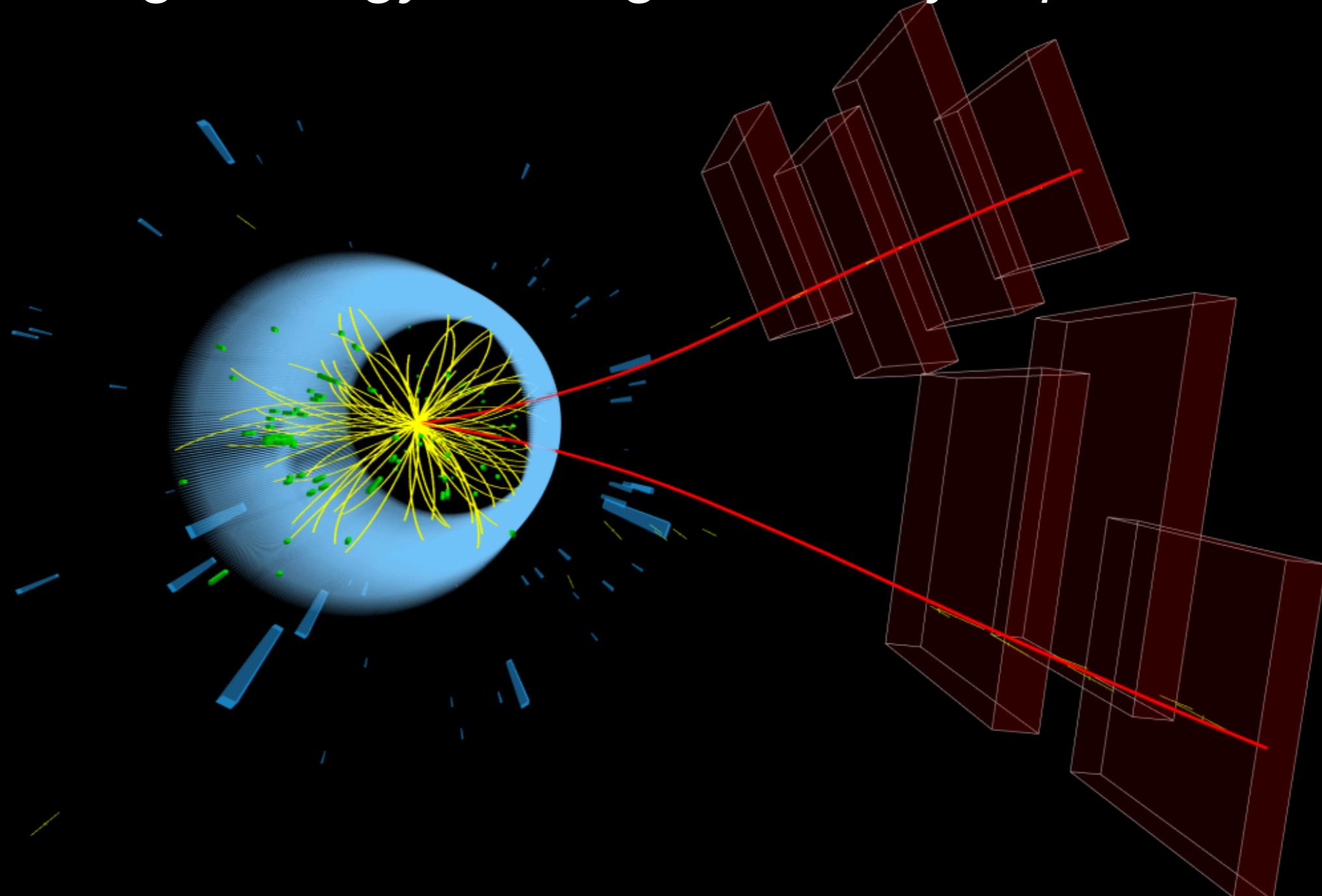


Models for long-lived particles at high-energy and high-intensity experiments



Simon Knapen
LBNL

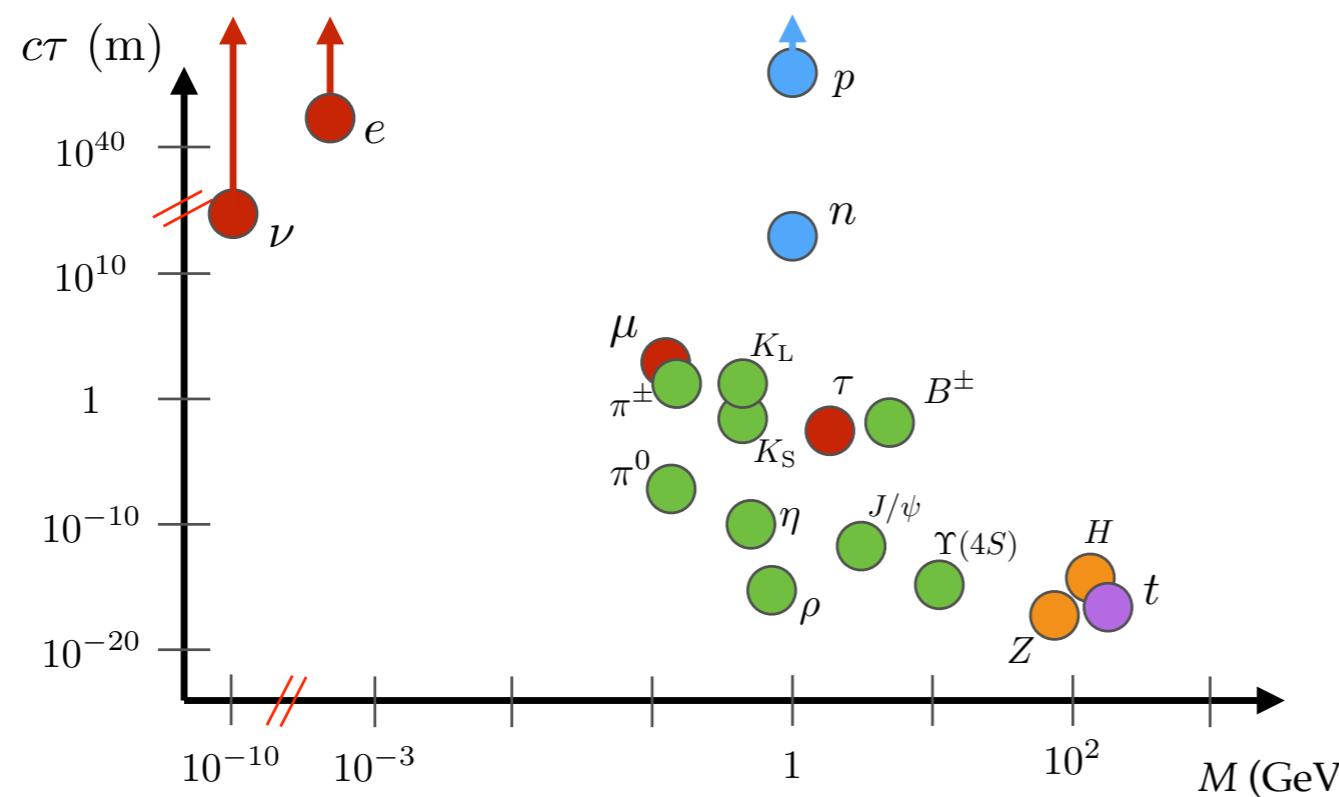
Why we expect new long-lived particles?

(1) Top down:

Many models predict them: SUSY, baryogenesis, dark matter etc

(2) Bottom up:

New “light” (< 10 GeV) particles must be neutral under SM (otherwise 💀 by LEP + LHC)

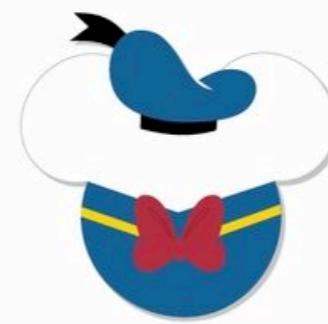


Low mass particles tend to be **long-lived**, especially if they decay through an **off-shell mediator** (e.g. W boson)

Dominant paradigm: The Fabulous Five

Aka “portals”

Axion-like particle
(ALP)



Heavy Neutral Lepton
(HNL)

Milicharged
particle



Dark Higgs

Dark photon

Dominant paradigm: The Fabulous Five

Aka “portals”

Axion-like particle
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Heavy Neutral Lepton
(HNL)

Milicharged
particle



Dark Higgs

Dark photon

Why expect these?

Unlike e.g. a WIMP, the dark photon does NOT predict its own existence, let alone a preferred parameter range!

What are “good” models?

Is my model:

Examples



Falsifiable?

If we don't see X, is the idea dead?



Predictive?

Does it predict new phenomena?



Self-consistent?

Unitarity, existing bounds,
viable UV completion exists

The distinction between “falsifiable” and “predictive” is of course subjective and up for interpretation...
e.g. Falsifiable by whom: Ourselves or our great-grandchildren? etc.

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Examples

Weak-scale SUSY
(Old fashioned) WIMP
...



Predictive?

Does it predict new phenomena?

Low scale seesaw
Relaxion
Heavy Axions
Hidden sector Dark Matter
...



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Fabulous Five vs “complete” models

Do the Fab 5 frequently appear in complete models?



YES



Are the Fab 5 sufficient?

NO

- Axion-like particle (ALP)
- Dark photon
- Milicharged particle
- Dark Higgs
- Heavy Neutral Lepton (HNL)

- Baryogenesis
- Low scale seesaw
- Relaxion
- Heavy Axions
- Hidden sector Dark Matter
- ...

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See back-up slides

- Baryogenesis
- Low scale seesaw
- Relaxion
- Heavy Axions
- Hidden sector Dark Matter
- ...

I will try to illustrate both points with a few examples

Asymmetric Dark Matter / Baryogenesis



Why is there more matter than anti-matter?

Dark photon

Baryogenesis needs:

- CP violation
- Out of equilibrium dynamics
- Baryon number violation

Standard Model offers:

- CKM phase
- Electroweak phase transition
- Electroweak sphaleron processes

Unfortunately, SM phase transition and CP violation are too weak. 😢

Asymmetric Dark Matter / Baryogenesis

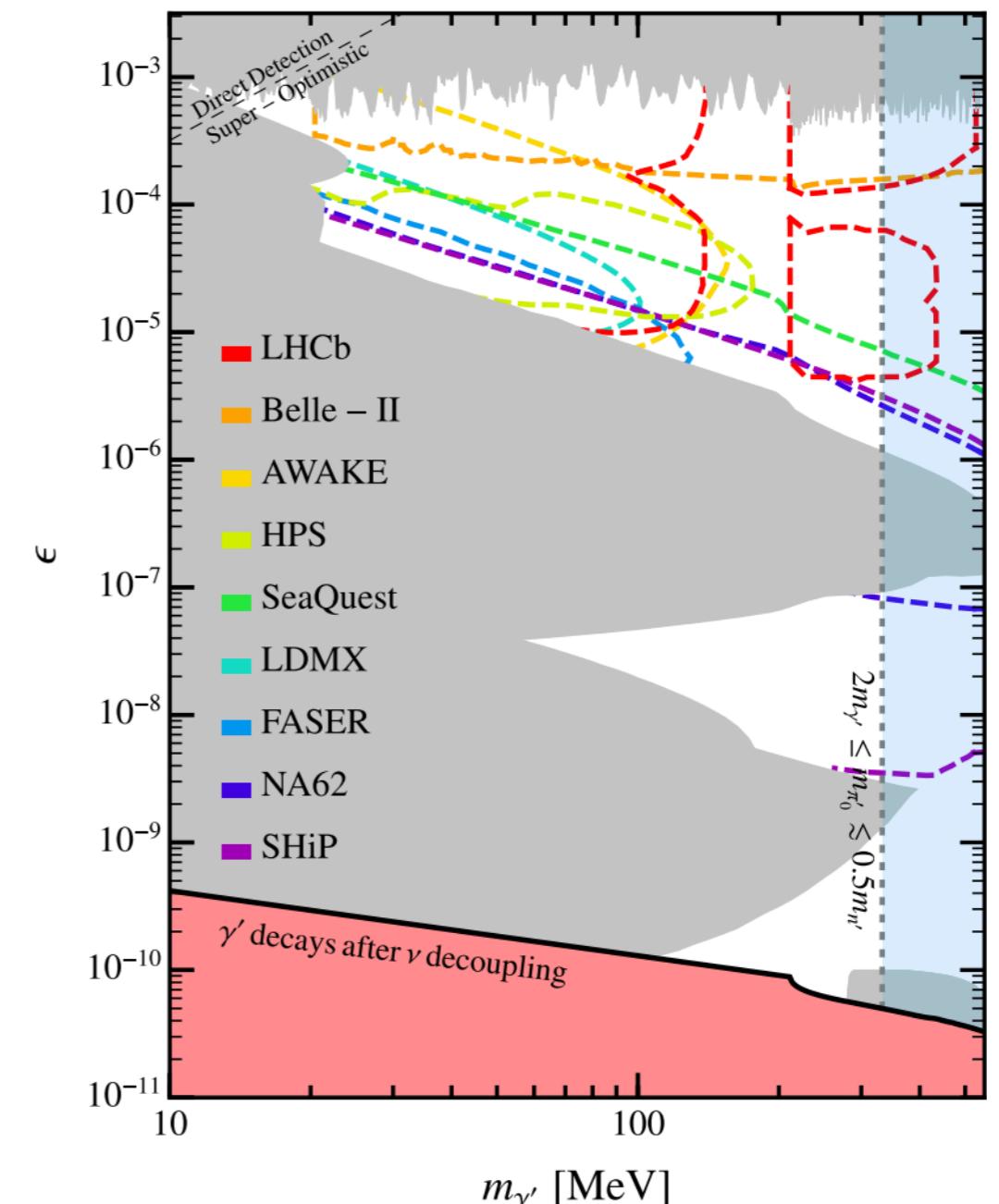


Solution: Put all your hopes and dreams in the dark sector!

