Effective theory description of shared asymmetry: dark matter and baryon asymmetry

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DESY, Hamburg
May 17, 2016

*Based on the work in collaboration with Nicolás Bernal & Nayara Fonseca (to appear hep-ph/1605.XXXXX *touch wood) and an earlier work hep-ph/1508.03648*

Sharing but not caring: dark matter and baryon asymmetry

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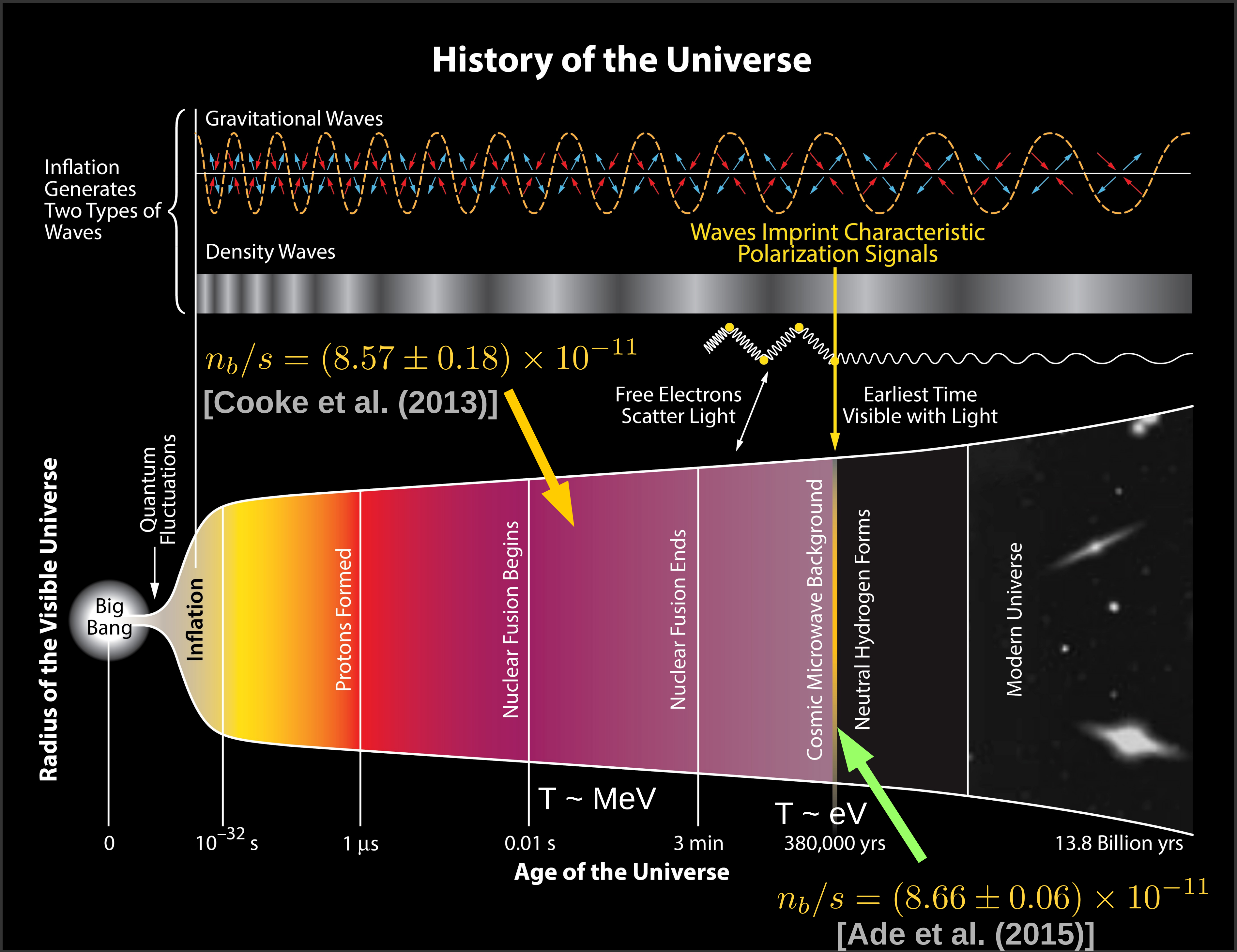
Outline

- Motivations
- Symmetries and Asymmetries
- Shared Asymmetry Scenarios
- Phenomenology

Motivations



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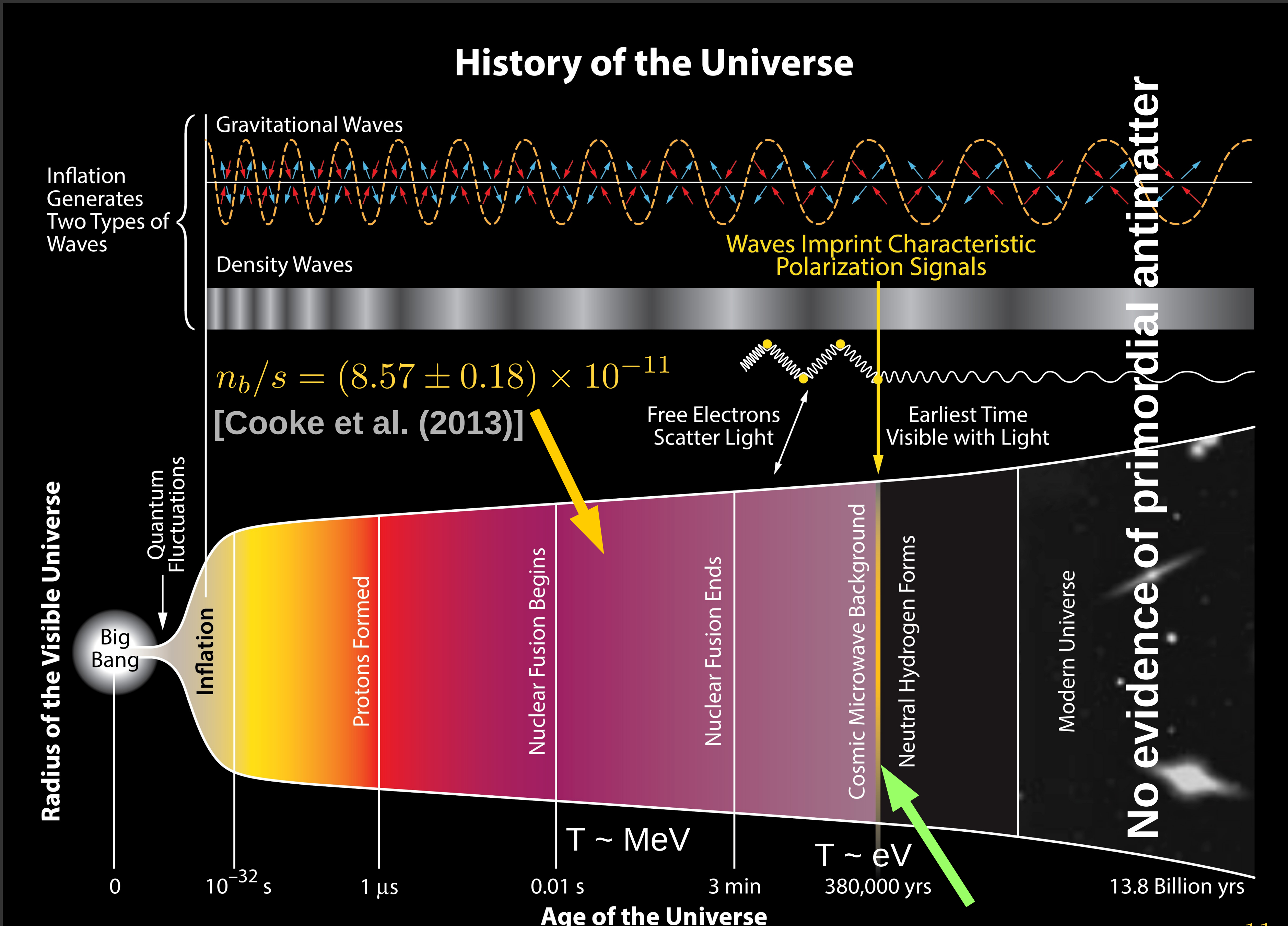


$n_b/s = (8.57 \pm 0.18) \times 10^{-11}$

[Cooke et al. (2013)]

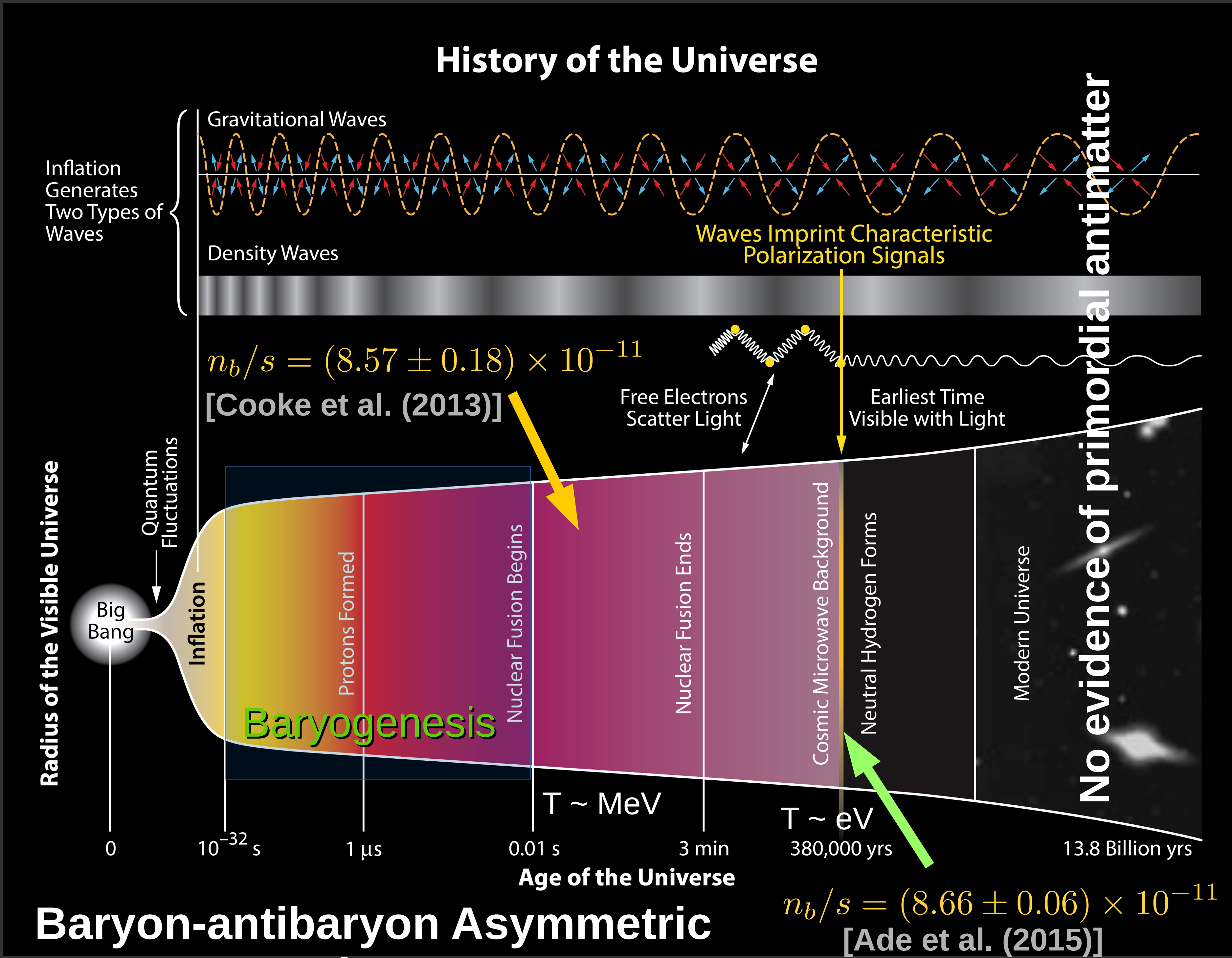
No evidence of primordial antimatter

$n_b/s = (8.66 \pm 0.06) \times 10^{-11}$

[Ade et al. (2015)]

Baryon-antibaryon Asymmetric Universe

http://bicepkeck.org/visuals.html



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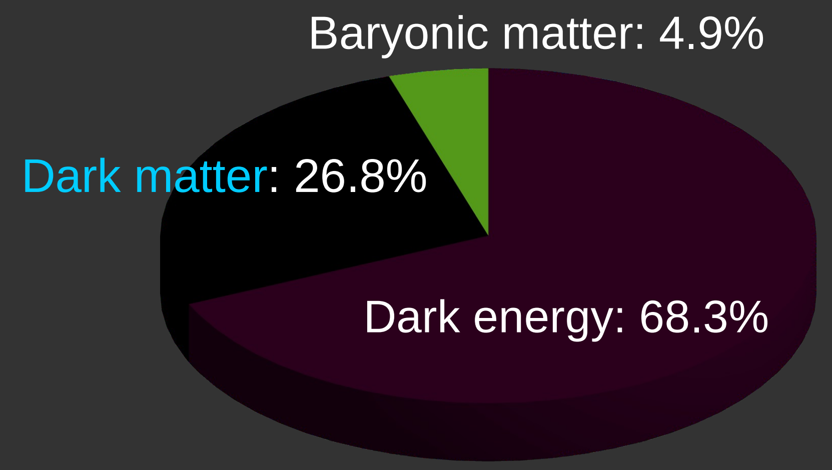
The existence of dark matter?

