# NEW WAYS OF PROBING QCD AXIONS WITH SUPERNOVAE

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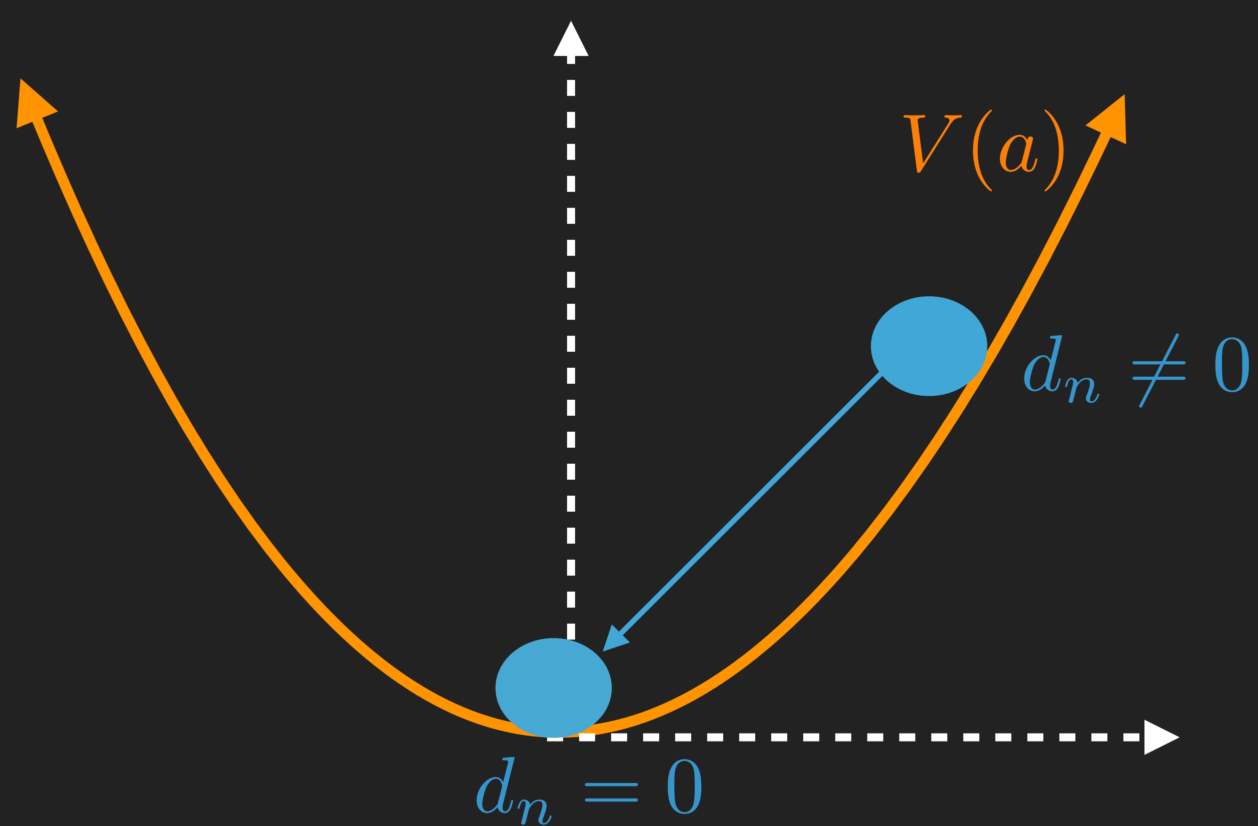
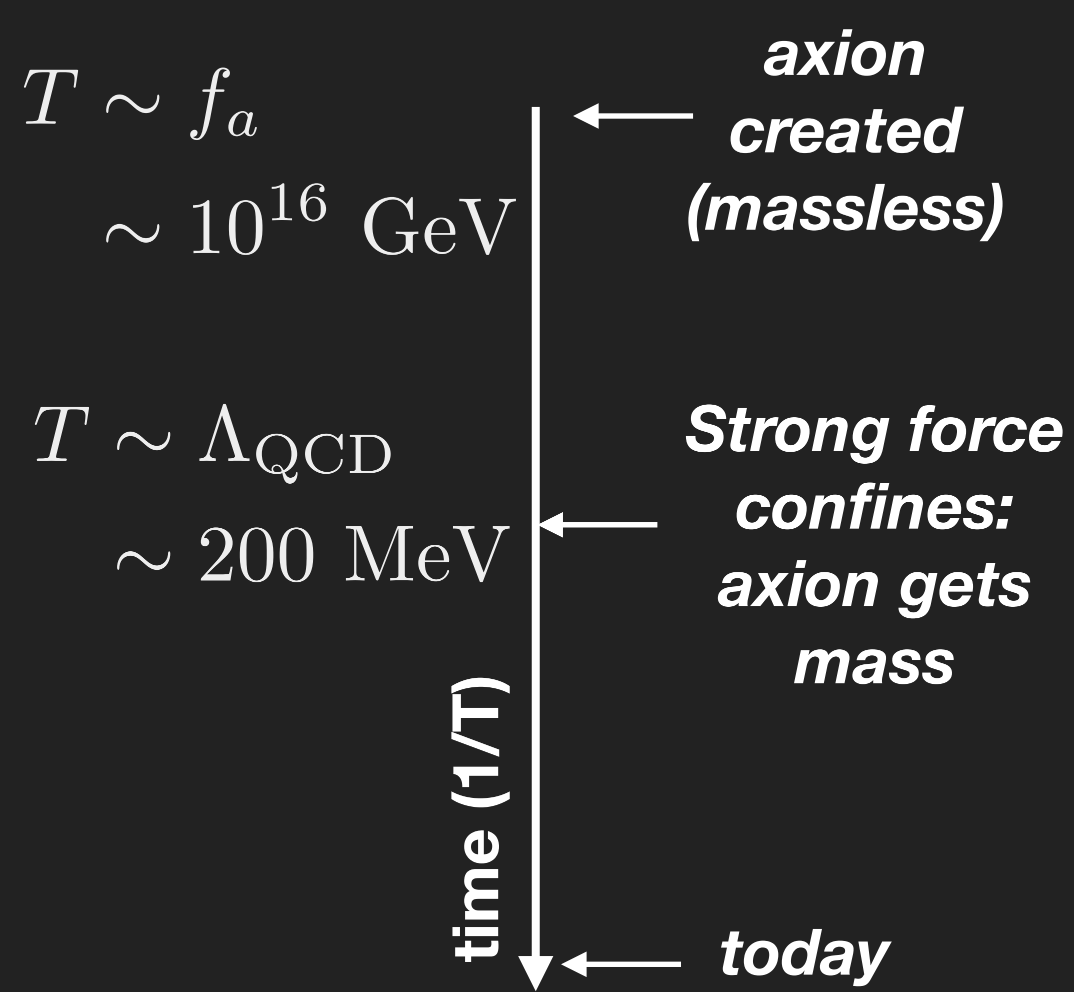
# Axion Introduced to Solve Strong CP Problem

