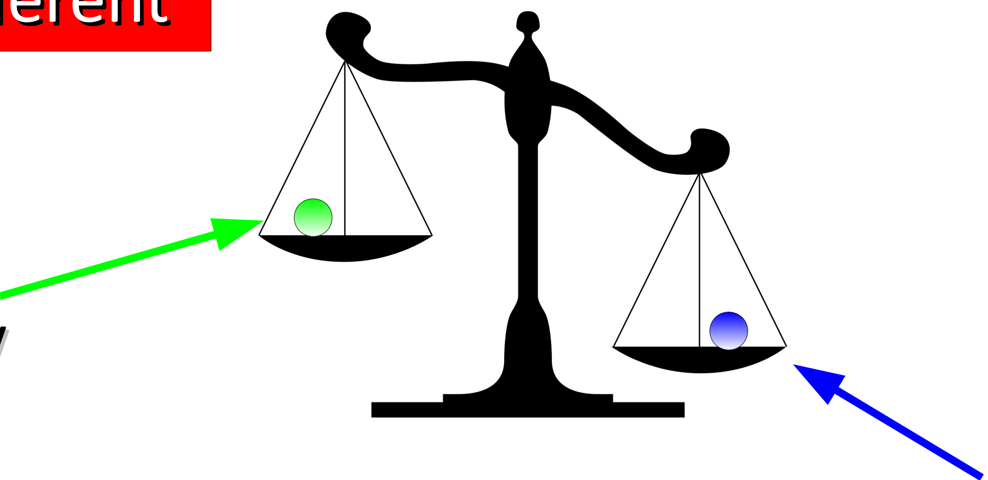
Why neutrinos are different

Simon MOLLET

Summer School and Workshop on the Standard Model and Beyond

Neutrinos are different !

Mass scale different



Very light < eV

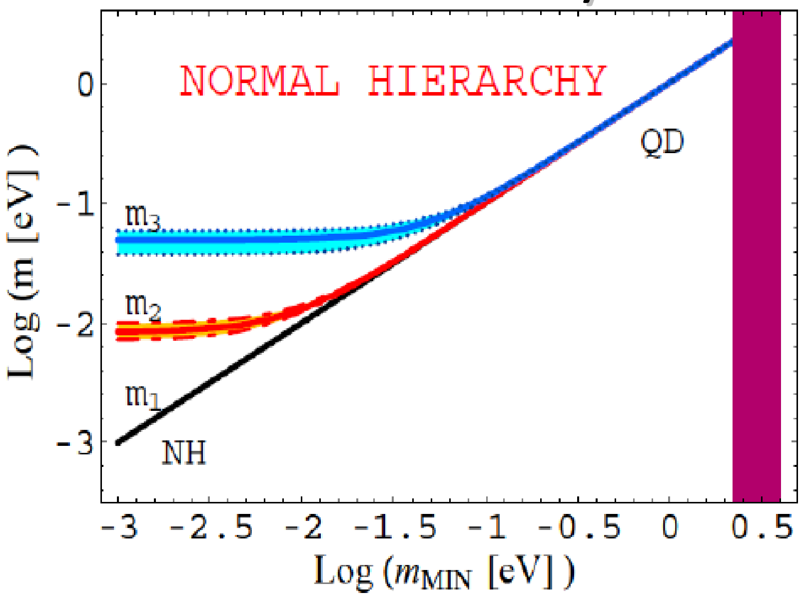
Electron = lightest
charged lepton >> eV

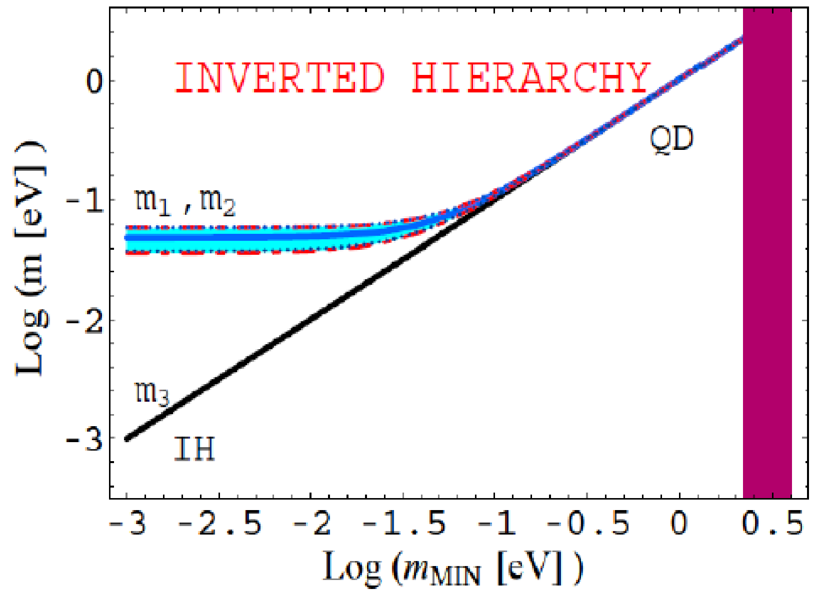
Mixing pattern different

PMNS →
$$\begin{pmatrix} 0.795-0.846 & 0.513-0.585 & 0.126-0.178 \\ 0.205-0.543 & 0.416-0.730 & 0.579-0.808 \\ 0.215-0.548 & 0.409-0.725 & 0.567-0.800 \end{pmatrix}$$

Neutrinos are badly known !

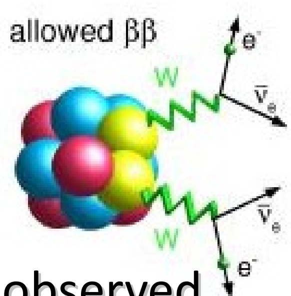
- What's the absolute mass scale?
- What's the hierarchy ?





