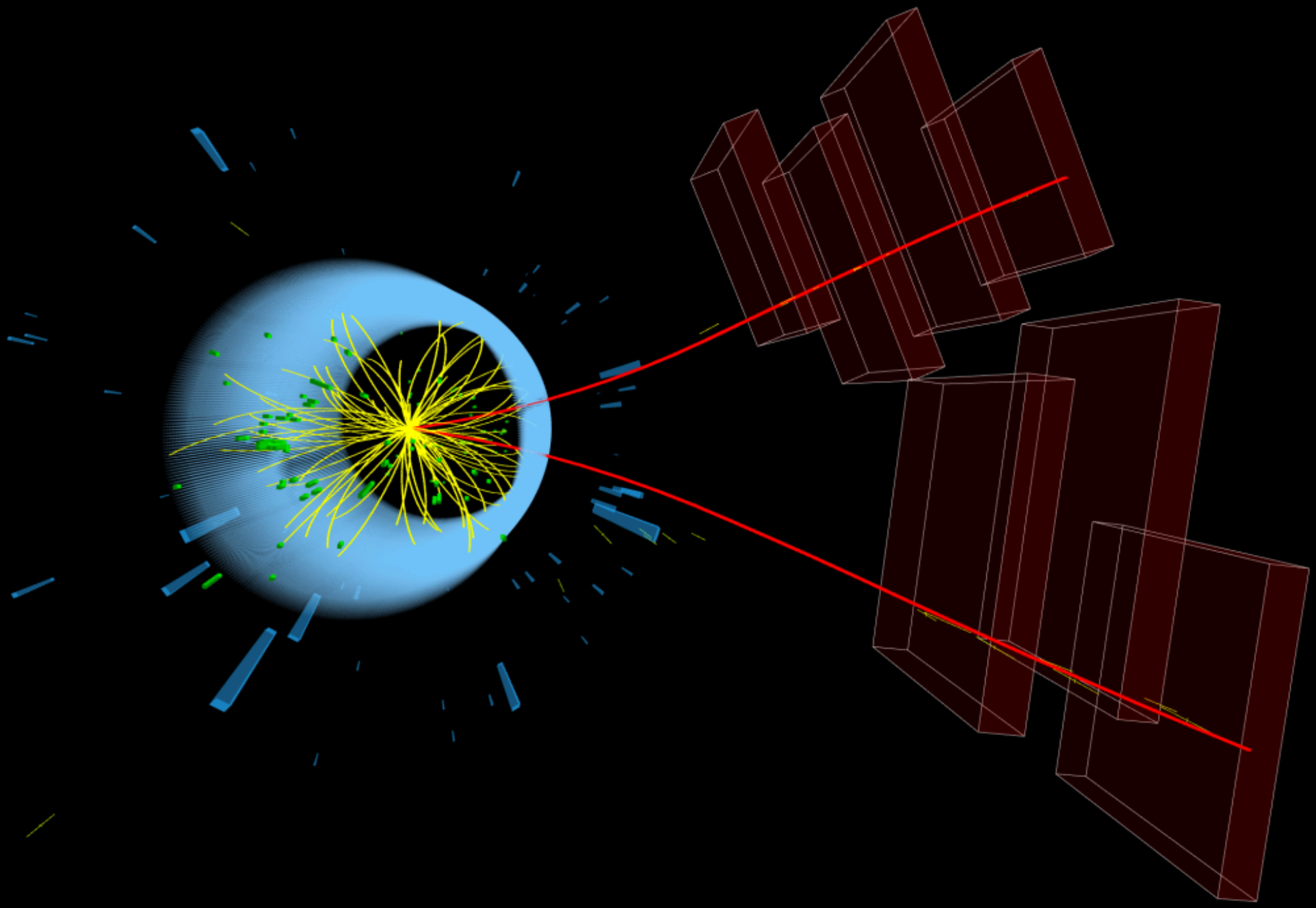
SM problems and FIPs from theoretical viewpoints



Simon Knapen
CERN

What are “feebly interacting particles”?

“I shall not today attempt further to define Feebly Interacting Particles, and perhaps I could never succeed in intelligibly doing so. But *I know it when I see it.*”

Justice Steward Potter
(sort of)

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Feeble $\not<$ Weak

A number of things classified as “FIPs” interact stronger than the Standard Model weak force

(2) however implies that their coupling to the Standard Model tends to be “small” to “very small”

If they are so feeble, how do we make them?

Broadly speaking, I know of 4 ways:

(1) We don't. They are already here (Dark Matter or other cosmological relic)

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(Boiarskyi, Berlin, Cebrian, Stadnik, Ruchayskiy, Pospelov, Ringwald, Irastorza, Bezrukov)

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(Russell, Echenard, Drewes, Lopez Pavon, Izmaylov, Shchutska, Serra, Fischer, Gninenko, Graziani, Ilten, Salfeld-Nebgen, Knight Nelson, Kahlhoefer, Cepeda, Hays, Swallow, Curtin, Gori)

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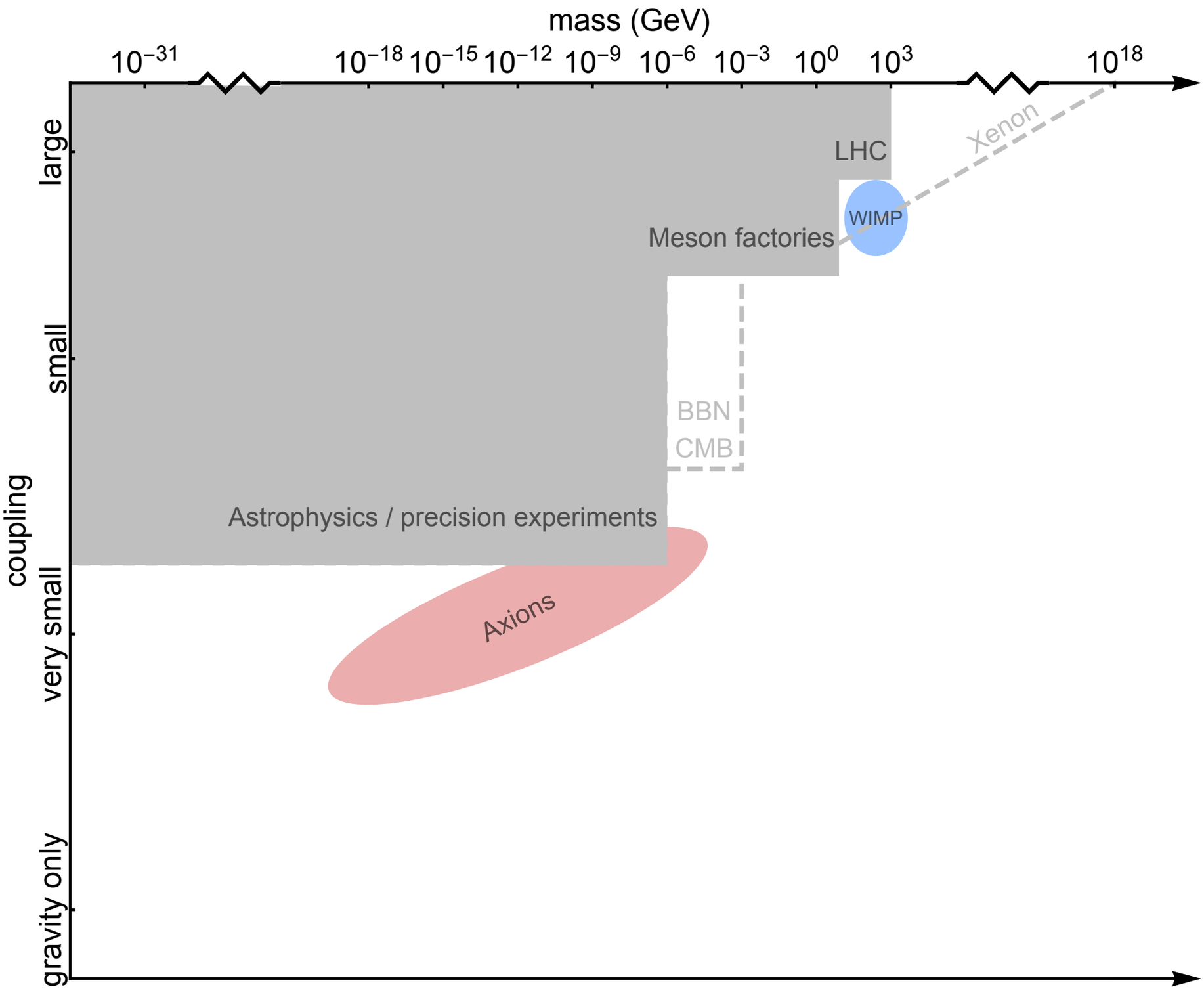
(Giannotti, Ringwald)

(Educated guesses based on talk titles and/or my knowledge of your previous work)

FIPS oversimplified



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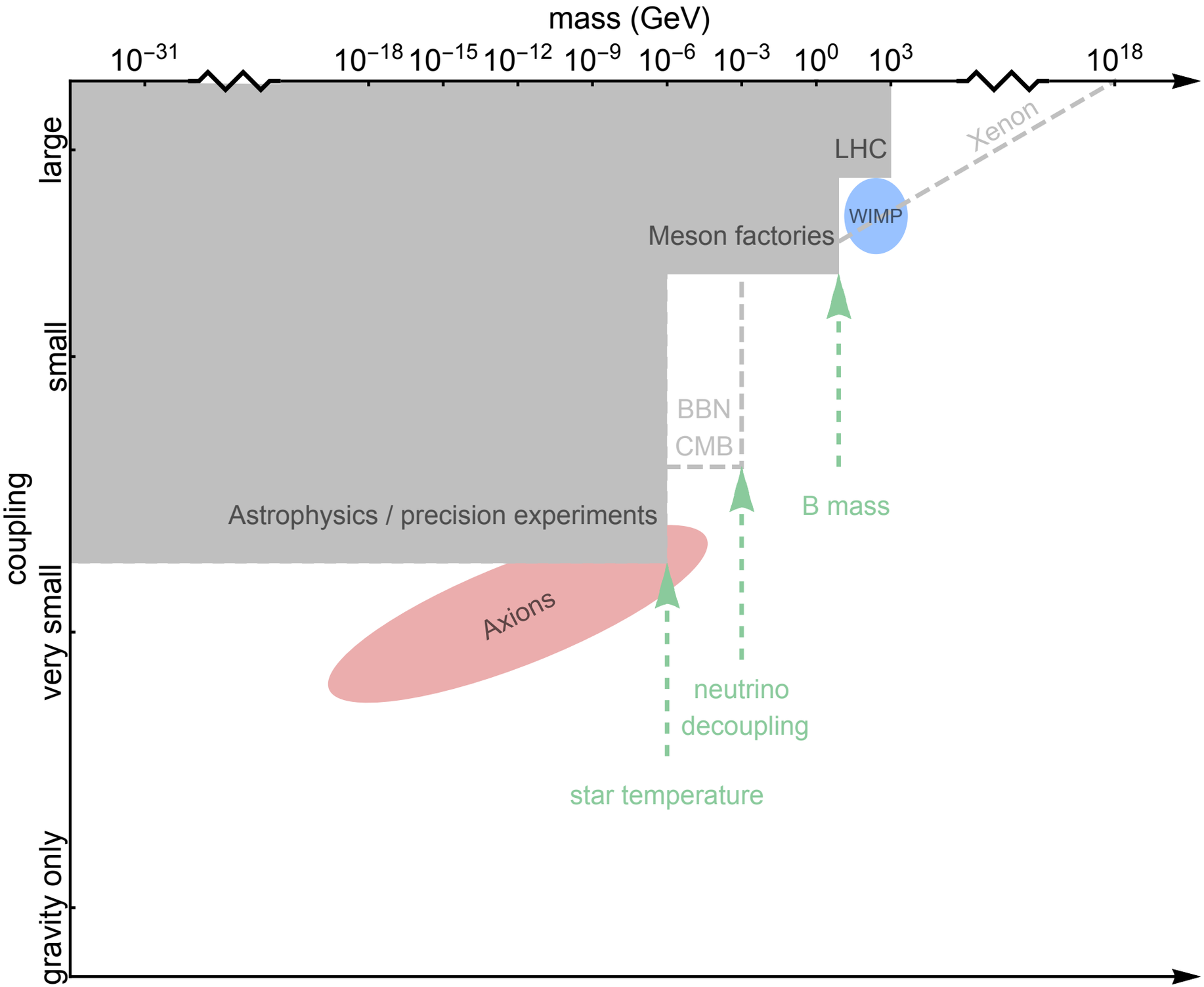

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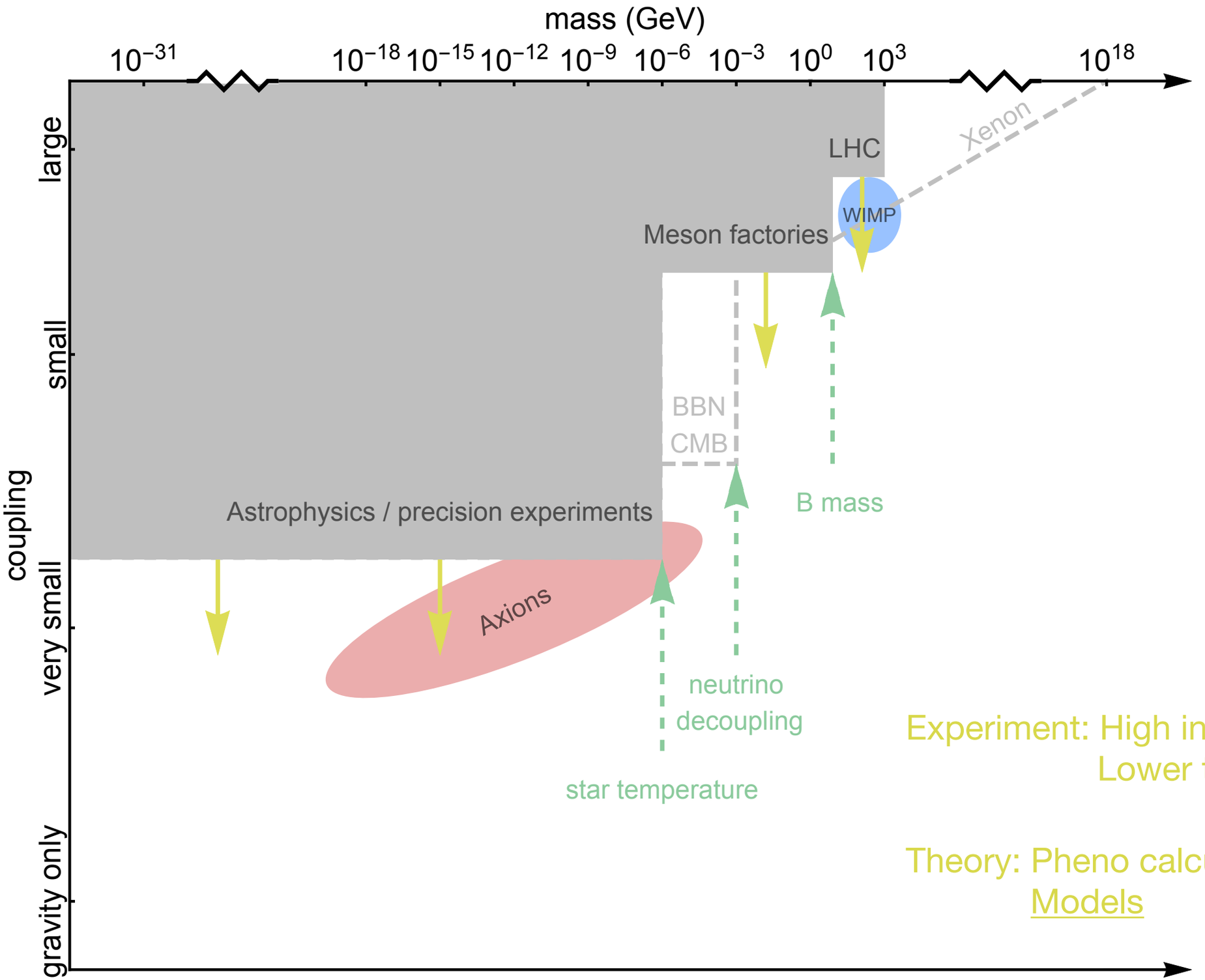

Experiment: High intensity/precision
Lower thresholds

Theory: Pheno calculations
Models

The Fabulous Five

Aka “portals”

Axion-like particle (ALP)

Heavy Neutral Lepton (HNL)

Millicharged particle

Dark Higgs

Dark photon

Variations of course possible: e.g. dark photon decays visibly or invisibly etc etc
Physics Beyond Colliders report identified 11 benchmarks (G. Lianfranchi et. al. 1901.09966)

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(Thursday)

Heavy Neutral Lepton (HNL)

(Tuesday)

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(Friday)

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(Wednesday)

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Sidebar: 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

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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Fabulous Five vs “complete” models

Do the Fab 5 frequently appear in complete models?

