IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

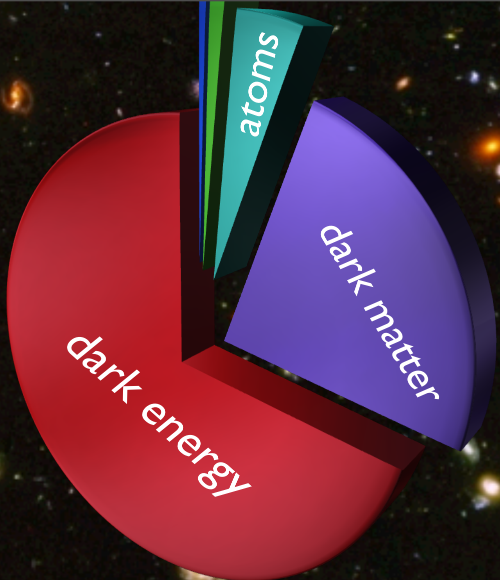
Baryogenesis I

Hitoshi Murayama
UC Berkeley, LBNL, and IPMU Tokyo

CERN Academic Training Lectures
May 25, 2010

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB



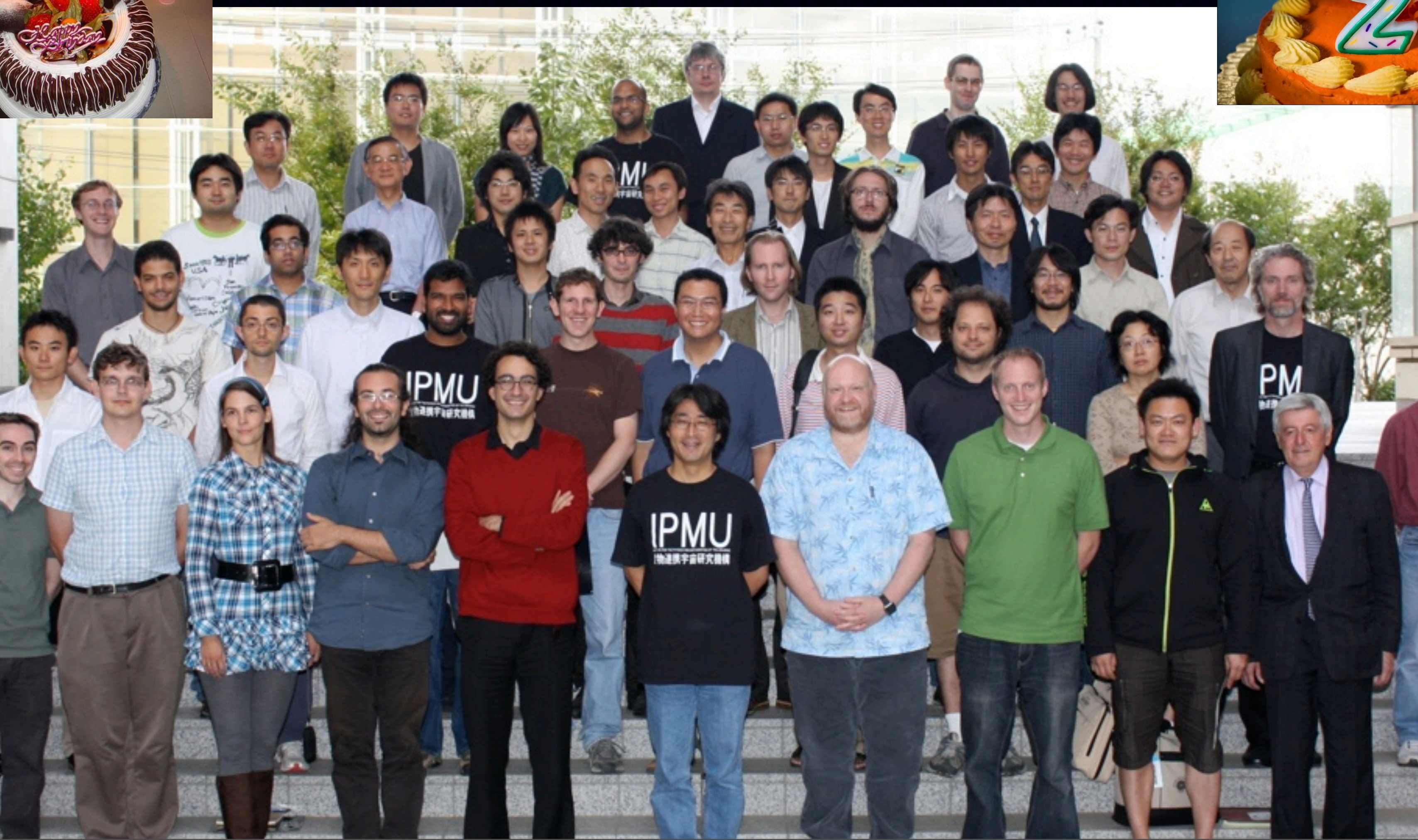
How did the Universe begin?
Does it have an end?
What is it made of?
How does it work?
Why do we exist?
Questions since the dawn of humankind now with science!

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

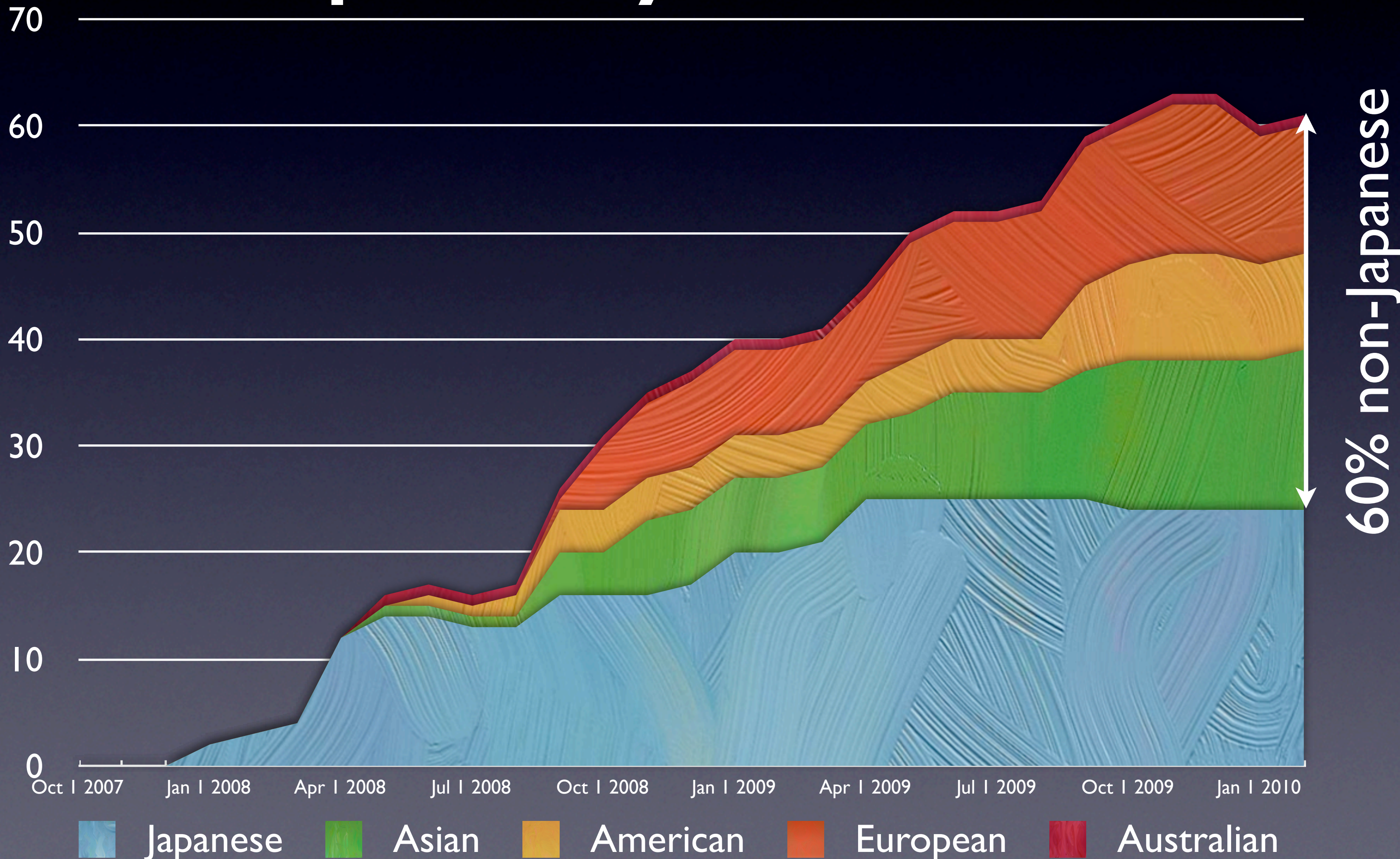
- New intl research institute in Japan
  - astrophysics
  - particle theory
  - particle expt
  - mathematics
- official language: English
- >30% non-Japanese
- ~$14M/yr for 10 years
- launched Oct 1, 2007

- ~80 now
- excellent new faculty, young and dynamic!
- will hire about 10~15 postdocs each year, some more faculty
- support visitors!
- new building
- intl guest house
- workshops about once every other month

Second Birthday



Full-time scientists paid by IPMU



Career Path

IPMU postdocs and students so far went to

Yasuhiro Shimizu: Assist. Prof. @ Tohoku
Yuji Sano: Assist. Prof. @ Kyushu
Damien Easson: Assist. Prof. @ Arizona State
Shuji Harashita: Assist. Prof. @ Kobe
Tathagata Basak: Assist. Prof. @ Iowa State
Yogesh Srivastava: Assist. Prof. @ NISER
Simon Dedeo: Pierre Omidyar Fellow@Santa Fe Institute
Brian Powell: Pentagon
Matthew Buckley: Prize Fellow @ Caltech
Daniel Krefl: postdoc @ Berkeley
Daniel Hernandez: postdoc @ CERN
Rajat Thomas: postdoc @ Toronto
Jan Schümann: Massachusetts General Hospital
Masahito Yamazaki: postdoc @ Princeton
Vikram Rentala: postdoc @ Arizona


occupancy since Jan 18, 2010
~5900 m2


interaction area ~400m²
like a
European town square
Piazza Fujiwara
Obelisk
"L'Universo é scritto in
lingua matematica"

Baryogenesis I

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Baryogenesis

- A question about "Why do we exist?"
- another way to phrase it is "Where did the anti-matter go?"
- big mystery in modern cosmology
- a fascinating subject!
- need to explain a number called "baryon asymmetry of the Universe"
- connections to flavor physics experiments ("intensity frontier")
- possibly also to LHC

too many theories for a single number

Outline

1. Why baryon asymmetry is a problem at all
2. Review of the Sakharov's conditions
3. Why old models based on GUT did not work.
4. Electroweak baryogenesis
5. Leptogenesis
6. Connections to the near-future experiments

1. baryon asymmetry

1. baryon asymmetry

- Introduction
- Observation
- Need for baryon asymmetry
- Anti-matter domain
- Initial condition

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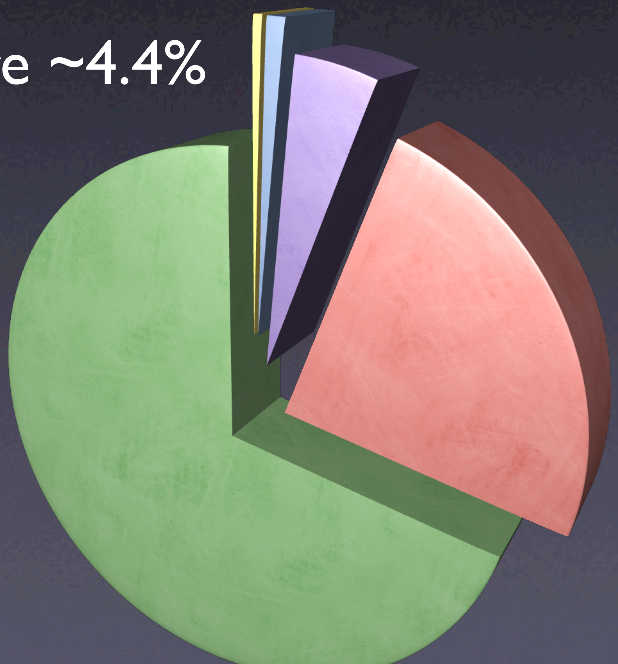
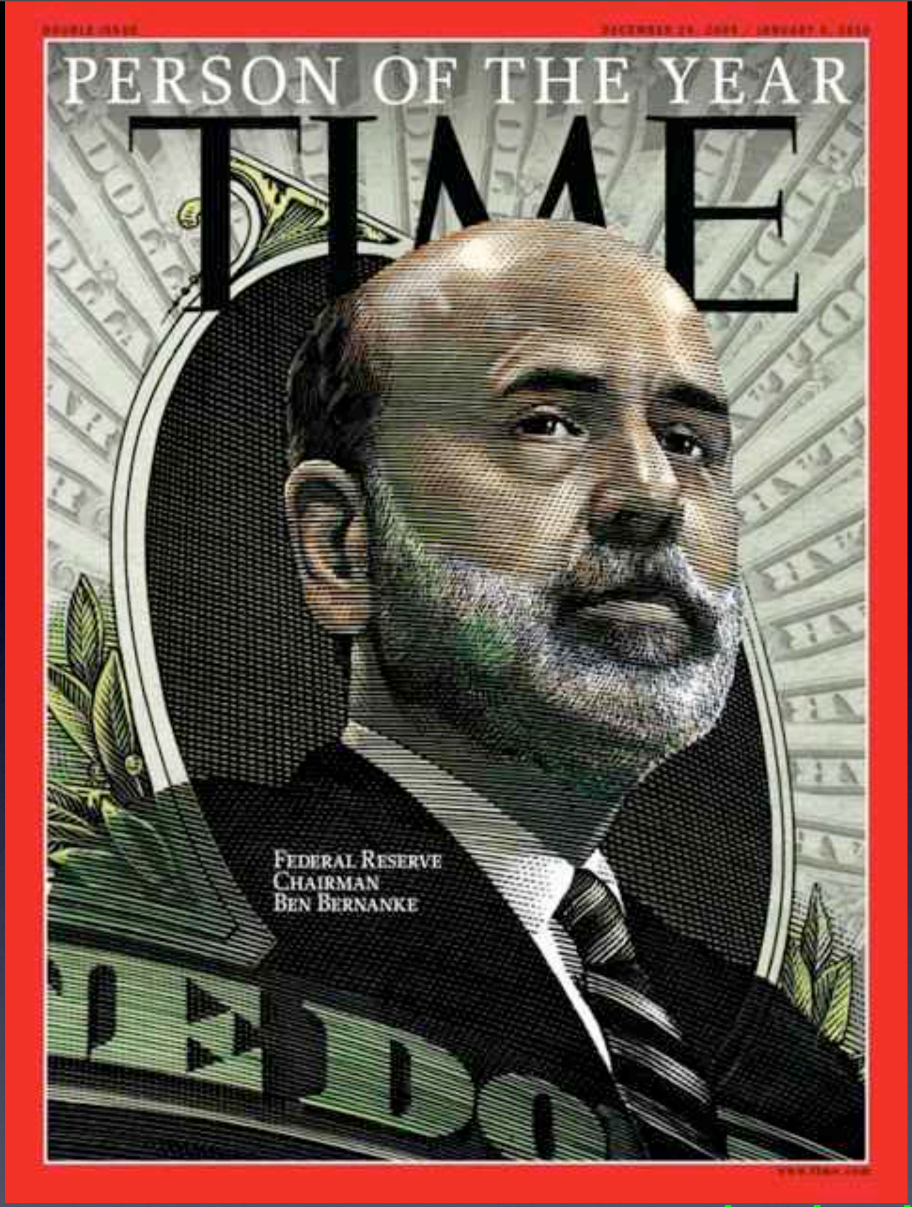
Energy Budget of the Universe

- 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}%??

budget deficit!





The prospective increase in the budget deficit will place risk at future living standards of our country

Five questions beyond the standard model

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

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*."
- I didn't get to explain what I meant....

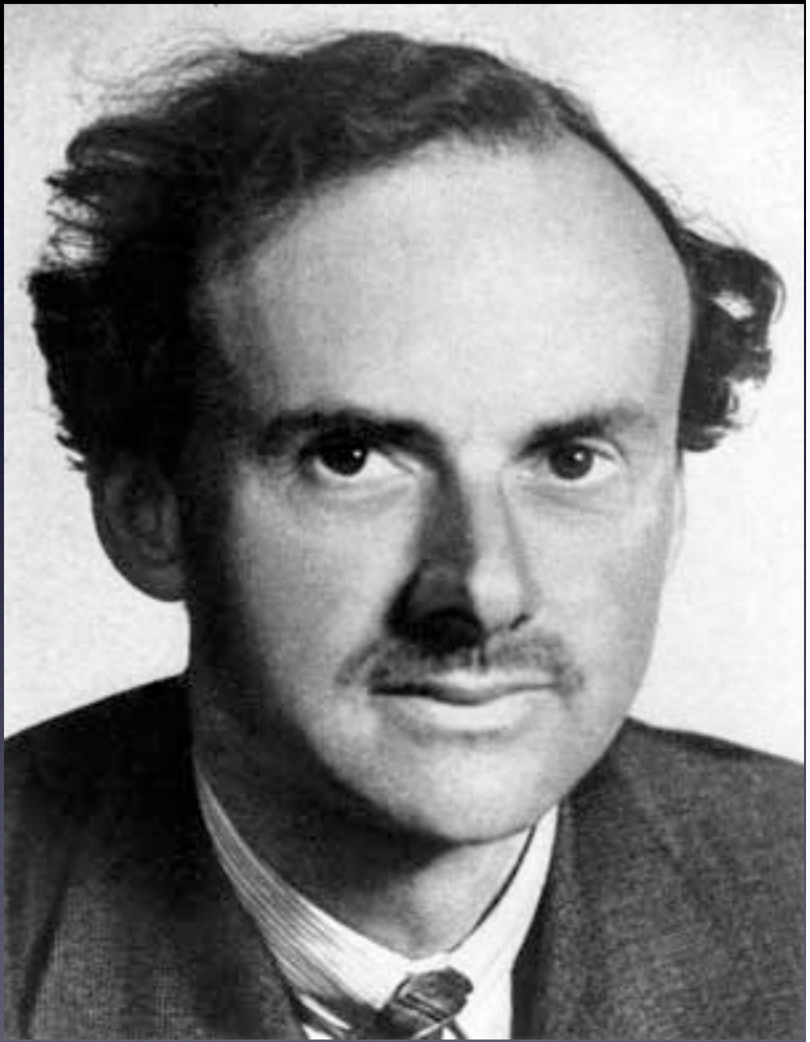
How did we survive?

Anti-matter

Matter

Anti-matter

Discovery



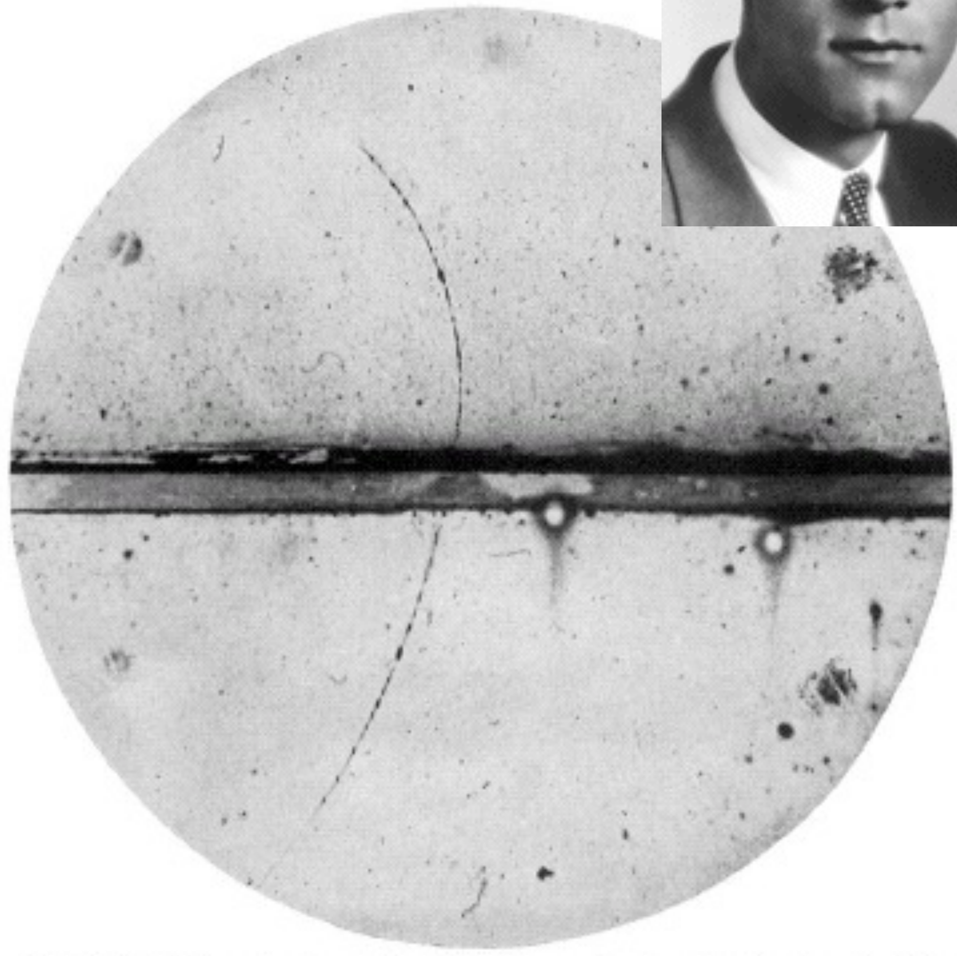


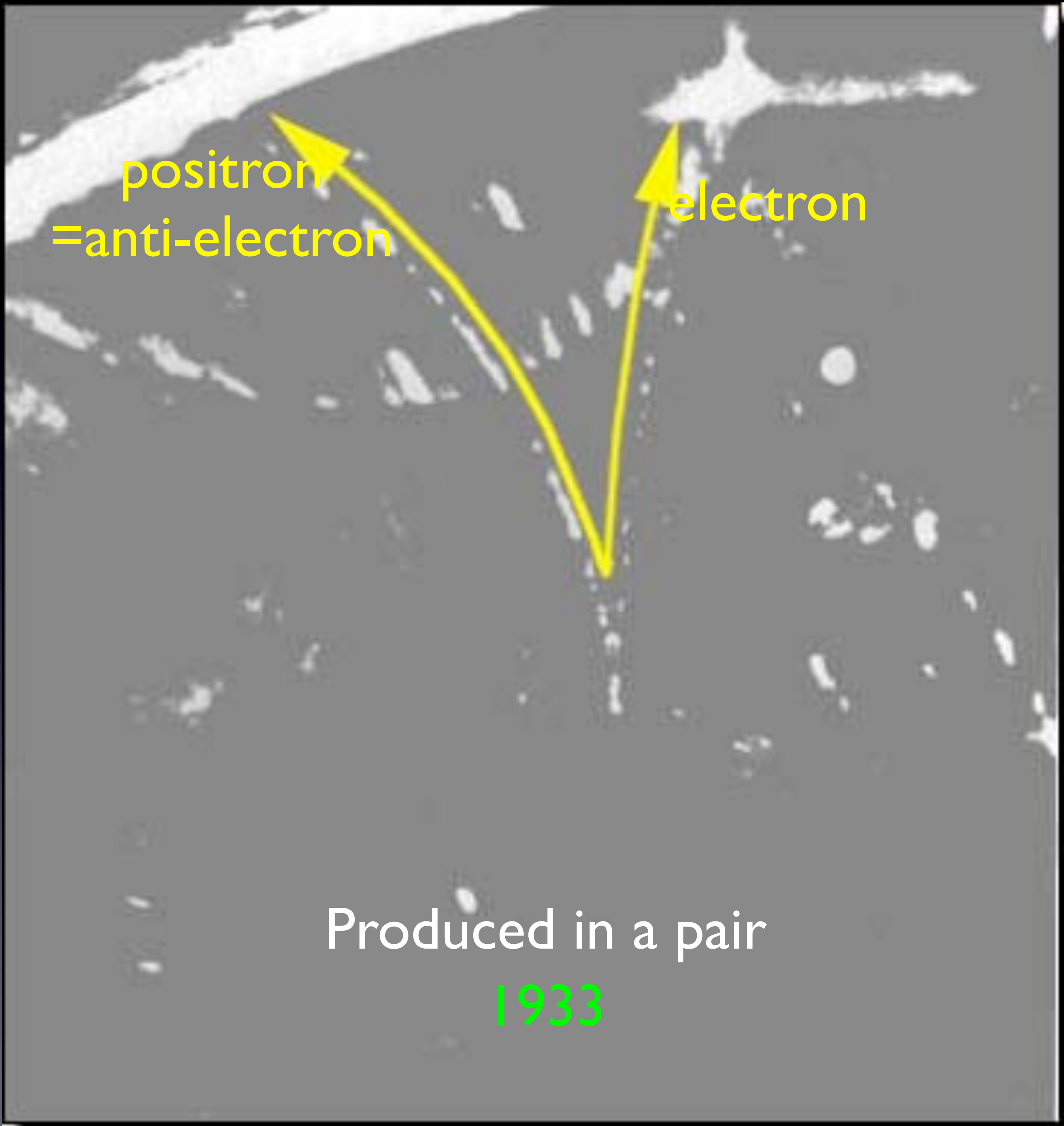
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

