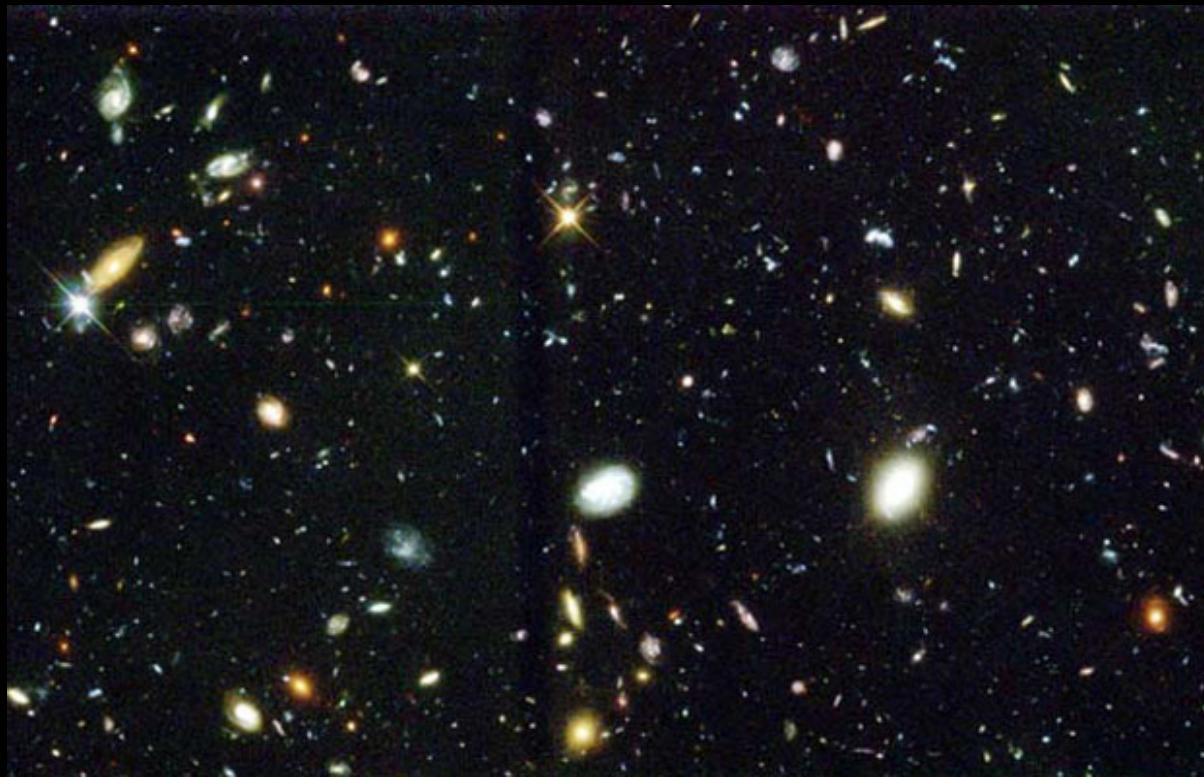


The Future of Particle Cosmology (after LHC Run II)

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Lecture 2: Visible Matter (Baryon Asymmetry)

- $\sim 5\%$ of energy budget
- Baryonic: protons, neutrons
- Asymmetric: $\Delta B \neq 0$.

From BBN (95% CL): [PDG 2016](#)

$$8.3 \times 10^{-11} < n_B/s < 9.4 \times 10^{-11}$$

$$s \sim g_s T^3, \text{ entropy density}$$

The Periodic Table of Elements, known as the NIST Atomic Properties of the Elements, is displayed. It includes the following features:

- Group 1 (IA):** Hydrogen (H), Lithium (Li), Beryllium (Be), Sodium (Na), Magnesium (Mg), Potassium (K), Calcium (Ca), Scandium (Sc), Titanium (Ti), Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Gallium (Ga), Germanium (Ge), Arsenic (As), Selenide (Se), Bromine (Br), Krypton (Kr).
- Group 2 (IIA):** Helium (He), Beryllium (Be), Magnesium (Mg), Aluminum (Al), Silicon (Si), Phosphorus (P), Sulfur (S), Chlorine (Cl), Argon (Ar), Potassium (K), Calcium (Ca), Scandium (Sc), Titanium (Ti), Vanadium (V), Chromium (Cr), Manganese (Mn), Iron (Fe), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Gallium (Ga), Germanium (Ge), Arsenic (As), Selenide (Se), Bromine (Br), Krypton (Kr).
- Group 3 (IIIA):** Boron (B), Carbon (C), Nitrogen (N), Oxygen (O), Fluorine (F), Neon (Ne).
- Group 4 (IVA):** Carbon (C), Silicon (Si), Phosphorus (P), Sulfur (S), Chlorine (Cl), Argon (Ar).
- Group 5 (VA):** Nitrogen (N), Oxygen (O), Fluorine (F), Neon (Ne).
- Group 6 (VIA):** Oxygen (O), Nitrogen (N), Helium (He).
- Group 7 (VIIA):** Fluorine (F), Chlorine (Cl), Bromine (Br), Krypton (Kr).
- Group 8 (VIII):** Helium (He).
- Artificially Prepared:** Technetium (Tc), Rhenium (Re), Rhodium (Rh), Ruthenium (Ru), Osmium (Os), Iridium (Ir), Platinum (Pt), Gold (Au), Cadmium (Cd), Tin (Sn), Antimony (Sb), Tellurium (Te), Iodine (I), Xenon (Xe), Ununtrium (Uuu), Ununpentium (Uupb), Ununseptium (Uus), Ununoctium (Uuo), Ununquadium (Uuq), Ununhexium (Uuh).
- Frequently used fundamental physical constants:** Speed of light in vacuum ($c = 299\,792\,458\, m/s$), Planck constant ($\hbar = 6.6251 \times 10^{-34} J\cdot s$), Elementary charge ($e = 1.6022 \times 10^{-19} C$), Electron mass ($m_e = 9.109389 \times 10^{-31} kg$), Proton mass ($m_p = 1.6726 \times 10^{-27} kg$), Fine-structure constant ($\alpha = 1/137.036$), Rydberg constant ($R_{\infty} = 109,735.729 \cdot 10^{10} m^{-1}$), Boltzmann constant ($k = 1.38065 \cdot 10^{-23} J/K$), and Avogadro constant ($N_A = 6.02214076 \cdot 10^{23} mol^{-1}$).
- Standard Reference Data Group:** wwwnist.gov
- NIST National Institute of Standards and Technology:** Technology Administration, U.S. Department of Commerce
- Physics Laboratory:** physics.nist.gov
- Periodic Table Legend:** Solids (light blue), Liquids (medium blue), Gases (dark blue), Artificially Prepared (yellow).