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I can only cover a small number of examples
(Largely leaving Dark Matter models for Asher Berlin’s talk)

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Are the Fab 5 sufficient?

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Open questions in the Standard Model

Origin of baryon asymmetry?

CP violation in QCD sector?

Origin of the neutrino masses?

Electroweak hierarchy problem?

Origin of the dark matter?

Open questions in the Standard Model

		Examples featuring
Origin of baryon asymmetry?	→ 	Dark photon
CP violation in QCD sector?	→ 	Axion-like particle (ALP)
Origin of the neutrino masses?	→ 	Heavy Neutral Lepton (HNL)
Electroweak hierarchy problem?	→ 	Dark Higgs
Origin of the dark matter?	→ 	Milicharged particle

These are just examples, other connections exist!
Especially ALPs, dark Higgs & dark photons are the “Swiss army knifes” in a model builder’s toolbox

Asymmetric Dark Matter / Baryogenesis

Why is there more matter than anti-matter?

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. 😢

Sakharov (1967)

Asymmetric Dark Matter / Baryogenesis

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

Dark baryogenesis / “darkogenesis”

J. Shelton, K. Zurek: arXiv 1008.1997

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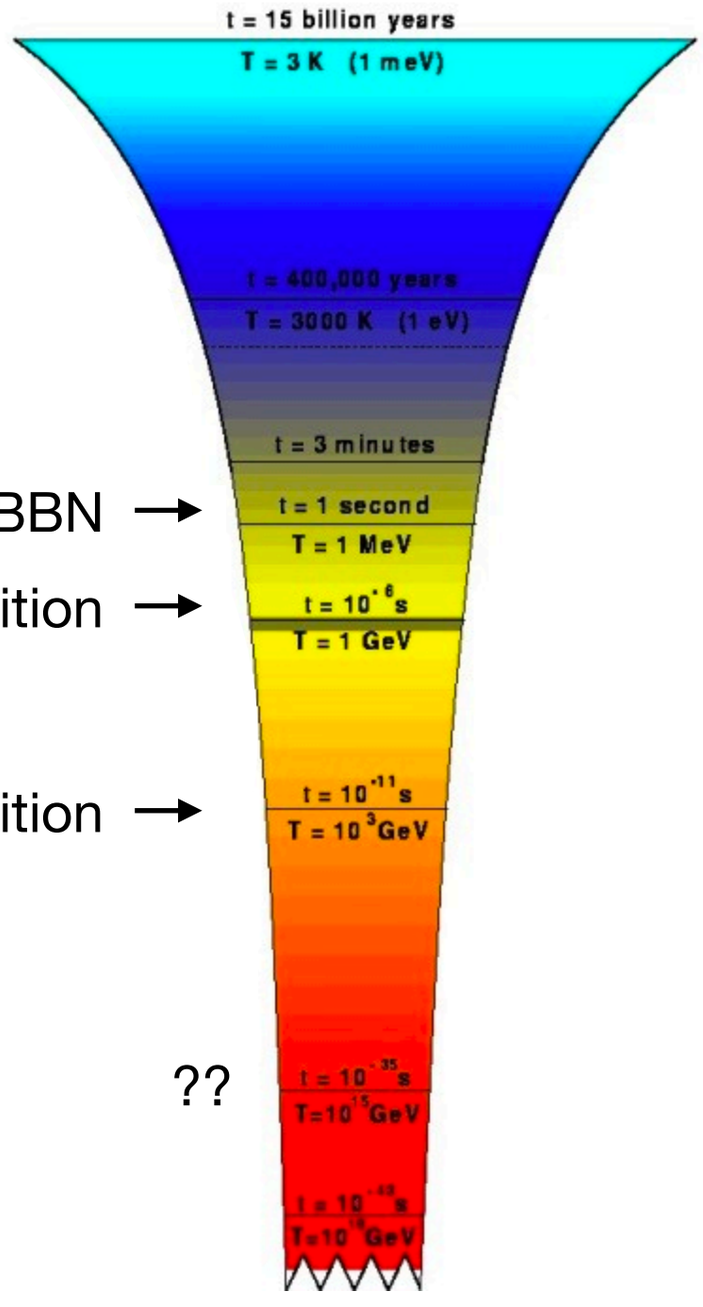

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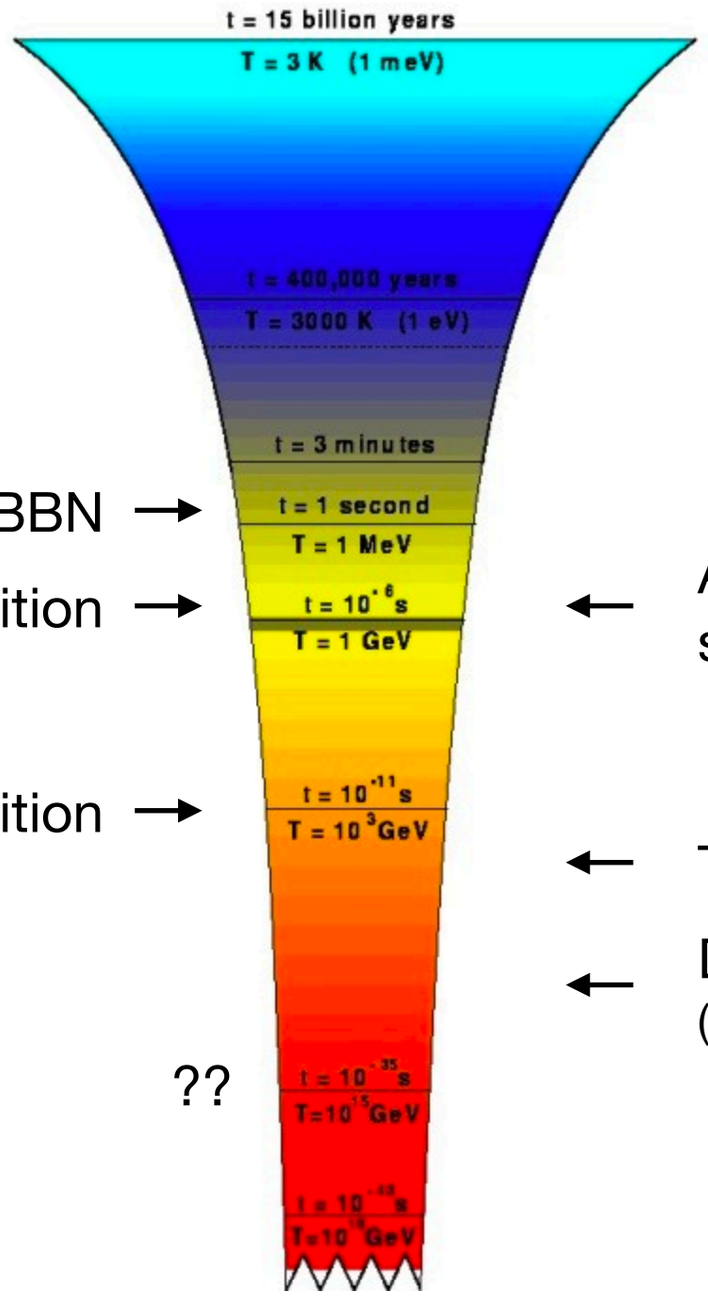

Dark sector

BBN →

QCD phase transition →

EW phase transition →

??

← Annihilate symmetric dark sector abundance

← Transfer asymmetry to SM

← Dark phase transition
(create dark baryon number)

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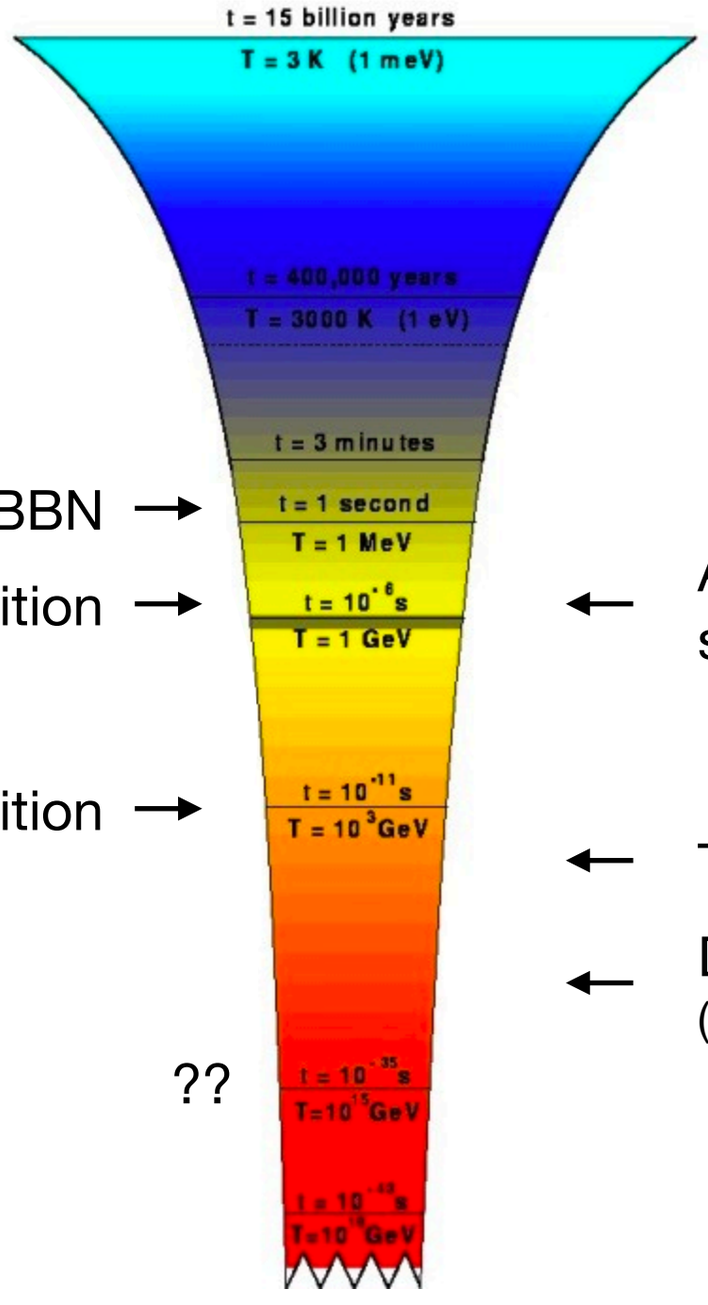

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Mandatory coupling to the SM

Asymmetric Dark Matter / Baryogenesis

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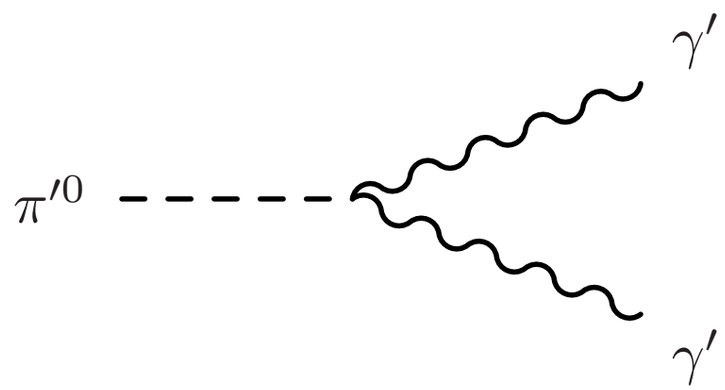
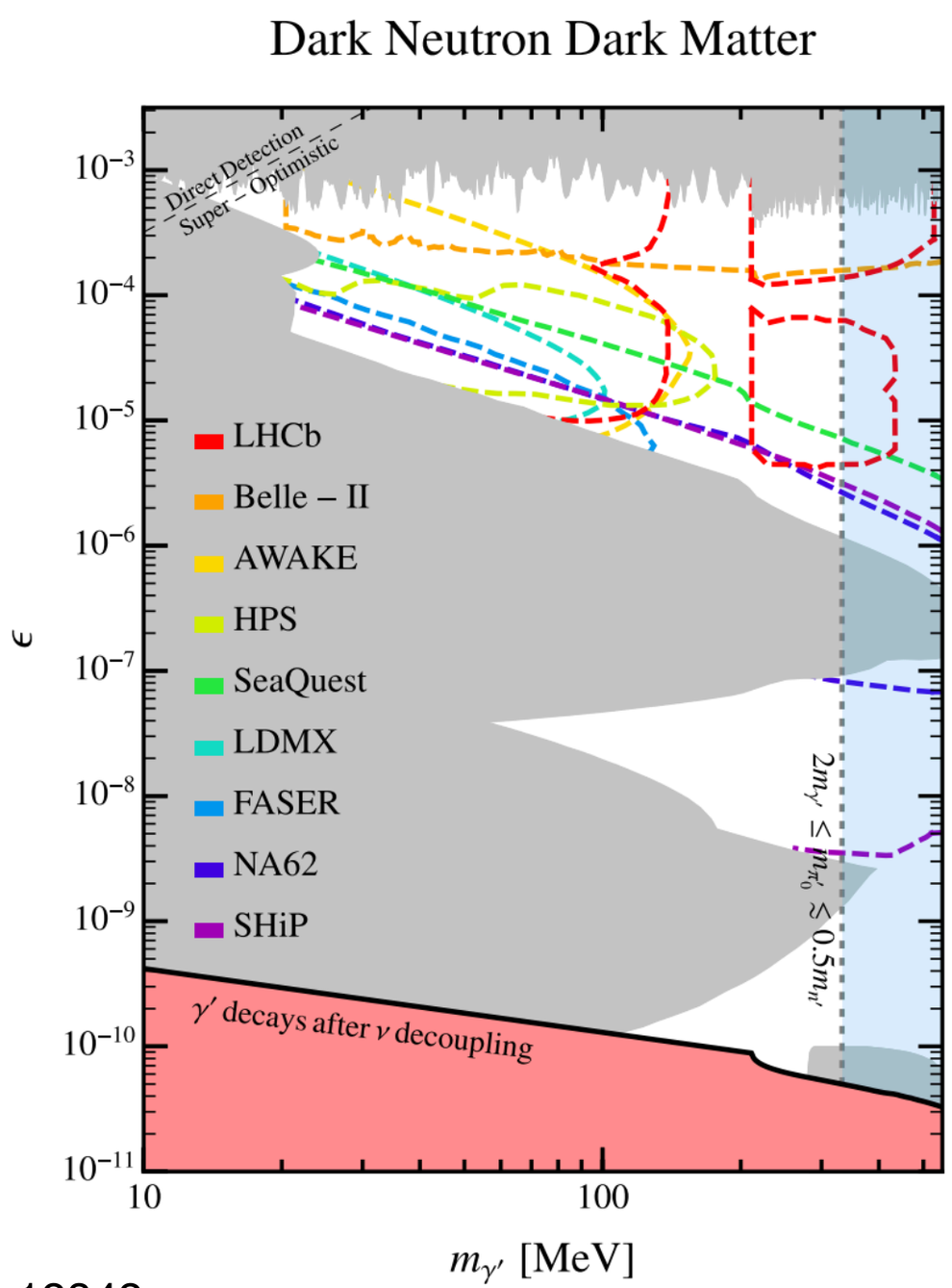
Solution: Put all your hopes and dreams in the dark sector!

