THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Axions as dark matter

Ciaran O'Hare

U. Sydney

Part 1: Axion theory & searches

Part 2: Axion dark matter simulations

CAJO & Vitagliano [2010.03889]
Caputo, Millar, **CAJO**, Vitagliano [2105.04565]
CAJO, Pierobon, Redondo, Wong [in prep.]
cajohare.github.io/AxionLimits/

CP violation and the neutron electric dipole moment

CP violation and the neutron electric dipole moment

Theory: Vacuum structure of QCD (instantons) generates a term

$$\mathcal{L}_{\mathrm{QCD}} = \ldots - \frac{\alpha_s}{8\pi}\theta_{\mathrm{QCD}} G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}$$

Some angle, not fixed by theory, so presumably $\mathcal{O}(1)$

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Experiment: $\theta_{\rm QCD}$ observable but bundled with phase from quark masses

$$\bar{\theta} = \theta_{\rm QCD} + \theta_q$$

Where it sets the electric dipole moment of the neutron

$$d_n = (2.4 \pm 1.0)\bar{\theta} \times 10^{-3}\, e\,\mathrm{fm}$$

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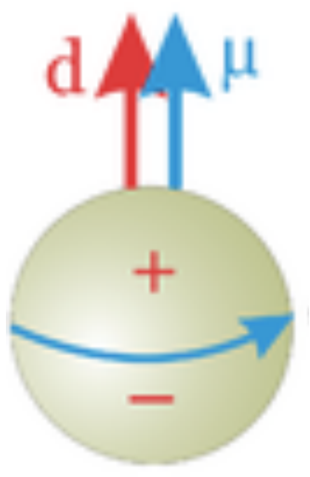
Put some spin-polarised neutrons in E, B fields



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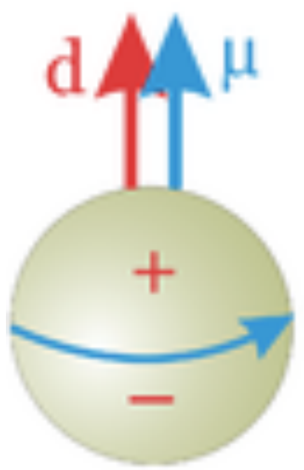
Put some spin-polarised neutrons in E, B fields → Measure spin precession frequencies



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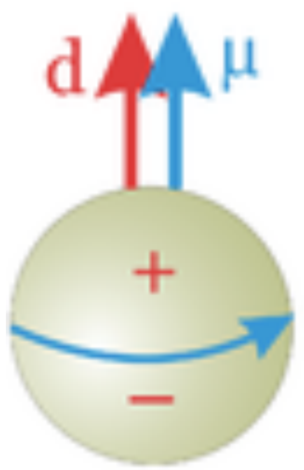
Put some spin-polarised neutrons in E, B fields → Measure spin precession frequencies → Calculate neutron EDM



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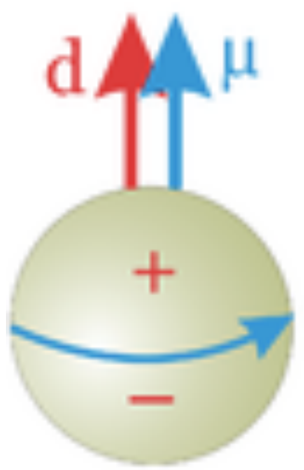
Put some spin-polarised neutrons in E, B fields → Measure spin precession frequencies → Calculate neutron EDM → Measure Fundamental parameter of SM



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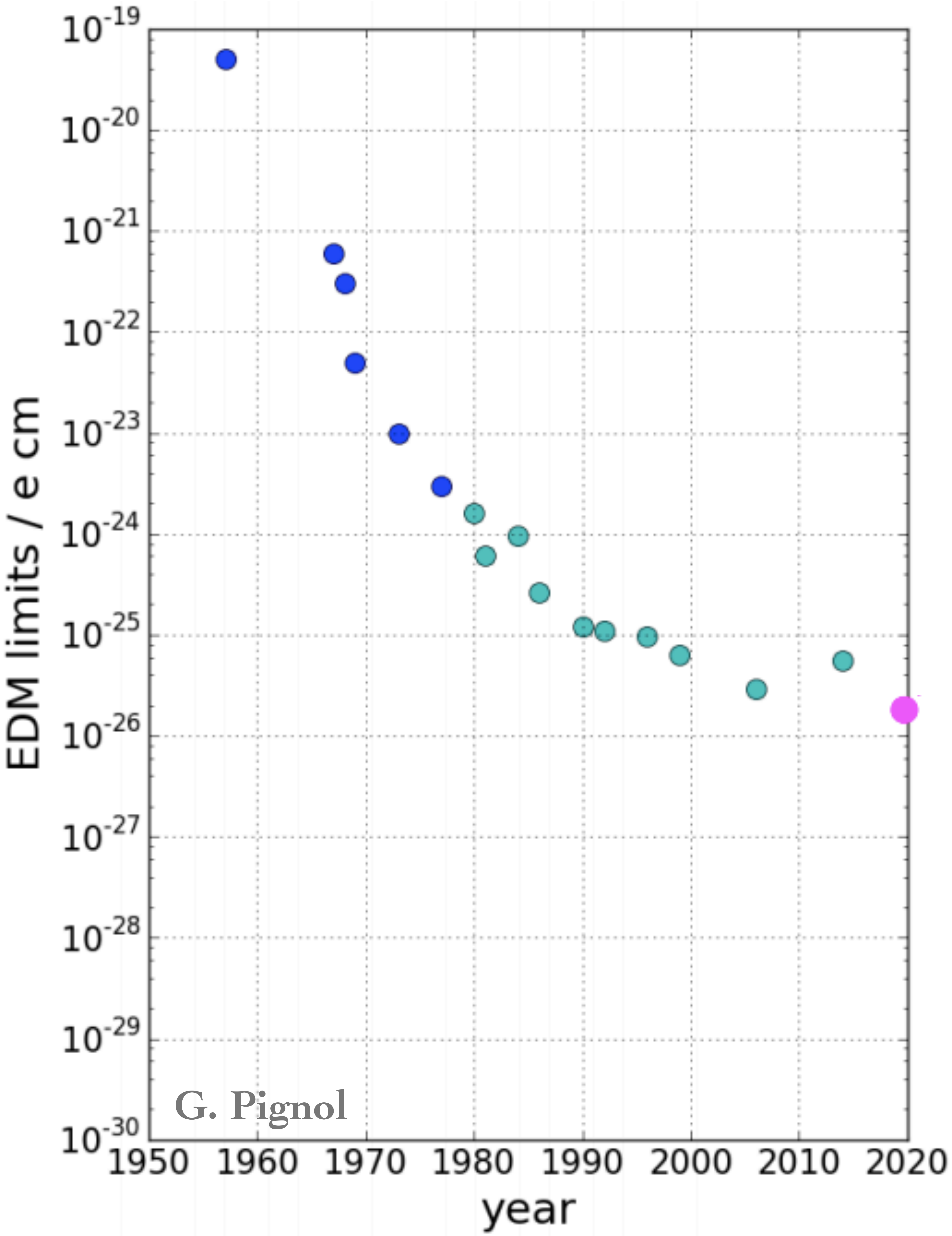
$$\theta_{\text{QCD}}$$

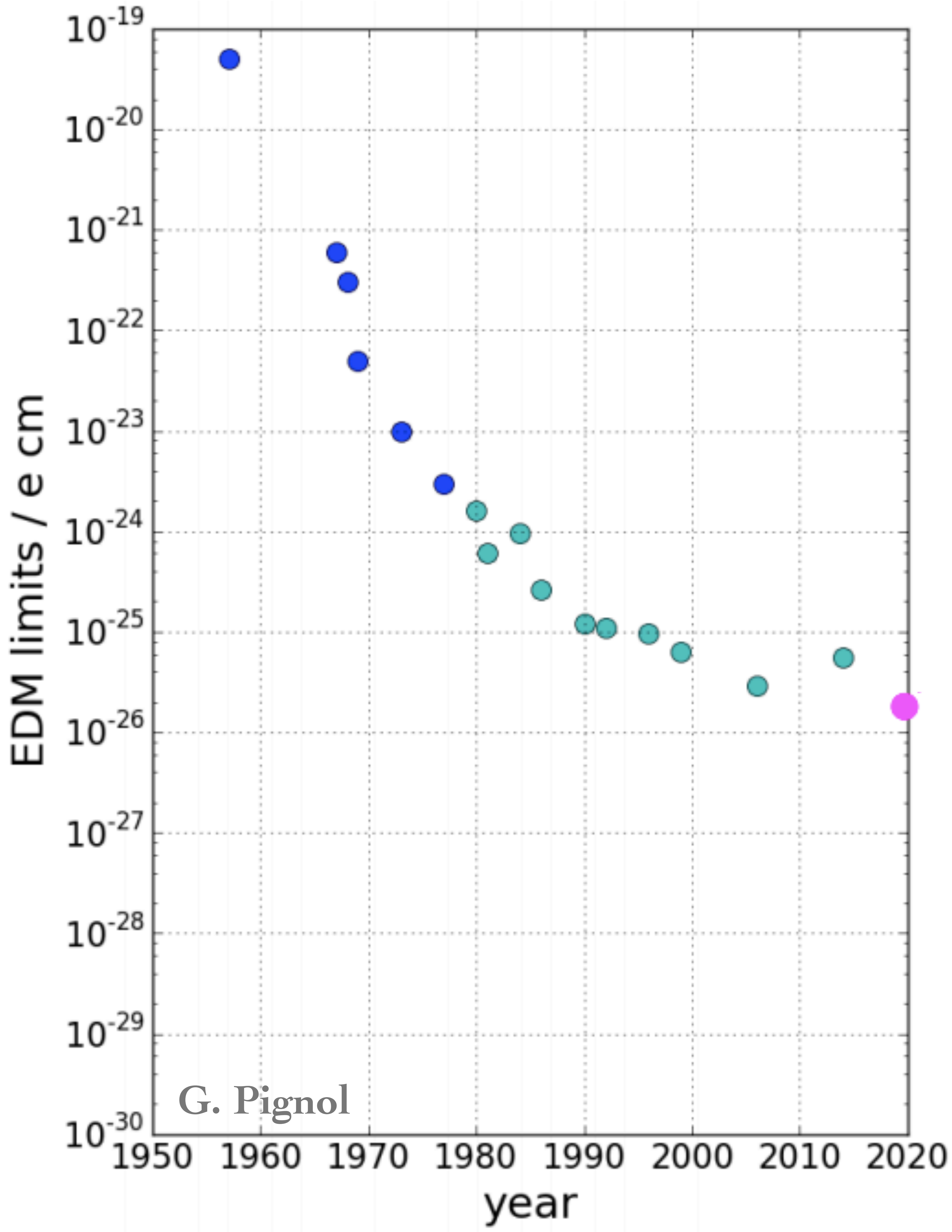


What do they see?

Recent measurement [2001.11966]

$$|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm} \quad (90\%\ \mathrm{CL})$$

$$\Rightarrow \theta \lesssim 10^{-10}$$



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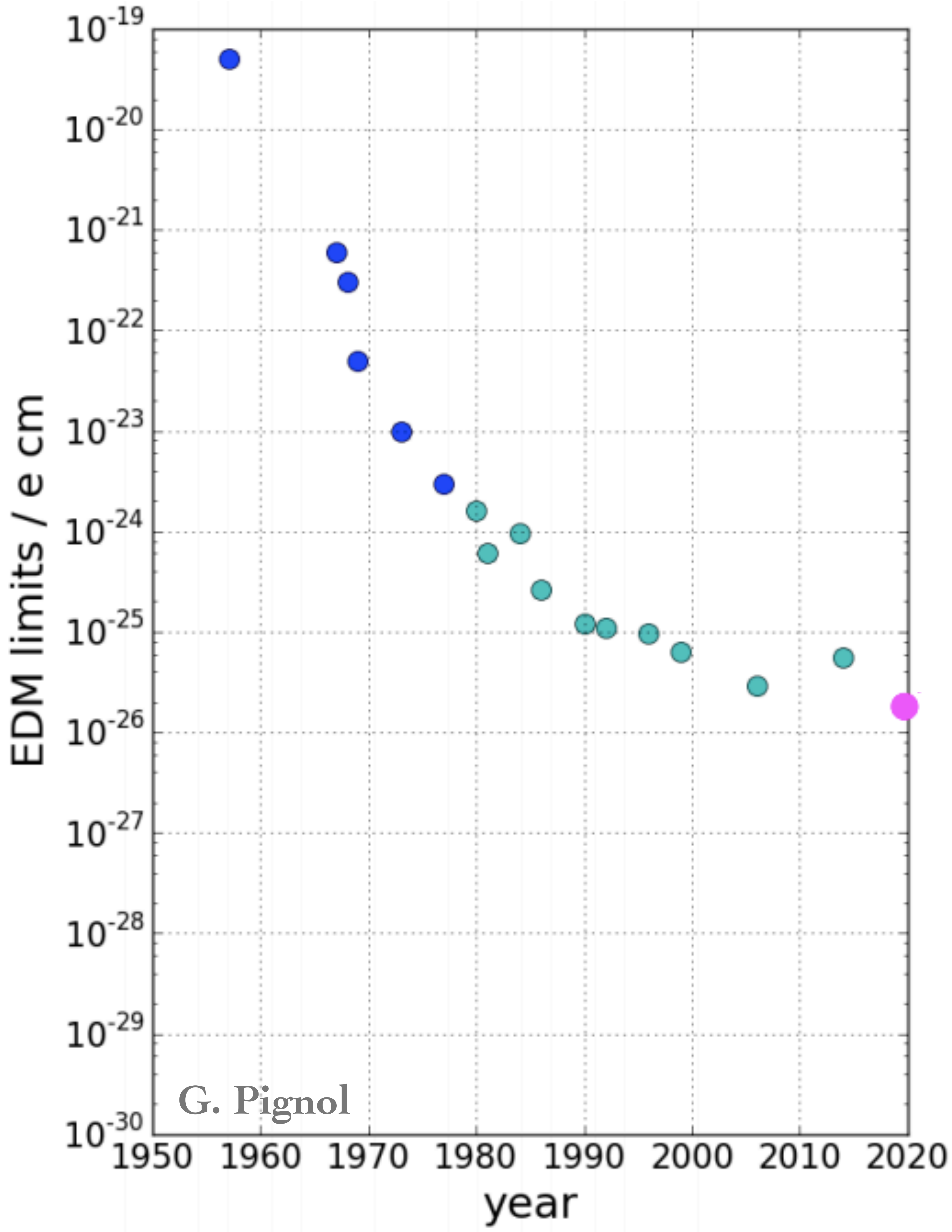
→ **The strong CP problem**



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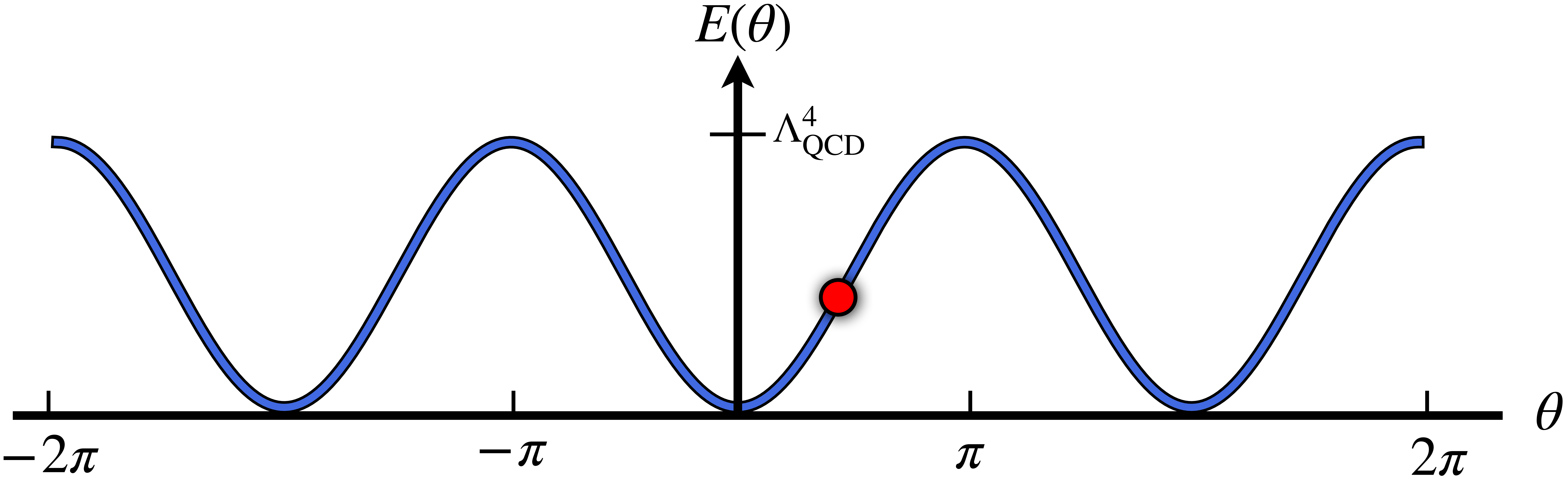
↓

The real problem: why are two completely unrelated numbers cancelling each other < ppb?

The solution, a la Peccei-Quinn

QCD vacuum energy density already has a minimum at $\theta = 0$ (Vafa-Witten theorem). However θ is just a parameter, there is no mechanism to cause it to want to minimise energy



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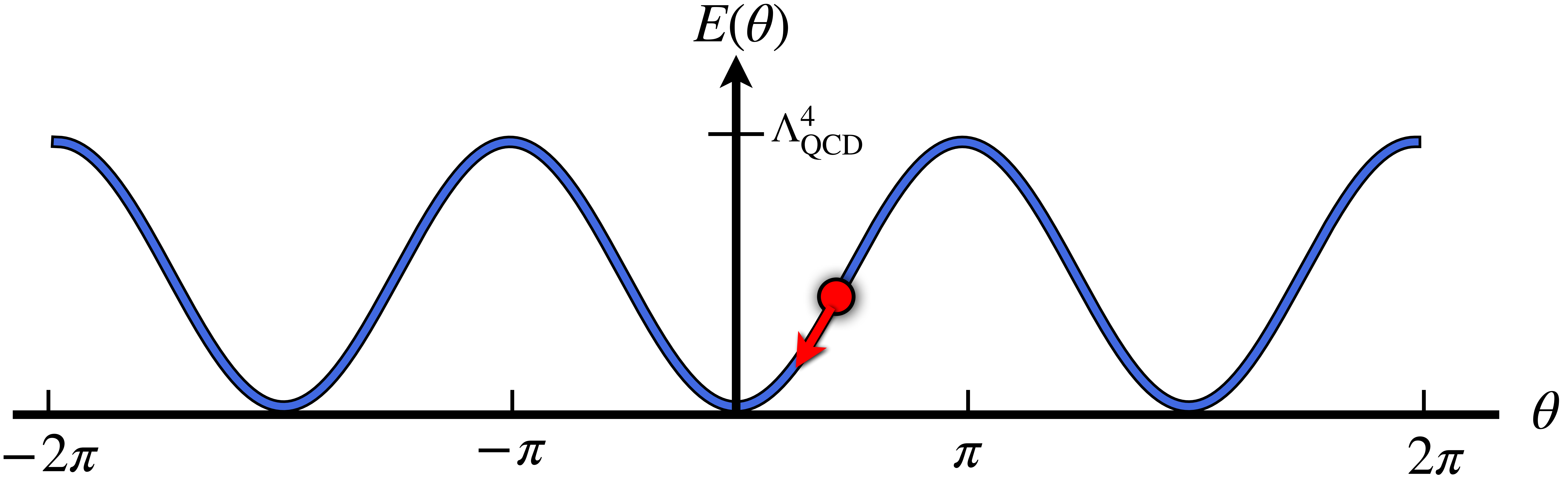
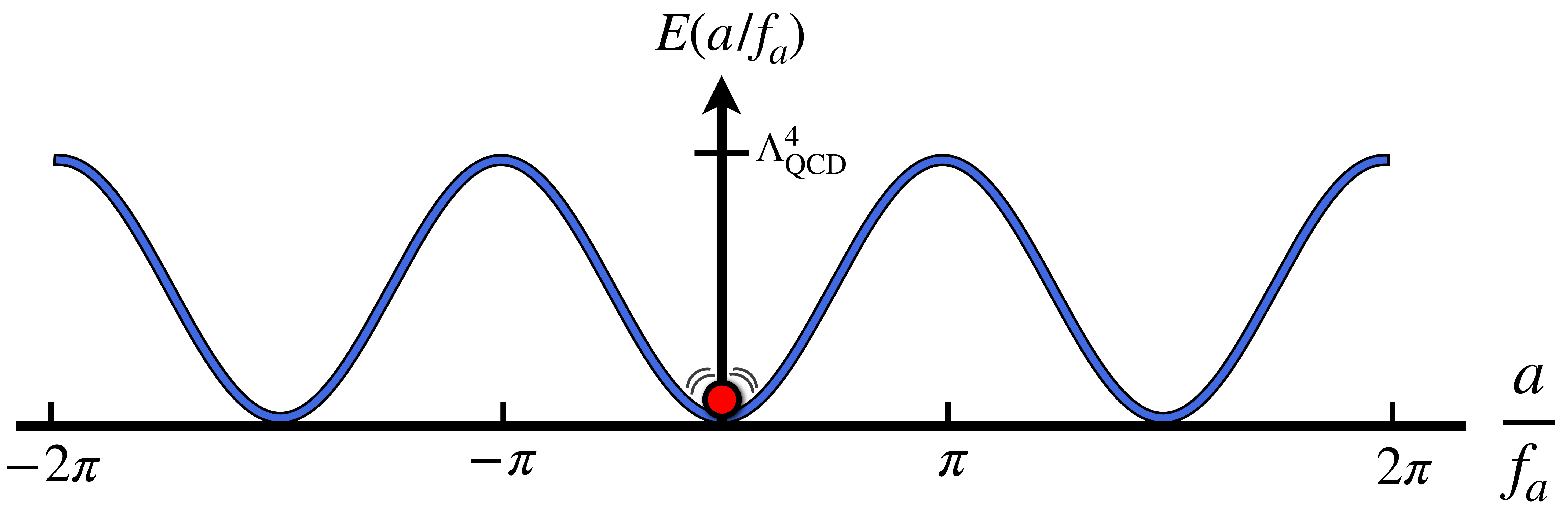


PQ mechanism: what if there was?

The axion



- Introduce field, a, that couples to gluons $\propto (a/f_a)\, G\tilde{G}$. It will have a shift symmetry that can be used to cancel off any unwanted CP violation while VW theorem ensures $\langle a \rangle = 0$
- QCD vacuum implies a potential for the axion and thus a small mass

$$V(a) \approx \Lambda^4_{\rm QCD}\left[1 - \cos\left(\bar{\theta} + \frac{a}{f_a}\right)\right] \longrightarrow m_a \simeq \frac{\Lambda^2_{\rm QCD}}{f_a} \simeq 6\,{\rm meV}\left(\frac{10^9\,{\rm GeV}}{f_a}\right)$$

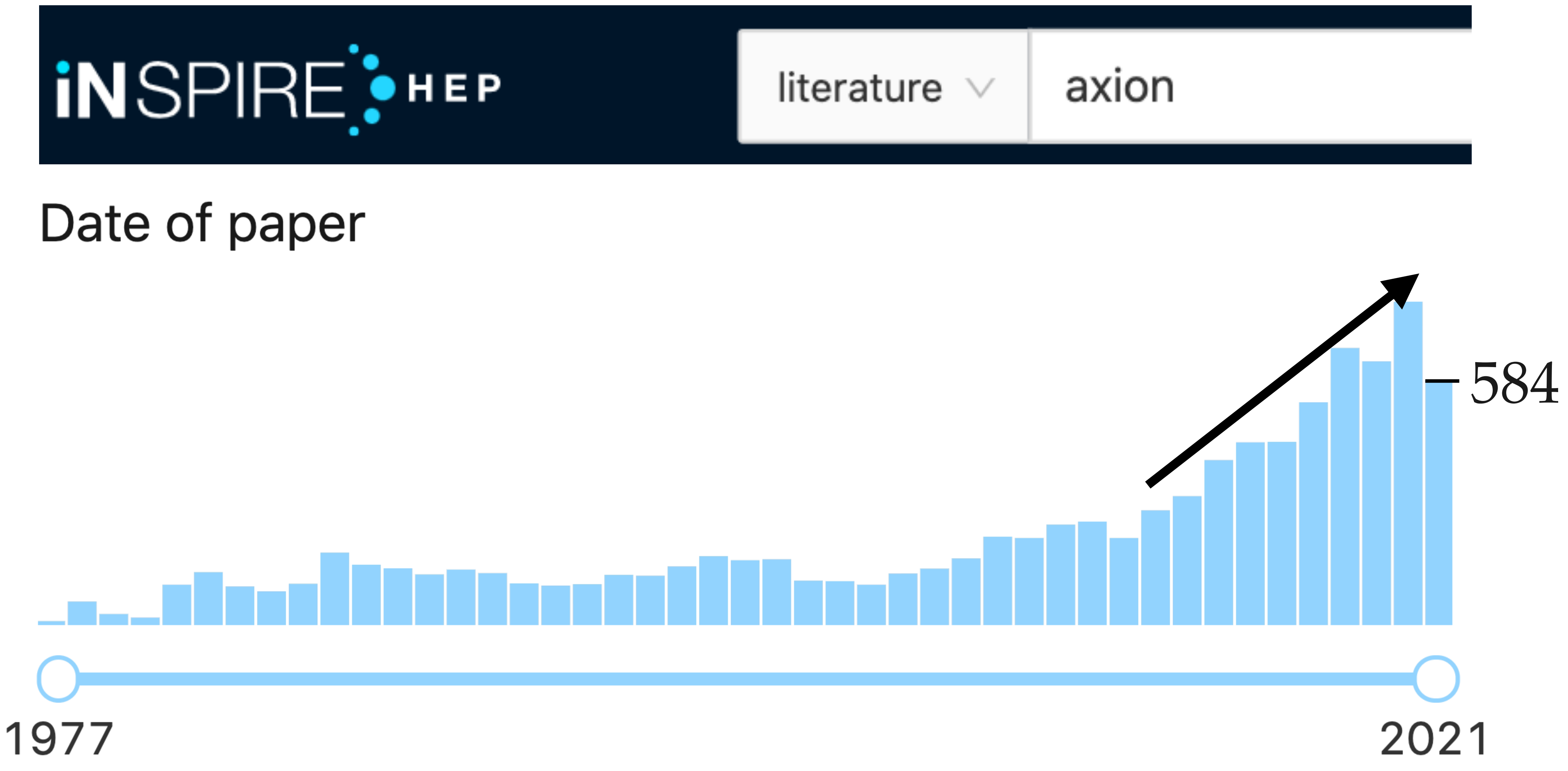
The axion effective theory

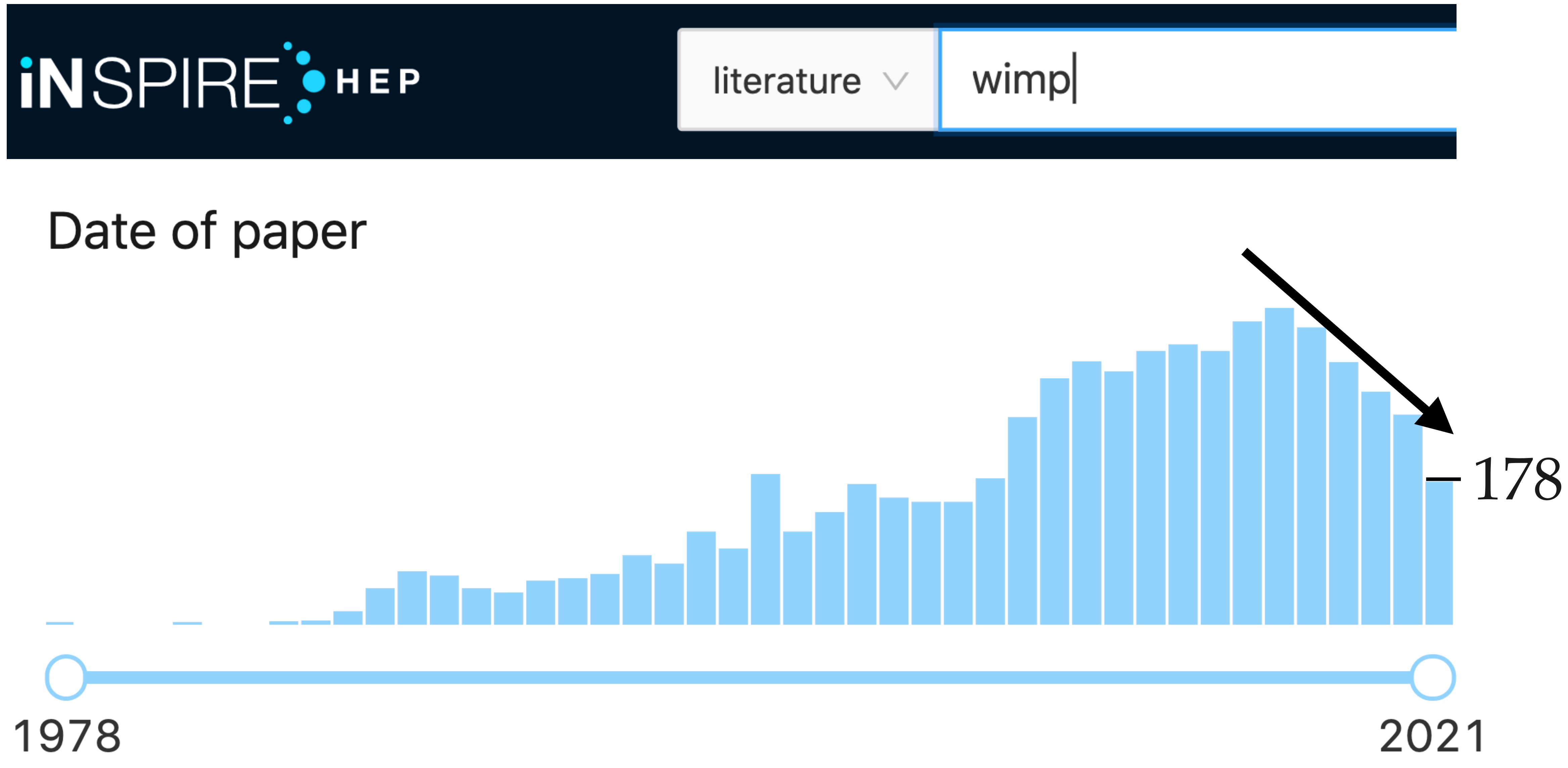
Introduce axion as the pseudo-Goldstone boson of a new global $U(1)$, spontaneously broken at scale f_a. After some extra work, it can also couple to the photon and fermions

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2} m_a^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu} + \partial_\mu a \sum_\psi \frac{g_{a\psi}}{2m_\psi}\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right)$$

Importantly, all couplings suppressed by $g \sim f_a^{-1}$. So set symmetry breaking scale as high as you like to evade observational constraints
→ ideal candidate for **dark matter**

The axion is fashionable

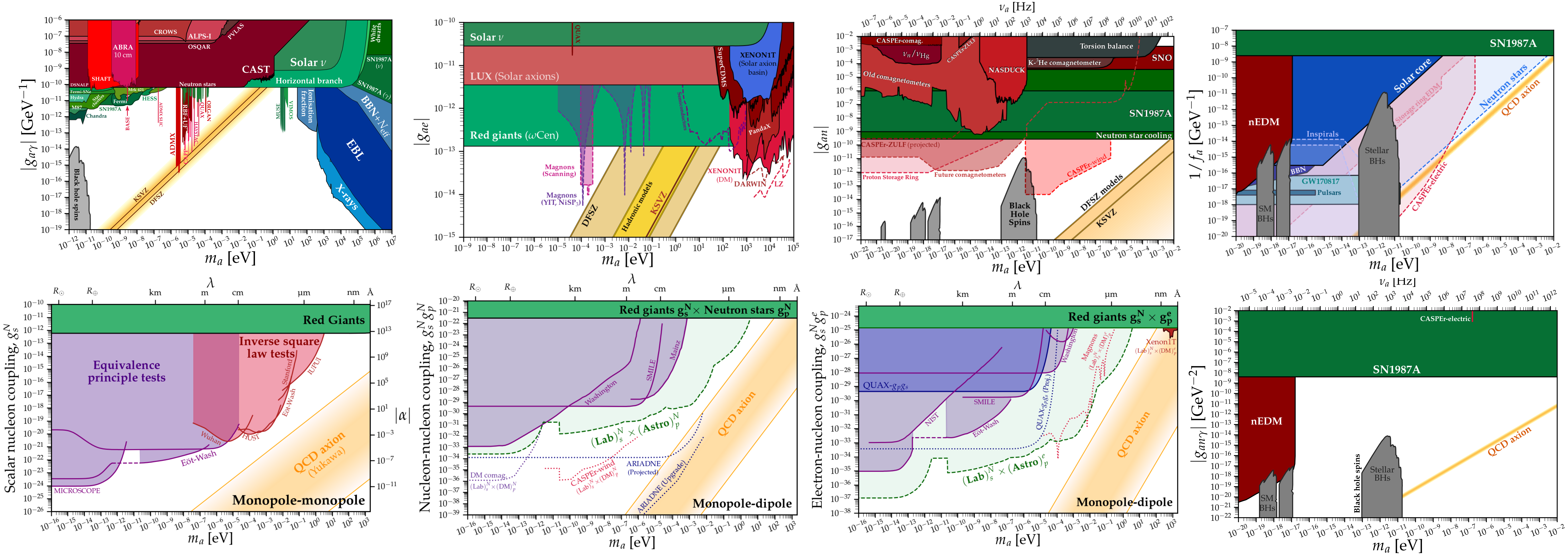




- Solves outstanding problem of the SM
- Cosmologically relevant as (all or some of) DM
- Many laboratory tests possible, almost totally falsifiable
- Testable in astrophysical environments as well

Lots of activity, but potentially many years away from a discovery

<u>This talk:</u> Can we do anything theoretically to accelerate us towards one?



For more, see <u>cajohare.github.io/AxionLimits/</u> → Now hosts results from >200 publications!

