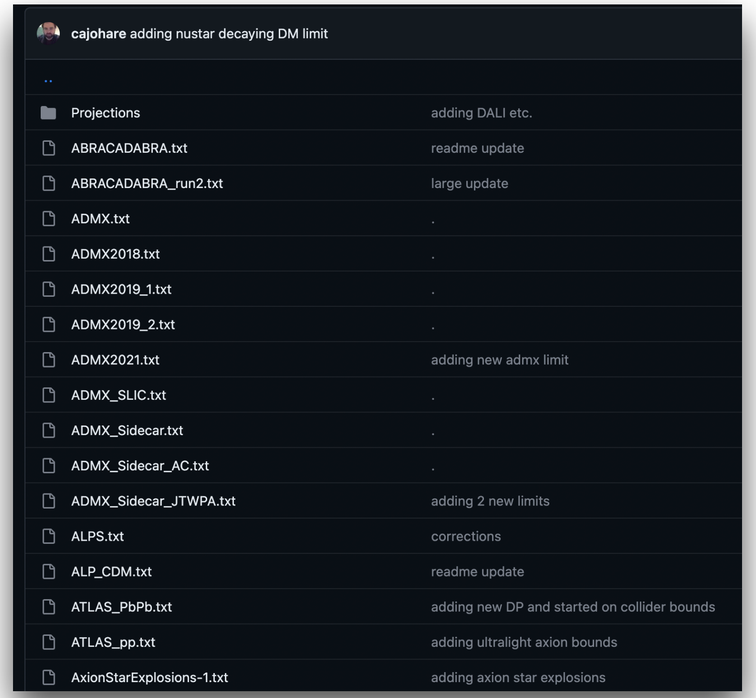
Axion (and other WISP) Limits, summary plots, and data comparison