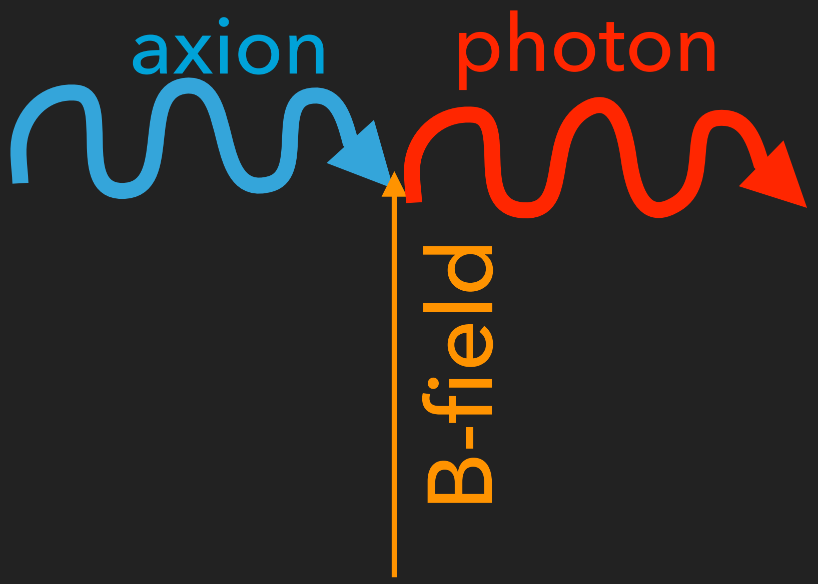
- CP-violation: $\mathcal{L}^{\rm CP} = -\frac{\bar{\theta} g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$
- Neutron EDM: $d_n \propto \bar{\theta}$
- Promote θ to field: $\bar{\theta} \rightarrow a/f_a$
- Axion potential: $V(a) \approx \frac{1}{2}\Lambda_{\rm QCD}^4 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$



