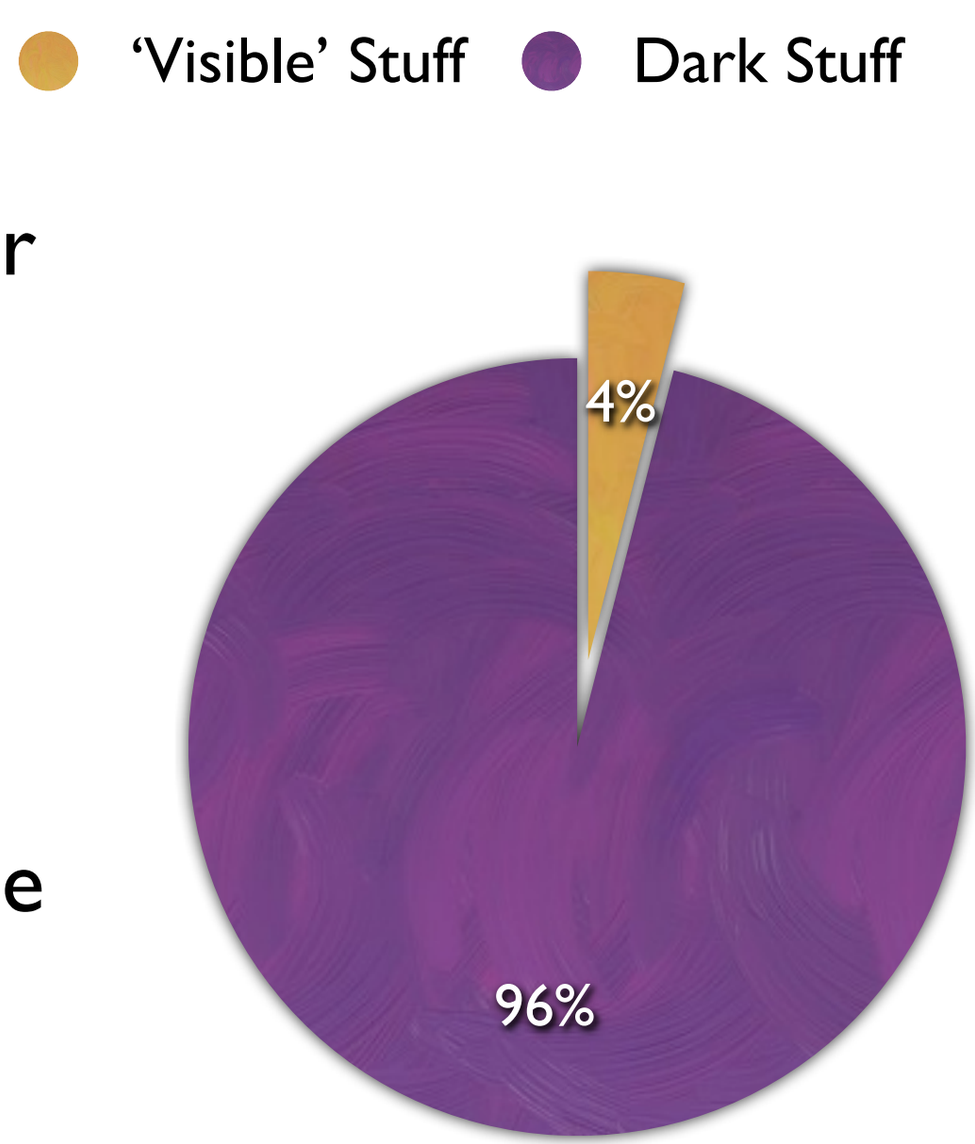
Accessible New Physics implications from the Cosmic Frontier

Talk given at Energy Frontier Workshop, Seattle, July 1, 2013

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 toy model with three key ingredients (now known as Sakharov conditions)
  - C violation and CP violation
  - B violation
  - 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)