Example

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

Deplete dark pions through decay to dark photon



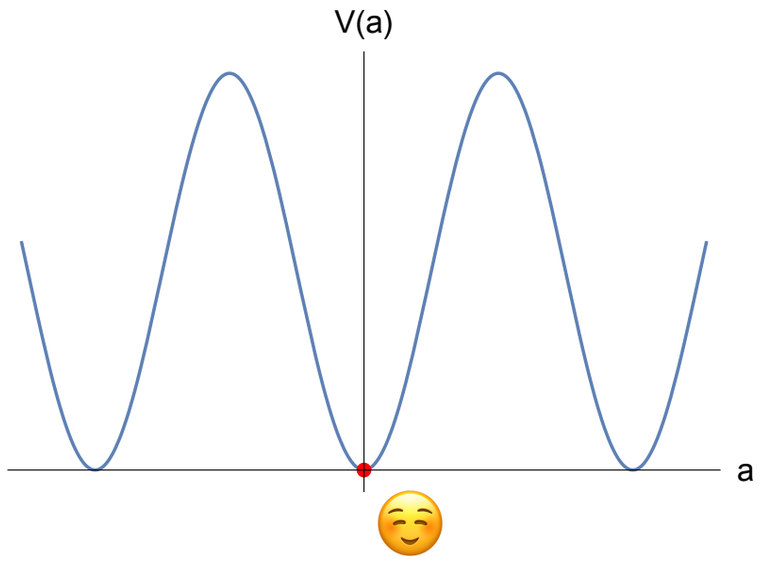


E. Hall, T. Konstandin, R. McGehee, H. Murayama: arXiv 1911.12342

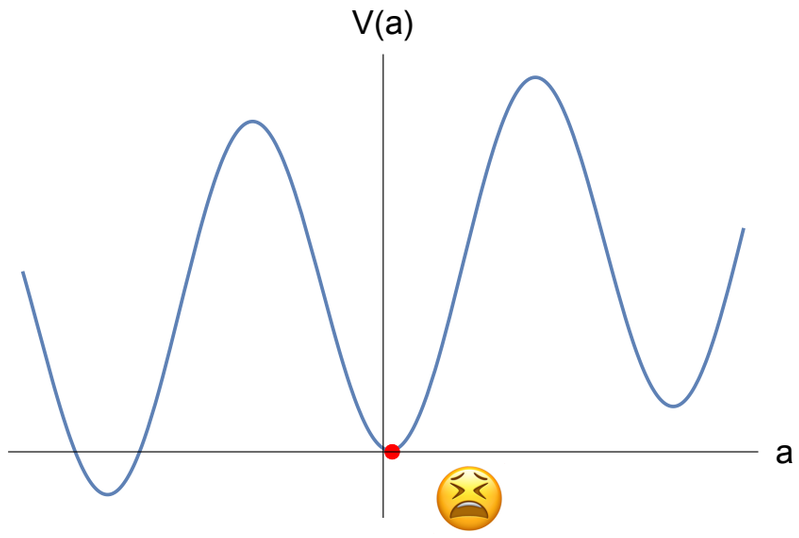
Axion quality problem

Axion solution to strong CP problem is fairly fragile:

Only QCD breaks Peccei Quin symmetry

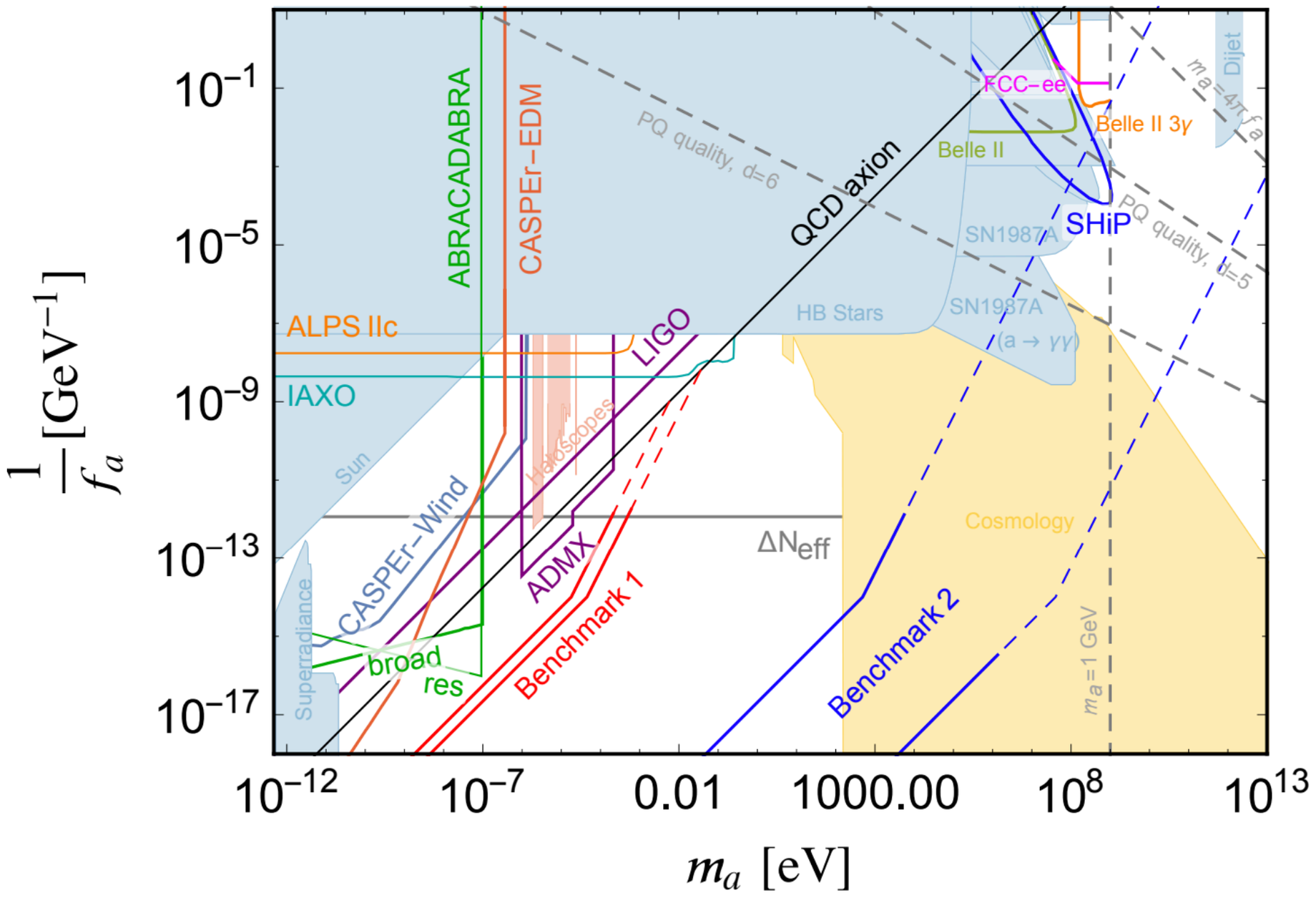


Other sources of Peccei Quin breaking (e.g. Gravity)



Problem most severe for low mass axions, additional UV model building is needed

Axion quality problem



P. Agrawal and K. Howe: arXiv 1710.04213

Many subtleties neglected on this slide → see Prateek's talk
For ALP pheno, see talks by Ringwald, Giannotti, Irastorza, Kahlhoefer, d'Enterria, Pospelov, …

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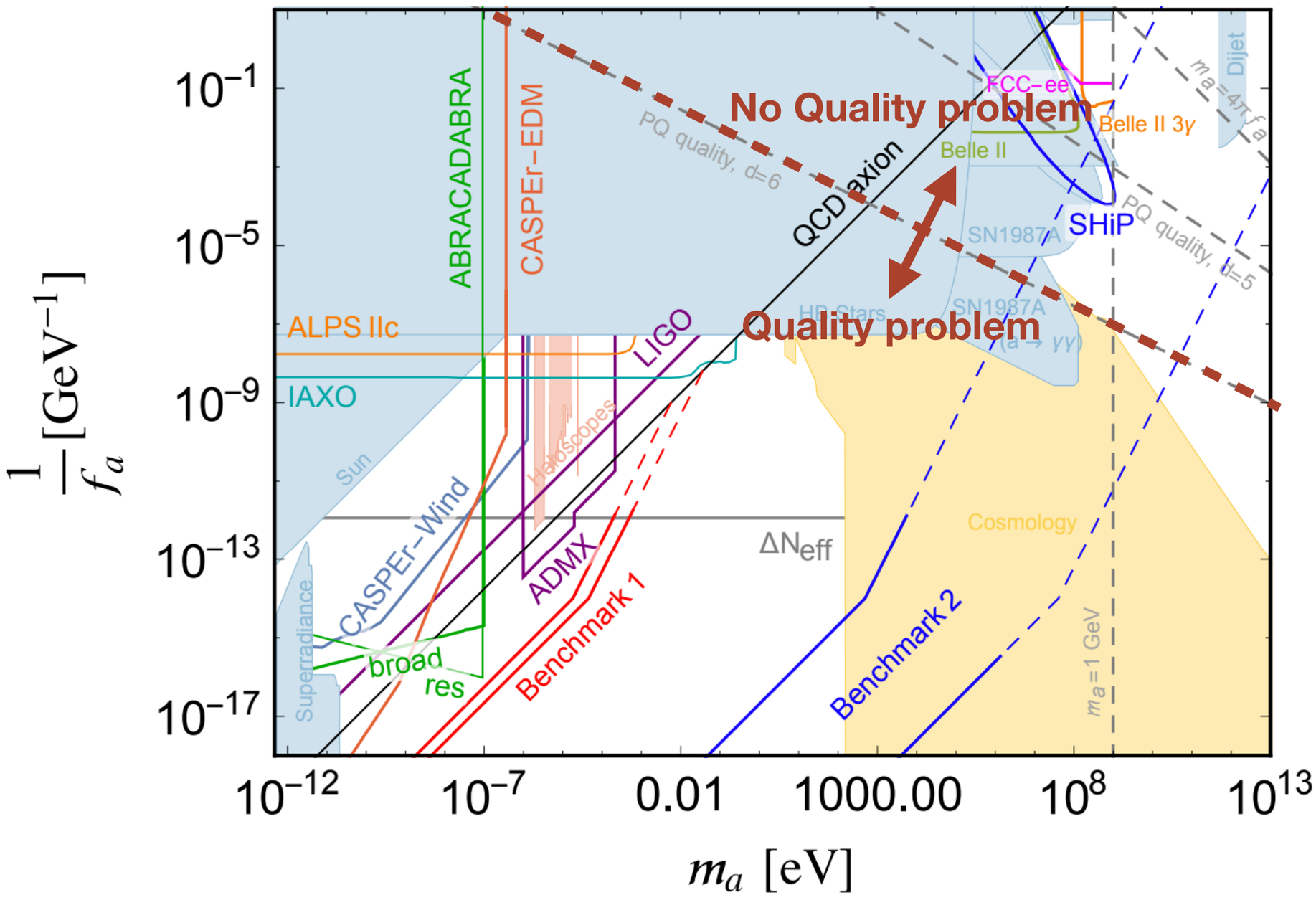

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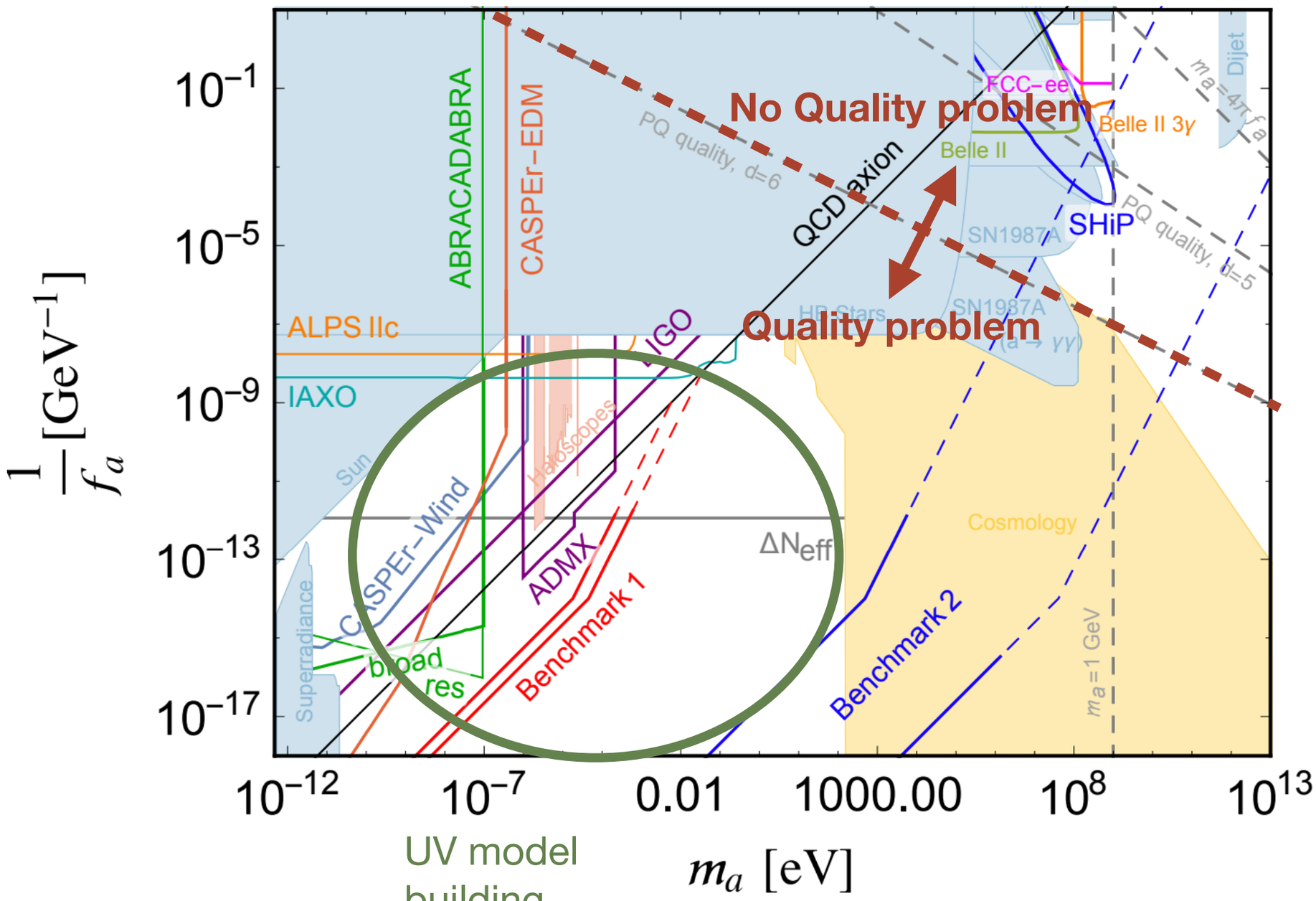

