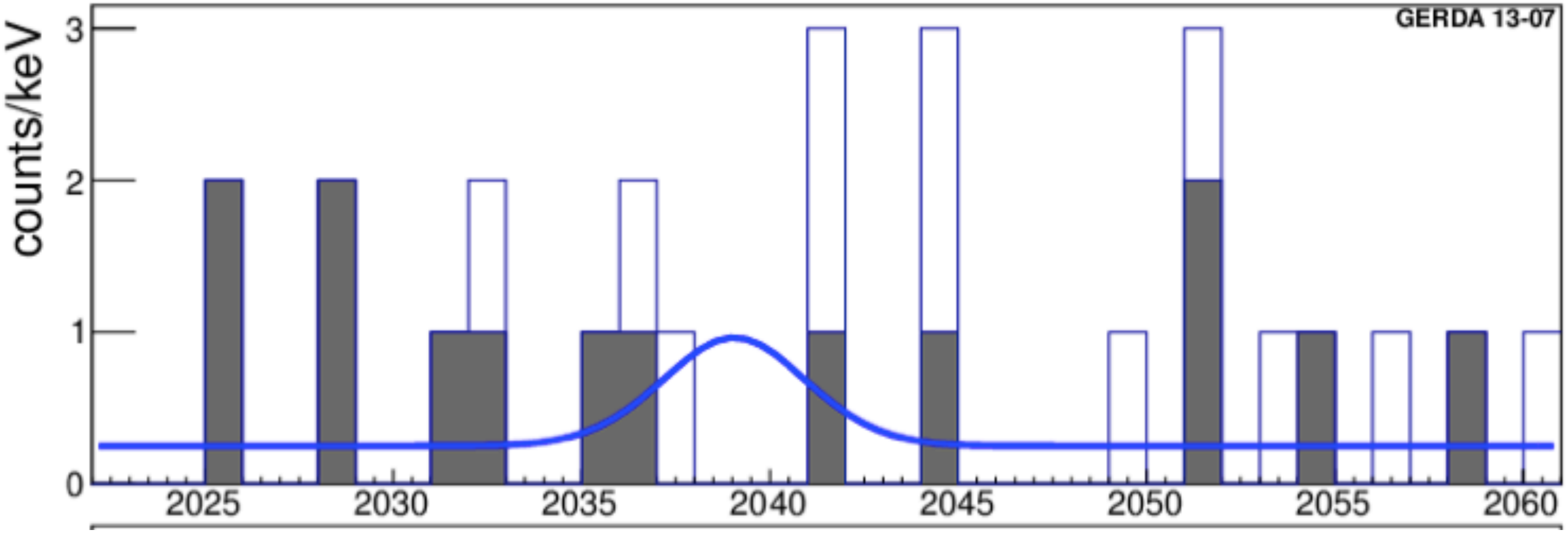


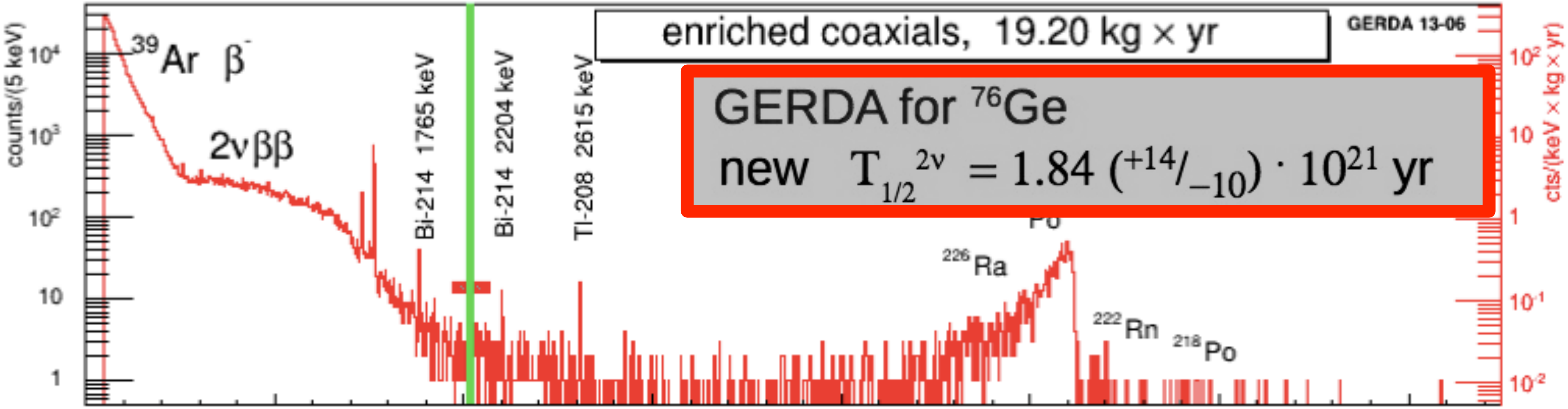
evt cnt in ±5 keV	golden	silver	BEGe	total
expt. w/o PSD	3.3	0.8	1.0	5.1
obs. w/o PSD	5	1	1	7
expt. w/ PSD	2.0	0.4	0.1	2.5
obs w/ PSD	2	1	0	3

no peak in spectrum at $Q_{\beta\beta}$,

event count consistent with bkg,
→ GERDA sets a limit

frequentist: profile likelihood fit → best fit $N^{0\nu}$=0, $T^{0\nu}_{1/2} > 2.1\cdot10^{25}$ yr (90% C.L.)

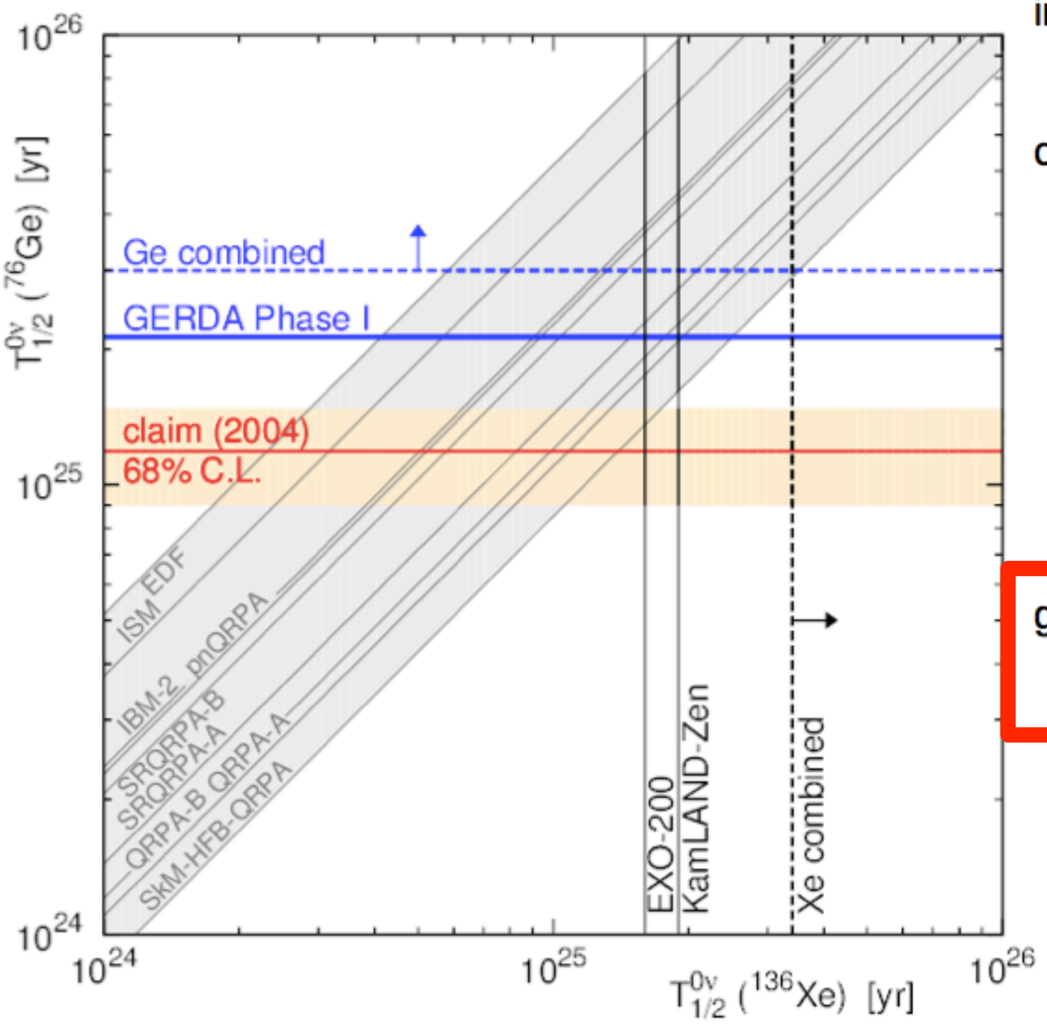




GERDA for ^{76}Ge

new $T_{1/2}^{2\nu} = 1.84\ (^{+14}/_{-10}) \cdot 10^{21}$ yr

Comparison



include HdM & IGEX

model free: no NME needed

compare to Xe:

NME needed, which ?

smallest NME ratio ^{136}Xe/^{76}Ge ~ 0.4

⇒ weakest exclusion

gives total Bayes factor H1/H0 = 0.0022

→ claim of ^{76}Ge signal is strongly disfavored

A. Wegmann

Future: Transition to phase II:

- inspection & re-filling of WT
- add BEGe's ➔ ~x2 of ^{76}Ge
- light instrumentation
- ➔ more mass, less BI, …

Gerda: tests Ge claim with Ge

NME's: Relating Lifetimes & Neutrino Masses

Simkovic
Suhonen
Fang

phase space   nuclear matrix elements   effectiveMajorana neutrino mass

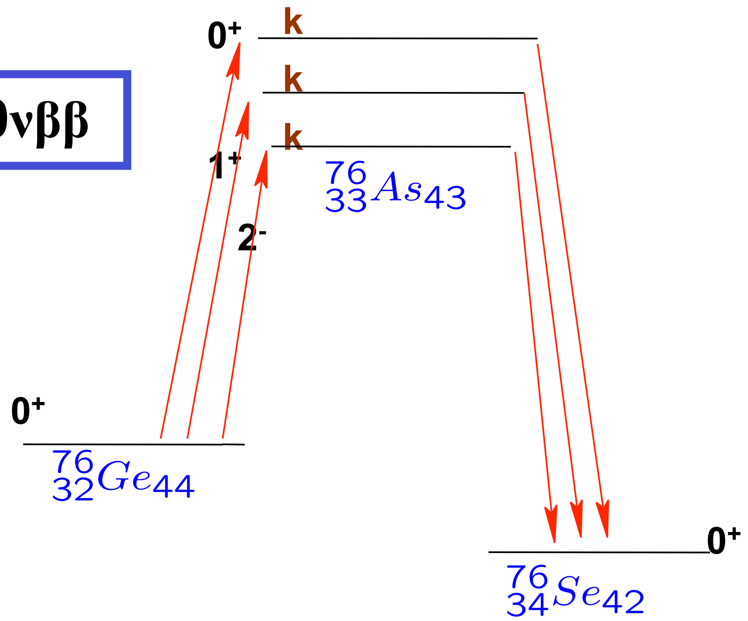
rate of $0\nu\beta\beta$

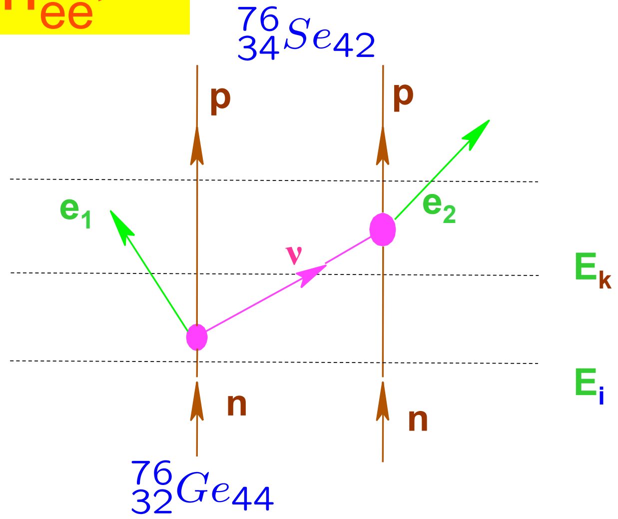
$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 <m_{ee}>^2$$

<u>nuclear matrix elements</u>:

➔ virtual excitations of intermediate states

$0\nu\beta\beta$





<u>in recent years:</u>
<u>good progress in TH errors</u>

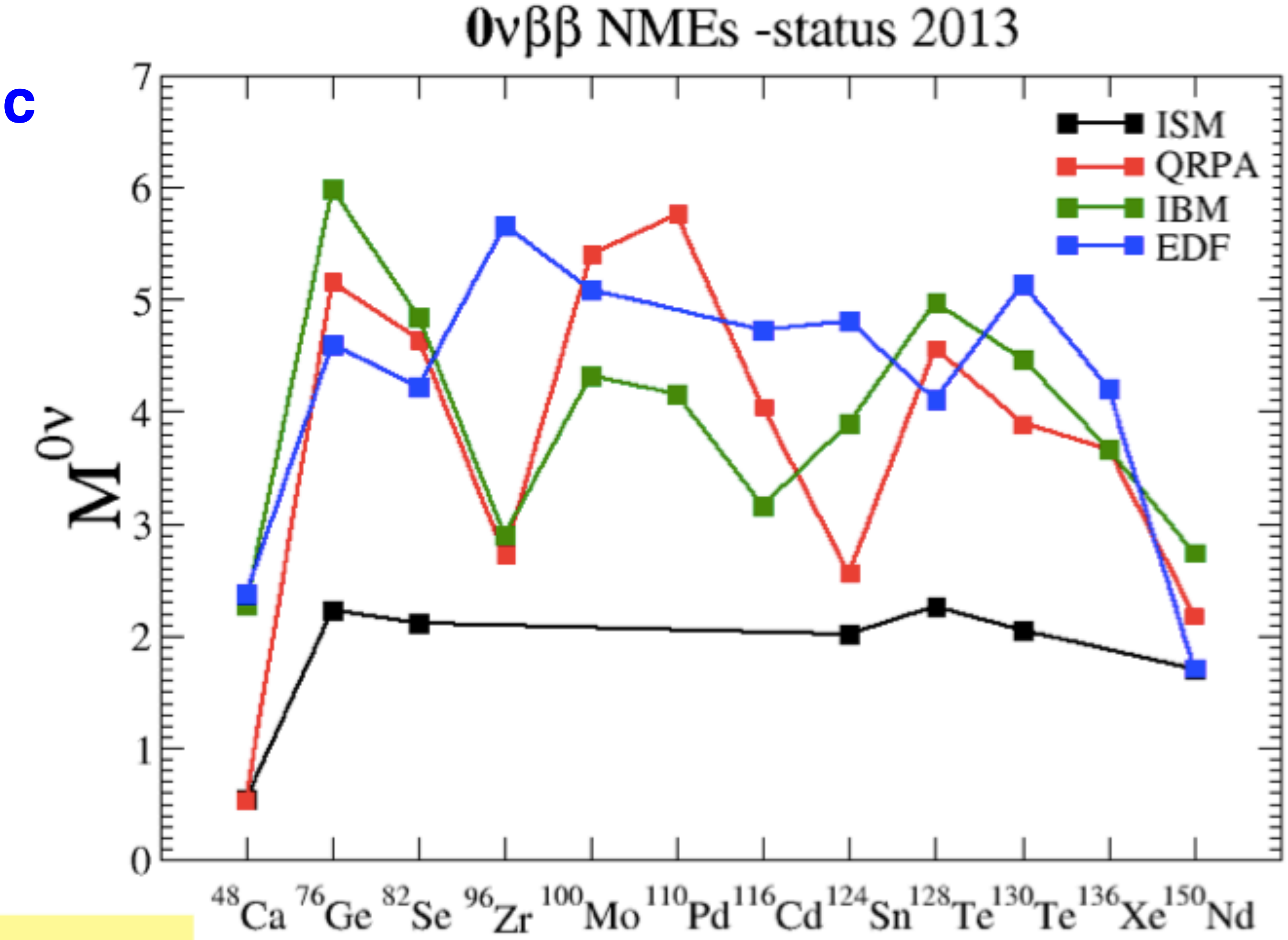
➔ reduced uncertainties
➔ which NME is correct?
➔ what is a 1σ theory error?

The $0\nu\beta\beta$-decay NMEs (Status:2013)

Nobody is perfect:

$g_A=1.25(7)$, CCm or UCOM s.r.c., $r_0=1.20$ fm

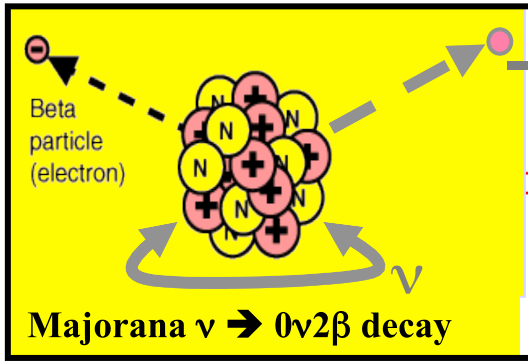
Simkovic



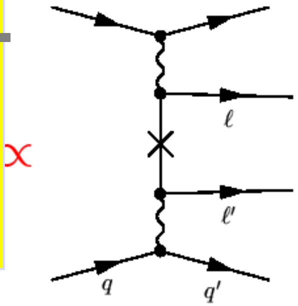
Differences:
- *i) mean field;*
- *ii) residual int.;*
- *iii) size of the m.s.*
- *iv) many-body appr.*

LSSM (small m.s., negative parity states)
PHFB (GT force neglected)
IBM (Hamiltonian truncated)
(R)QRPA (g.s. correlations not accurate enough)

m_{ee}: The Effective Neutrino Mass



Majorana ν → 0ν2β decay

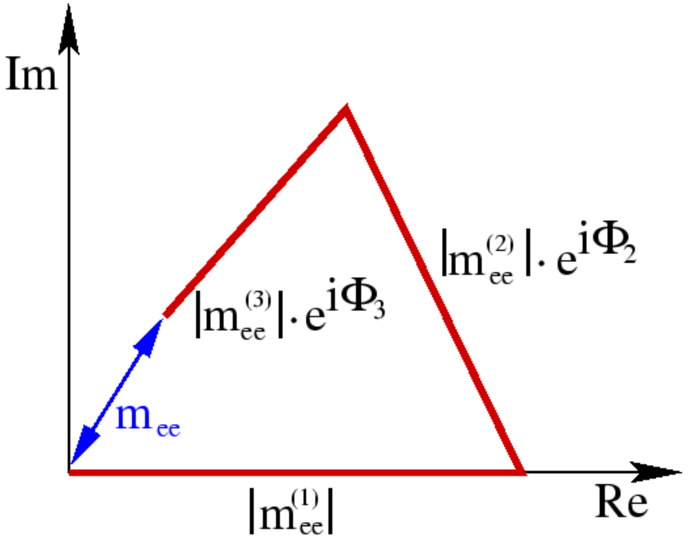


$$\propto |\langle m_{ee} \rangle| = |\sum m_i U_{ei}^2| \underline{<} 0.35 \text{ eV ?}$$

Heidelberg-Moscow experiment

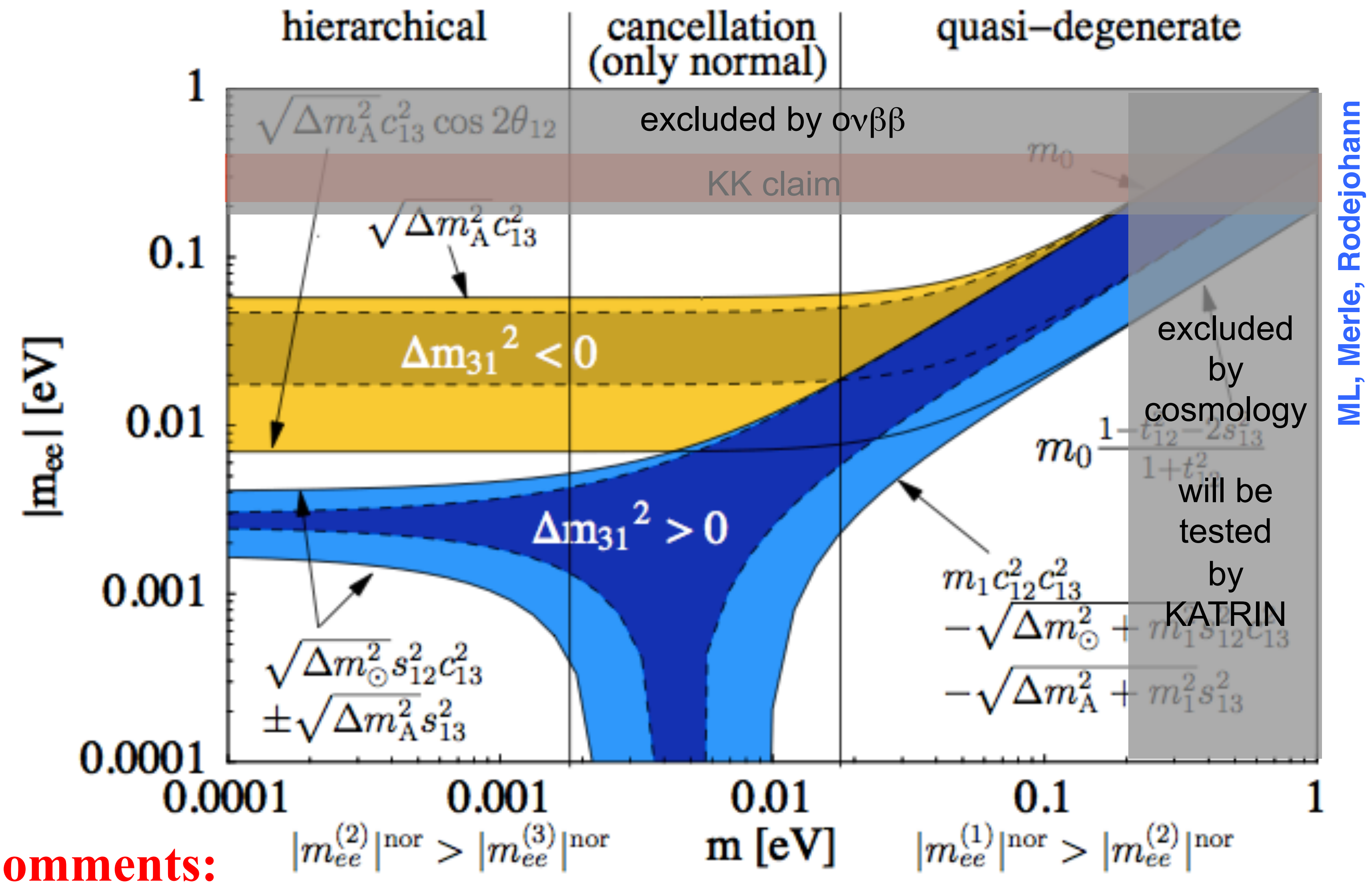
$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

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



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**



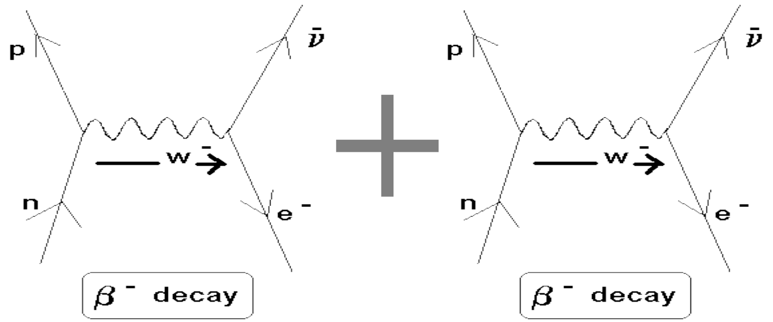
ML, Merle, Rodejohann

Comments:

- **cosmology: further improvements ←→ systematical errors**
- **NMEs→ unavoidable theory error in m_{ee}**
- **assumptions: no *other* ΔL=2 physics, no sterile neutrinos, ...**

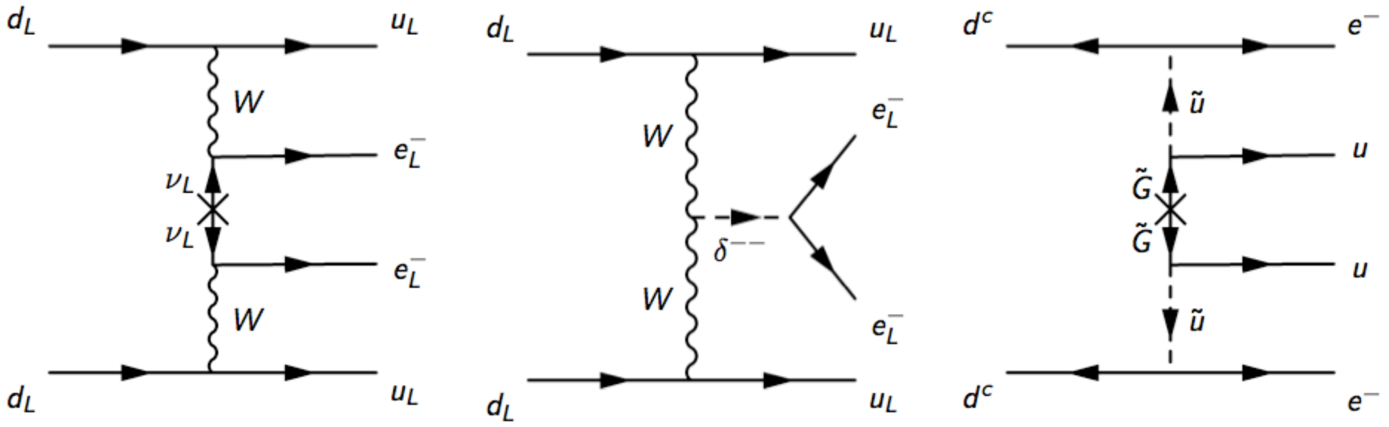
Double Beta Decay Processes

Standard Model:



→ 2 electrons + 2 neutrinos

Majorana ν-masses or other ΔL=2 physics: → 2 electrons



Simkovic
Krivoruchenko

+interferences

Majorana
neutrino masses
←→ Dirac?

SM + Higgs triplet

SUSY

important connections to LHC and LFV …

Two non-interfering mechanisms of the 0νββ-decay (light LH and heavy RH neutrino exchange)

Simkovic

$$T^{0\nu}_{1/2}(^{76}Ge) \geq 1.9\times 10^{25} y, \qquad T^{0\nu}_{1/2}(^{76}Ge) = 2.23^{+0.44}_{-0.31}\times 10^{25} y$$

$$5.8\times 10^{23} y \leq T^{0\nu}_{1/2}(^{100}Mo) \leq 5.8\times 10^{24} y, \qquad 3.0\times 10^{24} y \leq T^{0\nu}_{1/2}(^{130}Te) \leq 3.0\times 10^{25} y$$

Half-life:

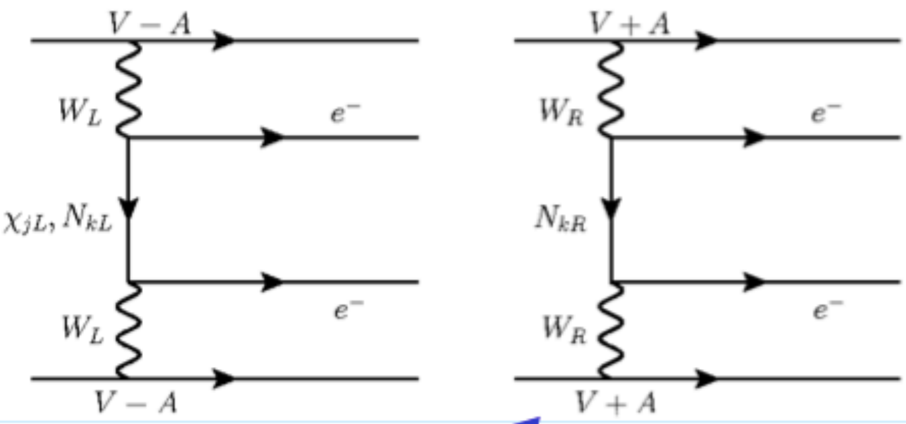
$$\frac{1}{T^{0\nu}_{1/2,i}G^{0\nu}_i(E,Z)} \cong |\eta_\nu|^2 |M'^{0\nu}_{i,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{i,N}|^2$$

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e}$$

Set of equations:

$$\frac{1}{T_1 G_1} = |\eta_\nu|^2 |M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{1,N}|^2$$

$$\frac{1}{T_2 G_2} = |\eta_\nu|^2 |M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2 |M'^{0\nu}_{2,N}|^2$$



Solutions:

$$|\eta_\nu|^2 = \frac{|M'^{0\nu}_{2,N}|^2/T_1G_1 - |M'^{0\nu}_{1,N}|^2/T_2G_2}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}$$

$$|\eta_R|^2 = \frac{|M'^{0\nu}_{1,\nu}|^2/T_2G_2 - |M'^{0\nu}_{2,\nu}|^2/T_1G_1}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}$$

$$\eta^R_N = \left(\frac{M_W}{M_{WR}}\right)^4 \sum_k^{heavy} V^2_{ek}\frac{m_p}{M_k}$$

A. Faessler, A. Meroni, S.T. Petcov, F. Š., J.D. Vergados, Phys. Rev. D 83, 113003 (2011); JHEP 1302, 025 (2013)

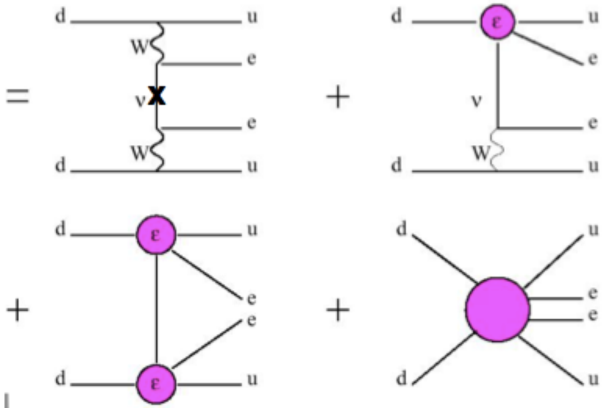
vic

Interferences in 0νββ Decays

Usually

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left(\frac{|m_{0\nu\beta\beta}|}{m_e}\right)^2 |\mathcal{M}^{0\nu}|^2 G^{0\nu}.$$

with interferences



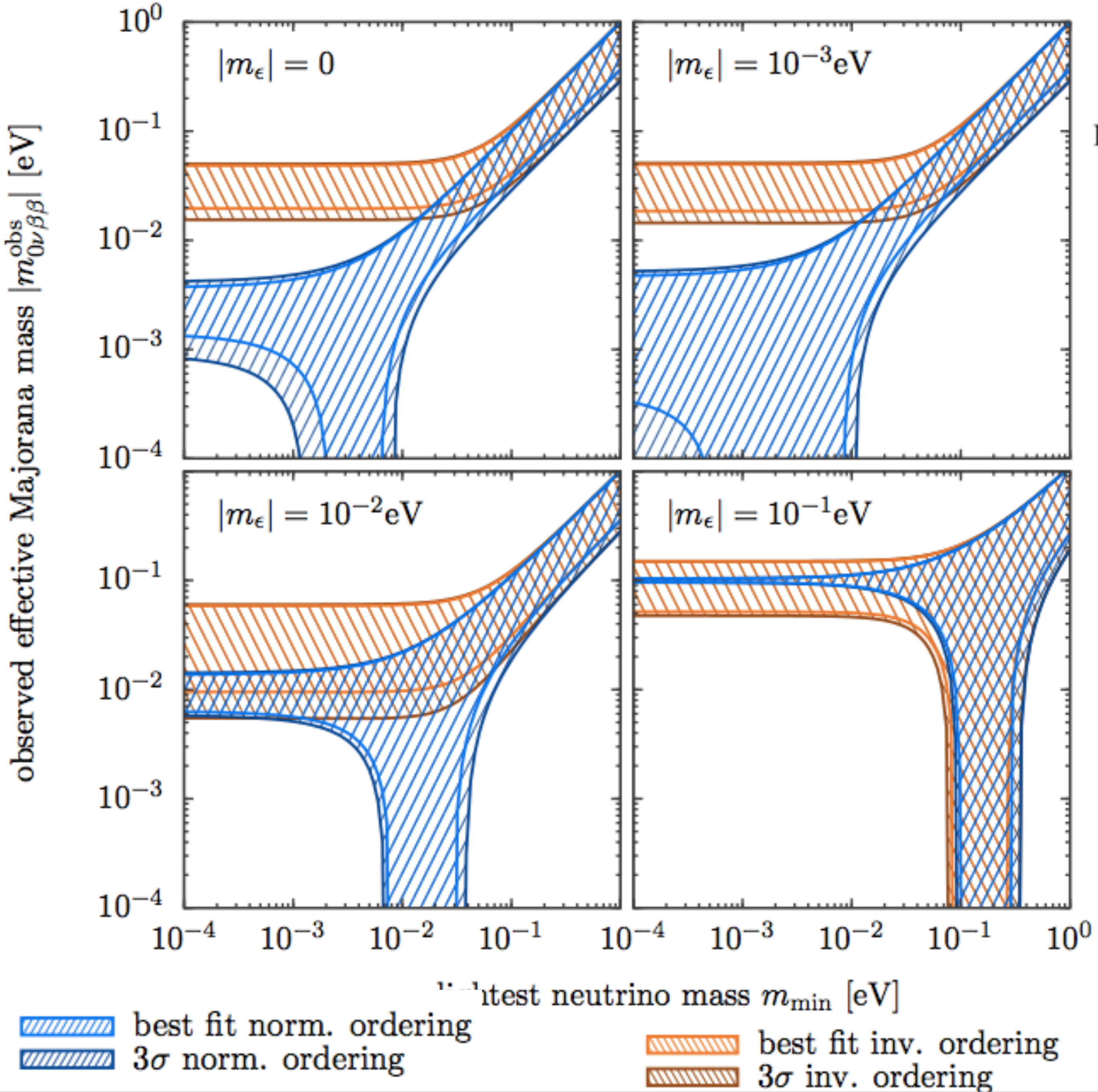
$$\boxed{\begin{aligned}\left(T^{0\nu}_{1/2}\right)^{-1} &= |m_{0\nu\beta\beta}\mathcal{M}^{0\nu} + \epsilon m_e \mathcal{M}^{\epsilon}|^2 \frac{G^{\mathrm{int}}}{m_e^2} \\ &= |(m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1})\mathcal{M}^{0\nu}|^2 \frac{G^{\mathrm{int}}}{m_e^2} \\ &= |m^{\mathrm{int}}_{0\nu\beta\beta}|^2 |\mathcal{M}^{0\nu}|^2 \frac{G^{\mathrm{int}}}{m_e^2},\end{aligned}}$$

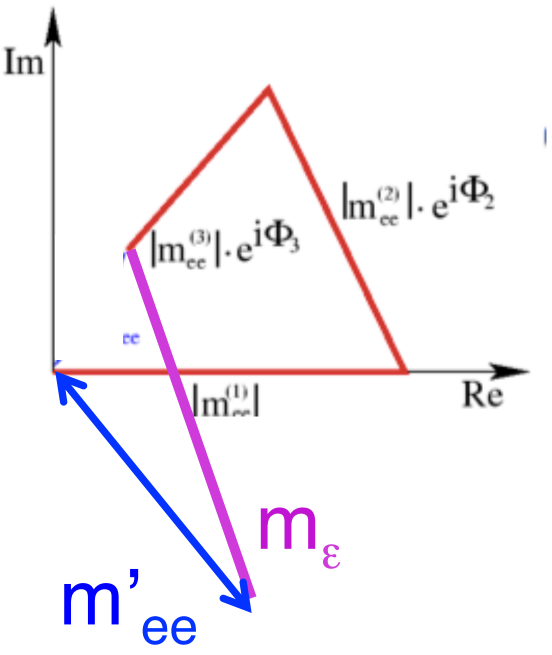
G^{int} = overall phase space factor

$\epsilon m_e \mathcal{M}^{\epsilon}$ ←→ determined by parameters of new physics

$$m^{\mathrm{int}}_{0\nu\beta\beta} \equiv m_{0\nu\beta\beta} + \epsilon m_e \mathcal{M}^{\epsilon}(\mathcal{M}^{0\nu})^{-1} \boxed{\equiv m_{0\nu\beta\beta} + m_{\epsilon}.}$$