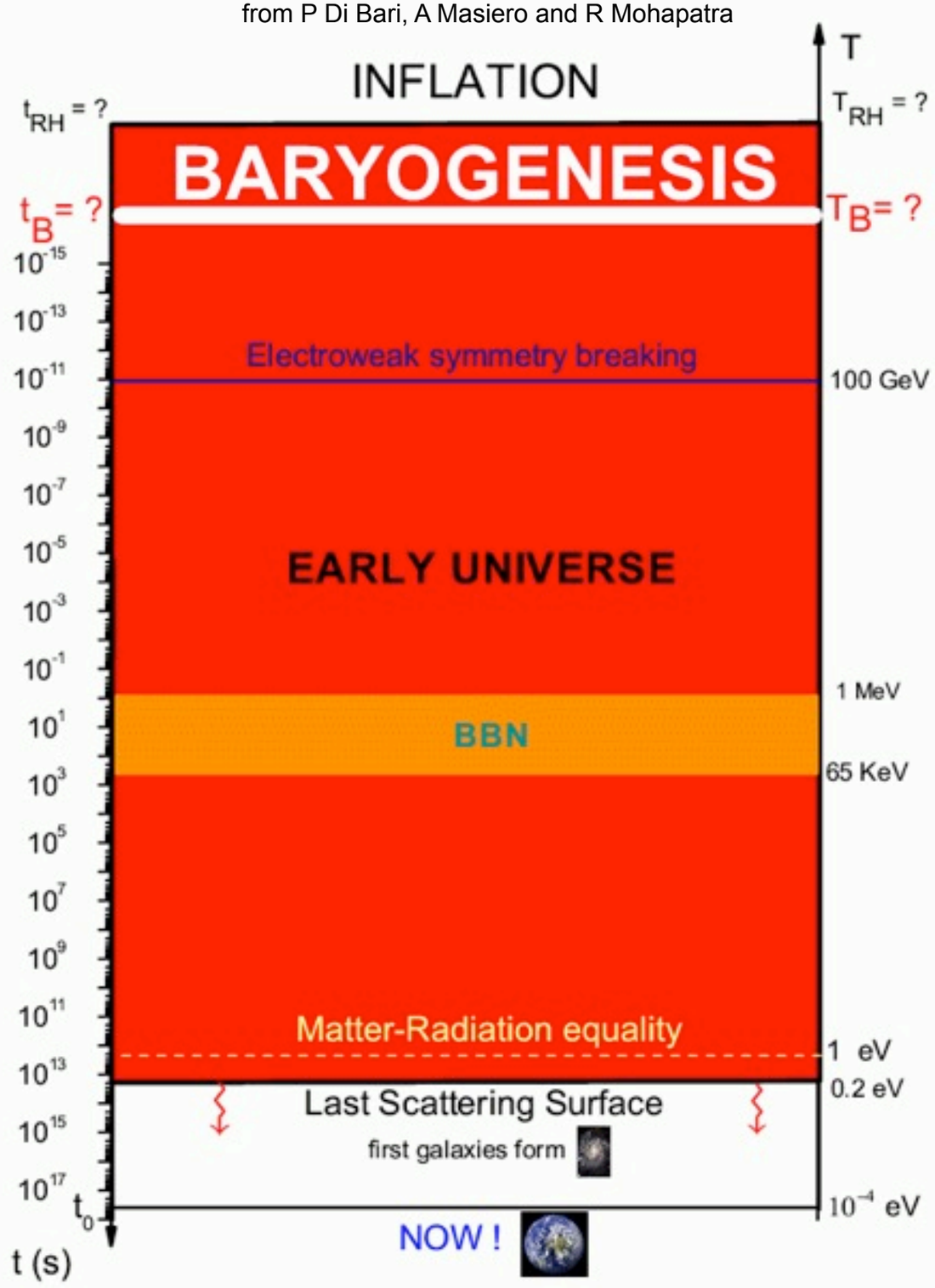
★ sphalerons conserve B-L

❑ Out of equilibrium (no phase transition for m_H=126)

High scale lepto/baryogenes

- 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

from P Di Bari, A Masiero and R Mohapatra



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 ⇒ high inflation scale
  - unacceptable isocurvature fluctuations from axion dark matter if axion exists during inflation

Cosmology almost-no-lose ⇒

Is the inflation scale high?

yes — no

Is dark matter an axion?

yes — no

Low Baryogenesis scale **needed,** new LHC physics probable

•axion produced after inflation in mass range ADMX can find

Low Baryogenesis scale possible

Is dark matter a WIMP?