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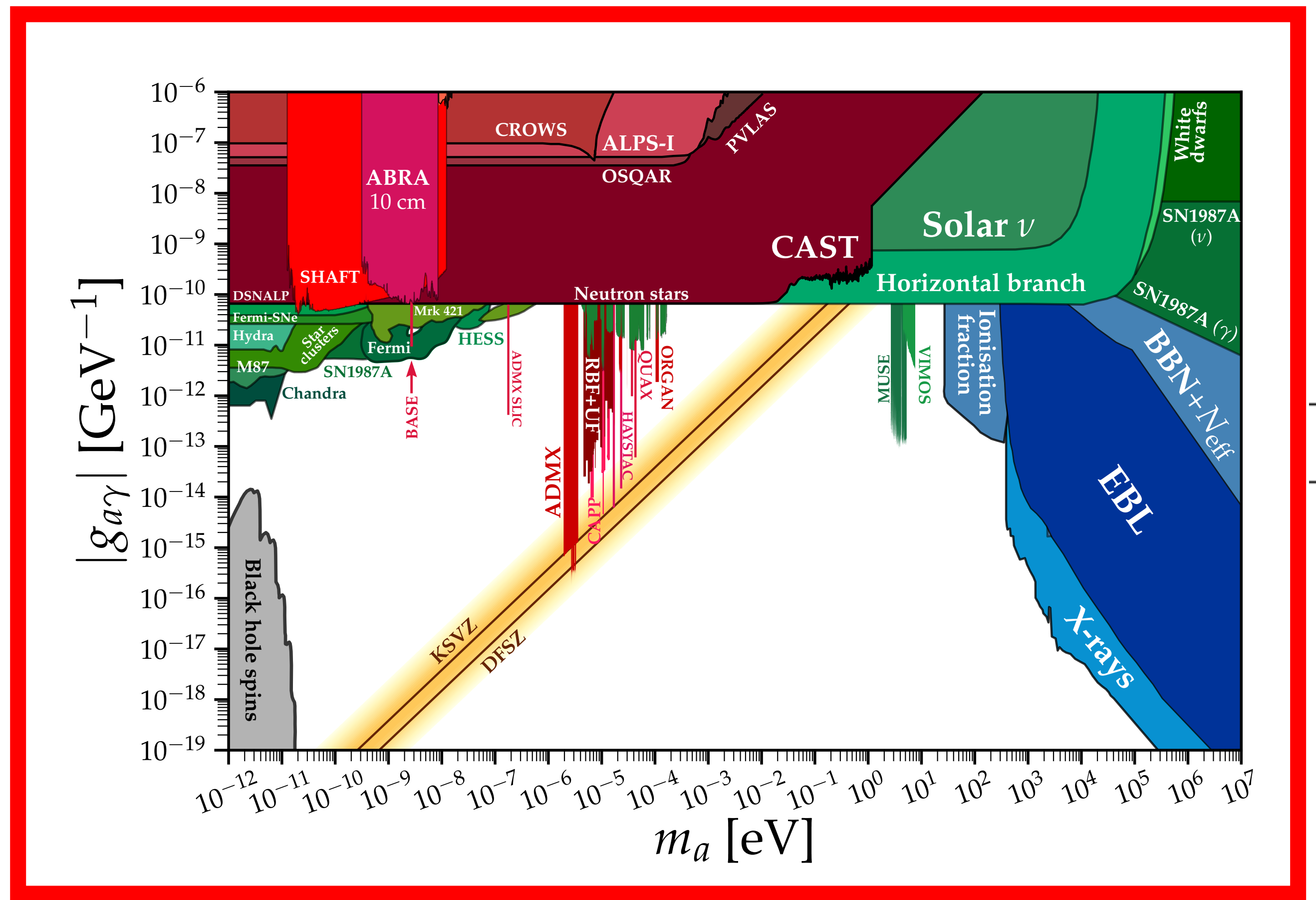

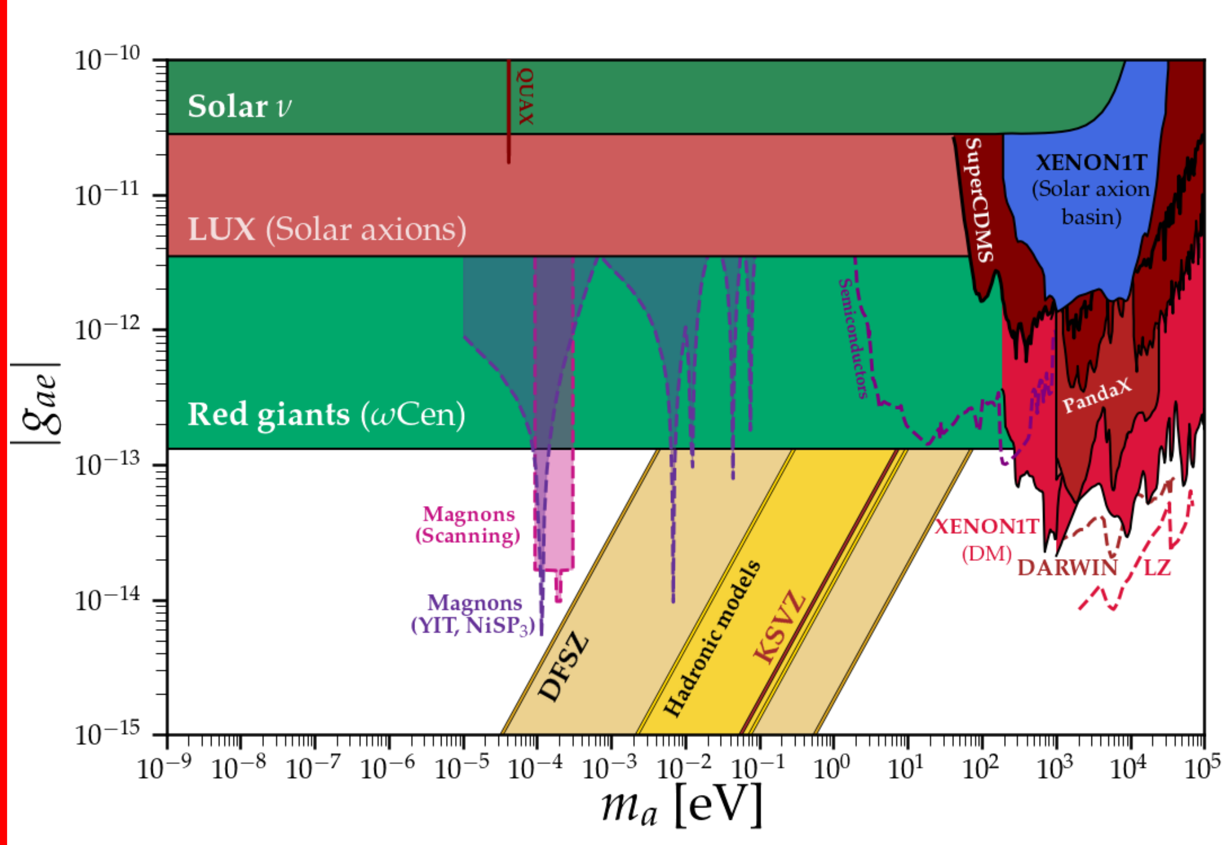

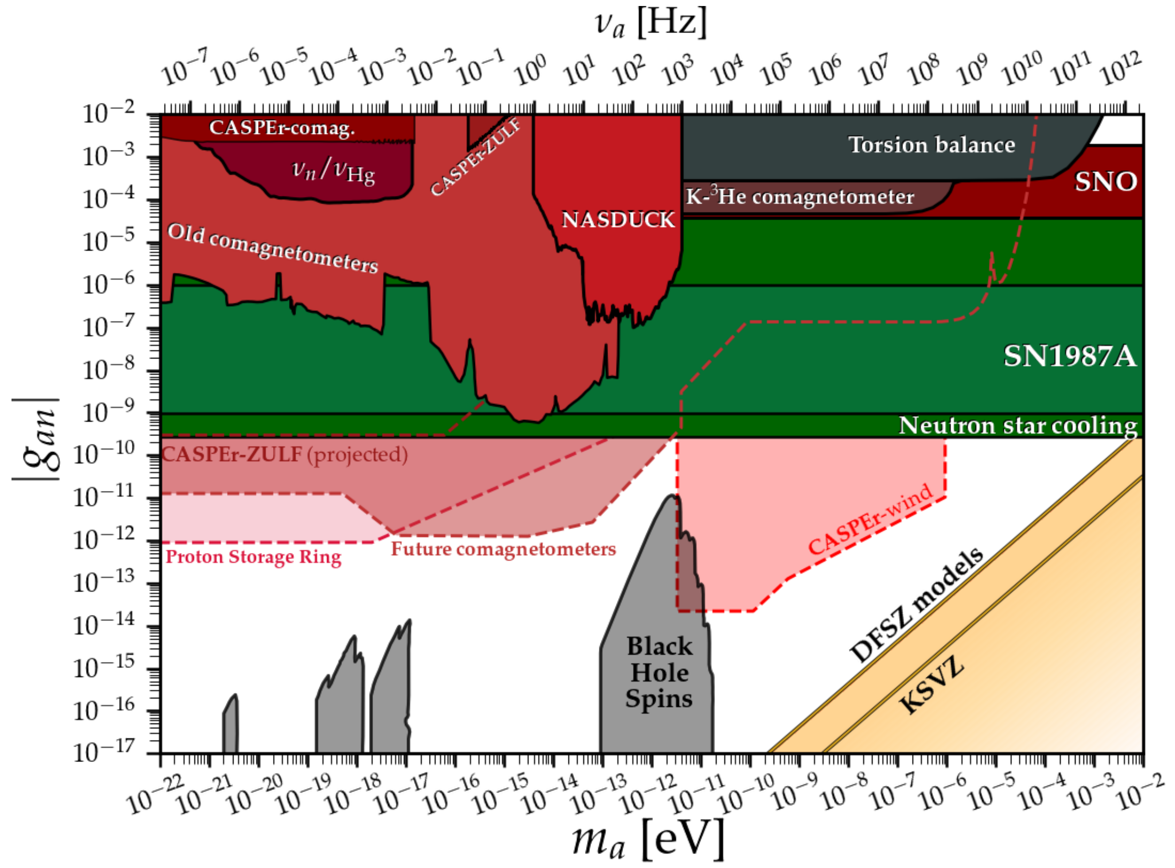

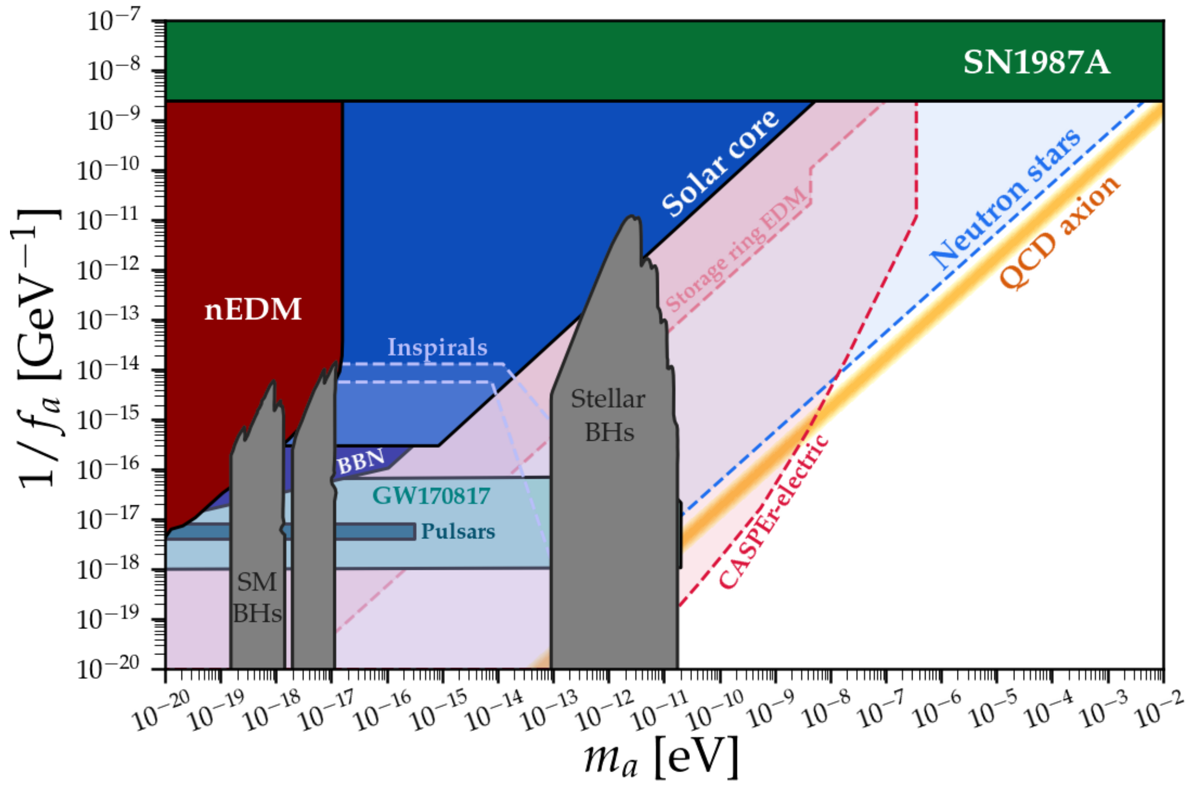

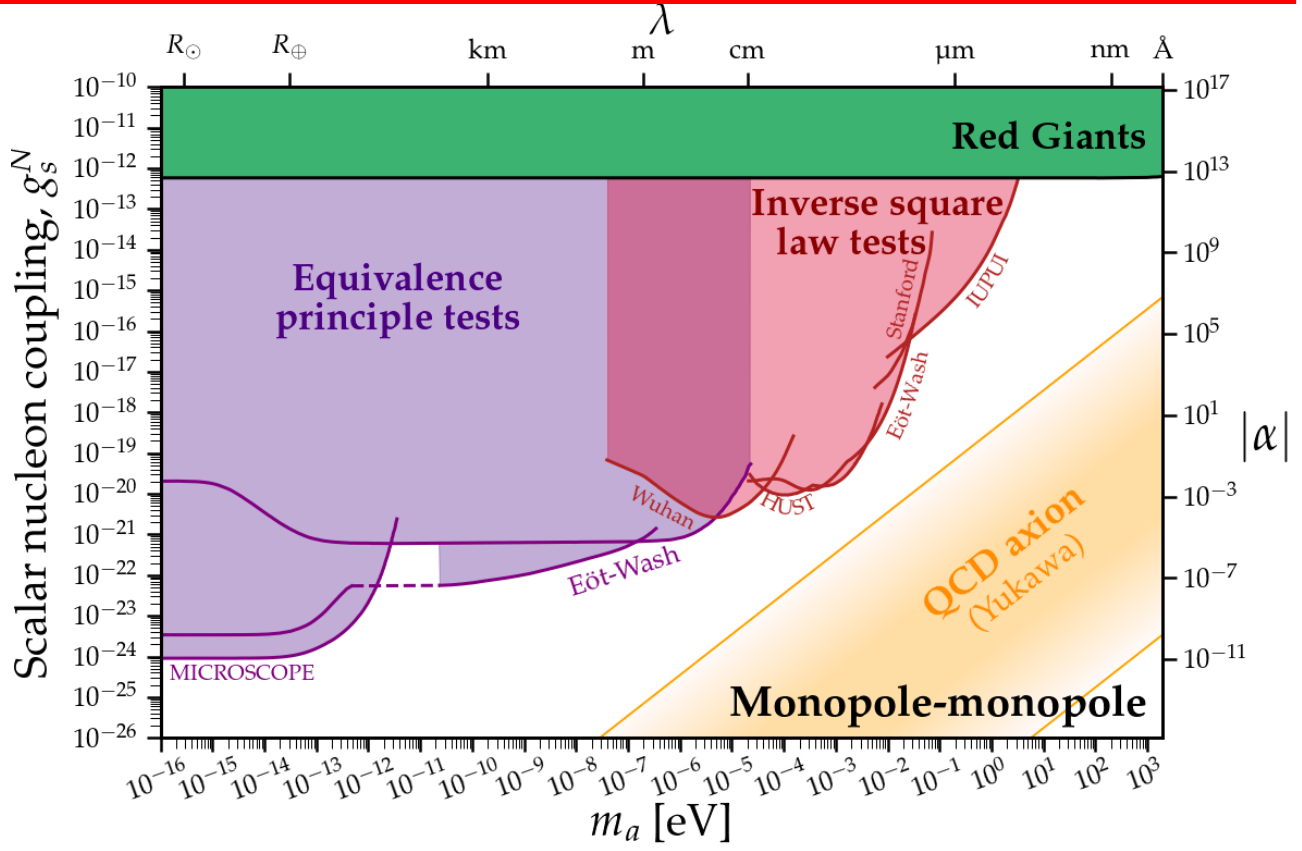

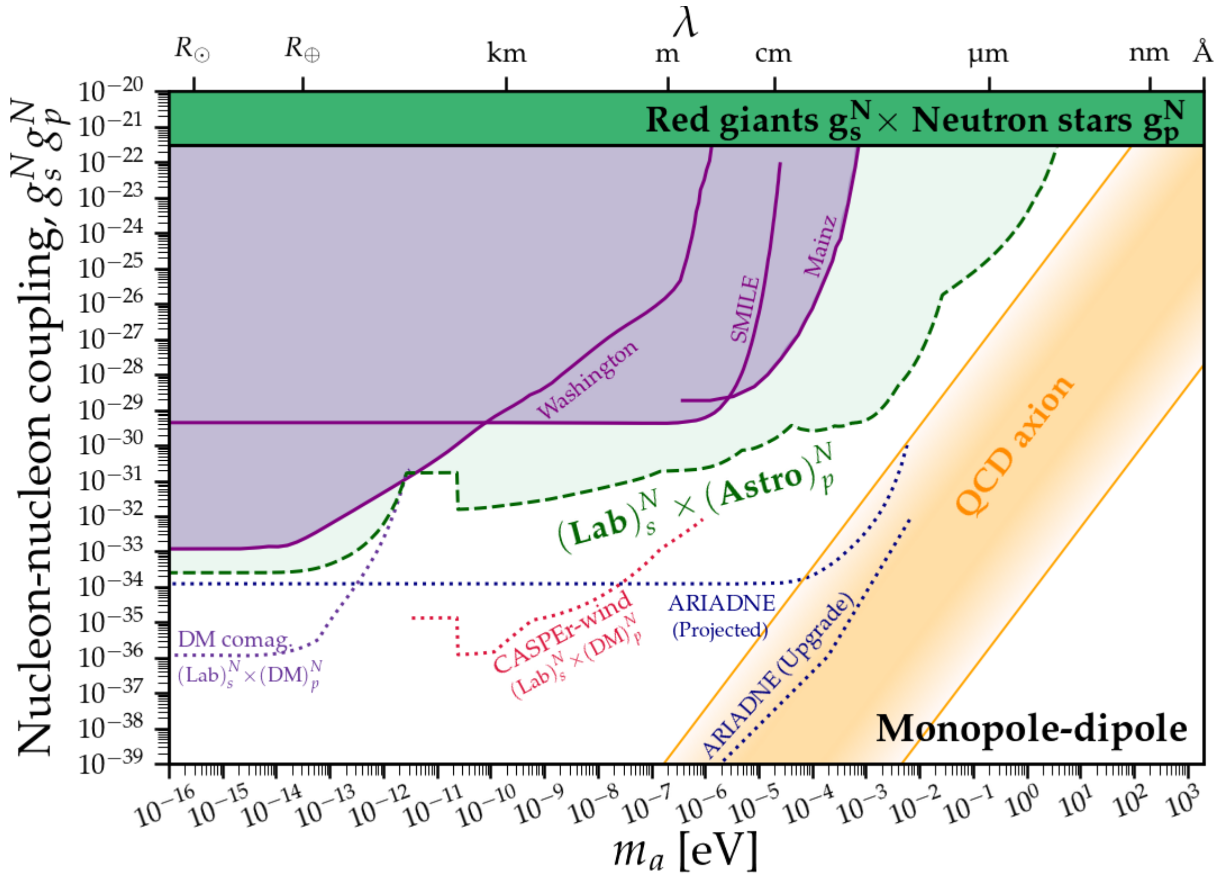

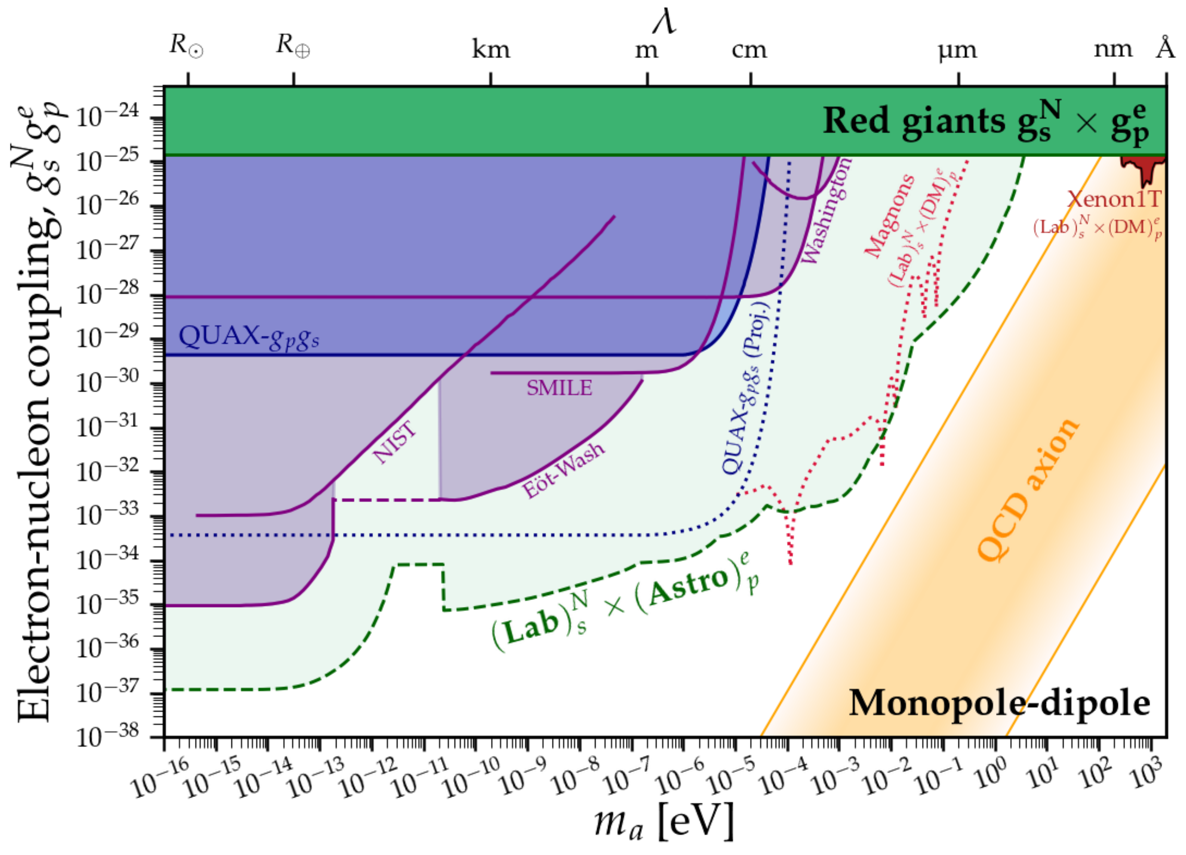

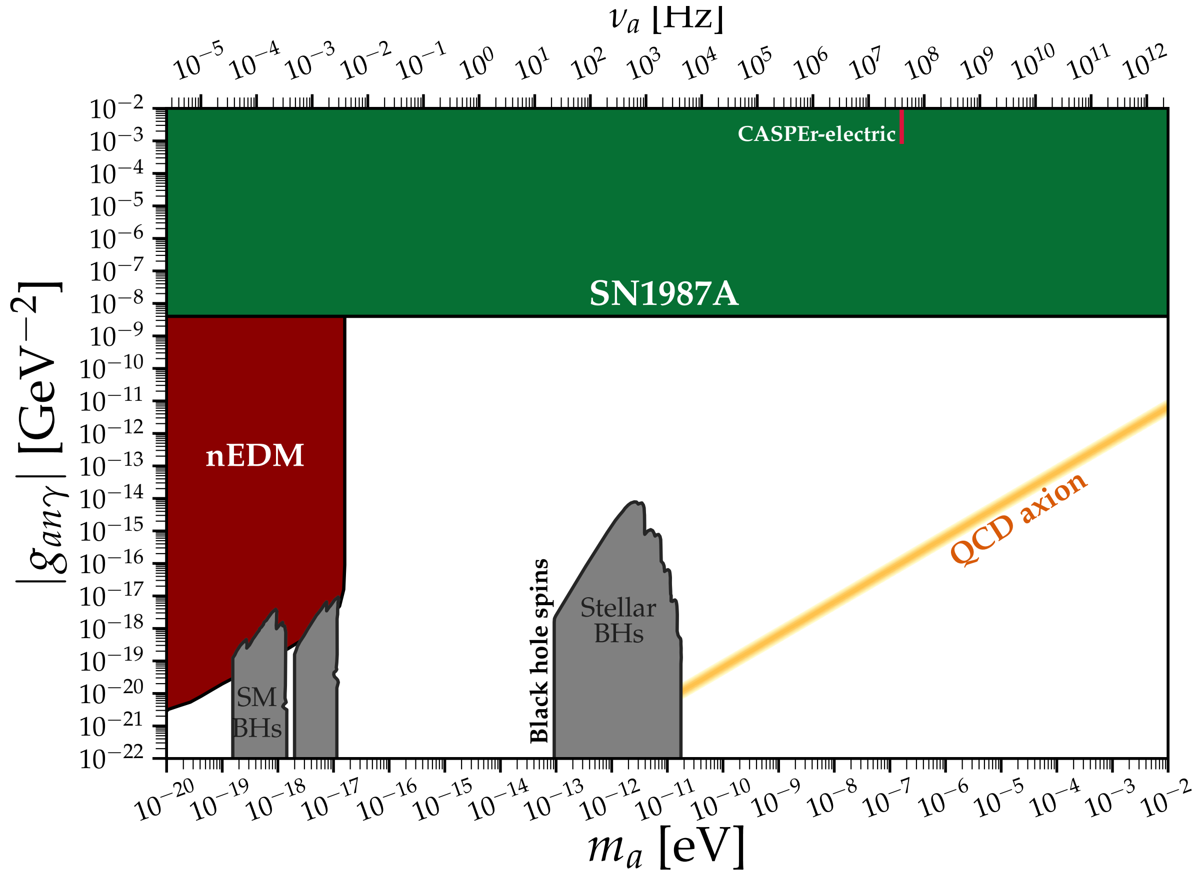

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Coupling to the photon

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma} a(\mathbf{x}, t) F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a(\mathbf{x}, t) \mathbf{E} \cdot \mathbf{B}$$

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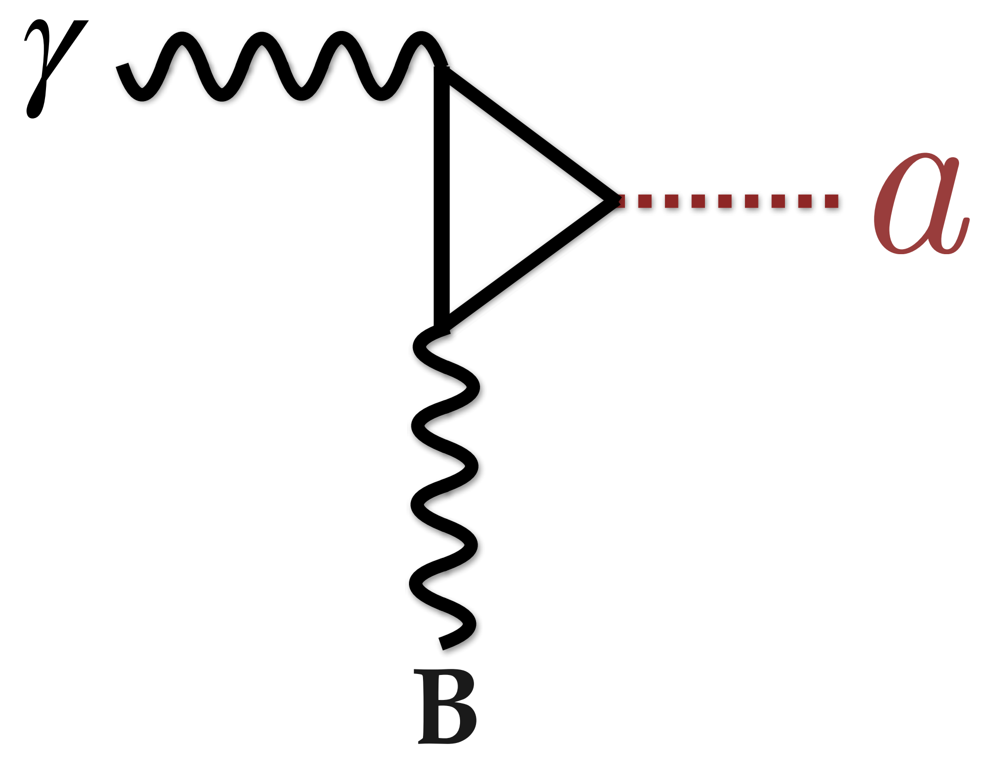
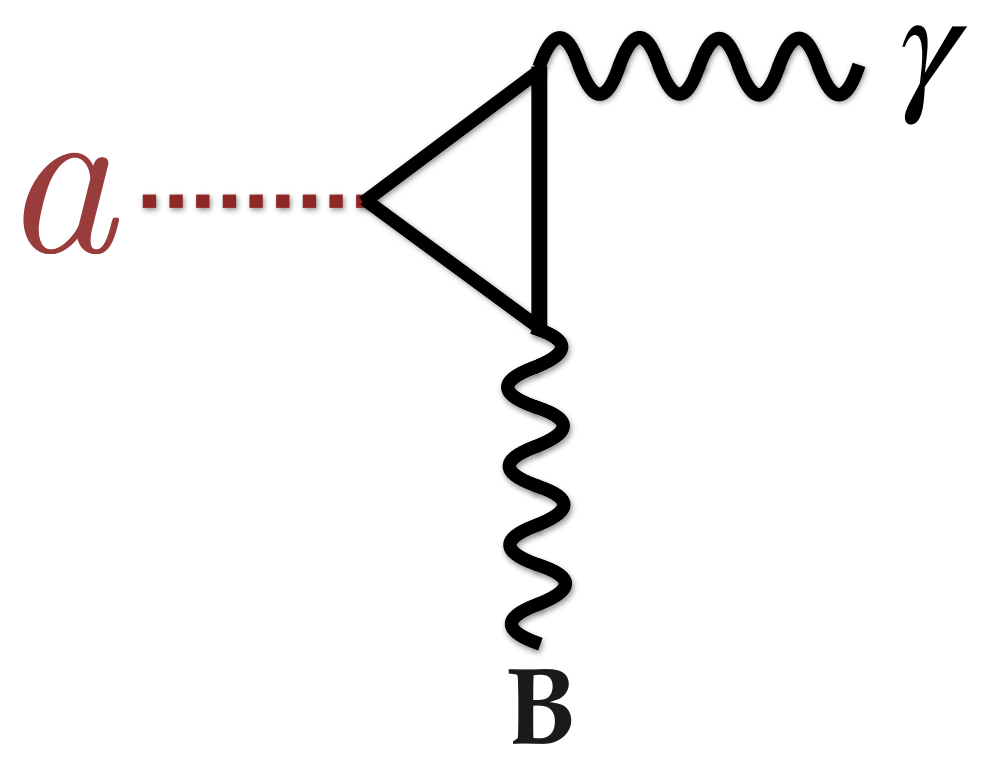
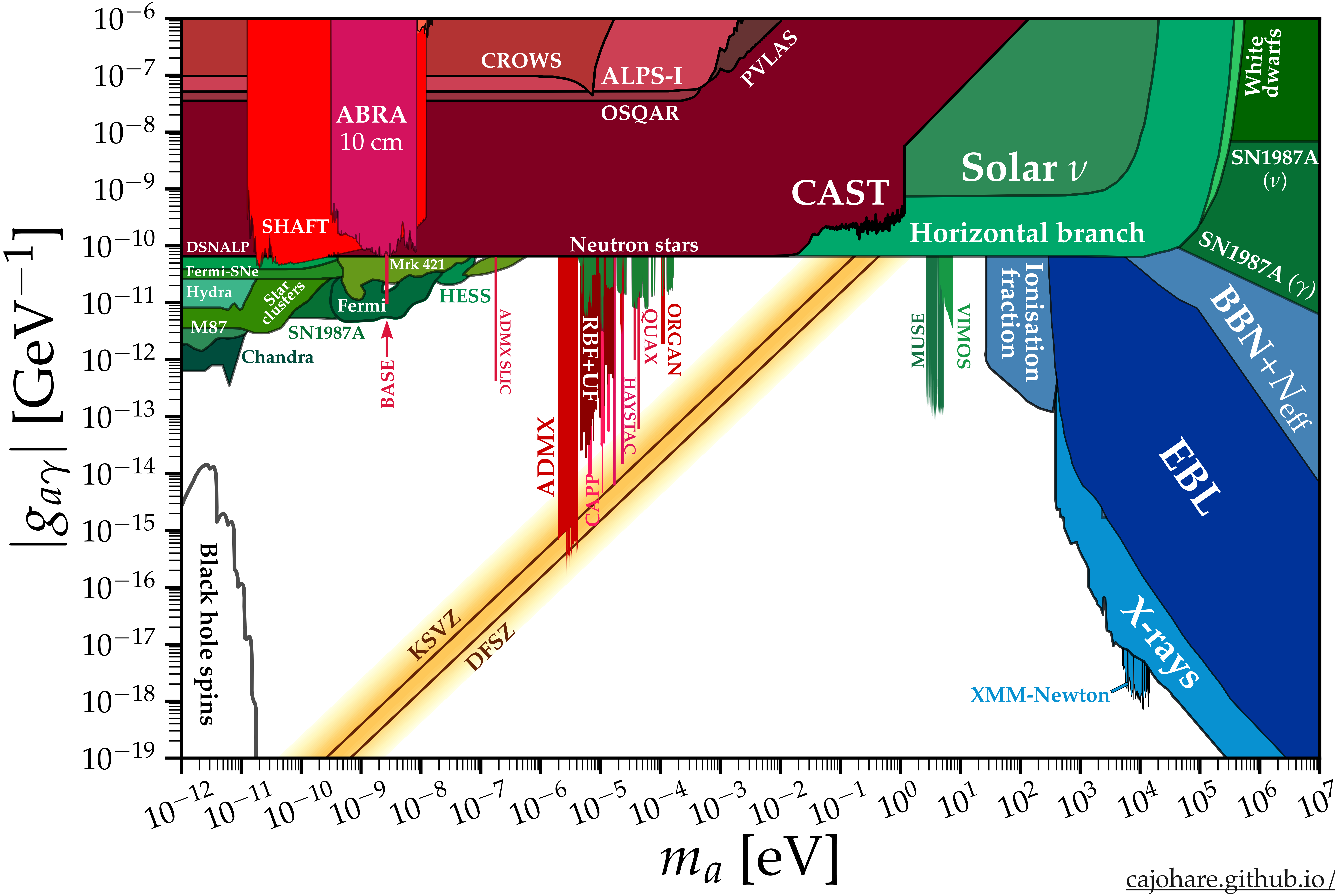
Photon → Axion



Axion → Photon





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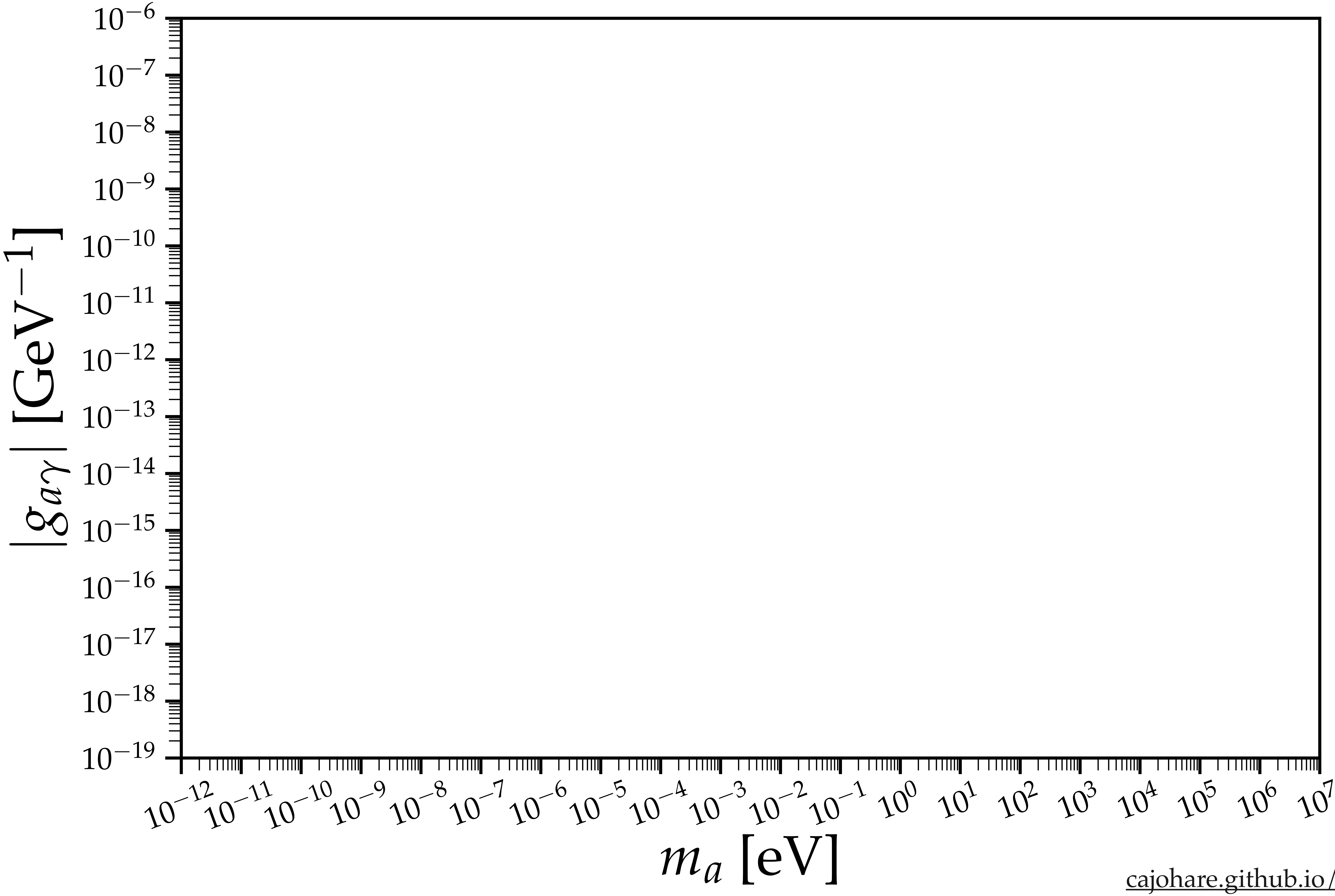

