The University of Tokyo 東京大学
TODIAS 東京大学国際高等研究所 Todai Institutes for Advanced Study
Kavli IPMU Institute for the Physics and Mathematics of the Universe

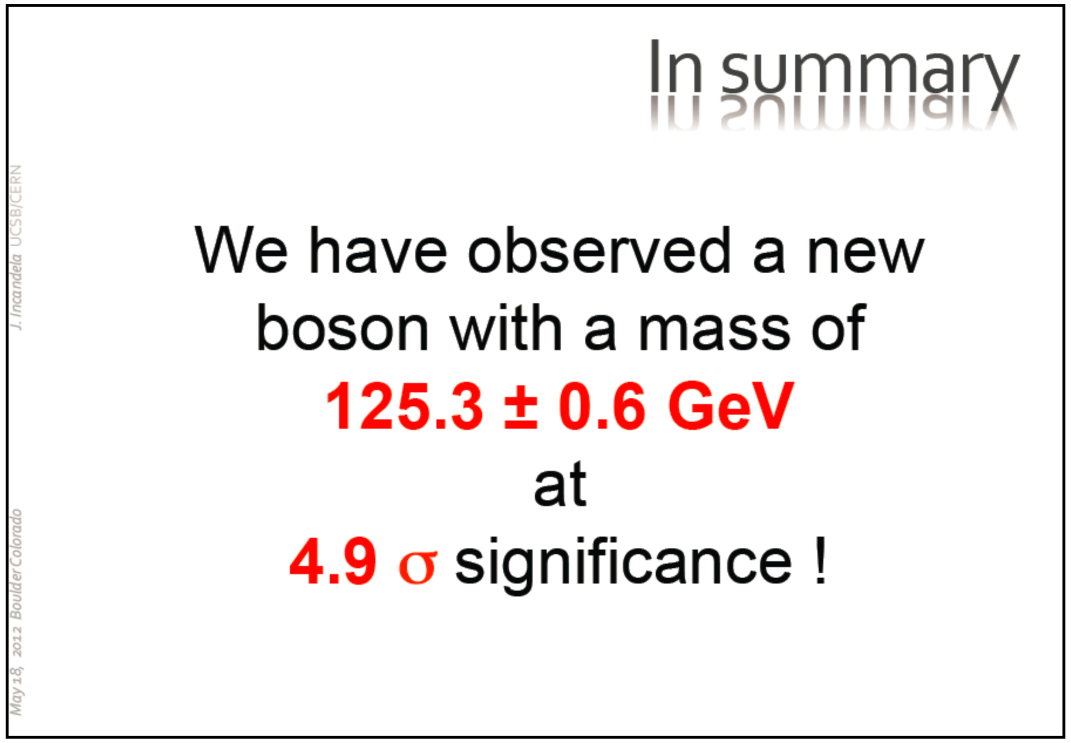
Workshop for Neutrino Programs with facilities in Japan

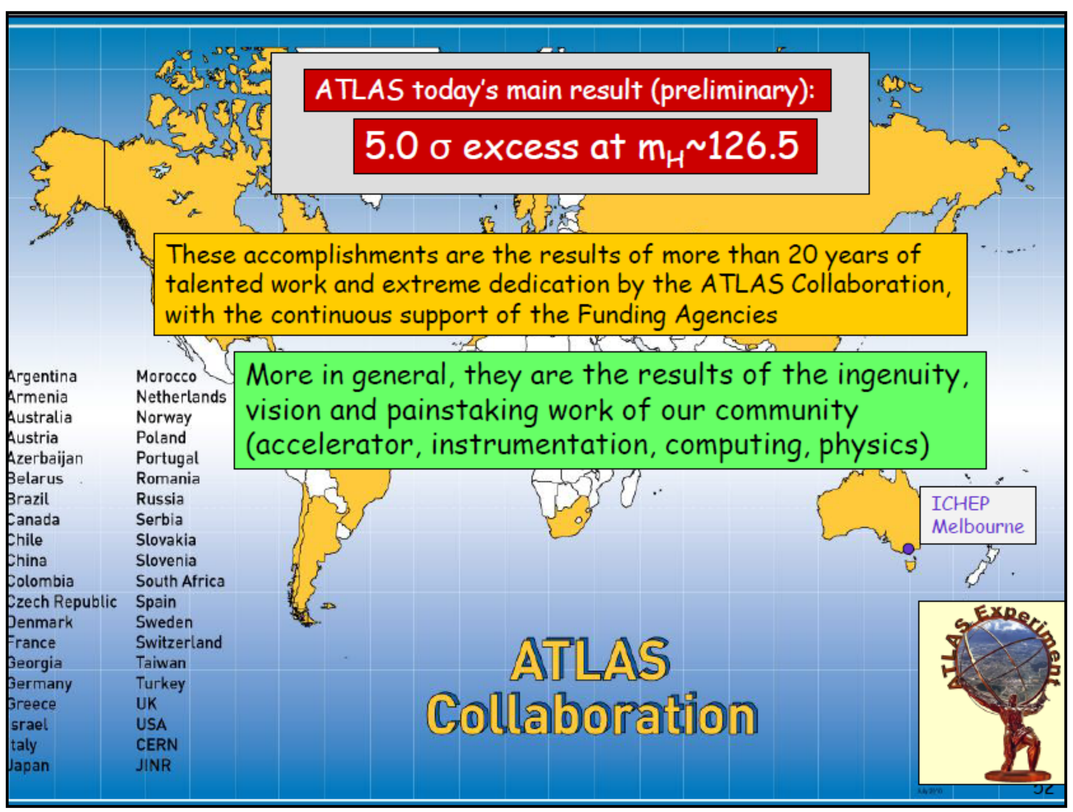
Theory Outlook

Hitoshi Murayama (Berkeley & Kavli IPMU)
J-PARC, Aug 6, 2015

Berkeley Center for Theoretical Physics
Berkeley Lab

July 4, 2012


In summary
We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !
J. Incandela UCSB/CERN
May 18, 2012 Boulder Colorado

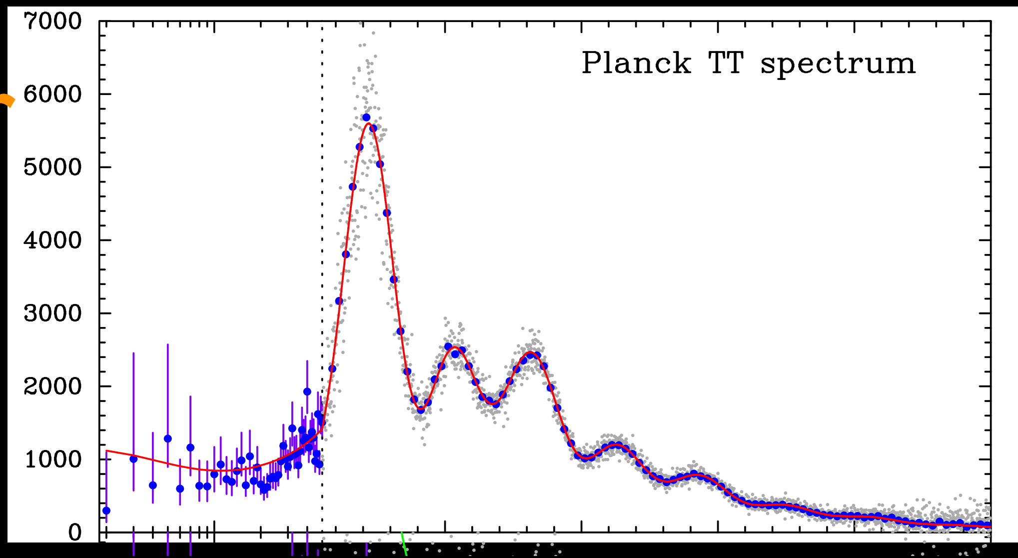

ATLAS today's main result (preliminary):
5.0 σ excess at m_H~126.5
These accomplishments are the results of more than 20 years of talented work and extreme dedication by the ATLAS Collaboration, with the continuous support of the Funding Agencies
More in general, they are the results of the ingenuity, vision and painstaking work of our community (accelerator, instrumentation, computing, physics)
Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
srael
taly
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR
ICHEP Melbourne
ATLAS Collaboration
ATLAS Experiment


CERN
Higgs search update 04.07.2012

Is particle physics over?

Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

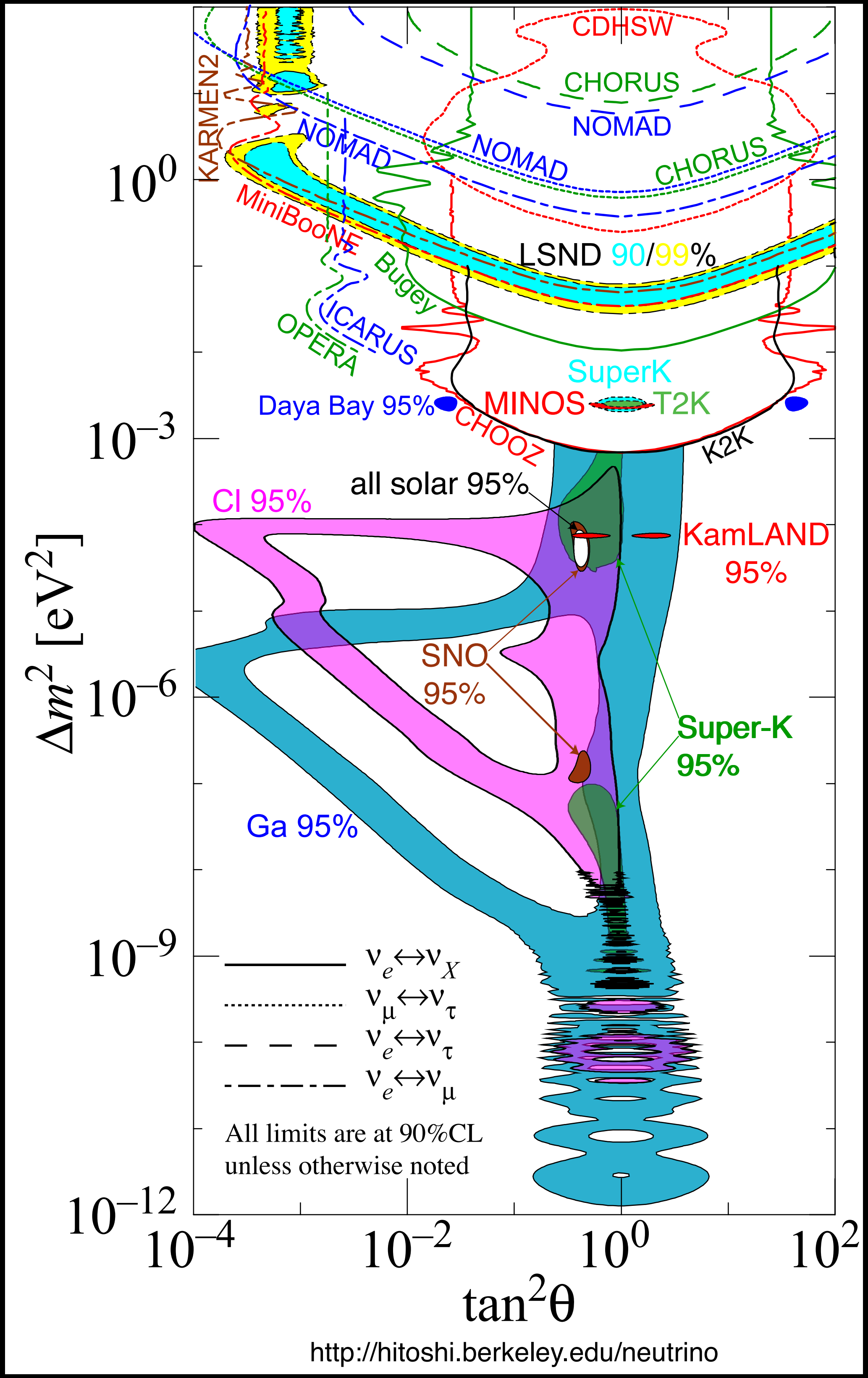


We don’t really know their energy scales…

neutrino mass

Amazing

HUGE progress since 1998

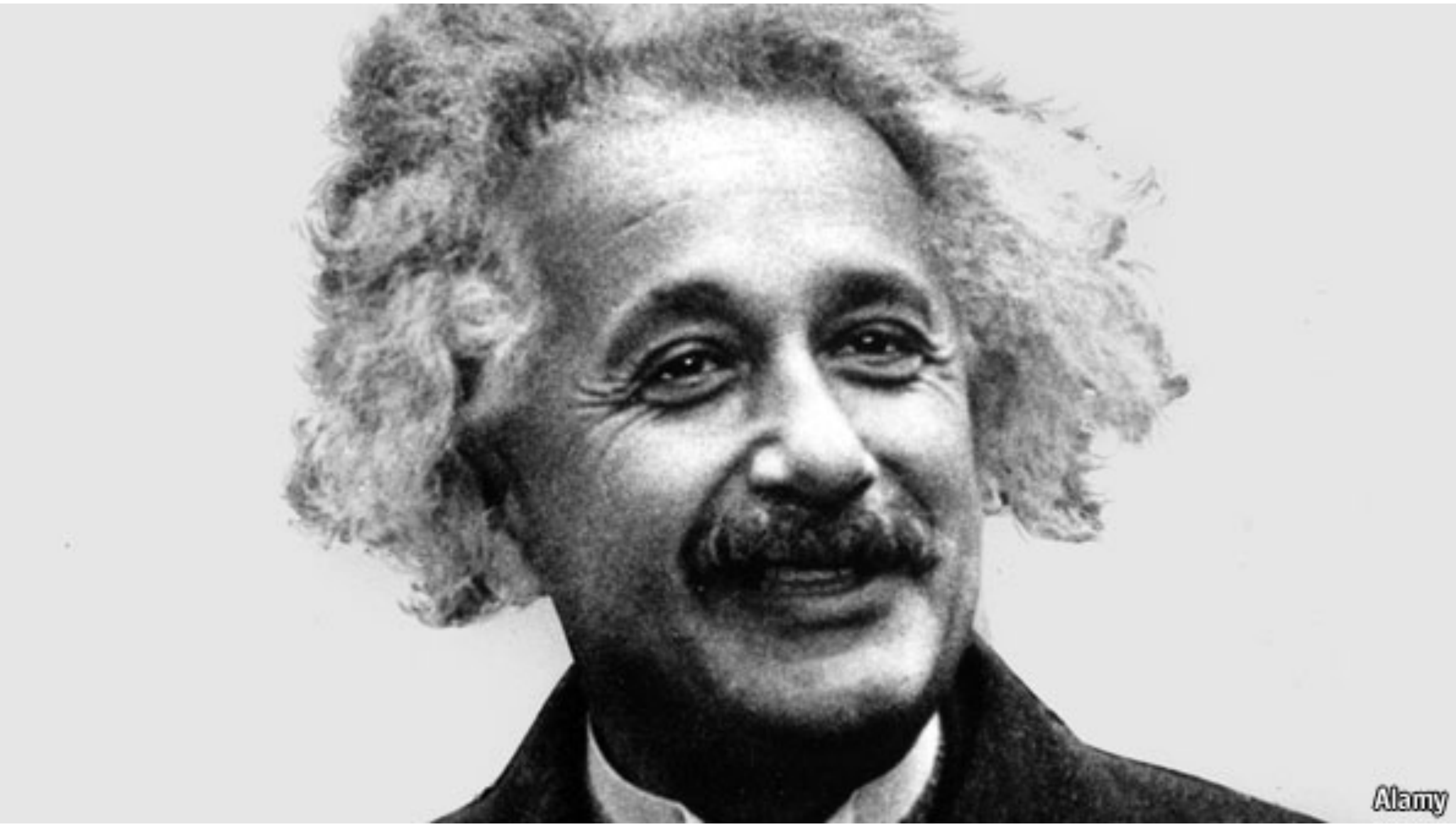


Neutrinos and relativity

Faster than the speed of light

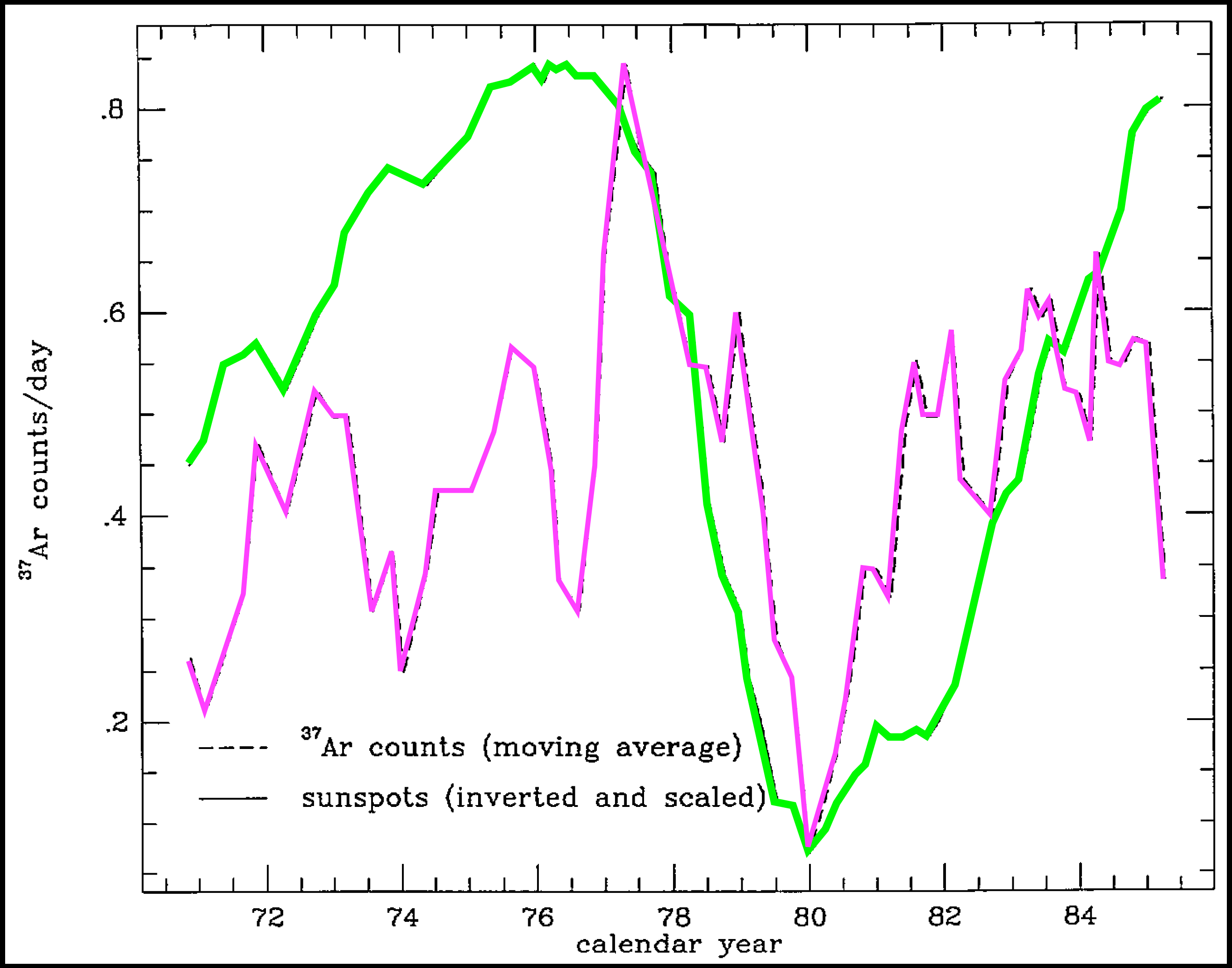
What does an experiment that seems to contradict Einstein's theory of relativity really mean?

Oct 1st 2011 | from the print edition



IN 1887 physicists were feeling pretty smug about their subject. They thought they understood reality well, and that the future would just be one of ever more precise measurements. They could not have been more wrong. The next three decades turned physics on its head, with the discovery of electrons, atomic nuclei, radioactivity, quantum theory and the theory of relativity. But the grit in the pearl for all this was a strange observation made that year by two researchers called Albert Michelson and Edward Morley that the speed of light was constant, no matter how fast the observer was travelling.

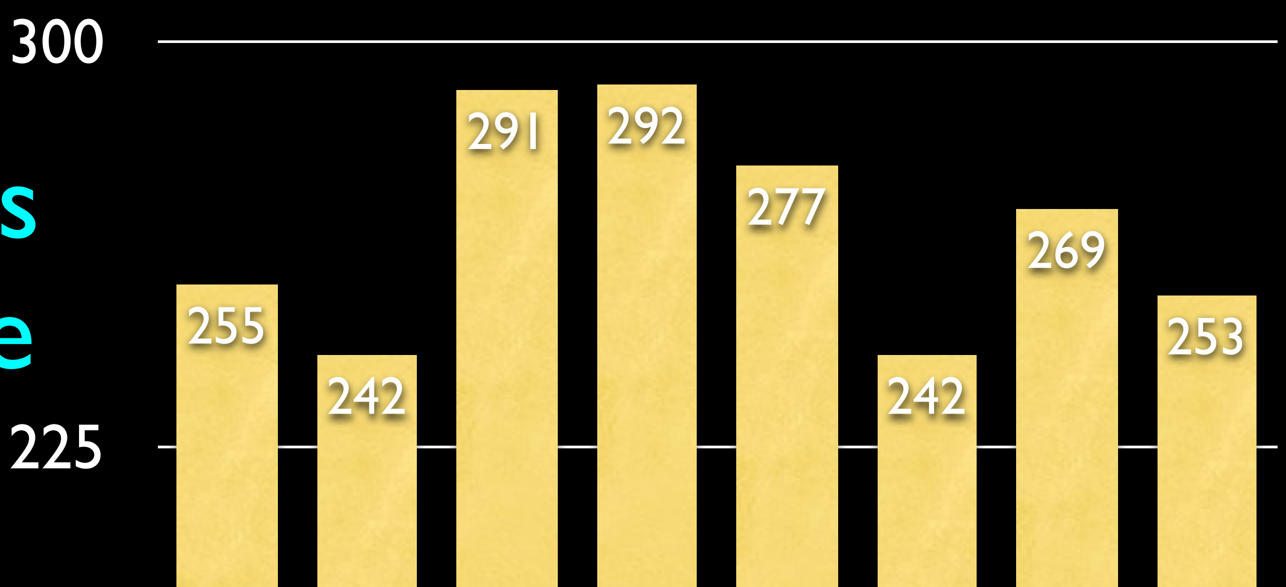
Confusing data



–#sunspot

Homestake

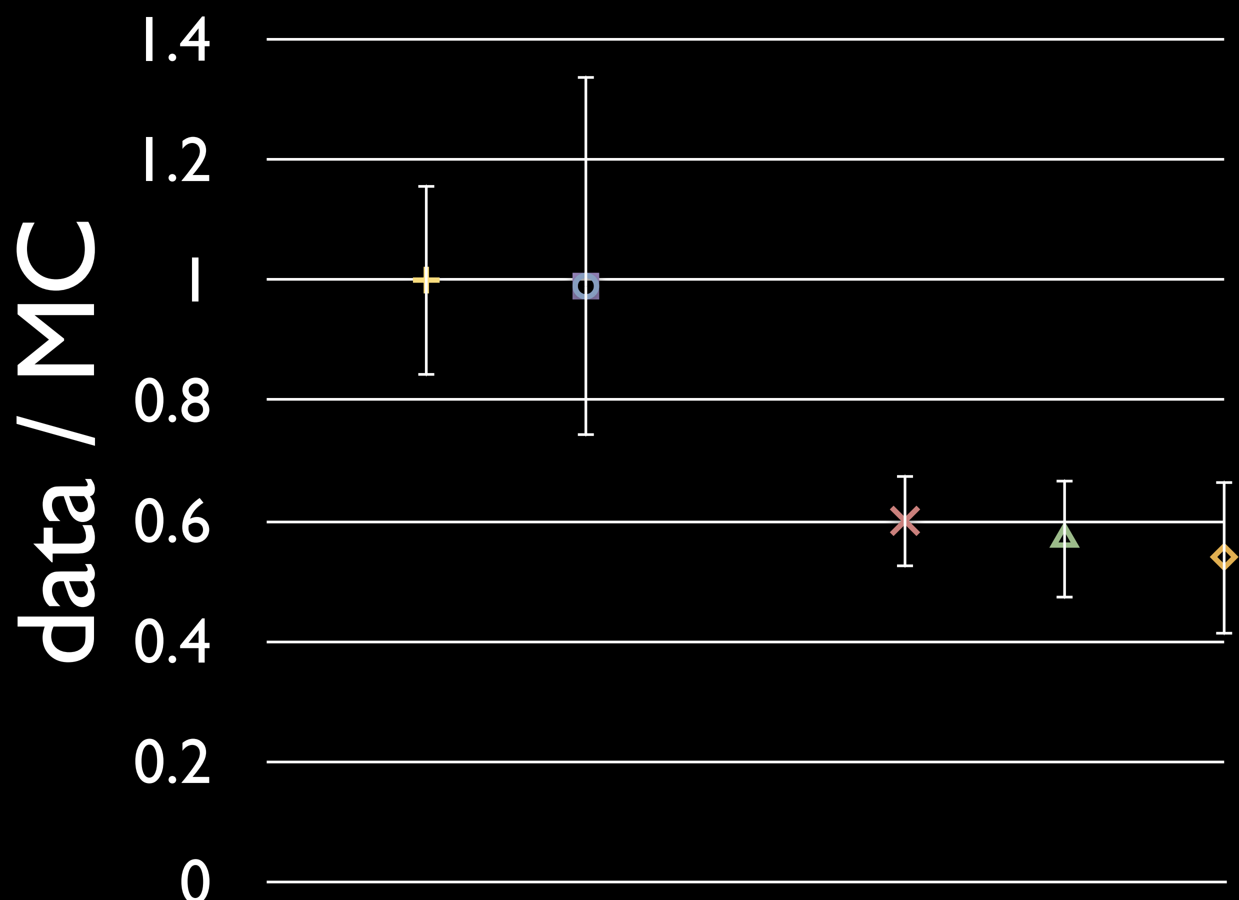
#Democrates in the House



Atmospheric neutrinos

1988

- mu/e ratio
  - problem w/ Water Ch?
  - neutron BG?
  - particle ID?
  - proton decay?



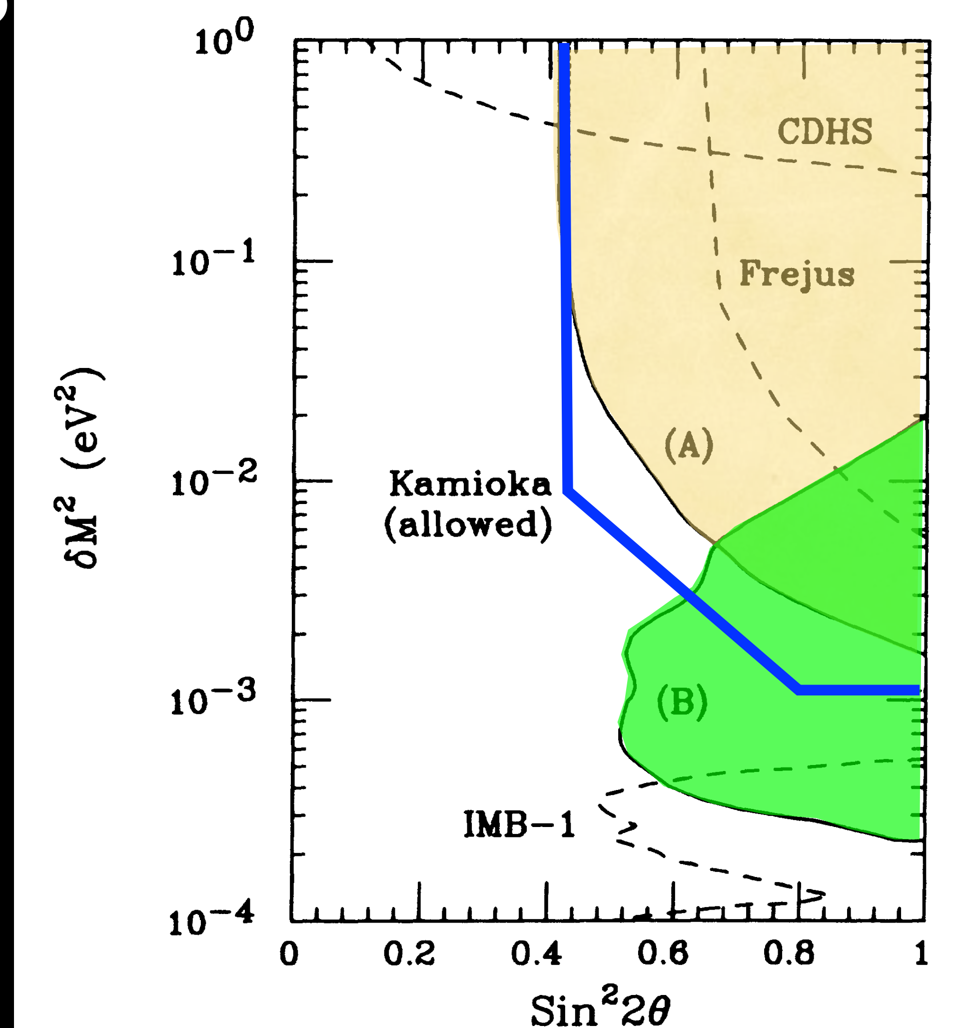
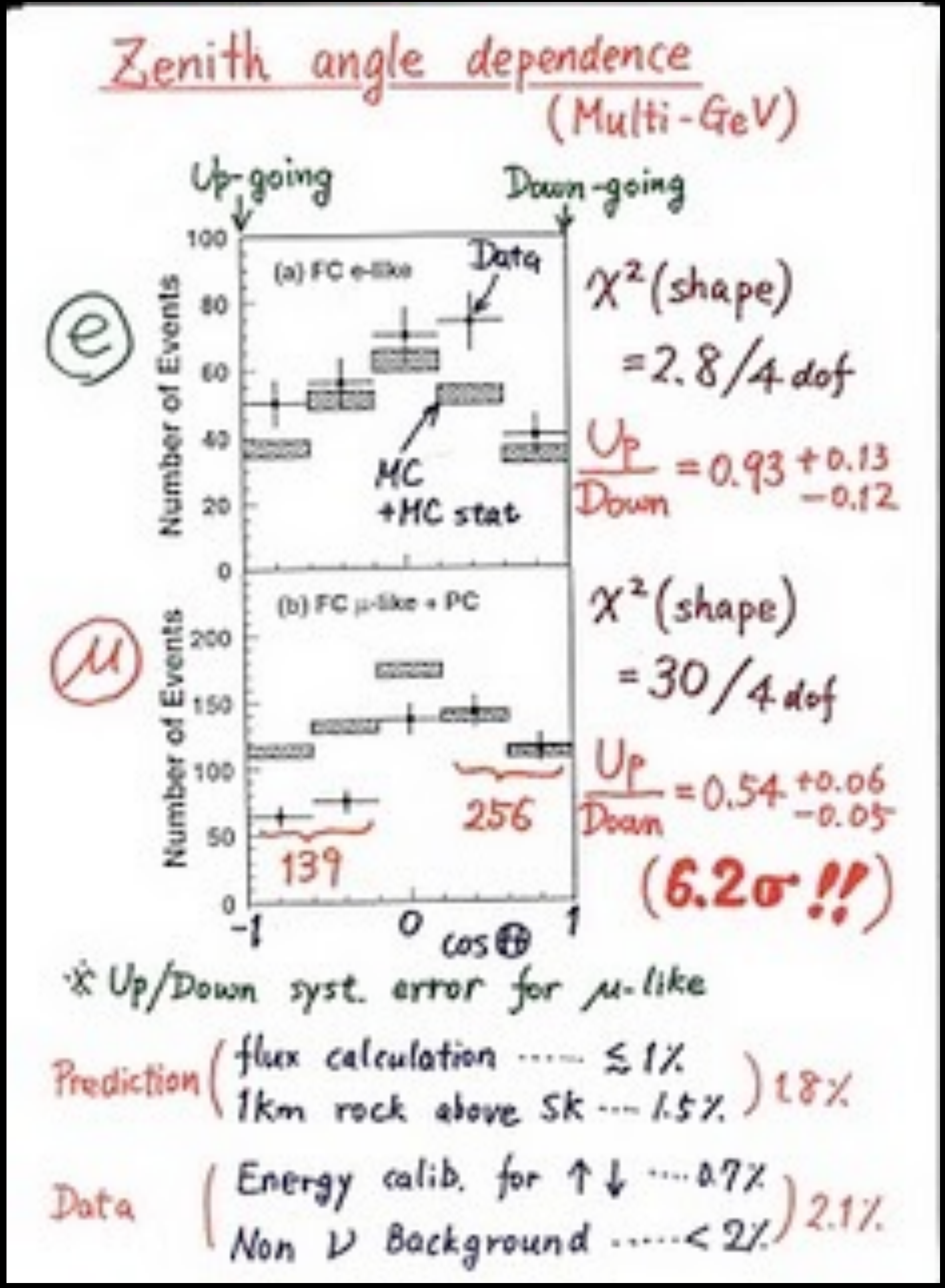