Example

Composite dark sector with “dark neutron” as the dark matter candidate

Dark Neutron Dark Matter



Asymmetric Dark Matter / Baryogenesis



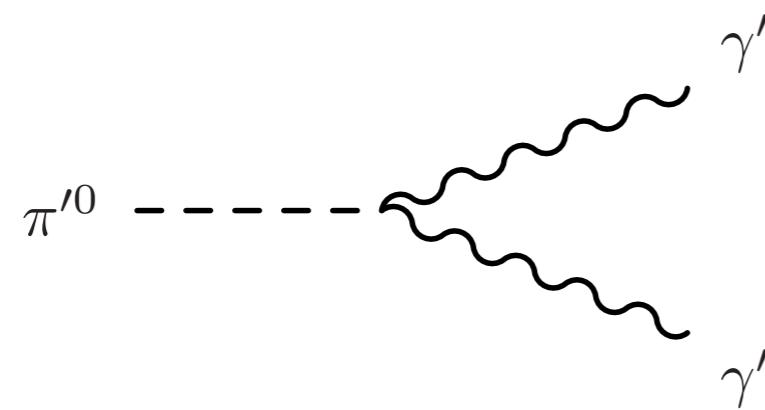
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Dark photon

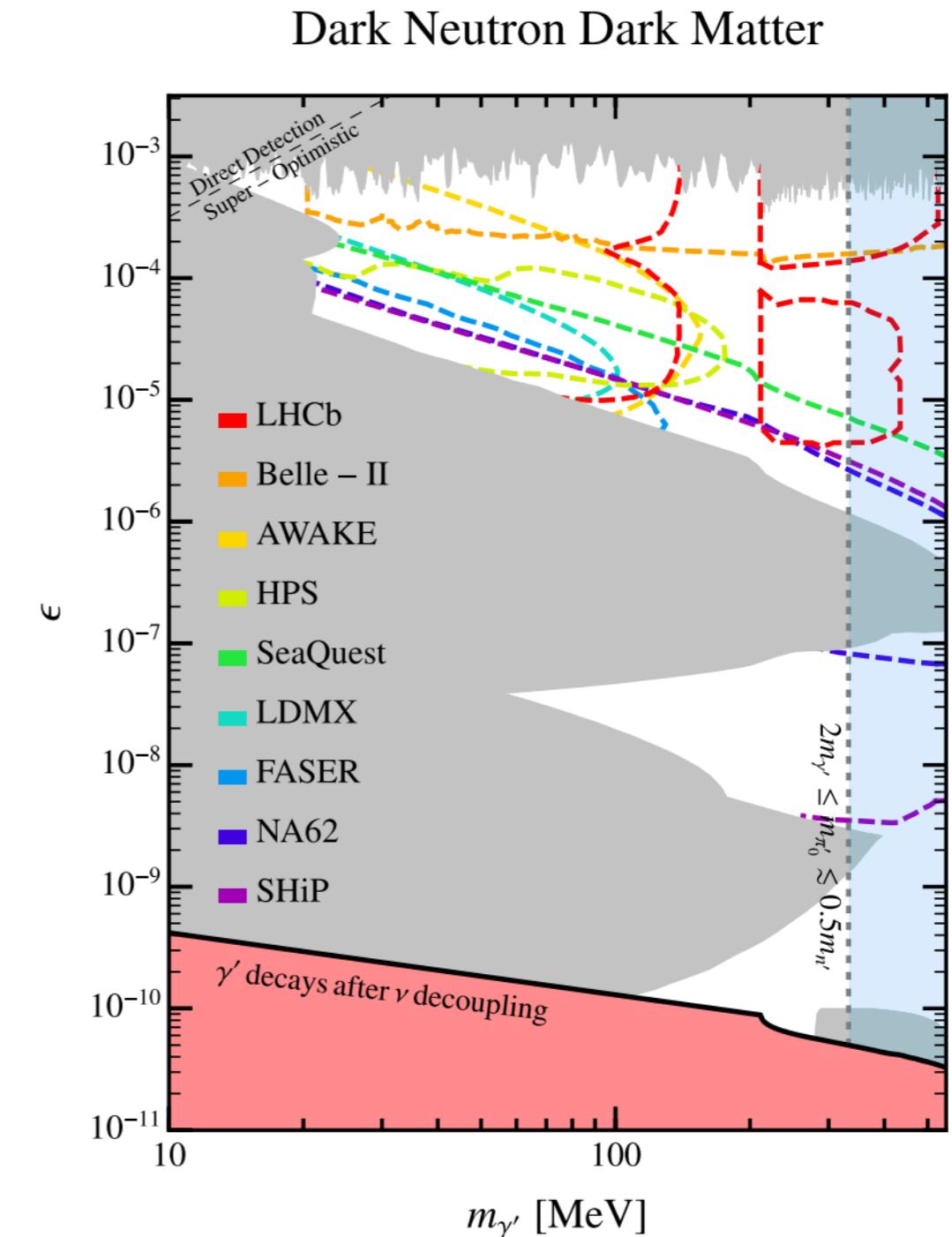
Example

Composite dark sector with “dark neutron” as the dark matter candidate

Deplete dark pions through decay to dark photon



Generally, dark photons are very useful to get rid of dangerous particles before BBN or to directly set DM relic abundance



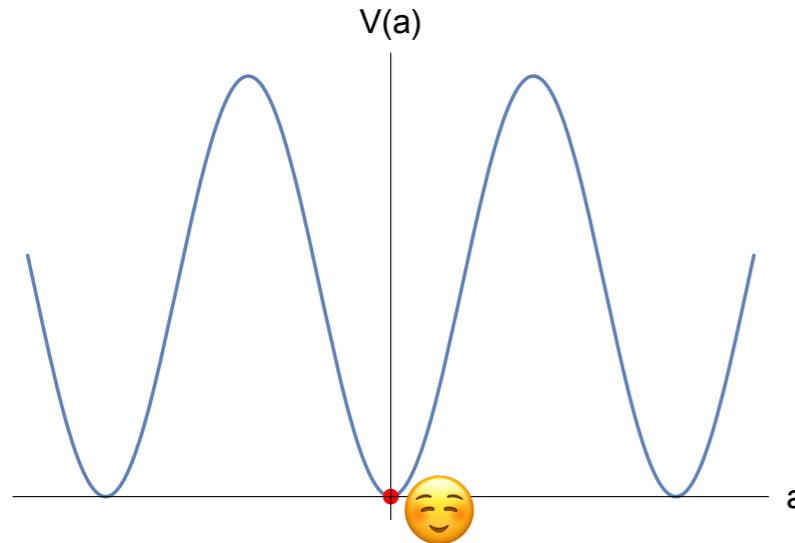
Axion quality problem



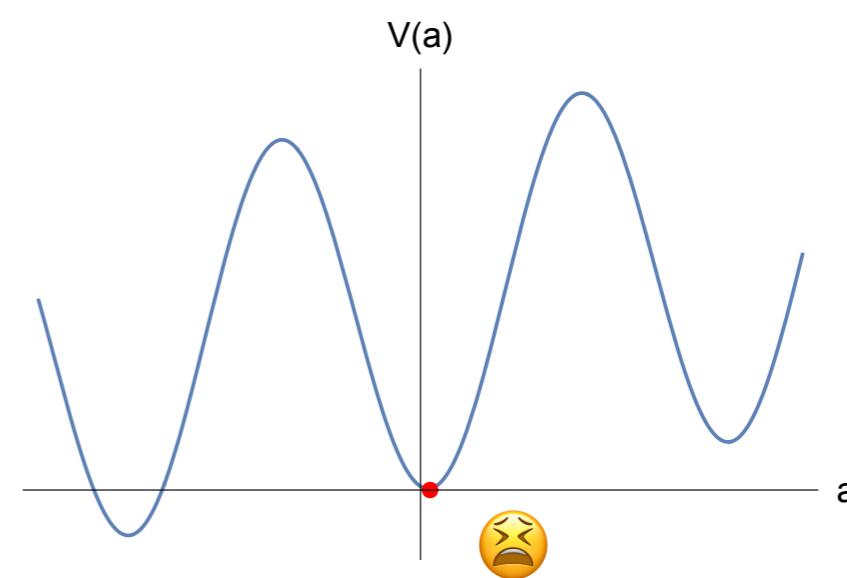
Axion solution to strong CP problem is fairly fragile:

ALP

Only QCD breaks Peccei Quin symmetry

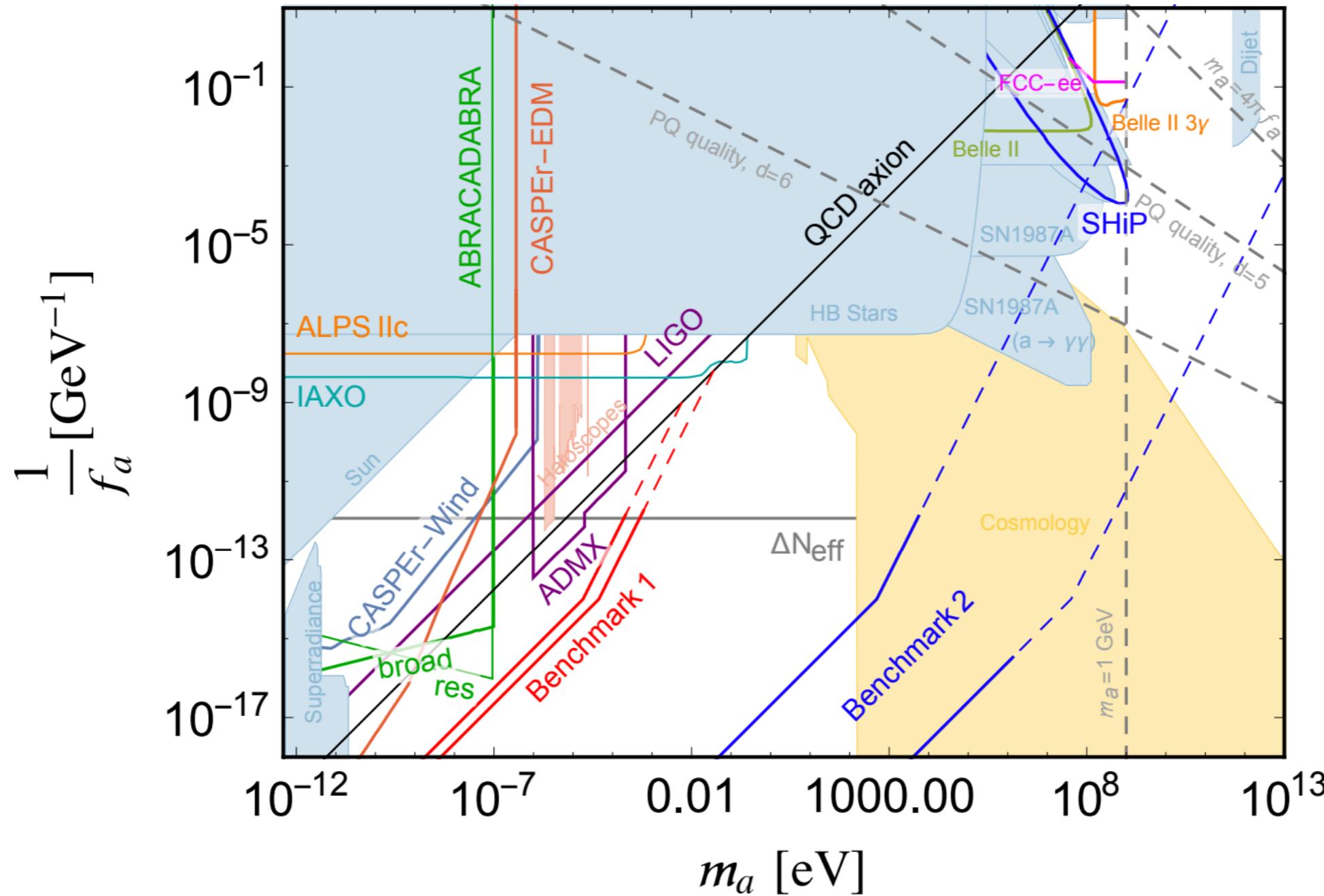


Other sources of Peccei Quin breaking (e.g. Gravity)