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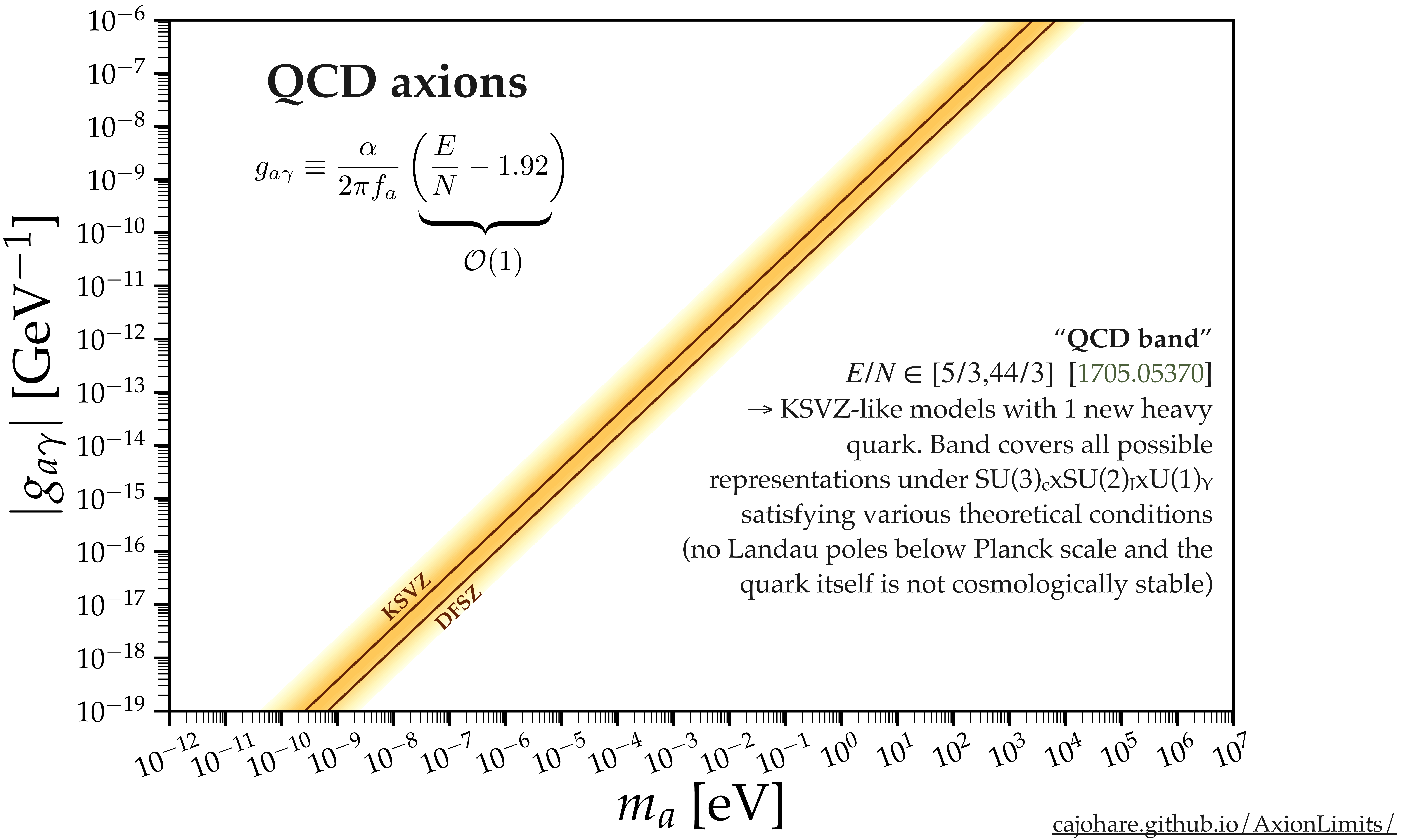
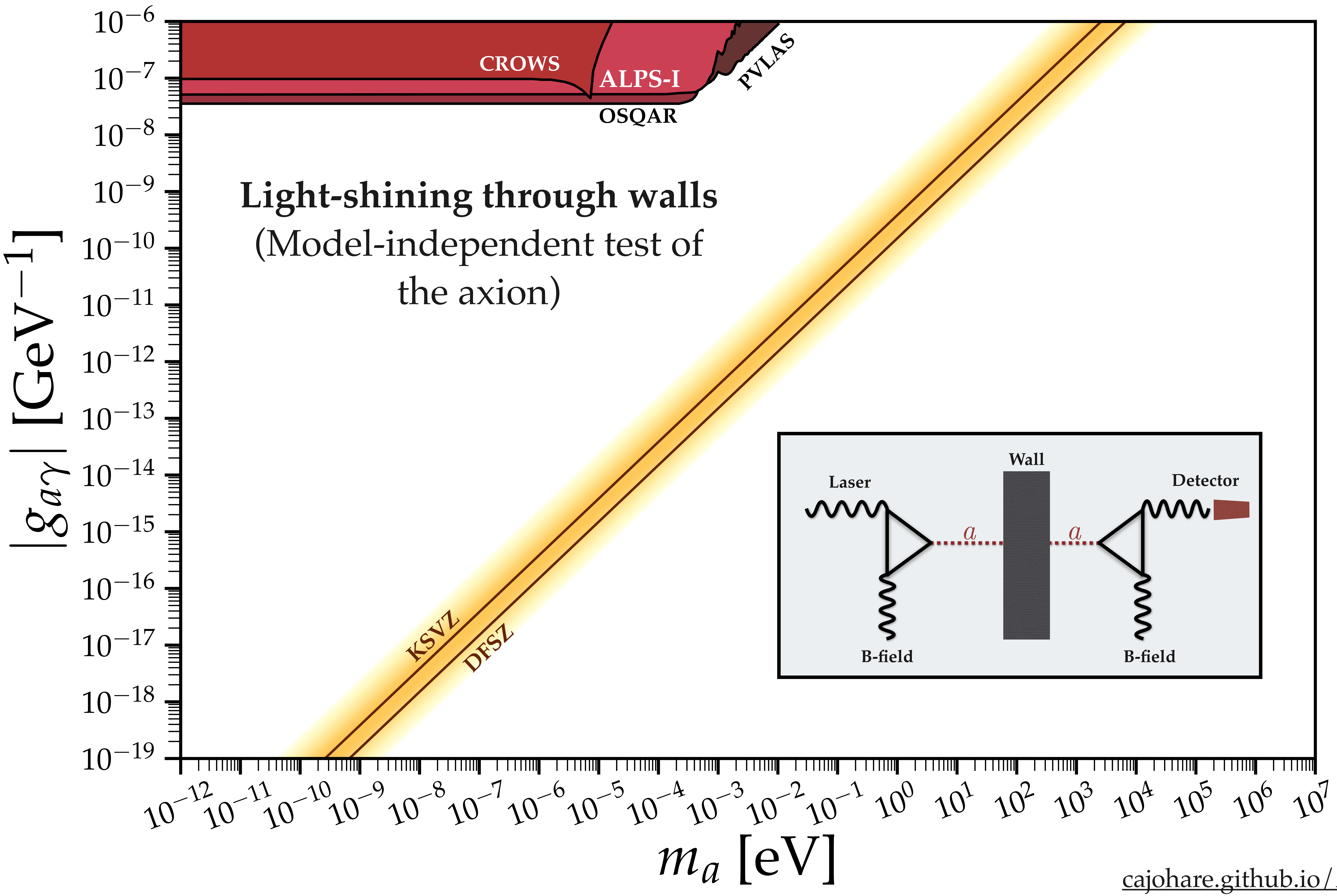


QCD axions
$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a}\underbrace{\left(\frac{E}{N} - 1.92\right)}_{\mathcal{O}(1)}$
"QCD band"
$E/N \in [5/3, 44/3]$ [1705.05370]
→ KSVZ-like models with 1 new heavy quark. Band covers all possible representations under SU(3)cxSU(2)LxU(1)Y satisfying various theoretical conditions (no Landau poles below Planck scale and the quark itself is not cosmologically stable)
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
cajohare.github.io/AxionLimits/



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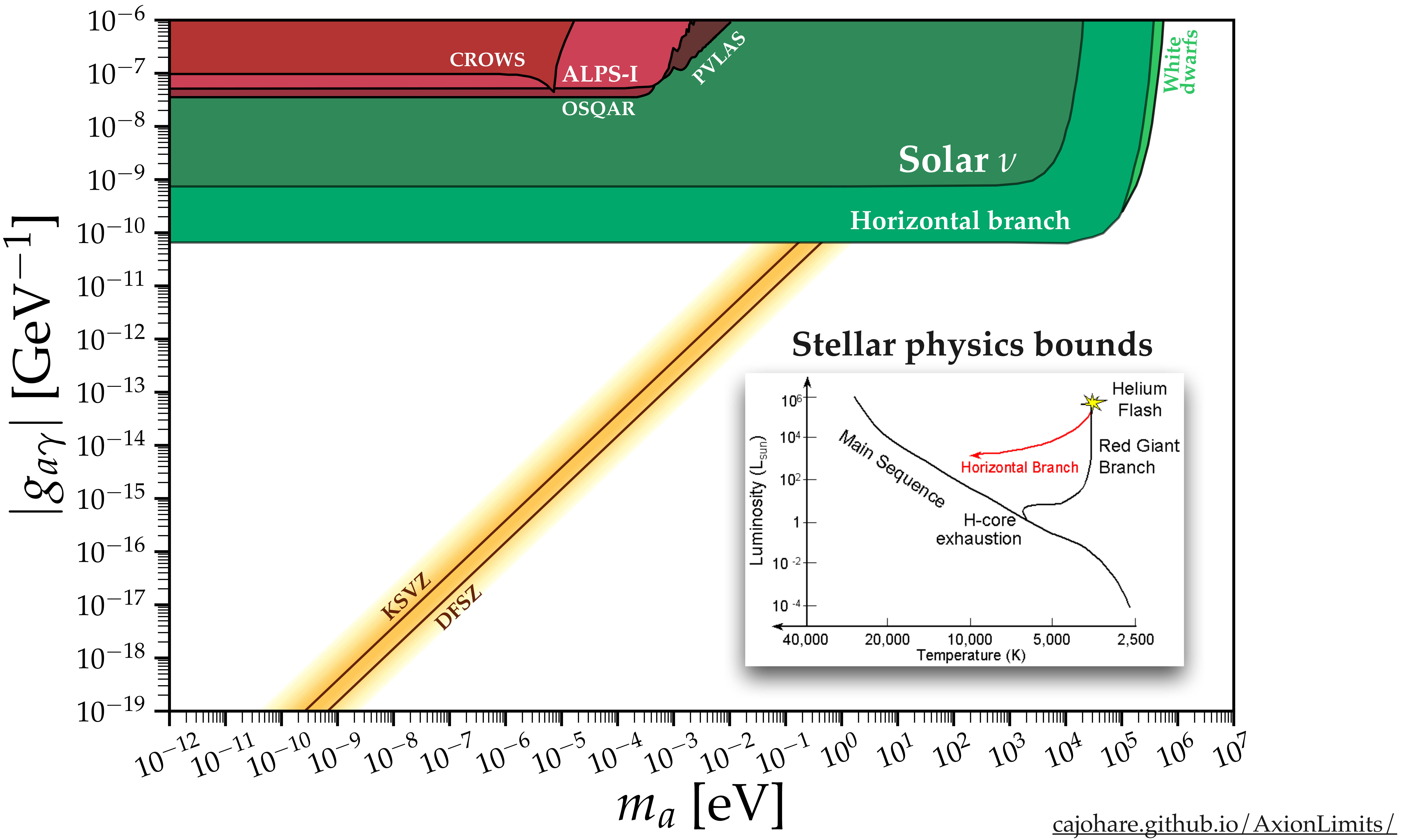

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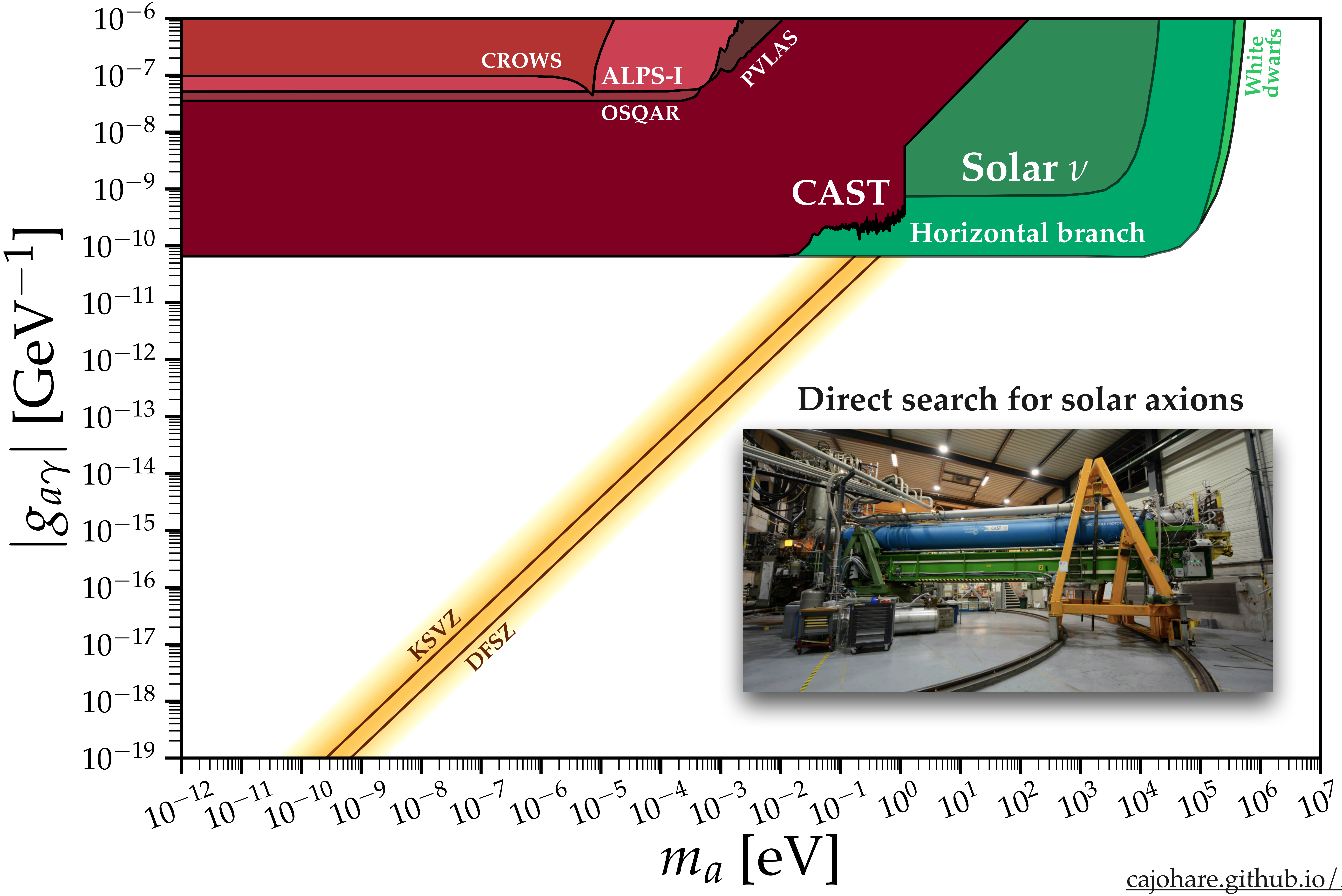

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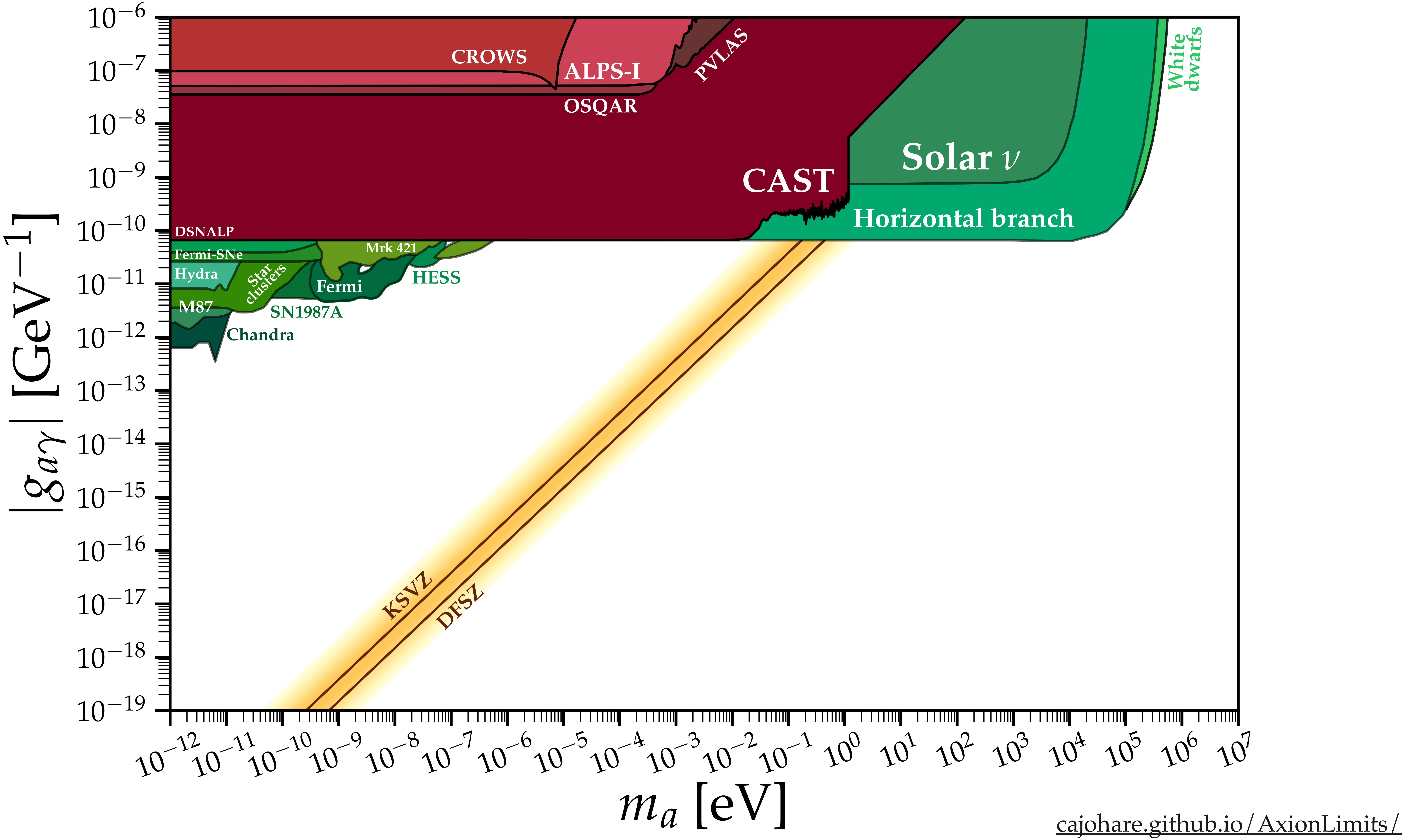
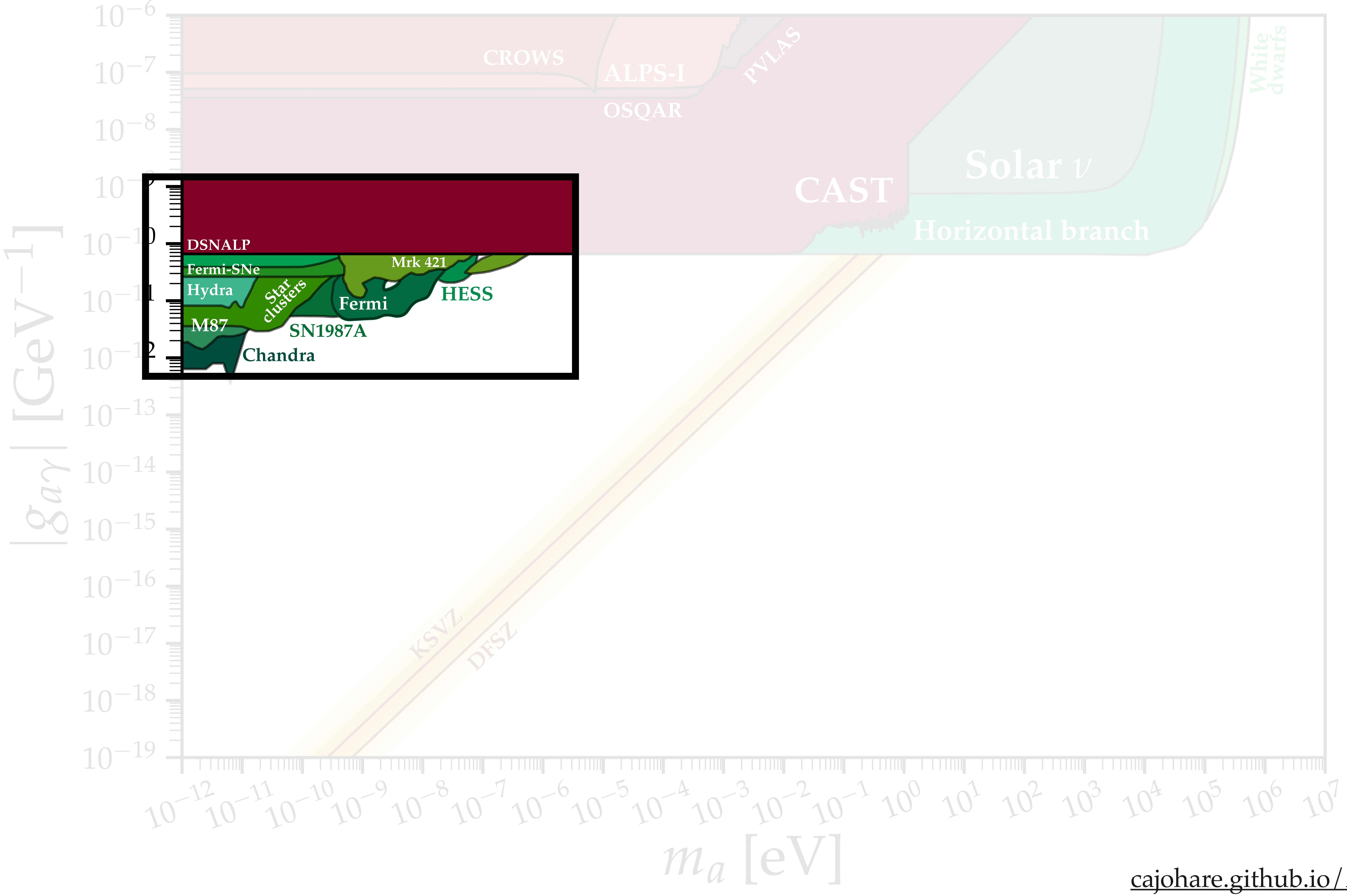
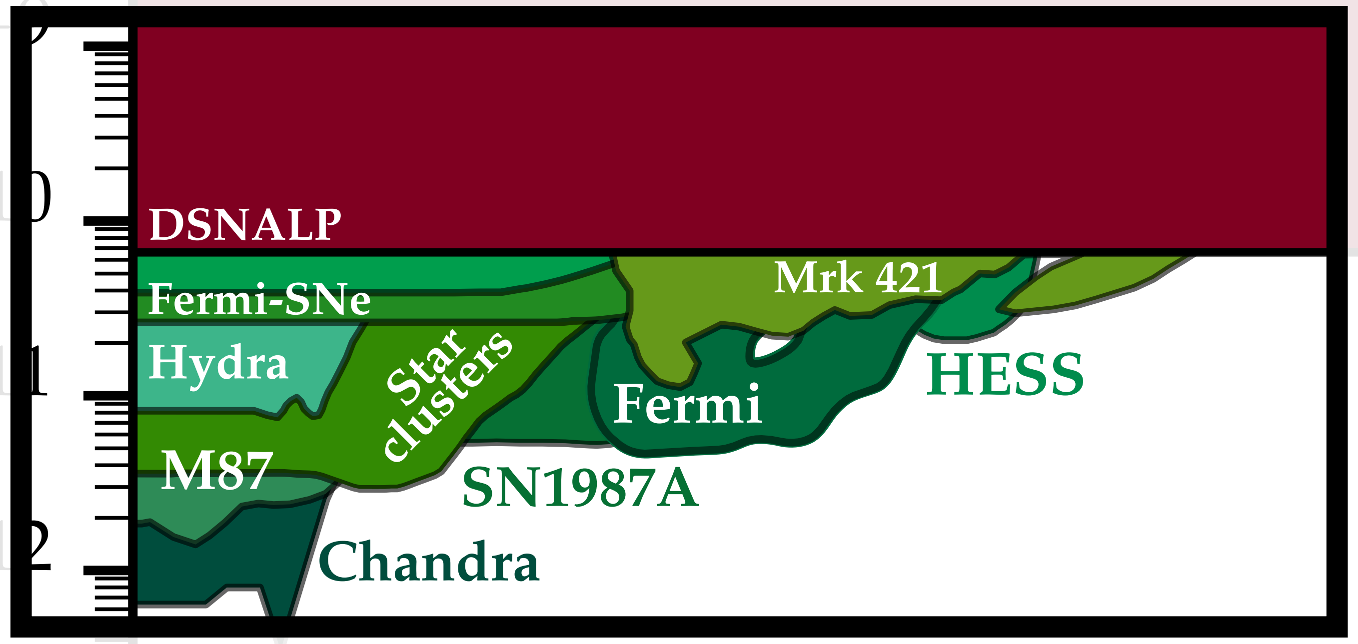
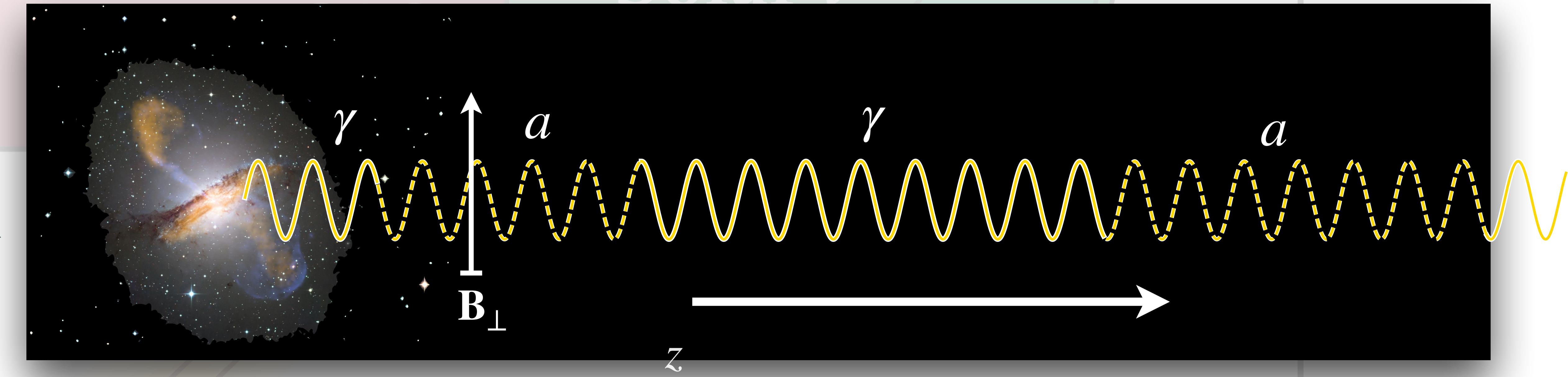

CROWS
ALPS-I
PVLAS
OSQAR
Solar ν
CAST
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
HESS
M87
SN1987A
Chandra
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
cajohare.github.io/AxionLimits/

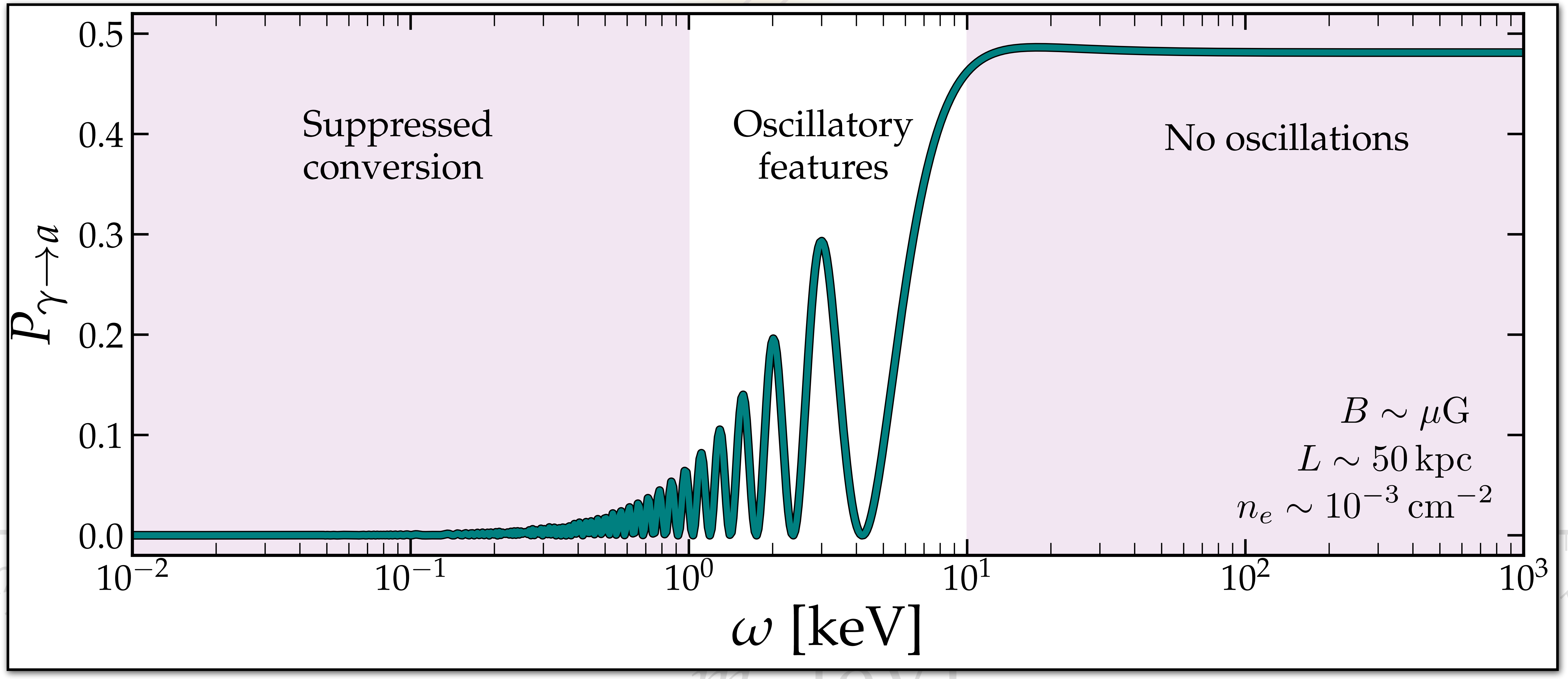


cajohare.github.io/AxionLimits/

Light ALP-photon oscillations in astrophysical B-fields (Galaxies, galaxy clusters, and the Milky Way)







