B-L: The Next Symmetry of Nature

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"What comes beyond the standard model"

Symmetries have played a fundamental role in our understanding of nature:

Old days (1960s)

$U(1)_{em}$ (local) , $SU(2)_{isospin}$, SU(3) (global)

These led to the quark model as the constituent picture of hadronic matter

Then came the standard model in late 1960s based on local symmetries

$$SU(3) \times SU(2)_L \times U(1)_Y$$

The symmetry path that led to standard model has been a winning path:

Could it be same for

"what comes beyond the Standard Model":

Many ideas that use symmetry approach to BSM: left right symmetric models, GUTs based on SU(5), SO(10) local symmetries, supersymmetry,..

To explore this, we start with details of standard model

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad u_R, \; d_R, \; e_R$$

- $+$ $\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ with $< \phi^0 >= v$

- Discovery of 125 GeV Higgs is a crowning success of the SM.

SM of course not the final story

- Small, non-vanishing neutrino masses- m_ν
- Origin of matter in the universe $\frac{n_B}{n_\gamma}$
- Dark matter,
- Dark energy
- Hints of experimental anomalies (MiniBooNe, muon g-2, B-anomalies)

They hint new symmetries

- One strongly suggested by neutrino mass is

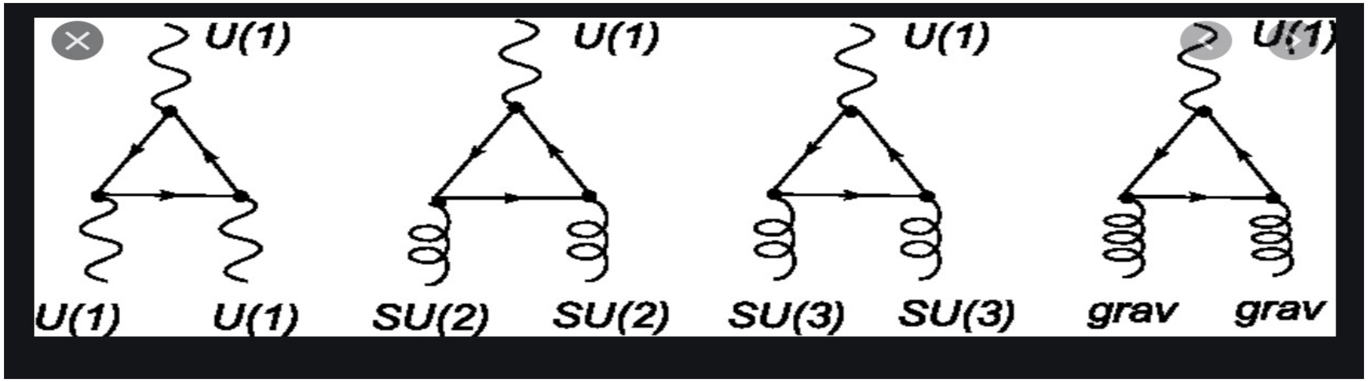
B-L

(Marshak, Mohapatra. 1979
Davidson, 1979)

(Subject of this talk)

Why B-L ?

- An important property of the SM is triangle anomaly cancellation:



- $Tr[Q_a \{Q_b,Q_c\}]=0$ for SM
- All gauge anomalies cancel and ensure renormalizability→ experimental tests

How to understand Neutrino mass?

- SM predicts m_ν=0.

- This is due to the chiral property of SM: Only Left handed neutrino is there in SM. So no nu mass possible. To get mass, add right handed neutrino N

Add RH nus N to SM

- Add Three right handed neutrinos (RHN) to SM→ new anomaly free symmetry, B-L emerges.
- $Tr[(B\text{-}L)\{Q_a , Q_b\}]=0$ (true in SM)
- $Tr[(B\text{-}L)^3]=0$ (not true in SM but true in SM+N)
- Implies B-L is a gaugeable symmetry!!

Suggests new theory beyond SM

- Suggests extending the standard model to

  G = $SU(2) \times U(1) \times U(1)_{B-L}$

- B-L → small nu mass via type I seesaw mechanism.

Nu mass from B-L

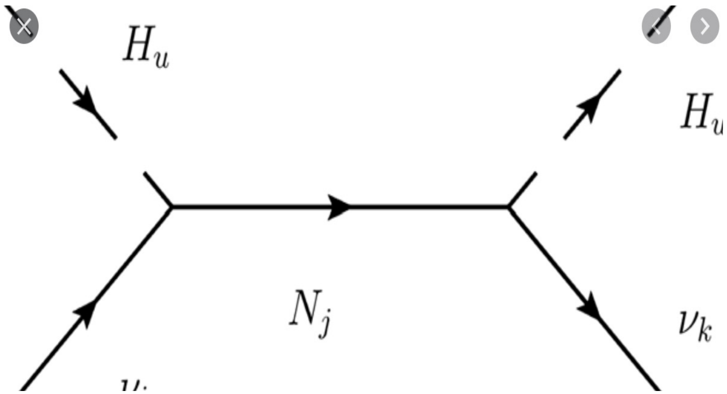
$$\mathcal{L}_Y = h\bar{L}HN + M_N NN + h.c.$$

M_N is a Majorana mass for RHNs and arises from breaking of B-L symmetry much as quark masses arise from breaking of SM symmetry. $M_N = f v_{BL}$

Neutrino mass from B-L

- Small neutrino mass via type I seesaw uses breaking B-L symmetry

$$m_\nu \simeq \frac{(h_\nu v_{wk})^2}{f v_{BL}}$$



(Minkowski; Mohapatra, Senjanovic; Yanagida; Gell-Mann, Ramond, Slansky)

Neutrinos allow two B-L paths

(i) Depends what first U(1) is. If it is $U(1)_{I_{3R}}$ i.e $G=SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$, then B-L contributes to electric charge (Type I B-L) i.e.

$$Q = I_{3L} + I_{3R} + \frac{(B-L)}{2}$$

- This implies→ $$\boxed{\frac{1}{e^2} = \frac{1}{g_L^2} + \frac{1}{g_R^2} + \frac{1}{g_{BL}^2}}$$
- → hence a lower bound on $g_{BL} > 0.34$

Embeds into Left-right models

- Gauge group: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- Number of nice features: (in addition to nu mass seesaw)

(i) Parity is a good symmetry of nature

(ii) Solves strong CP problem without axion

Predicts a W_R and Z' (LHC lower bounds their masses in the few TeV range.

Second kind of B-L (Type II)

(ii) If first U(1) is $U(1)_Y$, then B-L does not contribute to electric charge: $Q=I_{3L}+Y/2$ but B-L breaking still gives seesaw and hence explains small neutrino masses.

- In this case, g_{BL} can be arbitrarily small;
- The Z' can also be light as can the Higgs
- This parameter domain of model can also explain both neutrino mass and dark matter, so is as relevant as the heavy mass domain.

Both kinds can be embedded in SO(10)

$SO(10)$

$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{BL}$ $SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_{BL}$

SM

Type II B-L model details

- SM+3N $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ $u_R, \; d_R, \; e_R$ +N

G $= SU(2) \times U(1)_Y \times U(1)_{B-L}$

- Higgs sector: $\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $< \phi^0 >= v$ B-L=0
- B-L breaking Higgs; Δ (B-L=2); < Δ>=v_{BL} >> v
- $M_N = f v_{BL}$ gives seesaw

& $M_{BL} = 2 g_{BL} v_B$

$$m_\nu \simeq \frac{(h_\nu v_{wk})^2}{f v_{BL}}$$

Lagrangian

- $\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{kin} + \mathcal{L}_Y - V(\phi, \Delta)$

$$\mathcal{L}_Y = h_u \bar{Q} \phi u_R + h_d \bar{Q} \tilde{\phi} d_R + h_e \bar{L} \tilde{\phi} e_R + h_\nu \bar{L} \phi N + f N N \Delta \ + \ h.c.$$

$$V(\phi, \Delta) = -\mu_\phi^2 \phi^\dagger \phi + \lambda_1 (\phi^\dagger \phi)^2 - \mu_\Delta^2 \Delta^\dagger \Delta + \lambda_2 (\Delta^\dagger \Delta)^2 + \lambda' \phi^\dagger \phi \Delta^\dagger \Delta$$

- Last two terms in $\mathcal{L}_Y$ give seesaw and are also important for DM discussion.

New particles in the theory

- When Δ field gets vev v_{BL}, we have:
- $\Delta = \varphi + i\zeta + v_{BL}$
- ζ gets absorbed as the longitudinal mode of the B-L gauge boson **Z_{BL}** and **φ** are new physical fields;
- φ can mix with SM Higgs *h* via a mixing angle $\sin\vartheta$.
- Four new parameters: $M_{Z_{BL}}, m_\varphi, g_{BL}, \vartheta$
- What else is new and how can experiments probe the different parameter ranges of this theory.

Testing at LHC : generic range

(i) $M_{Z_{BL}} > 2M_N$

Production: pp→Z_{BL} +X

signature: Z_{BL} →ll, qq,...NN

$$\frac{M_{Z_{BL}}}{g_{BL}} \geq 6\mathrm{TeV}$$ (LHC)

No signal !

