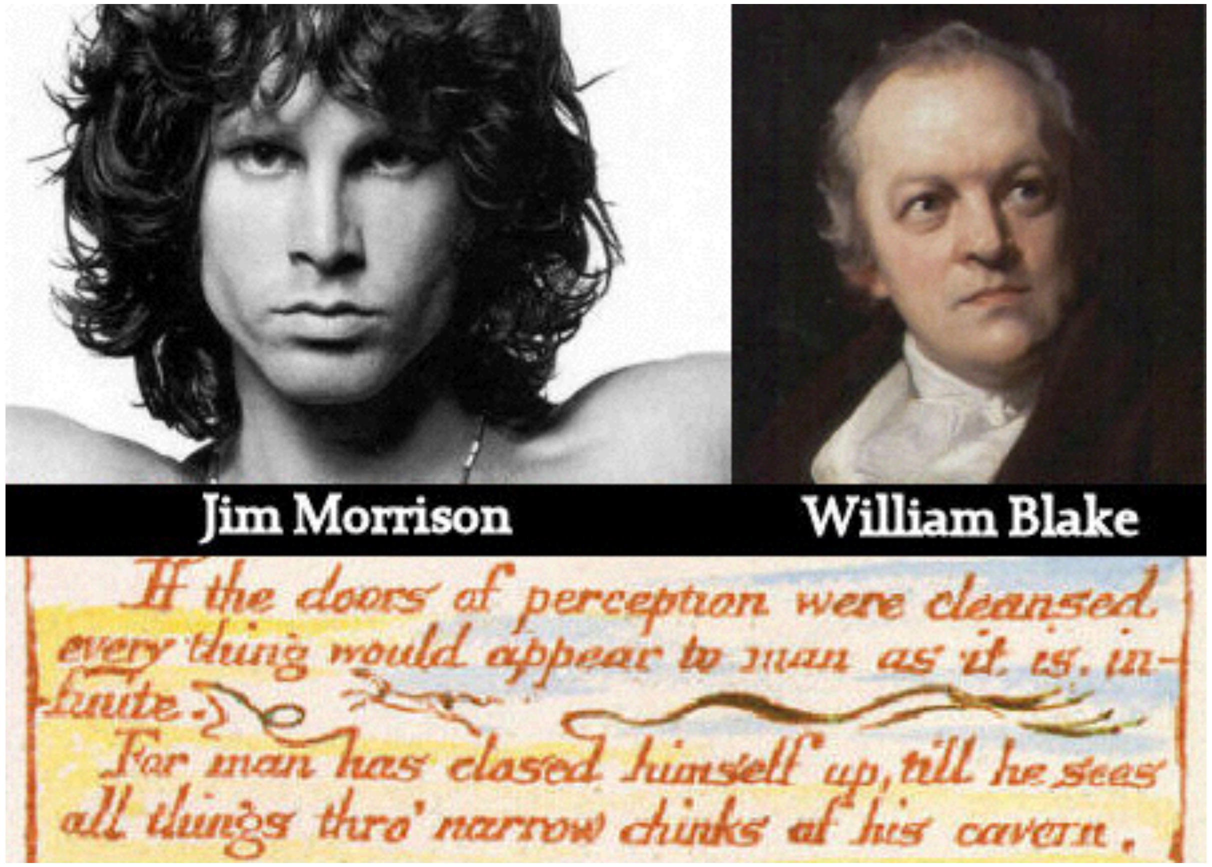
Measuring the neutrino mass

J.J. Gómez Cadenas
IFIC (CSIC & UV)

St. Andrews, INSS, 2014
Lecture 1



There are things known, and things unknown, and in between are the Doors.