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (*A*) and stopping fraction (*B*). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

IMB, PRL 69, 1010 (1992)

mospheric neutrinos

1998



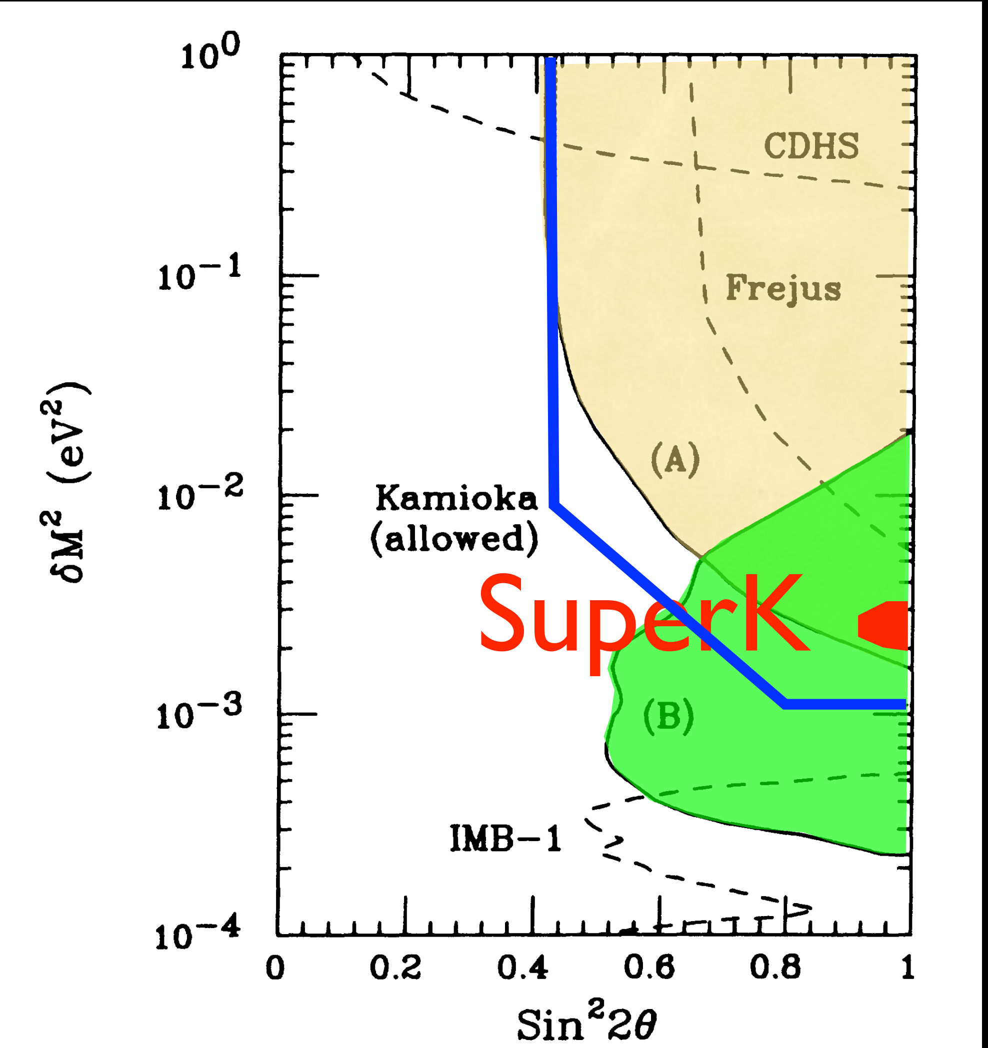


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (*A*) and stopping fraction (*B*). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

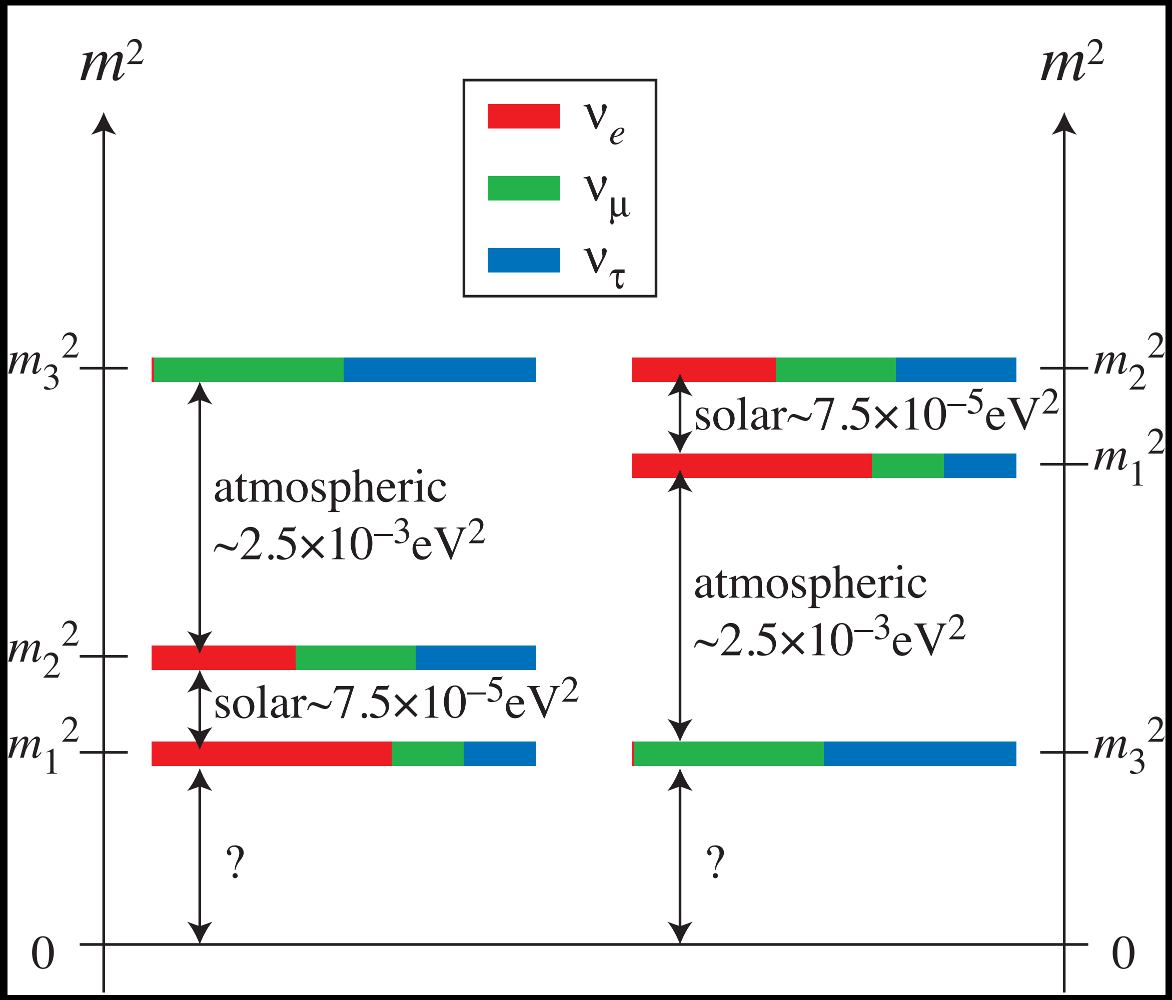
IMB, PRL 69, 1010 (1992)

Typical Theorist's View ca. 1990

- Solar Neutrino Problem must be solved by Small Angle MSW solution because it is so beautiful Wrong!
- Important scale for oscillation is $\Delta m^2 \approx 10\text{-}100$ eV^2 because it is cosmologically relevant Wrong!
- θ_{23} must be about $\theta_{23} \approx V_{cb} \approx 0.04$ Wrong!
- atmospheric neutrino anomaly must go away because it requires large mixing angle Wrong!

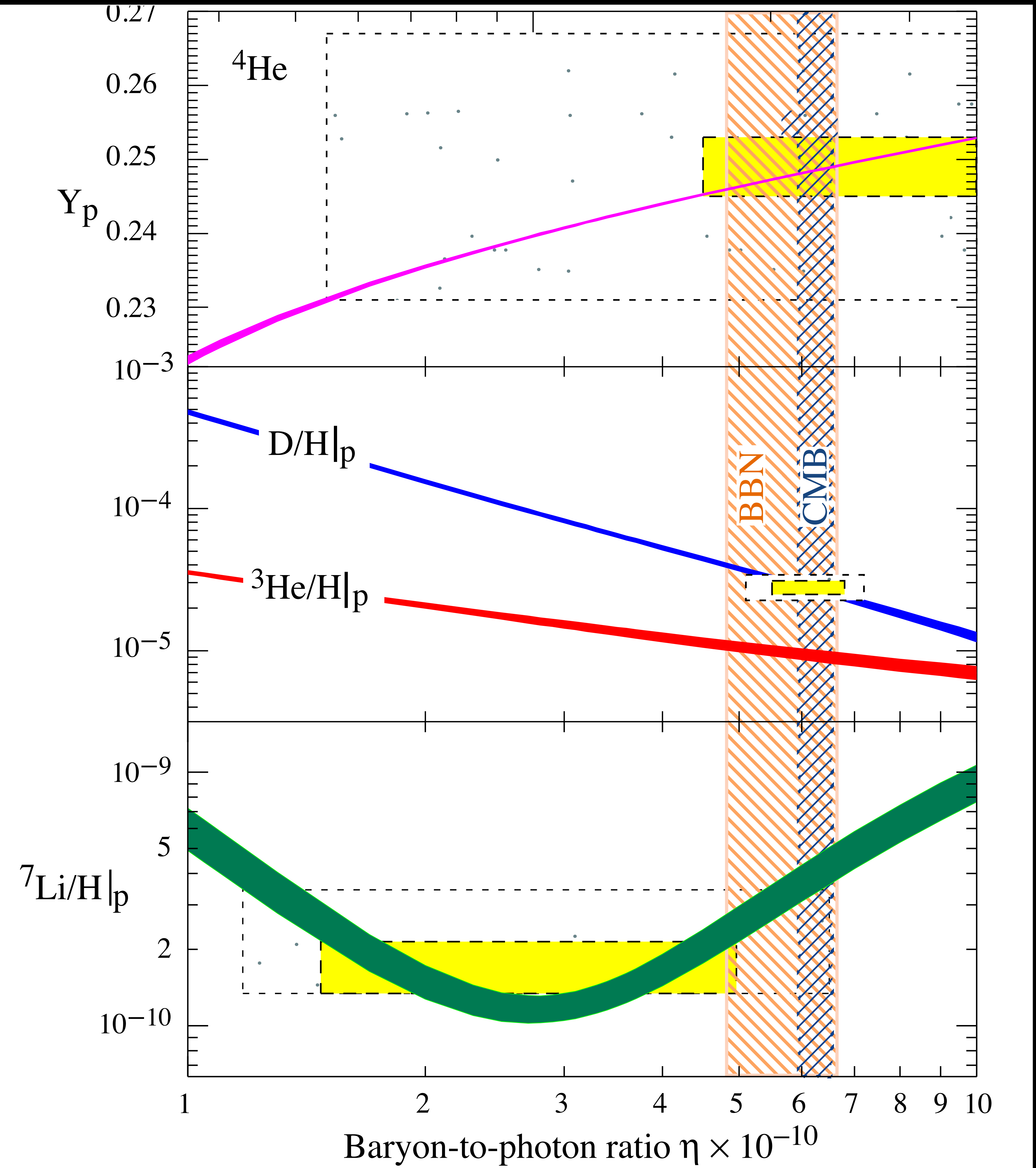
Questions

- mass hierarchy?
- mass scale?
- which octant?
- Is θ_{23} maximal?
- CP violation?
- Dirac or Majorana?
- sterile neutrinos?
- non-std interactions?
- origin of neutrino mass?
- seesaw? which type?
- leptogenesis?
- dark matter?



2.5% measurements!

