Matter-Antimatter Asymmetry and the Early Universe

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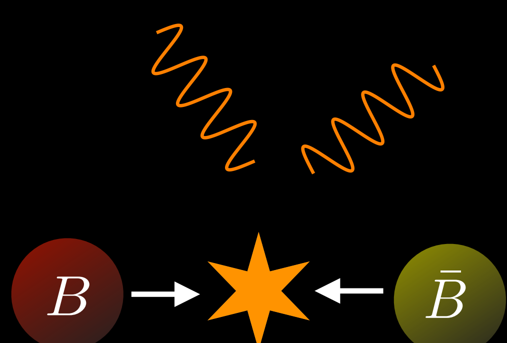
RICE

*thanks to Dr. Marcos Garcia for help in preparation of this talk.

synopsis

- evidence for matter-antimatter asymmetry
- quantifying the asymmetry
- mechanism ?
- summary

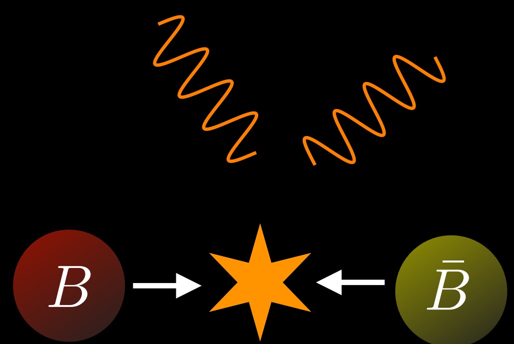
antimatter ?

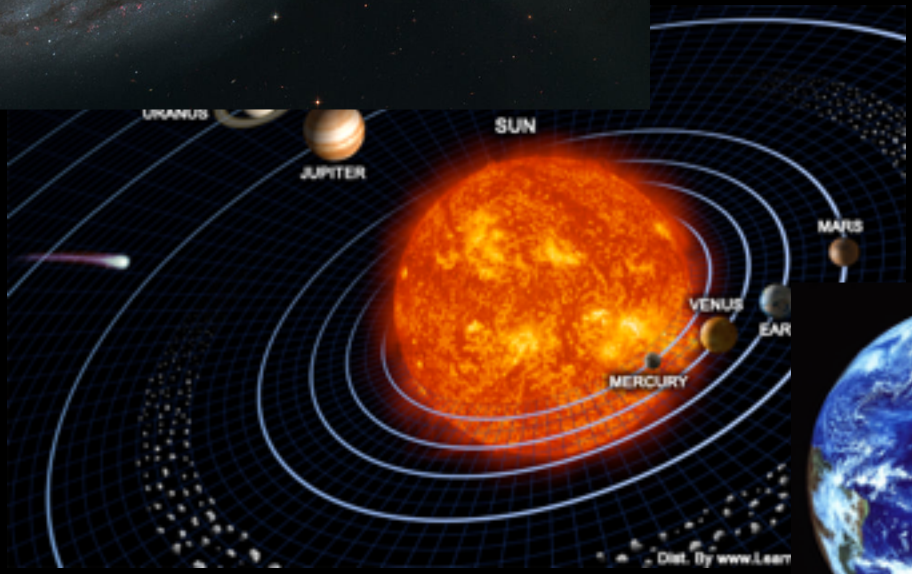


antiprotons ?

clusters : $R \sim 10^7$ lyrs

$$\frac{n_{\bar{B}}}{n_B + n_{\bar{B}}} \lesssim 10^{-7}$$ antiproton fraction



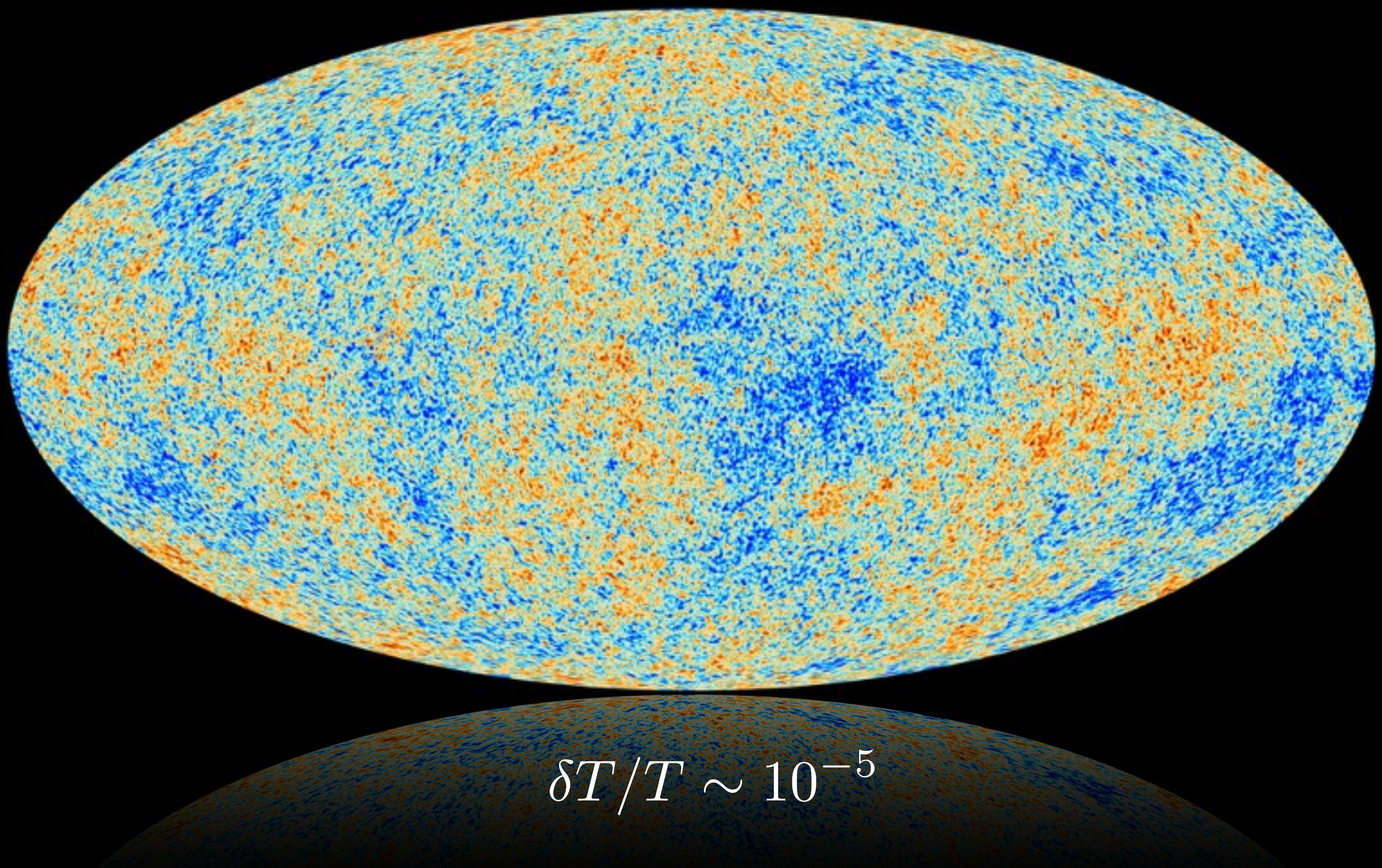


for overview of limits, see for e.g. Balmoos (2014)
& review by Canetti et. al (2012)