1928

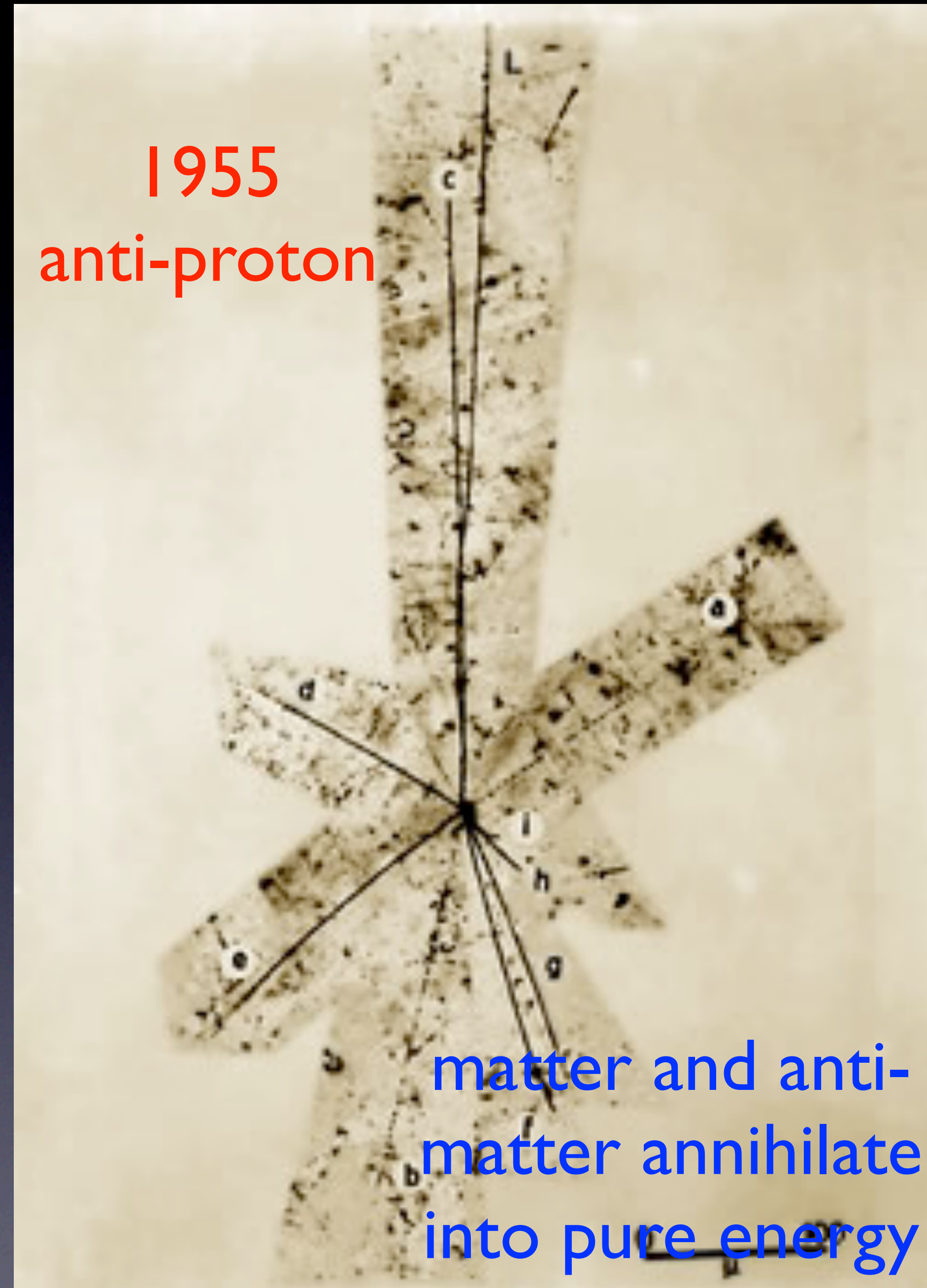
1932

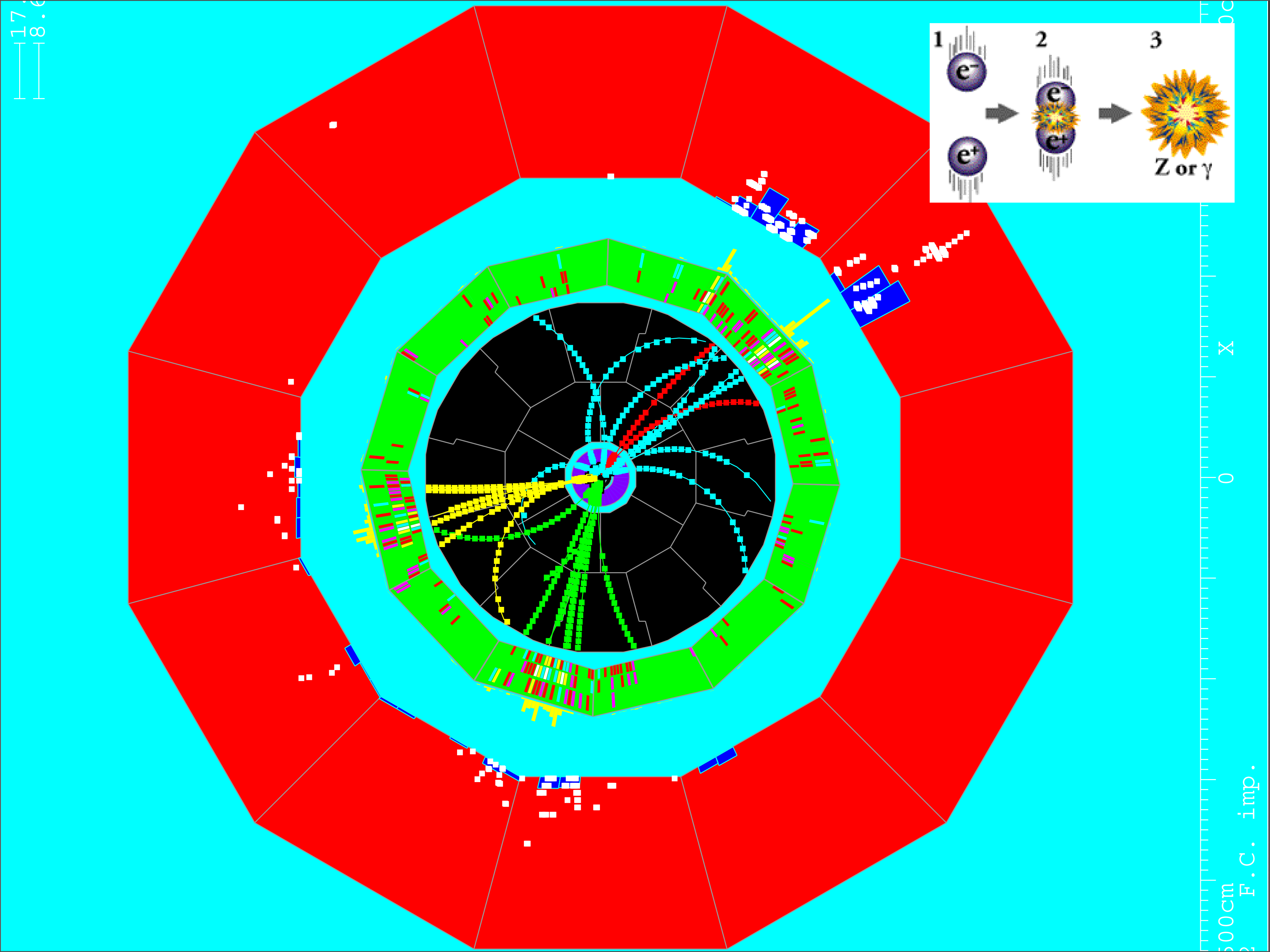
Irène

Frédéric Joliot-Curie

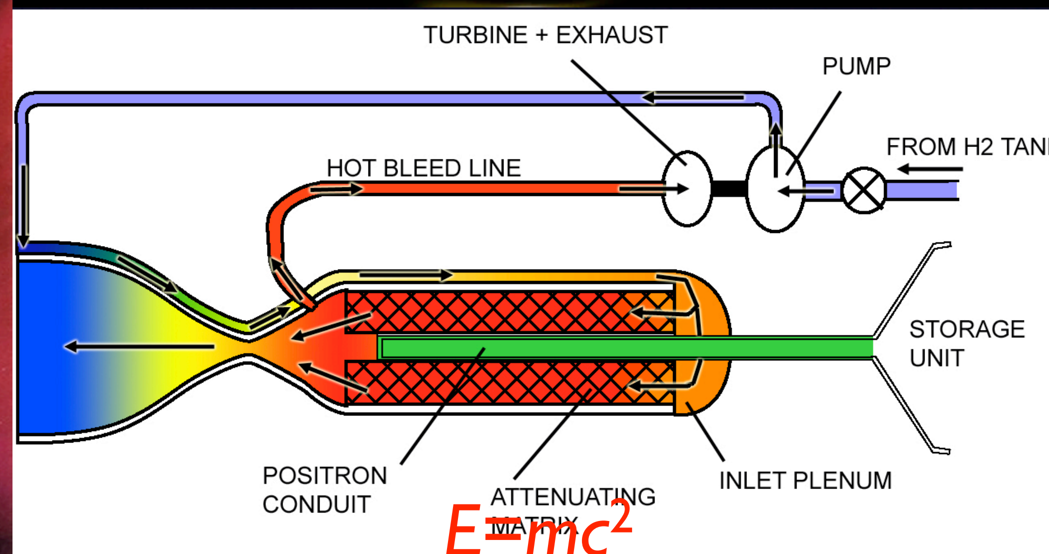



Berkeley
Emilio Segrè
Owen Chamberlain


1955
anti-proton
matter and anti-matter annihilate into pure energy

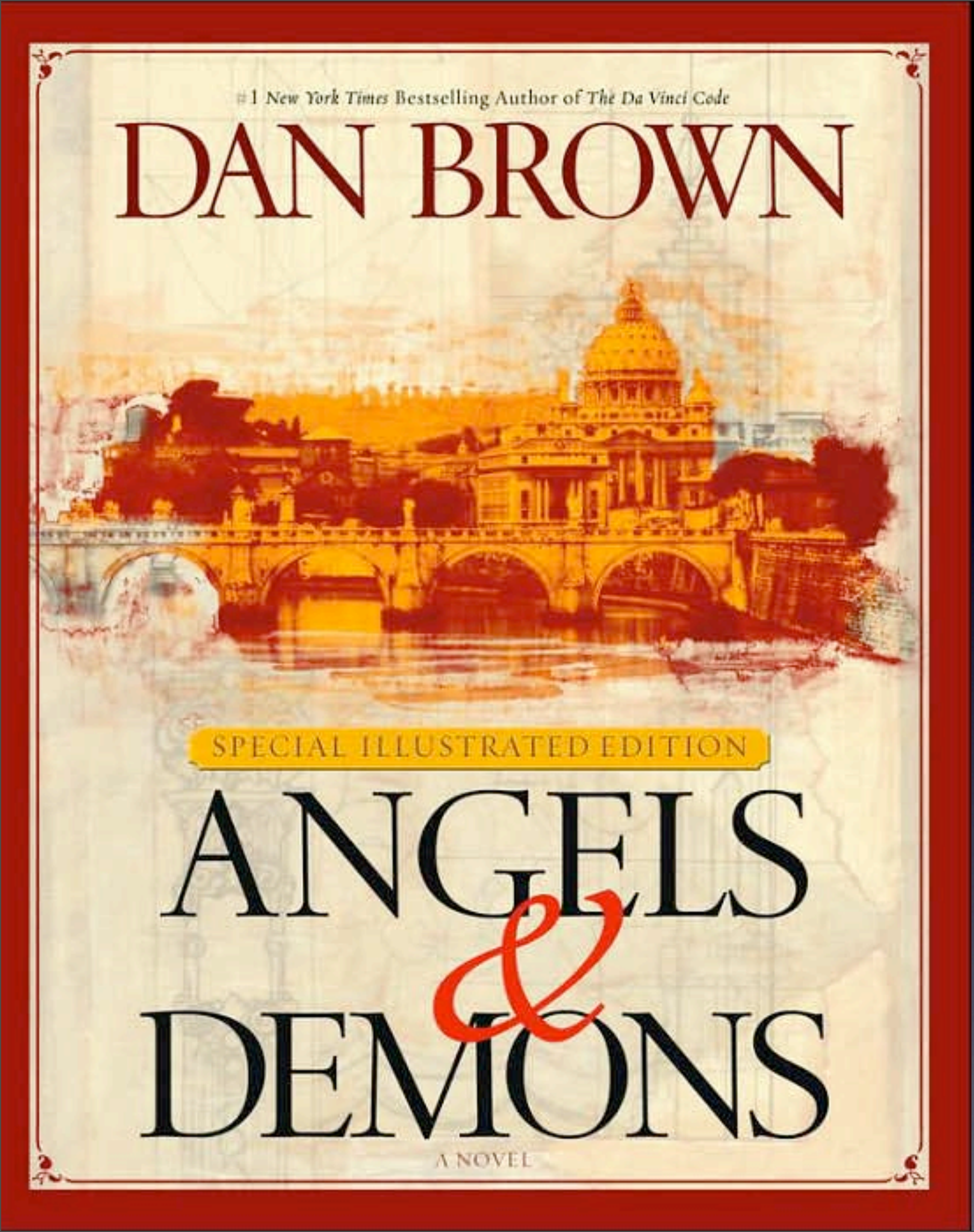


1
2
3
e⁻
e⁺
Z or γ
X
0
F.C. imp.



$E=mc^2$

300 million times more efficient than regular gasoline



- CERN!
- A scientist produced a quarter gram of anti-matter without the knowledge of the Director General
- *falls into wrong hands!*

billion trillion trillion dollars


TOM HANKS
ANGELS & DEMONS
MAY 2009
REGISTER FOR UPDATES
WORLDWIDE RELEASE DATES
BASED ON THE BEST-SELLING NOVEL
BY THE AUTHOR OF
THE DAVINCI CODE


BASED ON THE BEST-SELLING NOVEL
BY THE AUTHOR OF
THE DAVINCI CODE

Anti-matter in the Universe

- Now we can make anti-matter with accelerators
- the ultimate accelerator: Big Bang must have made them
- apparently not around us
- where did they go?

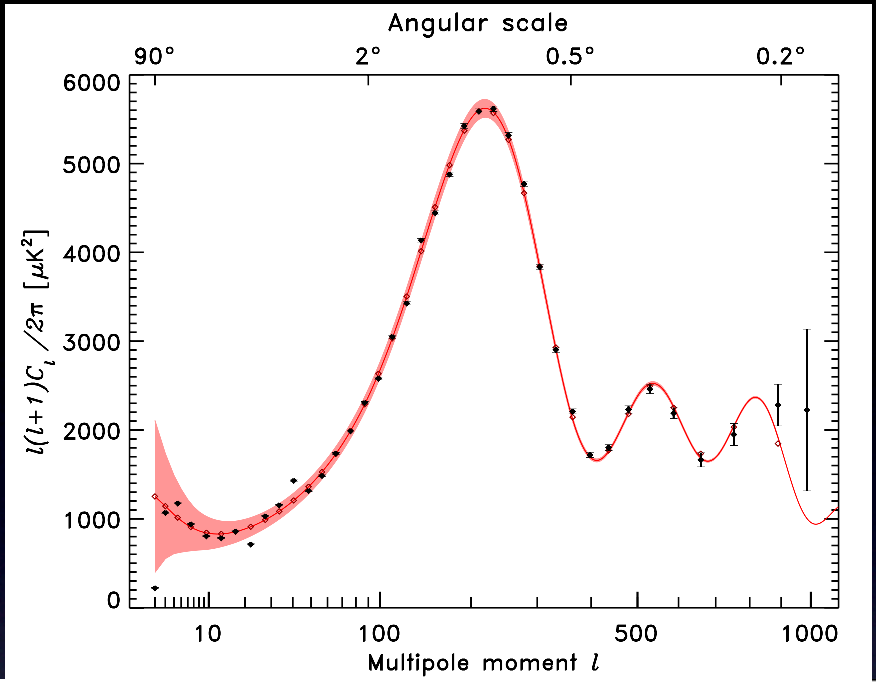
Observation

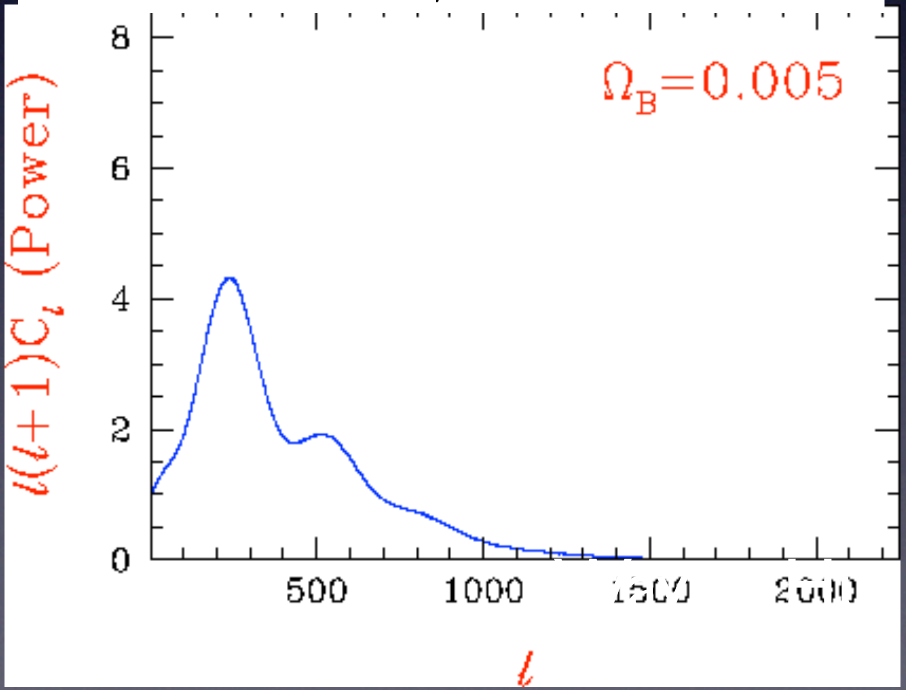
WMAP

- 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

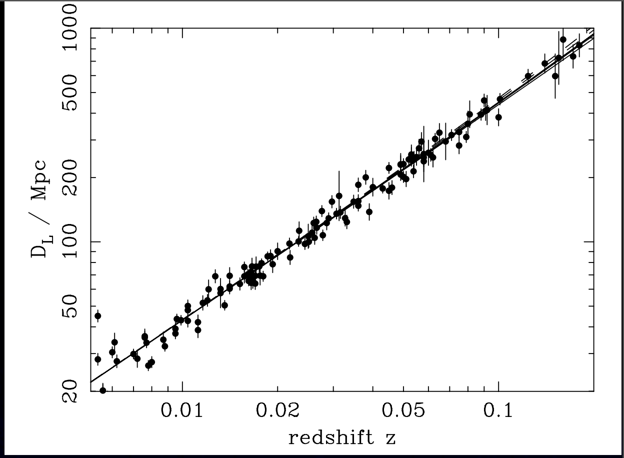
$\Omega_b h^2$=0.02258±0.00057

Ω_b=0.0449±0.0028





notations



- Hubble "constant" is the expansion rate of the Universe

$$H_0 = \frac{\dot{a}}{a} = 100h\mathrm{km/s/Mpc}$$

$$h = 0.710 \pm 0.025(\mathrm{WMAP7})$$

- critical density is related to H_0 by Einstein's equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G_N\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\rho_c = \frac{3}{8\pi G_N}H_0^2 = 1.05\times 10^{-5}h^2\mathrm{GeV/cm}^3$$

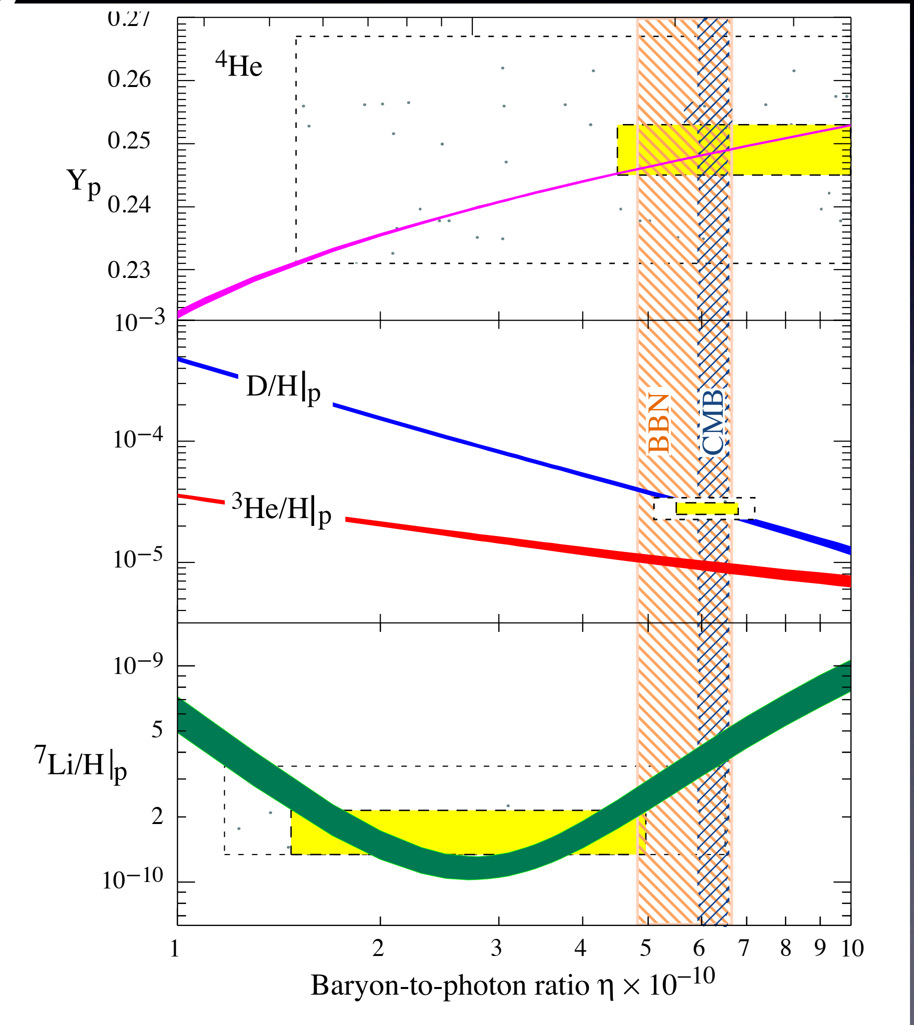
- Omega is the ratio to the critical density

$$\Omega_i = \frac{\rho_i}{\rho_c}$$

$$\Omega_i h^2 = \frac{\rho_i}{1.05\times 10^{-5}\mathrm{GeV/cm}^3}$$

Big Bang Nucleosynthesis

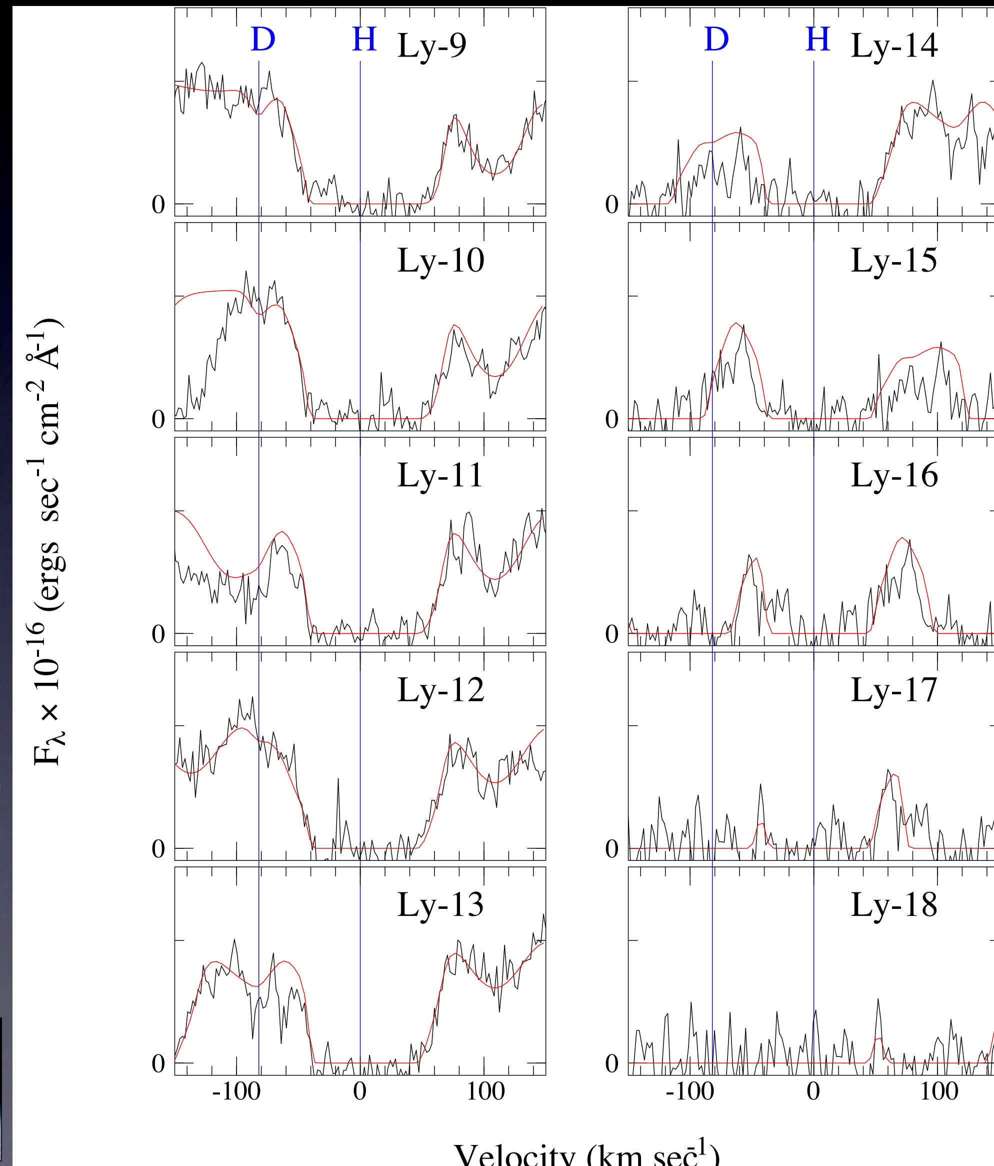
- At T>MeV, the soup of e^+, e^-, ν, $\bar{\nu}$
- small amount of p, n
- they start to fuse, forming light elements
- abundance of light elements depends on amount of baryon



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



end result

- WMAP7 (*T*~3000K)

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

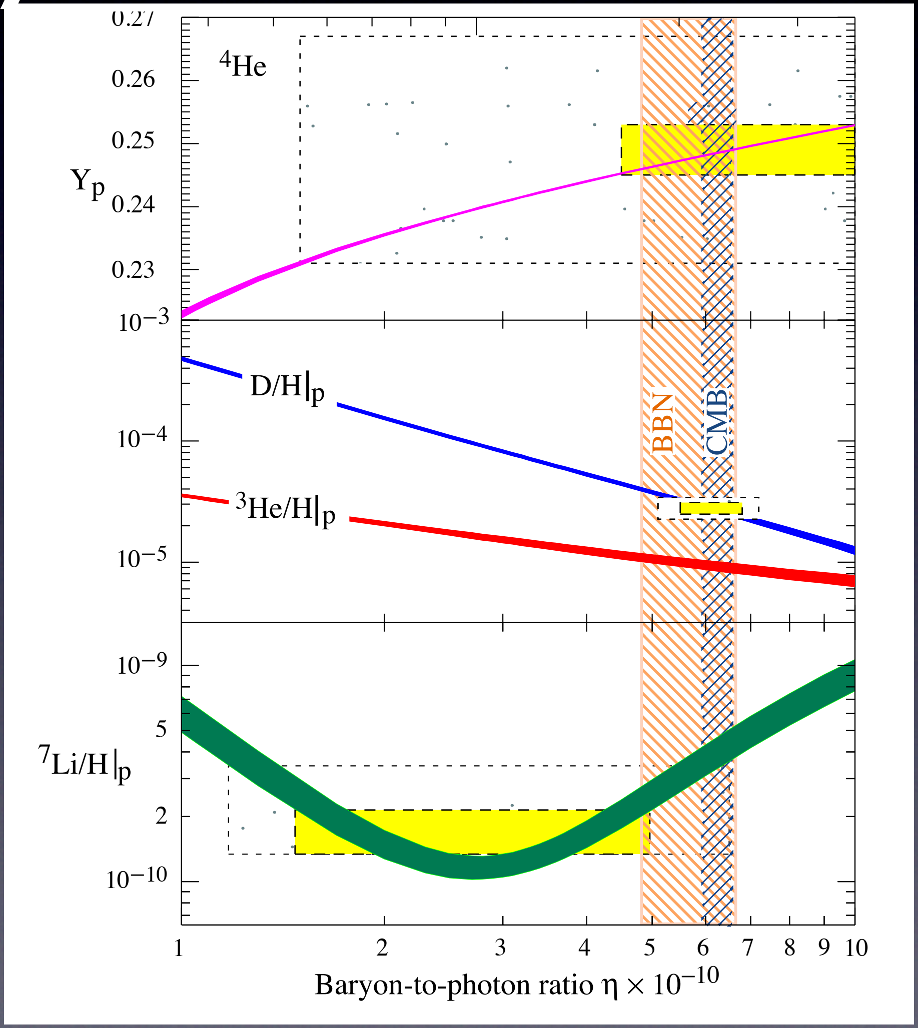
- BBN based on D/H (Kirkman 2003) (*T*~0.1–1 MeV)

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

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

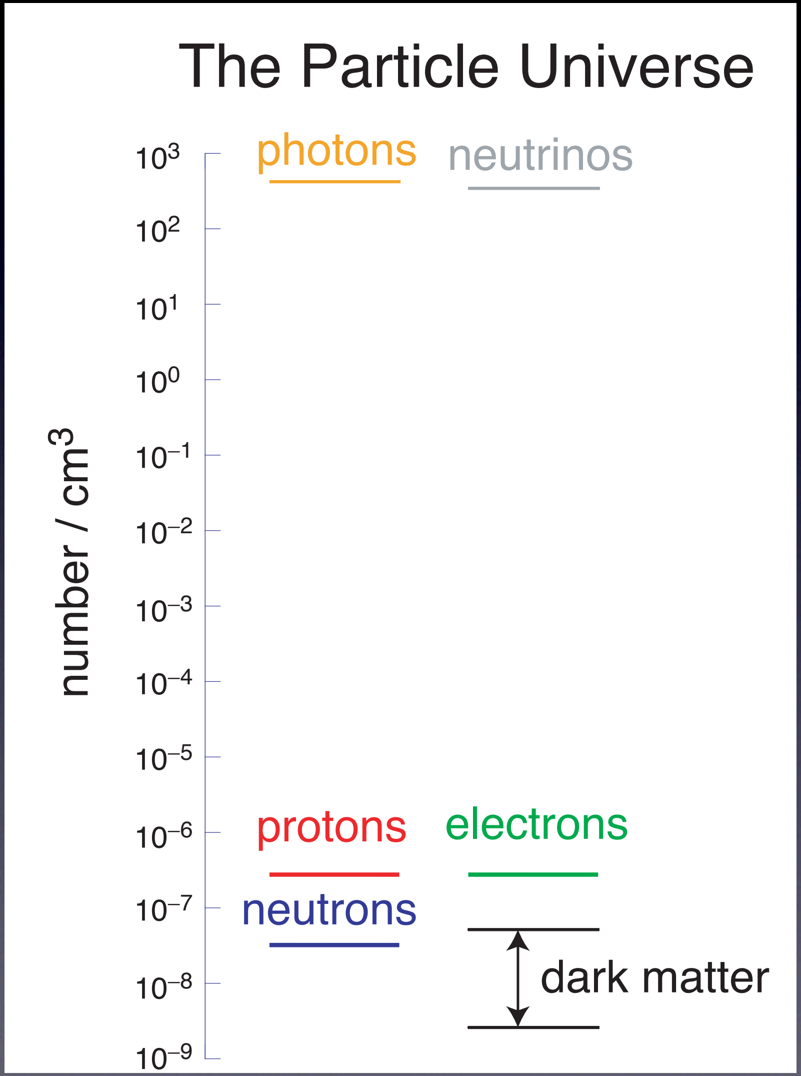
Big Bang Nucleosynthesis

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



Particle Universe

- The best information we have on the number of particles in the universe (assumes 0.1–1 TeV WIMP)



more convenient quantity

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

- in late universe, both n_b and n_γ dilute as a^{-3}
- however n_γ has been "heated up" earlier on by e^+e^- annihilation, QCD phase transition, etc
- "yield" n_b/s has been conserved unless injection of heat (entropy) or baryon number violation

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

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

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

Need for baryon asymmetry

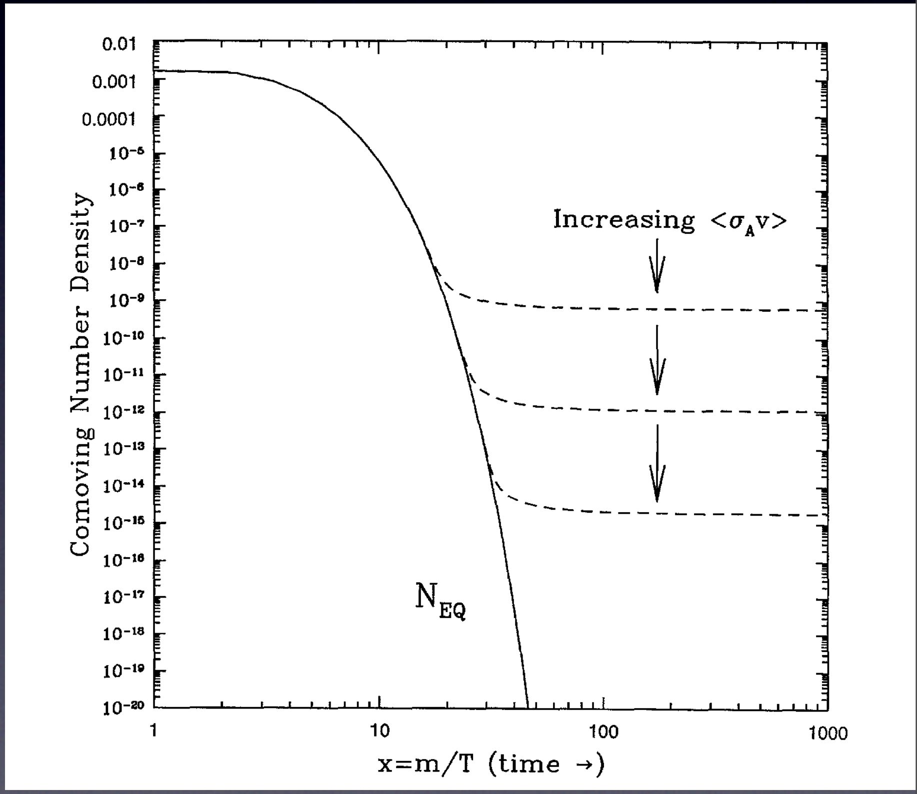
Baryo-symmetric Universe

- At high temperatures T>100MeV, Universe was a soup of quarks and gluons
- with the confinement transition, quarks and anti-quarks end up in mesons and baryons
- mesons decay, baryons and anti-baryons annihilate
- end up with a plasma of e^+, e^-, ν, $\bar{\nu}$, γ, and a very small density of p, $\bar{p}$, n, $\bar{n}$

$$\Omega_b \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2} \approx 10^{-12}$$

thermal relic

- Once $T<m_p$, no more p created
- if stable, only way to lose them is annihilation
- but universe expands and p get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate
- Yield Y=n/s constant under expansion
- stronger annihilation ⇒ less abundance

$$H \approx g_*^{1/2} \frac{T^2}{M_{Pl}}$$

$$\Gamma_{\rm ann} \approx \langle \sigma_{\rm ann} v \rangle n$$

$$H(T_f) = \Gamma_{\rm ann}$$

$$n \approx g_*^{1/2} \frac{T_f^2}{M_{Pl} \langle \sigma_{\rm ann} v \rangle}$$

$$s \approx g_* T^3$$

$$Y = \frac{n}{s} \approx g_*^{-1/2} \frac{1}{M_{Pl} T_f \langle \sigma_{\rm ann} v \rangle}$$

$$\Omega_\chi = \frac{m_\chi Y s_0}{\rho_c}$$

$$\approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

Baryo-symmetric Universe

- At high temperatures T>100MeV, Universe was a soup of quarks and gluons
- with the confinement transition, quarks and anti-quarks end up in mesons and baryons
- mesons decay, baryons and anti-baryons annihilate
- end up with a plasma of e^+, e^-, ν, $\bar{\nu}$, γ, and a very small density of p, $\bar{p}$, n, $\bar{n}$

$$\Omega_b \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2} \approx 10^{-12}$$

Baryo-asymmetric Universe

- At high temperatures T>100MeV, Universe was a soup of quarks and gluons
- with a confinement transitions, quarks and anti-quarks end up in mesons and baryons
- mesons decay, baryons and anti-baryons annihilate, asymmetric component remains
- end up with a plasma of e^+, e^-, ν, $\bar{\nu}$, and a small density of p and n

Early Universe

1,000,000,002	1,000,000,000
matter	*anti-matter*

Current Universe

2

us

matter *anti-matter*

We won! But *why?*

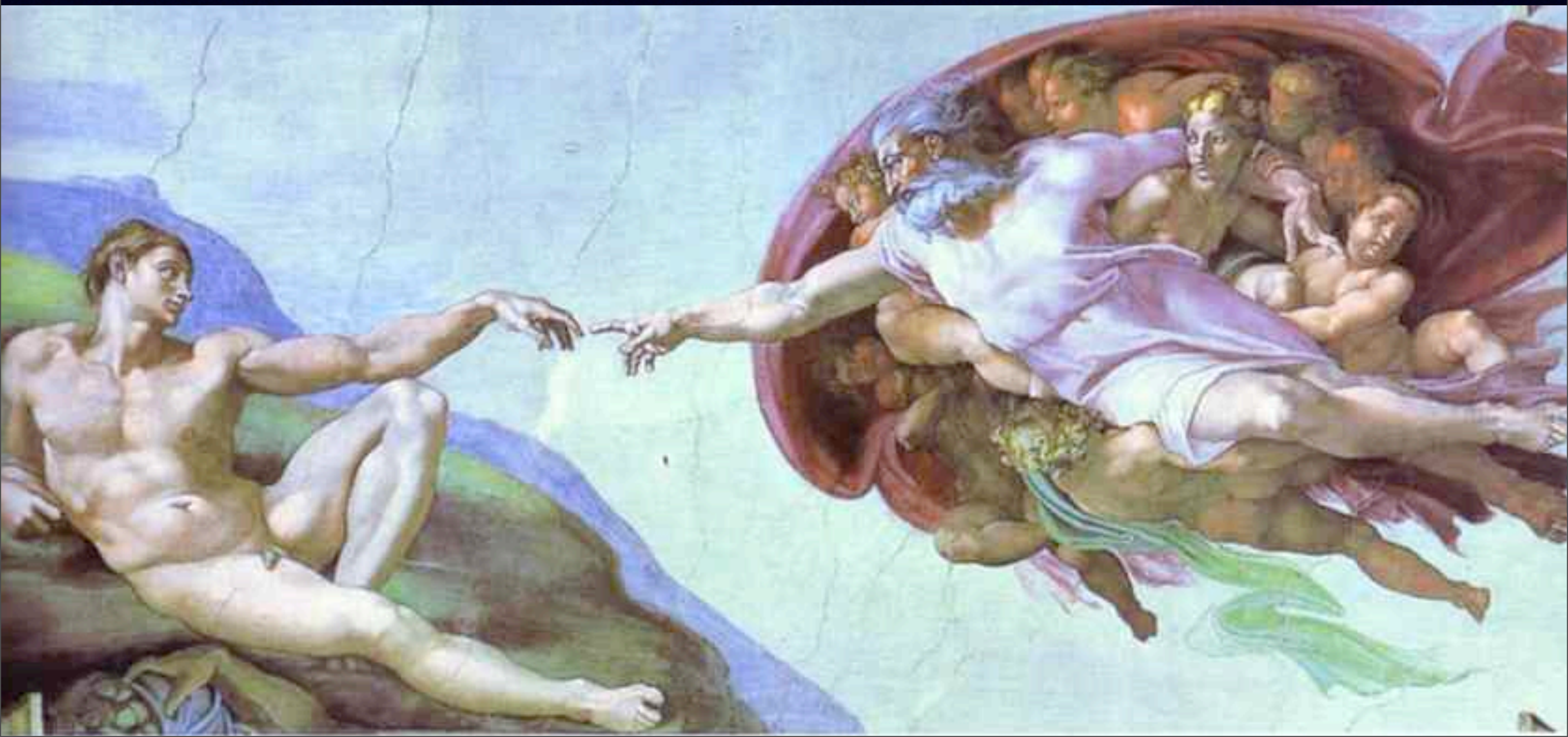
How we survived the Big Bang

- 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?

