SHINING AXIONS THROUGH ASTROPHYSICAL WALLS

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Pre-talk advertisement: new paper on higgsinos (talk to Linda Xu!)

CTA and SWGO can Discover Higgsino Dark Matter Annihilation

2405.13104

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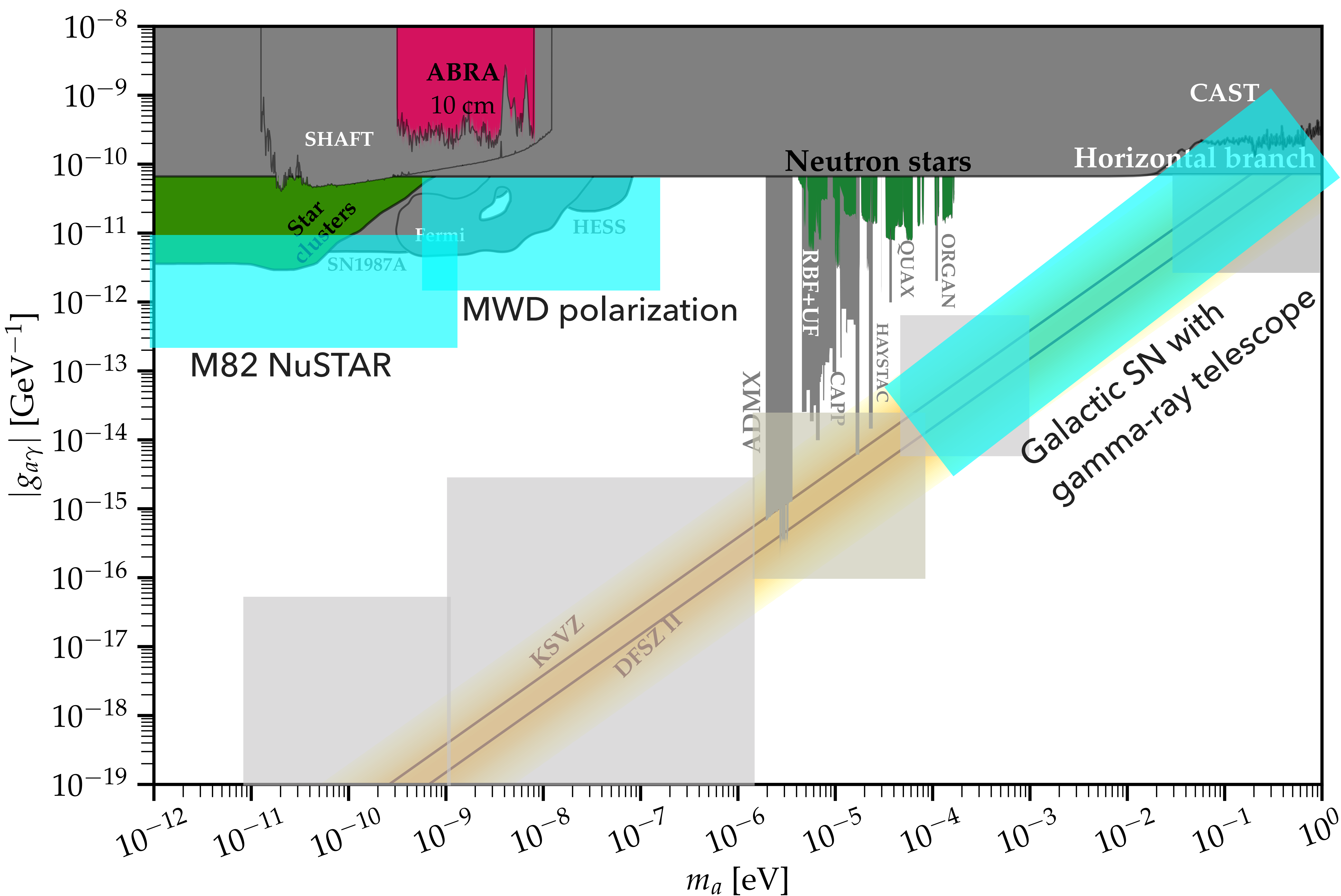
(Dated: May 24, 2024)

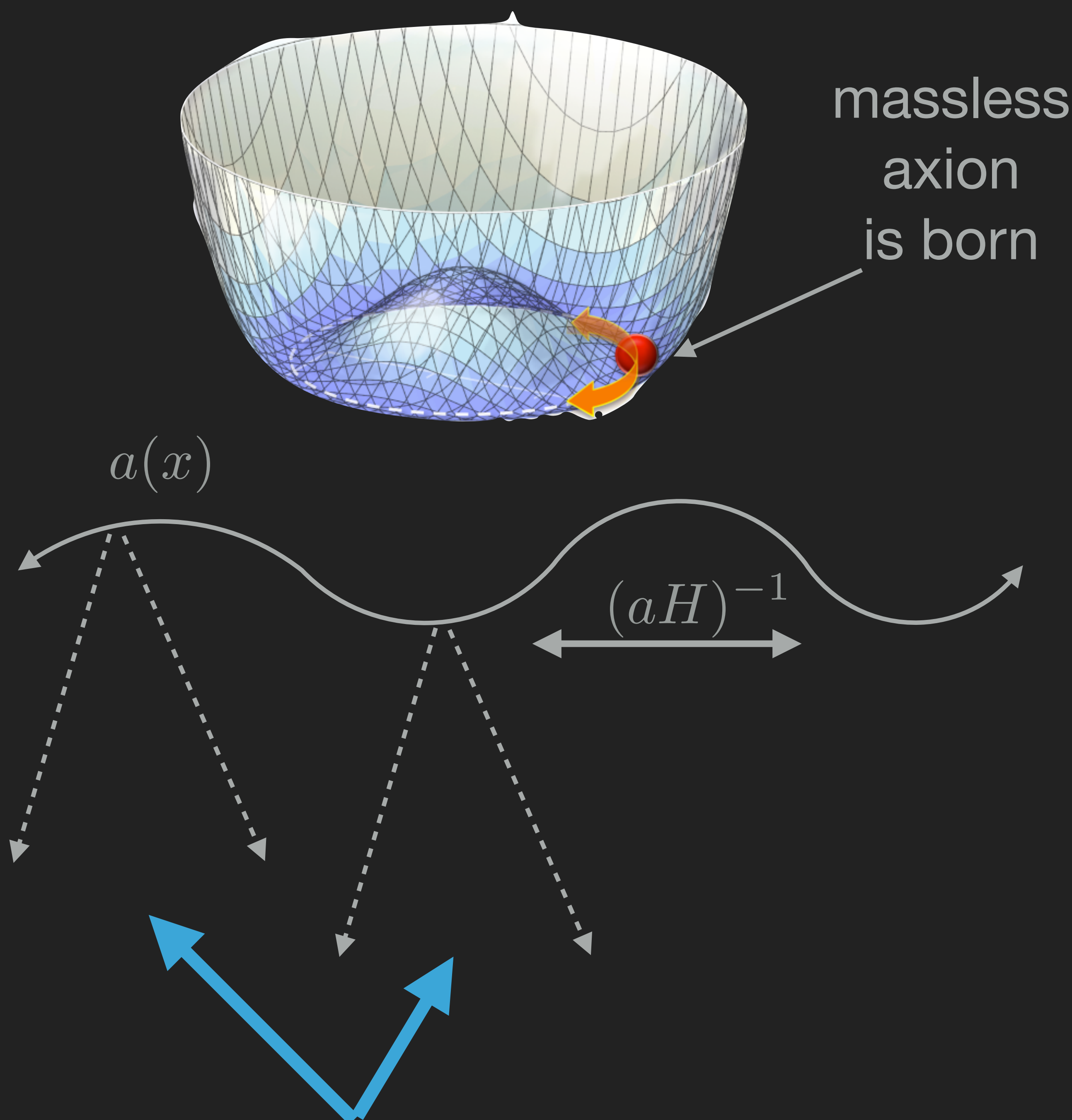
1. Thermal higgsino DM one of remaining, WIMP benchmarks (1.08 TeV)
2. Within reach of upcoming CTA
   1. Even accounting for astrophysical uncertainties on DM and gamma-ray backgrounds
3. Existing H.E.S.S. results wrong by ~order of magnitude but wino still ruled out

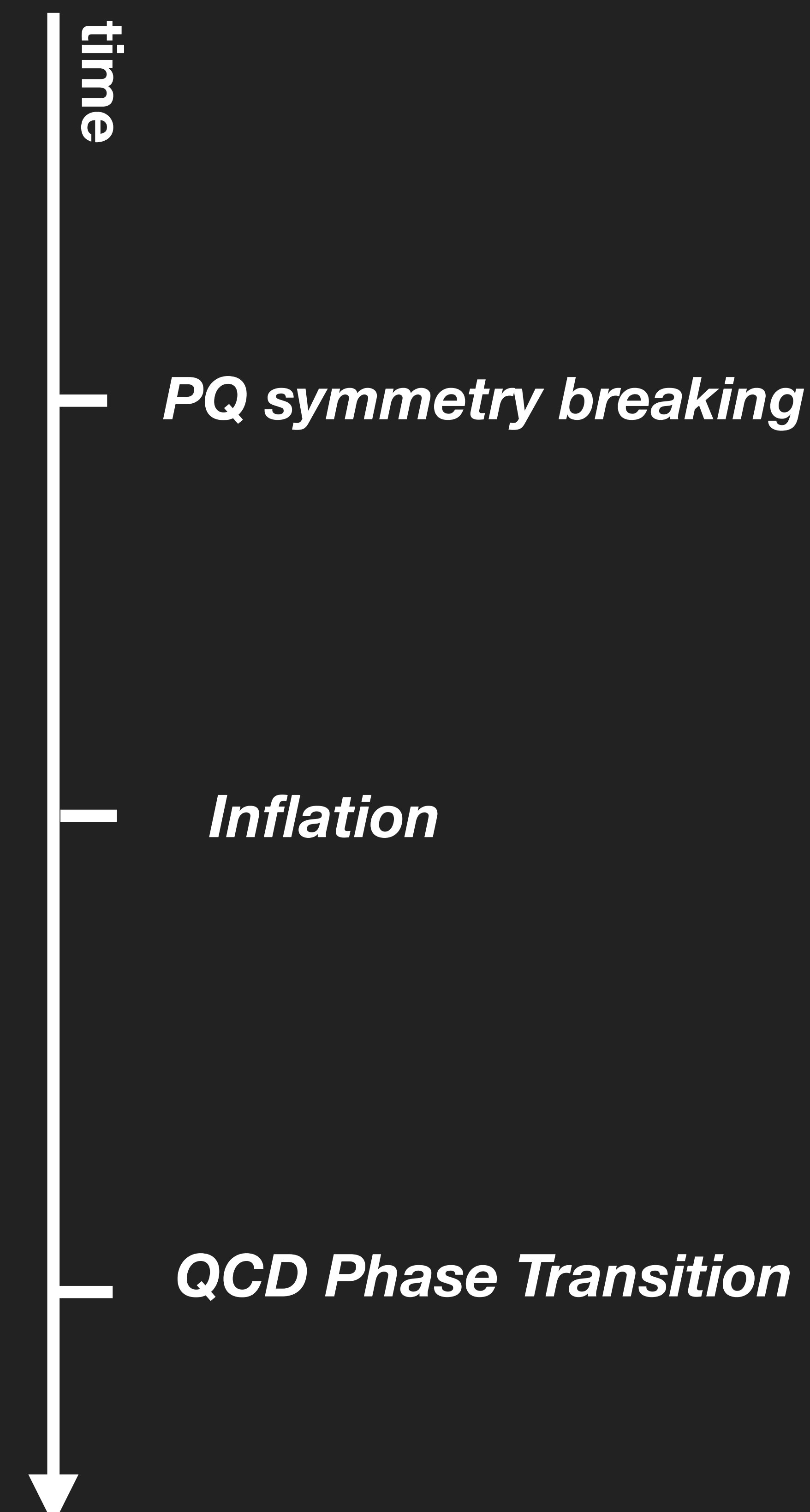
Linda is here!

New ideas for axion detection (blue) without dark matter

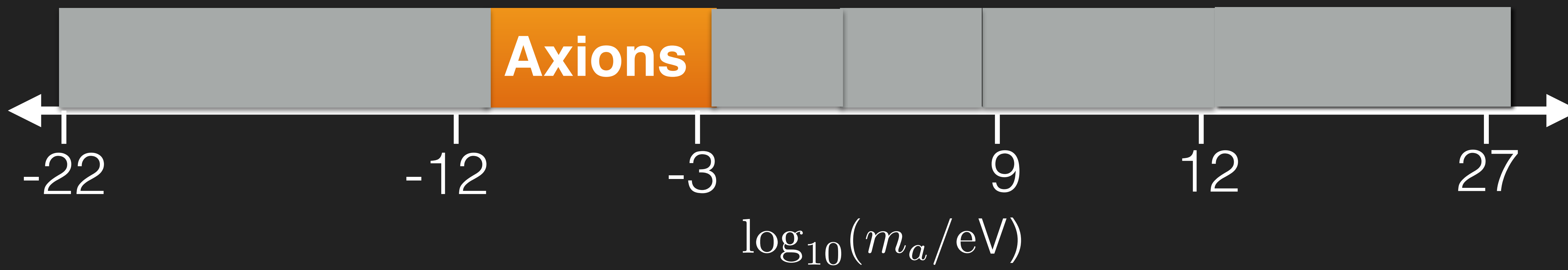


Axion generated before inflation

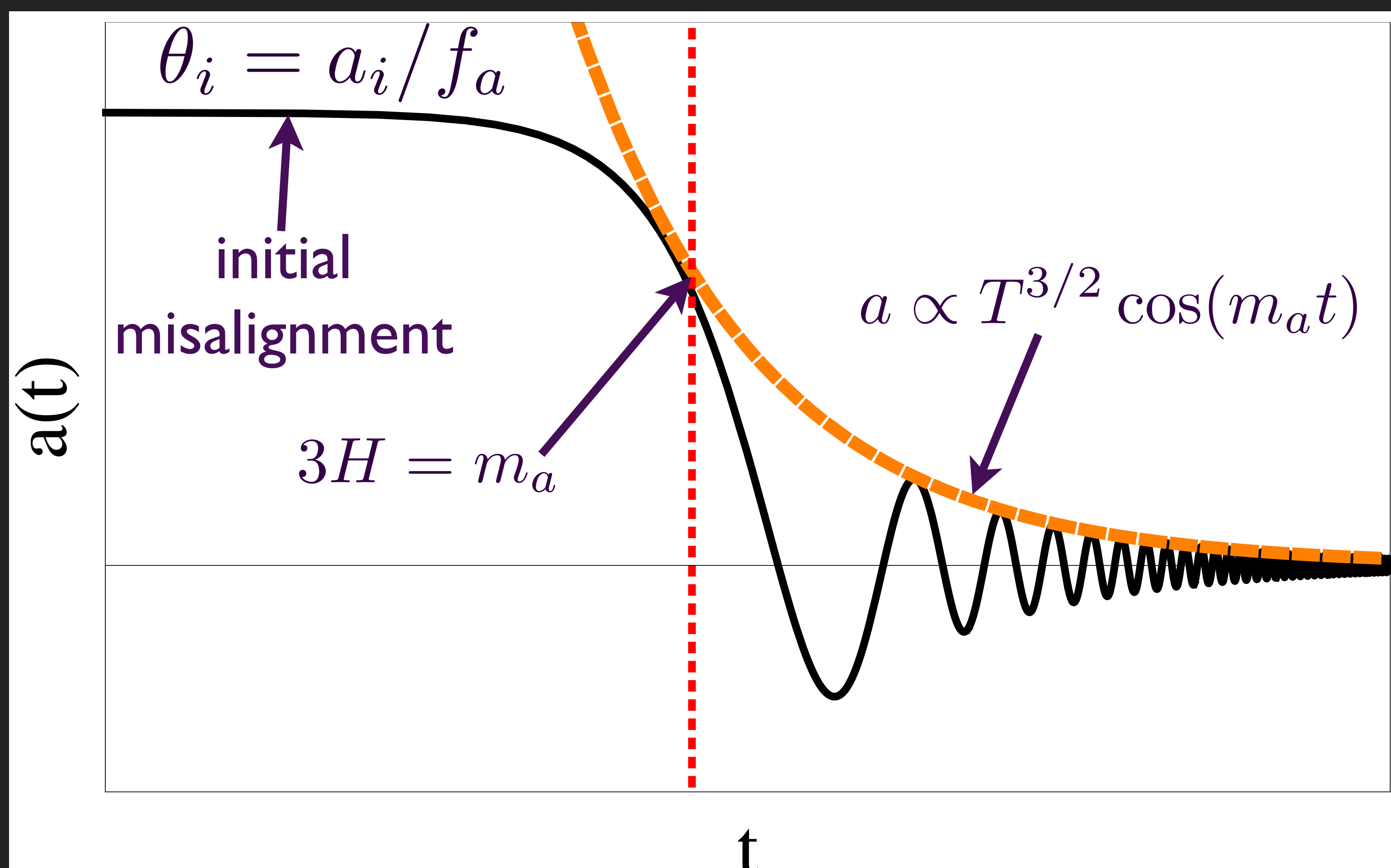




Causally disconnected regions with different homogeneous initial misalignment angles -> different DM densities

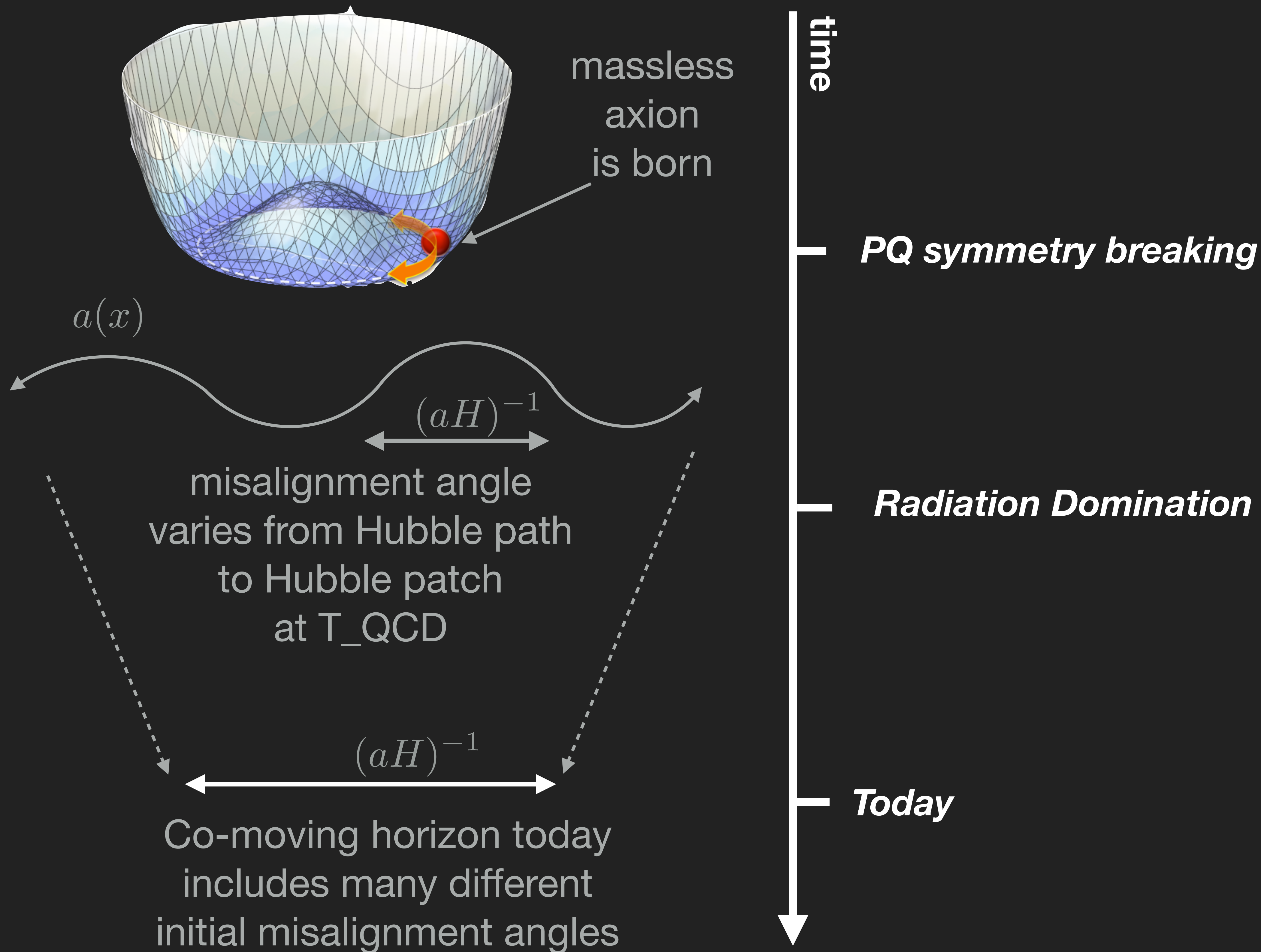


$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0 \longleftarrow H \sim \frac{T^2}{m_{\rm pl}} \sim \frac{1}{t}$$



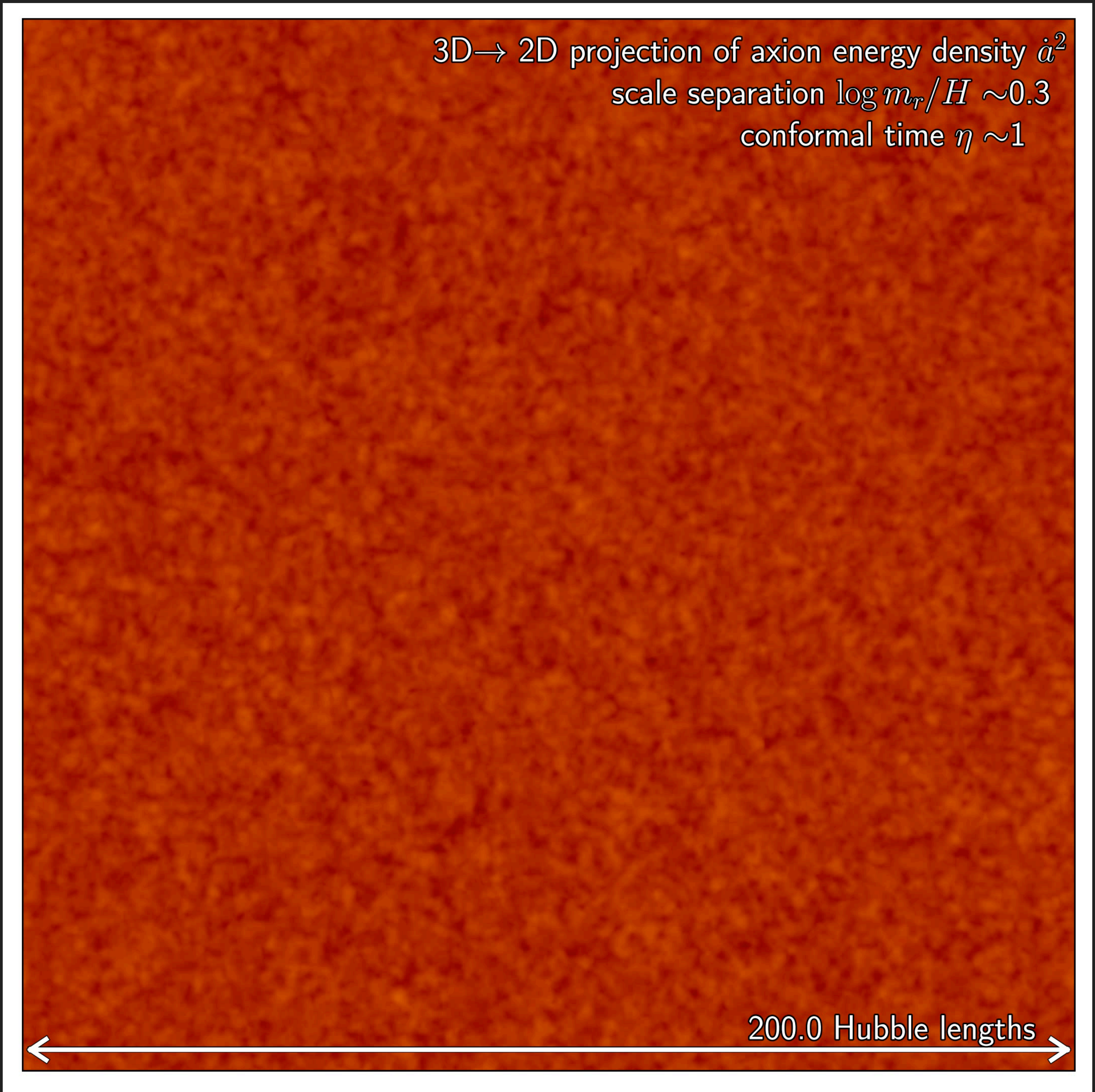
$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \theta_i^2$$