for positrons fraction in cosmic rays, see
for example AMS-02, PAMELA, Fermi etc.
also see AMS-01/02 for limits on He nuclei

widely separated matter/antimatter regions not feasible

Planck 2015

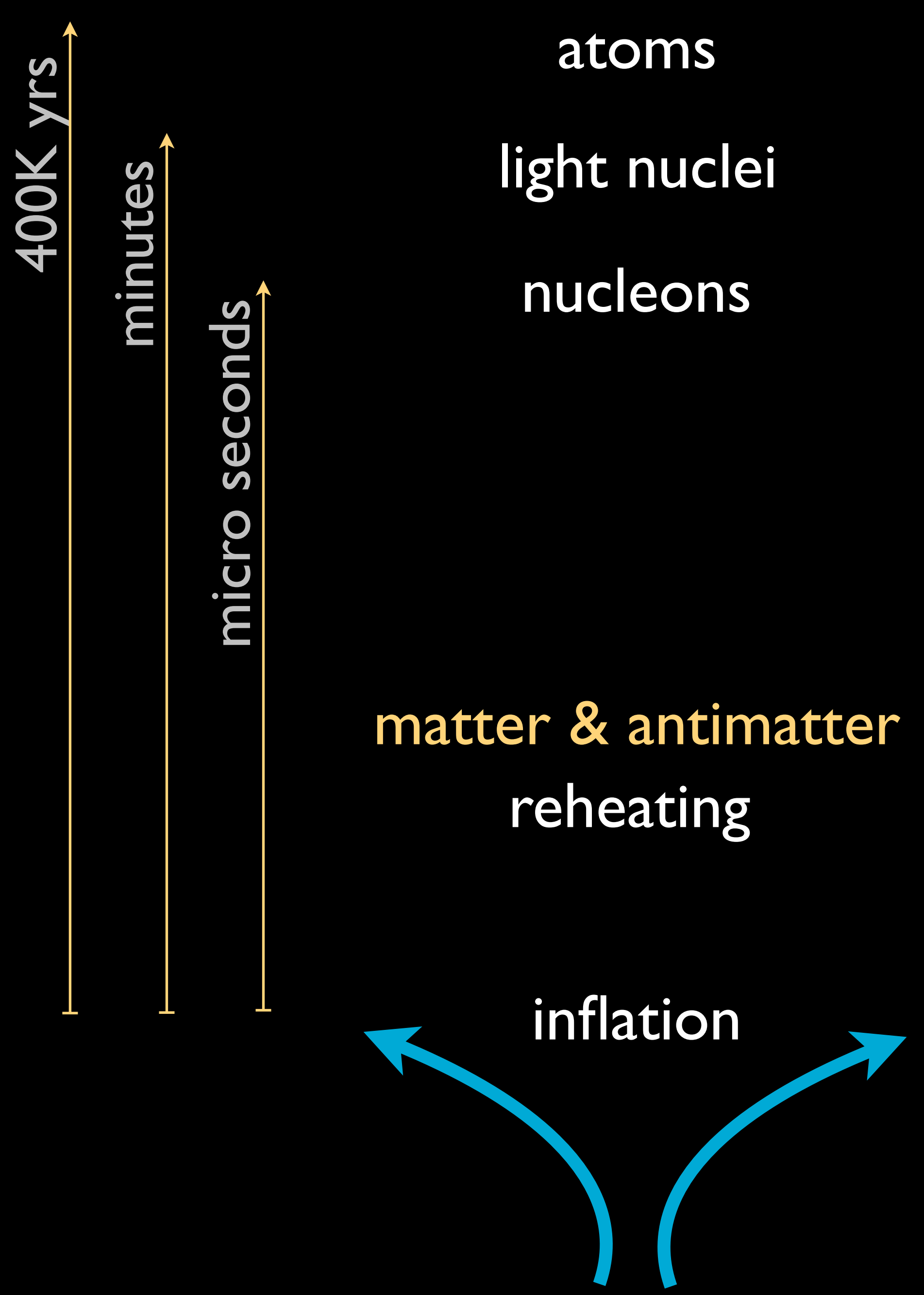


$$\delta T/T \sim 10^{-5}$$

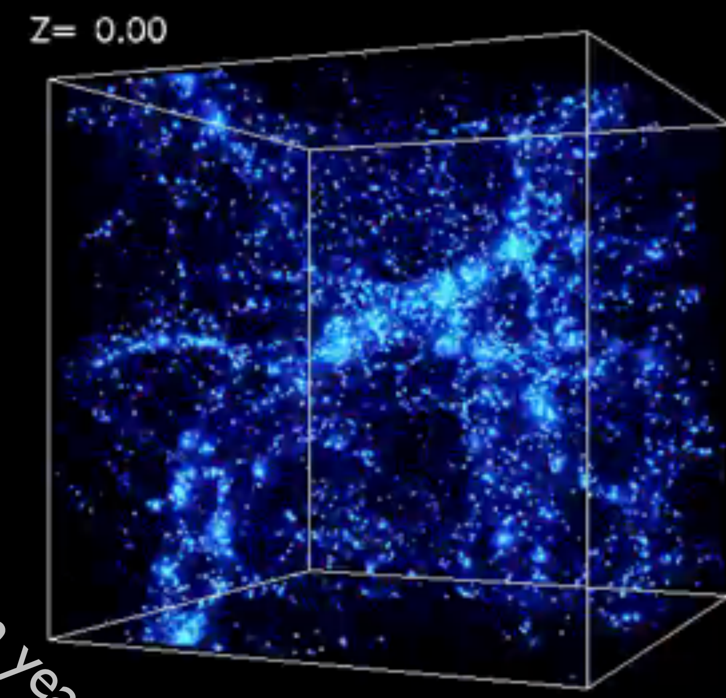
uniformity in the cosmic microwave background precludes large separations between matter and antimatter regions at recombination (Cohen et. al 1997)

when was
the asymmetry generated ?