Small g_{BL} and MeV Z_{BL}

- Why small g_{BL}? Apparently large volume compactification in string theories lead to tiny gauge couplings:
- For us, it allows a dark matter (RNM, Okada'2020)
- Allows experimental probes by looking for long lived particles in colliders;
- Anyway LHC or DM searches have not found anything in the TeV scale domain! So why not look in the light mass range.

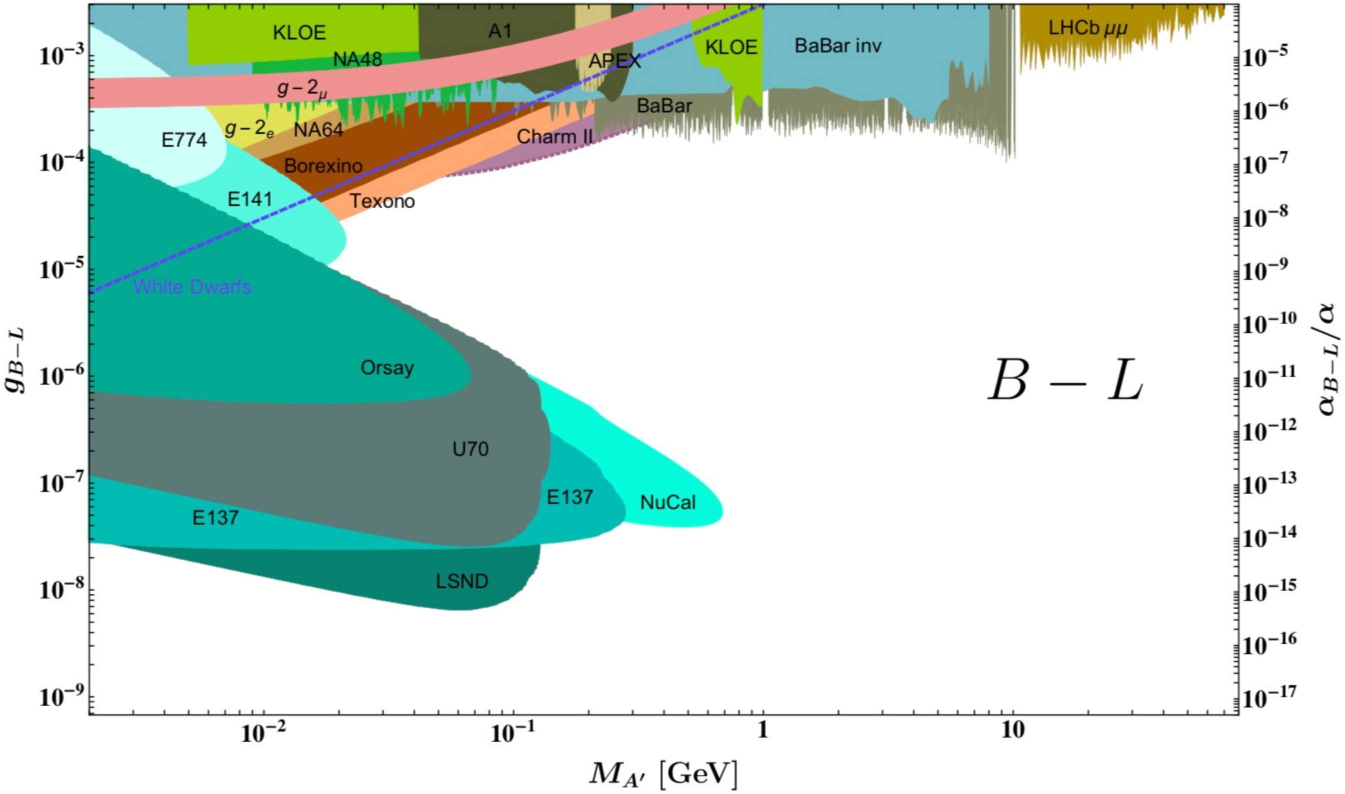
(ii) $m_N >> m_\varphi > 2M_{Z'}$

- We focus in the low $M_{Z'}$ (<1 GeV) and low g_{BL} range.
- $Z' \rightarrow e^+ e^-$, $\mu\mu, \pi\pi\pi$ etc; displaced vertices

- There already exist strong constraints from low energy experiments e.g. NA62(CERN), E141(SLAC), Babar, CharmII (CERN), KLOE(Frascati), E949(BNL),..

Limits in range II (pure Z')

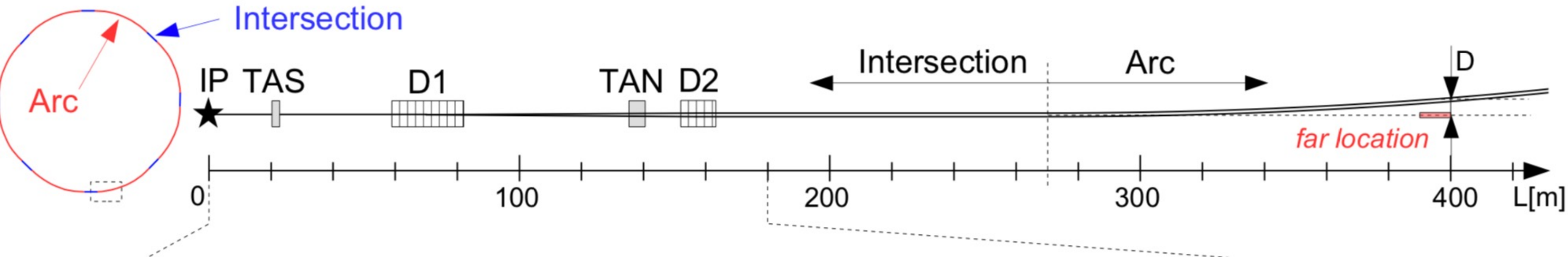
- .(Bauer, Foldendeur, Jaeckel'18)



