Axion physics and experiments

Pre-SUSY 2021 Summer School, August 2021

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Lecture plan

- This two-part lecture is intended to provide a gentle introduction to axion physics, for senior graduate students and postdocs who are new to the topic

- On the theory side we will cover:

  1. Theoretical motivations for the axion
  2. Properties of axions
  3. Cosmological aspects of axion physics

- On the experimental side we will cover:

  4. Direct detection mechanisms
  5. Astrophysical and cosmological signatures
  6. Current experimental status

- Some personal introduction:
    - PhD King's College London, 2015
    - Postdoc at the ITP-CAS, Beijing, then Peking University
    - Junior faculty at Beijing University of Technology 2019, teaching in the BDIC with University College Dublin
    - My research is mostly into axion physics, dark matter and related topics

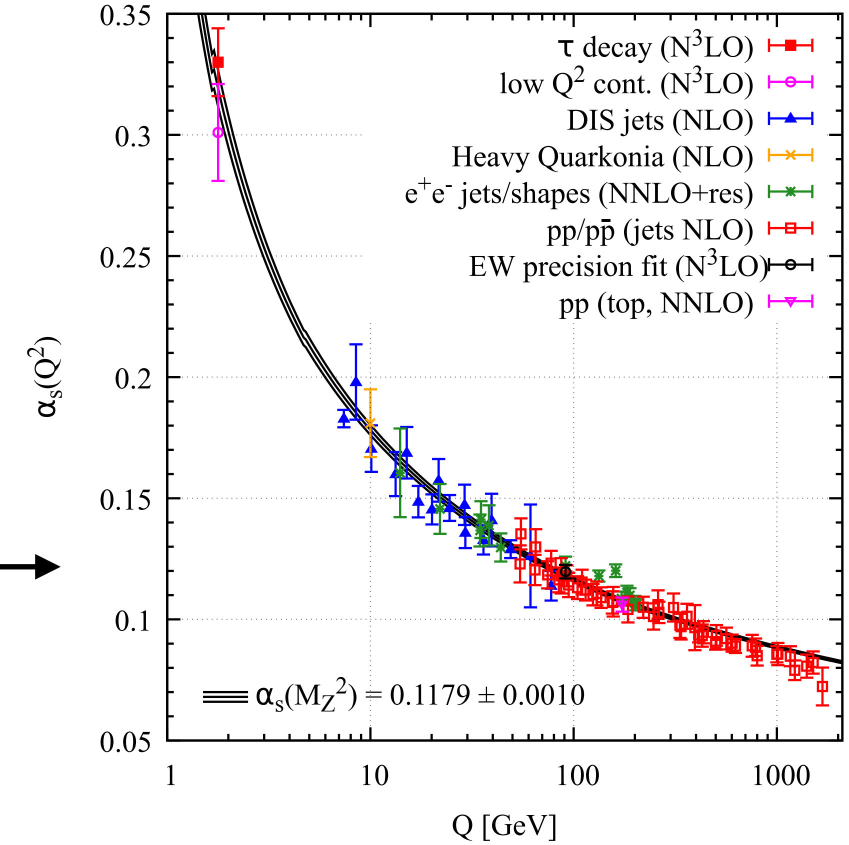
Axion theory

Why axions?

- QCD is a very successful and elegant theory:

$$\mathscr{L} = -\frac{1}{4}F^i_{\mu\nu}F^{\mu\nu i} - \sum_f \bar{q}_f\left(iD_\mu\gamma^\mu - m\right)q_f$$

- With only a few parameters we can find excellent agreement between theory and experiment →



- However, we there is another Lagrangian term we can't avoid

$$\mathscr{L}_{\bar{\theta}} = -\bar{\theta}\frac{\alpha_S}{8\pi}G^i_{\mu\nu}\tilde{G}^{\mu\nu i}, \quad \tilde{G}^{\mu\nu i} \equiv \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}G^i_{\alpha\beta}$$

- Although $G^i_{\mu\nu}\tilde{G}^{\mu\nu i}$ is a total derivative it has non-zero effect in the presence of topologically non-trivial field (e.g. instanton) configurations. We can think of it as the 'topological charge density'

- As it violates CP symmetry this term contributes to the neutron electron dipole moment d_n. Since experimentally d_n is unobserved, we know that $|\bar{\theta}| \lesssim 10^{-10}$. Why does $\bar{\theta}$ appear to be so unnaturally small?

$$d_n = \frac{g_{\pi NN}}{4\pi}\left(\frac{e}{m_p f_\pi}\right) \times \ln\left(\frac{m_\rho}{m_\pi}\right)\left(\frac{m_u m_d}{m_u + m_d}\right)\bar{\theta} \simeq 10^{-15}\,\bar{\theta}\,e\,\mathrm{cm}$$

- This is the so-called **Strong CP problem**

Figure courtesy of QCD PDG

The Peccei-Quinn mechanism

- In QCD the vacuum energy is minimised when $\bar{\theta} = 0$. So, if $\bar{\theta}$ can be replaced by a field then it should dynamically relax to zero, solving the Strong CP problem!

- To enable this, we require a field $a(x)$ with a shift symmetry $a \to a + 2\pi f$, which is **anomalous** under QCD due to instanton contributions

    - A symmetry is anomalous if it is violated in the full quantum theory, but present in the $\hbar \to 0$ (classical) limit

- In the low energy Lagrangian, expect all possible terms compatible with the symmetries of the theory

- This now includes terms proportional to the (anomalous) divergence of the corresponding Noether current: $\partial_\mu J_5^\mu \sim \frac{\alpha_S}{8\pi} G^i_{\mu\nu} \tilde{G}^{\mu\nu i}$

$$\mathscr{L} = \frac{1}{2}(\partial_\mu a)^2 - \left(\bar{\theta} - \frac{a}{f}\right) \frac{\alpha_S}{8\pi} G^i_{\mu\nu} \tilde{G}^{\mu\nu i} + \ldots$$

- The axion field will dynamically cancel $\bar{\theta}$ as required!

"CP Conservation in the Presence of Instantons" R. Peccei and H. Quinn, PRL. 38 (1977) 1440.

The Peccei-Quinn mechanism

- To engineer this, we add an axial ‘Peccei-Quinn’ symmetry, which is spontaneously broken around some high energy scale f

- The axion is the (pseudo) Nambu-Goldstone boson associated to this symmetry, which gives the desired shift symmetry, and an interaction Lagrangian

$$\mathscr{L} = f^{-1} J^{\mu}_{PQ} \partial_\mu a = \sum_i \frac{C_i}{f} \left(\overline{\psi}_i \gamma_\mu \gamma^5 \psi_i \right) \partial_\mu a$$

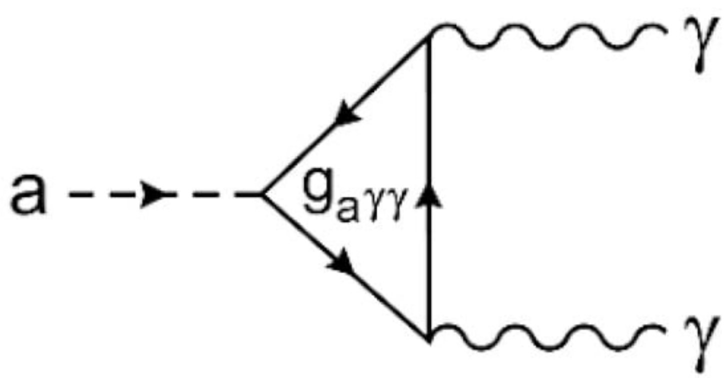
  - Only a ‘true’ NG boson is massless, however the axion can still be naturally light, since the symmetry is approximate. From chiral perturbation theory we can calculate:

$$V(a) \simeq m_u \Lambda^3_{QCD} \left(1 - \cos\left(\frac{a}{f}\right)\right), \quad m_a \simeq 6\,\mu\mathrm{eV} \left(\frac{10^{12}\,\mathrm{GeV}}{f} \right)$$

- Many specific models exist: 'DFSZ' and ‘KSVZ’ are common benchmarks. For low energy physics they mainly differ in their specific charge assignments, which enter into C_i, and the anomaly coefficients E and N

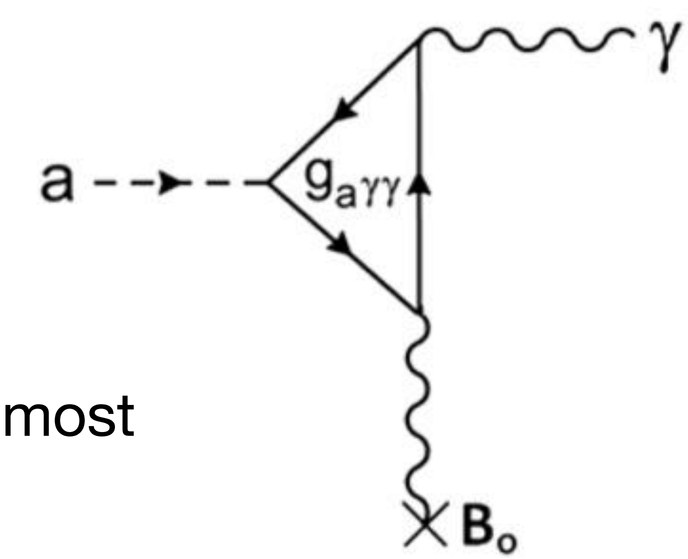
Primakoff conversion

- From couplings to SM fermions, an effective coupling to EM is induced:



$$\longrightarrow \quad \mathscr{L} = -\frac{1}{4} G_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = G_{a\gamma\gamma} a \, \overrightarrow{E} \cdot \overrightarrow{B}$$

$$G_{a\gamma\gamma} = \frac{\alpha}{2\pi f} \left(\frac{E}{N} - 1.92 \right)$$



- This interaction leads to the **Primakoff effect:** probably the most important mechanism for axion discovery

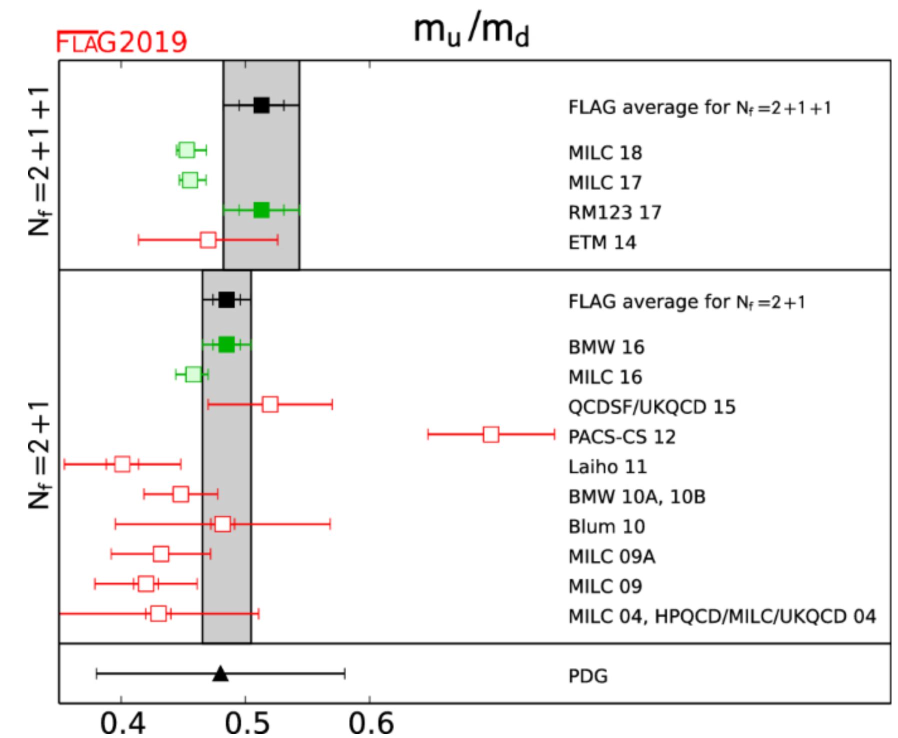
- Why? Generally we’re pretty good at detecting/creating photons, also magnetic fields are pretty abundant in the universe, and can be easily made in the laboratory

- Decays to 2 photons are also possible: $\Gamma_{a \to \gamma\gamma} = \dfrac{G_{a\gamma\gamma}^2 m_a^3}{64\pi}$

Are there other solutions to the strong CP problem?

- If the lightest quark is massless, then $\bar{\theta}$ is unobservable. Actually, we only require $|m_u/\Lambda_{QCD}| \lesssim 10^{-10}$ at Λ_{SM}

- Nonetheless, not compatible with lattice gauge theory



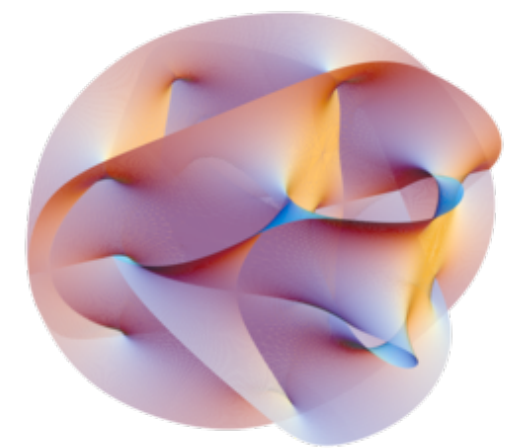
- Could CP be fundamentally exact?
  In this scenario the 'bare' value of $\bar{\theta}$ is zero, and spontaneous breaking generates the observed EW CP

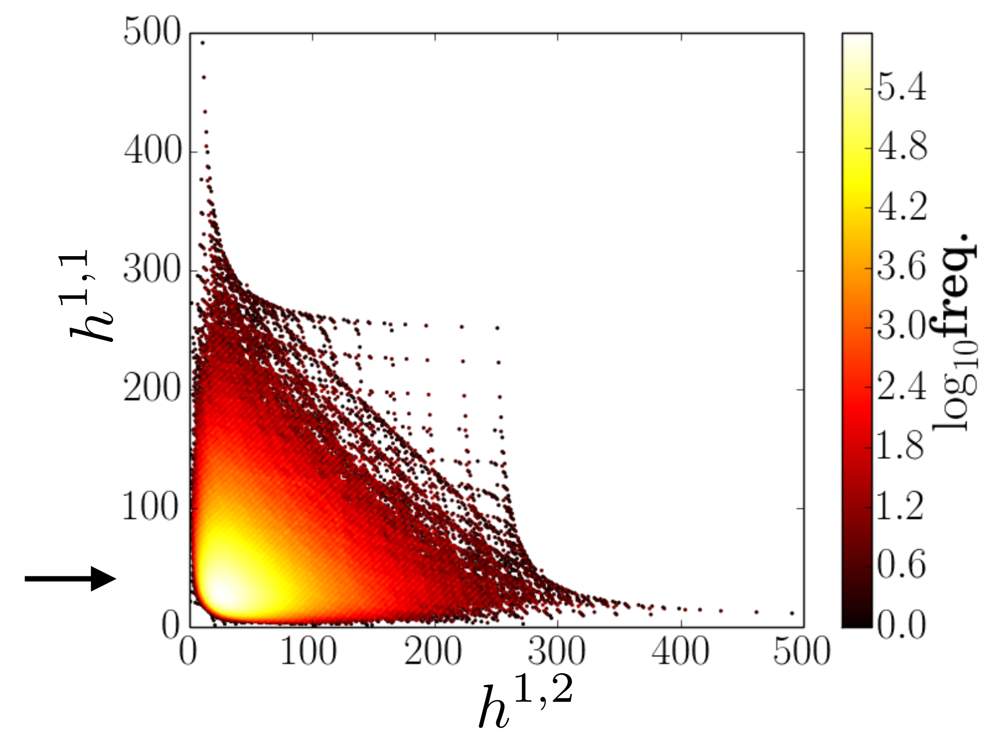
- Barr-Nelson models give a concrete realisation of this, but seem to require more tuning than the original Strong CP problem. Supersymmetry or new strong dynamics would help, but they have yet to be found…

E. Nelson "Naturally Weak CP Violation", S. M. Barr "Solving the Strong CP Problem without the Peccei-Quinn Symmetry" PRL 1984
Figure courtesy of FLAG working group

String compactifications

- In fact, the strong CP problem is a compelling motivation for axions, but it's not the only one
- String theory requires extra dimensions which must be compactified. Typically, for appropriate phenomenology (some unbroken SUSY and chiral matter), this manifold should be Calabi-Yau (more details in Prof. Antoniadis' lectures)
- When we compactify, the Kaluza–Klein (KK) zero modes of antisymmetric tensor fields generically give low-energy fields with axion-like properties
- Studies of known Calabi-Yau manifolds suggest large numbers of such axions are typical ($\mathcal{O}(30)$?)
- This scenario is known as the **'String Axiverse'**





"String axiverse" A. Arvanitaki *et al*, PRD 2010, 0905.4720

Figure courtesy of 'Axion Cosmology', D. J. E. Marsh, 1510.07633, using data from Kreuzer-Skarke, math/0001106

Terminology: ALPs

- In general, axions which solve the strong CP problem are 'QCD axions'
- Axions which may or may not solve the strong CP problem are 'Axion Like Particles', although generally people use 'axion' flexibly to refer to both QCD axions and ALPs
- **Take-home point: QCD axions are well-described by just a single quantity, since m_a and f are related:** $m_a \simeq 6\,\mu\mathrm{eV}\left(10^{12}\,\mathrm{GeV}/f\right)$
- **More general (ALPs) are well-described by just two quantities, since the energy scale of their couplings is set by f**
- Exceptions exist (e.g. photophobic, leptophilic ALPs), but they are rare
- This is a great advantage for theorists and experimentalists working with axions: the parameter space is low-dimensional

Axions/ALPs as a topic in theoretical physics

``CP Conservation in the Presence of Instantons,'' R. Peccei and H. Quinn, PRL 38 (1977) 1440.