Ciaran O’Hare

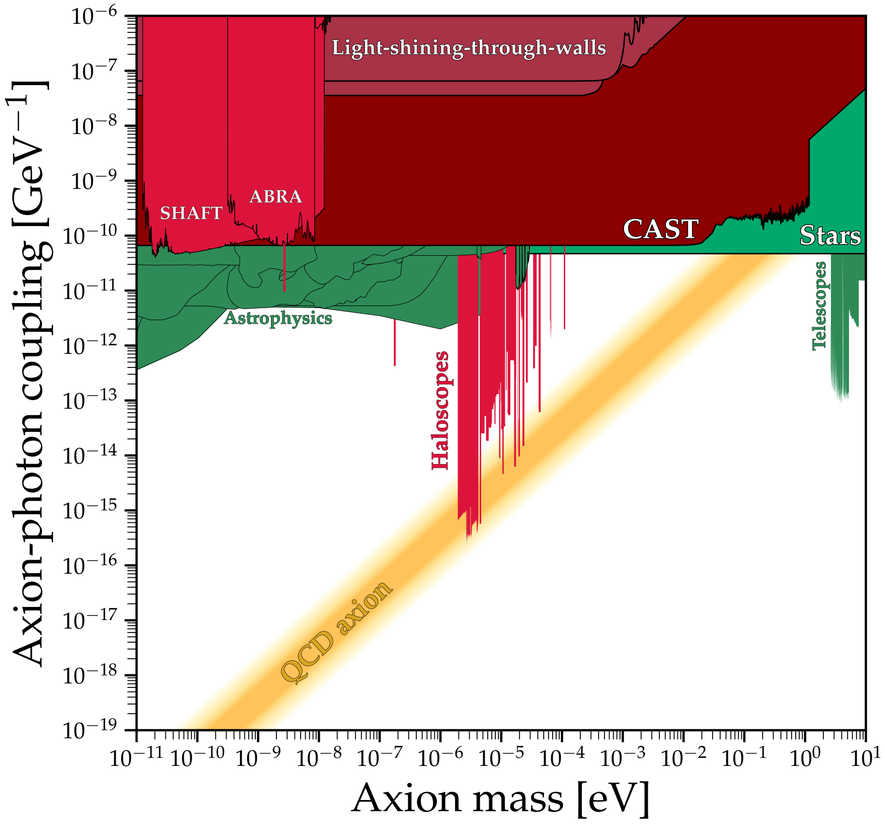
AxionLimits

GitHub: https://github.com/cajohare/AxionLimits

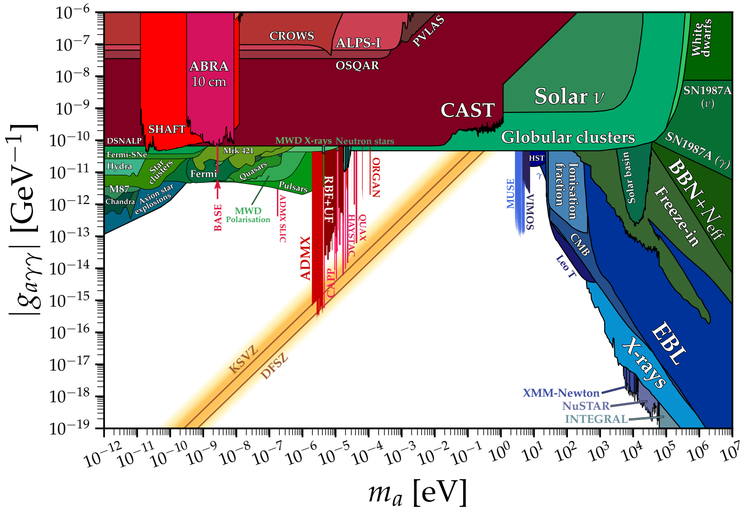
Data for constraints and projections

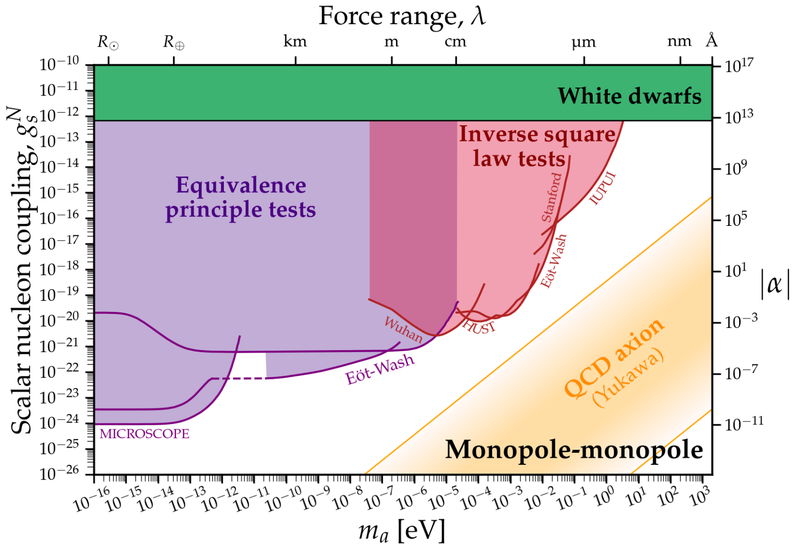


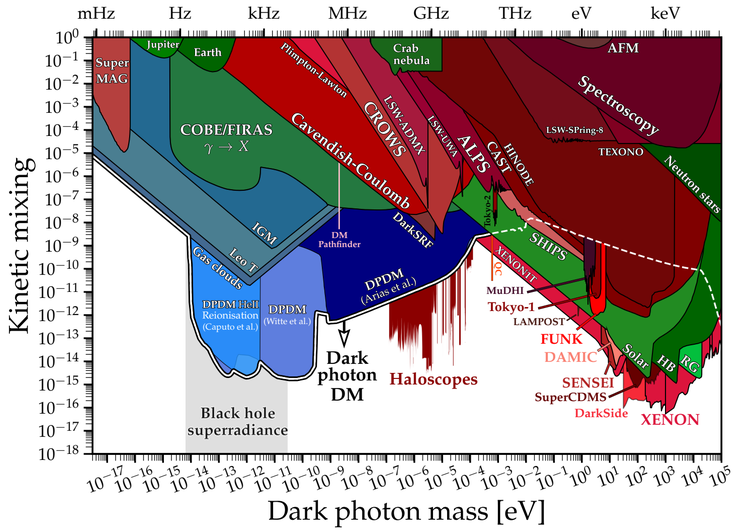
Plots via python notebooks

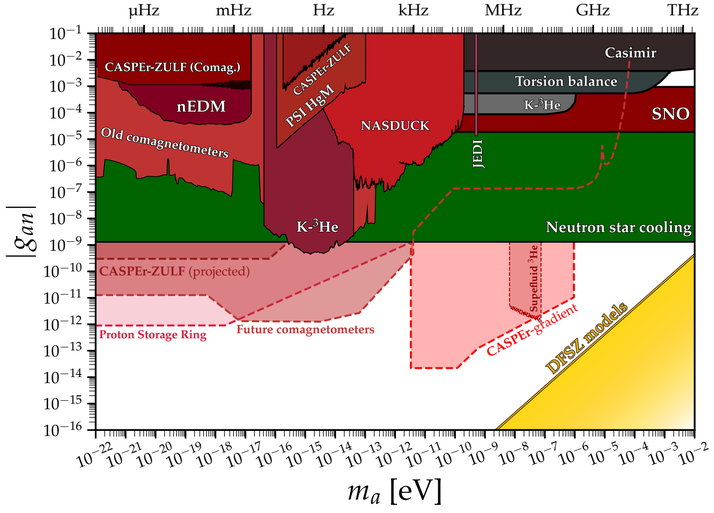


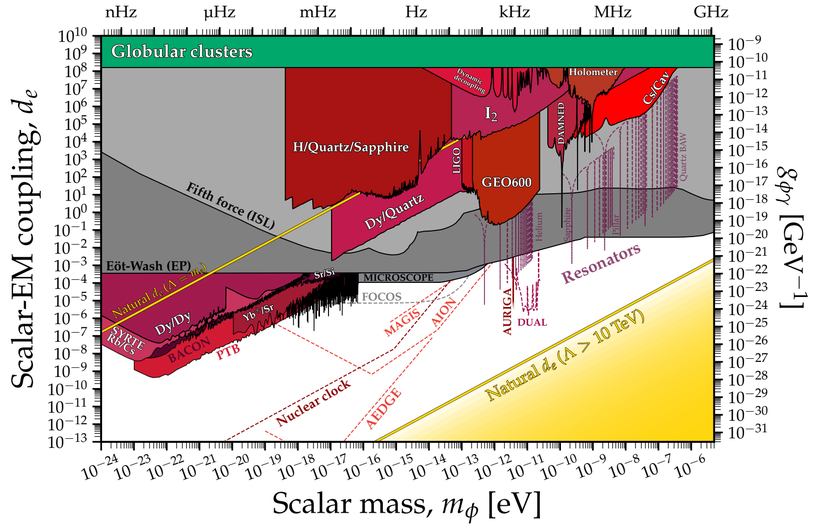
Axions

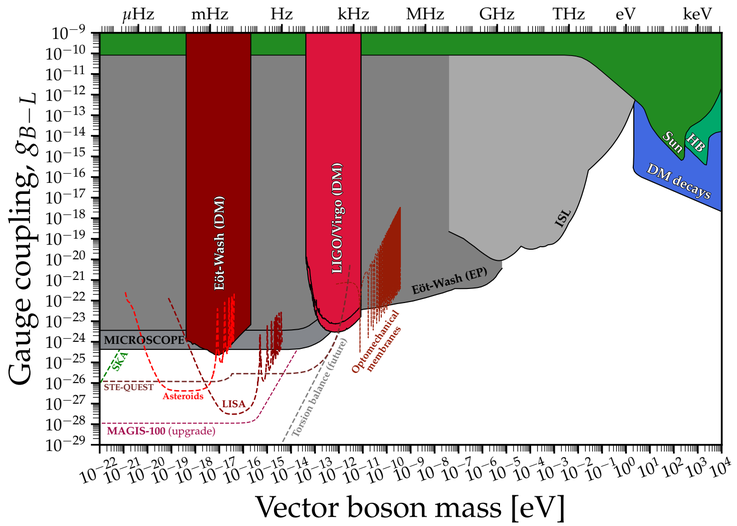

$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
OSQAR
PVLAS
ABRA 10 cm
CAST
Solar ν
Globular clusters
White dwarfs
SN1987A (ν)
SN1987A (γ)
SHAFT
DSNALP
Fermi-SNe
Hydra
Fermi
Quasars
M87
Chandra
Axion star explosions
MWD X-rays
Neutron stars
Pulsars
MWD Polarisation
BASE
ADMX SLIC
RBF-UF
ADMX
CAPP
ORGAN
QUAX
TOKYO
MUSE
HST
SONIA
Ionisation fraction
Stellar basins
CMB
Ly-α
BBN+$N_{\rm eff}$
Free-e-in
EBL
X-rays
XMM-Newton
NuSTAR
INTEGRAL
KSVZ
DFSZ


Force range, λ
$R_\odot$
$R_\oplus$
km
m
cm
μm
nm
Å
Scalar nucleon coupling, g_s^N
$|\alpha|$
m_a [eV]
White dwarfs
Inverse square law tests
Equivalence principle tests
Stanford
IUPUI
Eöt-Wash
Wuhan
HUST
Eöt-Wash
MICROSCOPE
QCD axion (Yukawa)
Monopole-monopole


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
Super MAG
Jupiter
Earth
Pimpton-Lawton
Crab nebula
AFM
Spectroscopy
LSW-SPring-8
TEXONO
Neutron stars
COBE/FIRAS $\gamma \to X$
Cavendish-Coulomb
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
HINODE
CAST-CAPP
SHIPS
XENONnT
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
Solar
HB
RG
SENSEI
SuperCDMS
DarkSide
XENON
IGM
Leo T
Gas clouds
DM Pathfinder
DarkSRF
DPDM (Arias et al.)
DPDM ERE Reionisation (Caputo et al.)
DPDM (Witte et al.)
Dark photon DM
Haloscopes
Black hole superradiance