# Axions interact with electromagnetism

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

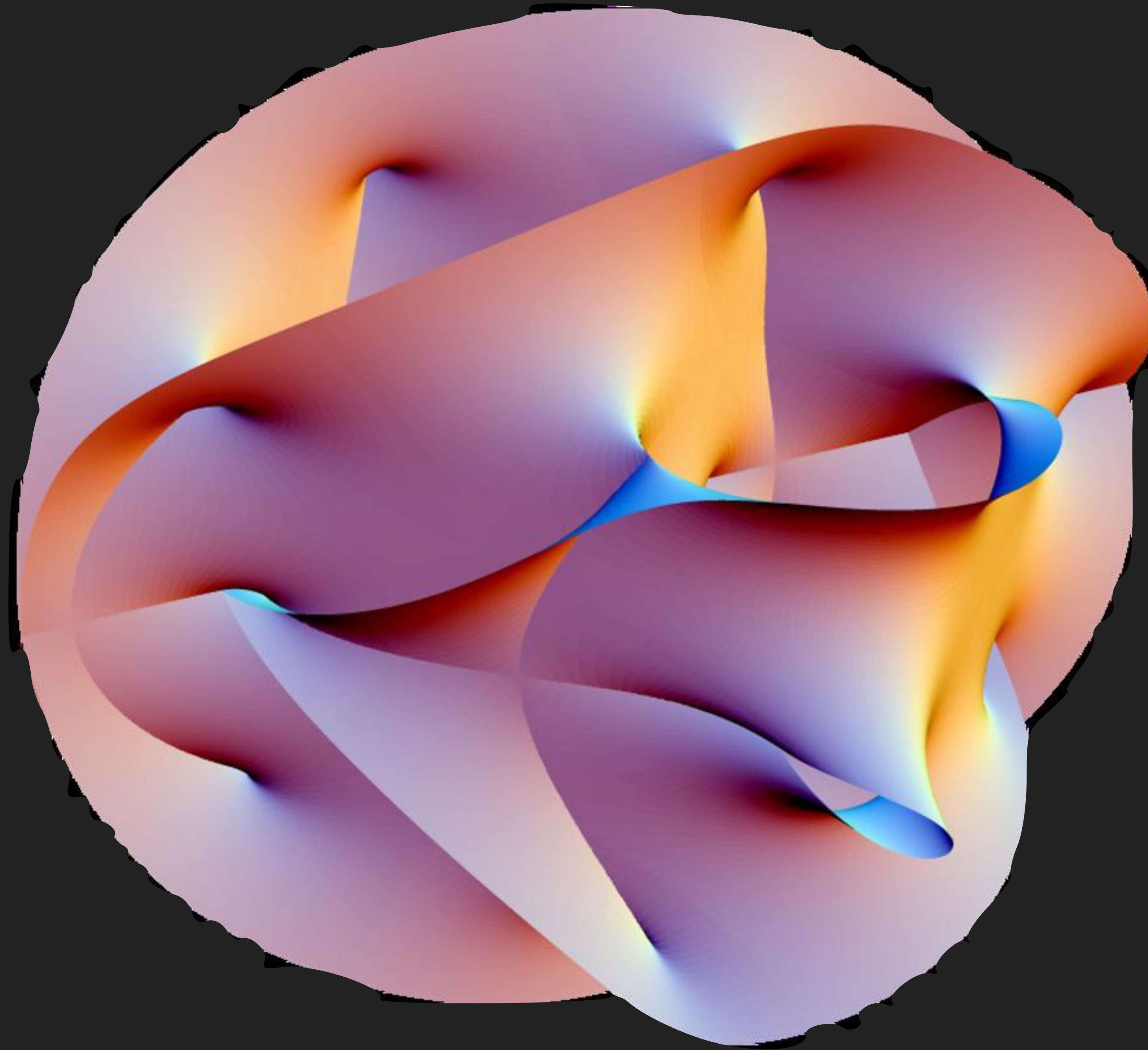



- Axion potential: $V(a) \approx \frac{1}{2}\Lambda_{\rm QCD}^4 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$

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

# Axions from string theory?

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



## Axion-like particles ALWAYS arise in string theory

QCD axion not guaranteed, but ingredients are there

# Axion-like particles versus QCD Axion

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

QCD axion and heavy ALPs only!