Problem most severe for low mass axions, though solutions certainly exist

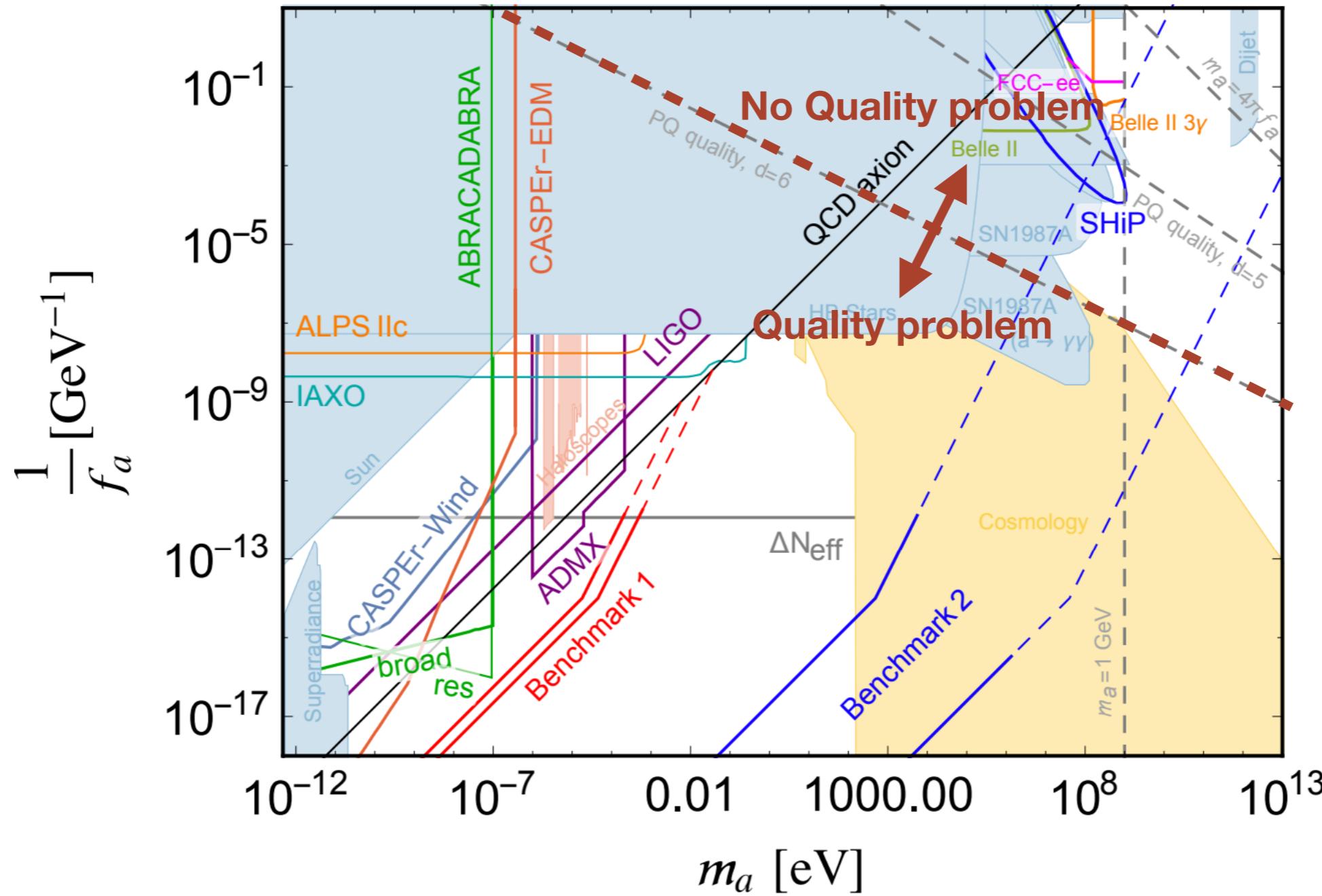
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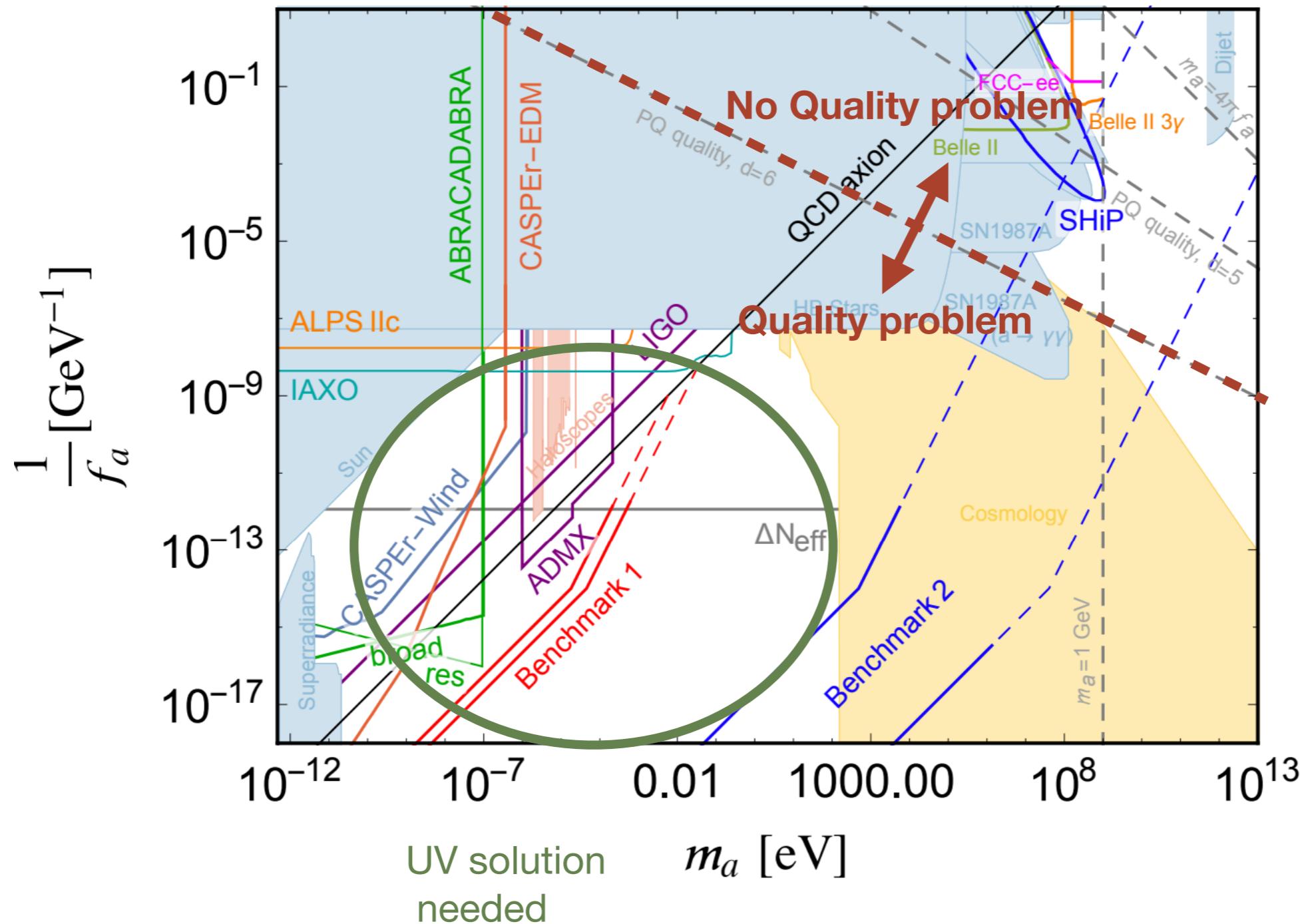
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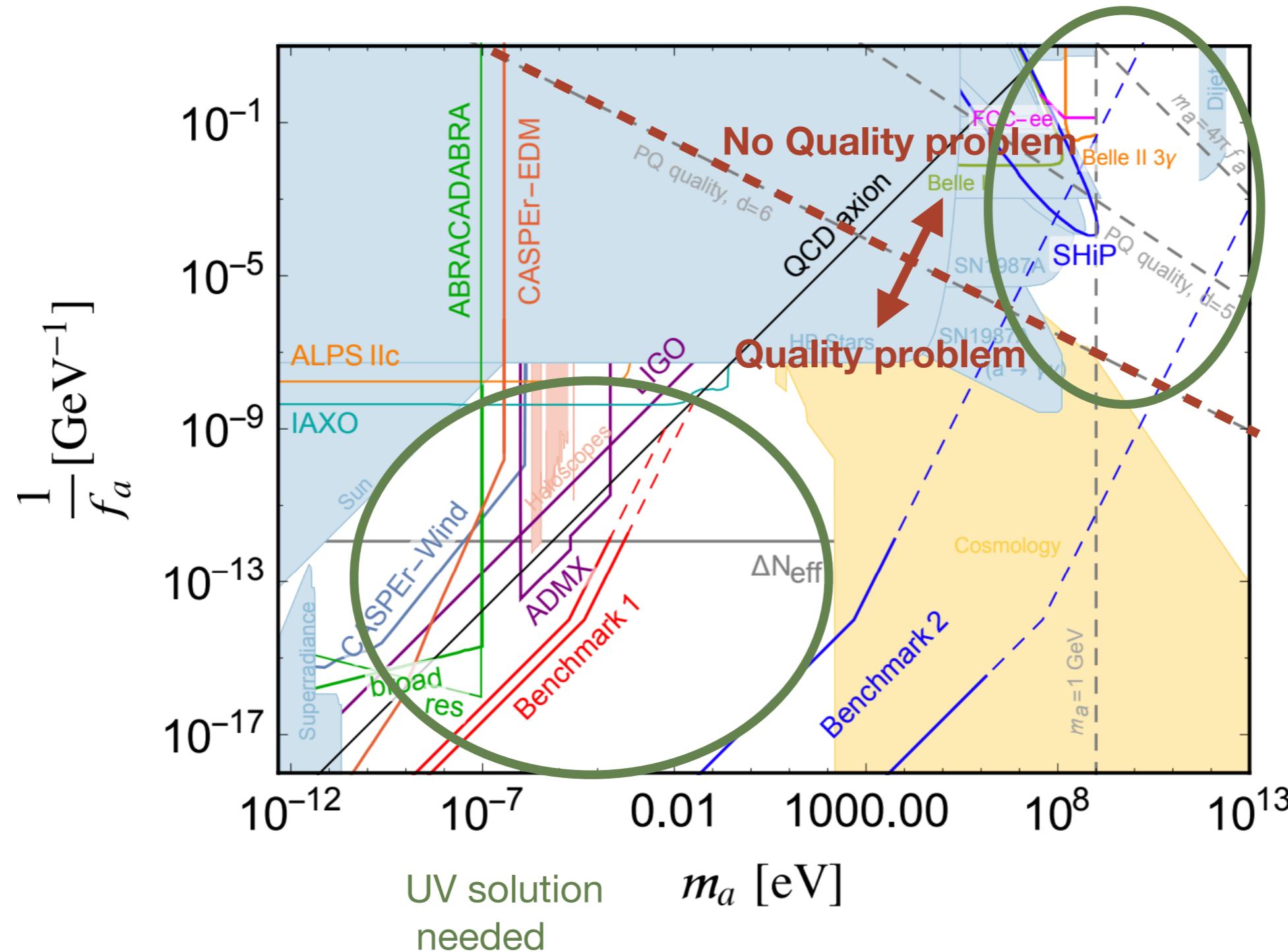
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Axion quality problem



Axion quality problem



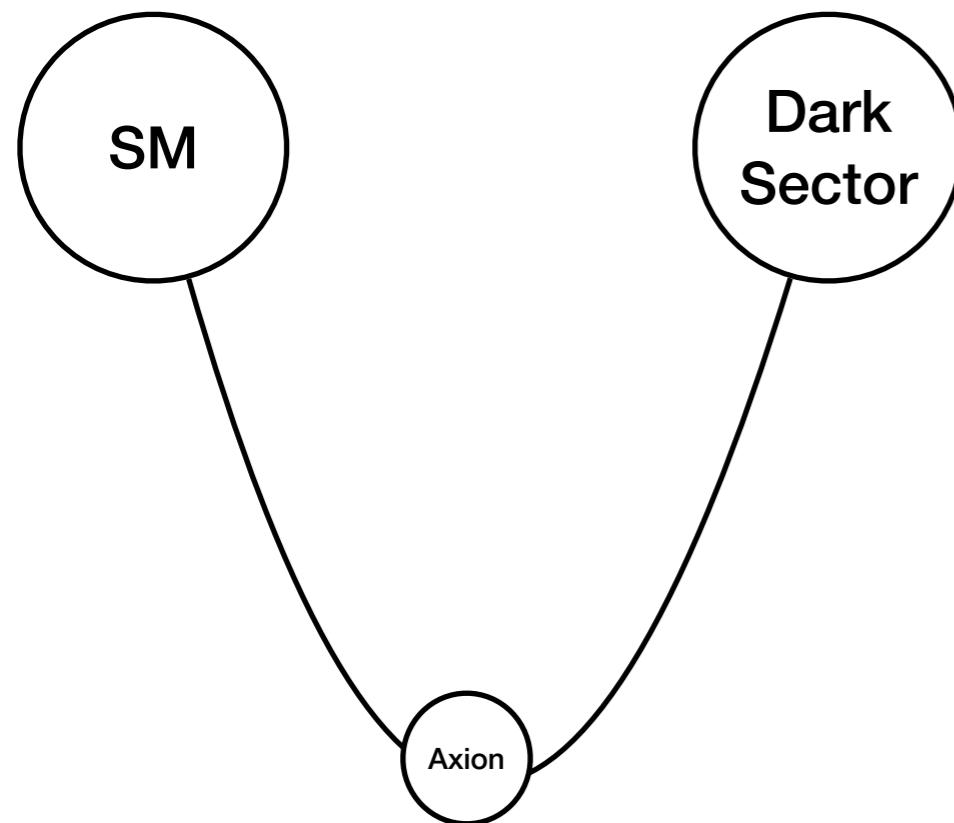
Axion quality problem



Can we make the axion heavier without spoiling the strong CP problem?

Enter: a dark sector

ALP



V. A. Rubakov: arXiv 9703409

P. Agrawal and K. Howe: arXiv 1710.04213, 1712.05803

A. Hook et. al.: arXiv 1911.12364

...

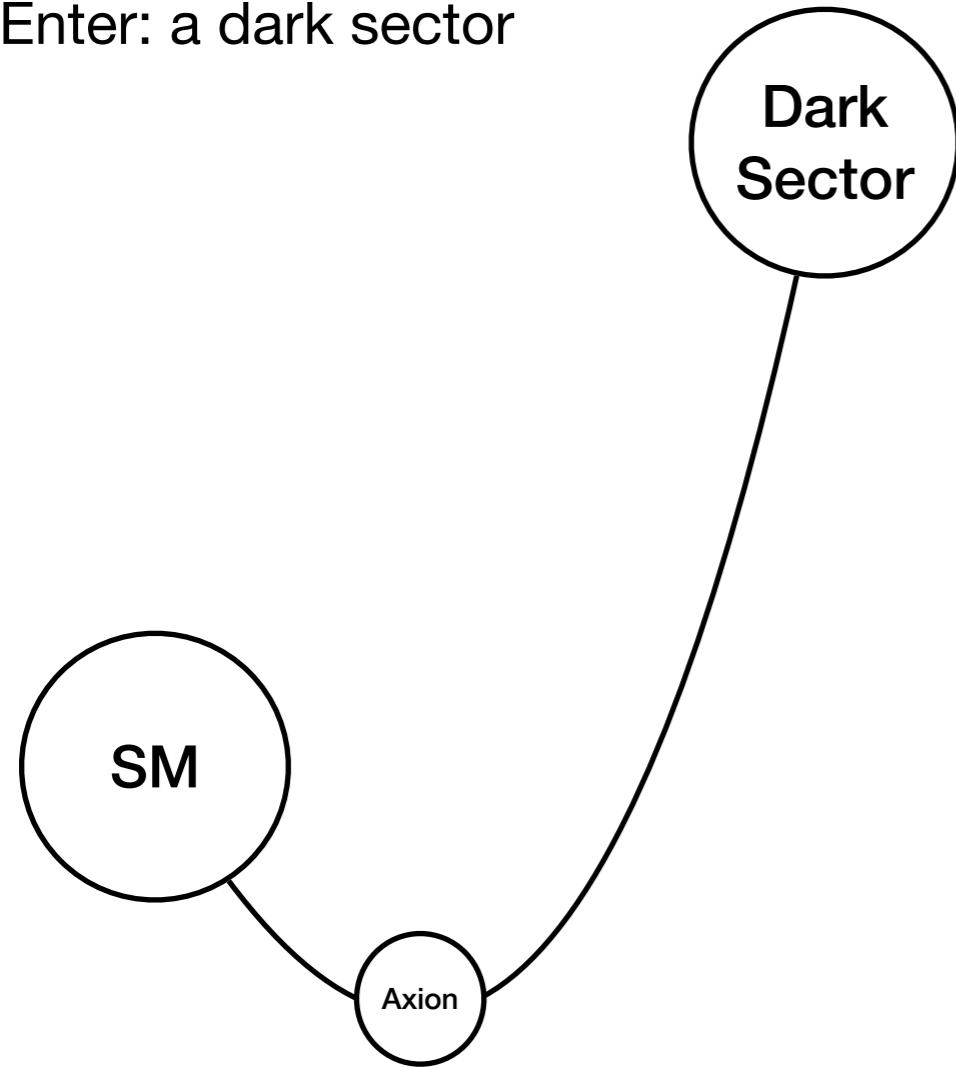
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Some cleverness is needed to not spoil the strong CP problem