R. N. Mohapatra *et al.*, Rept. Prog. Phys. **70** (2007) 1757.

- What's their nature ?

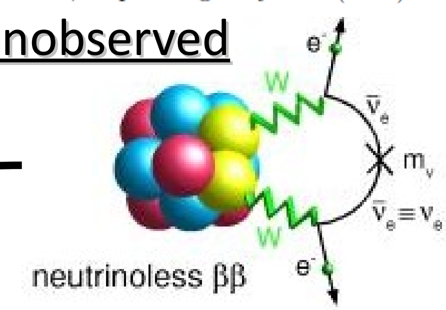


observed

$$\tau_{\beta\beta 2\nu} \approx 10^{17} \text{ ans}$$

$$\tau_{\beta\beta 0\nu} > 10^{22} \text{ ans}$$

unobserved



http://www.lhep.unibe.ch/lhep/pages/experimentshow.php?lang=en&expid=16&lang=en

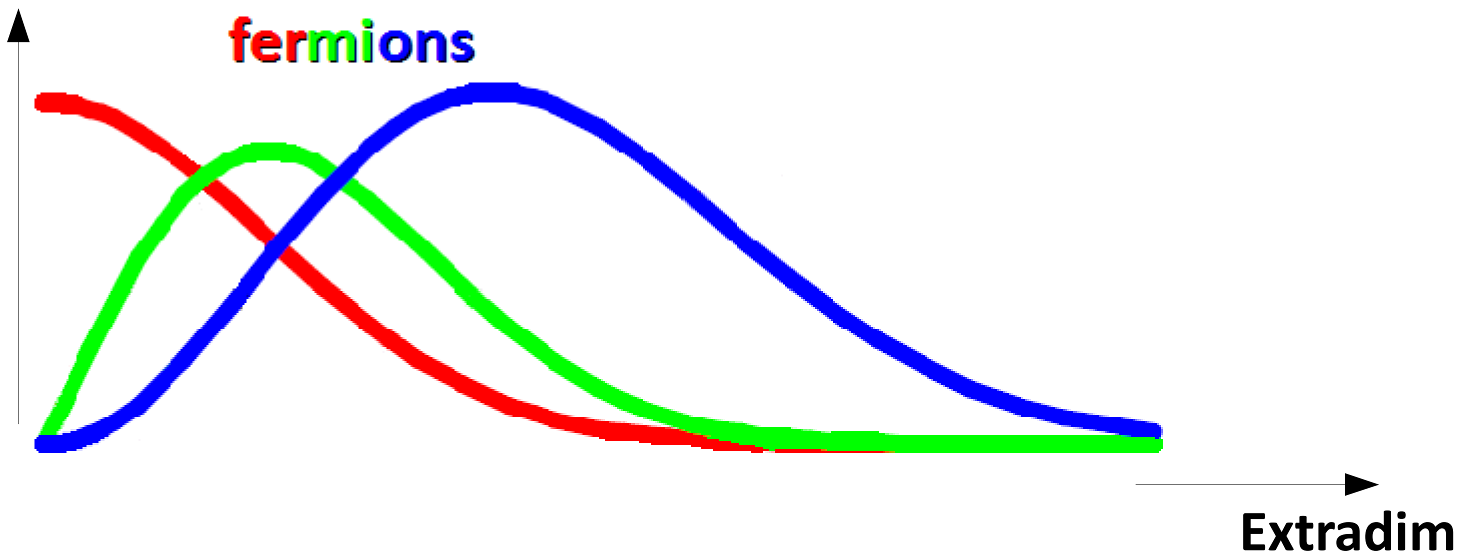
- θ_{13} predicted by model before measurement
- CP violation ?

Extradimensions could help ?

Already nice features to explain quark sector

2 extradim + vortex structure

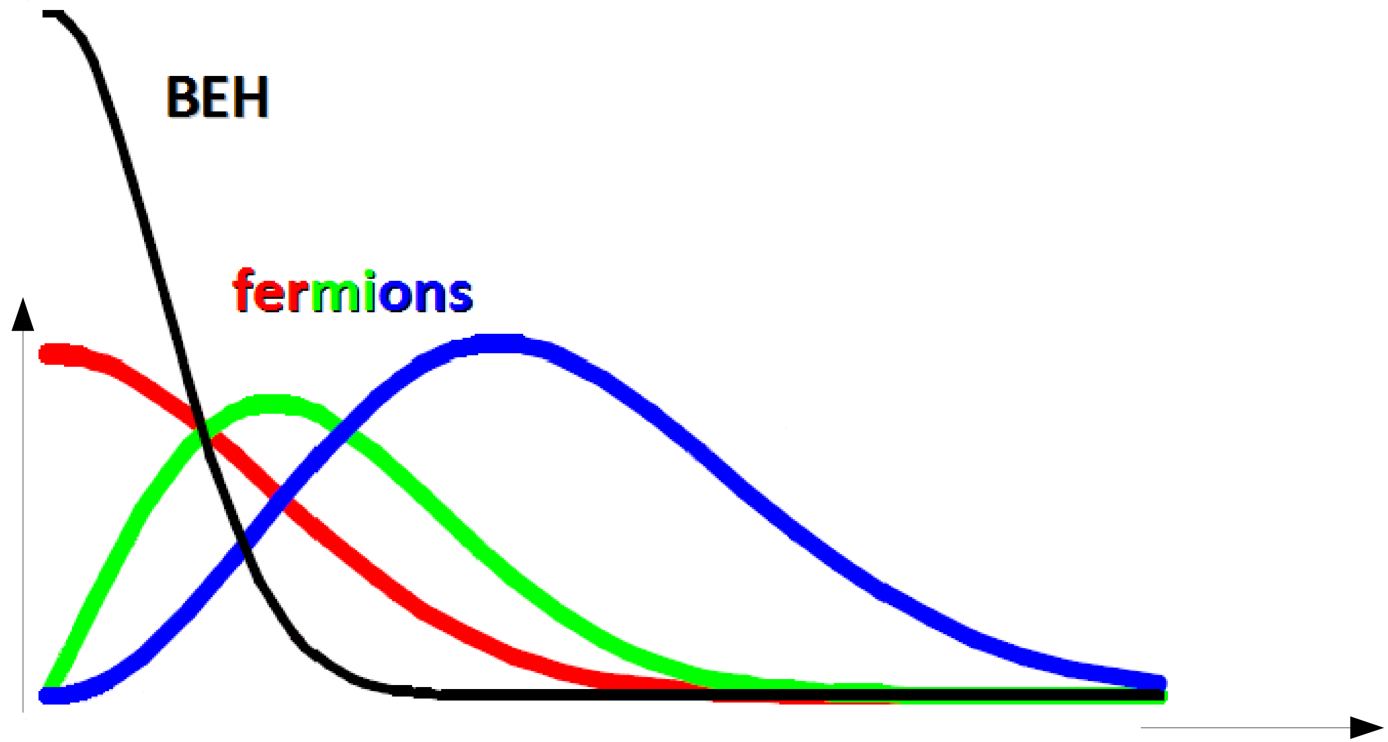
Index theorem: # flux units = # fermion zero-modes



