KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Why Neutrinos?

Hitoshi Murayama (Berkeley & Kavli IPMU)

ICFA Neutrino Panel Asian Neutrino Community Mtg

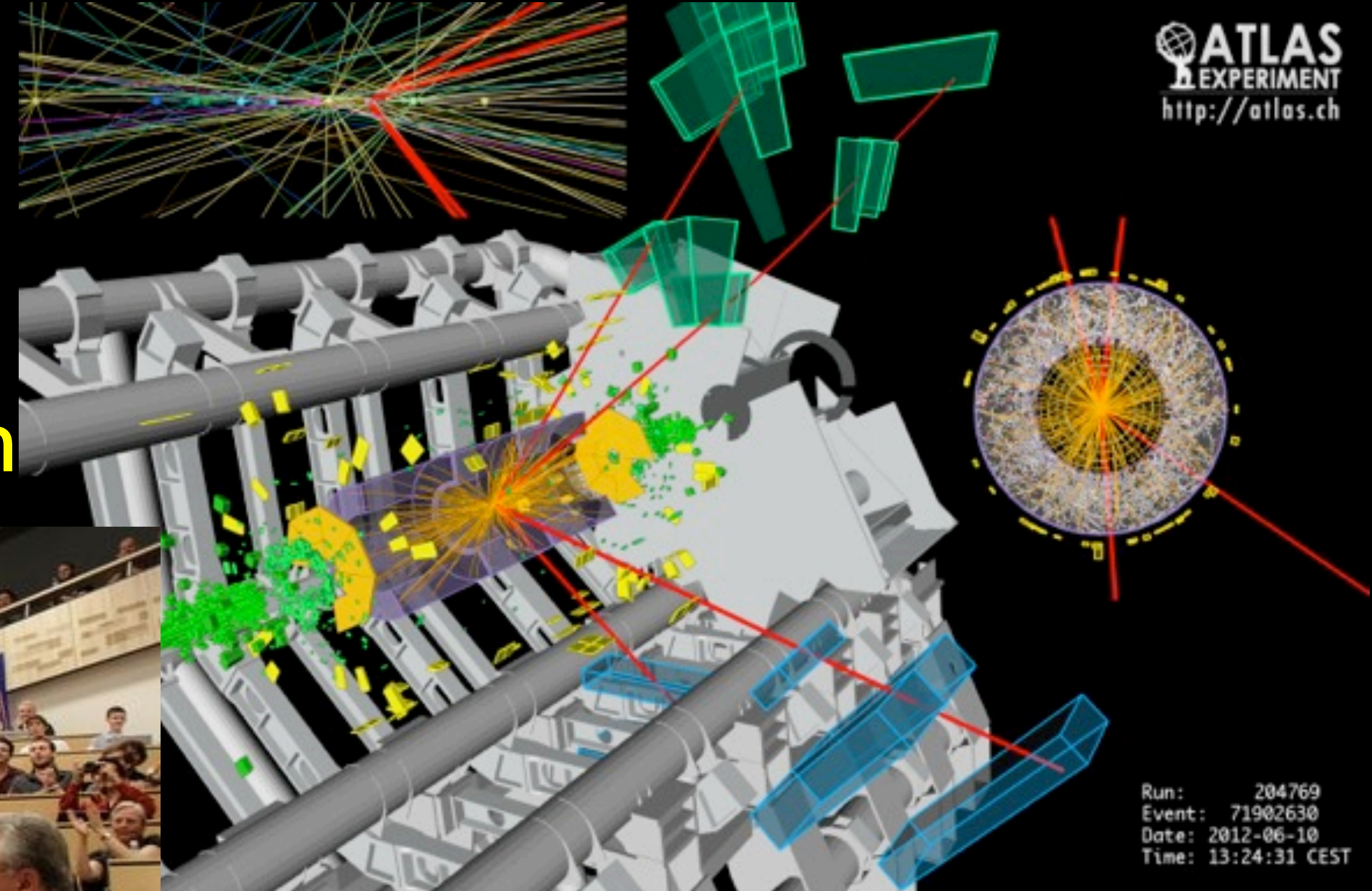
Nov 13, 2013 Kavli IPMU

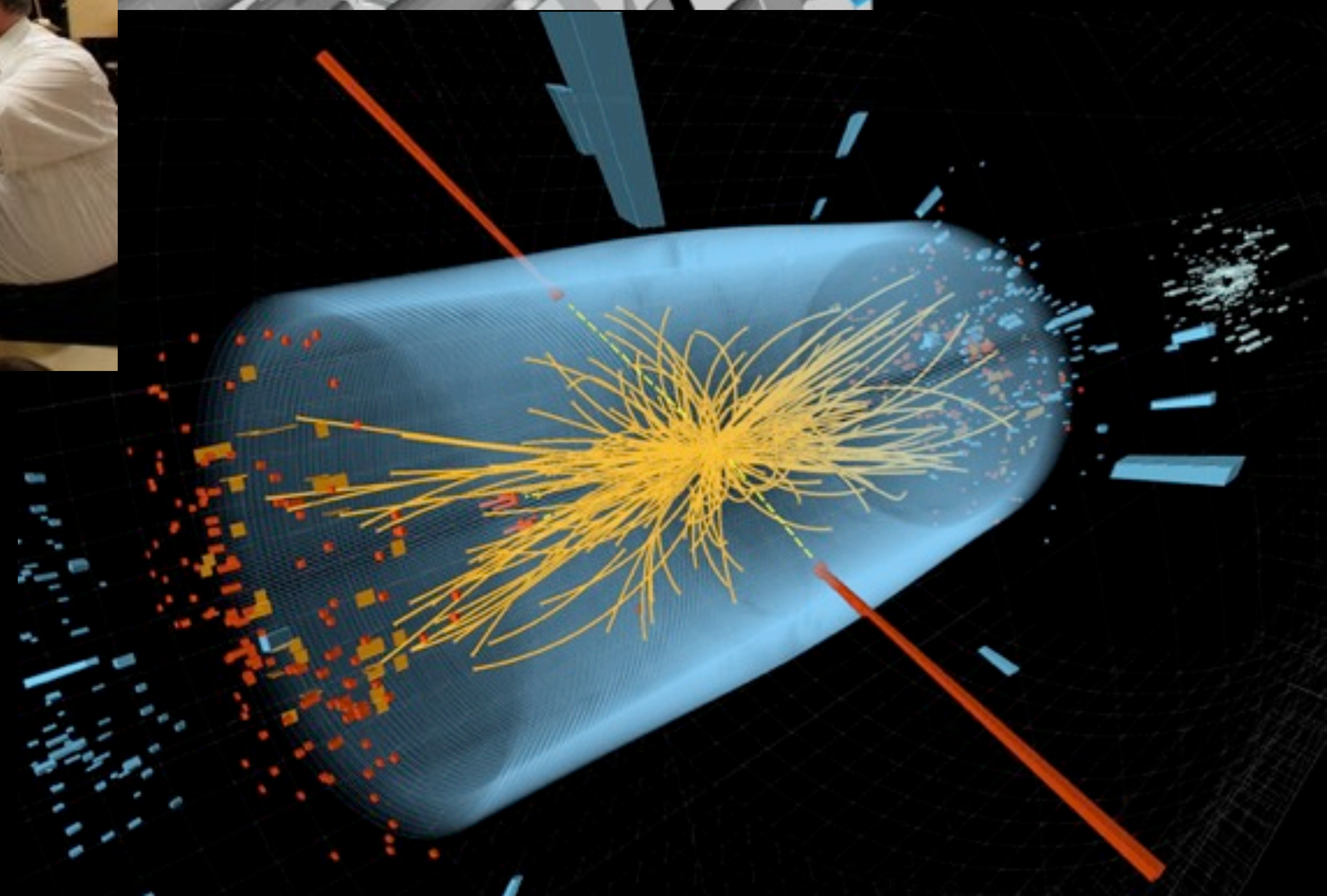
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

2012.7.4

discovery of Higgs boson





theory：1964

design：1984

construction：1998


Higgsdependence Day
July 4, 2012

CERN official statements

Higgs-like boson

↓

a Higgs boson

~~$hZ_{\mu\nu}Z^{\mu\nu}$~~

~~$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$~~

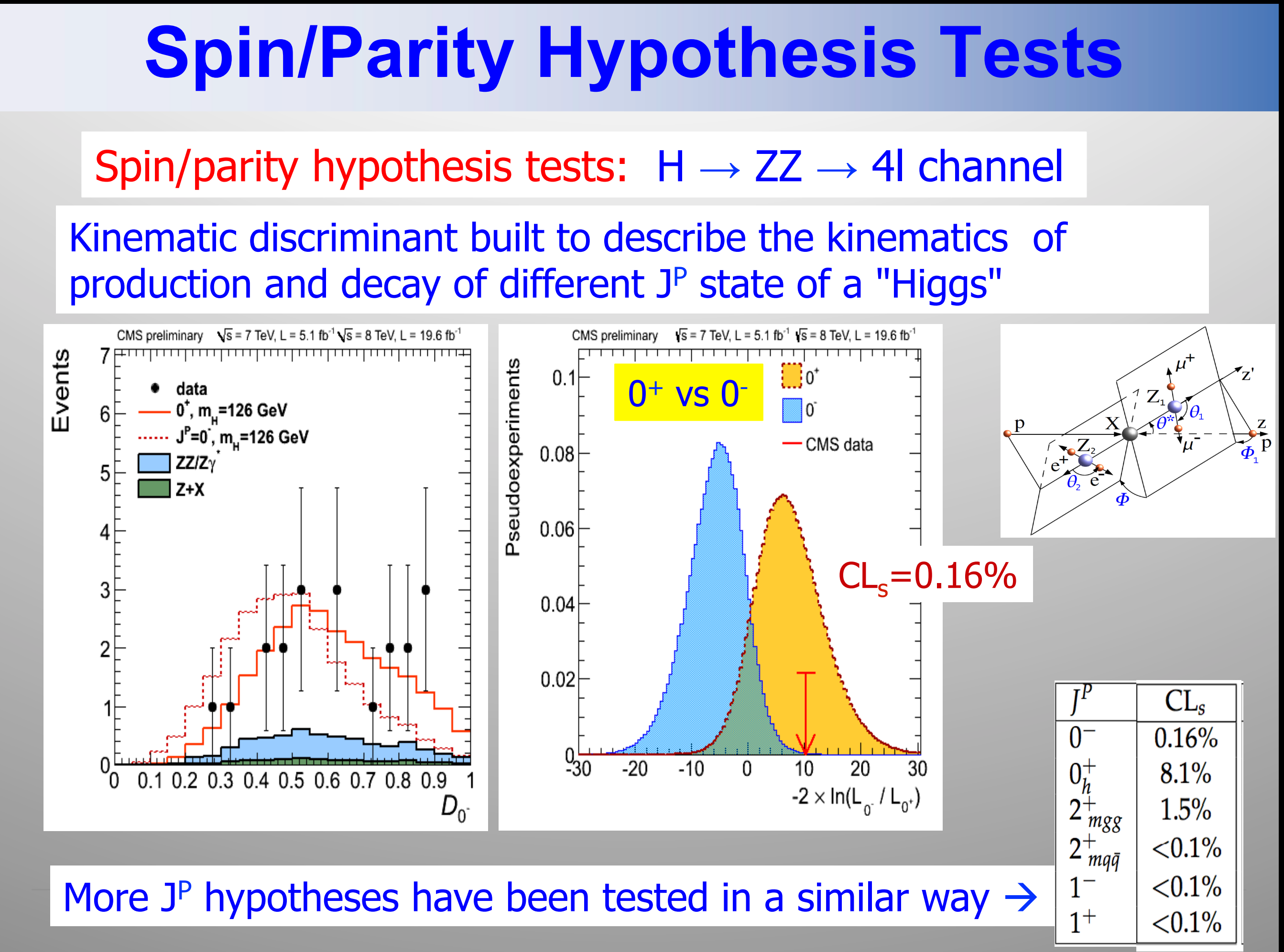
~~$h_{\mu\nu}Z^{\mu\rho}Z^{\nu}_{\rho}$~~

have seen $hZ_{\mu}Z^{\mu}$

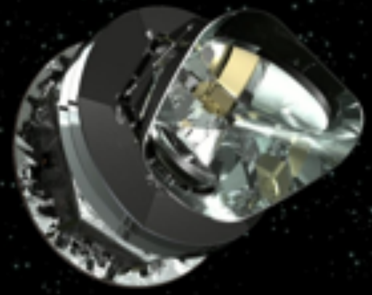
but a gauge boson $\phi^{\dagger}\phi Z_{\mu}Z^{\mu}$

only way $h\langle h\rangle Z_{\mu}Z^{\mu}$

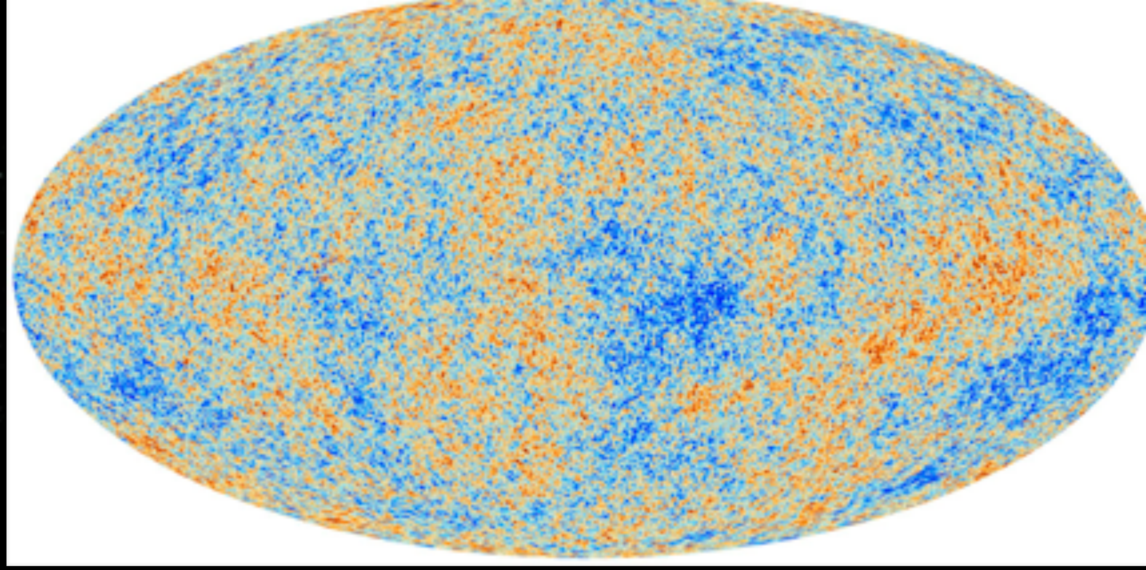
we have discovered a particle that **has a value in vacuum**



