BSM Theory Context

Clare Burrage
University of Nottingham
Clare.Burrage@nottingham.ac.uk

Outline:

Motivation for BSM physics

Energy scales of BSM physics

Types of BSM physics and current constraints

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 1^{st} order EW phase transition)

Evidence for BSM Physics

Galactic Dynamics

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

CMB

- More non-relativistic matter than can be accounted for with baryons
- Component of the universe which looks like a small but non-zero cosmological constant
- Spectrum of density perturbations requires period of inflation

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

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

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

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

Types of New Physics – (pseudo) Scalars

Pseudo-scalars

- Axions (can be light even if scale of new physics is high)
- PNGB of spontaneously broken flavour symmetries

Heavy scalars

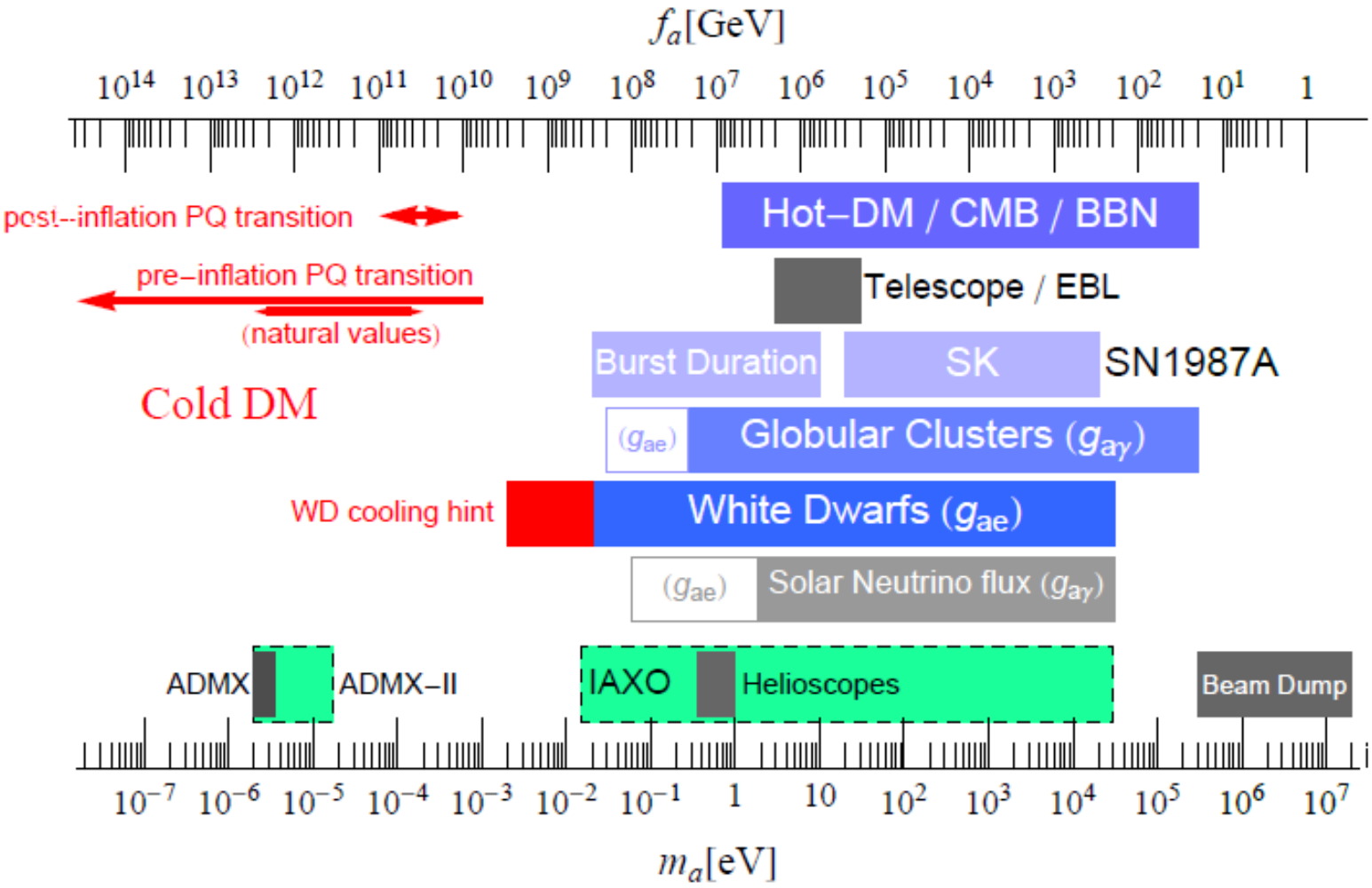
- Inflation
- Dark Matter

Light scalars

- Dark energy
- Dark matter

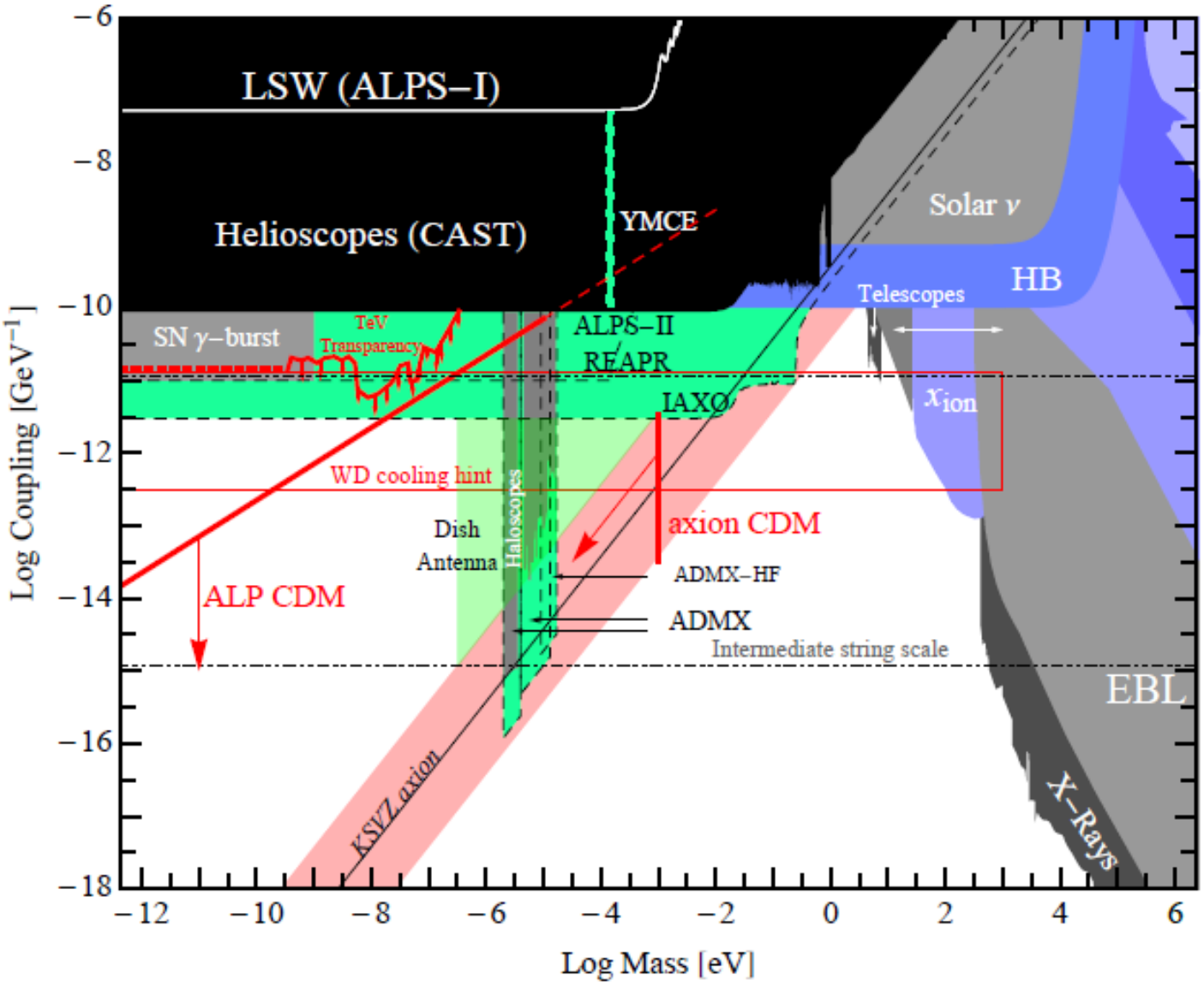
Scalars and pseudo scalars of all masses can be generated in string theory compactifications - the axiverse

