

# Light particles with baryon and lepton numbers

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Based on arXiv:2009.01256 (PLB 2021)



# Particles beyond the SM

- *Heavy* new particles are captured in SMEFT, no matter their quantum numbers.
- *Light* new particles  $\varphi$  require new EFT of **SM +  $\varphi$** .
- Need to know the quantum numbers of  $\varphi$ !
  - For  $m_\varphi$  at or below GeV:  $\varphi$  is **neutral** under  $U(1)\times SU(3)$ .
  - Spin 0: light scalar or pseudoscalar (ALP EFT).
  - Spin  $\frac{1}{2}$ : sterile neutrino.
  - Spin 1: dark photon or coupled to  $B/L_\alpha$  currents.

Can  $\varphi$  carry **global** symmetries?

# Global symmetries

- Simplest case:  $\varphi$  carries a  $Z_N$  or dark  $U(1)$  or  $SU(N)$ .
  - EFT operators factorize:  $|\varphi|^2 \times$  (SMEFT operator),...
  - Exhaustively discussed as (light) dark matter.

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  - EFT operators factorize:  $|\varphi|^2 \times$  (SMEFT operator), ...
  - Exhaustively discussed as (light) dark matter.
- ~ final possibility:  $\varphi$  carries baryon/lepton number:
  - Fermion  $N$  with  $L = 1$ :  $\bar{L}HN$  coupling, mixing with neutrinos  $\Rightarrow$  sterile neutrino.  
[recent collection of constraints: Bolton, Deppisch and Dev, 1912.03058]
  - Fermion  $\chi$  with  $B = 1$ : EFT coupling to e.g.  $\bar{\chi}udd/\Lambda^2$ , mixing with neutral baryons  $\Rightarrow$  sterile neutron.  
[popular for neutron decay anomaly, e.g. Fornal & Grinstein, 2007.13931]

# Sterile neutron: fermion with B=1

- Effective Lagrangian:

$$\mathcal{L}_\chi = \bar{\chi}(i\not{\partial} - m_\chi)\chi + \left( \frac{u_i d_j d_k \chi_L^c}{\Lambda_{ijk}^2} + \frac{Q_i Q_j d_k \chi_L^c}{\tilde{\Lambda}_{ijk}^2} + \text{h.c.} \right)$$

- For  $m_\chi \lesssim m_n$ , one has search channels

- $n \rightarrow \chi \gamma$ , [Davoudiasl, PRL '15; Fornal & Grinstein, 1801.01124]
- hydrogen  $\rightarrow \chi \nu$ , [Berezhiani, 1812.11089; McKeen & Pospelov, 2003.02270; McKeen, Pospelov, Raj, 2006.15140 & 2012.09865]
- $p \rightarrow \chi e^+ \nu$ , [McKeen, Pospelov, Raj, 2006.15140 & 2012.09865]
- $n \rightarrow \pi^0 \chi$ ,  $p \rightarrow \pi^+ \chi$ , [Davoudiasl, PRD '13 & PRL '15; Helo et al, 1803.00035]
- The latter probe  $\Lambda_{\text{udd}} < 10^{15}$  GeV if  $m_\chi \sim 0$ .
- All couplings  $\Lambda_{ijk}$  lead to these channels at loop level!

- Notice that  $\chi$  is stable here and thus (asymmetric) DM.

See talk by N. Raj!

