Physics Beyond Colliders - Theory

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Outline:

Physics Beyond the Standard Model

Beyond Colliders – Beyond the Standard Model

Portals and Effective Operators

Minimal Models

Evidence for BSM Physics

Neutrino Oscillations

-Imply that neutrinos have masses, which are absent in the Standard Model

- Can be generated, via the sea-saw mechanism, by including heavy sterile neutrinos

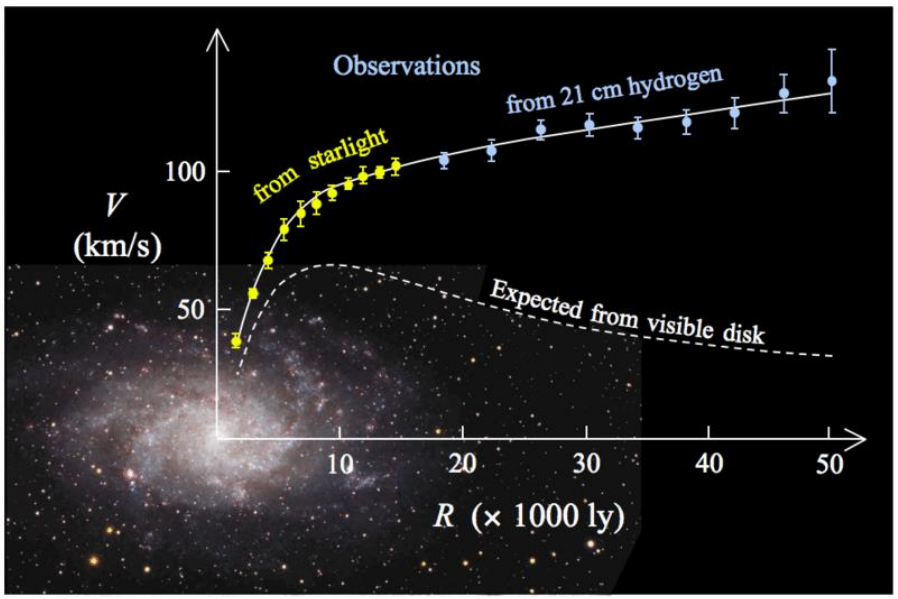
Abundance of matter, lack of anti-matter

- Requires: B number violation, C and CP violation, Out of thermal equilibrium
- Within the Standard Model not enough CP violation, not out of equilibrium enough (no strong 1st order EW phase transition)

Evidence for BSM Physics

Galactic Dynamics

- Requires new physics on galactic scales to explain rotation curves and make galaxies stable



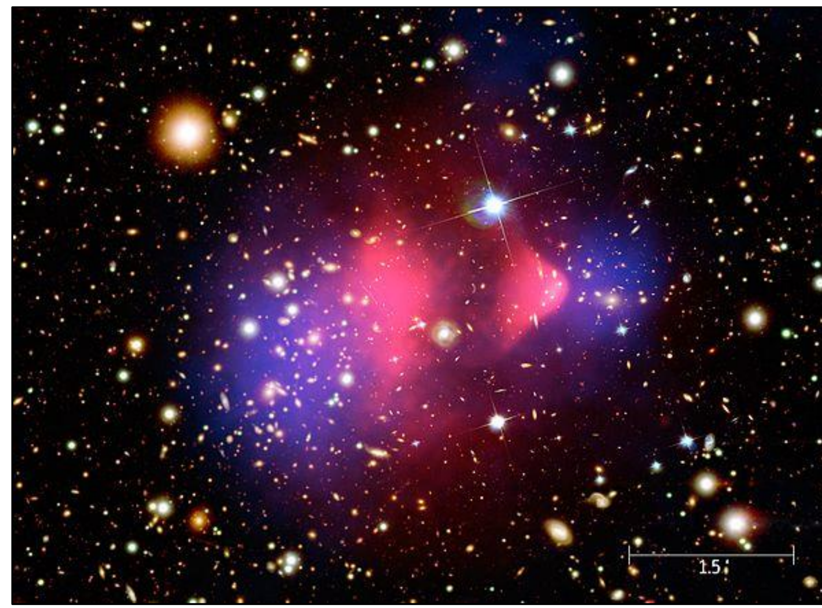


Image Credit: Stefania.deluca, XMASS 2018

Evidence for BSM Physics

CMB

- More non-relativistic matter than just baryons
- Density perturbations require period of inflation
- Power spectrum requires non-zero Λ

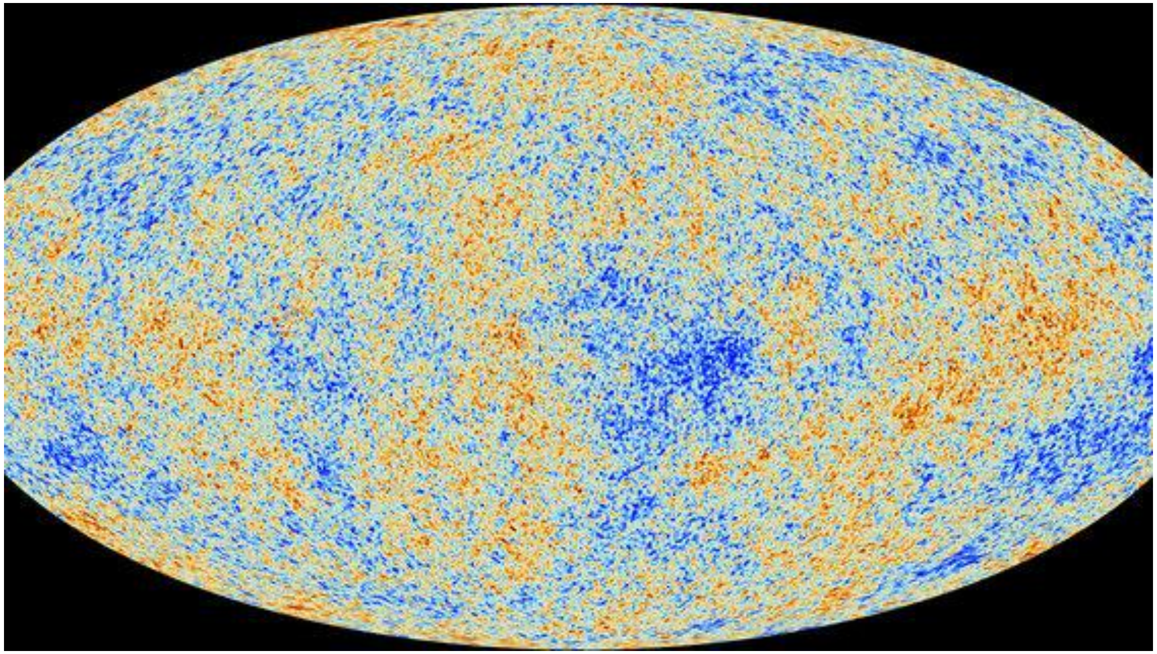


Image Credit: ESA/Planck

Evidence for BSM Physics

Higgs mass fine tuning

- No way to protect scalar masses from UV corrections
- Possible solutions include low scale SUSY, extra dimensions, dynamical relaxation
- Related: Stability of the cosmological vacuum

No evidence of strong CP violation

- Requires fine tuning of ϑ_{QCD}
- Dynamical explanation introduces pseudo-scalar axion
- Axion can also be dark matter

Evidence for BSM Physics

Muon magnetic dipole moment (g-2)

- Evidence only from one experiment, ~3.6 sigma signal
- Origins of anomaly could be uncoloured BSM physics at the EW scale, or light vectors / scalars at the muon mass

Fine tuning of the cosmological constant

- No robust theoretical explanation for small but non-zero cosmological constant
- Suggestion of new physics on very large scales?

