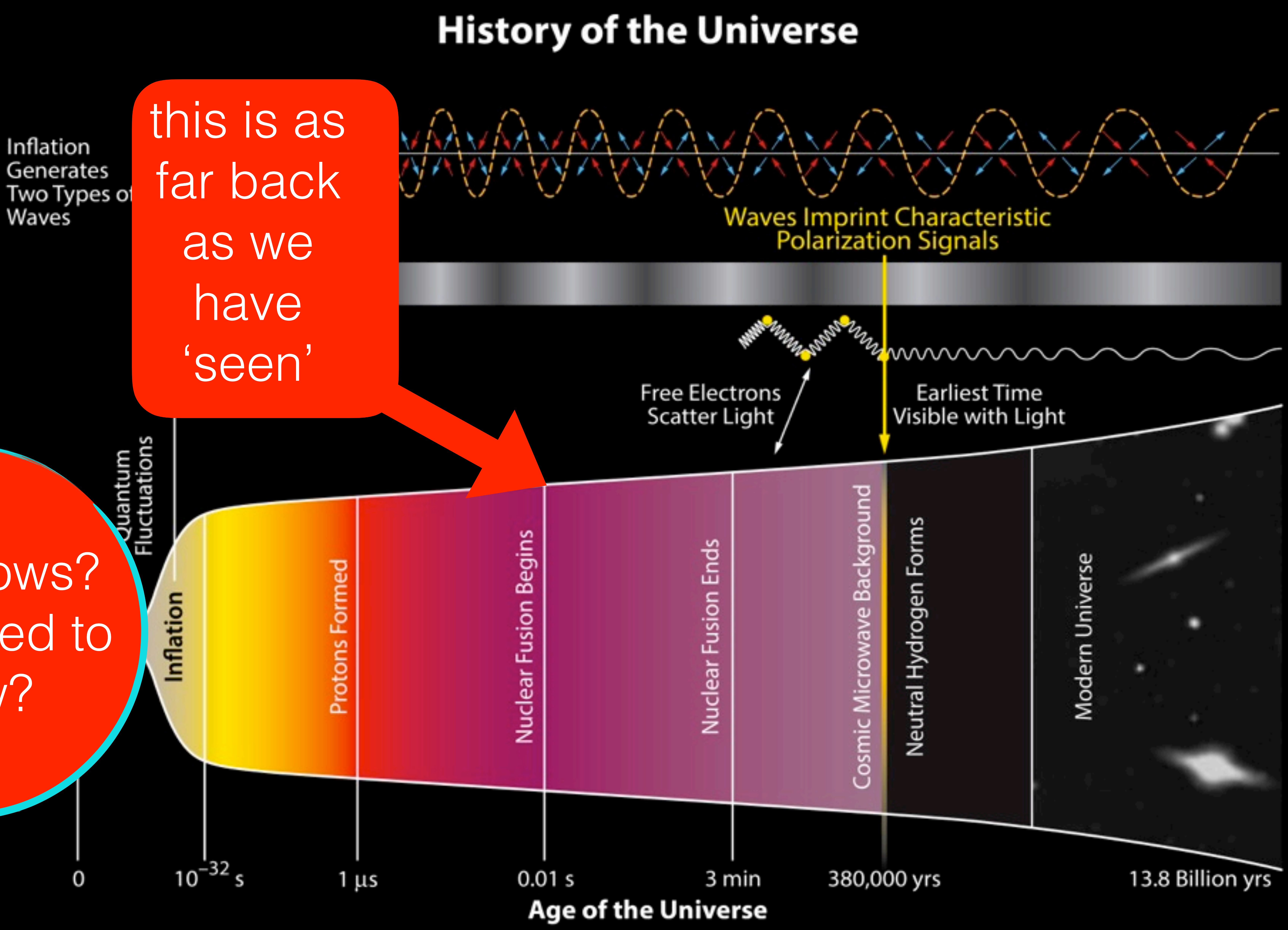
Why is there more matter than antimatter?

recommended reading: arXiv:1706.03138

Ann Nelson, University of Washington, August 8, 2018

this is as far back as we have ‘seen’

who knows? Don’t need to know?

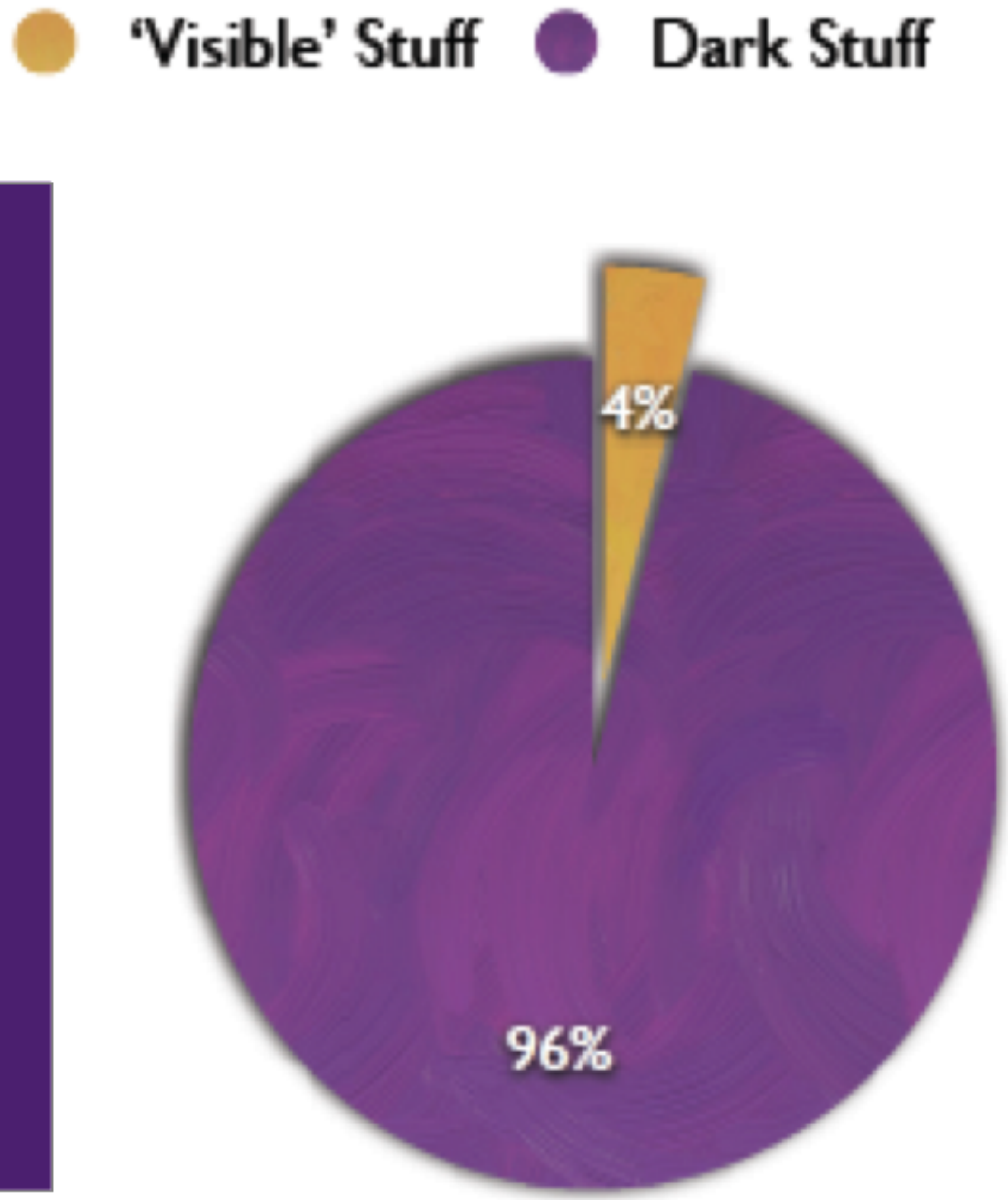


Message for Particle Physics from observations of cosmological light element production

- Nucleosynthesis of primordial He etc
  - 0.1 sec-3 minutes
  - ~MeV temperature, radiation dominated
  - ***Predicted*** # neutrinos~3 to agree with observed primordial Helium
- ***Confirmed*** when Z boson discovered to decay to 3.00 neutrinos in 1990's (Z width)
  - 3 generations of Standard quarks and leptons

any more messages?

Q: What fraction of the Energy Density of the Universe comes From Physics Beyond the Standard Model?



99.7% !

