SHINING AXIONS THROUGH ASTROPHYSICAL WALLS

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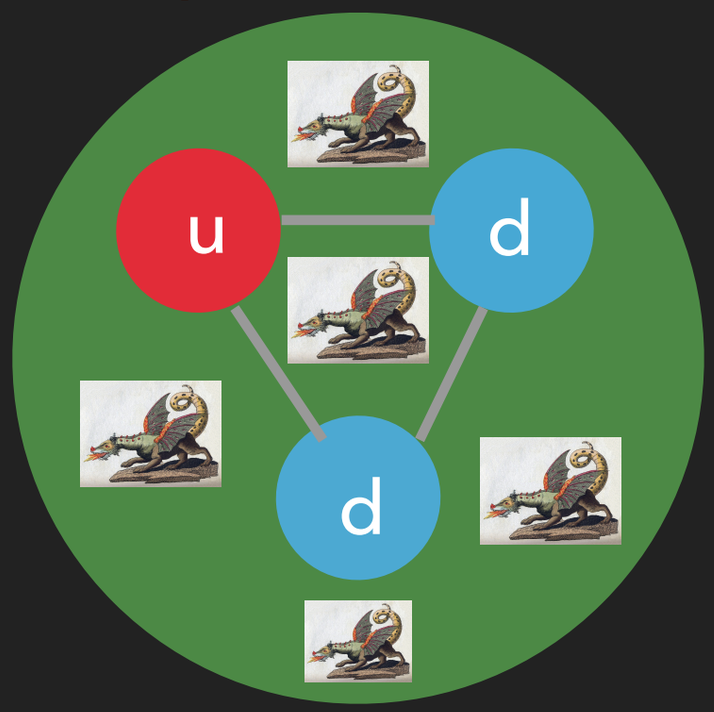
U.S. DEPARTMENT OF ENERGY | Office of Science

axion timeline

Motivation:
Strong CP
problem



Can be dark
matter

experimental
effort in full swing

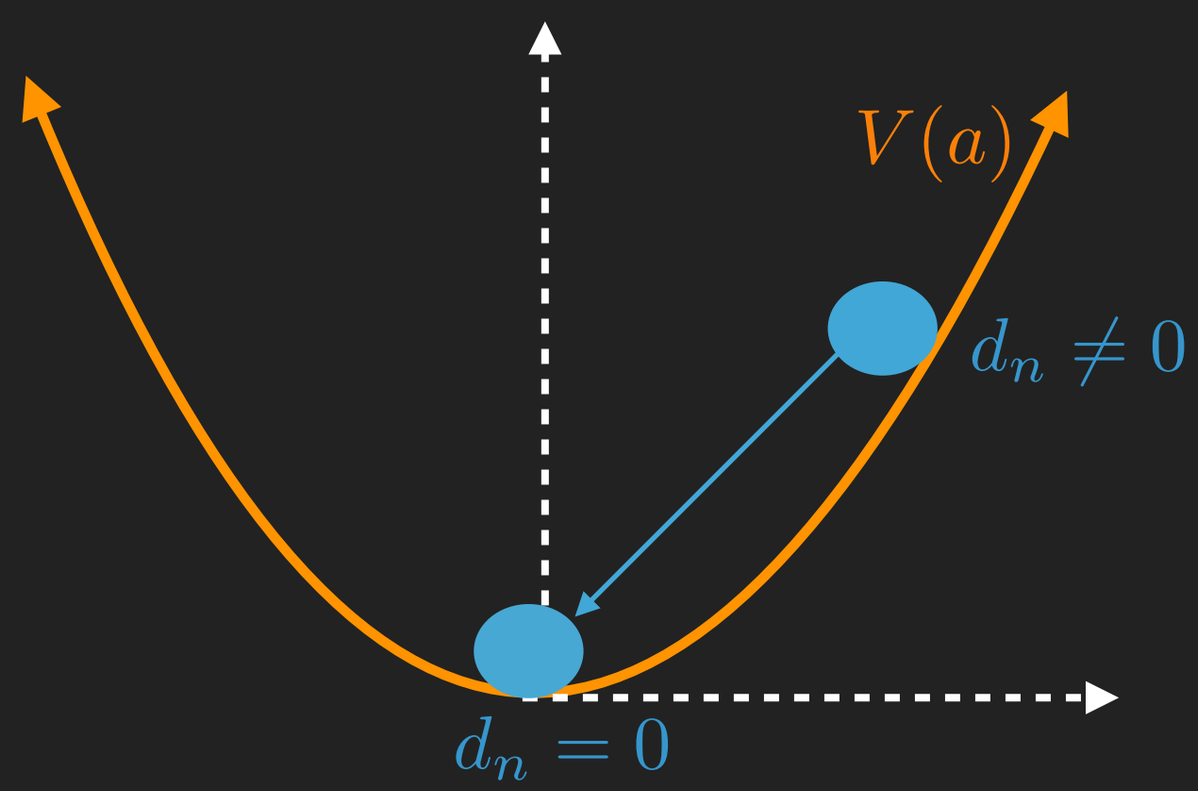
1977

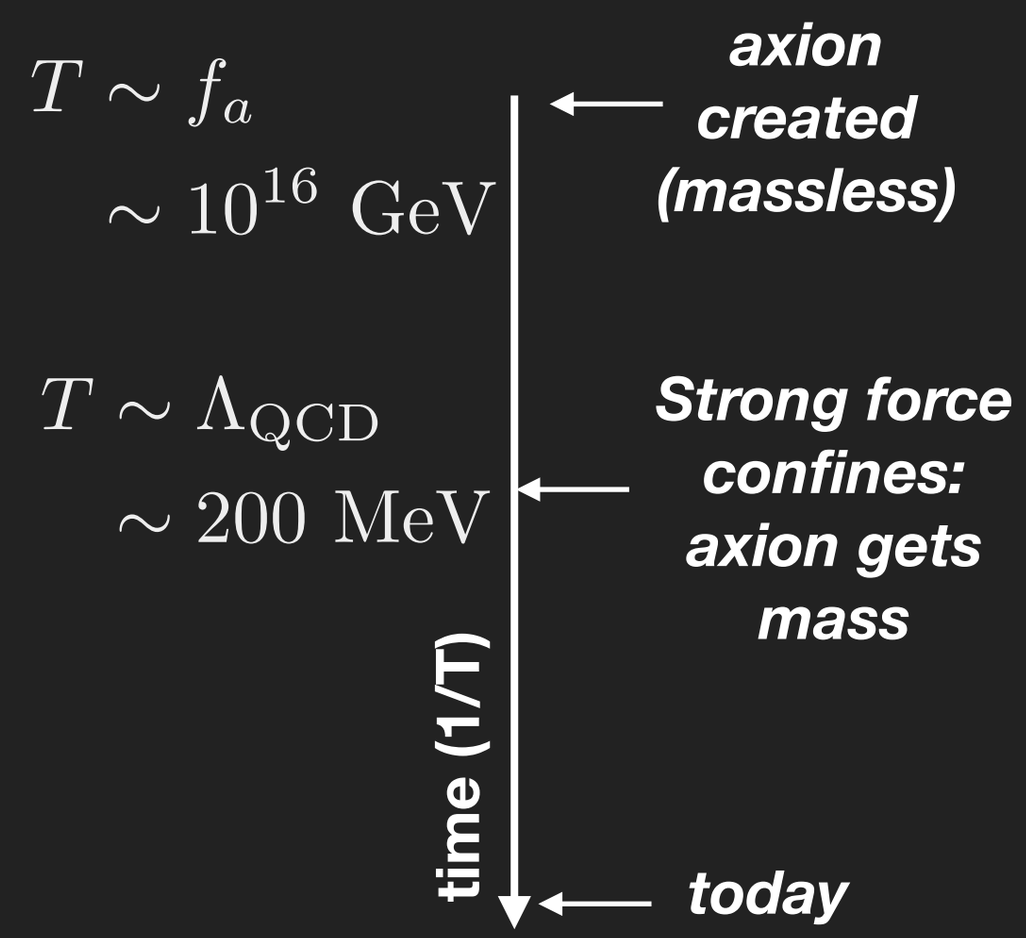
1983

today

Axion Introduced to Solve Strong CP Problem

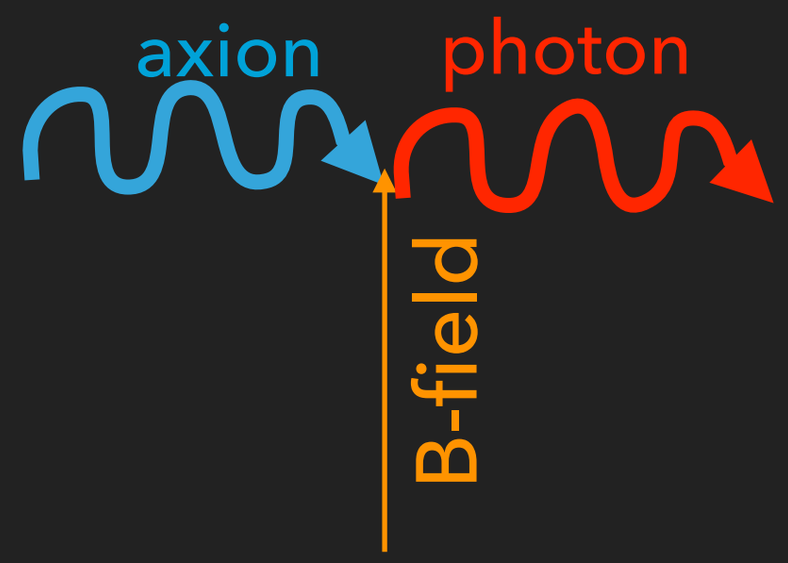
- CP-violation: $\mathcal{L}^{\rm CP} = -\frac{\bar{\theta} g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$
- Neutron EDM: $d_n \propto \bar{\theta}$
- Promote θ to field: $\bar{\theta} \to a/f_a$
- Axion potential: $V(a) \approx \frac{1}{2}\Lambda_{\rm QCD}^4 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$





Axions interact with electromagnetism

- Axion: $\mathcal{L} \sim \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$ $\mathcal{L} \sim \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \sim \frac{a}{f_a}\mathbf{E}\cdot\mathbf{B}$



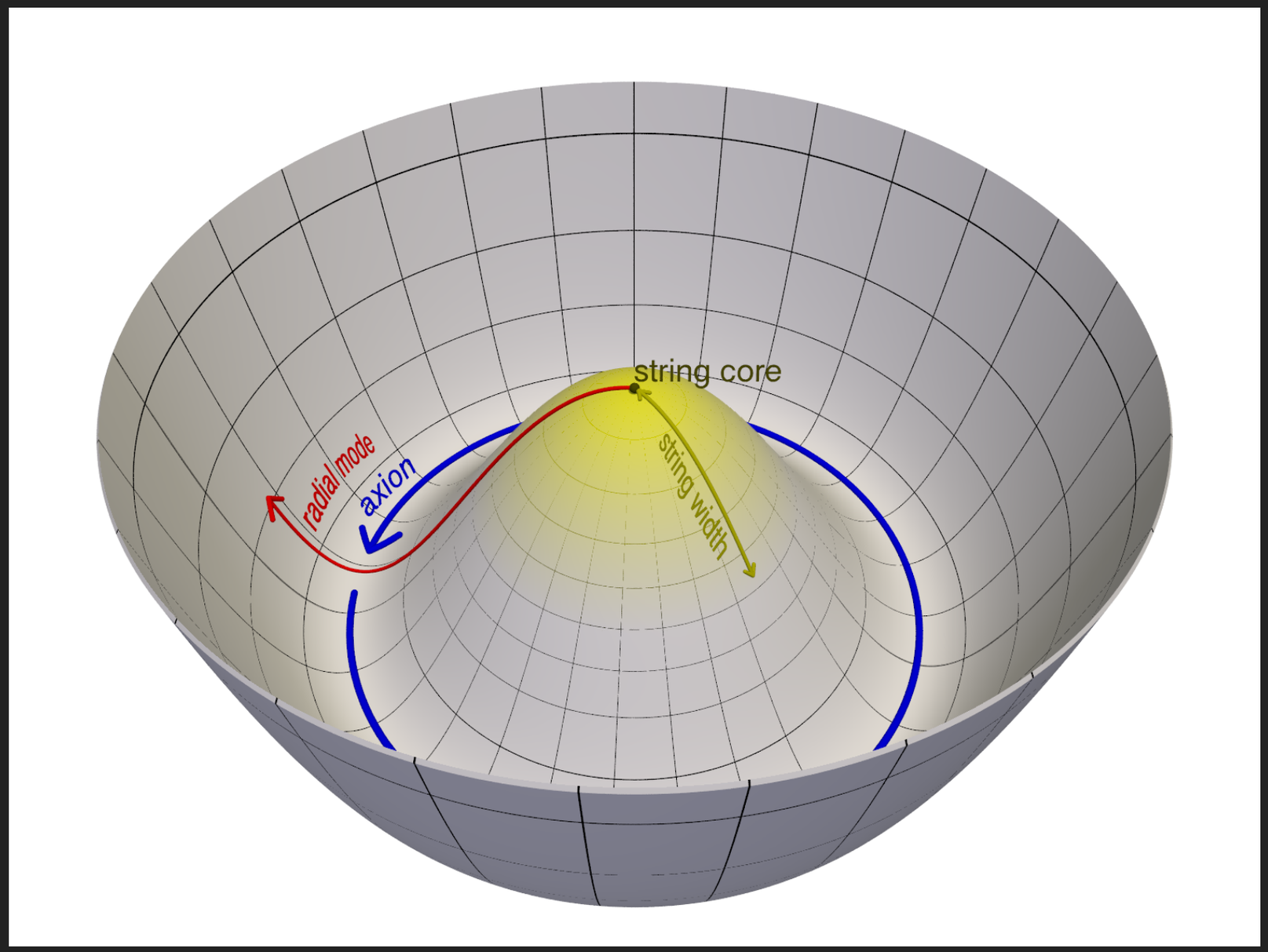
- Axion potential: $V(a) \approx \frac{1}{2}\Lambda_{\rm QCD}^4 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$

- Axion mass: $m_a \approx \frac{\Lambda_{\rm QCD}^2}{f_a} \sim 10^{-9}\ \text{eV} \left(\frac{10^{16}\ \text{GeV}}{f_a}\right)$

Axions as pseudo-Goldstone bosons

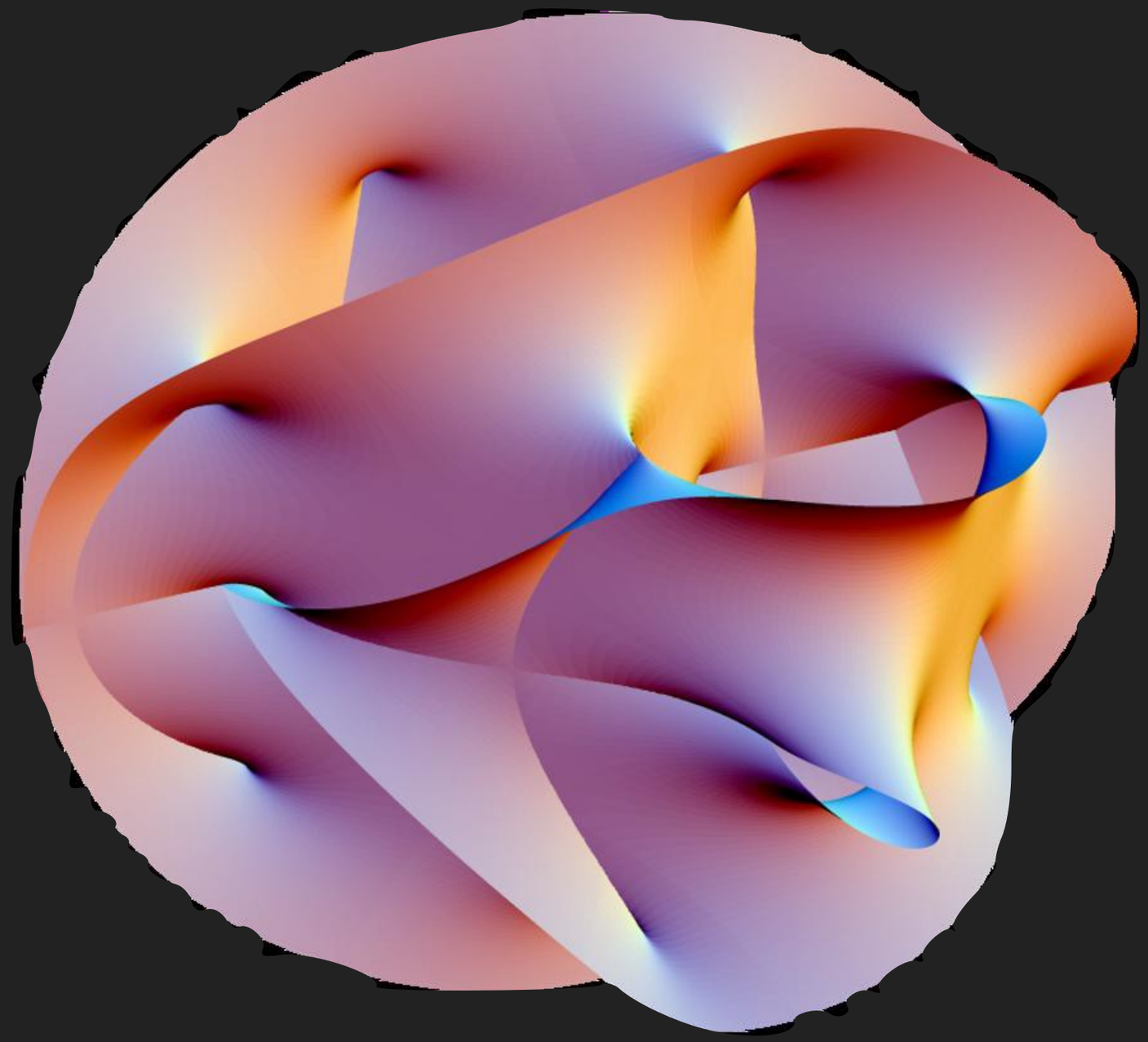
$$\mathcal{L} = |\partial\Phi|^2 - \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2 - \frac{\lambda T^2}{6}|\Phi|^2$$

$$\Phi(x) = \frac{r(x) + f_a}{\sqrt{2}} e^{ia(x)/f_a}$$



Axions from string theory?

Axions from zero modes of 2-form fields generate **10's - 100's of ALPs** from compactifion on internal space



Axions could be only way to experimentally probe string theory compactifications!

(Ultra-light) Axion-like particles versus QCD Axion

$$\mathcal{L} = \cancel{\frac{-g^2}{32\pi^2}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}} - \frac{C_\gamma \alpha_{\rm EM}}{8\pi f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_f \frac{C_f}{2 f_a}\partial_\mu a \bar{f}\gamma^\mu\gamma_5 f$$

QCD axion and heavy ALPs only!

$$-\frac{1}{2}m_{\rm bare}^2 a^2$$

$$m_a^{\rm QCD} \gg m_{\rm bare}$$

small (or large)

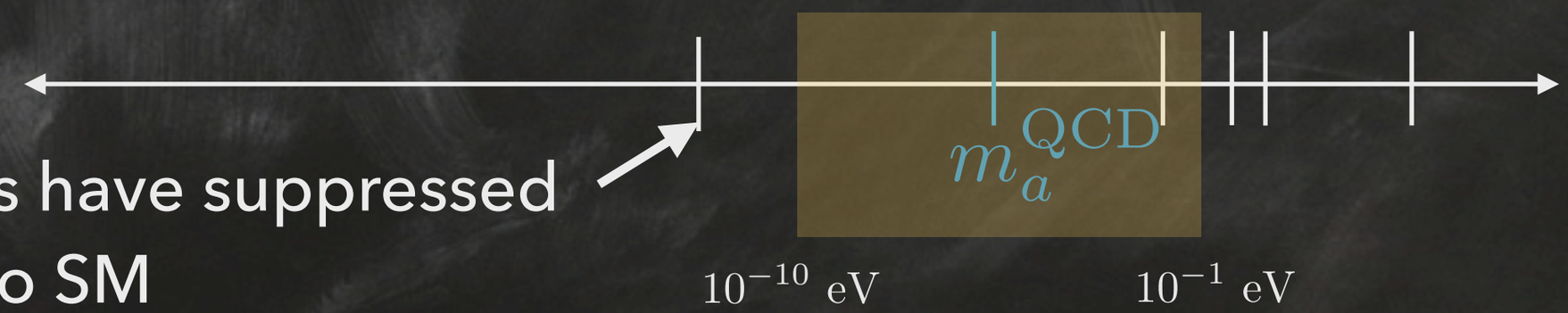
Sring Axiverse: *N* pseudo-scalars -> *N-1* ALPs + 1 QCD axion

ALPs in grand unification: QCD -> mass threshold

$$\mathcal{L} \supset \frac{-g^2}{32\pi^2}\left(\sum \frac{a_i}{f_a^i}\right) G^{\mathrm{GUT}}_{\mu\nu}\tilde{G}^{\mu\nu}_{\mathrm{GUT}} - \frac{1}{2}\sum_i m^2_{\mathrm{bare},i} a_i^2$$

All ALPs lie to "right" of the QCD axion line

2206.07053: Agrawal, Nee, Reig



lighter ALPs have suppressed couplings to SM

ALPs in grand unification: QCD -> mass threshold

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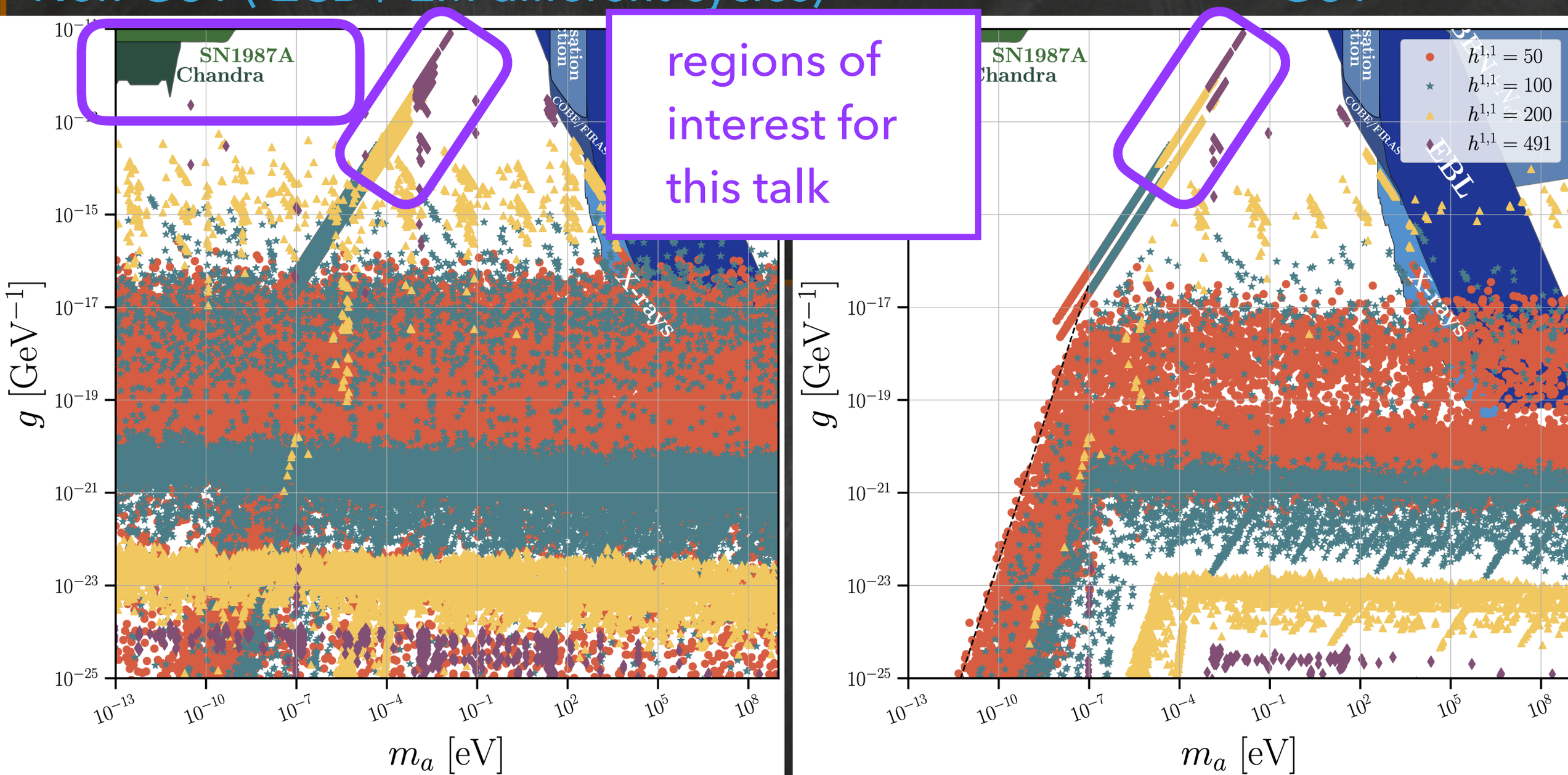
Explicit type IIB compactifications: 2309.123145: Gendler, Marsh, McAllister, Moritz

Non-GUT (QCD / EM different cycles)