# Sterile neutron: fermion with B=1

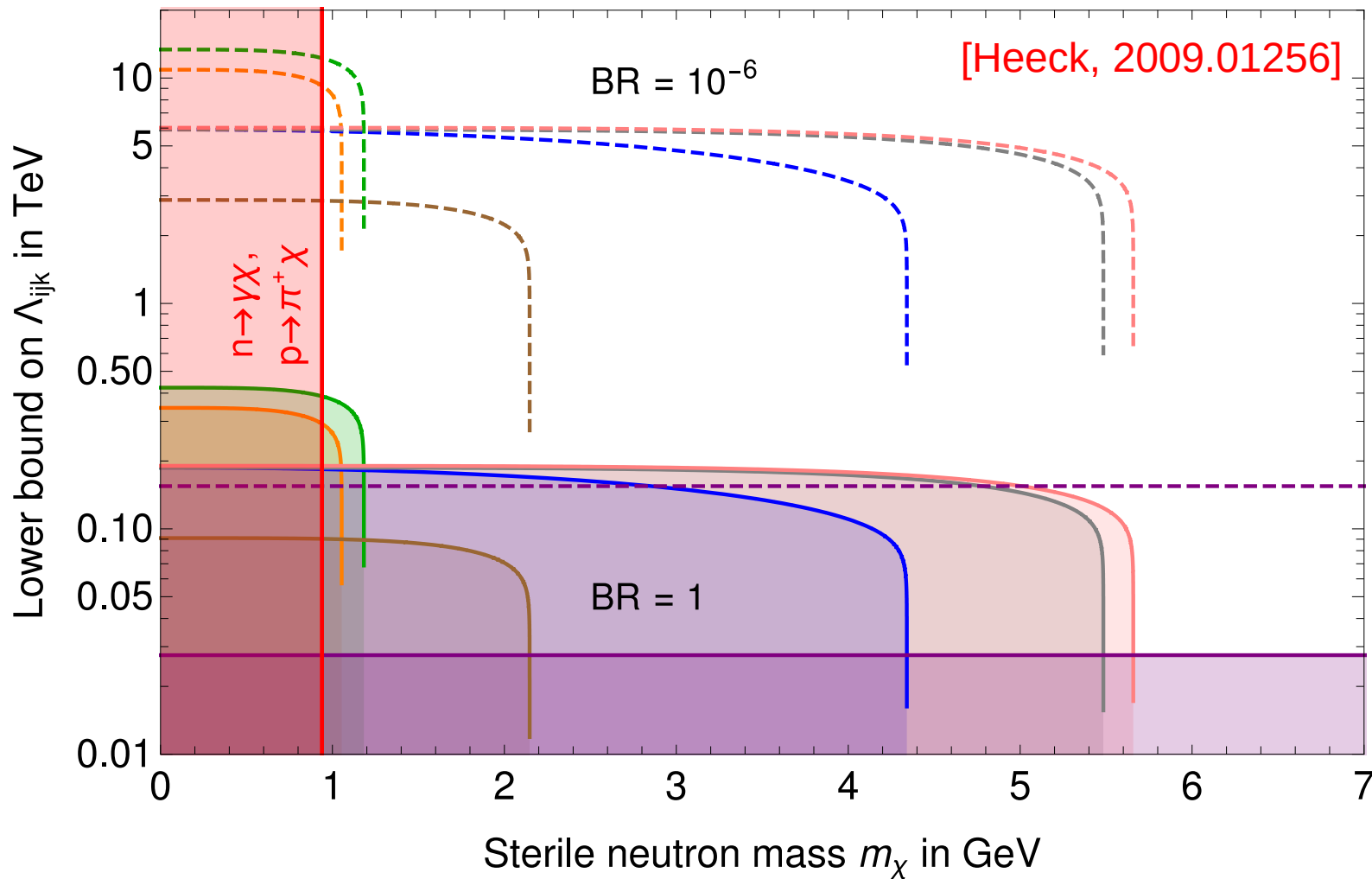
- For  $m_\chi > m_n$ , no more proton/neutron decays.
- Still possible to look for rare decays in b/c/ $\tau$  factories via

$$\text{baryon} \rightarrow \text{meson} + \chi$$

$$\text{meson} \rightarrow \text{baryon} + \bar{\chi}$$

- Requires  $\chi$  coupling to 2<sup>nd</sup>/3<sup>rd</sup> gen quarks. [Nelson++, PRD '17 & '19]
- Matrix elements  $\langle \text{baryon} | \text{qqq} | \text{meson} \rangle$  unknown.
- $\chi$  is **unstable**, but typically leaves detector; mimics baryon-number violating decays!

New signatures to look for!



Dedicated analyses required to obtain sensitivity, but

LHCb already has  $10^{14}$   $\Sigma^+$ ; HyperCP has  $10^9$   $\Xi^-$ .

$\Lambda_c$  abundantly produced at Belle II, BESIII, LHCb.