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

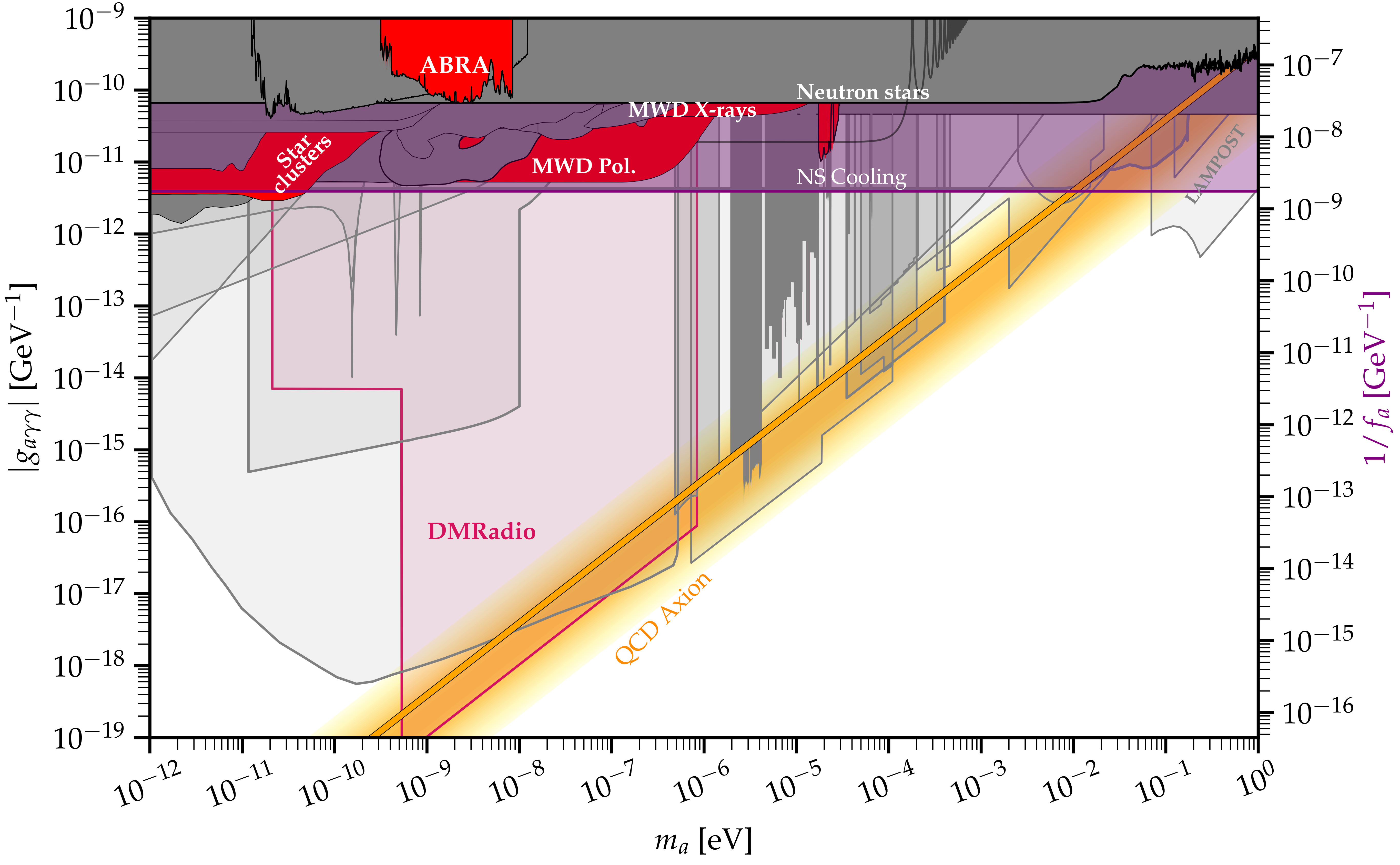
$$-\frac{1}{2}m_{\rm bare}^2 a^2$$

small (or large)


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