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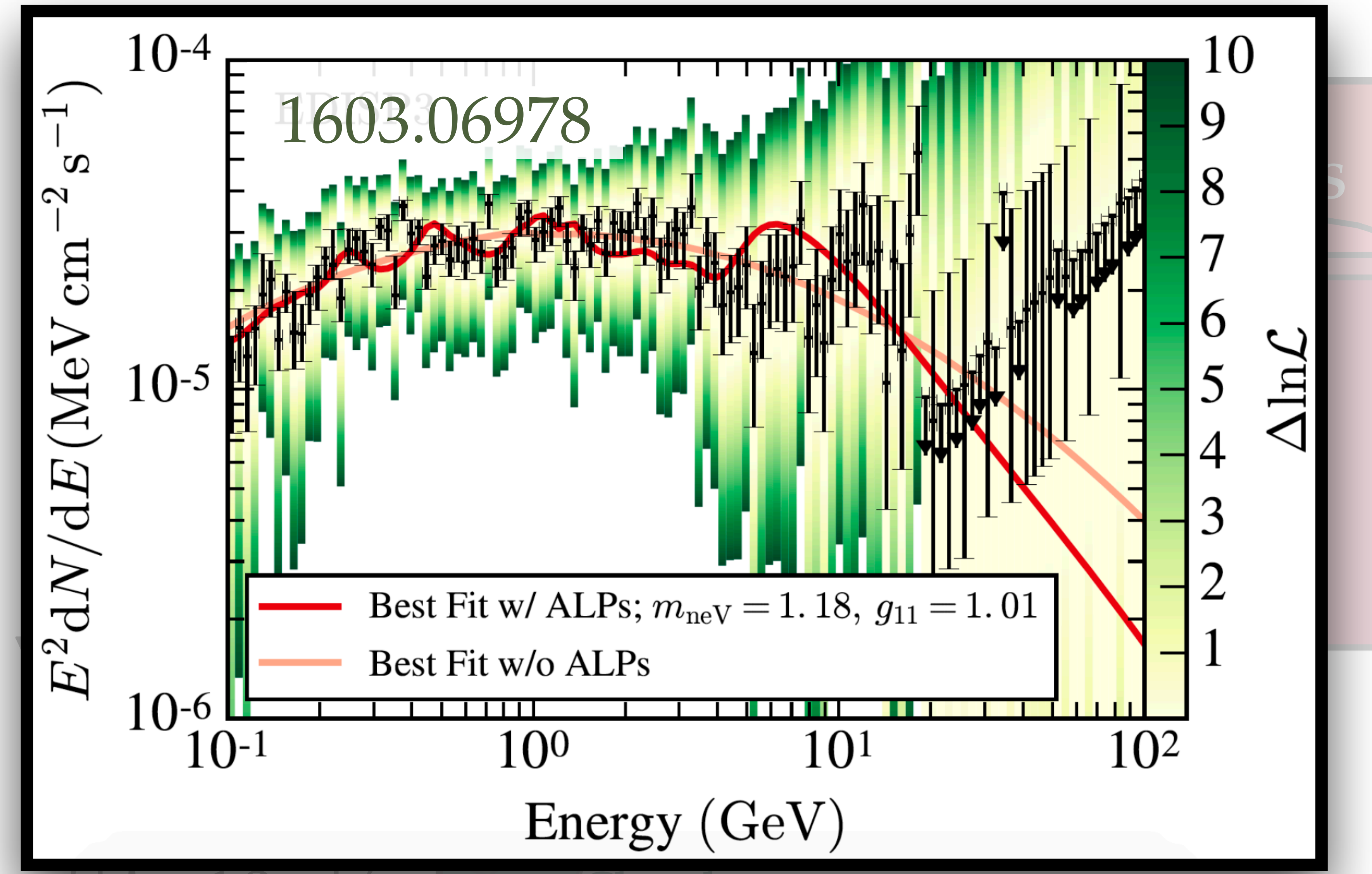
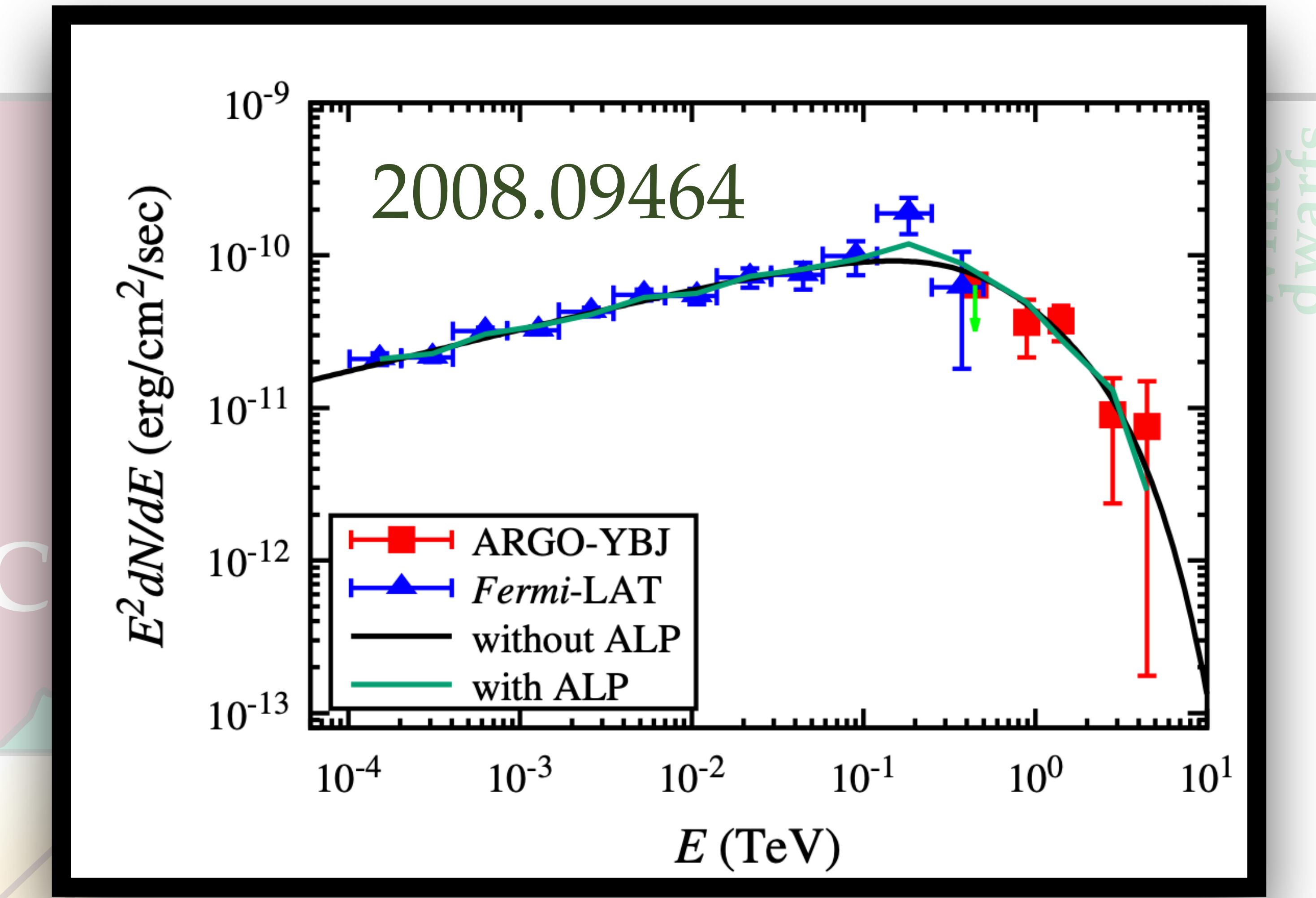
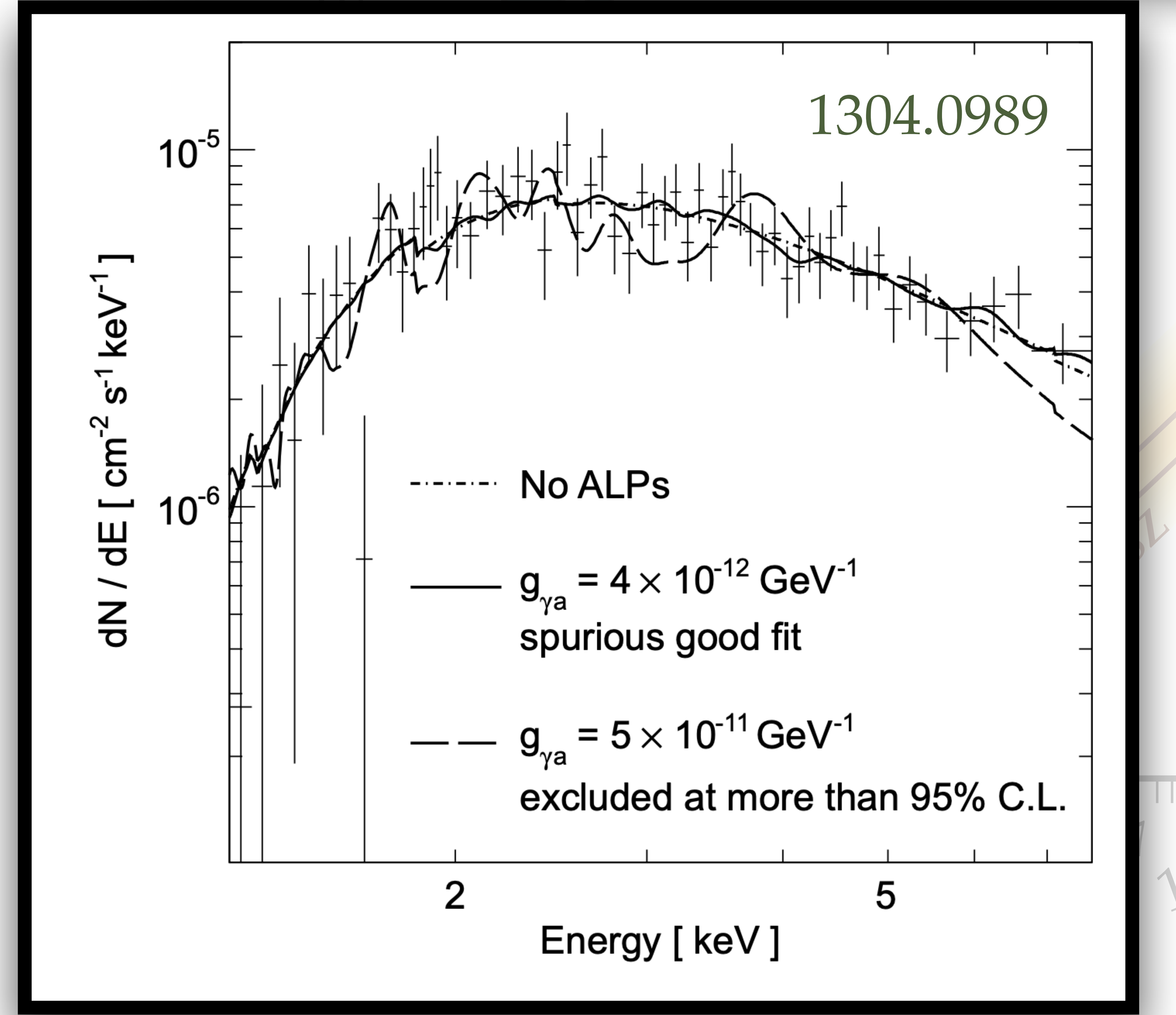
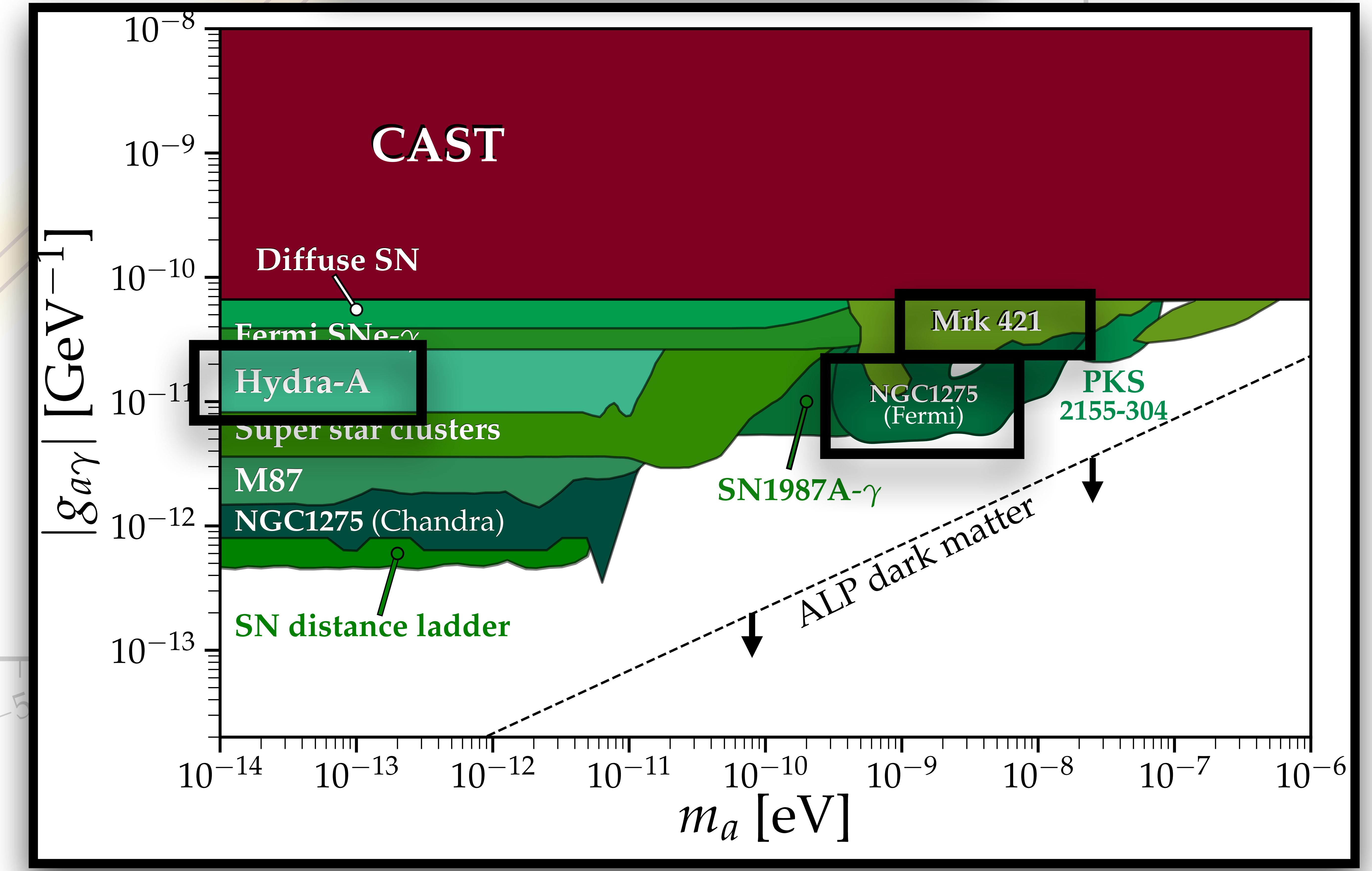
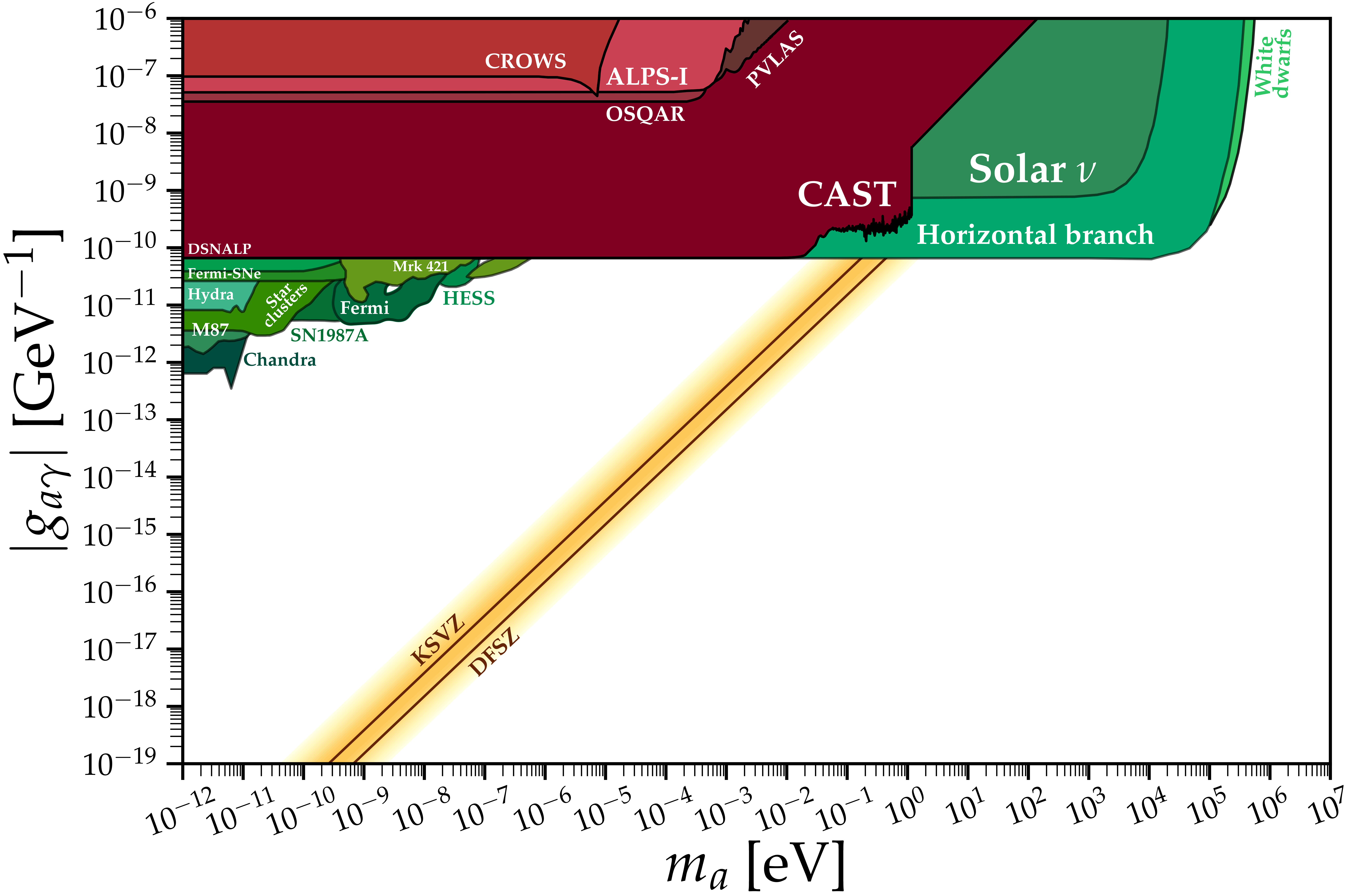

1603.06978
Best Fit w/ ALPs; $m_{\rm neV} = 1.18$, $g_{11} = 1.01$
Best Fit w/o ALPs
Energy (GeV)
$E^2 dN/dE$ (MeV cm^{-2} s^{-1})
$\Delta \ln \mathcal{L}$


2008.09464
ARGO-YBJ
Fermi-LAT
without ALP
with ALP
E (TeV)
$E^2 dN/dE$ (erg/cm^2/sec)


1304.0989
No ALPs
$g_{\gamma a} = 4 \times 10^{-12}$ GeV^{-1}
spurious good fit
$g_{\gamma a} = 5 \times 10^{-11}$ GeV^{-1}
excluded at more than 95% C.L.
Energy [keV]
dN / dE [cm^{-2} s^{-1} keV^{-1}]


CAST
Diffuse SN
Fermi SNe-γ
Hydra-A
Super star clusters
M87
NGC1275 (Chandra)
SN distance ladder
Mrk 421
NGC1275
(Fermi)
PKS
2155-304
SN1987A-γ
ALP dark matter
m_a [eV]
$|g_{a\gamma}|$ [GeV^{-1}]



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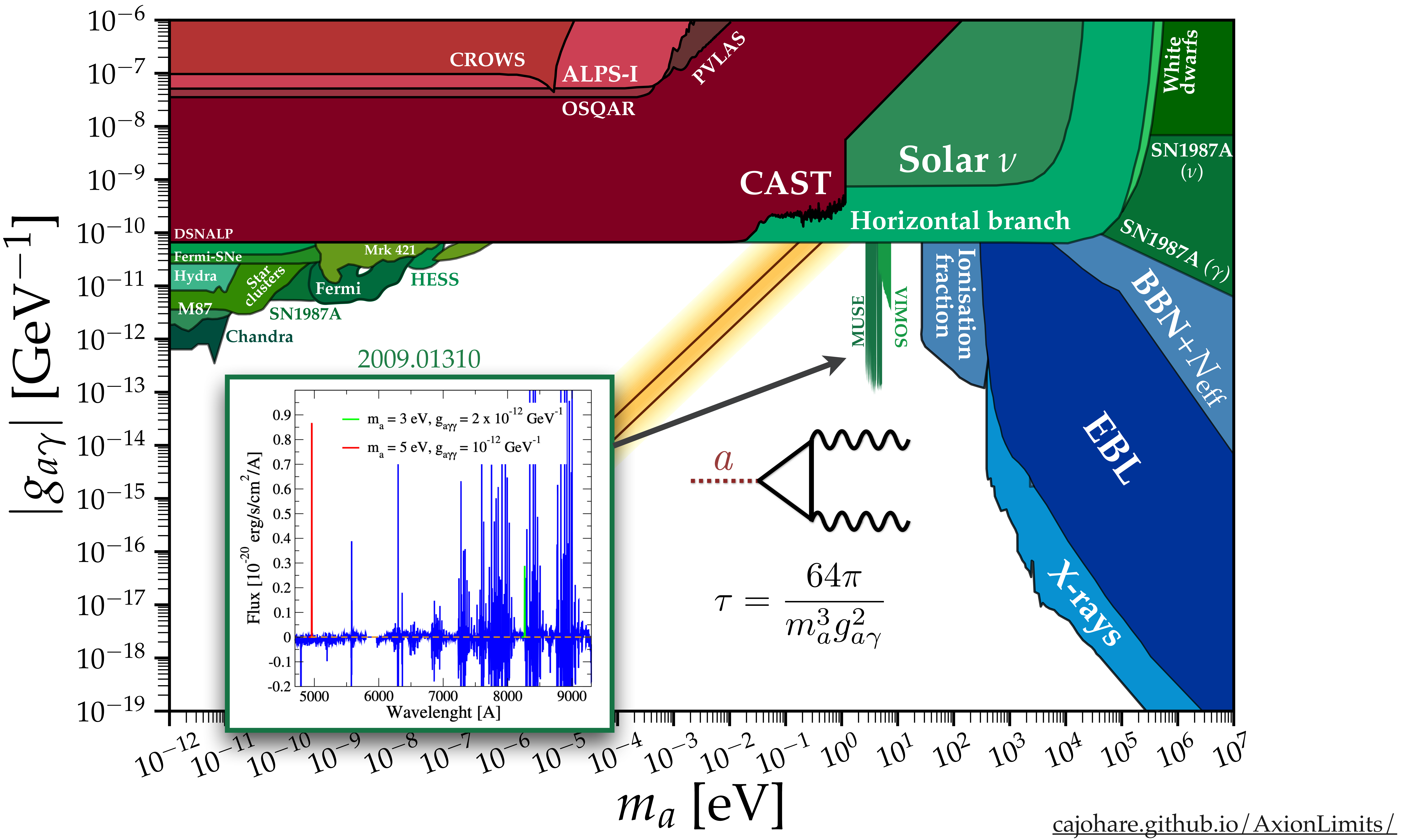
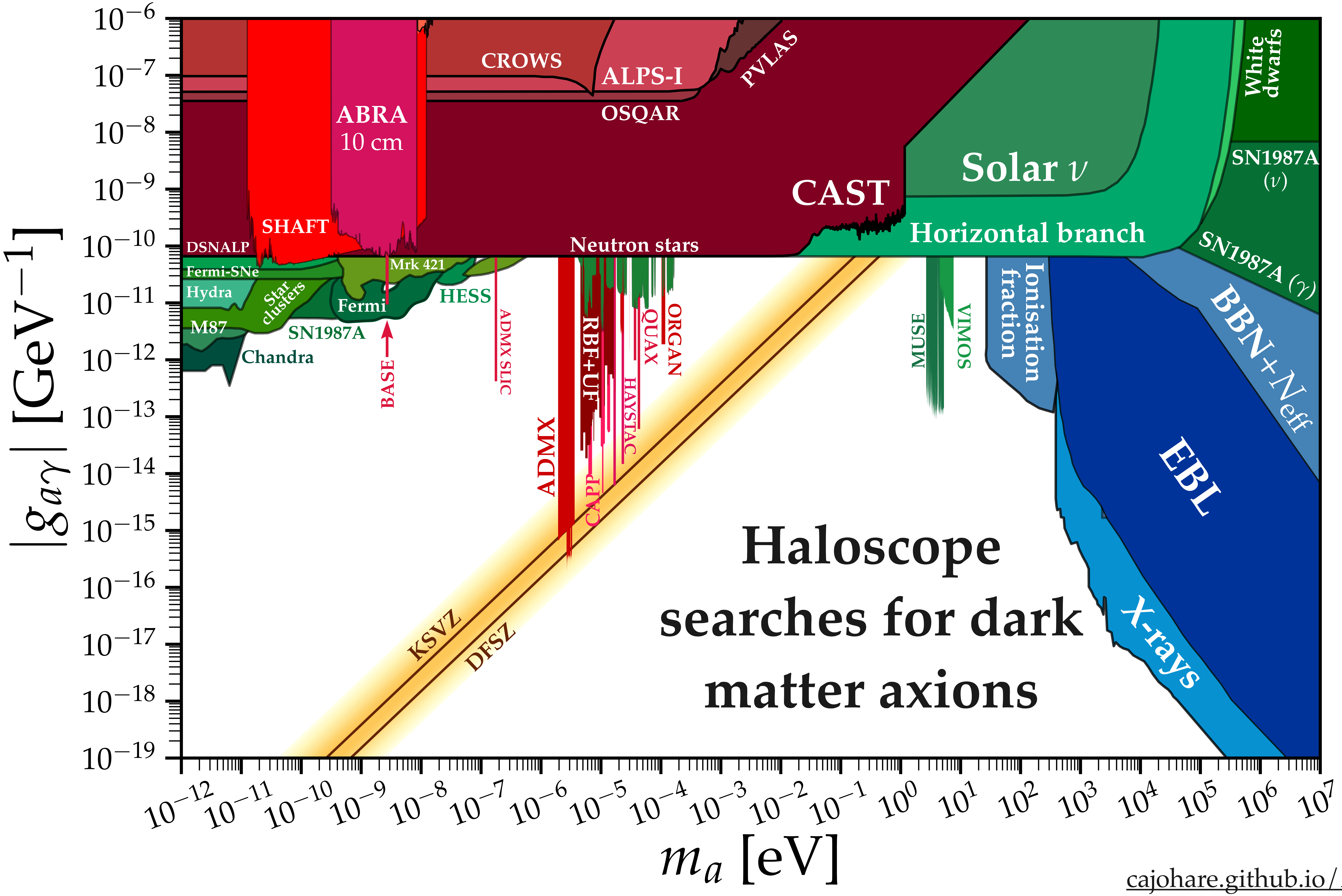
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



CROWS
ALPS-I
PVLAS
OSQAR
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
MUSE
VIMOS
Ionisation fraction
BBN+N_{eff}
EBL
X-rays
2009.01310
m_a = 3 eV, $g_{a\gamma\gamma}$ = 2 x 10^{-12} GeV^{-1}
m_a = 5 eV, $g_{a\gamma\gamma}$ = 10^{-12} GeV^{-1}
Flux [10^{-20} erg/s/cm^2/A]
Wavelenght [A]
a
$\tau = \frac{64\pi}{m_a^3 g_{a\gamma}^2}$
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
cajohare.github.io/AxionLimits/



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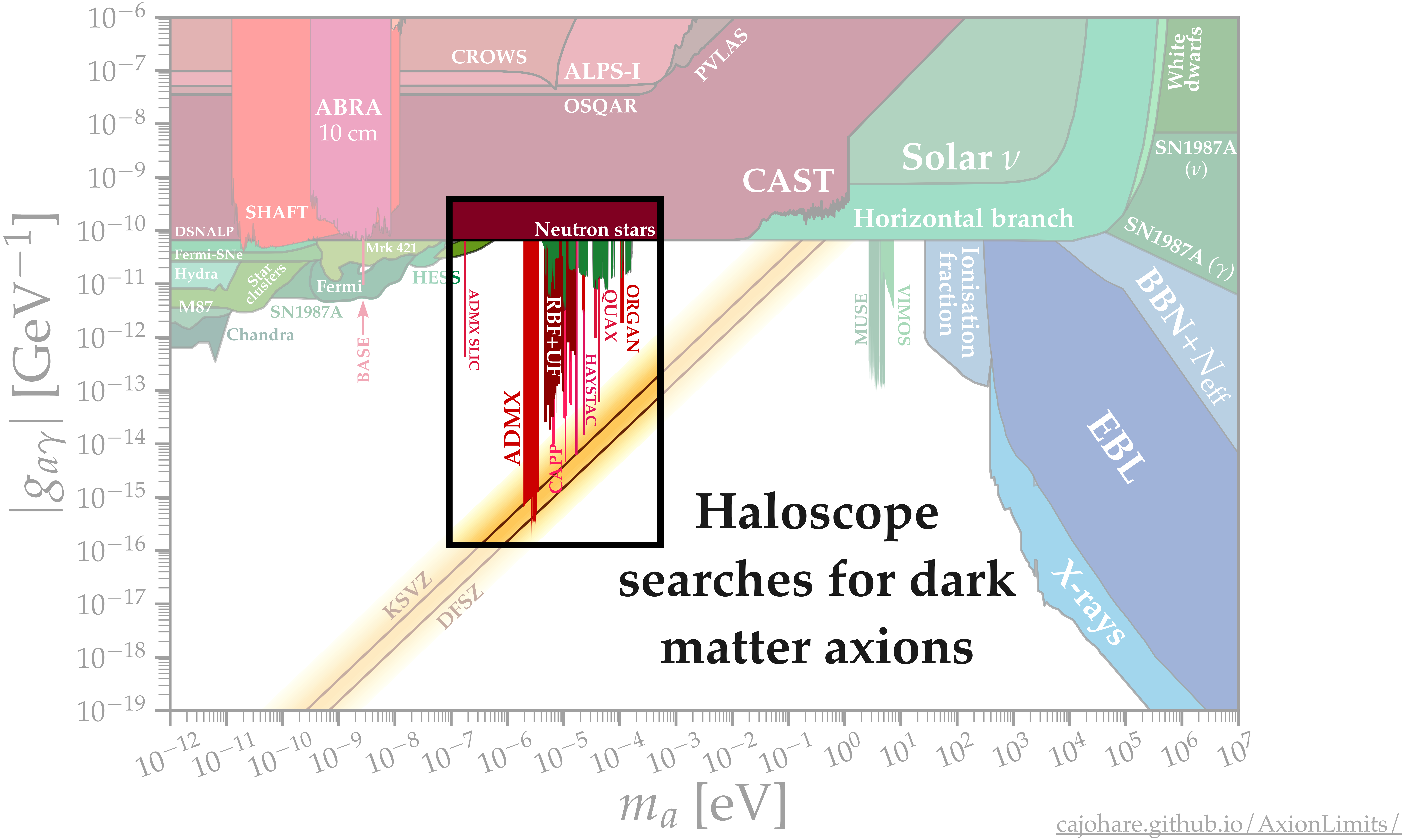

CROWS
ALPS-I
PVLAS
OSQAR
ABRA 10 cm
SHAFT
DSNALP
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
Neutron stars
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
HESS
M87
SN1987A
Chandra
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
BBN+Neff
EBL
X-rays
KSVZ
DFSZ
Haloscope searches for dark matter axions
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
cajohare.github.io/AxionLimits/

Dark matter axions

Dark matter axions

behave like a classical field : $a(\mathbf{x}, t) \approx \frac{\sqrt{2\rho_a}}{m_a} \cos\left(\omega t - \mathbf{p} \cdot \mathbf{x} + \alpha\right)$

$\omega \approx m_a$

Oscillating at the axion mass

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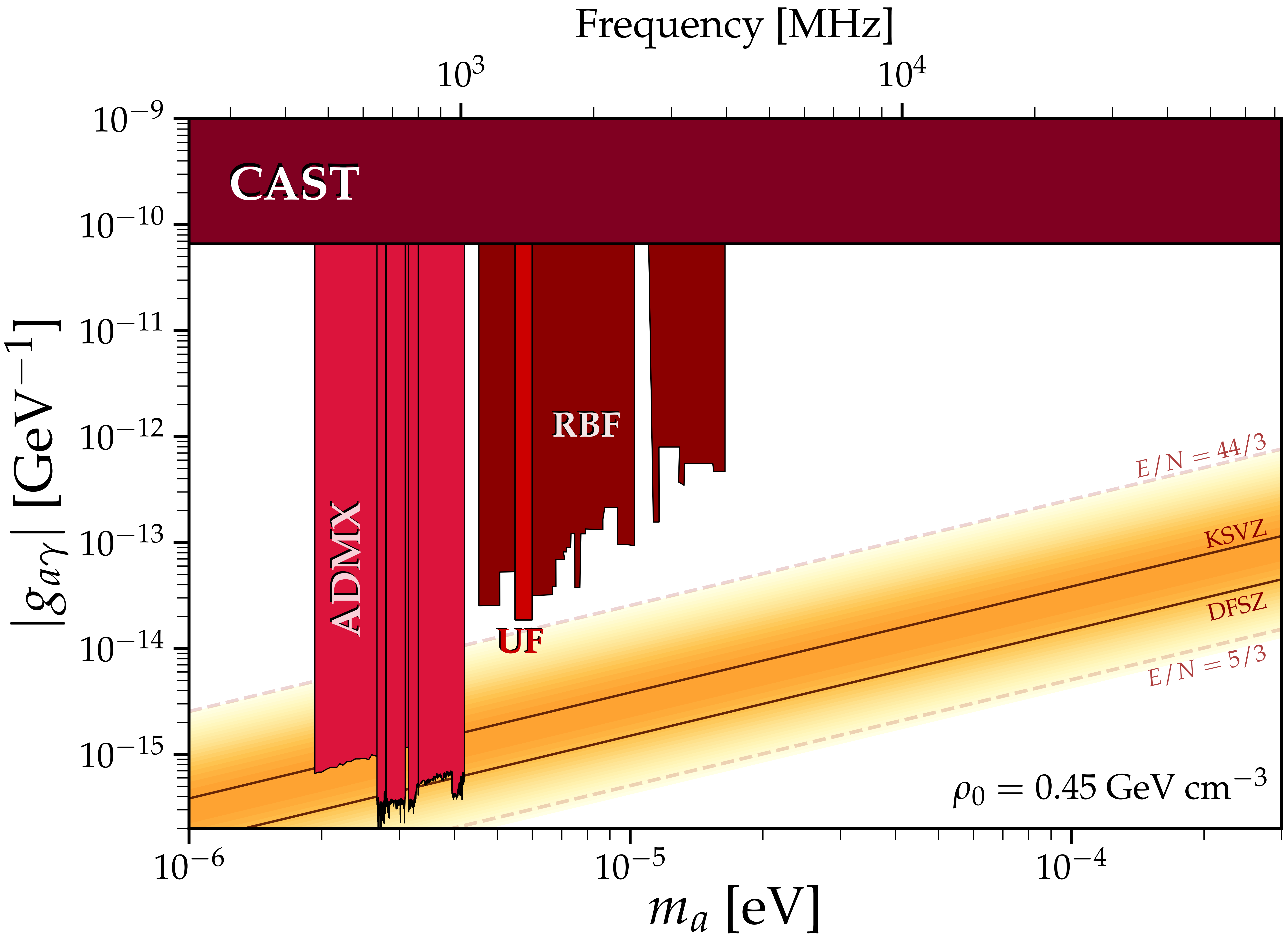
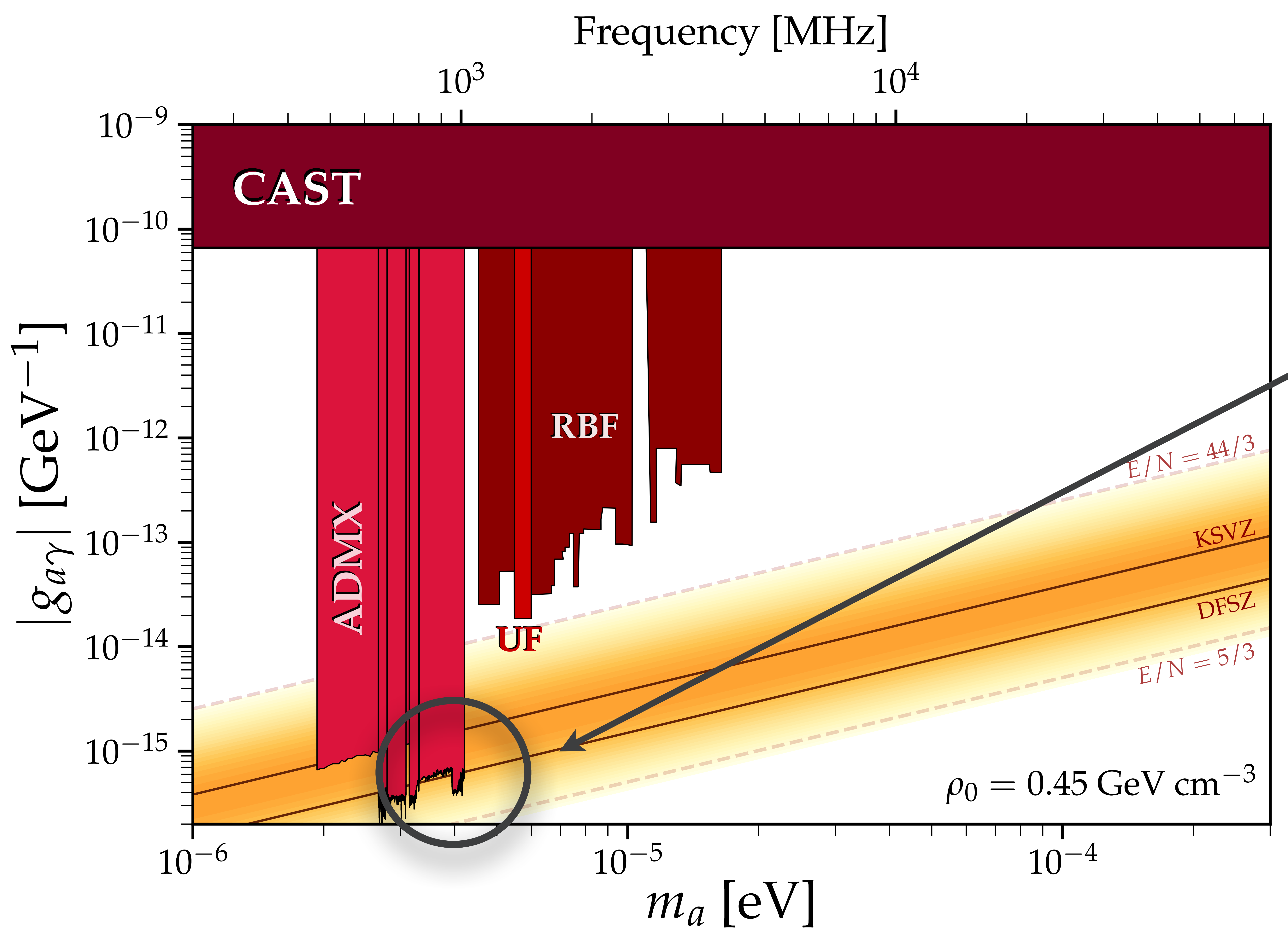
Oscillating at the axion mass

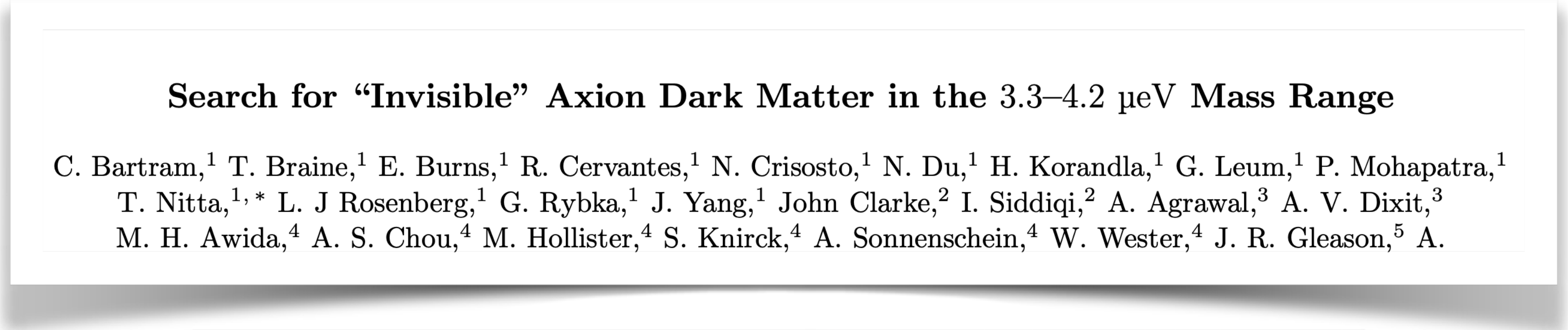


cajohare.github.io/AxionLimits/



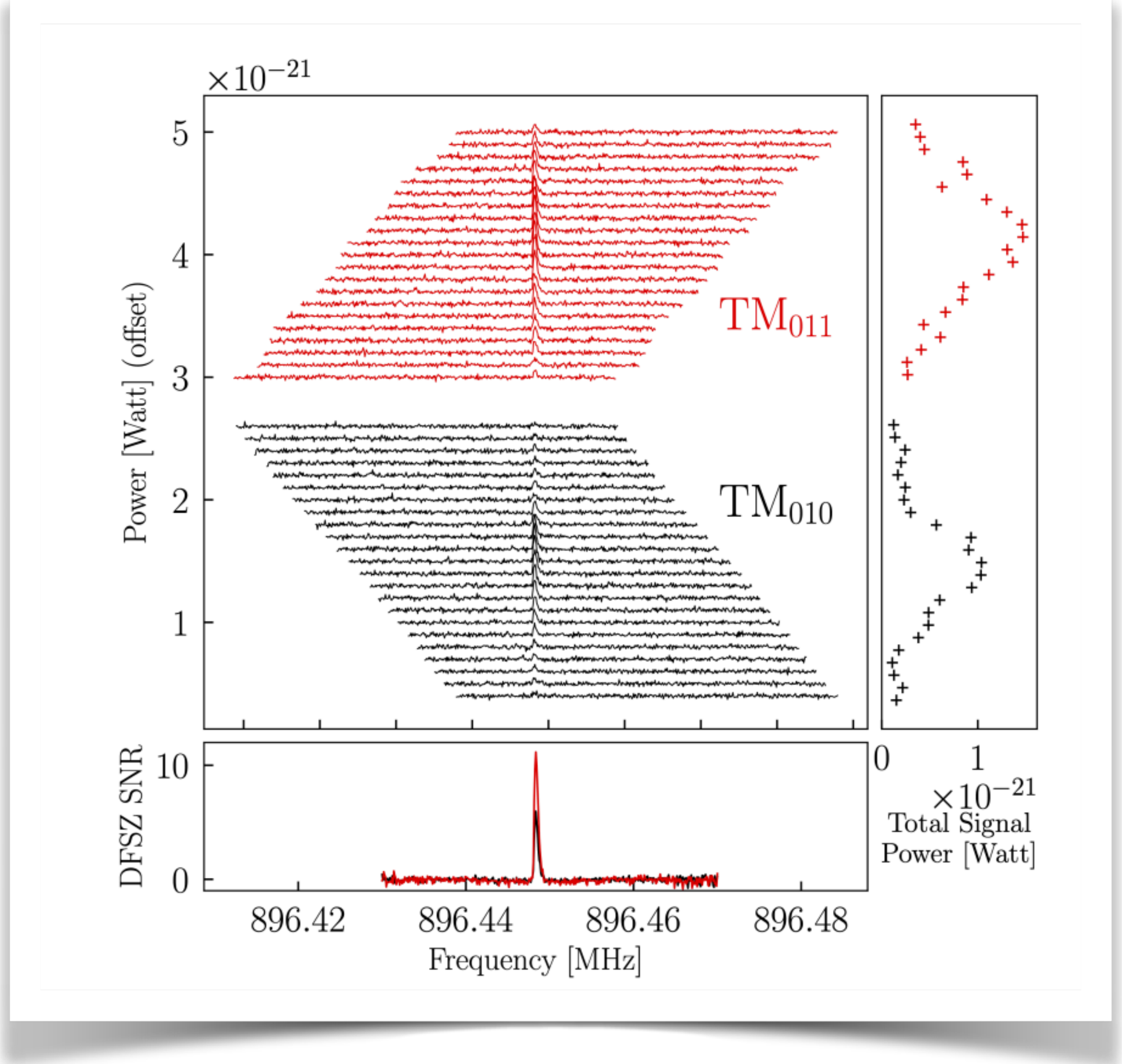
Brand new!

ADMX constrains DFSZ axions above 3 μeV [2110.06096]



Search for "Invisible" Axion Dark Matter in the 3.3–4.2 μeV Mass Range

C. Bartram,[1] T. Braine,[1] E. Burns,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] H. Korandla,[1] G. Leum,[1] P. Mohapatra,[1] T. Nitta,[1,*] L. J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] John Clarke,[2] I. Siddiqi,[2] A. Agrawal,[3] A. V. Dixit,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S. Knirck,[4] A. Sonnenschein,[4] W. Wester,[4] J. R. Gleason,[5] A.