Things known about neutrinos

$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}|\nu_j\rangle$$

$$\begin{cases} |\nu_\alpha\rangle & : \text{Flavor weak eigenstate;} \\ U_{\alpha j} & : \text{Neutrino mixing matrix;} \\ |\nu_j\rangle & : \text{Mass eigenstate.} \end{cases}$$

- **Neutrinos are fermions.**
- **There are 3 active neutrinos flavours (νe,νμ,ντ).**
- **Neutrino flavour states are a mixture of neutrino mass states (ν1,ν2,ν3). As a consequence, we have observed neutrino oscillations.**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

$$\delta m_{ij}^2 = |m_i^2 - m_j^2|$$

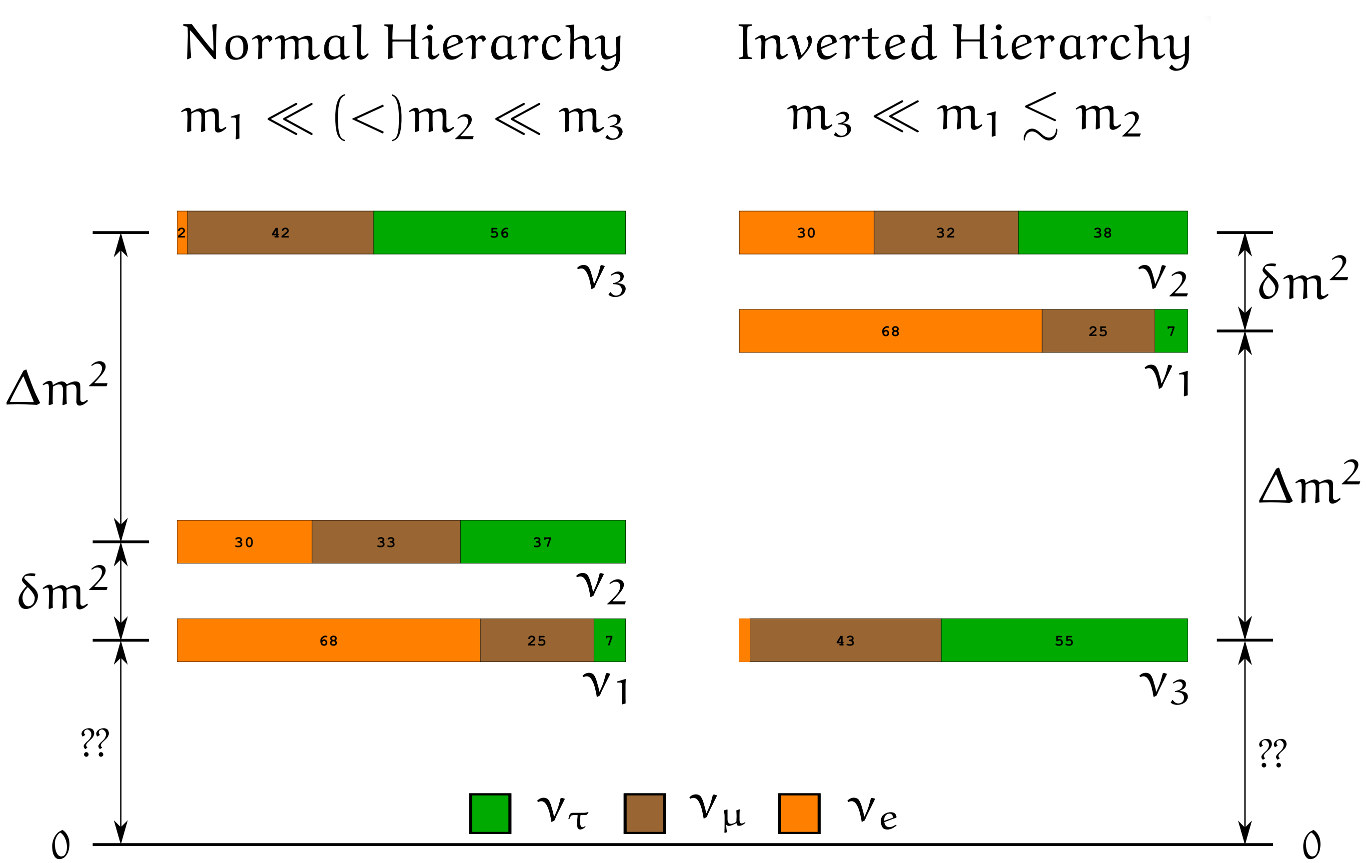
$$\sin^2\theta_{ij} = f(|U_{ij}|^2)$$

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}.$$

- **Neutrinos oscillation experiments are sensitive to the difference of mass squared between states**
- **The mixing angles measured by oscillation experiments are functions of the elements of the PMNS matrix and allow its determination.**