cosmic history



cosmic history



400K yrs

minutes

micro seconds

atoms

light nuclei

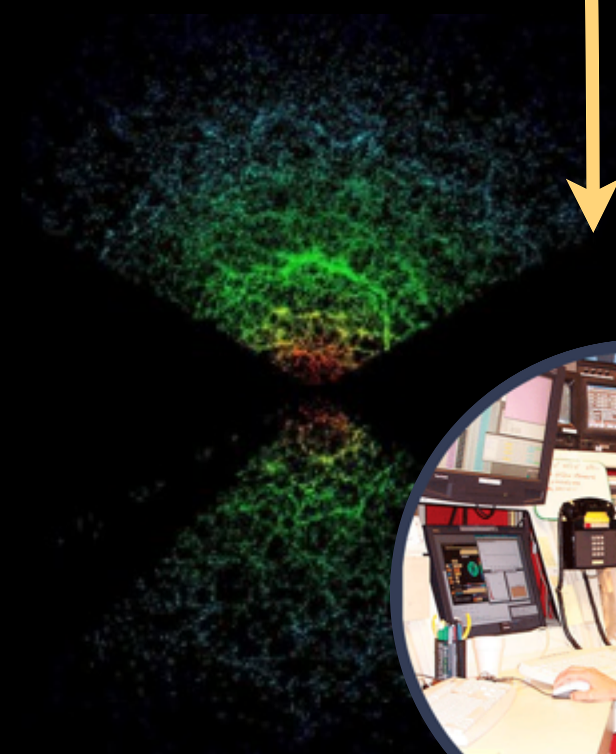
nucleons

matter & antimatter

reheating

inflation

14 billion years



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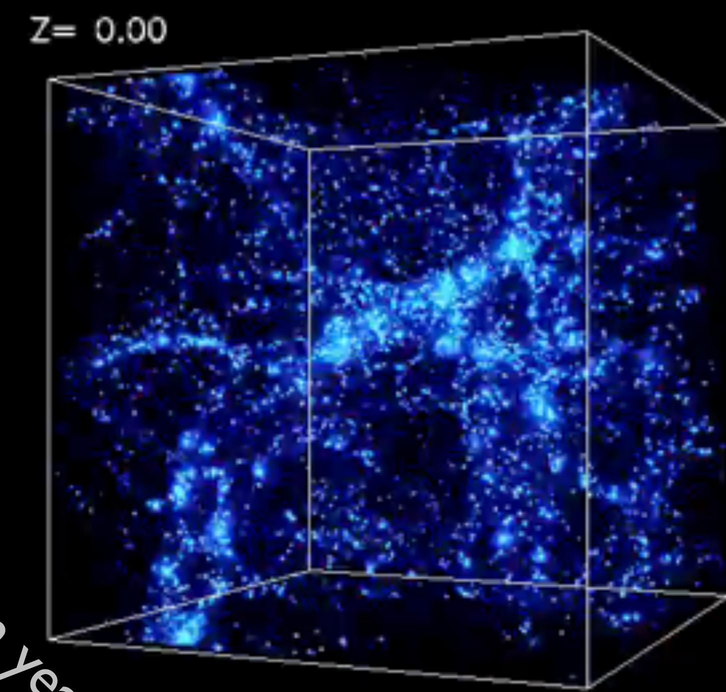
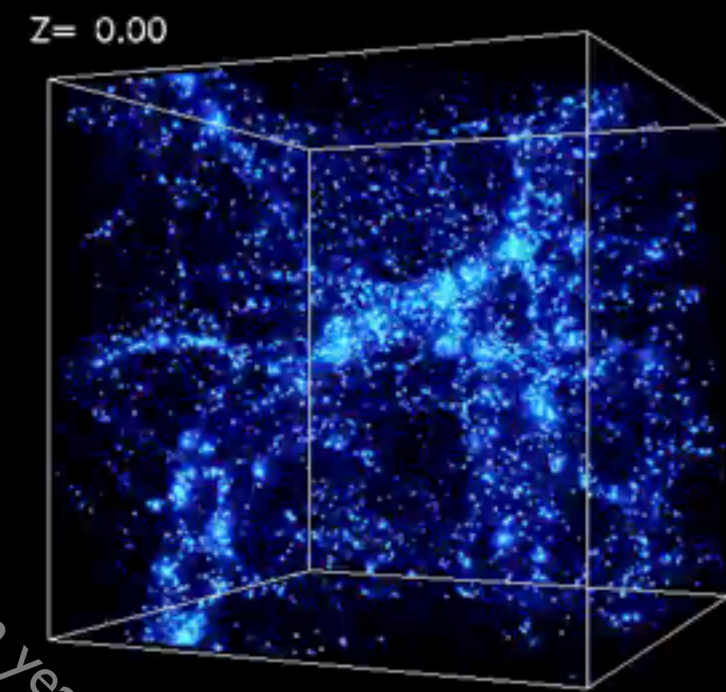
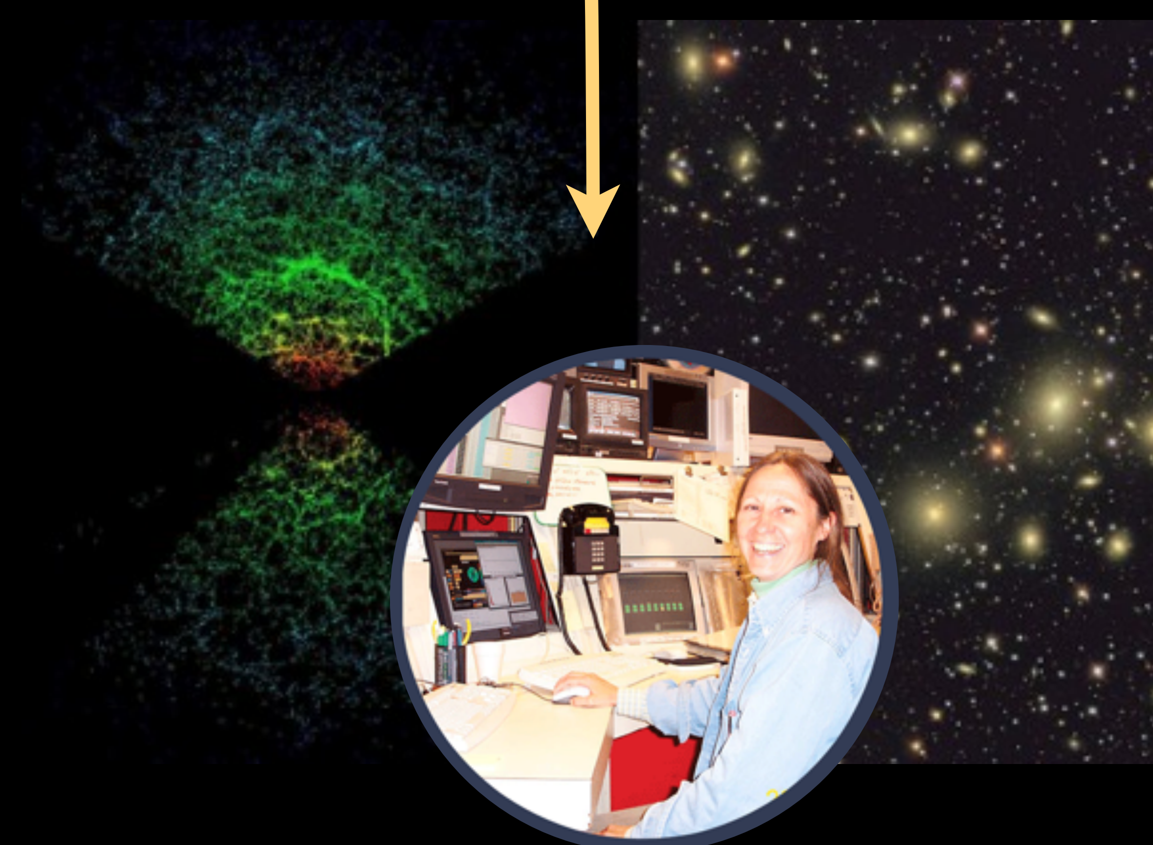


relevant energy scales



14 billion years



400K yrs

minutes

micro seconds

pico seconds

atoms	E ~ 0.1 MeV
light nuclei	E ~ 0.3 eV
nucleons	E ~ 1 GeV
electroweak phase transition	E ~ 100 GeV
reheating inflation	

asymmetry generated ?