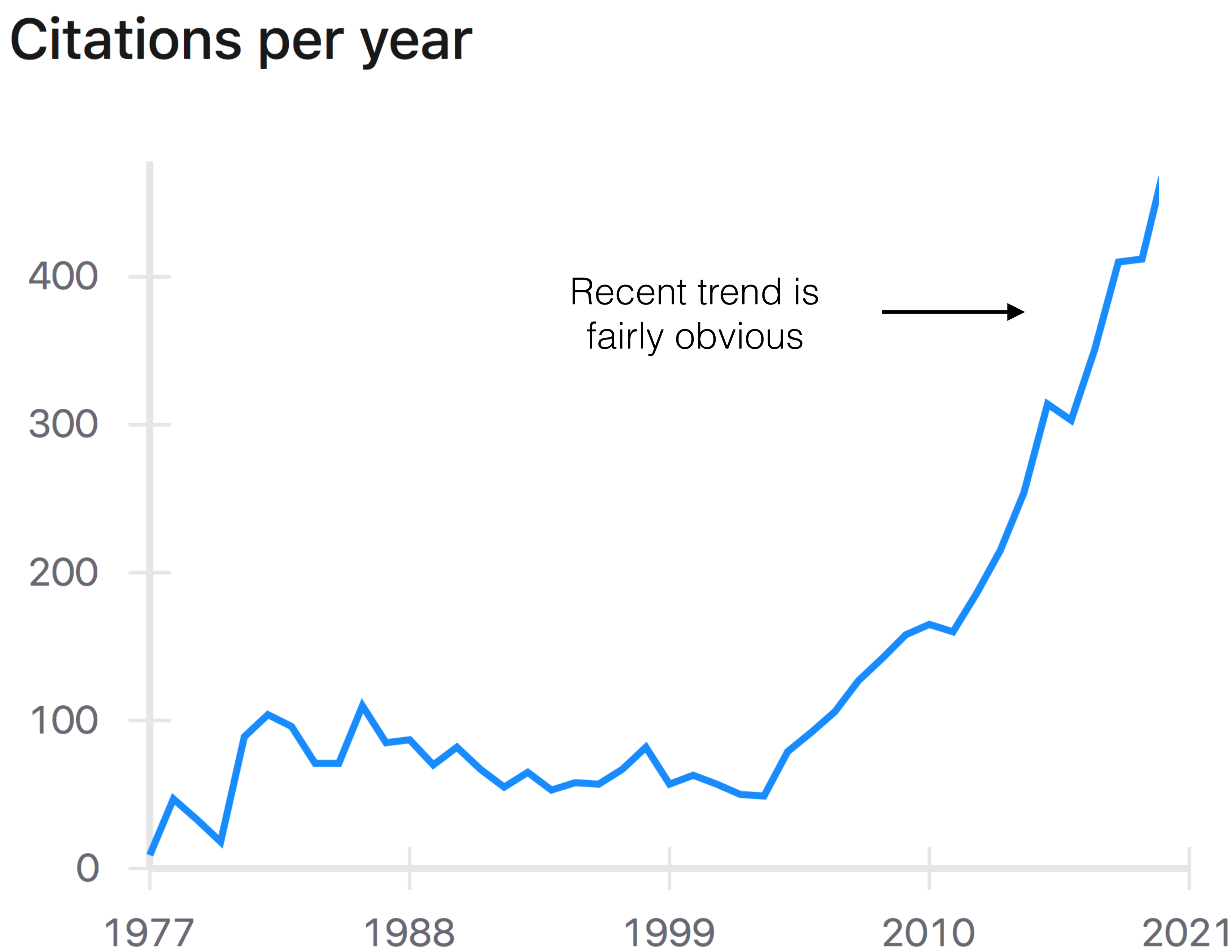


Figure courtesy of Inspire

Axion cosmology

- Not long after the first axion papers, people realised that this wonderful new particle could be dangerous….

THE NOT-SO-HARMLESS AXION

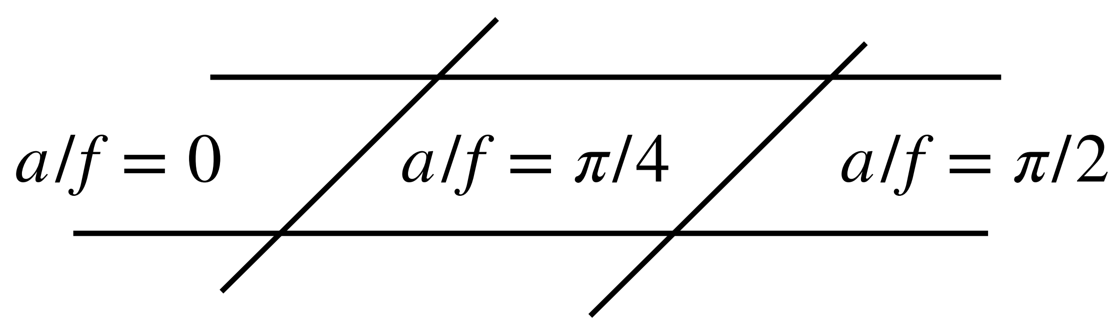
Michael DINE
The Institute for Advanced Study, Princeton, NJ 08540, USA

and

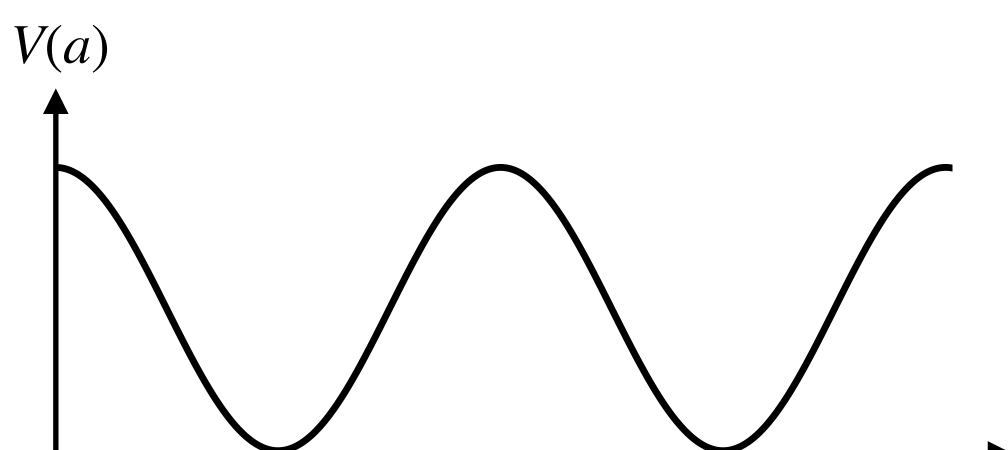
Willy FISCHLER
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

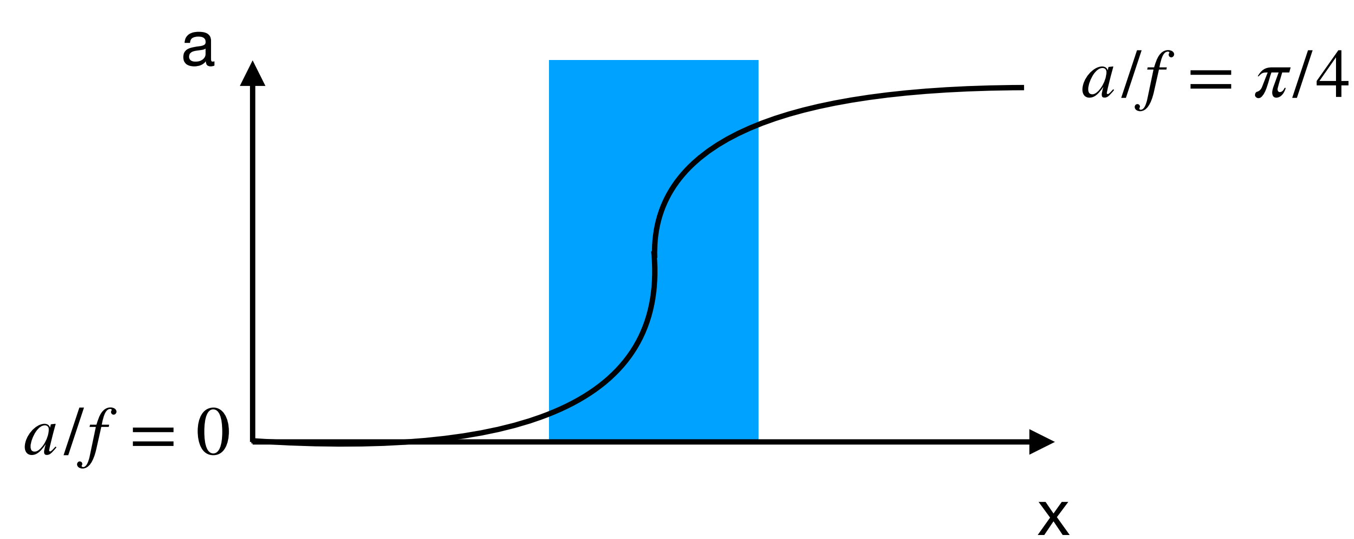
Received 17 September 1982

- When the PQ symmetry breaking phase transition occurs in the early universe, causality dictates that the field value in each Hubble patch is independent



- In models (like DFSZ) that have multiple degenerate vacua, this creates domain walls and cosmic strings:

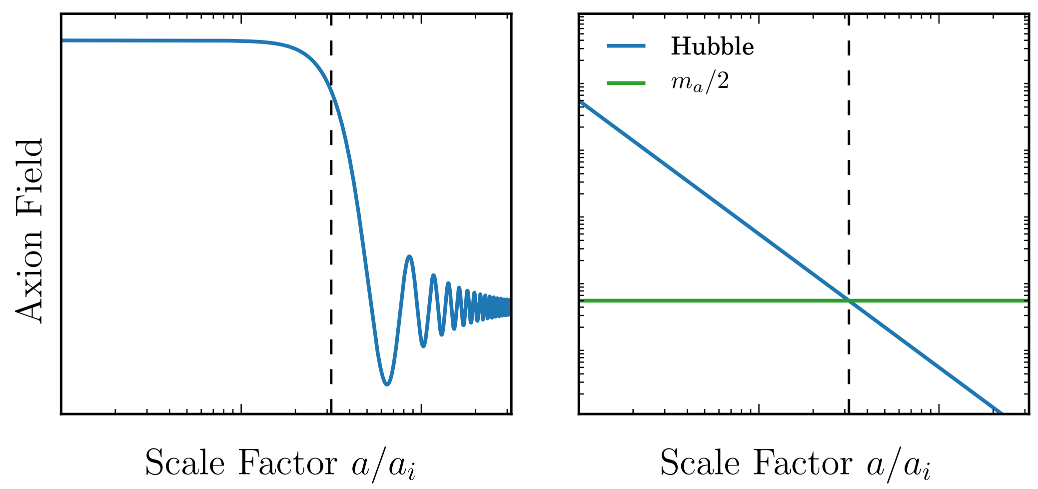




Axion cosmology

- We can use inflation to get rid of domain walls/cosmic strings, or possibly enable them to decay, but a more serious issue remains

- In an FRW Universe, our equation of motion is $\ddot{a} + 3H\dot{a} + m_a^2 a = 0$. When $H >> m_a$ the field is overdamped, and so a is fixed. However, once the Universe expands sufficiently that $H \simeq m_a$, the field will begin to roll

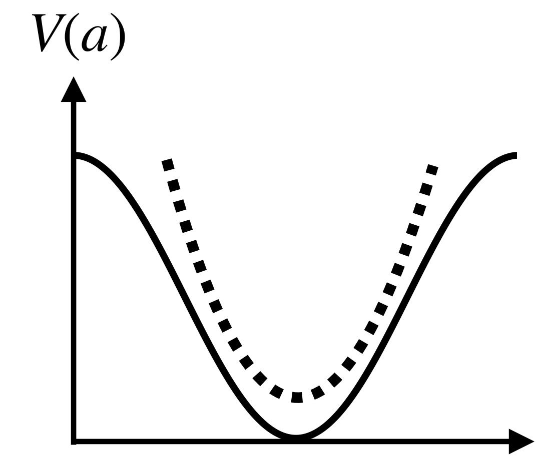


- An overdamped (pseudo)scalar field gives a constant energy density: a cosmological constant! This can be quite useful, if we wish to explain dark energy, or inflation (See the inflation lecture on Friday, next week's String Inflation plenary)

- But what about an oscillating field?

Figure courtesy of 'Axion Cosmology', D. J. E. Marsh, 1510.07633

The misalignment mechanism



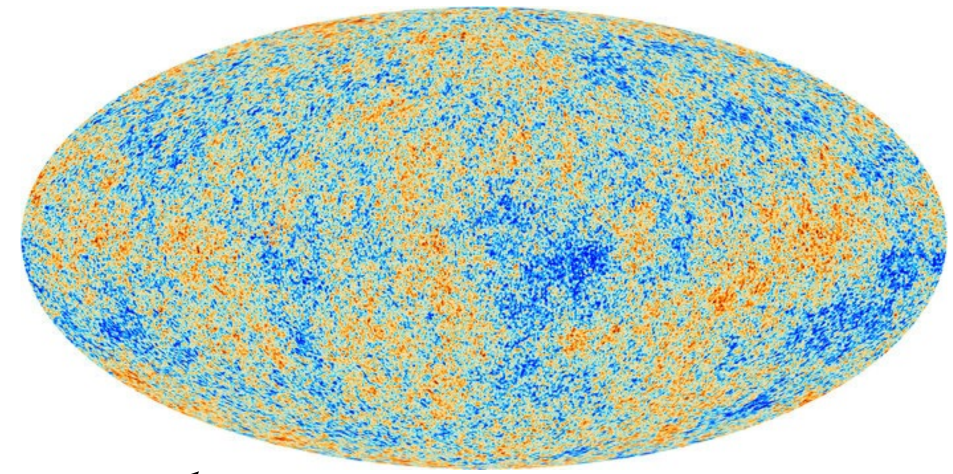
- Once the axion begins to oscillate, $\phi \simeq \phi_0 \cos(m_a t + \varphi)$
- Inserting into the EOM gives $\phi_0 \propto a^{-3/2}$, and so $\rho_a \propto |\phi_0|^2 \propto a^{-3}$
- At the top of the potential we have (the equation of state parameter) $\omega_a = -1$ (dark energy), at the bottom $\omega_a = 1$ (free scalar field). Therefore $\langle \omega_a \rangle = 0$
- **This like just like ordinary non-relativistic matter: the coherent oscillations of the axion field function as a natural cold dark matter candidate**
- The energy density in the misalignment population is fixed by the initial field displacement and the mass alone. For QCD axions, with an initial misalignment angle $\theta_{a,i}$ we have an approximate relic density:

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}} \right)^{7/6} \langle \theta_{a,i}^2 \rangle$$

