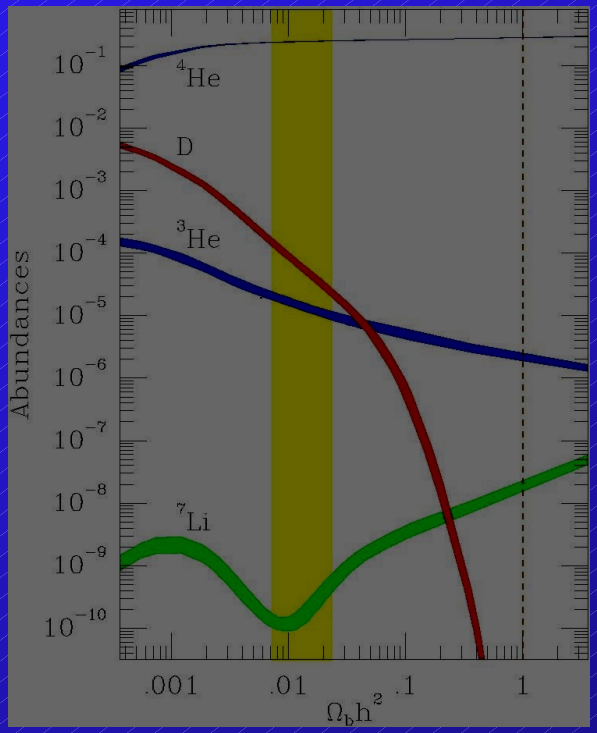
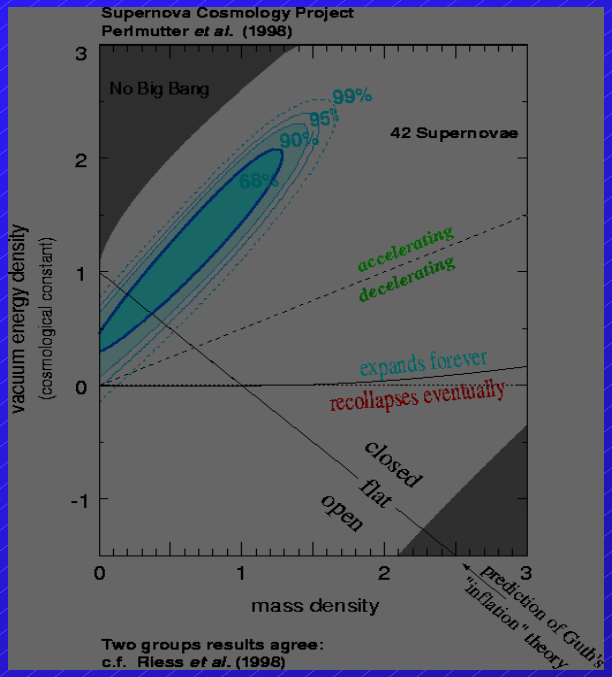
Baryogenesis and the New Cosmology