Current Axion bounds



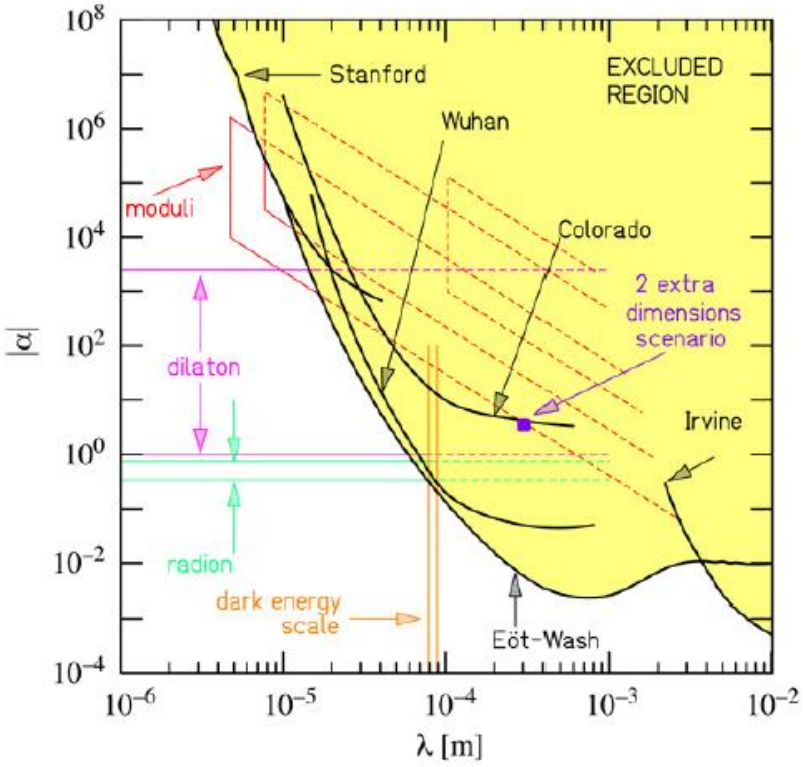
Snowmass Report. Essig et al 2013

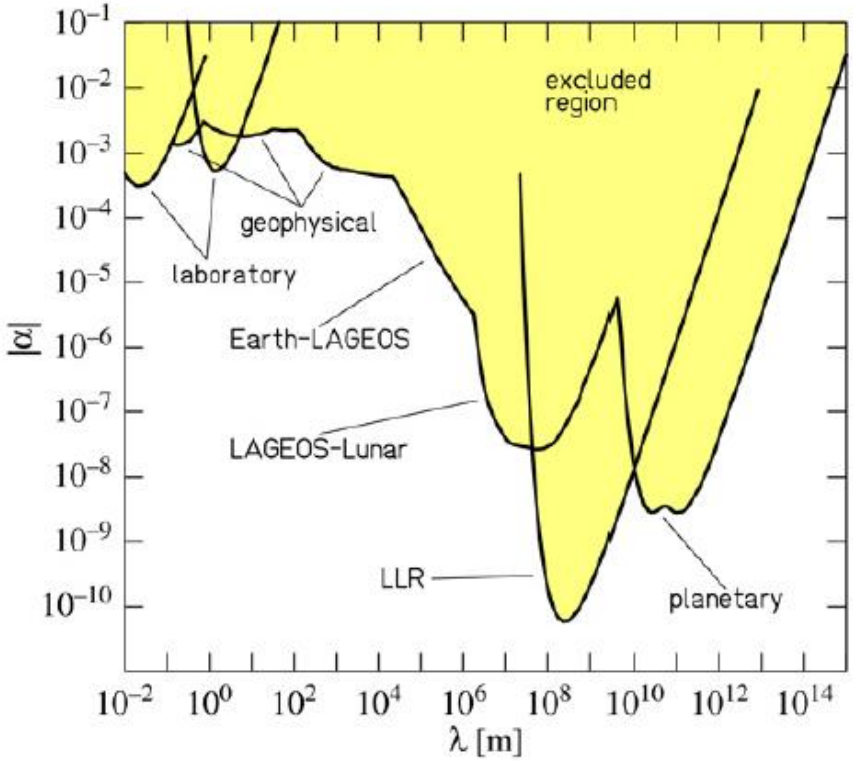