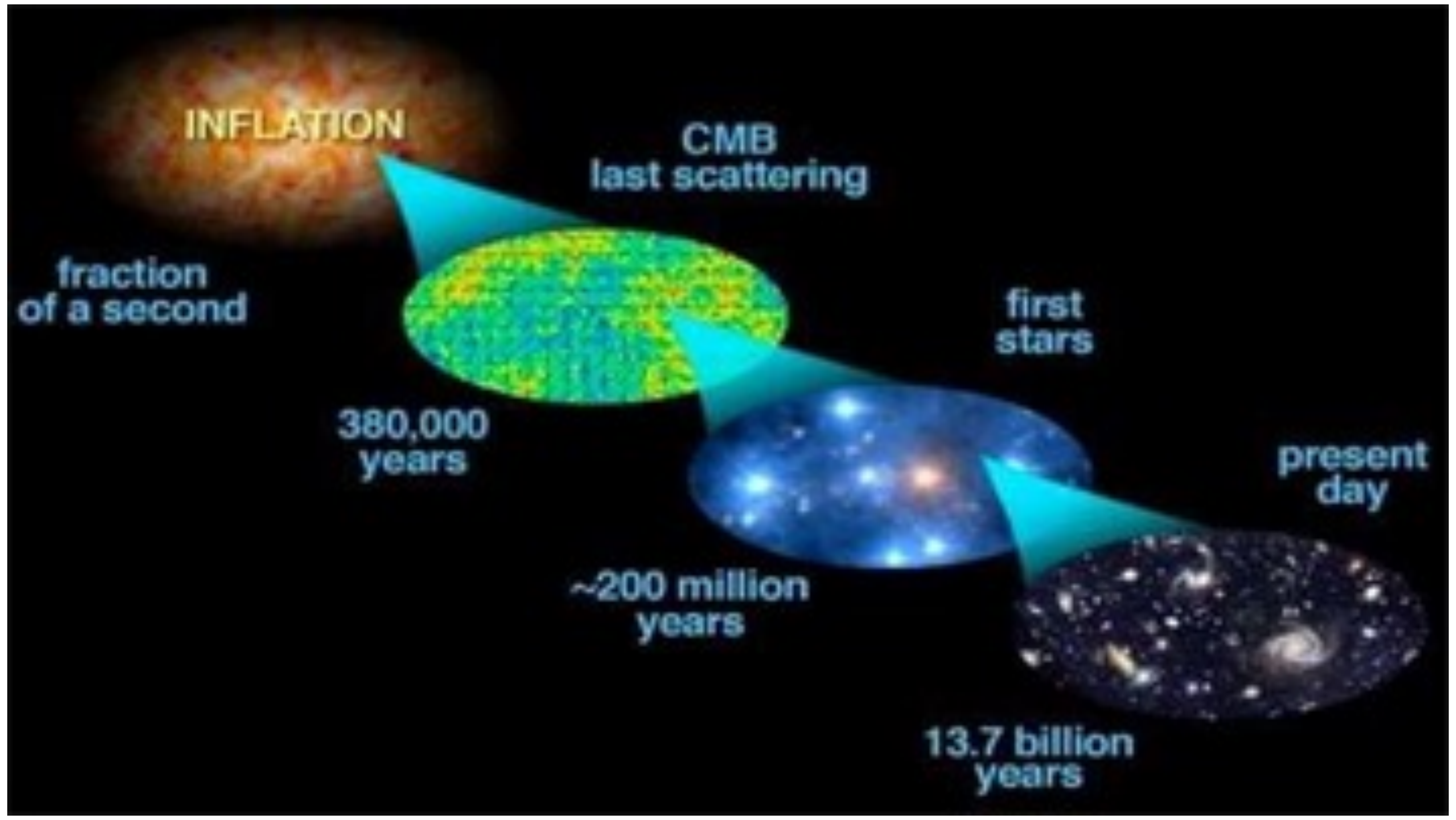
Origin story

- Nuclei synthesized from protons and neutrons (baryons) at T~MeV
- Baryons are synthesized from quarks at T~100 MeV
- Quarks are elementary (?) but tiny excess of quarks over anti quarks in hot early universe

- How did that asymmetry arise?

Just-so “Primordial” Asymmetry at the beginning of time?
Set by initial conditions?

“Big Bang Theory” of origins now replaced by Inflation—much more predictive



Inflation

Universe begins from a tiny (~10^{-24} cm)
patch of space
which expanded by factor > 10^{25} in 10^{-32} s

- Inflation smooths, dilutes universe

- Replaces "Big Bang" singularity with theory for conditions at 10^{-32} s

- Theory for spectrum of temperature fluctuations
  - confirmed by CMB observations
- Prediction (not confirmed yet) for spectrum of gravitational waves

Implications of Inflation

- Immediately after inflation universe is
  - hot, thermal (causality issue for thermal equilibrium solved)
  - flat (k=0)
  - uniform
  - small deviations from uniform temperature (eventually grow into galaxies etc)
  - symmetrical (equal numbers of quarks and anti-quarks)

Inflation+Standard Model predicts that our present universe would mostly consist of photons and neutrinos

Why are we (the baryons) here?

- As universe expands and cools, particles and antiparticles annihilate
- Observed ratio of baryon density to entropy density is 10^{-10}
- after inflation (10^{-32} s) and before nucleosynthesis
- (.01 sec—3 minutes), an asymmetry of 10^{-8} arose between quarks and anti-quarks

- We don't know how the asymmetry happened. We call the process ***Baryogenesis***

Sakharov’s 1967 paper

- Andrei Sakharov: nuclear physicist (designer of Soviet H-bomb)
- human rights activist
- Nobel peace Prize winner
- Seminal paper in particle physics and cosmology including foundational idea and principles of Baryogenesis

Sakharov Conditions for Baryogenesis

- **Baryon number violation: Universe must evolve from a symmetrical state with initally net baryon number (baryons -antibaryons) zero, to state with more baryons than anti-baryons**

- **C, CP violation: C (charge conjugation symmetry) and CP (charge conjugation times parity) to give difference between matter and anti-matter**

- **departure from thermal equilibrium. CPT theorem implies particles and anti-particles have exactly same energy and same abundance in thermal equilibrium**

Standard Model and Baryon number violation

- **Perturbative interactions of Standard Model (represented by Feynman diagrams) Conserve baryon number (difference between quarks and anti-quarks)**
- **Nonperturbatively, there is Anomalous baryon number violation from the weak interactions**

$\partial_\mu j_B{}^\mu = (\alpha_W / 8\pi)\, \varepsilon_{\mu\nu\lambda\sigma}\, W^{\mu\nu} W^{\lambda\sigma} \sim$ weak electric · weak magnetic

$\Delta B = \int d^4x\, (\alpha_W / 8\pi)\, \varepsilon_{\mu\nu\lambda\sigma}\, W^{\mu\nu} W^{\lambda\sigma}$

•*right hand side is topological invariant, requires large fields.*

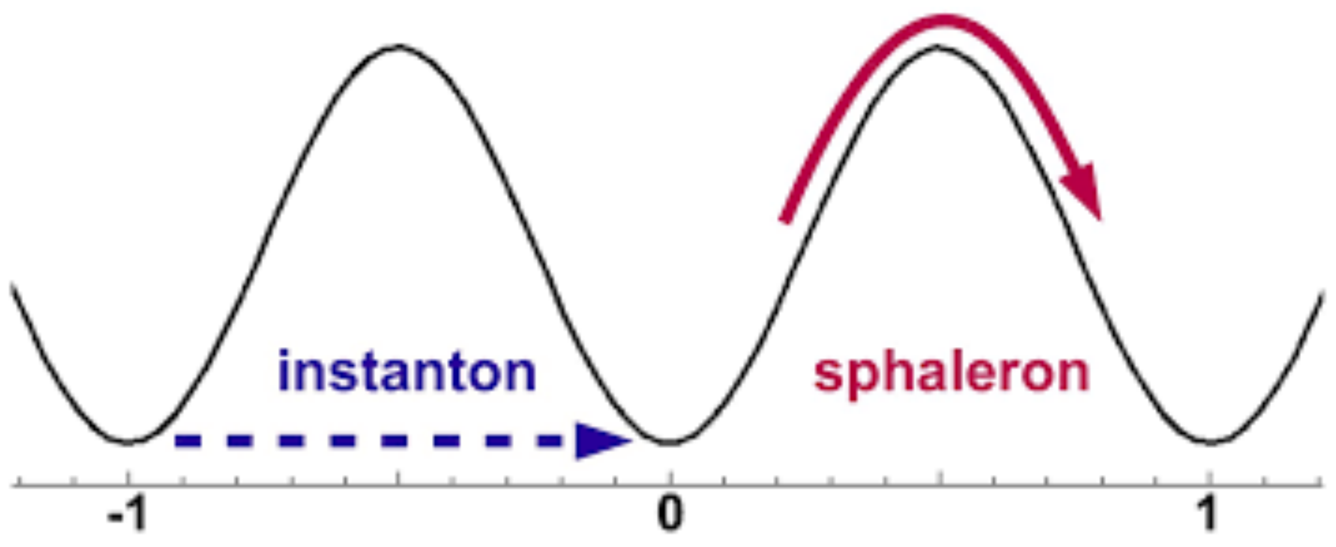
•*rate of baryon number violation negligible today due to large energy required to produce heavy weak fields.*

