IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Big World of Little Neutrinos

Hitoshi Murayama

(IPMU Tokyo & Berkeley)

CERN Theory Colloquium, Sep 15, 2010

THE UNIVERSITY OF CALIFORNIA BERKELEY 1868

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- New *international* research center in Japan

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- *Young and active group!*

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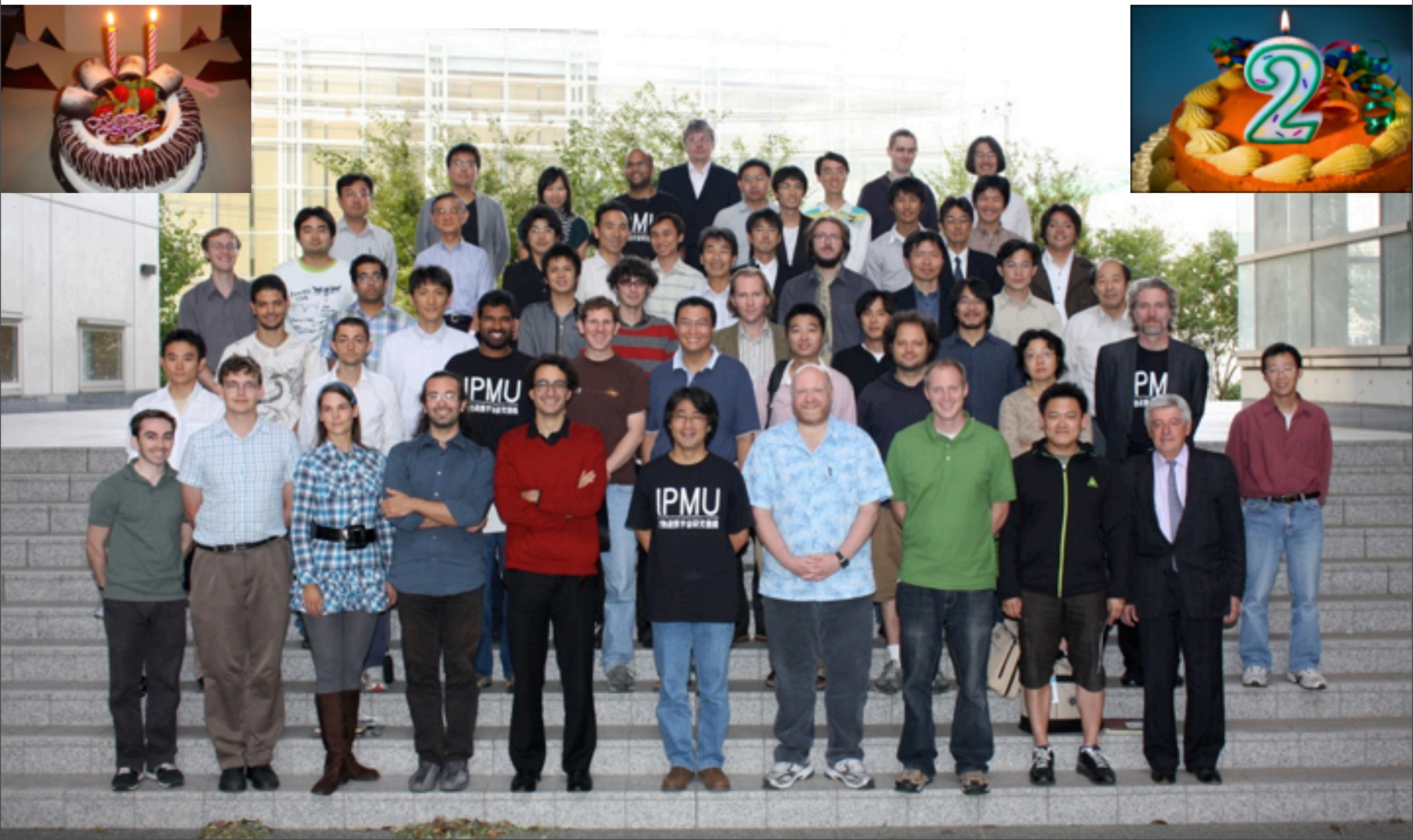

Full-time Scientists

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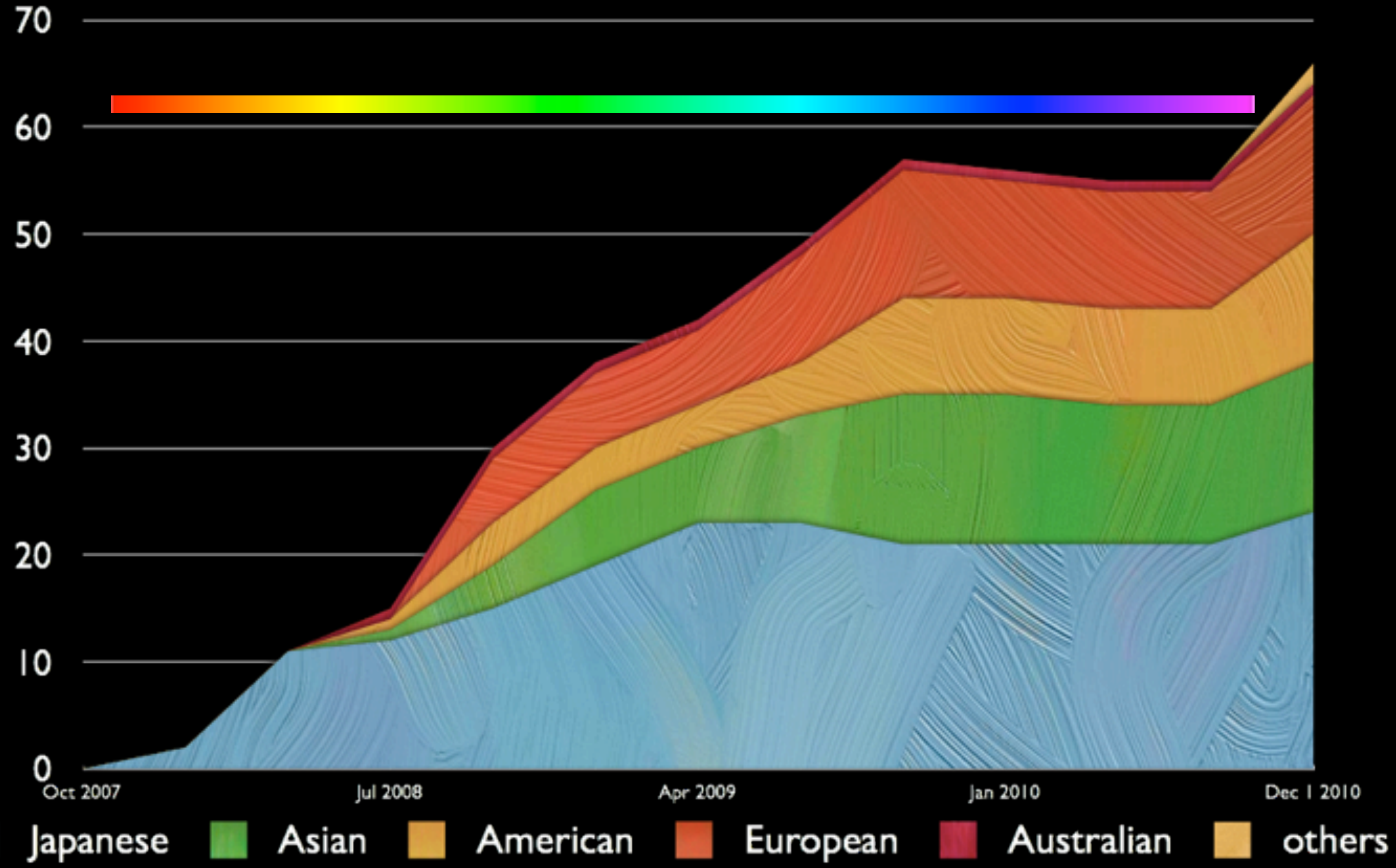

Moved in Jan 2010

emphasis on large interaction area

"like a European town square" ~400 m^2

tables, chairs, blackboards, Espresso machines

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L'Universo è scritto
in lingua matematica

ν TheME: Neutrino Theory, Models, and Experimental perspectives

13-22 September 2010 *CERN*
Europe/Zurich timezone

Overview
Scientific Programme
Timetable
Contribution List
Author index
Registration
Registration Form
List of registrants

Support

The Institute will focus on a review of the present status of neutrino physics from a theoretical, phenomenological and astroparticle physics point of view, aiming at a critical analysis of the physics case for present and future neutrino facilities

The deadline for registration is 16 May 2010.

Sponsors: The event is co-sponsored by Fermilab and IPPP

Accommodation: Participants are expected to arrange their accomodation by themselves:

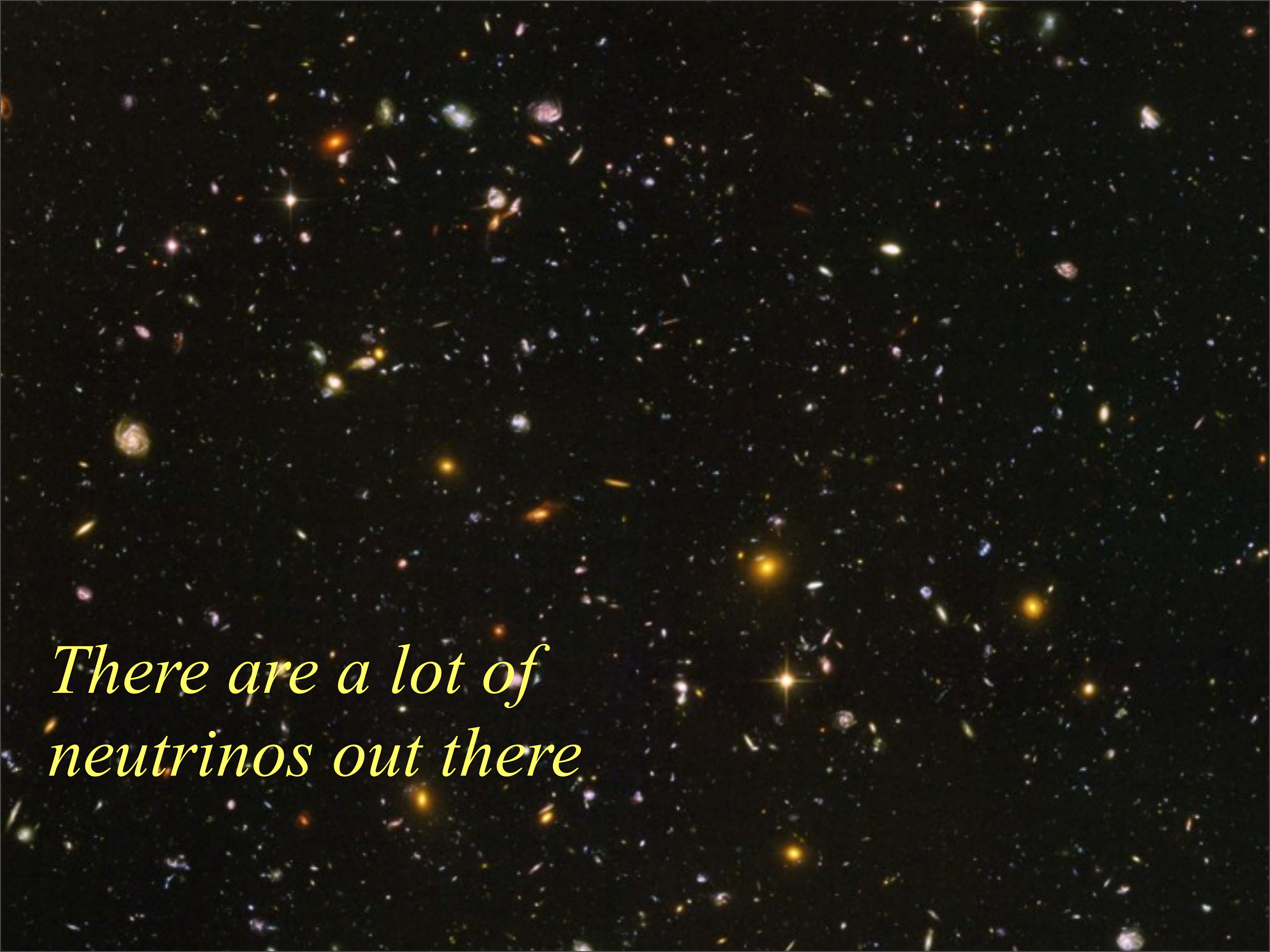
- some rooms with shower, wc and washbasin will be available at the CERN hostel; booking will be possible according to CERN policy, i.e. two months in advance (no block booking is possible anymore, unfortunately)
- You can book a hotel in Geneva or in the area surrounding CERN using this list. If you book a hotel on the French side, be sure to have a passport or a visa valid also in France.

All participants are expected to be in possession of a passport or a visa valid in Swizerland (if relevant), and to be covered by their own health insurance during their visit.

Dates:	from 13 September 2010 08:00 to 22 September 2010 18:00
Timezone:	Europe/Zurich

Outline

- Introduction
- Pressing Questions
- Big Questions
- Can we ever test this?
- Conclusion


There are a lot of neutrinos out there

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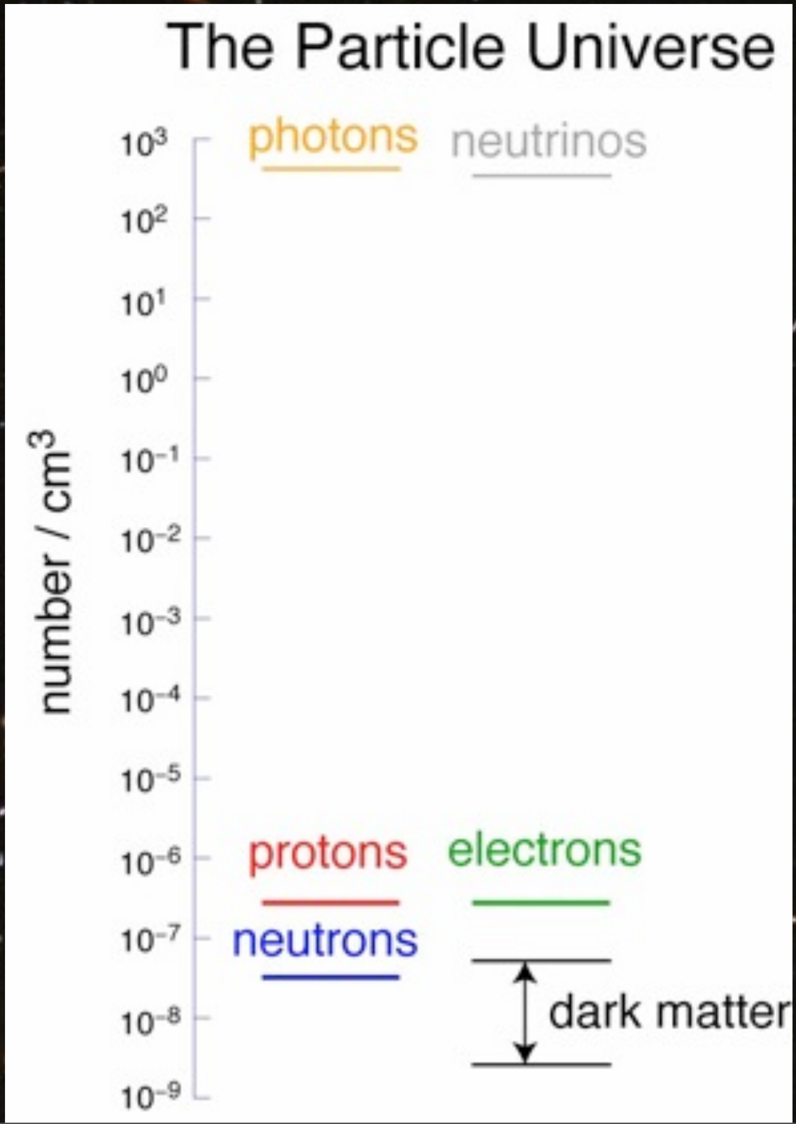


Beyond the Standard Model

Beyond the Standard Model

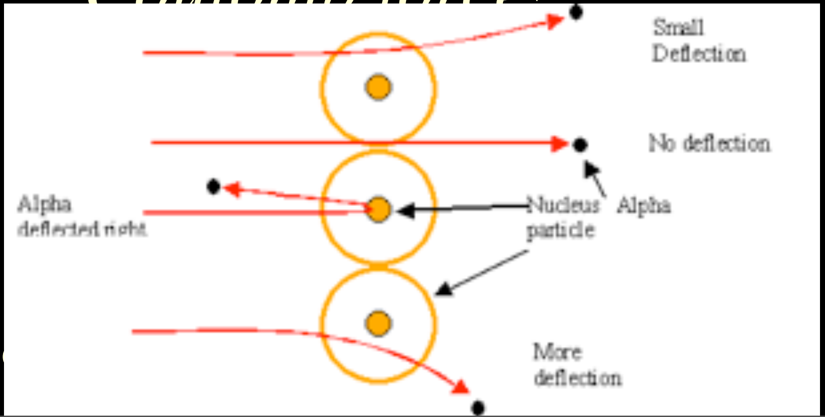
- We are all looking forward to discover physics beyond the standard model

Beyond the Standard Model

- We are all looking forward to discover physics beyond the standard model
- Two ways:
  - Go to highest energy possible (LHC, ILC/CLIC, UHECR?)
  - Look for rare phenomena (flavor, neutrinos, proton decay, dark matter detection)

Discovery of strong force

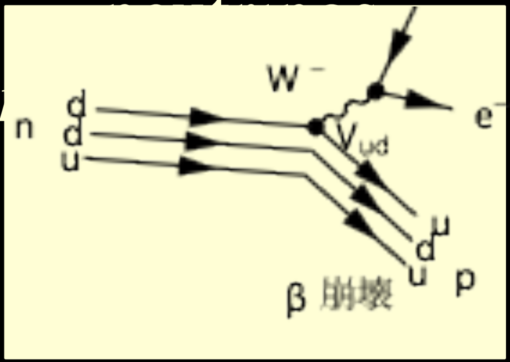
- The famous Rutherford experiment was the energy frontier experiment back then
- Use high-energy (7.7 MeV) alpha particles
- Maximum momentum transfer (backward scattering) is Q=480 MeV
- Can resolve $\Delta x \approx \hbar/Q \approx 0.4$ fm
- Could see *inelastic* scattering on proton
- *New force beyond Coulomb force!*

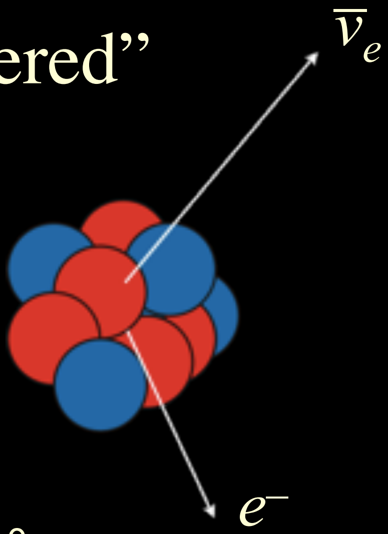


Discovery of weak interaction

- Nuclear beta decay a rare phenomenon
- ^{14}C half-life 5730 yrs
- Could be discovered because it violates a conservation law: *proton number, neutro number, electron number*

- Could discover new physics at $\Delta x \approx \hbar / m_W \approx 0.002$ fm
- Even “discovered”





Window to Short Distances

- Effects of physics beyond the SM as effective operators

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

- Can be classified systematically (Weinberg)

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

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

$$\begin{aligned}\mathcal{L}_6 \;=\;& QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He, \\ & \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots\end{aligned}$$

Unique Role of Neutrino Mass

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  - Need coherent source
  - Need interference (*i.e.*, large mixing angles)
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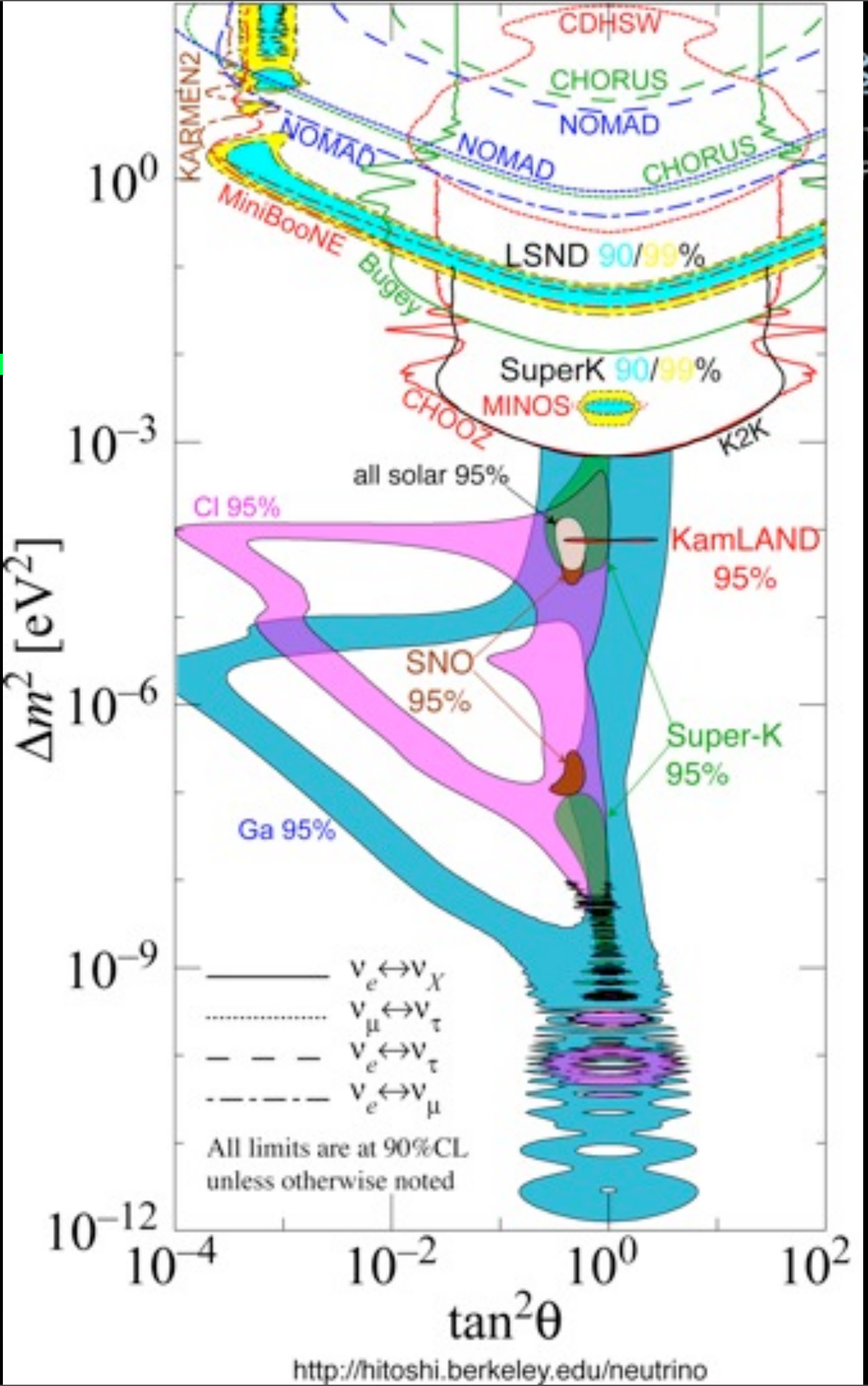
- "neutrino interferometry" (a.k.a. neutrino oscillation) a unique tool to study physics at very high scales

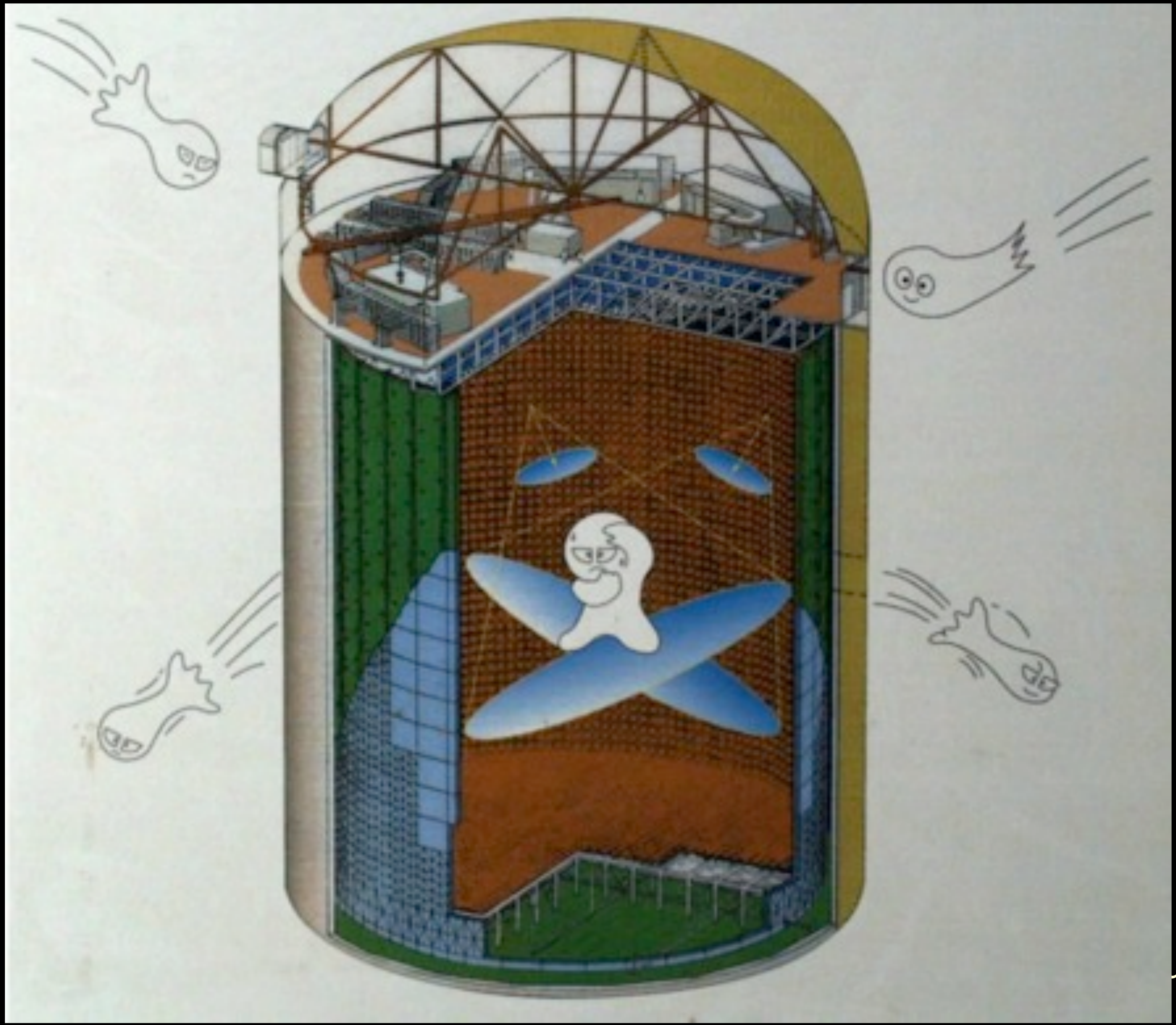
Lot of effort since '60s

Finally convincing evidence for "neutrino oscillation"

Neutrinos have tiny but finite mass

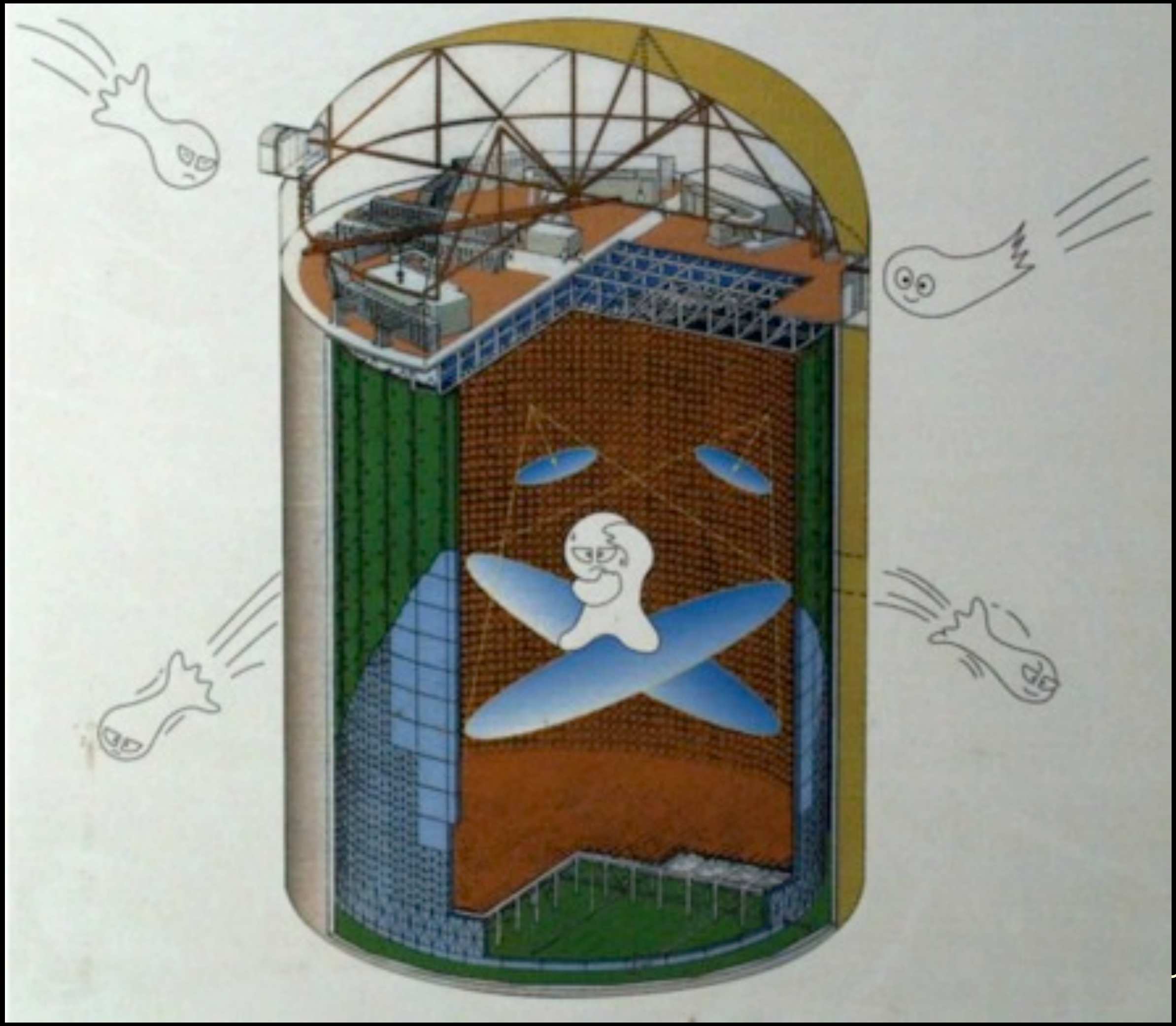


Super-K



- Kamioka Mine in central Japan
- ~1000m underground
- 50kt water
- Inner Detector
  - 11,200 PMTs
- Outer Detector
  - 2,000 PMTs

Super-K



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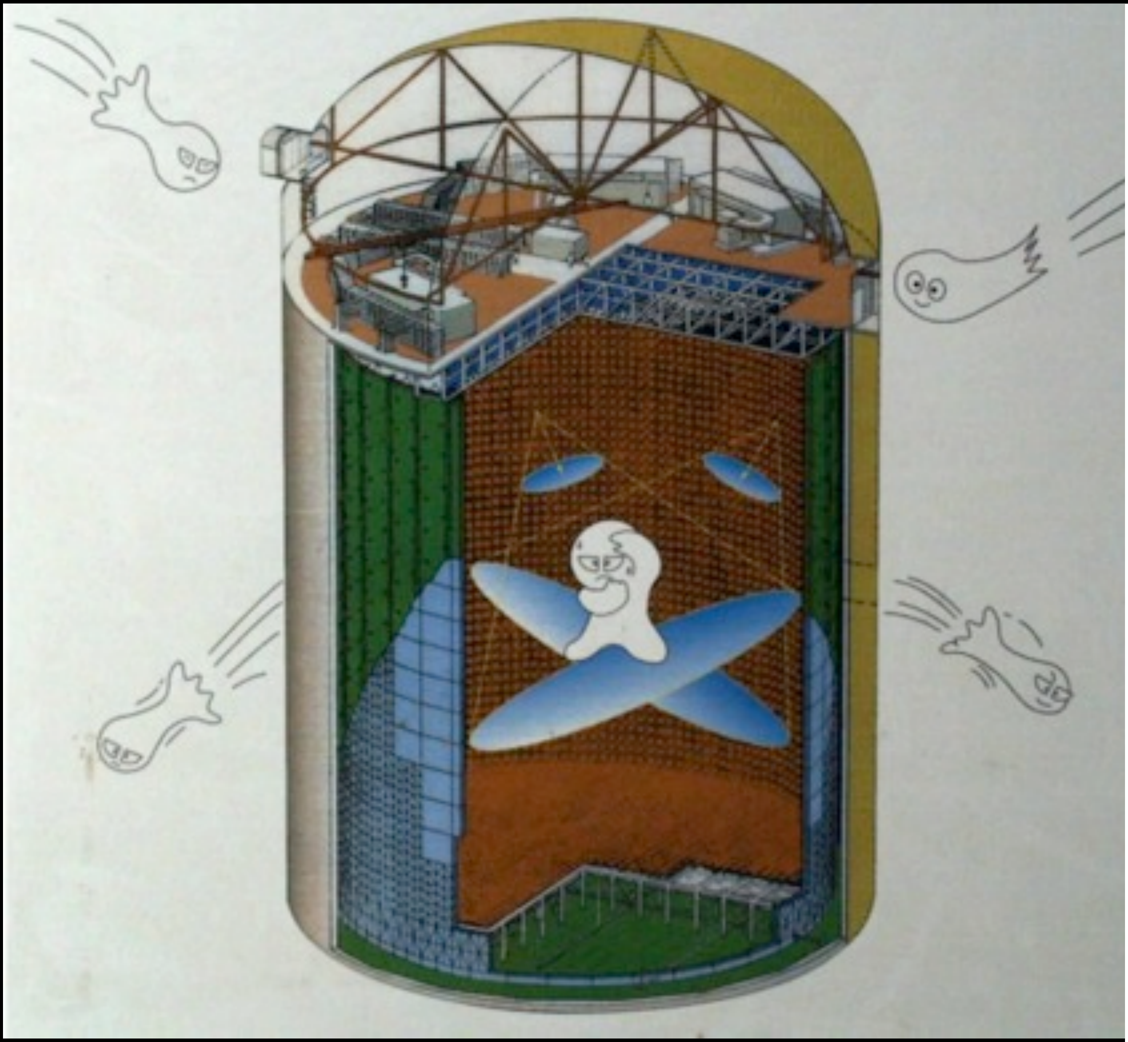
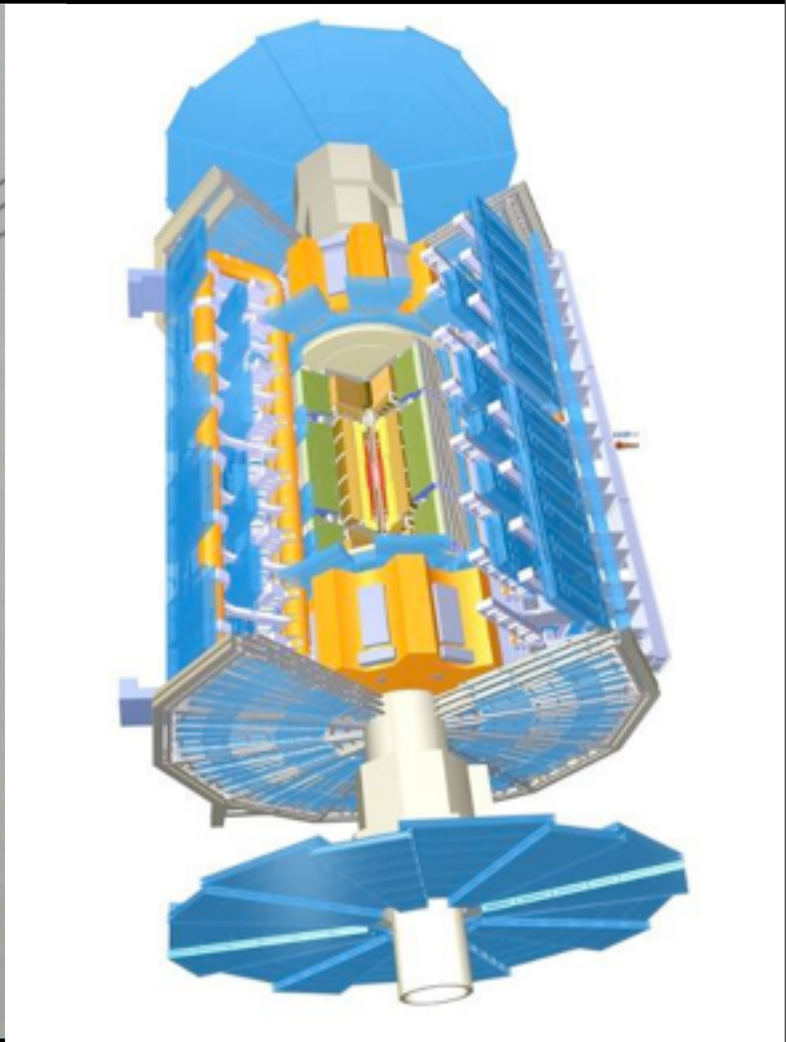




