Prospects for finding new physics with theory and experiment

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XIII Meeting on B Physics : Synergy between LHC and SUPERKEKB in the Quest for New Physics

Events drastically changing our viewpoint of BSM physics

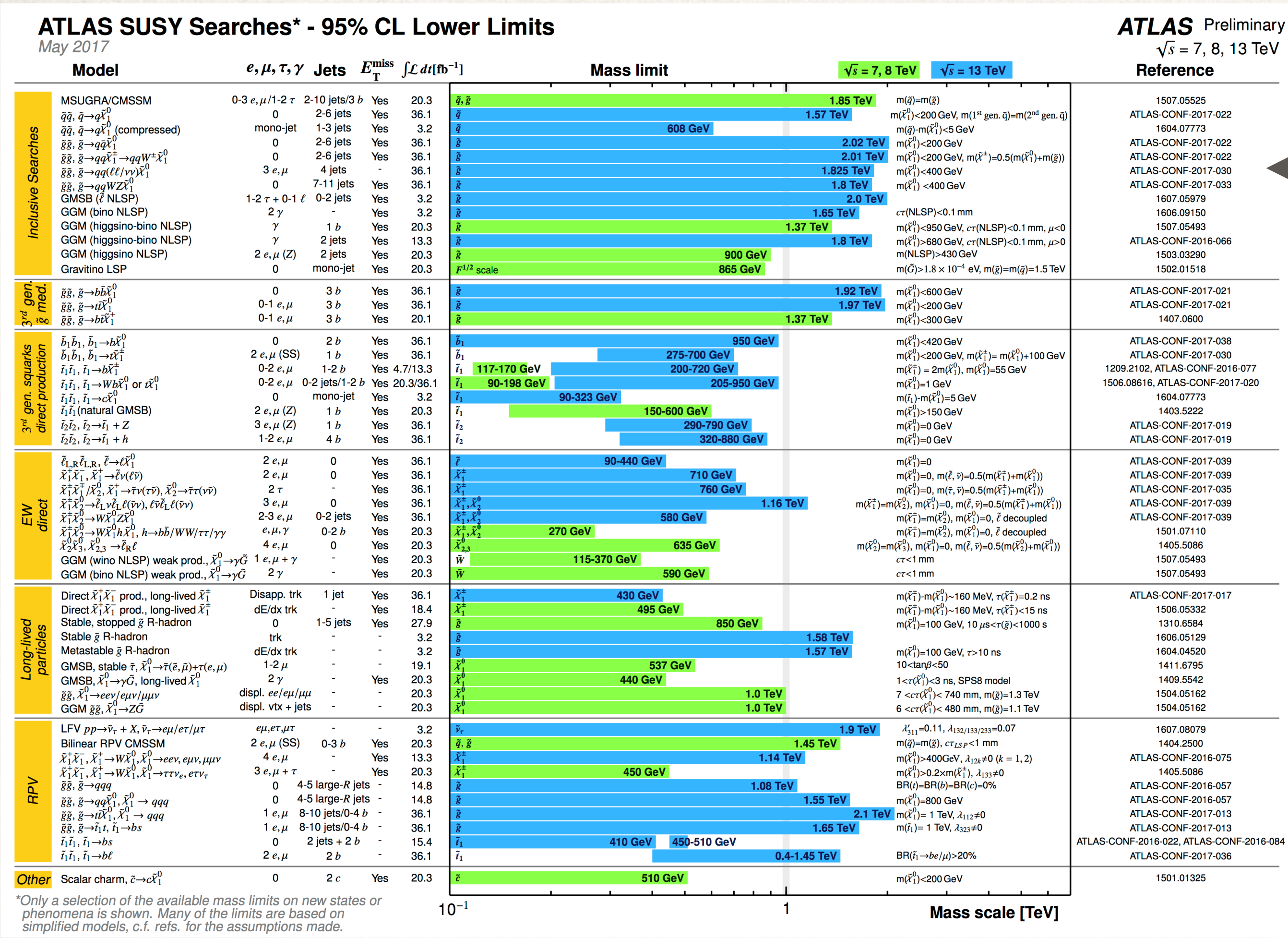
- CKM triangle measurement at Belle/Babar 2008.

- The Higgs in 2012 (note that in the wikipedia article they mention “the origin of mass”, this is somewhat solved though the origins of the hierarchy in flavours is unexplained)

- Non-observations in FCNCs@B factories, at collider and Dark matter experiments (and the flavour anomalies?)

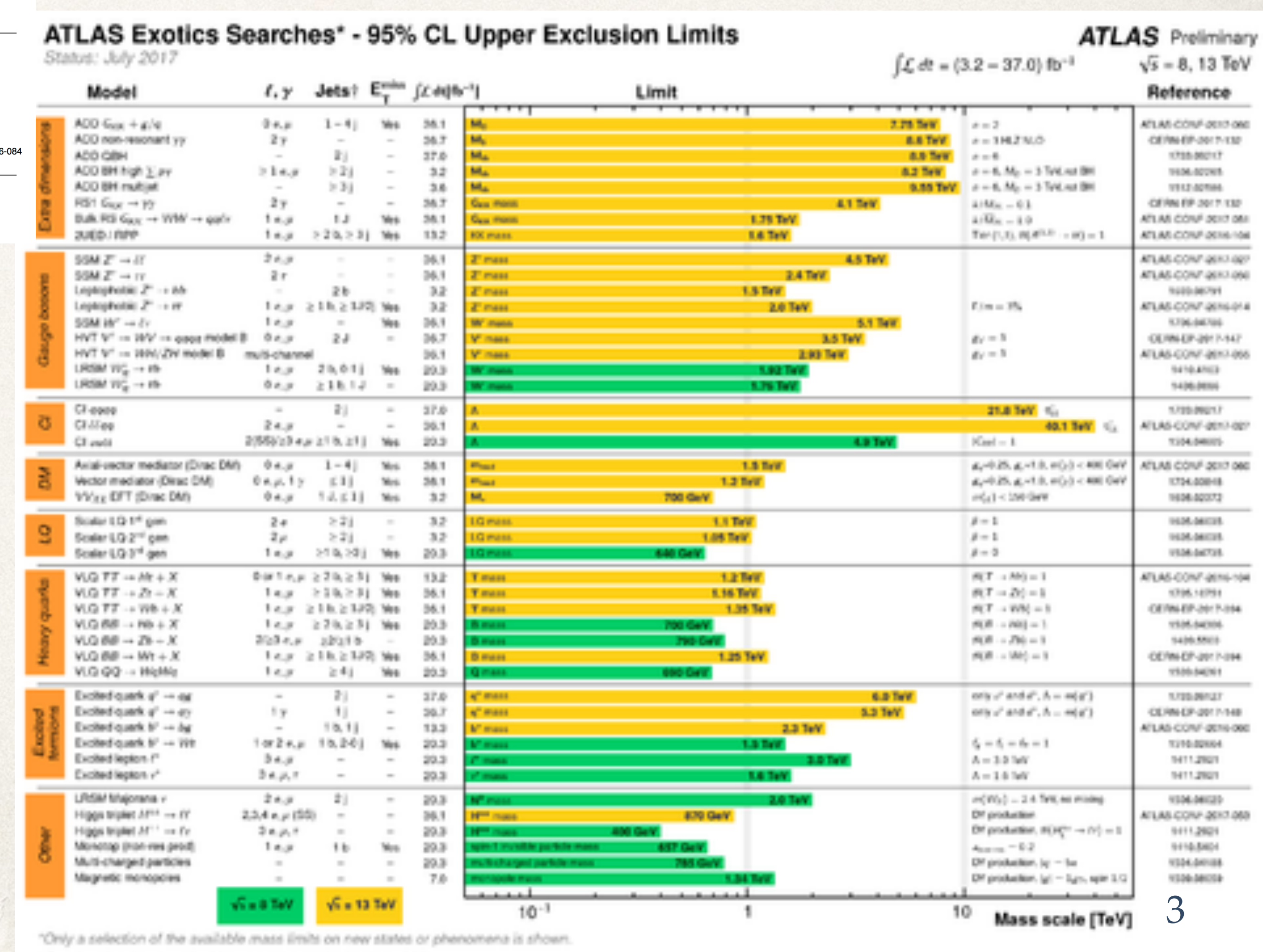
No Nobel prize though arguably most radical information!?