V. A. Rubakov: arXiv 9703409

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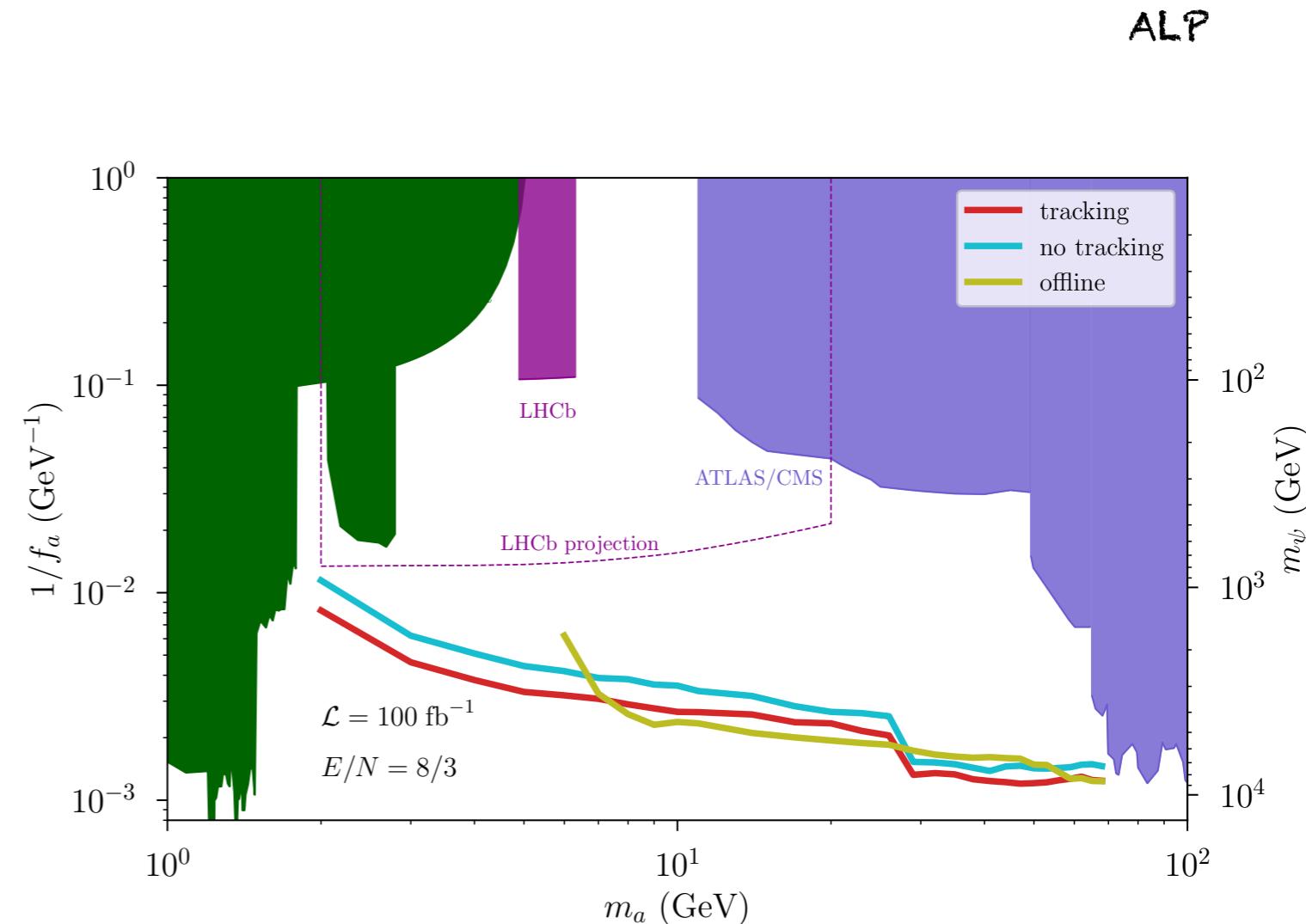
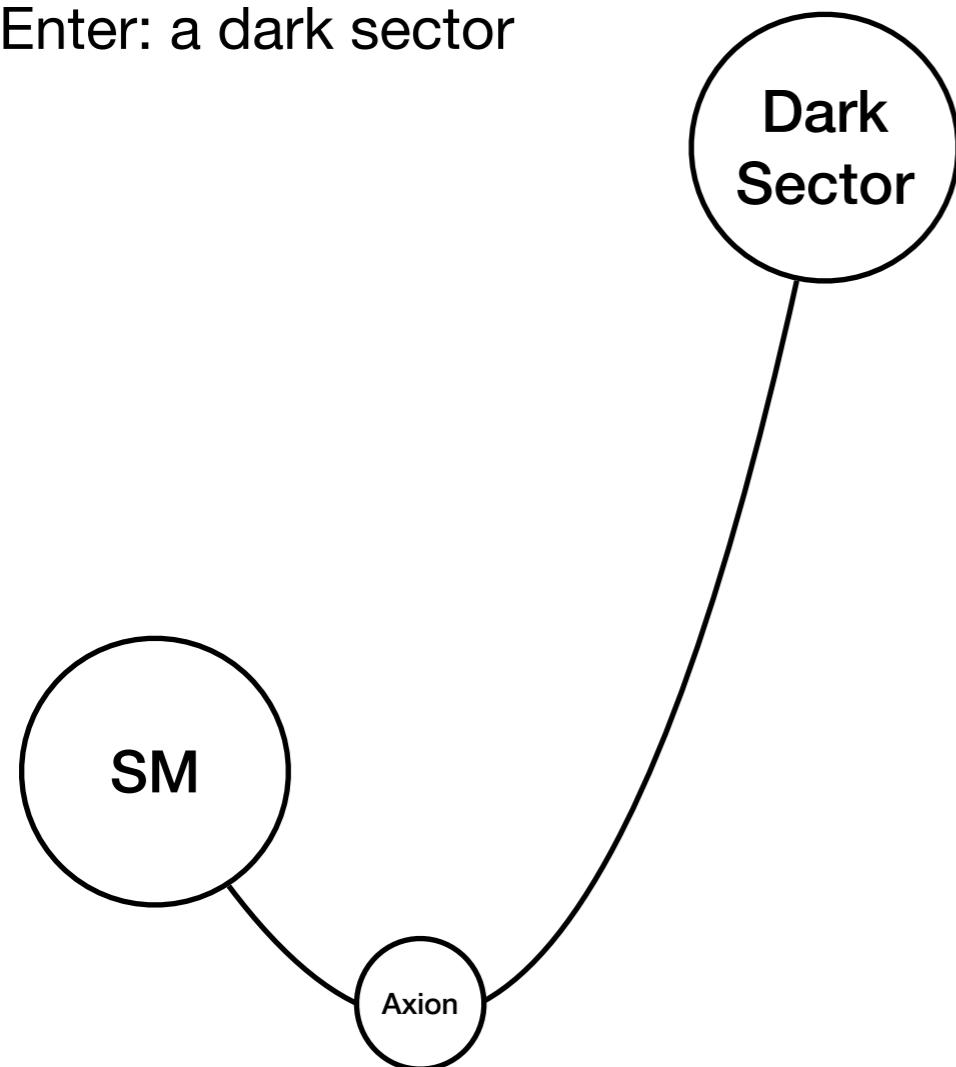
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...

Axion MUST couple to gluons, and likely couples to photons (photon jets)

SK, S. Kumar, D. Redigolo: arXiv 2112.07720

X. Cid Vidal et. al. : arXiv 1810.09452

See also A. Hook et. al.: arXiv 1911.12364

....

Fabulous 5 vs other dark sector models

Do the Fab 5 frequently appear in complete models?



Yes
(but “falsifying” often difficult)



Are the Fab 5 sufficient?

Axion-like particle (ALP)
Dark photon
Milicharged particle
Dark Higgs
Heavy Neutral Lepton (HNL)

Low scale seesaw
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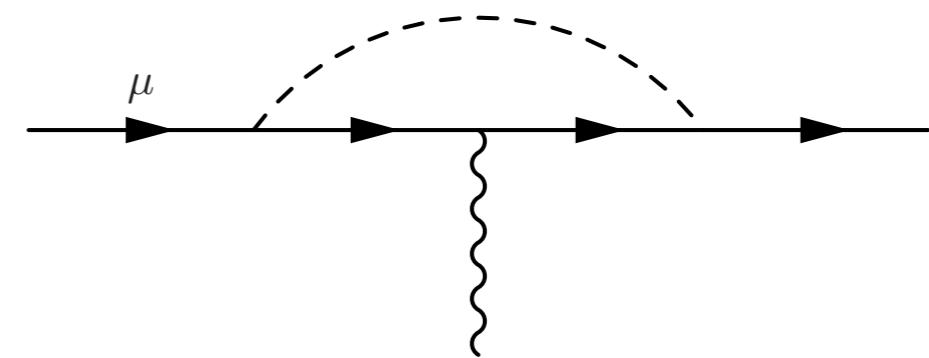
Now let's take a look at three examples of “non-Fab 5” models

Example 1: muon-phylic bosons

Motivated by the muon g-2 anomaly

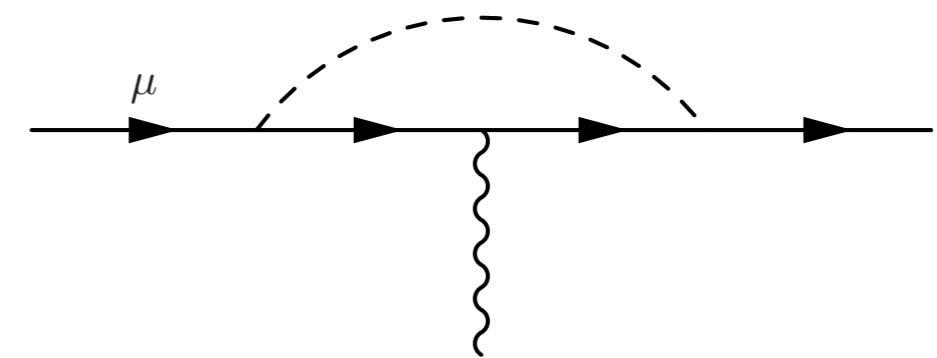
Two types:

1. muon-phylic scalar (couples to photons at 1 loop)
2. $L_\mu - L_\tau$ gauge boson (couples to τ , v_μ and v_τ at tree-level)



Example 1: muon-phylic bosons

Motivated by the [muon g-2 anomaly](#)



Two types:

1. muon-phylic scalar (couples to photons at 1 loop)
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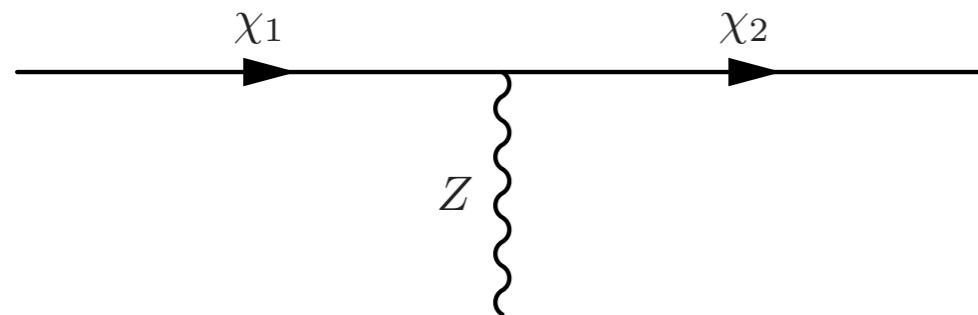
Both require either tuning or a [non-trivial mechanism in the UV](#) to pick out this particular flavor pattern without adding dangerous flavor violation

The latter can certainly be engineered, but at the moment still unclear whether “being muon-phylic” can be made into a prediction, as opposed to a postdiction

Muon-phylic bosons are therefore most useful a stand-in for a more general boson with suppressed couplings to electrons

Example 2: inelastic dark matter

Similar the Z-Higgsino coupling in MSSM

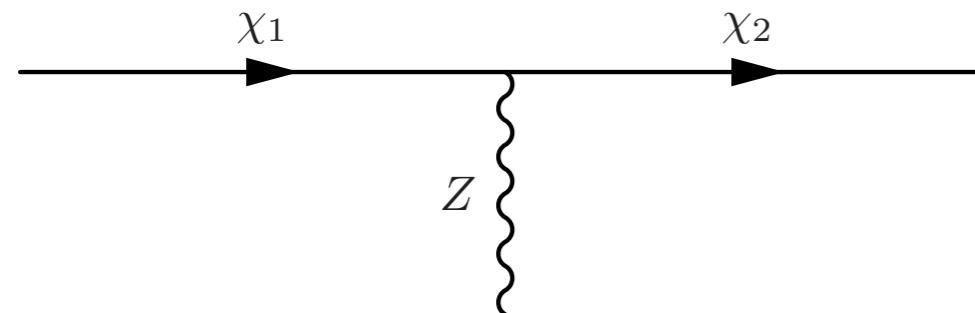


Irrelevant operators can naturally introduce a tiny splitting between χ_1 and χ_2
→ no Z-mediated direct detection

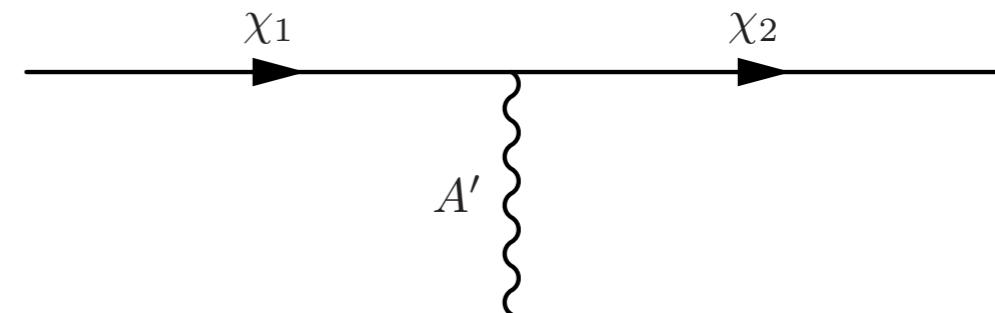
But disappearing tracks from $\chi^\pm \rightarrow \chi_1 + \text{SM}!$

Example 2: inelastic dark matter

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Easily replicated in a dark sector



Irrelevant operators can naturally introduce a tiny splitting between χ_1 and χ_2
 \rightarrow no Z-mediated direct detection

But disappearing tracks from $\chi^\pm \rightarrow \chi_1 + \text{SM}!$

Collider pheno: MET + soft displaced vertex

$\chi_2 \rightarrow \chi_1 + \text{SM}$ decay naturally long-lived due to phase space suppression