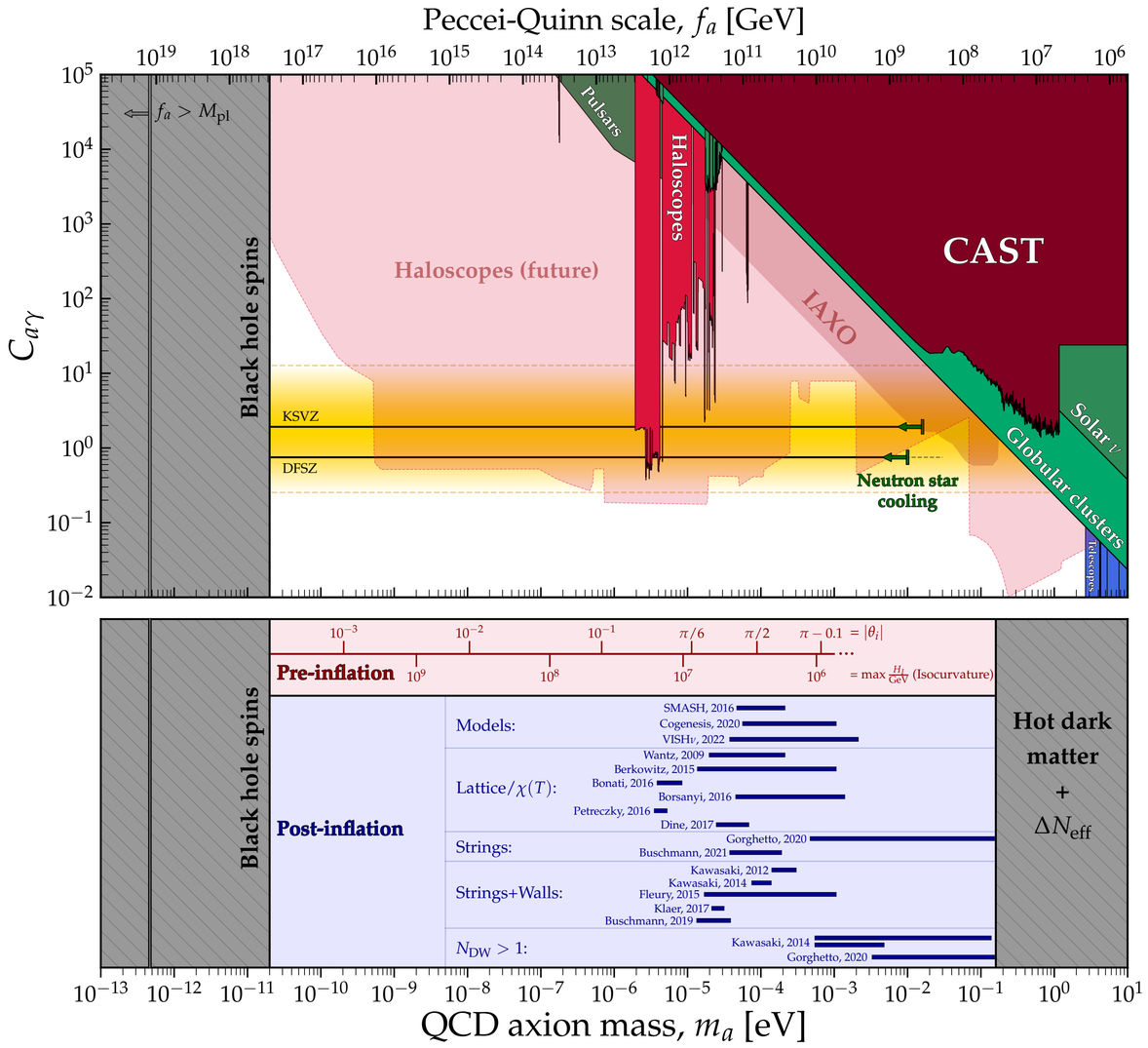

μHz
mHz
Hz
kHz
MHz
GHz
THz
$|g_{an}|$
m_a [eV]
CASPEr-ZULF (Comag.)
CASPEr-ZULF
PSI ^{199}Hg
nEDM
Old comagnetometers
NASDUCK
JEDI
K-^{3}He
Casimir
Torsion balance
K-^{3}He
SNO
Neutron star cooling
CASPEr-ZULF (projected)
Proton Storage Ring
Future comagnetometers
Superfluid ^{3}He
CASPEr-gradient
DFSZ models

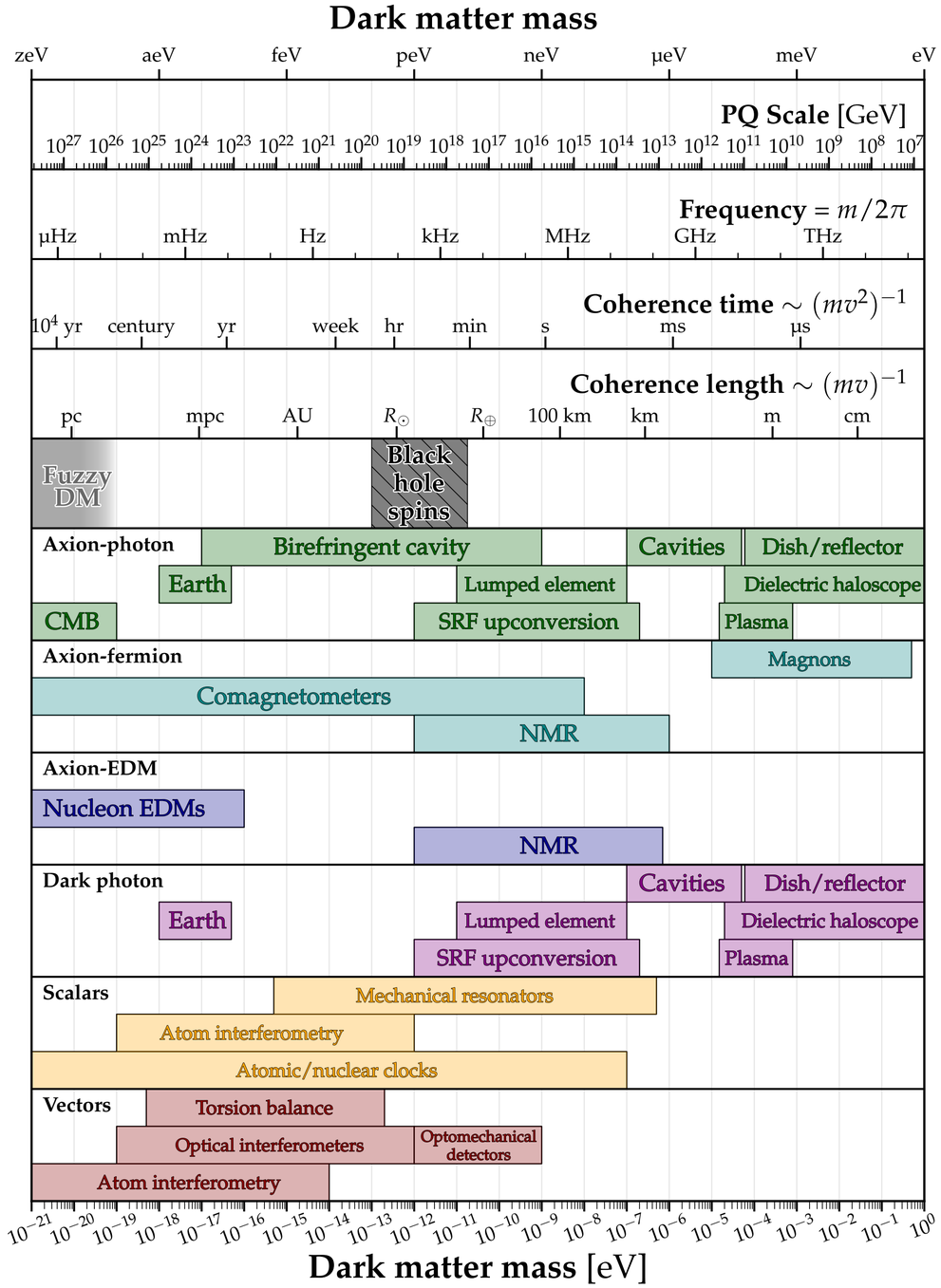

nHz
μHz
mHz
Hz
kHz
MHz
GHz
Scalar-EM coupling, d_e
$g_{\phi\gamma}$ [GeV^{-1}]
Scalar mass, m_ϕ [eV]
Globular clusters
Holometer
Dynamic decoupling
I_2
Cs/CaF
H/Quartz/Sapphire
LIGO
GEO600
Dy/Quartz
DAMNED
Quartz BAW
Sapphire
Helium
Fifth force (ISL)
Eöt-Wash (EP)
Natural d_e/d_n
SrSr
MICROSCOPE
FOCOS
Dy/Dy
Yb$^+$/Sr
BACON
PTB
RbRb
MAGIS
AION
AURIGA
DUAL
Resonators
Nuclear clock
AEDGE
Natural d_e ($\Lambda > 10$ TeV)


μHz
mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Gauge coupling, g_{B-L}
Vector boson mass [eV]
Sun
HB
DM decays
ISL
Eöt-Wash (DM)
LIGO/Virgo (DM)
Eöt-Wash (EP)
MICROSCOPE
SK-I
STE-QUEST
Asteroids
LISA
Torsion balance (future)
Optomechanical membranes
MAGIS-100 (upgrade)