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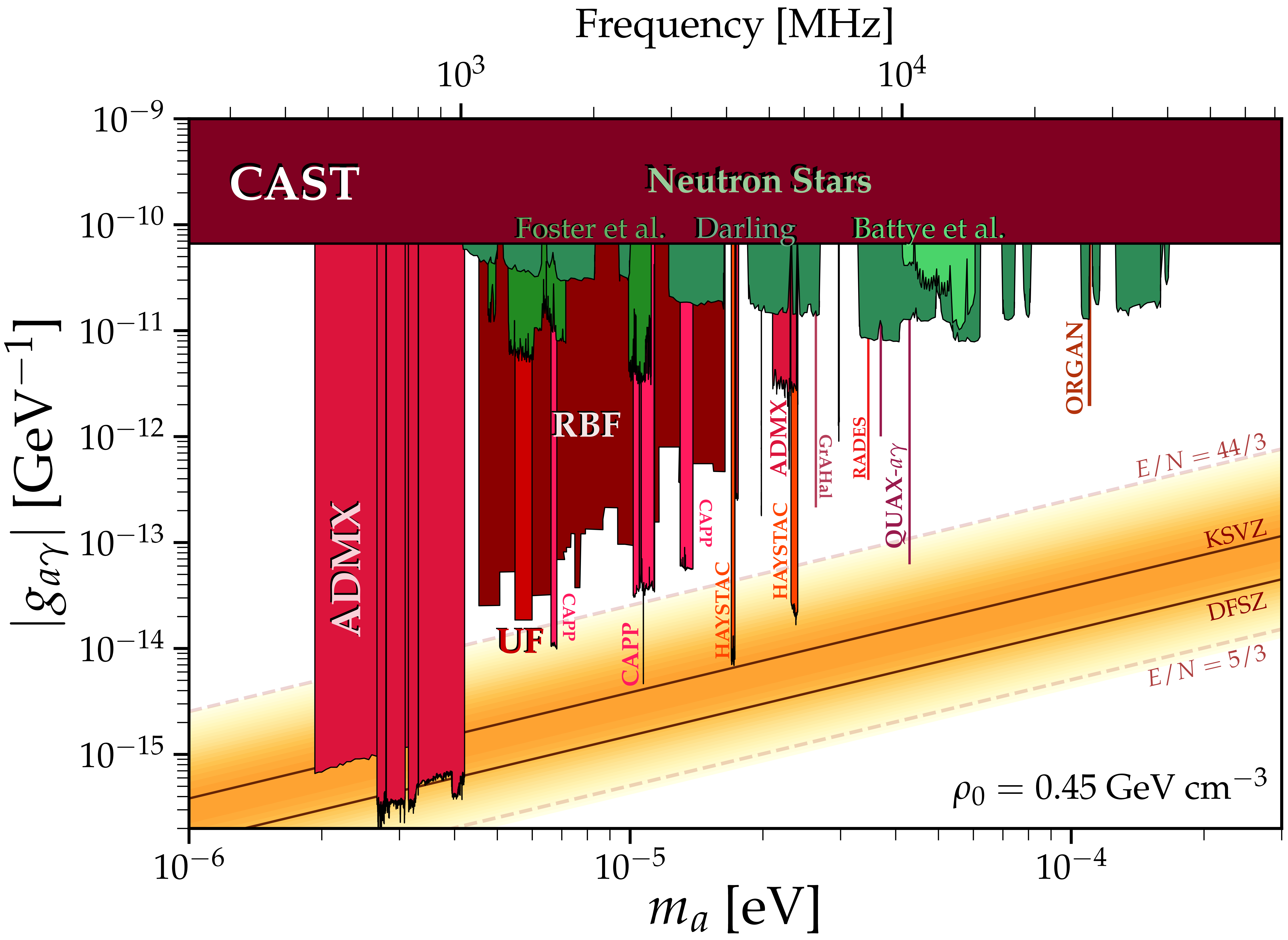
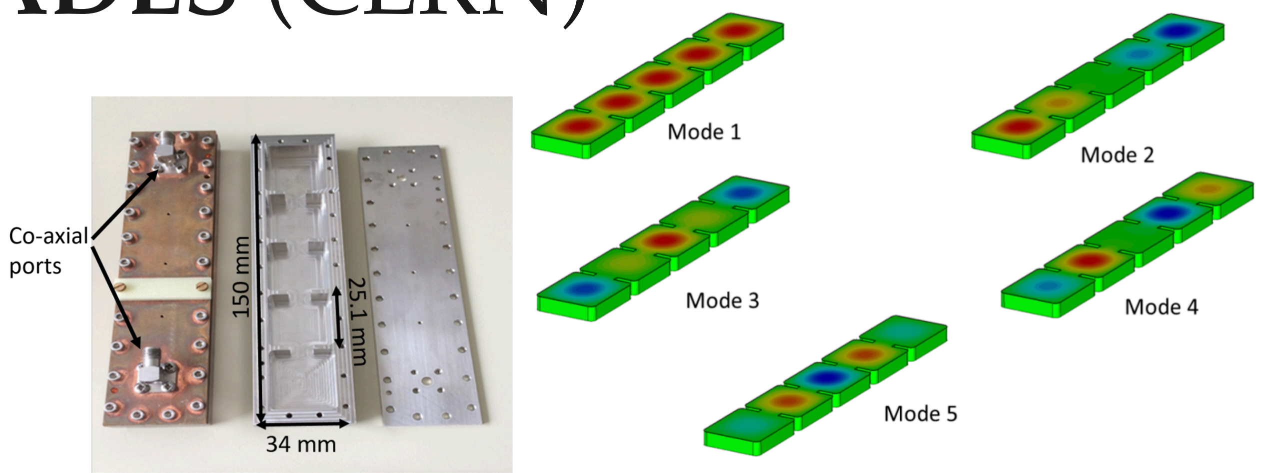
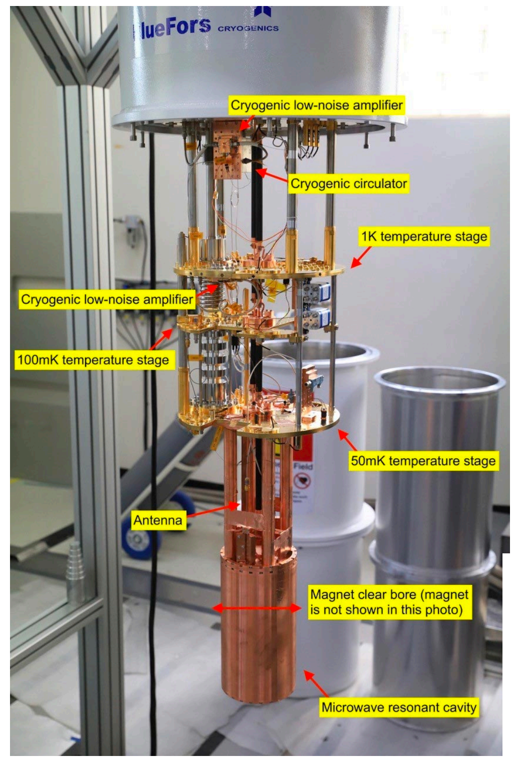


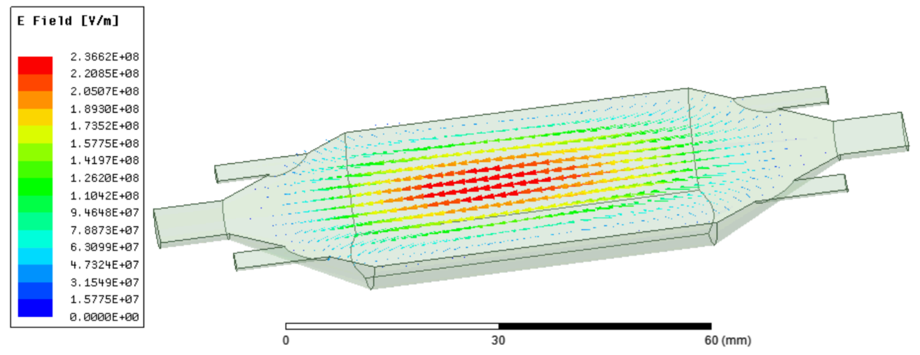
RADES (CERN)



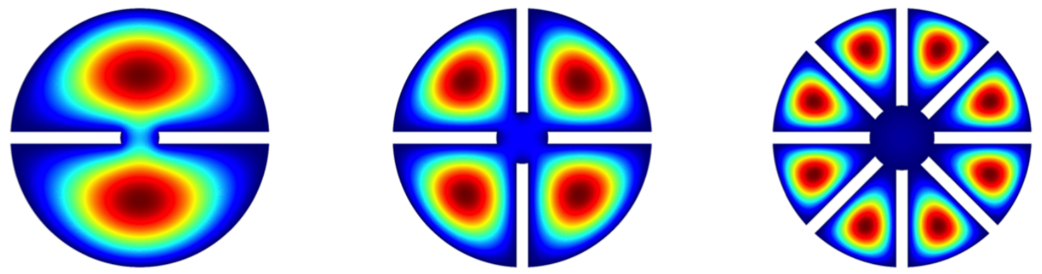
ORGAN (UWA)



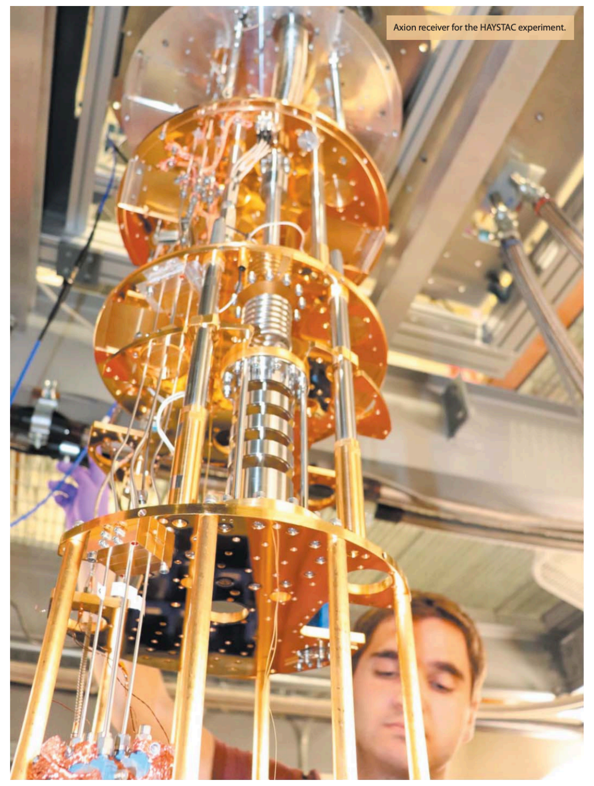
QUAX (Frascati)



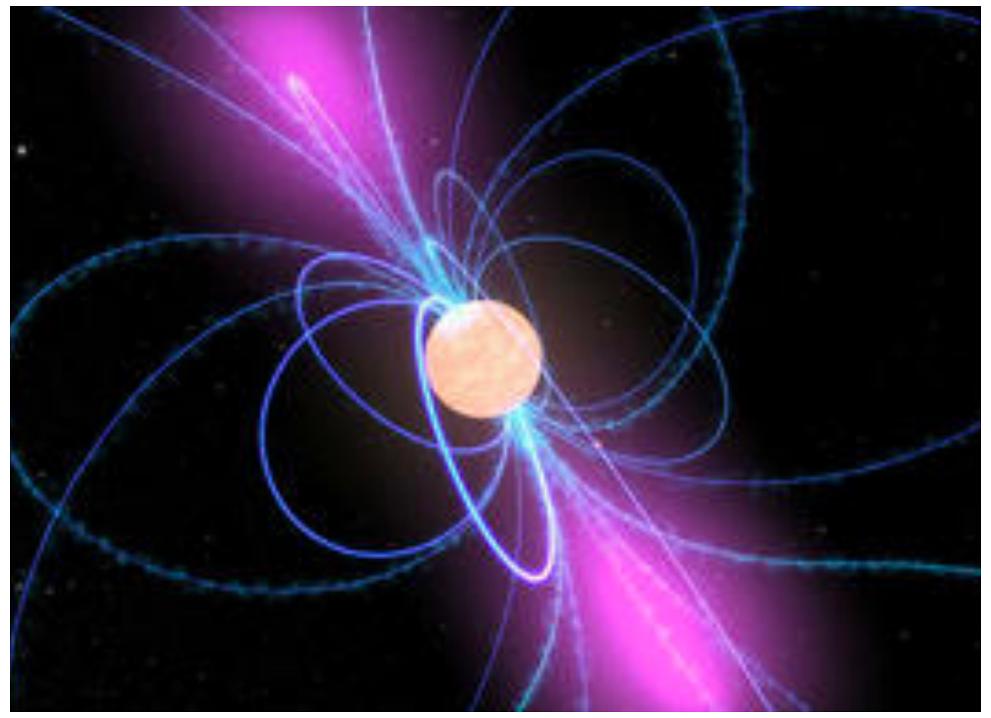
CAPP (IBS)



HAYSTAC (Yale)

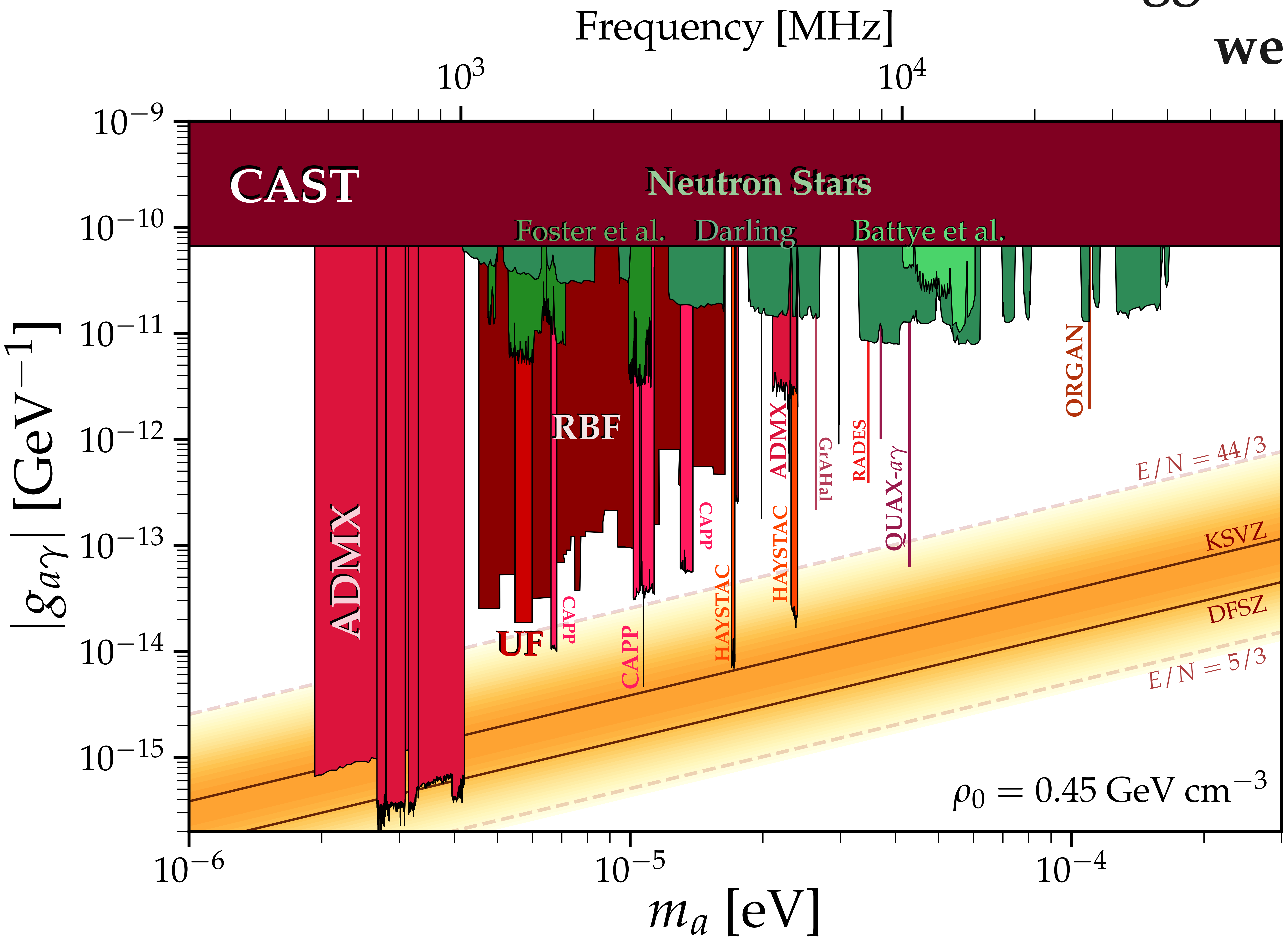


Neutron stars



cajohare.github.io/AxionLimits/

Biggest challenge right now is that we don't know the axon mass



Sensitivity:

$$g_{a\gamma} \propto T^{-1/4}$$

Will take a long time to cover DFSZ from μeV —100 μeV

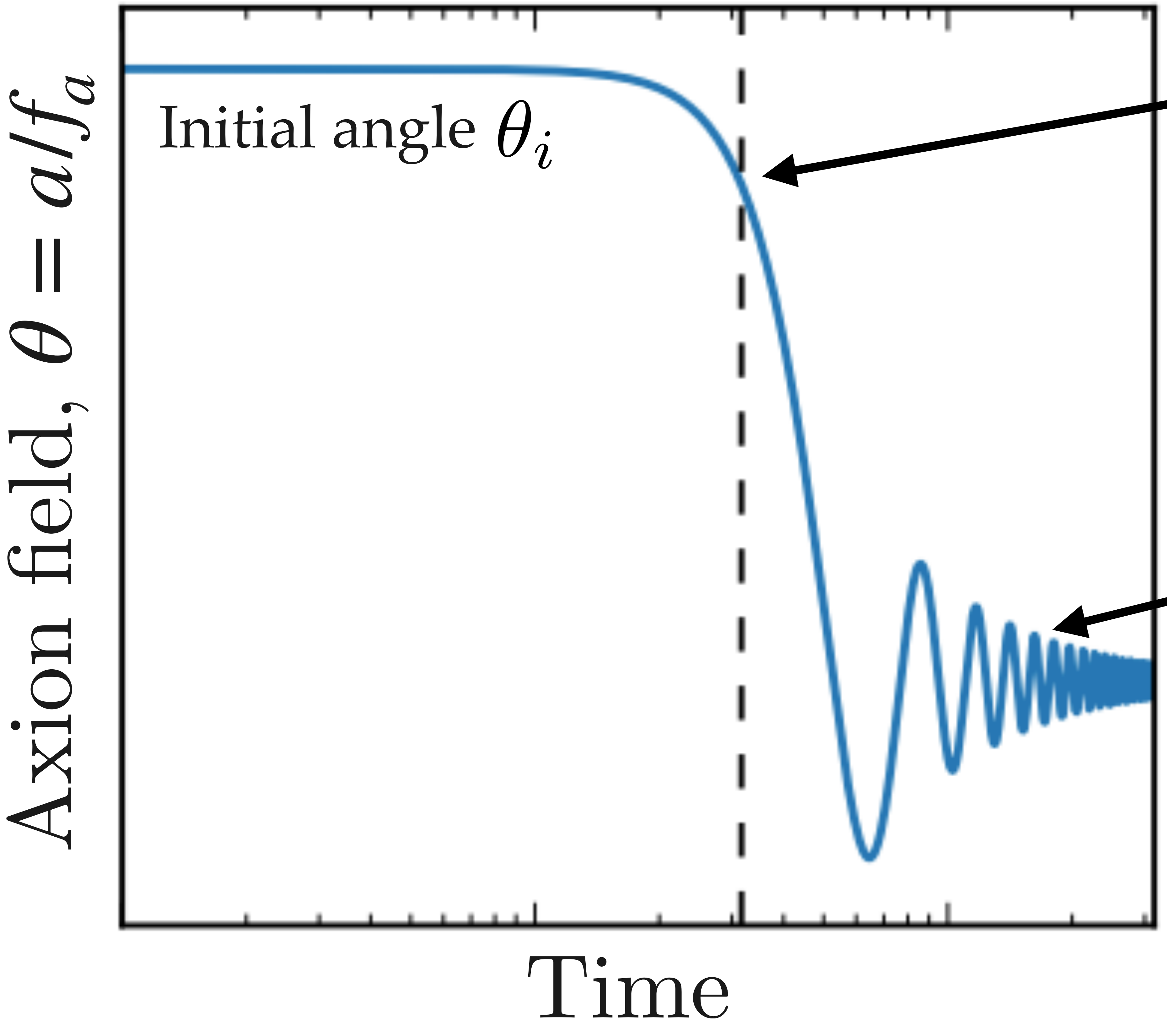
cajohare.github.io/AxionLimits/

How good are our chances of detecting the axion?

For the sake of argument, let's assume that a canonical QCD axion model to make up 100% of dark matter

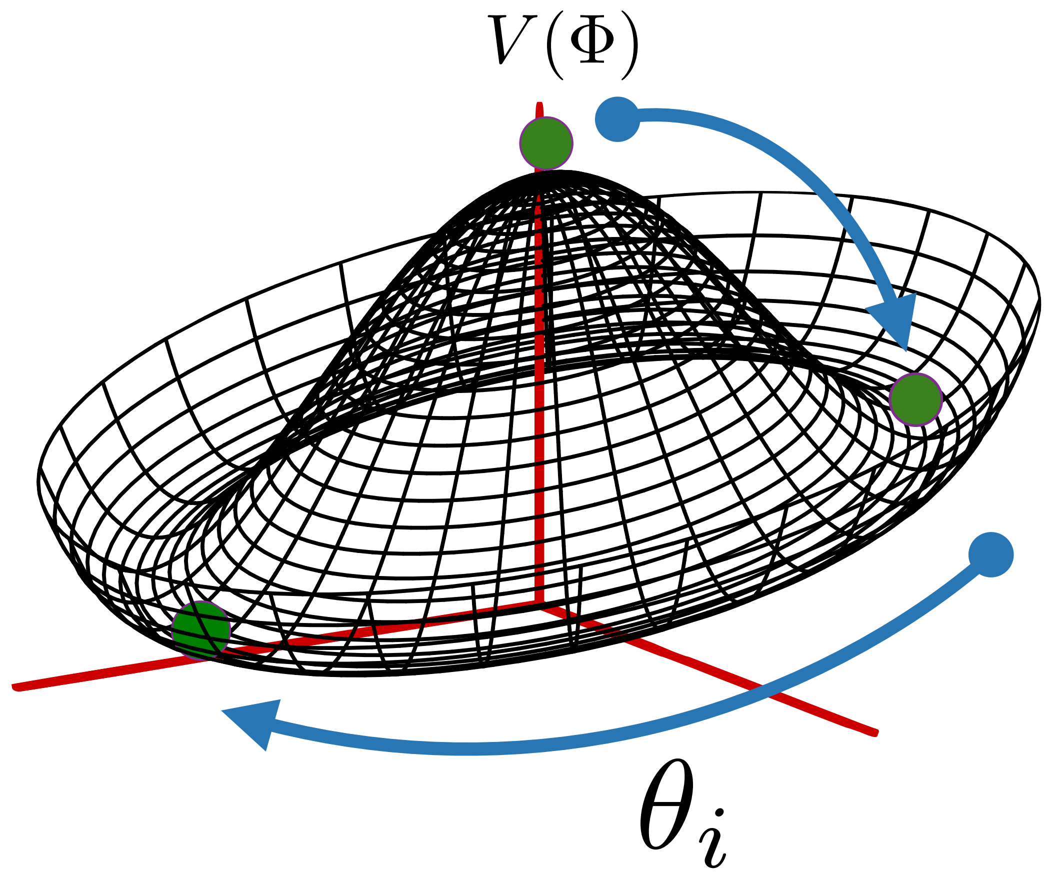
Predicting the mass of the axion with cosmology: Misalignment mechanism

$$\ddot{a} + 3H\dot{a} + \frac{\partial \mathcal{V}(a)}{\partial a} = 0 \quad \text{where,} \quad \mathcal{V}(a) \approx \frac{1}{2} m_a^2 a^2$$

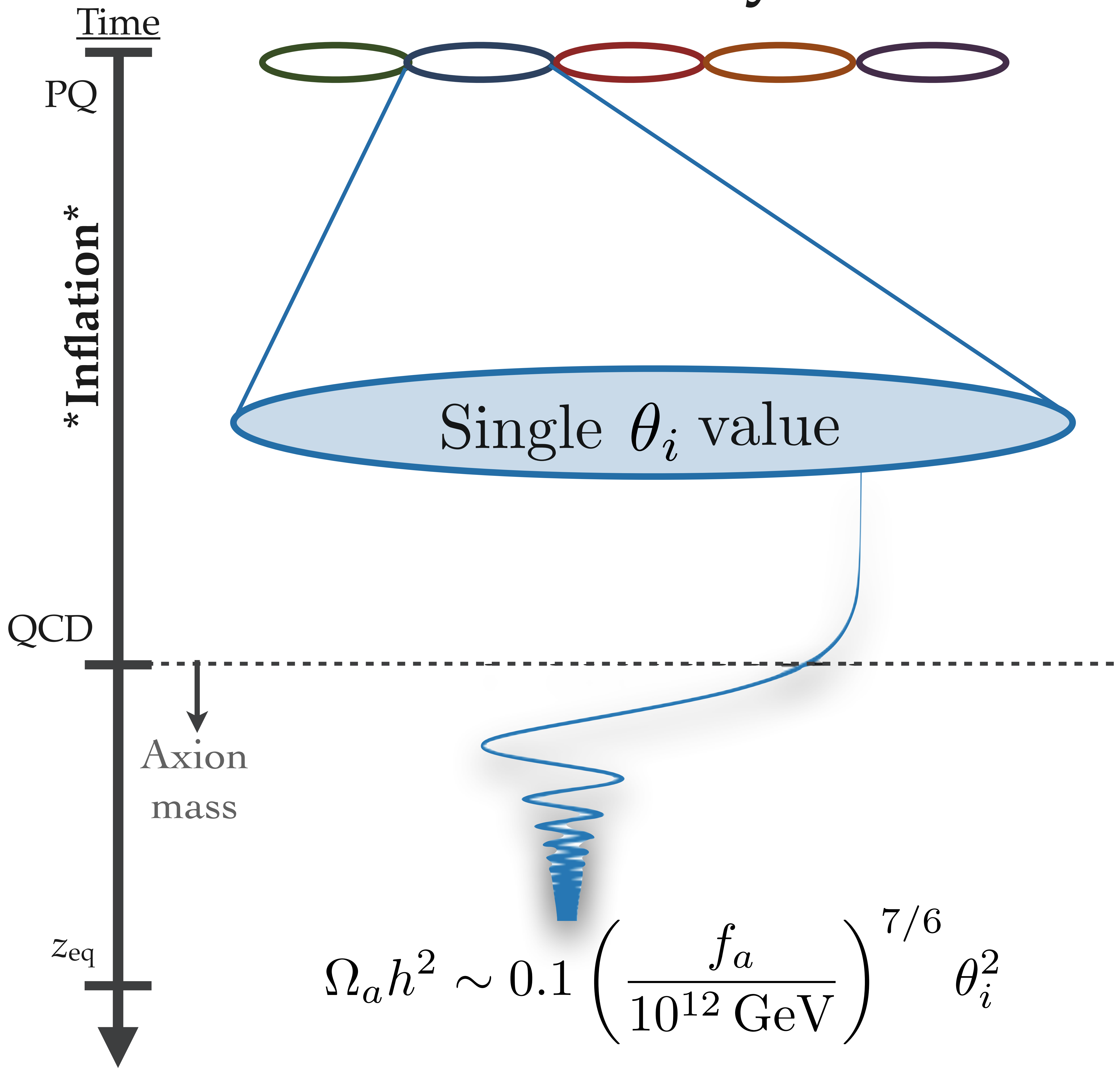


$m_a(t) \approx 3H(t)$
Axion field rolls down potential

$m_a(t) \gtrsim 3H(t)$
Axion field starts damped oscillations with frequency $\sim m_a$
→ **cold axions dark matter**

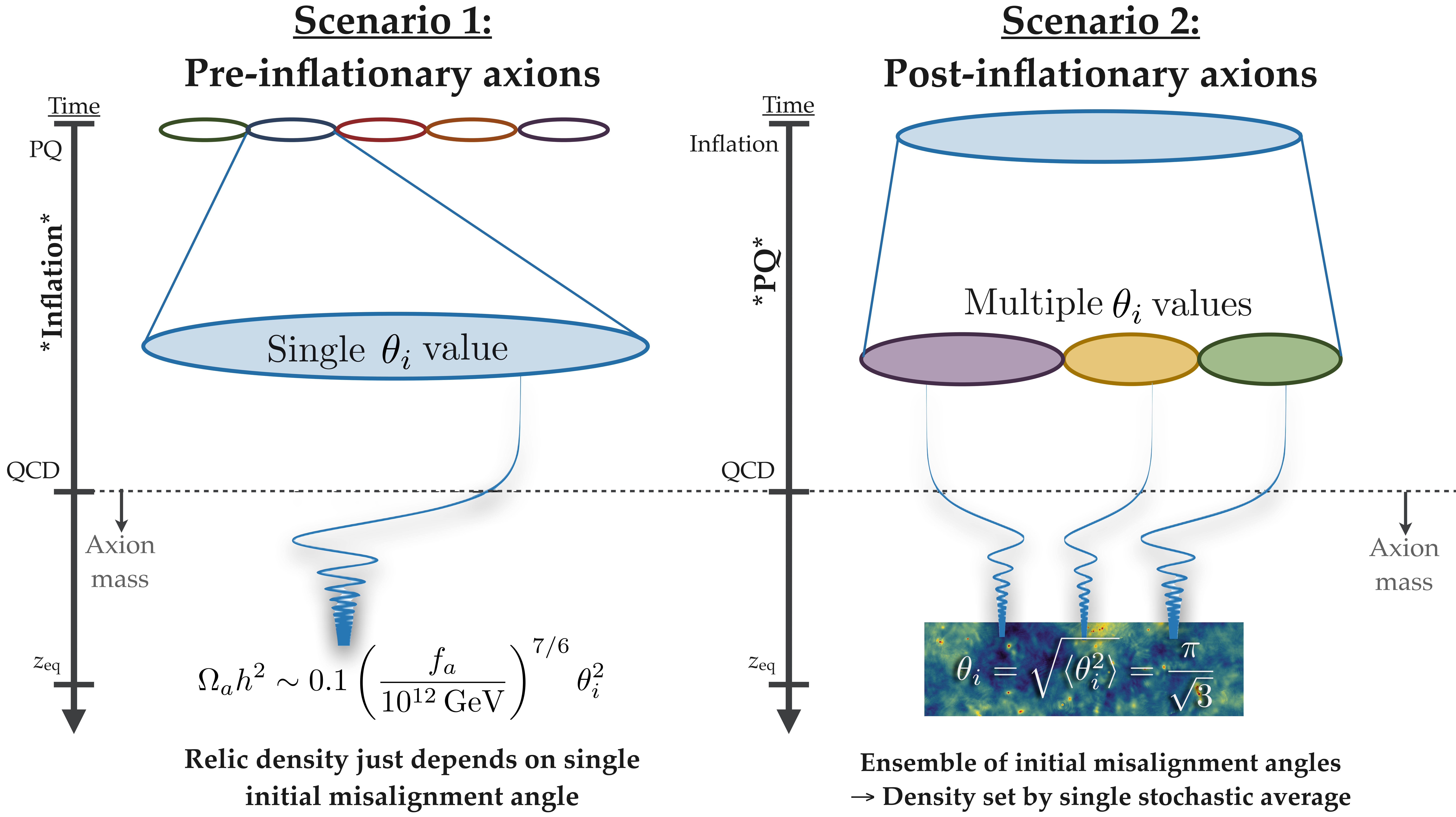


Scenario 1:
Pre-inflationary axions

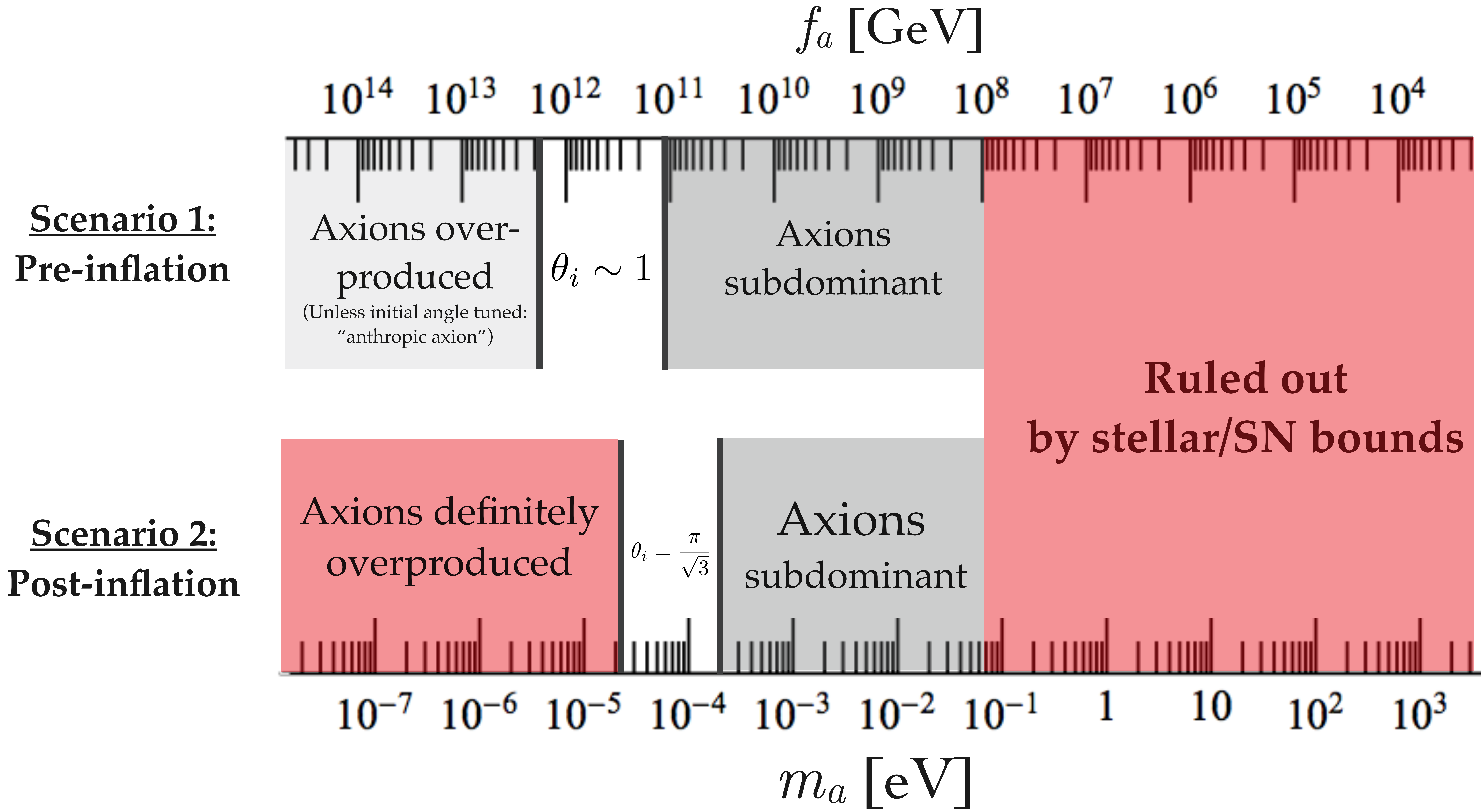


$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \theta_i^2$$

Relic density just depends on single initial misalignment angle

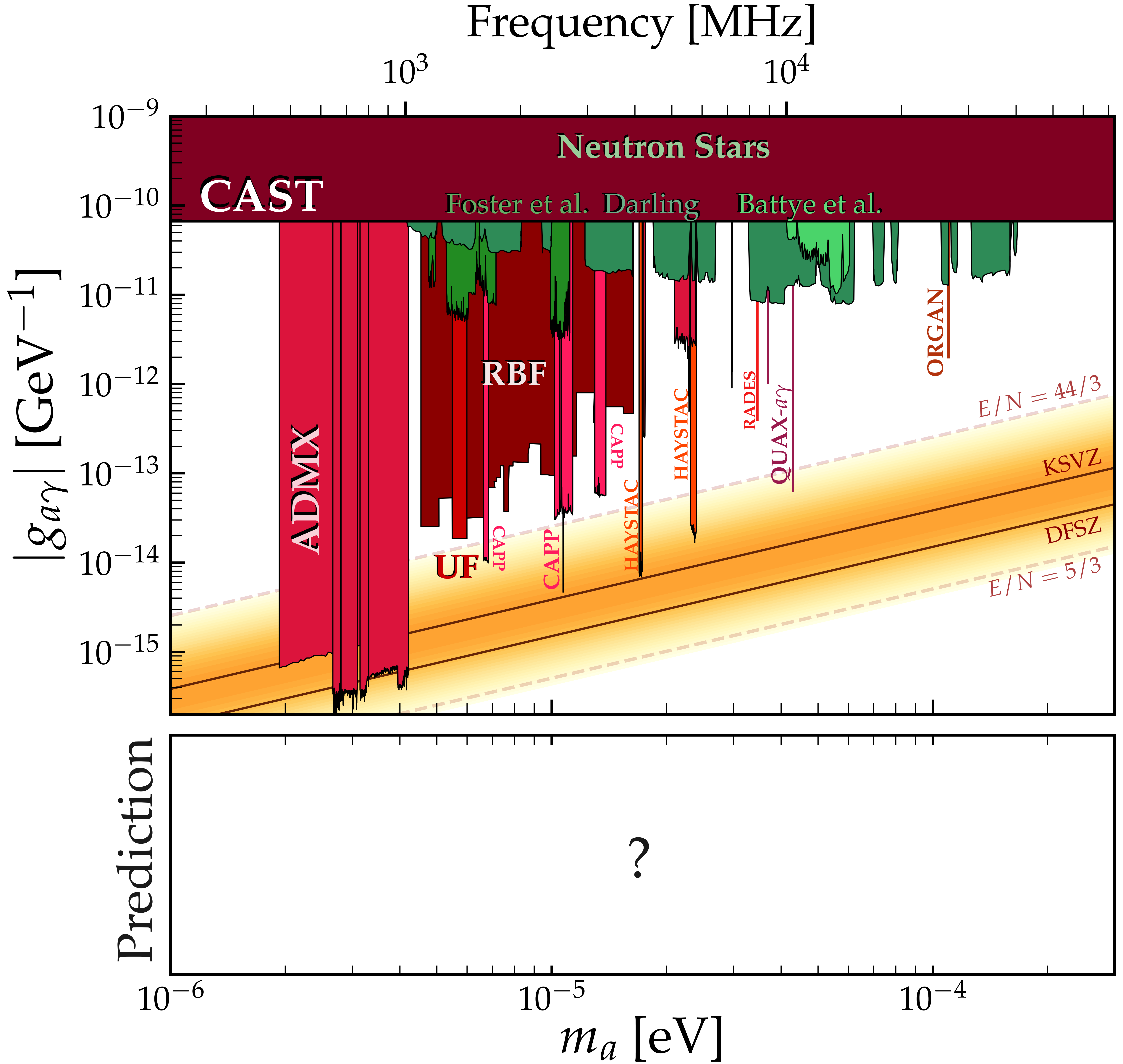


Scenario 1:
Pre-inflationary axions
Time
PQ
Inflation
Single θ_i value
QCD
Axion mass
$z_{\rm eq}$
$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\,{\rm GeV}}\right)^{7/6} \theta_i^2$
Relic density just depends on single initial misalignment angle
Scenario 2:
Post-inflationary axions
Time
Inflation
PQ
Multiple θ_i values
QCD
Axion mass
$z_{\rm eq}$
$\theta_i = \sqrt{\langle \theta_i^2 \rangle} = \frac{\pi}{\sqrt{3}}$
Ensemble of initial misalignment angles
→ Density set by single stochastic average



f_a [GeV]
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4}
Scenario 1:
Pre-inflation
Axions over-produced
(Unless initial angle tuned: "anthropic axion")
$\theta_i \sim 1$
Axions subdominant
Ruled out by stellar/SN bounds
Scenario 2:
Post-inflation
Axions definitely overproduced
$\theta_i = \frac{\pi}{\sqrt{3}}$
Axions subdominant
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3}
m_a [eV]