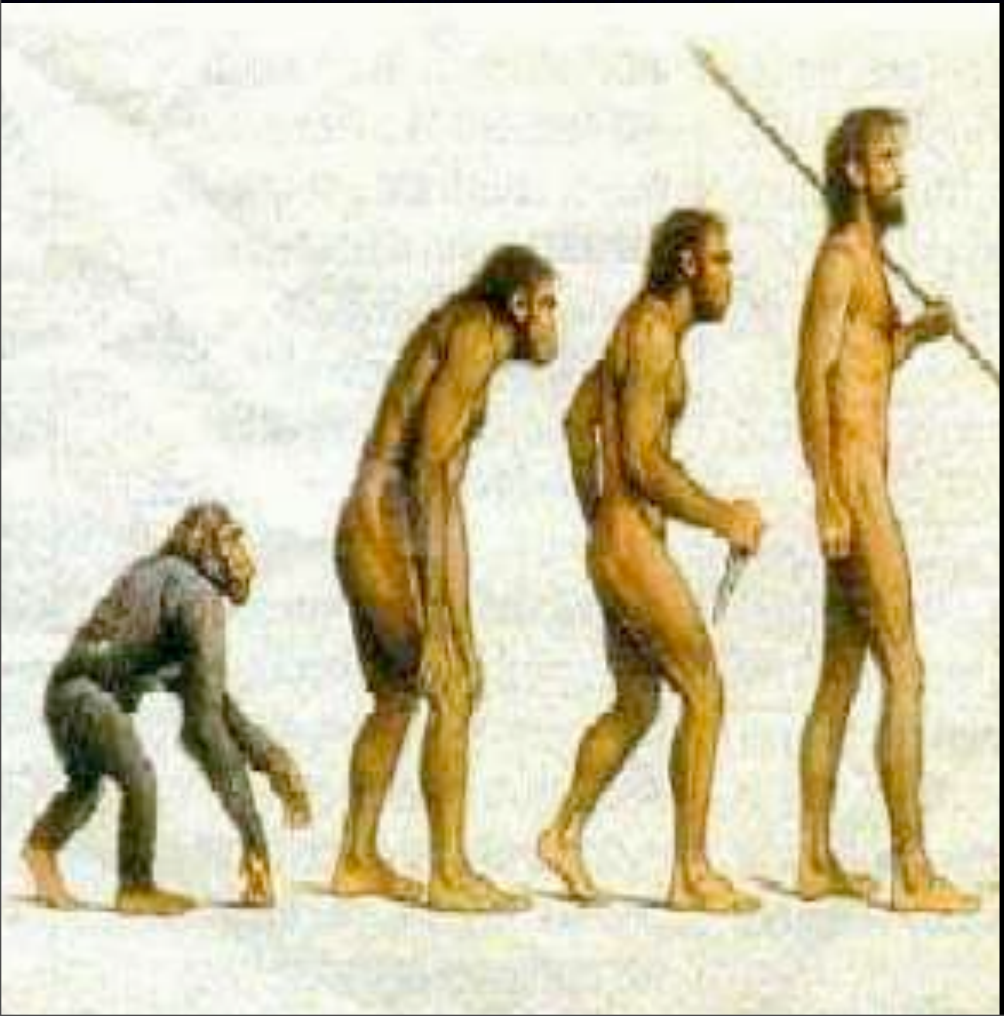
Creation

$n_b(t=0) \neq 0$

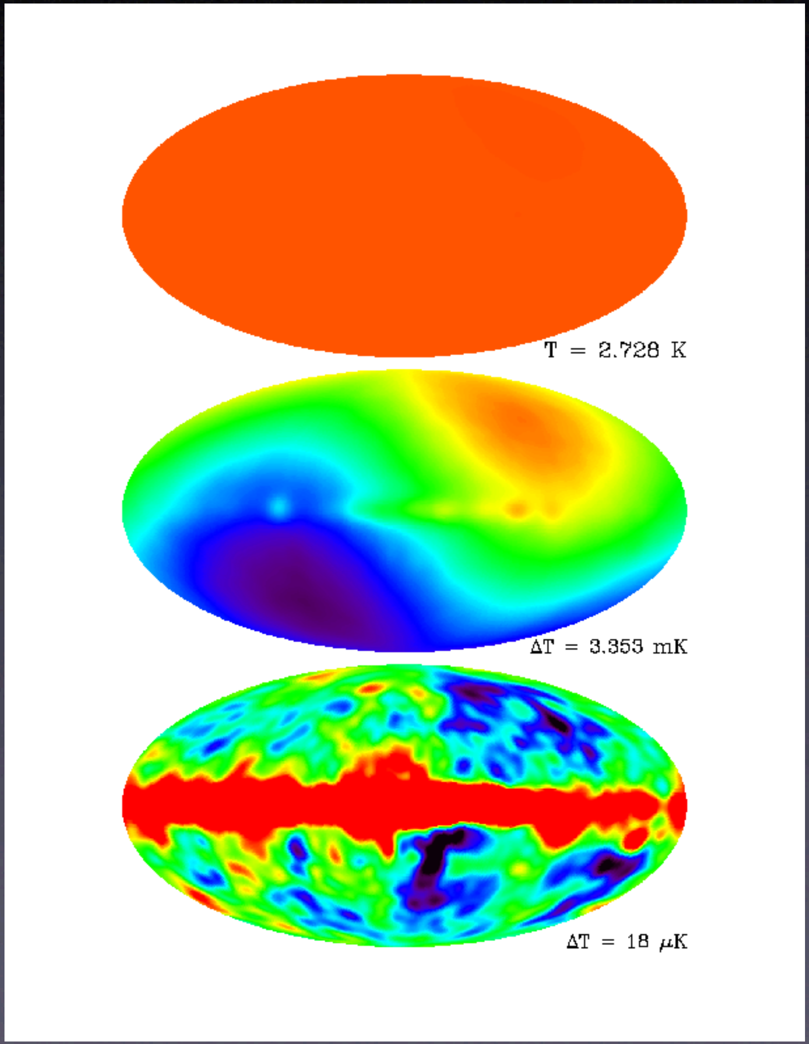


Or Evolution?

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



Why same T_0=2.75K?



- Like having found two remote islands in different parts of the world
- but the locals speak the same language
- even the same *dialect* with 10^{-5} accuracy
- we would suspect they *communicated*, must have come from the same place

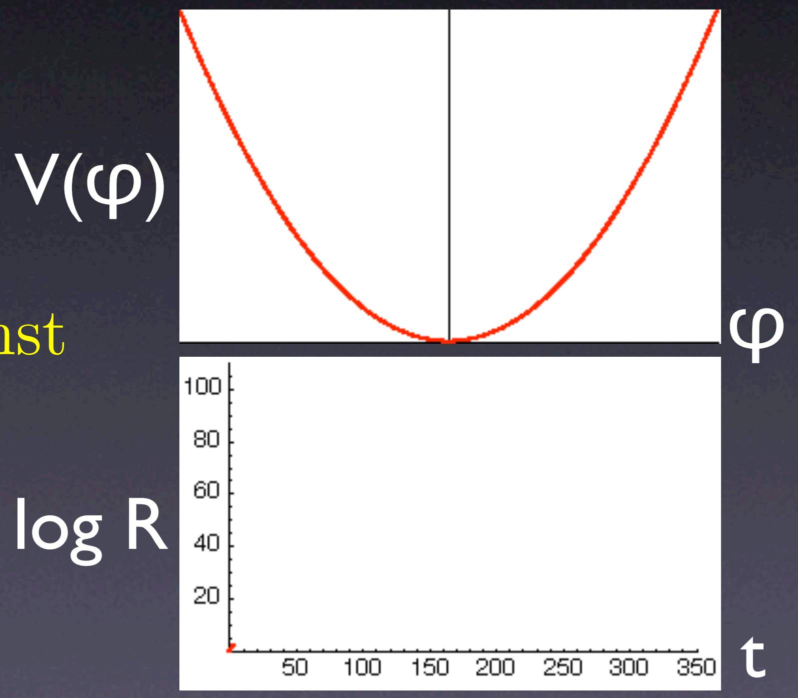
inflaton

- a scalar field displaced from the minimum at the beginning
- rolls down slowly: inflation
- constant potential leads to exponential expansion

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho = \text{const}$$

$$a(t) = a(0) e^{Ht}$$

- quantum fluctuation source of later structure, become *classical* after they go out of the horizon



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

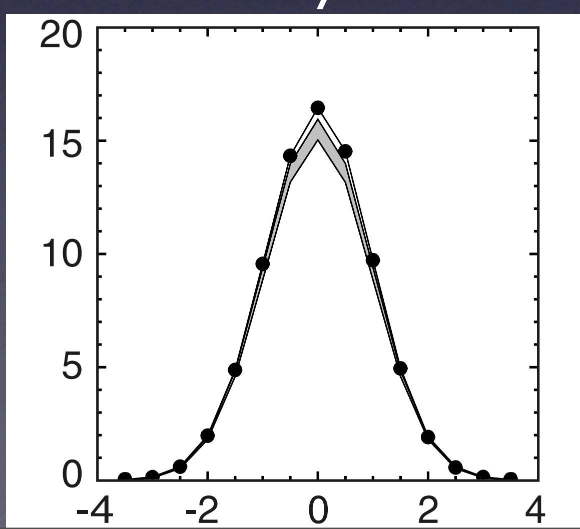
$$\rho_f \propto a^{-4}$$

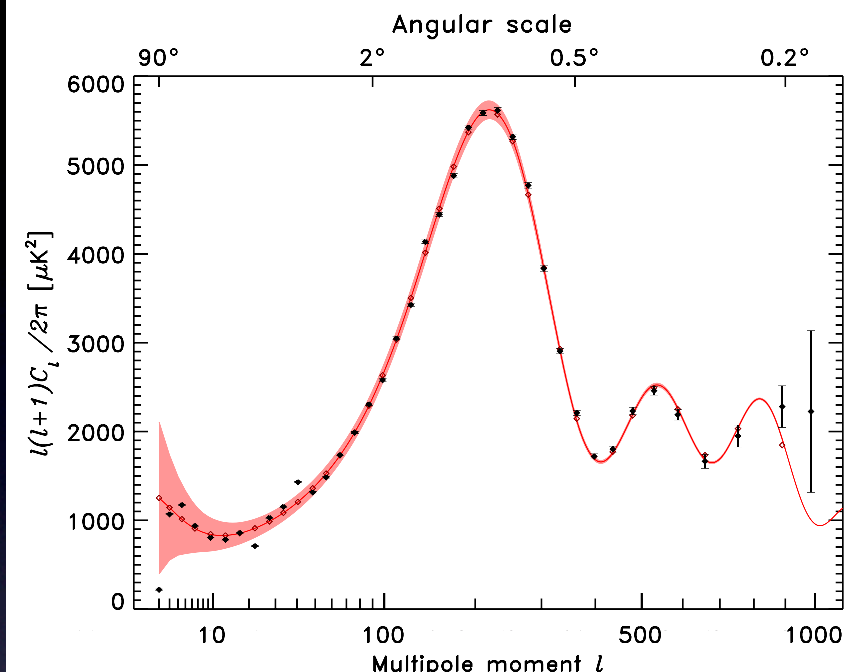
assume *instant* reheating at the end of inflation to obtain the most conservative limit

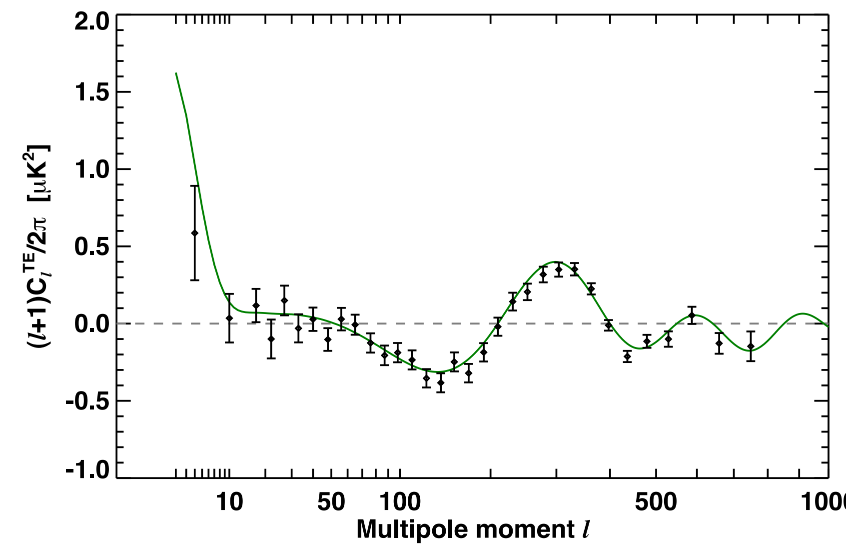
$$N \leq 8$$

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?

- 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

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

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

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

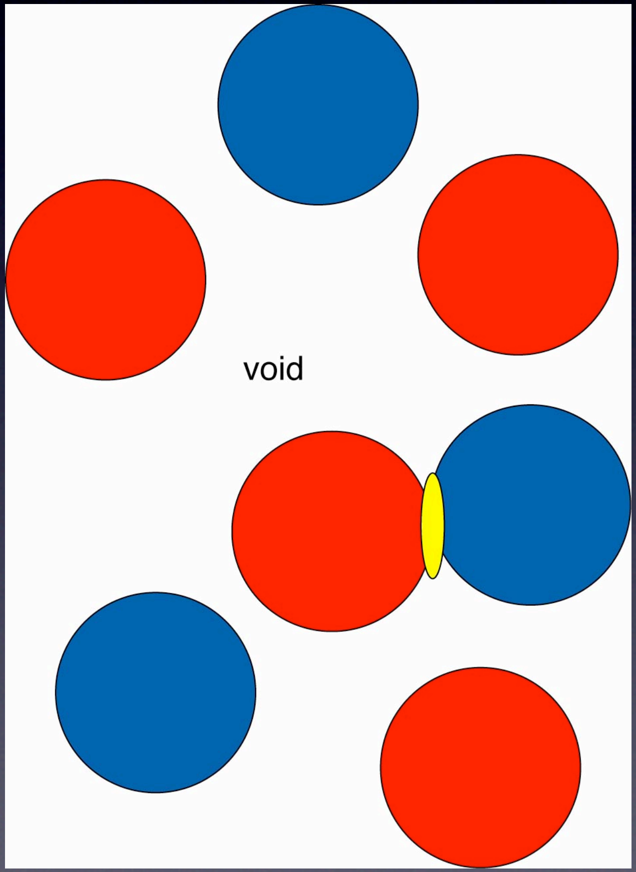
$$m < (H_I M_{Pl})^{1/2} 10^{10} e^{-3N} \approx 10^{-70} \mathrm{GeV}$$

We assume *evolution* for the remainder

Anti-matter domain?

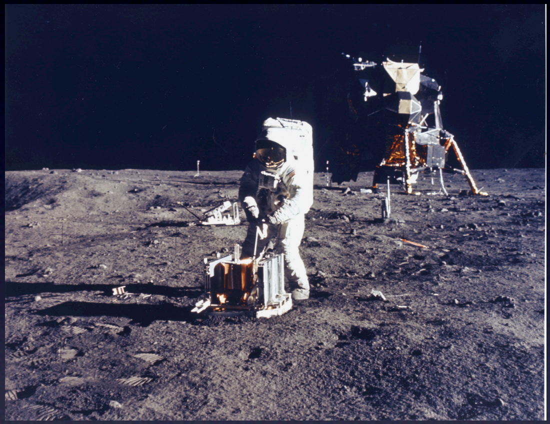
Anti-matter domain?

- Big Bang made presumably both matter and anti-matter
- Where did it go?
- Are there anti-matter domains in the universe?
- Could the universe be *baryosymmetric*?



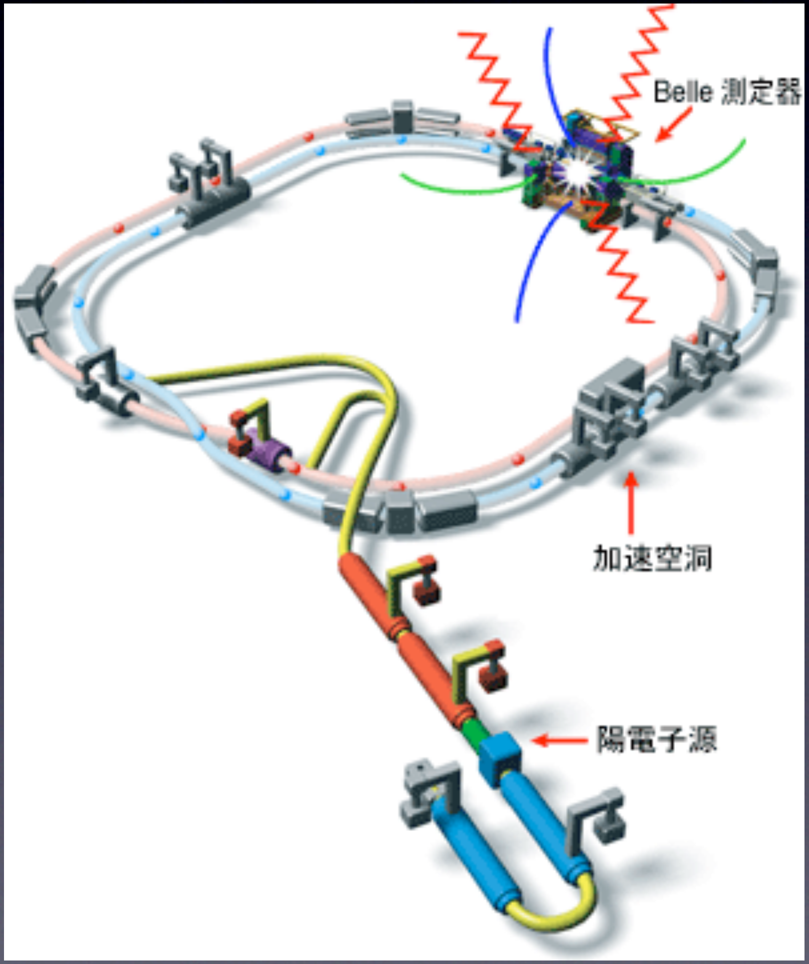
Solar system

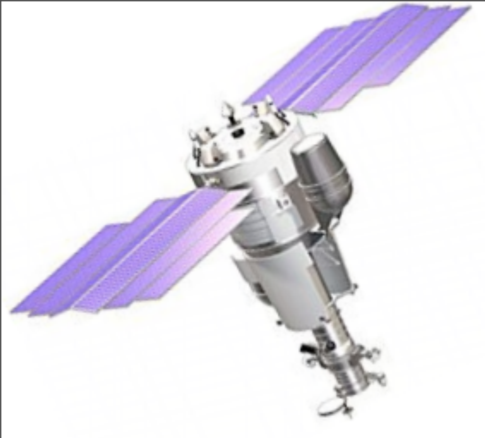
- Landing on the moon
- Past asteroid/ meteor impact
- Solar cosmic rays
- Voyager spacecraft



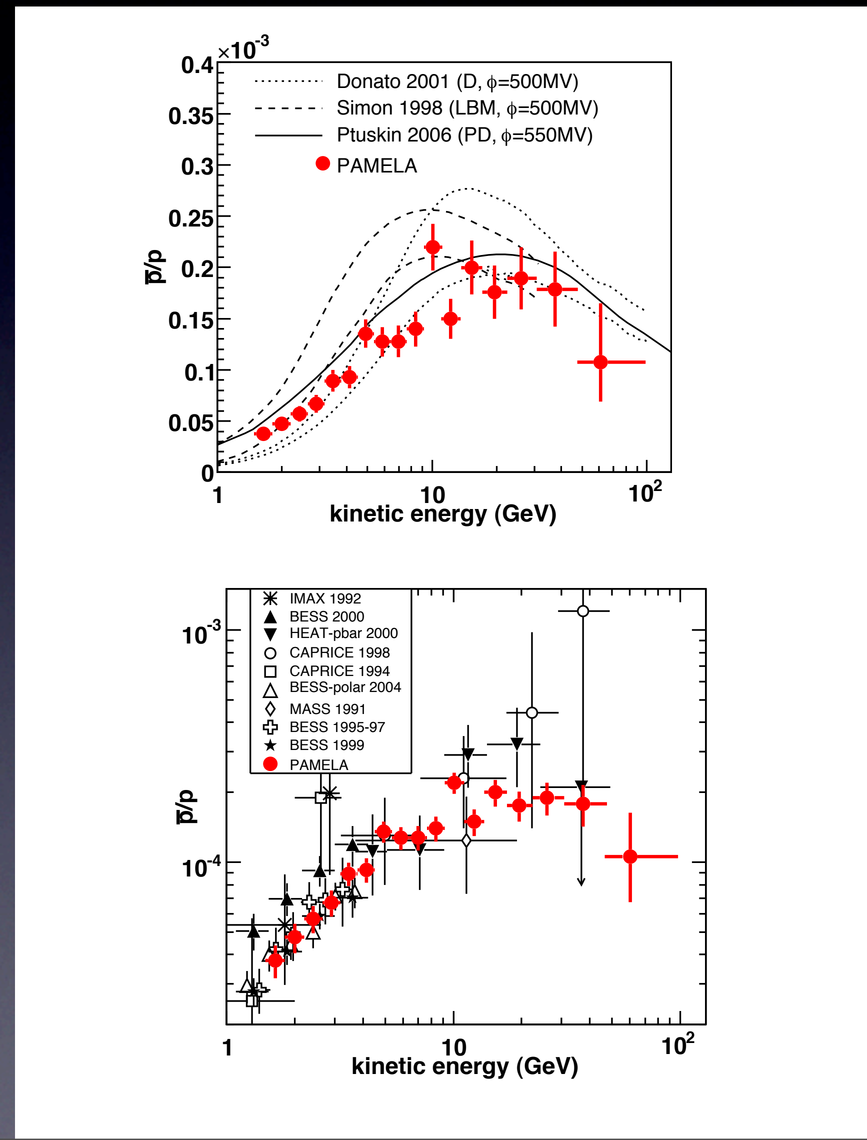
largest concentration of anti-matter

- KEK-B has 10^{14} positrons inside the ring
- Fermilab Tevatron has 3 10^{12} anti-protons





Galactic Scale



- There are anti-protons in cosmic rays
- ~10^{-4} of protons
- Consistent as secondaries due to the interaction of cosmic-ray protons in the ISM (InterStellar Medium)
- Certainly not 1:1

Extragalactic Anti-Helium

- Anti-nuclei unlikely form as secondaries
- Anti-helium product of BBN in anti-matter domains
- Extragalactic anti-matter within ~10Mpc should give ~10^{-6} anti-helium flux (Stecker)
- BESS 2002 excluded this level
- Not conclusive?

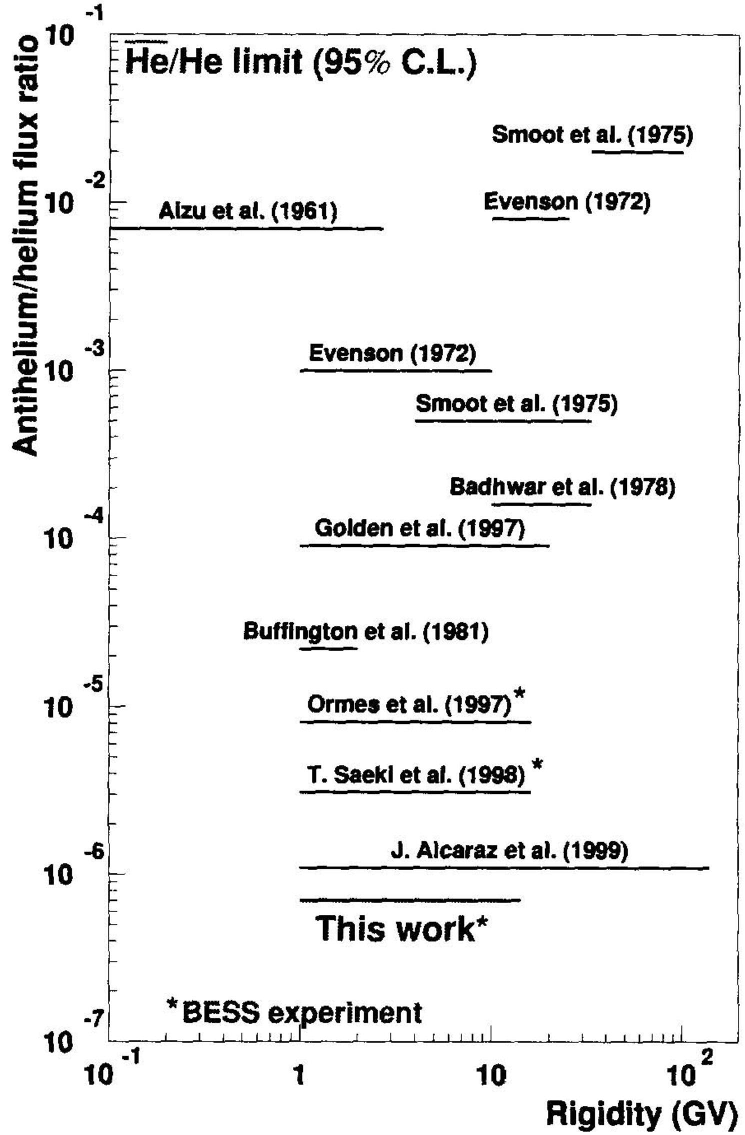
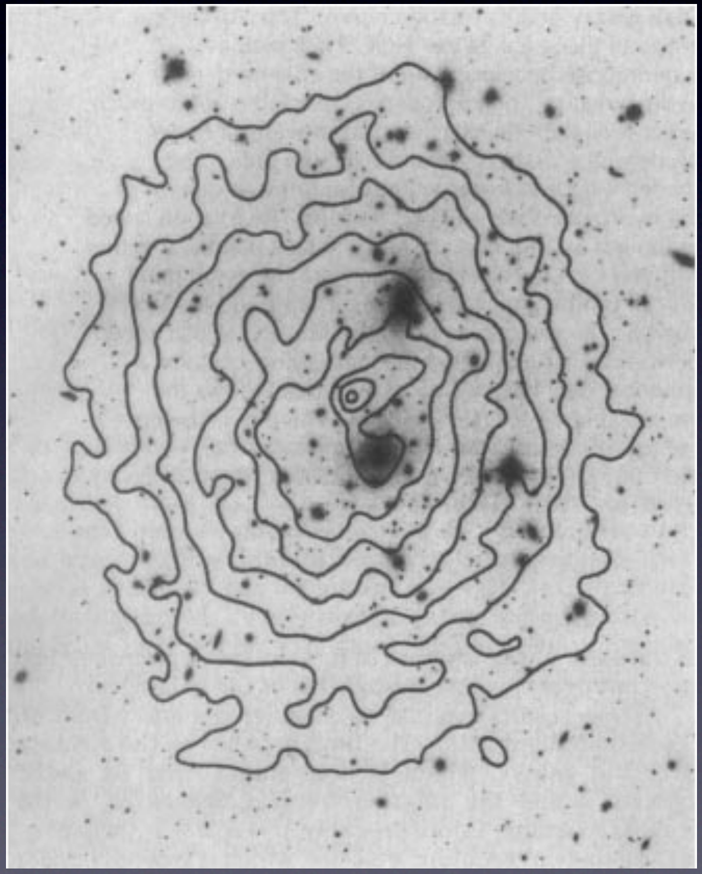


Figure 6. New upper limit of $\overline{He}$/He obtained in this work shown with previous BESS results(BESS 1993-1995 and 1997-2000), and with other experiment results.