ATLAS summary plots



SUSY searches

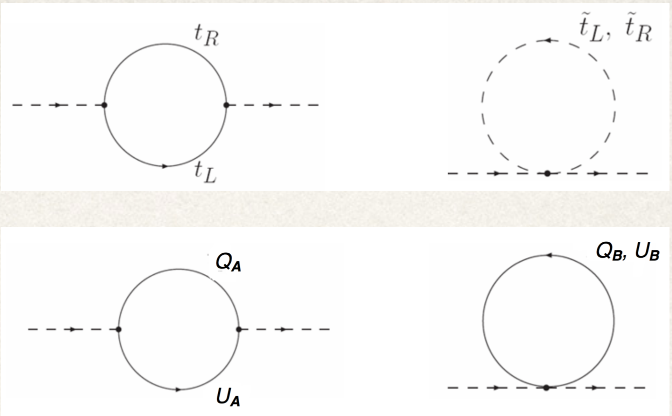
exotic searches



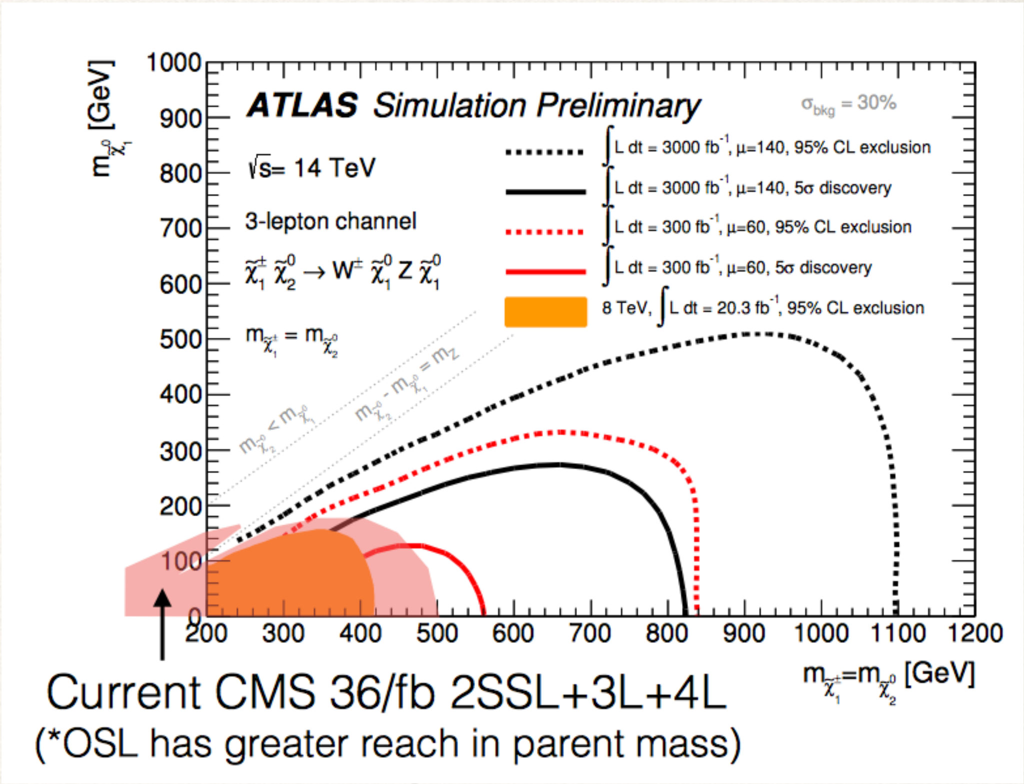
Show that for coloured particles the bounds stretch to 1.5 TeV, whereas for electroweak particles more like 500 GeV

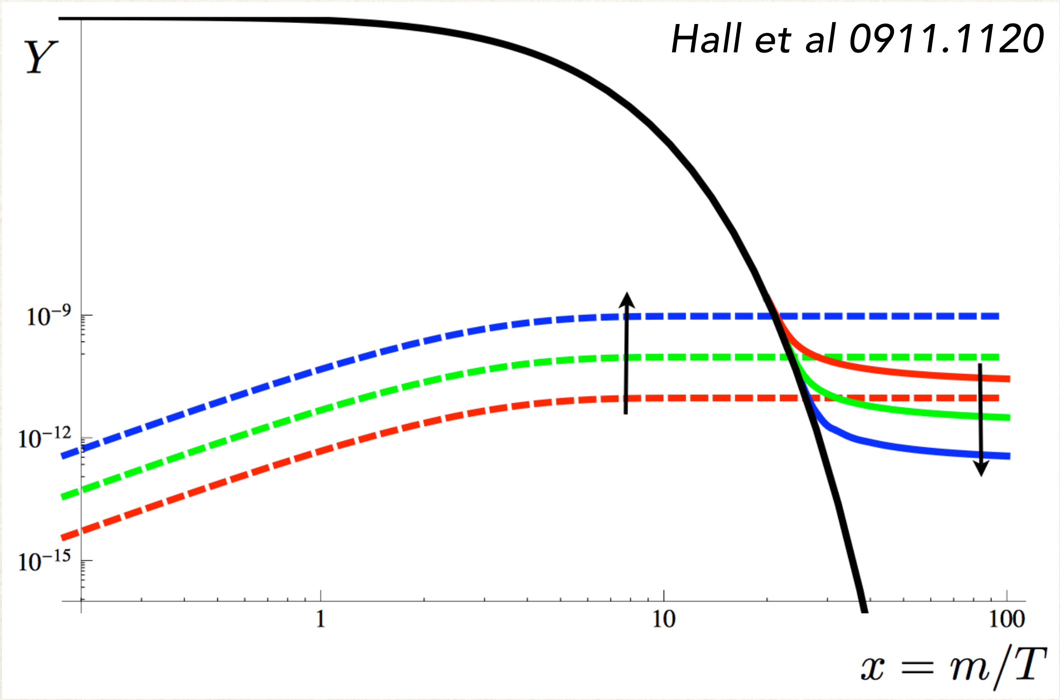
Theoretical ways forward I: Hierarchy problem alternatives:

Chacko, Talk Santa Fe 2014



- Models escaping LHC bounds: split SUSY, light higgsinos Graham et al 2015, Nelson et al 2017
- Twin Higgs/Neutral naturalness - particles which explain cancellation of top loop not coloured, Hierarchy problem still solved by symmetries Chacko et al 2005
- Relaxion - Hierarchy problem not directly controlled by symmetries, weak scale selected by dynamics





Conventional DM alternatives: Heavy (Sommerfeld enhancement)-100 TeV collider. Alternative mechanisms to freeze-out e.g. freeze-in, still testable at next generation DD experiments. *Beneke AB et al 2016*

Theoretical ways forward II

See Dario Buttazzo's talk

- Look for weakly coupled particles/ very light particles, axions (CP problem) or axion-like particles (ALPs), as mediators between SM and dark sector. Testable at flavour/astrophysics/cosmology and dedicated experiments.
- B anomaly driven model building: Correlate with other channels via EFT, Leptoquarks, Z', new ideas for unifications, test via further measurements
- Lattice QCD: much progress recently, crucial inputs for B physics, g-2, DM…

Isidori, LHCb implications 2017

E.g.: correlations among down-type FCNCs [*using the results of* U(2)-*based EFT*]:

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\tau\tau$ $\to$ 100×SM	$B \to K^{(*)}\nu\nu$ O(1)	$B \to K\tau\mu$ $\to \sim 10^{-6}$	$B \to K\mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\mu\mu$ $B_s \to K^{(*)}\mu\mu$ O(20%) [R_K=R_π]	$B \to \pi\tau\tau$ $\to$ 100×SM	$B \to \pi\nu\nu$ O(1)	$B \to \pi\tau\mu$ $\to \sim 10^{-7}$	$B \to \pi\mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\nu\nu$ O(1)	*NA*	$K \to \mu e$???

Theoretical ways forward II

- **Look for weakly coupled particles/ very light particles, e.g. axions (CP problem) or axion-like particles (ALPs), as mediators between SM and dark sector. Testable at flavour/astrophysics/cosmology and dedicated experiments.**

- Flavour probes/model building: Anomalies in b to s and b to c channels, lepton flavour plays important role: Correlate with other channels via EFT, Leptoquarks, Z', new ideas for unifications, test via further measurements

Isidori, LHCb implications 2017

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$b \to d$	$B_d \to \mu\mu$, $B \to \pi \mu\mu$, $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi \tau\tau$ $\to$ 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ $\to \sim 10^{-7}$	$B \to \pi \mu e$???
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- Lattice QCD: much progress recently, crucial inputs for B physics, g-2, DM…

Contents

- Models with light mediators and motivation
- Generation of dark matter + cosmological constraints
- Searches/prospects at Belle II
- Searches/prospects at LHCb

Disclaimer: not an expert, hoping for corrections and comments!

Models with light mediators

- Vector Portal → $\mathcal{L} \supset \epsilon V_\mu J^\mu_{\rm SM}$
- Higgs Portal → $\mathcal{L} \supset \lambda S^2 (H^\dagger H)$
- Axions / ALPS → $\mathcal{L} \supset \frac{\partial_\mu P}{f_A} \bar{f} \gamma^\mu \gamma^5 f$

  → $\mathcal{L} \supset \frac{g_{\gamma\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} P$

Each of these can be mediators between the DM and the SM: can have significant interactions with the SM and be probed via collider experiments

Motivation for light mediators

- Strong CP problem (PQ axion)
- Hierarchy problem (Relaxion)
- Small-scale structures
- probably more

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

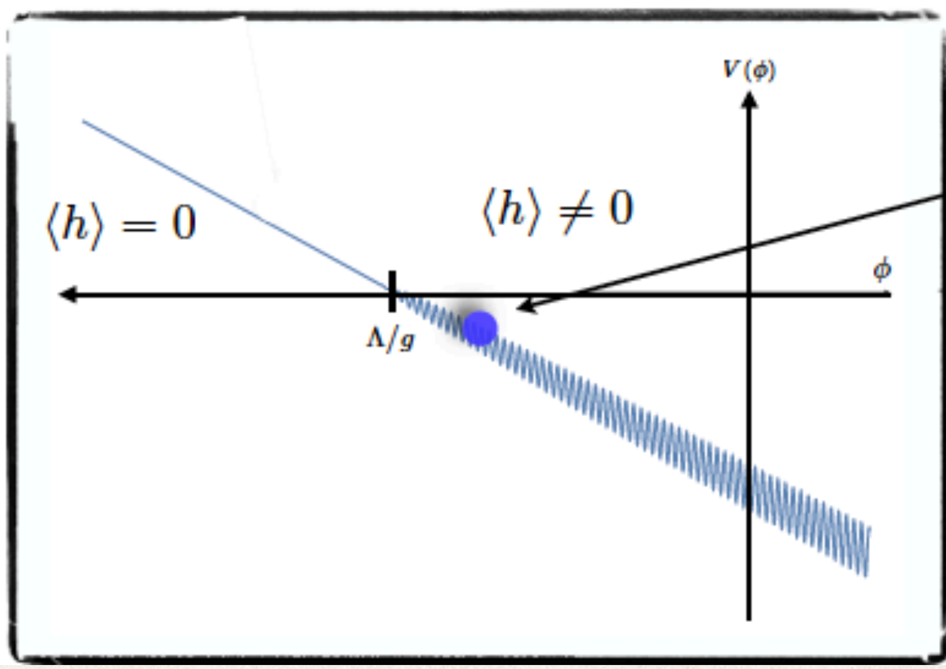
$$\Lambda^2 \left(-1 + f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2 + \Lambda^4 V\left(\frac{g\phi}{\Lambda}\right) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

$$\Lambda^3_{\rm QCD}\, h \cos\frac{\phi}{f}$$



If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately prevents ϕ from rolling down further