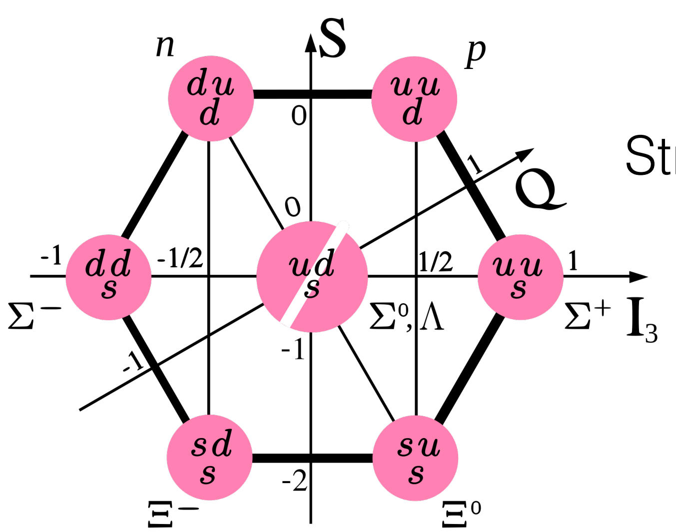
- Of course, we should realise that with large numbers of axions we may overproduce dark matter in this way, for example in the string axiverse scenario. We can reduce the dark matter abundance via axion decays, but then their decays products may unacceptably modify the thermal history of our Universe
- This is known as the **cosmological moduli problem**

Theory summary: Axions are light (sub-eV) pseudo-Goldstone bosons, characterised broadly by just their mass and decay constant

They arise both as a minimal extension of the Standard Model, to solve the Strong CP problem, whilst also being a generic prediction of the exotic physics of string and M theory

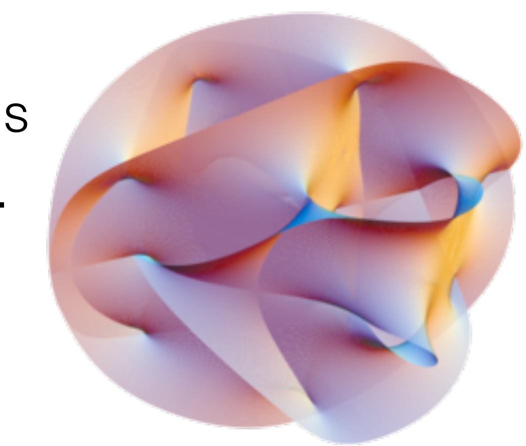


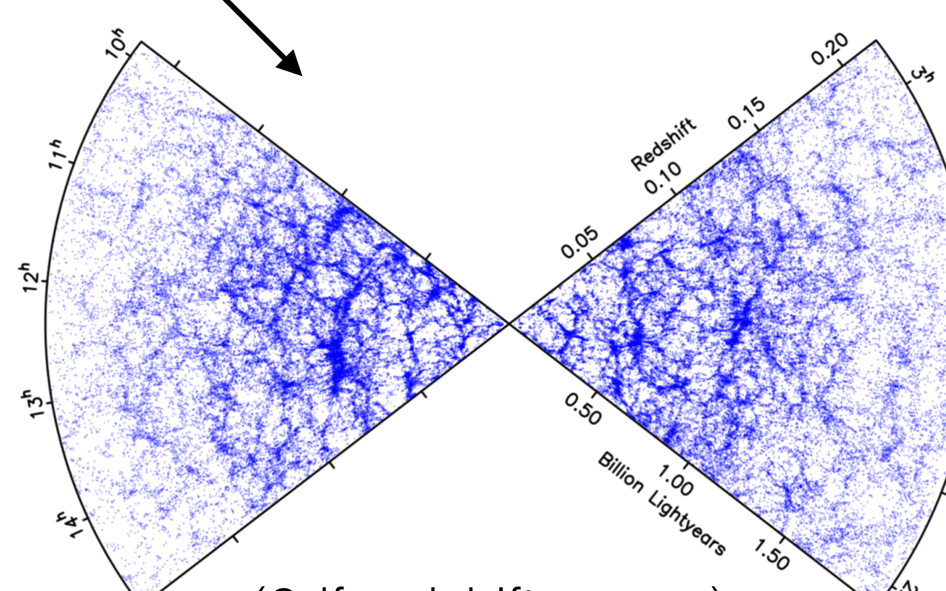
(Planck 2015)



Strong CP problem

Compactifications



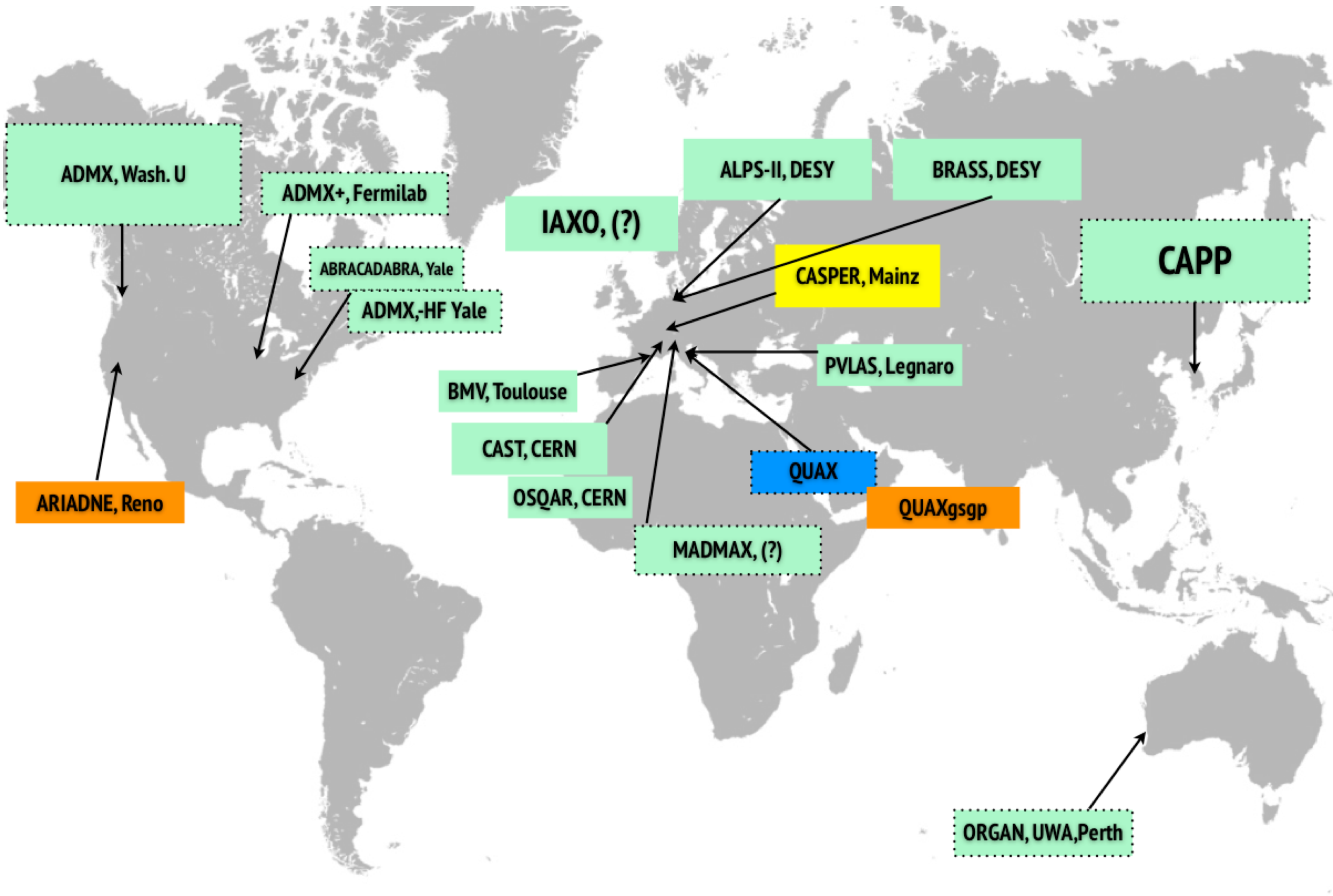


(2df redshift survey)

Axion experiments and observations

- As we have already seen
  - Axions can convert directly to photons via the Primakoff effect
  - They are naturally light, and provide a good candidate for dark matter
  - Axions which solve the Strong CP problem should also couple to Standard Model particles in a predictable way
- This leads to a lot of observational constraints and possible detection mechanisms
- Indeed, much of the present-day research into axions is about exploring new methods to detect these elusive particles
- This is well summarised in “New experimental approaches in the search for axion-like particles” by I. Irastorza and J. Redondo, arxiv:1801.08127

Experiments are both planned and ongoing worldwide to discover the axion



(Figure courtesy of W. Bonivento, apologies to any experiments not shown!)

- We can't discuss every possible experiment, but we can identify a few general principles.

- For a general counting experiment with N_s signal and N_b background events, the statistical significance of some excess is (assuming background domination):

$$S = 2\left(\sqrt{N_s + N_b} - \sqrt{N_b}\right) \simeq N_s/\sqrt{N_b}$$

- How to increase $N_S \sim$ (Axion flux)×(Detector area)×(Observation time)×(Interaction probability) ?

  - Choose a good source of axions

  - Bigger 'exposure': more observing time with a bigger detector

  - Increase the interaction probability: $\Gamma_{i \to f} = \frac{2\pi}{\hbar} \left| \langle f \,|\, H' \,|\, i \rangle \right|^2 \rho(E_f)$

Matrix element ($\langle f \,|\, H' \,|\, i \rangle$)

Density of states ($\rho(E_f)$)

- How to decrease N_b?

  - Reduce intrinsic noise (decrease detector noise temperature)

  - Increase shielding to sources of background (cosmic rays, radioactive decays etc)

What is the current experimental status of the axion?

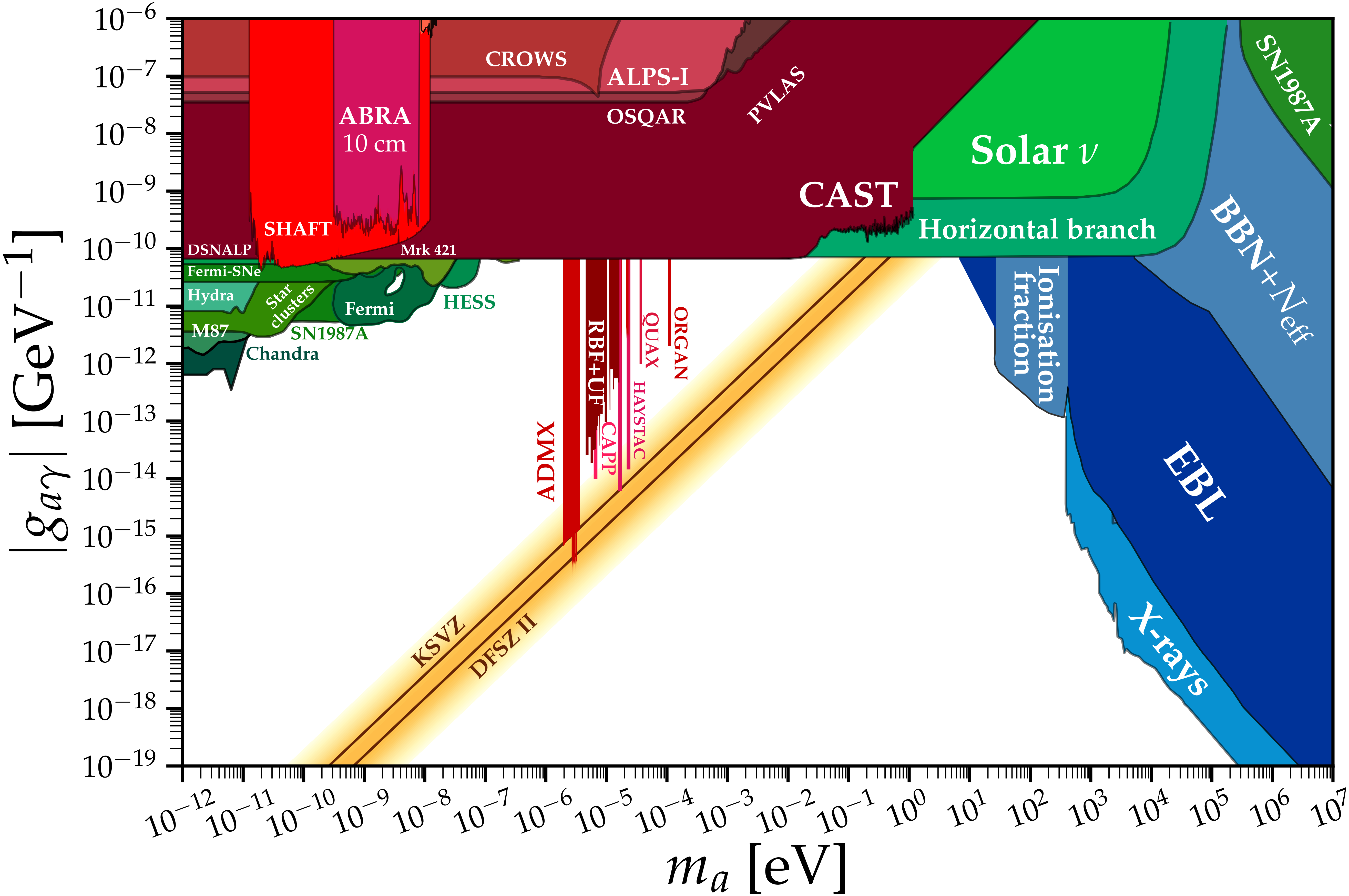
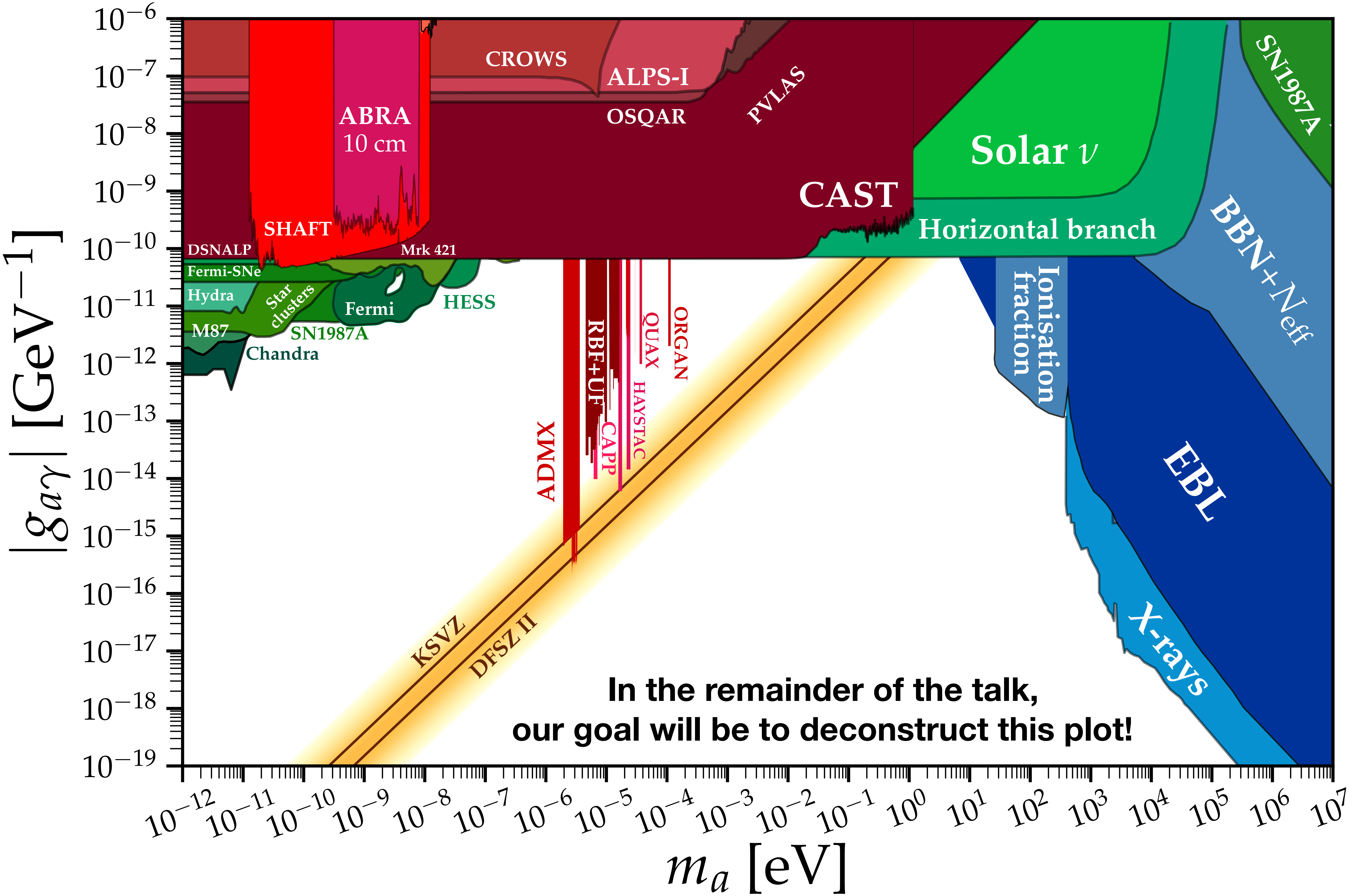
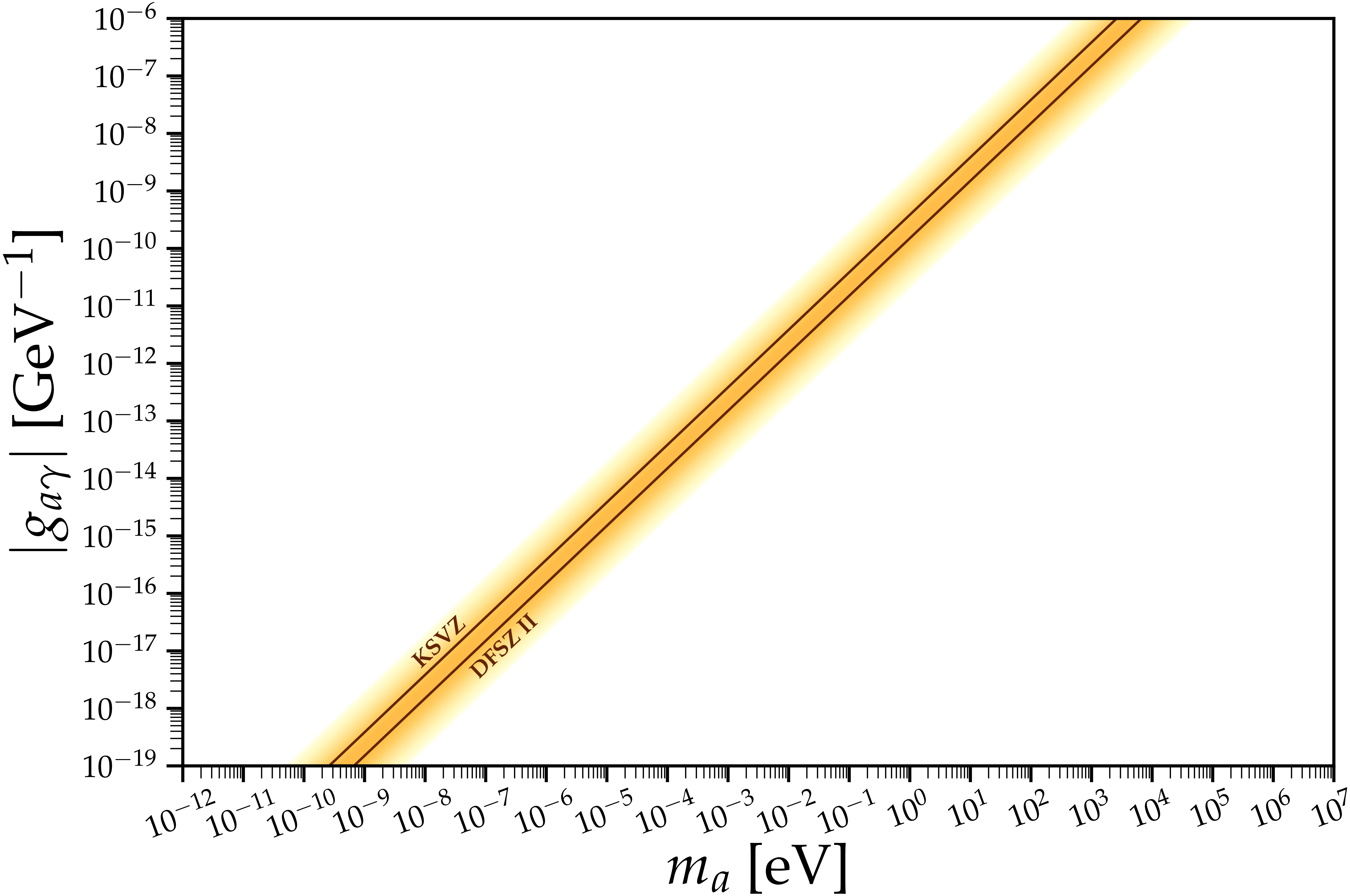