AxionLimits

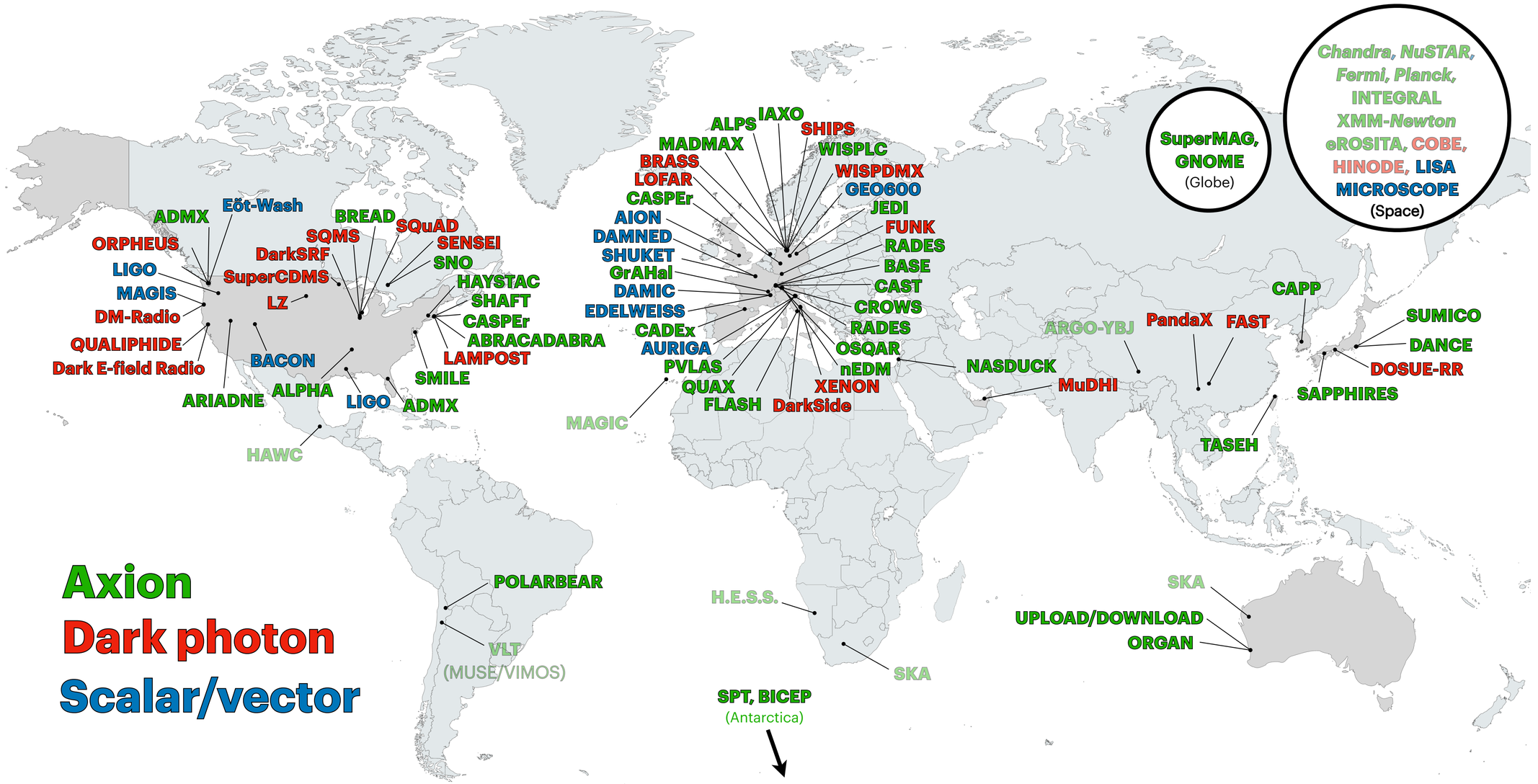
Recently added...





AxionLimits

Work in progress...



AxionLimits

Current scope:

Axions/ALPs

- Axion-EDM/f_a: $(a/f_a)G\tilde{G}$
- Axion-photon: $\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$
- Axion-electron: $\frac{g_{ae}}{2m_n}\partial_\mu a\,\bar{e}\gamma^\mu\gamma_5 e$
- Axion-neutron/proton: $\frac{g_{an}}{2m_n}\partial_\mu a\,\bar{n}\gamma^\mu\gamma_5 n$

Mass range = $[10^{-22}, 10^{9}]$ eV

Missing: $g_{a\gamma}g_{ae}$, $g_{a\gamma}g_{an}$, g^1_{aN}, g^3_{aN}, $g_{a\mu}$

Scalars

- Scalar-nucleon: $g_{\phi n}\,\phi\,\bar{n}n$
- Scalar-electron: $g_{\phi e}\,\phi\,\bar{e}e$
- Scalar-photon: $\frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}F^{\mu\nu}$
- Scalar-nucleon x pseudoscalar-nucleon: $g_s^N g_p^N$
- Scalar-nucleon x pseudoscalar-electron: $g_s^N g_p^e$

Mass range = $[10^{-22}, 10^{3}]$ eV

Missing: $d_{\hat{m}}$, $d_{\delta m}$, d_g, $d_i^{(2)}$

Vectors

- Dark photon kinetic mixing: $\frac{\epsilon}{2}X_{\mu\nu}F^{\mu\nu}$
- *B-L* Gauge coupling: $g_{B-L}V_\mu J^\mu_{B-L}$

Mass range = $[10^{-22}, 10^{3}]$ eV

Missing: g_B, g_L, $g_{L_\mu - L_\tau}$

Other WISPs missing: chameleon, relaxion, sub-eV sterile-ν

AxionLimits

Obvious room for improvement & input from community

- Constraints are very incomplete at >MeV masses (so far only axion-photon coupling goes that high)
- Bounds are mostly not true-to-source, and accuracy is driven largely by how easy a particular plot from a paper was to digitise. (Some people have sent me data directly - thank you!)
- Lacking several interesting couplings and coupling combinations
- Levels of model-dependence/assumption could be highlighted better on plots (discussed in later slides)
- Not user-friendly. Code is something of a Frankenstein, a lot of inconsistency and needs organisation and streamlining

COST outcomes

One possible outcome of COST that could be very useful for the community is to put forward an agreed set of conventions:

Limits:

→ Consistent approach for reporting limits (e.g. CL)

→ Agreed assumptions for dark matter searches: DM density, lineshape, handling of stochastic effects etc.

→ Agree to avoid sloppy definitions of couplings (esp. the case for nucleons)

→ Agreed tiers of theory model targets. e.g. when should a haloscope search “stop”?

Visualisation:

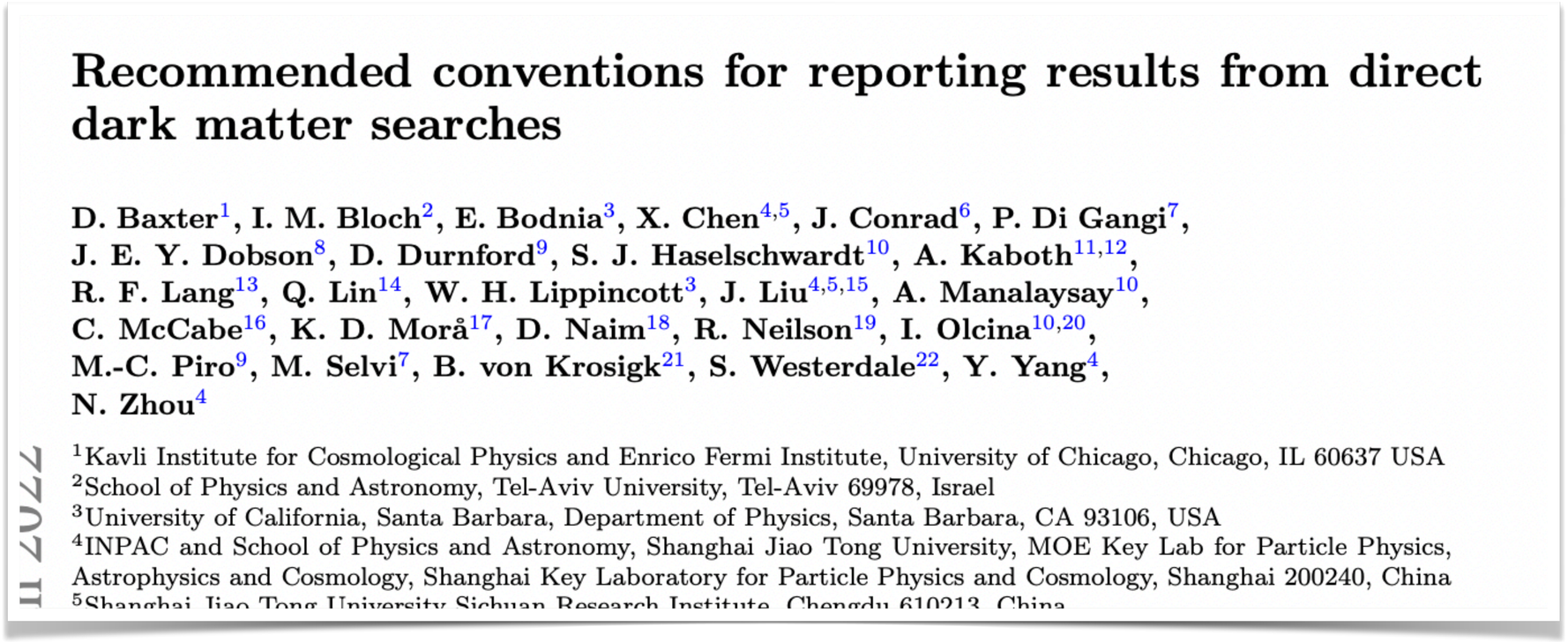
→ Agreed notation

→ Consistent approach to summary plots where colours are used meaningfully to represent assumptions or some other feature

