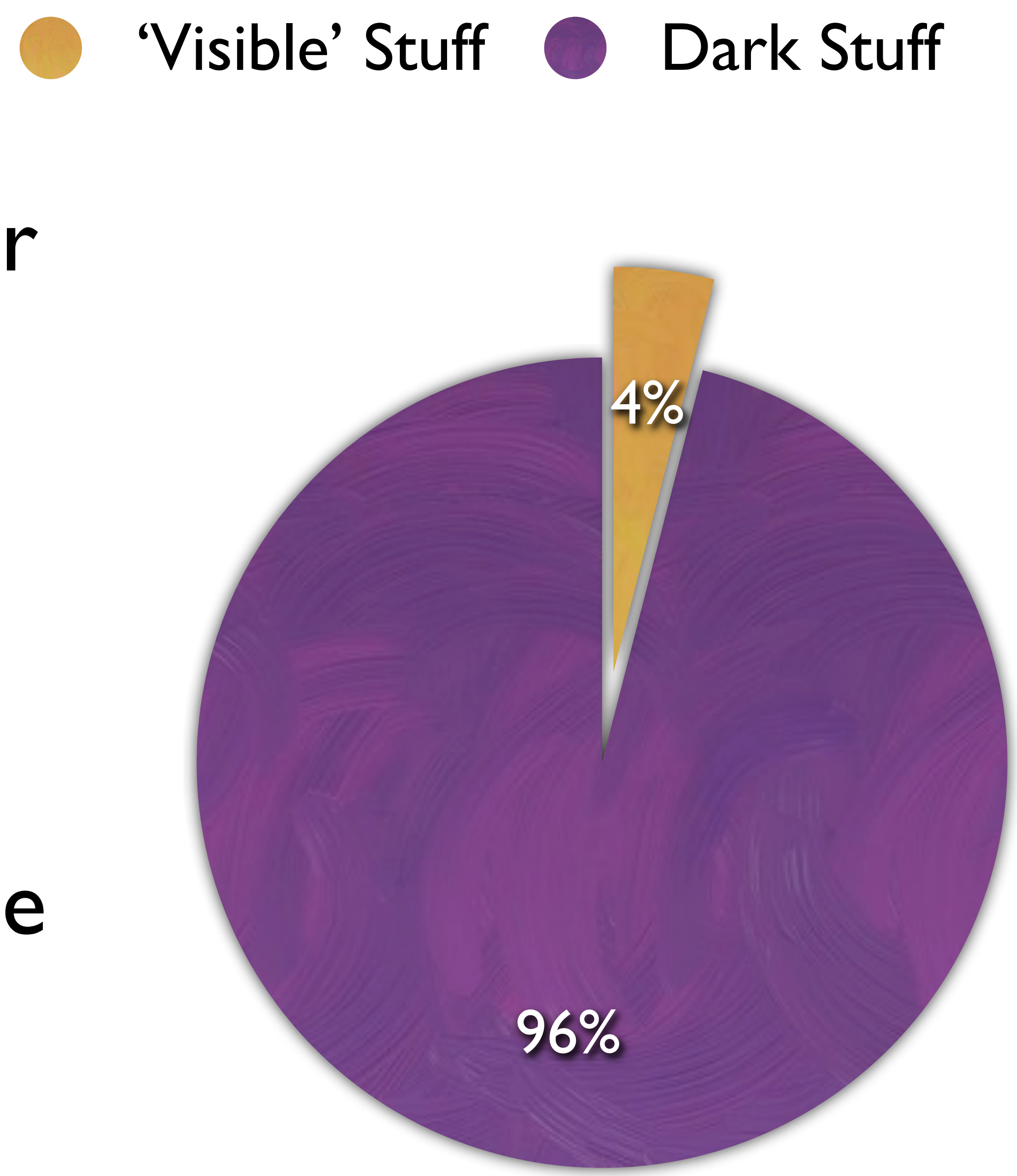
CF 6B

The Origin of the Matter-anti-Matter asymmetry

Ann Nelson, Mu-Chun Chen, with many thanks to speakers at Cosmic Frontier and Minnesota workshops

Without baryogenesis, the 'visible' 4% would be only ~0.3% (mostly ν).