Figure is courtesy of C. O'Hare's excellent AxionLimits code (doi.org/10.5281/zenodo.3932430)



In the remainder of the talk, our goal will be to deconstruct this plot!

Figure is courtesy of C. O'Hare's excellent AxionLimits code (doi.org/10.5281/zenodo.3932430)



KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
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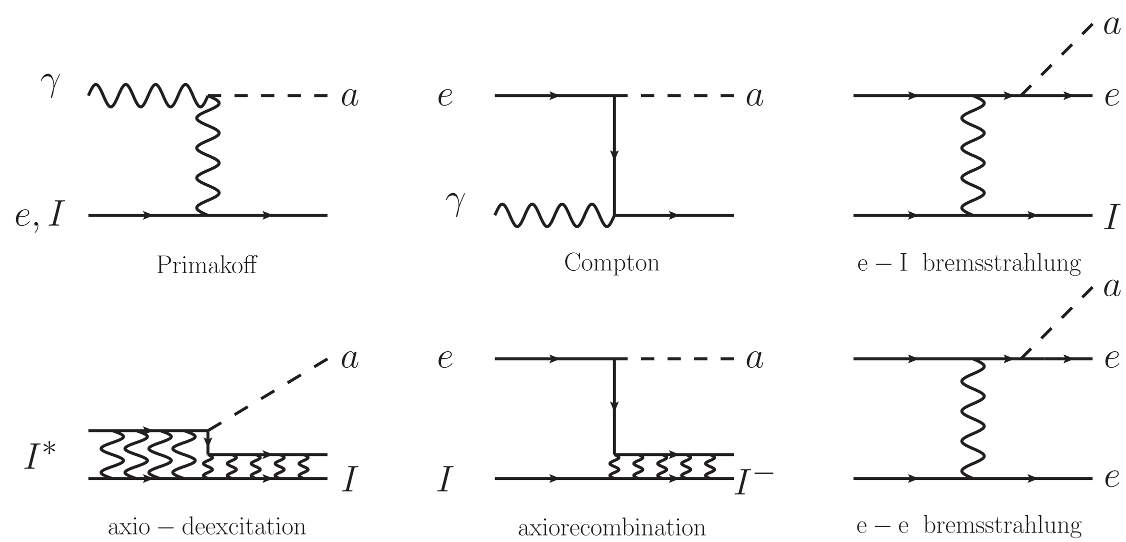
Helioscope searches

- Our sun is expected to be a good source of axions, via a variety of channels



- This leads to a characteristic flux at Earth (left is Primakoff only, right is from couplings to electrons)

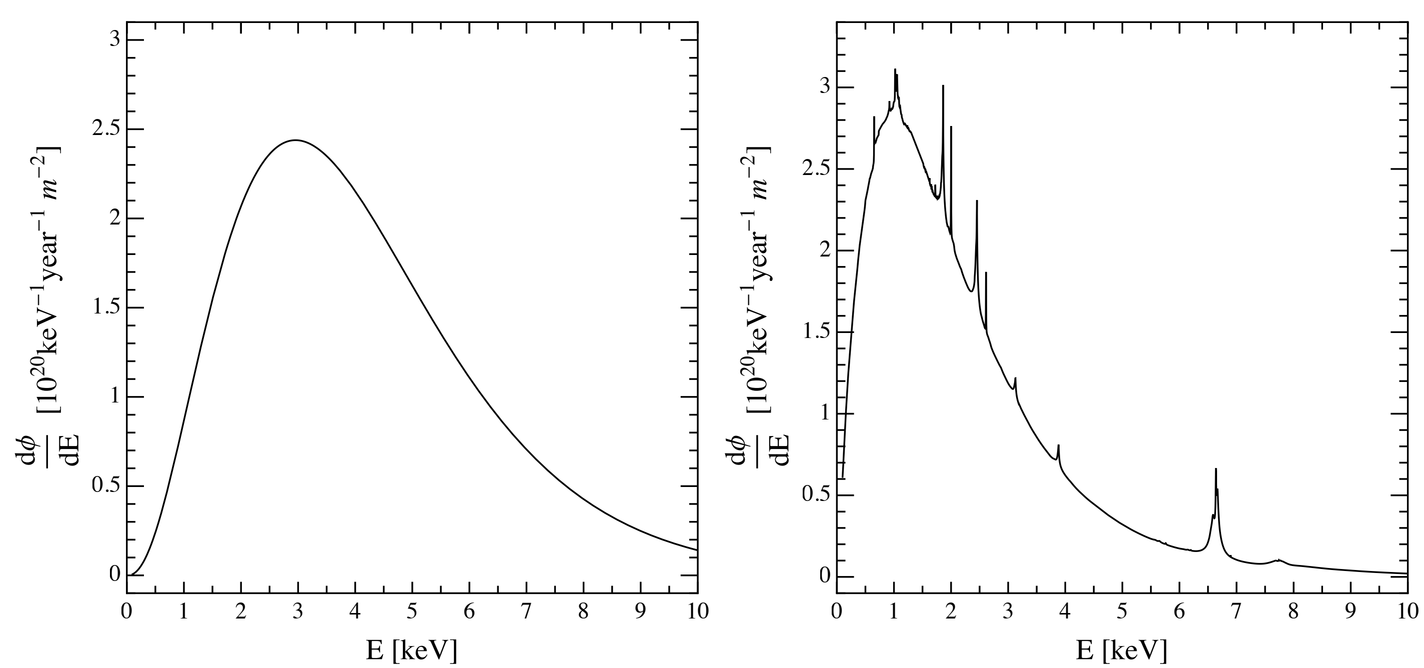


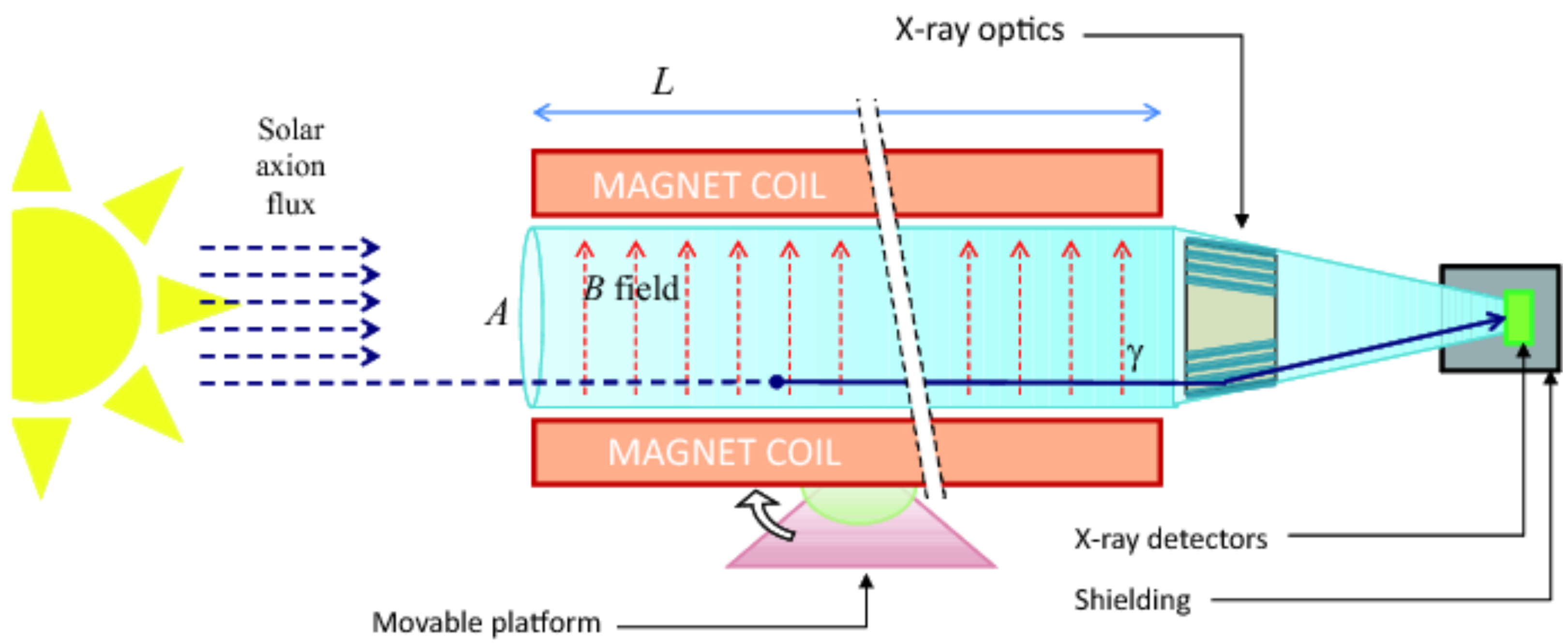
Figure taken from Irastorza *et al.*, "The International Axion Observatory IAXO. Letter of Intent…"

Helioscope searches

- Integrating over energy leads to a characteristic (Primakoff) flux at Earth

$$\phi_a \simeq 10^{11}\left(\frac{G_{a\gamma\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 \mathrm{cm}^{-2}\mathrm{s}^{-1}, \quad (\phi_{\mathrm{solar}\,\nu} \simeq 10^{11}\mathrm{cm}^{-2}\mathrm{s}^{-1})$$

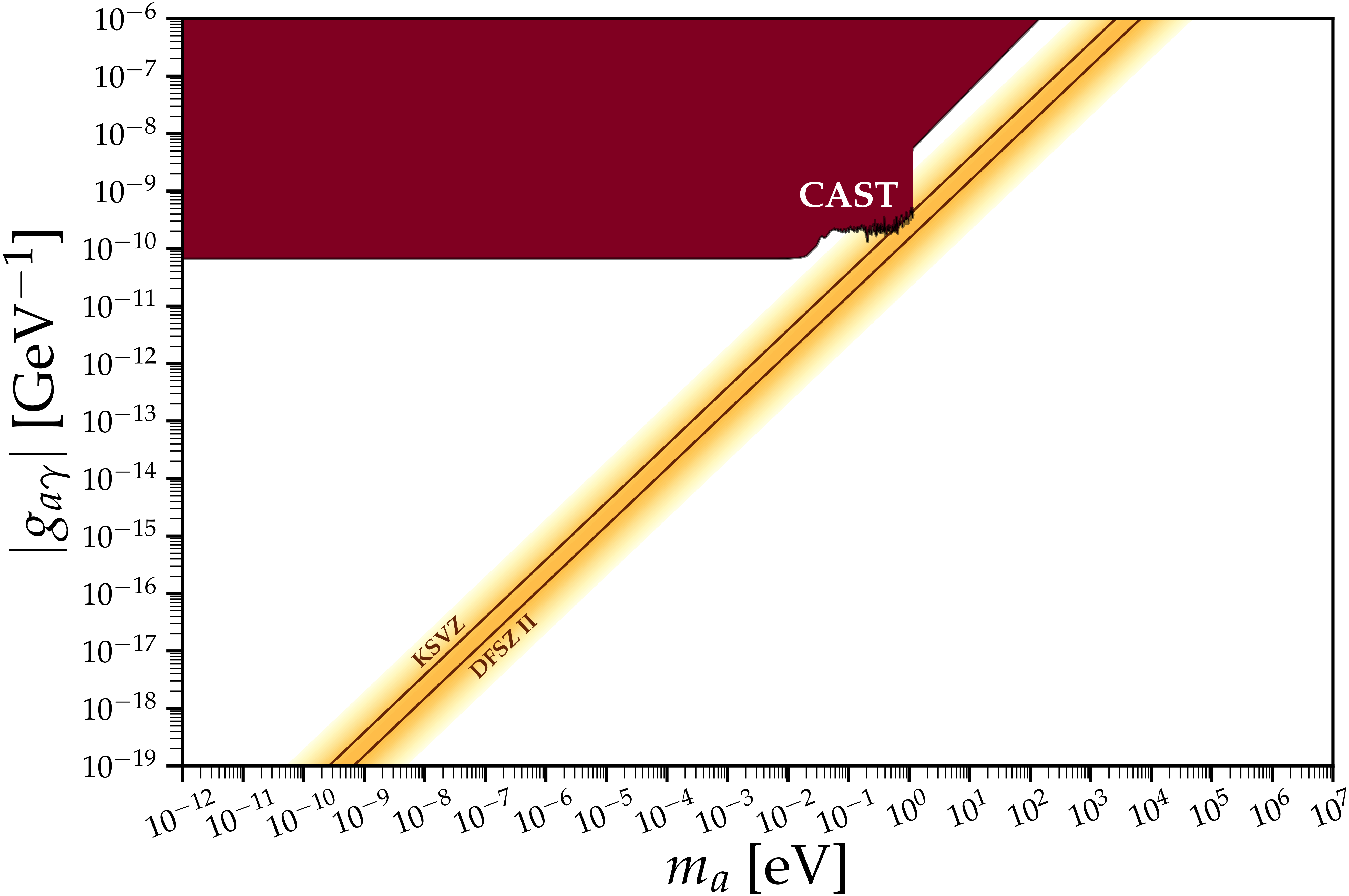
- Helioscope experiments (such as CAST, SUMICO and the planned IAXO) use the Primakoff effect to convert these axions back into x-ray photons



$$P_{a\to\gamma} = \left(g_{a\gamma} B\,\frac{\sin(qL/2)}{q}\right)^2$$

$q = m_a^2/2E$ is momentum transfer

Figure taken from Irastorza *et al.*, "Towards a new generation axion helioscope" arxiv:1103.5334