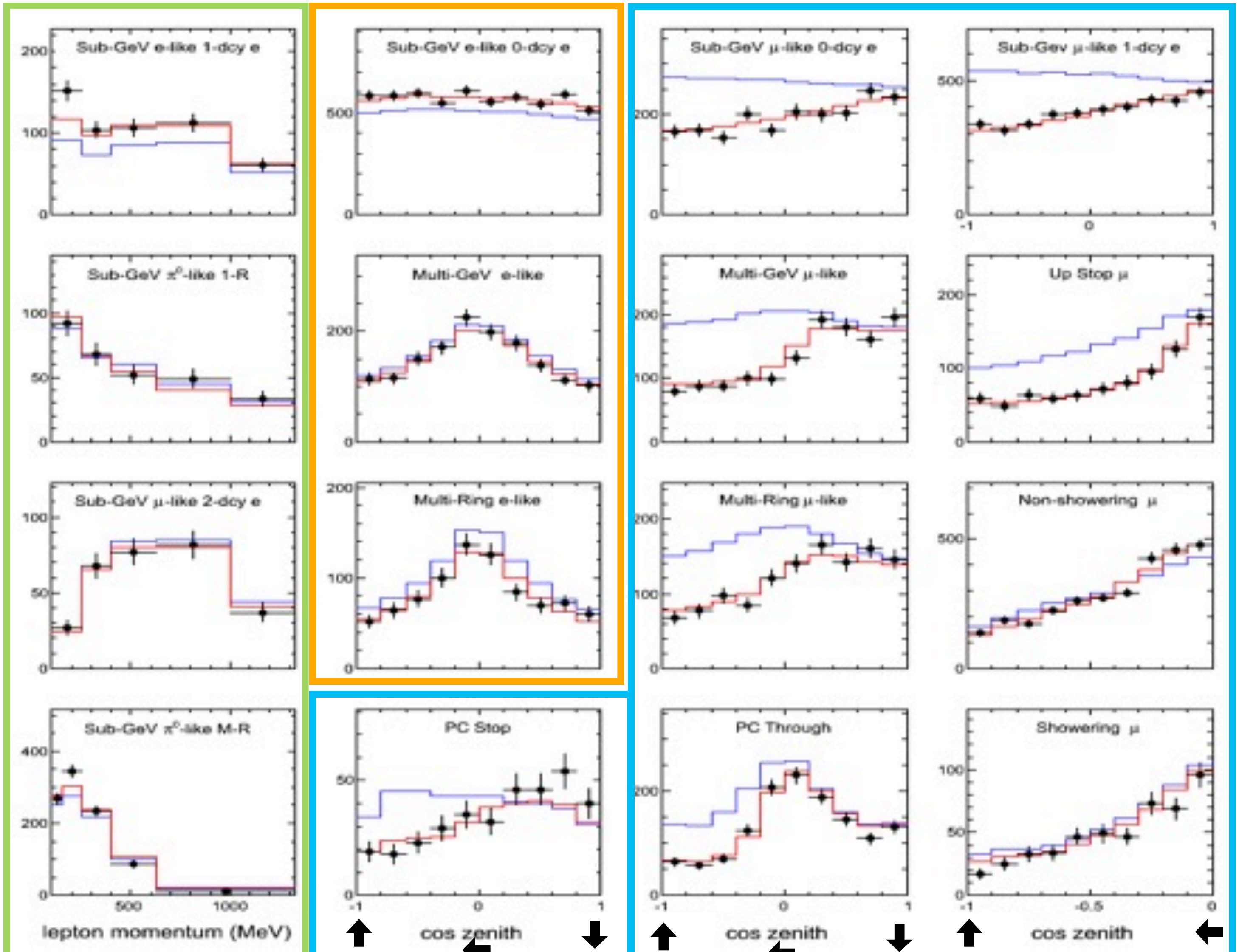
Zenith angle & lepton momentum distributions

Takeuchi, Neutrino 2010

— $\nu_\mu - \nu_\tau$ oscillation (best fit)
— null oscillation

momentum | e-like | μ-like

SK-I+II+III
Preliminary

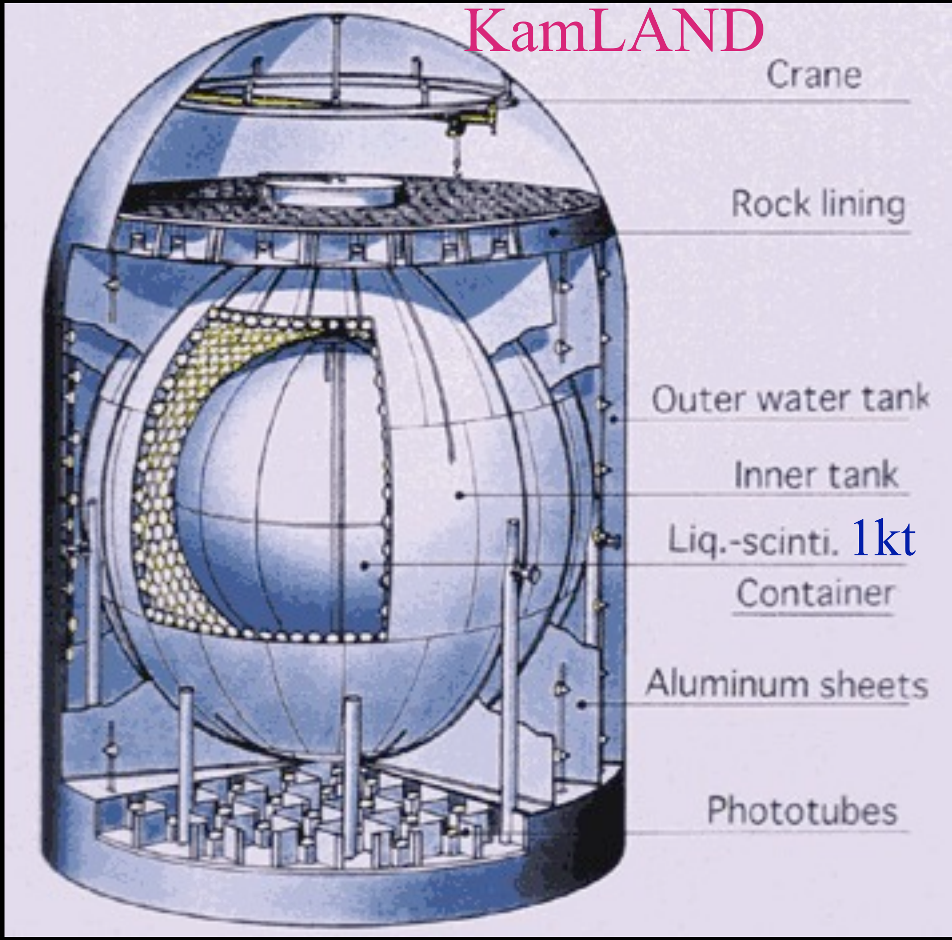


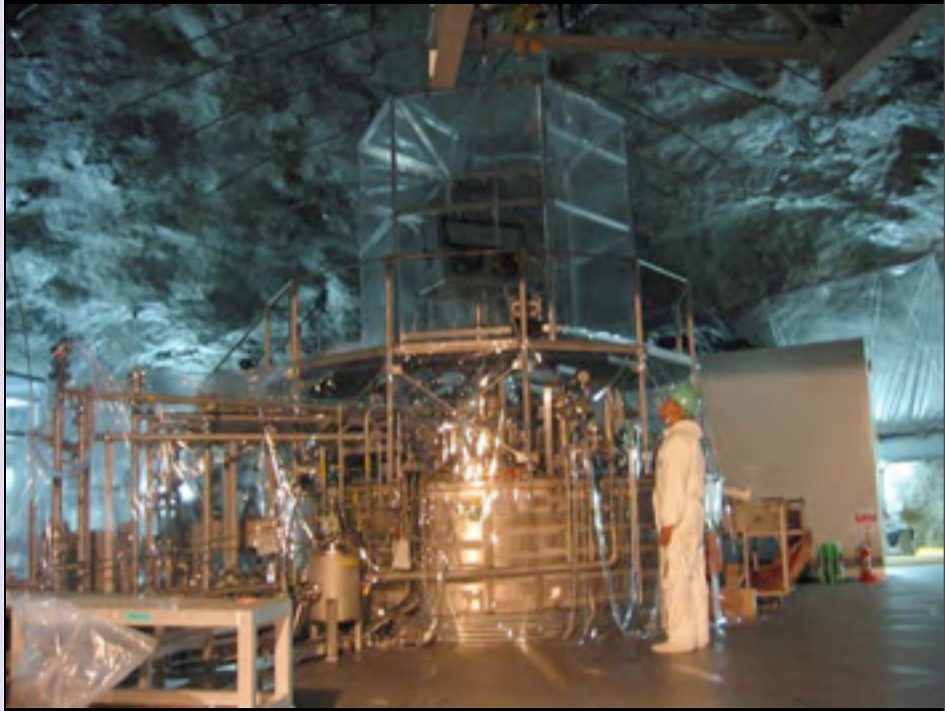
Live time:
SK-I
1489d (FCPC)
1646d (Upmu)
SK-II
799d (FCPC)
827d (Upmu)
SK-III
518d (FCPC)
636d (Upmu)

Sub-GeV samples are divided to improve sensitivity to low-energy oscillation effects

Jun 2009

KamLAND ’08 neutrinos do oscillate!





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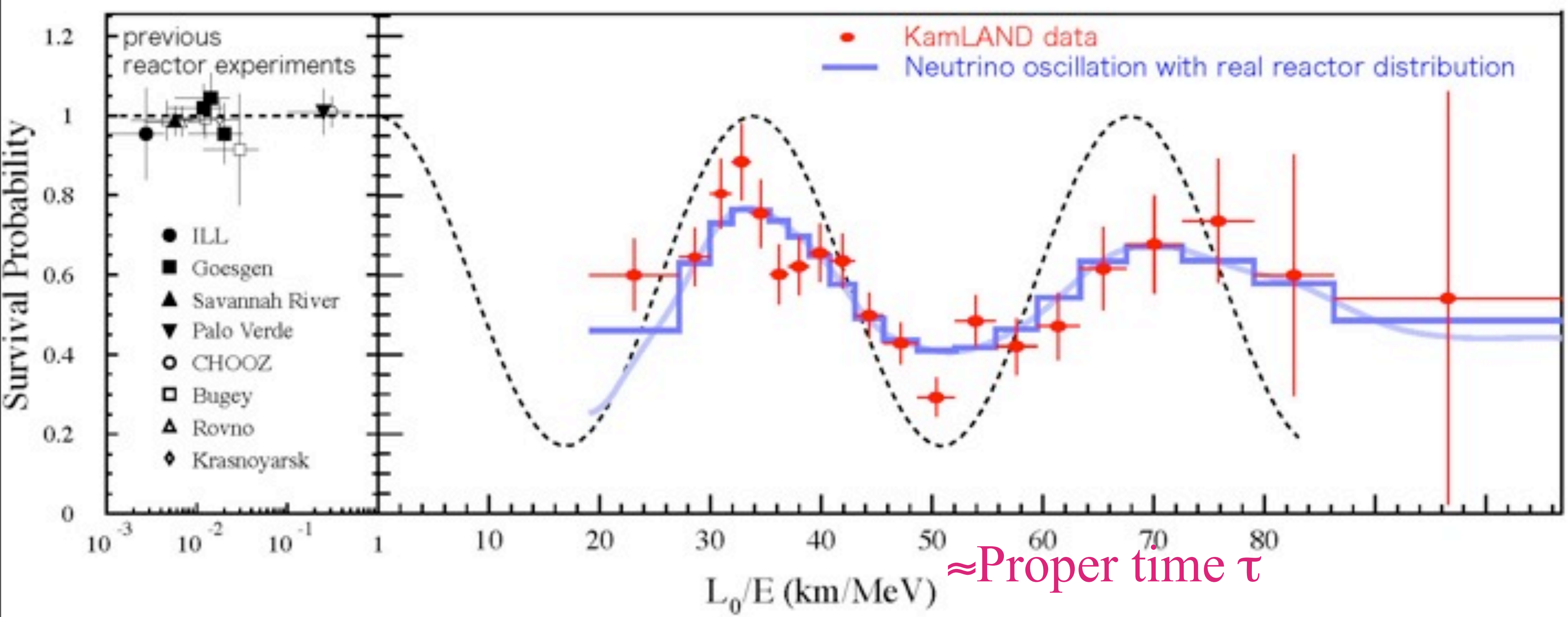

≈Proper time τ

L_0=180 km

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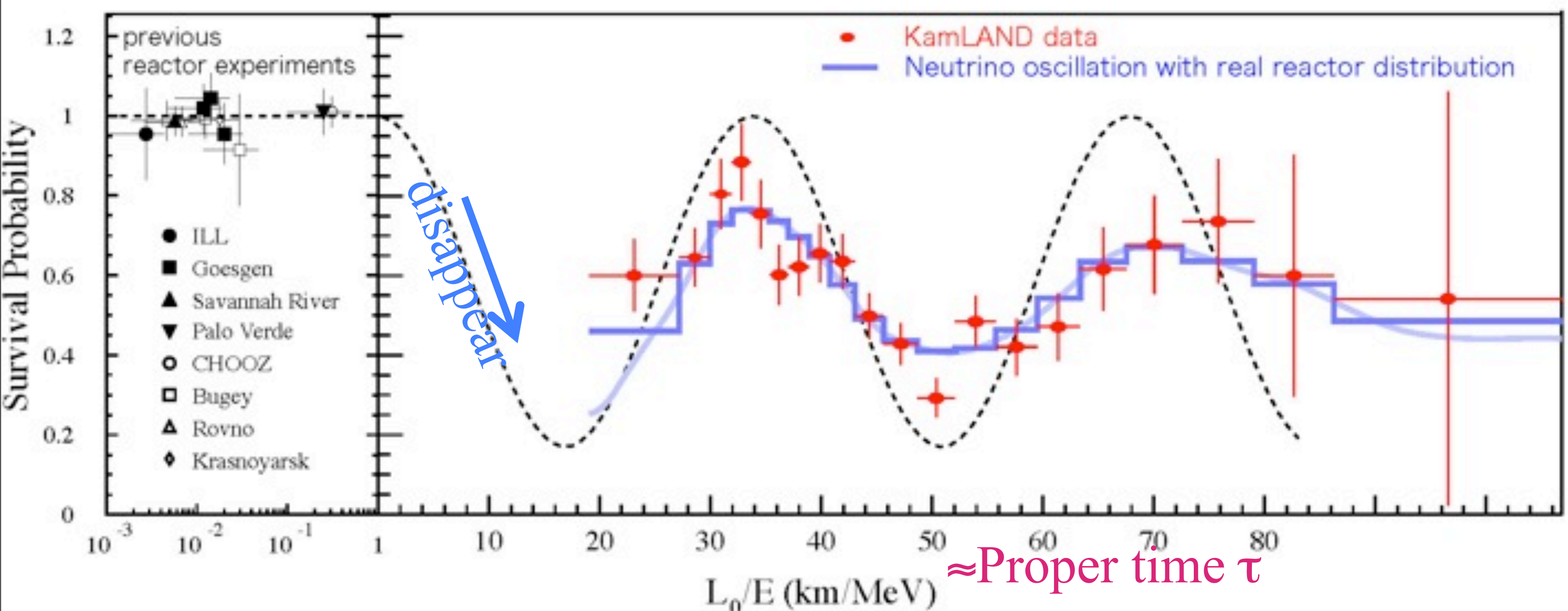

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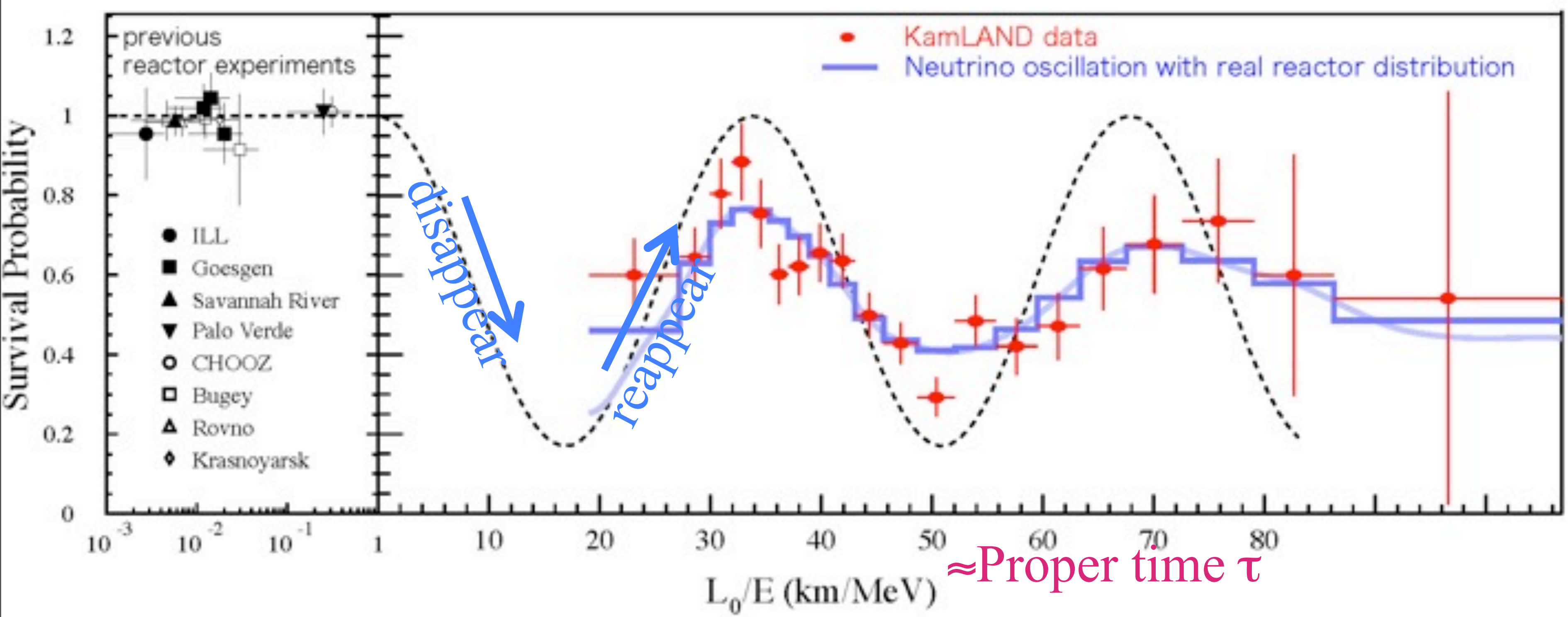

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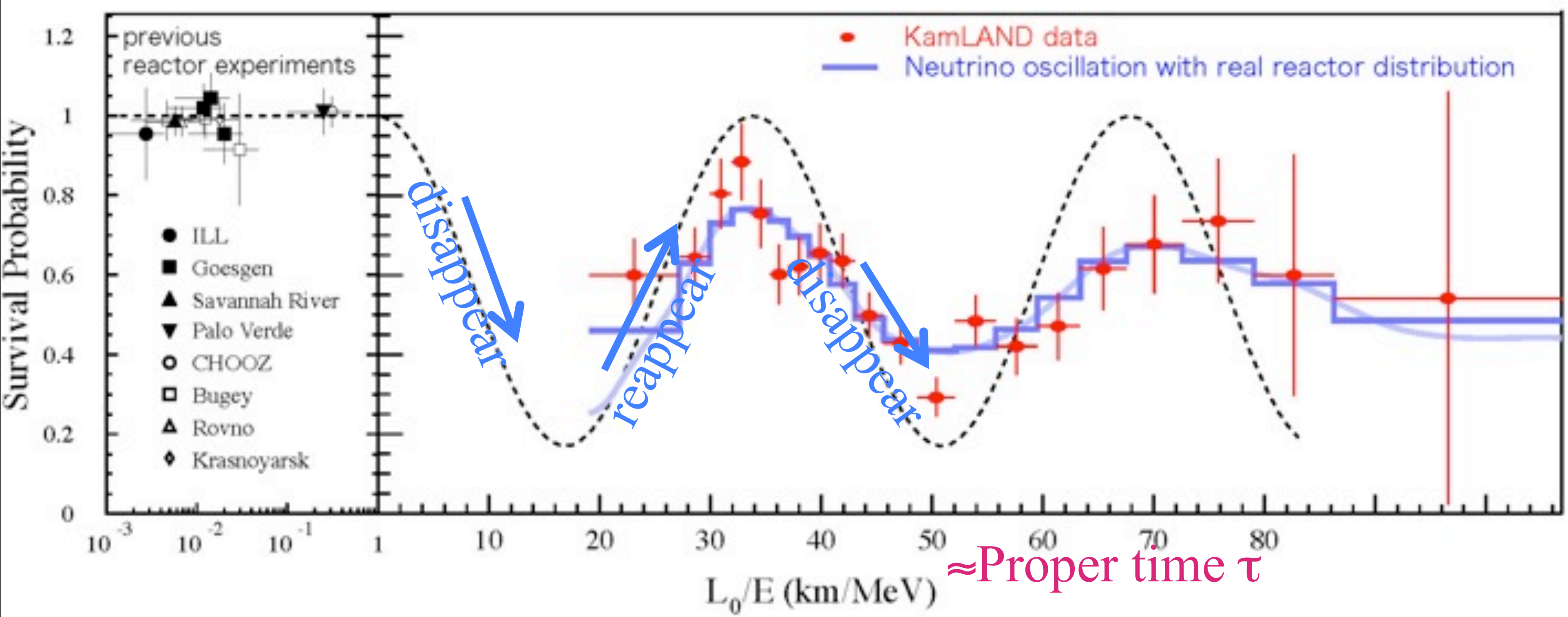

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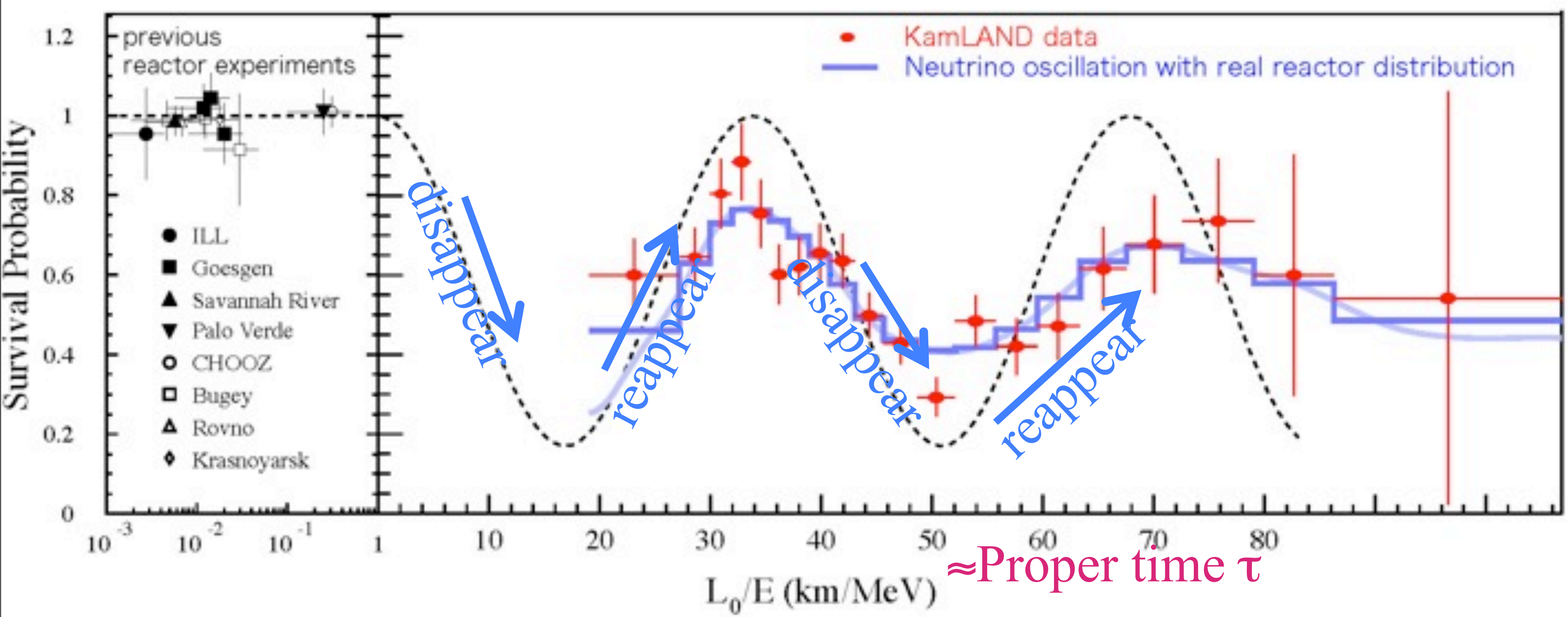

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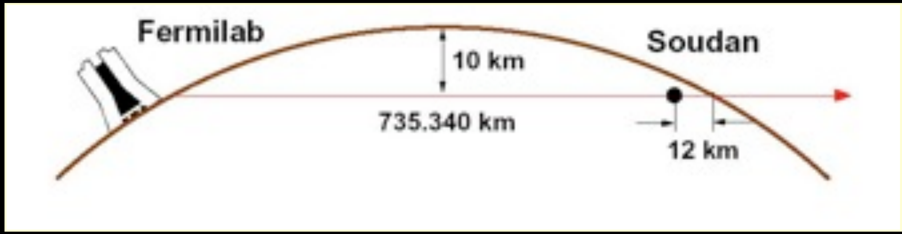
MINOS

- SuperK atmospheric neutrino result confirmed with manmade neutrinos



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Neutrino 2010

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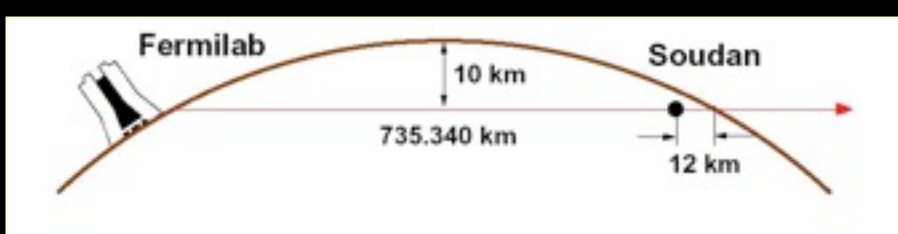
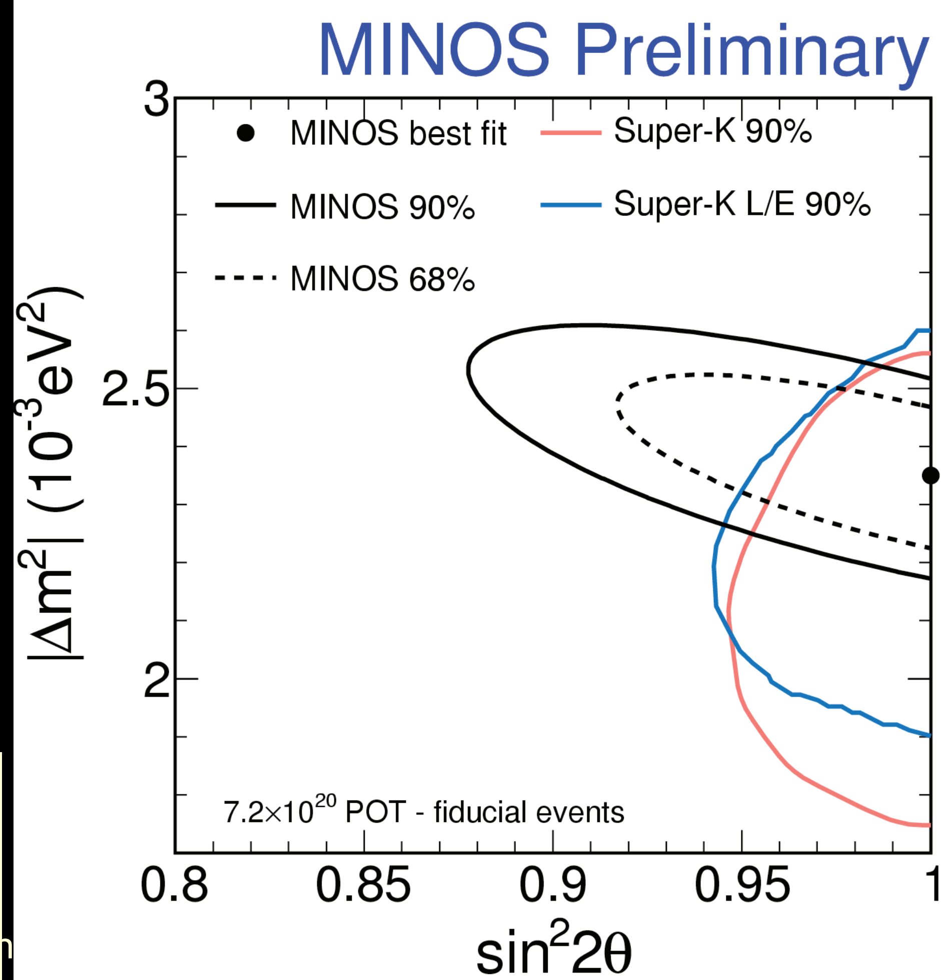
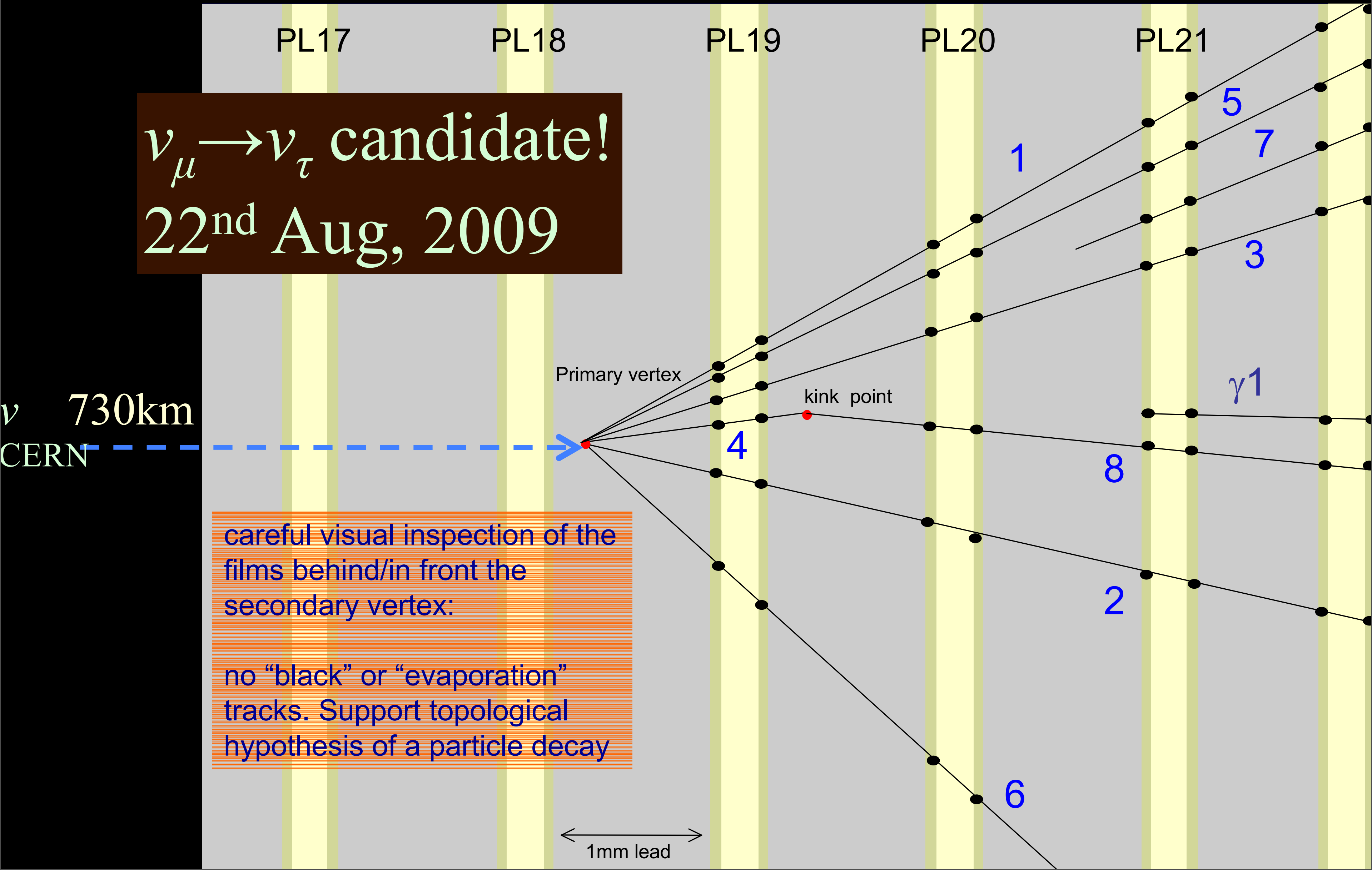




OPERA CERN to Gran Sasso

$\nu_\mu \rightarrow \nu_\tau$ candidate!
22nd Aug, 2009



careful visual inspection of the films behind/in front the secondary vertex:

no “black” or “evaporation” tracks. Support topological hypothesis of a particle decay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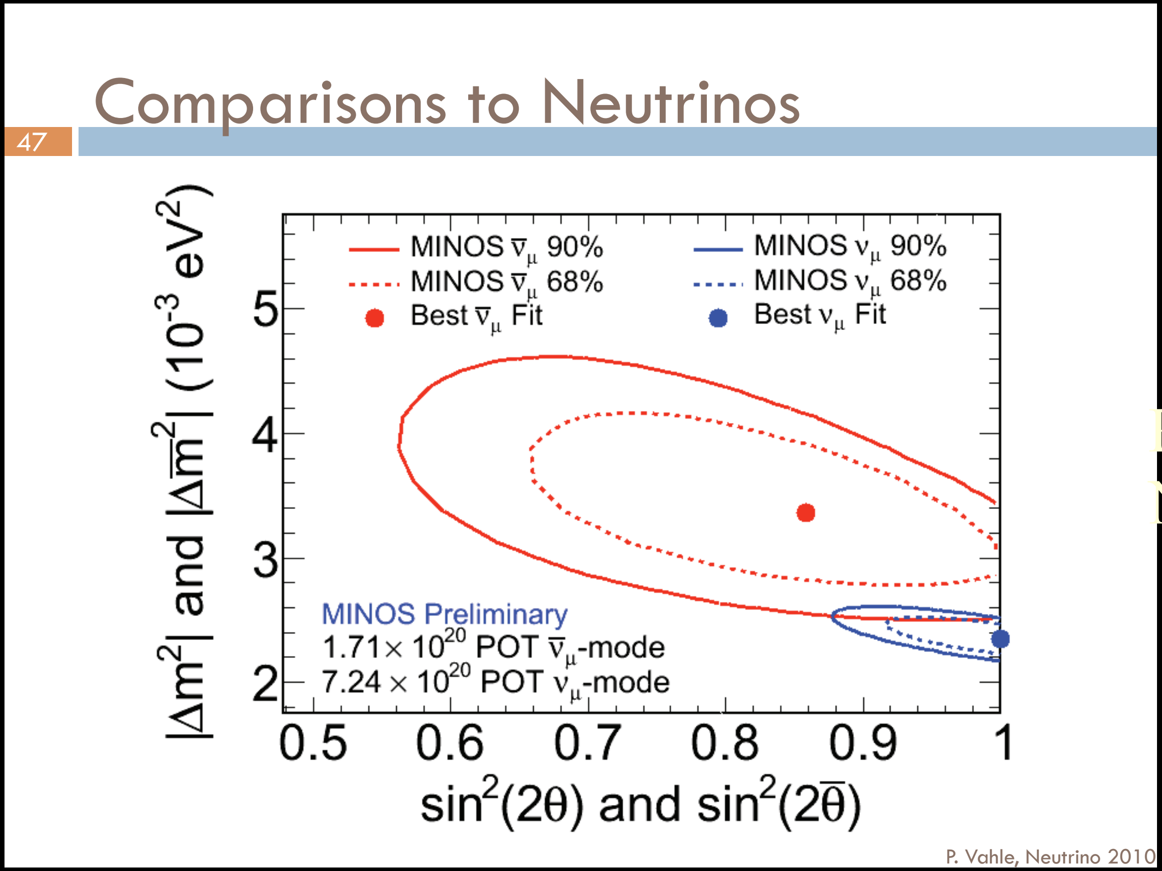
MINOS '10
CPT Violation?