•*important in early universe when energy density high.*

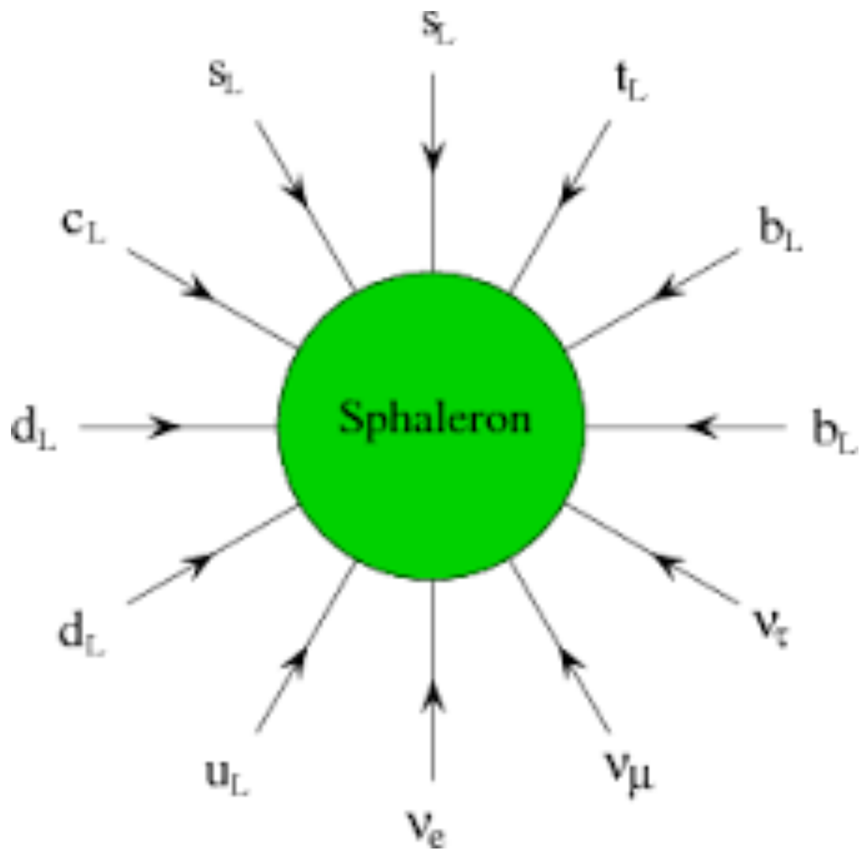
"Sphalerons" in standard model weak interactions

- **Sphaleron is greek for "ready to fall"**

Note: Barrier height depends on Higgs expectation value



topological quantum number



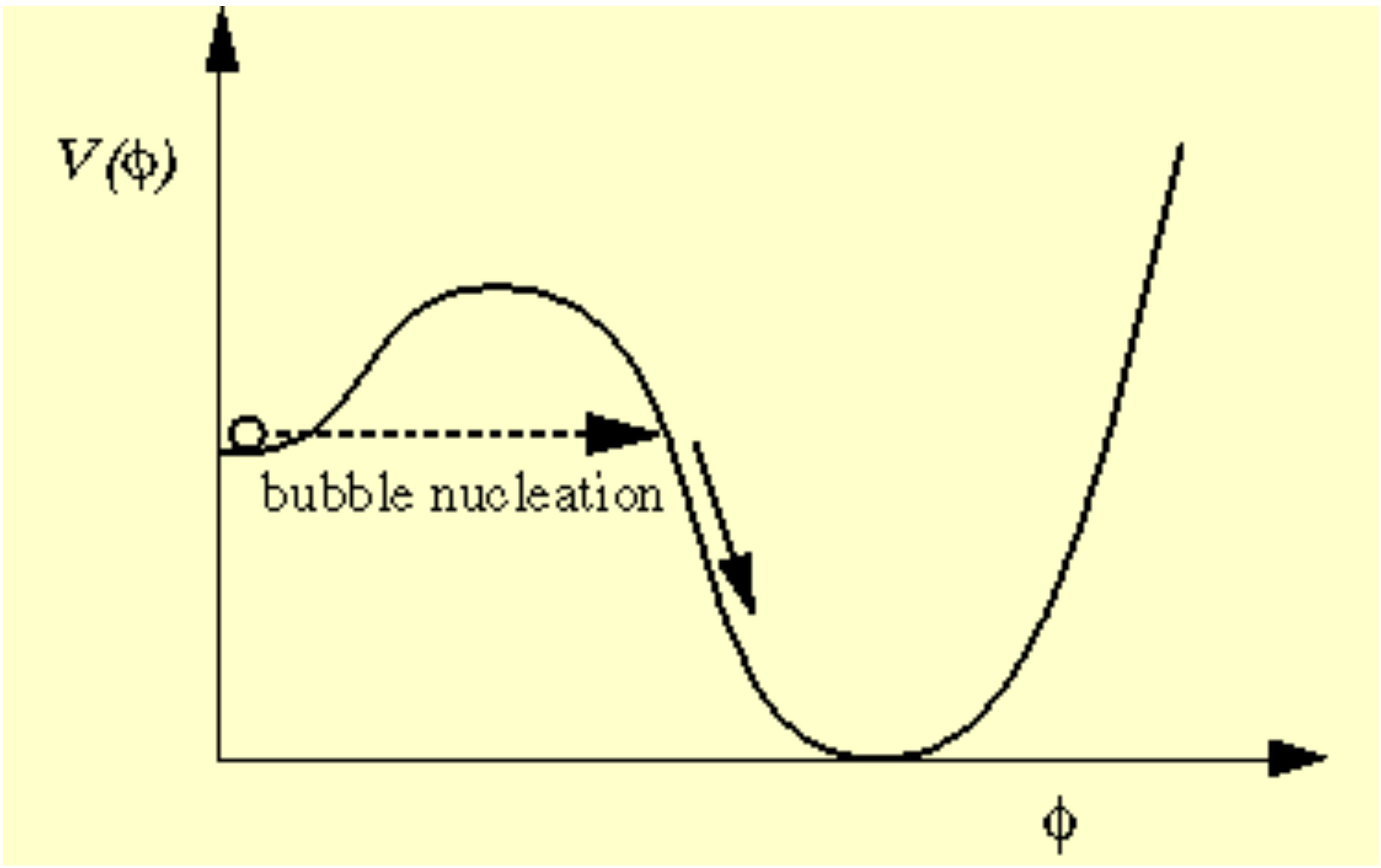
weak configuration with different topological number=different baryon number

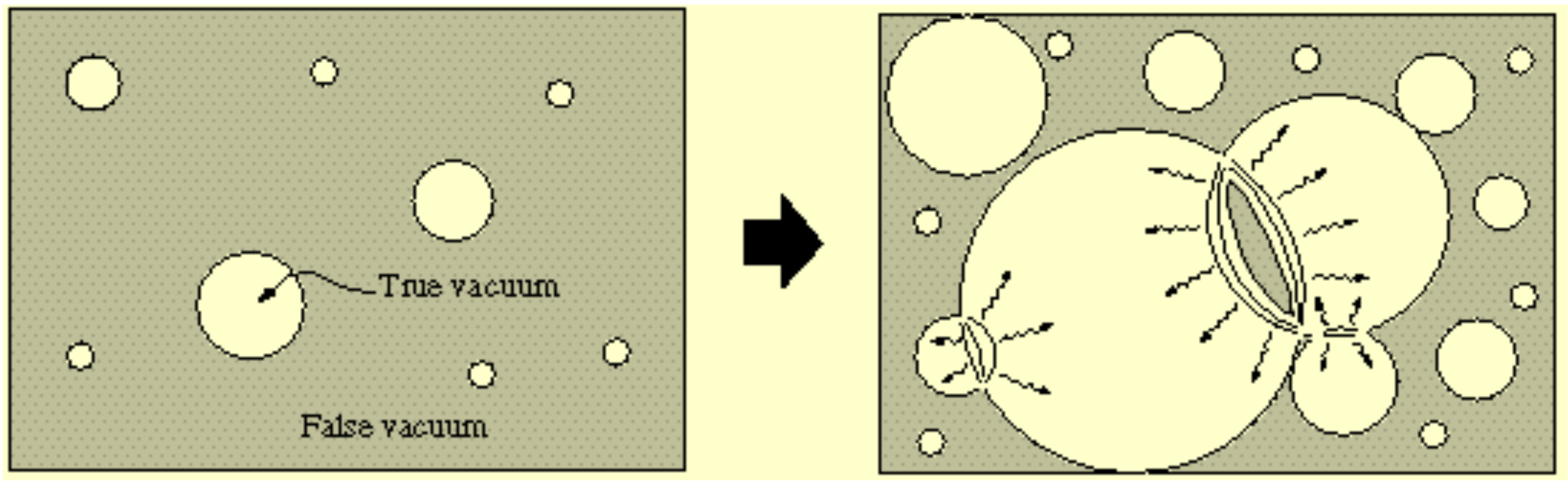
Standard Model and C, CP violation

- weak interactions maximally violate C, P
- weak interactions rarely violate CP (only small amounts in rare processes)
  - seems not to be enough CP violation
    - Standard Model CP violation occurs due to phases in interference between different paths for quark flavor change. Suppressed by the small parameters (CKM parameters) that govern flavor change.