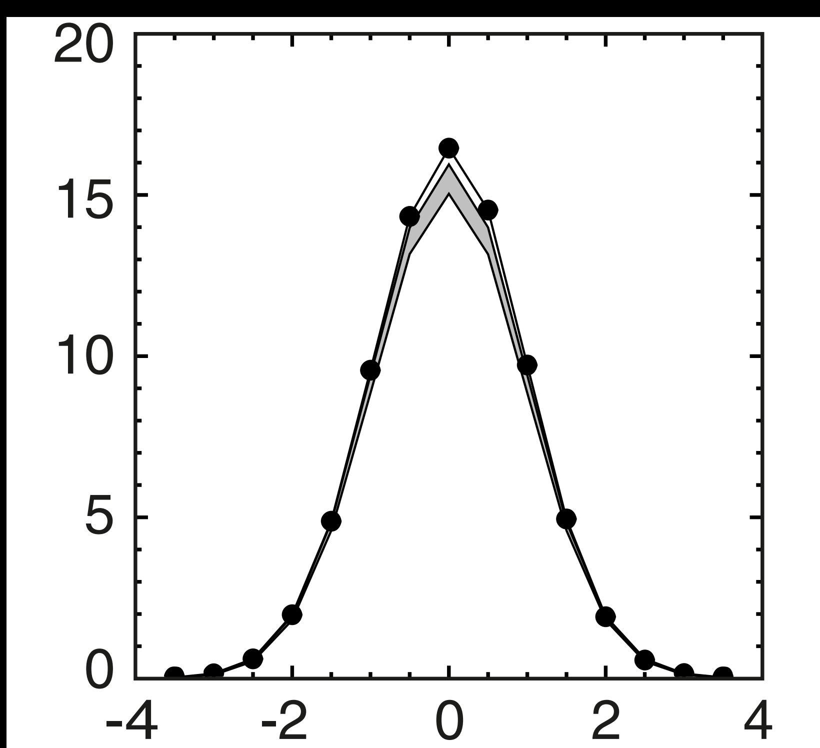
baryon asymmetry

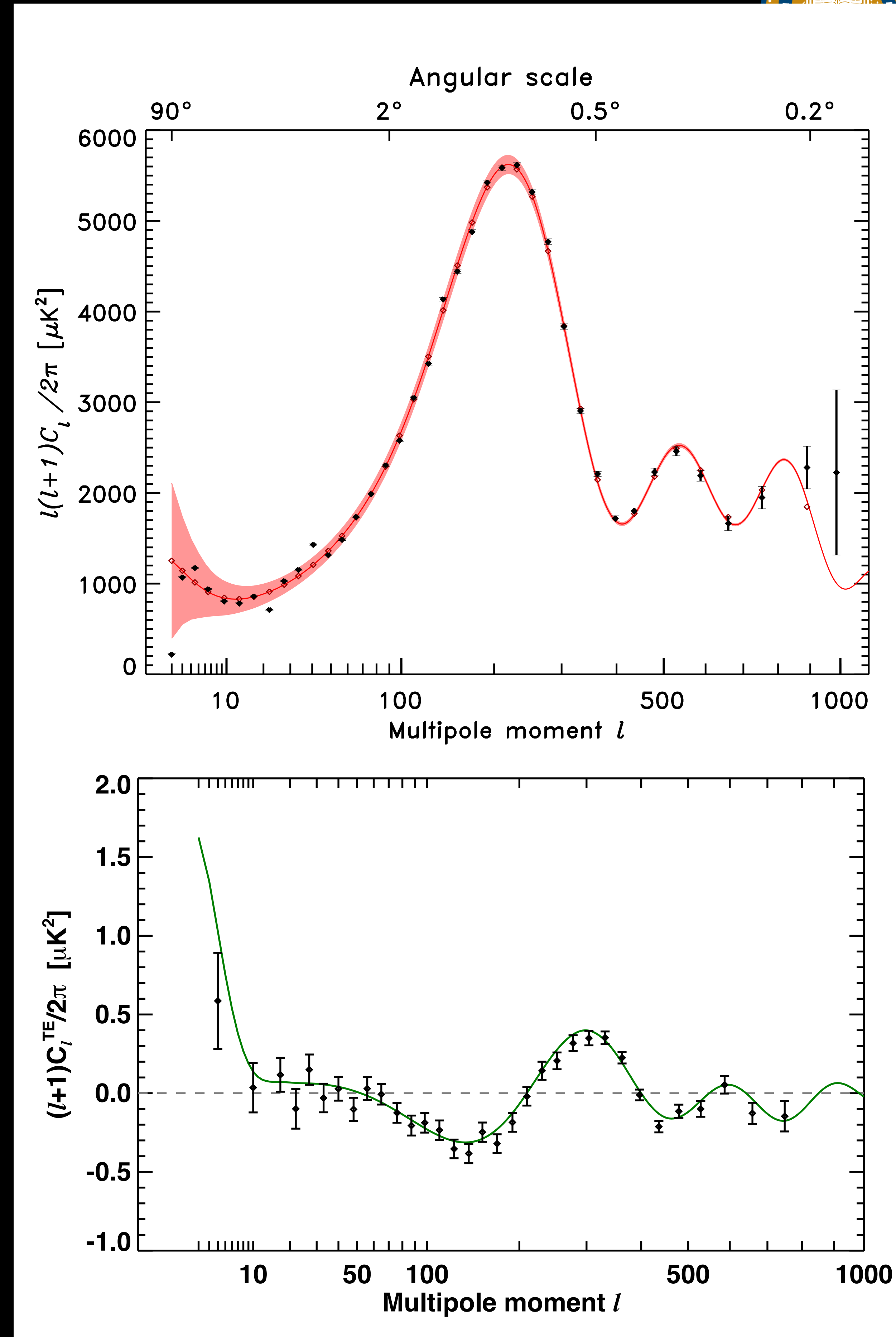


$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

Inflation

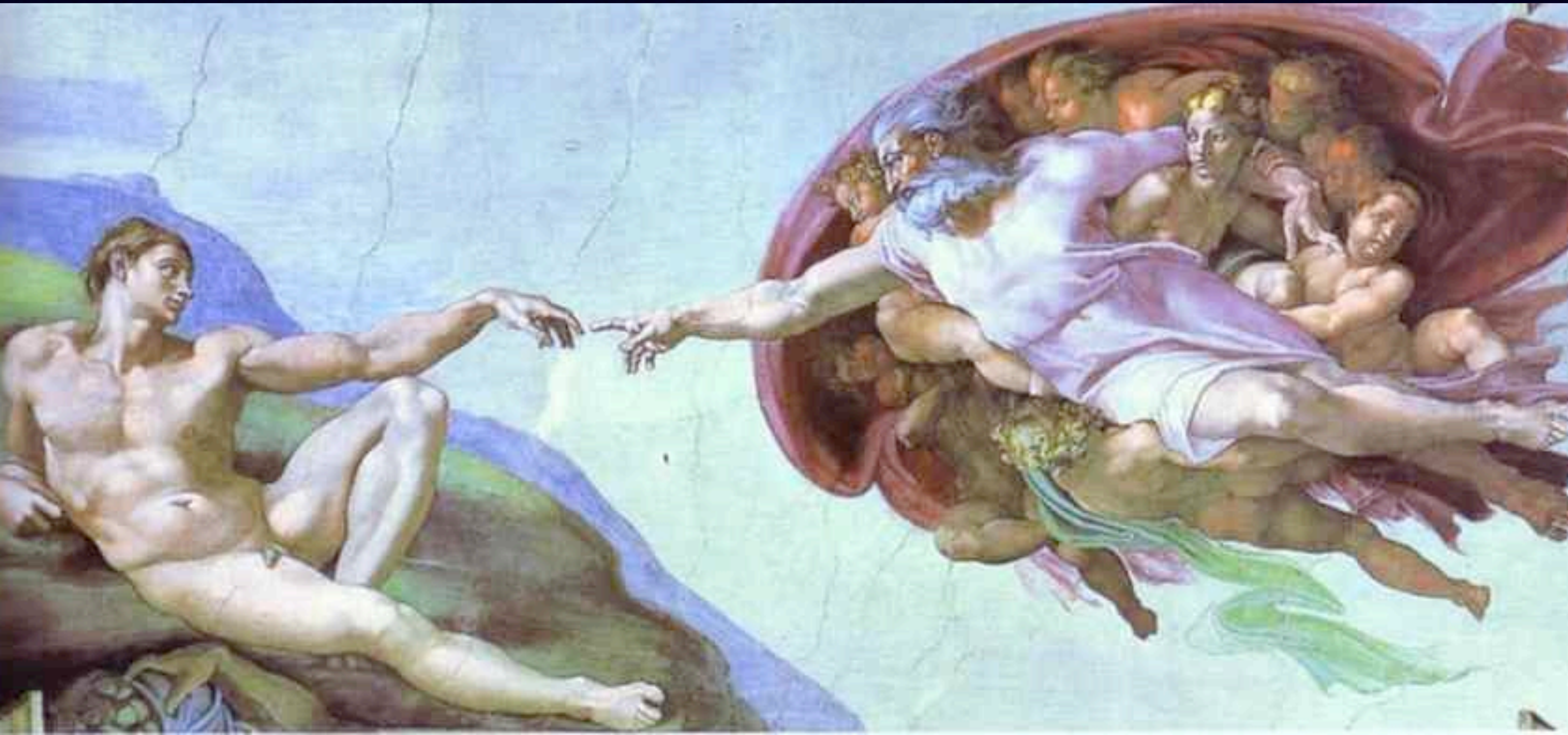
- density fluctuation is apparently *acausal*
- Also T-E correlation shows photons flowed out from dense region, unlike in causal mechanisms (e.g. strings)
- beautifully Gaussian





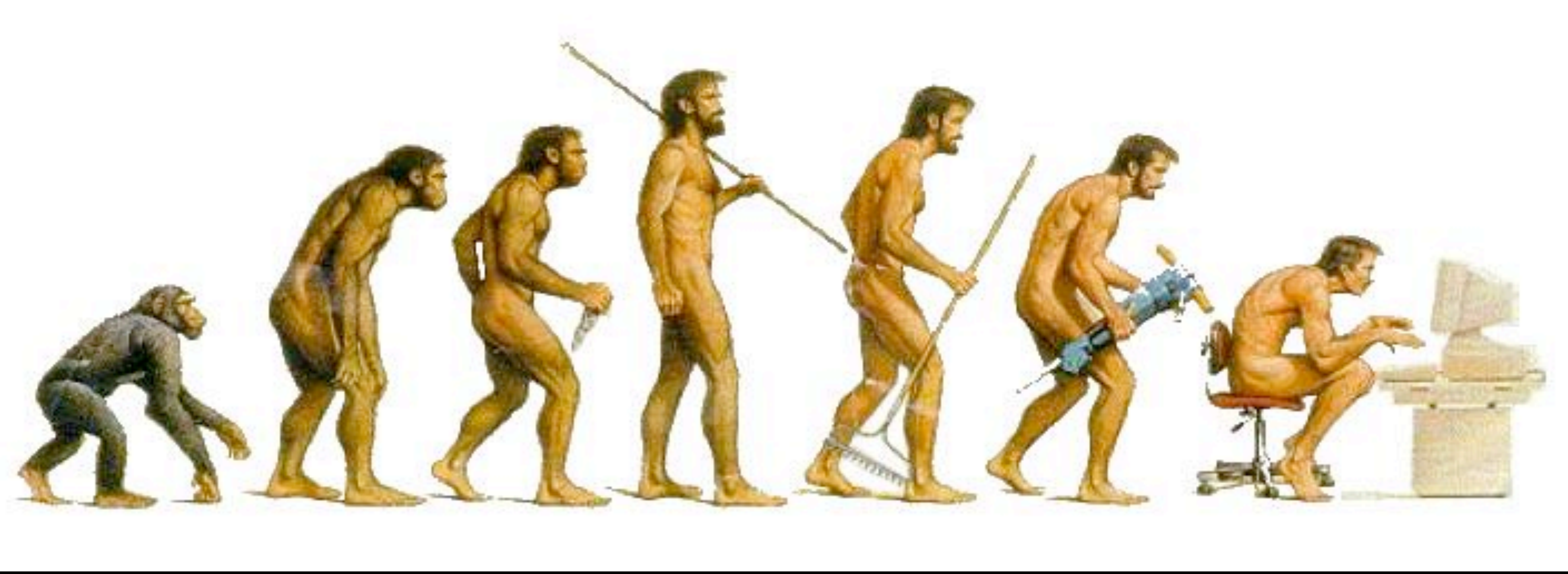
Creation?

$n_b(t=0) \neq 0$



Evolution!

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



beginning of the Universe

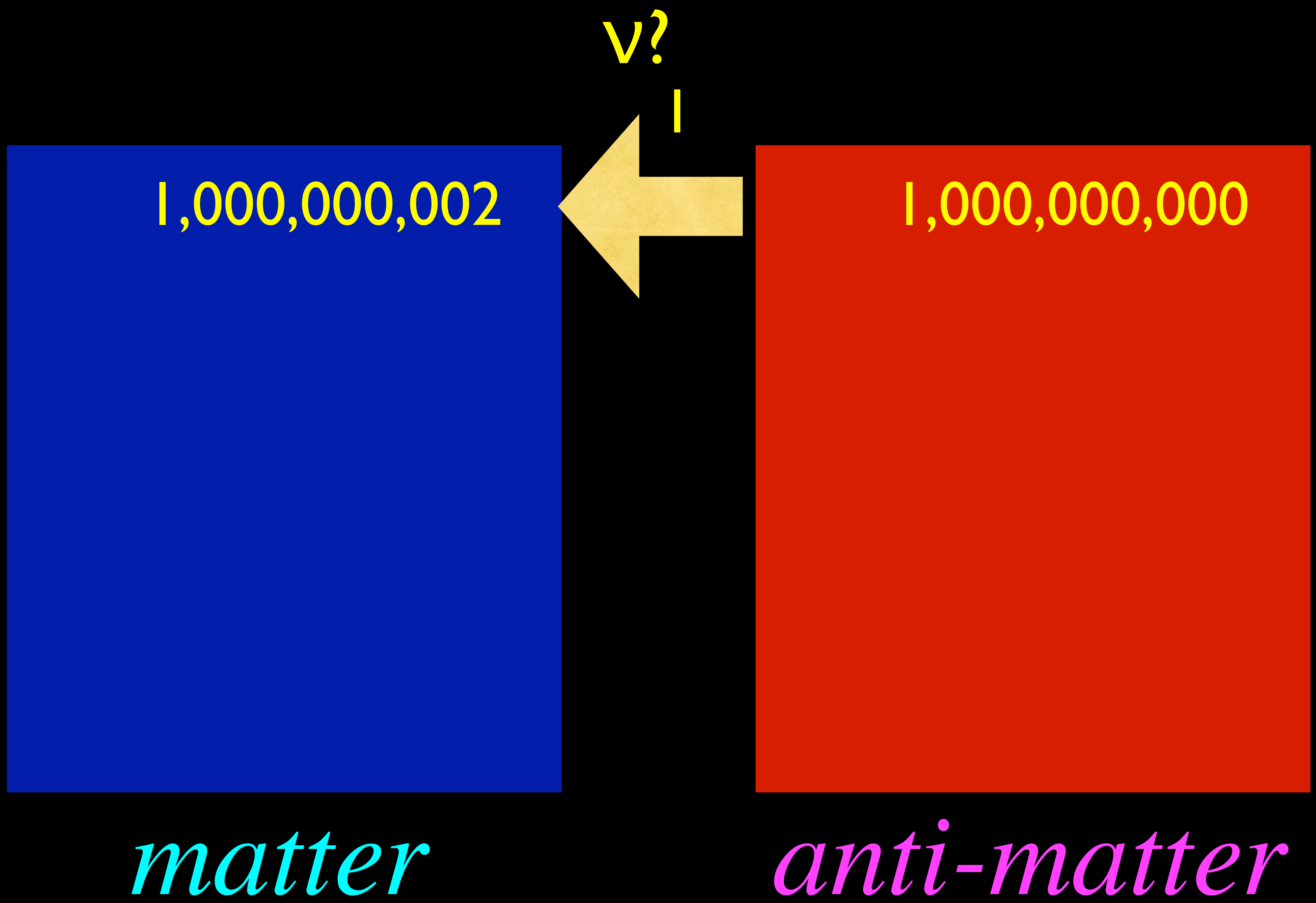
1,000,000,001

1,000,000,001

matter

anti-matter

shortly after



anti-matter needs to convert into matter

Universe now

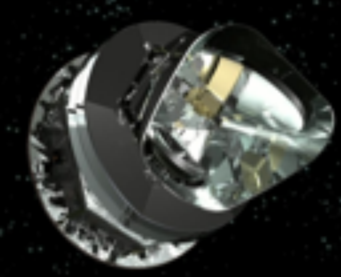
2

us

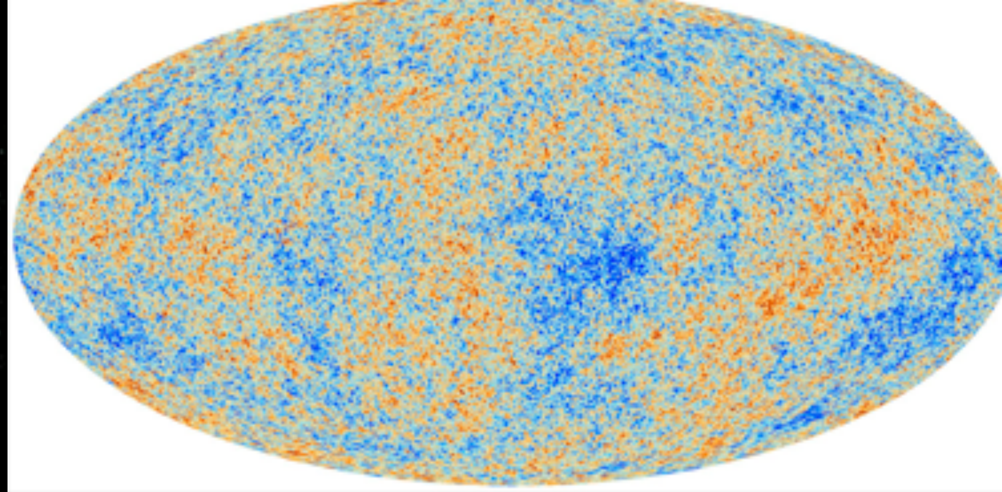
matter *anti-matter*

This is how we survived!

Baryon Asymmetry



Planck



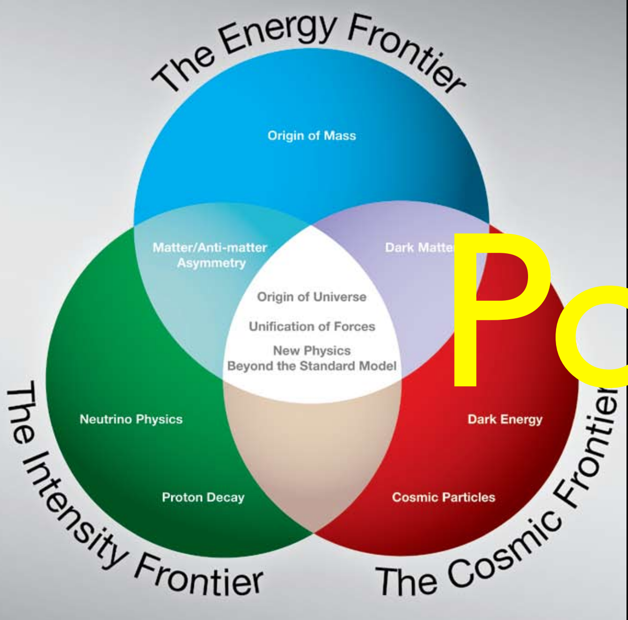
- Kobayashi and Maskawa phase can only explain $\eta_b \approx \alpha_W^5 J \approx 10^{-27}$ ($J = \mathrm{Im}\det[Y_u^\dagger Y_u, Y_d^\dagger Y_d] \approx 10^{-20}$)

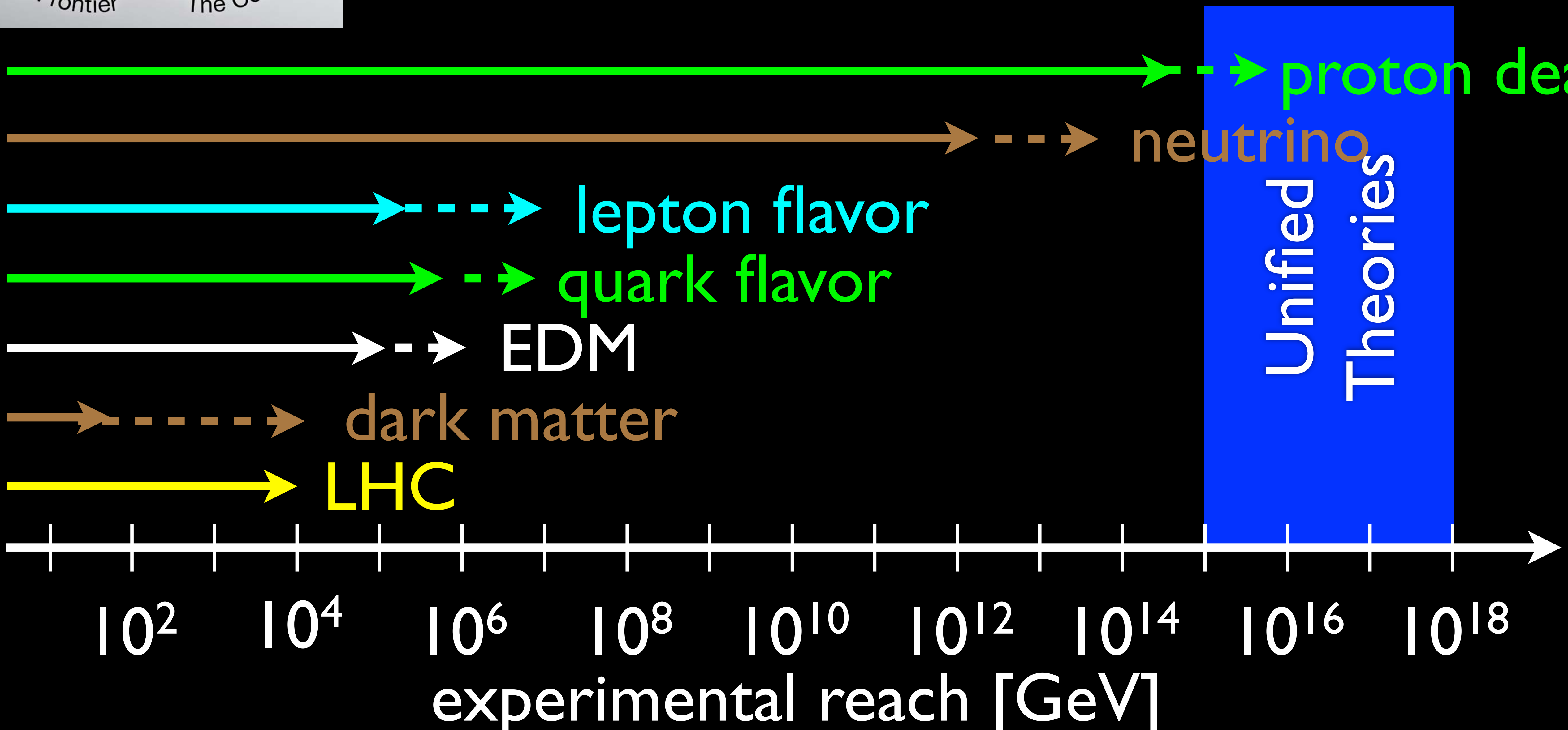
1. new sources of CPV are needed
2. we also need to see how anti-matter can turn into matter
3. non-equilibrium to break detailed balance

quark sector: LHCb, SuperKEKB, rare kaon decays
lepton sector: CPV in neutrinos, $0\nu\beta\beta$, LFV
both sectors: proton decay

energy scale?

