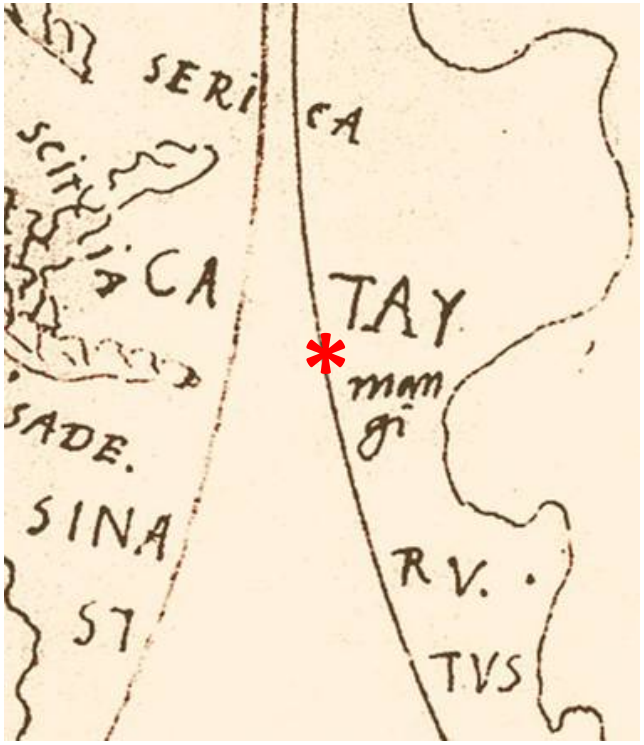
Neutrino Physics – Theory and Phenomenology



Serica (*Land of Silk*)

Catay (*Northern China*)

Mangi (*Southern China*)

Sinaru[m] Situs (*Chinese Land*)

* **We are here**

Eligio Lisi
INFN, Bari, Italy

Prologue: 500 years ago (A.D. ~ 1514)

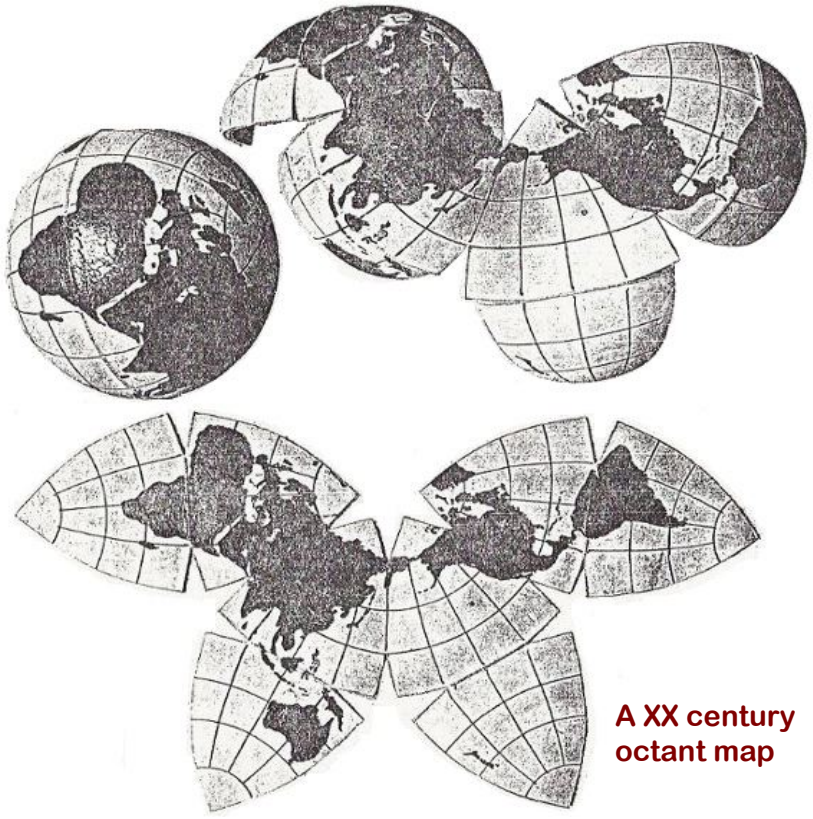
Northern hemisphere

Southern hemisphere

A remarkable world map by Leonardo da Vinci…

[Royal Library, Windsor Collection. Executed by one of Leonardo's workshop assistants.]

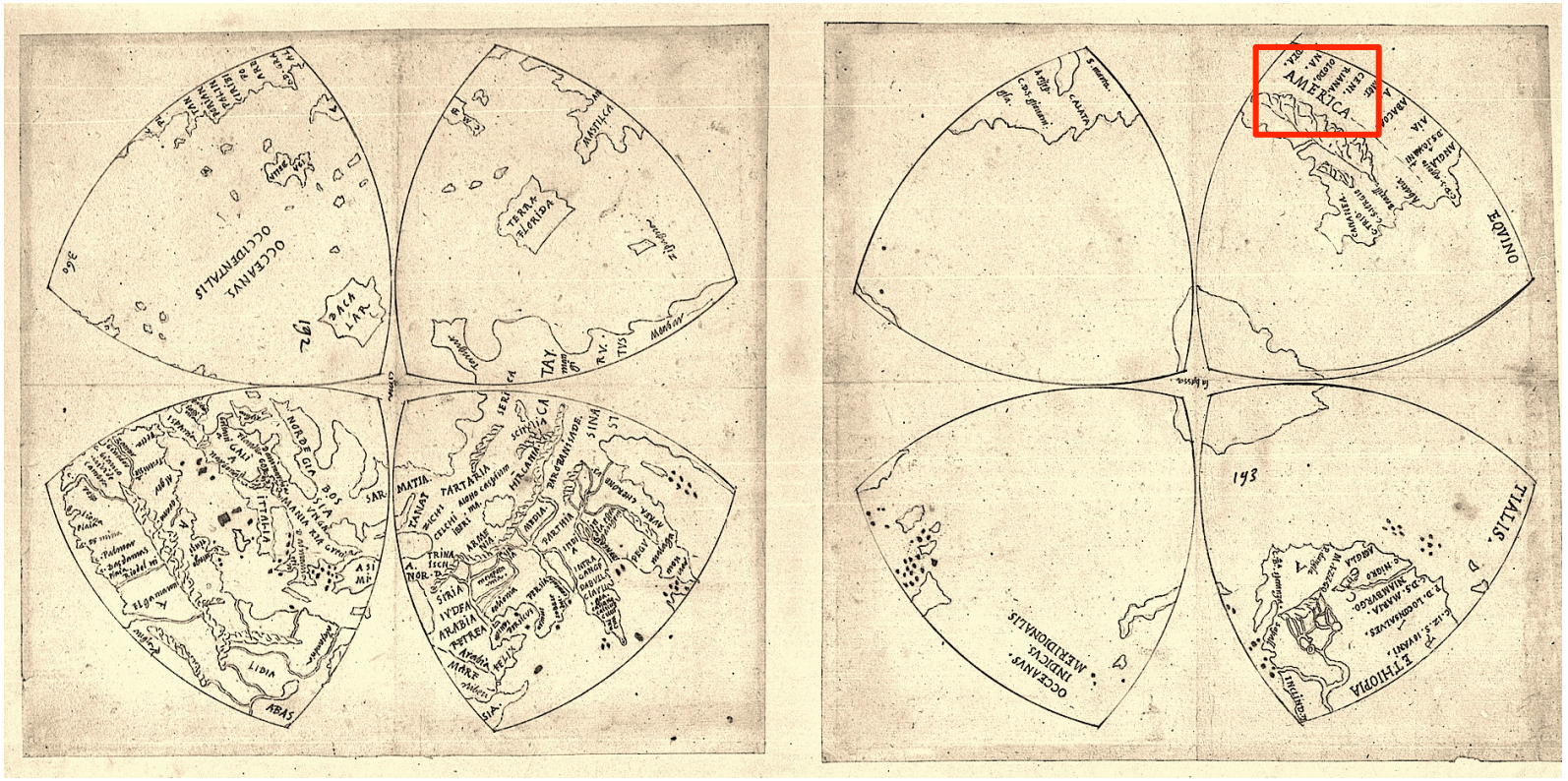
Earliest known world map …



A XX century octant map

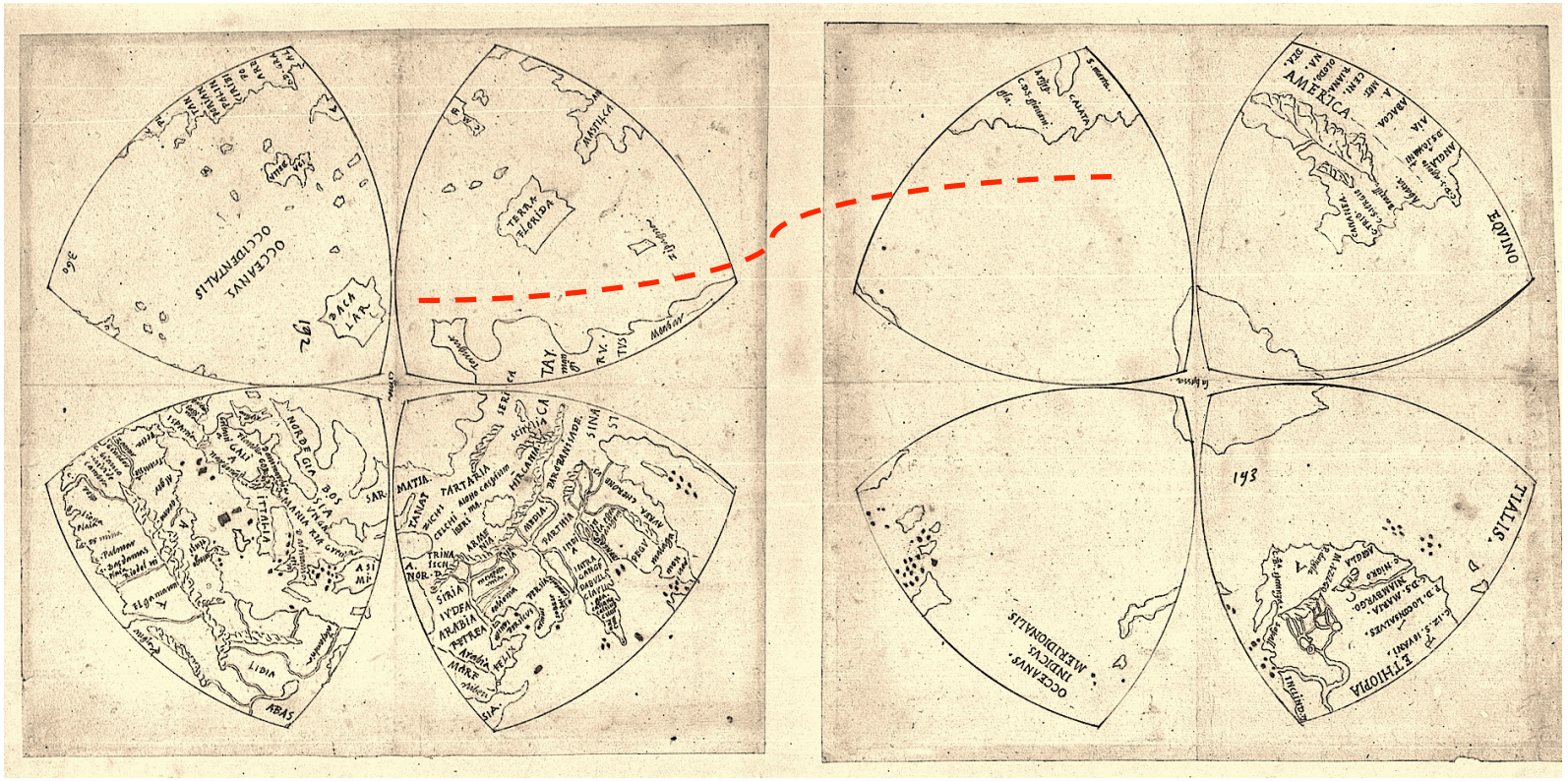
… made with octant projections

Earliest known world map …



… made with octant projections
… showing the name “America”

Earliest known world map …

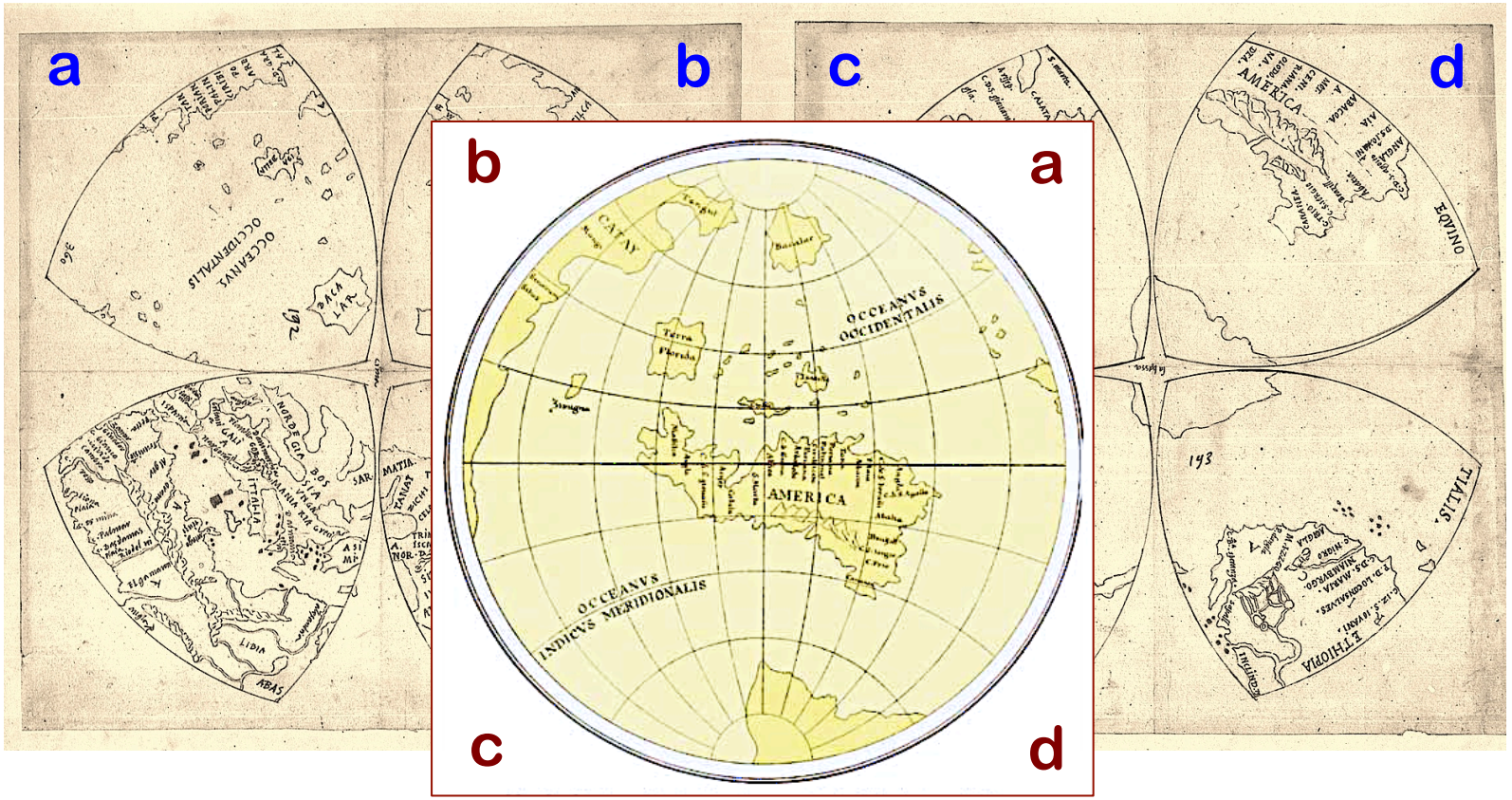


… made with octant projections
… showing the name “America”
… with America’s west coast disconnected from Asia