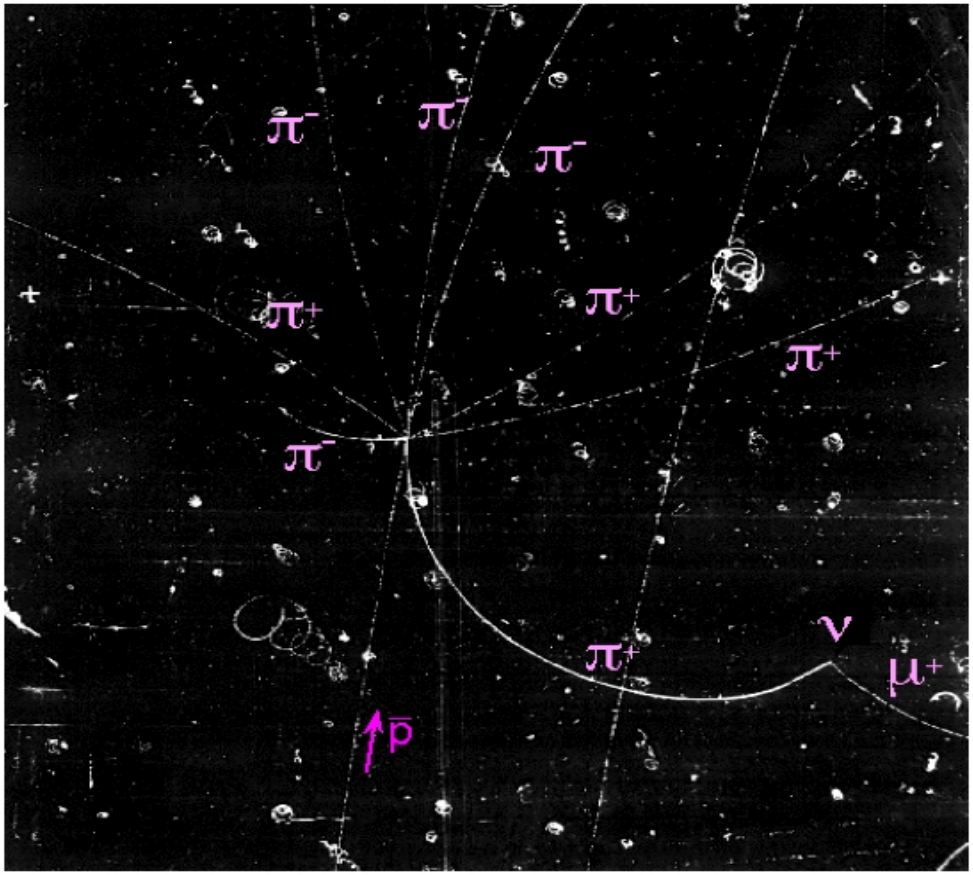


Mark Trodden
Syracuse University

COSMO-02
Adler Planetarium, Chicago

9/18/2002

What's it All About?