Dürr, ML, Neuenfeld



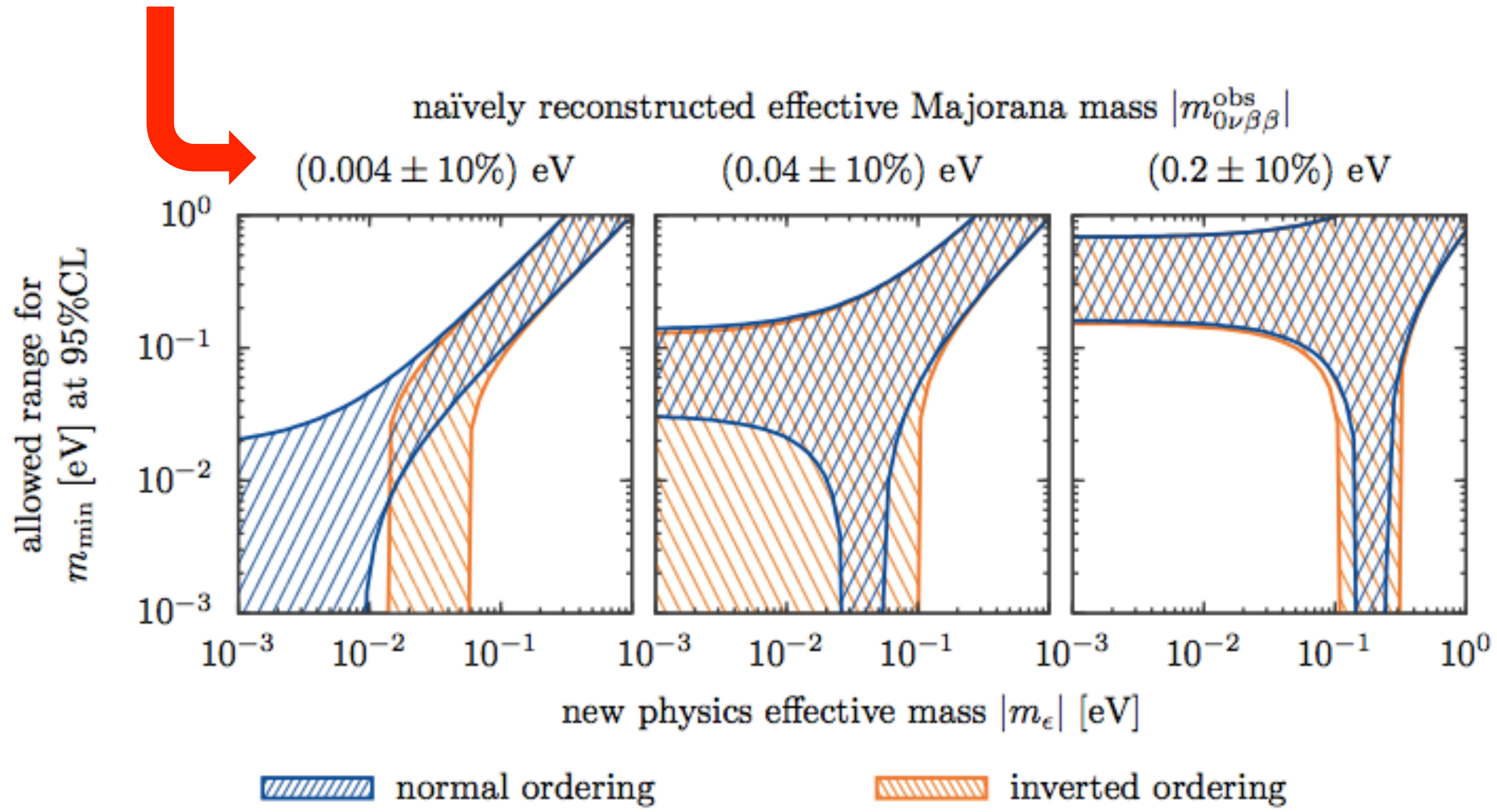


growing m_ε

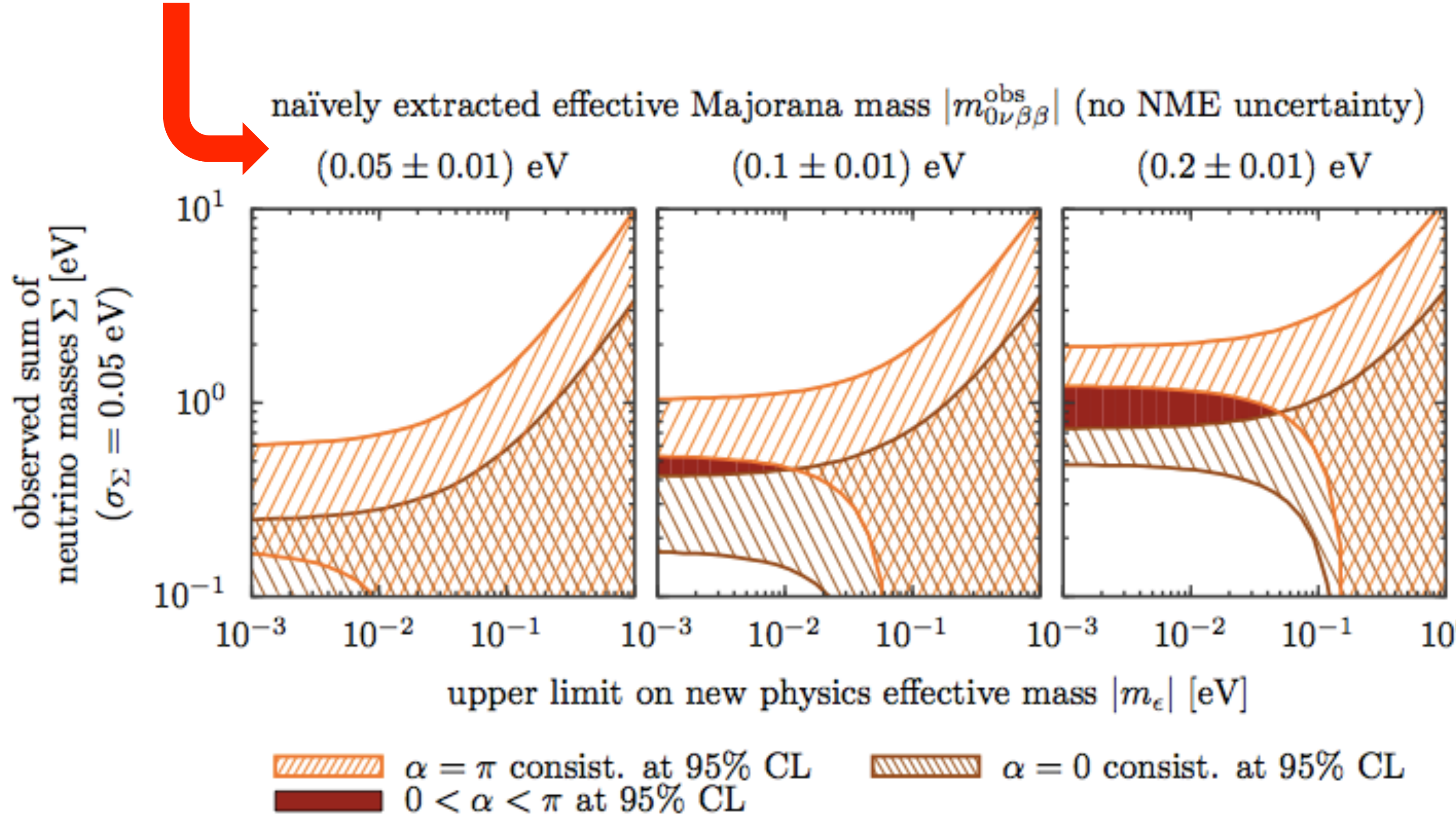
fixed $0\nu\beta\beta$→ shifts

- masses
- mixings
- CP phases
- intereferences

The lightest neutrino mass m_{min} as function of ε (95%CL) for different assumed observed values



Regions where CP violation can be established as function of upper limits for new physics (95%CL) for different assumed observed values



→ No limits without upper bounds on ε!

0νββ Experiments: Future

R&D and preparations for ton-scale projects:
- nEXO **(A. Piepke)**
- Ge-1t

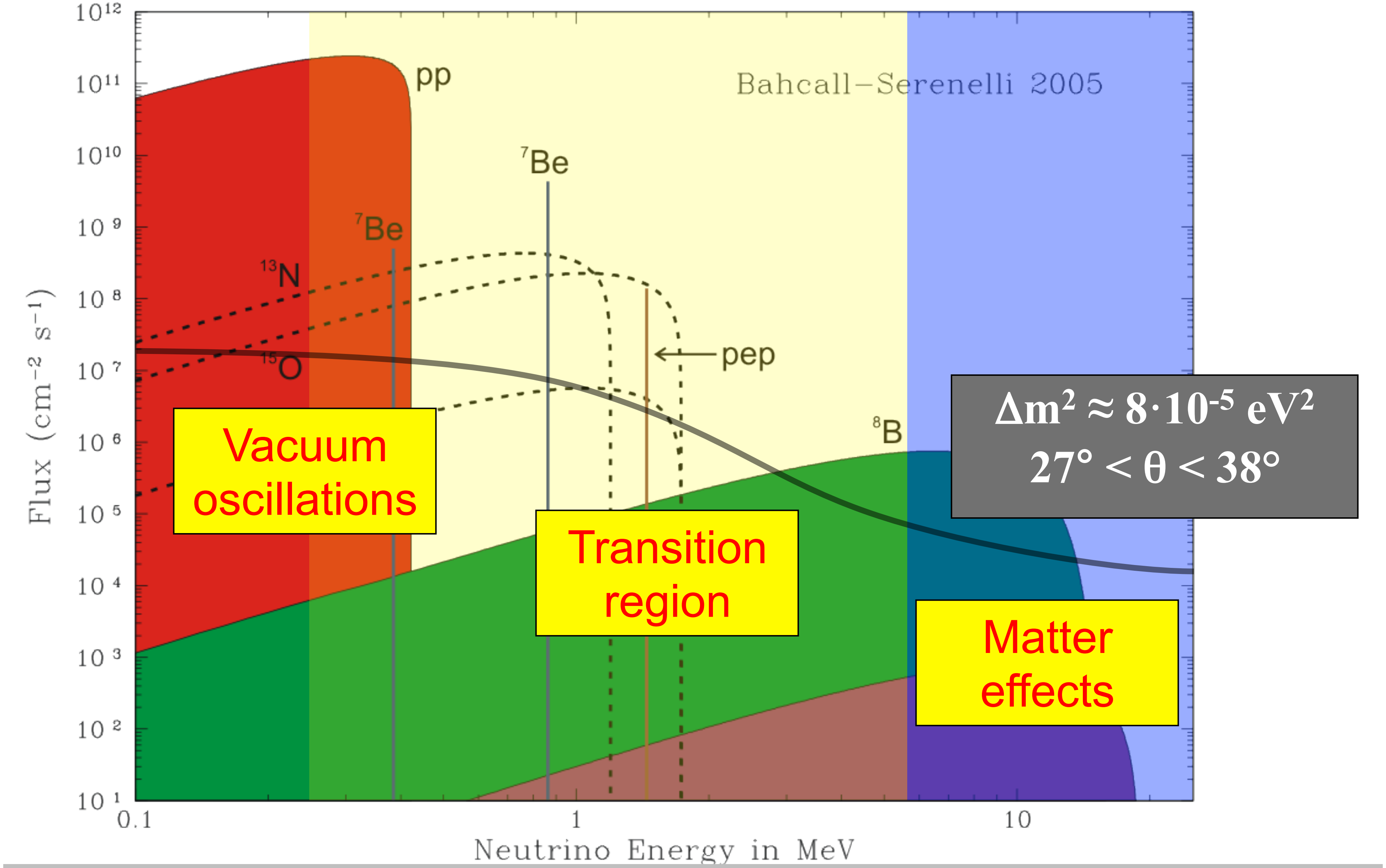
new ideas:
COBRA **(K. Zuber)**
palladium isotopes **(R. Lehnert)**
…

➔ exciting 0νββ times:
- running 100kg-scale experiments with results
- R&D and preparations for next generation(s) on-going

Four Methods of Mass Determination

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

Solar Neutrino Spectroscopy



Vacuum oscillations

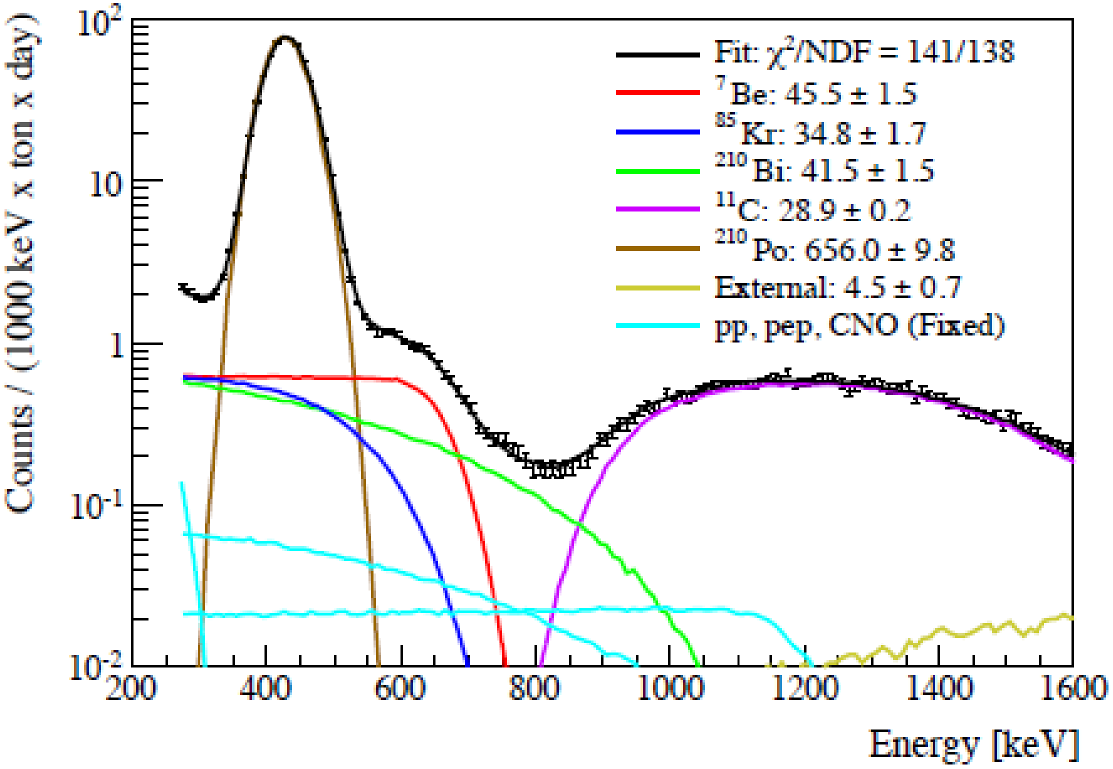
Transition region

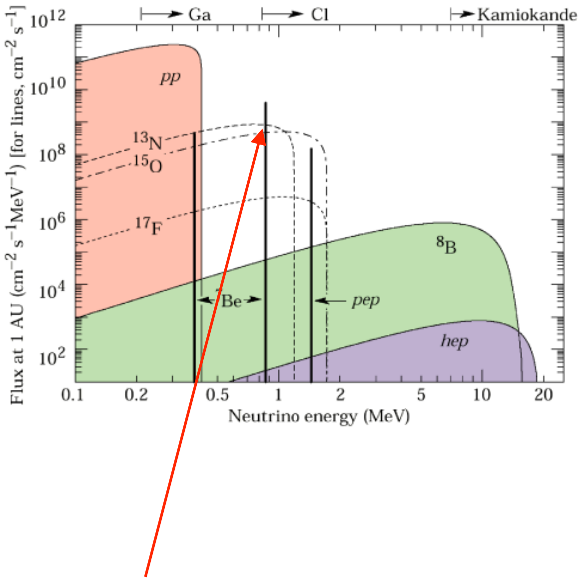
Matter effects

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

27° < θ < 38°

^{7}Be (0.862 MeV) solar flux from Borexino





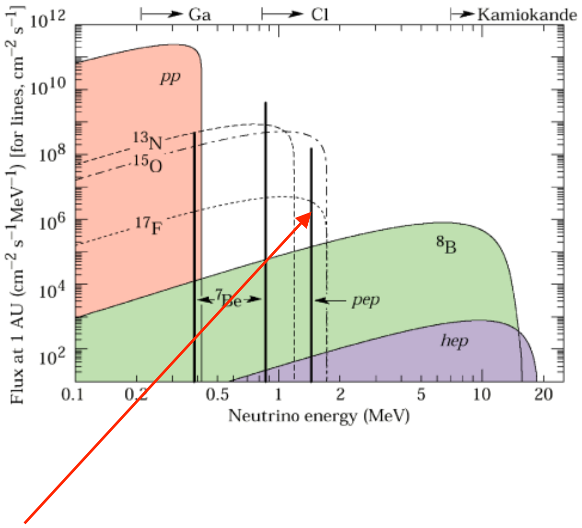
$$R_{^7Be} = 46 \pm 1.5\ (stat)^{+1.5}_{-1.6}\ (syst)\quad cpd/100t$$

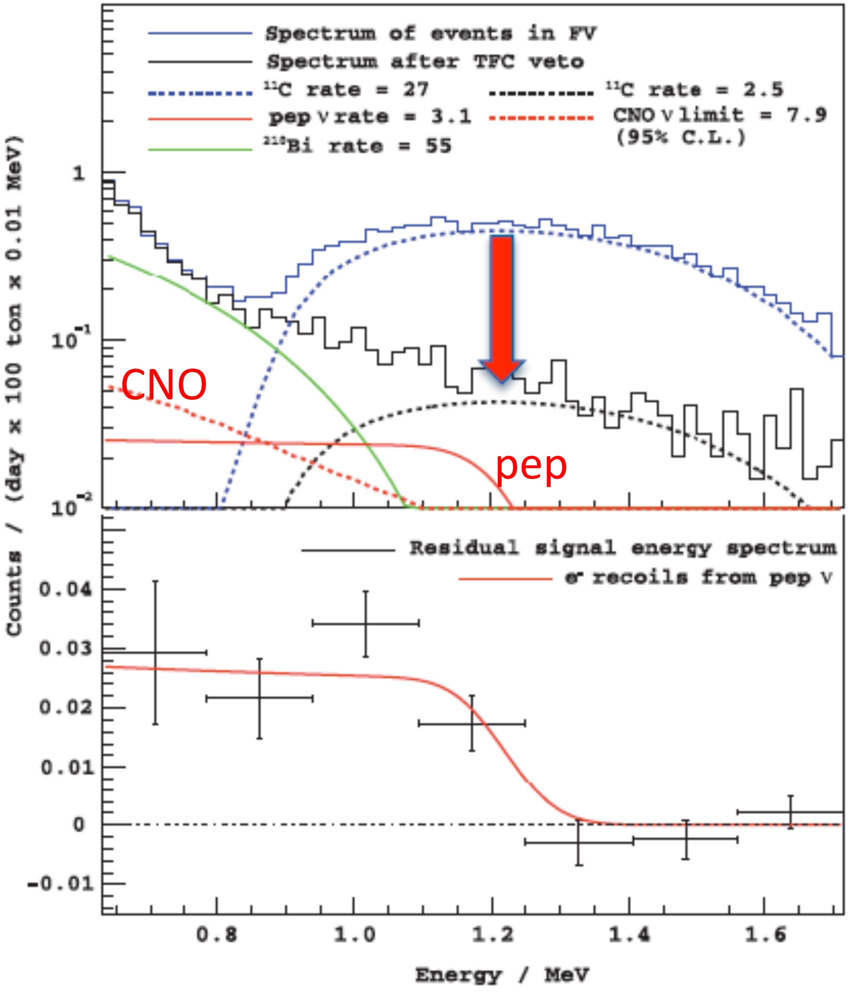
$$R_{no\ oscillation} = 74 \pm 5.2\quad cpd/100t$$

- ν_e flux reduction 0.62 +- 0.05
- ν_e survival probability   0.51 +- 0.07 @0.862MeV

G. Bellini et al., Borexino Collaboration +C Pena Garay, Phys. Lett. B707 (2012) 22.
G. Bellini et al., Borexino Collaboration, Phys. Rev. Lett. 107 (2011) 141362.

pep (1.44 MeV) solar flux measurement and CNO limits in Borexino





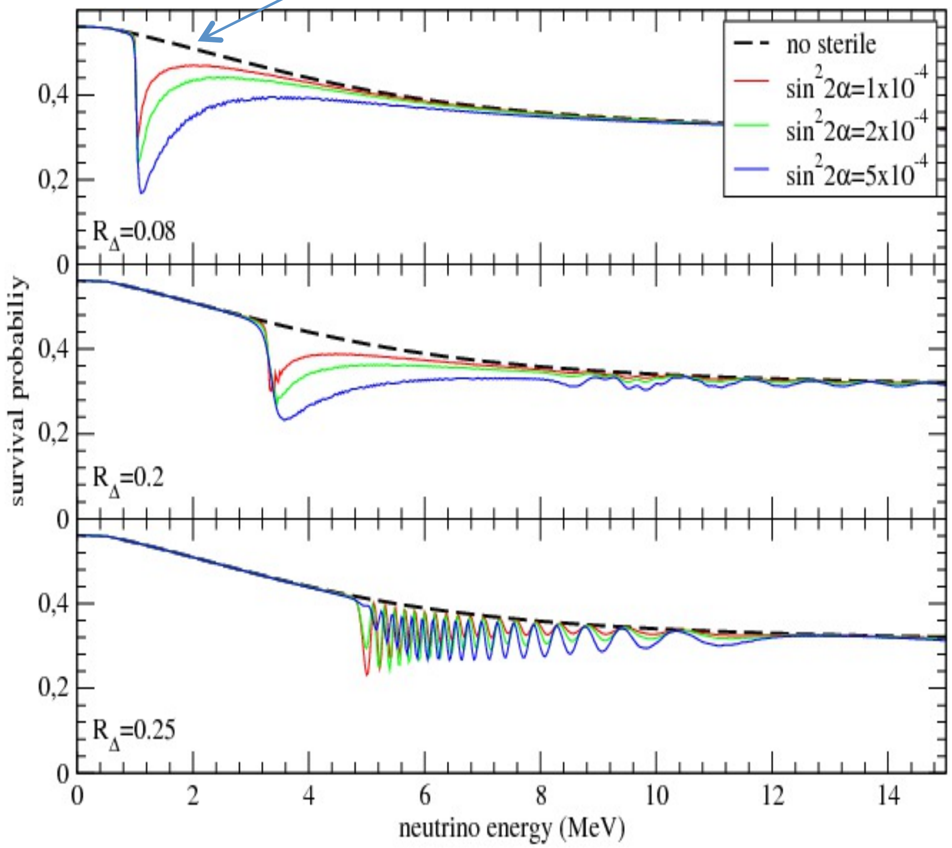
ν	**Interaction Rate (cpd/ 100t)**	**DATA/SSM (high metallicity)**
	Counts/(days 100 t)	ratio
pep	3.1±0.6 (stat) ± 0.3(sys)	1.1±0.2
CNO	<7.9	<1.5

G. Bellini et al., Borexino Coll., Phys. Rev. Lett. 108 (2012) 051302

Best limit on CNO- not yet enough to select solar models….

Solar ^{8}B : the Up-turn???

LMA survival probability



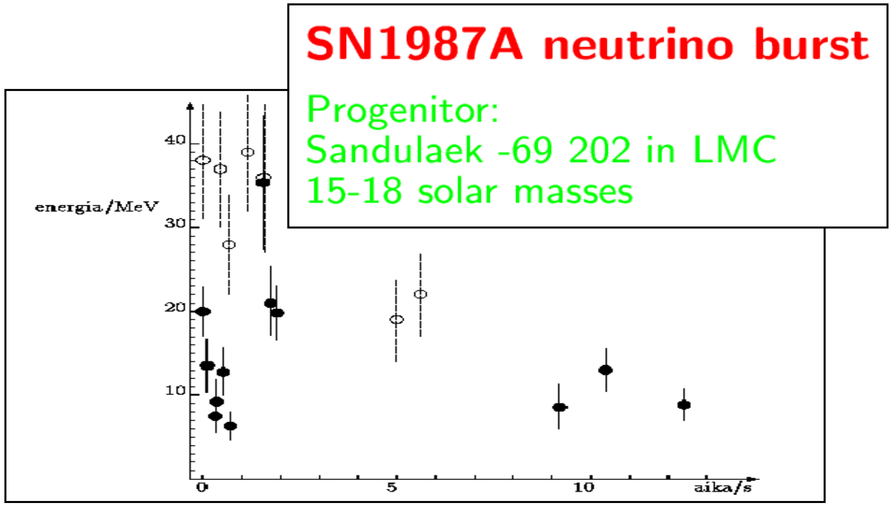
arxiv 1012.5627v2 (2011)

- lower the thereshold as much as possible
- Hints for new physics??
- Background issues
- Statistics
- SuperKamiokande can see the effect

important ←→
new physics
e.g. pseudo-Dirac ν's

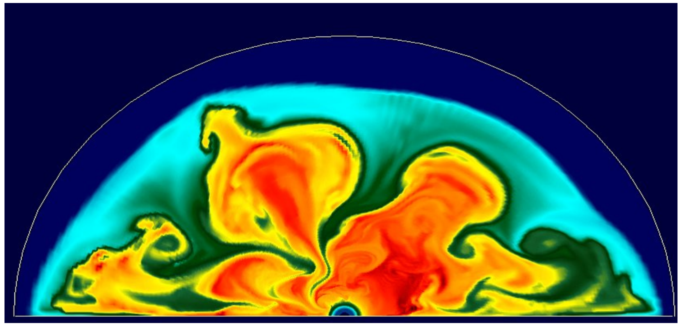
Supernova Neutrinos

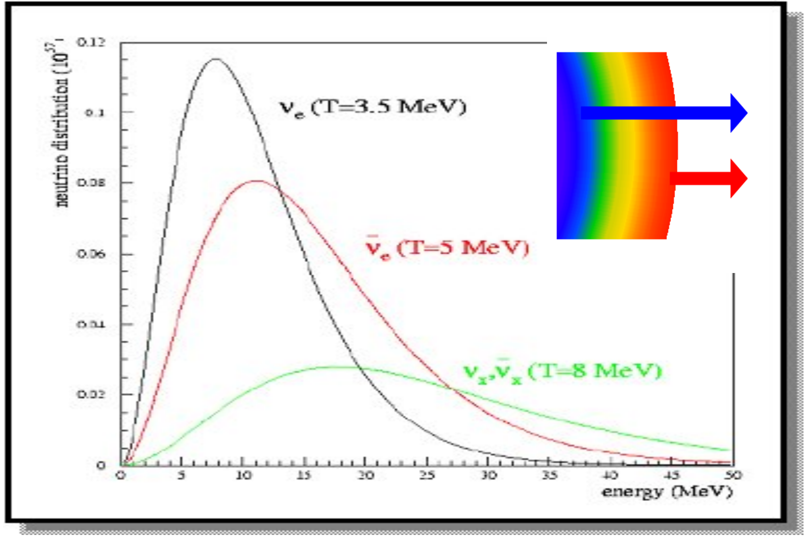
- Collaps of a typical star ➔ ~10^{57} ν's
- ~99% of the energy in ν's
- ν's essential for explosion
- do simulations explode?
  (1d➔2d➔3d ➔convection...)



SN1987A neutrino burst

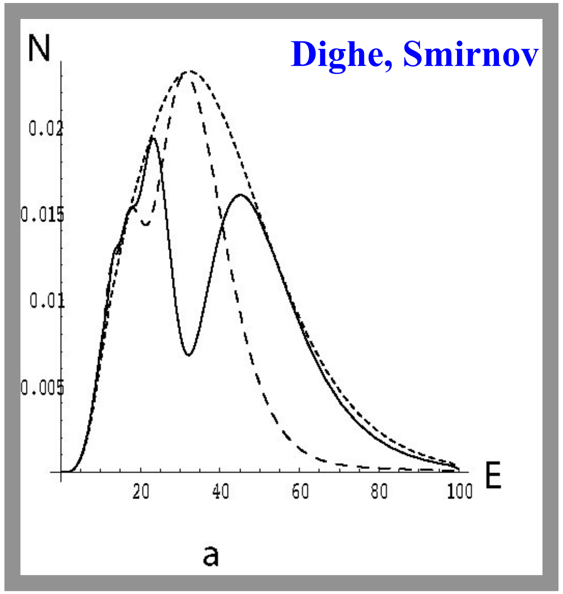
Progenitor:
Sandulaek -69 202 in LMC
15-18 solar masses





MSW: SN & Earth

sensitive to
sgn(Δm^2)

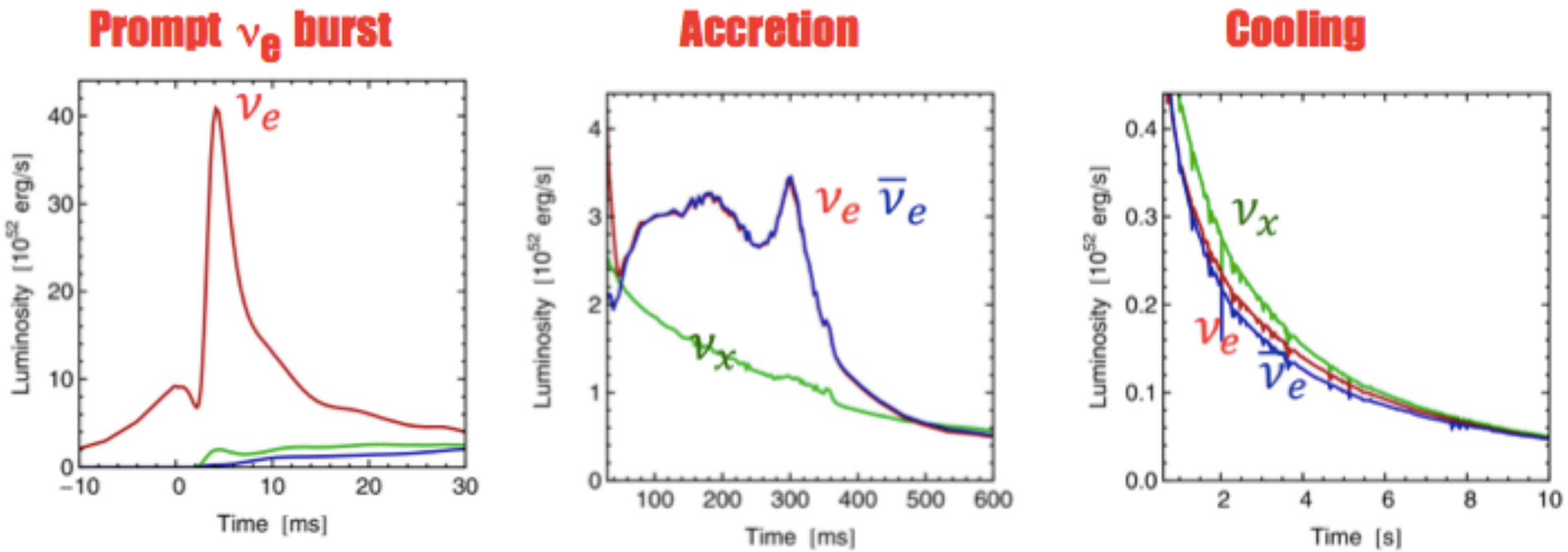


Dighe, Smirnov

Understanding Supernovae

neutrino spectrum:

e.g. Fisher et al.



many other details: important & complex

➔ neutrino spectrum

➔ light emission

➔ processes

➔ ejected material

➔gravitational waves

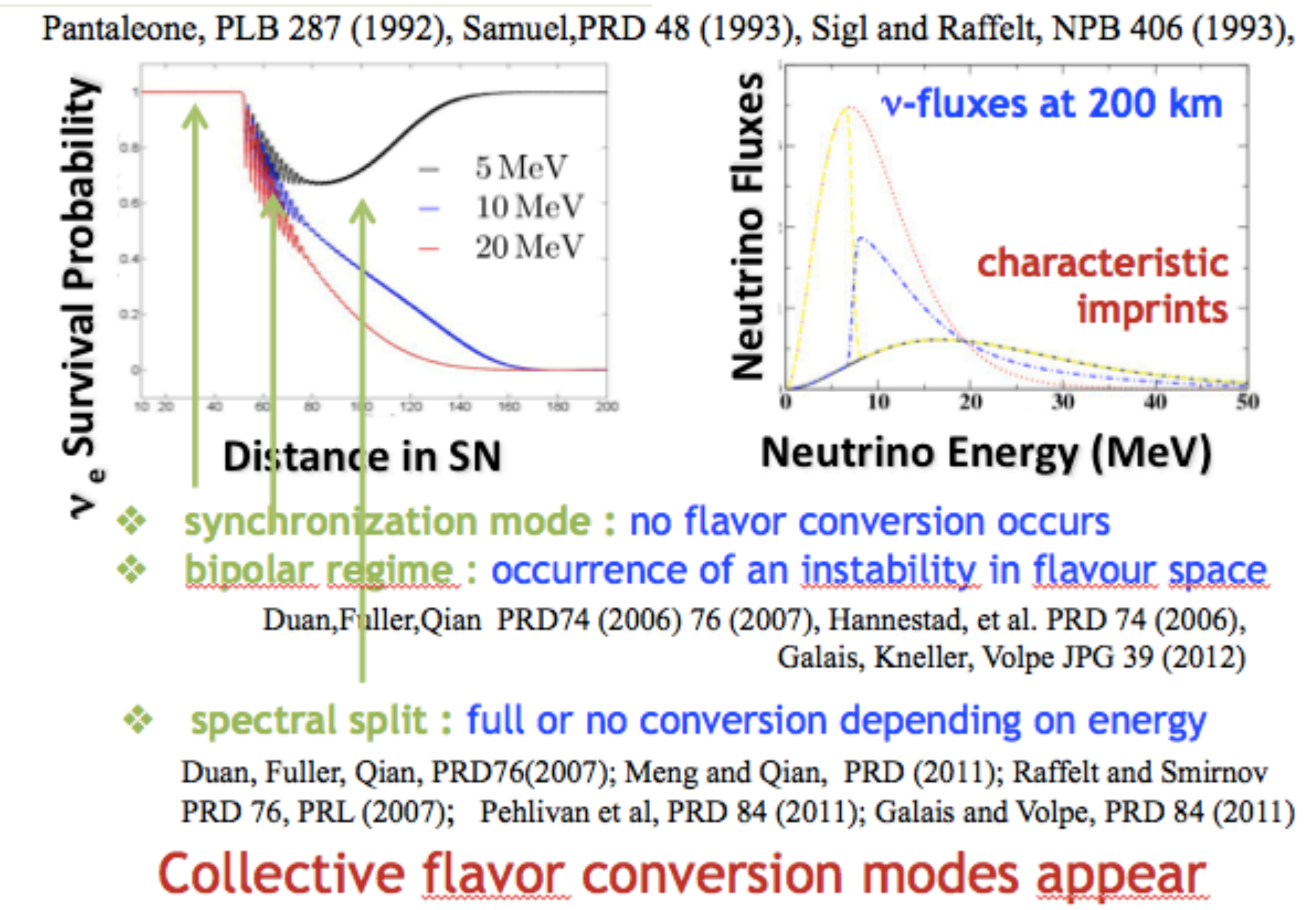
Langanke, Suzuki:

improved ν-nucleus x-sections

impact on dynamics and nucleosynthesis

Wu: impact of sterile ν's

Volpe



Pantaleone, PLB 287 (1992), Samuel,PRD 48 (1993), Sigl and Raffelt, NPB 406 (1993),

- synchronization mode : no flavor conversion occurs
- bipolar regime : occurrence of an instability in flavour space

Duan,Fuller,Qian PRD74 (2006) 76 (2007), Hannestad, et al. PRD 74 (2006), Galais, Kneller, Volpe JPG 39 (2012)

- spectral split : full or no conversion depending on energy

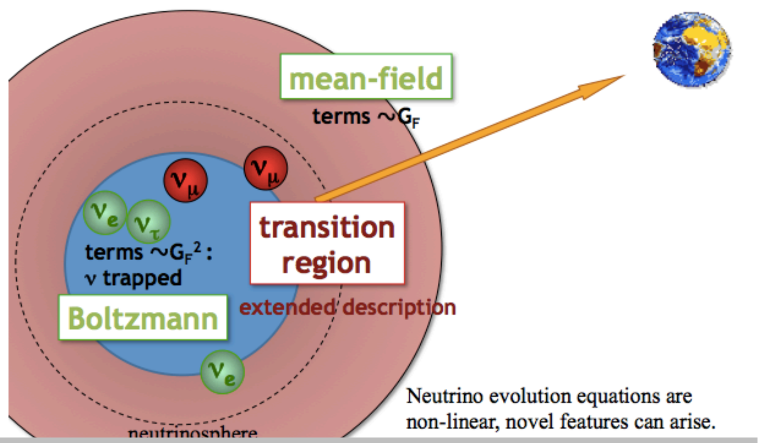
Duan, Fuller, Qian, PRD76(2007); Meng and Qian, PRD (2011); Raffelt and Smirnov PRD 76, PRL (2007); Pehlivan et al, PRD 84 (2011); Galais and Volpe, PRD 84 (2011)

Collective flavor conversion modes appear

➔ Neutrino evolution equations are non-linear, novel features can arise.

