IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京 [redacted]

Neutrinos

Hitoshi Murayama

UC Berkeley, LBNL, and IPMU Tokyo

Centro de Ciencias de Benasque Pedro Pascual

Feb 14, 2011

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Neutrino is swift of foot:
Neutrino's a particle of war,
And can shoot,
And can hit from far
But wouldn't hurt you

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東京大学 THE UNIVERSITY OF TOKYO

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~70 researchers, 60% non-Japanese

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Global career path

IPMU

IPMU members move(d) to:

Donfeng Gao: Assoc. Prof. @ Wuhan Inst of Phys and Math, China
Fuminobu Takahashi: Assoc. Prof. @ Tohoku
Shuji Harashita: Assoc. Prof. @ Yokohama National
Yasuhiro Shimizu: Assist. Prof. @ Tohoku
Yuji Sano: Assist. Prof. @ Kyushu
Damien Easson: Assist. Prof.@ Arizona State, USA
Tathagata Basak: Assist. Prof. @ Iowa State, USA
Yogesh Srivastava: Assist. Prof. @ NISER, India
Andrey Mikhailov: Assist. Prof. @ San Paolo, Brazil
Johanna Knapp: Assist. Prof. @ Vienna Tech, Austria
Yen Ting Lin: Assist. Prof. @ ASIAA, Taiwan
Sugumi Kanno: postdoc @ Durham, UK
Simon Dedeo: Pierre Omidyar Fellow@Santa Fe Institute, USA
Brian Powell: Pentagon, USA
Matthew Buckley: Prize Fellow @ Caltech, USA
Daniel Krefl: Simons Fellow @ Berkeley, USA
Daniel Hernandez: postdoc @ CERN, Switzerland
Rajat Thomas: postdoc @ Toronto, Canada
Jan Schümann: Massachusetts General Hospital, USA
Masahito Yamazaki: postdoc @ Princeton, USA
Vikram Rentala: postdoc @ Arizona, USA
Guillaume Lambard: postdoc @ IFIC, Spain
Marcos Valdes: postdoc @ Scuola Normale, Pisa, Italy

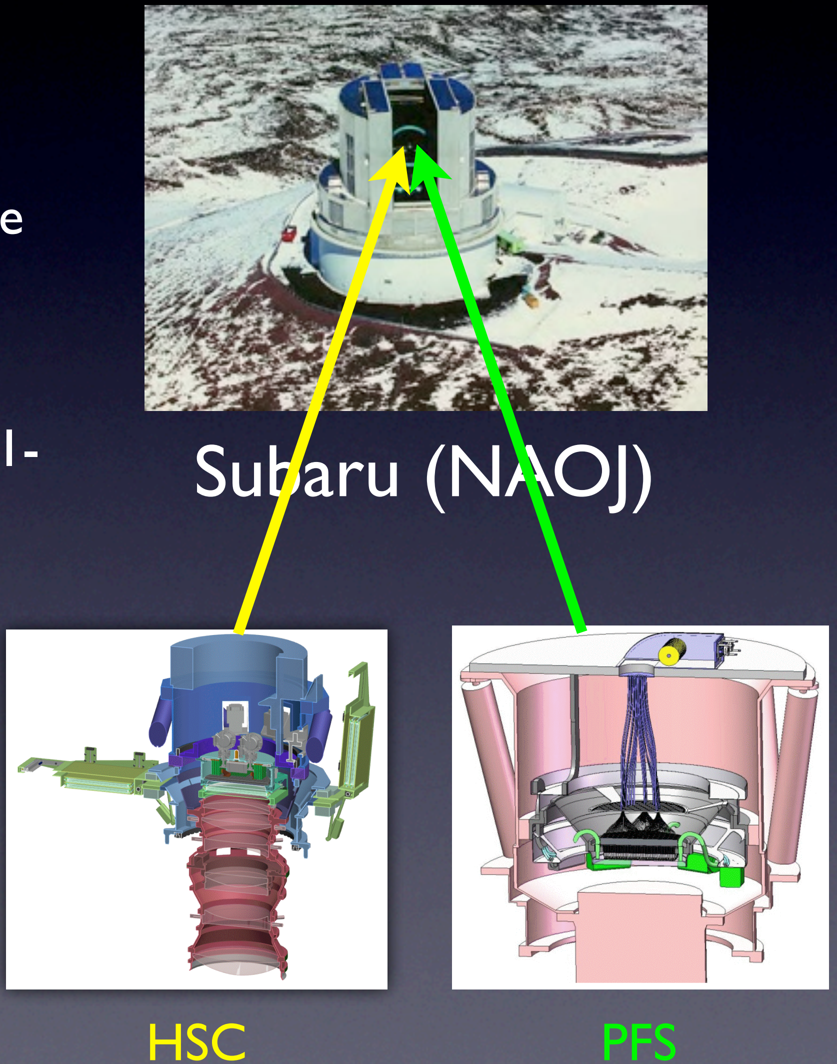

occupancy since Jan 18, 2010
~5900 m²


interaction area ~400m^2
like a
European town square
Piazza Fujiwara
Obelisk
“L’Universo è scritto in
lingua matematica”
IN LINGUA MATEMATICA

SuMIRe

Subaru Measurement of Images and Redshifts

- 8.2 m telescope, excellent seeing 0.6”, wide field of view 1.77 sq. dg.
- HyperSuprimeCam: weak lensing survey, based on growth of structure
    - 0.9 B pixels, 3 ton camera
    - billions of galaxies
    - ~$50M, nearly fully funded, 2011-
- PrimeFocusSpectrograph: baryon acoustic oscillation
    - 2400 fibers, 2000 sq. dg.
    - >2M redshifts, 380–1300nm
    - ~$55M, ~$20M raised, 2016?-
- same telescope for both imaging and spectroscopy *like SDSS!*



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CENTRO DE CIENCIAS DE BENASQUE PEDRO PASCUAL

SCIENTIFIC ACTIVITY

PRESENT

2011

2012

Unsolved problems in Astrophysics and Cosmology

2011, Feb 13 -- Feb 19

Organizers:
H. Peiris (U. College London)
R. Jiménez (ICREA, ICC, U. Barcelona)
C. Pena-Garay (IFIC, CSIC, U. Valencia)

Neutrinos

Hitoshi Murayama
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Feb 14, 2011

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Baryon Asymmetry and Neutrinos

Hitoshi Murayama
UC Berkeley, LBNL, and IPMU Tokyo
Centro de Ciencias de Benasque Pedro Pascual
Feb 14, 2011

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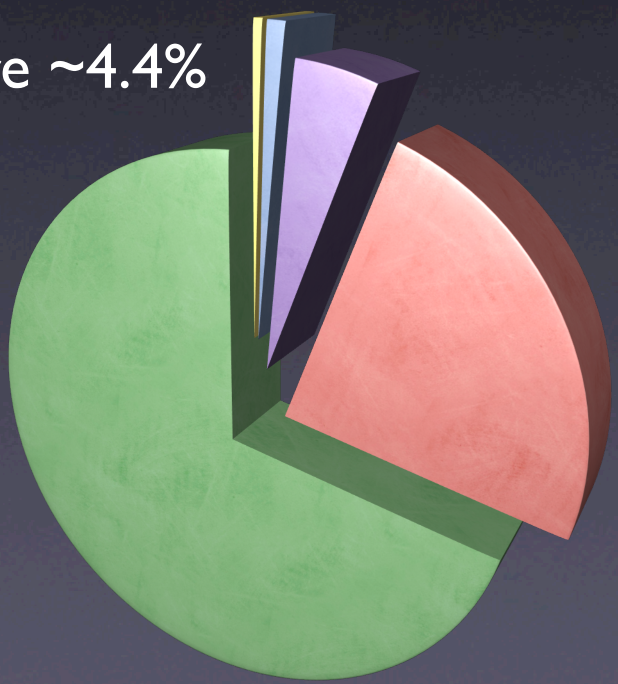
Energy Budget of the Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter (electrons, protons & neutrons) are ~4.4%
- Dark Matter ~23%
- Dark Energy ~73%
- Anti-Matter 0%
- Dark Field ~10^{62}%??

no! understood?

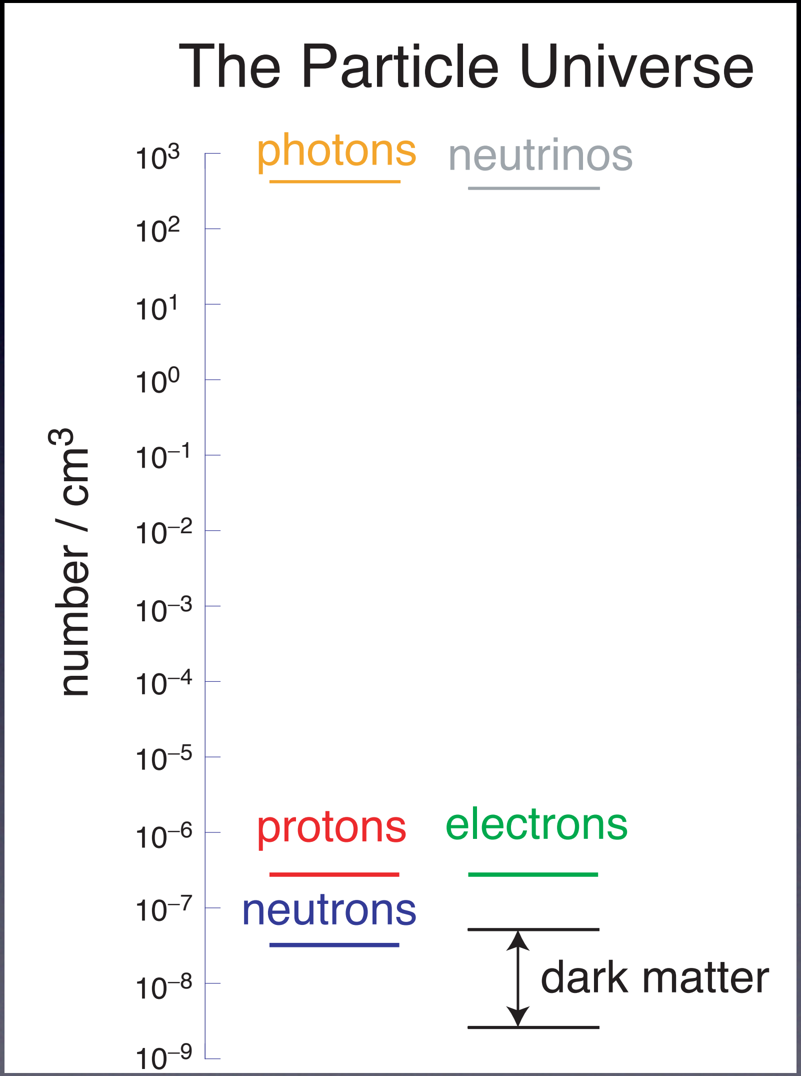


Five questions beyond the standard model

- Now it is clear that the standard model of particle physics is incomplete
- five empirical questions (w/o aesthetics)
  - neutrino mass
  - dark matter
  - accelerated expansion (dark energy)
  - acausal density fluctuation (inflation)
  - baryon asymmetry

Particle Universe

- there are *a lot of* neutrinos!
- (assumes 0.1–1 TeV WIMP)



Outline

- Observation
- Initial condition?
- Sakharov's conditions
- Leptogenesis
- How do we test it?

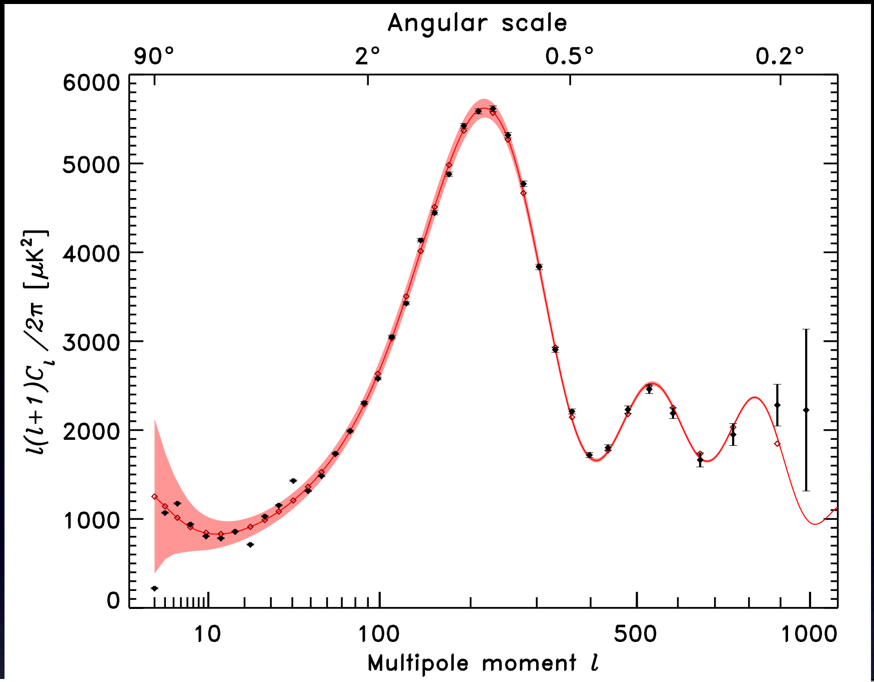
Observation

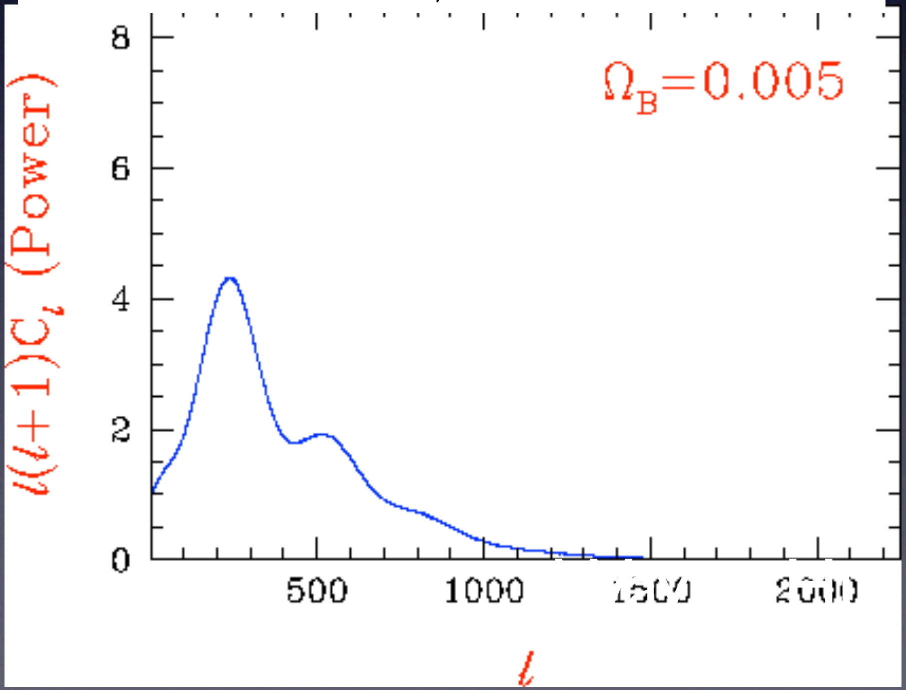
WMAP

- acoustic peaks in the CMB anisotropy power spectrum are due to the sound waves (oscillations) in photon-baryon fluid at T~3000K
- amount of baryon particularly affects the ratio of even and odd peaks