Axion generated after inflation



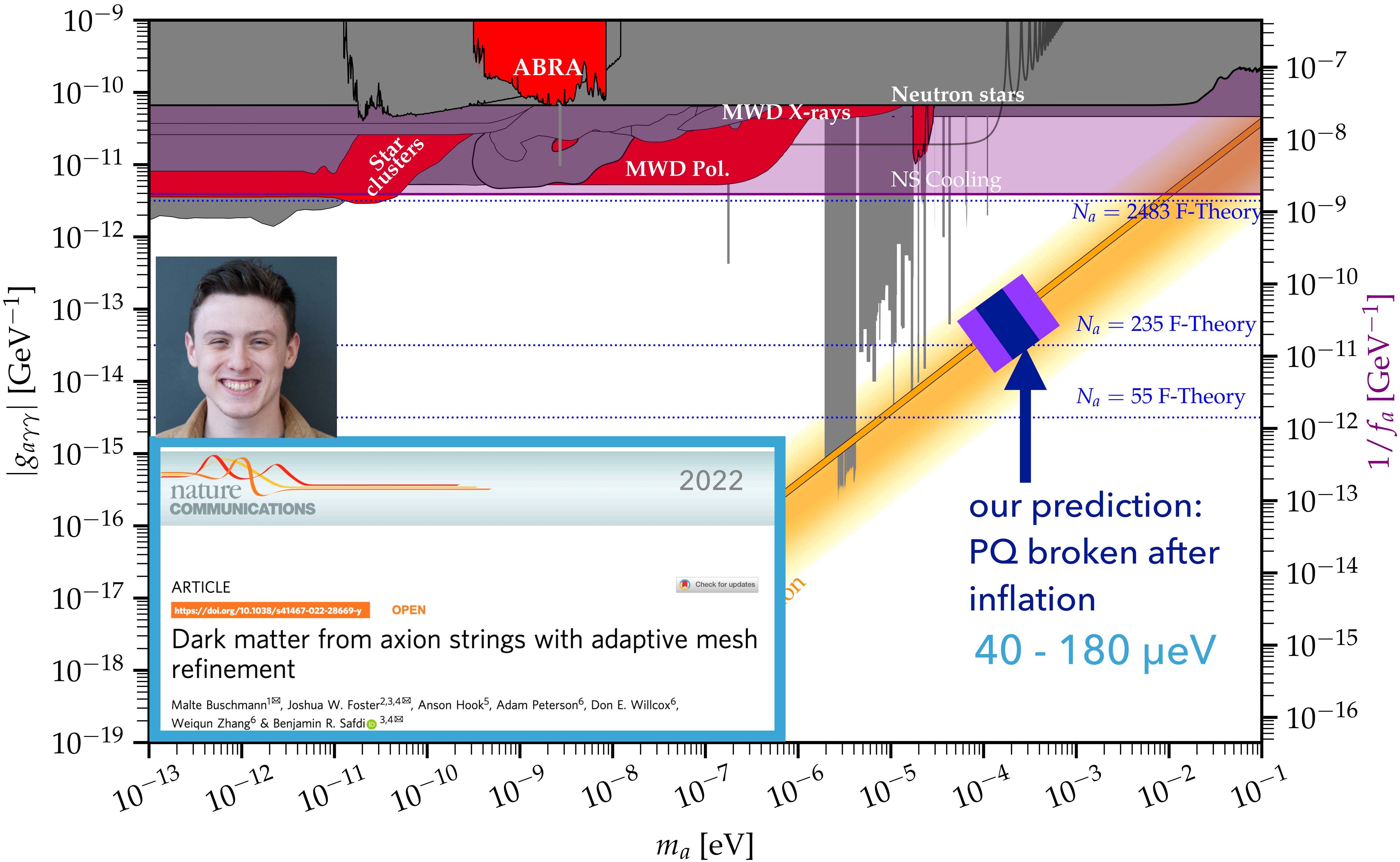
M. Buschmann, J. Foster, **B.S.**, A. Hook, AMReX Collaboration, Nature Communications (2022) + work in progress

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



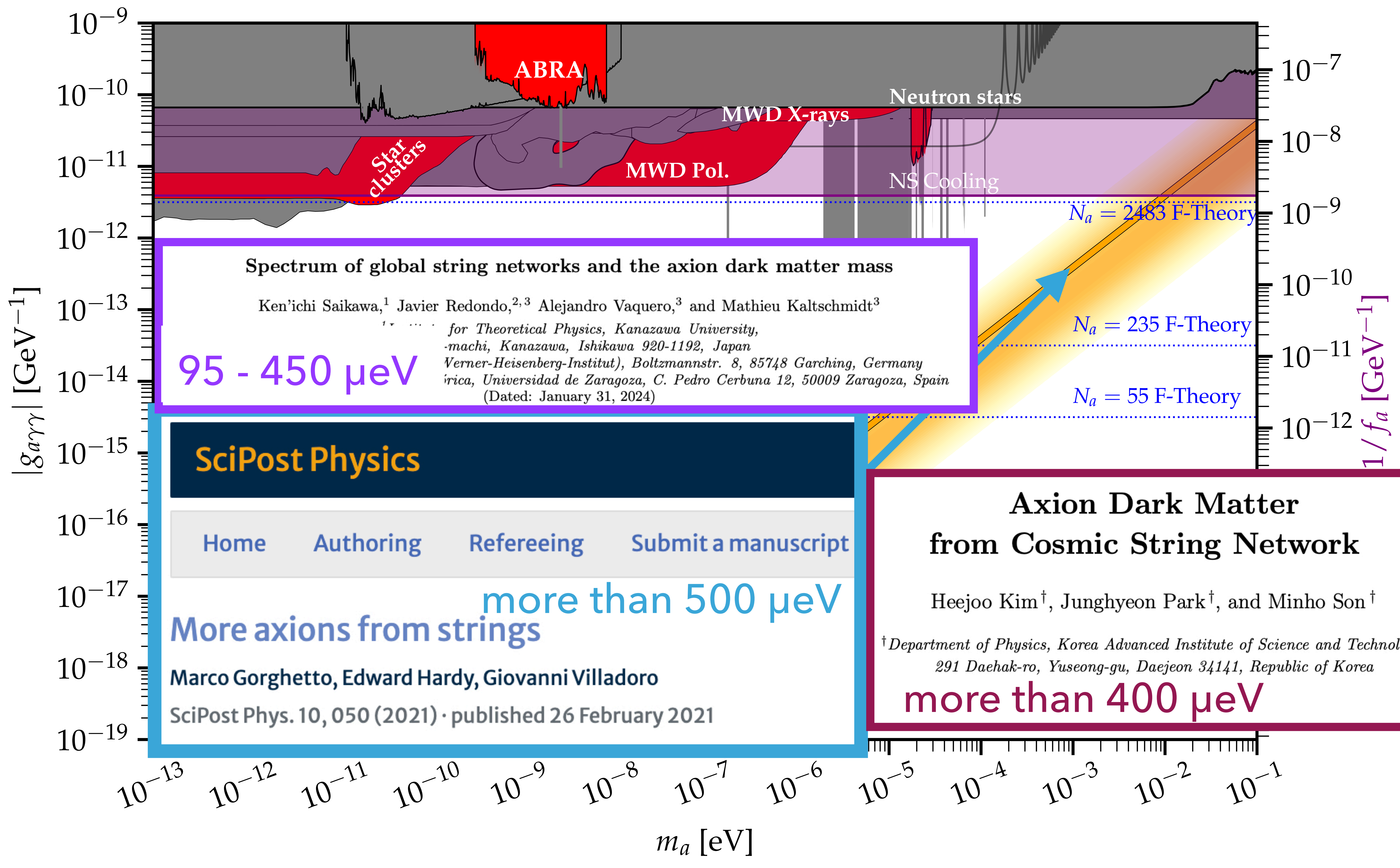
Motivated axion dark matter mass ranges

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



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

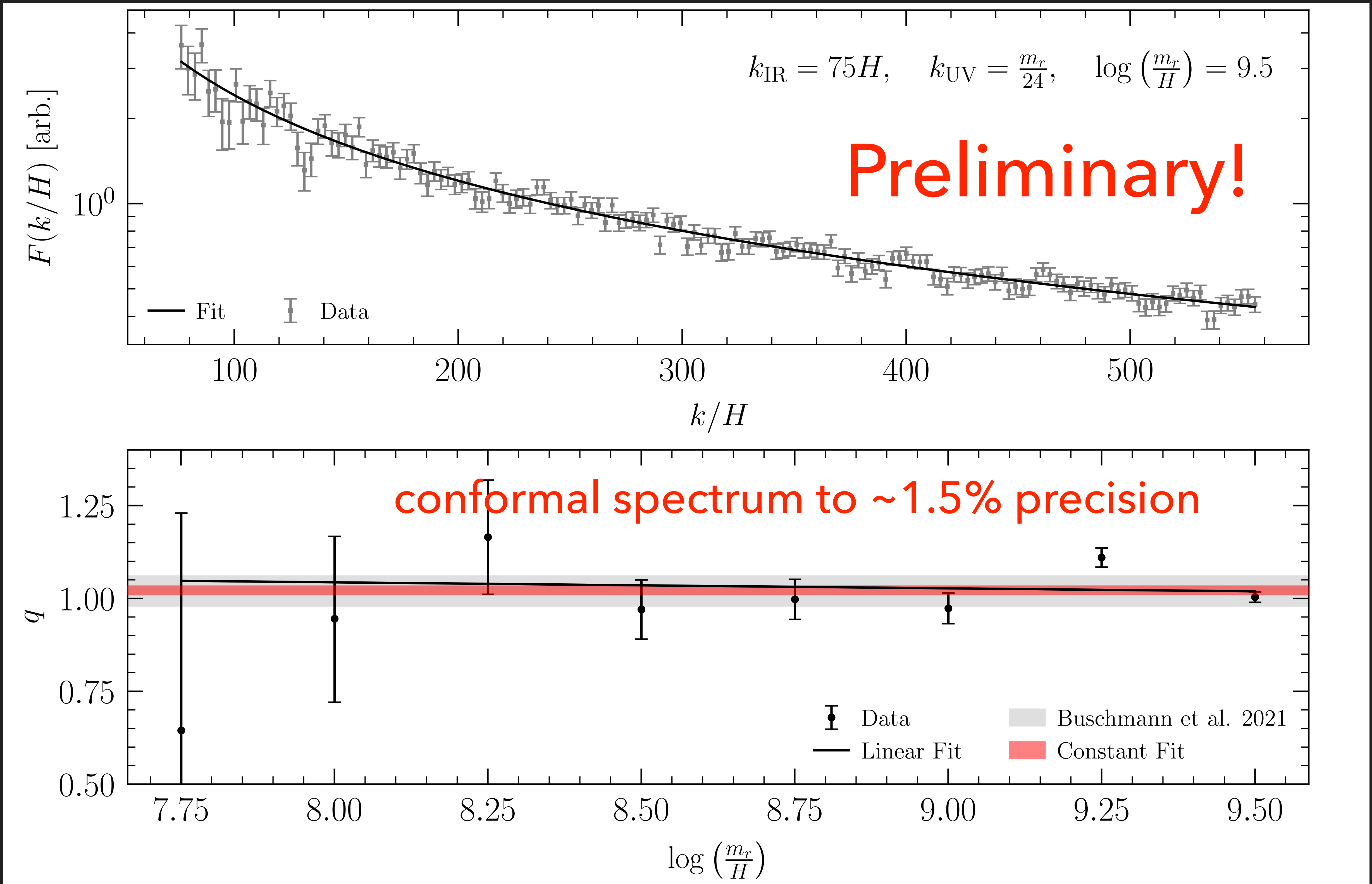
2022: $\log(m_r/H) \sim 9$

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

In Progress: large-scale AMR axion strings simulations

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

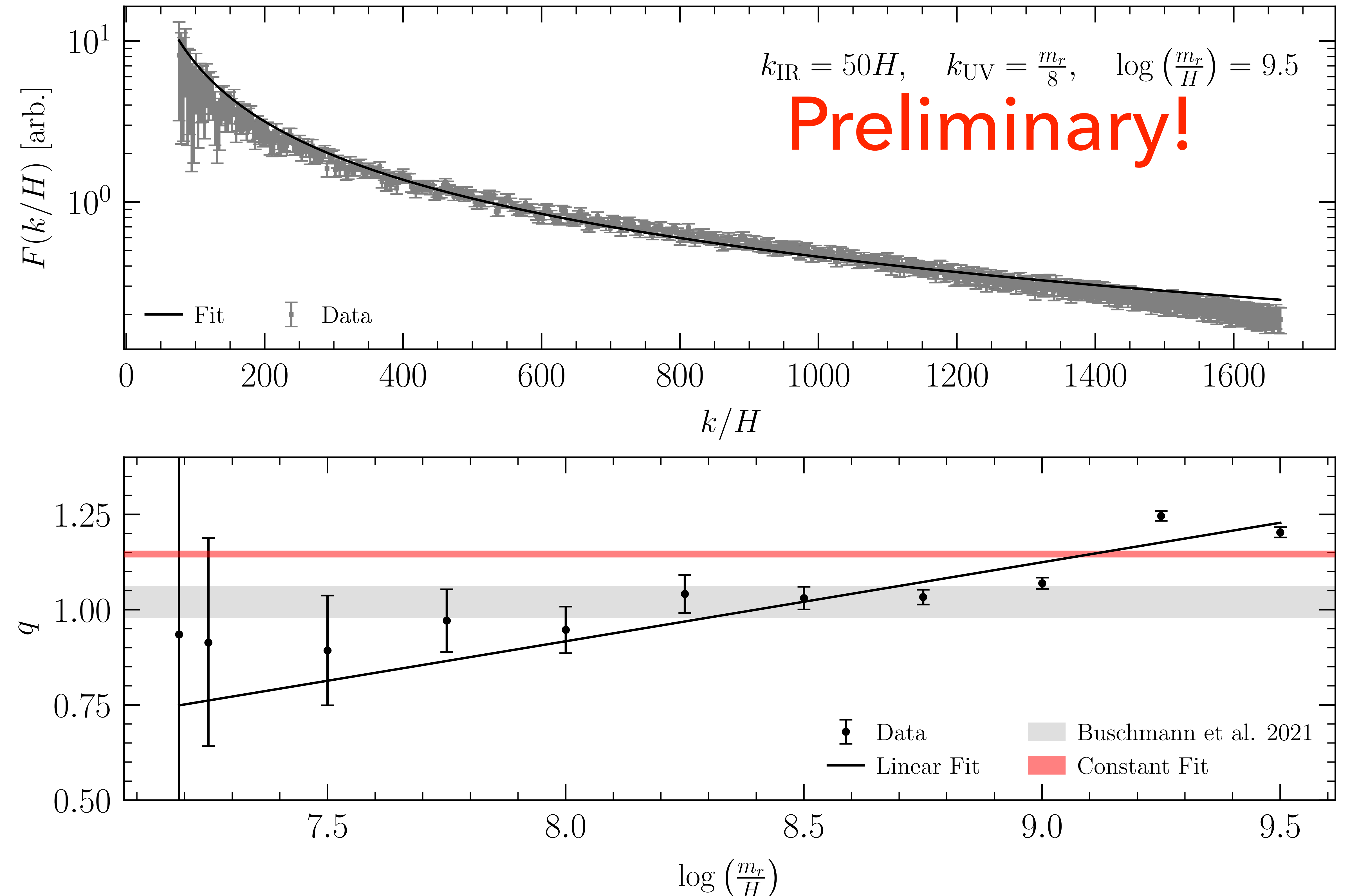
1. Large-scale AMR simulation of axion string from PQ into scaling regime



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

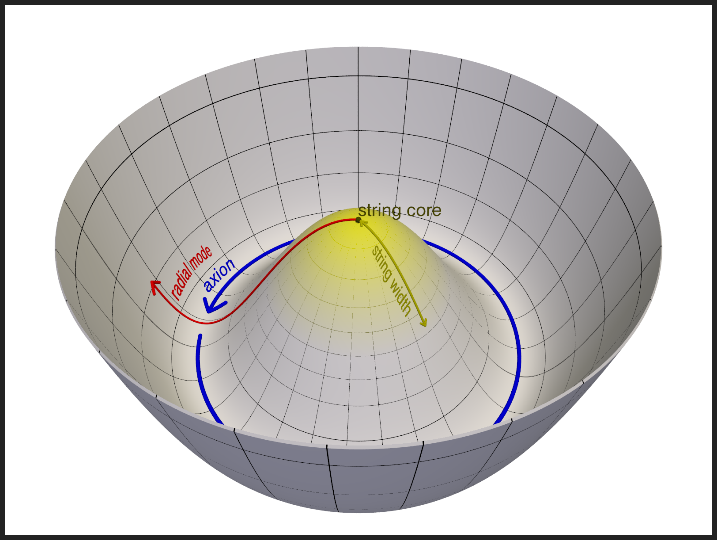
Joshua N. Benabou,[1,2,*] Quentin Bonnefoy,[1,2,†] Malte Buschmann,[3,4,‡]
Soubhik Kumar,[5,1,2,§] and Benjamin R. Safdi[1,2,¶]

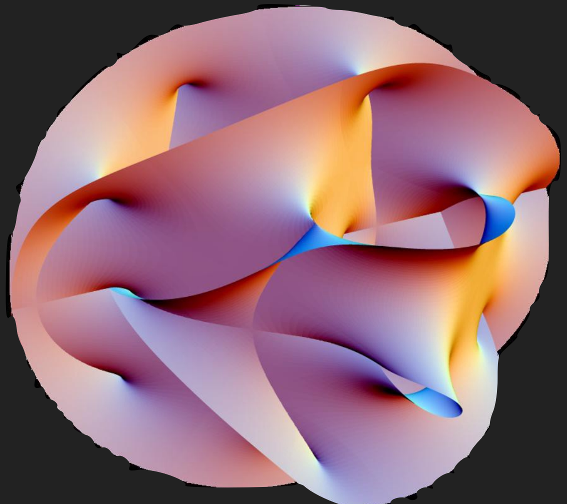
Kibble-Zurek: defect formation requires a spontaneously broken global symmetry

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)

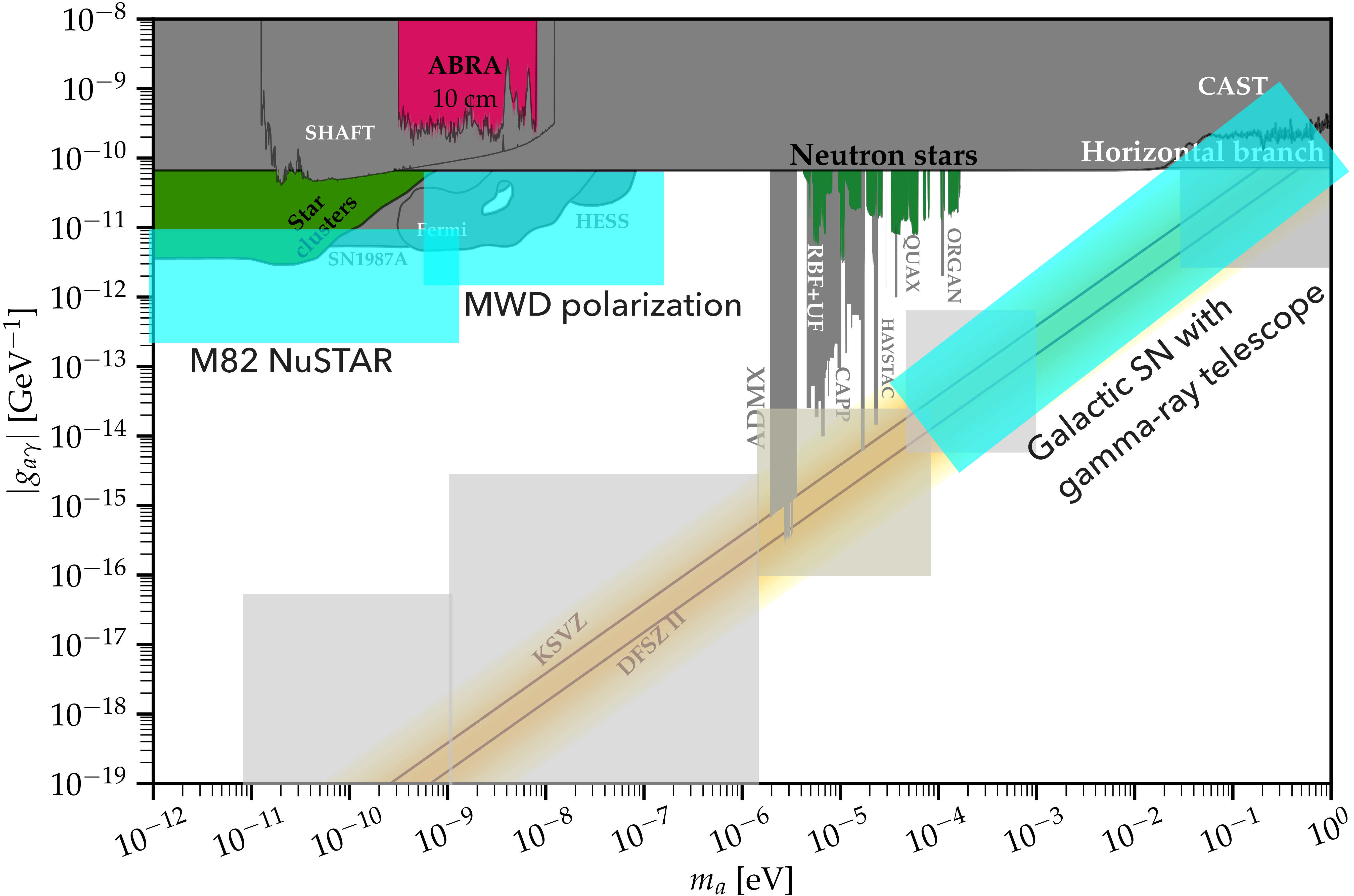
PQ theory: radial mode -> 0 at core

string theory: extra dim decompactifies at core





None of following probes require axion to be DM



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]

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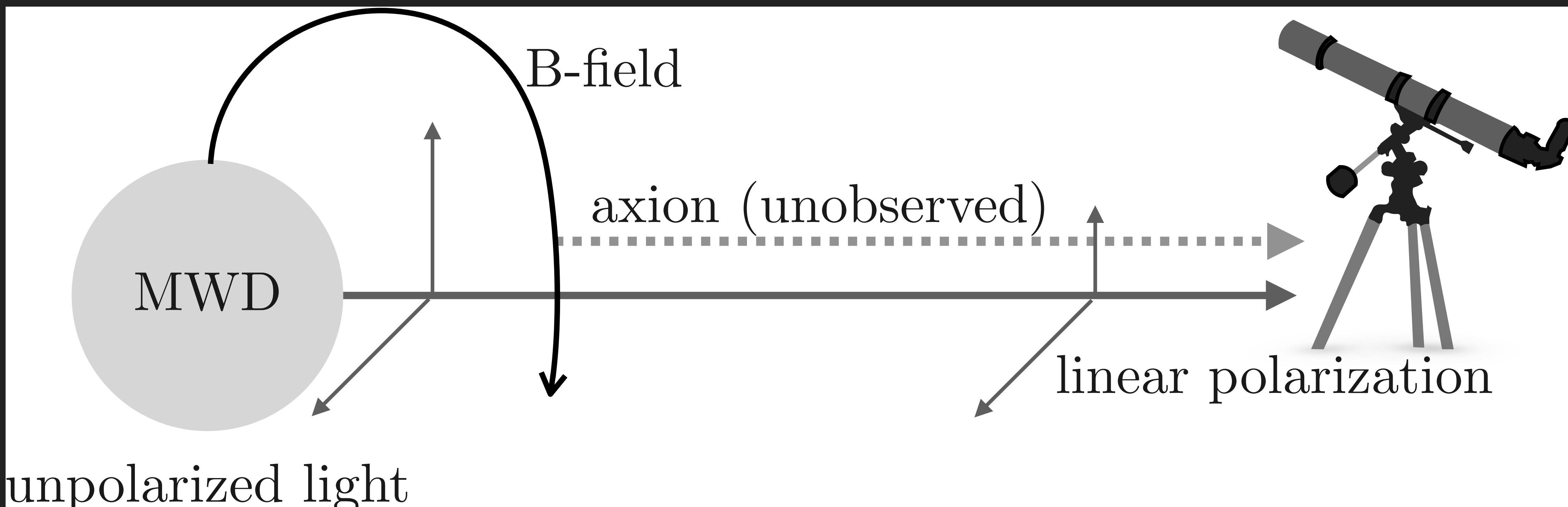
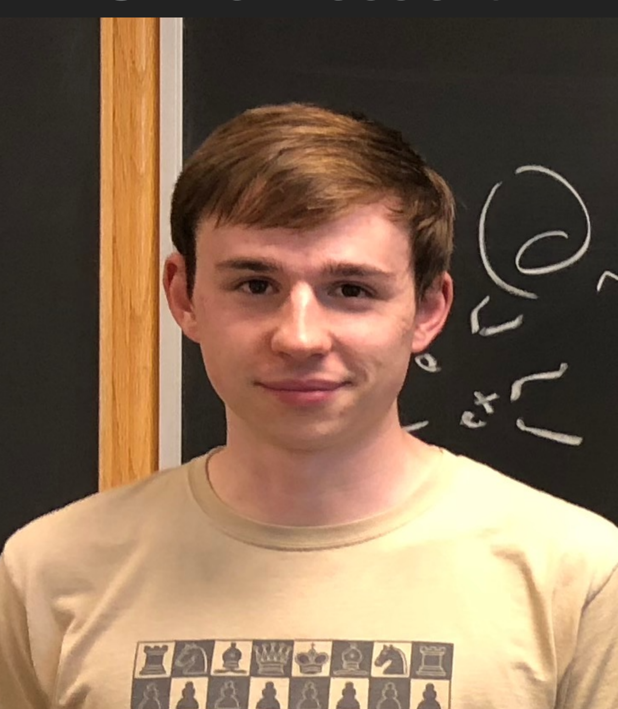
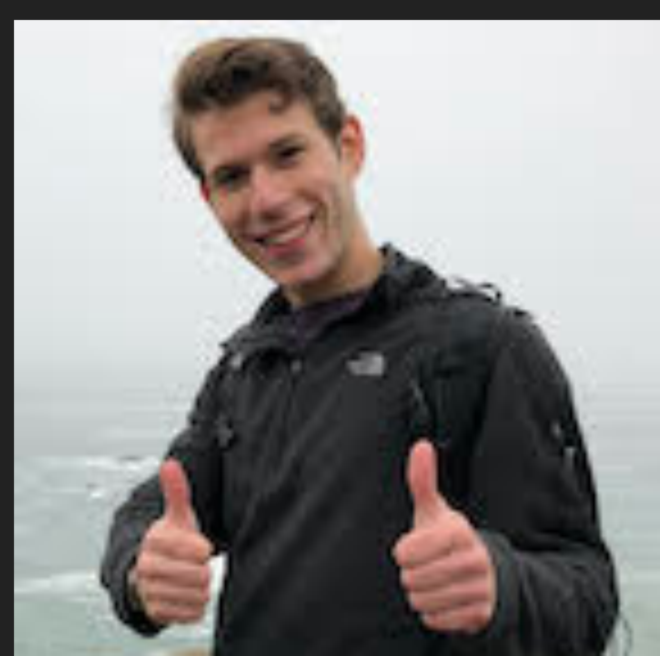