Two new expts looking for such particles

- FASER at LHC
- DUNE at Fermilab

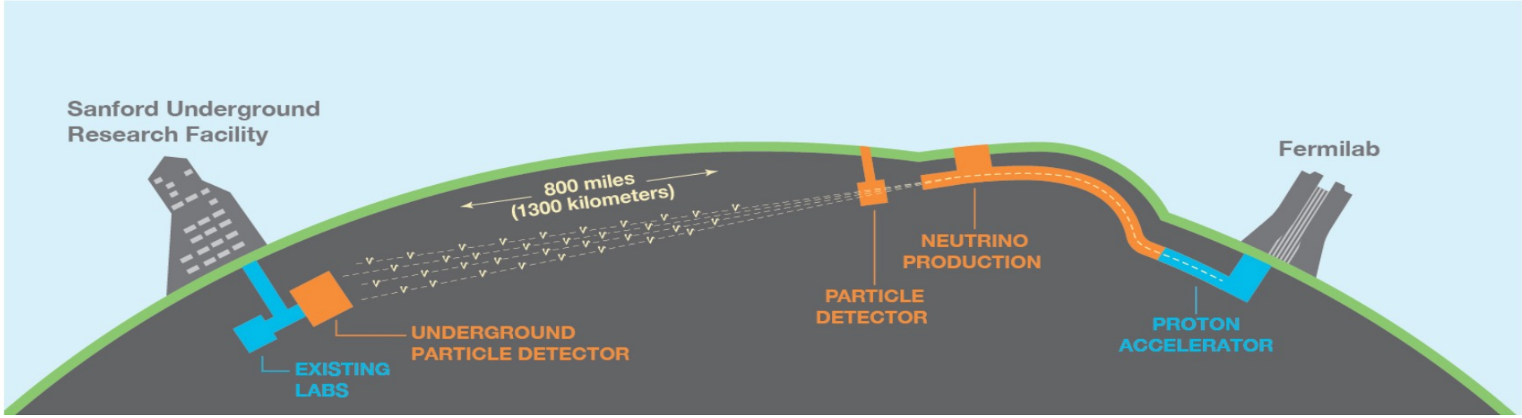
FASER is a detector near ATLAS at LHC



Feng, Kling, Stroyanoski

DUNE and LLP study

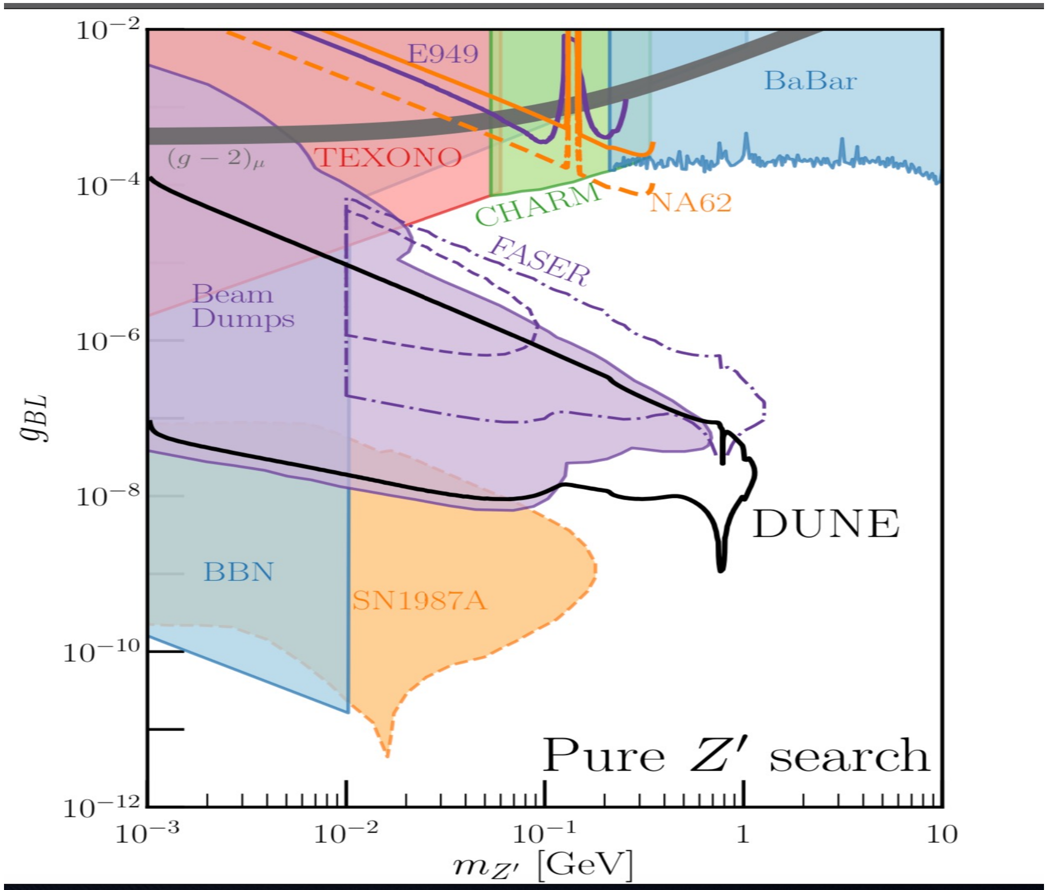
- Fermilab neutrino expt



- Near detector; Z′ produced in the target in decays of $\boldsymbol{\pi}, \boldsymbol{\eta} \;--\!\!\rightarrow\; \boldsymbol{\gamma} + \boldsymbol{Z'}$, also pp →ppZ′;
- Due to small g_{BL}, Z′ decays displaced from production point at detector located ~500 m away

DUNE prospects for Z′ search

- (.Kelly, Y. Zhang, Dutta,Dev, RNM arXiv:2104.07681 JHEP to appear)



New Higgs and its impact

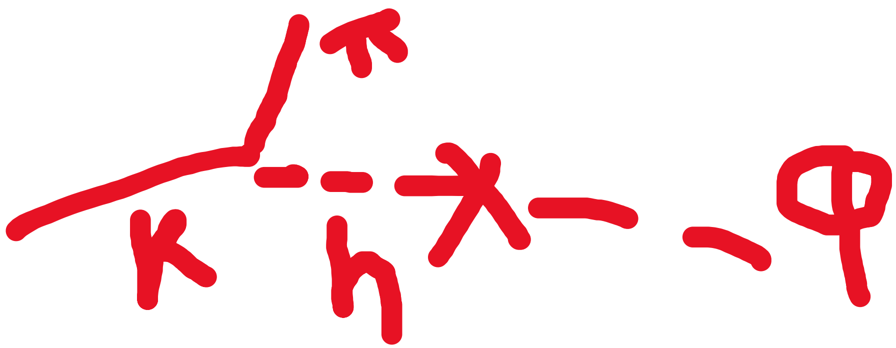
- Higgs φ can mix with SM Higgs and can decay to two Z' s if kinematically allowed.
- This has impact on its search and also other properties of Z'
- For the dark matter discussion later, we will ignore Higgs mixing. (set $\vartheta = 0$)

- How to look for the new Higgs?

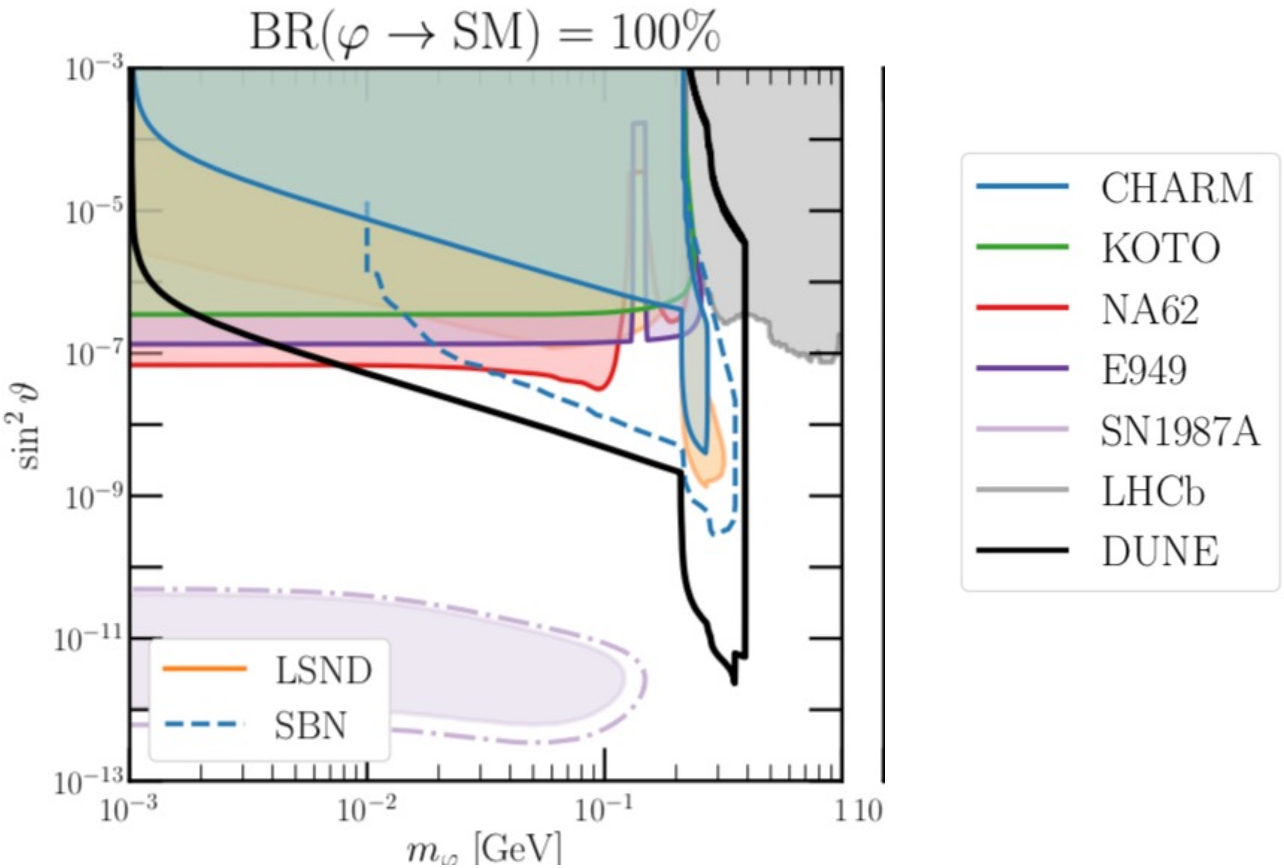
Current constraints on the new Higgs in low mass regime

- It can be produced in K decay experiments e.g NA62 at CERN, E949 at BNL via h-mixing
- It can be produced in beam dump

Experiments (CHARM)



Different collider expts



(Kelly et al'21)