Power of Expedition





(with significant simplifying assumptions)

⇒ baryon asymmetry

Rare effects from high energies

- Effects of high-energy physics mostly disappear by power suppression

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

- can be classified systematically

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

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

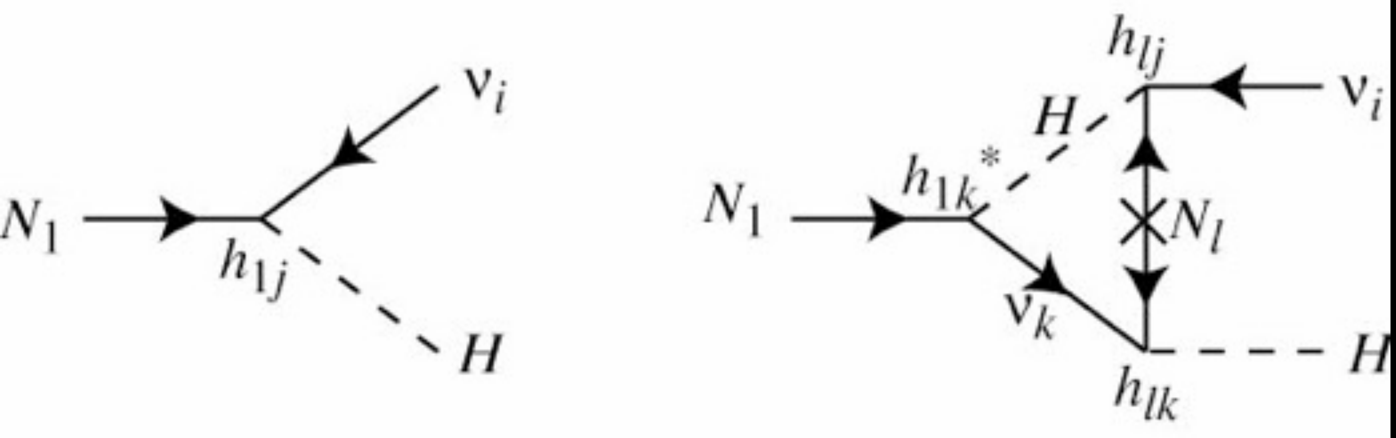
unique role of m_ν

- Lowest order effect of physics at short distances
- tiny effect: $(m_\nu/E_\nu)^2 \approx (0.1\text{eV/GeV})^2 \approx 10^{-20}$!
- interferometry (e.g. Michaelson-Morley)
  - need a coherent source
  - need a long baseline
  - need interference (i.e. large mixing angle)
- Nature was kind to provide them all!
- neutrino interferometry (a.k.a. oscillation) a unique tool to study physics at very high E
- probing up to $\Lambda \approx 10^{14}$ GeV

Leptogenesis

- Presumably three ν_R
- One of them lives long and decays late
- Majorana: $\nu_R = \bar{\nu}_R$
- @tree-level, decays 50:50 to ν_L+h, $\bar{\nu}_L$+h*
- @one-loop,

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

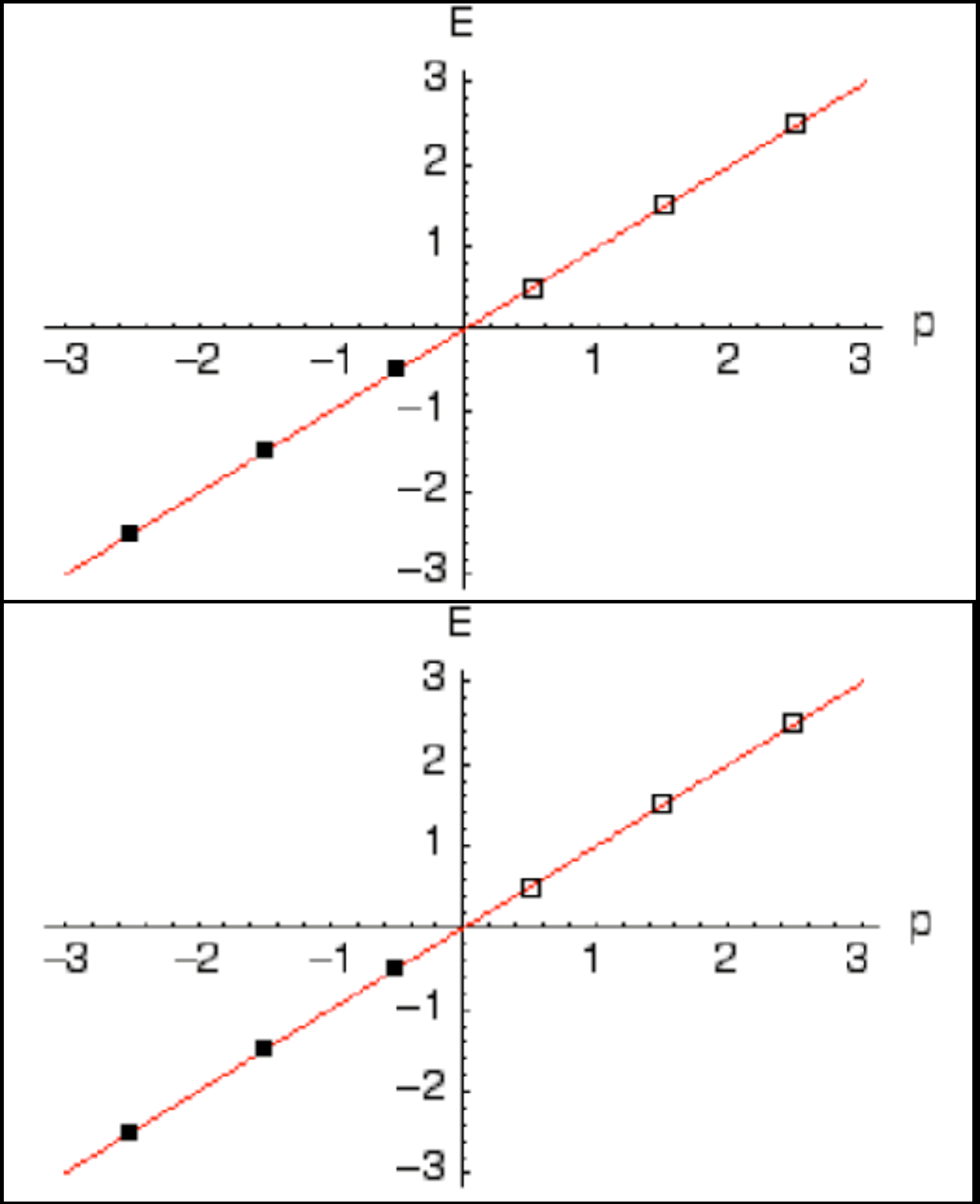


$\Rightarrow \Delta L \neq 0$

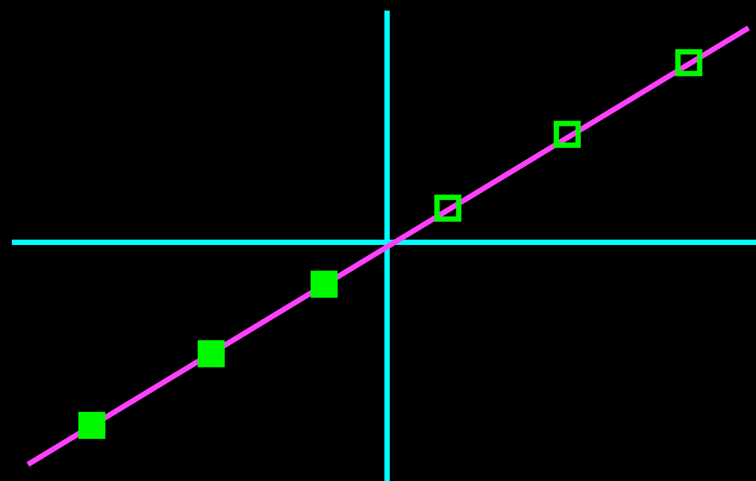
Anomaly!

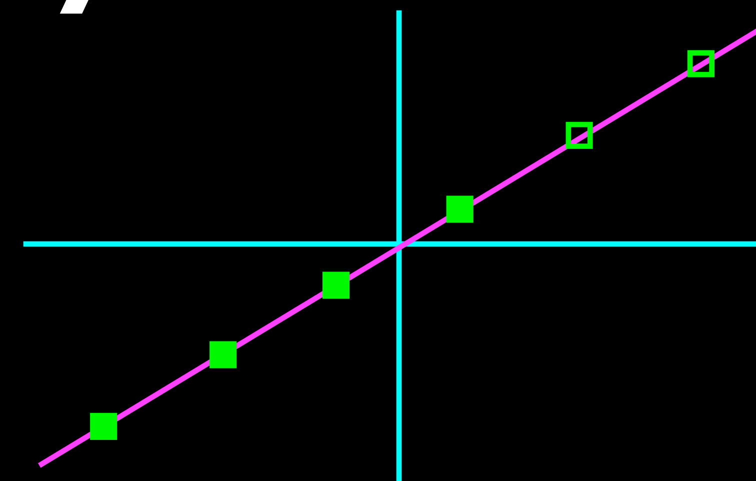
- *W* and *Z* bosons massless at high temperature
- *W* field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating *W* field

$\Delta q = \Delta q = \Delta q = \Delta L$



What anomaly can do



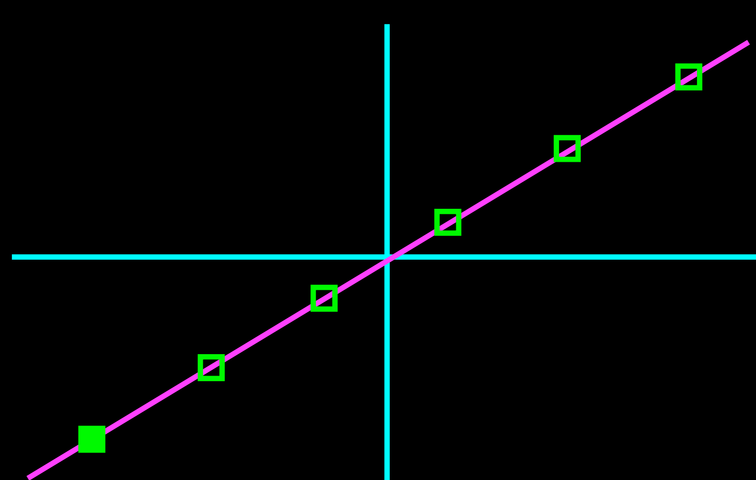


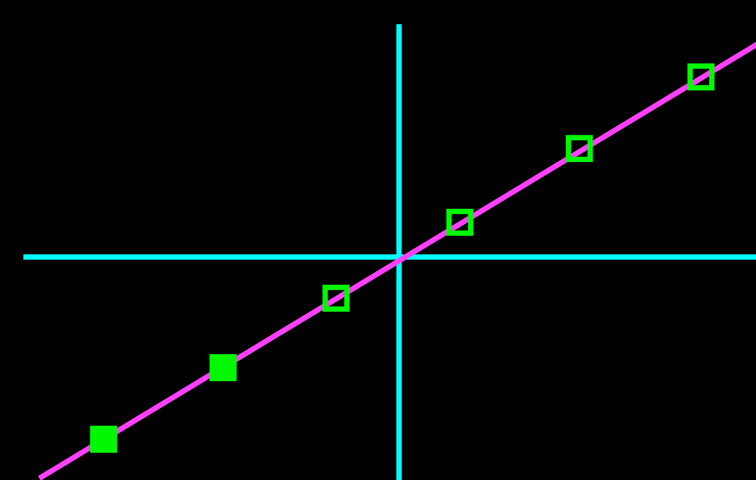
$B=0$
$L\neq 0$

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

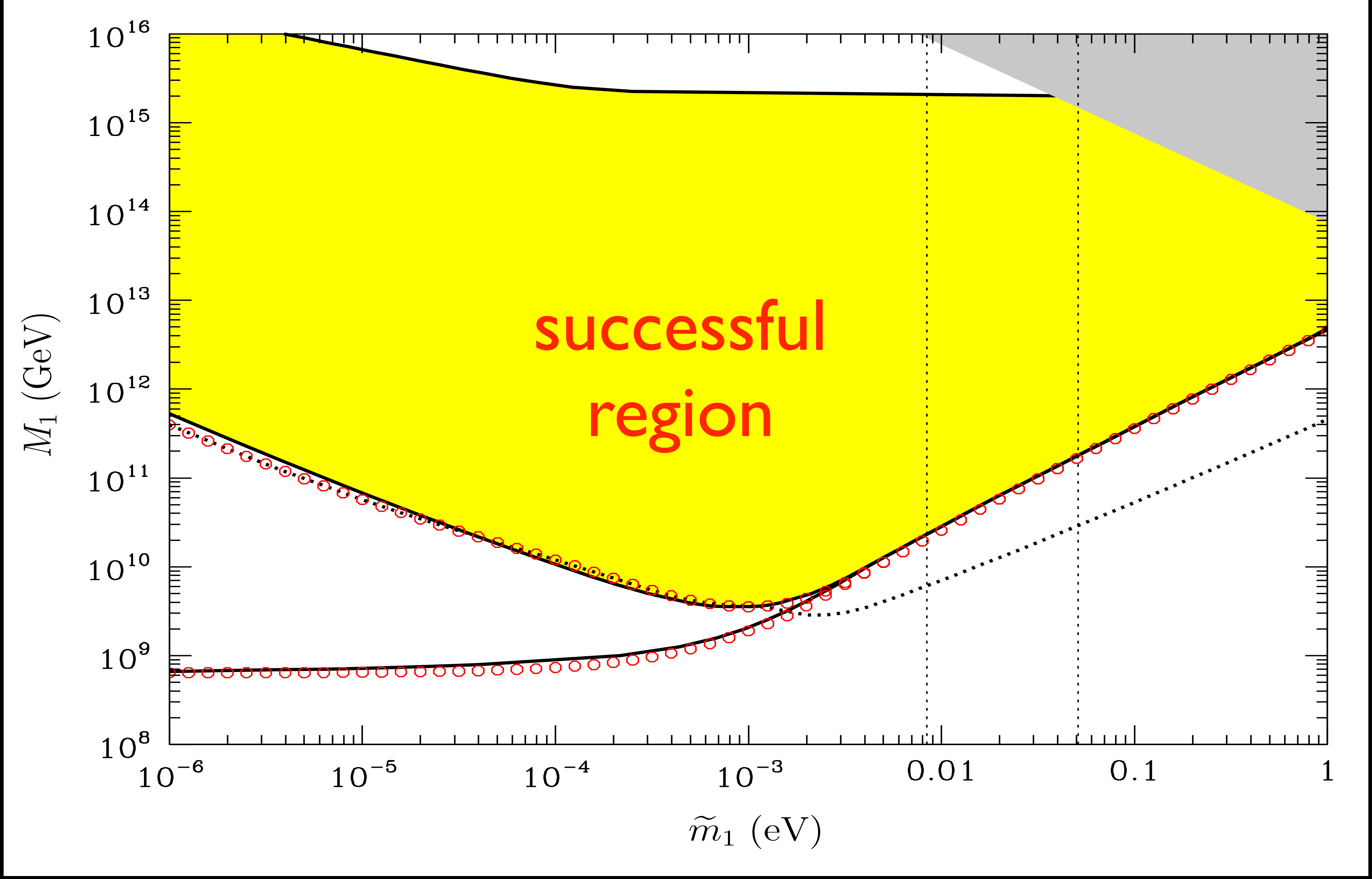
- 1,000,000,001 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,001 $\bar{\nu}$

$B\neq 0$
$L\neq 0$





Non-trivial success!