$\Omega_b h^2$=0.02258±0.00057

Ω_b=0.0449±0.0028

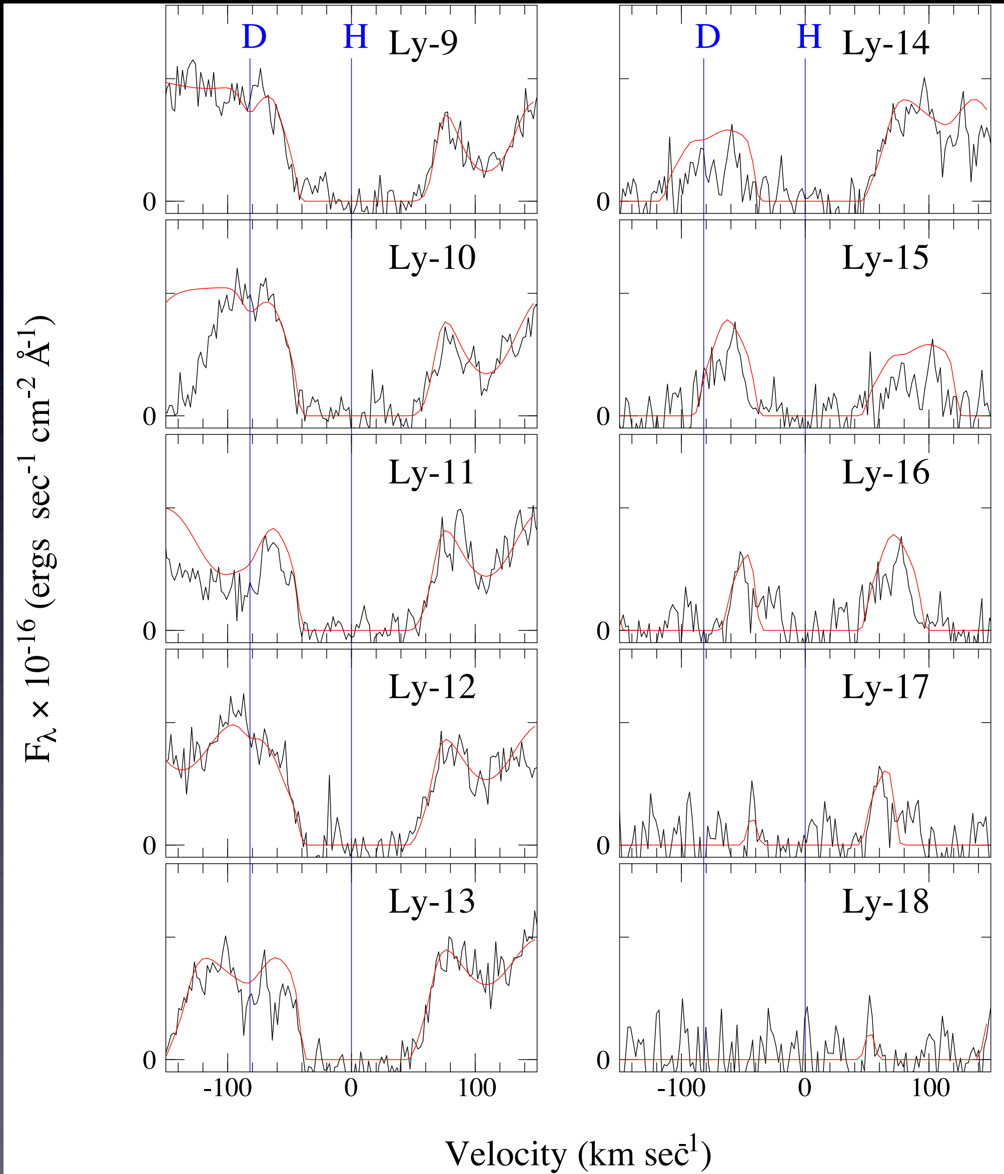




deuterium abundance

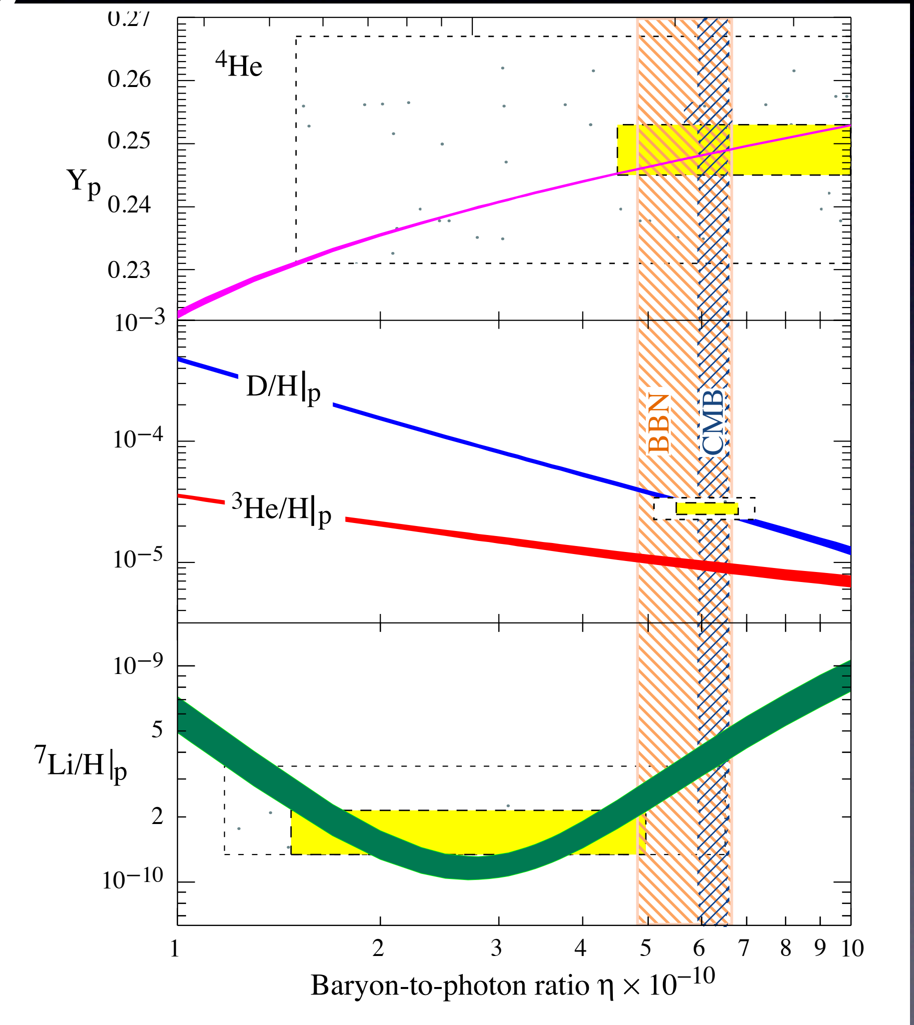
Kirkman, Tytler, Suzuki, O'Meara, Lubin

- believed to be the most accurate, most primordial
- hydrogen backlit by quasar, Lyman absorption lines
- reduced mass different by 1/4000 between H and D



Big Bang Nucleosynthesis

- there appears to be a discrepancy between ^{7}Li and D/H & CMB
- ^{7}Li abundance measured at surface of stars
- convection? new physics?



end result

- WMAP7 (*T*~3000K)

$$\Omega_b h^2 = 0.02258 \pm 0.00057$$

- BBN based on D/H (Kirkman 2003) (*T*~0.1–1 MeV)

$$\eta = \frac{n_b}{n_\gamma} = (5.9 \pm 0.5) \times 10^{-10}$$

$$\Omega_b h^2 = 0.0214 \pm 0.0020$$

quark asymmetry

- for all quarks and anti-quarks in thermal equilibrium, we can translate

$$Y_b = \frac{n_b}{s} = (0.84 \pm 0.07) \times 10^{-10}$$

- need to specify the particle content. Let us take the whole SM at $T >$ TeV

$$A_q = \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} = 1.8 \times 10^{-9}$$

Early Universe

1,000,000,002

quarks

1,000,000,000

anti-quarks

Current Universe

2

•

us

quarks *anti-quarks*

We won! But *why?*

Why do we exist?

- I told my Berkeley colleagues that this was one of the problems I work on
- Rhetorician: "You are asking a wrong question. *Why* implies purpose. You must ask *How*."
- Philosopher: "I can see why he asks *why*."
- They got into a big argument
- I didn't get to explain what I meant....

How did we survive the Big Bang?

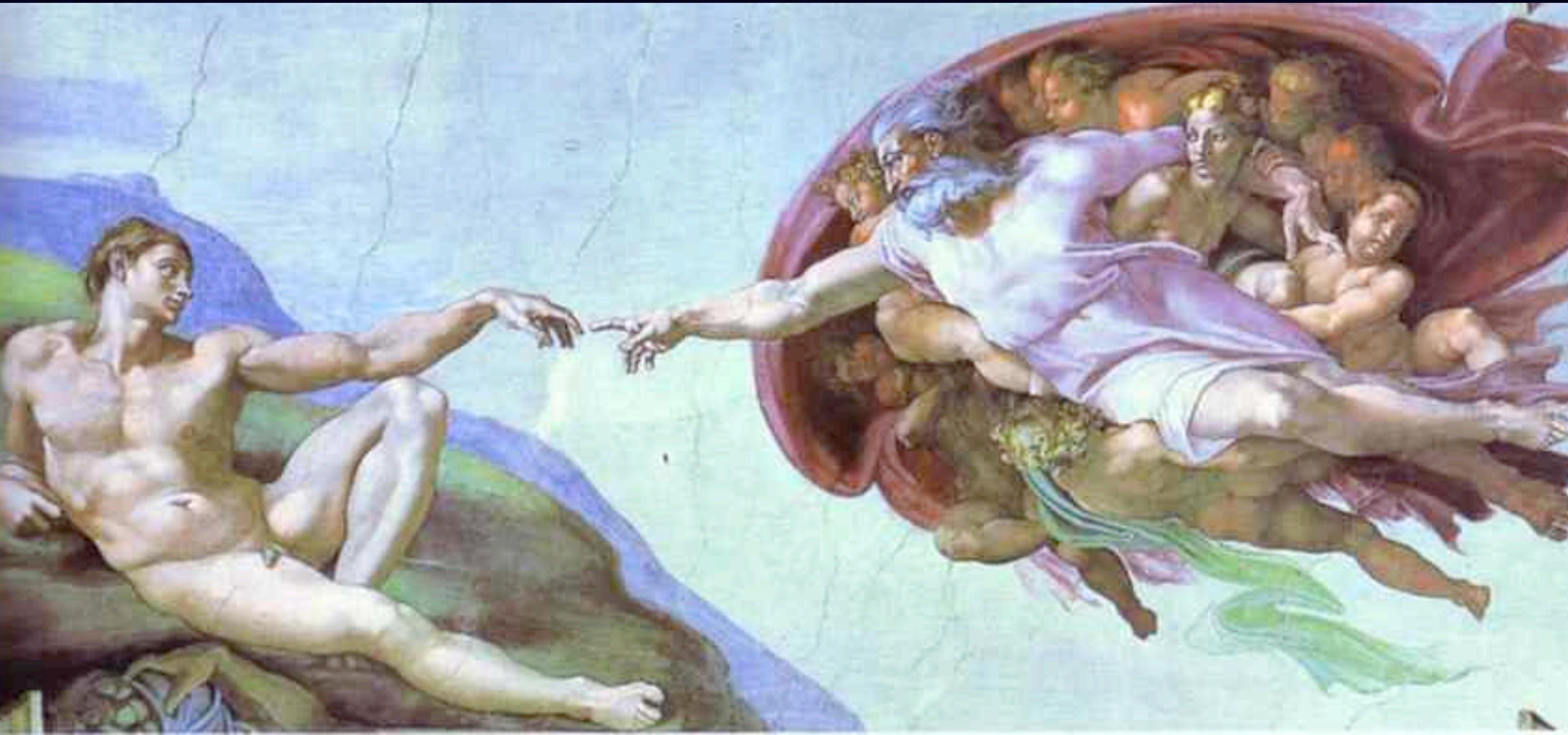
How we survived the Big Bang

- We (matter) have annihilated anti-matter
- we won at the expense of a billion friends
- why was there a tiny asymmetry so that we could survive?
- was it planted (initial condition) or was it generated (evolution)?

Initial Condition?

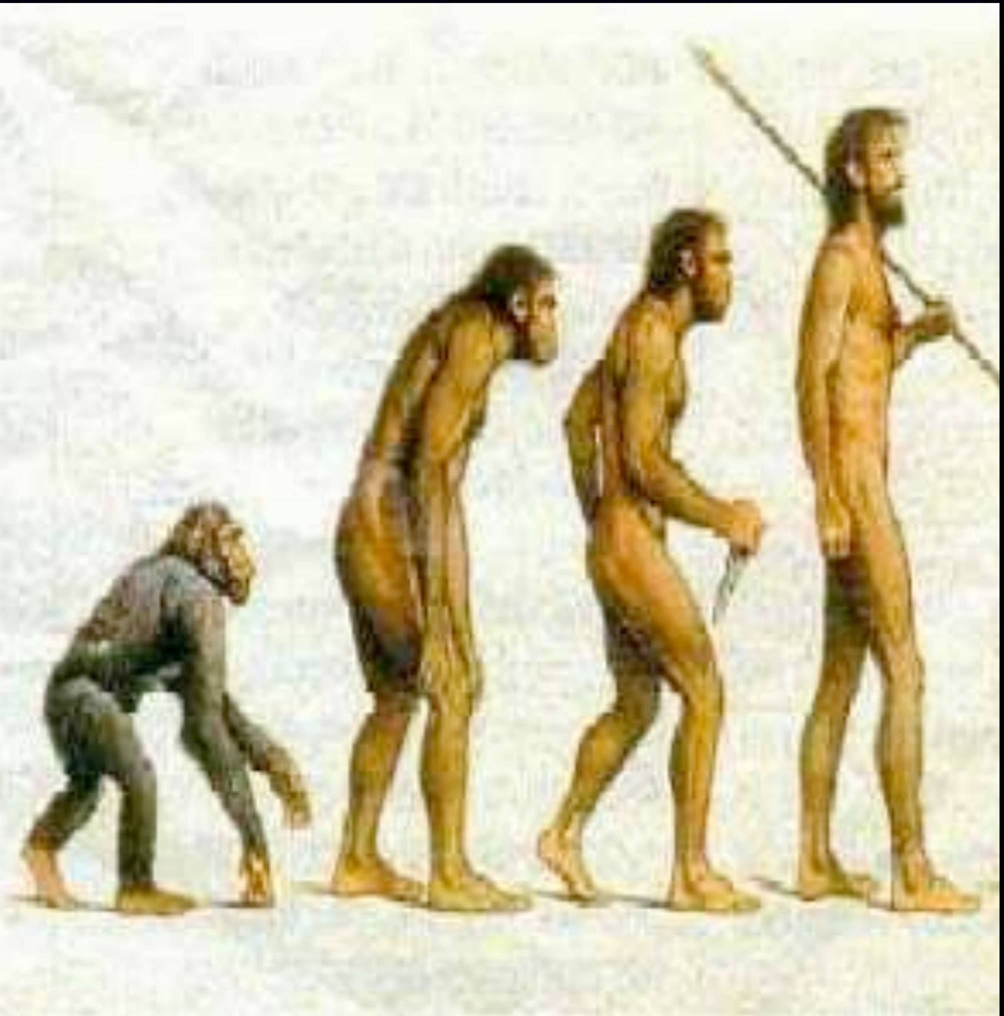
Creation

$n_b(t=0) \neq 0$



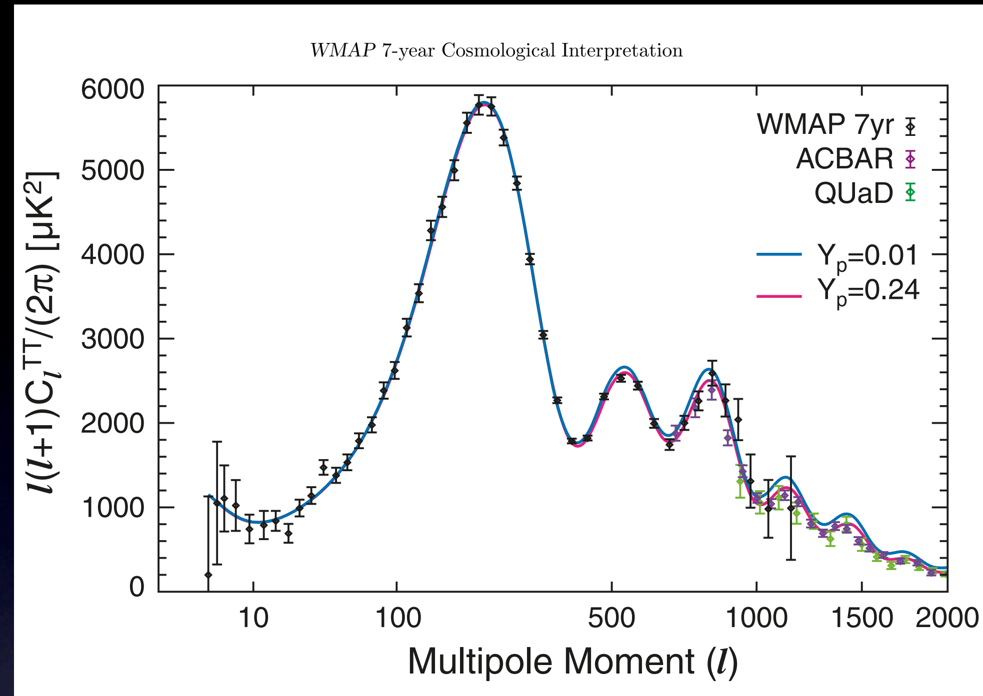
Or Devolution?

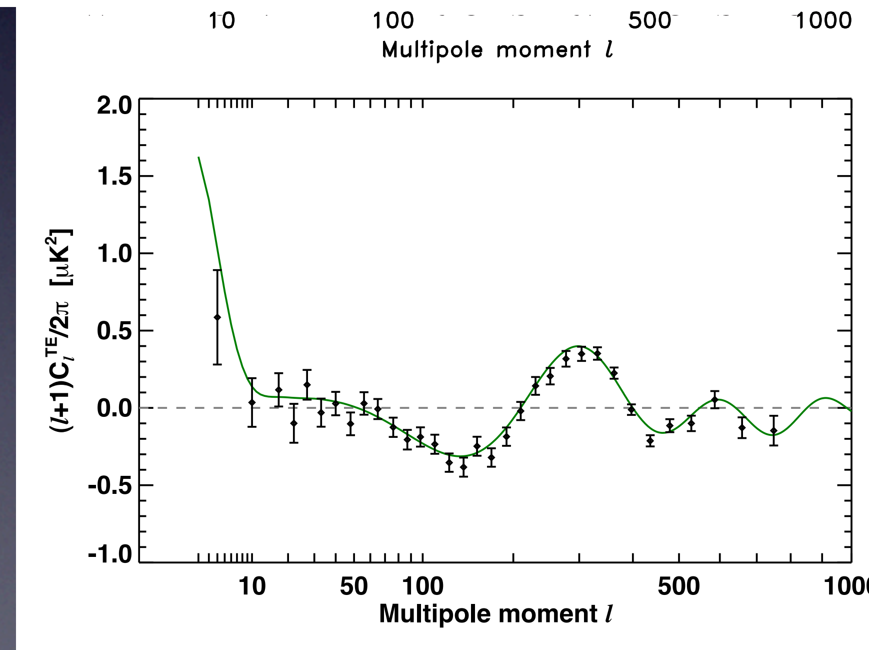
$n_b(t=0)=0 \Rightarrow n_b(t>t_b)\neq 0$

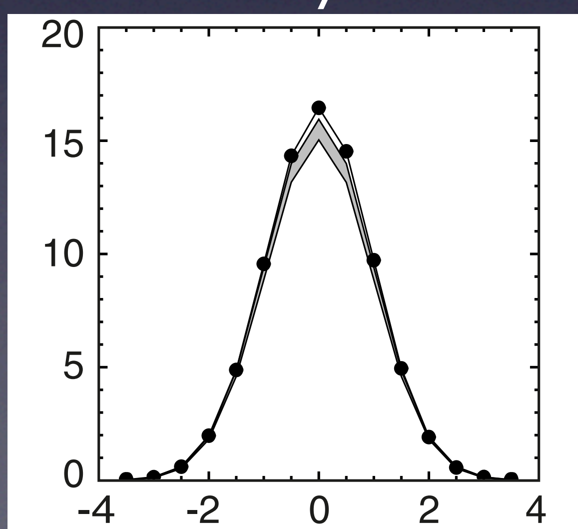


Inflation

- density fluctuation is apparently *acausal*
- Also T-E correlation shows photons flowed out from dense region, unlike in causal mechanisms (e.g. strings)
- beautifully Gaussian







Can the initial condition survive inflation?

- No, in the Standard Model
- baryon density extrapolated backwards leads to fermi degenerate gas
- energy density will exceed inflaton and can't inflate the universe as much as we need N>60–100

$$\rho_f \propto a^{-4}$$

assume *instant* reheating at the end of inflation to obtain the most conservative limit

$$N \leq 8$$

Can the initial condition survive inflation?