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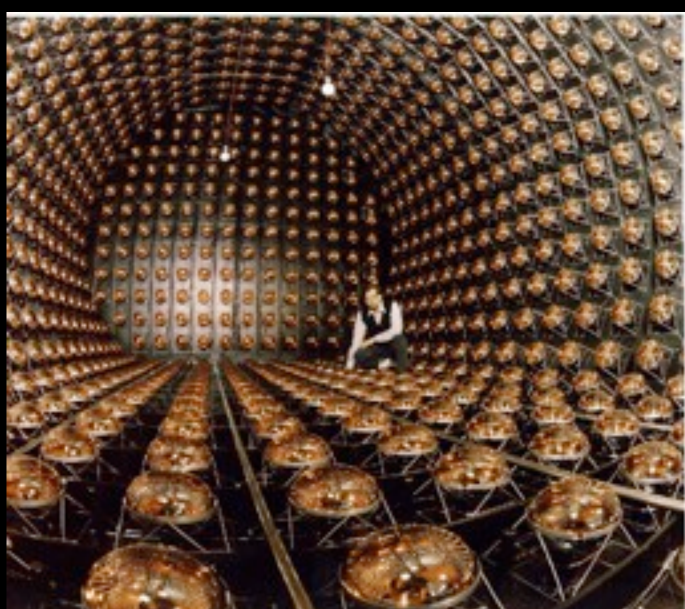
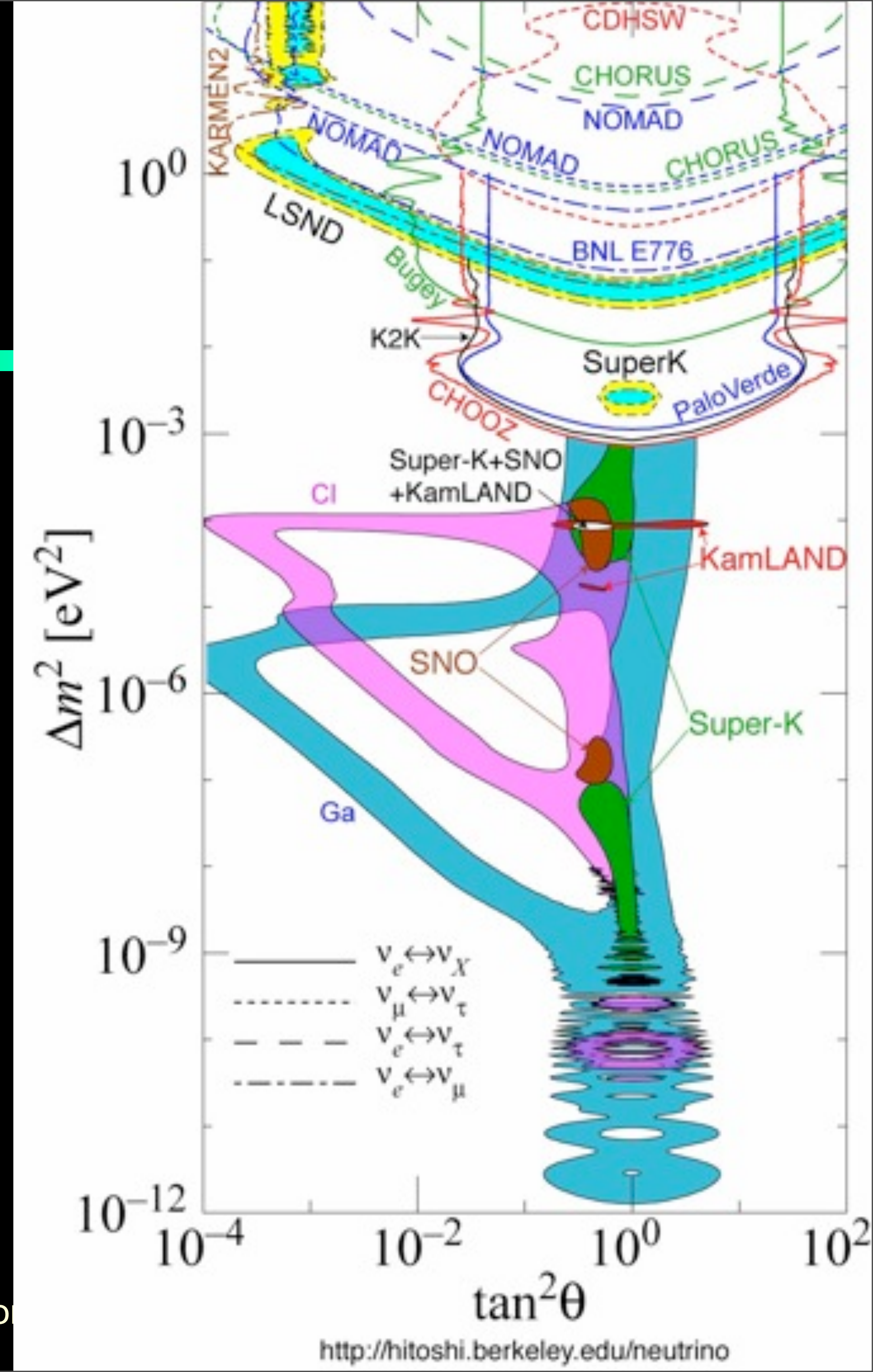
Neutrino 2010

3.3σ LSND signal

- Excess positron events over calculated BG





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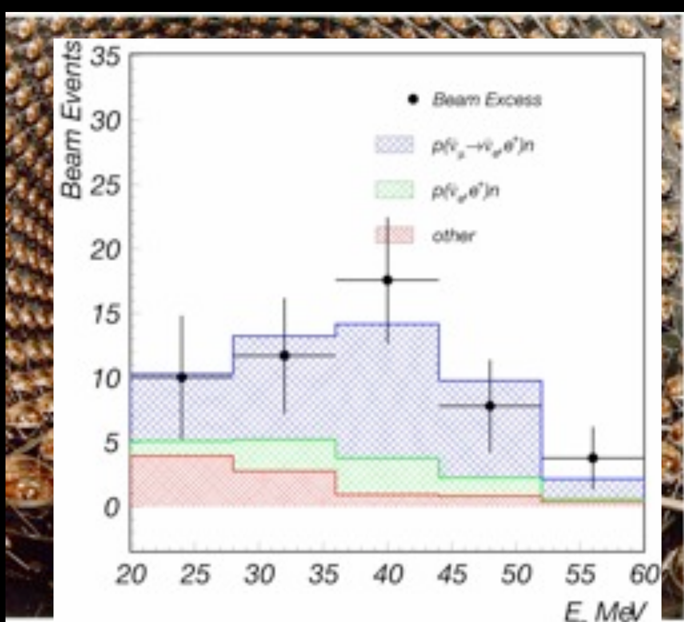

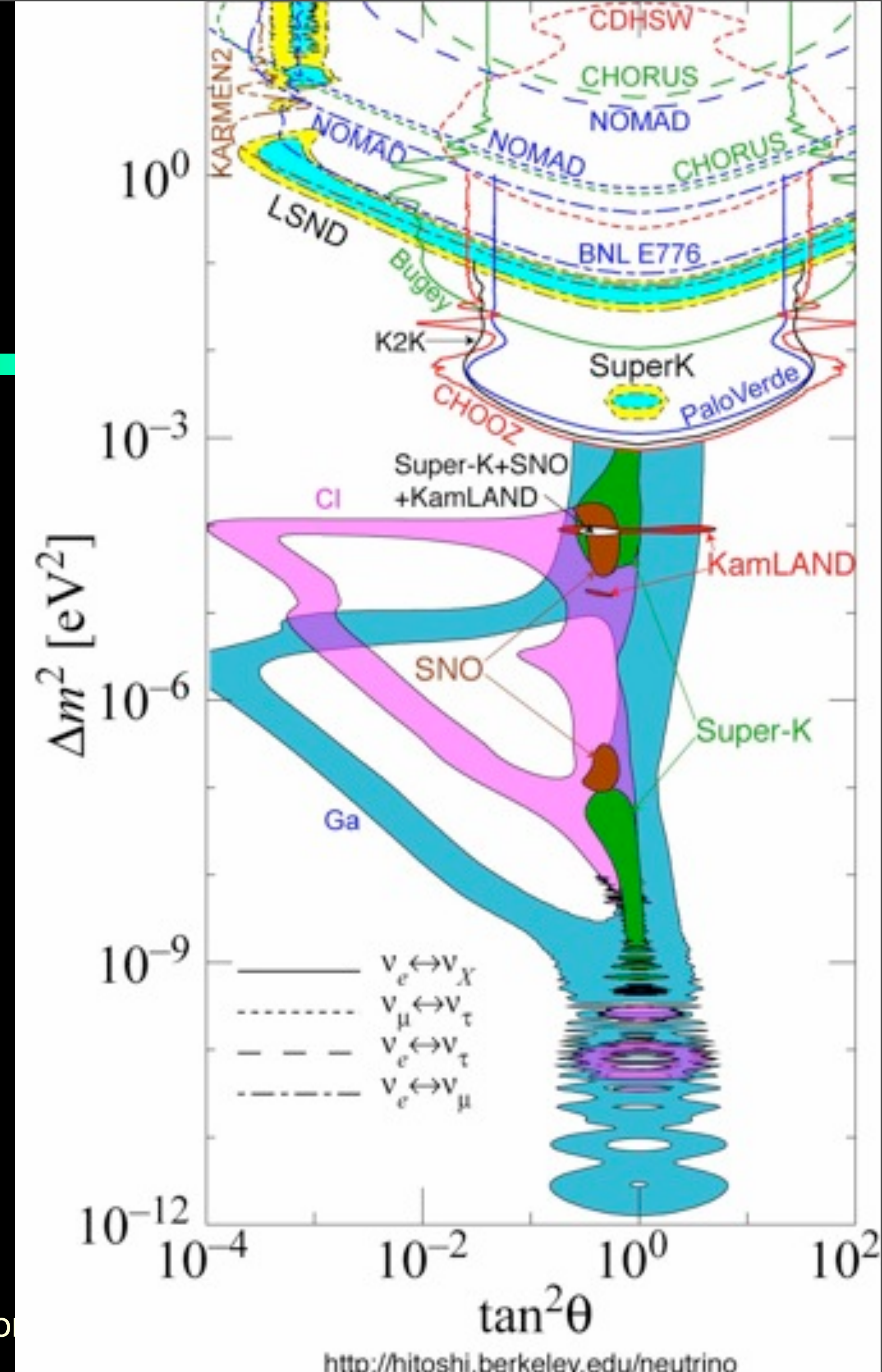

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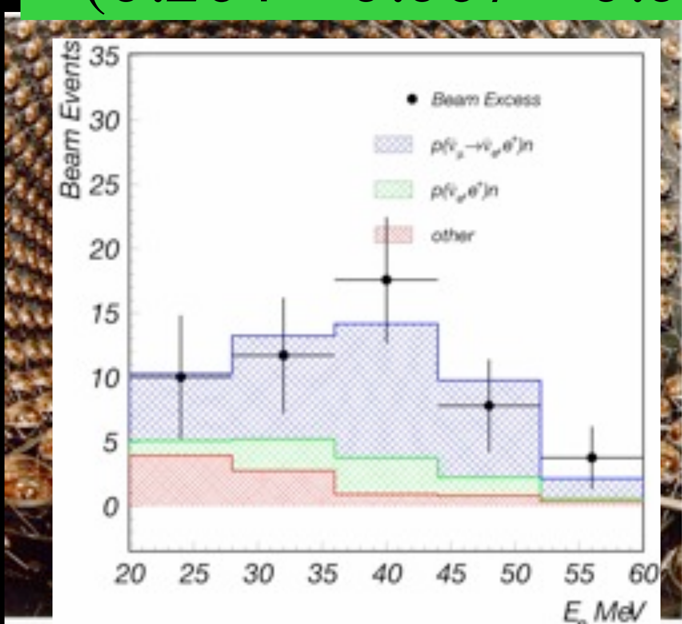
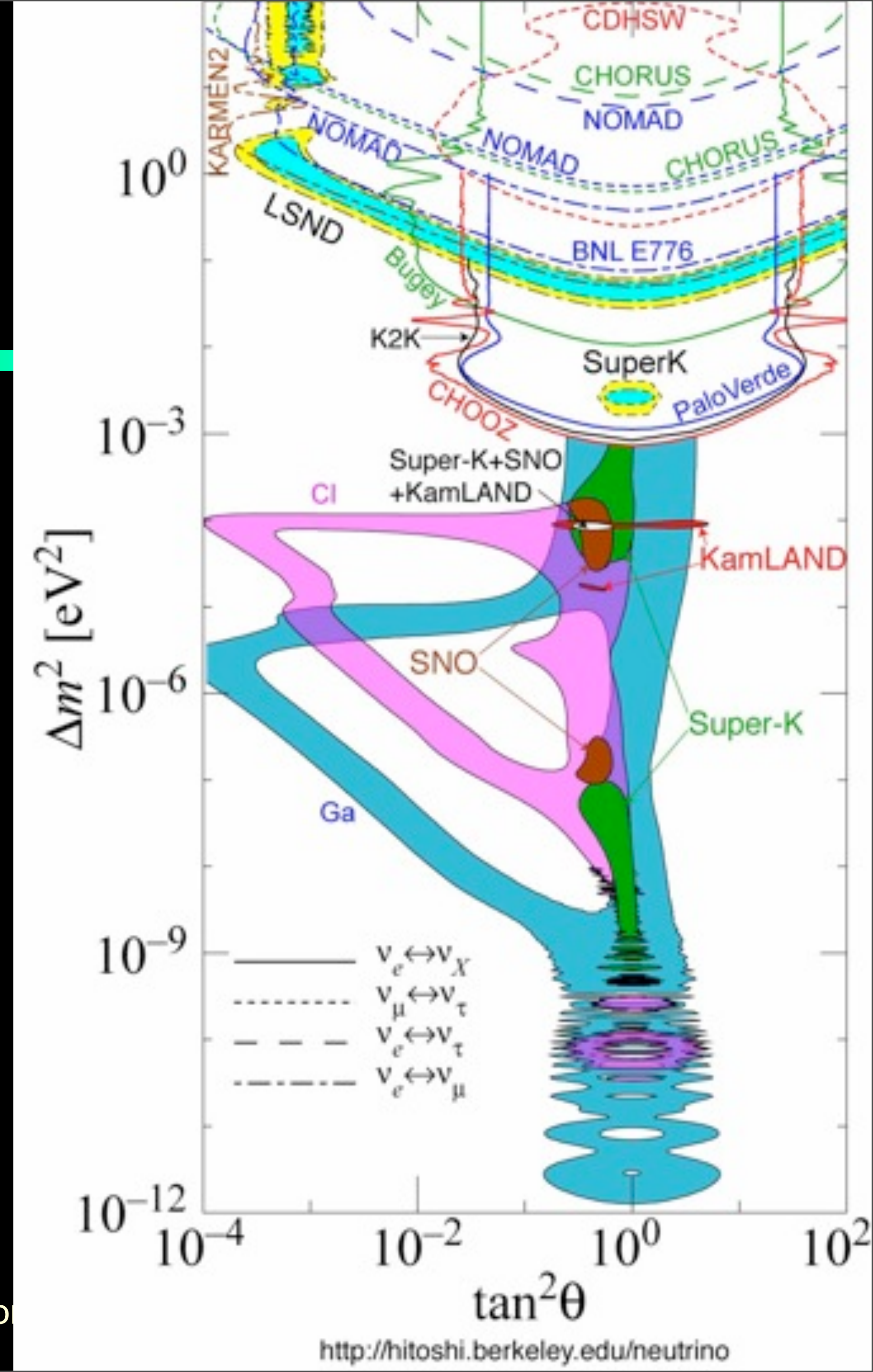
$$P(\bar{\nu}_\mu \to \bar{\nu}_e)$$
$$= (0.264 \pm 0.067 \pm 0.045)\%$$



, CERN Theor



Mini-BooNE '10 CPT Violation?

Richard Vandewater
Neutrino 2010

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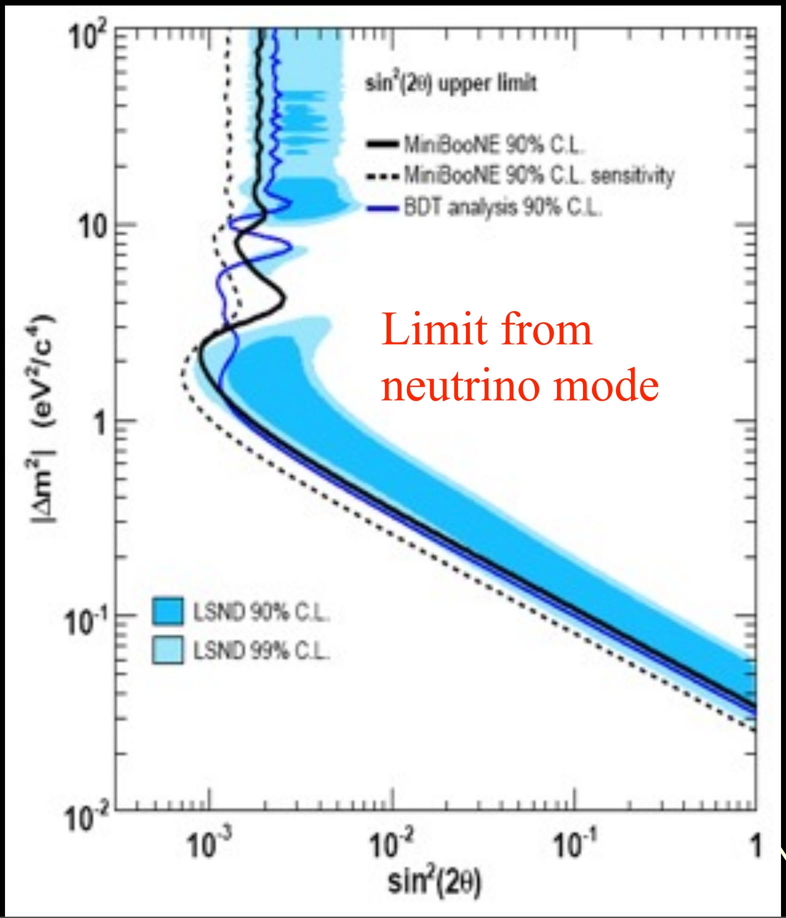

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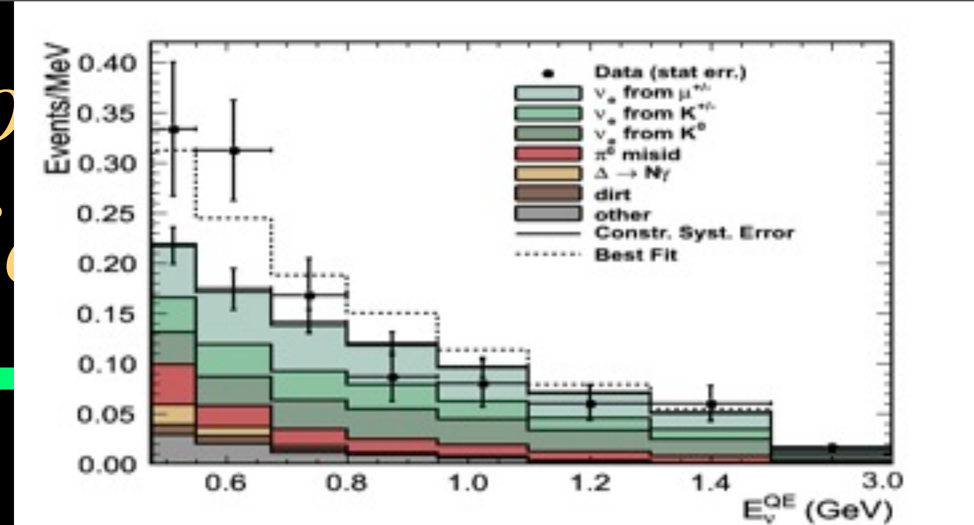
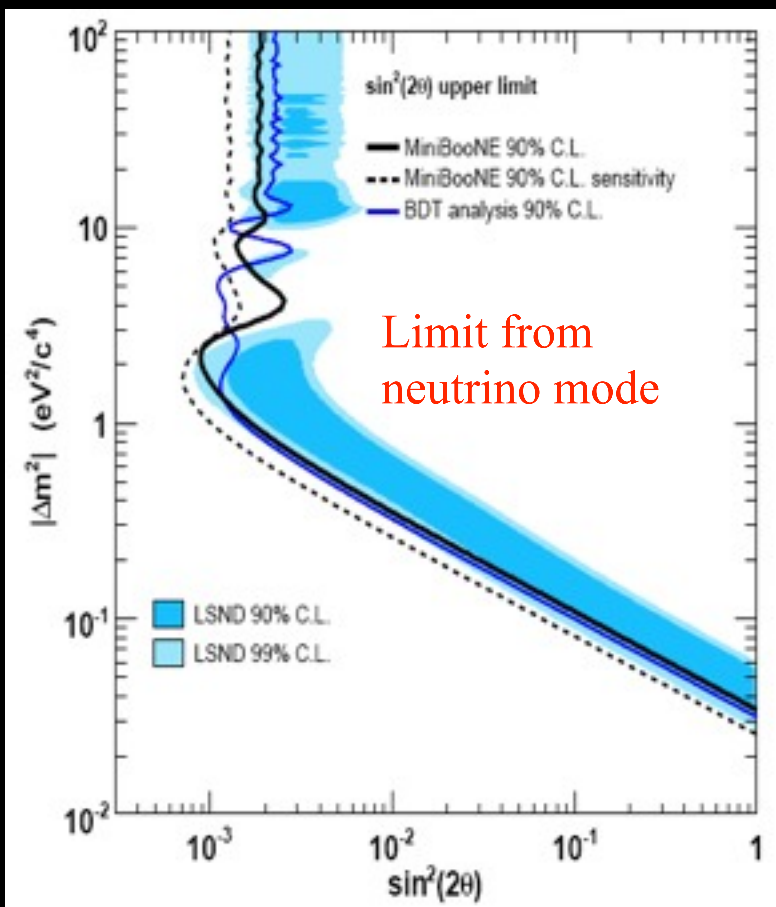
Mini-Bo
CPT Vi





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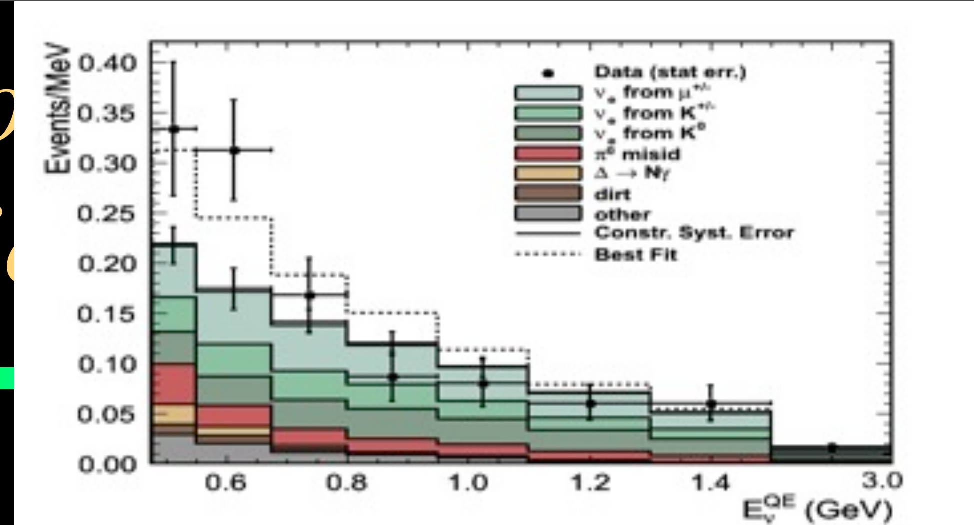
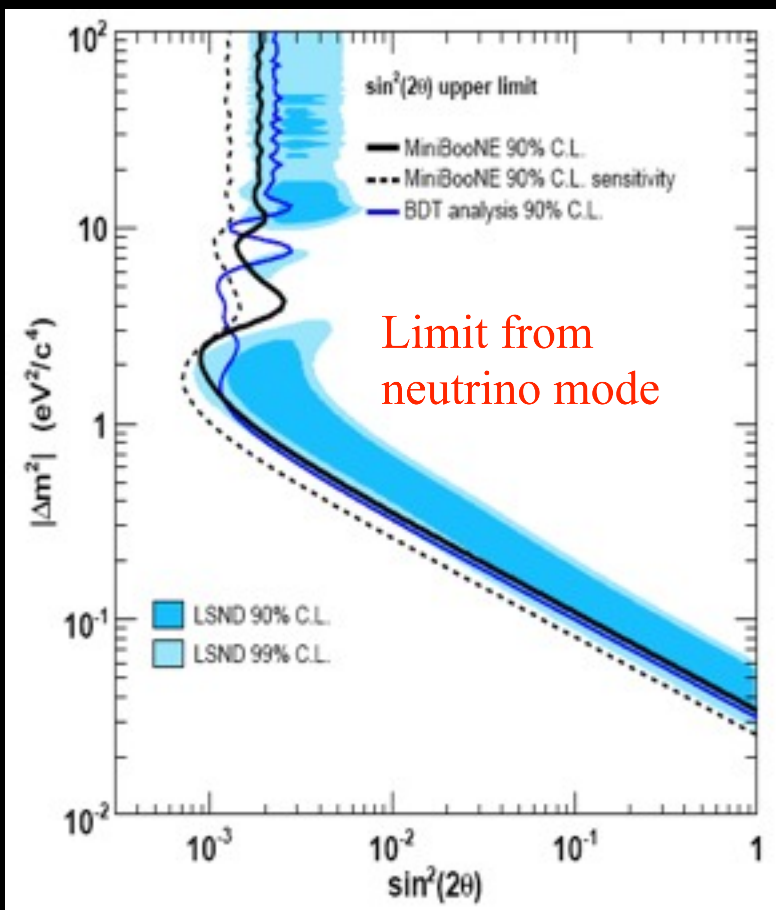
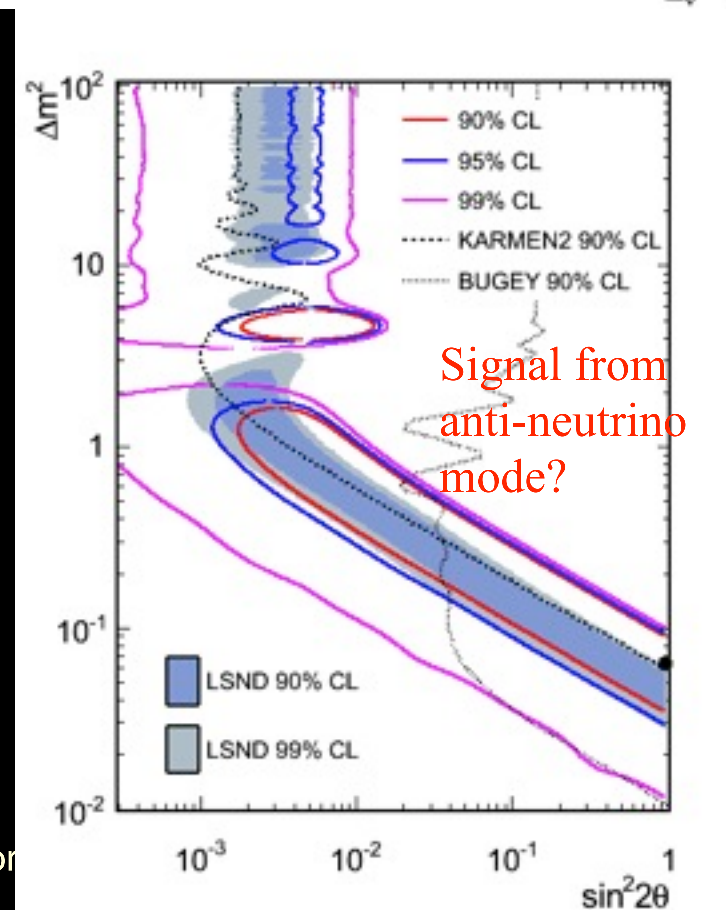




N Theor



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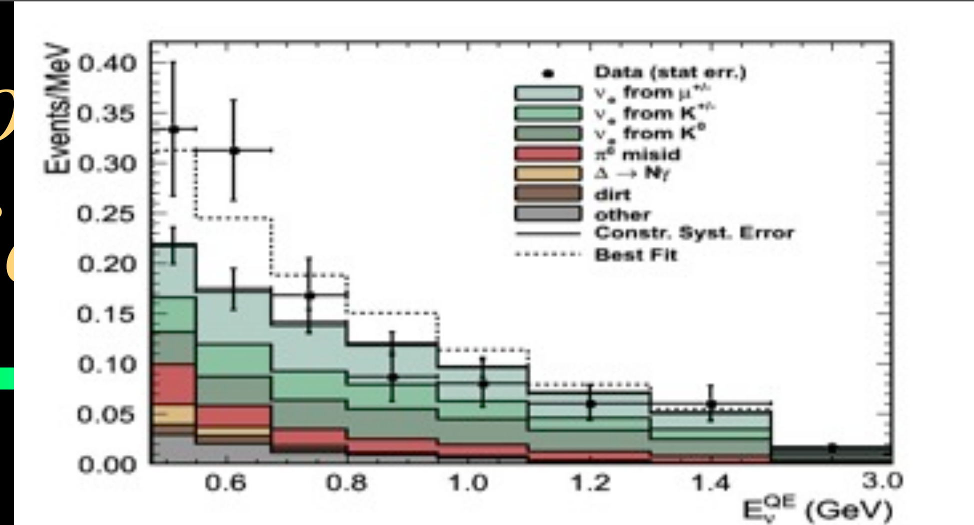

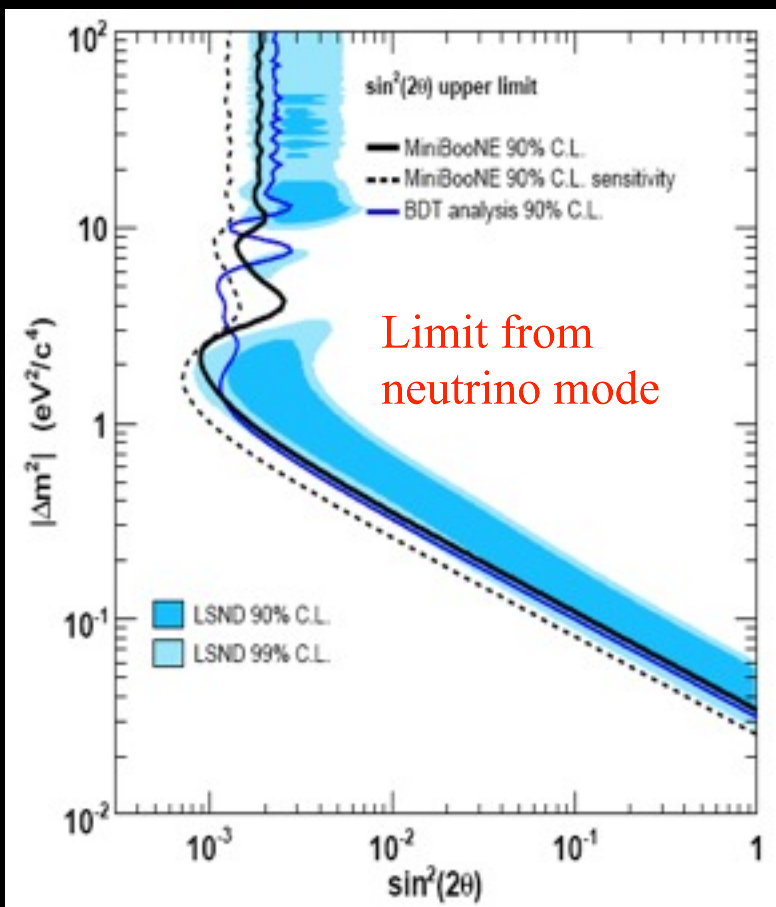

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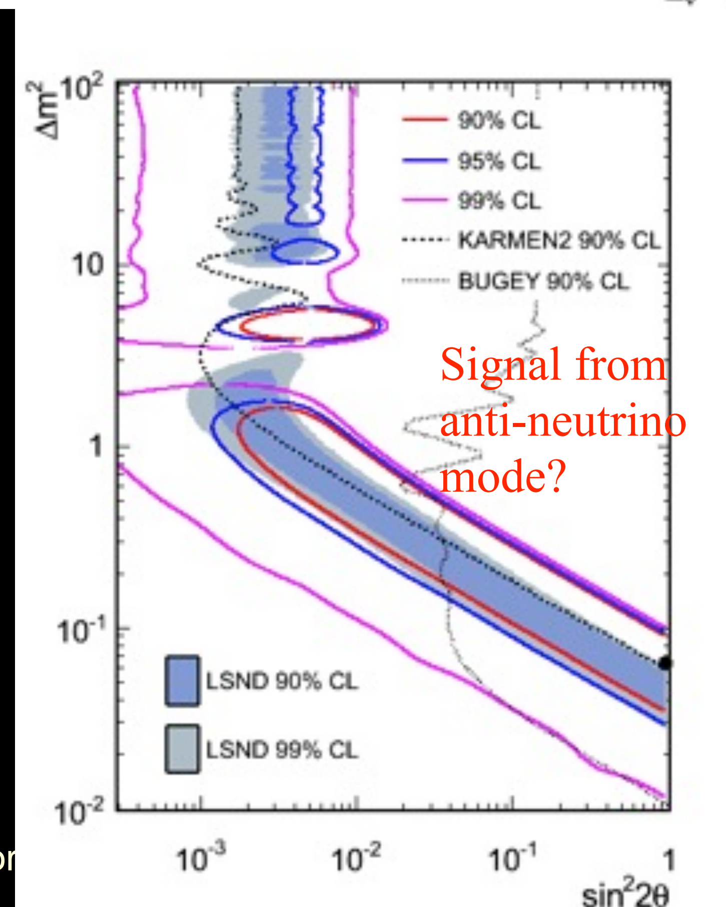
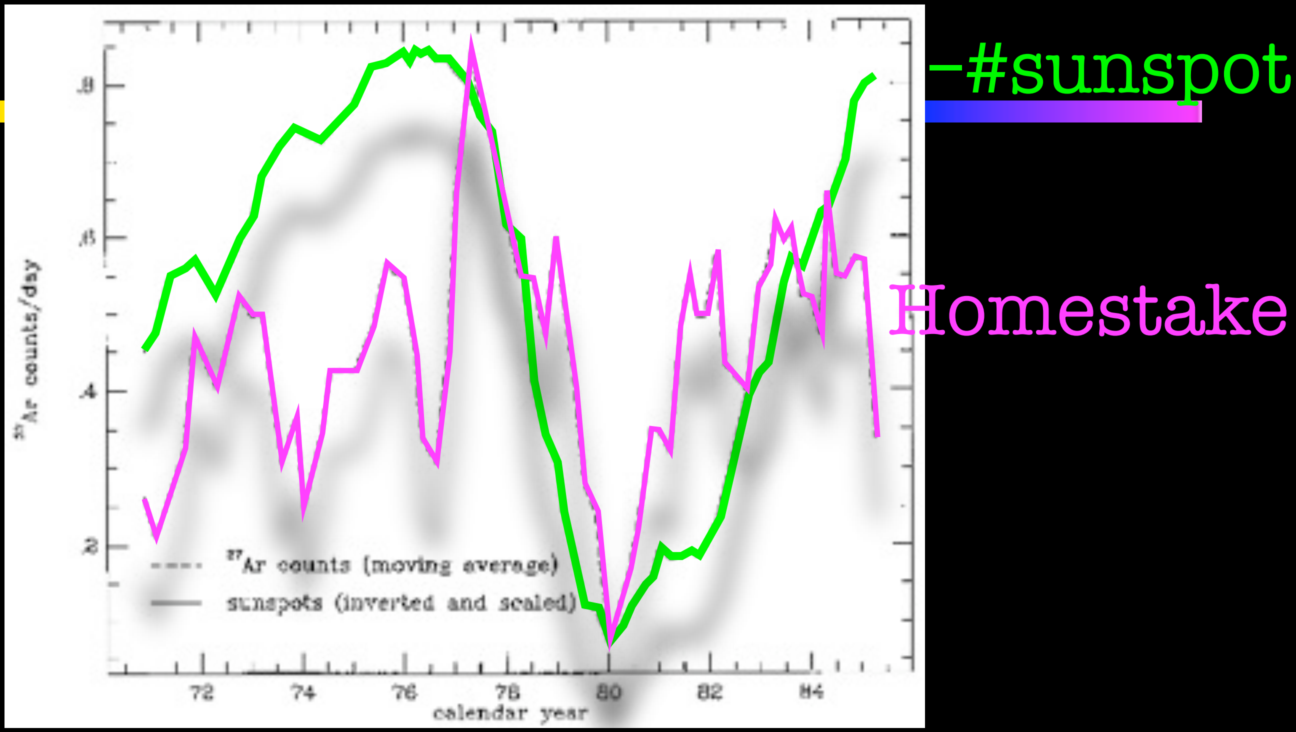