3 families

Extradimensions could help ?

Add a localized BEH scalar (see JMF talk)

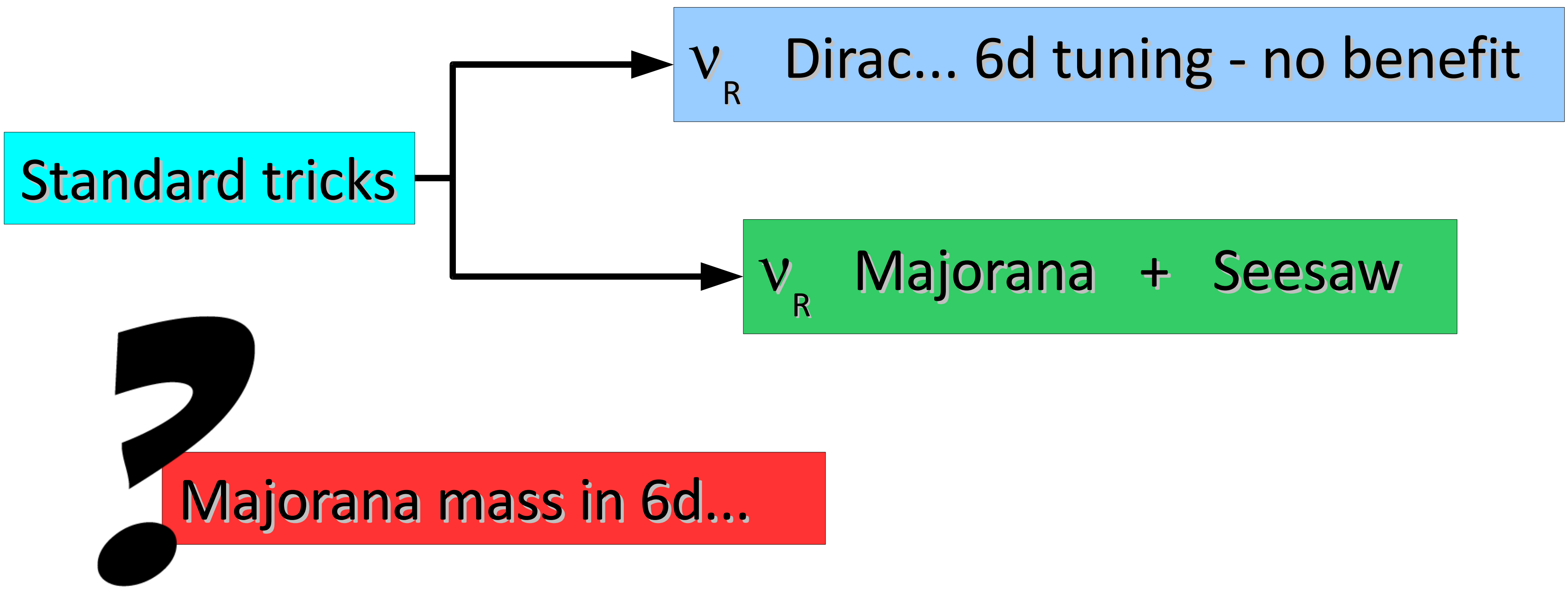


4D effective masses = convolution

Natural hierarchy

$$M \sim \begin{pmatrix} small & & \\ & medium & \\ & & large \end{pmatrix}$$

How to give masses to neutrinos ?



No Majorana particles in 6d... but what about a $\overline{N}^{c}N$ term ?