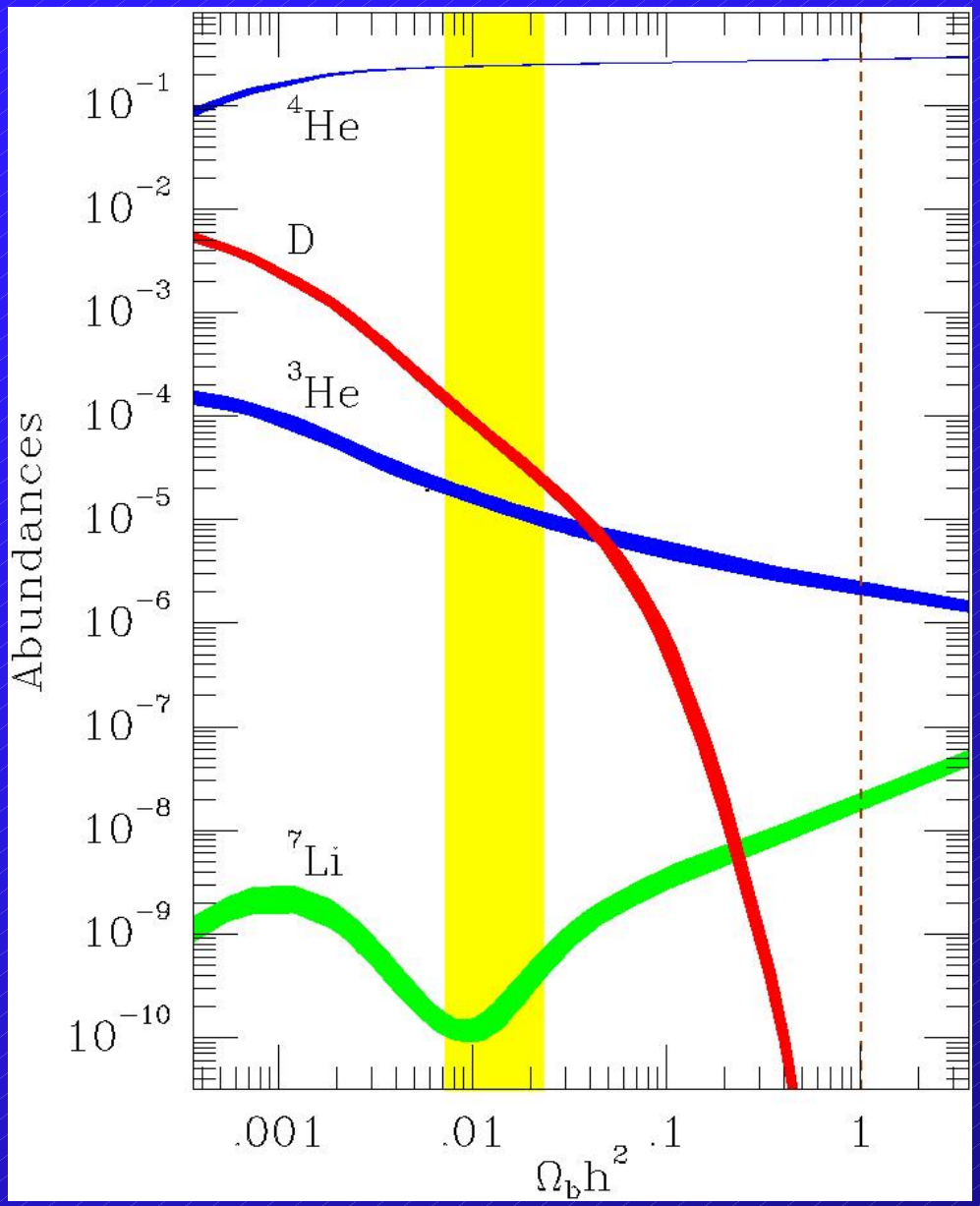


Matter
Vs
Antimatter

A Classic Particle Cosmology Problem

- Wherever you look you see matter and not antimatter.
- Particle physics teaches us matter and antimatter are the same.
- Cosmology teaches us they must exist in equal abundances in the early universe.
- What happened between then and now?
- Baryogenesis!

Quantifying the Asymmetry



- Remarkable region of concordance.
- Possible for a single value of $\eta \sim 10^{-10}$.
- A major test of the Big Bang theory …
- … and our earliest direct cosmological data.

Outline

- A reminder to get us all on the same page.
- A quick status summary of a popular mechanism - electroweak baryogenesis.
- A plea for cosmological economy.
- Quintessential Baryogenesis.
- I'll just sketch the main ideas here - please come to discuss the details with me later

"*Quintessential Baryogenesis*", Antonio De Felice, Salah Nasri & M.T. hep-ph/0207211

(See also parallel session talk by Xinmin Zhang)

What's a Particle Theory to do?

- Sakharov (1968) :
- Violate Baryon number (B) symmetry
- Violate the Charge conjugation and Charge-Parity symmetries (C & CP)
- Depart from thermal equilibrium (because of the CPT theorem !!! More about this later.)
- There are **LOTS** of ways to do this!

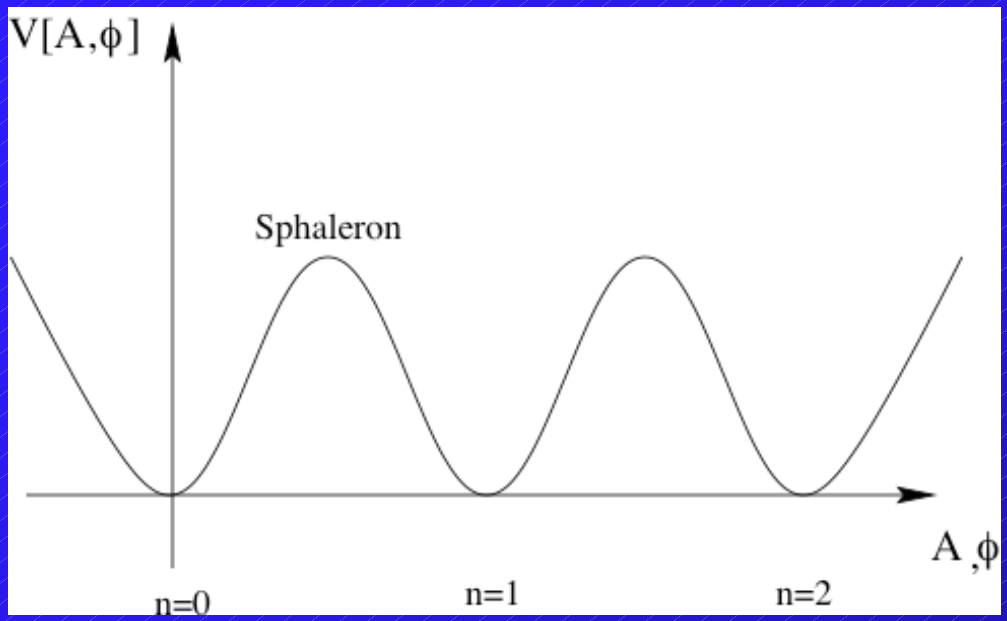
Also an Important Clue for Particle Physics