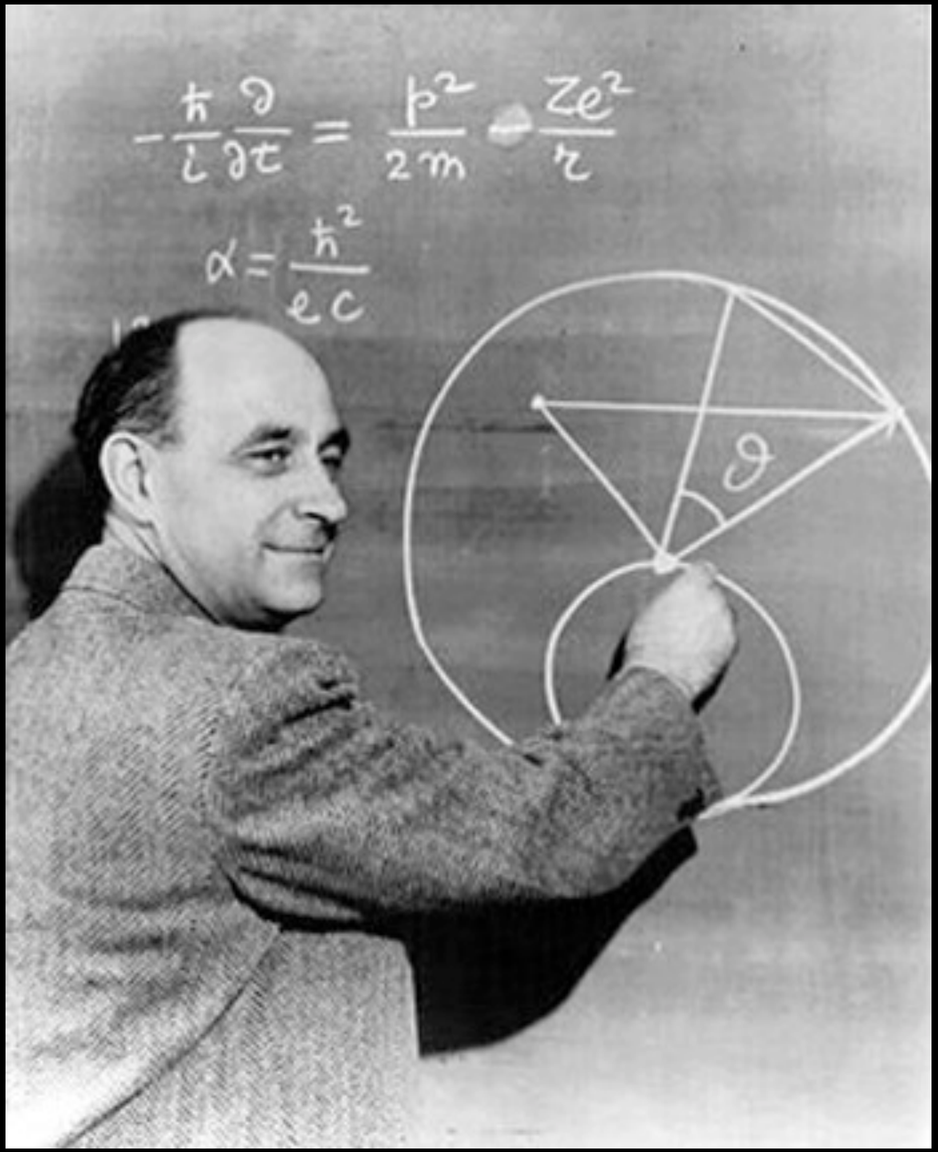
Minimal



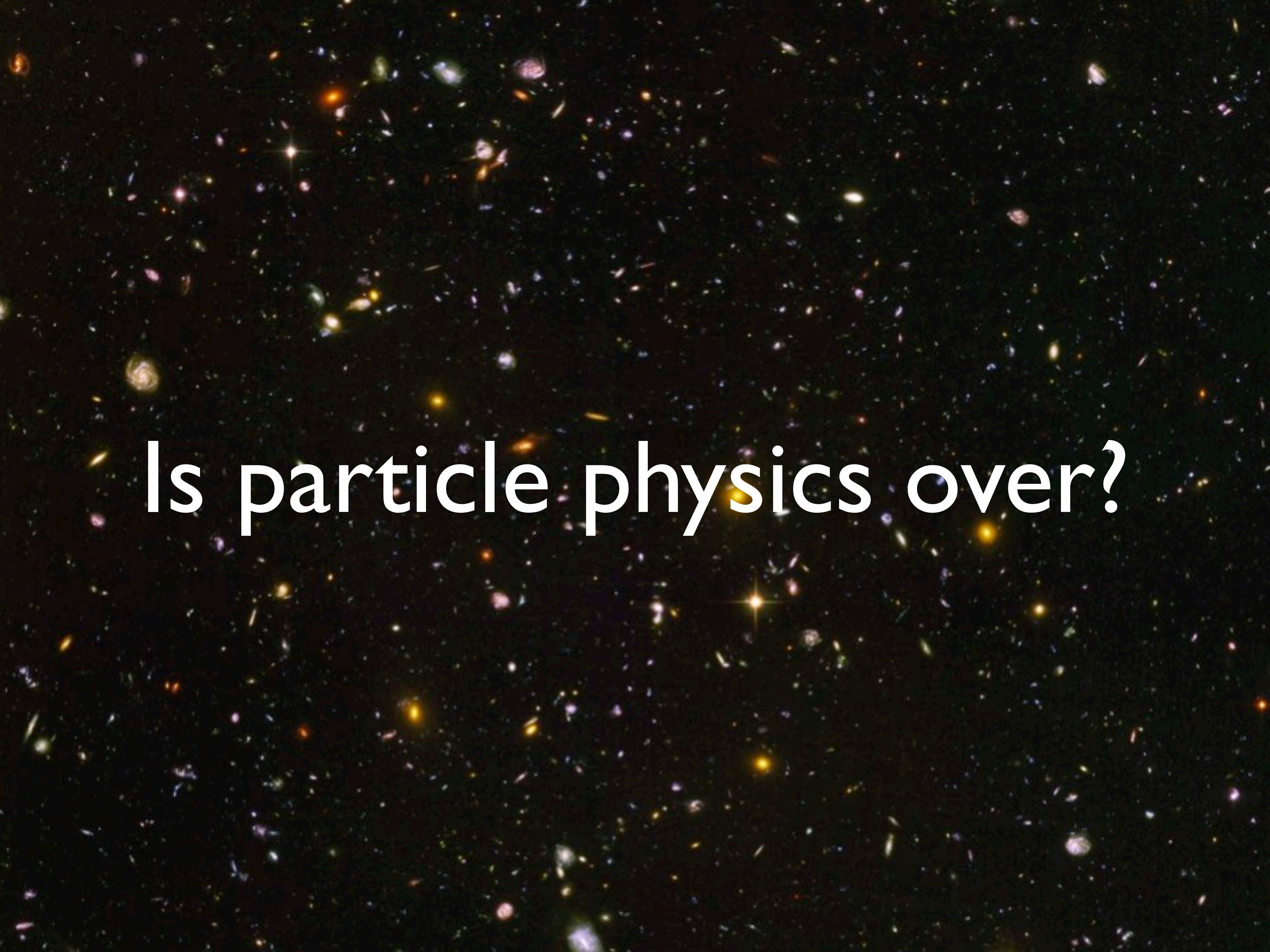
Planck



- It looks very much like *the* Standard Model Higgs boson
- We've known the energy scale to probe since 1933
- now a UV complete theory of strong, weak, EM forces possibly valid up to even M_{Pl}
- cosmology also looks minimal single-field inflation (Planck)
- *the year of elementary scalars!!!*

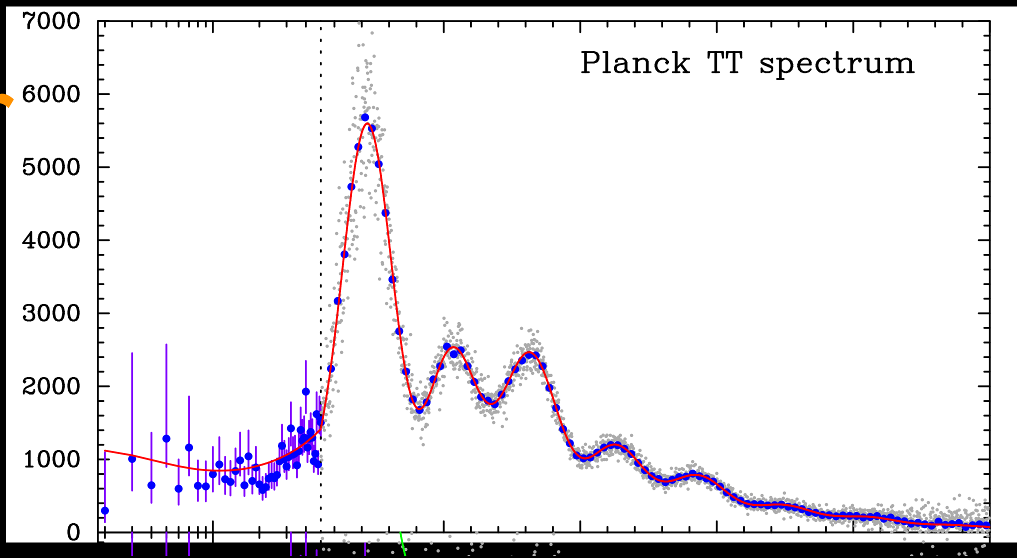


Where do we go next?

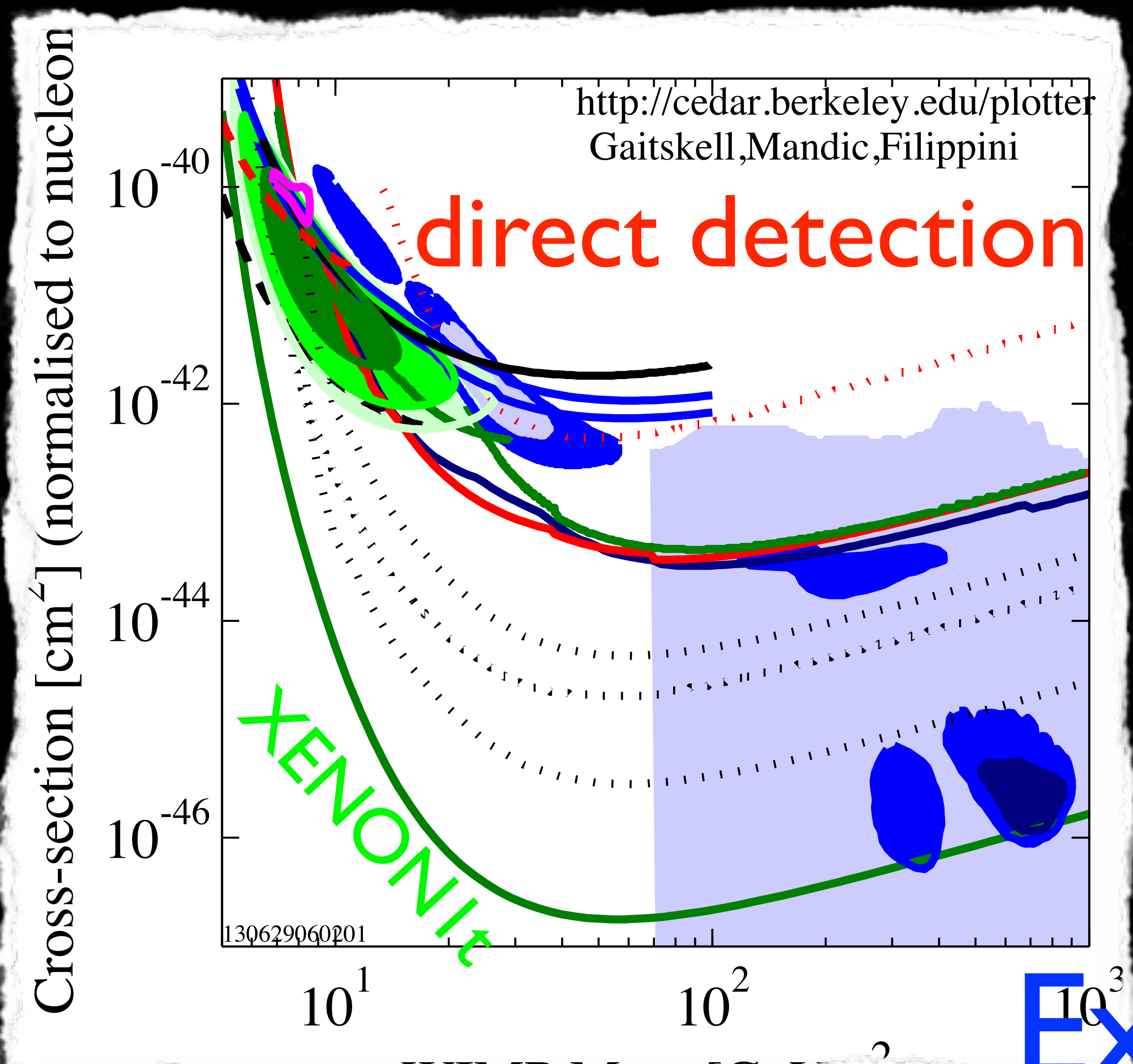

Is particle physics over?