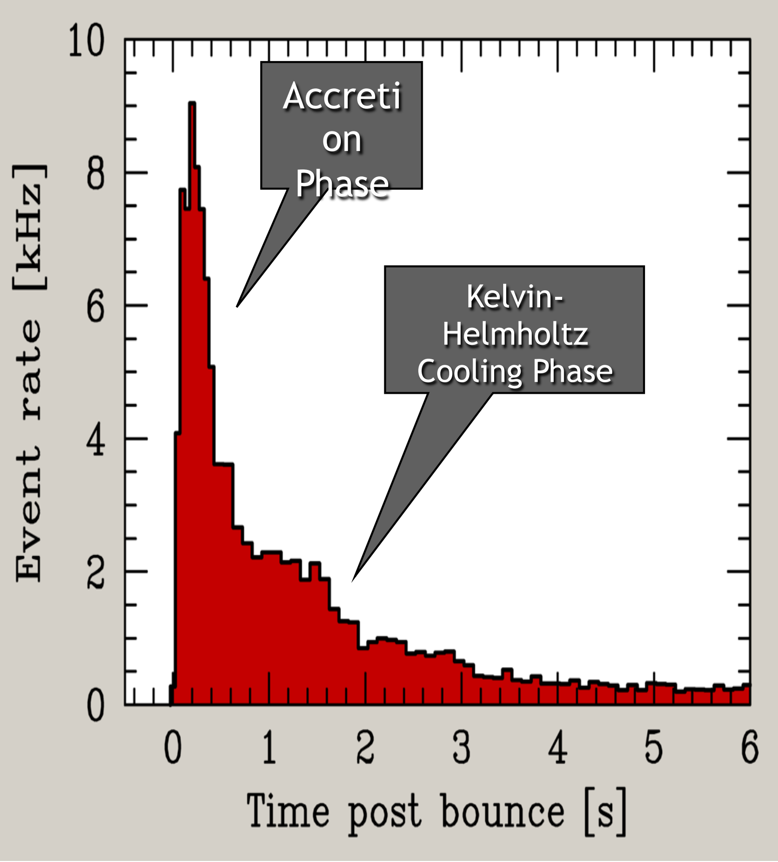
➔ applied Born-Bogoliubov-Green-Kirkwood-Yvon (BBGKY) hierarchy

➔ beyond mean field ➔ extended eqs.



Neutrino evolution equations are non-linear, novel features can arise.

Simulated Supernova Signals



Simulation for Super-Kamiokande
SN@10kpc
Totani, Sato, Dalhed, Wilson

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980-present
LVD	C_nH_{2n}	1	Italy	300	1992-present
Super-Kamiokande	H_2O	32	Japan	7,000	1996-present
KamLAND	C_nH_{2n}	1	Japan	300	2002-present
MiniBooNE*	C_nH_{2n}	0.7	USA	200	2002-present
Borexino	C_nH_{2n}	0.3	Italy	100	2005-present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007-present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE*	Ar	0.17	USA	17	Near future
NOνA*	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

compilation by Scholberg

von Krosigk: detection with SNO+

Problem: Rate – at most a few galactic SN per century

SUPERNOVA neutrinos: several channels in present and future detectors

Testera

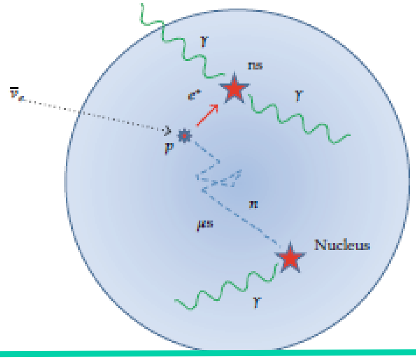
Inverse beta decay $\overline{\upsilon}_e + p \rightarrow n + e^+$

- "prompt signal"

e+: energy loss + annihilation
(2 γ 511 KeV each)

- "delayed signal"

n capture after thermalization (2.2 γ in H)



1.8 MeV threshold, high cross section
Clean signature if n can be detected
(Liquid scint., Gd in water at Superk)
Largest cross section
En> 1.8 MeV

Elastic scatt. $\upsilon_x + e^- \rightarrow \upsilon_x + e^-$

All flavour, directionality, no energy threshold

CC reactions on nuclei

$$\upsilon_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$

$$\overline{\upsilon}_e + (N,Z) \rightarrow (N+1, Z-1) + e^+$$

E threshold,
signature (daughter in excited states)

νp elastic scattering $\nu + p \rightarrow \nu + p$

Low recoil energy
Ok for scintillators (many free protons)
Sensitive to ν_x

ν Nucleus elastic scattering

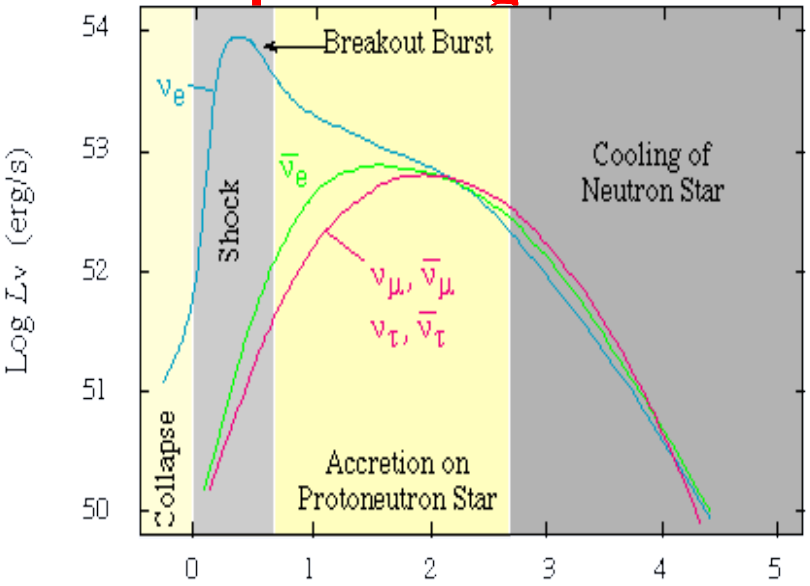
Low recoil energy
Possible in cryogenic noble liquid scintillators

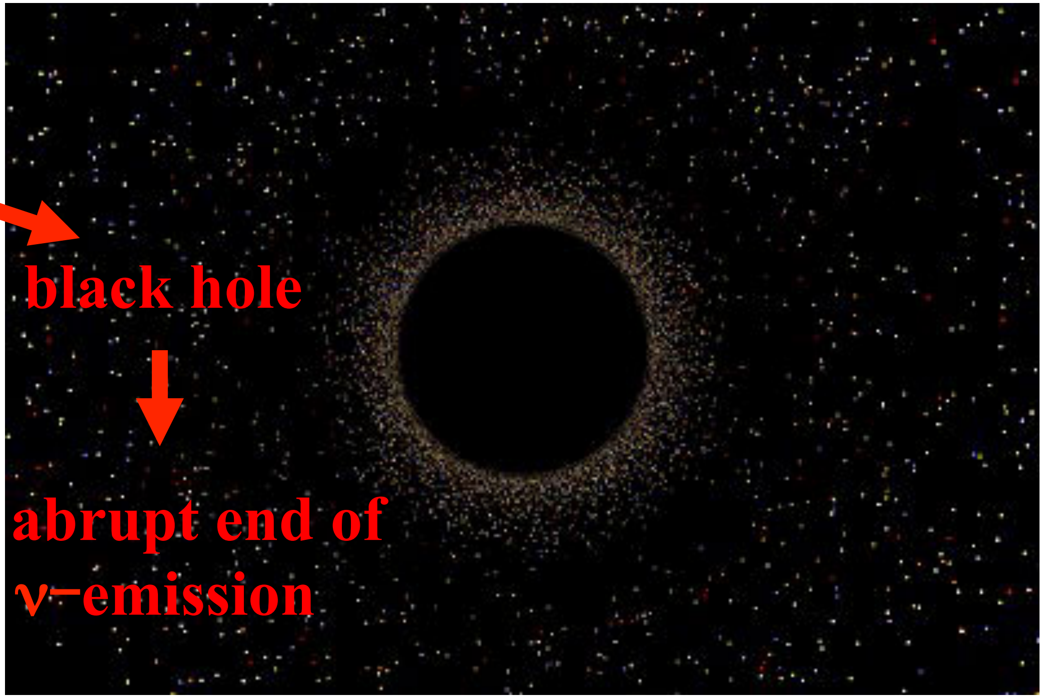
2 possibilities:

Supernova

neutron star or black hole

Keeps cooling…

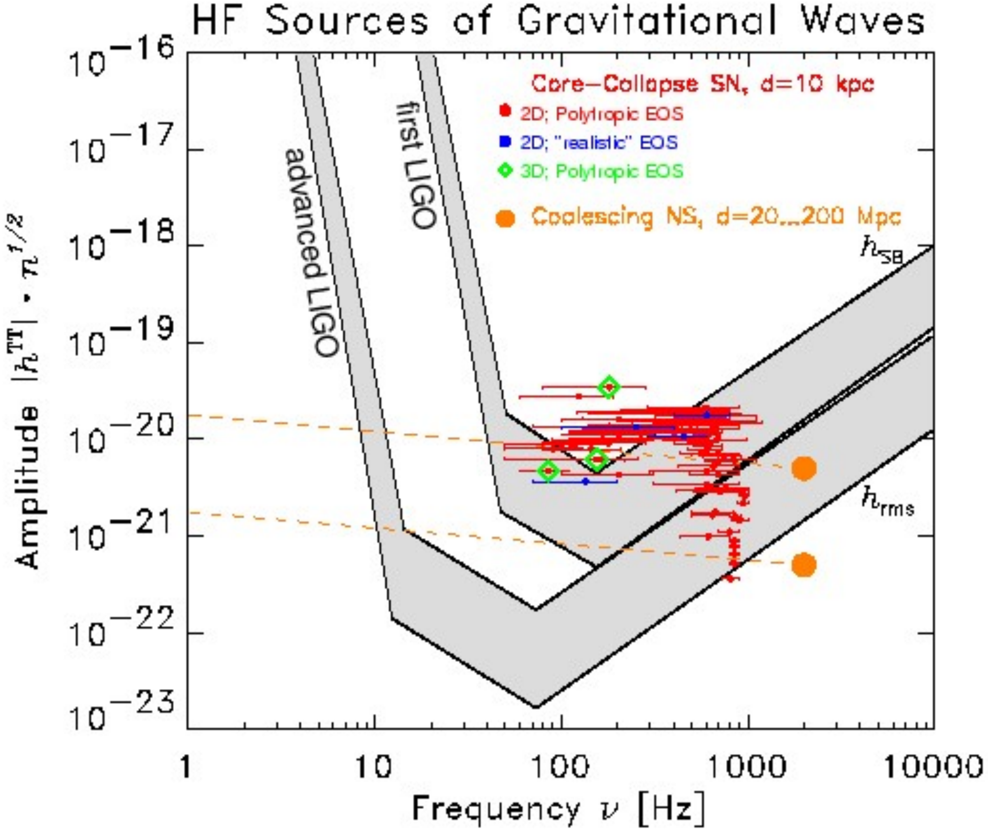


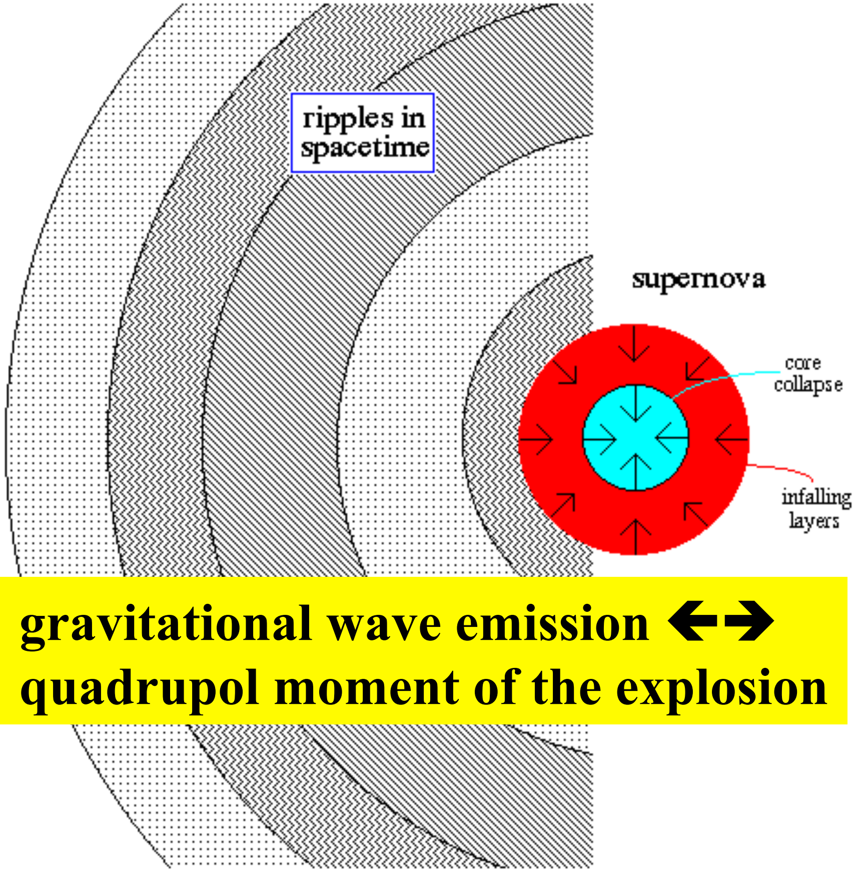


abrupt end of ν−emission

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

Supernovae & Gravitational Waves





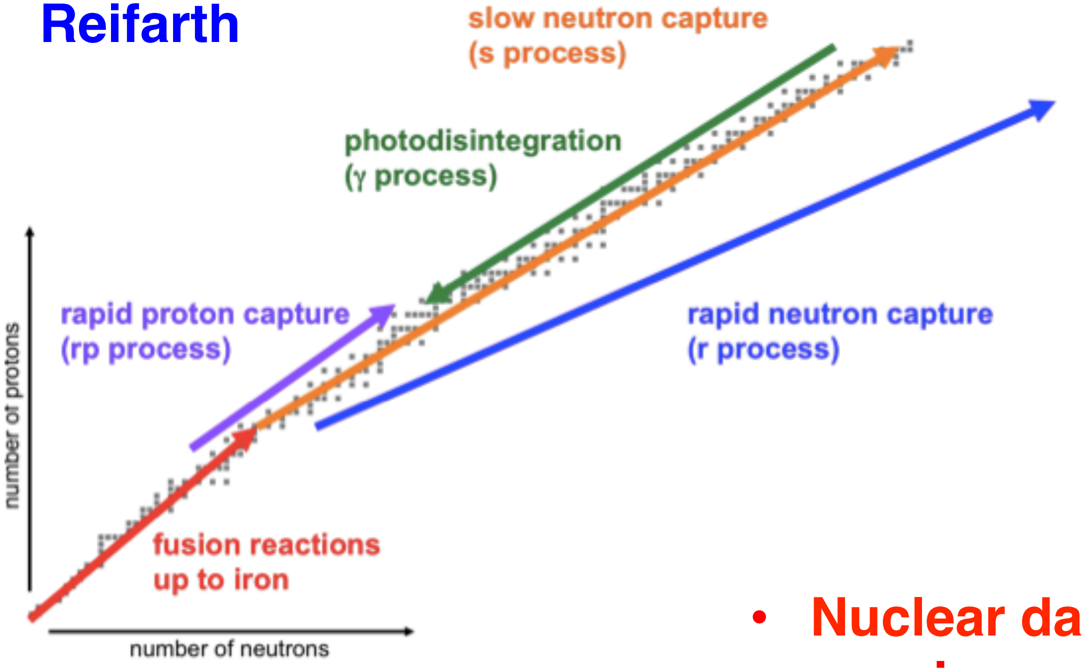
gravitational wave emission ←→ quadrupol moment of the explosion

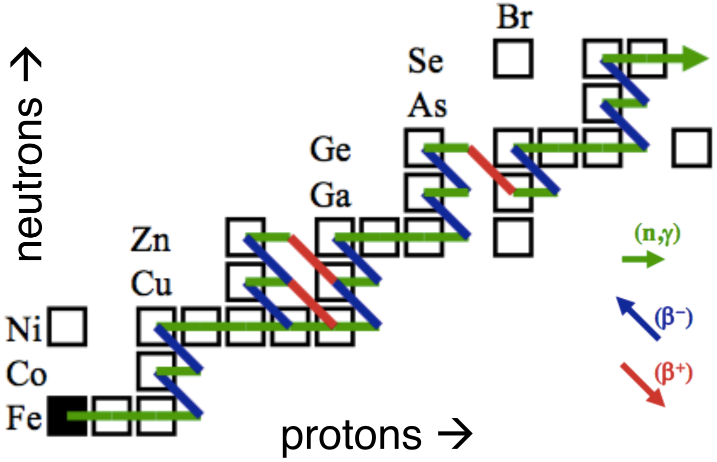
Dimmelmeier, Font, Müller

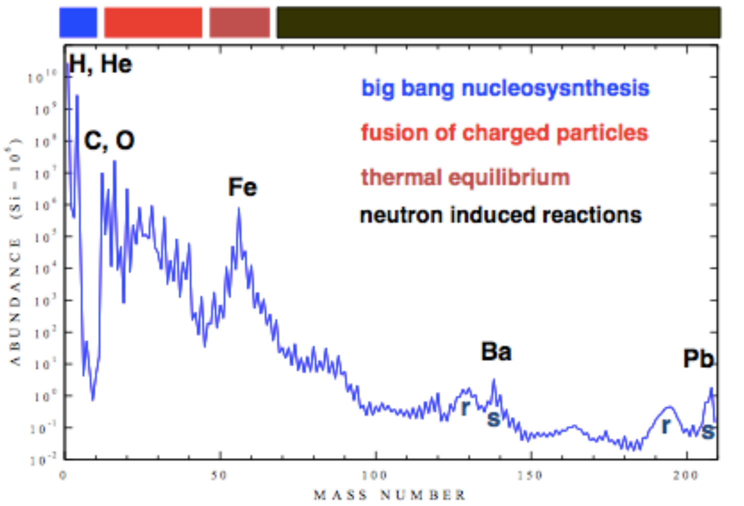
- → additional information about galactic SN
- → **global fits:** optical + neutrinos + gravitational waves
- → neutrino properties + SN explosion dynamics
- → SN1987A: strongest constraints on large extra dimensions

Element Synthesis

Reifarth



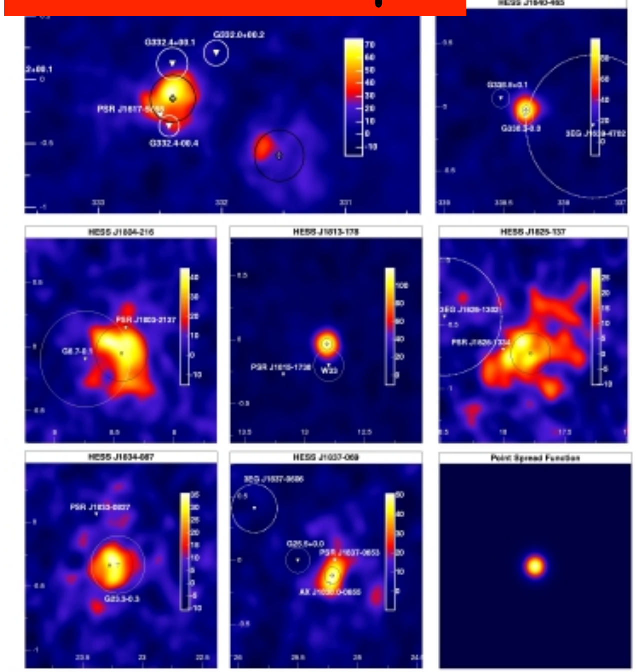




- Nuclear data on radioactive isotopes are very important for modern astrophysics
- Direct investigations are very difficult
- Indirect methods for neutron-induced reactions cover the entire range from s- via to r-process
- Neutrinos usually play a minor role, but can be a very important observable for stellar evolution

Neutrinos & TeV γ´s

HESS: TeV γ's



HESS and EGRET:

- TeV γ's from galactic center and galactic plane
- various sources observed
- some are at the position of known SN remnants
- others do not correlate to anything known?

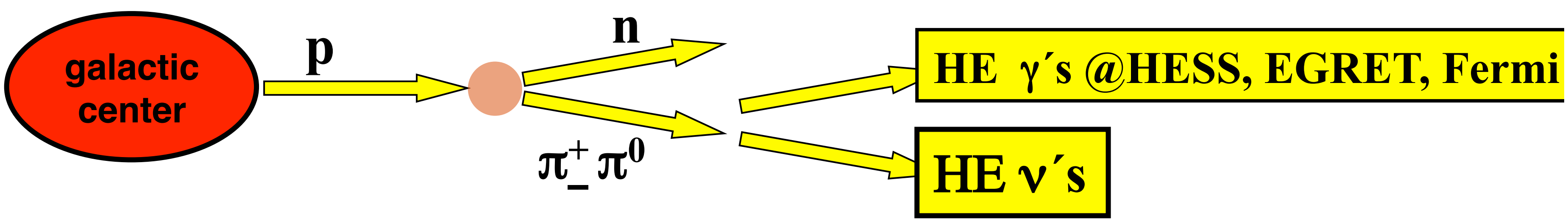
Plausible explanation:

-SN shock front acceleration

- γ´s from π^0 decay

➔ ν flux from GC

➔ ν signal @ km^3 detectors



galactic center

p

n

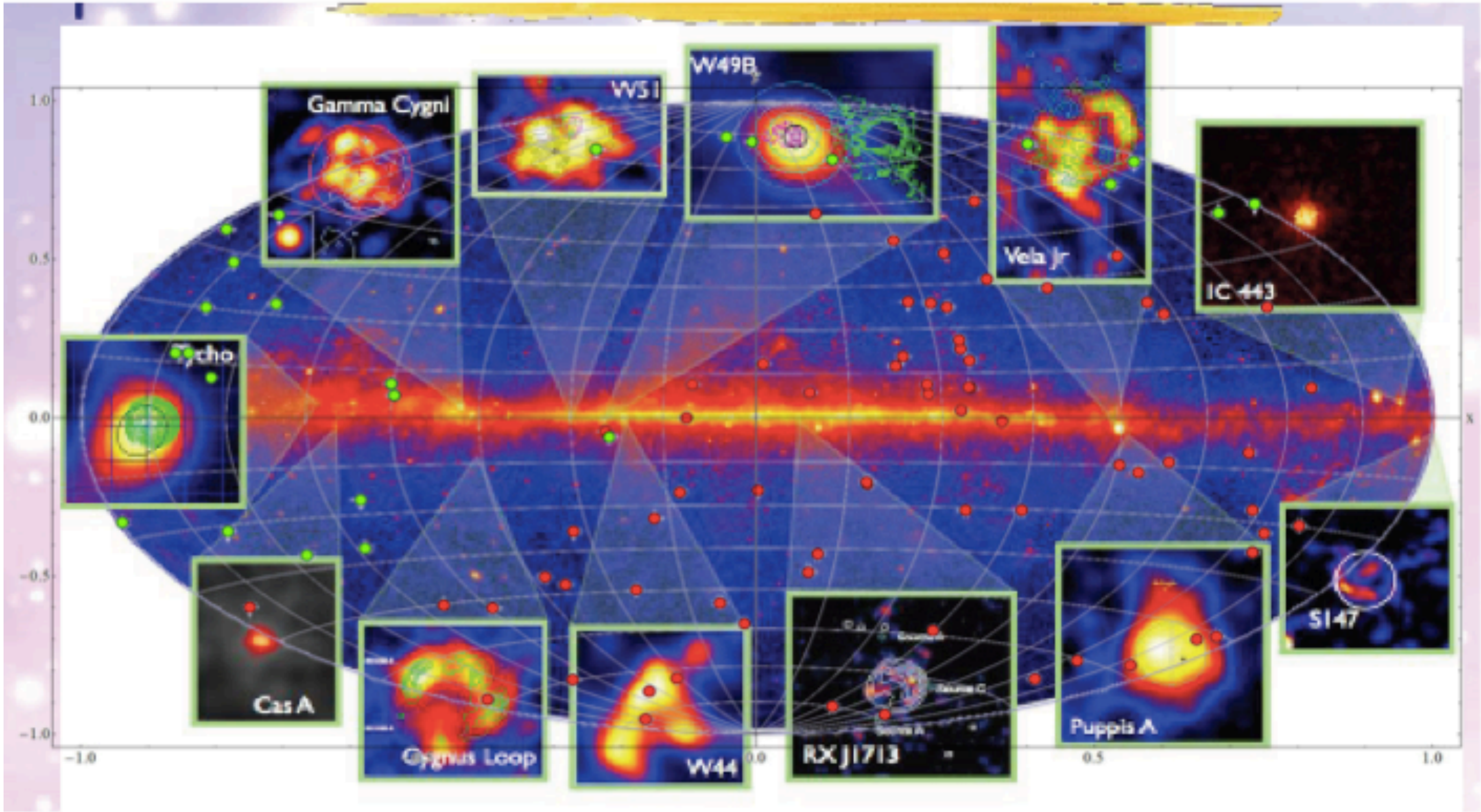
$\pi^\pm \pi^0$

HE γ´s @HESS, EGRET, Fermi

HE ν´s

Fargion

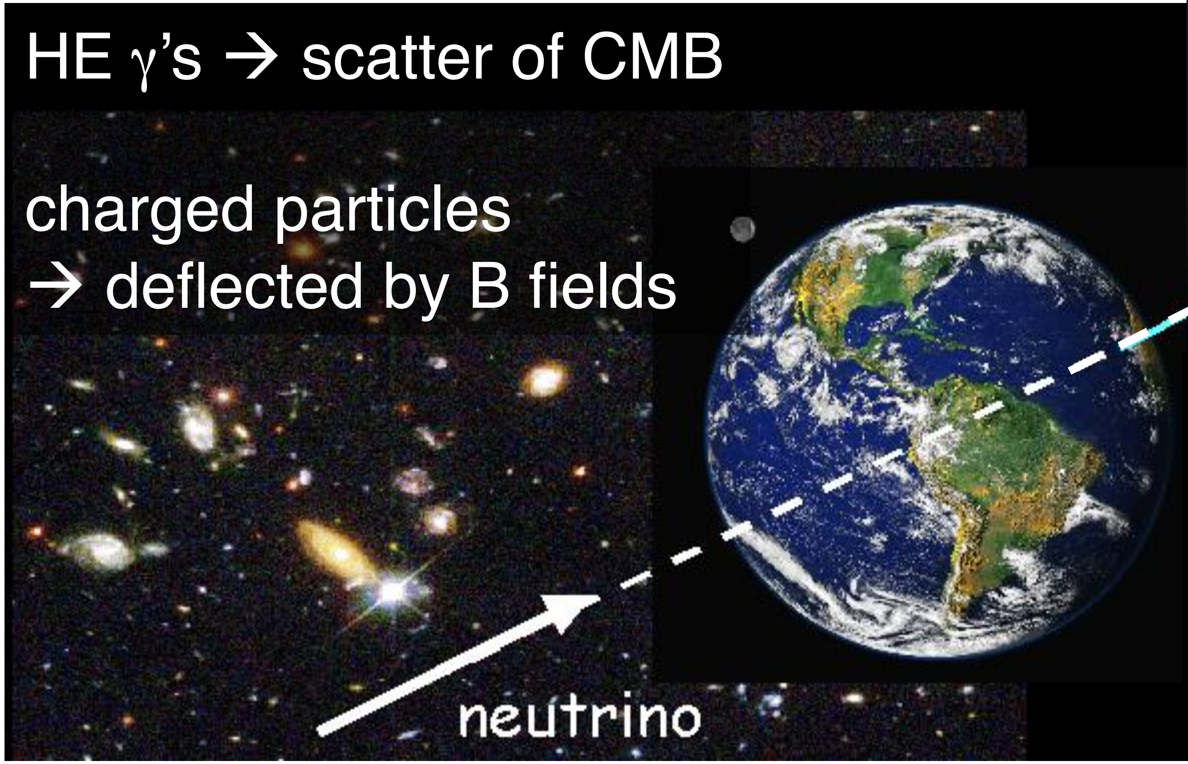
Fermi gamma sources and UHECR



Neutrino Telescopes

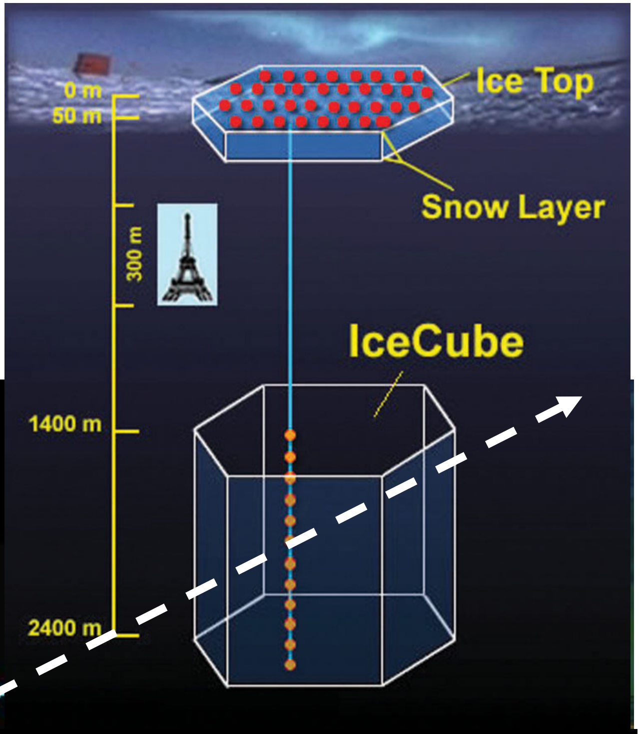
ν astronomy ←→ cosmic neutrino sources

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



HE γ's → scatter of CMB

charged particles
→ deflected by B fields



**Baikal, Amanda
IceCube, Antares,
DeepCore, …, Auger**

Paggi

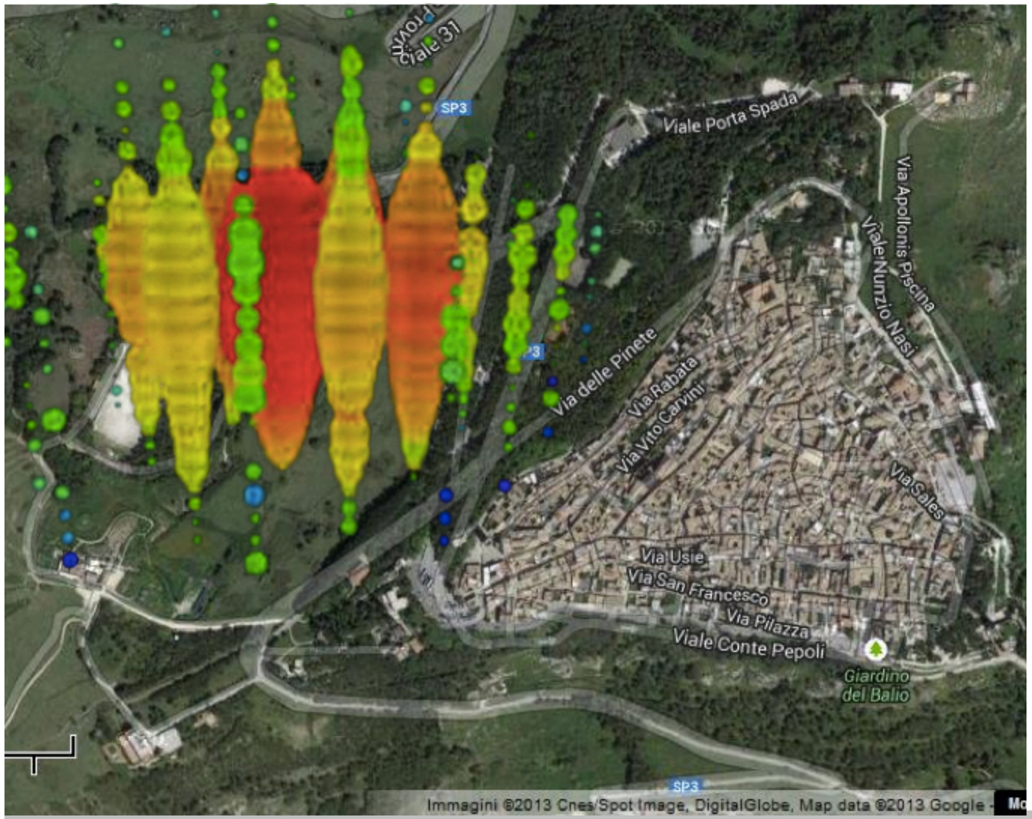
Ishihara: IceCube ➔ events up to PeV observed

Run118545-Event6373366

NPE 6.9928×10^4

GMT time: 2011/8/8 12:23:18

1.1PeV = 1100000000 MeV



<u>events in 2 years data:</u>

➔ cosistent with flavour ratio 1:1:1

➔ more statistics

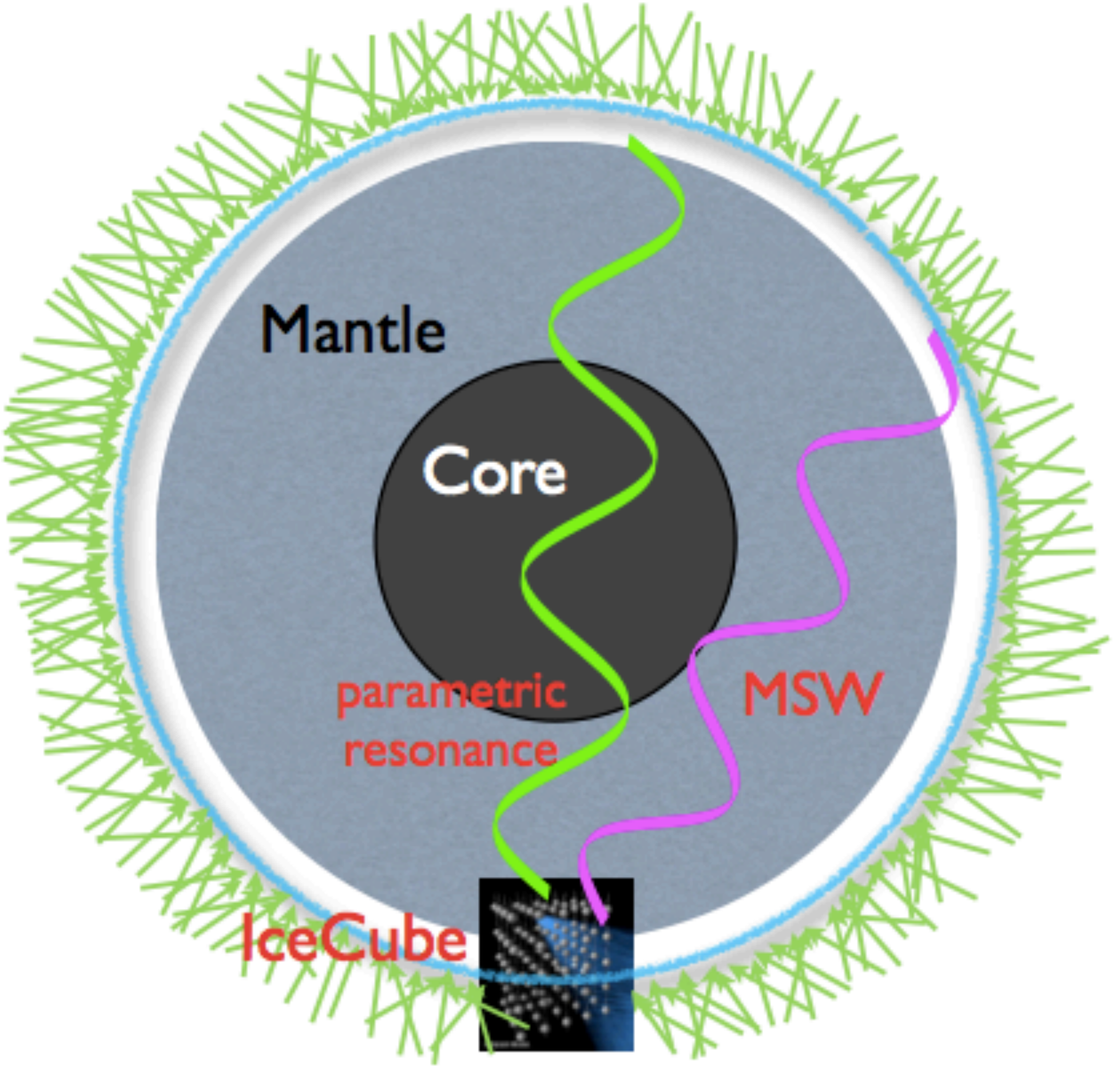
➔ rate vs. WB bound?