See Nelson and Prescod-Weinstein 1708.00010

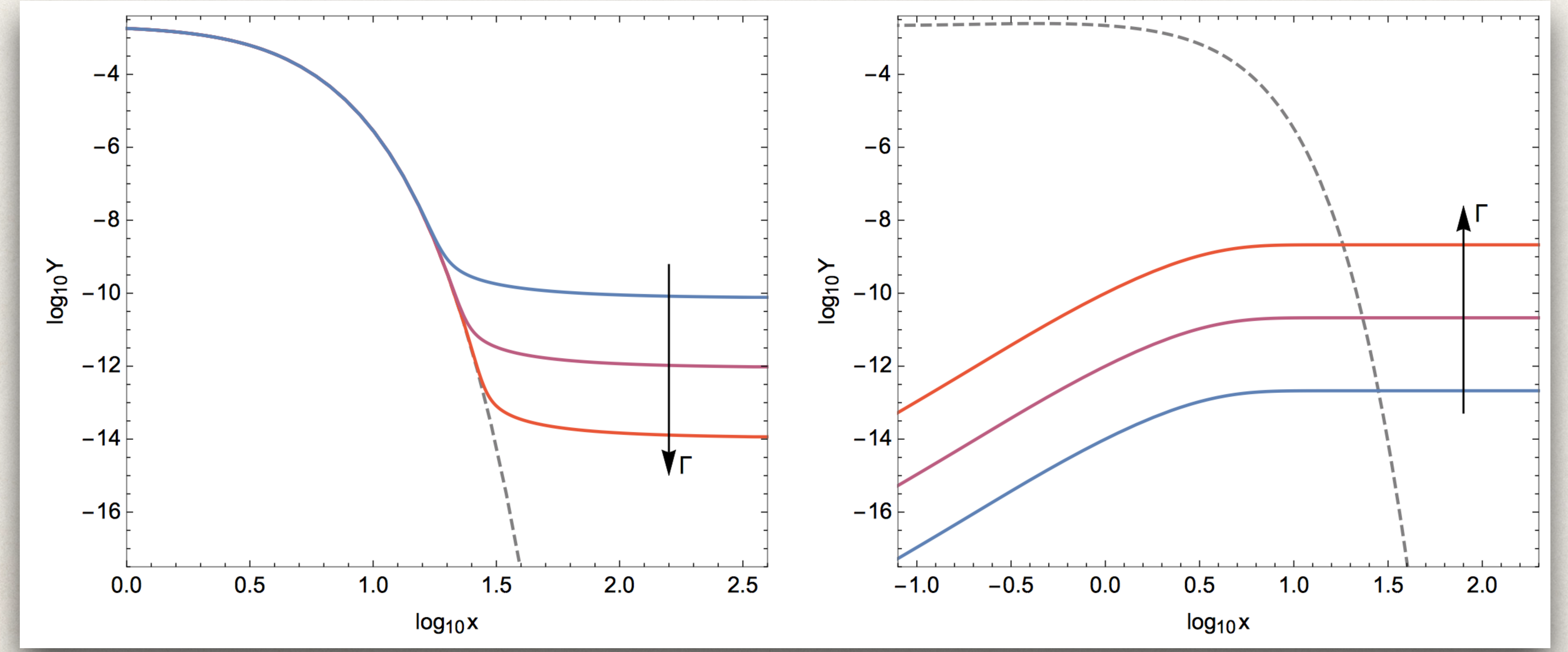
…….and as a gateway to the Dark sector!

Experimental signatures/constraints

- Dark matter relic density generation
- Cosmology / Astrophysics bounds: BBN, Horizontal branch stars, DM self interactions, SN1987A
- Electron and proton Beam dump experiments: SLAC E131, SLAC E137, CHARM, NuCal, NA62
- Production at Flavour experiments: FCNC K and B decays, upsilon decays, direct production

Freeze in and freeze out

Bernal, Heikinheimo, Tenkanen, Tuominen and Vaskonen arXiv:1706.07442



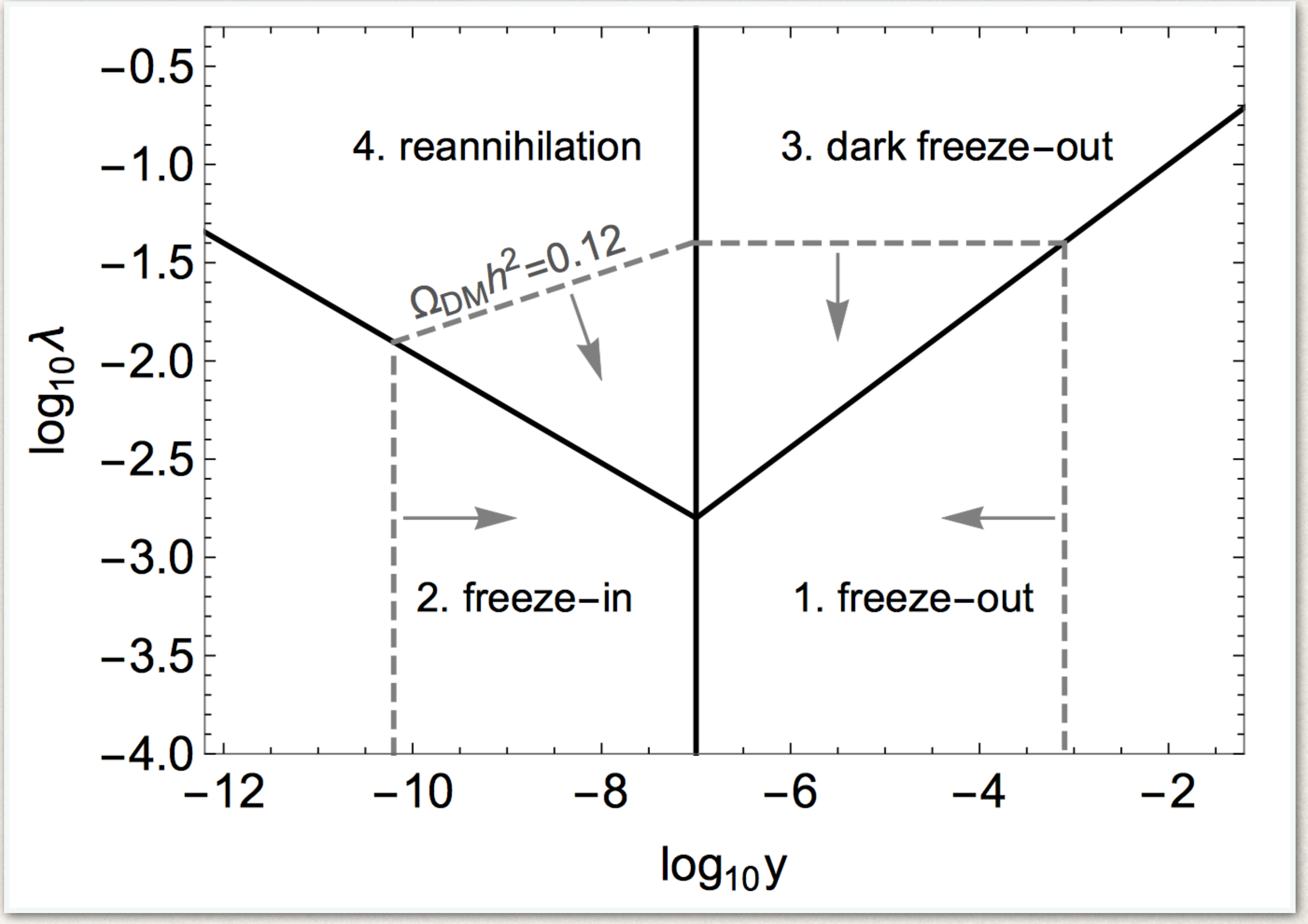
Three values of the rate Γ between the visible sector and DM particles χ, where arrows indicate the effect of increasing Γ . For freeze-out $x = m\chi / T$ For freeze-in, $x = m\sigma / T$ and for both $Y = n\chi / s$.