yes — no

new LHC scale physics

Low Baryogenesis scale possible

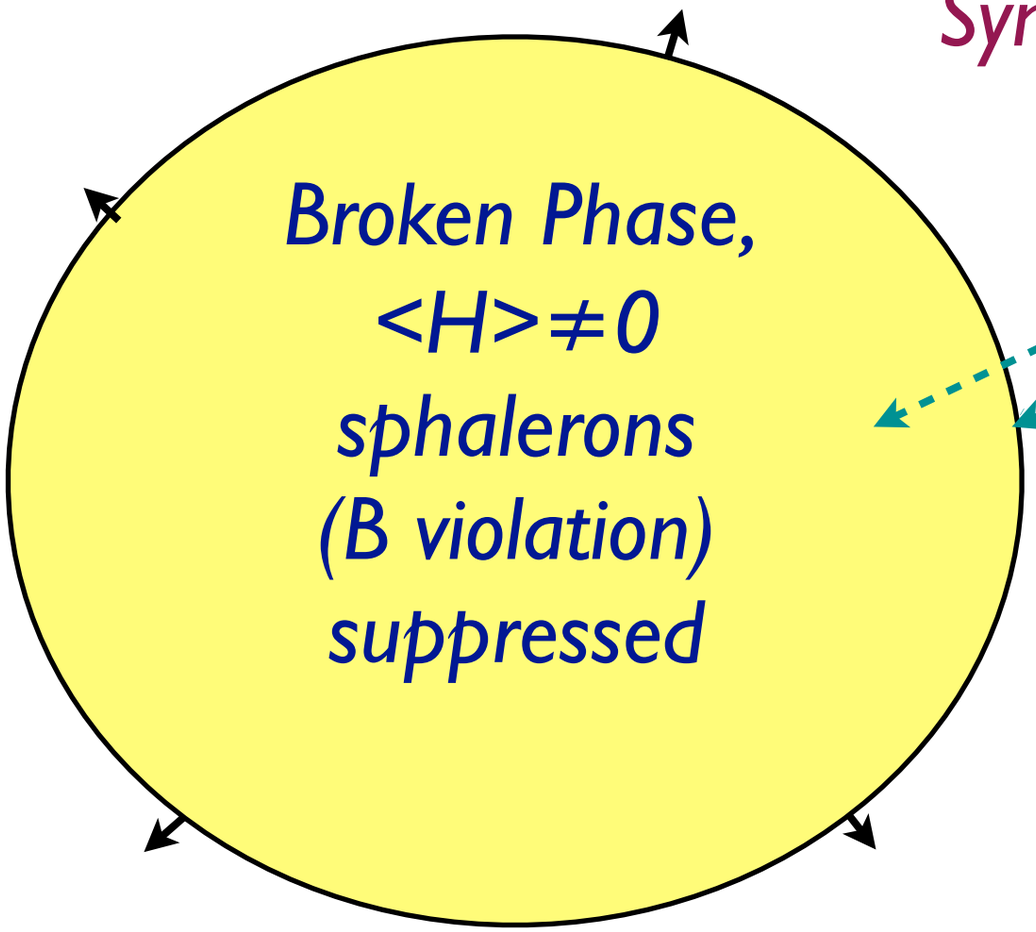
many possibilities

Low Baryogenesis scale possible

Electroweak Baryogenesis

(Kuzmin, Rubakov, Shaposhnikov)

strongly first order electroweak phase transition



Symmetric Phase, <H>=0,
B violation rapid

CP Violation in particle reflection and transmission

(Cohen, Kaplan, A.N.)

BSM ingredients of electroweak baryogenesis

- Strongly first order electroweak phase transition
  - new bosons, e.g. 2HDM *(Turok and Zadrozny)*
- New source of CP Violation
  - e.g. phase in potential of 2HDM

Implications 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

Light stop in MSSM?

- mostly right handed stop lighter than top
- gluino, left handed stop heavy (TeV)
- considerable uncertainty in requirement for new CPV phase
- possible tension with Electric Dipole Moments

Very Light stop searches

- usual search wont work $\tilde{t} \not\to t\chi_0$
- Flavor violating decay: $\tilde{t} \to c\chi_0$
- 3 and 4 body modes: $\tilde{t} \to bW\chi_0$ $\tilde{t} \to bf\bar{f}\chi_0$