COST outcomes

Common assumptions:

- Note WIMP DD community has already done this: https://arxiv.org/abs/2105.00599
- WISP DD may be more challenging but something should probably be attempted



Recommended conventions for reporting results from direct dark matter searches

D. Baxter[1], I. M. Bloch[2], E. Bodnia[3], X. Chen[4,5], J. Conrad[6], P. Di Gangi[7], J. E. Y. Dobson[8], D. Durnford[9], S. J. Haselschwardt[10], A. Kaboth[11,12], R. F. Lang[13], Q. Lin[14], W. H. Lippincott[3], J. Liu[4,5,15], A. Manalaysay[10], C. McCabe[16], K. D. Morå[17], D. Naim[18], R. Neilson[19], I. Olcina[10,20], M.-C. Piro[9], M. Selvi[7], B. von Krosigk[21], S. Westerdale[22], Y. Yang[4], N. Zhou[4]

[1]Kavli Institute for Cosmological Physics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637 USA
[2]School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israel
[3]University of California, Santa Barbara, Department of Physics, Santa Barbara, CA 93106, USA
[4]INPAC and School of Physics and Astronomy, Shanghai Jiao Tong University, MOE Key Lab for Particle Physics, Astrophysics and Cosmology, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai 200240, China
[5]Shanghai Jiao Tong University Sichuan Research Institute, Chengdu 610213, China

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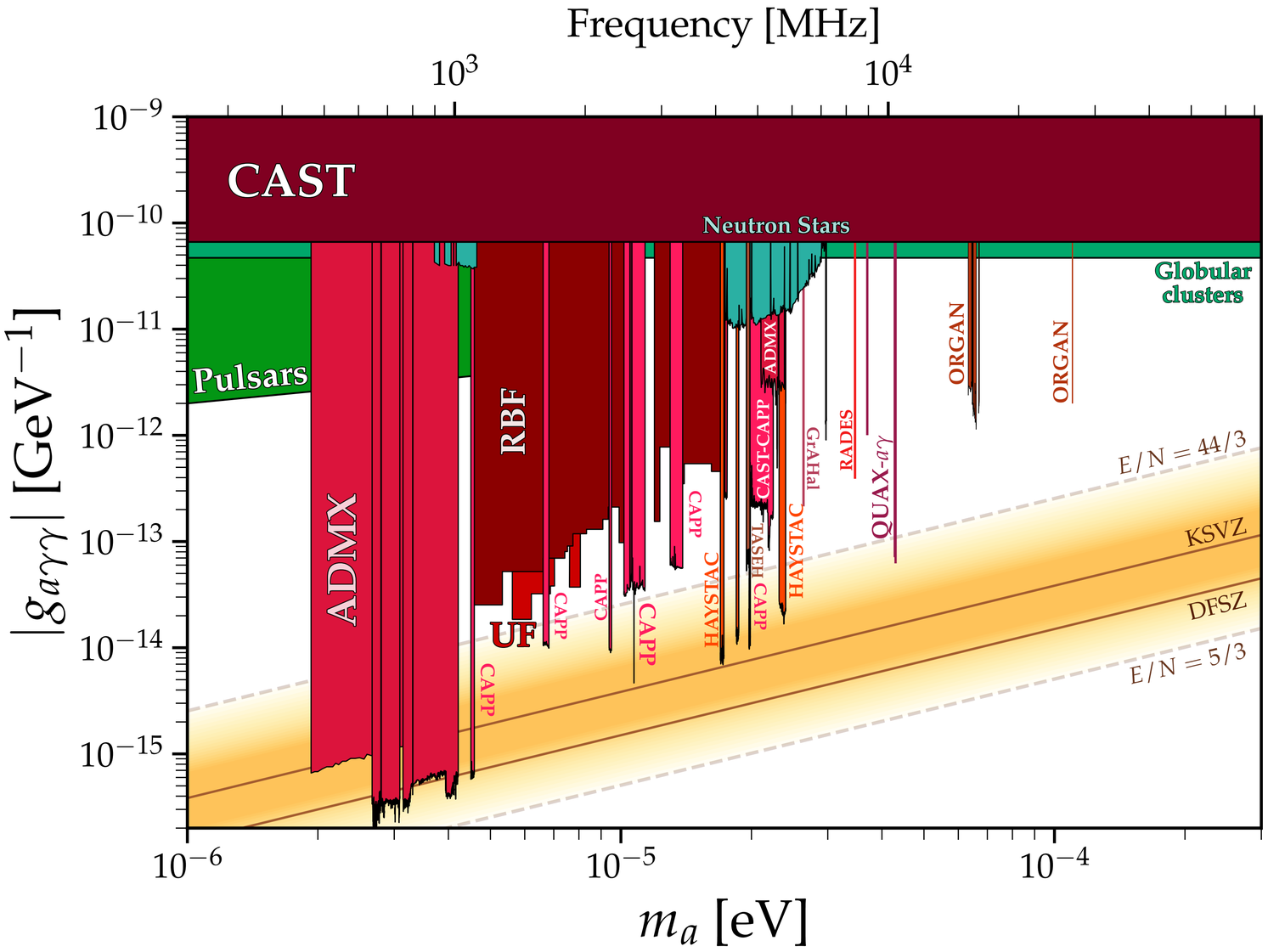
AxionLimits

- One thing that would be great to address this, is a more systematised library for constraint data, e.g. via a Google spreadsheet:

Label	Interaction	File	Mass unit	Coupling unit	CL	Location	Type	DM density	Year	arxiv number
ADMX	axion-photon	AxionPhoton/ADMX2021.txt	eV	1/GeV	90	Washington, USA	darkmatter-haloscope	0.45	2021	2110.06096
Globular clusters	axion-photon	AxionPhoton/GlobularClusters.txt	eV	1/GeV	N/A	N/A	stellar-cooling	N/A	2022	2207.03102
CAST	axion-photon	AxionPhoton/CAST.txt	eV	1/GeV	95	CERN	stellar-helioscope	N/A	2017	1705.02290
ALPS	axion-photon	AxionPhoton/ALPS	eV	1/GeV	95	DESY	laboratory-LSW	N/A	2010	1004.1313

...