- cosmological matter-antimatter asymmetry is BSM
- The new physics must couple to us
- Cosmology suggests the new physics is probably at accessible energies

Today's baryons are but a tiny remnant

- 10^8+1 quarks for every 10^8 antiquarks created in the very early universe
- ***inflation would erase any initial asymmetry***
- Sakharov coined idea of Baryogenesis in 1967 and proposed a model with three key ingredients (now known as Sakharov conditions)

1. C violation and CP violation
2. B violation
3. out of equilibrium process in early universe (CPT guarantees B=0 in equilibrium)

Sakharov Conditions and the Standard Model

✓ C and CP violation (but not enough)

✓ 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=126)

Baryogenesis Contenders

- 3 viable proposals which use Lagrangian of "pre-existing" models that were proposed for other reasons
  - Leptogenesis
  - Electroweak baryogenesis
  - Affleck-Dine baryogenesis
- A plethora of other viable proposals which involve theories invented primarily for the purpose of baryogenesis and in some cases baryogenesis/dark matter

MeV < The ***Scale*** of baryogenesis < 10^{16} GeV

- the scale of inflation is an upper bound

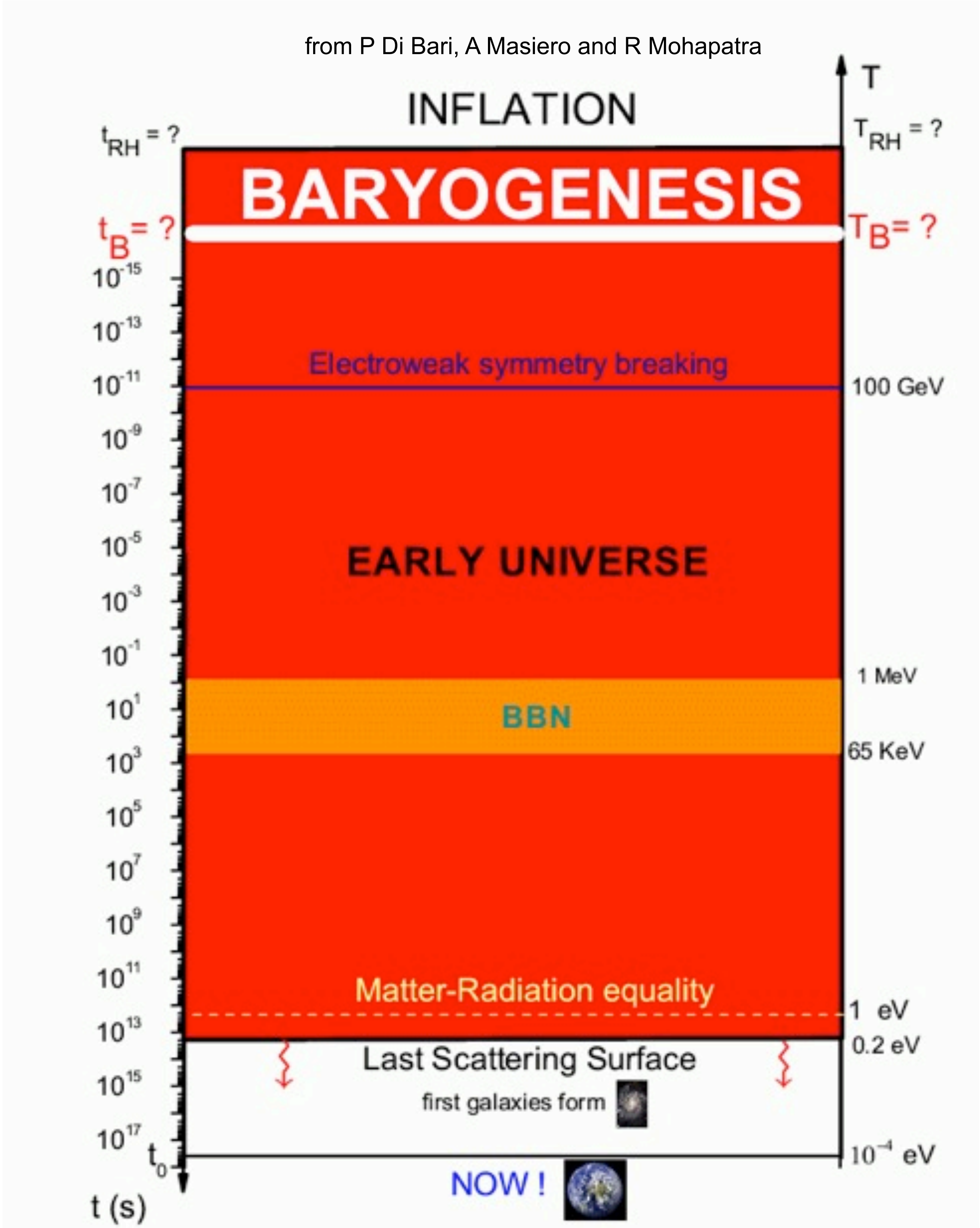
➡B mode signature of inflation in CMB

➡some models of baryogenesis or dark matter predict isocurvature perturbations in CMB unless inflation scale is LOW