Impact of scalar on Z′ search

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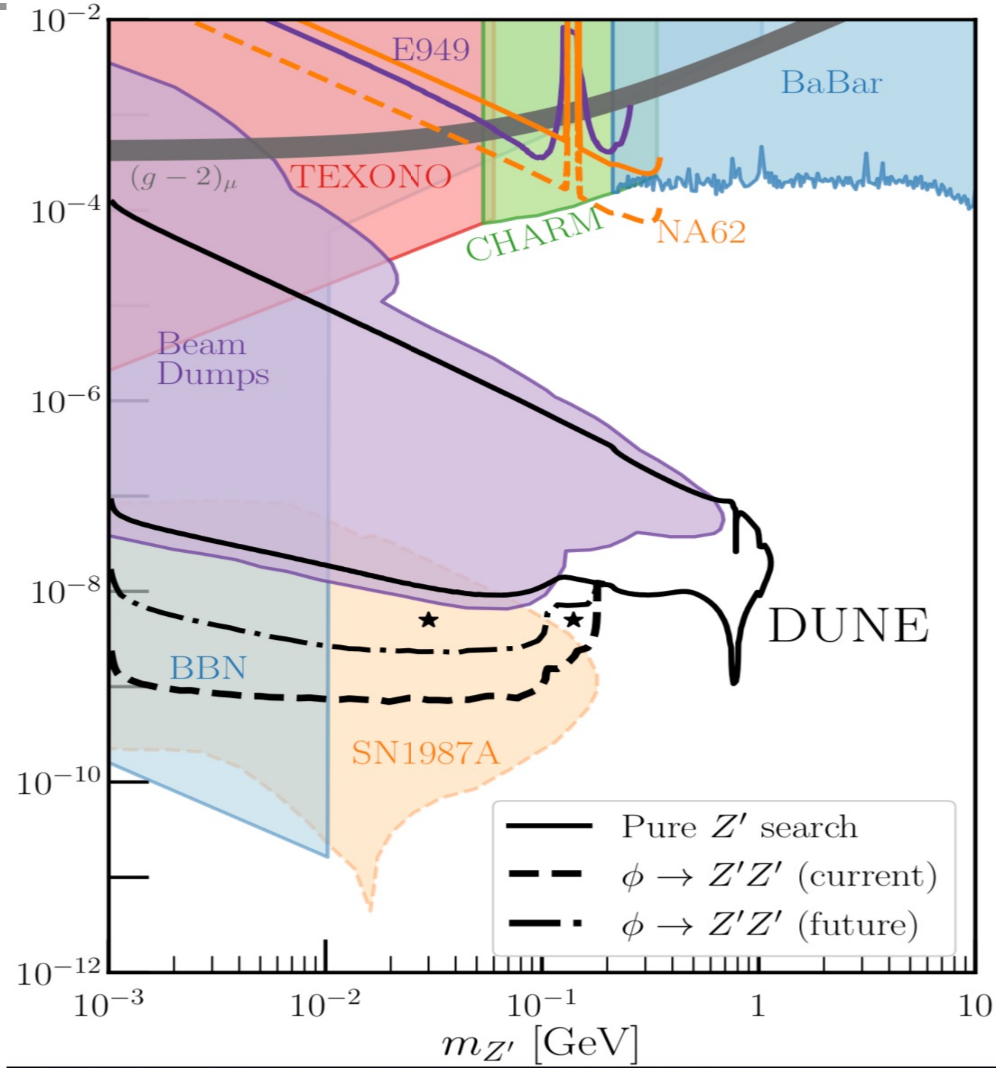


Dark Matter and B-L

(i) Add a vector-like fermion coupled to B-L;

- It is electrically neutral and stable and can be a dark matter

(ii) The Higgs in the minimal model can be a dark matter

Does the model have a dark matter particle?

- Yes, it is the φ , particle, the B-L Higgs field

(RNM, N. Okada'2020)

Two most important properties of DM are:

- (i) It must be stable or very stable: For us, it needs investigation since. φ connects to particles e.g. N, Z′ →implies constraints on model parameters
- (ii) It must be electrically neutral

Stability of Dark matter

- DM decays and eventually→ gamma rays;
- Fermilat looked for energetic gamma rays from dSph galaxies- satellites of Milkyway –
- Allows to put a strong limit on DM lifetime
- $\tau_\sigma > 10^{25}$ sec.

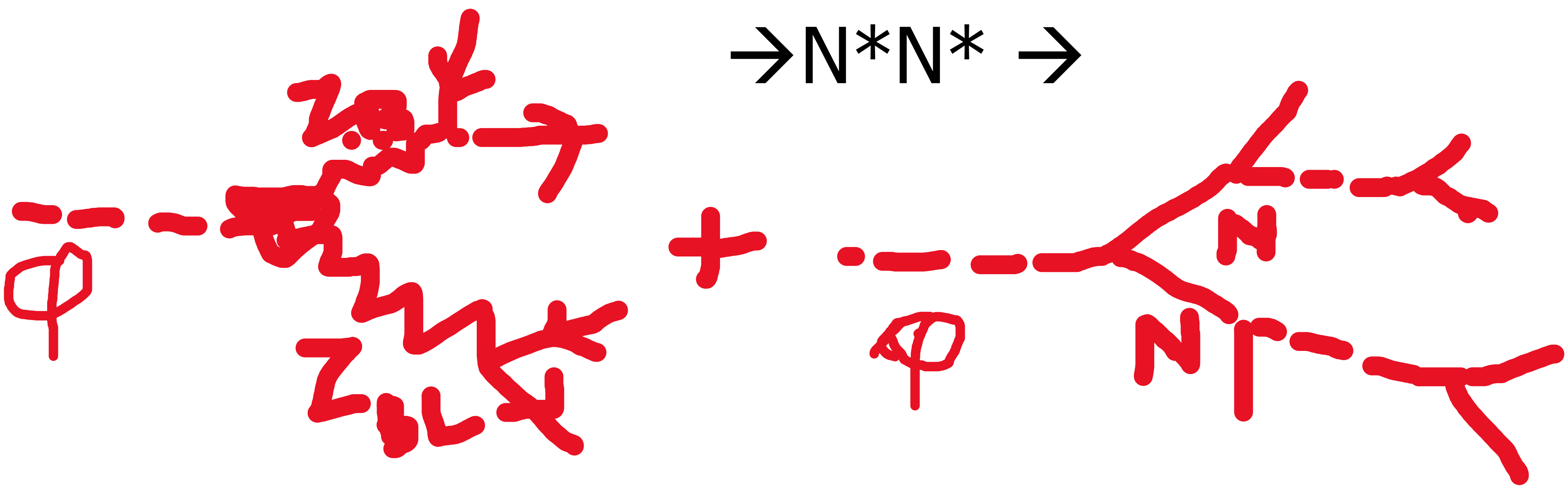
(Dugger, Jeltema, Profumo, 2010; Baring, Ghosh, Queiroz, Sinha'2015+…..)

- Can we satisfy this limit in the model? What are the constraints?

φ decays via N, Z_{BL} mediation. Is lifetime long enough?

- Assume $m\varphi << M_N$, M_{ZBL}: keep $\varphi\ \varphi$ HH coupling tiny $(\vartheta = 0)$
- Decay modes of φ: $\varphi \rightarrow 2Z^*_{BL} \rightarrow ffff$ (SM fermions)

  $\rightarrow N^*N^* \rightarrow$



RNM and N. Okada'20

φ lifetime→ Z_{BL} , N mediation

- Assume mφ<< M_N , M_{ZBL}: keepφ φ HH tiny.
- Decay modes of φ:φ→2Z^*_{BL} →ffff (SM fermions)

→N*N* →ffffff

$$\Gamma_{Z_{BL}Z_{BL}} \simeq \frac{g_{BL}^8 v_{BL}^2 m_\sigma^7}{(2\pi)^5 M_{BL}^8}$$

Prefers light DM; low g_{BL} coupling

$$\Gamma_{NN} \simeq \frac{(f h^2 h_{SM}^2)^2}{(2\pi)^8} \frac{m_\sigma^{13}}{M_N^4 M_h^8}$$

Easily satisfied

Life time Constraints on g_{BL}

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$$g_{BL} \leq 10^{-7.5} \left(\frac{M_{Z_{BL}}}{\text{GeV}}\right) \left(\frac{\text{GeV}}{m_{\varphi}}\right)^{7/6}$$

- Low DM mass ~ MeV-GeV, low M_{ZBL}~ 10 MeV-100 GeV, one preferred region.
- (low g_{BL} ~10^{-7}-10^{-4} ; M_N ~TeV; v_{BL} ~10^6 GeV; f~10^{-3}).

Radiative h and φ mixing?

- It comes from $\lambda' \phi^\dagger \phi \Delta^\dagger \Delta$ term in potential.
- Tree level set $\lambda'=0$; implied by high scale SUSY.
- At 1 loop level, no gauge induced terms;
- Fermion induced term ~$f^2 h^2/16\pi^2$ which is ~10^{-20} for our benchmark choice of parameters.

- Tiny h- φ mixing consistent with life time requirement.

Next requirement: right relic densiy of DM: $\Omega_{DM} h^2 = .12$

- Usual WIMP scenarios: thermal freeze-out;
- Typically DM is in equilibrium for $T > M_{DM}$.
- As T goes down, DM+DM→ff freezes out and
- n_{DM} becomes Dark matter of the universe now.
- Works for larger couplings, when DM decays fast and is no more a dark matter.
- Our couplings are small due to lifetime constraint- then it is not in equilibrium in the early universe-so how do we get relic density?