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KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
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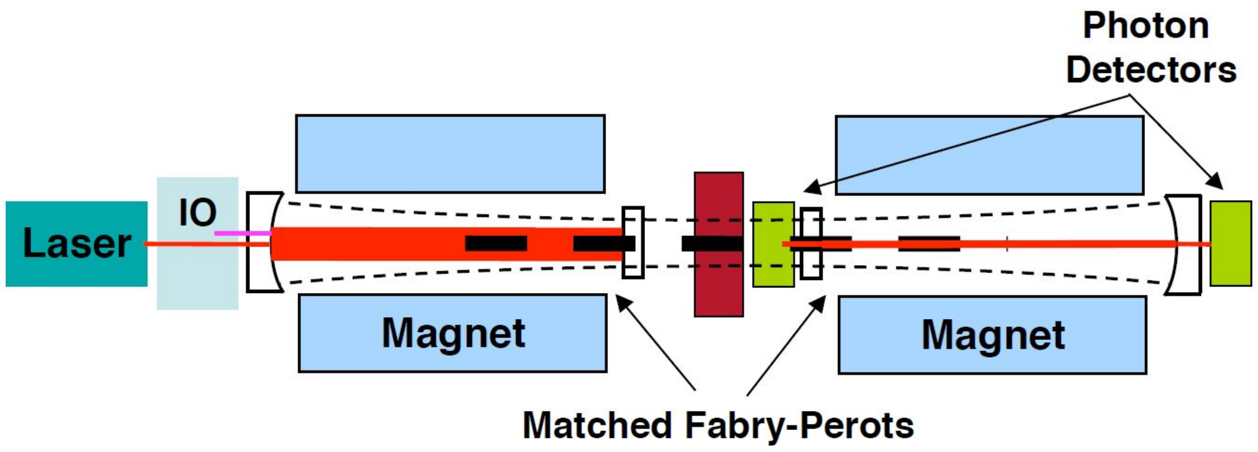
Photon regeneration

- Alternatively, we can try to create our own axions in the lab. Photon regeneration (or 'light shining through a wall') experiments like ALPS use lasers to create a beam of axions, which can pass through a solid barrier and then reconvert into photons



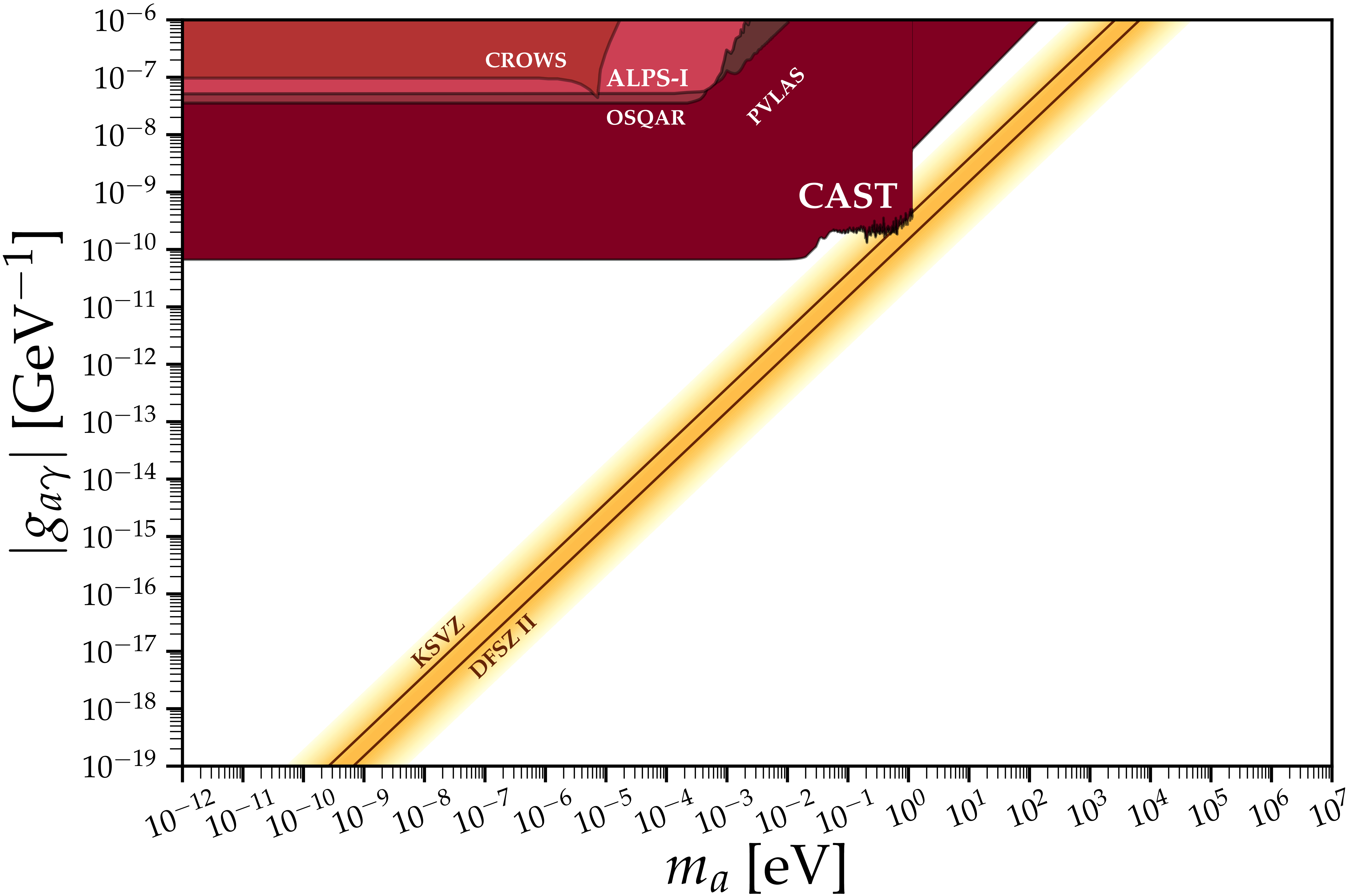
- As before, we want a large $B \times L \times t$. More laser photons also helps, since this creates more axions.

- However, the Fabry Perot cavities here are also crucial: the first increases the amount of time laser photons spend inside the magnetic field, increasing the conversion probability. What about the second? Recall the interaction probability: $\Gamma_{i \to f} = \frac{2\pi}{\hbar} \left| \langle f | H' | i \rangle \right|^2 \rho(E_f)$

- By tuning the two cavities onto resonance with each other we concentrate the density of states at exactly the energy of the emitted axions

- For optical photons this typically enhances the conversion probability by $\min(Q_1, Q_2) \sim 10{,}000$

Figure courtesy of the ALPs collaboration



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$|g_{a\gamma}|$ [GeV^{-1}]
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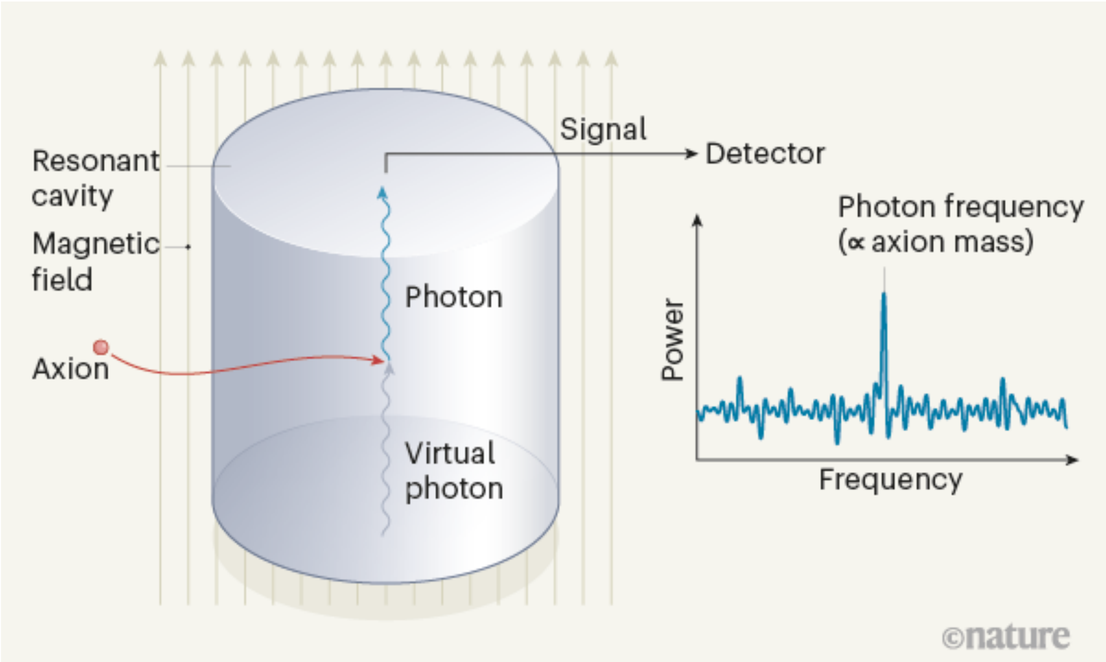
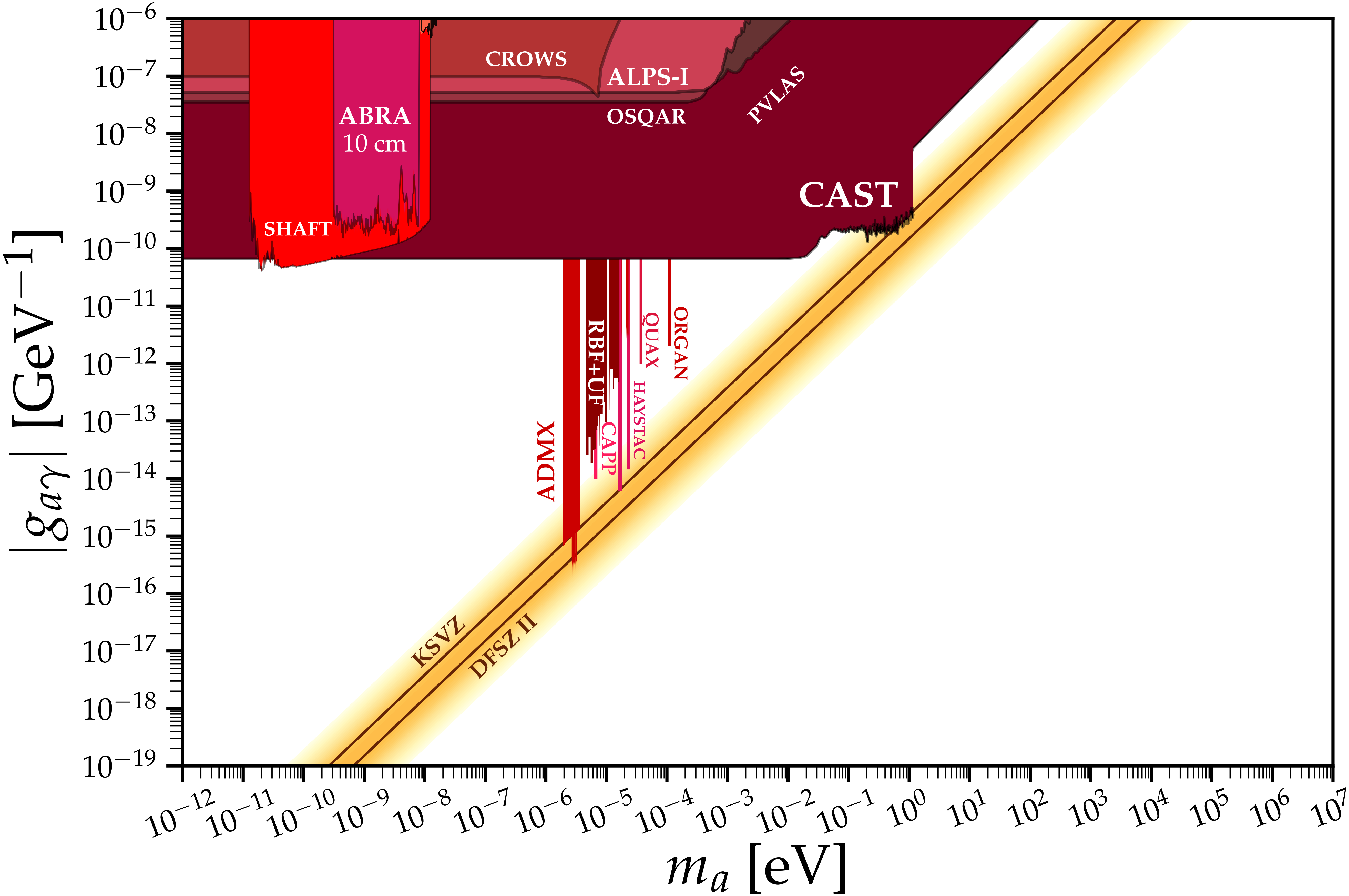
Haloscope searches

- If axions are the primary component of DM, then our galactic halo should provide an excellent laboratory source . As before, we need a large $B \times V \times t$ and sensitive photodetectors



- As DM axions are presumably cold, $\omega_a \sim m_a$, we can again enhance our sensitivity by increasing the density of states, using a resonant cavity tuned to m_a

$$P \sim \frac{1}{2} G_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a} \right) B^2 V C Q$$