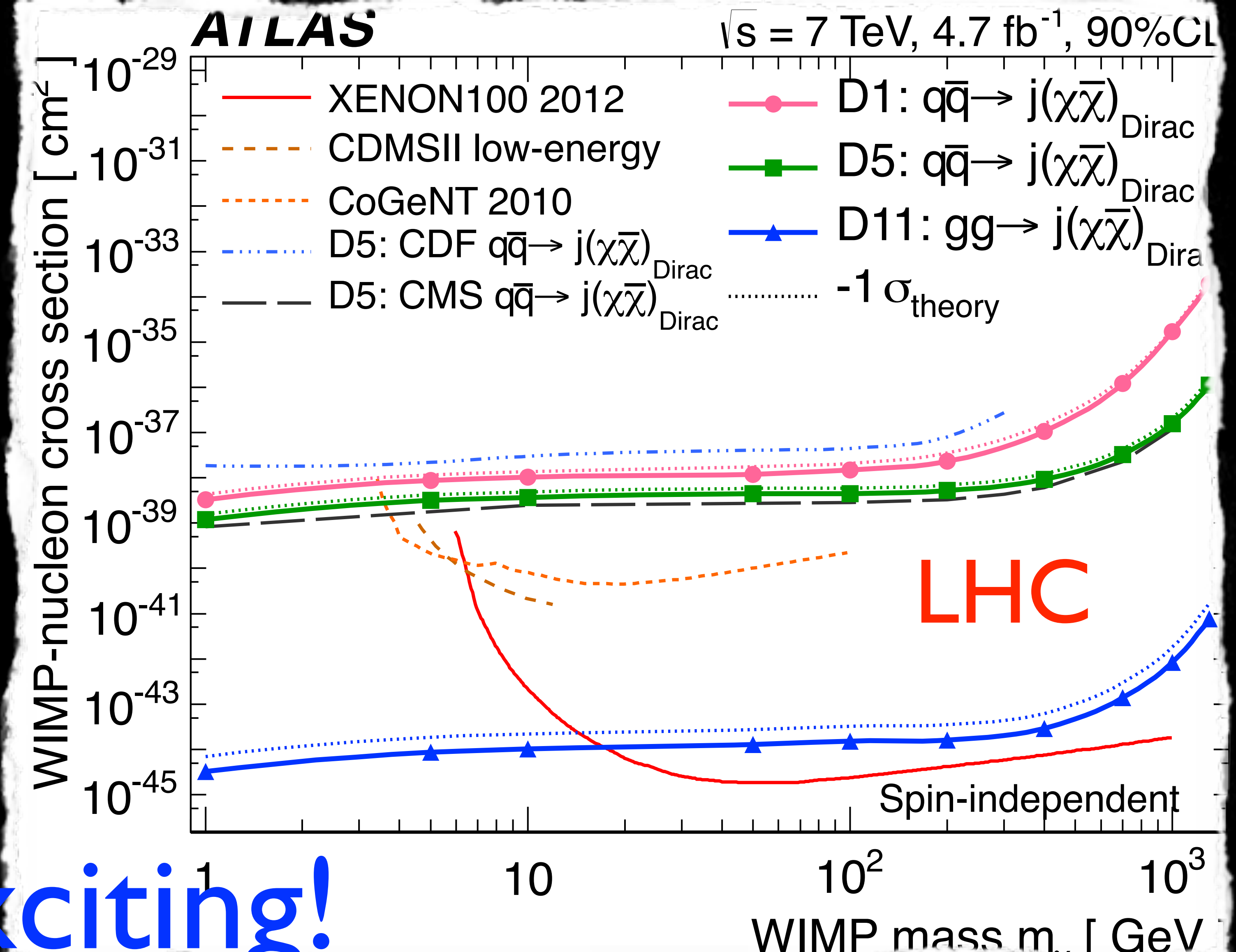
Five evidences for physics beyond SM

- 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

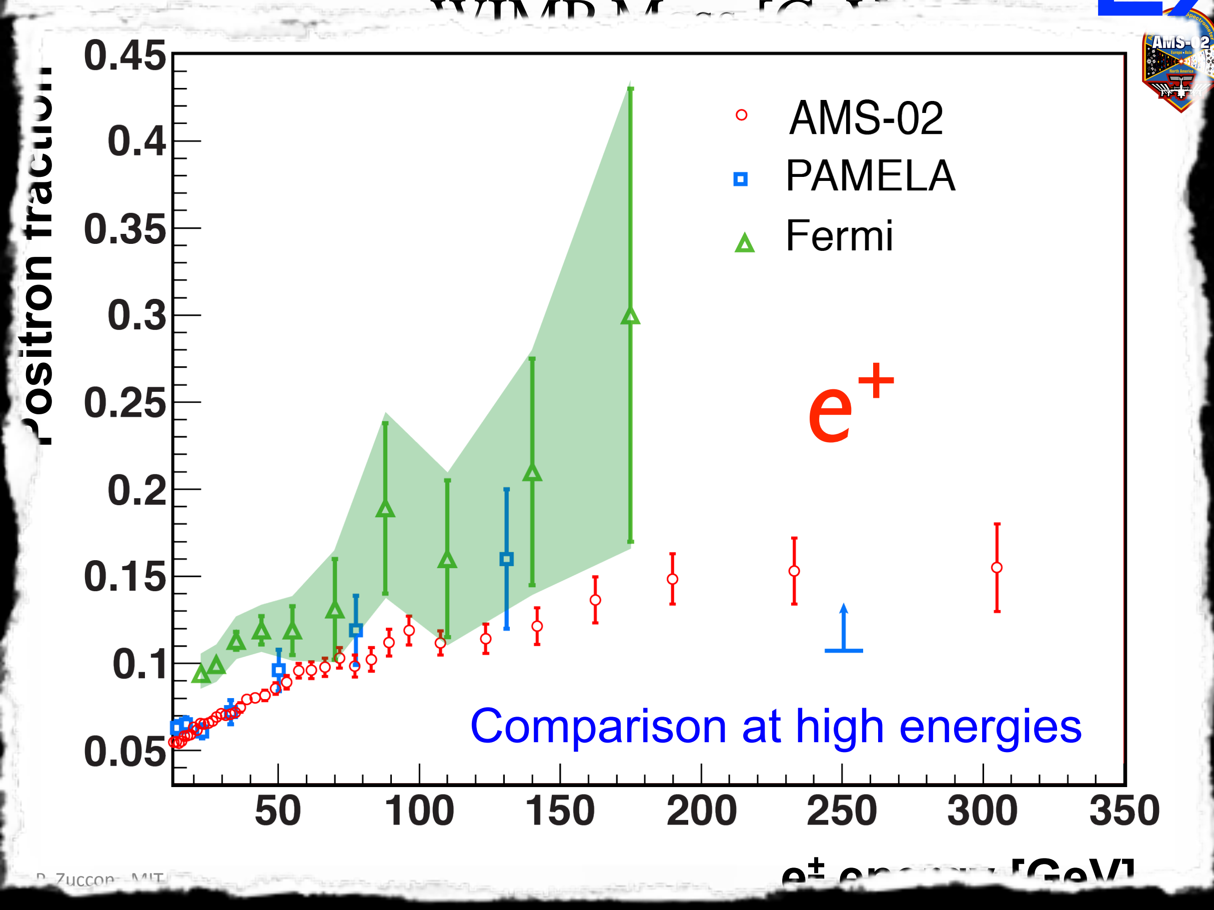


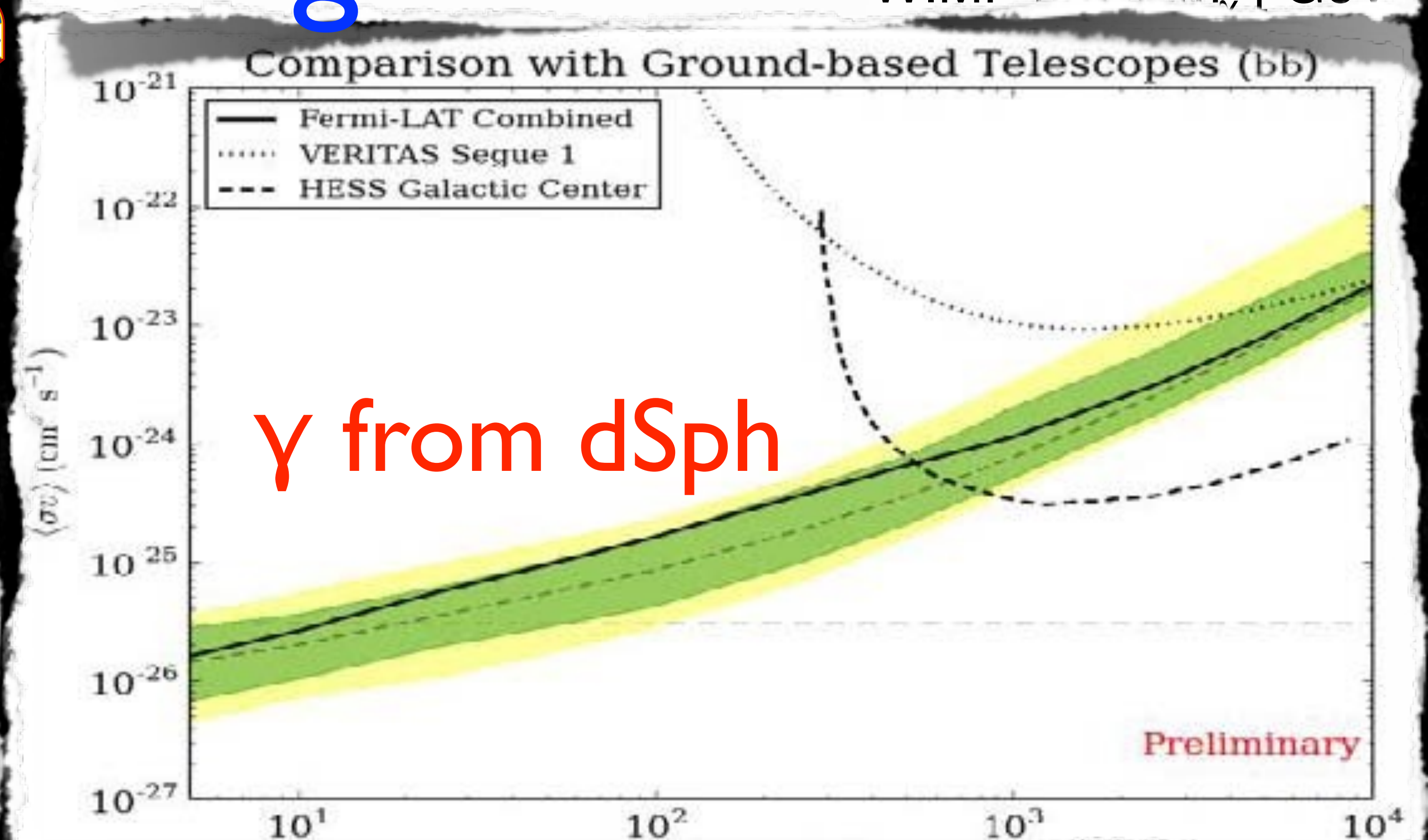
We don't really know their energy scales...


http://cedar.berkeley.edu/plotter
Gaitskell,Mandic,Filippini
direct detection
XENON1t
Cross-section [cm^2] (normalised to nucleon
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^1
10^2
10^3
130629060201


ATLAS
$\sqrt{s}$ = 7 TeV, 4.7 fb^{-1}, 90%CL
XENON100 2012
CDMSII low-energy
CoGeNT 2010
D5: CDF $q\bar{q} \rightarrow j(\chi\bar{\chi})_{Dirac}$
D5: CMS $q\bar{q} \rightarrow j(\chi\bar{\chi})_{Dirac}$
D1: $q\bar{q} \rightarrow j(\chi\bar{\chi})_{Dirac}$
D5: $q\bar{q} \rightarrow j(\chi\bar{\chi})_{Dirac}$
D11: $gg \rightarrow j(\chi\bar{\chi})_{Dirac}$
-1 σ_{theory}
LHC
Spin-independent
WIMP-nucleon cross section [cm^2]
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
10^{-41}
10^{-43}
10^{-45}
1
10
10^2
10^3
WIMP mass m_χ [GeV]

Exciting!

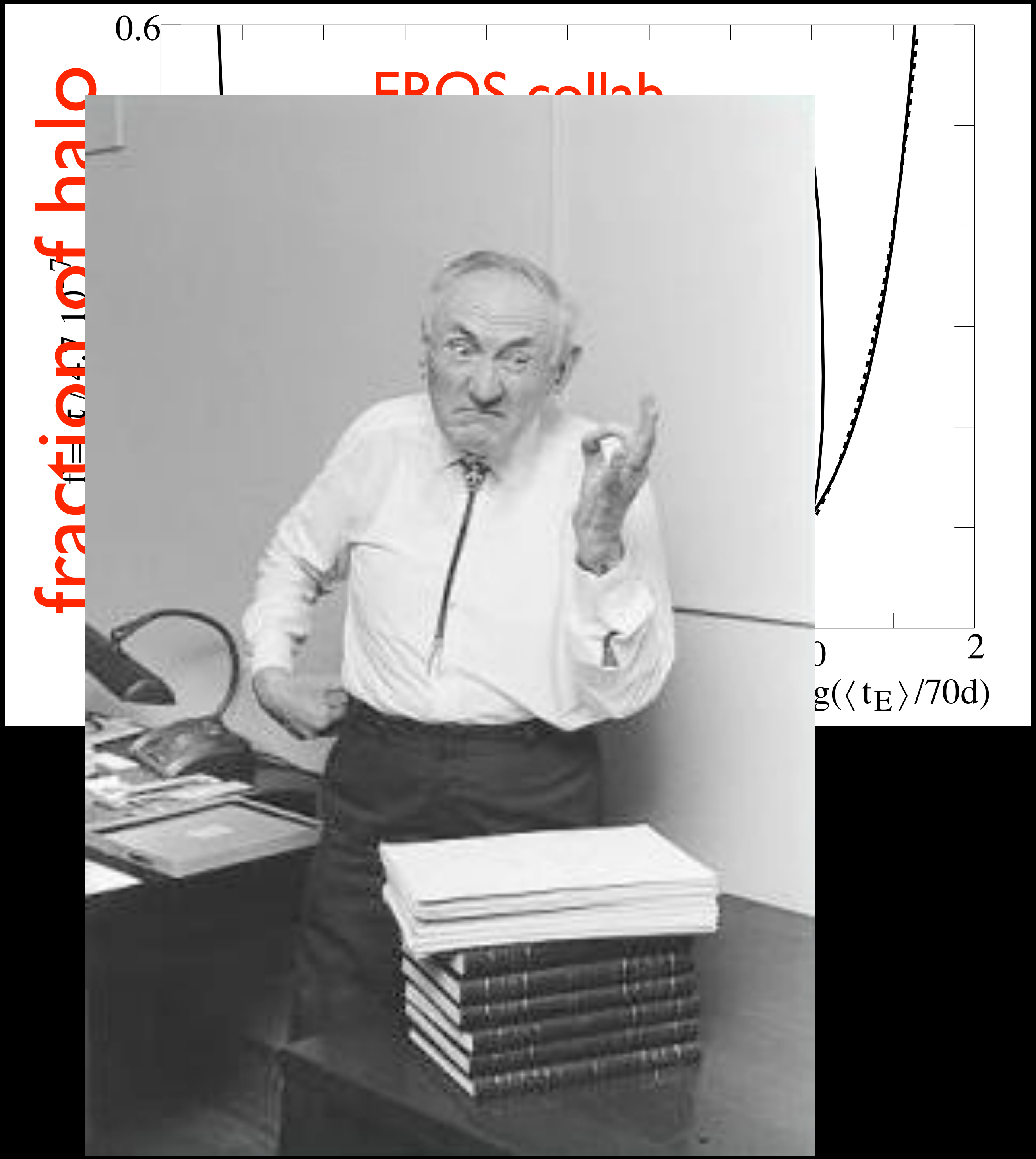

AMS-02
PAMELA
Fermi
e^+
Comparison at high energies
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
50
100
150
200
250
300
350


Comparison with Ground-based Telescopes (bb)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
γ from dSph
Preliminary
$\langle\sigma v\rangle$ [cm^3 s^{-1}]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3
10^4

mass of dark matter

- upper limit comes from search for using gravitational microlensing
- lower limit comes from *uncertainty principle*
- 10^{-31} GeV to 10^{50} GeV
- we narrowed it down to within 81 orders of magnitude
- a big progress in 80 years since Zwicky

need to keep our mind open



beginning of the Universe

1,000,000,001

matter

1,000,000,001

anti-matter

shortly after

??????