Earliest known world map …

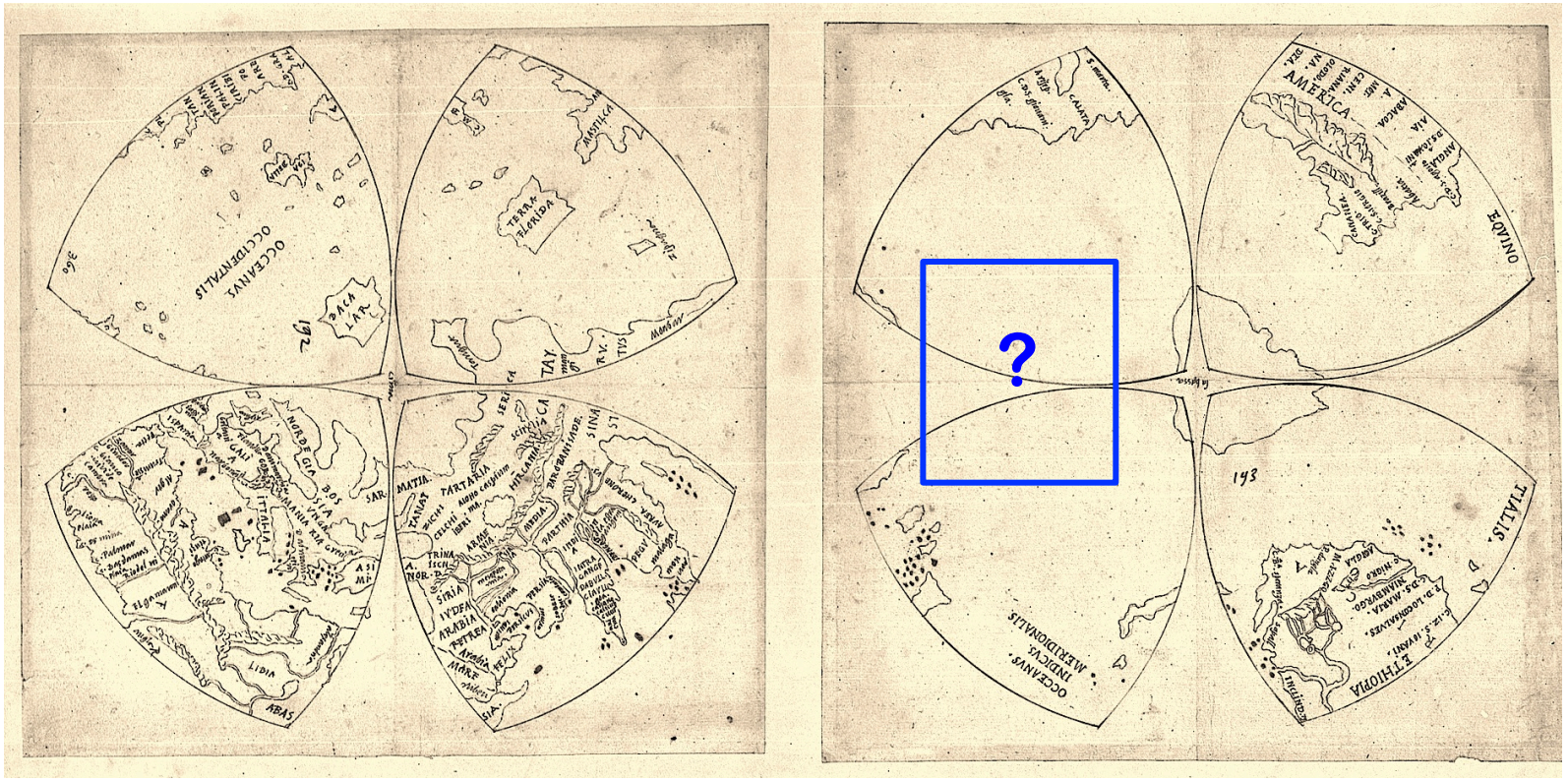
… made with octant projections
… showing the name “America”
… with America’s west coast disconnected from Asia
… indicating a large Southern continent

But, A.D. 1514 too early to...



... avoid strong mapping distortions and biases

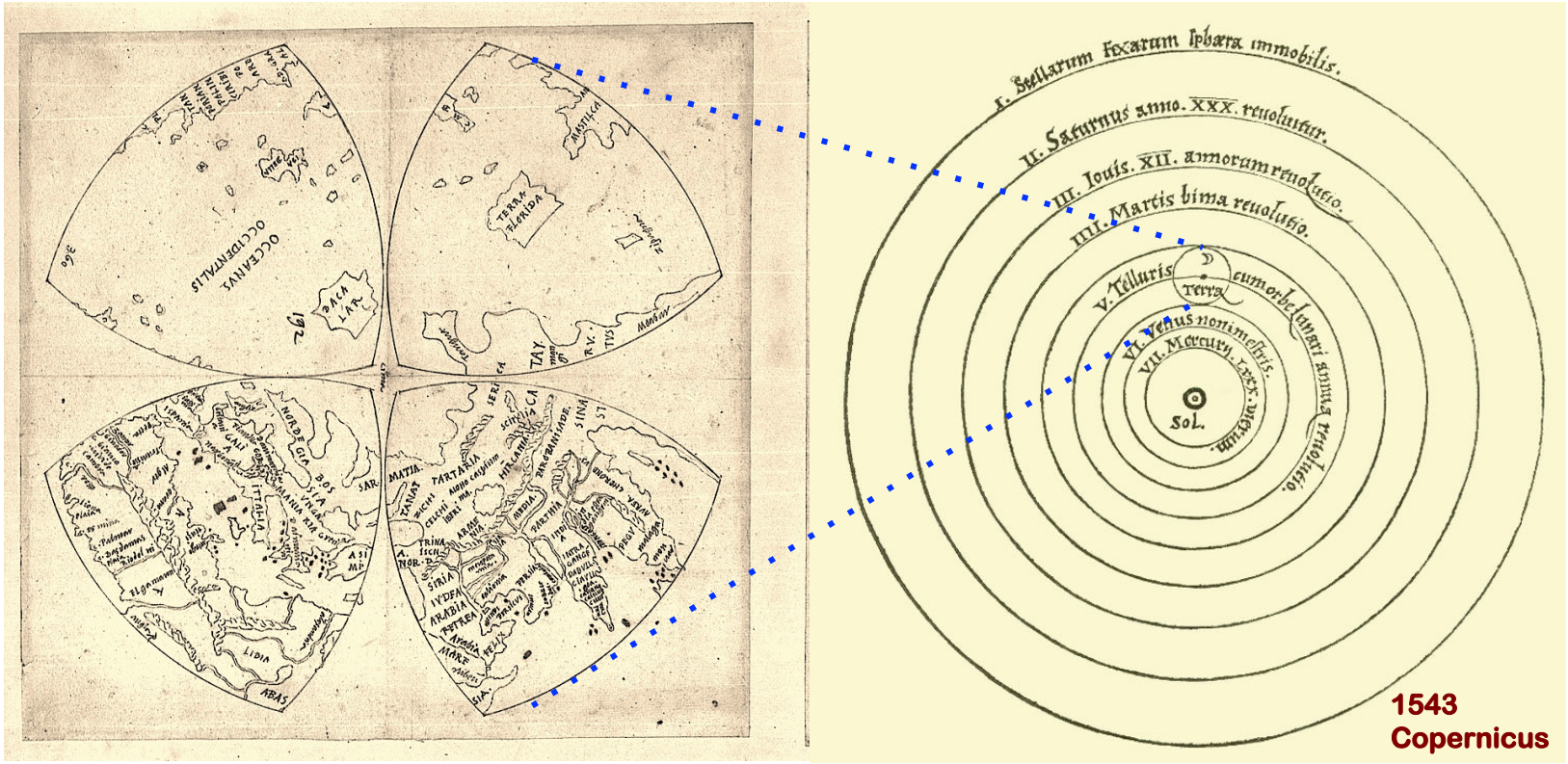
But, A.D. 1514 too early to...



... avoid strong mapping distortions and biases

... know about Australian continent (~ 90 years later)

But, A.D. 1514 too early to...



... avoid strong mapping distortions and biases
... know about Australian continent (~ 90 years later)
... know about a larger world picture (~ 30 years later)

500 years later...

...we are in a similar situation in neutrino (and particle) physics:

- being excited by recent discoveries
- mapping (quasi)known lands (with biases?)
- planning expeditions to unknown lands
- trying to find a larger "world picture"

Theory may give some guidance in this (probably) long and difficult enterprise, largely driven by new experiments.

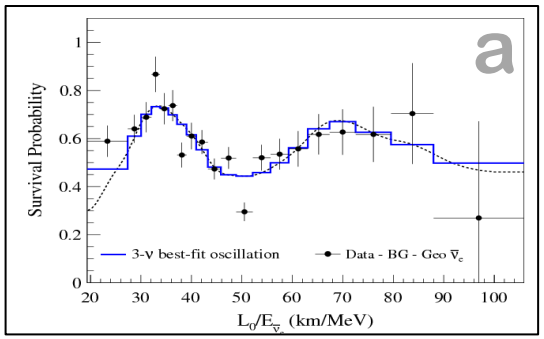
TALK OUTLINE:

- being excited by recent discoveries
- mapping (quasi)known lands (with biases?)
- planning expeditions to unknown lands
- trying to find a larger “world picture”

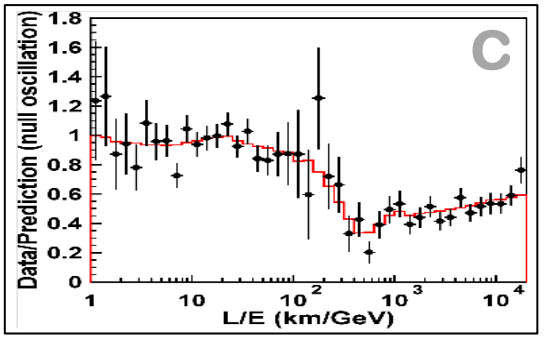
…charting the neutrino world…

Recent discoveries: α → β oscillations in vacuum and matter

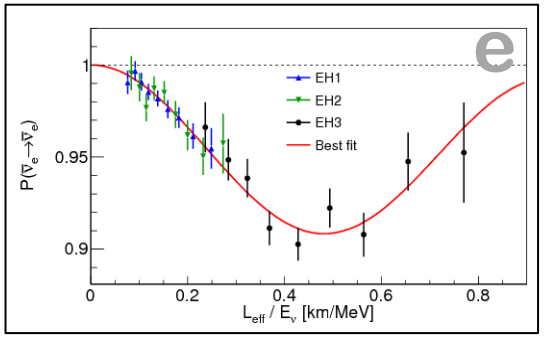
e→e



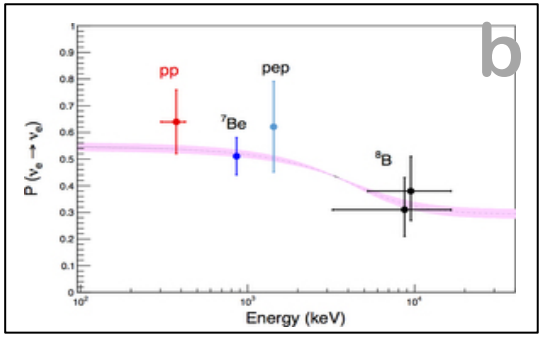
μ→μ



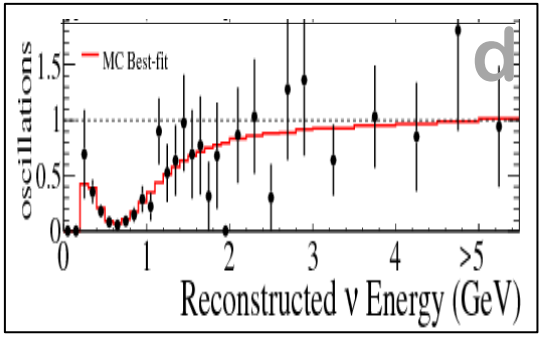
e→e



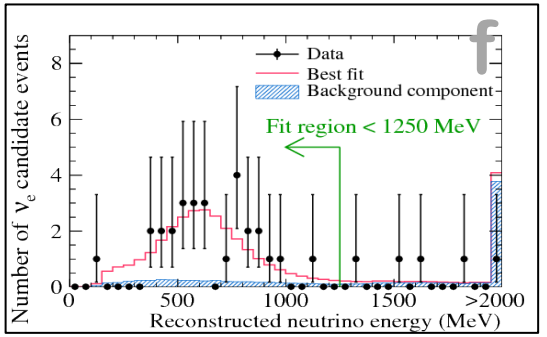
e→e



μ→μ



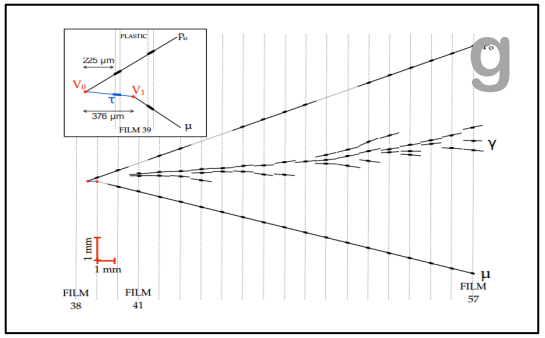
μ→e



Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS; (g) OPERA [plot], Super-K atmospheric.

