Title: Dark matter with baryon and lepton numbers

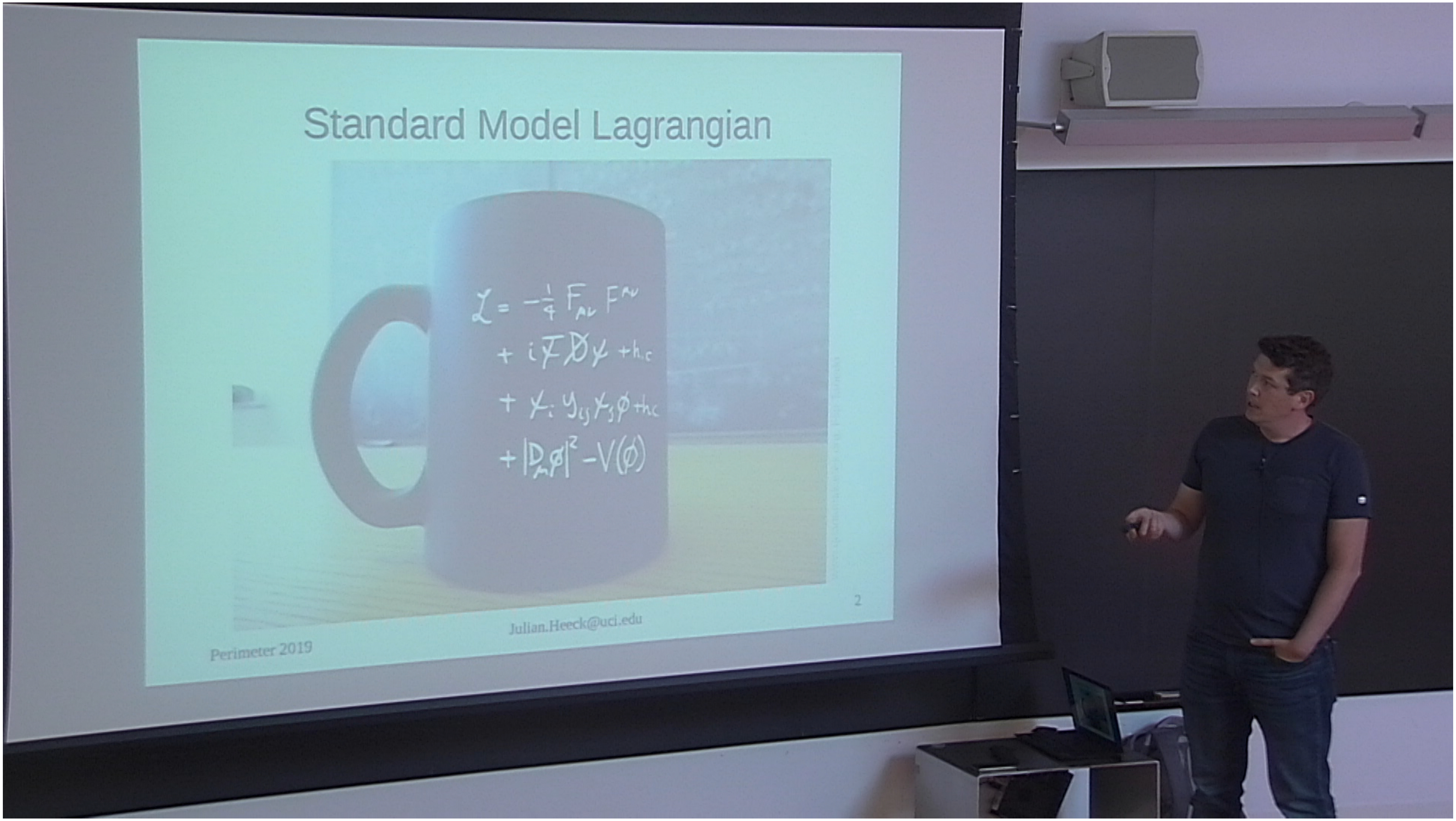
Speakers: Julian Heeck

Series: Particle Physics

Date: July 23, 2019 - 1:00 PM

URL: http://pirsa.org/19070082

Abstract: The stability of dark matter and its interactions with the Standard Model remain some of the biggest mysteries of our time. Instead of inventing ad hoc stabilization symmetries I propose to economically use the existing baryon and lepton number symmetries of the SM. This can lead to interesting signatures in terrestrial experiments, shower us in anti-helium, and keep neutron stars warm.


Standard Model Lagrangian
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
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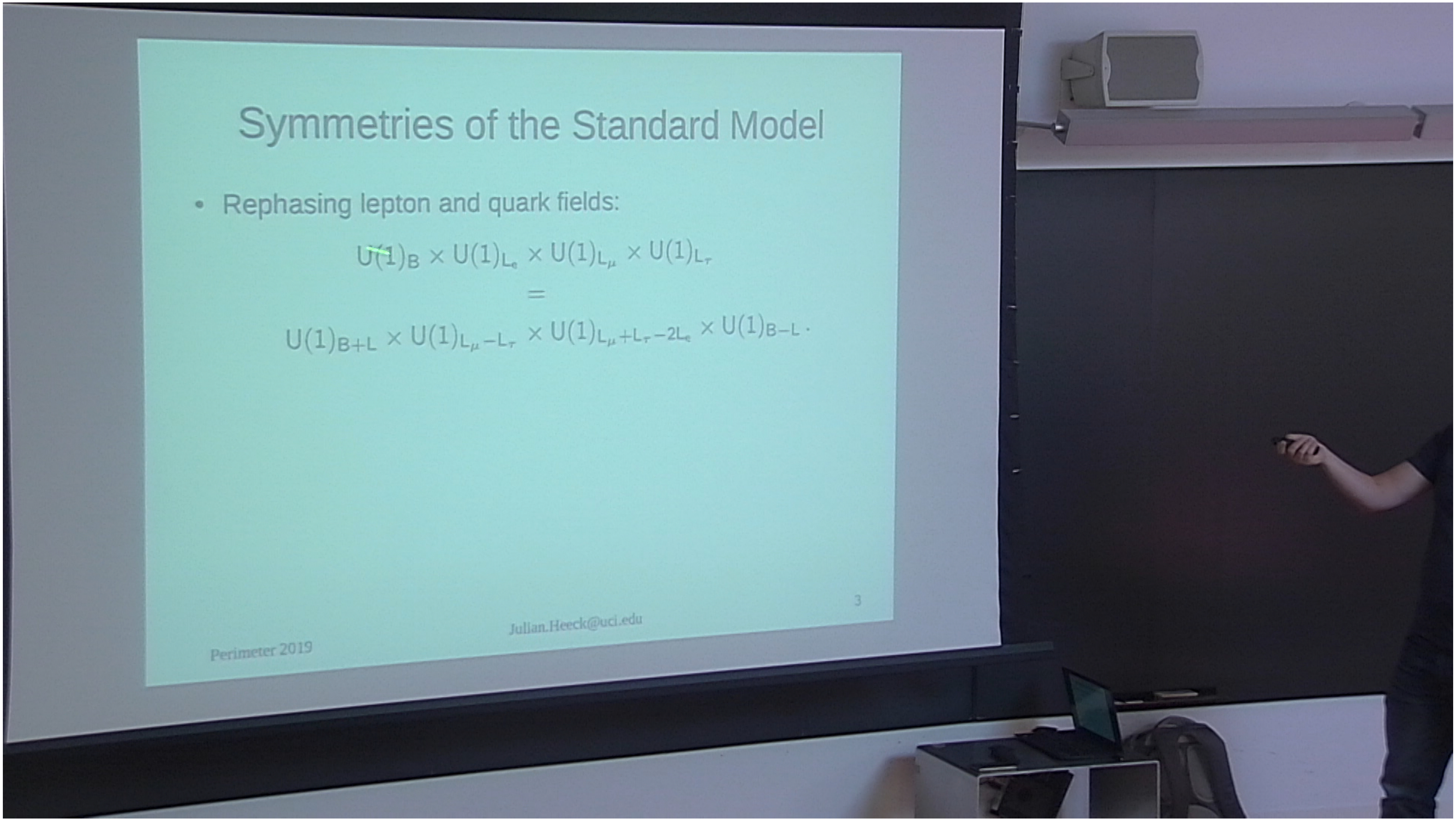
Symmetries of the Standard Model
• Rephasing lepton and quark fields:
$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$
$=$
$U(1)_{B+L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e} \times U(1)_{B-L}$.
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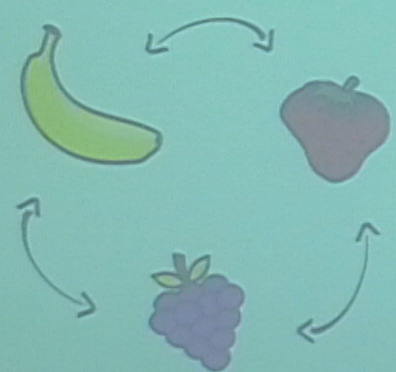
Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$
$$=$$
$$\cancel{U(1)}_{B+L} \times \underbrace{\cancel{U(1)}_{L_\mu - L_\tau} \times \cancel{U(1)}_{L_\mu + L_\tau - 2L_e}} \times U(1)_{B-L}\,.$$



- Broken by $\nu_\alpha \to \nu_\beta$.
- *Charged* lepton flavor violation suppressed by M_ν?
- Still useful for charged leptons.

[JH, 1610.07623; JH, Hambye, 1712.04871]

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Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$
$$=$$
$$\cancel{U(1)_{B+L}} \times \cancel{U(1)_{L_\mu - L_\tau}} \times \cancel{U(1)_{L_\mu + L_\tau - 2L_e}} \times U(1)_{B-L} \,.$$