1

1,000,000,002

1,000,000,000

matter

anti-matter

anti-matter needs to

convert into matter

Universe now

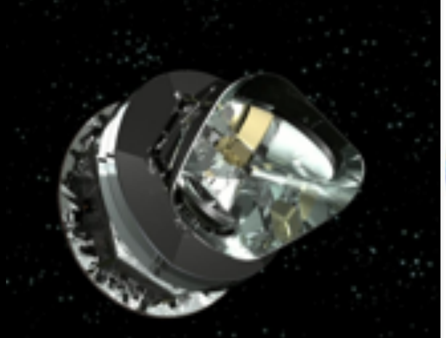
2

us

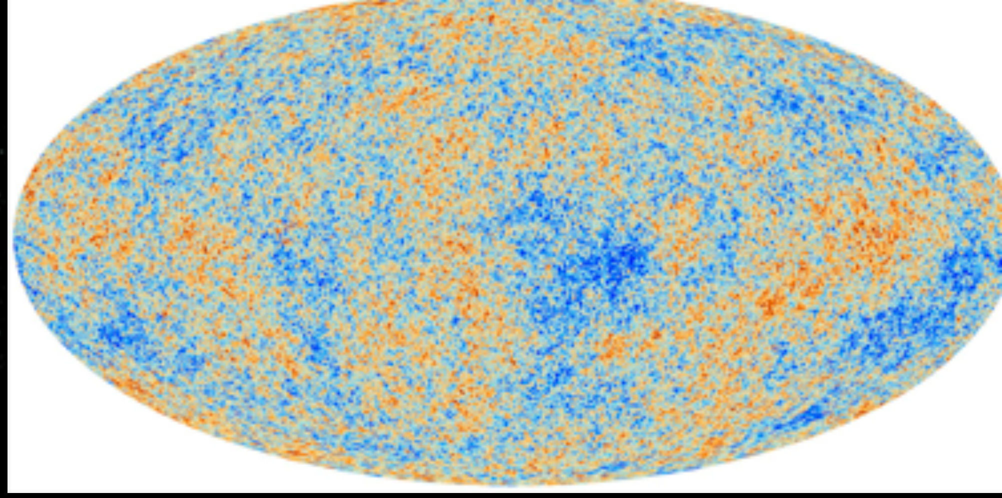
matter *anti-matter*

This is how we survived!

Puzzle is sharpened



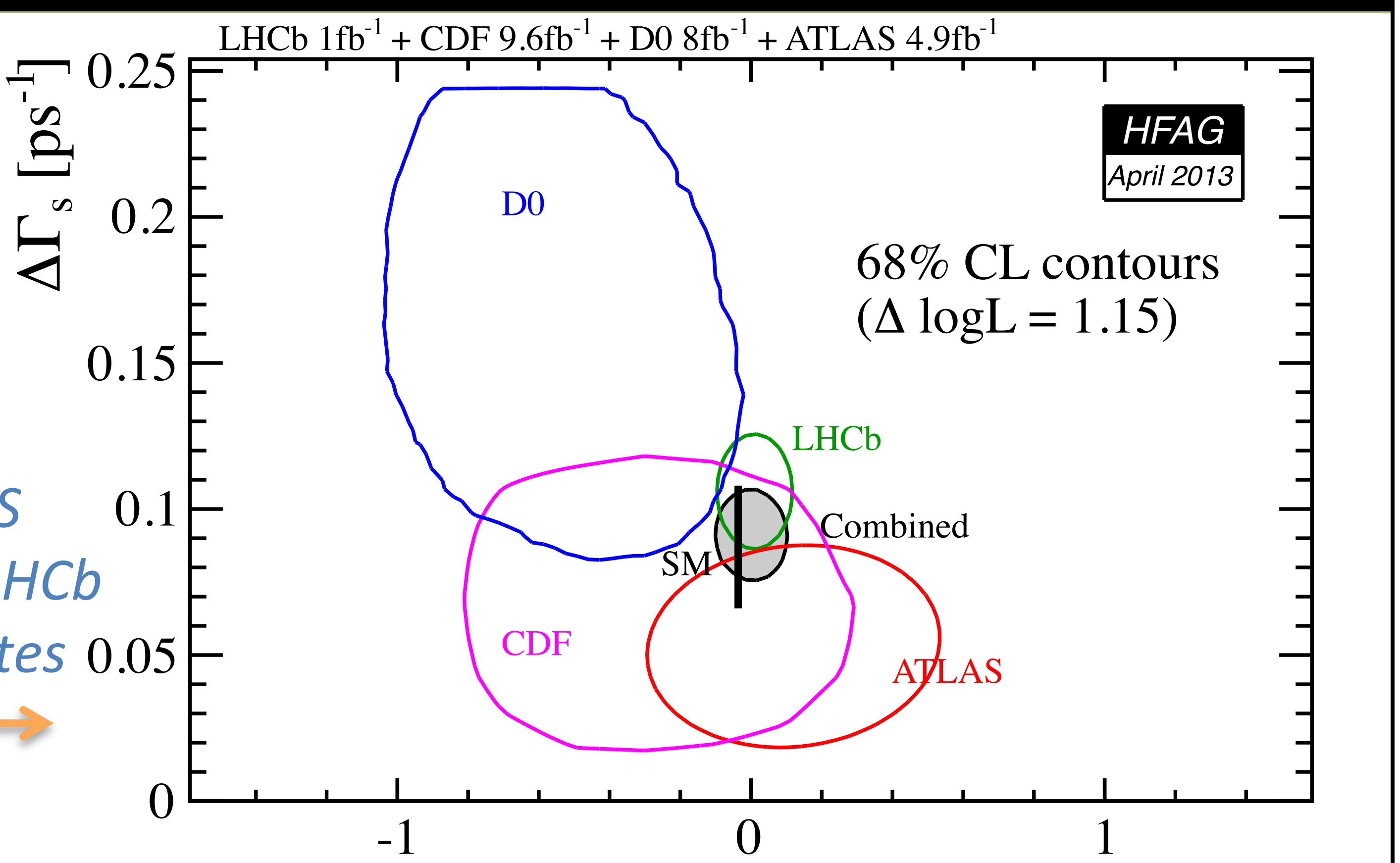
Planck



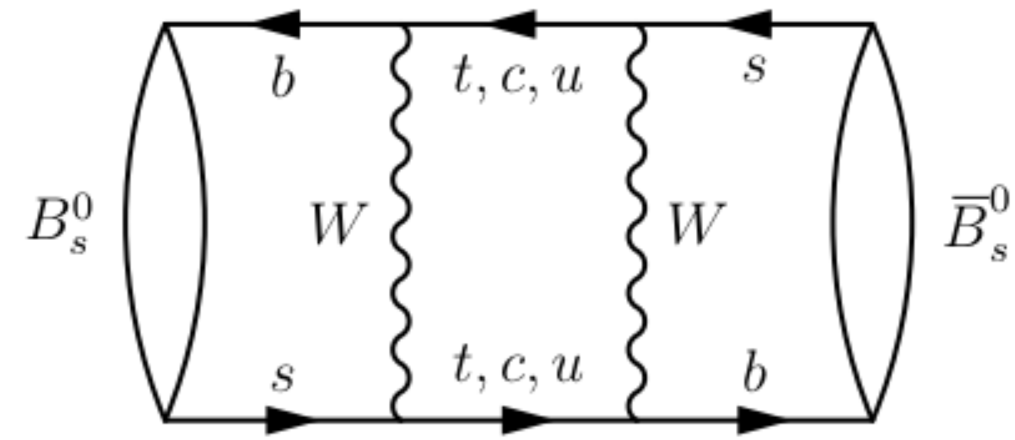
- with success of inflation, it can't be the initial condition of the Universe
- Kobayashi and Maskawa phase can only explain $\eta_b \approx \alpha_W^5 J \approx 10^{-27}$
- new sources of CPV are needed
- we also need to see how anti-matter can turn into matter

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

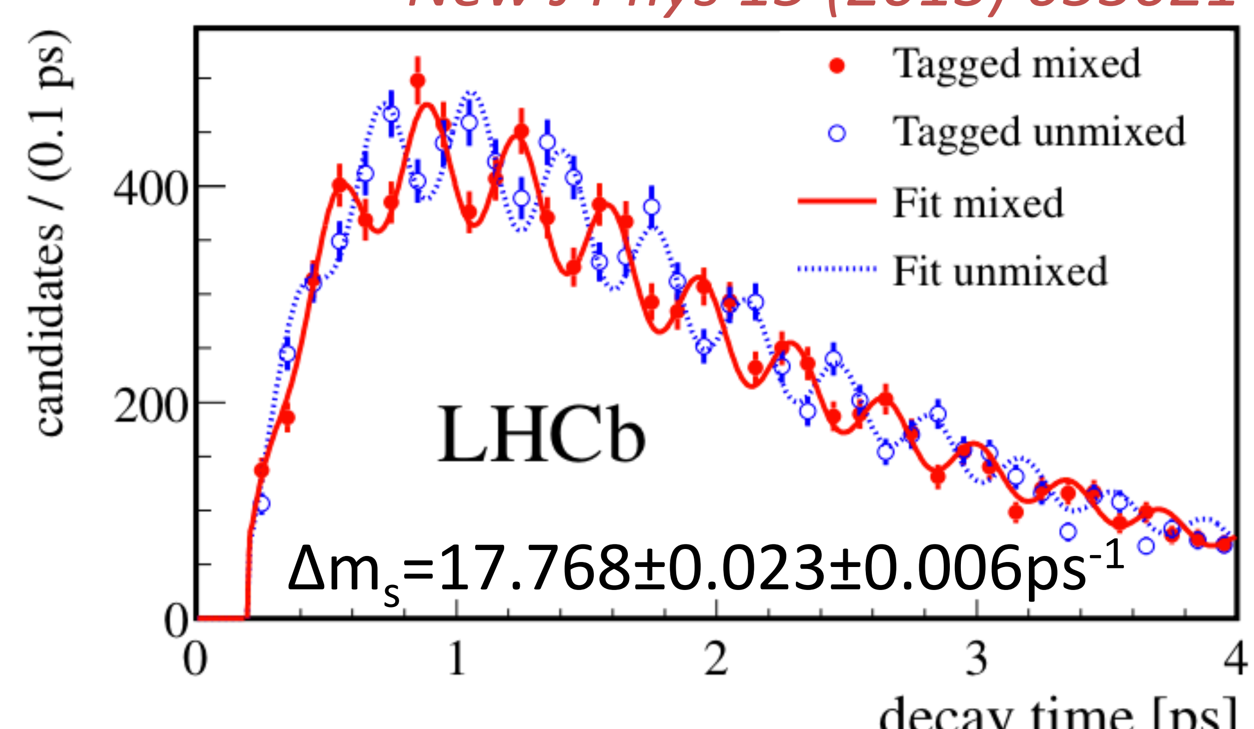
B_s: Strangely Beautiful



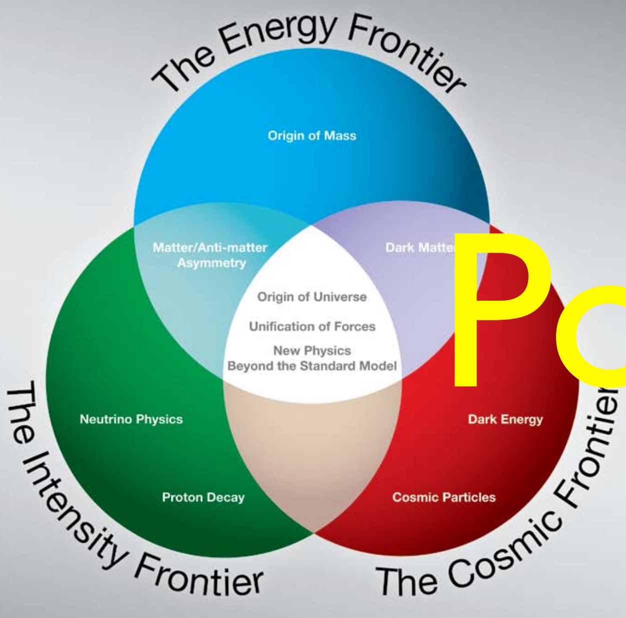
S
HCb
tes

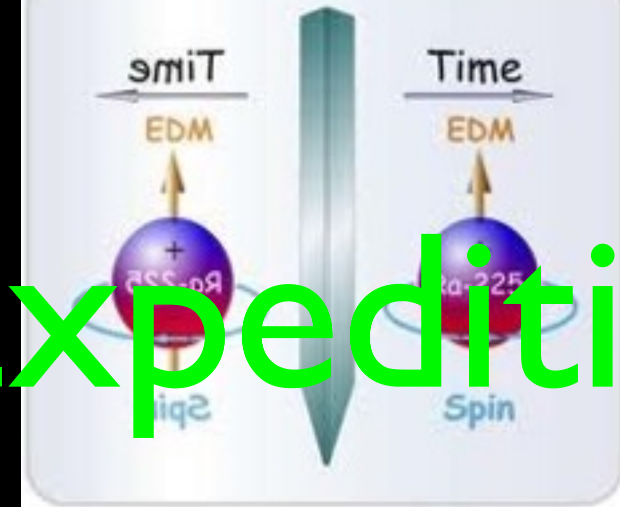


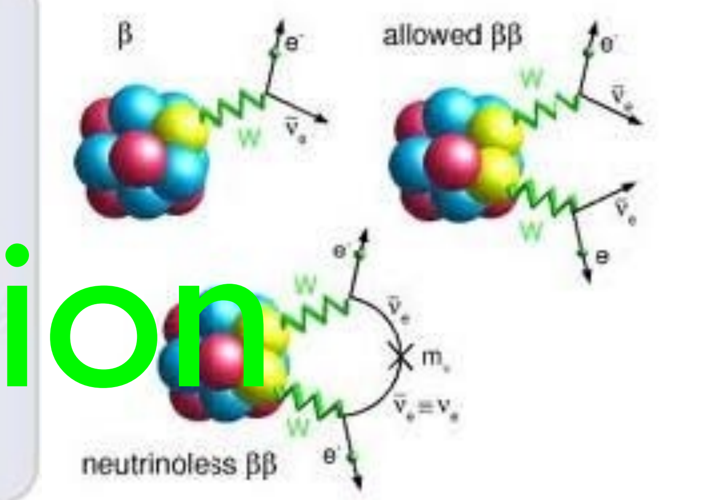
New J Phys 15 (2013) 053021

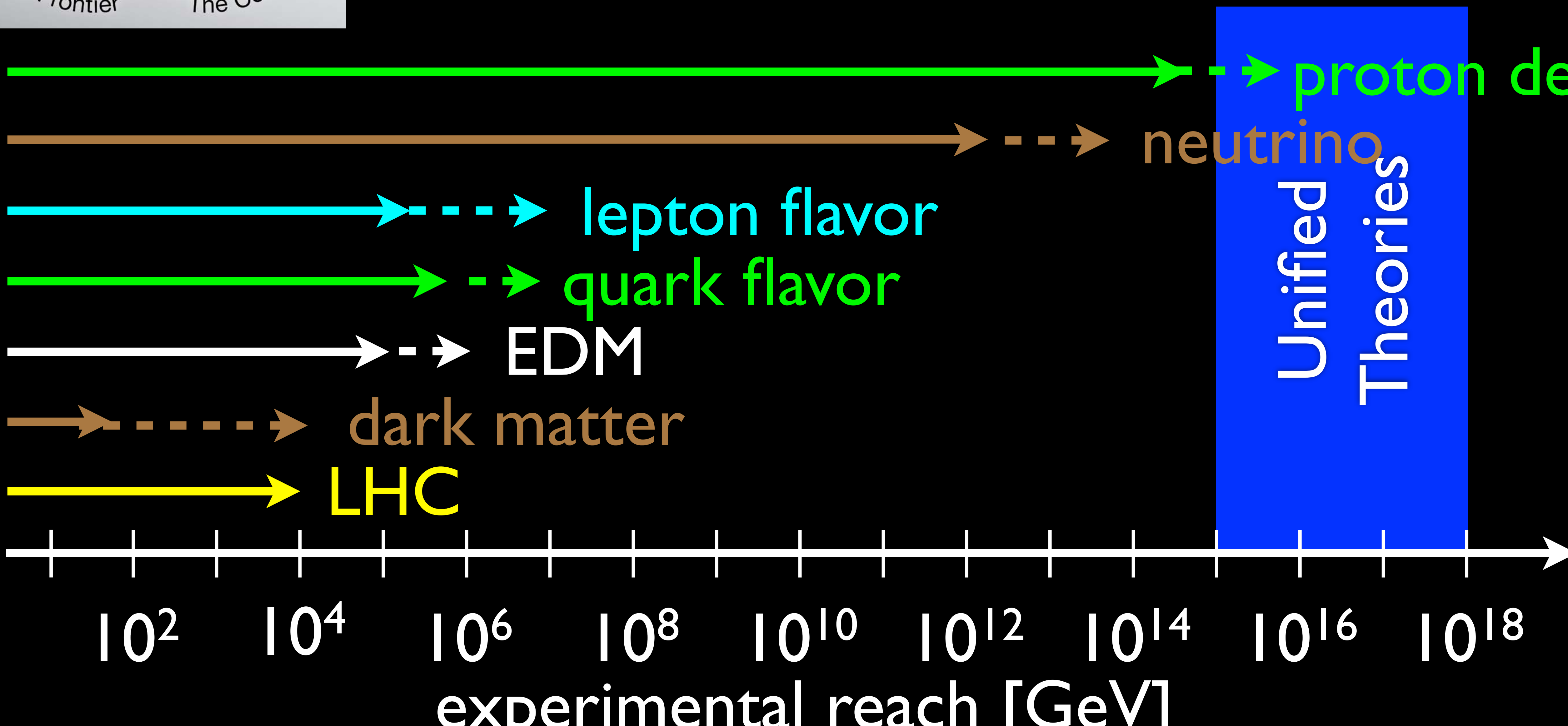


Power of Expedition









(with significant simplifying assumptions)