GUT



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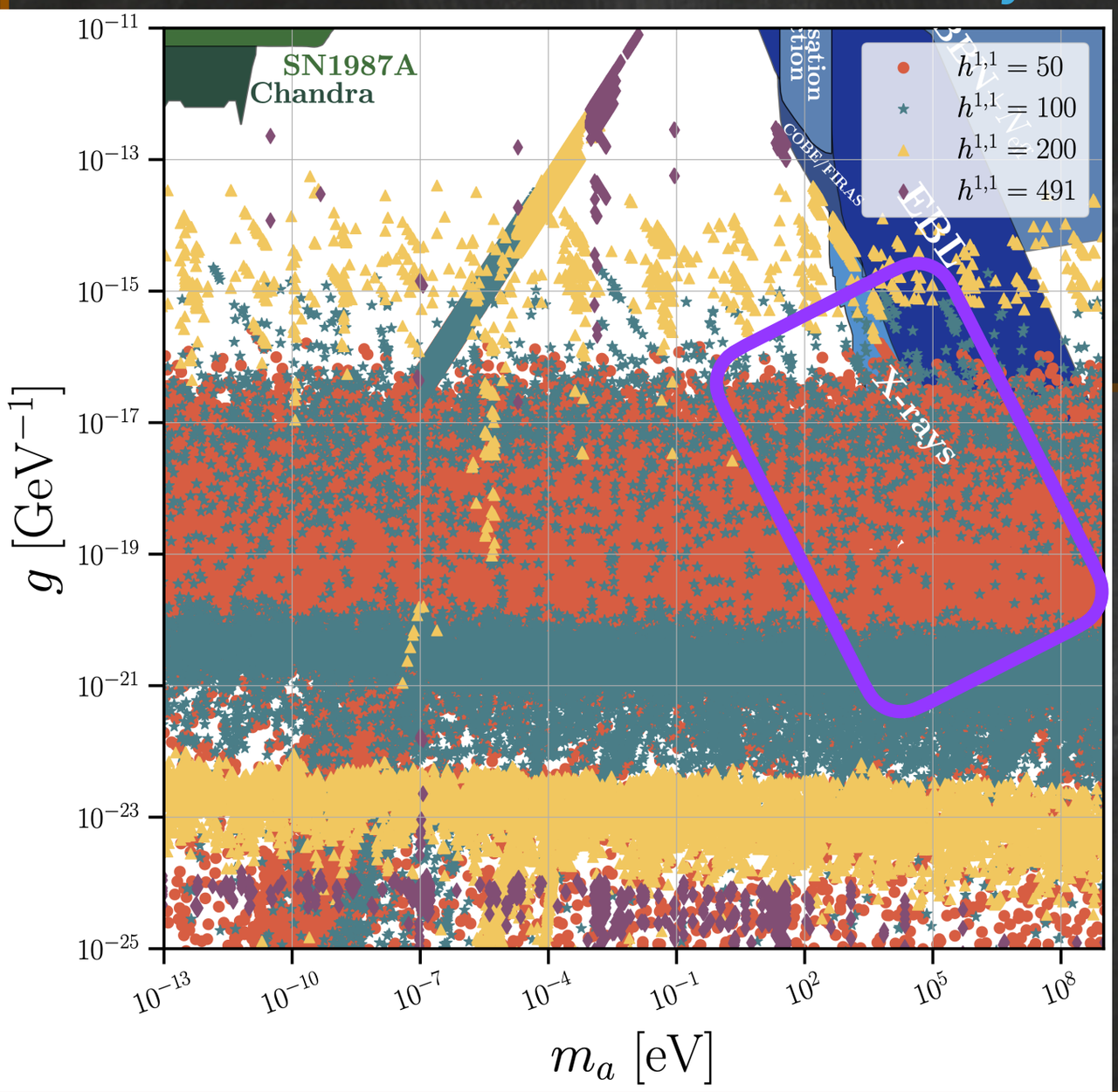
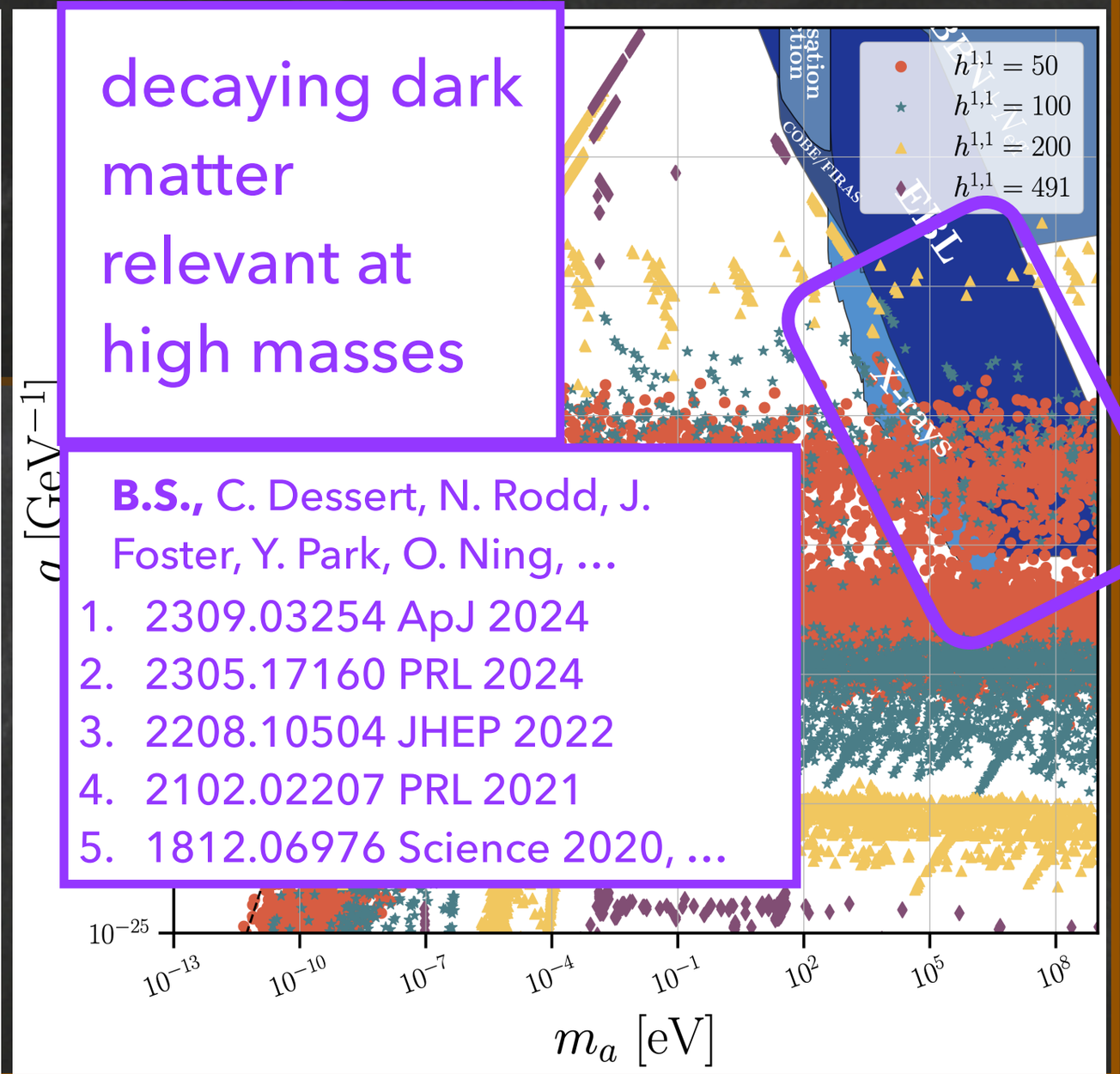


GUT



decaying dark matter relevant at high masses

B.S., C. Dessert, N. Rodd, J. Foster, Y. Park, O. Ning, …

1. 2309.03254 ApJ 2024
2. 2305.17160 PRL 2024
3. 2208.10504 JHEP 2022
4. 2102.02207 PRL 2021
5. 1812.06976 Science 2020, …

axion timeline

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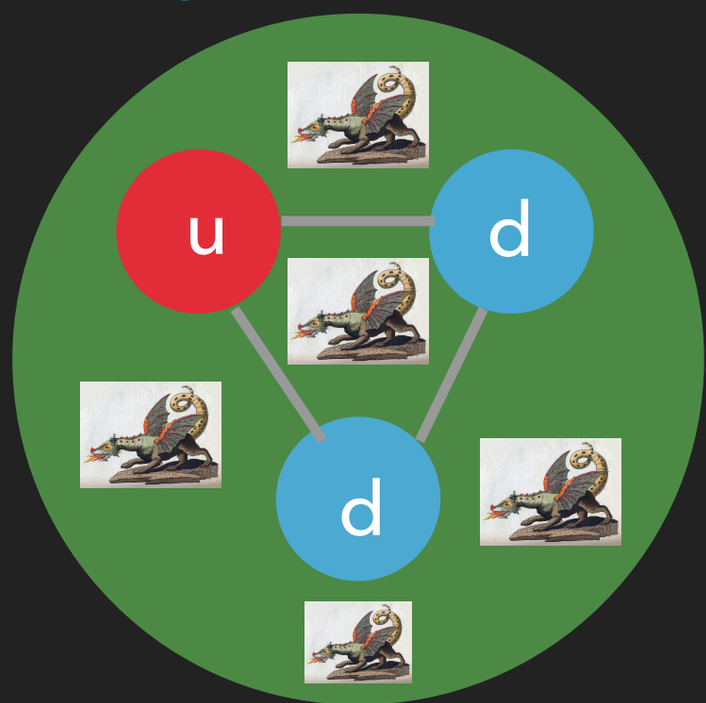
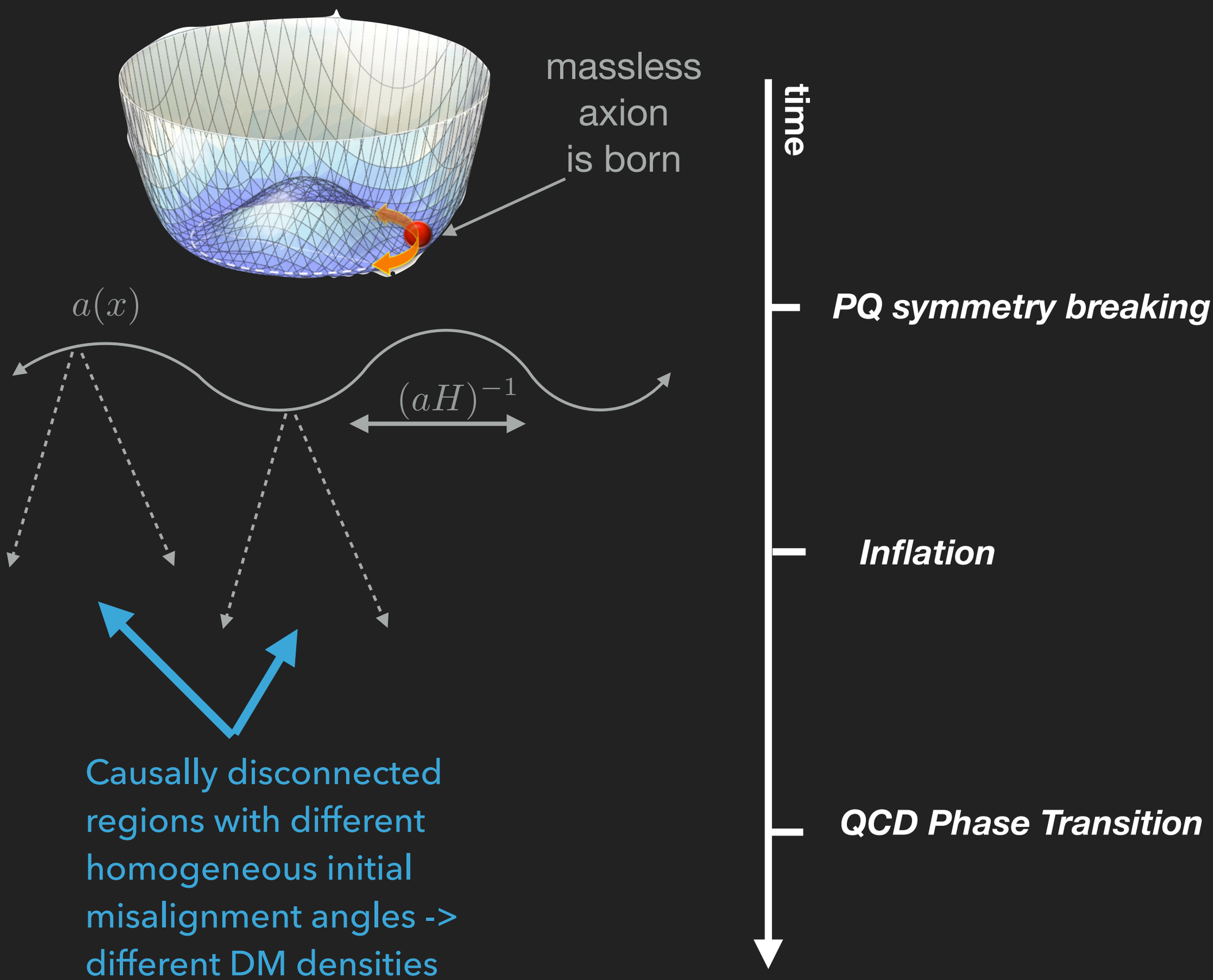


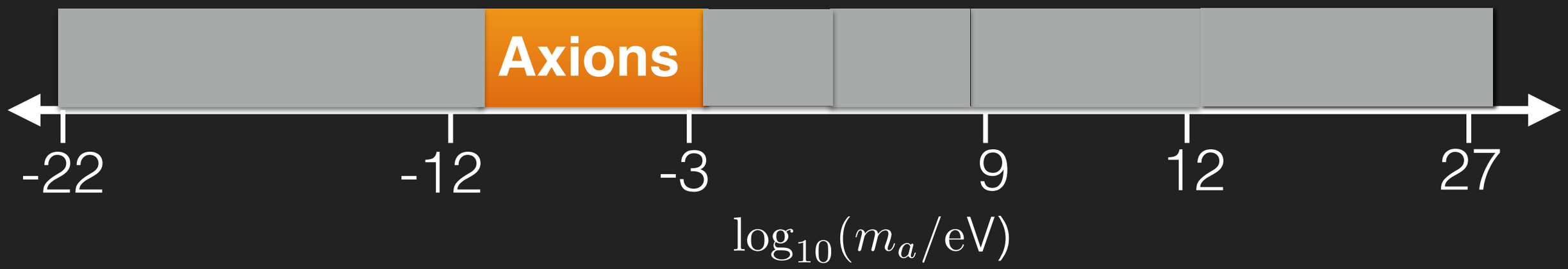
Can be dark
matter

1977

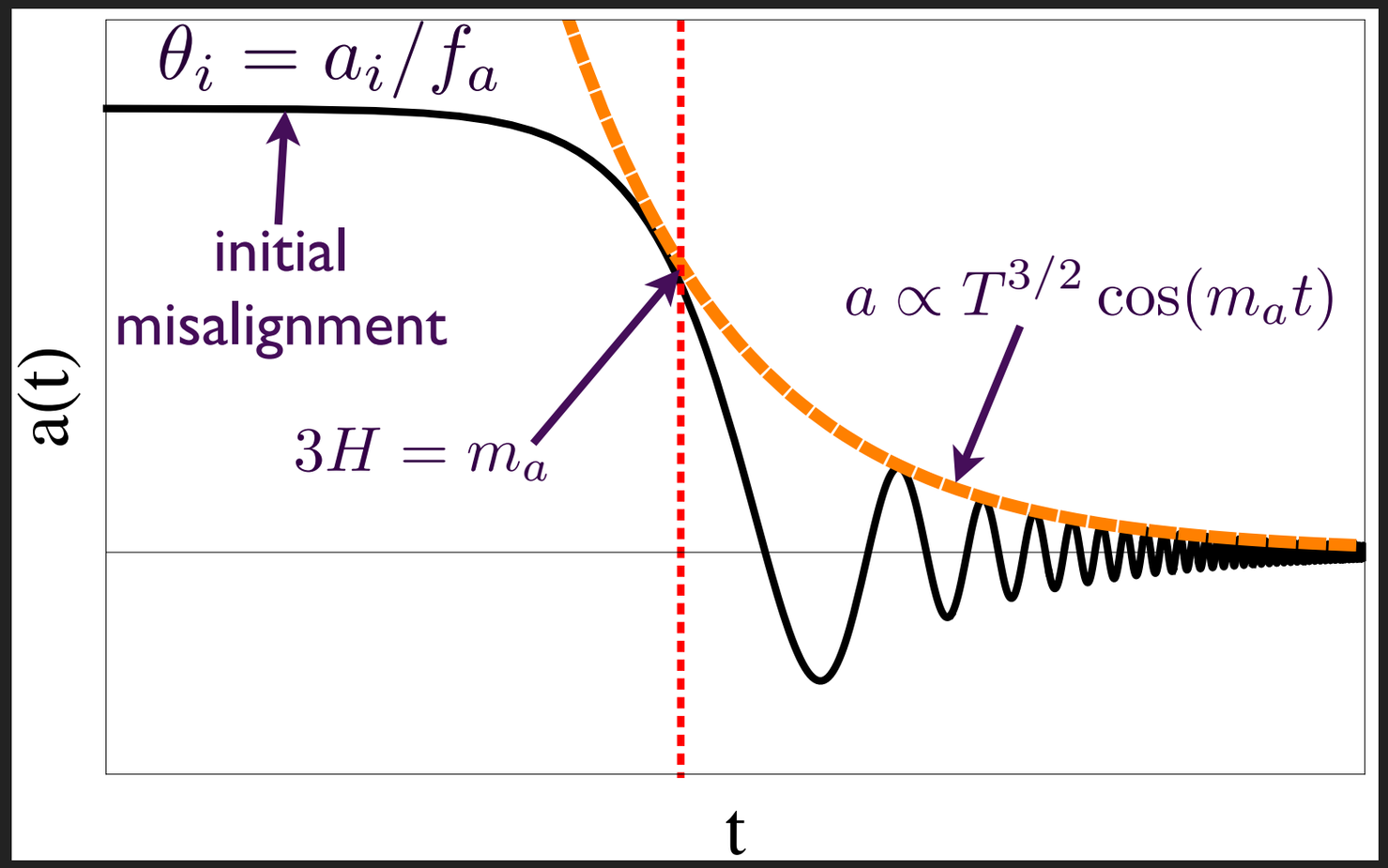
1983

Axion generated before inflation



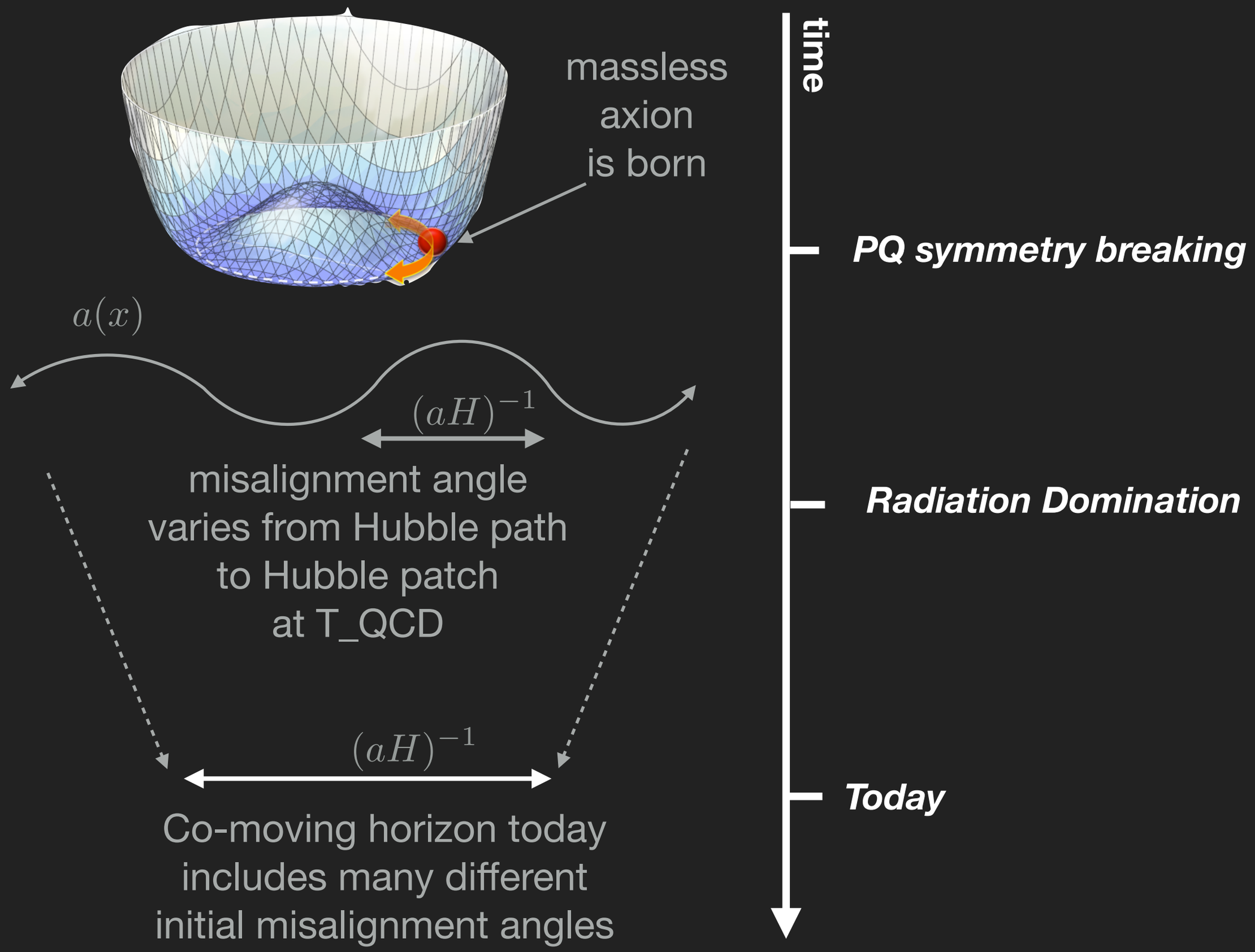


$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \longleftarrow H \sim \frac{T^2}{m_{\rm pl}} \sim \frac{1}{t}$$



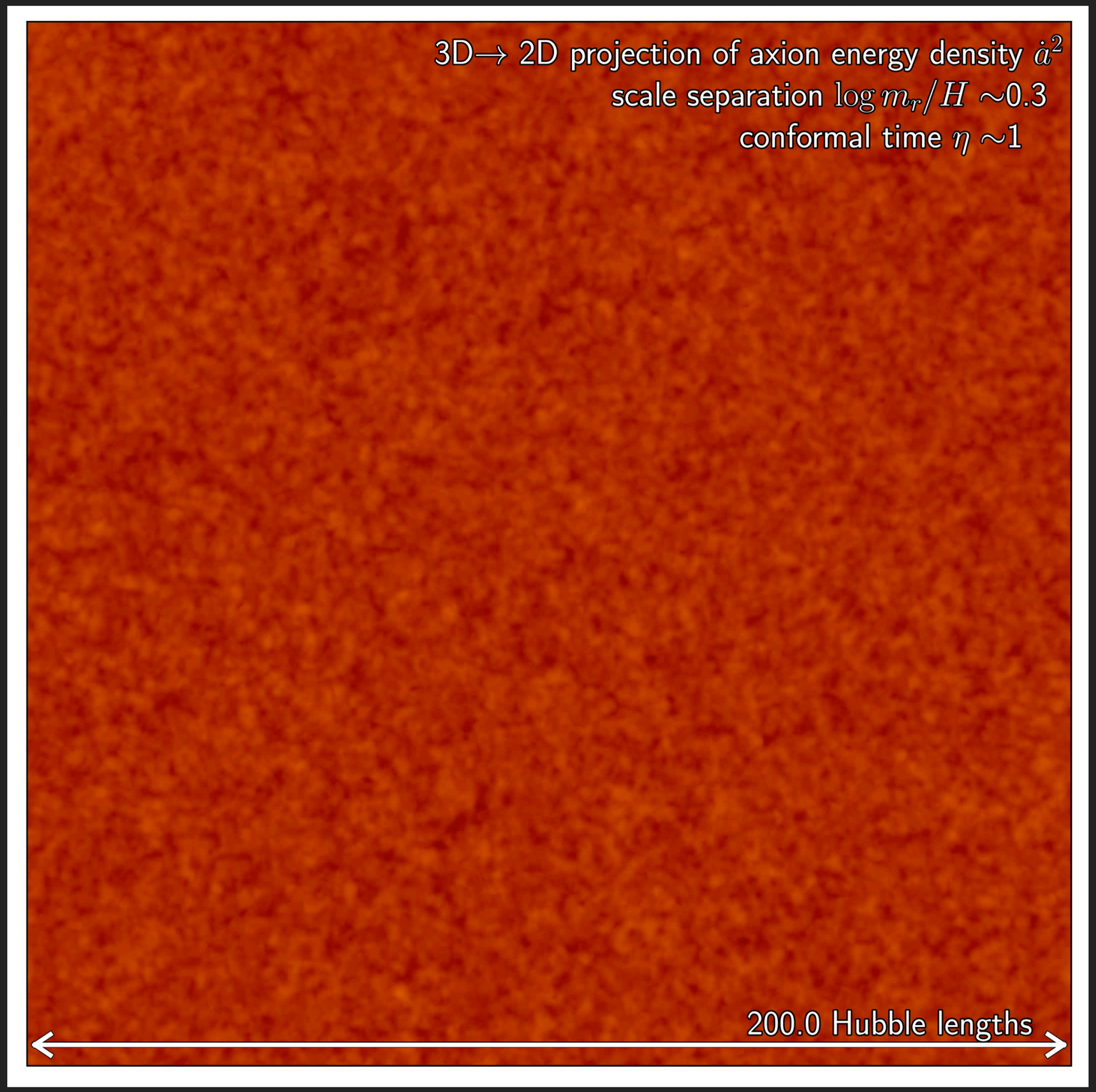
$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \theta_i^2$$

Axion generated after inflation



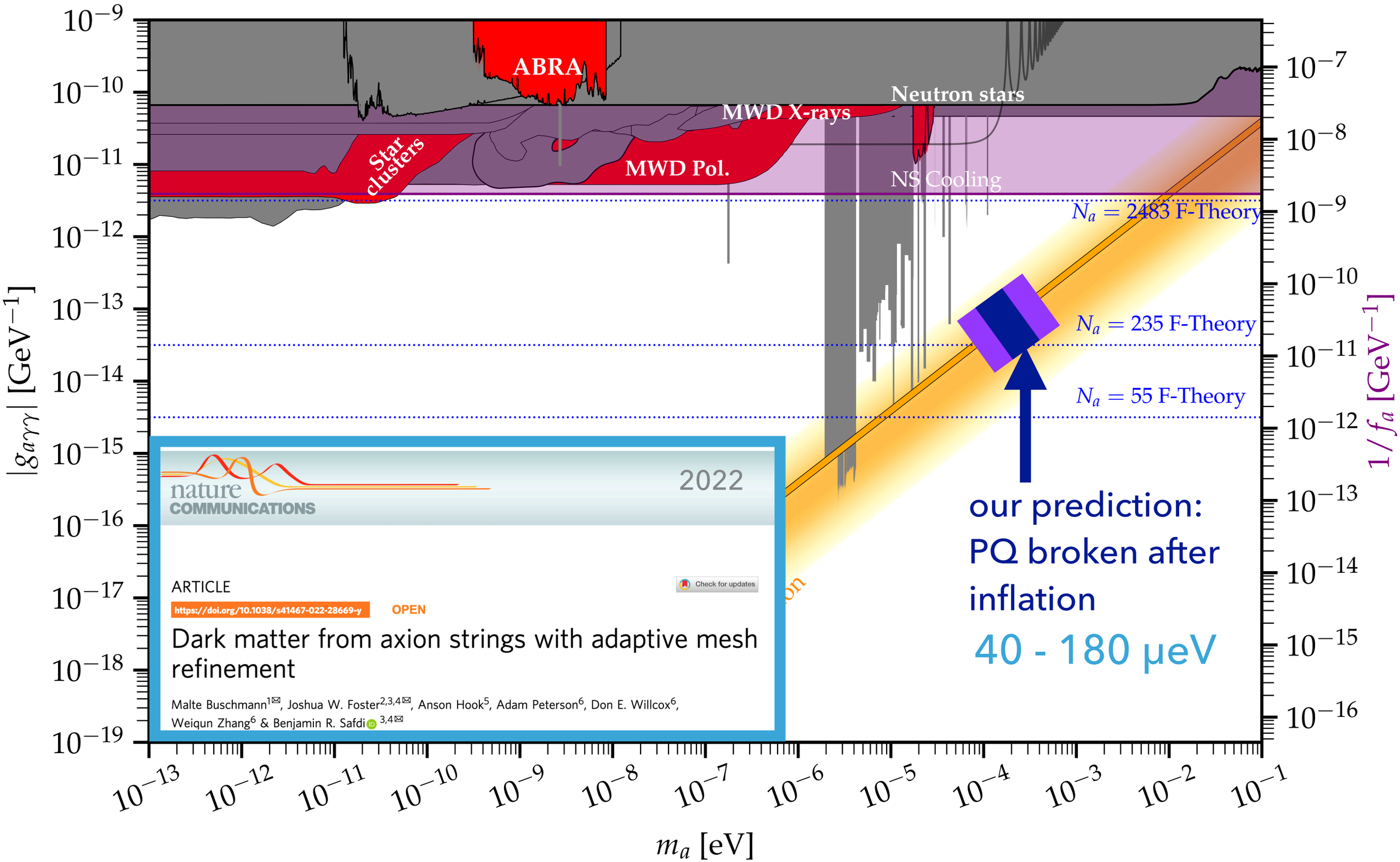
M. Buschmann, J. Foster, **B.S.,** A. Hook, AMReX Collaboration,
Nature Communications (2022) + work in progress