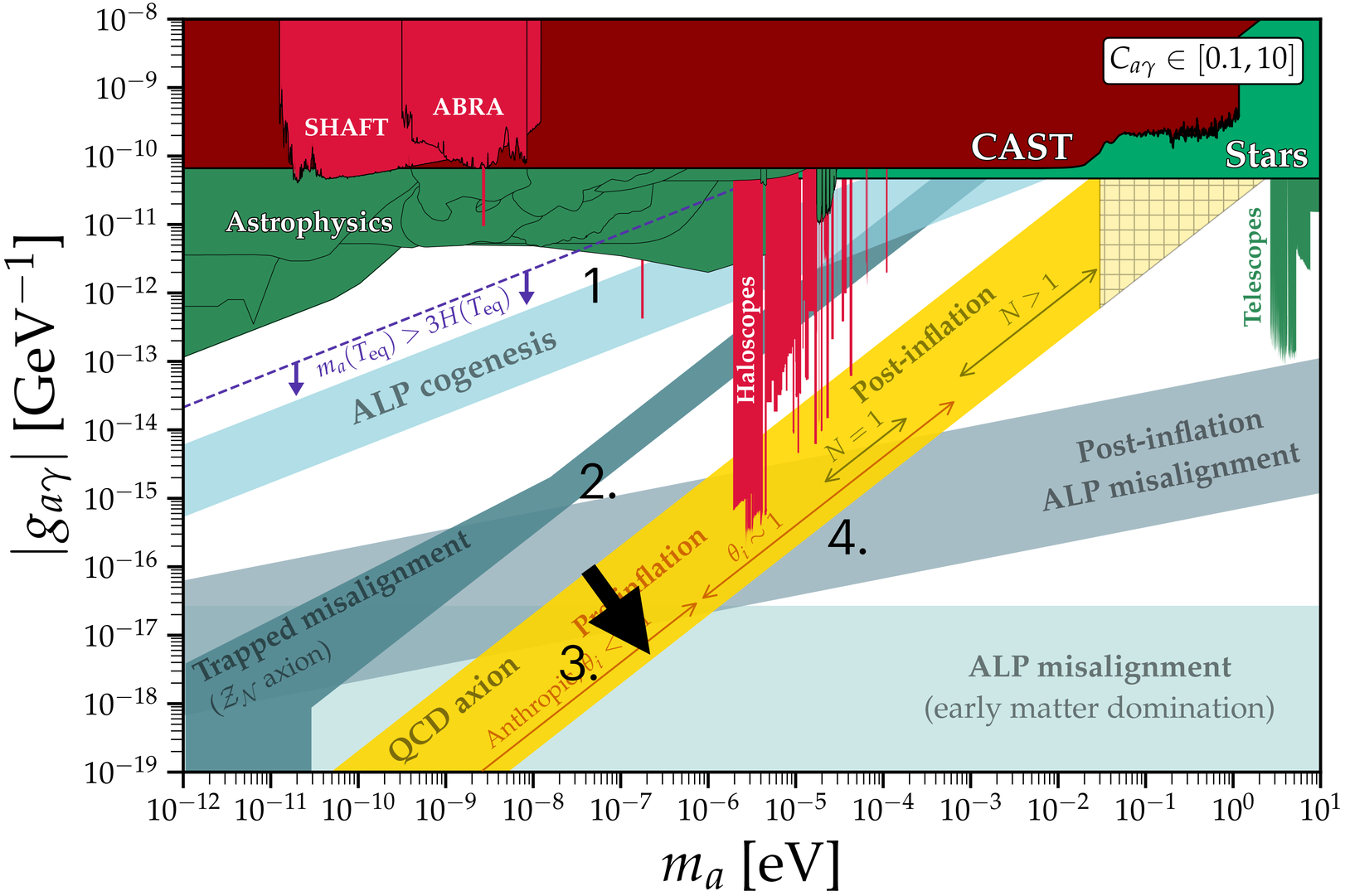
COST outcomes



Perhaps the most critical area is axion haloscopes. Tight interplay between assumed dark matter signal model, reported CL, and ultimate theory target.

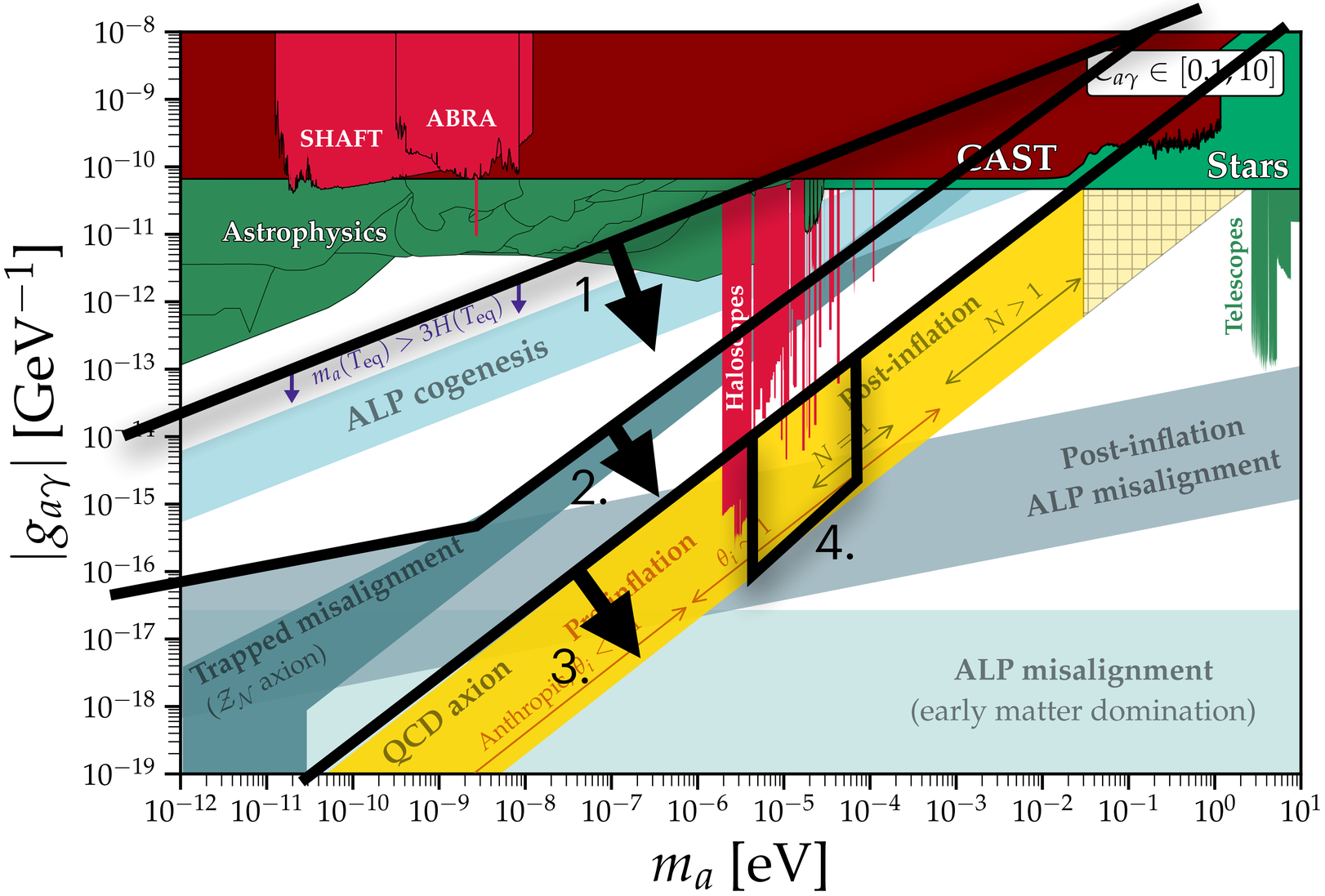
COST outcomes

Theory targets for future searches and proposals. Clear synergy with WG1&2 needed



COST outcomes

Theory targets for future searches and proposals. Clear synergy with WG1&2 needed