- Negligible anti-matter today:
 - No annihilation signals nearby
 - Cosmic ray \bar{p} consistent with secondaries,...
- Matter/antimatter separation unlikely on large scales
 - Note: $e^{-m/T} \sim 10^{-10}$ at $T \sim 40$ MeV; horizon contains $\sim 10^{-7} M_\odot$

Generation of Baryon Asymmetry

- Requires Sakharov's conditions for *baryogenesis*:
 - (i) Baryon number violation
 - An intuitive requirement: otherwise, starting from a baryon symmetric Universe, no asymmetry would be generated
 - (ii) C and CP violation
 - If density operator ρ preserves $X = C, CP$: $X^{-1}\rho X = \rho$, while $X^{-1}n_B X = -n_B$
 $\Rightarrow \text{Tr}[\rho n_B] = \text{Tr}[X^{-1}\rho X n_B] = \text{Tr}[\rho X n_B X^{-1}] = -\text{Tr}[\rho n_B] = 0$
 - (iii) Departure from equilibrium
 - B violating processes drive n_B to zero in chemical equilibrium (assuming CPT conservation).

- Ingredients of Sakharov's conditions present in SM, but not at sufficient degrees

(i): EW anomaly: tunneling via instantons at $T = 0$; “sphalerons” at $T \gg M_W$

Under $SU(2)_L \times U(1)_Y$; N_g generations:

$$(\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta})$$

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_g}{32\pi^2} (g_2^2 W_{\mu\nu} \tilde{W}^{\mu\nu} - g_1^2 B_{\mu\nu} \tilde{B}^{\mu\nu})$$

$$\Rightarrow \Delta(B - L) = 0 \text{ and } \Delta(B + L) \neq 0$$

$$T = 0 \text{ instanton rate} \propto e^{-16\pi^2/g_2^2} \sim 10^{-180}$$

$$T < T_c \text{ rate} \propto e^{-\xi M_W(T)/(\alpha_W T)}; T_c \sim 100 \text{ GeV, with } \xi = 2B\lambda/g_2^2, B \sim 2, \alpha_W \sim 1/30$$

$$T > T_c \text{ rate} \sim \kappa \alpha_W^5 T^4; \kappa \sim 30$$

(ii): Quark mass matrix (CKM), but CP violation too small

Asymmetry from SM CP violation $\lesssim 10^{-20}$

(Gavela, Hernandez, Orloff, Pène, Quimbay, 1994)

$$\Delta_{CP} \sim \alpha_W^3 J m_t^4 m_c^2 m_b^4 m_s^2 M_W^{-6} T^{-6} \text{ for } T \gtrsim 100 \text{ GeV}$$

(iii) EW phase transition: not strongly first order (Higgs too heavy)

- n_B/s small, but still too big to explain in SM! \Rightarrow New Physics

Electroweak Baryogenesis

For a review, see e.g., Morrissey and Ramsey-Musolf, 1206.2942

- EW baryogenesis could become feasible in SM extensions
- Interesting possibility: testable at colliders probing $E \gtrsim 100$ GeV
- Various extensions of EW sector motivated by the hierarchy problem
- Hierarchy models: typically new states, $M_{\text{new}} \gtrsim M_H$ coupled to H
- In particular, new bosonic thermal loop effects \rightarrow Enhanced cubic term in effective potential: $V(\phi, T) \approx D(T^2 - T_0^2)\phi^2 - ET\phi^3 + (\lambda_T/4)\phi^4$
- Strong first order phase transition: $\phi_c/T_c = 2E/\lambda_T \gtrsim 1$
For models using fermions see, e.g. Carena, Megevand, Quiros, Wagner, [hep-ph/0410352]; HD, Lewis, Ponton, 1211.3449.
- Also, generic new physics introduces additional needed CP violation
- Contributions to electric dipole moments of n, e, \dots : Constraints and potential future signals $d_n < 0.3 \times 10^{-25} \text{ e cm}$; $d_e < 0.87 \times 10^{-28} \text{ e cm}$; 90% CL PDG 2016
- Possible signals of CP violation in meson decays (LHCb, Belle II)