6d « *Majorana mass* »

6d chirality

$$\Psi = \begin{pmatrix} \Psi_{+R} \\ \Psi_{+L} \\ \Psi_{-L} \\ \Psi_{-R} \end{pmatrix} \begin{matrix} \Big\} + \\ \Big\} - \end{matrix}$$

Opposed chiralities

	4D	6D
Dirac	$\bar{\varphi}\psi = \varphi_R^\dagger \psi_L + \psi_R^\dagger \varphi_L$	$\bar{\Phi}\Psi = \Phi_-^\dagger \Psi_+ + \Psi_-^\dagger \Phi_+$
Majorana	$\bar{\varphi}^c \psi = \varphi_L^T \varepsilon \psi_L + \varphi_R^T \varepsilon \psi_R$	$\bar{\Phi}^c \Psi = \Phi_-^T E \Psi_+ + \Phi_+^T E \Psi_-$

Same chiralities

Opposed chiralities

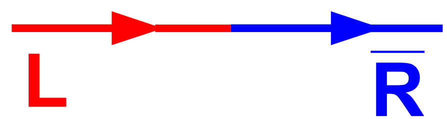
BUT...

$$\bar{\Phi}^c \Psi = \Phi^T_{+R} \varepsilon \Psi_{-R} + \Phi^T_{+L} \varepsilon \Psi_{-L} + \Phi^T_{-L} \varepsilon \Psi_{+L} + \Phi^T_{-R} \varepsilon \Psi_{+R}$$

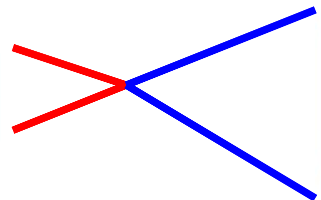
Same 4d chiralities → Effective 4d Majorana mass

Selection rules – quarks

Dirac



$$\begin{pmatrix} 0 \\ \chi_L(x;n).e^{i\varphi\frac{2k-2n+1}{2}} f_2(\theta;n) \\ \chi_L(x;n).e^{-i\varphi\frac{2n-1}{2}} f_3(\theta;n) \\ 0 \end{pmatrix}$$



$$\begin{pmatrix} \chi_R(x;n).e^{-i\varphi\frac{2n-1}{2}} f_3(\theta;n) \\ 0 \\ 0 \\ \chi_R(x;n).e^{i\varphi\frac{2k-2n+1}{2}} f_2(\theta;n) \end{pmatrix}$$

$$m_{ij} \sim \int \mathrm{d}\varphi \; \bar{R}_i L_j \sim \delta_{ij}$$

Dirac

$$M_q \sim \begin{pmatrix} \times & & \\ & \times & \\ & & \times \end{pmatrix}$$

Selection rules – neutrinos

« Majorana »

$$\begin{pmatrix} 0 \\ \chi_L(x;n).e^{i\varphi\frac{2k-2n+1}{2}} f_2(\theta;n) \\ \chi_L(x;n).e^{-i\varphi\frac{2n-1}{2}} f_3(\theta;n) \\ 0 \end{pmatrix}$$

$$m_{ij} \sim \int \mathrm{d}\varphi \; L_i L_j \sim \delta_{i+j,k+1}$$

(k=3)

Majorana

$$M_\nu \sim \begin{pmatrix} & & \times \\ & \times & \\ \times & & \end{pmatrix}$$

Why neutrinos are different: model predictions

Quite naturally...

$$M_\nu \sim \begin{pmatrix} & & m \\ & \mu & \\ m & & \end{pmatrix} \qquad m \gg \mu$$

Diagonalisation →

$$\begin{pmatrix} m & & \\ & -m & \\ & & \mu \end{pmatrix}$$

→

- Inverted hierarchy $|m_1|, |m_2| \sim m$ et $|m_3| \sim \mu$
- $\Pi/2$ angle → Large mixing !
- $\beta\beta_{0\nu}$ (partial) suppression $\langle m_{\beta\beta}\rangle \equiv |\sum_i U_{ei}^2 m_i|$

Pseudo-Dirac

$$M_\nu \sim \begin{pmatrix} & m \\ m & \end{pmatrix}$$

Diagonalization

$$\begin{pmatrix} m & \\ & -m \end{pmatrix}$$

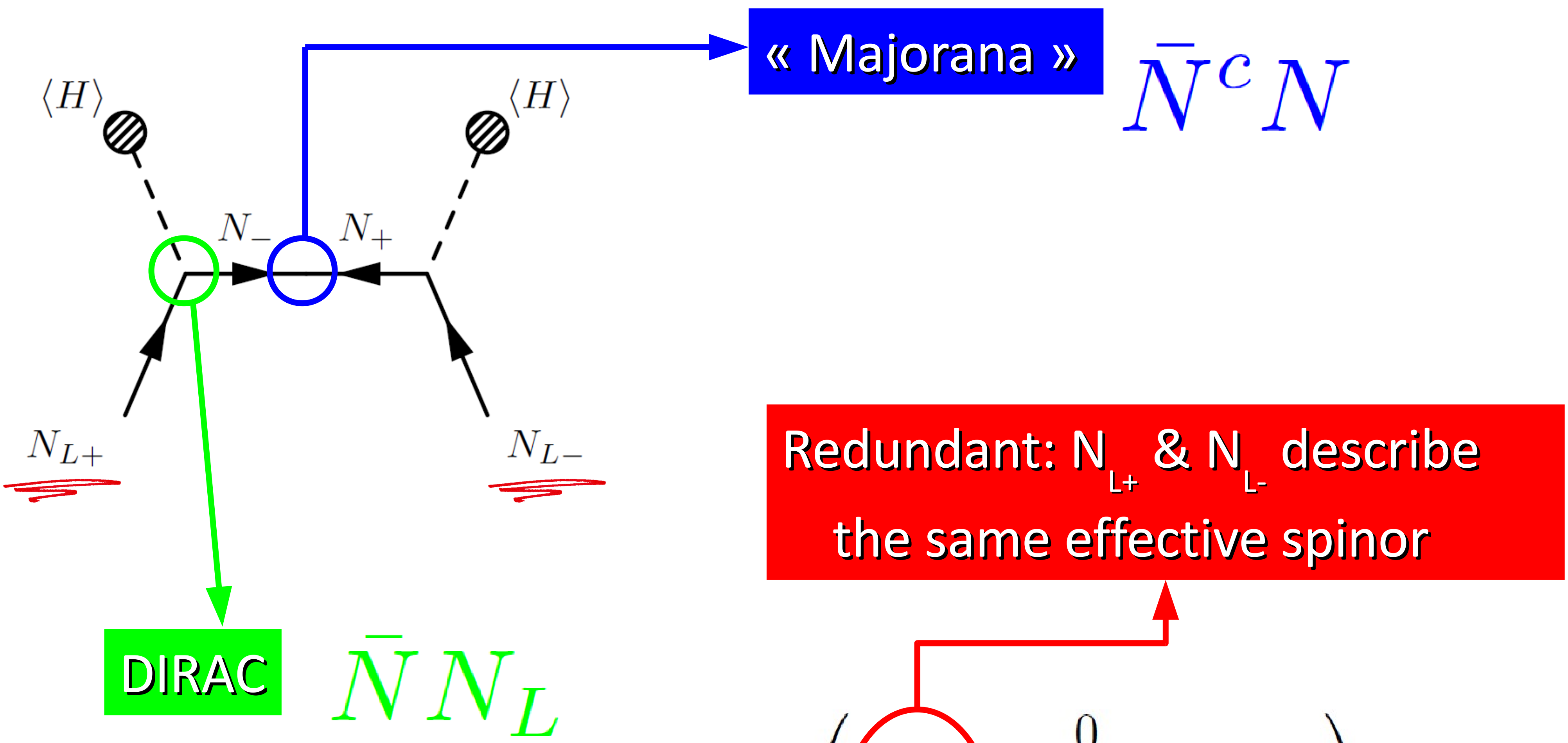
$$U = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} \end{pmatrix}$$