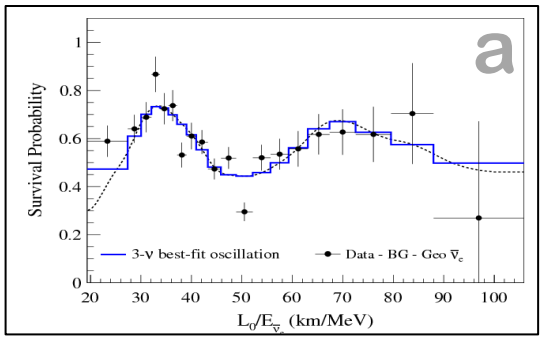
μ→τ



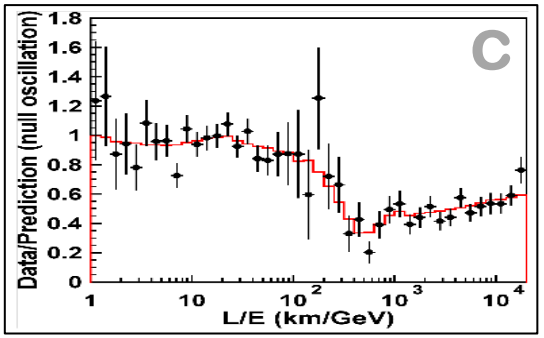
See next talks by Jung, Shiozawa, Cao

Can be charted in a simple 3ν theoretical framework

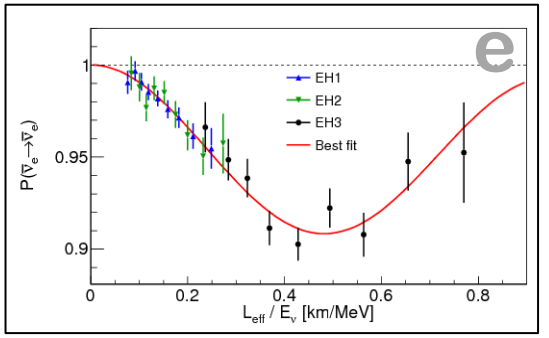
e→e (δm^2 , θ_{12})



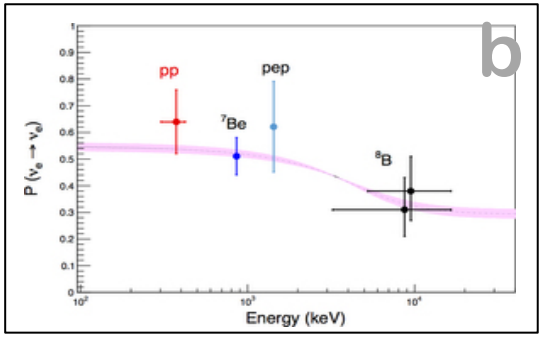
μ→μ (Δm^2 , θ_{23})



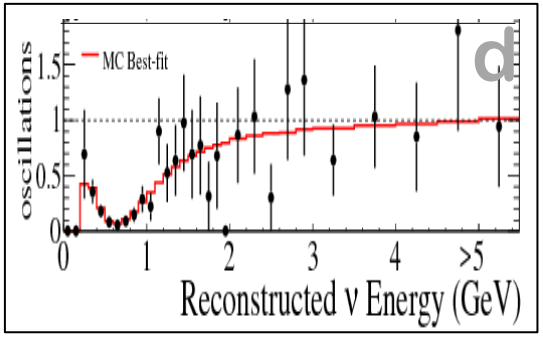
e→e (Δm^2 , θ_{13})



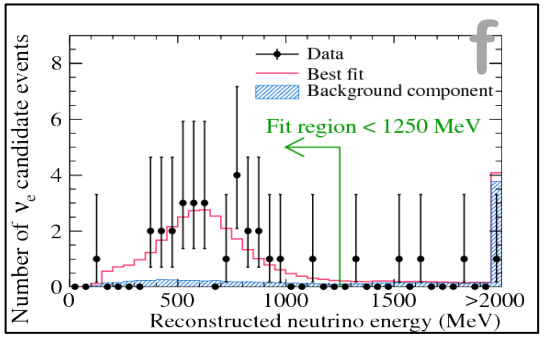
e→e (δm^2 , θ_{12})



μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})

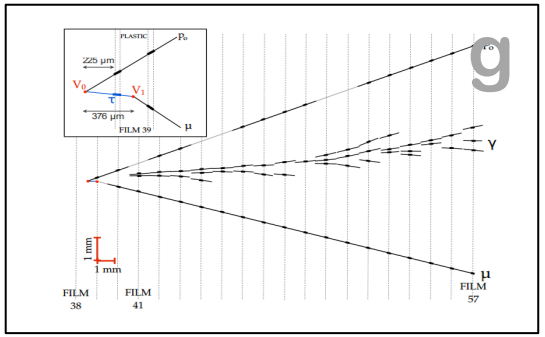


Terra cognita:

δm^2 $|\Delta m^2|$

θ_{12} θ_{23} θ_{13}

μ→τ (Δm^2 , θ_{23})



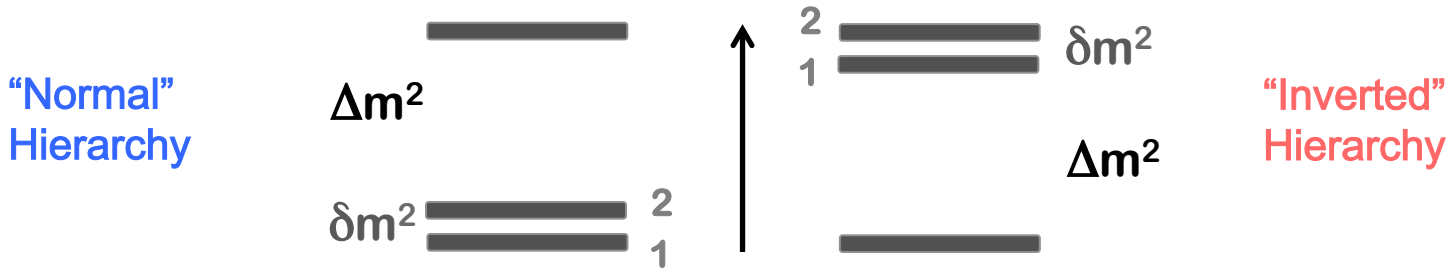
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

[only if Majorana]

Mixing angles θ_{23}, θ_{13}, θ_{12} : known ✔ CP-violat. phase(s) δ (α, β) : unknown ✗

Mass-squared spectrum (up to absolute scale)

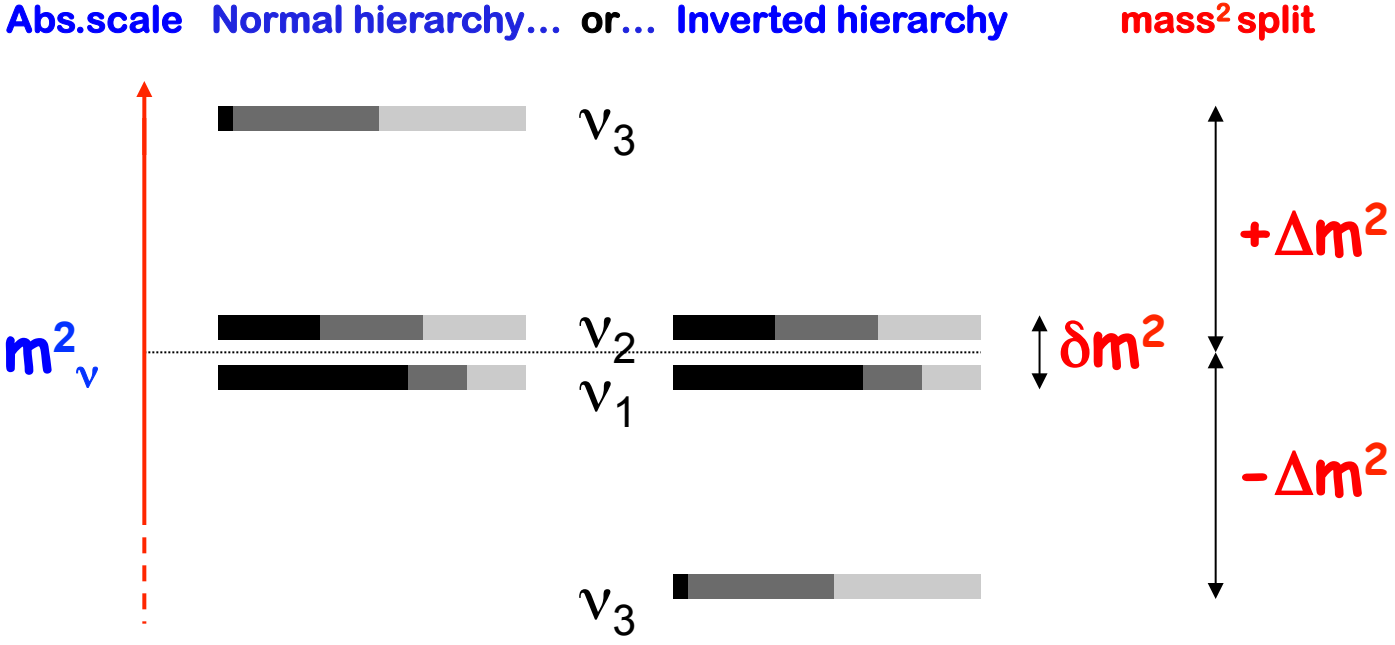


[+ contribution in matter ~ $G_F \cdot E \cdot$ density]

δm^2, Δm^2: known ✔ **Matter effects (solar ν): ✔** Hierarchy : unknown ✗

Current 3ν picture in just one slide (with 1-digit accuracy)

Flavors = e μ τ



Terra Cognita:

$\delta m^2 \sim 8 \times 10^{-5}\ eV^2$
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

Terra Incognita:

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute mass scale
Dirac/Majorana nature

Old but still strong theoretical argument for Majorana ν's as messengers of new physics scale (see-saw + Weinberg):

- Effects of high-energy physics as effective operators added to the standard model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- can be classified systematically

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda},$$
$$(H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

(H. Murayama at ICFA Seminar 2011, CERN)

Old but still unique experimental probe of Maiorana ν's nature via ΔL=2 process: neutrinoless double beta decay.
See next talk by Schoenert

Charting 3ν param. with more digits: global analysis →

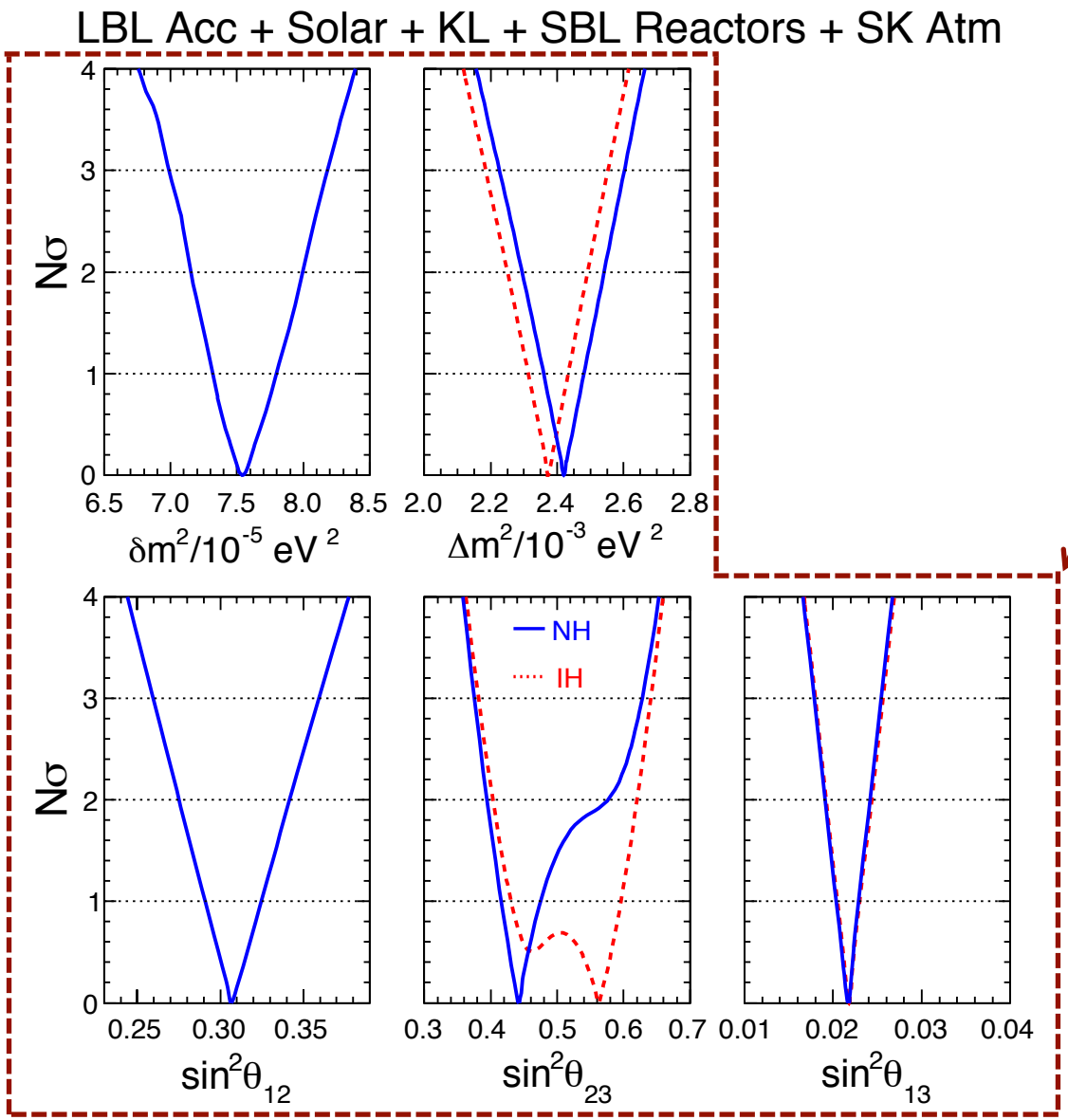
Analysis includes increasingly rich oscill. data sets:

LBL Acc + Solar + KL
LBL Acc + Solar + KL + SBL Reactor
LBL Acc + Solar + KL + SBL Reactor + SK Atm.

Parameters not shown are marginalized away.

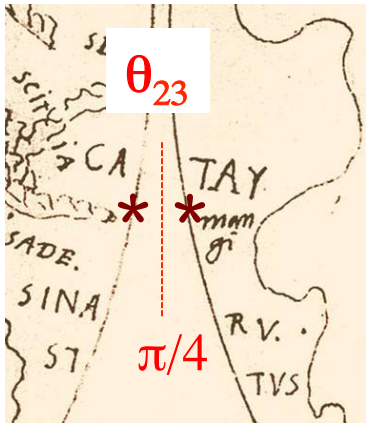
C.L.'s are drawn at $\Delta\chi^2 = 1, 4, 9$ →
Nσ = 1, 2, 3 for projections over single parameters.