What is the scale of new physics?

Current Hubble Scale ~ 10^{-42} GeV

1 / Galactic size ~ 10^{-36} GeV

Cosmological Constant scale ~ 10^{-12} GeV

Neutrino masses < 10^{-10} GeV

Higgs mass ~ 10^{2} GeV

Energy scale of Baryogenesis > 10^{3} GeV

Energy scale of Inflation > 10^{3} GeV

Planck scale ~ 10^{18} GeV

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Non-linearities reprocess scales

What is the scale of new physics?

Masses of right handed neutrinos

$10^{-9} - 10^{15}$ GeV

Mass of dark matter particle

$10^{-31} - 10^{20}$ GeV

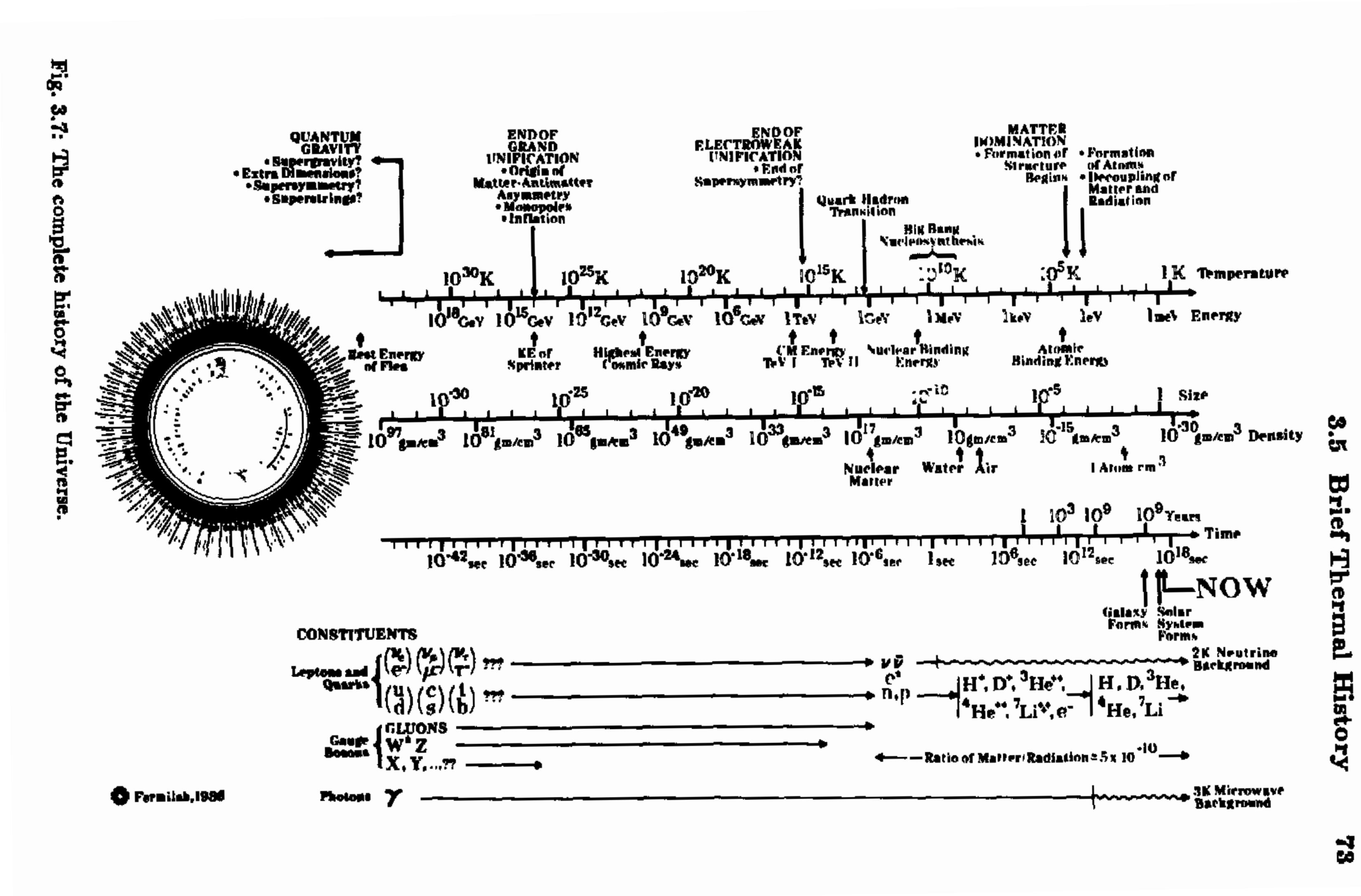
Mass of new particles required for baryogenesis