Aside: Effective Potential at Finite Temperatures

- $V_{eff}(\phi, T) = V_0(\phi) + V_1(\phi) + V_1(\phi, T)$

V_0 tree level ; V_1 : 1-loop at $T = 0$; $V_1(T)$: 1-loop thermal contributions

$$V_1(\phi) = \sum_i \frac{n_i(-1)^{2s_i}}{64\pi^2} m_i^4(\phi) \left[\ln \left(\frac{m_i^2(\phi)^2}{\mu^2} \right) - c_i \right]$$

Sum over particles i with n_i degrees of freedom, spin s_i , and ϕ -dependent masses m_i ; μ is the renormalization scale and c_i is scheme dependent

$$V_1(\phi, T) = \frac{T^4}{2\pi^2} \left[\sum_{i=\text{Boson}} n_B^i J_B \left(\frac{m_i^2}{T^2} \right) - \sum_{i=\text{Fermion}} n_F^i J_F \left(\frac{m_i^2}{T^2} \right) \right]$$

- Expansion valid for $x \ll 1$

$$J_B(x^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}x^2 - \boxed{\frac{\pi}{6}x^3} - \frac{1}{32}x^4 \ln(x^2/a_B) + \mathcal{O}(x^6) \quad ; \quad \ln a_B \approx 5.4076$$

$$J_F(x^2) = -\frac{7\pi^4}{360} - \frac{\pi^2}{24}x^2 - \frac{1}{32}x^4 \ln(x^2/a_F) + \mathcal{O}(x^6) \quad ; \quad \ln a_F \approx 2.6351$$

For example: Quiros, hep-ph/9901312; Morrissey and Ramsey-Musolf, 1206.2942

- Generically, particles with substantial coupling to Higgs can affect the phase transition
- May typically expect modifications of the Higgs properties, other collider signals
- For example, new scalars that can run in thermal loops and generate the cubic term (barrier in V_{eff})

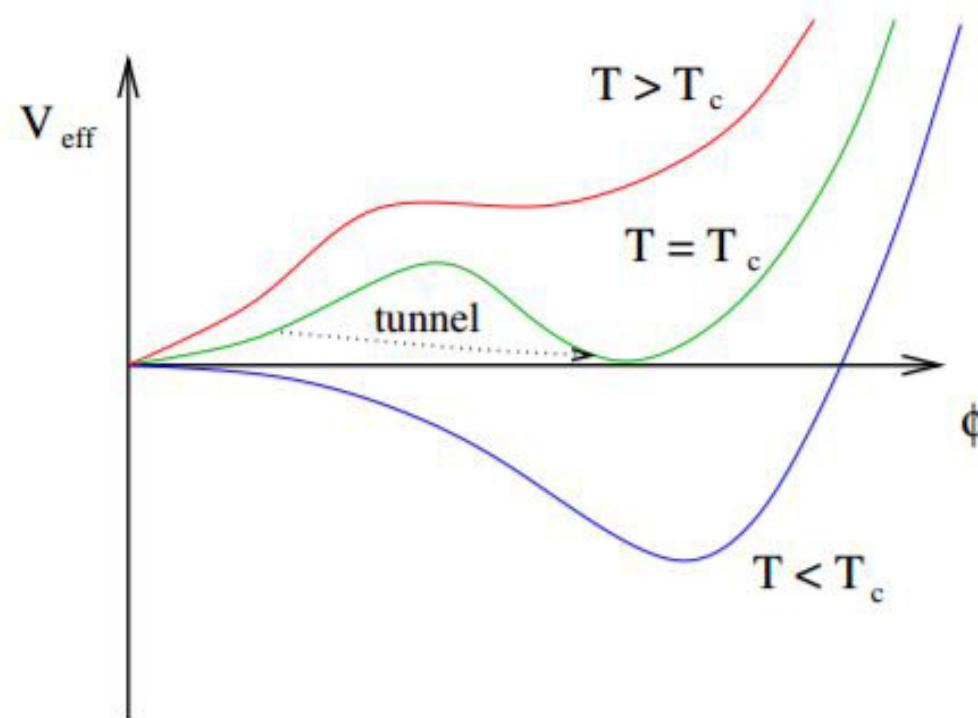
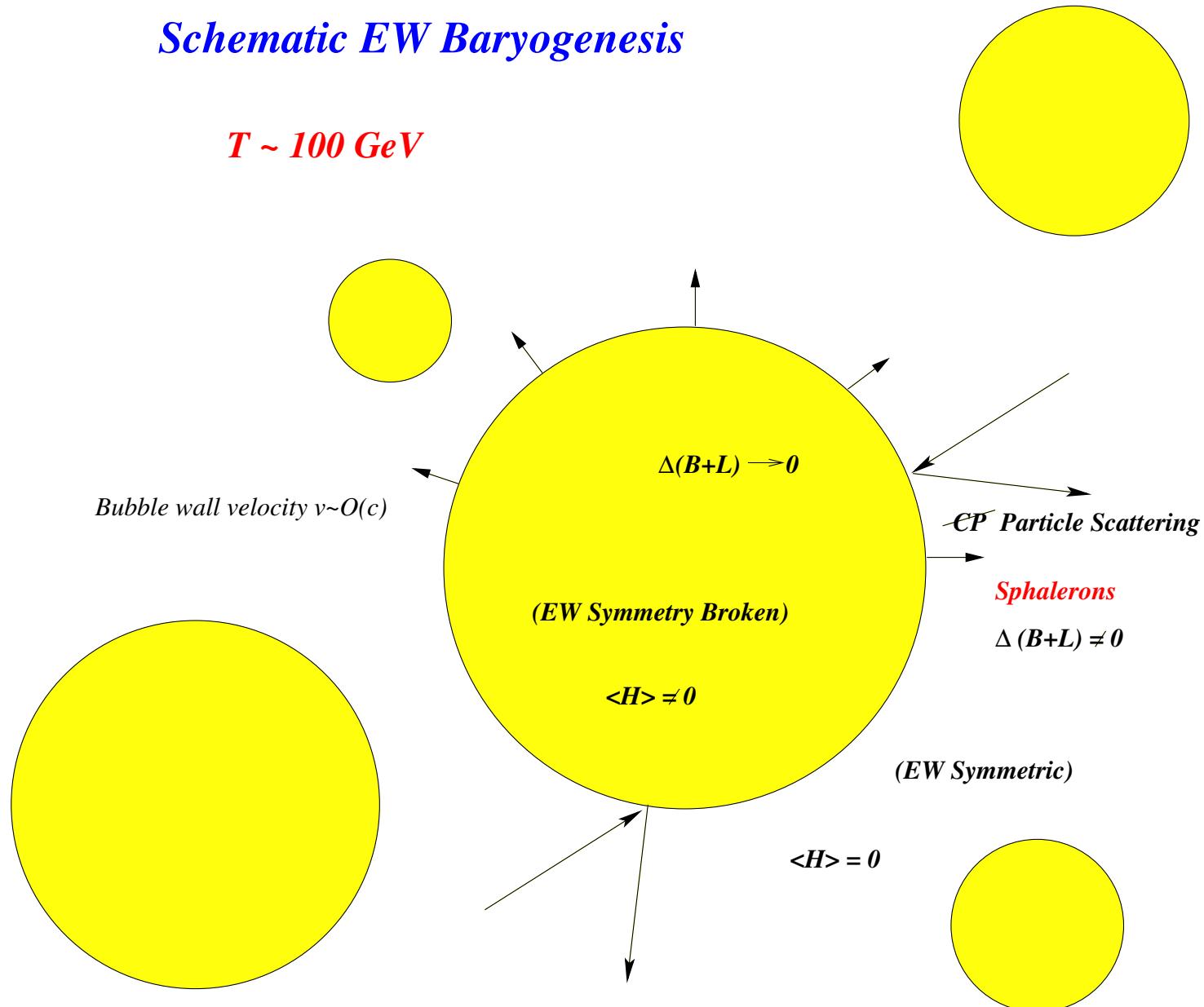