Non-standard DM generation

Chu, Hambye and Tytgat, arXiv:1112.0493

Bernal et al. arXiv:1706.07442

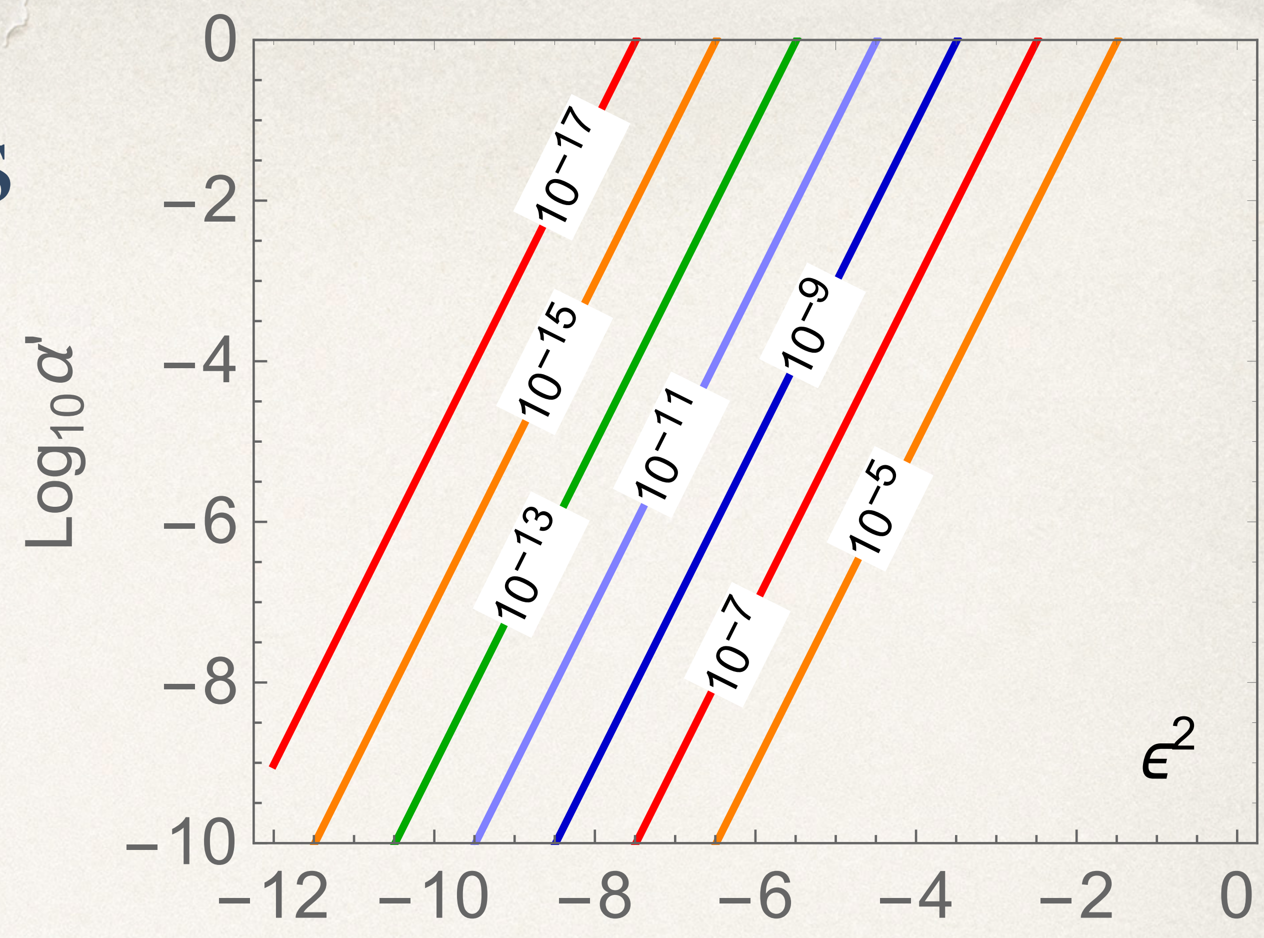
- **Dark freeze-out:** DM not in thermal eq. with SM but with dark sector, generated from as in freeze in. DM annihilates into dark sector, different temperatures.

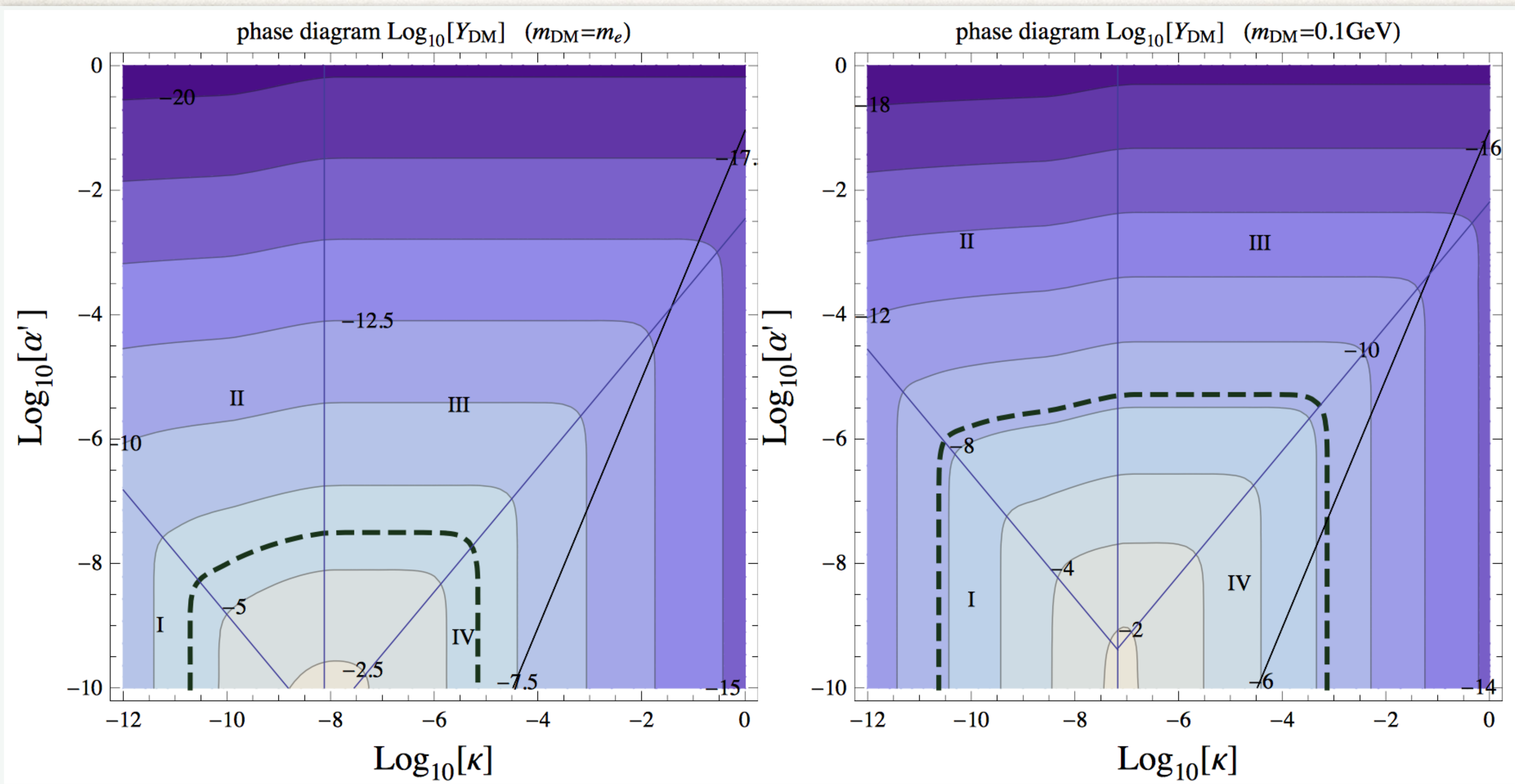


- **Reannihilation:** DS in eq. within itself but dark freeze-out would occur before yield from SM has ended. DM freezes out only when production has ended.

Dark Photon couplings

- **Freeze-in:** $\epsilon^2 \sim 10^{-17}$ to 10^{-15}
- **Reannihilation:** $\epsilon^2 \sim 10^{-15}$ to 10^{-9}
- **Dark freeze-out:** $\epsilon^2 \sim 10^{-9}$ to 10^{-5}





where κ represents the strength of the interaction between the SM and the dark sector

$$\kappa = c_W \frac{\epsilon}{1-\epsilon^2}\sqrt{\frac{\alpha'}{\alpha}}$$

Cosmological motivation

Hints for self interactions from small-scale structures:

Unclear if N-body simulations can reproduce small-scale structures where structure formation is strongly non-linear.

Problem	N-body	Observation
Core-cusp	Mass density profile for CDM halos increases toward the center: $\rho \propto r^{-1}$	Galaxy rotation curves prefer a constant "cored" density profile $\rho \propto r^0$
Diversity	Density profiles of galaxy halos quite uniform for given mass	Disk galaxies with same max circular velocity have large scatter, i.e. core densities can vary by factor O(10)
Missing satellites	In Milky-way predict O(100–1000) subhalos large enough to host galaxies	Only O(10) dwarf spheroidal galaxies discovered
Too-big-to-fail	Brightest galaxies at centre of largest sub-halos.	Central region of largest sub-halos too dense to be consistent with stellar formation of brightest dwarf spheroidals

From review on self-interactions and small scale structure by Tulin and Yu, arXiv:1705.02358