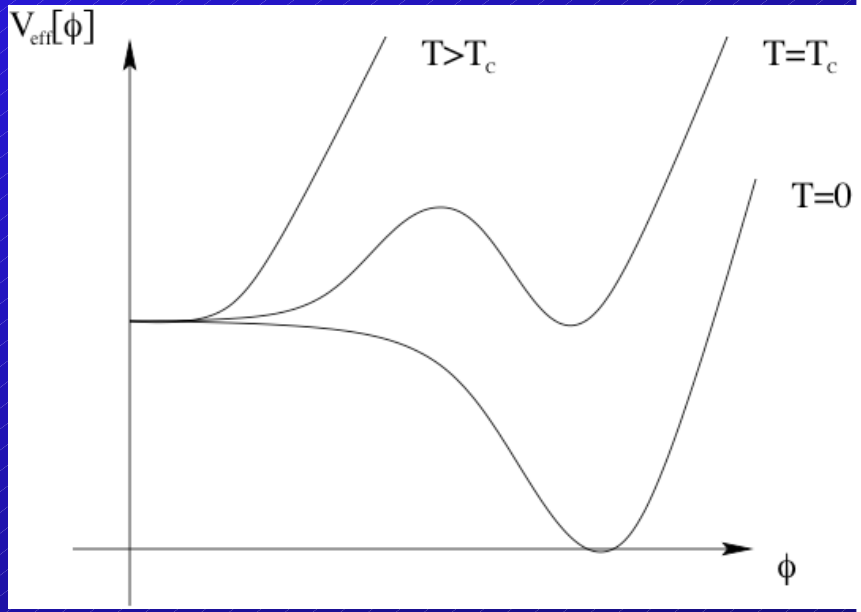
- The Standard Model of particle physics, even though in principle it satisfies all 3 Sakharov criteria, (anomaly, CKM matrix, finite-temperature phase transition) cannot be sufficient to explain the baryon asymmetry!
- This is a clear indication, from observations of the universe, of physics beyond the standard model!

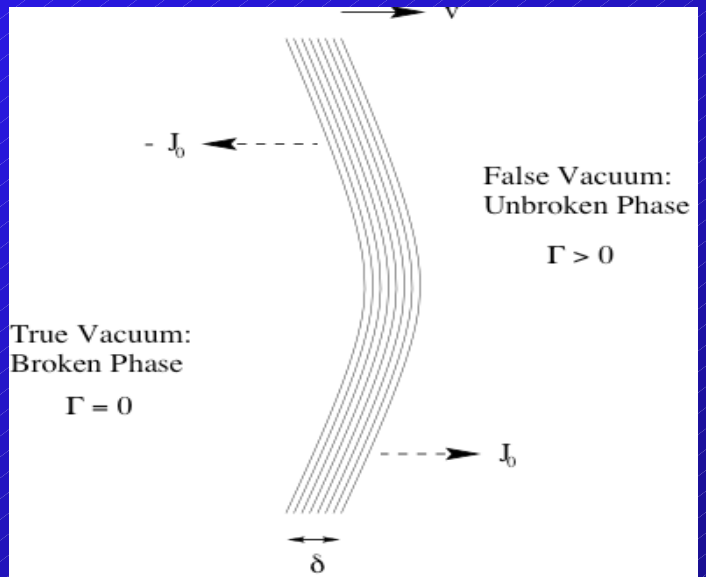
So What's Viable?