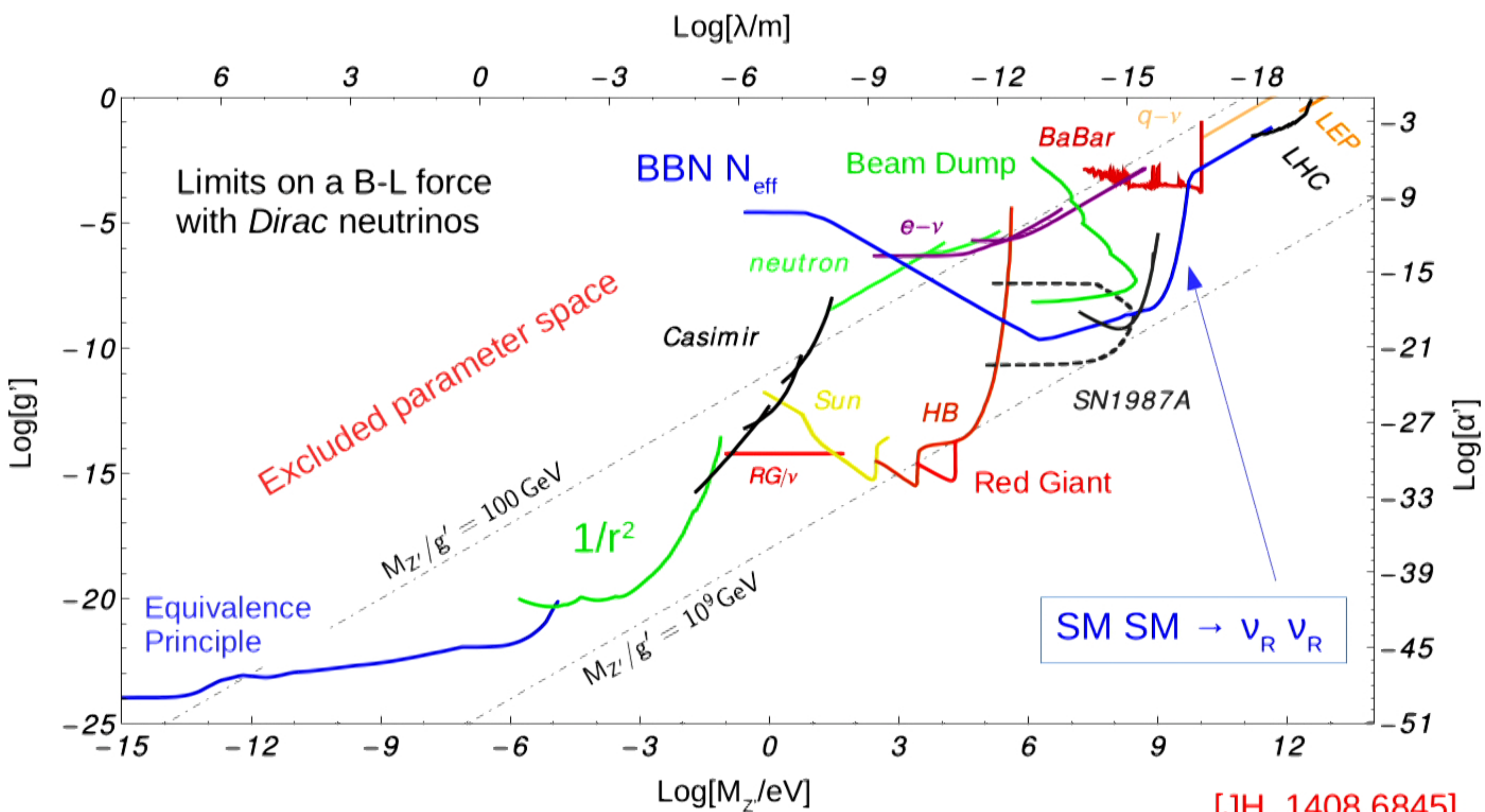
- Anomaly free, never seen violated.
- B – L could be conserved if neutrinos are Dirac fermions.

[JH, 1408.6845]

- Dirac leptogenesis to get matter > anti-matter.

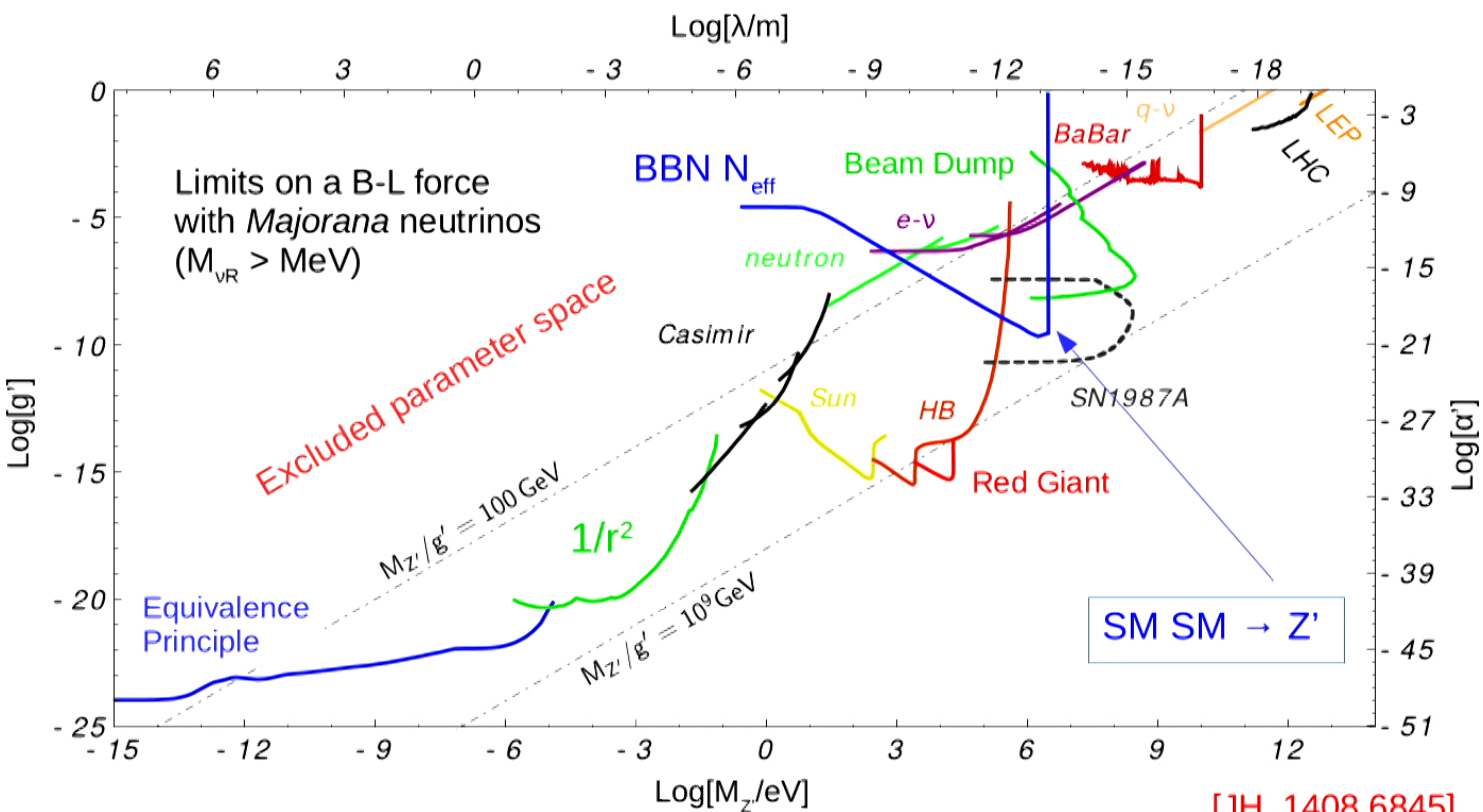
[Dick, Lindner, Ratz, Wright, '00]

Forcing unbroken $U(1)_{B-L}$



[JH, 1408.6845]

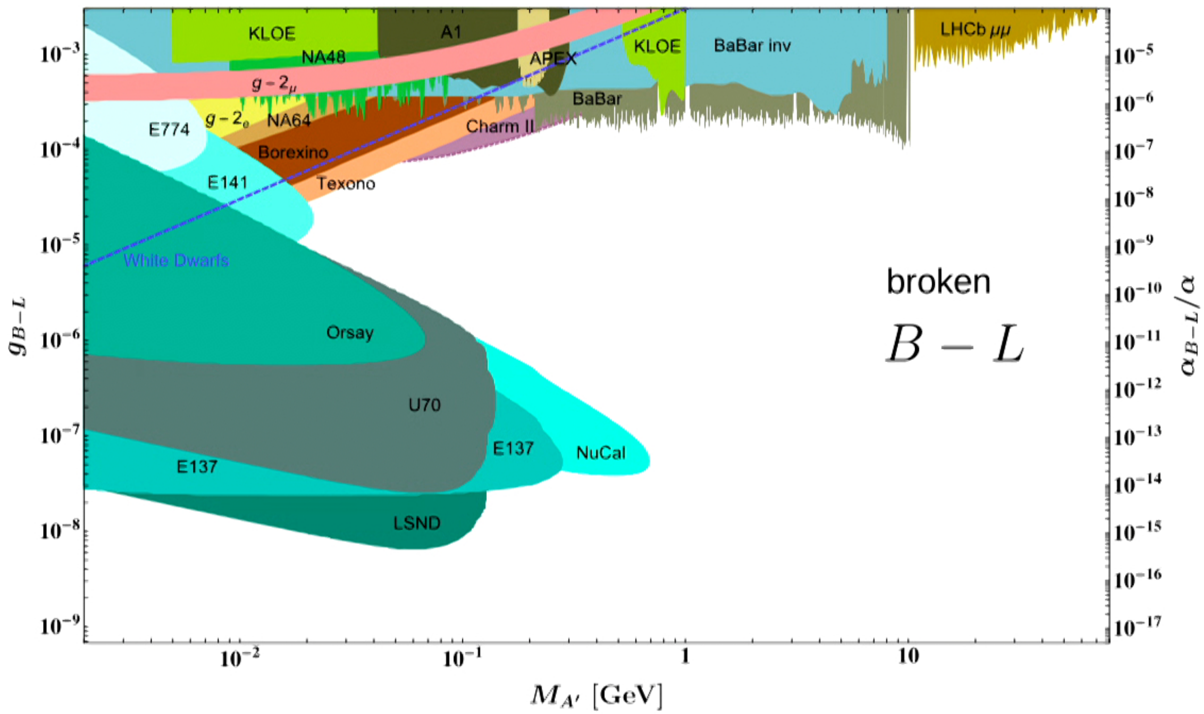
Forcing *broken* $\mathrm{U}(1)_{\mathrm{B-L}}$



[JH, 1408.6845]

Spontaneously broken B−L

- Broken B-L with $M_{Z'}, M_{\nu_R} > \text{MeV}$ is safe from N_{eff}.
- Testable in many experiments.



[Bauer, Foldenauer, Jaeckel, 1803.05466]

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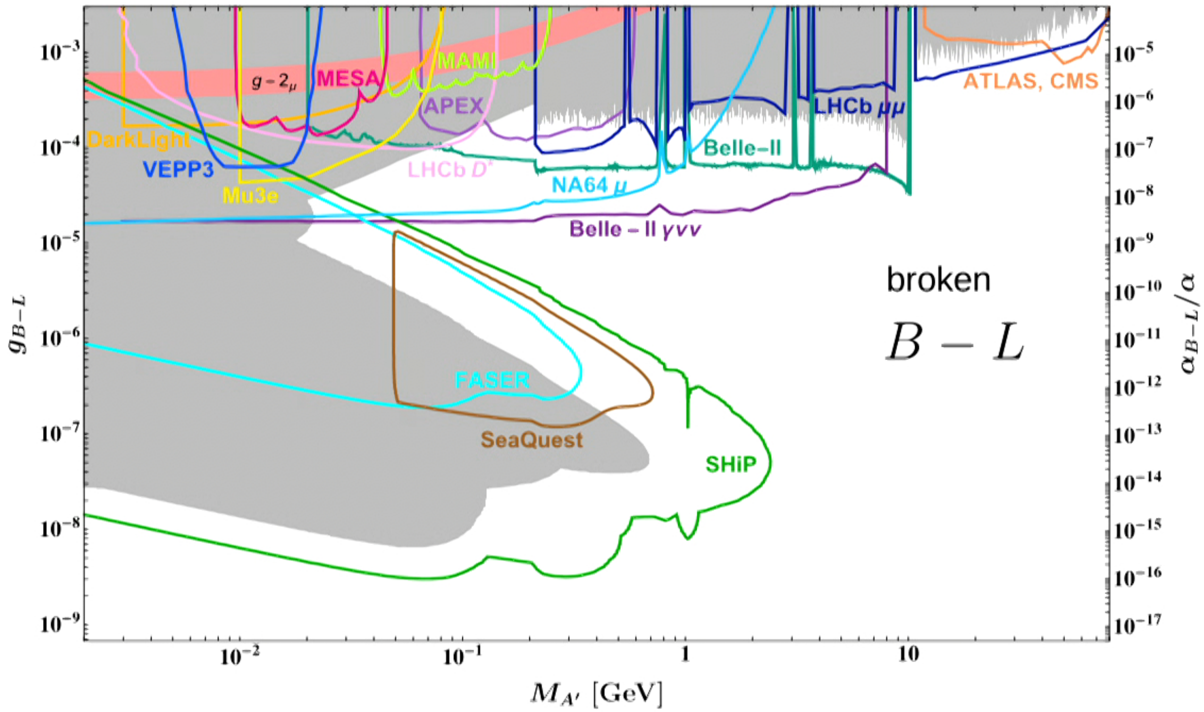