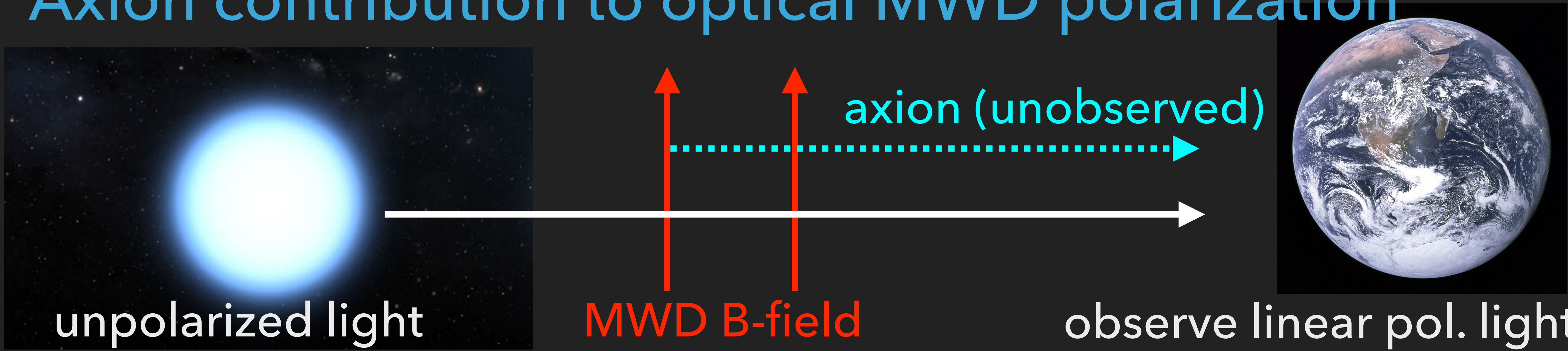
Chris Dessert



David Dunsky



Axion contribution to optical MWD polarization



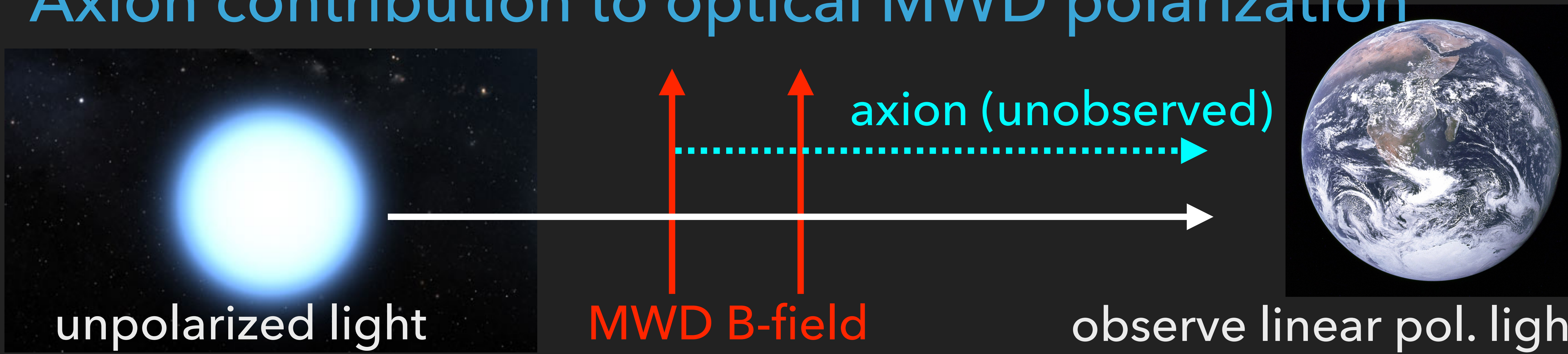
$$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4} = g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$

*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



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

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

not important at optical frequencies

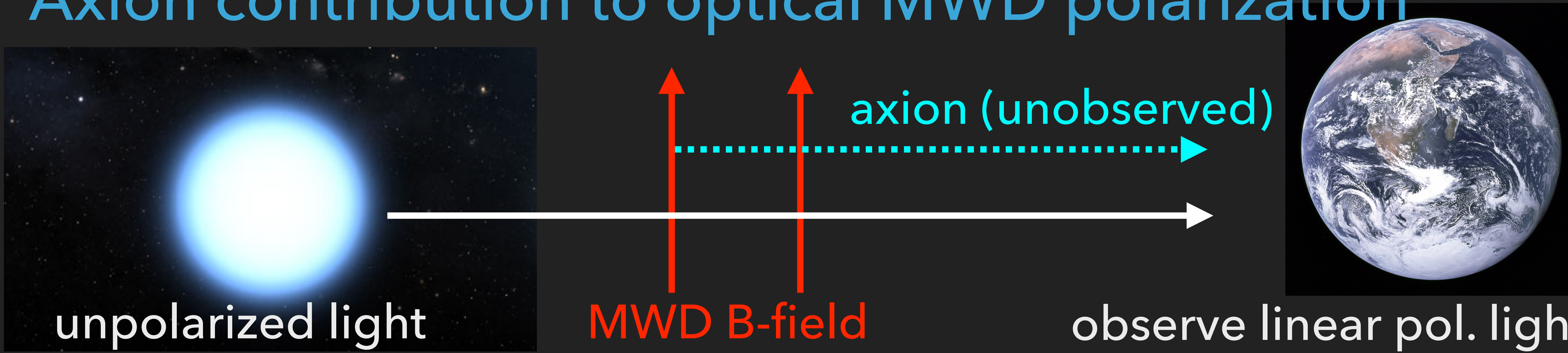
$$P_L \sim 1 - p_{\gamma\to\gamma} \sim 10^{-2}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\,{\rm GeV}^{-1}}\right)^2\left(\frac{B_0}{1000\,{\rm MG}}\right)^2\left(\frac{R_{\rm WD}}{0.01\ {\rm R}_\odot}\right)^2$$

polarization fraction

many MWD polarizations at this level

true at optical frequencies but not X-ray!

Axion contribution to optical MWD polarization



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

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

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

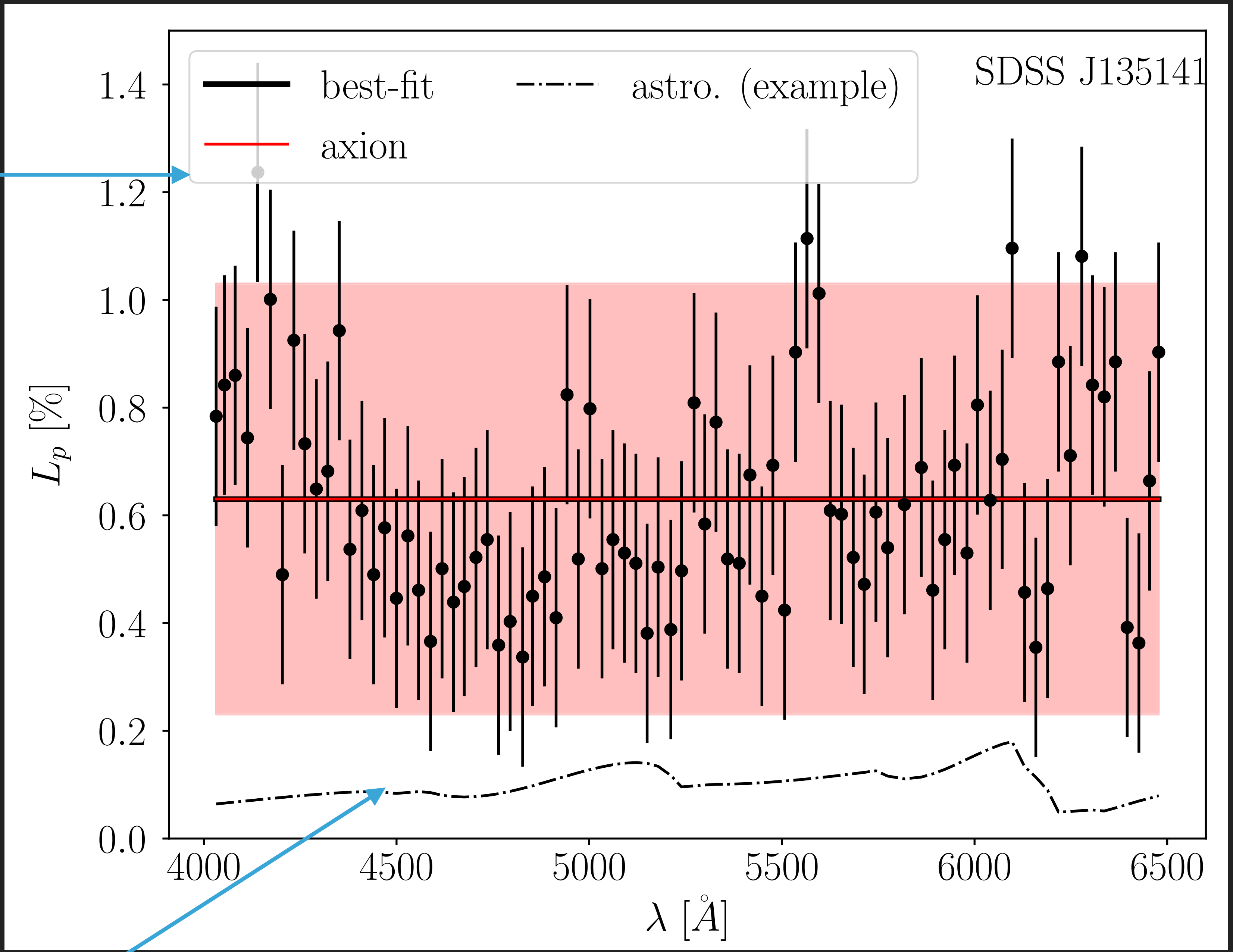
In practice: solve mixing numerically, including EH term and non-radial trajectories