UV model building needed

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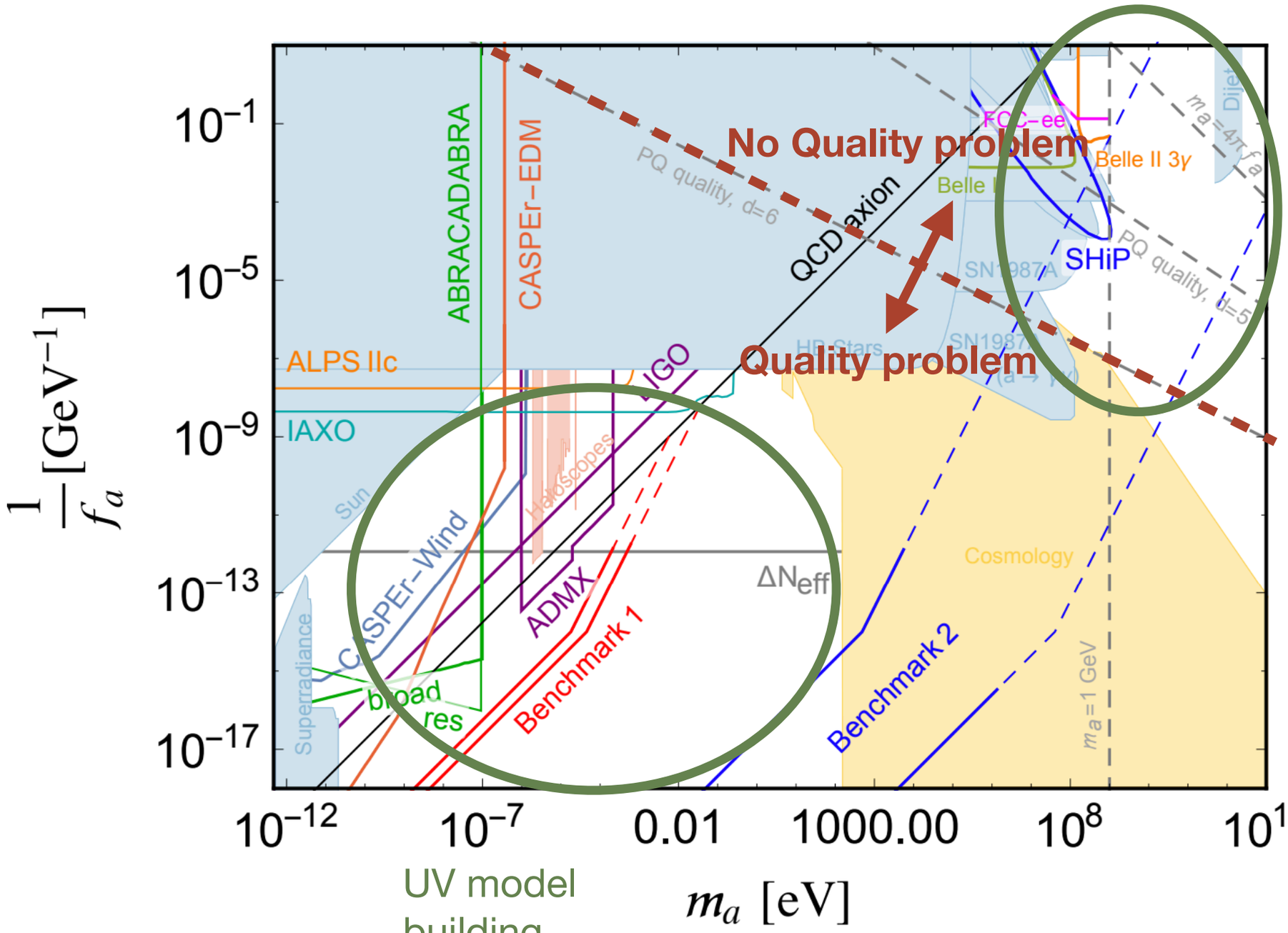

Can we make the axion heavier without spoiling the strong CP problem?

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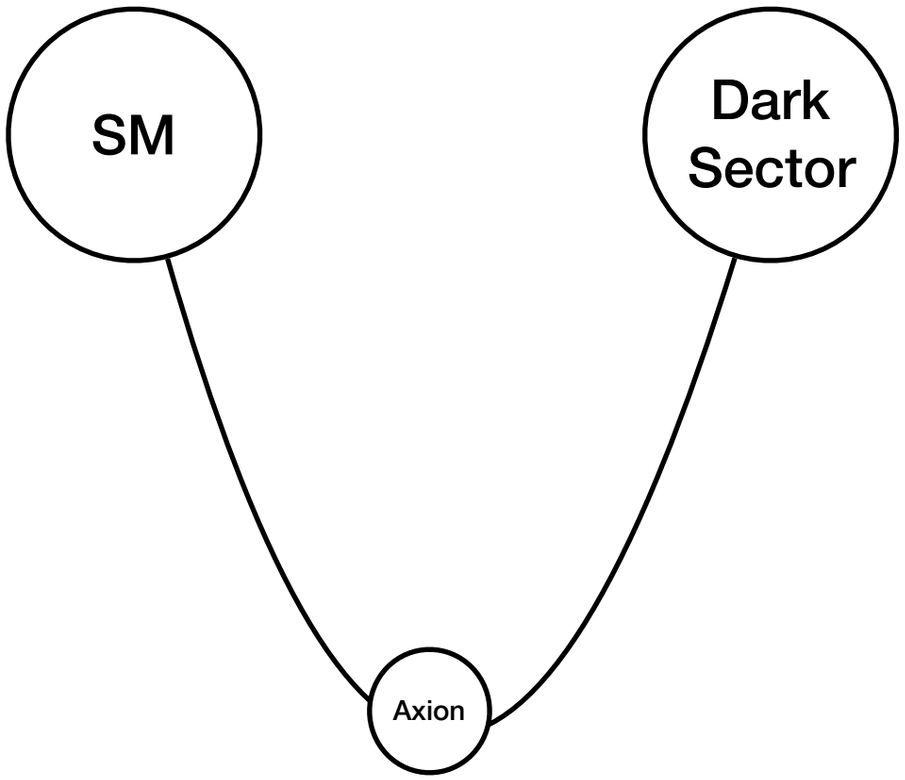
Axion quality problem

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

Enter: a dark sector



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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Axion quality problem

ALP

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

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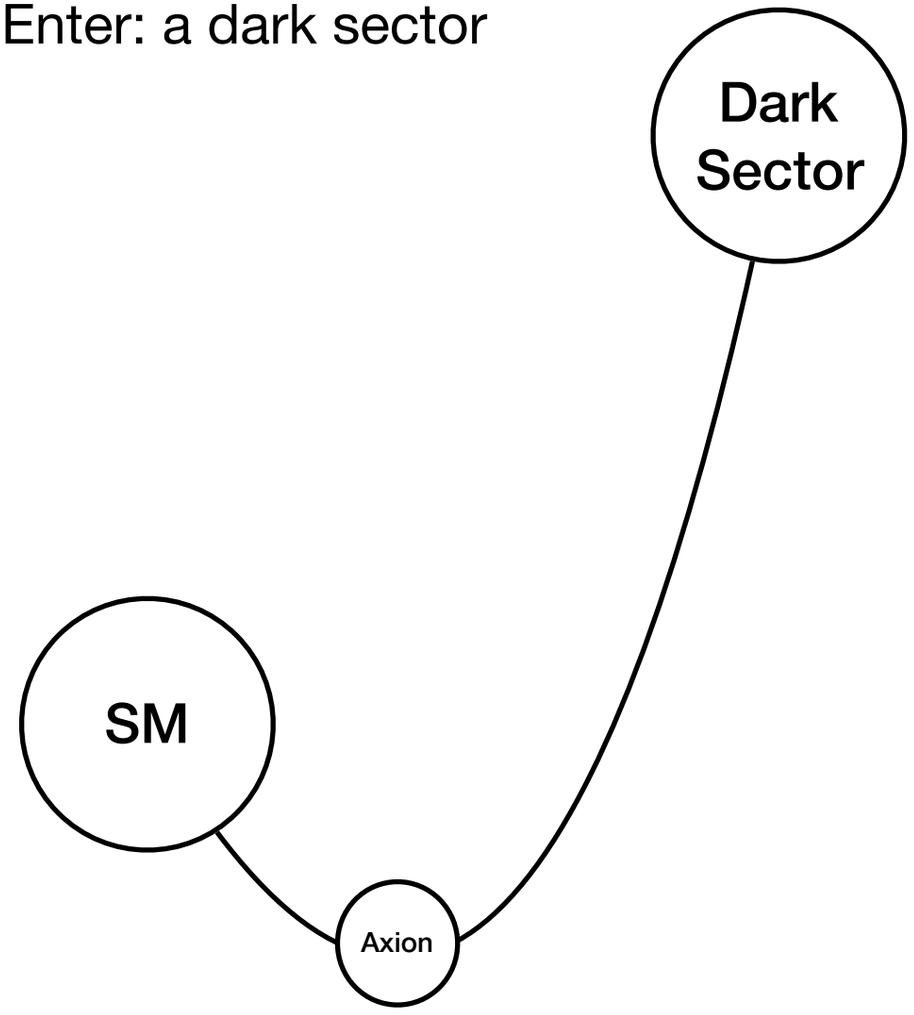

Some cleverness is needed to not spoil the strong CP problem

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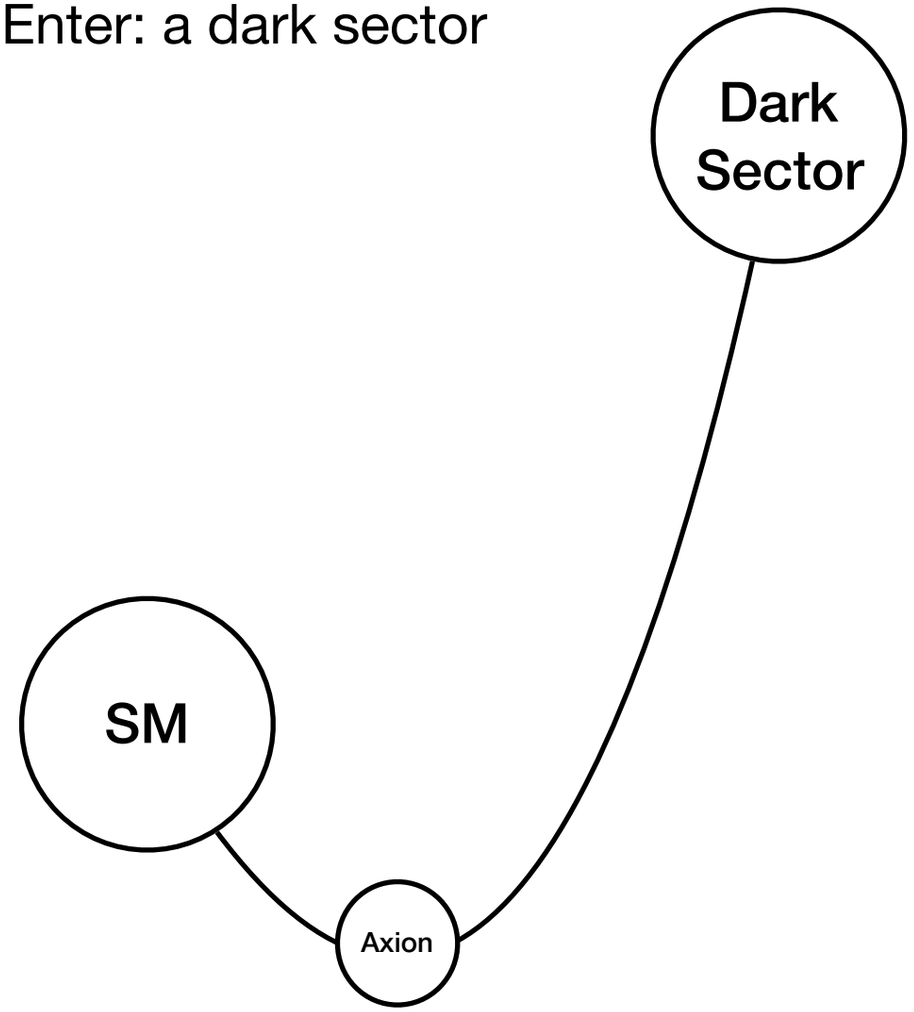

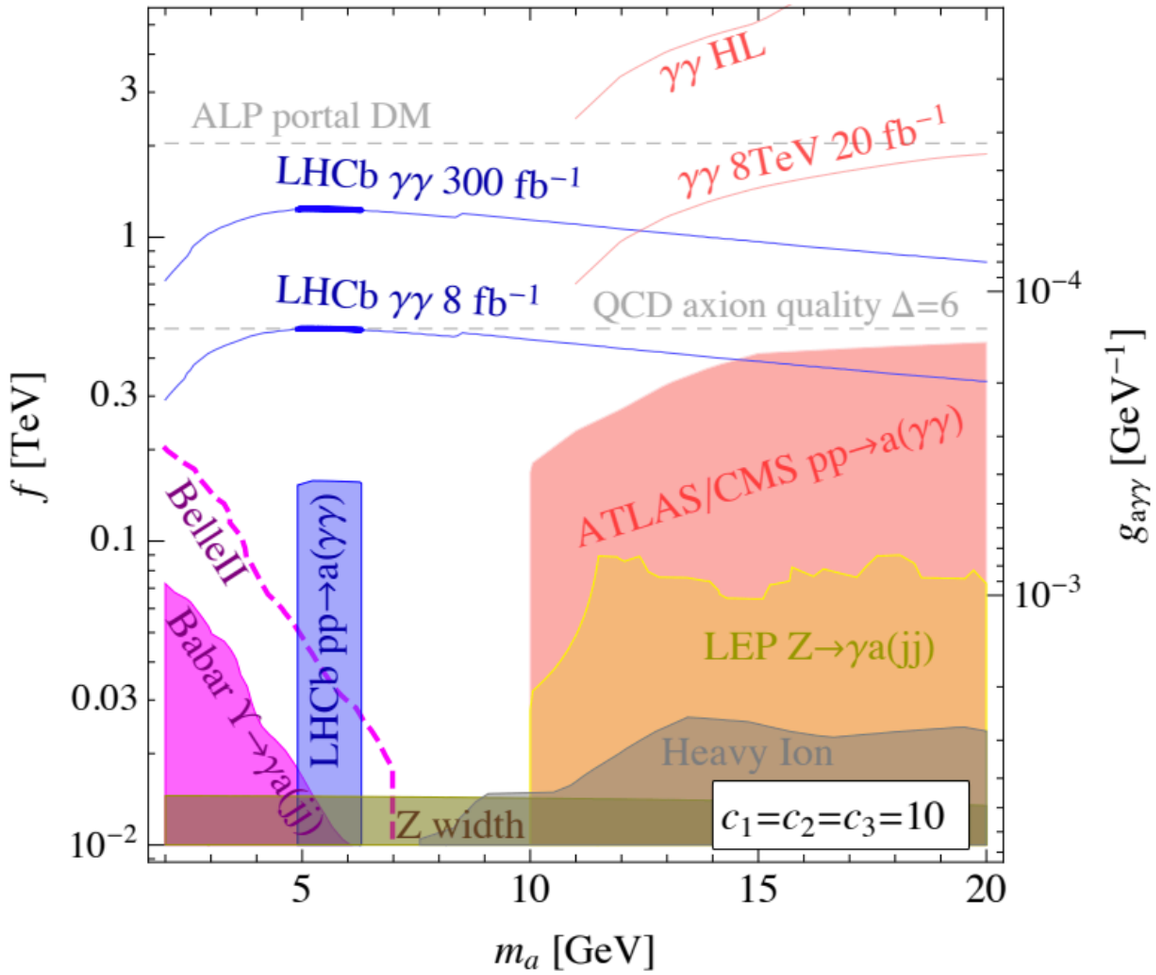

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Axion MUST couple to gluons, and likely couples to photons (photon jets)