Things known about neutrinos

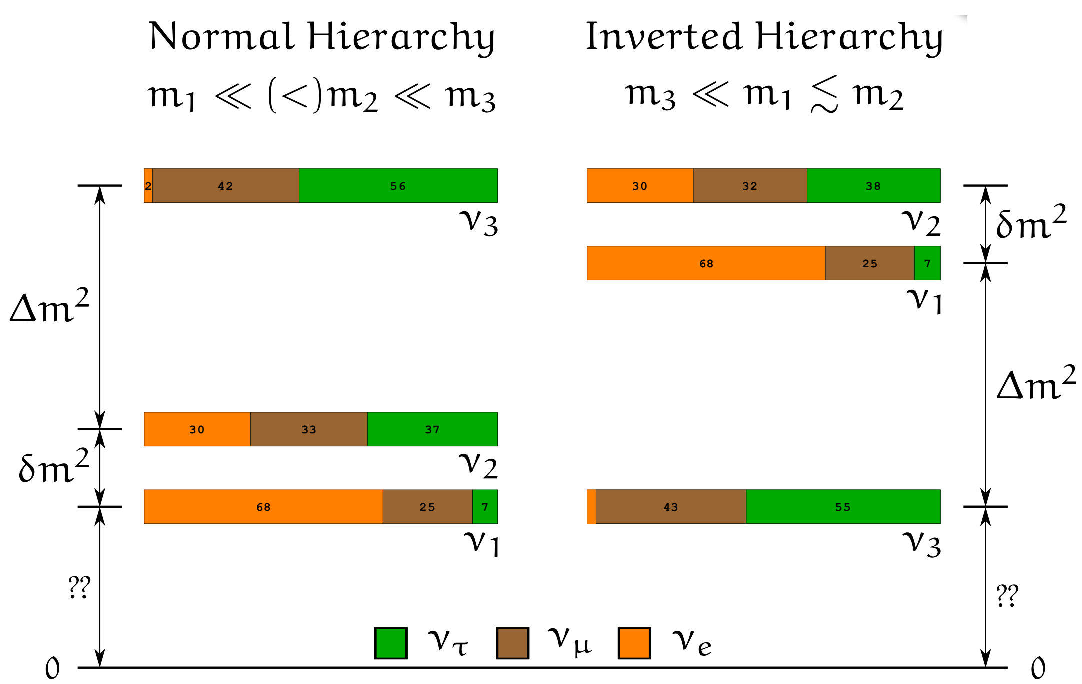
$\Delta m^2_{21} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\,\mathrm{eV}^2$ $\Delta m^2_{32} = 2.43^{-0.06}_{+0.1} \times 10^{-3}\,\mathrm{eV}^2$



$$\begin{cases} \delta m^2 = m_2^2 - m_1^2 \\ \Delta m^2 = m_3^2 - \dfrac{m_1^2 + m_2^2}{2} \end{cases}$$

- **Two mass splits measured by oscillation experiments.**
- **Two mass hierarchies possible.**