→ baryon asymmetry


KamLAND
control room

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

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

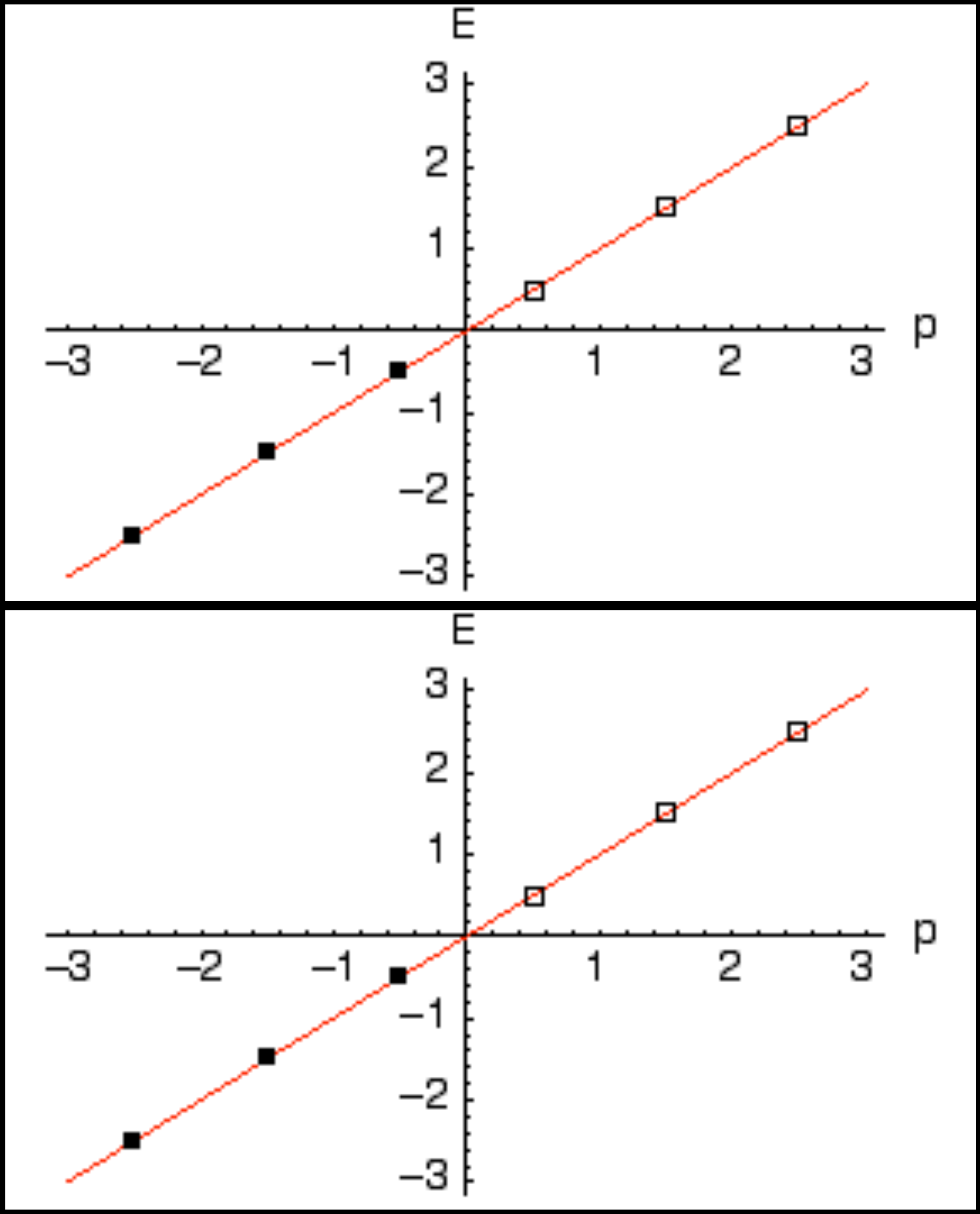
$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, \\ (H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

unique role of m_ν

- Lowest order effect of physics at short distances
- tiny effect: $(m_\nu/E_\nu)^2 \approx (0.1\text{eV}/\text{GeV})^2 \approx 10^{-20}$!
- 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

Electroweak Anomaly

- Actually, 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 correspondingly

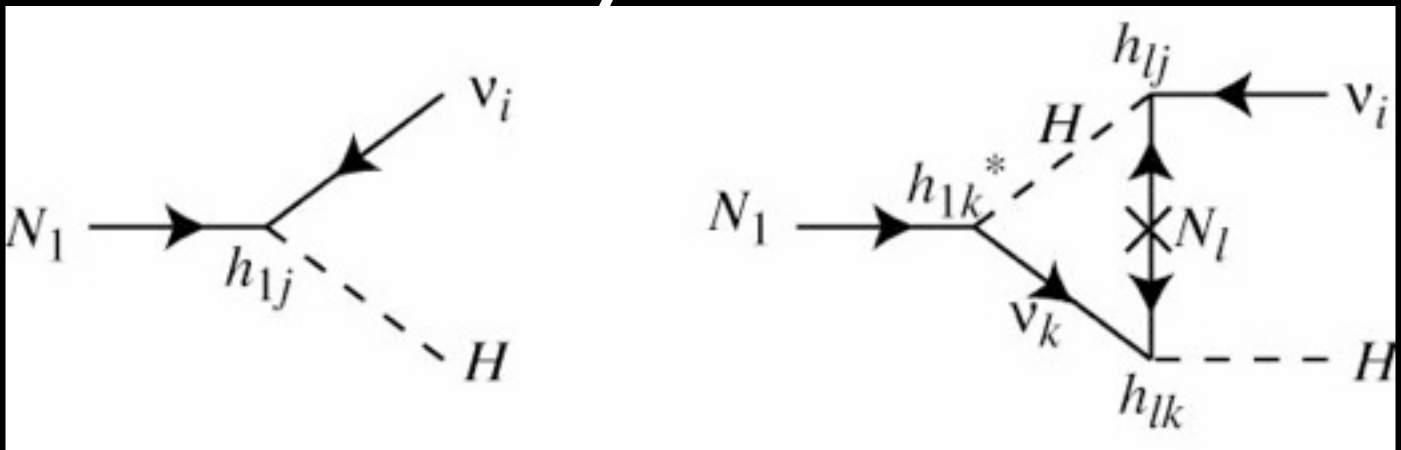


Leptogenesis

Fukugita

Yanagida

- You generate Lepton Asymmetry first.
- Generate L from the direct CP violation in right-handed neutrino decay
- Like ε'/ε!



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

- L gets converted to B via EW anomaly

⇒ More matter than anti-matter

⇒ We have survived "The Great Annihilation"

Excitement

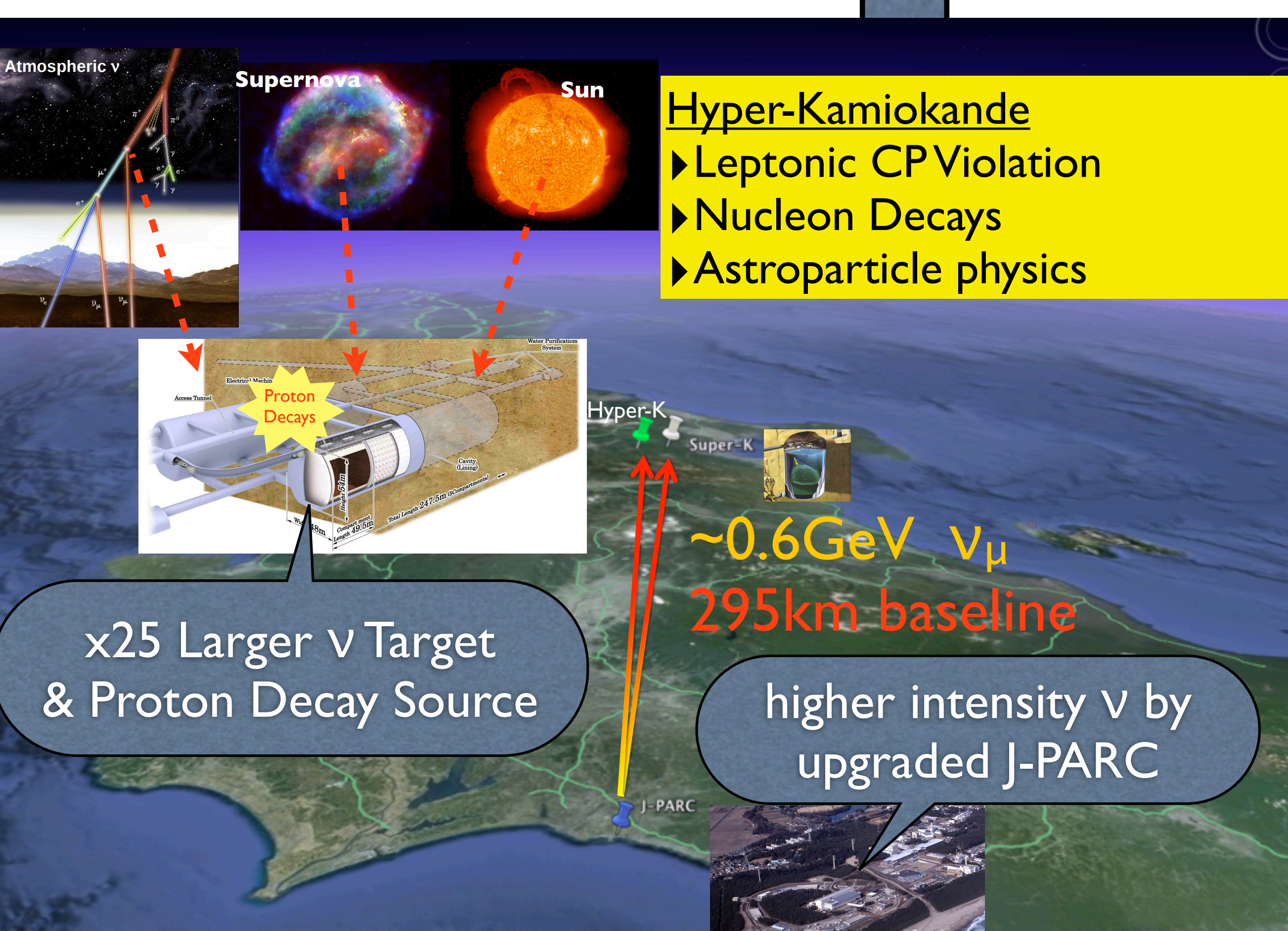
- CP violation in neutrino sector may be observable with conventional technique

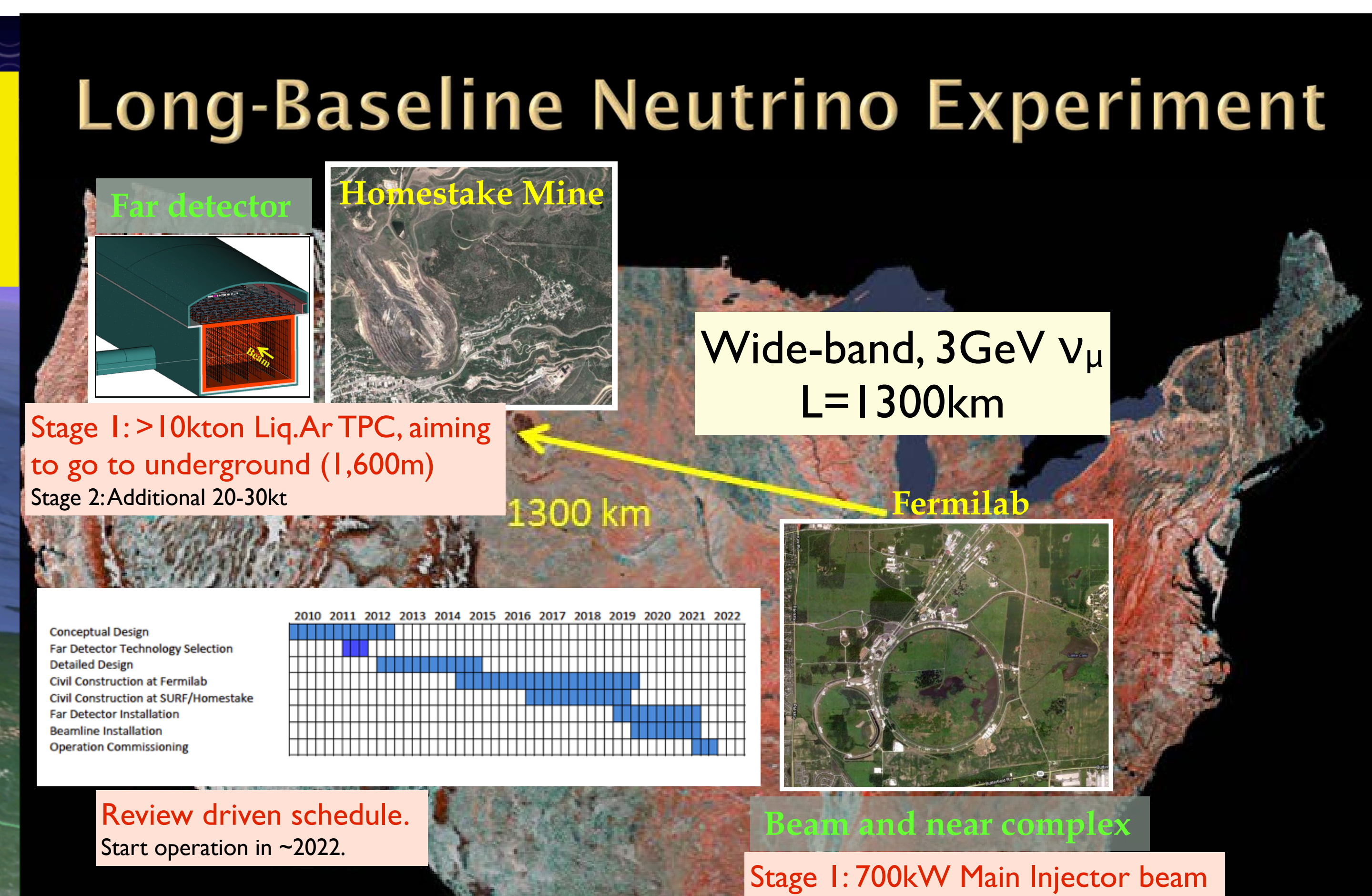
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\frac{\Delta m^2_{12} L}{4E} \sin\frac{\Delta m^2_{13} L}{4E} \sin\frac{\Delta m^2_{23} L}{4E}$$