[Bauer, Foldenauer, Jaeckel, 1803.05466]

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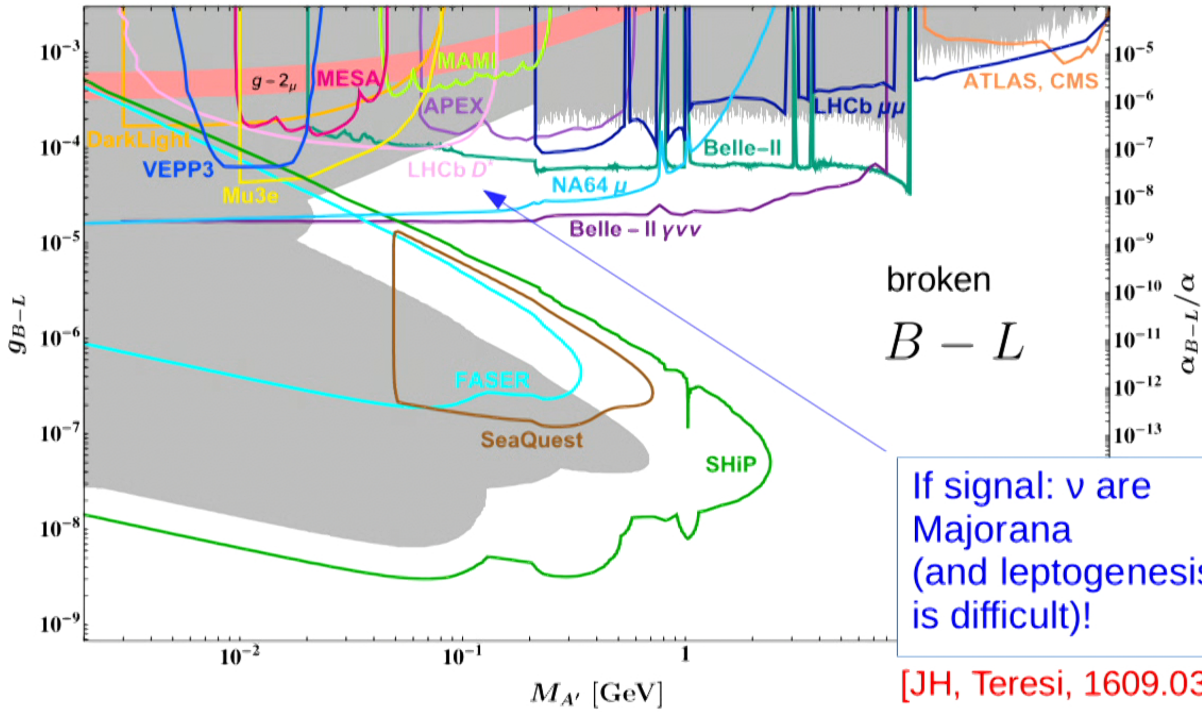


If signal: ν are Majorana (and leptogenesis is difficult)!

[Bauer, Foldenauer, Jaeckel, 1803.05466]

[JH, Teresi, 1609.03594]

Breaking-in some flavor

- SM + 3 ν_R has anomaly free

$$U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}.$$

[Araki, JH, Kubo, 1203.4951. Without ν_R just $L_\alpha - L_\beta$, He, Joshi, Lew, Volkas, '91]

- *Broken* B-L can mix with broken flavor.
- New gauge boson(s) Z' coupled to linear combination of

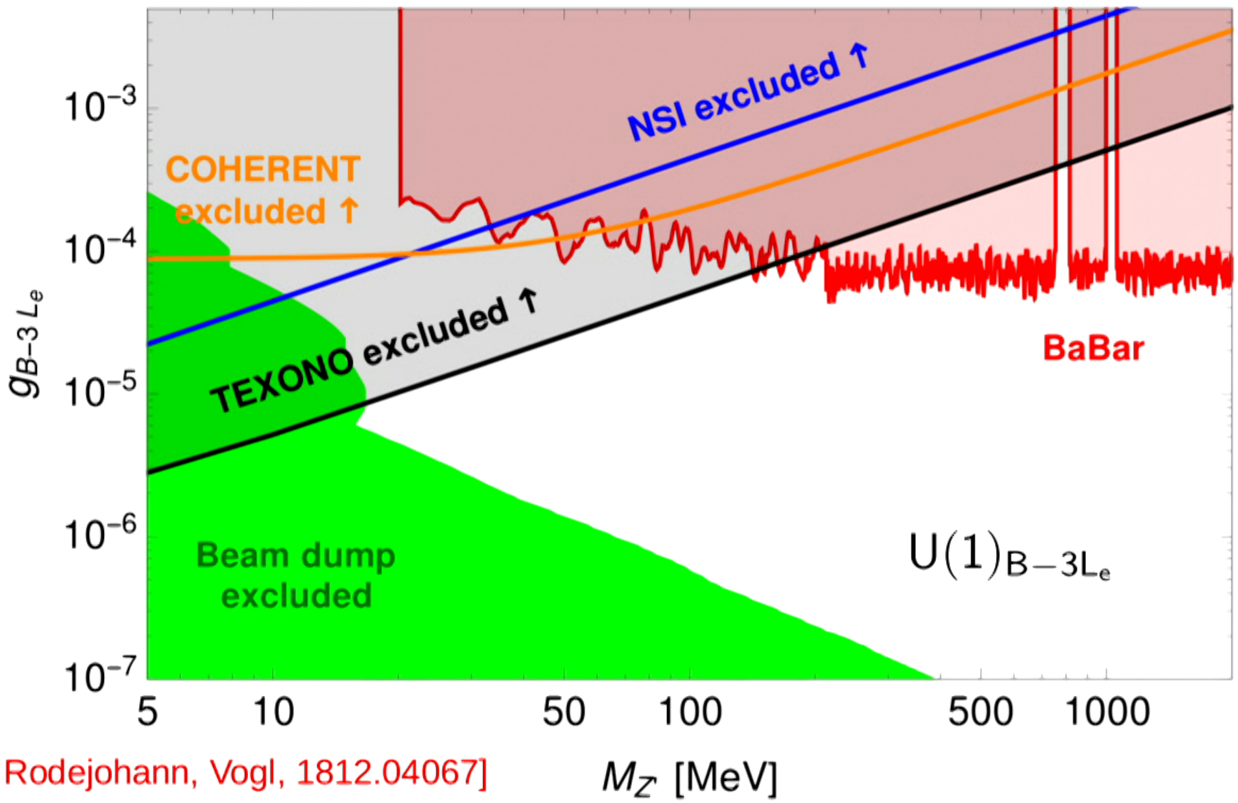
$$B - L,\ L_\mu - L_\tau,\ \text{and}\ L_\mu + L_\tau - 2L_e.$$

- Gives lepton-flavor non-universality.

How to search for these?

Electronphilic

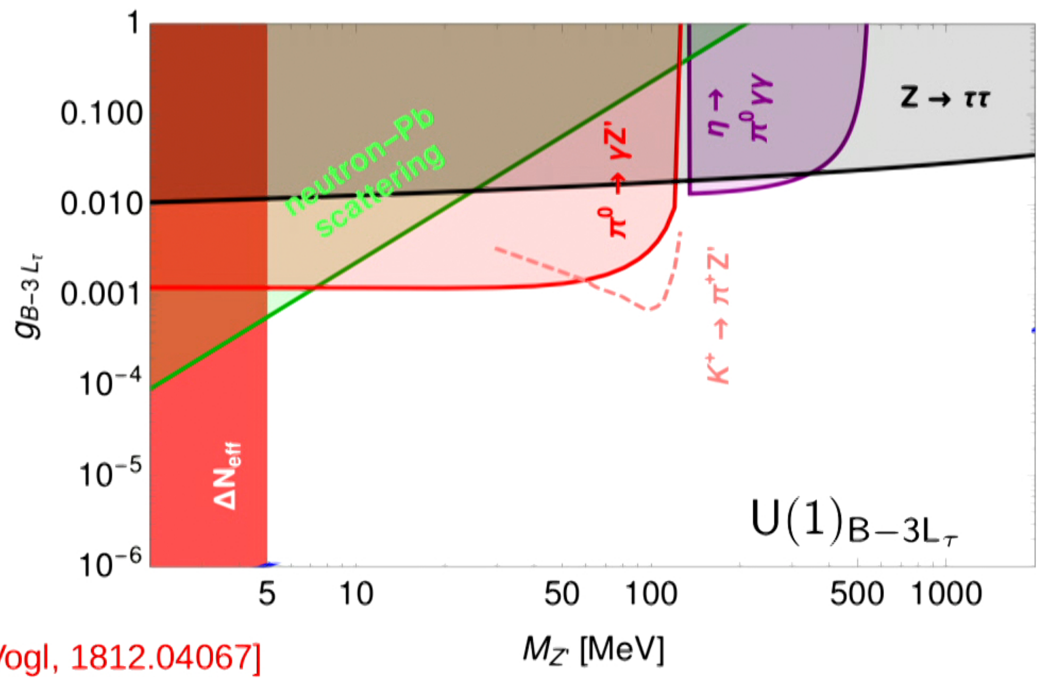
- ν-electron scattering (TEXONO) relevant for L_e.



[JH, Lindner, Rodejohann, Vogl, 1812.04067]

Electronphobic

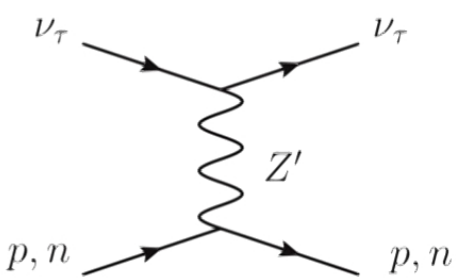
- E.g.: $U(1)_{B-3L_\tau}$



[JH, Lindner, Rodejohann, Vogl, 1812.04067]

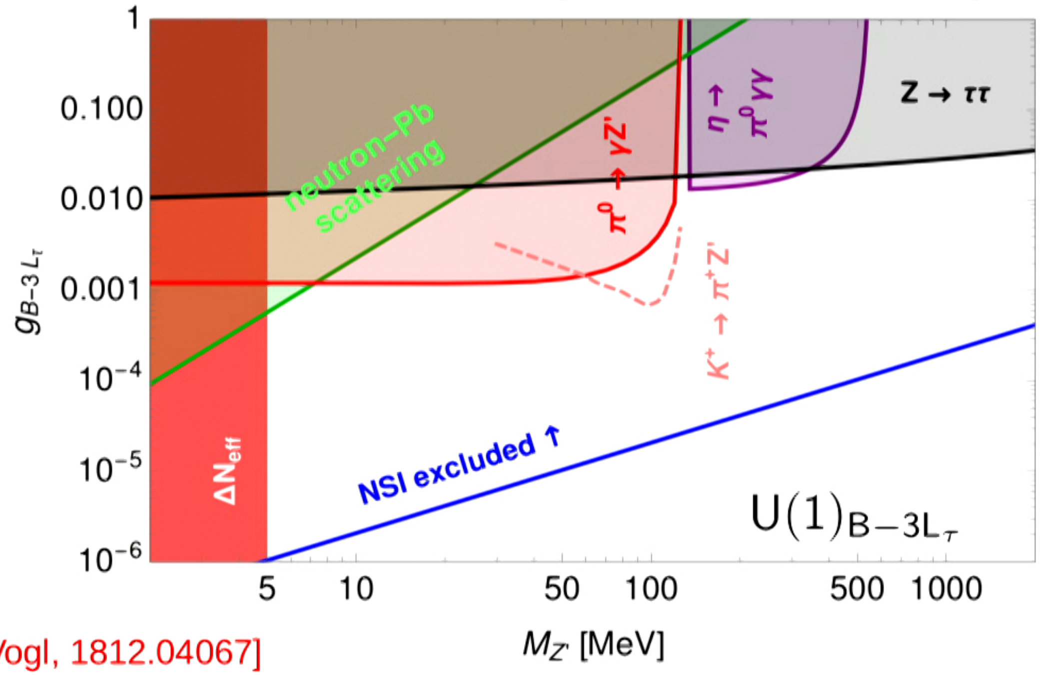
Electronphobic

- Every Z' (except $L_\mu - L_\tau$) leads to ν scattering in matter.
- Strong constraints from Non-Standard ν Interactions.
- E.g.: $U(1)_{B-3L_\tau}$



$M_{Z'}/g' > 4.8$ TeV!