- logically possible if there are baryonic scalars
- need the super-super-Planckian initial conditions
- need extremely flat potential
- gauge-mediation?
- all baryon number may end up in Q-balls

$$n_b = i(\phi^* \dot{\phi} - \dot{\phi}^* \phi)$$

$$\dot{\phi}(t_{RH}) = \dot{\phi}(0) e^{-3Ht}$$

$$\phi(0) > (H_I M_{Pl})^{1/2} 10^{-10} e^{3N} \approx 10^{90} M_{Pl}$$

$$m < (H_I M_{Pl})^{1/2} 10^{10} e^{-3N} \approx 10^{-70} \mathrm{GeV}$$

We assume *evolution* for the remainder

looking for a collaborator to study Q-ball constraints

Sakharov’s Conditions

Beginning of Universe

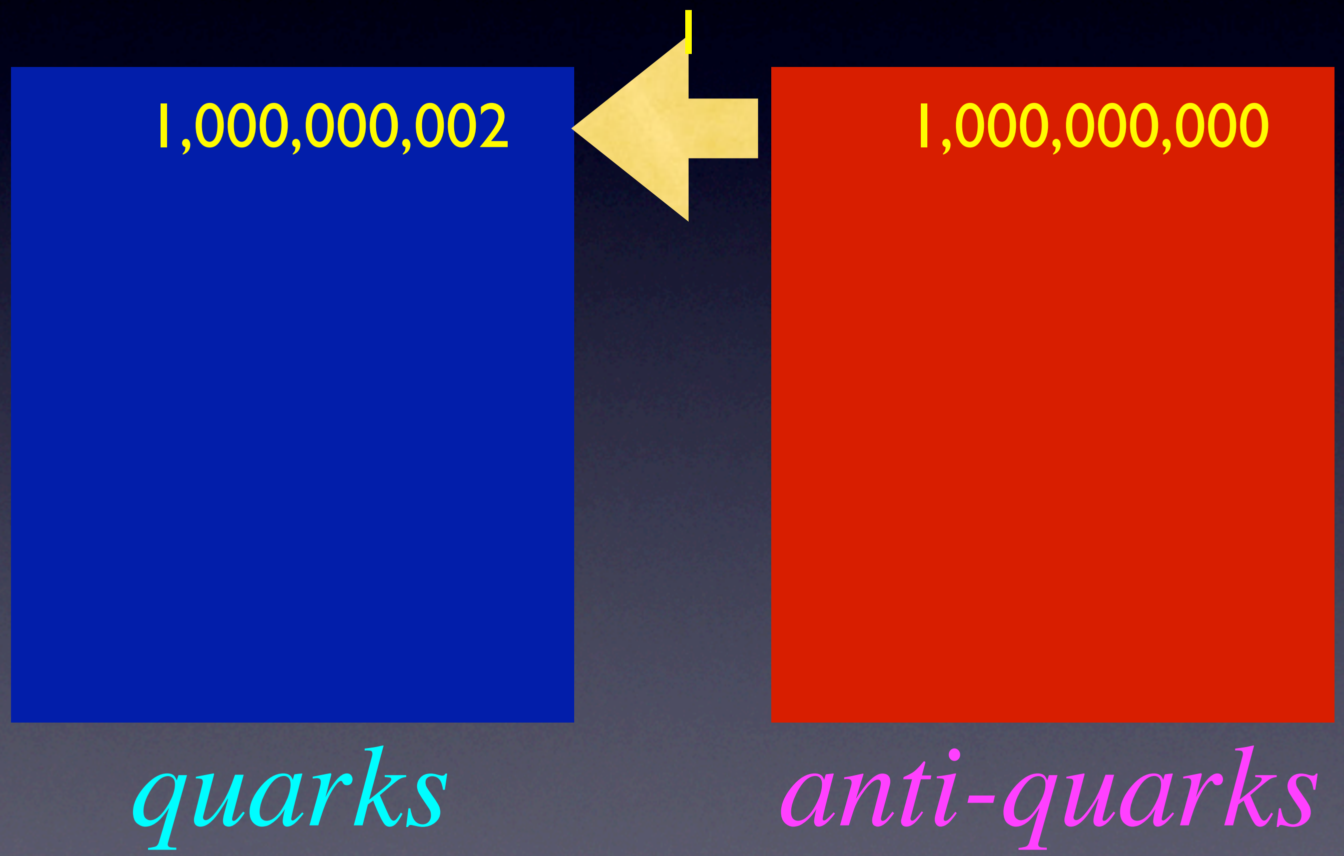
1,000,000,001

1,000,000,001

quarks

anti-quarks

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

•

us

quarks *anti-quarks*

This must be how we survived the Big Bang!

Sakharov's conditions

- Need to reshuffle matter and anti-matter
  - baryon-number violation
- need to prefer matter over anti-matter
  - CP violation
- need process to go one way
  - departure from equilibrium

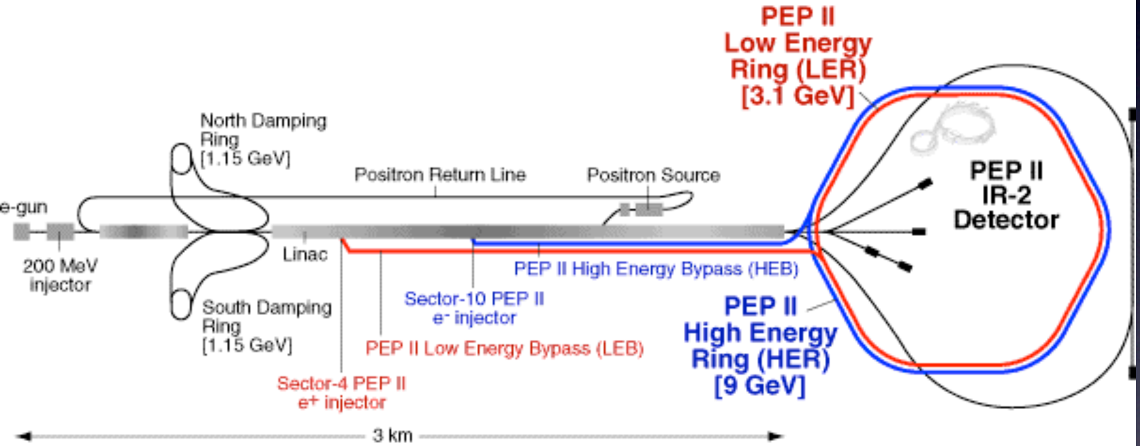
$\tau(p \rightarrow e^+\pi^0) > 10^{34}$ yrs suggests $M_{GUT} > 10^{15}$GeV

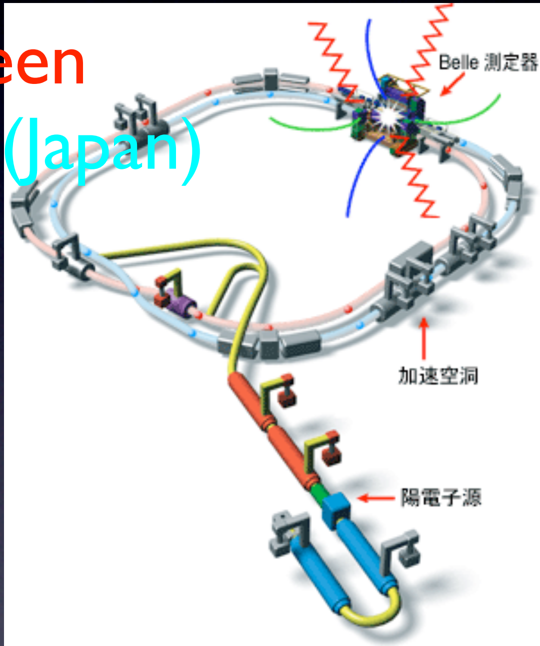
tensor-mode constraint $T_{RH} < 10^{16}$GeV

many inflation models $T_{RH} << 10^{16}$GeV

Progress!

- Head-to-head competition between Stanford/Berkeley (US) and KEK (Japan)





- *Super high-tech machine* with micron precision over 4 miles and colliding beams every 4 nanoseconds at speed of light

CP Violation

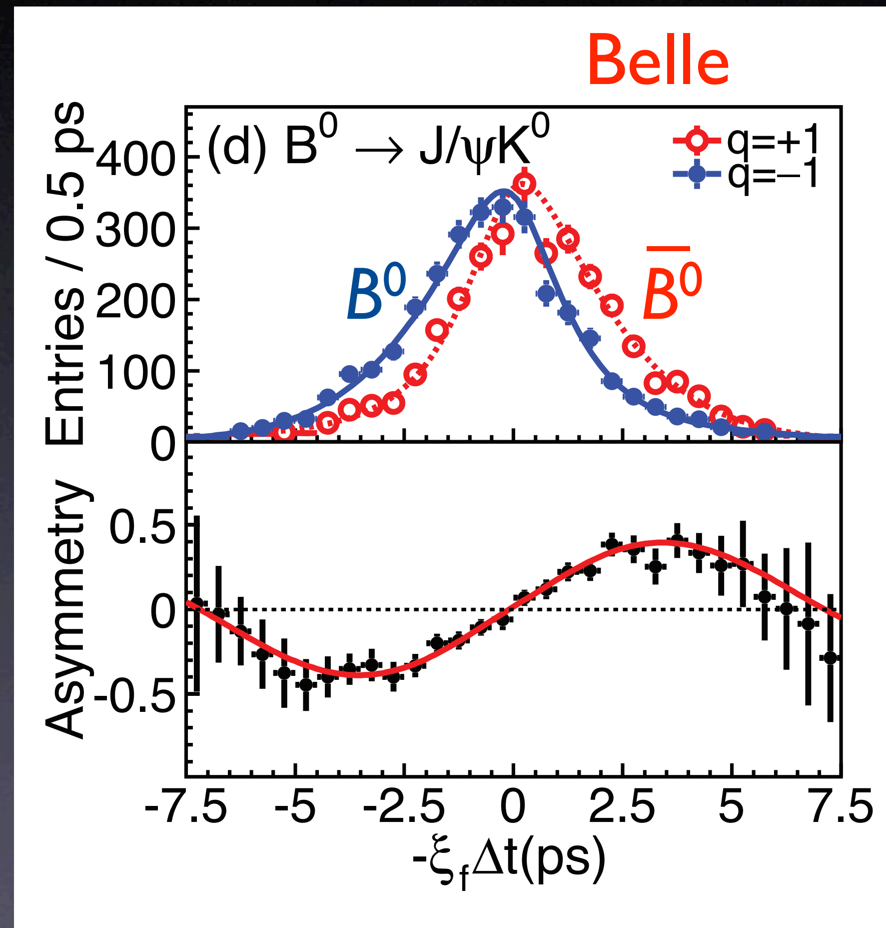
- Is anti-matter the exact mirror of matter?

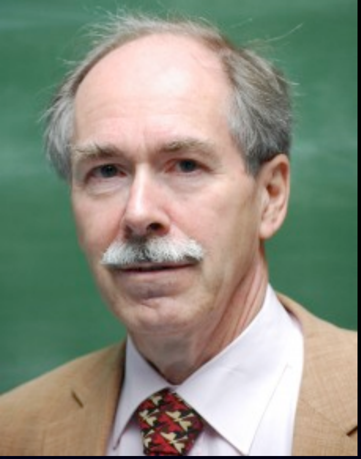
1964 discovery of CP violation

- But only one system, hard to tell what is going on.

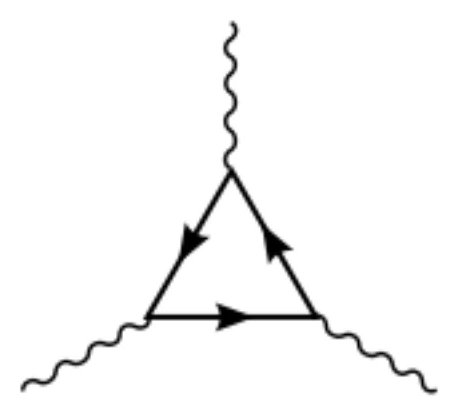
2001, 2002 Two new CP-violating phenomena

- Kobayashi-Maskawa theory
- But no CP violation observed so far is not large enough to explain the absence of anti-matter
- short by $\sim 10^{-10}$!





‘t Hooft



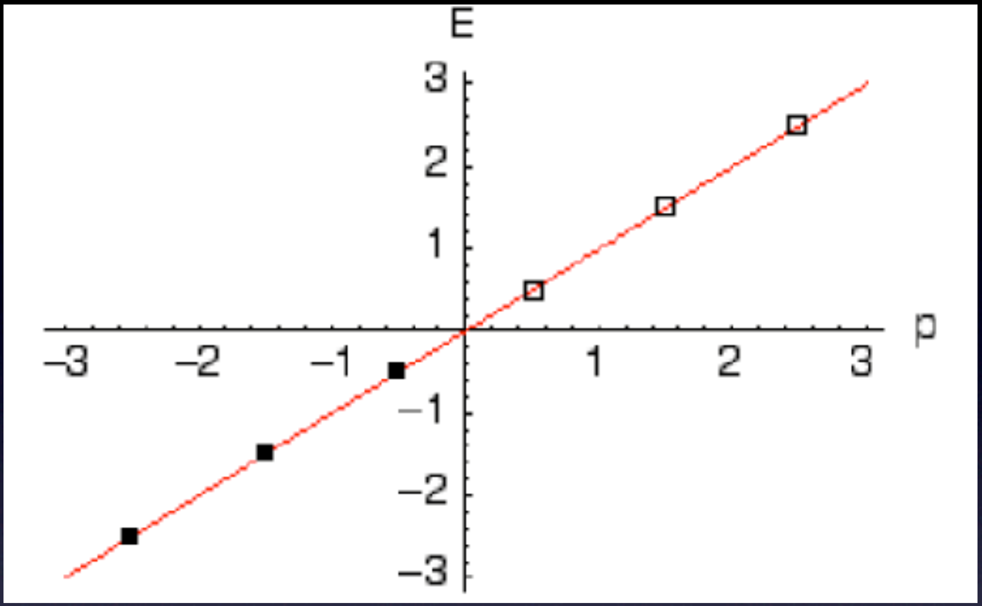
$$\partial_\mu j^\mu_L = \partial_\mu j^\mu_B = \frac{N_g}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}W^a_{\mu\nu}W^a_{\rho\sigma}$$

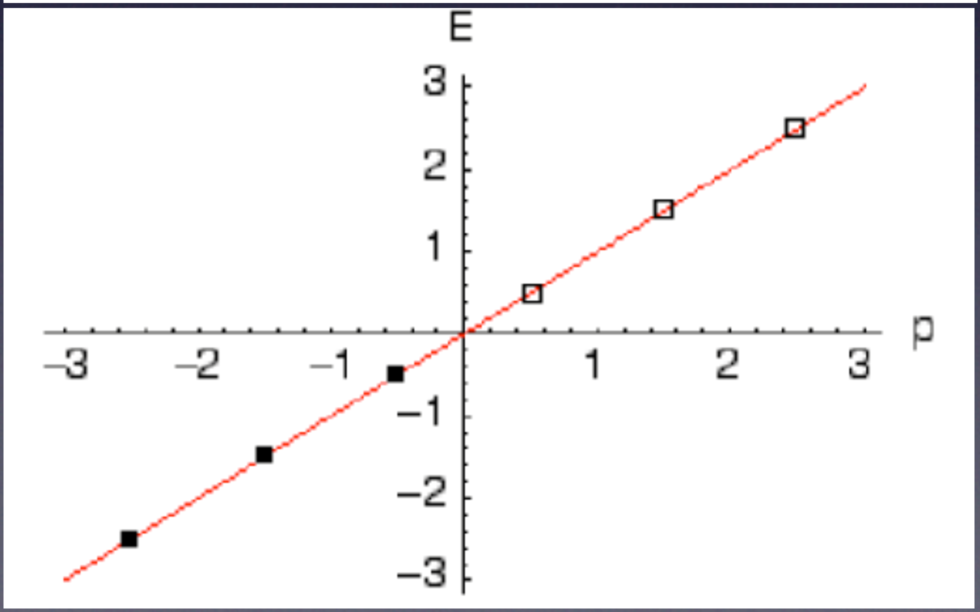
- Standard Model actually violates the baryon number from the triangle anomalies
- conserves *B*–*L*
- can in principle lead to $^3He \rightarrow e^+\mu^+\bar{\nu}_\tau$
- my back-on-envelope estimate $\tau \sim 10^{150}$ yrs
- but can have impact in early universe

Electroweak anomaly!

- *W* and *Z* bosons massless at high temperature
- *W* field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating W field

change $\#q$, $\#\ell$
preserves $B\text{–}L$





washout

- estimate of B-violating transition rate is $\Gamma \approx 20\ \alpha_W^5\ T$ (Shaposhnikov & co.)
- in thermal equilibrium below T<10^{12} GeV
- $F \sim 12B^2 + 3L^2$
  - $B \sim 0.2(B-L)_0$, $L \sim -0.8(B-L)_0$
- all preexisting B washed out if $B-L=0$

choices

- produce B–L asymmetry above T_{EW}
  - e.g. leptogenesis from heavy ν_R
- produce B=L at T_{EW}
  - e.g. electroweak baryogenesis
- produce B below T_{EW}
  - e.g. exotic scalar field decays

Kitano, HM, Ratz

- protect B=L
  - e.g. fourth generation or technicolor

HM, Rentala, Shu, Yanagida

too many theories for a single number

Leptogenesis

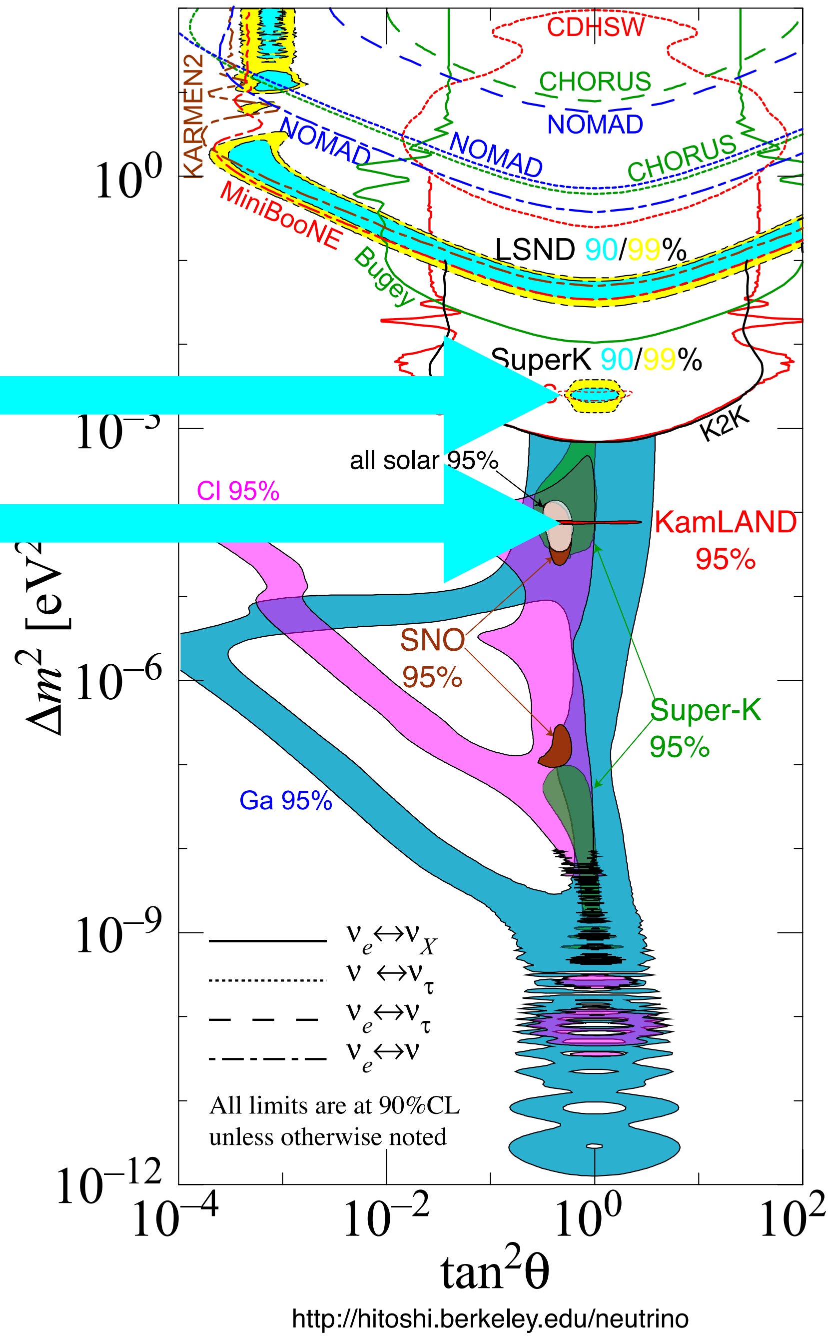
the basic idea

- generate first the *lepton asymmetry* $L<0$
- Then the anomaly in the standard model converts it to the *quark asymmetry* $B>0$
- safe from proton-decay constraints
- very well motivated by the discovery of finite mass of neutrinos since 1998