Things unknown about neutrinos



- **See Boris Kayser lectures**

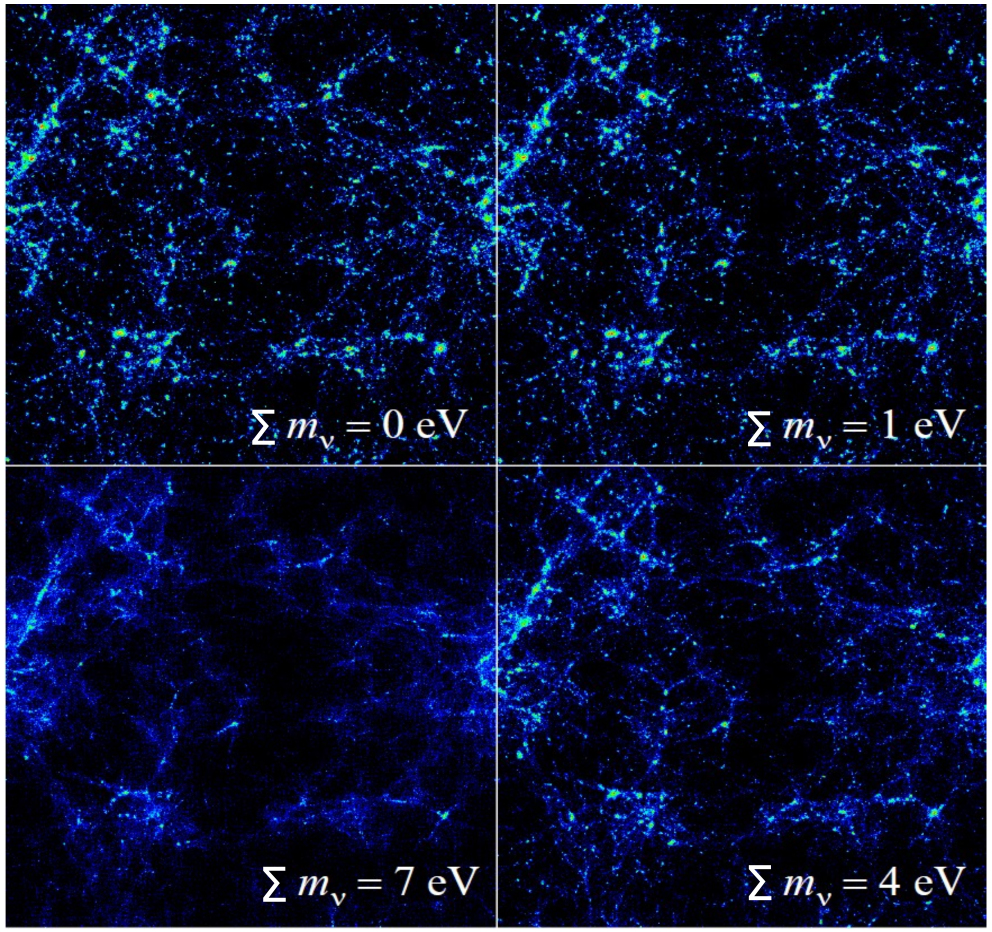
- **We don't know the mass scale**
    - **the mass of the lightest neutrino, m_l). In fact, nothing prevents m_l from being ~0.**
    - **Alternatively, the masses of the neutrinos could be roughly the same (the degenerate scenario), e.g, m_ν~0.1 eV, to satisfy cosmological bounds.**
- **Neutrinos could be Majorana particles.**
- **Neutrino interactions could violate CP (as in the quark sector)**
- **There could be additional neutrinos (e.g, sterile).**

The Doors

- … of experimentation!

- Neutrino oscillation experiments to measure CP violating phase and determine mass hierarchy. Also sensitive to additional (sterile neutrinos)
- Cosmological measurements sensitive to the number of neutrino species and to the absolute scale of (the sum) of neutrino masses.
- Beta decay experiments sensitive to the "m_β" (recall that ve is a lineal superposition of (v1,v2,v3) masses.
- Neutrinoless double beta decay experiments can demonstrate (if successful) the Majorana nature of neutrino. They are sensitive to mass hierarchy and to the "$m_{\beta\beta}$".

Cosmological measurements of neutrino masses



simulation Chung-Pei Ma 1996

- **Neutrinos masses affect the structure of CMB and the large scale structure of the universe.**
- **Measurement sensitive to the sum of neutrino masses.**
- **"Model dependent"**

WMAP CMB only	$\sum m_i \leq 1.3eV$
CMB+BAO	$\sum m_i \leq 0.58eV$
CMB+BAO+ H0	$\sum m_i \leq 0.48eV$
Physical Review Letters, 105 (3)	$\sum m_i \leq 0.23eV$