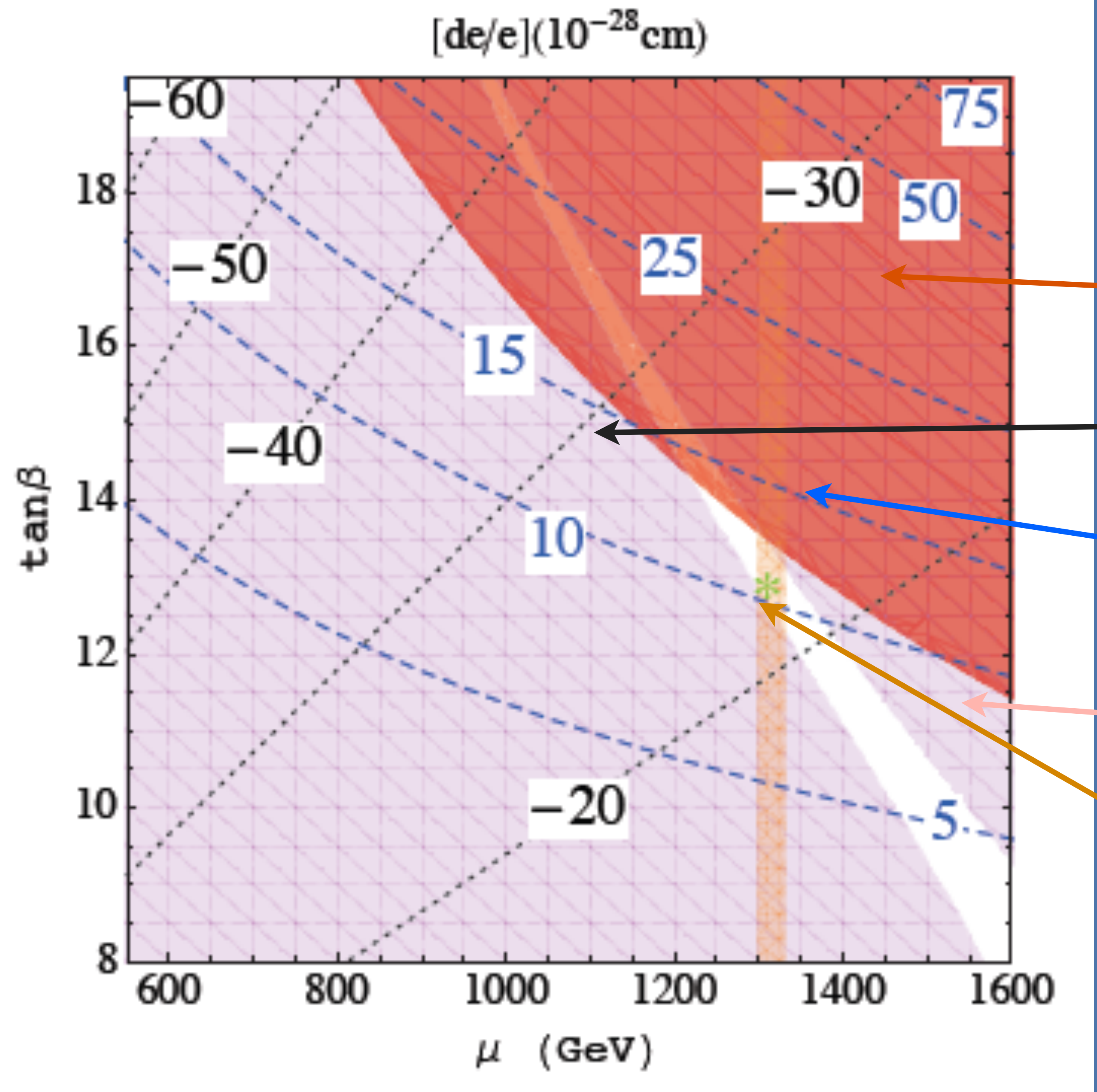


$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller

EW baryogenesis

Final Results



Open the Heavy Higgs CPV search

Mercury exclusion

Chargino contour

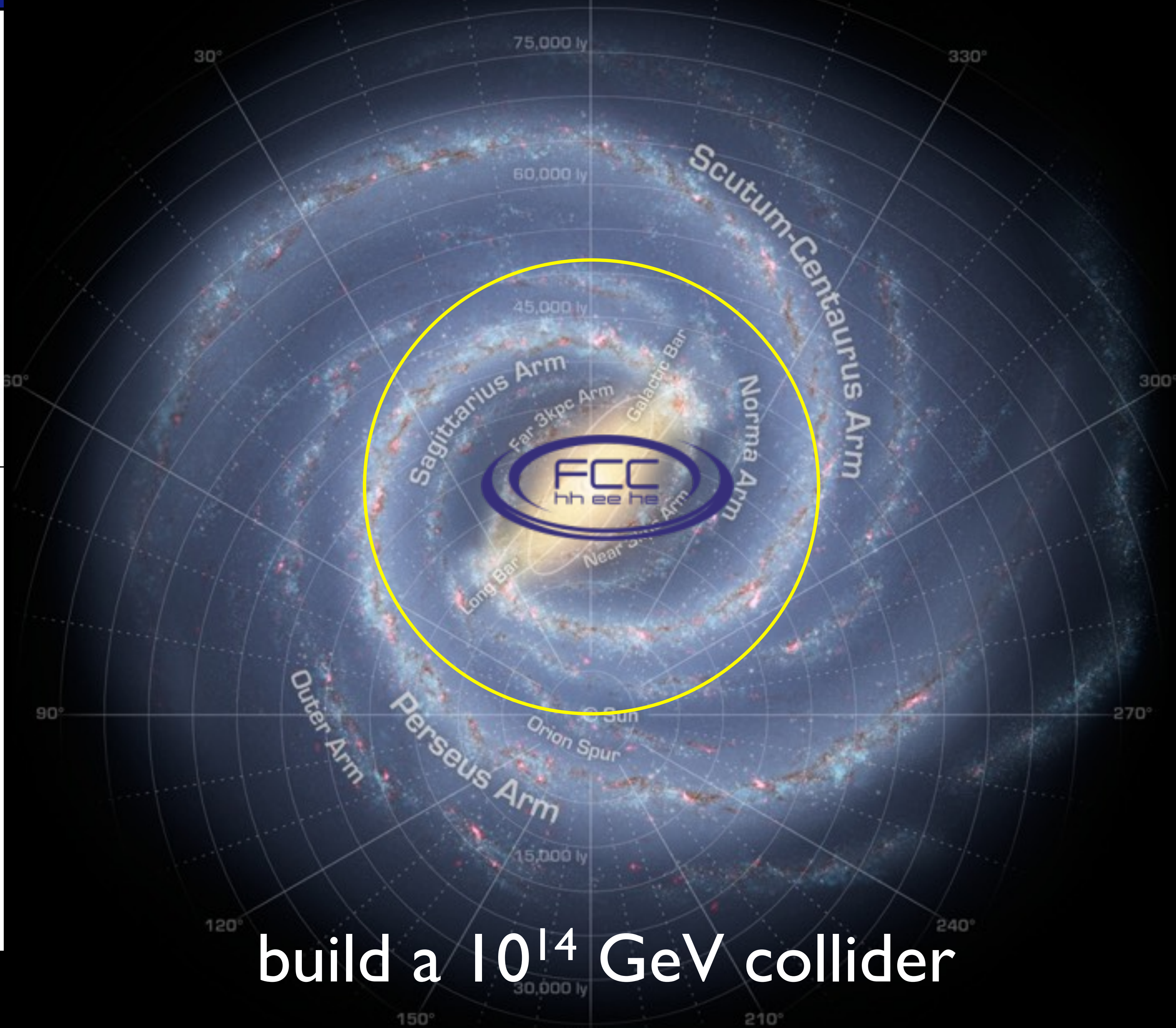
Stau contour

ACME exclusion $|d_e|<8.7\times10^{-29}$ ecm

Preferred by EWBG

LG. Bian, T. Liu, J. S, 1411.6695

How do we test it?



build a 10^{14} GeV collider

indirect evidences

- Is CP violated in neutrino sector?
- Is neutrino Majorana?
- collect archaeological evidences

prospects

Excitement

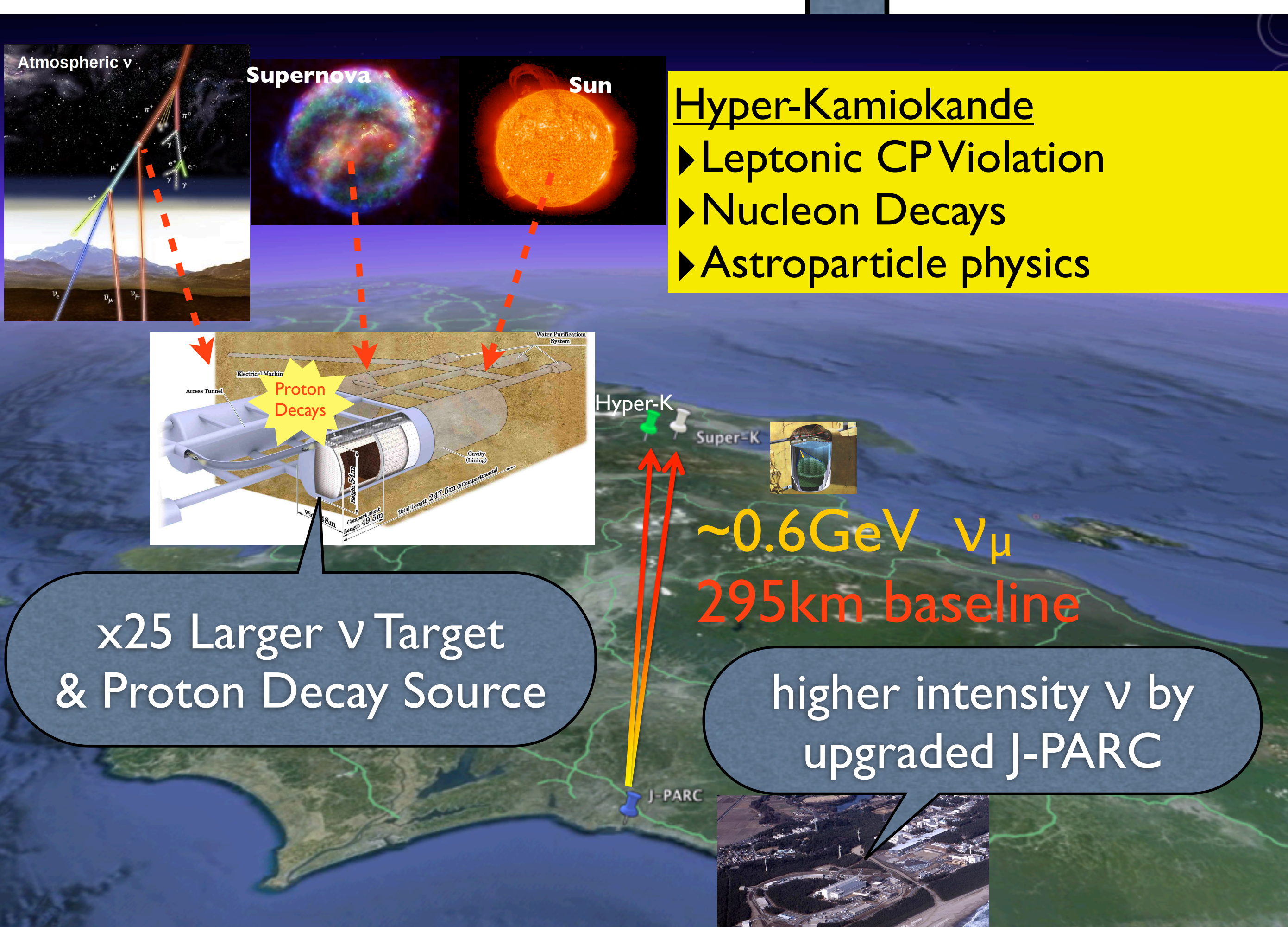
- CP violation in neutrino sector may be observable with conventional technique

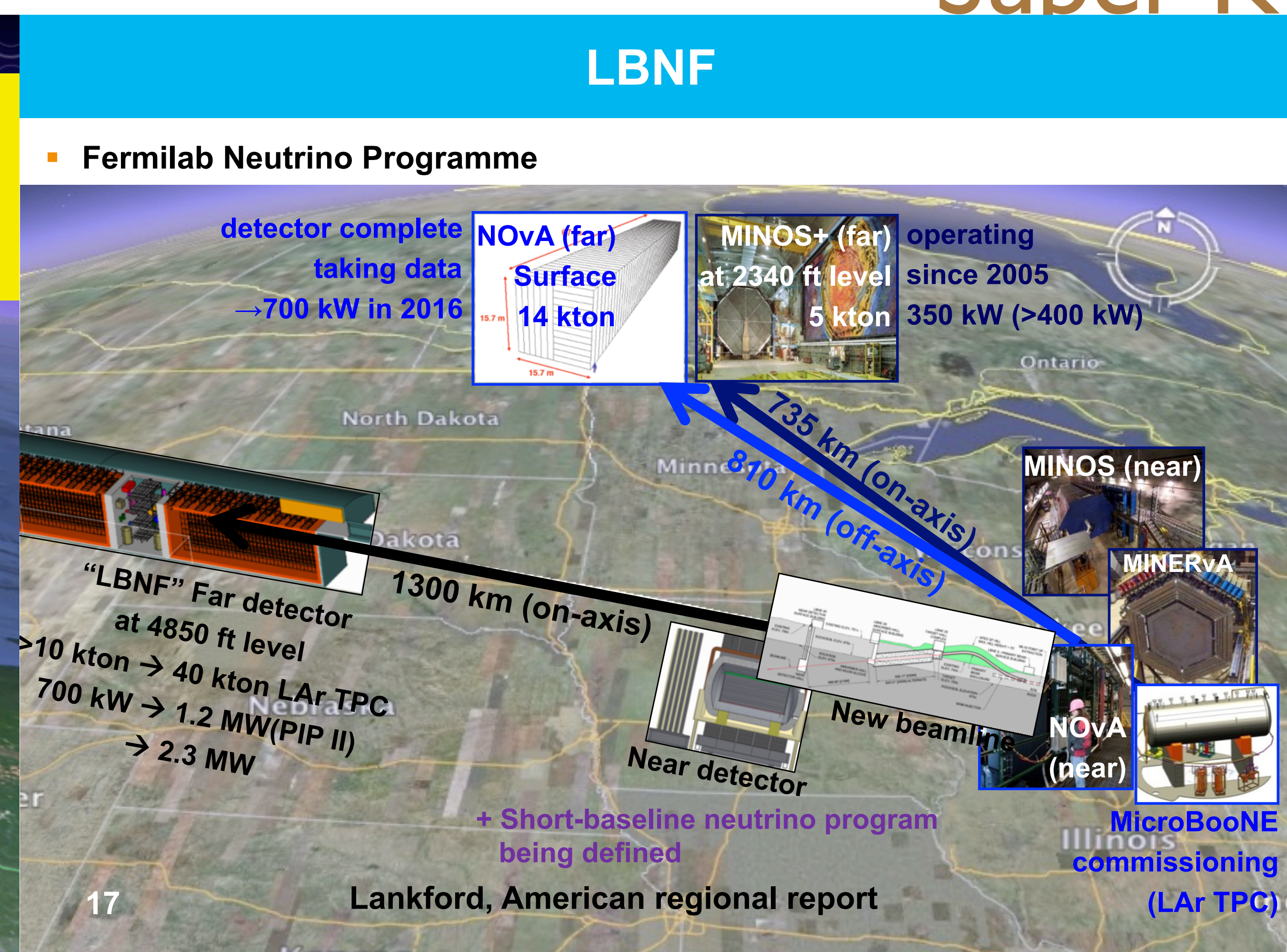
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\frac{\Delta m_{12}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{23}^2 L}{4E}$$