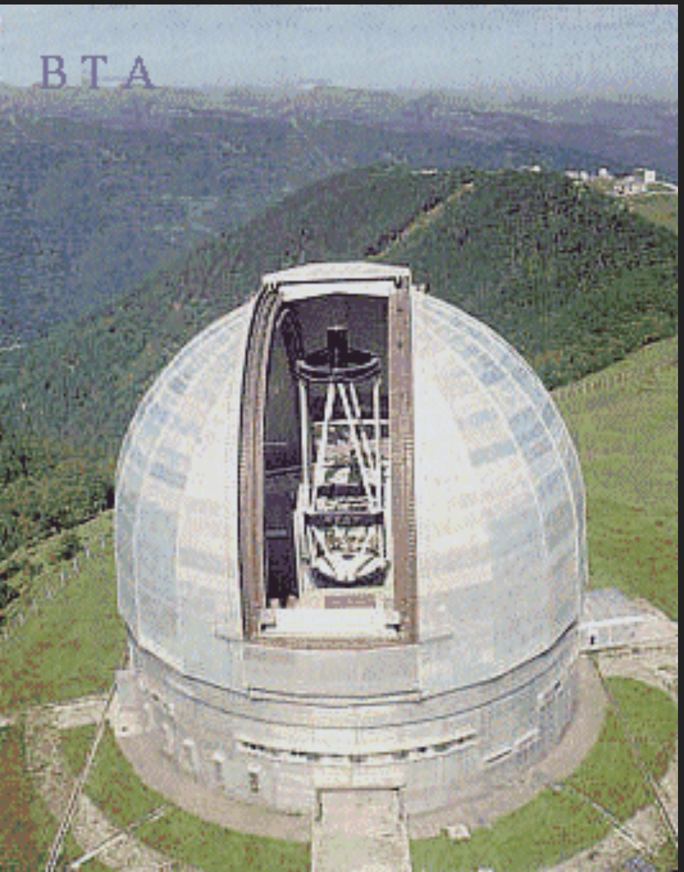
Compare to Linear Polarization Data

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

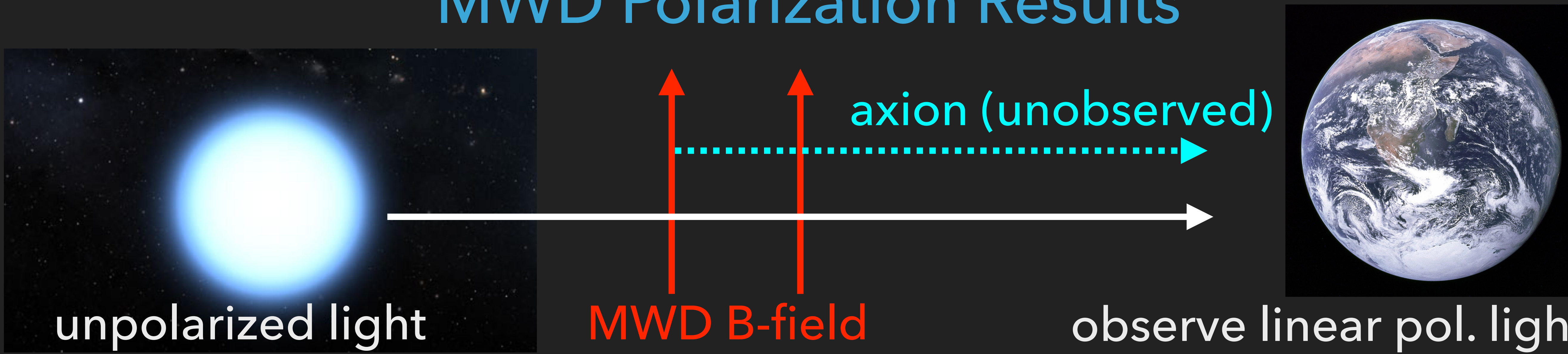


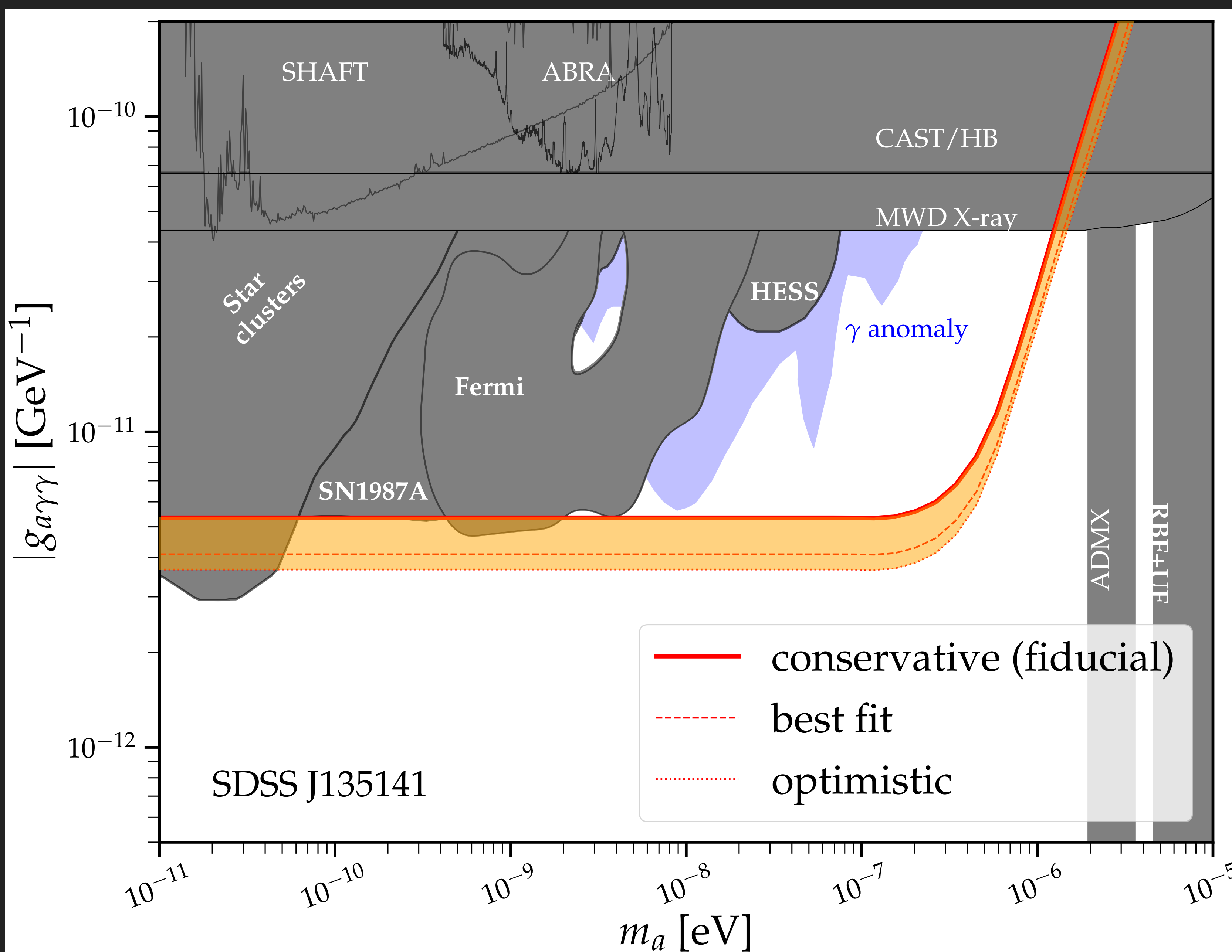


Astro model (arb norm) – we find no evidence

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

MWD Polarization Results





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

Zeeman shifts in bound-bound transitions

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

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

$P_L \lesssim 1\% \, (4000 - 6500 \, \AA)$

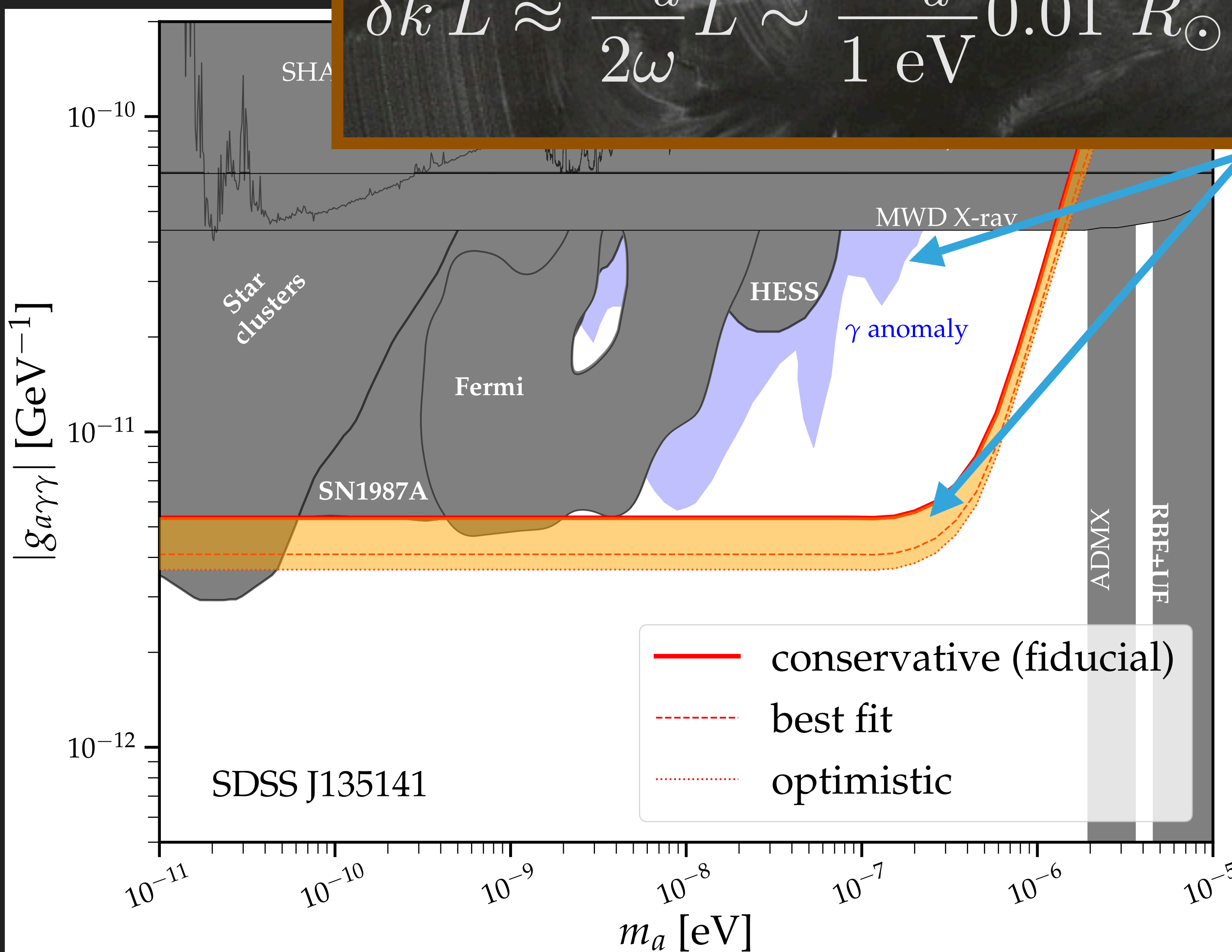
$d \sim 70 \, {\rm pc}$

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

MWD Polarization Results

mass dependence:
photon-axion dispersion relations

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

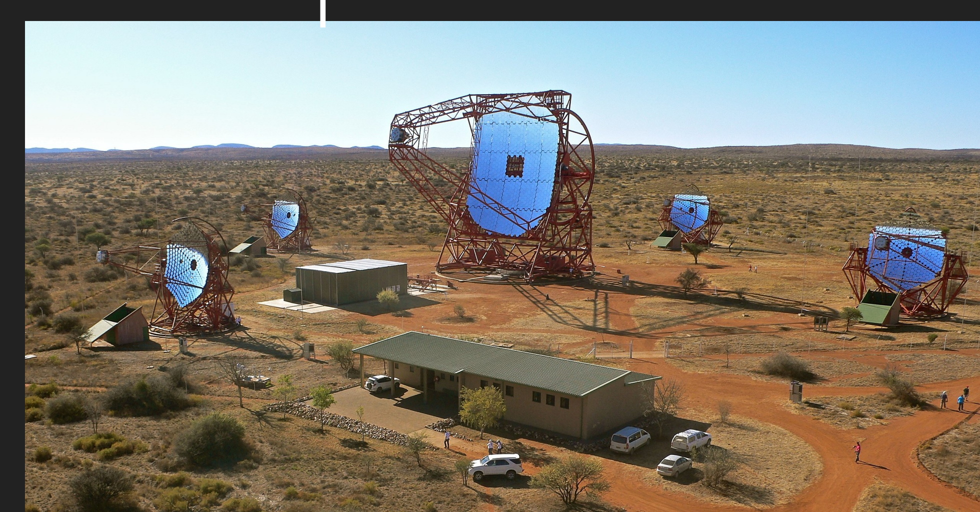


Meyer et al. 2013, +

AGN

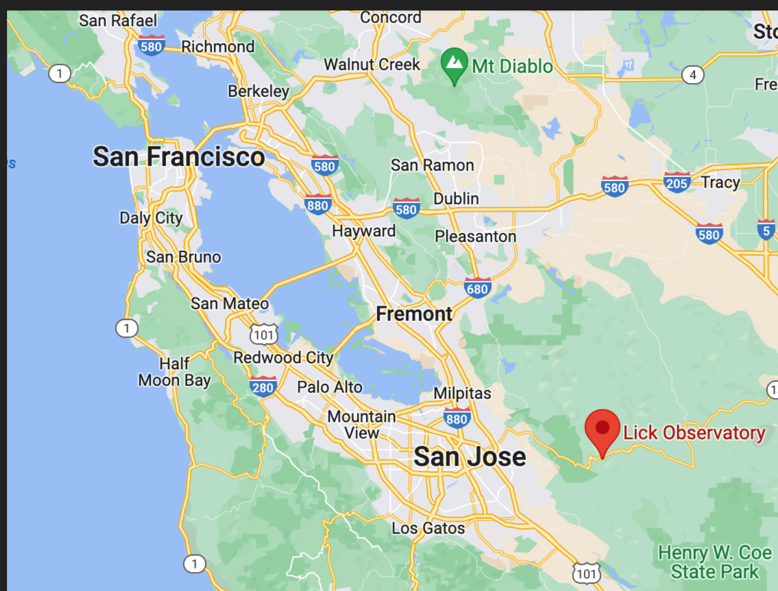
photons absorbed on EBL

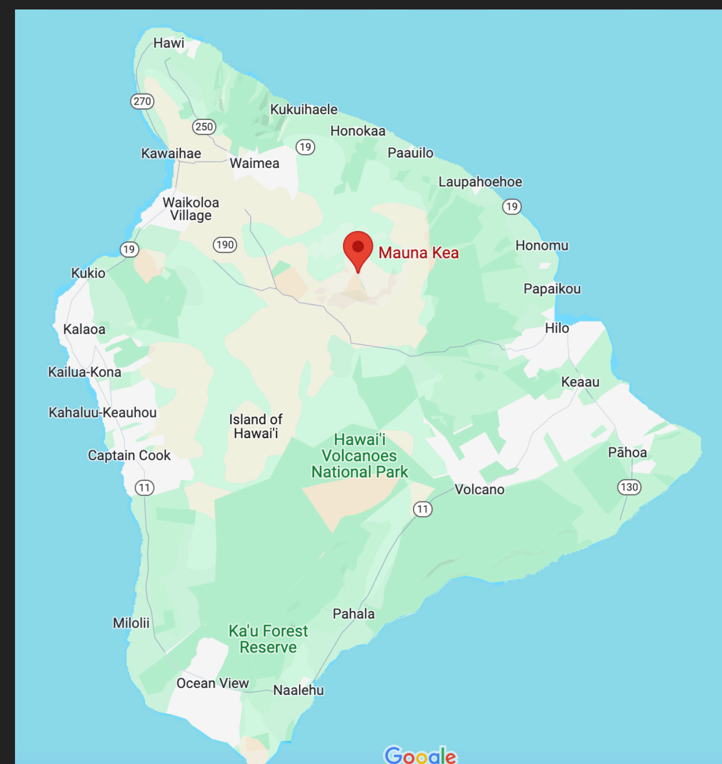
conversion to and back from axions increase prop length



MWD Polarization: Ongoing Work

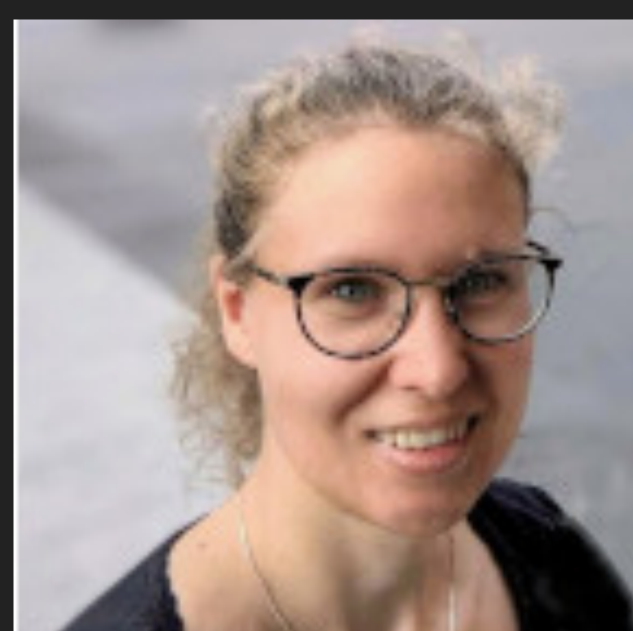
Dedicated observations: Shane telescope and Keck





Chris Dessert

Christiane Scherb



Josh Benabou

Alex Filippenko + group (astronomy)

Axions can "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]

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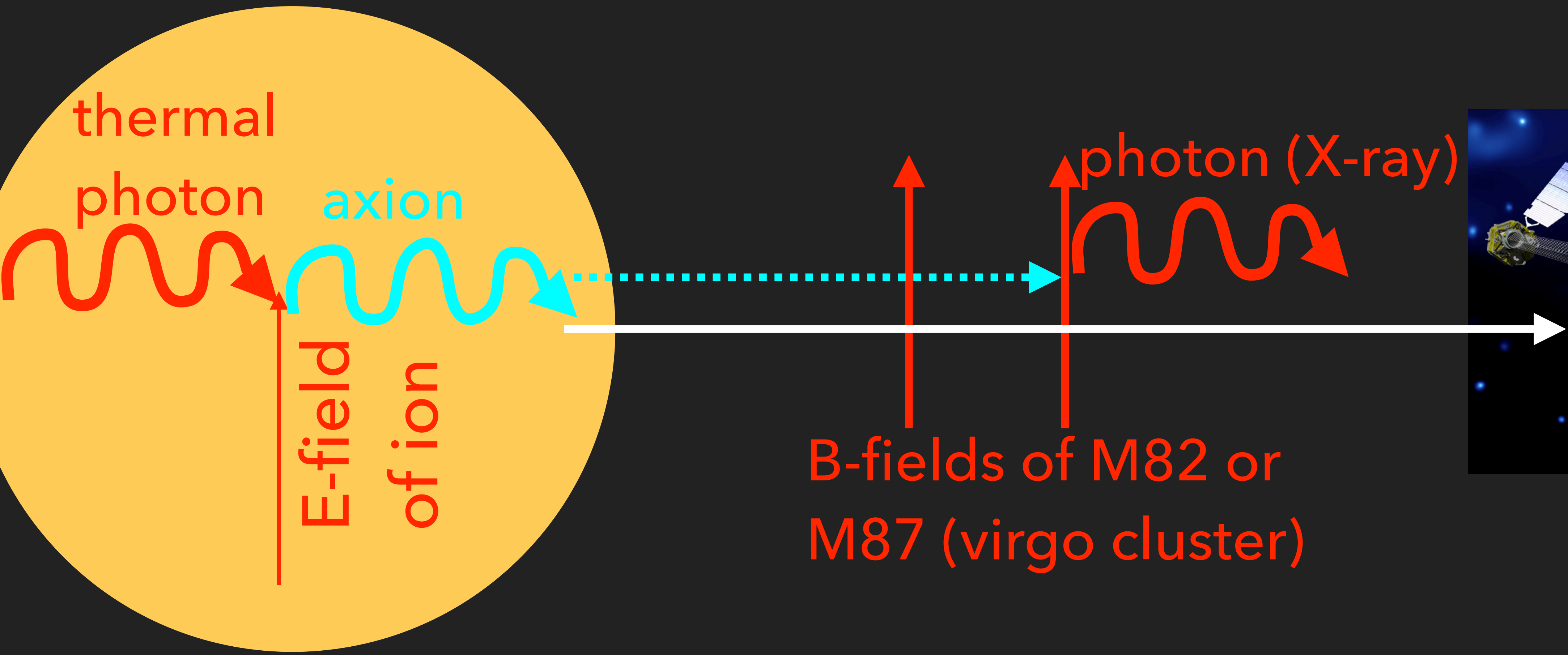
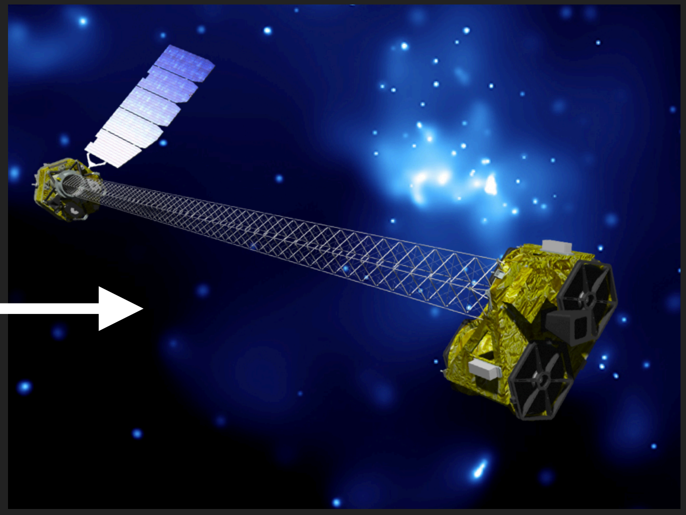
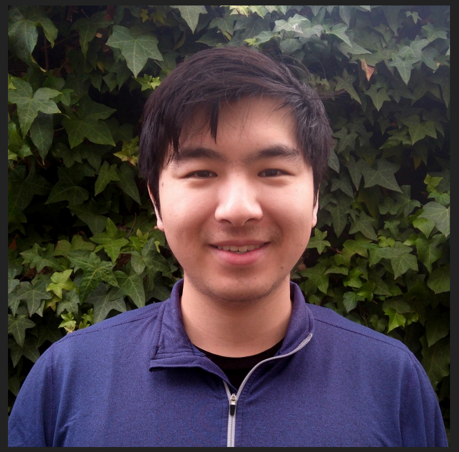
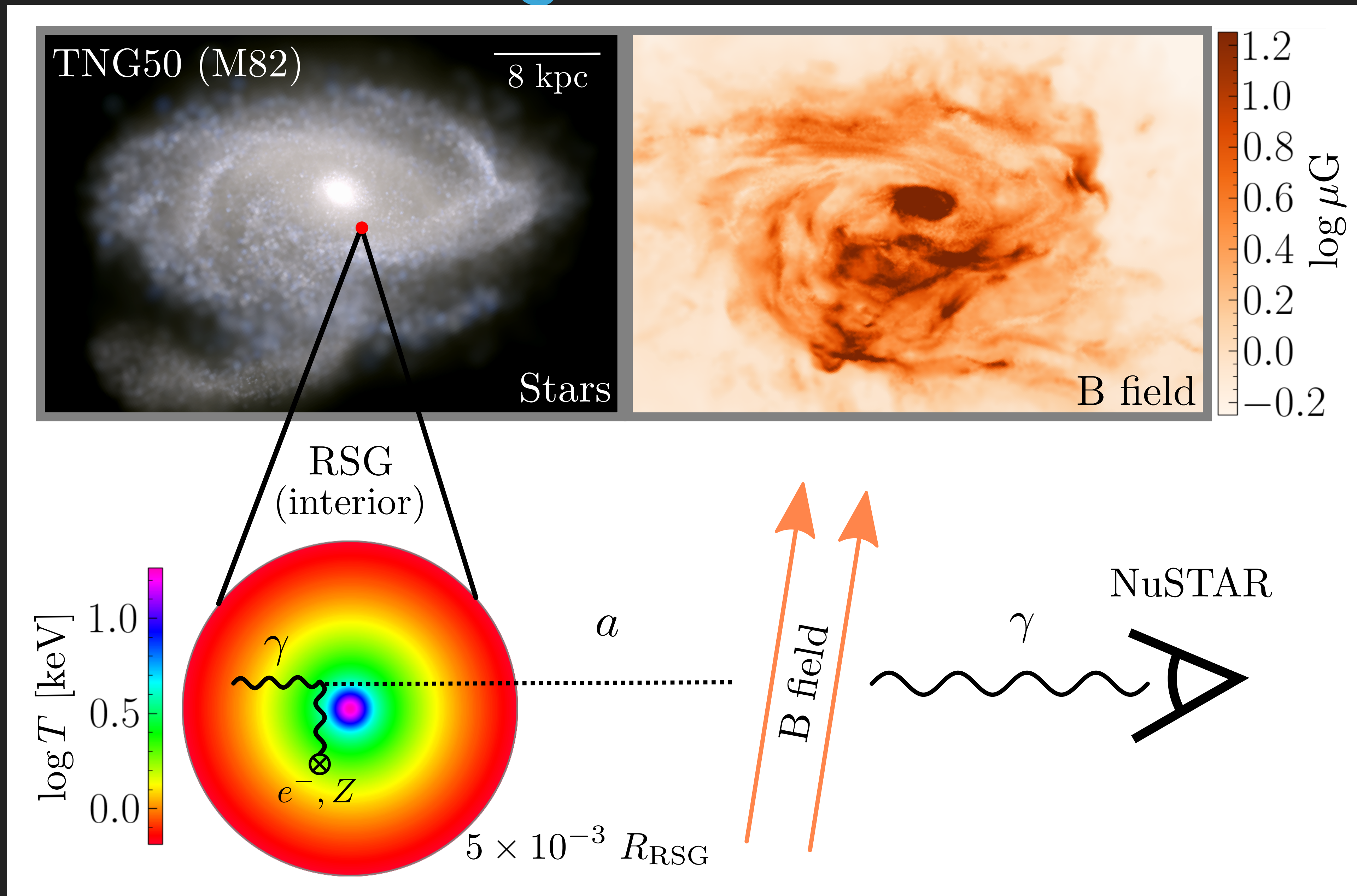




NuSTAR



Axion Signal in M82/M87



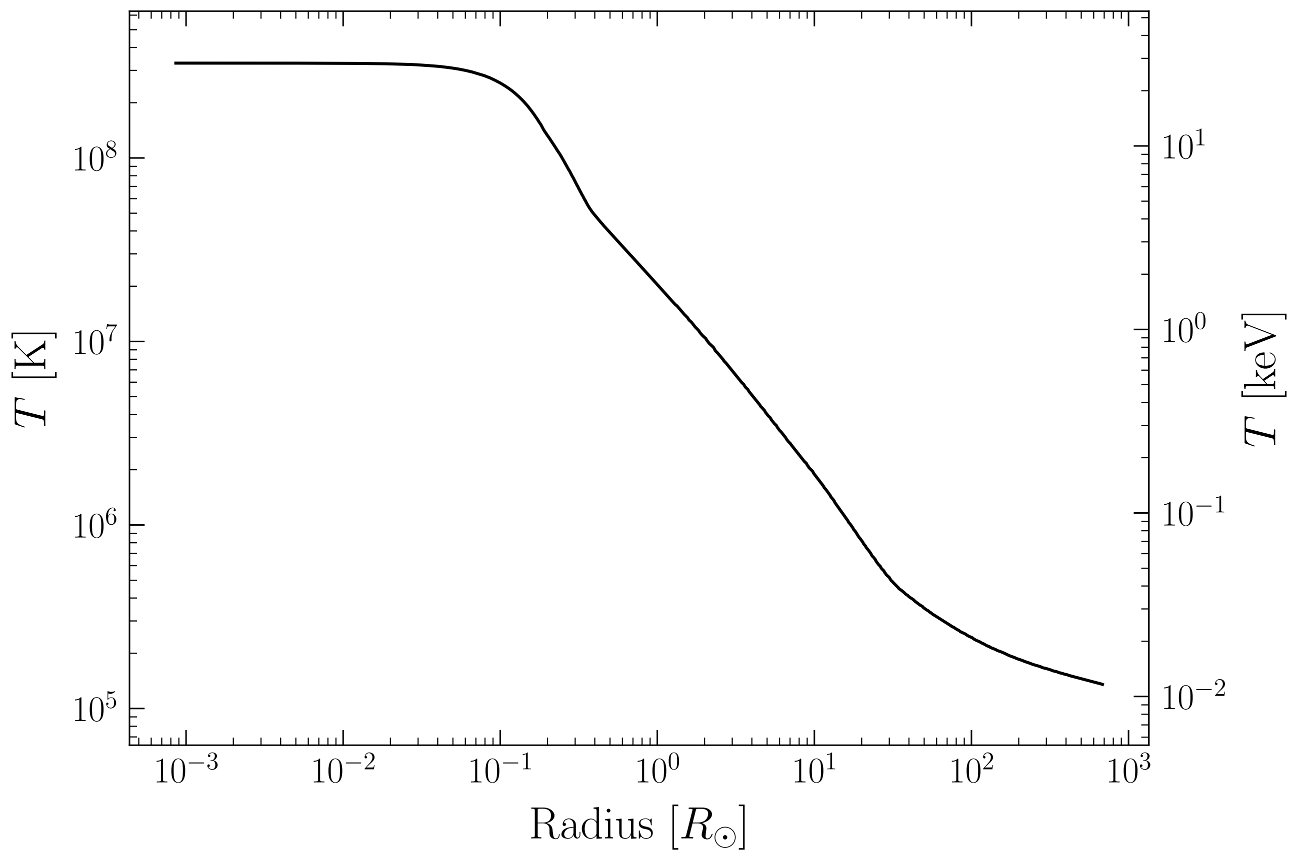
$$\frac{dL_a(E)}{dE} = \frac{g_{a\gamma\gamma}^2}{8\pi^2}\frac{\xi^2 T^3 E}{e^{E/T}-1}\sqrt{1-\frac{\omega_{\rm pl}^2}{E^2}}\left[(E^2+\xi^2T^2)\log\left(1+\frac{E^2}{\xi^2T^2}\right)-E^2\right]$$