- We have evidences only at large scales (and only *gravitationally*)
  - Rotation curves of spiral galaxies
  - Gravitational lensing
  - Cosmic Microwave Background
  - Large Scale Structures simulation
  - Collision of bullet cluster



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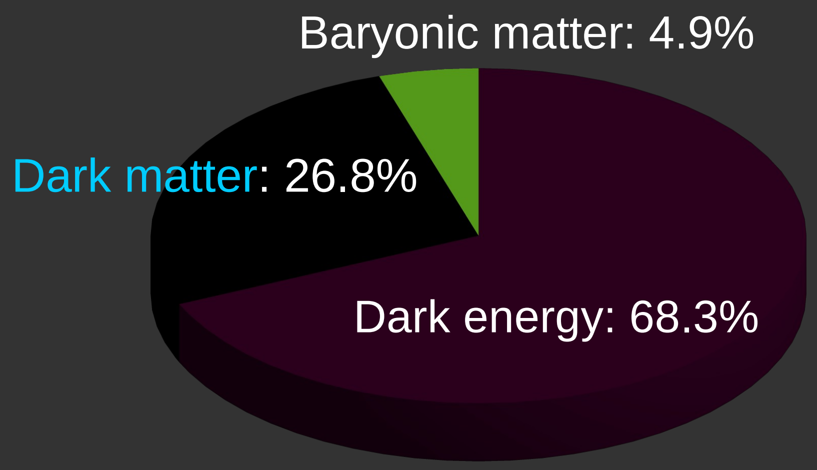


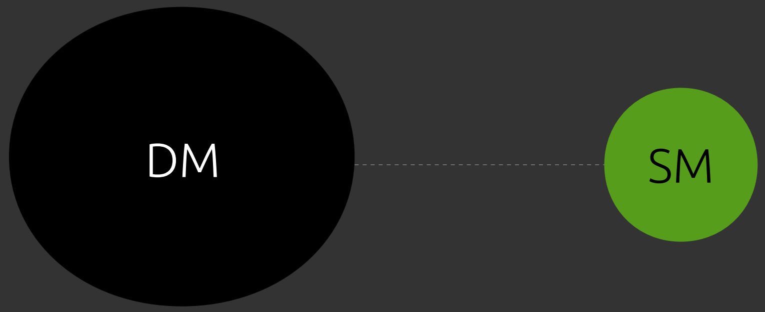
So far there is no definite evidence of dark matter through particle physics interactions and this might as well be so

Dark matter particle properties?

- If true, all the experiments designed to detect them in such a way will give ...

Dark matter particle properties?

- Okay let's be more optimistic :)



- Three possible ways to detect Dark Matter (DM) particle properties (mass & interactions):
  - Direct detection: wait for them to hit our detectors
  - Indirect detection: if they annihilation or decay to something detectable - the Standard Model (SM) particles
  - Collider: missing energy/momentum

What we know about dark matter?

- They are nonrelativistic, collisionless(?) matter
- Color and electric charged neutral
- They are stable on cosmological timescale
- Motivated from what we know about the SM:
  - DM can be non self-conjugate (particles ≠ antiparticles): few-decade-old idea e.g. **[Nussinov (1985)]** i.e. *Asymmetric DM*; Recently gain renew impetus, see some recent reviews: **[Davoudiasl & Mohapatra (2012)], [Petraki & Volkas (2013)], [Zurek (2014)]**

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  - DM can be charged under the same (approximate) symmetries of the SM: baryon and/or lepton number see e.g. **[Kaplan, Luty & Zurek (2009)];** as *gauge symmetry* **[Fileviez Perez & Wise (2010)], [Duerr, Fileviez Perez & Wise (2013)], [Duerr & Fileviez Perez (2014)]**

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Another hint: $\Omega_{DM} \approx 5\Omega_B$

Asymmetric dark matter

- Motivation? $\Omega_{DM} \approx 5\Omega_B$ => $Y_{\Delta DM} m_{DM} \approx 5 m_n Y_{\Delta B}$
  - *Chemical Equilibrium* (CE) could => $n_{\Delta DM} \approx n_{\Delta B}$ => $m_{DM} \approx 5 m_n$

    → simply replacing one coincidence with another but see e.g. dark QCD **[Bai & Schwaller (2014)]**
  - In fact CE => $\mu_{DM} \approx \mu_B$, and if decoupling happens when nonrelativisitic => $m_{DM} >> m_n$
- *Maximally* asymmetric DM requires *fast* DM-$\overline{\text{DM}}$ annihilation to annihilate the symmetric component

  => unitarity bound **[Griest & Kamionkowski (1990)], [Hui (2001)]**

  m_{DM} <~100 TeV
- Mixed scenario is less predictive but as interesting e.g. **[Graesser, Shoemaker & Vecchi (2011)]**

Symmetries and Asymmetries

Symmetries and asymmetries

- Symmetry is a *double-edged sword*: it prevents the generation of an asymmetry; it also protects an existing asymmetry from being erased

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- Symmetry is a *double-edged sword*: it prevents the generation of an asymmetry; it also protects an existing asymmetry from being erased
- A *slightly broken* symmetry allows the creation and destruction of an asymmetry

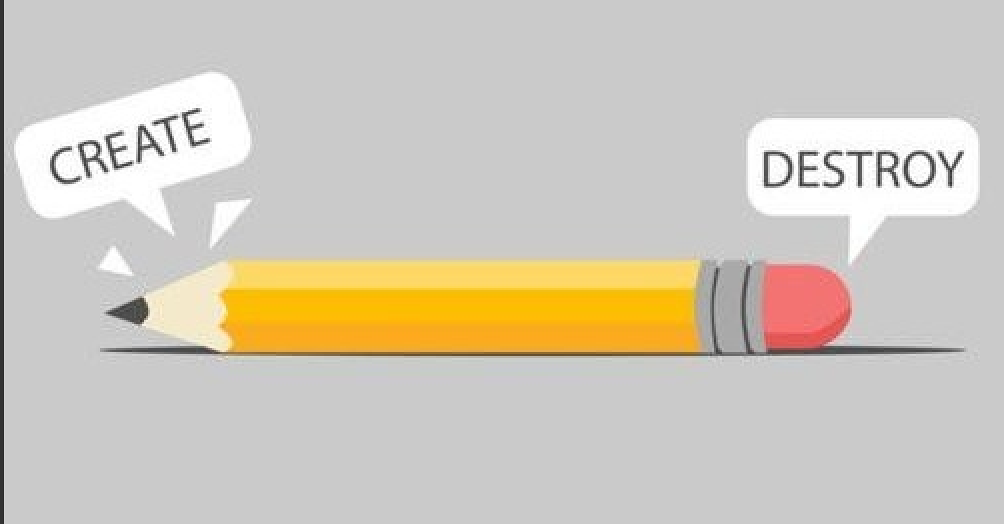

image credit: https://swedishgarden.wordpress.com/2011/12/10/double-edged-sword-rebellion/

Early Universe effective theories

e.g. **[CSF, Gonzalez-Garcia & Nardi (2011)]**

For the range of temperatures of interest T, three types of reactions according their timescale:

(i) Fast: Γ(T) >> H(T): absence of symmetry, in CE $\sum_i \mu_i = 0$

(ii) Slow: Γ(T) << H(T): exact/effective symmetries

=> *conserved Noether's charges*

(iii) Relevant: Γ(T) ~ H(T): quasi/approximate symmetries

=> *evolving Noether's charges* described by

non-equilibrium dynamics like Boltzmann equations

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non-equilibrium dynamics like Boltzmann equations

Goal: Rewrite all the particle asymmetries in terms of only *Noether's charges* where the effects of (i) can be resummed [CSF (2016)]

U(1) symmetries and charges

Formalism first introduced in **[Antaramian, Hall & Rasin (1994)]**

- By symmetry, refer to U(1) symmetry which characterizes the *charge asymmetry* between particle & antiparticle (the diagonal generators of nonabelian group do not contribute)
- For each *complex* particle i (not real scalar or Majorana fermion), they can be assigned a *chemical potential* μ_i with charge q_i^x under $U(1)_x$
- For reactions of type (i), we have sets of linear equations

$$\sum_i \mu_i = 0$$

- By construction, if $U(1)_x$ is a symmetry of the system

$$\sum_i q_i^x = 0$$

- Hence the *most general solution* is $\mu_i = \sum_x C_x q_i^x$

Constants to be solved later

Some thermodynamics ...

- Particle i in *kinetic equilibrium* follows FD/BE distribution

$$f_i = \frac{1}{\exp(E_i - \mu_i)/T \pm 1}$$

Assumption: $i \to \bar{i}, \quad \mu_i \to -\mu_i$

$$i + \bar{i} \to g$$

- The number density is

$$n_i = g_i \int \frac{d^3p}{(2\pi)^3} f_i$$

- The number density *asymmetry* is

$$n_{\Delta i} \equiv n_i - n_{\bar{i}} = \frac{T^2}{6} g_i \zeta_i \mu_i$$

Assumption: $\mu_i/T \ll 1$

$$\zeta_i \to 1(2) \quad \text{for} \quad m_i \ll T; \quad \zeta_i \to 0 \quad \text{for} \quad m_i \gg T$$

- For each $U(1)_x$, the corresponding *Noether's charge*

$$n_{\Delta x} = \sum_i q_i^x n_{\Delta i}$$

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$$n_{\Delta x} = \sum_i q_i^x n_{\Delta i} \longrightarrow \frac{T^2}{6} \sum_i q_i^x g_i \zeta_i \mu_i \longrightarrow \frac{T^2}{6} \sum_y C_y \sum_i q_i^x g_i \zeta_i q_i^y$$

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J_{xy}

$$n_{\Delta x} = \sum_i q_i^x n_{\Delta i} \longrightarrow \frac{T^2}{6} \sum_i q_i^x g_i \zeta_i \mu_i \longrightarrow \frac{T^2}{6} \sum_y C_y \sum_i q_i^x g_i \zeta_i q_i^y$$

Constants can be solved in terms of the *Noether's charge* and J_{xy}

Solutions

- The type (i) reactions are "resummed" in $J_{xy} \equiv \sum_i q_i^x g_i \zeta_i q_i^y$

$$C_y = \frac{6}{T^2} \sum_x J_{yx}^{-1} n_{\Delta x}$$

- The solutions in terms of only *Noether's charge*

$$n_{\Delta i} = g_i \zeta_i \sum_{x,y} q_i^y J_{yx}^{-1} n_{\Delta x}$$

- We can easily write down the *baryon asymmetry*

$$n_{\Delta B} = \sum_i q_i^B n_{\Delta i} = \sum_{x,y} J_{By} J_{yx}^{-1} n_{\Delta x}$$

