Theoretical Overview of Neutrino Physics III

Hitoshi Murayama (IPMU/Berkeley)

September 18th, 2008

九华山庄

INSTITUTE FO
MATHEMATIC

New intl research institute in Japan
- astrophysics
- particle theory
- particle expt
- mathematics

official language: English

>30% non-Japanese

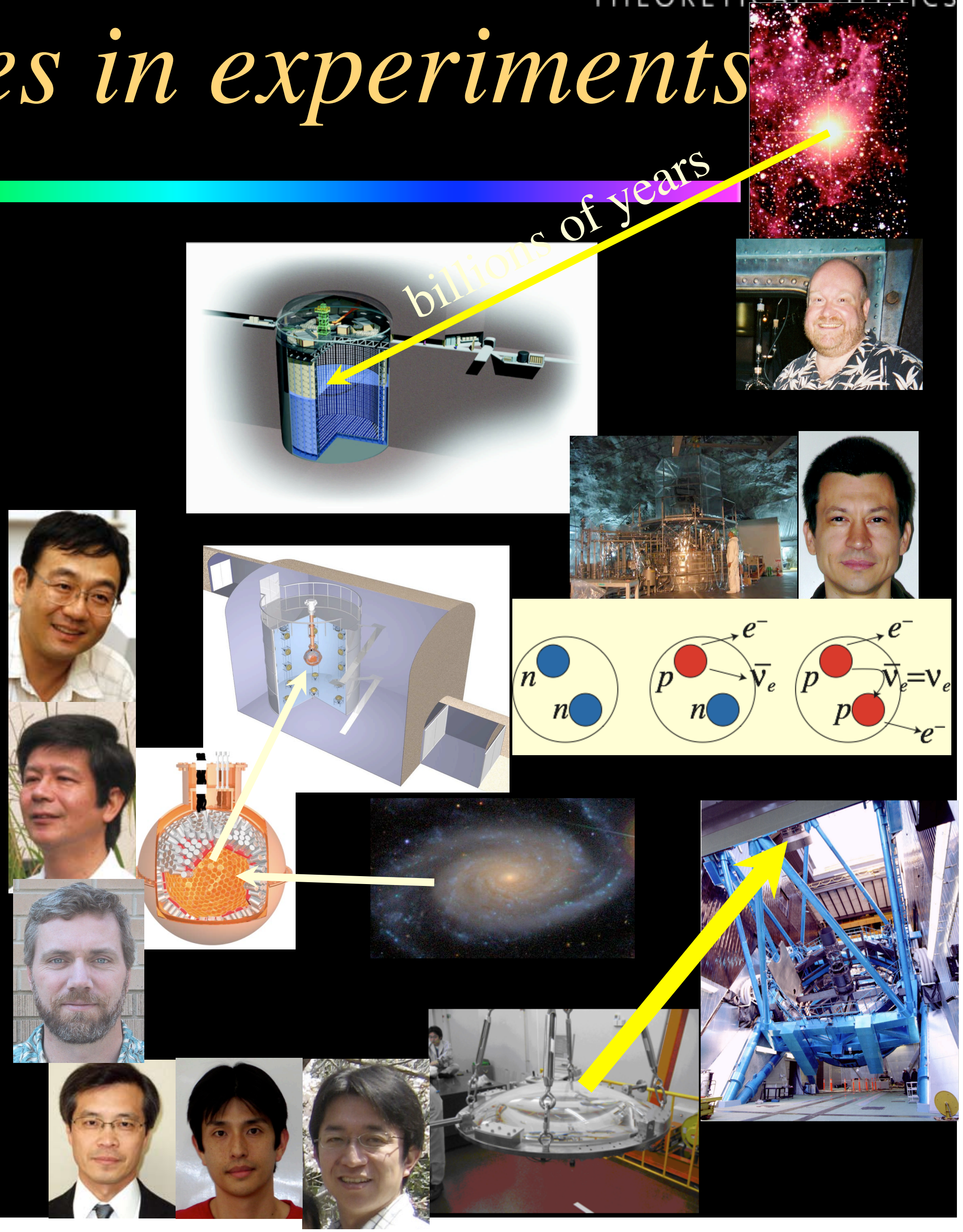
$13M/yr for 10 years

- launched O
- ≈25 now, >40 in
- excellent new fac hires, young and dynamic!
- will hire about 3(scientists
- new bui
- intl gue
- wkshp

Also photo detector development
for future experiments

IPMU initiatives in experiments

- Vagins: let SuperK detect relic supernova with Gd
- Kozlov: use KamLAND to see if $\nu=\bar{\nu}$ with Xe
- Suzuki/Nakahata /Martens: XMASS to detect dark matter
- Aihara/Takada/Yoshida: HyperSuprimeCam at Subaru and data analysis to study dark energy



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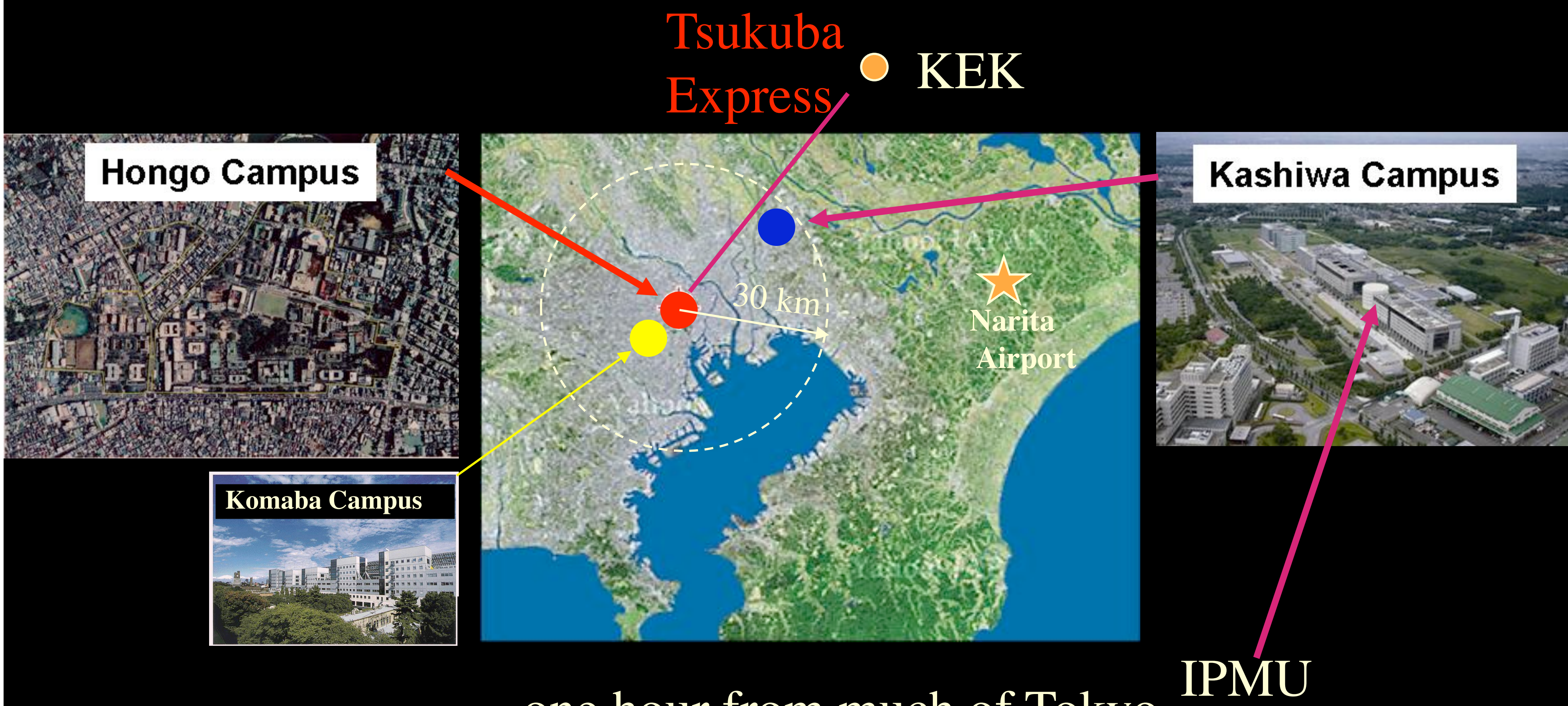
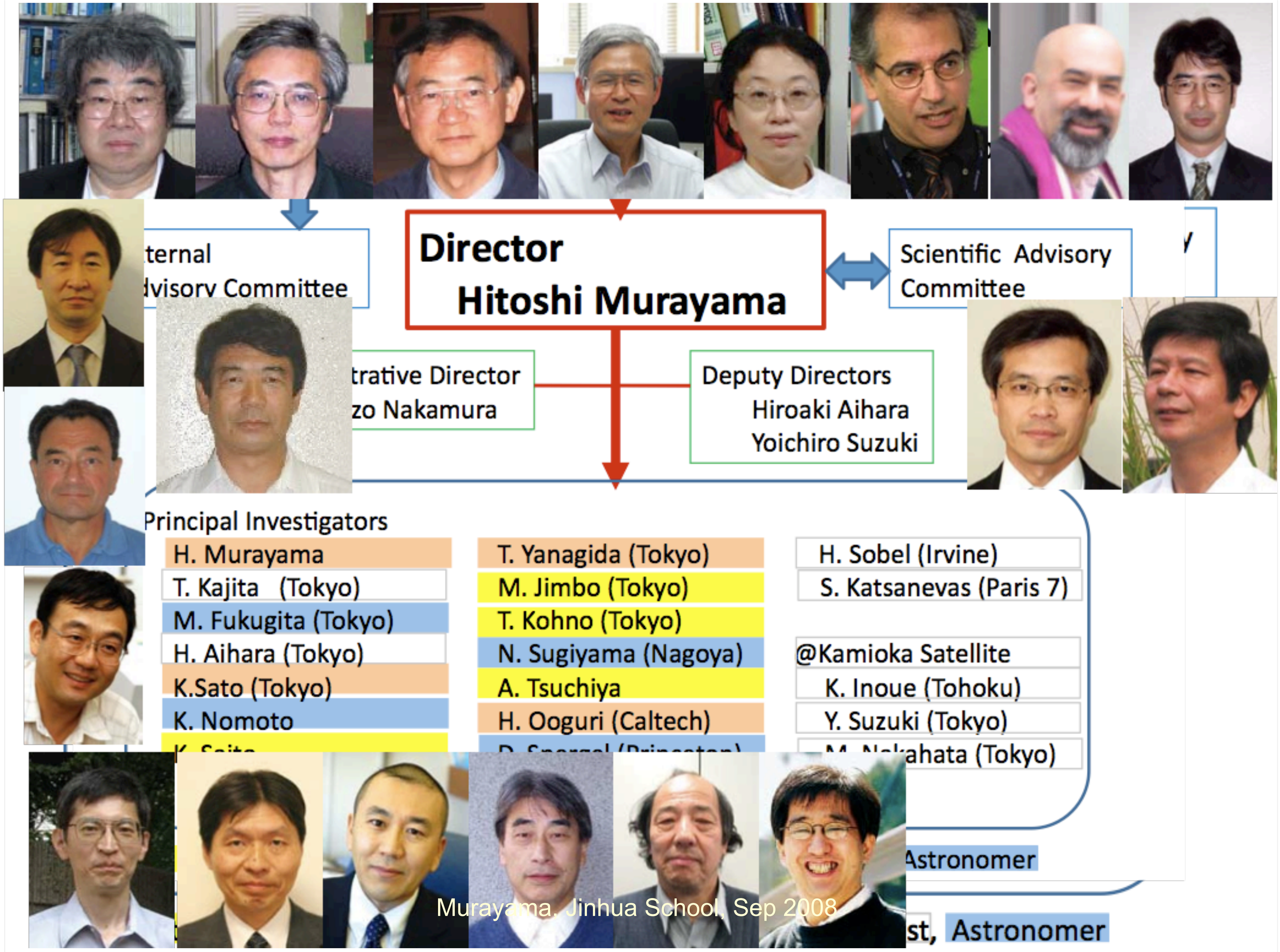
Where it is



~one hour from much of Tokyo
Also a satellite in Kamioka



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dvisory Committee
Director
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Committee
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Hiroaki Aihara
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N. Sugiyama (Nagoya)
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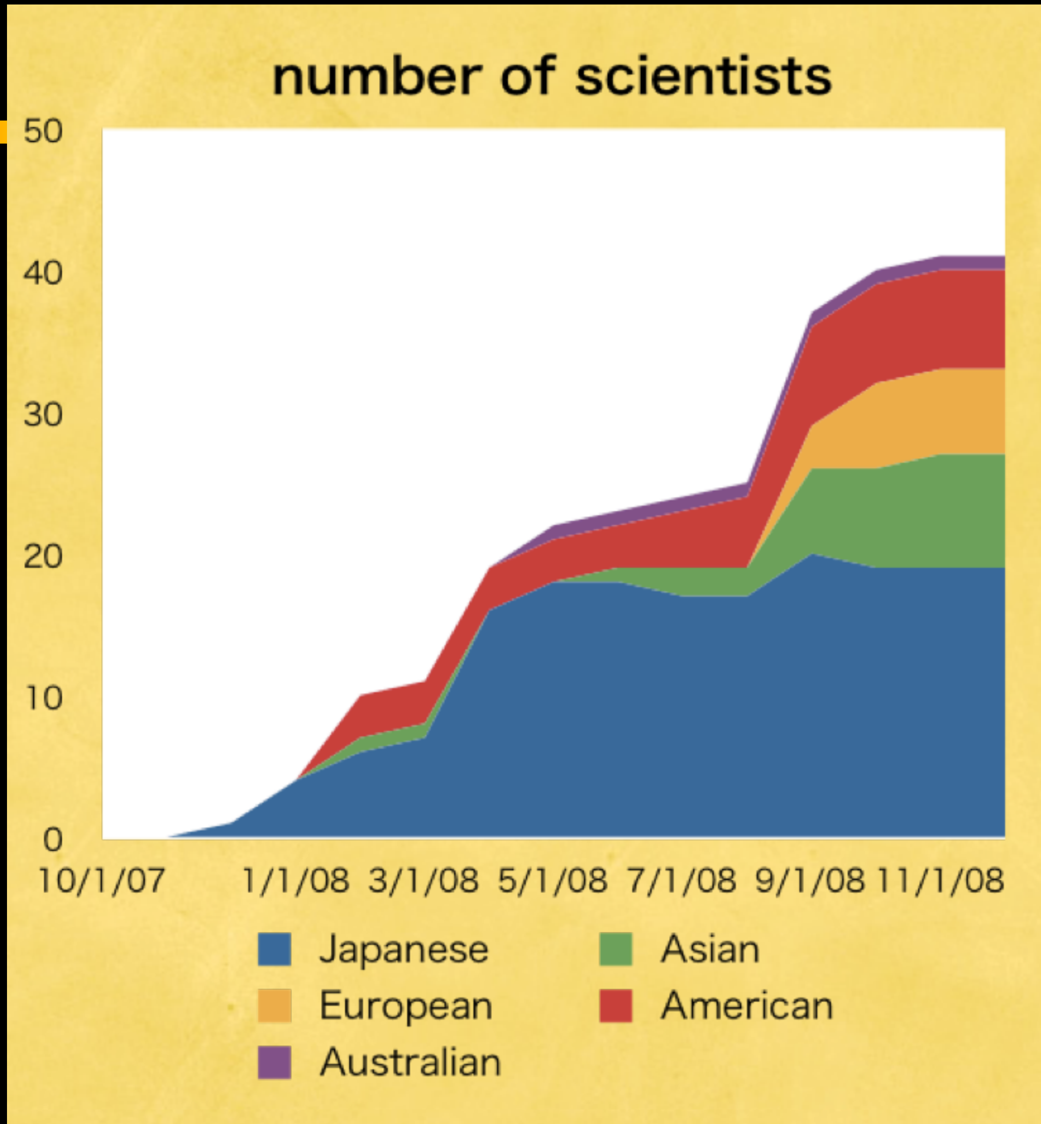
H. Ooguri (Caltech)
H. Sobel (Irvine)
S. Katsanevas (Paris 7)
@Kamioka Satellite
K. Inoue (Tohoku)
Y. Suzuki (Tokyo)
Astronomer
st, Astronomer
Murayama, Jinhua School, Sep 2008