- Electroweak-like baryogenesis models using 2-higgs, SUSY, …
- Affleck-Dine models – inflation driven
- GUT baryogenesis
- Baryogenesis through preheating after inflation (high and low scale)
- Baryogenesis through leptogenesis
- And many more …

Electroweak Baryogenesis I







Electroweak Baryogenesis II

- Requires more CP violation than in SM
- (Usually) requires a (sufficiently strong) 1st order thermal EW phase transition in the early universe.
- Our most popular model of recent years

- Popularity of this idea is tightly bound to its testability.
- Physics involved is all testable in principle at realistic colliders.
- Small extensions needed can all be found in SUSY, which is an independently attractive
- However, the testability of electroweak scenarios also leads to tight constraints.

Bounds and Tests

- Exists only a small window of parameter space in extensions of the electroweak theory in which baryogenesis is viable
- Because electroweak baryogenesis requires a strong enough first order phase transition
- Severe upper bound on lightest Higgs boson mass, m_h <120 GeV (in the MSSM)
- Stop mass may be close to experimental bound and must be < top quark mass.

(See Carena, Quiros, Seco and Wagner, hep-ph/0208043)

Direct Tests

- Search for the lightest Higgs at Tevatron or LHC.
- Search for the lightest stop at the Tevatron or LHC.
- Crucial test may come from B-physics - CP-violating effects (but not guaranteed at B factories)
- Essential to have new measurements of CP-violation, particularly in the B-sector

Testable Alternatives

- Might hope that Affleck-Dine occurs at low enough energies - new particles

  (Dine, Randall & Thomas)

- BUT low scale inflation is very hard to make work
- Leptogenesis hard to test if have heavy right-handed neutrinos (Low-scale versions might help)

What Might We Hope For?

- EWBG is so great because it is testable and uses physics that is ***already there for a good particle physics reason***
- If EWBG is successful, it is a triumph of the particle physics/cosmology union
- If EWBG is unsuccessful, ***our primary attention should be focused on models with the same properties***

A Plea for Cosmological Economy

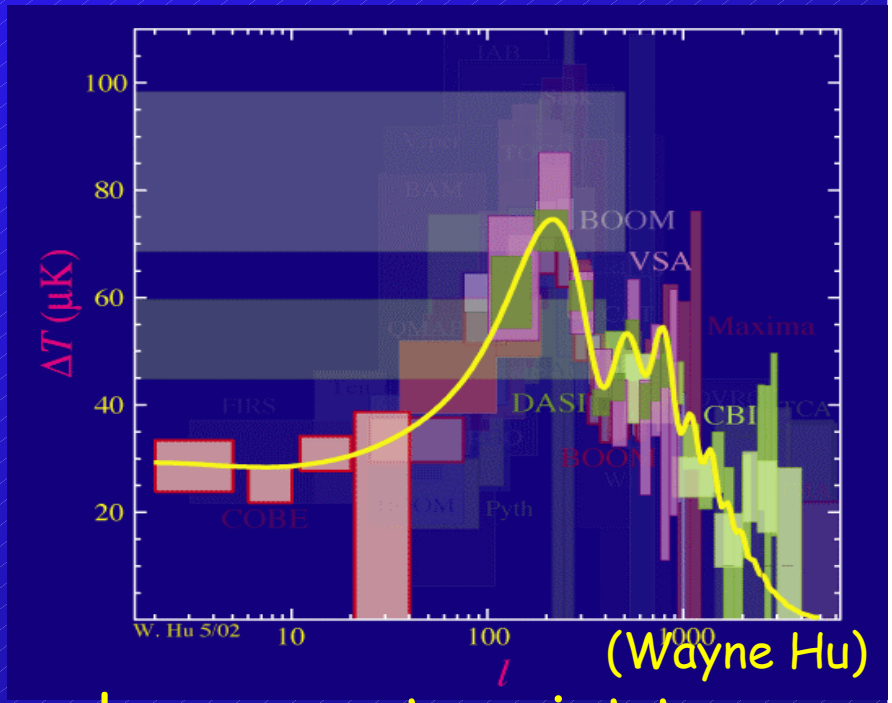
- Despite indicators to the contrary (none discovered in nature to date)
- Cosmology continues to experience a robust period of growth in the scalar field sector

- Possible that this scalar field bubble may burst
- At the very least we may consider limiting our exposure in this sector.
- …and do our best to avoid accounting scandals.