Current ALP bounds



Snowmass Report. Essig et al 2013

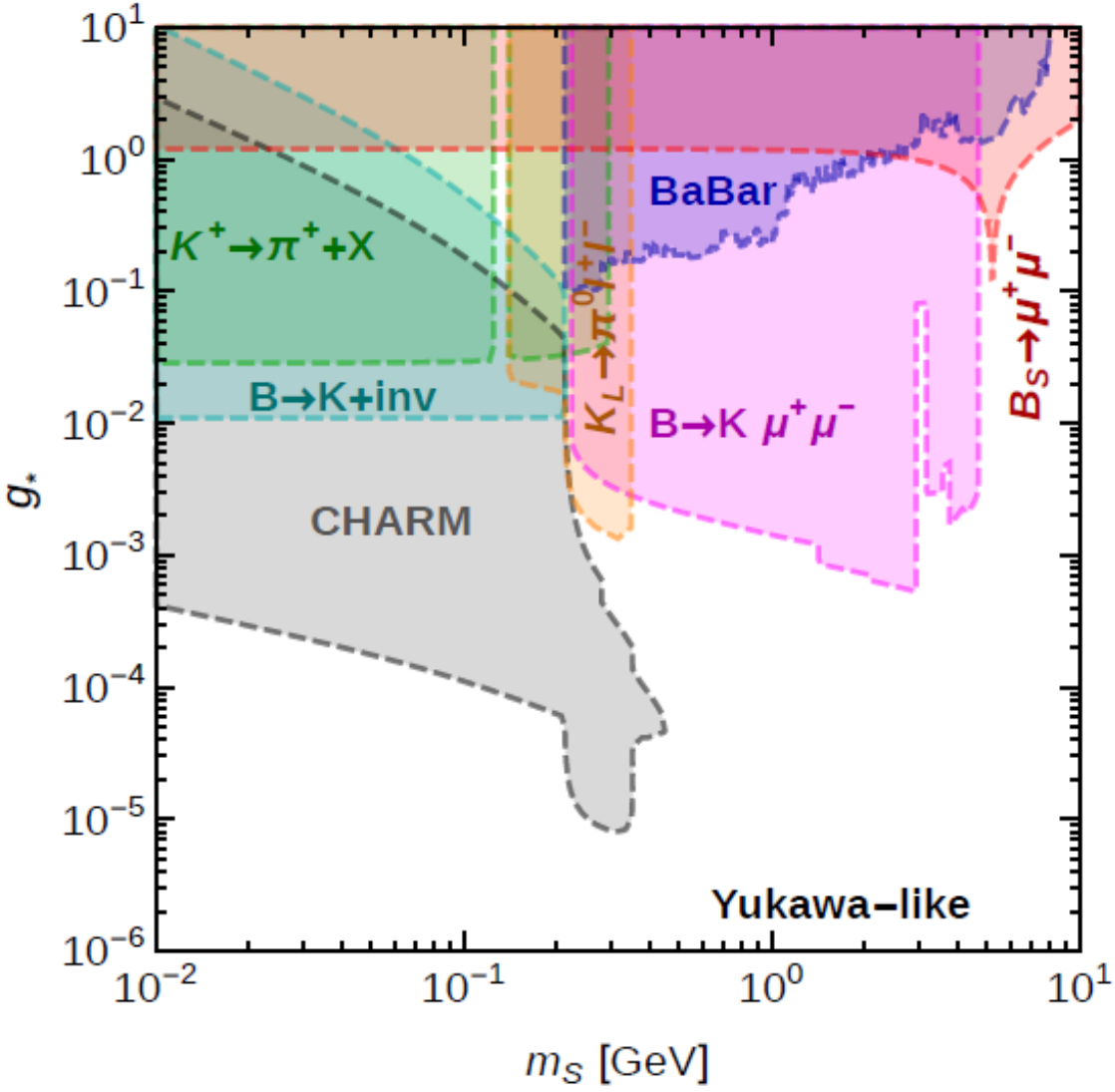
(Very) Light scalars with Yukawa couplings