$m_a \in (40, 180)\ \mu\mathrm{eV}$



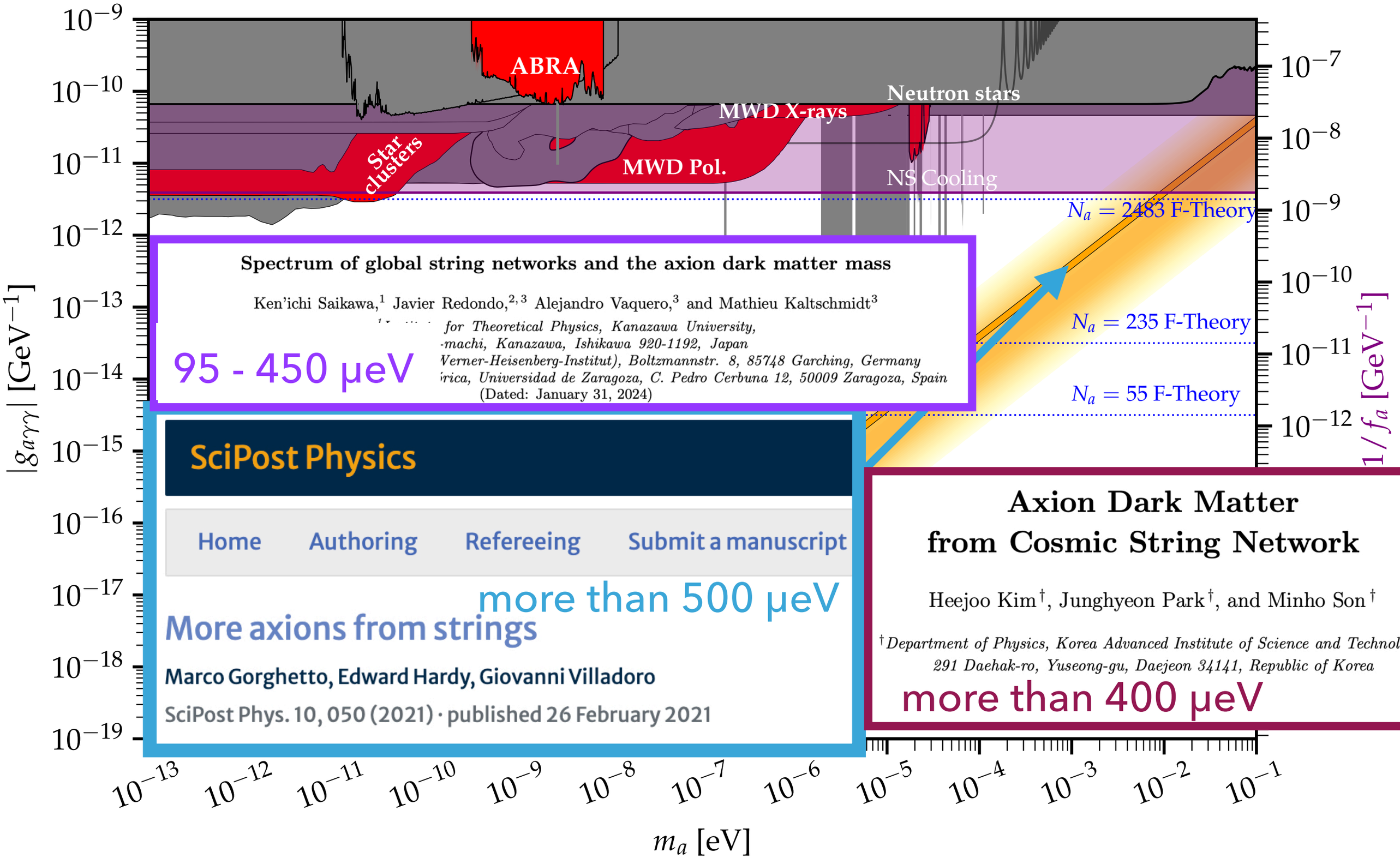
Motivated axion dark matter mass ranges

$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



Other groups disagree with our mass prediction

$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



In Progress: large-scale AMR axion strings simulations

Joshua Benabou, Malte Buschmann, Joshua Foster, **B.S.**

1. Large-scale AMR simulation of axion string from PQ into scaling regime

Size

2022: 120^3 Hubble volumes at PQ phase transition

New simulation: 200^3 Hubble volumes at PQ phase transition

Dynamic Range

2022: finest level would need 65,536^3 cells to fill full lattice

New Simulation: finest level would need 262,144^3 cells to fill full lattice

Evolution time

2022: $\log(m_r/H) \sim 9$

New Simulation: $\log(m_r/H) \sim 10$

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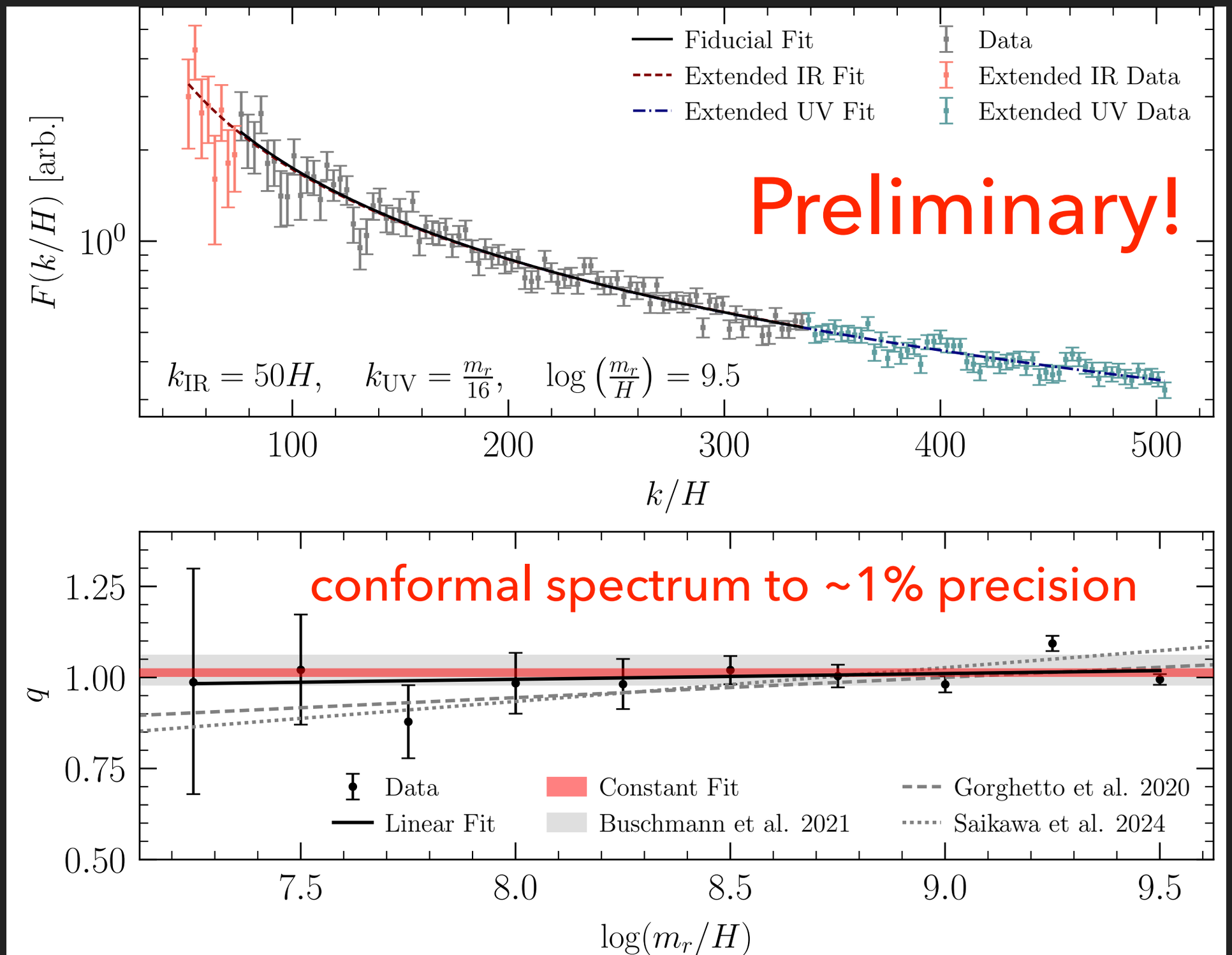
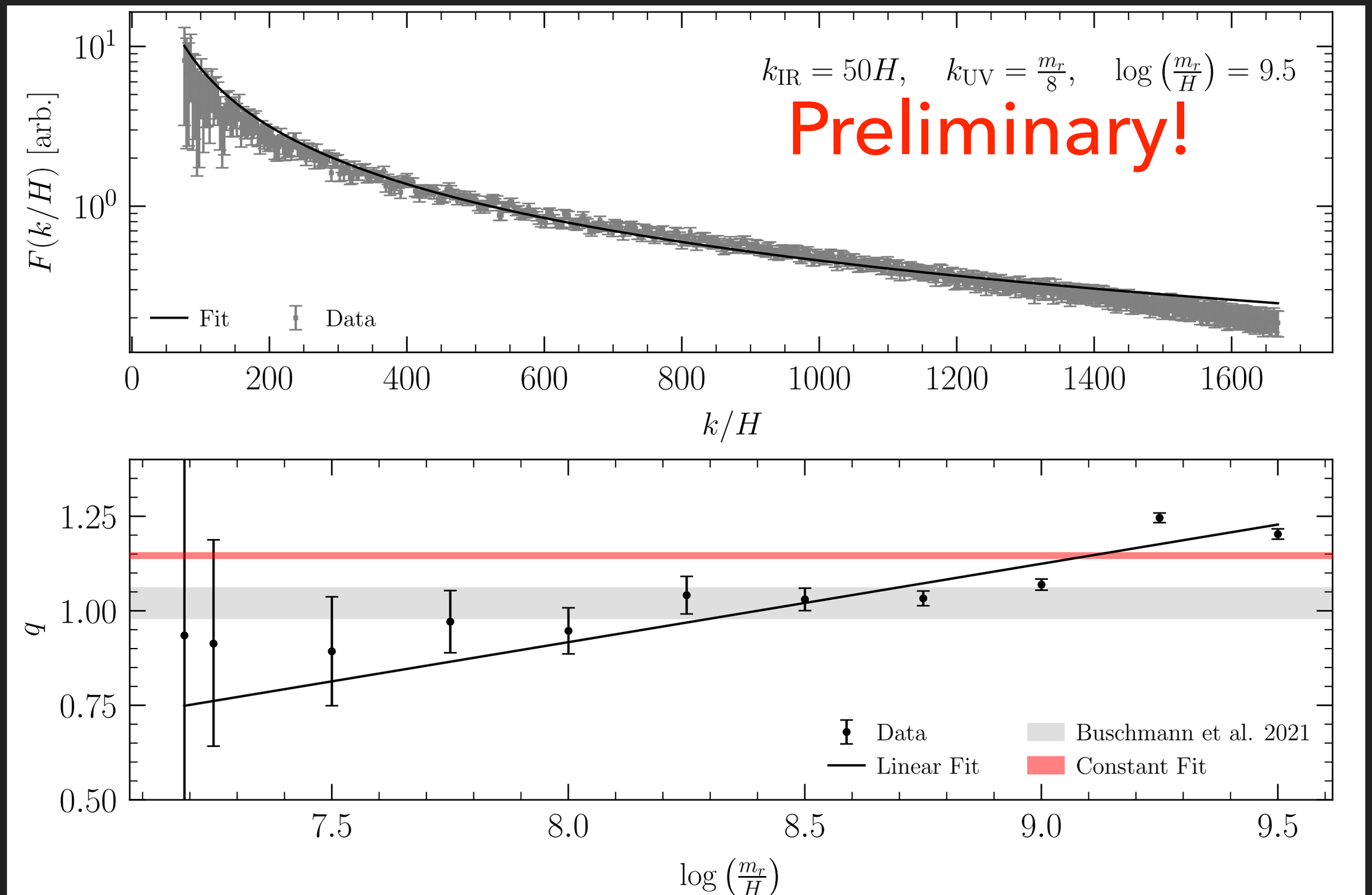


In Progress: large-scale AMR axion strings simulations

"fake" log growth of index by choosing too aggressive UV/IR cut-offs

- Suspicion: source of other group's log growth (can discuss more)



2312.08425

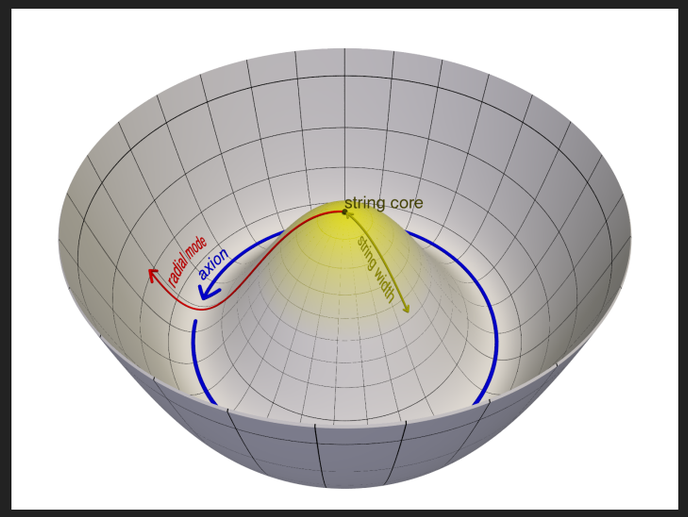
The Cosmological Dynamics of String Theory Axion Strings

Joshua N. Benabou,[1,2,*] Quentin Bonnefoy,[1,2,†] Malte Buschmann,[3,4,‡]
Soubhik Kumar,[5,1,2,§] and Benjamin R. Safdi[1,2,¶]

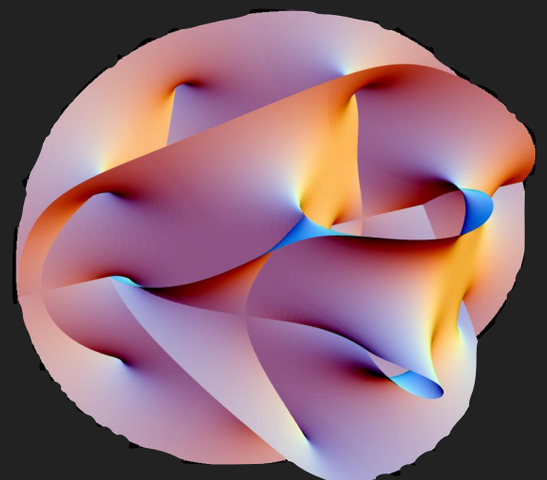
Kibble-Zurek: defect formation requires a spontaneously broken global symmetry

1. **PQ theory:** U(1)_PQ is spontaneously broken -> strings
2. **Extra-dimension scenario:** no spontaneous symmetry breaking as T passes below f_a ~ 1/R -> no strings
    1. **Exception:** brane inflation gives second order phase transition for tachyonic mode -> string formation possible (e.g., wrapped brane production that may source axion strings)

PQ theory: radial mode -> 0 at core

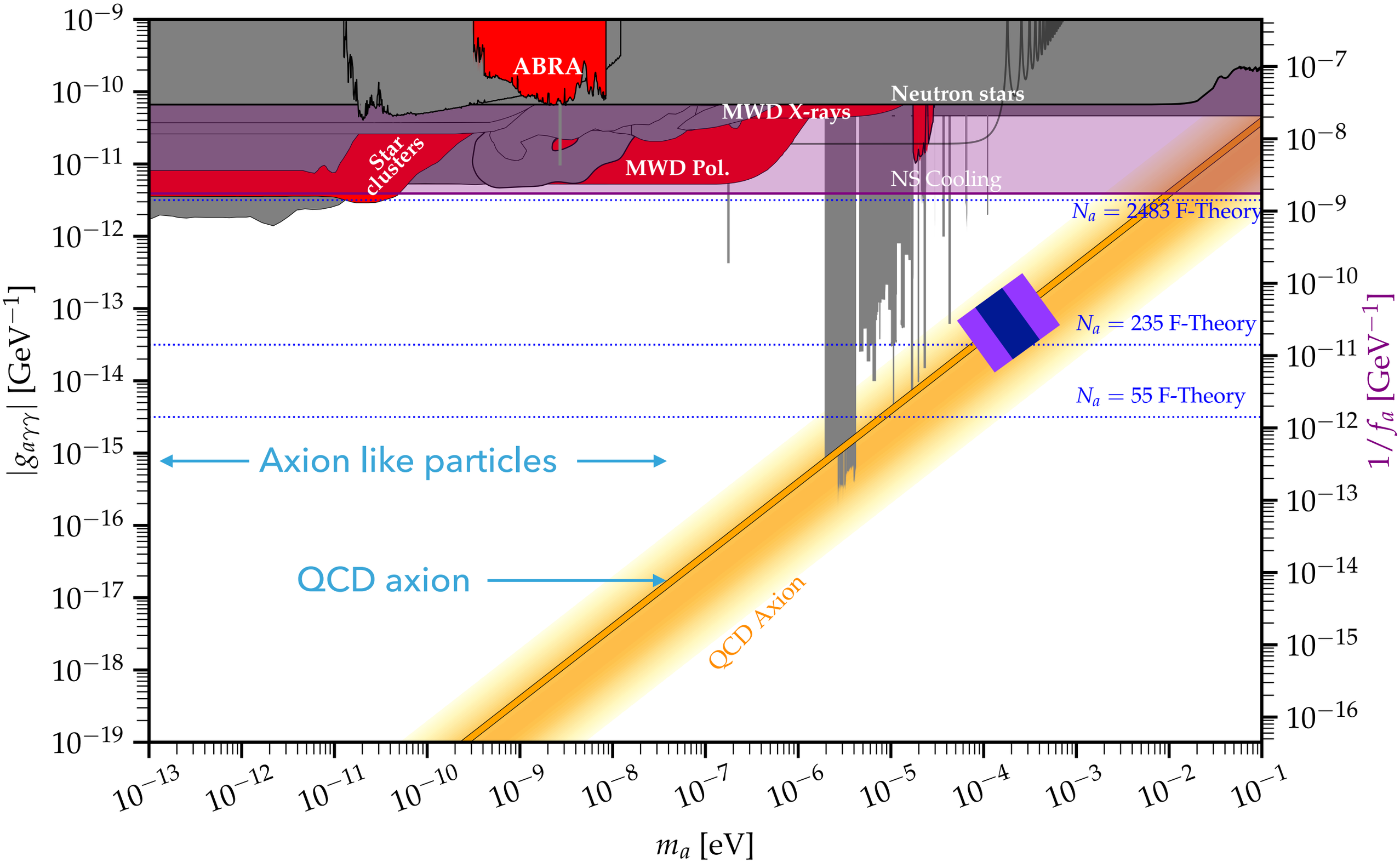


string theory: extra dim decompactifies at core



Motivated axion dark matter mass ranges

$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



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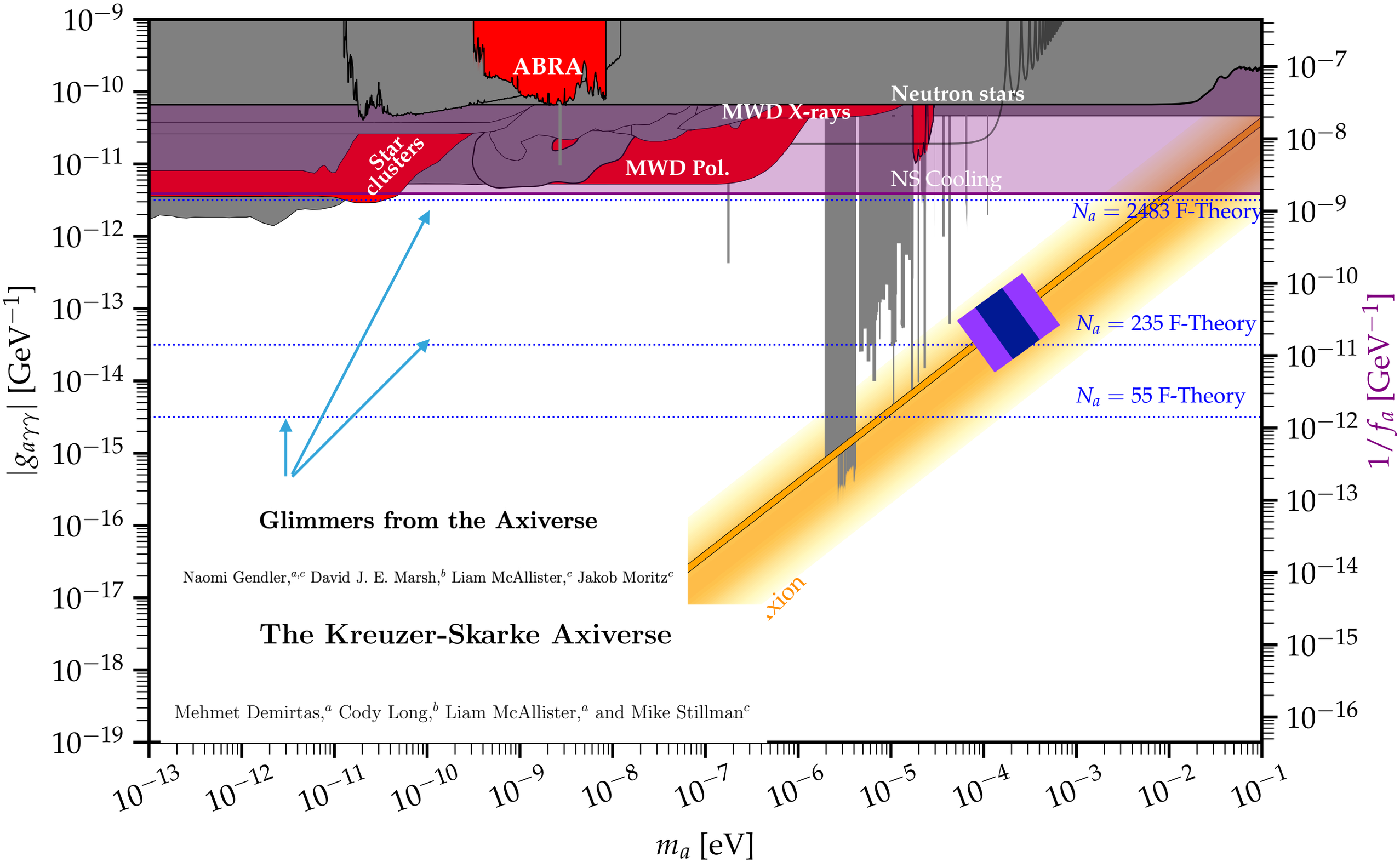

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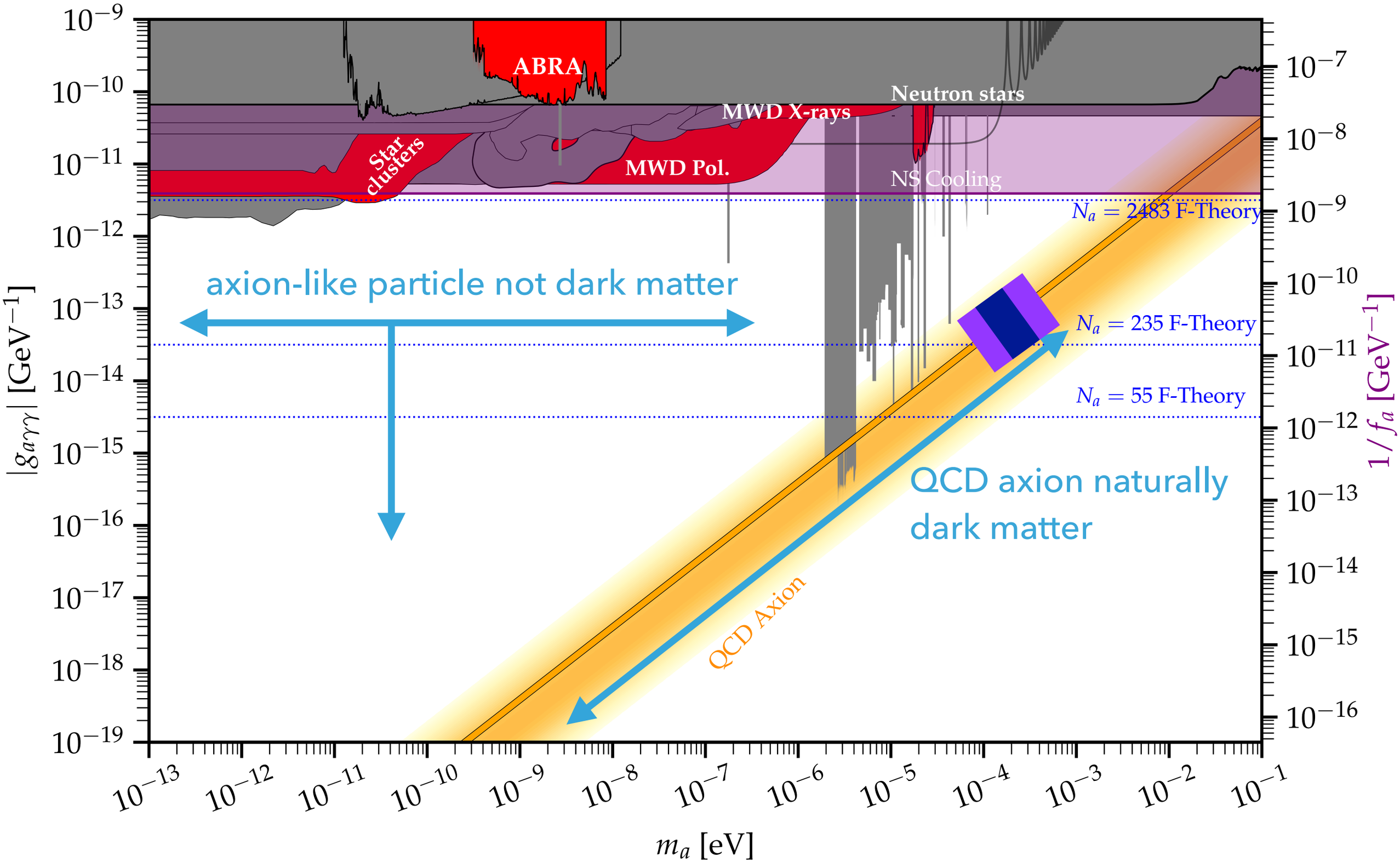