$10^{-2} - 10^{15}$ GeV

Mass of new particles for Higgs hierarchy

$10^{3} - 10^{18}$ GeV

The Complete History of the Universe

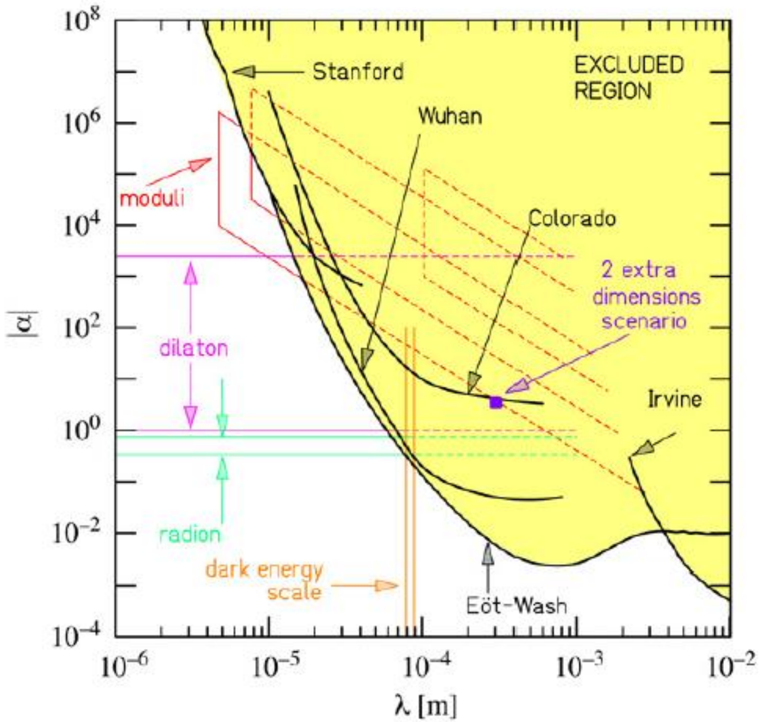


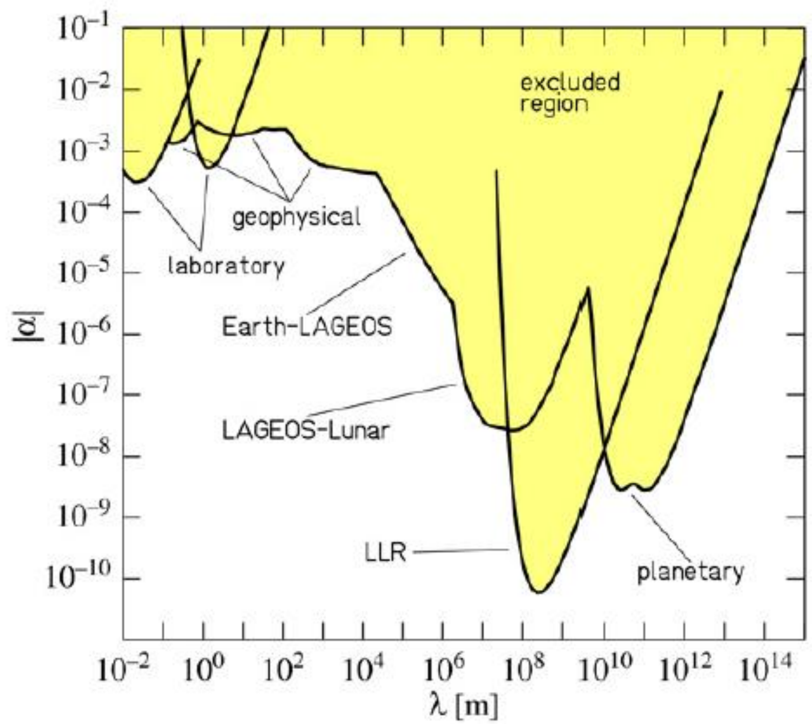
Kolb & Turner, The Early Universe, 1990

Beyond Colliders: Intensity and Precision

E.g. Gravitational experiments probing couplings at and above the Planck scale

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$





Adelberger et al. (2009)

Physics Beyond Colliders

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

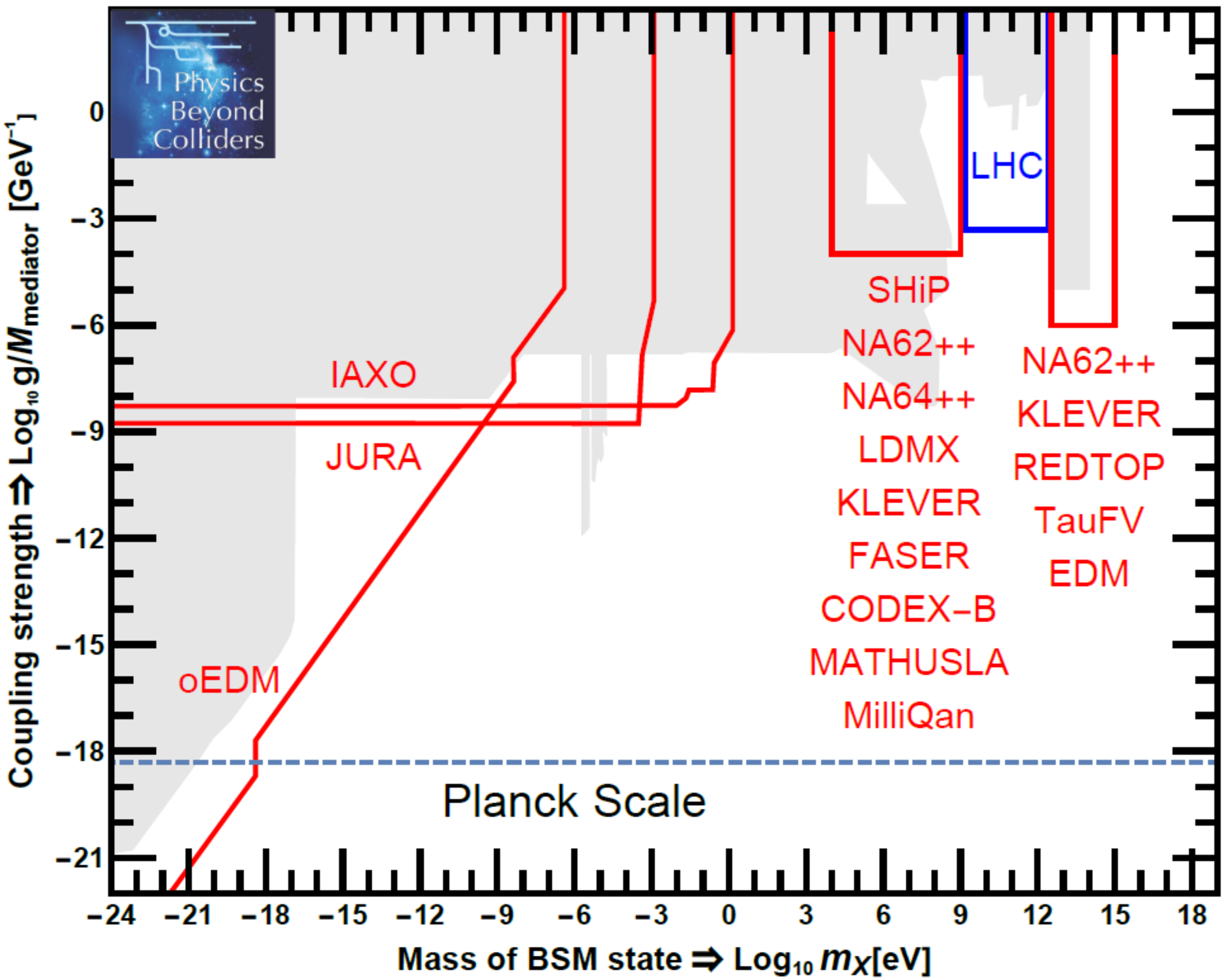
CERN-PBC-REPORT-2018-007

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].

arXiv:1901.09966

Physics Beyond Colliders: Overview



WEAKLY COUPLED PARTICLES

Benchmark models - Portals

Mên-an-Tol, Cornwall

Portals

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

Operator of standard model fields

Operator of dark sector fields

In the absence of a symmetry assume that lowest order operators will be most important

Vector Portals

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$$

Kinetic mixing parameter

Field strength of new U(1) gauge field

Hypercharge field strength

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 + |(\partial_\mu + i g_D A'_\mu)\chi|^2 + \ldots$$

Dark photon mass

Possible new matter field

Vector Portal Benchmark Models

- **BC1.** Minimal Dark Photon Model

  Only one new field.

  Dark Matter assumed to be elsewhere

  Dark Photons decay back to SM states

  Parameters: $m_{A'}$, ε

- **BC2.** Light Dark Matter Coupled to Dark Photon

  Minimally coupled WIMP dark matter

  Preferred values of dark coupling $\alpha_D = g_D^2/(4\pi)$ s.t. decay of dark photon is primarily into dark fermion states

  Parameters: $m_{A'}$, ε , m_χ , α_D

Vector Portal Benchmark Models

- **BC3.** Millicharged Particles

  Zero dark photon mass

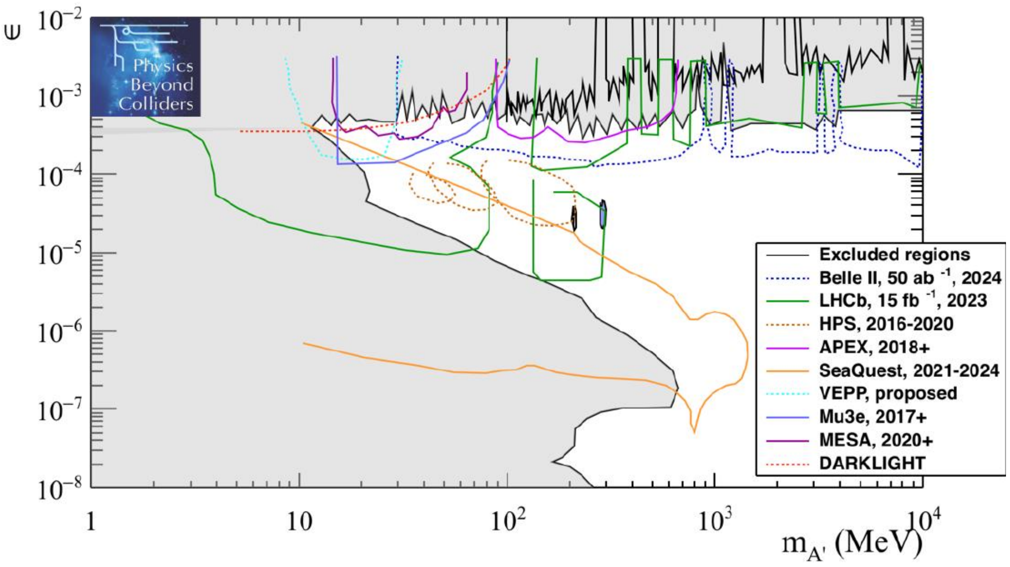
  Dark fermions get a small effective U(1) charge;