Figure from Morrissey and Ramsey-Musolf, 1206.2942

Schematic EW Baryogenesis

$T \sim 100 \text{ GeV}$



MSSM

- Hierarchy, gauge coupling unification, possible DM candidate
- Supersymmetric partners for SM particles:
- Scalar partners for fermions
- Fermion partners for gauge fields and the Higgs
- Loop corrections to m_H^2 cancel between SM and supersymmetric partners (up to supersymmetry breaking mass effects)
- Can resolve the hierarchy if super partner masses $\lesssim 1$ TeV:

$$\delta m_H^2 \sim \frac{g^2}{16\pi^2} M_{new}^2 \Rightarrow \delta m_H^2 \lesssim (100)^2 \text{ GeV}^2 \Rightarrow \text{"Natural" } M_H$$

- The scalar partners of top quark, *stops*, significant couplings to H
- Light stop contributions to $V(T)$ can lead to a strong first order EW phase transition

- The measured Higgs mass $M_H \approx 125$ GeV implies

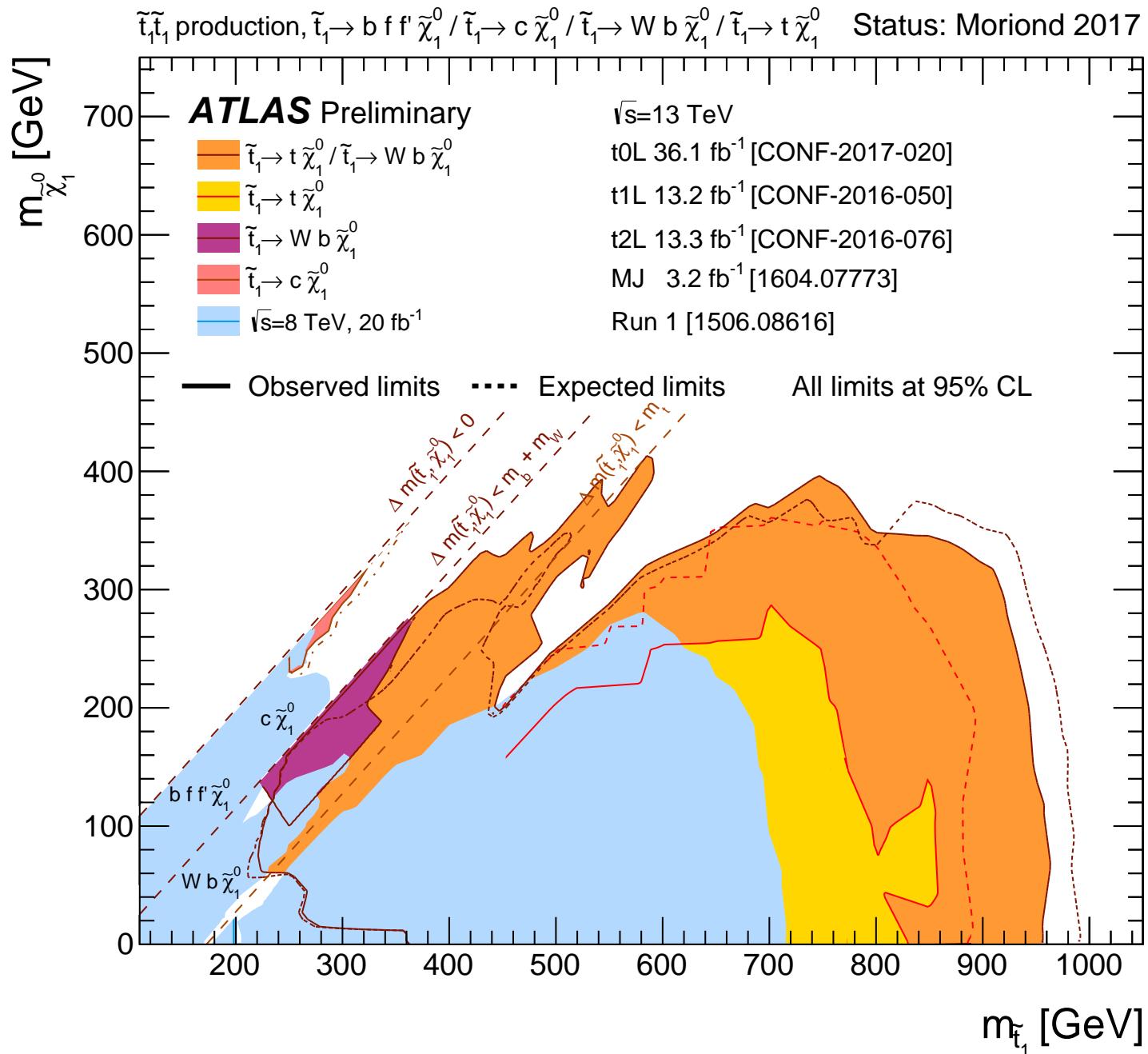
MSSM: $\tilde{m}_{tR} \lesssim 120$ GeV (EW baryogenesis) ; $\tilde{m}_{tL} \gg 1$ TeV (Higgs mass)

[Carena, Nardini, Quiros, Wagner, 0809.3760](#)

- This already gives up on the idea of a “natural” Higgs mass
- Setup deemed disfavored early on [Curtin, Jaiswal, Meade, 1203.2932](#)
- By now, the LHC data has largely removed this possibility (MSSM)
- Parts of parameter space could still potentially be viable
[Liebler, Profumo, Stefaniak, 1512.09172](#)

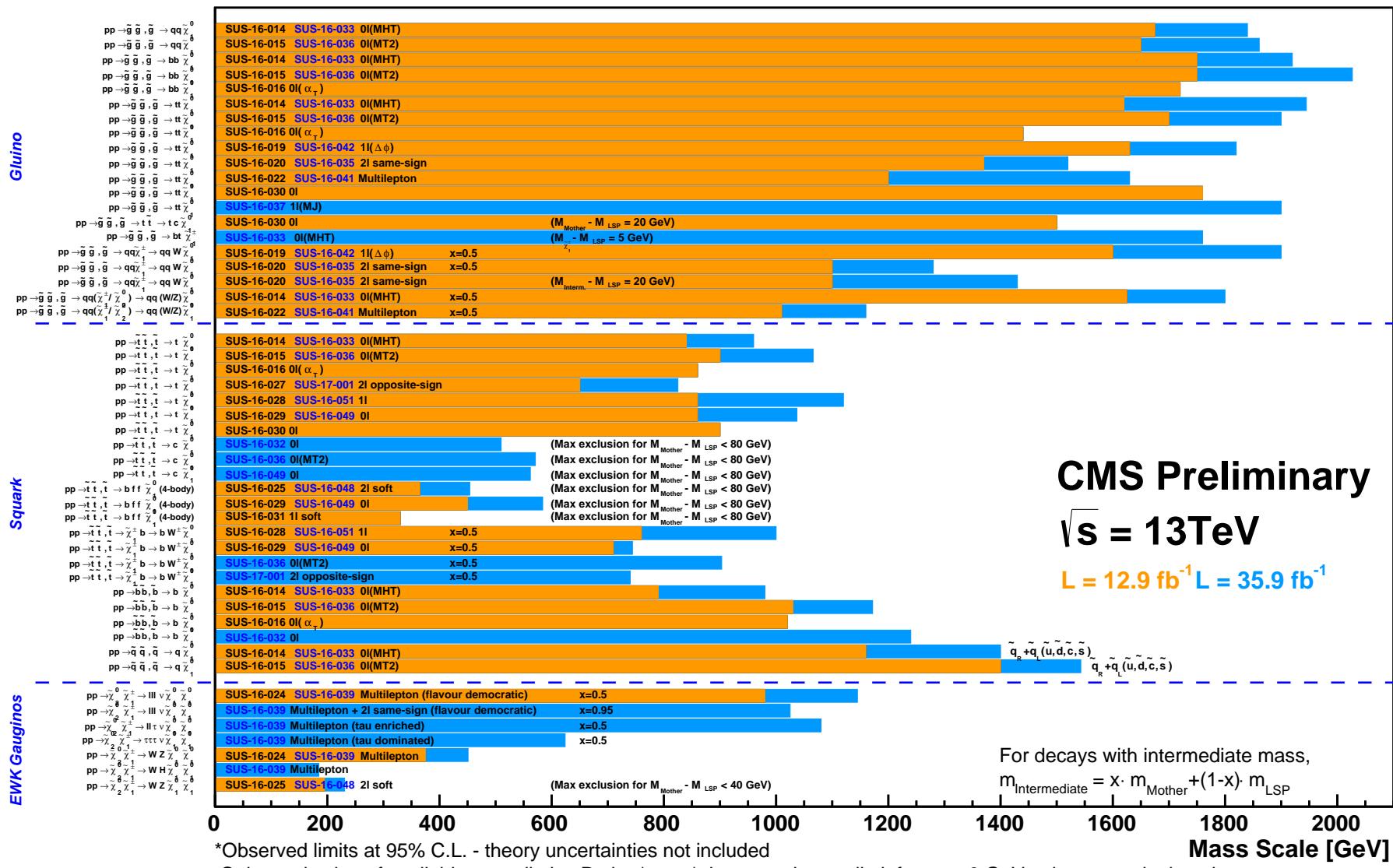
- Strong first order EW phase transition may also be possible by coupling new scalars, with non-zero vevs near the weak scale, to the Higgs potential (tree-level effect) [Choi, Volkas, 1993](#)
- Possible effects on Higgs properties, from loops or scalar mixing
- The new scalars can also be produced directly at colliders