2002
KamLAND
SNO

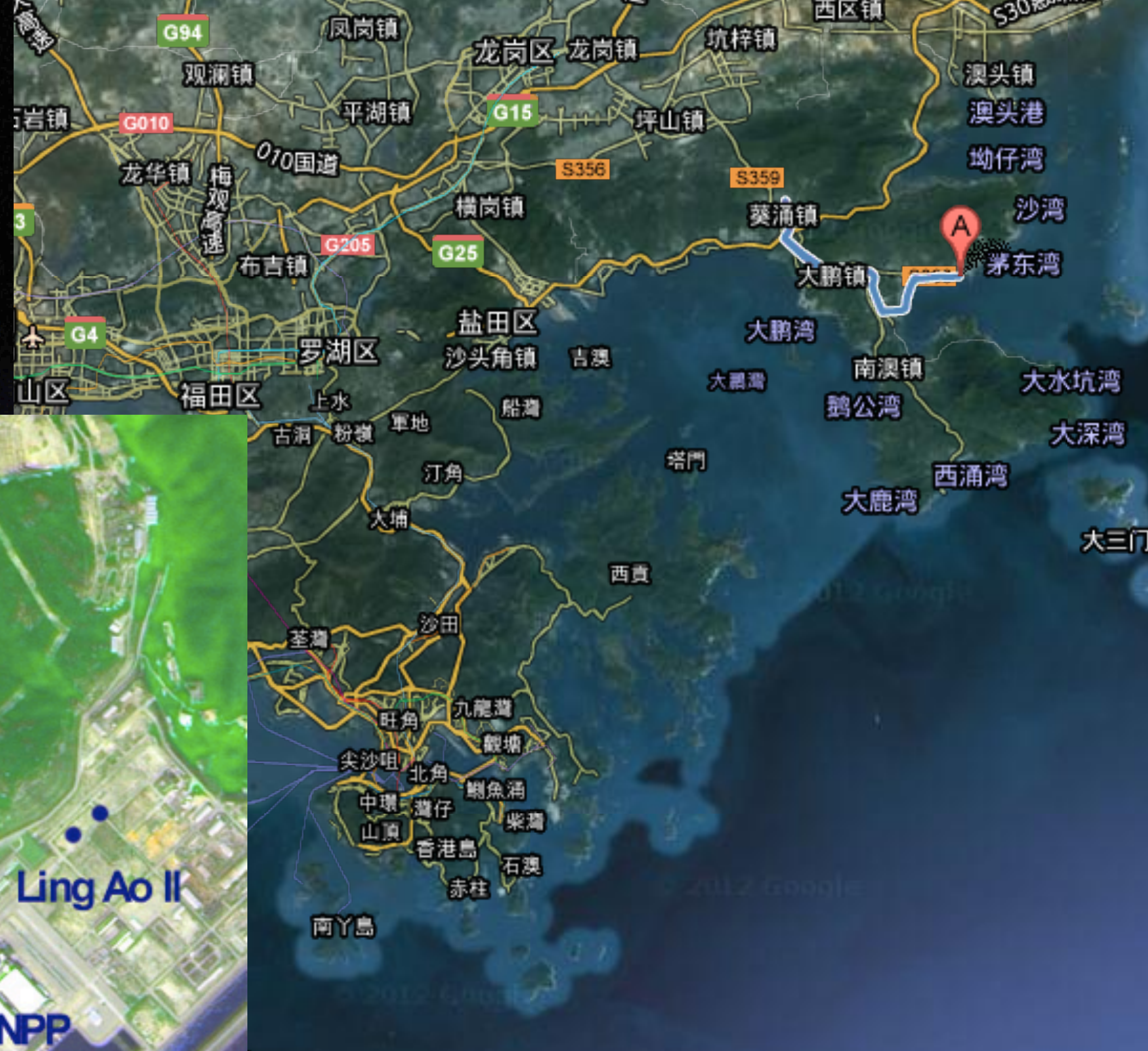
2012
Daya
Bay

1998
Super-K





Daya Bay Reactors

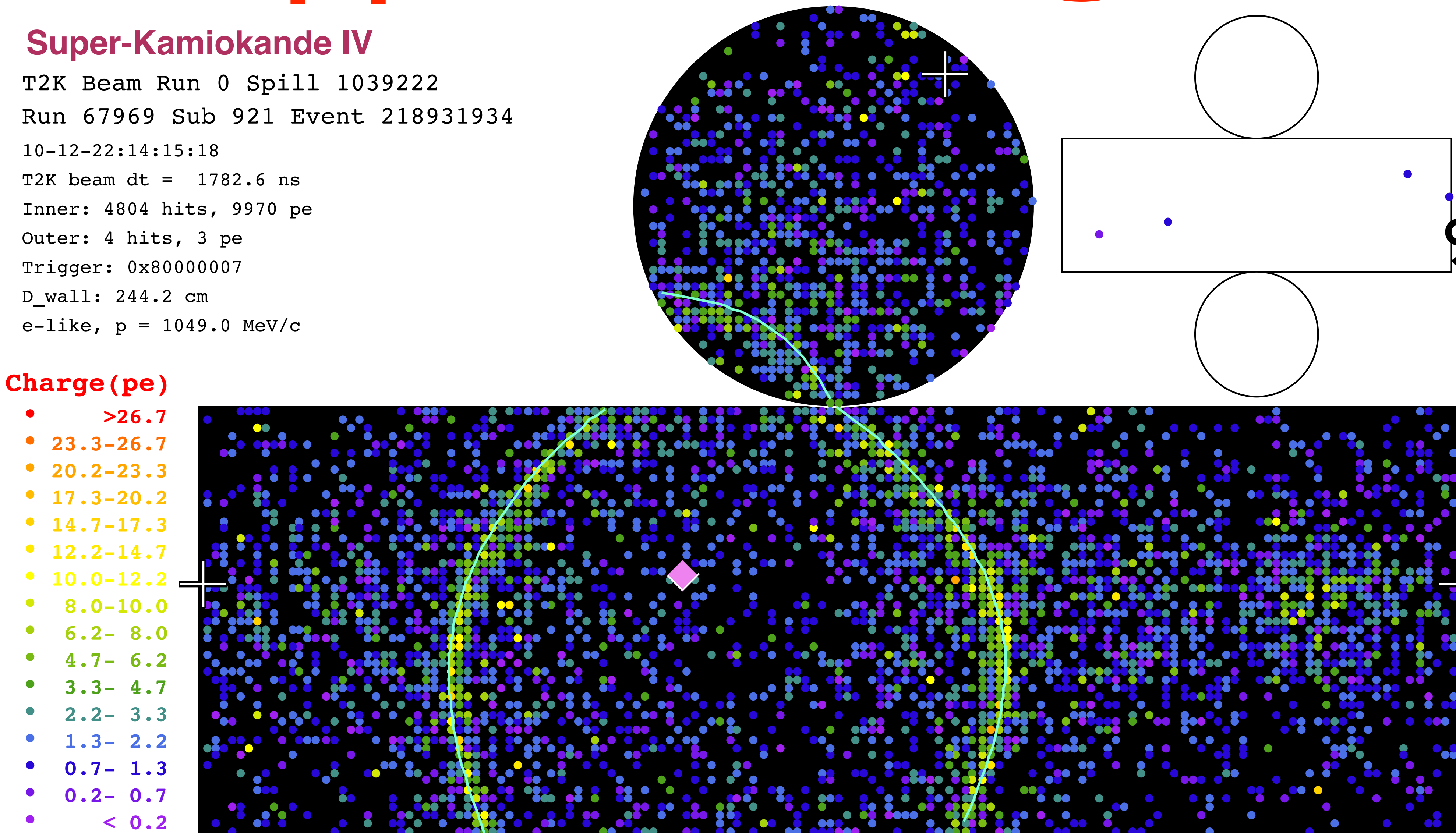


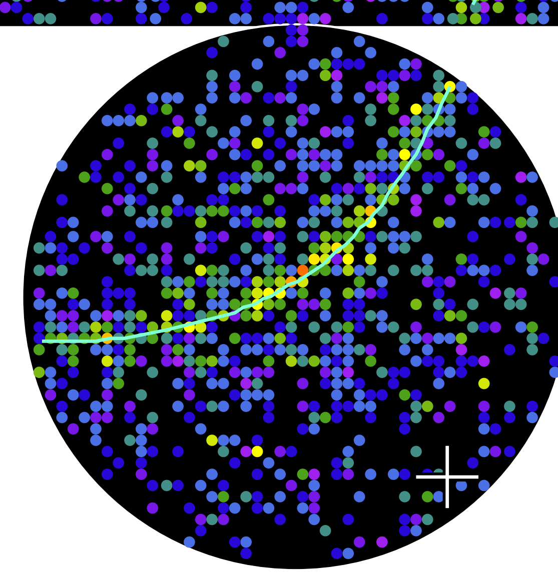
10530 events expected
only 9901 observed
5.2 sigma!

RENO

ν_e appearance @T2K

11/6/14





6 events

1.5 BG

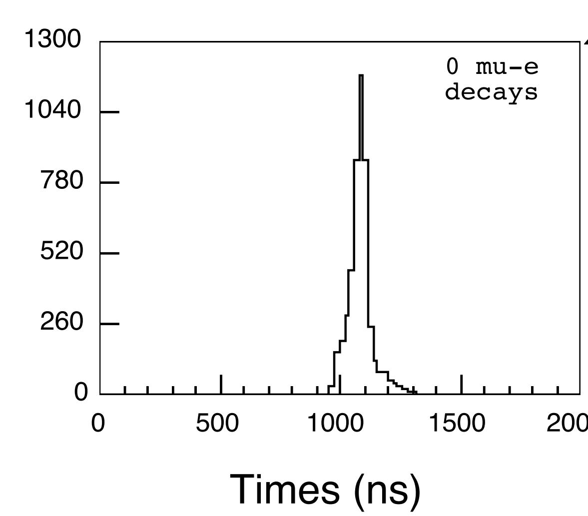
99.3% CL

12/6/5

28 events

4.6 BG

7.5σ!!