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Detection of ("fast") B violation does not invalidate baryogensis (due to fast washout) but is a <u>source</u> of B violation

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The roles of U(1) symmetries

- To clarify the roles of U(1) symmetries, let us single out the *exact symmetries* $U_0=\{U(1)_a, U(1)_b, \ldots\}$ and denote the rest of them as $\bar{U}=U-U_0=\{U(1)_m, U(1)_n, \ldots\}$. We can eliminate the U_0 charges using the relations $n_{\Delta a} = \text{constant}$

$$n_{\Delta a} = 0 \implies \sum_b J_{ab} C_b + \sum_m J_{am} C_m = 0 \implies C_a = -\sum_{b,m} J^{-1}_{ab} J_{bm} C_m$$

- The number density asymmetry is

$$n_{\Delta i} = g_i \zeta_i \sum_{m,n} \bar{q}_i^m \bar{J}^{-1}_{mn} n_{\Delta n}$$

$$\bar{q}_i^m \equiv q_i^m - \sum_{a,b} q_i^a J^{-1}_{ab} J_{bm}$$

$$\bar{J}_{mn} \equiv J_{mn} - \sum_{a,b} J_{ma} J^{-1}_{ab} J_{bn}$$

Matrix with reduced dimension

Only nonexact symmetries

The roles of U(1) symmetries

- The baryon asymmetry is

$$n_{\Delta B} = \sum_{m,n} \left[J_{Bm} - \sum_{a,b} J_{Ba} J^{-1}_{ab} J_{bm} \right] \bar{J}^{-1}_{mn} n_{\Delta n} = \sum_{m,n} \bar{J}_{Bm} \bar{J}^{-1}_{mn} n_{\Delta n}$$

Direct contributions

particles charged under $\bar{U}$ and carry B

Matrix with reduced dimension

Only nonexact symmetries

Indirect contributions

particles charged under U_0 and $\bar{U}$ but do not carry B e.g. Higgsogenesis **[Servant & Tulin (2013)]**

Generalization of the result of **[Antaramian, Hall & Rasin (1994)]** which states that a nonzero asymmetry in a preserved sector $\bar{U}$ that has nonzero hypercharge U_0 implies nonzero baryon asymmetry (a=b=Y).

The roles of U(1) symmetries

Creator/destroyer: type (iii) reactions;

dynamical violation $n_{\Delta m} = 0 \rightarrow n_{\Delta m} \neq 0$

$\overline{U}$

Preserver: type (ii) reactions with $n_{\Delta m} \neq 0$

The lightest electrically neutral particle (if stable) can be *dark matter*

Nonbaryons

Messenger: type (ii) reactions with conservation law e.g. $n_{\Delta a} = 0$

U_0

Baryons

Example: The SM

Identity all the U(1)'s

- Let us define the $U(1)_x$-SU(N)-SU(N) mixed anomaly coefficient as $A_{xNN} \equiv \sum_i c_2(R) g_i q_i^x$

$c_2(R) = \frac{1}{2}$ fundamental $\qquad c_2(R) = N$ adjoint

$$-\mathcal{L}_Y = (y_u)_{\alpha\beta} \overline{Q_\alpha} \epsilon H^* U_\beta + (y_d)_{\alpha\beta} \overline{Q_\alpha} H D_\beta + (y_e)_{\alpha\beta} \overline{\ell_\alpha} H E_\beta + \text{H.c.}$$

- We identify five U(1)'s: $U(1)_Y$, $U(1)_B$, $U(1)_{L\alpha}$

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- The last four are anomalous: $A_{B22}=A_{L\alpha 22} = N_f/2$

$$\mathcal{O}_{\mathrm{EWsp}} = \sum_\alpha (QQQ\ell)_\alpha \longleftarrow$$ Type (i) reactions for T>100 GeV

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- We identify ~~five~~ four U(1)'s: $U(1)_Y$, ~~$U(1)_B$, $U(1)_{L\alpha}$~~, $U(1)_{(B-L)\alpha}$
- The last four are anomalous: $A_{B22}=A_{L\alpha 22} = N_f/2$

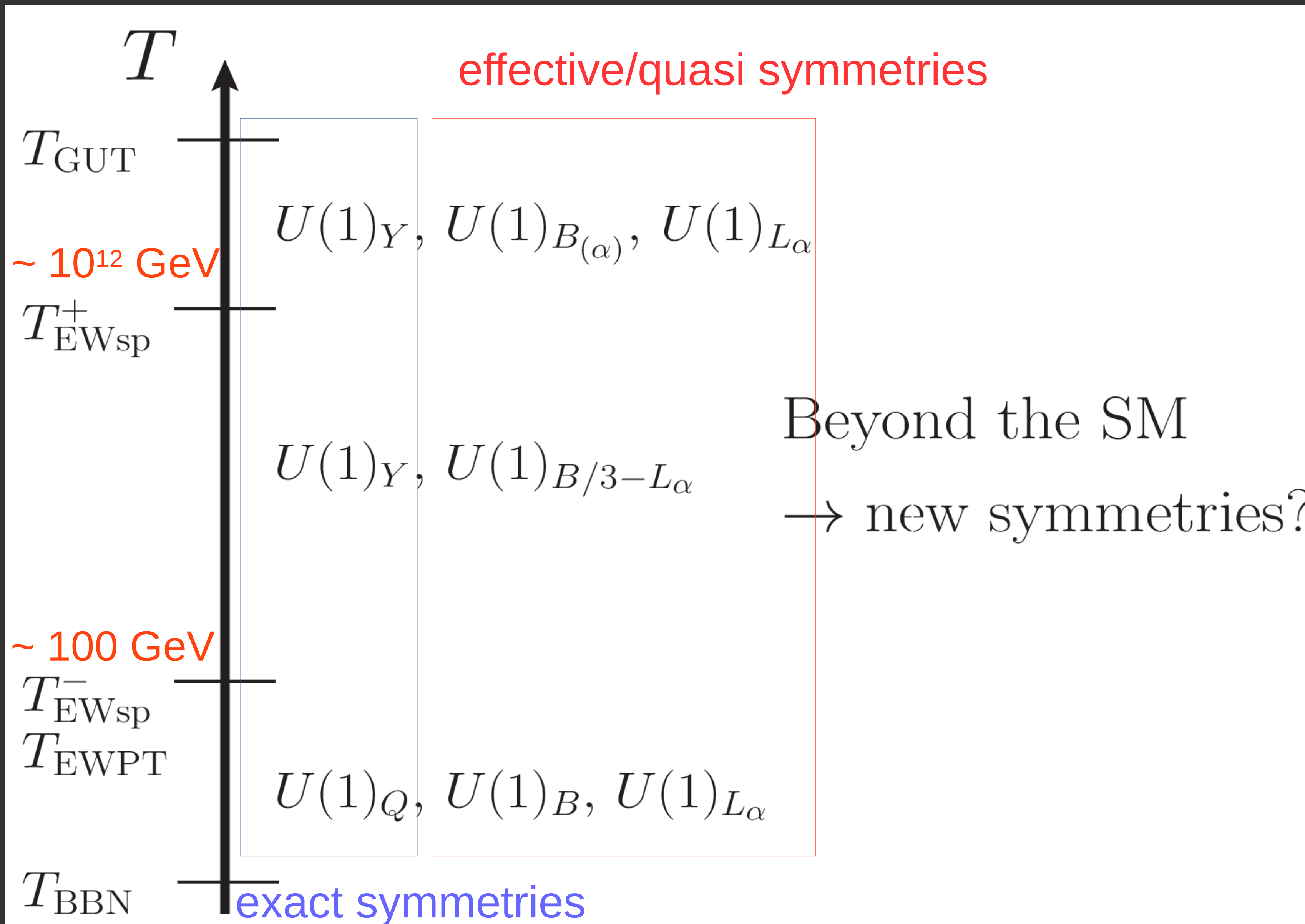
Anomaly free

$$\mathcal{O}_{\mathrm{EWsp}} = \sum_\alpha (QQQ\ell)_\alpha$$

Type (i) reactions for T>100 GeV

Due to quark mixing, $U(1)_{(B-L)\alpha} \rightarrow U(1)_{B/3-L\alpha}$

Example: The SM



Example: The SM

Solve the system: Calculate J

Define the vectors: $q_i^T \equiv \left(q_i^{\Delta_\alpha}, q_i^Y\right), \quad n^T \equiv (n_{\Delta_\alpha}, n_{\Delta_Y} = 0)$

$\Delta_\alpha \equiv B/3 - L_\alpha$

Table 1

The list of SM fields, their $U(1)$ charges q_i^x and gauge degrees of freedom g_i with fermion family index α. Here $N_H - 1$ is number of extra pairs of Higgses H' with the assumption that they maintain chemical equilibrium with the SM Higgs H.

$i =$	Q_α	U_α	D_α	ℓ_α	E_α	H	H'
$q_i^{\Delta_\alpha}$	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	-1	-1	0	0
q_i^Y	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$\frac{1}{2}$
q_i^B	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0
$q_i^{L_\alpha}$	0	0	0	1	1	0	0
g_i	3×2	3	3	2	1	2	$2(N_H - 1)$

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$$\Delta_\alpha \equiv B/3 - L_\alpha$$

At $T \sim 10^9$ GeV, 1st gen. Yukawa interactions are out of chemical eq.

Setting $y_e, y_u, y_d \to 0$, we gain $U(1)_e$, ~~$U(1)_u$, $U(1)_d$~~

U(1)-SU(3)-SU(3) anomaly!

- Formally, construct $n_{\Delta e}$ and set to zero (assuming initial $n_{\Delta e}$=0); in practice, set $g_e = 0$.

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$\Delta_\alpha \equiv B/3 - L_\alpha$

At T ~ 10^9 GeV, 1^{st} gen. Yukawa interactions are out of chemical eq.

Setting $y_e, y_u, y_d \to 0$, we gain $U(1)_e$, $\cancel{U(1)_u}$, $\cancel{U(1)_d}$

U(1)-SU(3)-SU(3) anomaly!

- Formally, construct $n_{\Delta e}$ and set to zero (assuming initial $n_{\Delta e}$=0); in practice, set $g_e = 0$.
- u and d are indistiguisable under SU(3) (enter the same way in QCD sphalerons), set $Y_u = Y_d = 1/6$.

$$n_{\Delta i} = g_i \zeta_i \sum_{x,y} q_i^y J^{-1}_{yx} n_{\Delta x}$$

$$J^{-1} = \frac{1}{12\,(138 + 41 N_H)} \times \begin{pmatrix} 807 + 210 N_H & 12\,(5 - 2N_H) & 12\,(5 - 2N_H) & -222 \\ 12\,(5 - 2N_H) & 696 + 148 N_H & 4\,(15 - 2N_H) & -312 \\ 12\,(5 - 2N_H) & 16\,(9 - N_H) & 696 + 148 N_H & -312 \\ -222 & -312 & -312 & 492 \end{pmatrix}$$

SM: $N_H = 1$

Another example: The SM

Relate B to B-L

Define the vectors: $q_i^T \equiv (q_i^{B-L}, q_i^Q), \qquad n^T \equiv (n_{B-L}, n_{\Delta Q} = 0)$

- Example: assuming EW sphalerons decouple after EW phase transition i.e. consider the degrees of freedom in broken EW theory

Table 2
Similar to Table 1 but for field components after EWPT where we use subscript 'L' to denote the left-handed fields which participate in weak interaction.