Winter 2009 occupancy
~5900m^2

emphasis on large interaction area

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

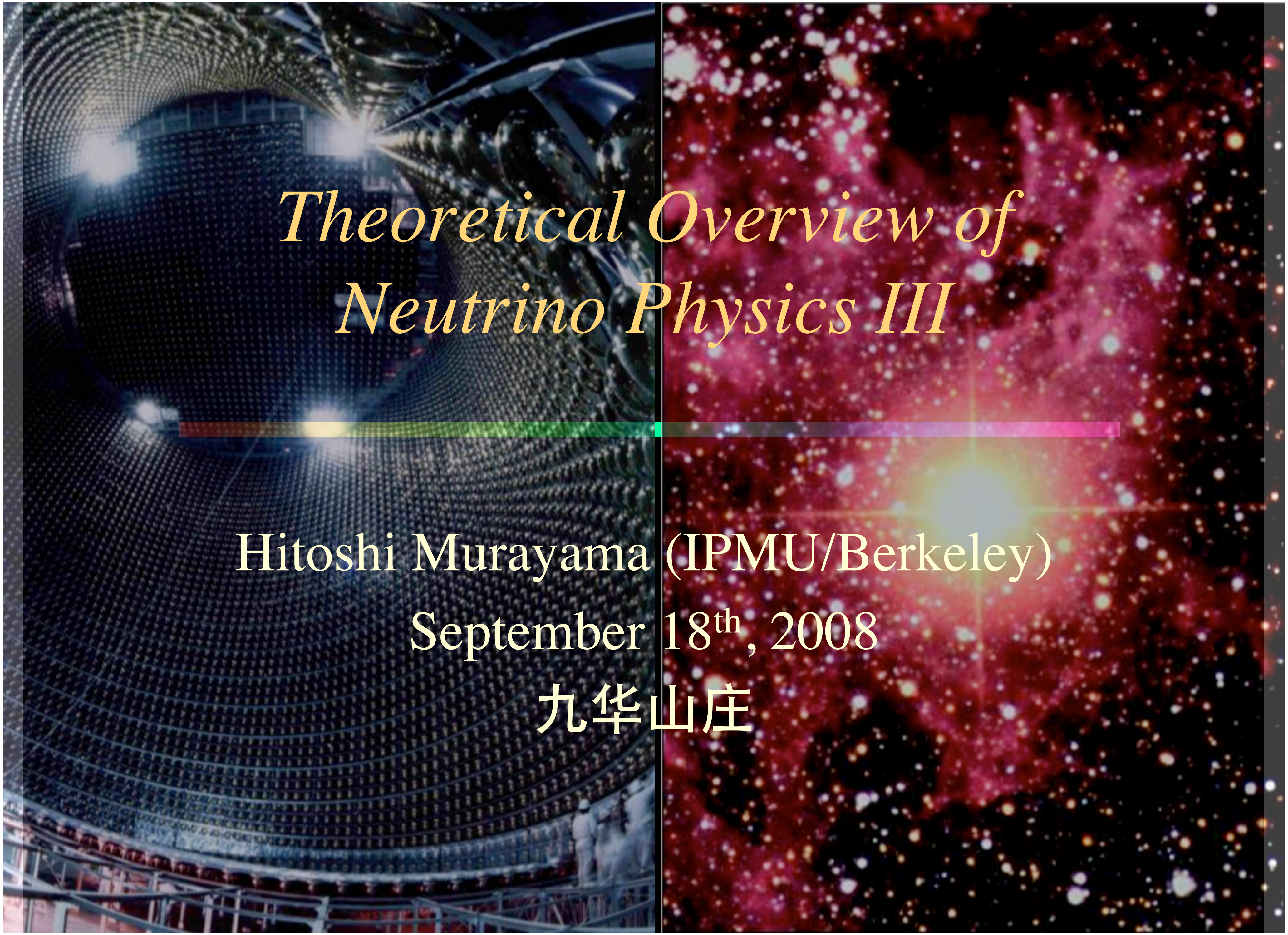
Full-time Scientists



non-Japanese 50%

Expect ~15-20 positions this year

Check out www.ipmu.jp



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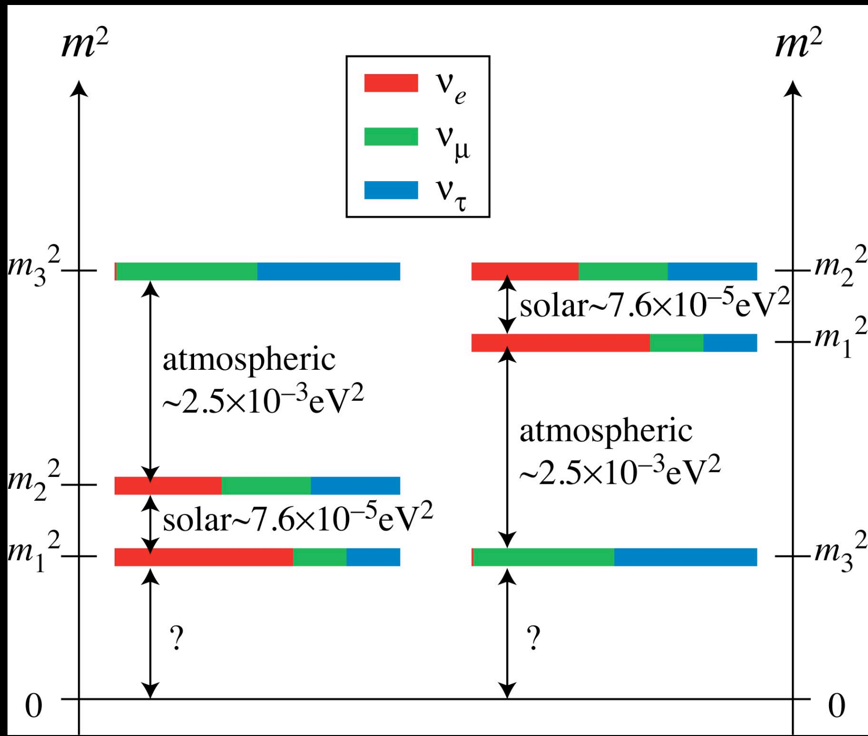
Big Questions

- What is the origin of neutrino mass?
- Why do they mix so much?
- 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

Seven Questions

- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- Is θ_{23} maximal?
- LSND? Sterile neutrino(s)? CPT violation?



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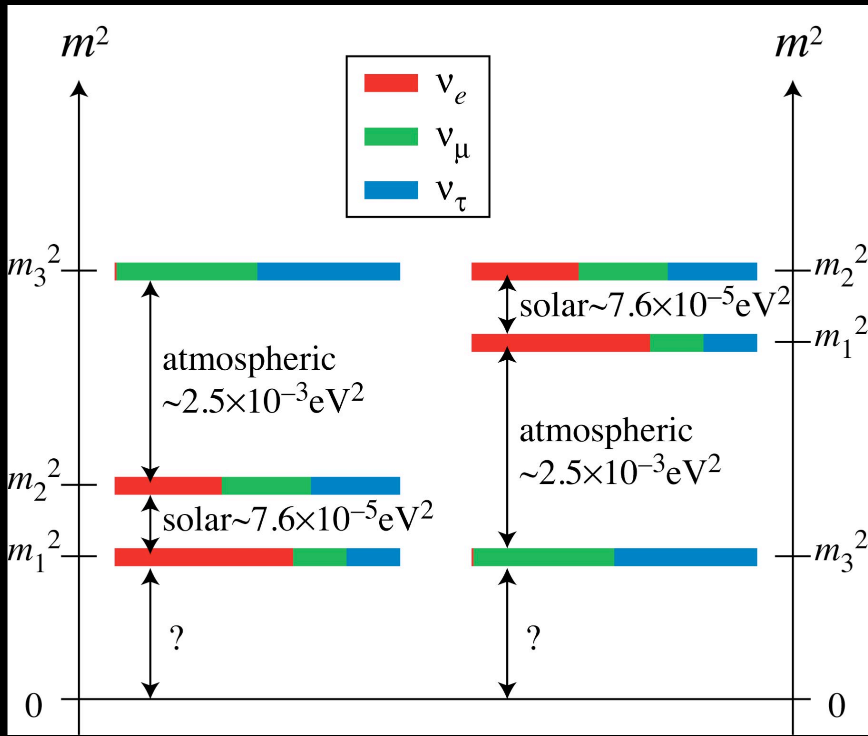


Extended Standard Model

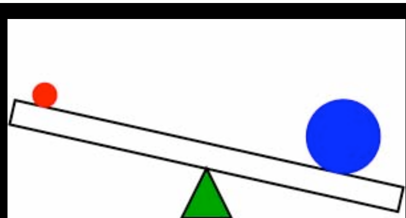
- Massive Neutrinos ⇒ Minimal SM incomplete
- How exactly do we extend it?
- Abandon either
  - Minimality: introduce new unobserved light degrees of freedom (right-handed neutrinos)
  - Lepton number: abandon distinction between neutrinos and anti-neutrinos and hence matter and anti-matter
- Dirac or Majorana neutrino
- Without knowing which, we don't know how to extend the Standard Model

Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

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

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



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

Neutrinos are Majorana

Neutrinoless Double-beta Decay

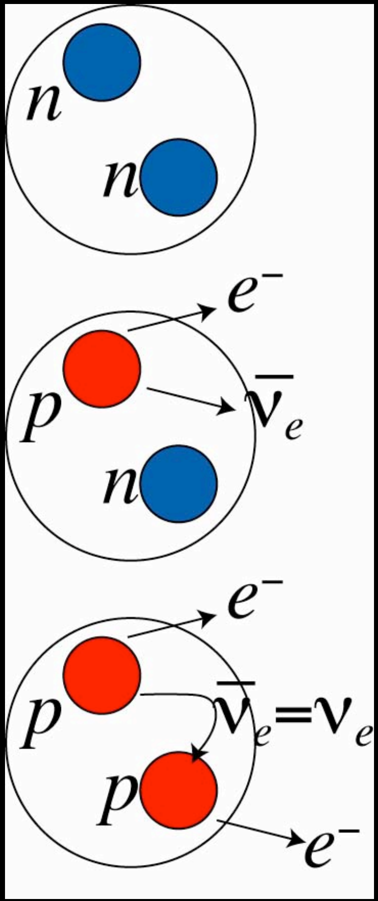
- The only known practical approach to discriminate Majorana vs Dirac neutrinos

  $0\nu\beta\beta$: $nn \to ppe^- e^-$ with no neutrinos
- Matrix element ∝

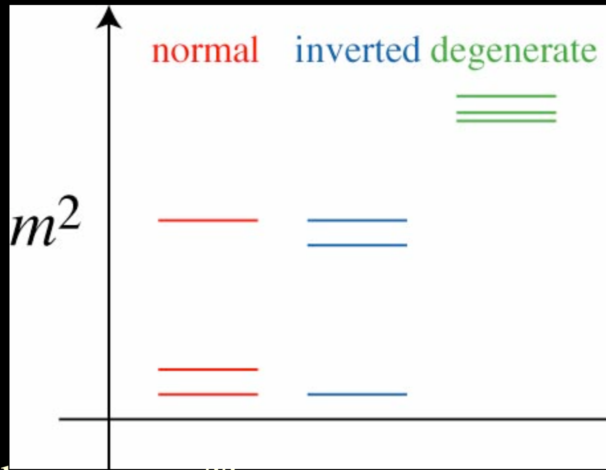
  $\langle m_{\nu e}\rangle = \Sigma_i m_{\nu i} U_{ei}^2$
- Current limit

  $|\langle m_{\nu e}\rangle| \le$ about 1eV
- Heidelberg-Moscow subset:

  $\langle m_{\nu e}\rangle = \Sigma_i m_{\nu i} U_{ei}^2 = 0.11\text{-}0.56$ eV



Three Types of Mass Spectrum



- Degenerate
  - All three around >0.1eV with small splittings
  - Laboratory limit: m<2.3eV
  - May be confirmed by KATRIN, cosmology
  - $|\langle m_{\nu e}\rangle| = |\Sigma_i m_{\nu i} U_{ei}^2| > m \cos^2 2\theta_{12} > 0.07m$
- Inverted
  - $m_3 \sim 0, m_1 \sim m_2 \sim (\Delta m^2_{23})^{1/2} \approx 0.05$eV
  - May be confirmed by long-baseline experiment with matter effect
  - $|\langle m_{\nu e}\rangle| = |\Sigma_i m_{\nu i} U_{ei}^2| > (\Delta m^2_{23})^{1/2} \cos^2 2\theta_{12} > 0.013$eV
- Normal
  - $m_1 \sim m_2 \sim 0, m_3 \sim (\Delta m^2_{23})^{1/2} \approx 0.05$eV
  - $|\langle m_{\nu e}\rangle| = |\Sigma_i m_{\nu i} U_{ei}^2|$ may be zero even if Majorana

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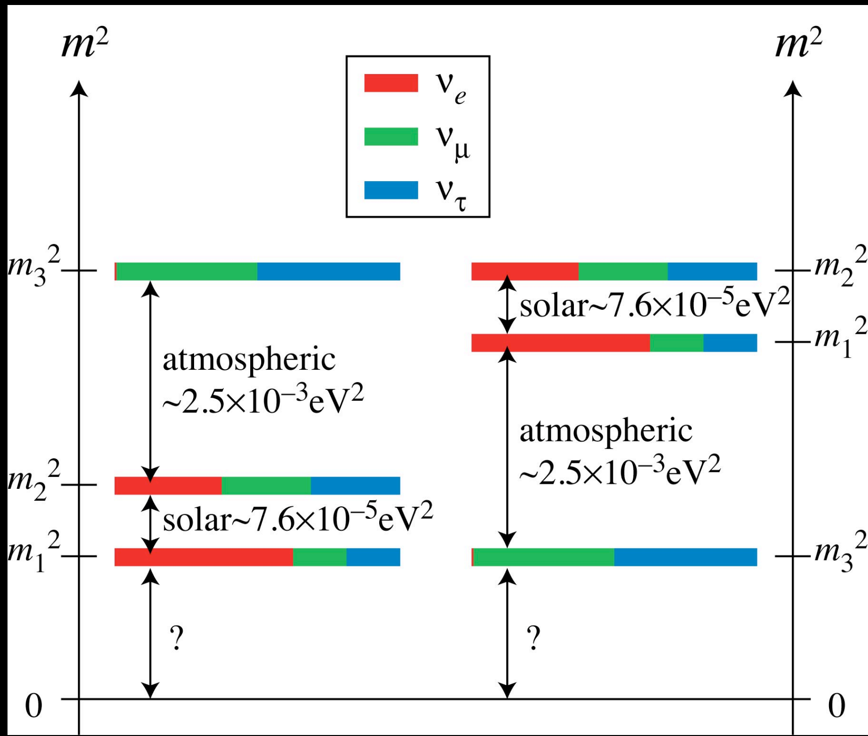
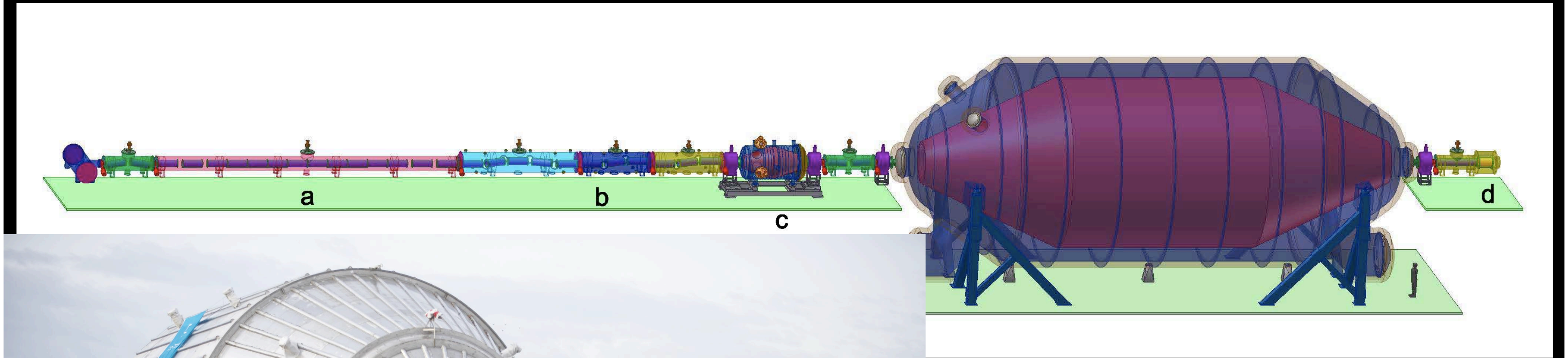


KArlsruhe TRItium Neutrino experiment (KATRIN)

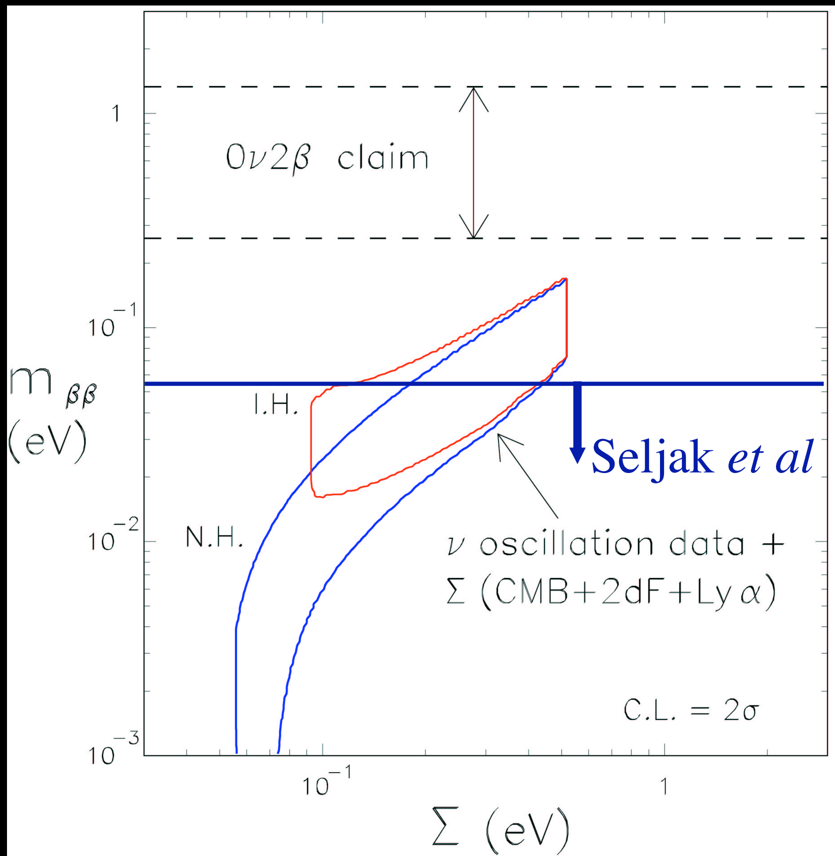


Aim:

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

Cosmology vs Laboratory

- $<m_{\nu e}>=\Sigma_i m_{\nu i} U_{ei}^2$
- tension between the Heidelberg-Moscow claim and cosmology
- Still subject to the uncertainties in nuclear matrix element (Bahcall, HM, Peña-Garay)
- Better data and theory needed!