In principle one can match the abundance of axions to $\Omega h^2 = 0.12$ and find the m_a that matches:



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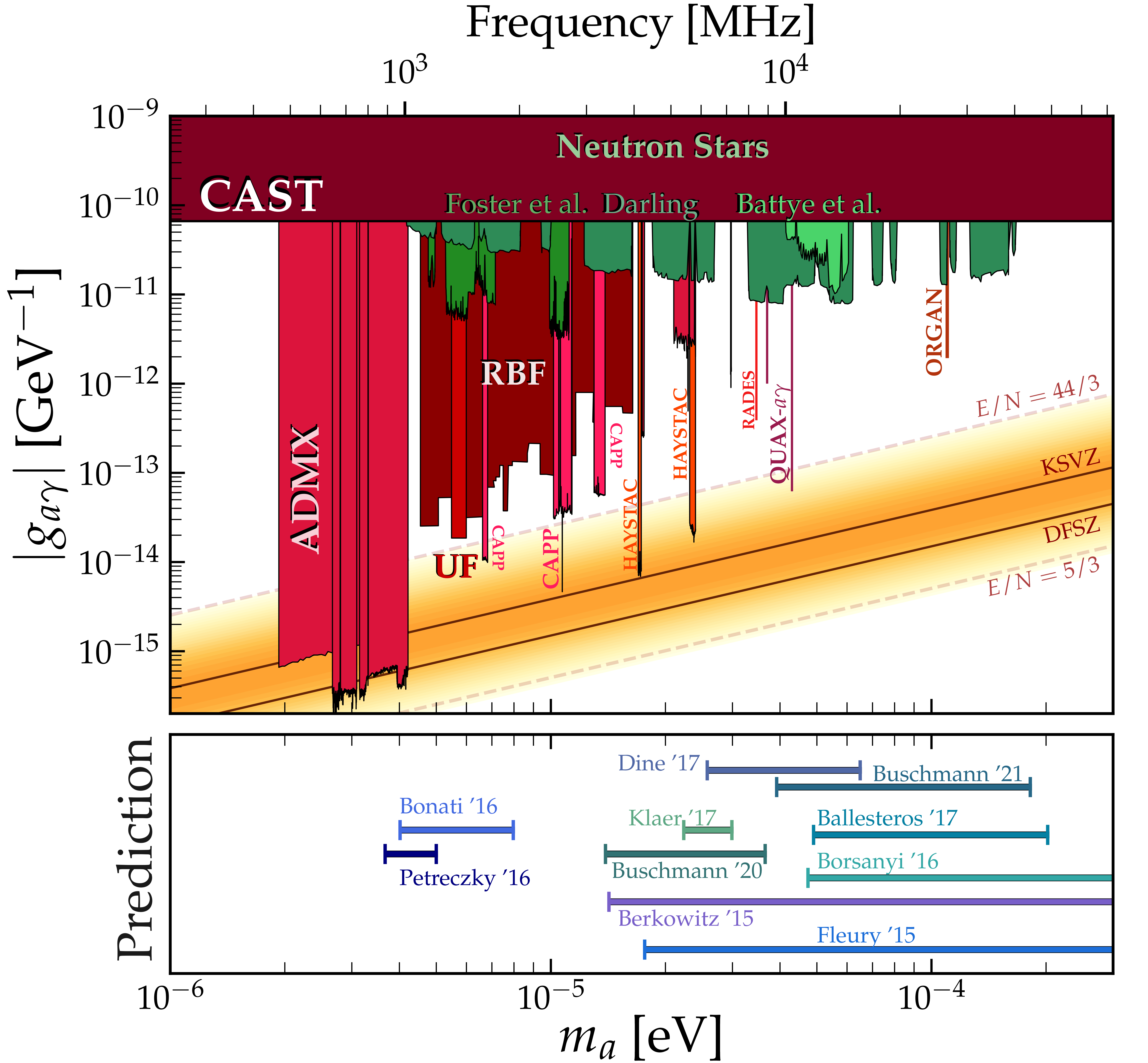
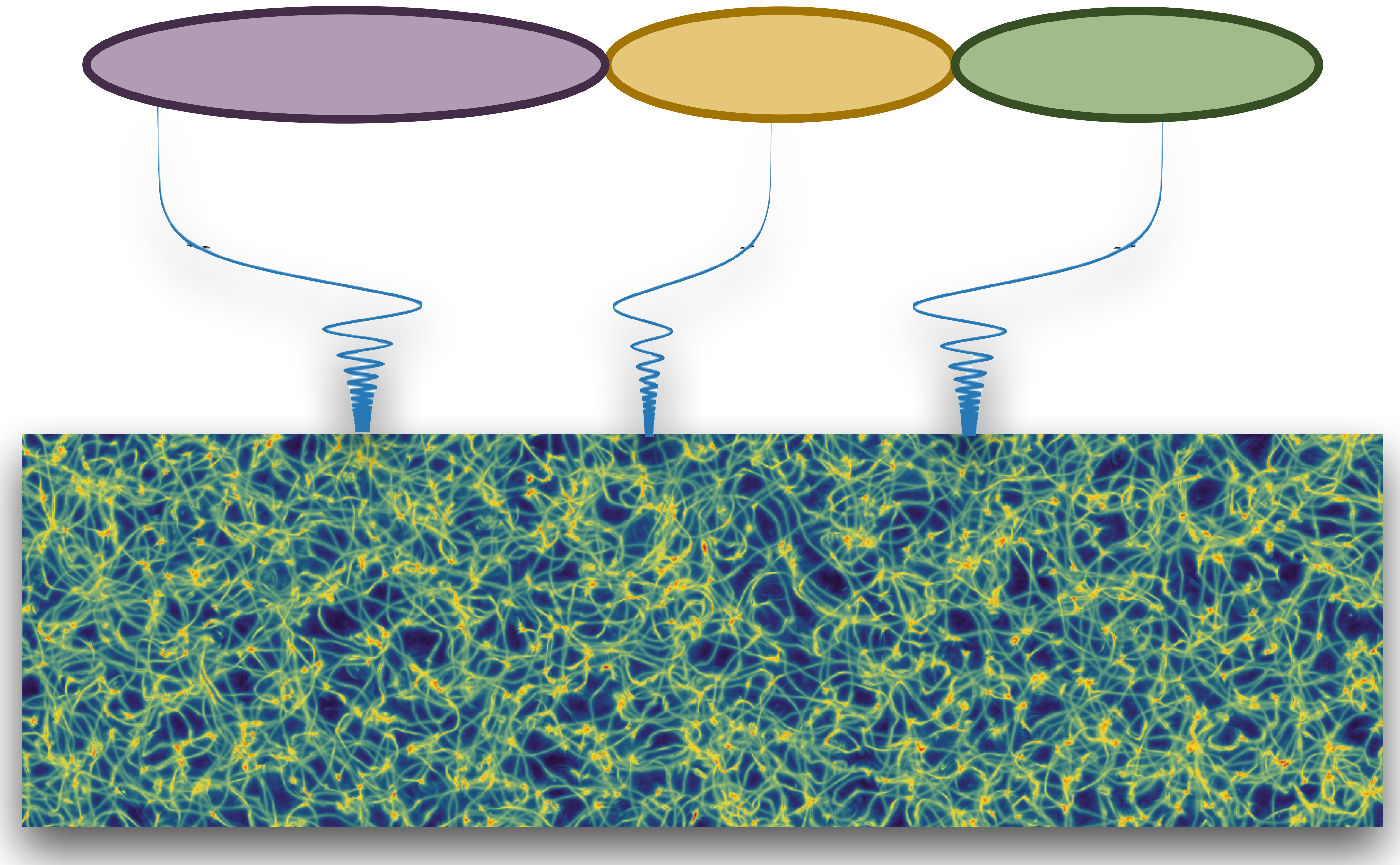


Why no agreement?

Complication in the post-inflationary scenario: topological defects



After U(1) spontaneous breaking (at T<f_a):

⇒ **Cosmic strings** from axion field winding around 2π

After explicit breaking (at T $\lesssim \Lambda_{QCD}$)

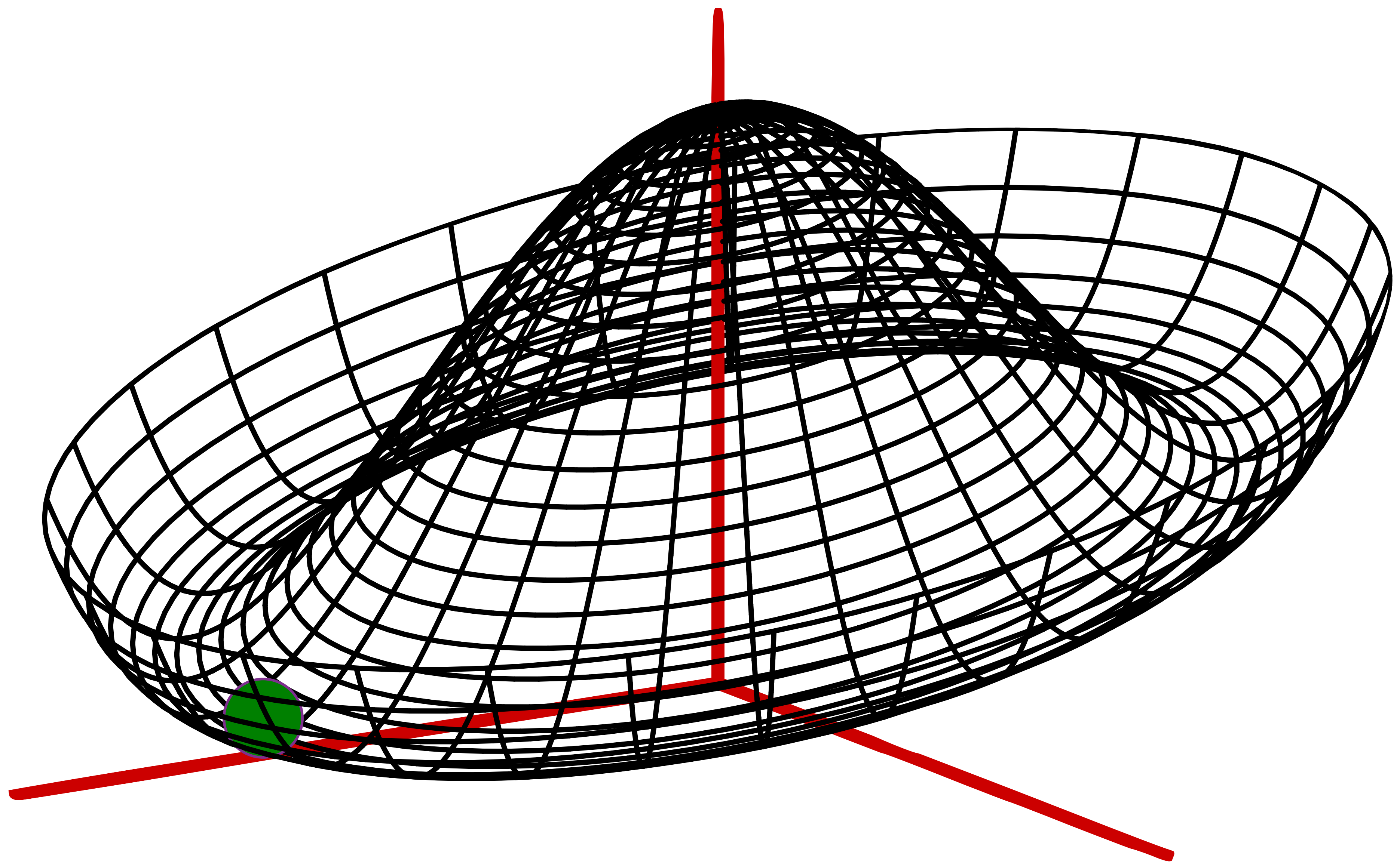
⇒ **Domain walls** between axion field at true/false vacuum (0 and π)

Numerical simulations

Evolve complex PQ scalar in expanding universe under potential:

$$V(\phi) = V_{\mathrm{PQ}}(|\phi|) + V_{\mathrm{QCD}}(\theta) = \frac{\lambda_\phi}{8}\left(|\phi|^2 - f_a^2\right)^2 + \chi(T)(1 - \cos\arg\phi)$$

$$\phi(\mathbf{x}) \sim |\phi(\mathbf{x})| e^{i\theta(\mathbf{x})}$$



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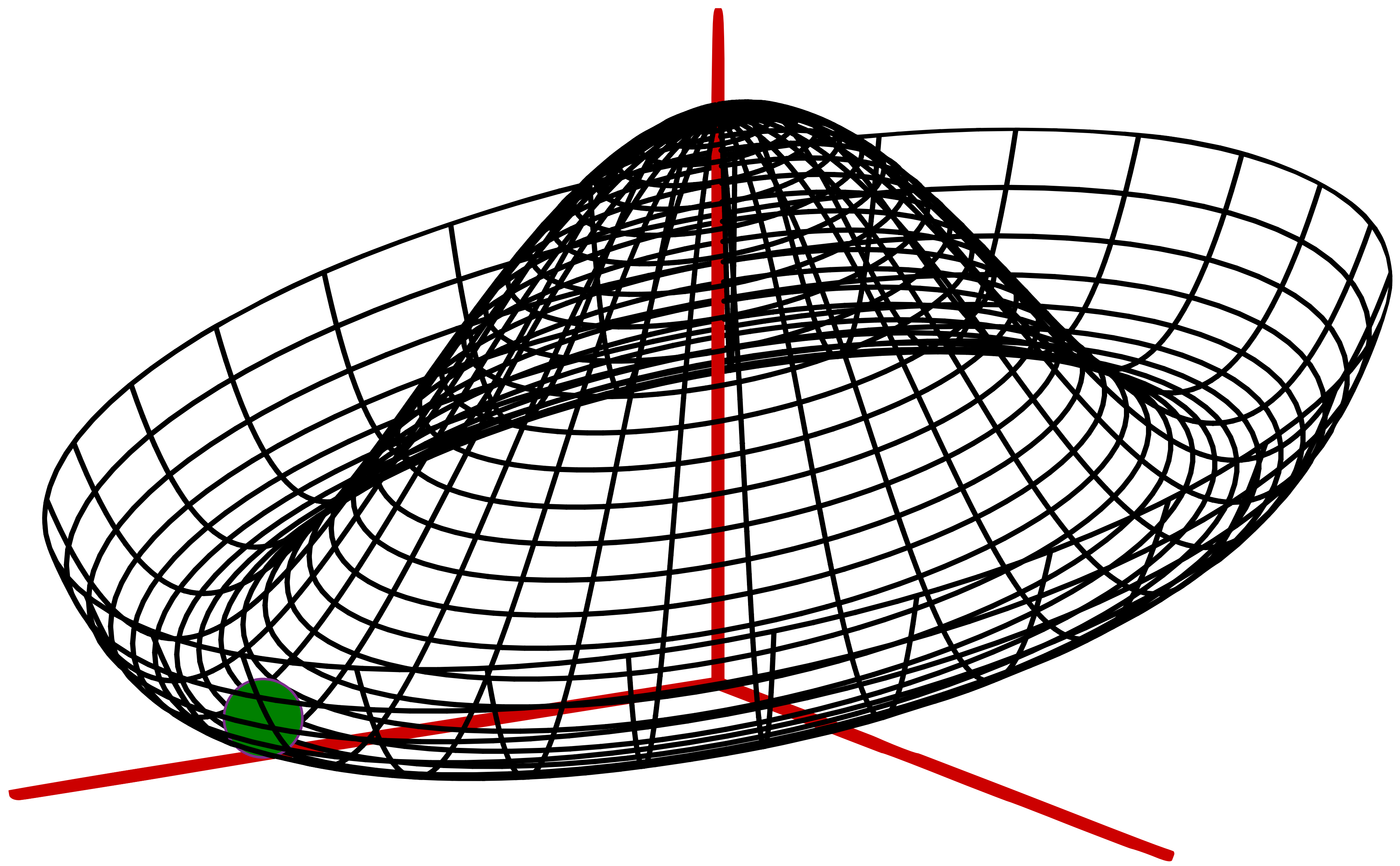

$$|\phi(\mathbf{x})|$$

Radial dof: "saxion"

Sets string width.

Mass =

$$m_s = \sqrt{\lambda_\phi} f_a$$

Numerical simulations

Evolve complex PQ scalar in expanding universe under potential:

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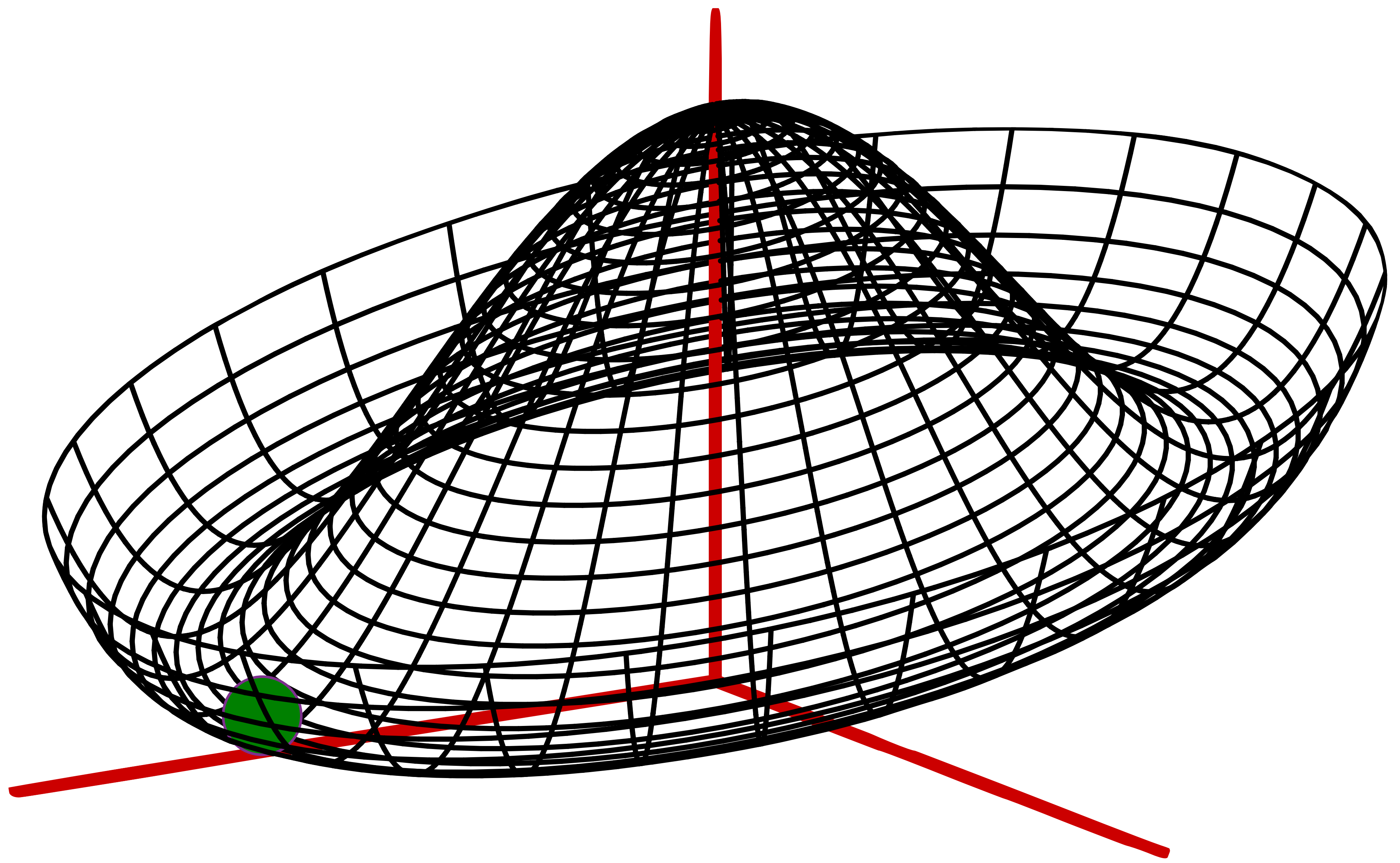


$$|\phi(\mathbf{x})|$$

Radial dof: "saxion"

Sets string width.

Mass =

$$m_s = \sqrt{\lambda_\phi} f_a$$

$$\theta(\mathbf{x}) = a(\mathbf{x})/f_a$$

Angular dof: "axion"

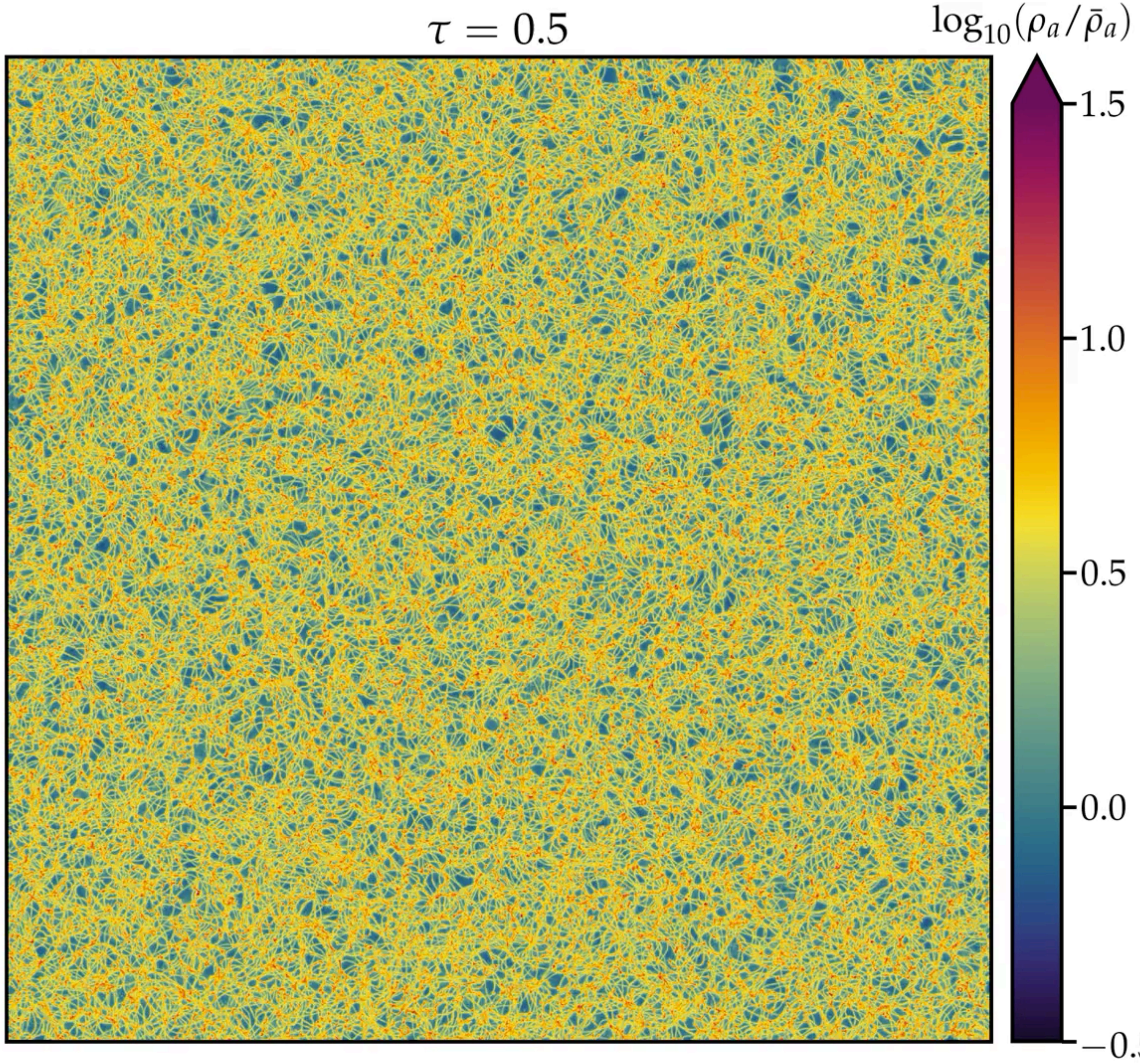
Sets domain walls

Temperature dependent mass:

$$m_a^2(T) = \frac{\chi_0}{f_a}\left(\frac{150\,\mathrm{MeV}}{T}\right)^n$$

$\chi_0 \approx (76\,\mathrm{MeV})^4$ and $n \sim 6-8$ can be calculated via e.g lattice QCD [1606.07494]

Evolution of the axion field in the post-inflationary scenario



(movie)

CAJO, Pierobon, Redondo, Wong [in prep.]

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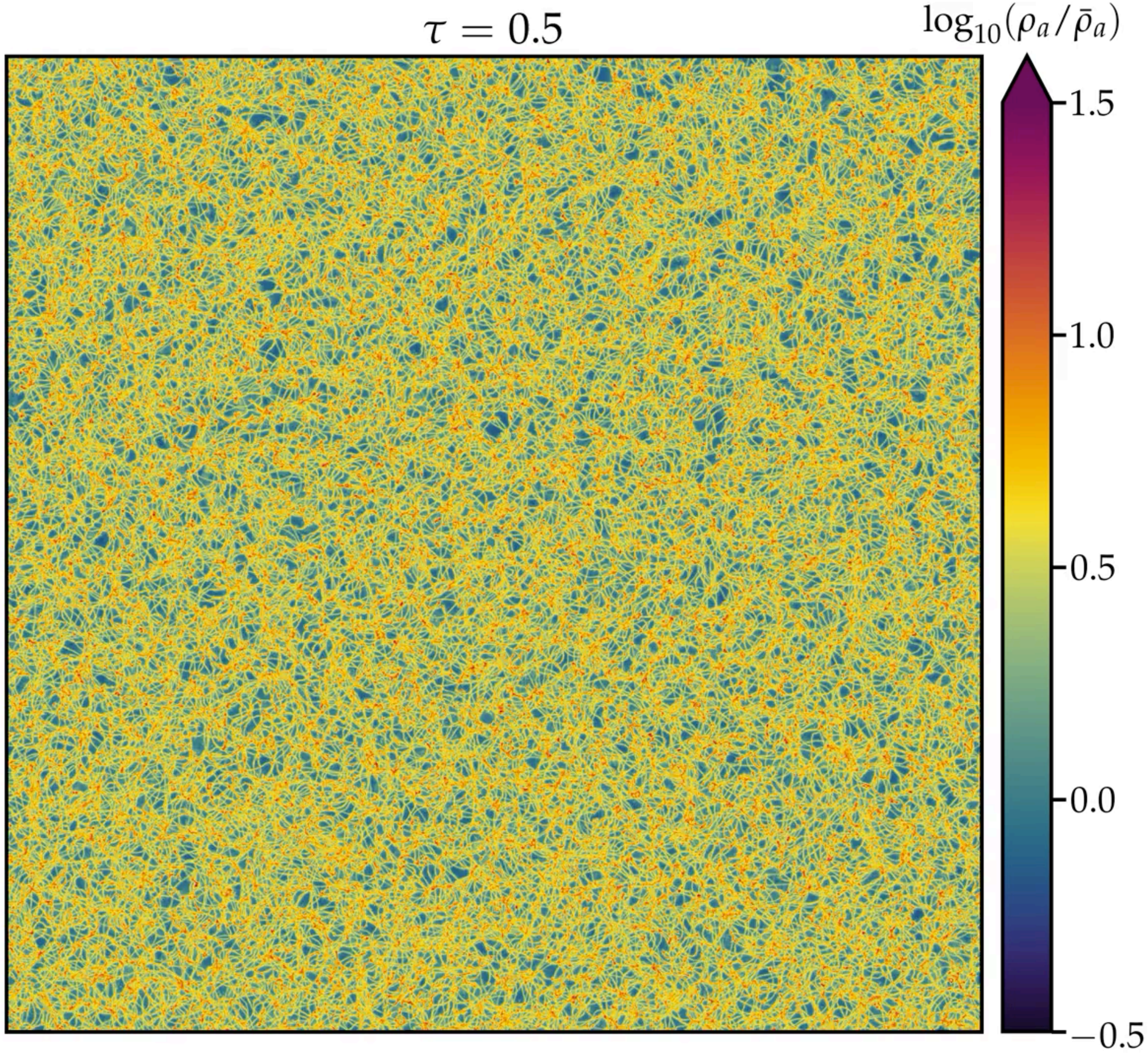

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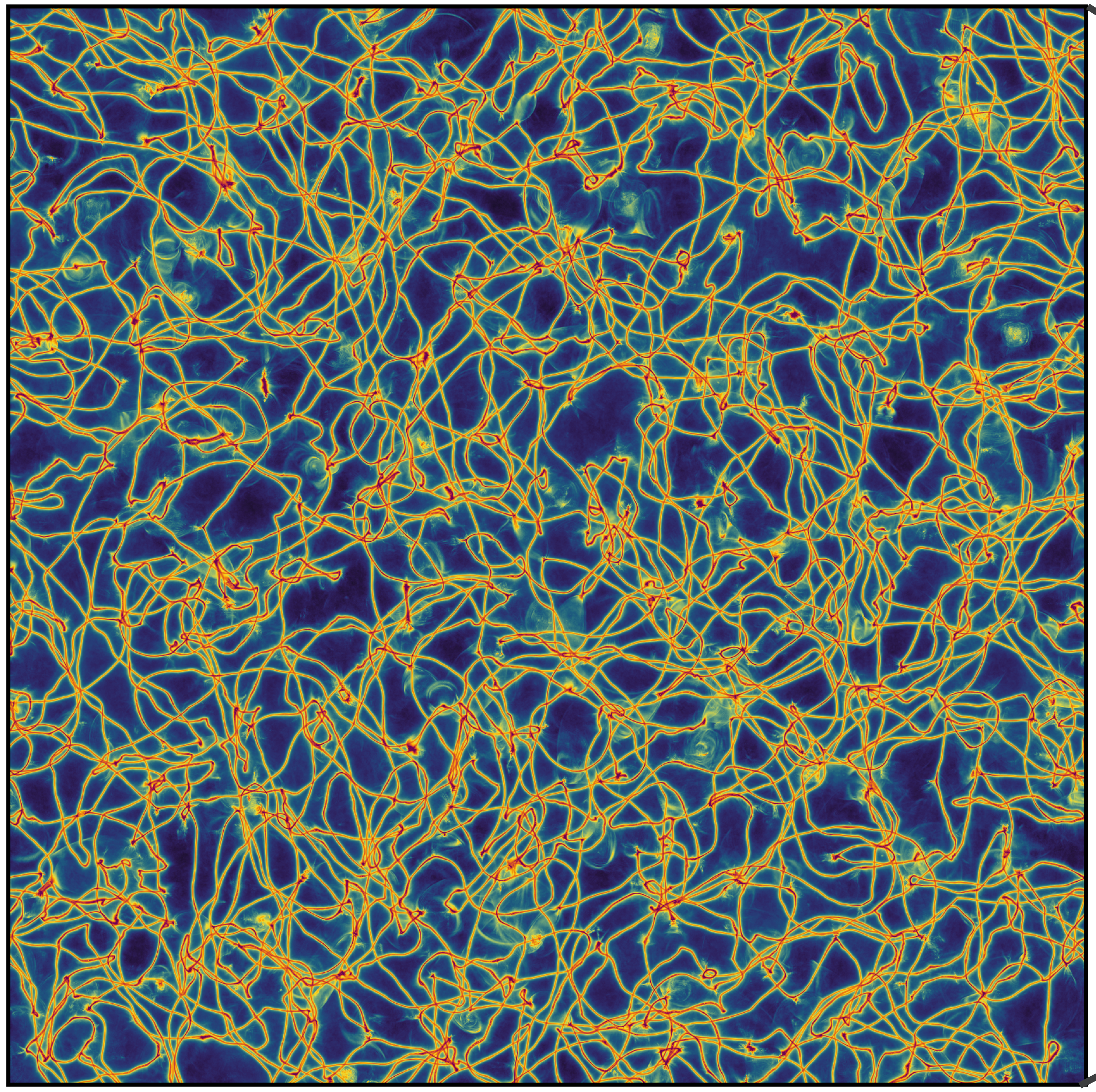

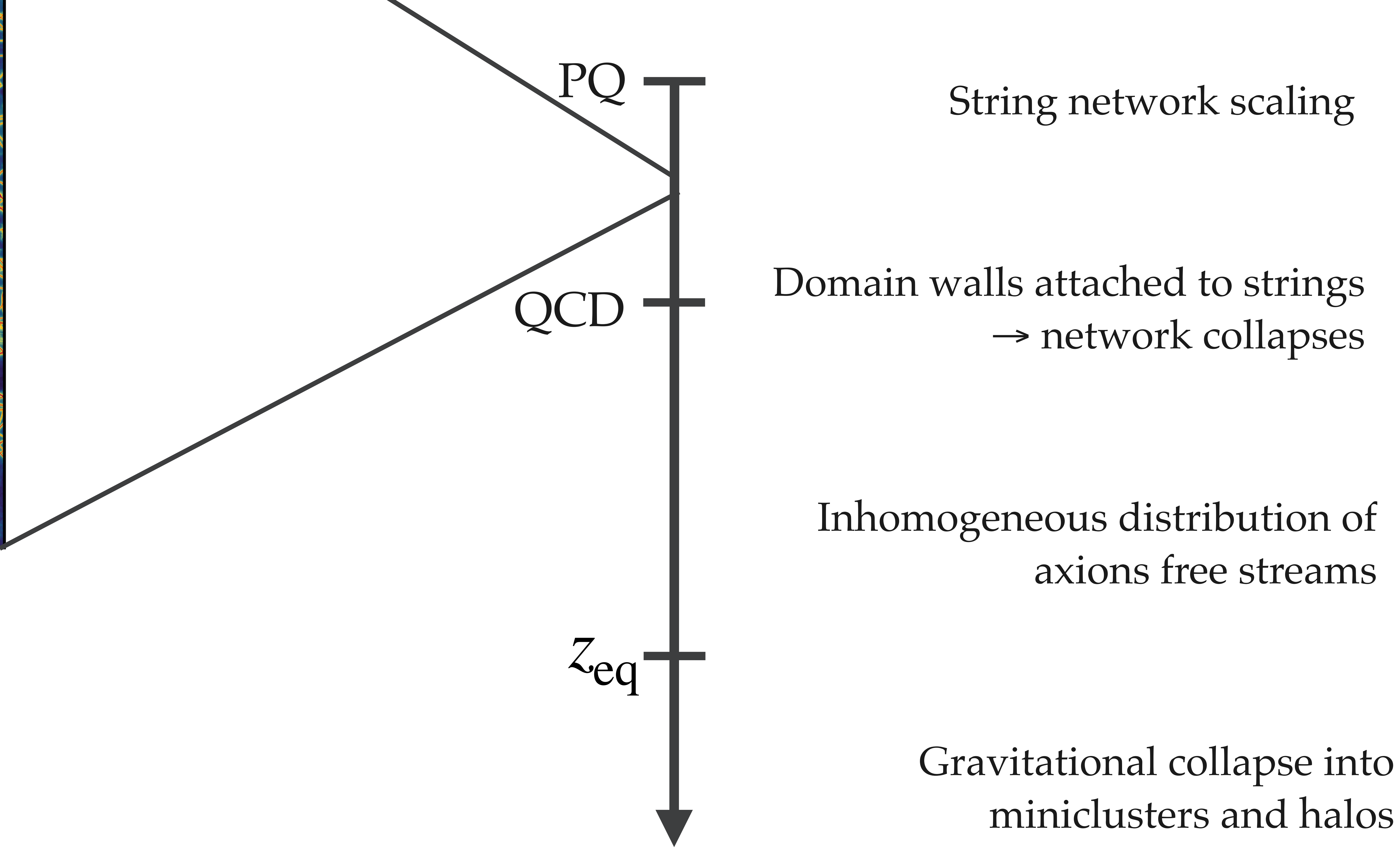

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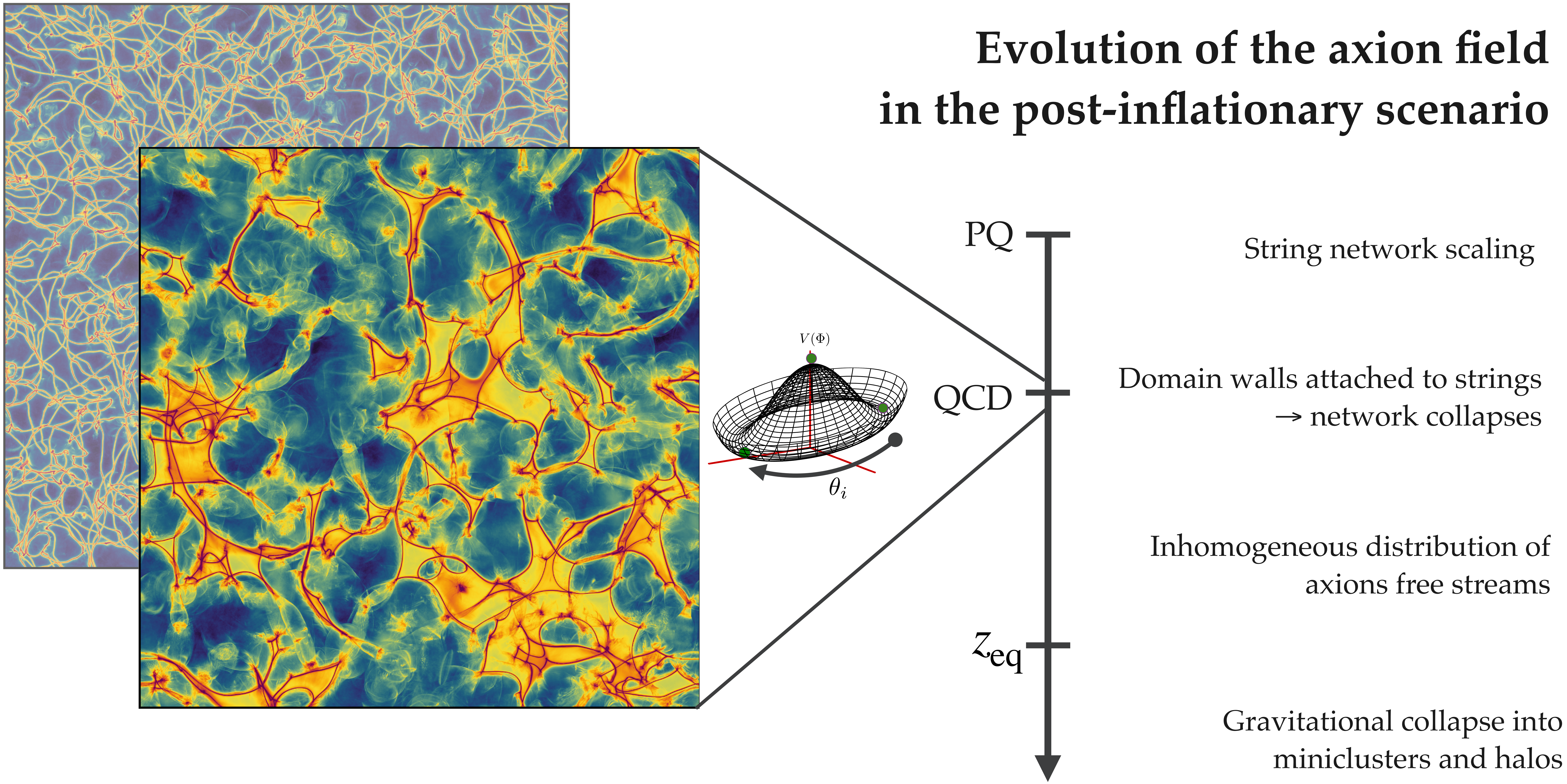

