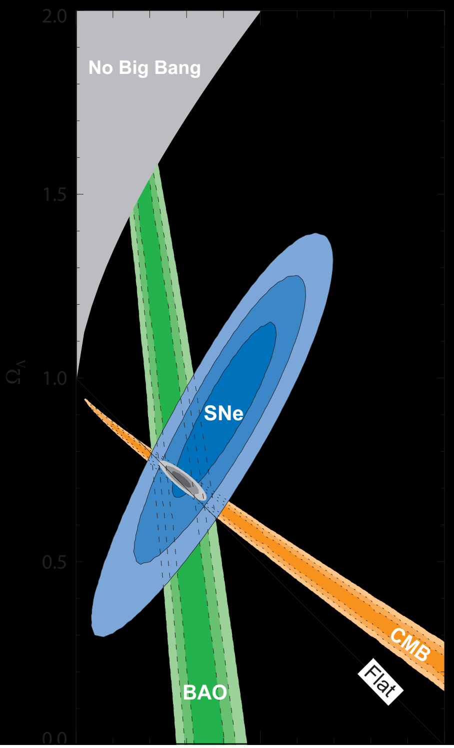
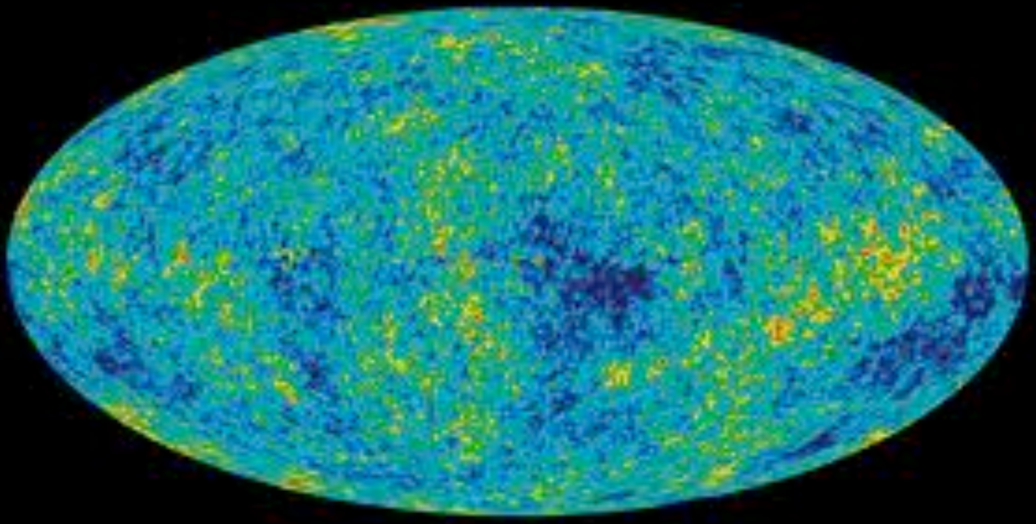
GGI 2012