# QCD Axion can also Explain Dark Matter

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



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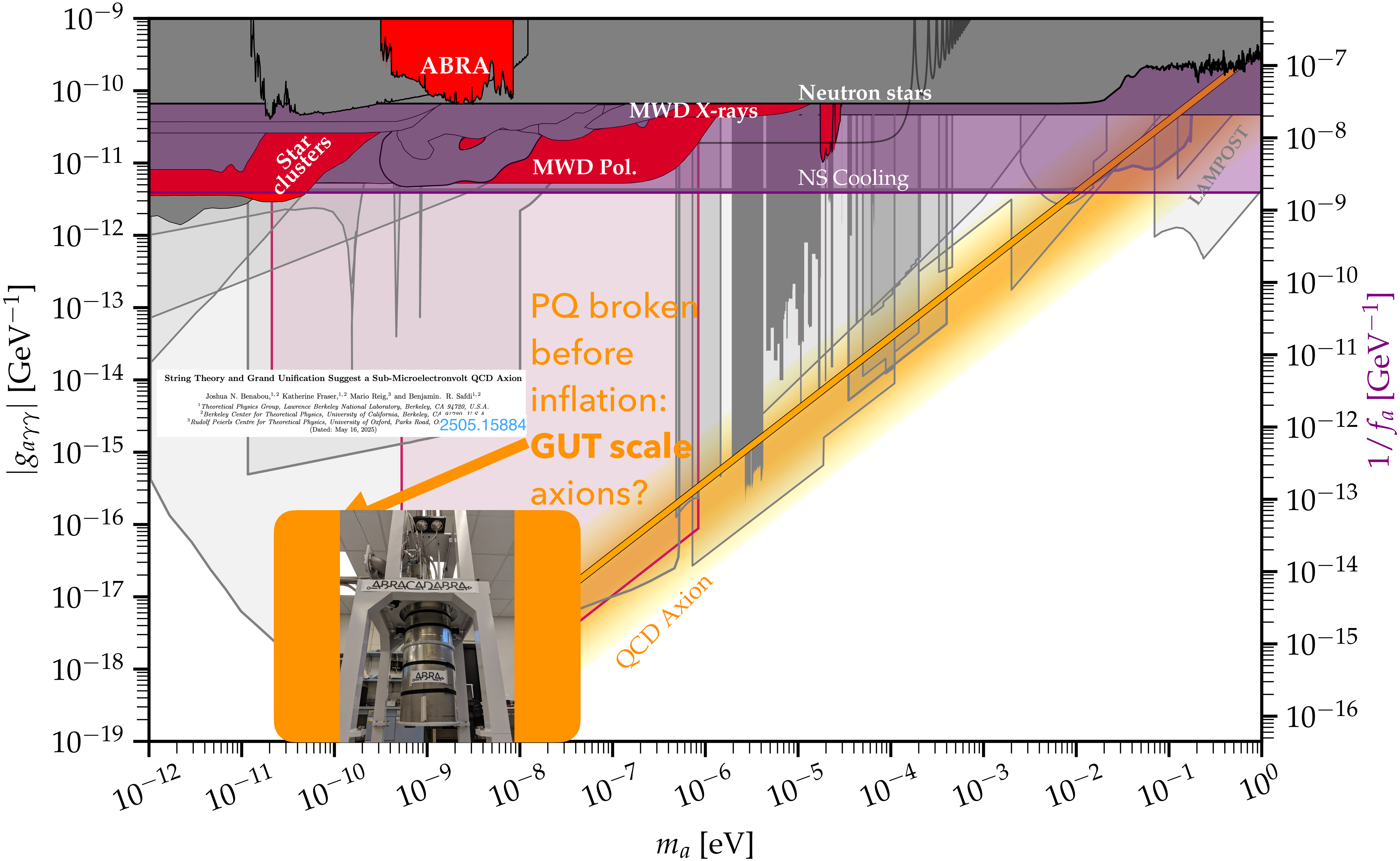