Adelberger et al. 2009

Light Scalars with Yukawa couplings



Alekhin et al. 2015

Types of New Physics - Leptons

Heavy neutral leptons

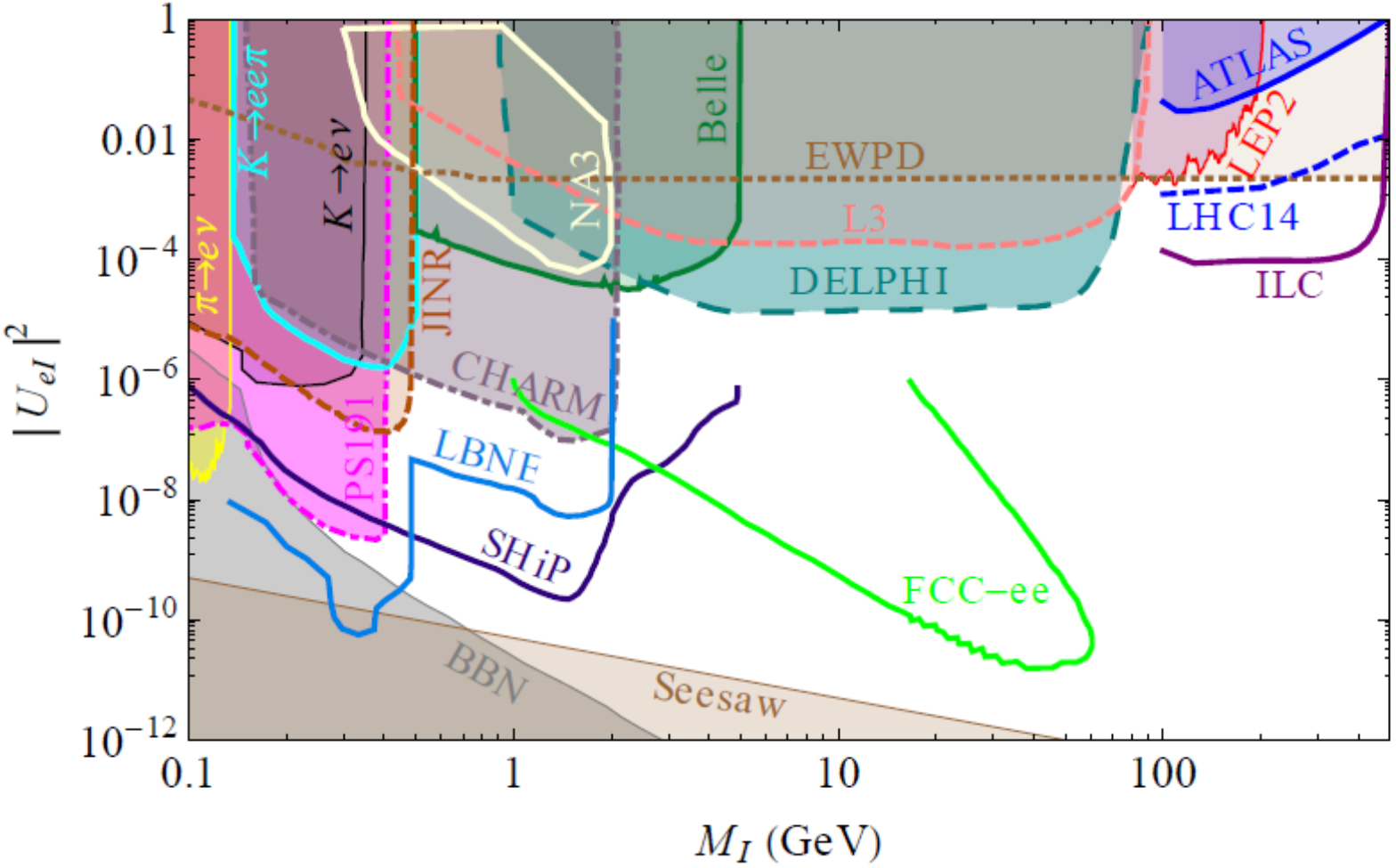
- Dark matter
- Baryon Asymmetry
- Neutrino masses

Heavy charged leptons

- Higgs mass hierarchy, (SUSY)

Can couple to SM through; vector portal (also requires new vector fields); Higgs portal, neutrino portal