- The reheat temperature is a stronger upper bound
  - some high reheat scale models have issues with overproduction of light particles e.g. gravitinos
- B-L violation (majorana neutrinos, neutron antineutron oscillations) give upper bound on baryogenesis scale)

Leptogenesis (*Fukugita and Yanagida*)

- Heavy, out of equilibrium CPV decay of very heavy Majorana neutrinos
  - electroweak sphalerons convert lepton asymmetry into baryon asymmetry
  - Observable leptogenesis consequences: light Majorana neutrino mass, CPV in neutrino sector



From Chen talk, previous session

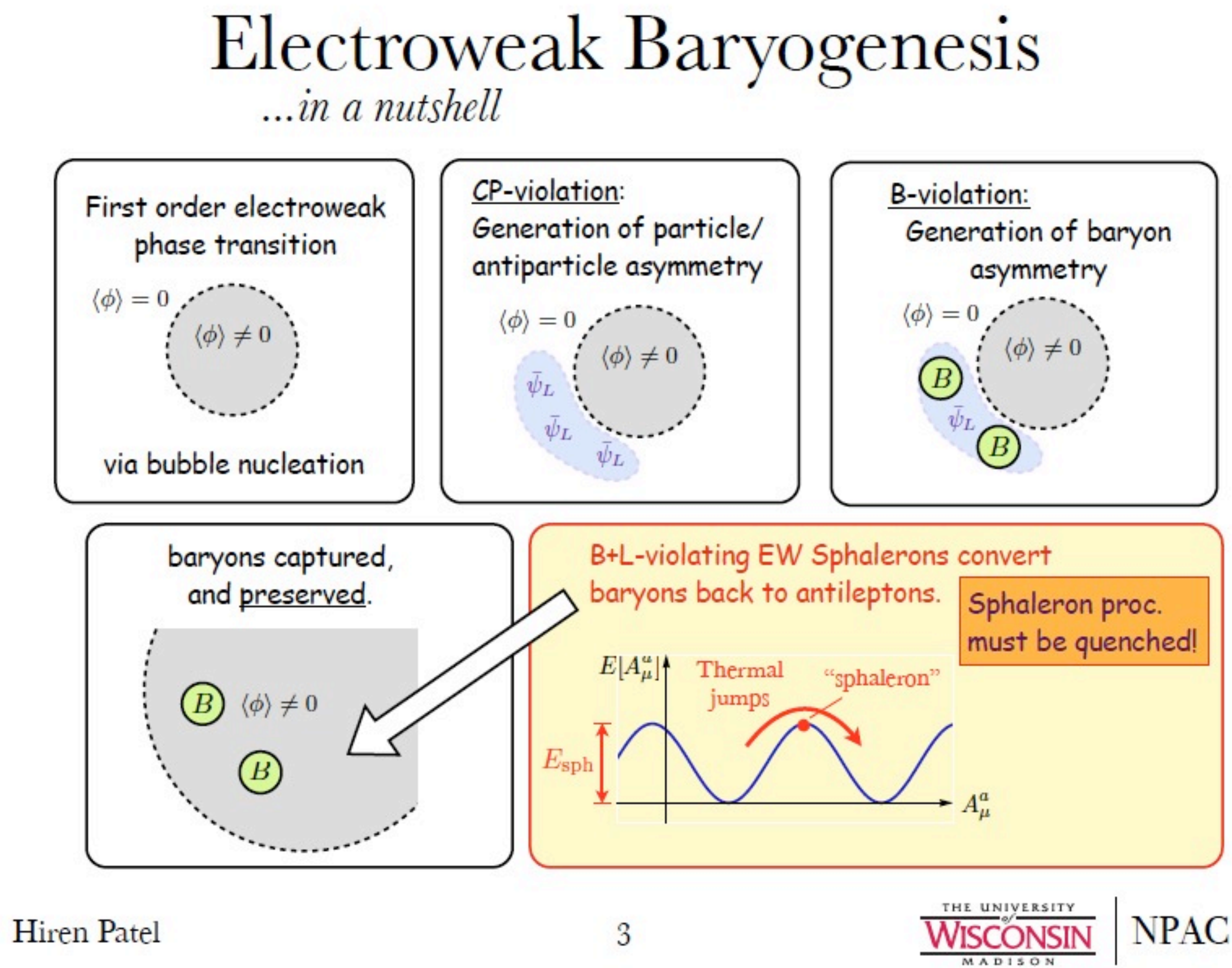
Conclusions

- tested by “archeological” evidences
- model-independent ways:
  - Kinematic test, Cosmology (absolute neutrino mass bound, N_{eff})
  - Neutrino-less double beta decay (Majorana vs Dirac leptogenesis)
- **Leptonic CP violation:**
  - **important fundamental property of neutrinos, independent of leptogenesis**
- model-dependent connections to CPV in other sectors possible
  - correlations: models with single source of CPV (J_{cp}, $\langle m_{\beta\beta} \rangle$, EDM, etc)
  - searches at neutrino experiments (leptonic CPV, mixing parameters)
  - complementarity test from other B or L violating processes
    - e.g. N-Nbar oscillation ⇒ constraint scale of leptogenesis

Electroweak Baryogenesis

- With Higgs discovery, Electroweak Baryogenesis still a well motivated and viable possibility, motivating searches for
  - Electric Dipole moments
  - New bosons (e.g. light stop)