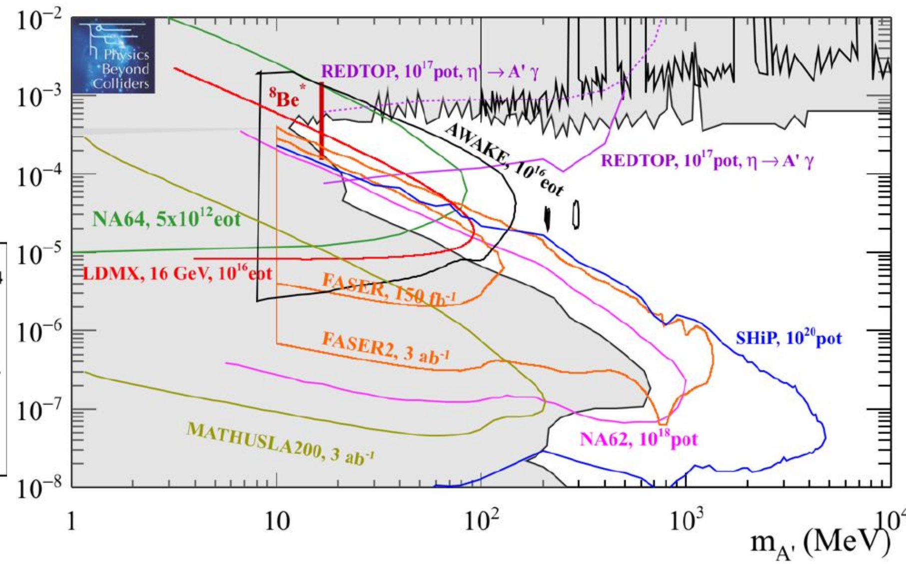
  $|Q_{\chi}|=|\varepsilon g_D e|$

  Parameters: m_{χ} , Q_{χ}/ε ,

BC1: Minimal Dark Photon

Once produced, dark photon decays to SM particles





Future Landscape

PBC 10-15 years

Scalar Portals

Only allowed 3 and 4 dimension operators interact with the Higgs

$$\mathcal{L}_{\mathrm{scalar}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DS}} - (\mu S + \lambda S^2) H^\dagger H$$

Higgs portal couplings

Dark sector may include dark (matter) fermion

$$\mathcal{L}_{\mathrm{DS}} = S\bar{\chi}\chi + \ldots.$$

After EW symmetry breaking, mixing of scalar with the Higgs. When this is small

$$\theta = \frac{\mu v}{m_h^2 - m_S^2}$$

Scalar Portal Benchmark Models

- **BC4.** Higgs Mixed Scalar

  No dimension four interaction

  Parameters: θ , m_S
- **BC5.** Higgs Mixed Scalar – Large Pair-Production

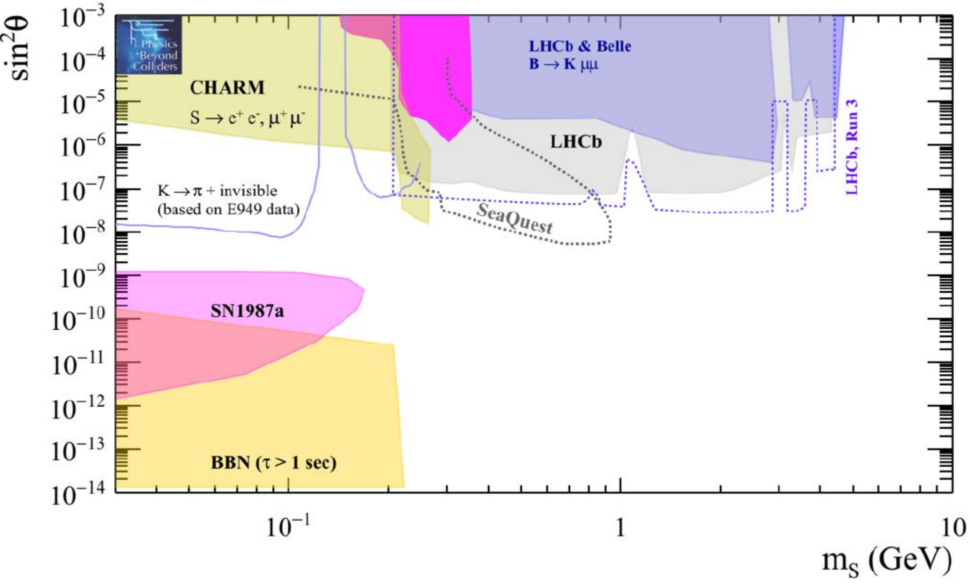
  Dimension four interaction dominates scalar production

  If, eg $\lambda \sim 5 \times 10^{-4}$, model avoids LHC direct searches

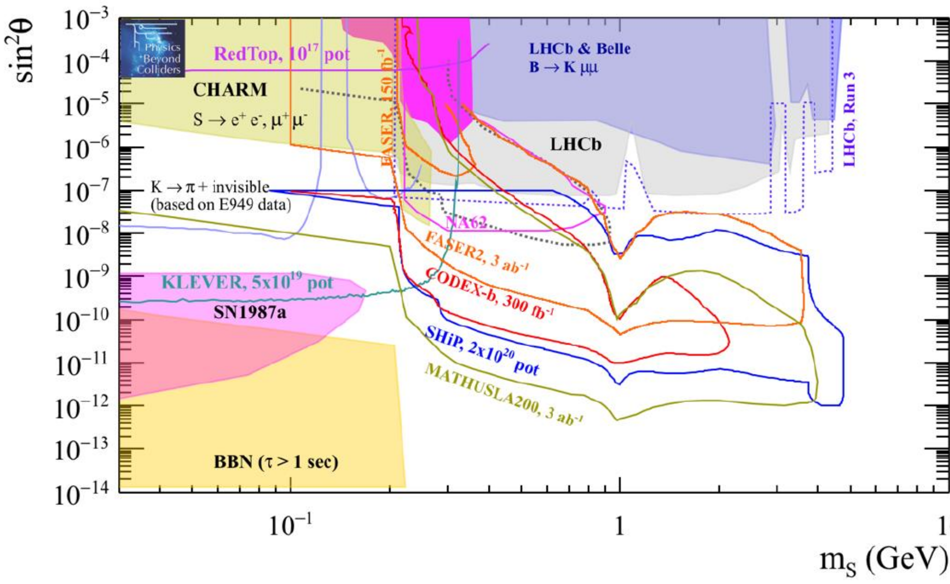
  Parameters: λ , θ , m_S

BC4: Higgs Mixed Scalar

Production via a large Yukawa, decay via a smaller, and so scalar long lived



Future Landscape



PBC 10-15 years

Neutrino Portals aka Heavy Neutral Leptons

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I}(\bar{L}_\alpha H)N_I$$

SM Lepton doublets

Heavy neutral lepton(s)

Dark sector Lagrangian can include both Dirac and Majorara mass terms for the HNLs