Maximal angle

$$\langle m_{\beta\beta} \rangle \equiv \left| \sum_i U_{ei}^2 m_i \right|$$

Suppression !

6d seesaw



$$N_L = \sum_n \begin{pmatrix} 0 \\ \nu_L(n).e^{i\varphi\frac{2k-2n+1}{2}} f_2(n) \\ \nu_L(n).e^{-i\varphi\frac{2n-1}{2}} f_3(n) \\ 0 \end{pmatrix}$$

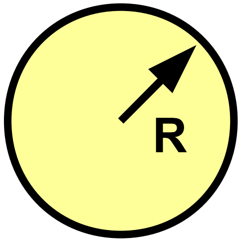
6d « *RH neutrino* »

Additional neutrinos unseen → DELOCALIZED

KK spectrum → $$M^2 + \frac{\lambda^2}{R^2}$$ $\lambda \neq 0$

M^2: « majorana mass »

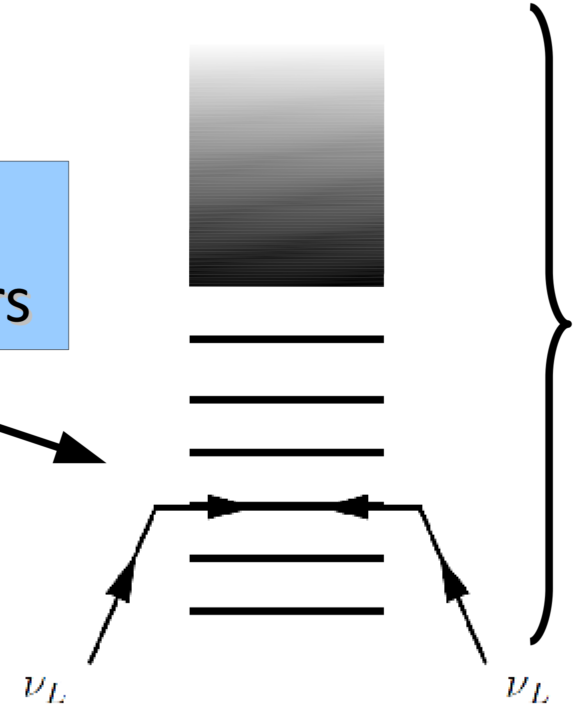
$\frac{\lambda^2}{R^2}$: compactification