Freeze-in scenario

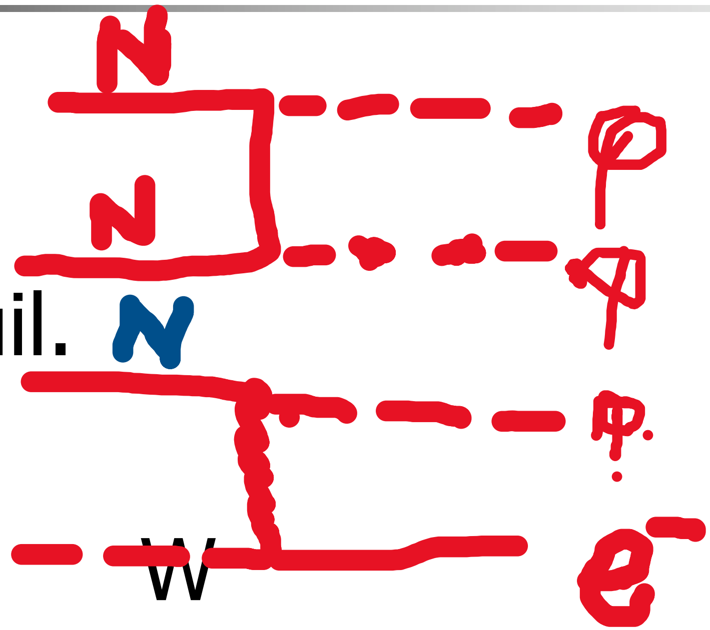
- DM was not in equilibrium with SM in early universe but Z_{BL} which weakly interacts with DM was. They slowly produce the DM until DM density builds up. (Hall, Jedamzik, March-Russell, West'2010)
- Condition for Z_{BL} eq. with ff→Z_{BL} Z_{BL}

$$2.7 \times 10^{-8} \left(\frac{M_{BL}}{\text{GeV}}\right)^{1/2} \leq g_{BL} \leq 6.4 \times 10^{-5} \left(\frac{M_{BL}}{\text{GeV}}\right)^{1/4}$$

- But φ: φ→ Z_{BL} Z_{BL} not in equilibrium for freeze in to apply→ upper bound

Other constraints on model for freeze-in to work

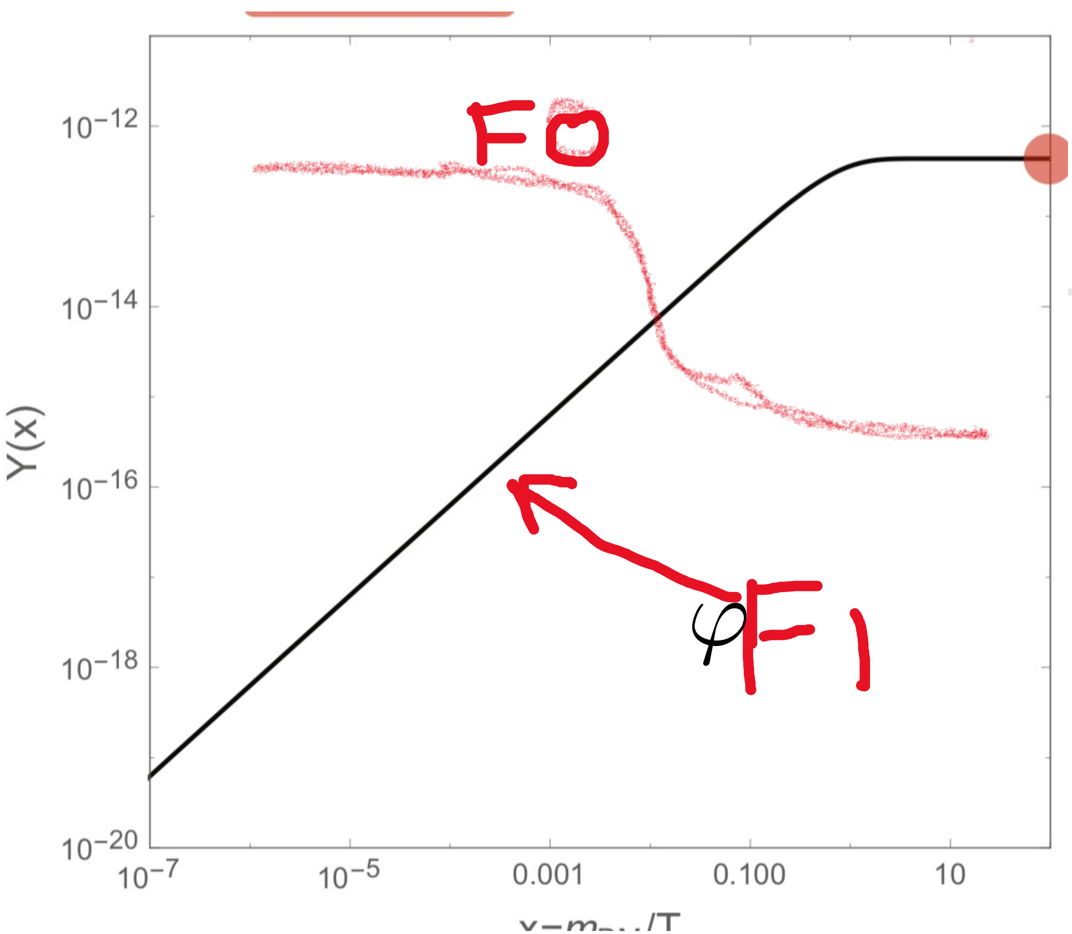
- Processes that need to be out of equil. for freeze-in



$$\sim \frac{f^2}{v_{BL}^2}$$

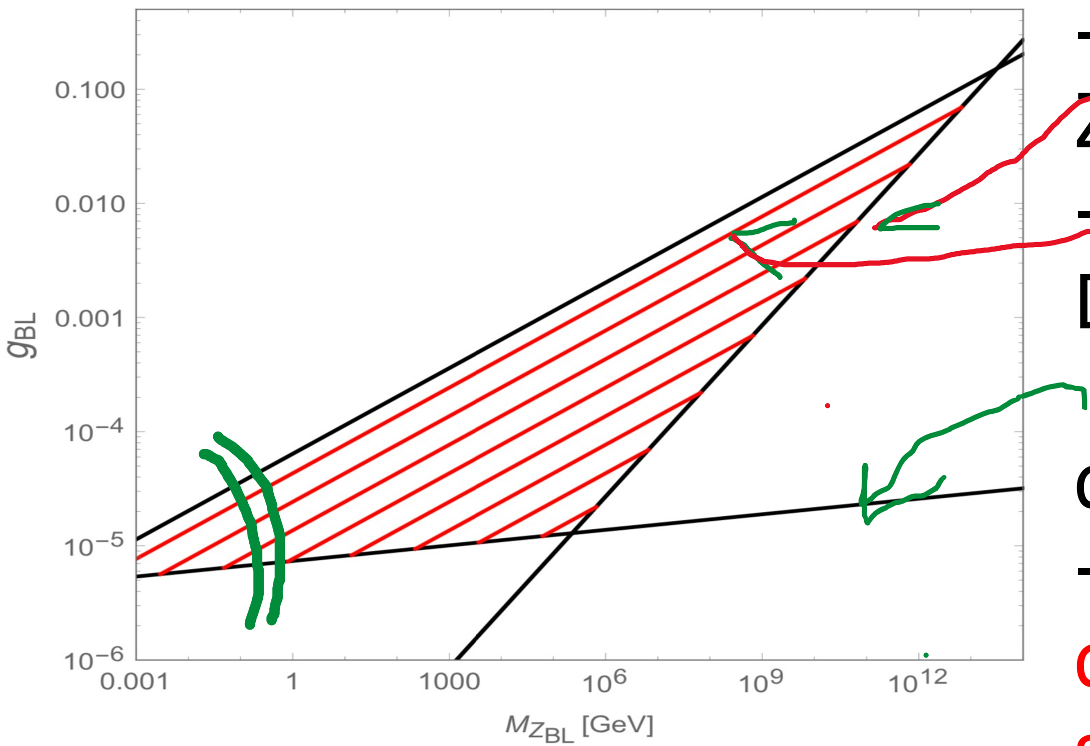
$$\sim \frac{h_e^2}{v_{BL}^2}$$

- These processes weaker than $Z_{BL}\, Z_{BL} \rightarrow \varphi\, \varphi$
- typical values: $f \sim 10^{-3}$, $v_{BL} \sim 10^6$ GeV; $g_{BL} \sim 10^{-5}$



$$g_{BL} \simeq 2.43 \times 10^{-6} \left(\frac{M_{BL}}{\text{GeV}}\right)^{1/4} \left(\frac{\text{GeV}}{m_{\varphi}}\right)^{1/4}$$

model parameters for right DM relic density and life time



- g_{BL} lower limit from Z_{BL} eq.
- g_{BL} upper limit from DM being out of eq.
- Lifetime limit+relic density
- Red lines are relic density constraints starting from 10 keV to 100 GeV DM (top to bottom);

Lower bound on Z_{BL} mass from relic density, lifetime

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$$m_{Z_{BL}} \geq 227 \left(\frac{m_\sigma}{\mathrm{GeV}}\right)^{11/9} \quad \mathrm{GeV}$$

Bottom line: DM could be anywhere from MeV to GeV, for Z_{BL} mass from few MeV – GeV range for $g_{BL} \sim 10^{-4}$ -10^{-7}

- Now focus on low mass range (testable)

Supernova constraints for M_{ZBL} < 100 MeV:

- $Q = n^2 <\sigma v> V <E> < 5\text{x}10^{53}$ ergs/sec.
- σv process is $ee \rightarrow eeZ_{BL} \propto (g_{BL})^2$
- The mean free path has to be less than 10 km
- Implies that $10^{-10} < g_{BL} < 10^{-7}$ disfavored by SN constraints.
- BBN constraints are also satisfied for