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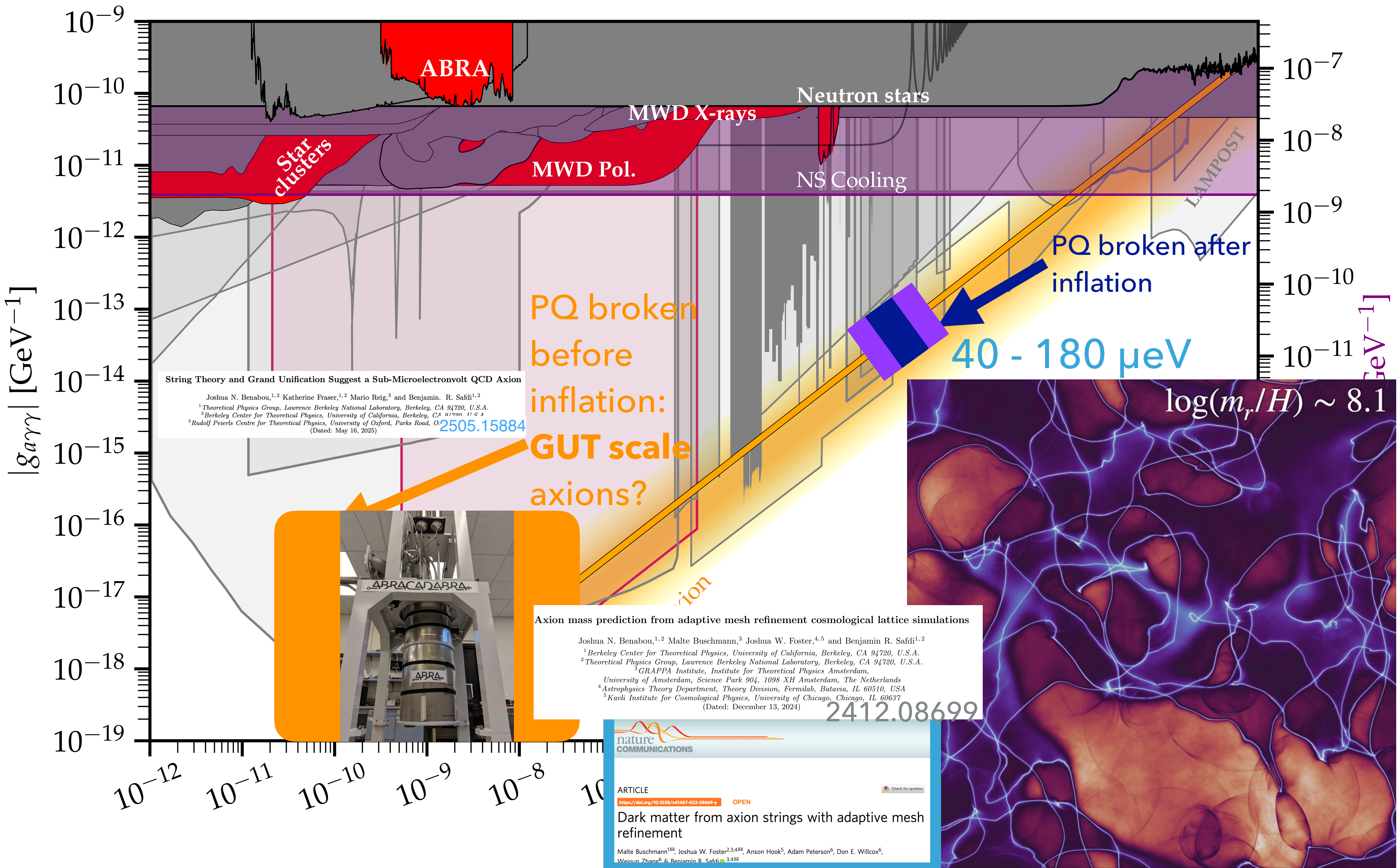