NEUTRINO WORKSHOP

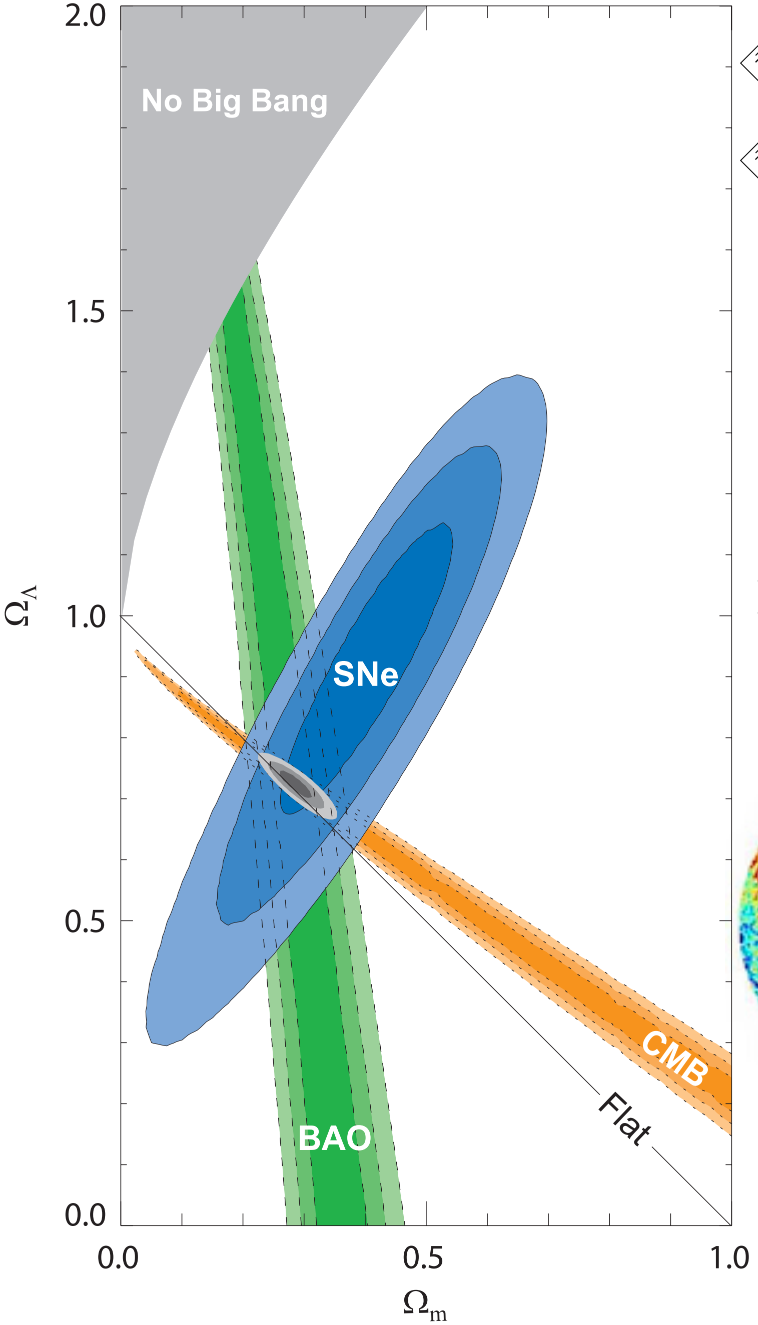
NEUTRINO COSMOLOGY

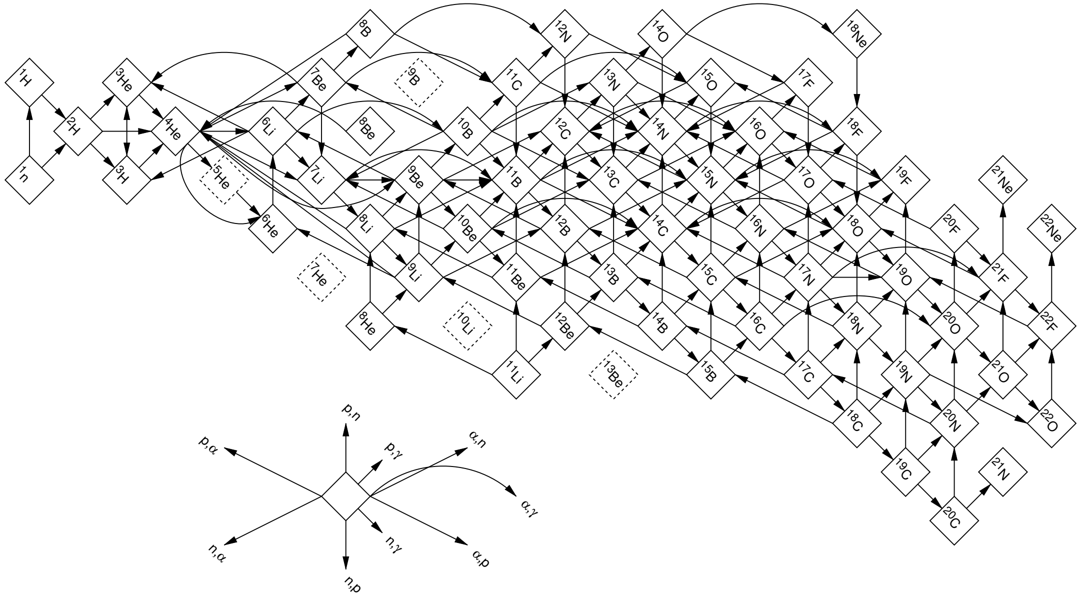




Haim Goldberg

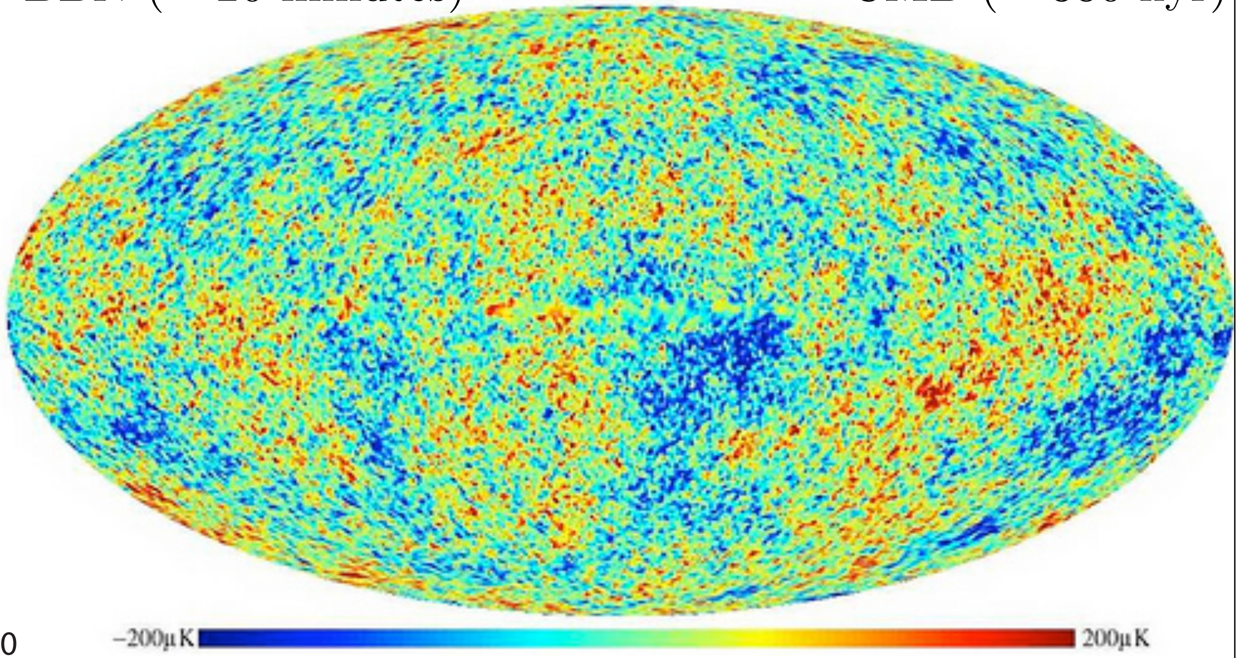
EARLIEST OBSERVATIONALLY VERIFIED LANDMARKS





BBN (~ 20 minutes)

CMB (~ 380 kyr)



Galaxy Formation ($\gtrsim$ 1 Gyr)

OUTLINE

- Effective number of neutrinos
- CMB and BBN data/theory predictions
- Right-handed neutrinos are necessary in...
- the best of all models: U(1) for everone
- Joint constraints on milliweak interactions (CMB-BBN-LHC)
- Summary and Conclusions

Work done in collaboration with:
Anchordoqui, Antoniadis, Huang, Lust, Taylor, Vlcek
PRL 108 (2012) 081805 and arXiv:1206.2537

EFFECTIVE NUMBER OF NEUTRINOS

➤ Most straightforward variation of Standard Big-Bang Cosmology

☛ extra energy contributed by new relativistic particles "X"

➤ When $X's$ don't share in energy released by $e^{\pm}$ annihilation

☛ convenient to account for extra contribution to SM energy density by normalizing it to that of an equivalent neutrino species

$$\rho_X \equiv \Delta N_\nu \rho_\nu = \frac{7}{8} \Delta N_\nu \rho_\gamma \qquad (\text{with } \Delta N_\nu = N_\nu - 3)$$

Steigman, Schramm, and Gunn, PLB66 (1977) 202

➤ For each additional relativistic degree of freedom:

$$\text{if } T_X = T_\nu \Rightarrow \begin{cases} \Delta N_\nu = 1 & \text{for} \quad X = \text{ any two} - \text{component fermion} \\ \Delta N_\nu = 4/7 & \text{for} \quad X = \text{ scalar} \end{cases}$$

➤ If $X's$ have decoupled even earlier and have failed to profit from heating when various other particle-antiparticle pairs annihilated (or unstable particles decayed)

contribution to ΔN_ν from each such particle will be $\begin{cases} <1 \\ <4/7 \end{cases}$

CMB

- Basic equation:

$$\boxed{\frac{\Delta N_\nu^{\rm eff}}{N_\nu^{\rm eff}} \simeq 2.45\,\frac{\Delta(\Omega_m h^2)}{\Omega_m h^2} - 2.45\,\frac{\Delta z_{\rm eq}}{z_{\rm eq}}}$$

- $\Delta(\Omega_m h^2)$ from galaxy distributions and precise H_0 measurements

SDSS Collaboration, MNRAS 401 (2010) 2148 Riess et al., ApJ 699 (2009) 539

- Wilkinson Microwave Anisotropy Probe ☛ $N_\nu^{\rm eff} = 4.34^{+0.86}_{-0.88}\ (2\sigma)$

WMAP Collaboration, ApJS 192 (2011) 18

- Atacama Cosmology Telescope ☛ $N_\nu^{\rm eff} = 4.56 \pm 0.75\ (68\%{\rm CL})$