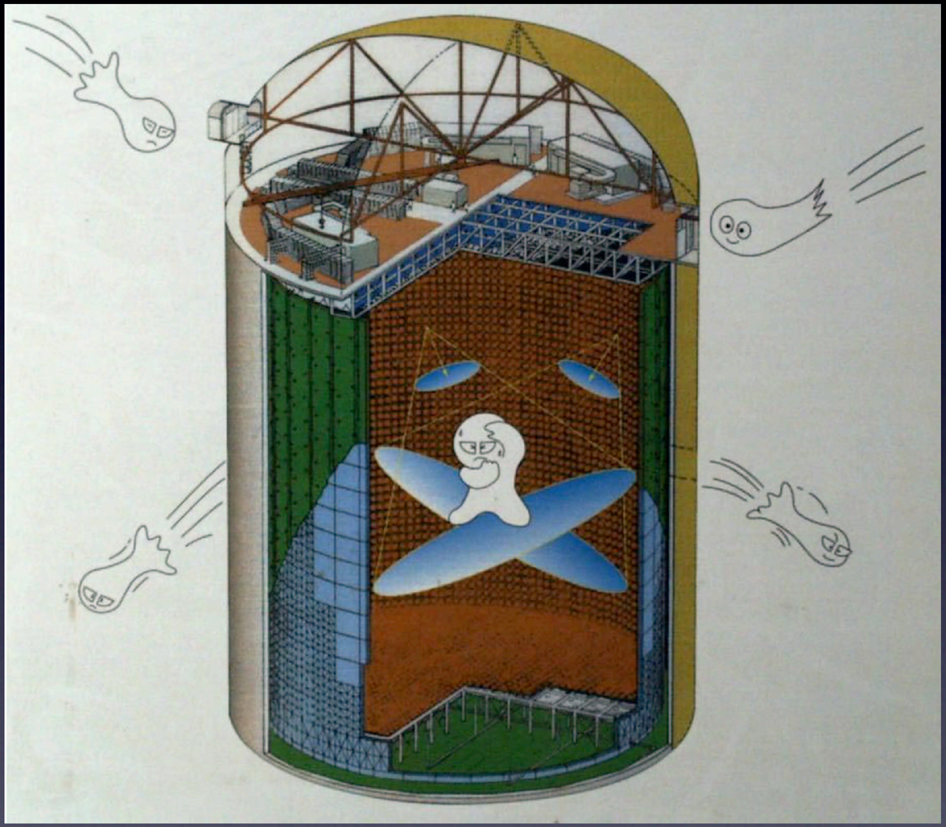
Fukugita and Yanagida, 1986

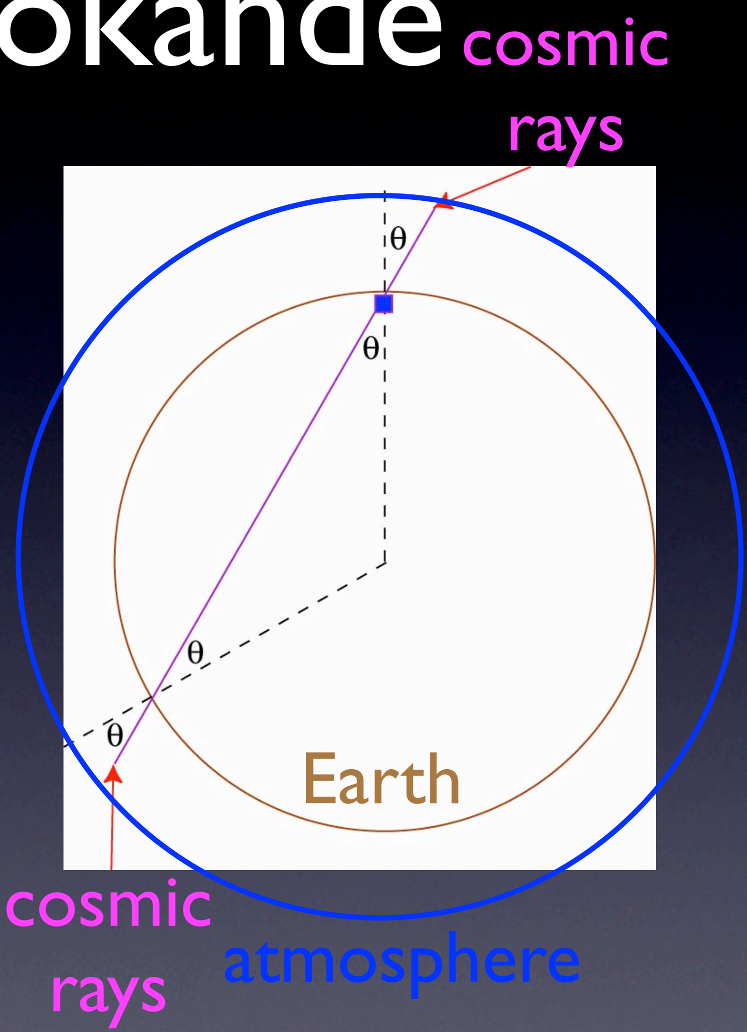
A new input

- progress in neutrinos
- 1998 & 2002
- Now now question that neutrinos have mass!



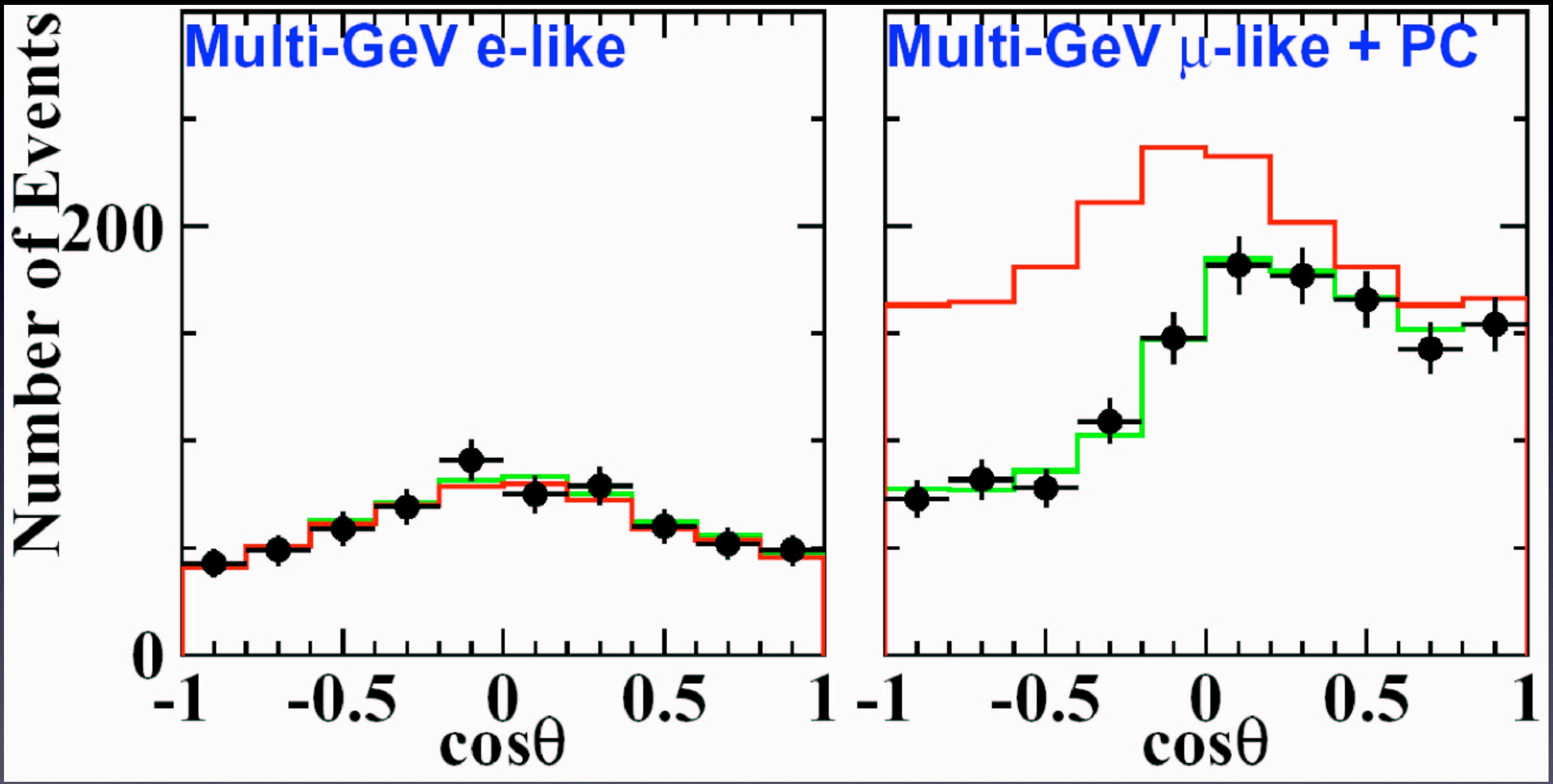
Super-Kamiokande





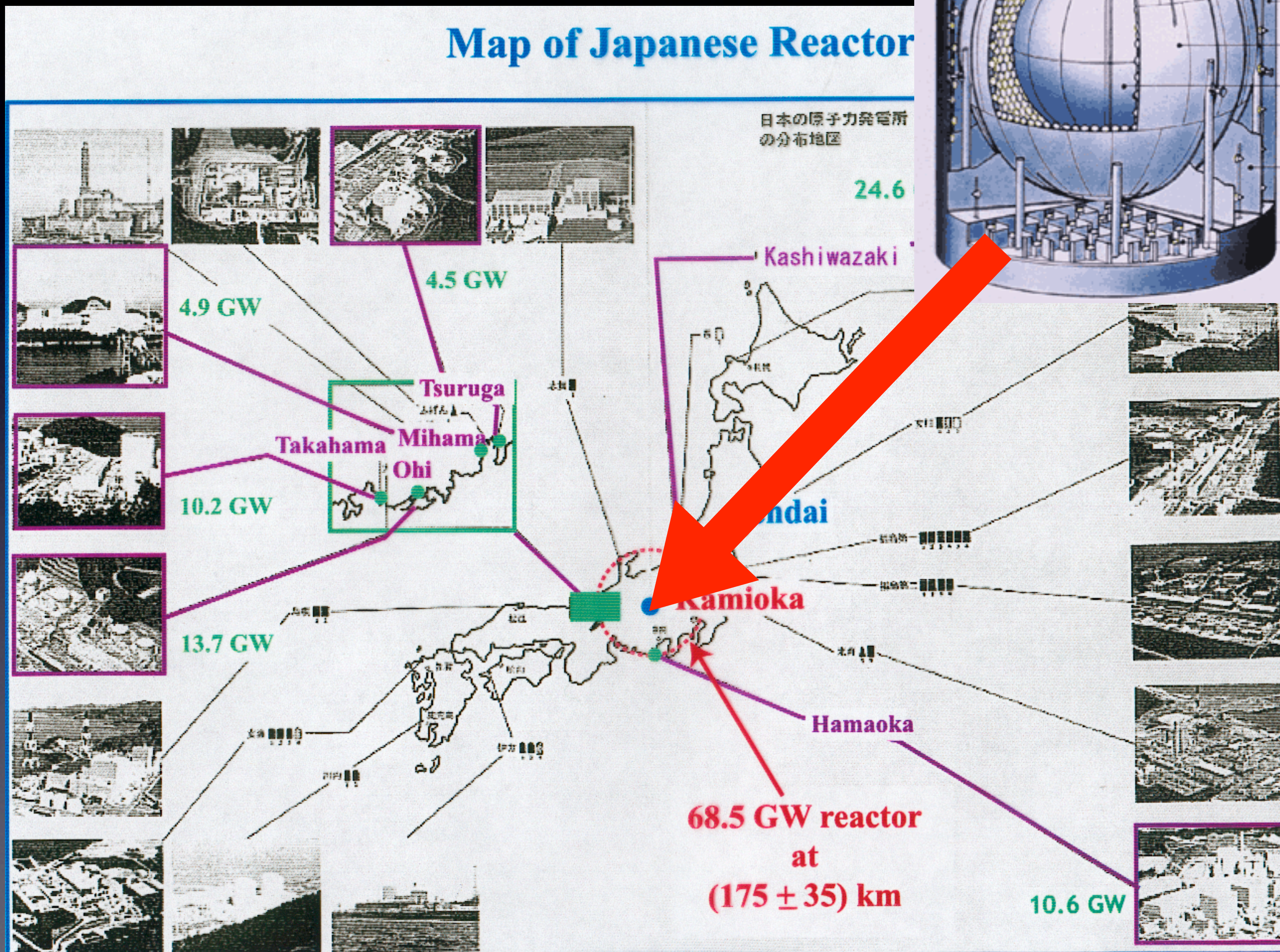
cosmic rays are isotropic
atmospheric neutrinos are up-down symmetric

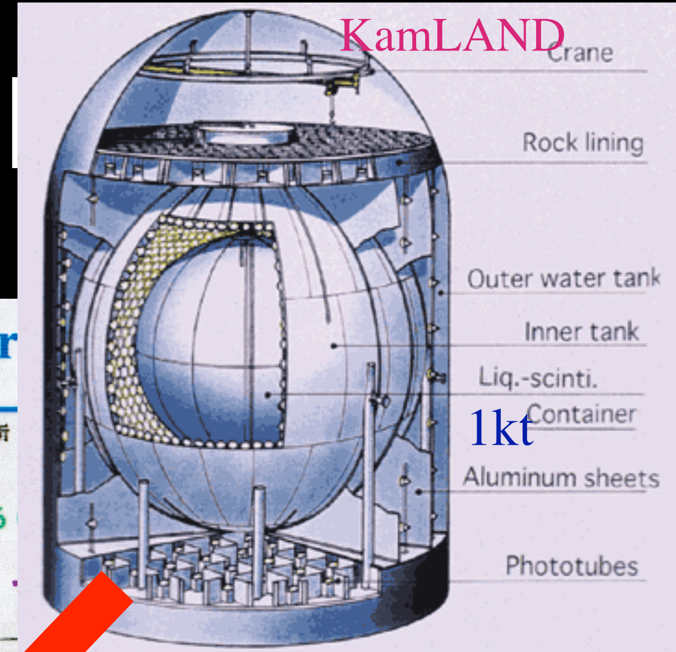
A half of ν_μ lost!



Neutrinos sense time ⇒ have mass!

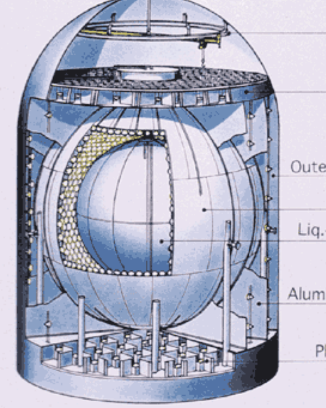
Location, Location, L

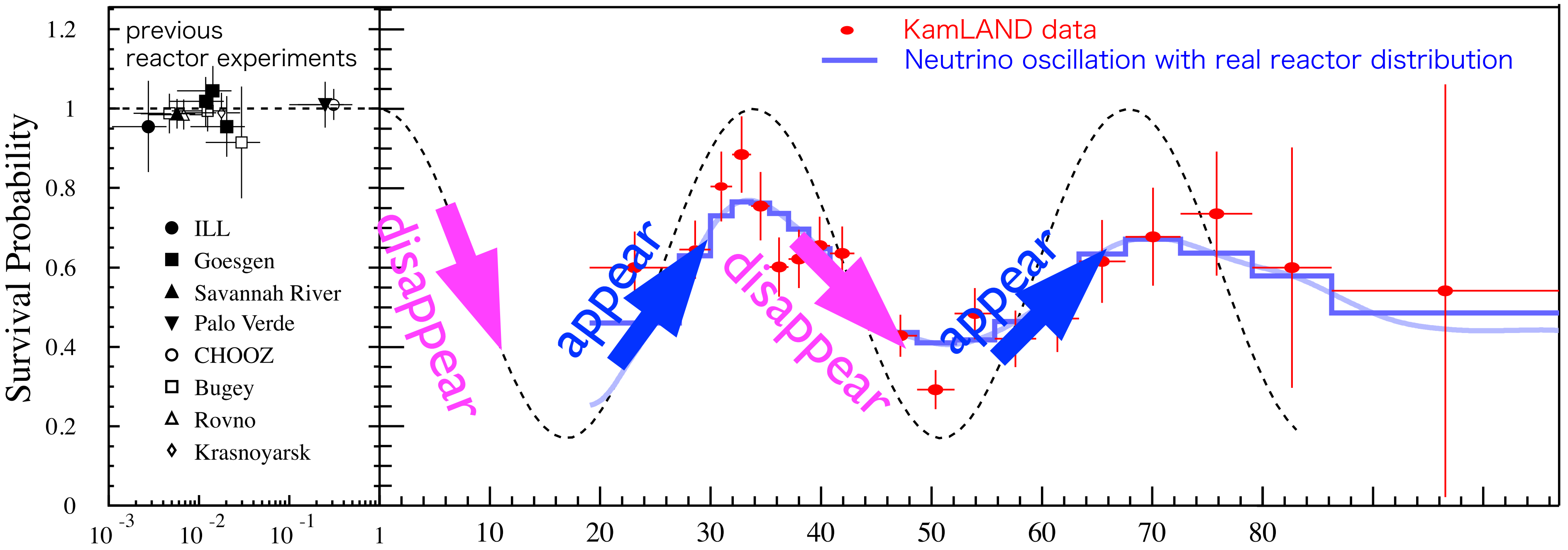




KamLAND

Reactor neutrinos do oscillate!

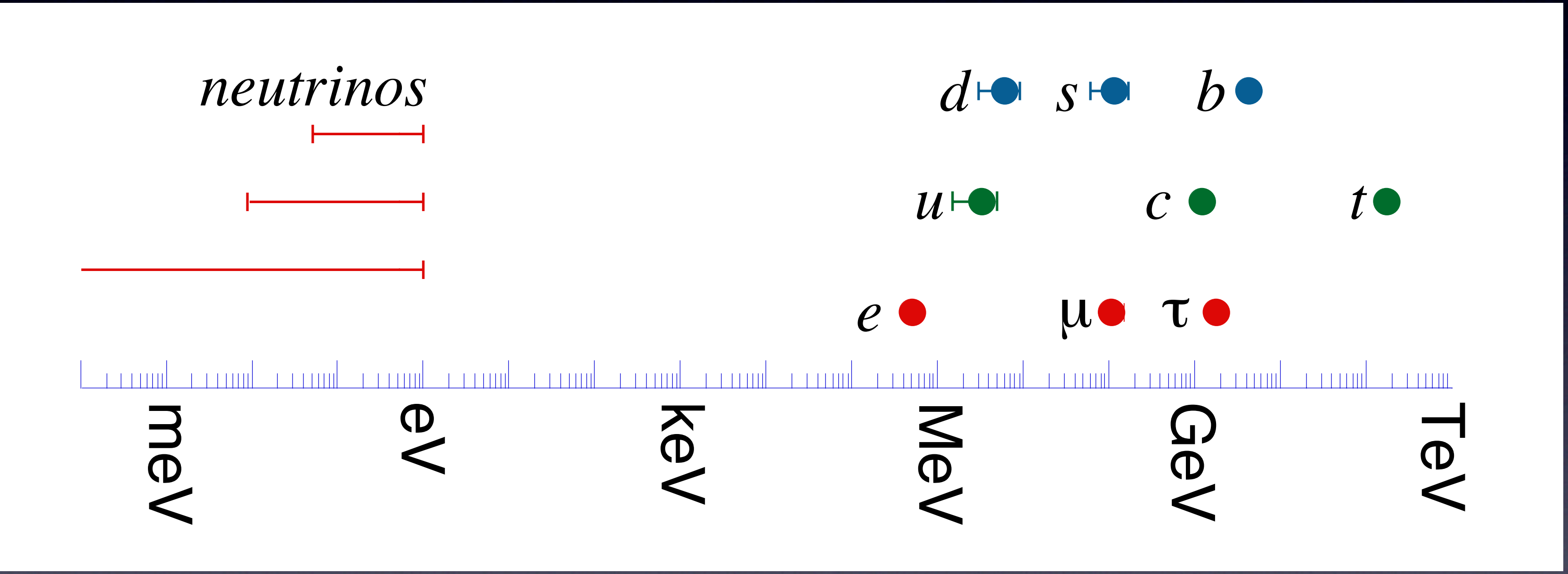




L_0=180 km $\approx$ Proper time τ

all neutrino oscillation data (but two)
consistent with 3-generation with masses and mixings

tiny masses

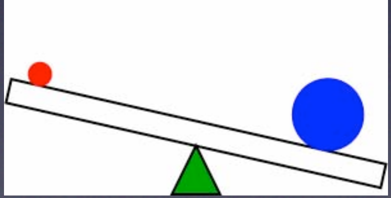


How do we explain tiny masses?