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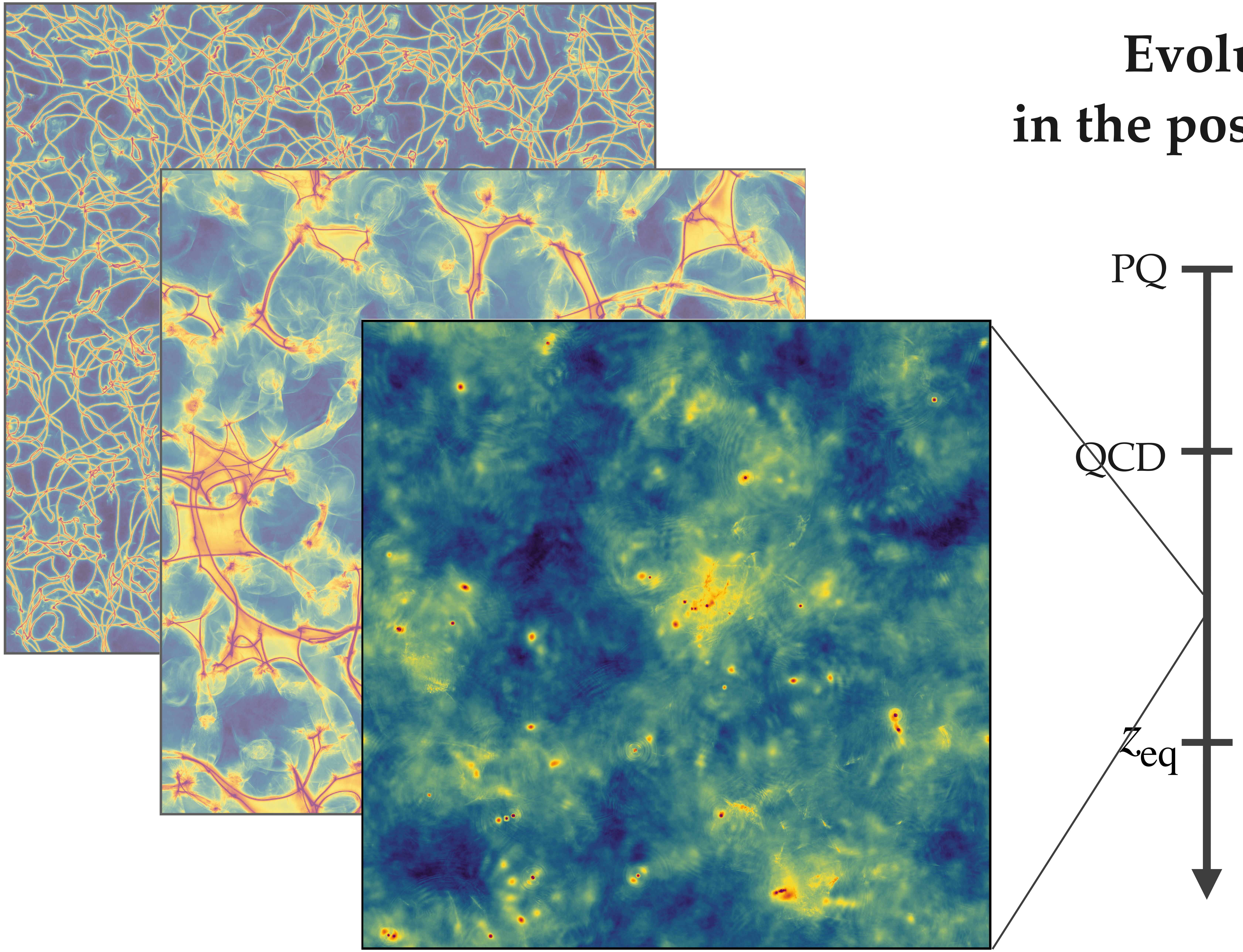


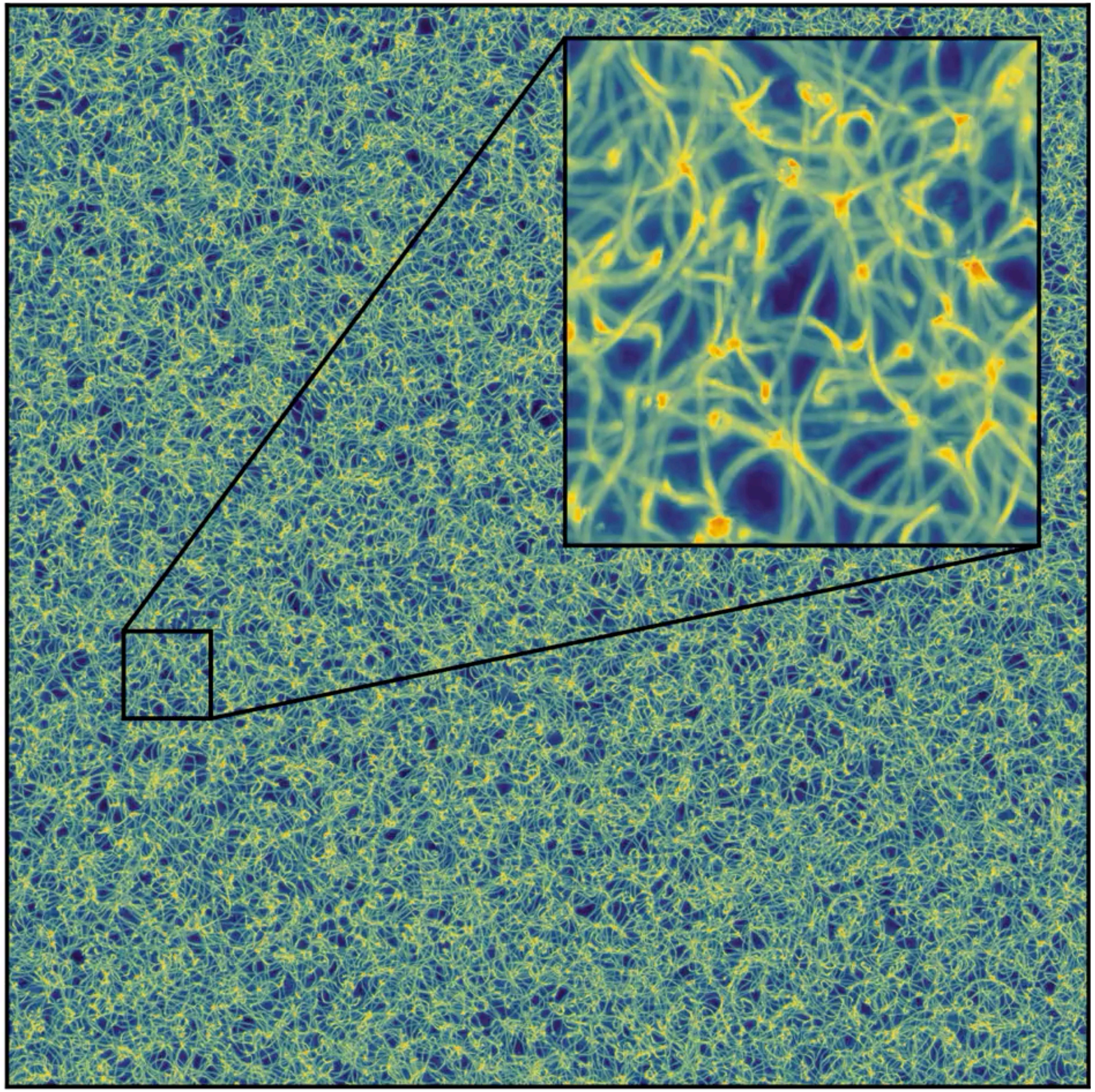
String network scaling

Domain walls attached to strings
→ network collapses

Inhomogeneous distribution of axions free streams until non-relativistic

Seeds of structure gravitationally collapse into miniclusters and halos

CAJO, Pierobon, Redondo, Wong [in prep.]

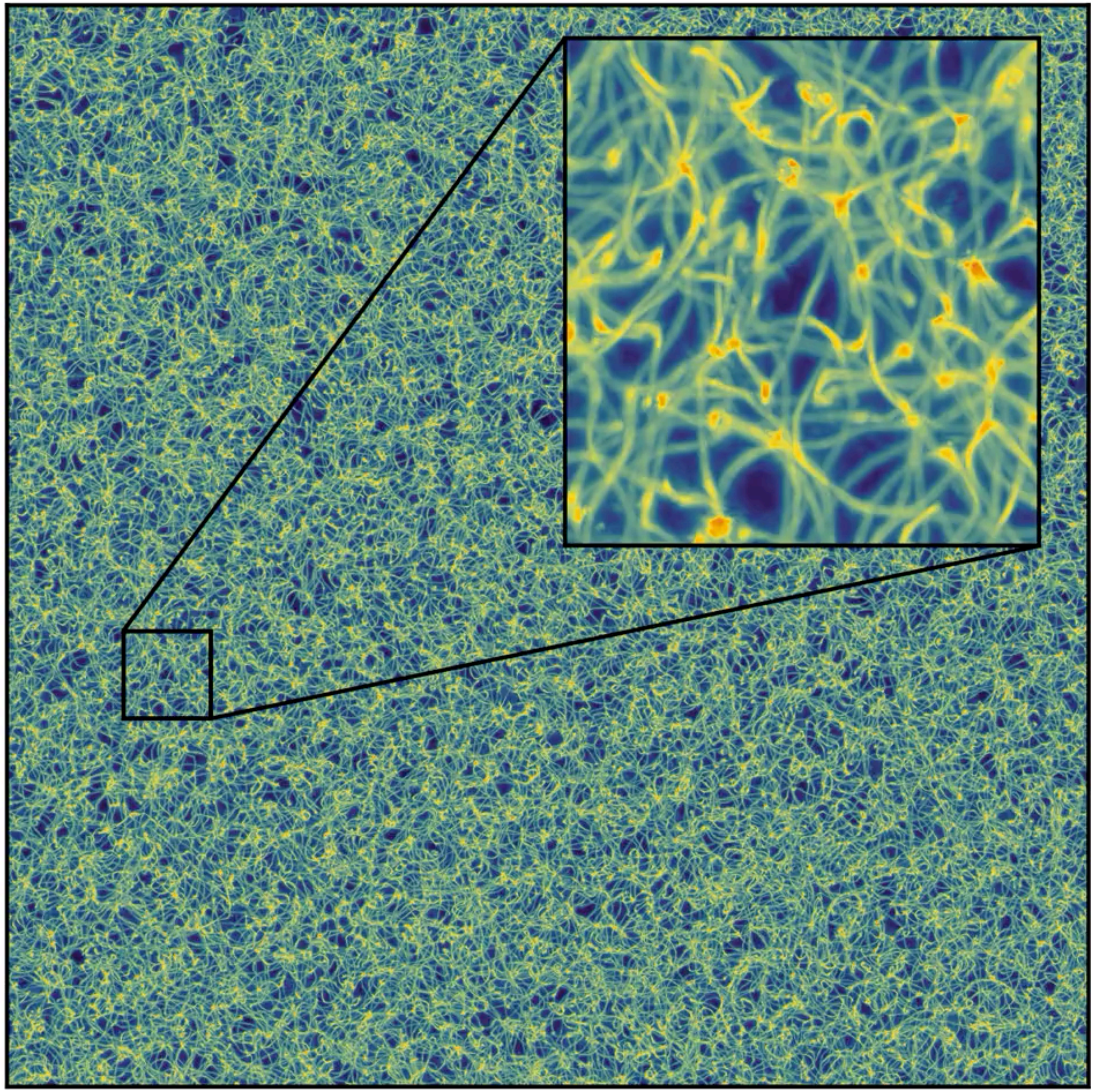


(Movie) CAJO, Pierobon, Redondo, Wong [in prep.]

Evolution of the axion field in the post-inflationary scenario

When the axion mass grows quickly with temperature (e.g. $m_a^2 \propto T^{-6.68}$) large numbers of high density oscillating lumps are seeded towards the end of the simulation with sizes $\lambda \sim m_a^{-1}$

→ "Axitons"



(Movie)

CAJO, Pierobon, Redondo, Wong [in prep.]

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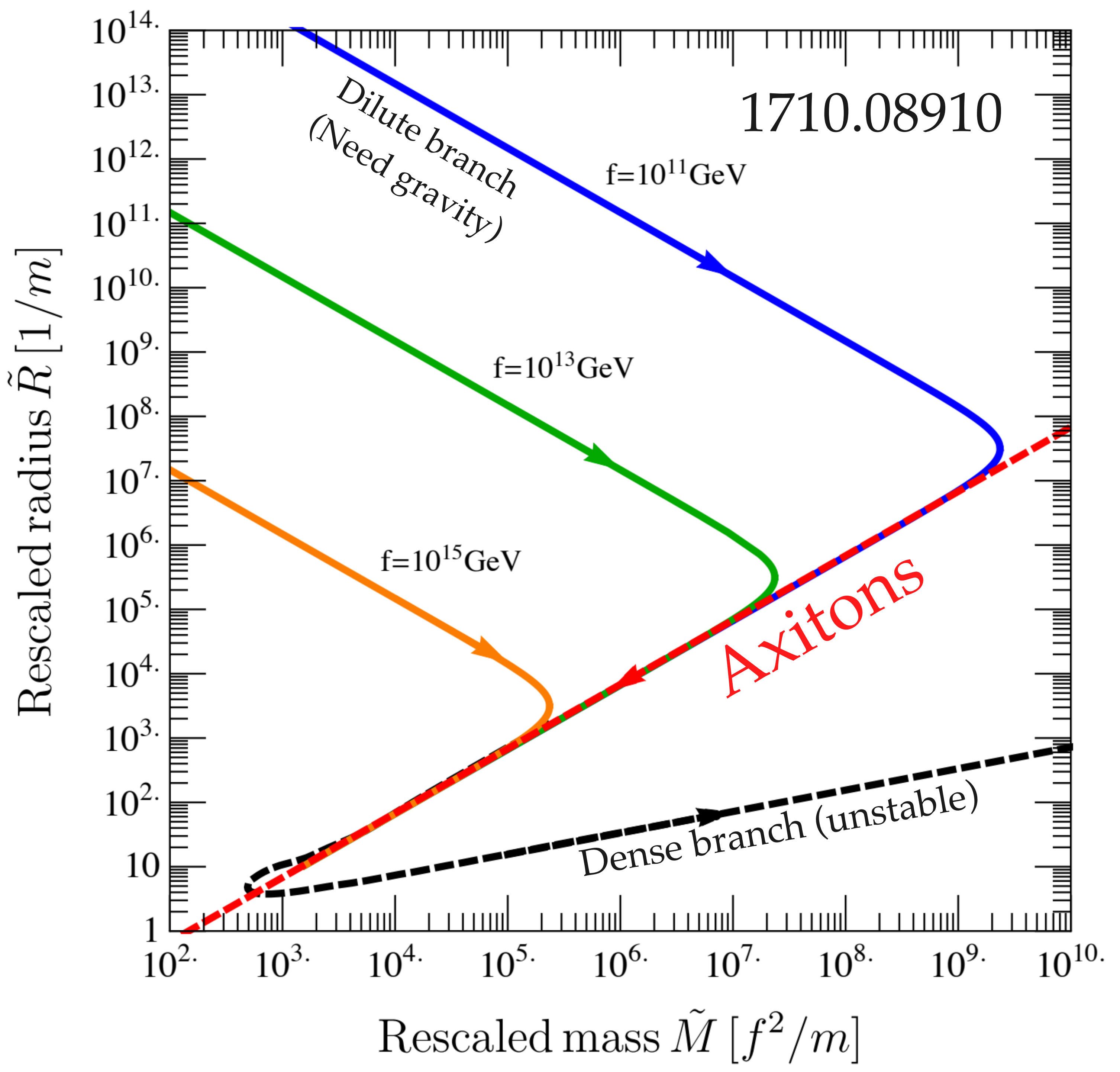
→ **"Axitons"**

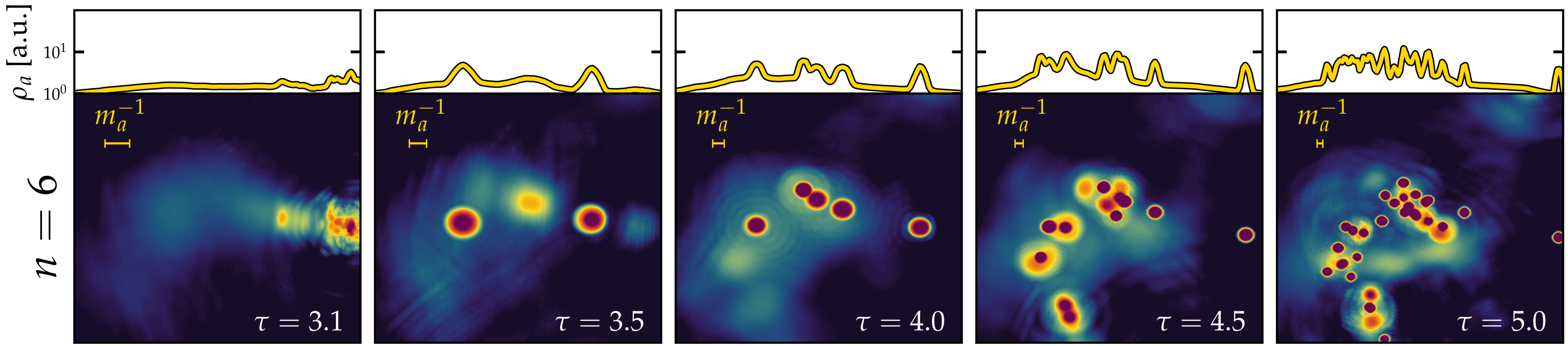
Axitons (aka oscillons)

- Pseudo-breathing solutions of the Sine-Gordon equation with a growing mass $m_a^2(T) \propto T^{-n}$
- Can also be thought of as the unstable transition between dilute and dense axion stars
- Radiate away axions but eventually will dissipate once the axion mass reaches its present day value

Axion star radius vs mass

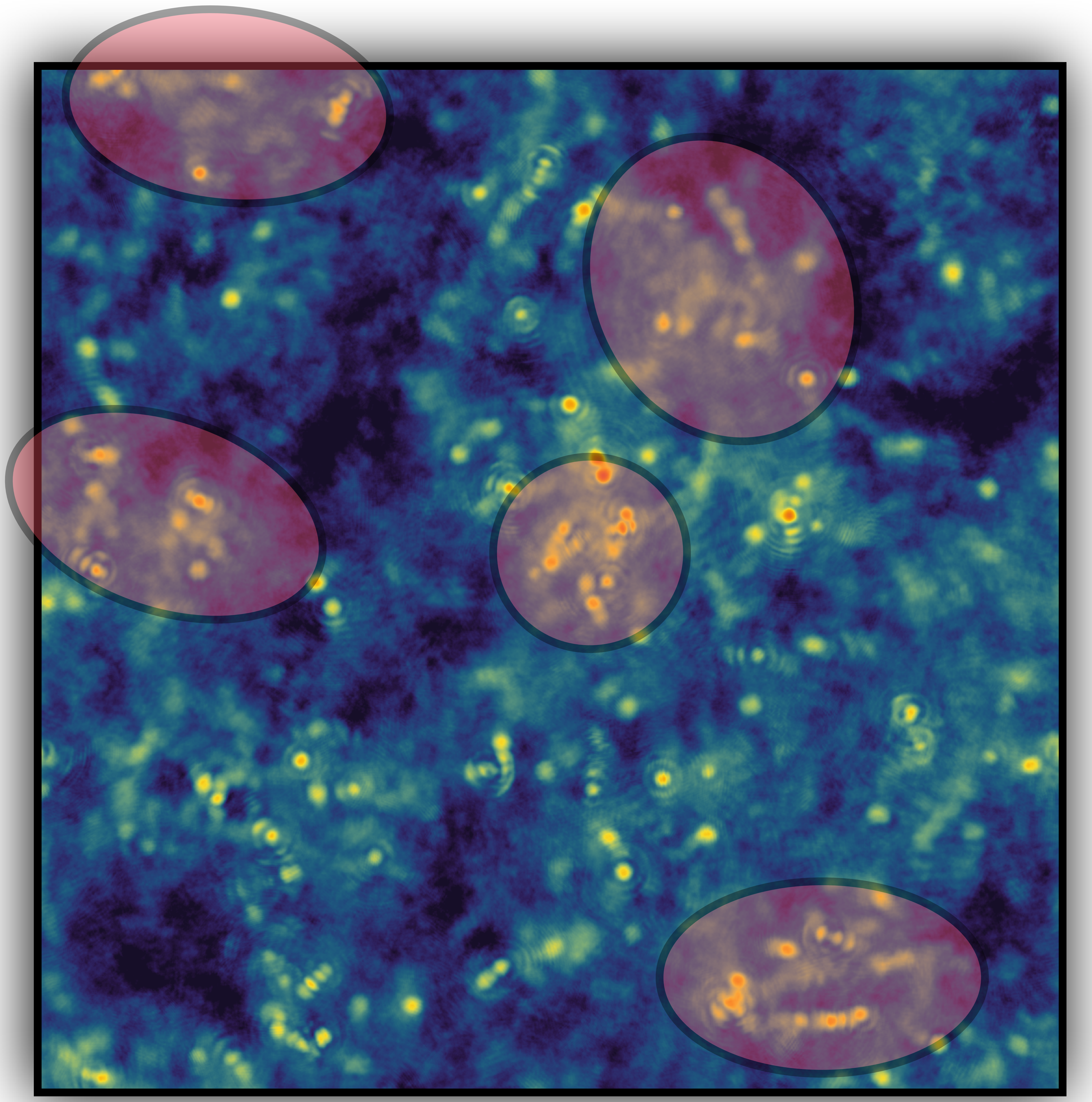


Mass increasing with time ⟶



CAJO, Pierobon, Redondo, Wong [in prep.]

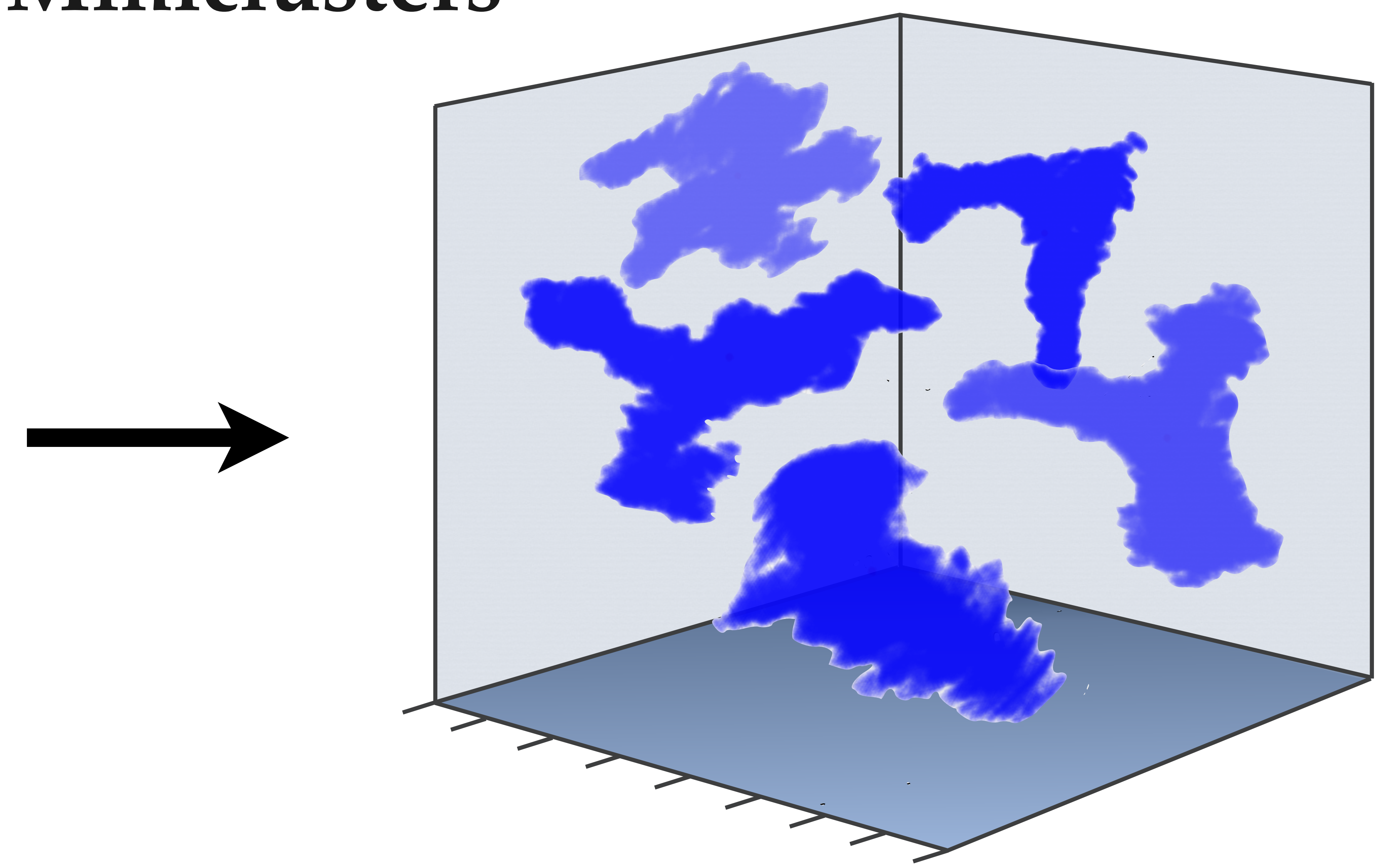
What next? → Gravity



Around z_{eq}~4000, field is inhomogeneities on small scales L~0.1 pc

→ Leads to gravitational collapse of structures much earlier conventional thermal CDM

→ **Miniclusters**



$M_{\rm mc} \sim 10^{-12} M_\odot$ $\rho_{\rm mc} \sim 10^4 \,{\rm GeV\,cm}^3$

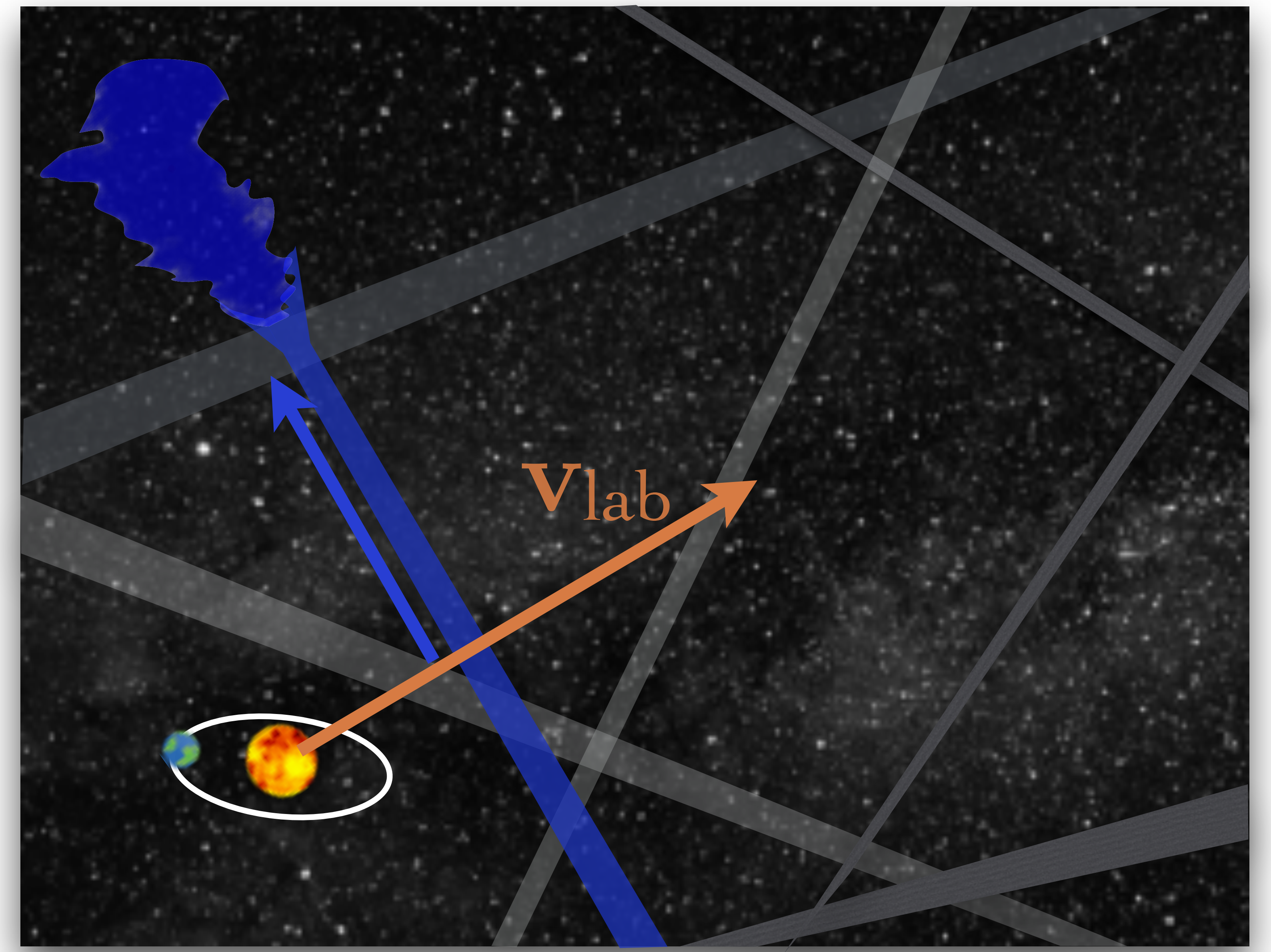
(For QCD axion, ALP miniclusters will be fluffier)

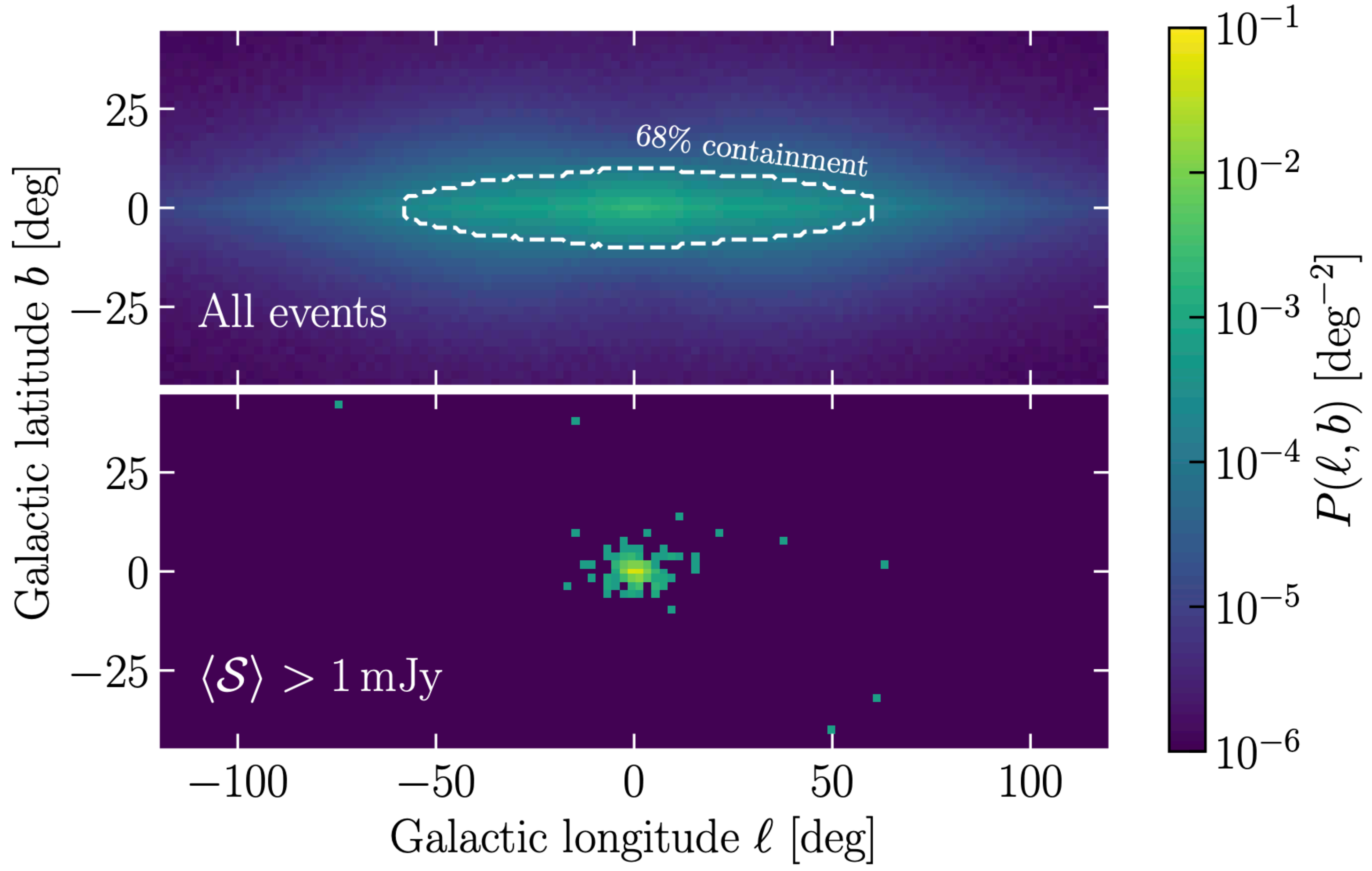
Outstanding problem 1: the DM distribution

Problems for direct detection

→ Encounter rate ~ once every 10^4—10^6 years.