After EW symmetry breaking find mixing between neutrinos determined by matrix U

Assume U controls both production and decay

Neutrino Portal Benchmark Models

- **BC6.** Single HNL, electron dominance

  Parameters: m_N , $|U_e|^2$

- **BC7.** Single HNL, muon dominance

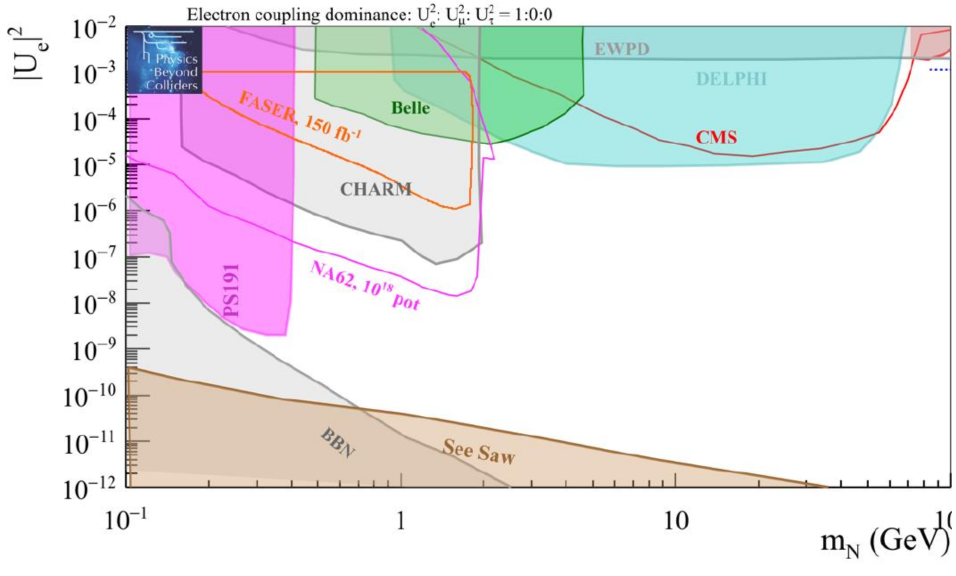
  Parameters: m_N , $|U_\mu|^2$

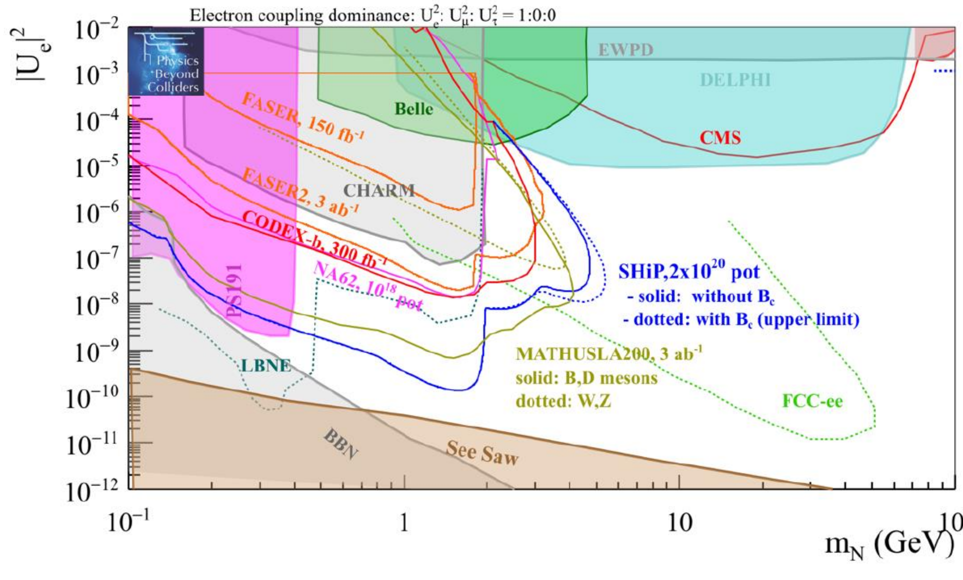
- **BC8.** Single HNL, tau dominance

  Parameters: m_N , $|U_\tau|^2$

BC6: HNLs Coupled to 1st Generation

Decay suppressed by G_F^2 compared to production, so naturally long lived





Future Landscape

PBC 10-15 years

Axion Portals – Pseudoscalar portals

Includes QCD axions, and axion-like particles

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4f_\gamma} F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G} \text{Tr} G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l} \sum_\alpha \bar{l}_\alpha \gamma_\mu \gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

Photon coupling

Gluon coupling

Lepton coupling

Quark coupling

Dark sector Lagrangian may contain new states required for UV completion

Cut off assumed to be 1 TeV

Axion Portal Benchmark Models

- **BC9.** Photon Dominance

  Dominant coupling to photons

  Parameters: m_a , $g_{a\gamma\gamma}=f_\gamma^{-1}$
- **BC10.** Fermion dominance