2002 KamLAND SNO

2012 Daya Bay

1998 Super-K



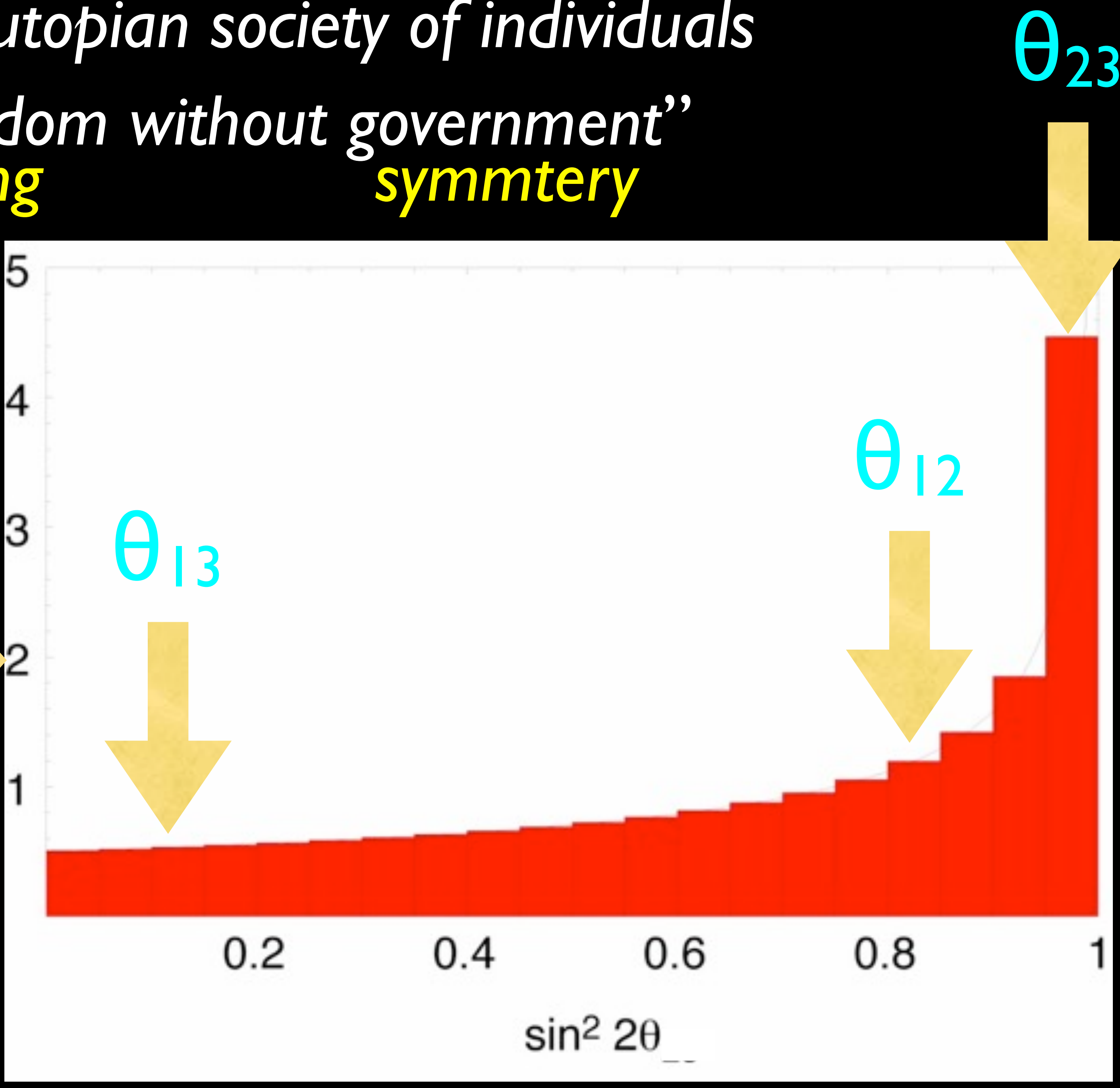


anarchy

neutrinos

Miriam-Webster: "*A utopian society of individuals who enjoy complete freedom without government*"

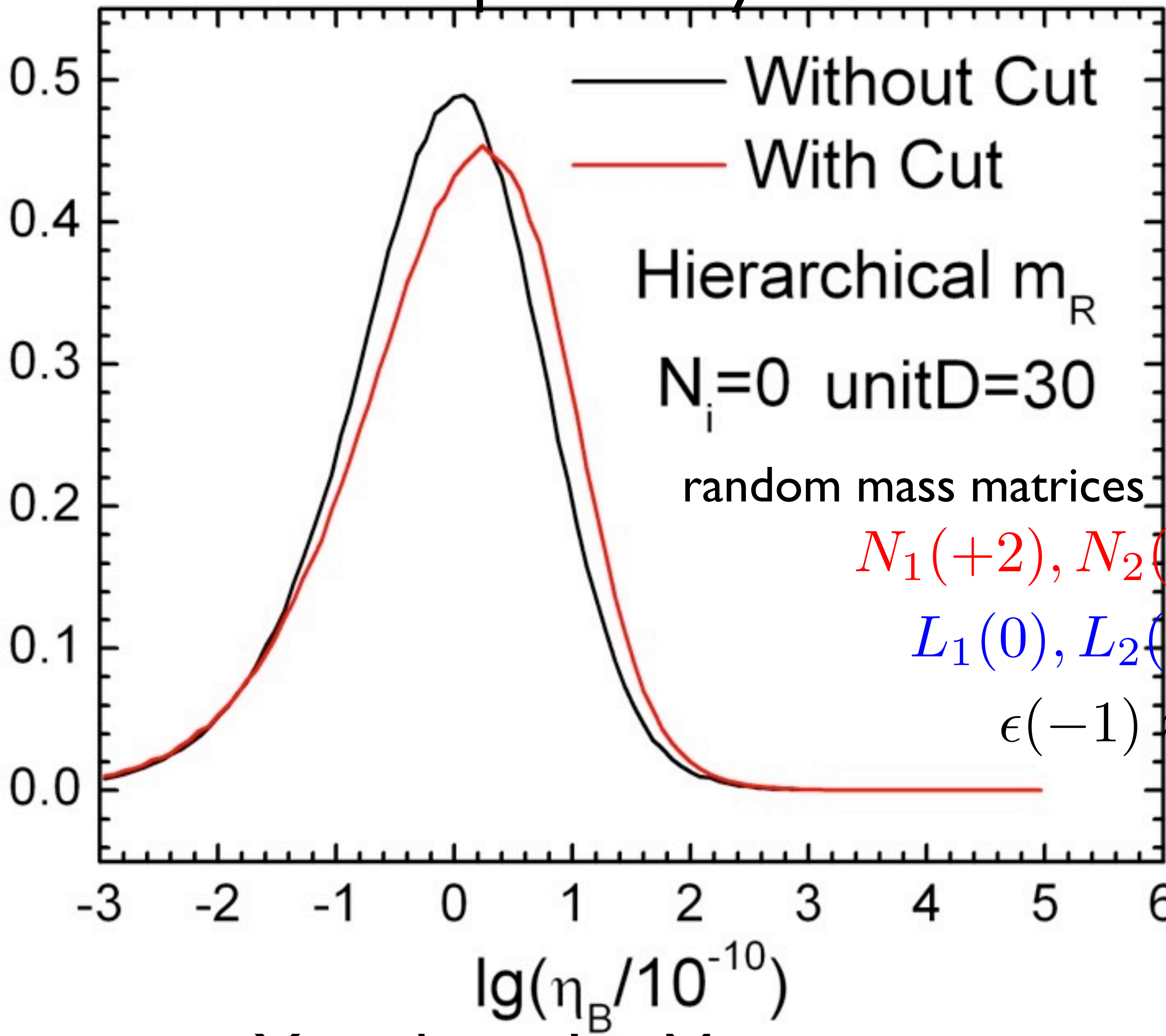
large mixing *symmtery*



Kolmogorov-Smirnov test (de Gouvêa, HM)

nature has 47% chance to choose this kind of numbers

no direct connection to CP violation in oscillation
but a plausibility test



random mass matrices

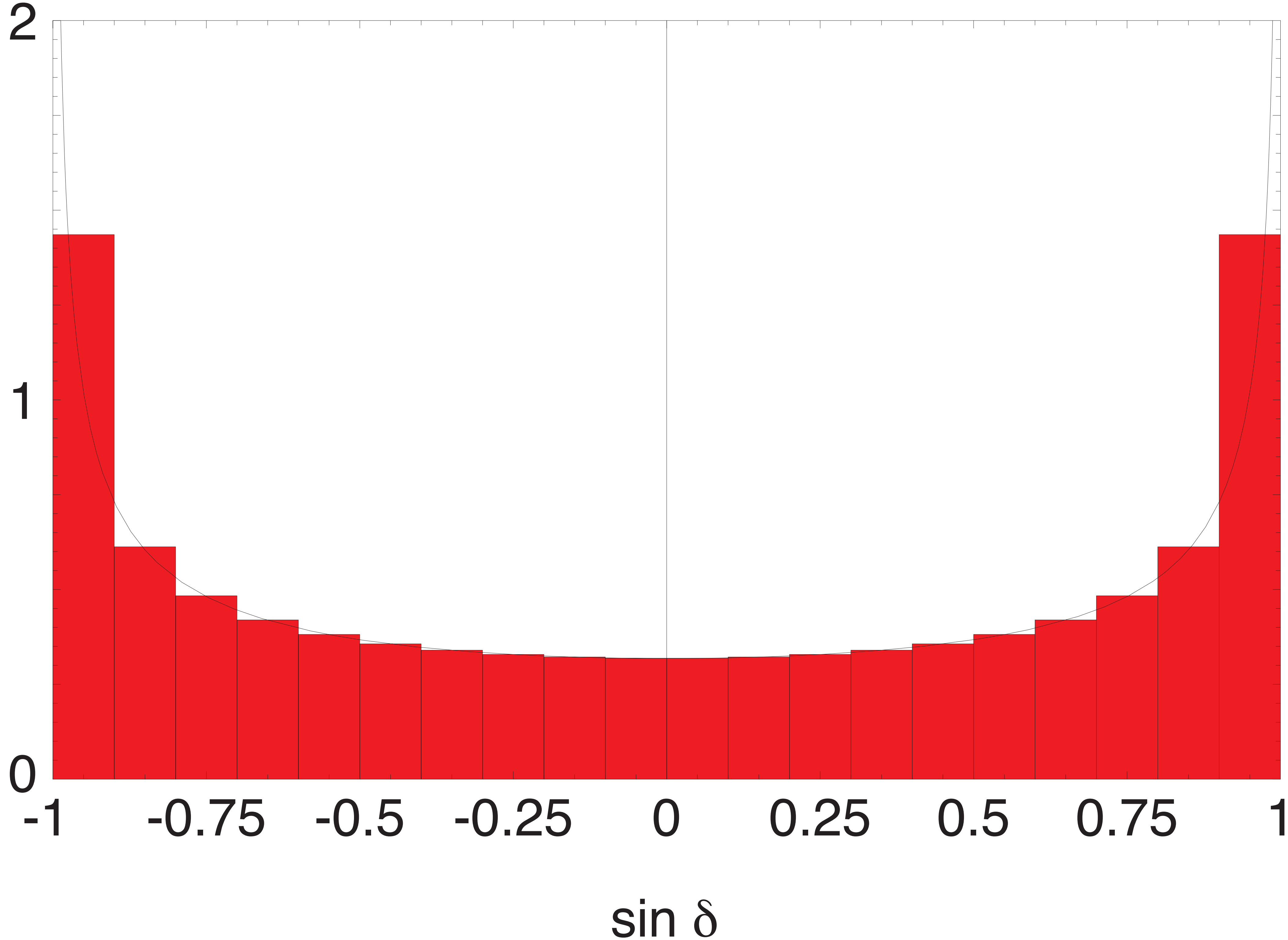
$N_1(+2), N_2(+1), N_3(0)$

$L_1(0), L_2(0), L_3(0)$

$\epsilon(-1) \approx 0.1$

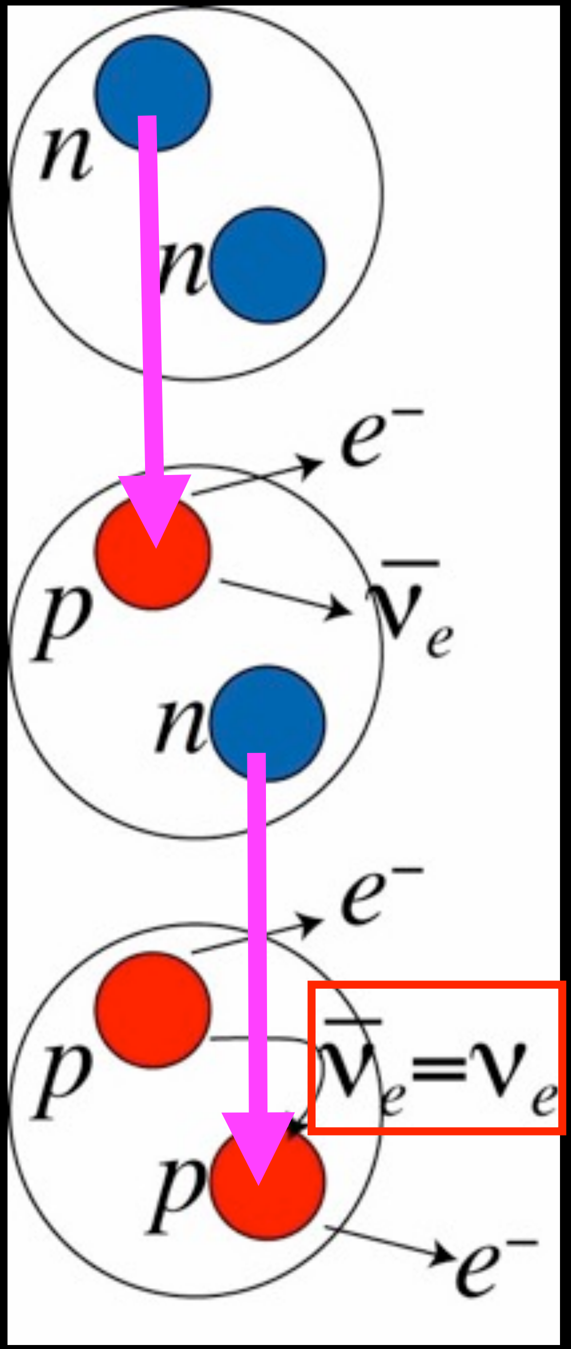
Xiaochuan Lu, Murayama

CPV preferred maximal



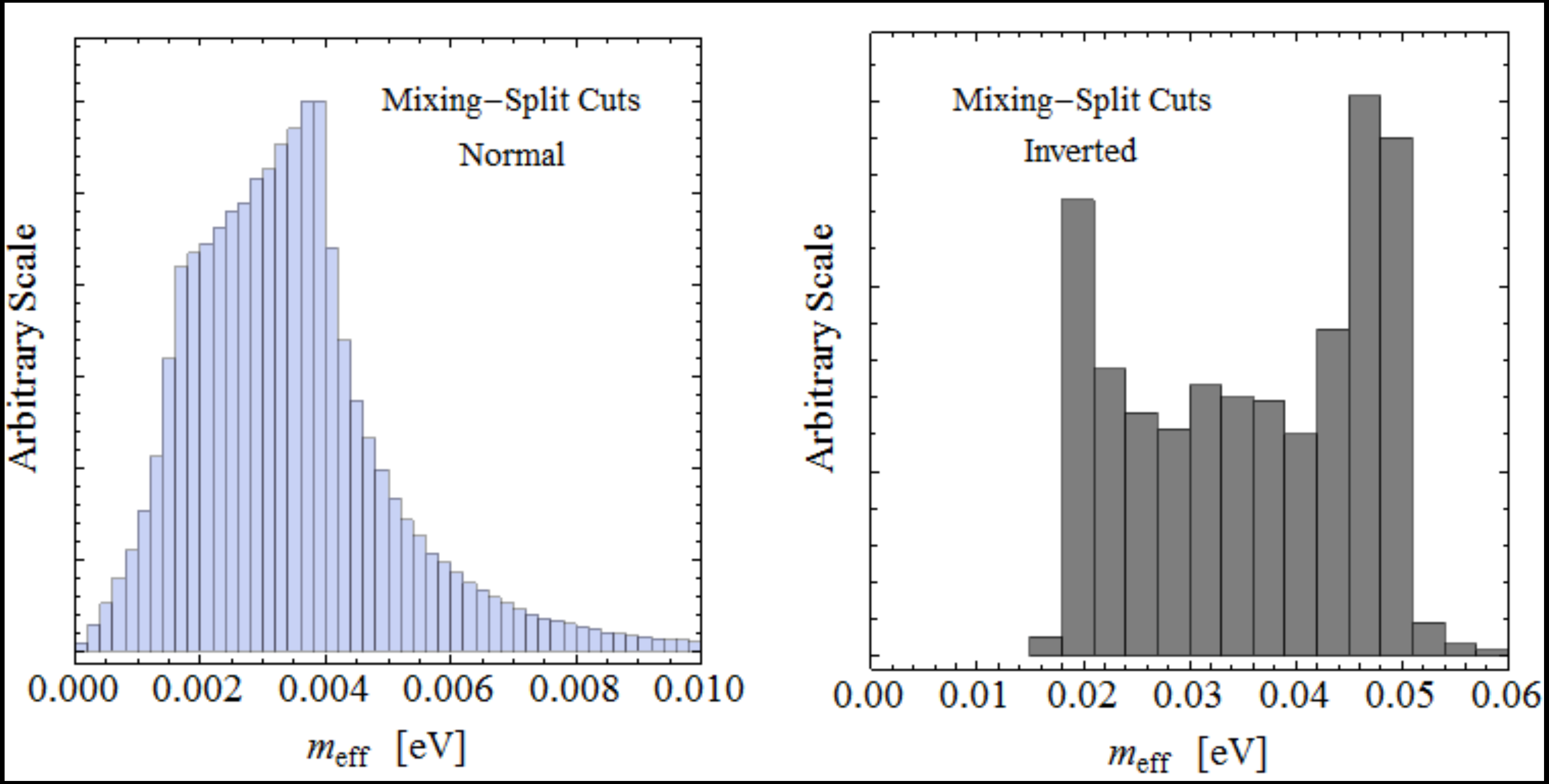
Can anti-matter turn into matter?