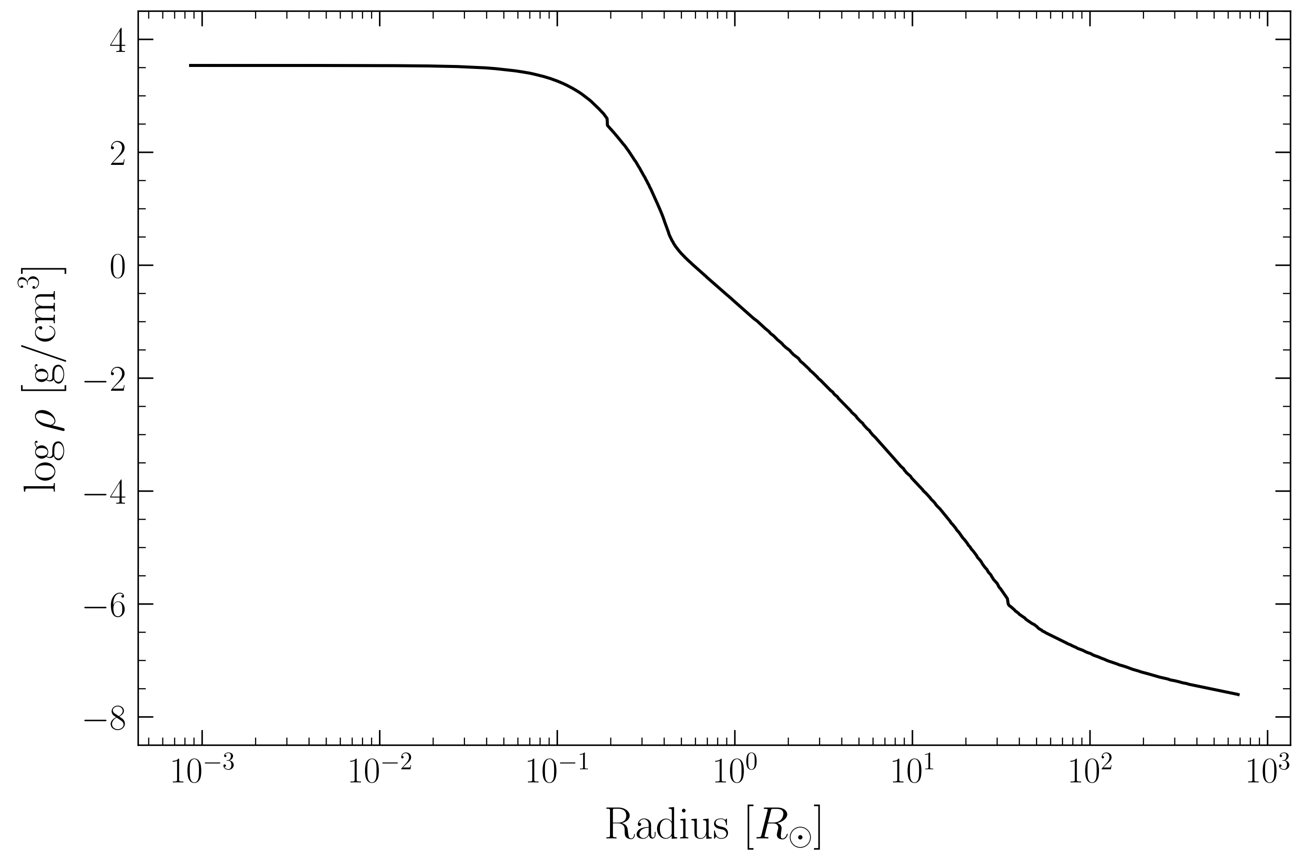
$$\xi = \kappa/(2T)$$

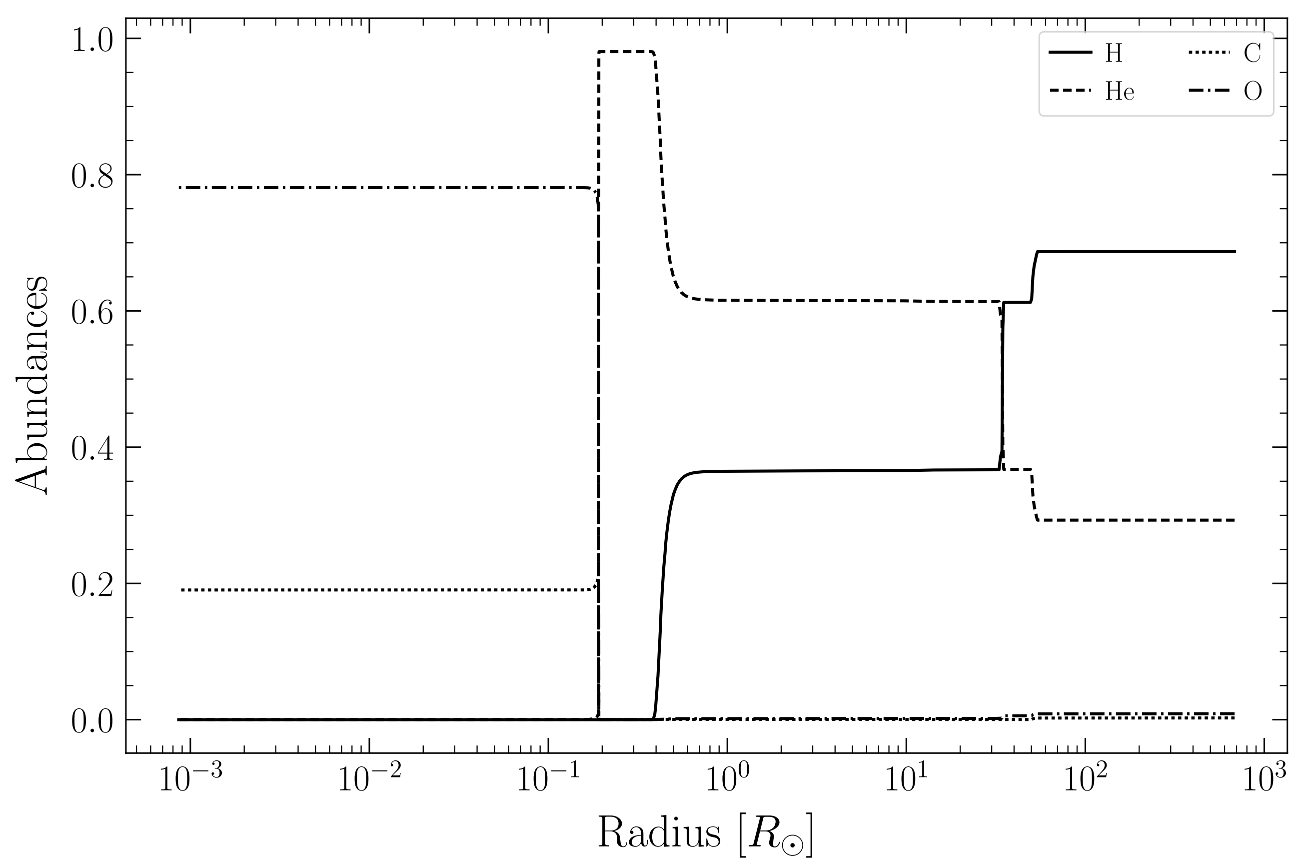
κ : Debye Screening Scale

Run MESA over Initial Stellar Mass Function

Example 20 Solar Mass star in RSG phase







MESA

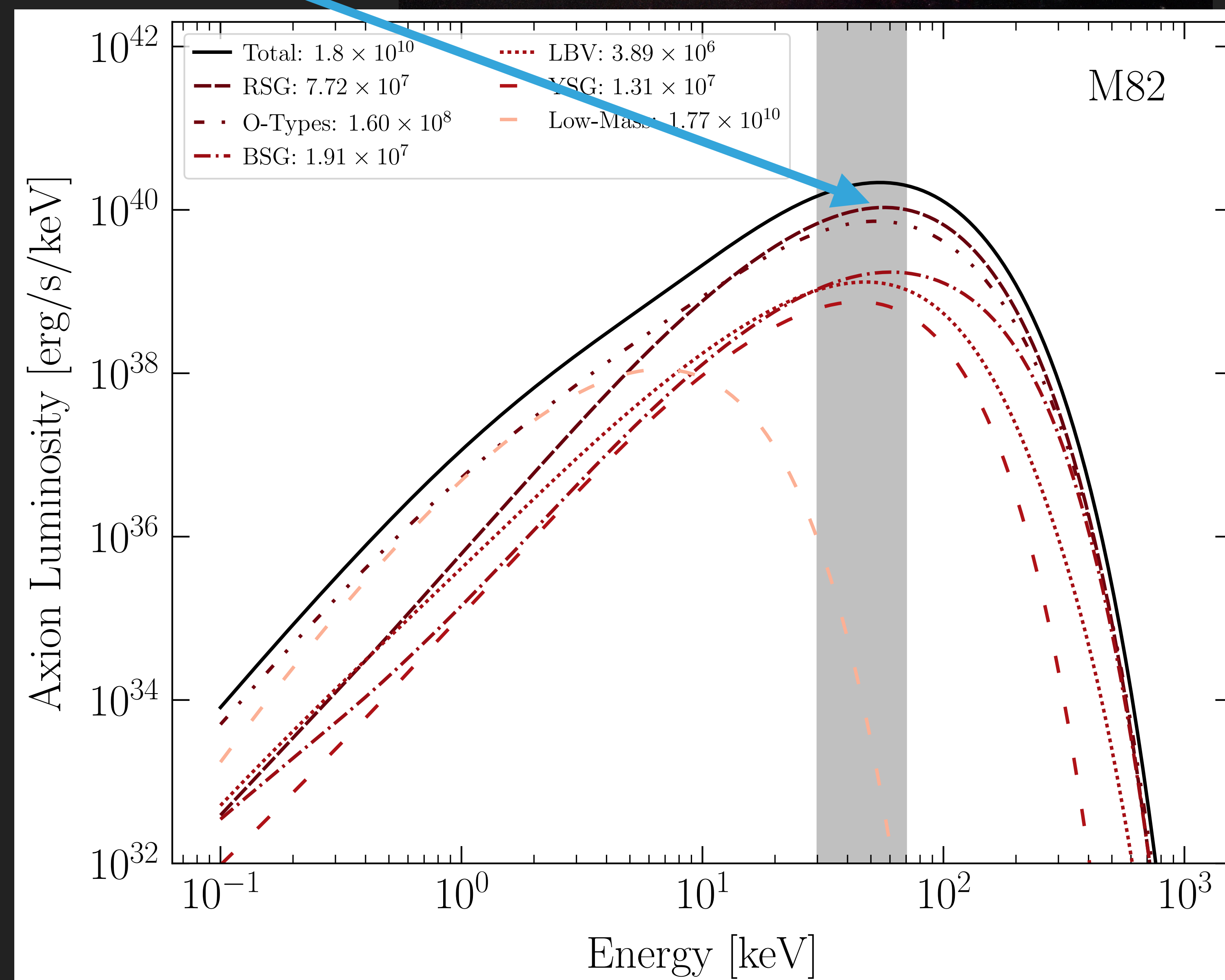
release/r24.03.1

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

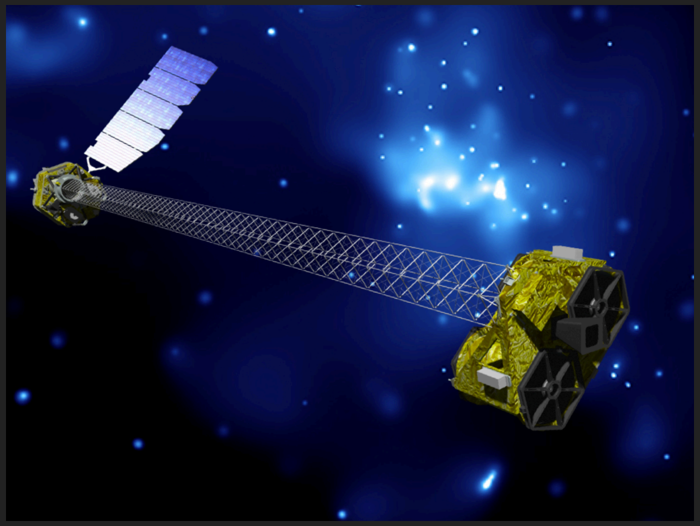
Axion luminosity dominated by RSG and O-type stars

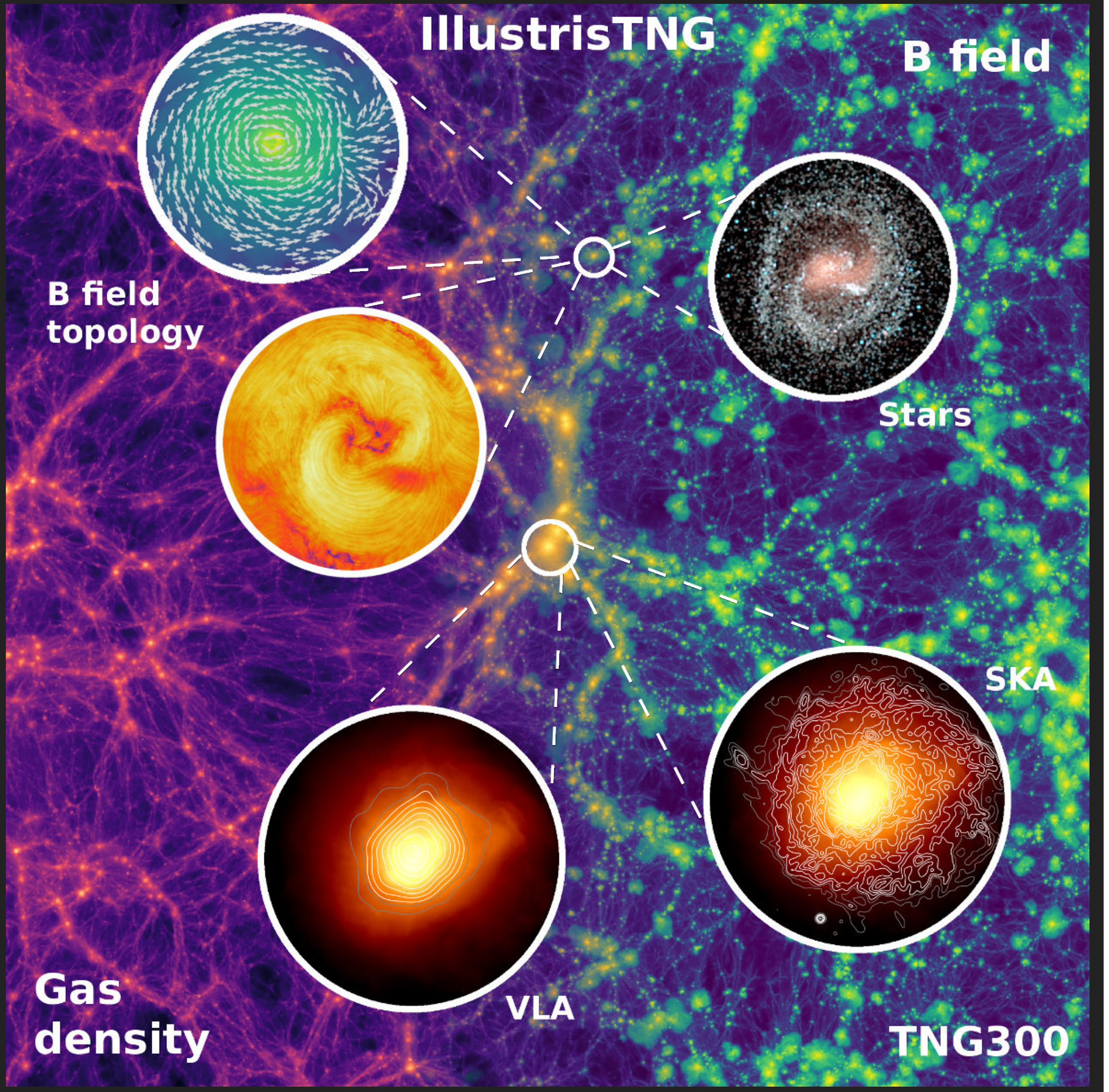


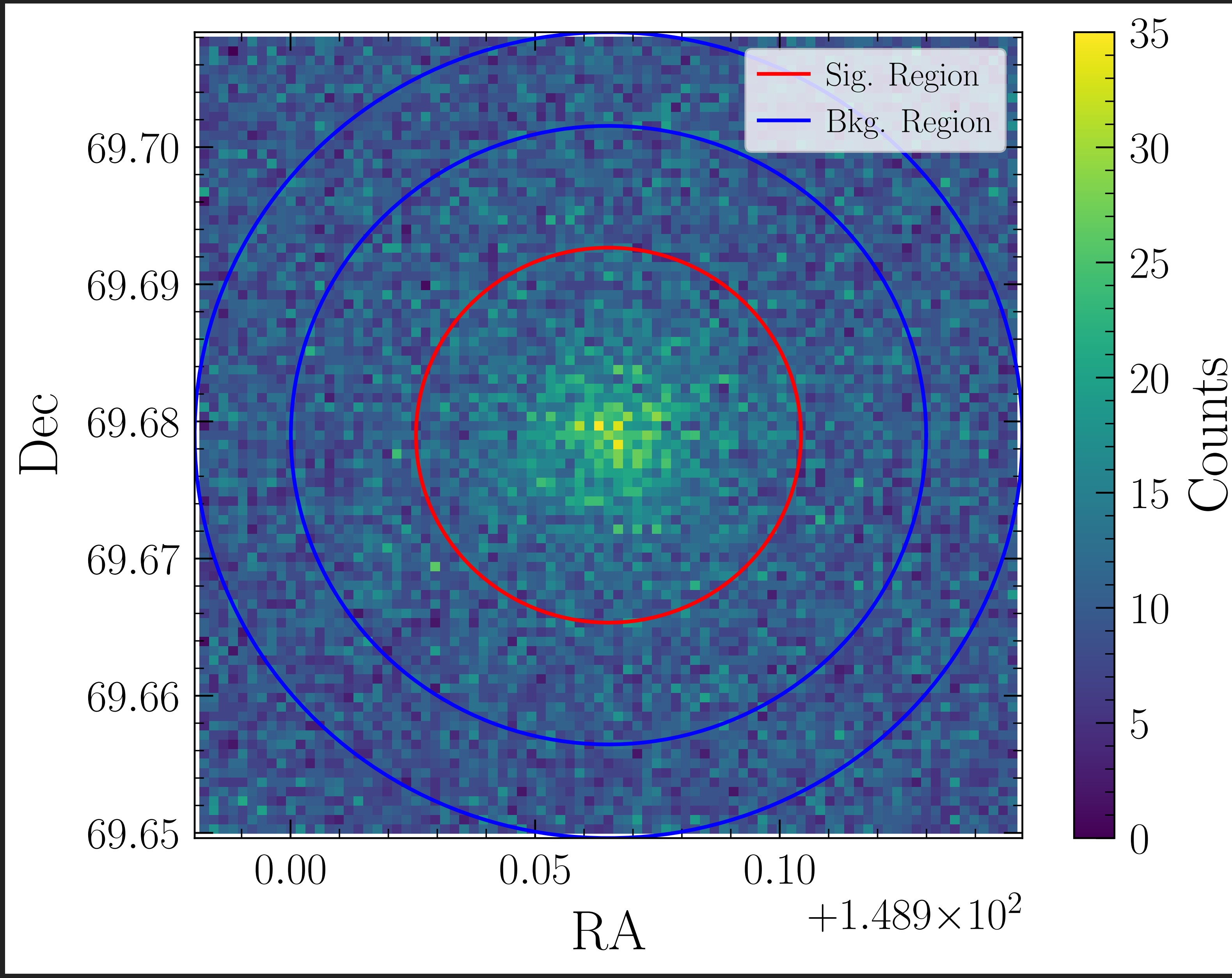
NuSTAR axion search – M82

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



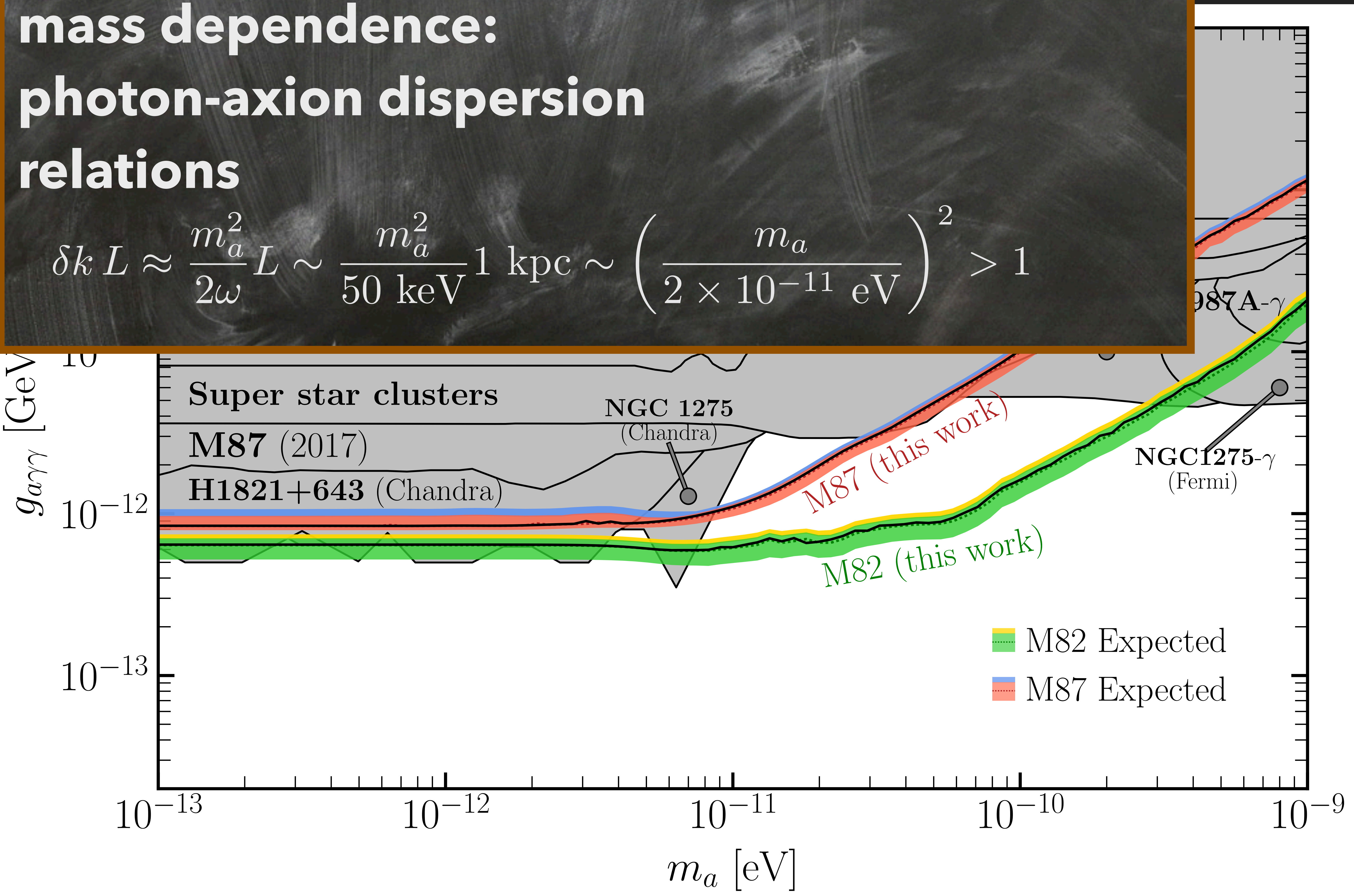




Leading Upper Limits from M82/M87

mass dependence: photon-axion dispersion relations

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



Extending reach to higher axion masses: higher energies, smaller length scales

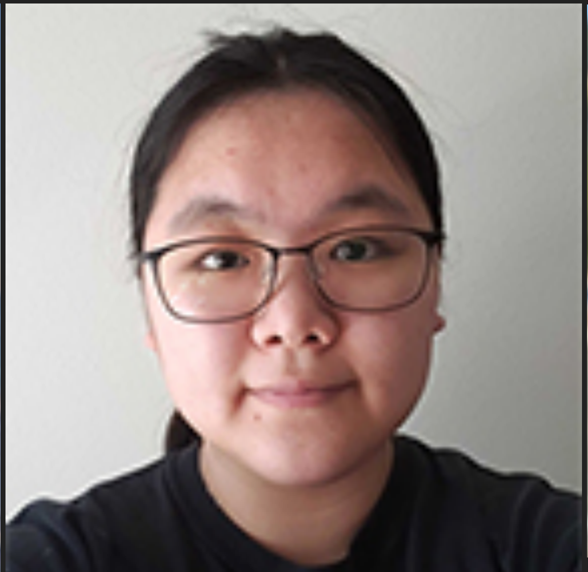
Supernova axions convert to gamma-rays in magnetic fields of progenitor stars

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

Yujin

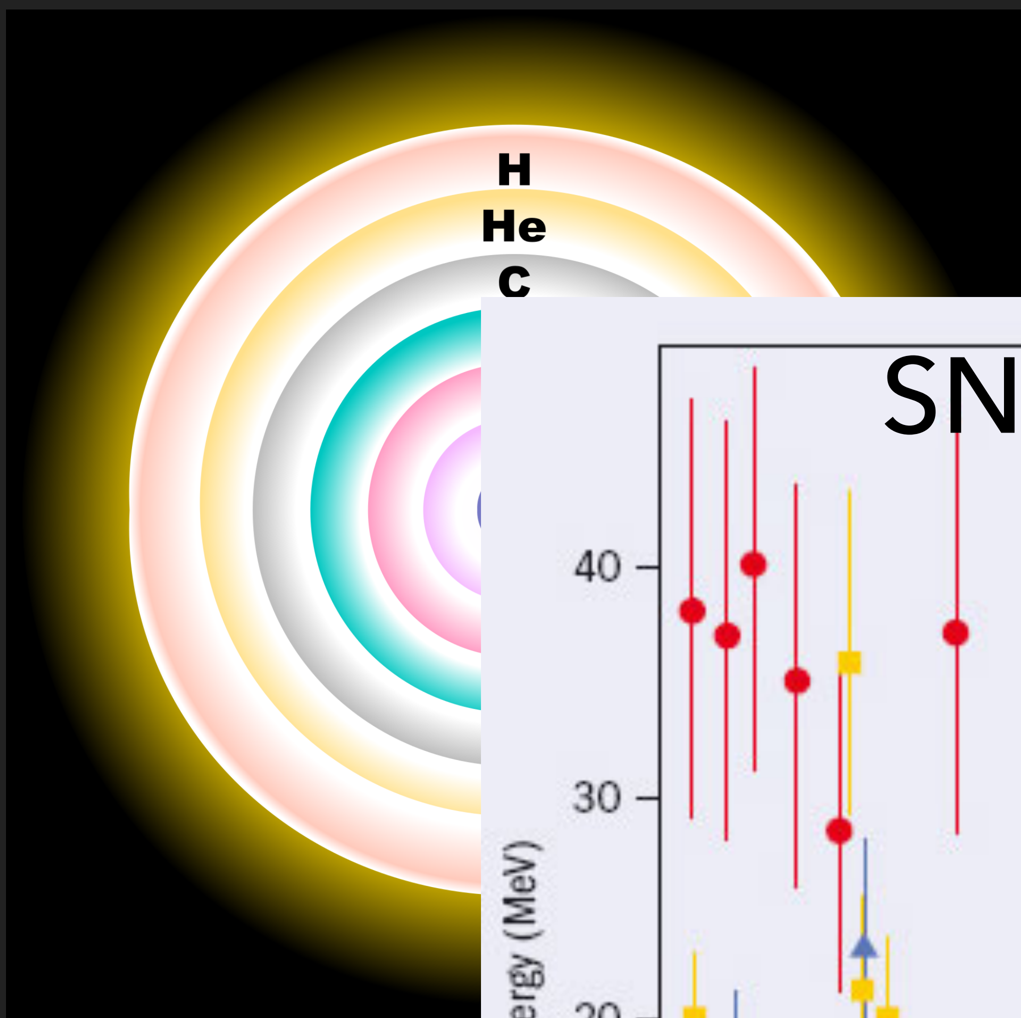


Inbar

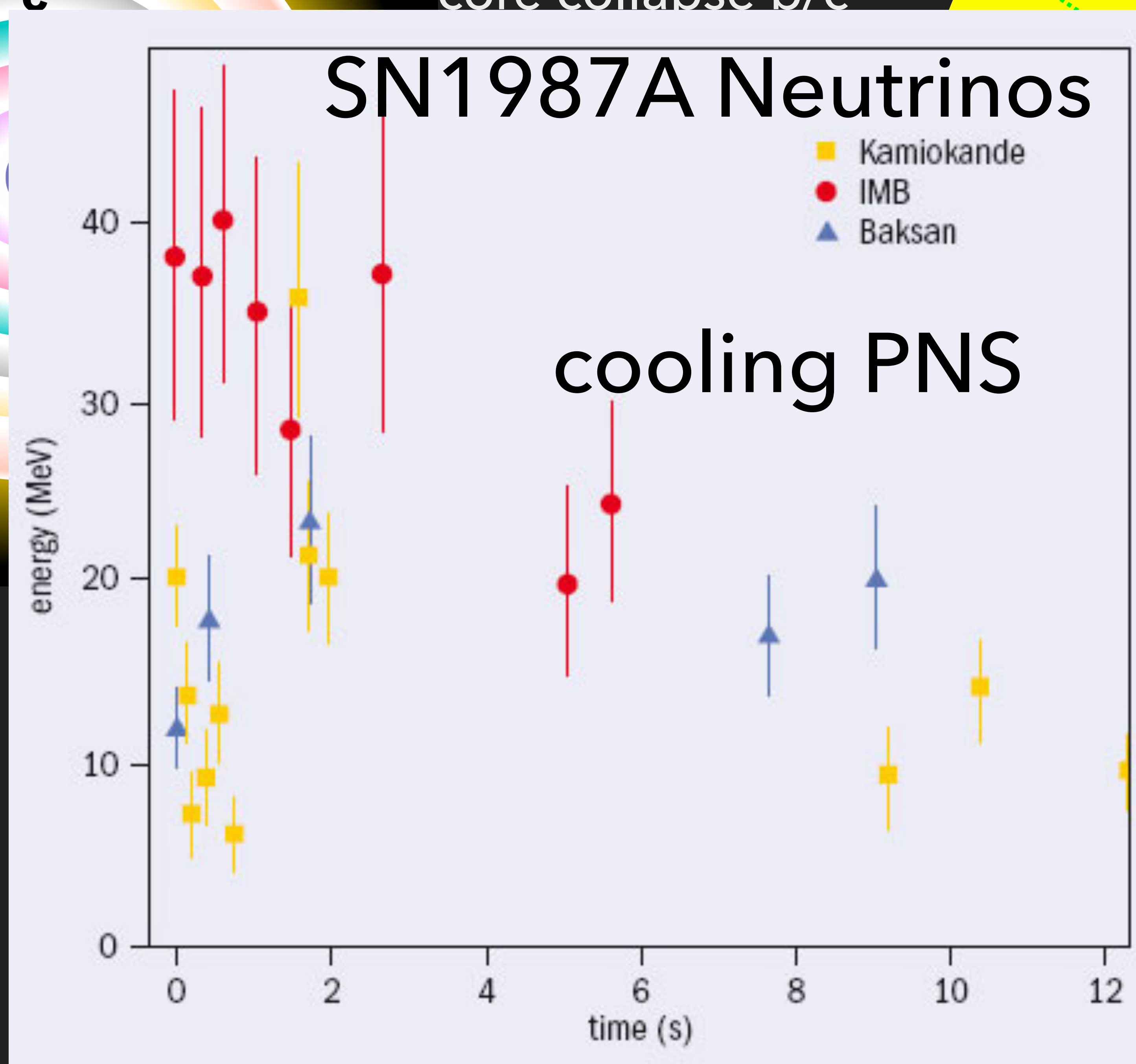
Neutrinos produced from cooling proto-NS in SN1987A