Effective 4d seesaw

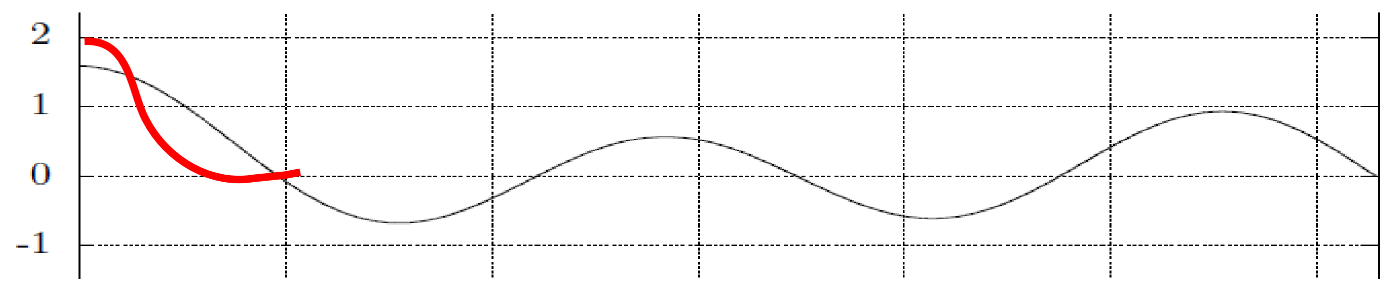
Mass scale ↘

Heavy mediators

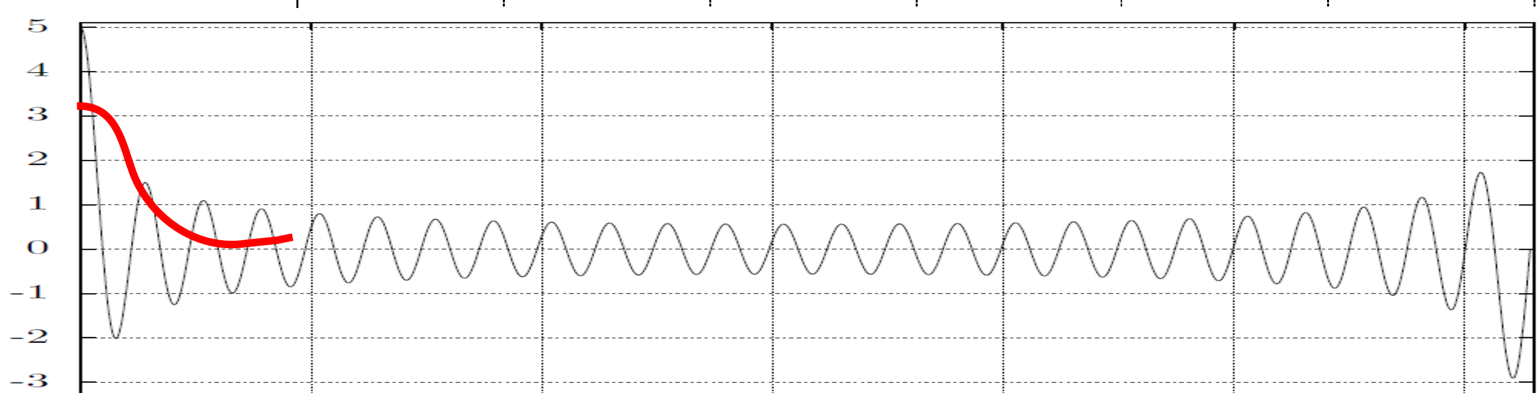


Summation on « an infinity » of KK modes

Small overlap



Effectively cut-off by oscillations



What's new ?

Before numerical estimation with step functions

(exact computation numerically tricky)

NOW

Now we have (exact) results

MORE

First complete set of parameters to reproduce quark, scalar and neutrino sectors !

Very last results

	Neutrino masses	
m_1	$5.46 \cdot 10^{-2}$ eV	–
m_2	$5.53 \cdot 10^{-2}$ eV	–
m_3	$4.17 \cdot 10^{-5}$ eV	–
Δm^2_{21}	$7.96 \cdot 10^{-5}$ eV^2	$(7.50 \pm 0.185) \cdot 10^{-5}$ eV^2
Δm^2_{13}	$2.98 \cdot 10^{-3}$ eV^2	$(2.47^{+0.069}_{-0.067}) \cdot 10^{-3}$ eV^2
	Lepton mixing matrix	
$\lvert U_{\mathrm{PMNS}} \rvert$	$\begin{pmatrix} 0.76 & 0.63 & 0.13 \\ 0.39 & 0.58 & 0.72 \\ 0.52 & 0.52 & 0.68 \end{pmatrix}$	$\simeq \begin{pmatrix} 0.795-0.846 & 0.513-0.585 & 0.126-0.178 \\ 0.205-0.543 & 0.416-0.730 & 0.579-0.808 \\ 0.215-0.548 & 0.409-0.725 & 0.567-0.800 \end{pmatrix}$
$\langle m_{\beta\beta} \rangle$	0.013 eV	$\lesssim 0.3$ eV[31]
J	0.019	$\lesssim 0.036$
θ_{12}	39.7°	$\simeq (31.09^\circ - 35.89^\circ)$
θ_{23}	46.5°	$\simeq (35.8^\circ - 54.8^\circ)$
θ_{13}	7.2°	$\simeq (7.19^\circ - 9.96^\circ)$

arXiv:1305.4320

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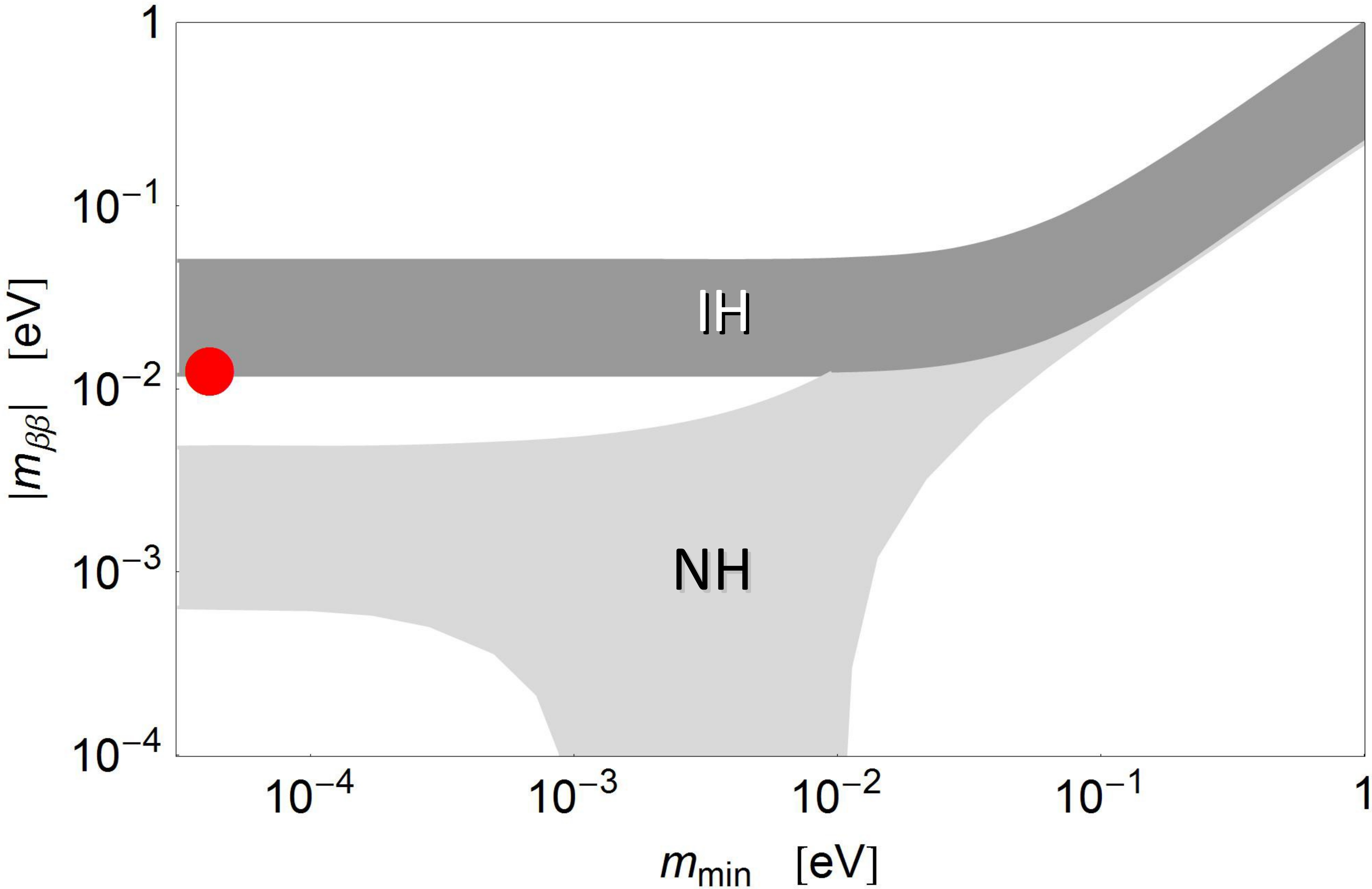
On the border