X. Cid Vidal et. al. : arXiv 1810.09452
See also A. Hook et. al.: arXiv 1911.12364

Low scale seesaw

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

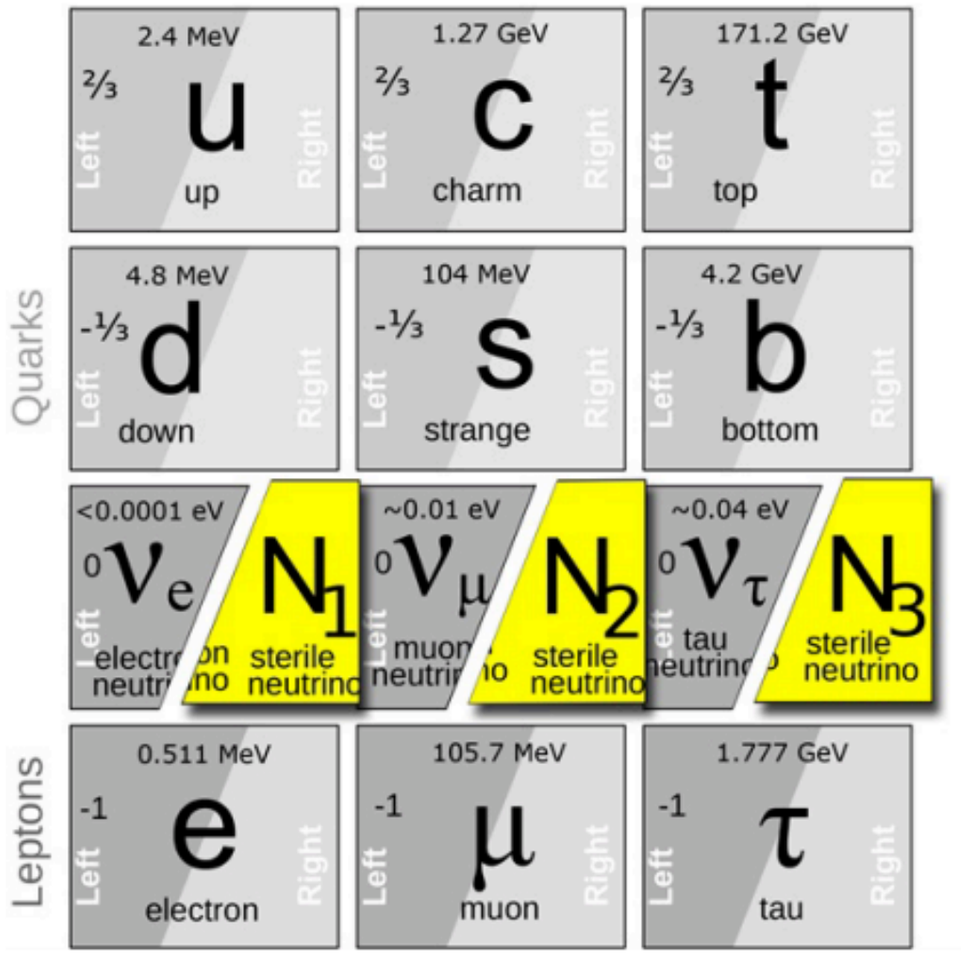
Seesaw mechanism:

Breaks lepton number

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

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

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



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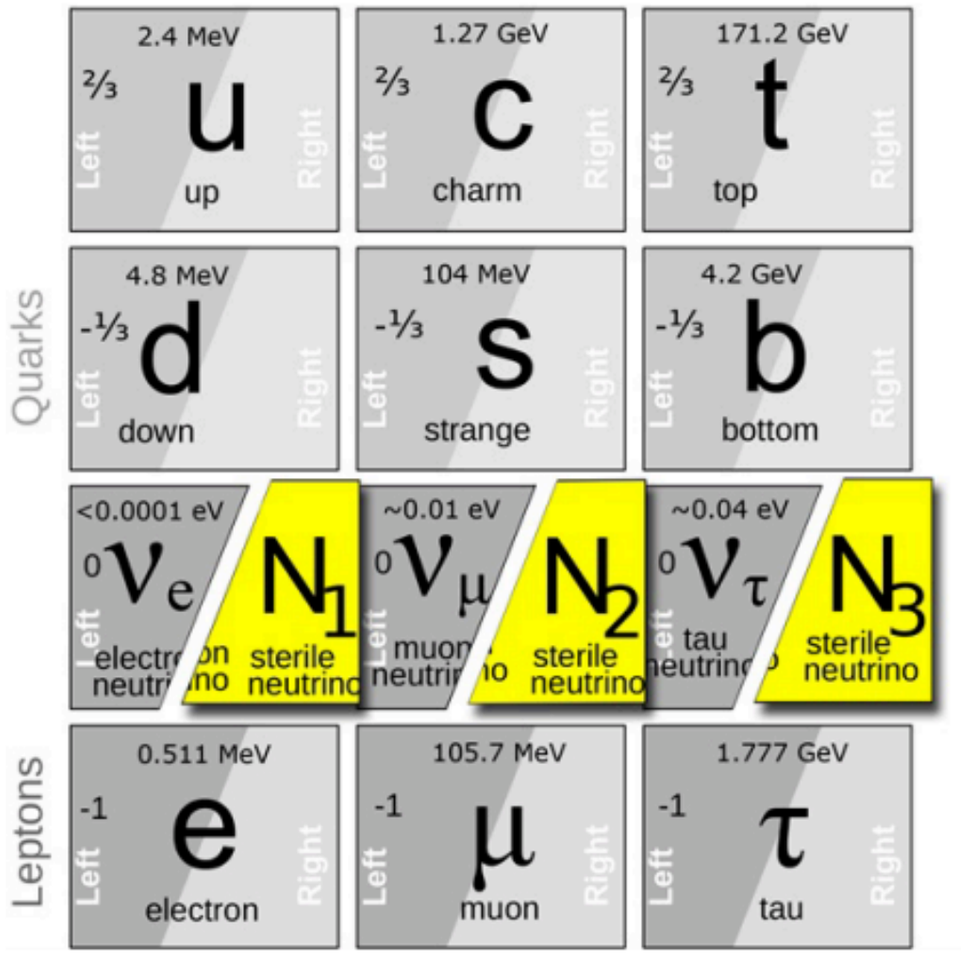

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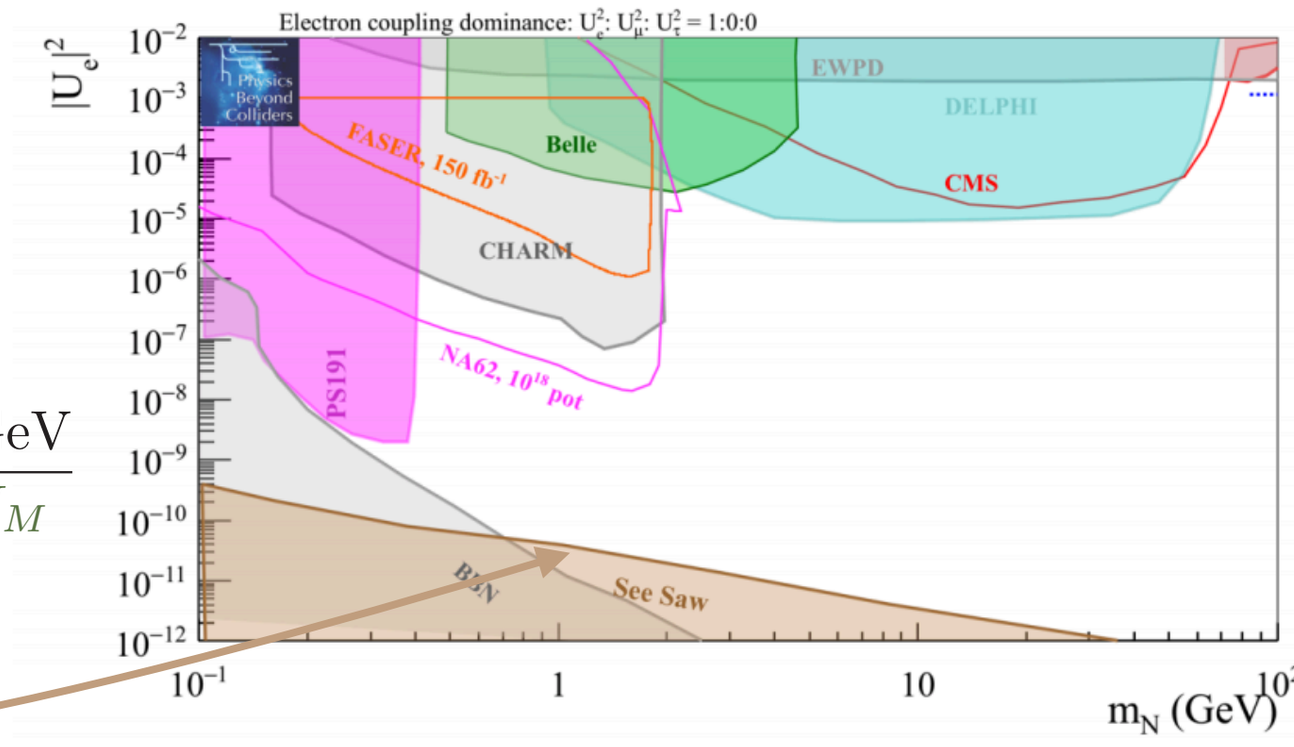

Physics Beyond Colliders: arXiv 1901.09966

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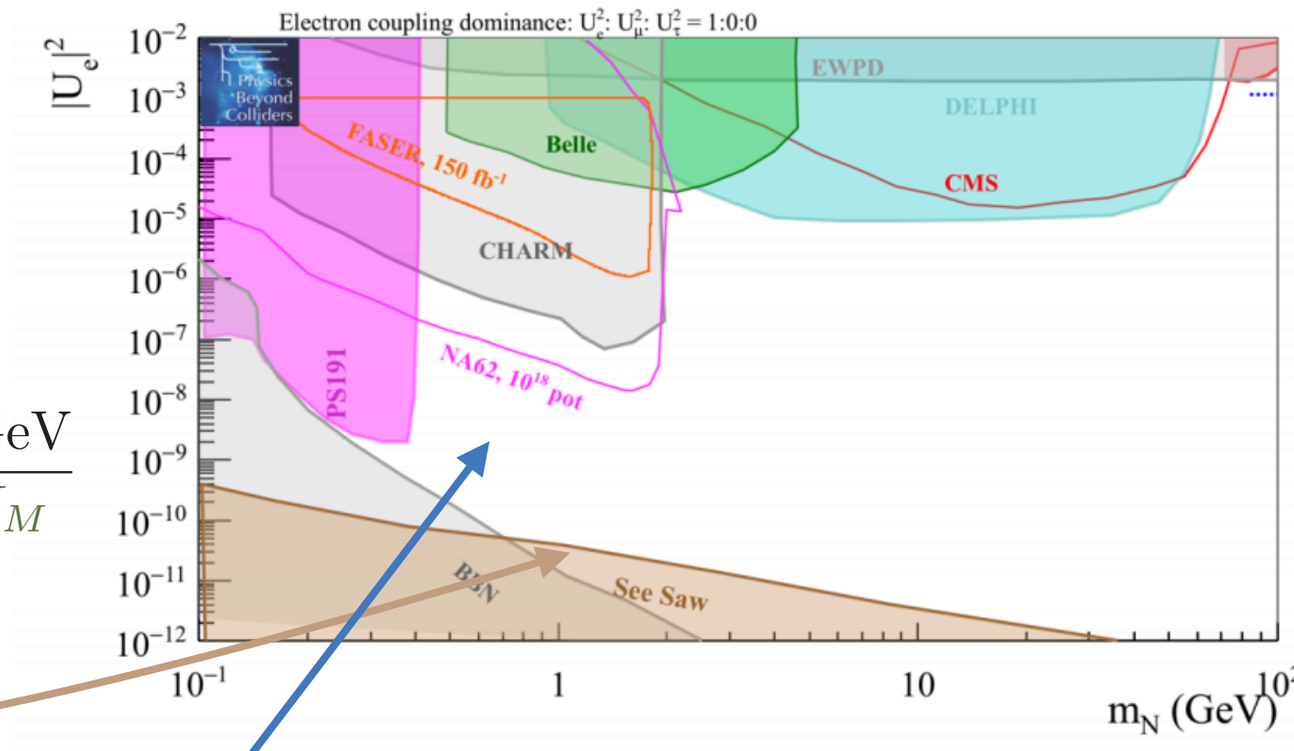

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Is there interesting parameter space here?

Low scale seesaw

Heavy neutral lepton

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Add a Dirac mass:

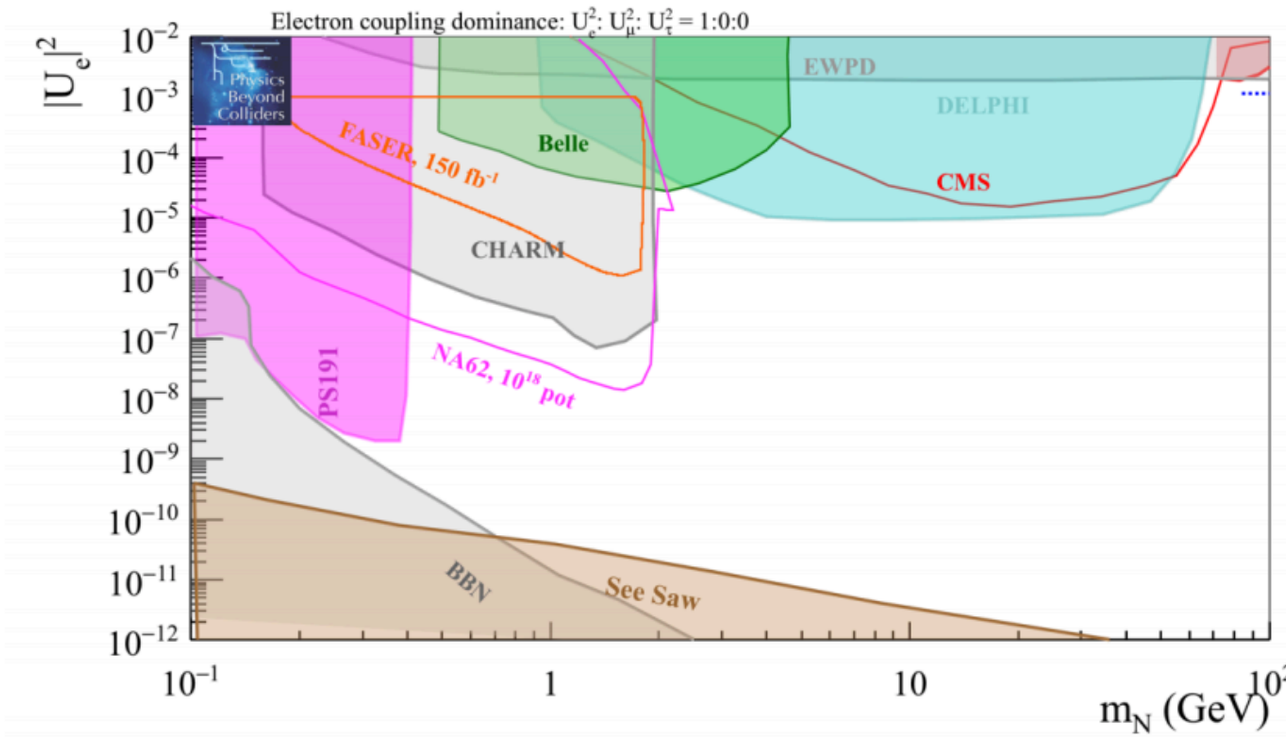
Preserves lepton number

$$\mathcal{L} \supset yHLN + M_M N^2 + M_D N\overline{N}$$

$$\rightarrow \quad \mathcal{L}^{IR} \supset \frac{y^2 M_M}{M_D^2} HLHL \qquad M_M \ll M_D$$

$$\rightarrow \quad m_\nu = \frac{y^2 M_M |\langle H \rangle|^2}{M_D^2}$$

$$\rightarrow \quad U^2 \approx \frac{y^2 |\langle H \rangle|^2}{M_D^2} = \frac{m_\nu}{M_M}$$