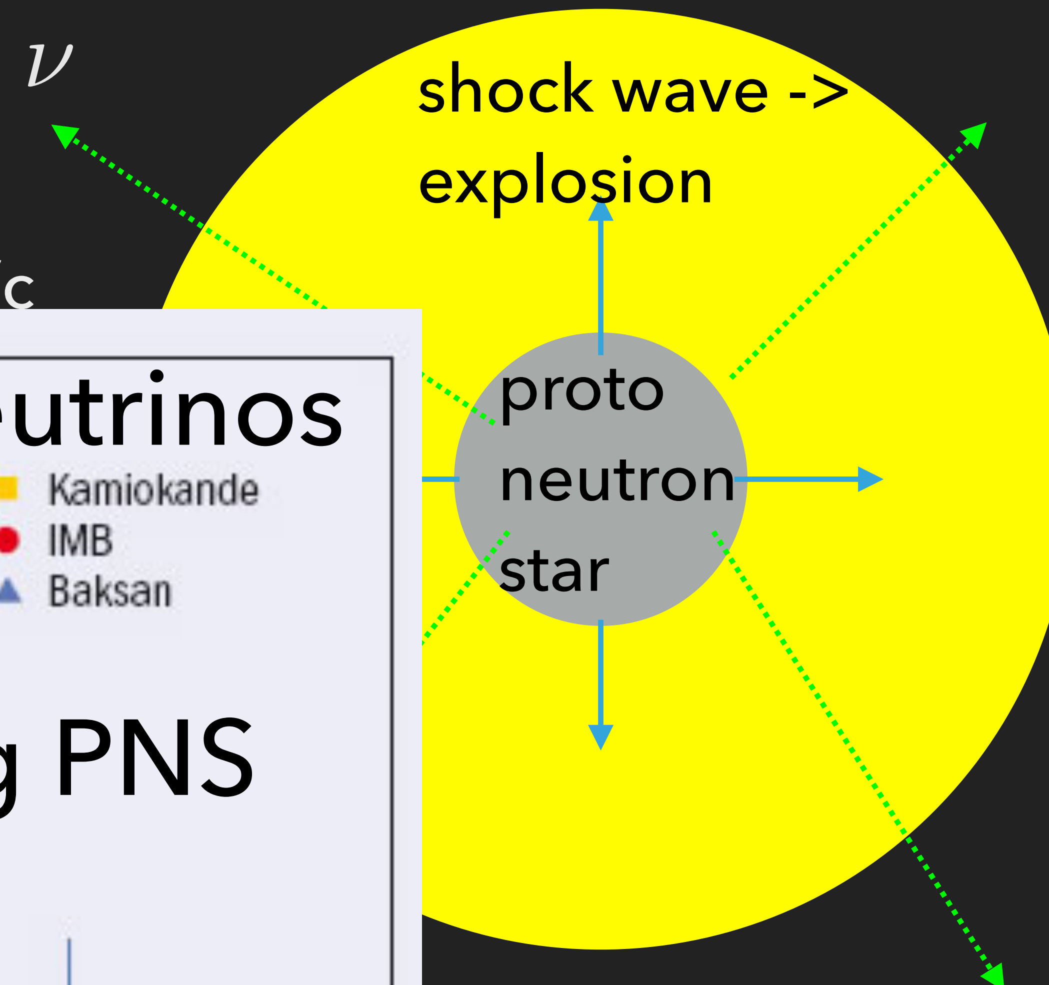
Type II supernova

neutrinos escape (and heat) –> SN1987A neutrino signal

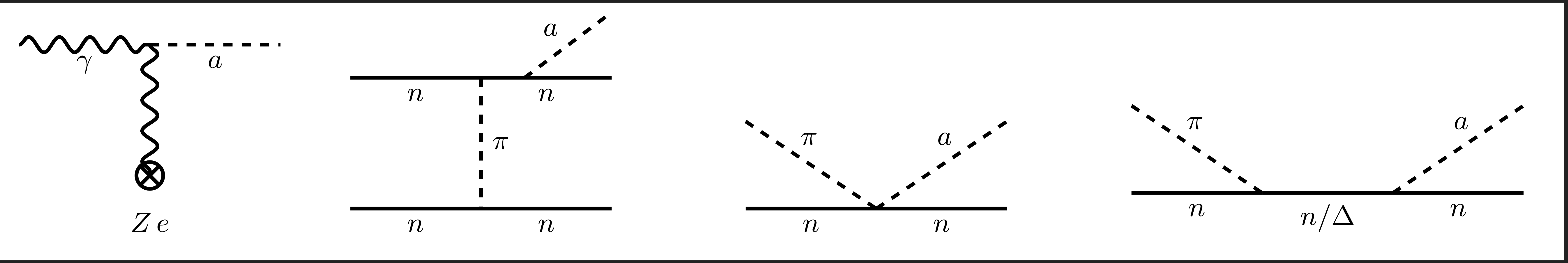


core collapse b/c





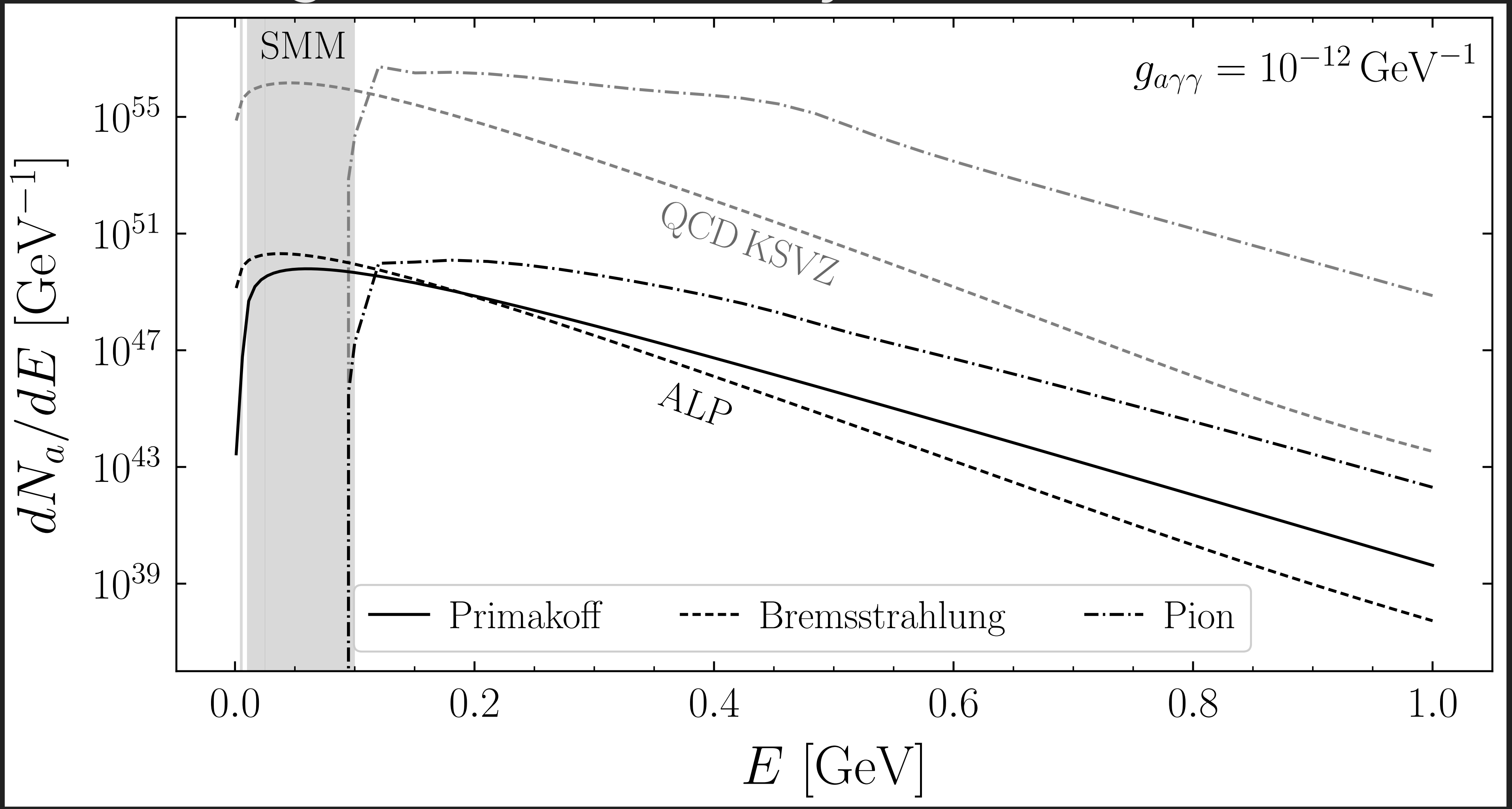
Proto Neutron Stars from SN also produce axions



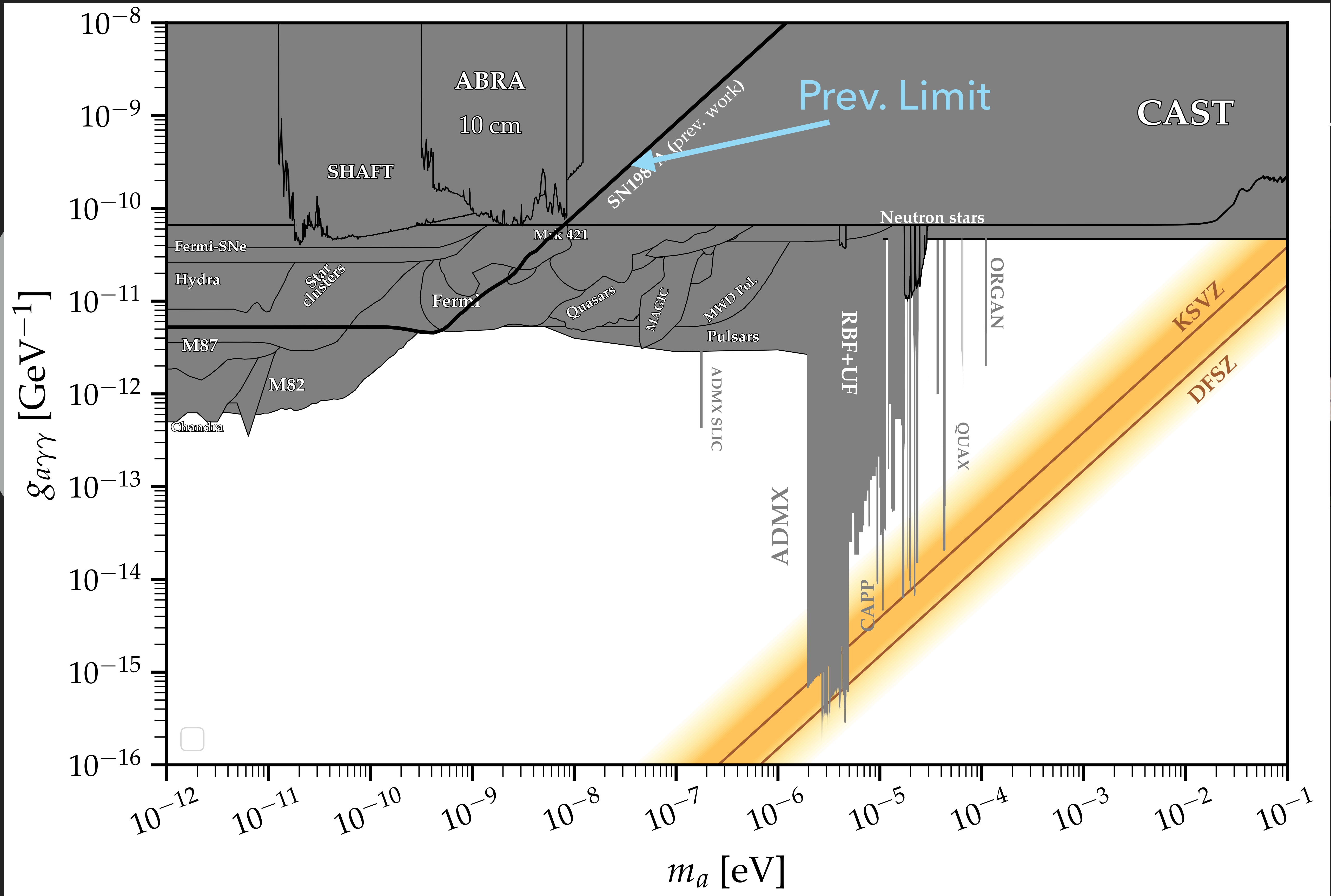
(Loop-induced production from nucleons important for ALPs)

(SN simulations from the Garching core-collapse supernova archive)

Average axion luminosity over 10 s (this work)



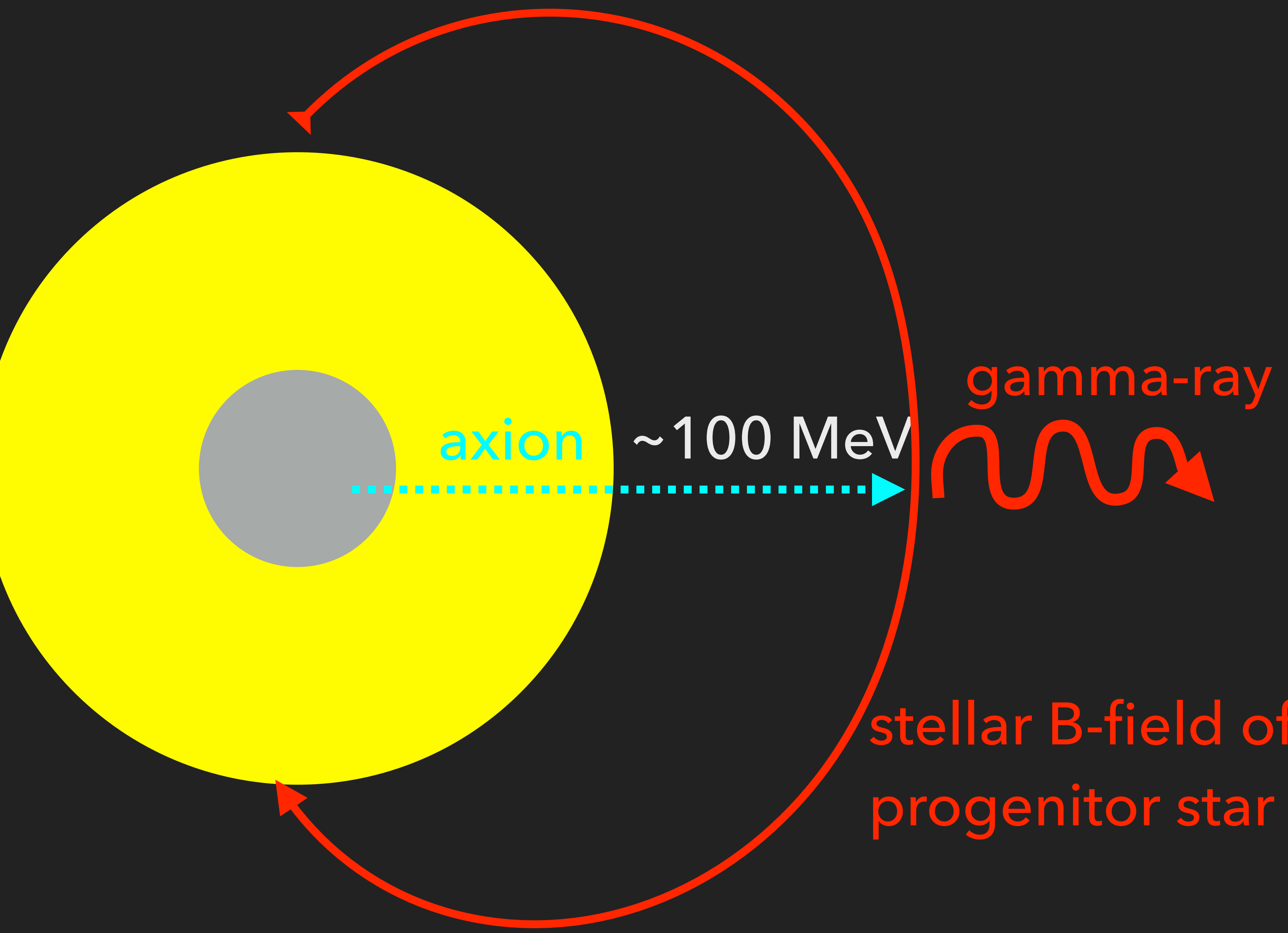
Old idea: SN axions convert to gamma-rays in Galactic fields



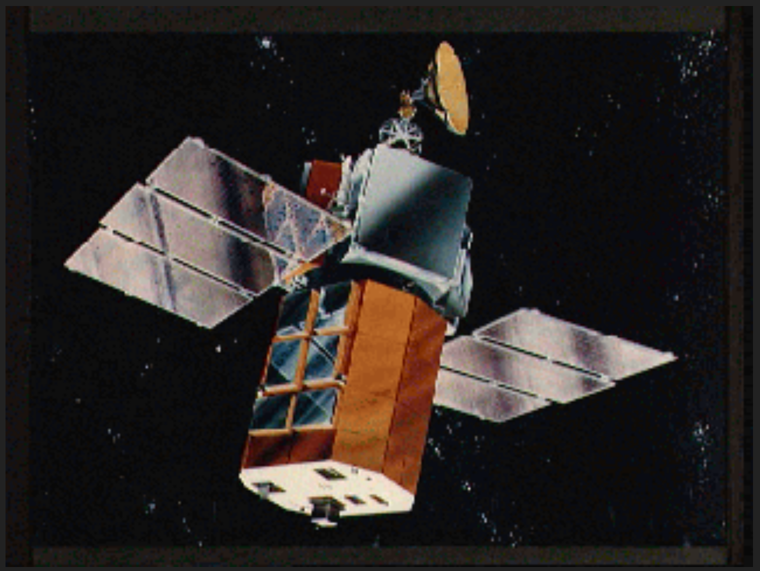
New Idea: gamma-rays from SN1987A progenitor B-field

New proposal! Convert on progenitor stellar magnetic field

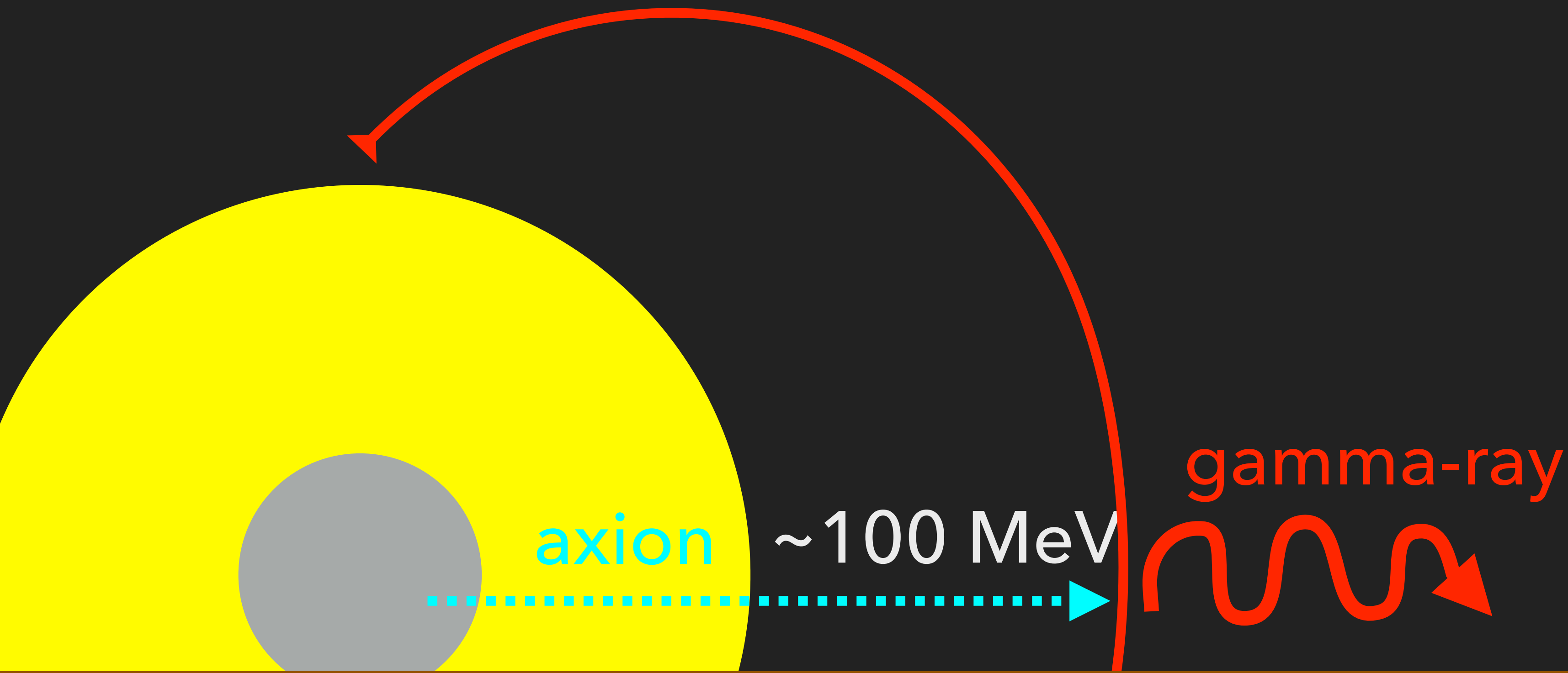
SN1987A: in the LMC at d ~ 50 Mpc



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:

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

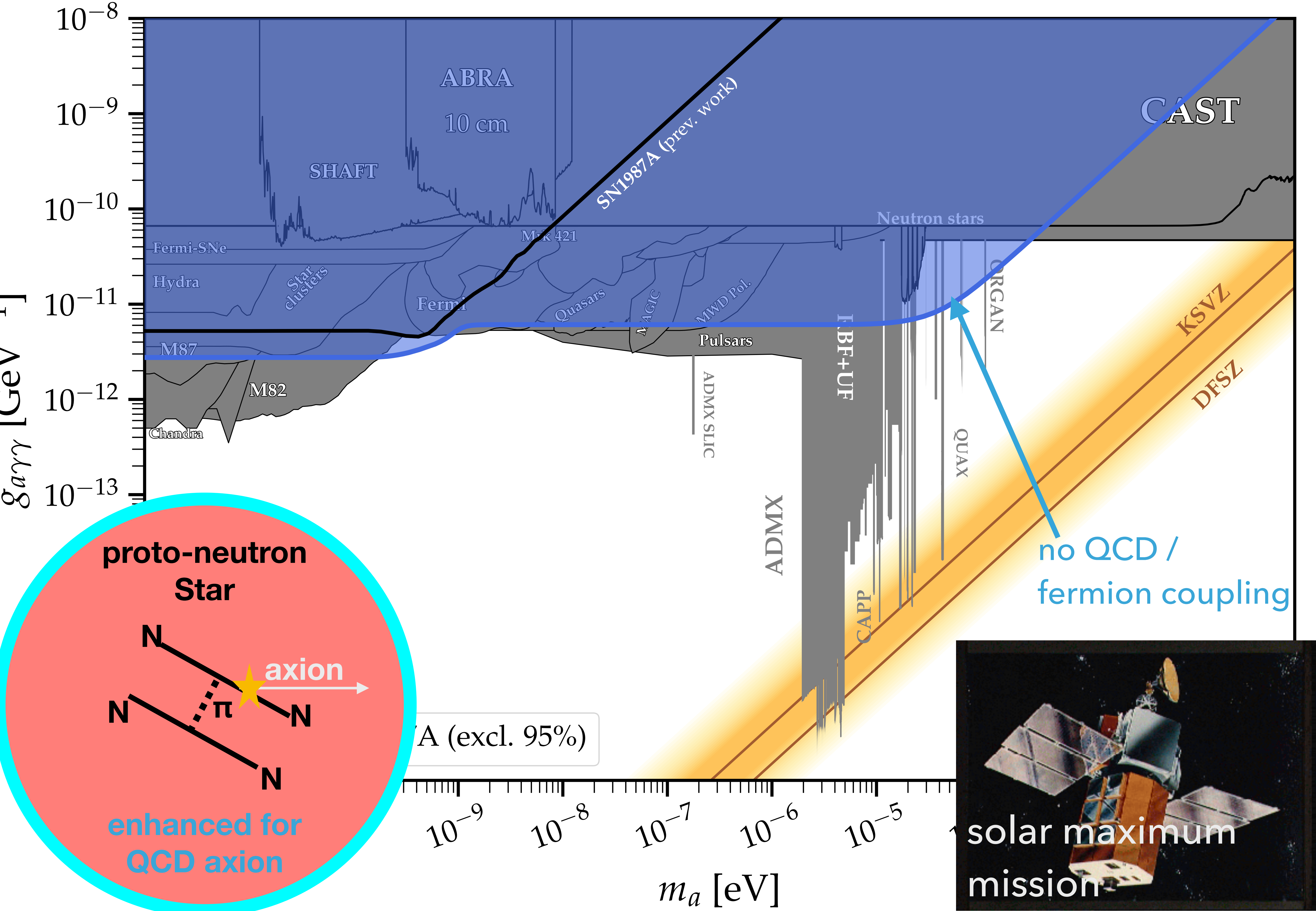
$$\sim 10^{-5} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}} \right)^2$$

Matches Galactic conversion prob.!