visible energy : 1049 MeV

\# of decay-e : 0

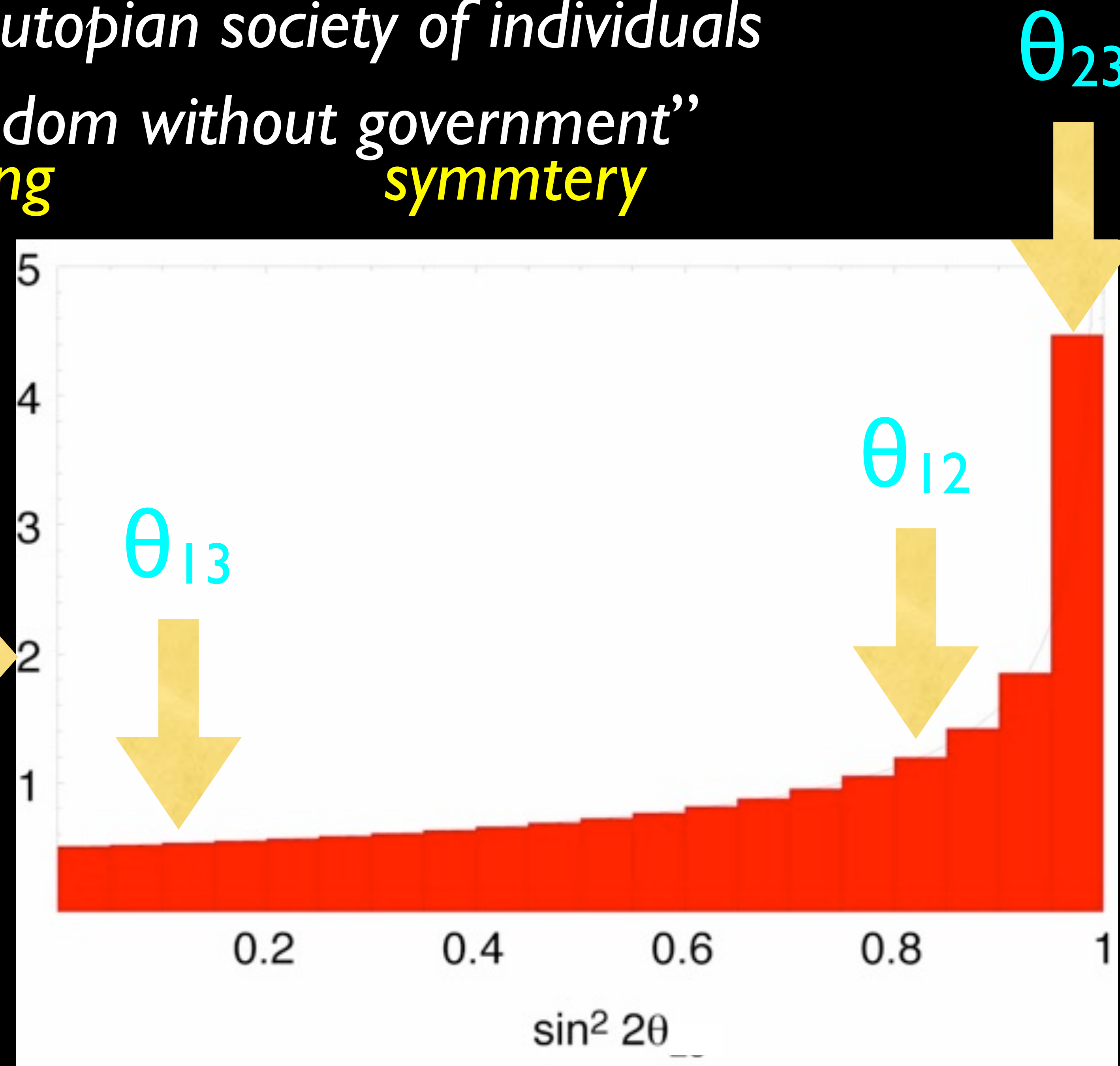
2γ Inv. mass : 0.04 MeV/c^2

recon. energy : 1120.9 MeV

anarchy

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

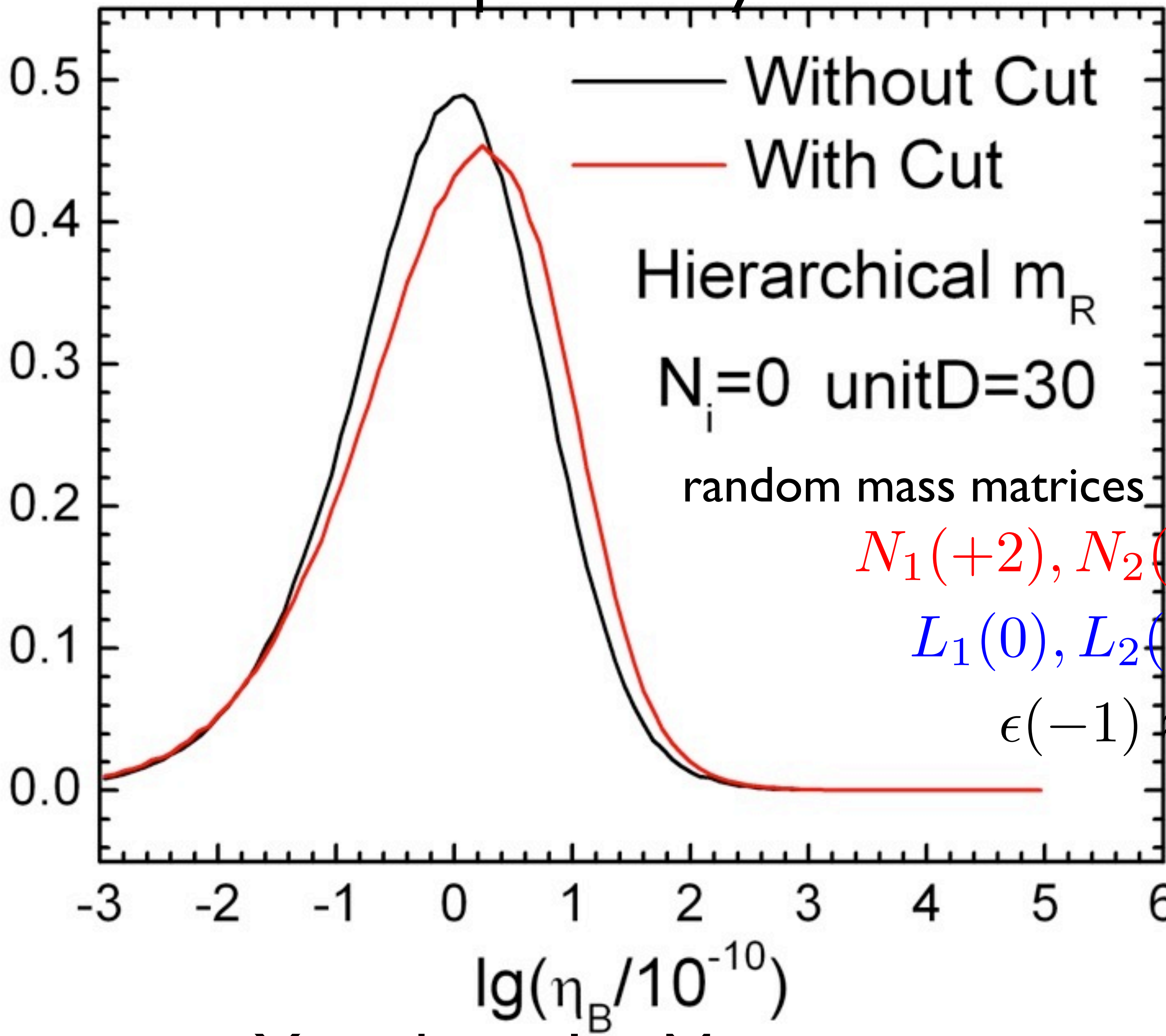
neutrinos *large mixing* *symmtery*



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

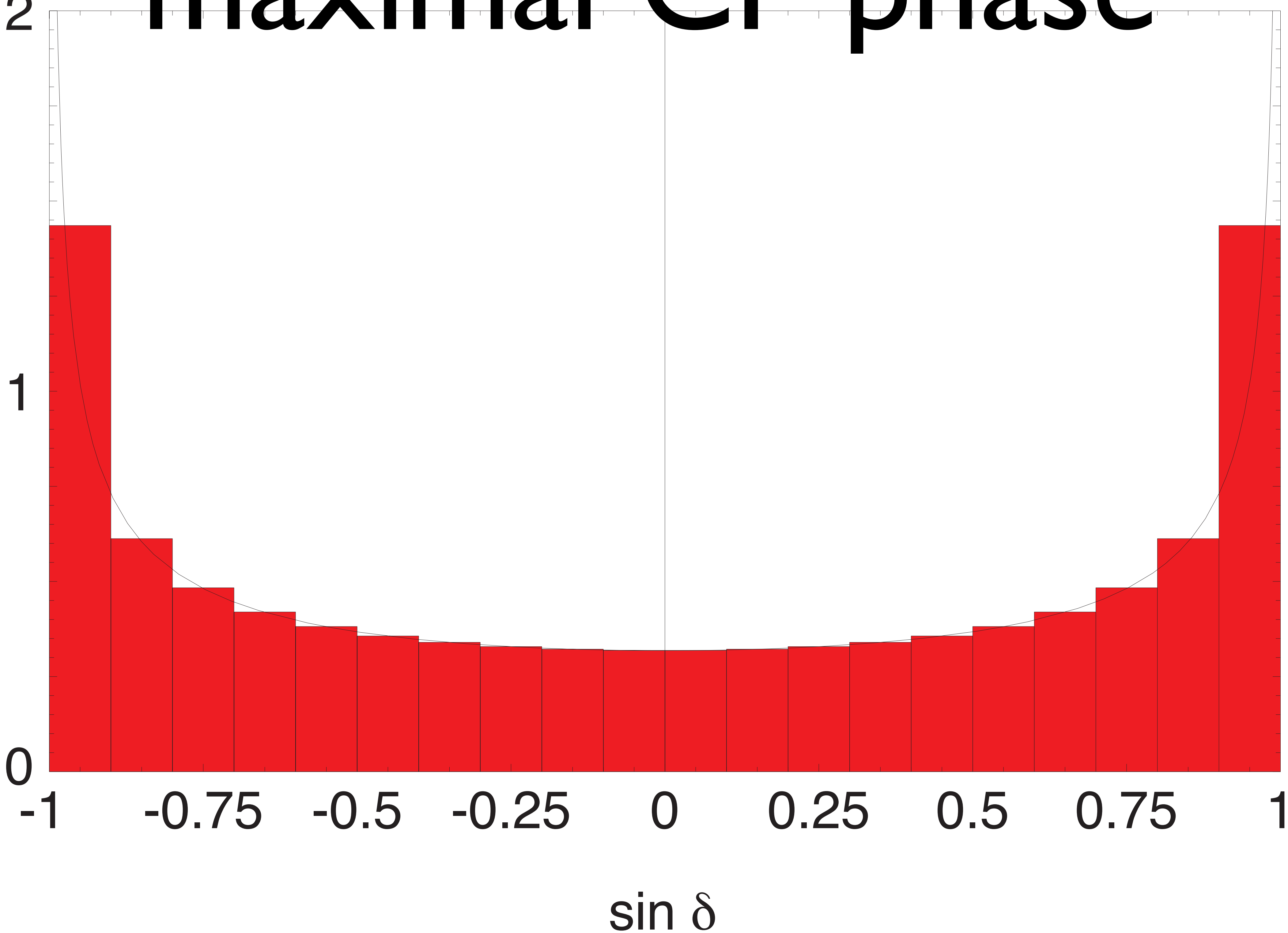
$N_1(+2), N_2(+1), N_3(0)$

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

$\epsilon(-1) \approx 0.1$

Xiaochuan Lu, Murayama

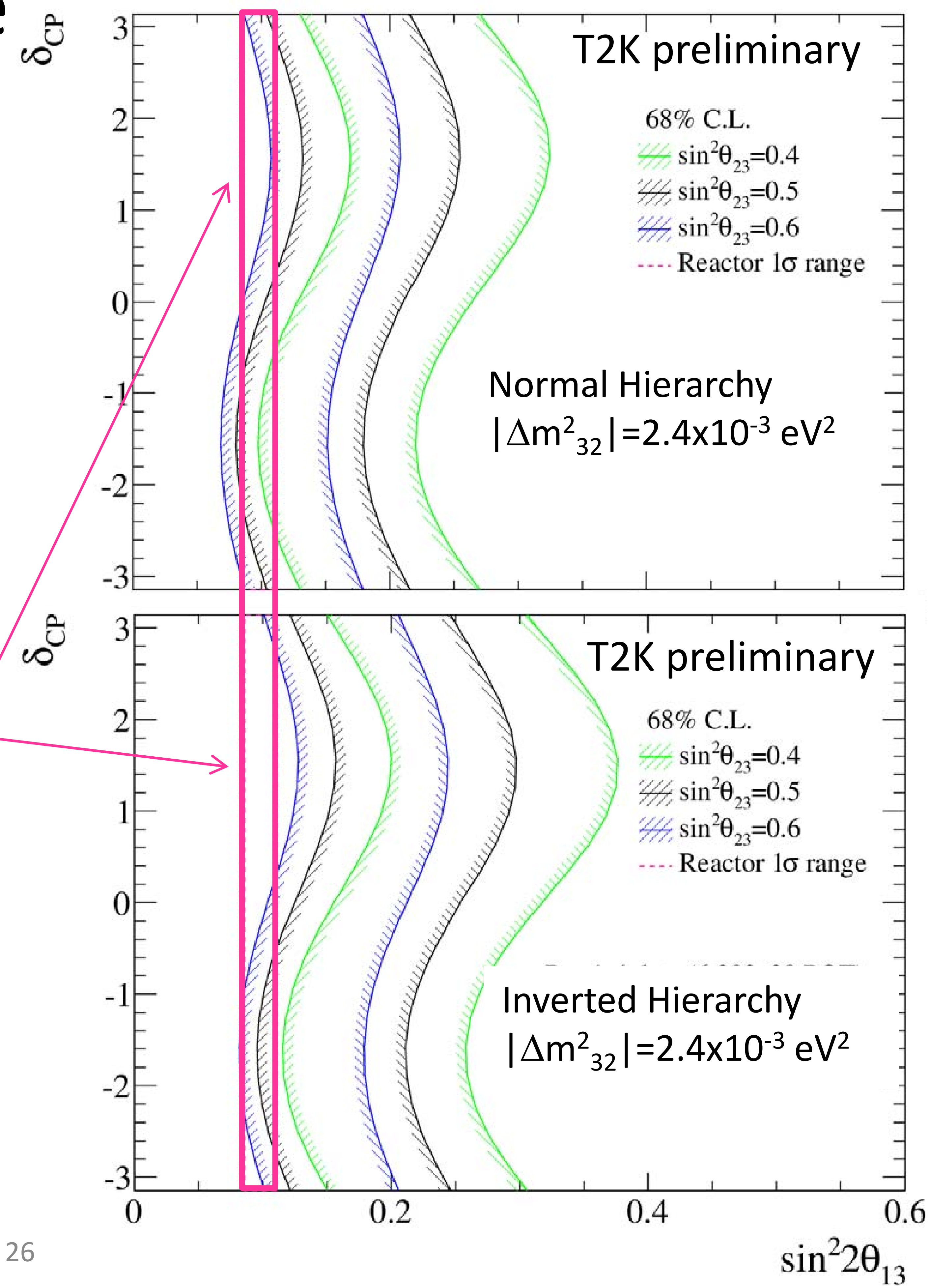
anarchy prefers maximal CP phase



T2K ν_e appearance δ_{CP} vs. $\sin^2 2\theta_{13}$ for different θ_{23}

NOTE: PDG'12 3σ region for $\sin^2\theta_{23}$:0.34-0.64

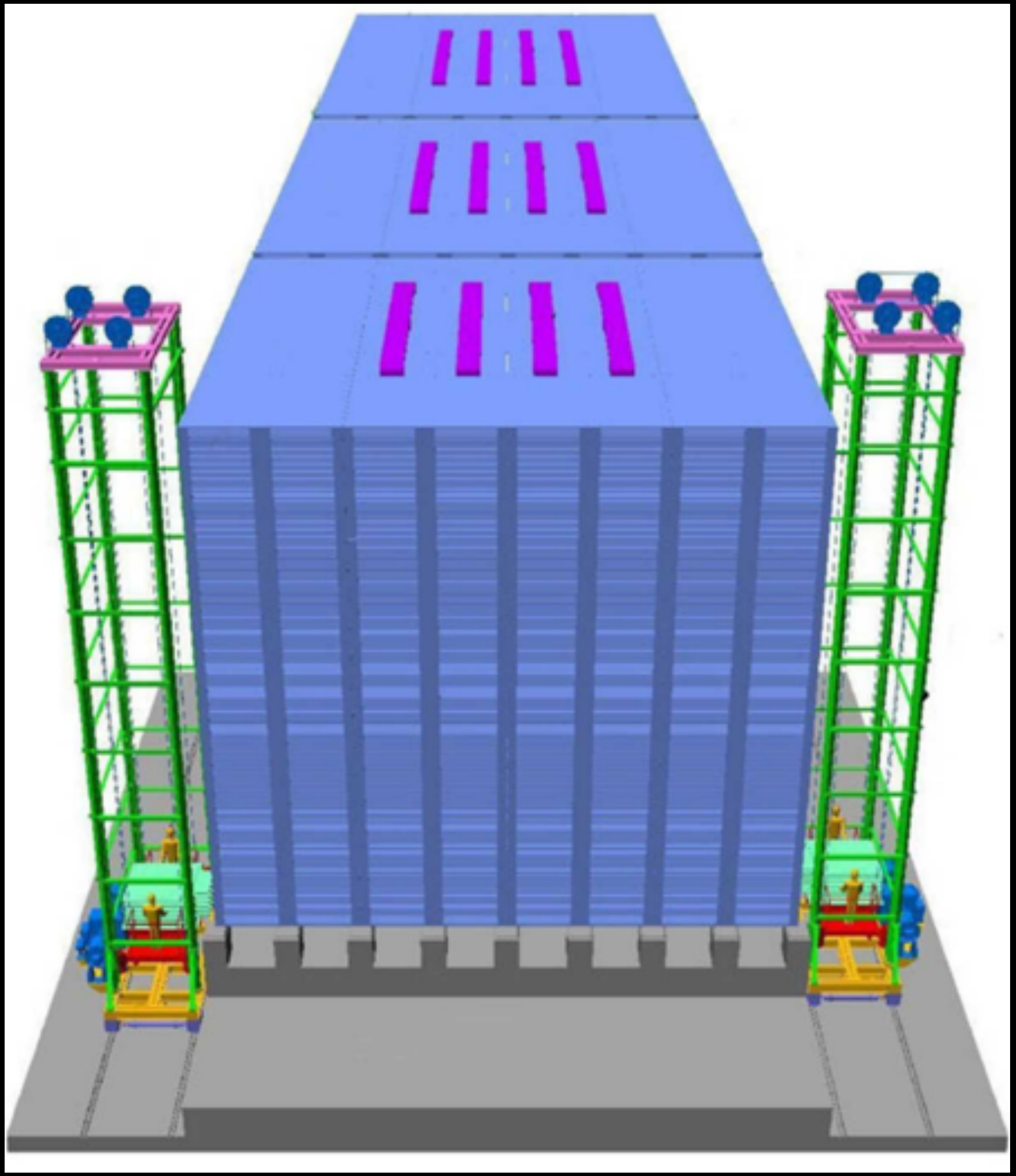
reactor 1σ region (PDG '12)
$\sin^2 2\theta_{13} = 0.098 \pm 0.013$



Ichikawa@EPS2013

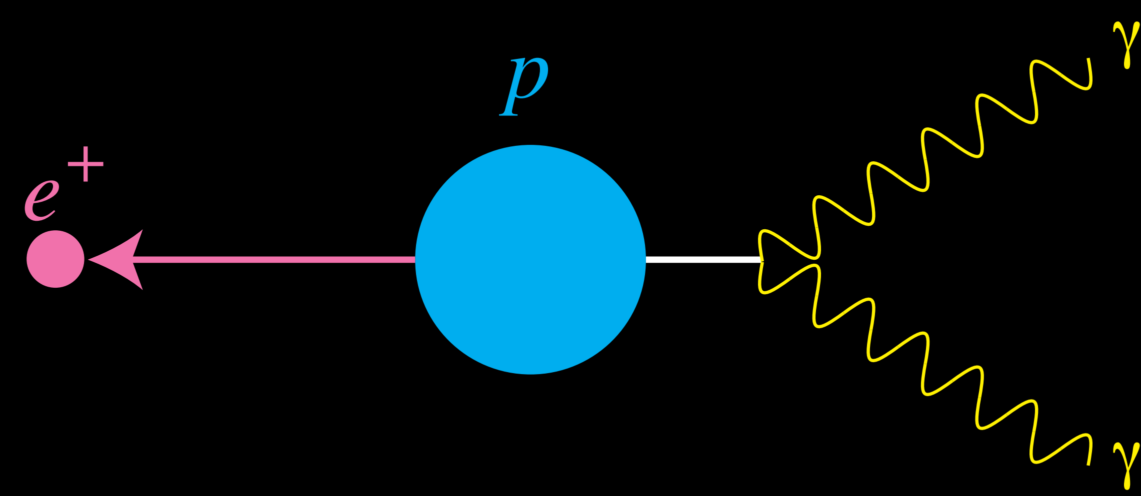
a provocative question

- Mass hierarchy may be determined well by
    - atmospheric neutrinos at HyperK, INO, PINGU
    - longer distance reactor neutrinos
- Do we really need long-baseline on-axis?