Effects on Higgs observables of light stop

- from 1203.2932 *(Curtin, Jaiswal, Meade)*

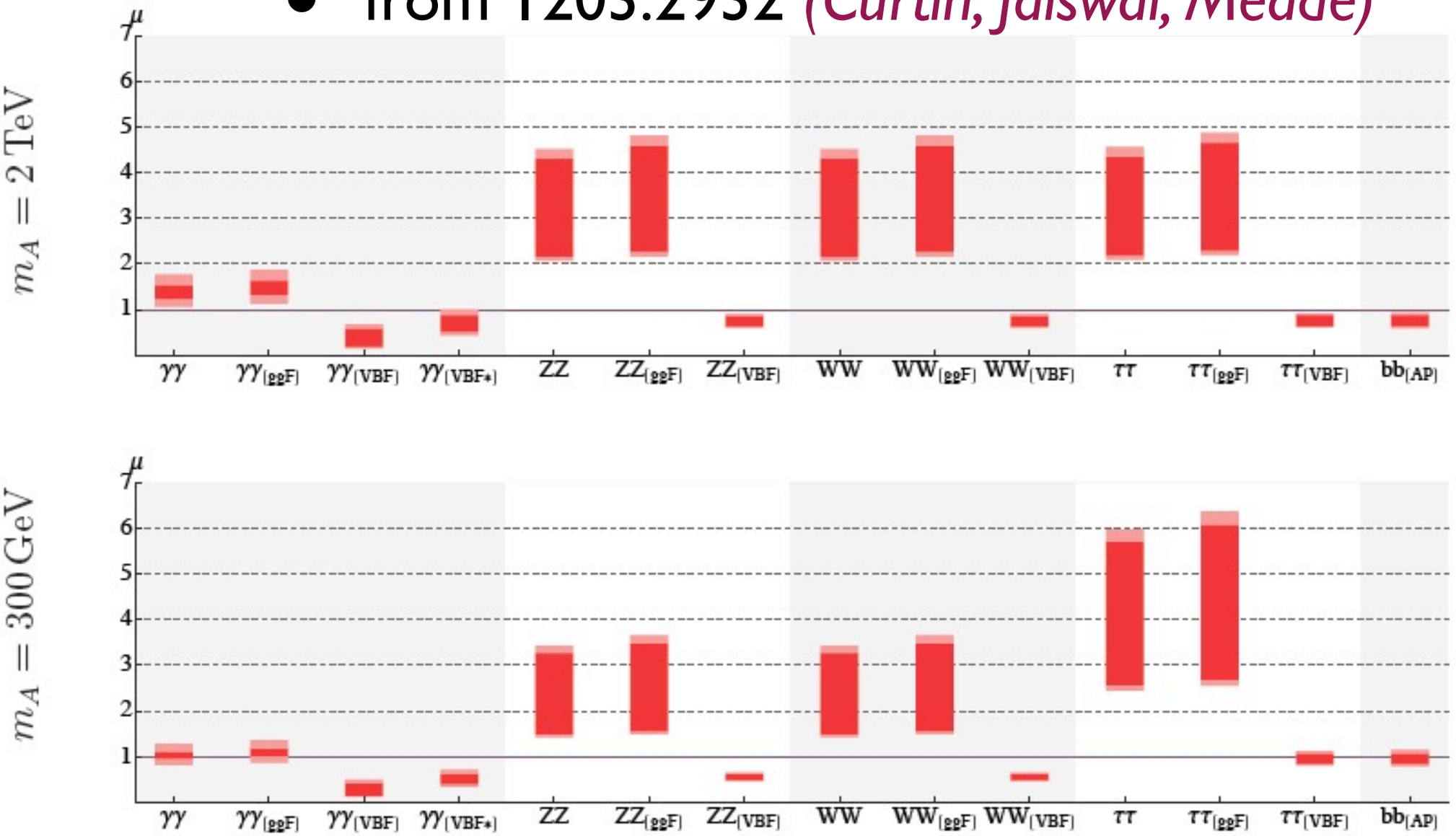
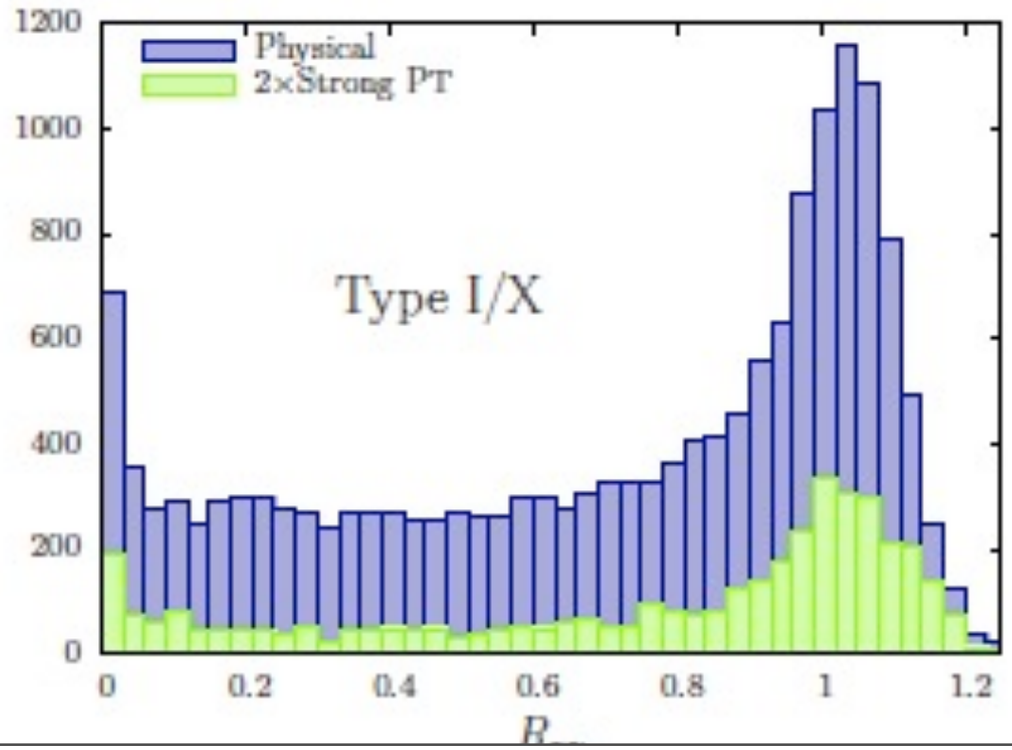
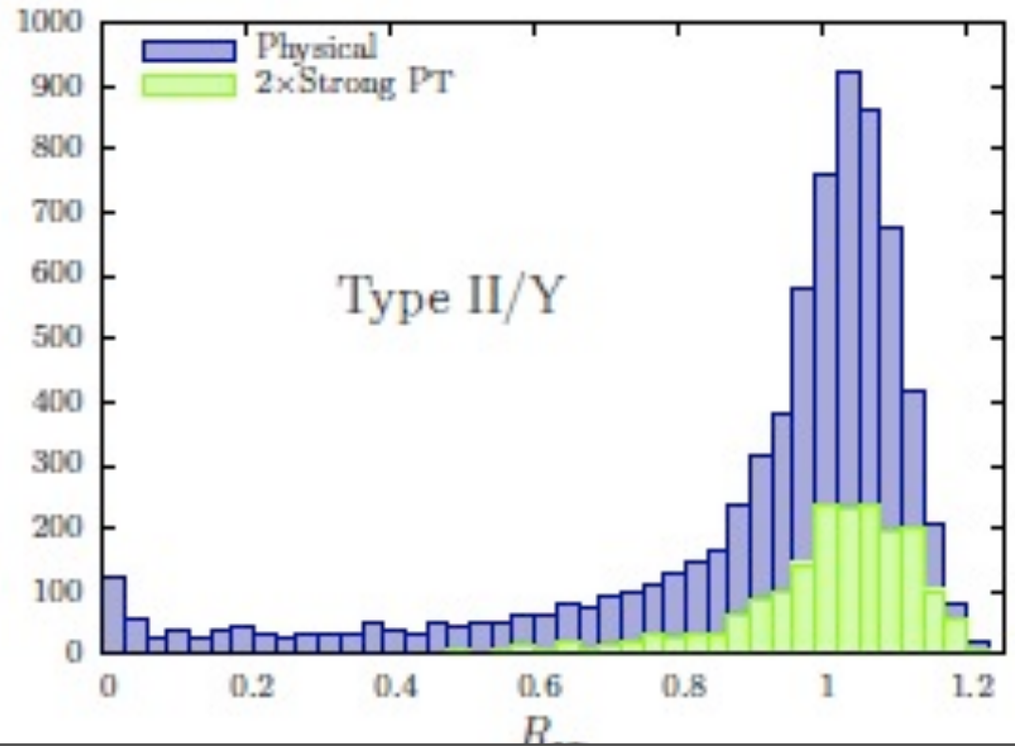