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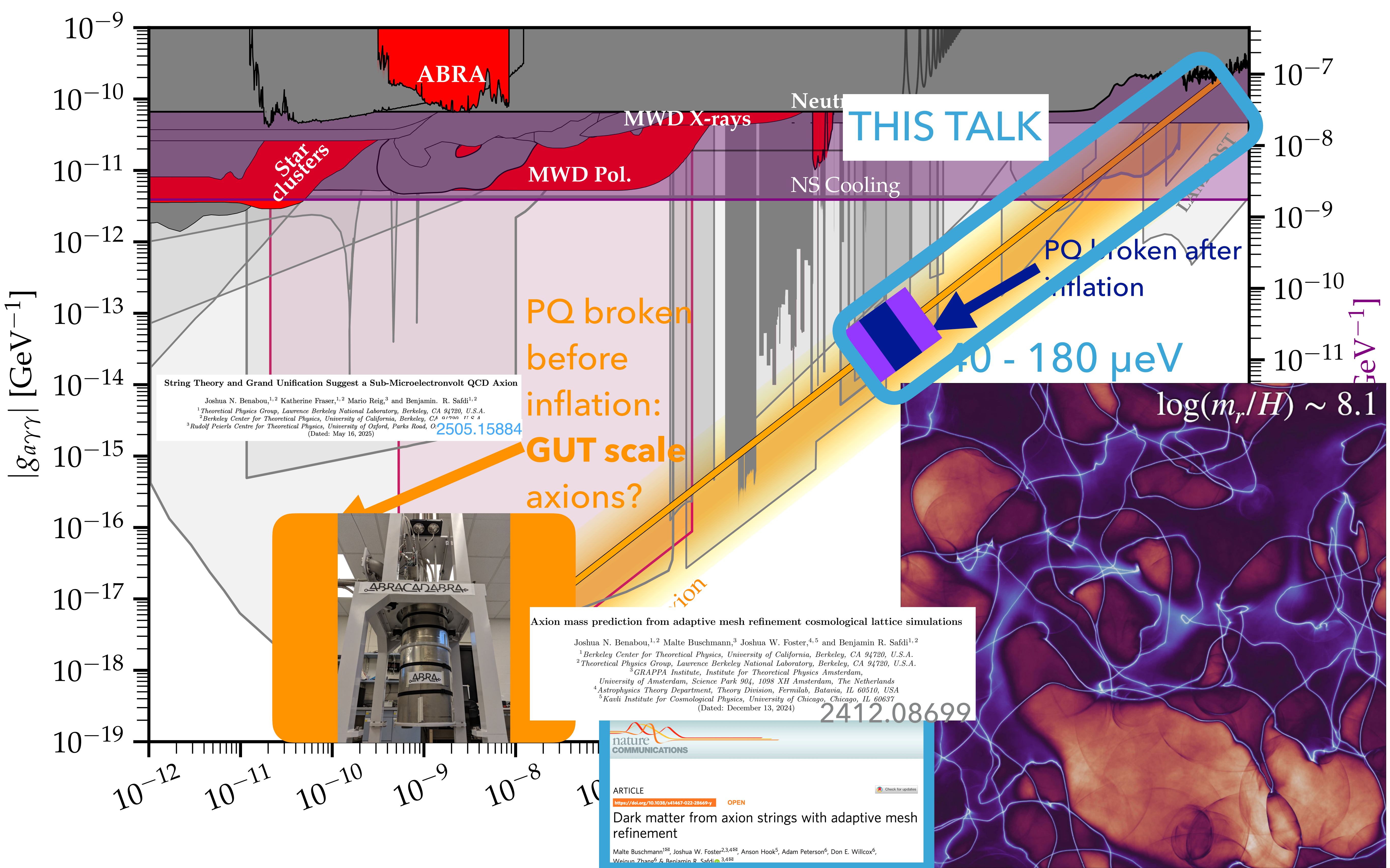


