PASCOS 2022: **S.M.A.S.H.E.D.**
Standard Model Axion Seesaw Higgs Inflation Extended for Dirac Neutrinos

based on **2207.08142**

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bctp

S.M.A.S.H.[1]

- **SM**: self explanatory...
- **A**xion:
  - strong $\not{C}\not{P}$ via $U(1)_{PQ}$
  - cold **DM** candidate
- **S**eesaw mechanism:
  - heavy N for Majorana m_ν
  - baryogenesis via leptogenesis
- **H**iggs-portal inflation:
  - $T_{RH} \simeq 10^9$ GeV
  - complete therm. history

A single new scale

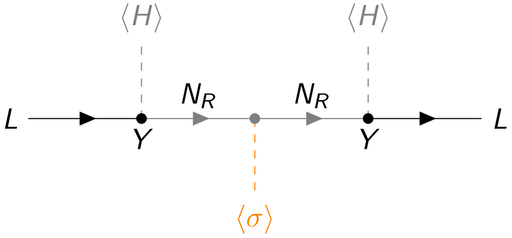
PQ breaking scale v_σ

$=$ axion decay constant f_a

$=$ Seesaw mass scale M

[1] *(Ballesteros, Redondo, Ringwald 2016)*

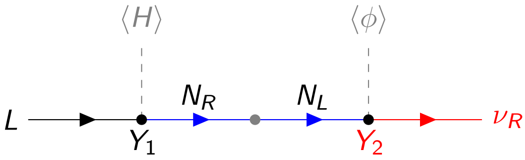
Type I Seesaw: Majorana vs. Dirac



$$m_\nu^{\text{Maj.}} \sim \frac{v_H^2}{M} \sim \frac{v_H^2}{v_\sigma}$$

(Yanagida 1979 et al.)

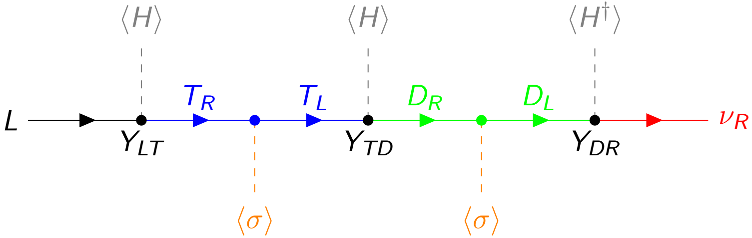
all N : SM singlets



$$m_\nu^{\text{Dir.}} \sim \frac{v_H v_\phi}{M} \sim \begin{cases} \frac{v_H v_\phi}{v_\sigma} \\ \frac{v_H v_\sigma}{M} \end{cases}$$

(Roncadelli, Wyler 1983)

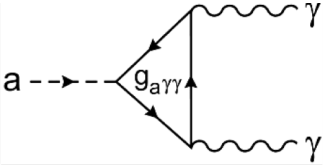
Dimension 6 Dirac Seesaw



$$T_{L,R} \sim (1,3,0), \quad D_{L,R} \sim (1,2,1/2), \quad M_T, M_D < 10^9 \text{ GeV}$$

$$m_\nu \sim Y_{LT} Y_{TD} Y_{DR} \frac{v_H^3}{M_T M_D} \sim \frac{v_H^3}{v_\sigma^2}$$

Axion Pheno in S.M.A.S.H.E.D. (1)



source: *2106.03424*

3 gens. of T and D in loops:

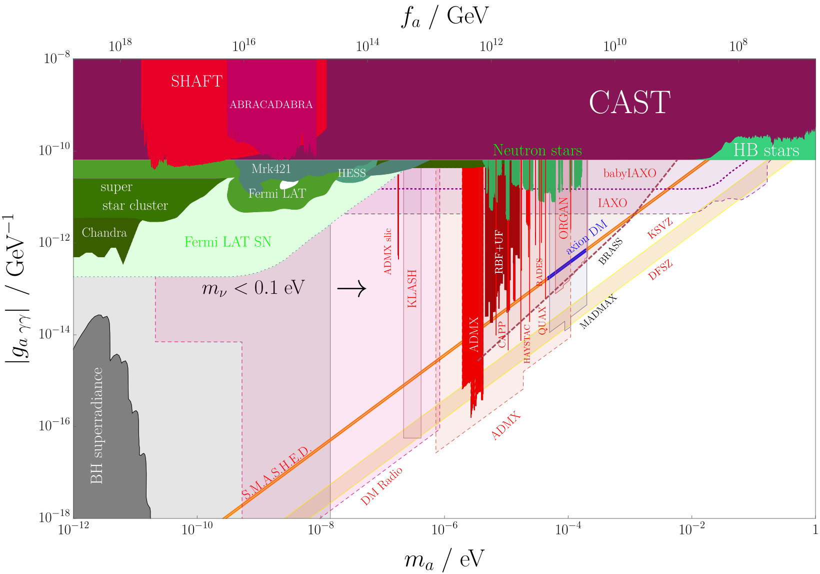
- QCD:
  $N = \sum_f (\chi_{f_L} - \chi_{f_R}) t(f)$,
- QED:
  $E = \sum_f (\chi_{f_L} - \chi_{f_R}) Q_{EM}(f)^2$