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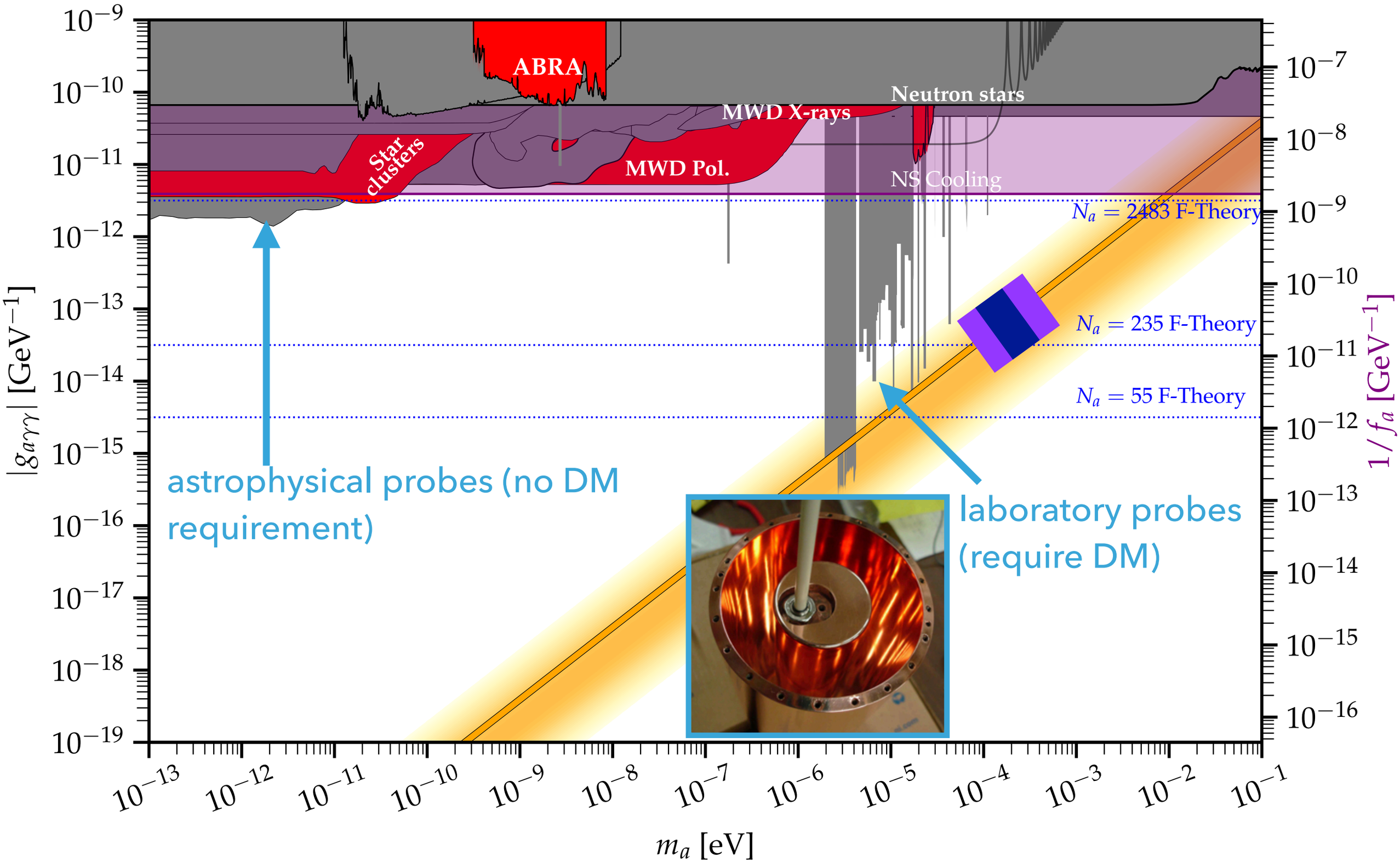
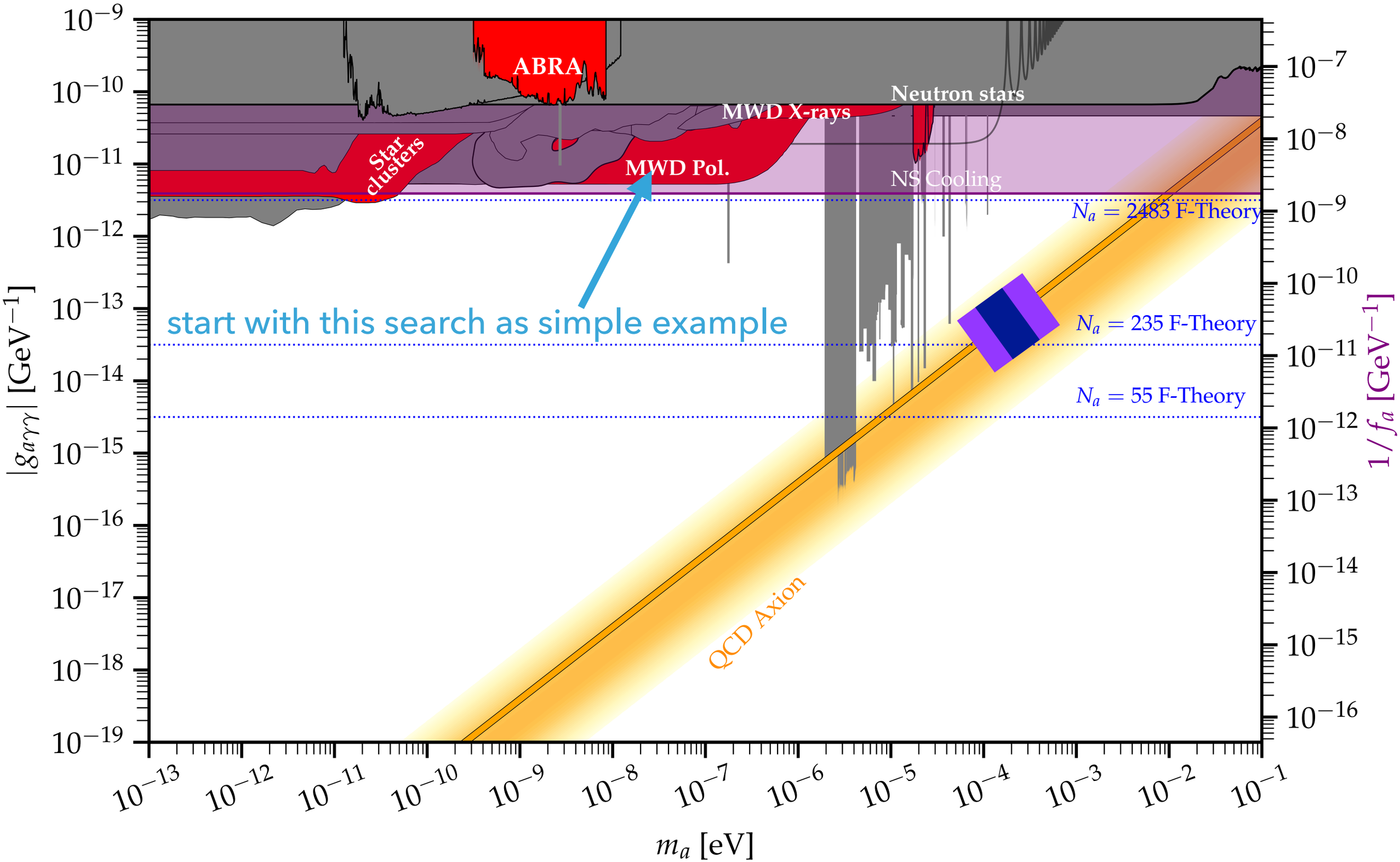


Example astrophysical probe: MWD polarization

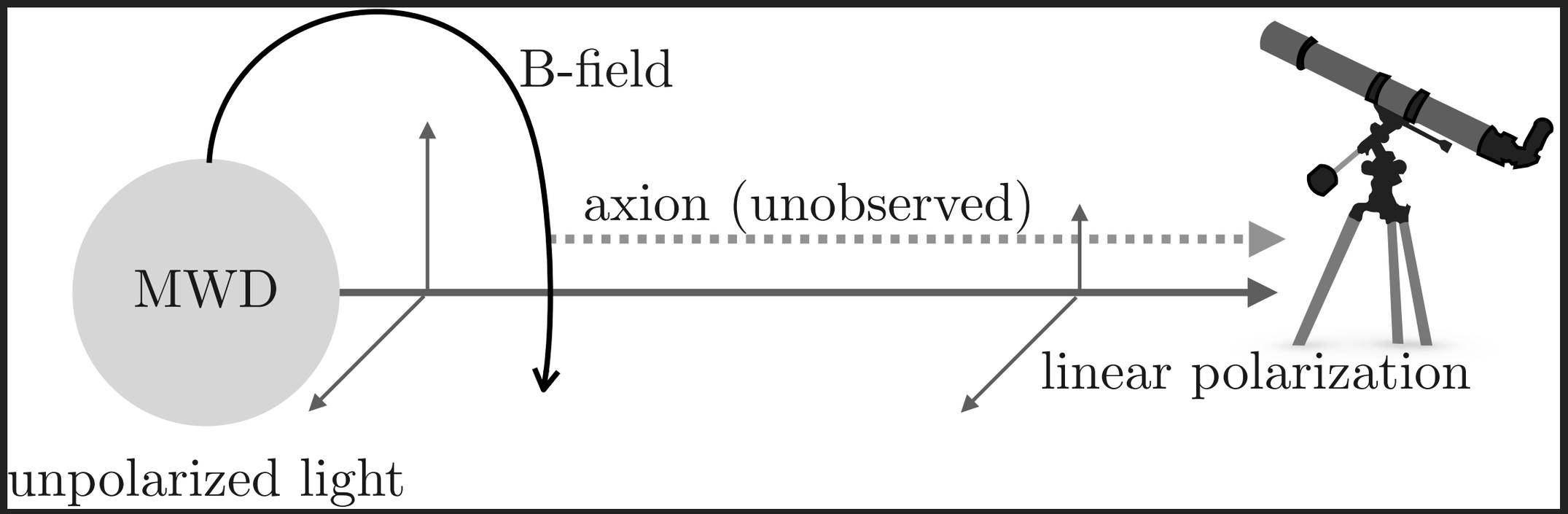
$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



Upper limit on the axion-photon coupling from magnetic white dwarf polarization

Christopher Dessert,[1,2,3] David Dunsky,[1,2] and Benjamin R. Safdi[1,2]

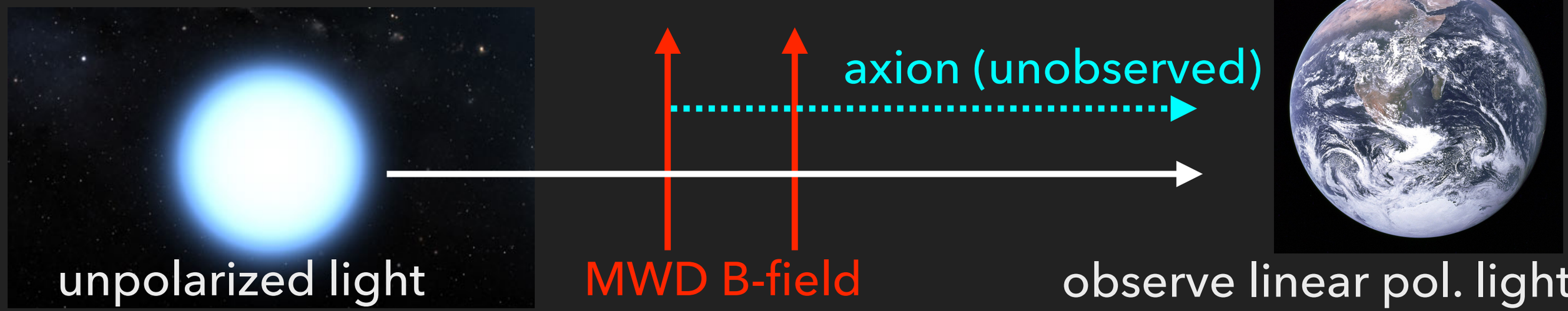
2203.04319



Chris Dessert

David Dunsky

Axion contribution to optical MWD polarization



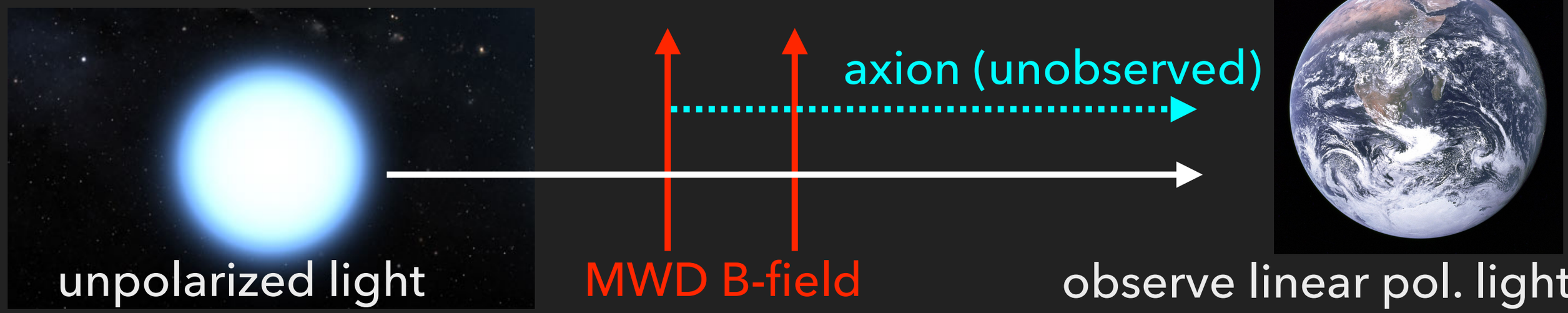
$$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4} = g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$

*Side-note: MWDs are optimal.
E.g. NS B-fields too large
(Euler-Heisenberg effect)

only convert photons
polarized along B-field

basic idea: Gill, Heyl 2011

Axion contribution to optical MWD polarization



$$\left[\omega + \begin{pmatrix} \Delta_{\rm EH} & \Delta_B \\ \Delta_B & \Delta_a \end{pmatrix} - i\partial_r\right]\begin{pmatrix} A_{||} \\ a \end{pmatrix} = 0 \qquad \Delta_a \sim \frac{m_a^2}{\omega} \qquad \Delta_B \sim g_{a\gamma\gamma}B$$

$$\Delta_{\rm EH} \sim \omega \cancel{\left(\frac{B}{B_C}\right)^2} \qquad \left(B_c = \frac{m_e^2}{e} \sim 4\times 10^{13}\ m{\rm G}\right)$$

not important at optical frequencies

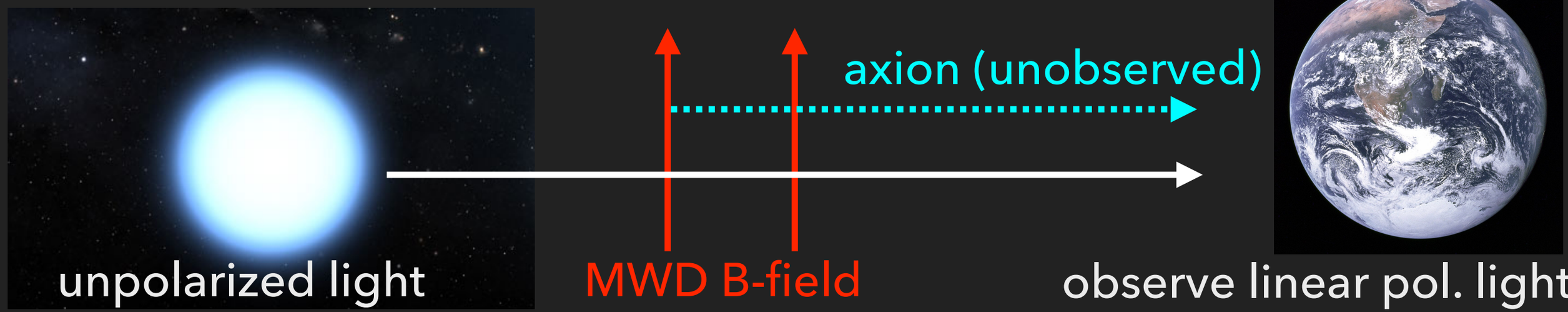
$$P_L \sim 1 - p_{\gamma\to\gamma} \sim 10^{-2}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\,{\rm GeV}^{-1}}\right)^2\left(\frac{B_0}{1000\,{\rm MG}}\right)^2\left(\frac{R_{\rm WD}}{0.01\ {\rm R}_\odot}\right)^2$$

polarization fraction

many MWD polarizations at this level

true at optical frequencies but not X-ray!

Axion contribution to optical MWD polarization



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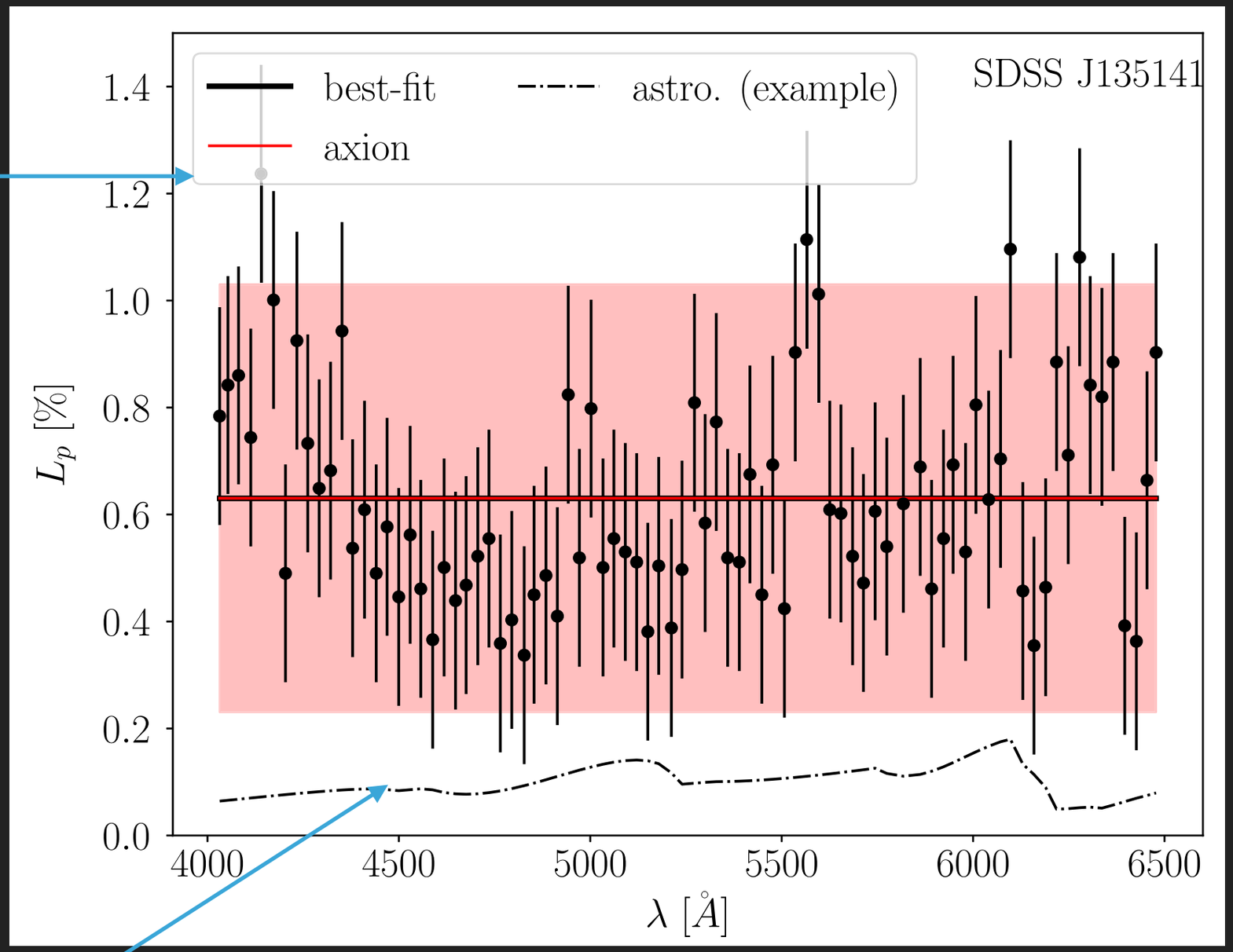
In practice: solve mixing numerically, including EH term and non-radial trajectories

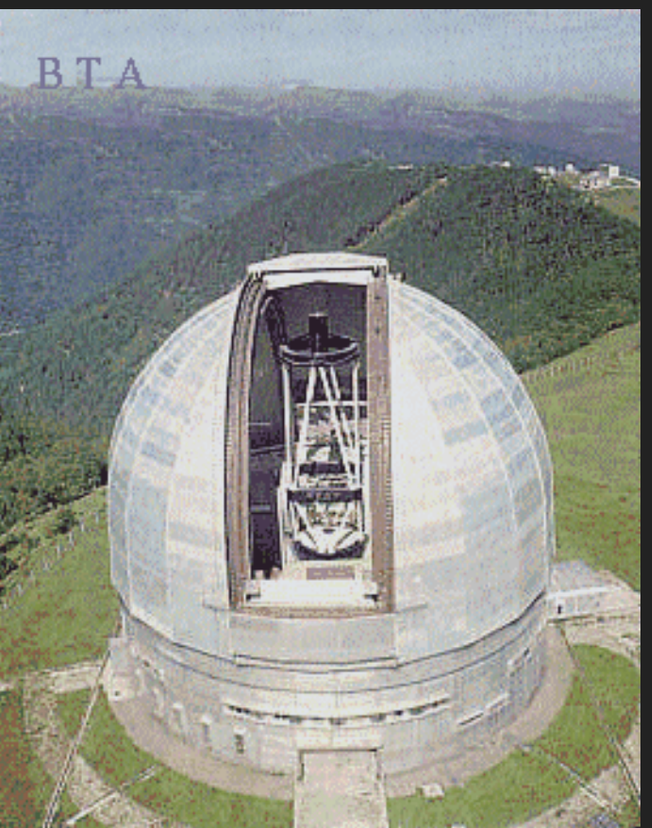
Compare to Linear Polarization Data

SAO 6m telescope (Russia)

95% U.L.

1. Only archival data available
2. People don't often look at MWD pol. because expected to be small

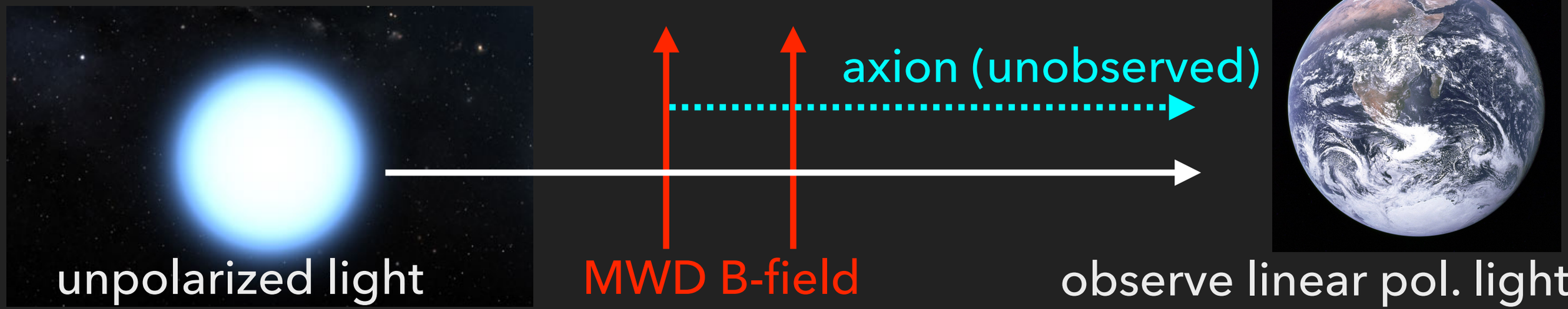


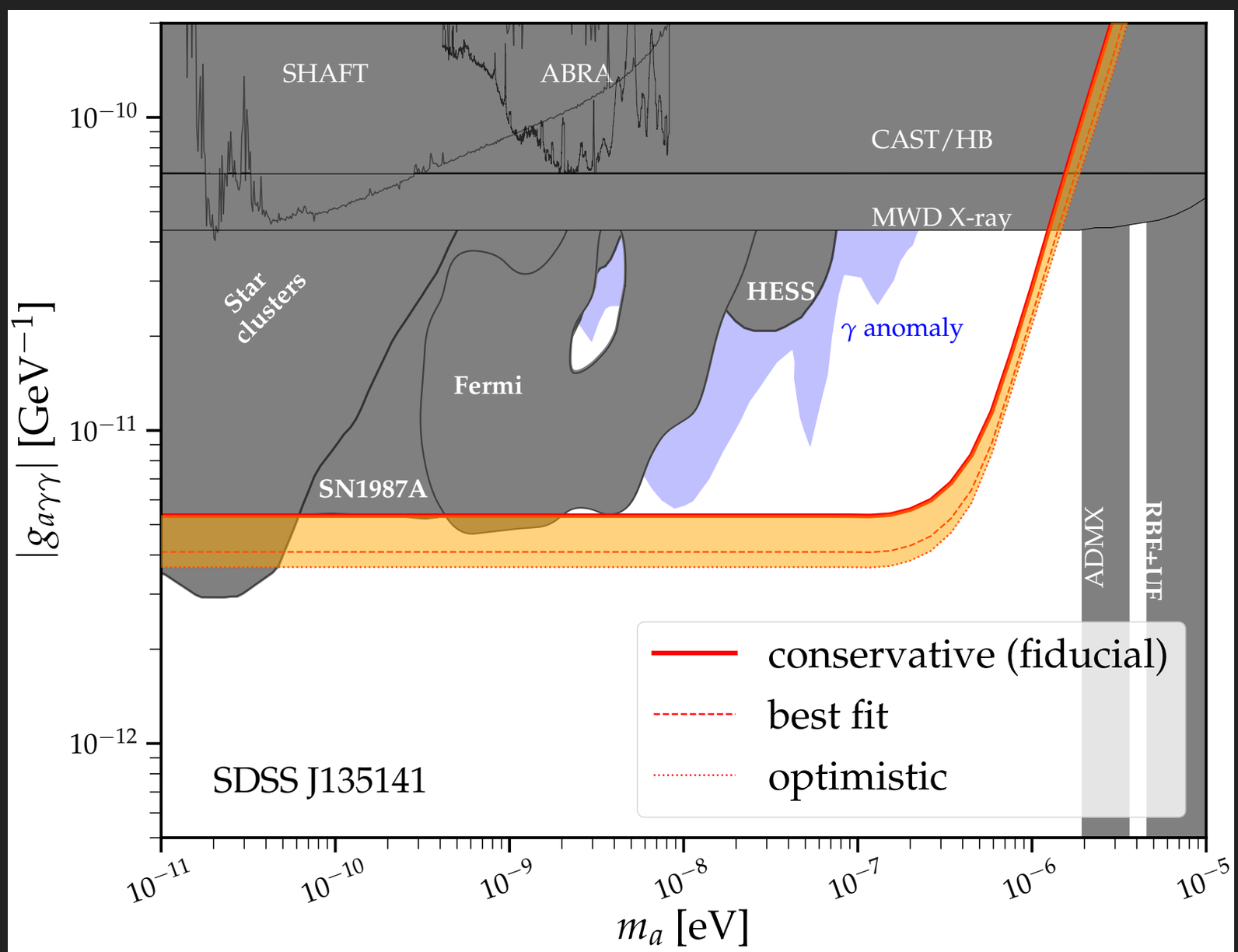


Astro model (arb norm) – we find no evidence

1. Zeeman effect has preferential absorption for different pols. -> large circular pol., small linear
2. Correlated systematic across wavelengths

MWD Polarization Results





$$B_{\rm pole} = 761 \pm 56 \text{ MG}$$

Zeeman shifts in bound-bound transitions

$$i = 74^\circ \pm 21^\circ$$

angle w.r.t Earth (from circular polarization modeling)

$$P_L \lesssim 1\% \, (4000 - 6500 \, \mathring{A})$$

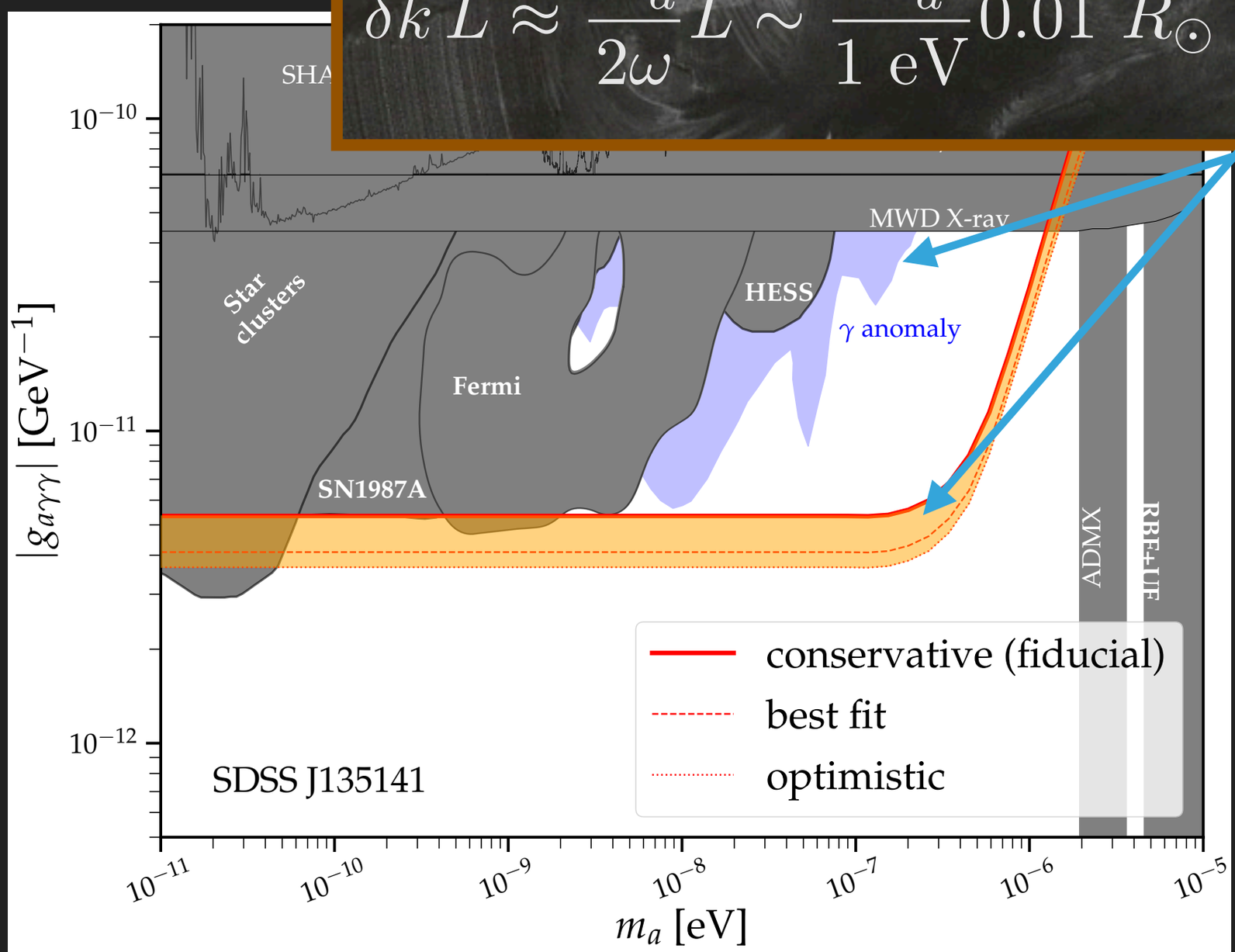
$$d \sim 70 \, \text{pc}$$

Many other MWDs available and better data could be obtained! (We are working on it ...)