Lisi et al, hep-ph/0408045

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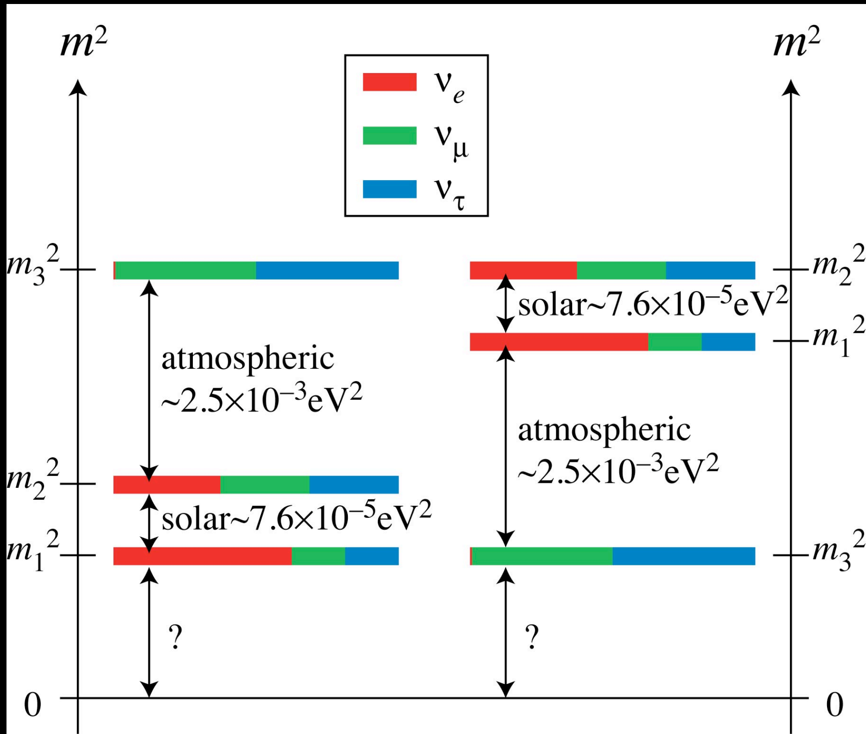
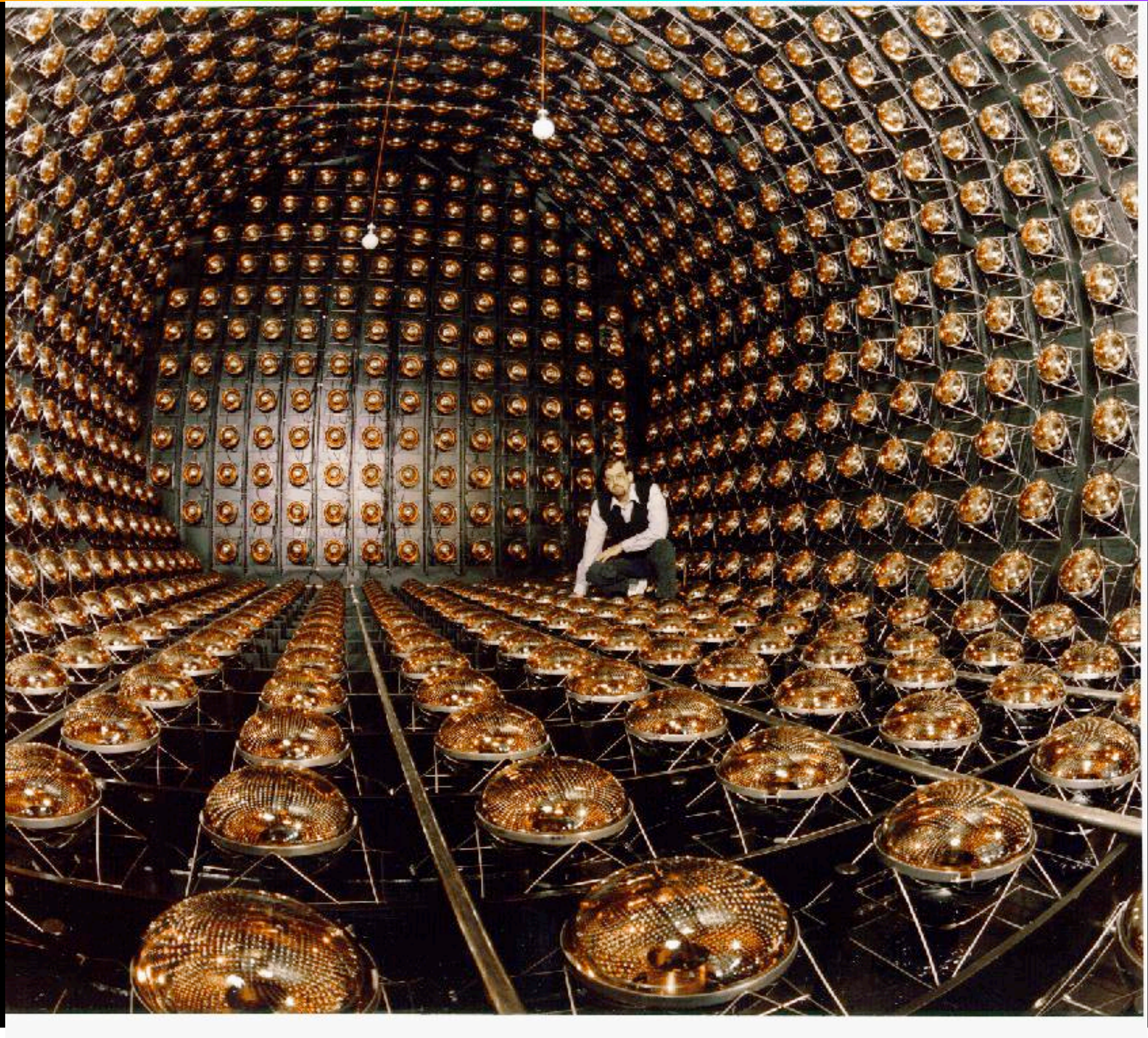
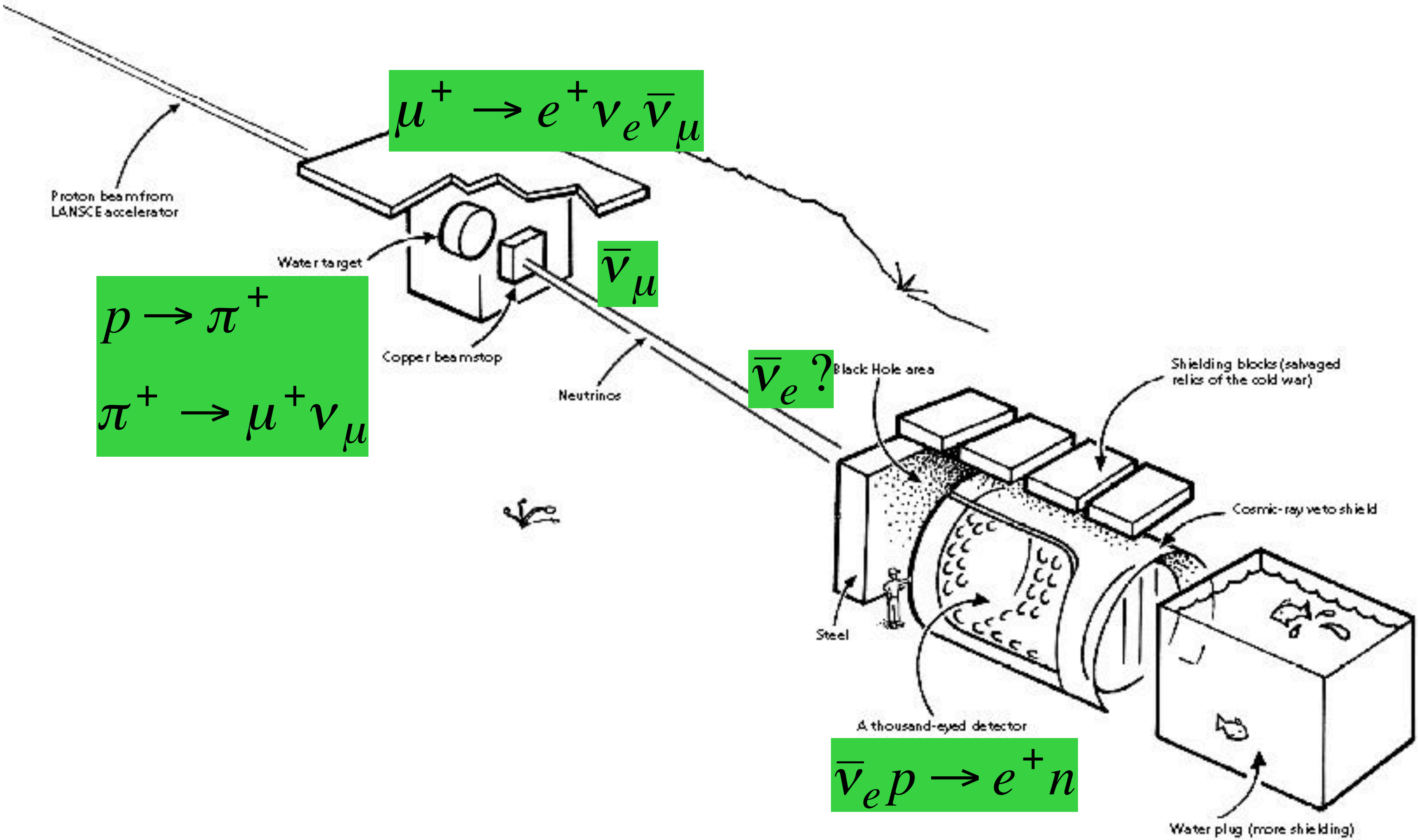


Liquid Scintillator Neutrino Detector (LSND) @ Los Alamos



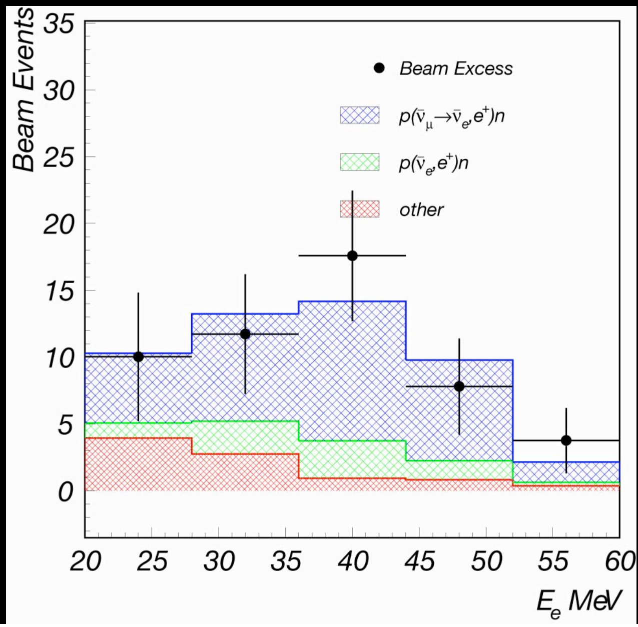


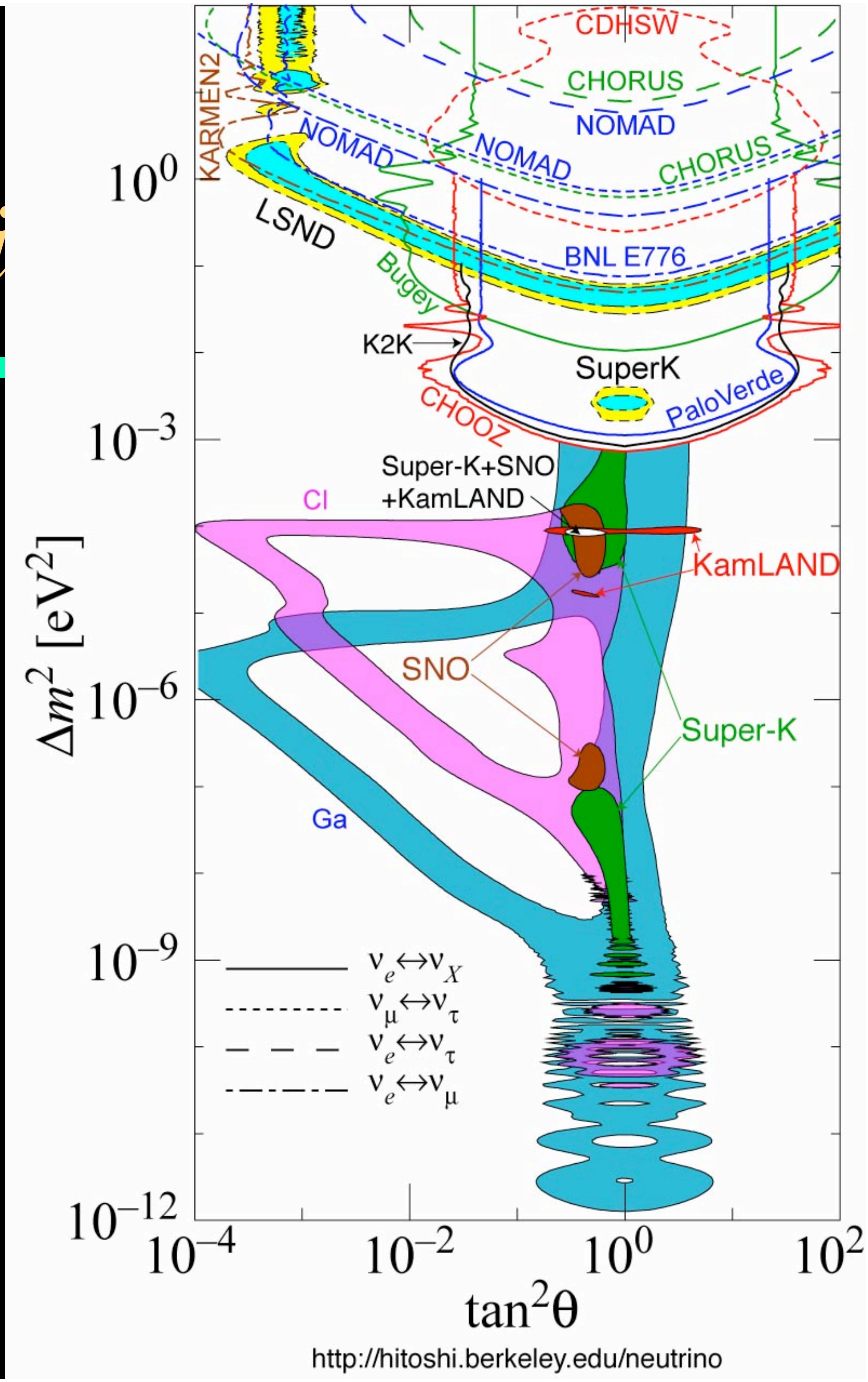
$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
Proton beam from LANSCE accelerator
Water target
$\bar{\nu}_\mu$
$p \to \pi^+$
$\pi^+ \to \mu^+ \nu_\mu$
Copper beamstop
Neutrinos
$\bar{\nu}_e$?
Black Hole area
Shielding blocks (salvaged relics of the cold war)
Cosmic-ray veto shield
Steel
A thousand-eyed detector
$\bar{\nu}_e p \to e^+ n$
Water plug (more shielding)

3.3σ Si

- Excess positron events over calculated BG

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





Sterile Neutrino

- LSND, atmospheric and solar neutrino oscillation signals

  $\Delta m^2_{\mathrm{LSND}} \sim \mathrm{eV}^2$

  $\Delta m^2_{\mathrm{atm}} \sim 3\times10^{-3}\mathrm{eV}^2$

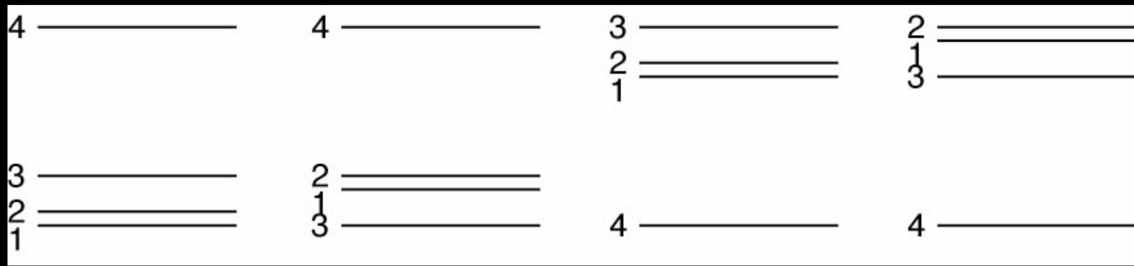
  $\Delta m^2_{\mathrm{solar}} < 10^{-3}\mathrm{eV}^2$

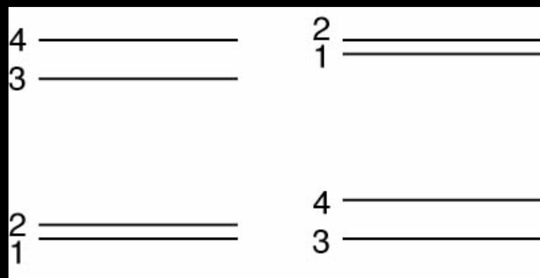
  ⇒ Can’t be accommodated with 3 neutrinos

  ⇒ Need a *sterile neutrino*

  New type of neutrino with no weak interaction

- 3+1 or 2+2 spectrum?