$i =$	$U_{\alpha,L}$	$D_{\alpha,L}$	U_α	D_α	$\nu_{\alpha,L}$	$E_{\alpha,L}$	E_α	W^+	H'^+
$q_i^{\Delta_\alpha}$	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{9}$	-1	-1	-1	0	0
q_i^Q	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	-1	-1	1	1
q_i^B	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	0	0	0
q_i^L	0	0	0	0	1	1	1	0	0
g_i	3	3	3	3	1	1	1	3	$N_H - 1$

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- Example: assuming EW sphalerons decouple after EW phase transition i.e. consider the degrees of freedom in broken EW theory
- Consider all particles relativistic $\xi_i = 1(2)$, N_f fermion generations and N_H pairs of Higgs.

$$J^{-1} = \frac{1}{2N_f\left[24N_f + 13\left(2+N_H\right)\right]}\begin{pmatrix} 2\left(6+8N_f+3N_H\right) & -8N_f \\ -8N_f & 13N_f \end{pmatrix}$$

$$n_{\Delta B} = \frac{4\left(2+2N_f+N_H\right)}{24N_f + 13\left(2+N_H\right)} n_{\Delta(B-L)}$$

Result of **[Harvey & Turner (1990)]** but simpler derivation and easy to extend or generalize i.e. to consider mass threshold effects with ξ_i **[Inui et al. (1994)]**, **[Chung et al. (2008)]**

Intermission: some takeaways

- The use of *symmetry formalism* makes it clear from the outset that the asymmetries of all particles will depend only on the *Noether's charges*
- Type (i) reactions are implicitly taken into account without having to be referred to explicitly. Useful for more complicated models e.g. MSSM
- Type (ii) reactions → effective/exact symmetries: act as *preserver* or *messenger*
- Type (iii) reactons → quasi symmetries: the only ones that need to be solved *dynamically* for *quantitative* results
- Detection of (“fast”) B violation does not invalidate baryogensis but will be a source of B violation and points to new U(1)'s as *creator/preserver/messenger*

Shared Asymmetry Scenarios

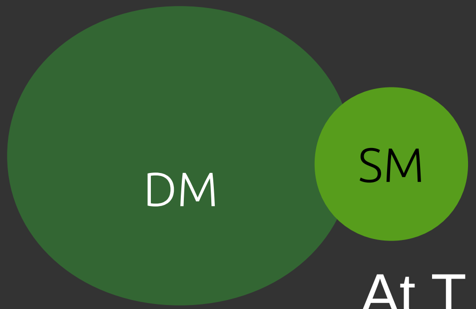
Sharing

- DM is not self-conjugate: X and $\bar{X}$ (complex scalar or Dirac fermion)
- X carries baryon and/or lepton number and *singlet* under the SM gauge group (can be electric charged neutral component of some SU(2) multiplet)
- Being ignorant about how an initial asymmetry is generated but they are shared among the two sectors through effective operator of the type

$$\frac{1}{\Lambda^{n-p}} X X \bar{\mathcal{O}}_{\rm SM}^{(n)}$$

p=1,2 for fermion, scalar

- X is stable



At T >> m_X

Sharing but not caring

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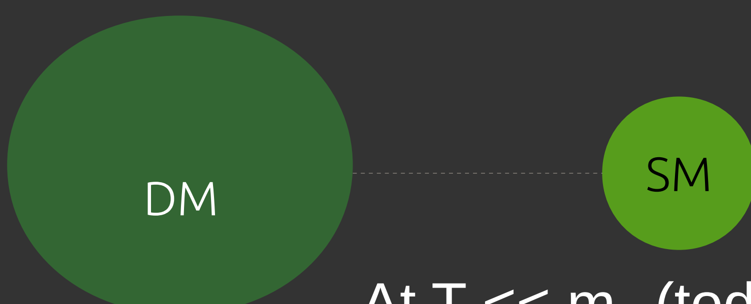
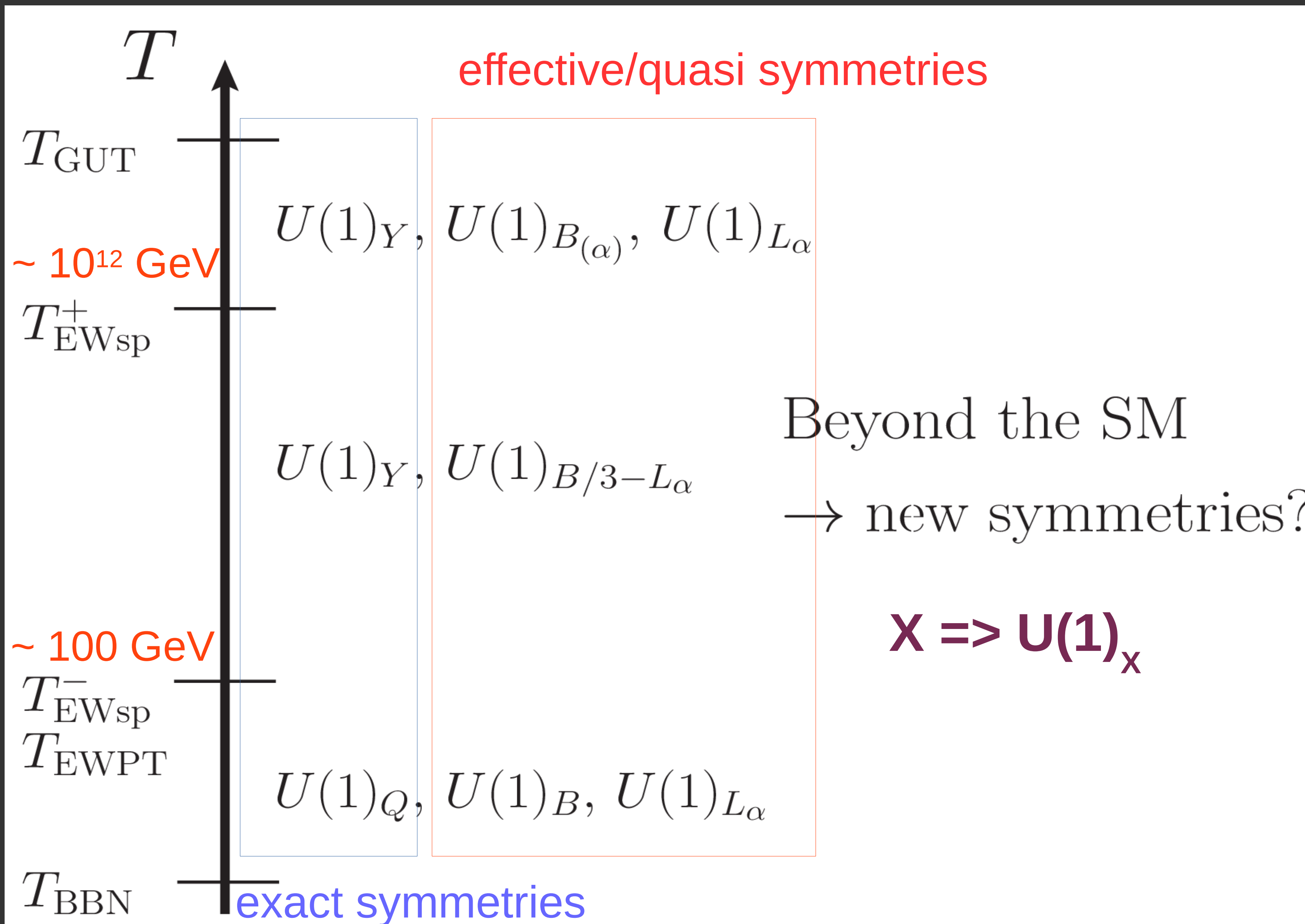


At T << m_X (today)

- X is stable
- The two sectors barely communicate

The SM + X



T
effective/quasi symmetries
T_{GUT}
$U(1)_Y$, $U(1)_{B_{(\alpha)}}$, $U(1)_{L_\alpha}$
~ 10^{12} GeV
T^+_{EWsp}
Beyond the SM
$\rightarrow$ new symmetries?
$U(1)_Y$, $U(1)_{B/3-L_\alpha}$
X => $U(1)_X$
~ 100 GeV
T^-_{EWsp}
T_{EWPT}
$U(1)_Q$, $U(1)_B$, $U(1)_{L_\alpha}$
T_{BBN}
exact symmetries

Some assumptions $\frac{1}{\Lambda^{n-p}} X X \bar{\mathcal{O}}^{(n)}_{\rm SM}$

- Assume $X\bar{X}$ annihilation is *fast* such that X is *maximally* asymmetric
  - unitarity bound m_X <~100 TeV
  - could give observable direct/detection signatures (model-dependent)
- If X carries B, $2m_X > m_n$ to avoid fast nucleon decay
- For simplicity, we assume couplings with only 1st family SM fermions => no charged lepton flavor violation

More assumptions $\frac{1}{\Lambda^{n-p}} X X \bar{\mathcal{O}}_{\rm SM}^{(n)}$

- Prior to the sharing, the B-L or B asymmetry is already fixed (by unspecified mechanism at higher scale)
  - **B-L** = B-L(X)+B-L(SM)

    $= |Y_{\Delta X}| + (78/29) Y_{\Delta B} = (5 m_n/m_X + 78/29) Y_{\Delta B}^{\rm obs}$
  - **B** = B(X)+B(SM)

    $= 1/2 |Y_{\Delta X}| + Y_{\Delta B} = (5/2 m_n/m_X + 1) Y_{\Delta B}^{\rm obs}$
- Assume the initial asymmetry either completely reside in the X or the SM sectors (irrelevant if the system achieve CE)

Possible SM operators $\frac{1}{\Lambda^{n-p}} X X \bar{\mathcal{O}}^{(n)}_{\rm SM}$

- Before EW sphalerons freeze out
  - The conserved charge is $B/3\text{-}L_\alpha$
  - The lowest dim one is of dim-5 (unique):

$$\mathcal{O}^{(5)}_{\alpha\beta} = \epsilon_{ik}\epsilon_{jl}\left(\ell^i_{L_\alpha}\ell^j_{L_\beta}\right) H^k H^l$$

[Weinberg (1979)], [Weinberg (1980)]

B(X)=0, L(X)=1

Possible SM operators $\frac{1}{\Lambda^{n-p}} X X \bar{\mathcal{O}}_{\rm SM}^{(n)}$

- After EW sphalerons freeze out
  - The conserved charges are B and L_α
  - The lowest dim ones are of dim-6:

$$\mathcal{O}^{(6)\rm I}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\epsilon_{ij}\left(q^{ia}_{L_\alpha}\ell^{j}_{L_\beta}\right)\left(d^{b}_{R_\delta}u^{c}_{R_\gamma}\right)$$

$$\mathcal{O}^{(6)\rm II}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\epsilon_{ij}\left(q^{ia}_{L_\alpha}q^{jb}_{L_\beta}\right)\left(u^{c}_{R_\delta}e_{R_\gamma}\right)$$

$$\mathcal{O}^{(6)\rm III}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\epsilon_{il}\epsilon_{jk}\left(q^{ai}_{L_\alpha}q^{jb}_{L_\beta}\right)\left(q^{kc}_{L_\delta}\ell^{l}_{L_\delta}\right)$$

$$\mathcal{O}^{(6)\rm IV}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\left(d^{a}_{R_\alpha}u^{b}_{R_\beta}\right)\left(u^{c}_{R_\delta}e_{R_\gamma}\right)$$

[Weinberg (1979)],
[Wilczek & Zee (1979)],
[Abbott & Wise (1980)]

B(X)=1/2, L(X)=1/2

Others are related by Fierz's reordering

We also impose $\Lambda > \langle H \rangle \equiv v = 174\ \mathrm{GeV}$ for consistency

$$\mathcal{O}^{(7)}_{\alpha\beta\delta\gamma} = \epsilon_{abc}\epsilon_{ij}\left(u^{a}_{R_\alpha}d^{b}_{R_\beta}\right)\left(\bar{\ell}^{i}_{L_\delta}d^{c}_{R_\gamma}\right)H^{j\dagger} \to \epsilon_{abc}\, v\left(u^{a}_{R_\alpha}d^{b}_{R_\beta}\right)\left(\bar{\nu}_{L_\delta}d^{c}_{R_\gamma}\right)$$