$E \sim k_B T$

* for the Standard Model, B violating processes inefficient below 100 GeV

quantifying the asymmetry

quantifying early universe asymmetry

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \qquad \sim \left.\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}\right|_{T \gtrsim \mathrm{GeV}} \equiv A(\mathrm{early})$$

baryon to photon ratio

(observable at late times)

asymmetry when
nucleons are relativistic

$s =$ entropy density

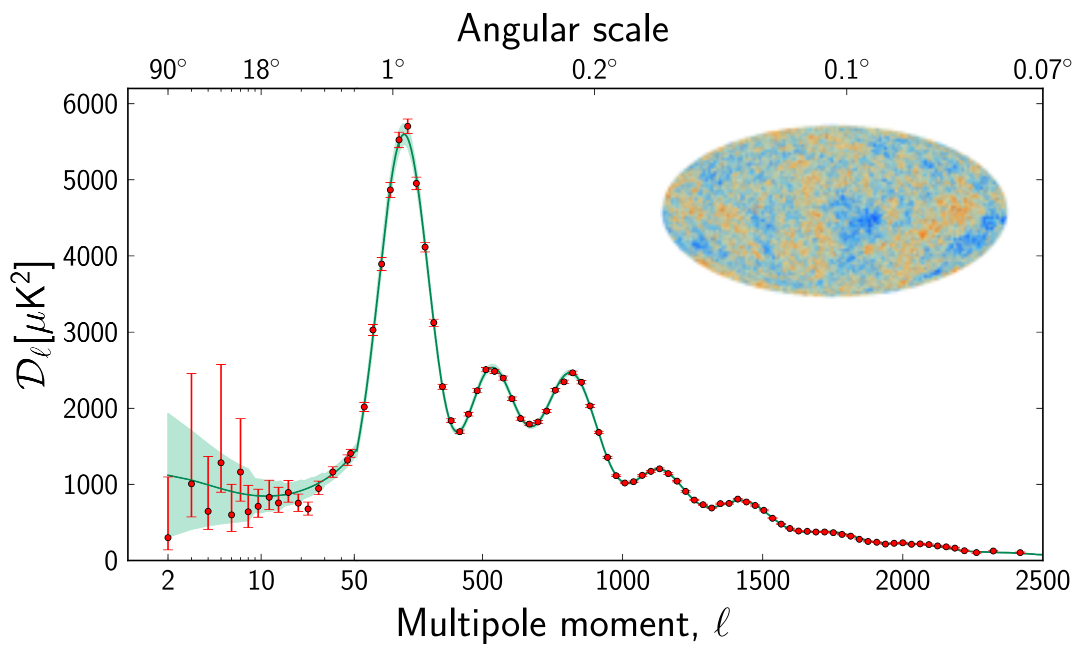
better to use $A = \frac{n_B - n_{\bar{B}}}{s}$ which does not evolve after baryon number violating processes have frozen