ACT Collaboration, ApJ 739 (2011) 52

- South Pole Telescope ☛ $N_\nu^{\rm eff} = 3.86 \pm 0.42\ (1\sigma)$

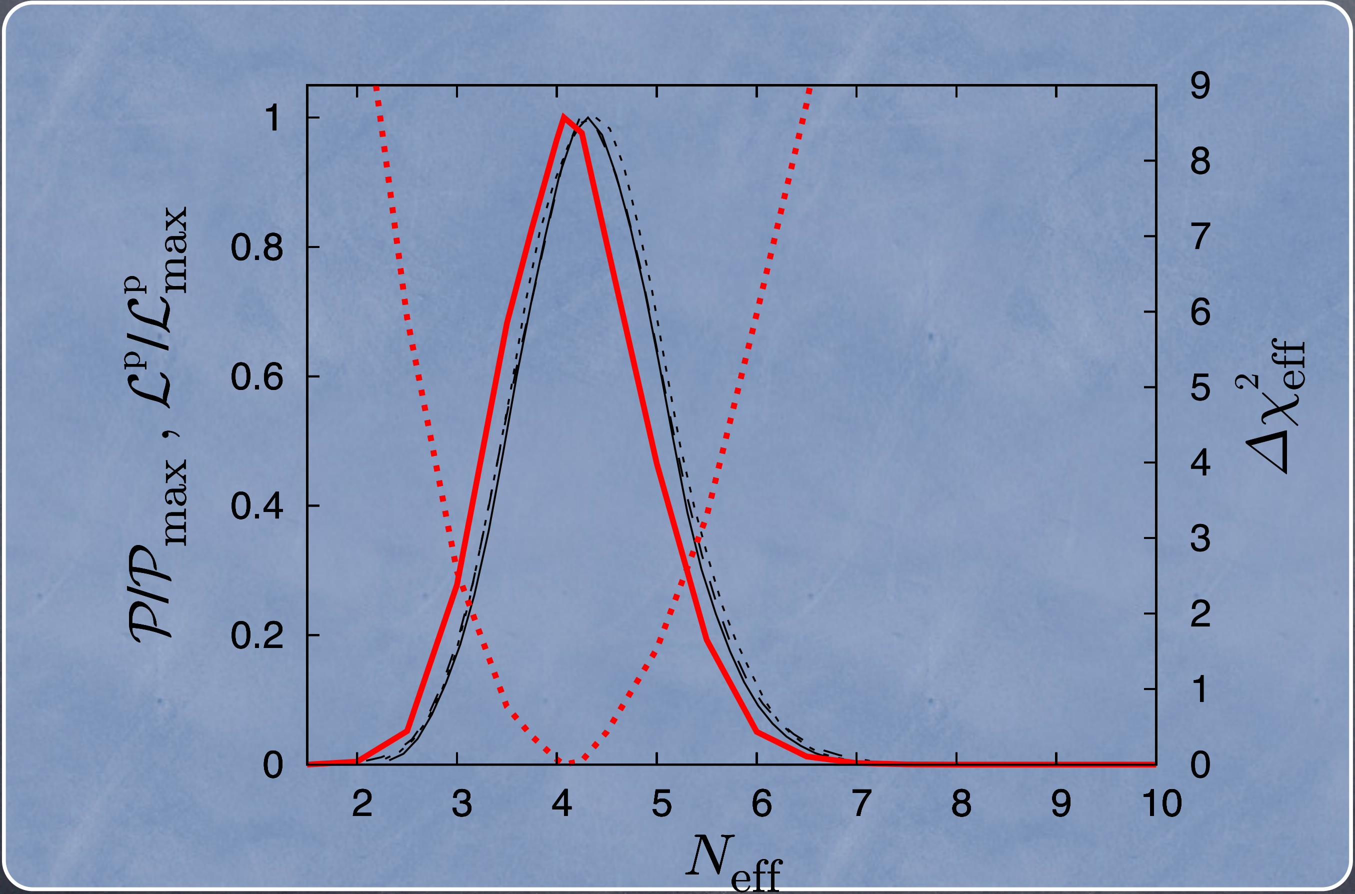
SPT Collaboration, ApJ 743 (2011) 28

- WMAP + SPT [ACP] + H(z) ☛ $N_\nu^{\rm eff} = 3.5 \pm 0.3\ (1\sigma)\ [3.7 \pm 0.4\ (1\sigma)]$

Moresco, Verde, Pozzetti, Jimenez, Cimatti, arXiv:1201.6658

COMBINED LIKELIHOOD ANALYSIS

WMAP7 + ACP + HST



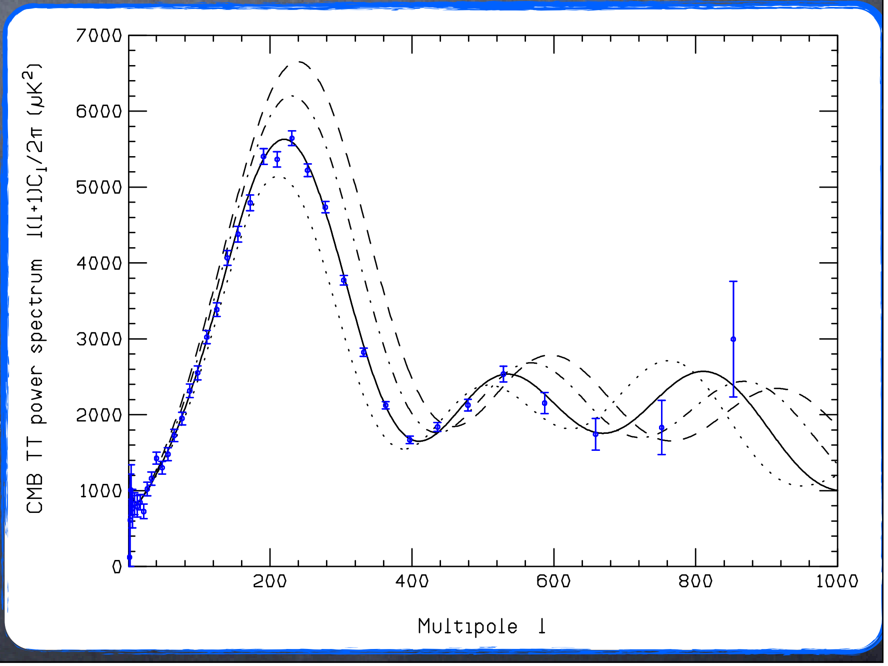
Hamann, JCAP 1203 (2012) 021

☛ Planck will reach sensitivity of 0.26 (see Georg lecture from Monday)

R.D.O.F. & CMB

- Competition between gravitational potential and pressure gradients is responsible for peaks and troughs in CMB TT power spectrum
- Redshift @ matter-radiation equality $z_{\rm eq} = 2.4 \times 10^4\, \Omega_m h^2/(t/t')^2_{post}$ affects time (redshift) duration over which this competition occurs
- If radiation content is increased ☛ matter-radiation equality is delayed and occurs closer to recombination epoch
- This implies universe is younger @ recombination with a correspondingly smaller sound horizon s_*
- Since location of $n^{\rm th}$ peak scales roughly as $n\pi D_*/s_*$
  ☛ peaks shift to larger l
  and with greater separation
- Key issue here: parameter degeneracy

multiple parameters affect same feature



BBN

- Primordial ^{4}He abundance is driven by decoupling of weak interaction (when neutrinos go out of equilibrium)

$$Y_p \propto e^{-(m_n - m_p)/T_{\rm dec}}$$

- $T_{\rm dec}$ determined via $\Gamma(T_{\rm dec}) = H(T_{\rm dec})$

$$T_{\rm dec}^5 \; (g/M_W)^4 M_{Pl} \sim \sqrt{N} \; T_{\rm dec}^2 \qquad (\text{with } M_W \sim \; 100 \text{ GeV})$$