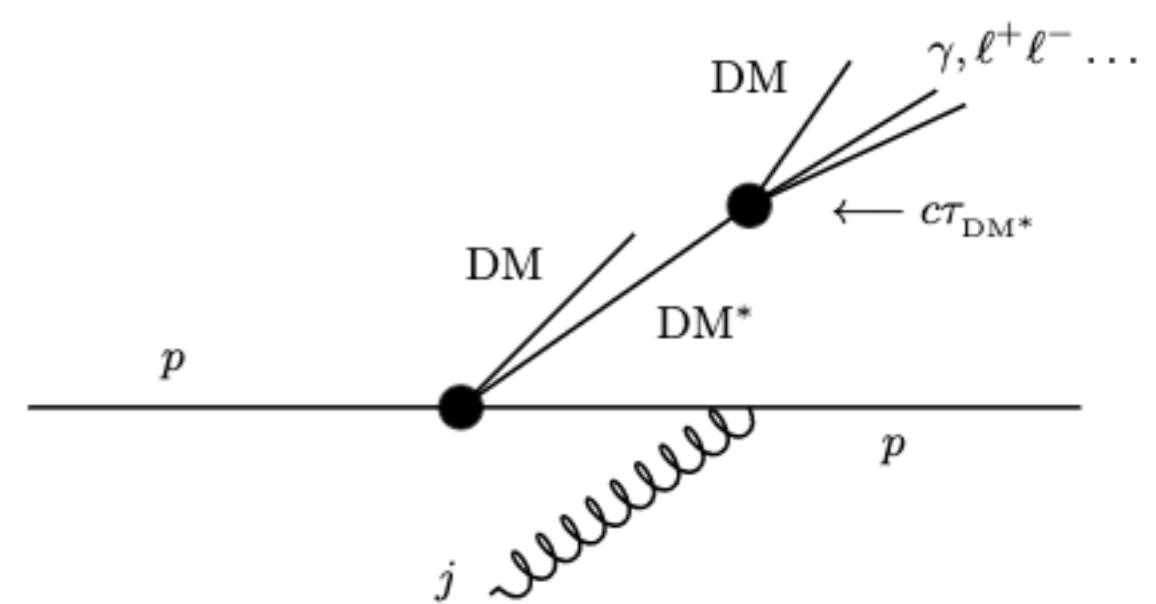
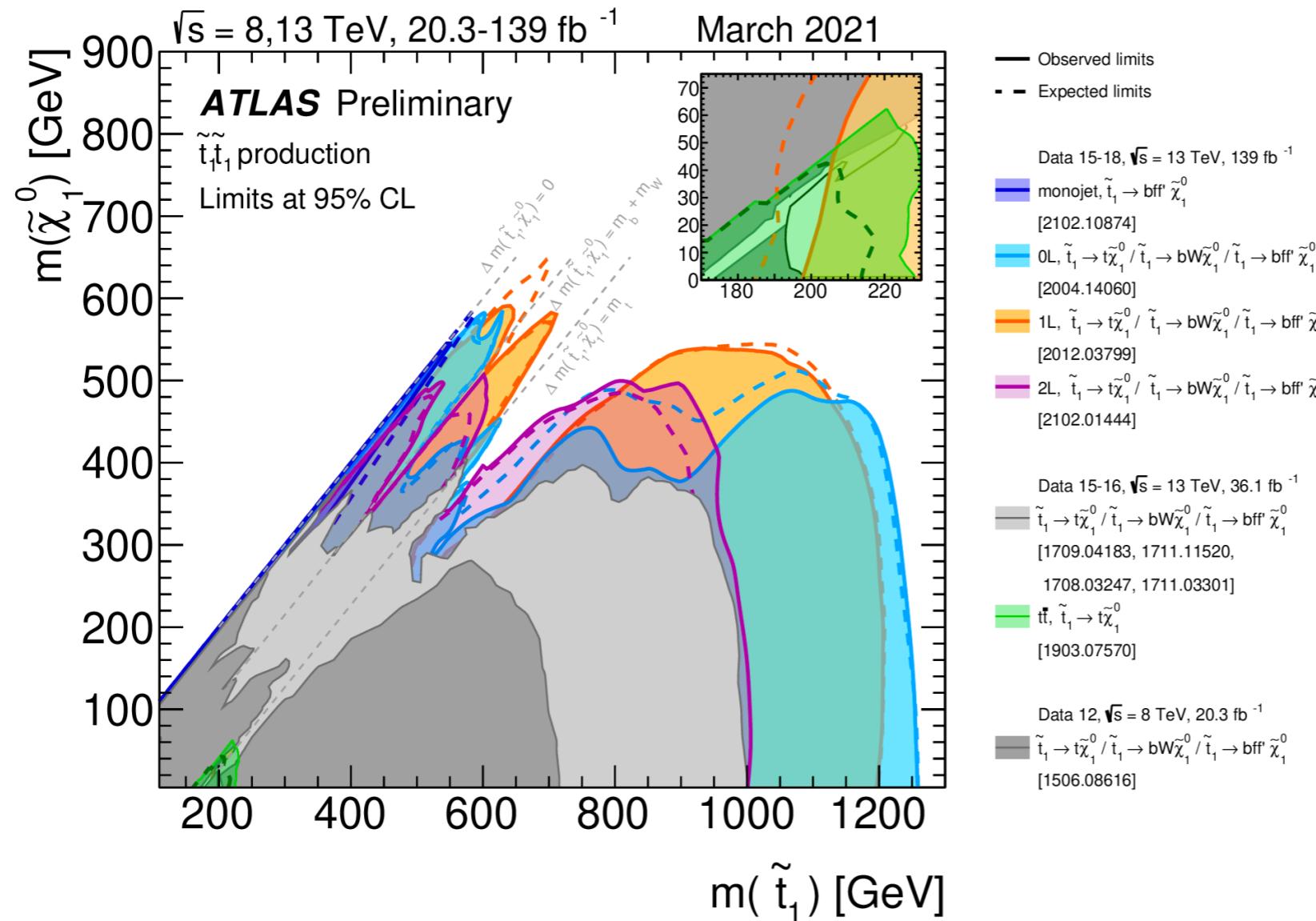


Figure from E. Izaguirre, G. Knrjaic and B. Shuve: arXiv 1508.03050

Example 3: Neutral Naturalness

Status of “vanilla” solutions to the hierarchy problem a bit bleak



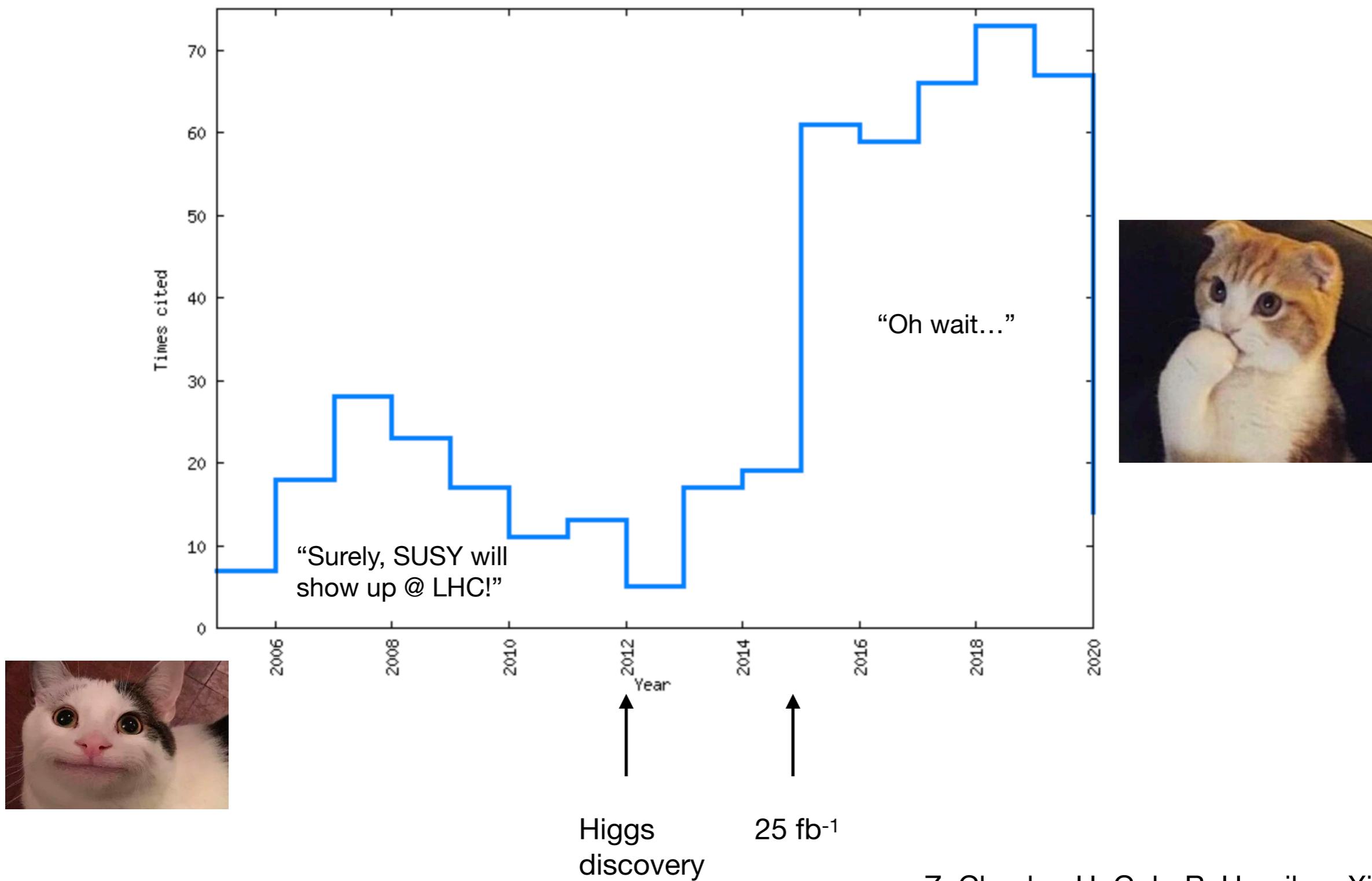
Can we still have $< 1 \text{ TeV}$ top partners?

Yes, if the top partner carries dark sector color instead of SM color

Example 3: Neutral Naturalness

“Twin Higgs” as the first & simplest example

Citation history:

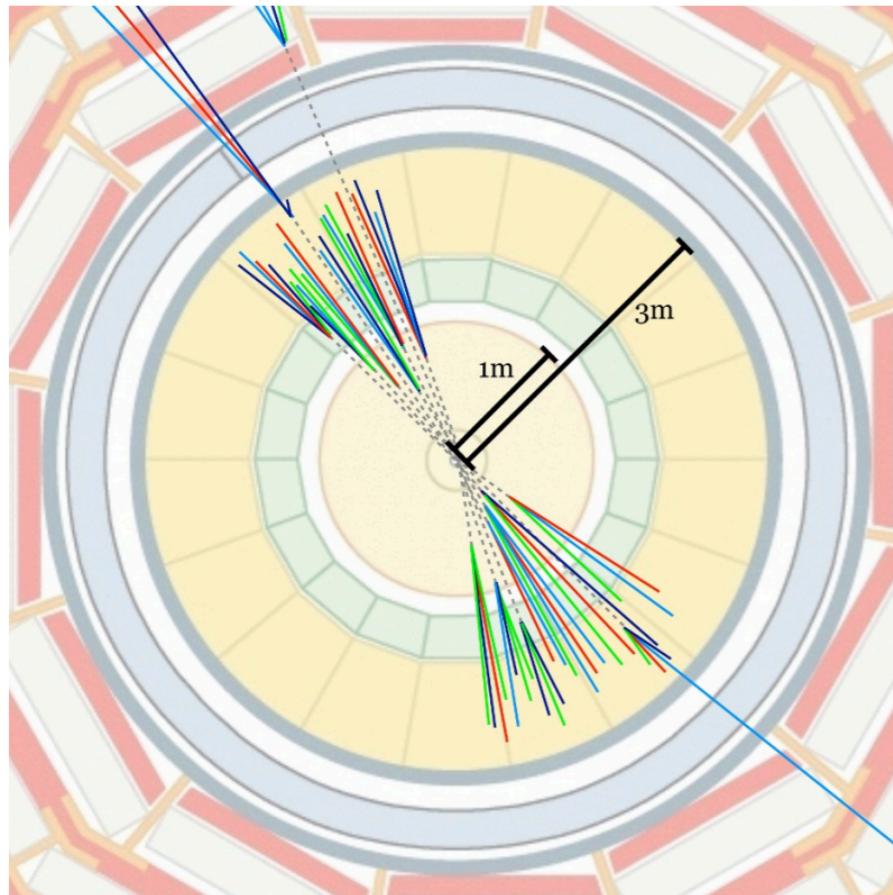


Example 3: Neutral Naturalness

Twin Higgs is an example of a “hidden valley”

M. Strassler, K. Zurek: arXiv 0604261

Some Twin Higgs models predict “dark shower” / “emerging jet” phenomenology:



P. Schwaller, et. al.: arXiv 1502.05409

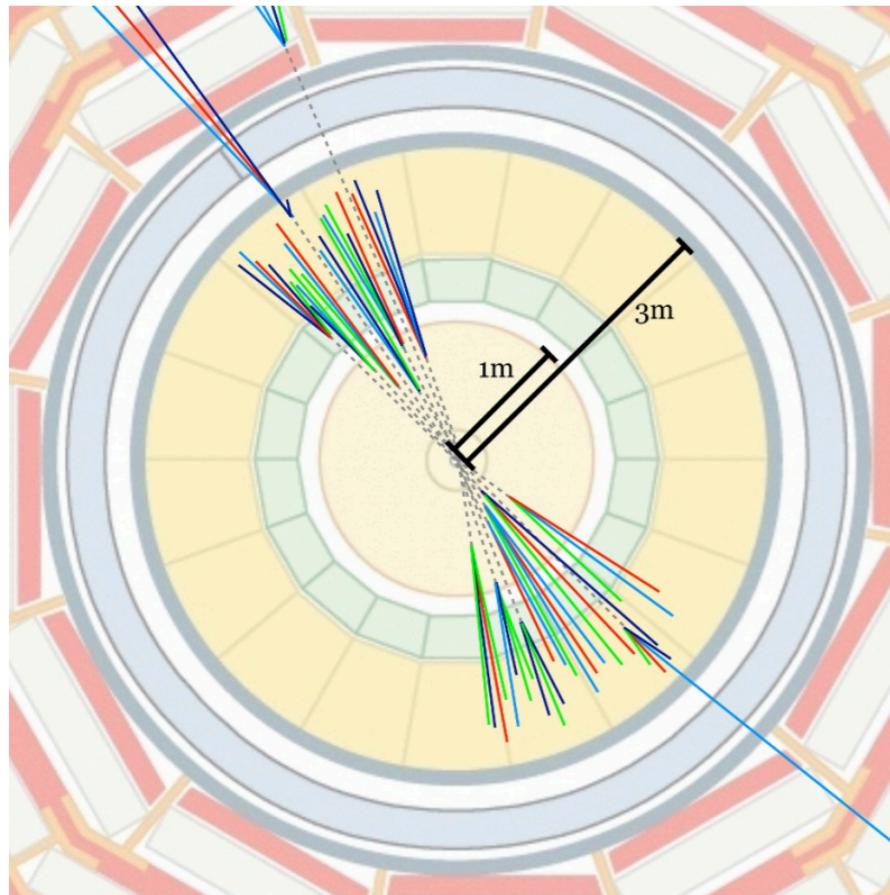
Some cool results on emerging jets (CMS 1810.10069)
and semi-visible jets (CMS 2112.11125 and ATLAS ATLAS-CONF-2022-038)

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Some Twin Higgs models predict “dark shower” / “emerging jet” phenomenology:



P. Schwaller, et. al.: arXiv 1502.05409

General question:

“How do we build a suite of maximally inclusive searches?”

See dark showers white paper: arXiv 2203.09503

- Long lived particle searches
- Jet substructure / precision QCD
- Machine learning

Much more theory work is needed / in progress.

Some cool results on emerging jets (CMS 1810.10069)
and semi-visible jets (CMS 2112.11125 and ATLAS ATLAS-CONF-2022-038)

Summary

Do the Fab 5 frequently appear in complete models?



Yes
(but “falsifying” appears difficult)

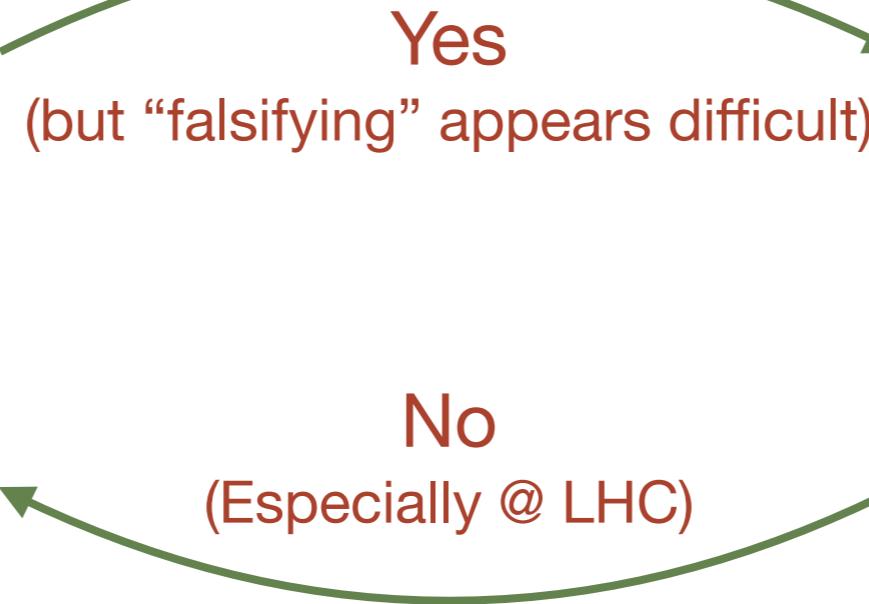
No
(Especially @ LHC)



Are the Fab 5 sufficient?