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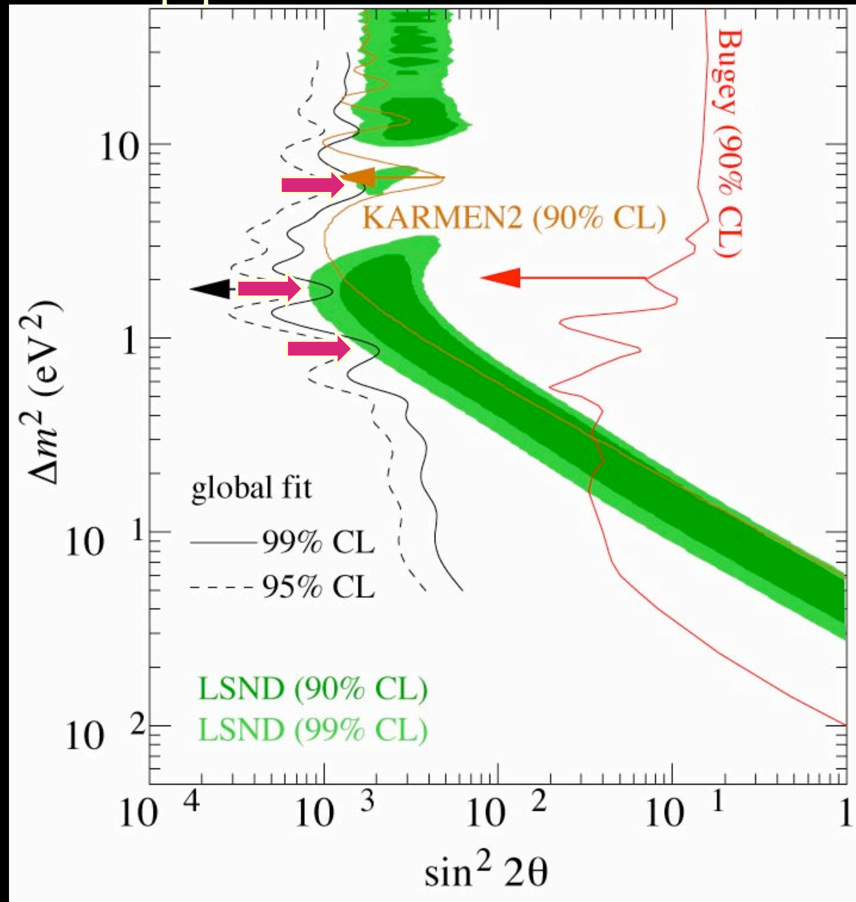
Sterile Neutrino disfavored

- 2+2 spectrum:
  preferred in past fits
  - Atmospheric mostly $\nu_\mu \leftrightarrow \nu_\tau$
  - Solar mostly $\nu_e \leftrightarrow \nu_a$ (or vice versa)
  - Now solar sterile getting tight due to SNO

  ⇒ *Disfavored 1.6 10^{-6}* (Maltoni et al)
- 3+1 spectrum:
  $\sin^2 2\theta_{LSND}=4|U_{4e}|^2|U_{4\mu}|^2$
  - $|U_{4\mu}|^2$ can't be big because of CDHS, SK U/D
  - $|U_{4e}|^2$ can't be big because of Bugey

  ⇒ *Disfavored 5.6 10^{-3}* (Maltoni et al)

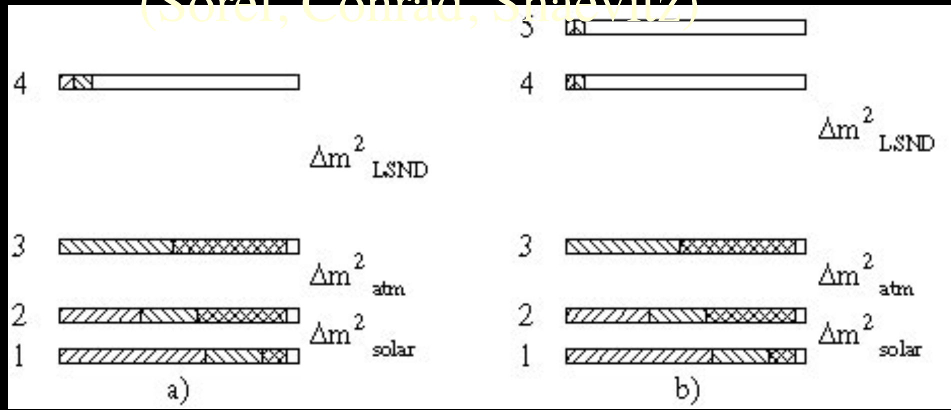
Maltoni, Schwetz, Tortola, Valle
hep-ph/0209368



More Sterile Neutrinos?

- Who said there is only one sterile neutrino?
- There could well be one for each generation
- Do more sterile neutrinos help?
- Maybe 3+2 better

(Sorel, Conrad, Shaevitz)

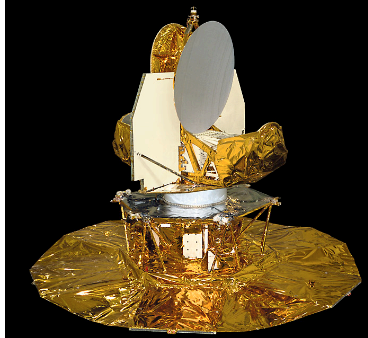


P_{LSND}<0.10% P_{LSND}< 0.20%

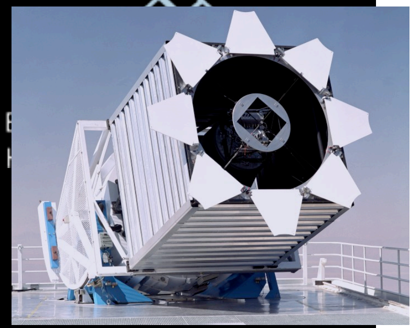
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$

LSND not as oscillation

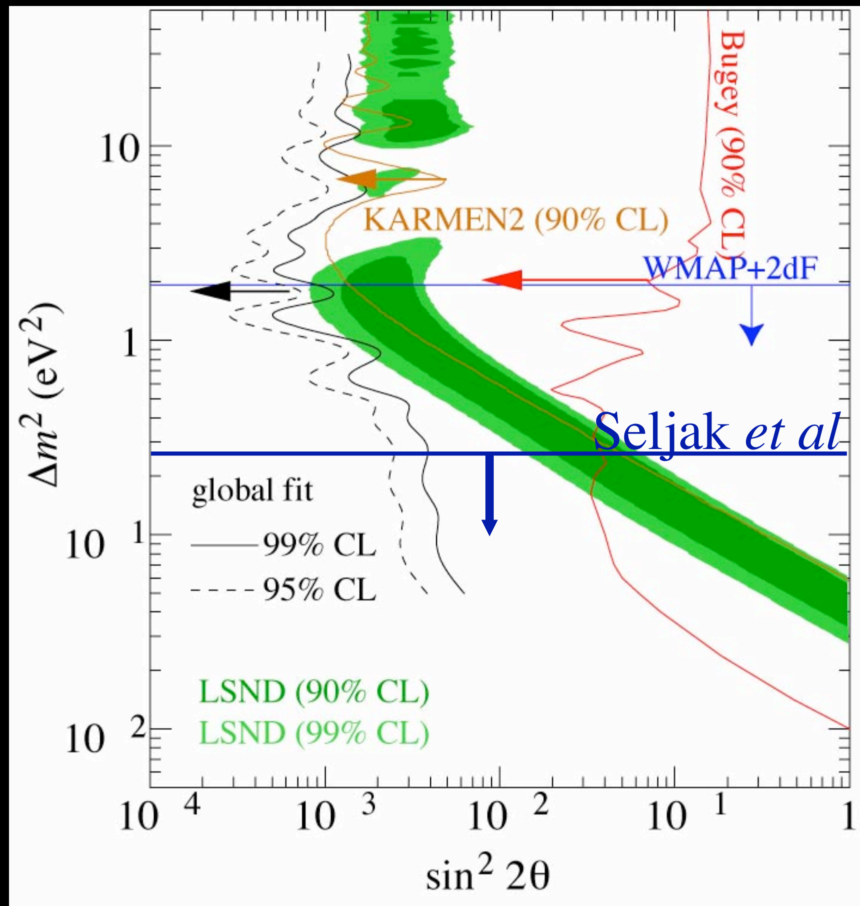
- Maybe LSND detected anomalous decay of muon (Babu, Pakvasa)
- Lepton-number violation $\mu^+ \to e^+ \overline{\nu_\mu} \overline{\nu_e}$
- KARMEN disfavors it
  - BR<0.009 (90%) while LSND wants BR=0.019–0.040
- No signal at Mini-BooNE
- Predicts Michel parameter ρ=0.7485 ≠ 0.75 (SM)
- Accuracy <2004: ρ=0.7518±0.0026
- TWIST experiment at TRIUMF measured Michel parameter: ρ=0.75080±0.00032±0.00097
- Doesn't work any more!



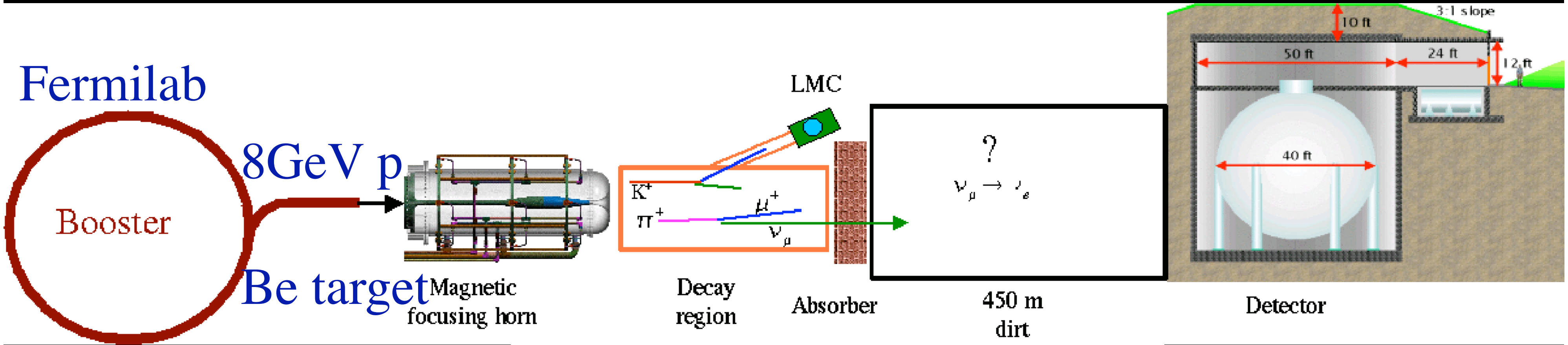
WMAP+SDSS+Lyman α



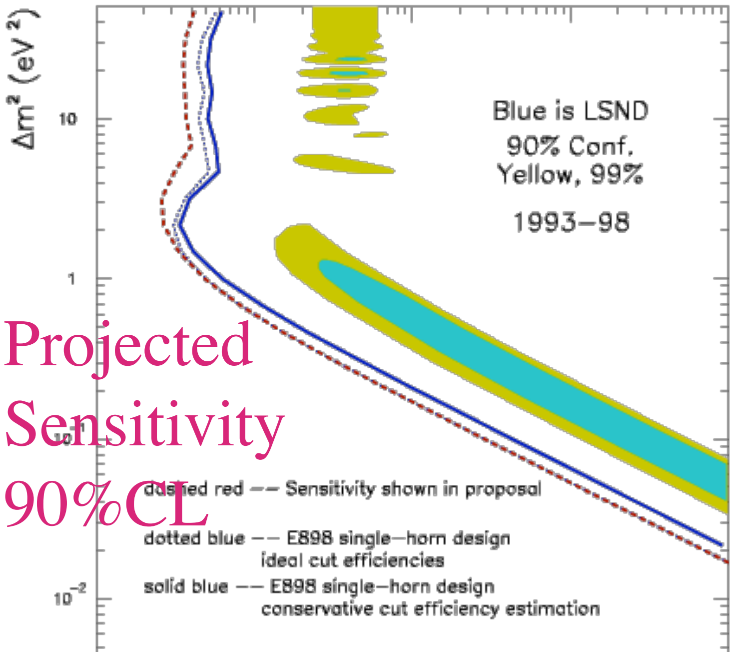
- Allowing for extra neutrino species, the mass bound weakens
- The most aggressive analysis still disfavors LSND mass scale $m_{\nu 4}<0.26$ eV
- Assumption: all species *thermalized*



Mini-BooNE



Same L/E
As LSND



Projected
Sensitivity
90%CL

Very challenging
with one detector
needs to understand
beam, cross section
efficiency, PID
very well

Mini-BooNE result April 2007

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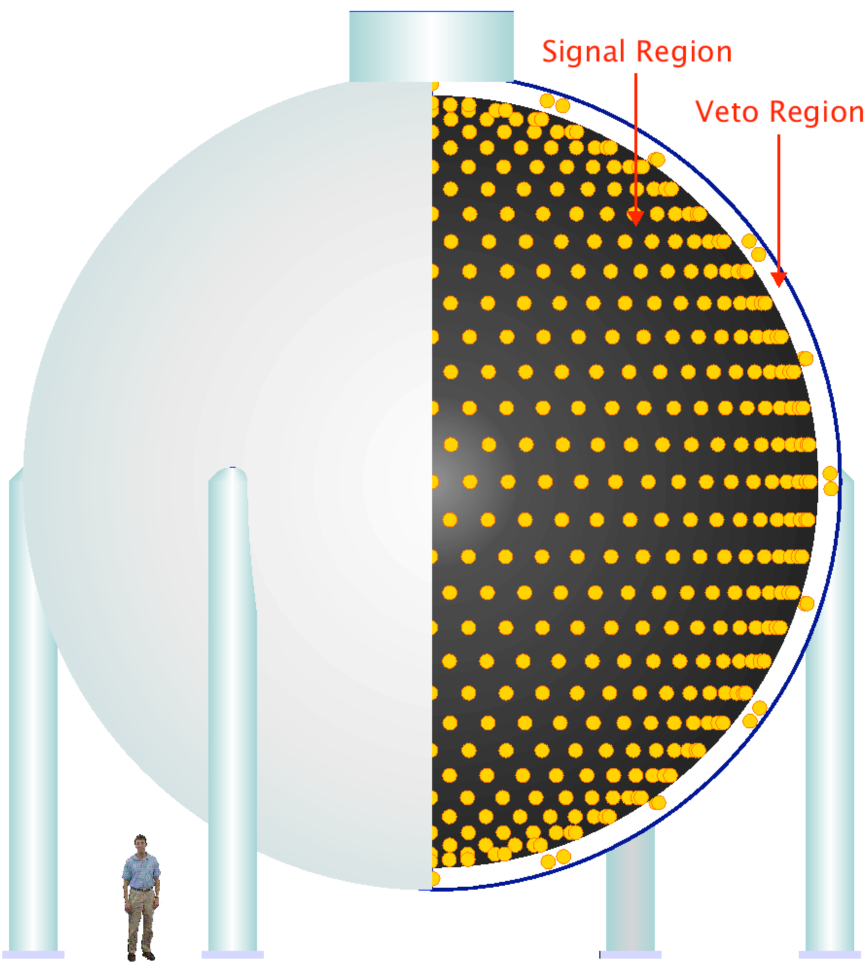
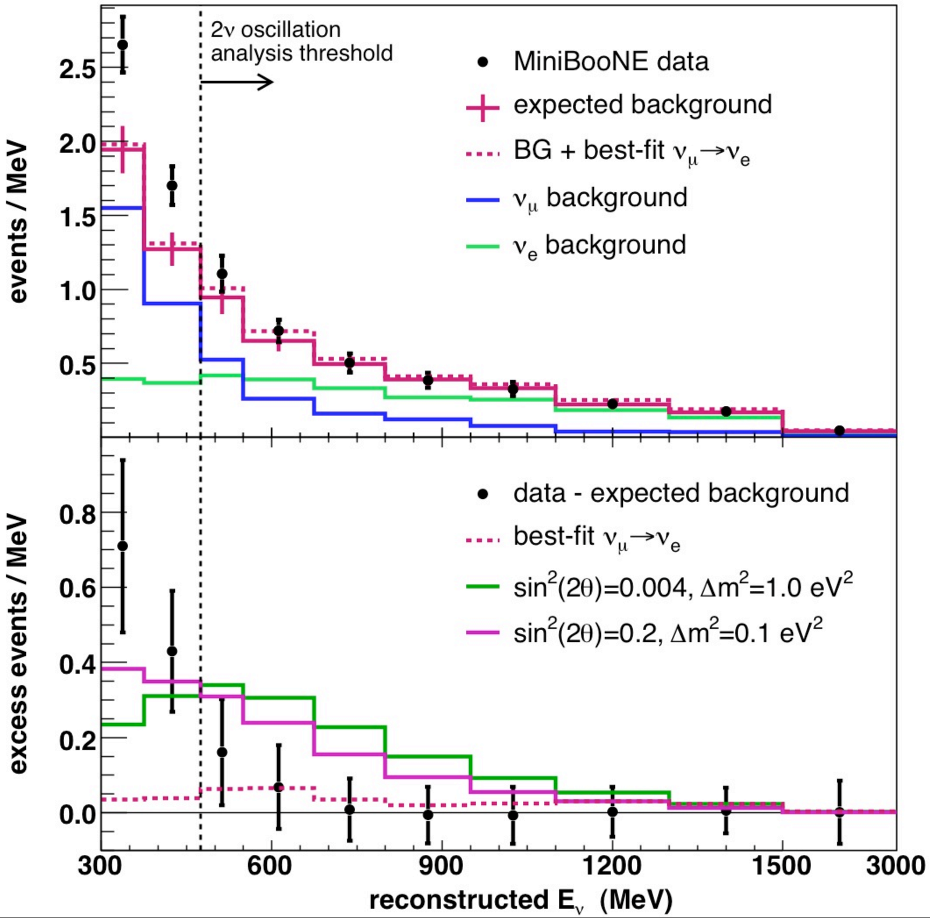
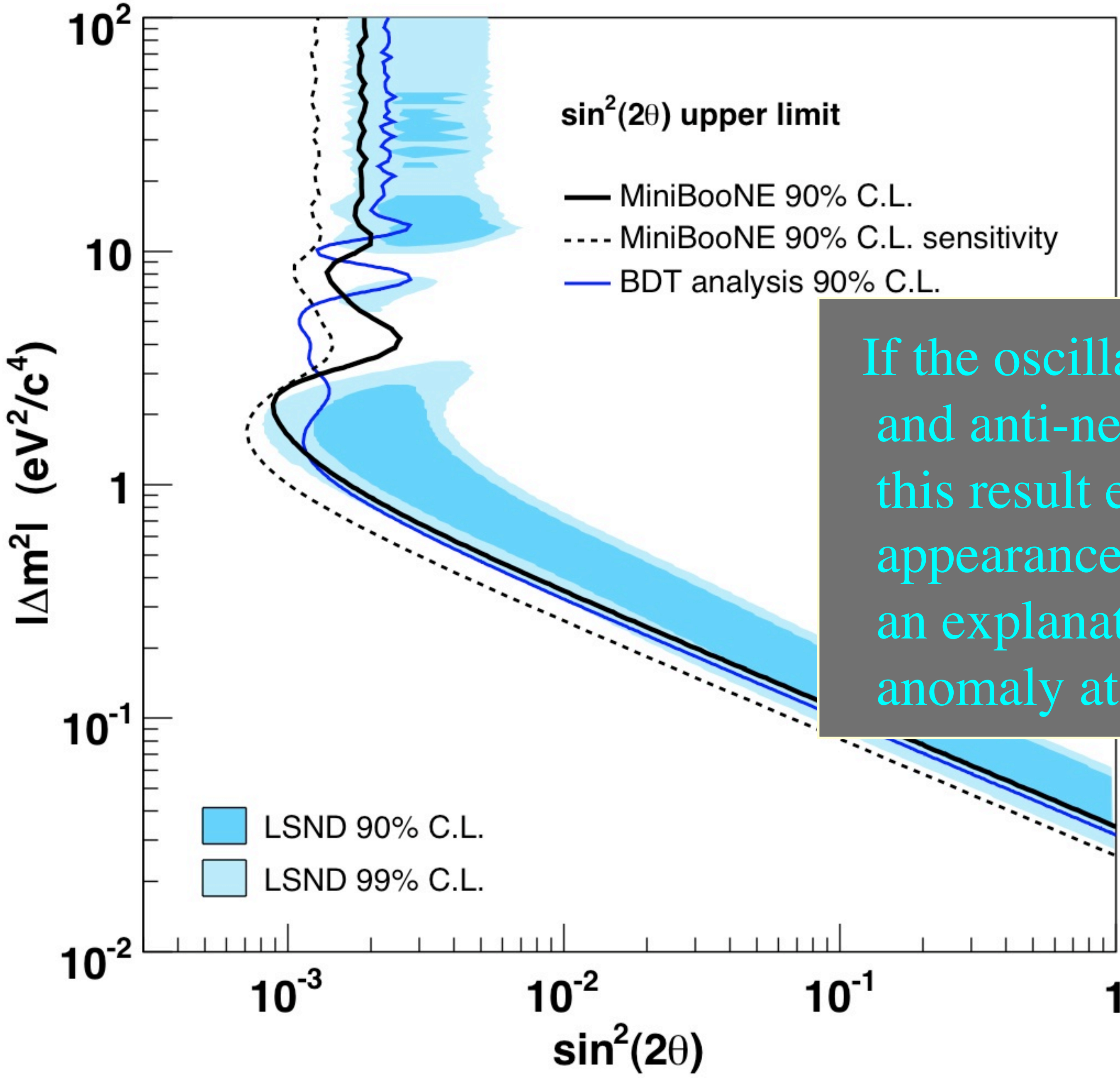
MiniBooNE Detector





2007



If the oscillations of neutrinos and anti-neutrinos are the same, this result excludes two neutrino appearance-only oscillations as an explanation of the LSND anomaly at 98% CL.