Analysis

- Assume EW phases transition happens when EW sphalerons freeze out
- We rewrite all the asymmetries in terms of Noether's charges and the Boltzmann equations for the sharing
- Once m_X is fixed, we can solve for Λ which gives the correct sharing
- With Λ determined, we can calculate the relevant *signatures*

$$\frac{1}{\Lambda^{n-p}} X X \bar{\mathcal{O}}^{(n)}_{\mathrm{SM}}$$

Boltzmann equations

Before EW sphalerons freeze out

$$\frac{n_{\Delta i}}{g_i \zeta_i} = c_i \left[n_{\Delta(B-L)} - (B-L)_X n_{\Delta X} \right]$$

$$sHz \frac{Y_{\Delta X}}{dz} = -2\gamma_{\ell\ell HH} \left[2 \frac{Y_{\Delta X}}{g_X \zeta_X Y_0} + \frac{22}{79} \left(\frac{Y_{\Delta(B-L)}}{Y_0} + \frac{Y_{\Delta X}}{Y_0} \right) \right]$$

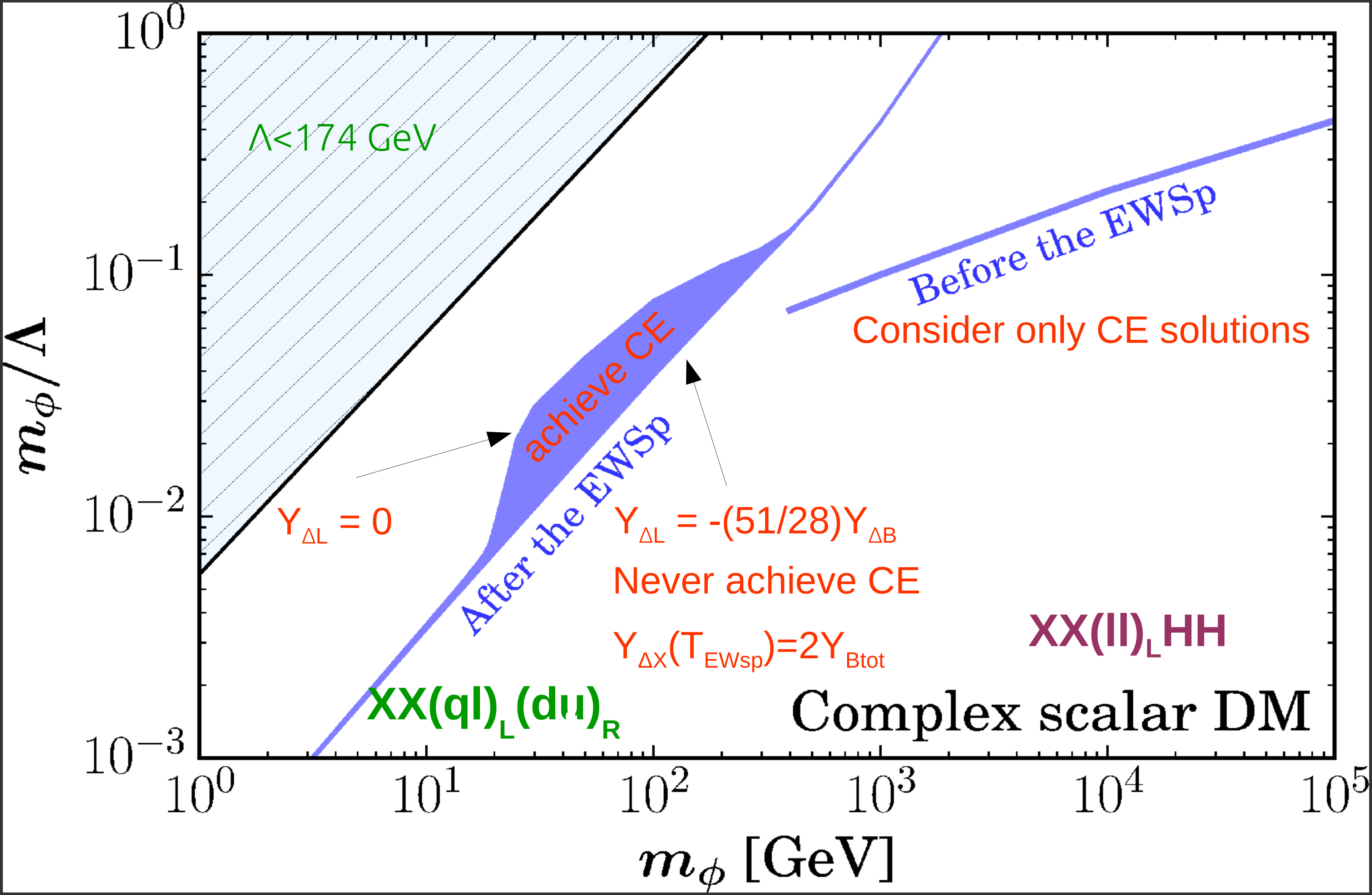
After EW sphalerons freeze out (*mass threshold effects*)

$$\frac{n_{\Delta i}}{g_i \zeta_i} = \frac{1}{c_0} \left[c_B^i n_{\Delta B} + c_L^i n_{\Delta L} - (B_X c_B^i + L_X c_L^i) n_{\Delta X} \right]$$

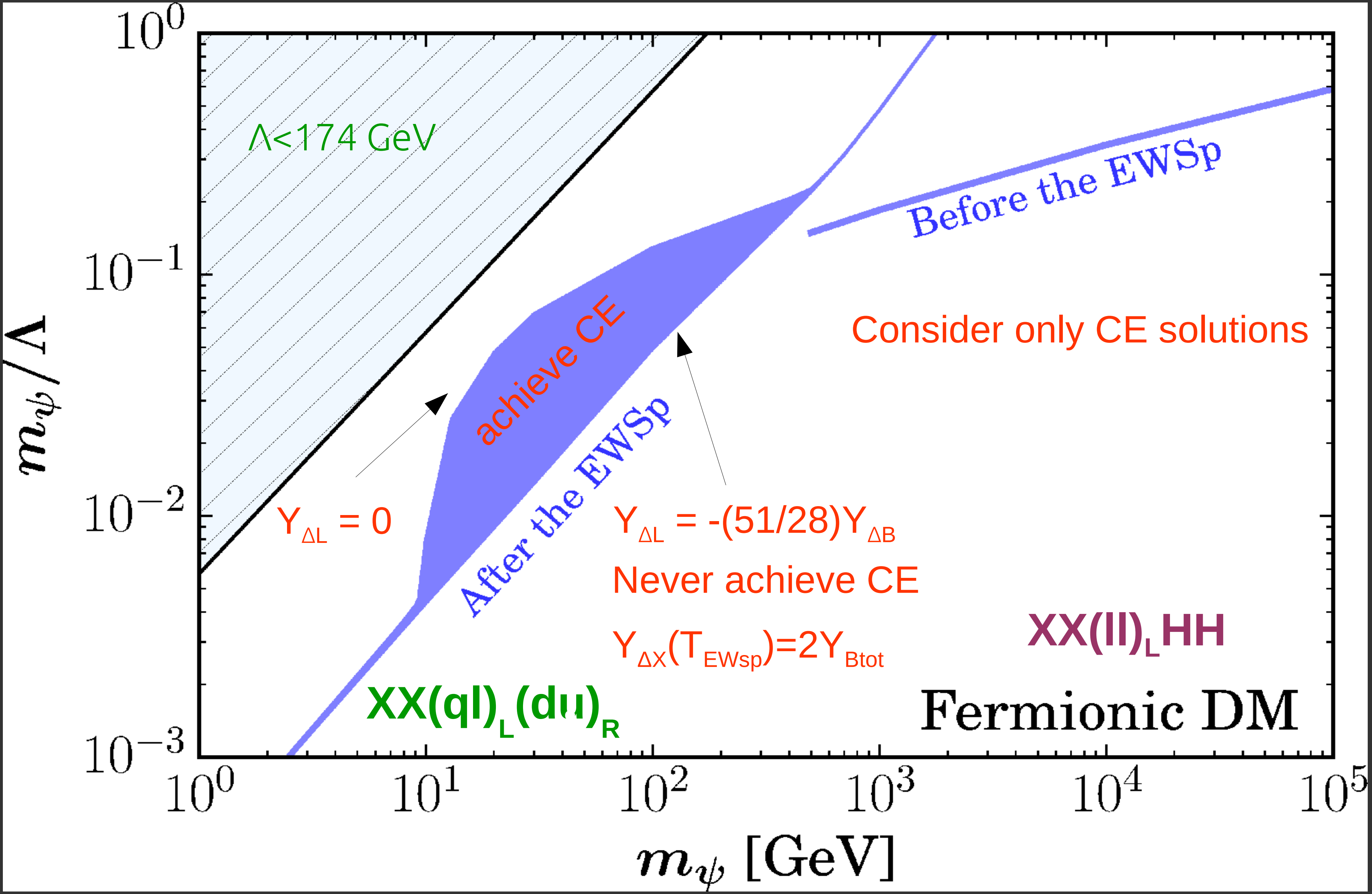
$$sHz \frac{Y_{\Delta X}}{dz} = -2\gamma_{qqq\ell} \left[2 \frac{Y_{\Delta X}}{g_X \zeta_X Y_0} - \frac{1}{c_0 Y_0} \left(c_B Y_{\Delta B} + c_L Y_{\Delta L} - \frac{1}{2}(c_B + c_L) Y_{\Delta X} \right) \right]$$

Temperature dependent

Complex scalar X



Dirac fermion X



Phenomenology

Collider signatures

$XX(ll)_L HH \Rightarrow e^- e^- \rightarrow W^- W^- \nu\, \nu$ or conjugate process

- Need large center of mass energy > $2(m_X + m_W)$
- No planned **$e^- e^-$** or **$e^+ e^+$** collider