Figures from Capozzi et al., arXiv:1312.2878 (+ Neutrino 2014 updates)
See also: Gonzalez-Garcia et al., 1409.5439; Forero et al., 1405.7540.



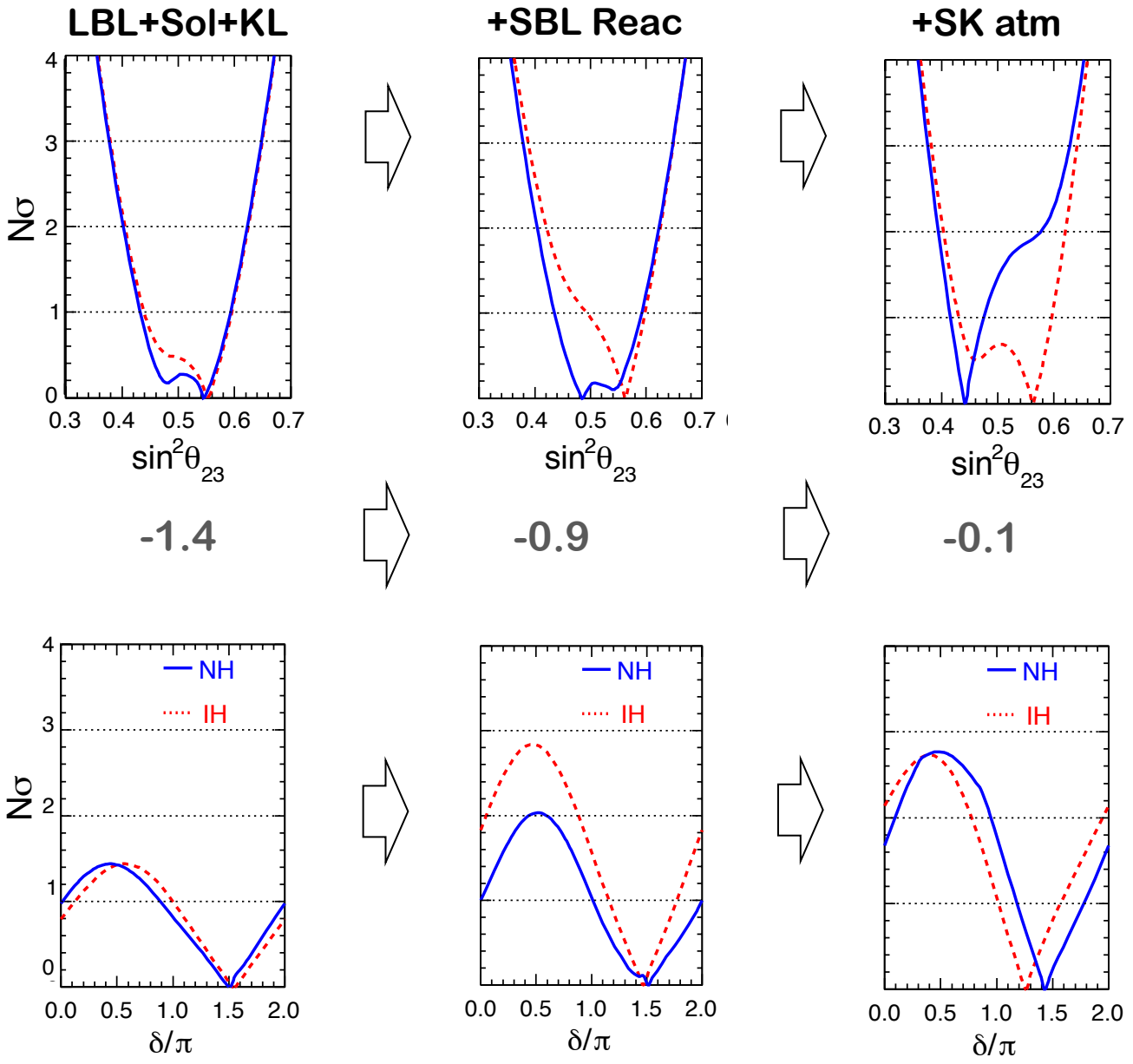
Current accuracy in mapping Terra Cognita:

δm^2	2.6 %
Δm^2	2.6 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	8.5 %
$\sin^2\theta_{23}$	~ 10 % *

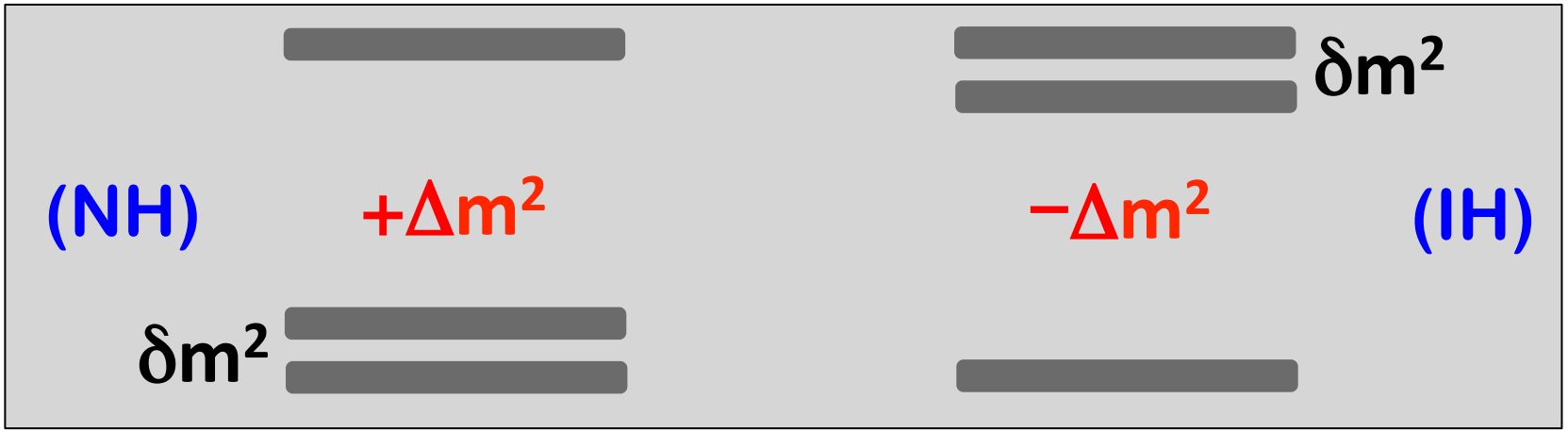


(but… in which octant?)

Terra Incognita I (oscill. param.): current hints



Oscillation searches can probe the hierarchy…



… if one can observe **interference** of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity **Q** with known sign. 3 options:

$Q = \delta m^2$	(medium-baseline reactors)
$Q = 2\sqrt{2}\, G_F\, N_e\, E$	(matter effects in accel./atmosph. ν)
$Q = 2\sqrt{2}\, G_F\, N_\nu\, E$	(collective effects in SNe)

All paths to the hierarchy are being actively investigated from the experimental - theoretical - phenomenological viewpoint.

The path towards a possible discovery of leptonic CP violation requires 6 steps:

3 mixing angles should be nonvanishing ✔

2 mass gaps should be nonvanishing ✔

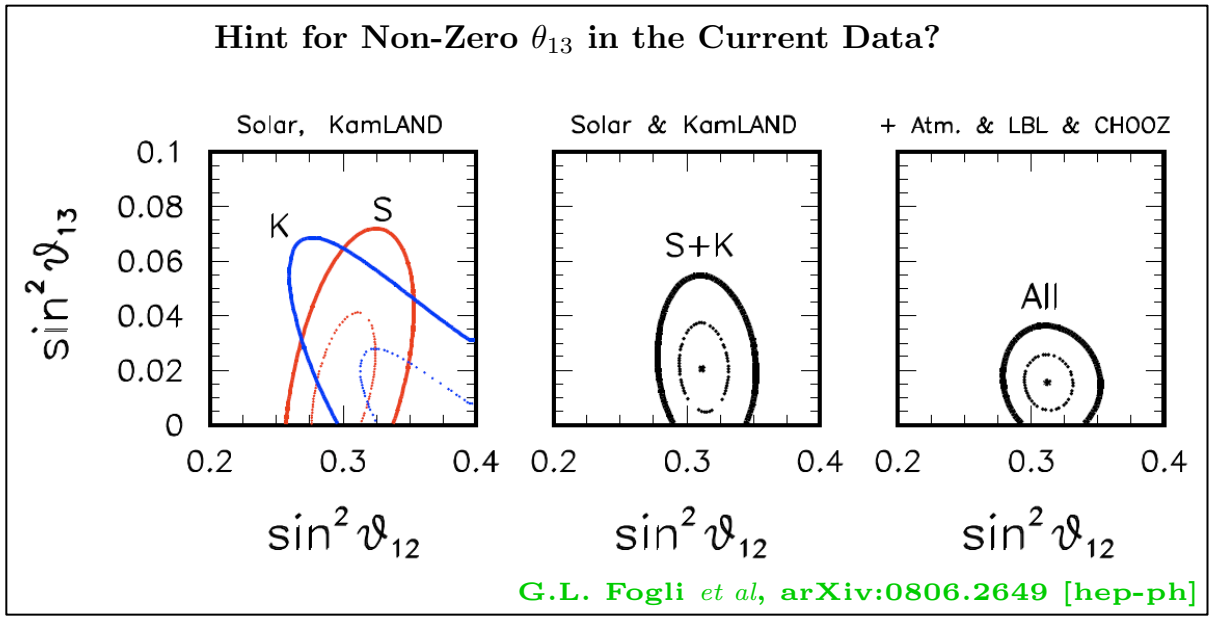
1 Dirac phase should be nonvanishing …

Nature has already allowed us 5 steps in favorable conditions, i.e., at accessible **terrestrial** scales …

Current hints suggest that the 6th may be at reach…
…expeditions to neutrino CPV-land are a must!

[and, if neutrinos are Majorana… CPV bonanza with 2 more phases !]

Let us hope that history may repeat itself, as for a previous lucky hint...



(A. de Gouvea at ICFA Seminar 2008, SLAC)

so that we may discuss about "nearly maximal leptonic CP violation" at ICFA seminar 20XX!

Terra Incognita II (absolute mass observables)

(m_β, $m_{\beta\beta}$, Σ)

In the 3ν framework:

β **decay**, sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

0νββ decay: only if Majorana. "Effective Majorana mass":

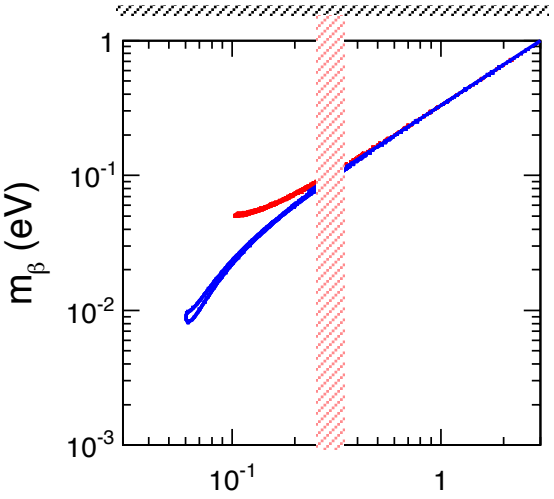
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Cosmology: Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$

Note 1: These observables may provide handles to distinguish NH/IH.
Note 2: Majorana case gives a new source of CPV (unconstrained)
Note 2: The three observables are correlated by oscillation data→

Upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.) + osc. constraints

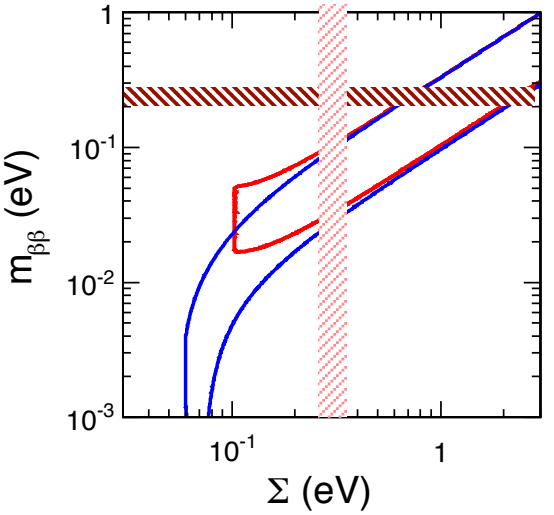


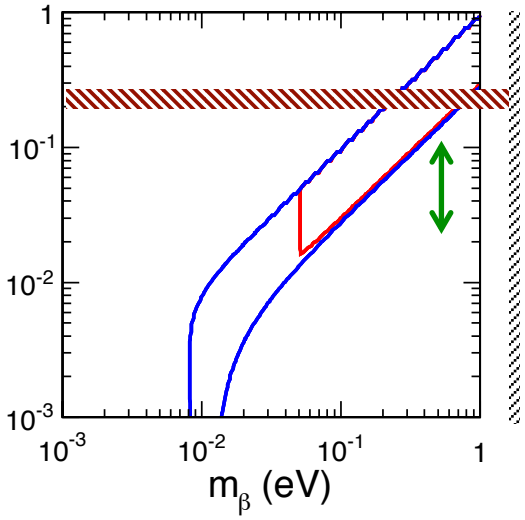
β : Mainz+Troitsk

0νββ : GERDA, EXO, KL-Zen, ...