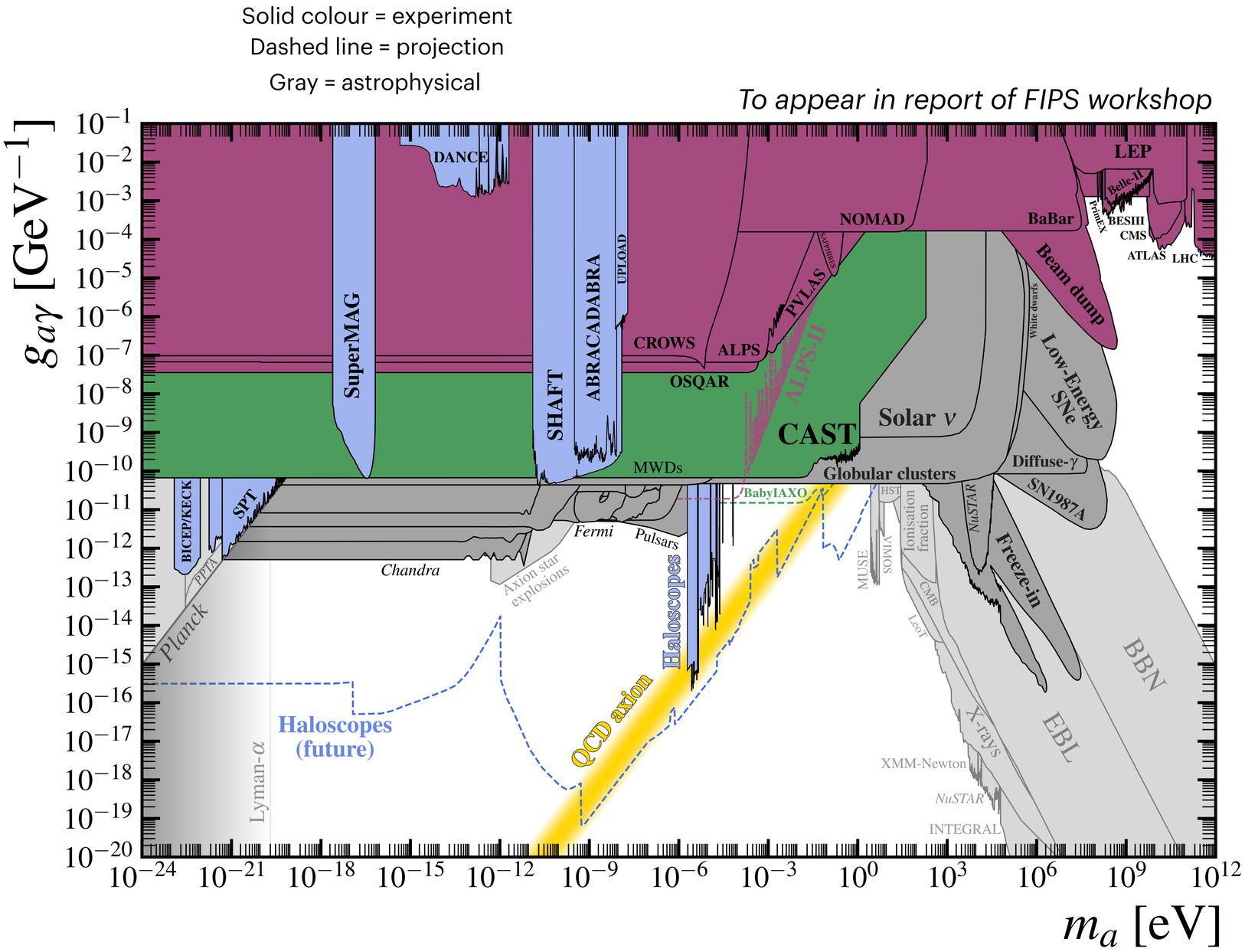
Example: ALP dark matter

1. Minimal ALP dark matter
2. Non-standard ALP/axion models
3. QCD axion
4. QCD axion + cosmological mass prediction

Possible summary plot

Visualisation: Plots are already complicated enough, more care needs to be taken to use visual information in a meaningful way.

Example: color/ transparency to represent layers of assumption and model-dependence



Possible summary plot

Solid colour = experiment
Dashed line = projection
Gray = astrophysical

To appear in report of FIPS workshop

Model-dependence:

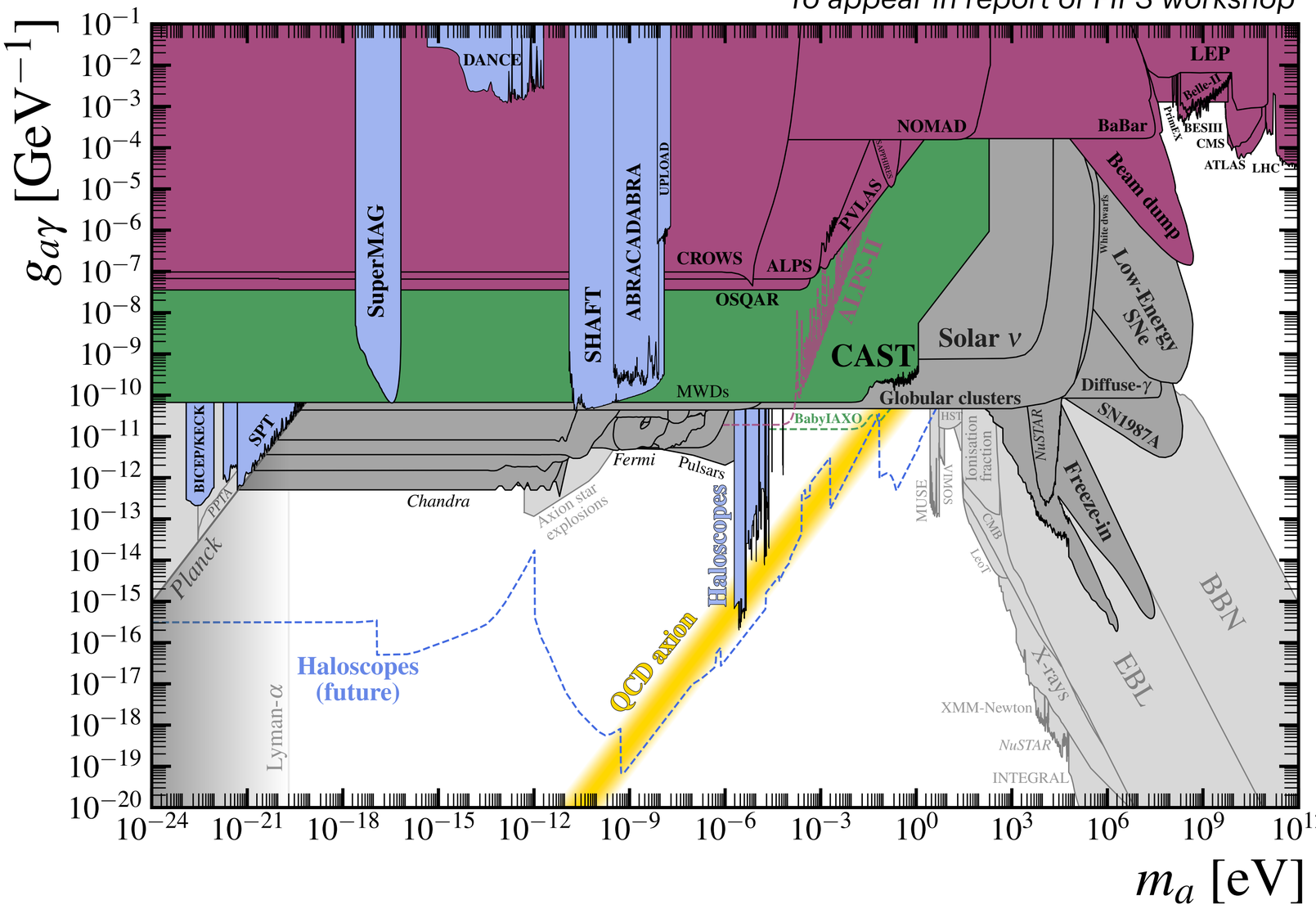
Axion-production experiments
(e.g. LSW, collider)

***Direct* astrophysical** searches
(e.g helioscopes)

***Indirect* astrophysical** searches
(Stellar cooling, axion-photon oscillations)

Direct dark matter searches
(Haloscopes)