Seesaw Mechanism

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

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$

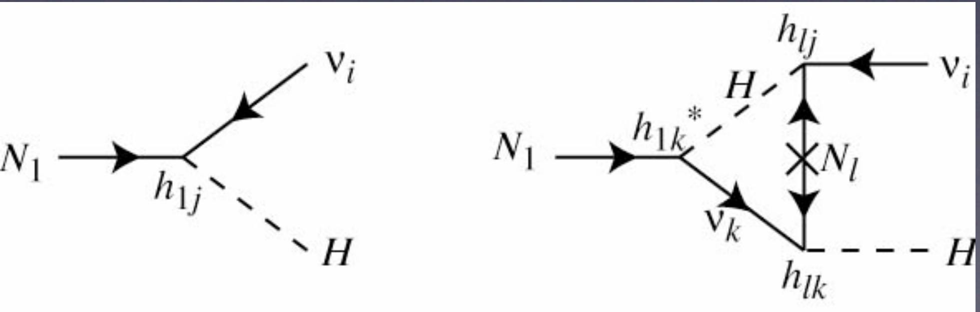


To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}$GeV

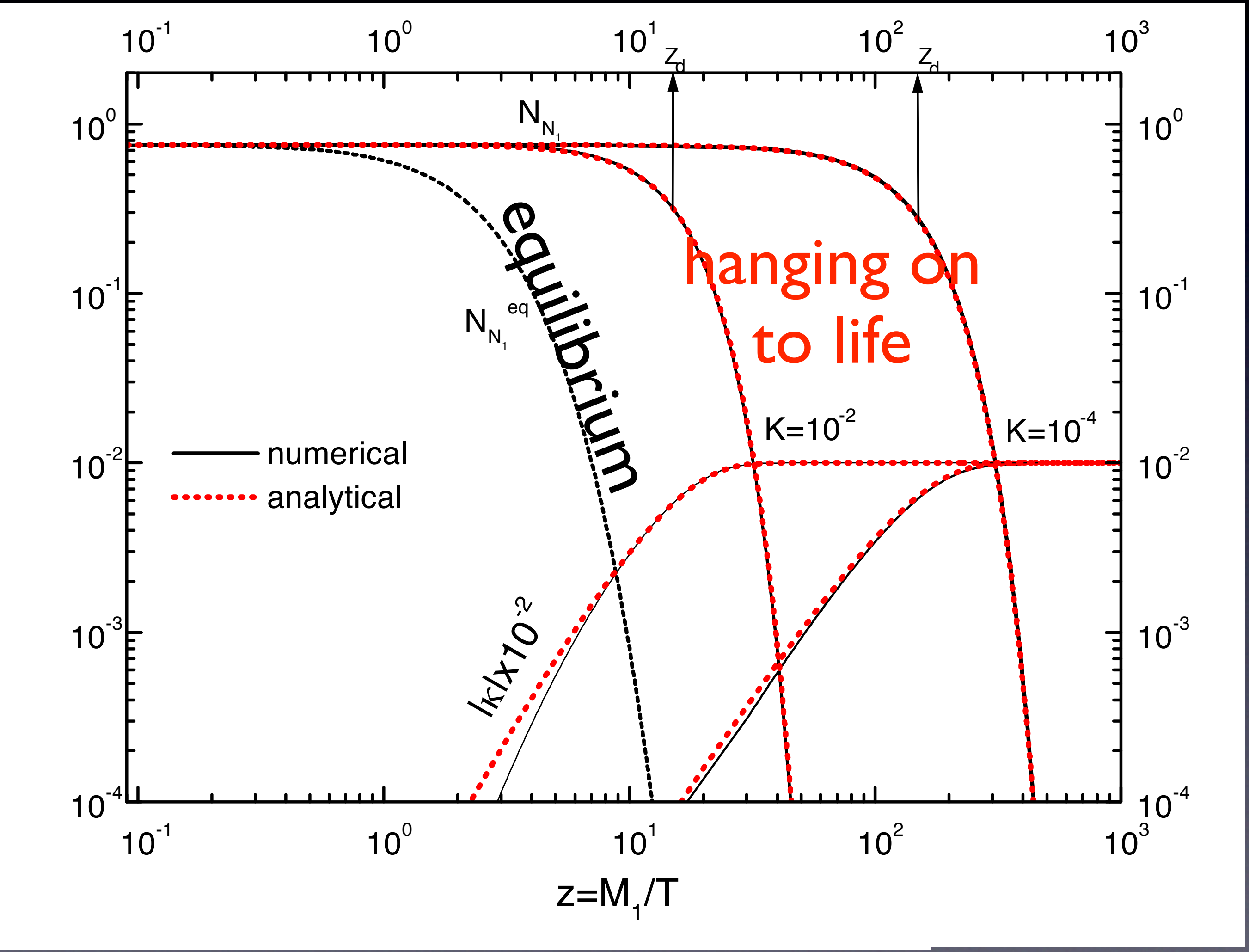
Leptogenesis

- Presumably three ν_R
- One of them lives long and decays late
- Majorana: $\nu_R = \bar{\nu}_R$
- @zero-loop, decays 50:50 to ν_L+h, $\bar{\nu}_L$+h*
- @one-loop, $\Gamma(\nu_R \to \nu_L + h) \propto 1 - \epsilon$

$$\Gamma(\nu_R \to \bar{\nu}_L + h^*) \propto 1 + \epsilon$$

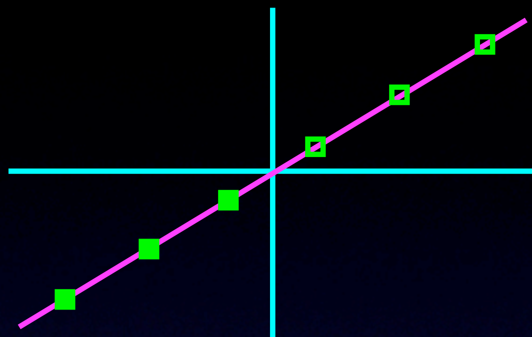


out of equilibrium decay

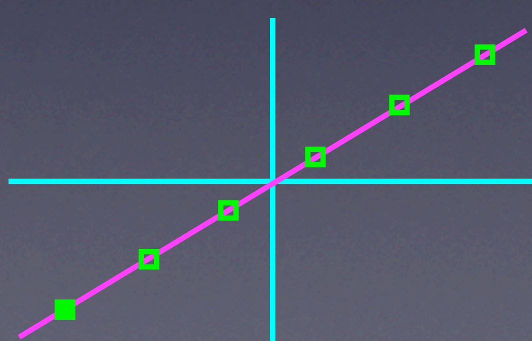


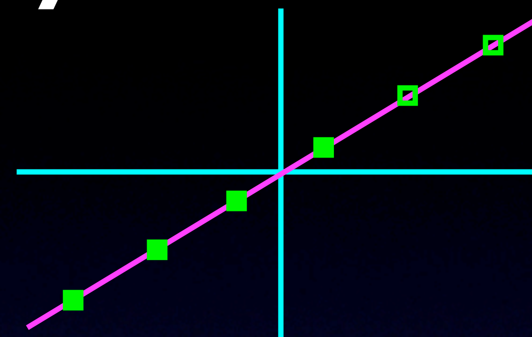
time →

What anomaly can do

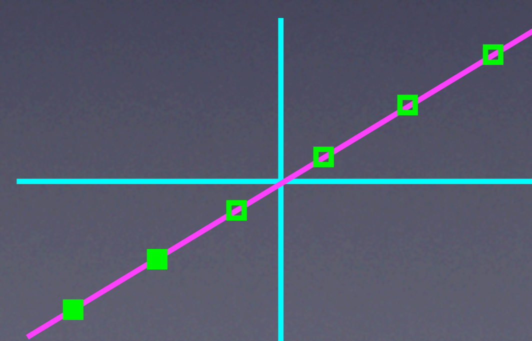


- 1,000,000,000 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,002 $\bar{\nu}$

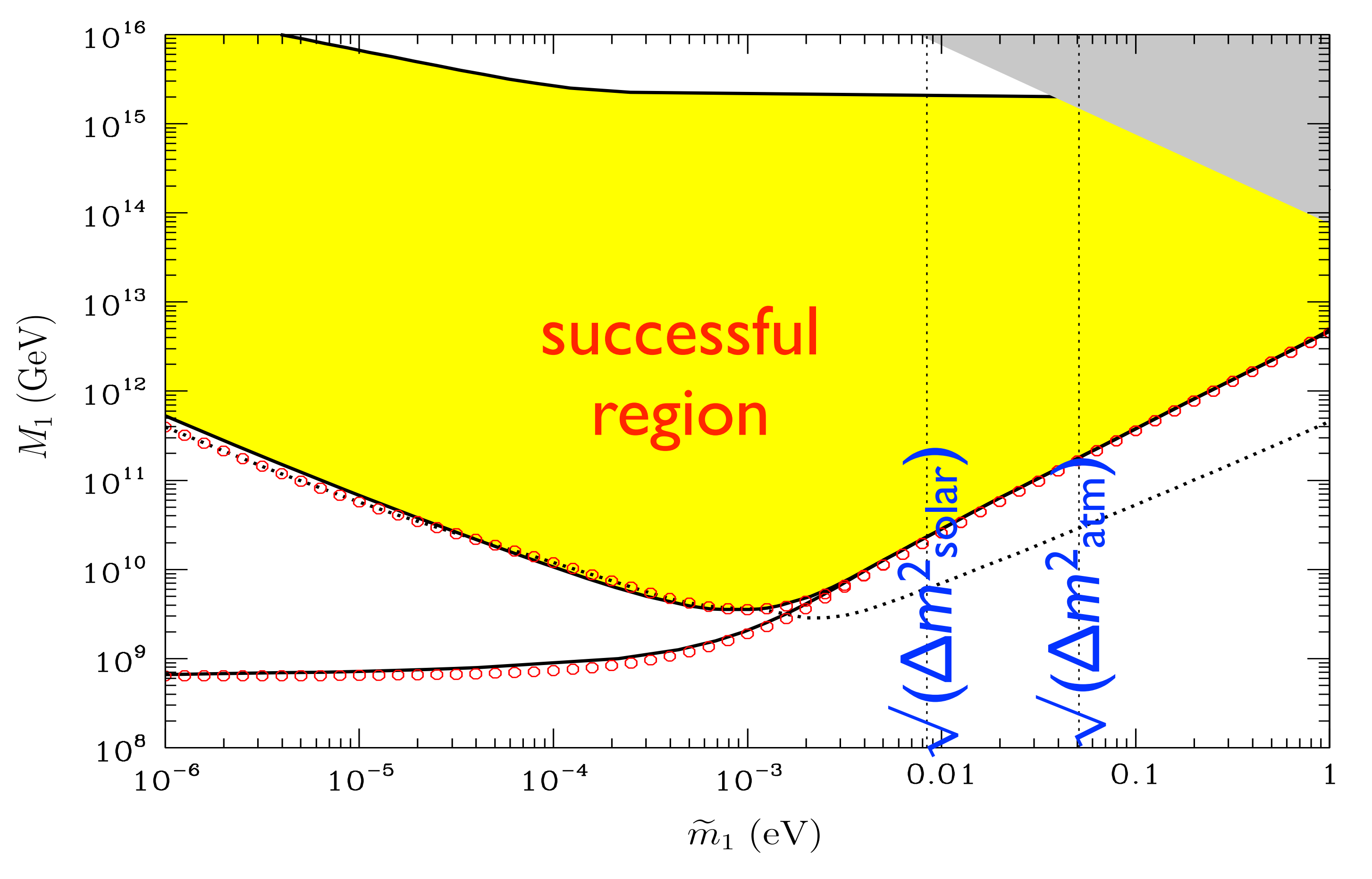




- 1,000,000,001 q !
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,001 $\bar{\nu}$



Non-trivial success!



$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller

How do we test it?

How do we test it?

build a 10^{14} GeV collider

Japan Aerospace Exploration Agency

文部科学省
MEXT
MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

indirect evidences

- Are all mixing angles large-ish?
- Is CP violated in neutrino sector?
- Is neutrino Majorana?
- collect archaeological evidences

Mixing Angles

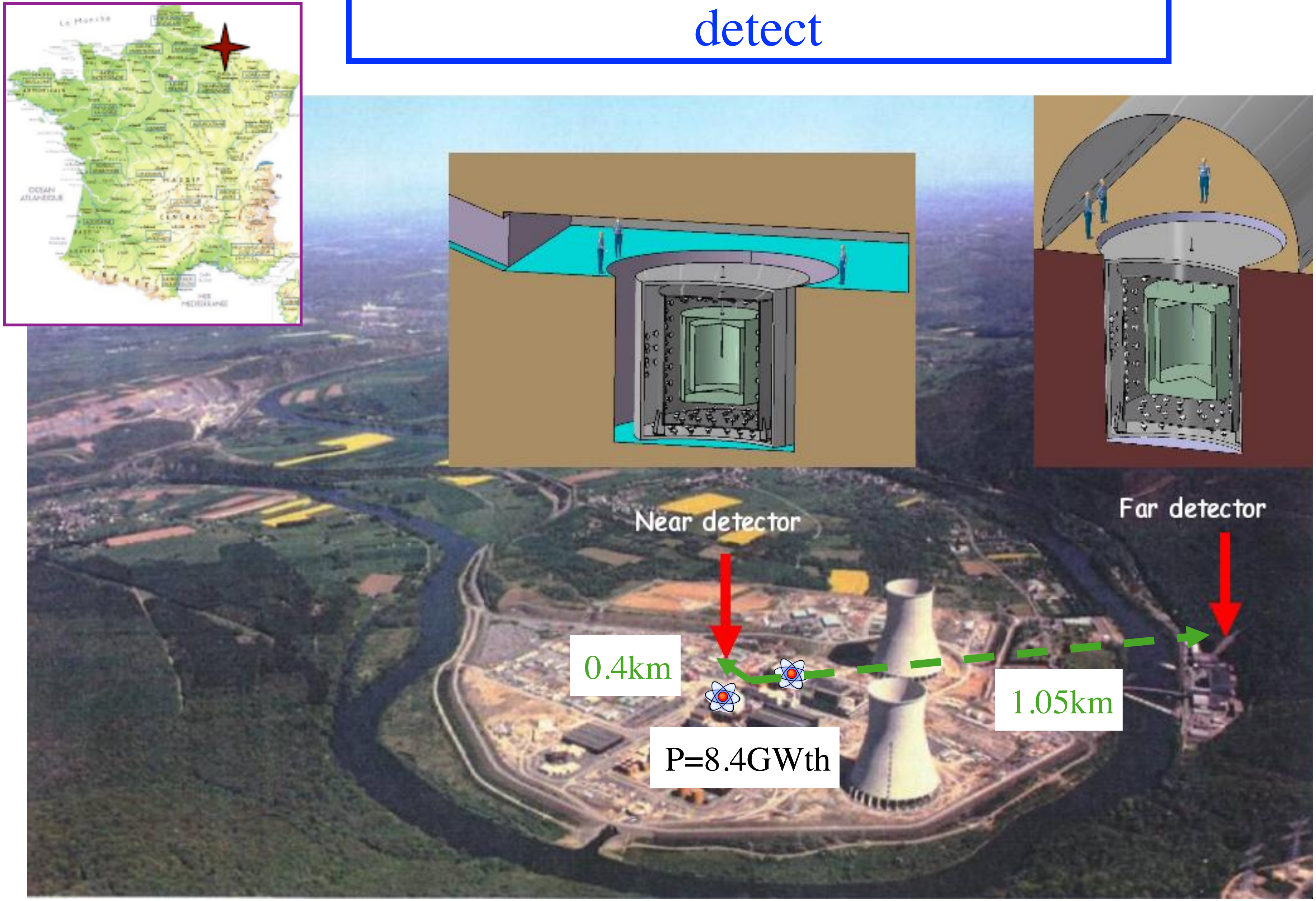
$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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

atmospheric	reactor limit	solar
$\theta_{23} \approx 45°$	$\theta_{13} < 7°$	$\theta_{12} \approx 35°$

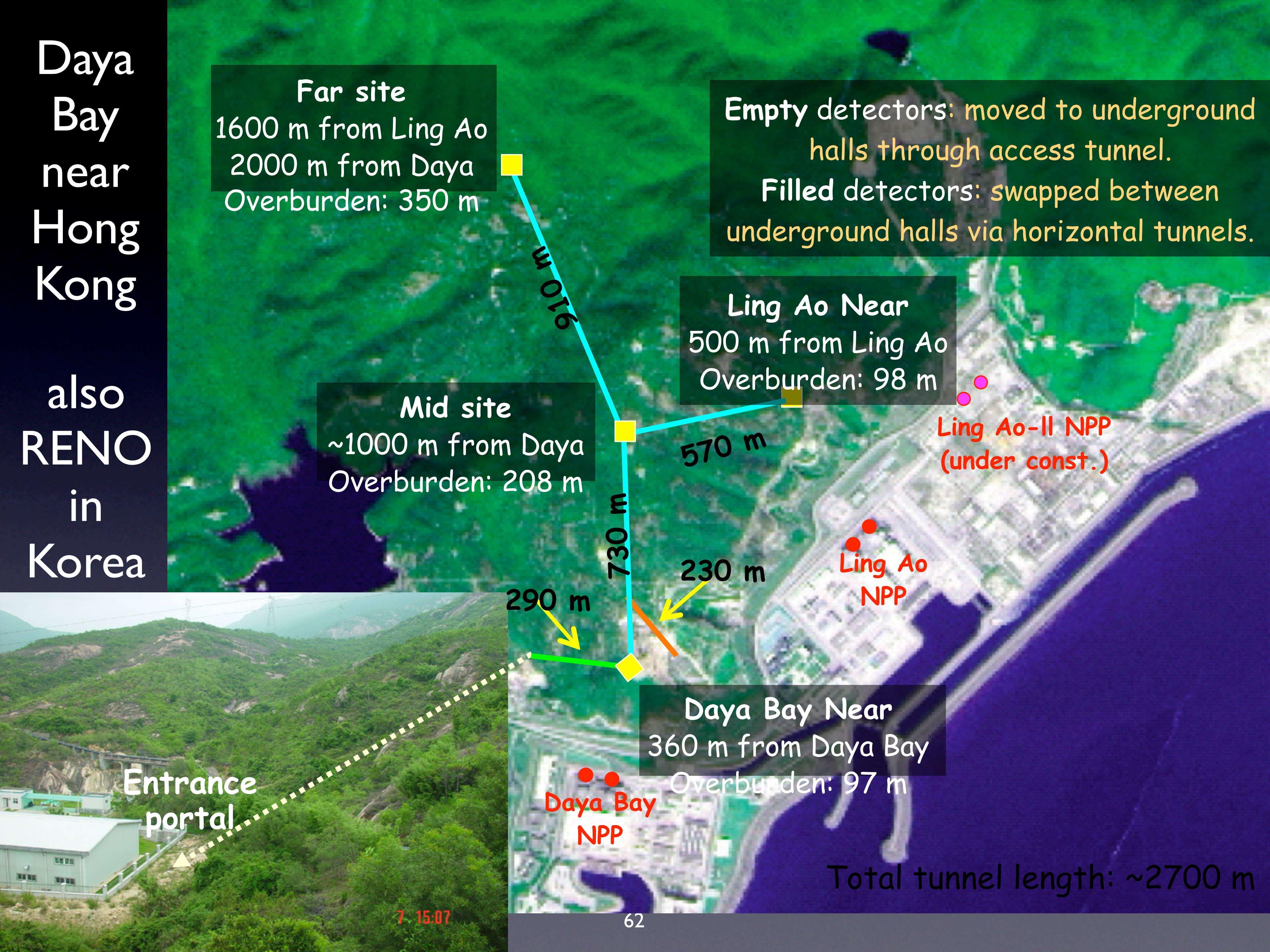
You want all angles to be "large"