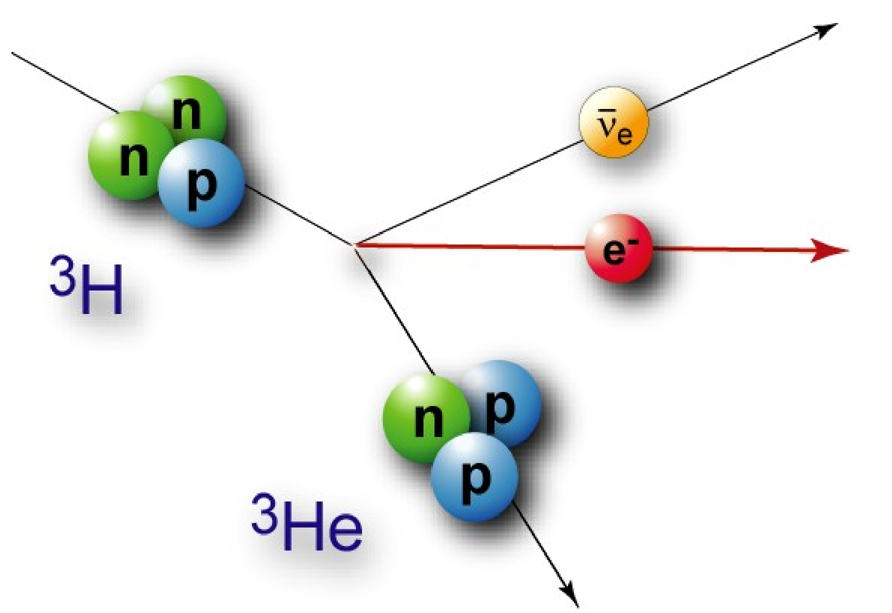
- **See Jenni Adams lectures**

Evidence for Massive Neutrinos from Cosmic Microwave Background and Lensing Observations

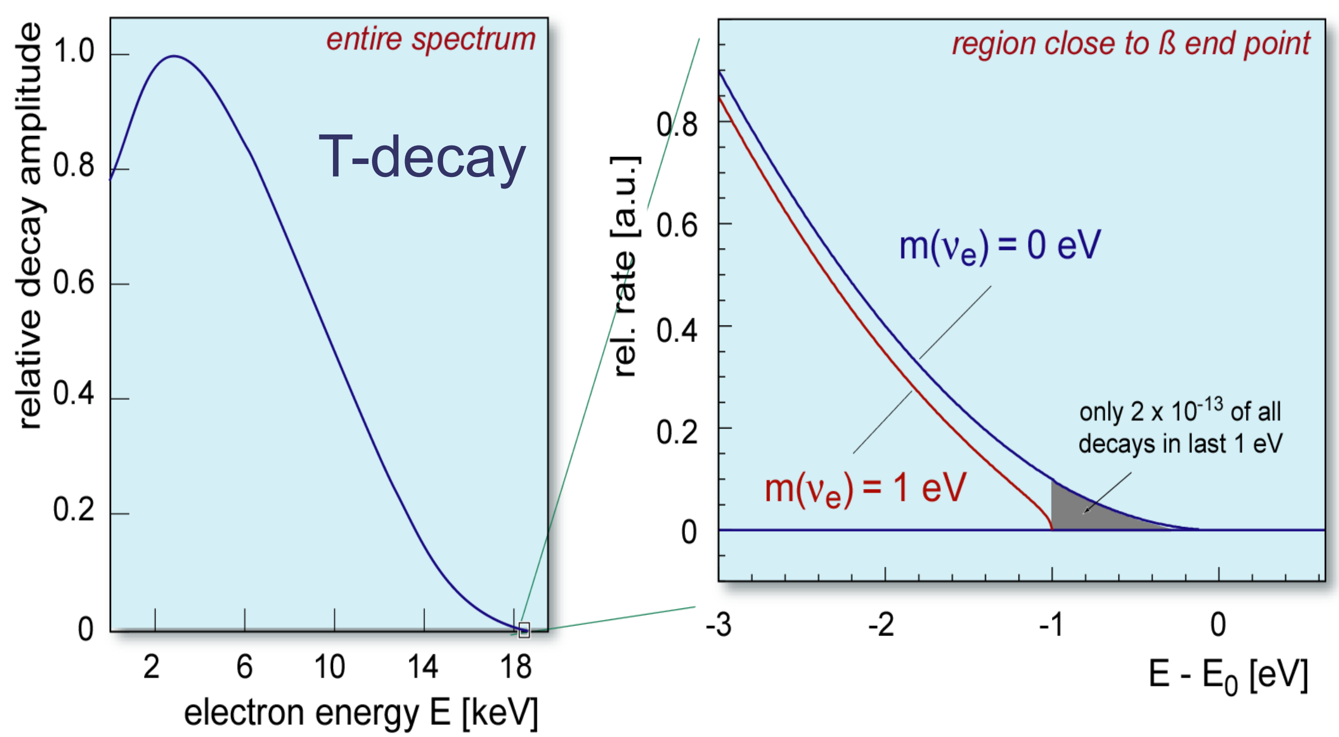
Phys. Rev. Lett. 112, 051303 (2014)