baryon/photon ratio

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma}$$

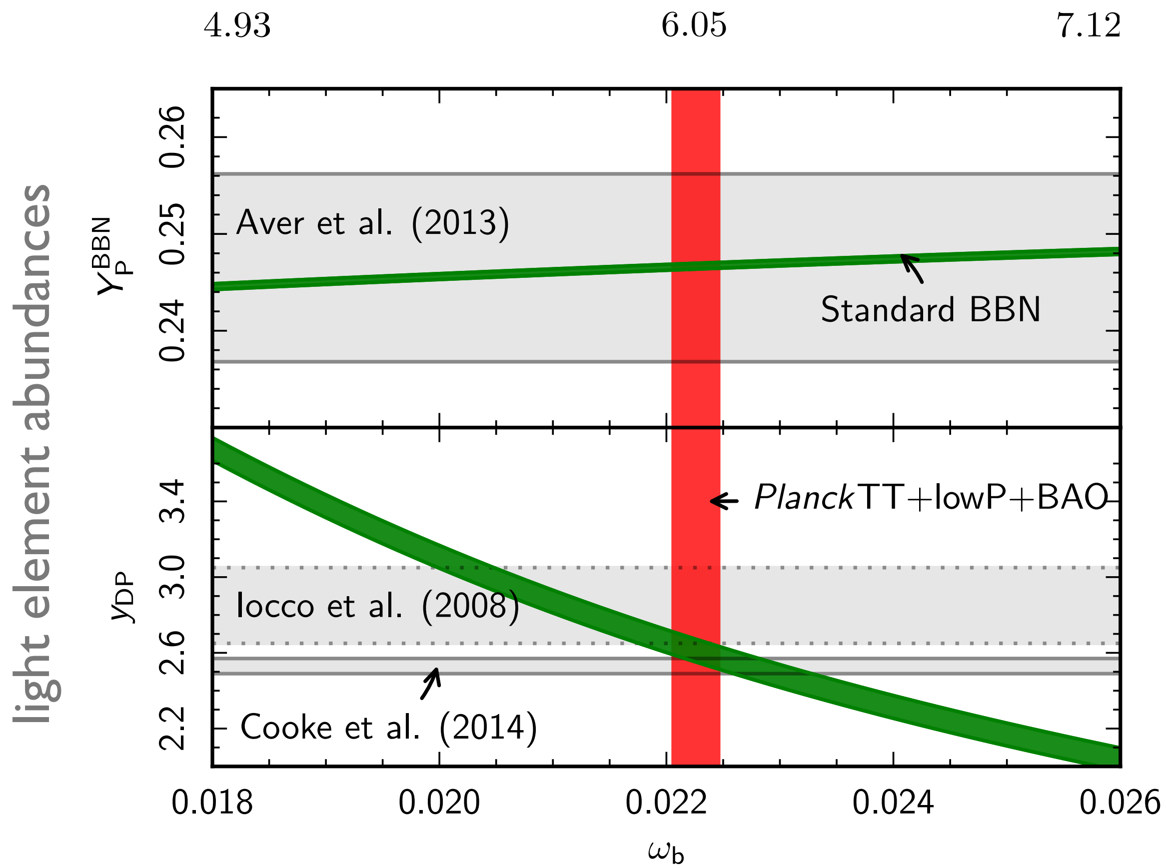
negligible
anti baryons

$$\eta = (6.047 \pm 0.074) \times 10^{-10}$$



$T \sim 10^{-1}\,\mathrm{eV}$

baryon/photon ratio $\eta \times 10^{10}$



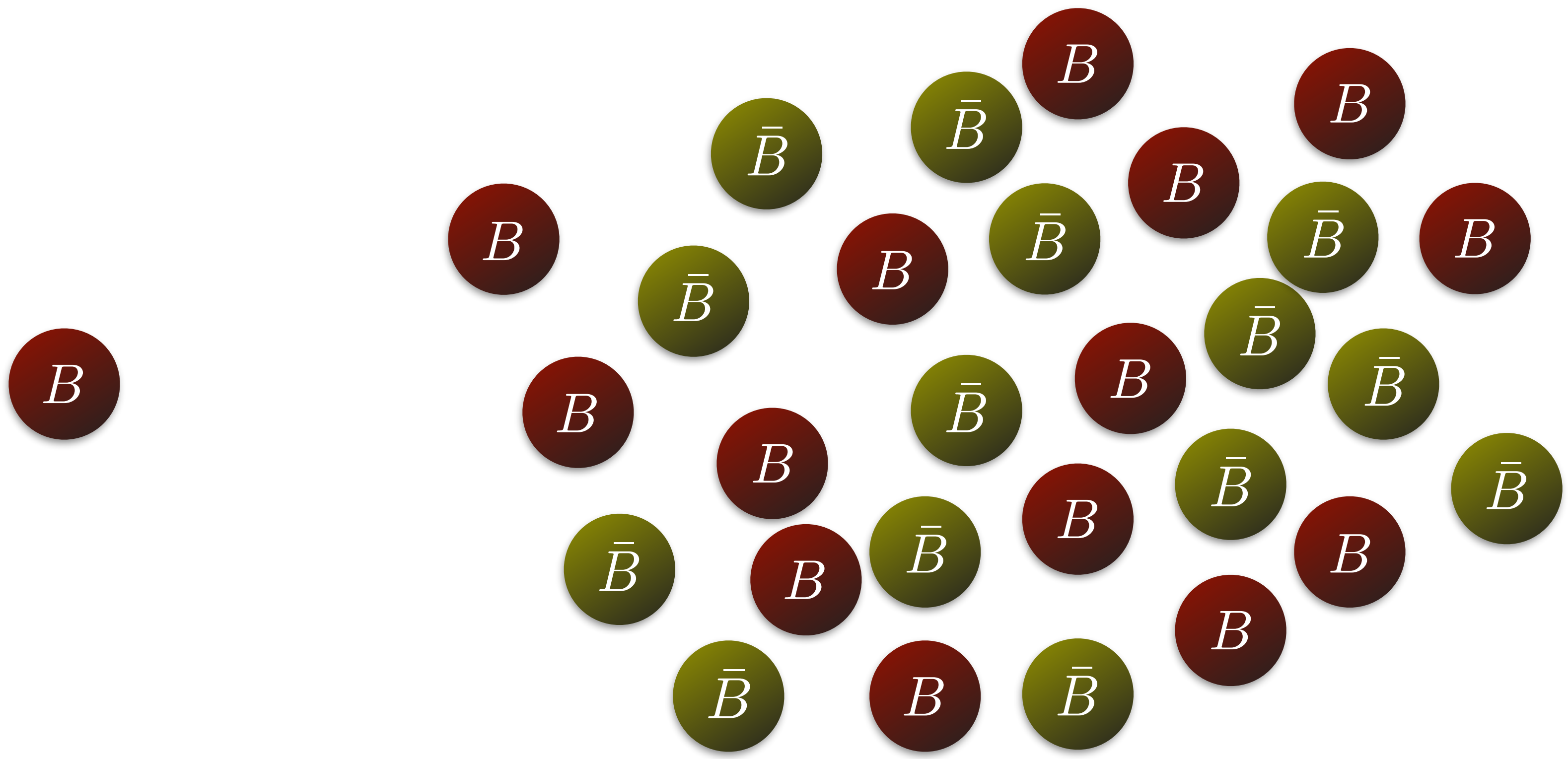
$T \sim 10^{-1}\,\mathrm{MeV}$

from Planck 2015

very early universe asymmetry

$$\eta = (6.047 \pm 0.074) \times 10^{-10} \quad \Longrightarrow \quad A(\text{early}) \equiv \left.\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}\right|_{T \gtrsim \text{GeV}} \sim 10^{-10}$$

One extra baryon for every Ten Billion baryon-antibaryon pairs



how was this symmetry generated? $\eta \sim 10^{-9}$

generating the asymmetry ?

option 1: start with an asymmetric universe *

option 2: dynamically generate the asymmetry

* typically, inflation and/or the entropy production during reheating wipes out initial asymmetry unless it is in the inflaton itself

Sakharov conditions

dynamically generate the asymmetry

Sakharov conditions (1967)

(1) $\not{B}$ (2) $\not{C}$ & $\not{CP}$ (3) ~~thermal equilibrium~~

baryon number violation

charge conjugation: C $B \longrightarrow \bar{B}$

parity: P $\mathbf{x} \to -\mathbf{x}$

CP violation : a fundamental question

credit: from G. Sciolla (MIT physics annual 2006)

how different are the laws of physics in a CP mirror world ?

violation discovered in (1964 — ongoing)

fundamental questions

- amount of CP violation consistent with the SM ?
- enough CP violation to address the matter antimatter asymmetry in the early universe ?
- new physics ?

how much/where is the CP violation ?
hints for beyond Standard Model physics ?

KTEV Kaons at the Tevatron

talk by Juliana Whitmore

talks by Andy Hocker
& Jason Bono

Mu2e

talks by Dmitri Denisov
& Julie Hogan

Fermilab

E683

talk by Don Lincoln

does the SM have the necessary ingredients ?

$(1)\ \not{B}$: non-perturbative, quantum effects (sphalerons)

$(2)\ \not{C}$: weak interaction (eg. charged pion decays)

$\not{C}\!P$: weak interactions (e.g. neutral Kaon decays, B-physics etc.)

(3) ~~thermal equilibrium~~ : expanding universe, phase transition etc.

* CP violation in strong interaction is small (see for example neutron EDM measurements)

an example:
Standard Model Electroweak Baryogengesis

EW phase transition: $T \sim 10^2\ \mathrm{GeV}, \qquad t \sim 20\ \mathrm{ps}$

W, *Z* bosons get their mass

asymmetry generation

(1) $\not{B}$ (2) $\not{C}$ & $\not{CP}$ (3) ~~thermal equilibrium~~

an example: SM Electroweak Baryogengesis

sufficient ?