Physics Beyond Colliders: arXiv 1901.09966

See talks by Drewes, Ruchayskiy, Lopez Pavon, Izmaylov, Shchutska, Serra, Fischer, …

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

Low scale seesaw

Heavy neutral lepton

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

Add a Dirac mass:

Preserves lepton number

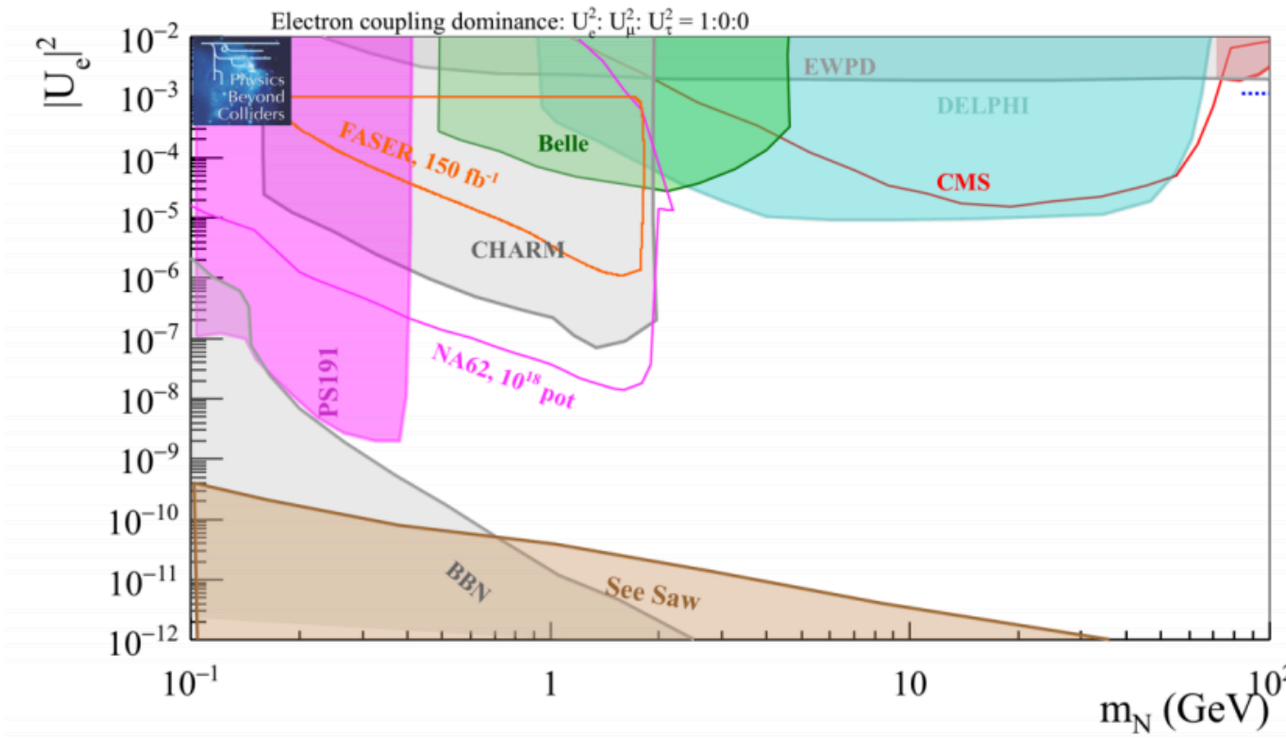
$$\mathcal{L} \supset yHLN + M_M N^2 + M_D N\overline{N}$$

$$\rightarrow \quad \mathcal{L}^{IR} \supset \frac{y^2 M_M}{M_D^2} HLHL \qquad M_M \ll M_D$$

$$\rightarrow \quad m_\nu = \frac{y^2 M_M |\langle H \rangle|^2}{M_D^2}$$

$$\rightarrow \quad U^2 \approx \frac{y^2 |\langle H \rangle|^2}{M_D^2} = \frac{m_\nu}{M_M}$$

Direct relation between neutrino masses and mixing angle is broken!



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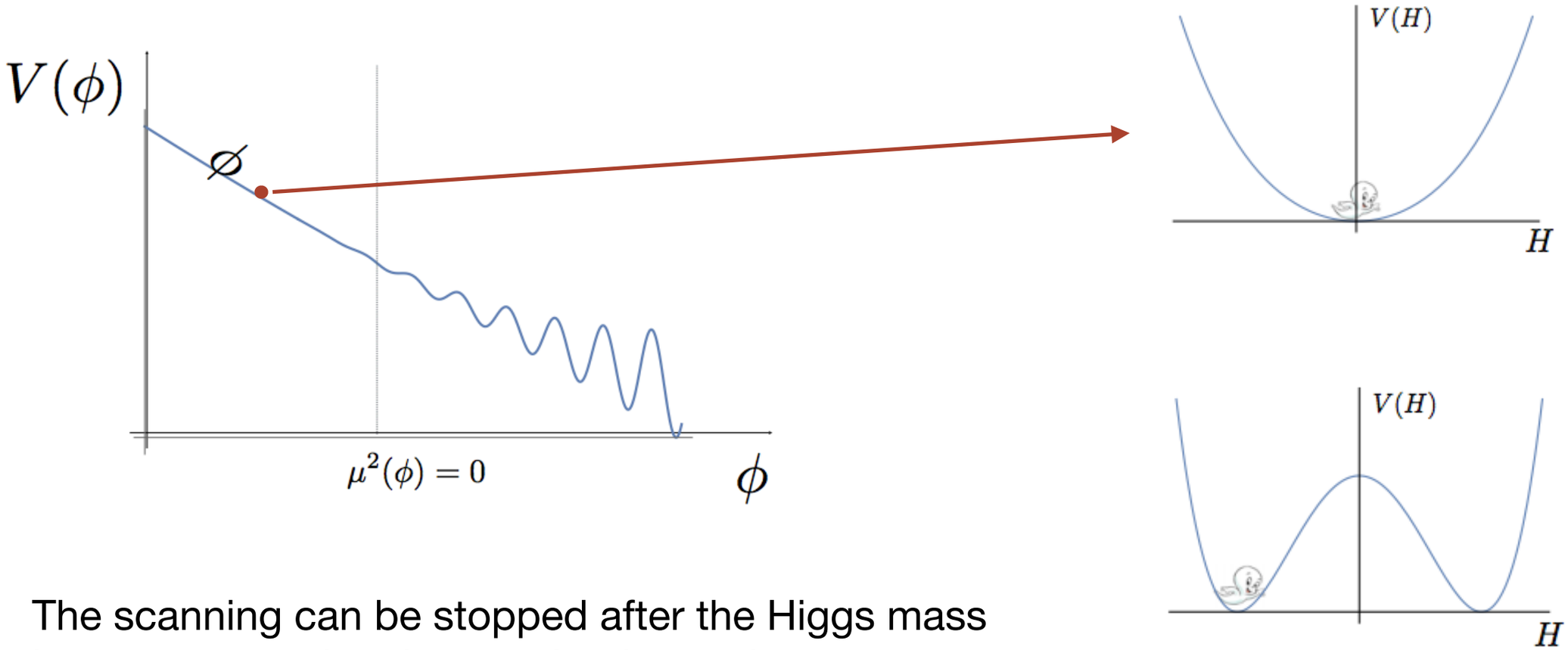
Relaxing the hierarchy problem

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

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

During inflation, the “relaxion” scans the Higgs mass



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

Figures from G. Perez
https://indico.cern.ch/event/910753/contributions/3831618/

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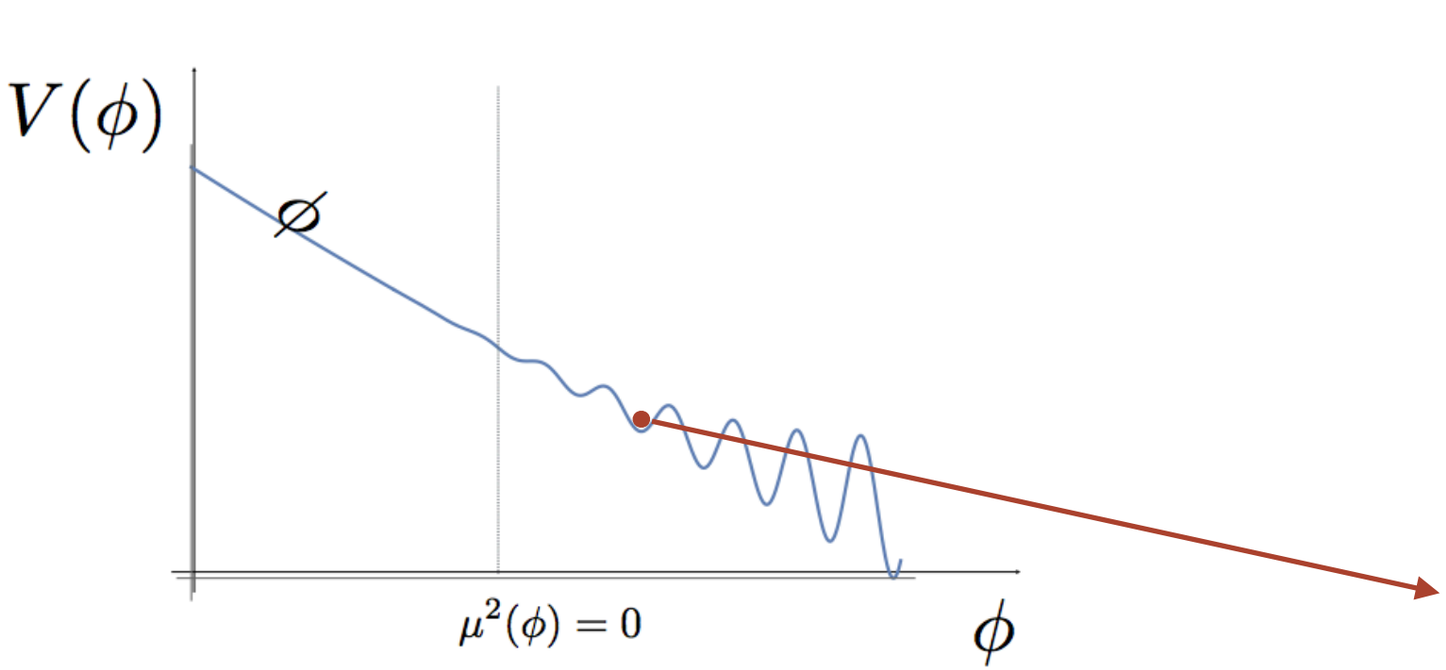

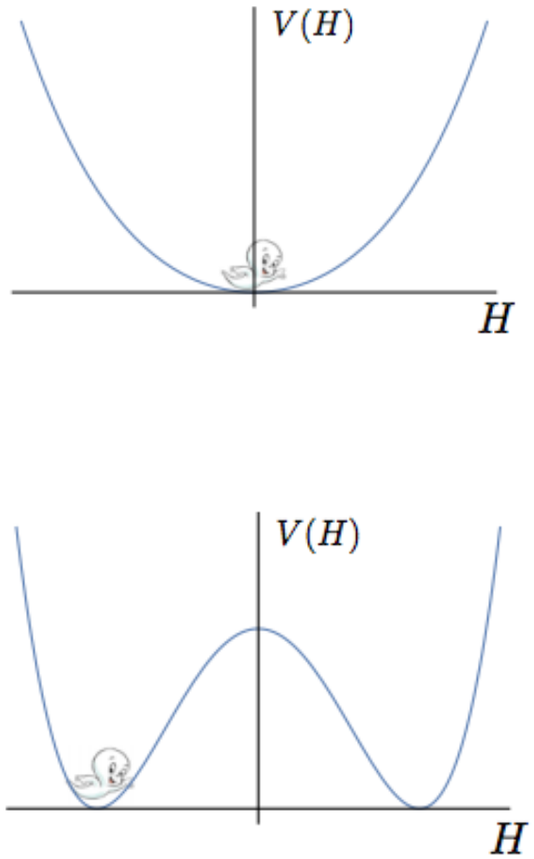

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$$\mathcal{L} \supset \underbrace{(\Lambda^2 - g\Lambda\phi)}_{\mu^2(\phi)} H^\dagger H \quad \rightarrow \quad \text{Dark Higgs}$$

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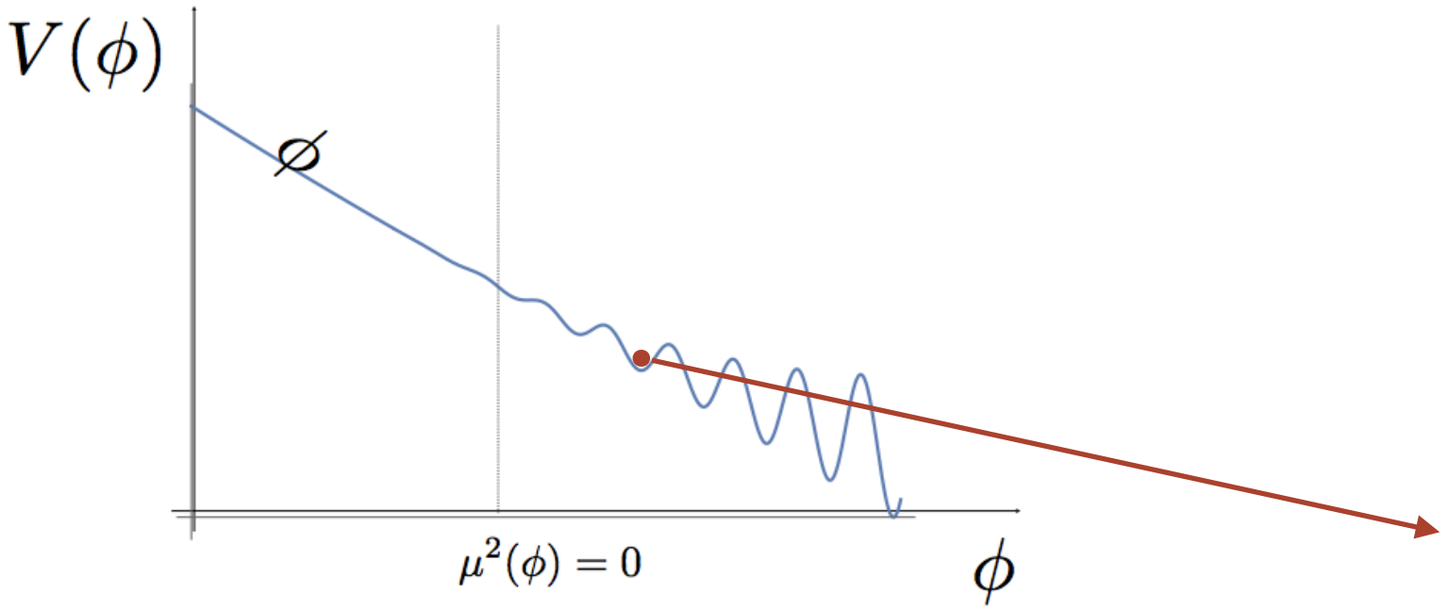