Summary

Do the Fab 5 frequently appear in complete models?



The Fab 5 appear to be good representatives of complete models and great benchmarks...

... but need to take care to not over interpret them! On their own, they have no predictive power

There are already a good number of other examples, but I think we probably need more
Fab 5 should NOT become the new CMSSM!

Thanks!



Low scale seesaw



Where do neutrino masses come from?
(Forbidden by gauge invariance in the Standard Model)

Heavy
neutral
lepton

Seesaw mechanism:

$$\mathcal{L} \supset y H L N + M_M N^2$$

Breaks lepton number

$$\rightarrow \mathcal{L}^{IR} \supset \frac{y^2}{M_M} H L H L$$

$$\rightarrow m_\nu = \frac{y^2 |\langle H \rangle|^2}{M_M} \approx 0.1 \text{ eV} \times \left(\frac{y}{1}\right)^2 \times \frac{10^{15} \text{ GeV}}{M_M}$$

Quarks					
Left	2.4 MeV $\frac{2}{3}$ u up	Right	Left	1.27 GeV $\frac{2}{3}$ c charm	Right
Left	4.8 MeV $-\frac{1}{3}$ d down	Right	Left	171.2 GeV $\frac{2}{3}$ t top	Right
Left	104 MeV $-\frac{1}{3}$ s strange	Right	Left	4.2 GeV $-\frac{1}{3}$ b bottom	Right
Leptons					
Left	<0.0001 eV 0 ν_e electron neutrino	Right	Left	~ 0.01 eV 0 ν_μ muon neutrino	Right
Left	0.511 MeV -1 e electron	Right	Left	~ 0.04 eV 0 ν_τ tau neutrino	Right
Left	105.7 MeV -1 μ muon	Right	Left	1.777 GeV -1 τ tau	Right

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$$\approx 0.1 \text{ eV} \times \left(\frac{y}{3 \times 10^{-8}}\right)^2 \times \frac{1 \text{ GeV}}{M_M}$$

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$-\frac{1}{3}$			$-\frac{1}{3}$		b bottom
	$<0.0001 \text{ eV}$	ν_e electron neutrino		$\sim 0.01 \text{ eV}$	ν_μ muon neutrino
		N₁ sterile neutrino			N₂ sterile neutrino
					ν_τ tau neutrino
					N₃ sterile neutrino
		Leptons			
-1	0.511 MeV	e electron	-1	105.7 MeV	μ muon
-1			-1		τ tau

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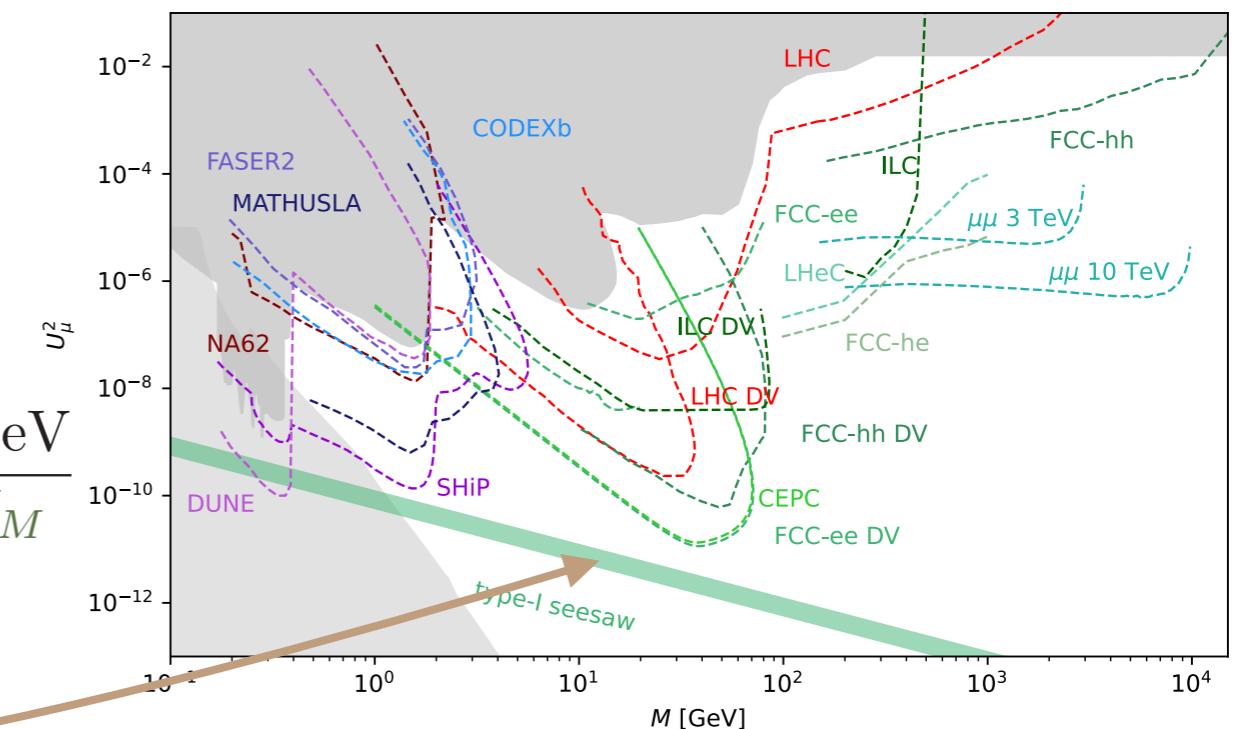
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$$\approx 0.1 \text{ eV} \times \left(\frac{y}{3 \times 10^{-8}}\right)^2 \times \frac{1 \text{ GeV}}{M_M}$$

$$\rightarrow U^2 \approx \frac{y^2 |\langle H \rangle|^2}{M_M^2} = \frac{m_\nu}{M_M} \approx 10^{-10} \times \frac{1 \text{ GeV}}{M_M}$$

Breaks lepton number



A. M. Abdullahi et al: arXiv 2203.08039

Low scale seesaw



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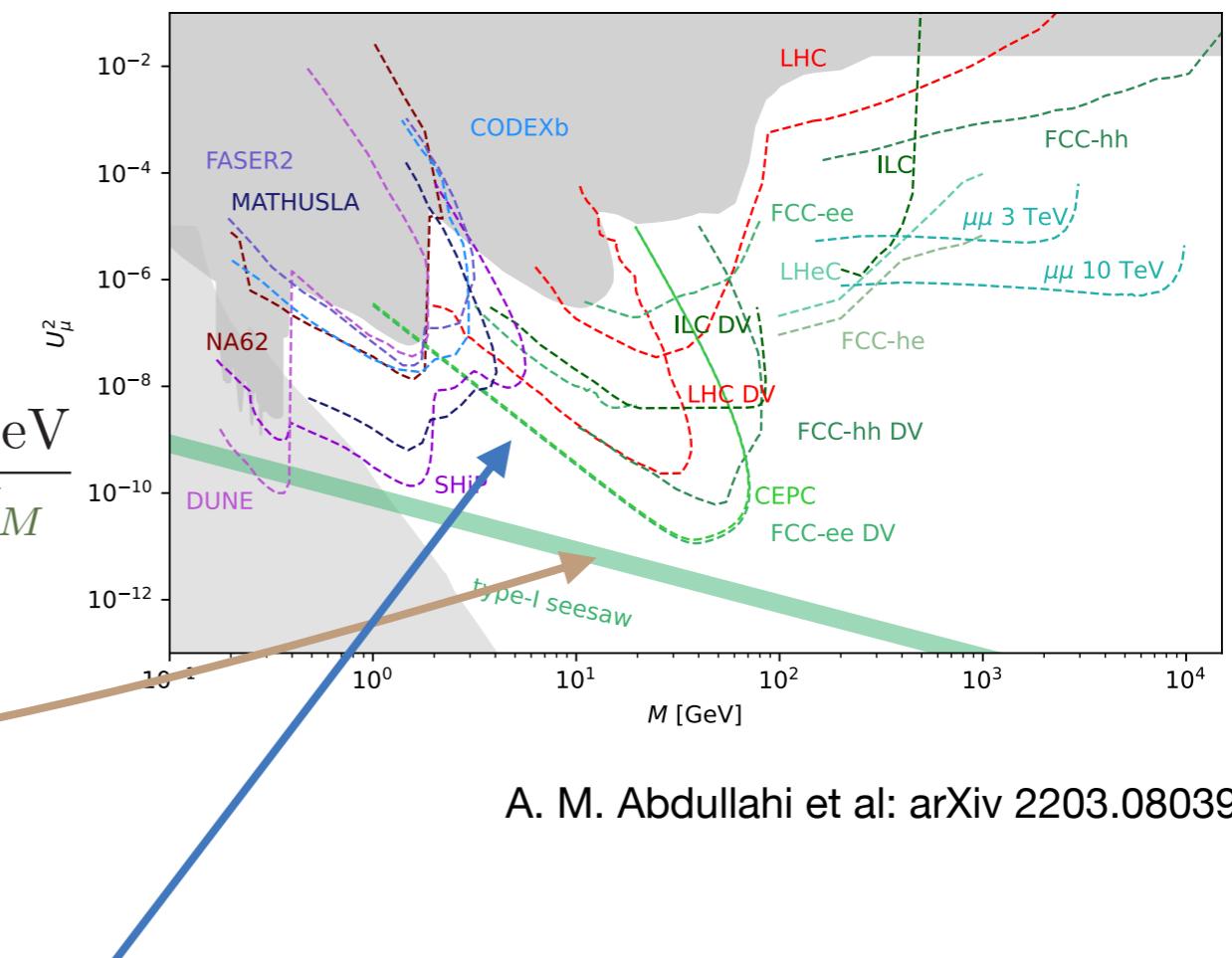
$$\mathcal{L} \supset y H L N + M_M N^2 \quad \xrightarrow{\text{Breaks lepton number}}$$

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Is there interesting parameter
space here?

Low scale seesaw



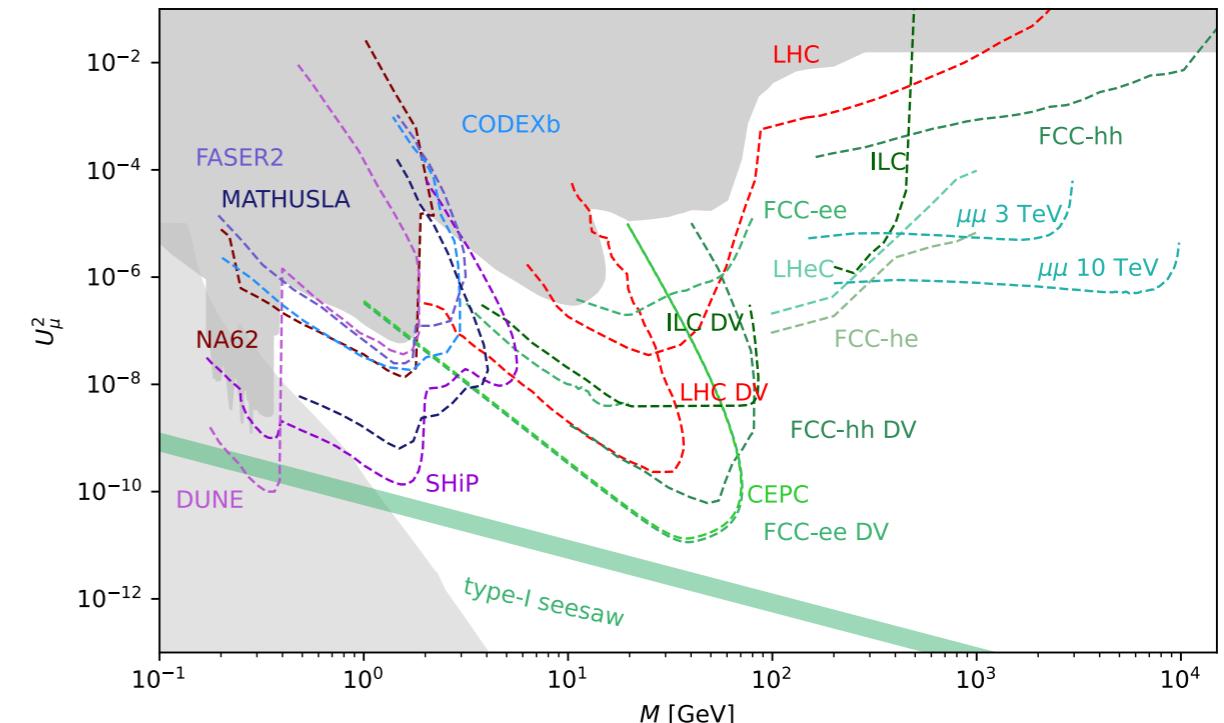
Where do neutrino masses come from?
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Add a Dirac mass:

$$\begin{aligned} \mathcal{L} &\supset y H L N + M_M N^2 + M_D N \bar{N} \\ \rightarrow \mathcal{L}^{IR} &\supset \frac{y^2 M_M}{M_D^2} H L H L \quad M_M \ll M_D \\ \rightarrow m_\nu &= \frac{y^2 M_M |\langle H \rangle|^2}{M_D^2} \\ \rightarrow U^2 &\approx \frac{y^2 |\langle H \rangle|^2}{M_D^2} = \frac{m_\nu}{M_M} \end{aligned}$$

Preserves lepton number



A. M. Abdullahi et al: arXiv 2203.08039

J. Kersten and A. Y. Smirnov: arXiv 0705.3221

...