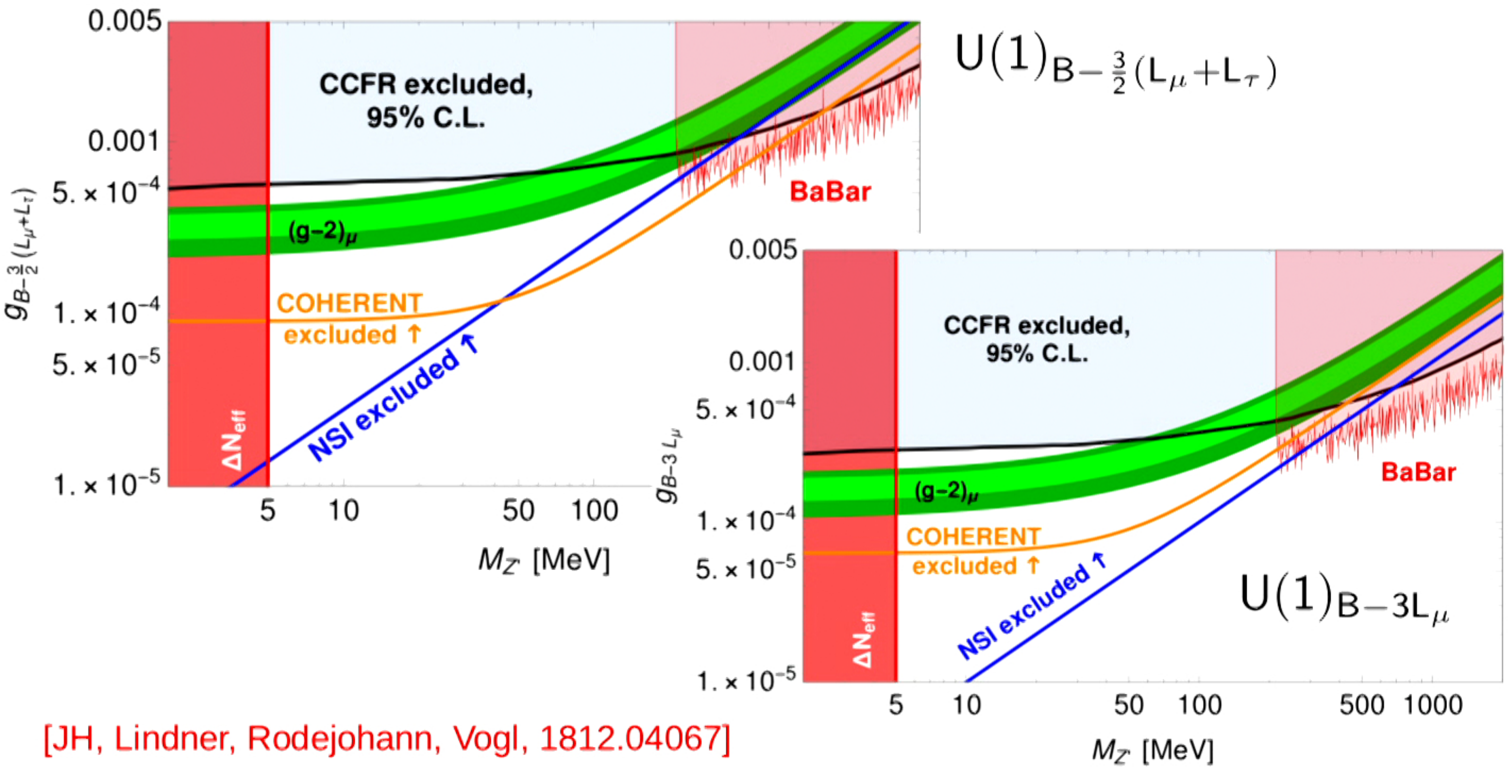
[Esteban et al, 1805.04530]



[JH, Lindner, Rodejohann, Vogl, 1812.04067]

Electronphobic II

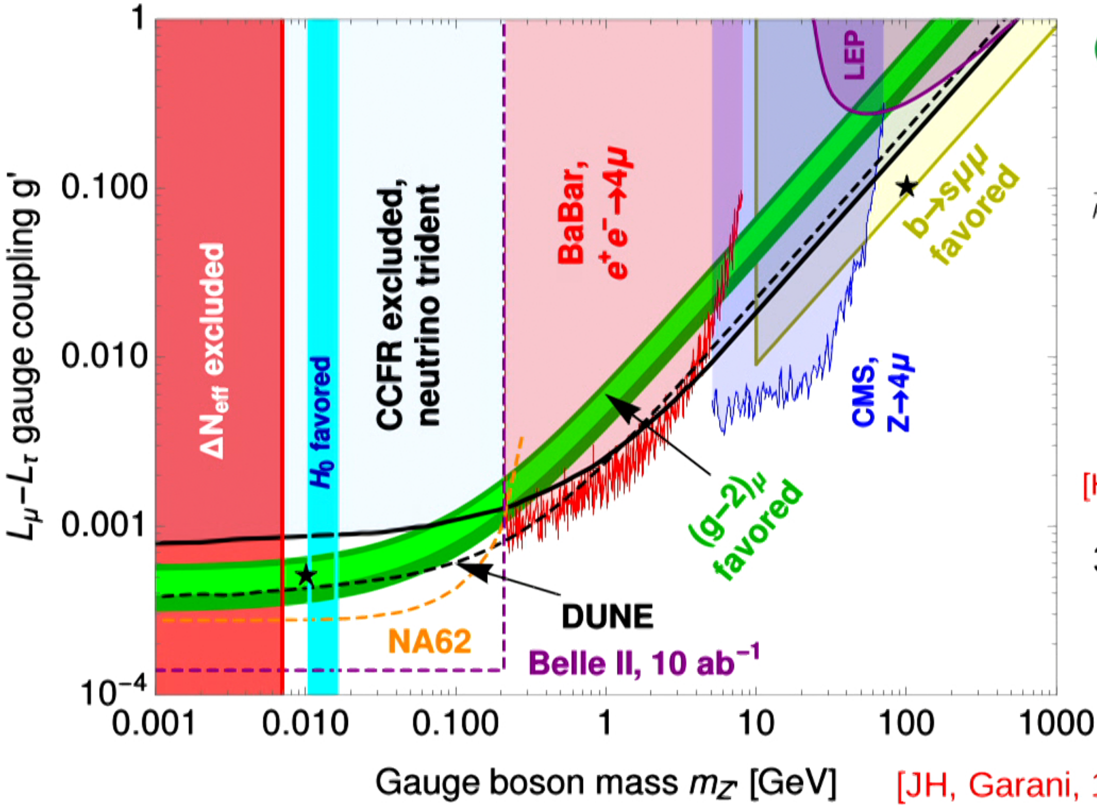
- COHERENT's CEνNS relevant for $\nu_{e,\mu}$ couplings.



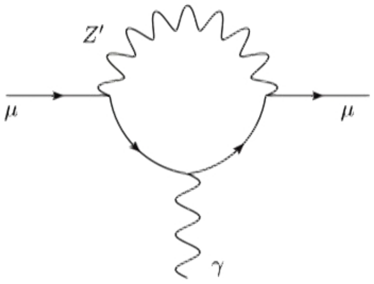
[JH, Lindner, Rodejohann, Vogl, 1812.04067]

Electronphobic & baryonphobic

- Weakest constraints: $U(1)_{L_\mu - L_\tau}$.



$(g\text{-}2)_\mu$:



[He, Joshi, Lew, Volkas, '91]

3-4σ deviation!

[JH, Garani, 1906.10145]

Electronphobic & baryonphobic

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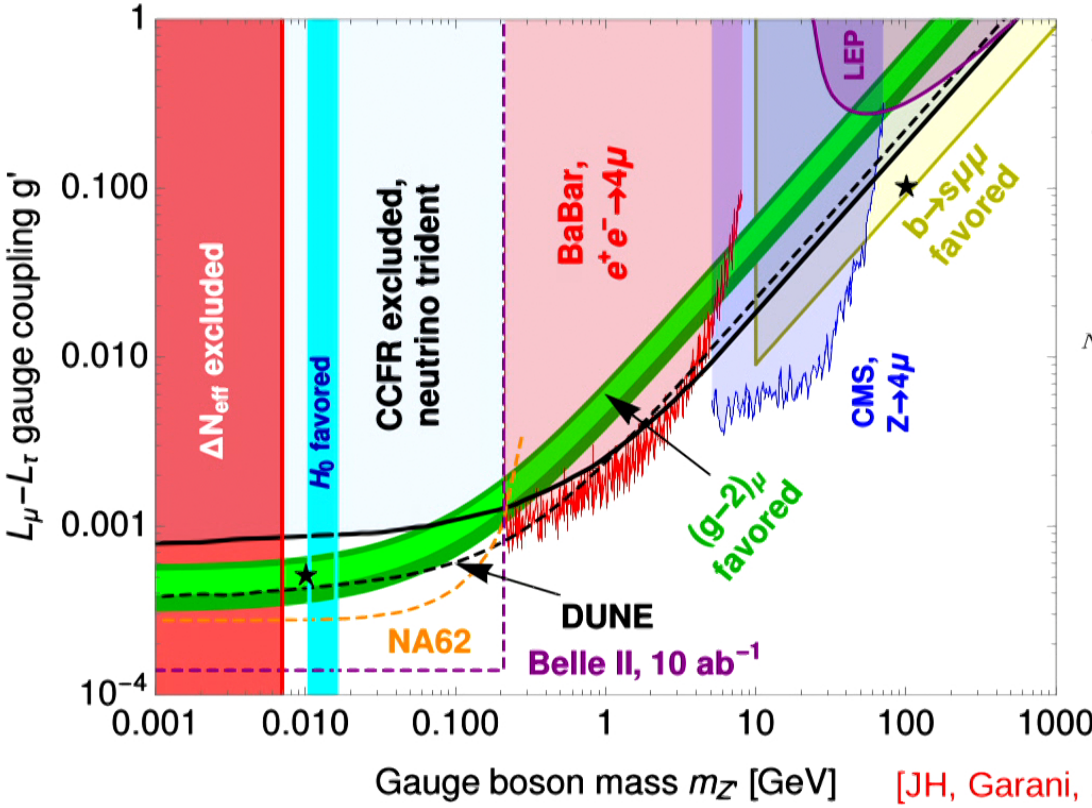
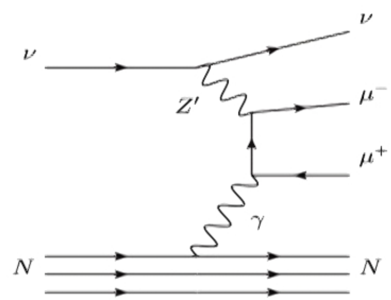