  $g_{BL}(> 10^{-5})$ for $M_{ZBL} > 10$ MeV

Super light Z_{BL} at LHC

- Small g_{BL} range, low mass Z_{BL} gives displaced vertices at LHC
- Production mode: pp→X (π, η); $\sigma \sim 75\, mb$
- (π, η)→$\gamma + Z_{BL}$, Z_{BL}→jj, ll,..
- For small g_{BL}, this is a displaced vertex
- Ideal detectors: FASER, SHIP set ups at LHC

Direct detection

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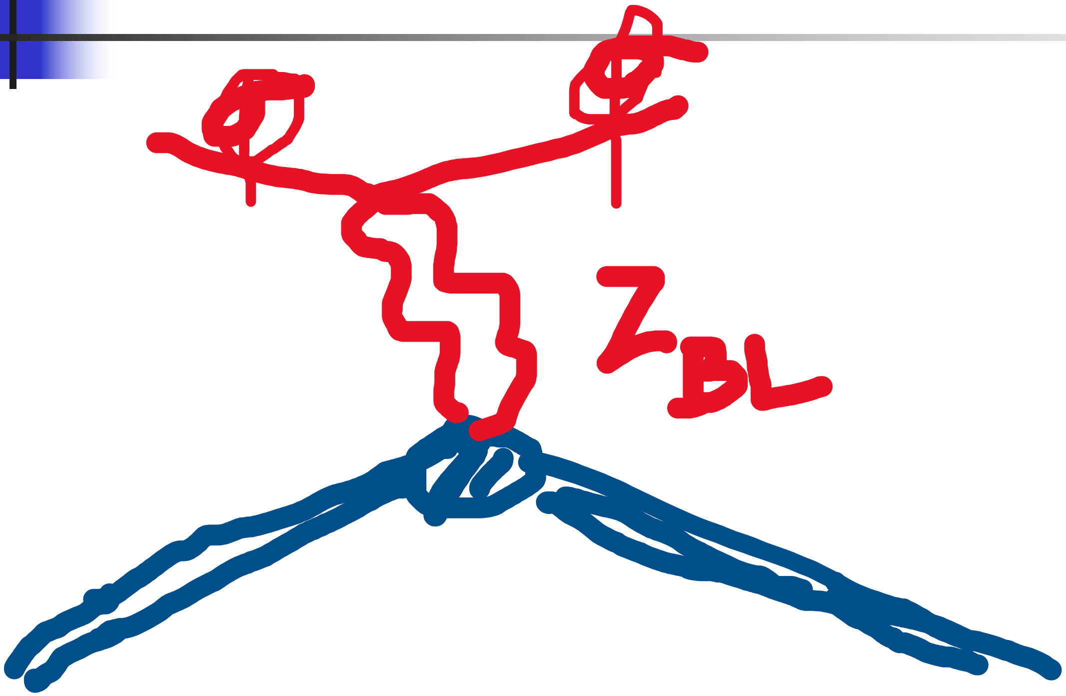

Rate much too small for our g_{BL} values to be observable

Could this theory originate from high scales?

- Seek a grand unified or higher dimensional space time origin of model ?

Rank 5 → SO(10) unification?

- Our gauge group $SU(3) \times SU(2) \times U(1)_Y \times U(1)_X$

- Assumed Chain: $SO(10) \rightarrow SU(5) \times U(1)_X \rightarrow SM \times U(1)_X$

- If X=B-L, cannot be grand unified since X is not orthogonal to Y i.e. $Tr\,(XY) \neq 0$

Rank 5 → SO(10) unification?

- $SU(3)xSU(2)xU(1)_Y\,xU(1)_X$
- If $X=-4I_{3R}+3(B-L)$, it is a generator of SO(10) together with Y to which it is orthogonal
- We can have $SO(10) \rightarrow SU(5)xU(1)_X$
- Some Y=0 scalar triplets and color octets added at TeV scale for non-susy SU(5) unif.
- Typically for such small g_{BL} , unification to SO(10) in 4-D is impossible.
- We assume at SU(5) scale, 5th dim opens up

5-D Picture

- Bulk has gauge fields and orbifold compactification.
- Branes at fixed points which have the fermions and Higgs fields.

Coupling unification

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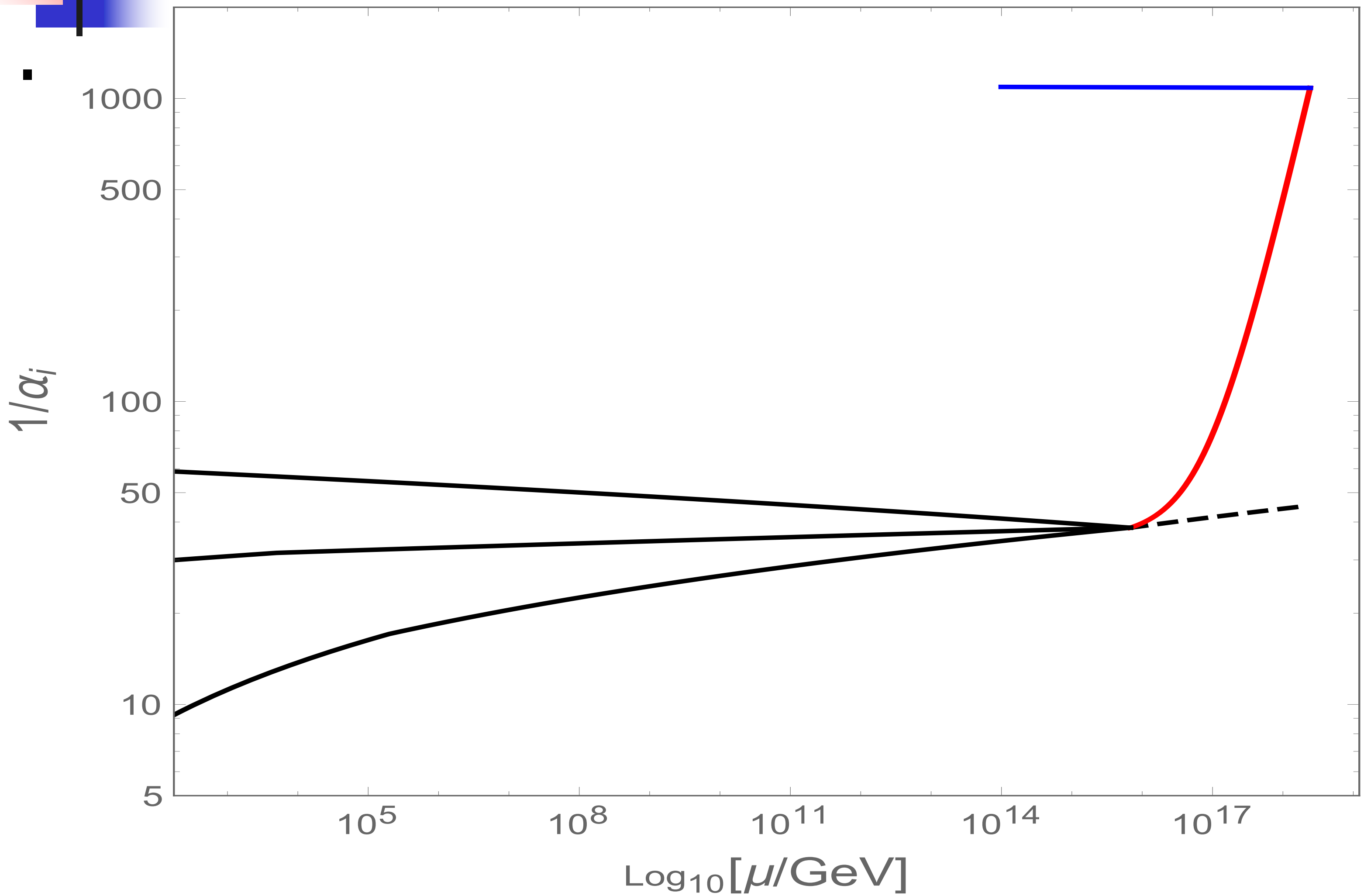


Proton decay prediction

- Proton decay gets contributions from KK modes which enhances its decay rate by a factor two. The prediction for $p \rightarrow e^+ \pi^0$

$$\tau_p \simeq \frac{\Lambda^4}{\alpha_{U}^2 m_p^5}, \qquad \tau_p \simeq 2.1 \times 10^{34} \text{ years}$$

$$\frac{1}{M_U^2} \to \frac{1}{M_U^2}\left(1 + \sum_{n=1}^{\infty} \frac{1}{1+n^2}\right) \simeq \frac{2.08}{M_U^2} \equiv \frac{1}{\Lambda^2}.$$