More exotic ideas

- *Desperate remedy…*
- CP violation?
  - 3+2 spectrum reconciles LSND & Mini-BooNE
  - But still tension with short baseline data (Maltoni, Schwetz)
- CPT violation? (HM, Yanagida)
  - 3+1 spectrum plus CPT violation best fit (Barger, Marfatia, Whisnant)
- Mass-Varying Neutrinos (MaVaN)? (Nelson, Weiner)
- Short cuts in Extra dimensions? (Päs, Pakvasa, Weiler)

LSND Conclusions

- Mini-BooNE disfavors LSND, but
  - Only at 98% CL, not quite definitive
  - Maybe neutrinos & anti-neutrinos oscillate differently?
  - CP violation not enough, need CPT violation and/or exotic matter effect (MaVaN)
  - Most people now dismiss LSND
  - May need new experiments, esp. with anti-neutrinos

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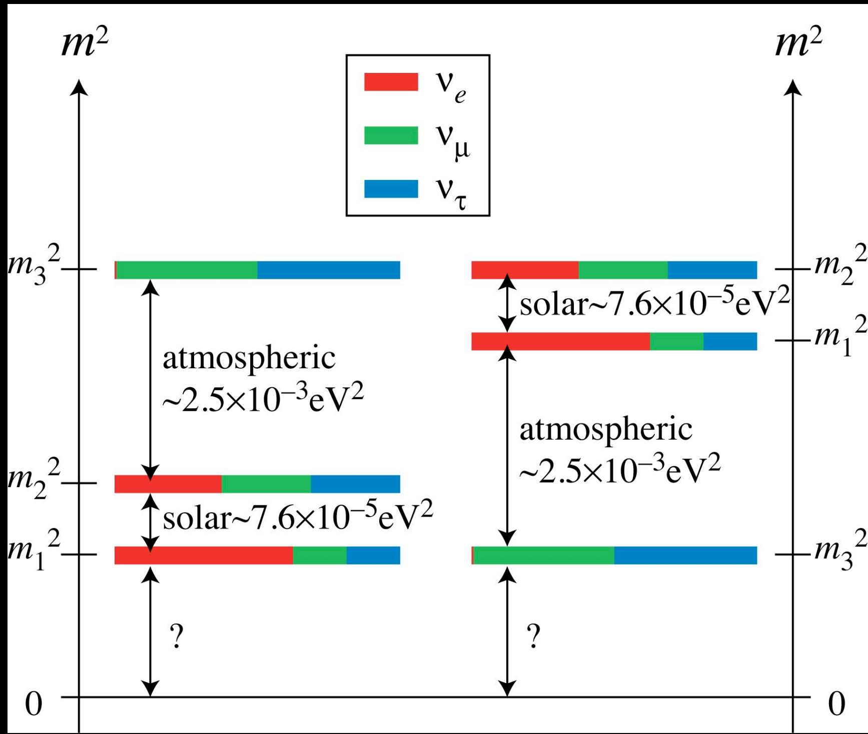
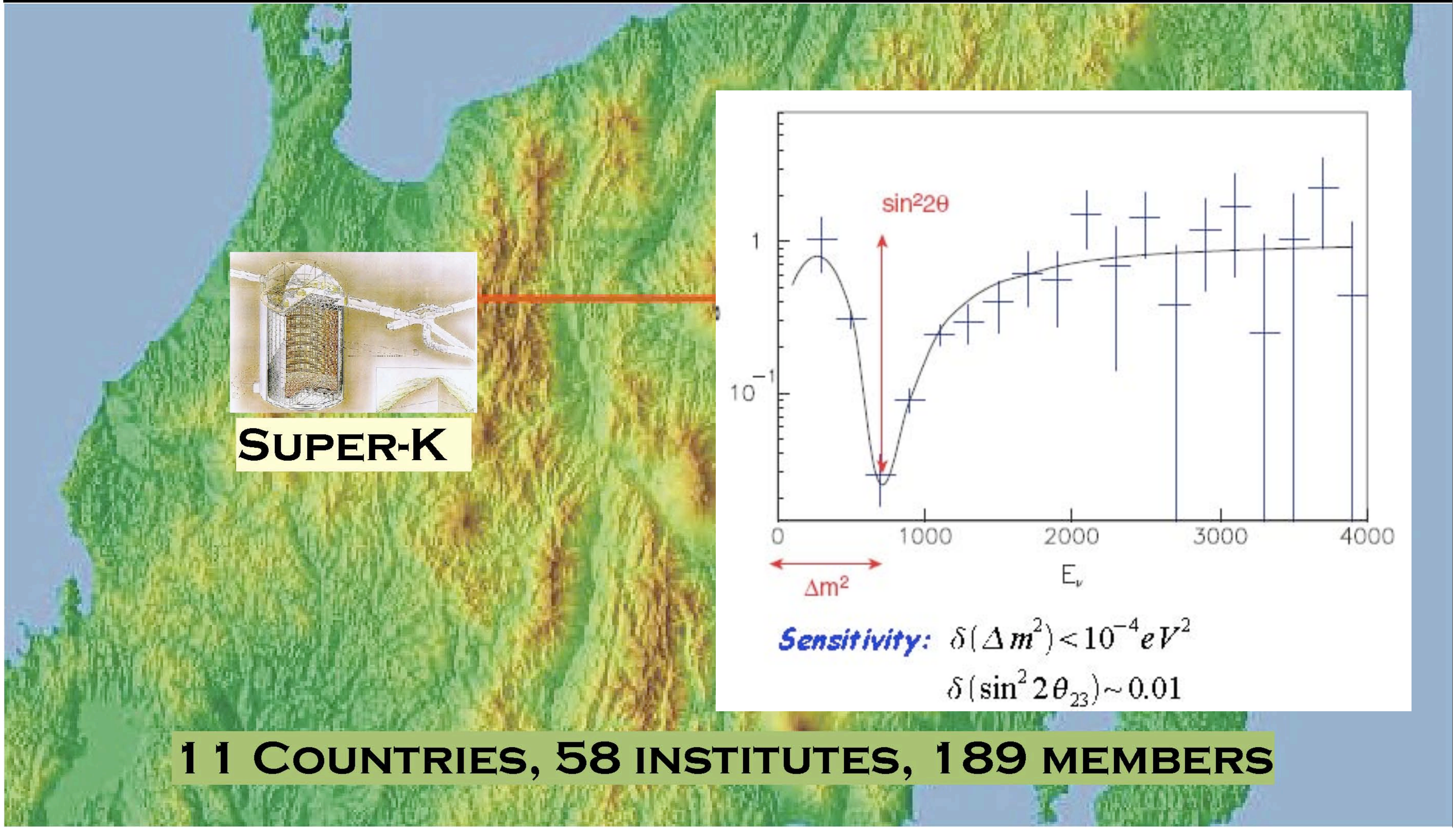


T2K (Tokai to Kamioka)



11 COUNTRIES, 58 INSTITUTES, 189 MEMBERS

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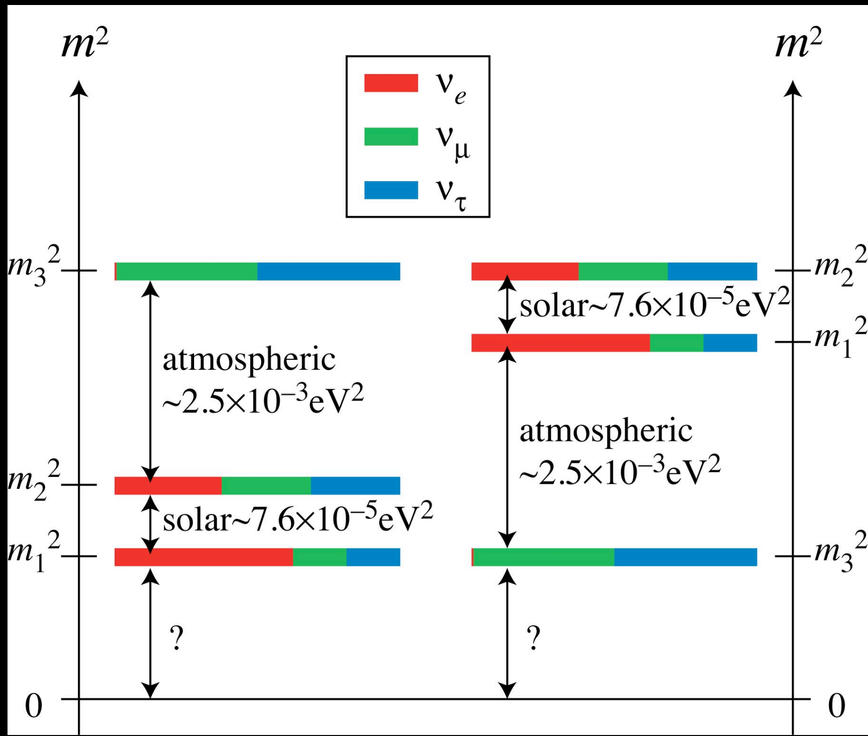


LMA confirmed by KamLAND

- Dream case for neutrino oscillation physics!
- $\Delta m^2_{\rm solar}$ within reach of long-baseline expts
- Even CP violation may be probable

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

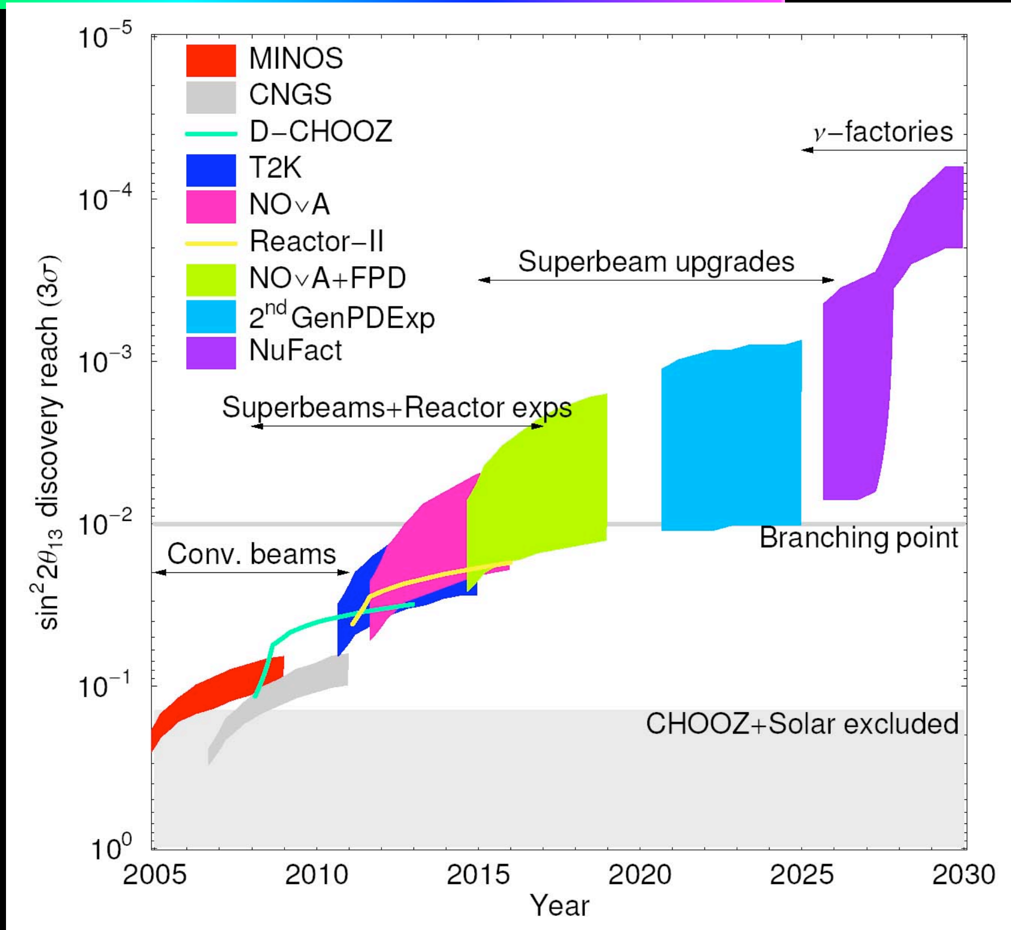
- Possible only if:
  - $\Delta m_{12}{}^2$, s_{12} large enough (LMA)
  - θ_{13} large enough

θ_{13} decides the future

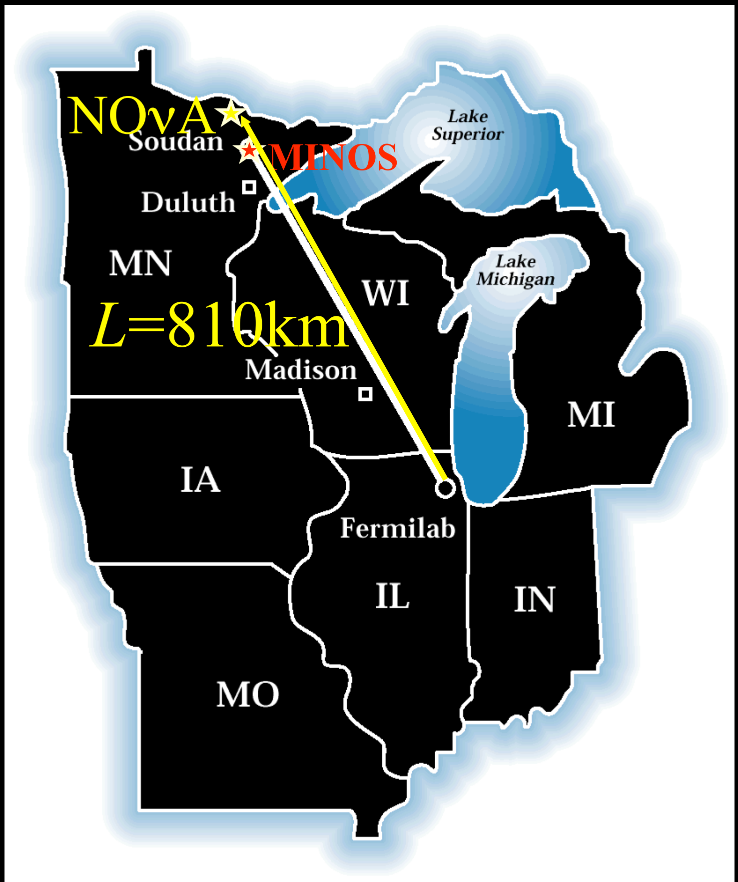
- The value of θ_{13} crucial for the future of neutrino oscillation physics
- Determines the required facility/parameters /baseline/energy
  - $\sin^2 2\theta_{13} > 0.01 \Rightarrow$ conventional neutrino beam
  - $\sin^2 2\theta_{13} < 0.01 \Rightarrow$ μ storage ring, β beam
- Two paths to determine θ_{13}
  - Long-baseline accelerator: T2K, NOνA
  - Reactor neutrino experiment: 2×CHOOZ, Daya Bay