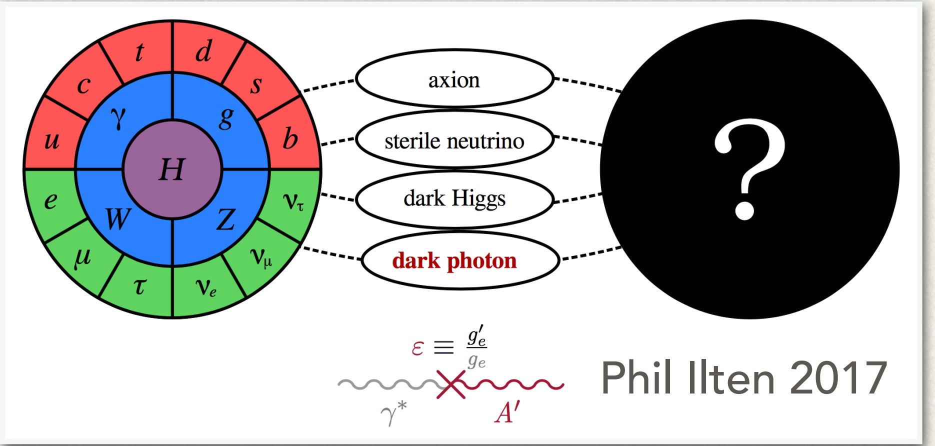
Cosmology and astro constraints

Cadamuro and Redondo, arXiv:1110.2895

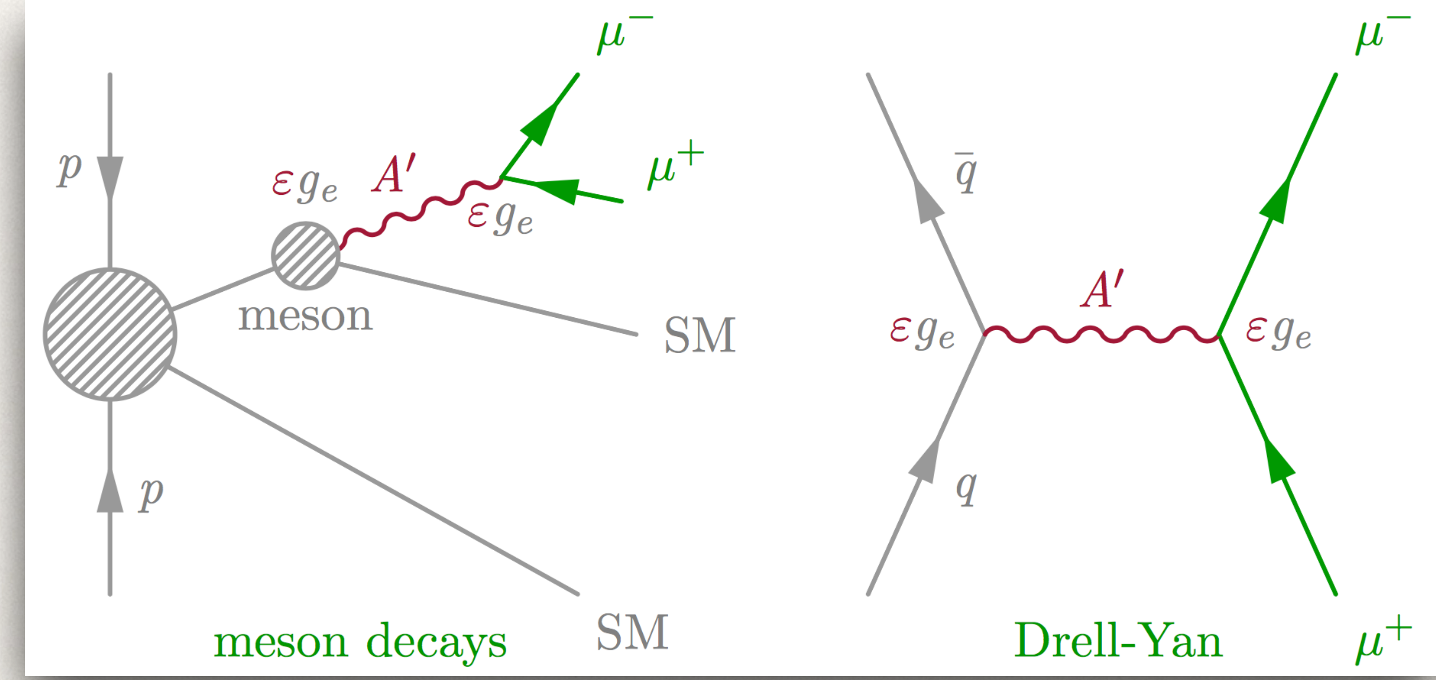
- SN1987A: Weakly coupled particles with masses up to 100 MeV could provide an energy loss mechanism similar to neutrinos before the explosion. Neutrino observation from SN1987A results in bound on other particles cooling the SN.
- Horizontal branch stars: Energy-loss mechanism here too, effecting evolution of stars, constraint from star counts in the colour-magnitude diagrams of globular clusters
- BBN bounds: mediators must decay sufficiently quickly before BBN to avoid changes to the expansion rate/entropy density/destruction of certain elements. Irrelevant if decay time< 1 s.

Dark Sector@LHCb

See Carlos Vazquez Sierra's talk



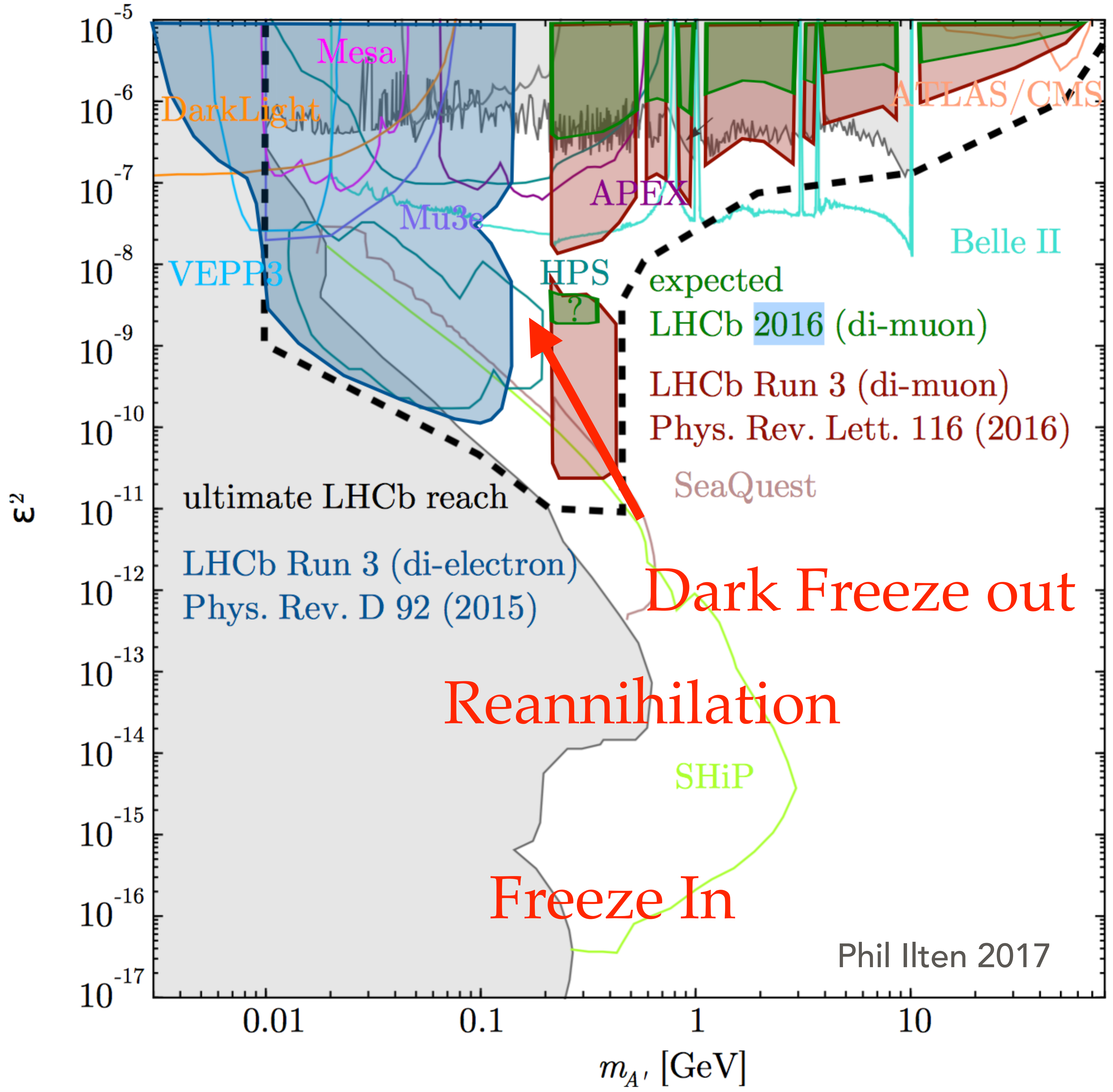
Ilten, (Soreq), Thaler, Williams and Xue, arXiv:1603.08926, arXiv:1509.06765



Dark photon searches proposed using inclusive di-muon production and $D^{*0} \to D^0 e^+e^-$

Prompt and displaced searches to be performed simultaneously, covering large region of parameter space with the full Run 3 LHCb dataset.

D^{*0} search (requires Run 3 triggers) will cover dark photon masses from the $2m_e$ to 1.9 GeV, and inclusive di-muon (possible with Run 2) above $2m_\mu$.



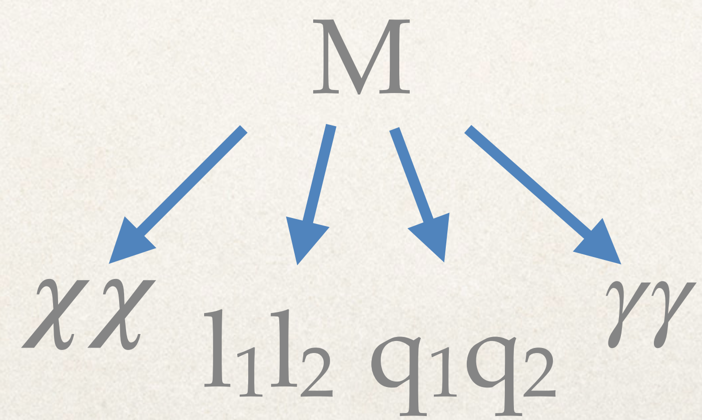
Mesa
DarkLight
APEX
Mu3e
ATLAS/CMS
Belle II
VEPP3
HPS
expected
LHCb 2016 (di-muon)
LHCb Run 3 (di-muon)
Phys. Rev. Lett. 116 (2016)
SeaQuest
ultimate LHCb reach
LHCb Run 3 (di-electron)
Phys. Rev. D 92 (2015)
Dark Freeze out
Reannihilation
SHiP
Freeze In
Phil Ilten 2017
ε²
m_A' [GeV]
0.01
0.1
1
10

Production and decay modes at B factories

Three fundamentally different ways to produce light mediators (M):

- Non-resonant annihilation of an electron-positron pair: $e^+e^- \rightarrow M + X$
- Resonant production from tree-level decay, e.g. $e^+e^- \rightarrow \Upsilon(nS) \rightarrow M + X$.
- Resonant production from loop-level rare decay, e.g. $e^+e^- \rightarrow B + X \rightarrow K + M + X$.