MWD Polarization Results

mass dependence:
photon-axion dispersion relations

$$\delta k\, L \approx \frac{m_a^2}{2\omega} L \sim \frac{m_a^2}{1\ \mathrm{eV}} 0.01\ R_\odot \sim \left(\frac{m_a}{2\times 10^{-7}\ \mathrm{eV}}\right)^2 > 1$$



Meyer et al. 2013, +

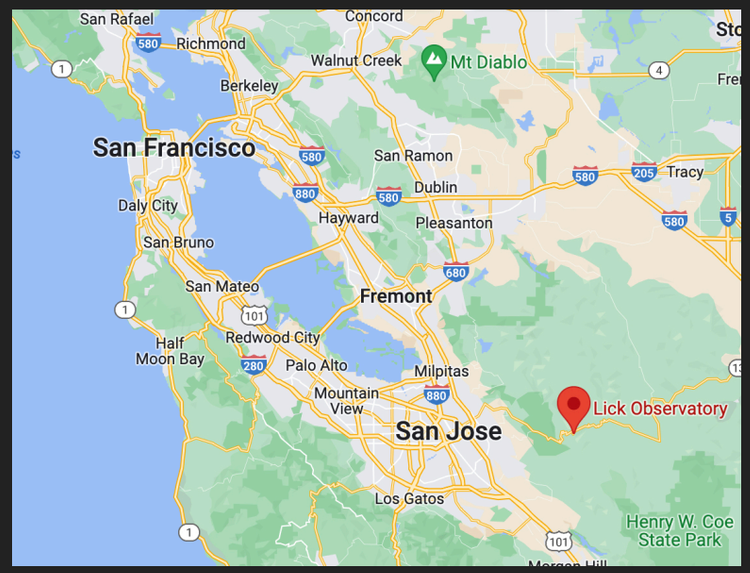
AGN

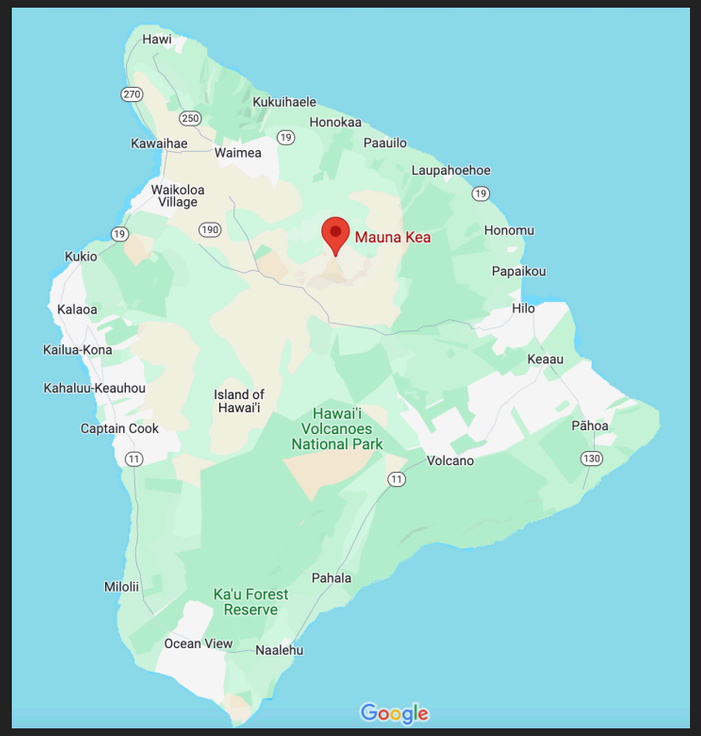
photons absorbed on EBL

conversion to and back from axions increase prop length

MWD Polarization: Ongoing Work

Dedicated observations: Shane telescope and Keck





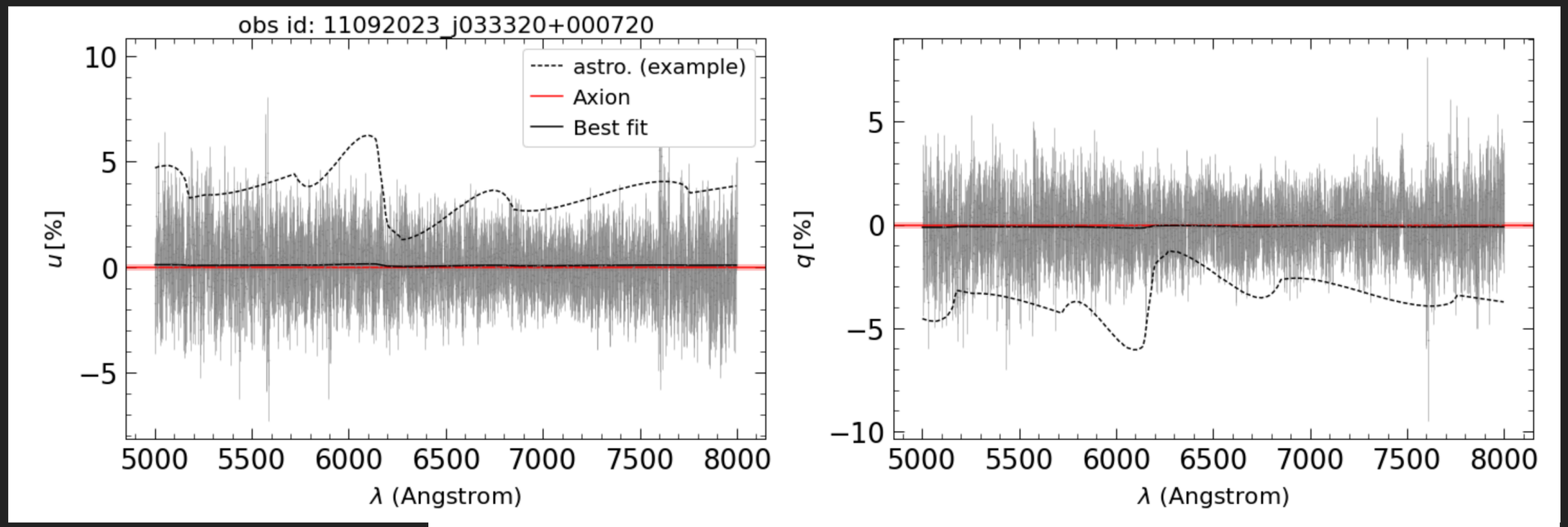
Chris Dessert

Christiane Scherb

Josh Benabou

Alex Filippenko + group (astronomy)

MWD Polarization: Ongoing Work

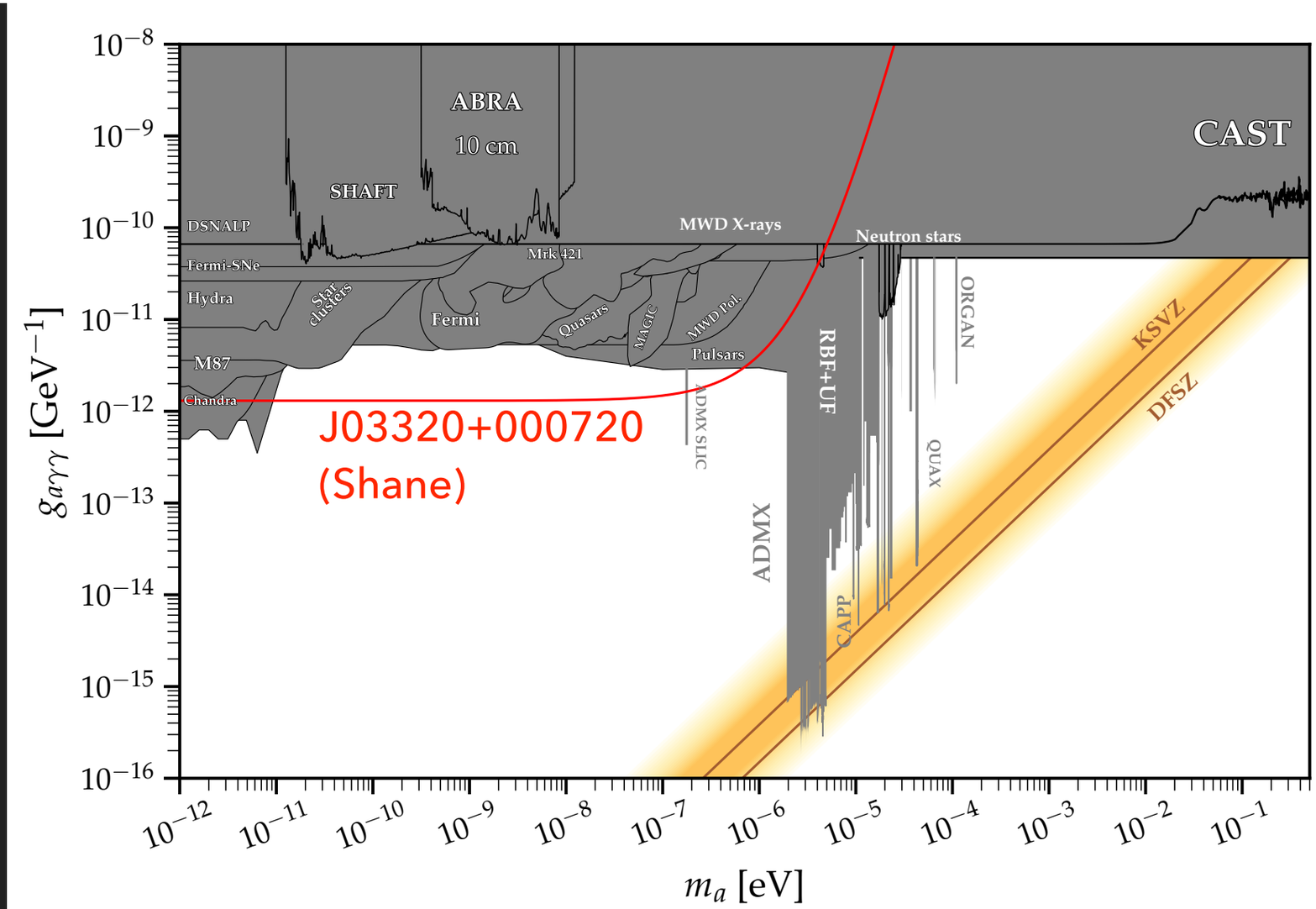


$B_{\rm pole} \sim 850$ MG

Preliminary
(Shane data)

No evidence
for polarization

$L_p \lesssim 0.23\%$



Axions can also "shine through walls" in astrophysics

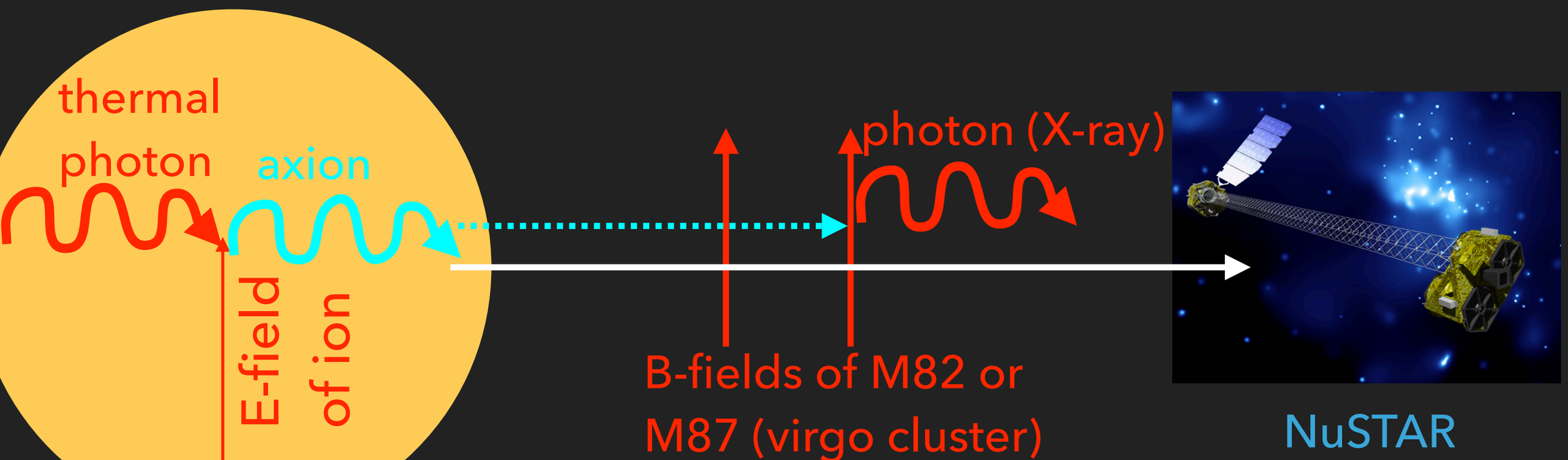
Leading Axion-Photon Sensitivity with NuSTAR Observations of M82 and M87

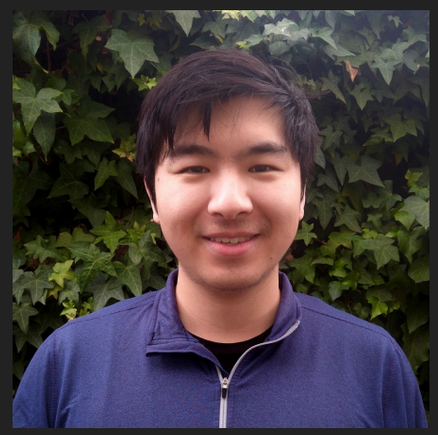
Orion Ning[1,2] and Benjamin R. Safdi[1,2]

[1] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, U.S.A.*
[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.*

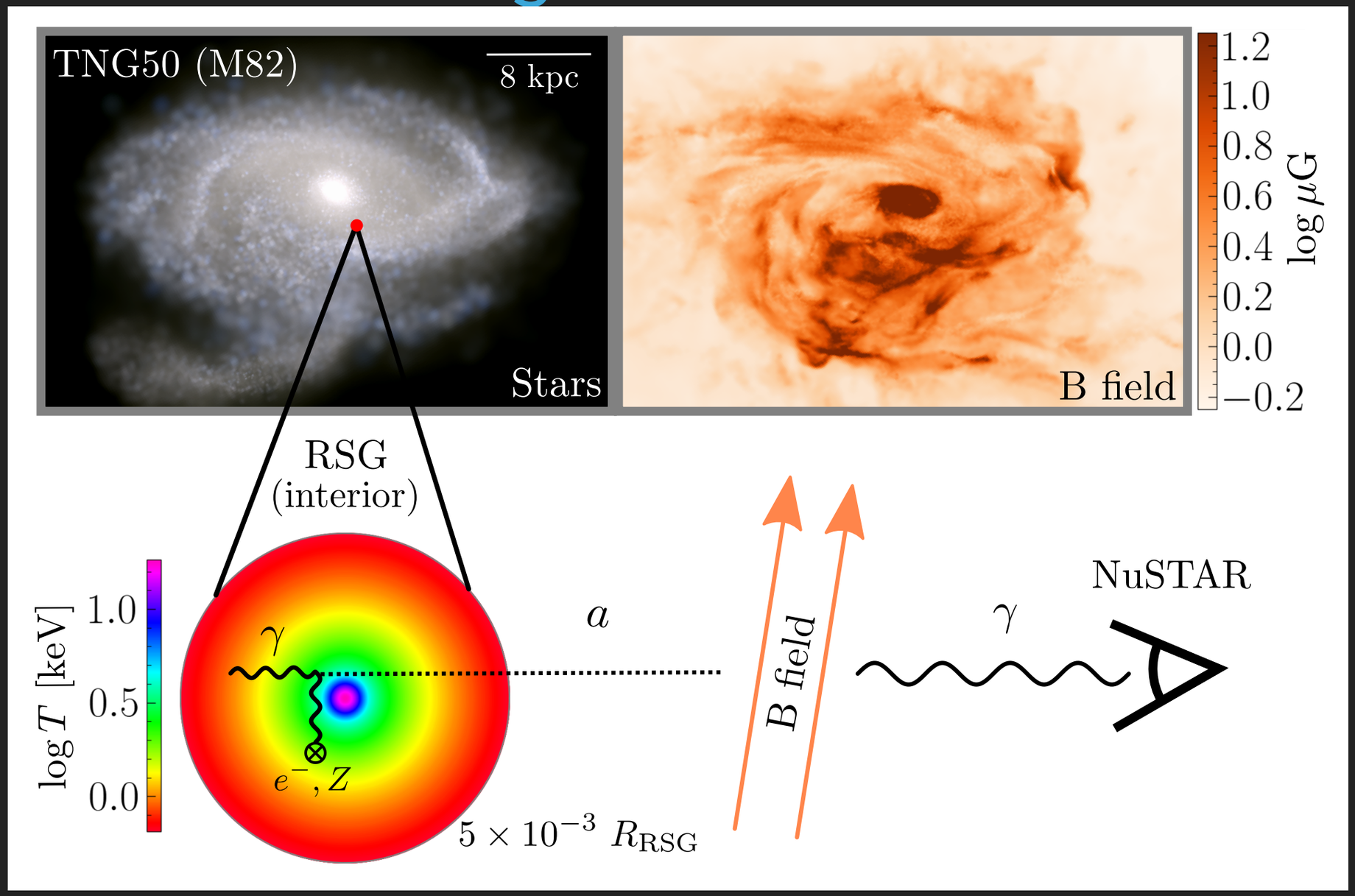
(Dated: April 22, 2024)

2404.14476





Axion Signal in M82/M87



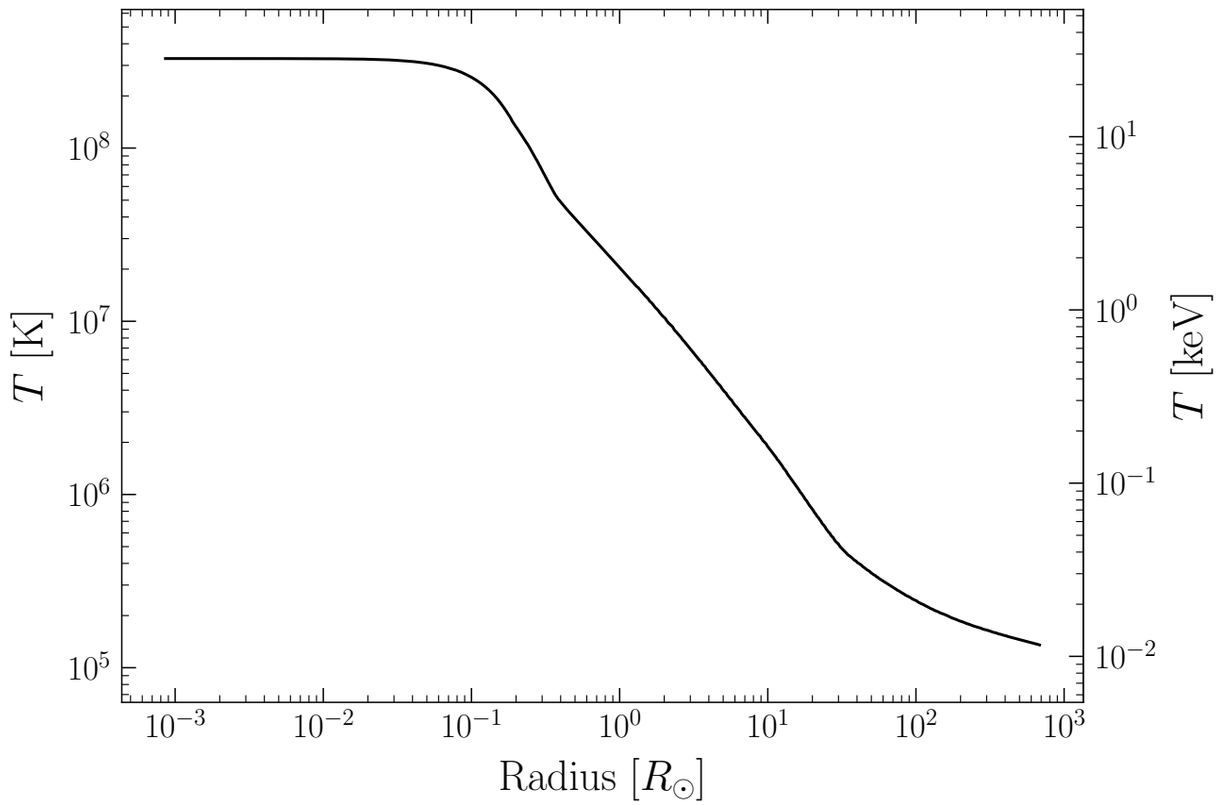
$$\frac{dL_a(E)}{dE} = \frac{g_{a\gamma\gamma}^2}{8\pi^2}\frac{\xi^2 T^3 E}{e^{E/T}-1}\sqrt{1-\frac{\omega_{\rm pl}^2}{E^2}}\left[(E^2+\xi^2T^2)\log\left(1+\frac{E^2}{\xi^2T^2}\right)-E^2\right]$$