→ If tidally disrupted by stars we could pass through streams [2011.05377], but this implies a radically different signal model for lab experiments



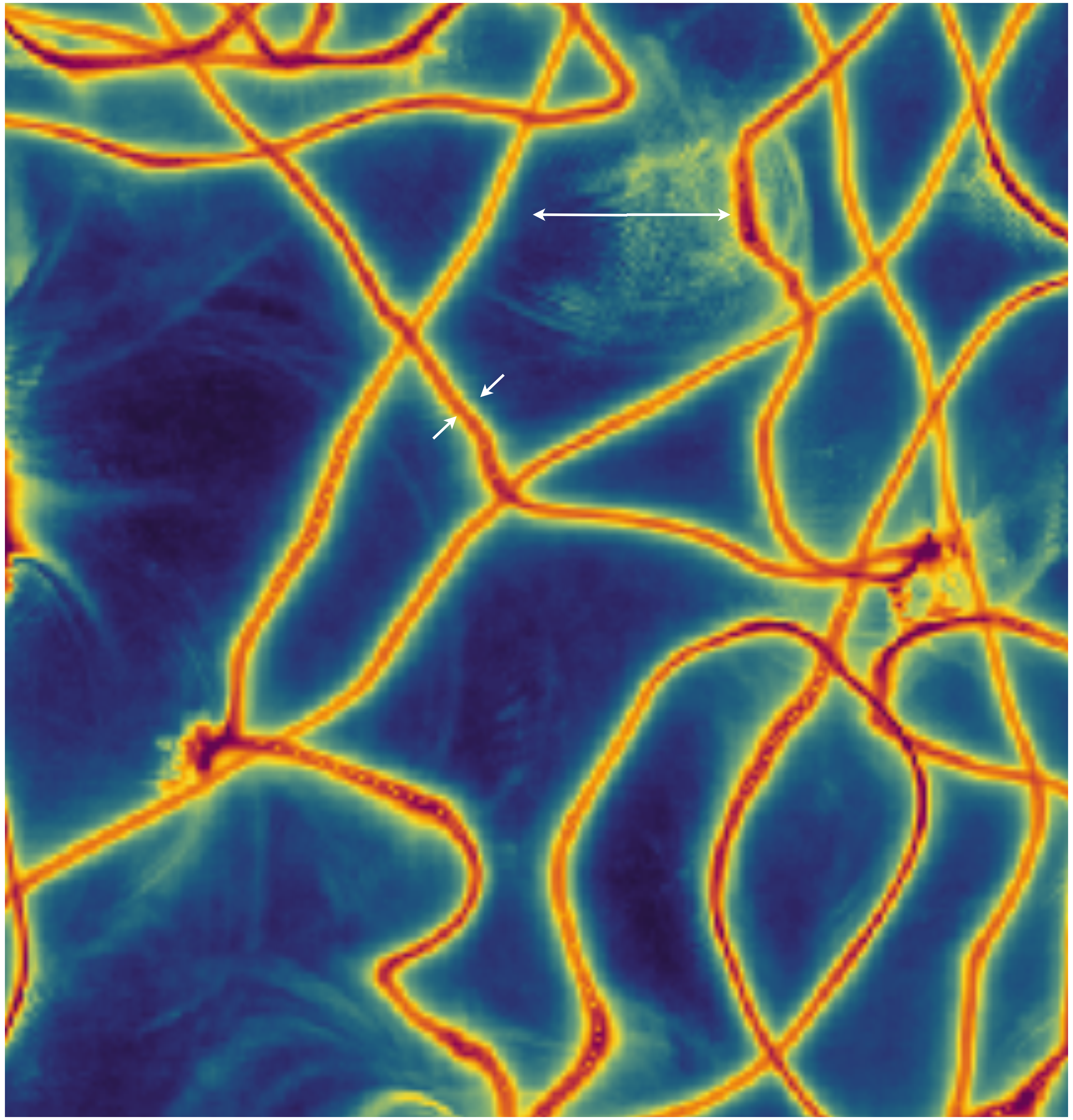


Opportunities for indirect detection

→ Collision of miniclusters with neutron stars, observe in radio [2011.05378]

→ Miniclusters passing line of sight (microlensing) [1908.01773],[1701.04787]

Problem 2: String radiation and the dynamical range



- Want to simulate larger than the causal horizon $L \sim 1/H$
- Whilst also resolving string cores $\Delta x \sim 1/m_s = (\sqrt{\lambda} f_a)^{-1}$
- For a realistic model e.g. $f_a = 10^{11}$ GeV $\rightarrow m_s/H \sim 10^{28}$
- With current resources $\lesssim 8192^3$ grid points, can only simulate $m_s/H \sim 10^{3-4}$
- Might be okay since this parameter enters as $\log m_s/H$ in the string tension but still needs to be checked, e.g. with AMR [2108.05368]

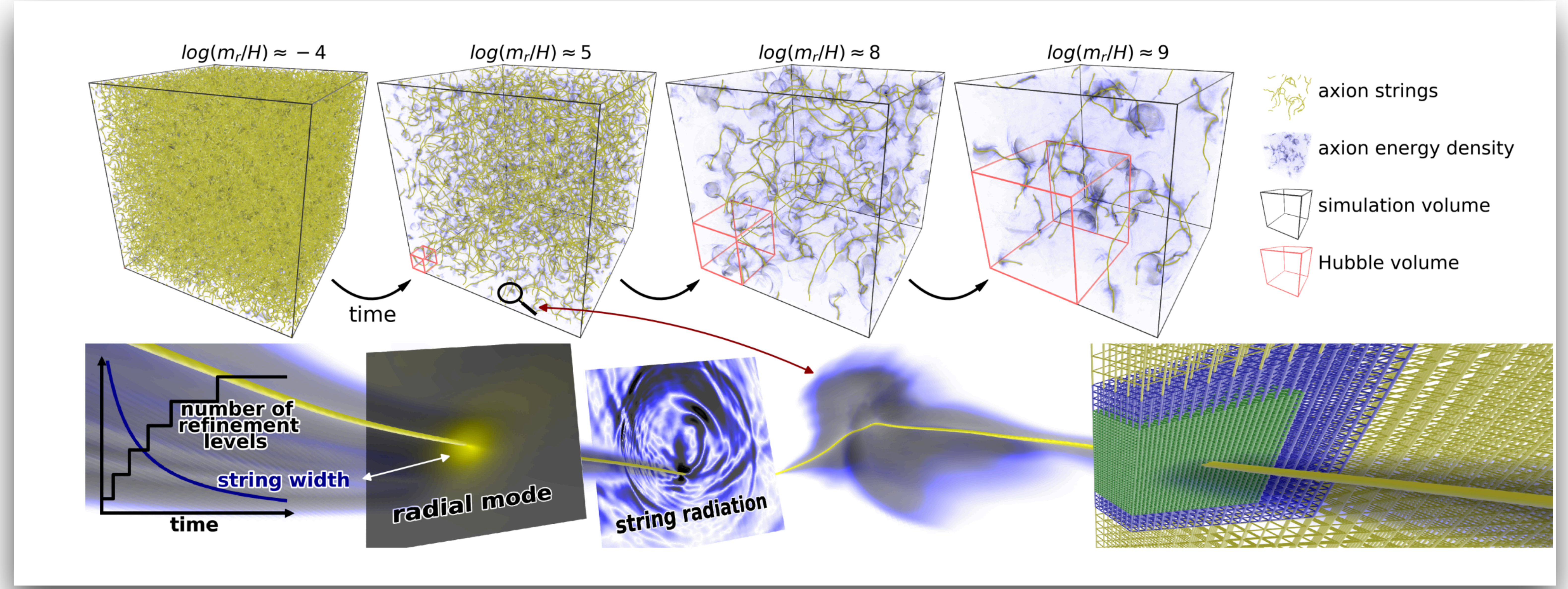
Summary

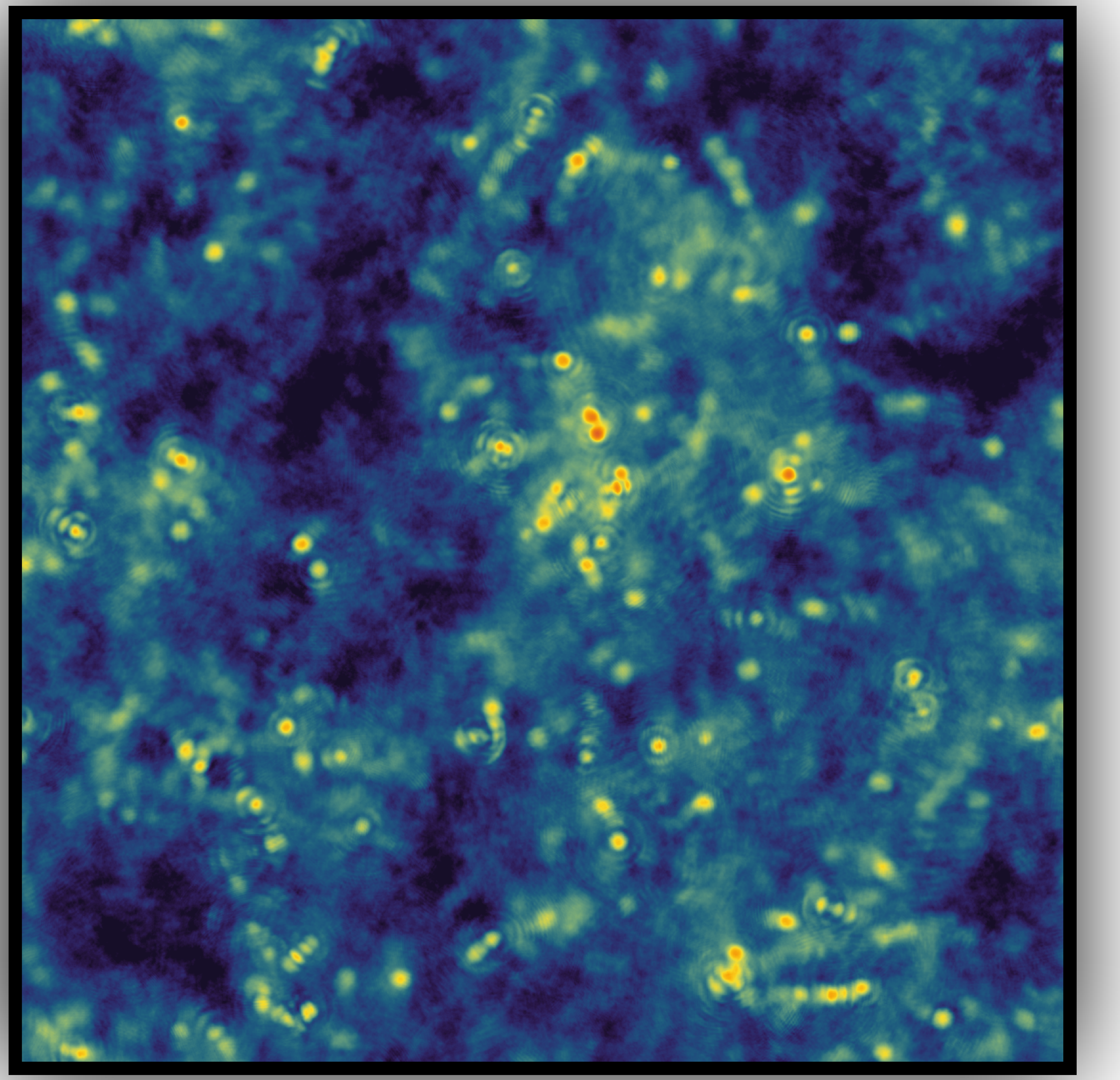
- The axion is the best candidate for dark matter
- The axion could be found tomorrow, or in 20 years time
- Need high-resolution numerical simulations to predict the axion mass and to study the clumpiness of axions in our Universe. Many open questions and avenues for further study

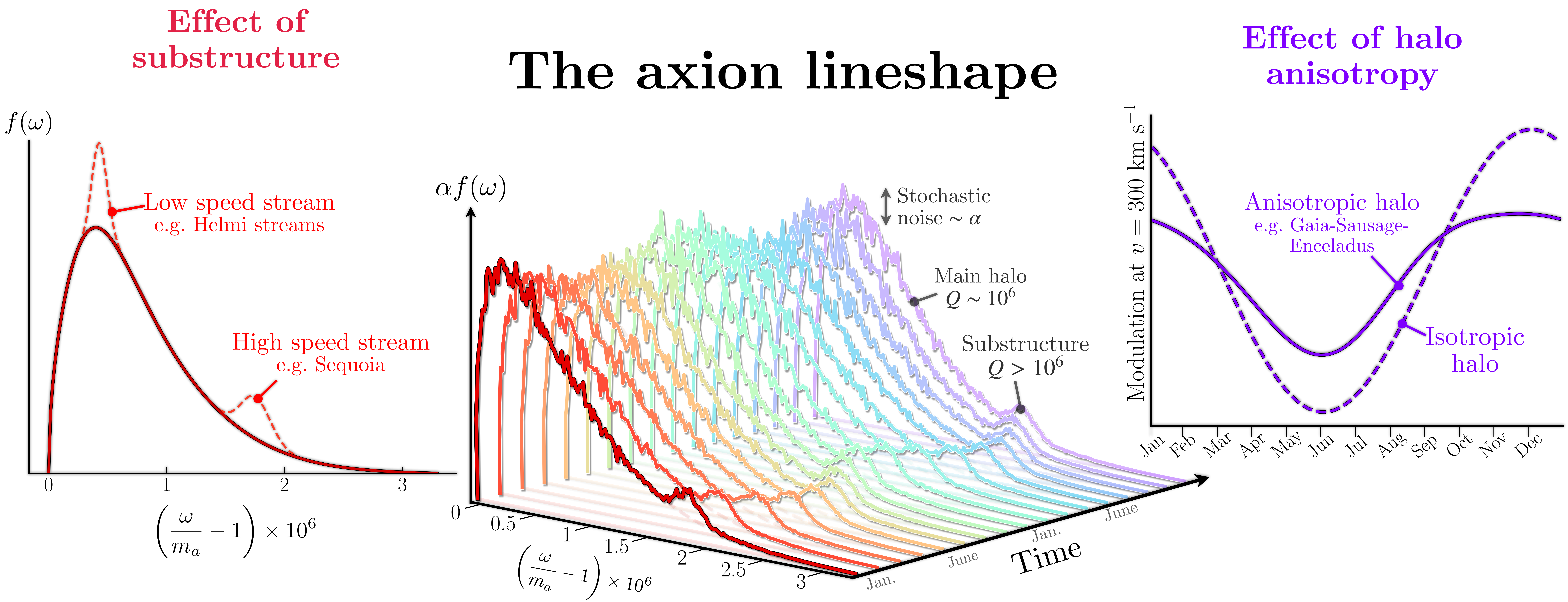
Key issues to be resolved

Axion dark matter abundance/axion mass
→ Current simulations cannot study the string scaling regime in full due to high required dynamical range, see e.g. [2007.04990]
→ Not clear if the spectrum is dominated by IR modes (meaning large overproduction) or UV modes (. Important for predicting the axion mass, see [2108.05368] for recent work with AMR

Implications of an inhomogeneous axion distribution
→ Formation of gravitationally bound structures "axion miniclusters"
→ Do miniclusters survive to present day? Could be important for direct and indirect searches
→ Can stable axion stars form? Could there be signals of these e.g. fast radio bursts?

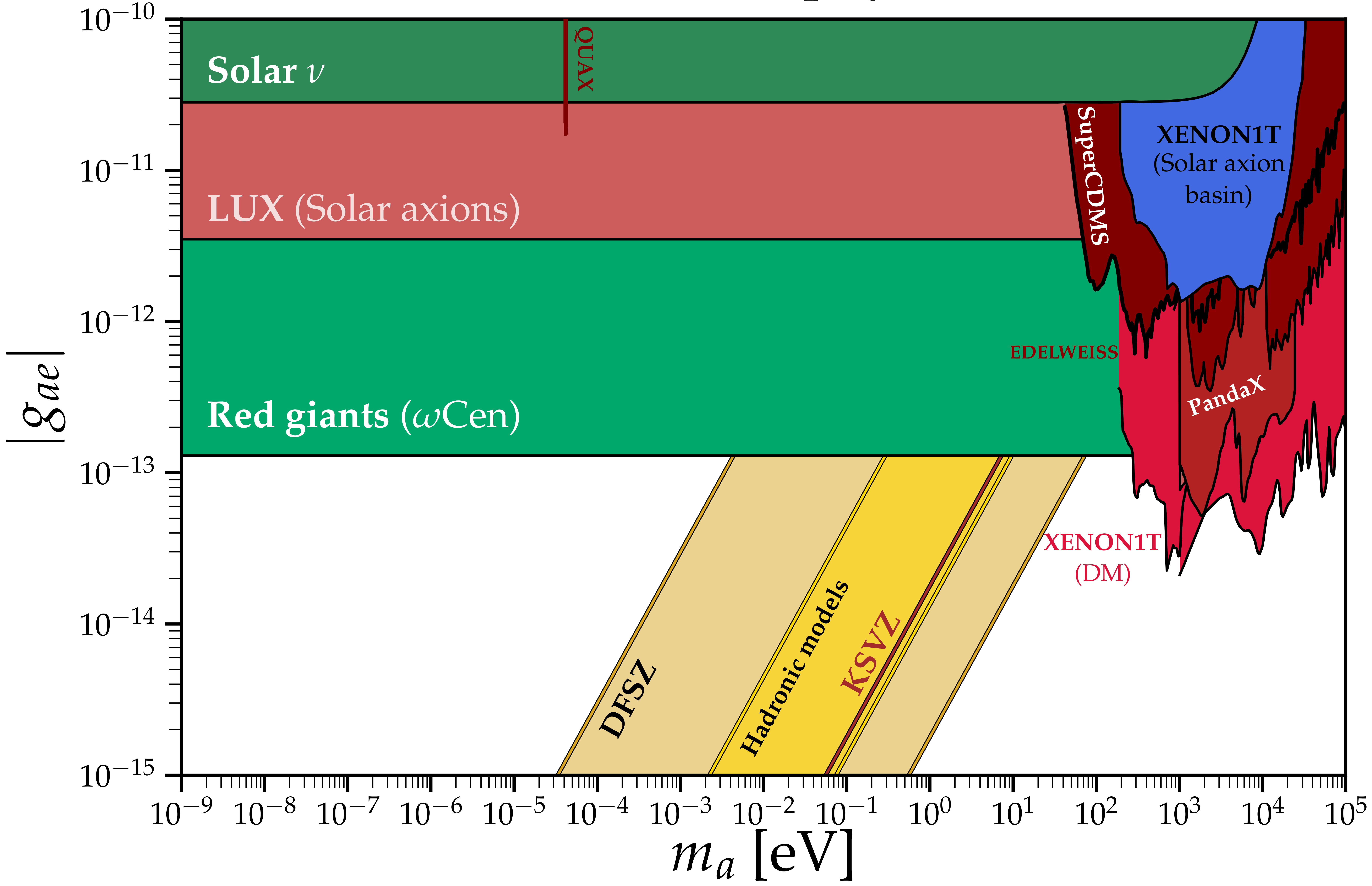





Effect of substructure
The axion lineshape
Effect of halo anisotropy
$f(\omega)$
Low speed stream
e.g. Helmi streams
High speed stream
e.g. Sequoia
0
1
2
3
$\left(\frac{\omega}{m_a} - 1\right) \times 10^6$
$\alpha f(\omega)$
Stochastic noise $\sim \alpha$
Main halo
$Q \sim 10^6$
Substructure
$Q > 10^6$
0
0.5
1
1.5
2
2.5
3
$\left(\frac{\omega}{m_a} - 1\right) \times 10^6$
Jan.
June
Jan.
June
Time
Modulation at $v = 300$ km s^{-1}
Anisotropic halo
e.g. Gaia-Sausage-Enceladus
Isotropic halo
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Fermion couplings, e.g. axion-electron.

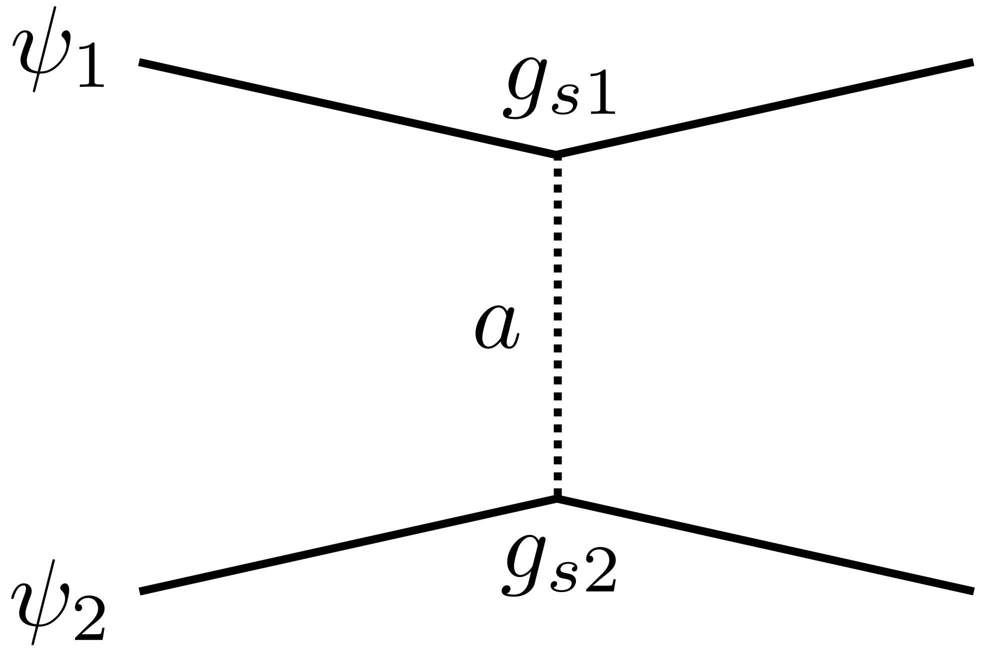
→ Hard to beat astrophysical bounds



Pure laboratory tests of axion-fermion fifth forces

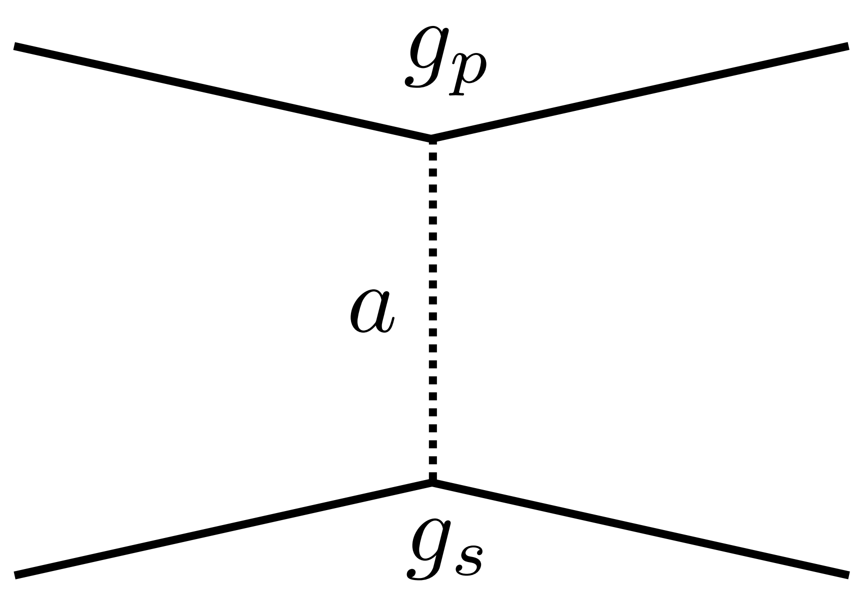
Key point: any SM or BSM CP-violation (could be e.g. size of Jarlskog invariant of CKM matrix) could shift axion vev and generate **CP-violating** axion-fermion couplings in addition to the **CP-conserving** ones

$$\mathcal{L} \supset -a \sum_{\psi} \underline{g_p^{\psi} \left(i\bar{\psi}\gamma^5\psi \right)} - a \sum_{\psi} \underline{g_s^{\psi} (\bar{\psi}\psi)}$$



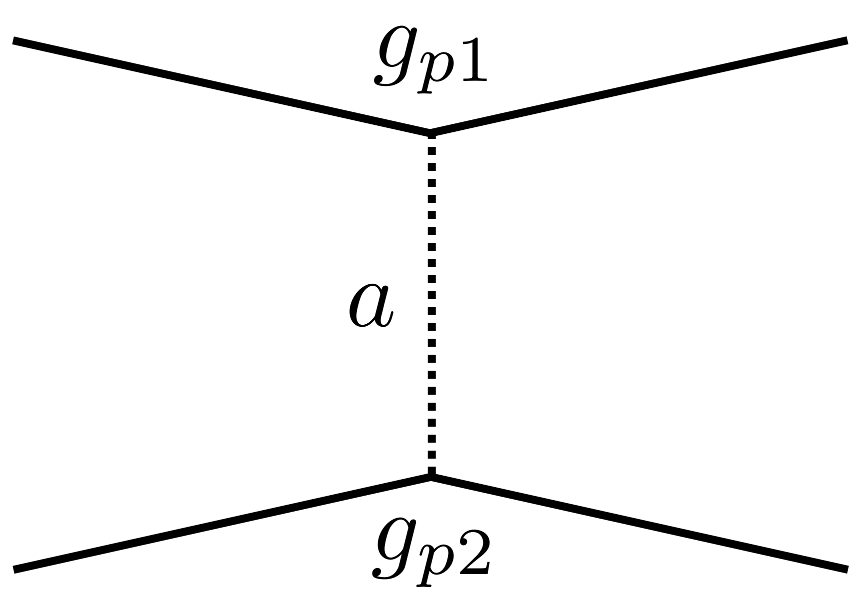
Monopole-monopole (Spin independent)

→ e.g. tests of inverse square law/WEP



Monopole-dipole (Spin dependent)

→ Spin-mass forces e.g. ARIADNE/QUAX



Dipole-dipole (Spin dependent)

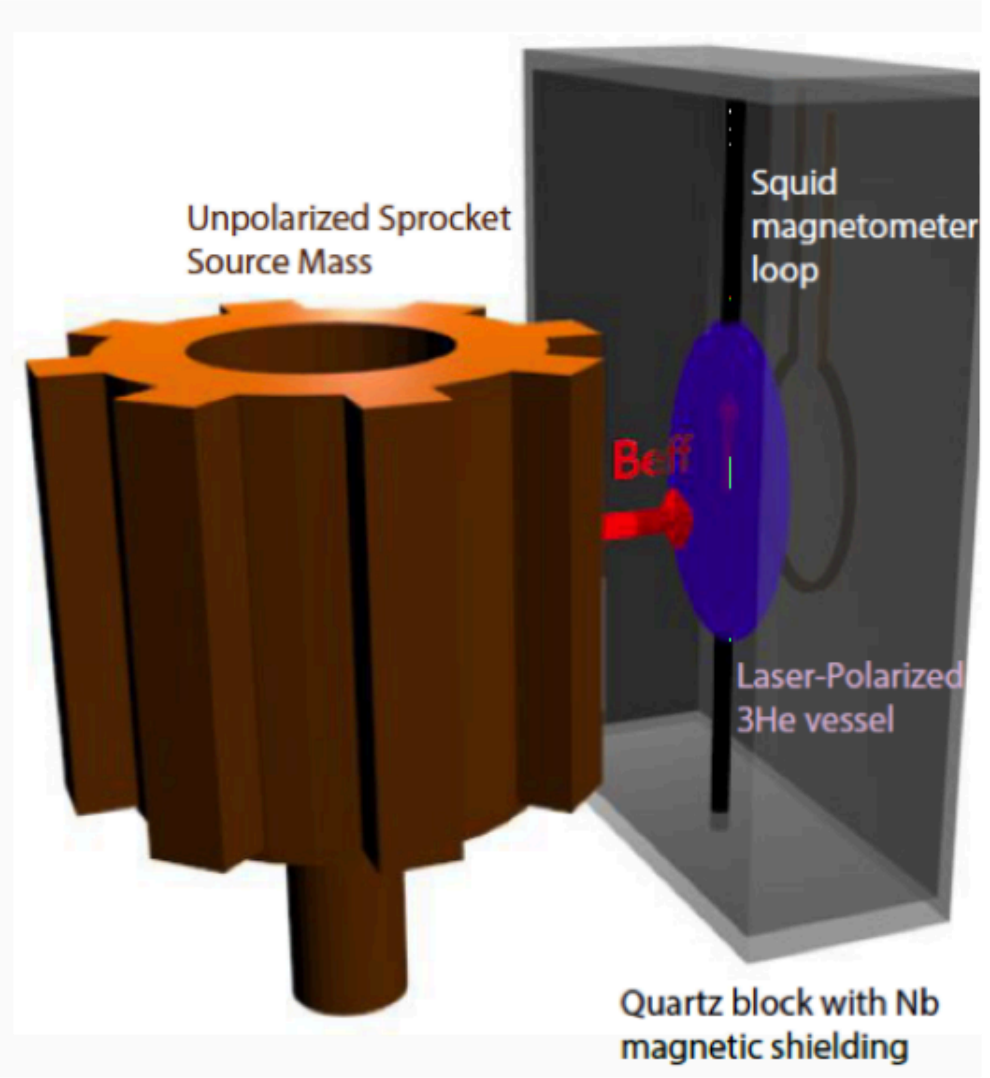
→ Forces between spin-polarised samples

Monopole-dipole searches

Conceptually similar, spin an unpolarised source mass near to a spin-polarised target

ARIADNE

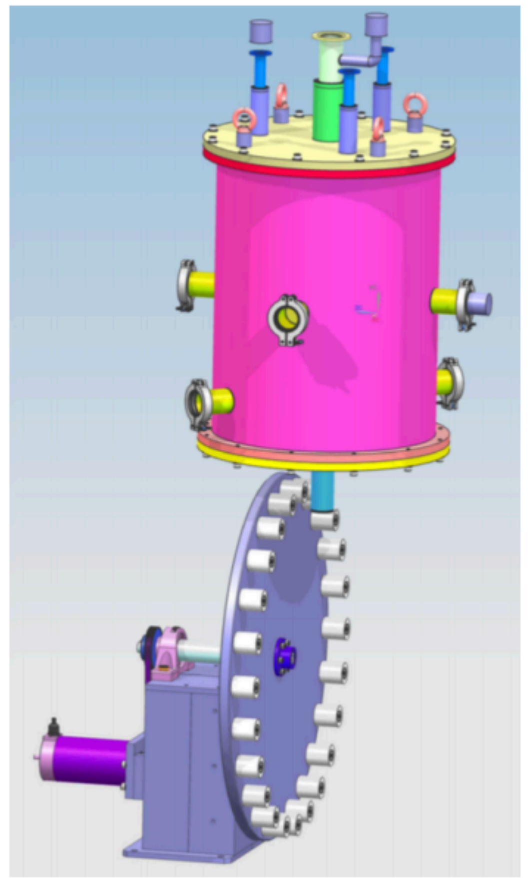
Constrains: g_p g_s (nucleon-nucleon)



QUAX

Constrains: g_p g_s (electron-nucleon)

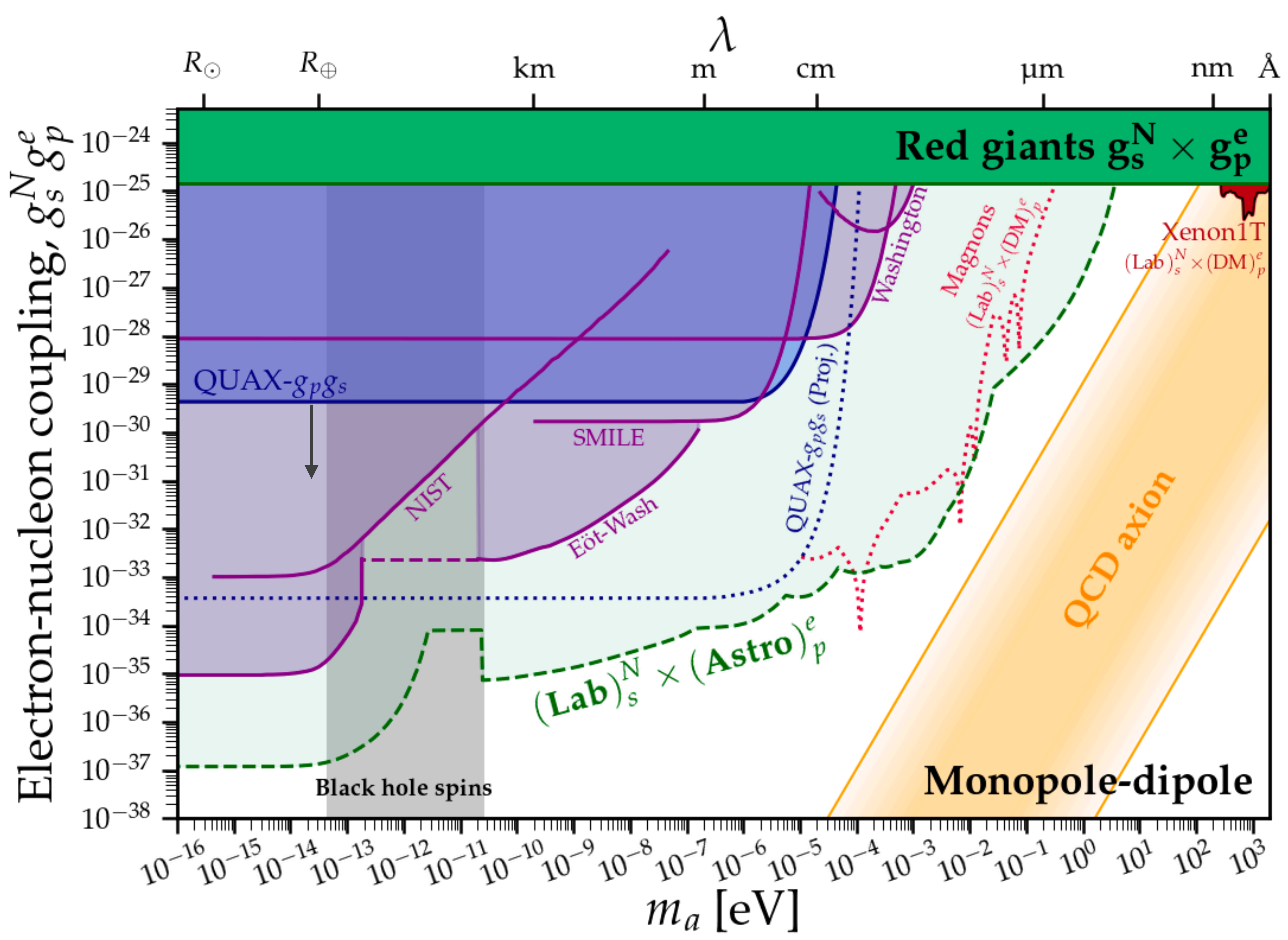
(Latest QUAX result **2011.07100)**



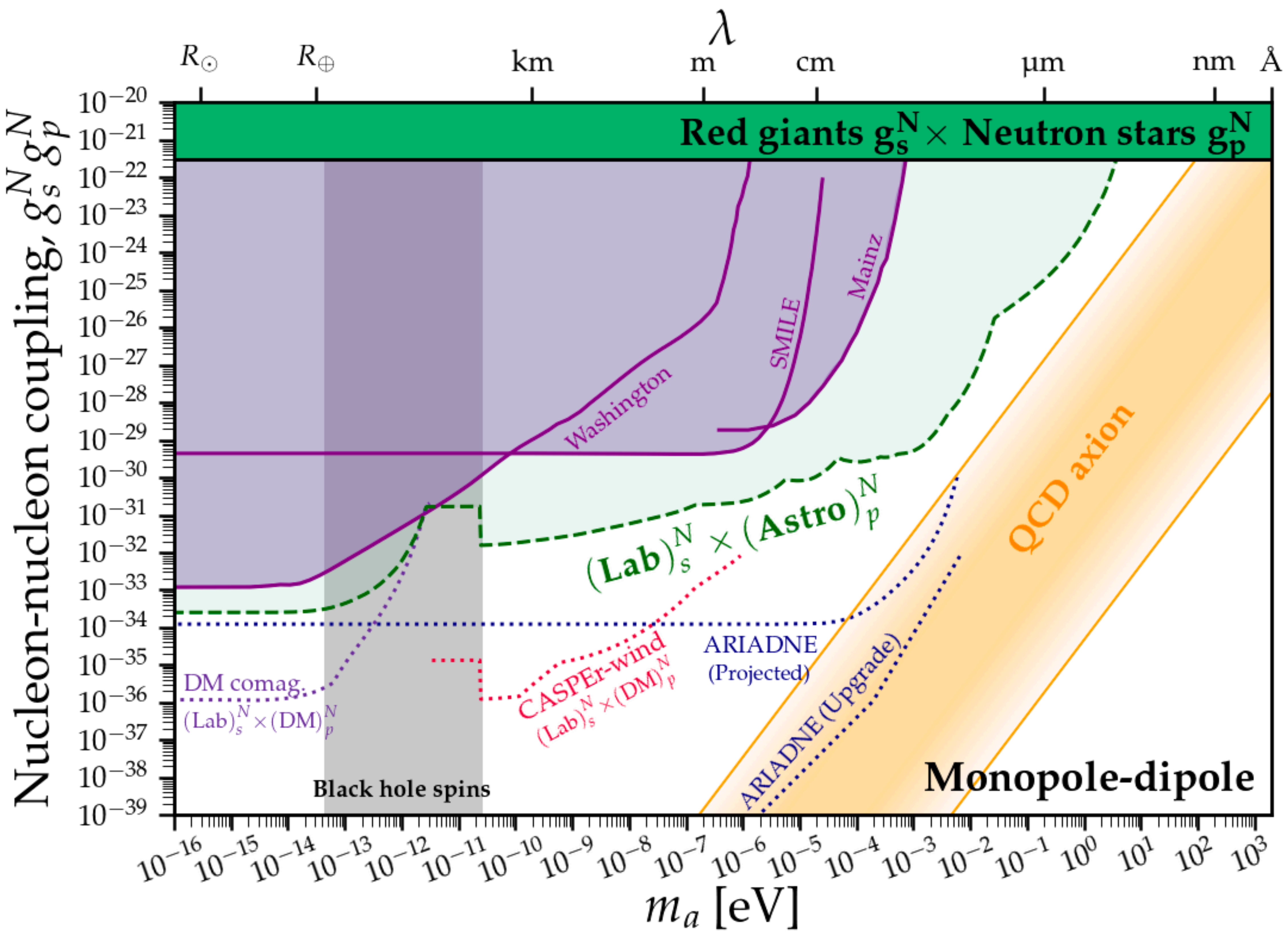
Challenge: stellar bounds tightly constrain g_p, and spin independent fifth force tests easily constrain g_s: so Astro x Lab bound on these coupling combos are very strong

Pure laboratory tests for monopole-dipole axion-mediated forces

Electron-nucleon coupling



Nucleon-nucleon coupling



Hard to beat the astrophysical bounds, but **ARIADNE** projects that it will

O'Hare & Vitagliano [2010.03889]

$$\Delta_k^2 = \frac{k^3}{2\pi^2}\frac{1}{V}\langle|\widetilde{\delta}(\mathbf{k})|^2\rangle_{|\mathbf{k}|=k}$$

Vaquero, Redondo, Stadler [1809.09241]

Evolution of dimensionless variance in the density contrast