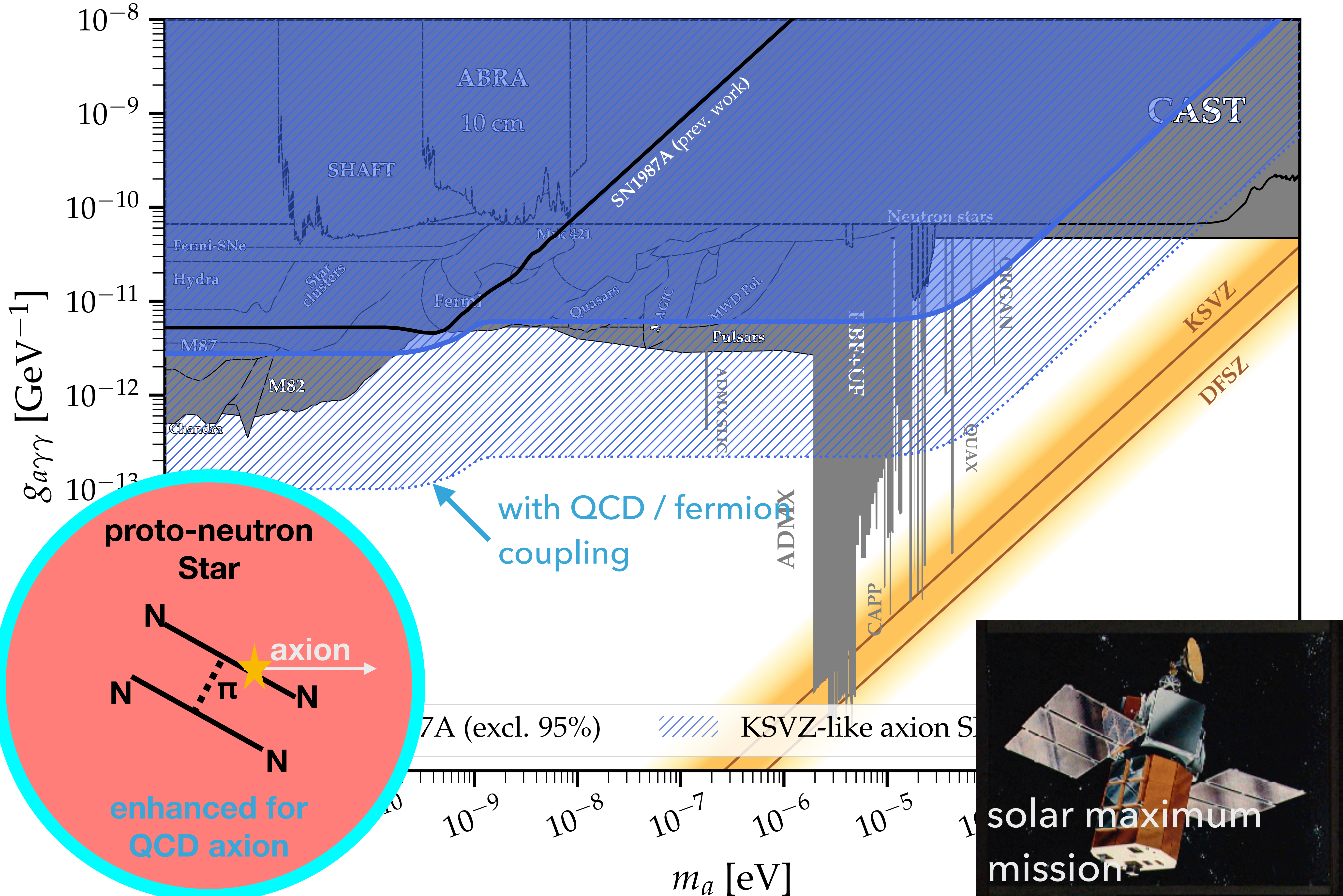
when does mass-dependence come in?

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

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!

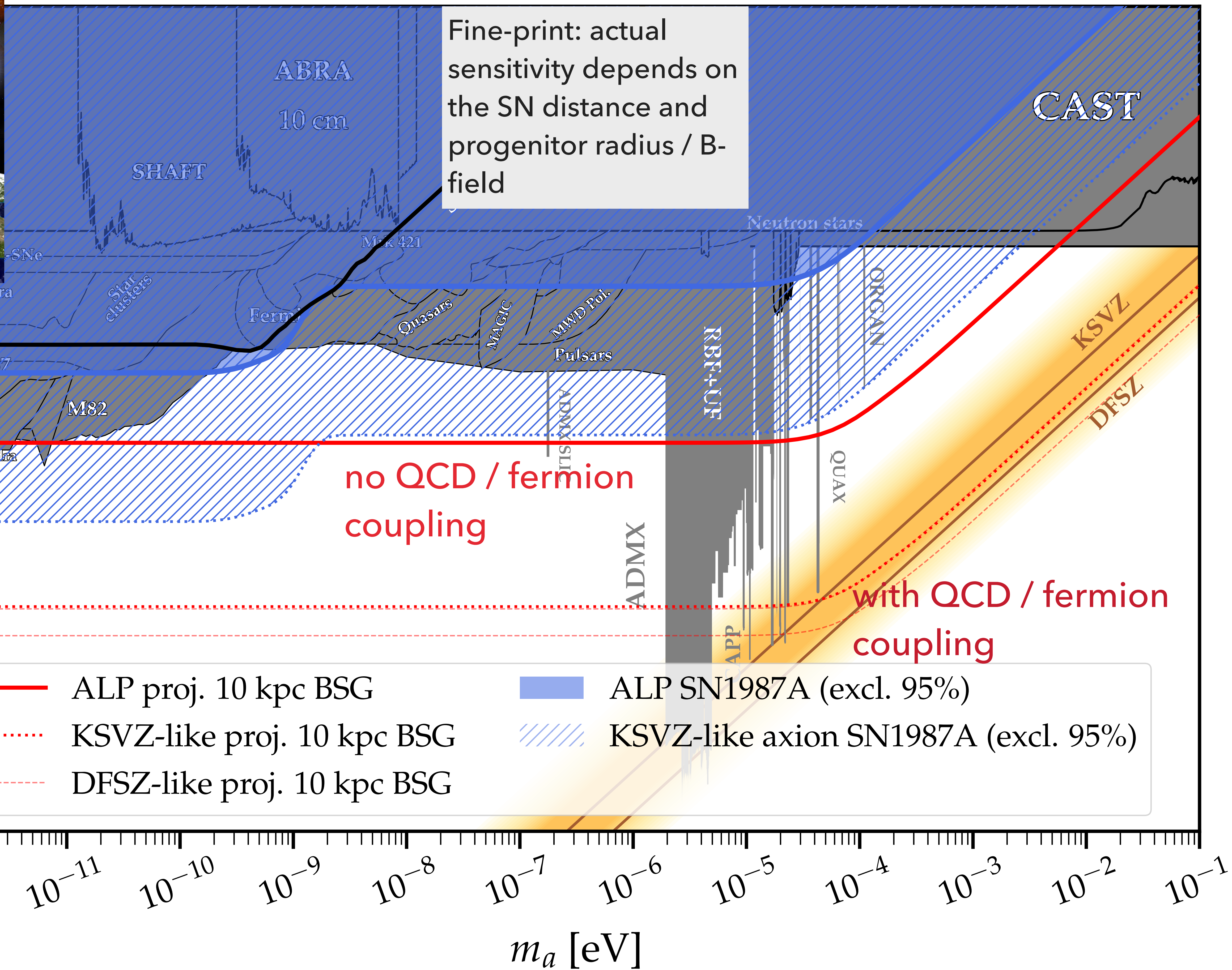
Chance of Fermi-LAT seeing next SN is ~1 in 10

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

Future supernova

But what if Fermi did catch the next Galactic SN?

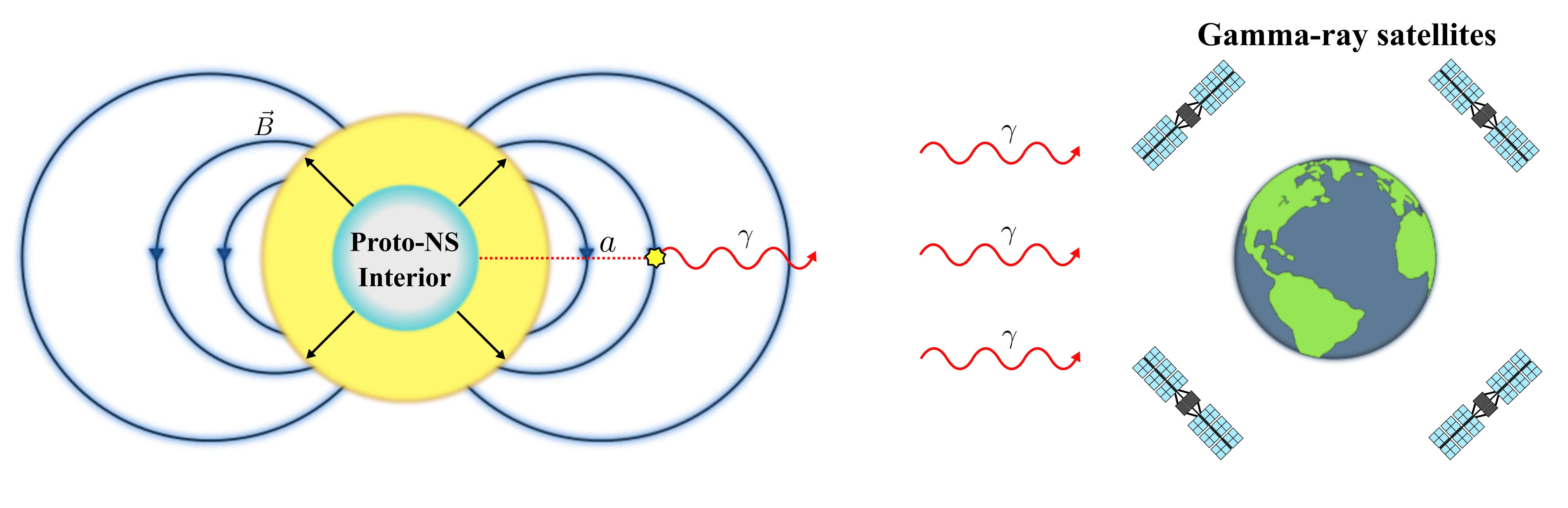
Future supernova: axion signal with Fermi-LAT



Future supernova

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

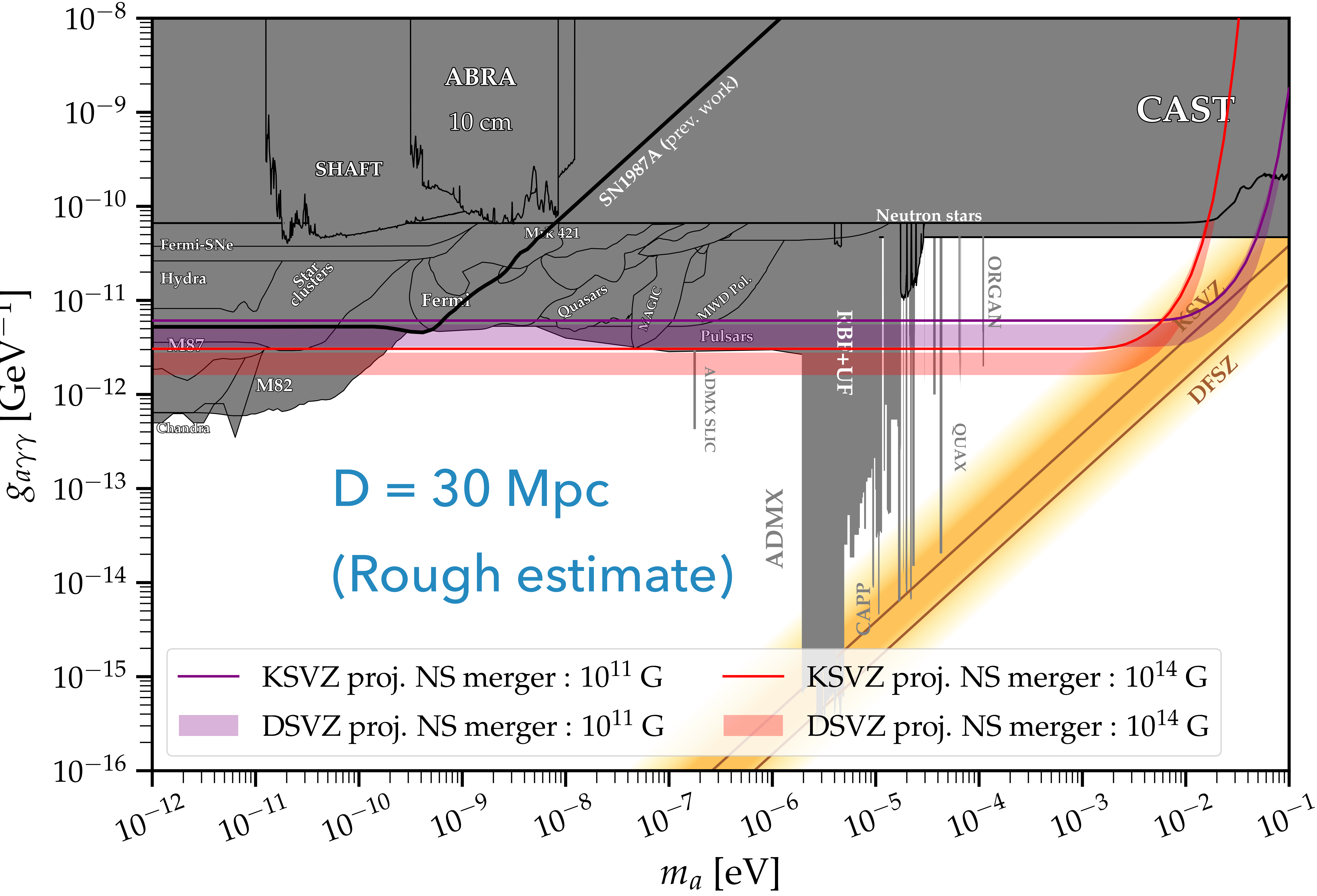
Proposal: Full-Sky constellation of SmallSats for continuous, full-sky ~100 - 500 MeV gamma-ray detection



GALactic AXion Instrument for Supernova (GALAXIS)

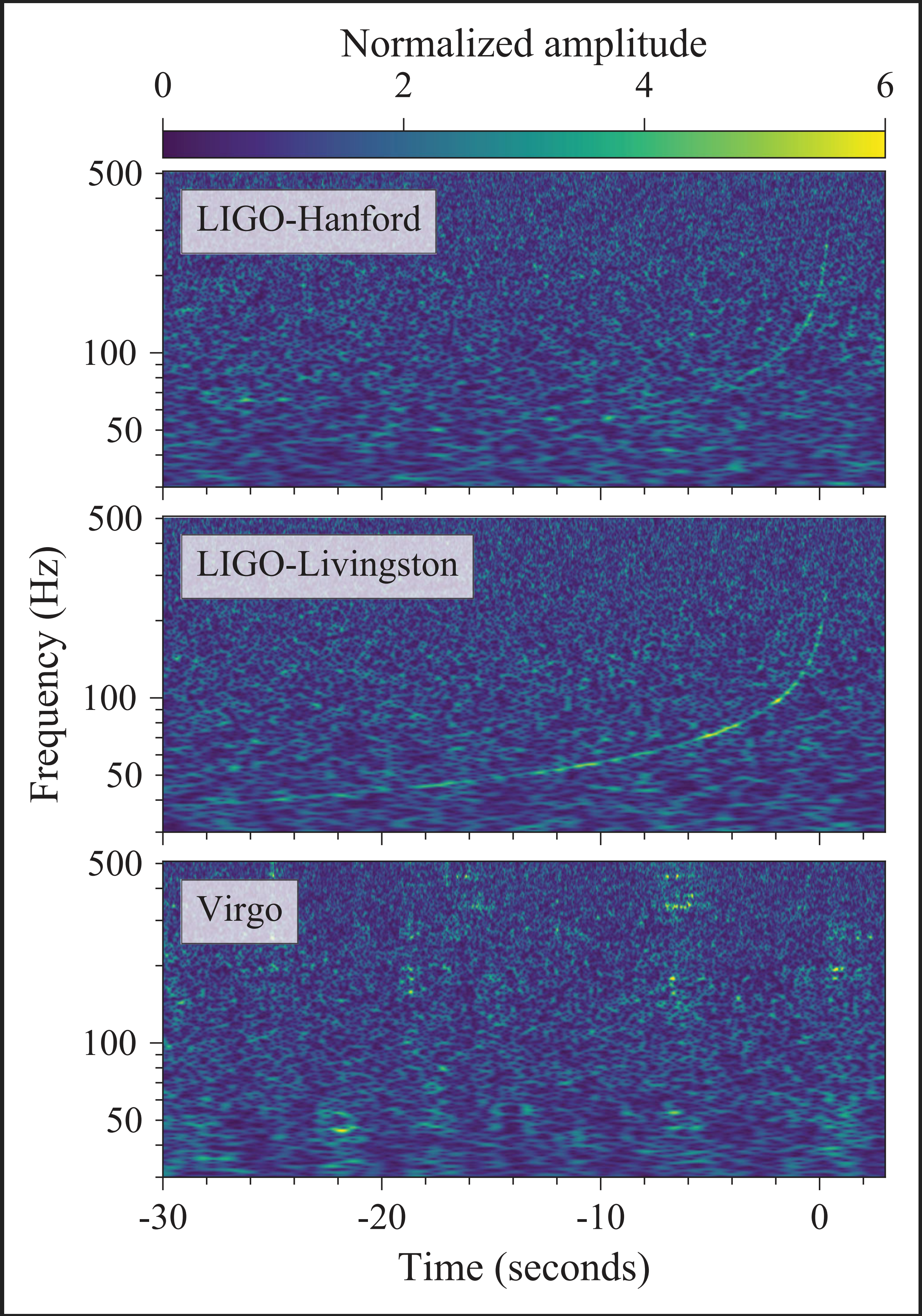
Also ~annual axion science from extragalactic SN and NS-NS mergers

Axions from NS-NS mergers may produce gamma rays



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

Fermi missed it!



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

QUESTIONS?

ALFRED P. SLOAN FOUNDATION

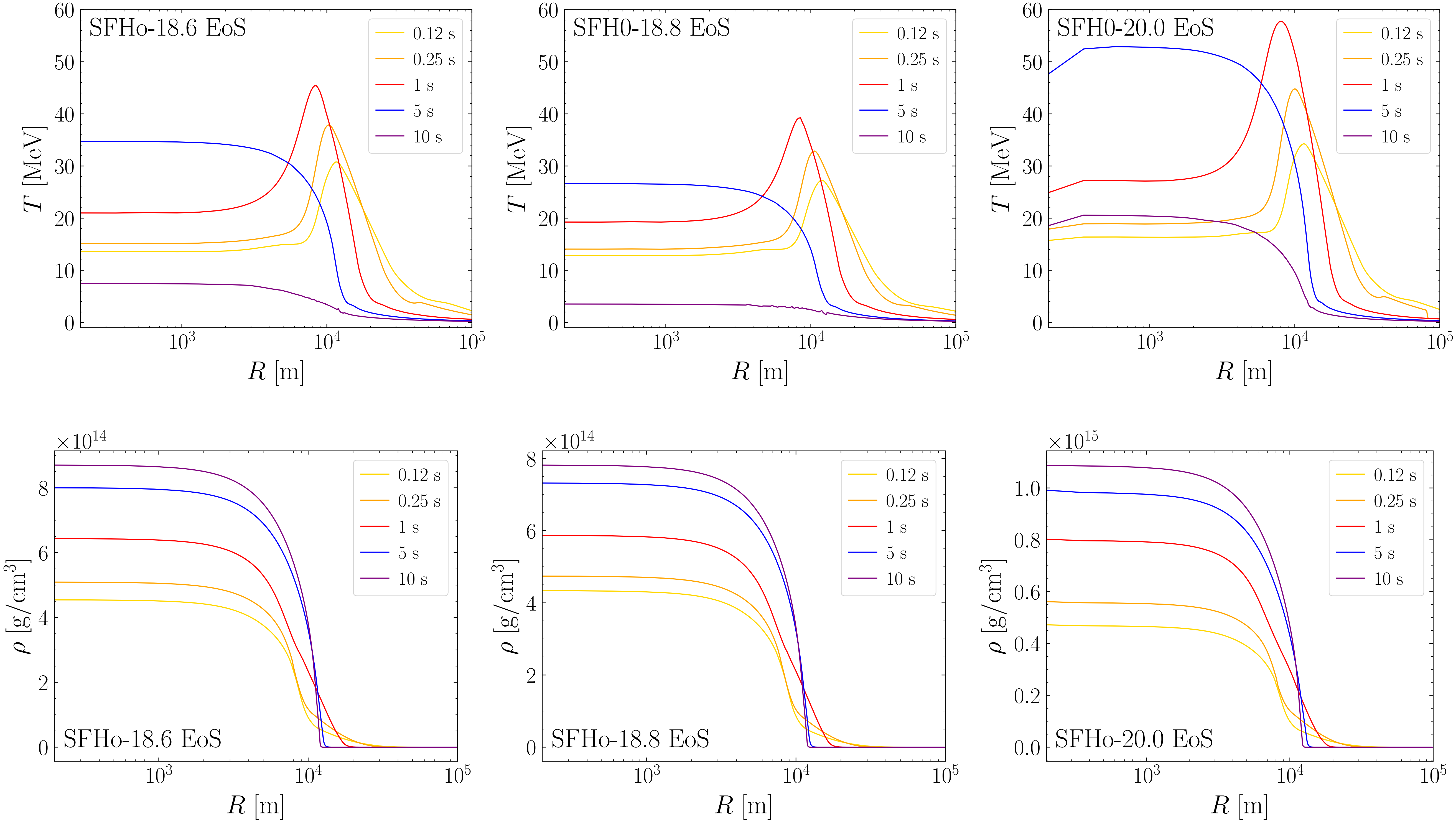
NASA

BSF
United States – Israel
Binational Science Foundation

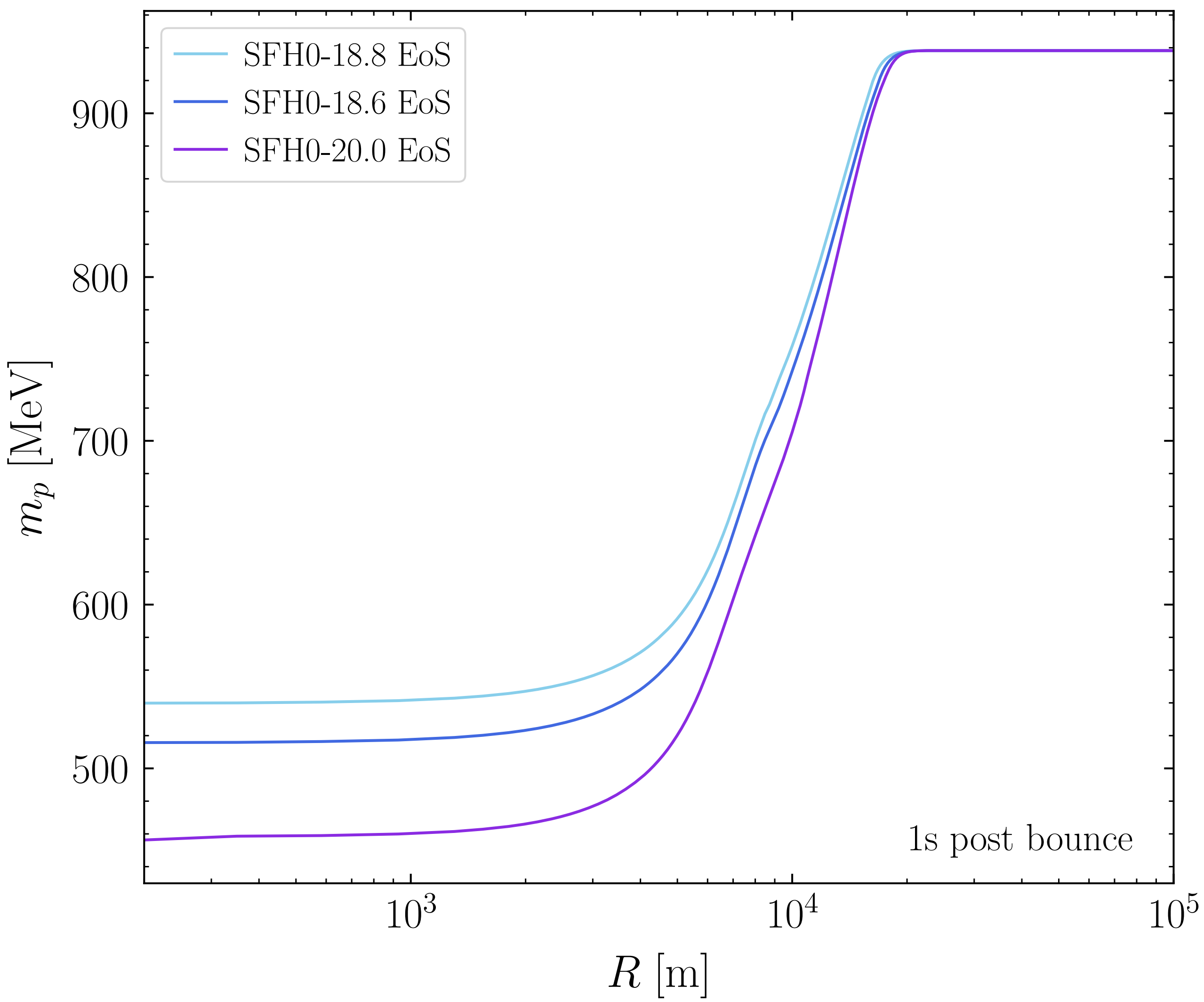
U.S. DEPARTMENT OF ENERGY
Office of Science