INO

Proton Decay



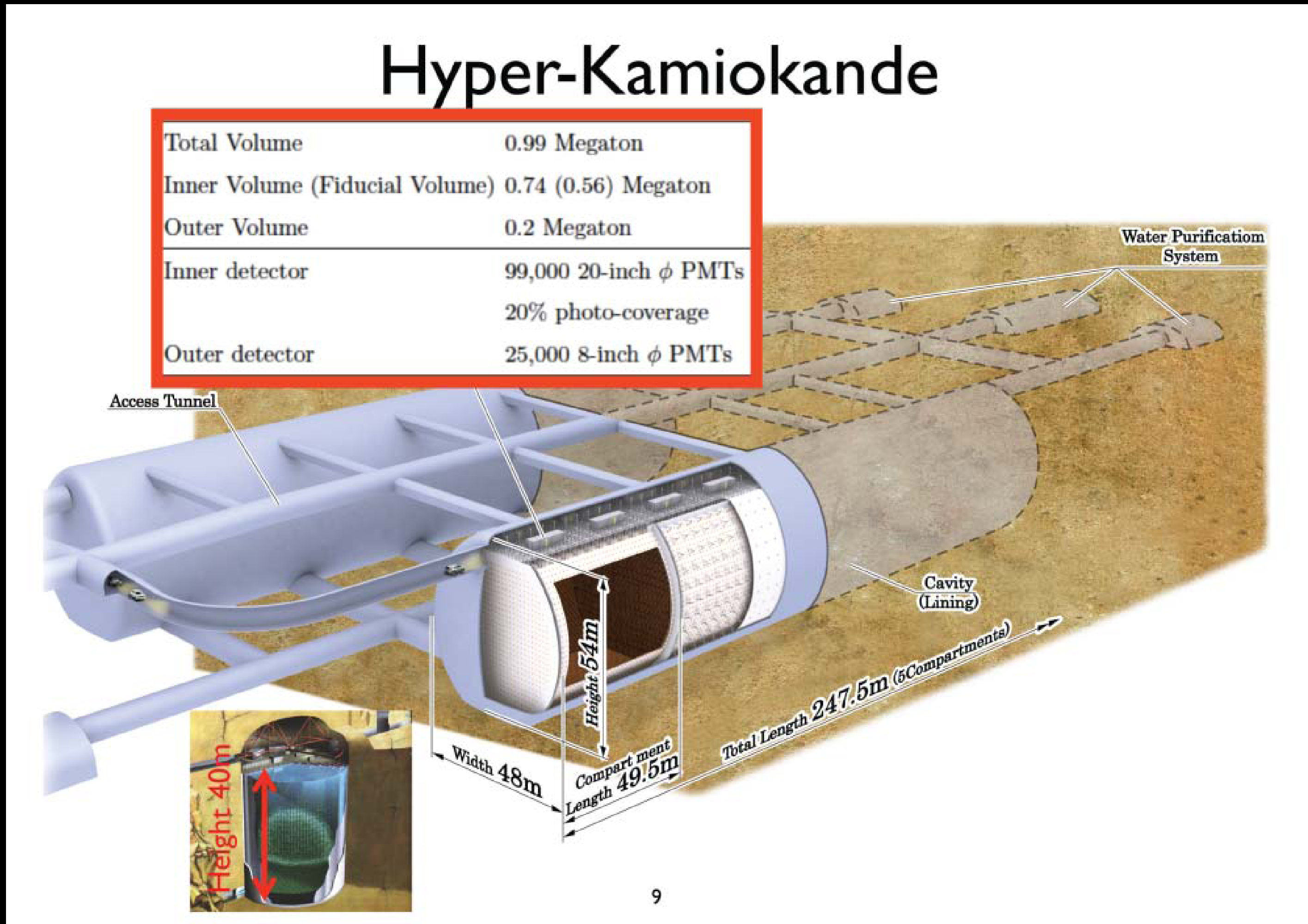
- If matter and anti-matter transform to each other, maybe $p \to e^{+}$+light

p: hydrogen (matter)

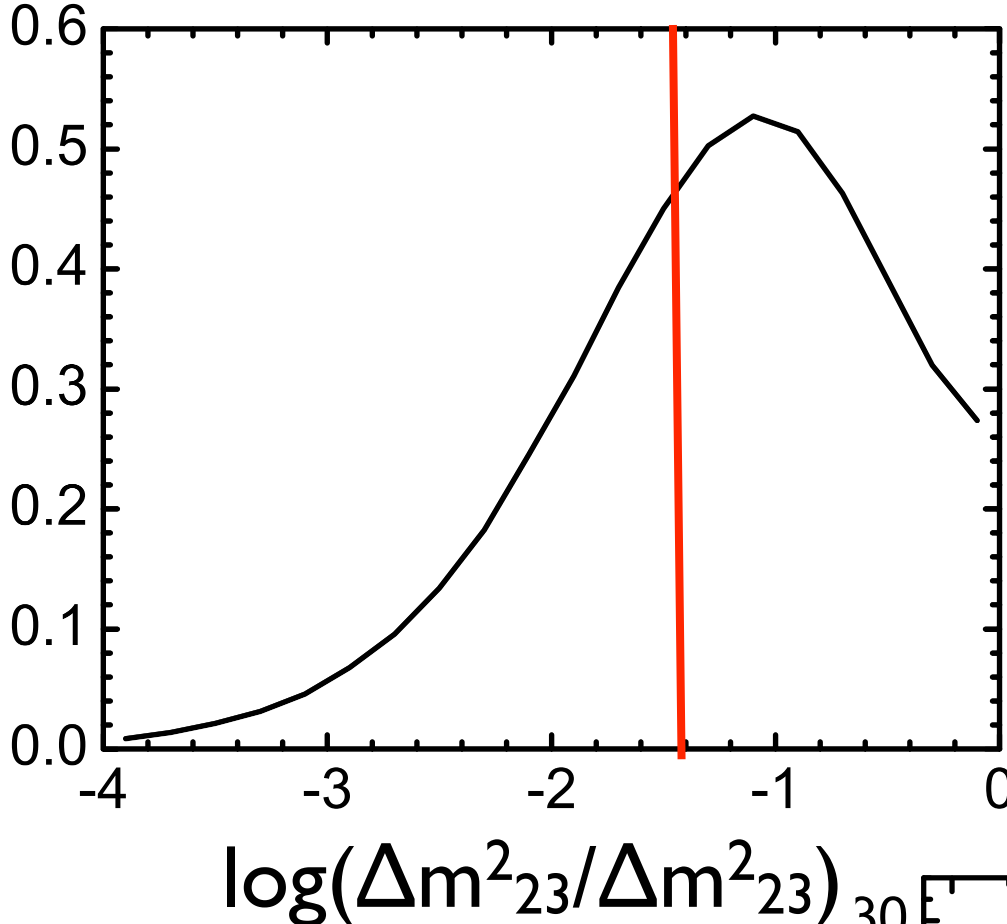
e^{+}: anti-electron (anti-matter)

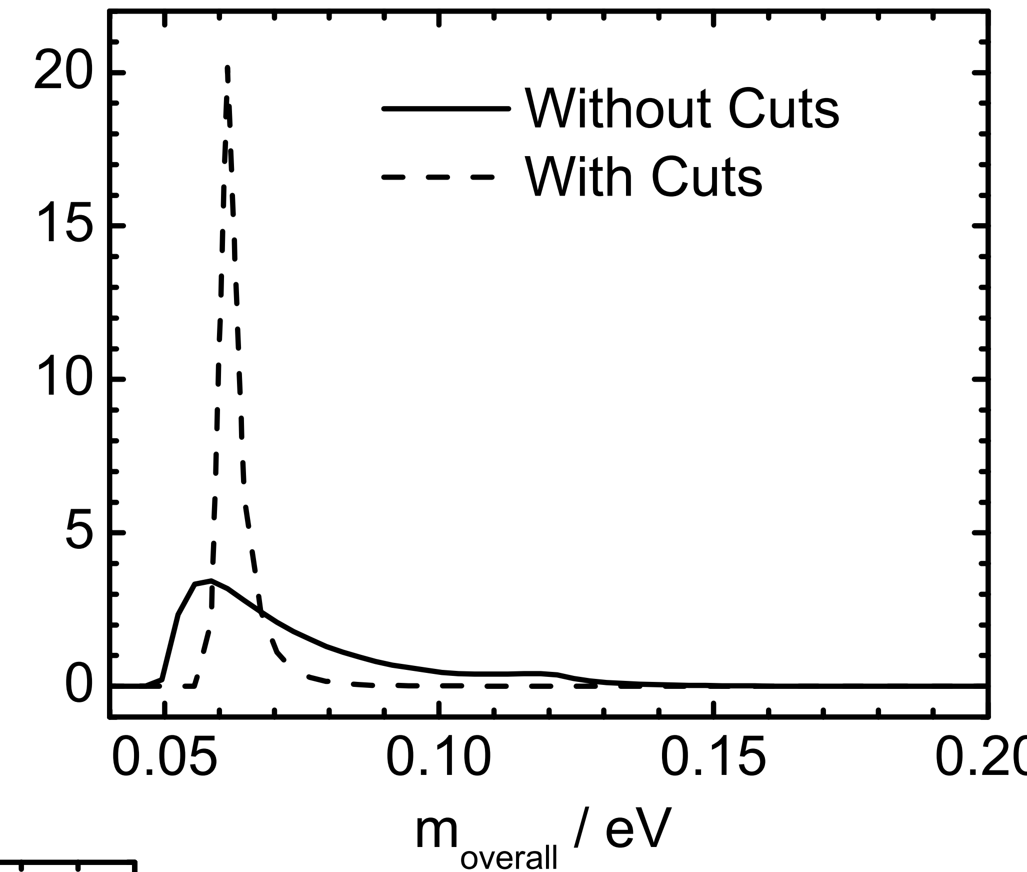
- Happens less than once every 10^{34} years
- May happen more than once a year if you have 10^{36} hydrogen atoms

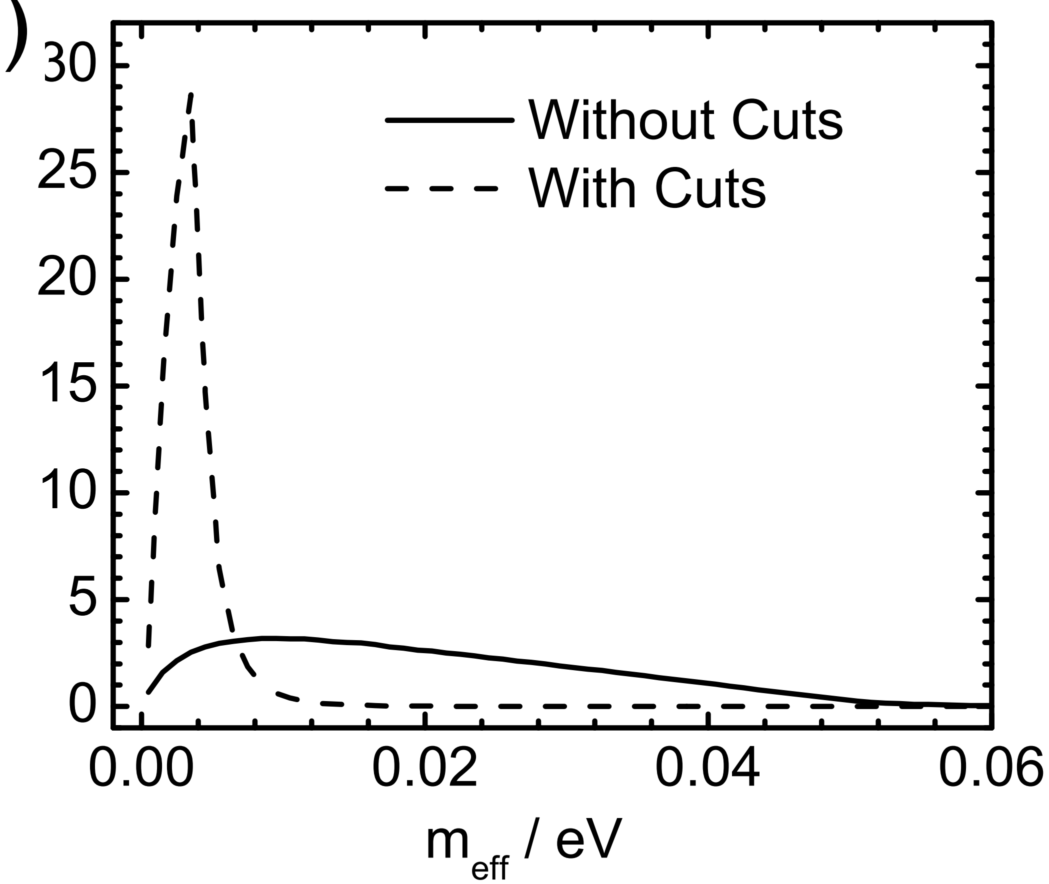
  ≈a million ton of water
- *Huge underground expt!*



masses


log(Δm²₂₃/Δm²₂₃)


Without Cuts
With Cuts
m_overall / eV


Without Cuts
With Cuts
m_eff / eV

History of the Universe