➔ start of ν-astronomy

atmospheric n background…

Atmospheric data and new physics:

Impact of sterile neutrinos on atm υ flux



- eV mass gives resonant enhanced matter effects in the TeV region

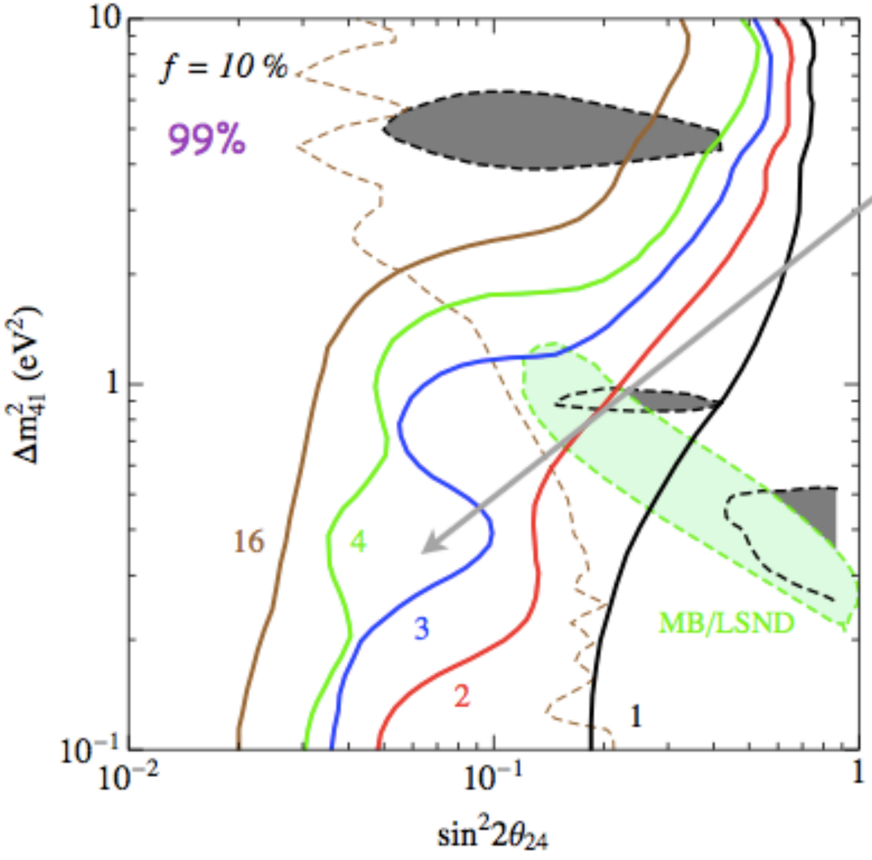
  H. Nunokawa, O. L. G. Peres,
  R. Zukanovich-Funchal
  Phys. Lett. B562 (2003) 279

- atmospheric neutrinos in IceCube

IceCube atmospheric ν's sensitivity to sterile neutrinos

(3x IceCube-79 data are available)

A. E., A. Yu. Smirnov,
arXiv: 1307.6824



sensitivity significantly enhanced by using energy spectrum (number of bins)

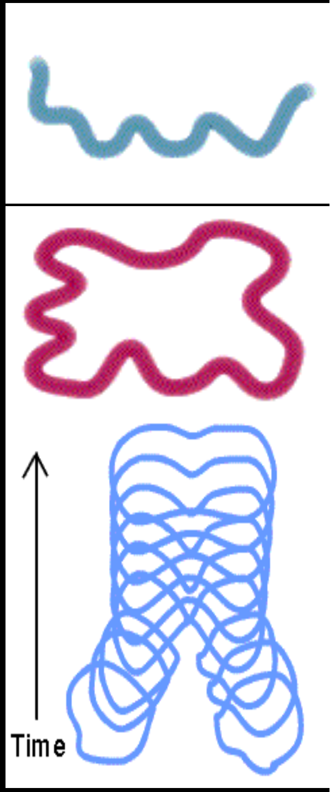
IceCube can test the LSND/MiniBooNE "evidence"

It's on the tapes
➔ look at it!

The thermal evolution of the Universe:

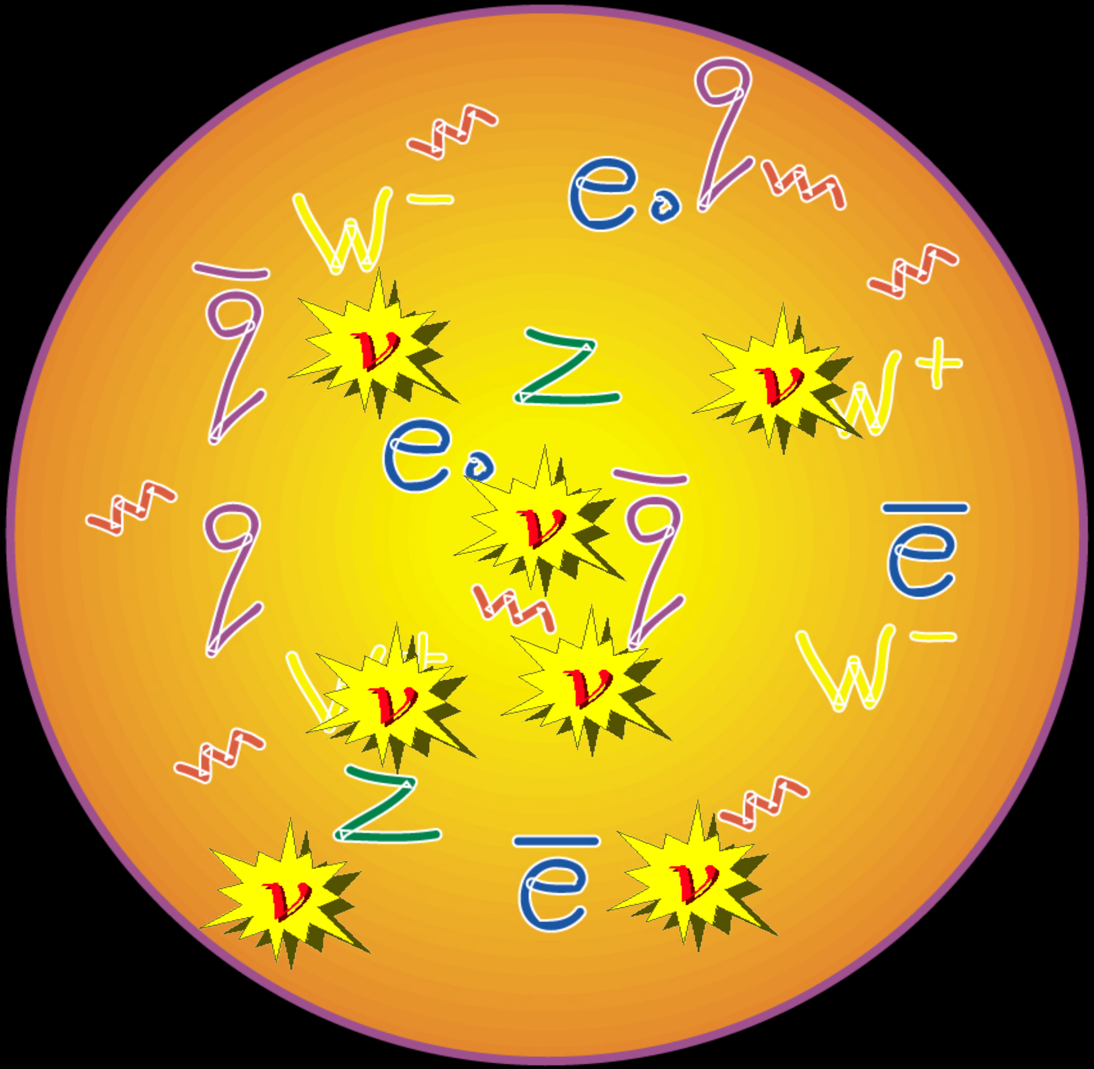
10^{-43} seconds

speculative physics:
10^{19}GeV:Strings, ...



10^{32} degrees

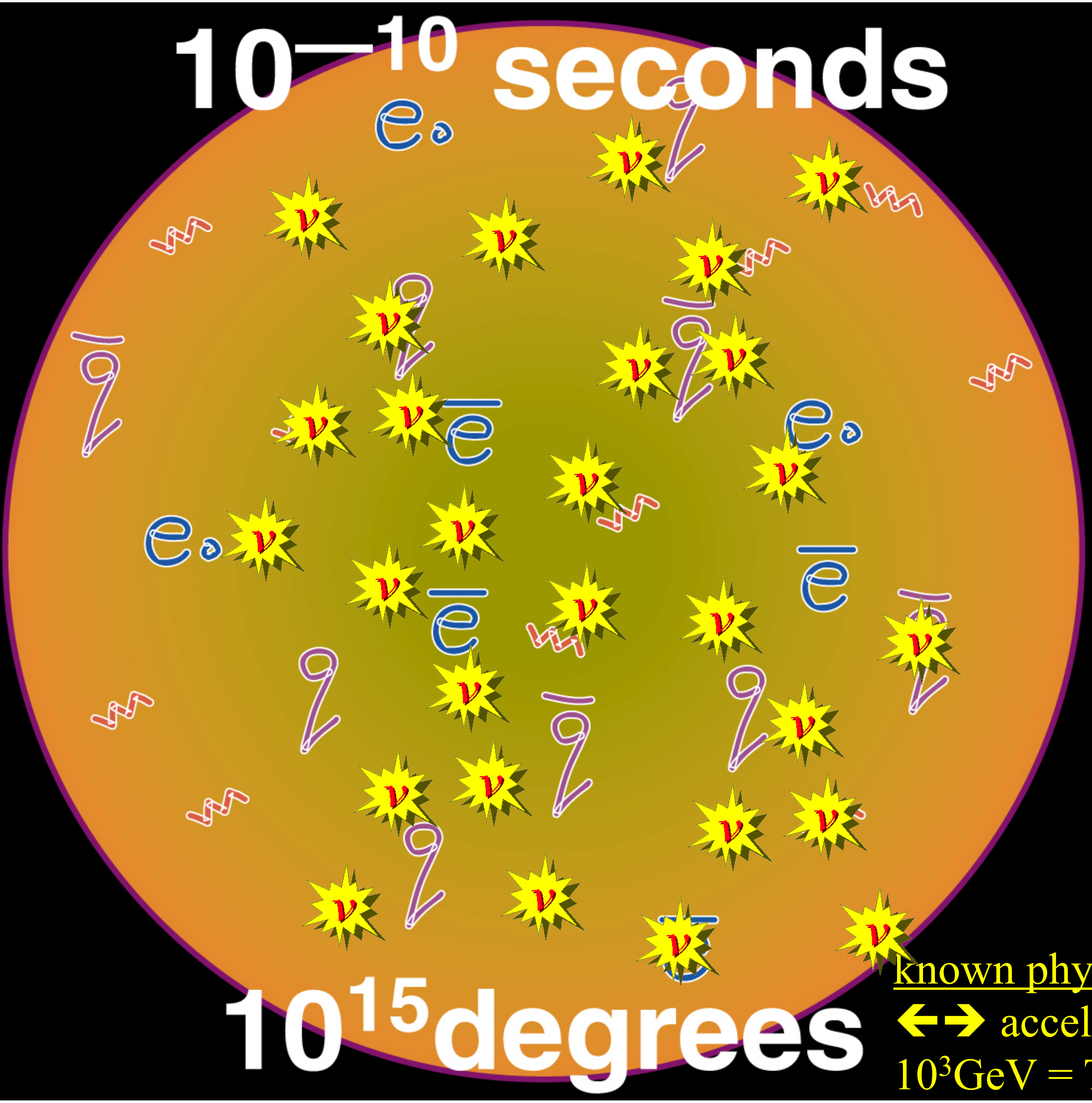
10^{-34} seconds



10^{27}degrees

GUT physics:
10^{16}GeV

10^{-10} seconds



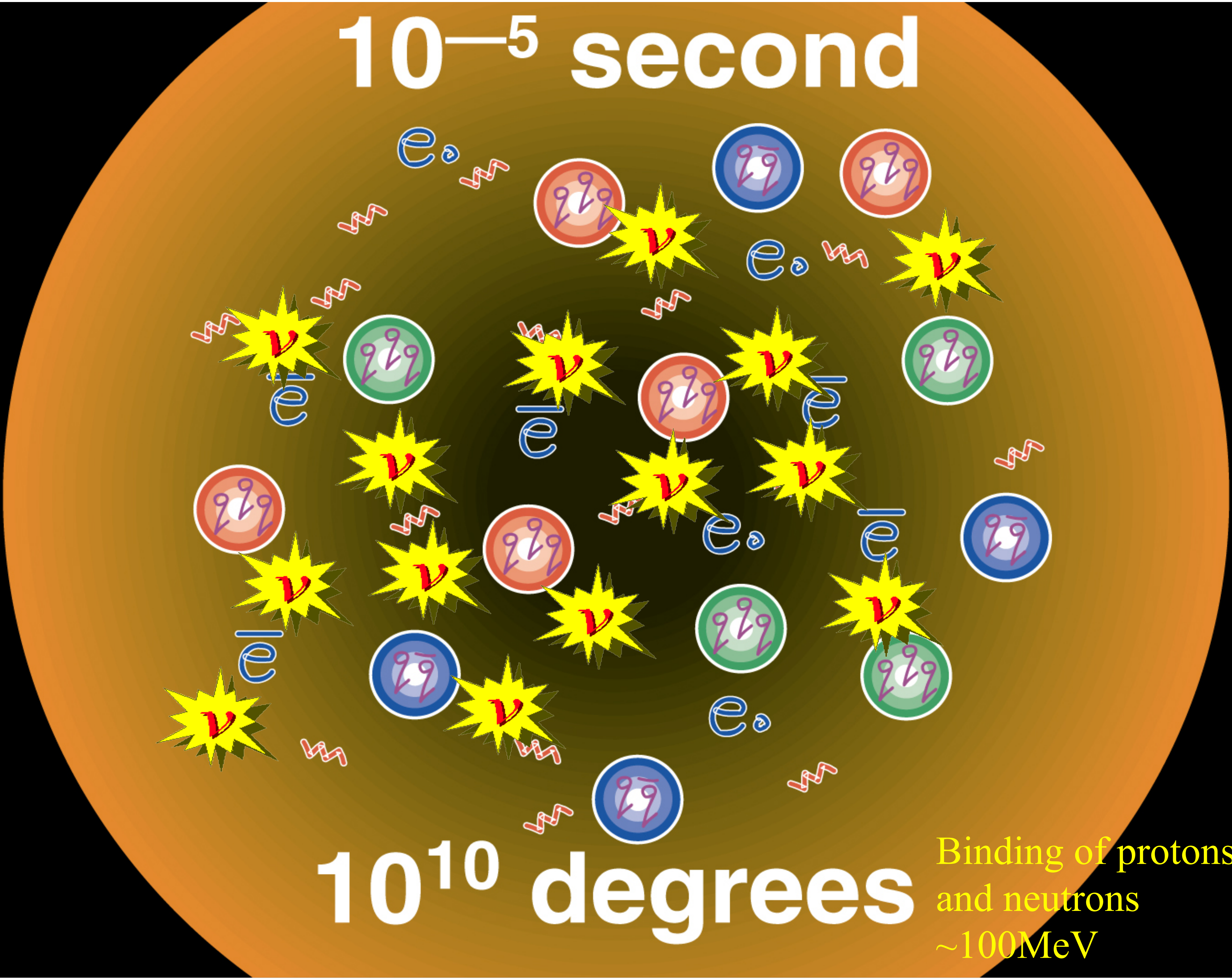
10^{15}degrees

known physics:

←→ accelerators

10^3GeV = TeV

10^{-5} second

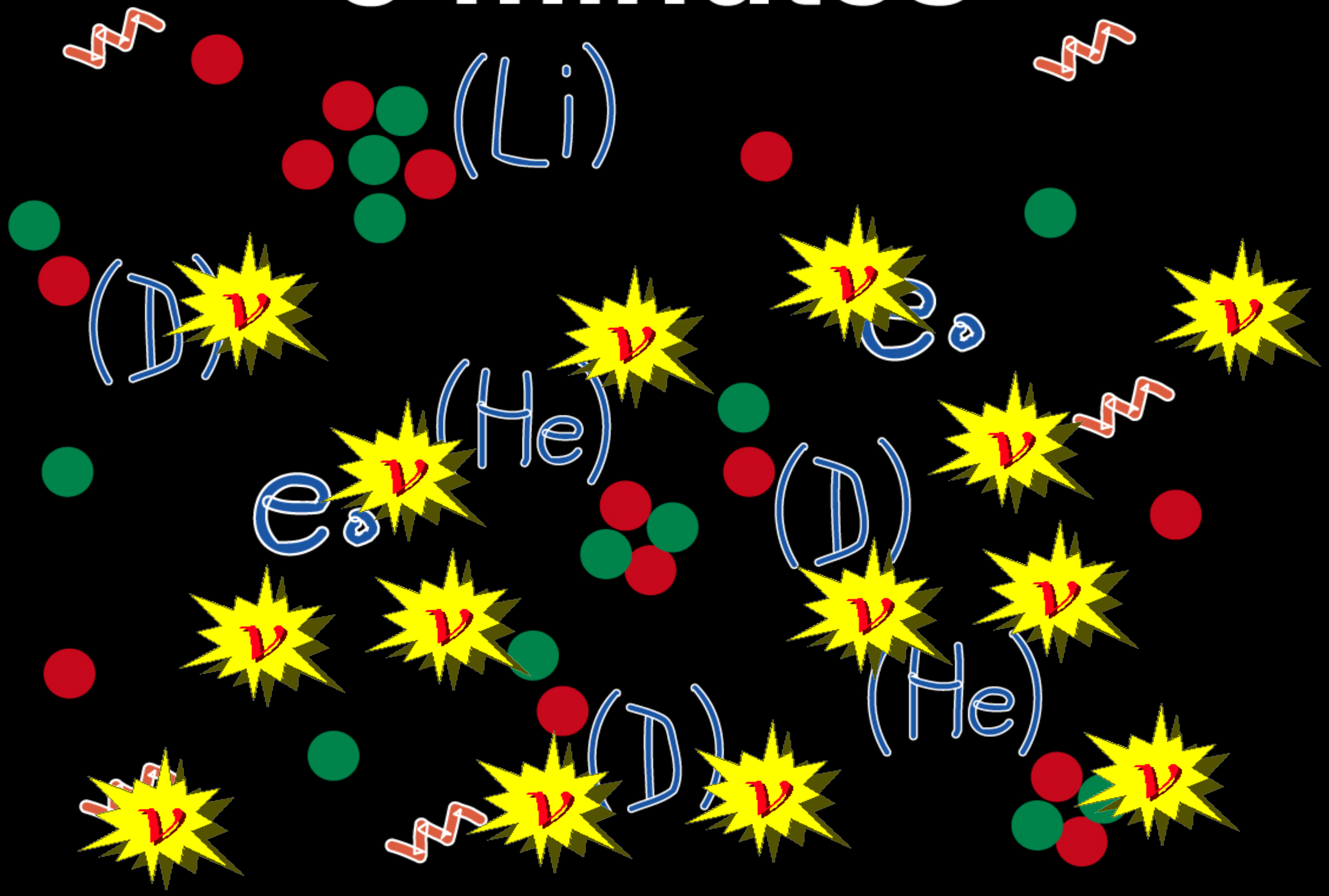


10^{10} degrees

Binding of protons and neutrons

~100MeV

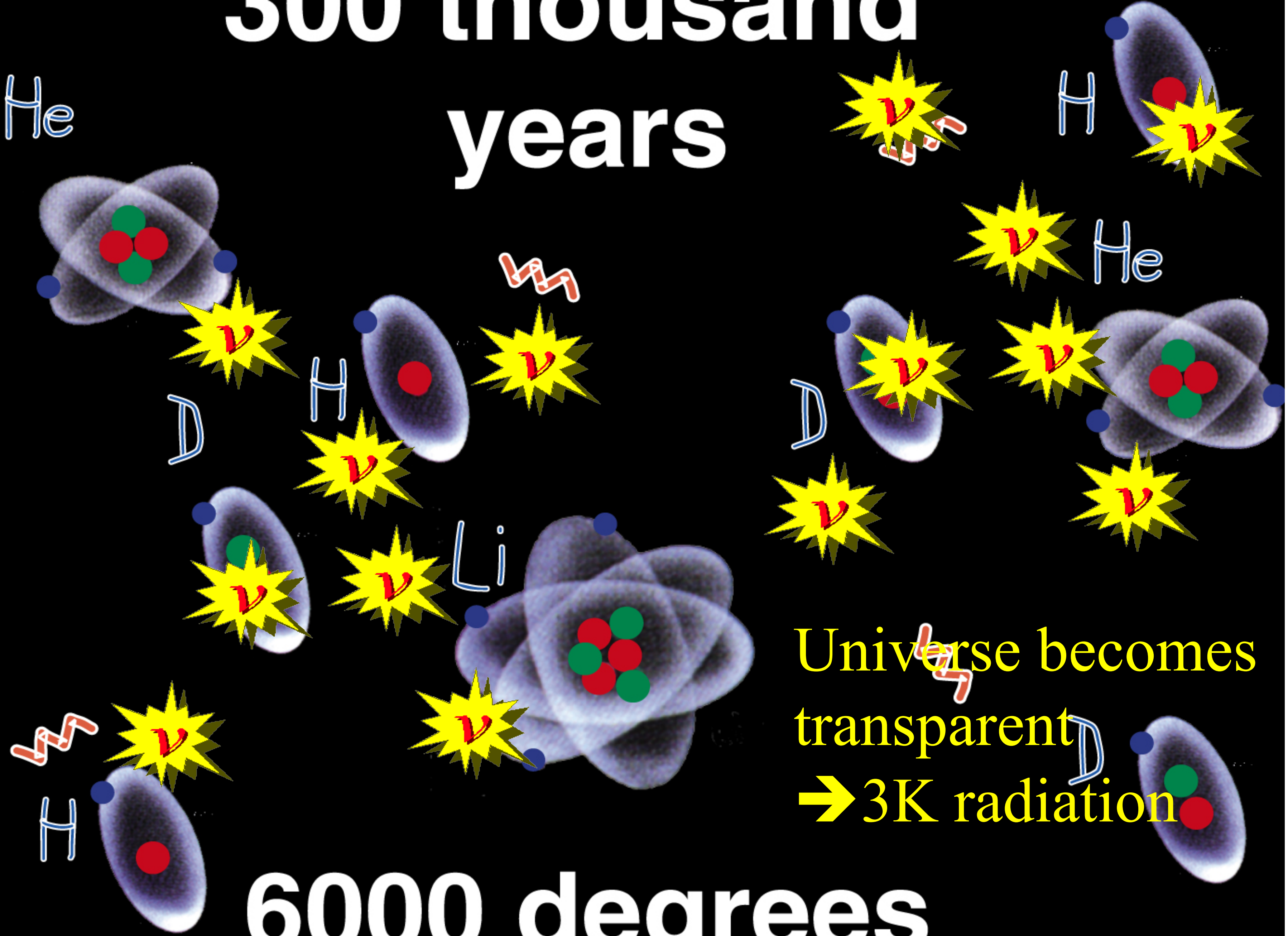
3 minutes



10^9 degrees

Synthesis of light elements

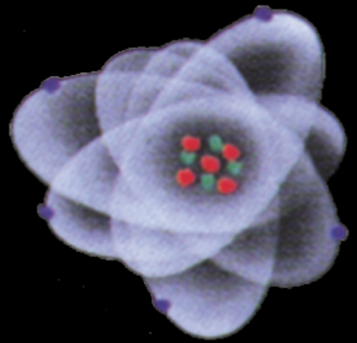
300 thousand years



Universe becomes transparent
→3K radiation

6000 degrees

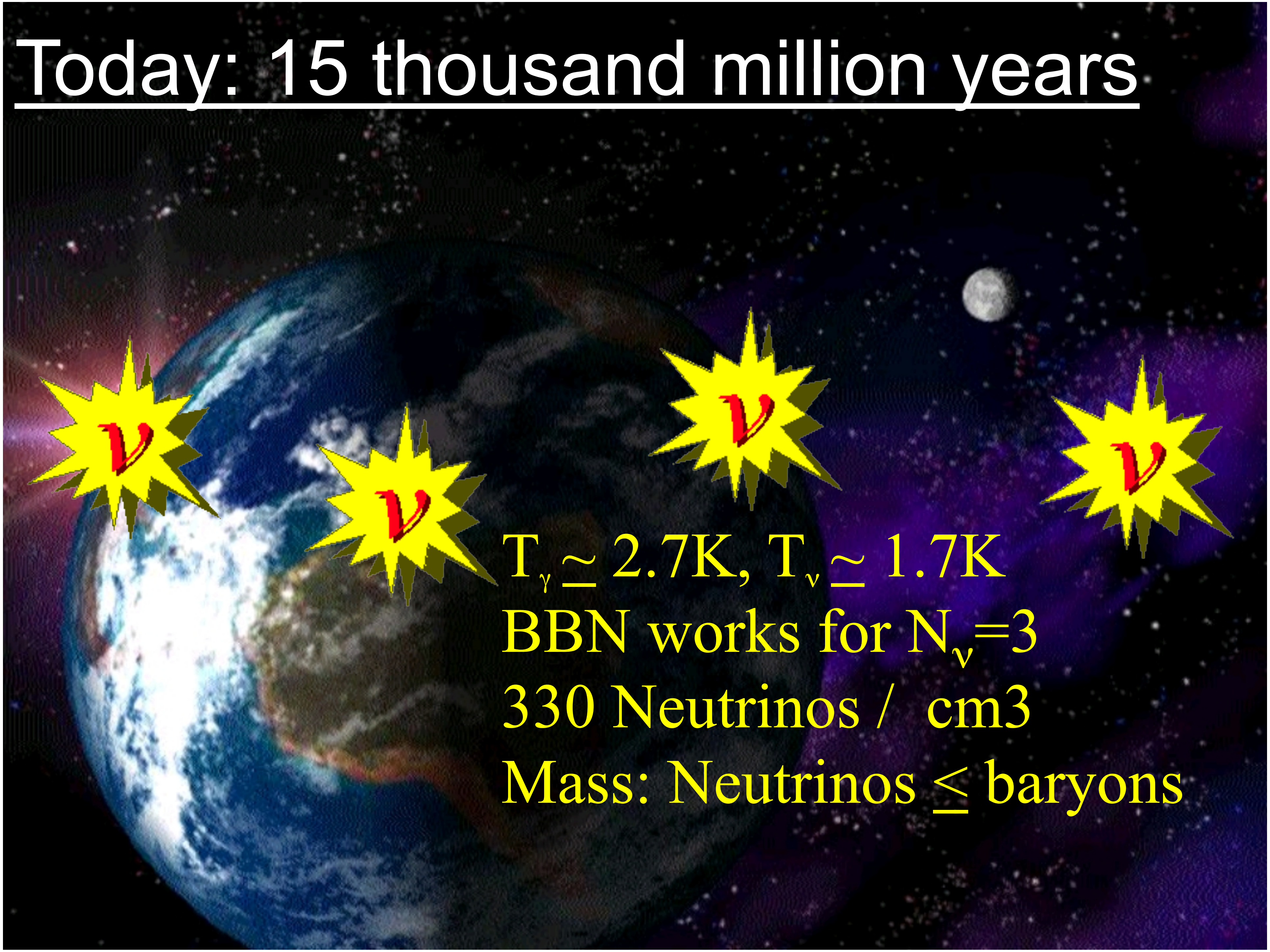
1 thousand million years



Structure formation,
molecules, …

18 degrees

Today: 15 thousand million years



$T_\gamma \simeq 2.7\text{K}$, $T_\nu \simeq 1.7\text{K}$

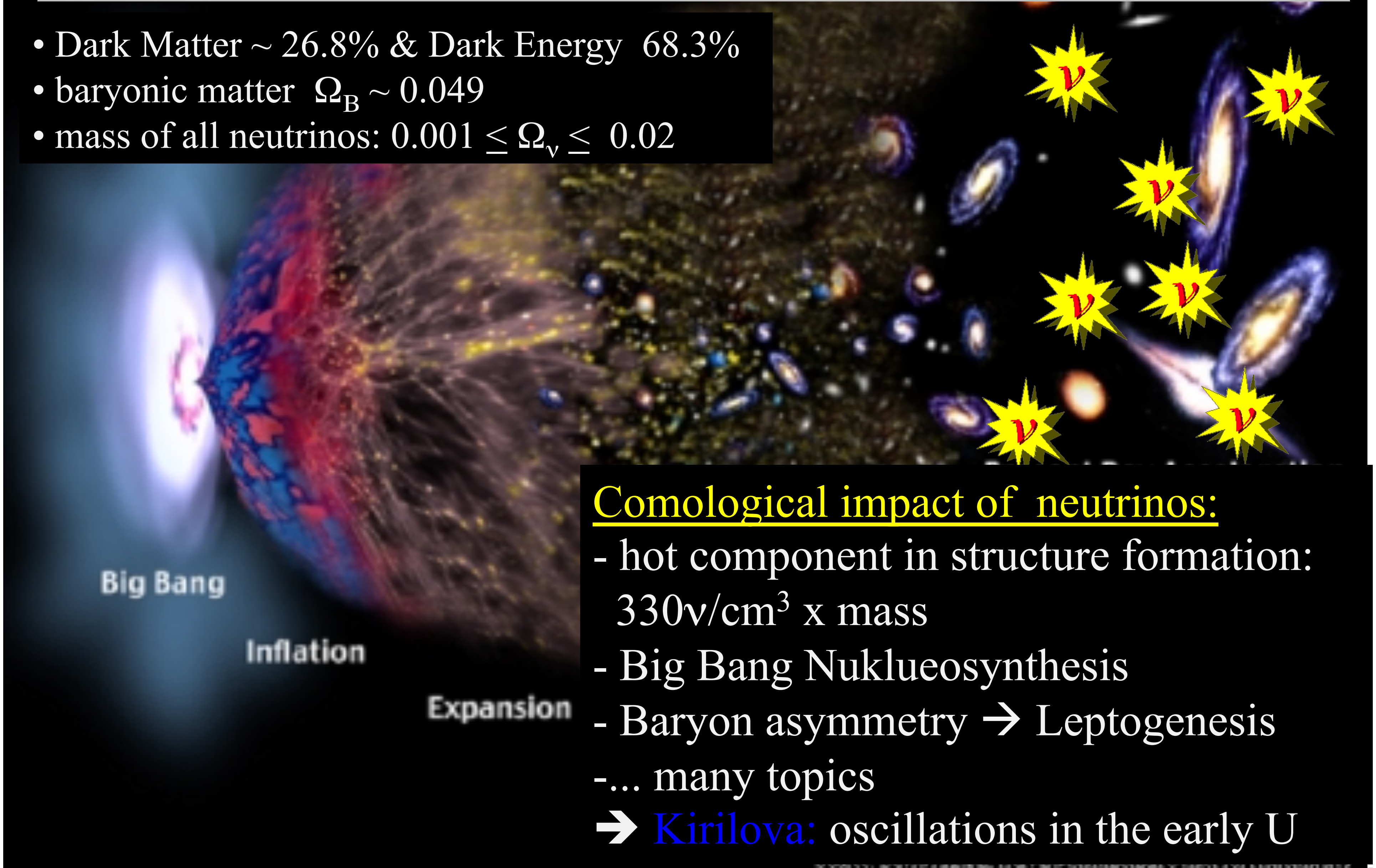
BBN works for $N_\nu=3$

330 Neutrinos / cm3

Mass: Neutrinos $\leq$ baryons

Neutrinos & Cosmology

- Dark Matter ~ 26.8% & Dark Energy 68.3%
- baryonic matter $\Omega_B \sim 0.049$
- mass of all neutrinos: $0.001 \leq \Omega_\nu \leq 0.02$



Comological impact of neutrinos:

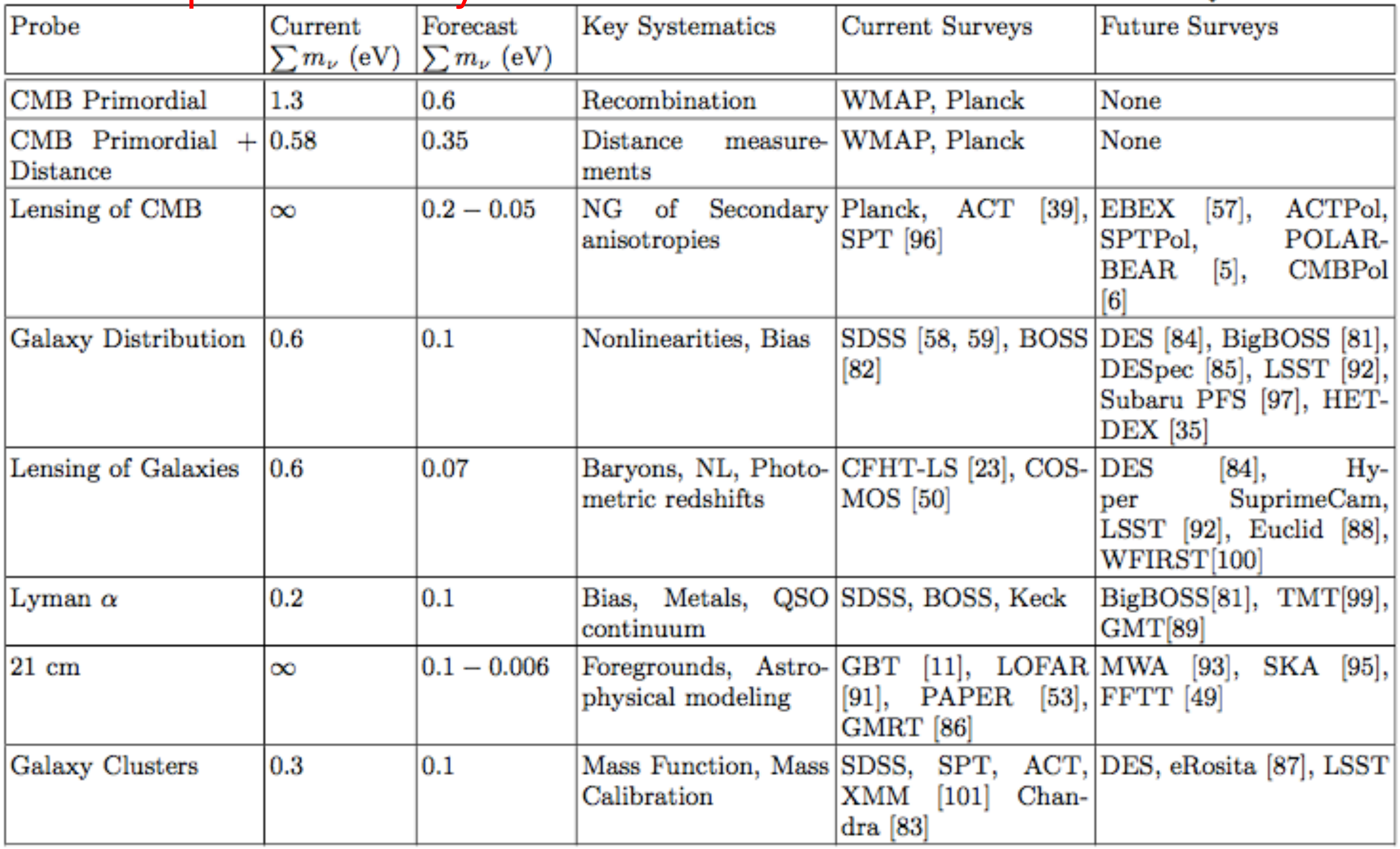
- hot component in structure formation: $330\nu/\mathrm{cm}^3$ x mass
- Big Bang Nuklueosynthesis
- Baryon asymmetry → Leptogenesis
-... many topics

→ Kirilova: oscillations in the early U

Neutrino Masses from Cosmology

Different probes and systematcis…

Abazajian et al.



Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

Planck 2013: Strongest bounds (CMB lensing):

$$\boxed{\sum m_i < 0.66 \text{ eV}}$$

(thermalized, no late decays, etc. …←→ sterile)

Four Methods of Mass Determination

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

reactor neutrino oscillations **Goeger-Neff, Dywer, Kim**
neutrino beams: **Jediny, Berger, Rahaman, Hagner**
new ideas/projects: **Oberauer, Vogel**

Precision Oscillation Physics

Precise measurements ➔ 3f oscillation formulae

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

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**

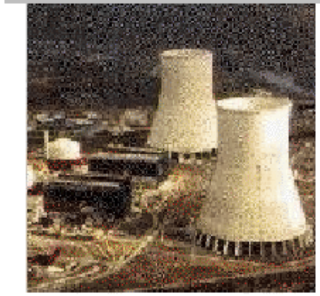
Complication: **Matter effects ➔ effective parameters in matter**

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

Burguet-Castell et al., Akhmedov, Johannsen, ML, Ohlssen, Schwetz

➔ **exact: numercial simulation with GLoBES** **Huber, Kopp, ML, Winter**

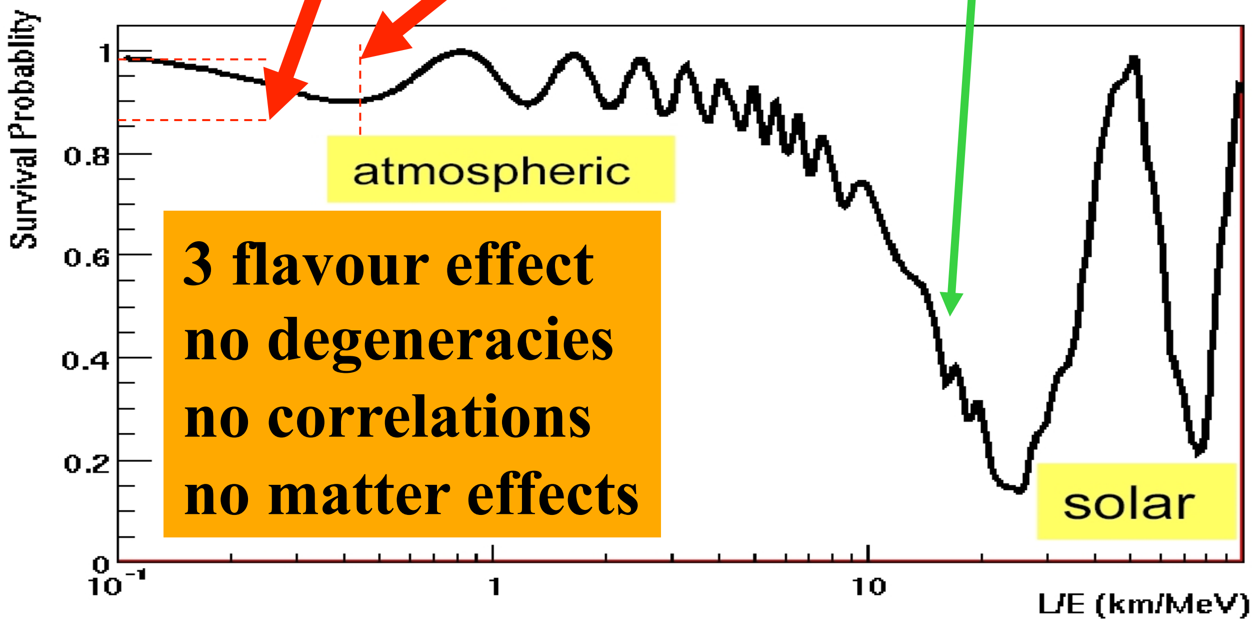
Future Precision with Reactor Experiments



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

identical detectors ➔ many errors cancel

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



3 flavour effect
no degeneracies
no correlations
no matter effects

E=4MeV ➔ 2km 4km 40km 80km

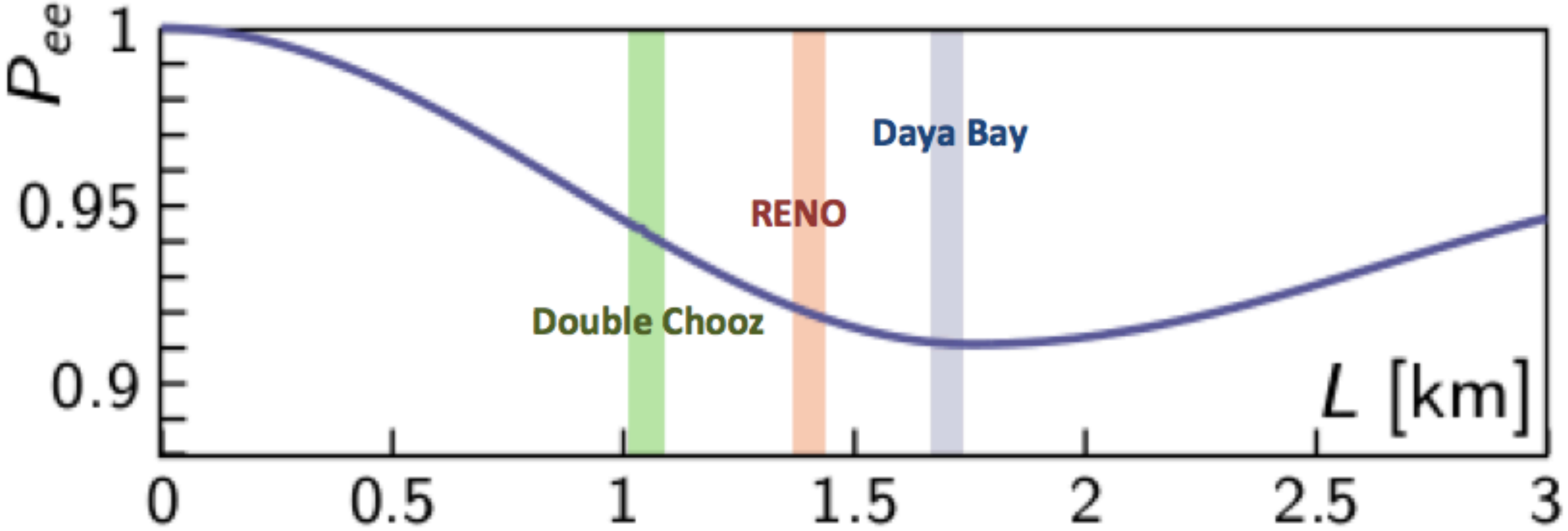
- ➔ **Double Chooz**
- ➔ **Daya Bay**
- ➔ **Reno**

clean & precise
θ_{13} measurments

Think in Event Rates – No Probability!

Baseline Optimization

Atmospheric and accelerator ν oscillation $\Delta m^2_{\mu\mu}$ suggest to search at ~1.8 km.



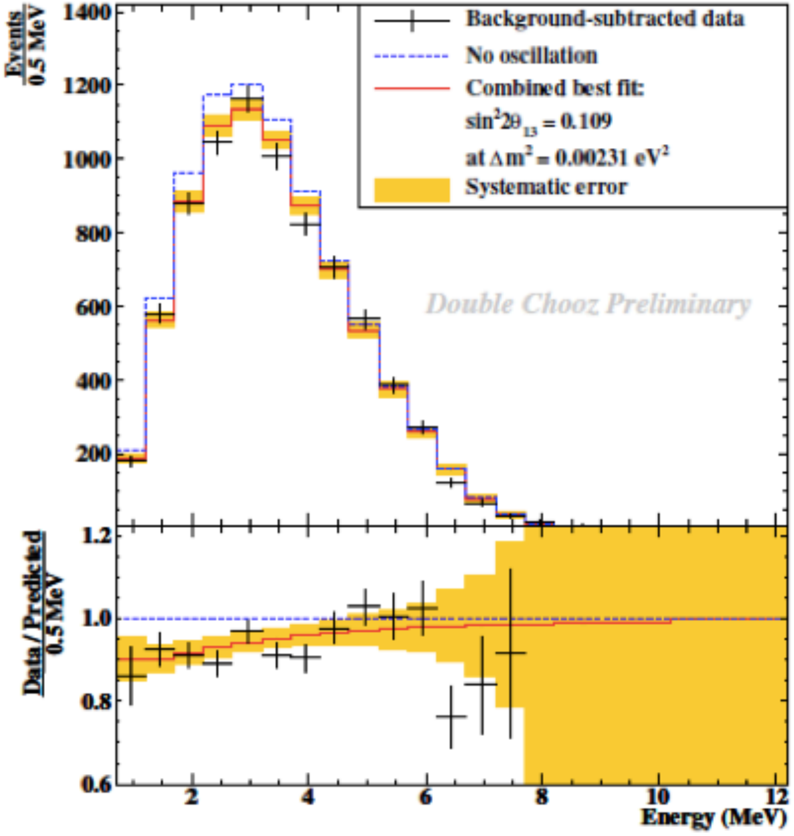
$\text{Rate} \simeq P_{\text{reactor}} * \boxed{P_{ee} * 1/R^2}$ ➔ optimal L < osc. minimum

distribution of reactors, cycles, …

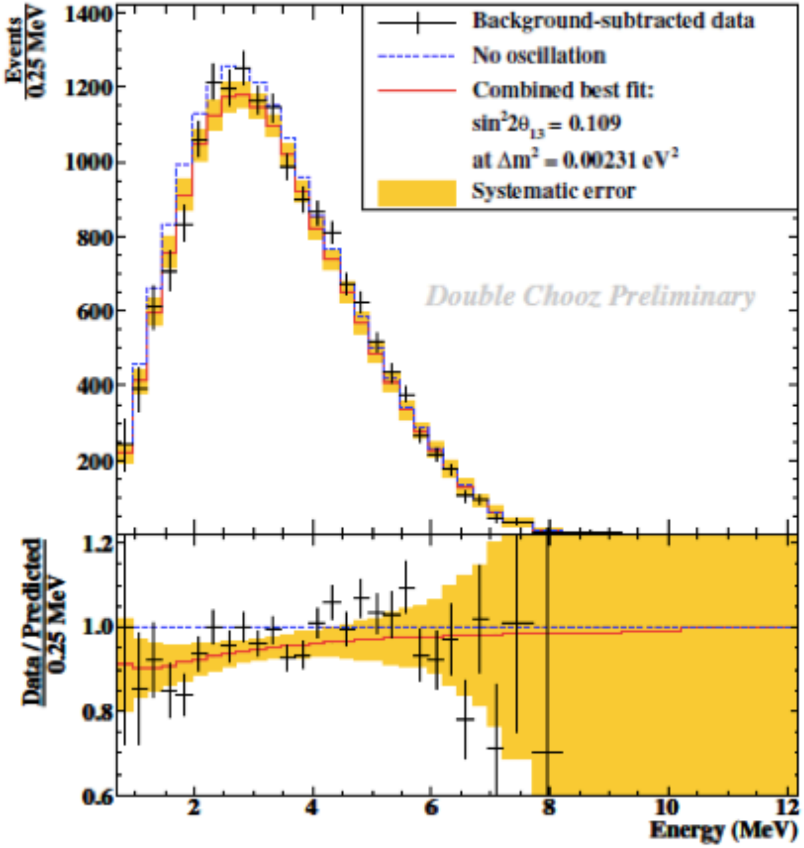
NEW: Combined Gd and H analysis

Goeger-Neff

Gd data



H data

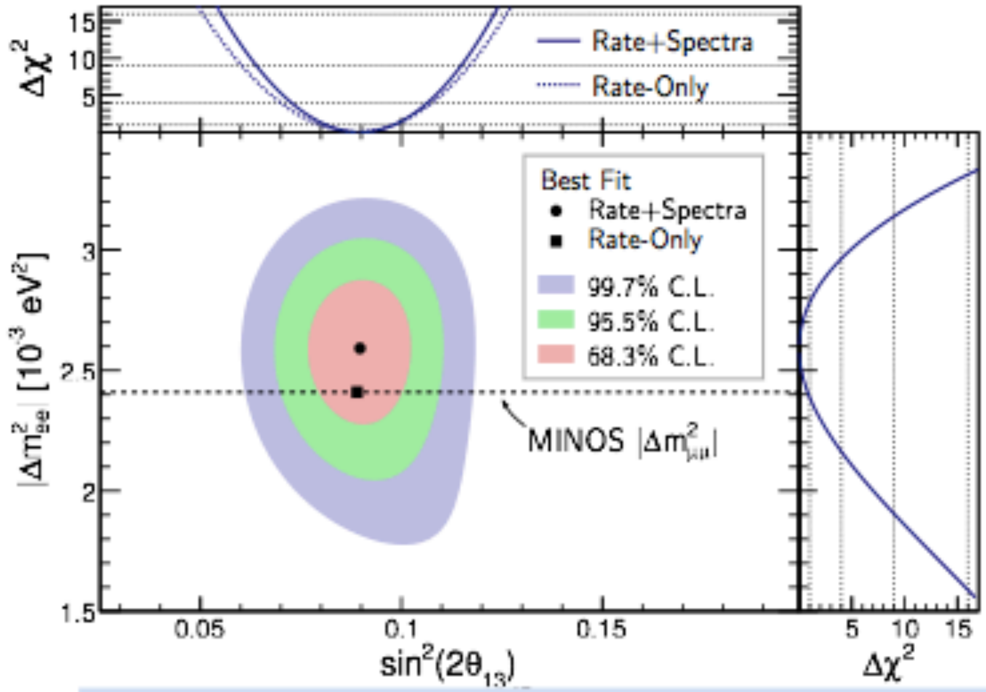


Combined Rate+Shape fit:

$\sin^2 2\theta_{13} = 0.109 \pm 0.035$ $\chi^2/\text{dof} = 61.2/50$

Rate+Spectra Oscillation Results

Dywer



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

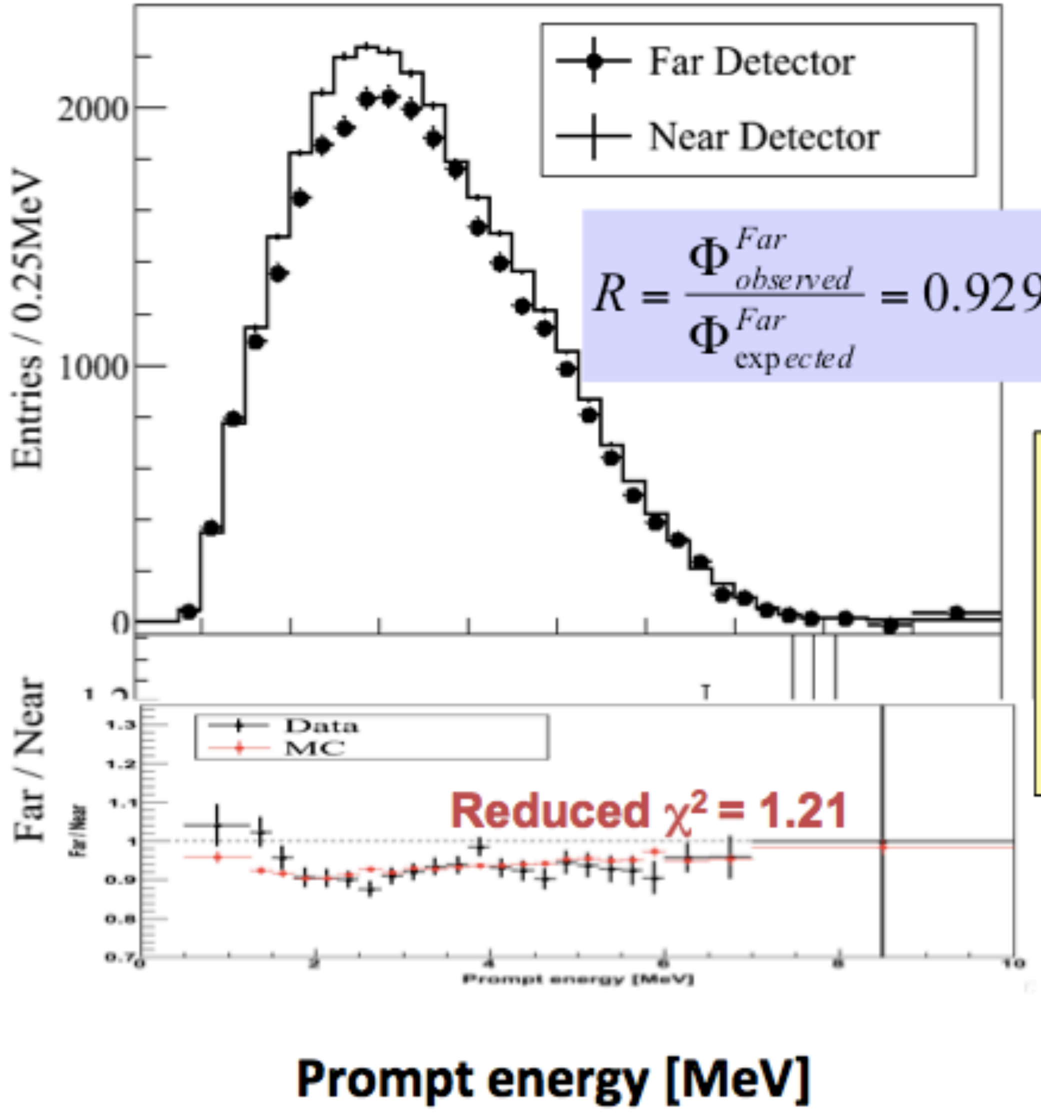
$$\chi^2/N_{\text{DoF}} = 162.7/153$$

Strong confirmation of three-flavor oscillation model

	Normal MH Δm^2_{32} $[10^{-3}\text{eV}^2]$	Inverted MH Δm^2_{32} $[10^{-3}\text{eV}^2]$
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

Reactor Antineutrino Disappearance

Kim



Reduced $\chi^2 = 1.21$

preliminary

$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006(stat) \pm 0.007(syst)$$

- A clear deficit in rate

  (~ 7 % reduction)

- Consistent with neutrino oscillation in the spectral distortion

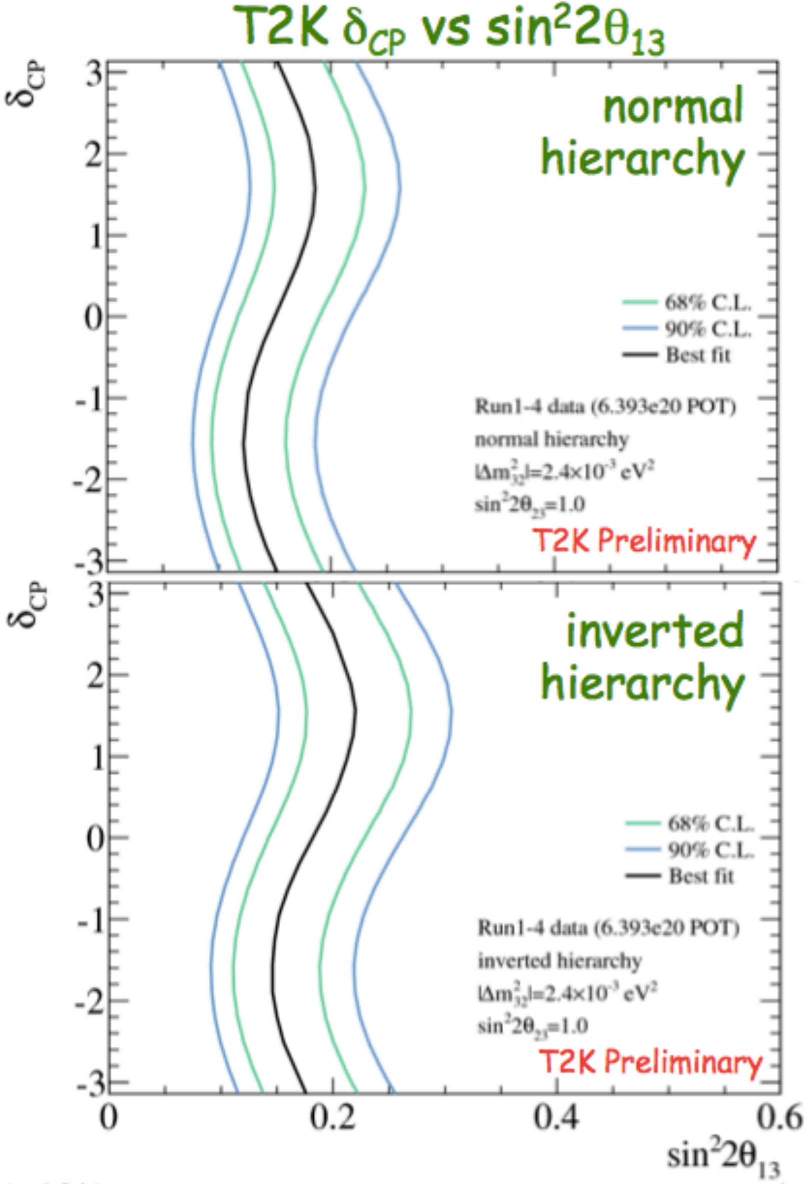
$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat.) \pm 0.012(syst.)$$

T2K: ν_e Appearance Results

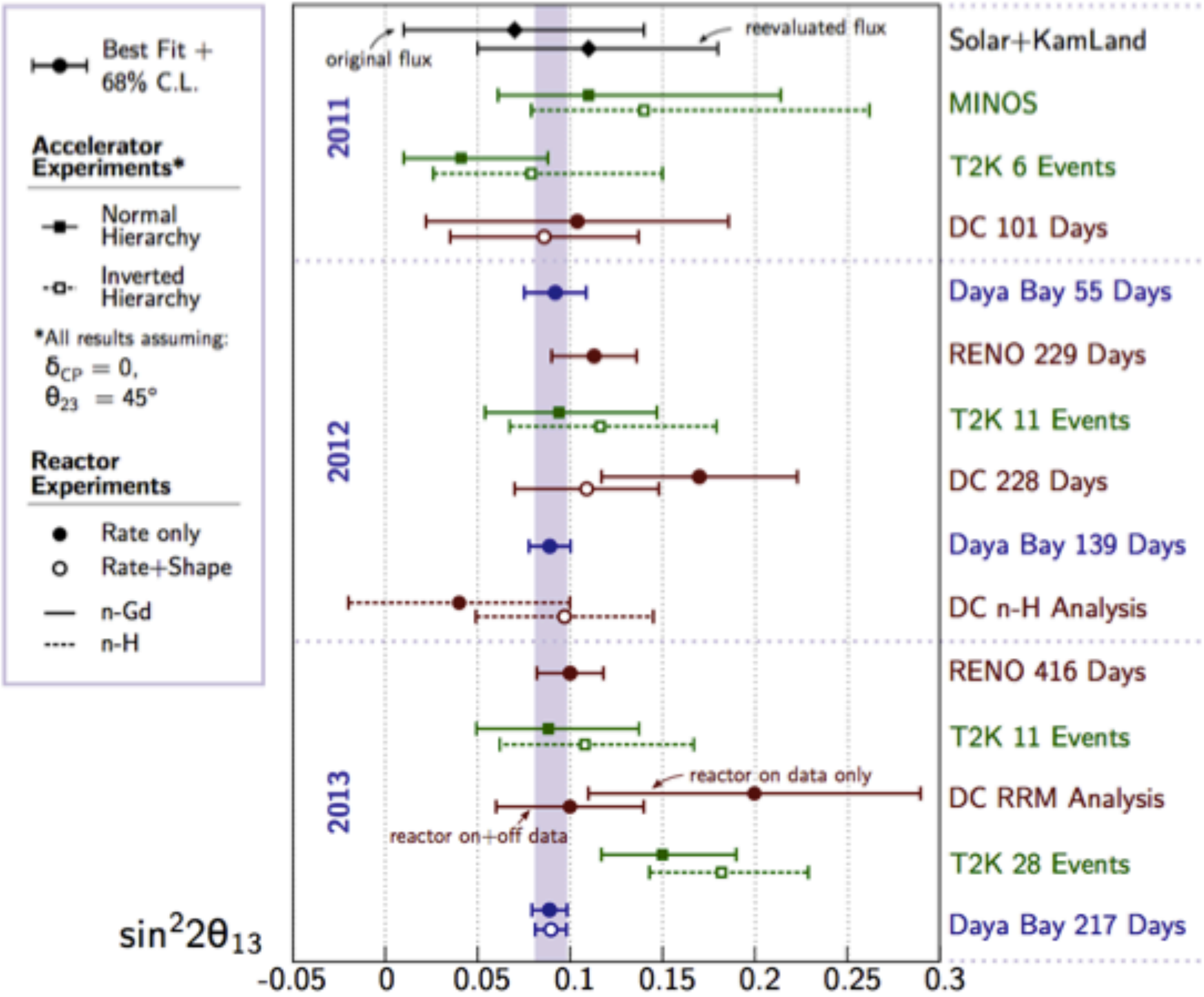
Berger

- Observed 28 events
  (vs. 4.64 ± 0.53 background)
- Comparing best fit vs. null hypothesis:
  7.5σ significance for non-zero θ_{13}
  (normal hierarchy, $\sin^2 2\theta_{23} = 1.0$, $\delta_{CP} = 0$)
- First observation (>5σ) of a
  neutrino appearance channel

Note: contours are 1D contours at
fixed values of δ_{CP}, not 2D contours


T2K δ_{CP} vs $\sin^2 2\theta_{13}$

Global Comparison of θ_{13} Measurements



cartoon removed

θ_{13} is now rather good known – what next?

- improvements of mass differences /mixing angles…
- important: CP violation and mass hierarchy ➔
- important: is the 3 flavour picture complete?

  ←→ do sterile neutrinos or other extra physics exist?
- AND: How to best find out?

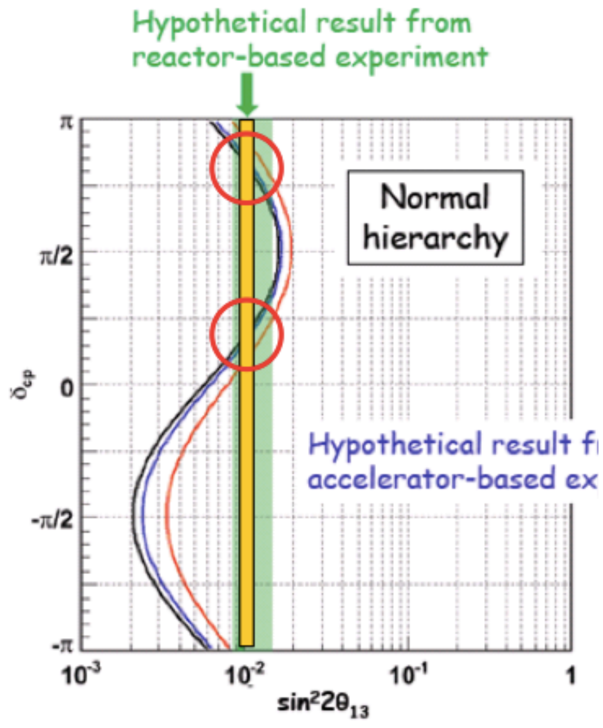
Future Precison with New Neutrino Beams

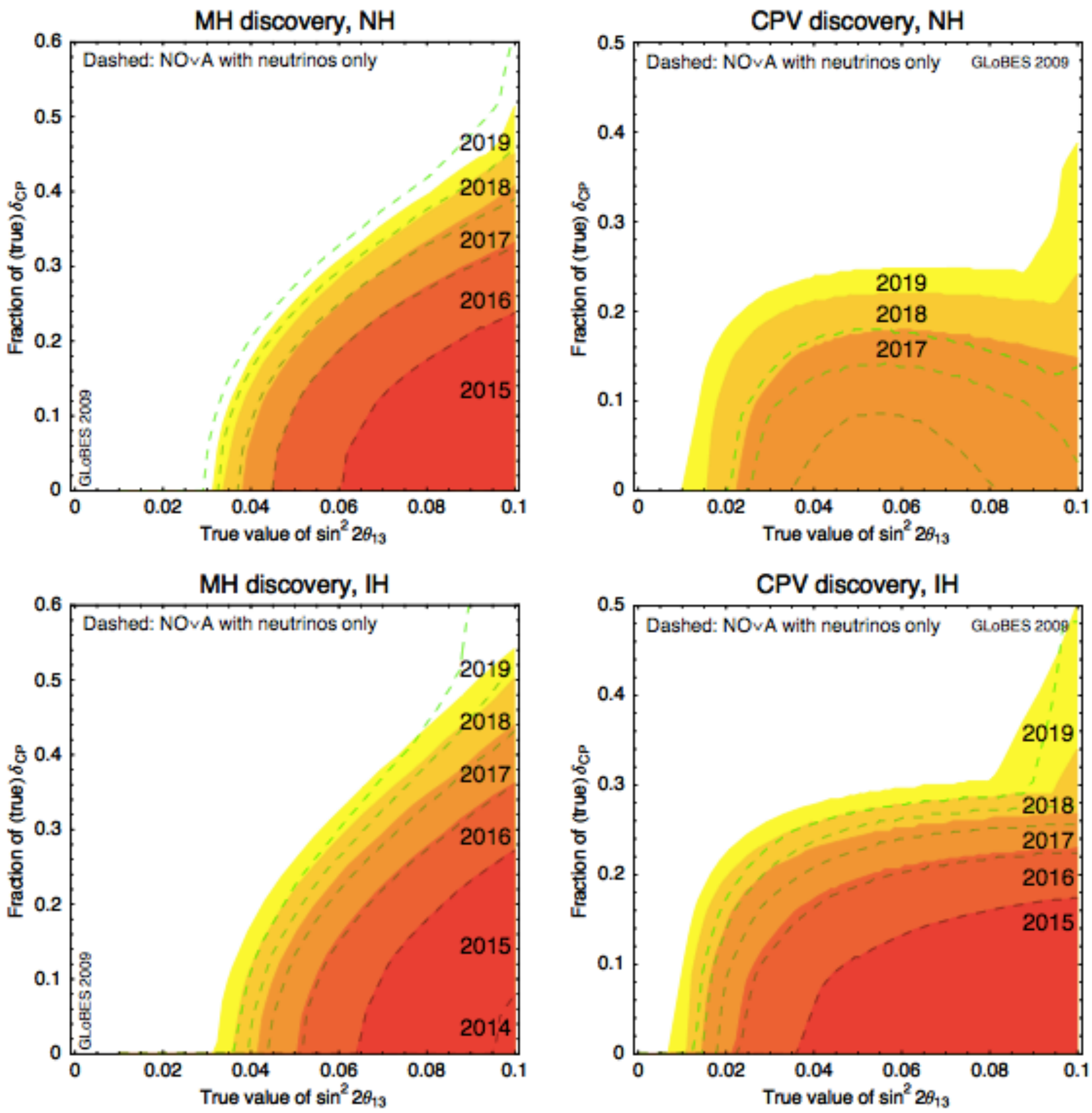
- **conventional beams, superbeams**
  ➔ **MINOS, CNGS, T2K, NOνA, T2H,…**
- **β-beams**
  ➔ **pure ν_e and $\bar{\nu}_e$ beams from radioactive decays; $\gamma \simeq 100$**
- **neutrino factories**
  ➔ **clean neutrino beams from decay of stored μ's**

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

➔ **correlations & degeneracies, matter effects**

Kim



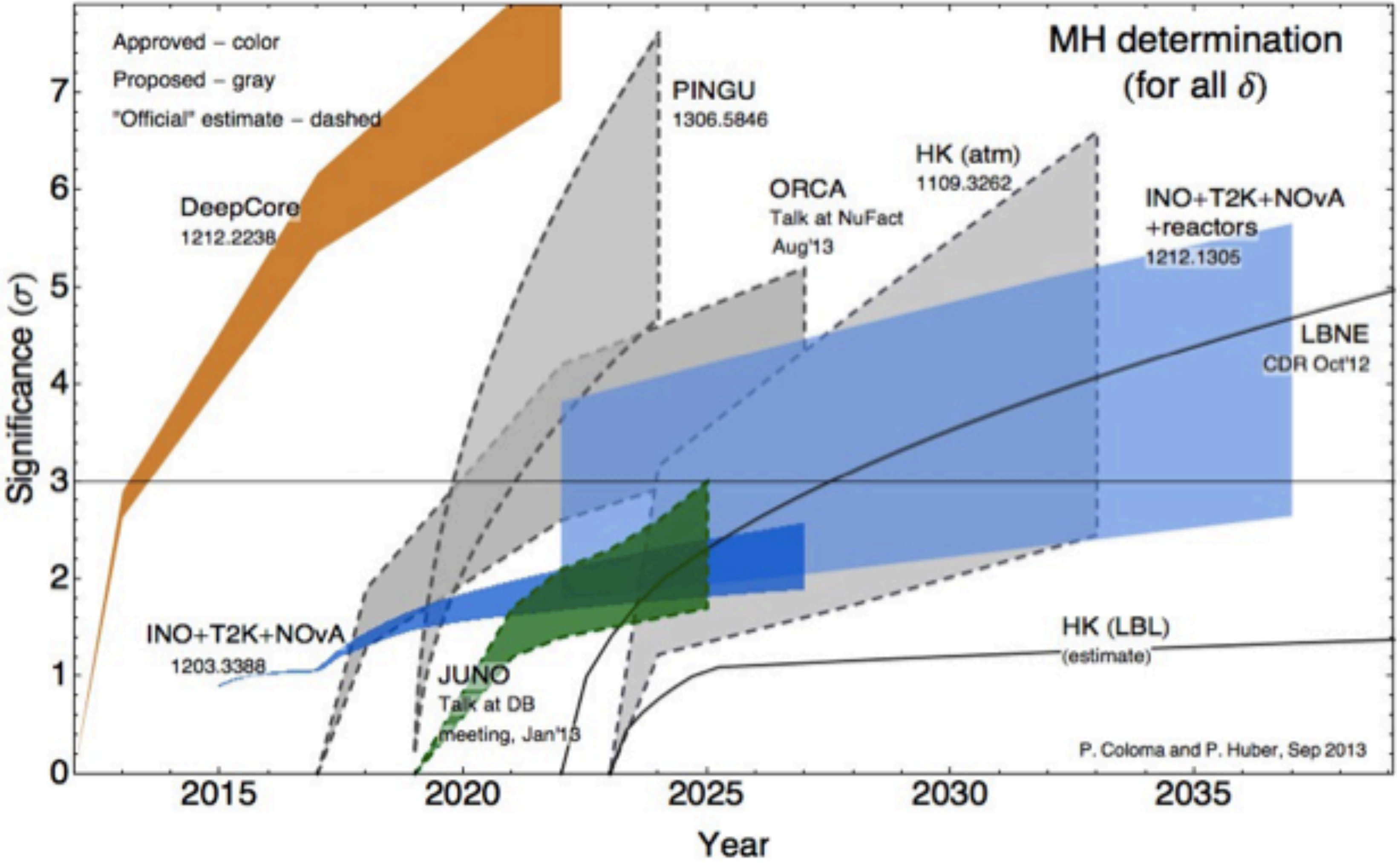


Huber, ML, Kopp, +Schwetz (2009)

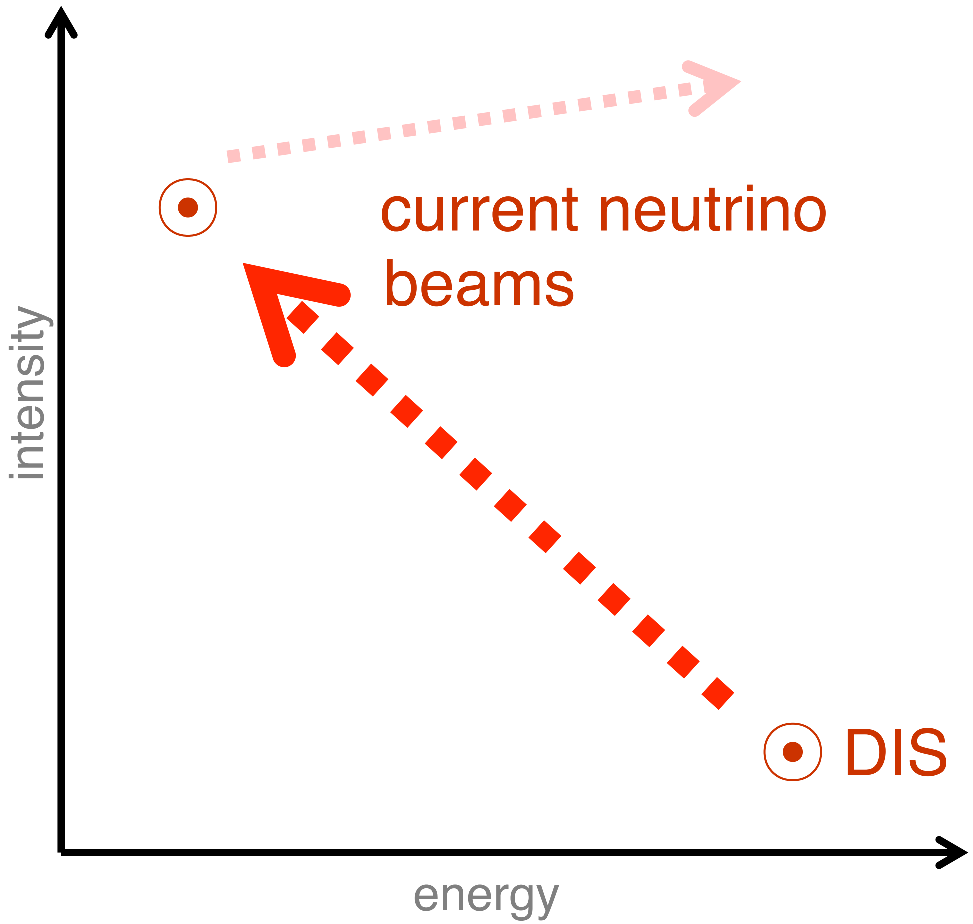
Double Chooz + Daya Bay + RENO + T2K + NoVA

➔ chance to see MH and/or CPV in the next years!