No oscillation excluded @99.4%CL

Neutrino data can be confusing



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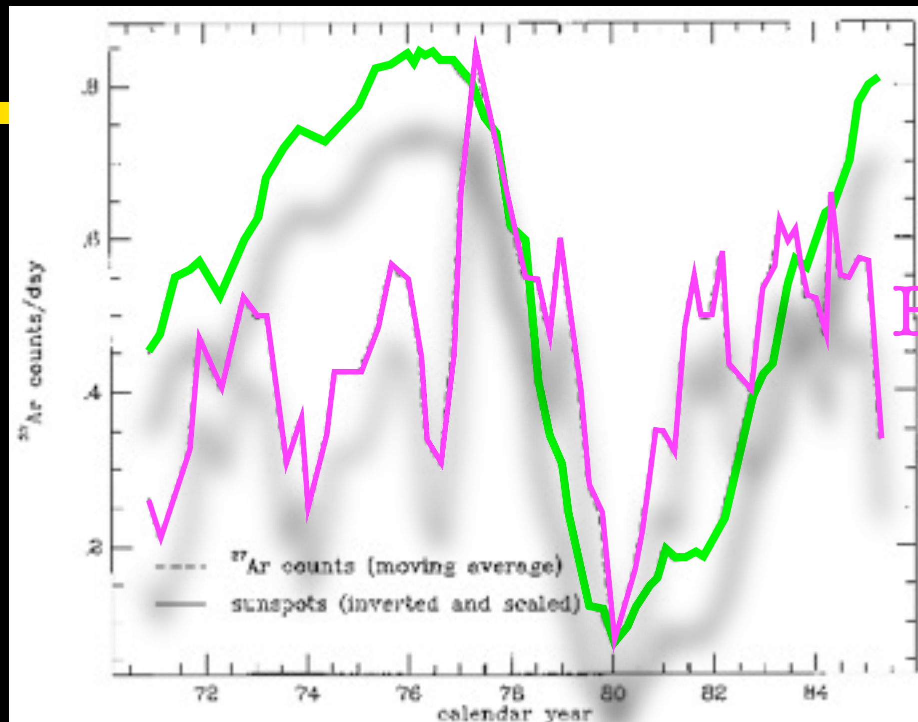
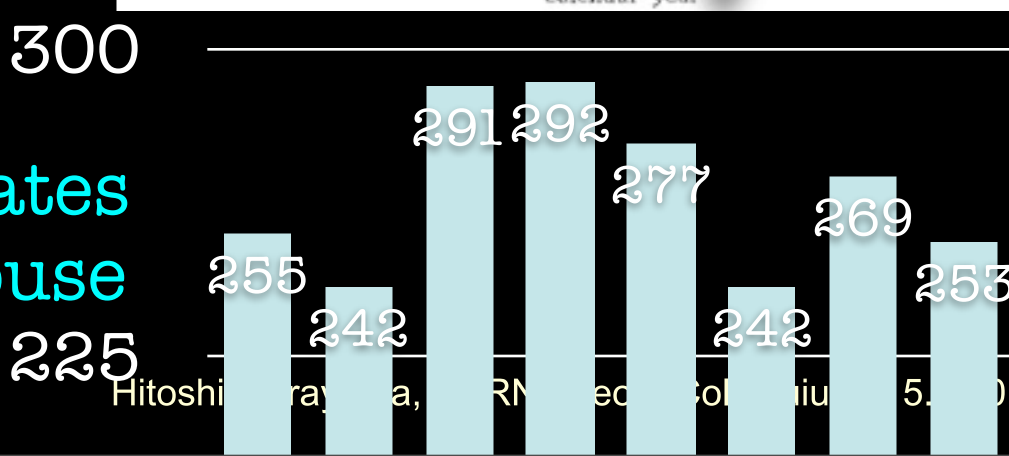


−#sunspot

Homestake

#Democrates in the House



Question to string theorists

- Is CPT conserved in string theory?
- The field-theory proof requires locality
- String theory is not local in the usual sense
- Maybe a loophole?
- But analytic continuation from Euclidean amplitudes with SO(4) symmetry seem to contain CPT…
- Any hard proof?

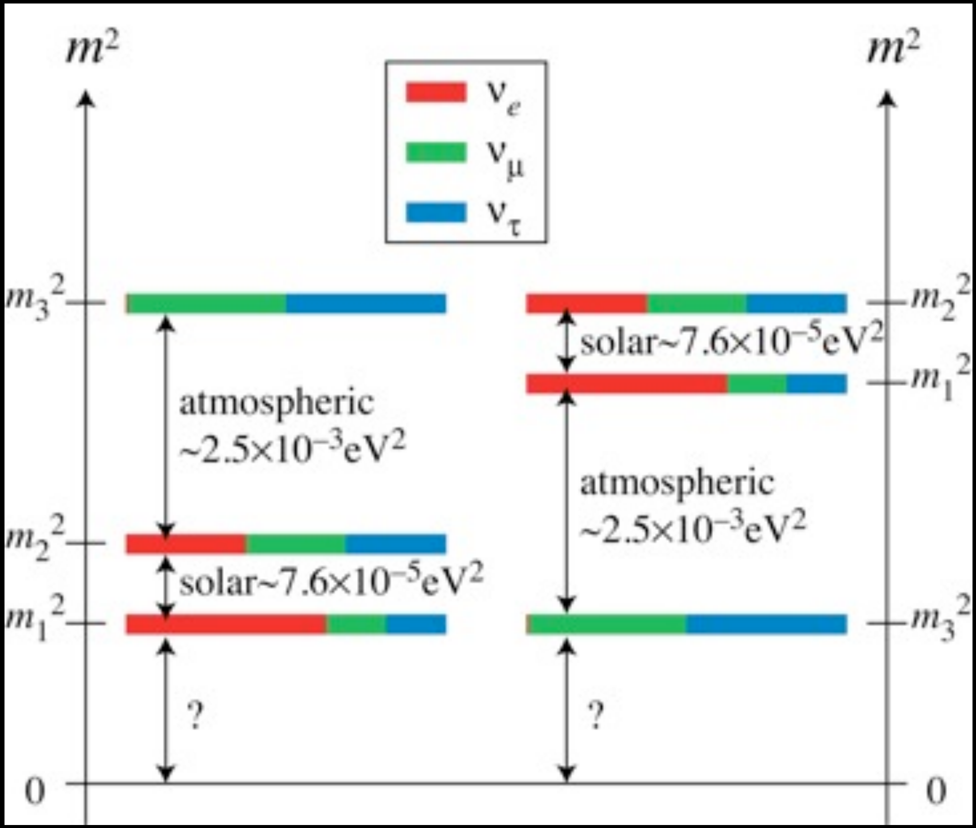
Five Evidences beyond the Standard Model

- We are now convinced that the standard model is grossly incomplete
  - Finite mass of neutrinos
  - Non-baryonic dark matter
  - Accelerating universe (dark energy)
  - Acausal density fluctutation (inflation)
  - Existing of matter (baryon asymmetry)

Pressing Questions

Raised More Questions

- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- Is θ_{23} maximal?



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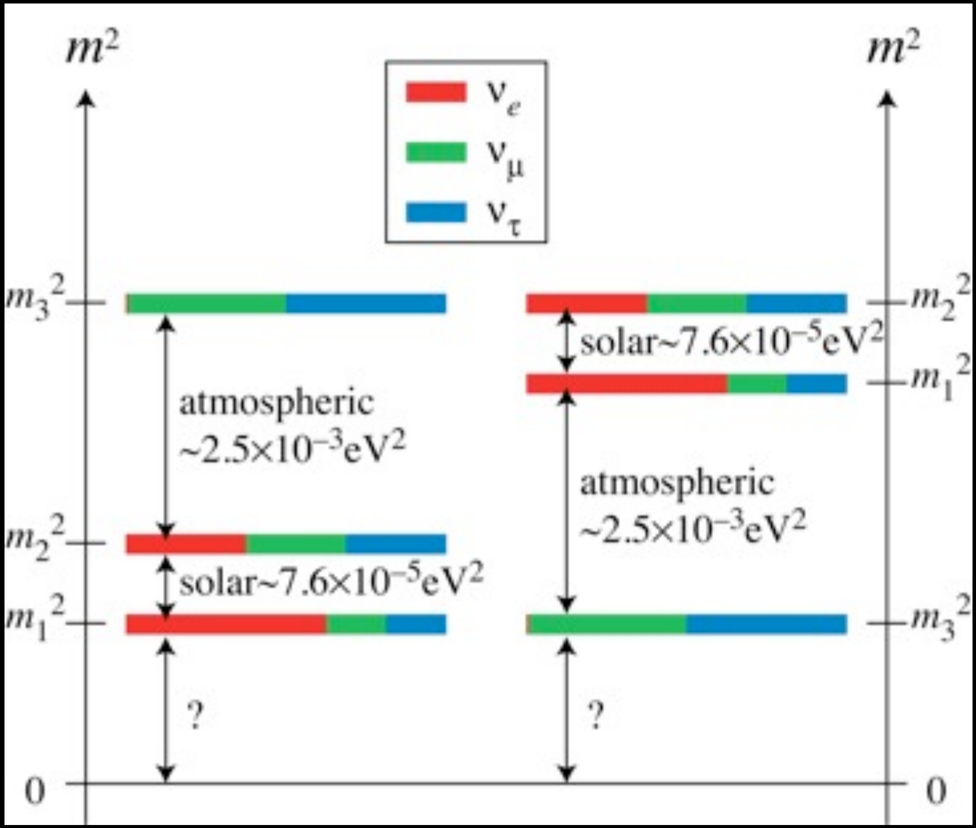
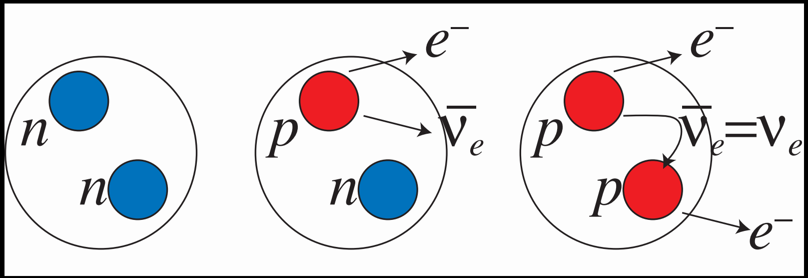
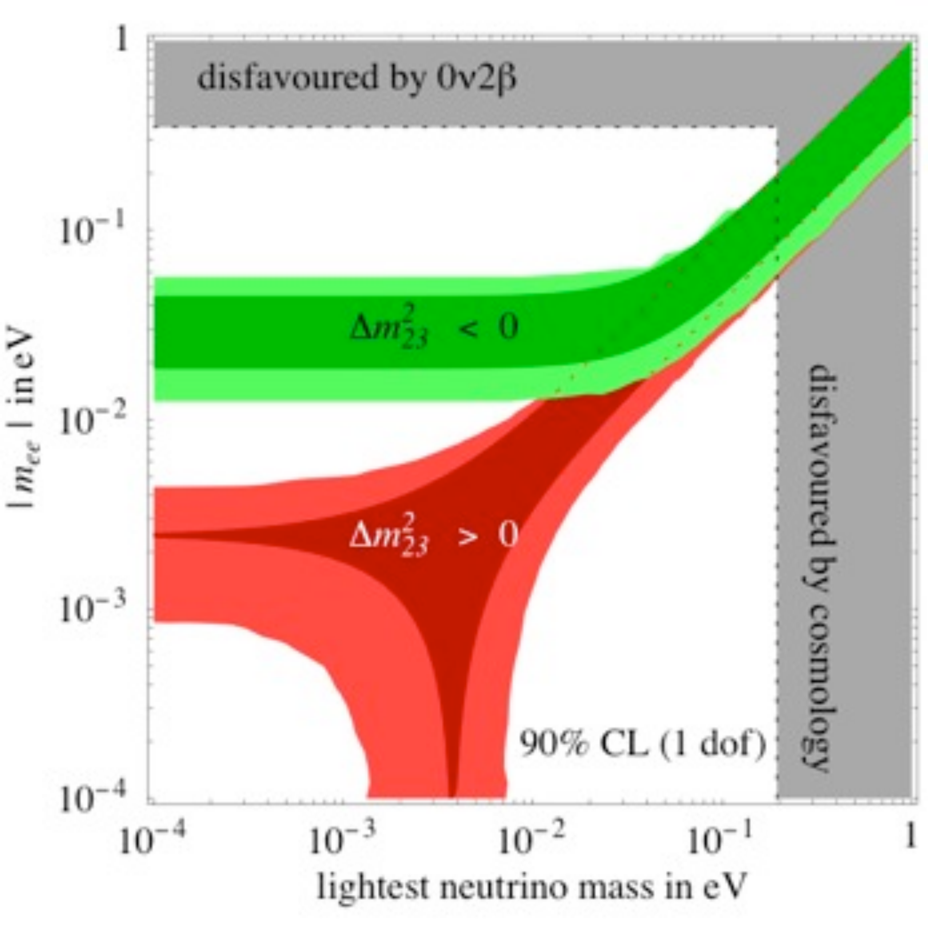


Dirac vs Majorana

- Many neutrinoless double beta decay experiments aiming at below 0.1eV





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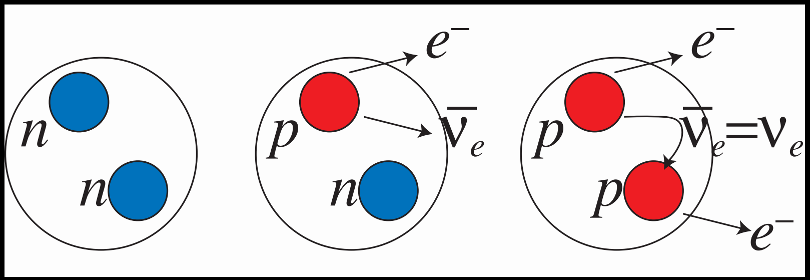

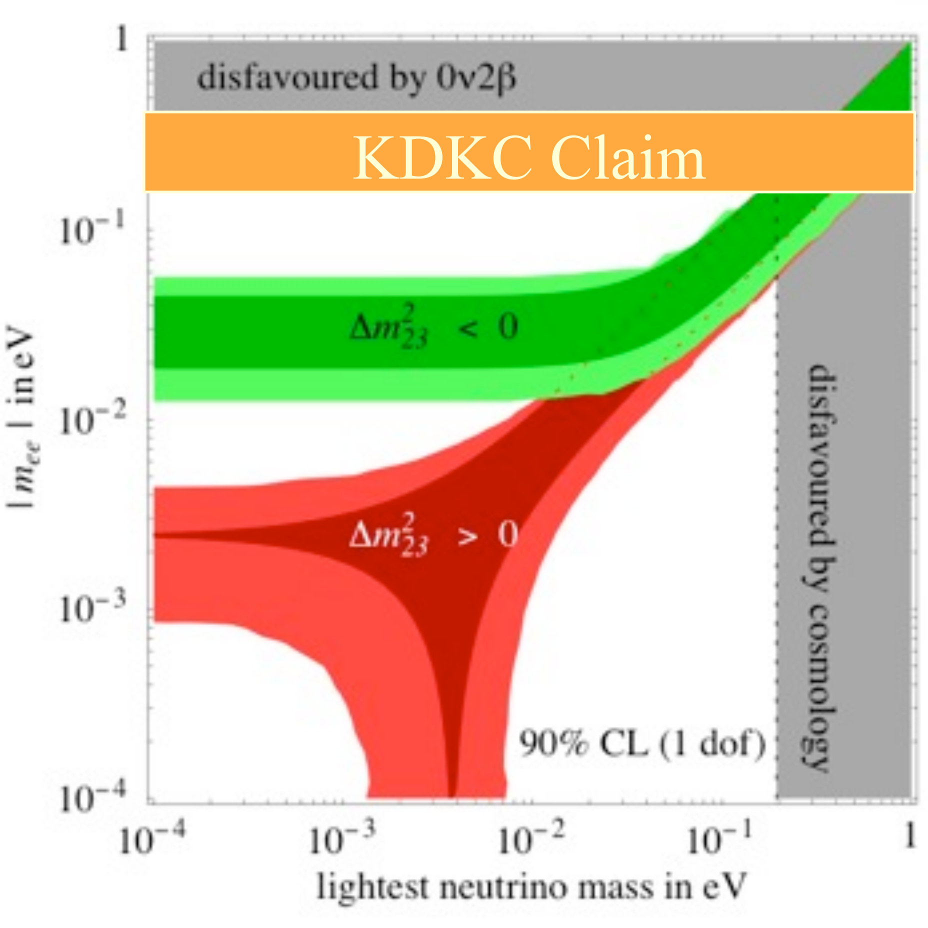

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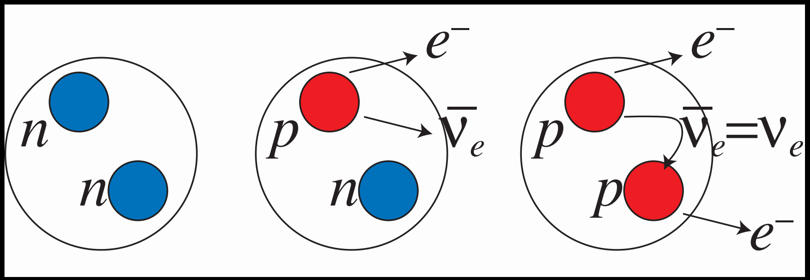

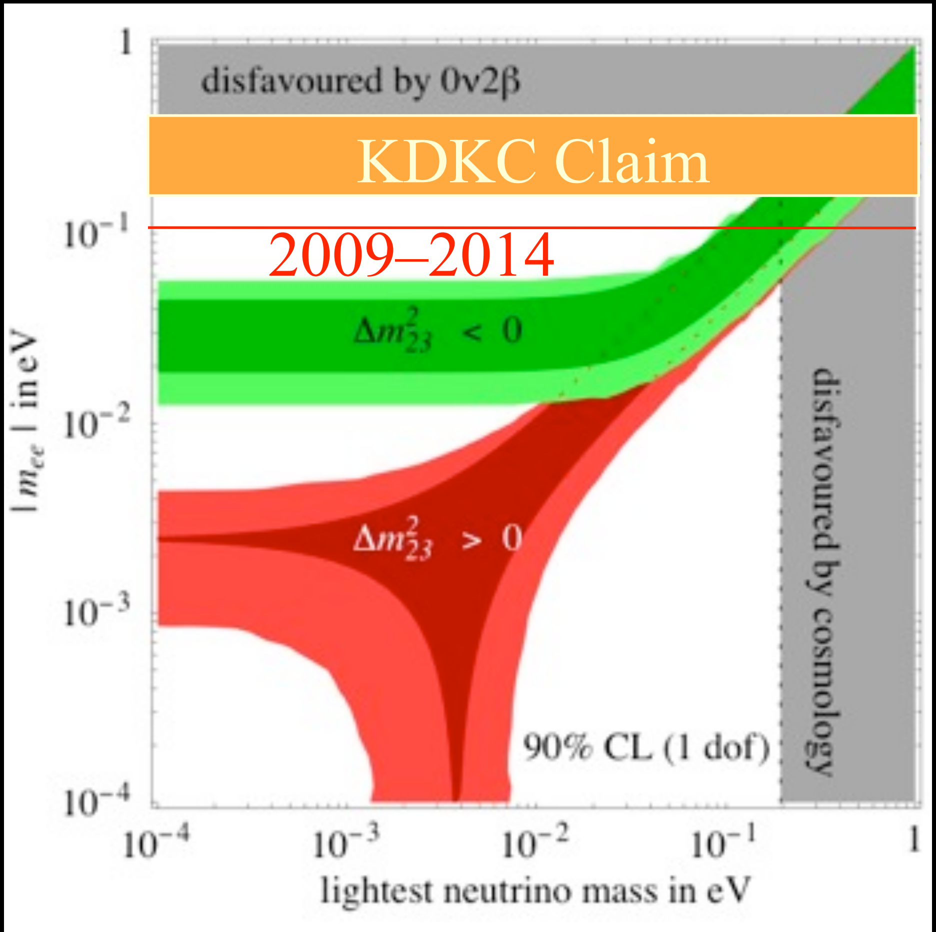

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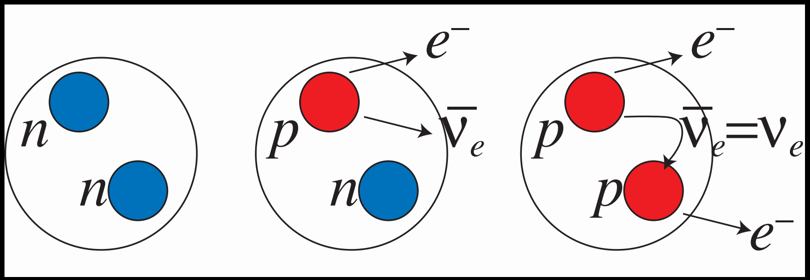

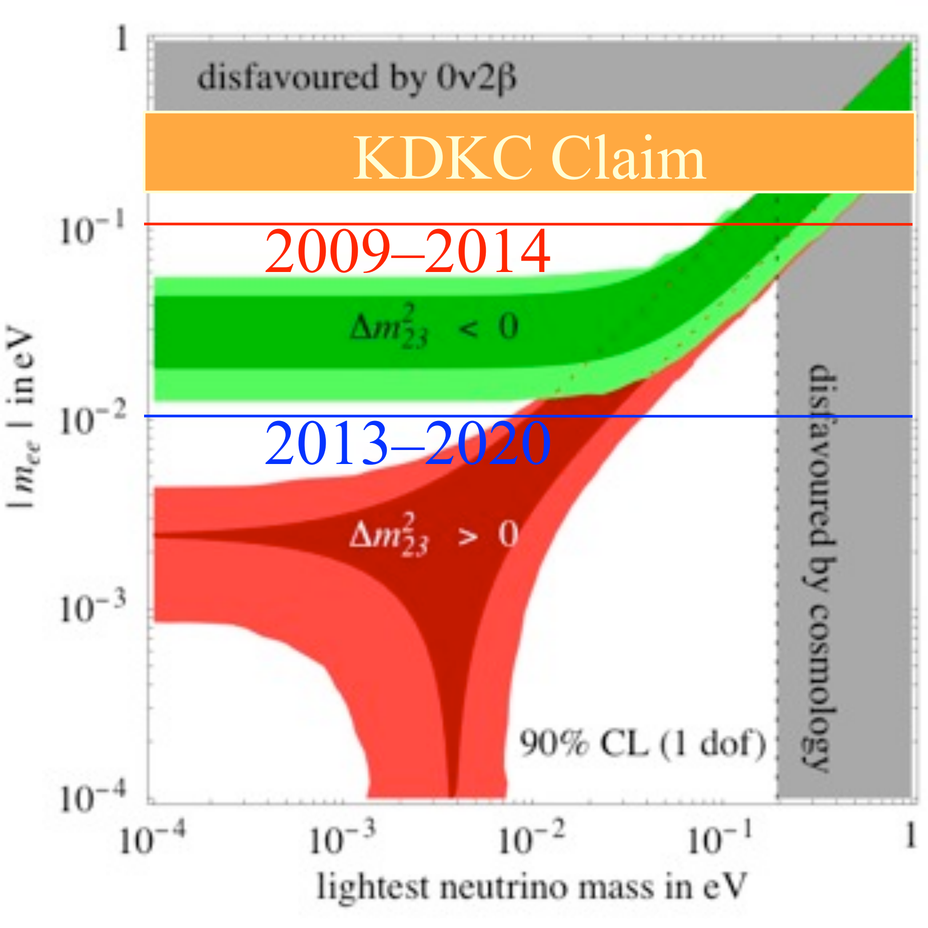

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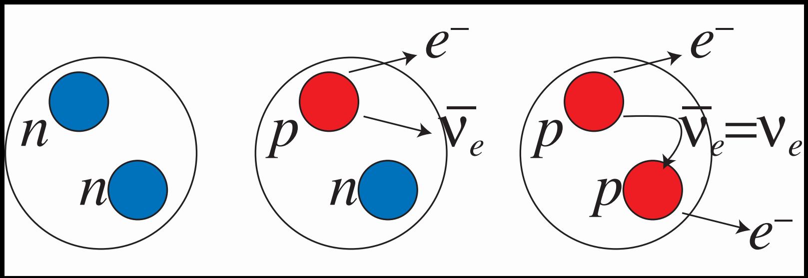
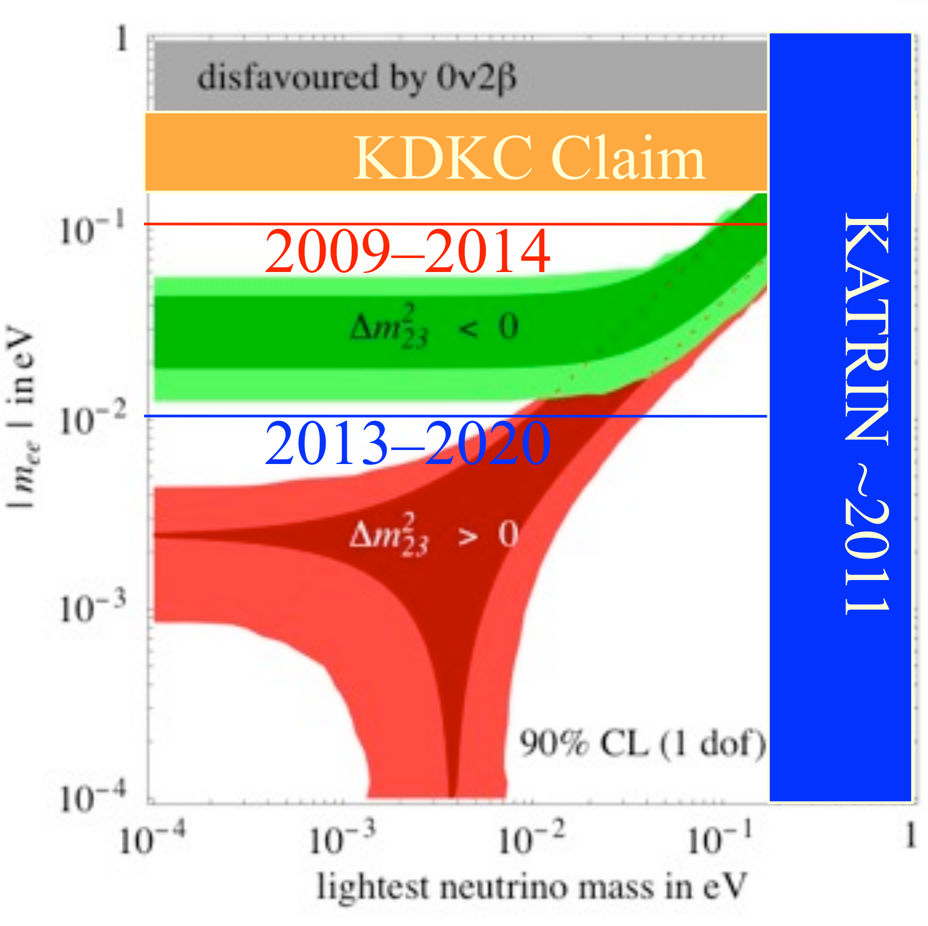
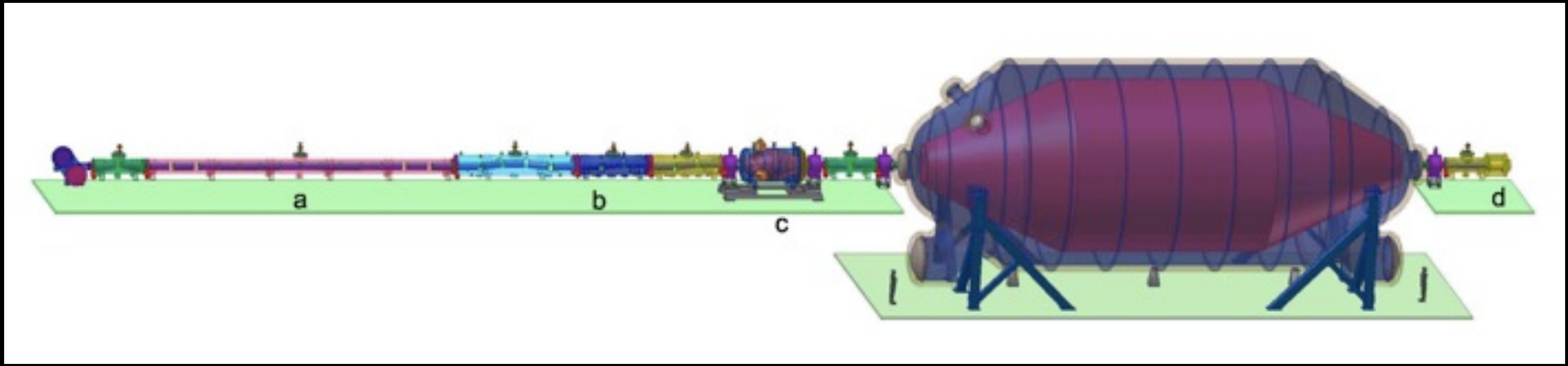




KArlsruhe TRItium Neutrino experiment (KATRIN)



end point of tritium β decay
aim: m_ν<0.2eV (90%CL)

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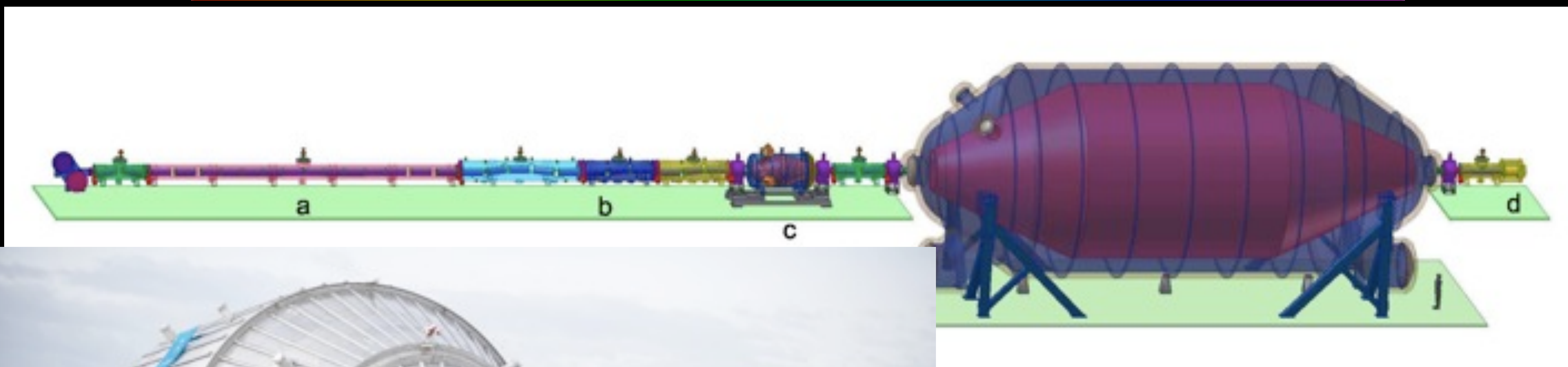

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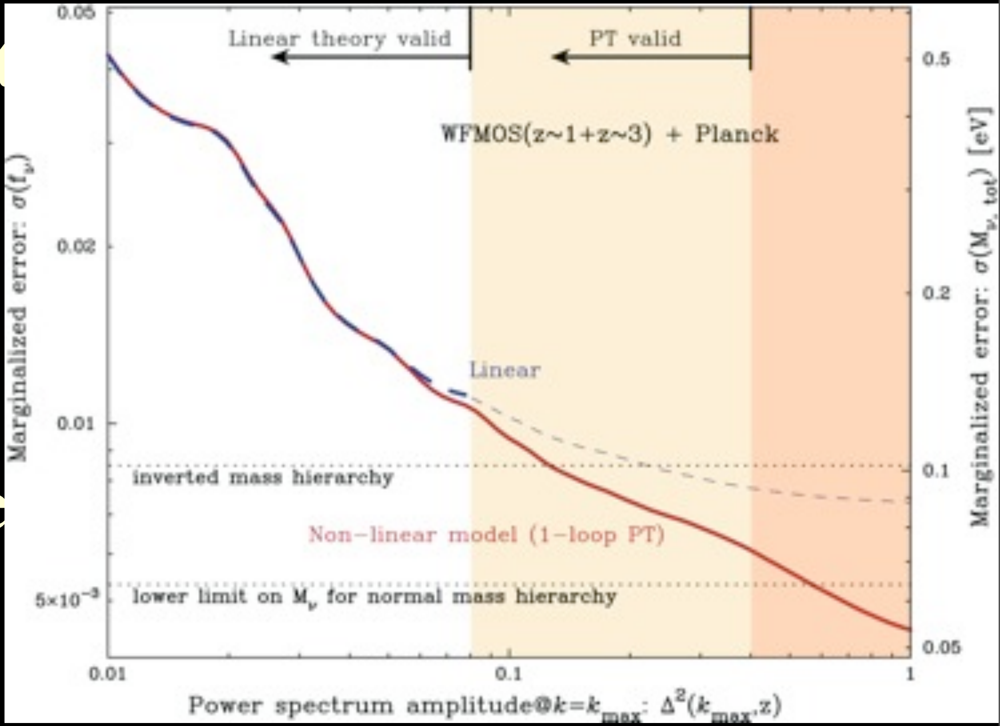
Absolute Neutrino Mass from Large Scale Structure

- Improved theory (one-loop) gives more robust understanding and better sensitivity
- and weak lensing (free from bias)
- Improved data in future dark-energy projects exclude inverted hierarchy