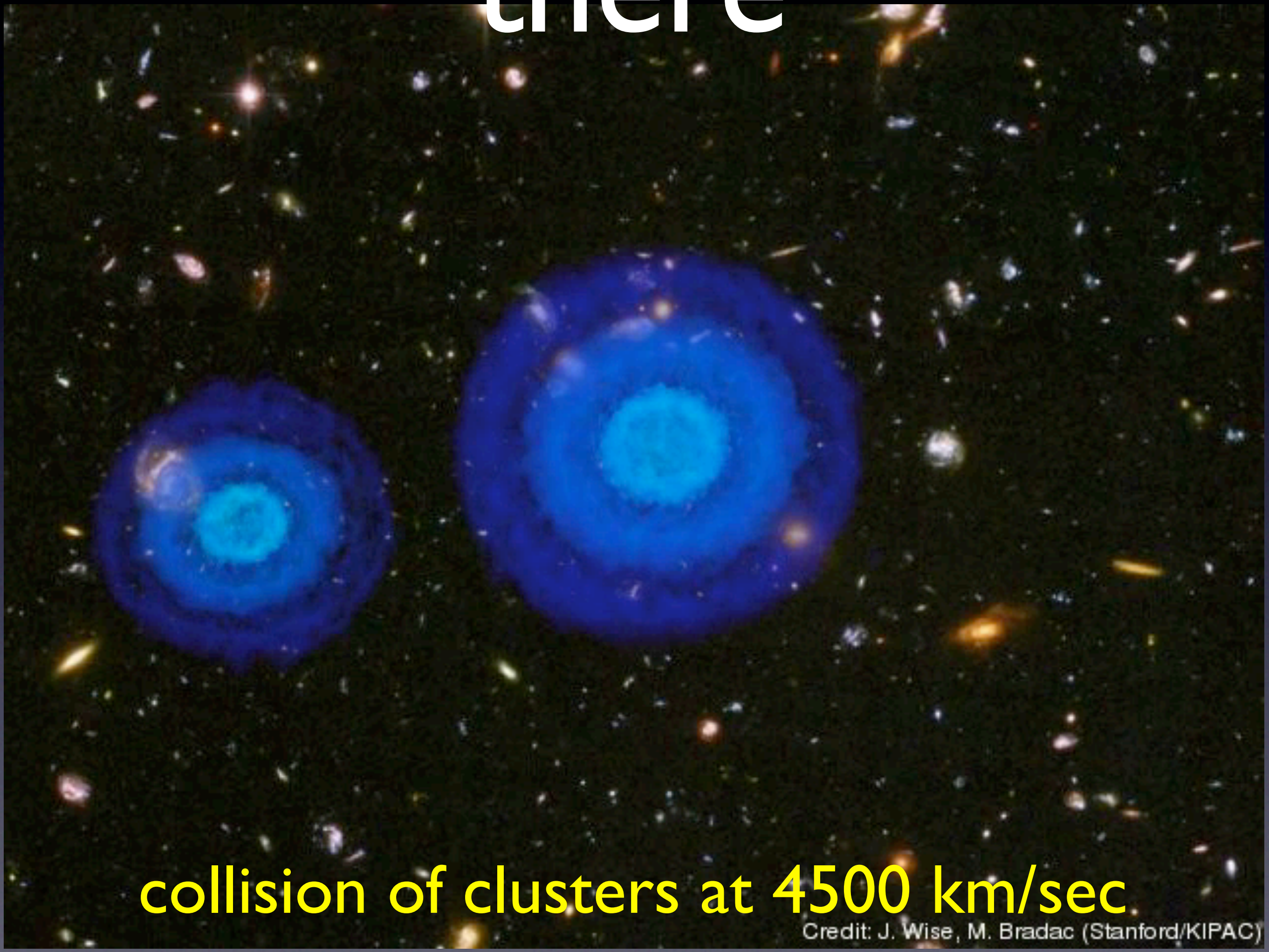
Galaxy Clusters

- No gamma rays from other X-ray emitting clusters (sure to have intracluster gas)
- No coexistence of matter and anti-matter within ~20Mpc scale
- $>10^{13}$–$10^{14} M_{\odot}$ only

  matter, little anti-matter



You don’t want to be there



Diffuse Gamma Ray Background

- Most of the gamma rays from π^0 are still around
- Contributing to the diffuse gamma ray background
- d_0<1Gpc excluded
- $M(d_0)>10^{20}M_\odot$

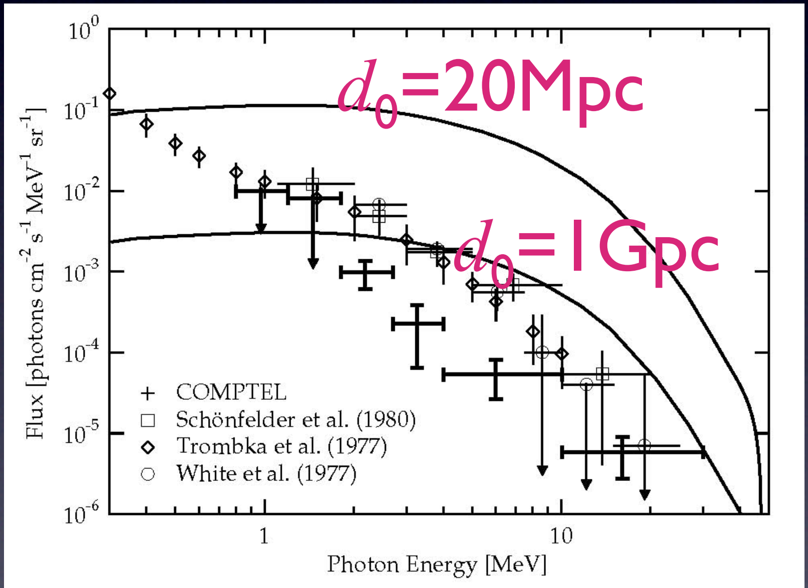


Figure 5: Data [23] and expectations for the diffuse γ-ray spectrum.

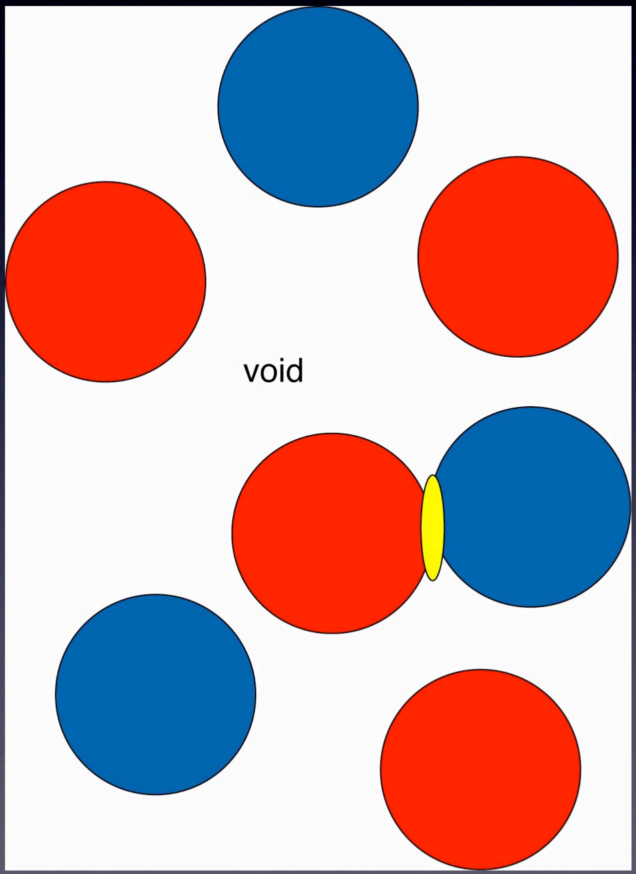
Cohen, De Rujula, Glashow (1997)

Causality

- We learned that matter and anti-matter domains (if they exist) must be separated beyond >1Gpc, basically the size of the visible universe now.
- A new force that repels matter and anti-matter?
- Distance of ~1Gpc has just come to see each other
- No causal mechanism could separate them
- Think what could have happened in earlier universe well before recombination

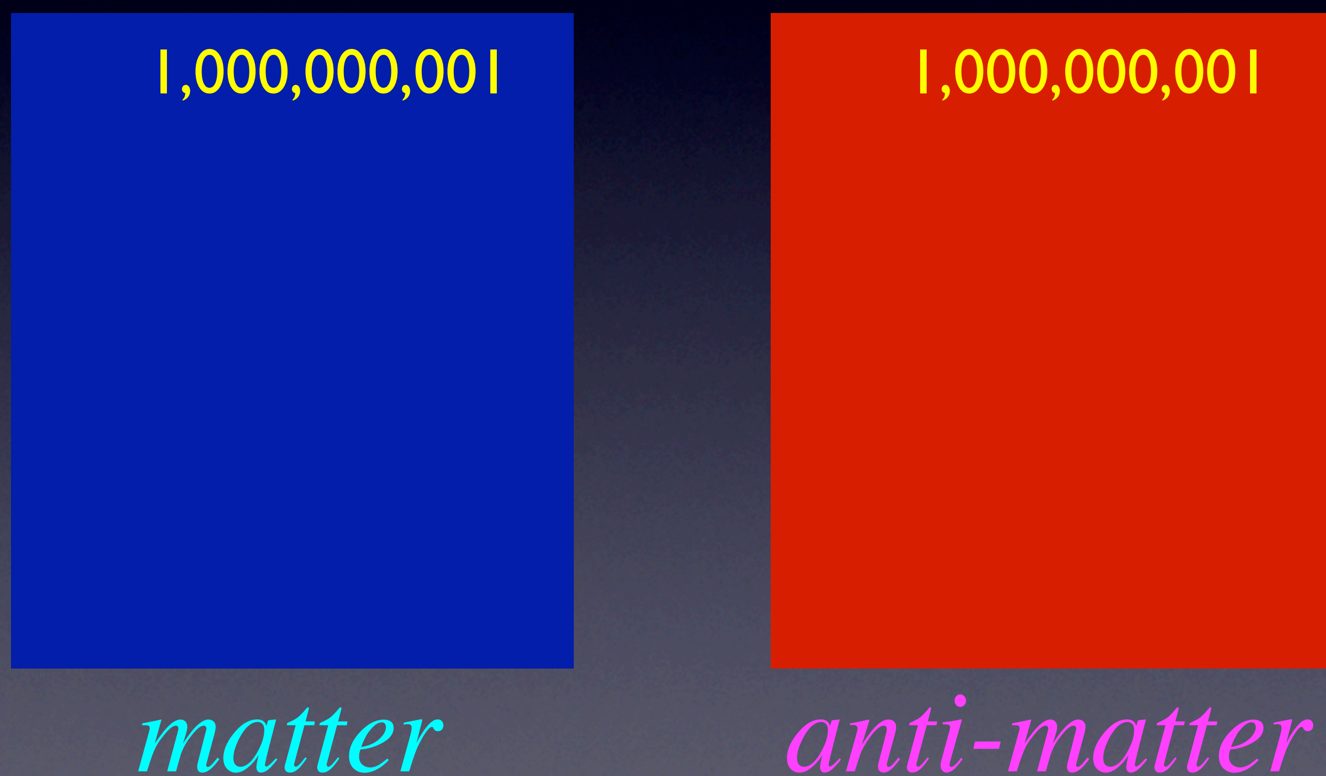
Requirement for separating domains

- Domains of matter and anti-matter must have been well separated *before* the QCD phase transition to avoid this near-total annihilation
- Horizon size back then $\sim 10^{-7} M_{\odot}$
- Need to separate $>> 10^{13} M_{\odot}$
- Need *acausal* mechanism

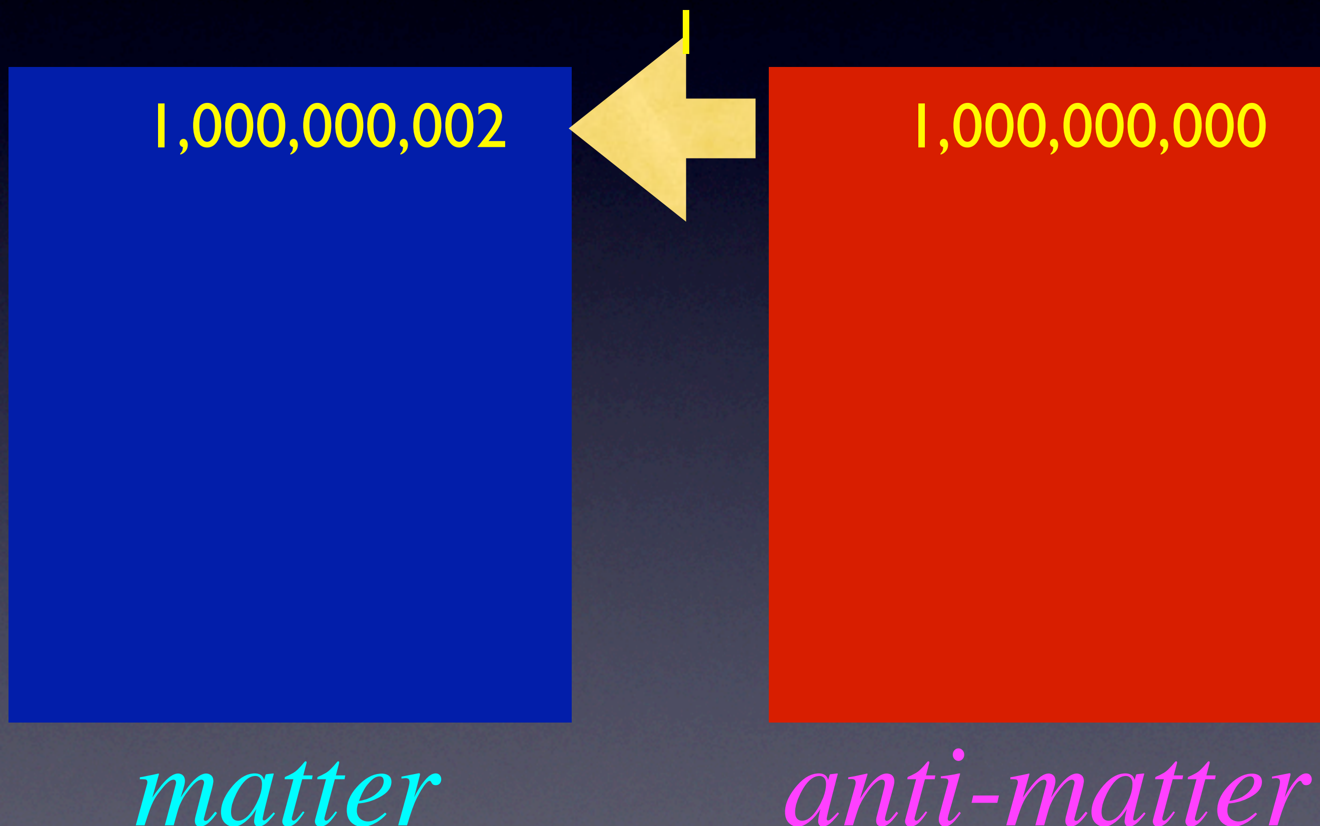


2. Sakharov's Conditions
3. Why old models died

Beginning of Universe



fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

•

us

matter *anti-matter*

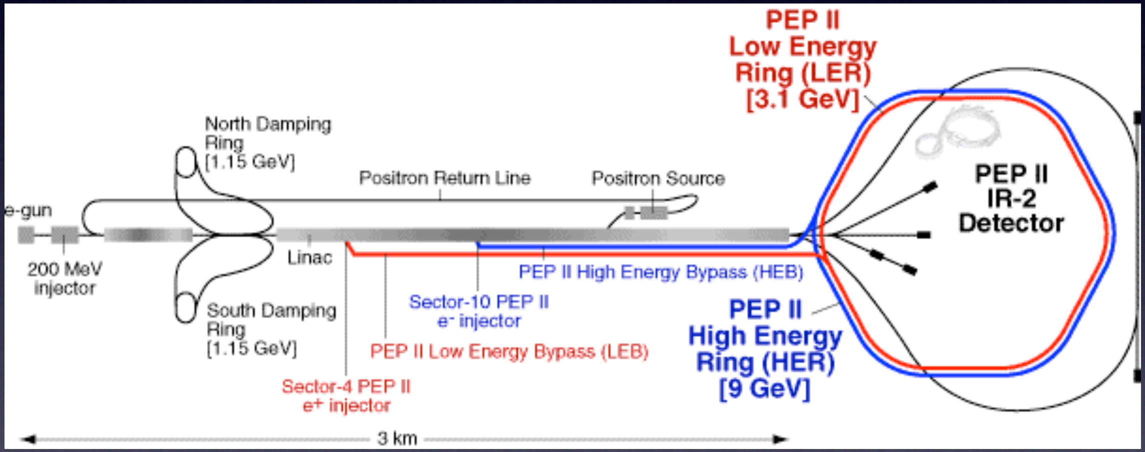
This must be how we survived the Big Bang!

Sakharov's conditions

- Need to reshuffle matter and anti-matter
    - baryon-number violation
- need to prefer matter over anti-matter
    - CP violation
- need an irreversible process
    - departure from equilibrium

Progress!

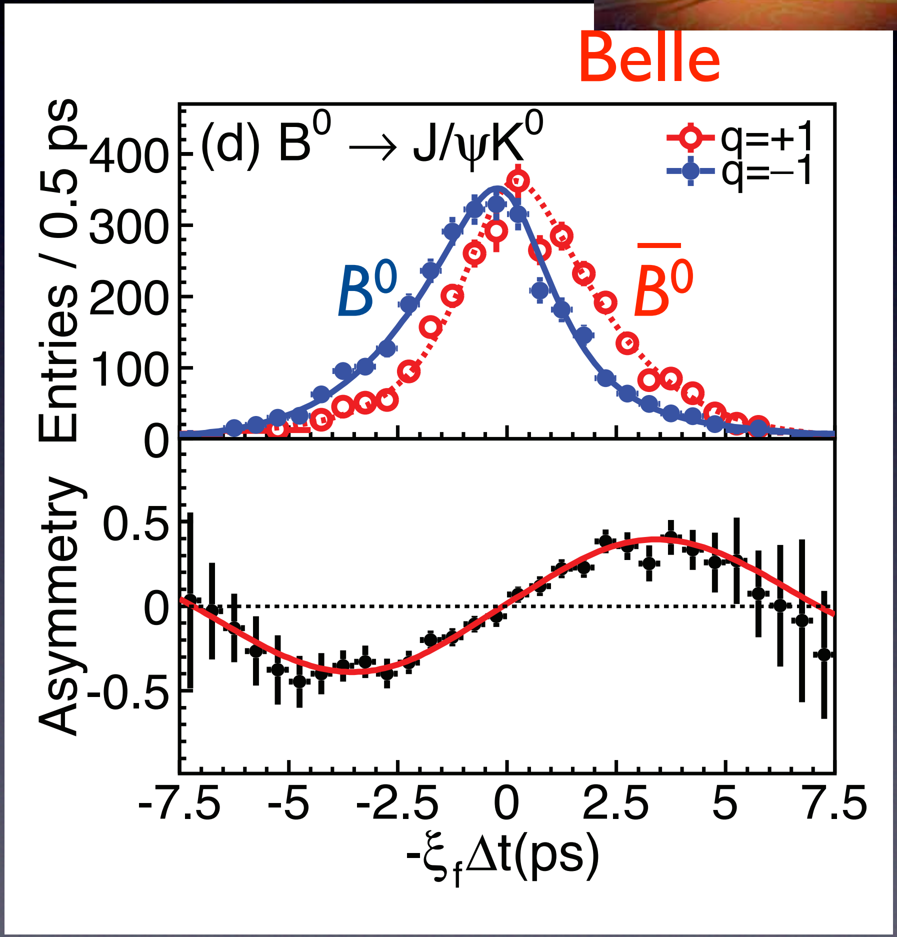
- Head-to-head competition between Stanford/Berkeley and KEK (Japan)



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

CP Violation

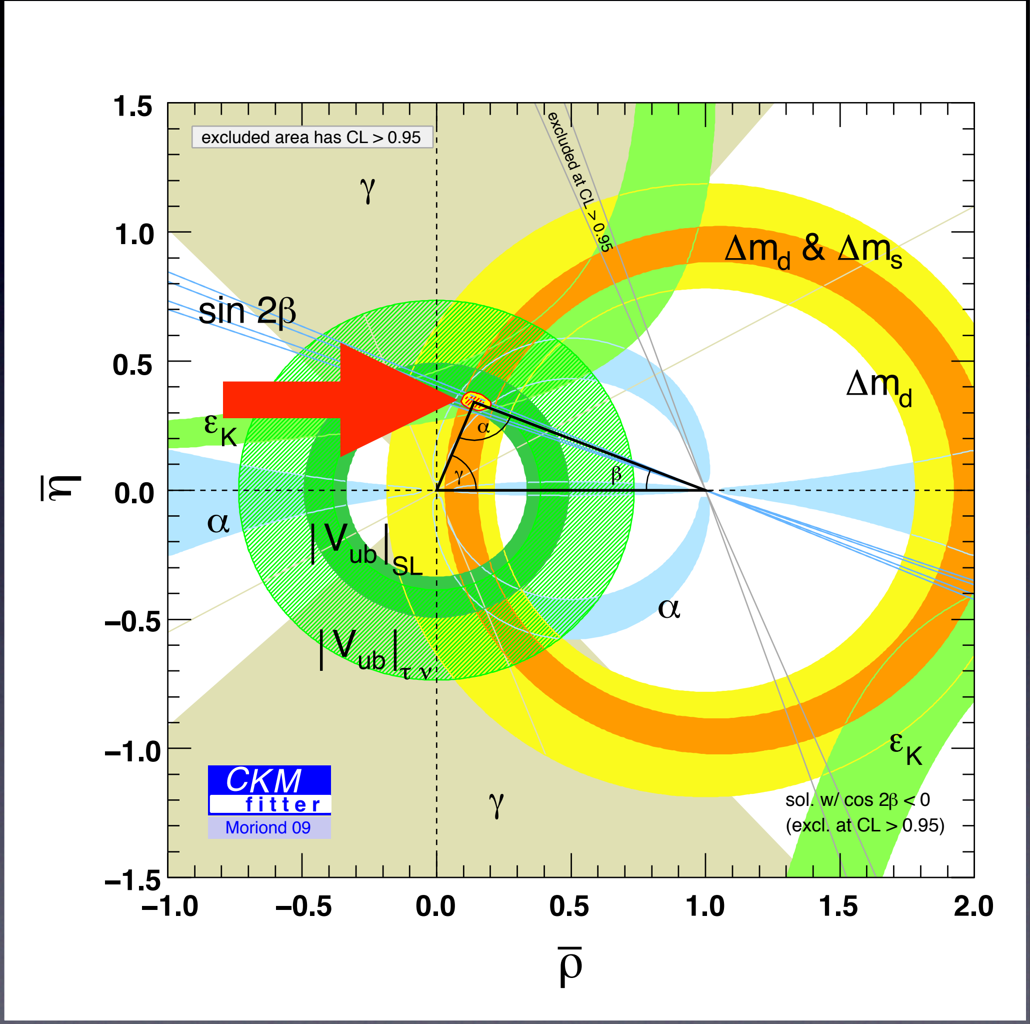
- Is the world of anti-matter an exact mirror?
- 1964 Fitch and Cronin: ε_K
- 1998 CPLEAR: *T*-violation
- 1999 NA48, KTeV: ε'_K
- 2002 *B*-factories: sin 2β=sin 2ϕ_1




Cal
GOLDEN BEARS
DANGER

Kobayashi-Maskawa

- Known CP-violating phenomena can all be explained by Kobayashi-Maskawa theory
- There is only a single CP-violating phase (2002)
- Not enough! Can't create excess quarks over anti-quarks



New Puzzle

- We could explain the subtle difference between matter and anti-matter thanks to Kobayashi and Maskawa
- Can we then explain the difference of 10^{-9} in our Universe?
- We can only explain 10^{-10} of what we need!
- more differences are needed
- we also need to see how anti-matter can turn into matter

Need new source of $\not{CP}$

- Now the KM theory is established
- KM phase requires full three generations, quark mixing, the only invariant is (v=1):

$$J = \Im m \left(\det[M_u^2, V_{CKM}^\dagger M_d^2 V_{CKM}] \right) \approx 10^{-20}$$

- Absolutely not enough (need 10^{-9}!)
- Need new source(s) of CP violation

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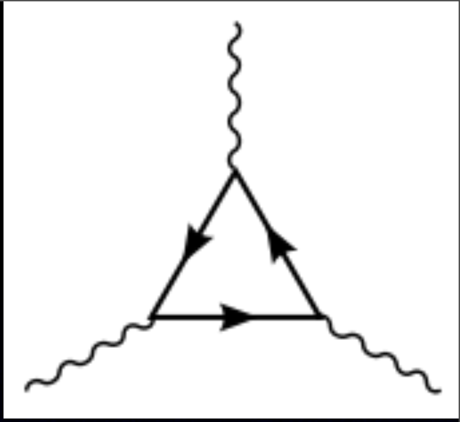
B-violation

- Grand Unification was prime example: e.g. $p \rightarrow e^+\pi^0$ (now $>10^{34}$ years! Nov. 09 Super-K)
- strong limit $M_{GUT}>10^{15}$ GeV
- monopole problem requires $T_{RH}<M_{GUT}/\alpha$
- can't count on GUT-scale particles for baryogenesis (loophole: *preheating*)
- *B–L* conserved
- getting enough CP violation was a challenge
- "best" scenario was to rely on color triplet Higgs ~ 10^{11}GeV, requires multi-Higgs

DEAD

't Hooft



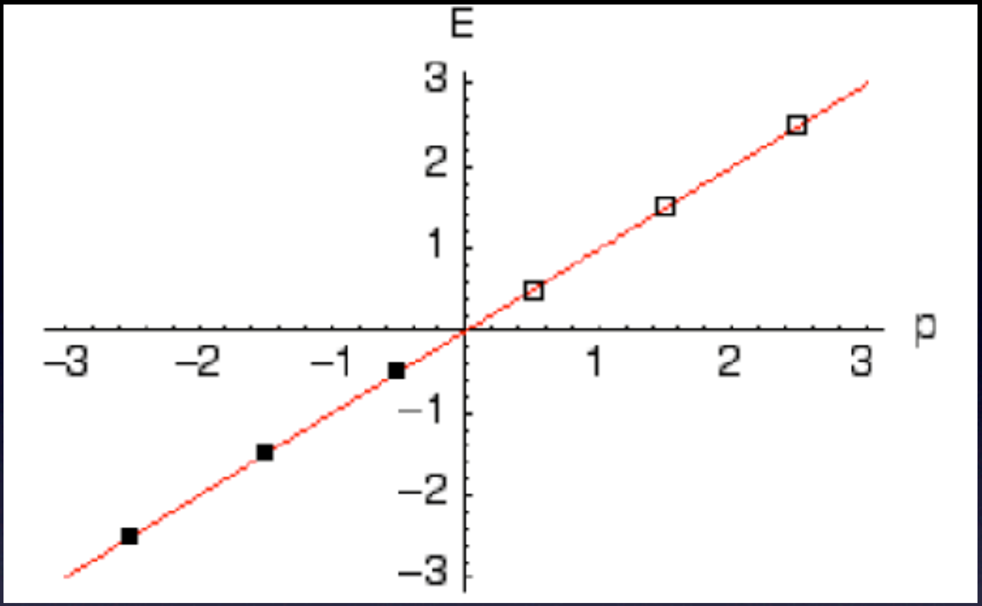
$$\partial_\mu j^\mu_L = \partial_\mu j^\mu_B = \frac{N_g}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}W^a_{\mu\nu}W^a_{\rho\sigma}$$

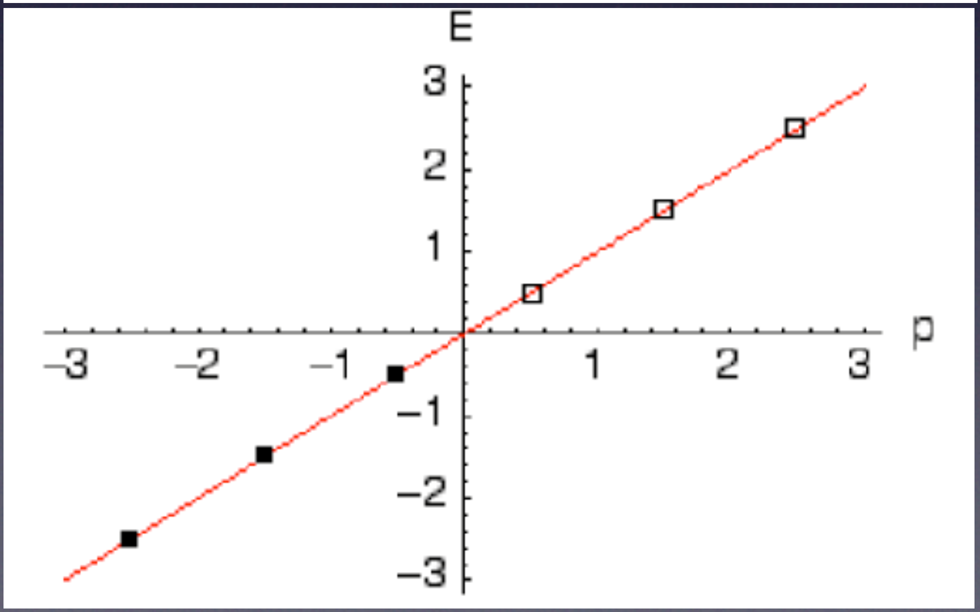
- Standard Model actually violates the baryon number from the triangle anomalies
- conserves *B*–*L*
- can in principle lead to $^3He \rightarrow e^+\mu^+\bar{\nu}_\tau$
- my back-on-envelope estimate $\tau \sim 10^{150}$ yrs
- but can have impact in early universe

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, #l





1D vs 3D

- 3+1 D gauge theory
- $\pi_3(SU(2))=Z$
- Atiyah-Patodi-Singer index theorem says instanton number corresponds to the number of zero crossing
- change *B* & *L* by $N_g \times N_{instanton}$

- same story with 1+1 D U(1) gauge theory
- $\pi_1(U(1))=Z$
- U(1) can have instantons = constant electric field
- $E=\pm(k-eA_1)$, $k=n/L$
- change eA_1 from 0 to 1/L
- change fermion numbers

$$\partial_\mu j_L^\mu = \partial_\mu j_B^\mu = \frac{N_g}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}W^a_{\mu\nu}W^a_{\rho\sigma}$$

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
- all preexisting *B* washed out if $B\!-\!L = 0$

choices

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

out-of-equilibrium

- detailed balance: process and inverse process have the same rate
- even if CP and B violated, B-increasing and B-decreasing processes cancel each other
- need to go out of equilibrium
- long-lived particle decays out of equilibrium
- first-order phase transitions

Questions?

INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Baryogenesis II

Hitoshi Murayama
UC Berkeley, LBNL, and IPMU Tokyo

CERN Academic Training Lectures
May 26, 2010

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

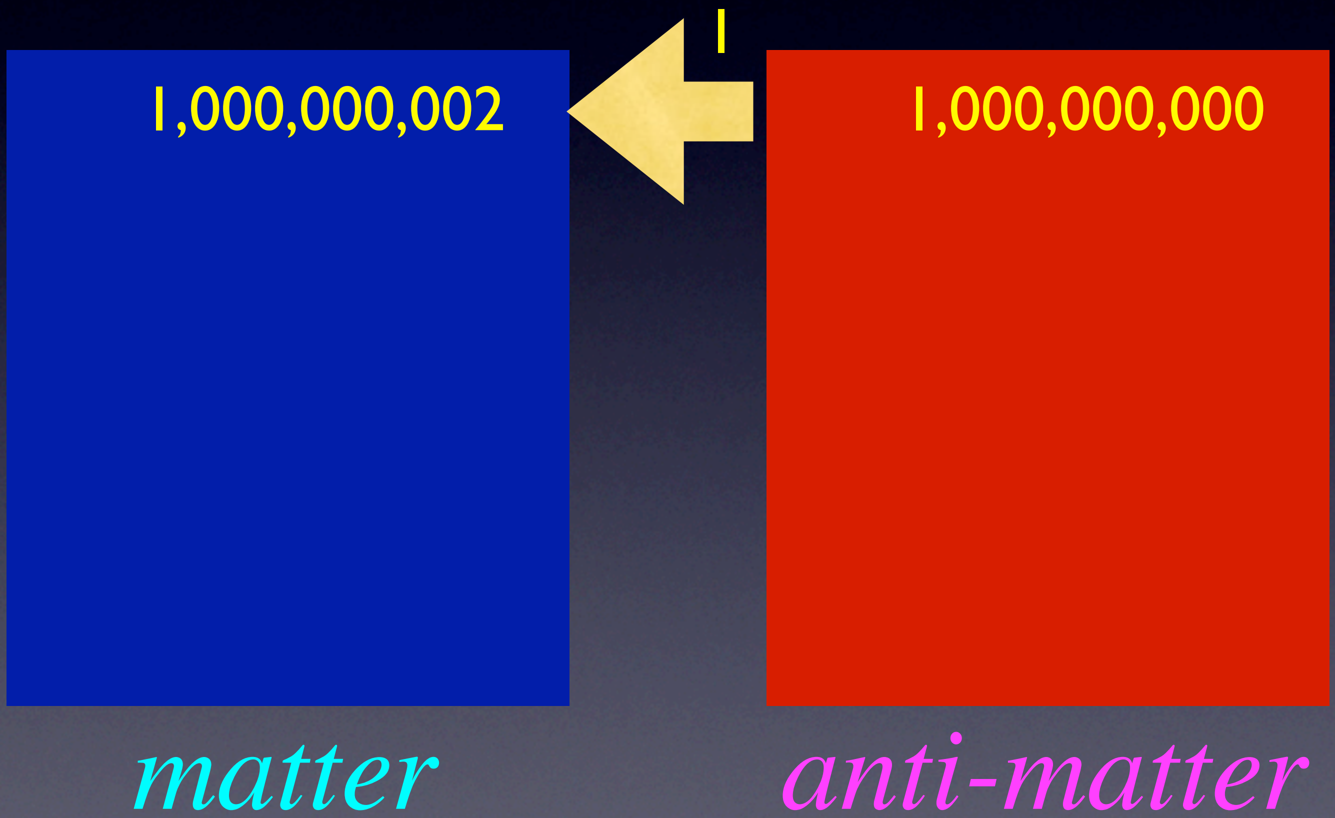
Recap

- No significant anti-matter within ~1Gpc
- Both CMB and BBN suggest $\Omega_b \approx 0.044$
- need an asymmetry of a few times 10^{-9}
- given the success of inflation, the asymmetry is not the initial condition (unless extreme measures)
- need to generate the baryon asymmetry in the course of evolution of the Universe

Beginning of Universe

matter	anti-matter
1,000,000,001	1,000,000,001

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

us

matter *anti-matter*

This must be how we survived the Big Bang!

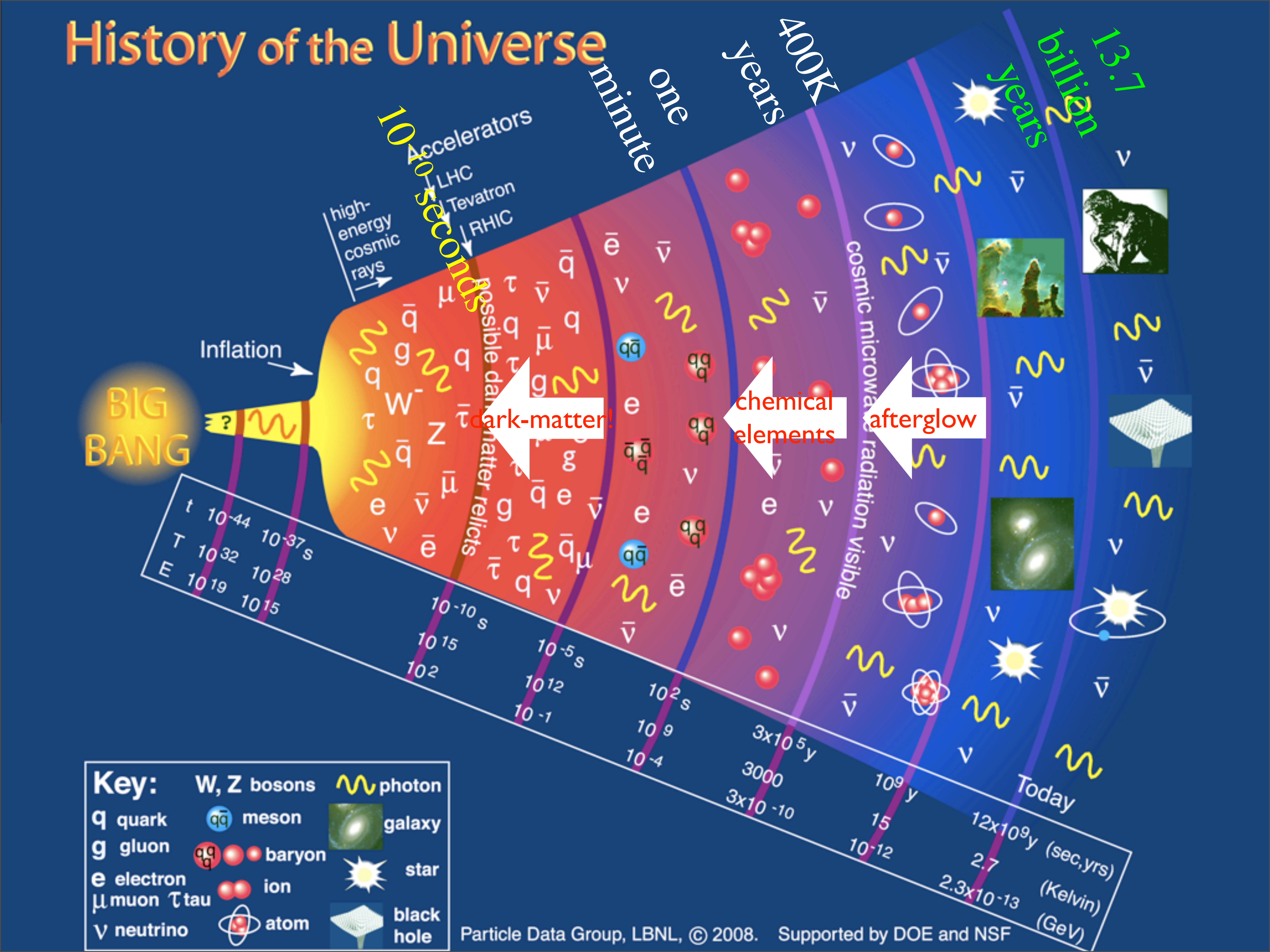
Sakharov's conditions

- Need to reshuffle matter and anti-matter
  - baryon-number violation
- need to prefer matter over anti-matter
  - CP violation
- need an irreversible process
  - departure from equilibrium

too many theories for a single number

choices

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



History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
10-40 seconds
one minute
400K years
13.7 billion years
possible dark-matter relicts
cosmic microwave radiation visible
dark-matter!
chemical elements
afterglow
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
star
μ muon τ tau
ion
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Outline

1. Why baryon asymmetry is a problem at all
2. Review of the Sakharov's conditions
3. Why old models based on GUT did not work.
4. Electroweak baryogenesis
5. Leptogenesis
6. Connections to the near-future experiments

Prototypical Model that doesn’t work

Grand Unification

$$\begin{pmatrix} H_C^{-1/3} \\ H_C^{-1/3} \\ H_C^{-1/3} \\ H^+ \\ H^0 \end{pmatrix}$$

- grand unified theories violate *B*
- most models based on SU(5) preserve *B*–*L*
- Standard Model Higgs is a part of 5-plet
- remainder is color-triplet
- Yukawa couplings may violate CP
- H_C can decay as $H_C^{-1/3} \to u^{+2/3} e^{-1}$ *B*=1/3

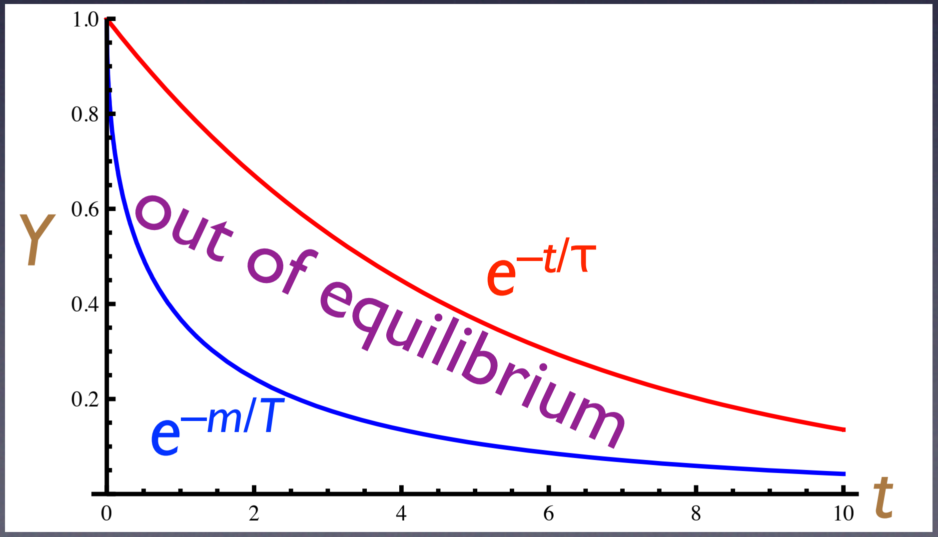
$$H_C^{-1/3} \to \bar{u}^{-2/3} \bar{d}^{+1/3}$$ *B*=–2/3

Out of equilibrium

- A static system would eventually relax to an equilibrium
- fortunately the universe is not static!
- expansion rate $H \approx T^2/M_{Pl}$
- if a process has a rate $\Gamma < H$, it would drop *out of equilibrium*
- the simplest possibility: decay $\Gamma = 1/\tau$

assume long life

- in thermal equilibrium, the abundance decreases with the Boltzmann factor $e^{-m/T}$
- once created, they disappear by decay $e^{-t/\tau}$
- if the lifetime long, they hang out for a while
- go *out of equilibrium*



CP conservation

		B
$H_C^{-1/3} \rightarrow u^{+2/3} e^{-1}$	33%	1/3
$H_C^{-1/3} \rightarrow \bar{u}^{-2/3} \bar{d}^{+1/3}$	67%	–2/3
$H_C^{*+1/3} \rightarrow \bar{u}^{-2/3} \bar{e}^{+1}$	33%	–1/3
$H_C^{*+1/3} \rightarrow u^{+2/3} d^{-1/3}$	67%	2/3

direct CP violation

		B	L
$H_C^{-1/3} \rightarrow u^{+2/3} e^{-1}$	33%+ε	1/3	1
$H_C^{-1/3} \rightarrow \bar{u}^{-2/3} \bar{d}^{+1/3}$	67%–ε	–2/3	0
$H_C^{*+1/3} \rightarrow \bar{u}^{-2/3} \bar{e}^{+1}$	33%–ε	–1/3	–1
$H_C^{*+1/3} \rightarrow u^{+2/3} d^{-1/3}$	67%+ε	2/3	0

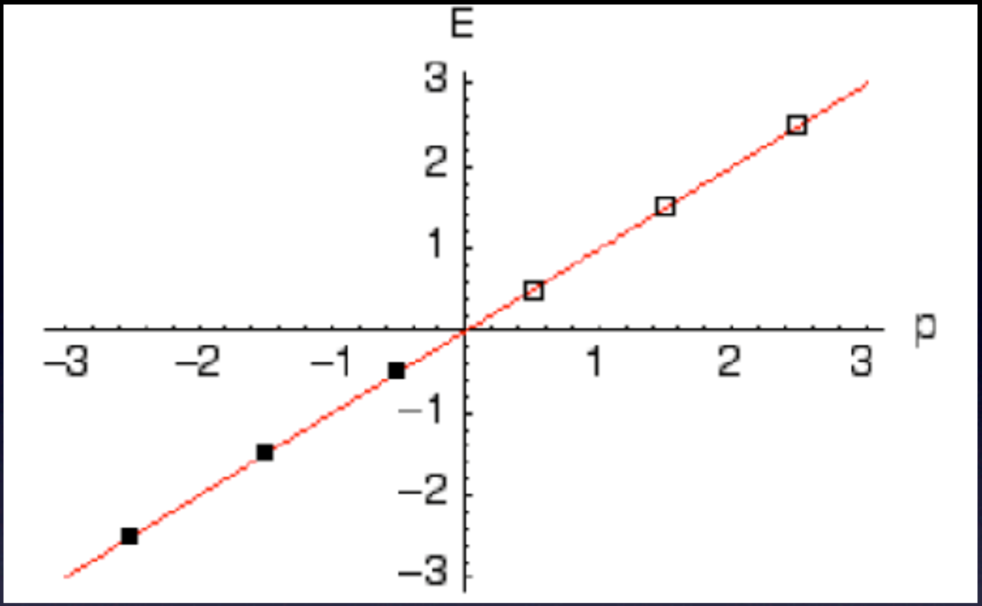
Whey they decay away, net baryon asymmetry!

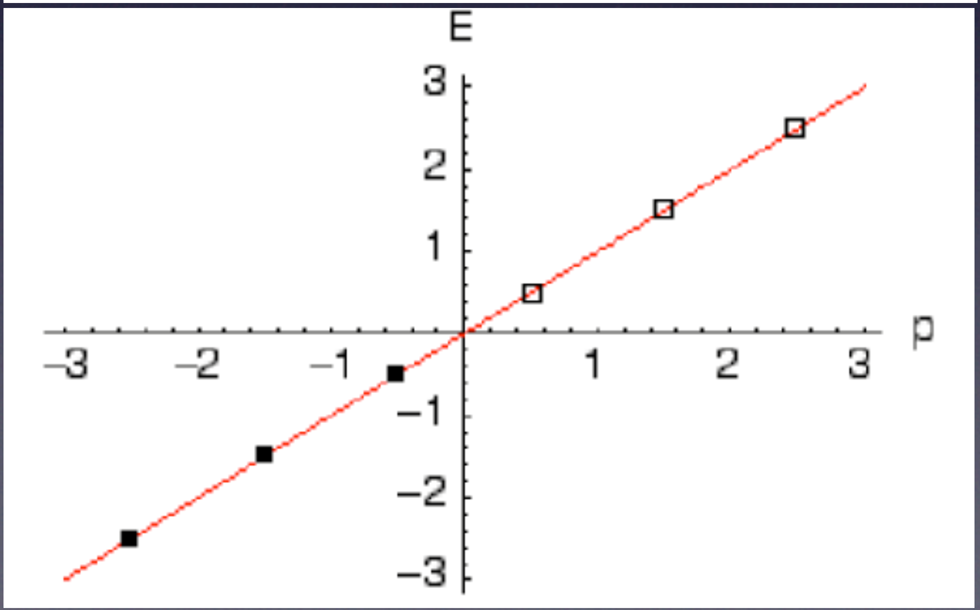
but no *B*–*L* asymmetry and *B* & *L* washed out

Anomaly!

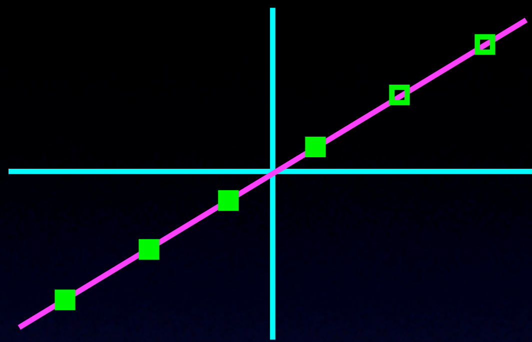
- W and Z bosons massless at high temperature
- W field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating W field

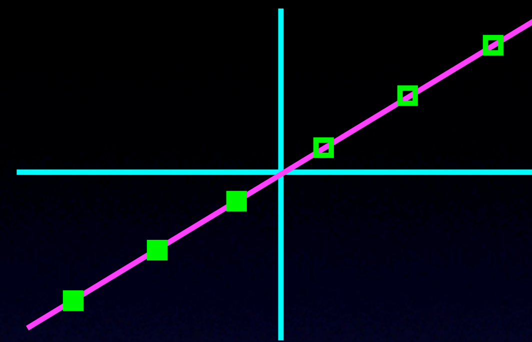
change #q, #l





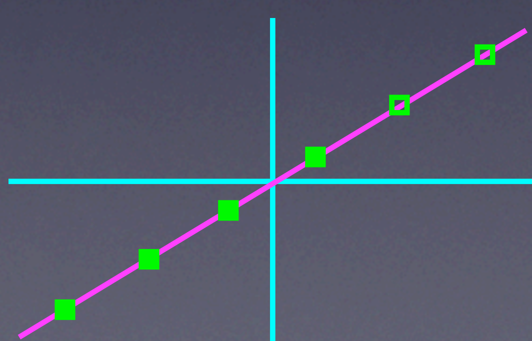
washout

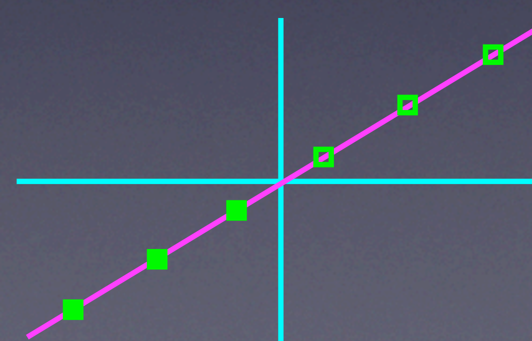




- 1,000,000,001 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,001 ν
- 1,000,000,000 $\bar{\nu}$

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





Morale

- If baryogenesis happens at $T \gg T_{EW}$, need to generate *B–L* asymmetry
- then the standard model anomaly takes care of the rest

$$\frac{n_B}{s} \approx 0.35 \frac{n_{B-L}}{s}$$

- How do generate *B–L* asymmetry?

Encouragement

- direct CP violation in neutral kaon ε' in '99
- ε'≈3.7×10^{-6}

$$\langle \pi^+\pi^- | K^0 \rangle \propto 1 + \epsilon'$$

$$\langle \pi^+\pi^- | \overline{K}^0 \rangle \propto 1 - \epsilon'$$

$$\langle \pi^0\pi^0 | K^0 \rangle \propto \frac{1}{\sqrt{2}} - \sqrt{2}\epsilon'$$

$$\langle \pi^0\pi^0 | \overline{K}^0 \rangle \propto \frac{1}{\sqrt{2}} + \sqrt{2}\epsilon'$$

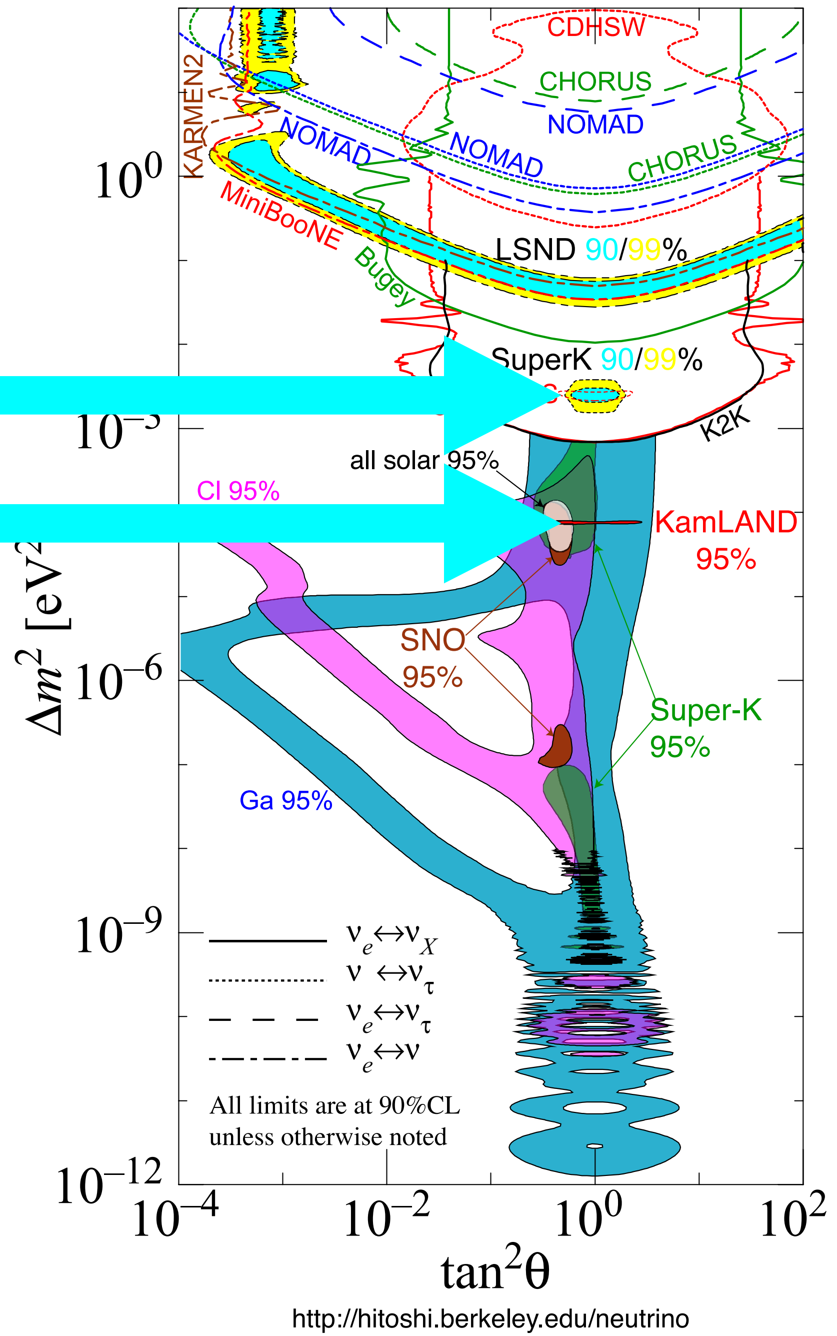
Leptogenesis

A new direction

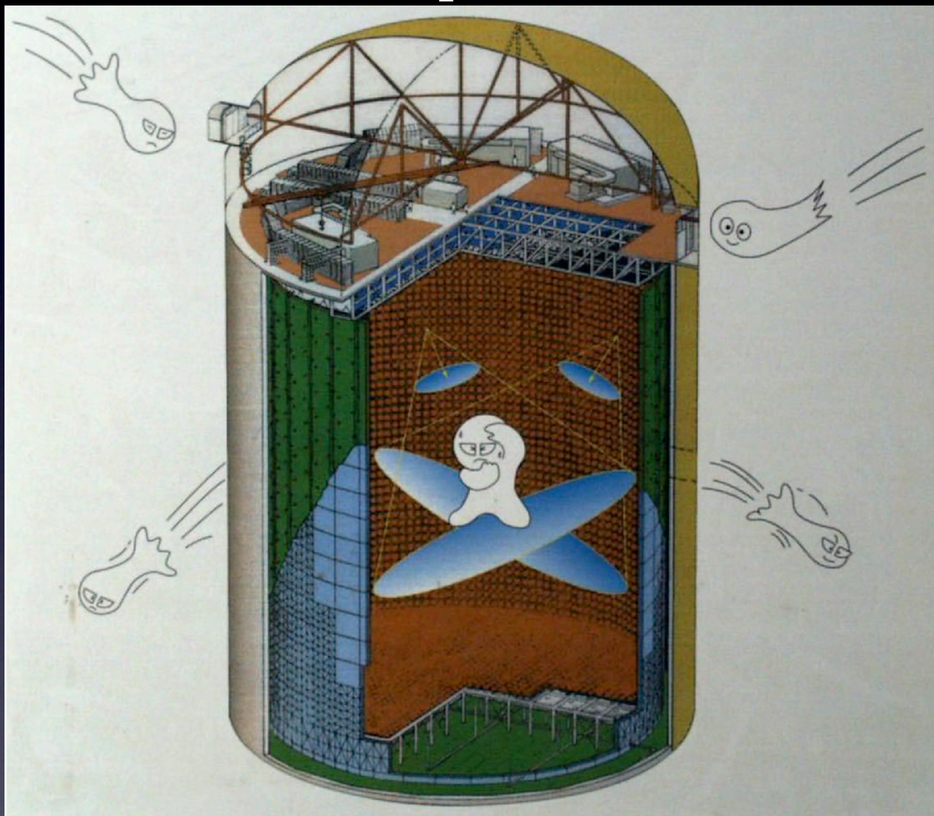
- generate first the *lepton asymmetry* $L<0$
- Then the anomaly in the standard model converts it to the *quark asymmetry* $B>0$

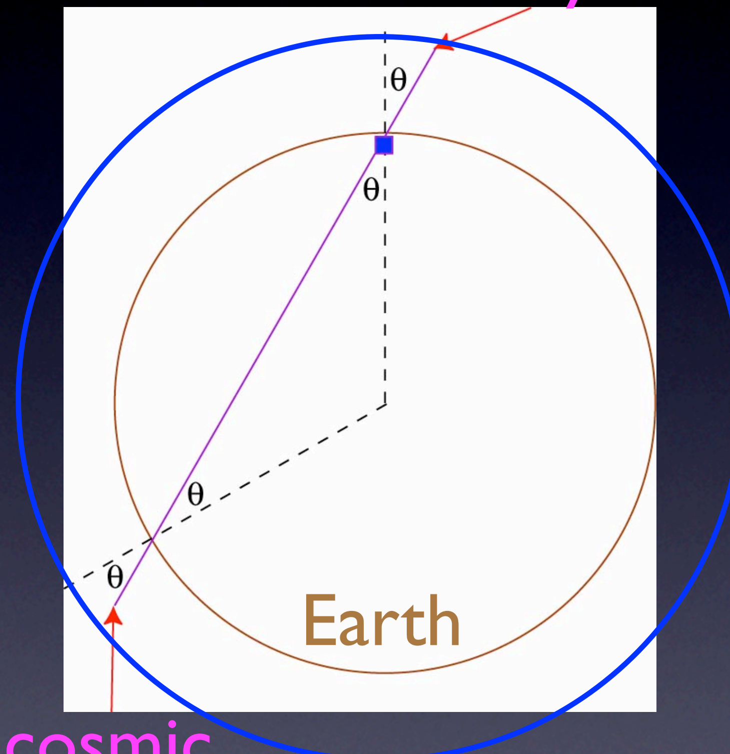
A new input

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



Super-Kamiokande

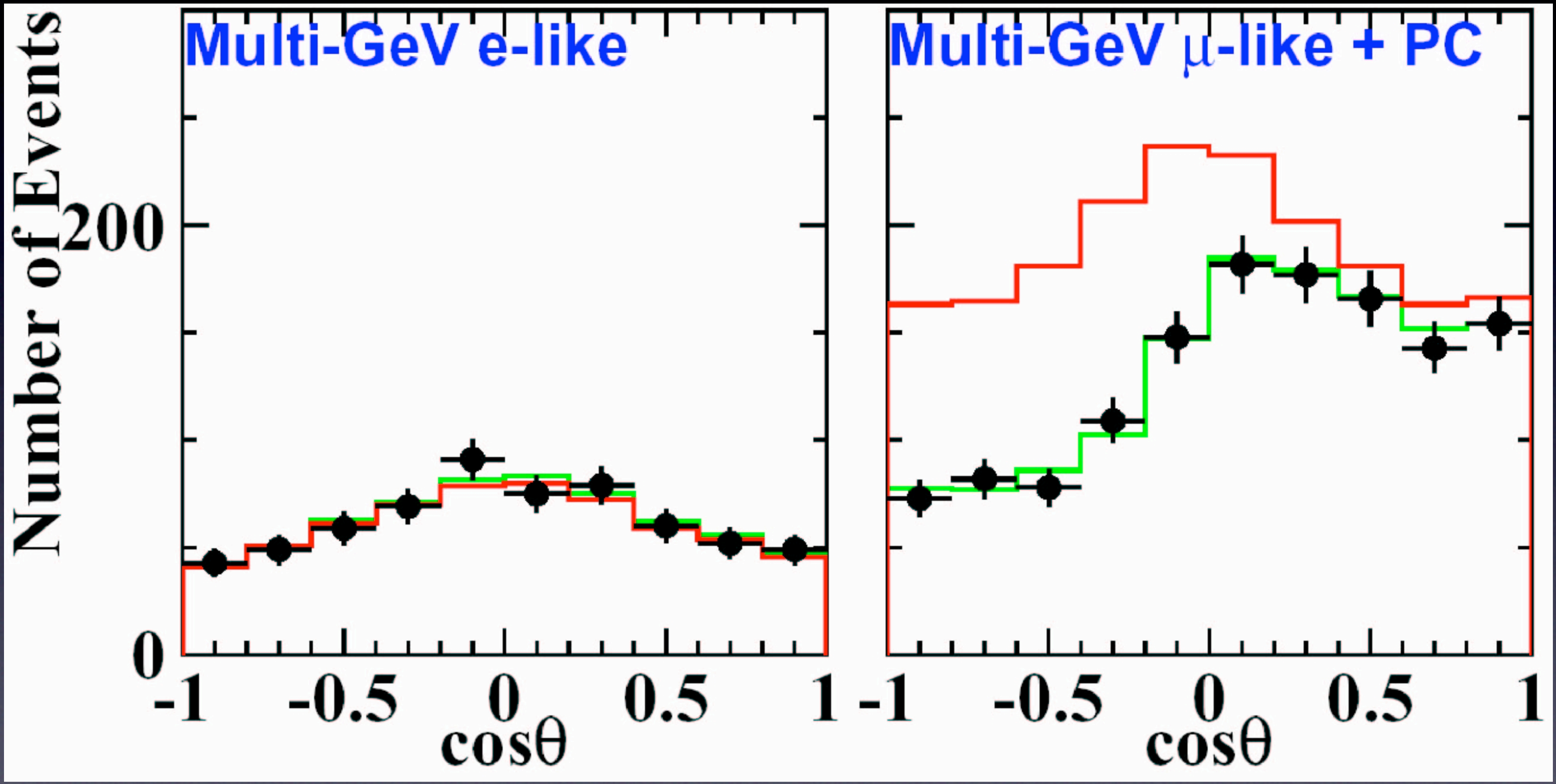




cosmic rays are isotropic

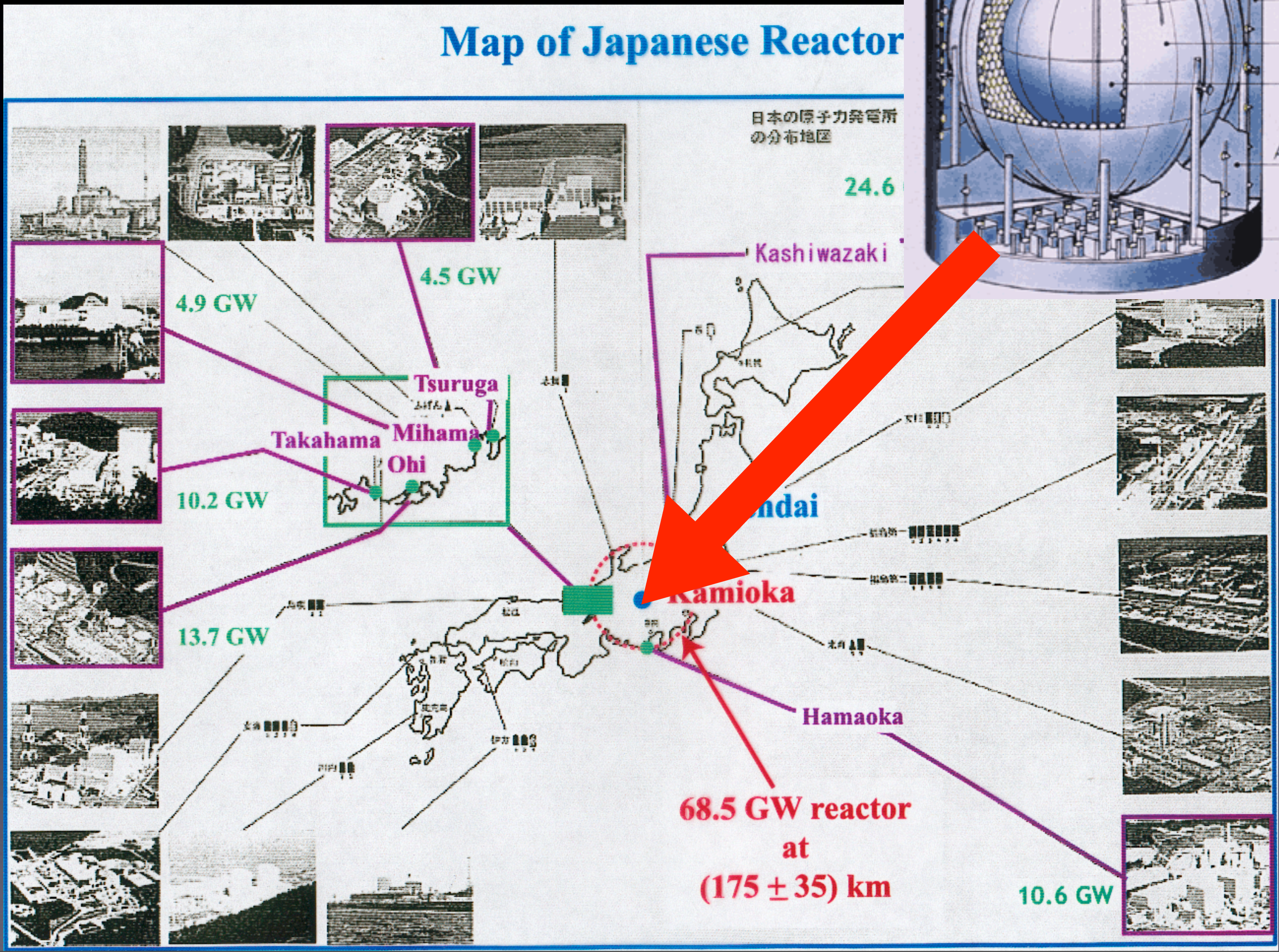
atmospheric neutrinos are up-down symmetric

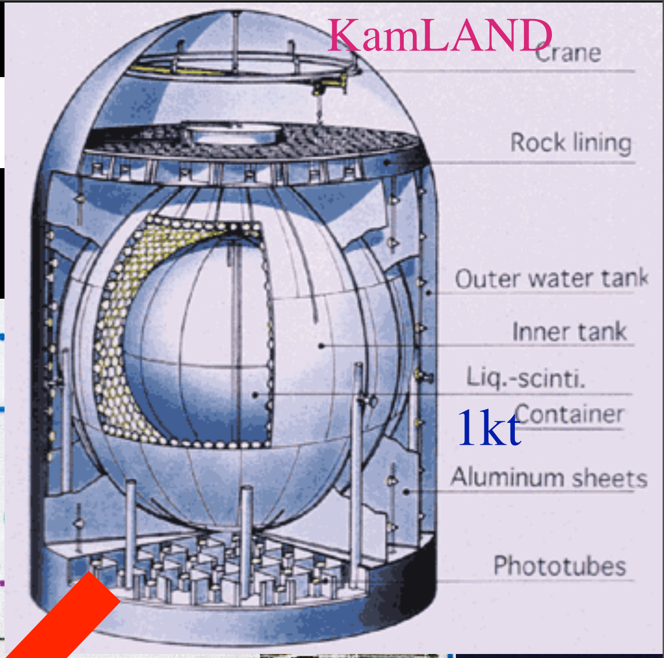
A half of ν_μ lost!