Once produced, the mediator can have four different types of decays:



Promising search channels at Belle II

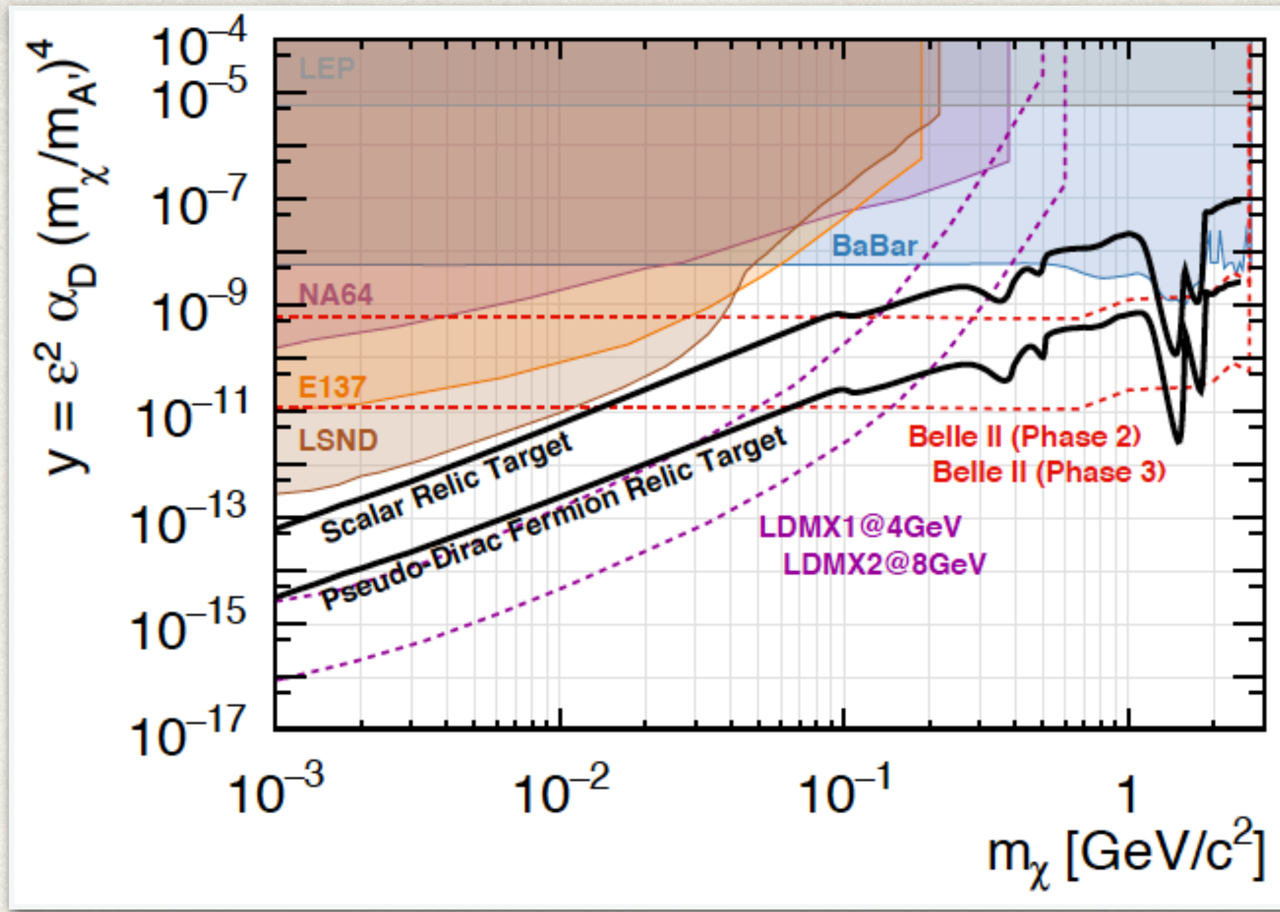
For more information see Belle II physics book.

- **$e^+e^- \to M + X$:**
  - Relies on e-coupling, best for vector, if pseudoscalar via alpsstrahlung $e^+e^- \to \gamma^* \to \gamma M$, or photon fusion $e^+e^- \to M + e^+e^- \to \gamma\gamma + e^+e^-$). or $e^+e^- \to \gamma^* \to \tau\tau \to M + \tau\tau$,
  - If invisible, γ needed for triggering ($e^+e^- \to M + \gamma$), if leptonic, γ can also help enhance trigger acceptance (Displaced vertices also possible.)

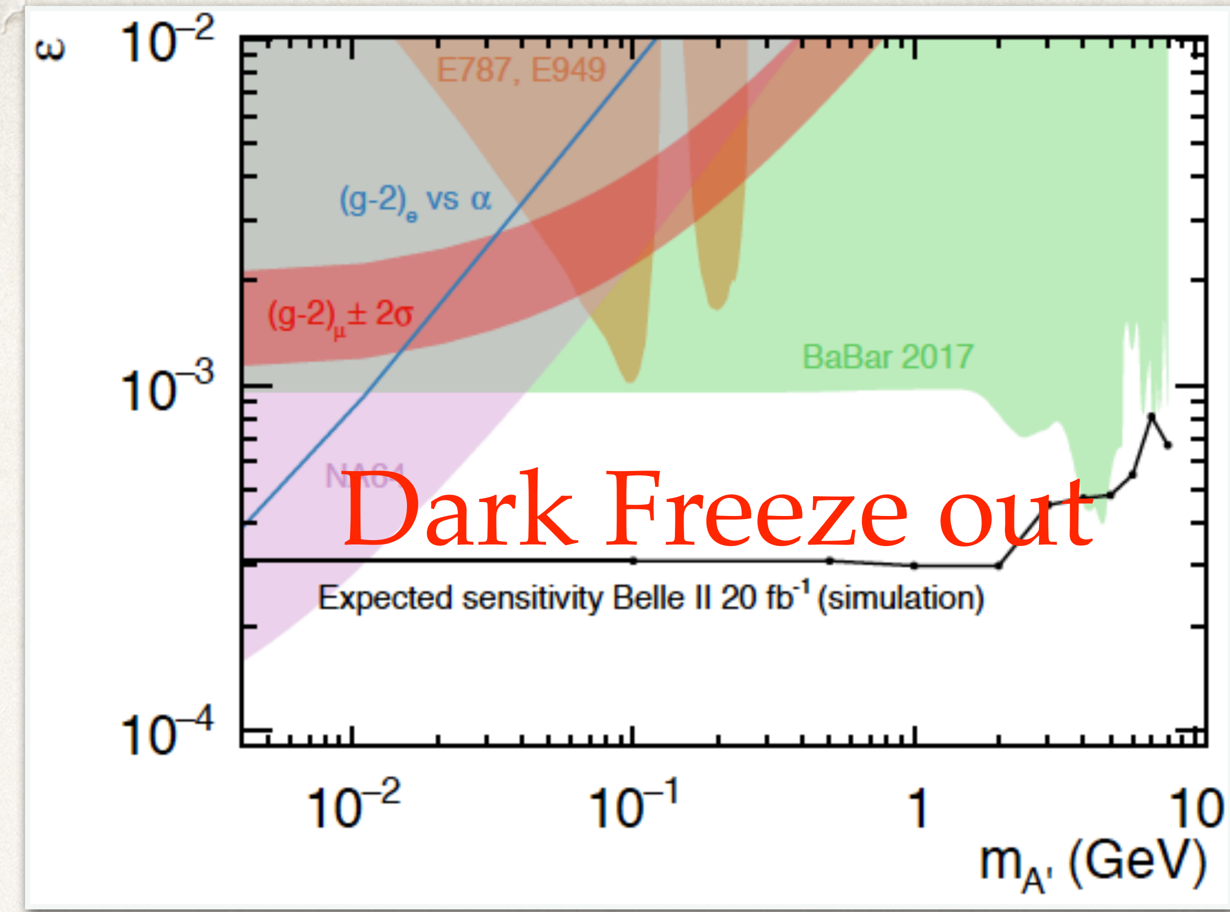
- **$e^+e^- \to \Upsilon(2S/3S) \to \Upsilon(1S) + \pi\pi \to M + \gamma + \pi\pi$:**
  - For spin-0 or axial-vector mediators $\Upsilon(1S) \to M\gamma$, (bump in photon spectrum). $M \to \ell\ell$, leptonic invariant mass shows peak.
  - $\tau\tau$, gg, hh final states also possible. Triggering on $\pi\pi$ allows $M \to$ inv, even if γ off shell.

- **$e^+e^- \to B + X \to K + M + X$:**
  - $M \to$ inv (like B to Kνν but diff. K distribution), $\gamma\gamma$ (good for pseudo-scalar with mass near $2m_\mu$) or $\mu\mu$ (strongest limit for spin-0).
  - Displaced vertices can also be identified.