Saito, Takada, Taruya, 2008



Wong, Pastor, next Wednesday

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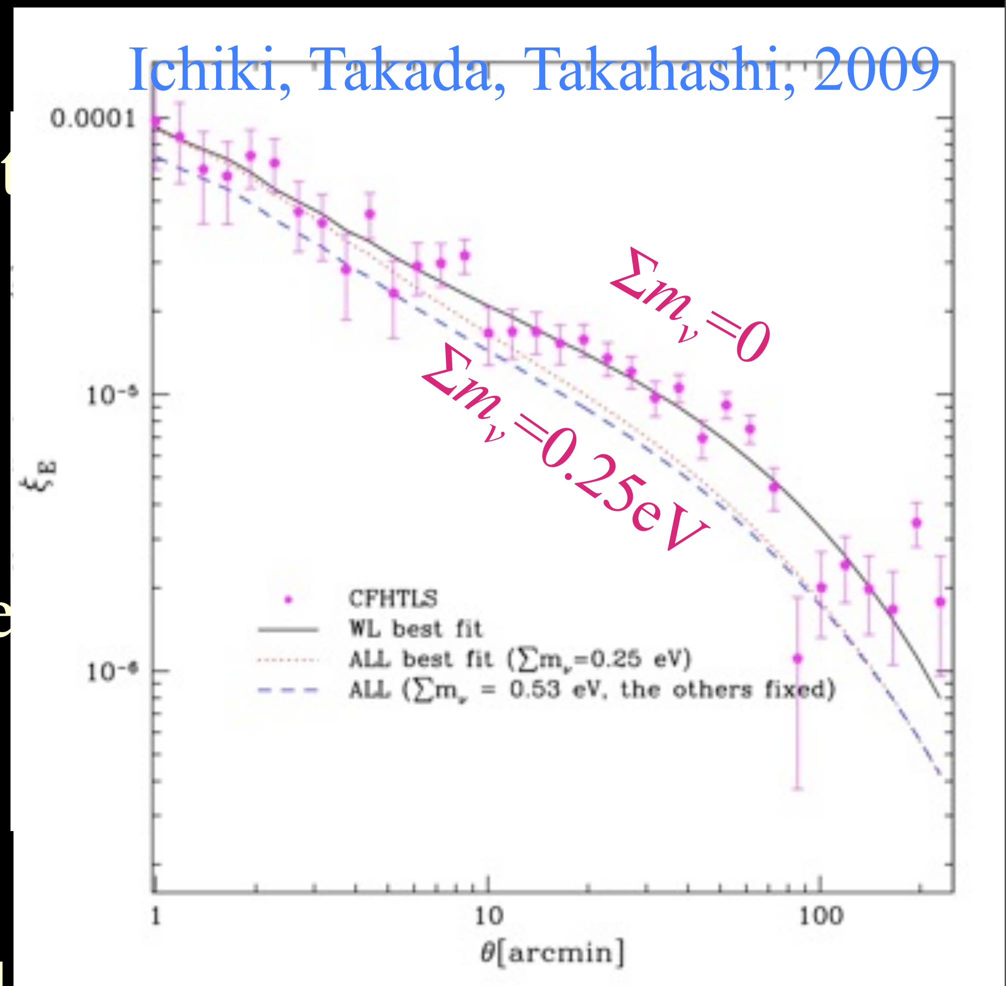
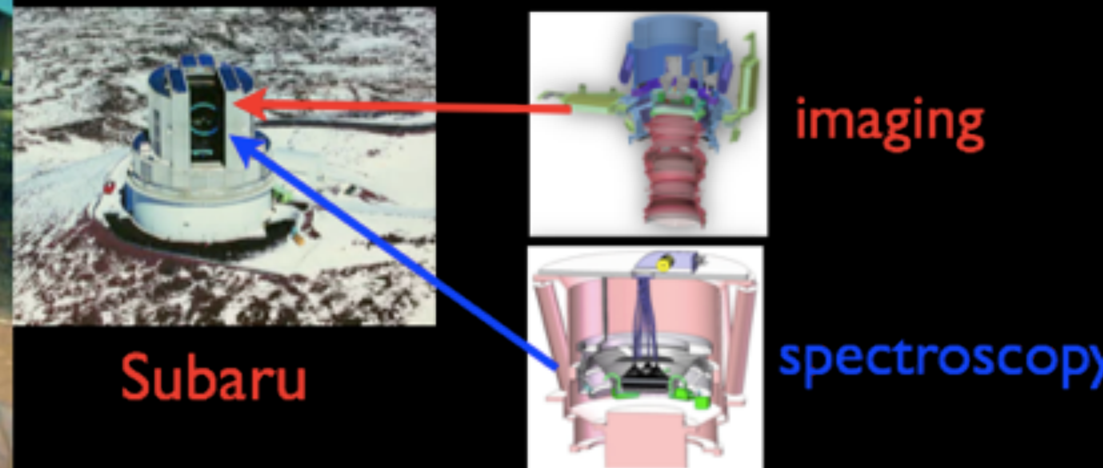


Wong, Pastor, next Wednesday

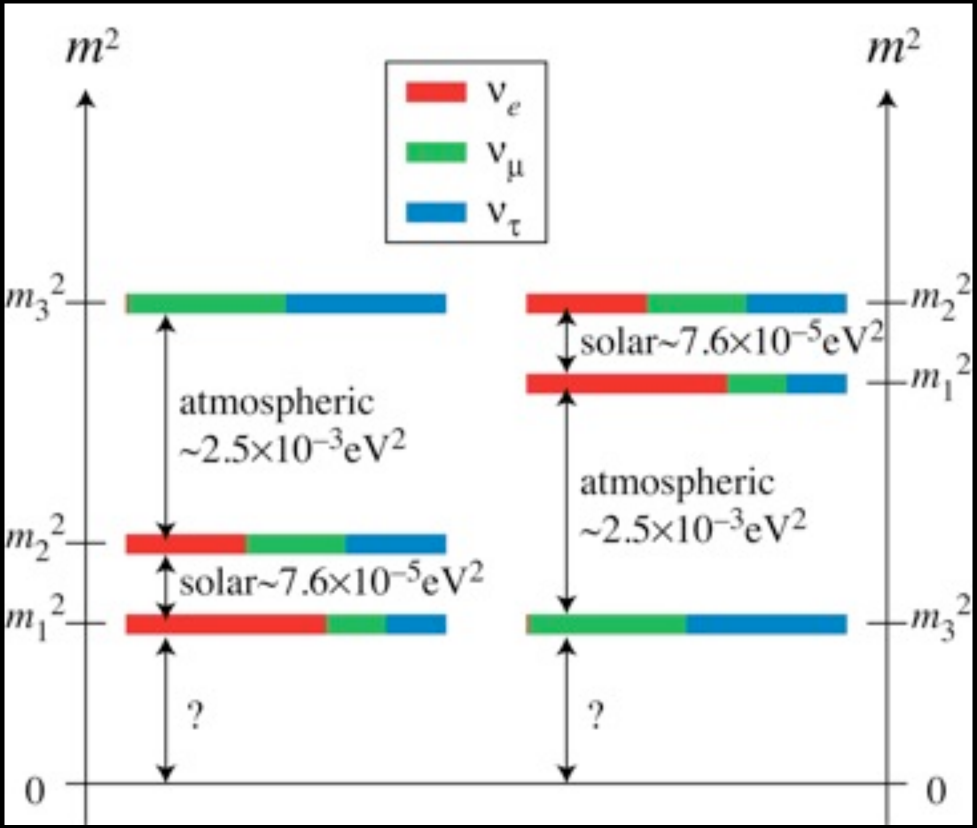
Weak lensing survey followed up by spectroscopy



- Imaging (HSC): 0.9billion pixels, 3t camera
- Spectroscopy (PFS): ~2400 fibers
- Also an excellent probe to dark energy

Raised More Questions

- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- Is θ_{23} maximal?



Now that LMA is established…

- Dream case for neutrino oscillation physics!
- $\Delta m^2_{\text{solar}}$ within reach of long-baseline expts
- Even CP violation may be probed by
  - neutrino superbeam
  - muon-storage ring neutrino factory
  - beta beam

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

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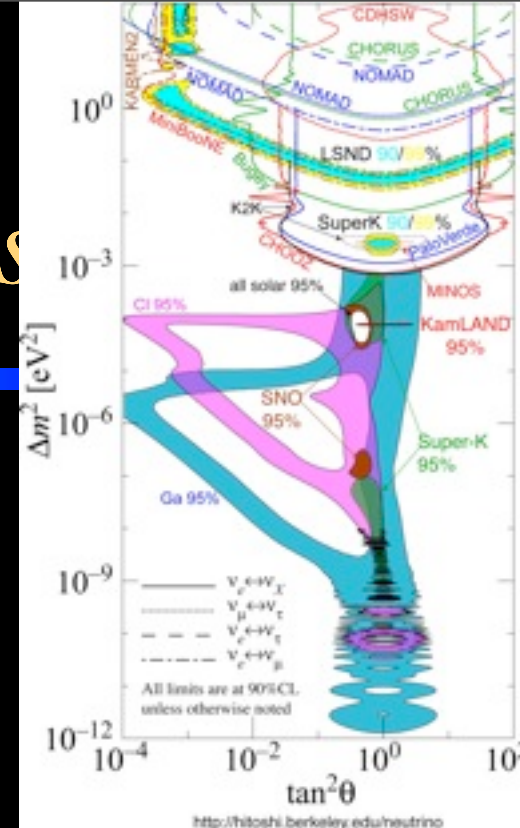

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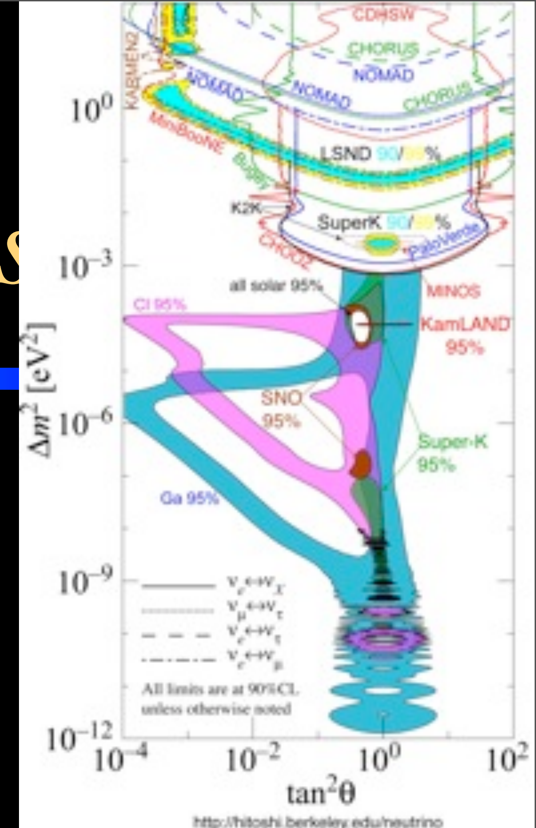

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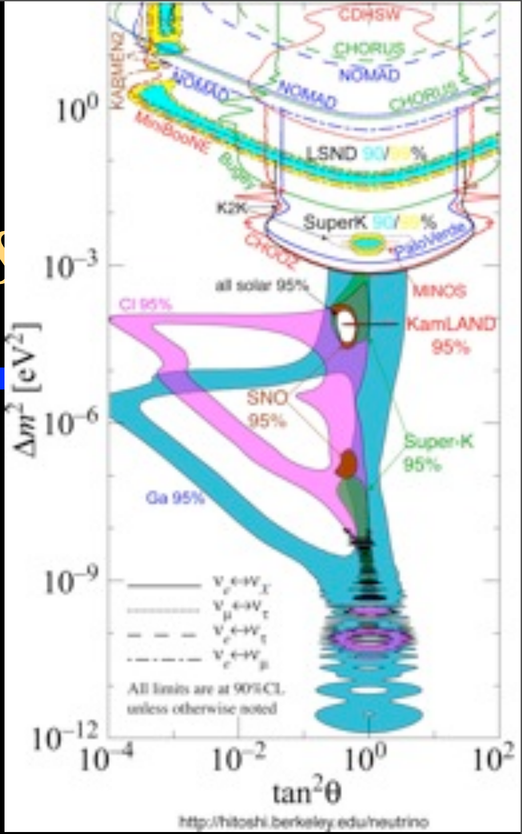

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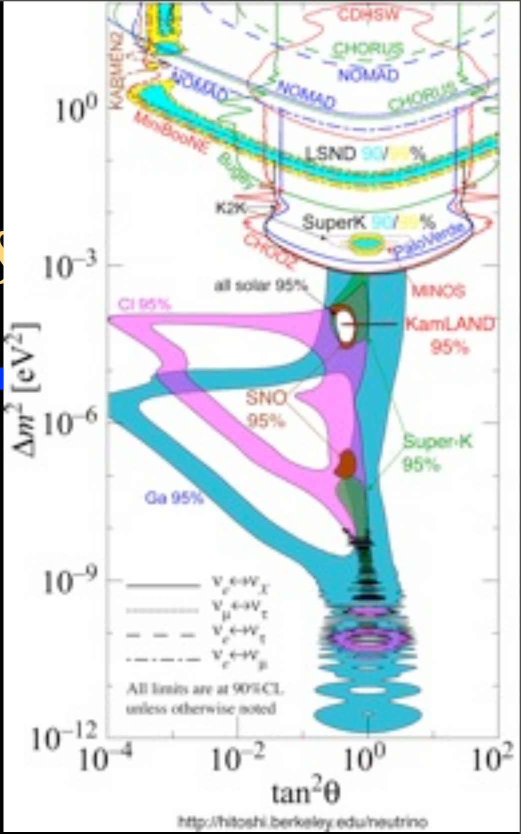

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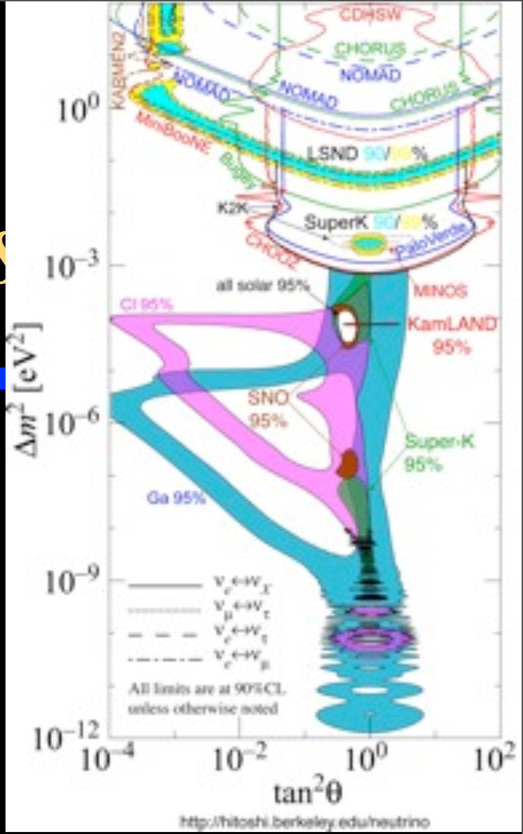

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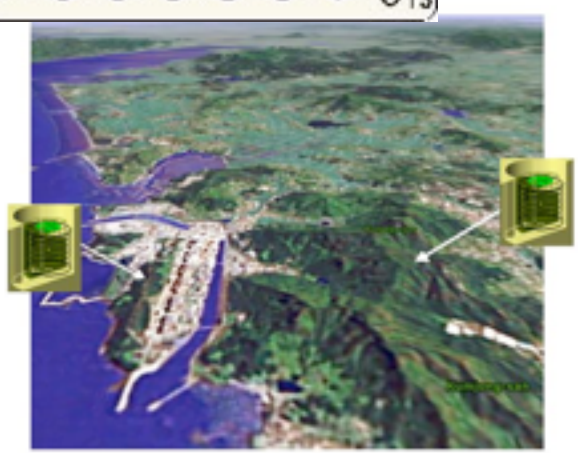
Reactor neutrino experiments looking for θ_{13}

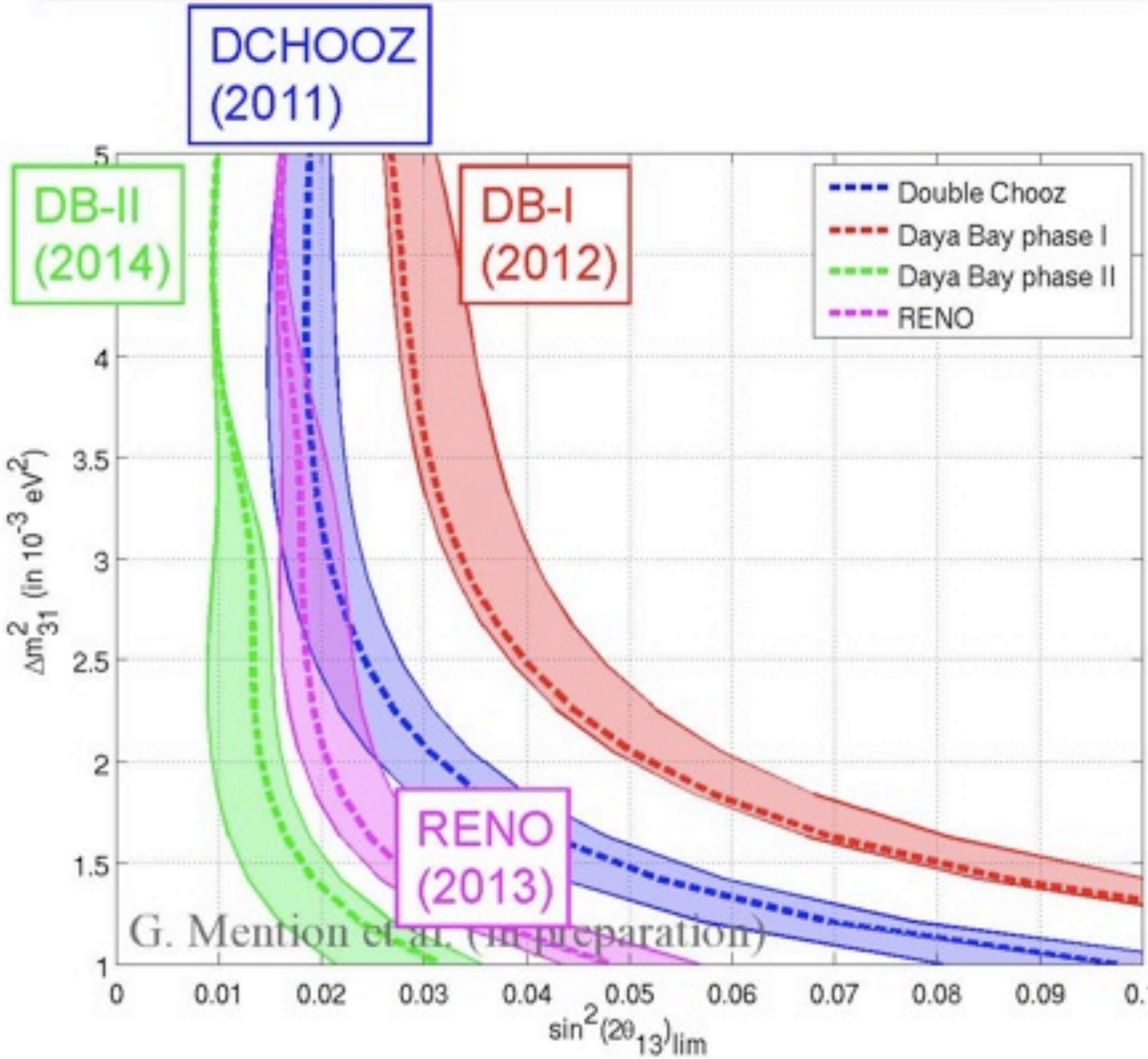
Sensitivity & Achievable year

France

Hong Kong

Korea





F.Suekane @AAP09

Near future LBL θ_{13} experiments

Precision θ_{23}
Search for θ_{13}

Need much higher sensitivity experiments

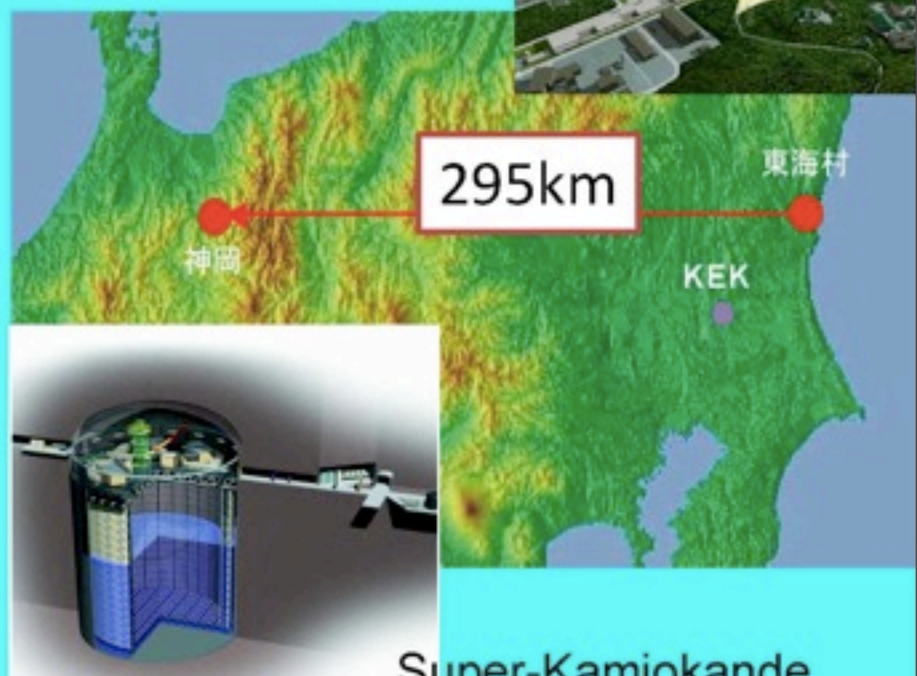
15 kton totally active detector

NOνA
(~2013 -)

NuMI beam intensity upgrade to 700 kW

T2K
(2009 -)

J-PARC
(750kW design)



Super-Kamiokande
(22.5 kton fid. vol)

Kajita@TAUP09

Near future LBL θ_{13} experiments

Precision θ_{23}
Search for θ_{13}

Need much higher sensitivity experiments

15 kton totally active detector

NOvA (~2013 -)

NuMI beam intensity upgrade to 700 kW

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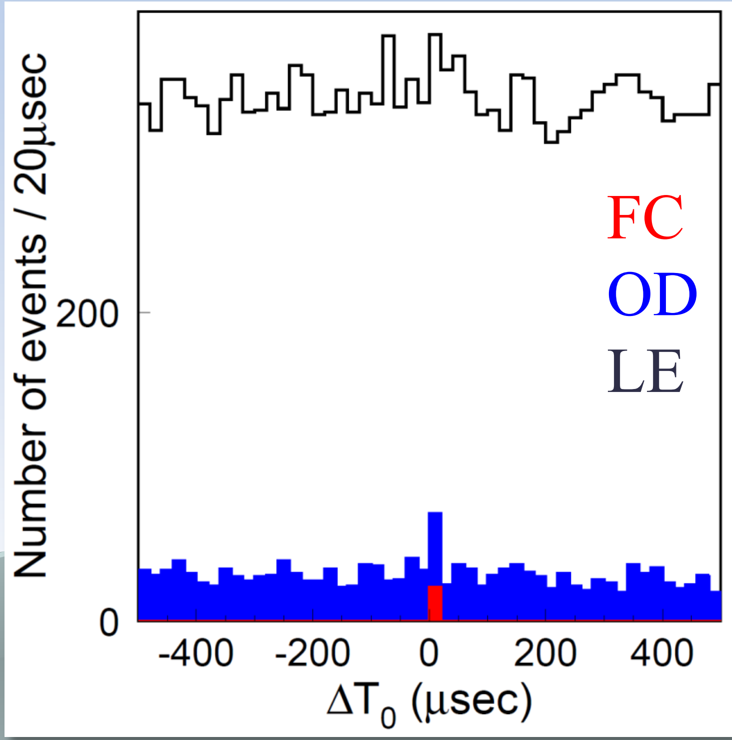
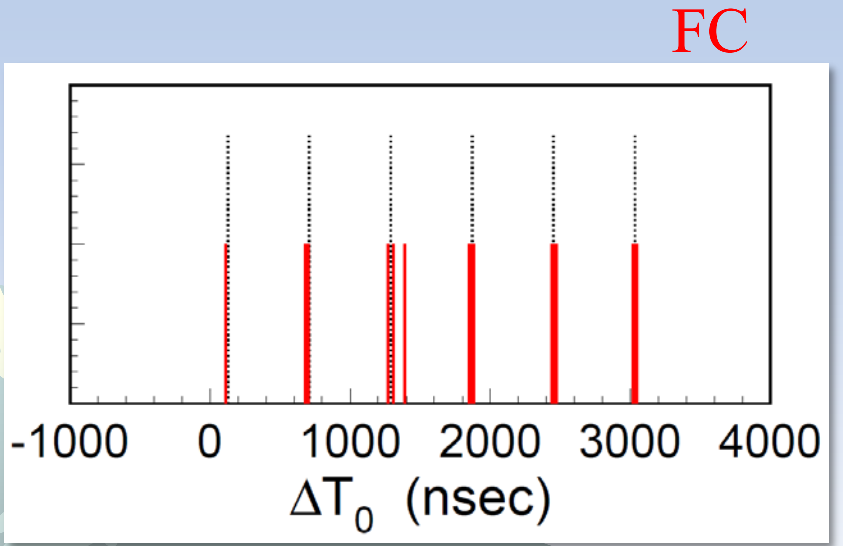
Observed SK events





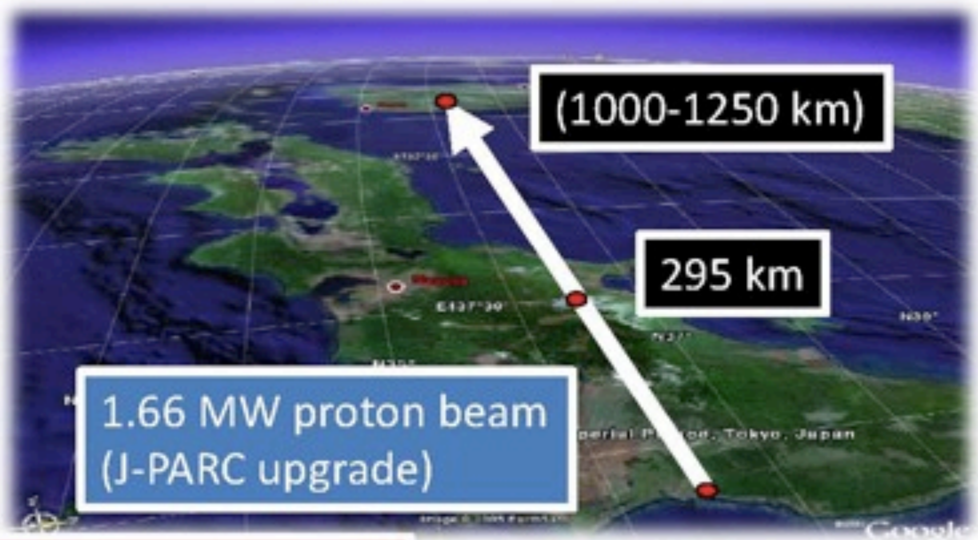
LE: Low energy triggered events
OD: Outer detector events
FC: Fully contained events

- Event time distribution clearly show beam structure
- Observed # of Fully contained events: 22 (by Mid. May)
- Expected non-beam BG: $<10^{-2}$evts

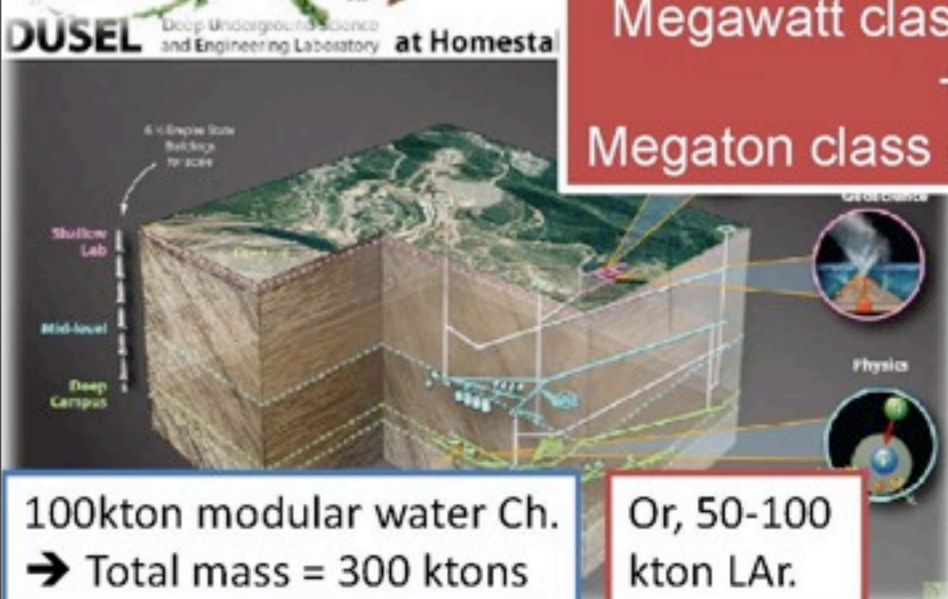
rchy

Kajita@TAUP09

Future LBL possibilities (assuming $\sin^2 2\theta_{13}$ is larger than 0.01)

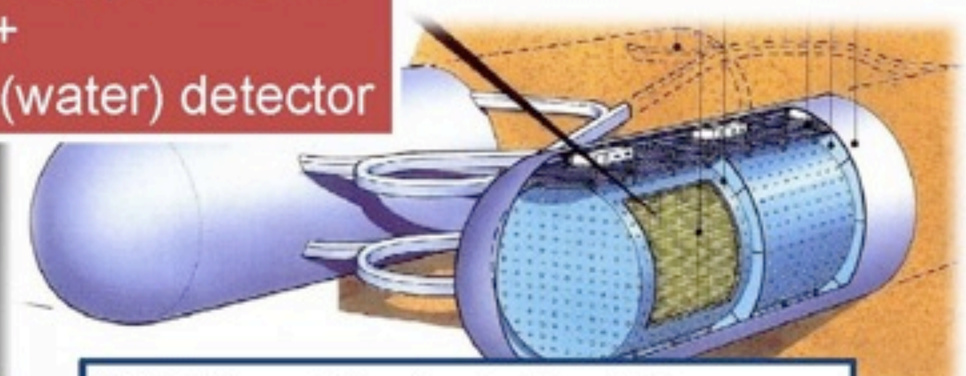


Megawatt class super-beam
+
Megaton class (water) detector



100kton modular water Ch.
→ Total mass = 300 ktons

Or, 50-100 kton LAr.



0.54Mton detector in Kamioka, or
0.27 Mton water Cherenkov detector
in Kamioka and Korea.

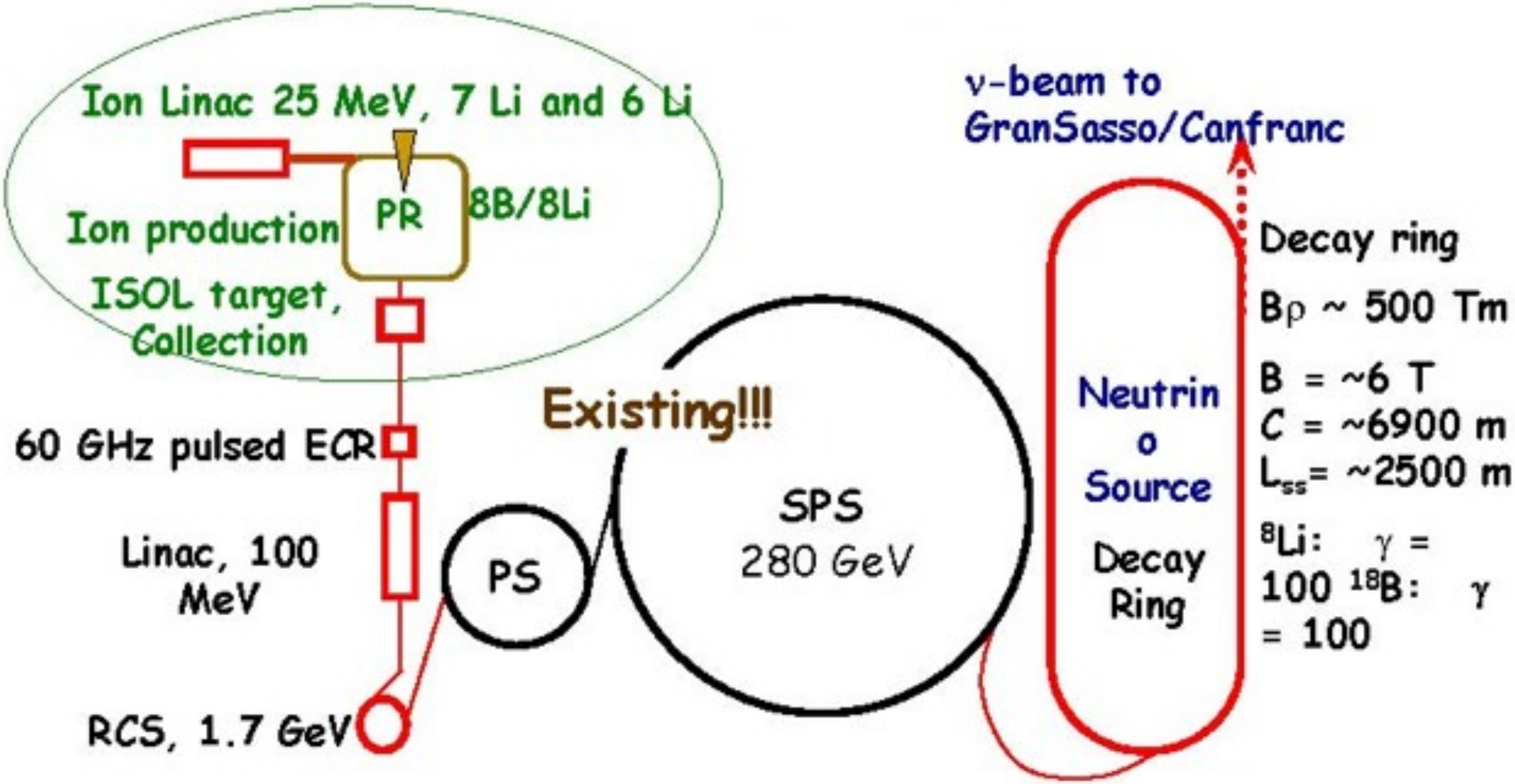
Fork

- Conventional proton-based neutrino beam has contamination of ν_e, making $\nu_\mu \to \nu_e$ search limited
- If $\sin^2\theta_{13} > 0.01$ OK
- If $\sin^2\theta_{13} < 0.01$, need a "pure" ν_e beam $\to \nu_\mu$
- Pure ν_e beam from ions: beta beam
- Pure ν_e beam from muons: neutrino factory

Huber, Rodejohann, Gonzalez-Garcia, Yesterday

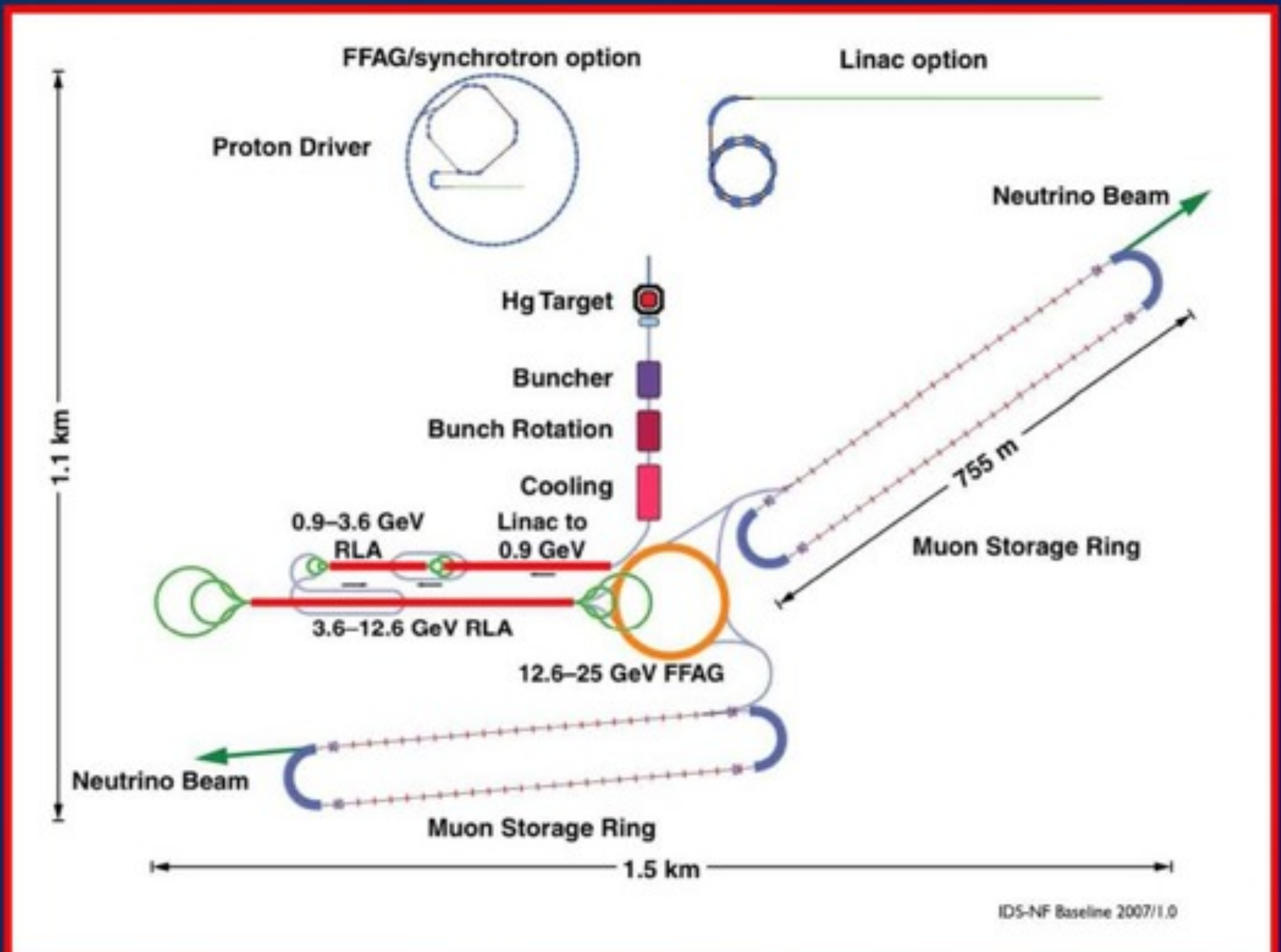
Elena Wildner, Neutrino 2010

Beta Beam scenario $^{8}Li/^{8}B$



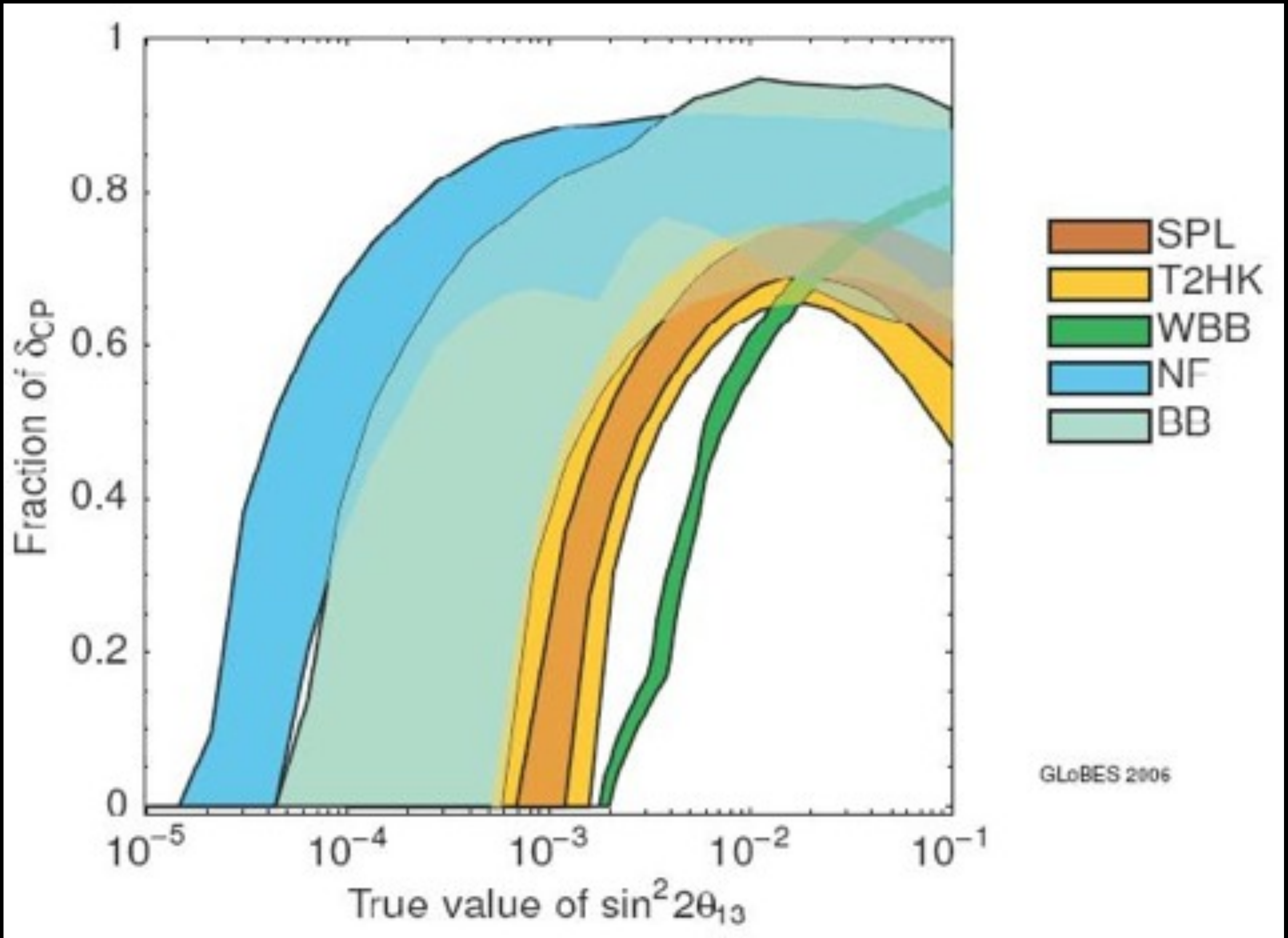
Ken Long, Neutrino 2010

IDS-NF baseline: accelerator:



IDS-NF-002: https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=view&target=IDS-NF-002-v1.1.pdf

Which one will we need?