ν trident:

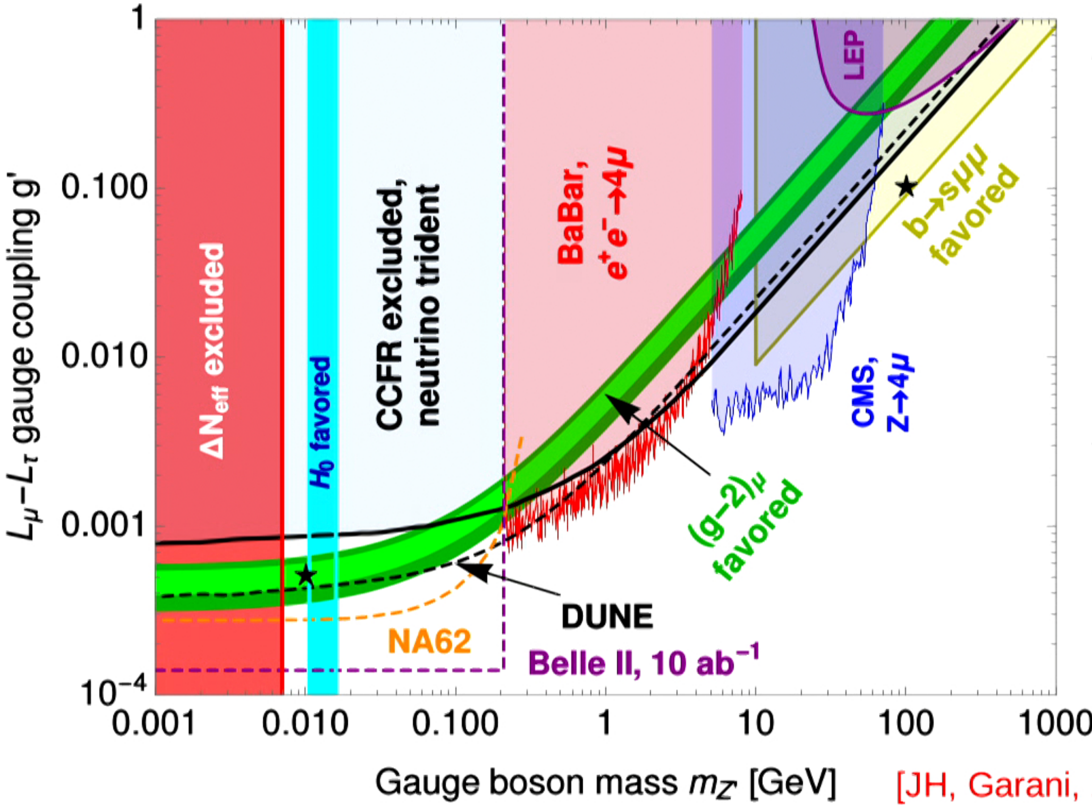


[Altmannshofer, Gori, Pospelov, Yavin, '14]

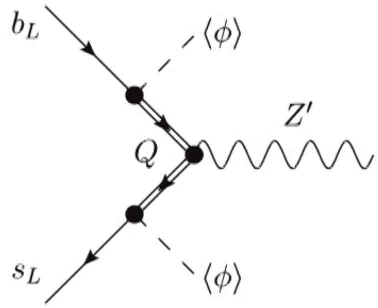
[JH, Garani, 1906.10145]

Electronphobic & baryonphobic

- Weakest constraints: $\mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau}$.



Add bs coupling



to explain $\mathrm{b} \to \mathrm{s}\mu\mu$ LHCb anomalies.

[Altmannshofer, Gori, Pospelov, Yavin, '14, many others...]

[JH, Garani, 1906.10145]

Mini summary I

$$\mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \Rightarrow Z'$$

- Very simple UV-complete Z' models.
- Dirac neutrinos: $N_{eff} > 3$ in CMB Stage 4.
- Majorana neutrinos:
  - Non-Standard ν Interactions and other ν scattering.
  - Only way to resolve $(g-2)_\mu$: $L_\mu - L_\tau$.
  - Connected to B-meson anomalies?

Can these Z’ have DM couplings?

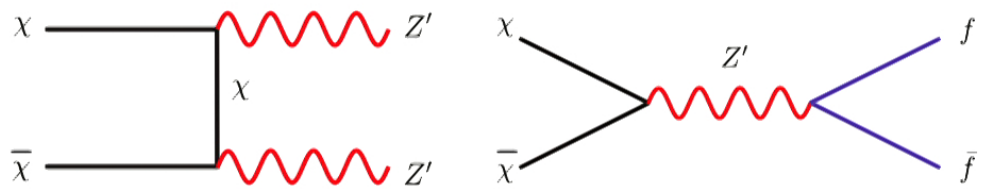
Can these Z' have DM couplings?

$\leftrightarrow$

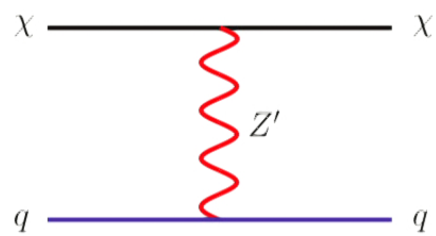
Can DM carry baryon/lepton number?

Dark matter from B−L?

- SM fermions are odd under 3(B-L), bosons are even.
- New fermion (boson) χ with even (odd) 3(B-L) is stable.
- SM-DM connection through Z'.
- DM abundance via freeze out:

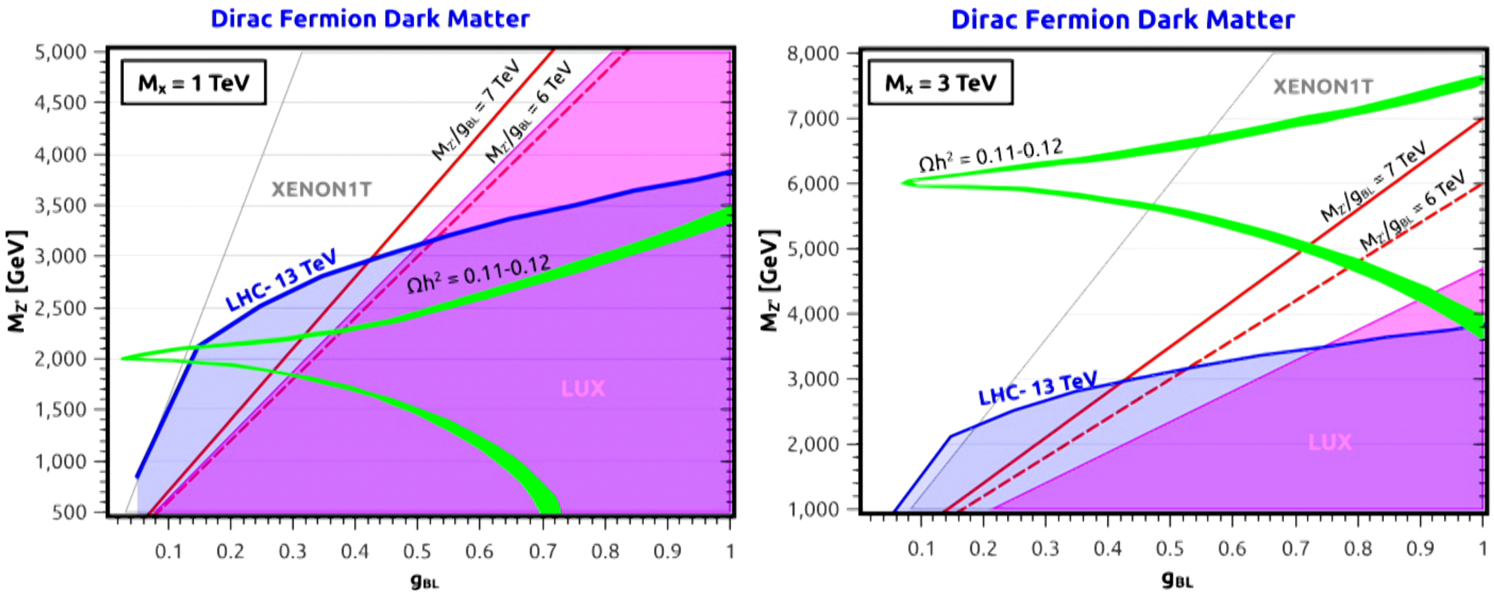


- Direct detection from Z' scattering:



[Klasen, Lyonnet, Queiroz, 1607.06468; see also Duerr, Perez, Smirnov '15; Rodejohann & Yaguna, '15; Jacques et al. '16, and many others]

Dark matter from B−L!



[Klasen, Lyonnet, Queiroz, 1607.06468]

Need to sit on the Z' resonance!

Dark matter from B−L!?

- Simple WIMP model.
- Strong constraints from direct detection.
  - Softened for Majorana DM (broken B-L).
- Finds embedding in left-right or even SO(10) model:

  Dark matter stability via B−L still works!
  - Gives WIMPs and often charged partners.
  - Requires low U(1)’, left-right or Pati-Salam scales.

    [JH, Patra, ‘15; Garcia-Cely, JH, ‘15; Ferrari, Hambye, JH, Tytgat, 1811.07910]

Dark matter from L_μ–L_τ?

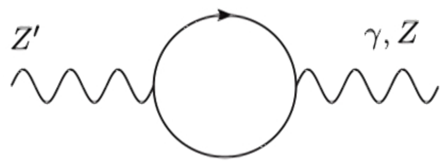
- Simple WIMP model. [Cirelli, Kadastik, Raidal, Strumia, 0809.2409; Baek, Ko, 0811.1646]
- Z' mediator could be light: DM DM $\rightarrow$ Z' Z'.
- **No** constraints from direct detection...