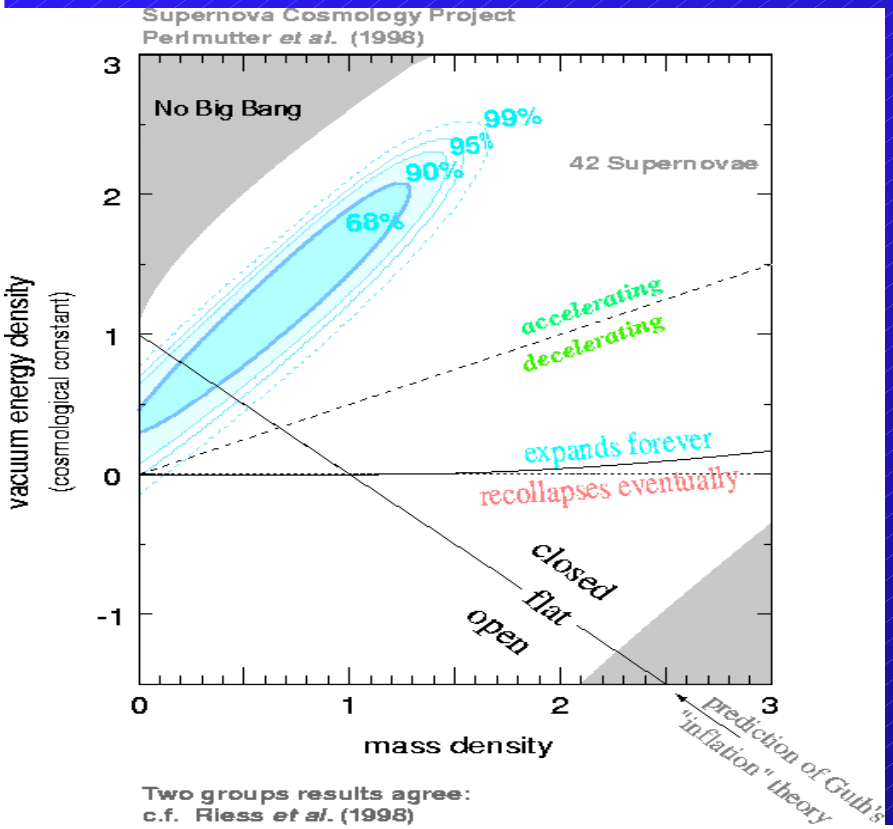
Quintessential Inflation I

(Peebles and Vilenkin)

- There is a considerable amount of data in agreement with predictions of a wide class of inflationary models



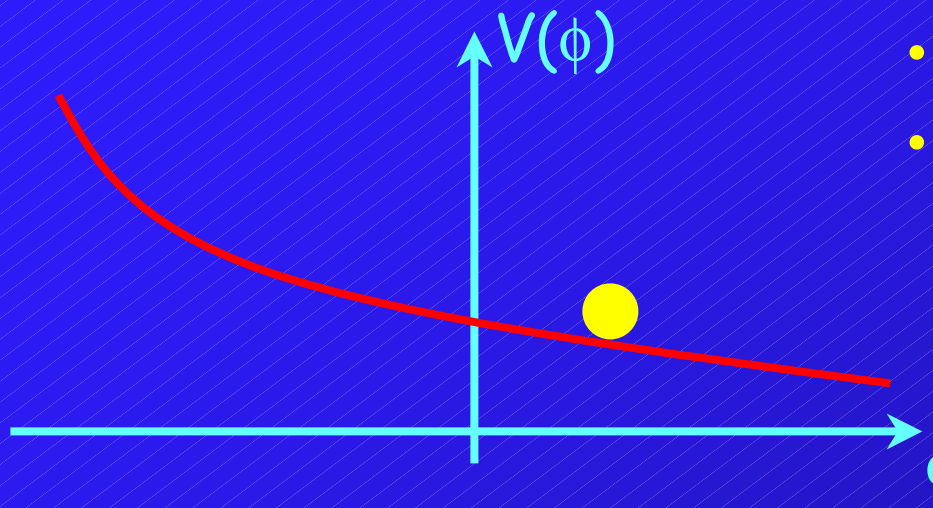
(Wayne Hu)