Big Questions

Raised More Questions

- Dirac or Majorana?
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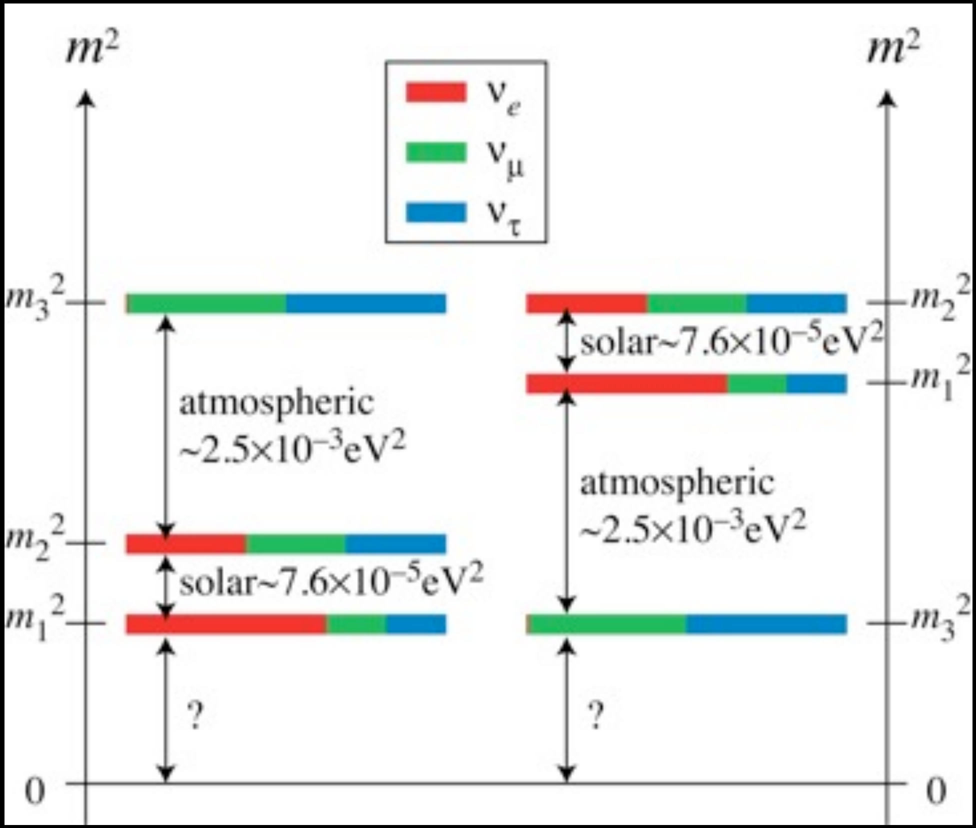

The Big Questions

- What is the origin of neutrino mass and mixings?
- Did neutrinos play a role in our existence?
- Did neutrinos play a role in forming galaxies?
- Did neutrinos play a role in birth of the universe?
- Are neutrinos telling us something about unification of matter and/or forces?
- Will neutrinos give us more surprises?

Big questions ≡ tough questions to answer

Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

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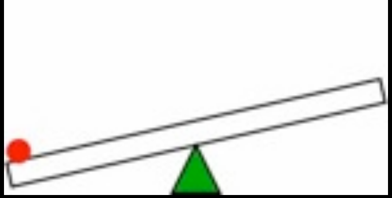

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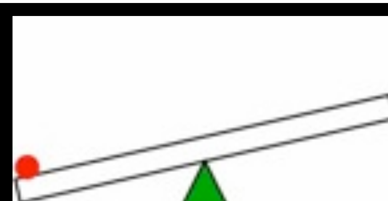

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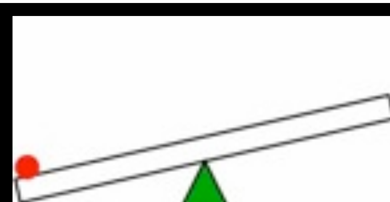

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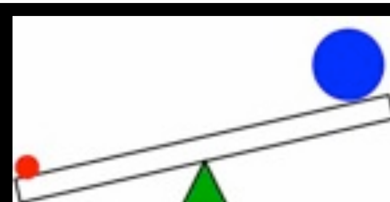

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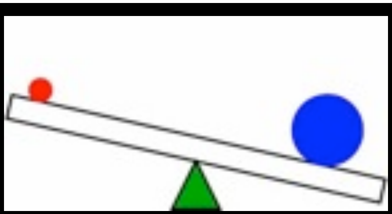

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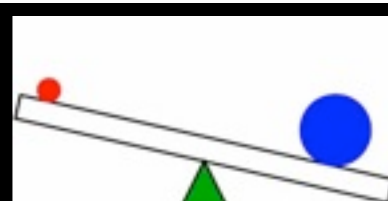
$$m_\nu = \frac{m_D^2}{M} << m_D$$



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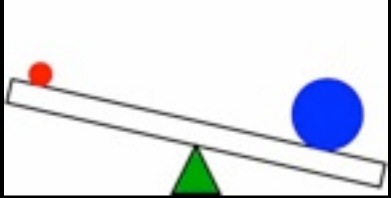


To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

Matter and Anti-Matter Early Universe

Matter	Anti-matter
1,000,000,001	1,000,000,000

Matter and Anti-Matter
Current Universe

us

1

Matter

Anti-matter

The Great Annihilation

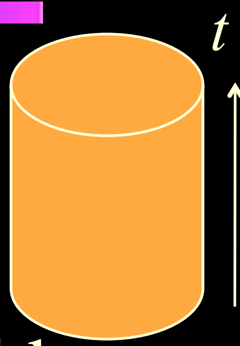
Baryogenesis

- What created this tiny excess matter?
- *Necessary* conditions for baryogenesis (Sakharov):
  - Baryon number non-conservation
  - CP violation

    (subtle difference between matter and anti-matter)
  - Non-equilibrium

    $\Rightarrow \Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- It looks like neutrinos have no role in this…

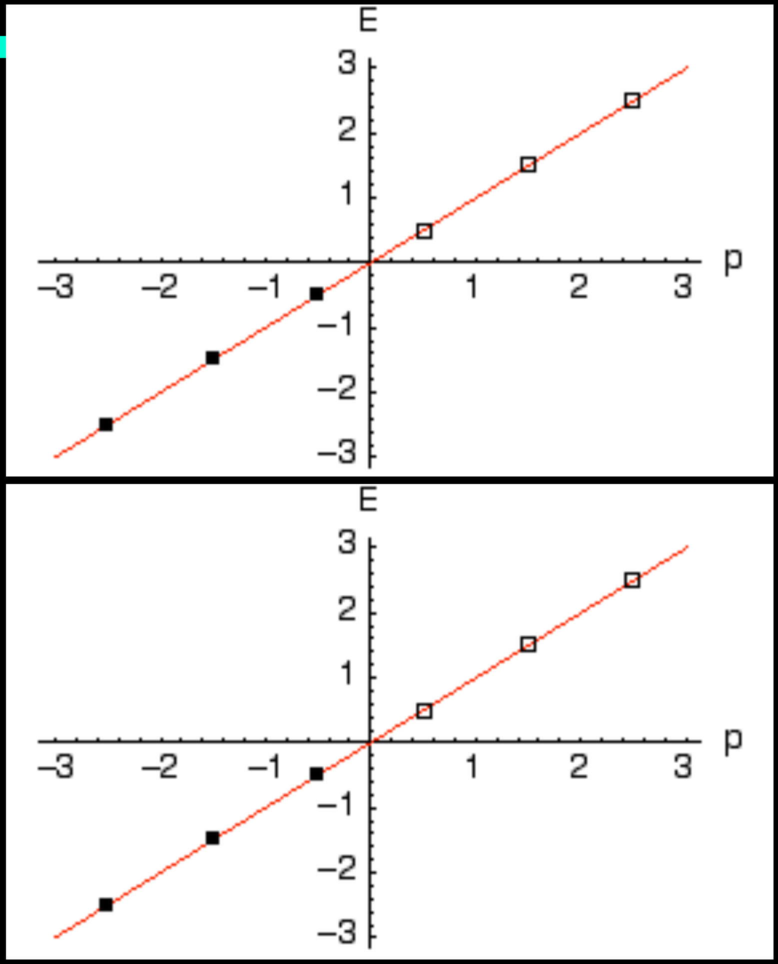
Index theorem



- Atiyah-Patodi-Singer index theorem
- SU(2) bundle on $S^3 \times R$; R="time"
- Assume pure gauge $t \rightarrow \pm\infty$, parameterized by the winding number $\pi_3(SU(2))=Z$
- Zero mode equation $(\partial_t - \vec{\alpha}\cdot\vec{D})\psi = 0$
- Follow instantaneous eigenstates adiabatically $\vec{\alpha}\cdot\vec{D}\psi_n = E_n\psi_n$
- Change in winding number=level crossing

Toy version: U(1) on $S^1 \times R$

- SM converts *L* (ν) to *B* (quarks).
  - In Early Universe (*T* > 200GeV), *W* is massless and fluctuate in *W plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspon-dingly



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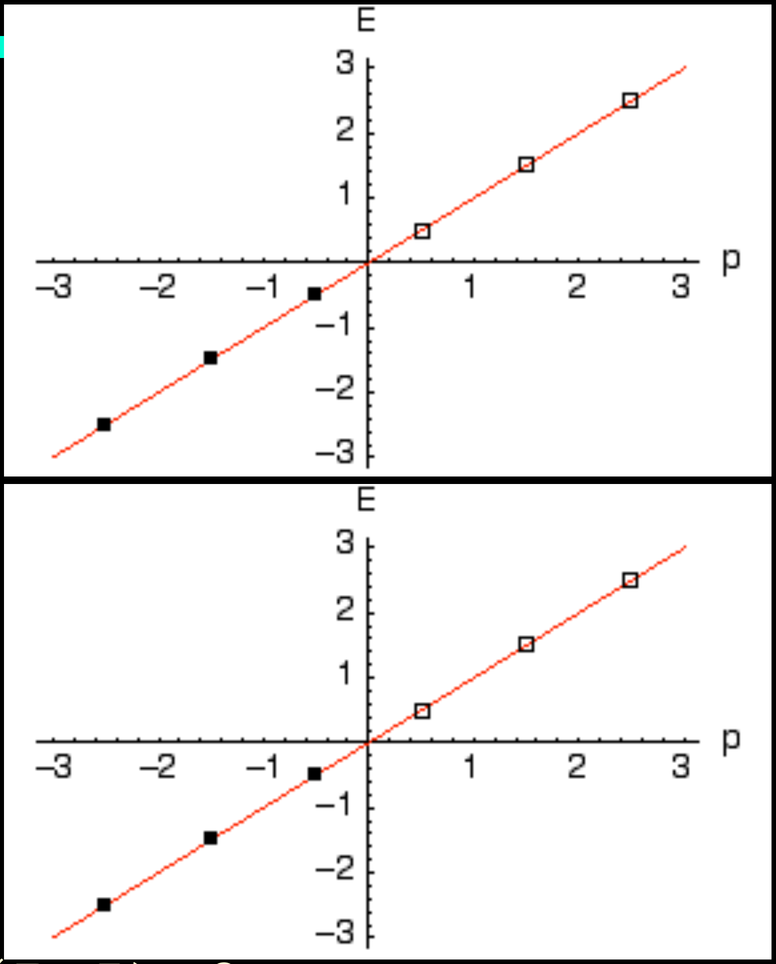
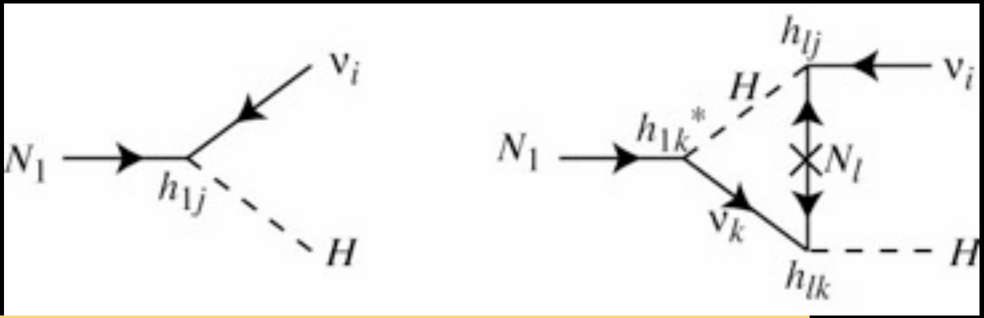


$\Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = 1 \Rightarrow \Delta(B-L) = 0$

Leptogenesis

- You generate *Lepton Asymmetry* first.
- Generate L from the direct CP violation in right-handed neutrino decay



$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

- *This type of CP violation confirmed in ε'*
- L gets converted to B via EW anomaly

⇒ More matter than anti-matter ⇒

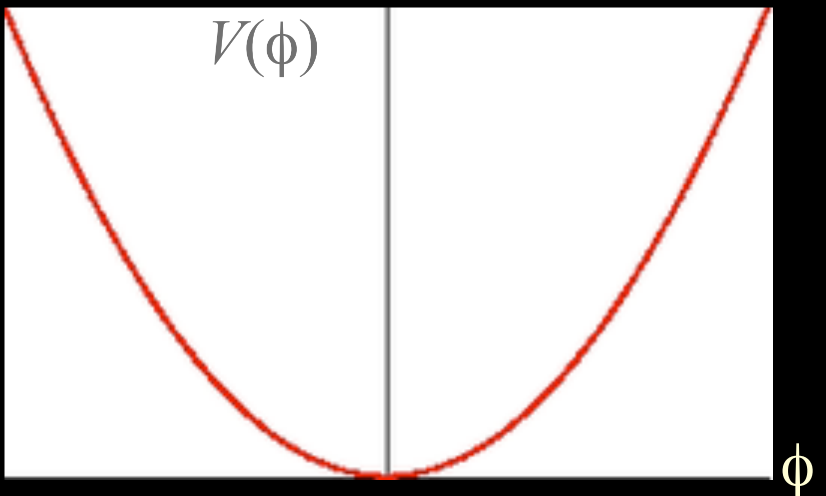
We have survived "The Great Annihilation"

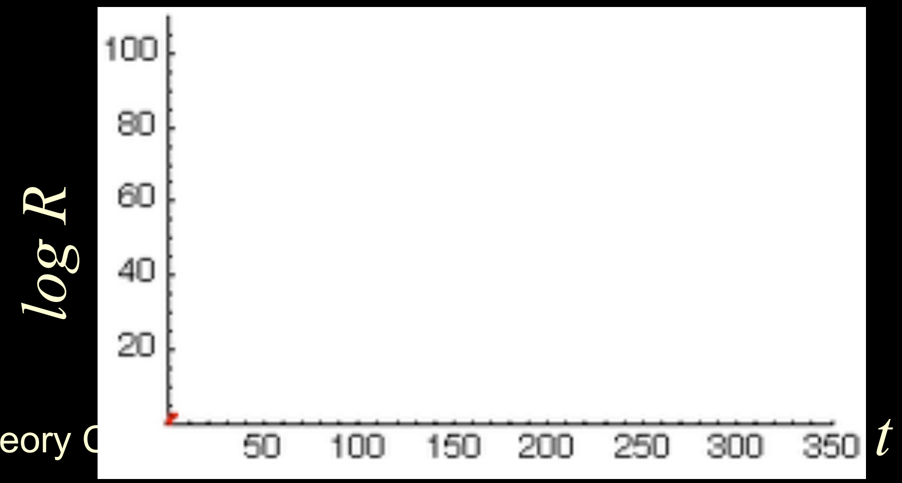
Origin of Universe

- *Who is the inflaton?*
- The *superpartner of right-handed neutrino* fits the bill
- Possibly the only inflaton candidate motivated bottom-up by particle physics
- Reheating produces the lepton asymmetry at the same time

(HM, Suzuki, Yanagida, Yokoyama)

Neutrino is mother of the Universe?





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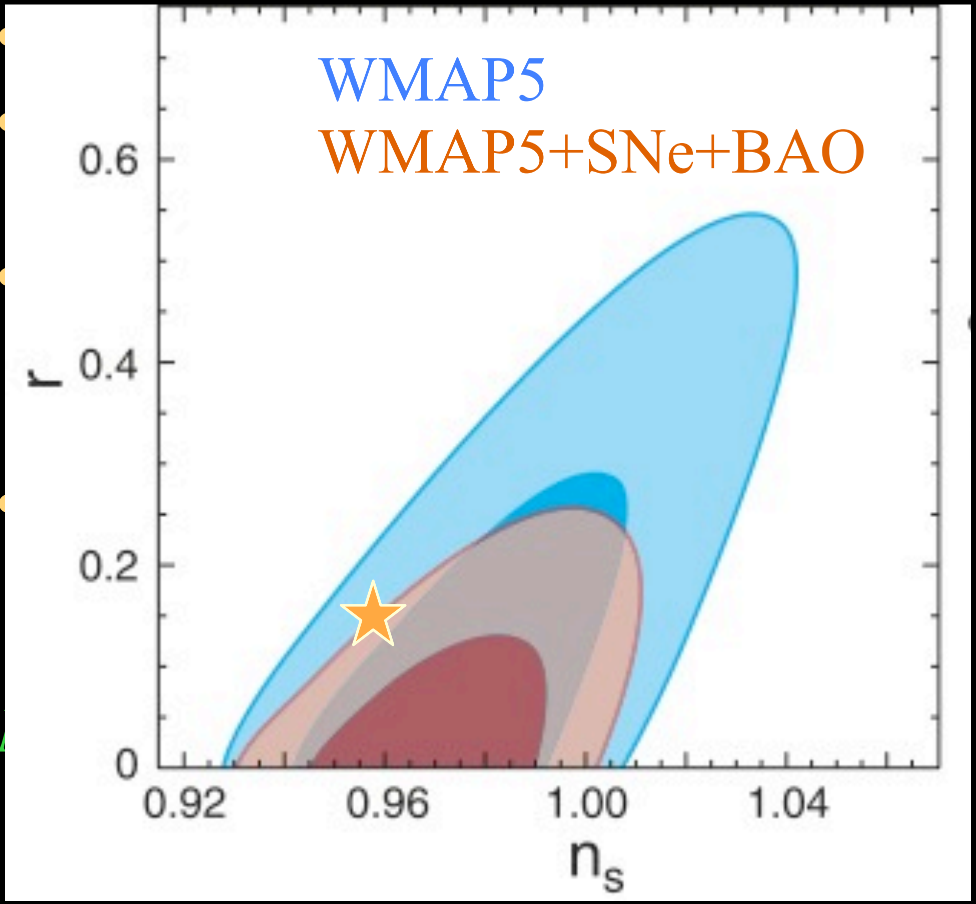
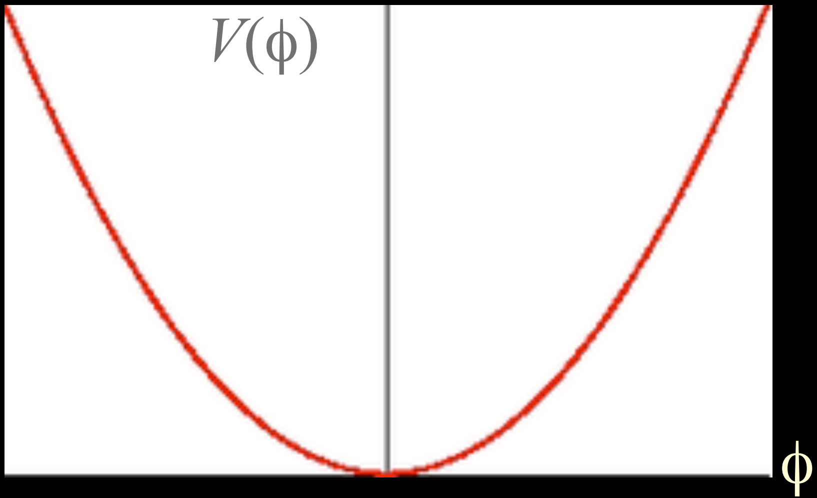
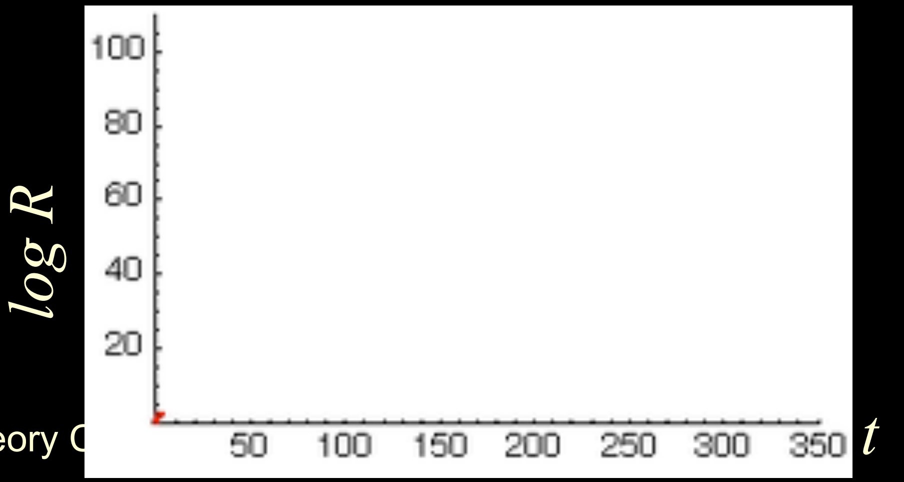
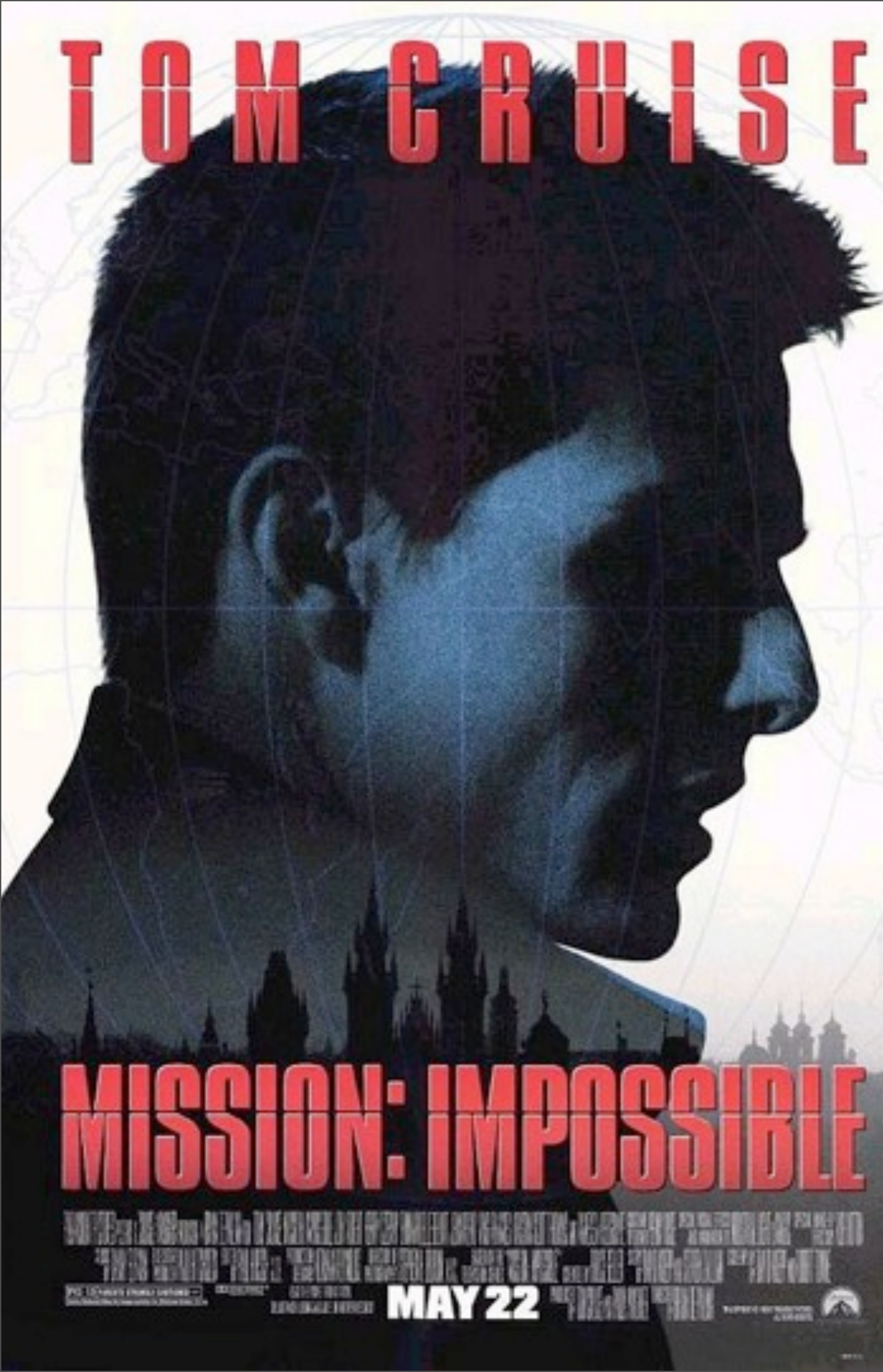
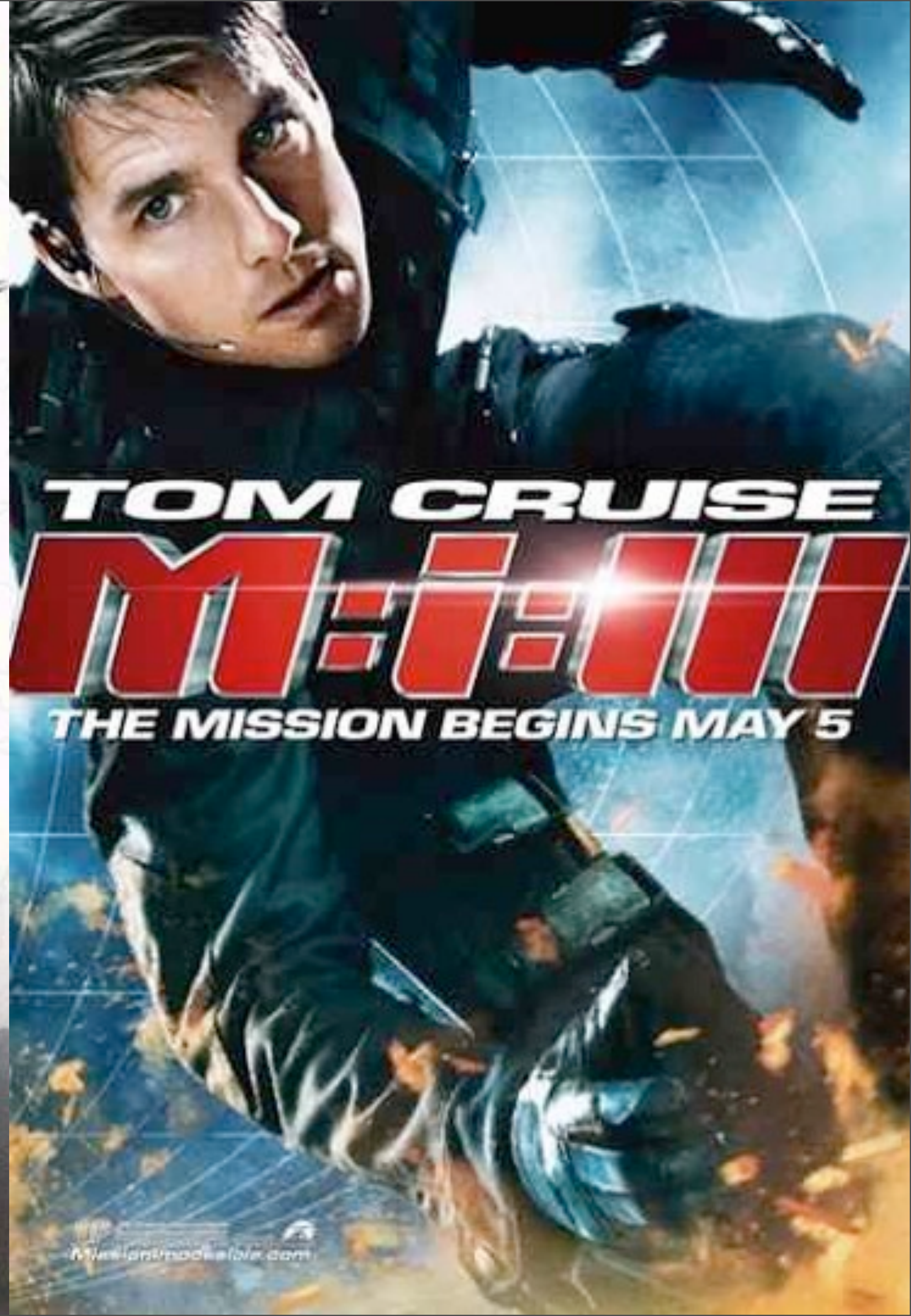






Can we ever test this?