Standard Model and departure from thermal equilibrium

- In early universe, prior to nucleosynthesis, all standard model scattering processes are in thermal equilibrium
- Only known way to get out of equilibrium in Standard Model would be a first order phase transition.

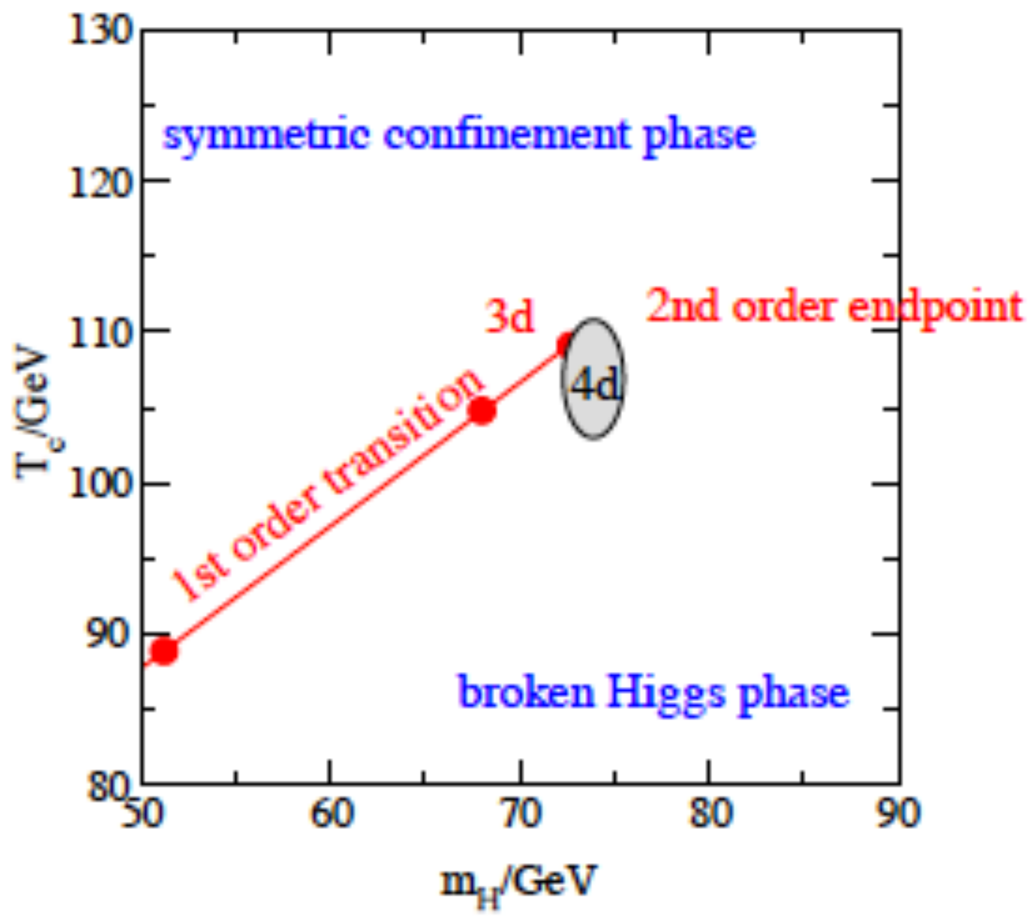


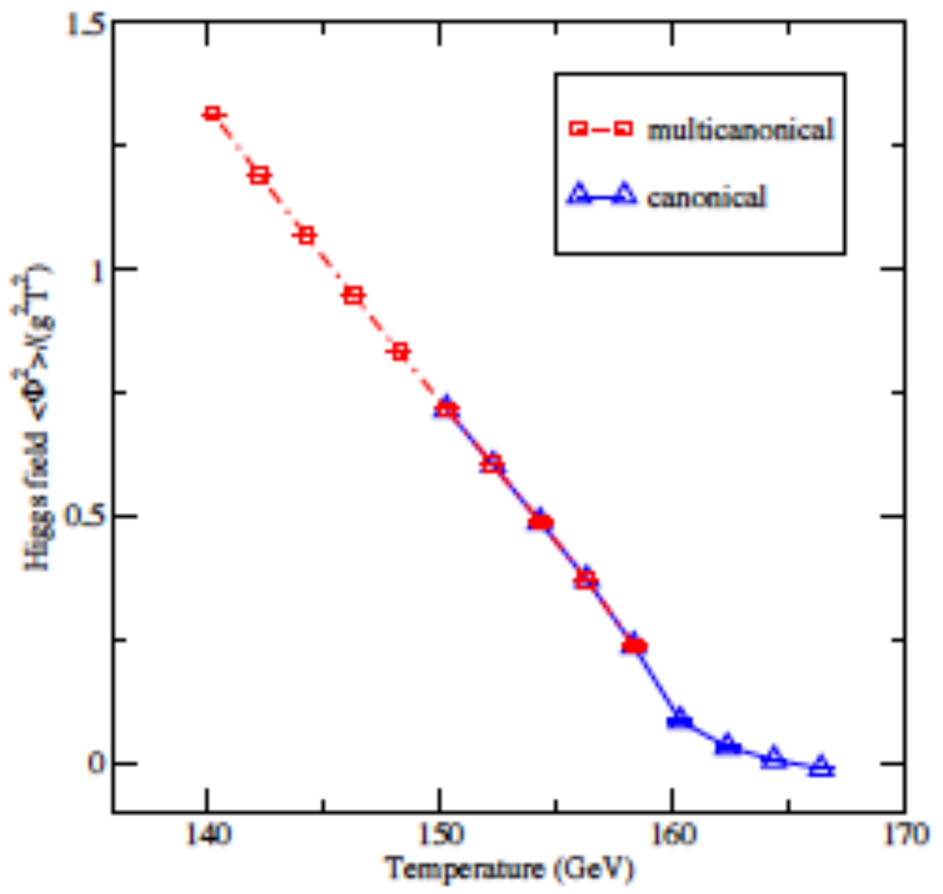


(picture credit
http://www.damtp.cam.ac.uk/research/gr/public/cs_phase.html)

Was the "Electroweak" Phase transition 1st order?

Phase diagram for the Standard Model:





3d: SU(2)×U(1)+Higgs+fermions
4d: SU(2)+Higgs; relative endpoint position conserved

$\langle \phi_3^\dagger \phi_3 \rangle$ for $m_H = 125$ GeV

No singularity $\Rightarrow$ no baryogenesis or gravity background.

- from, e.g. Laine talk: physik.uni-graz.at/STRONGnet2013/talks/laine.pdf answer is no in minimal model. Need a more extended Higgs sector. Still viable.

Sakharov Conditions and the Standard Model

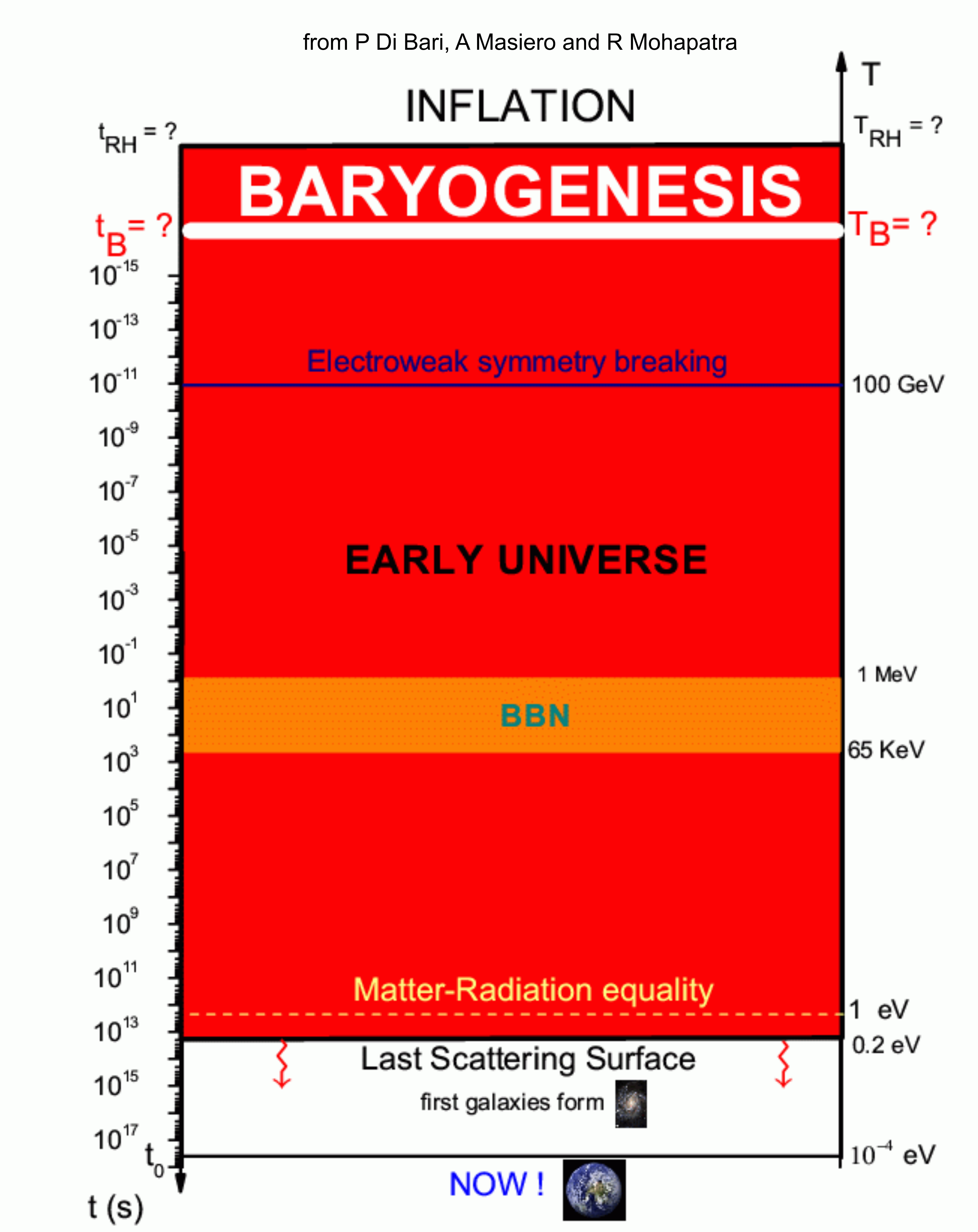
- ✓ C and CP violation (but not enough CPV)
- ✓ Baryon number violation (electroweak anomalous nonperturbative field configurations known as *sphalerons,* which are common at very high temperature, above electroweak phase transition at 100 TeV)
  - ★ sphalerons conserve B-L
- ☐ Out of equilibrium (no phase transition for m_H=125) but if Higgs sector is extended still possible (also could allow for new source of CP violation)