- For BBN ☛ $T \sim 5$ MeV & $N \sim 10$
- Y_p increases with N
- Observationally inferred primordial fractions of baryonic mass in ^{4}He have been constantly favoring $N_\nu^{\rm eff} \lesssim 3$

Simha and Steigman, JCAP 06 (2008) 016

BBN OBSERVATIONS

- Unexpectedly ☛ recent determination of primordial ^{4}He mass fraction

  leads to $Y_p = 0.2565 \pm 0.0010(\mathrm{stat}) \pm 0.0050(\mathrm{syst})$

  (2σ higher than value given by standard BBN)

  For $\tau_n = 878 \pm 0.8$ s ☛ $N_\nu^{\mathrm{eff}} = 3.80^{0.80}_{-0.70}\ (2\sigma)$

  Izotov and Thuan, ApJ 710 (2010) L67

- ^{4}He observed primordial abundance has relative large systematic errors

  Aver, Olive, and Skillman, JCAP 1103 (2011) 043

- Y_p is predicted with precision of $\sim 0.2\%$

  D, ^{3}He, and ^{7}Li with precisions of roughly $5\%,\ 4\%$ and 8%

  BUT

  because of very precise measurement ☛ constraint on N_ν^{eff}

  from D/H is competitive with that from Y_p

- Setting aside ^{4}He constraints

  and combining CMB with BBN theory and observed D/H

$$N_\nu^{\mathrm{eff}} = 3.9 \pm 0.44\ (1\sigma)$$

Nollett and Holder, arXiv:1112.2683

HOW TO GET $N_\nu^{\rm eff} \neq 6$

- If ν_X decouples
- before reheating $\longrightarrow$ contribution to $\rho_{\rm rad}$ washed out $\longrightarrow N_\nu^{\rm eff} = 3$
- after reheating $\longrightarrow$ full contribution to $\rho_{\rm rad} \to N_\nu^{\rm eff} = 6$
- during reheating $\rho_{\rm rad} \to 3 < N_\nu^{\rm eff} < 6$

DECOUPLING

$g_X \sim g_2$

- Thermal decoupling when

$$\boxed{\begin{aligned} \Gamma_{\rm sc} = \sigma_{\rm sc}\, nv \quad &\sim \quad H \\ \frac{g_X^4\ T^2}{M_X^4}\, T^3 \quad &\sim \quad \frac{N\ T^2}{M_{\rm Pl}} \end{aligned}}$$

- Normalize w.r.t. ν_L decoupling at a few MeV via weak scattering

$$\boxed{\frac{M_X}{M_W} \equiv \left(\frac{T_X^{\rm dec}}{T_{\nu_L}^{\rm dec}}\right)^{3/4}}$$ with $g_X \sim g_2$

- For decoupling during the QCD crossover, $T^{\rm dec} \simeq 200$

$$\boxed{M_X \sim 3\ {\rm TeV}}$$

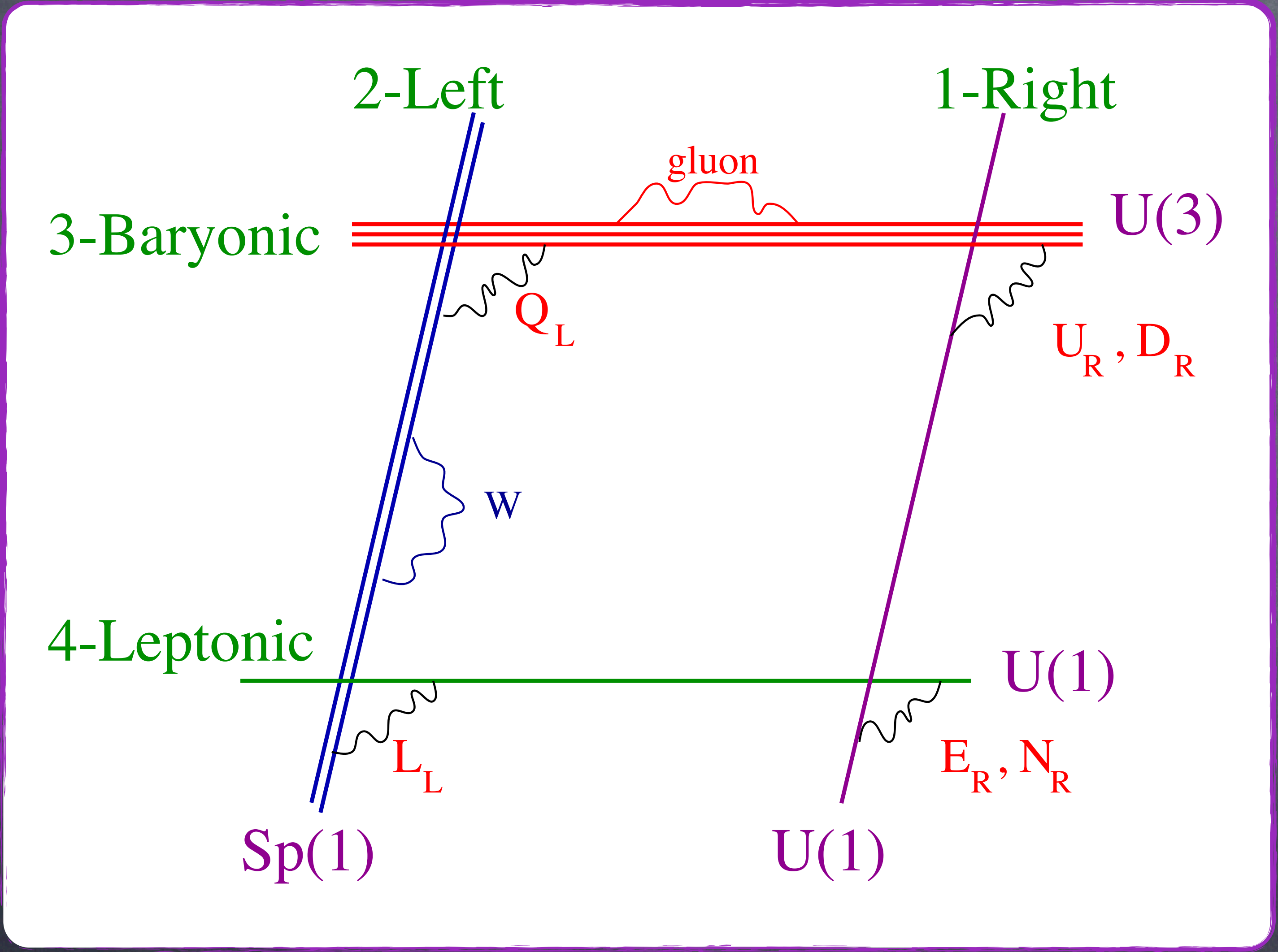
HOW DO WE GET $\Delta N_\nu^{\rm eff} \sim 1$ WITH RIGHT-HANDED NEUTRINOS?