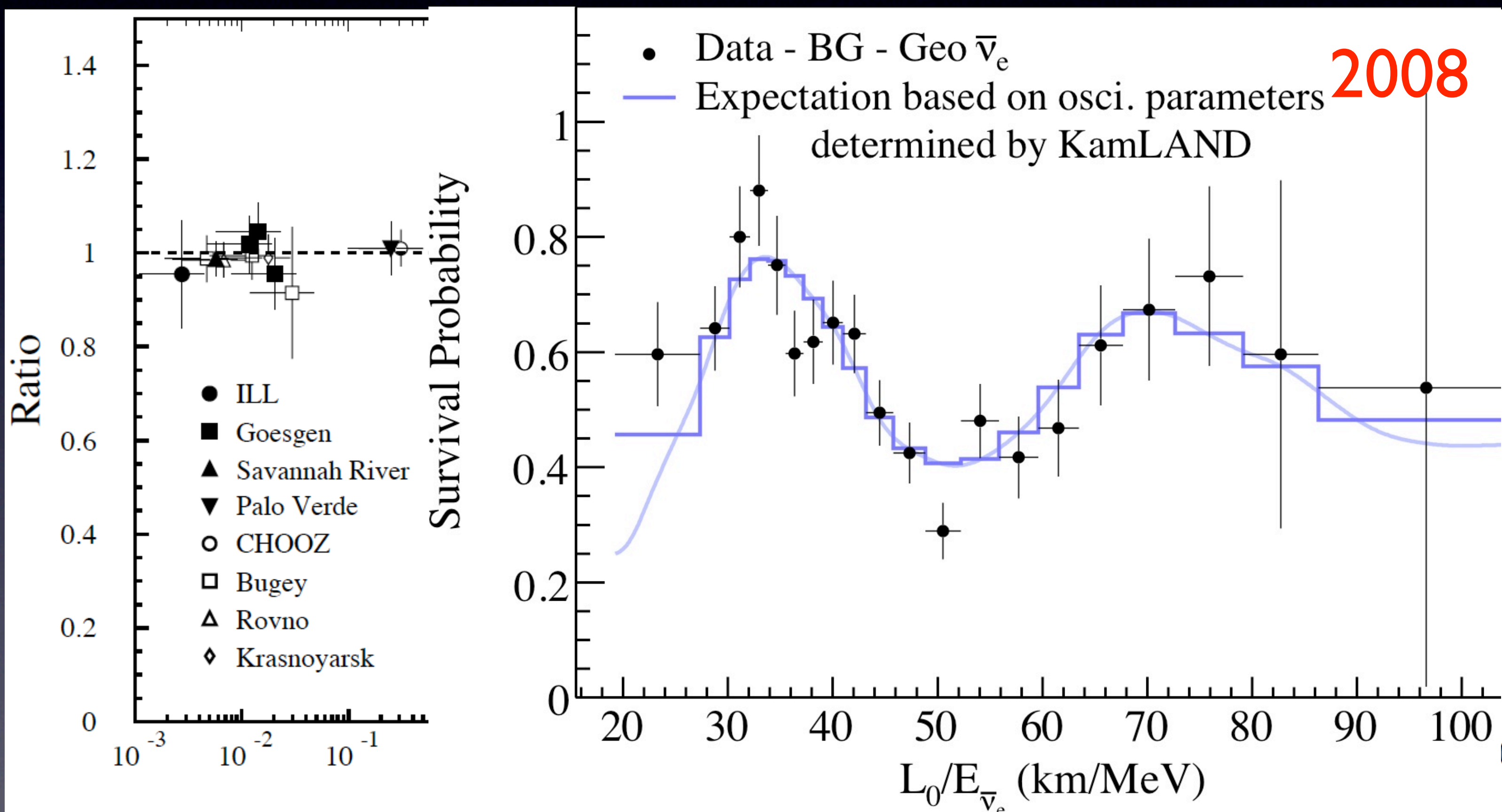
Neutrinos sense time ⇒ have mass!

Location, Location, L





KamLAND
Reactor neutrinos do oscillate!



L_0=180 km

≈Proper time τ

Homer Simpson can taste only strawberry, not chocolate

Homer Simpson can taste only strawberry, not chocolate

Homer Simpson can taste only strawberry, not chocolate

Homer Simpson can taste only strawberry, not chocolate

Homer Simpson can taste only strawberry, not chocolate

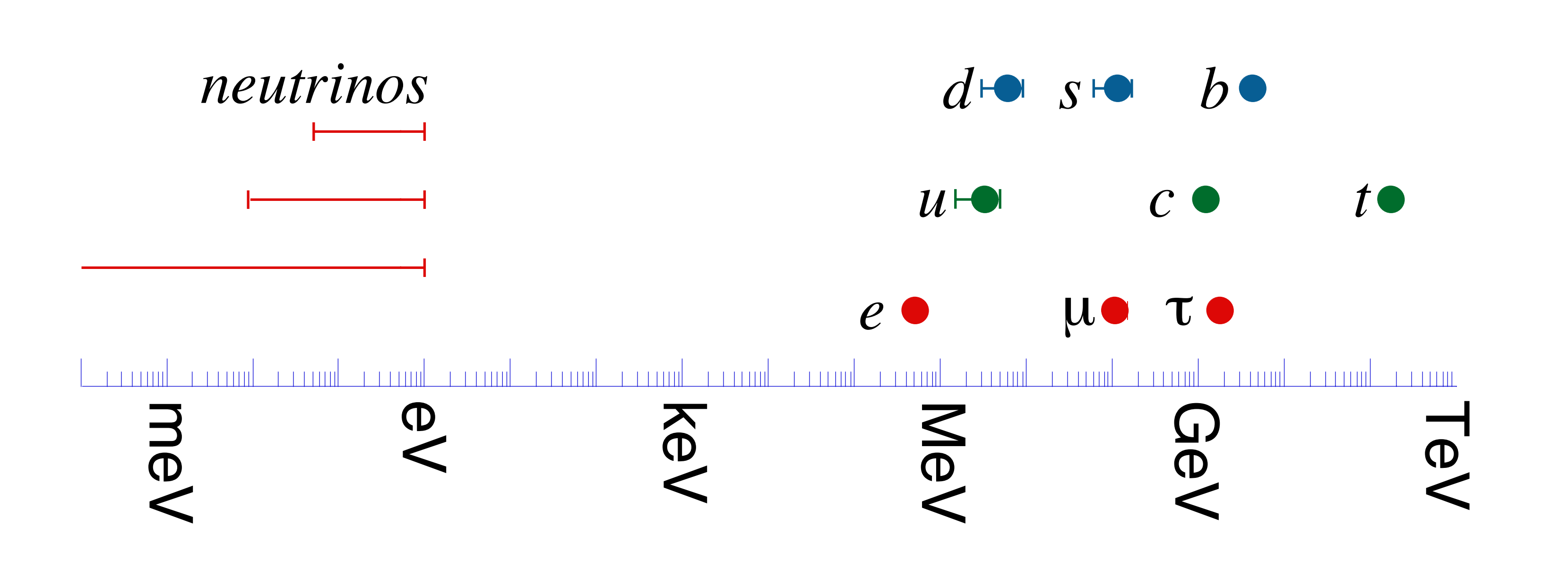
Homer Simpson can taste only strawberry, not chocolate

Homer Simpson can taste only strawberry, not chocolate

Homer Simpson can taste only strawberry, not chocolate

He tastes only a half of the size!

tiny masses



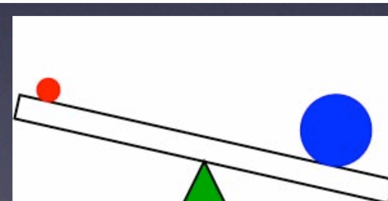
How do we explain tiny masses?

Seesaw Mechanism

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

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

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

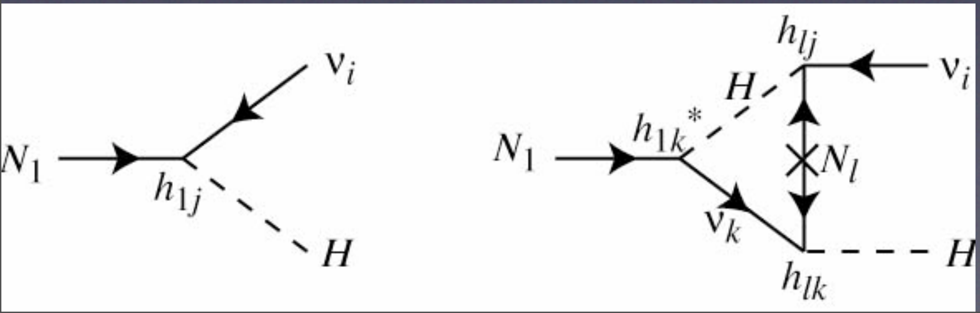


To obtain $m_3 \sim (\Delta m^2_{\mathrm{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}\,\mathrm{GeV}$

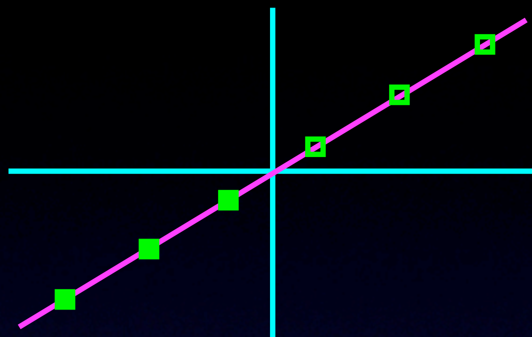
Leptogenesis

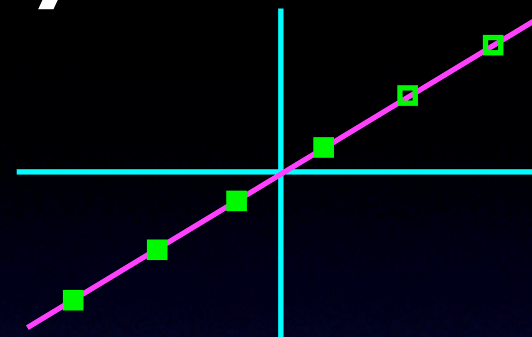
- Presumably three ν_R
- One of them lives long and decays late
- Majorana: $\nu_R = \bar{\nu}_R$
- @tree-level, decays 50:50 to ν_L+h, $\bar{\nu}_L$+h*
- @one-loop, $\Gamma(\nu_R \to \nu_L + h) \propto 1 - \epsilon$

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



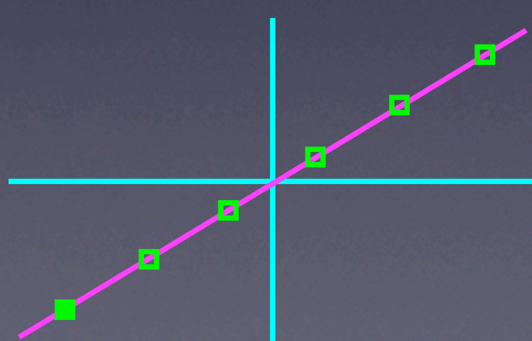
What anomaly can do

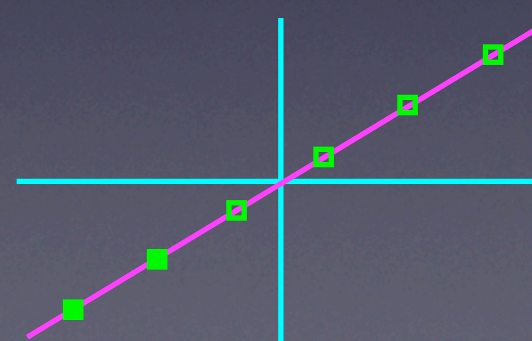




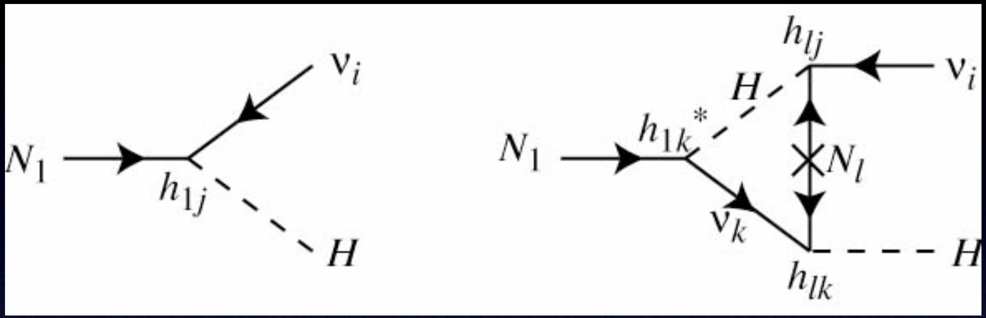
- 1,000,000,000 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,002 $\bar{\nu}$

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





How does it work?



- absorptive (imaginary) part of the amplitude

$$\log(m^2 - p^2 - i\epsilon) = \text{real part} - i\pi\theta(p^2 - m^2)$$

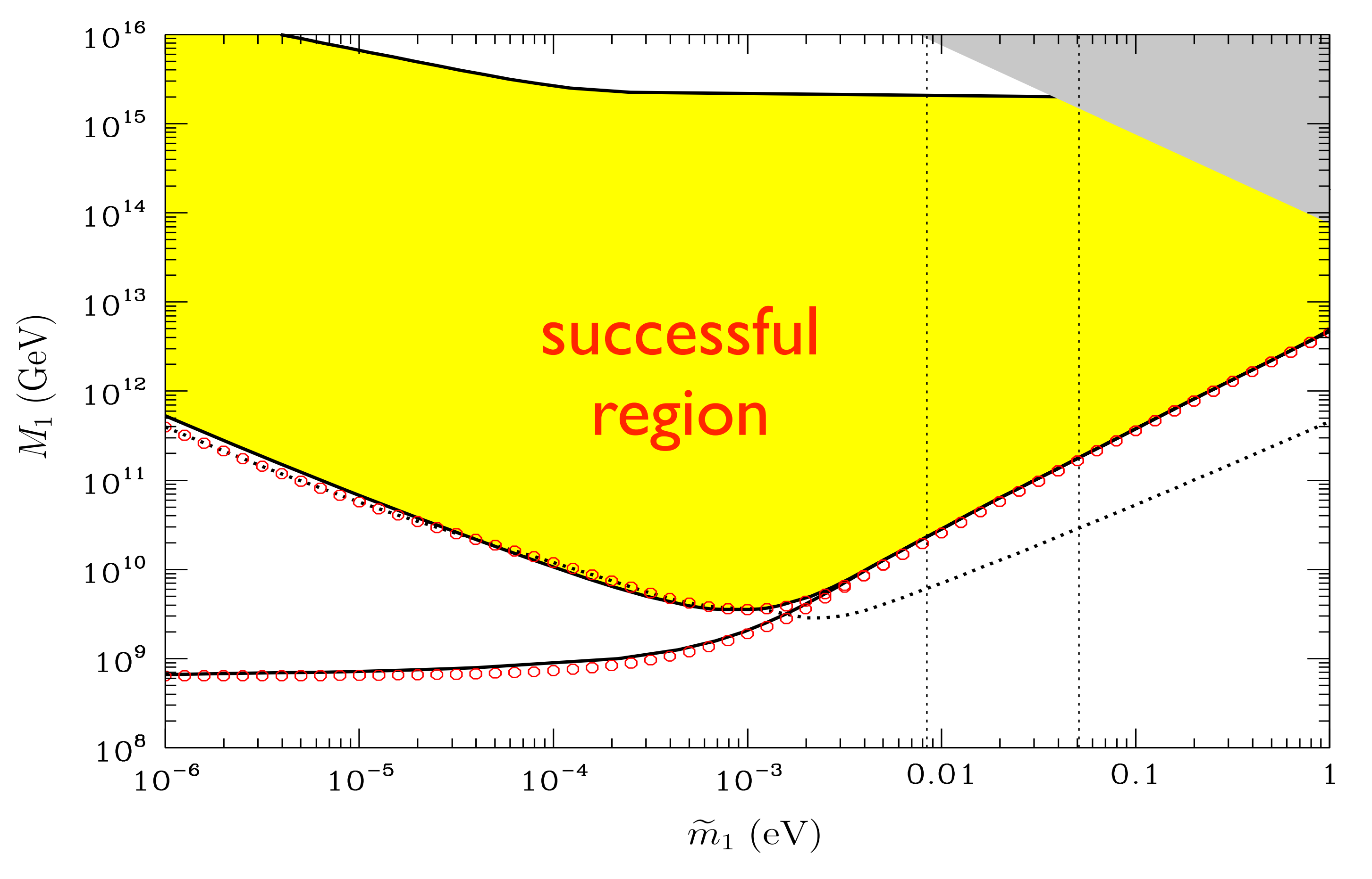
$$A(\nu_{R1} \to \nu_i h) \sim h_{1j} - i\pi h^*_{1k} h_{lk} h_{lj}$$

$$A(\nu_{R1} \to \bar{\nu}_i h^*) \sim h^*_{1j} - i\pi h_{1k} h^*_{lk} h^*_{lj}$$

$$\Gamma(\nu_{R1} \to \nu_i h) - \Gamma(\nu_{R1} \to \bar{\nu}_i h^*)$$

$$\propto \Im m(h_{1j} h_{1k} h^*_{lk} h^*_{lj})$$

Non-trivial success!



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

di Bari, Plümacher, Buchmüller

How do we test it?

build a 10^{14} GeV collider

indirect evidences

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

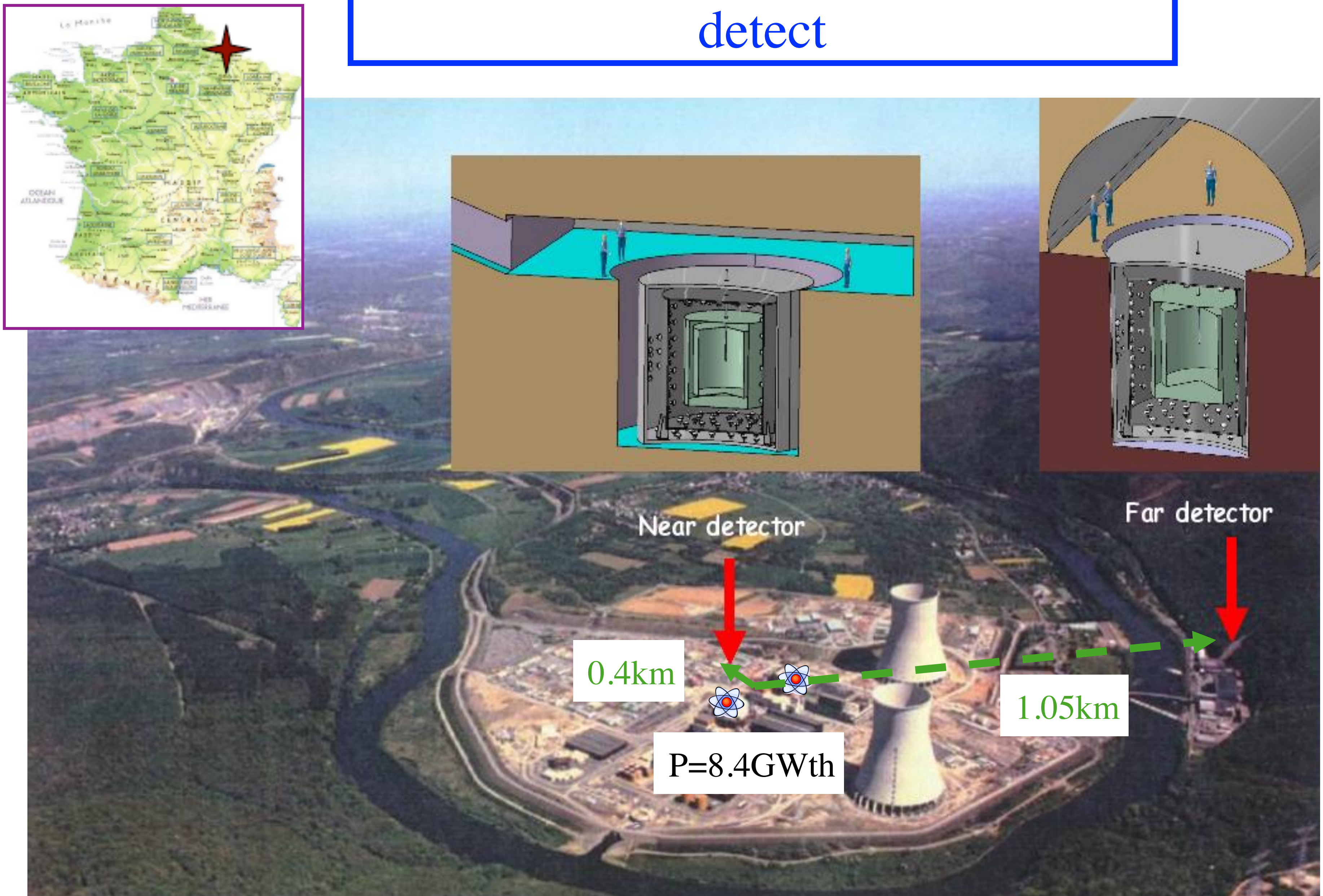
Mixing Angles

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

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

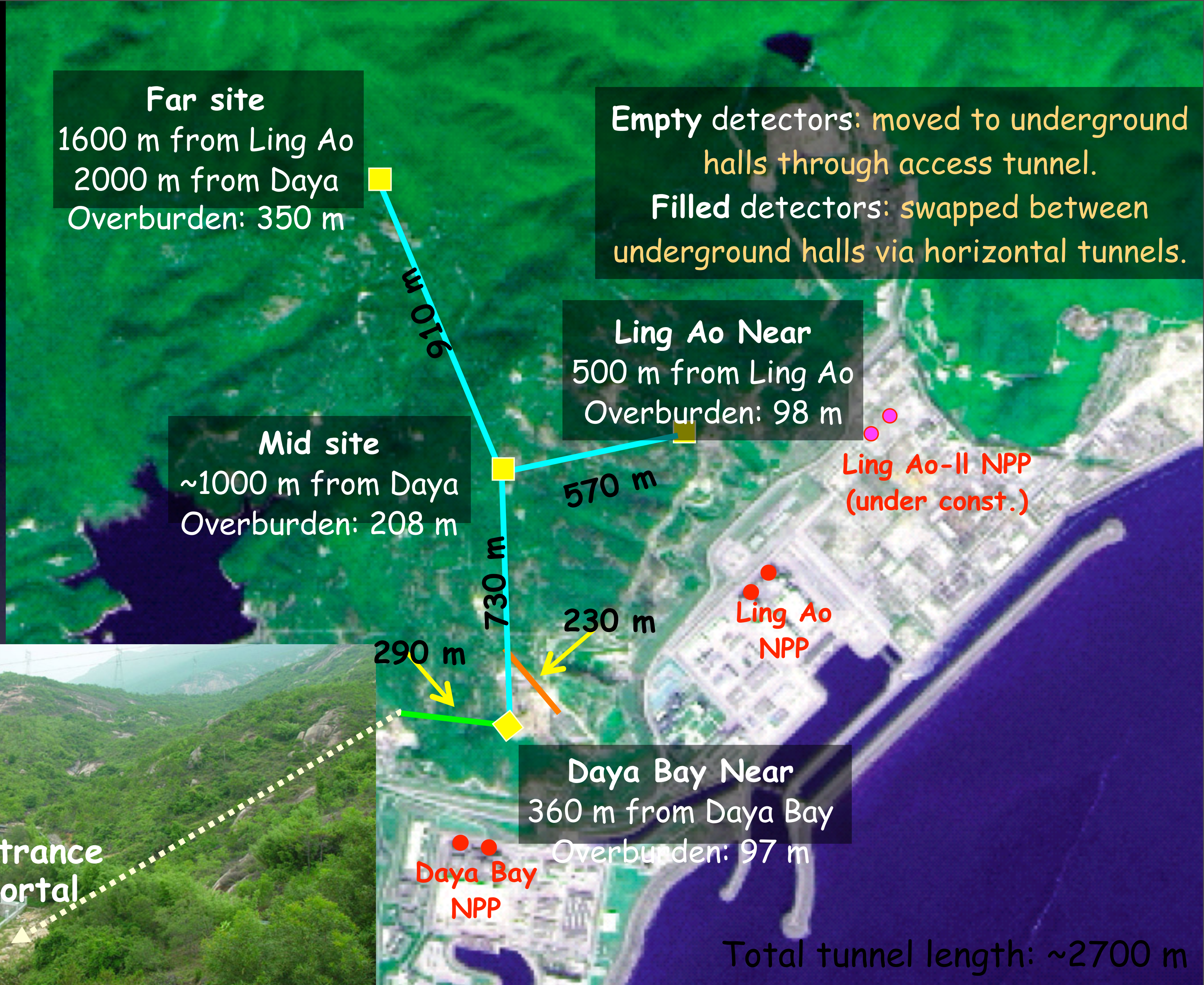
atmospheric reactor limit solar

Double Chooz Experiment to detect



Daya Bay near Hong Kong

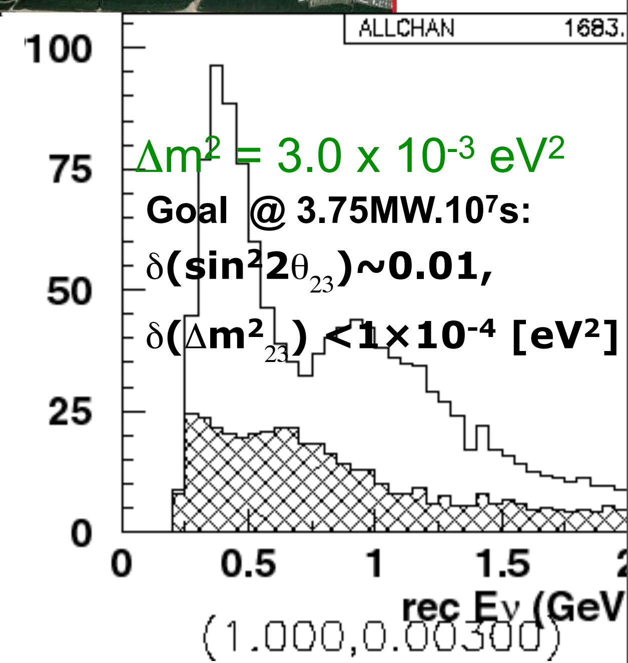
also RENO in Korea



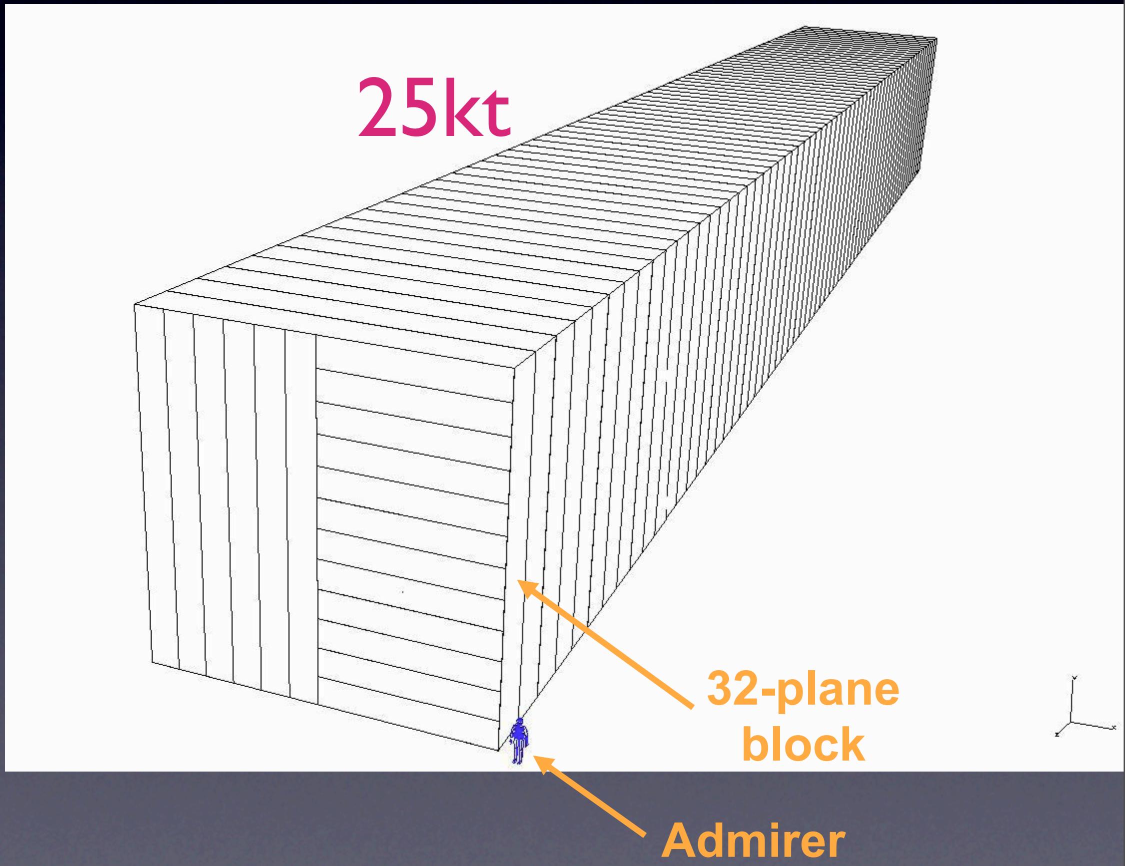
Tokai-to-Kamioka (T2K)
long baseline neutrino oscillation experiment