Low scale seesaw



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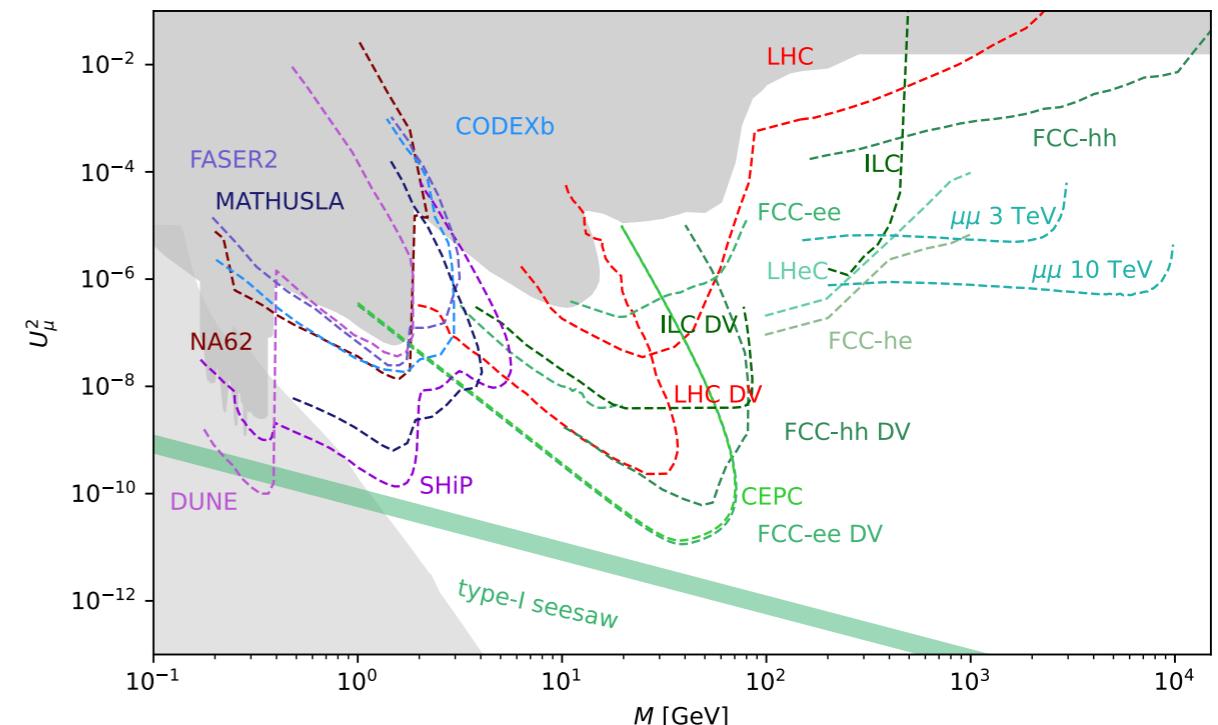
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↓

Preserves lepton number



Direct relation between neutrino masses and mixing angle is broken!

A. M. Abdullahi et al: arXiv 2203.08039

J. Kersten and A. Y. Smirnov: arXiv 0705.3221

...

Relaxing the hierarchy problem

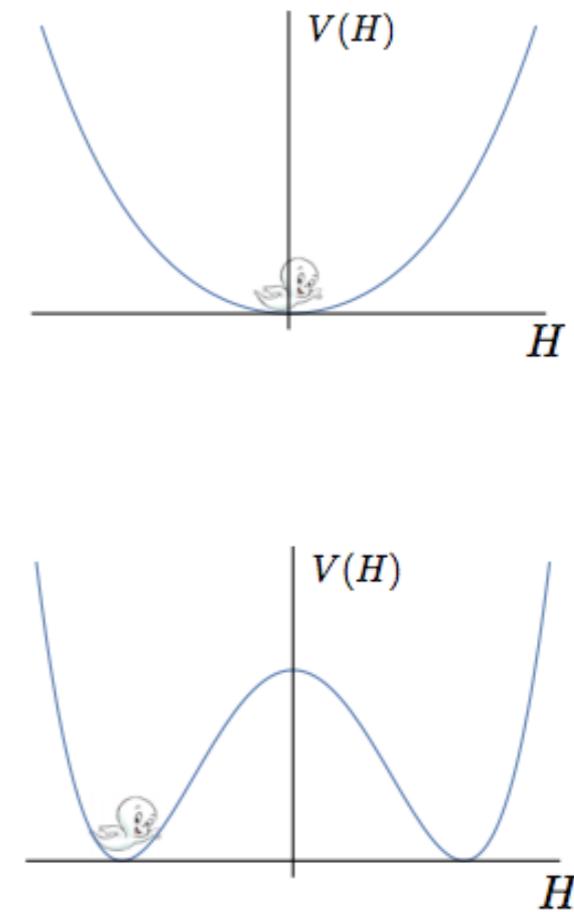
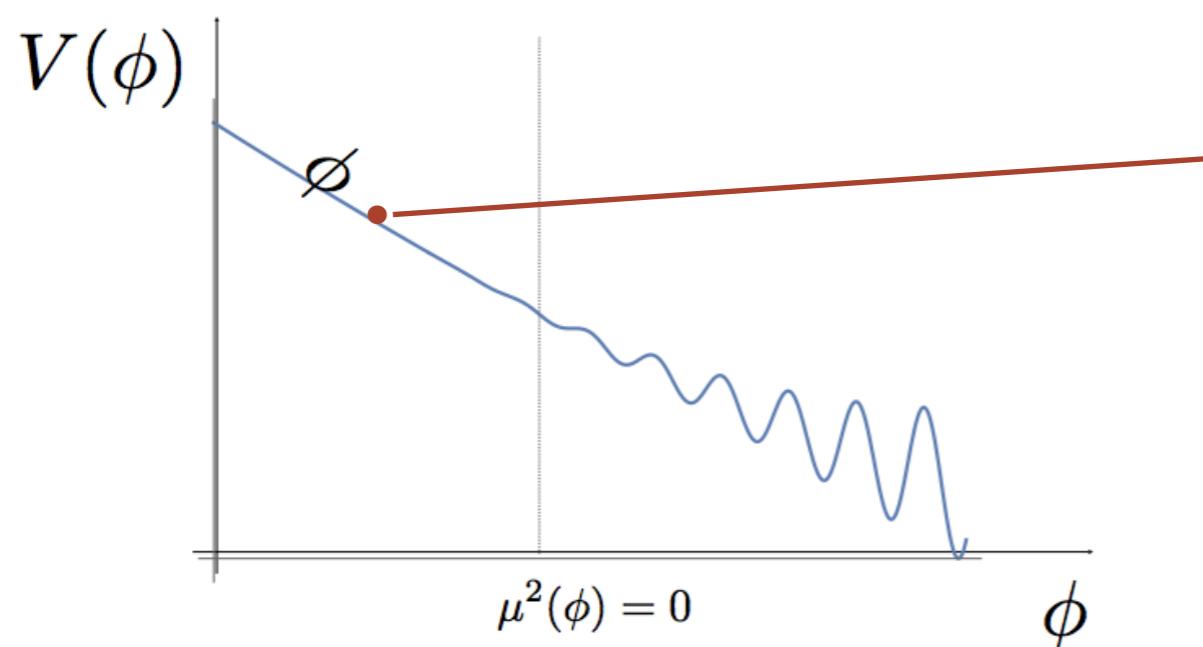
P. Graham, D. Kaplan, S. Rajendran: arXiv 1504.07551



$$\mathcal{L} \supset \underbrace{(\Lambda^2 - g\Lambda\phi)}_{\mu^2(\phi)} H^\dagger H$$

Dark
Higgs

During inflation, the “relaxion” scans the Higgs mass



The scanning can be stopped after the Higgs mass becomes negative due to a back reaction

Relaxing the hierarchy problem

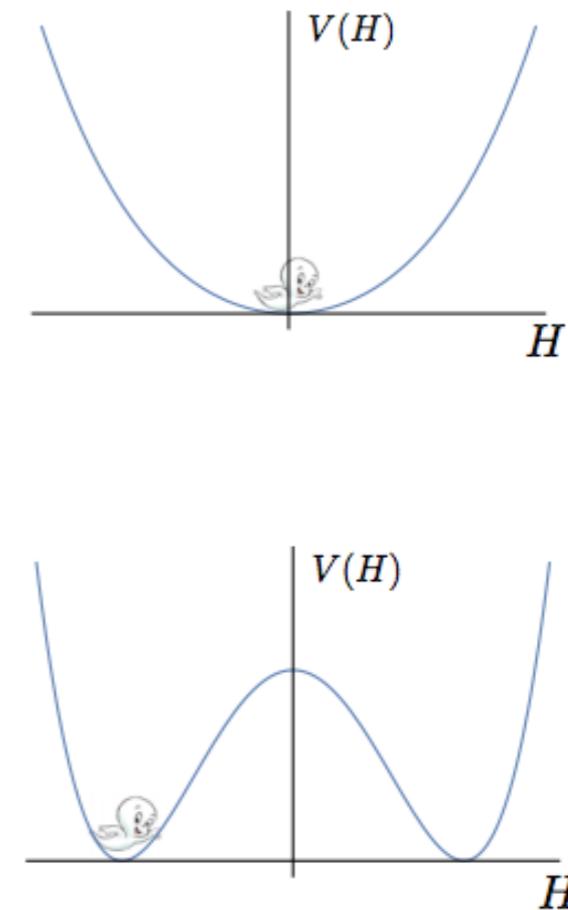
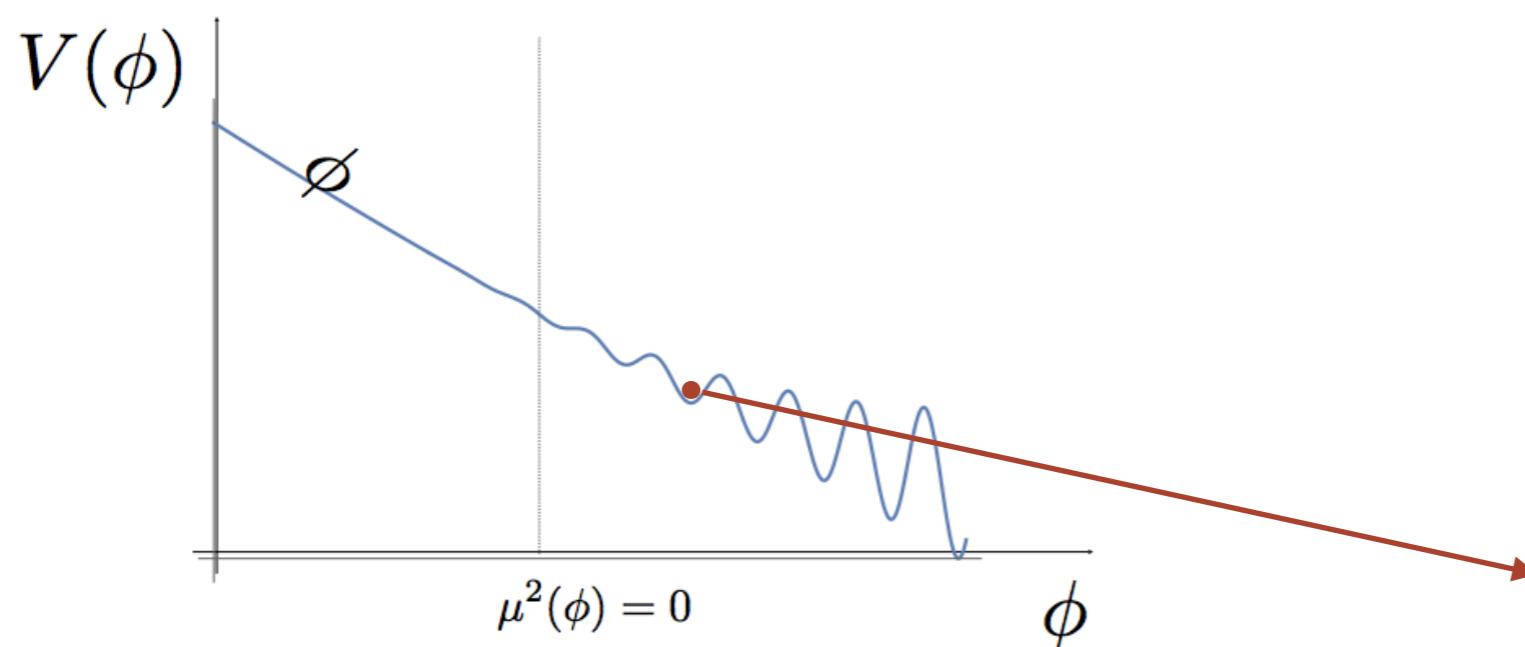
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The scanning can be stopped after the Higgs mass becomes negative due to a back reaction

Relaxing the hierarchy problem

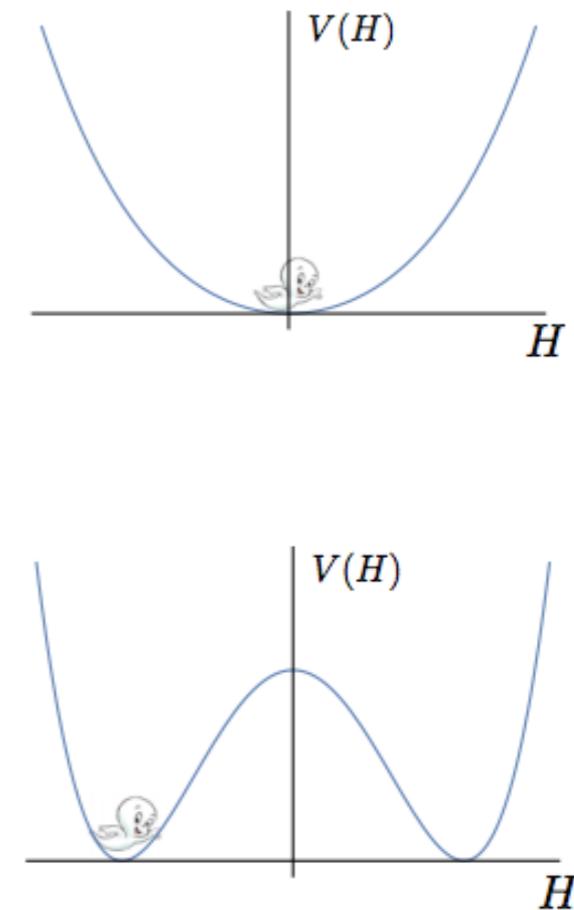
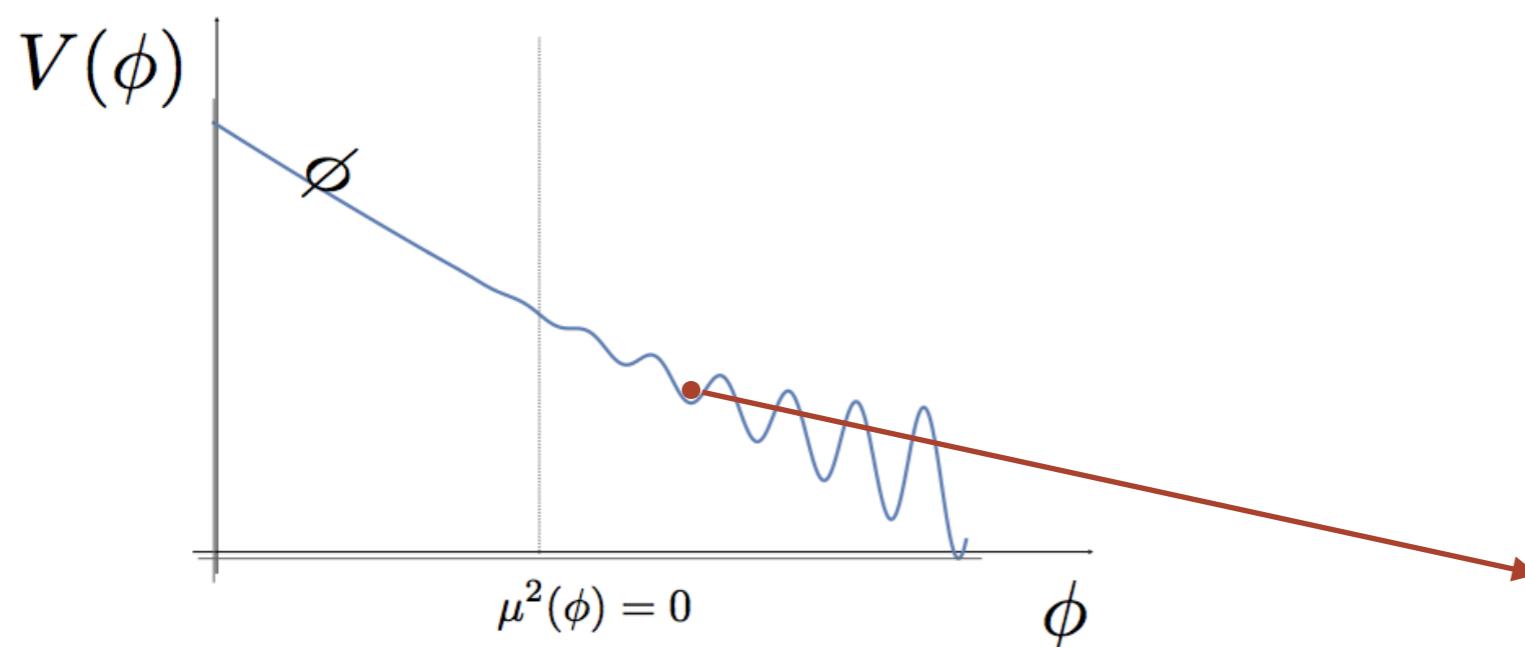
P. Graham, D. Kaplan, S. Rajendran: arXiv 1504.07551



$$\mathcal{L} \supset (\underbrace{\Lambda^2 - g\Lambda\phi}_{\mu^2(\phi)}) H^\dagger H \rightarrow \text{Dark Higgs}$$