TOM CRUISE
MISSION: IMPOSSIBLE
MAY 22

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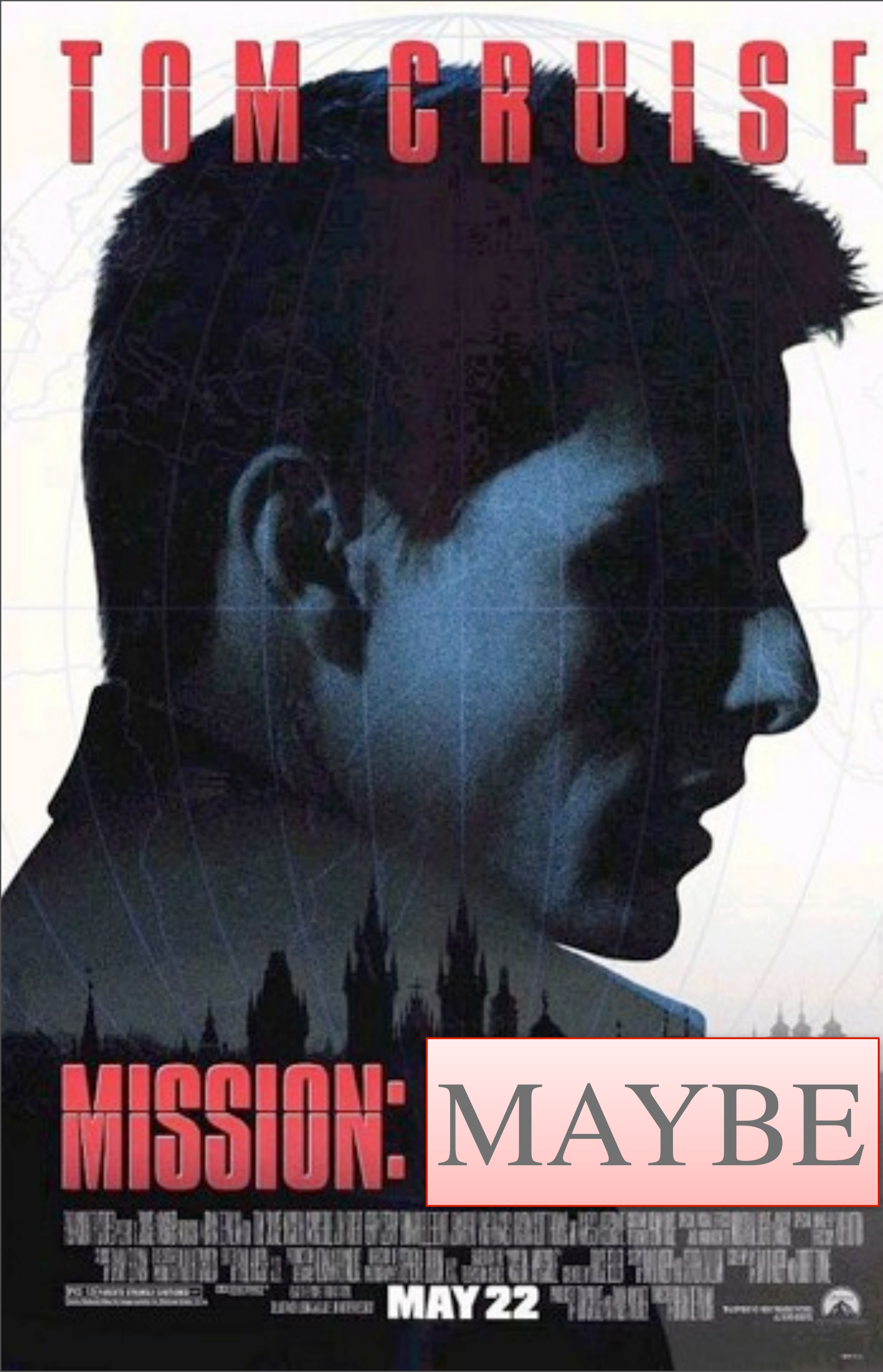
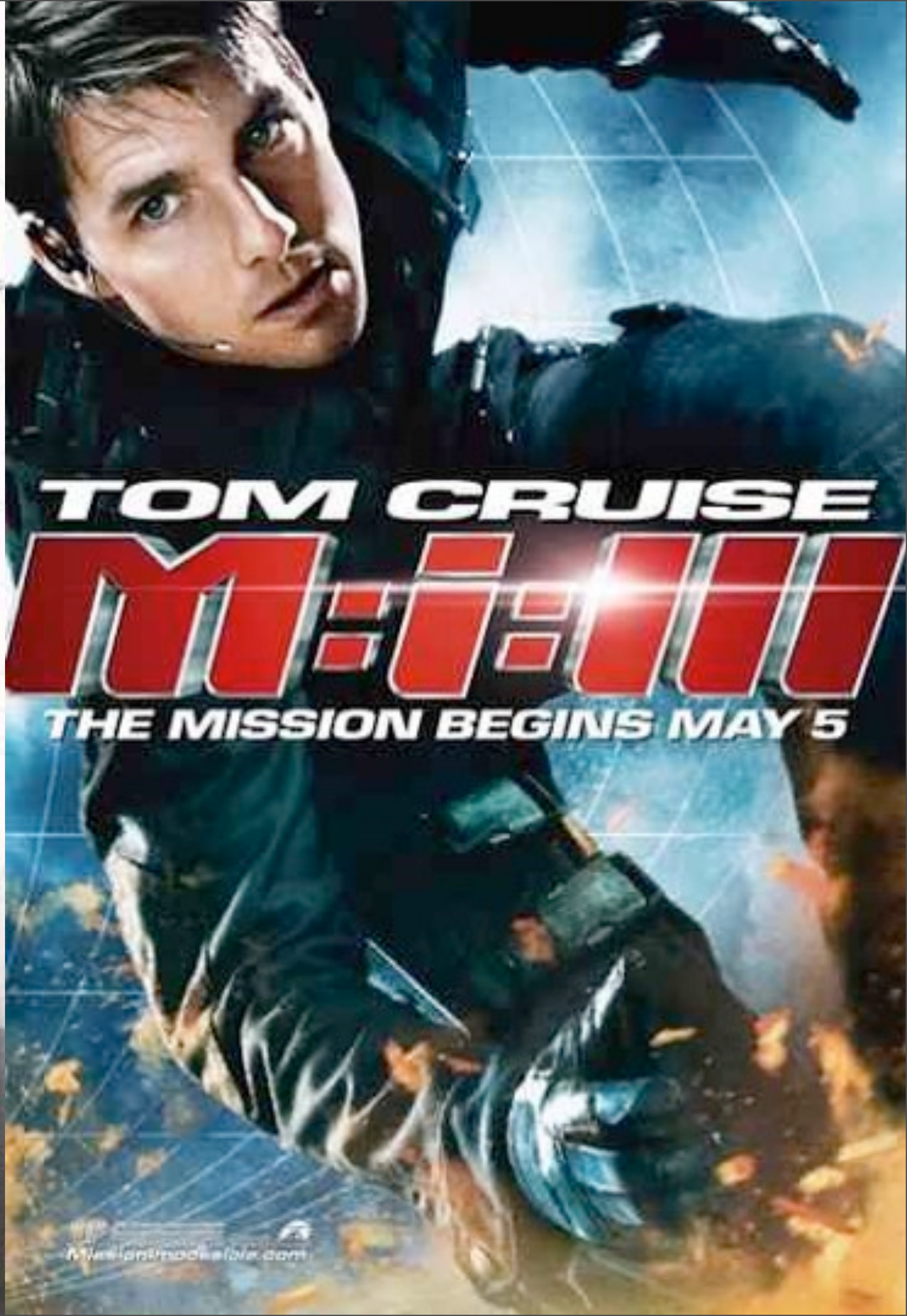

TOM CRUISE
MISSION: MAYBE
MAY 22

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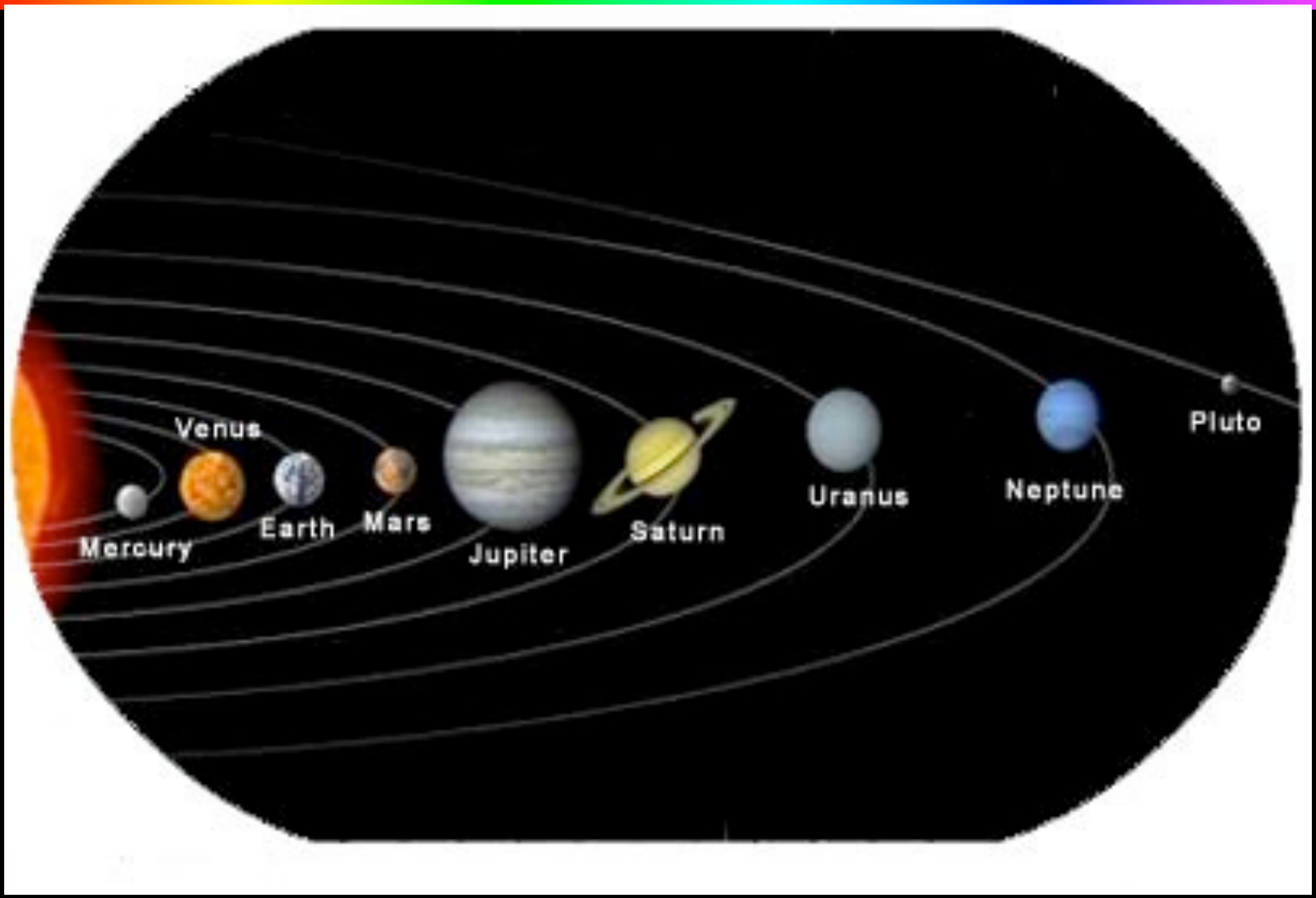
Alignment of the Planets



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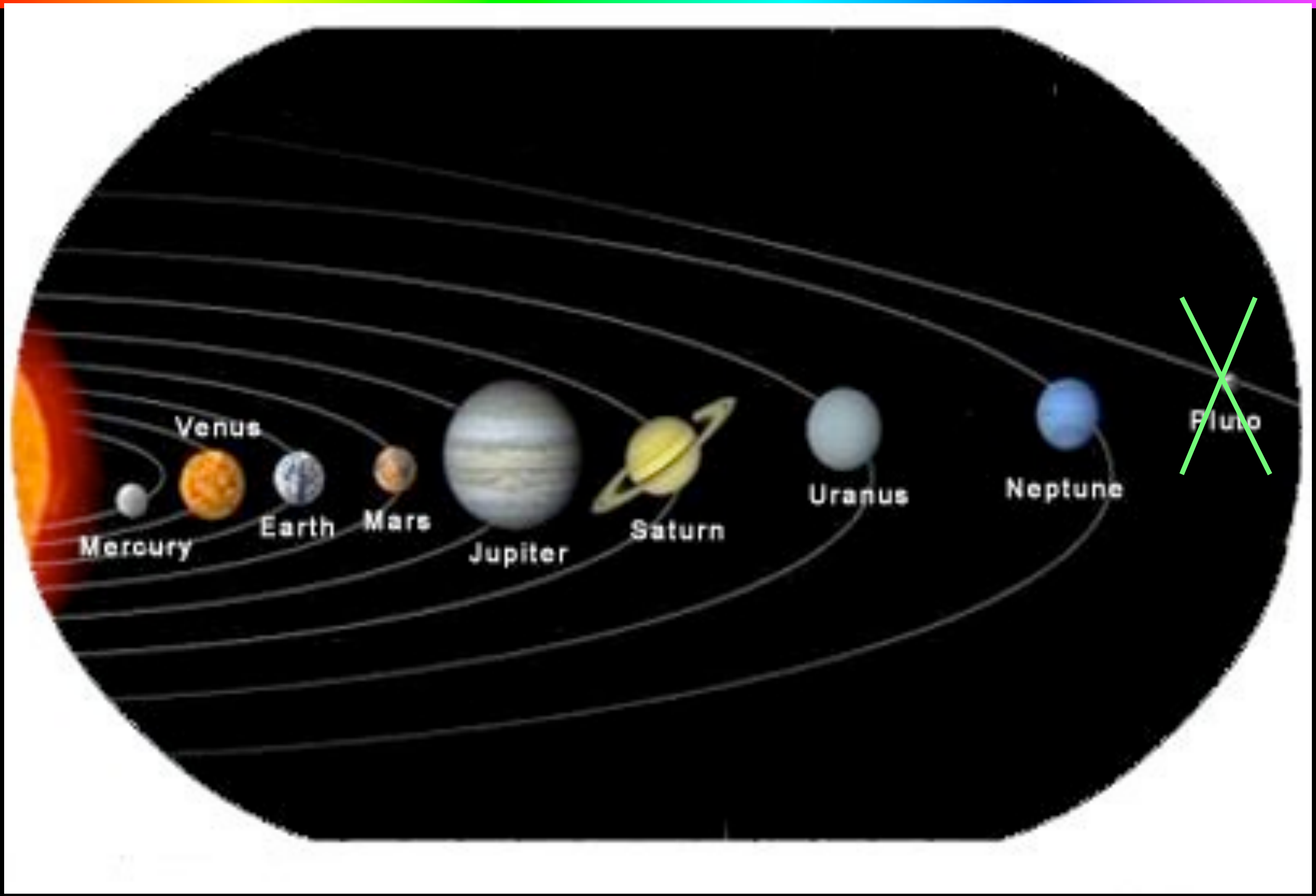

A scenario to "establish" seesaw

Buckley & HM, 2006 and in preparation

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- 0νββ discovered: neutrinos are Majorana
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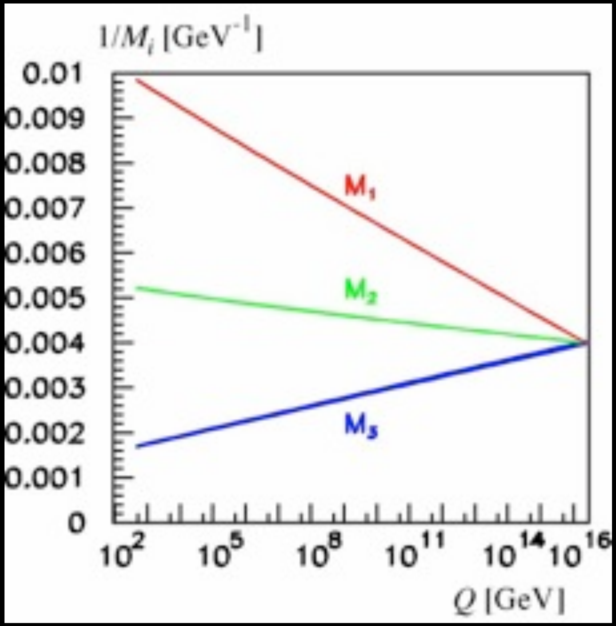
⇒ strong hint that there are no additional particles beyond the MSSM below M_{GUT} except for gauge singlets.

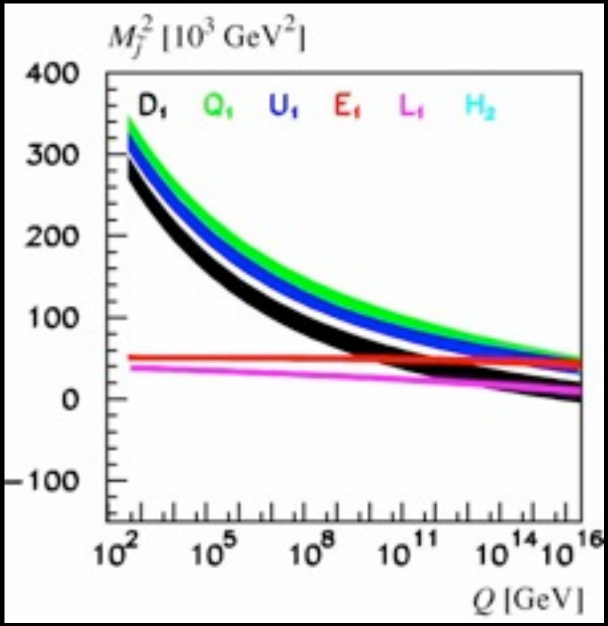
Buckley & HM, 2006 and in preparation

Gaugino and scalars

- Gaugino masses test unification itself independent of intermediate scales and extra complete SU(5) multiplets
- Scalar masses test beta functions at all scales, depend on the particle content

Kawamura, HM, Yamaguchi

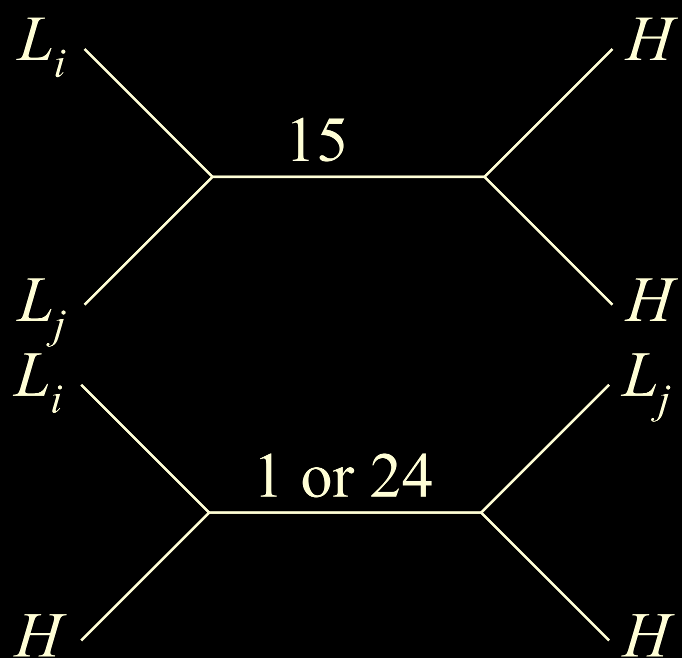




Possibilities

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

- L is in 5^*, H in 5 of SU(5)



Needs to be in a symmetric combination of two L: 15

Need three (at least two) 1 or 24 to have rank two or three neutrino mass matrix

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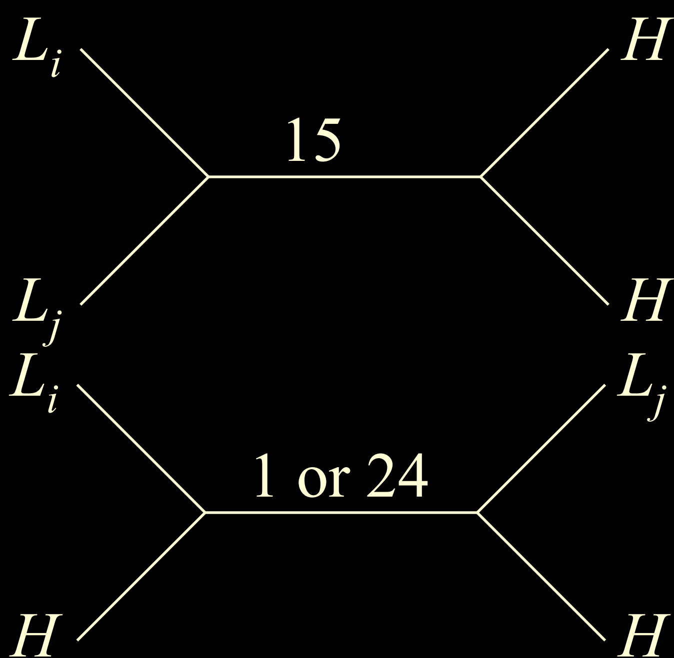

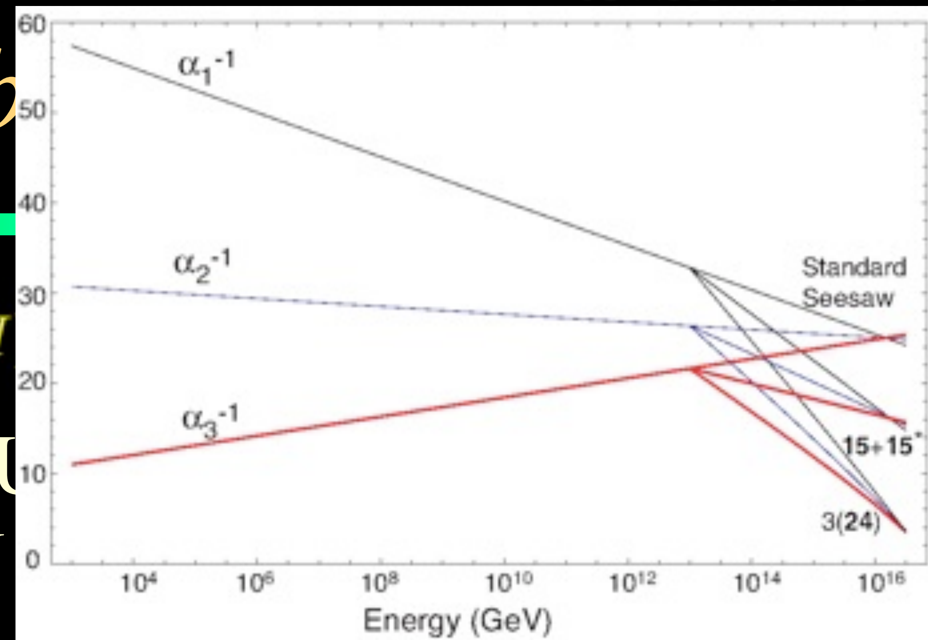

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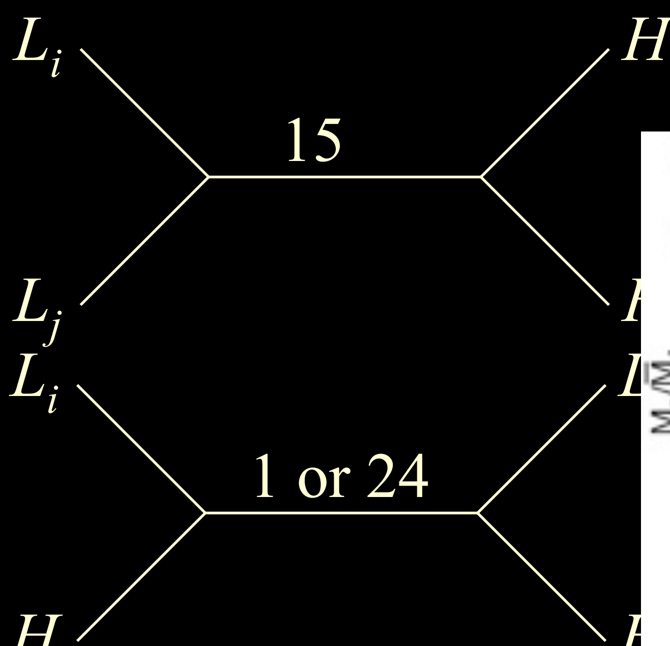

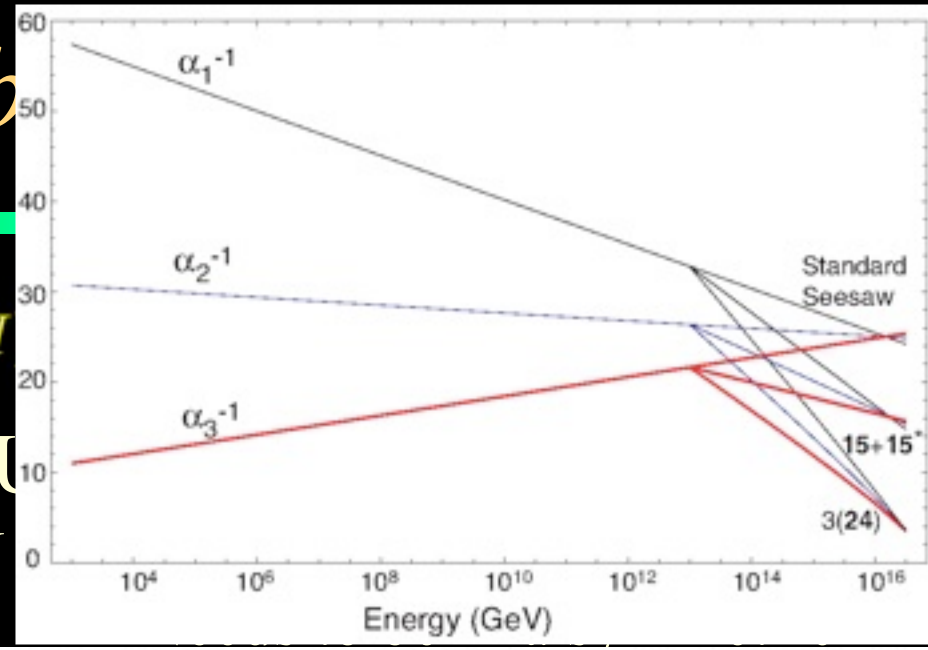

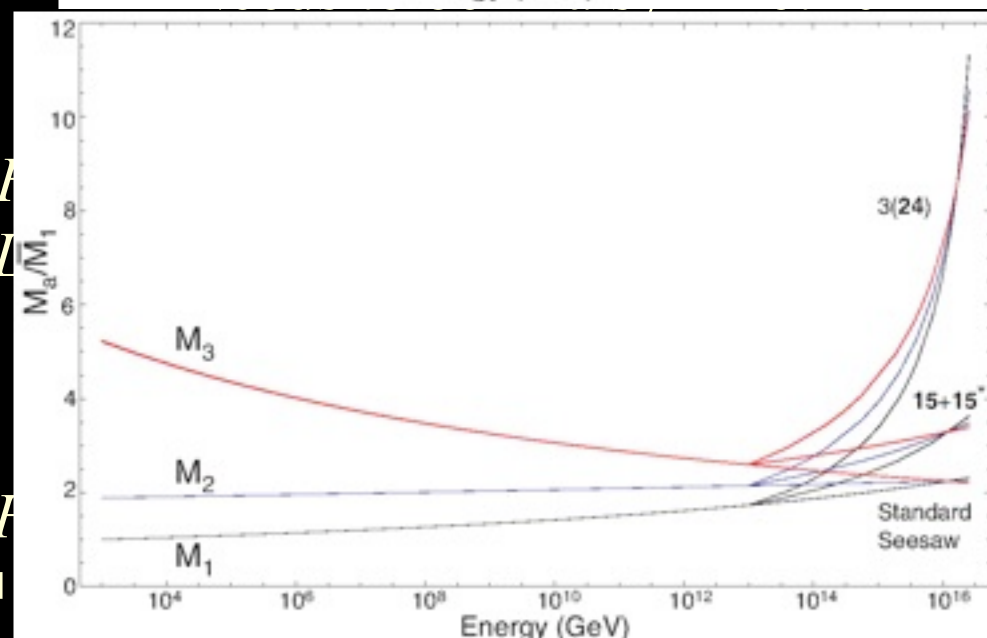

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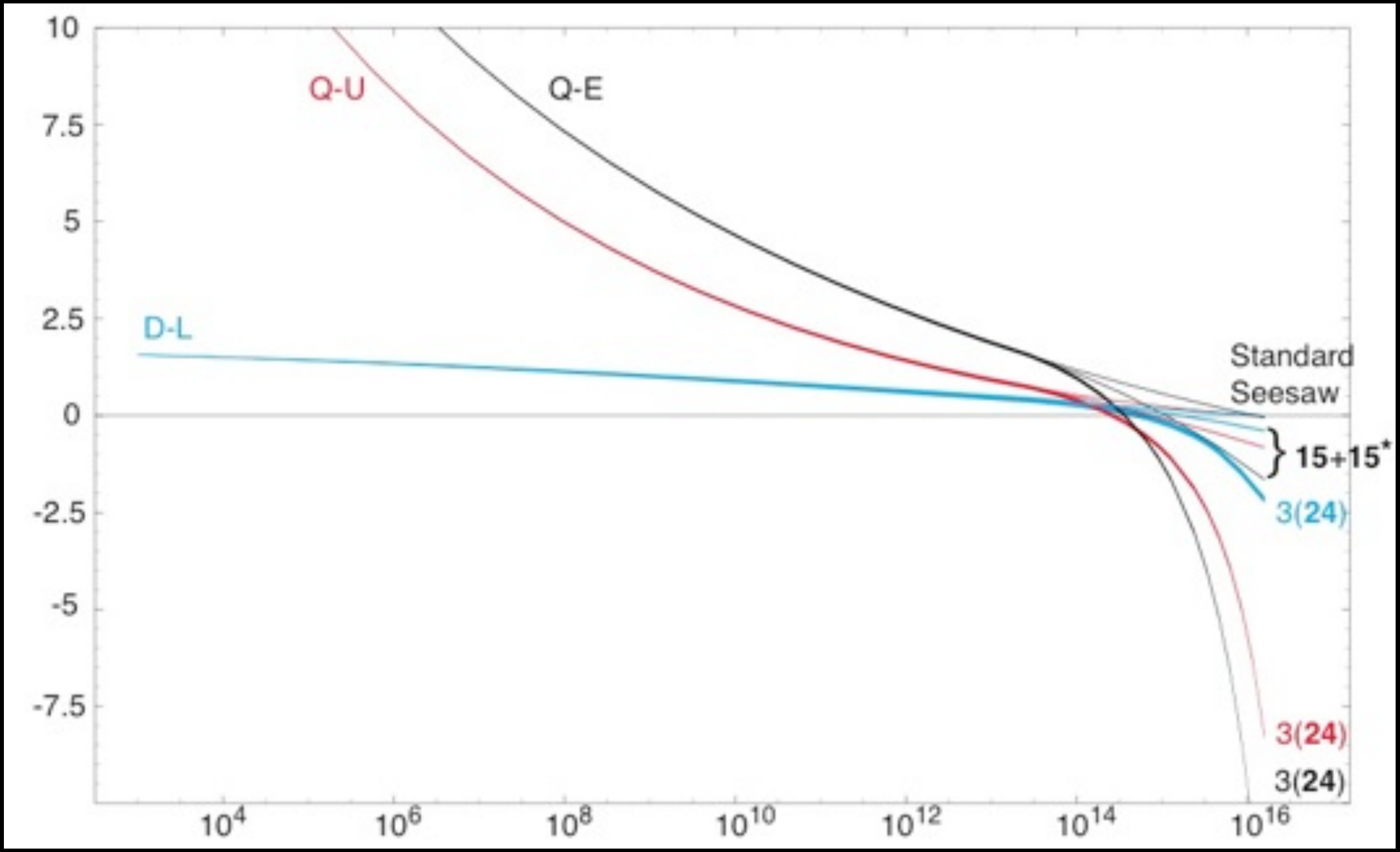
Scalar Masses



Leptogenesis?

Cirigliano, Antusch
Monday

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Cirigliano, Antusch
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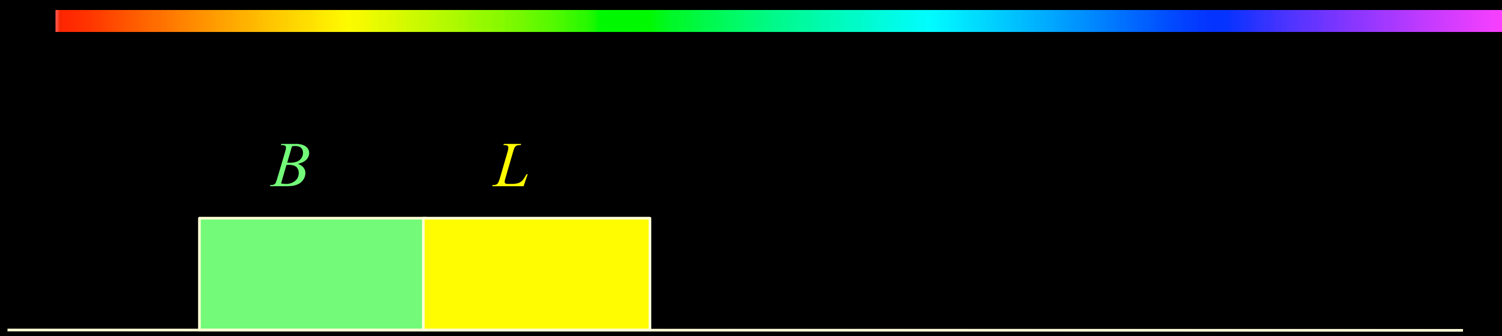
Cirigliano, Antusch
Monday

⇒*Archaeological* evidences

other possibilities

- $B=L\neq 0$ gets wiped out by sphaleron
- Leptogenesis at TeV scale
  - Degenerate leptogenesis? (Probably not testable because of tiny couplings) Nardi, Nir
  - EW phase transition with heavy leptons? (Hall, HM, Perez)
  - Or fourth generation with GUT-like baryogenesis w/ $B=L\neq 0$ because mass blocks sphaleron (HM, Rentala, Shu, Yanagida)

Without 4th generation



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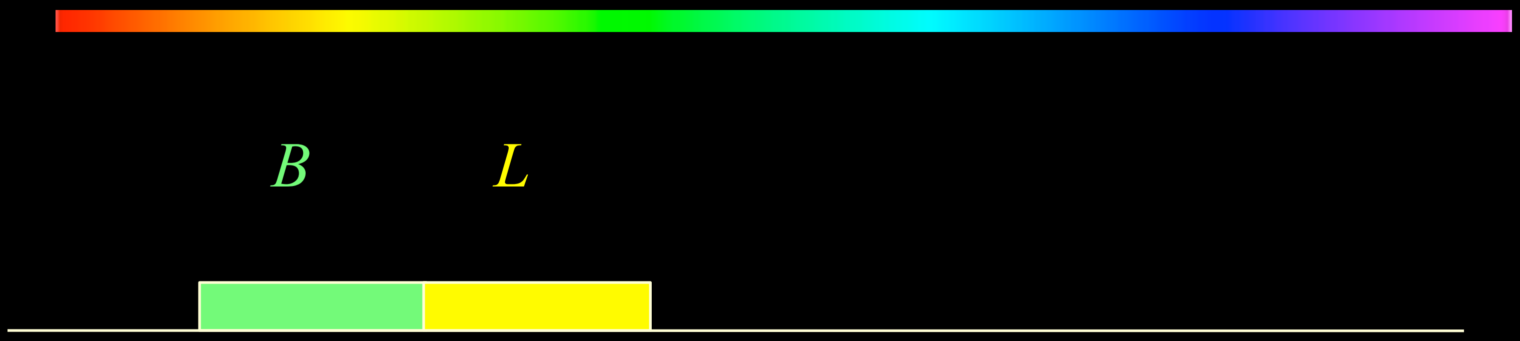
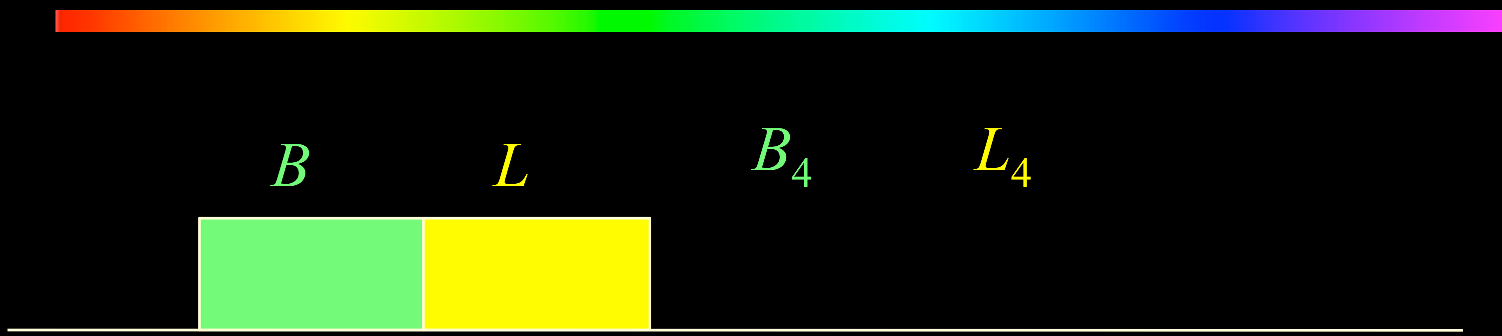