Four motivated, viable theories of Baryogenesis

- 1. Baryogenesis via Leptogenesis
- 2.Electroweak baryogenesis
- 3. Affleck Dine baryogenesis
- 4. Low scale baryogenesis from b-physics
- (there are many other viable theories)

High scale lepto/baryogenesis

- Heavy, out of equilibrium particle decay?
  - e.g. out of equilibrium CPV decay of very heavy Majorana neutrinos (*leptogenesis*, *Fukugita and Yanagida*)
  - electroweak sphalerons convert lepton asymmetry into baryon asymmetry
  - Observable leptogenesis consequences: light Majorana neutrino mass, CPV in neutrino sector



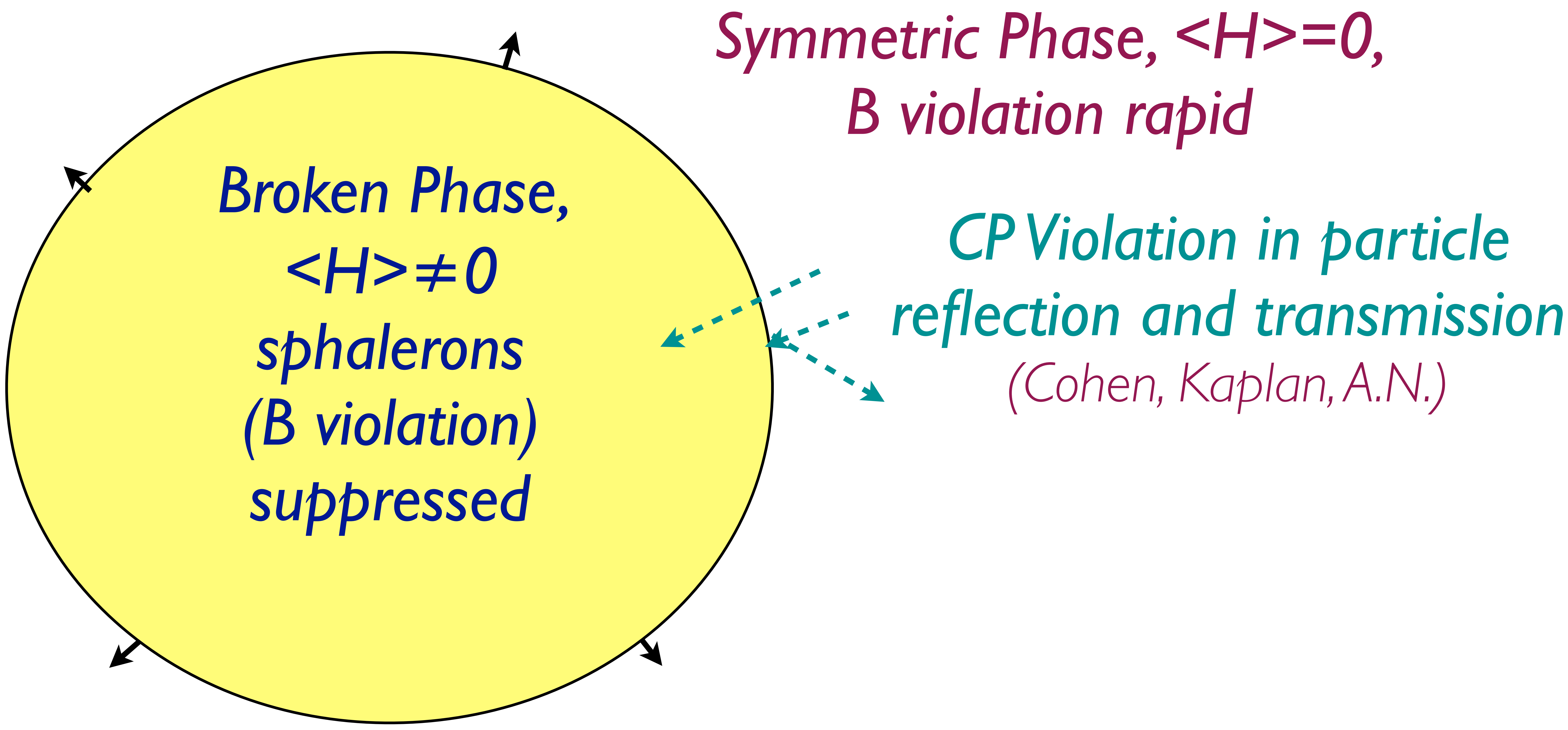
Consequences of High Scale Lepto/Baryogenesis

- Requires lightest neutrino lighter than 0.1 eV
- requires decay of heavy neutrino heavier than 10^9 GeV
- High reheating temperature (10^9 GeV) after inflation
- Overproduction of gravitinos and other hypothetical states
- High reheat scale $\Rightarrow$ high inflation scale
  - unacceptable isocurvature fluctuations from axion dark matter if axion exists during inflation

Electroweak Baryogenesis

(Kuzmin, Rubakov, Shaposhnikov)

strongly first order electroweak phase transition



Implications of electroweak baryogenesis for Higgs physics at LHC

- Preservation of baryon number requires $\xi \equiv \langle H \rangle / T > 1$ in broken phase at critical temperature.
  - In MSM any phase transition requires a light Higgs (< 80 GeV)
  - In MSSM $\langle H \rangle / T > 1$ requires light Higgs (< 127 GeV), light stop (lighter than top) *(Carena, Quiros, Wagner)*
  - More general 2HDM models easily satisfy condition
    - Can still implement natural flavor conservation
- **CPV at weak scale, in Higgs physics ⇒ electric dipole moment of electron**

Affleck-Dine Baryogenesis

- **In Supersymmetric theories quarks and leptons have spin 0 partners called squarks and sleptons**
- **Light spin 0 Bosons carrying baryon and lepton number!**

- Squark or slepton condensates produced during inflation decays affected by high scale CPV

  Requires low scale supersymmetry

- No other necessary low energy consequences ?

Baryon abundance not predictable

- High scale inflation *excludes Affleck Dine* (non adiabatic cosmological perturbations from squark fluctuations)

“Testable Post-Sphaleron Baryogenesis from B physics”

(with David McKeen, Akshay Ghalsasi, Seyda Ipek, Thomas Neder, Kyle Aitken, Gilly Elor, Miguel Escudero)

- “post sphaleron”=need to violate Baryon number in new physics?
  - constrained from neutron oscillations, nucleon decay, dinucleon decay
    - conservation of lepton number mod 2 stabilizes proton
    - still have dicnucleon decay, e.g. $^{16}O(pp) \rightarrow\ ^{14}C\pi^+\pi^+$
    - violation primarily in heavy flavors (b, c quarks)?
    - dark matter carries anti baryon number? e.g. “hylogenesis” model (H. Davoudiasl, D. E. Morrissey, K. Sigurdson, S. Tulin, arXiv:1008.2399)

getting B hadrons in early universe

- “standard” cosmology: hadrons form at T< 100 MeV, b-quarks expoentially Boltzmann suppressed
- Late decaying particle cosmology: long lived inflaton or heavy scalar (moduli?) lifetime ~0.1 sec, decays into Higgs, top, W, Z, b quarks
  - Higgs, top, W, Z all decay promptly, large branching fraction into b quarks
  - b quarks hadronize before decay,
  - Can we make baryon asymmetry from B mesons and/or baryons?