Indirect dark matter searches



Possible summary plot

Alternative ordering

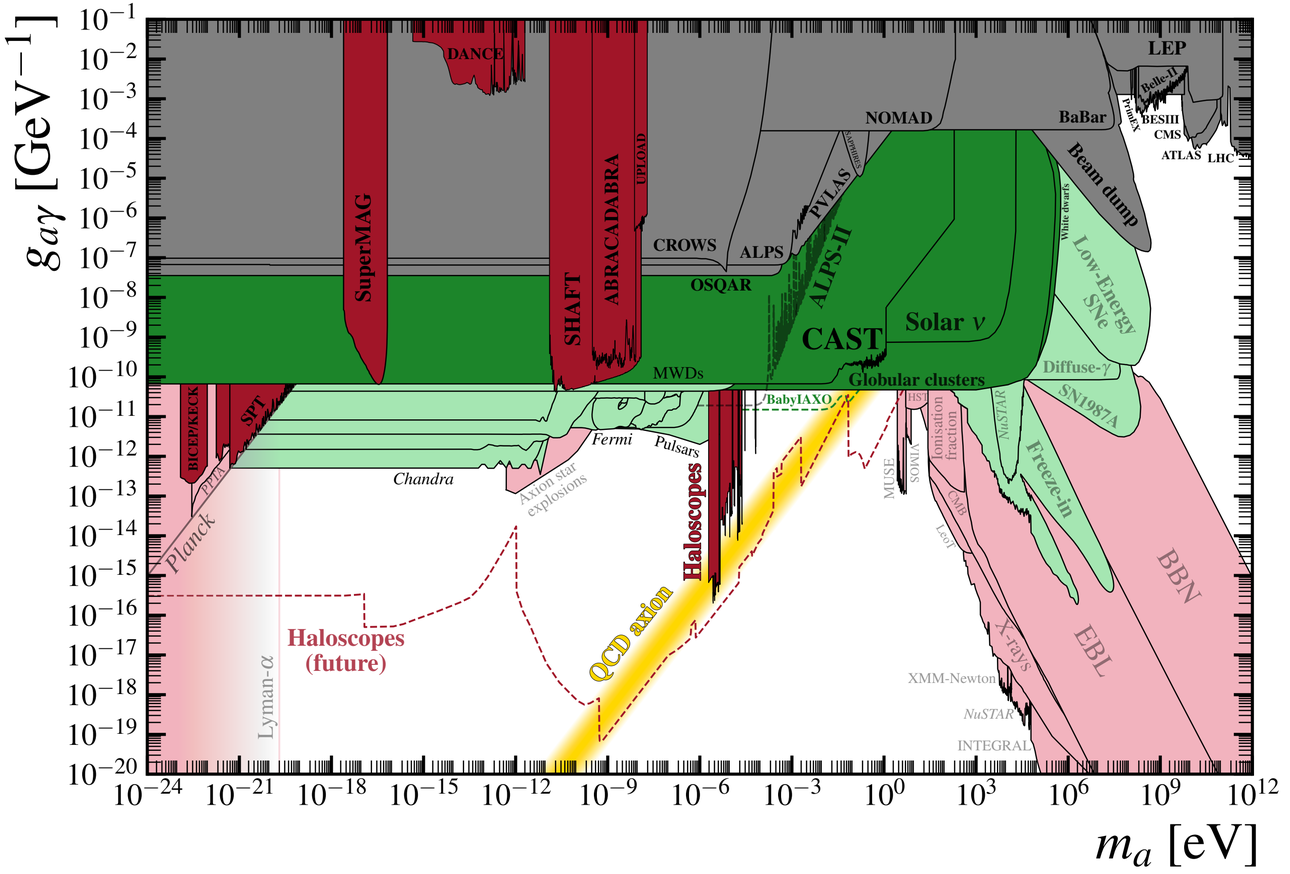
Assumption-free
(e.g. LSW, collider)

Assumption-free w/ minimal astro uncertainties
(e.g. helioscopes, solar-ν)

Assumption-free w/ moderate astro uncertainties
(e.g. axion-photon oscillations/astrophysical B-fields)

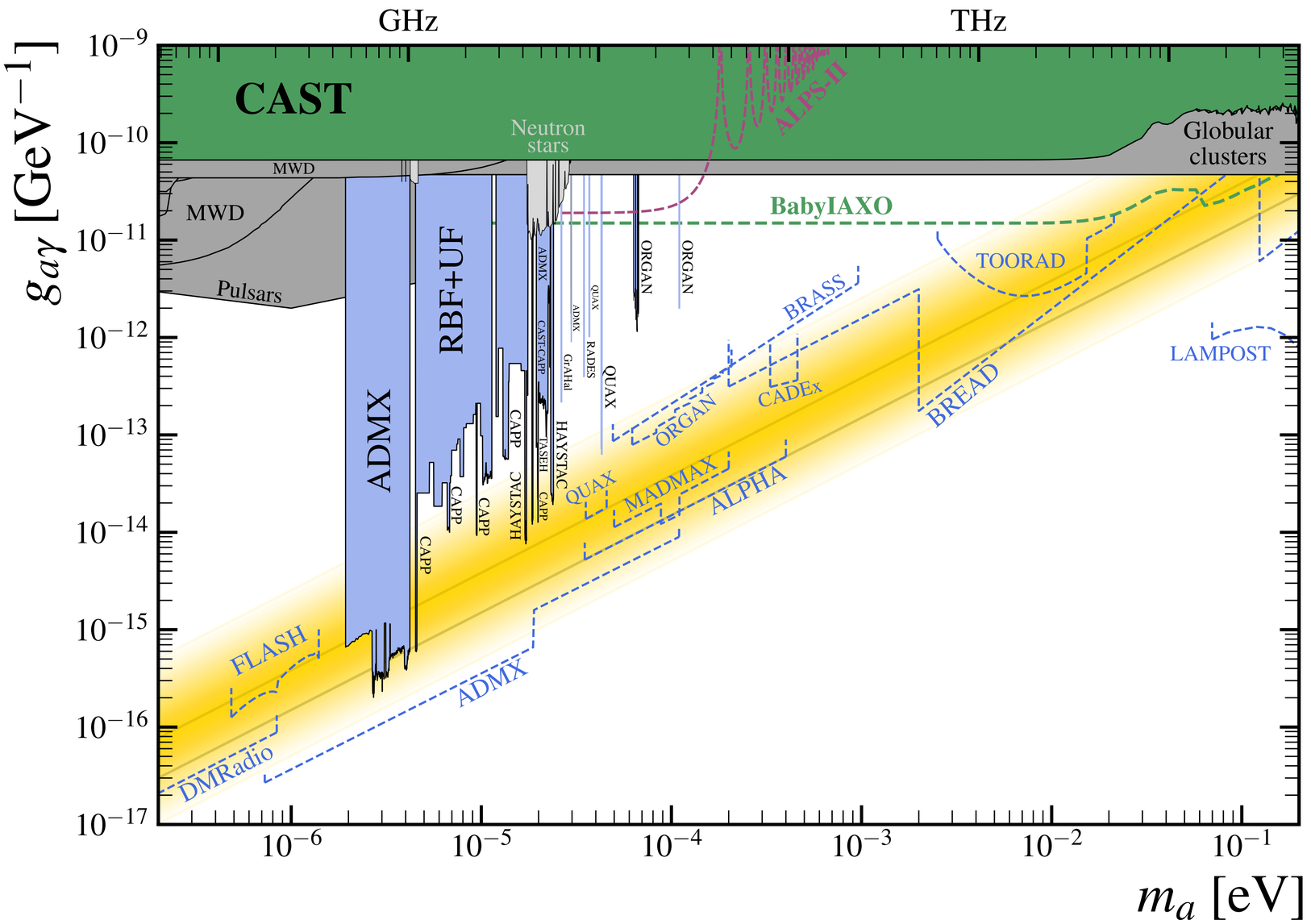
Dark matter w/ minimal model-dependence
(e.g. haloscopes)

Dark matter w/ moderate model-dependence
(e.g. cosmological dark matter bounds)



Experimental projections

→ No one knows how to interpret projected limits.
→ Assumptions aside, it becomes especially unclear when projections are displayed together on the same plot.
→ Most people (I think) just take them to be“marking territory”
→ Not always clear to what extent frequency range covered is based on existing/realistic technology.
→ Should projections be scaled to a common set of assumptions, or shown true to original publication?



The plots so far have been a community effort thanks to many helpful comments I've received over the last few years.

Please email me for requests/changes/updates etc.

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