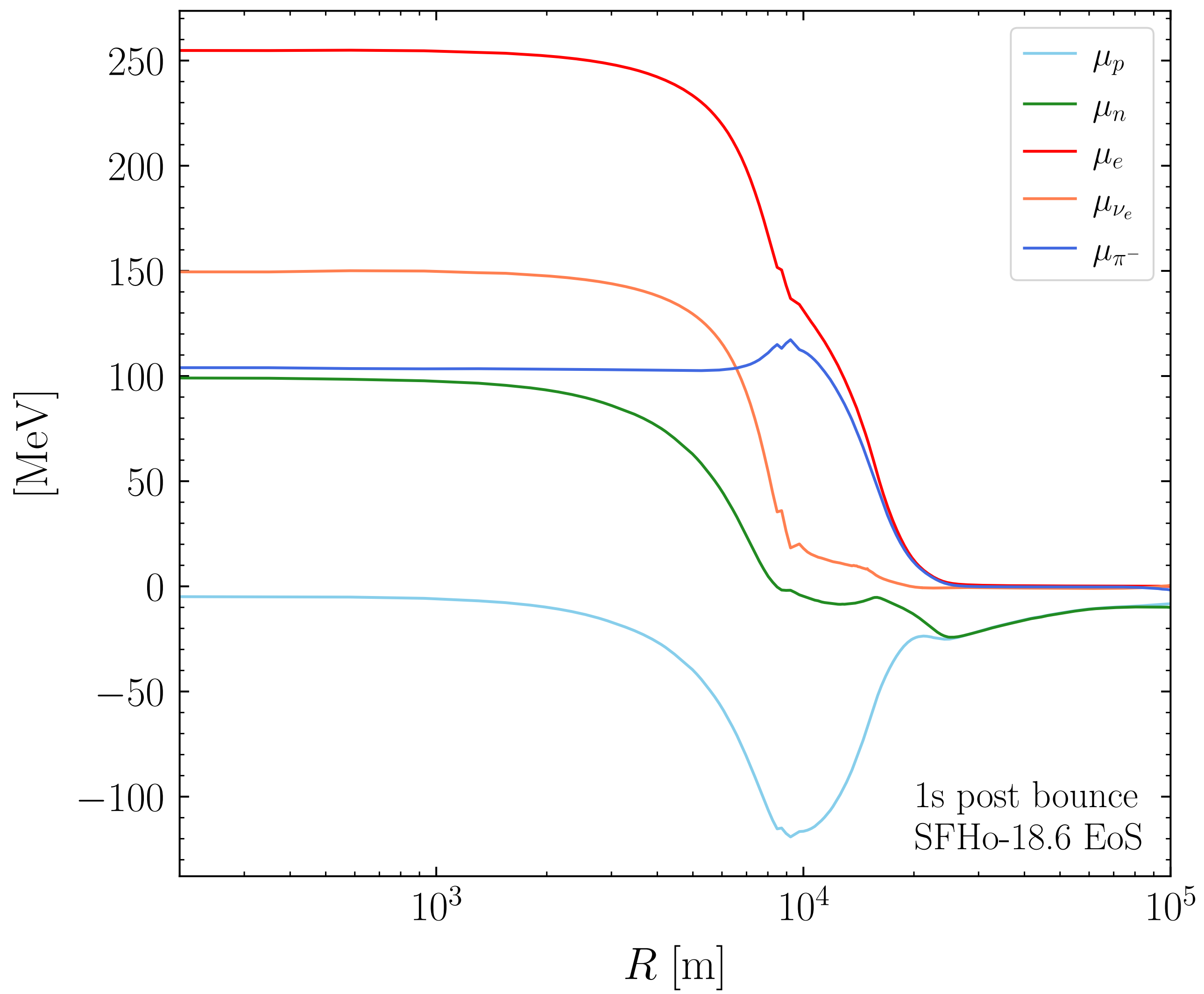
Internal simulation quantities

Garching core-collapse supernova archive: 2005.07141, …

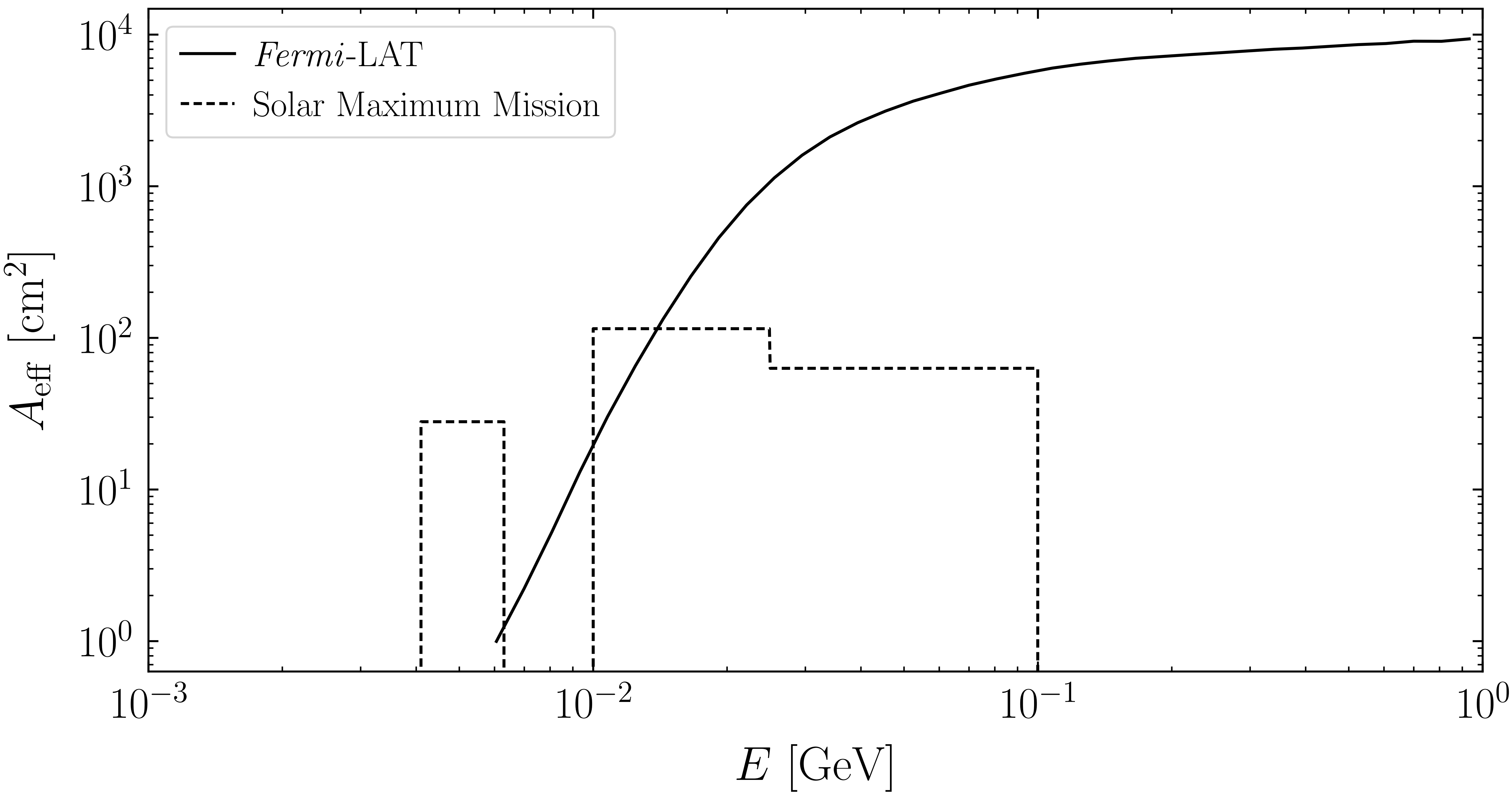


Internal simulation quantities

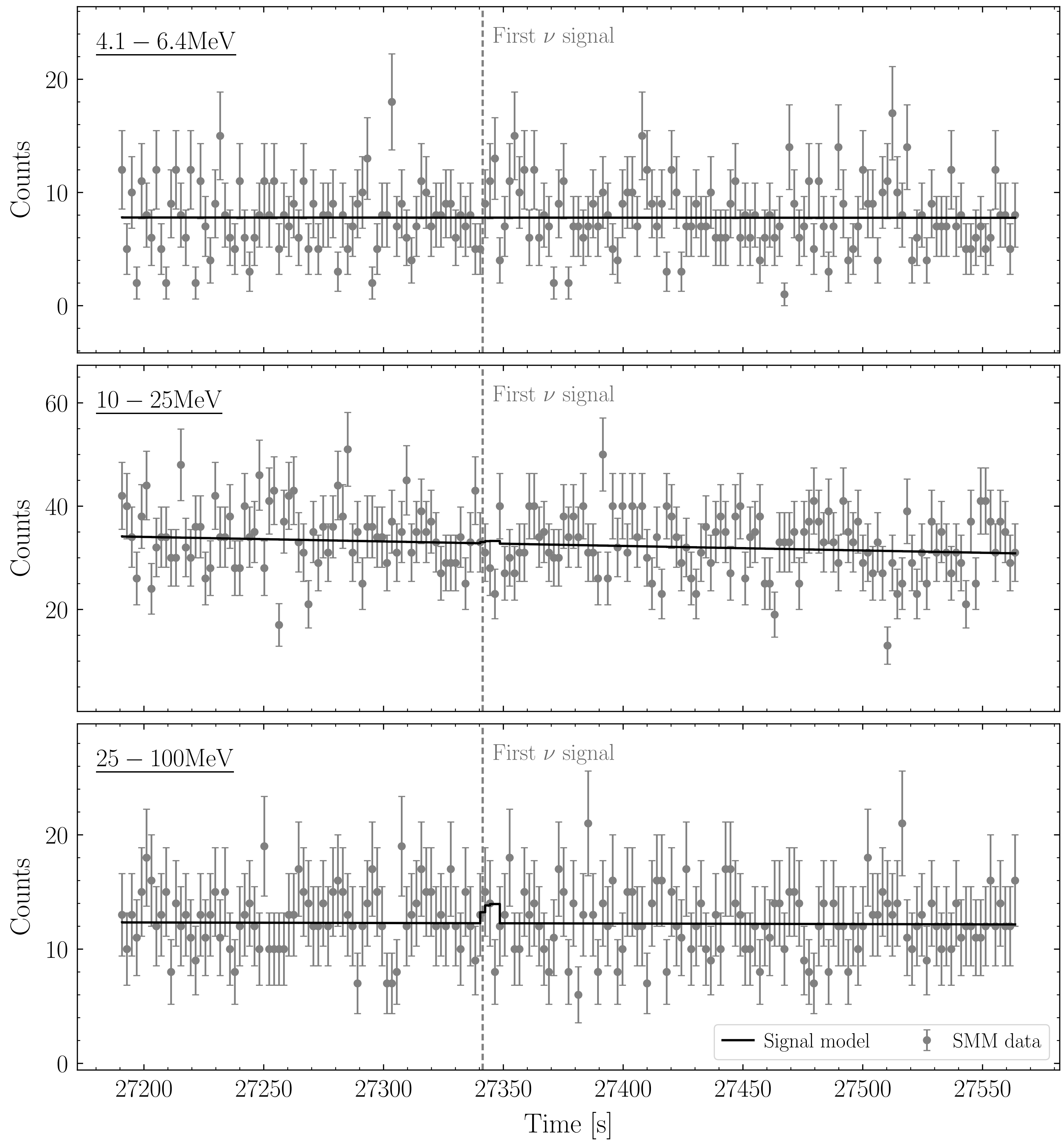




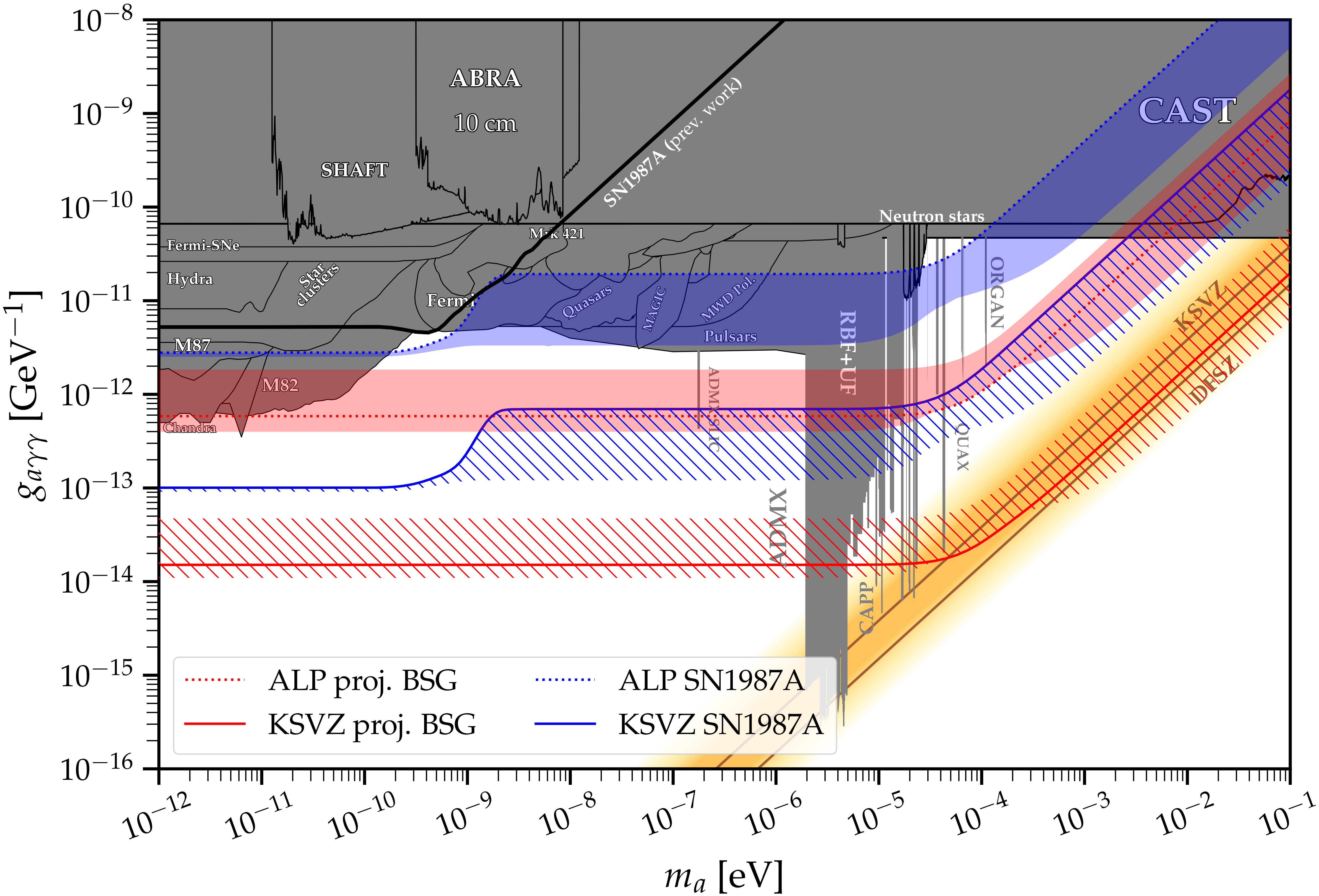
Effective Area



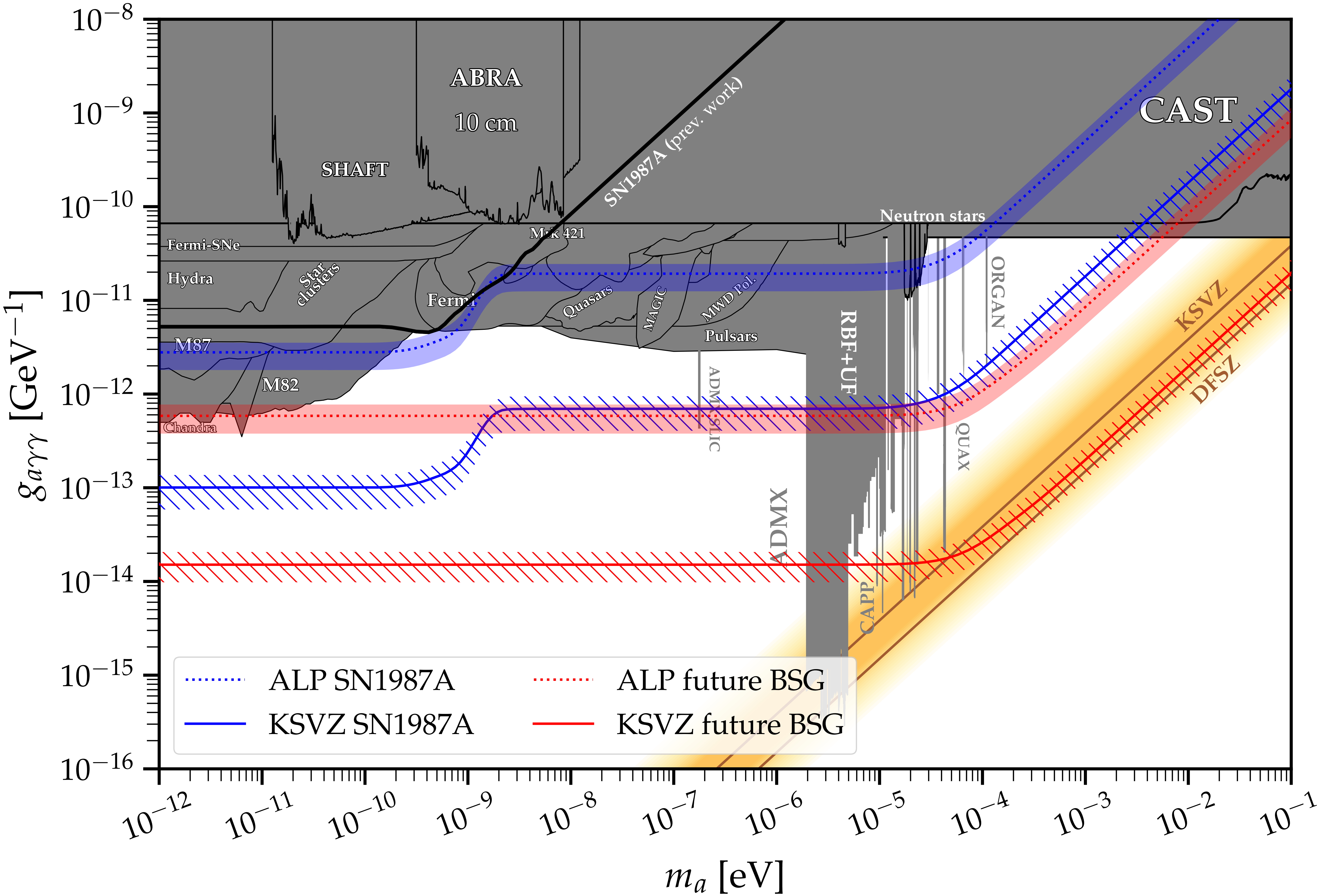
SMM gamma-ray data SN1987A



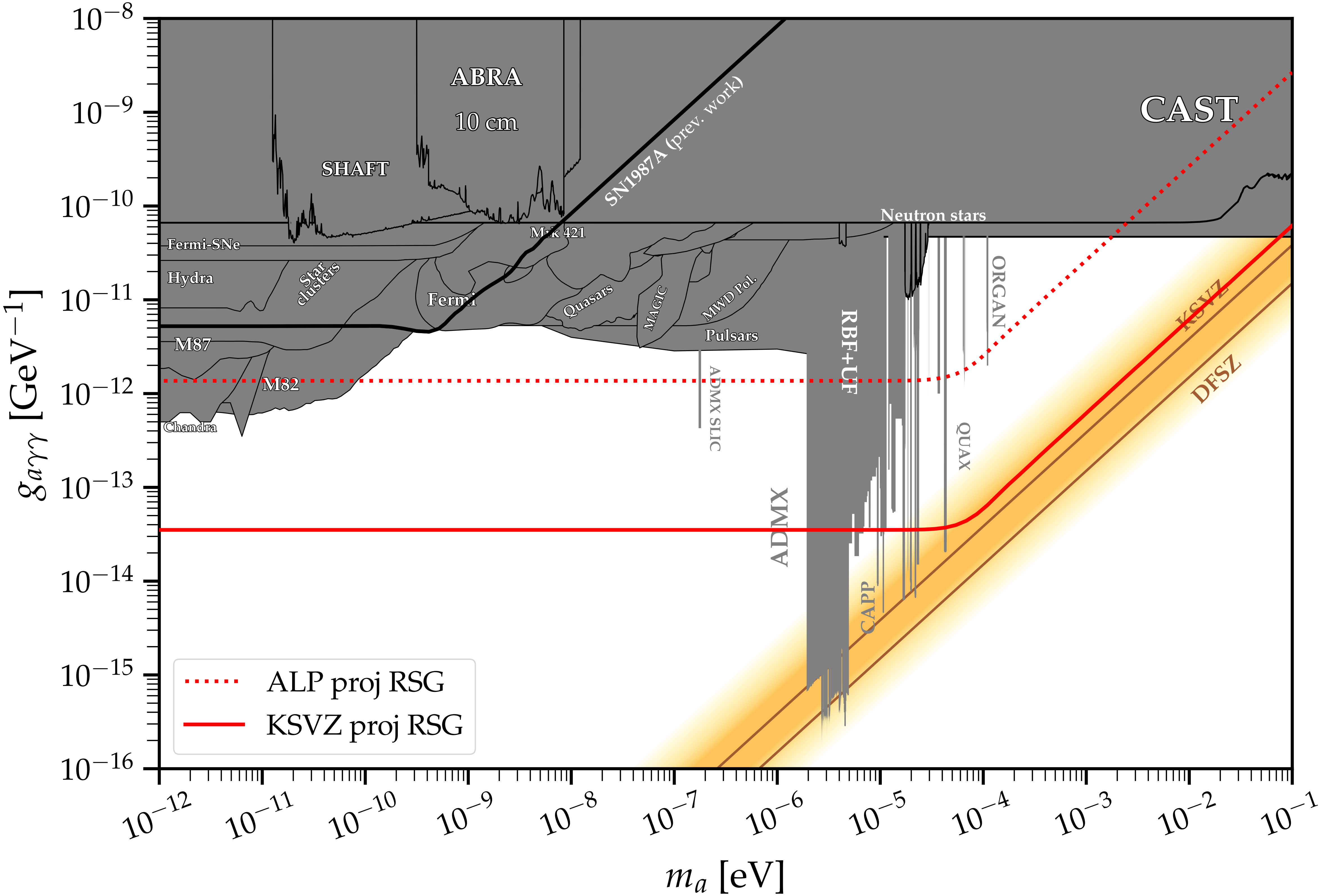
Systematic: changing the BSG surface field strength



Systematic: changing the SN simulation



Systematic: BSG instead of RSG



Systematic: removing pions