- **Version 1: Baryogenesis from CPV in Oscillating Heavy flavor Neutral Baryons**

Search for baryon-number-violating Ξ_b^0 oscillations

LHCb collaboration[†]

Abstract

A search for baryon-number-violating Ξ_b^0 oscillations is performed with a sample of pp collision data recorded by the LHCb experiment, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. The baryon number at the moment of production is identified by requiring that the Ξ_b^0 come from the decay of a resonance $\Xi_b^{*-} \to \Xi_b^0\pi^-$ or $\Xi_b^{\prime-} \to \Xi_b^0\pi^-$, and the baryon number at the moment of decay is identified from the final state using the decays $\Xi_b^0 \to \Xi_c^+\pi^-$, $\Xi_c^+ \to pK^-\pi^+$. No evidence of baryon number violation is found, and an upper limit is set on the oscillation rate of $\omega < 0.08\ \mathrm{ps}^{-1}$, where ω is the associated angular frequency.

Constraints still very weak! Only one search so far!

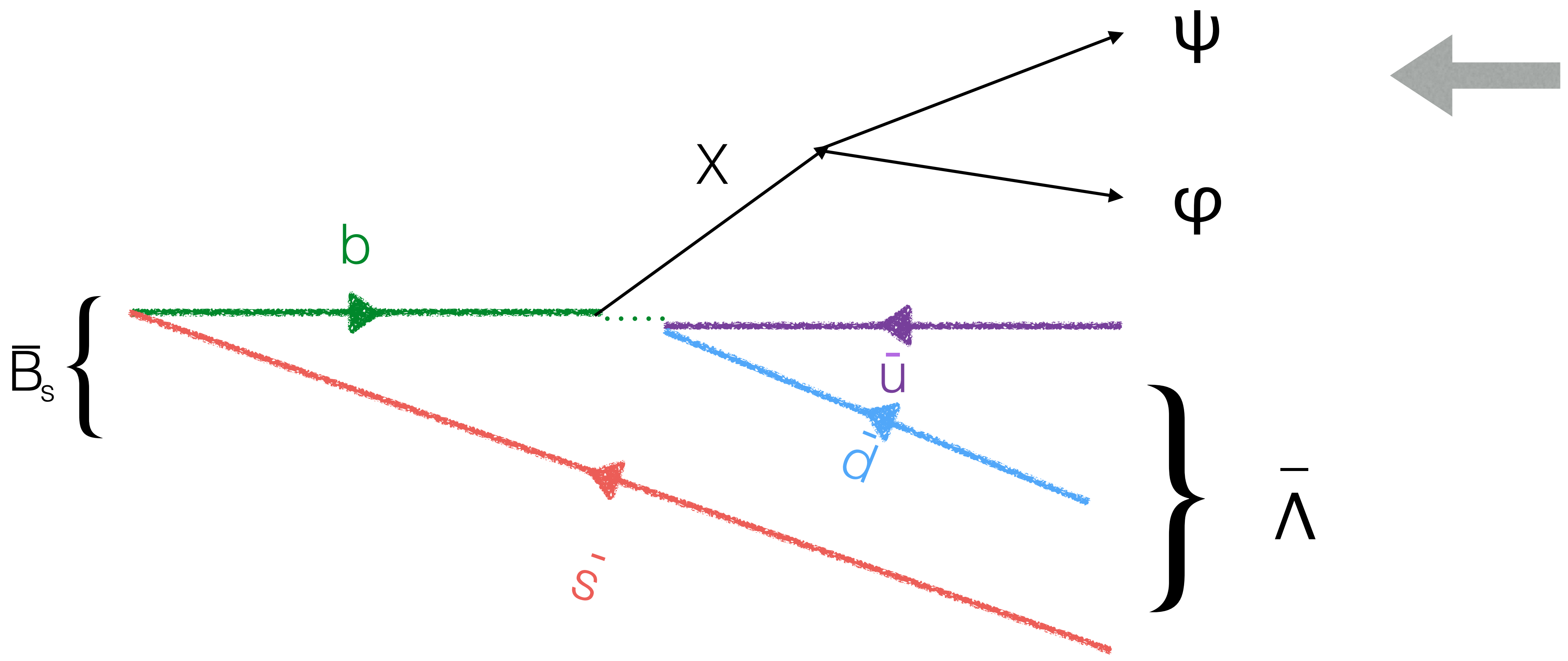
$0.08\ \mathrm{ps}^{-1} \sim 5 \times 10^{-14}$ GeV

$\Gamma \sim 4.5 \times 10^{-13}$ GeV

(Indirect Dinucleon decay bound~ 10^{-10} GeV)

• Version 2: Baryogenesis from CPV in Oscillating neutral B mesons

- B mesons oscillate and decay in CPV violating way
- B mesons have no magnetic moments, slow decoherence from scattering rate
- negligible decoherence from charge radius scattering on 10 MeV plasma before decay
- Baryon production from charge asymmetry in decay



both Z_2 charged, stable dark matter. Could carry baryon number in which case no dinucleon decay (similar to hylogenesis)

lower bound on new B physics

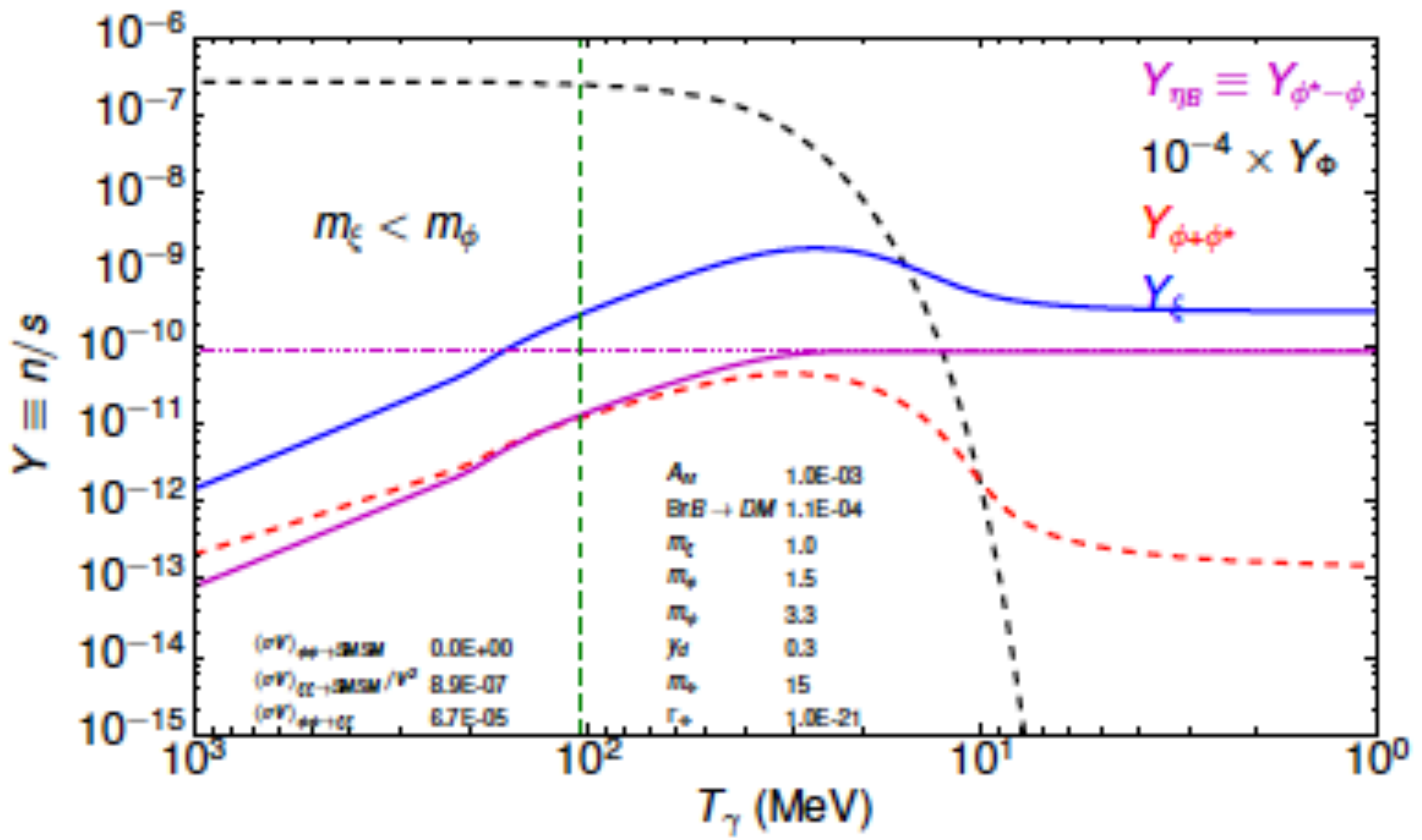
- Interesting observables:
  - semileptonic charge asymmetry $a_{sl}^{d,s}$ (asymmetry between b and $\bar{b}$ quarks at time of decay)
  - ($\bar{b}\to$diquark + dark matter) $\Rightarrow$B meson $\to$ Baryon+ dark matter+ mesons
  - BAU $\propto$ ($f_d\, a_{sl}^d + f_s\, a_{sl}^s$)Br (B meson $\to$ Baryon+ dark matter+…)
    - $f_{d,s}$=fraction of b quarks which hadronize as $B_{d,s}$ mesons