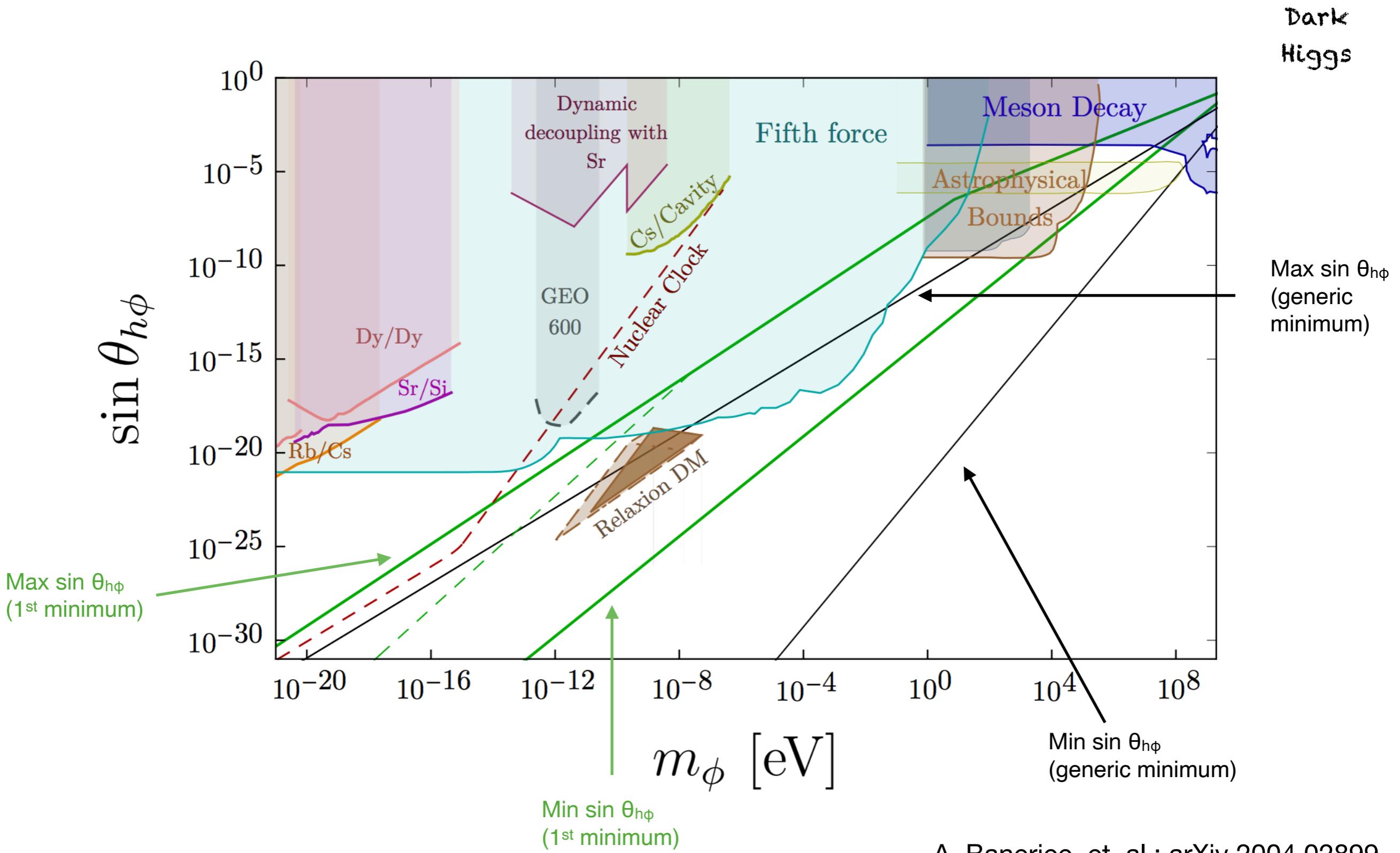
Dark
Higgs

During inflation, the “relaxion” scans the Higgs mass



The scanning can be stopped after the Higgs mass becomes negative due to a back reaction

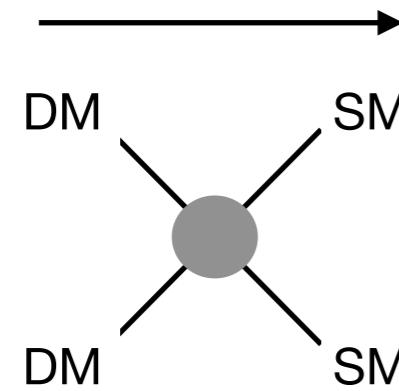
Relaxing the hierarchy problem



Freeze-in dark matter

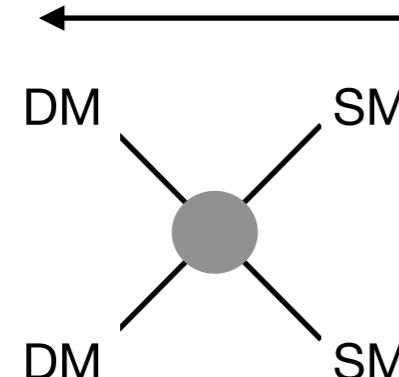


Freeze-out

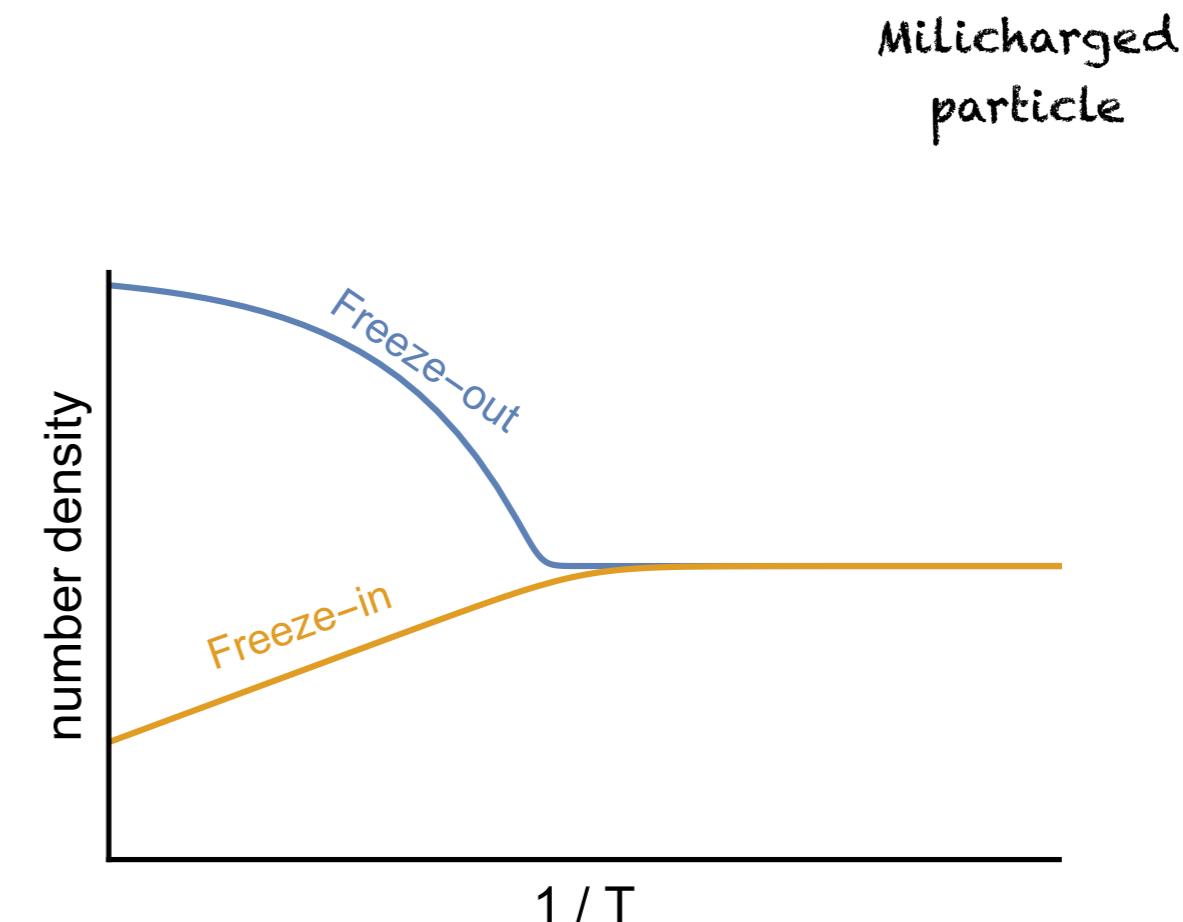


Relic density set by DM annihilations to the SM

Freeze-in



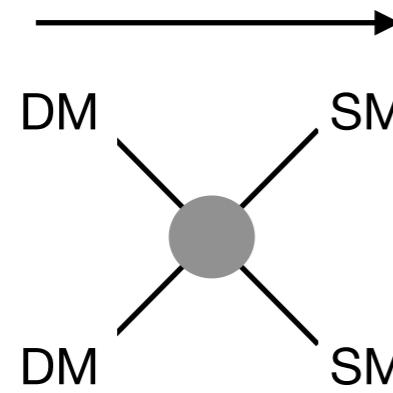
Similar interactions to freeze-out, but with very small coupling



Freeze-in dark matter

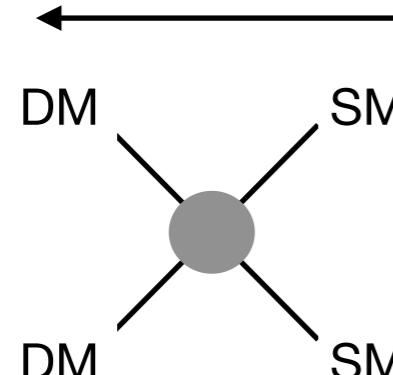


Freeze-out



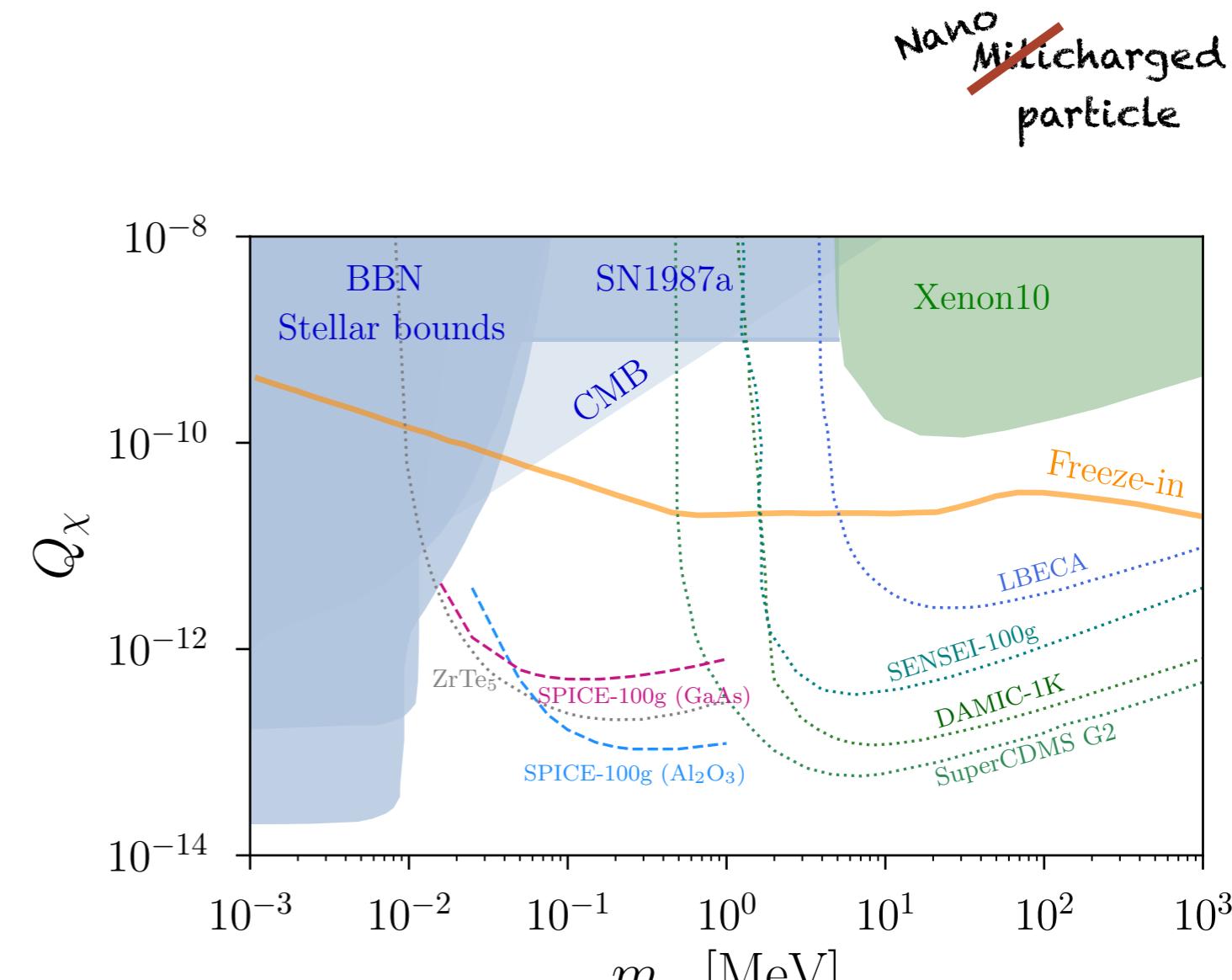
Relic density set by **DM annihilations to the SM**

Freeze-in



Similar interactions to freeze-out, but with **very small coupling**

L. Hall, et. al.: arXiv 0911.1120



(adapted from Griffin et. al.: arXiv 1807.10291)

R. Essig, J. Mardon, T. Volansky: arXiv 1108.5383
X. Chu, T. Hambye, M. Tytgat: arXiv 1112.0493

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