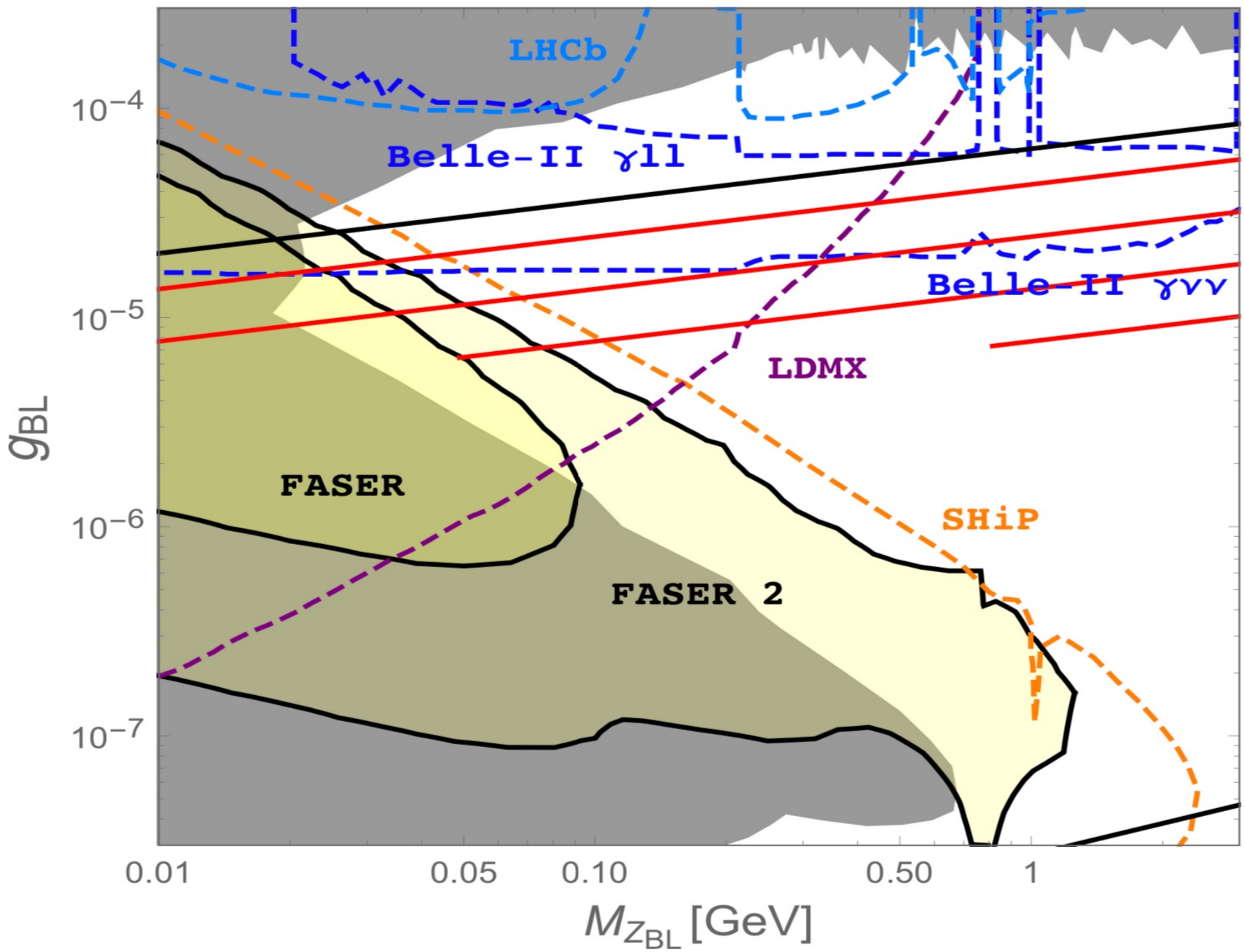
Summary

- Most likely there is a B-L symmetry in our future to explain neutrino mass
- The same model in low g_{BL} range can also explain dark matter using the Higgs that breaks B-L: "almost dark" Higgs DM
- Part of parameter region testable at the LHC
- An ideal set up to probe this small parameter range of model is DUNE near detector.
- GUT version can be checked by p-decay search

Thank you

Extra slides

FASER probes for low mass DM, Z_{BL} region



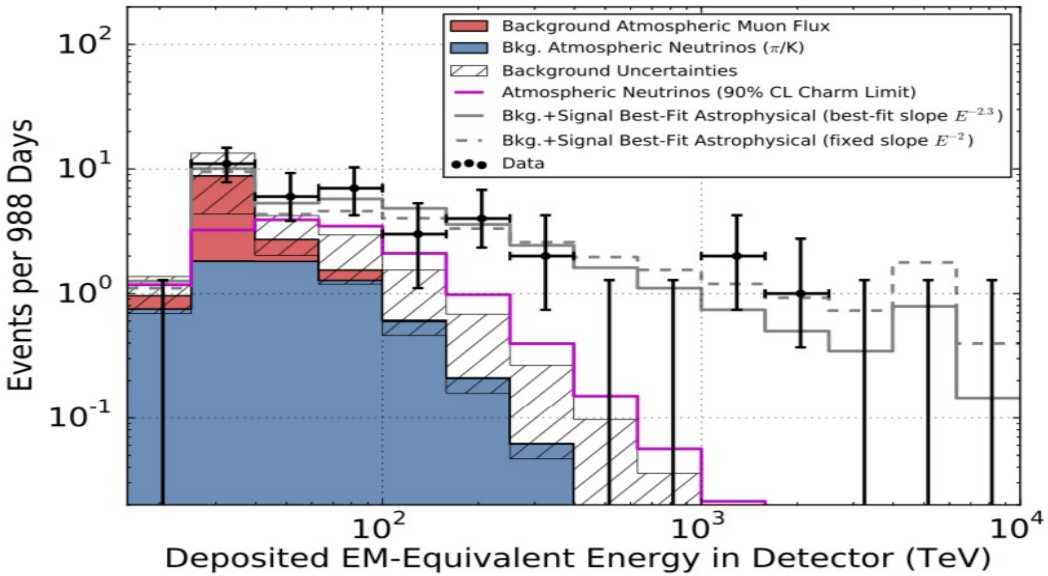
Grey Shaded regions ruled out by existing collider data: Bauer et al.'14

Red lines: DM mass 10 keV to 10 MeV

PeV DM possibility

Decaying PeV DMs have been of interest in connection with ICE CUBE observations of PeV neutrinos: Can our model be useful there?

ICE CUBE DATA



Model constraints for this possibility

τ_{DM}:

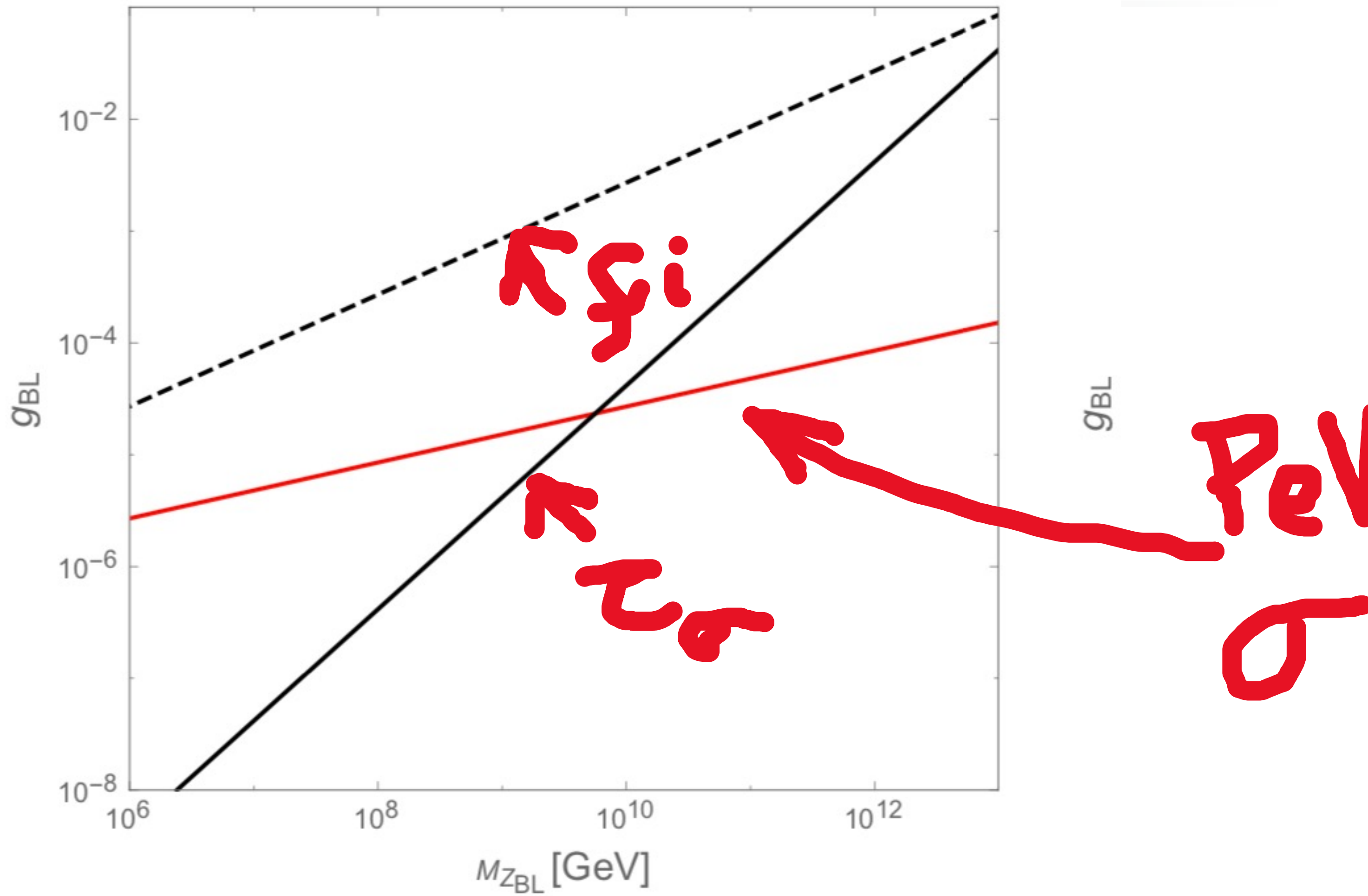
$$g_{BL} \leq 4.2 \times 10^{-8} \left(\frac{M_{Z_{BL}}}{1\,\mathrm{PeV}}\right) \left(\frac{1\,\mathrm{PeV}}{m_\sigma}\right)^{7/6}$$