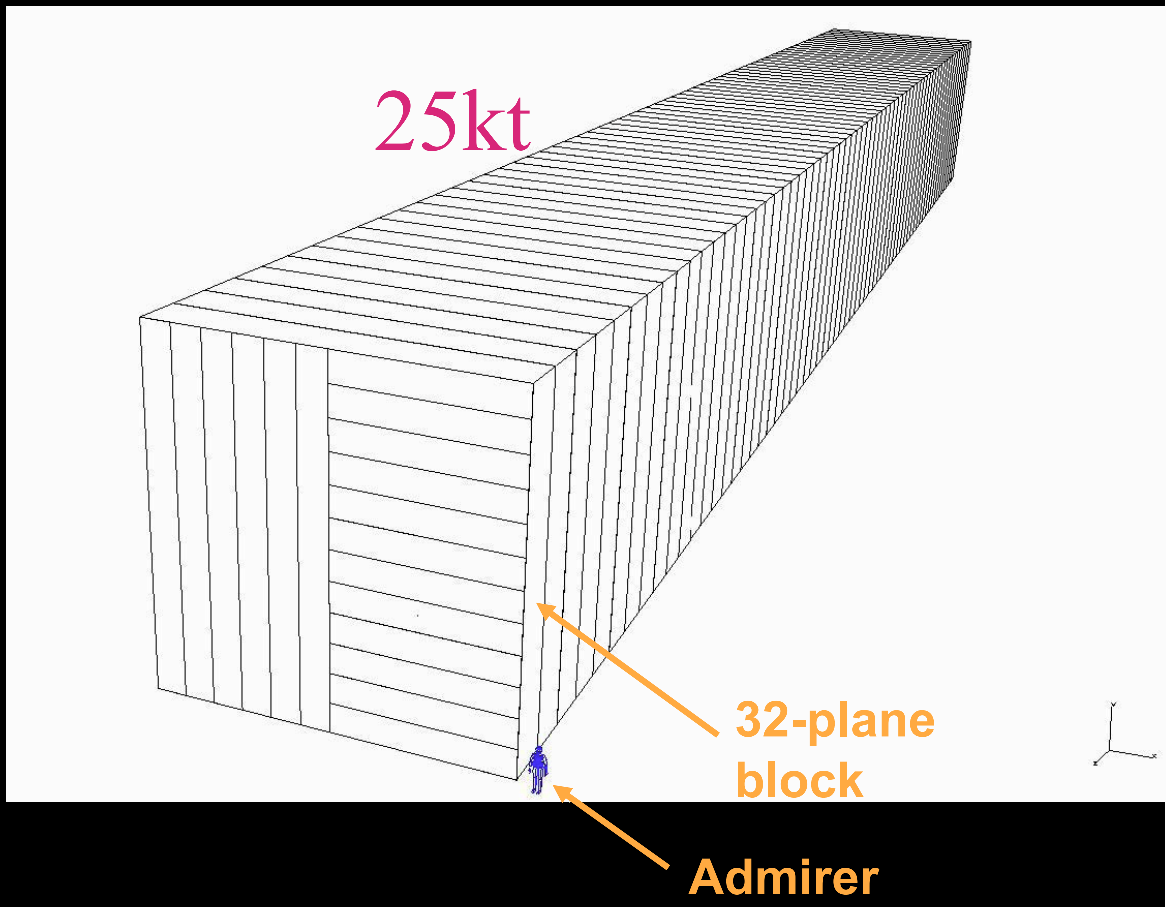
Need for new facilities

- The answer depends on what we will find in the near future

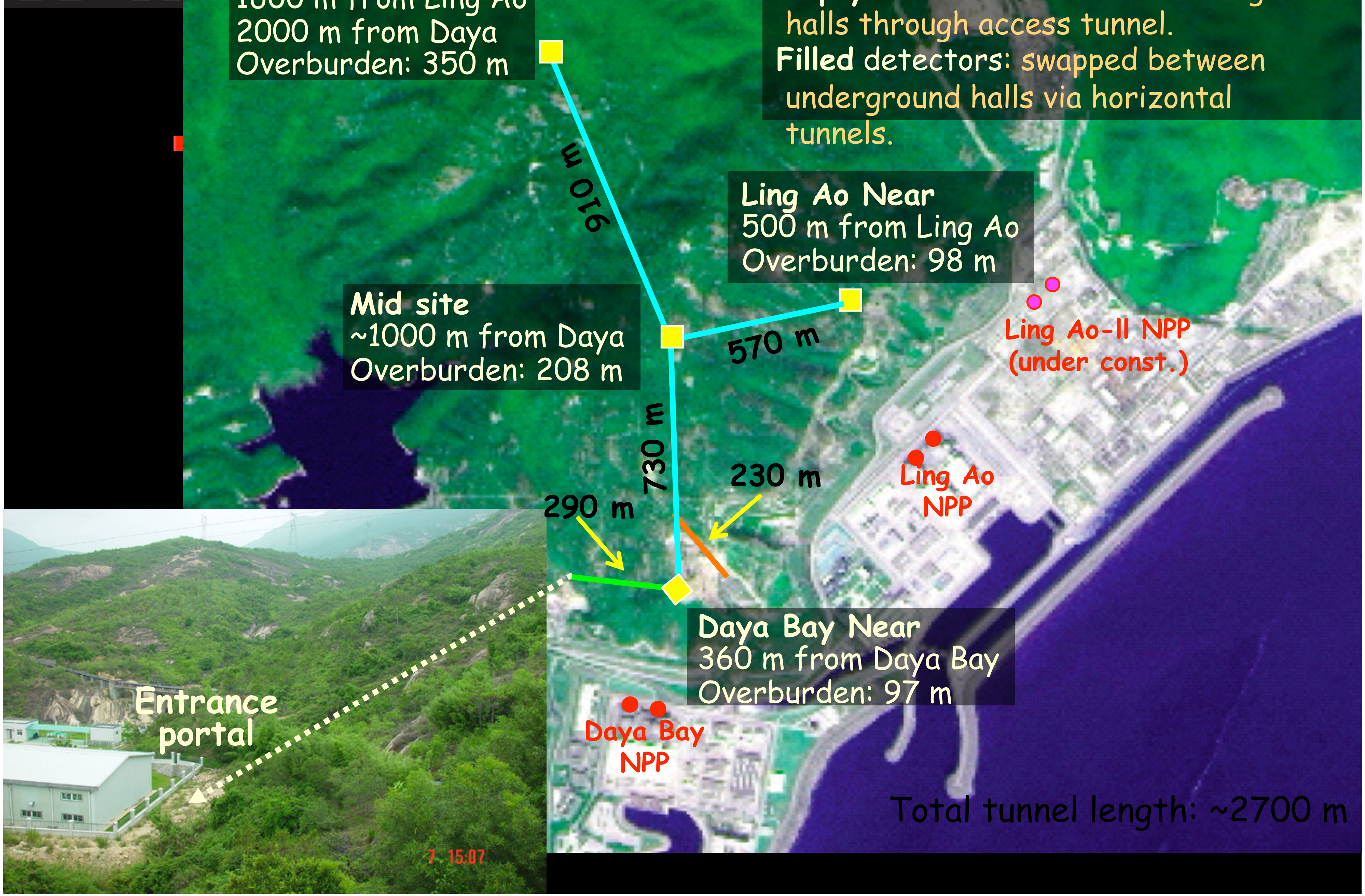


NOνA
Fermilab to Minnesota

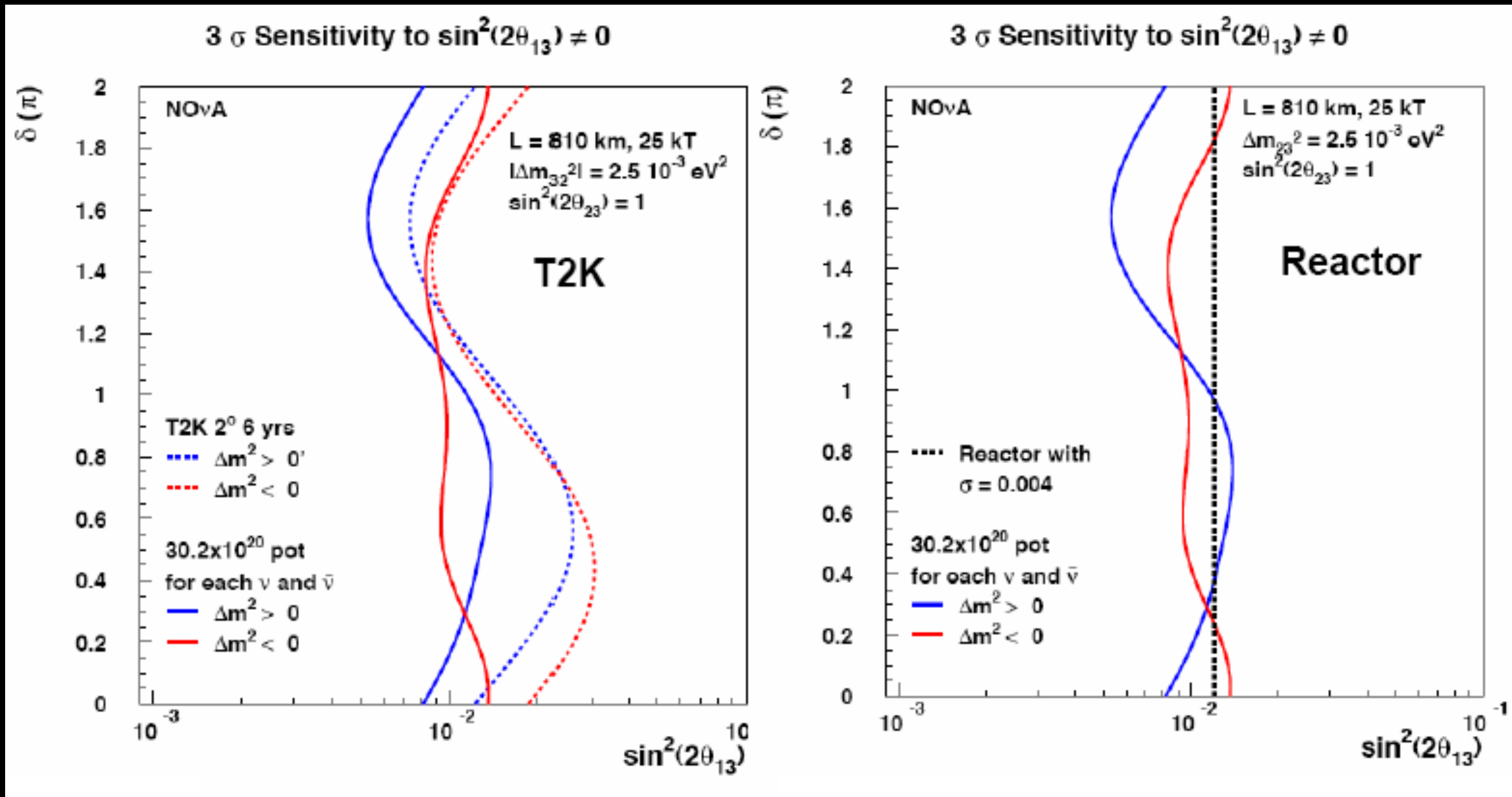




Daya Bay


Far site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.
910 m
Ling Ao Near
500 m from Ling Ao
Overburden: 98 m
Mid site
~1000 m from Daya
Overburden: 208 m
570 m
Ling Ao-II NPP
(under const.)
730 m
230 m
290 m
Ling Ao
NPP
Daya Bay Near
360 m from Daya Bay
Overburden: 97 m
Entrance
portal
Daya Bay
NPP
Total tunnel length: ~2700 m
7 15:07

3σ *sensitivity on* $\sin^2 2\theta_{13}$



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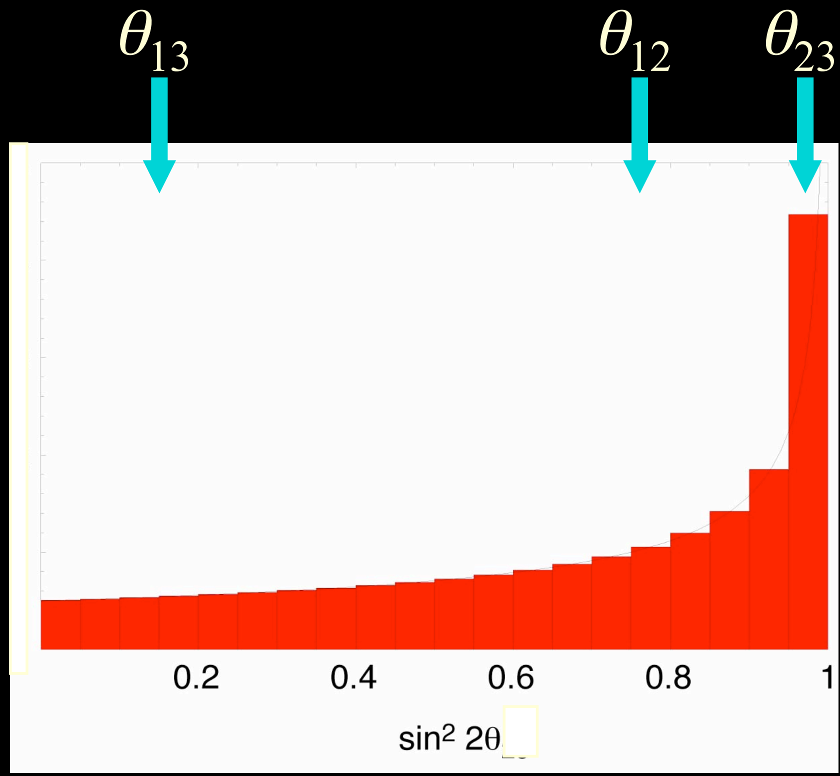
My prejudice

- 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)

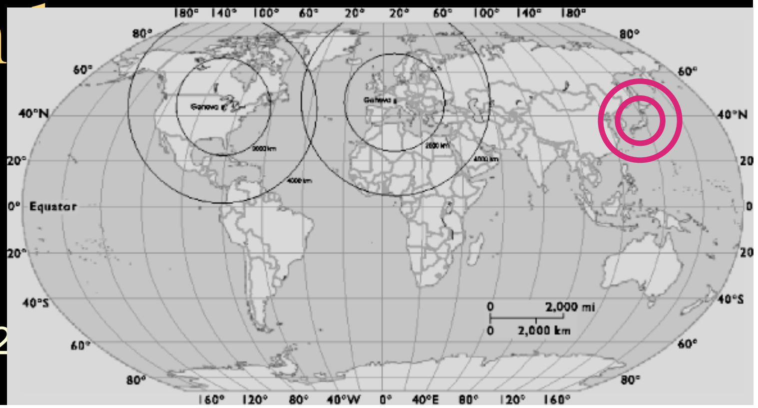


Neutrino mass anarchy

(Hall, HM, Weiner; Haba, HM)

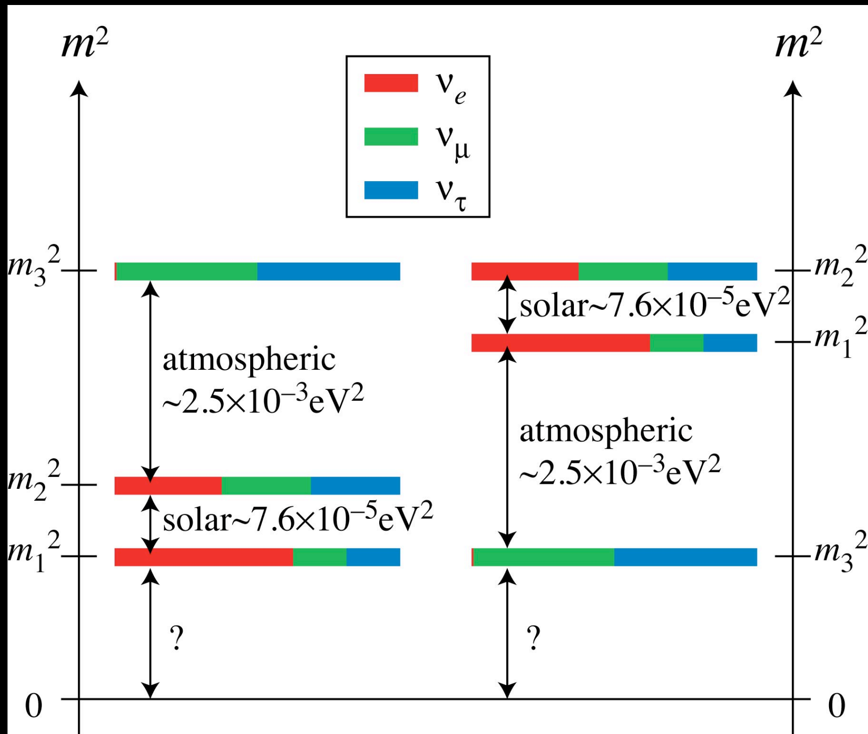
Anarchy is Peaceful

- Anarchy (Miriam-Webster): "*A utopian society of individuals who enjoy complete freedom without government*"
- Peaceful ideology that neutrinos work together based on their good will
- Predicts large mixings, LMA
- $\sin^2 2\theta_{13}$ just below the boun
- Wants *globalization*!



Immediate Questions

- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- Is θ_{23} maximal?
- LSND? Sterile neutrino(s)? CPT violation?



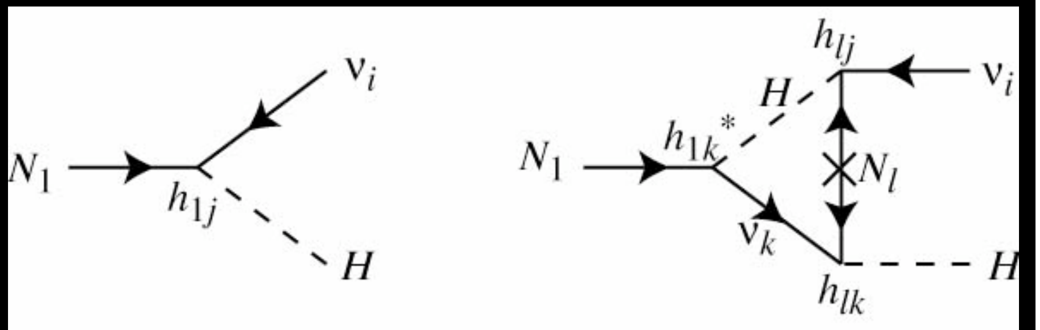
What about the Big Questions?