The Hunt for the Mass Hierarchy



Crossections



higher intensity → lower E
shorter baseline
off-axis – better S/B
➔x-sections toward low E

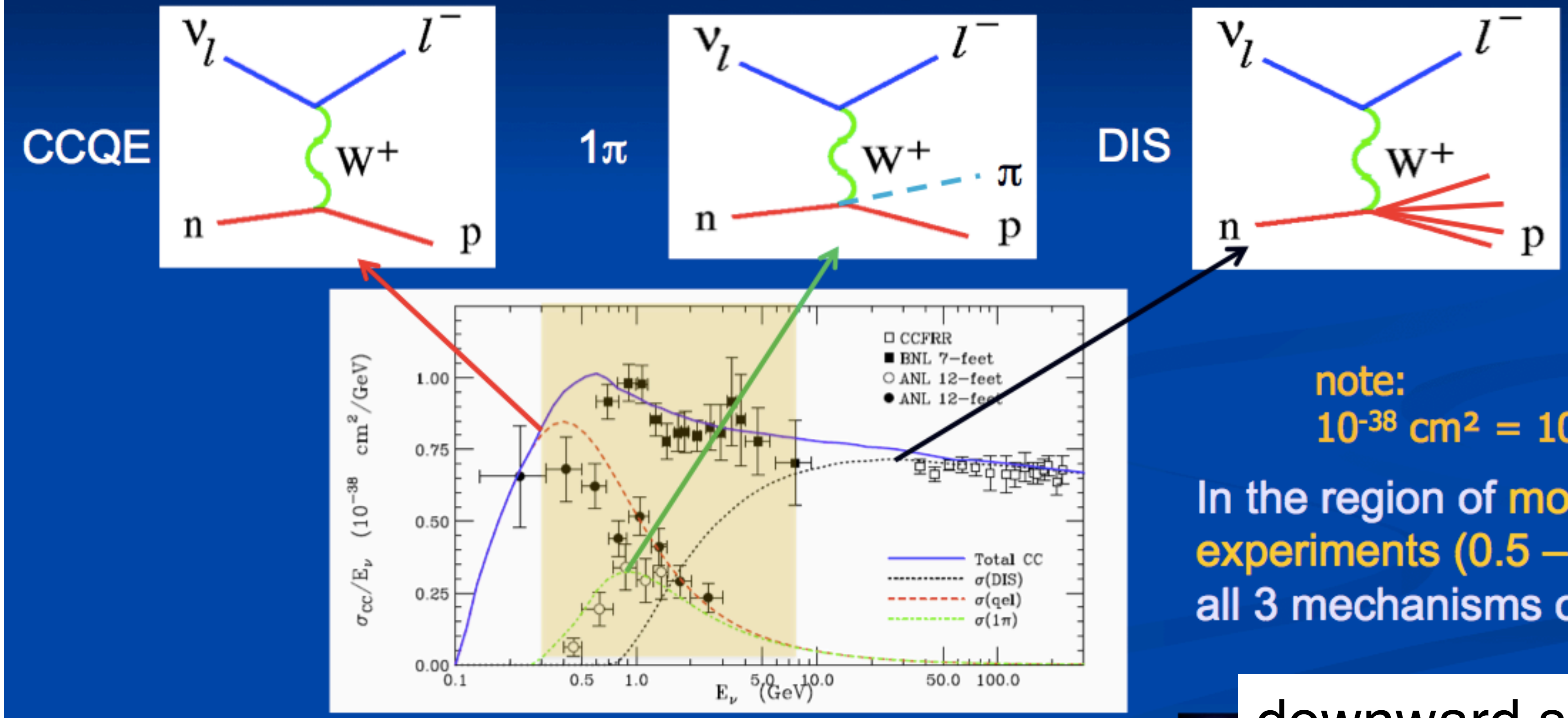
x-sections @ UHE

Mosel
Lenske
Chanfray
Schildknecht
Redij

reliable x-sections are
important in precision era!

Mosel

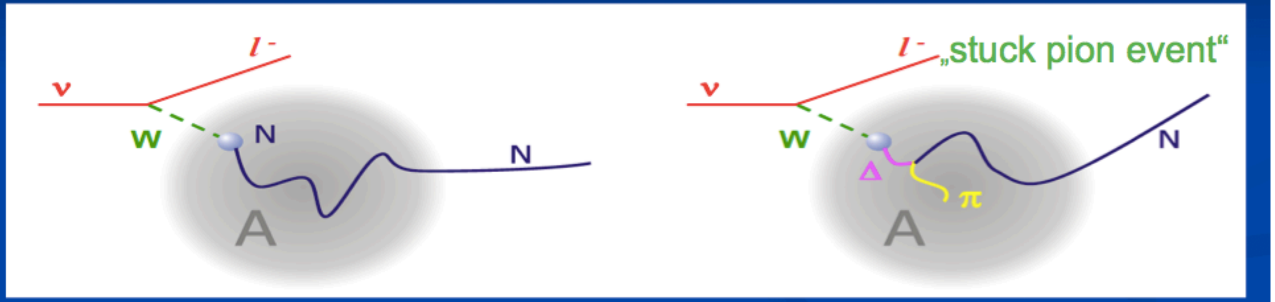
Neutrino-nucleon cross section



note:
10^{-38} cm² = 10^{-11} mb

In the region of most experiments (0.5 – 10 GeV) all 3 mechanisms overlap

Erice 09/2013



downward shifts in E reconstruction

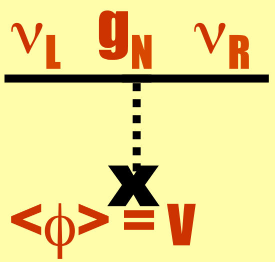
➔offset in Δm^2
➔important

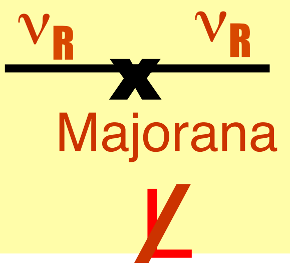
Complication to identify QE, entangled with π productio

Motivations for Sterile Neutrinos

- ν_R are simplest way to add m_ν
- most general mass terms
  ←→ lepton number?

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2





→

$$\begin{pmatrix}\nu_L & \nu_R^c\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix}$$

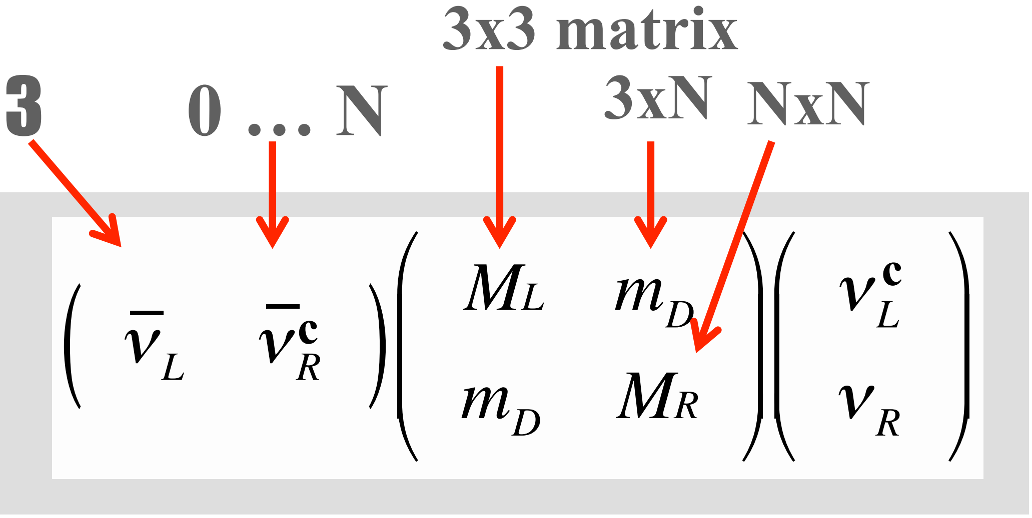
like quarks and charged leptons → Dirac mass terms (including NMS mixing)

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

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

- see-saw 'explains' smallness of neutrino masses
- leptogenesis → minimal explanation of BAU, …

Neutrino Masses



$$\begin{pmatrix}\bar{\nu}_L & \bar{\nu}^c_R\end{pmatrix}\begin{pmatrix}M_L & m_D\\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu^c_L\\ \nu_R\end{pmatrix}$$

M_L, m_D, M_R may have almost any form / values:

- zeros (symmetries)
- 0 + tiny corrections
- scales: M_W, M_{GUT}, …

➔ diagonalization: 3+N EV

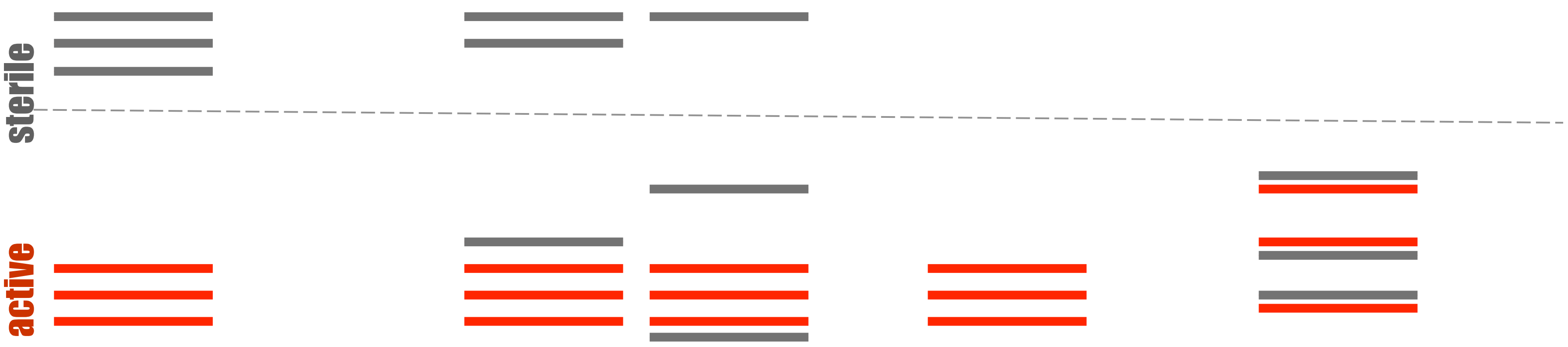
➔ 3x3 active almost unitary

$M_L=0$, $m_D = M_W$,
M_R=high: see-saw

M_R singular
singular-SS

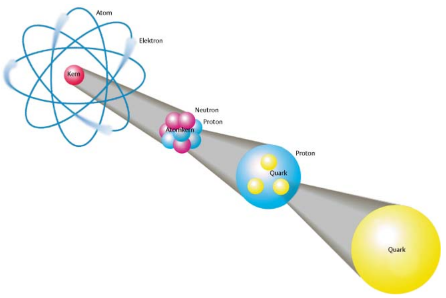
$M_L = M_R = 0$
Dirac

$M_L = M_R = \varepsilon$
pseudo Dirac



Sterile Neutrinos: The Ghosts of Ghosts

ordinary matter



the visible world
- EM interactions
- strong forces
- weak forces

weak bosons

active neutrinos

invisible
- only weak force
- could have been hot dark matter…

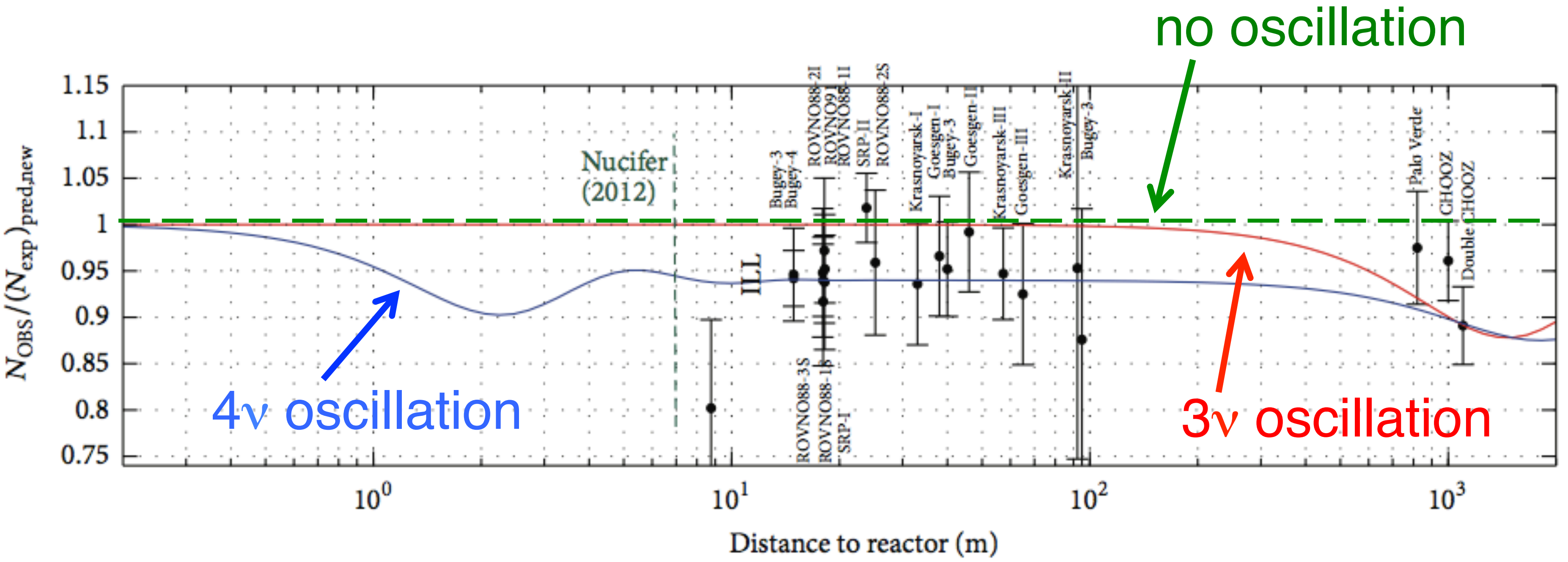
small mixing

sterile neutrinos

extremely invisible
- might explain one or more hints
- could be WDM
- …

neutrinos have always been surprising
+ no good argument why steriles should not exist!

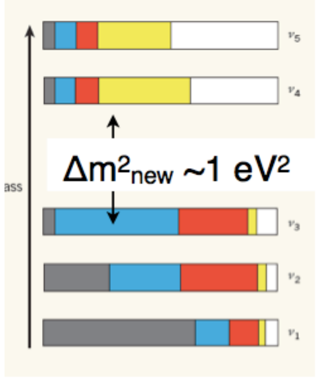
Various Evidences / Hints: Reactor Anomaly



➔ an extra (sterile) neutrino with a small mixing angle and a mass O(eV) or heavier would have oscillated @ 10-100m

averaged out: reduction by ½ * $\sin^2(\theta_s) \simeq 0.06$

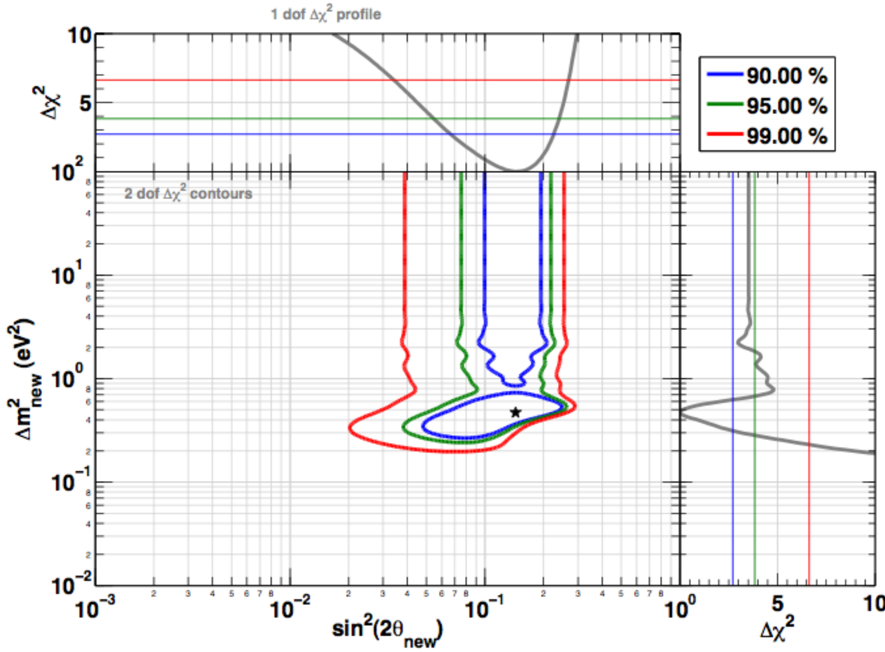
←➔ active ν-unitarity tested @ few % ➔ consistent ➔



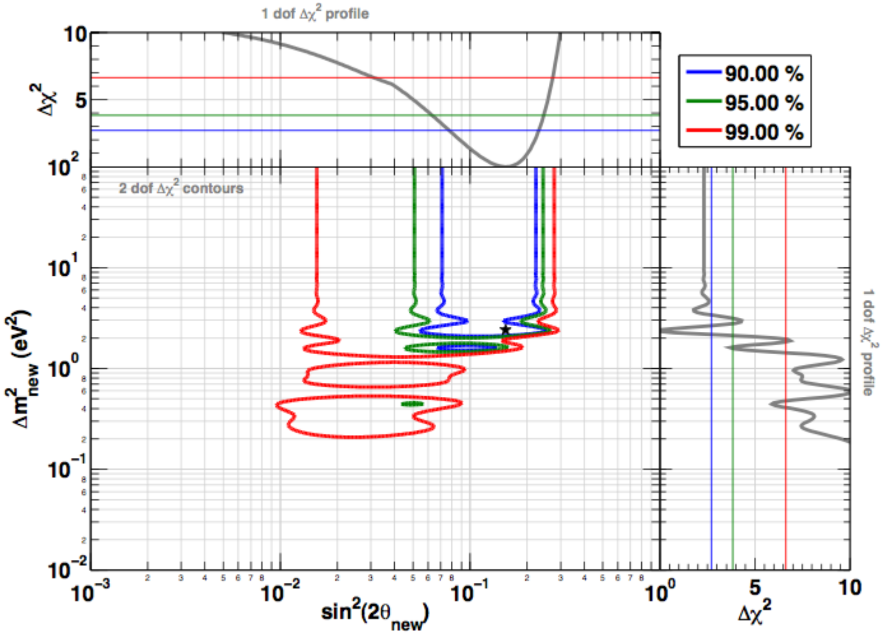
➔ check with a new experiment at shorter baseline

Oscillation Parameters

Rate only analysis



Rate + Shape (Bugey 3) analysis



- **Best fit:** $\Delta m^2 = 2.4\ \mathrm{eV}^2$ $\sin^2(2\theta_{new}) = 0.14$
- **2.9 σ significance**

Sterile Neutrinos & improved EW Fits

Akhmedov, Kartavtsev, ML, Michaels and J. Smirnov

Global fits usually assume 3x3 unitarity!

→ **unconstraint fits allow ~ up to few% changes** Antusch et al.

→ assume TeV-scale sterile ν's (small mixings) ➔ improves EW fits!

6x6 mixing matrix:

$$\mathbf{U} = \begin{pmatrix} \mathscr{U} & \mathscr{R} \\ \mathscr{W} & \mathscr{V} \end{pmatrix}$$

$$\boxed{\epsilon_\alpha \equiv \sum_{i\geq 4} |\mathbf{U}_{\alpha i}|^2}$$

$$\begin{aligned} \epsilon_e - \epsilon_\mu &= 0.0022 \pm 0.0025 \\ \epsilon_\mu - \epsilon_\tau &= 0.0017 \pm 0.0038 \\ \epsilon_e - \epsilon_\tau &= 0.0039 \pm 0.0040 \end{aligned}$$

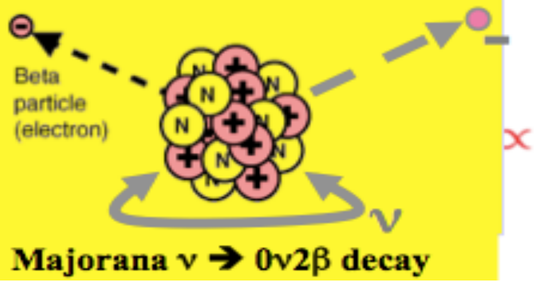
(3×3) PMNS matrix $\mathscr{U}$

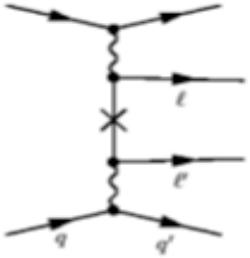
is not exactly unitary

→ **small deviations**

Consequences of sterile Neutrinos

- **Shifts in active neutrino parameters in global analyses**
- **L-violating admixture in light ν's → 0νββ Beta Decay**





$$\propto |\langle \mathbf{m_{ee}} \rangle| = |\sum \mathbf{m_i U_{ei}^2}|$$

- **Effective mass including all states:**

$$|\langle m_{ee} \rangle| \approx |\sum_{i=1}^{3} \mathbf{U}_{ei}^2 m_i - \sum_{i=4}^{3+n} F(A, M_i) \mathbf{U}_{ei}^2 m_i|$$

$$F(A, m_i) \approx (m_a/m_i)^2 f(A)$$

f(A) depends on the decaying isotope

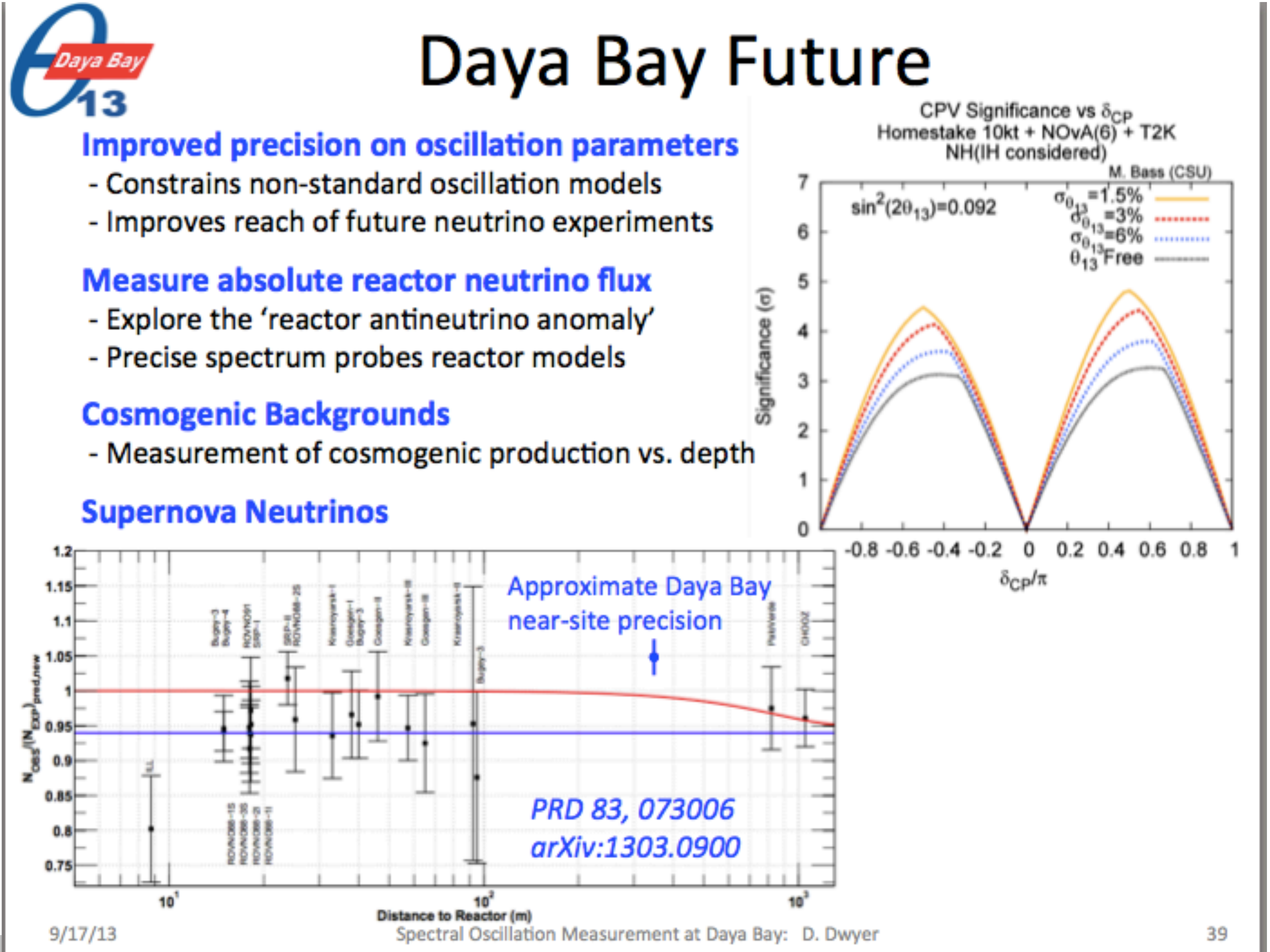
today $|\langle m_{ee} \rangle| < 0.4$ eV → will improve … soon!

Important: New Sterile Experiments & Plans

Experiment Type	Appearance / Disappearance	Oscillation Channel	Projects
Reactor	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	Nucifer, Stéréo, Scraam, Neutrino-4, DANSS, Poséidon, MARS, ...
Radioactive Source	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	CeLAND, SOX (Cr & Ce), Sage2, SNO+, LENS-s
Cyclotron	Disappearance	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest	Apparition & Disappearance	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Pion Decay-in-Flight (Beam)	Appearance & Disappearance	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, Icarus/Nessie@CERN
Low-E Neutrino Factory	Appearance & Disappearance	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	νSTORM@Fermilab

Potential ←→ hints, speed, cost←→ funding, challenges, ...

Daya Bay Future



Improved precision on oscillation parameters

- Constrains non-standard oscillation models
- Improves reach of future neutrino experiments

Measure absolute reactor neutrino flux

- Explore the 'reactor antineutrino anomaly'
- Precise spectrum probes reactor models

Cosmogenic Backgrounds

- Measurement of cosmogenic production vs. depth

Supernova Neutrinos

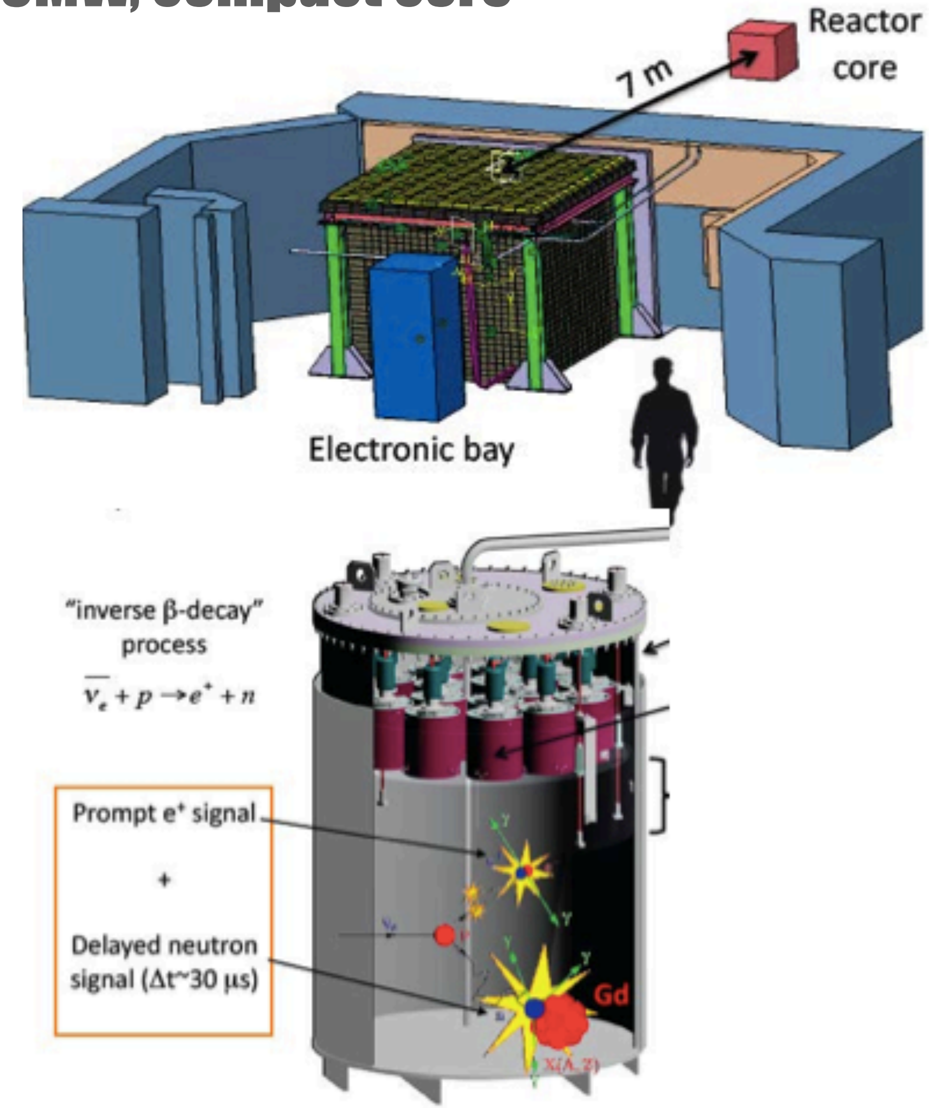
Approximate Daya Bay near-site precision

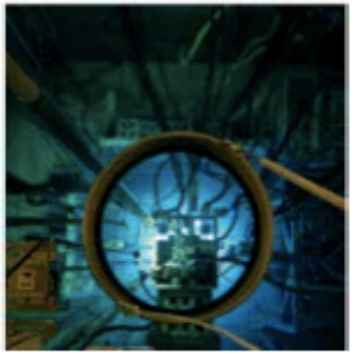
PRD 83, 073006
arXiv:1303.0900

9/17/13 Spectral Oscillation Measurement at Daya Bay: D. Dwyer 39

NUCIFER @ Osiris (Paris)

70MW, compact core





core: σ~0.3m
baseline: 7m

- Norm error = 4%
- 100 days full power @ Osiris
- S/B = 1 (?), assuming same shapes (worst case).
- E resol = 0.15*E

Commissioning and Data Taking

Since April 2012 fully operational → data taking

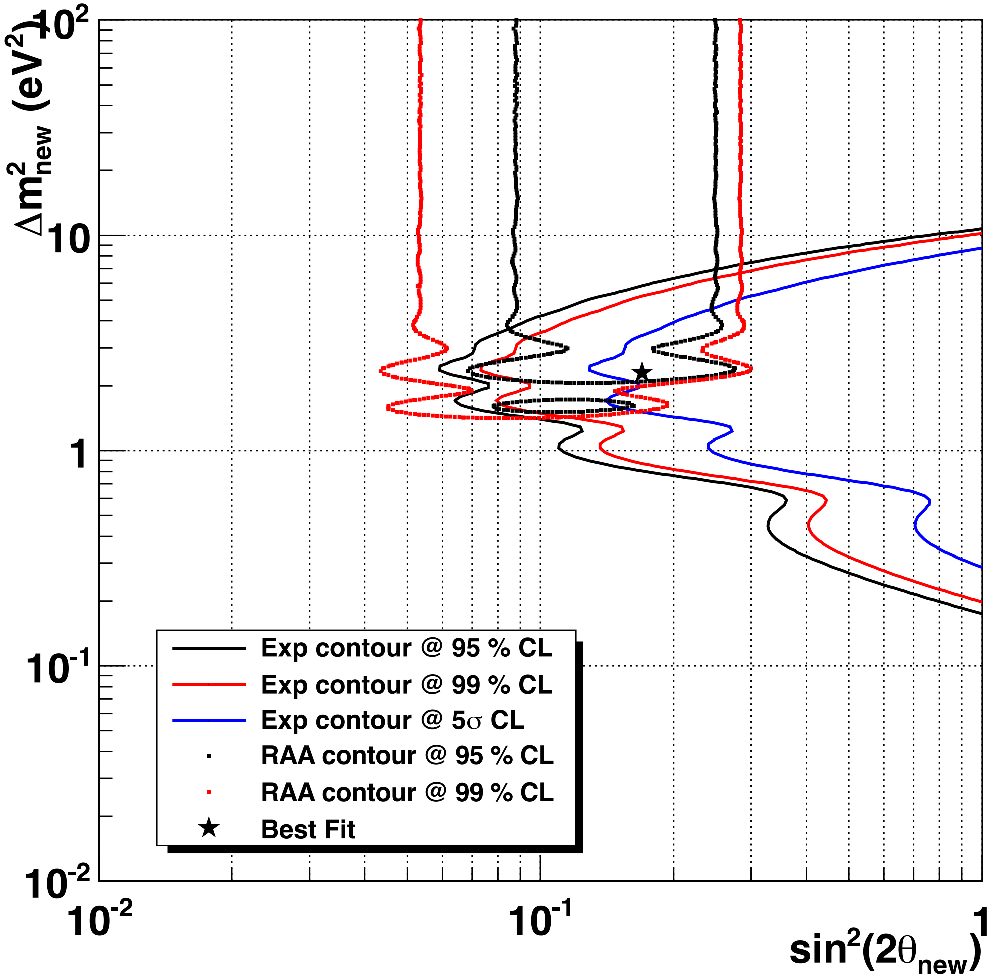
Since 2013 data taking with Double Chooz type scintillator

→ stable operation, O(50k ν/year)

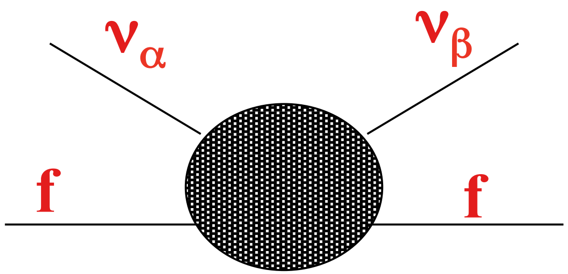
Now: Few months interruption due to reactor service…

NUCIFER Sensitivity versus Hints

300 days @ Osiris



New Physics, NSIs & ν-Oscillations



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

Future precision oscillation experiments:

Source ⊗ **Oscillation** ⊗ **Detector**

- neutrino energy E
- flux and spectrum
- flavour composition
- contamination
- symmetric $\nu/\overline{\nu}$ operation

- oscillation channels
- realistic baselines
- MSW matter profile
- degeneracies
- correlations

- effective mass, material
- threshold, resolution
- particle ID (flavour, charge, event reconstruction, ...)
- backgrounds
- x-sections (at low E)

precision experiments migh see new effects beyond oscillations!