Belle II will collect  $5 \times 10^{10}$  B-meson decays.

# Global symmetries for scalars

- ~final possibility: scalar  $\phi$  carries baryon/lepton number:
  - $\delta$  with  $L = 2$ : EFT coupling to Weinberg op.  $\delta(\bar{L}H)^2/\Lambda^2$ .  
[Berryman et al, 1802.00009; De Gouvêa et al, 1910.01132]
  - $\phi$  with  $B = L = 1$ : EFT coupling  $\bar{\phi}QQQL/\Lambda^3$ ,  
=> sterile leptoquark.  
[McKeen & Pospelov, 2003.02270]
  - $\xi$  with  $B = 2$ : EFT coupling  $\bar{\xi}(udd)^2/\Lambda^6$ .
- Assume that scalars don't get VEVs.



# Sterile leptoquark: scalar with B=L=1

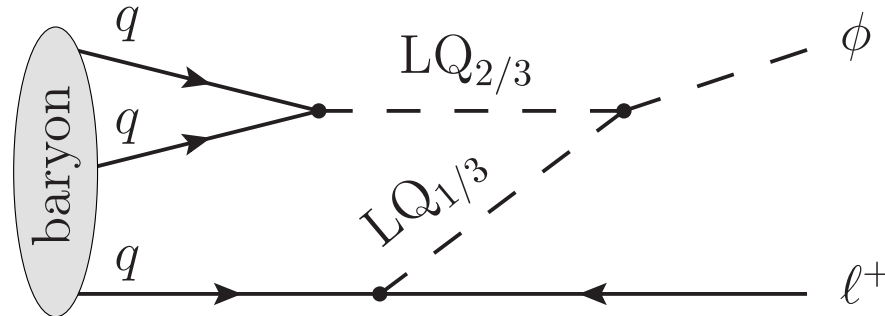
- Effective Lagrangian for SM +  $\phi$ :

$$\mathcal{L}_\phi = |\partial\phi|^2 - m_\phi^2 |\phi|^2 + \left( \frac{d_i u_j u_k \ell_l \phi^*}{\Lambda_{ijkl}^3} + \frac{d_i u_j Q_k L_l \phi^*}{\tilde{\Lambda}_{ijkl}^3} + \frac{Q_i Q_j u_k \ell_l \phi^*}{\Lambda_{ijkl}^{\prime 3}} + \frac{Q_i Q_j Q_k L_l \phi^*}{\tilde{\Lambda}_{ijkl}^{\prime 3}} + \text{hc} \right)$$

- Further restriction possible by assigning lepton flavor.

- Low energy:  $\frac{\Lambda_{\text{QCD}}^3}{\Lambda_{\text{udde}}^3} p e \phi^* + \dots$

- Possible UV completion with **leptoquarks**:



# Sterile leptoquark: scalar with $B=L=1$

- For  $m_\phi < m_n$ , we have

$$n \rightarrow \phi \nu$$

for all  $\Lambda_{ijkl}$  indices!

$$\text{For lighter } \phi: p \rightarrow \phi \ell^+$$

[for  $m_\phi = 0$ : Super-K, PRL '15]