Axion to photon coupling:

$$g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$$

- KSVZ, DFSZ: $E/N = 2/3,\ 8/3$
- S.M.A.S.H.E.D: $E/N = 18 + 2/3,\ 18 + 8/3$

Axion pheno in S.M.A.S.H.E.D.[2] (2)

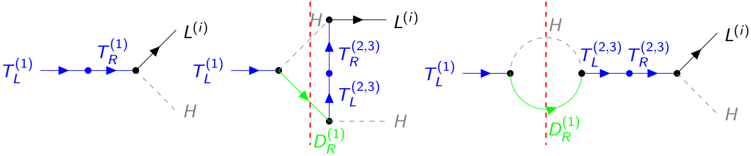


[2] limits from C. O'hare at https://cajohare.github.io/AxionLimits/

Dirac Leptogenesis[3] in S.M.A.S.H.E.D.

$$\frac{n_B - n_{\overline{B}}}{s} \simeq \kappa \cdot \varepsilon_L \cdot \underbrace{c_{sph}}_{\simeq 0.37} \cdot \underbrace{\frac{n_T + n_{\overline{T}}}{s}}_{\text{no. of } T \text{ and } \overline{T}} \stackrel{!}{=} 10^{-10}$$

- κ: efficiency from **Boltzmann equations**
  - larger κ for **Dirac-T**
- ε_L: CP violating asymmetry from **decays** $\downarrow$
  - larger due to **dim. 6** m_ν



3 *(Dick, Lindner, Ratz, Wright 1999)*

Summary

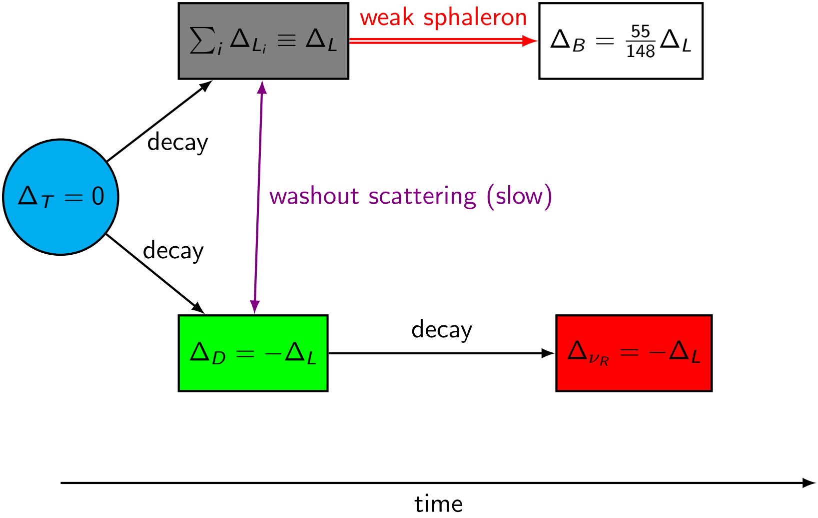
- extended S.M.A.S.H. for Dirac ν without spoiling anything (so far...)
- **dimension 6** operator for m_ν
- $|g_{a\gamma\gamma}|$ enhanced by **one order of magnitude**
- dark radiation $\Delta N_{\text{eff.}} \simeq 0.142\ (3\ \nu_R) + 0.027\ (\text{axion}) \simeq 0.17$
- Dirac Leptogenesis with larger κ & ε_L

$\Rightarrow$ Don't dismiss Dirac neutrinos!

Appendix

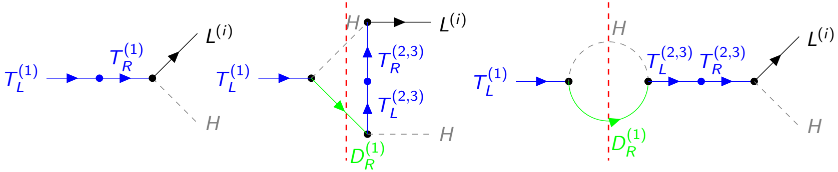
Here be dragons

Dirac Leptogenesis in S.M.A.S.H.E.D. (2)[4]



[4] $\Delta_\psi \equiv (n_\psi - n_{\overline{\psi}})/s$ with s the entropy density

Dirac Leptogenesis in S.M.A.S.H.E.D. (3)



- **Enhancement** of ε_L:
  - Type III Seesaw *(Davidson, Ibarra 2002)*:
    $\varepsilon_L < 3 \times 10^{-9} \cdot \left(\frac{M_T}{10^8\text{ GeV}}\right) \cdot \left(\frac{m_\nu}{0.1\text{ eV}}\right) \quad \Rightarrow \quad M_T \gtrsim 1.5 \times 10^{10}\text{ GeV}$
  - S.M.A.S.H.E.D.:
    $\varepsilon_L < 3 \times 10^{-3} \cdot \left(\frac{M_T}{10^8\text{ GeV}}\right) \cdot \left(\frac{m^{\text{eff.}}}{100\text{ keV}}\right)$
  - $m_\nu = Y_{LT} Y_{TD} Y_{DR} v_H^3 / (M_T^{(2,3)} M_D^{(2,3)})$
  - $m^{\text{eff.}} = Y_{LT} Y_{TD} v_H^2 / M_T^{(2,3)}$ missing $\sim Y_{DR} v_H / M_D^{(2,3)}$ b.c. no ν_R