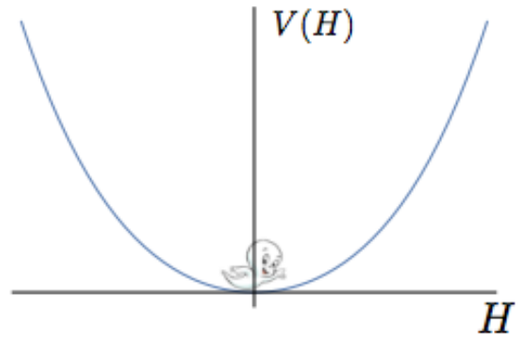

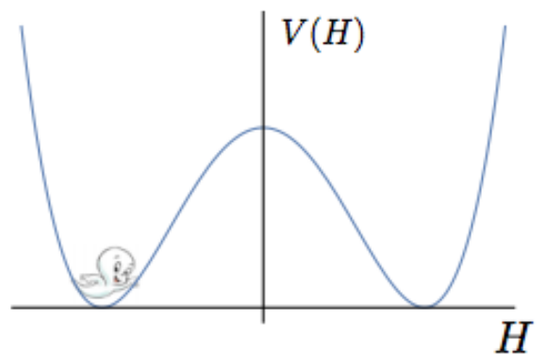

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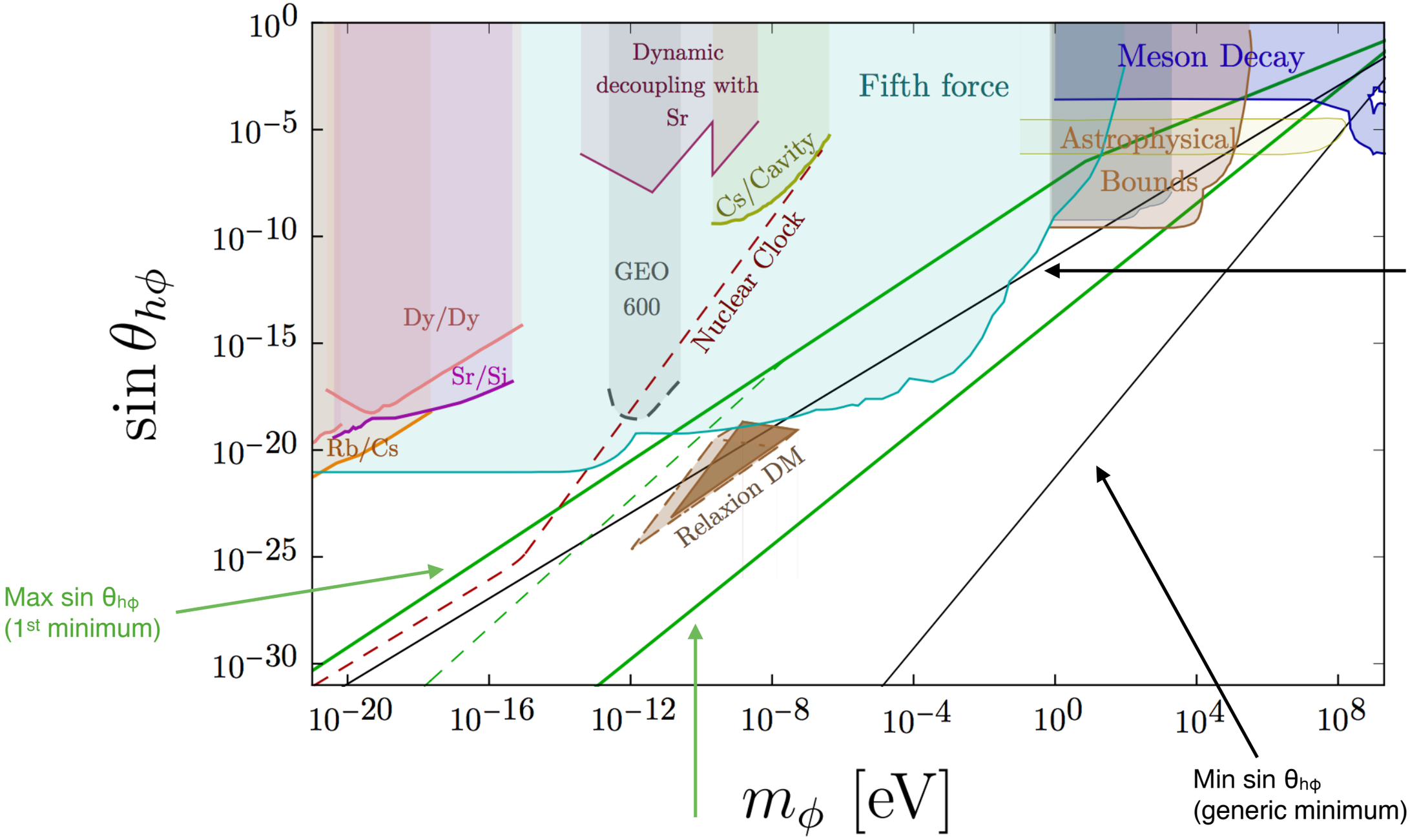
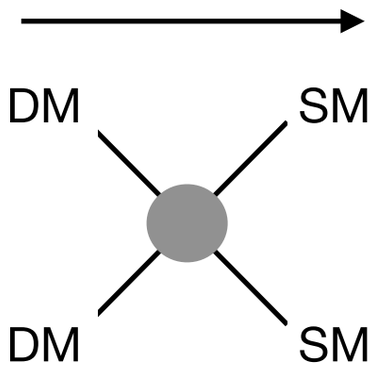


A. Banerjee, et. al.: arXiv 2004.02899

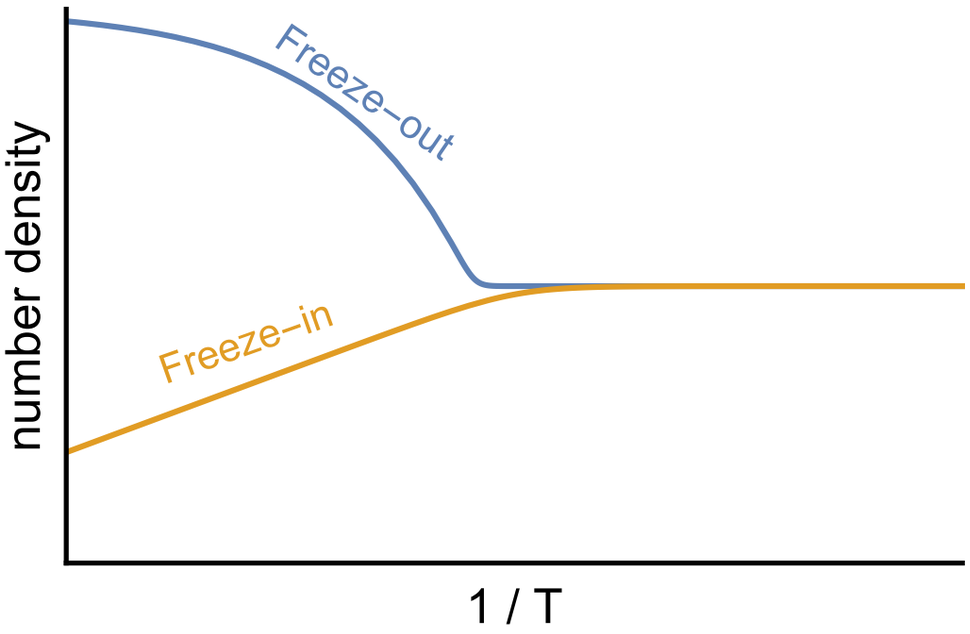
Freeze-in dark matter

Milicharged particle

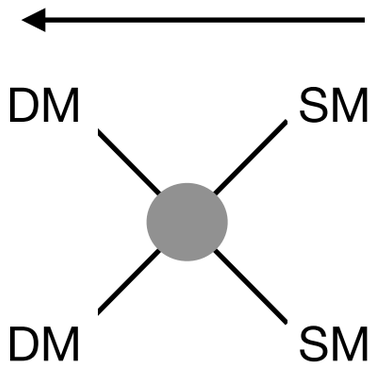
Freeze-out



Relic density set by DM annihilations to the SM



Freeze-in



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

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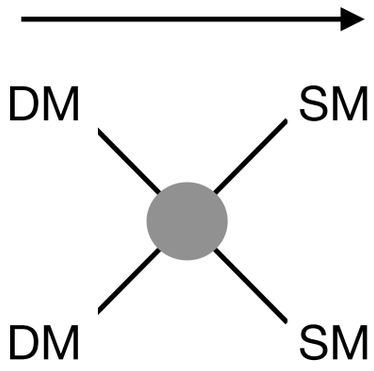

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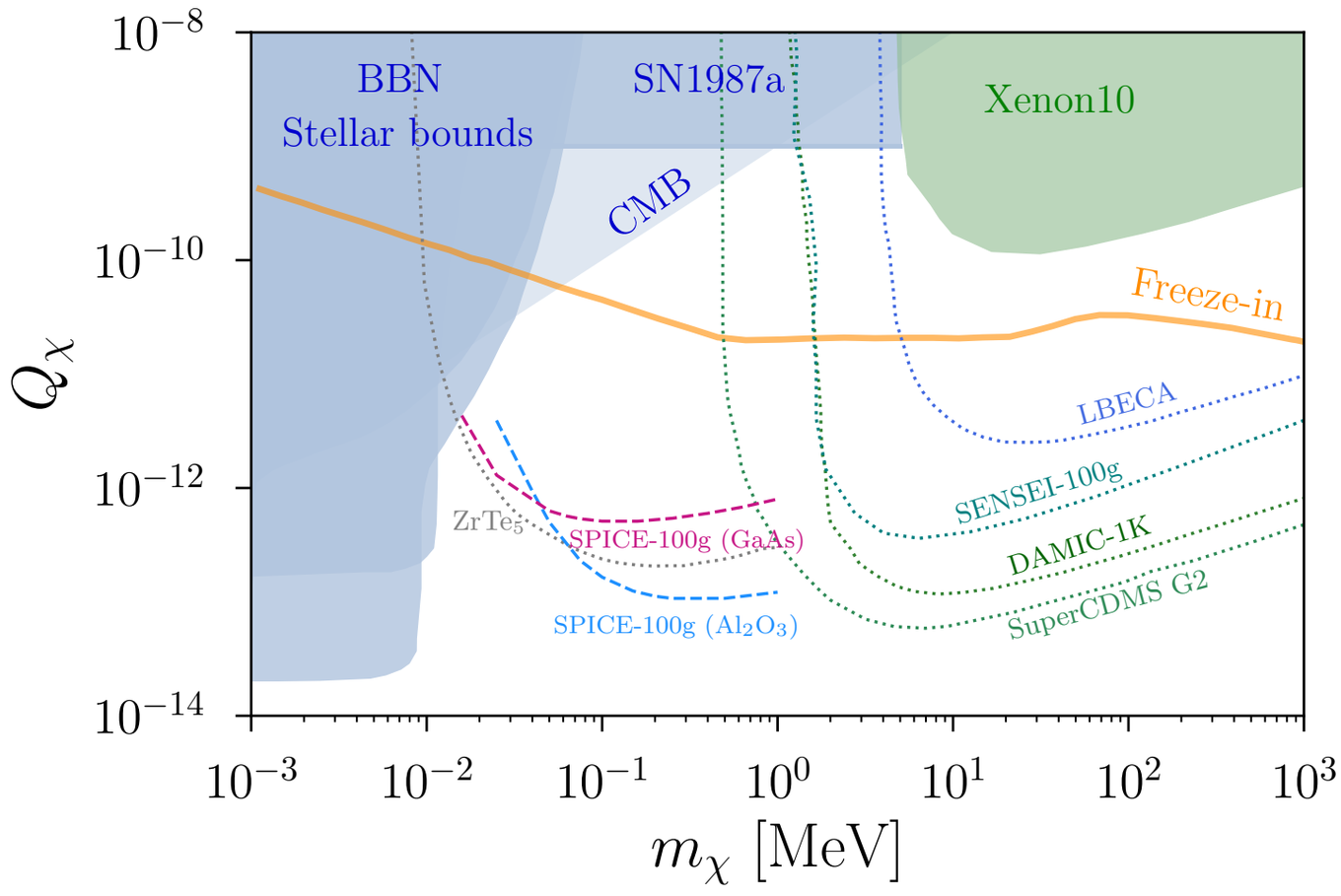
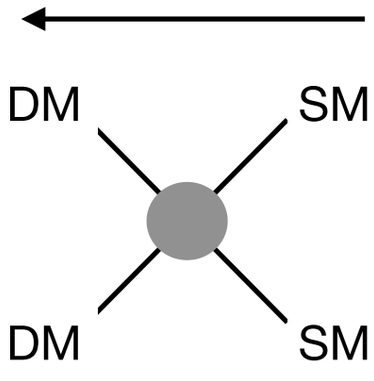


(adapted from Griffin et. al.: arXiv 1807.10291)

Freeze-in



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L. Hall, et. al.: arXiv 0911.1120

R. Essig, J. Mardon, T. Volansky: arXiv 1108.5383
X. Chu, T. Hambye, M. Tytgat: arXiv 1112.0493
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Fabulous Five vs “complete” models

Do the Fab 5 frequently appear in complete models?

Yes

(but “falsifying” appears difficult)

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

Low scale seesaw
Relaxion
Heavy Axions
Hidden sector Dark Matter
…

Let’s take a look at an exception!

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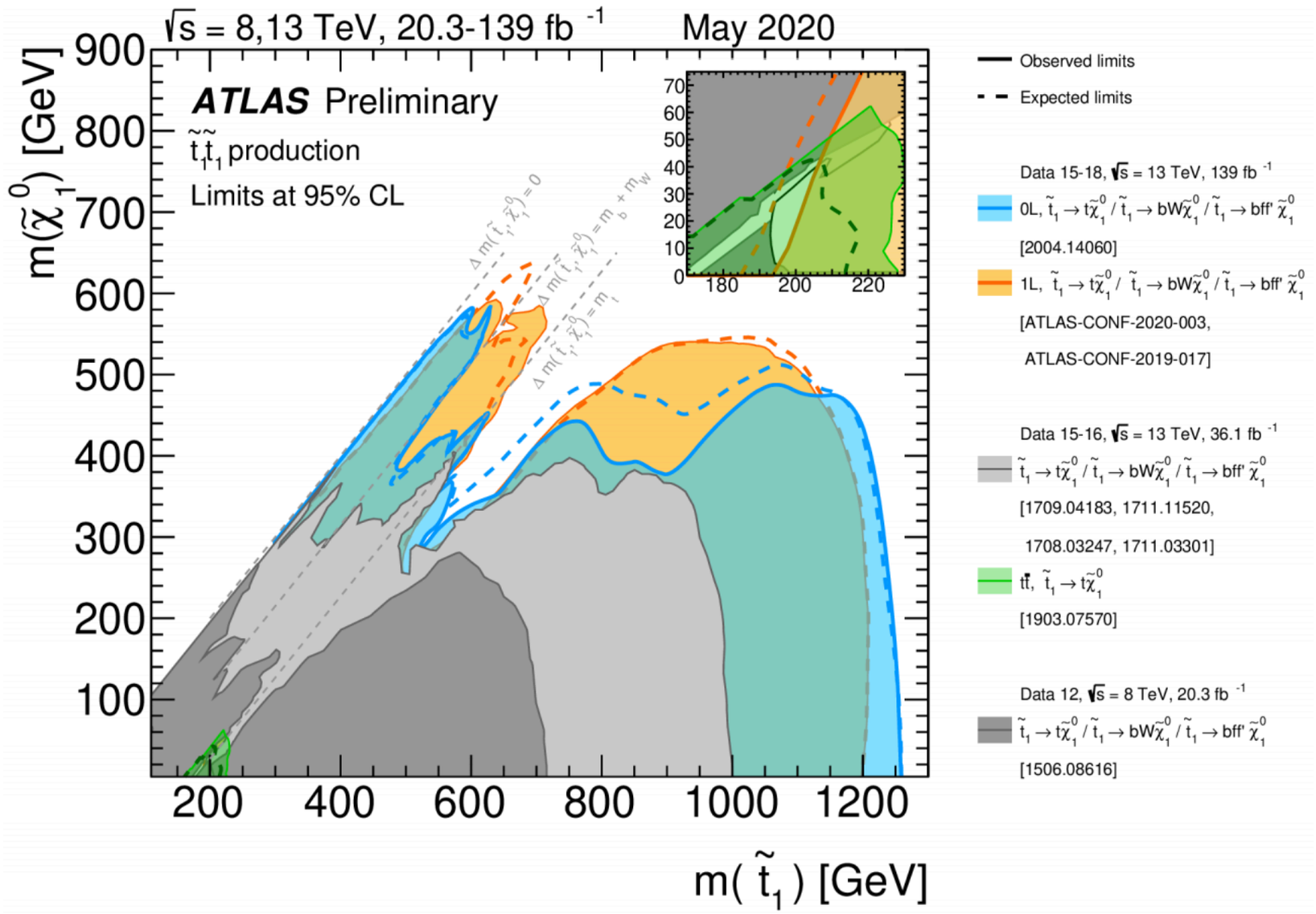
Twin Higgs