  Dominant coupling to fermions

  For simplicity assume $f_q=f_l$

  Parameters: m_a , f_l^{-1} , f_q^{-1}
- **BC11.** Gluon dominance

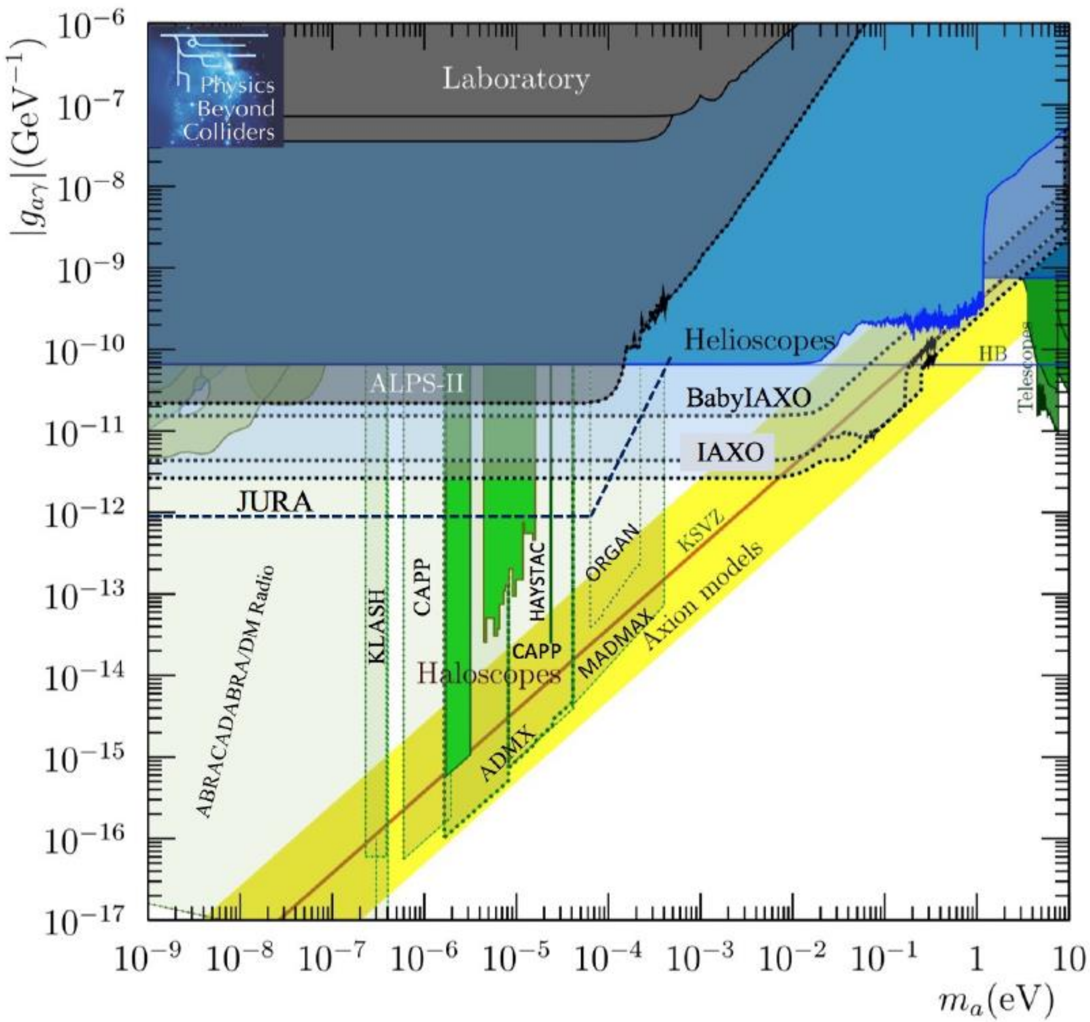
  Dominant coupling to gluons

  Requires fine tuning of axion mass

  Parameters: m_a , f_G^{-1}

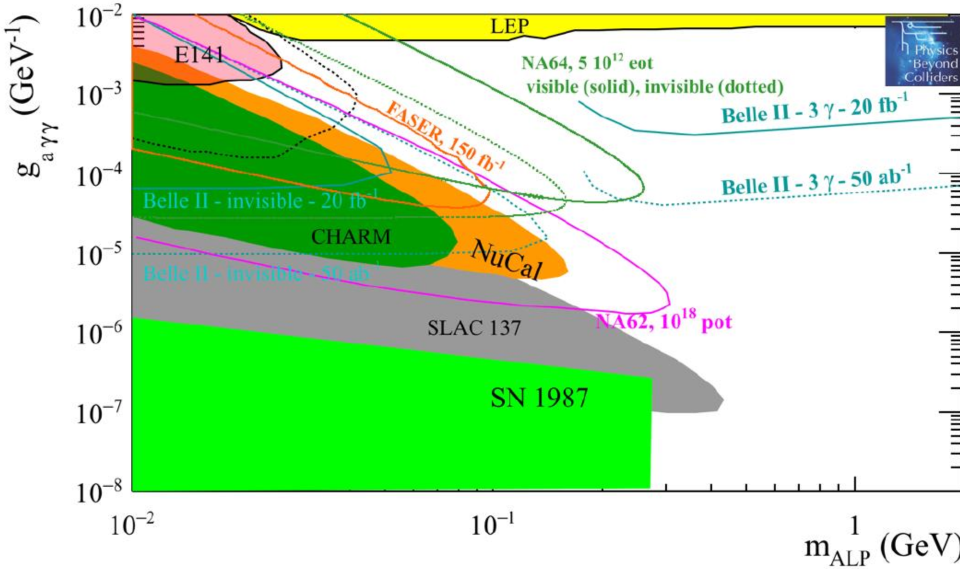
BC9: ALPs and photon couplings

Weak couplings and small masses

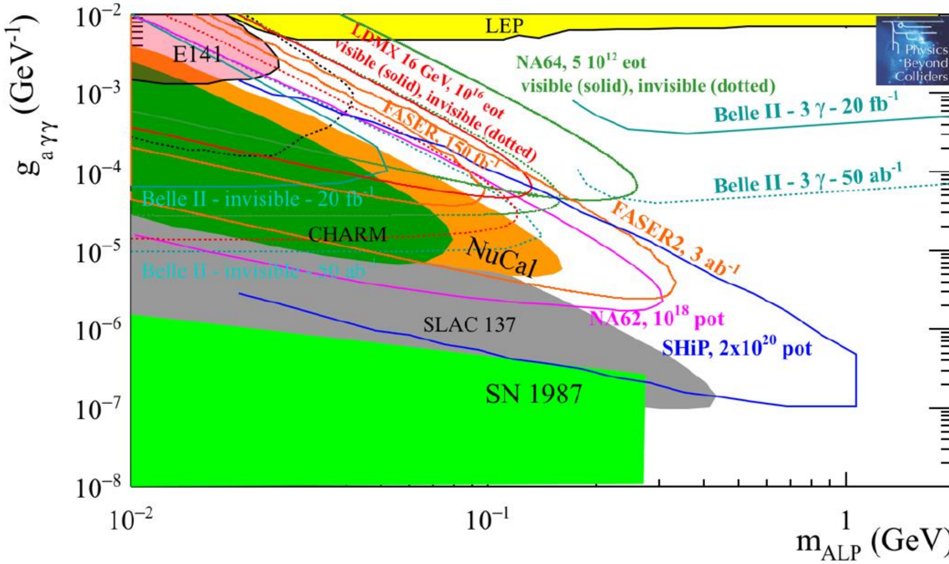


BC9: ALPs and photon couplings

ALPS could be portal to dark matter



Future Landscape



PBC 10-15 years

STRONGLY COUPLED TEV MASS PARTICLES

Strongly coupled TeV mass particles

Centre of mass energy of experiments below TeV

Precision measurements of SM processes still sensitive to corrections from virtual heavy particles

Particularly when new physics violates (approximate-) symmetries of SM

New physics breaks CP

Heavy new CP violating particles lead to new effective operators at lower energies

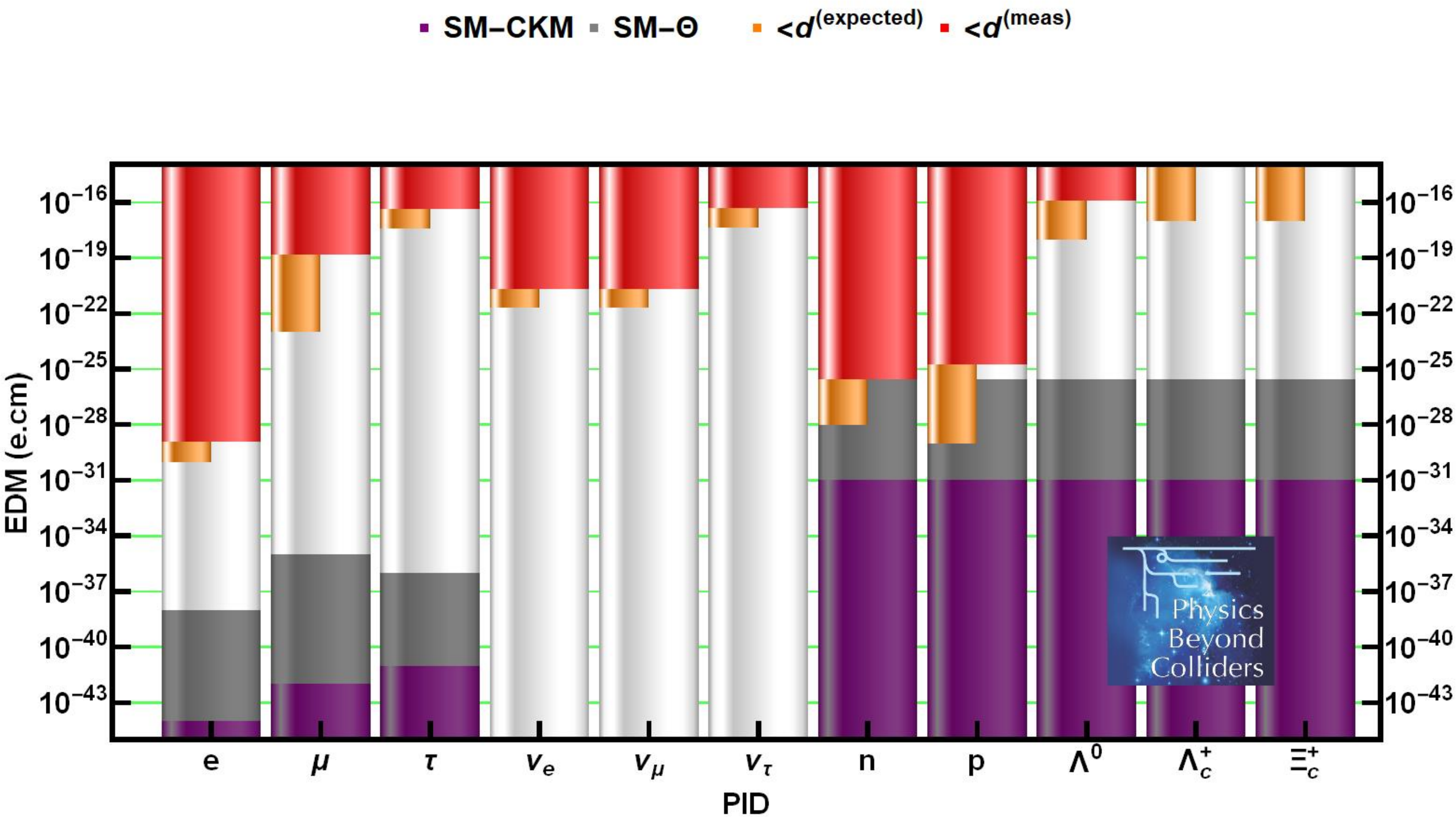
$$\mathcal{L} = \frac{v \times \sin\left(\phi^{(u)}\right)}{\Lambda_u^2} \times \frac{ie}{2}\bar{u}F_{\mu\nu}\sigma_{\mu\nu}\gamma_5 u + \frac{v \times \sin\left(\phi^{(d)}\right)}{\Lambda_d^2} \times \frac{ie}{2}\bar{d}F_{\mu\nu}\sigma_{\mu\nu}\gamma_5 d + ...$$