Σ : CMB+LSS

2 σ (NH)
2 σ (IH)
oscillation constraints

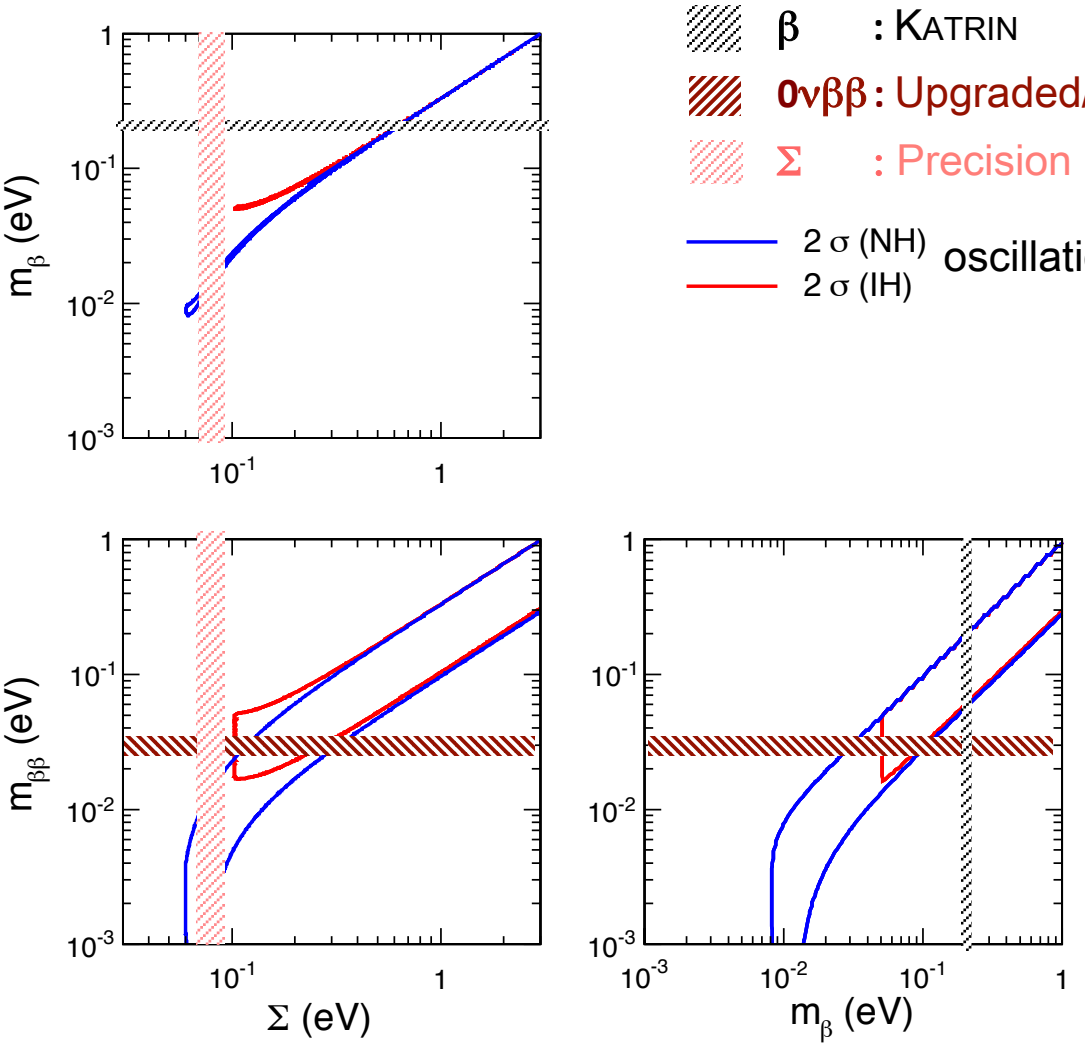




$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

[Clearly, the inverted hierarchy case would make life easier...]

Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?

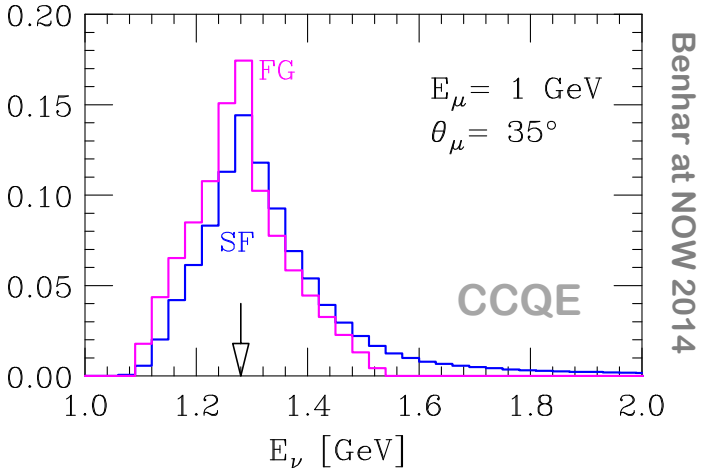


Large phase space for discoveries about ν mass and nature.

Theory can help in both "mapping" and "discovery" expeditions

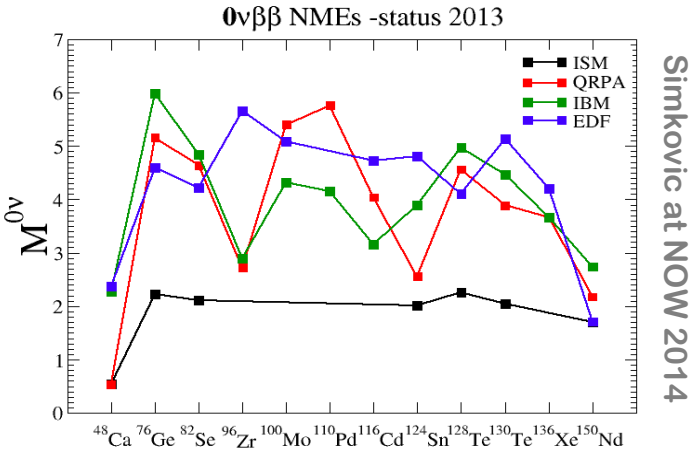
Two examples of well-defined, long-term theory programs:

Must improve modeling of ν-nucleus cross sections, to understand energy spectra in accelerator and atmospheric searches for CPV and mass hierarchy



Benhar at NOW 2014

Must improve modeling of nuclear structure, to understand and compare signals or limits on 0νββ decay rates and related weak/strong processes

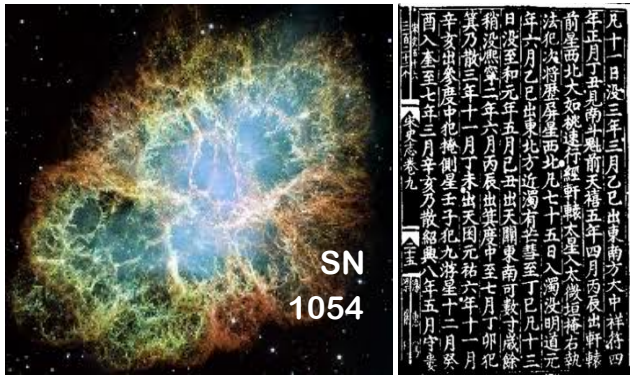


Simkovic at NOW 2014

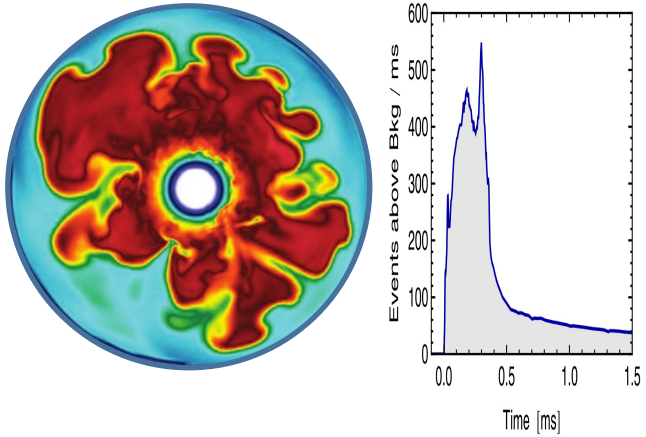
Require joint effort from nuclear and particle phys. communities

Another long-term theory program for an "unpredictable" event:

Sooner or later (say, 10±10 years ?), another galactic SN should explode... Its "autopsy" will keep us busy for decades, and teach us a lot about astrophysics and neutrino physics.



Simulations of SN explosions, (anti)nu fluences and flavor transitions, which are already very demanding, will need to reach complexity levels comparable -probably- to QCD lattice calculations.

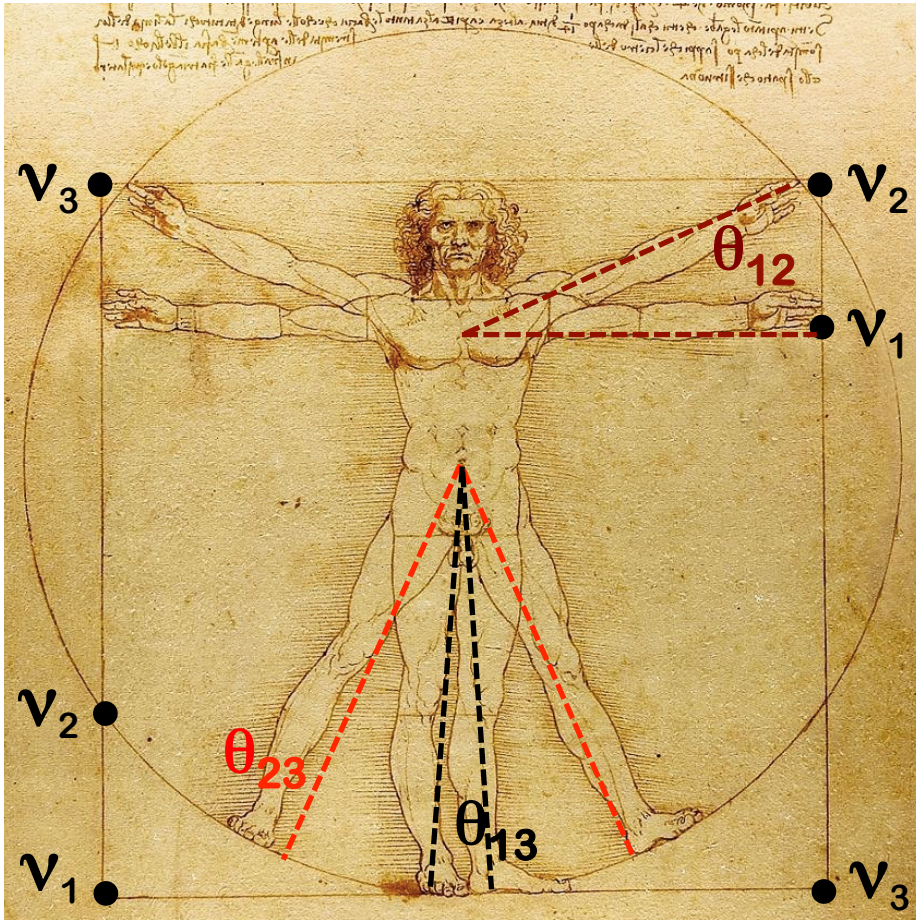


Raffelt at NOW 2014

Will spark a truly interdisciplinary program from diverse communities

see also next talk by Halzen

Neutrino flavor theory: is the current picture suggestive of some "simmetry"?
Or the symmetry is only in our mind, and there is just randomness?
Are there possible connections with the quark flavor sector?



Many interesting ideas, but no obvious answer/guidance so far

Specific outcomes (a few examples from a vast literature)

No organizing principle
("anarchy")

Discrete family simmetries
("geometry")

linear relations between
$\theta_{13}\cos\delta$ and θ_{12}, θ_{23}

Continuous flavor simmetries
("dynamics")

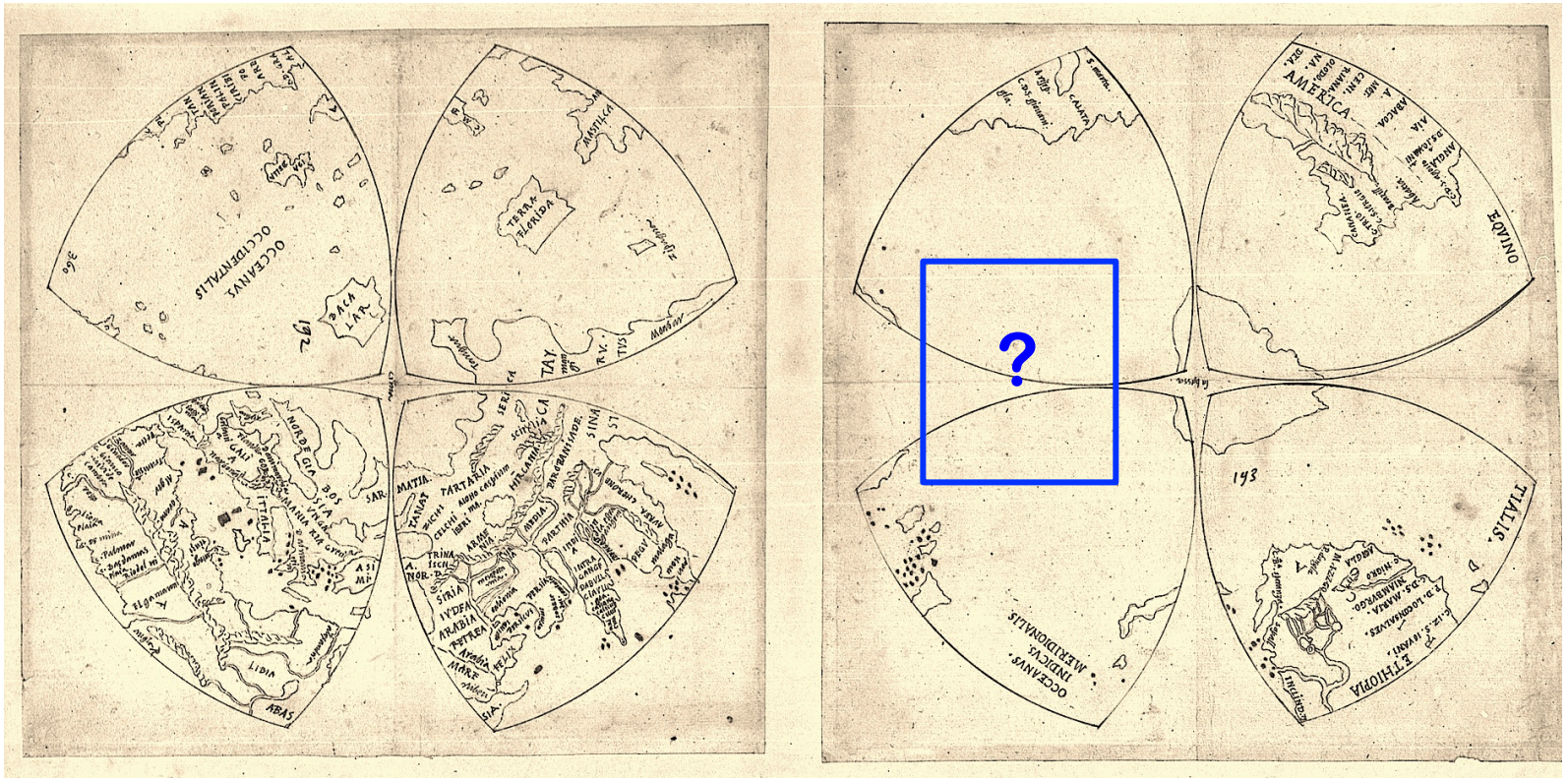
links between neutrino
spectra/angles/phases

Common quark/lepton features
("complementarity")

links between
θ_{13} and θ_C

Model selection will benefit from higher precision

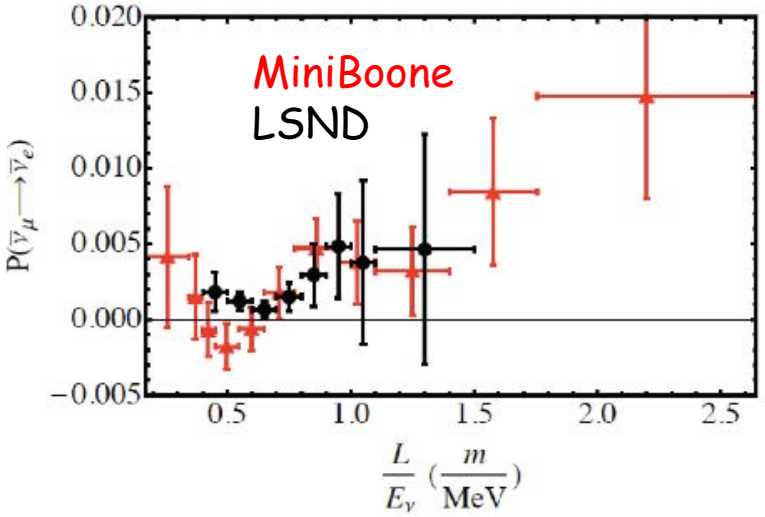
Beyond the 3ν paradigm



We should not be biased by the success of the 3ν scheme…

If we sail too close to the 3ν coastline … we might miss an entire new continent (new neutrino states and interactions)

Light states: conflicting sightings of ν_s with (sub)eV mass from various sailors in the last 20 years... new land or mirage?