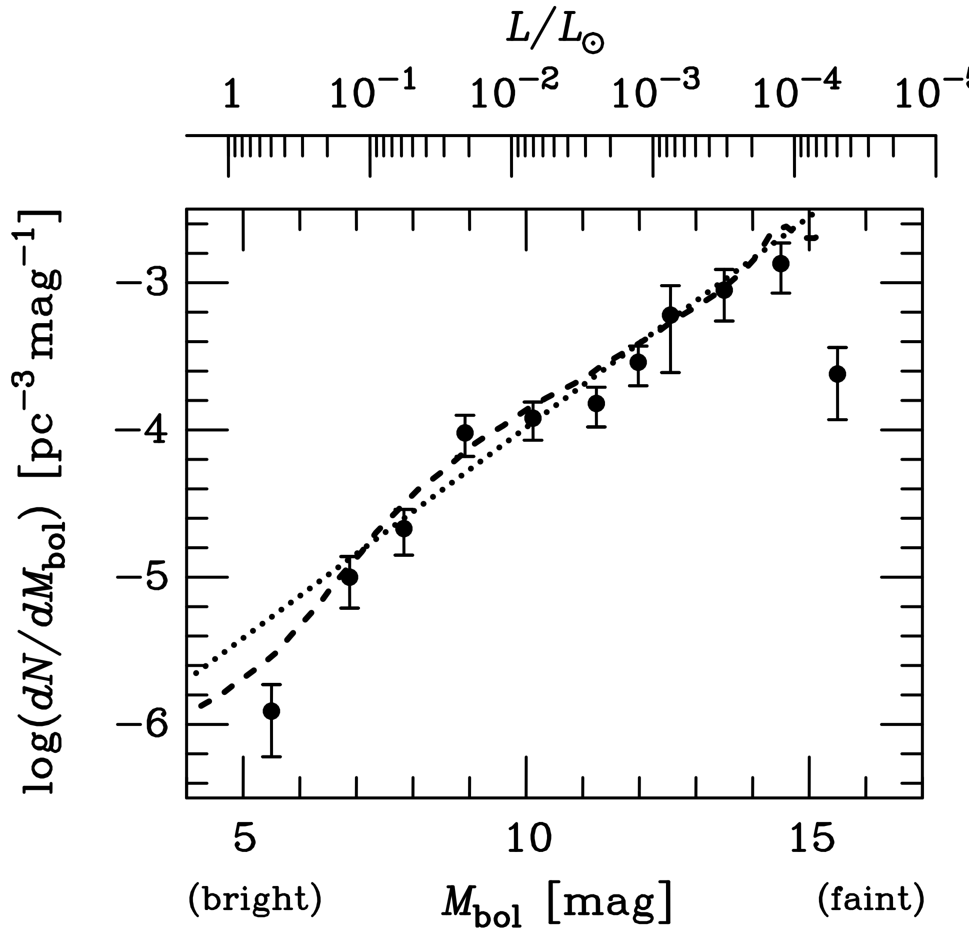
CROWS
ALPS-I
OSQAR
PVLAS
ABRA
10 cm
SHAFT
CAST
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]

Observational effect: anomalous cooling

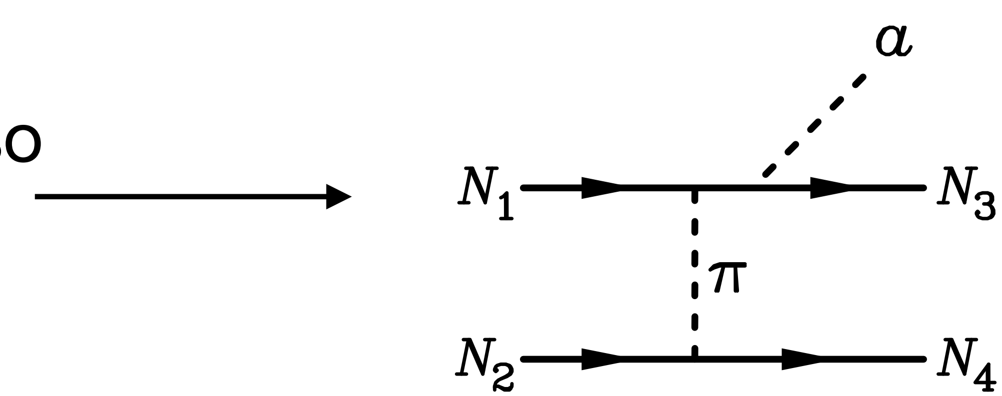
- As light, weakly coupled particles axions are expected to free-stream, carrying energy away from astrophysical objects (stars, neutron stars, white dwarfs etc)

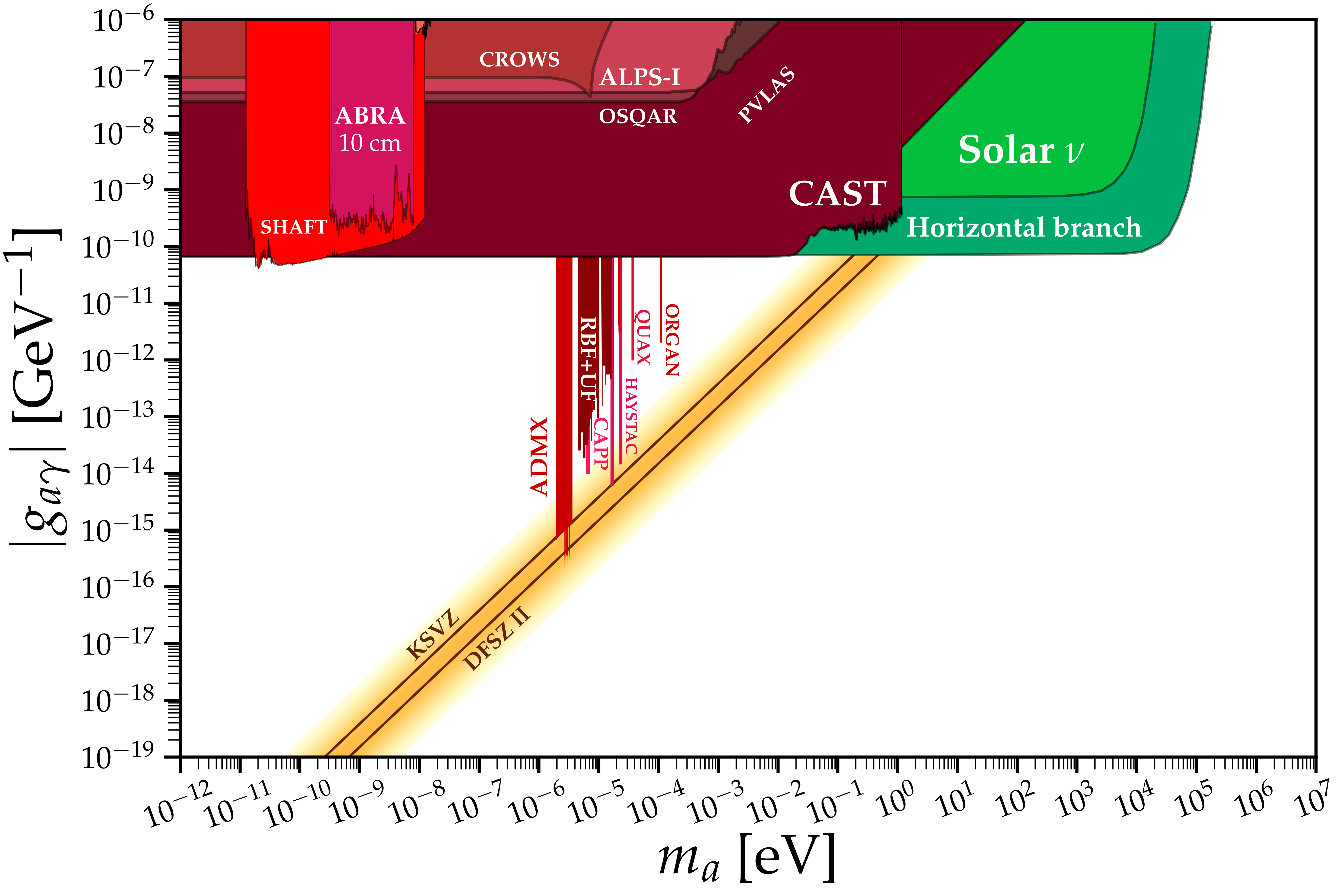
- By inferring the temperatures of populations of these objects, we can bound any anomalous energy loss

- Most famously, the duration of the SN1987A neutrino burst also provided strong constraints on axion/nucleon bremsstrahlung



Observed white dwarf luminosity function, courtesy "Stars as Laboratories for Fundamental Physics", G. Raffelt

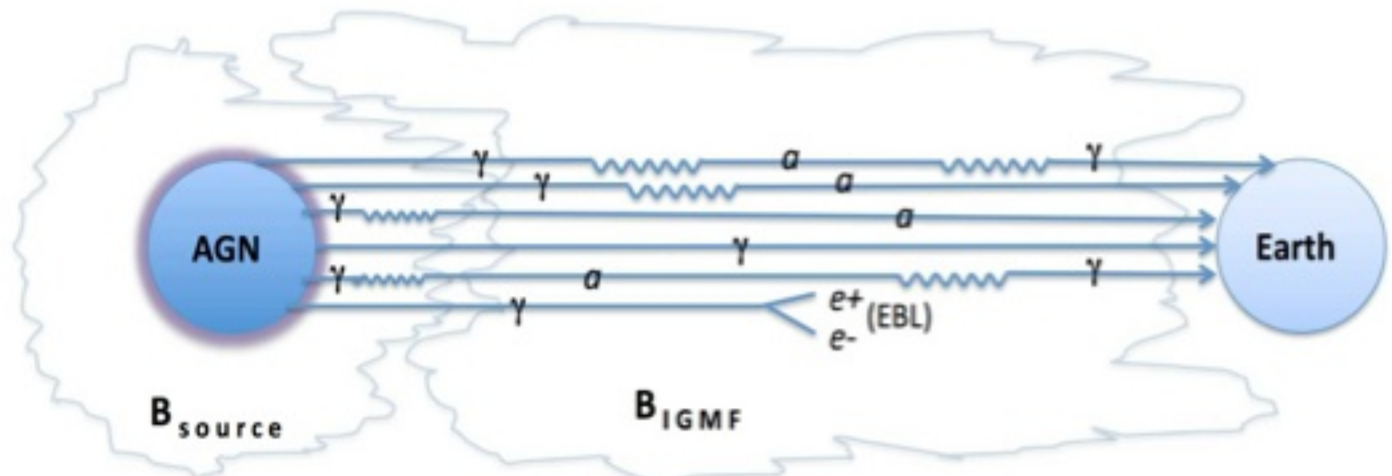




CROWS
ALPS-I
OSQAR
PVLAS
ABRA
10 cm
SHAFT
CAST
Solar ν
Horizontal branch
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]

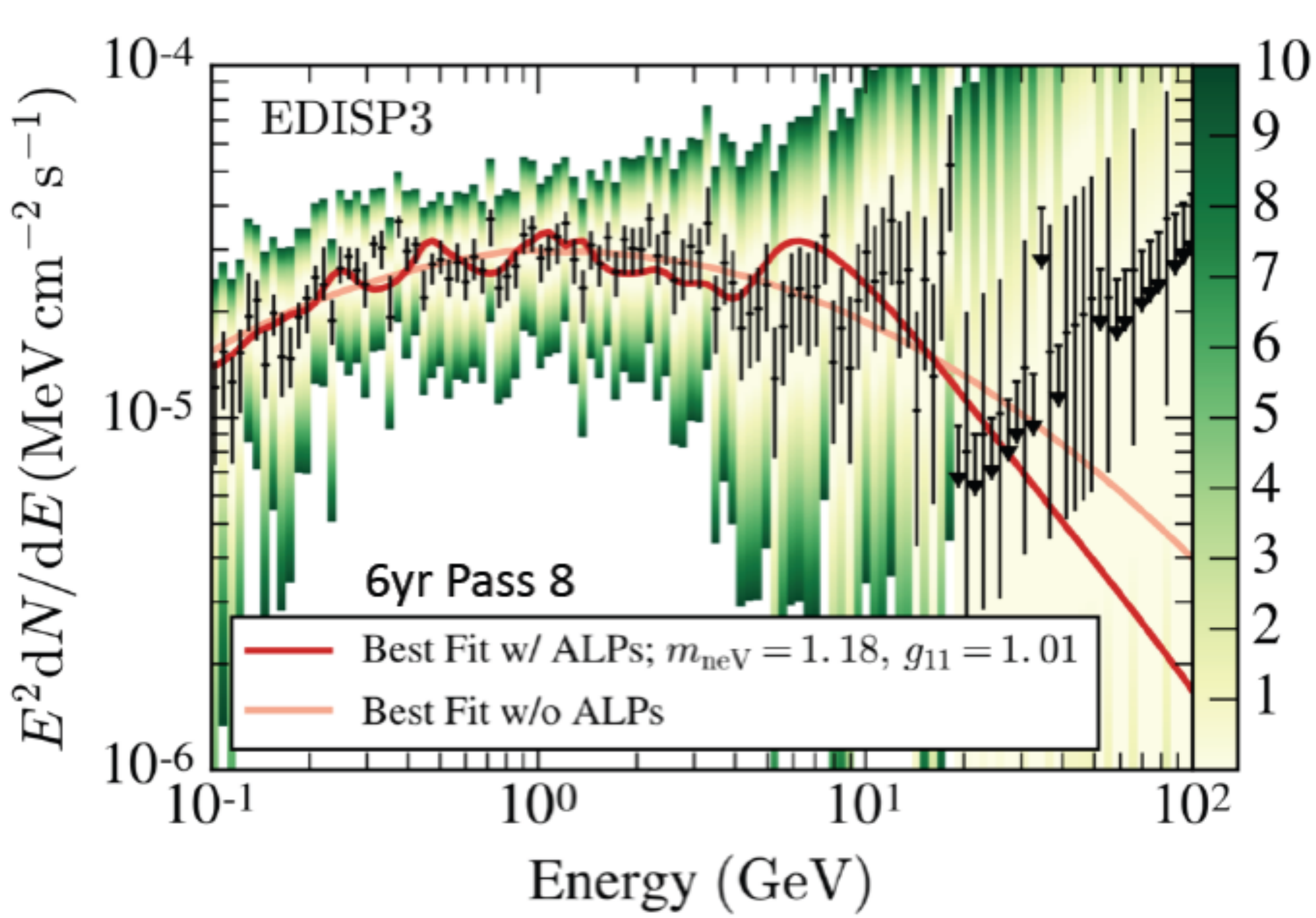
Observational effect: anomalous transparency, spectral oscillations

- Energetic photons from distant sources travel Megaparsec distances through intergalactic magnetic fields to reach Earth

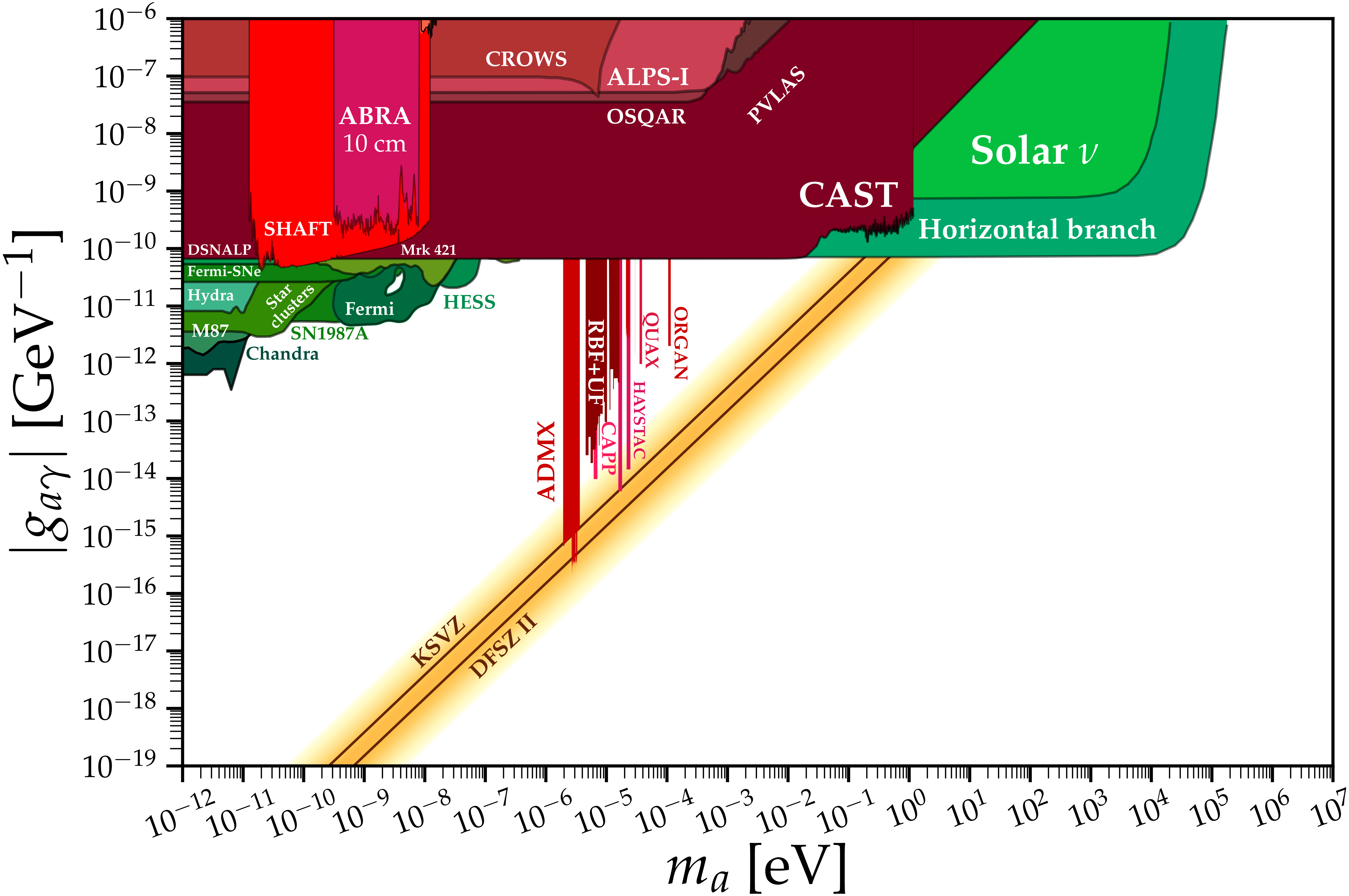


- If conversion to axions is possible, their propagation distance is enhanced

- As the conversion probability is energy-dependent this also leads to a characteristic modulation of the observed gamma and x-ray spectrum