(1) $\not{B}$ (2) $\not{C}$ & $\not{CP}$ (3) ~~thermal equilibrium~~

$$D = \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\delta_{KM} \times \prod_{a=1}^{3}\prod_{b\neq a}^{3}(m_a^2 - m_b^2)$$

$$\frac{D}{T^{12}} \sim 10^{-20} \ll \eta_{\rm obs}$$

CP violation is nonzero & consistent with SM

phase transition:

~~first order~~

second order

↑

$$\text{LHC} \rightarrow m_H \approx 126\text{GeV}$$

SM Electroweak Baryogengesis does not generate enough asymmetry

(1) $\not{B}$ (2) $\not{C}$ & $\not{CP}$ (3) ~~thermal equilibrium~~

consistent with SM

phase transition:

~~first order~~

second order

NOT ENOUGH asymmetry generated !
(exponentially small)

asymmetry from beyond the SM ?

- standard lore: Standard Model not sufficient *

- beyond the Standard Model **

  - experiments:
    - quark sector — past/ongoing searches — eg. BaBar, Belle, D0, KTeV, LHCb
    - neutrinos, leptons — eg. GERDA, HyperKamiokande, mu2e, DUNE upcoming)

  - theory:
    - heavy particle decays (eg. Weinberg 1978 —)
    - neutrinos, leptogenesis (eg. Fukugita & Yanagida 1986 —)
    - extra scalar field (susy) condensate — (Affleck Dine mechanism 1985 —)

** also needed for neutrino oscillations, dark matter, inflation …

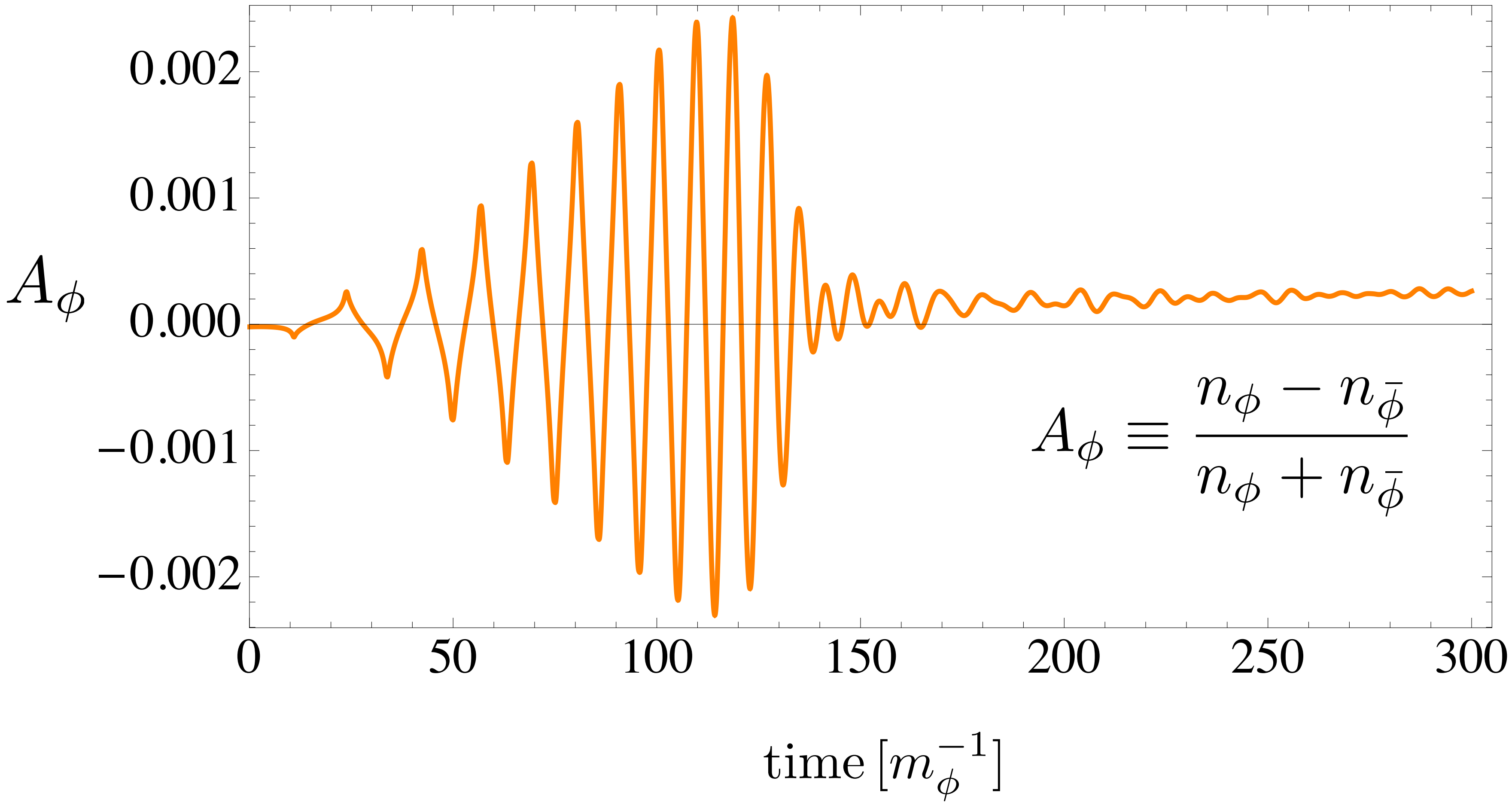
* no proof

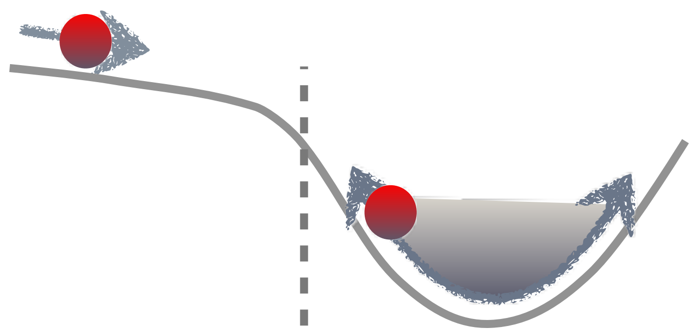
can the inflaton (a scalar field) generate the matter-antimatter asymmetry ?

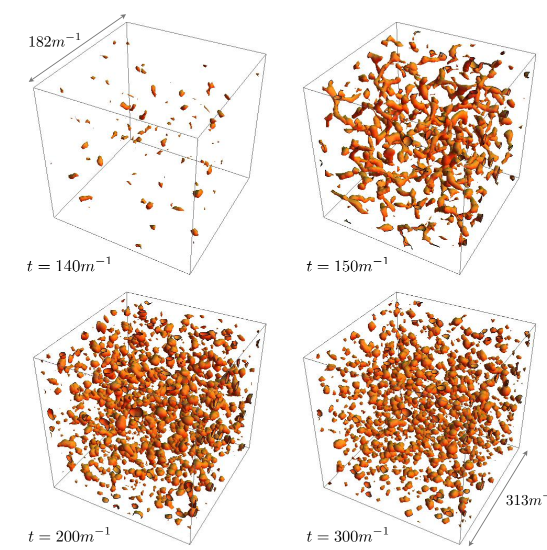
Hertzberg & Karouby (2013)

variant of Affleck Dine (1985), but spontaneous breaking of C & CP symmetries

asymmetry generation after inflation







asymmetry between particles and antiparticles generated by the dynamics

asymmetry generated at the end of inflation, and "freezes" in

Lozanov & MA (2014)

transfer from inflaton to matter is model dependent

$$\eta \sim \mathcal{O}[10^2] \times A_\phi \left(\frac{T_{\rm reh}}{m_\phi}\right) \sim 10^{-9}$$