Double Chooz Experiment to detect



Daya Bay near Hong Kong

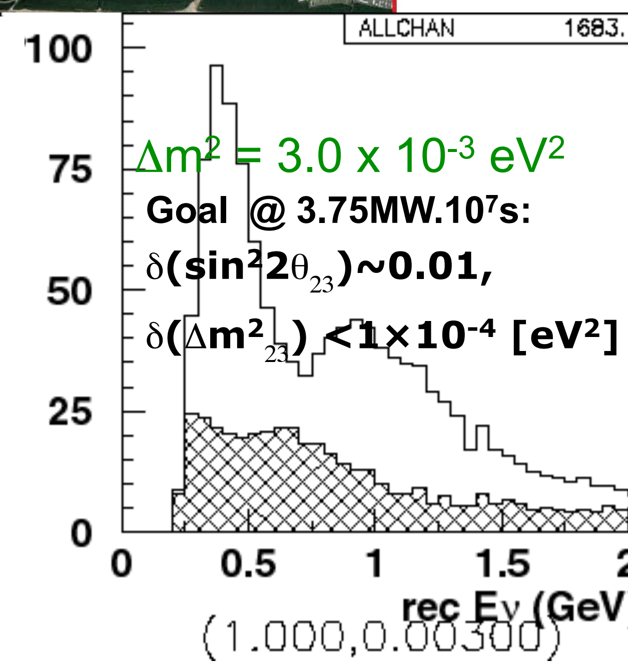
also RENO in Korea



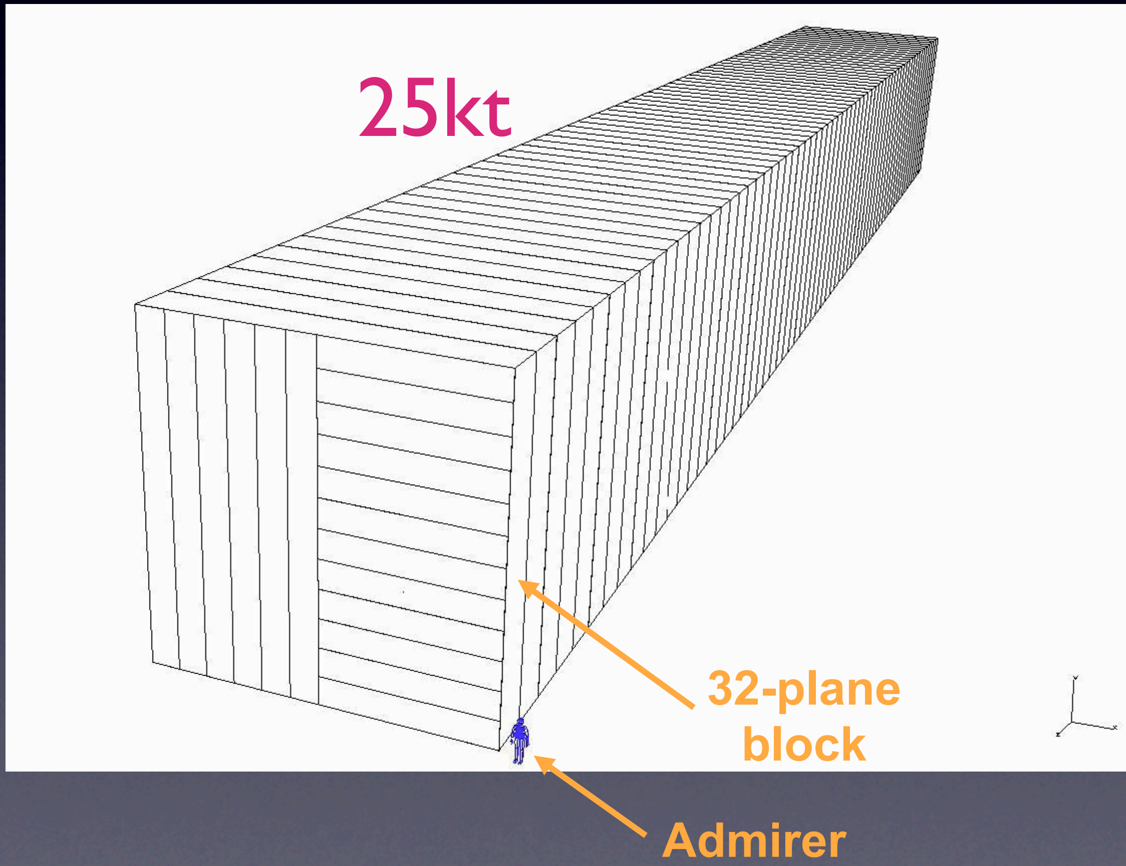
Tokai-to-Kamioka (T2K) long baseline neutrino oscillation experiment

- Goal
  - νe appearance measure → measure θ_{13}
  - precision measurement of νμ disappearance
- Intense narrow spectrum νμ beam from J-PARC MR
  - Off-axis w/ 2~2.5deg
  - Tuned at osci. max.
- SK: largest, high PID performance

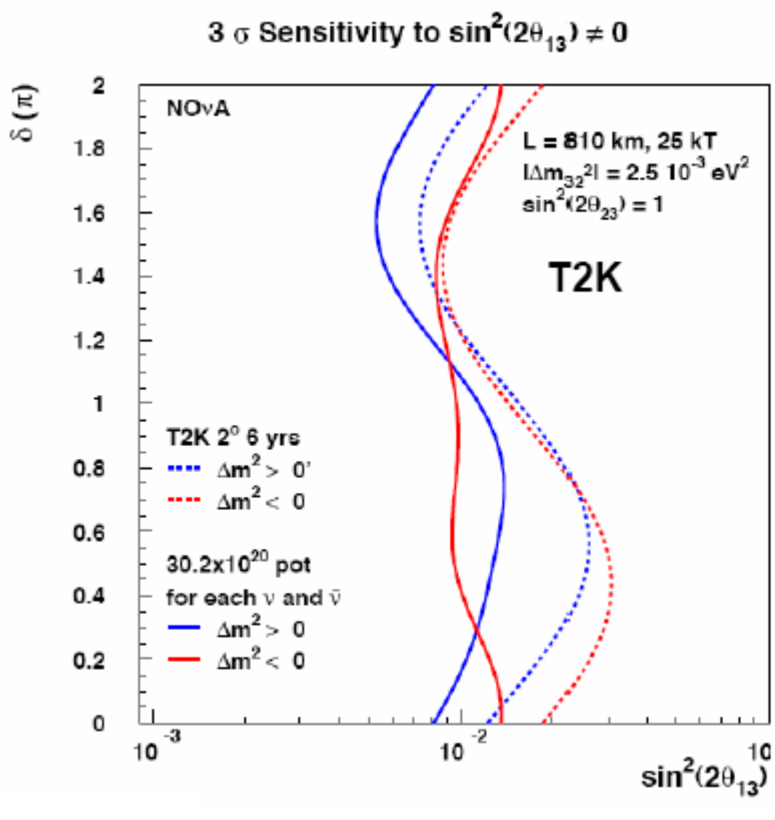
$1600\nu_\mu CC/yr/22.5kt$ (2.5deg)

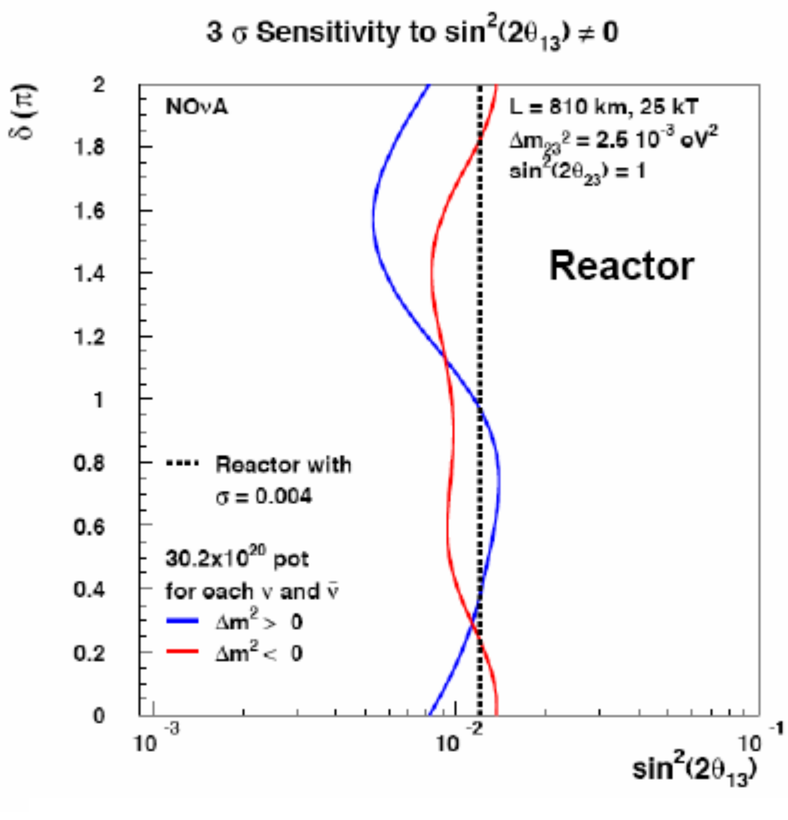


NOνA
Fermilab to Minnesota



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





CP violation

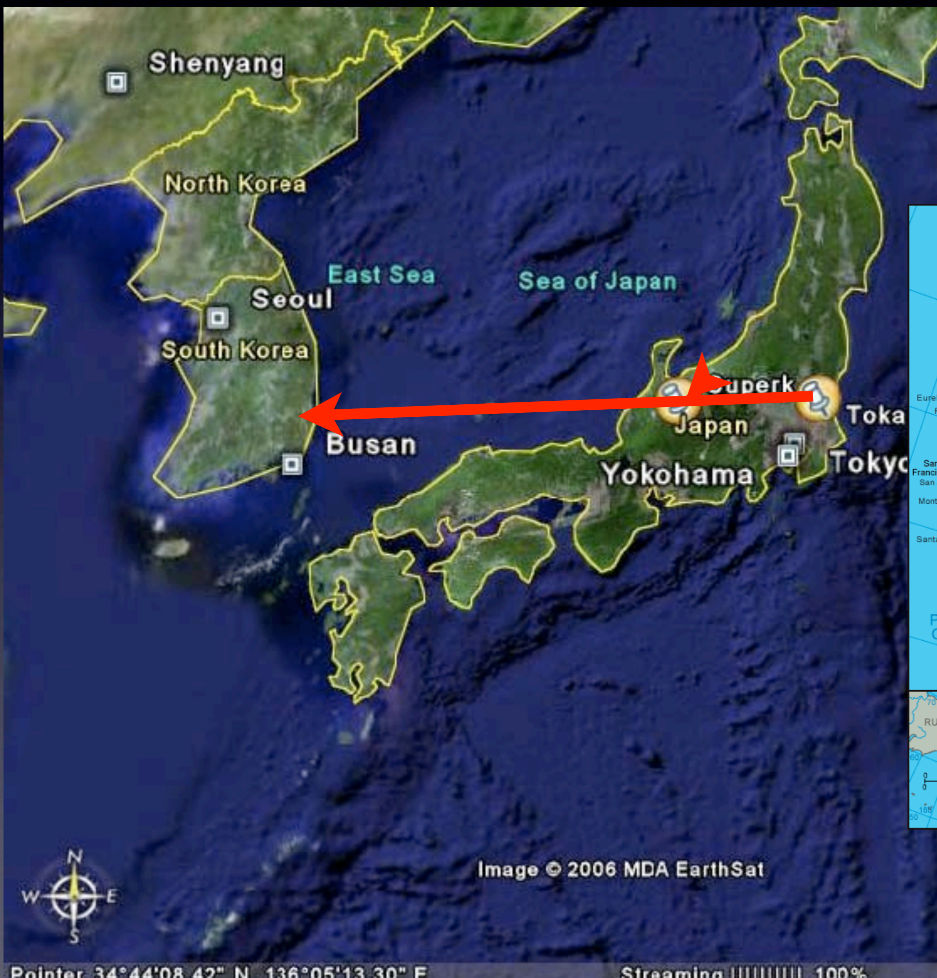
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- all parameters came out to be large
- θ_{13} is the key
- CP violation may be probed on terrestrial scale experiments

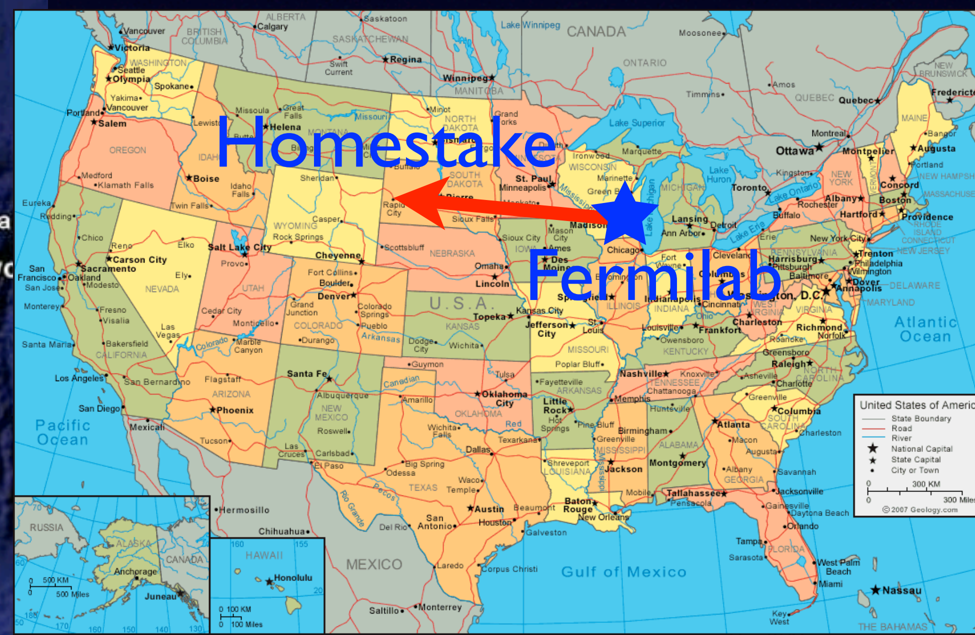
But this CP violation is *not* the one needed for leptogenesis

plausibility test

CP Violation?



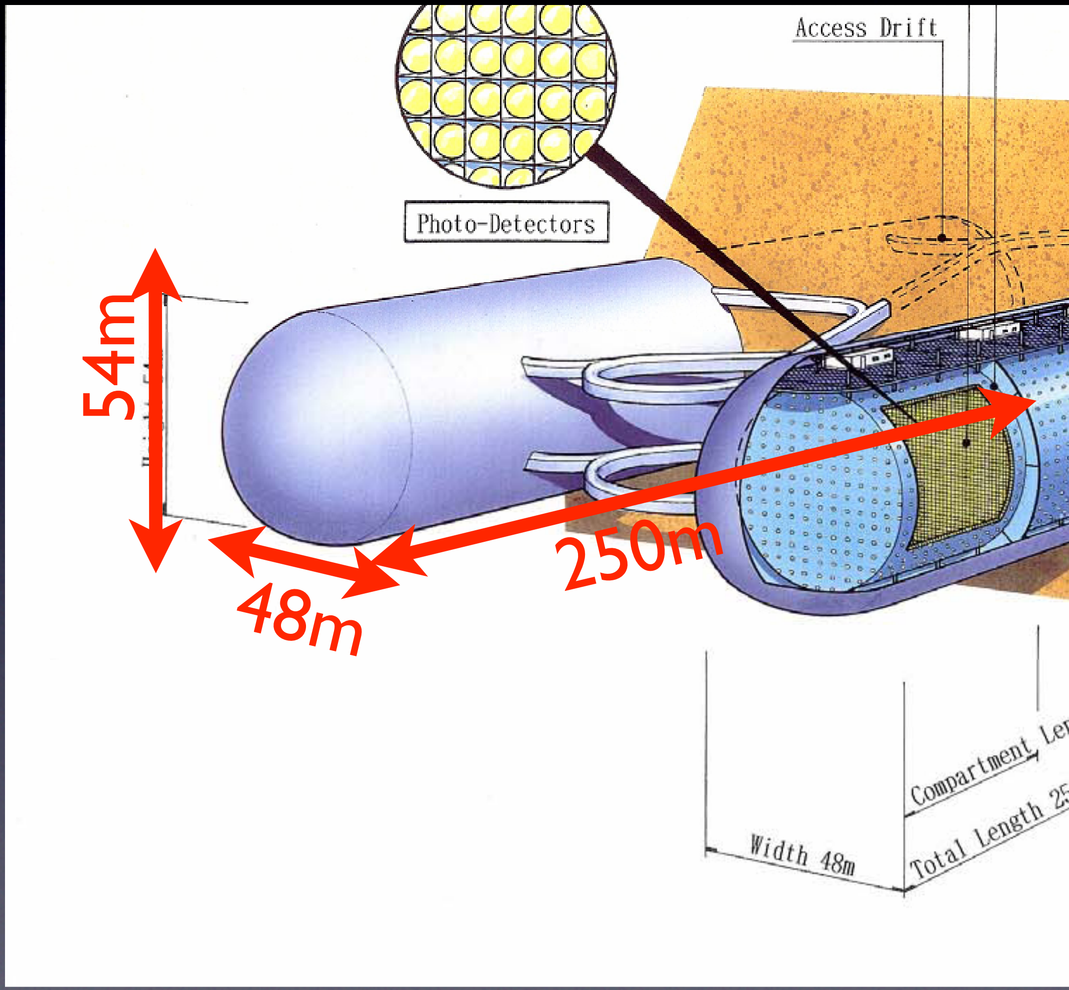
Shoot neutrinos over a thousand miles



Try to see difference between neutrinos and anti-neutrinos

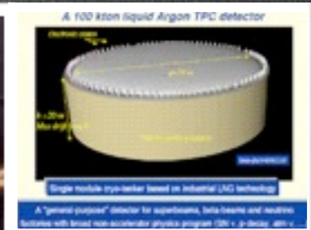
Need large detectors

- 1Mt is the right order of magnitude
- Super-K is 22.5kt (fiducial)



LARGE UNDERGROUND OBSERVATORY FOR PROTON DECAY, NEUTRINO ASTROPHYSICS AND CP-VIOLATION IN THE LEPTON SECTOR





A High Intensity Neutrino Oscillation Facility in Europe

A+ A A-

MAIN MENU

- **Home**
- What is EUROnu?
- Participants & Contributors

EUROnu

EUROnu

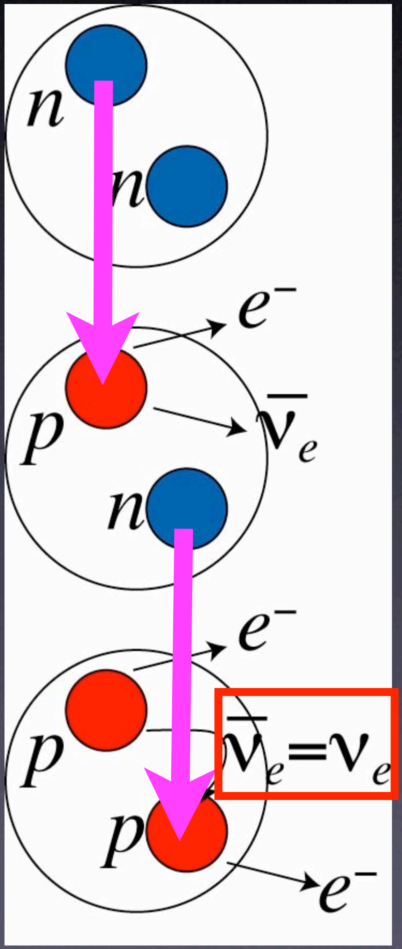
LATEST NEW

- Governance Structure
- What is EUROnu?