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

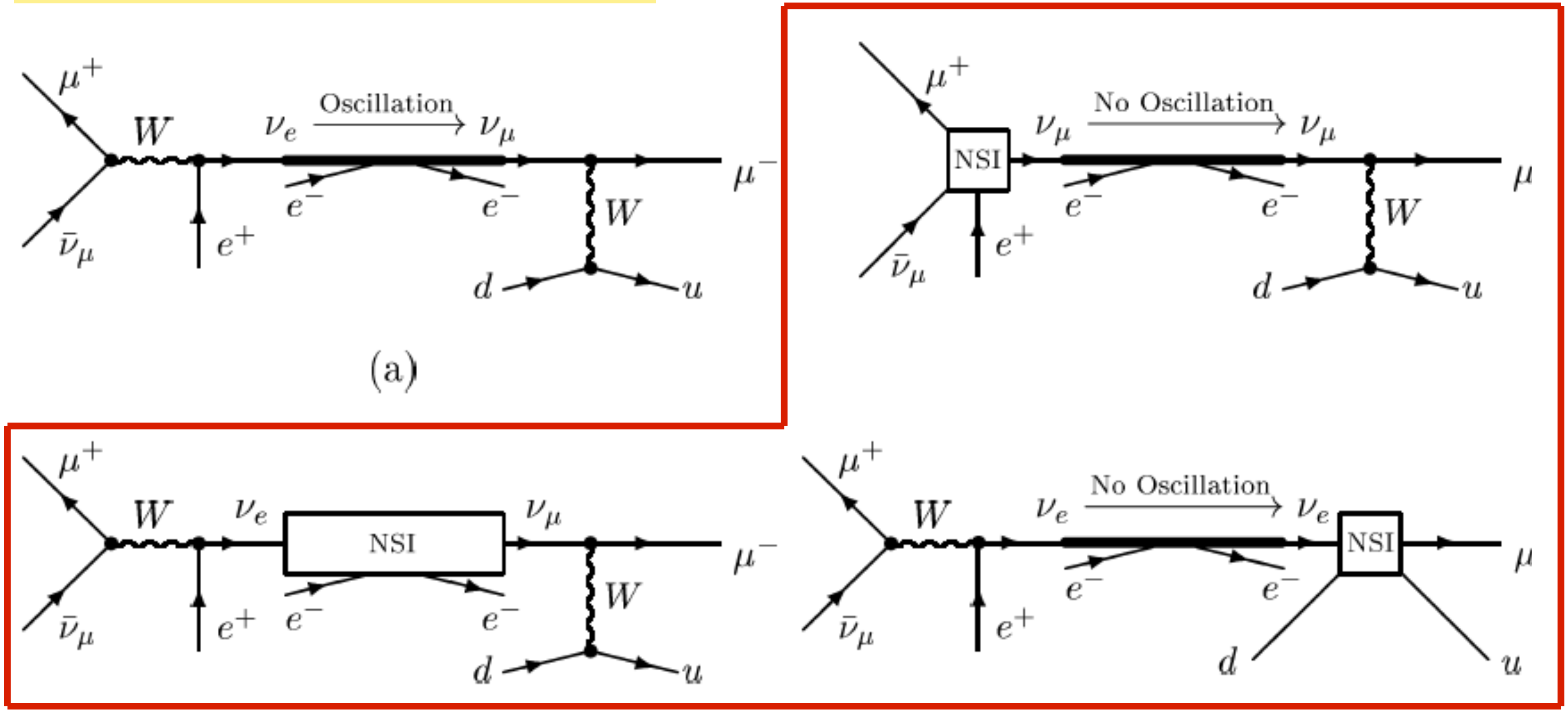
➔ small event rates: offset in oscillation parameters

➔ Non Standard Interactions = NSI's

NSIs interfere with Oscillations

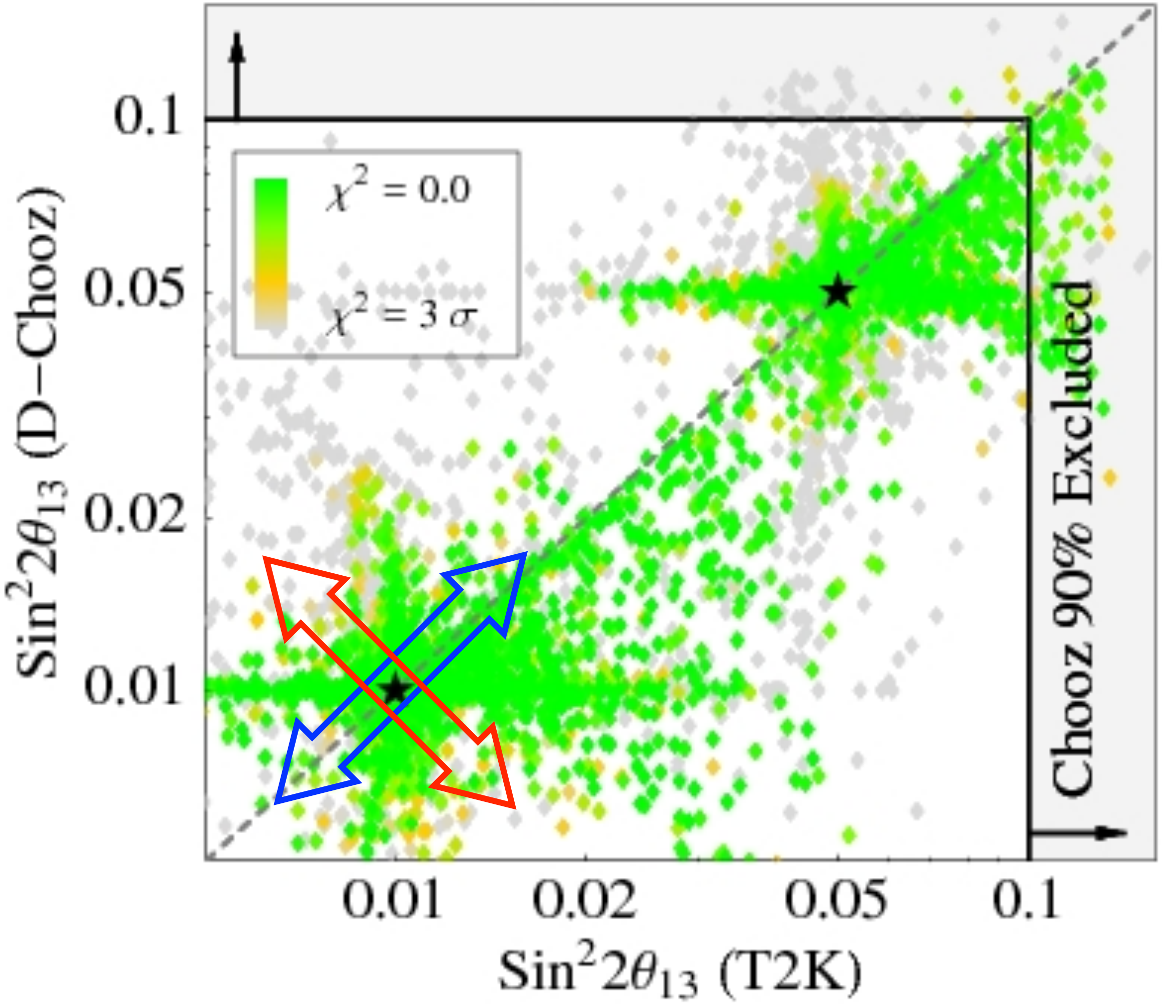
the “golden” oscillation channel

NSI contributions to the “golden” channel



note: interference in oscillations ~ε ⇔ FCNC effects ~ε^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**

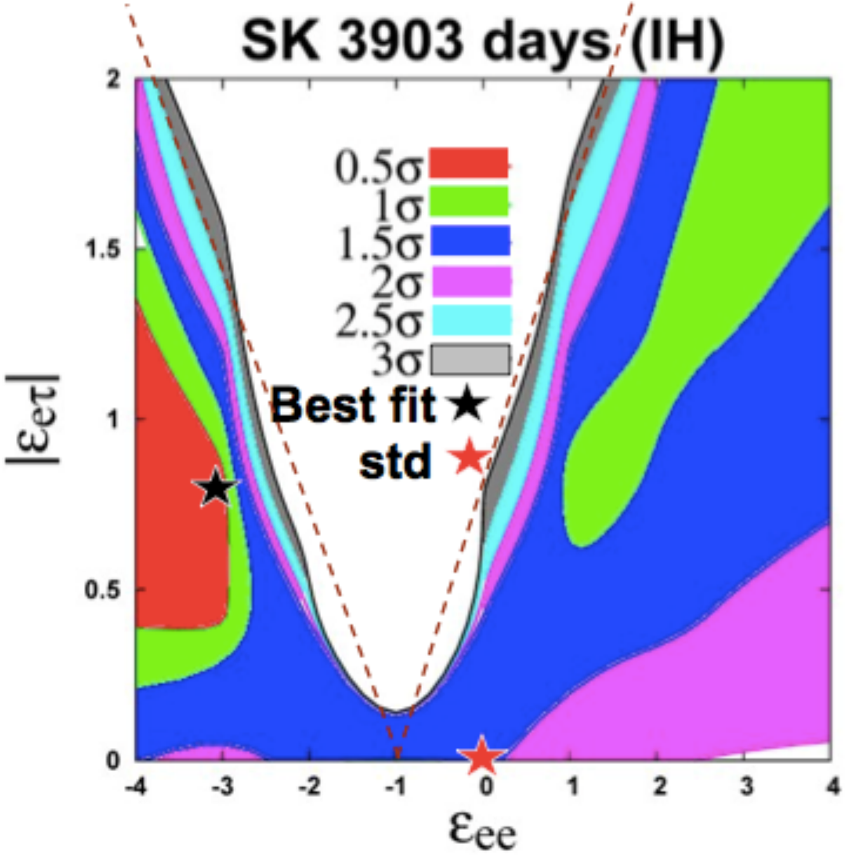
➔ **redundancy**

➔ **interesting potential**

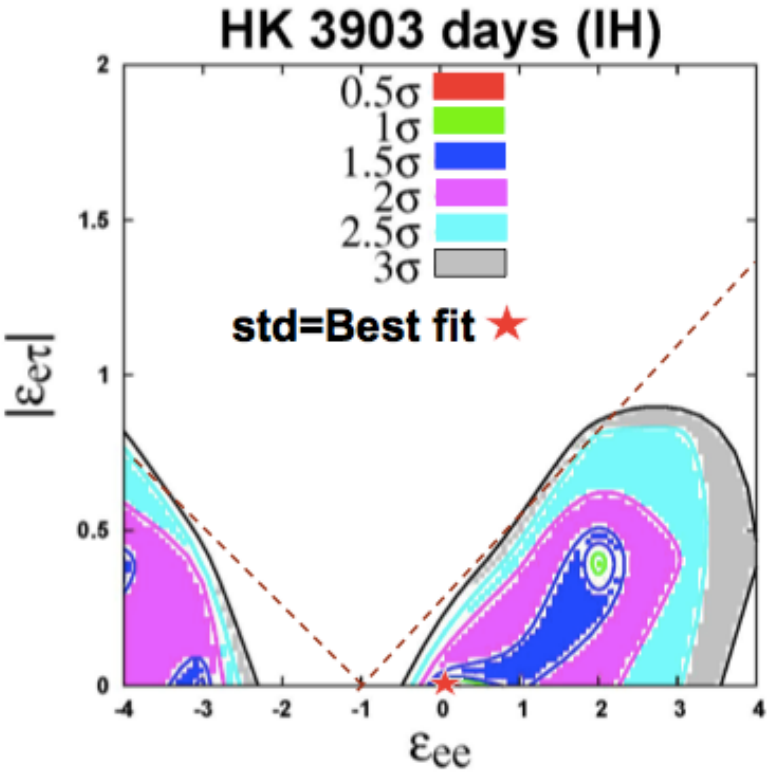
Yasuda

- Under the assumptions $\varepsilon_{e\mu} = \varepsilon_{\mu\mu} = \varepsilon_{\mu\tau} = 0$ & $\varepsilon_{\tau\tau}=|\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$, we studied sensitivity to NSI in propagation of ν_{atm} at SK & HK.

Constraint by SK on ε_{ee}, $|\varepsilon_{e\tau}|$



Sensitivity of HK



Interesting R&D and New Ideas

experimental physics is driven by

- technological inventions

- improvements in instrumentation

- great ideas

➔ scaling-up of projects + healthy spectrum of new developments

←➔ trend to bigger project with constant (reduced) overall funds

➔ healthy base budget of all research groups (esp. universities)

→ would also lead to the realization of new ideas

➔ less road maps… with 100% of the communities budget

two examples ➔

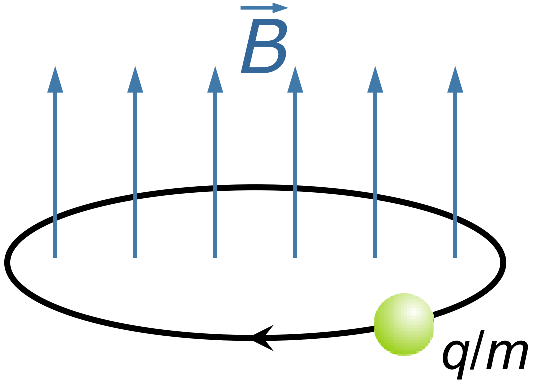
Blaum

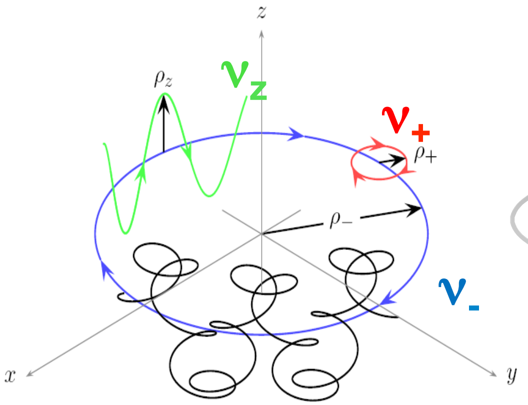
Atom Traps & Neutrino Physics

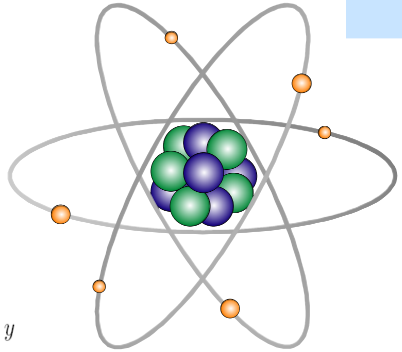
Penning-trap spectrometry ➔ high precision

cyclotron frequency:

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

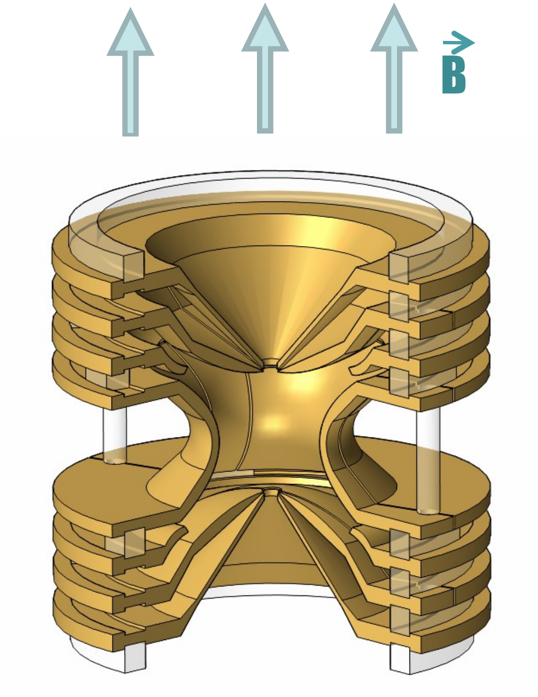






= N · 🟢 + Z · 🔵 + Z · 🟠

– binding energy



Topics:

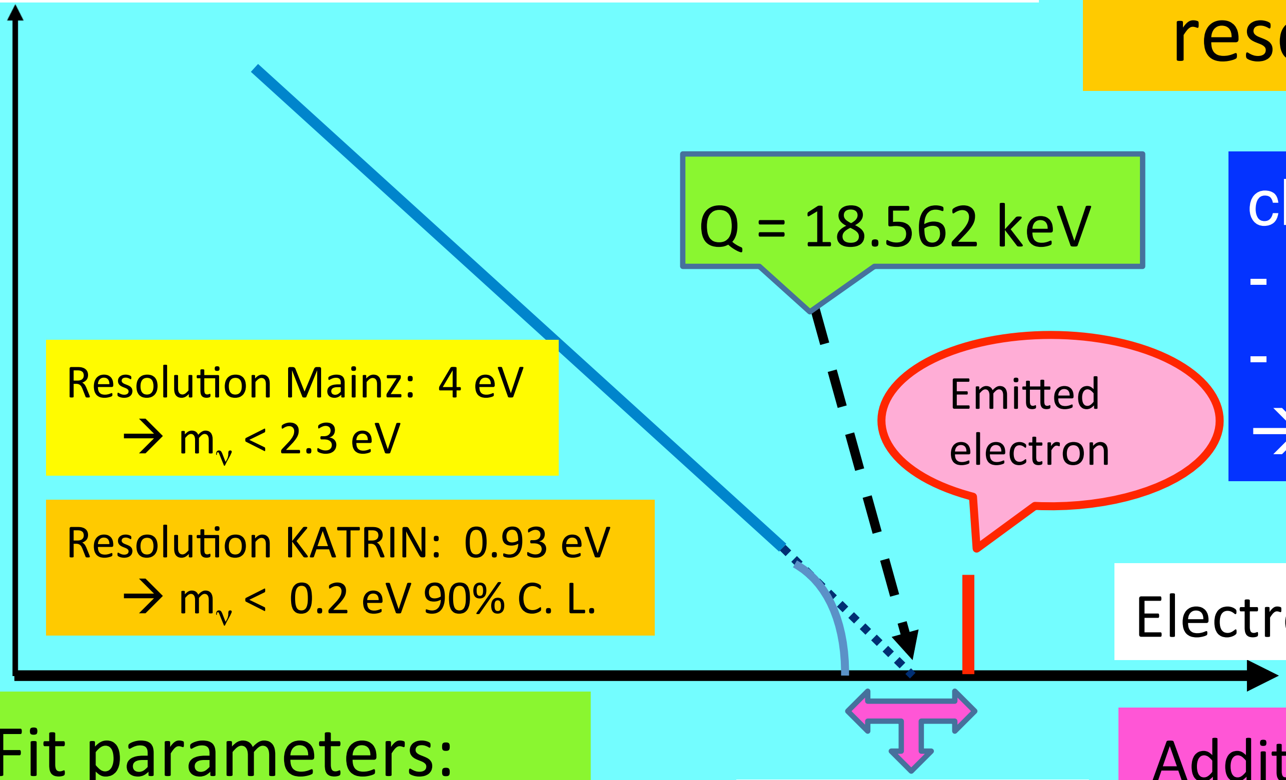
- nuclear masses for KATRIN and ECHO
- resonance enhanced 0νββ candidates
- precision determination of $Q_{\beta\beta}$
- …
- precision at the level of 10^{-11} expected

Faessler

Search for Cosmic Neutrino Background CνB by Beta decay: Tritium

Kurie-Plot of Beta and induced Beta Decay: $\nu(CB) + {}^3H(1/2^+) \rightarrow {}^3He\,(1/2^+) + e^-$

Infinite good resolution



Q = 18.562 keV

Emitted electron

Resolution Mainz: 4 eV
→ $m_\nu < 2.3$ eV

Resolution KATRIN: 0.93 eV
→ $m_\nu <$ 0.2 eV 90% C. L.

Electron Energy

2xNeutrino Masses

challenges:
- backgrounds
- signal rate

→ more studies

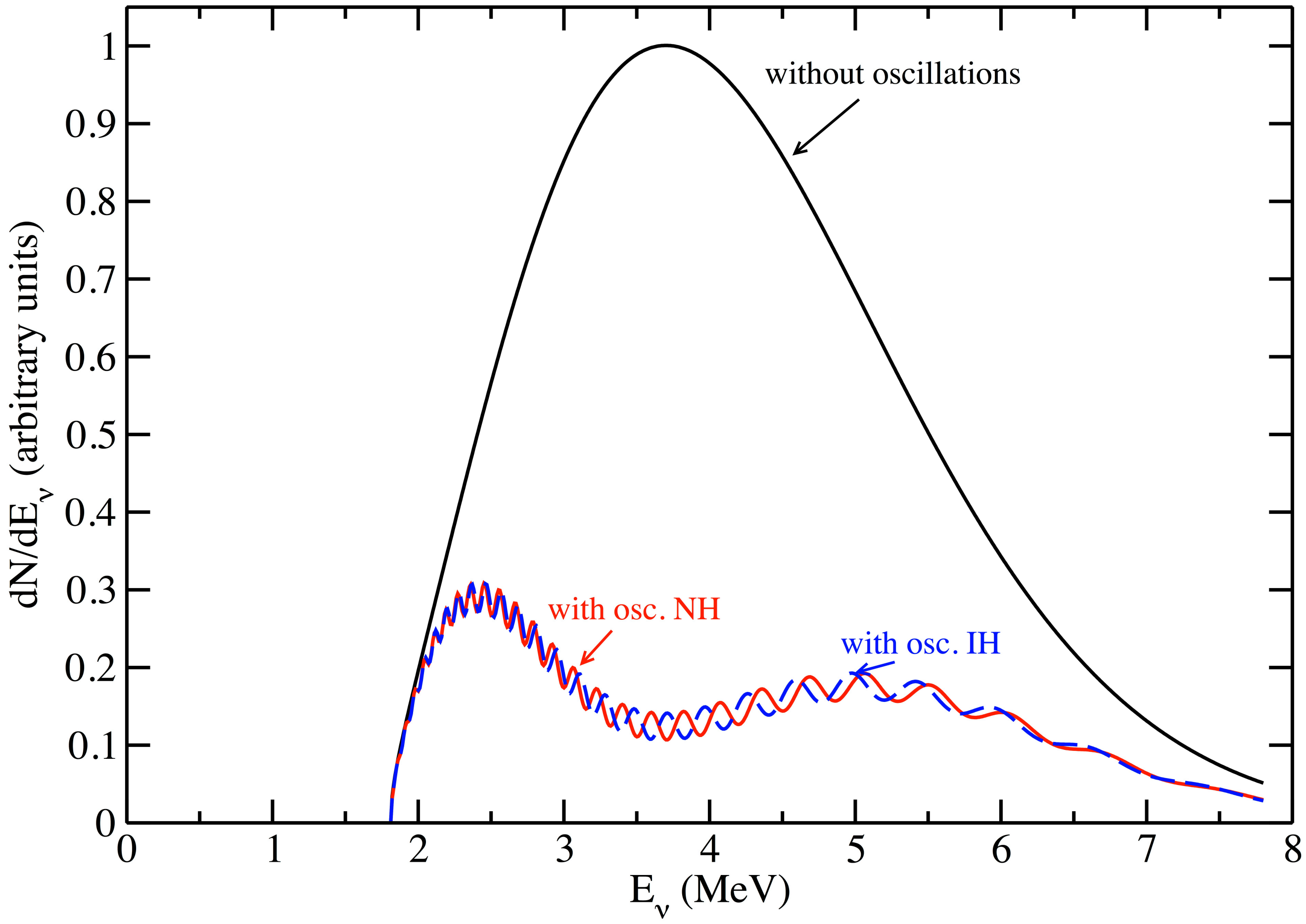
Fit parameters:
m_ν^2 and Q value meV

Additional fit: only intensity of CνB

Mass Hierarchy from Reactor Neutrinos

Vogel

reactor neutrino spectrum at 60 km



interesting idea
challenging

- resolution
- energy scale
- nonlinearity
- multiple reactor smearing

➔ further studies

Theory: The SM –a Synergy of Concepts

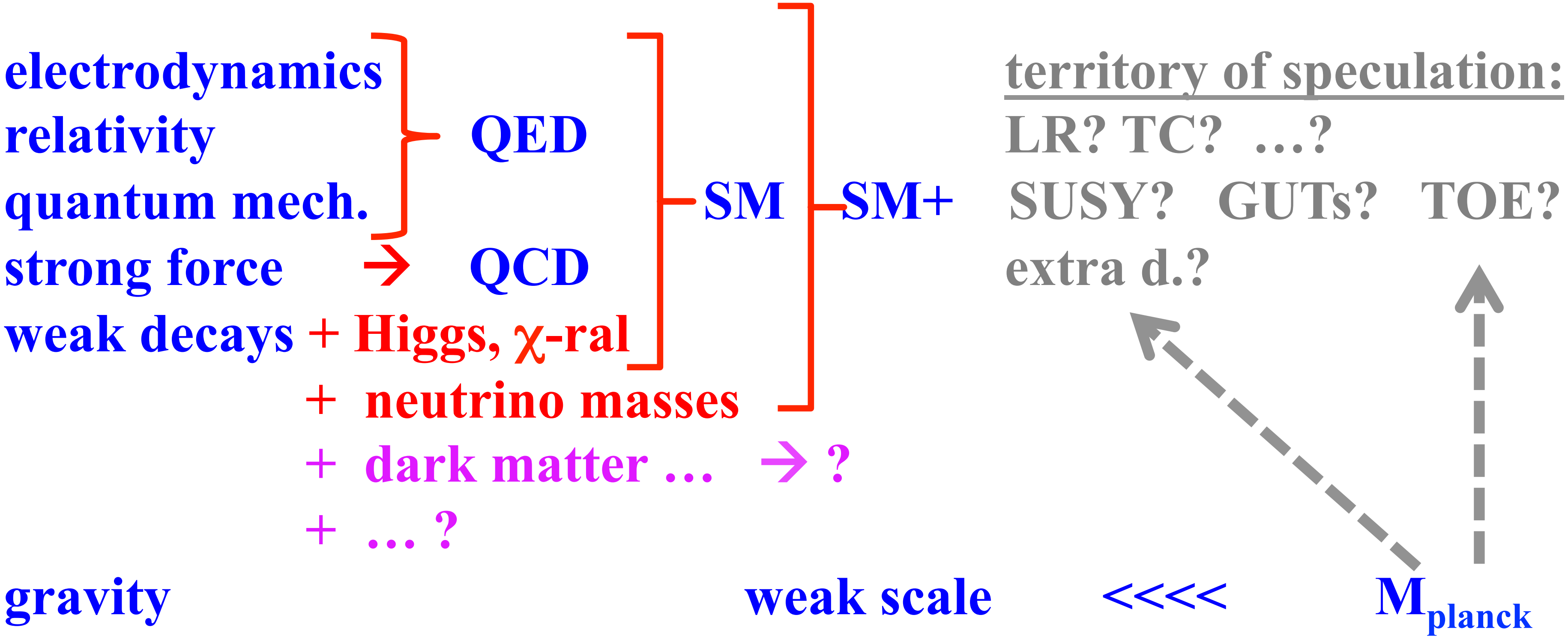
d=4 QFTs:

QED ➔ QCD ➔ SM

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

Physics: concepts (variables) ⊕ equations / principles

initial conditions ➔ predictions



Note: GR non-renormalizable… maybe good: QFT's cannot explain scales→other concepts

cartoon removed

neutrinos

Adding Neutrino Mass Terms to the SM

Fermion fields

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2

← ???

Dirac equation → mass terms: $m\overline{\Psi}\Psi = m\,(\,\overline{L}\,r + \overline{r}\,L\,)$

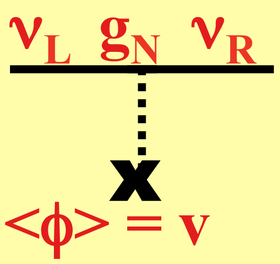
$L=2_L$, $r=1_L$ ➔ SM has no $SU(2)_L$ singlet mass terms

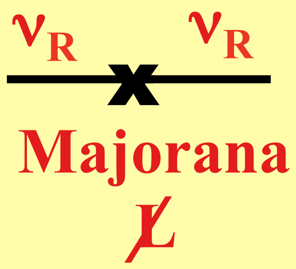
➔ Yukawa couplings:

$\Phi=2_L$ ➔ $m\,(\,\overline{L}\,\Phi\,r + \overline{r}\,\Phi\,L\,)$ **➔ singlet mass via $\langle\Phi\rangle = v$**

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

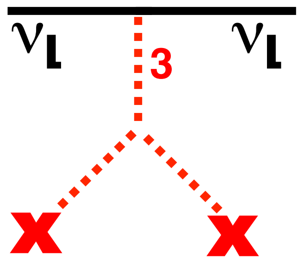
NEW ingredients, 9 parameters → SM+

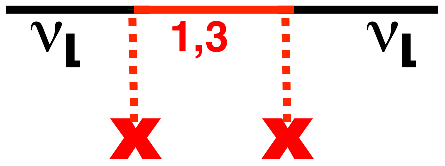
2) Maybe 3+N right handed neutrino fields

➔ (6+N) x (6+N) mass matrix

➔ how many of the 6+N eigenvalues are light (also for N=0)

3) new: scalar tripelts (3_L) or fermionic 1_L ro 3_L





➔left-handed Majorana mass term:

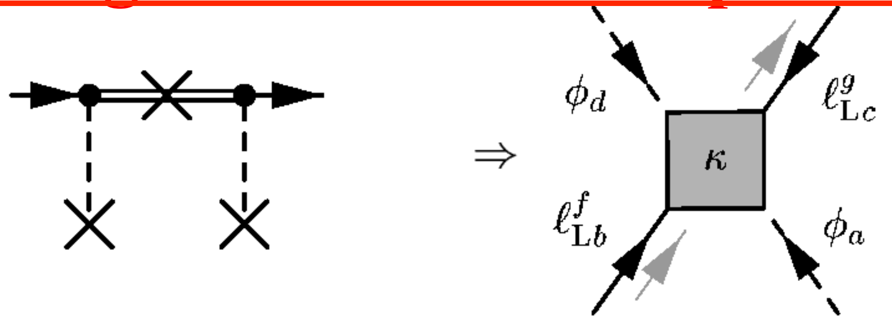
$\rightarrow M_L \overline{L} L^c$

4) Both ν_R and new singlets / triplets:

➔ see-saw type II, III

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

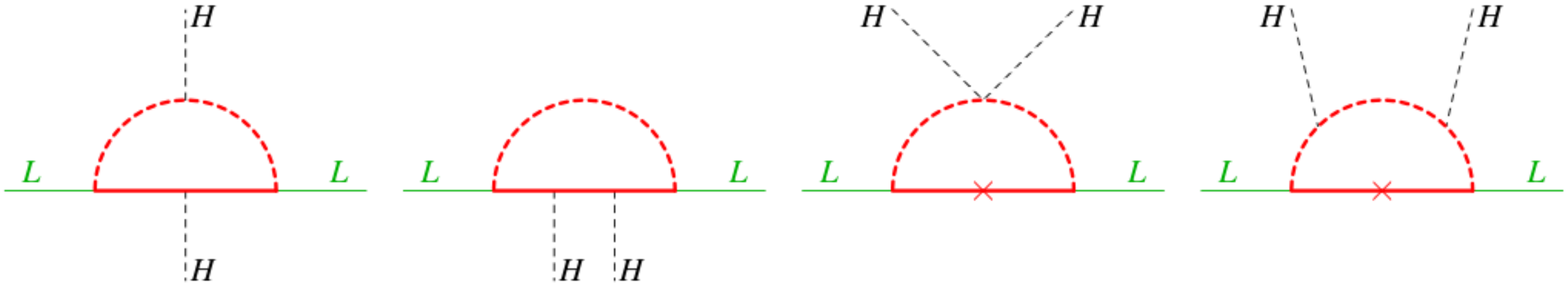
5) Higher dimensional operators: d=5, …



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

→ $M_L \overline{L} L^c$

6) Radiative neutrino mass generation



7-N) SUSY, extra dimensions, …

→ many options… ←→ few ν parameters

Other effective BSM Operators ←→NSI

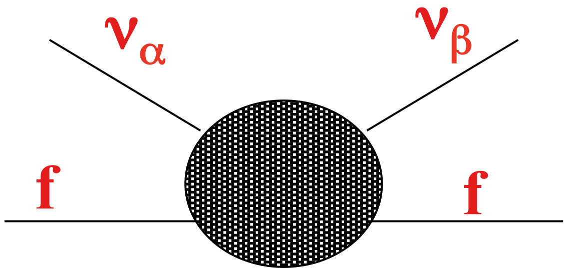
➔effects beyond 3 flavours

➔ 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)

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



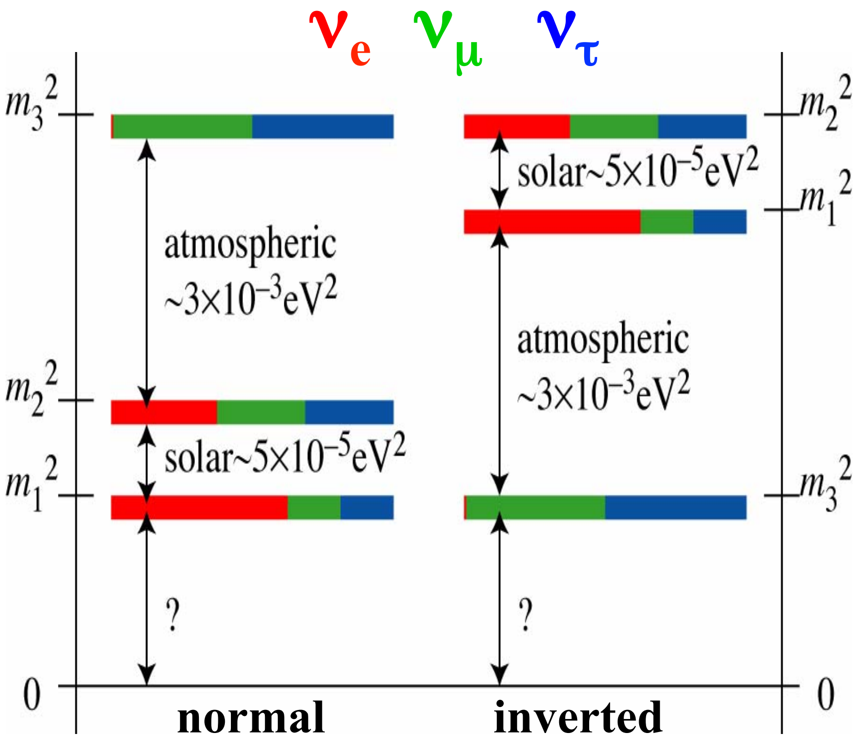
Parameters for 3 Light Neutrinos

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, …



normal **inverted**

hierarchical or degenerate

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

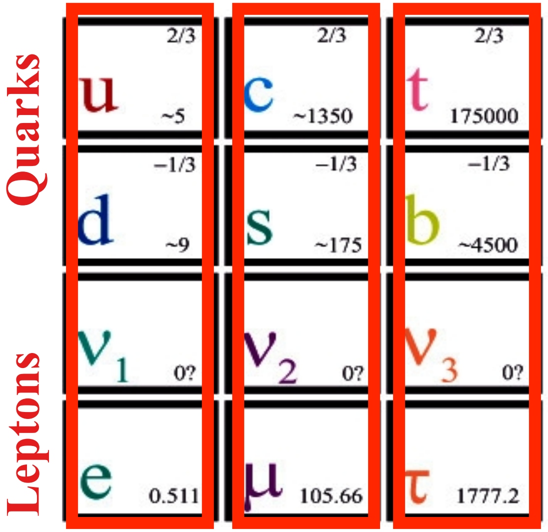
<u>**Requirements:**</u>

gauge unification

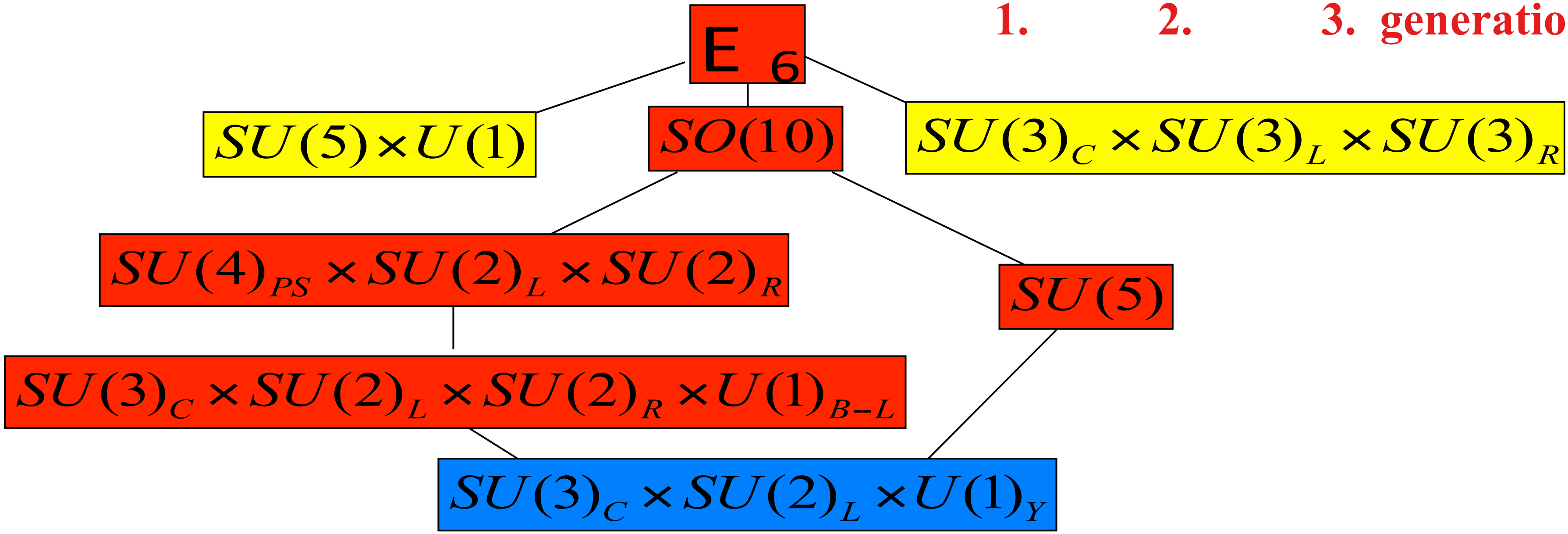
particle multiplets ←→ ν_R

proton decay

…



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



E_6

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

$SO(10)$

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

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

$SU(5)$

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

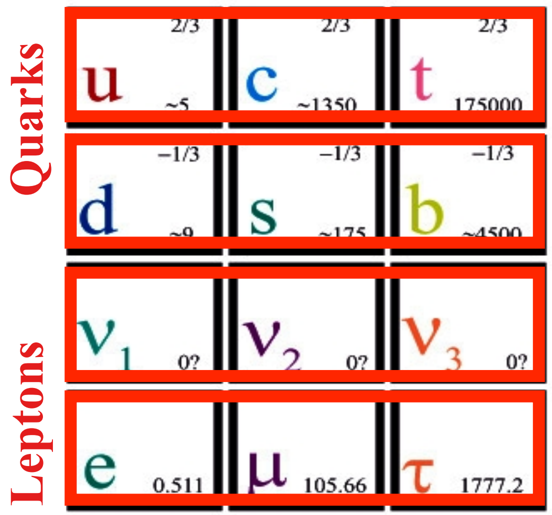
$SU(3)_C\times SU(2)_L\times U(1)_Y$

Flavour Unification

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

➔ flavour symmetries (finite number for limited rank)

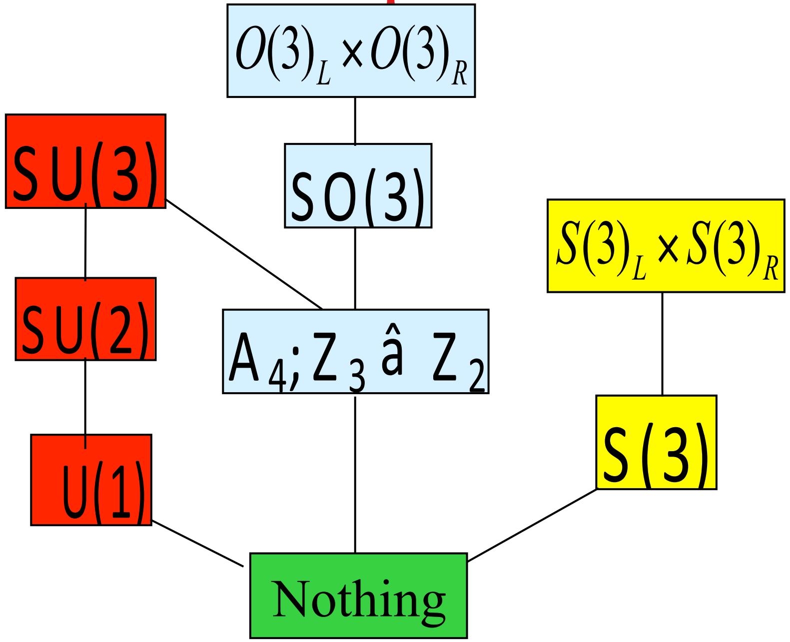
➔ symmetry not texture zeros



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

generation

Examples:



$O(3)_L \times O(3)_R$

$SO(3)$

$SU(3)$

$SU(2)$

$U(1)$

$A_4; Z_3$ â Z_2

$S(3)_L \times S(3)_R$

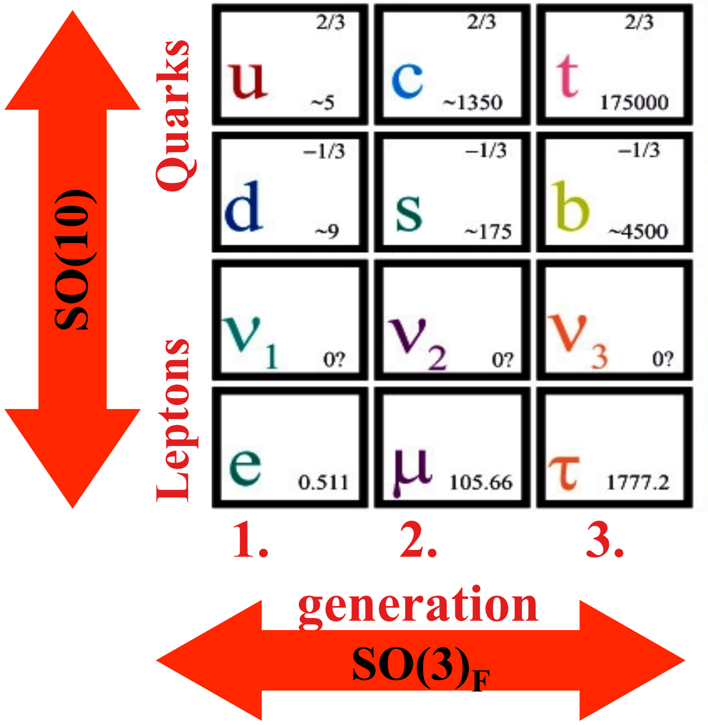
$S(3)$

Nothing

See talks by:

xxx

GUT & Flavour Unification



	1.	2.	3.
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

➔ GUT group x flavour group

example: $SO(10) \times SU(3)_F$

- 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: distinguish models further by future precision

➔one hope: smallness of θ_{13}

Neutrino Mass Sum Rules

Rule 1

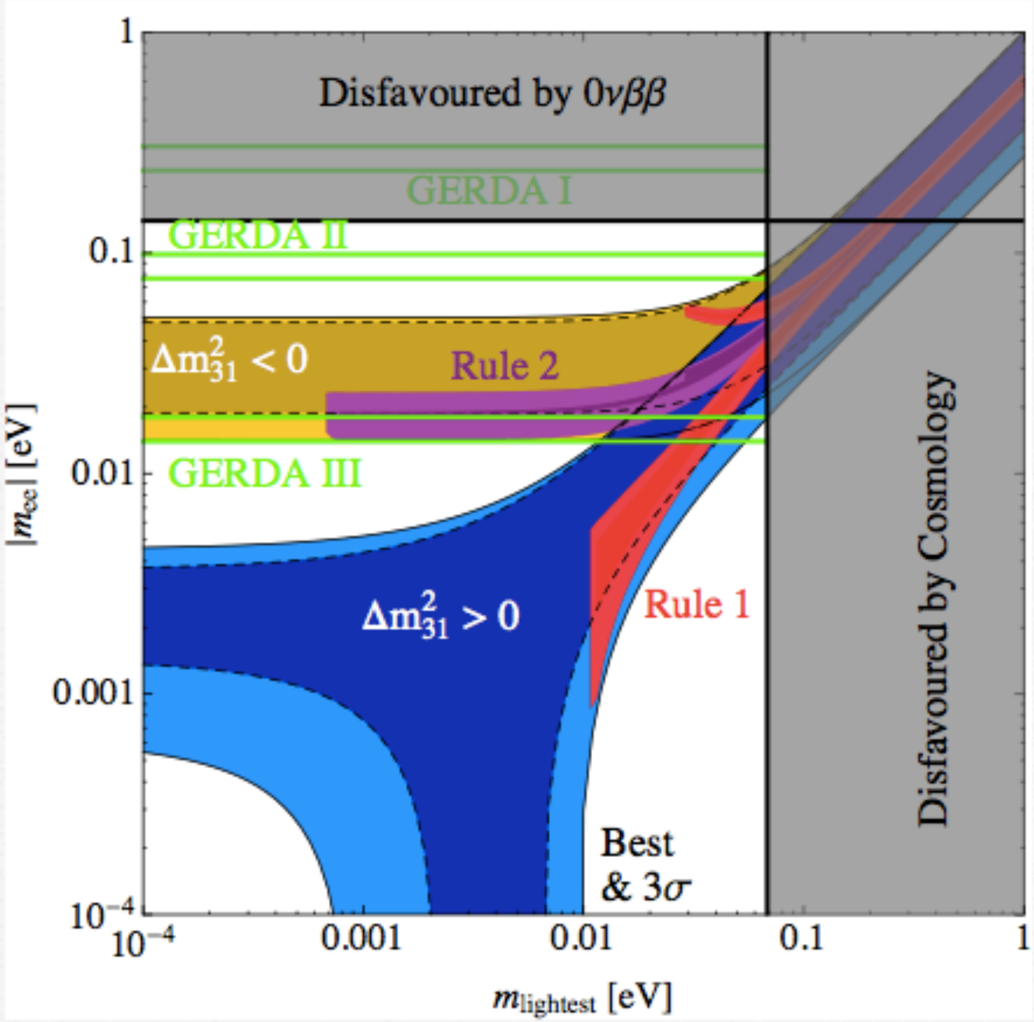
$$\frac{1}{m_1}+\frac{1}{m_2}=\frac{1}{m_3}$$

Rule 2

$$m_1+m_2=m_3$$

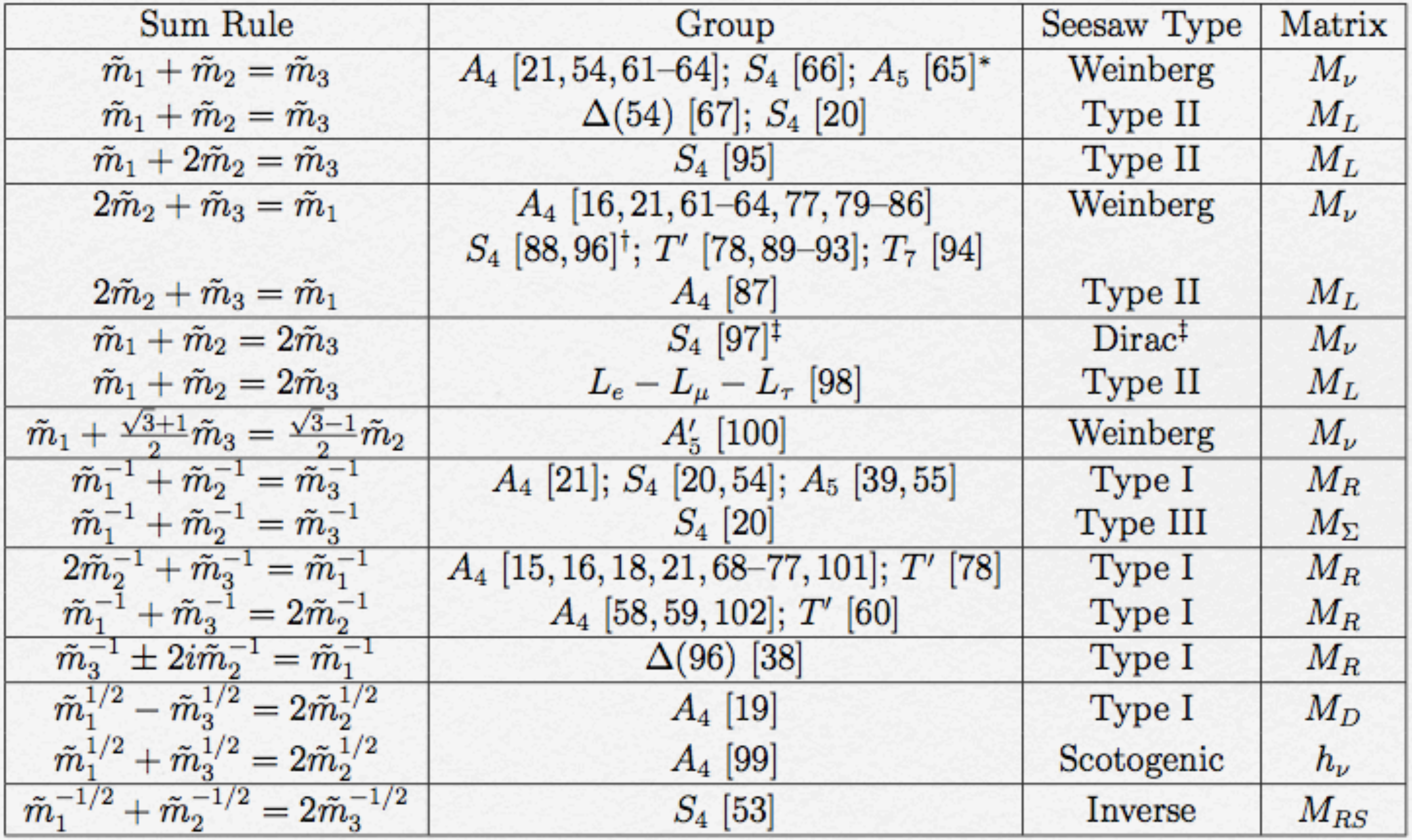
Give restricted regions

SFK, Merle, Stuart



Sum Rules in Models

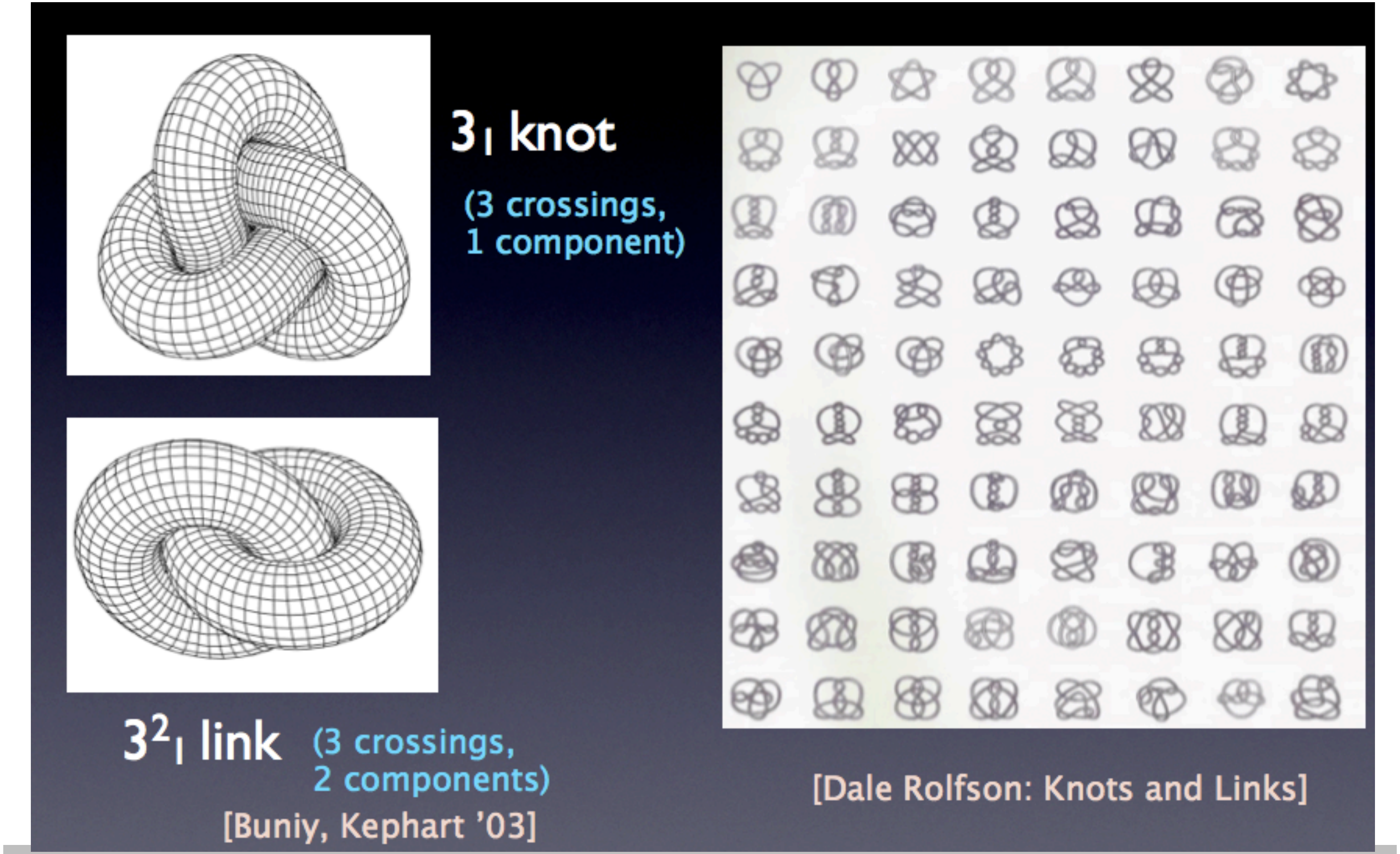
SFK, Merle, Stuart



Sum Rule	Group	Seesaw Type	Matrix
$\tilde{m}_1 + \tilde{m}_2 = \tilde{m}_3$	A_4 [21, 54, 61–64]; S_4 [66]; A_5 [65]*	Weinberg	M_ν
$\tilde{m}_1 + \tilde{m}_2 = \tilde{m}_3$	$\Delta(54)$ [67]; S_4 [20]	Type II	M_L
$\tilde{m}_1 + 2\tilde{m}_2 = \tilde{m}_3$	S_4 [95]	Type II	M_L
$2\tilde{m}_2 + \tilde{m}_3 = \tilde{m}_1$	A_4 [16, 21, 61–64, 77, 79–86] S_4 [88, 96]†; T' [78, 89–93]; T_7 [94]	Weinberg	M_ν
$2\tilde{m}_2 + \tilde{m}_3 = \tilde{m}_1$	A_4 [87]	Type II	M_L
$\tilde{m}_1 + \tilde{m}_2 = 2\tilde{m}_3$	S_4 [97]‡	Dirac‡	M_ν
$\tilde{m}_1 + \tilde{m}_2 = 2\tilde{m}_3$	$L_e - L_\mu - L_\tau$ [98]	Type II	M_L
$\tilde{m}_1 + \frac{\sqrt{3}+1}{2}\tilde{m}_3 = \frac{\sqrt{3}-1}{2}\tilde{m}_2$	A_5' [100]	Weinberg	M_ν
$\tilde{m}_1^{-1} + \tilde{m}_2^{-1} = \tilde{m}_3^{-1}$	A_4 [21]; S_4 [20, 54]; A_5 [39, 55]	Type I	M_R
$\tilde{m}_1^{-1} + \tilde{m}_2^{-1} = \tilde{m}_3^{-1}$	S_4 [20]	Type III	M_Σ
$2\tilde{m}_2^{-1} + \tilde{m}_3^{-1} = \tilde{m}_1^{-1}$	A_4 [15, 16, 18, 21, 68–77, 101]; T' [78]	Type I	M_R
$\tilde{m}_1^{-1} + \tilde{m}_3^{-1} = 2\tilde{m}_2^{-1}$	A_4 [58, 59, 102]; T' [60]	Type I	M_R
$\tilde{m}_3^{-1} \pm 2i\tilde{m}_2^{-1} = \tilde{m}_1^{-1}$	$\Delta(96)$ [38]	Type I	M_R
$\tilde{m}_1^{1/2} - \tilde{m}_3^{1/2} = 2\tilde{m}_2^{1/2}$	A_4 [19]	Type I	M_D
$\tilde{m}_1^{1/2} + \tilde{m}_3^{1/2} = 2\tilde{m}_2^{1/2}$	A_4 [99]	Scotogenic	h_ν
$\tilde{m}_1^{-1/2} + \tilde{m}_2^{-1/2} = 2\tilde{m}_3^{-1/2}$	S_4 [53]	Inverse	M_{RS}

Paes

flavour symetries, anarchy
→ alternative: knotted strings & flavour



3_1 knot

(3 crossings,
1 component)

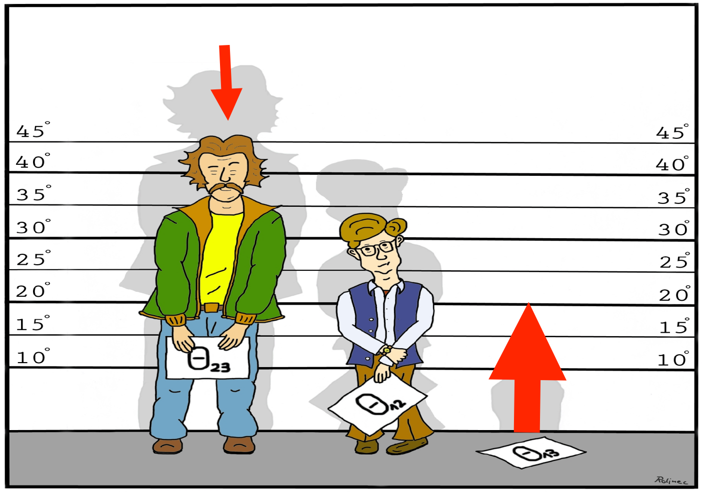
3^2_1 link (3 crossings,
2 components)

[Buniy, Kephart '03]

[Dale Rolfson: Knots and Links]

Lessons from sizable $\sin^2(2\theta_{13})$

- no apparent necessity for a special suppression of $\theta_{13} = 0° + \varepsilon$ (symmetry, …)



- TBM ($\theta_{13} = 0$ + small corrections) ruled out *OR* sizable corrections:
  9° = 0 + 9° but also 9°= 20°-11° or …

➔ no obvious flavour information
9°, 33°, 43° looks like 3 random numbers (besides maybe 45…)

➔ still very valuable information: large mixing; quarks←➔ leptons

- 3x3 unitarity rather good – max. few percent admixtures by …➔ TEST

3 ν-oscillations may still not be the complete story:

➔ NSI's, decay, Lorentz invariance violation, … ➔

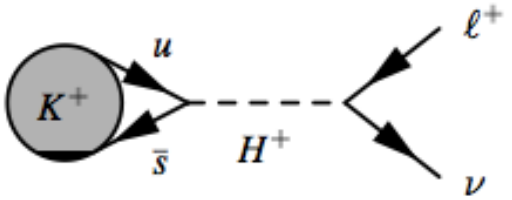
➔ sterile neutrinos (with small mixing angles) ➔

Weiland

- Deviations from LFU ⇒ Evidence of New Physics

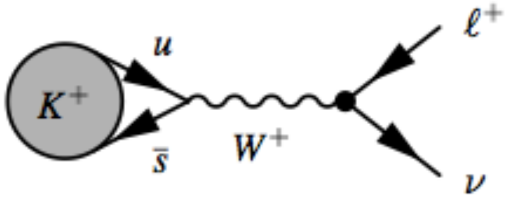
origins
of
LFU:

  - New Lorentz structure in the four-fermion interaction



New fields, new couplings
e.g. 2 Higgs doublet models [Hou, 1993],
Supersymmetry [Masiero et al., 2006,
Fonseca et al., 2012]

  - Corrections to the SM $W\ell\nu$ vertex



New states, Higher-order effects
e.g. Additional neutrinos: low-scale
seesaw, inverse seesaw

- Source: modified $W\ell\nu$ vertex from extra sterile neutrinos
- Mechanism: phase space effect
  non-unitarity of $\widetilde{U}_{\text{PMNS}}$
- Large LFU violation in the inverse seesaw
  ⇒ Constraint on the parameter space from R_K, R_π, R_e, $R_K^{\ell\tau}$
- May reduce the tension for R_{D_s}

→ sensitivity
to new physics
via LFU

Sterile Neutrinos and Mass Scenarios

M_L=0, m_D = M_W, M_R=high: see-saw	M_R singular singular-SS	M_L = M_R = 0 Dirac	M_L = M_R = ε pseudo Dirac

maybe we are seeing mixing with one of those?
or SK up-turn…

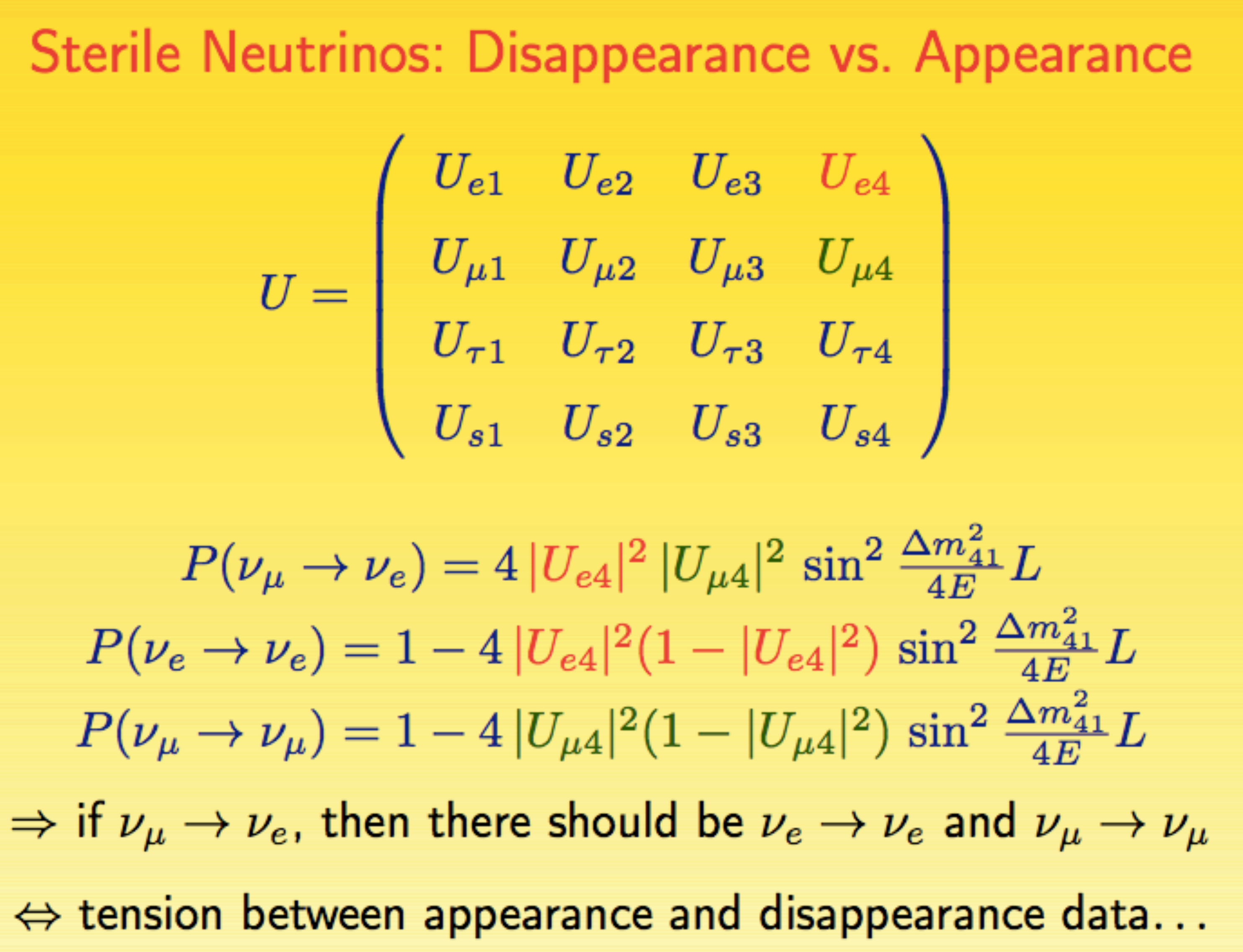
Evidences/hints/arguments:

reactor anomaly, LSND, Gallium, MiniBooNE, TeV-EW-fits, keV as WDM, …

Most likely not all of them true, but one is enough:

VERY IMPORTANT! ➔ experimental tests

Rodejohann possible sterile scales: eV. keV, TeV, heavy



Sterile Neutrinos: Disappearance vs. Appearance

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

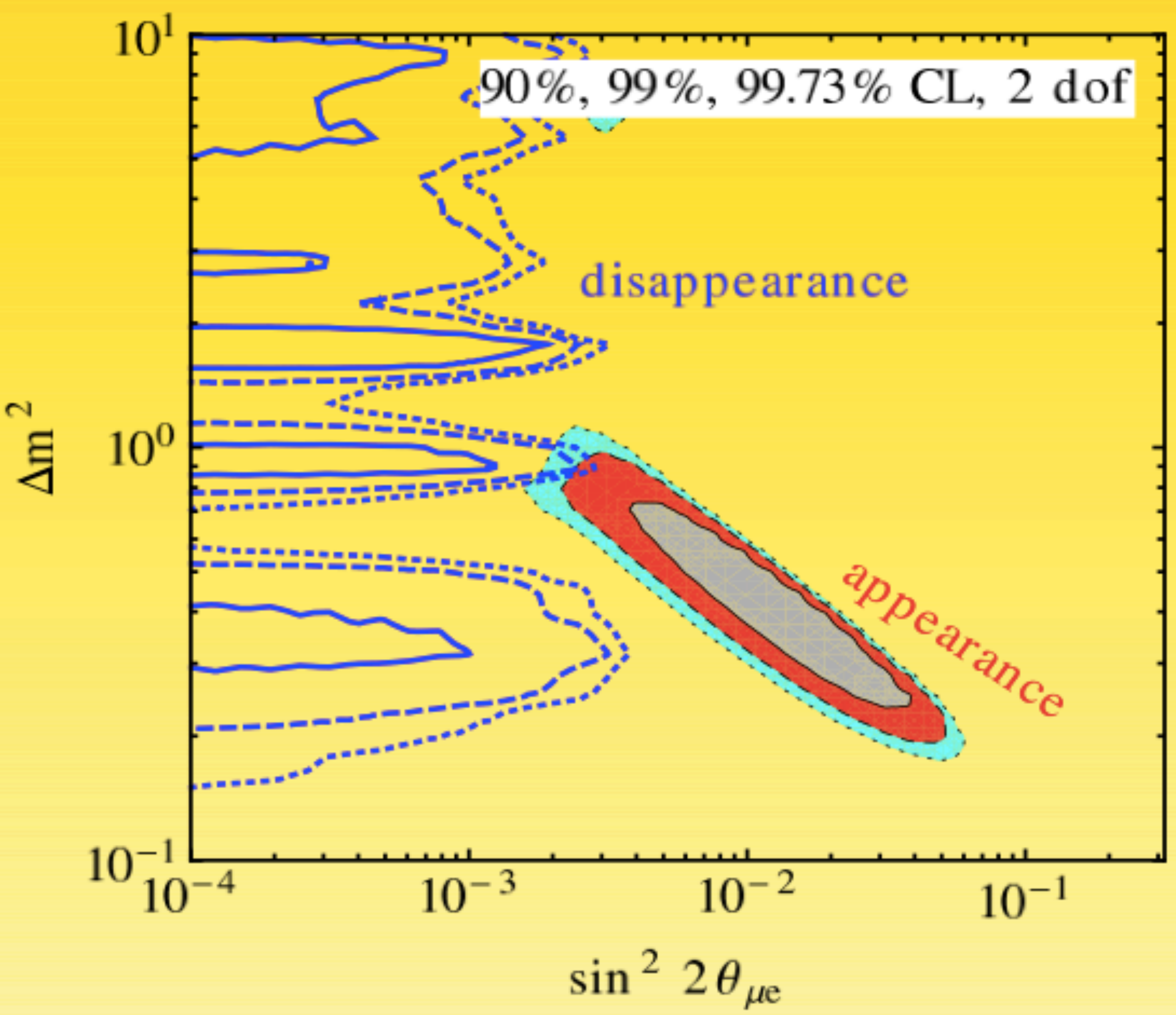
$$P(\nu_\mu \to \nu_e) = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2 \,\sin^2 \frac{\Delta m_{41}^2}{4E} L$$

$$P(\nu_e \to \nu_e) = 1 - 4\,|U_{e4}|^2 (1 - |U_{e4}|^2)\,\sin^2 \frac{\Delta m_{41}^2}{4E} L$$

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\,|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)\,\sin^2 \frac{\Delta m_{41}^2}{4E} L$$

$\Rightarrow$ if $\nu_\mu \to \nu_e$, then there should be $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$

$\Leftrightarrow$ tension between appearance and disappearance data...



some overlap at 99 % CL, consistency has p-value $\simeq 10^{-4}$ . . .

Kopp, Machado, Maltoni, Schwetz, 1303.3031

Sterile Neutrinos and $0\nu\beta\beta$

- recall $|m_{ee}|^{\rm act}_{\rm NH}$ can vanish and $|m_{ee}|^{\rm act}_{\rm IH}$ cannot vanish
- $|m_{ee}| = |\,\underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2\, e^{2i\alpha} + |U^2_{e3}| m_3\, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2 m_4\, e^{2i\Phi_1}}_{m_{ee}^{\rm st}}\,|$
- sterile contribution to $0\nu\beta\beta$:

$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}}\,|U_{e4}|^2 \begin{cases} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{cases}$$

- $\Rightarrow$ $|m_{ee}|_{\rm NH}$ cannot vanish and $|m_{ee}|_{\rm IH}$ can vanish!

Barry, W.R., Zhang, JHEP 1107; Giunti *et al.*, PRD **87**; Girardi, Meroni, Petcov, 1308.5802

keV steriles as Warm Dark Matter

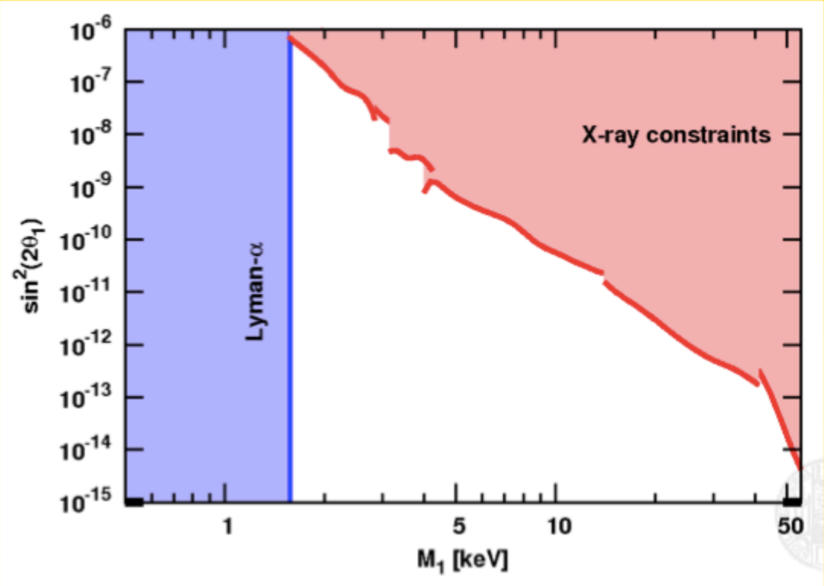
→ WDM has same large scale structure formation as CDM, but suppresses small scale formations

⇒ predicts less cuspy (=smoother) DM profiles, and less dwarf satellites

keV sterile is excellent candidate

parameters: mass M_1 and mixing θ

- X-ray searches $\Gamma \sim G_F^2 M_1^5\, \theta^2$
- Ly-α: structure formation at low scales ∼ MPc
- Tremaine-Gunn
- $\tau \sim \tau_{\mathrm{U}}$
- etc.



Theory Topics left out

Heeck: Lepton Number Violation with Dirac Neutrinos
Stefanik: $2\nu\beta\beta$ in GUTs
Zralek: neutrino masses
Suematsu: Neutrino mass and DM direct detection

apologies…

other topics not covered (or onlytouched) at this conference:
- magnetic moments
-
- leptogenesis
- unification
- pseudo Dirac neutrinos
- …many more

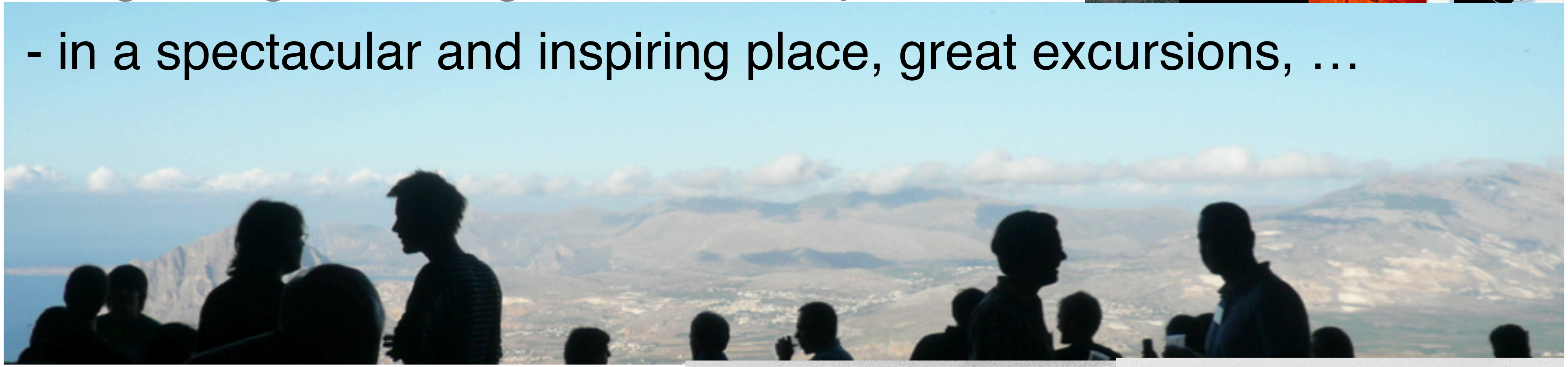
Summary

- neutrino physics has great results, rich physics, is lively,…
- improvements in known quantities…
- focus for the years to come:
  - θ_{13} → δ_{CP} und mass hierarchy
  - do sterile neutrinos exist
    - → 3x3 or (3+N)x(3+N) unitarity
    - → effects on oscillations, $0\nu\beta\beta$, unitarity, DM, ..
  - Dirac or Majorana mass ; other $\Delta L=2$ physics
  - connections to Dark Matter
  - galactic Supernova with ν+GR+light signal
  - …other topics: magnetic moments, ν-astronomy,…

- running or upcoming experiments will push forward
- new ieas & continued R&D towards new methods

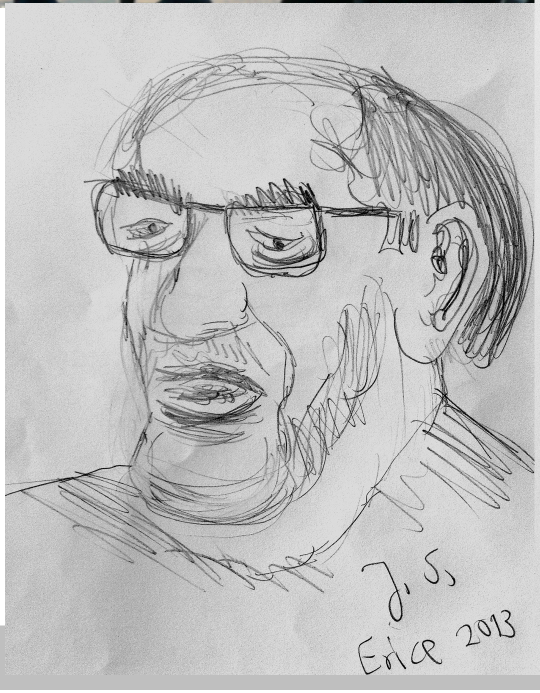
apologies again for whyt I left out…

we had a great conference
- in an exciting field
- with very rich & broad physics…
  huge range of energies, scales, topics, …



- in a spectacular and inspiring place, great excursions, …

thanks to the organizers:
Armand Faessler
Jochen Wambach
…others
+ local staff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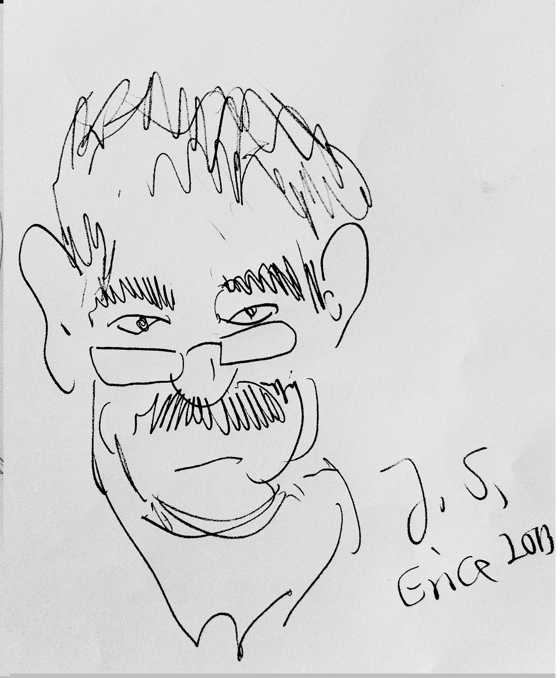
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