- Find model in which ν_R decouples during quark-hadron transition
- From previous equation ☛ need non-zero coupling to gauge fields with $M \sim$ TeV
- D-brane candidate: $SU(3)_C \times SU(2)_L \times U(1)_B \times U(1)_L \times U(1)_{I_R}$
- $Y = \frac{1}{2}(B - L) + I_R$
- $B - L$ is non-anomalous if $3\ \nu_L$'s are accompanied by $3\ \nu_R$'s
- Matter fields consist of six sets of Weyl fermion-antifermion pairs (labeled by index $i = 1 \dots 6$)
- Gauging of B prevents fast proton decay

  ☛ mass via Green-Schwarz/Stuckelberg mechanism
- Gauging of L disallows heavy Majorana

  ☛ just 3 Dirac neutrinos with tiny Yukawas

PICTORIAL REPRESENTATION OF D-BRANE CONSTRUCT



Cremades, Ibañez, and Marchesano, JHEP 0307 (2003) 0388

MODEL PARAMETERS

- 3 couplings g_B, g_L, g_{I_R}
- 3 Euler angles ☛ field rotation to coupling diagonal in Y fixes 2 angles
- Orthogonal nature of rotation ☛ one constraint on couplings

$$\boxed{\frac{1}{g_Y^2} = \left(\frac{1}{2g_L}\right)^2 + \left(\frac{1}{6g_B}\right)^2 + \left(\frac{1}{2g_{I_R}}\right)^2}$$

- Baryon number coupling g_B

  fixed to be $1/\sqrt{6}$ of $SU(3)$ coupling at $U(3)$ unification

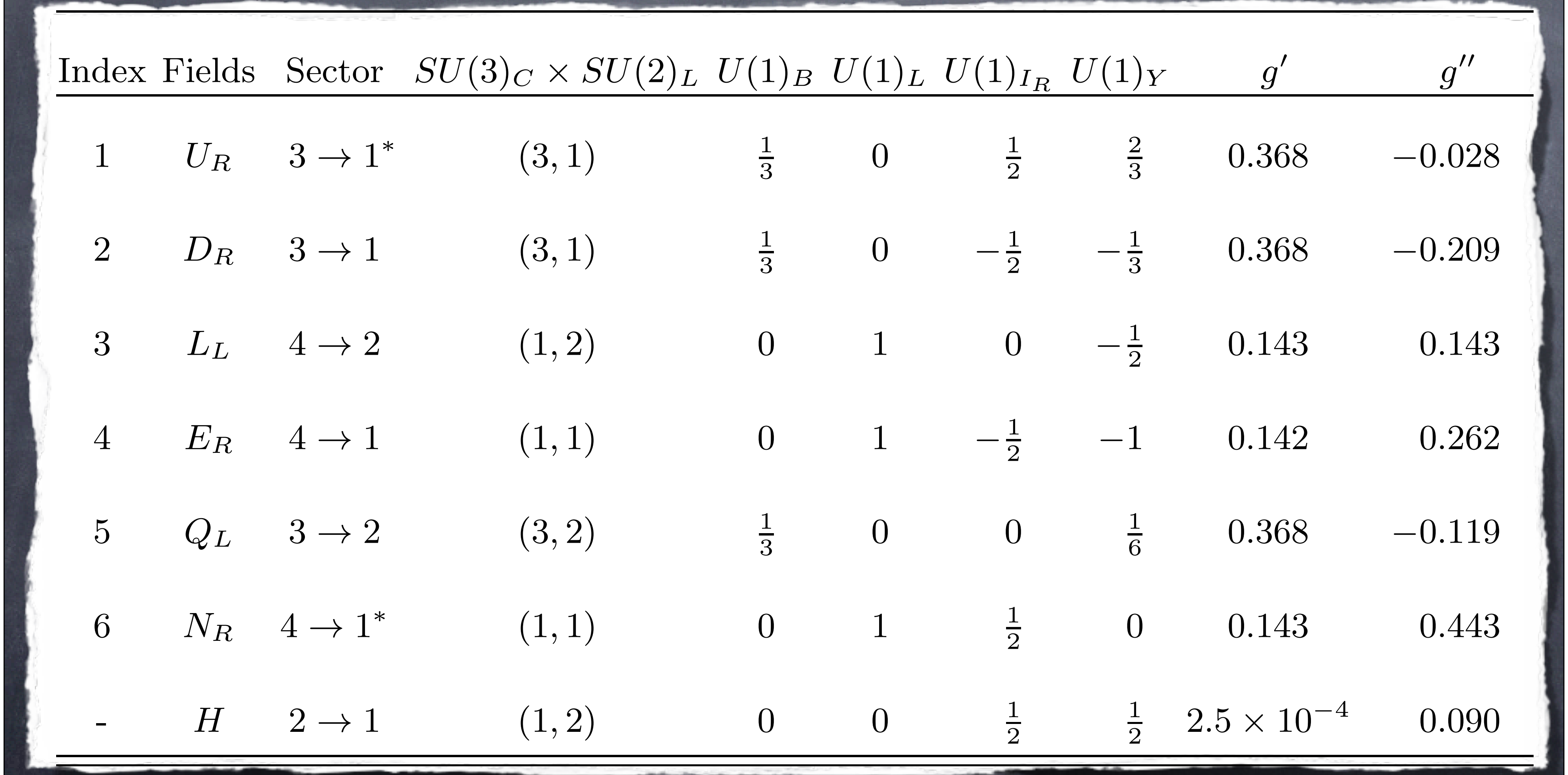
  ☛ determined elsewhere via RG running
- 2 remaining d.o.f. allow further rotation leaving in addition to Y

  Z' to couple to B (super-heavey string scale)

  Z'' to couple to linear combinaion of $B-L$ and I_R

-- only boson masses are free --

THE DRAMATIS PERSONAE



Index	Fields	Sector	$SU(3)_C \times SU(2)_L$	$U(1)_B$	$U(1)_L$	$U(1)_{I_R}$	$U(1)_Y$	g'	g''
1	U_R	$3 \to 1^*$	$(3,1)$	$\frac{1}{3}$	0	$\frac{1}{2}$	$\frac{2}{3}$	0.368	-0.028
2	D_R	$3 \to 1$	$(3,1)$	$\frac{1}{3}$	0	$-\frac{1}{2}$	$-\frac{1}{3}$	0.368	-0.209
3	L_L	$4 \to 2$	$(1,2)$	0	1	0	$-\frac{1}{2}$	0.143	0.143
4	E_R	$4 \to 1$	$(1,1)$	0	1	$-\frac{1}{2}$	-1	0.142	0.262
5	Q_L	$3 \to 2$	$(3,2)$	$\frac{1}{3}$	0	0	$\frac{1}{6}$	0.368	-0.119
6	N_R	$4 \to 1^*$	$(1,1)$	0	1	$\frac{1}{2}$	0	0.143	0.443
-	H	$2 \to 1$	$(1,2)$	0	0	$\frac{1}{2}$	$\frac{1}{2}$	2.5×10^{-4}	0.090

$$\mathcal{L}_{\text{Yukawa}} = -Y_d^{ij}\,\bar{Q}_i\,H\,D_j - Y_u^{ij}\,\epsilon^{ab}\,\bar{Q}_{ia}\,H_b^\dagger\,U_j - Y_\ell^{ij}\,\bar{L}_i\,H\,E_j + Y_\nu^{ij}\,\epsilon^{ab}\,\bar{L}_{ia}\,H_b^\dagger\,N_j + \text{ h.c.}$$