[For a recent discussion of collider signals see, for example, Chen, Kozaczuk, Lewis, 1704.05844](#)



Selected CMS SUSY Results* - SMS Interpretation

ICHEP '16 - Moriond '17



Other SM Extensions

- MSSM not the only way to address the hierarchy
- Other SM extensions at or above the weak scale:
 - Strong dynamics, composite Higgs
 - Large or warped extra dimensions, lower gravity scales
- Generally, no sign of new physics up to ~ 1 TeV
 - This statement is model dependent
- There could be extensions that do not necessarily address hierarchy
 - They may not be within experimental reach

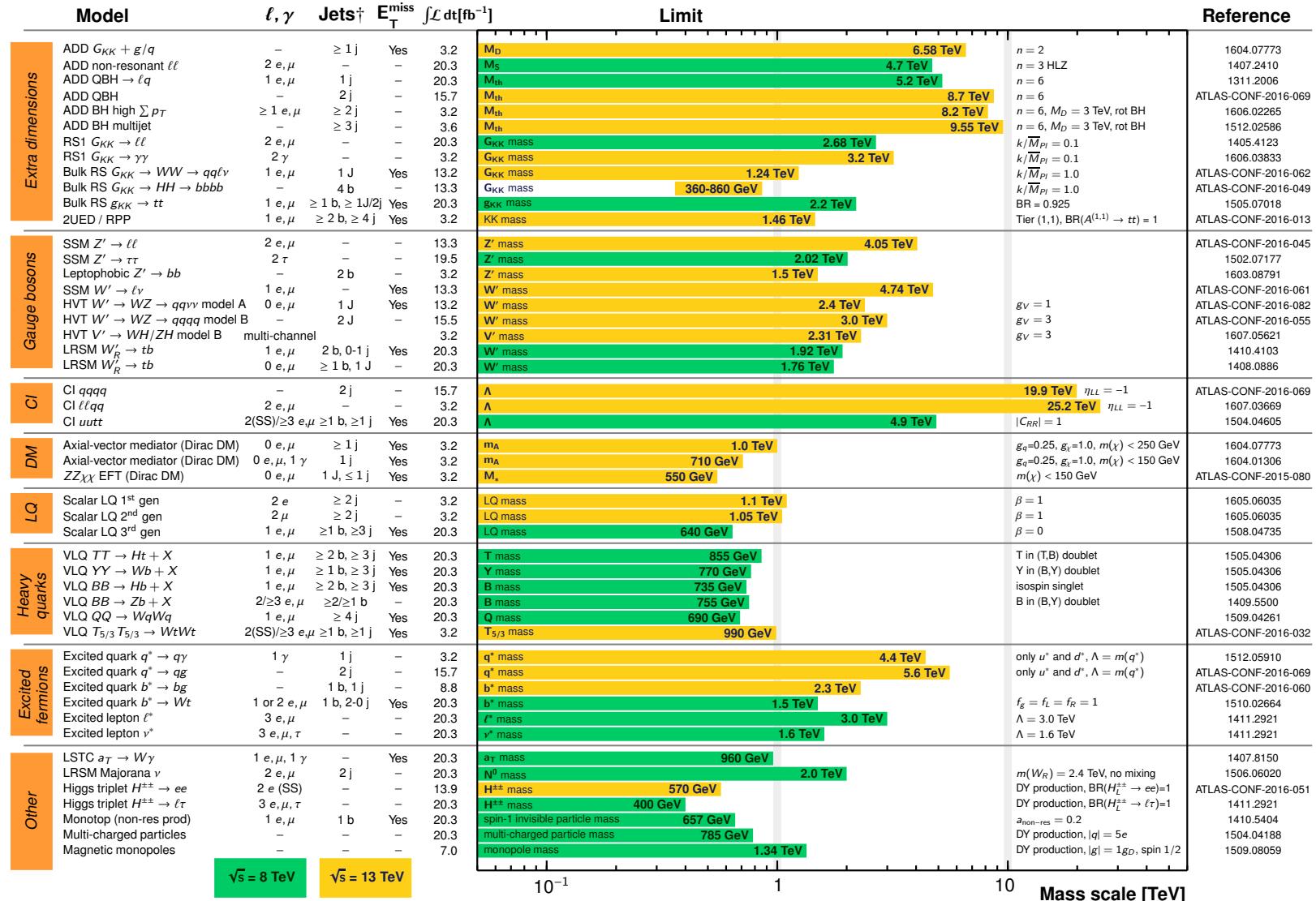
ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$