- What is the origin of neutrino mass?
- Why do they mix so much?
- 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

Leptogenesis

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



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

- L gets converted to B via EW anomaly

$\Rightarrow$ More matter than anti-matter

$\Rightarrow$ *We have survived "The Great Annihilation"*

Detaile

- Büchmuller and Plümacher
- Solve Boltzmann equation numerically

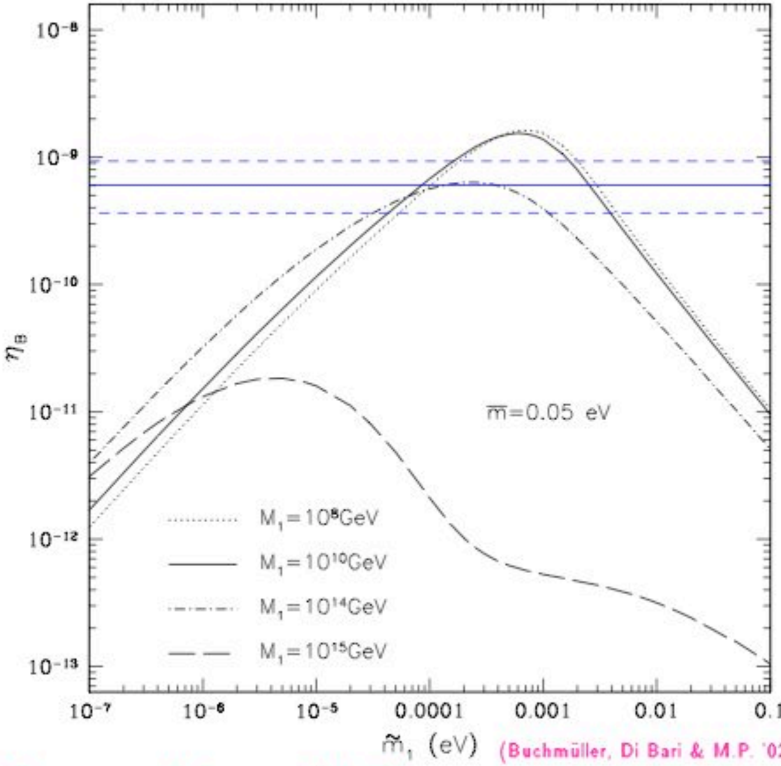
$$\Gamma_D \propto \tilde{m}_1 = \frac{1}{M_1}\left(m_D^\dagger m_D\right)_{11}$$

η_B as a function of $\tilde{m}_1$ (M.P. '96)

for hierarchical light neutrinos: $\overline{m} = 0.05$ eV

naive expectation:

$\varepsilon_1 = 10^{-6} \rightarrow \eta_B^{\max} \sim 10^{-2}\varepsilon_1 = 10^{-8}$



(Buchmüller, Di Bari & M.P. '02)

Baryogenesis is possible if

$$10^{-4}\text{ eV} \lesssim \tilde{m}_1 \lesssim 10^{-2}\text{ eV}$$

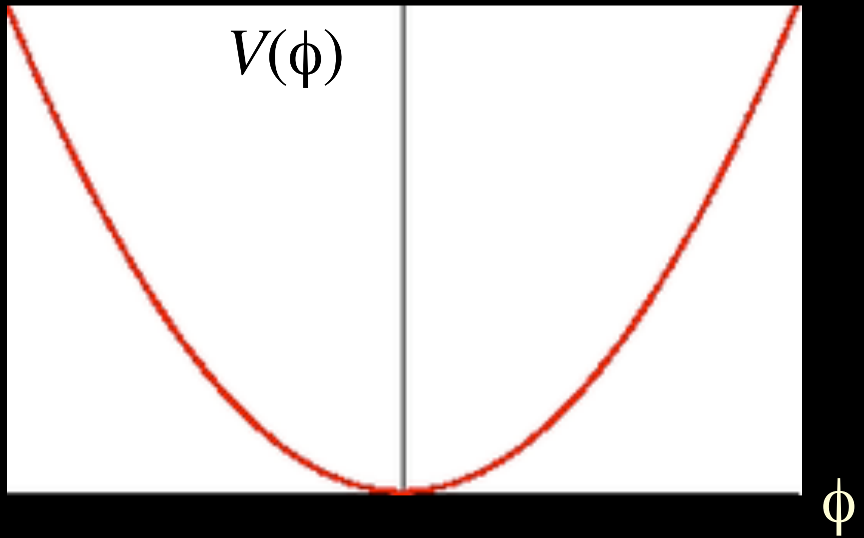
Origin of Universe

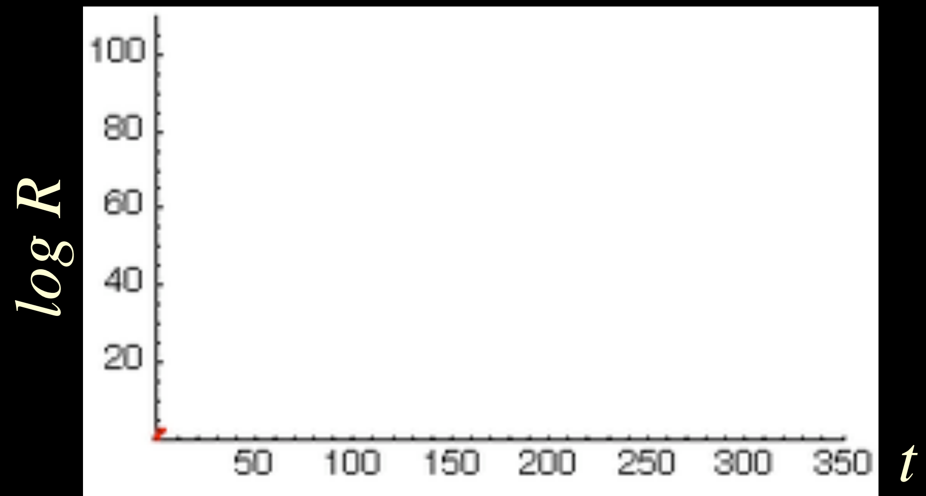
- Maybe an *even bigger* role
- Microscopically small Universe at Big Bang got stretched by an exponential expansion (inflation)
- Need a spinless field that
  - slowly rolls down the potential
  - oscillates around it minimum
  - decays to produce a thermal bath
- *The superpartner of right-handed neutrino fits the bill*
- When it decays, it produces the lepton asymmetry at the same time

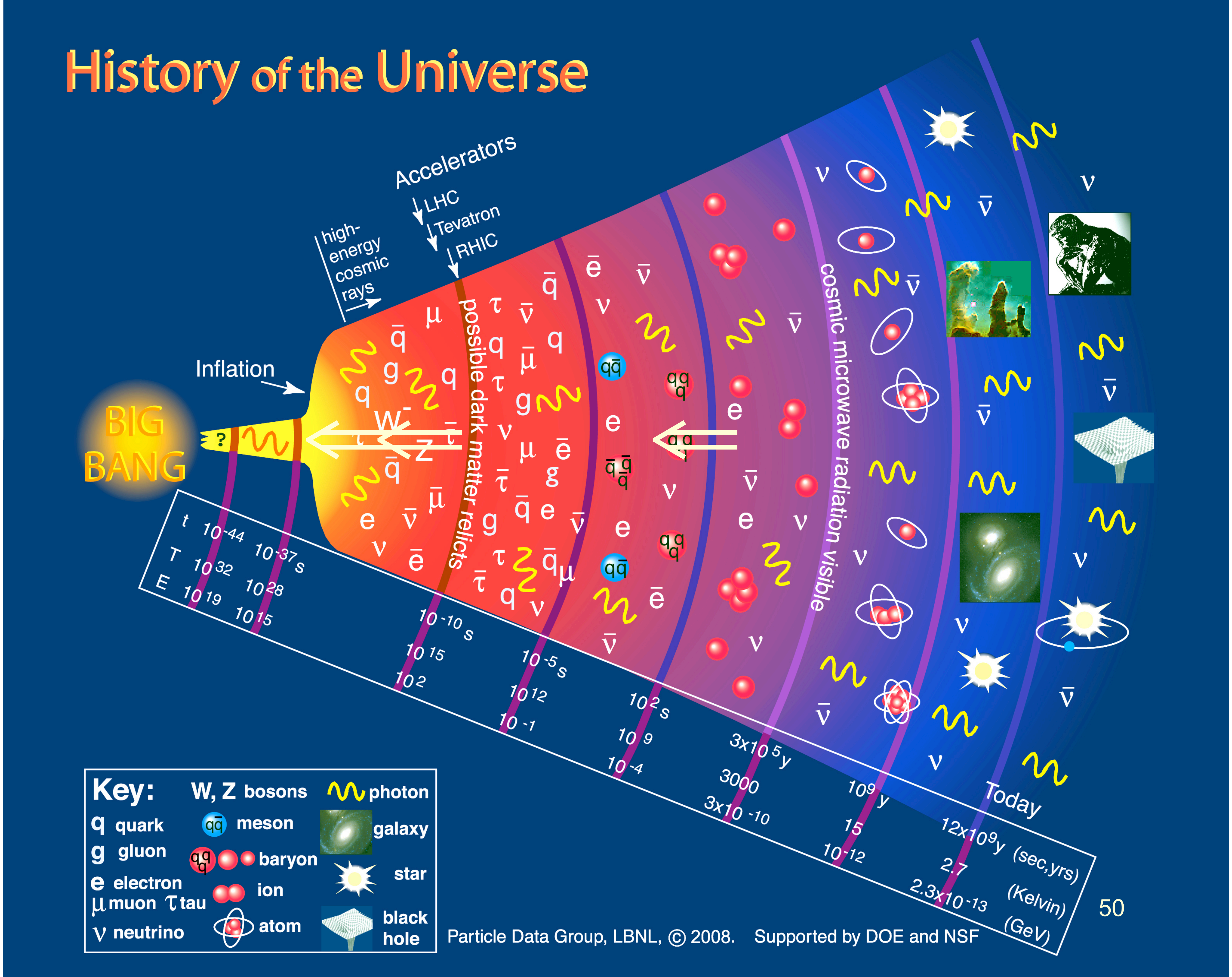
(HM, Suzuki, Yanagida, Yokoyama)

Neutrino is mother of the Universe?

$\Rightarrow$ *m*=10^{13} GeV, *consistent w/ seesaw!*






History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
µ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Experimental Tests

Can we prove it experimentally?

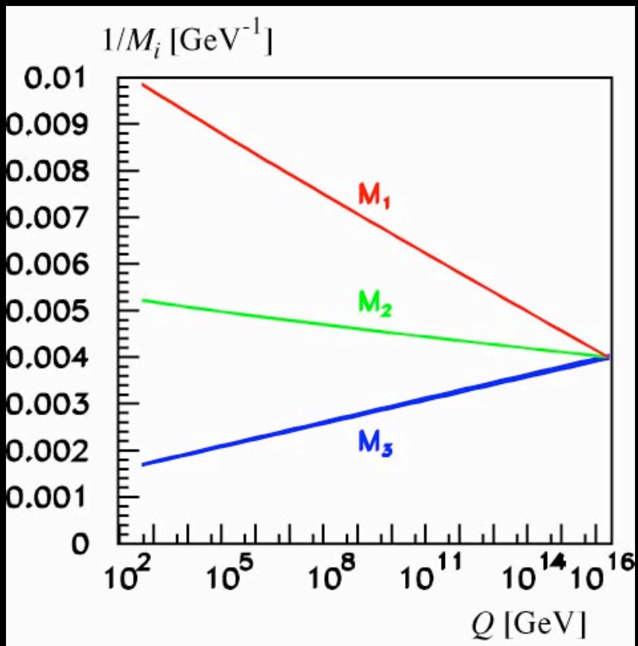
- Short answer: no. We can't access physics at $>10^{10}$ GeV with accelerators directly
- But: we will probably believe it if SUSY GUT turns out to be "proven" by data

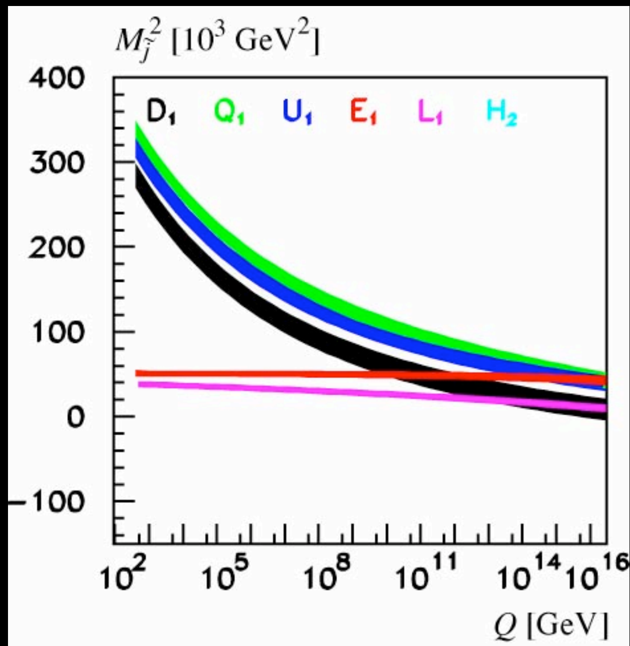
Archeological evidences

LHC/ILC may help

- LHC finds SUSY
- ILC measures masses precisely

- If both gaugino and sfermion masses unify, there can't be new particles < 10^{14}GeV except for gauge-singlets





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Plausible scenario

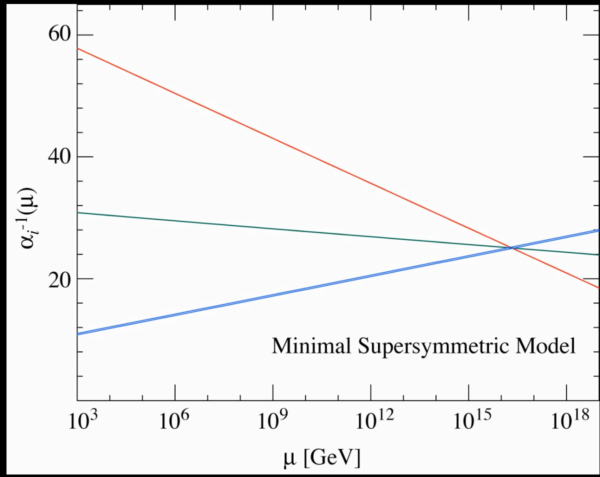
- $0\nu\beta\beta$ found
- LHC discovers SUSY
- LHC/ILC show unification of gaugino and scalar masses
- Dark matter concordance between collider, cosmology, direct detection
- CP in ν-oscillation found
- Lepton flavor violation limits ($\mu\to e\gamma$, $\mu\to e$ conversion, $\tau\to\mu\gamma$ etc) improve
- Tevatron and EDM (e and n) exclude Electroweak Baryogenesis
- CMB B-mode polarization gives tensor mode r=0.16

If this happens, we will be led to believe seesaw+leptogenesis (Buckley, HM)

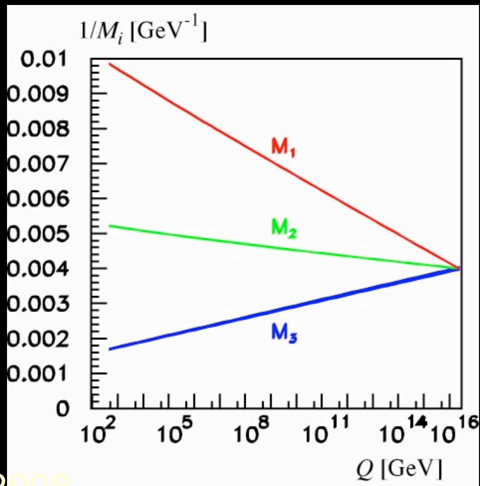
Need "New Physics" $\Lambda<10^{14}$GeV

- Now that there must be D=5 operator at Λ<a few $\times 10^{14}$GeV < M_{GUT}, we need new particles below M_{GUT}

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



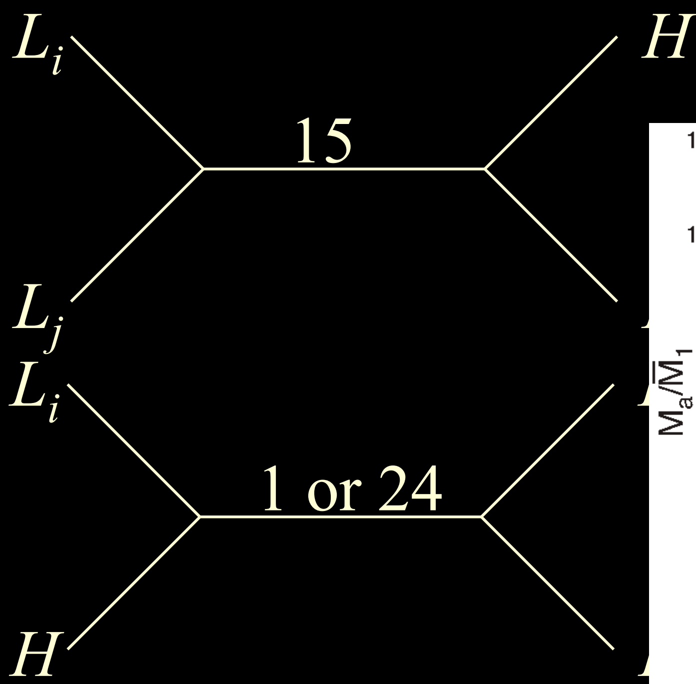
- Given gauge coupling and gaugino mass unification, they have to come in complete $SU(5)$ multiplets