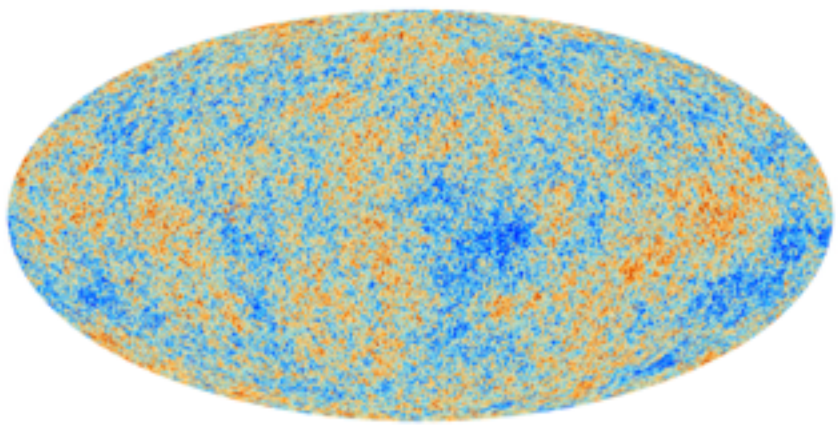
from end of inflation (A_ϕ)

decay rate to baryons ($T_{\rm reh}/m_\phi$)

sample numbers: $A_\phi \sim 10^{-4},\ T \sim 10^7\,\mathrm{GeV},\ m_\phi \sim 10^{14}\,\mathrm{GeV}$

Hertzberg & Karouby (2013)

not a unique prediction



cross check

- amount of isocurvature fluctuations ? $\alpha_{II} \sim 2.6 \times 10^{-4}$

- predictions for particle physics experiments ?

- connections to dark matter ?

no unique/ confirmed/ favored model yet

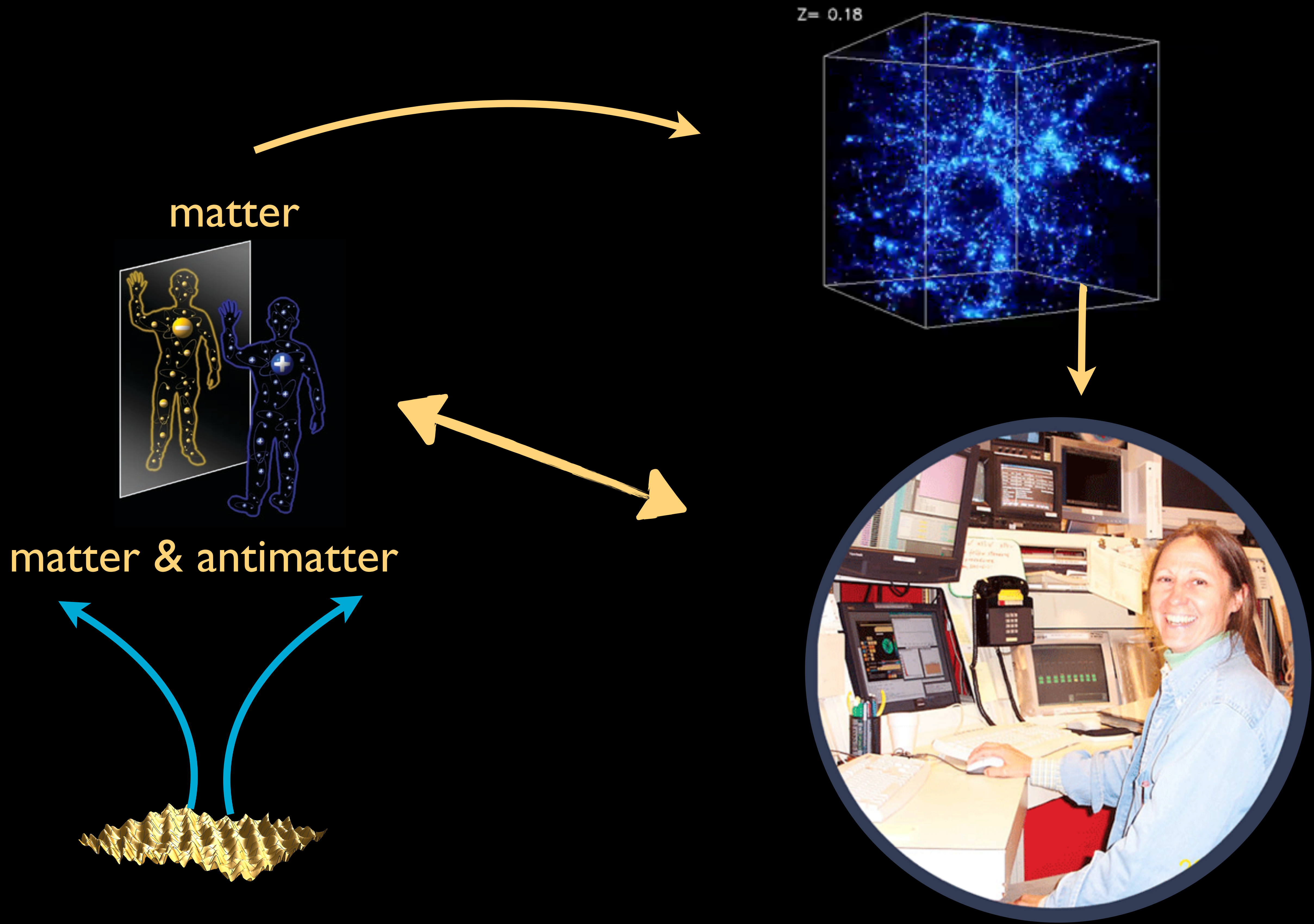
mechanism for matter/antimatter asymmetry remains an unsolved problem

search continues with theoretical and experimental + obs. efforts from High Energy Physics & Astrophysics/Cosmology

matter/antimatter asymmetry & Marj

how are the laws of physics different in a (CP) mirror world ?