Z_{BL} out of eq:

$$g_{BL} < 2.7 \times 10^{-8} \left(\frac{M_{Z_{BL}}}{\mathrm{GeV}}\right)^{1/2} .$$

Relic density:

$$g_{BL} \simeq 2.7 \times 10^{-6} \left(\frac{M_{Z_{BL}}}{m_\sigma}\right)^{1/4} .$$



10^-2
10^-4
10^-6
10^-8
g_BL
10^6
10^8
10^10
10^12
M_ZBL [GeV]
fi
PeV

PeV DM possibility works

Bench mark points: $M_{DM} = \text{PeV}$

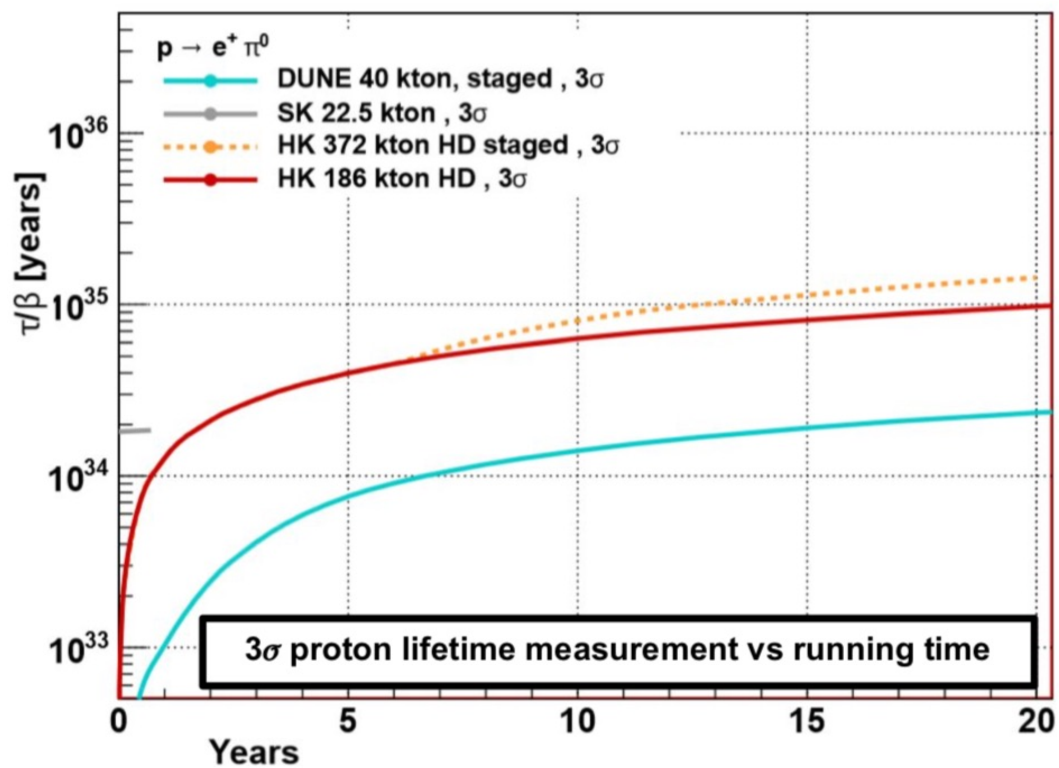
$M_{ZBL} = 10^{10}$ GeV

$v_{BL} = 10^{16}$ GeV

$g_{BL} \sim 10^{-5}$

Search for proton decay

- Current lower limit: $\tau_p > 1.6\text{x}10^{34}$ yrs.
- Hyper-K in Japan will go up another order and can test this theory.



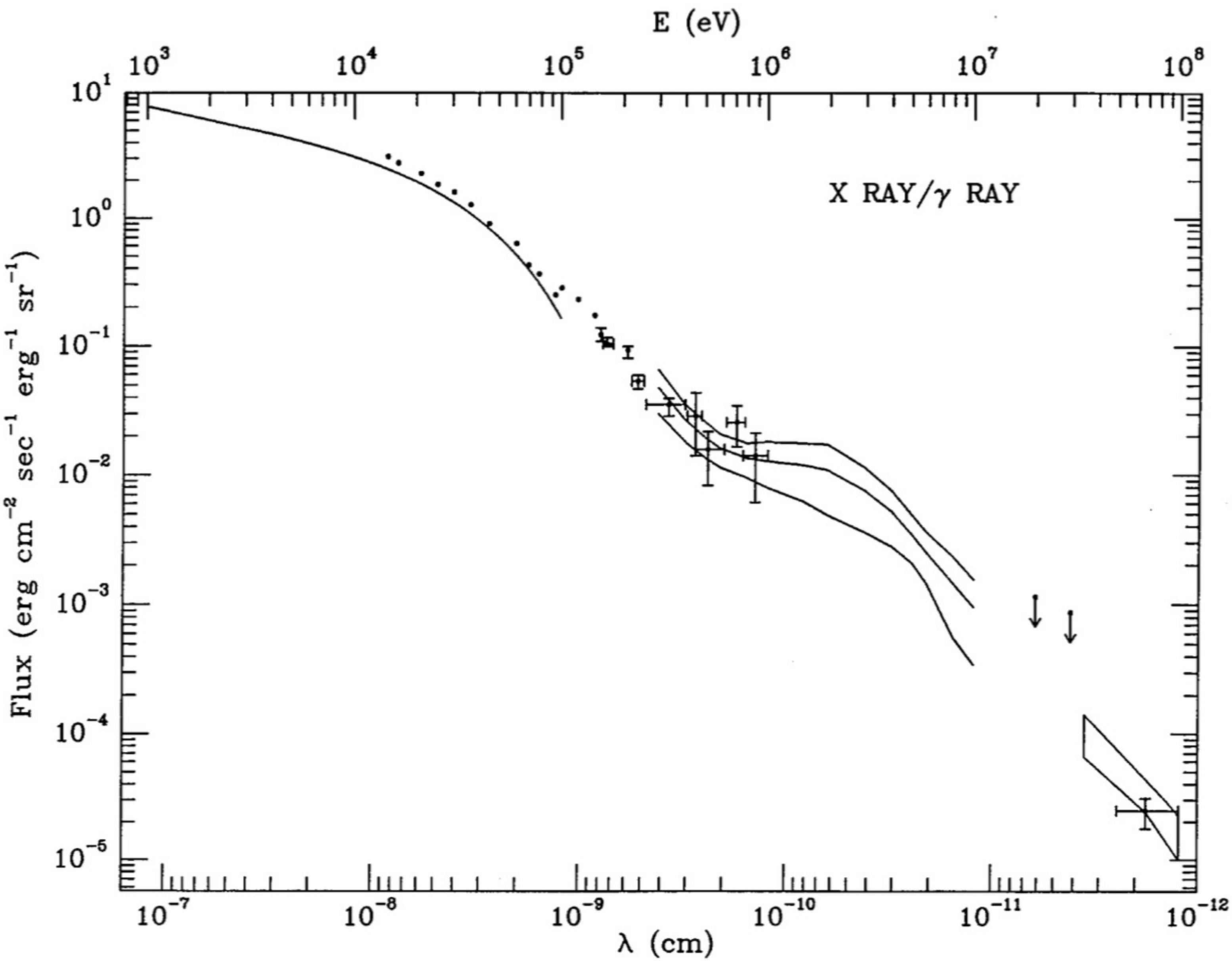

E (eV)
10^3
10^4
10^5
10^6
10^7
10^8
X RAY/γ RAY
Flux (erg cm^-2 sec^-1 erg^-1 sr^-1)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
λ (cm)

FIGURE 5