  - New Higgs bosons
  - Deviations from SM Higgs properties especially triple Higgs coupling

from Patel, previous session



recipe for EW baryogenesis model

- need to change the Higgs sector
  - strong 1st order phase transition

➡2HDM

➡Higgs singlets

➡new light boson coupled to Higgs (e.g. light right handed stop in SUSY)

New CP Violation

- Cosmology requires $q/(q+\overline{q}) \sim 10^{-8}$
- EWB comes with small numbers
  ~ rate of baryon number violating events/(volume T^4)
  $\sim 30\alpha_W^5 \sim 10^{-6}$
- Effects of new CP phases cannot be suppressed by too many small factors
- CKM phase won't work because its effects are
  $\propto V_{cb} V_{ub} V_{us} (m_c^2 - m_u^2)(m_s^2 - m_d^2)(m_b^2 - m_s^2)/T^6$
- **Great news for EDM hunters**
- **EDM constraints $\rightarrow$ small phases affecting Higgs Physics**

from Kozaczuk, MSSM EWB

Observational Constraints

Intensity frontier:

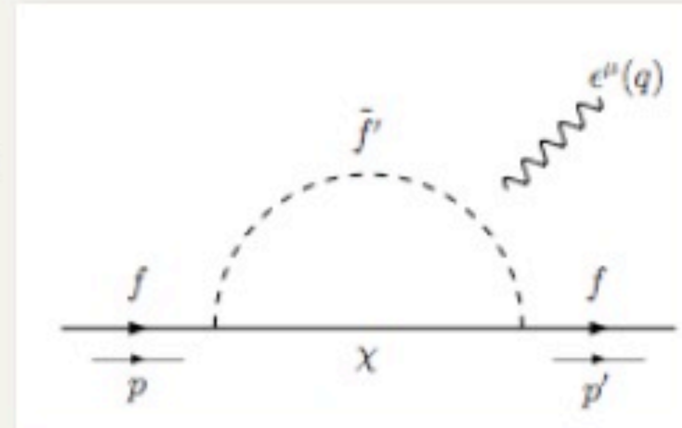
-Electric Dipole Moments sensitive to CP-violation

$$H = -\mu_f^B \mathbf{B}\cdot\frac{\mathbf{S}}{S} - d_f^E \mathbf{E}\cdot\frac{\mathbf{S}}{S} \longrightarrow \mathcal{L} = -d_f^E \frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$

P-odd, *T*-odd (*CP*-odd)

$$\mathcal{L}_{(C)EDM} = -\frac{i}{2} d_f^E F^{\mu\nu}\bar{f}\sigma_{\mu\nu}\gamma_5 f - \frac{i}{2} d_q^C G^{a\mu\nu}\bar{q}\sigma_{\mu\nu}\gamma_5 T^a q$$

(Chromo-EDM)



-EDM can be induced at one-loop and beyond. With heavy sfermions, two-loop contributions can still be sizable

Energy frontier:

-Collider searches constrain new SUSY degrees of freedom which must be light (O(100 GeV)) to avoid thermal suppression near the EWPT

-Predictions for mass and properties of observed 126 GeV Higgs affected by new particles

Cosmic Frontier:

-Light gauginos for CPV sources have implications for dark matter

Affleck-Dine

- SUSY+inflation intrinsic, relies on squark and slepton condensates with relatively low energy density ("flat directions").
- "Q-ball" (leftover squark/slepton lumps) dark matter would be strong evidence (but not necessary consequence)
- high inflation scale could exclude (isocurvature fluctuations)
- compatible with low reheat temperature

Summary

- Cosmology: Inflation+ Dark Matter+Baryogenesis=probable new experimentally accessible physics
- With Higgs discovery, Electroweak Baryogenesis still a well motivated and viable possibility, motivating searches for
  - Electric Dipole moments
  - New bosons (e.g. light stop)
  - New Higgs bosons
  - Deviations from SM Higgs properties

CF6-C

The Fundamental Nature of Spacetime

Quantum Geometry and The Holographic Universe

- slides thanks to Craig Hogan

from Craig Hogan

Planckian quantum-geometrical position uncertainty

Gravitational theory suggests that quantum geometrical degrees of freedom have information with Planck areal density

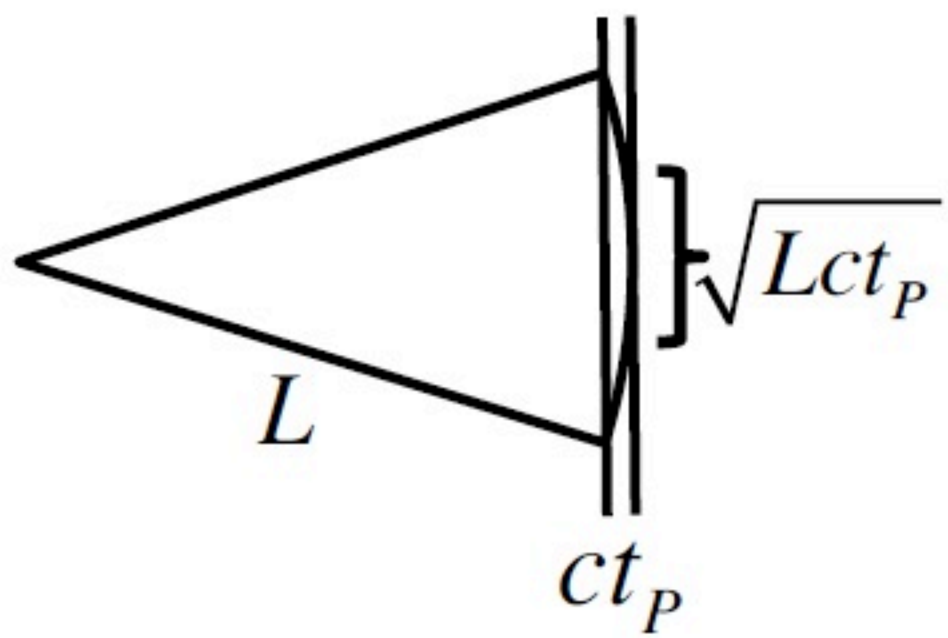
Information on spatial position is much less than in field theory; limits angular or transverse degrees of freedom

Quantum geometry may not respect locality or separation of scales; geometrical position uncertainty may be much larger than the Planck length

Introduces new source of noise in macroscopic position detectable with nonlocal measurements of position of massive bodies in two directions

May be relevant to new physics of Dark Energy

There may be no such thing as a massive body at rest



Uncertainty in transverse position defined with Planck frequency waves; much larger than Planck length at macroscopic separation L

Fermilab Holometer Experimental Concept

Measure correlated optical phase fluctuations in a pair of isolated but collocated power recycled 40-meter Michelson interferometers

exploit the spatial coherence of entangled quantum-geometrical noise

measure at high frequencies (MHz) where other correlated noise is small

Sensitive to nonlocal entanglement of quantum-geometrical position states

Sensitivity goal: measure or rule out spectral density of transverse position noise given by the Planck time:

$$h^2 \approx \frac{\langle \hat{x}_\perp^2 \rangle}{cL_a} = t_P/\sqrt{4\pi} = (1.23 \times 10^{-22}\mathrm{Hz}^{-1/2})^2$$

Experiment is now built, currently in commissioning stage