arXiv:1305.4320

Back up slides

Very last results (more)

The scalar-boson mass		
m_H	125 GeV	$125.5 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})$ [3] $125.7 \pm 0.3(\text{stat.}) \pm 0.3(\text{syst.})$ [4]
Quark masses at Z scale		
m_d	0.01 GeV	(0.00282 ± 0.00048) GeV
m_s	0.051 GeV	$(0.057^{+0.018}_{-0.012})$ GeV
m_b	2.86 GeV	$2.86^{+0.16}_{-0.06}$ GeV
m_u	0.023 GeV	$0.00138^{+0.00042}_{-0.00041}$ GeV
m_c	0.72 GeV	$0.638^{+0.043}_{-0.084}$ GeV
m_t	172 GeV	172.1 ± 1.2 GeV
Quark mixing matrix		
$\lvert U_{\text{CKM}} \rvert$	$\begin{pmatrix} 0.979 & 0.207 & 0.0015 \\ 0.206 & 0.9730 & 0.046 \\ 0.011 & 0.049 & 0.999 \end{pmatrix}$	$\begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$
Charged-lepton masses		
m_e	0.00061 GeV	0.0004866 GeV
m_μ	0.089 GeV	0.1027 GeV
m_τ	1.74 GeV	1.746 GeV