LAA, Antoniadis, Goldberg, Huang, Lüst, and Taylor, PRD 85 (2012) 086003

OBTAINING DECOUPLING TEMPERATURE

- Adiabatic reheating of all particles except $\nu_R{'}\mathrm{s}$ after decoupling gives relation

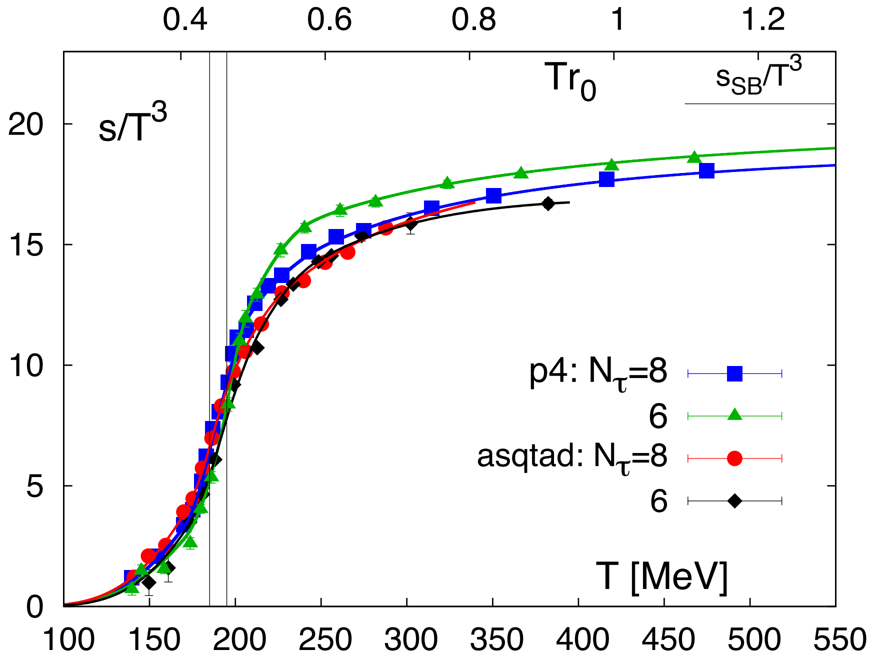
⇓

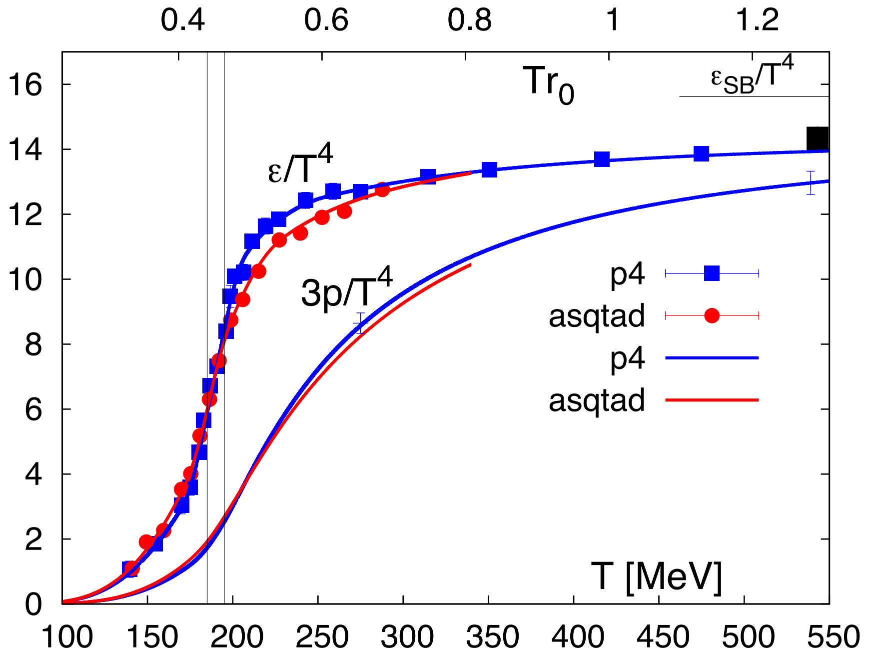
$$\Delta N_\nu^{\mathrm{eff}} = 3 \left(\frac{N(T_{\mathrm{end}})}{N(T_{\mathrm{dec}})} \right)^{4/3}$$

- T_{end} ☛ temperature at end of reheating phase
- $N(T) = r(T)(N_{\mathrm{B}} + \frac{7}{8} N_{\mathrm{F}})$ ☛ effective number of r.d.o.f. at T
- $r(T) = 1$ for lepton/photon and $r(T) = s(T)/s_{\mathrm{SB}}$ for qg plasma
- $N(T_{\mathrm{dec}}) = 37\, r(T_{\mathrm{dec}}) + 14.25$
- $N(T_{\mathrm{end}}) = 10.75$

LATTICE QCD

- Lower T coincides with most rapid rise of entropy





Bazavov et al., PRD 80 (2009) 014504

QUARK-HADRON CROSSOVER TRANSITION

- Excess r.d.o.f. within 1σ of central value of each if

$$\begin{array}{rrcl} & 0.46 < & \Delta N_\nu^{\rm eff} & < 1.08 \\ \rightarrow & 23 < & N(T_{\rm dec}) & < 44 \\ \rightarrow & 0.24 < & r(T_{\rm dec}) & < 0.80 \end{array}$$

- From lattice QCD study ☛ this translates to a temperature range

$$175 \text{ MeV} < T_{\rm dec} < 250 \text{ MeV}$$

Bazavov et al., PRD 80 (2009) 014504

- Decoupling of ν_R occurs when

$$\nu_R \text{ m.f.p. } \geq \text{horizon size } \Rightarrow \Gamma^{\rm int}(T_{\rm dec}) = H(T_{\rm dec})$$

$$\Downarrow$$

$$\begin{array}{lcl} \text{Thermal equilibrium} & \rightarrow & \text{int} = \text{scatt} + \text{ann} \\ \text{Chemical equilibrium} & \rightarrow & \text{int} = \text{ann} \end{array}$$