*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

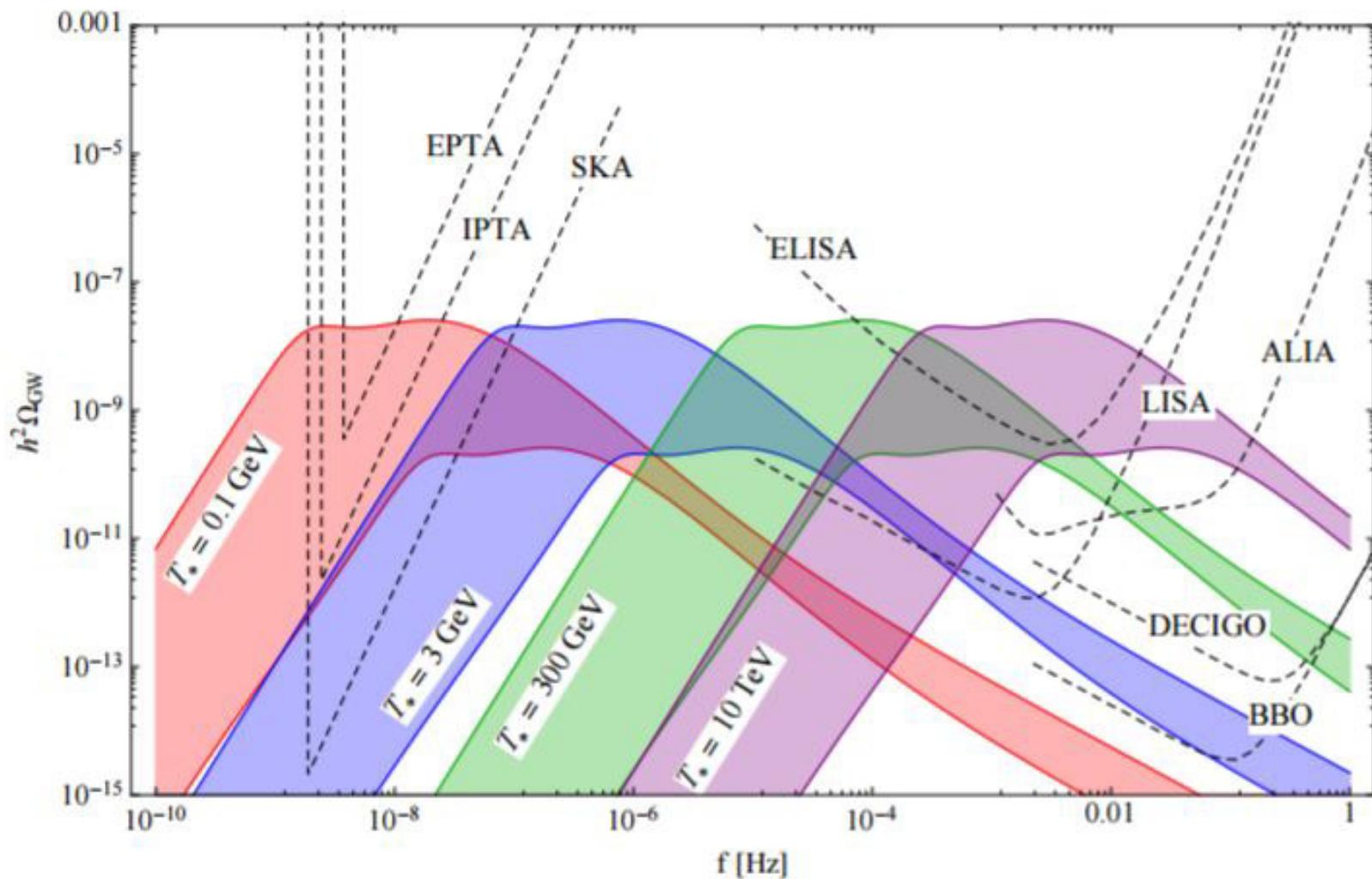
[†]Small-radius (large-radius) jets are denoted by the letter j (J).

- Roughly 3 times the current 13 TeV data could be collected before end of Run 2
- A discovery may provide a link to EW baryogenesis
- In particular, a relation to strong EW phase transition
 - Direct production and detection of new states
 - Loop-effects on Higgs properties, *e.g.* cross section
 - This, depending on the model, may be difficult to establish at the LHC

For example, [Katz and Perelstein, 1401.1827](#)

- Remarkably, future gravitational wave detectors may find a signal
 - Primordial gravitational waves from bubble collisions, sound waves, MHD turbulence

See, *e.g.*, [Grojean, Servant, hep-ph/0607107](#); [Schwaller, 1504.07263](#); [Caprini et al., 1512.06239](#)



From Schwaller, 1504.07263

(PTA = Pulsar Timing Array)