- proton is positively charged, anti-proton negatively
- can never turn into each other
- But neutrinos or anti-neutrinos do not have electric charge
- neutrinoless double beta decay: $nn \rightarrow ppe^-e^-$
- can we look for anti-matter turning into matter?



Tough

- anarchy prefers normal hierarchy
- quite difficult to reach the sensitivity levels
- but if LBL discovers inverted hierarchy, it is in a much better shape!

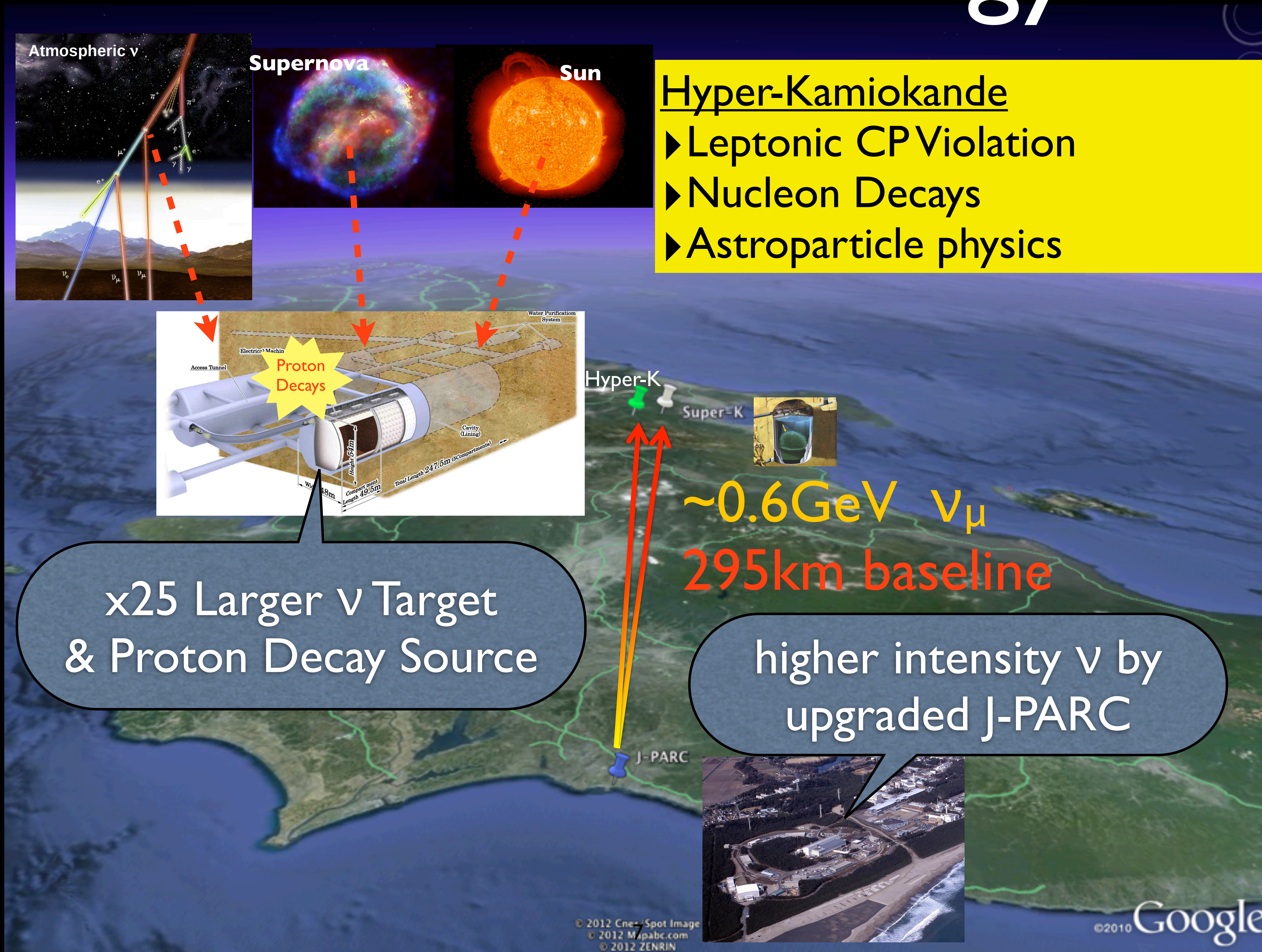


Strategy in Japan

obvious

- amazing tradition in neutrino physics since 1987, especially since 1998
- great assets
  - J-PARC
  - Kamioka observatory
  - strong public interest
- US is "catching up", Europe dropped it

Excellent Strategy



Strategy in Japan?

- Too expensive?
  - Can it be staged? 1Mt = 4×250kt
  - multiple technologies?
- SuperKamLAND for multiple oscillations?
  - shorter baseline, lower energy, on-axis
  - or Gd-HK?
- Are systematics really under control?
- Can J-PARC host short-baseline program?
  - near detector complex already exists
- DAEδALUS-like accelerator in Toyama? (Jarah Evslin)
- what is beyond KamLAND-ZEN?

don't forget *p*-decay

- Minimal SUSY SU(5) GUT was "excluded" (HM, Pierce)
- But m_h=125GeV suggests $m_{\rm SUSY}\geq$10TeV
- νK^+ suppressed, $e^+\pi^0$ enhanced

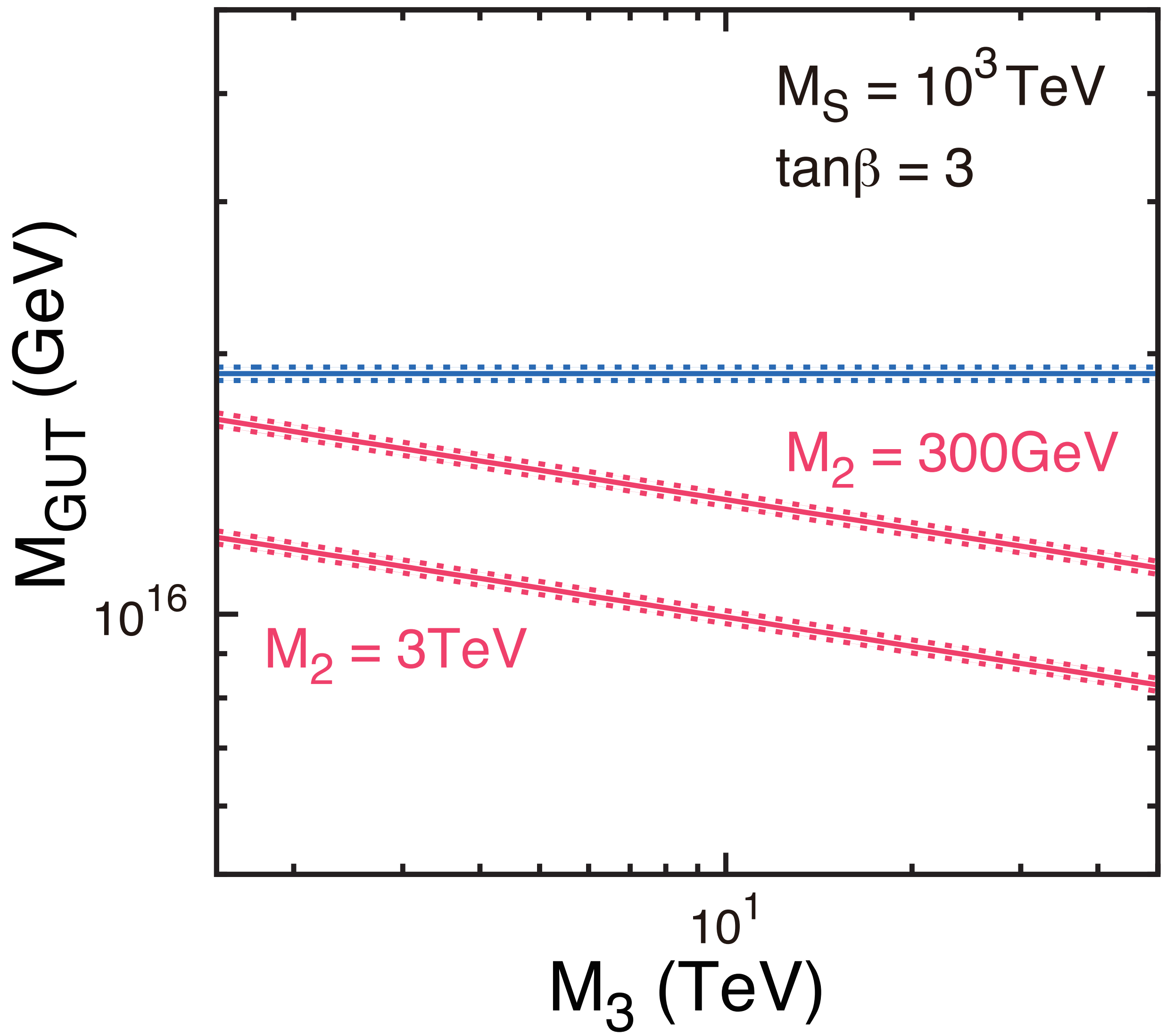
$$\tau_p(\bar{\nu}K) = 4\times 10^{35}\text{yrs}\sin^4 2\beta\left(\frac{0.1}{\bar{A}_R}\right)^2\left(\frac{M_S}{10^2\text{TeV}}\right)^2\left(\frac{M_{H_C}}{10^{16}\text{GeV}}\right)^2$$

$$\tau_p(e^+\pi^0) = 5\times 10^{34}\text{yrs}\left(\frac{M_X}{0.8\times 10^{16}\text{GeV}}\right)^4$$

J. Hisano *et al*, arXiv:1304.0343, 1304.3651

$e^+\pi^0$ further enhanced ×10, no νK^+

focus point gauge mediation, Fukuda *et al* arXiv:1508.00445



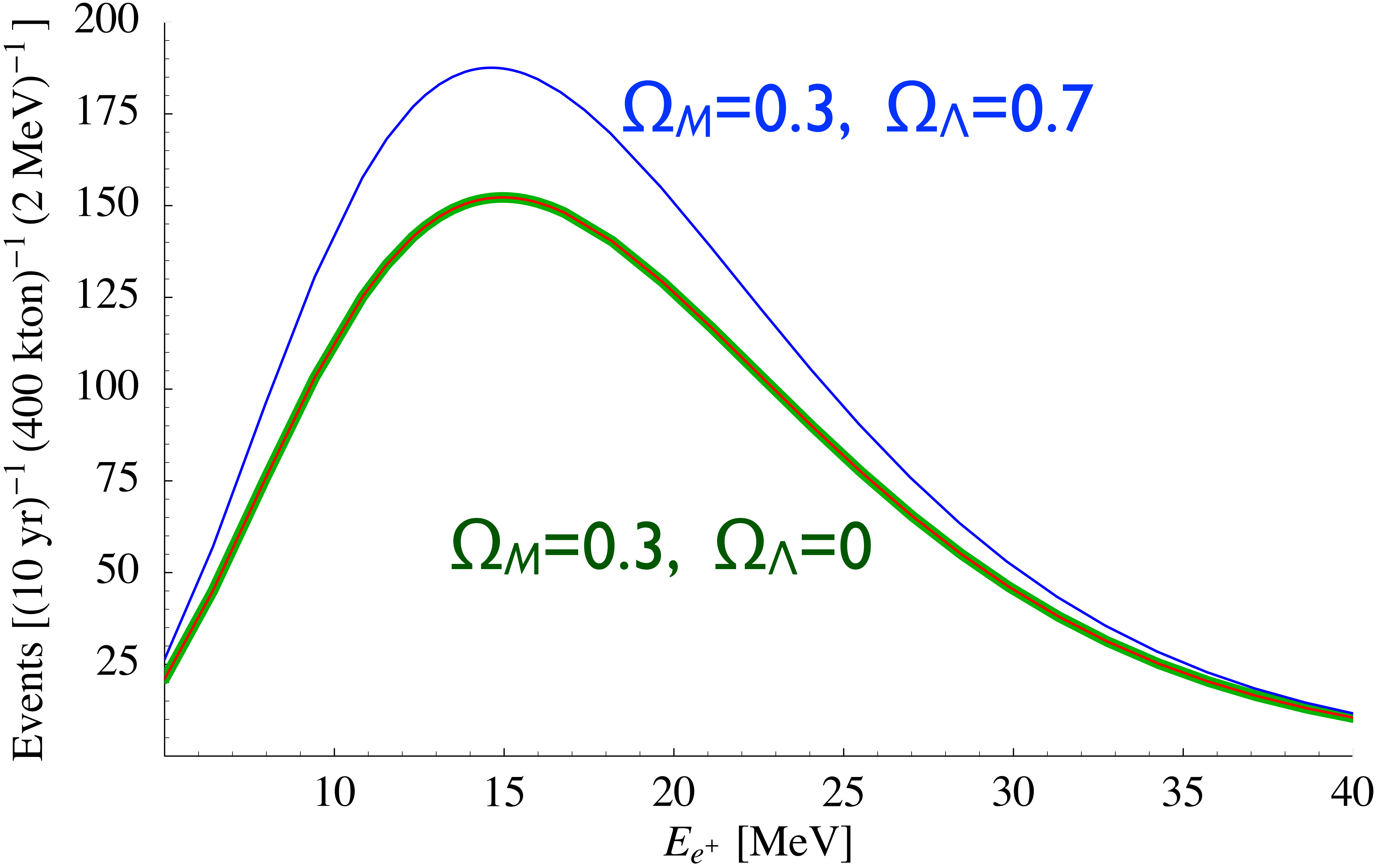
2E36

5E34

M_X=M_Σ assumed

Figure 3: GUT scale $M_{\rm GUT} \equiv (M_X^2 M_\Sigma)^{1/3}$ as functions of gluino mass M_3 (pink lines). Here, $\tan\beta = 3$ and $M_S = 10^3$ TeV. Upper and lower lines correspond to $M_2 = 300$ GeV and 3 TeV, respectively. Error bars indicate the input error of the strong coupling constant $\alpha_s(m_Z) = 0.1184(7)$ [49]. Horizontal blue line shows a result in the case of low-energy SUSY ($M_S = 1$ TeV, $M_2 = 200$ GeV, and $M_3/M_2 = 3.5$).

dark energy in SNRN



Hall, HM, Papucci, Perez, hep-ph/0607109

dreaming up

- dream: detect cosmic background neutrinos
  - AND detect the asymmetry in them
  - ultimate test of leptogenesis
- dream: anisotropy to test standard cosmology back to t=1 sec
  - (cf. 380k yr in CMB)


KamLAND
control room

v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