$$\sum m_i = 0.32 \pm 0.11eV$$

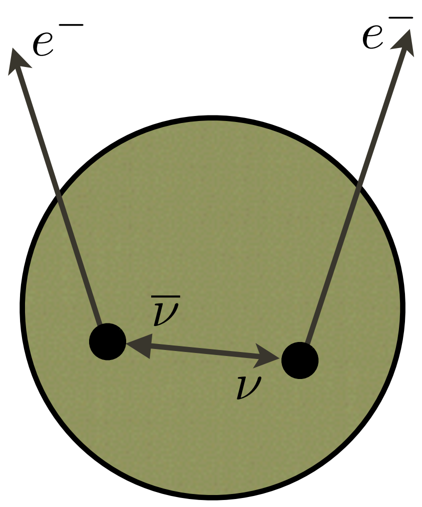
End-point of β decay



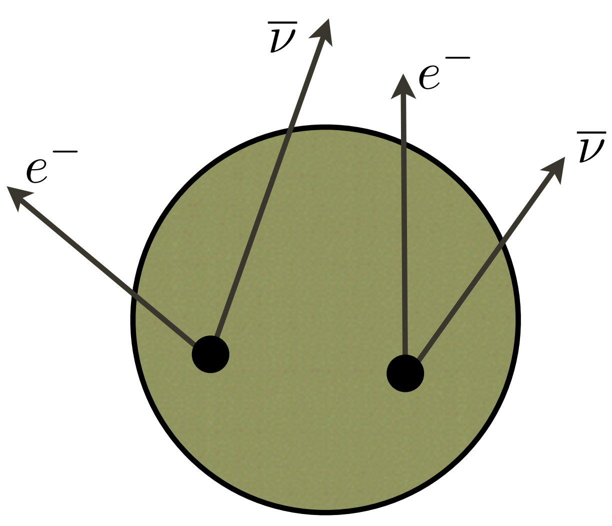
- **The presence of a massive neutrino affects the shape of the electron energy distribution (very) near the end point.**
- **Measurement is “model independent”.**
- **One measures $m_{\nu e}$ (an incoherent sum of mass eigenstates)**



$\beta\beta 0\nu$ decays



$\beta\beta 0\nu$



$\beta\beta 2\nu$

- **Lepton number violating process.**
- **Requires Majorana neutrinos** $\nu = \bar{\nu}$
- **Measures $m_{\beta\beta}$ (coherent sum of states)**
- **Result depends on mass hierarchy (eg cancelations in the case of normal hierarchy)**
- **Theoretical uncertainties related with NME**

- **A discovery would be crucial to determine the mass hierarchy, the scale of the neutrino mass and the nature of the neutrino.**

Direct mass measurements

Cosmology, single and double β decay

Cosmology, single and double β decay measure different combinations of the neutrino mass eigenvalues, constraining the neutrino mass scale

In a standard three active neutrino scenario:

$$\Sigma \equiv \sum_{i=1}^{3} M_i$$

cosmology
simple sum
pure kinematical effect

$$\langle M_\beta \rangle \equiv \left(\sum_{i=1}^{3} M_i^2 \, |U_{ei}|^2 \right)^{1/2}$$

β decay
incoherent sum
real neutrino

$$\langle M_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} M_i \, |U_{ei}|^2 \, e^{i\alpha_i} \right|$$

double β decay
coherent sum
virtual neutrino
Majorana phases

A. Giuliani, IMFP 2012