Turn anti-matter into matter

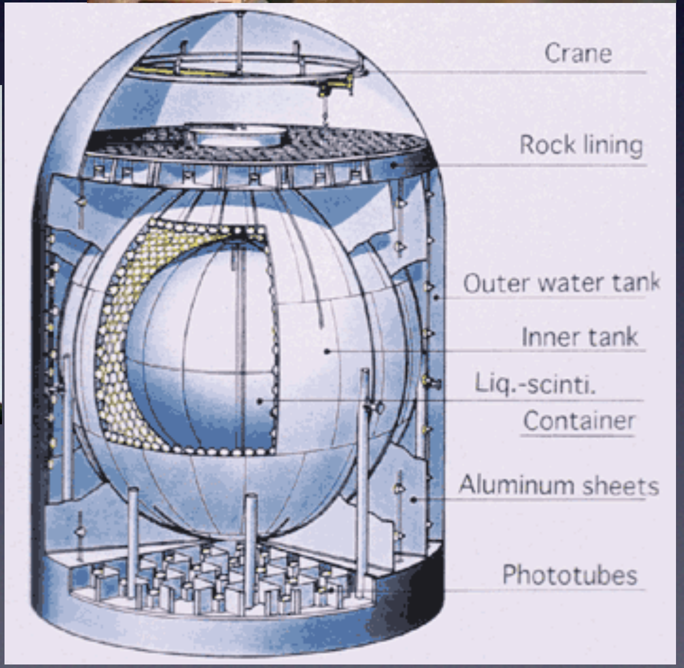
- Can anti-matter turn into matter?
- Maybe anti-neutrino can turn into neutrino because they don't carry electricity!
- $0\nu\beta\beta$: $nn \to ppe^-e^-$ with no neutrinos
- can happen only once 10^{24} (trillion trillion) years

patience!



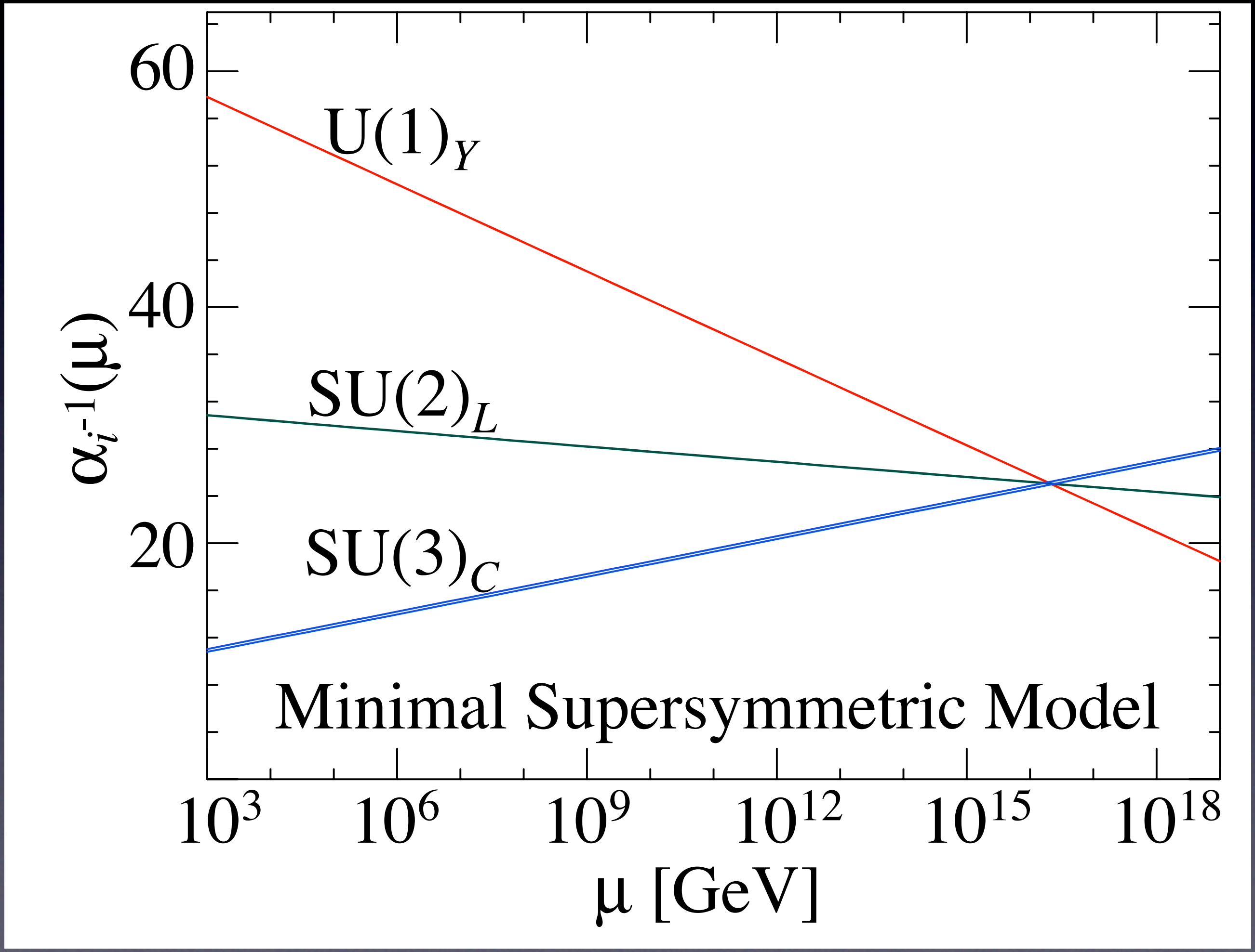
Need big underground experiments

Cuore (Italy)
Majorana (US)
NEMO (France)
EXO (US)
KamLAND (Japan)
etc
etc



KamLAND=1000t

Supersymmetry

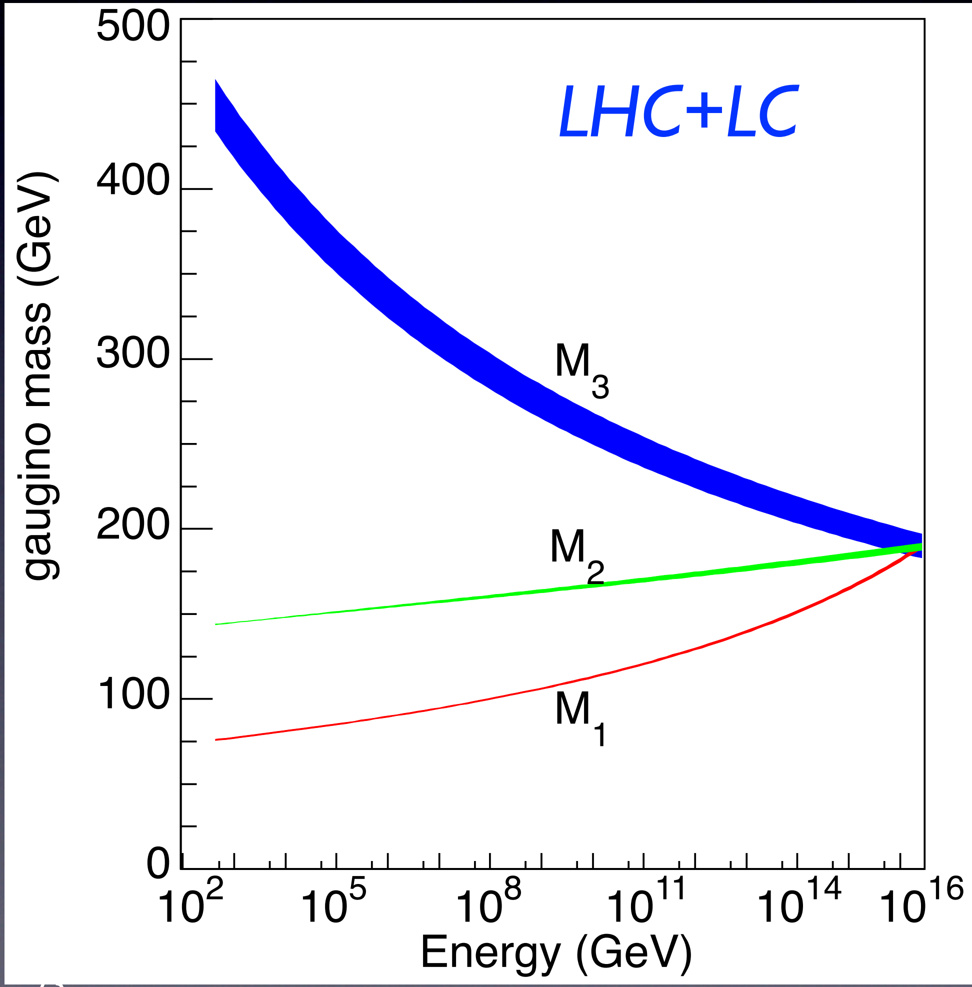


Superpartners probe high-scale physics

- Most exciting thing about superpartners beyond existence:

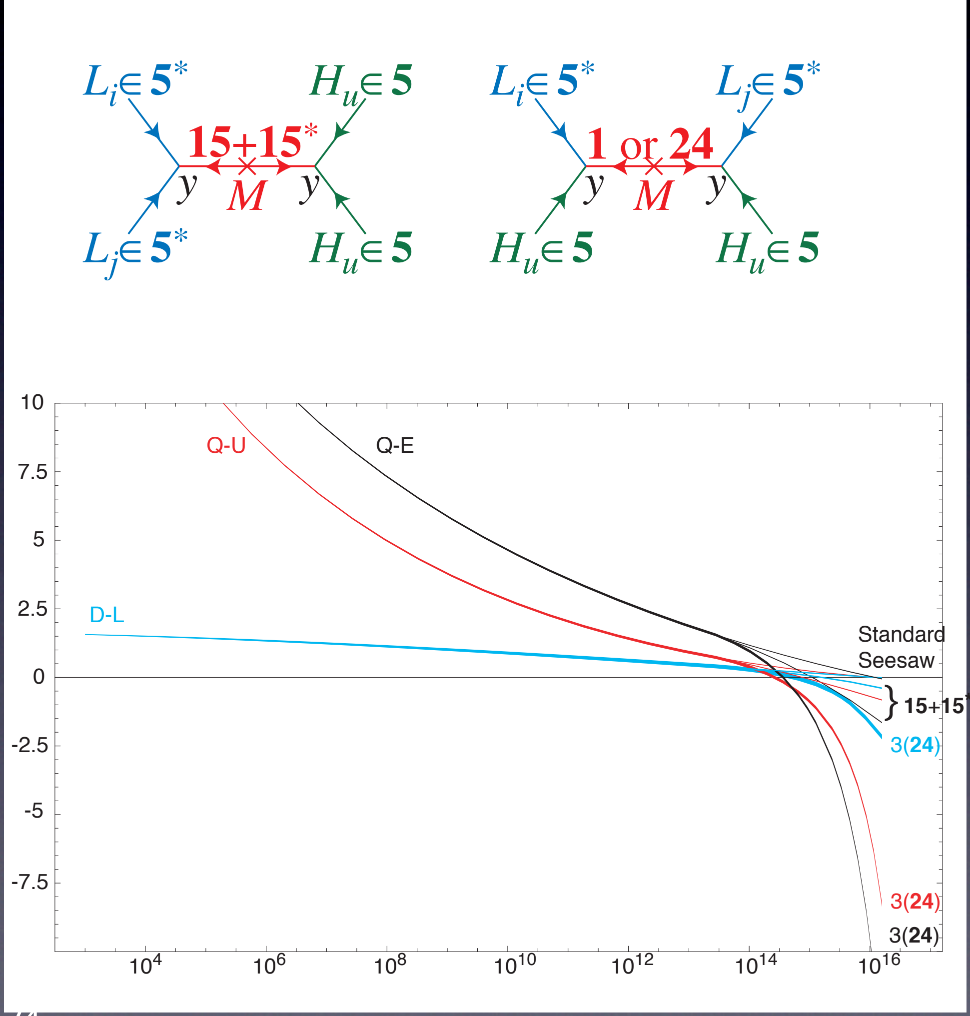
They carry information of small-distance physics to something we can measure

"Are forces unified?"



Why neutrino mass?

- Neutrino mass likely comes from physics at $>10^{10}$ GeV
- How will we ever know?
- Precision measurements at LHC/ILC determine boundary conditions at 10^{16} GeV
- With both ends fixed, we can constrain physics in between



Buckley, HM

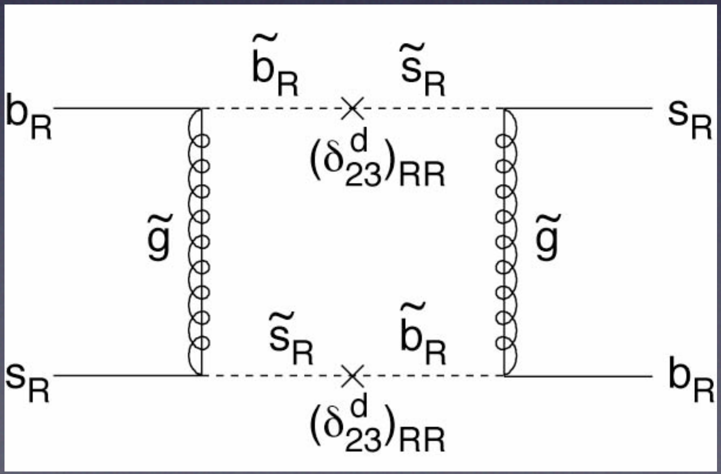
squark mixing

- Mixing among right-handed quarks not physical because there is no right-handed charged current

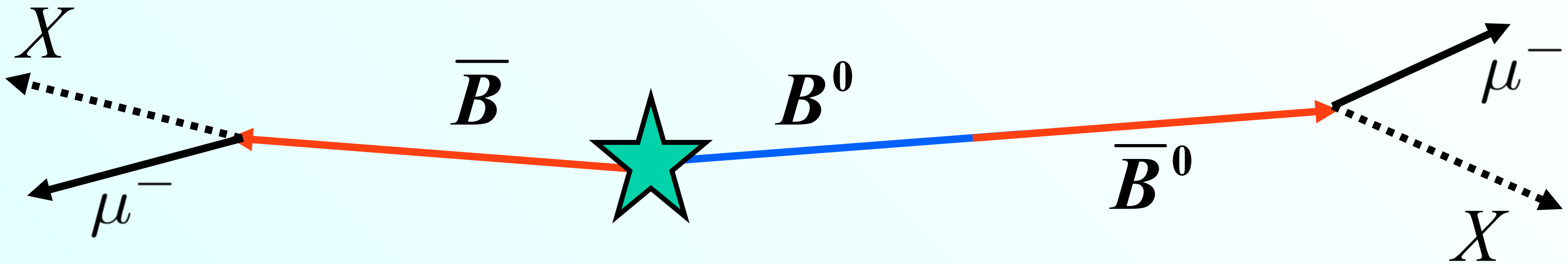
- but mixing among right-handed *squarks* physical

- large neutrino mixing may show up in B_s

$$\begin{pmatrix} s_R \\ s_R \\ s_R \\ \mu^+ \\ \bar{\nu}_\mu \end{pmatrix} \longleftrightarrow \begin{pmatrix} b_R \\ b_R \\ b_R \\ \tau^+ \\ \bar{\nu}_\tau \end{pmatrix}$$



Dimuon charge asymmetry



- We measure *CP* violation in mixing using **the dimuon charge asymmetry of semileptonic *B* decays:**

$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

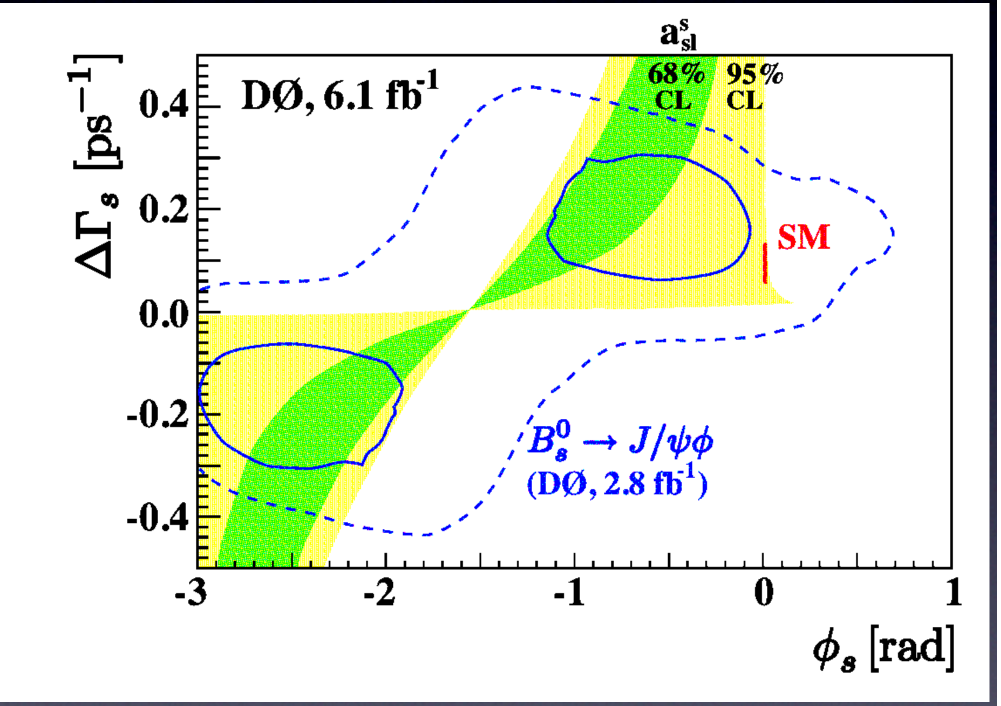
$$A_{sl}^b = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst})\,)\%$$