- Data also seems to point to a dominant dark energy component in the universe.

Maybe they are due to the Same field!

Quintessential Inflation II



- One field drives inflation
- Much later, it then drives quintessence

- In interim, universe is kinetic energy dominated $\rightarrow$ radiation-dominated $\rightarrow$ matter-dominated
- Matter creation not through reheating but through particle creation during transition from inflation to "kination".

Quintessential Baryogenesis

(De Felice, Nasri & MT; see also Li, Wang, Feng & Zhang)

- When I told you about the departure from equilibrium I omitted a loophole. (Nice review in Dolgov)
- If CPT is broken - asymmetry can be generated in equilibrium!
  - Can't break CPT explicitly
  - But if broken *spontaneously*, can generate a baryon asymmetry.

Spontaneous Baryogenesis (Cohen & Kaplan)

Might the Quintessential Inflation field play this role?

What is Required?

Terms in effective Lagrangian of form

$$L_{eff} = \frac{\lambda'}{M^2}\partial_\mu \phi J^\mu$$

J^μ : current $\leftrightarrow$ some global symmetry (e.g. B or B-L)
Since ϕ homogeneous can write

$$L_{eff} = \frac{\lambda'}{M^2}\dot{\phi}\Delta n \equiv \mu(t)\Delta n$$

A time-dependent "chemical potential" for (e.g.) baryon number

What net baryon number does this yield?

Calculating the Asymmetry

$$\Delta n(T;\mu) = \int \frac{d^3\vec{p}}{(2\pi)^3}\left[f(E,\mu) - f(E,-\mu)\right]$$

Number density at nonzero chemical potl.

So $$\Delta n(T) \sim \frac{\lambda' g}{6M} T^2 \phi_Y$$

(This is all standard spontaneous baryogenesis)

- Divide by entropy density
- Note that baryon number violating processes "freeze out" at temperature T_F
- Resulting baryon to entropy ratio is

$$\eta_F \equiv \eta(T_F) \equiv \frac{\Delta n}{s}(T_F) \sim 0.38\lambda'\left(\frac{g}{g_*}\right)\frac{\phi_Y(T_F)}{MT_F}$$