Figure 1: Theoretical EWBG fingerprint for $m_A = 2\,\mathrm{TeV}$ and 300 GeV, for a range of stop masses from 80-115 GeV including theory errors. Shown are signal strength predictions for each channel, with subscripts indicating an exclusive production mode. The exception is $\gamma\gamma_{[\mathrm{VBF}*]}$, which denotes the signal strength prediction for a $h \to \gamma\gamma$ search with VBF cuts [23], such that $\xi_{\mathrm{VBF}}/\xi_{\mathrm{ggF}} \approx 30$ in Eq. (4.9). The purple line is the SM expectation. This fingerprint is for $m_t = 125\,\mathrm{GeV}$, but the dependence on m_t is very small in the 123−128 GeV

More general 2 Higgs Doublets -10 parameters

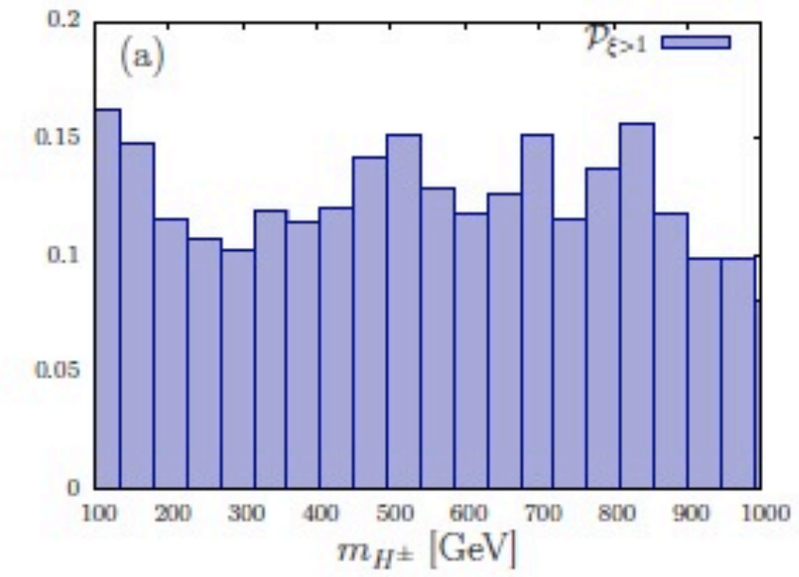
- recent parameter space scan in arXiv:1305.6610 by *Dorsch, Huber, No*
- Large EWB Viable parameter space with mH=125 GeV
  - 125 GeV Higgs properties mostly SM-like
  - possible enhancement or suppression of γγ
  - precision electroweak, flavor not too constraining
  - Did not include CPV