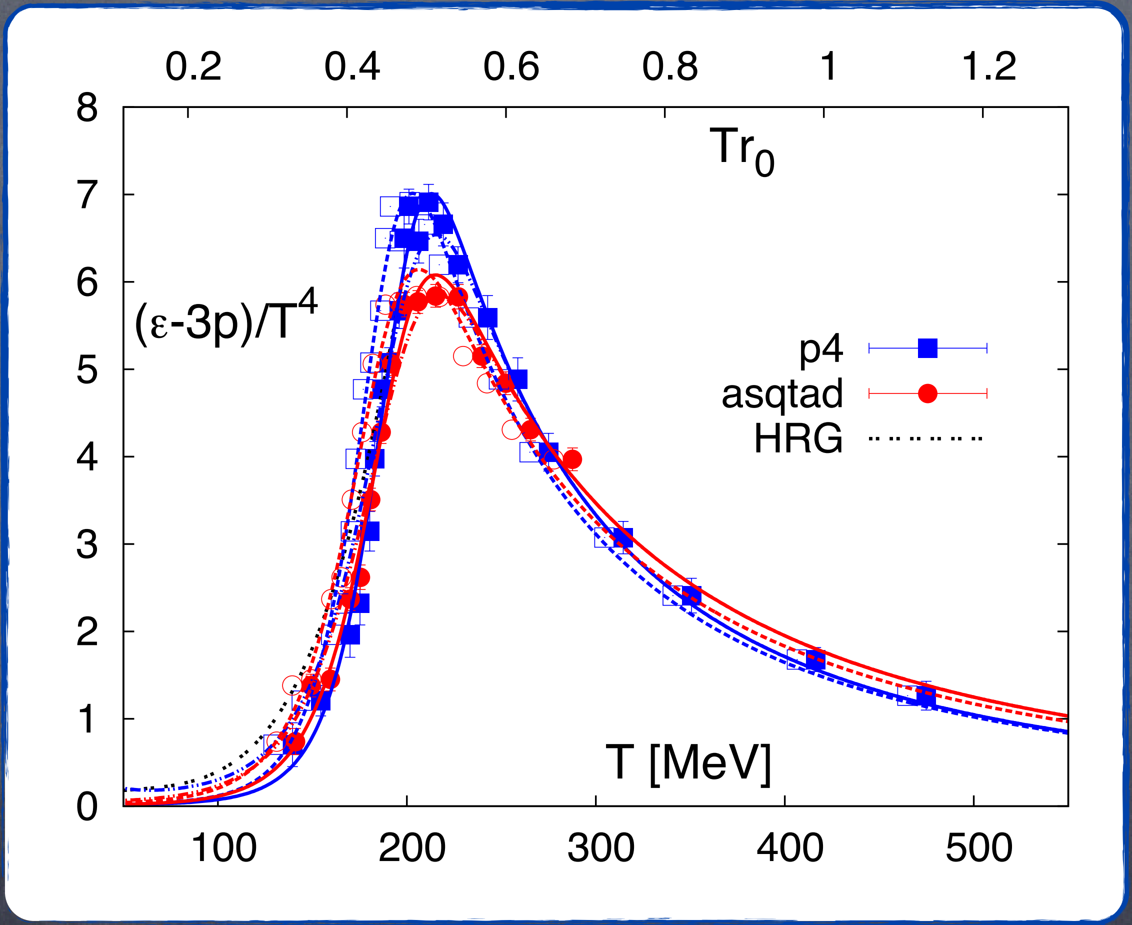
$$\Downarrow$$

$$H(T) = 1.66 \, \langle N(T) \rangle^{1/2} \, T^2 / M_{\rm Pl}$$

AS A CHECK ...

behavior of trace anomaly

(which is very sensitive to behavior in crossover region)



shows a sharp peak at $200\ \text{MeV}$

and our range for $T_{\rm dec}$ straddles this region

- ➤ Including s ☛ $0.18 < r(T) < 0.63$

CROSS SECTIONS

- All is fixed except for Z' and Z'' masses
- For interaction rate
  - ☛ take average over angles and thermal average over energies

$$\Gamma^{\rm scat}(T) \simeq 2.0\ G^2_{\rm eff}\, T^5$$

$$\Gamma^{\rm ann}(T) \simeq 0.50\ G^2_{\rm eff}\ T^5$$

$$G^2_{\rm eff} \sim \sum G_i^2 \qquad \text{with} \qquad 4\frac{G_i}{\sqrt{2}} = \frac{g'_6\ g'_i}{M^2_{Z'}} + \frac{g''_6\ g''_i}{M^2_{Z''}}$$

- By setting in turn $\Gamma^{\rm ann}(T) = H(T) \simeq 10.4\ T^2/M_{\rm Pl}$

and

$$\Gamma^{\rm ann}(T) + \Gamma^{\rm scatt}(T) = H(T) \simeq 10.4\ T^2/M_{\rm Pl}$$

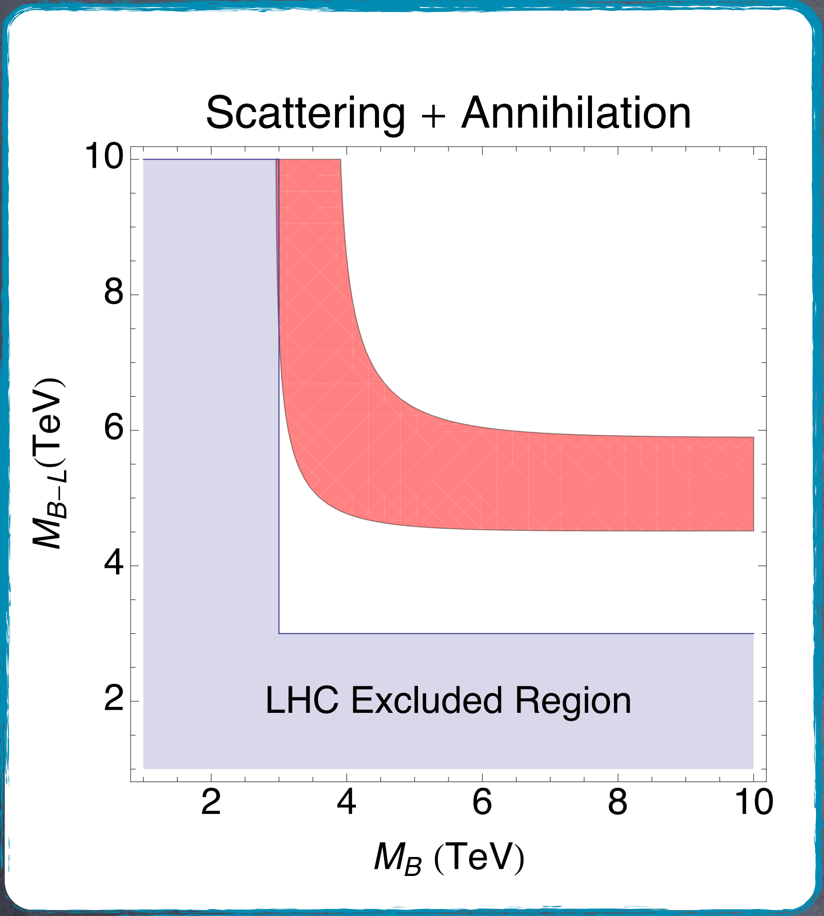
one arrives at two values of $T_{\rm dec}$