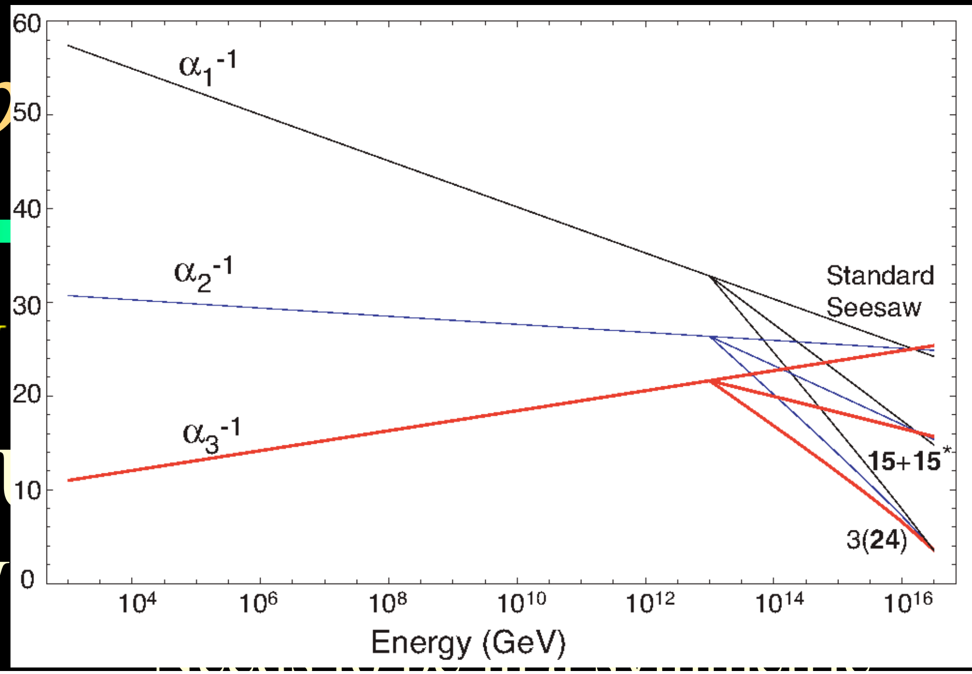


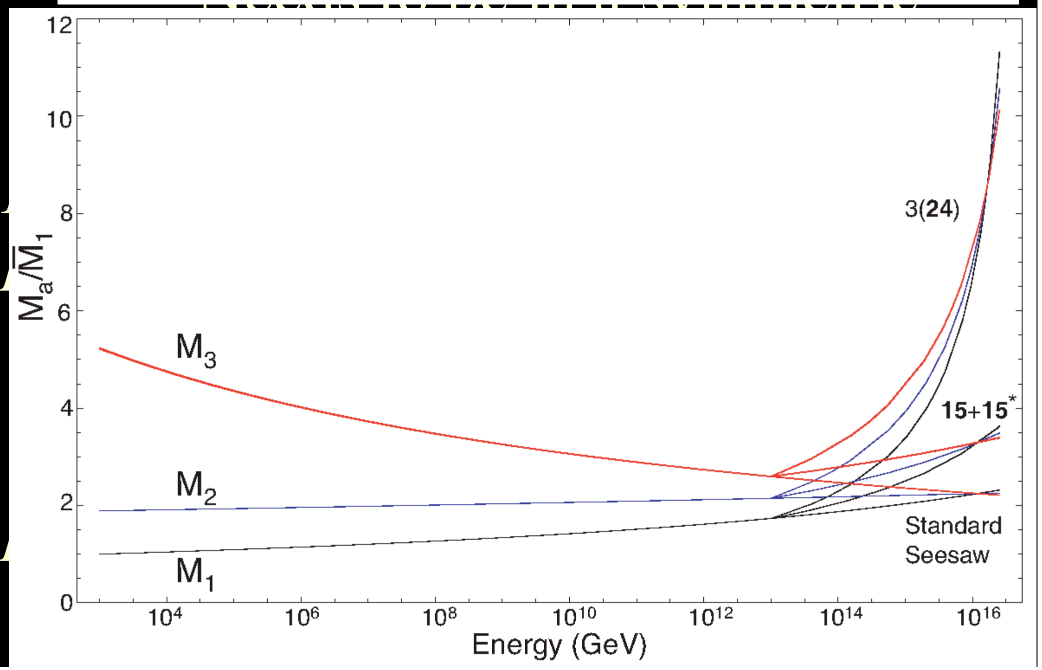
Possib

$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H$$

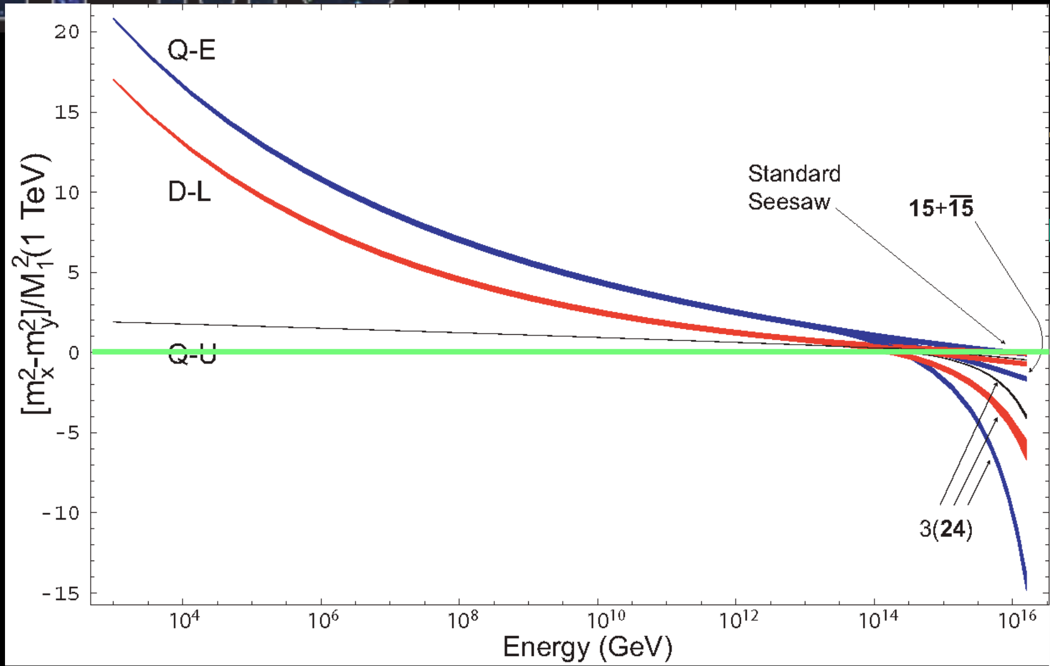
- L is in 5^*, H in 5 of SU





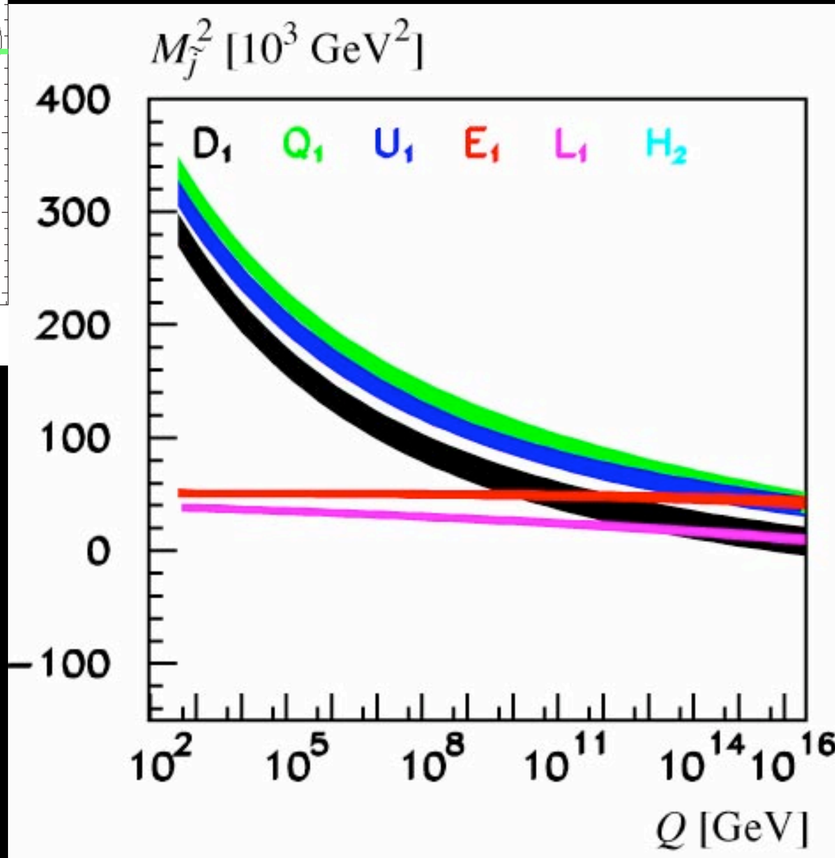


Unification

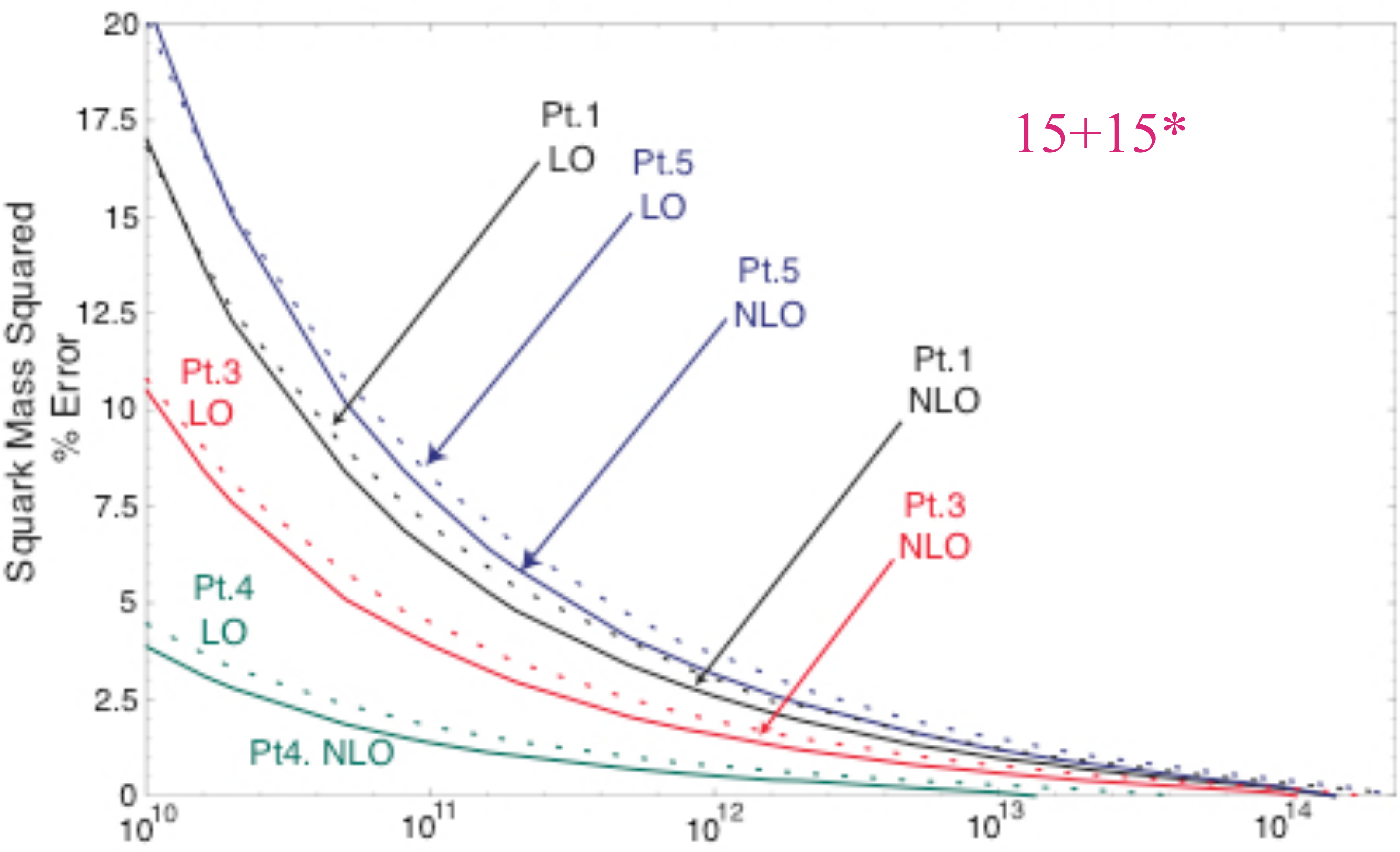


- 3×24 (modified Type I), 15+15* (Type II) generate mismatch
- 3×1 (Standard seesaw) that does not modify the scalar mass unification

(Kawamura, HM, Yamaguchi)



Needed accuracy (3σ)



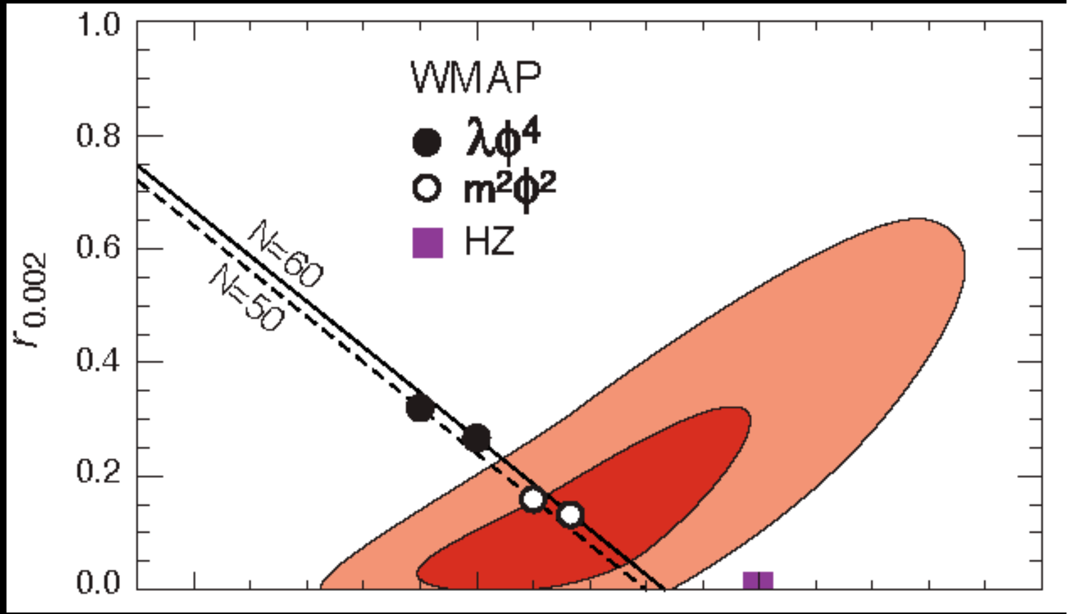
Leptogenesis?

- No new gauge non-singlets below M_{GUT} ⇒seesaw
- Either
  - Baryogenesis due to particles we know at TeV scale, *i.e.*, electroweak baryogenesis
  - Baryogenesis due to gauge-singlets well above TeV, *i.e.*, leptogenesis by ν_R
- The former can be excluded by colliders & EDM
- The latter gets support from Dark Matter concordance, *B*-mode CMB fluctuation that point to "normal" cosmology after inflation
- Additional helps from Lepton Flavor Violation (*e.g.*, $\mu \rightarrow e\gamma$), θ_{13}, CP violation in neutrino oscillation

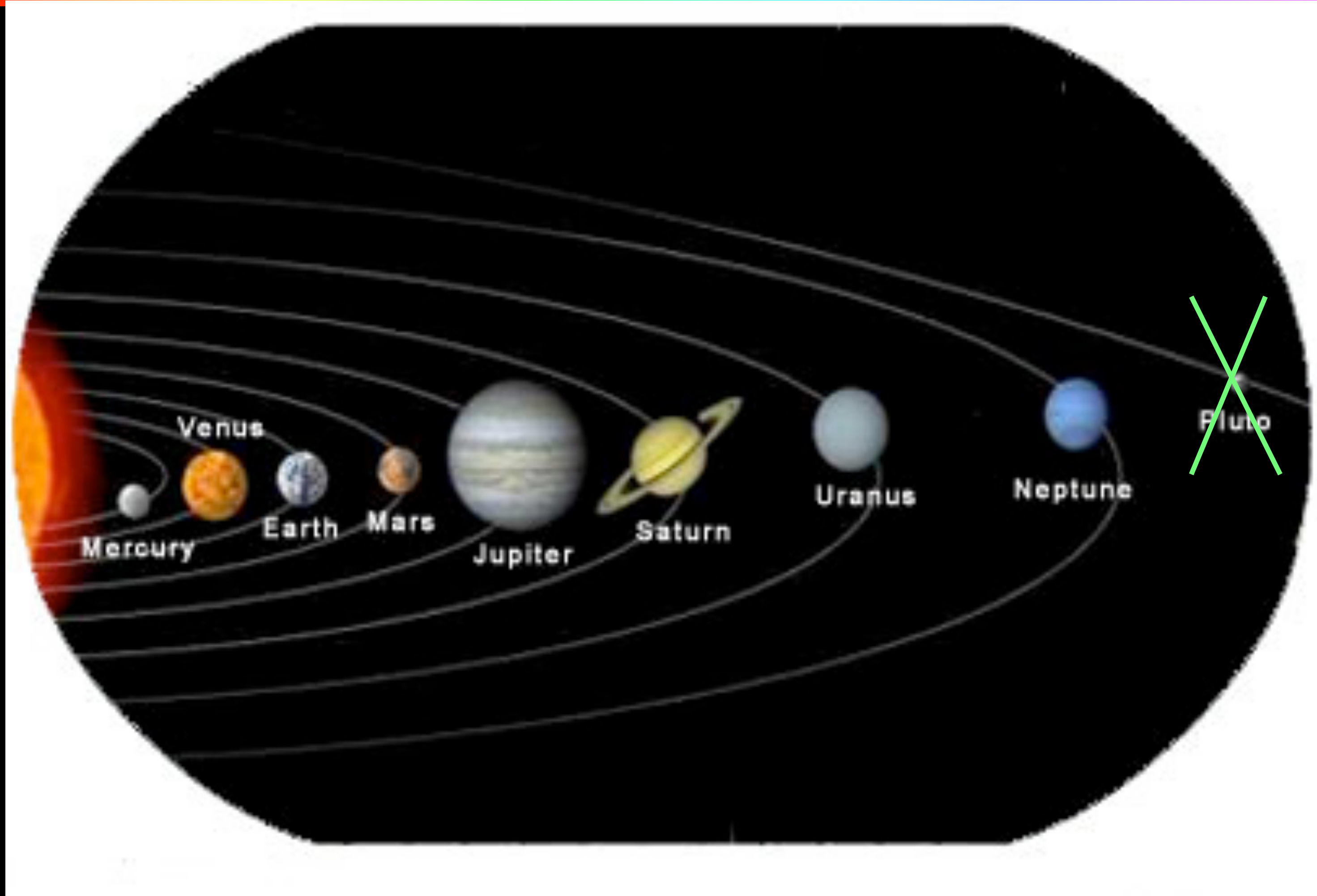
  ⇒ make leptogenesis highly plausible
- Ultimate: measure asymmetry in background ν's

Origin of the Universe

- Right-handed scalar neutrino: $V=m^2\phi^2$
- n_s~0.96
- r~0.16
- Need m~10^{13}GeV
- Still consistent with latest cosmology data
- But $V=\lambda\phi^4$ is excluded
- Verification possible in the near future



Alignment of the Planets



Conclusions

- Neutrinos: the most elusive particle we know
- Neutrino mass discovered!
  - First evidence of physics beyond the SM
- Don't know yet how to extend the SM
- *The Seven Questions*
  - Near-future experiments address them
- *Neutrinos may be responsible for our existence*
  - even the Universe as a whole
- A lot to look forward to in the future

ν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