Kinetic mixing

- Every U(1)’ has kinetic mixing with hypercharge,

$$\mathcal{L} = -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} - \tfrac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \tfrac{1}{2}\, \epsilon\, F'_{\mu\nu} F^{\mu\nu},$$

plus loop level mixing. [Galison, Manohar, ‘84; Holdom, ‘86]



- Couples light Z’ to electric current; important for $L_\mu - L_\tau$, e.g. in direct detection:

$$\sigma_{\chi N} = \frac{Z^2}{A^2} \frac{m^2_{\mathrm{red},\chi N}}{\pi m^4_{Z'}} (g' q_\chi)^2 \left[e\epsilon + \frac{\alpha g'}{3\pi} \log\left(\frac{m^2_\tau}{m^2_\mu}\right)\right]^2$$

[Kopp, Niro, Schwetz, Zupan, ‘09; Altmannshofer, Gori, Profumo, Queiroz, ‘09]

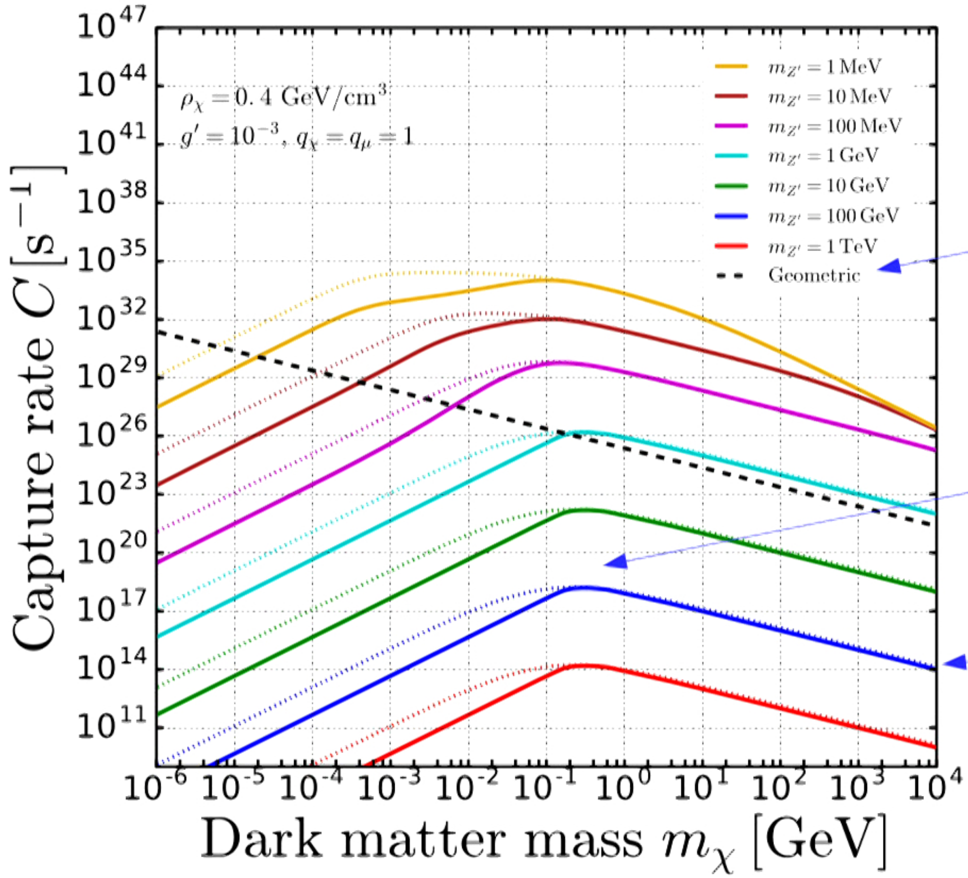
Dark matter from L_μ–L_τ?

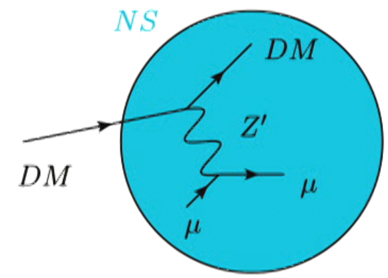
- Simple WIMP model. [Cirelli, Kadastik, Raidal, Strumia, 0809.2409; Baek, Ko, 0811.1646]
- Z' mediator could be light: DM DM → Z' Z'.
- **No** constraints from direct detection...

  … but could still be captured in neutron stars! [Garani, Genolini, Hambye, 1812.08773; Bell, Busoni, Robles, 1904.09803]
  - NS contain 10^{57} neutrons and 10^{55} muons.
  - Capture for $\sigma_{\mathrm{DM}\mu} > 5 \times 10^{-43}\mathrm{cm}^2$.
  - Also take Pauli blocking and velocities into account.

[JH, Garani, 1906.10145]

DM capture in neutron star?





Everything is captured!

Capture most efficient for $m_{DM} \sim m_\mu$.

$C \propto q_\chi^2 g'^4 / m_{Z'}^4$

[JH, Garani, 1906.10145]

(Muonic) DM in neutron stars

- Easily saturate the capture rate for WIMPs. Then what?
- Asymmetric DM: collect enough to form black hole?
  - Fermi pressure. ↯ [Kouvaris, Tinyakov, '10, '11]
  - Repulsive self-interactions. ↯ [Bell, Melatos, Petraki, '13, Bramante, Fukushima, Kumar, '13]

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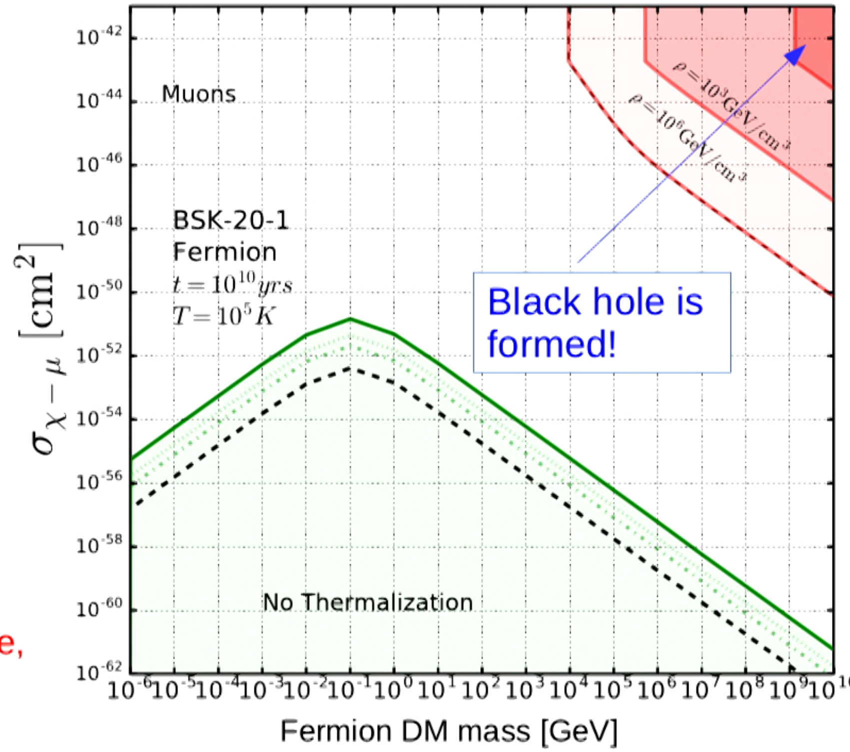

[Garani, Genolini, Hambye, 1812.08773]

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(Muonic) DM in neutron stars

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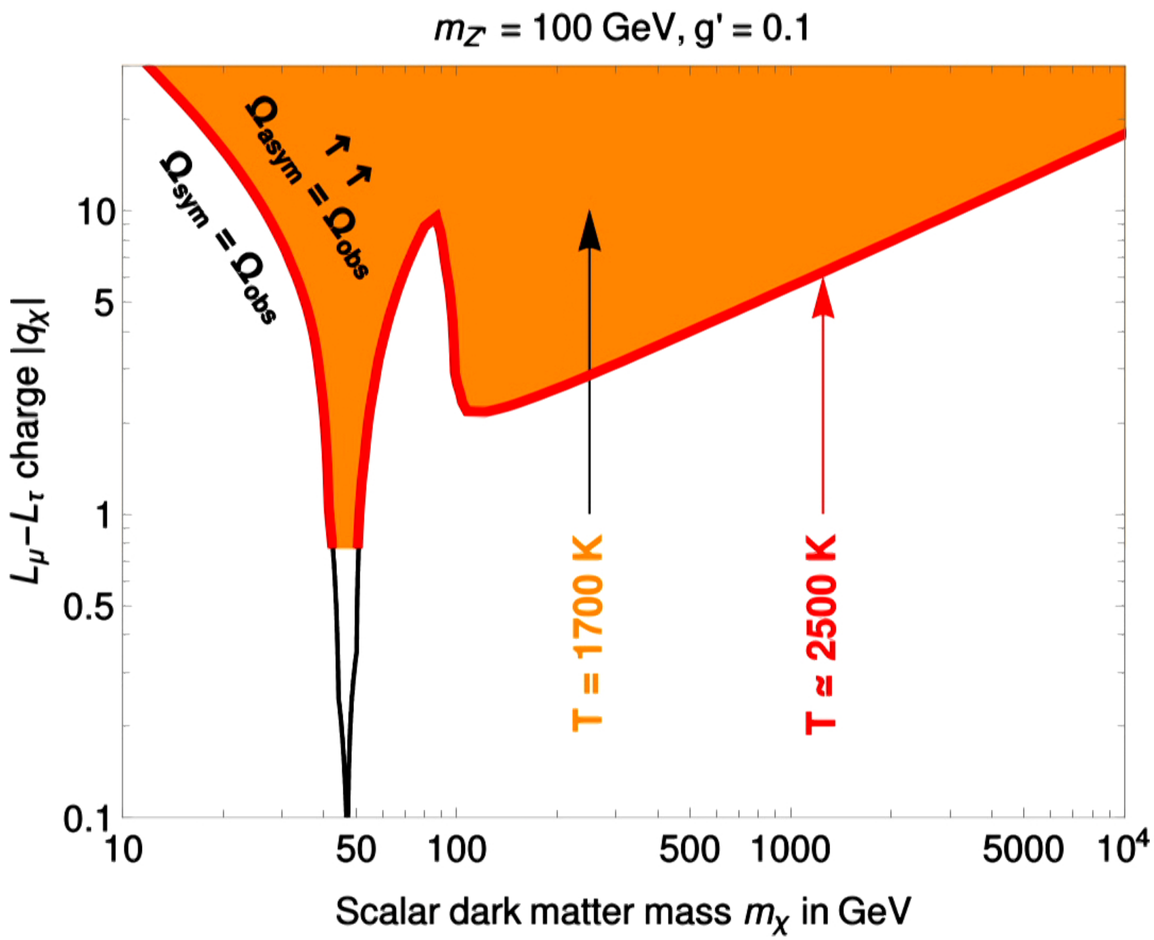
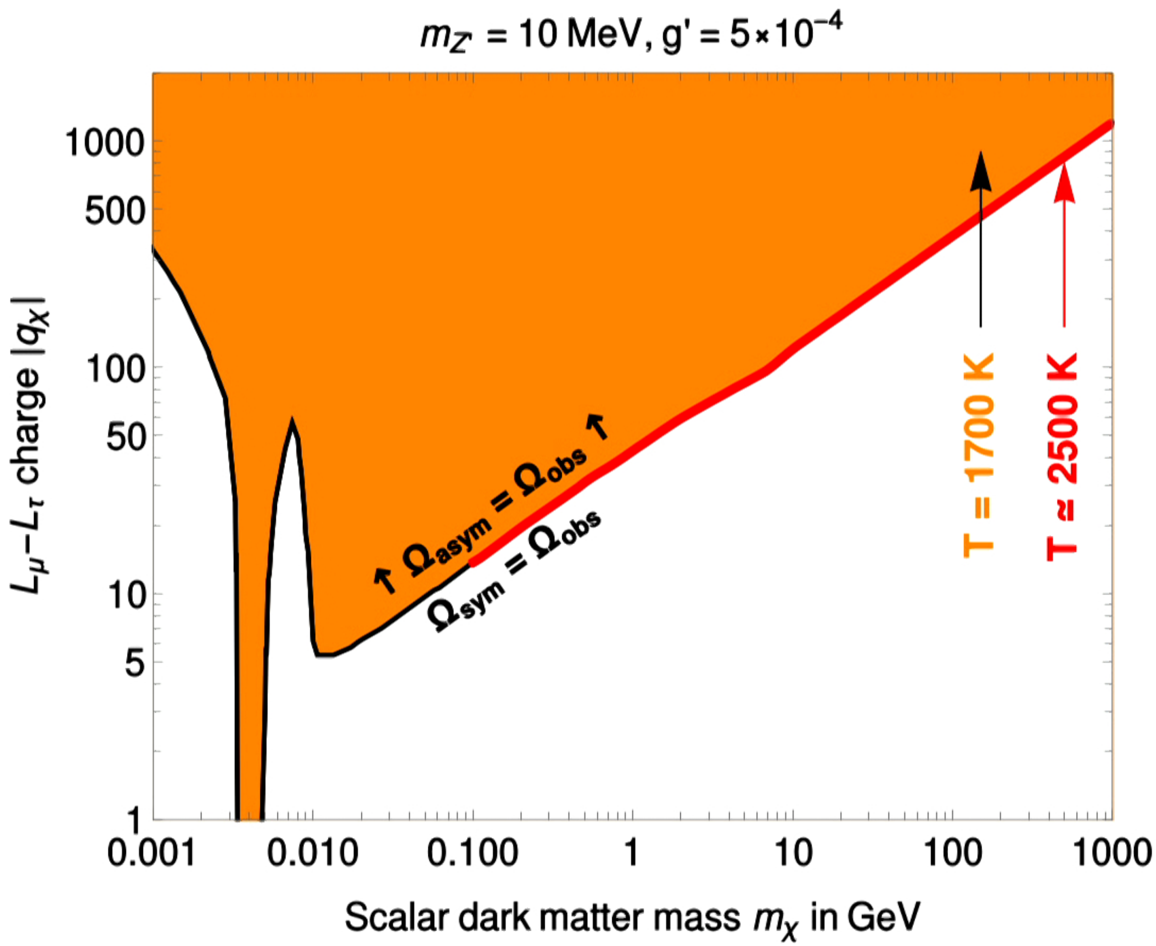
  - Fermi pressure. ↯ [Kouvaris, Tinyakov, '10, '11]
  - Repulsive self-interactions. ↯ [Bell, Melatos, Petraki, '13, Bramante, Fukushima, Kumar, '13]
- Always: infalling DM heats the NS! (from < 1000K to ~2000K)