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

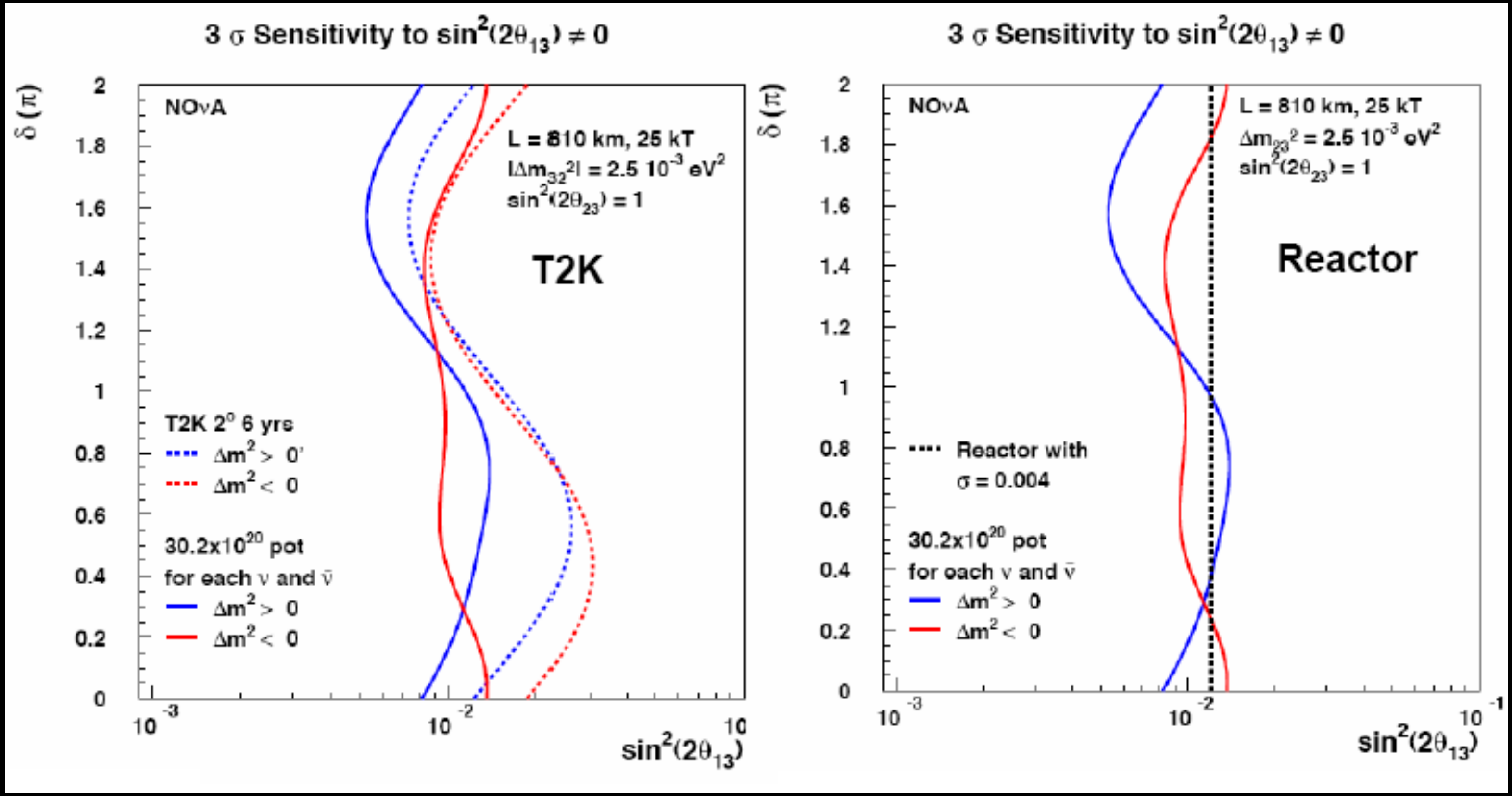
$1600\nu_\mu CC/yr/22.5kt$ (2.5deg)



NOνA
Fermilab to Minnesota



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

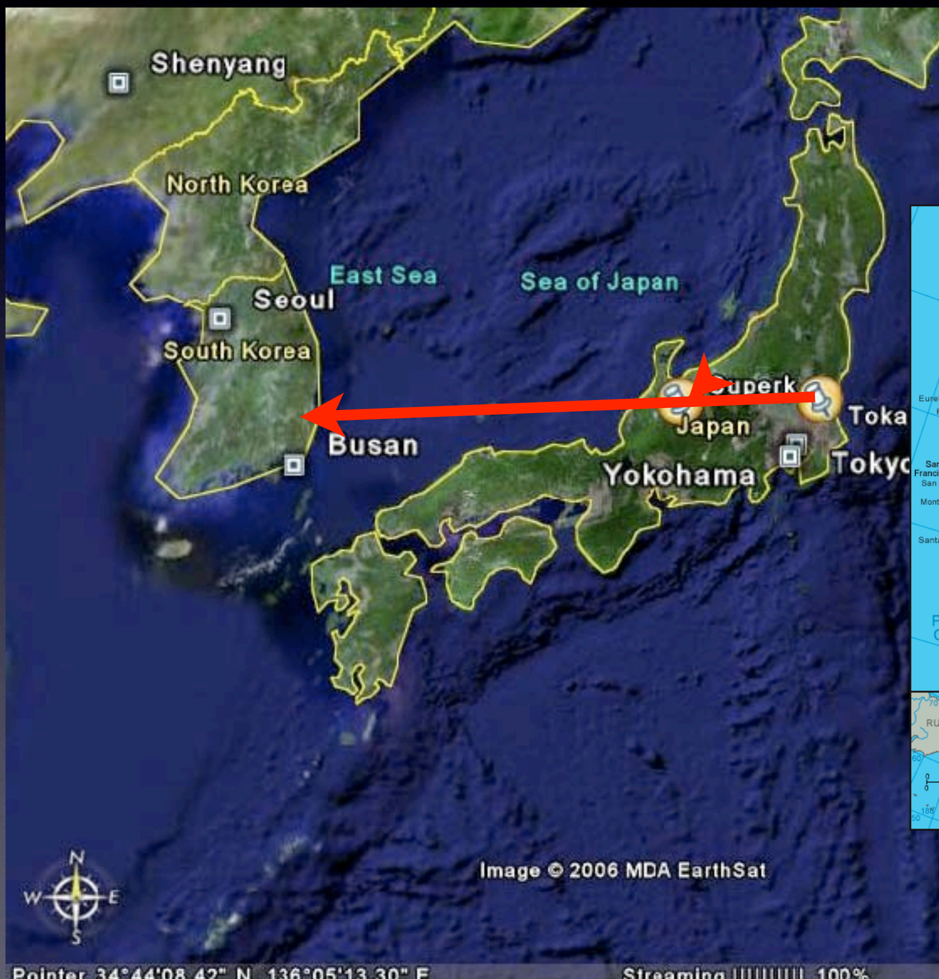


CP violation

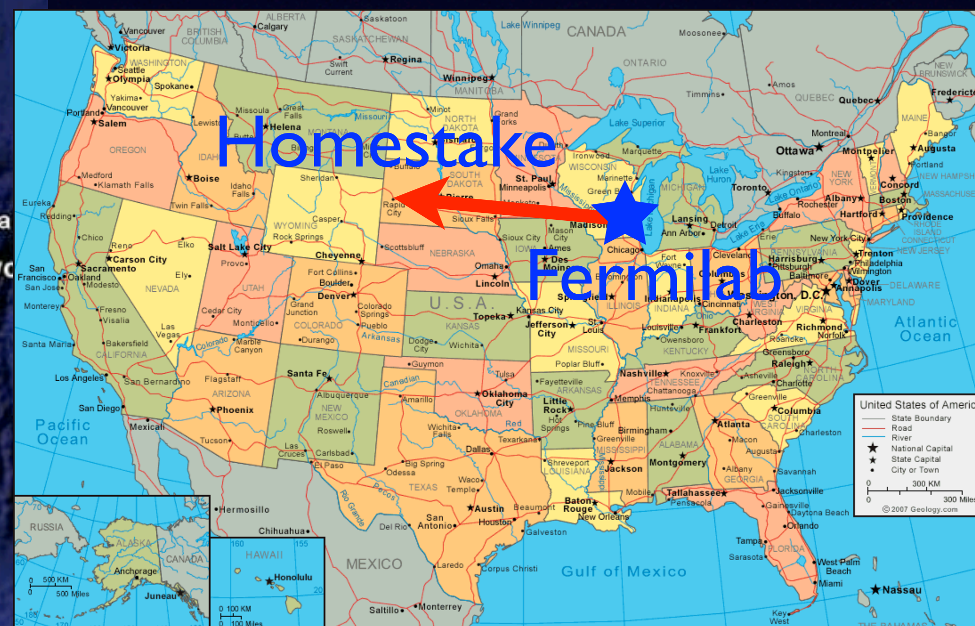
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

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

CP Violation?



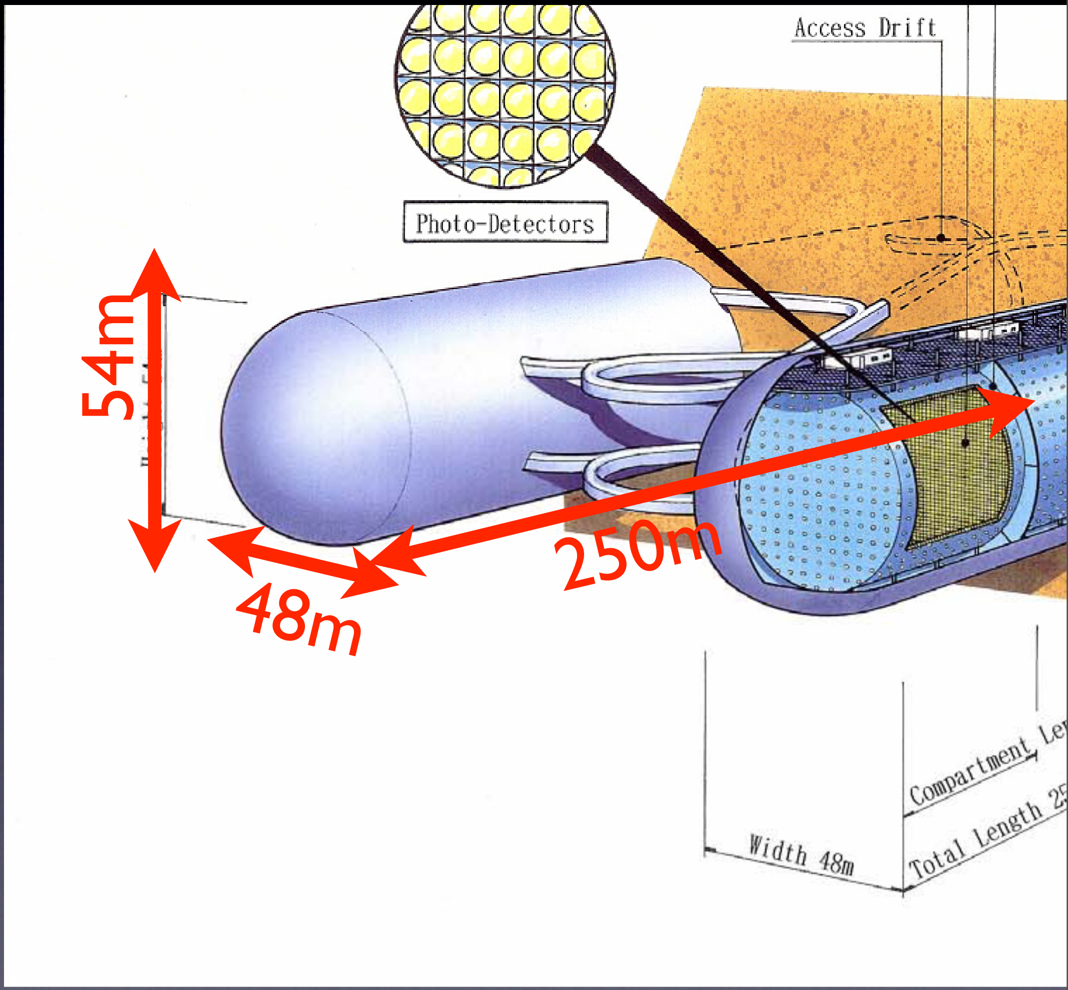
Shoot neutrinos over a thousand miles



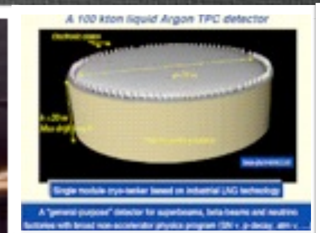
Try to see difference between neutrinos and anti-neutrinos

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



ν A High Intensity Neutrino Oscillation Facility in Europe

A⁺ A A⁻

MAIN MENU

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

EUROnu

EURONu

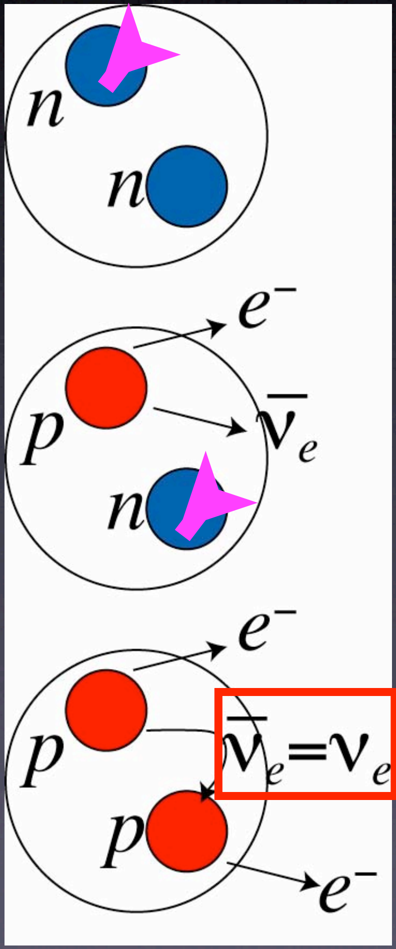
LATEST NEW

- Governance Structure
- What is EUROnu?

Turn anti-matter into matter

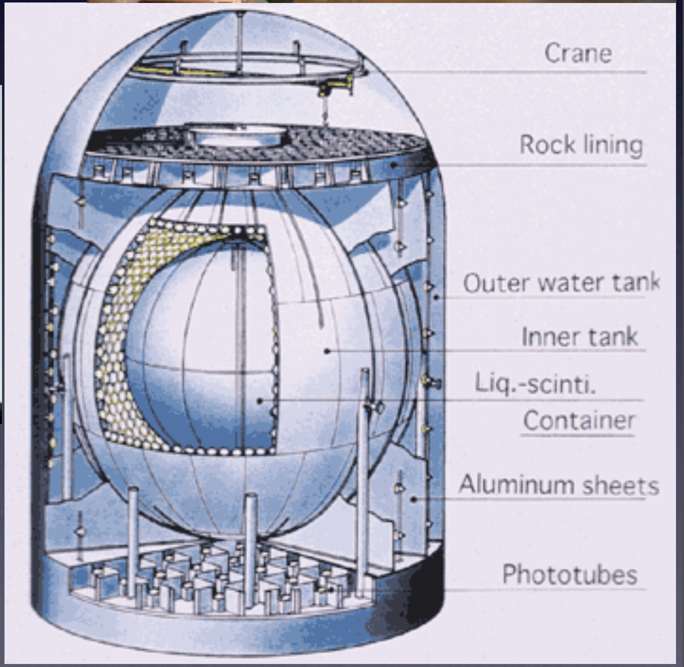
- Can anti-matter turn into matter?
- Maybe anti-neutrino can turn into neutrino because they don't carry electricity!
- 0νββ: $nn \rightarrow ppe^-e^-$ with no neutrinos
- can happen only once 10^{24} (trillion trillion) years

patience!



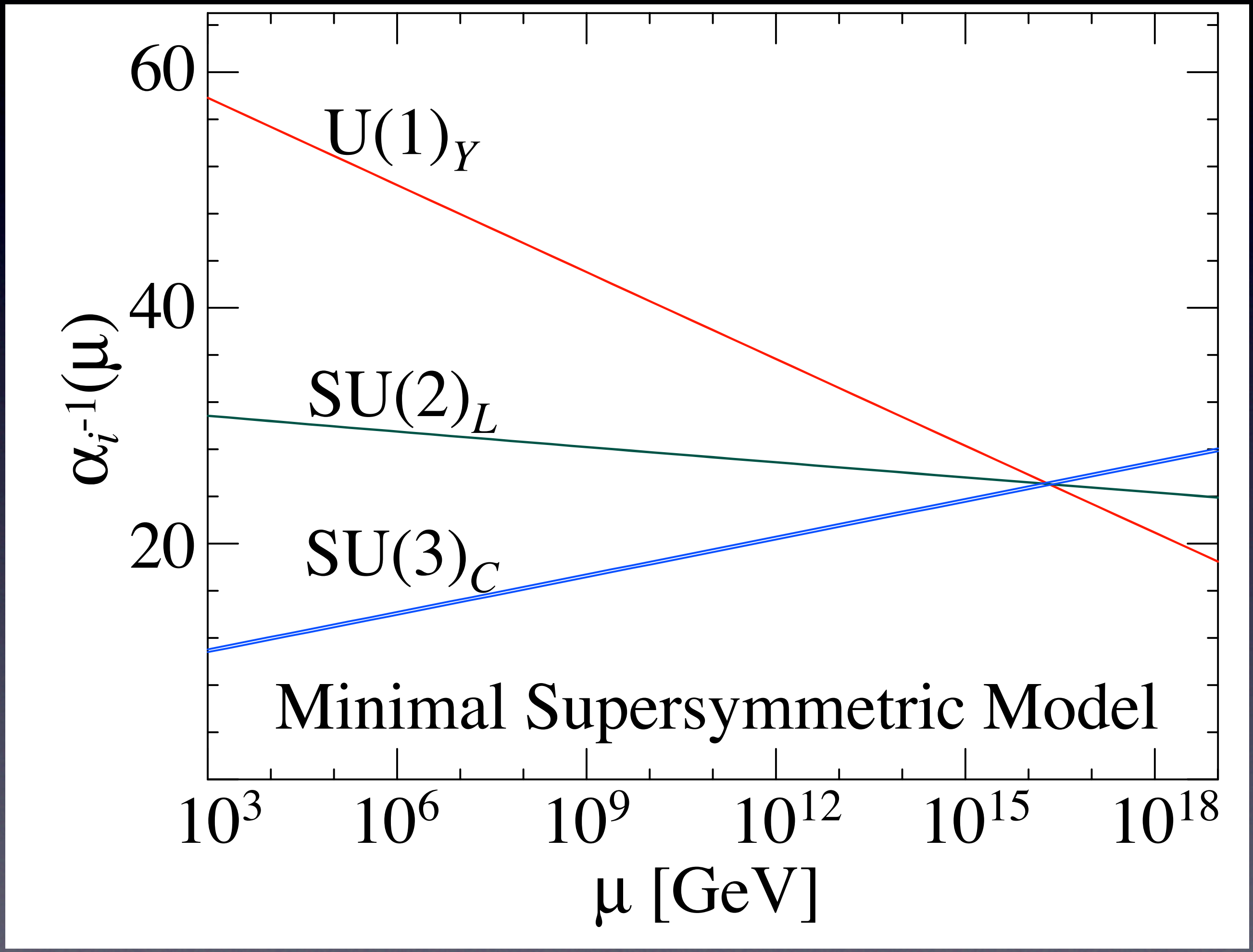
Need big underground experiments

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



KamLAND=1000t

Supersymmetry

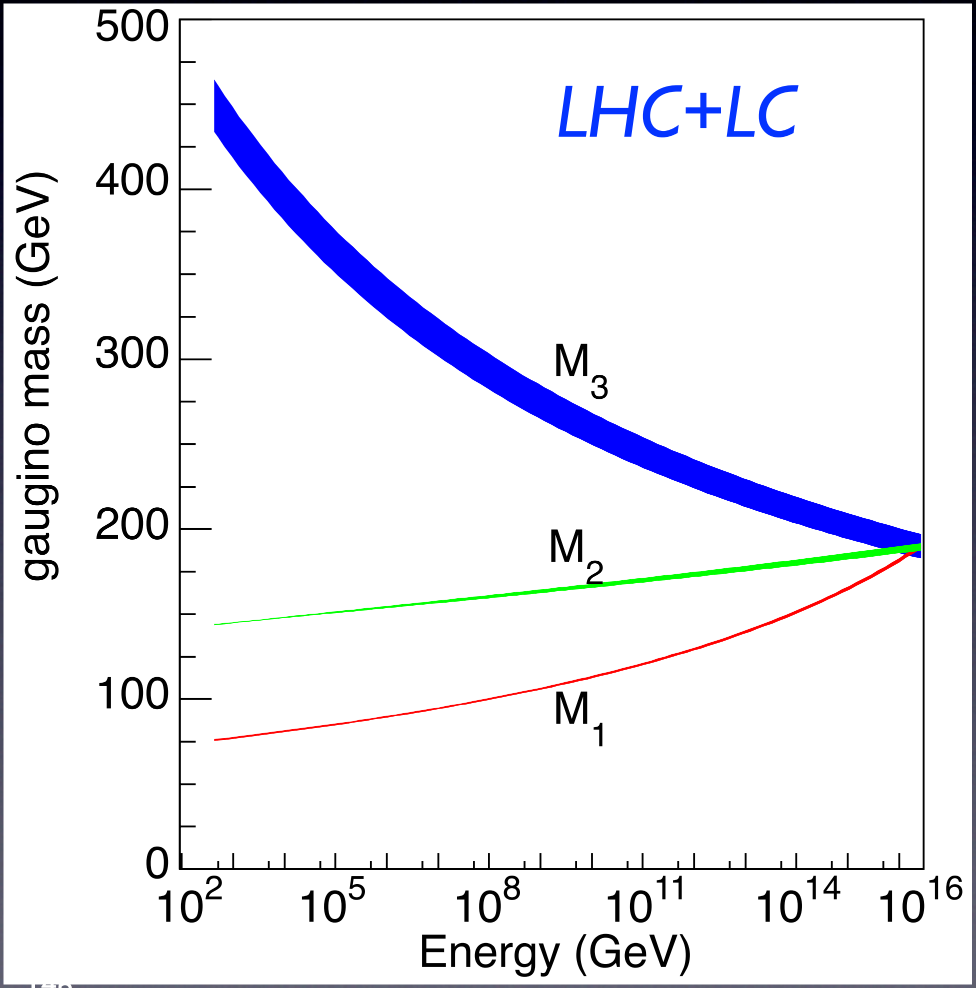


Superpartners probe high-scale physics

- Most exciting thing about superpartners beyond existence:

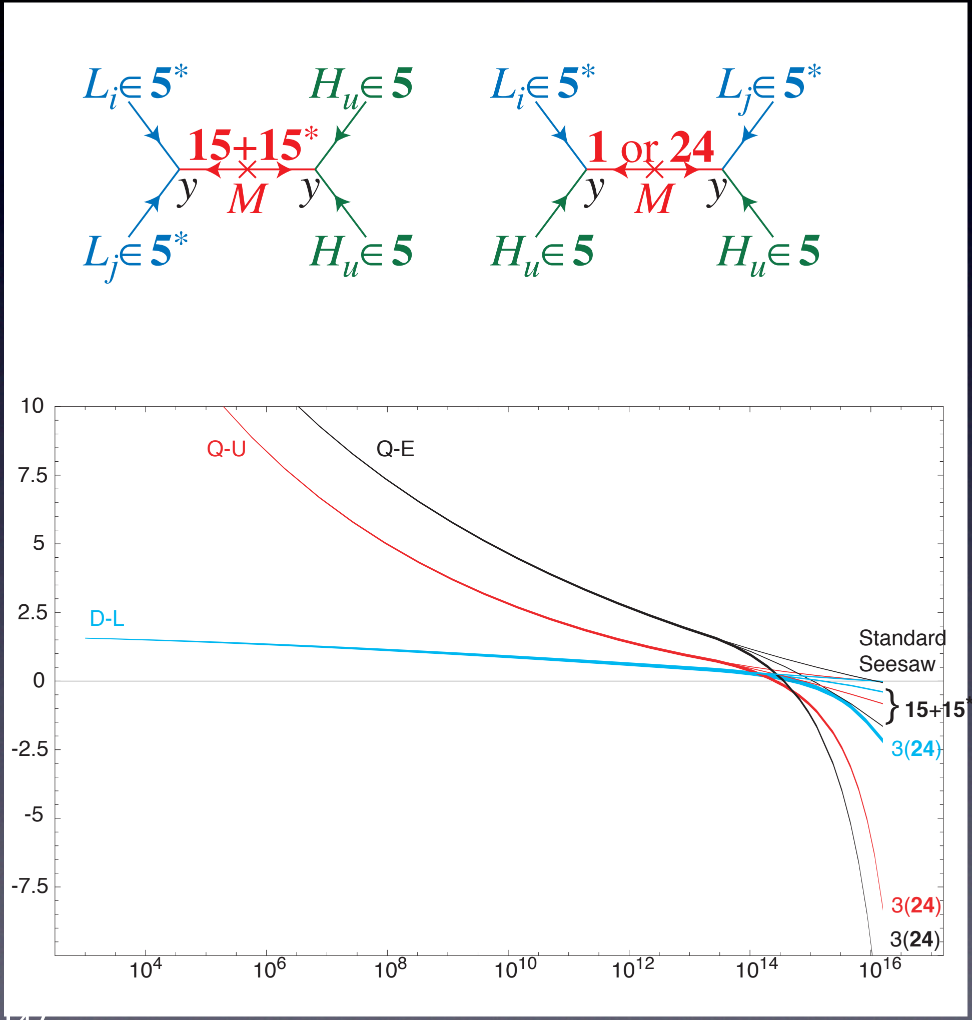
They carry information of small-distance physics to something we can measure

“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

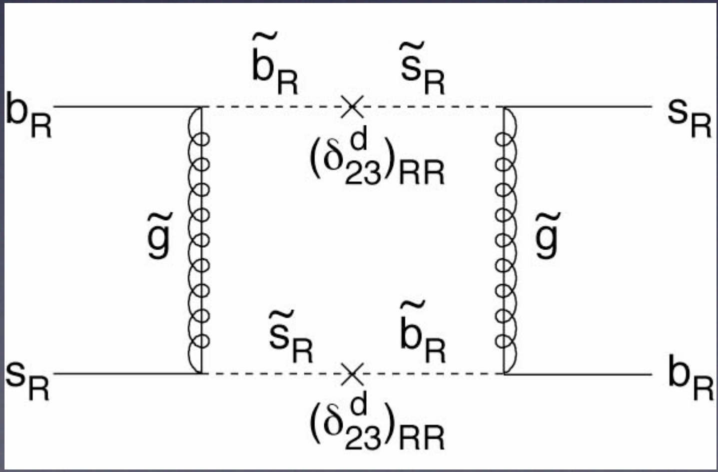


Buckley, HM

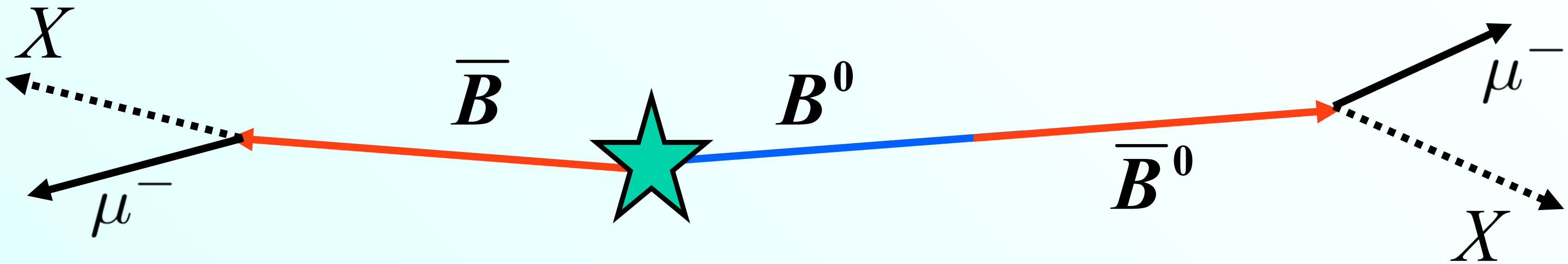
squark mixing

- 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:**

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

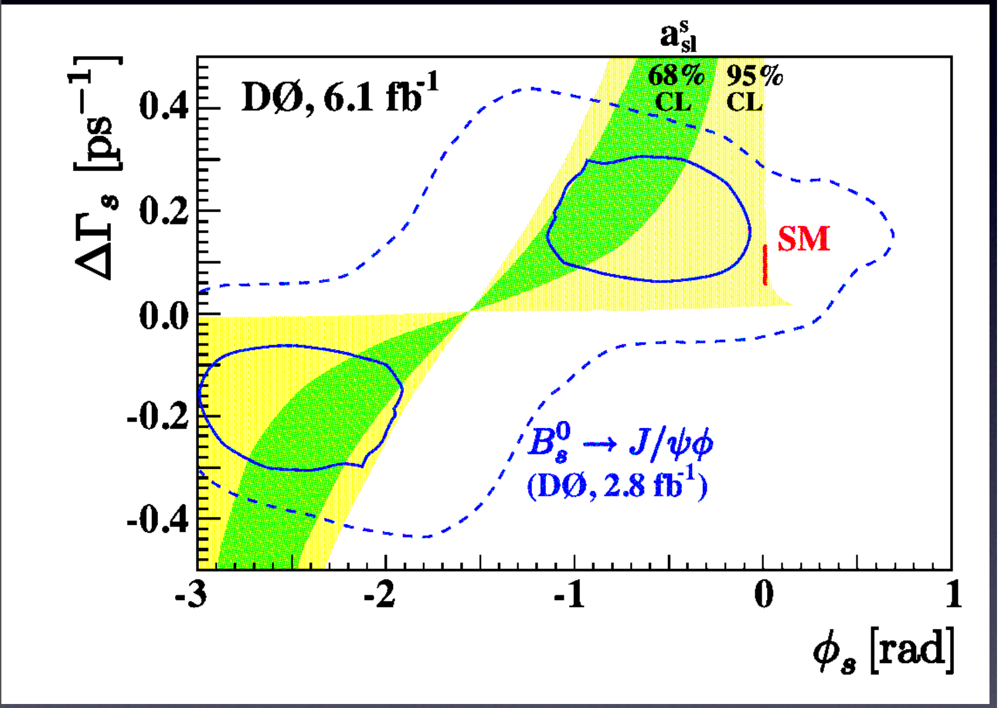
$$A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