Suppressing flavour dependence

$$\frac{|\sin\left(\phi^{(q)}\right)|}{\Lambda_q^2} \sim \frac{1}{(7 \times 10^5\ \mathrm{TeV})^2} \times \left(\frac{d_p}{10^{-29} e\mathrm{cm}}\right)^{1/2}$$

PBC proton storage ring proposal sensitive to new physics at ~ 100 TeV

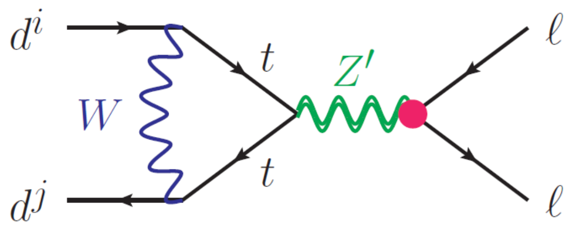
EDM



SM–CKM
SM–Θ
<$d^{(\mathrm{expected})}$
<$d^{(\mathrm{meas})}$
EDM (e.cm)
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
10^{-34}
10^{-37}
10^{-40}
10^{-43}
e
μ
τ
ν_e
ν_μ
ν_τ
n
p
Λ^0
Λ_c^+
Ξ_c^+
PID
Physics Beyond Colliders

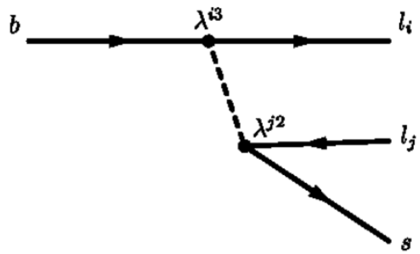
Lepton Flavour Violation

Possible sources introduce new four fermion operators



e.g.

- Z’
- Leptoquarks



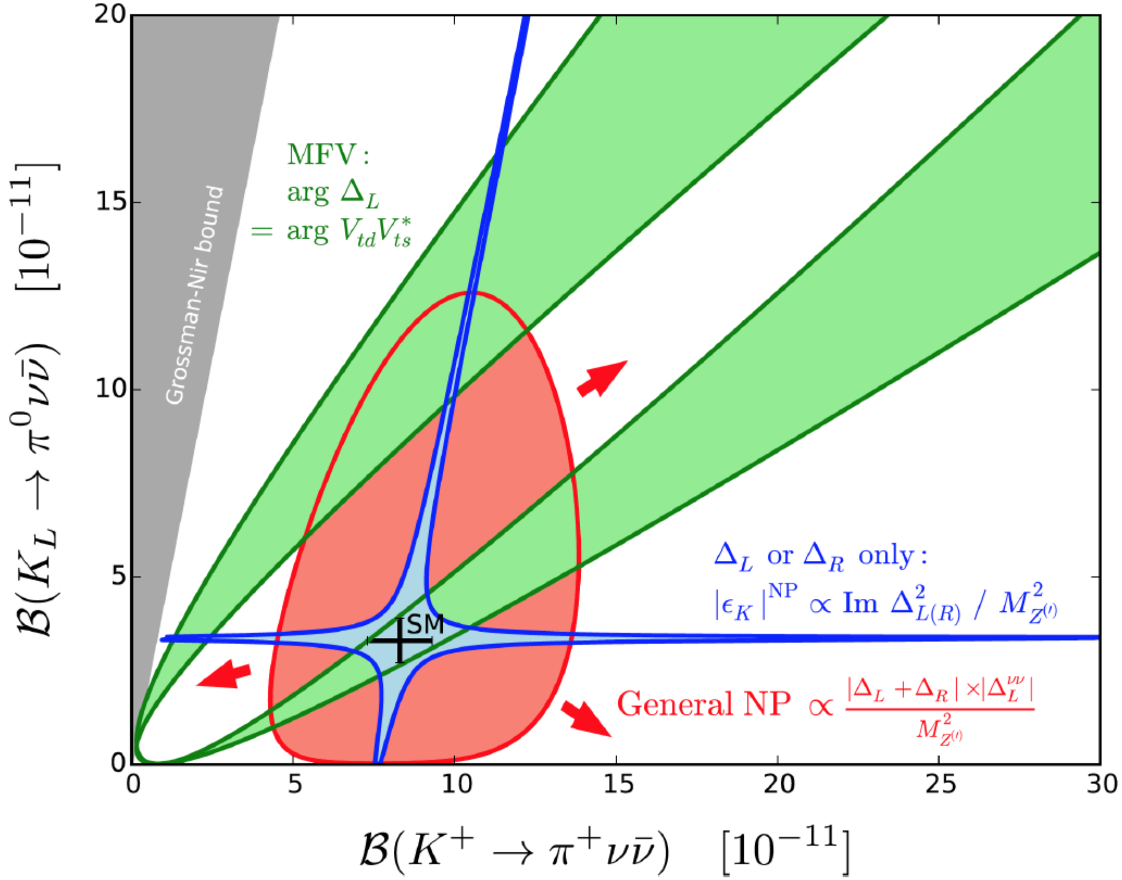
Quantify new physics reach with effective operators

$$\mathcal{L} = \frac{e^{i\phi}}{\Lambda^2_{\mu\tau}} \times (\bar{\mu}\gamma_\alpha\mu)(\bar{\mu}\gamma_\alpha\tau) \;\; + (h.c.) + \text{ other Lorentz structures}$$

E.g. Proposed TauFV experiment

$$\Lambda_{\mu\tau} > 55\,\mathrm{TeV} \times \left(\frac{10^{-10}}{\mathrm{Br}_{\tau\to 3\mu}}\right)^{1/4}$$