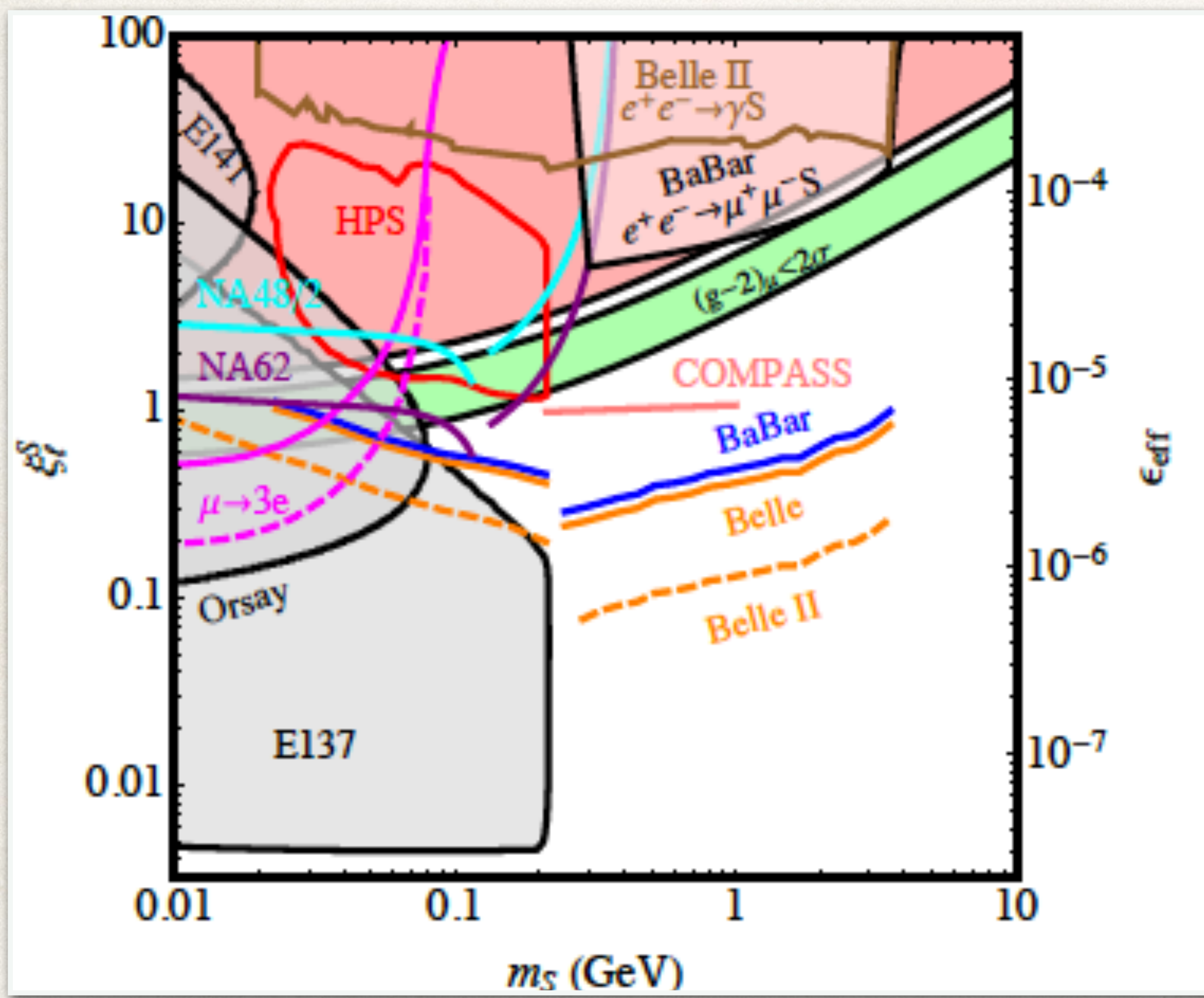
See Laura Zani's talk



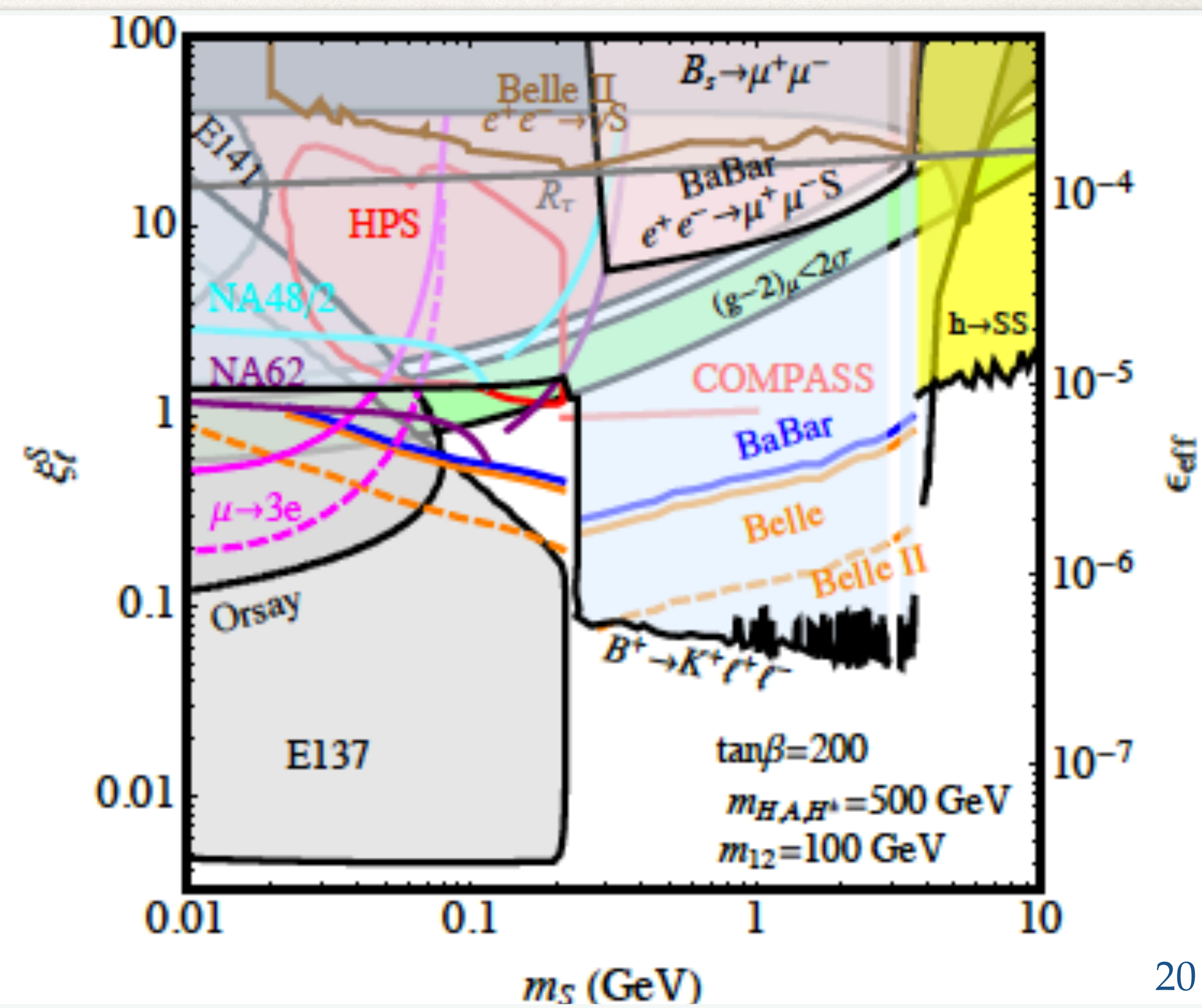
$y = \varepsilon^2 \alpha_D (m_\chi/m_{A'})^4$
LEP
BaBar
NA64
E137
LSND
Scalar Relic Target
Pseudo-Dirac Fermion Relic Target
Belle II (Phase 2)
Belle II (Phase 3)
LDMX1@4GeV
LDMX2@8GeV
m_χ [GeV/c^2]



ε
E787, E949
$(g-2)_e$ vs α
$(g-2)_\mu \pm 2\sigma$
BaBar 2017
NA64
Dark Freeze out
Expected sensitivity Belle II 20 fb^{-1} (simulation)
$m_{A'}$ (GeV)



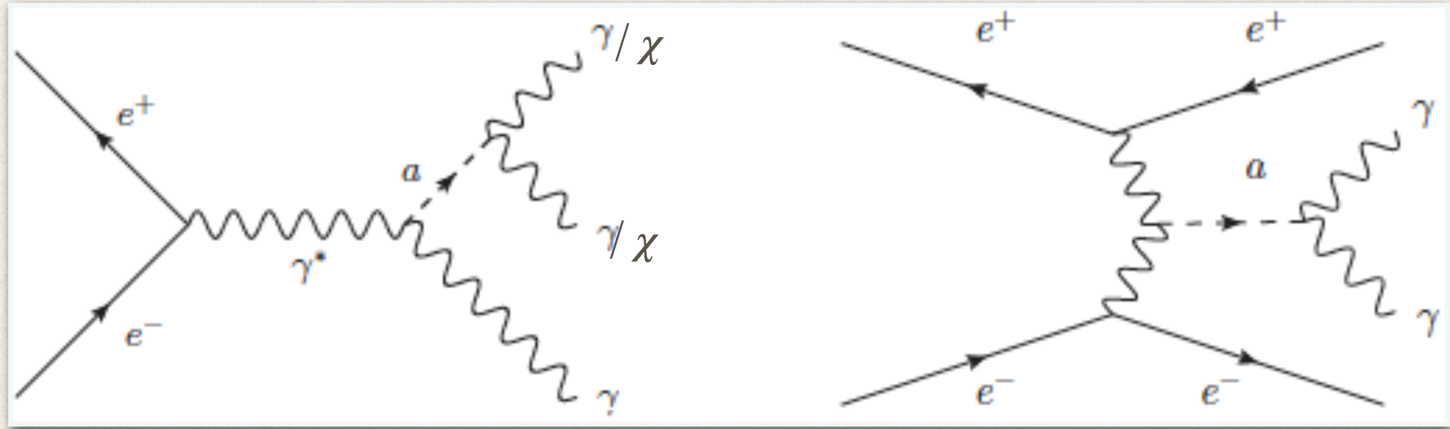
Belle II
$e^+e^- \to \gamma S$
BaBar
$e^+e^- \to \mu^+\mu^- S$
E141
HPS
NA48/2
NA62
$(g-2)_\mu < 2\sigma$
COMPASS
BaBar
Belle
Belle II
$\mu \to 3e$
Orsay
E137
ξ_ℓ^S
ϵ_{eff}
m_S (GeV)