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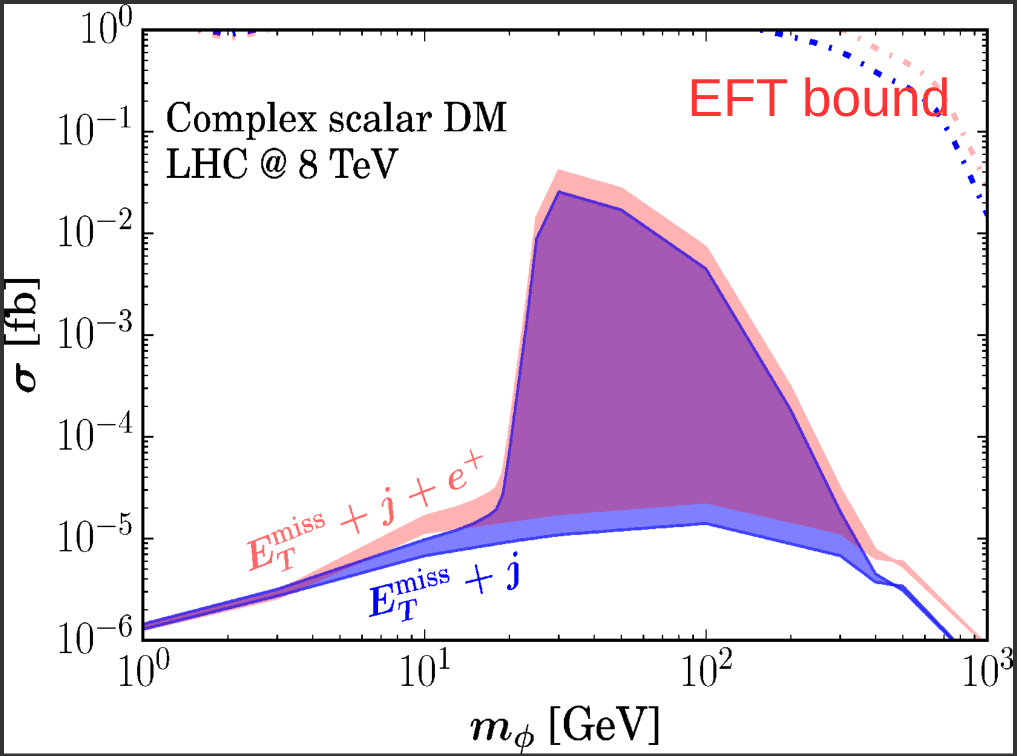
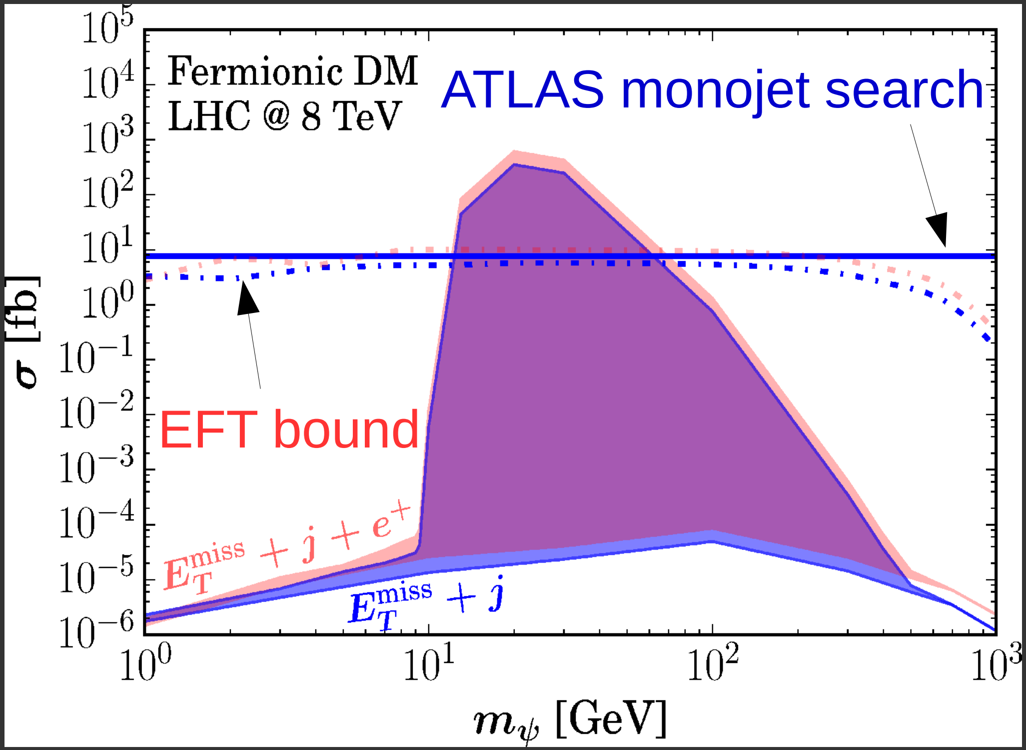
$XX(ql)_L(du)_R \Rightarrow pp \to j$ + missing; $pp \to j + e^+$ + missing

- Both signatures are correlated
- **$pp \to j + e^-$ + missing** very suppressed due to scarcity of antiquarks in the protons
- Due to the scaling at high energy $E \gg m_X$, $\sigma \sim E^{2(5-p)}/\Lambda^{2(6-p)}$, can be quite relevant for the collider searches (compared to indirect/direct searches)
- Have to be careful about when effective operator description breaks down

Collider signatures at LHC8

$XX(ql)_L(du)_R \Rightarrow pp \rightarrow j + \text{missing}; \; pp \rightarrow j + e^+ + \text{missing}$

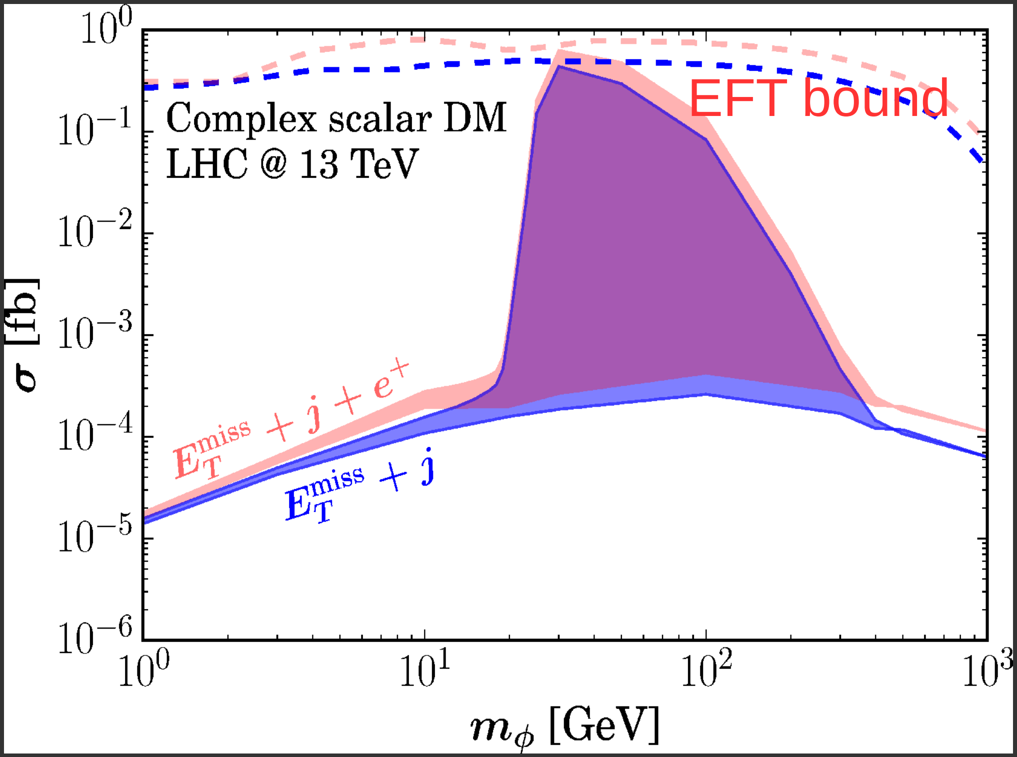


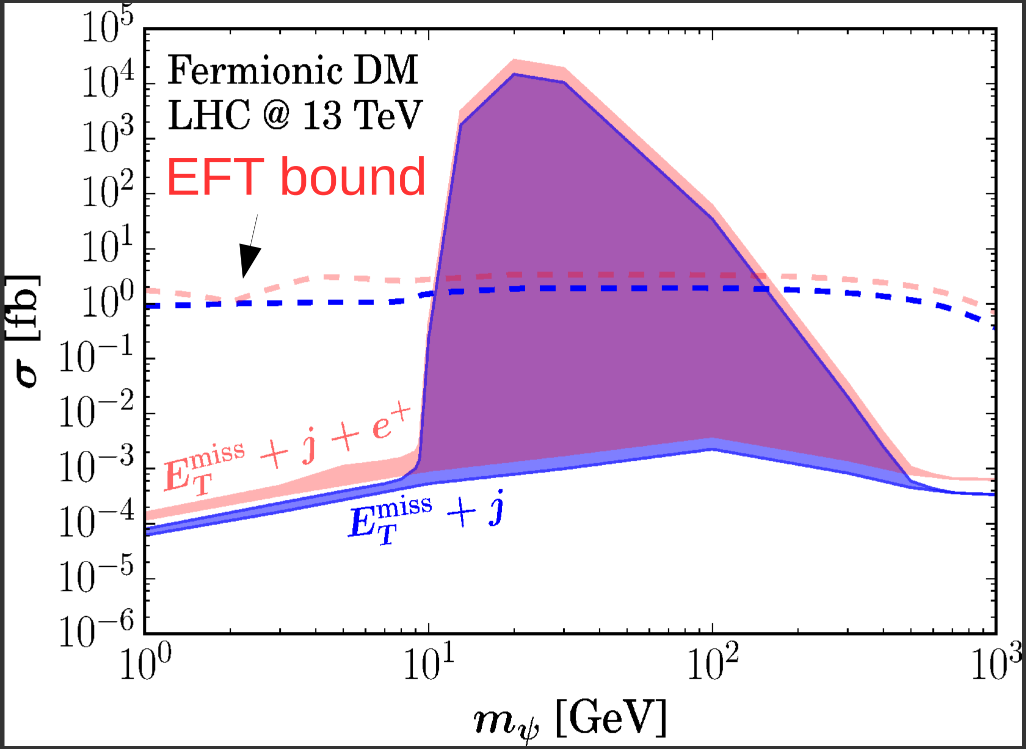


ATLAS estimated bound from monojet search cut on the quark E_T; detail analysis considering UV model with monolepton search [work in progress])

Collider signatures at LHC13

$XX(ql)_L(du)_R$ => pp → j + missing; pp → j + e^+ + missing





Indirect signatures

Although there are only X or $\bar{X}$ today, we can still have XX or $\overline{XX}$ annihilation signatures (positrons, gamma rays, neutrinos ...)

$XX(ll)_L HH$ => dominant one: $XX \rightarrow \nu\nu$

$XX(ql)_L(du)_R$ => $XX \rightarrow e^+$ + hadrons ...

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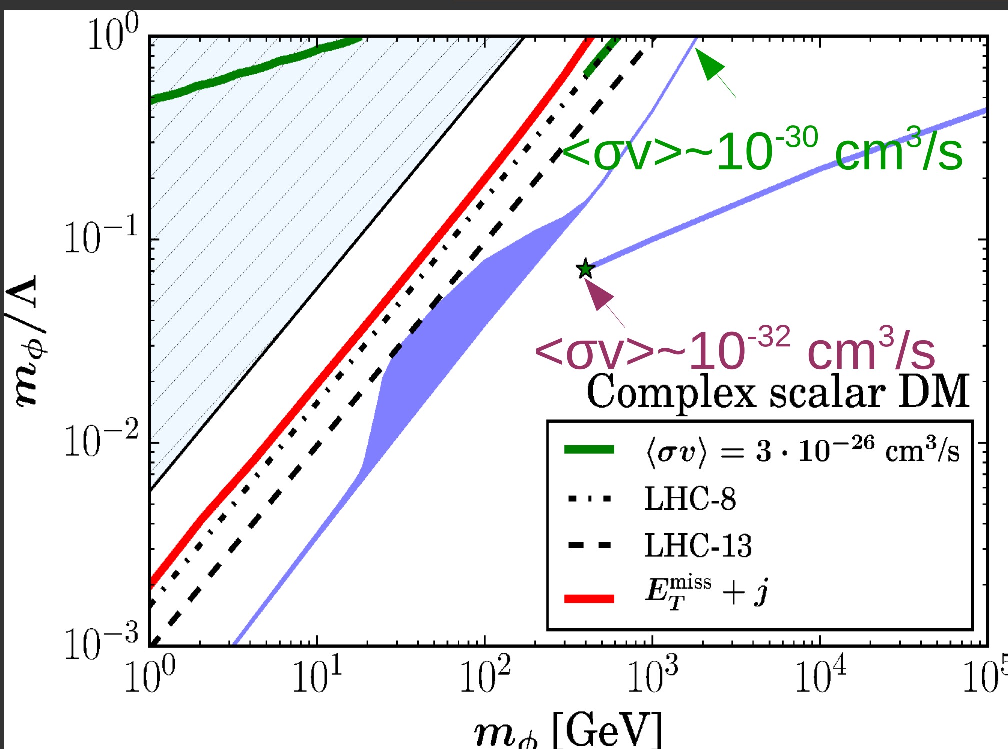