Current Heavy Neutral Lepton bounds



Alekhin et al. 2015

Types of New Physics - Vectors

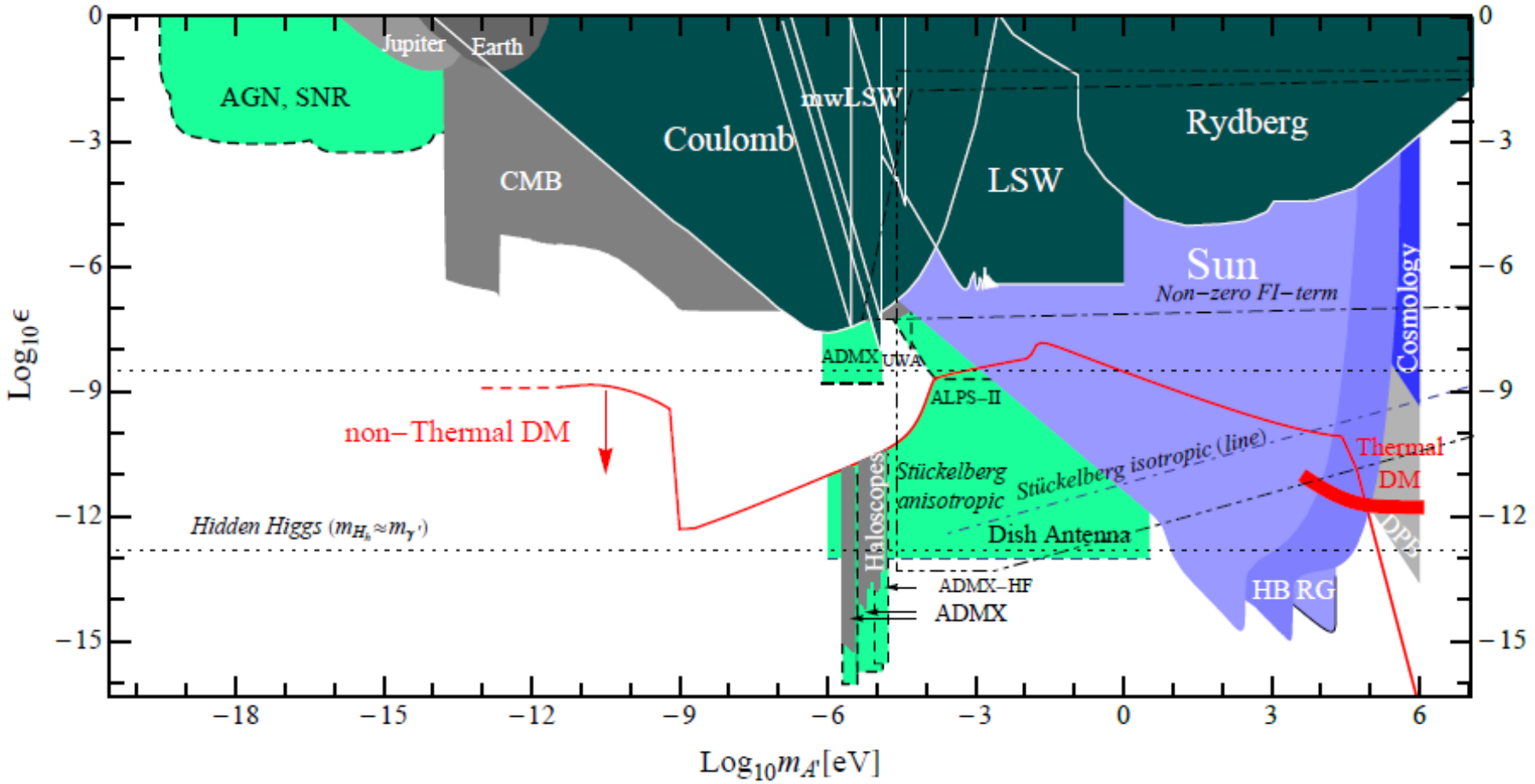
New vector fields

- g-2 anomaly
- Dark matter

- Dark matter mediator (essential for light WIMPS)
- Extra gauge forces (GUTs)
- Gauging of accidental symmetries of the standard model, B-L