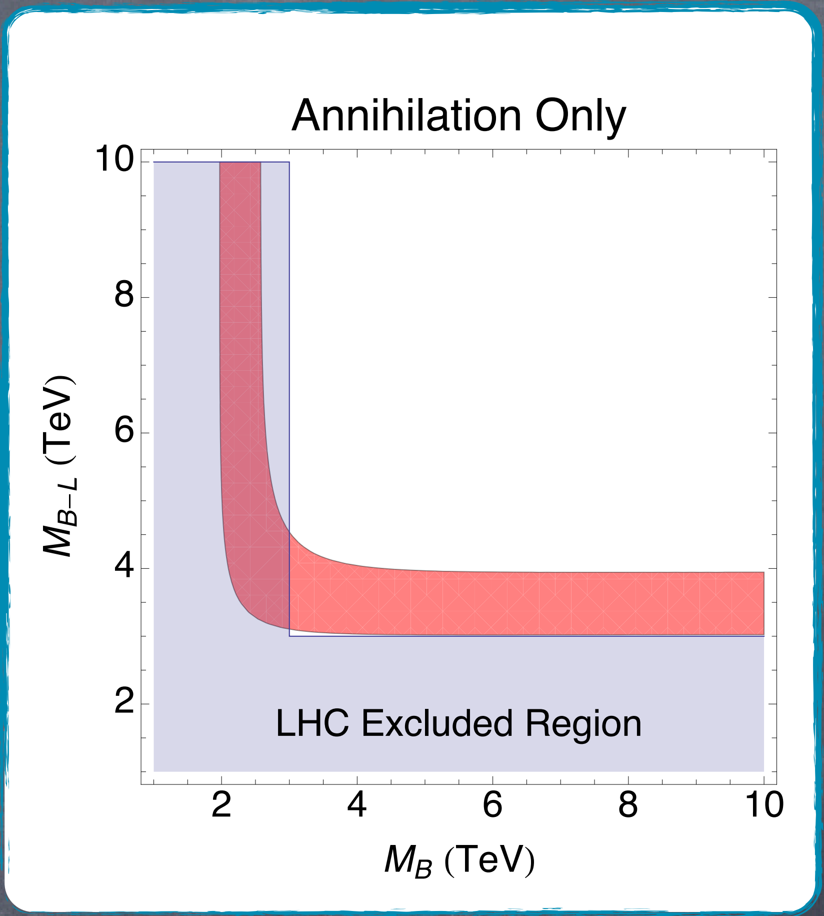
$$\text{Chemical equilibrium} \quad \rightarrow \quad T_{\rm dec} = 2.75\ (G^2_{\rm eff}\ M_{\rm Pl})^{-1/3}$$

$$\text{Thermal equilibrium} \quad \rightarrow \quad T_{\rm dec} = 1.60\ (G^2_{\rm eff}\ M_{\rm Pl})^{-1/3}$$

- When each of these is required to lie between 175 MeV and 250 MeV
- ☛ allowed regions of Z' and Z'' masses are defined in each case

CONSTRAINTS

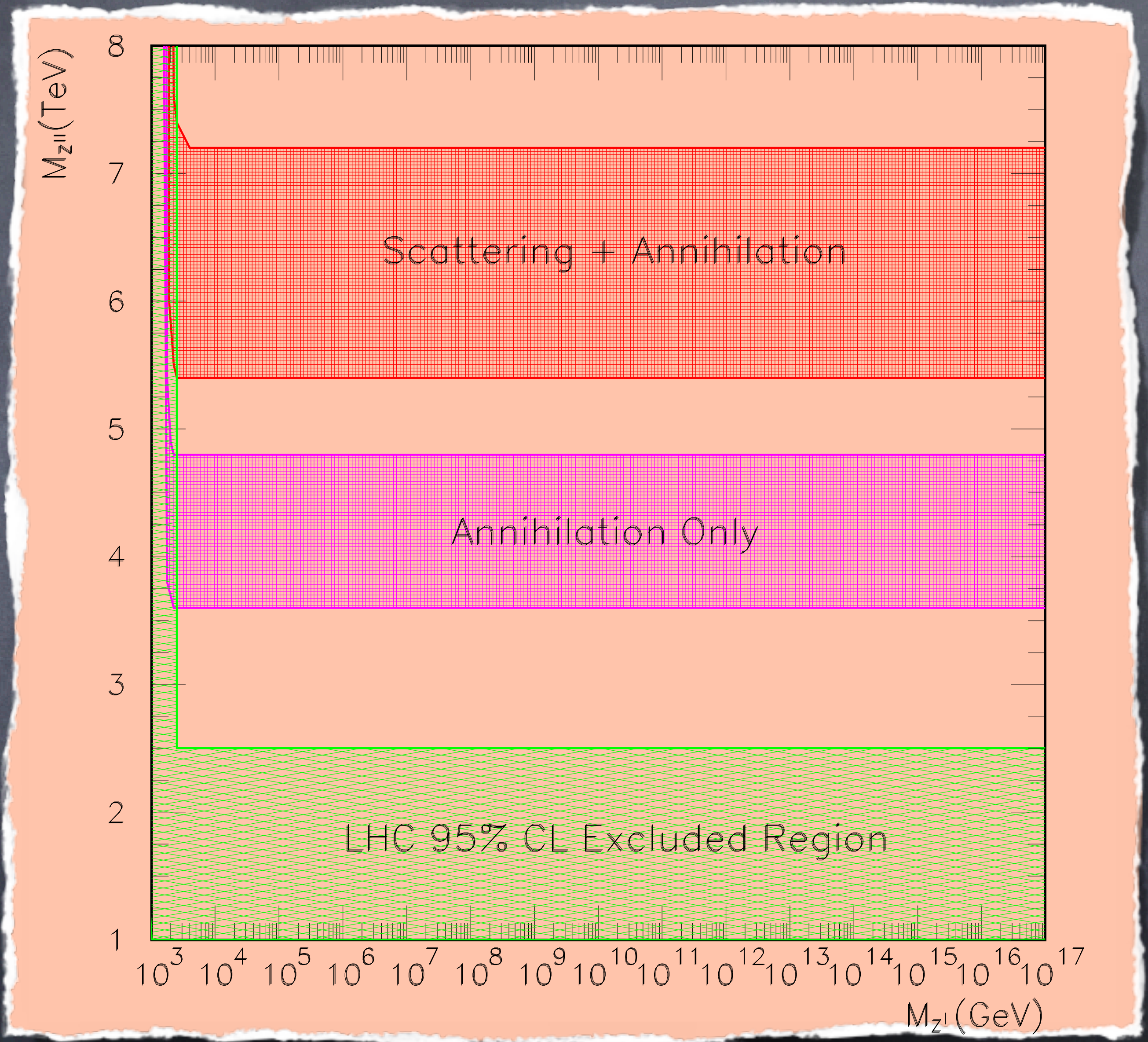




- Dark shaded areas show region allowed from decoupling requirements to accommodate CMB and BBN data
- Light shaded regions indicate masses excluded by LHC7 dijet searches
- These two estimates should serve to bracket size of actual effect
- Designation of B corresponds to Z' and $B-L$ to Z''

LAA and Goldberg, PRL 108 (2012) 081805

ZOOM OUT



Anchordoqui, Antoniadis, H.G, Huang, Lust, Taylor, Vlcek, arXiv:1206.2537

SUMMARY AND CONCLUSIONS

- ☐ We developed dynamic explanation of recent hints that relativistic component of energy during BBN and CMB epochs is equivalent to about 1 extra Weyl neutrino
- ☐ We work within (string base) $U(3)_C \times SU(2)_L \times U(1)_R \times U(1)_L$ gauge theory
  - ☐ Model endowed with $3\,U(1)$ gauge symmetries coupled to $B,\ L,\ I_R$
  - ☐ Rotation of gauge fields to basis exactly diagonal in Y and very nearly diagonal in $B-L$ and B fixes all mixing angles and gauge couplings
  - ☐ Requiring $B-L$ current be anomaly free implies existence of 3 right-handed Weyl neutrinos
- ☐ Task then reverts to explain why there are not 3 additional r.d.o.f.
- ☐ We find that for certain ranges of M_B and M_{B-L} decoupling of ν_R's occurs during course of quark-hadron crossover transition
  - ☛ just so that they are only partially reheated compared to ν_L's
- ☐ Corresponding upper and lower bounds on gauge field masses yield ranges to be probed at LHC