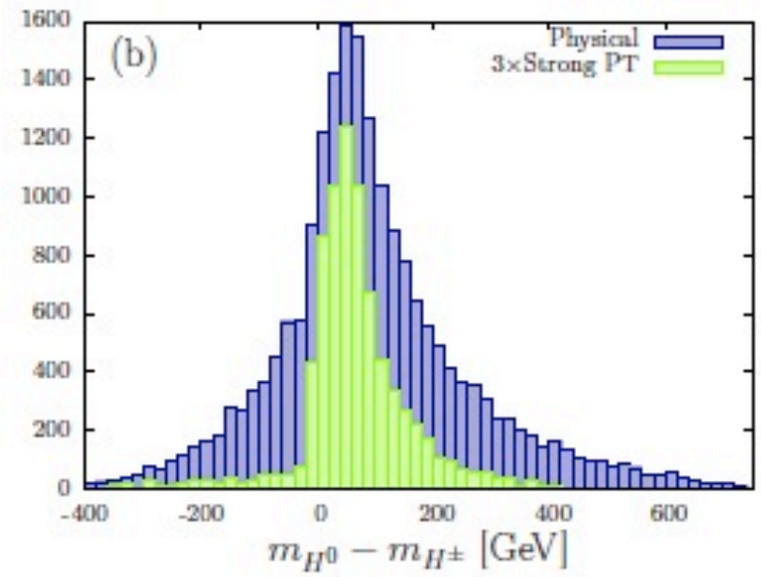


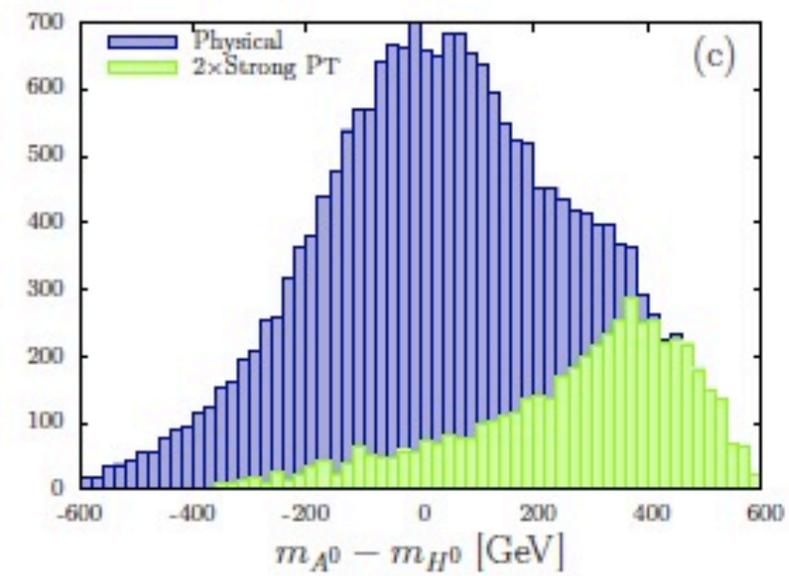


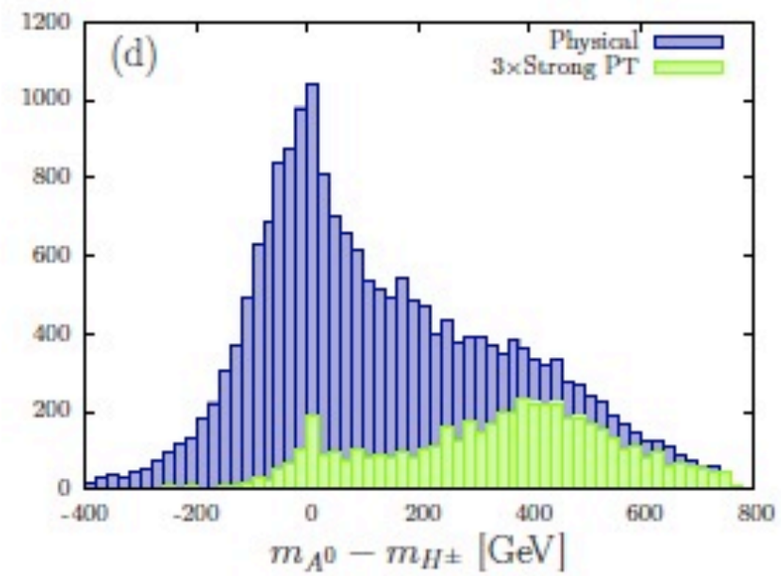
$$\mathcal{P}_{\xi>1} \equiv \frac{\#\text{ strong PT points}}{\#\text{ physical points}}$$

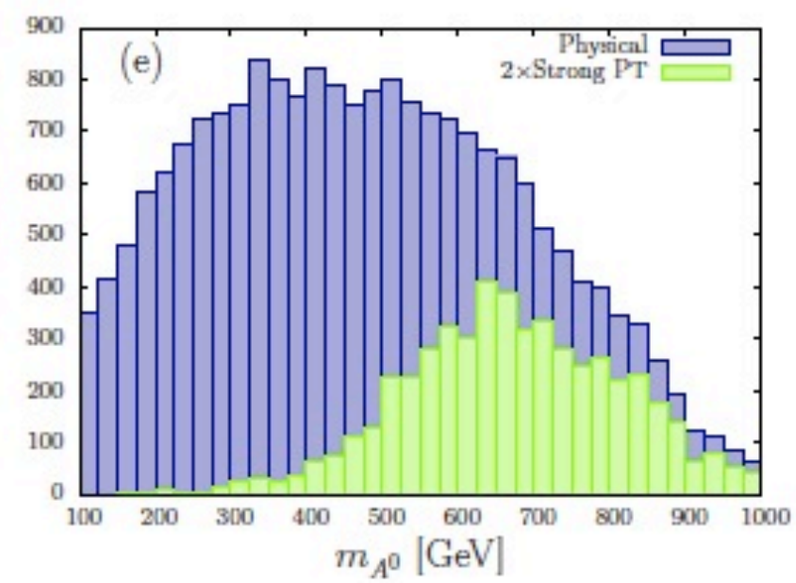
- predictions in 2HDM: Heavy additional Higgs bosons
- Heavy pseudoscalar preferred
- $M_A > M_{H0} > M_{H^+}$ preferred