Lepton Flavour Violation



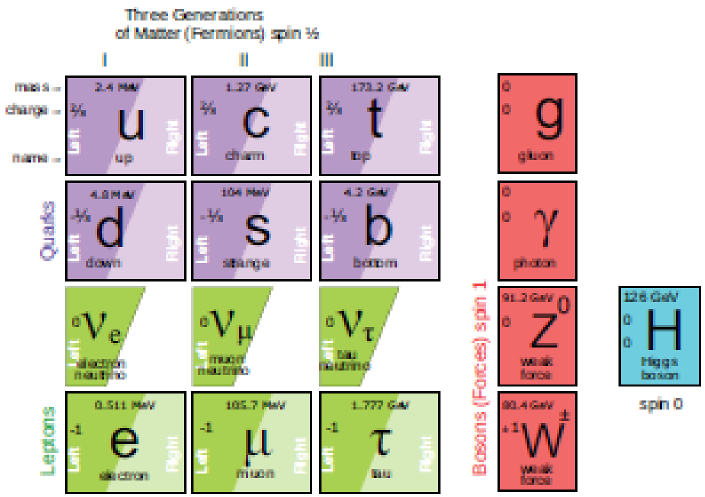
Minimal Scenarios

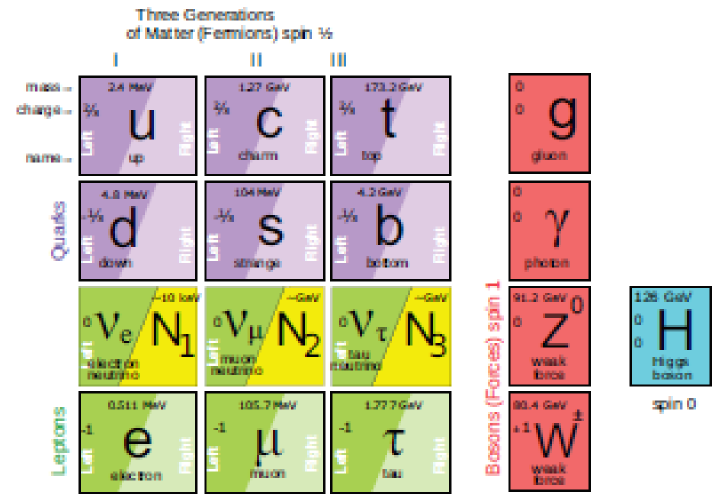
Some combination of:

- Higgs for inflation
- Sea-saw mechanism for neutrino masses and leptogenesis
- Dark matter heavy lepton
- Dark matter axion

Not easy to do, identifies benchmark points in parameter space

An example: νMSM





N = Heavy Neutral Lepton - HNL, Majorana fermion

Role of N_1 with mass in keV region: dark matter

Role of $N_2,\ N_3$ with mass in 100 MeV – 100 GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Shaposhnikov, PBC kick off meeting, 2016

Predictions, 2005-2009

Prediction	assumptions	status
No deviations from SM at LHC	structure of νMSM	OK
SM Higgs boson with $M_H > 127 \pm 2$ GeV	Higgs inflation	OK within 2σ
SM Higgs boson with $M_H = 127 \pm 2$ GeV	asymptotic safety	OK within 2σ
No WIMPS	structure of νMSM	OK
DM is a keV scale HNL , $N \to \nu\gamma$	structure of νMSM	3.5 keV X-ray line?
New particles - HNL	structure of νMSM	constraints only
Unitarity of PMNS matrix	structure of νMSM	OK
no light sterile ν	structure of νMSM	OK
neutrino mass $m_1 \lesssim 10^{-5}$ eV	dark matter	constraints only
No visible $\mu \to e\gamma,\ \mu \to 3e, etc$	BAU	OK
$N_\nu = 3$	structure of νMSM	OK, Planck
spectral index $n_s = 0.967$	Higgs inflation	OK, Planck
small tensor to scalar ratio $r = 0.003$	Higgs inflation	Planck, constraints only
no non-Gaussianities	Higgs inflation	Planck, constraints only

Shaposhnikov, PBC kick off meeting, 2016

SM*A*S*H: Solving Five Problems at One Stroke

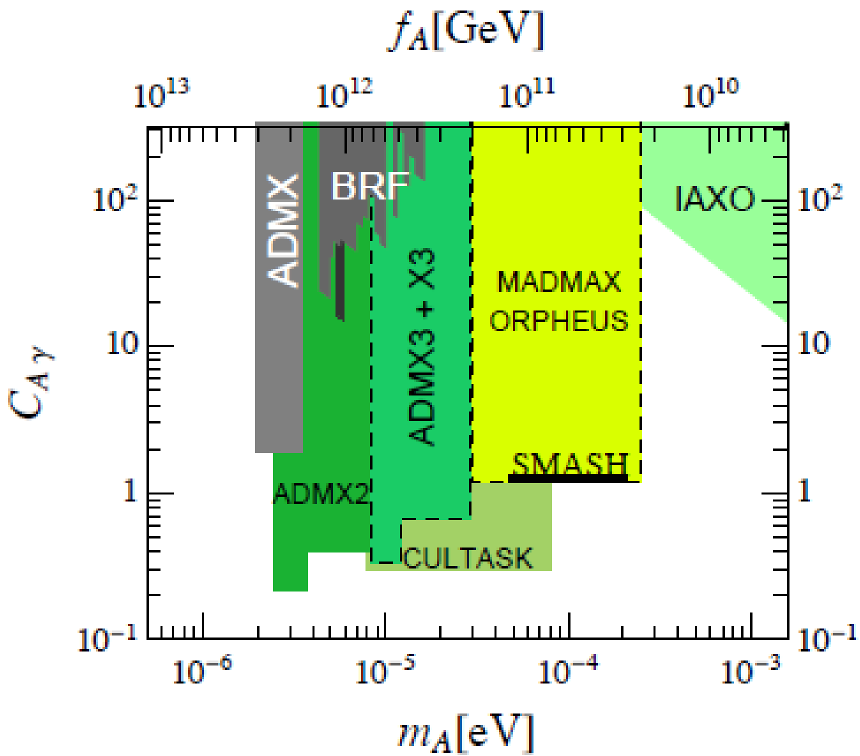
- Unify PQ U(1) symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges [Dias et al. `14]

$$\mathcal{L} \supset -\left[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + y\, \tilde{Q} \sigma Q + y_{Q_{d}i} \sigma Q d_i + h.c.\right]$$

- VEV $v_\sigma \sim 10^{11}\,\mathrm{GeV}$:
  - Determines Majorana masses
  - Explains smallness of active neutrino masses by see-saw relation

$$m_\nu = 0.04\,\mathrm{eV} \left(\frac{10^{11}\,\mathrm{GeV}}{v_\sigma}\right)\left(\frac{-F Y^{-1} F^T}{10^{-4}}\right)$$

- Thermal leptogenesis (out of equilibrium decay of RHN)
- Axion cold DM



[Ballesteros,Redondo,AR,Tamarit, 1608.05414]

Ringwald, PBC kick off meeting, 2016

Changing Funding Climate

"On 30 September STFC and EPSRC will open a research call for the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

The call has total funding of c.£36m and will look to fund up to seven projects of £2m and above each (80% fEC)…"

Contact: Rachel Reynolds, QTFP Programme Manager, QTFP@stfc.ukri.org

Summary

Compelling evidence for BSM physics

A wide range of possibilities for what this could be
(and large parameter spaces)

Model agnostic approach utilises portals and effective operators, but essentially infinite parameter space

Minimal models identify points in parameter space that can be excluded (in principle)