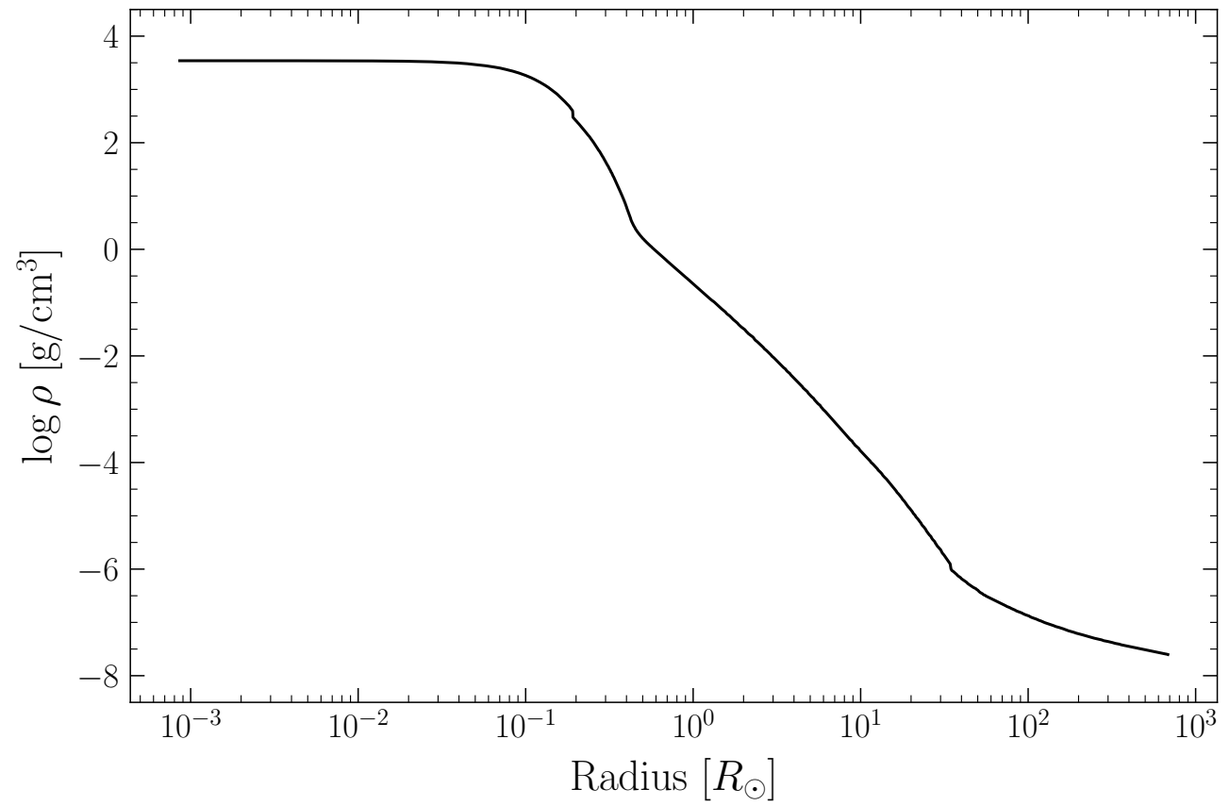
$$\xi = \kappa/(2T)$$

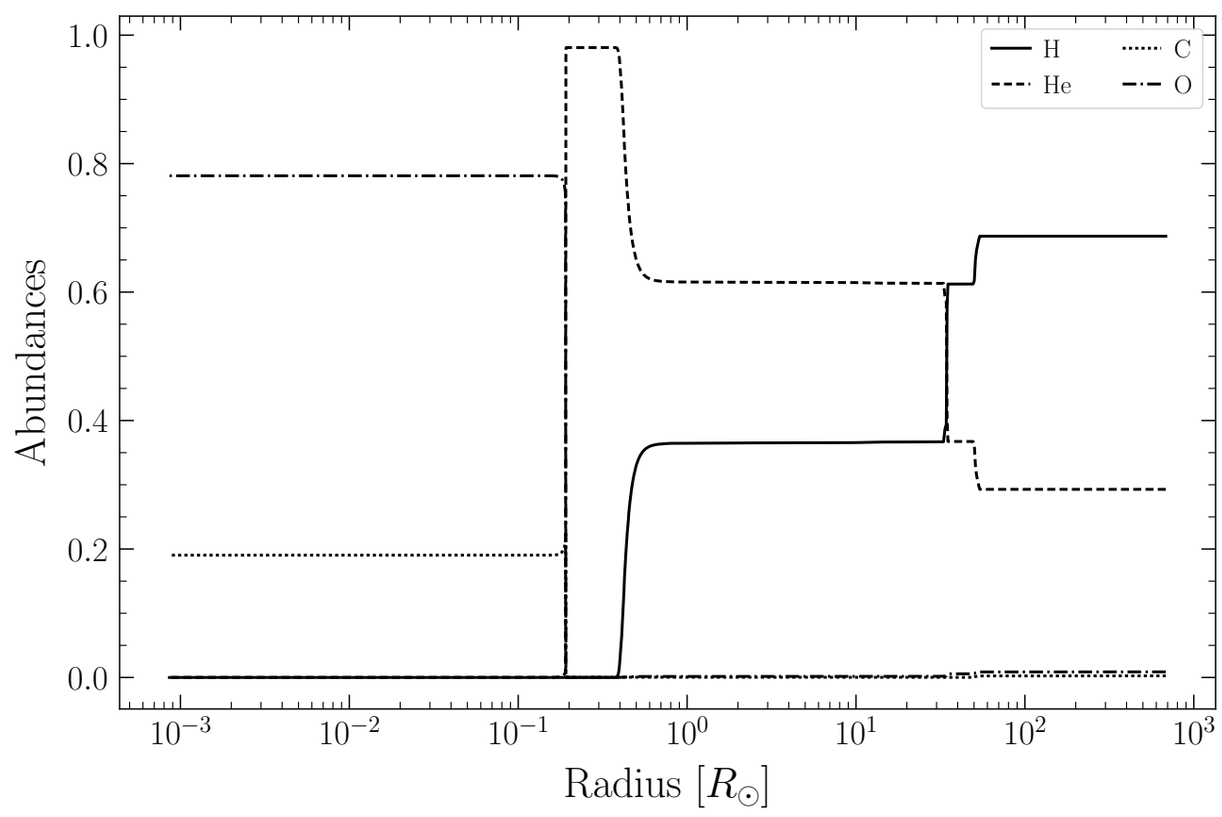
κ : Debye Screening Scale

Run MESA over Initial Stellar Mass Function

Example 20 Solar Mass star in RSG phase







MESA

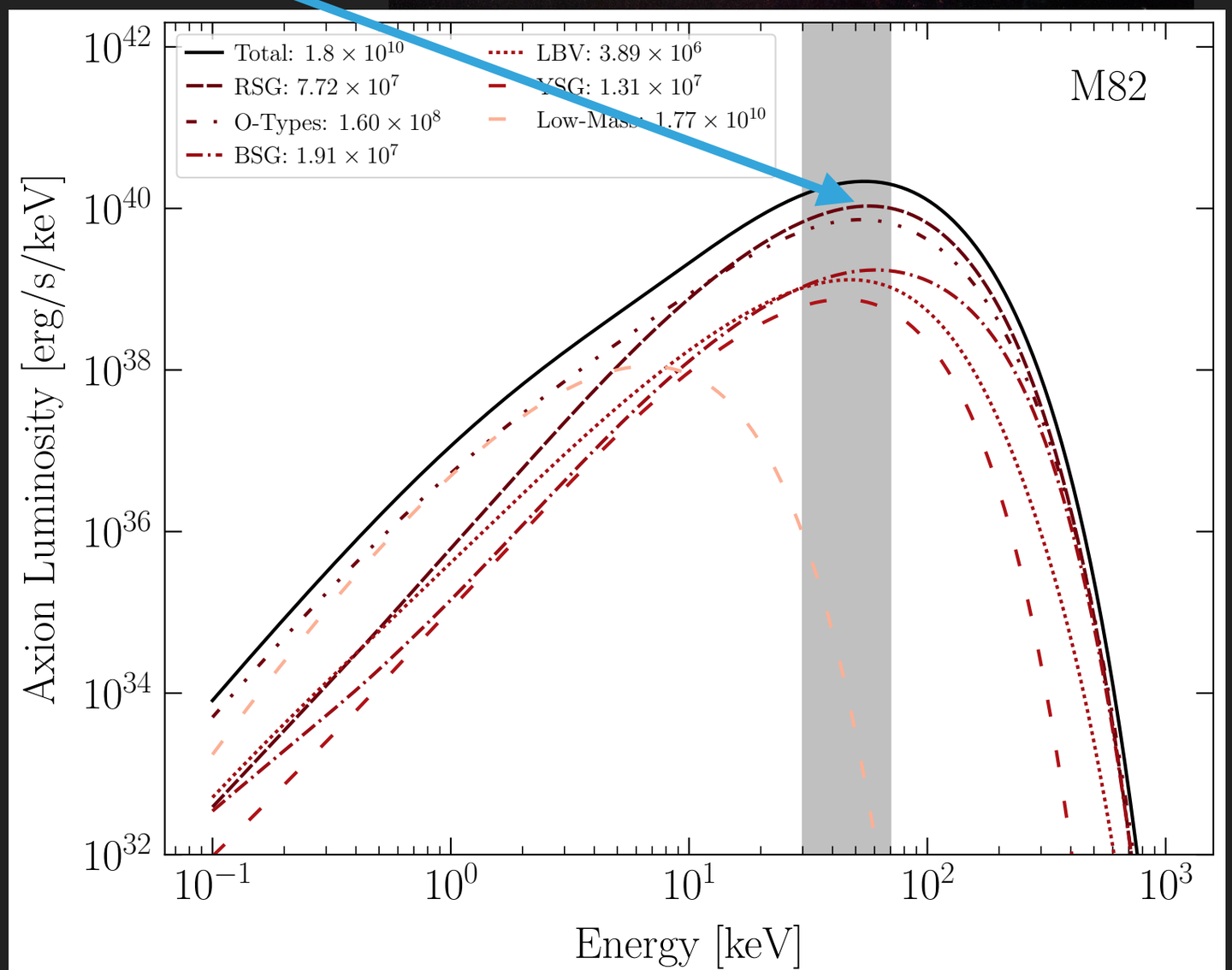
release/r24.03.1

NuSTAR axion search – M82

M82 Facts

1. Starburst galaxy: high star-formation rate = lots of hot, young, massive stars
2. Around 3×10^{10} stars
3. ~3.5 Mpc from Earth
4. Starburst = high magnetic fields
5. Seen almost edge on -> high axion-photon conversion

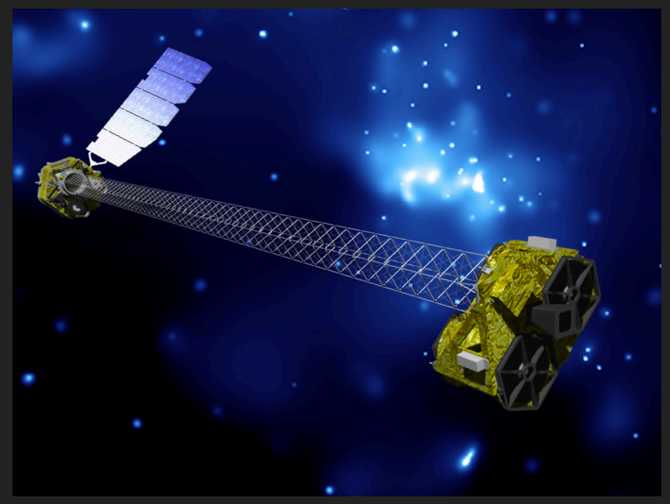
Axion luminosity dominated by RSG and O-type stars

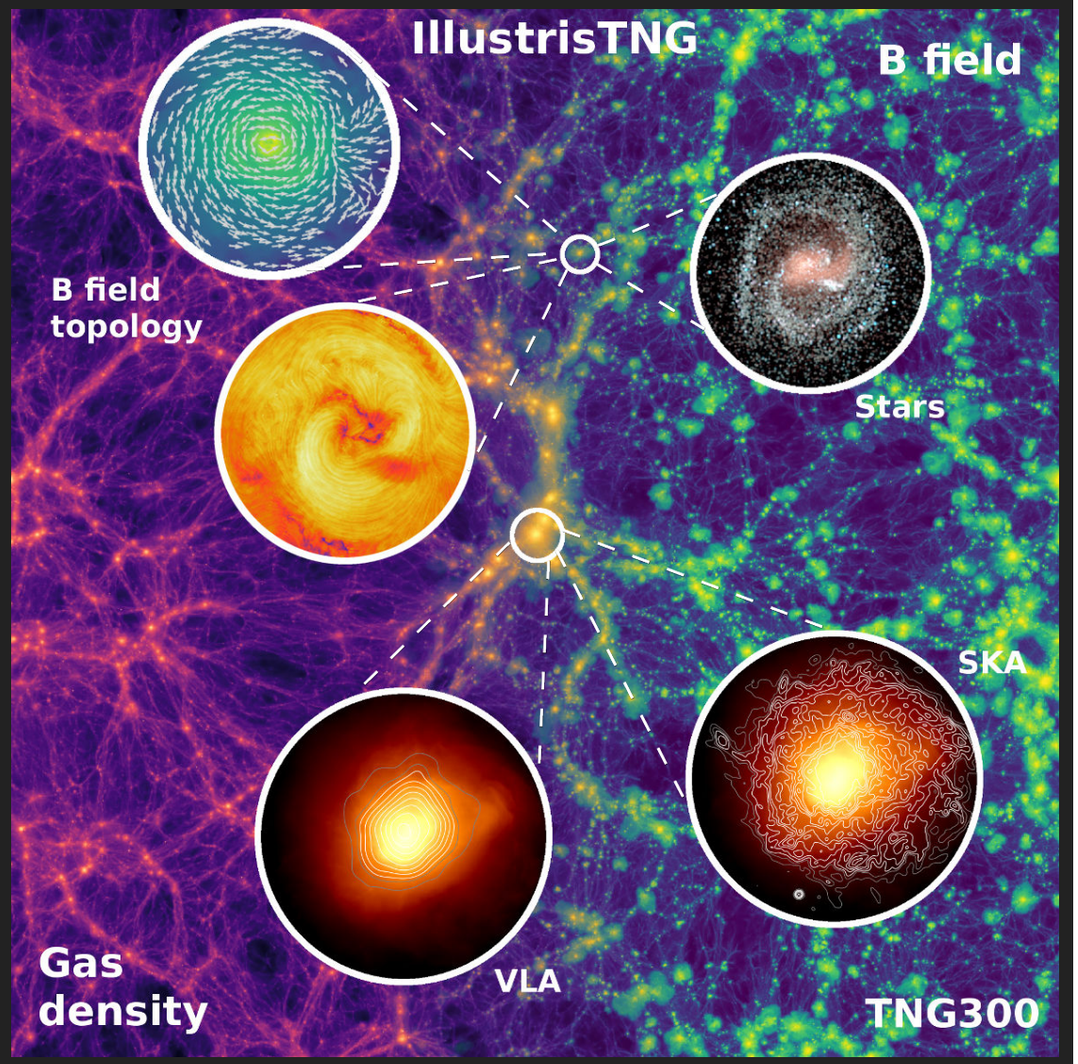


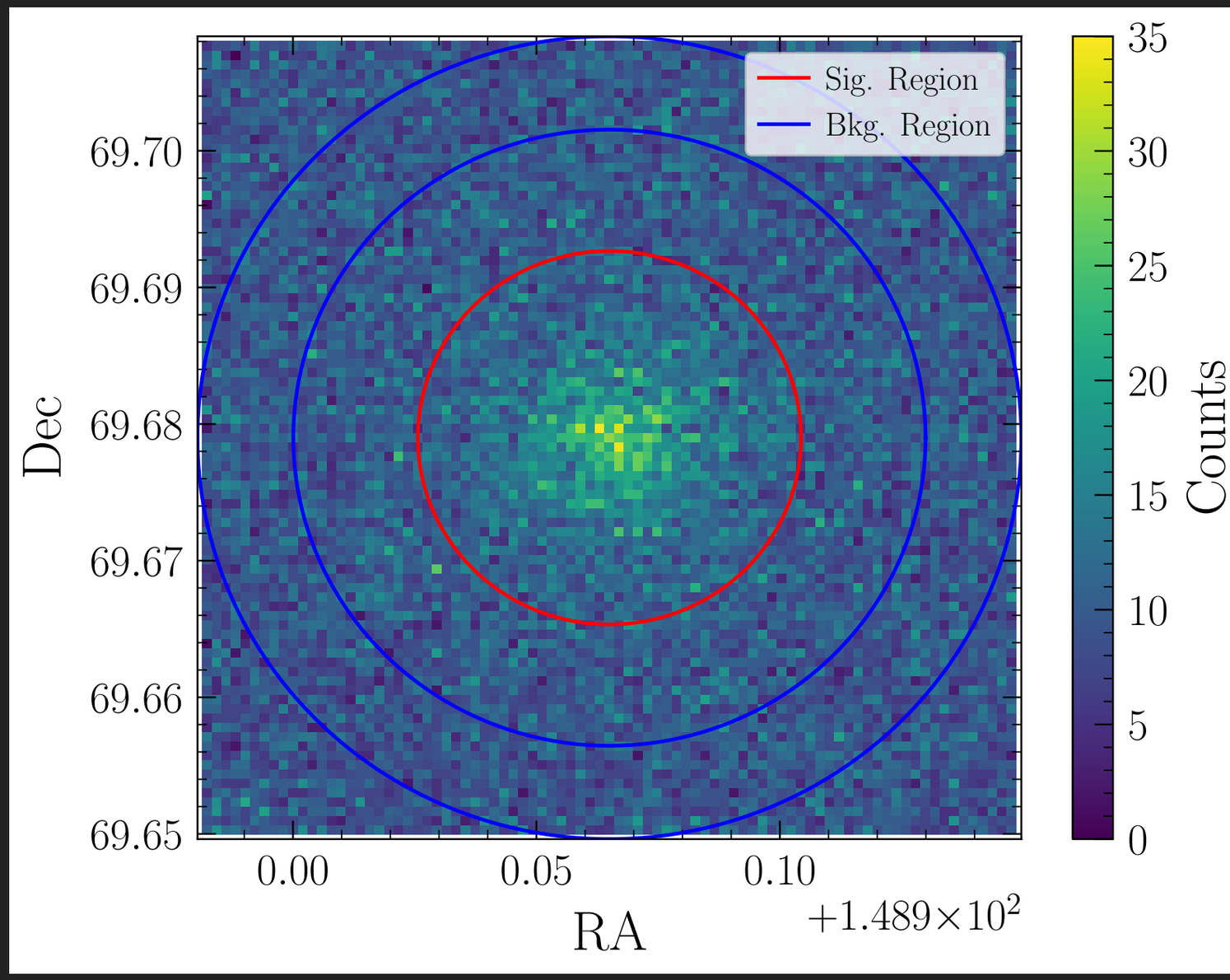
NuSTAR axion search – M82

M82 Analysis

1. ~4 Ms of archival NuSTAR data
    1. no excess over bkg. + astro model (PL)
2. Model magnetic field using analogues in IllustrisTNG



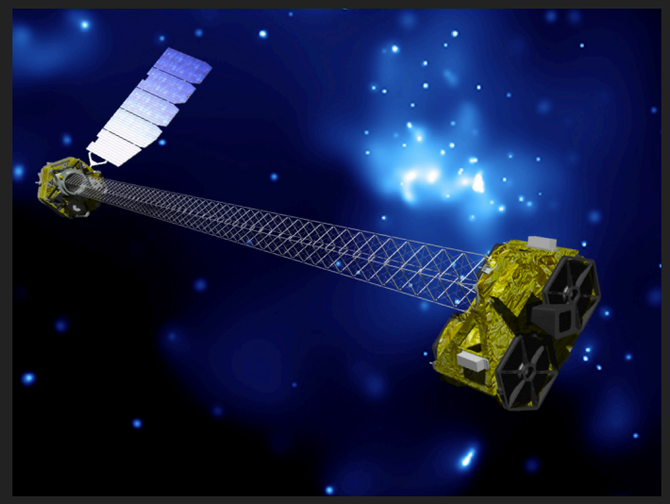


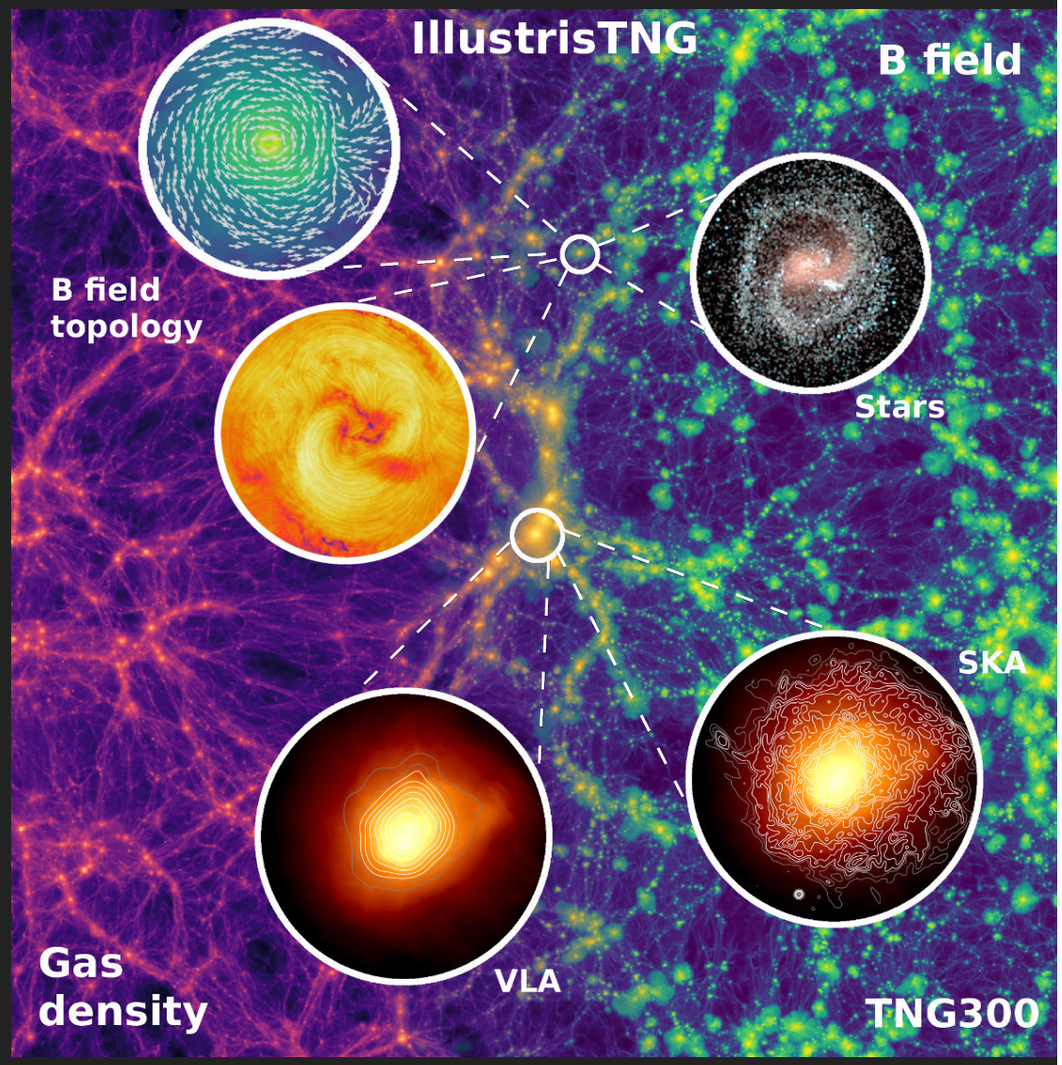


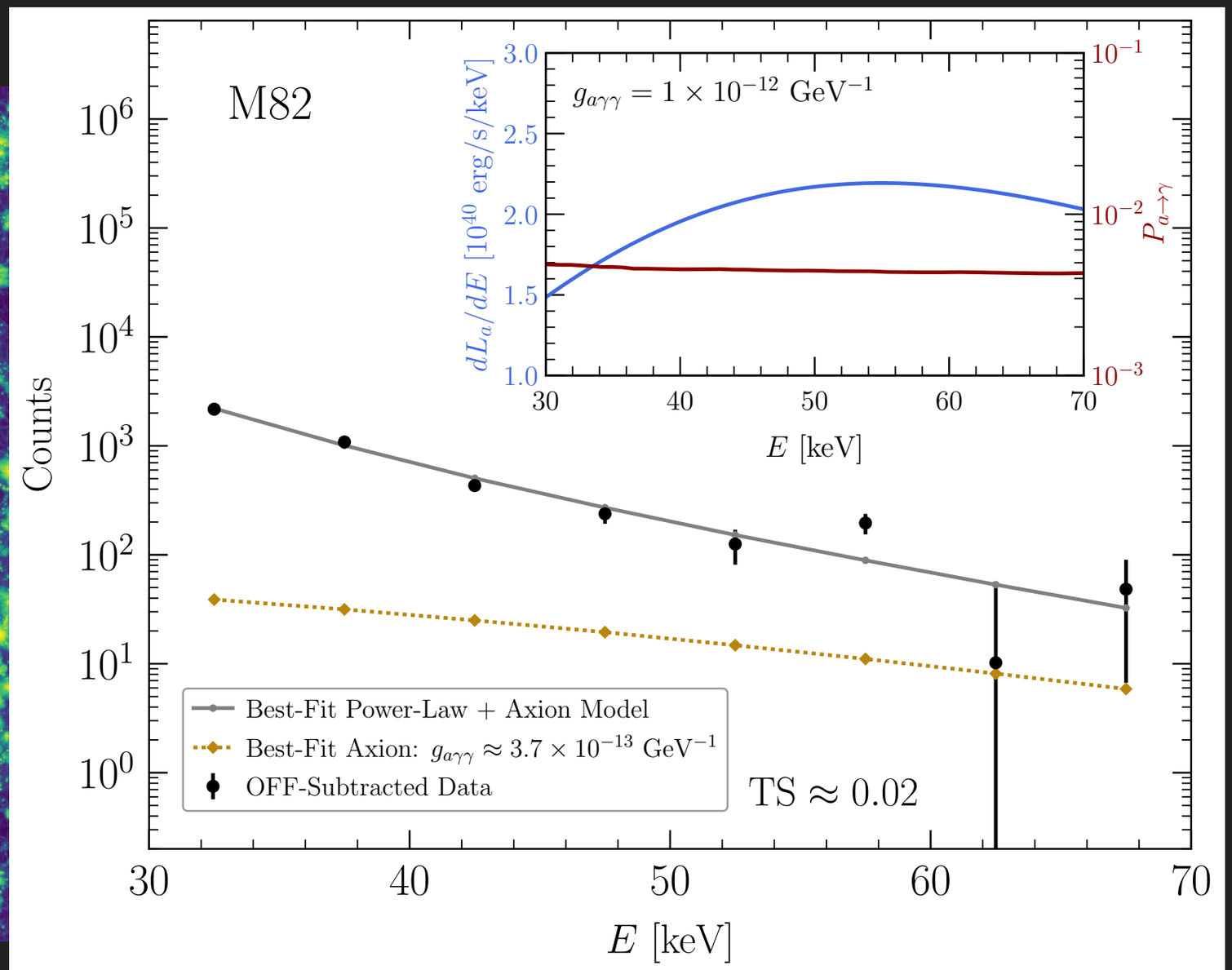
In progress: NuSTAR axion search – M82

M82 Analysis

1. ~4 Ms of archival NuSTAR data
    1. no excess over bkg. + astro model (PL)
2. Model magnetic field using analogues in IllustrisTNG



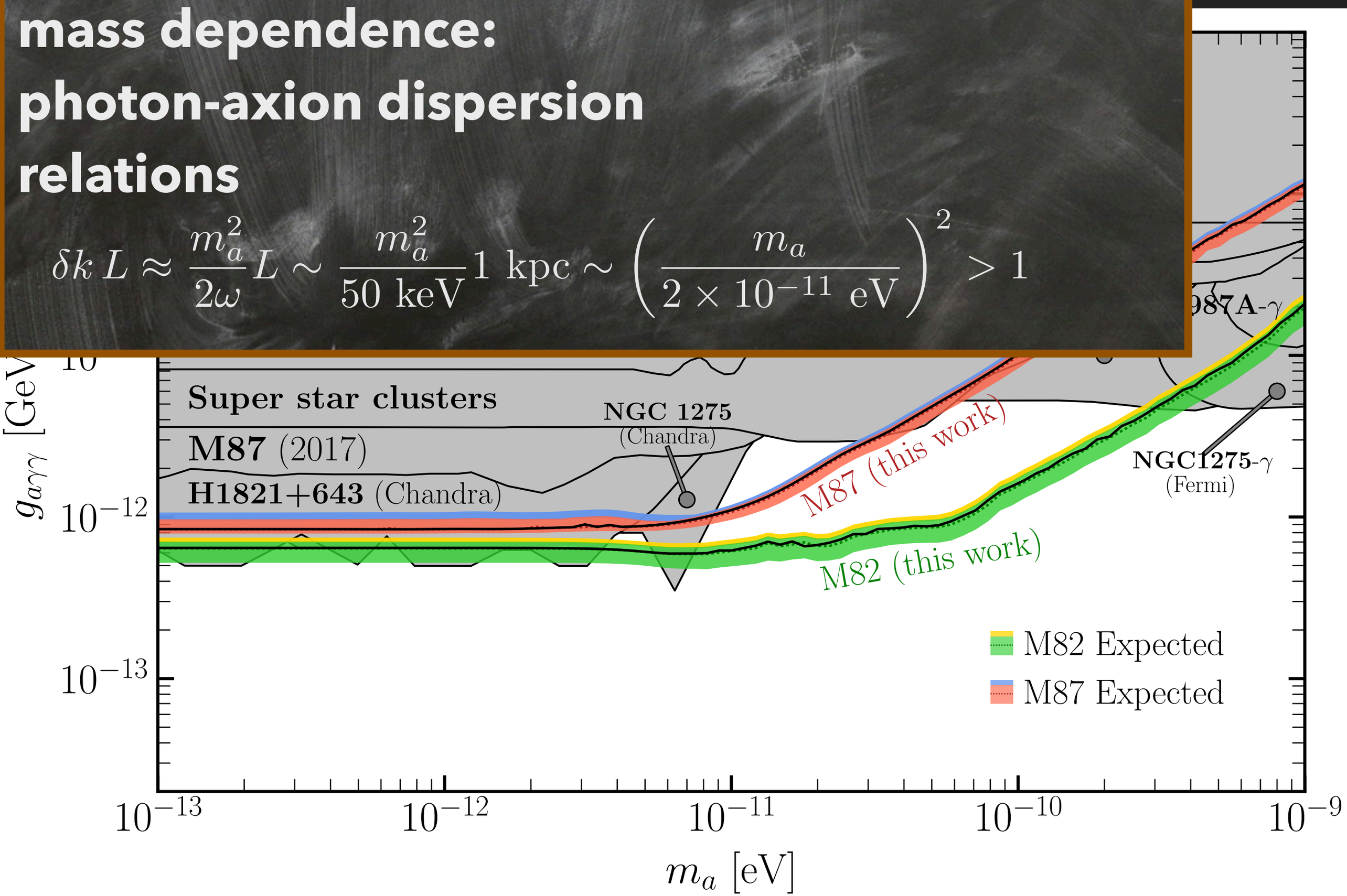




Leading Upper Limits from M82/M87

mass dependence: photon-axion dispersion relations

$$\delta k\, L \approx \frac{m_a^2}{2\omega} L \sim \frac{m_a^2}{50\ \mathrm{keV}} 1\ \mathrm{kpc} \sim \left(\frac{m_a}{2\times 10^{-11}\ \mathrm{eV}}\right)^2 > 1$$



Extending reach to higher axion masses:

higher energies, smaller length scales

Supernova axions convert to gamma-rays in magnetic fields of progenitor stars

Claudio Andrea Manzari,[1,2] Yujin Park,[1,2] Benjamin R. Safdi,[1,2] and Inbar Savoray[1,2]