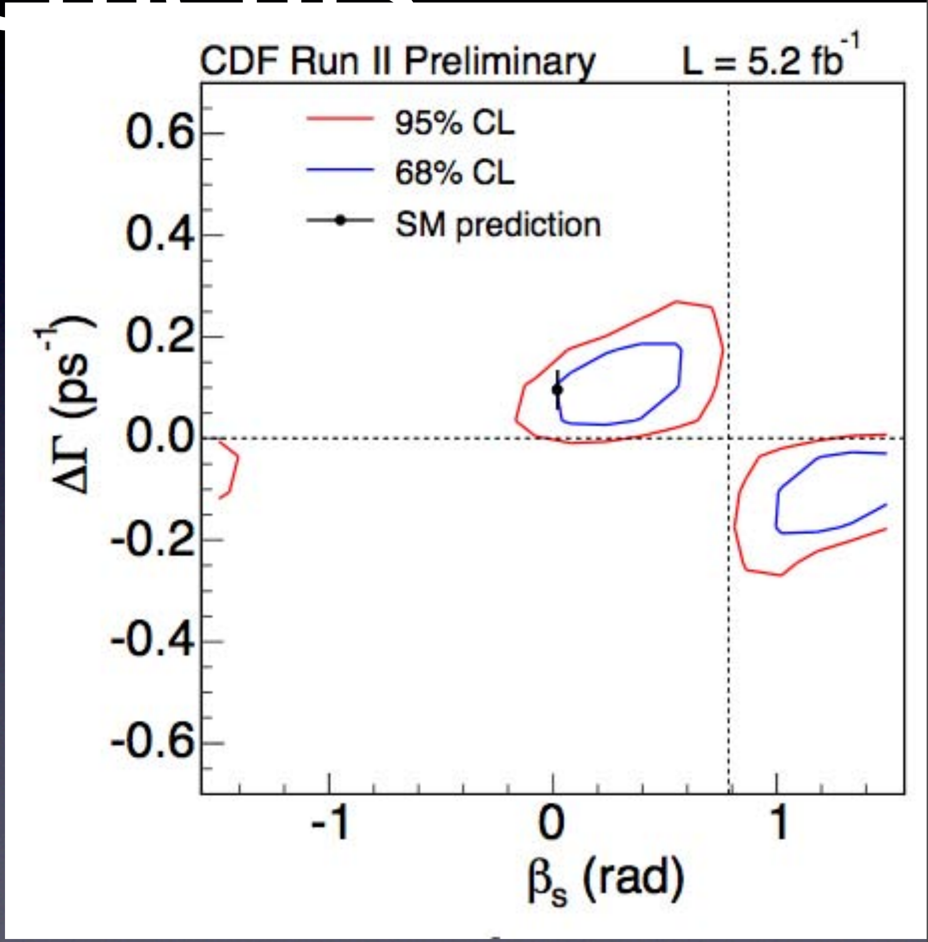
$$A_{sl}^{b}(SM) = (-0.023^{+0.005}_{-0.006})\%$$

G.Borissov@Fermilab

May 14, 2010

Comparison with other measurements





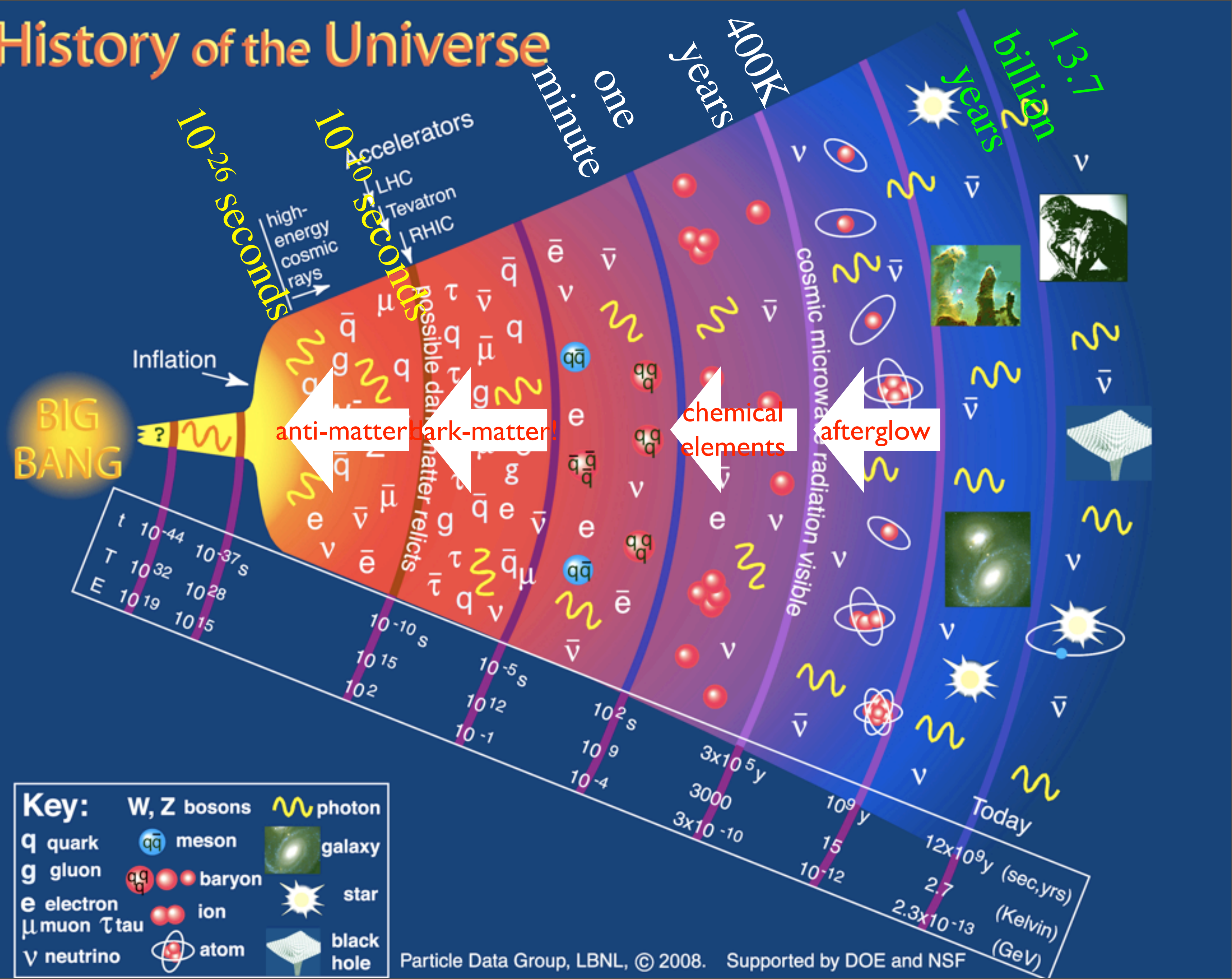
LHCb will have a large sample of $B_s \to J/\psi\ \phi$

May 25@FPCP2010
Louise Oakes

How we survived the Big Bang

- ν_R without distinction between matter and matter (possibly only with neutral particles!)
- once they are produced, they eventually decay
- 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!

History of the Universe



Electroweak Baryogenesis

testable baryogenesis?

- If the energy scale of baryogenesis is the electroweak scale, it may be directly testable!
- Lower the energy=temperature, slower then expansion rate $H \approx T^2/M_{Pl}$
- less likely to go out of equilibrium
- need something "violent"

Standard Model

- Standard Model has all three ingredients
- Baryon number violation
  - Electroweak anomaly (sphaleron effect)
- CP violation
  - Kobayashi–Maskawa phase
- Non-equilibrium
  - First-order phase transition of Higgs Bose–Einstein condensate

Electroweak Baryogenesis

- Two big problems in the Standard Model
  - First order phase transition requires m_H<60GeV
  - Need new source of CP violation because

$J \propto \det[M_u^\dagger M_u, M_d^\dagger M_d]/T_{EW}^{12} \sim 10^{-20} << 10^{-10}$

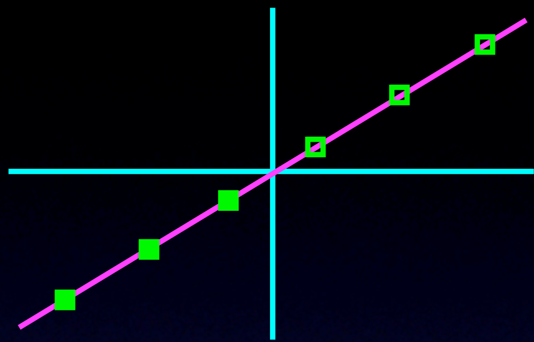
- Minimal Supersymmetric Standard Model
  - First order phase transition possible if $m_{\tilde{t}_R} < 160\mathrm{GeV}$
  - New CP violating phase $\arg(\mu^* M_2)$

$e.g.$, (Carena, Quiros, Wagner), (Cline, Joyce, Kainulainen)

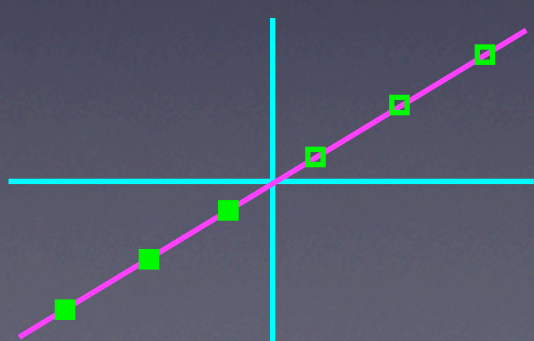
B-violation in the Standard Model

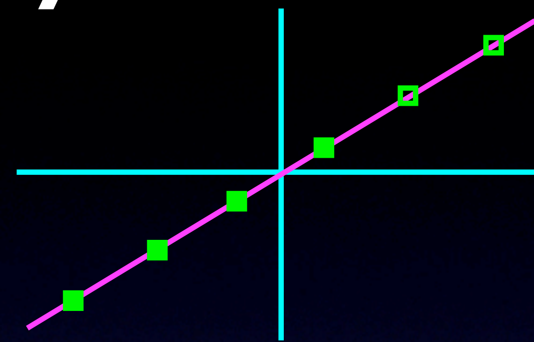
- Start with $B=L=0$
- $B-L$ preserved
- some process creates $B=L\neq 0$
- immediately shut off anomaly to protect it
- Key: right-handed fermions do not couple to *W* and not subject to anomaly

What anomaly can do

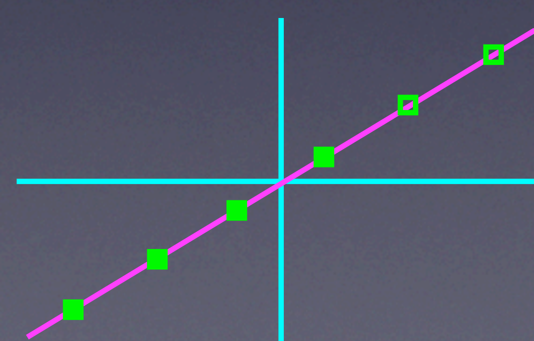


- 1,000,000,000 q
- 1,000,000,000 $\bar{q}$
- 1,000,000,000 ν
- 1,000,000,000 $\bar{\nu}$

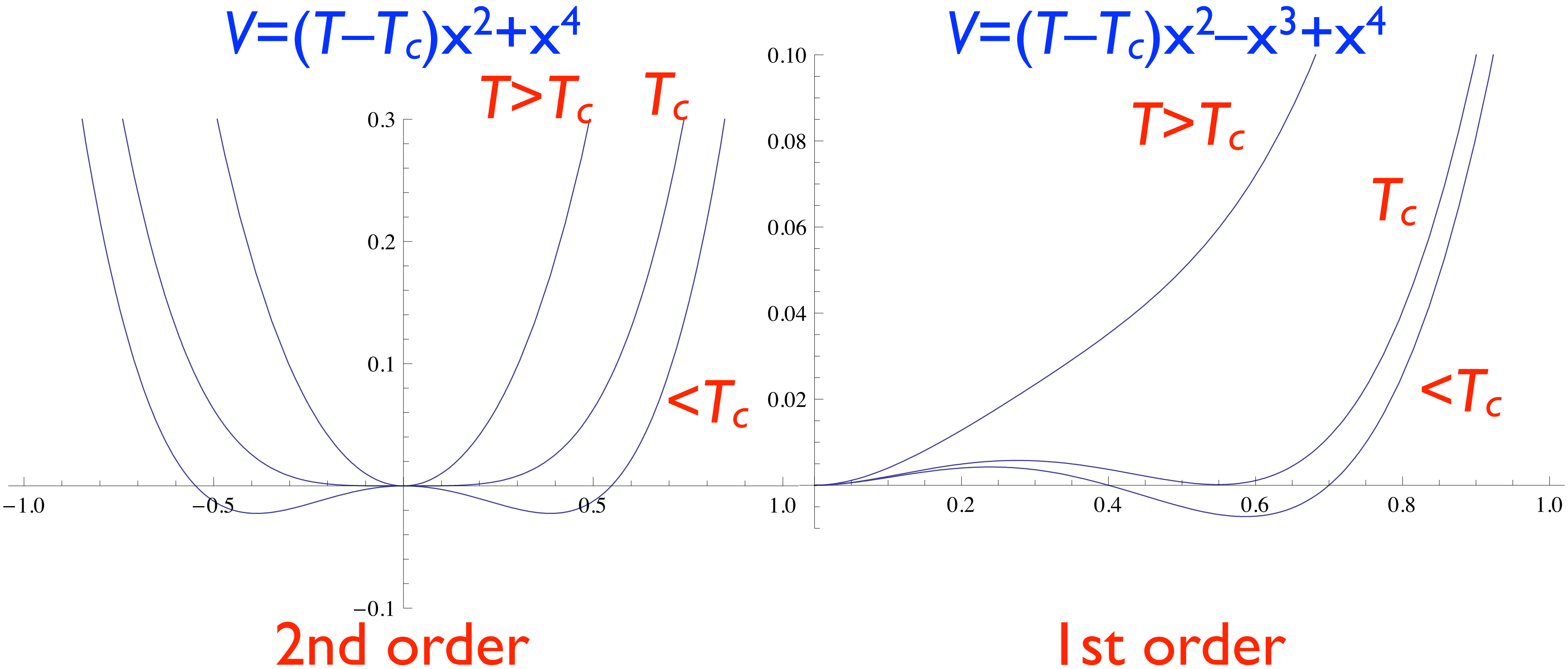




- 1,000,000,001 q !
- 1,000,000,000 $\bar{q}$
- 1,000,000,001 ν
- 1,000,000,000 $\bar{\nu}$



Order of phase transition



in relativistic QFT, ϕ^3 term possible from a loop of massless boson coupled to ϕ

Phase Transition

- If Higgs light, its own loop contributes to H^3 term and can achieve the 1st order PT
- But it would require m_h<60 GeV
- need a new massless scalar with a substantial coupling to Higgs
- scalar top quark $\tilde{t}$ in supersymmetry an excellent candidate

$$\Rightarrow m_{\tilde{t}} \sim m_t$$

CP Violation

- Minimal Supersymmetric Standard Model has many parameters that can violate CP
- Example: mixing between charged wino and charged higgsino

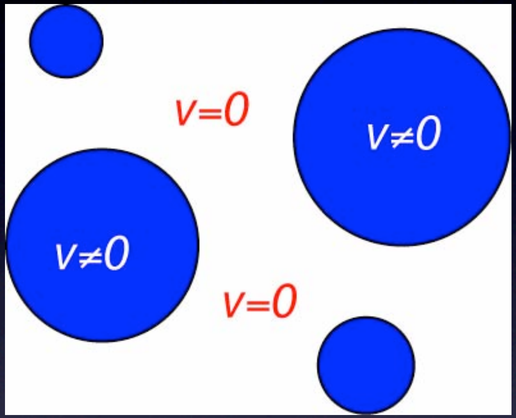
$$\begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

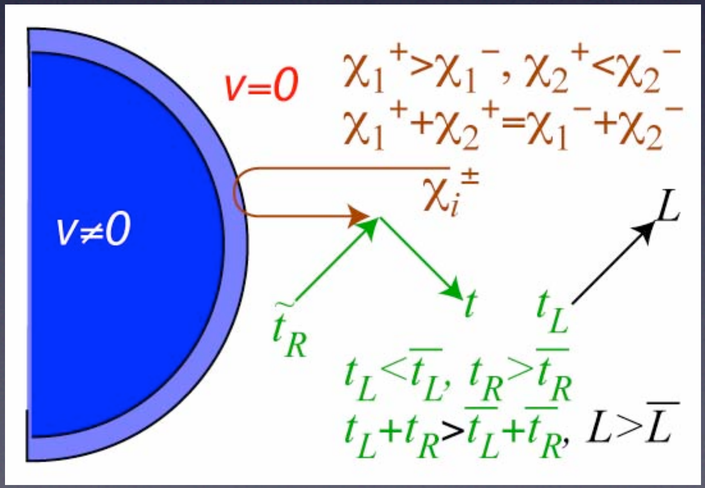
- Both M_2 and μ complex
- their relative phase $\arg(M_2 \mu^*)$ physical


FASTEN
SEAT
BELT

Scenario

- First order phase transition
- Different reflection probabilities for chargino species
- Chargino interaction with thermal bath produces an asymmetry in top quark
- Left-handed top quark asymmetry partially converted to lepton asymmetry via anomaly
- Remaining top quark asymmetry becomes baryon asymmetry





Parameters

- Chargino mass matrix

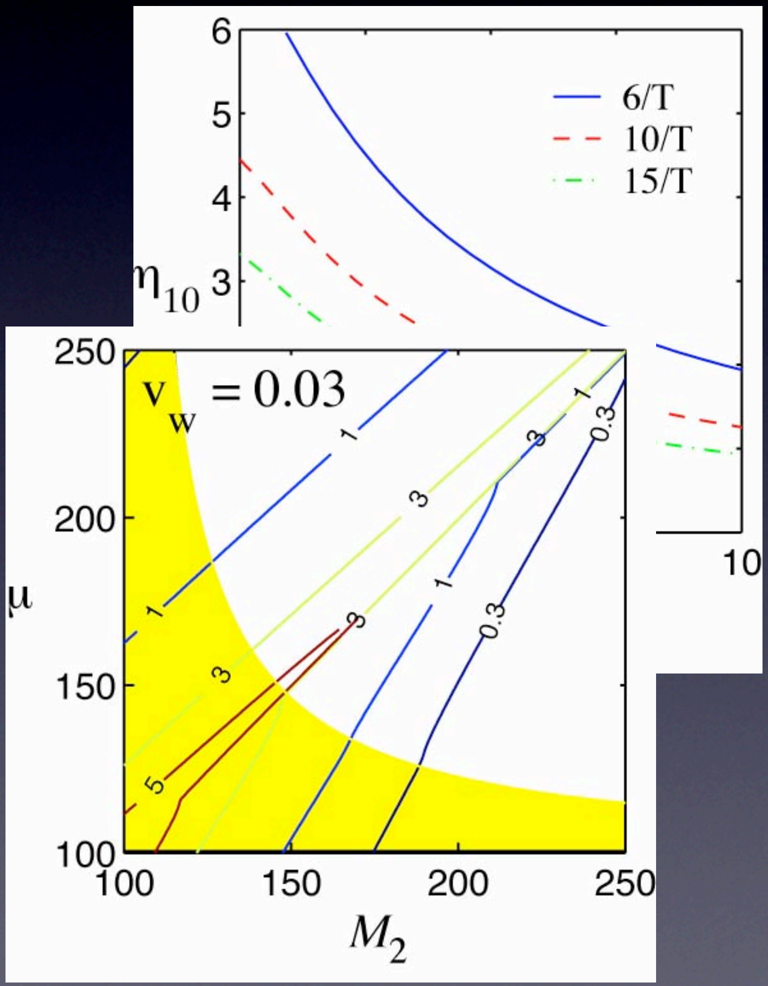
$$\begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

Relative phase $\arg(\mu^* M_2)$

unphysical if $\tan\beta \to \infty$

- Need fully mixed charginos $\Rightarrow \mu \sim M_2$

(Cline, Joyce, Kainulainen)



SUSY Mass Spectrum

- To avoid LEP limit on lightest Higgs boson, need left-handed scalar top > TeV
- Light right-handed scalar top, charginos
- Need $\arg(M_2\mu^*) \sim O(1)$ with severe EDM (two-loop!) constraints from e, n, Hg

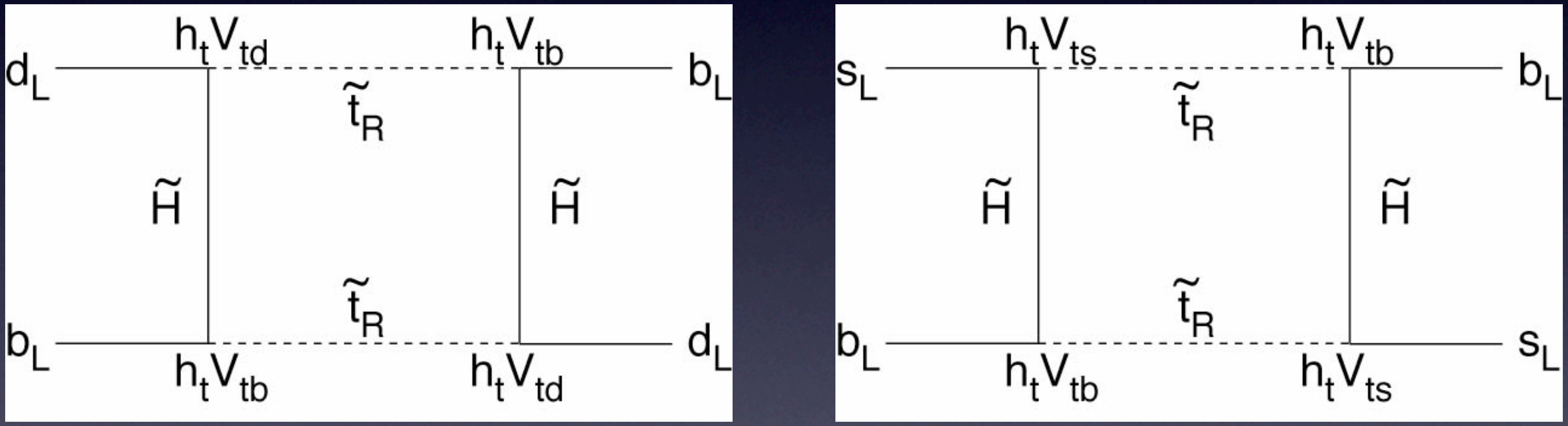
$\Rightarrow$ 1st, 2nd generation scalars > 10 TeV

cf. Carena, Quiros, Wagner claim $\arg(M_2\mu^*) > 0.04$ enough

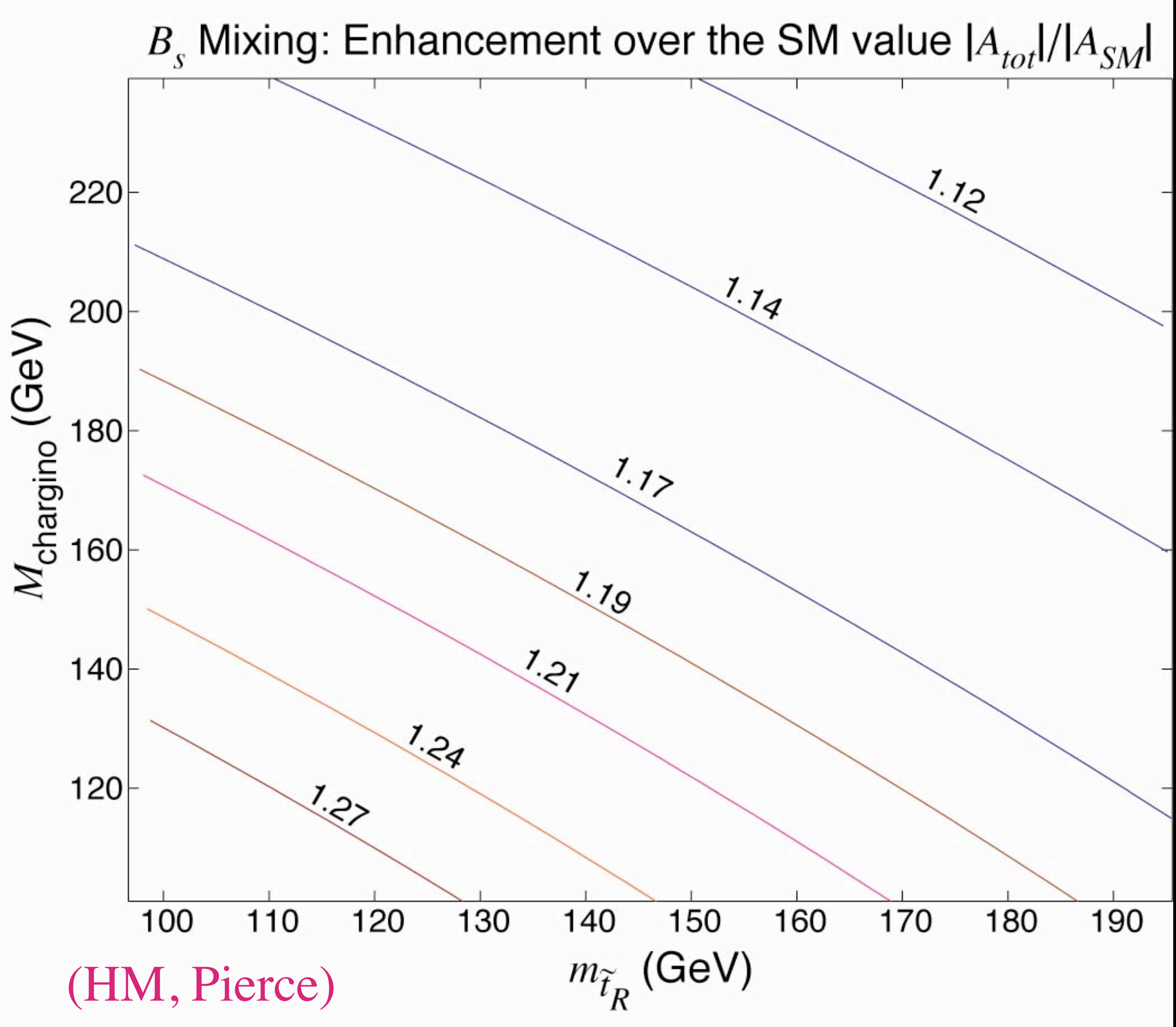
EDM constraint is weaker, but rest of phenomenology

Signals of Electroweak Baryogenesis

- ~20% enhancements to Δm_d, Δm_s with the same phase as in the SM (HM, Pierce)



- Find Higgs, stop, charginos
- Eventually need to measure the phase in the chargino sector at LC to establish it (Barger et al)


B_s Mixing: Enhancement over the SM value $|A_{tot}|/|A_{SM}|$
1.12
1.14
1.17
1.19
1.21
1.24
1.27
$M_{chargino}$ (GeV)
220
200
180
160
140
120
100
110
120
130
140
150
160
170
180
190
$m_{\tilde{t}_R}$ (GeV)
(HM, Pierce)

B-physics Challenges

- Lattice QCD: need B parameters at 5%
  $\Rightarrow$ then B_s mixing in business
- V_{td} has been determined from B mixing

Not legitimate in presence of SUSY loop

- Need to determine V_{td} from other sides, angles for consistency check
- $K^+ \to \pi^+ \nu \bar{\nu}$ a *clean* measurement of V_{td}

Caveat

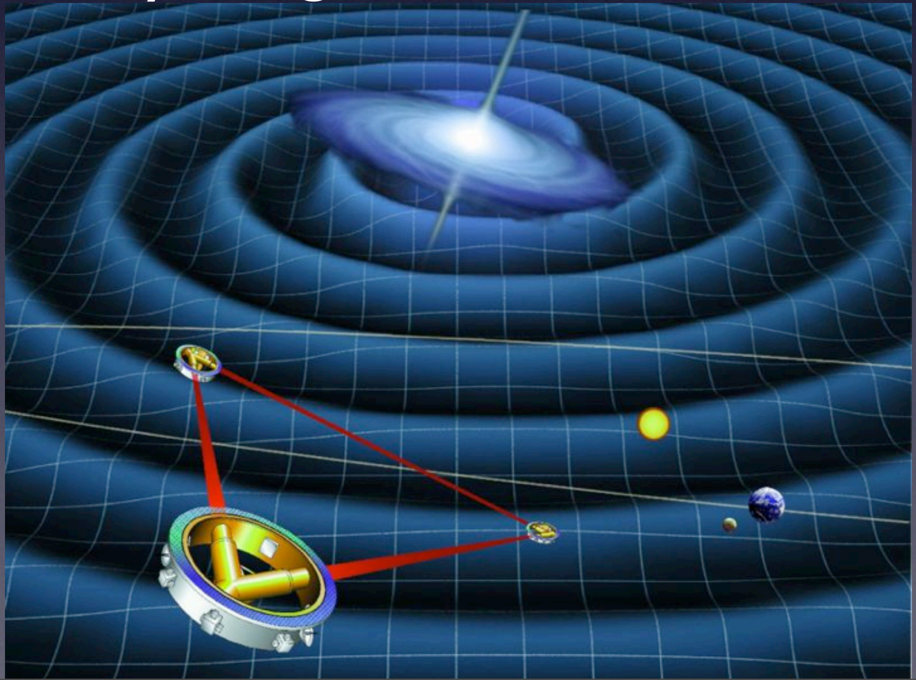
- Many of the tensions in the model are specific to MSSM
  - CP violation requires small $\tan\beta$
  - first order PT requires light $\tilde{t}$
  - Higgs limit requires heavy $\tilde{t}$, large $\tan\beta$
  - nearly maximal CP vs EDM
- More general Higgs sector not studied in detail
- some of them may lead to interesting flavor physics signature

Caveat

- dynamics of phase transition quite complicated and all prediction are subject to some large uncertainties

gravitational wave

- 1st order phase transition at the electroweak scale may produce gravitational waves from bubble coalescence in the LISA frequency range



too many theories for a single number

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!