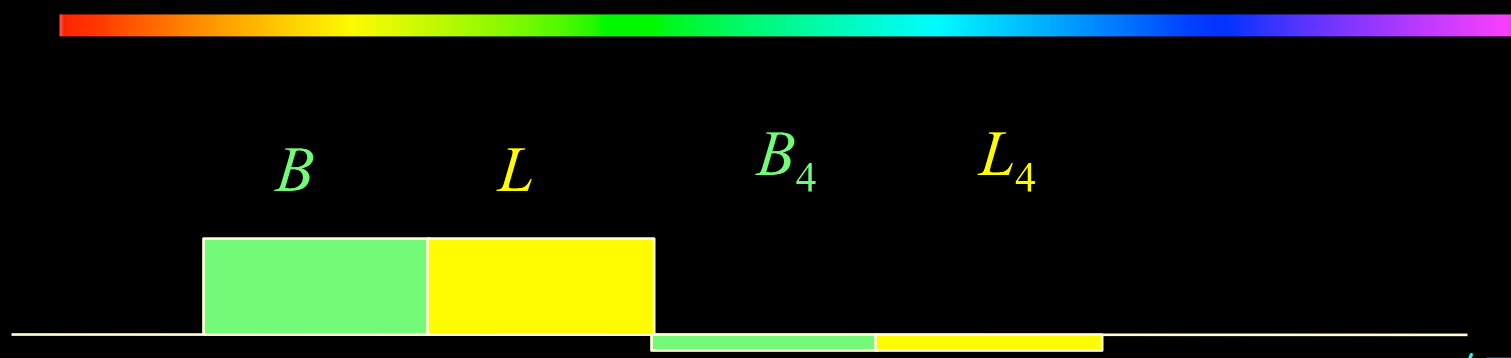
Without 4th generation

B *L*

With 4th generation

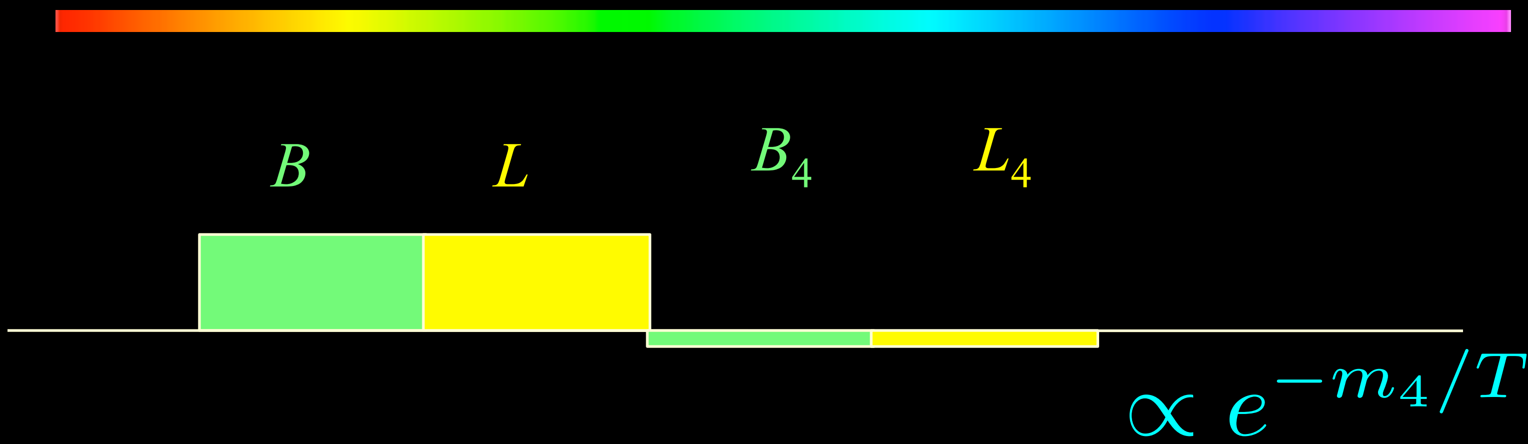


With 4th generation



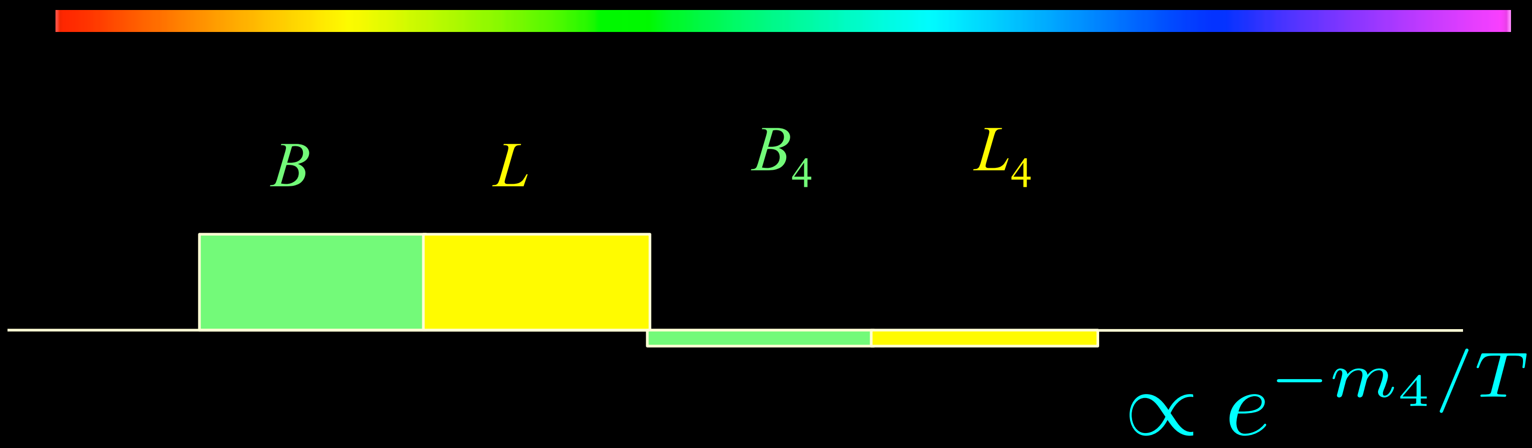
$$\propto e^{-m_4/T}$$

With 4th generation



- Predicts long-lived fourth generation@LHC

With 4th generation



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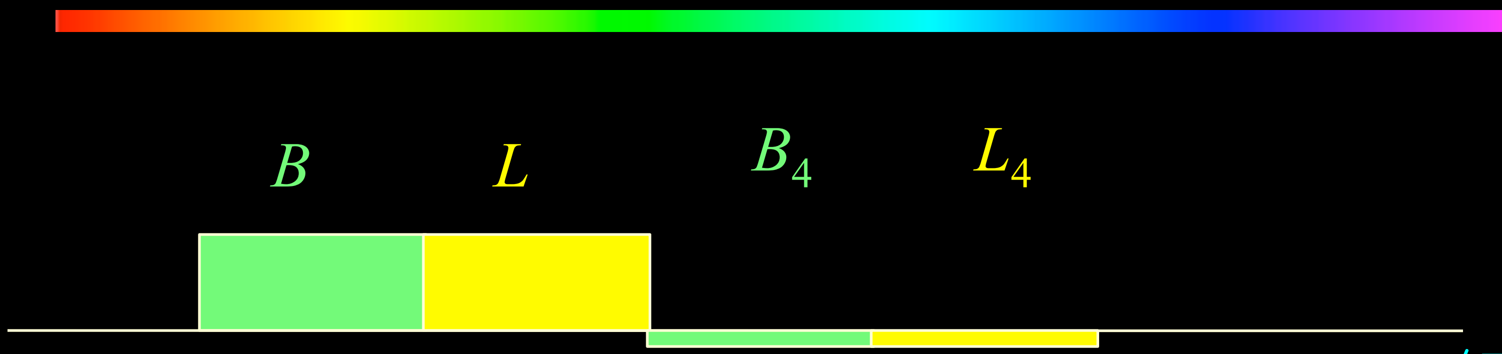

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$$\frac{\Omega_{TB}}{\Omega_B} \sim \frac{m_{TB}}{m_p} e^{-m_{TB}/T_{sh}}$$

Origin of Mixing?

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- $s_{23}{}^2 \sim 1/2$
- $s_{12}{}^2 \sim 1/3$
- $s_{13}{}^2 < 0.05$
- Neutrinos mix a lot more than quarks
- A_4 symmetry? Tri-bimaximal?

Feruglio, Chen

artists' rendition of multiverse

Landscape without anthropics

- Don't assume any fundamental distinction among three generation of neutrinos
- Measure to be independent of rotation of flavor basis
- Can show that the MNS mixing matrix is distributed according to the SU(3) Haar measure (left & right translation invariant)

$$dU_{MNS} = ds_{12}^2 dc_{13}^4 ds_{23}^2 d\delta_{CP}$$

Haba, HM

Random 3×3 seesaw "Anarchy" (Hall, HM, Weiner; Haba, HM)

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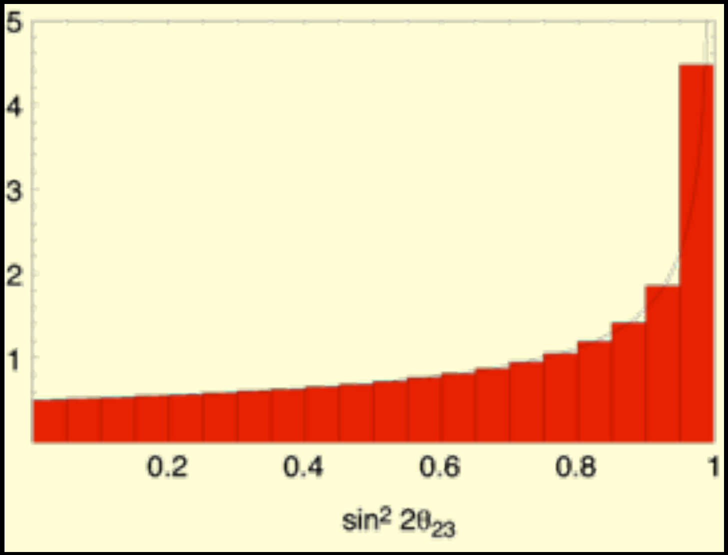

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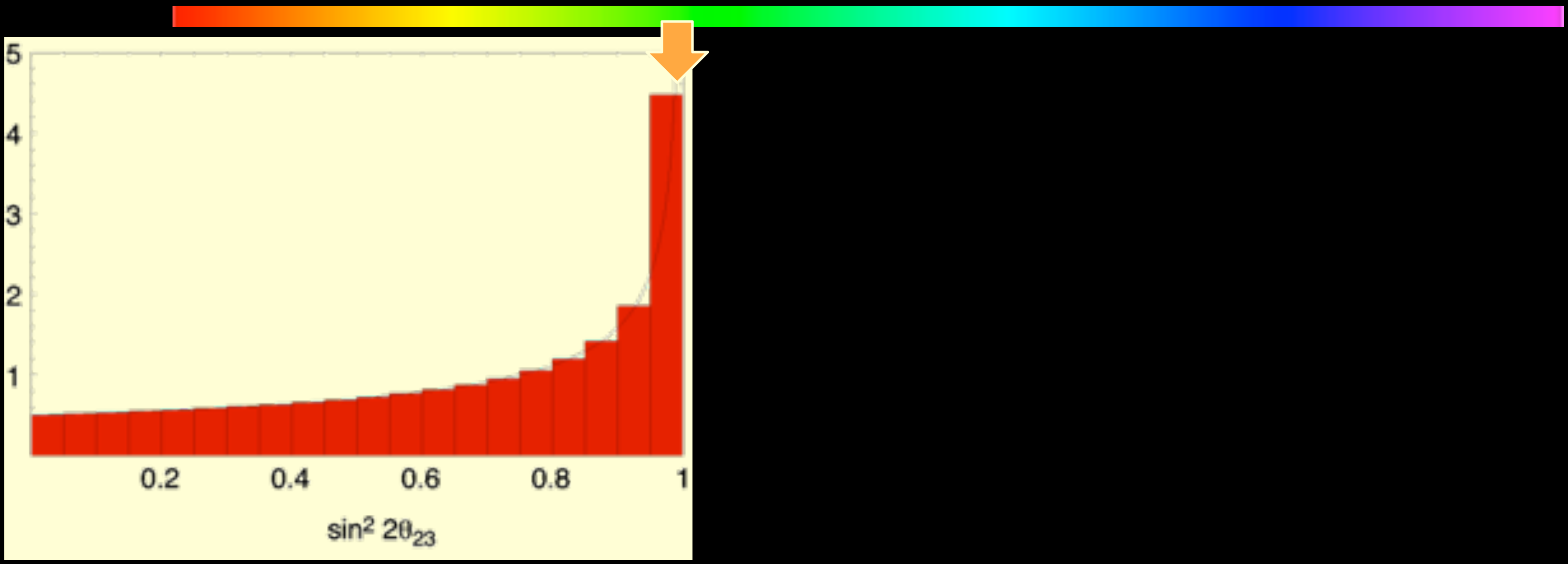

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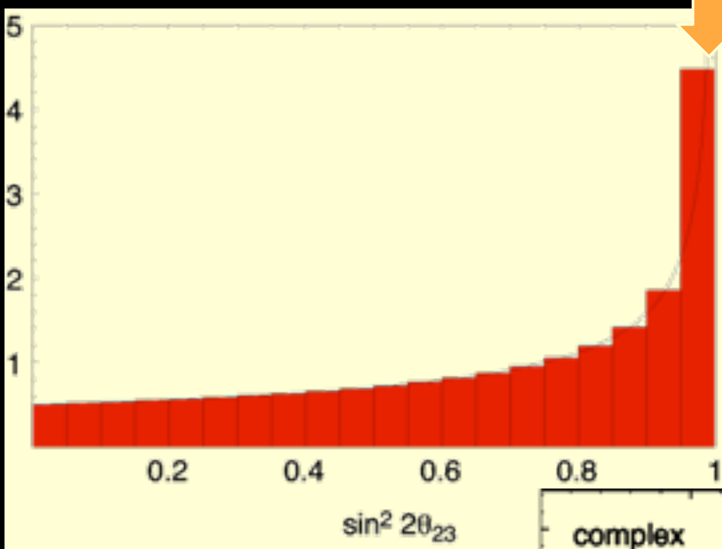

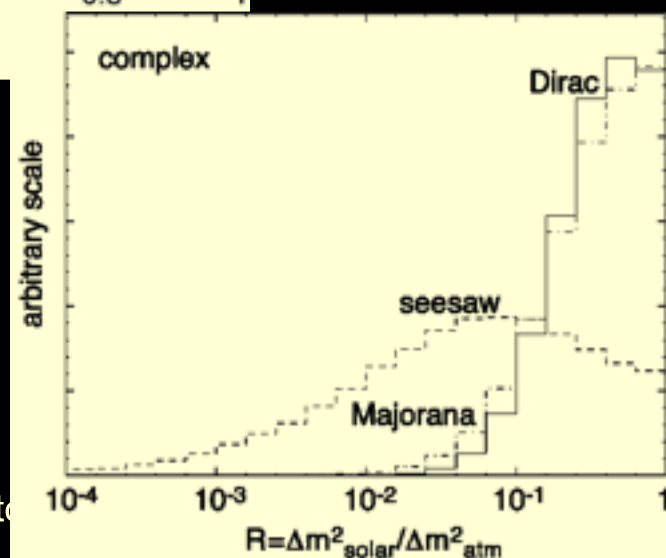

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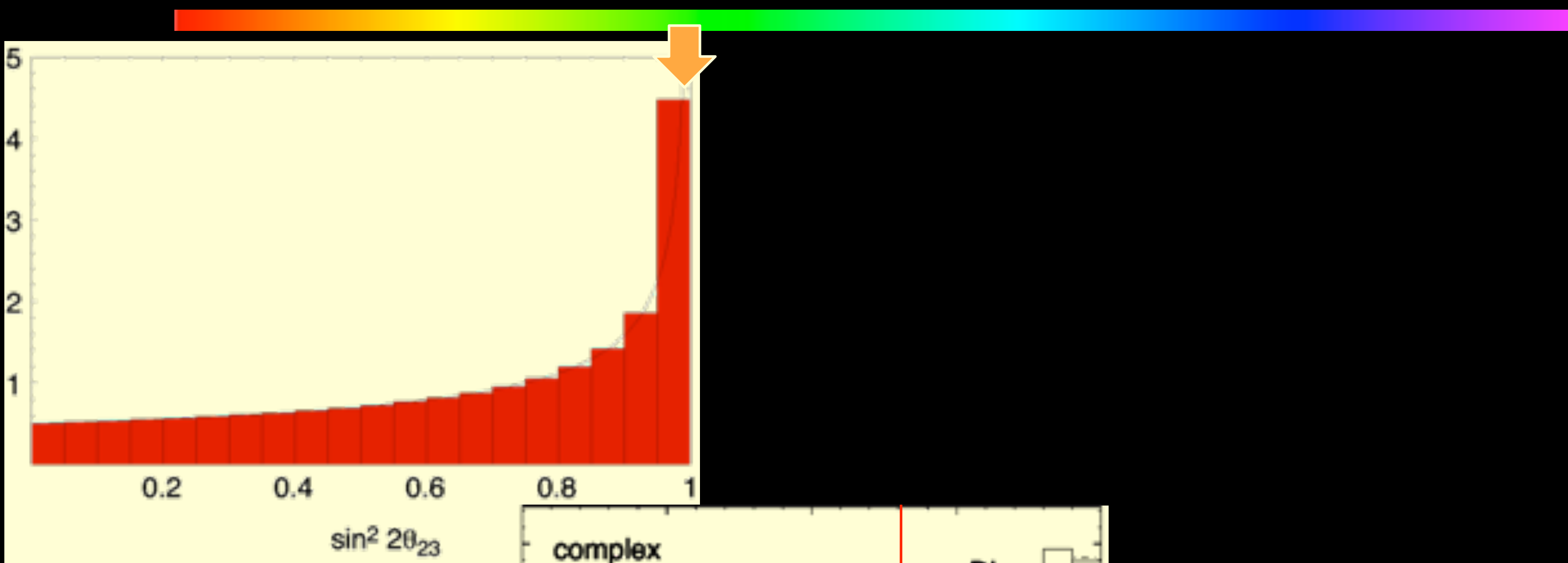

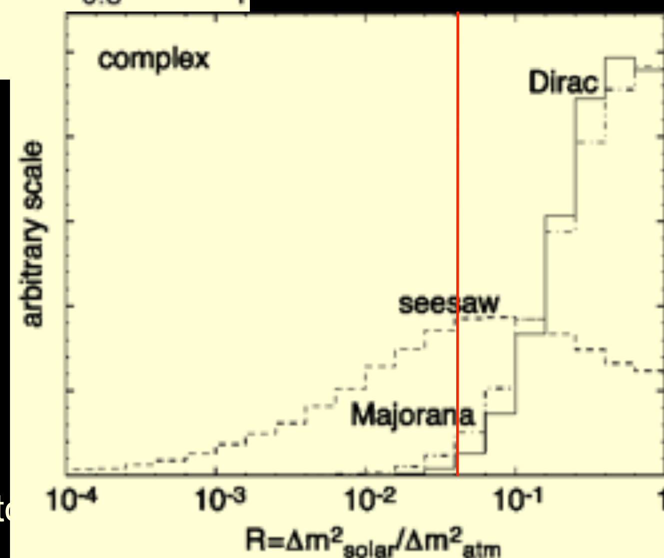

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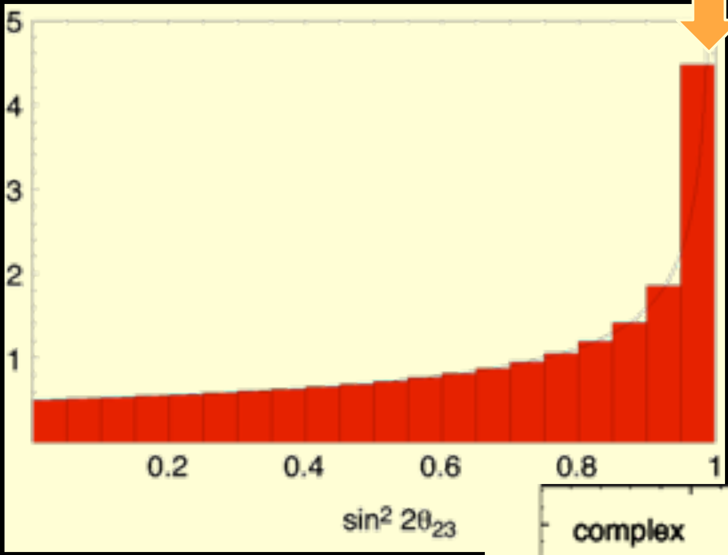

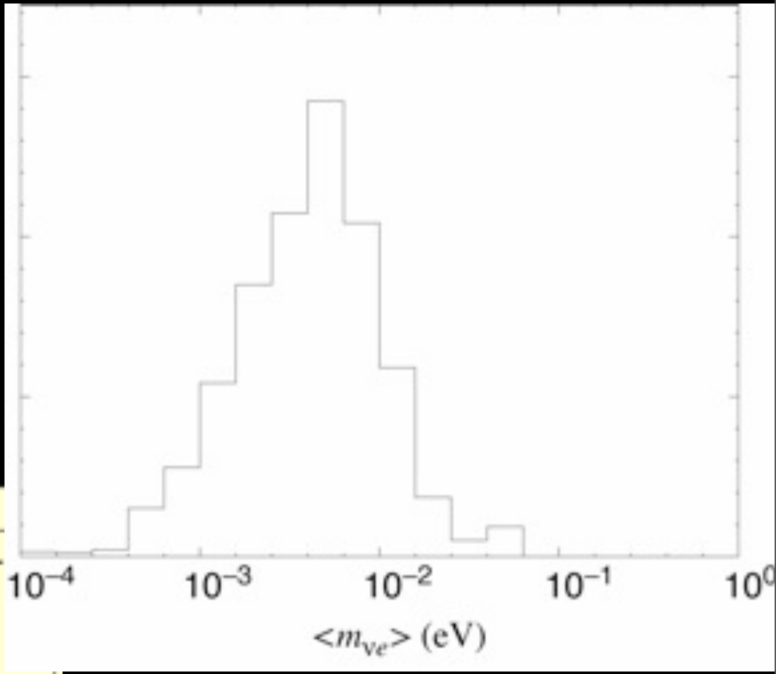

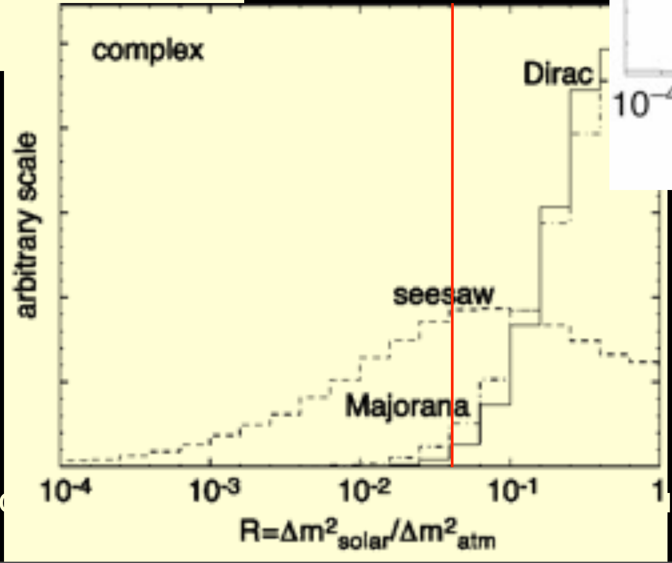

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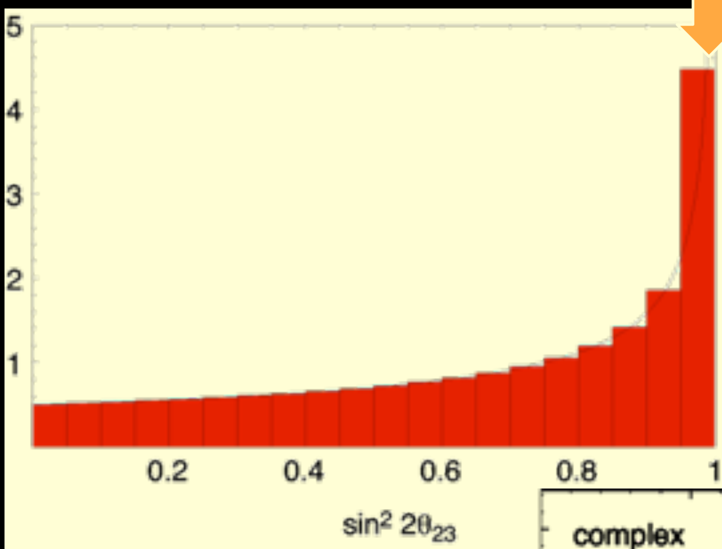
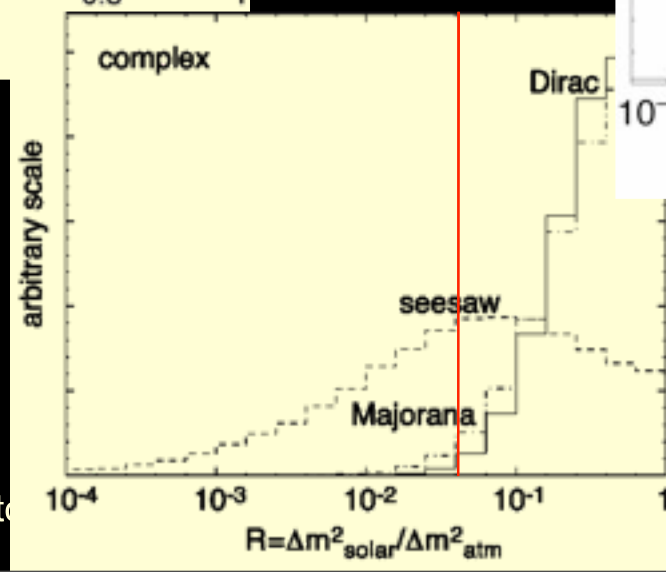
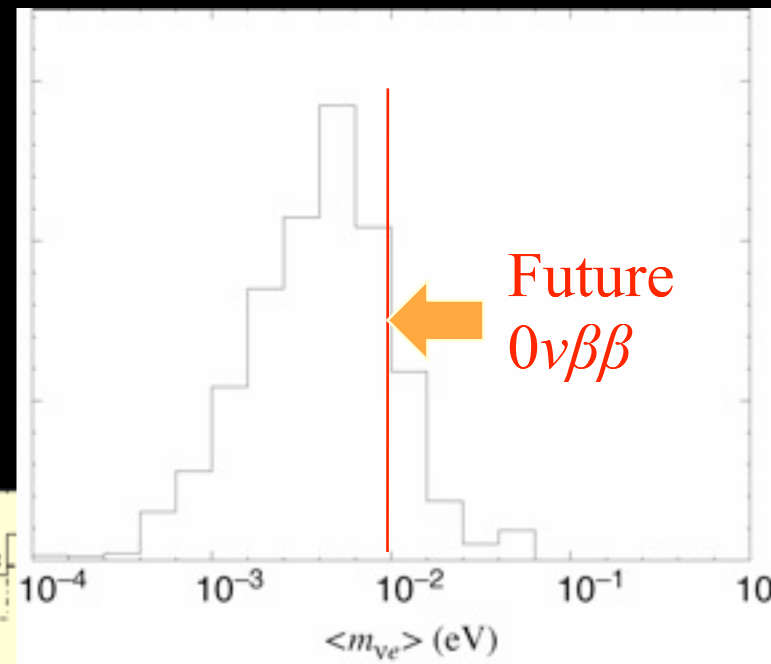
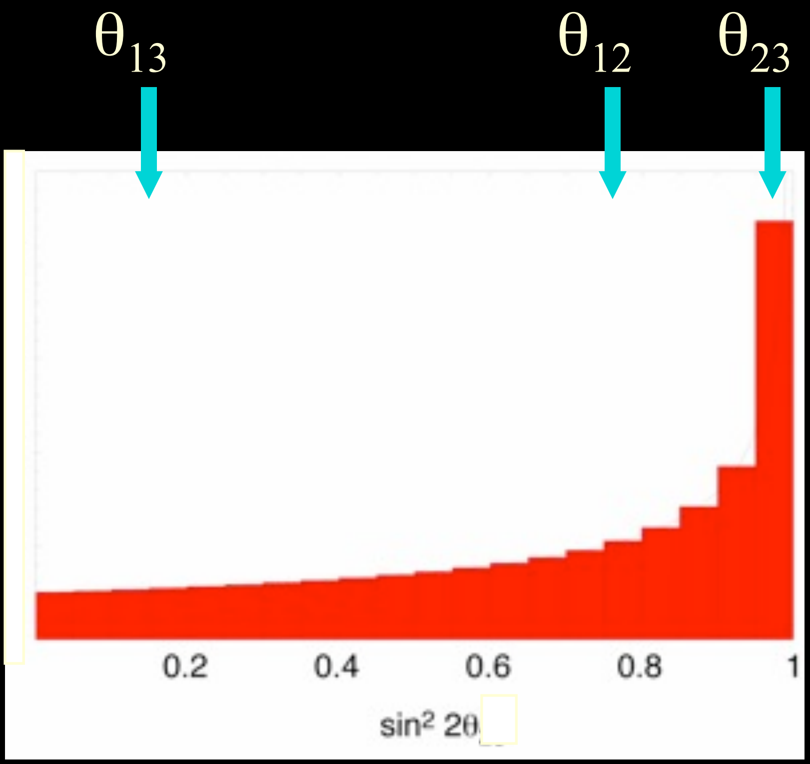






My prejudice

- Let's not write a detailed theory
- The only natural measure for mixing angles is the group-theoretical invariant Haar measure
- Kolmogorov–Smirnov test: 64%
- $\sin^2 2\theta_{13} > 0.04$ (2σ)
- $\sin^2 2\theta_{13} > 0.01$ (99%CL)



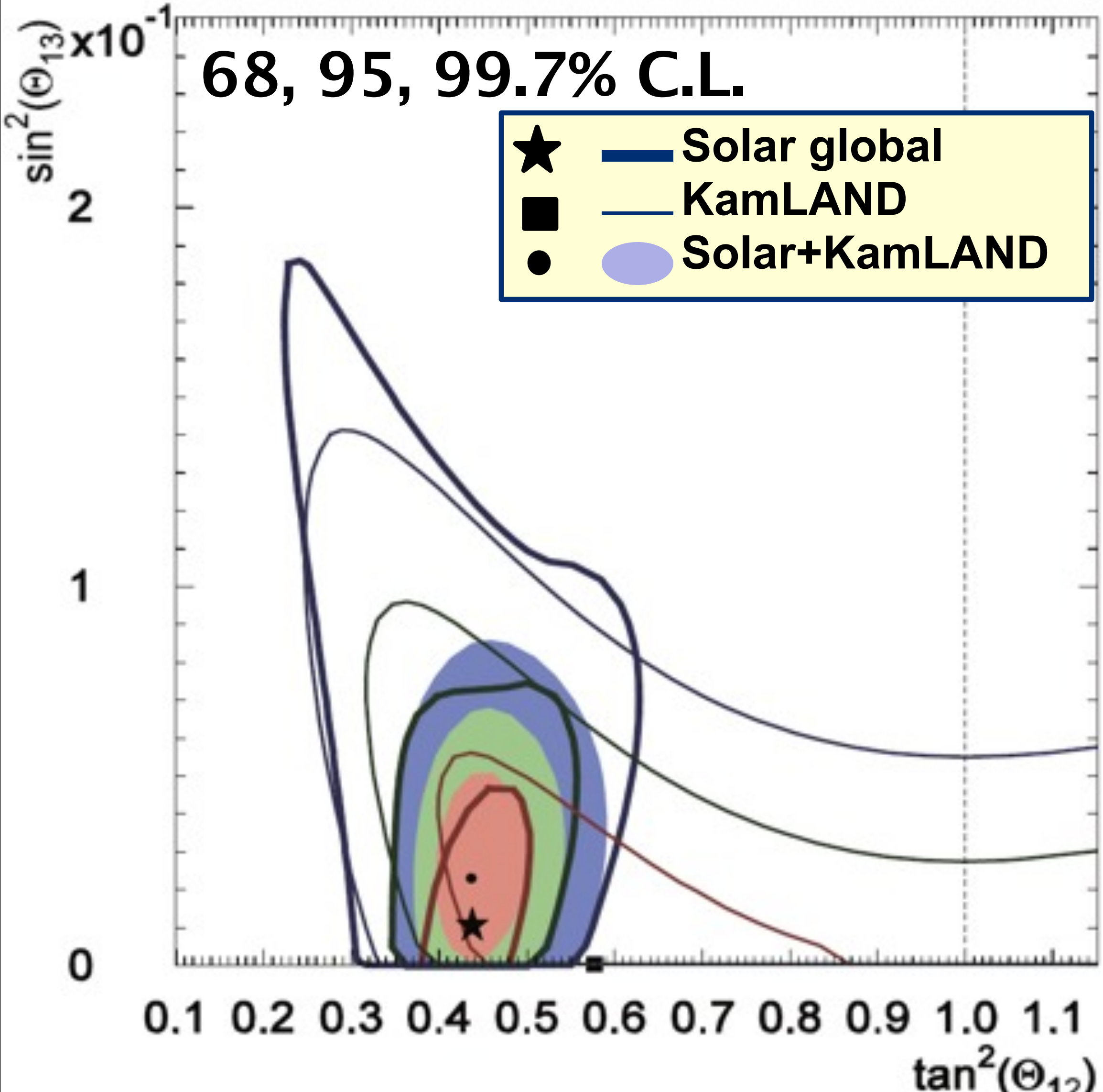
Neutrino mass anarchy

(with Hall, Weiner; Haba; de Gouvêa)

3-flavor analysis: θ_{12} - θ_{13}

Preliminary

May 2010



Solar global:

$\sin^2\theta_{13} < 0.060$ @95%C.L.

Solar global + KamLAND:

$\sin^2\theta_{13} = 0.025^{+0.018}_{-0.016}$ (<0.059 @95%C.L.)

Cf. PRC81; 055504 (2010)
$\sin^2\theta_{13}$=0.020+0.021-0.016
(<0.057 @95%C.L.)

Poster-54 Byeongsu Yang

3-flavor analysis: θ_{12} - θ_{13}

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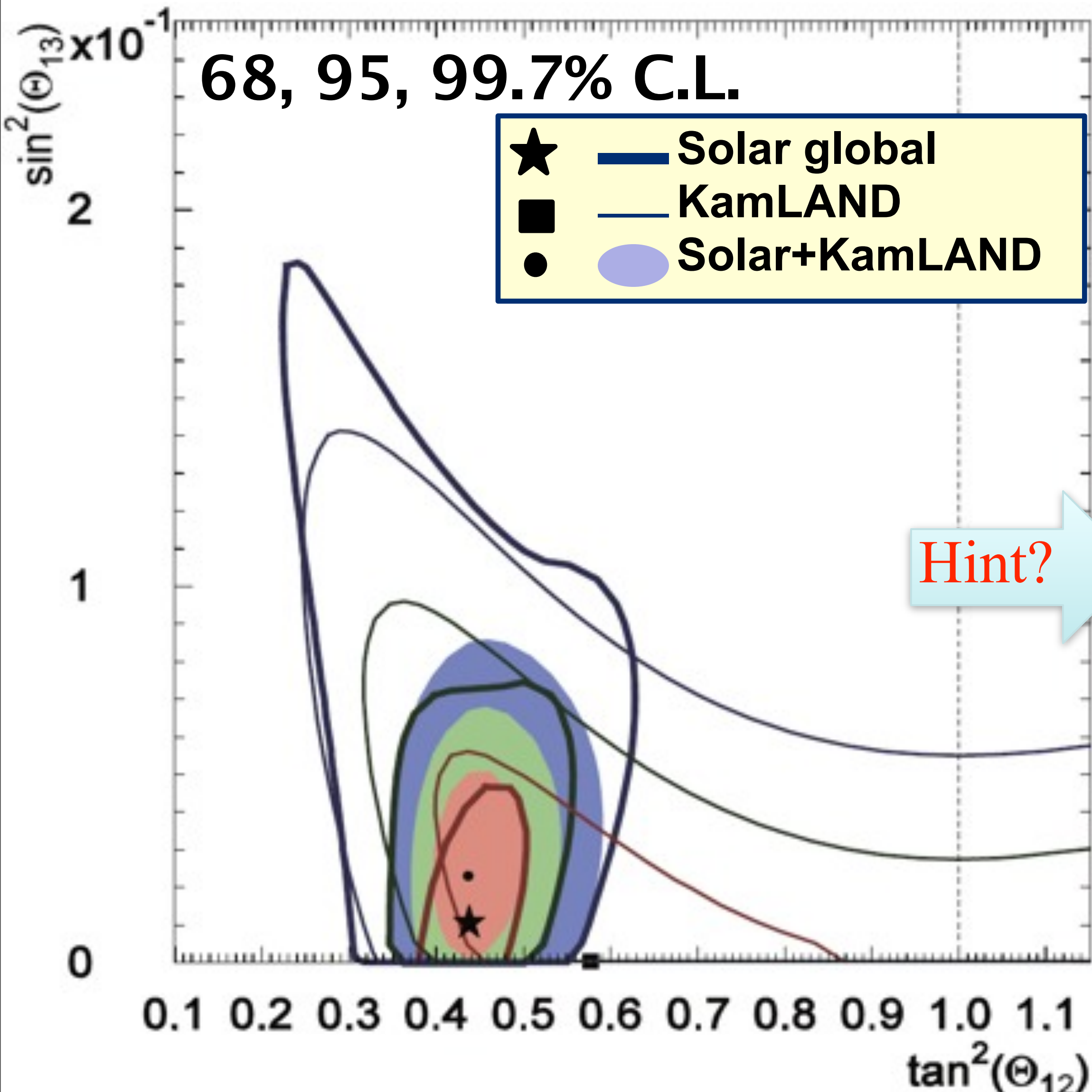
May 2010



Hint?

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$\sin^2\theta_{13} = 0.025^{+0.018}_{-0.016}$ (<0.059 @95%C.L.)

Cf. PRC81; 055504 (2010)
$\sin^2\theta_{13}$=0.020+0.021-0.016
(<0.057 @95%C.L.)

Poster-54 Byeongsu Yang

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