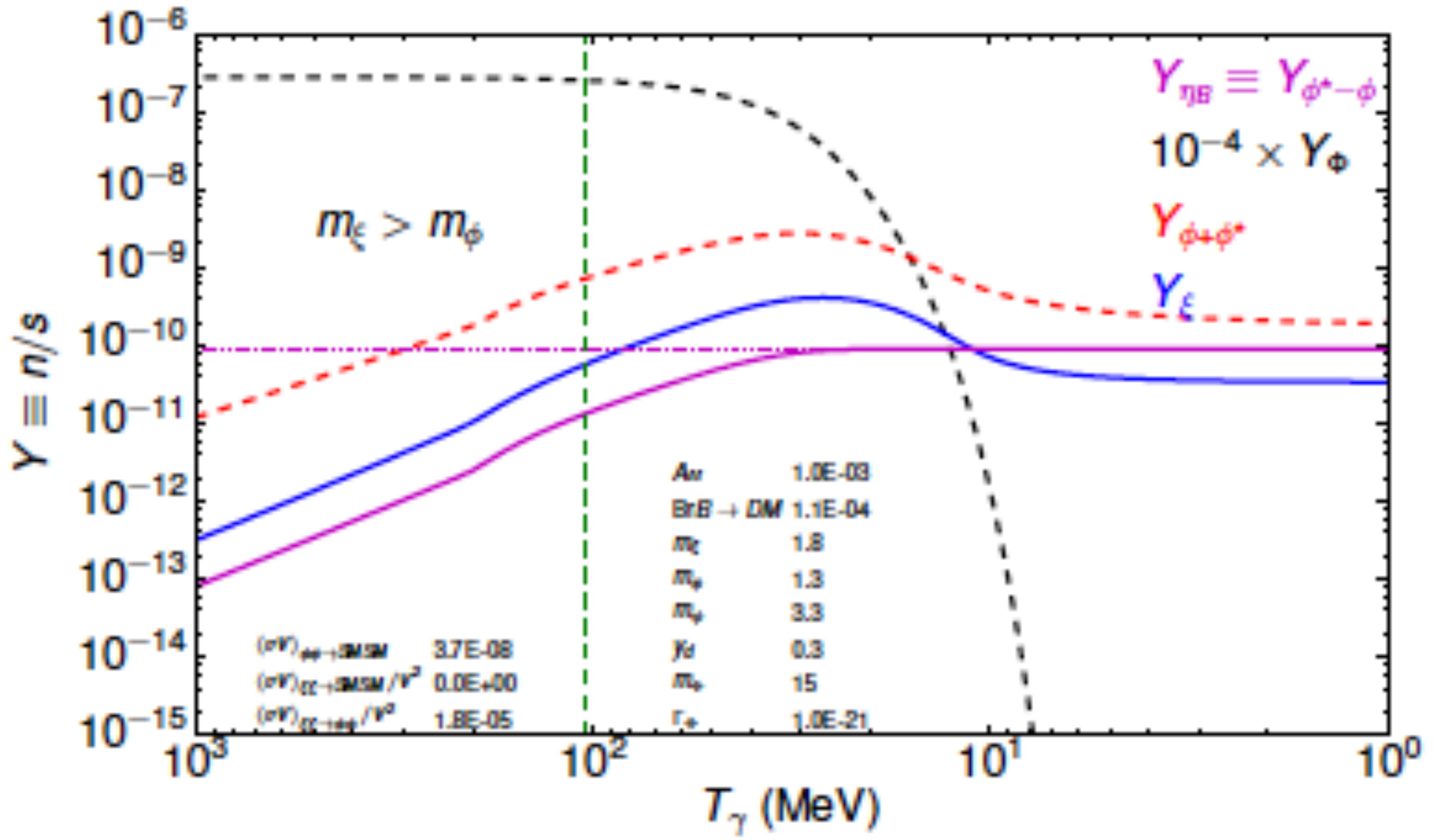
Table 4. Summary of the latest results for the B^0 mixing (a_{sl}^d) and B_s^0 mixing (a_{sl}^s) *CP* asymmetries, as well as the inclusive dimuon asymmetry A_{sl}^b measured at D0. In all cases the statistical uncertainty is quoted first and the systematic second. All values are percentages. The world averages [12] are from a fit to all a_{sl}^d, a_{sl}^s and A_{sl}^b results, except for the latest LHCb a_{sl}^s result [104]; an earlier result [105] is included instead. The latest SM predictions [9, 101] are given for comparison.

	a_{sl}^d (%)	a_{sl}^s (%)	A_{sl}^b (%)
BaBar *K*-tag [84, 106]	$0.06 \pm 0.17\,^{+0.38}_{-0.32}$	—	
BaBar $\ell\ell$ [107]	$-0.39 \pm 0.35 \pm 0.19$	—	
Belle $\ell\ell$ [85]	$-0.11 \pm 0.79 \pm 0.70$	—	—
LHCb [83, 104]	$-0.02 \pm 0.19 \pm 0.30$	$0.39 \pm 0.26 \pm 0.20$	—
D0 [86, 108, 109]	$0.68 \pm 0.45 \pm 0.14$	$-1.12 \pm 0.74 \pm 0.17$	$-0.496 \pm 0.153 \pm 0.072$
World average [12]	-0.15 ± 0.17	-0.75 ± 0.41	
SM	$-0.000\,47 \pm 0.000\,06$	$0.000\,0222 \pm 0.000\,0027$	-0.023 ± 0.004

need positive $f_d\, a_{sl}^d + f_s\, a_{sl}^s$

Bolltzmann eq solutions giving observed BAU+DM



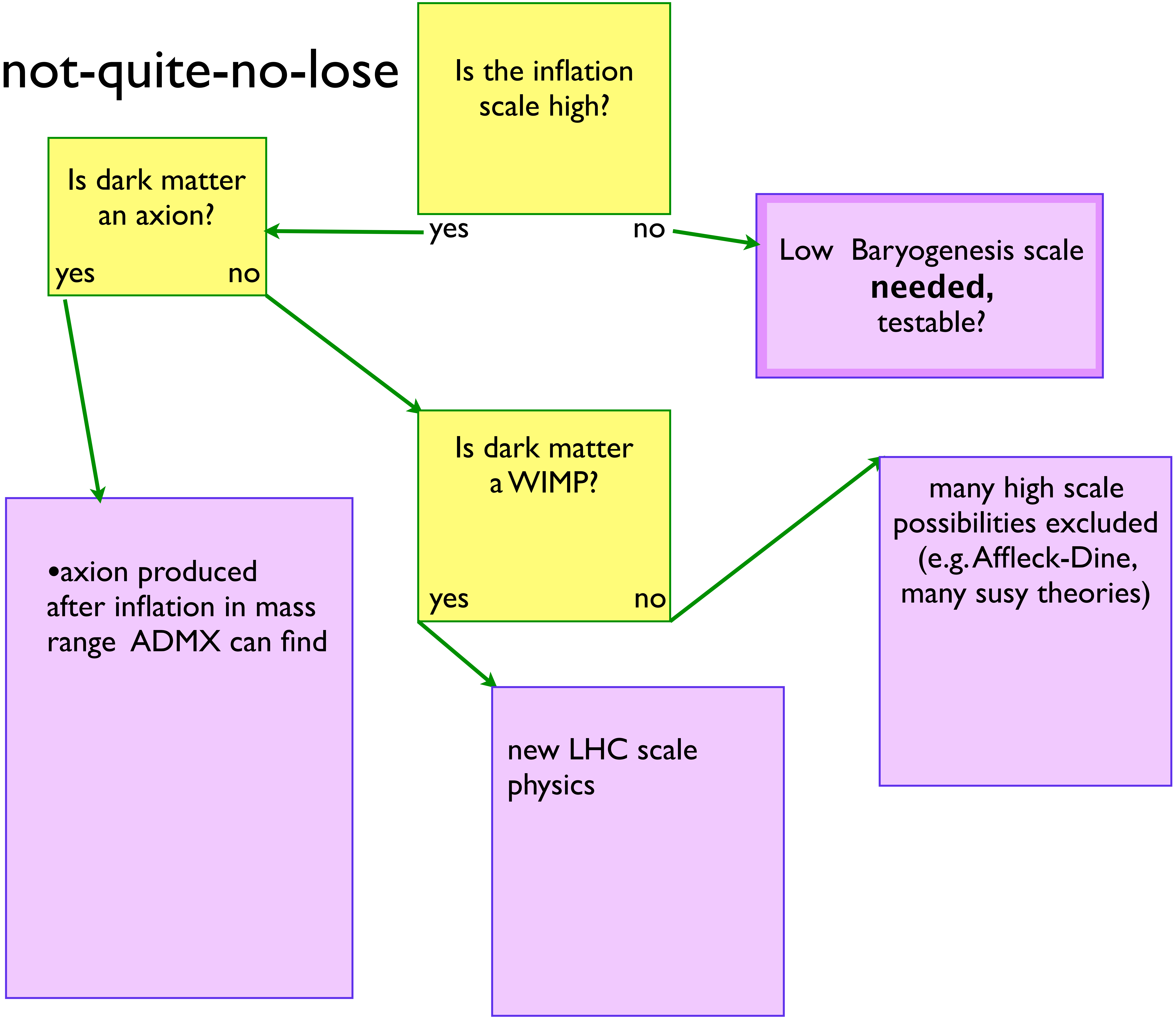


- exotic B decays into baryon+ dark matter
- B semileptonic asymmetry must be positive
- B semileptonic asymmetry $\times$ branching fraction B→ baryon+ dark matter > 10^{-7}