Available data: intriguing, but not conclusive or convergent.

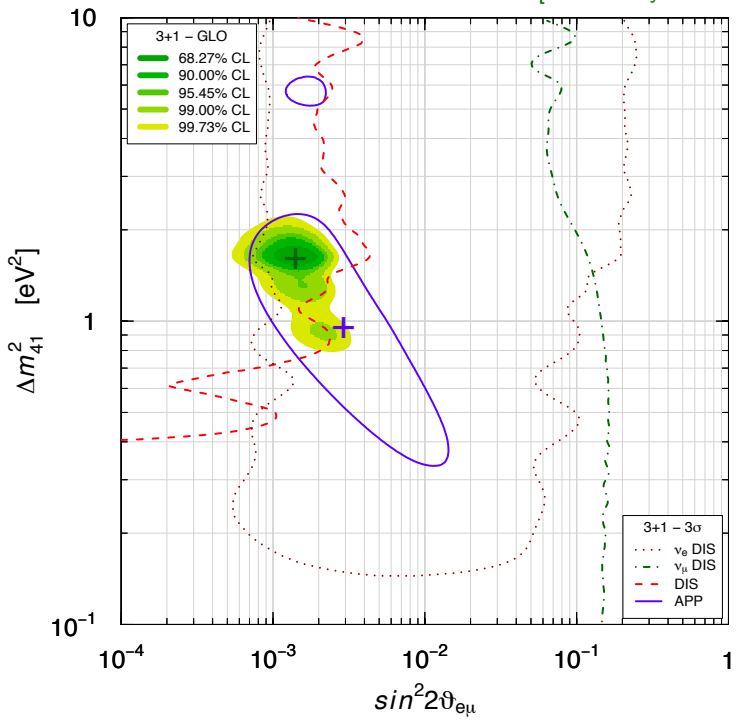
The question raised by the LSND claim is still with us:
Is there $\nu_\mu \to \nu_e$ appearance at a scale $\sqrt{\Delta M^2} \sim O(0.1\text{-}1)$ eV ?

In recent years, further interest in light sterile ν raised by:

1) Possible associated $\nu_e \to \nu_e$ disappearance signals
2) Possible associated extra radiation in cosmology

3+1 Global Fit

[Preliminary 2014 Update]



- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND (Y), MiniBooNE (?), OPERA (N), ICARUS (N), KARMEN (N), NOMAD (N), BNL-E776 (N)
- DIS ν_e & $\bar{\nu}_e$: Reactors (Y), Gallium (Y), ν_eC (N), Solar (N)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

MiniBooNE $E > 475$ MeV

GoF $= 26\%$ PGoF $= 7\%$

No Osc. excluded at 6.3σ

$\Delta\chi^2/\text{NDF} = 47.7/3$

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008]

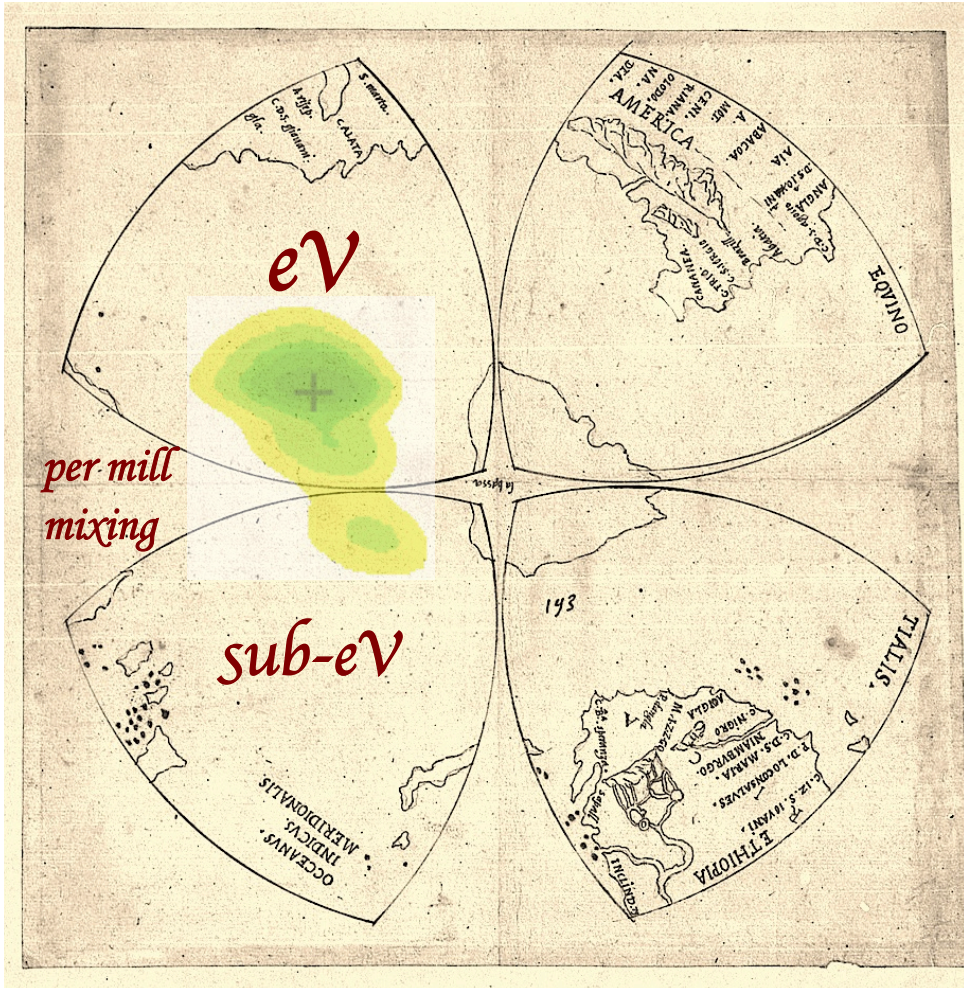
[different approach and conclusions: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

From Giunti et al. 2014. Note: Kopp et al. 2014 find worse GOF.

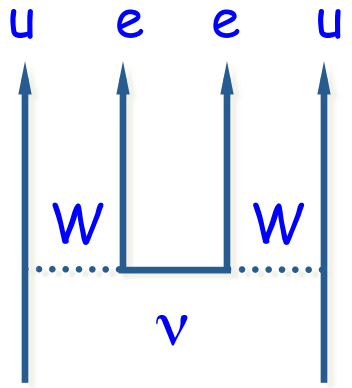
In general, tension between appearance and disappearance oscillations.

Also: some tension between oscillation and cosmology (not included above)

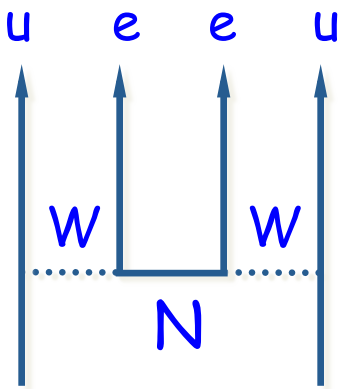
Need a "redundant" oscillation search, exploring a wide mass-mixing range, and cross-checking both appearance and disappearance, in order to discover (or rule out) conclusively light sterile neutrino states.



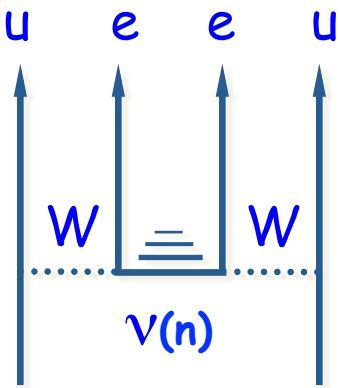
Nonstandard interactions/processes in neutrino physics: no sightings so far, but they should always be kept in mind; **examples in $0\nu\beta\beta$ decay:**



Standard

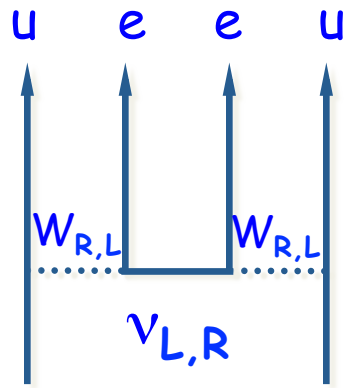


Heavy ν



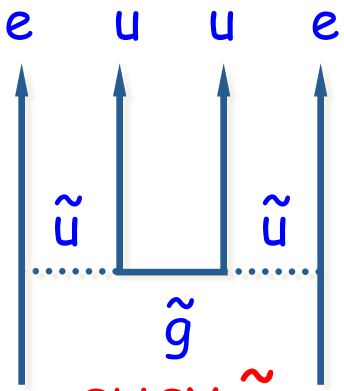
Kaluza-Klein

(KK±1 Brane:a=$10^{\pm1}$/GeV)