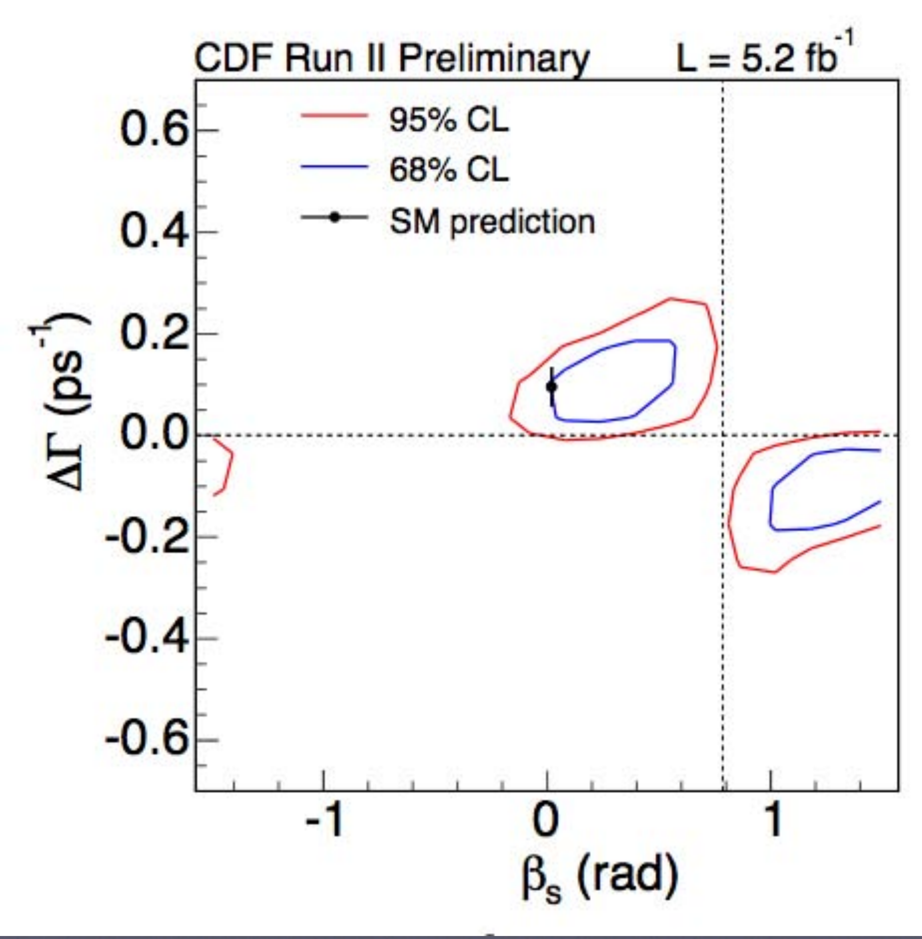
$$A_{sl}^b(SM) = (-0.023^{+0.005}_{-0.006})\%$$

G.Borissov@Fermilab

May 14, 2010

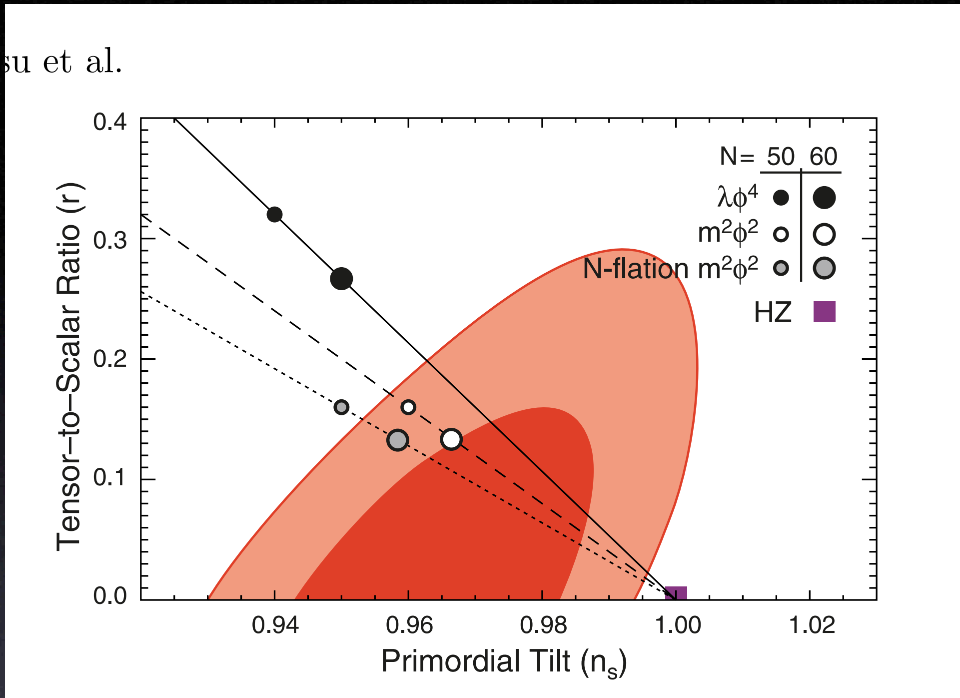
Comparison with other measurements



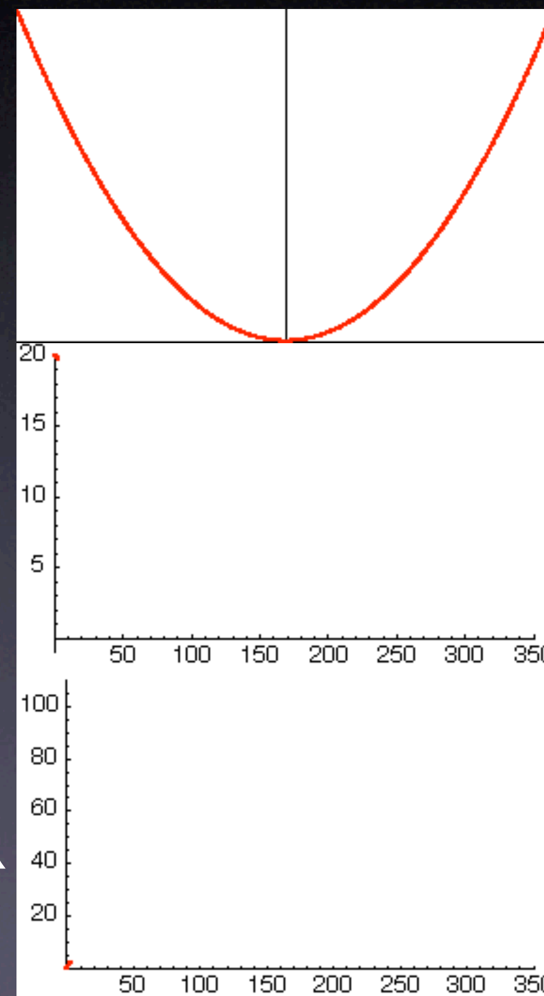


LHCb will have a large sample of $B_s \to J/\psi\ \phi$

May 25@FPCP2010
Louise Oakes



Inflation

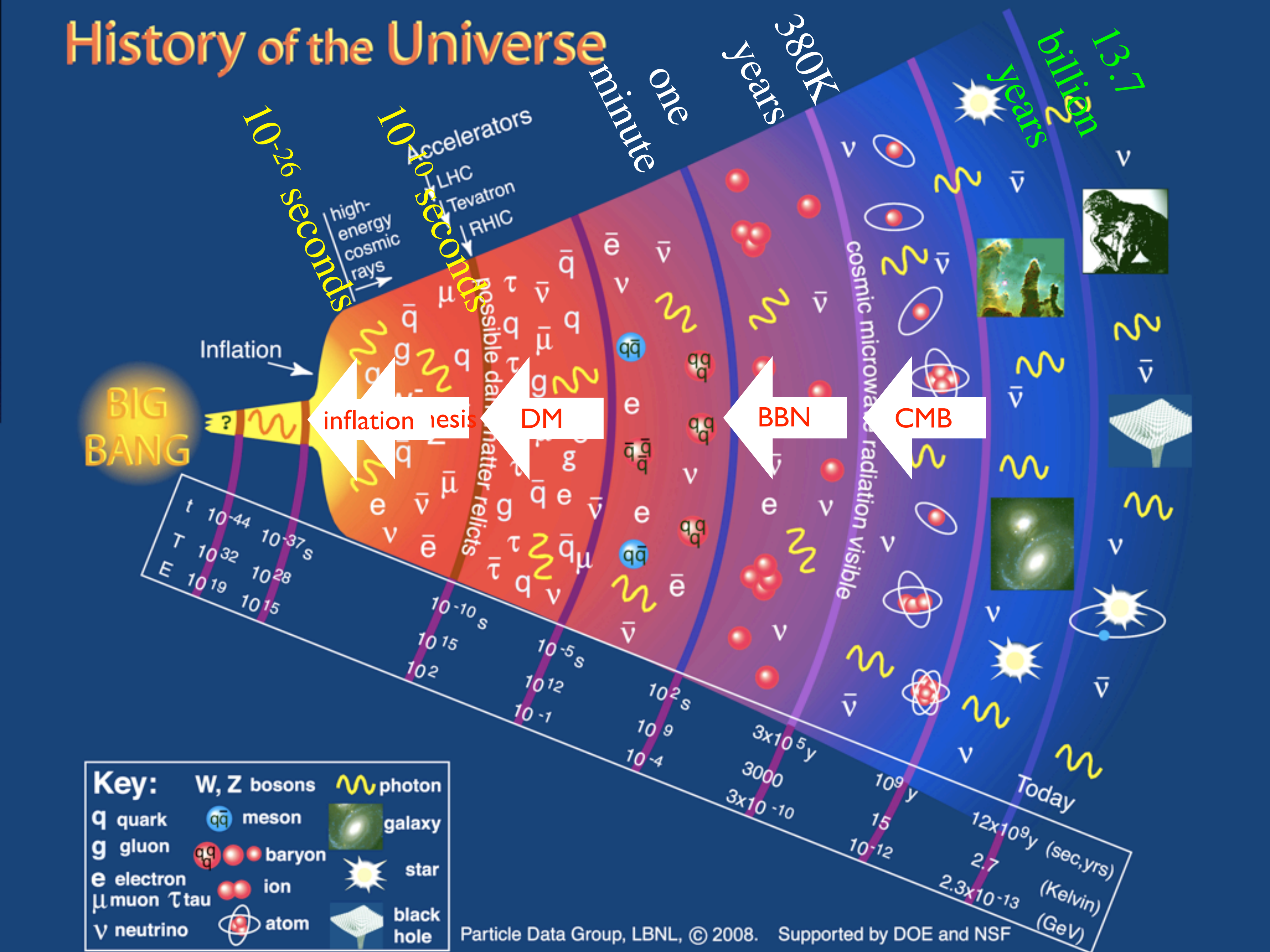


source of later structure

- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter

How we survived the Big Bang

- ν_R without distinction between matter and matter (possible only for neutral particles!)
- once they are produced, they eventually decay into light leptons
- CP violation in Yukawa couplings let ν_R decay preferentially into anti-leptons ($L<0$)
- SM anomaly converts it to baryons ($B>0$)
- anti-baryons annihilated by baryons
- we won at the expense of a billion friends!


History of the Universe
10^{-26} seconds
10^{-10} seconds
one minute
380K years
13.7 billion years
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
inflation
DM
BBN
CMB
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}
3×10^{5} y
3000
3×10^{-10}
10^{9} y
15
10^{-12}
Today
12×10^{9} y (sec,yrs)
2.7 (Kelvin)
2.3×10^{-13} (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Challenges

- detect cosmic background neutrinos
  - test Big Bang directly back to $z \sim 3\times 10^9$
- detect the *asymmetry* in neutrinos
  - leptogenesis $L \sim 3B$
  - EW baryogenesis $L=B$
  - low-scale scalar decay $L \approx 0$
  - test Big Bang directly back to $z \sim 10^{29}$

Open problems

- We don’t understand 4% of the Universe either
- Little information on when baryogenesis occured, still many possibilties
- connections between leptogenesis and observable neutrino parameters not clear
- any ideas to probe background neutrinos?

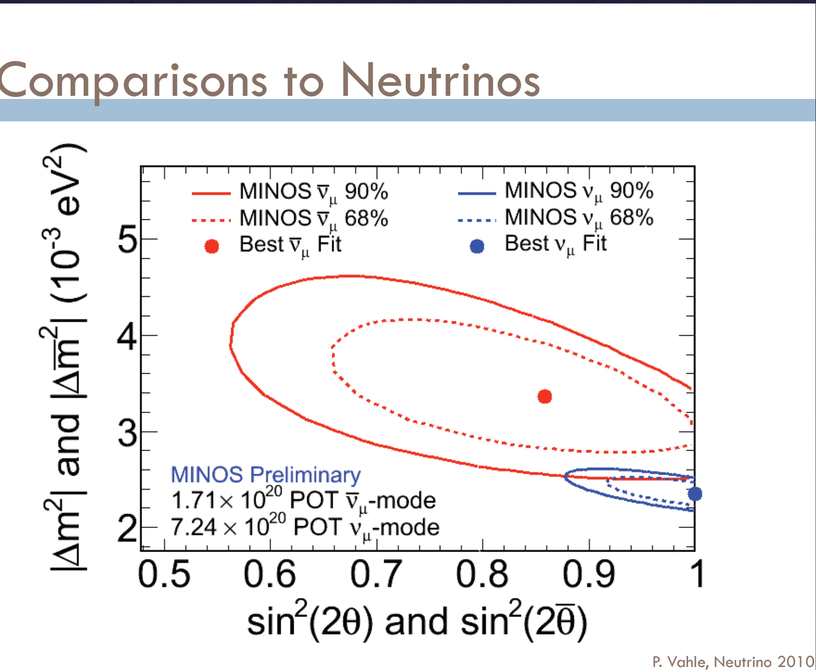
Baryogenesis

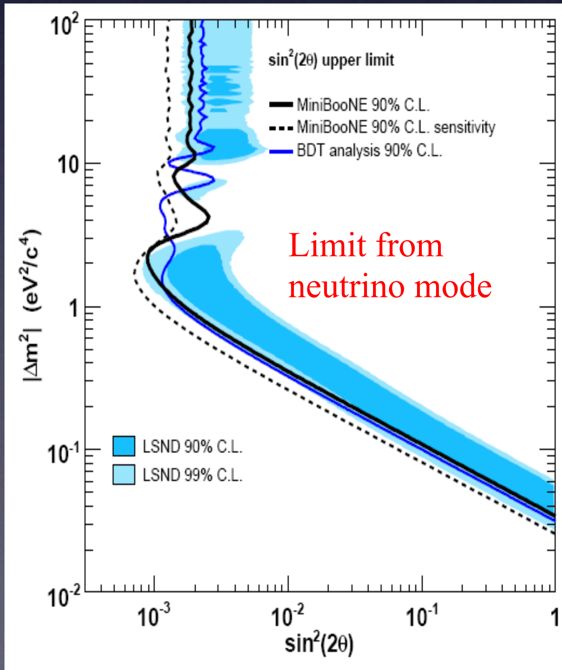
- Why do we exist?
- No wonder it is a big question
- it involves many areas of particle physics and cosmology
  - LHC/LC, flavor, neutrino, LFV, CMB B-mode, dark matter, gravitational wave
- many experiments now and in the near future relevant to this question
- Small step at a time!

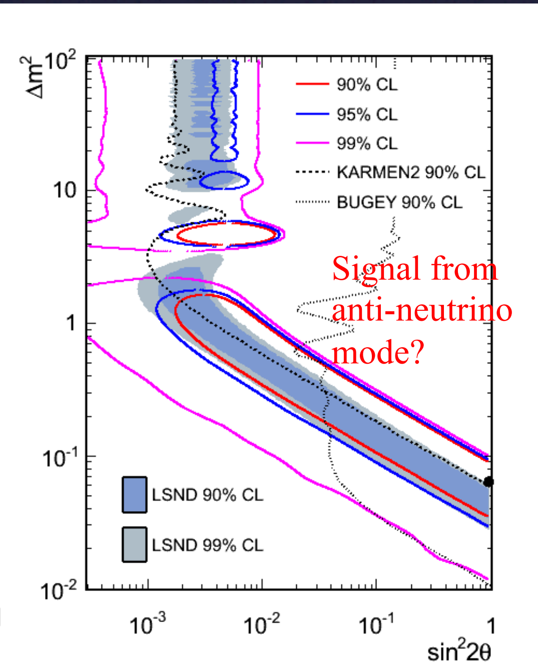
too many theories for a single number

Other talking points

- recent data from MINOS and Mini-BooNE suggest CPT violation?
- can one prove CPT in string theory?
- or many sterile neutrinos with CPV, U(1)'?







Other talking points

- What is the best way to measure neutrino mass in cosmology with least systematics?

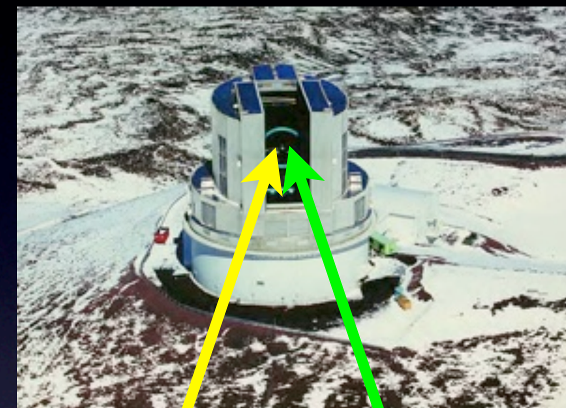
more powerful
larger systematics
↓

- CMB
- weak lensing (+spectroscopic z)
- galaxy power spectrum
- Lyman alpha forest

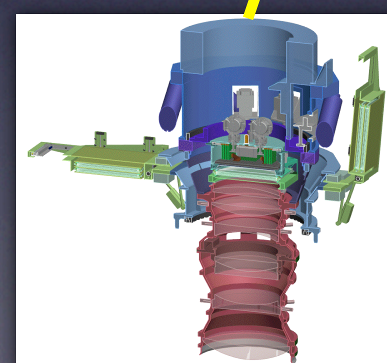
SuMIRe

Subaru Measurement of Images and Redshifts

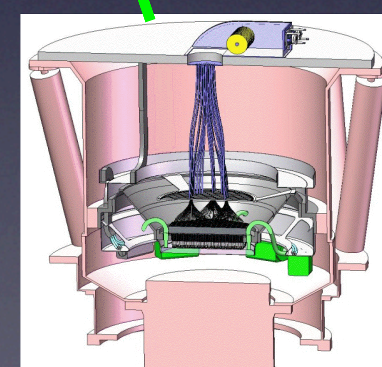
- cosmological limits on neutrino mass are important
- erasure of small scale perturbations
- need better theory (quasi-non-linear regime, e.g. Ichiki, Takada, Takahashi)
- need better data
- imaging (HyperSuprimeCam)
  - 0.9 B pixels, 3 tonnes
  - first light later this year
- spectroscopy (PrimeFocusSpectrograph)
  - 2400 objects, R~2000–5000
  - aiming at 2016
- $\delta\Sigma_i \, m_{\nu i} < 0.06$ eV



Subaru



HSC



PFS