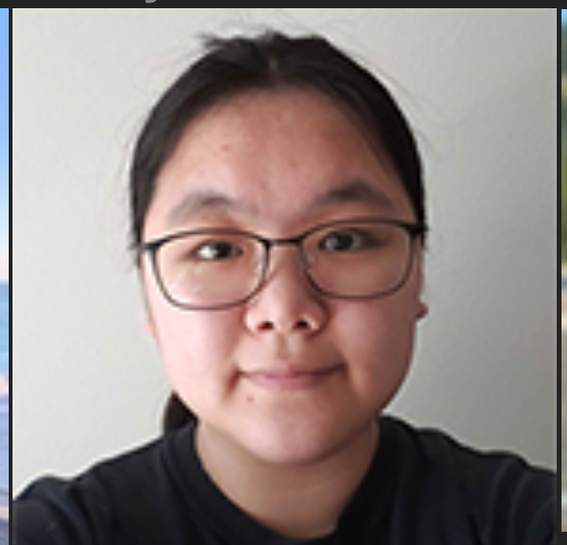
[1] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, U.S.A.*
[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.*

(Dated: May 31, 2024)

2405.19393

Claudio (postdoc)

Yujin (student)

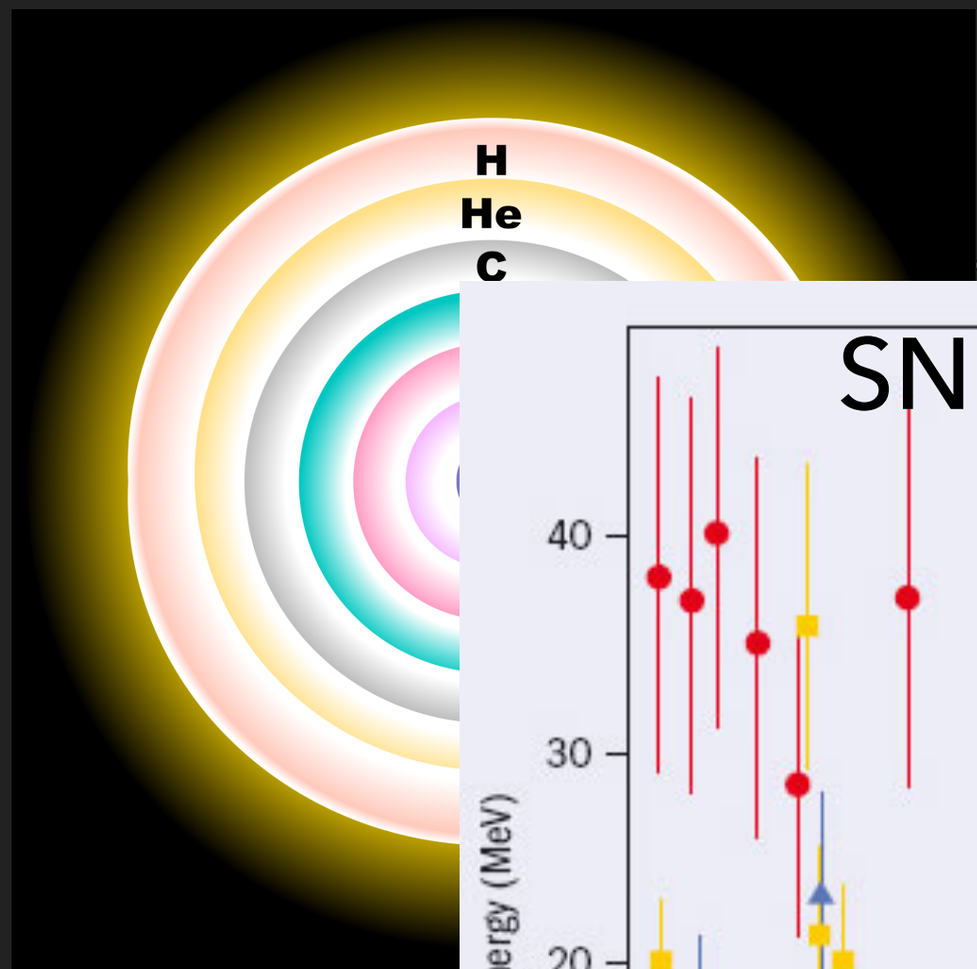


Inbar (postdoc)

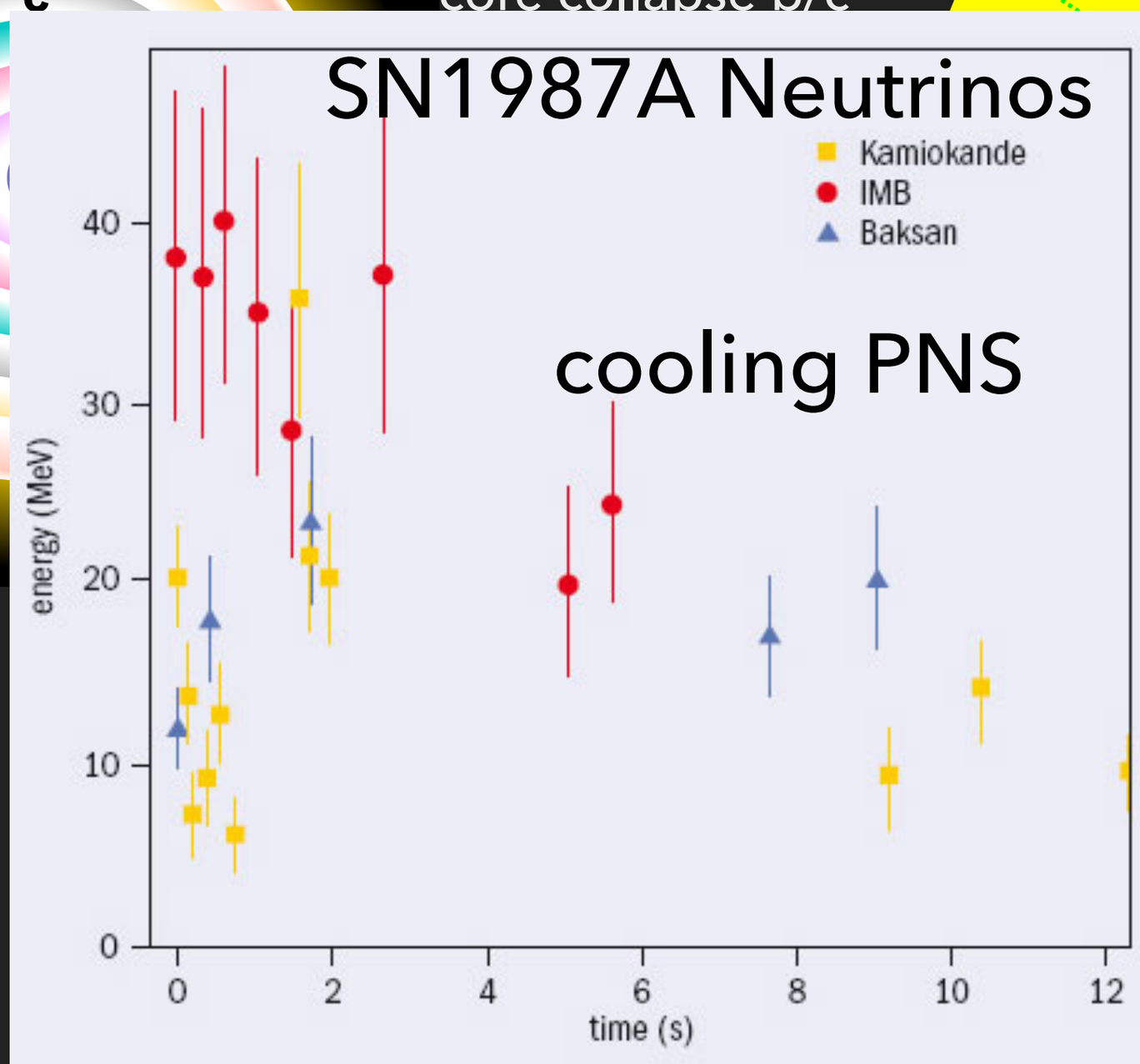
Neutrinos produced from cooling proto-NS in SN1987A

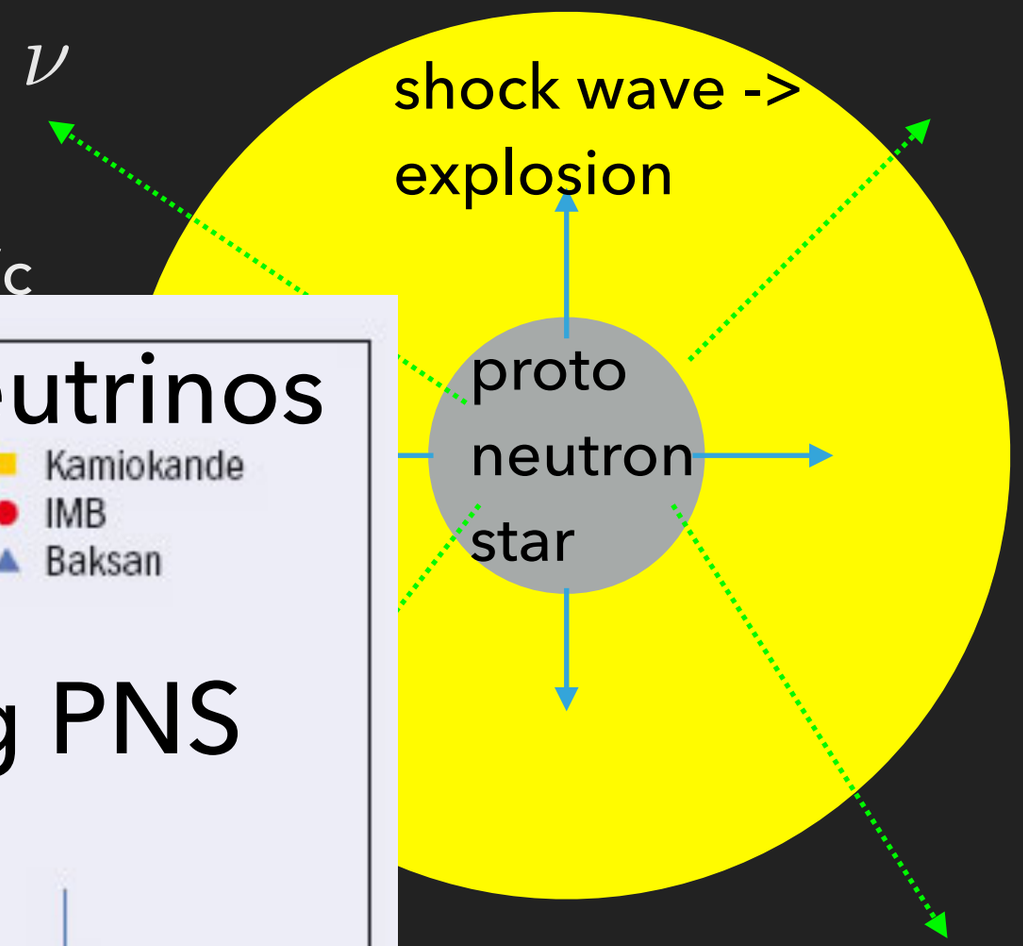
Type II supernova

neutrinos escape (and heat) –> SN1987A neutrino signal

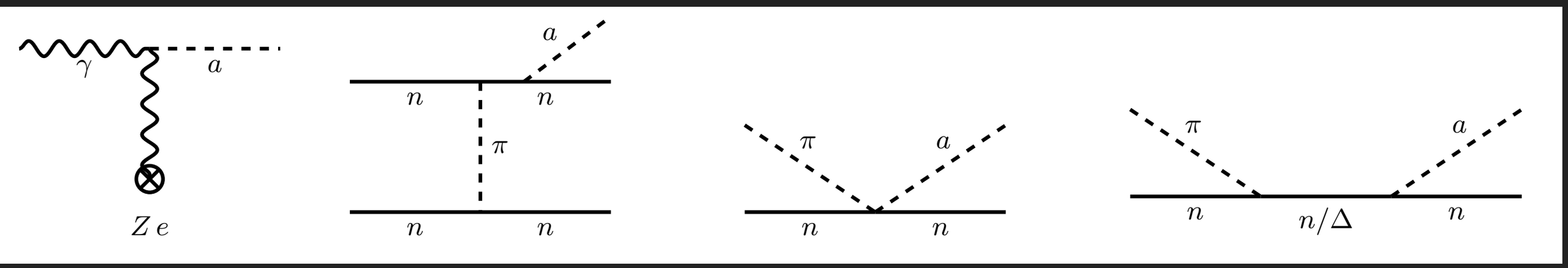


core collapse b/c



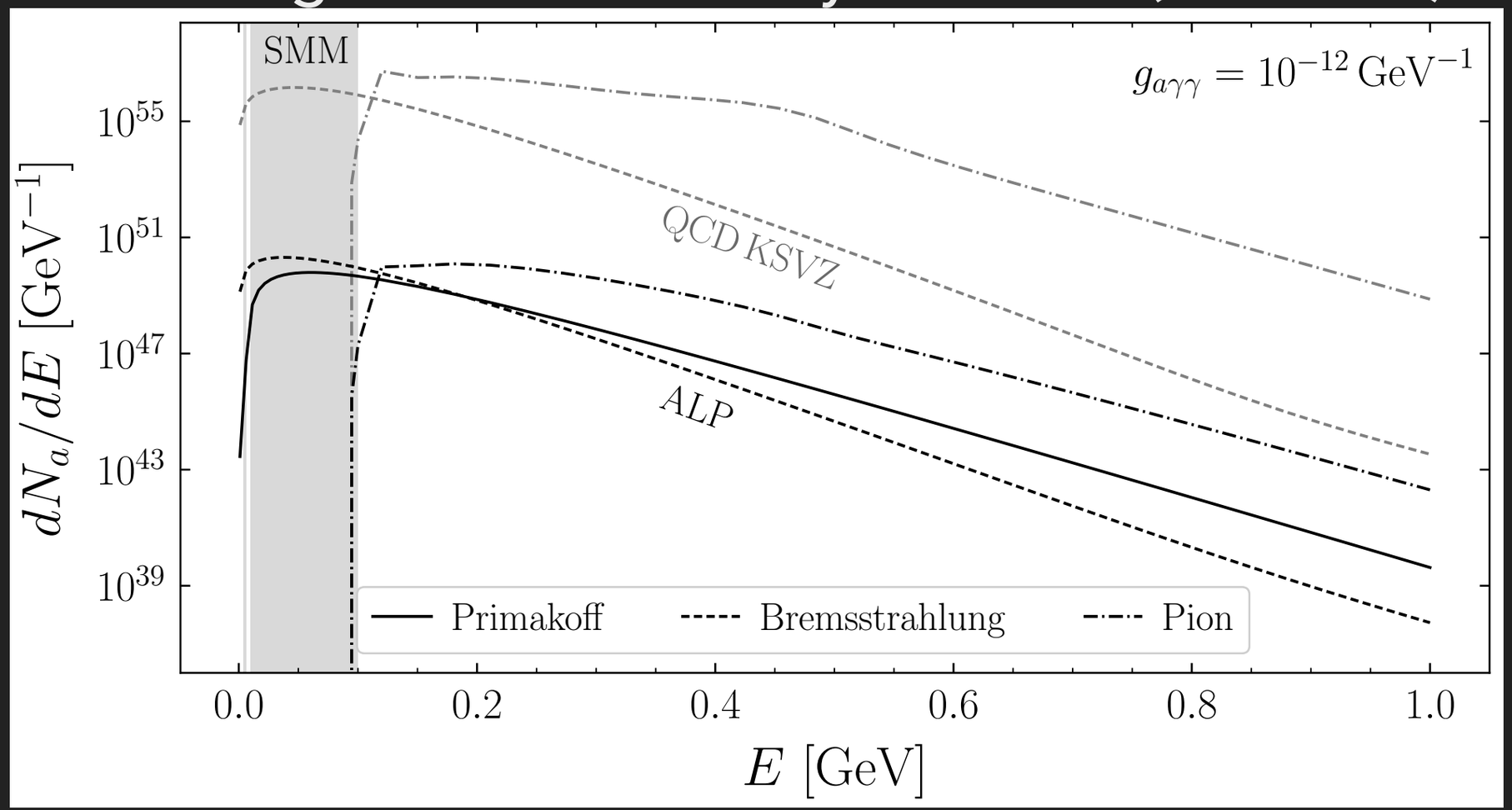


Proto Neutron Stars from SN also produce axions

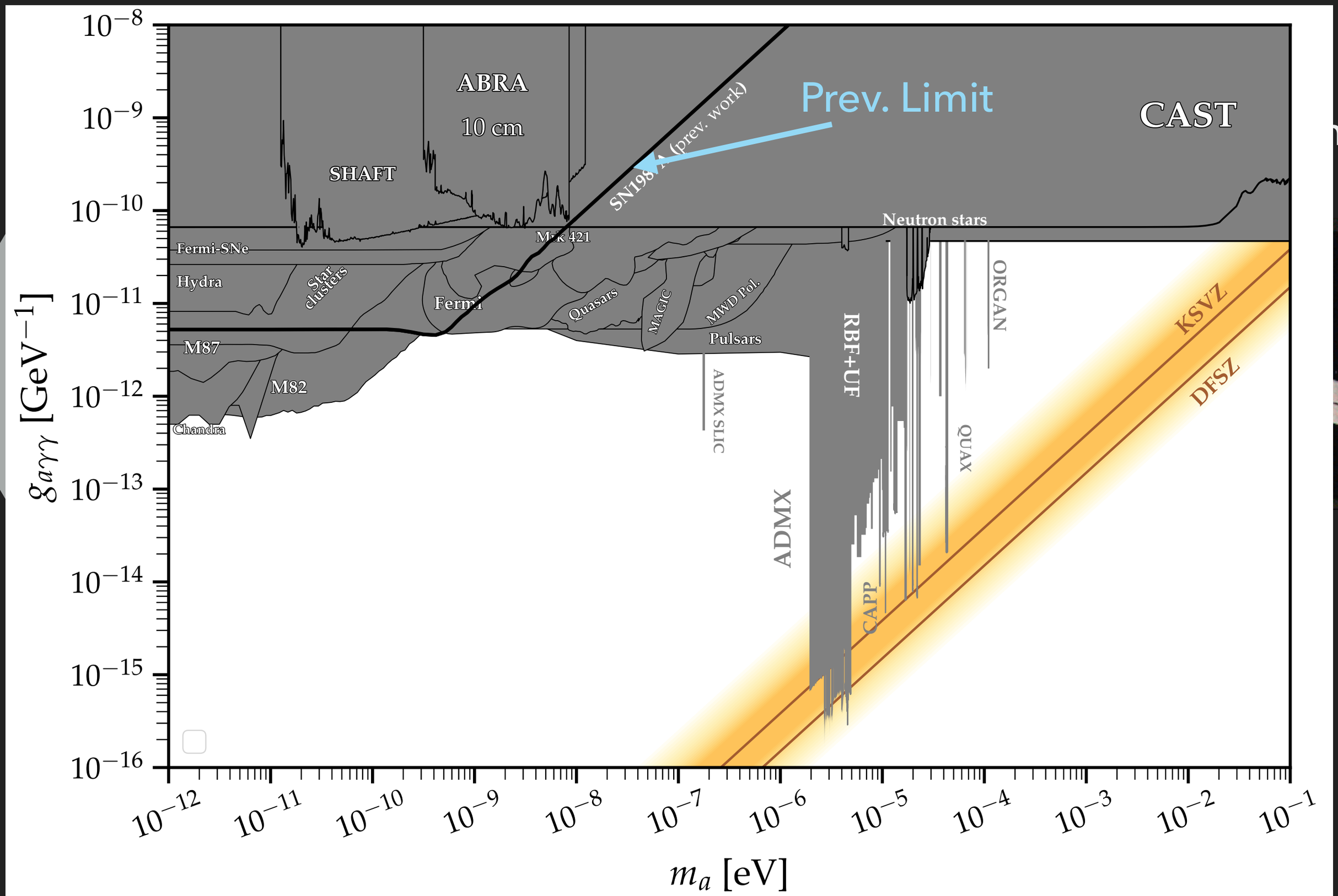


(Loop-induced production from nucleons important for ALPs)

Average axion luminosity over 10 s (this work)



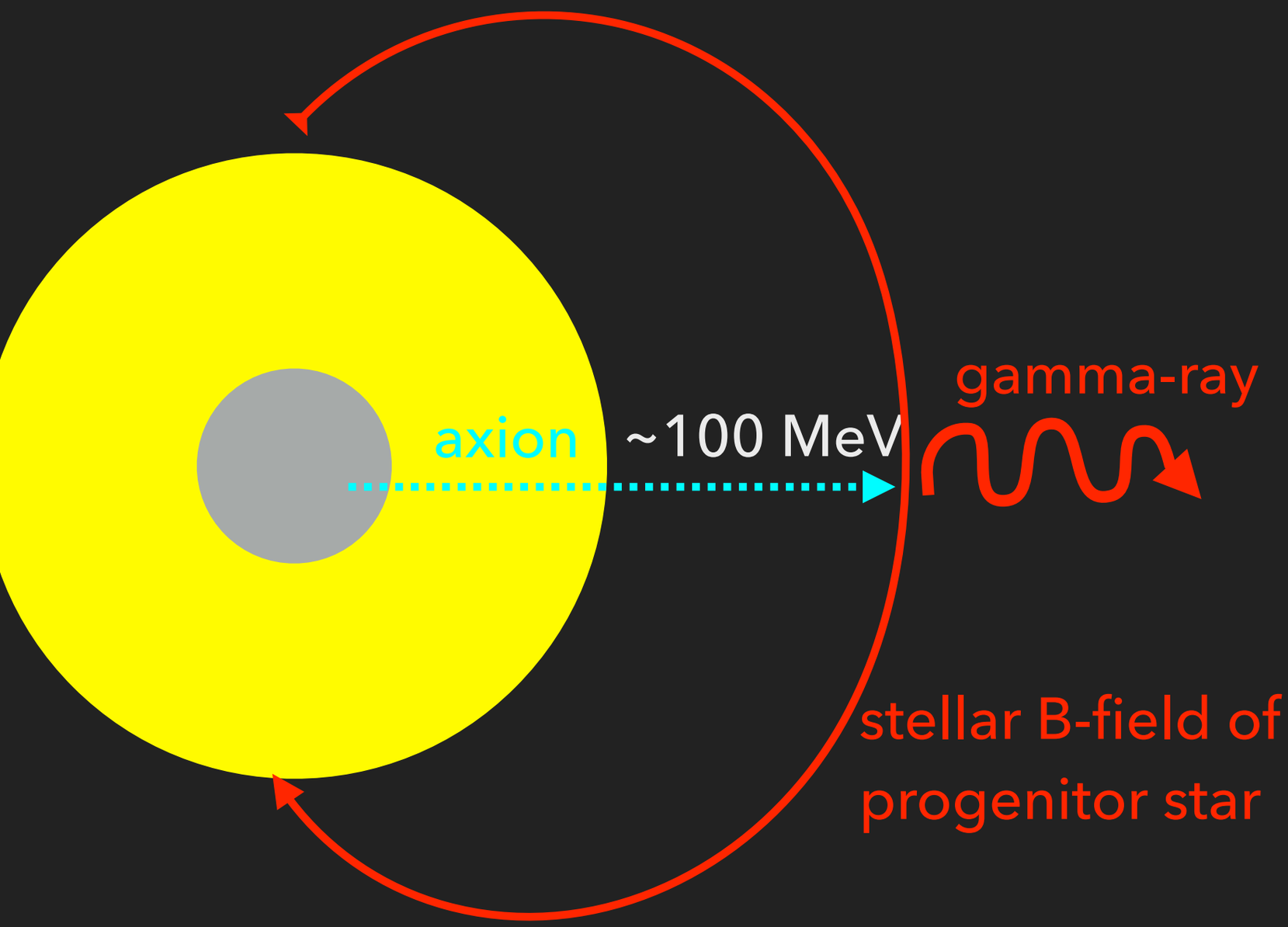
Old idea: SN axions convert to gamma-rays in Galactic fields



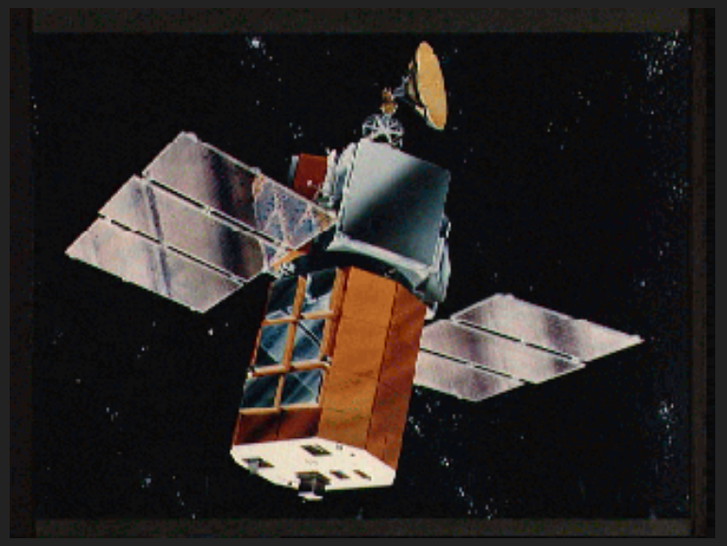
New Idea: gamma-rays from SN1987A progenitor B-field