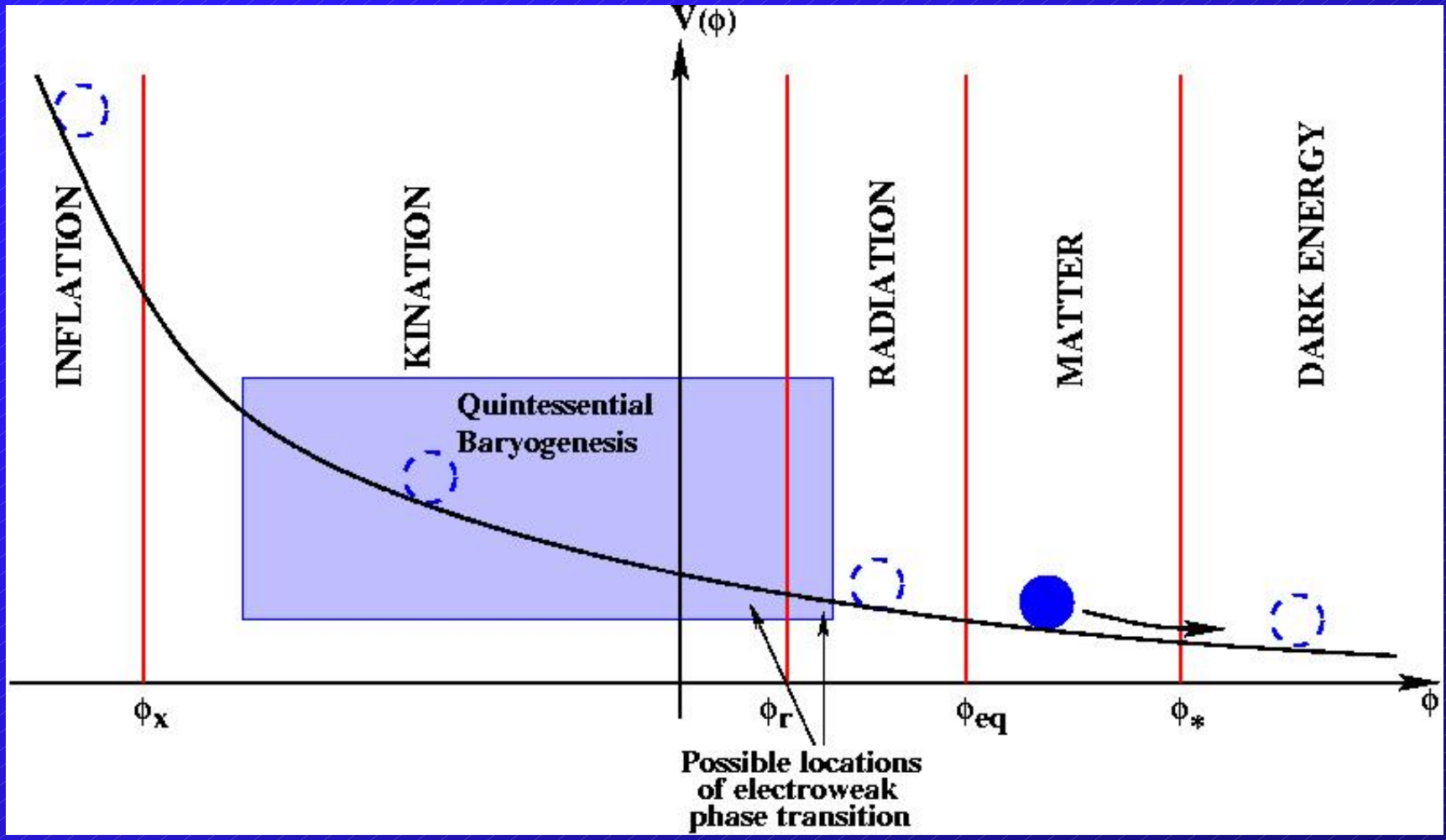
Calculating T_F

This is where the details of quintessential inflation are crucial. Answer depends on:

- The potential $V(\phi)$ (but not really a free parameter - constrained through cosmology)
- The source of baryon number violation
- The evolution of the universe before and at T_F

- Important to take into account that universe could be kinetic-energy dominated down to below T_F (Joyce; Joyce & Prokopec)
- Affects not only the asymmetry produced, but how much it may be diluted by anomalous electroweak processes.

Graphical Summary



Constraints and Tests

- If our current is that for baryon number, then

$$L_{eff} = -\frac{\lambda'}{M}\phi n_f \left(\frac{g^2}{32\pi^2} W^a_{\mu\nu} \tilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} B_{\mu\nu} \tilde{B}^{\mu\nu} \right)$$

- Electromagnetic part $\rightarrow$ rotation of polarized light from radio sources

$$\Rightarrow \quad \lambda' \frac{M_P}{M} < 8$$

In Peebles-Vilenkin model

Consistent with quintessential baryogenesis !

(See Carroll, PRL **81**, 3067 (1998), astro-ph/9806099)

Conclusions I

- There are many models out there that have a chance to explain the asymmetry.
- We should focus on those that are consequences of other physics.
- Upcoming collider experiments will test some of our favorite models

Conclusions II

- Have demonstrated how a single scalar field can be responsible for:
  - Inflation
  - Baryogenesis
  - Dark energy

- Model may be testable if the scales and couplings are of the right size
- An attempt to understand how independently-motivated models may explain other cosmological phenomena

-Thank You -