Summary of testable models

- Baryogenesis is strong motivation for new CPV in heavy flavors
- Dark matter in B meson decays?
- Baryon number violation in heavy flavor baryon oscillations?
- Baryogenesis from oscillating heavy flavor Baryons
- Baryogenesis from oscillating B mesons
- Baryogenesis with dark matter and no baryon # violation from B meson decays

Cosmology not-quite-no-lose

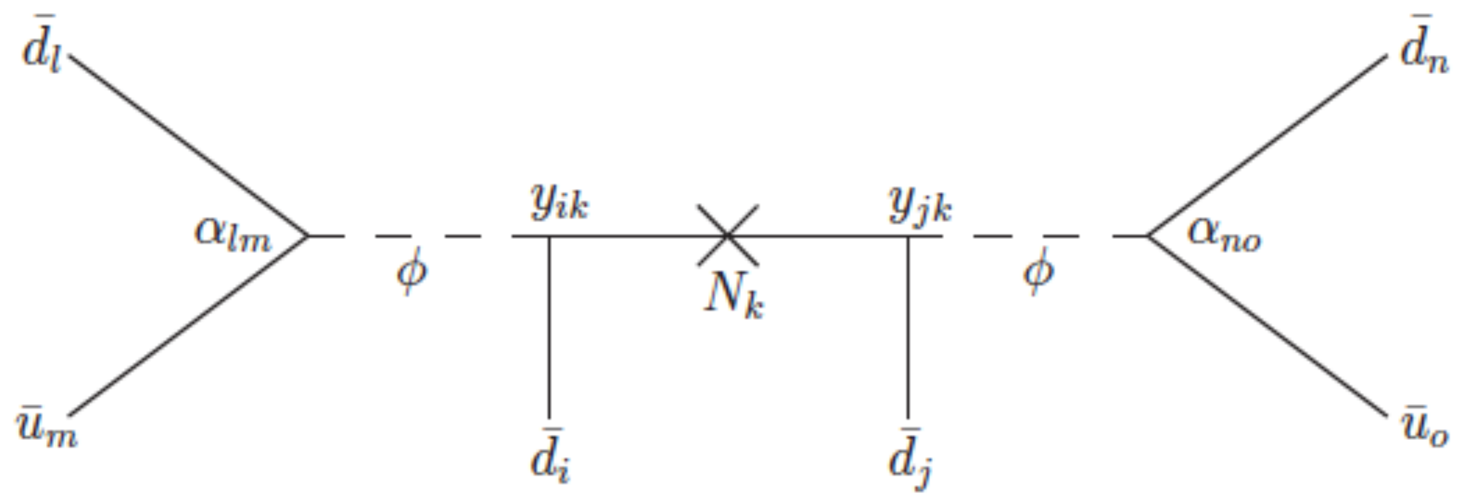


recap

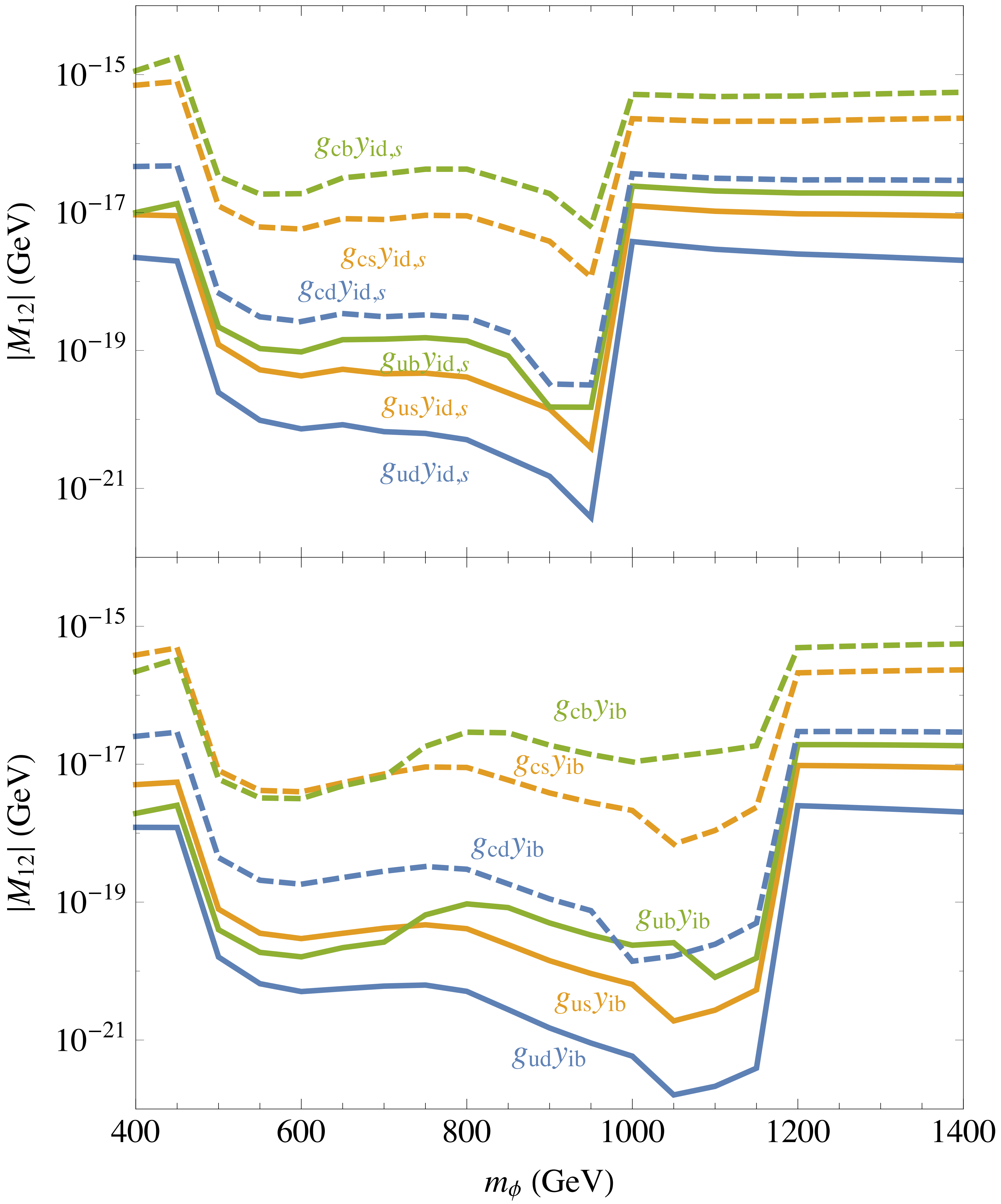
- success of nucleosynthesis in predicting 3 generations of quarks and leptons is inspiring
- We need to explain how a small asymmetry between quarks and anti-quarks arose after inflation and before nucleosynthesis
- Sakharov conditions: B violation, C and CP violation, departure from equilibrium
- Minimal Standard Model does not give any departure from thermal equilibrium or enough CPV
- 3 'theoretically favored' baryogenesis theories: lepto-genesis, electroweak phase transition baryogenesis, Affleck-Dine baryogenesis
- Many other possibilities including testable baryogenesis

Backup

Collider constraints



- ϕ colored scalar
- pair production: mϕ > ~400-600 GeV (4 jet events)
- resonant production: depends on ϕ couplings but severe limits for coupling to up quark (Angelo Monteux, JHEP 03, 216 (2016), arXiv:1601.03737 [hep-ph]).
- some operators more constrained from LHC *(in this model)* than from dinucleon decay



Upper limits on M_{12} as functions of m that result from collider searches for dijet resonances and jets plus MET, assuming the dominance of the product of couplings indicated .

Top: The limits when y_{id} or y_{is} are dominant.
Bottom: The limits when y_{ib} is dominant.

Solid curves show the limits in the case where the charge 2/3 quark involved is up while dashed lines show the limit in the case of the c quark.