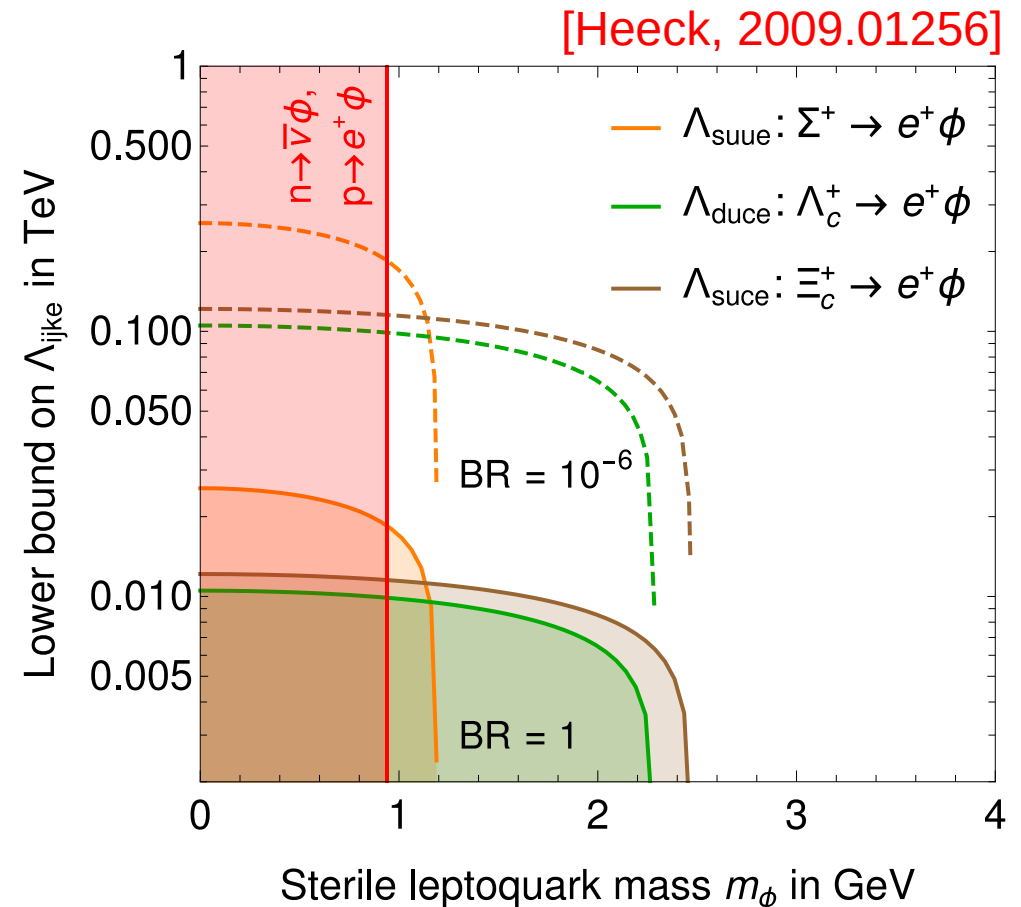
- Can be improved with inclusive searches.

[Heeck & Takhistov, 1910.07647]

- Mass close to H: hydrogen  $\rightarrow \phi \gamma$ .

[McKeen & Pospelov, 2003.02270]

- $m_\phi > m_n$  difficult to probe in rare decays, better constrained by LQ searches at LHC.



# Larger B and L?

- E.g. scalar  $\xi$  with  $B = 2$ : EFT coupling  $\bar{\xi}(udd)^2/\Lambda^6$ .
  - Light  $\xi$  can give  $nn \rightarrow \xi \pi^0$  or  $(A,Z) \rightarrow (A-2,Z) + \xi$ .
  - Heavier  $\xi$  difficult to probe, *unless it is dark matter!*

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  - Heavier  $\xi$  difficult to probe, *unless it is dark matter!*
- DM with B/L could decay specific antimatter final states:
  - $\phi$  with  $B=-2$  and  $L=-1$ :  $\mathcal{L} = \frac{\bar{\phi}^c n \bar{p}^c e}{\Lambda^2} + \text{h.c.}$
  - For  $m_d < m_\phi < m_n + m_p$ ,  
DM decays into **anti-deuteron** +  $e^+$ , not into  $\bar{p}$ .
  - Same trick to generate **anti-helium** without  $\bar{p}$ ,  
might explain **AMS** events.

[Heeck & Rajaraman, 1906.01667]

# Summary

- **Light new particles** becoming more popular, e.g. dark photons, sterile neutrinos, ALPs.
- Often overlooked: new particles could carry **B or L**.
  - Changes allowed couplings and pheno.
  - For sub-GeV masses: neutron and proton decays, can be improved in **SK, HK, JUNO, DUNE**.
  - Invisible n decays ( $n \rightarrow \phi \nu$ ,  $nn \rightarrow \xi$ ) powerful probe.
  - For  $m > \text{GeV}$ , hadron decays testable in **b/c/ $\tau$  factories**
  - Often kinematically stable, forms (asymmetric) DM.
  - DM decays can produce odd anti-matter signals.

More baryons & leptons out there?!