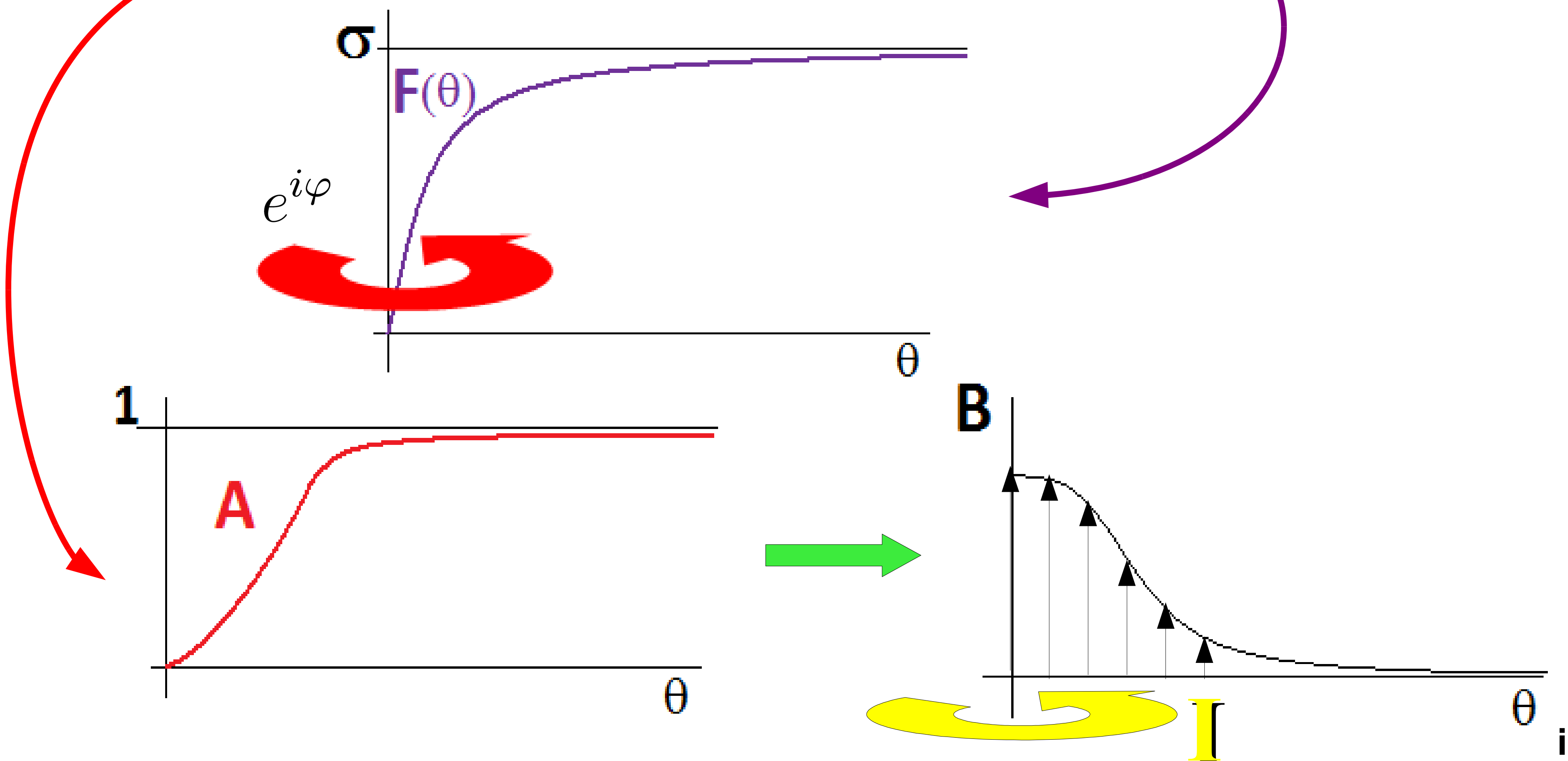
i

Vortex structure

<u>2 fields</u>

Φ ~ order parameter

A_μ ~ potential => magnetic field



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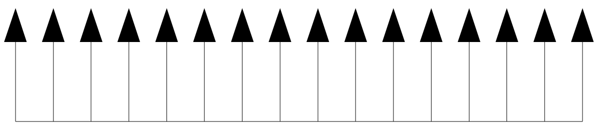
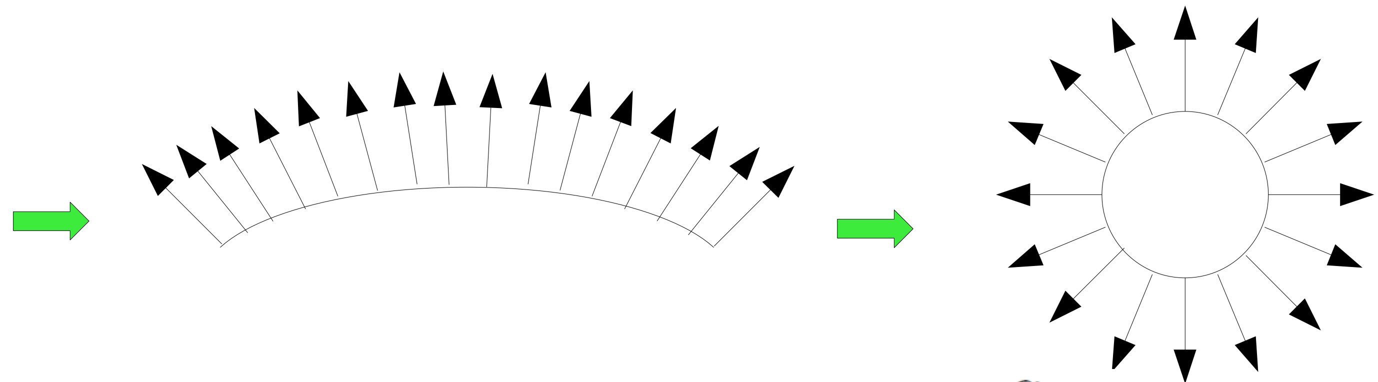
Vortex on a sphere

Bend the sample...





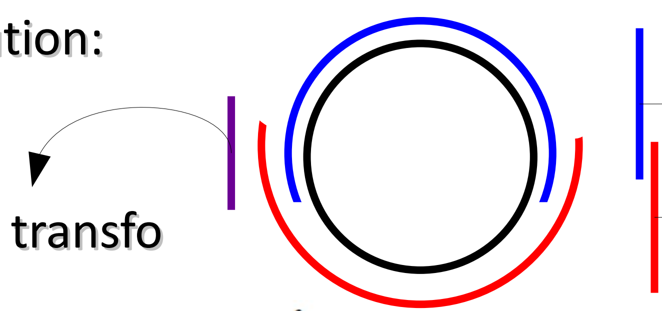
Magnetic monopole $\mathrm{div}\boldsymbol{B} = 4\pi g \delta(\boldsymbol{r}) \longrightarrow \boldsymbol{B} = \frac{g}{r^2}\mathbf{1}_r$

Potential $\boldsymbol{A} = g\frac{1-\cos\theta}{r\sin\theta}\mathbf{1}_\varphi$ singular in π

Other gauge ? ... $\boldsymbol{A} = -g\frac{1+\cos\theta}{r\sin\theta}\mathbf{1}_\varphi$ singular in 0

Description of the entire sphere with a unique potential impossible !

Solution:



Gauge transfo

$\Phi = \Phi\, e^{-i\varphi}$ **well-defined in π**

« single valued »

Fermions: $\Psi = \Psi\, e^{-iQ\varphi} \longrightarrow Q \in \mathbb{Z}$

Charge quantization !

What's new ? (1)

2010 Frère, Libanov, Ling

First implemention

Big tendencies

BUT...

Numerical estimation with step functions

(exact computation numerically tricky)

2013

Now we have results

What's new ? (2)

First apparition of the model... back in...

2001	Libanov, Troitsky	2 flat extra dim
	Frère, Lib., Troit.	
2002	Lib., Nugaev	Realistic quark mass pattern
2003	Fr., Lib., Nug., Troit.	Sphere compactifiction
2004	Fr., Lib., Nug., Troit.	FCNC
2005	Lib., Nug.	Scalar sector
2010	Fr., Lib., Ling	Neutrino
2012-2013	First complete set of parameters to reproduce quark, scalar and neutrino sectors !	

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