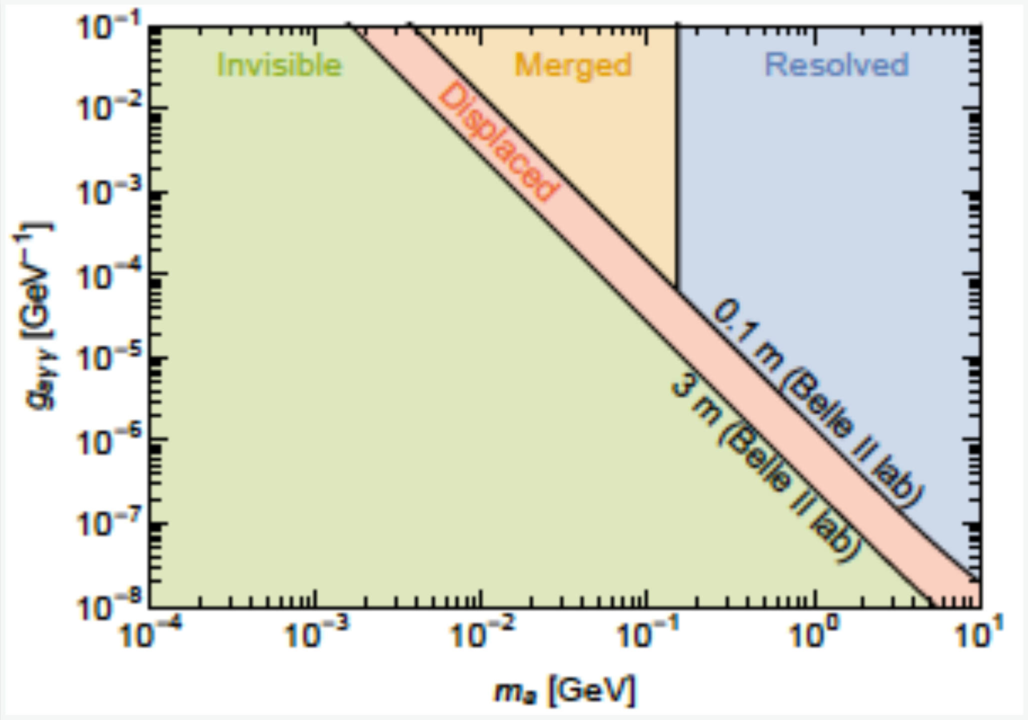


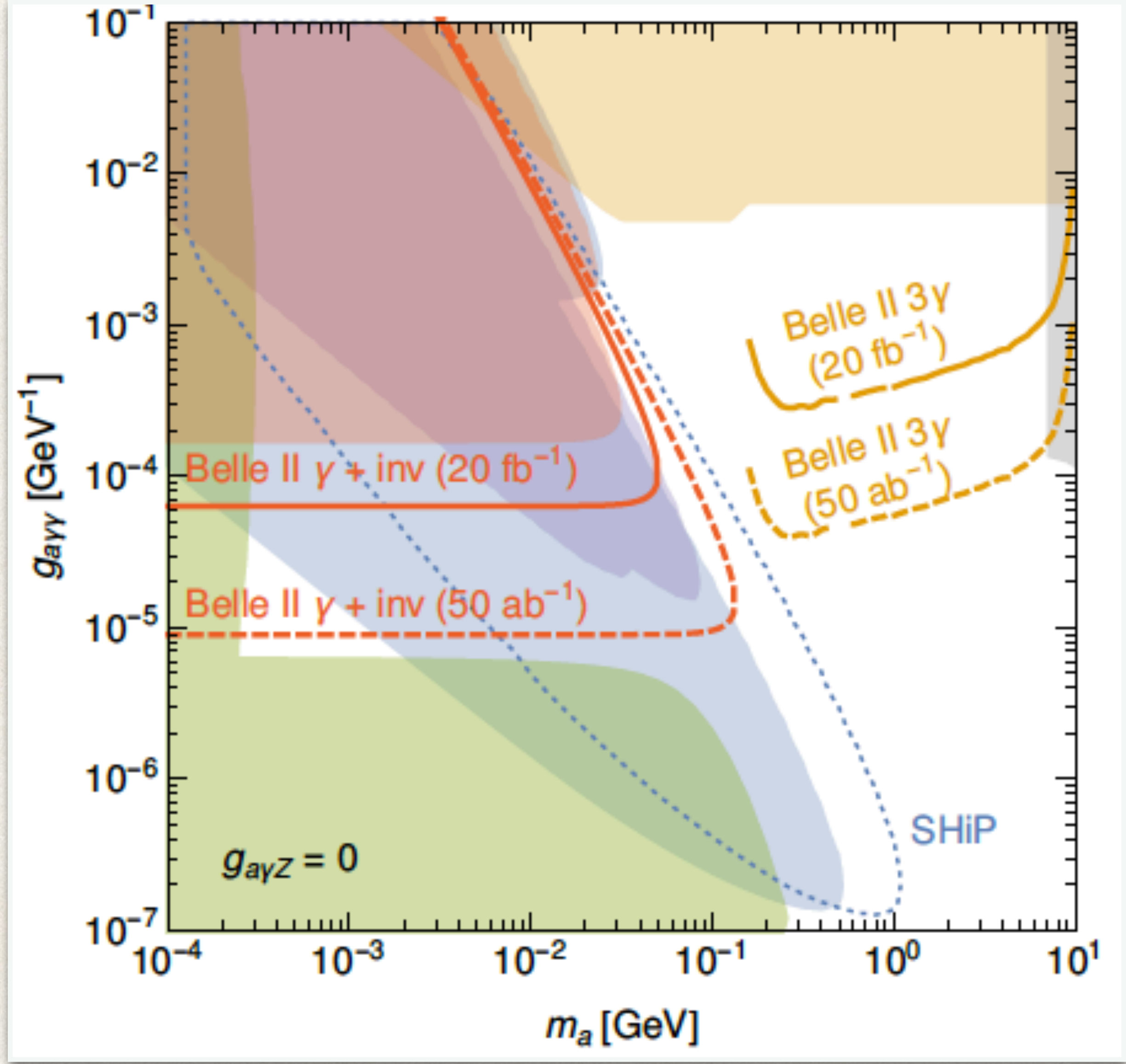
$B_s \to \mu^+\mu^-$
Belle II
$e^+e^- \to \gamma S$
BaBar
$e^+e^- \to \mu^+\mu^- S$
R_τ
E141
HPS
NA48/2
NA62
$(g-2)_\mu < 2\sigma$
$h \to SS$
COMPASS
BaBar
Belle
Belle II
$\mu \to 3e$
Orsay
$B^+ \to K^+ \ell^+ \ell^-$
E137
$\tan\beta = 200$
$m_{H,A,H^\pm} = 500$ GeV
$m_{12} = 100$ GeV
ξ_ℓ^S
ϵ_{eff}
m_S (GeV)

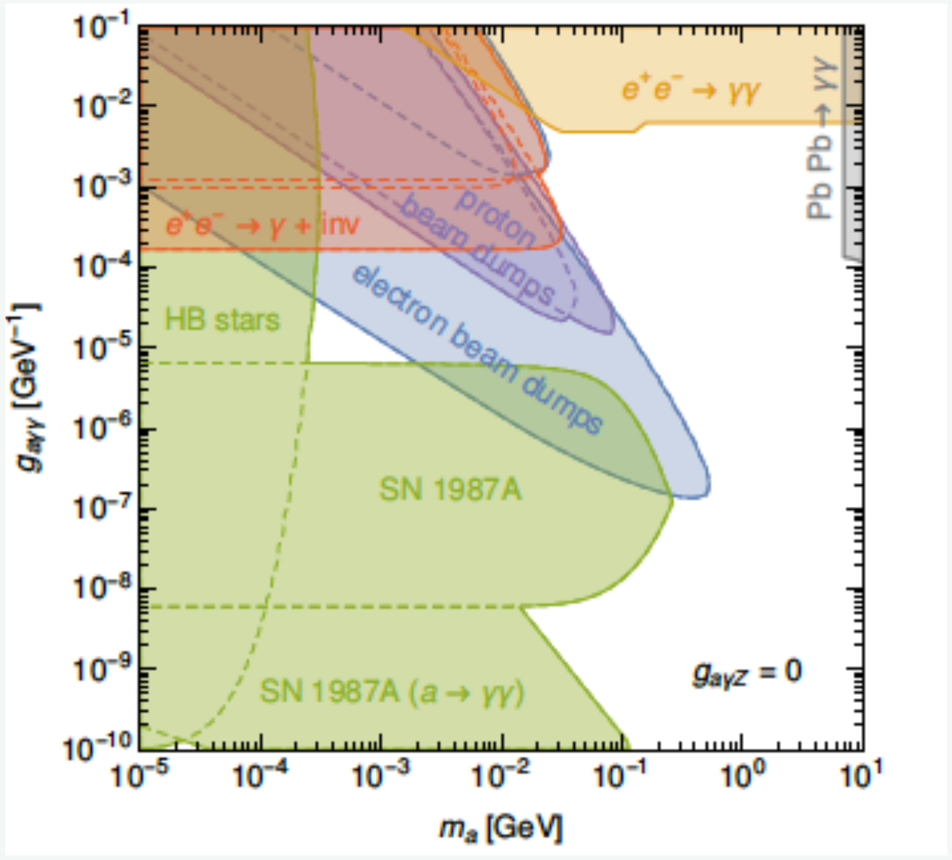
ALPs searches at Belle II

Dolan, Ferber, Hearty, Kahlhoefer and Schmidt-Hoberg arXiv:1709.00009









Conclusions

- LHC and worldwide particle physics experimental programme playing major role in how we look at physics beyond the SM
- Lack of signs of BSM@LHC resulting in new ideas for potential solutions to hierarchy problem, e.g. neutral naturalness, relaxions, LHC(b) and Belle results are putting flavour in the spotlight with the B anomalies, attracting attention to leptoquark and Z′ models
- Lot of model building activity in the light sector, trying to find innovative ways of solving the DM, strong CP, neutrino mass and hierarchy problems.
- Prospects of Belle II and LHCb look promising but need continuous thinking of new channels to further probe this sector experimentally!

Creativity of theorists moulded by experimental revelations