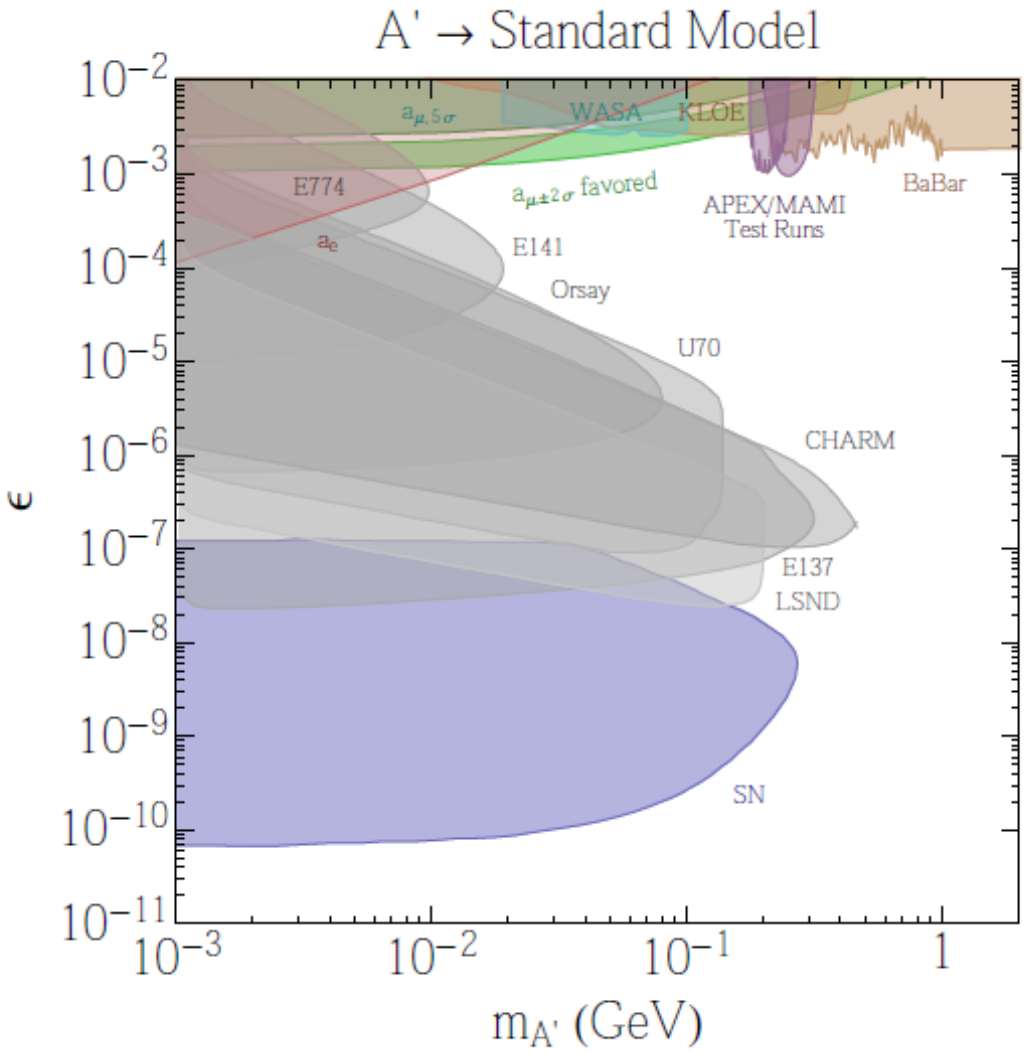
SUSY and stringy motivation

Current Dark Photon Bounds



Snowmass Report. Essig et al 2013

Current Dark Photon Bounds



Snowmass Report. Essig et al 2013

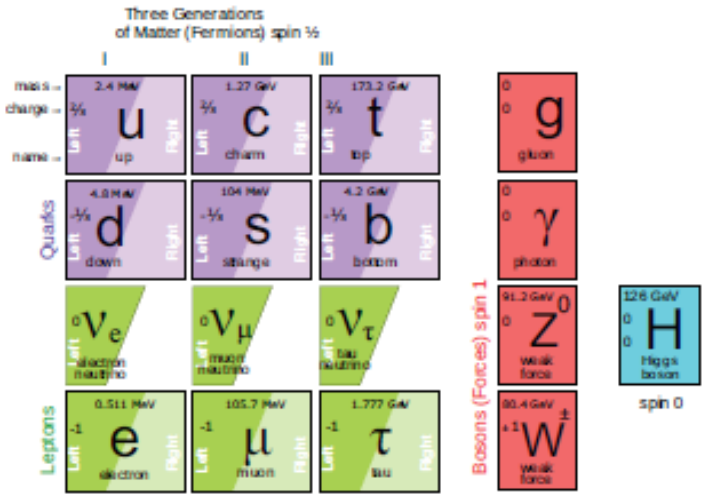
Minimal Scenarios

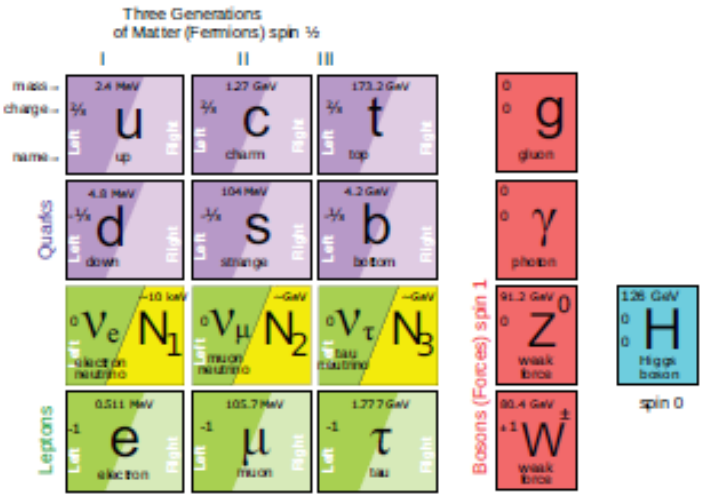
Some combination of:

- 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

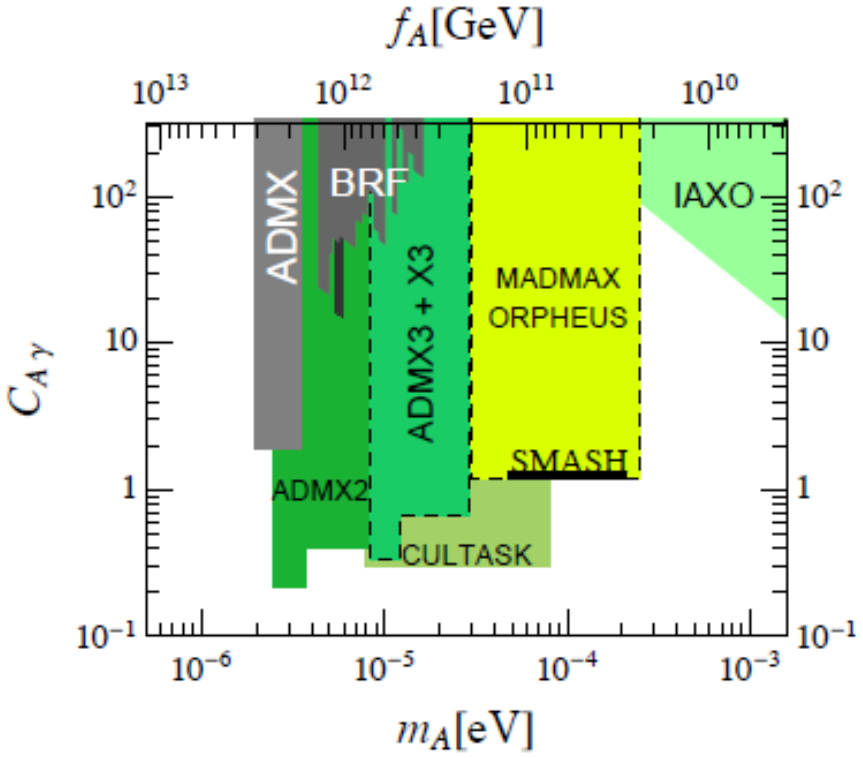
- Unify PQ U(1) symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges [Dias et al. `14]

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

- 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]

DESY

Ringwald, PBC kick off meeting, 2016

Detection Possibilities

- Small corrections to Standard Model processes
- New particles decay into standard model particles
- Standard model processes produce undetectable new particles
- New processes/interactions absent from the standard model

Which process is the best depends both on type of new physics and where you are in parameter space

PBC experiments

EDM experiments

- directly probe CP violating interactions
  - Baryogenesis
- Oscillating EDM for axions and scalar dark matter

LSW & IAXO

- Searches for axions and ALPS
- Are there opportunities to look for other types of new physics here? Eg dark energy fields

Fixed target experiments

- Broad search for weakly interacting particles

PBC experiments

Flavour violation

– New physics is not necessarily flavour blind, present in SUSY scenarios, CP violation

High luminosity, or high precision gives us the possibility to access high scale physics

Are we missing ways of exploiting these experiments?

Can theory help to further the reach of these experiments?

Further possibilities

Atom interferometry

- dark matter
- gravitational waves
- dark energy

Dark matter direct detection for WIMPS

Astrophysical and cosmological measurements

Much, much more….

Conclusions

The case for BSM physics is compelling

This new physics is not necessarily heavy

No one energy scale / type of particle / part of parameter space that is most interesting

Not possible to cover full parameter space with one type of experiment

Minimal scenarios helpful, but need to keep an open mind