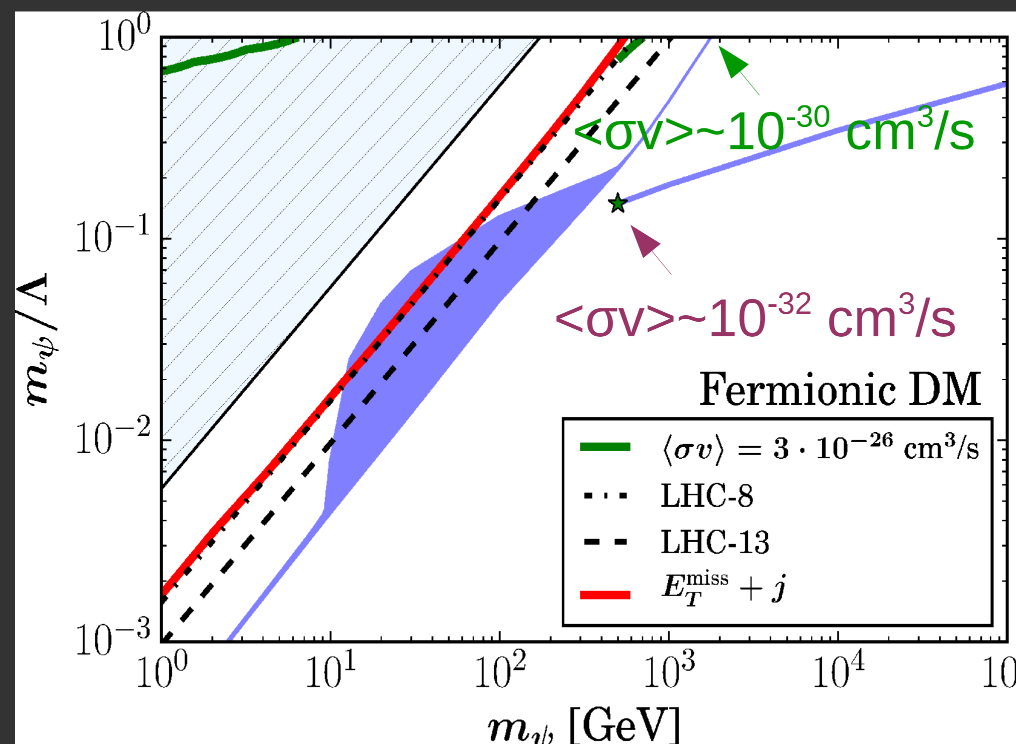

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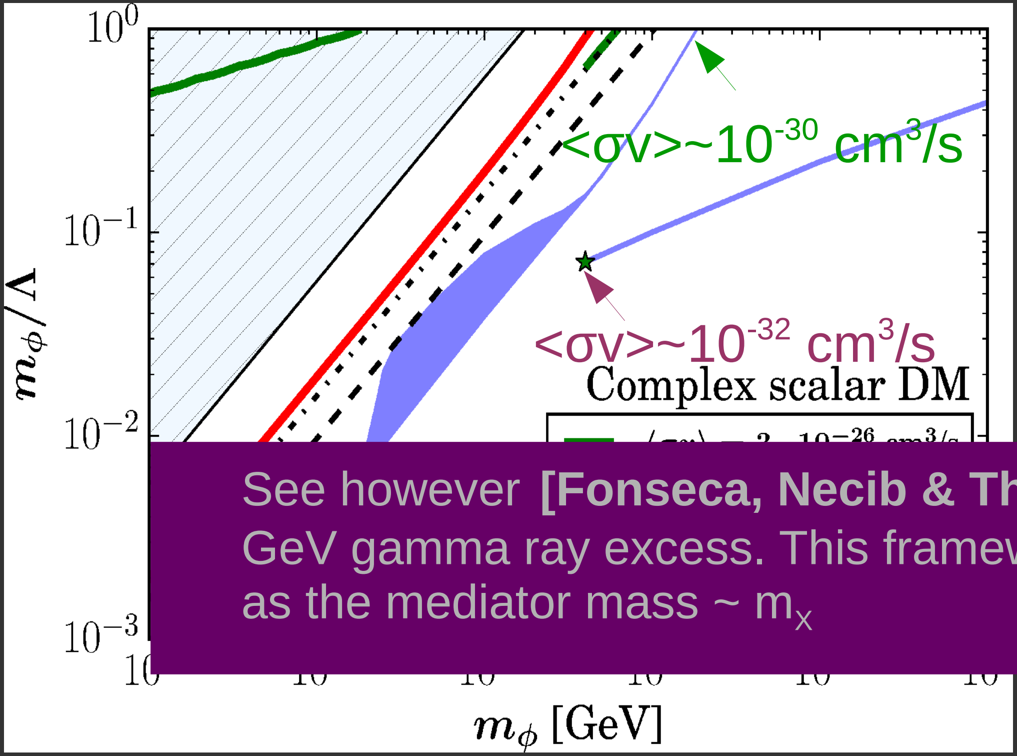

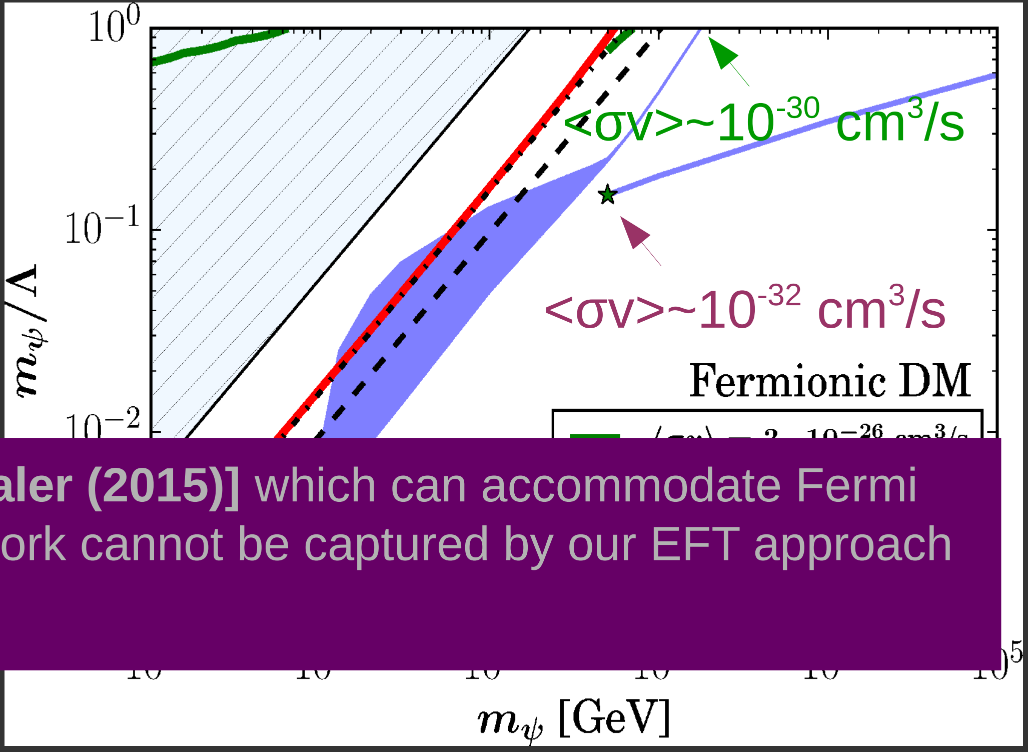

See however **[Fonseca, Necib & Thaler (2015)]** which can accommodate Fermi GeV gamma ray excess. This framework cannot be captured by our EFT approach as the mediator mass ~ m_X

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$XX(ll)_L HH \Rightarrow X + N \rightarrow \overline{X} + N + \nu + \nu$ through Higgs exchange

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for mx = 400(500) GeV for X scalar (fermion)

=> Well within “neutrino floor” **[Billard et al. (2014)]**

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In **[Davoudiasl et al. (2011)]**, hylogenesis generates equal in magnitude and opposite in sign asymmetry in the DM and SM sectors
=> can have IND
=> sharing operators cannot be in CE to avoid asymmetry washout

Remarks

- That the DM and the SM share an asymmetry in early time is an interesting possibility

$$\frac{1}{\Lambda^{n-p}} X X \bar{\mathcal{O}}_{\rm SM}^{(n)}$$

- Our EFT analysis
  - Asymmetry generation is complete prior to sharing
  - Today the DM is maximally asymmetric, unitarity bound m_X <~ 100 TeV
  - No induced nucleon decay signature
  - Due to steep energy dependence $\sigma \sim E^{2(5-p)}/\Lambda^{2(6-p)}$, although indirect and direct signatures are suppressed, LHC is already probing this scenario