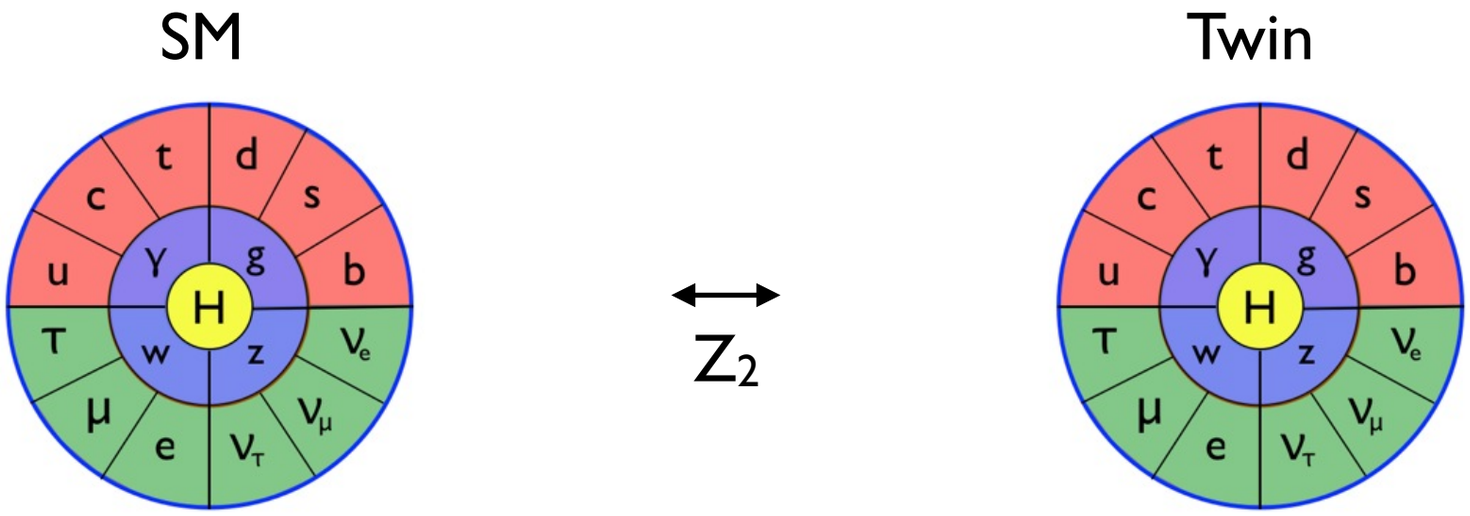
Status of “vanilla” solutions to the hierarchy problem a bit bleak



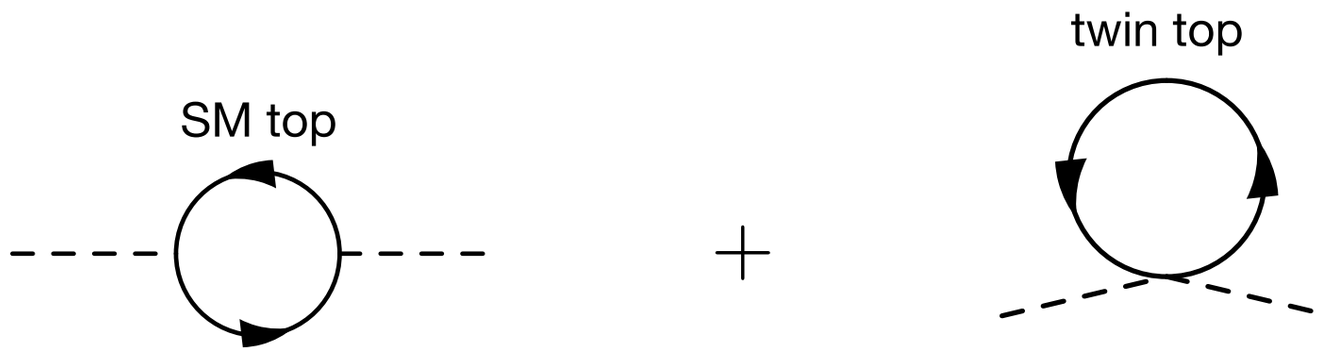
Can we still have < 1 TeV top partners?

Twin Higgs

Dark sector = (approximate) copy of the Standard Model



Twin top can (partially) cancel the divergent contribution from the SM top

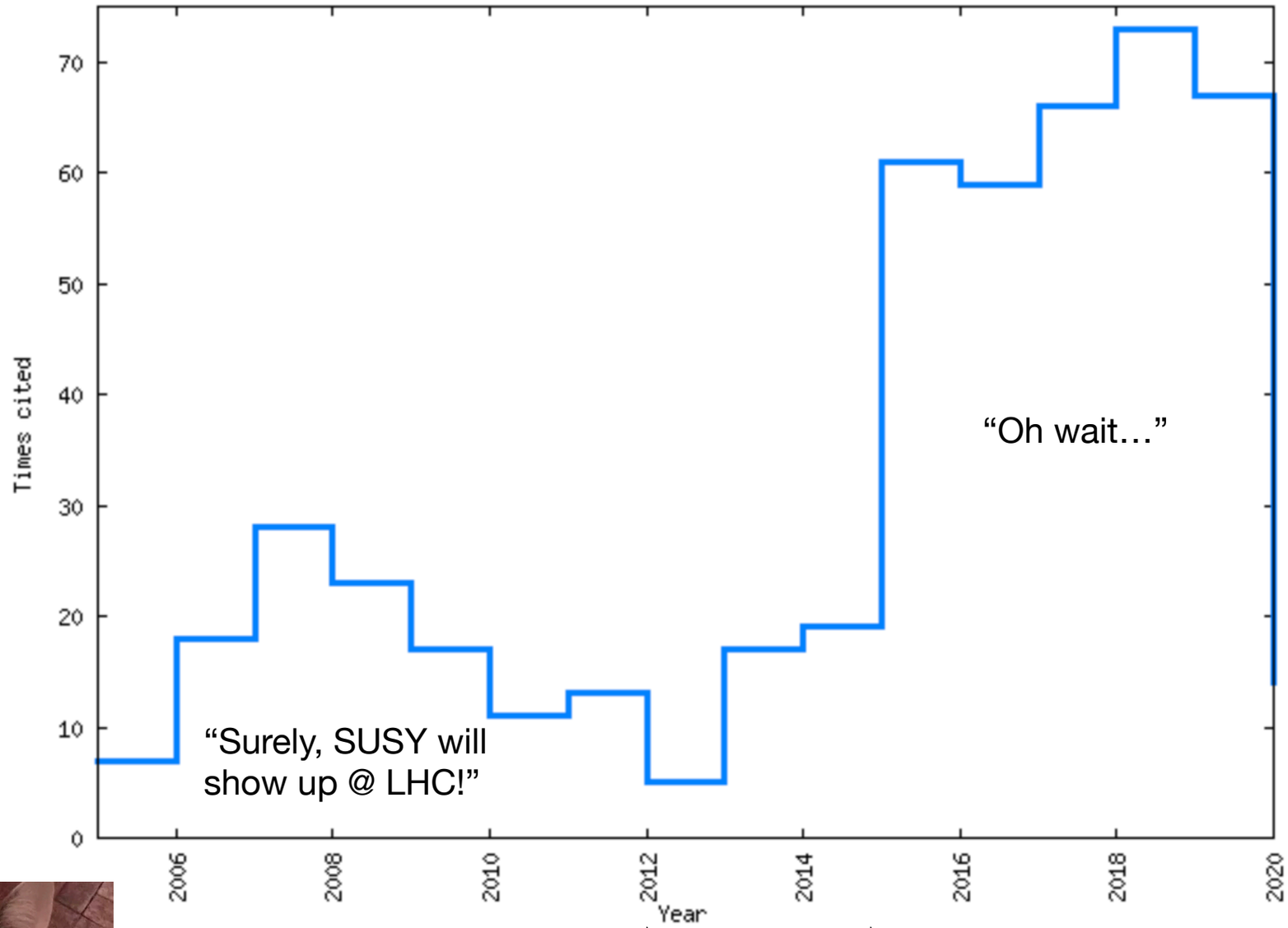


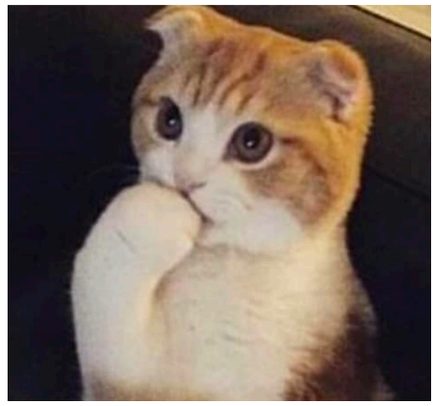
(Of course, some cleverness required)

Z. Chacko, H. Goh, R. Harnik: arXiv 0506256

Twin Higgs

Citation history:





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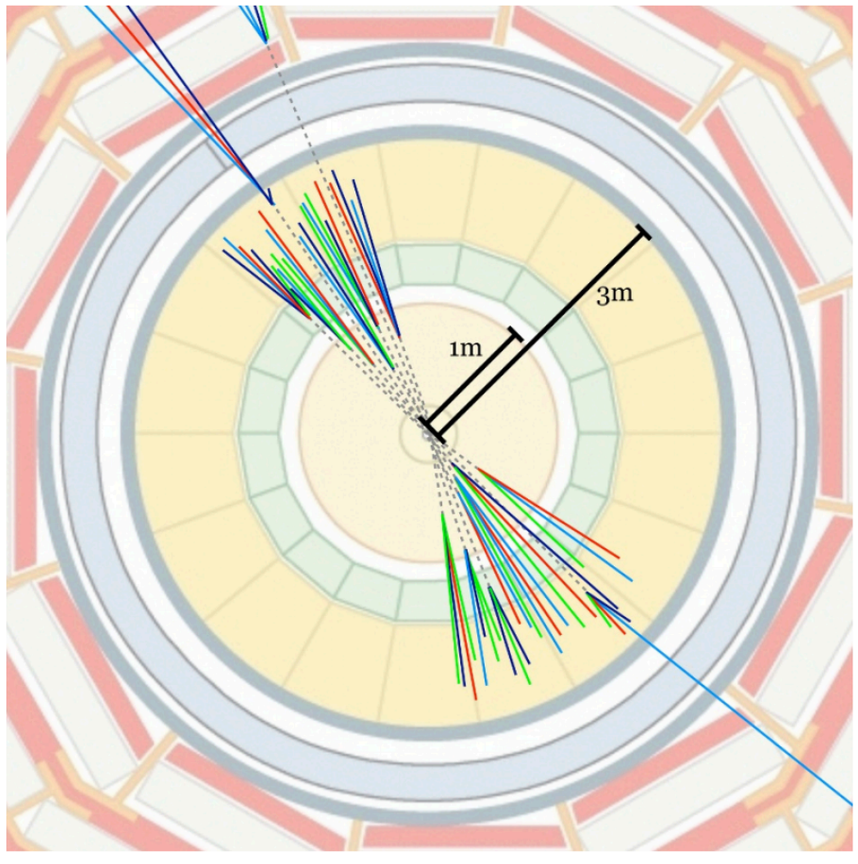
Twin Higgs

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

Also check out CMS result: arXiv:1810.10069

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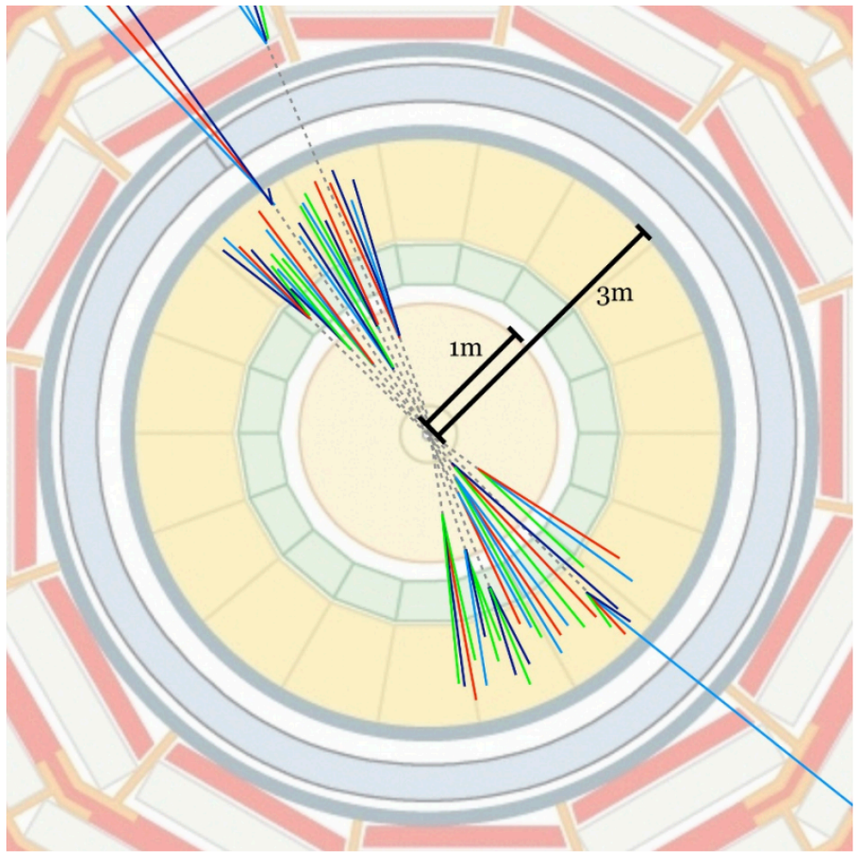

P. Schwaller, et. al.: arXiv 1502.05409

General question:

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

See “dark showers" chapter of long-lived particle community white paper: arXiv 1903.04497

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

Much more theory work is needed / in progress.

Also check out CMS result: arXiv:1810.10069

Conclusions

Do the Fab 5 frequently appear in complete models?

Yes
(but “falsifying” appears difficult)

No
(Especially @ LHC)

Are the Fab 5 sufficient?

The Fab 5 appear to be good representatives of complete models…

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

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Question: Is our focus on the Fab 5 too narrow? Are we missing important alternatives?

Maybe… My feeling is that progress on this will come from top-down model building…

Thanks!

Thanks for listening, and stay healthy!

I look forward to an exciting workshop

Many thanks to the CERN TH group for useful discussions when preparing this talk
In particular Admir, Toby, Bibushan, Tevong, Joachim, Matthew, Dorota, Ennio, Diego, Valerie and Kai