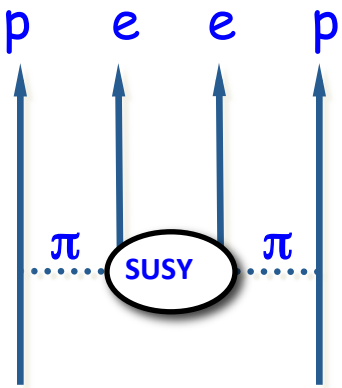


RHC λ,η

λ=RH had, η=LH had

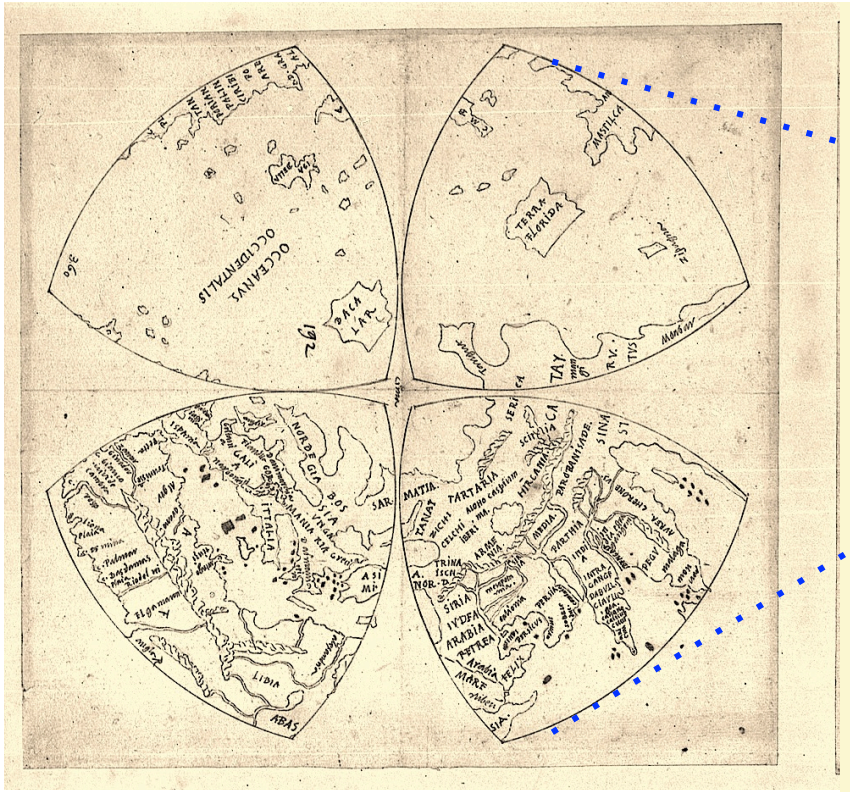


SUSY $\tilde{g}$

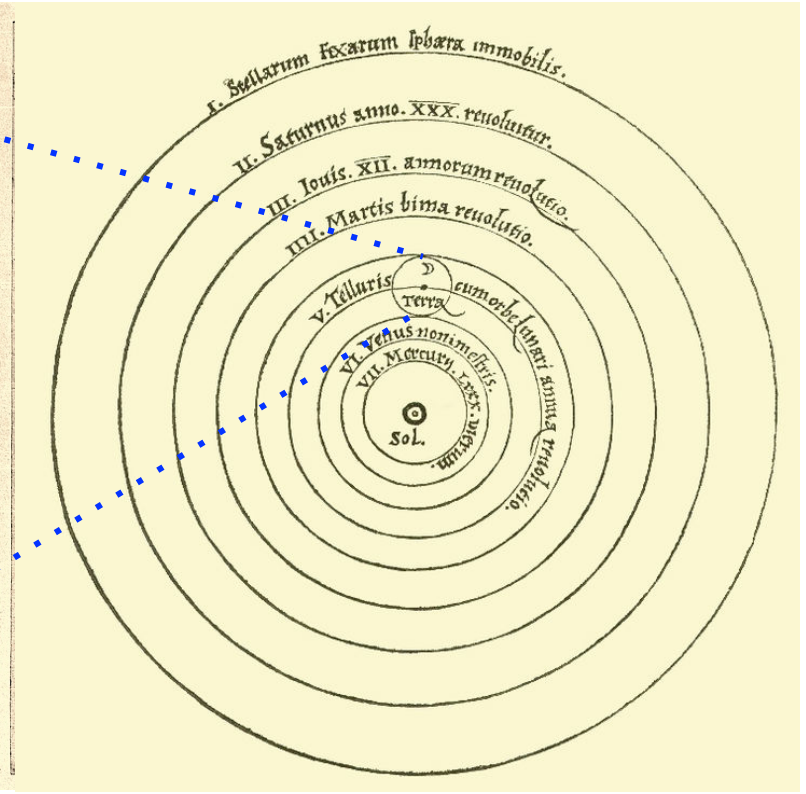


SUSY π

Towards a larger picture and higher scales



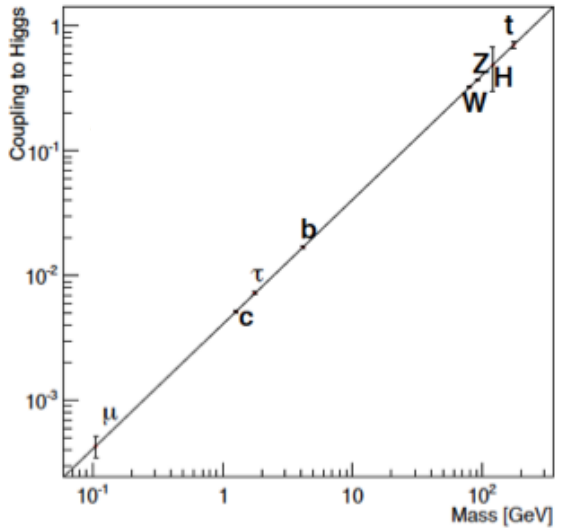
1514 Leonardo



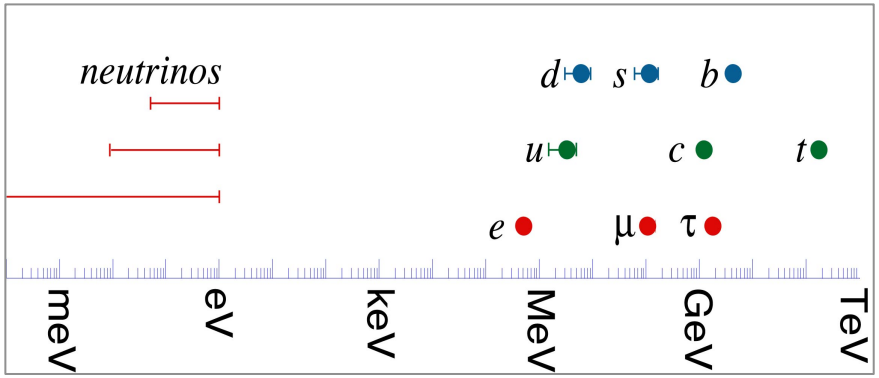
1543 Copernicus

Linking two fundamental research expeditions:

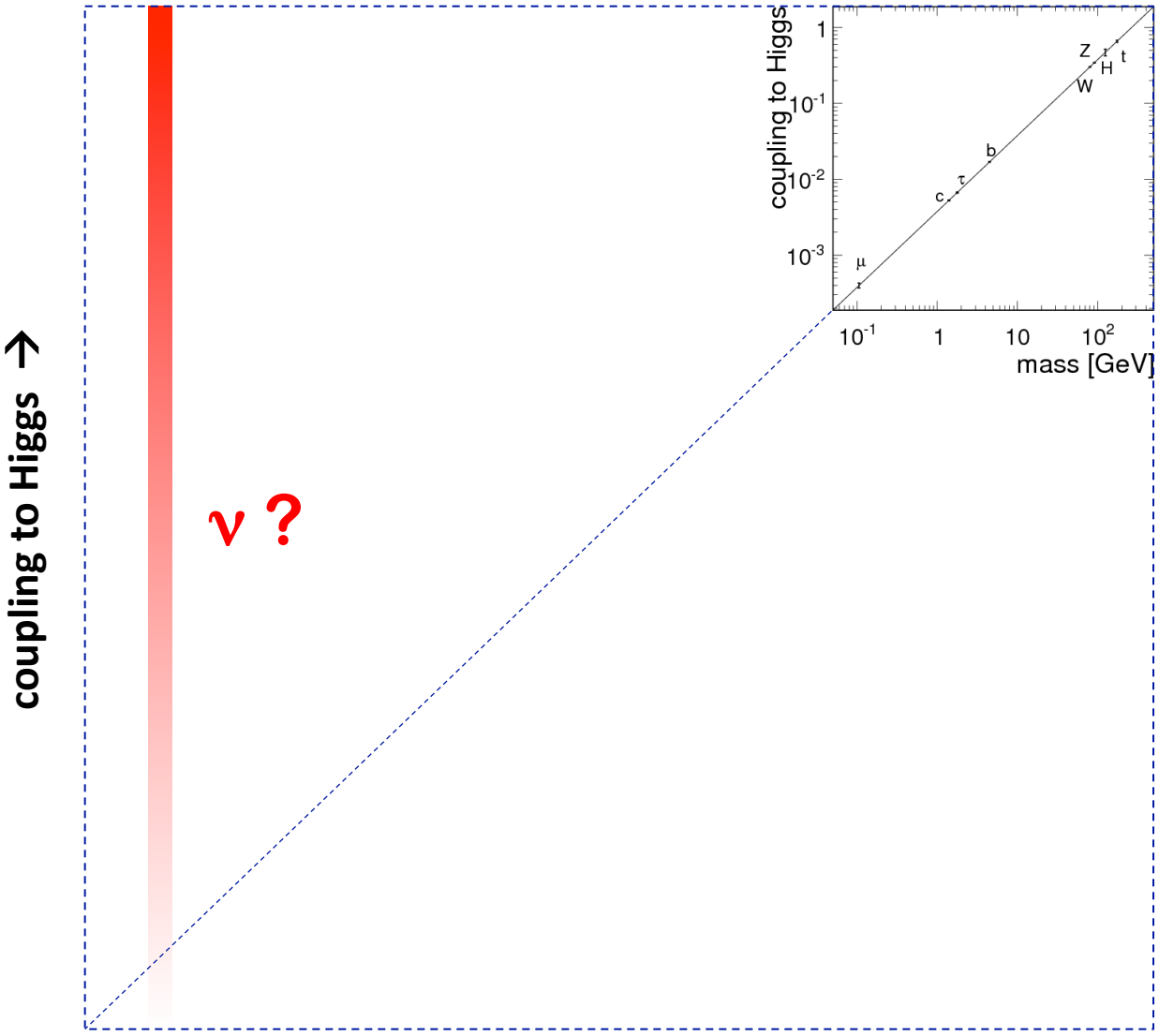
1. Test Higgs sector



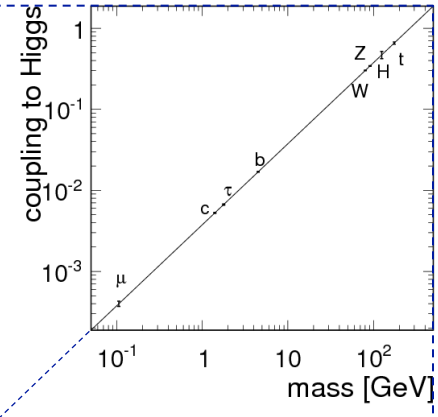
2. Find ν masses



1 + 2 **Where are the ν's on this plot? Why are they so light?**



Options:



coupling to Higgs →

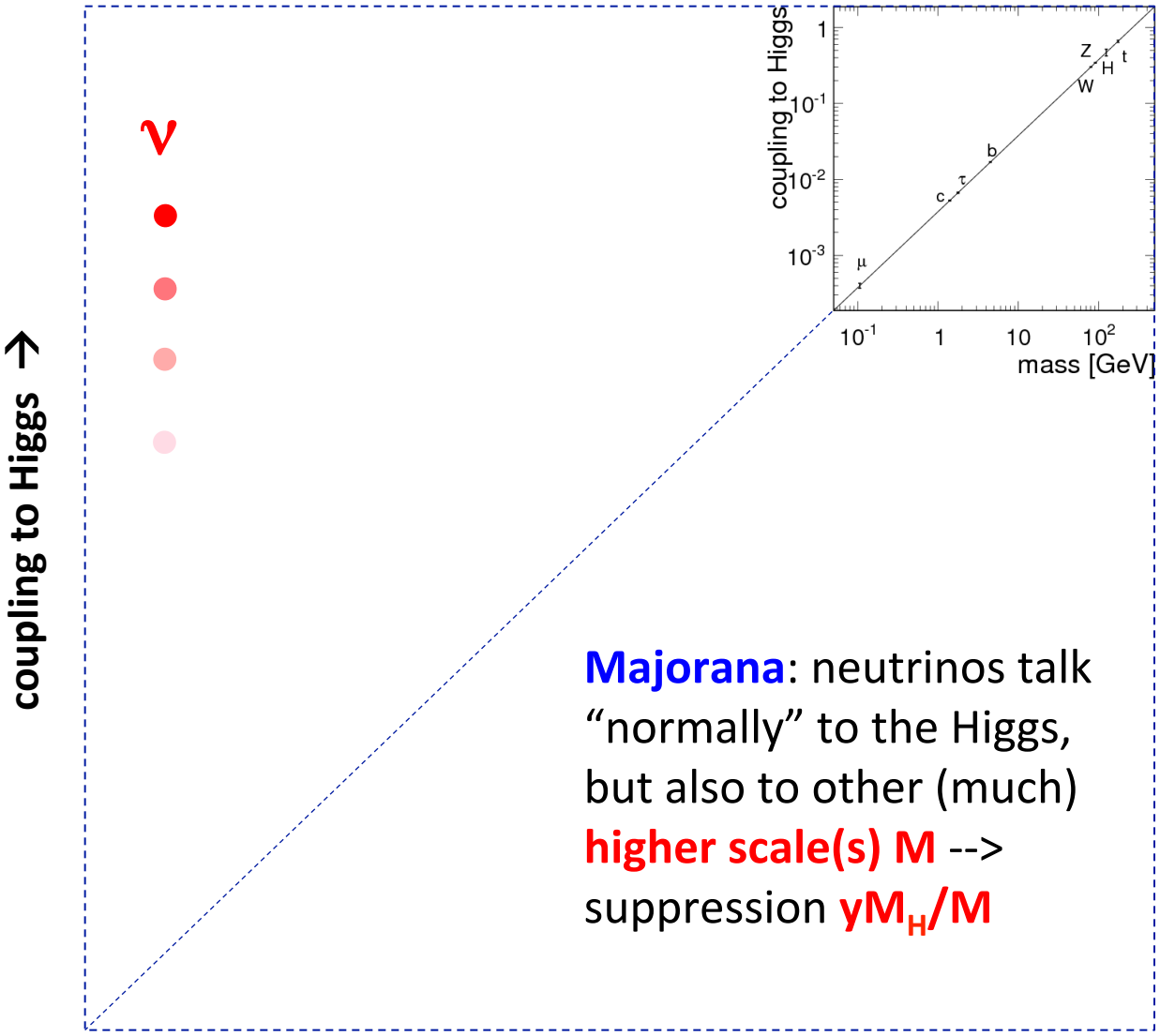
Dirac: neutrinos "talk" very weakly to the Higgs boson, **$y < 10^{-12}$** for unknown reasons...

ν

< 1 eV

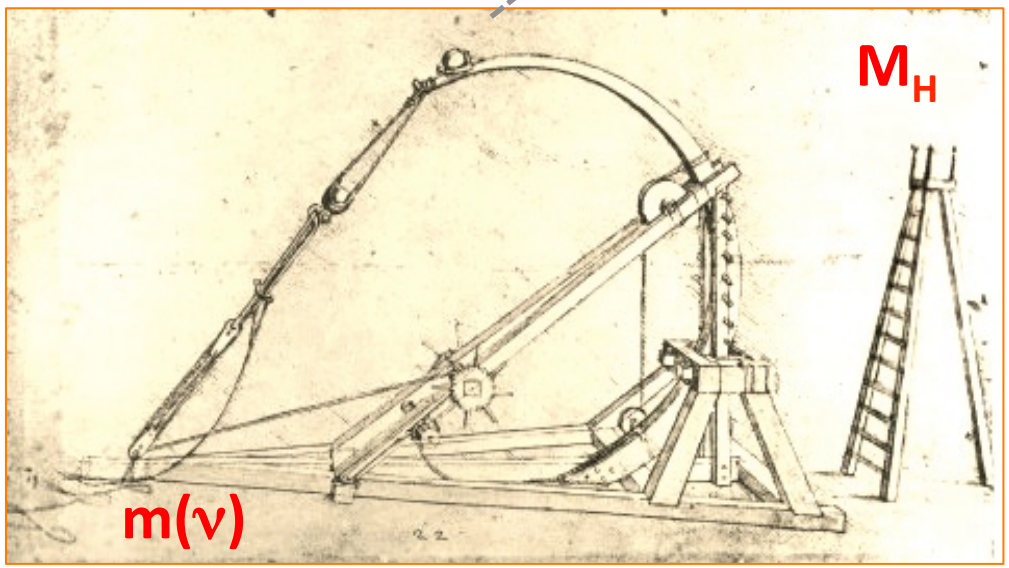
particle mass →

Options:



Majorana: neutrinos talk "normally" to the Higgs, but also to other (much) **higher scale(s) M** --> suppression yM_H/M

Neutrinos masses may offer
a great opportunity to jump
beyond the EW framework
via see-saw …



M

… and to address fundamental physics issues, such as:

- new sources of CP violation at low and high energies
- lepton number violation and associated phenomena
- **matter-antimatter asymmetry of the universe …**

M ~ GUT scale

CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis):

Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

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M ~ low scale

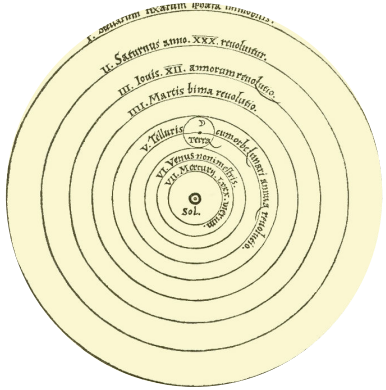
At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP

CP-violating decays of heavy neutrinos at scale M may generate lepton asymmetry (leptogenesis). Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP

In principle, several sterile states might even be split among widely difference energy scales, and contribute to various phenomena in (astro)particle physics.
Let us remain open-minded!

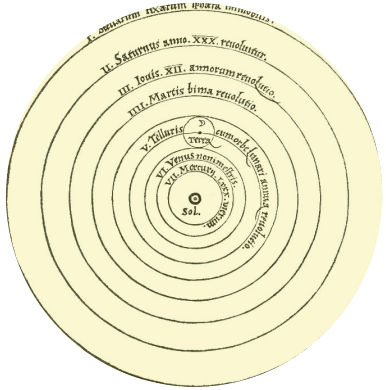
EPILOGUE


VI. Saturnus anno. XXX. revolutus.
III. Iouis. XII. annorum revolutio.
IIII. Martis bima revolutio.
V. Veneris
VI. Veneris
VII. Mercurii
Sol.