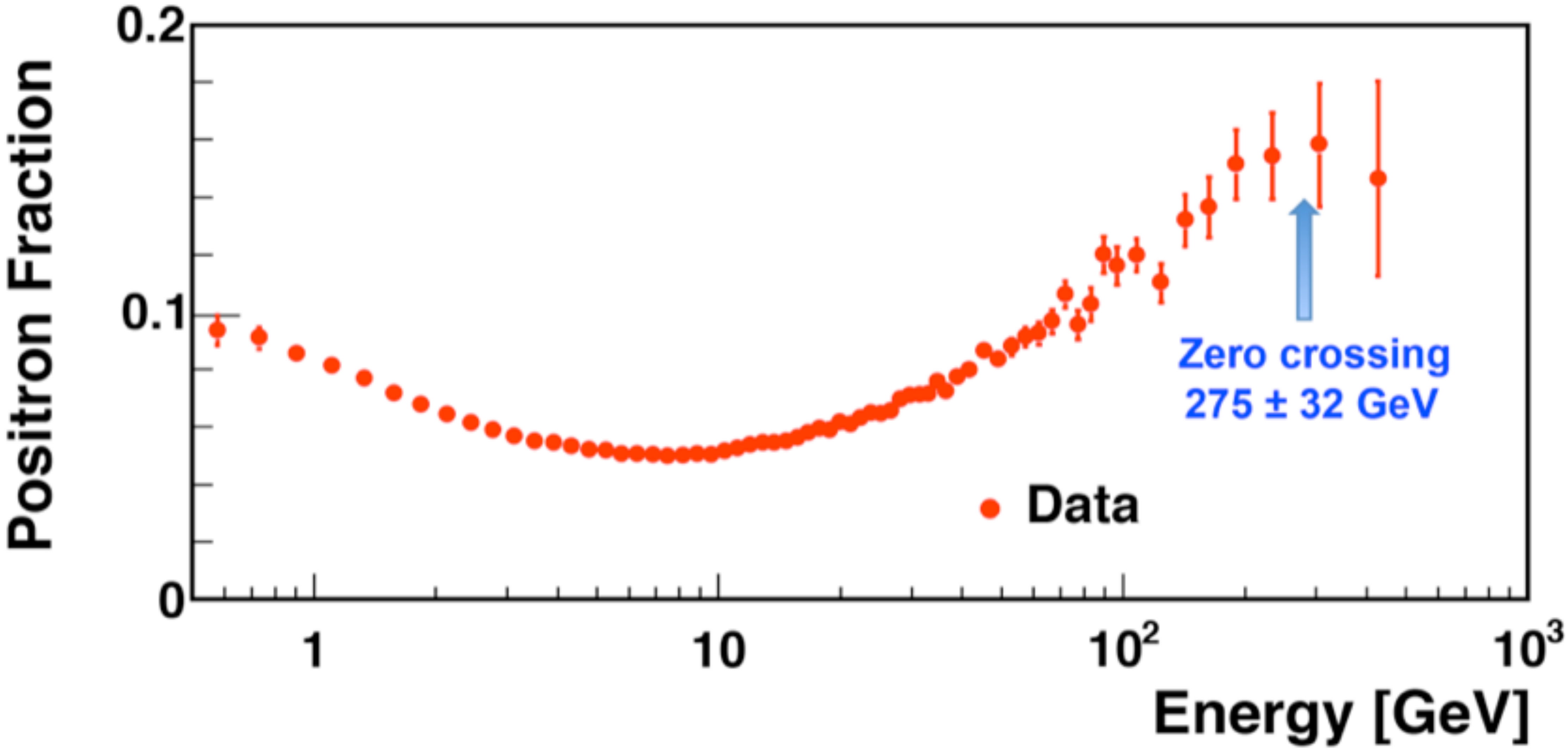
matter antimatter asymmetry — and our origins



insatiable curiosity and unwavering encouragement

extra slides

AMS-02 positron fraction



CP violation Standard Model ?

CP violation from B physics (A. Lazaro 2007)

$$V_{CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

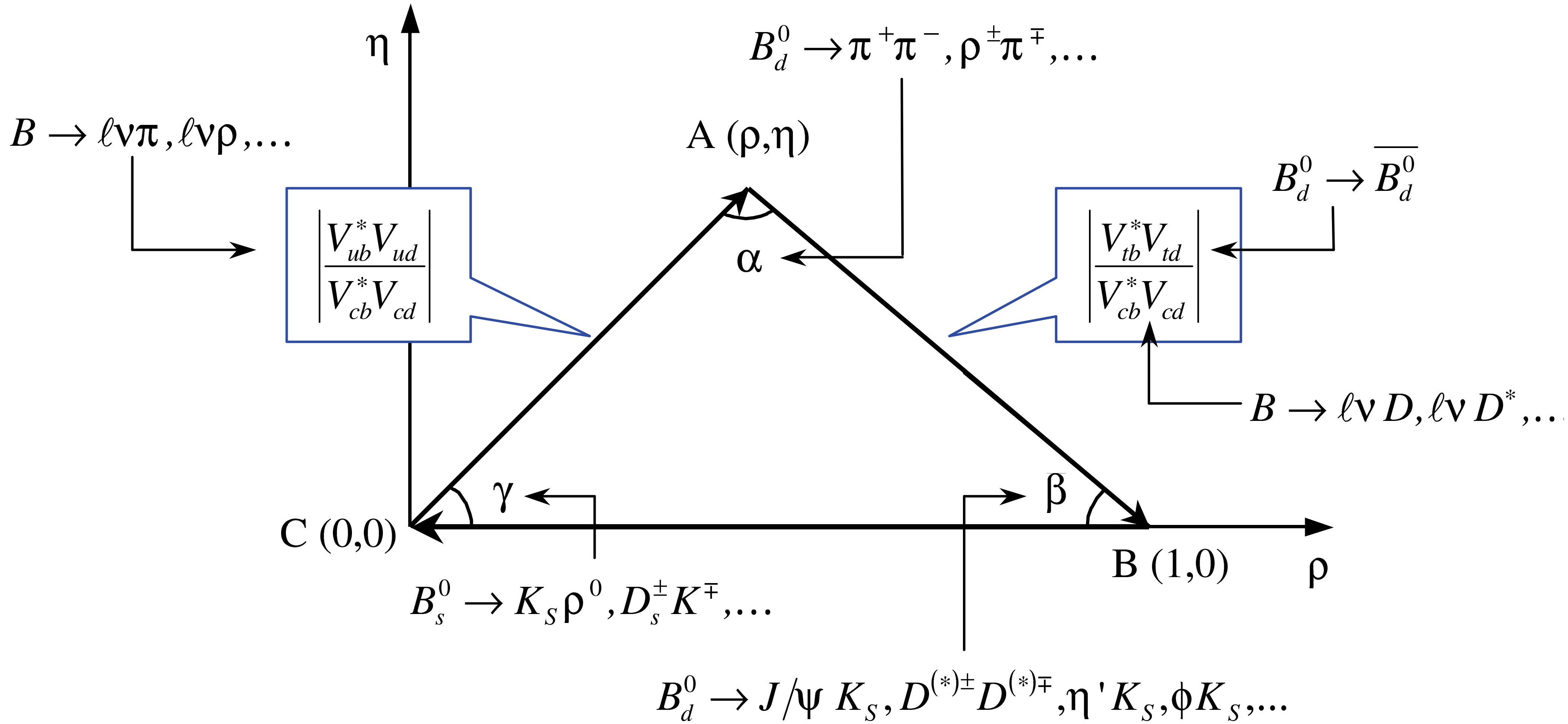


Figure 3: Unitary triangle and main decays to measure the sides and the angles.

CP violation in the SM

$$V_{CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$