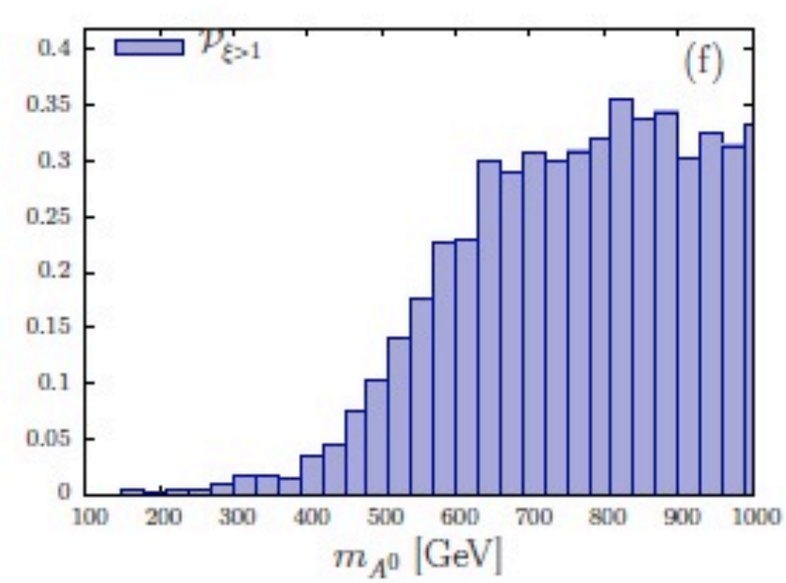












Impact of EWB on triple Higgs coupling

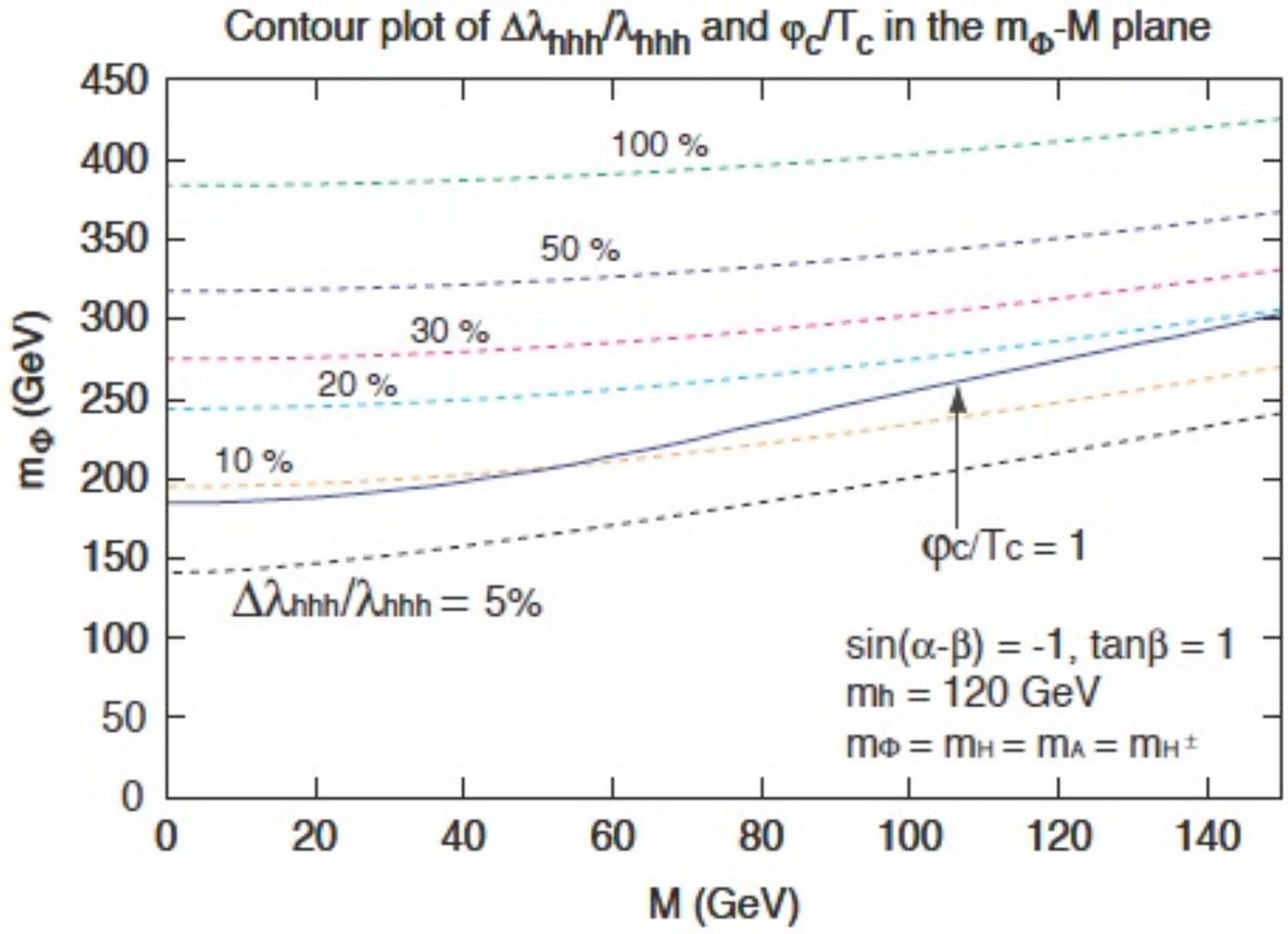


FIG. 3: The correlation between $\Delta\lambda_{hhh}^{\rm 2HDM}/\lambda_{hhh}^{\rm SM}$ and v_C/T_C.

from 1305.1563, *Senaha*

Other EWB models

- To achieve strongly first order transition need new particles coupeld to Higgs to change effective High temperature potential

  ➡ Additional gauge singlet scalars in potential

  ➡ Additional non gauge singlet bosons coupled to Higgs

  ➡ Effective higher dimension operators from TeV scale physics

- Impact on usual Higgs observables typically not large.

New CP Violation

- Cosmology requires $q/(q+\bar{q}) \sim 10^{-8}$
- 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**

New CPV in 2HDM

$$V_{tree} \propto \frac{\mu^2}{2}\left(e^{i\phi}H_1^\dagger H_2 + h.c.\right) + \frac{\lambda_5}{2}\left(\left(H_1^\dagger H_2\right)^2 + h.c.\right) + \dots$$

- Softly broken Z_2 symmetry protects FCNC
- Allows new CPV phase in Higgs potential
- Considerable theoretical uncertainty in EWB requirements for ϕ, but potential tension with Electric Dipole Moment of electron from 2 loop diagram

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 non neutral bosons (e.g. light stop)
  - New Higgs bosons
  - Deviations from SM Higgs properties