EPILOGUE

Terra Cognita...

$\delta m^2 \sim 8 \times 10^{-5}\ eV^2$
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$



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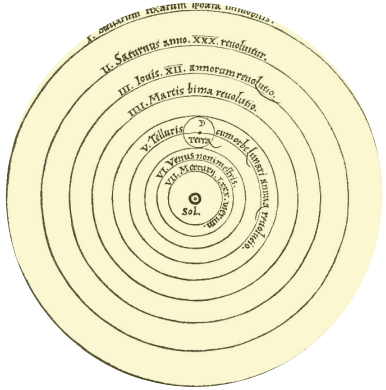
Terra Incognita...

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute masses
Dirac/Majorana



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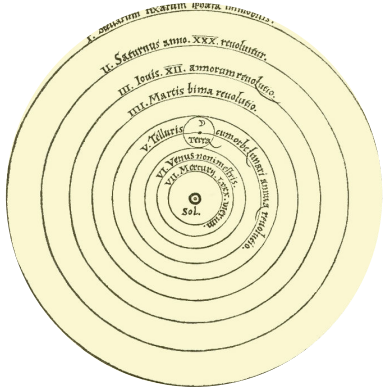
Terra Incognita...

δ (CP)
sign(Δm^2)
octant(θ_{23})
absolute masses
Dirac/Majorana

....and beyond...

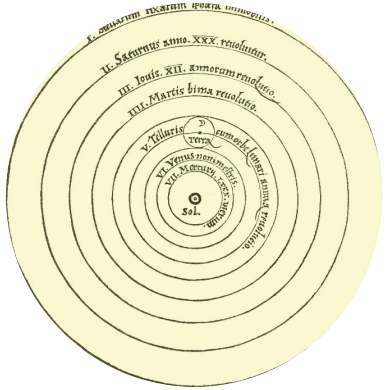
new light states
new heavy states
nonstandard inter.
flavor structure
baryon asymmetry



EPILOGUE

Further theoretical and experimental explorations will require significant time, resources and … good fortune!

So, for neutrino physics, let us wish…



EPILOGUE

Further theoretical and experimental explorations will require significant time, resources and … good fortune!

So, for neutrino physics, let us wish…

Lu

Luck

Fu

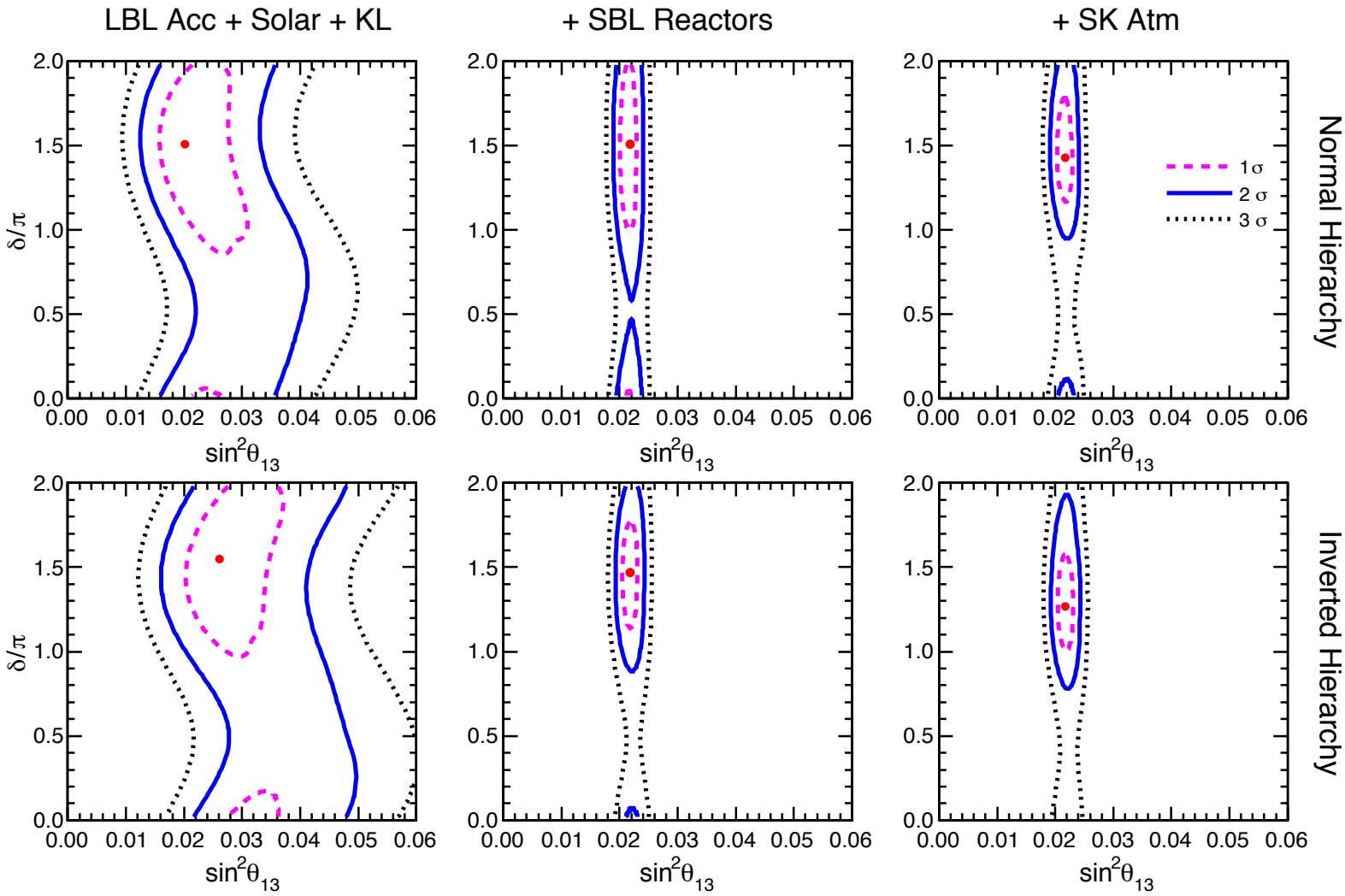
Prosperity

Shou

Longevity

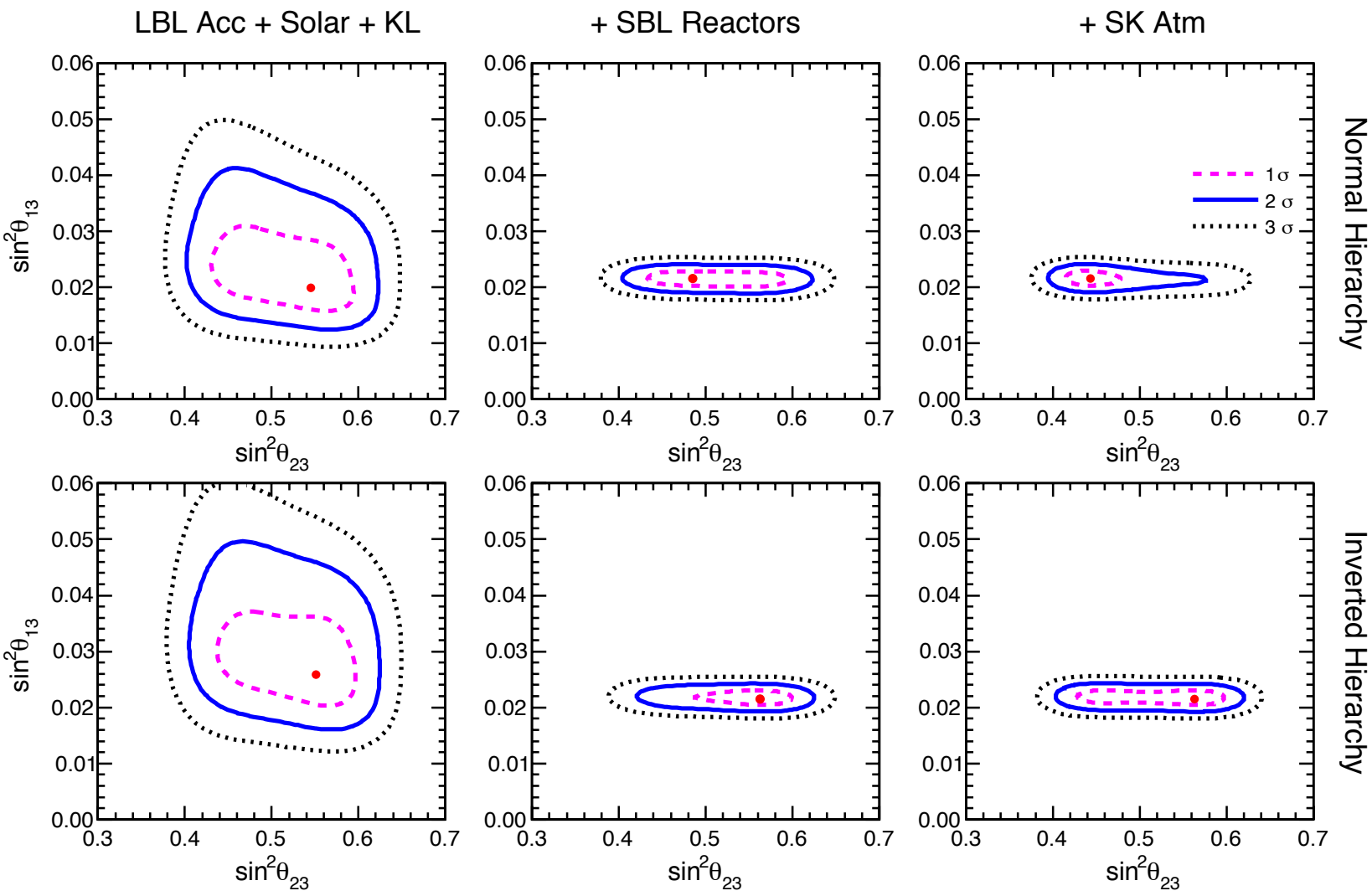
Additional slides

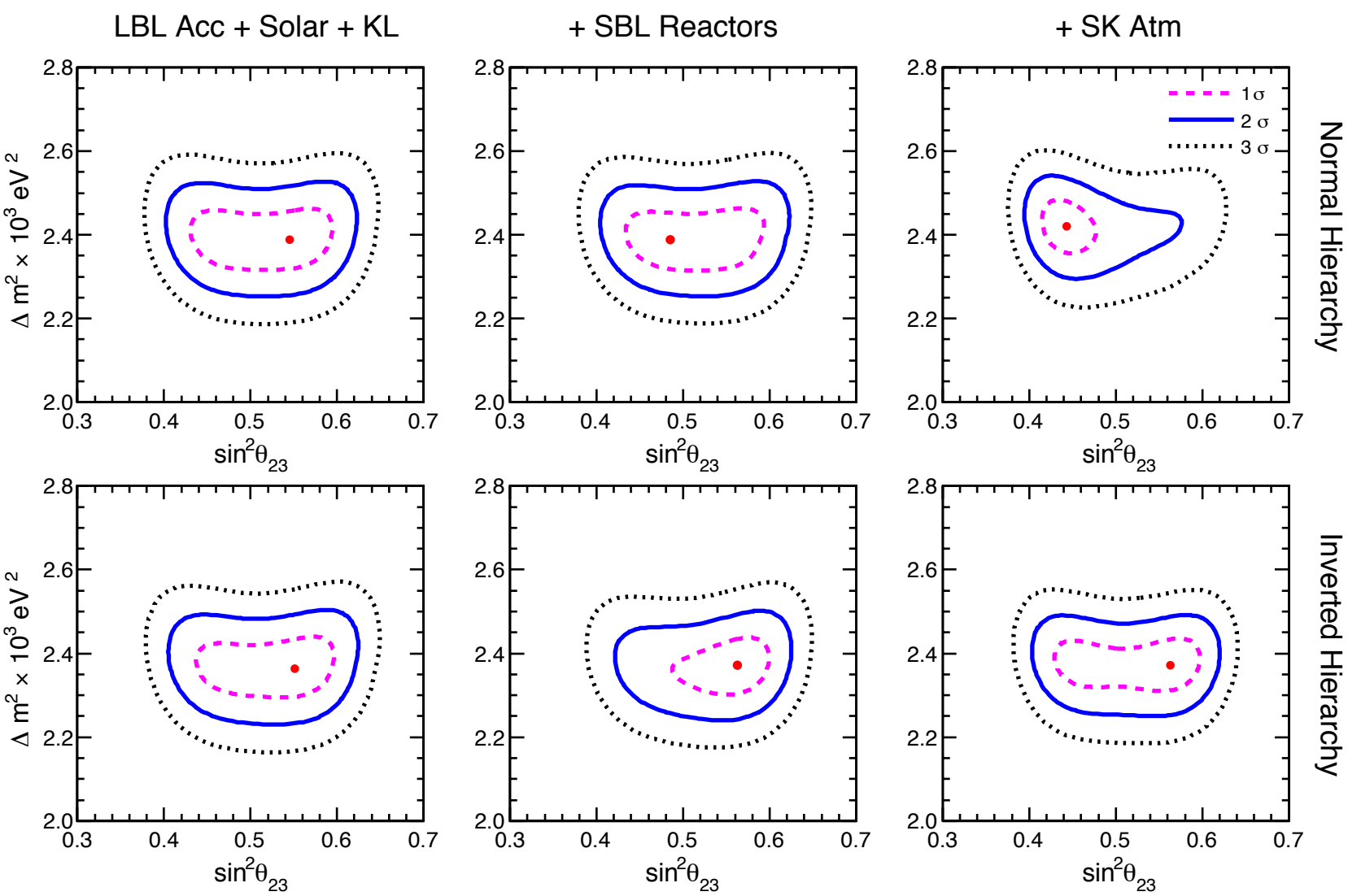
(θ_{13}, δ) covariance plot



Current CP hint apparently stable for increasingly rich data sets.

In combination, $\delta/\pi \sim 1.4$ and $\sin\delta < 0$ favored in both hierarchies.


LBL Acc + Solar + KL
+ SBL Reactors
+ SK Atm
Normal Hierarchy
Inverted Hierarchy
1σ
2 σ
3 σ
sin²θ13
sin²θ23
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.3
0.4
0.5
0.6
0.7


LBL Acc + Solar + KL
+ SBL Reactors
+ SK Atm
1σ
2 σ
3 σ
Normal Hierarchy
Inverted Hierarchy
Δ m² × 10³ eV²
sin²θ23
2.0
2.2
2.4
2.6
2.8
0.3
0.4
0.5
0.6
0.7