[Baryakhtar, Bramante, Li, Linden, Raj, '17; Raj, Tanedo, Yu, '17; Bell, Busoni, Robles, '18/'19]

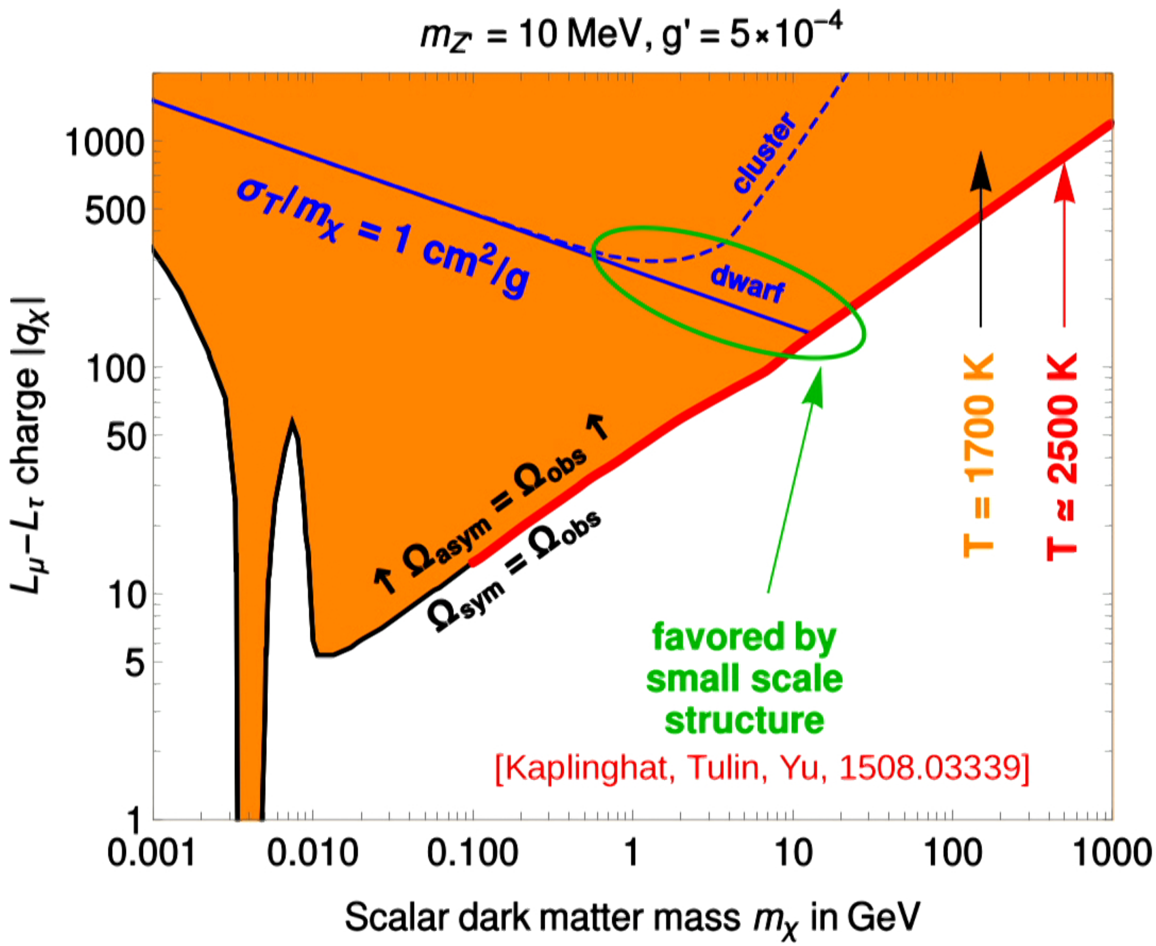
- Symmetric DM: more heating from DM annihilations.
- Measure IR spectrum of nearby old NS with JWST?



[JH, Garani, 1906.10145]



[JH, Garani, 1906.10145]



[JH, Garani, 1906.10145]

Mini summary II

$$\mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \Rightarrow \mathrm{Z}' \,\&\, \mathrm{DM}$$

- Use U(1)' for DM stability and Z' for portal.
- Typically strongly constrained by direct detection.
- Only way to evade: $L_\mu - L_\tau$.
  - Muonphilic DM still captured in neutron stars → heating!
  - Light Z' allows for self-interactions $\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$ → resolves small-scale structure anomalies!

DM with *special* baryon and lepton numbers

DM with baryon and lepton numbers

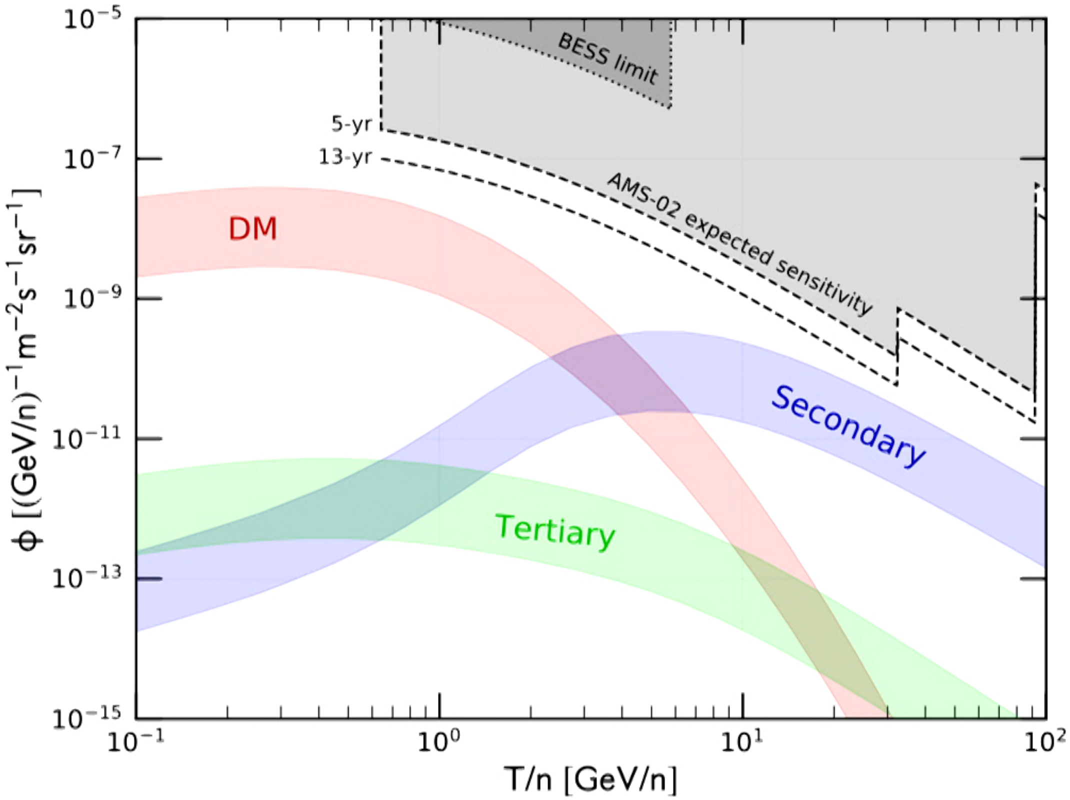
- So far: DM carries *x* units of B or L_α to make it stable.
- Not necessarily *exactly* stable:
  - Fermion DM with L = 3 can decay to 3 neutrinos.
  - Fermion DM with B = -3 can decay to 3 anti-neutrons.
  - …
- Higher-dimensional operator: long lifetime!
- Dominant decay mode can be unusual…

Anti-matter in AMS on the ISS

- Since 2011, Alpha Magnetic Spectrometer has collected
  - 120 billion cosmic rays.
  - 10 billion protons, 100 million deuterons, 700 million He.
  - 1 million $\overline{p}$, ? $\overline{d}$, 6 $^{3}\overline{He}$, 2 $^{4}\overline{He}$. [A. Olivia, talk at d-bar 2019, UCLA]
- Simulation of misidentification ongoing.
- Anti-helium impossible from astro, difficult from DM!
- Coalescence = fusion of $\overline{p}$ and $\overline{n}$ into $\overline{d}$ and $\overline{He}$:

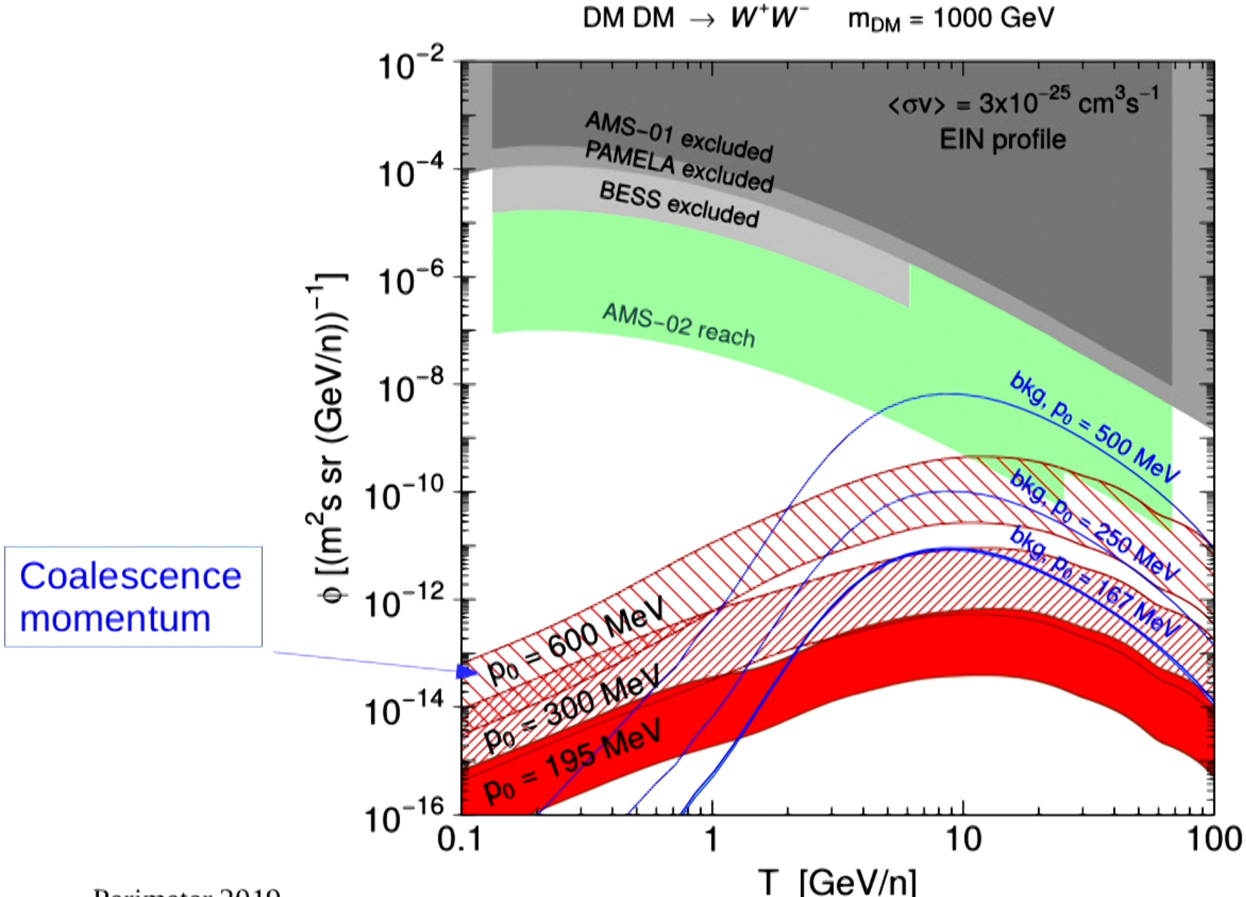
$$\#\bar{p} \gg \#\bar{d} \gg \#^{3}\overline{He} \gg \#^{4}\overline{He}\,.$$

Anti-^{3}He flux



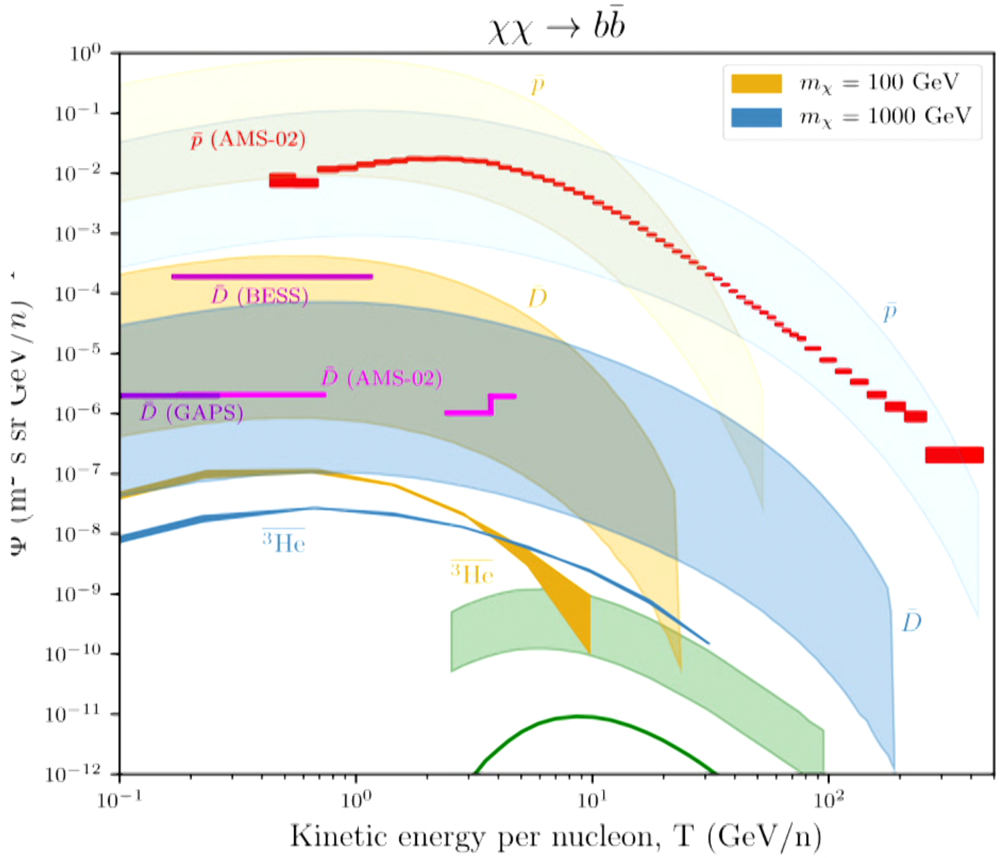
[Korsmeier, Donato, Fornengo, 1711.08465]

Anti-^{3}He flux



[Cirelli, Fornengo, Taoso, Vittino, 1401.4017]

1 anti-^{3}He per year from DM



$\langle \sigma v \rangle =$

$7.3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$

$4.8 \times 10^{-25} \frac{\text{cm}^3}{\text{s}}$

[Coogan, Profumo, 1705.09664]

Anti-helium in AMS

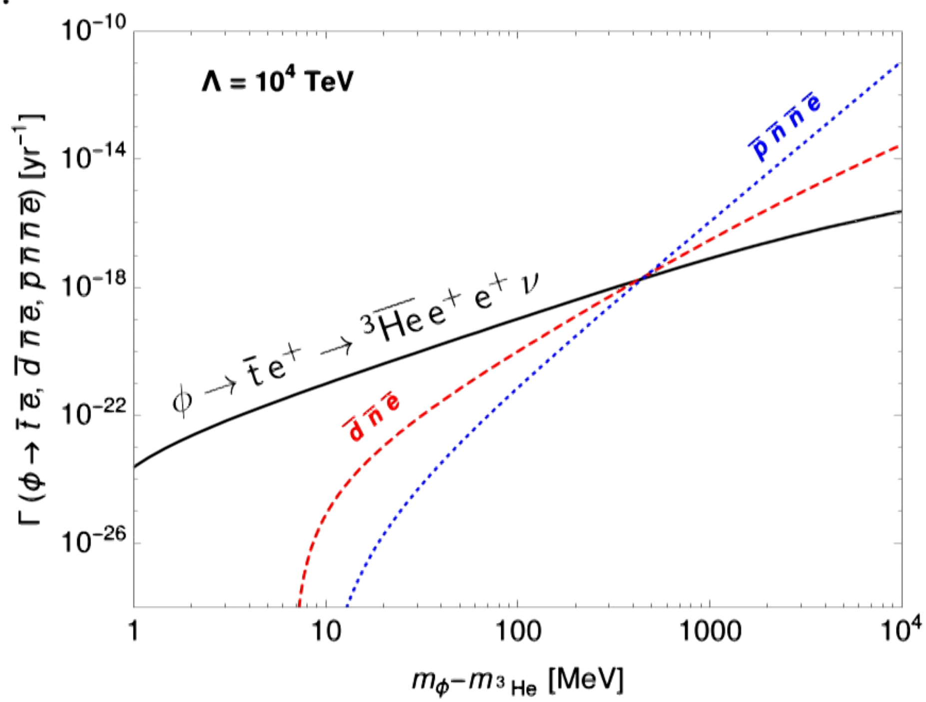
- No anti-helium from astrophysics.
- Difficult to get $^3\overline{\mathrm{He}}$ from DM.
  - Should see features in $\bar{p}$ and many $\bar{d}$.
- Impossible to get $^4\overline{\mathrm{He}}$ from anything!?
  - Anti-matter regions? [Dolgov, Silk, '93; Dolgov++; Poulin, Salati, Cholis, Kamionkowski, Silk, '18]
    - Anisotropic BBN.
    - Highly segregated anti-cloud or compact object.
    - Unknown acceleration mechanism
  - DM with baryon number? [JH, Rajaraman, 1906.01667]

DM with baryon number

- Complex scalar ϕ with B = -3, decays via

$$\mathcal{L} = \frac{\phi\, \overline{\mathrm{n}}^c \gamma_5 \mathrm{n}\, \overline{\mathrm{p}}^c \gamma_5 \mathrm{e}}{\Lambda^3} + \mathrm{h.c.}$$

[JH, Rajaraman, 1906.01667]

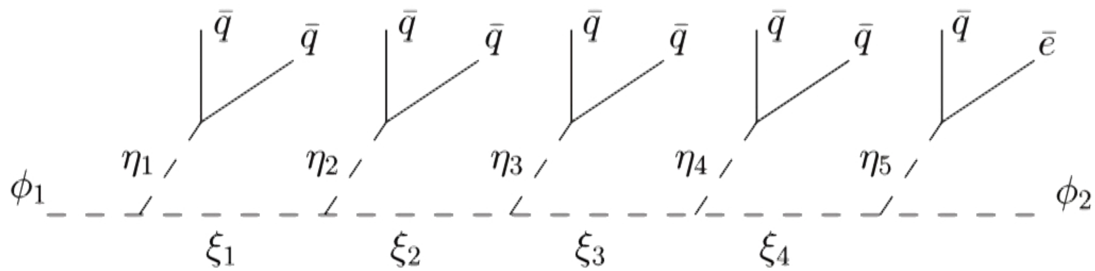


- Phase space can reduce $\bar{\mathrm{p}}$ flux.
- Accelerate ${}^3\overline{\mathrm{He}}$ or boost ϕ.
- Main issue:

$$\frac{1}{\Lambda^3} \lesssim \frac{\Lambda_{\rm QCD}^9}{\Lambda_{\rm UV}^{12}}\,.$$

Variations

- Add second scalar $\phi_1 \to \bar{t}\, e^+\, \phi_2$:



- Resonances can compensate for Λ_{QCD} : $m_{\phi_1} \sim m_{\xi_j} \sim m_{\phi_2}$.
- Dominantly $^3\overline{He}$ from TeV physics.
- $^4\overline{He}$ similar but more (nuclear physics) uncertainties.
- New model-building avenue!

[JH, Rajaraman, 1906.01667]

Summary

- SM symmetry: $U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$.
- Easy to gauge: Z'!
  - Dirac ν: $N_{eff} > 3$ in CMB Stage 4.
  - Majorana ν: collider, ν scattering on e, N, matter,…
  - Possible Z' portal to dark matter and origin of stability.
  - $L_\mu - L_\tau$: $(g-2)_\mu$, $b \to s\mu\mu$, self-interacting DM, hot NS.
- Enforce DM decay modes:
  - E.g. DM → anti-helium to explain AMS-02.

More parameter space probed soon!