Post LHC Run 2

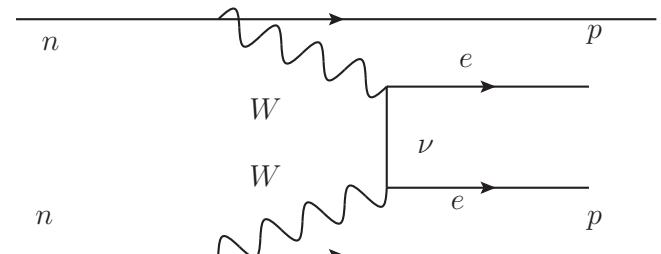
- If no new physics $\lesssim 1$ TeV: hierarchy solutions less motivated
- Need for other guiding principles, motivations
- High scale *leptogenesis* not directly related to hierarchy, but naturally motivated by $m_\nu \ll \langle H \rangle$ [Fukugita, Yanagida, 1986](#)

See, e.g., [Di Bari 1206.3168](#); [Petcov, 1405.2263](#) for introductory reviews of related physics

- Seesaw mechanism: Heavy right-handed Majorana neutrinos N

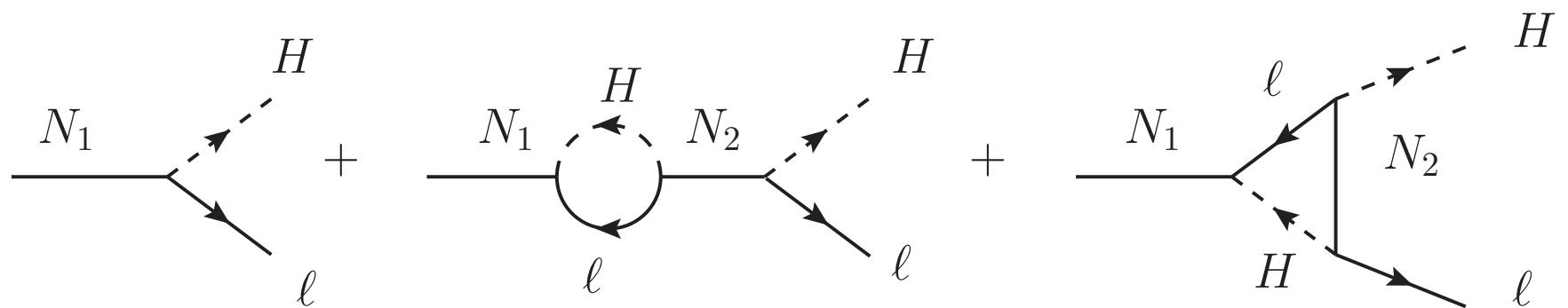
$$y_\nu \tilde{H} \bar{L} N + M_N \bar{N}^c N \Rightarrow m_\nu \approx \frac{(y_\nu \langle H \rangle)^2}{M_N} \quad (M_N \gg \langle H \rangle; \tilde{H} \equiv \epsilon^{ab} H_b^*)$$

- Generic prediction: SM ν s are Majorana
- $0\nu\beta\beta$ decay, low energy signal of L violation
- Rare nuclear decay with $T_{1/2} \gtrsim 5 \times 10^{25}$ yr
- Active experimental program ([CUORE](#), [GERDA](#), ...)



- General 3×3 neutrino mass matrix: three angles and three phases
- CP violation: One Dirac phase (like CKM), two Majorana phases
- Oscillation experiments sensitive to Dirac phase
- CP violating decay of heavy N can result in a ΔL asymmetry

$N \rightarrow H\ell$ and $N \rightarrow H^\dagger \bar{\ell}$ out of equilibrium (at $T \lesssim M_N$)



- Leptogenesis, with 3 right handed neutrinos, a natural outcome in $SO(10)$ grand unified models; $M_N \lesssim M_{\text{GUT}} \sim 10^{15} \text{ GeV}$

- Asymmetry from quantum interference

$$\varepsilon \equiv \frac{\Gamma_1 - \bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1} = \frac{3}{16\pi} f(M_1, M_2) \frac{\text{Im}(y_\nu y_\nu^\dagger)_{12}^2}{(y_\nu y_\nu^\dagger)_{11}}$$

$f(M_1, M_2)$ a function of masses of N_1 and N_2

- SM sphalerons process $\Delta(B-L)$ into ΔB and ΔL via $B+L$ violation
- First order EW phase transition not needed (out of equilibrium N decay)
- Motivated and economical scenario, but typically challenging to test
 - Generically, N very heavy, well beyond the reach of colliders
- Baryogenesis possible through a variety of alternative scenarios
 - For example, spontaneous baryogenesis, using a time varying modulus coupled to a baryon current ($\partial_\mu \phi \bar{\psi} \gamma^\mu \psi$) to induce dynamical CPT violation: baryon number generation in thermal equilibrium Cohen and Kaplan, 1987
- Depending on scenario, new signals may be accessible

Summary

- The origin of baryon asymmetry remains unknown
- The SM cannot successfully account for it → New physics
- EW baryogenesis an interesting idea, also motivated by the hierarchy problem, implies new states possibly accessible to LHC
- If such states not found, can become less compelling
- Leptogenesis an interesting alternative, tied to neutrino mass generation
- However, leptogenesis not readily testable, but typically implies Majorana neutrinos and rare nuclear $0\nu\beta\beta$ decays
- Given our lack of knowledge of the early Universe for $T \gtrsim$ few MeV many ideas can be invoked, some with accessible signals