New proposal! Convert on progenitor stellar magnetic field

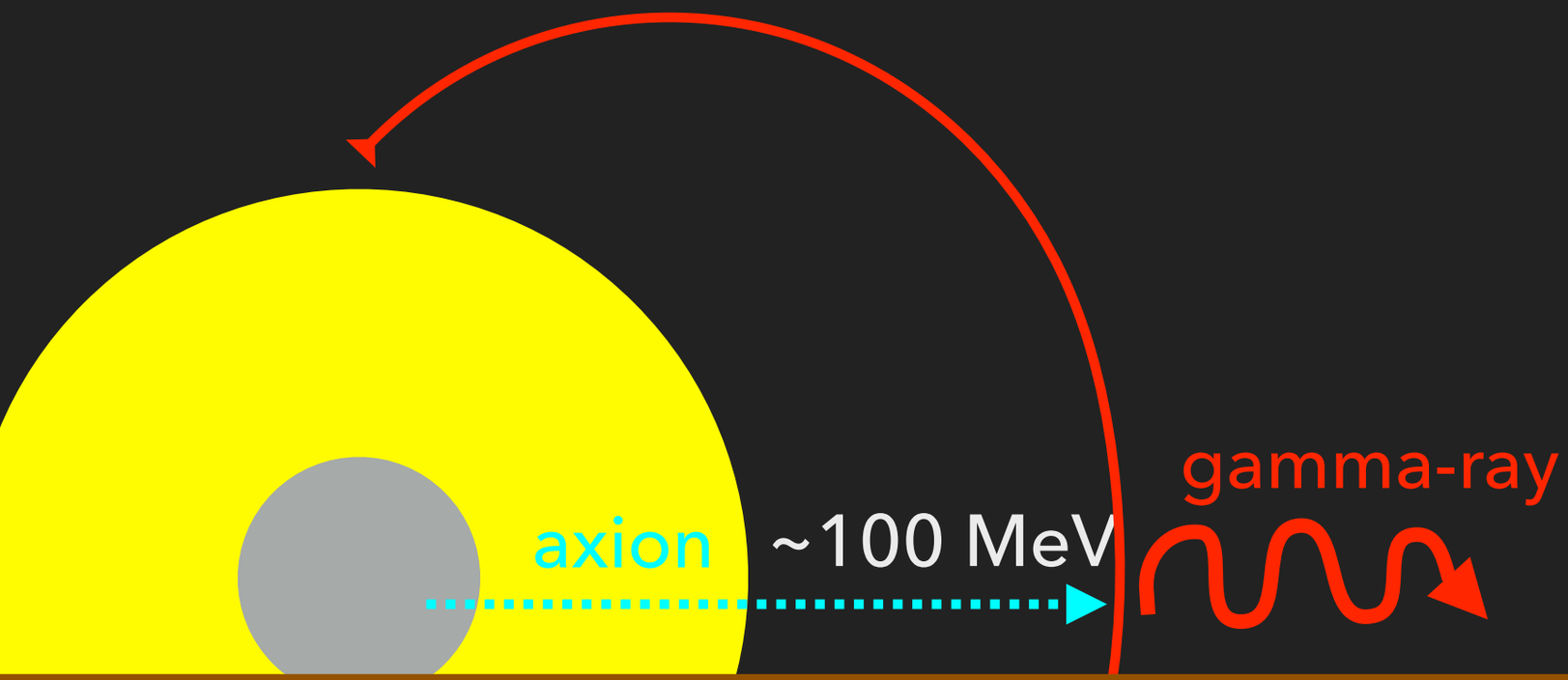
SN1987A: in the LMC at d ~ 50 Mpc



solar maximum
mission



New Idea: gamma-rays from SN1987A progenitor B-field



solar maximum mission

SN1987A progenitor: Sk -69 202

1. Blue Supergiant
2. $R \approx 45 R_\odot$
3. B ~ 1 kG

progenitor conversion probability:

$$P_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 L^2$$

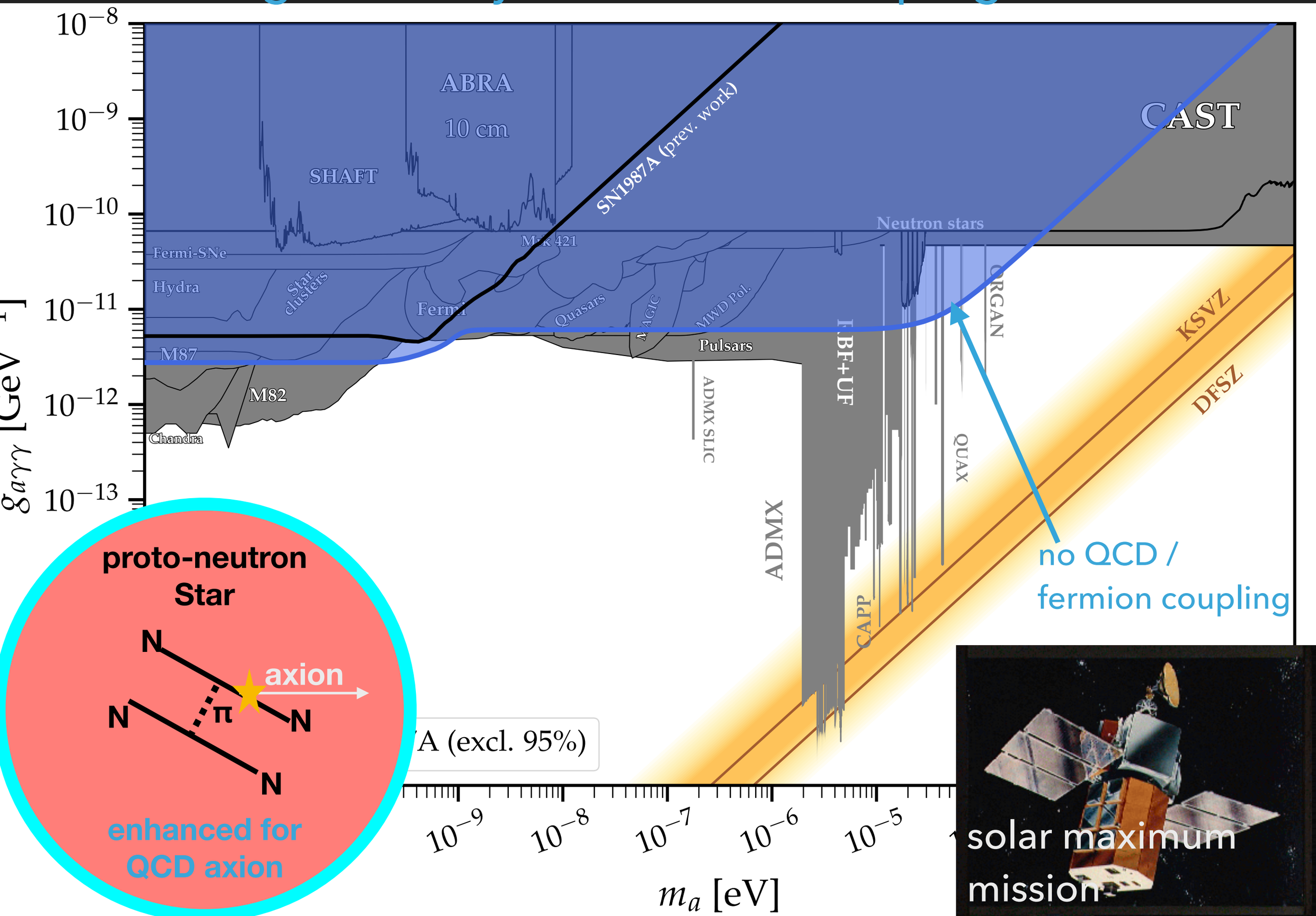
$$\sim 10^{-5} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}} \right)^2$$

Matches Galactic conversion prob.!

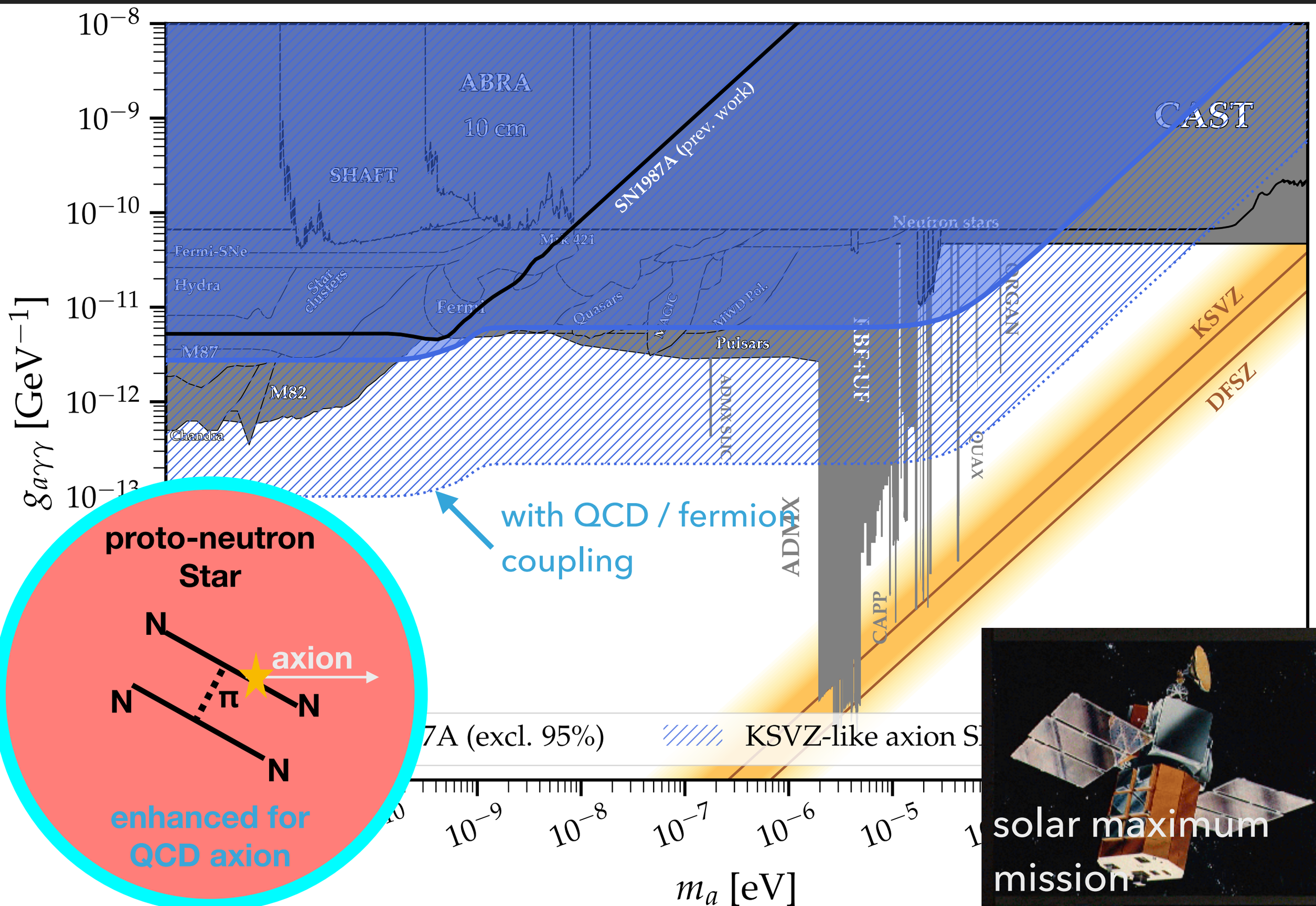
when does mass-dependence come in?

$$\delta k L \approx \frac{m_a^2}{2\omega} L \sim \frac{m_a^2}{200\ \mathrm{MeV}} 45 R_\odot \sim \left(\frac{m_a}{4 \cdot 10^{-5}\ \mathrm{eV}} \right)^2 > 1$$

New Idea: gamma-rays from SN1987A progenitor B-field



New Idea: gamma-rays from SN1987A progenitor B-field



Future supernova

Galactic supernova rate ~1 per 100 years:

what would we learn about axions from next Galactic supernova?

Answer: likely nothing!

Chance of Fermi-LAT seeing next SN is ~1 in 10

(pre-SN neutrinos could give indication for SN within ~1 kpc)

Future supernova

But what if Fermi did catch the next Galactic SN?

Future supernova: axion signal with Fermi-LAT

Fine-print: actual sensitivity depends on the SN distance and progenitor radius / B-field

ABRA 10 cm
SHAFT
CAST
Neutron stars
Mrk 421
Hydra
Star clusters
Fermi
Quasars
MAGIC
MWD Pol.
Pulsars
M87
M82
Chandra
RBF+UF
ADMX SLIM
ADMX
ORGAN
QUAX
APP
KSVZ
DFSZ
no QCD / fermion coupling
with QCD / fermion coupling

ALP proj. 10 kpc BSG
KSVZ-like proj. 10 kpc BSG
DFSZ-like proj. 10 kpc BSG
ALP SN1987A (excl. 95%)
KSVZ-like axion SN1987A (excl. 95%)

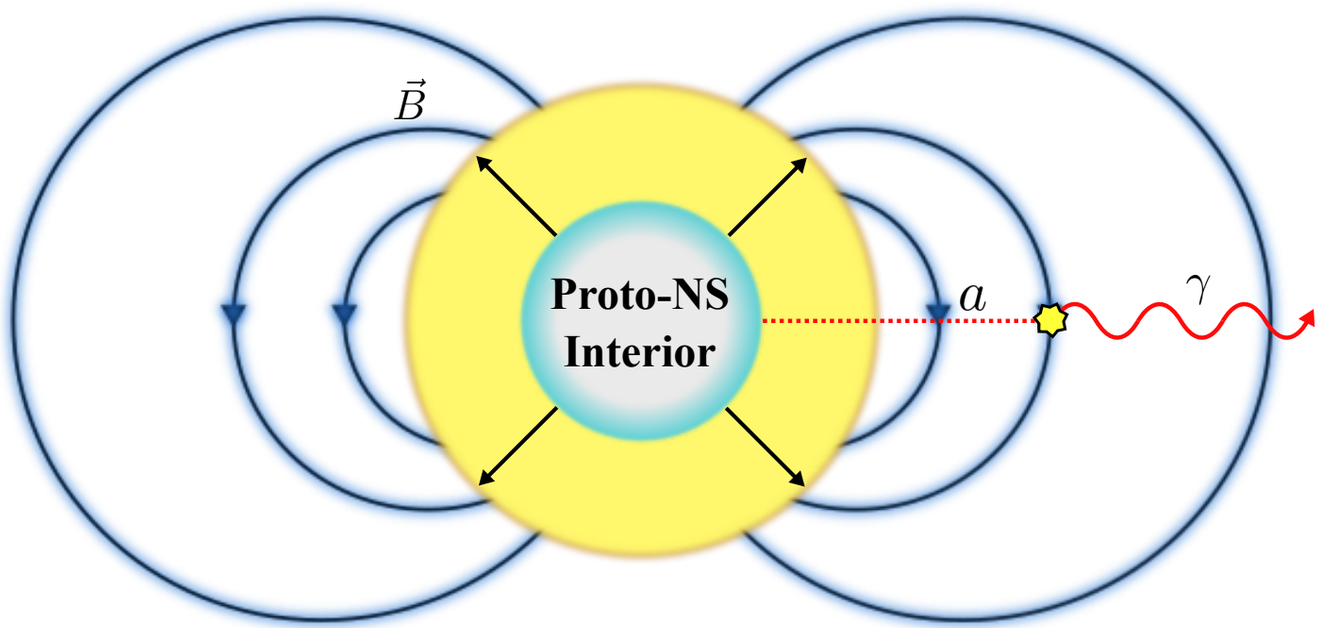
$g_{a\gamma\gamma}$ [GeV^{-1}]: 10^{-11}, 10^{-12}, 10^{-13}, 10^{-14}, 10^{-15}, 10^{-16}

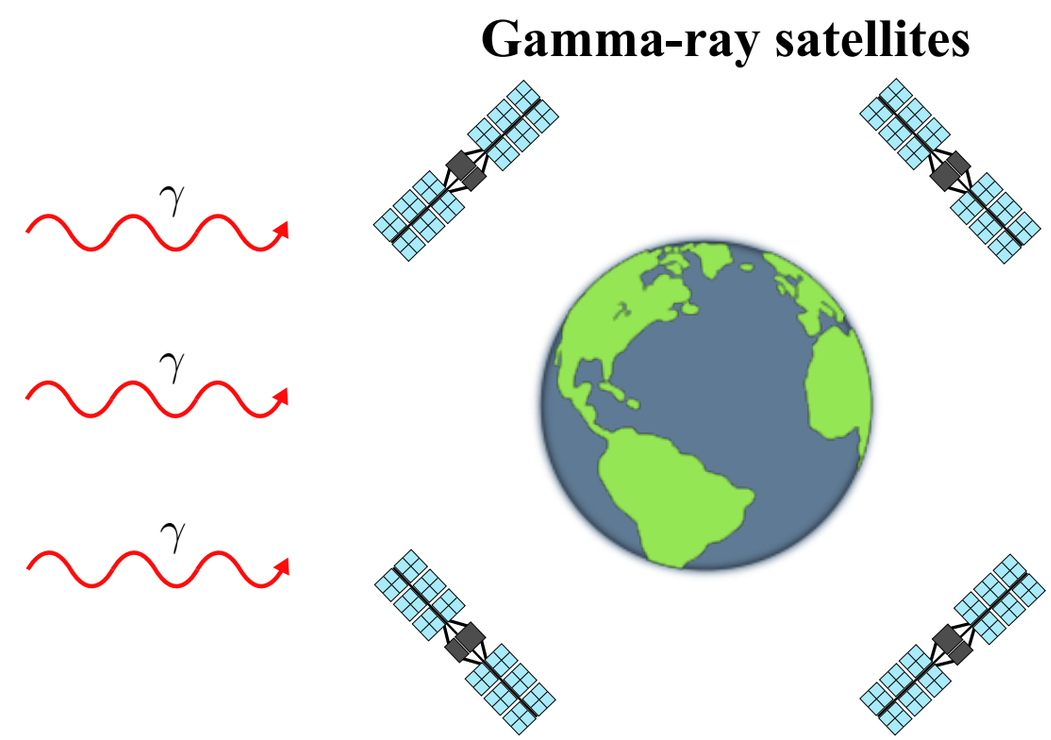
m_a [eV]: 10^{-12}, 10^{-11}, 10^{-10}, 10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}

Future supernova

Huge opportunity for axion physics, but we are not even close to being ready!

Proposal: Full-Sky constellation of SmallSats for continuous, full-sky ~100 - 500 MeV gamma-ray detection

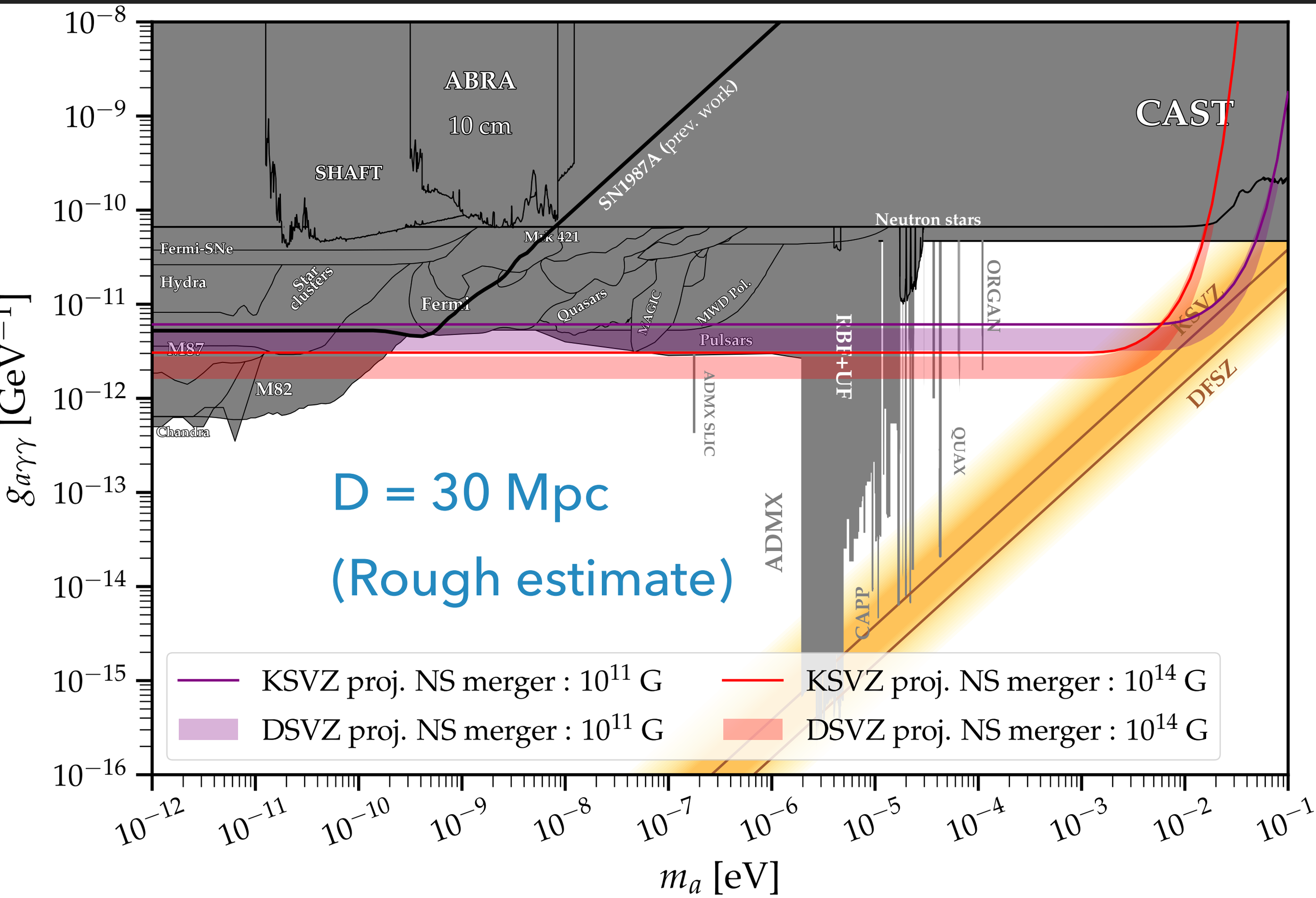




GALactic AXion Instrument for Supernova (GALAXIS)

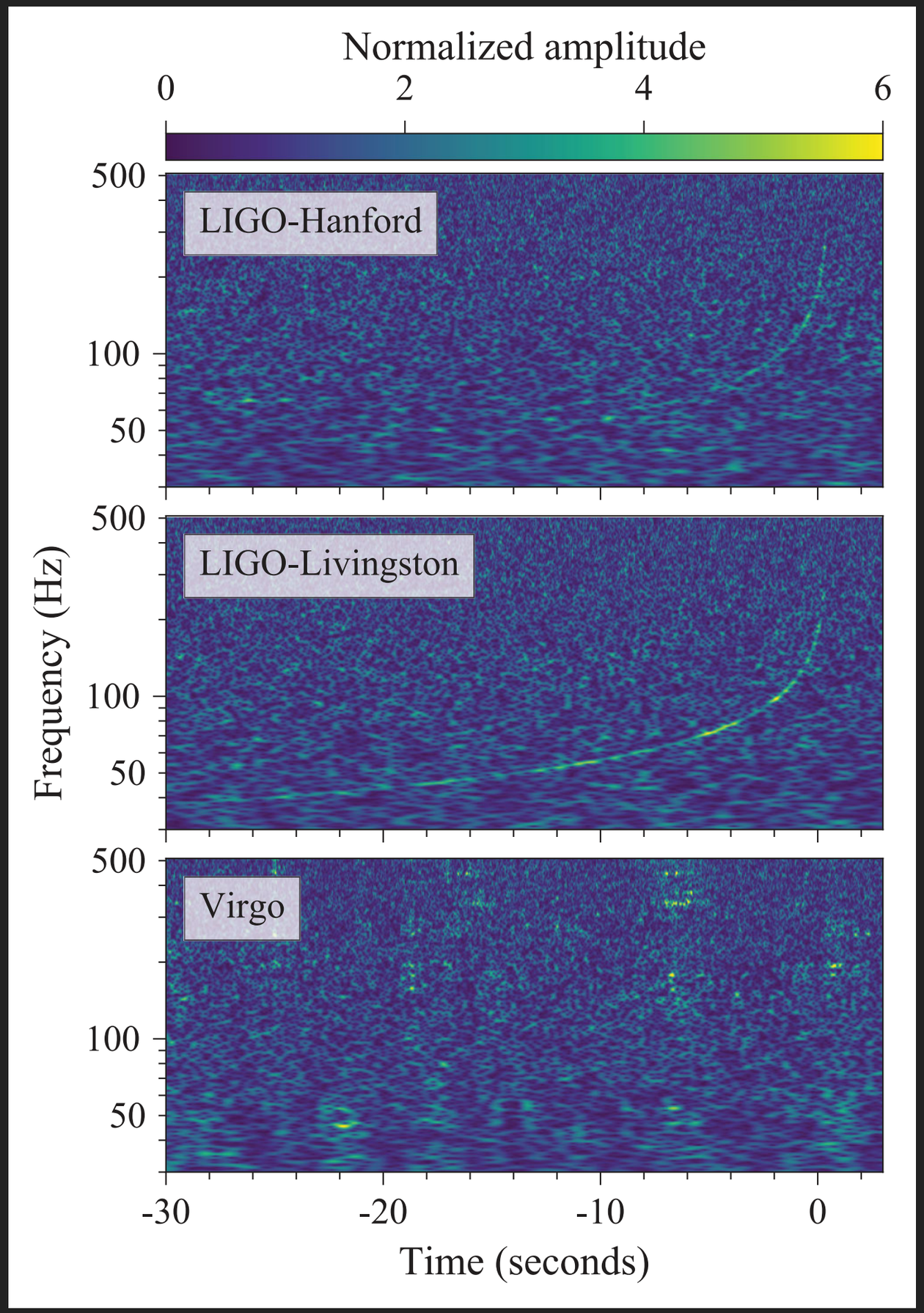
Also ~annual axion science from extragalactic SN and NS-NS mergers

Axions from NS-NS mergers may produce gamma rays

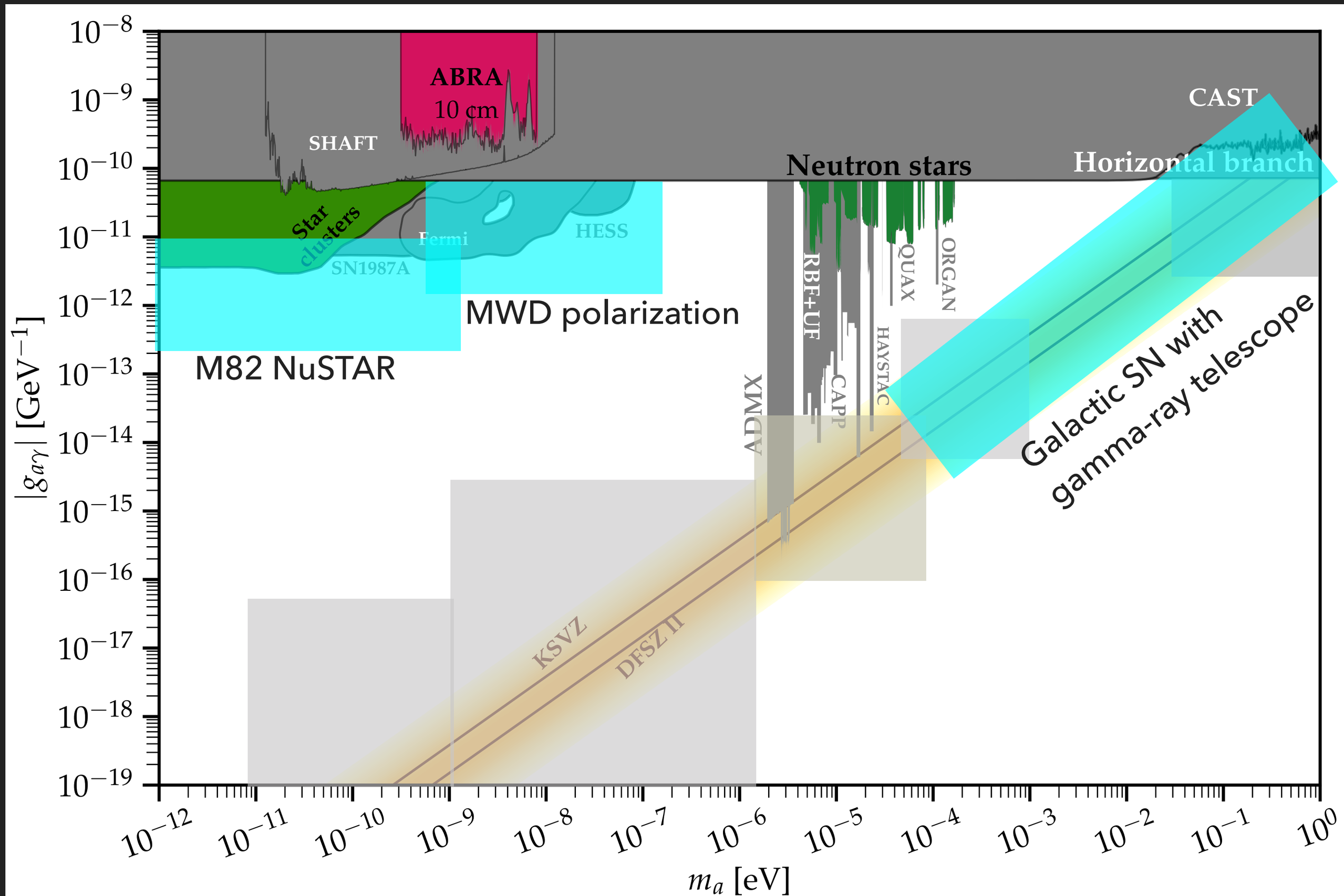


GW170817 (NS-NS merger) in 2017 at d = 40 Mpc

Fermi missed it!



Axion Summary: Indirect Detection



IF IT'S OUT THERE, WE WILL FIND IT!

QUESTIONS?

NASA

BSF
United States – Israel
Binational Science Foundation

ALFRED P. SLOAN FOUNDATION

U.S. DEPARTMENT OF ENERGY | Office of Science