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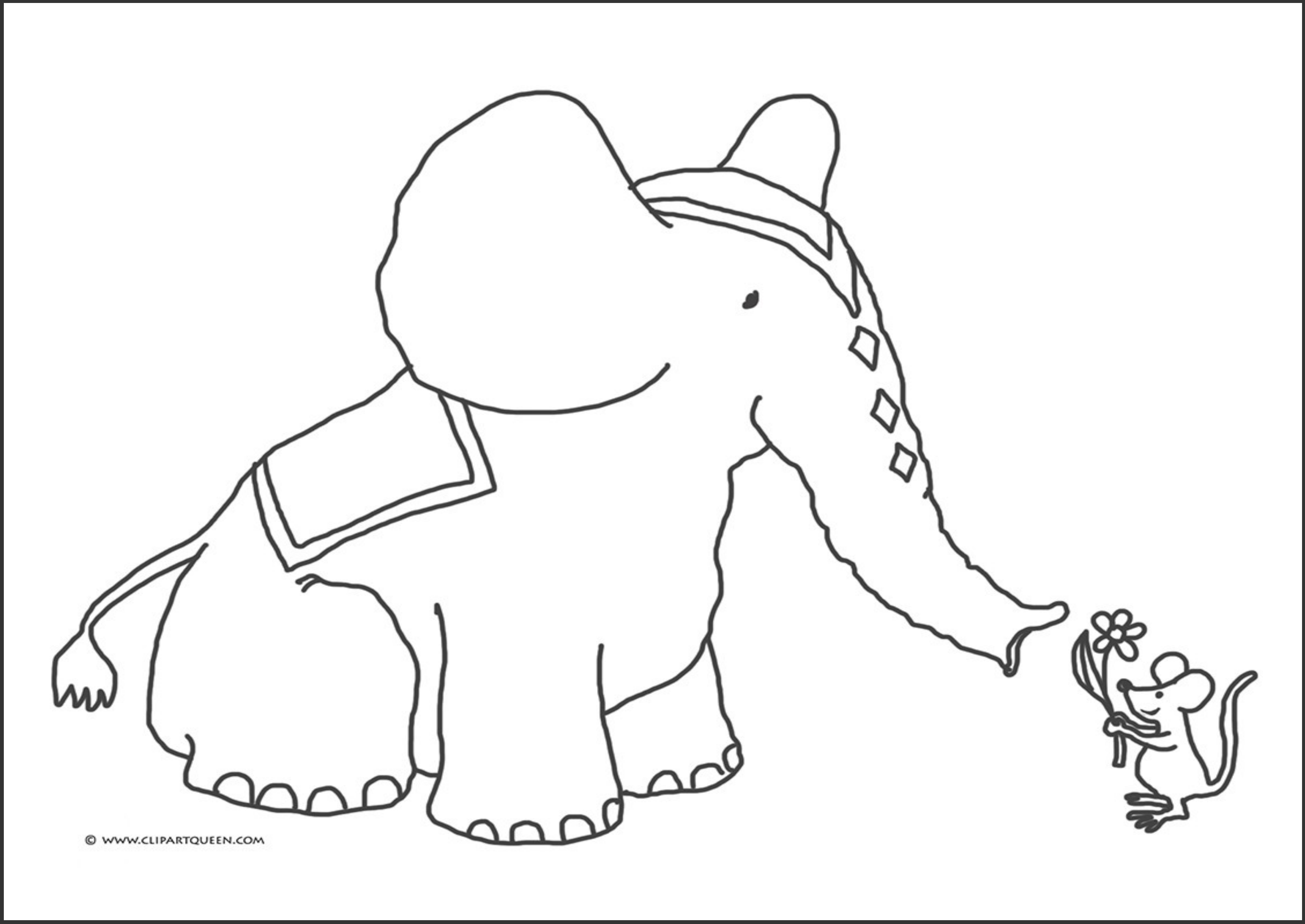
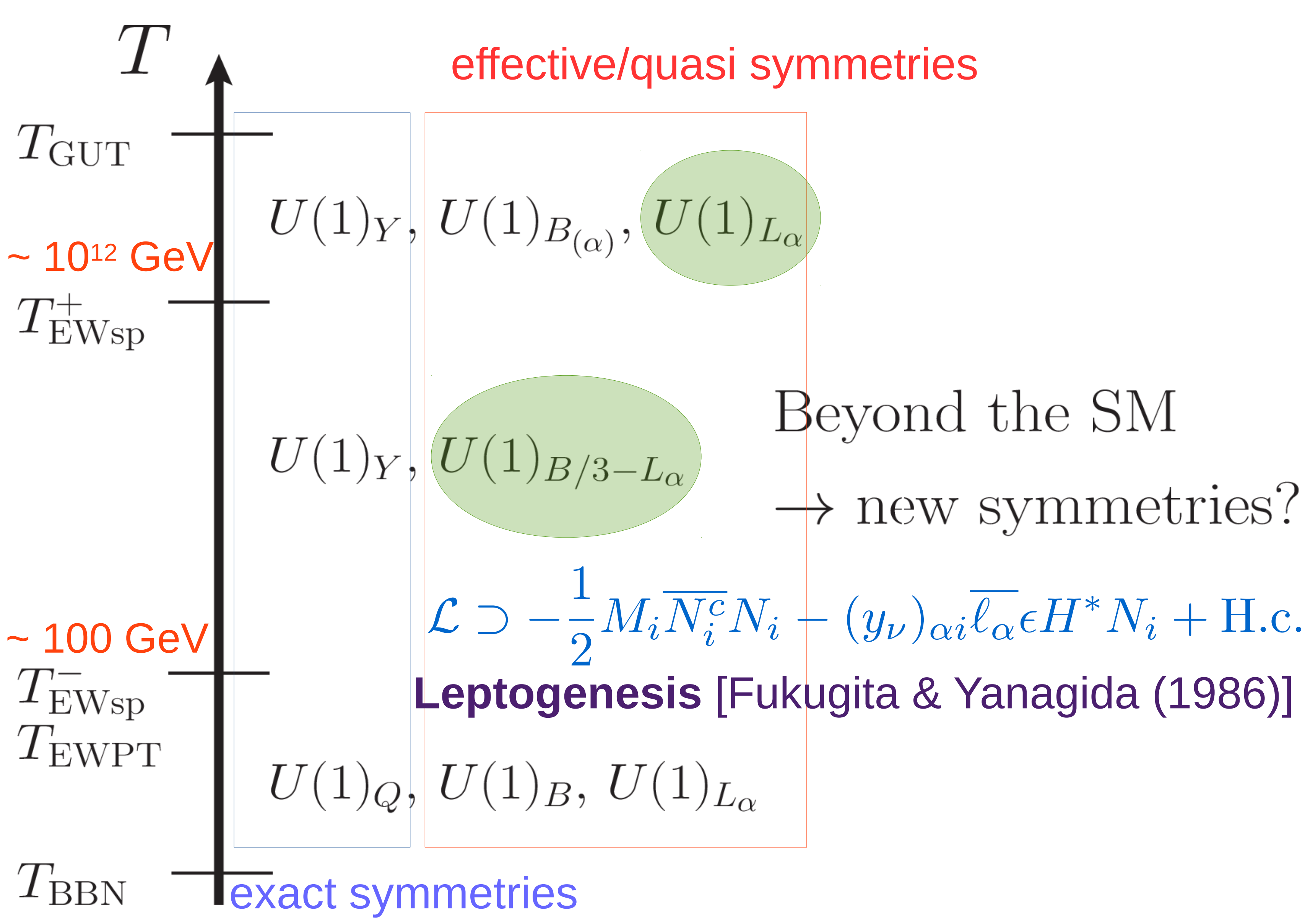
  - No induced nucleon decay signature
  - Due to steep energy dependence $\sigma \sim E^{2(5-p)}/\Lambda^{2(6-p)}$, although indirect and direct signatures are suppressed, LHC is already probing this scenario
- Caveat: EFT can fail at LHC energy and higher energy
- Resort to a UV model
  - Asymmetry generation
  - Reanalyze collider phenomenology

Thank you for your attention



Extra slides

Example: The SM



Example: The SM

Solve the system: Calculate J

Define the vectors: $q_i^T \equiv \left(q_i^{\Delta_\alpha}, q_i^Y\right), \quad n^T \equiv (n_{\Delta_\alpha}, n_{\Delta_Y})$

$$\Delta_\alpha \equiv B/3 - L_\alpha$$

At T ~ 10^4 GeV, all Yukawa interactions are in chemical eq.

Setting $n_{\Delta Y} = 0$, we obtain

$$J^{-1} = \frac{1}{3\,(198+39N_H)} \times \begin{pmatrix} 222+35N_H & 4\,(6-N_H) & 4\,(6-N_H) & -72 \\ 4\,(6-N_H) & 222+35N_H & 4\,(6-N_H) & -72 \\ 4\,(6-N_H) & 4\,(6-N_H) & 222+35N_H & -72 \\ -72 & -72 & -72 & 117 \end{pmatrix}$$

SM: $N_H = 1$

Equivalently, we can use the second formalism by constructing reduced matrix of 3 x 3 $\bar{J}$

Another example: The SM

Relate B to B-L

Define the vectors: $q_i^T \equiv (q_i^{B-L}, q_i^Y), \quad n^T \equiv (n_{B-L}, n_{\Delta Y} = 0)$

- Assuming EW sphalerons decouple before EW phase transition (EWPT) i.e. consider the degrees of freedom in unbroken EW
- Consider all particles relativistic $\xi_i = 1(2)$, N_f fermion generations and N_H pairs of Higgs.

$$J^{-1} = \frac{1}{N_f (N_f + 13N_H)} \begin{pmatrix} 10N_f + 3N_H & -8N_f \\ -8N_f & 13N_f \end{pmatrix}$$

$$n_{\Delta B} = \frac{4(2N_f + N_H)}{22N_f + 13N_H} n_{\Delta(B-L)}$$

Result of [Harvey & Turner (1990)] but simpler derivation and easy to extend or generalize i.e. to consider mass threshold effects with ξ_i [Inui et al. (1994), Chung et al. (2008)])

Example 2: The MSSM

- The superpotential

$$W = \mu_H H_u \epsilon H_d + (y_u)_{\alpha\beta} Q_\alpha \epsilon H_u U^c_\beta + (y_d)_{\alpha\beta} Q_\alpha \epsilon H_d D^c_\beta + (y_e)_{\alpha\beta} \ell_\alpha \epsilon H_d E^c_\beta$$

- Besides $U(1)_Y$, $U(1)_{(B-L)\alpha}$, we have an *R-symmetry* e.g.

  $$q^R(H_d) = q^R(\ell_\alpha) = q^R(U^c_\alpha) = -q^R(E^c_\alpha) = 2$$

- This remains also with *R-parity violating* terms as well as *type-I seesaw* with $q^R(N_i^c) = 0$

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Contruct <u>*anomaly-free*</u> charge:

$$\bar{R} \equiv R + \frac{2}{3c_{BL}}(c_B B + c_L L), \quad c_{BL} \equiv c_B + c_L$$

Example 2: The MSSM

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$$\Gamma_R \sim m_{\tilde{g}}^2/T, \quad \Gamma_R < H \implies T \gtrsim 8 \times 10^7 \left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^{2/3} \mathrm{GeV}$$

[Ibanez & Quevedo (1992)]

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e.g. $-q^{PQ}(Q_\alpha) = q^{PQ}(\ell_\alpha) = q^{PQ}(H_u) = q^{PQ}(H_d) = 1,\ q^R(E_\alpha^c) = -2$

- Anomalies: $A_{PQ22} = -N_f + N_H$, $A_{PQ33} = -N_f$

With $N_f=3$, $N_H=1$, contruct A_{PQ22} anomaly-free charge:

$$\bar{P} \equiv \frac{3}{4} c_{BL} PQ + c_B B + c_L L, \quad c_{BL} \equiv c_B + c_L$$

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With $N_f=3$, $N_H=1$, contruct A_{PQ22} *anomaly-free* charge:

We still have to cancel A_{PQ33}!

$$\bar{P} \equiv \frac{3}{4} c_{BL} PQ + c_B B + c_L L, \quad c_{BL} \equiv c_B + c_L$$

Example 2: The MSSM

- We can make use of quark chiral symmetry discussed earlier. E.g. at T >> 10^6 GeV, up quark Yukawa interactions are out-of-equilibrium: $y_u \to 0$, gain anomalous $U(1)_u$
- <u>Anomaly-free</u> charge

$$\bar{\chi}_{u^c} \equiv \bar{P} + \frac{9}{2} c_{BL} u^c / q^{u^c}$$

$i =$	Q_a	U_a^c	D_a^c	ℓ_α	E_α^c	H_u	H_d
$q_i^{\Delta_\alpha}$	$\frac{1}{9}$	$-\frac{1}{9}$	$-\frac{1}{9}$	-1	1	0	0
q_i^Y	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	$\frac{1}{2}$	$-\frac{1}{2}$
$q_i^{\overline{R}}$	$\frac{2c_B}{9c_{BL}}$	$2-\frac{2c_B}{9c_{BL}}$	$-\frac{2c_B}{9c_{BL}}$	$2+\frac{2c_L}{3c_{BL}}$	$-2-\frac{2c_L}{3c_{BL}}$	0	2
$q_i^{\overline{P}}$	$\frac{c_B}{3}-\frac{3c_{BL}}{4}$	$-\frac{c_B}{3}$	$-\frac{c_B}{3}$	$c_L+\frac{3c_{BL}}{4}$	$-c_L-\frac{3c_{BL}}{2}$	$\frac{3c_{BL}}{4}$	$\frac{3c_{BL}}{4}$
q_i^B	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	0	0	0
q_i^L	0	0	0	1	-1	0	0
q_i^{PQ}	-1	0	0	1	-2	1	1
q_i^R	0	2	0	2	-2	0	2
g_i	3×2	3	3	2	1	2	2

Table 3: The $U(1)$ charges of left-handed chiral superfields. All gauginos $\widetilde{G}$, $\widetilde{W}$ and $\widetilde{B}$ have both R and $\overline{R}$ charges equal 1. Since all fermions in chiral superfields have R charges one less than that of bosons i.e. $R\,(\text{fermion}) = R\,(\text{boson}) - 1$, the differences between number density asymmetries of bosons and fermions are equal to that of gauginos.

Example 2: The MSSM

- We can make use of quark chiral symmetry discussed earlier. E.g. at T >> 10^6 GeV, up quark Yukawa interactions are out-of-equilibrium: $y_u \to 0$, gain anomalous $U(1)_u$
- Anomaly-free charge

$$\bar{\chi}_{u^c} \equiv \bar{P} + \frac{9}{2} c_{BL} u^c / q^{u^c}$$

- Several comments:
  - c_B and c_L can be chosen at will as is convenient e.g. consider a model with $\mathcal{O}_B = U^c_\alpha D^c_\beta D^c_\delta$, choose c_B=0, $c_L \neq 0$ such that $\bar{R}$ and $\bar{P}$ are conserved by $\mathcal{O}_B$
  - Choosing c_B=c_L, the results are in *disagreement* with [Ibanez & Quevedo (1992)] due to sign error of gaugino chem. potential (could be avoided)
  - Effects of R-symmetry in supersymmetric leptogenesis (O(1) effect) [CSF, Gonzalez-Garcia, Nardi & Racker (2010)] and soft leptogenesis (O(100) effect) [CSF, Gonzalez-Garcia & Nardi (2011)]