"Constraints on axion-like particles with H.E.S.S. from observations of PKS 2155-304", P. Brun *et al*,
"Search for Spectral Irregularities due to Photon–Axionlike-Particle Oscillations with the Fermi Large Area Telescope", M. Ajello *et al*

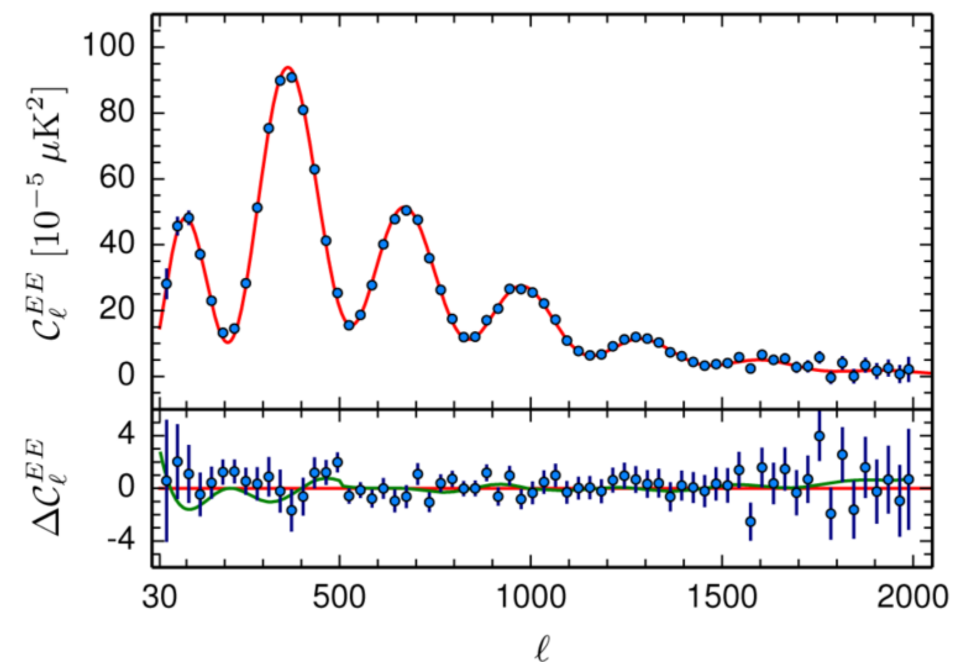

$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
OSQAR
PVLAS
ABRA
10 cm
SHAFT
CAST
Solar ν
Horizontal branch
DSNALP
Mrk 421
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
ADMX
RBF+UF
CAPP
QUAX
HAYSTAC
ORGAN
KSVZ
DFSZ II

Cosmological axion decays

- In general, our standard 6 parameter ΛCDM model does a very good job of matching to observations

- However, when heavy axions decay to 2 photons in the early Universe they can alter primordial nucleosynthesis and CMB formation simply by injecting too much energy

- For late time decays, we can directly search for this anomalous gamma or x-ray background via telescope



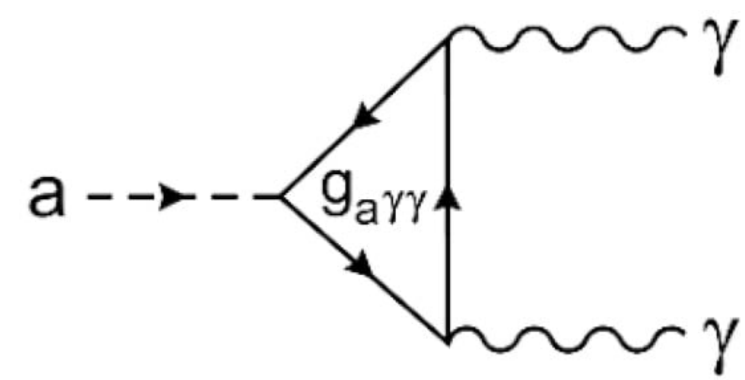
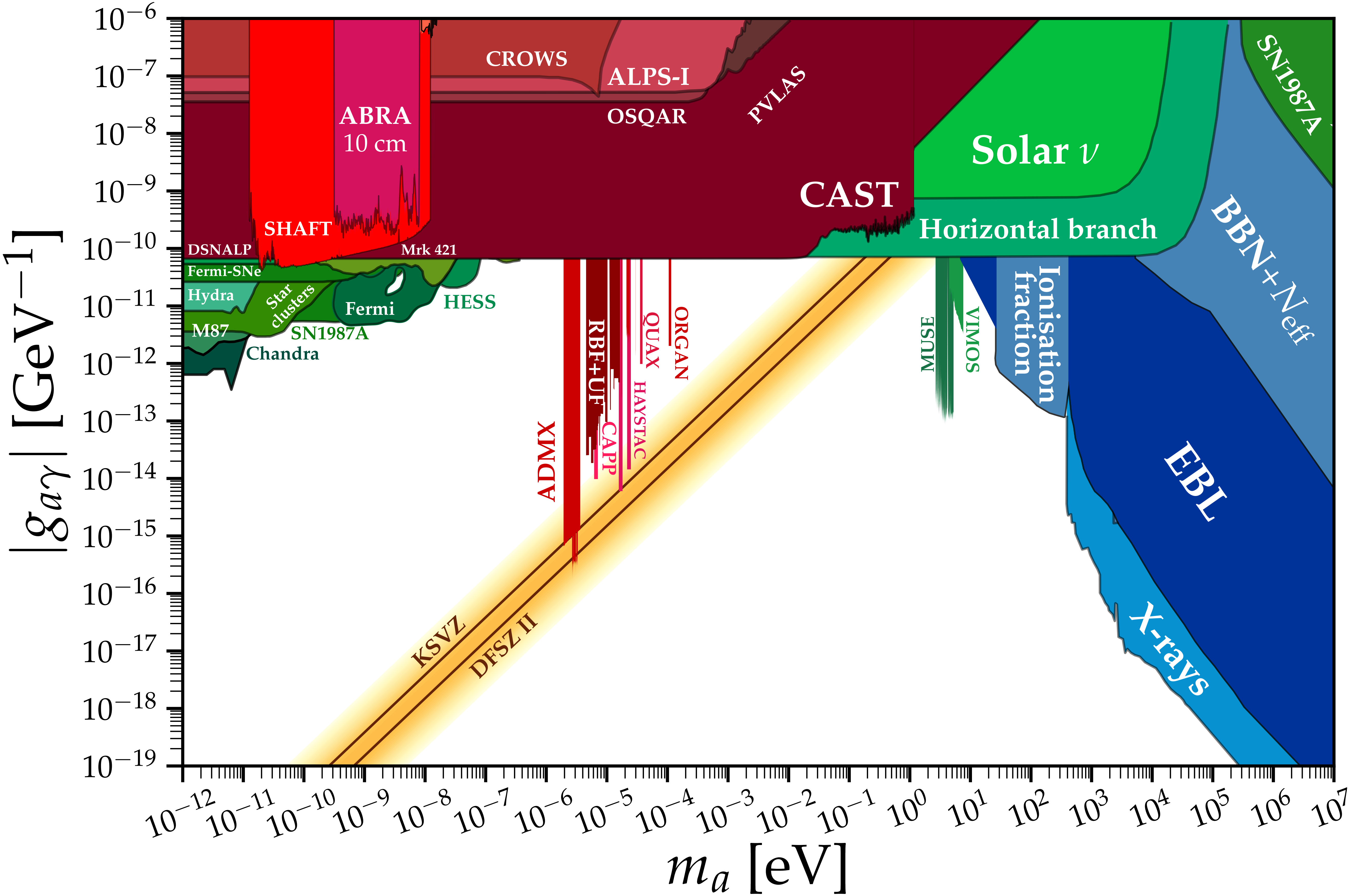


Figure taken from Planck 2015 data release



CROWS
ALPS-I
OSQAR
PVLAS
ABRA
10 cm
SHAFT
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Solar ν
Horizontal branch
SN1987A
BBN+Neff
DSNALP
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Hydra
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Fermi
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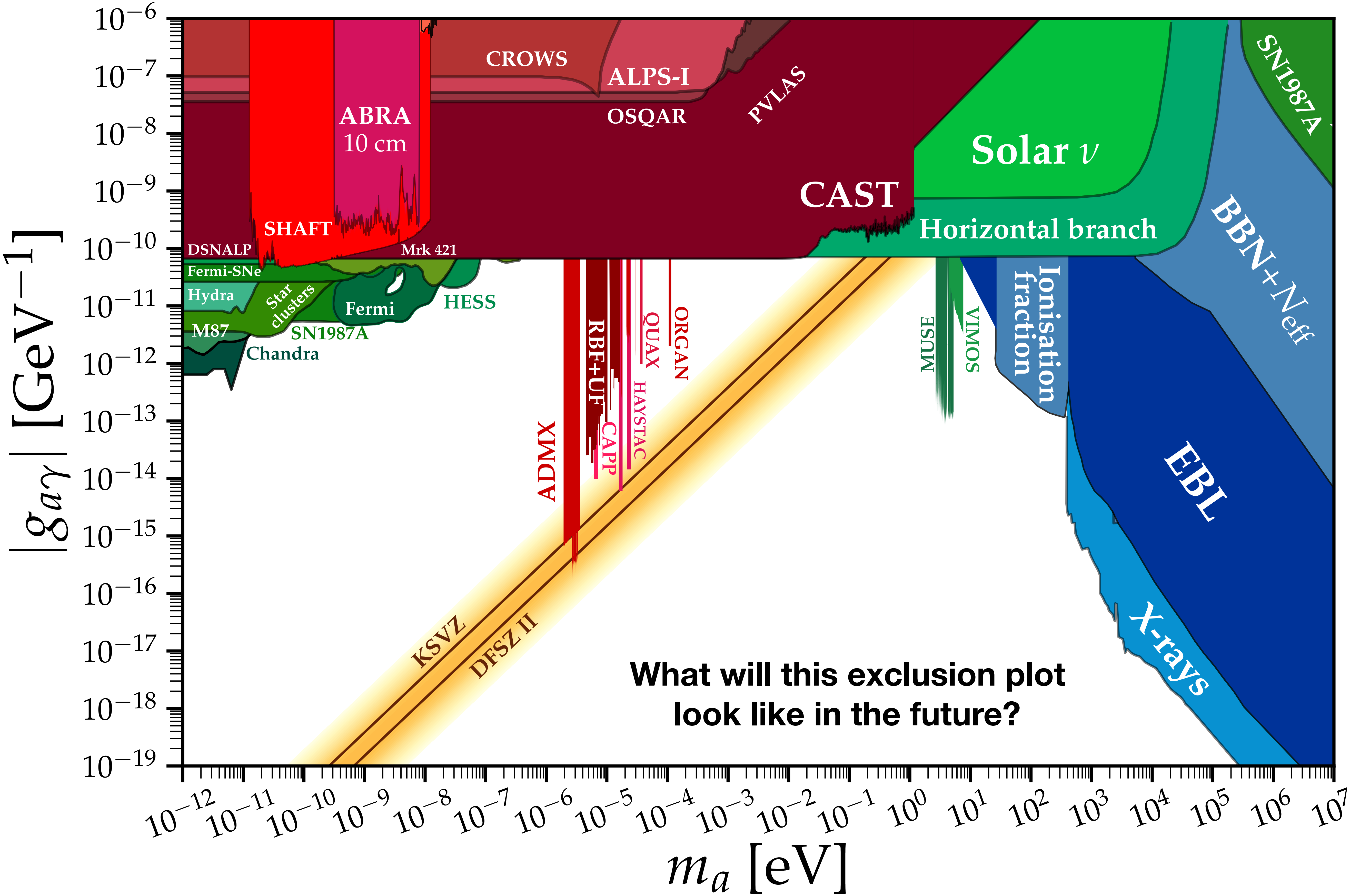
M87
SN1987A
Chandra
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
OSQAR
PVLAS
ABRA 10 cm
SHAFT
Mrk 421
CAST
Solar ν
Horizontal branch
SN1987A
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DSNALP
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
SN1987A
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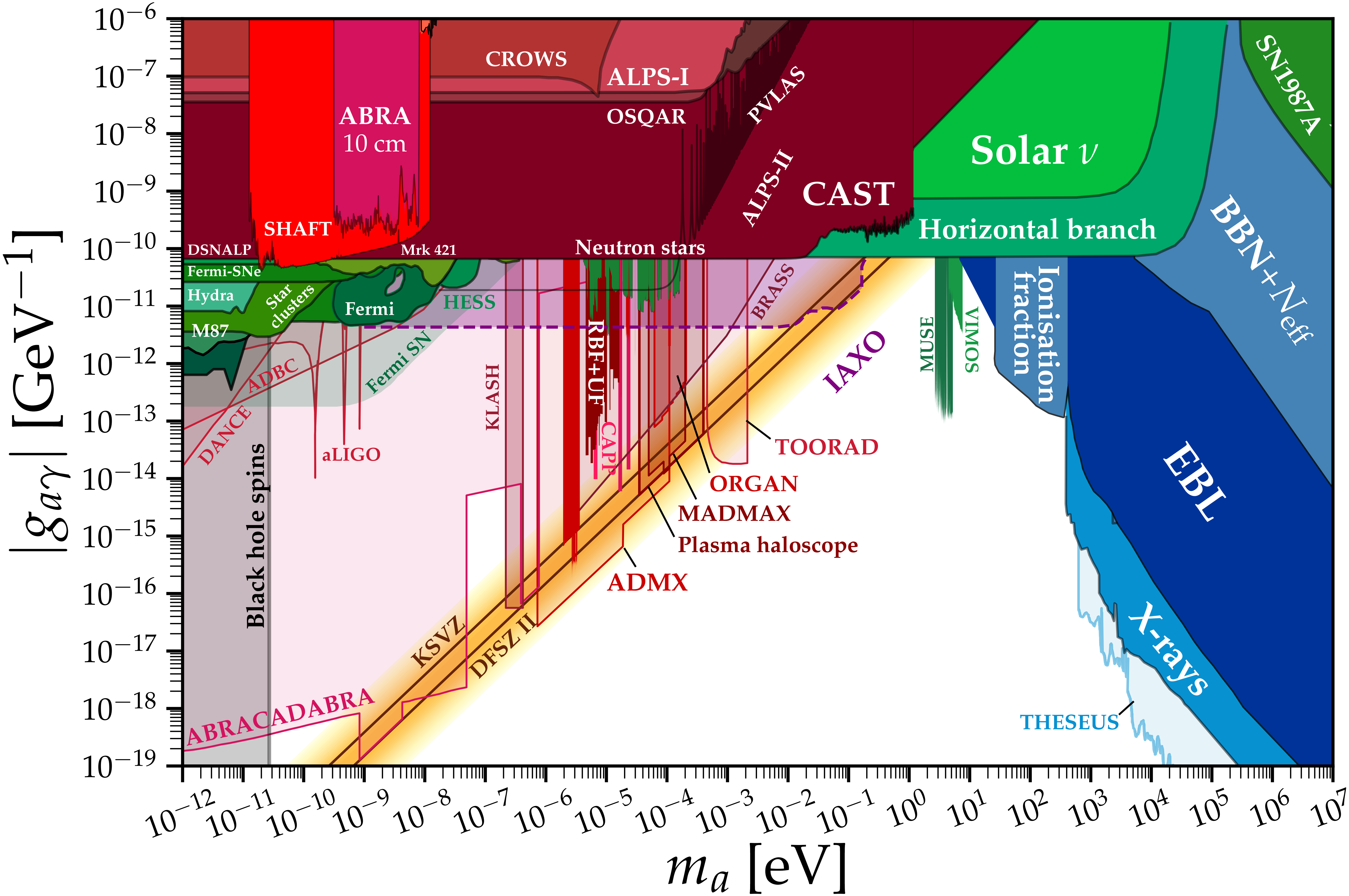
Chandra
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
KSVZ
DFSZ II
What will this exclusion plot look like in the future?



$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CROWS
ALPS-I
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10 cm
ALPS-II
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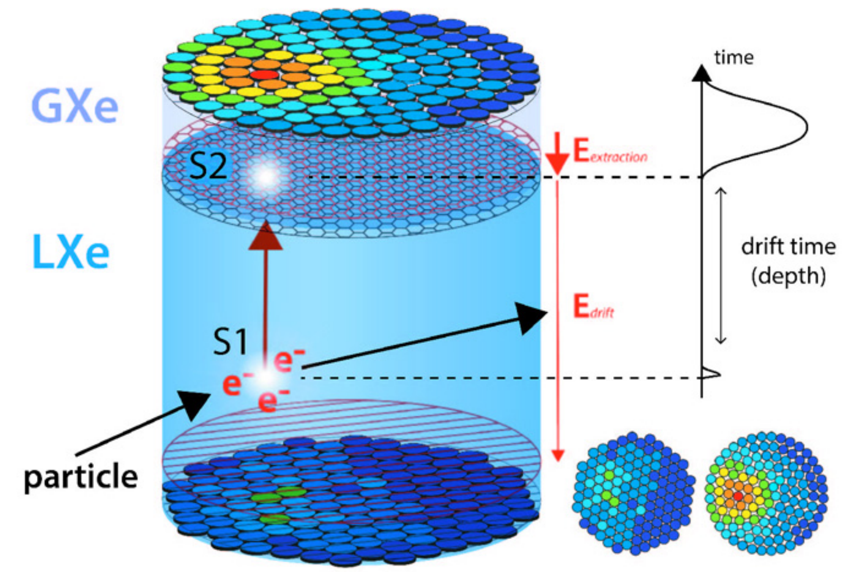
SN1987A
Horizontal branch
BBN+$N_{\rm eff}$
SHAFT
DSNALP
Mrk 421
Neutron stars
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
RBF+UF
BRASS
IAXO
MUSE
VIMOS
Ionisation fraction
Fermi SN
ADBC
DANCE
KLASH
CAPP
aLIGO
TOORAD
ORGAN
MADMAX
Plasma haloscope
ADMX
EBL
Black hole spins
KSVZ
DFSZ II
X-rays
THESEUS
ABRACADABRA

Notable mention: direct detection

- Conventional dark matter detectors can also be used to search for solar and keV-mass DM axions via their coupling to electrons

- In fact, last year Xenon1T reported a ~ 3σ excess which could be interpreted in terms of solar axions

- Admittedly, the axion parameters required are in tension with other constraints, particularly those from anomalous stellar cooling. Nonetheless, something to watch.



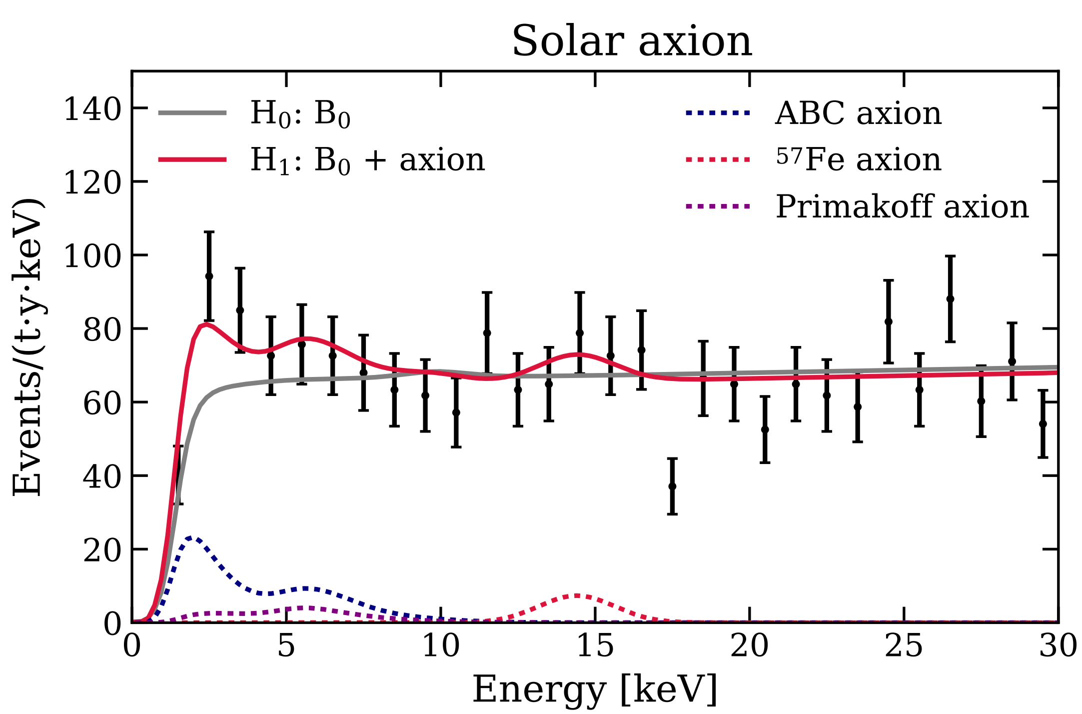
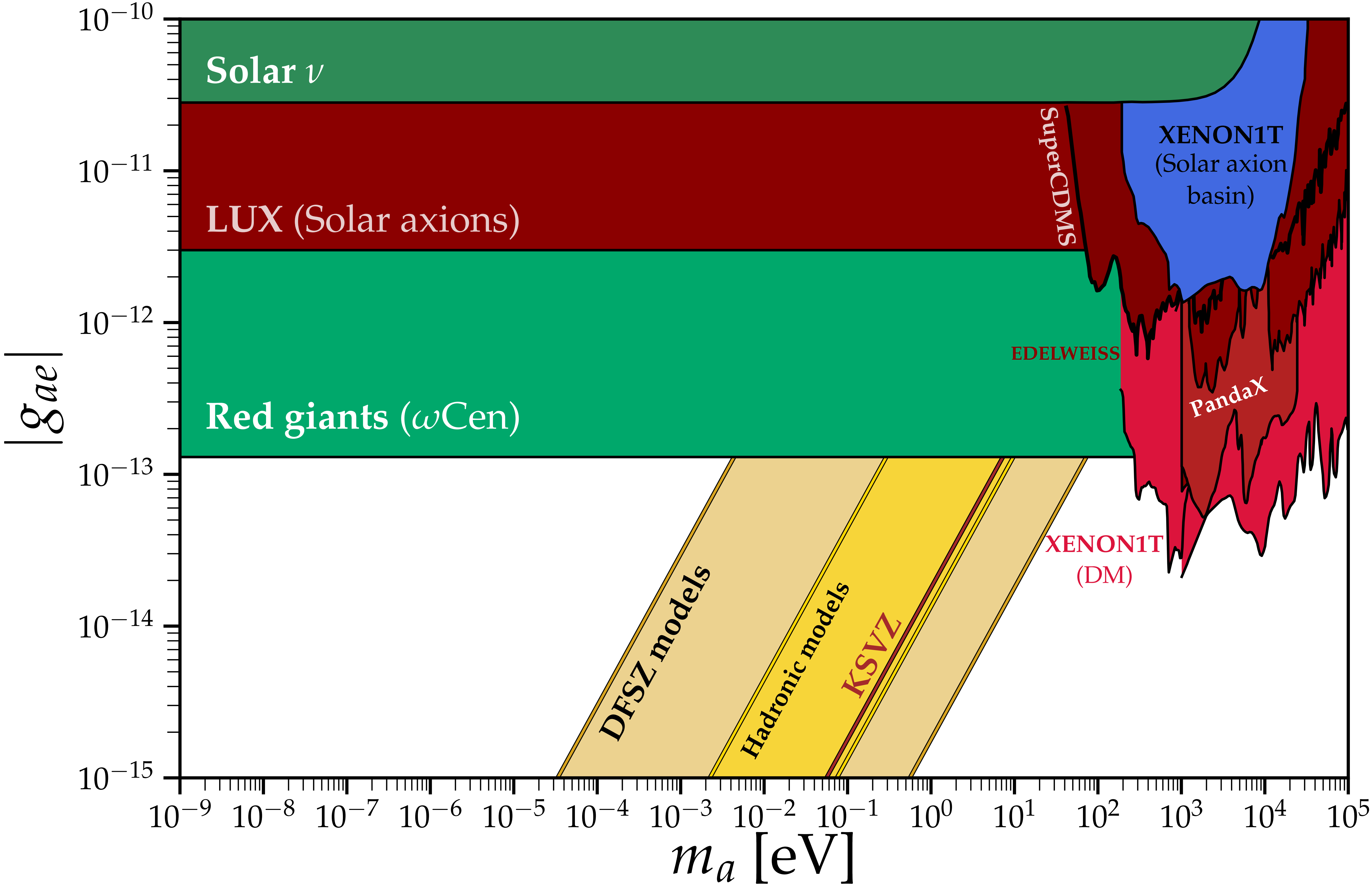


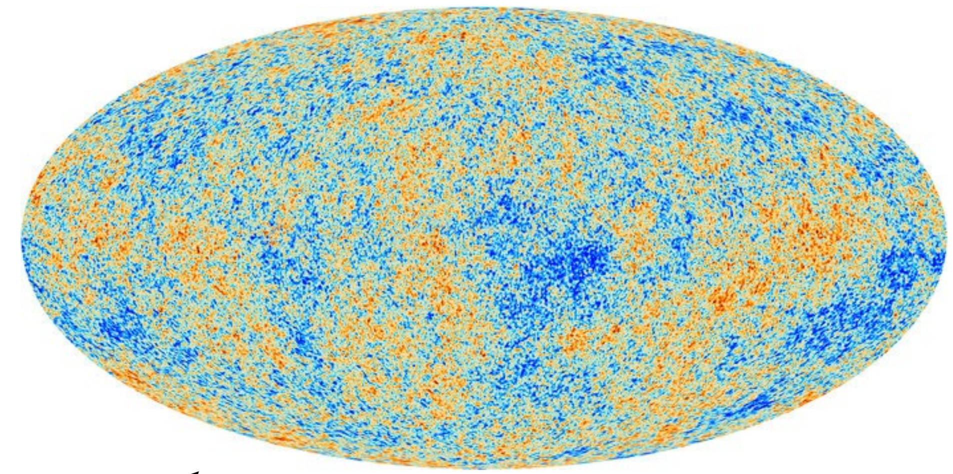
Figure taken from Aprile *et al.*, “Excess Electronic Recoil Events in XENON1T ” arxiv:2006.09721



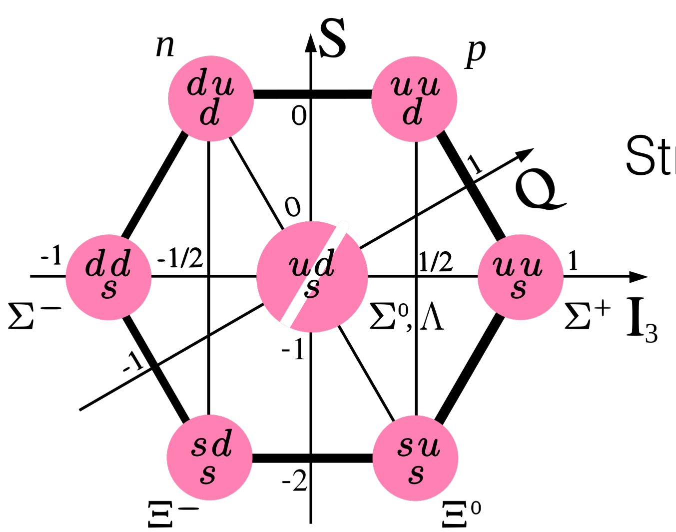
Solar ν
LUX (Solar axions)
Red giants (ωCen)
SuperCDMS
XENON1T
(Solar axion
basin)
EDELWEISS
PandaX
XENON1T
(DM)
DFSZ models
Hadronic models
KSVZ
$|g_{ae}|$
m_a [eV]

Theory summary: Axions are light (sub-eV) pseudo-Goldstone bosons, characterised broadly by just their mass and decay constant

They arise both as a minimal extension of the Standard Model, to solve the Strong CP problem, whilst also being a generic prediction of the exotic physics of string and M theory

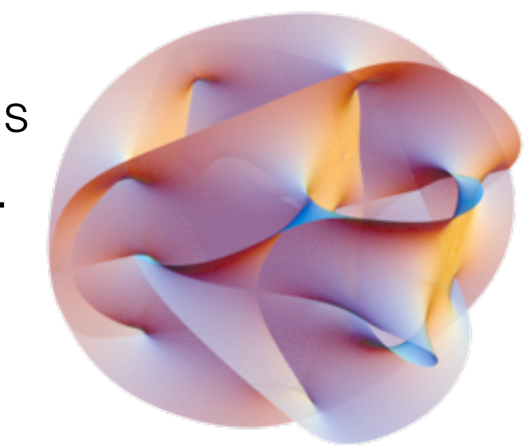


(Planck 2015)

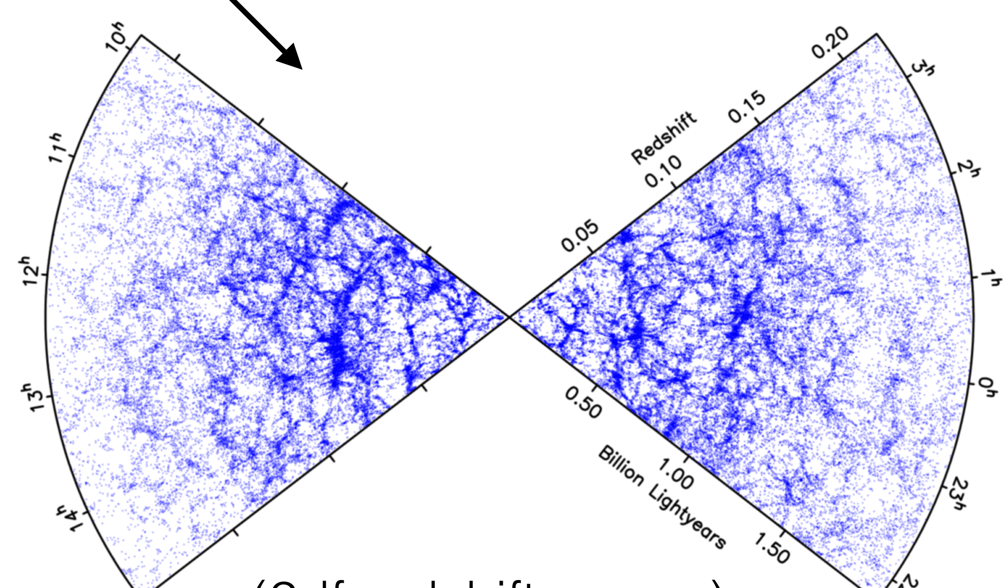


Strong CP problem

Compactifications



Observation summary: dedicated experiments are looking for the axion, while we also search for their signatures in dark matter, dark energy, early Universe cosmology, big bang nucleosynthesis, CMB formation, stellar evolution, large scale structure…



(2df redshift survey)

What have we learned?

- Axions are a particularly well-motivated aspect of BSM physics, thanks to the strong CP problem, and string axiverse scenario
- They connect to a wide variety of physical contexts; from the beginning of our Universe to the present day, from UV to IR, and yet present an easily characterisable theoretical target
- Experimental efforts are ongoing worldwide
- If you would like to learn more, please join us in the ‘Axion physics and Experiments’ parallel sessions next week!
- Thank you all for your attention

Useful references

- “The Strong CP Problem and Axions”, R. Peccei, arxiv: 0607268
- “Axions and the Strong CP Problem”, J. Kim and G. Carosi, arxiv: 0807.3125
- “New experimental approaches in the search for axion-like particles” I. Irastorza and J. Redondo, arxiv:1801.08127
- “Axion cosmology” D. J. E. Marsh, arxiv: 1510.07633