# **Warmup**: axion induced MWD polarization

**Search for Axions in Magnetic White Dwarf Polarization at Lick and Keck Observatories**

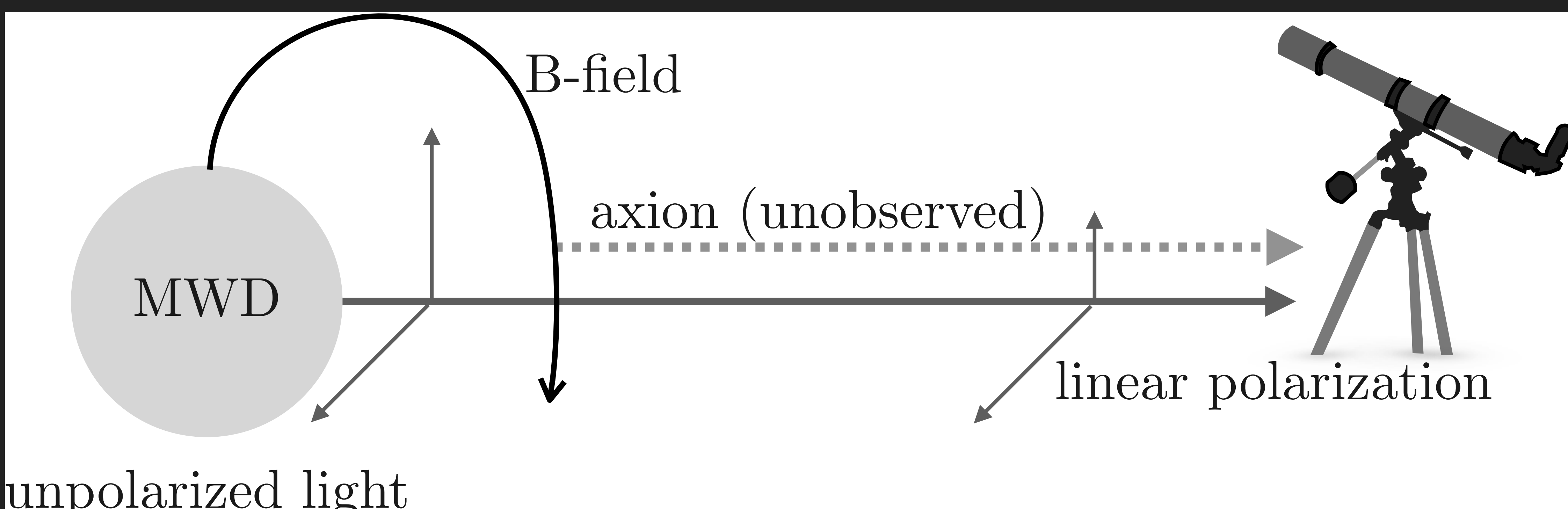
2504.12377

Joshua N. Benabou,[1,2,*] Christopher Dessert,[3,†] Kishore C. Patra,[4,5] Thomas G. Brink,[4] WeiKang Zheng,[4] Alexei V. Filippenko,[4] and Benjamin R. Safdi[1,2,‡]

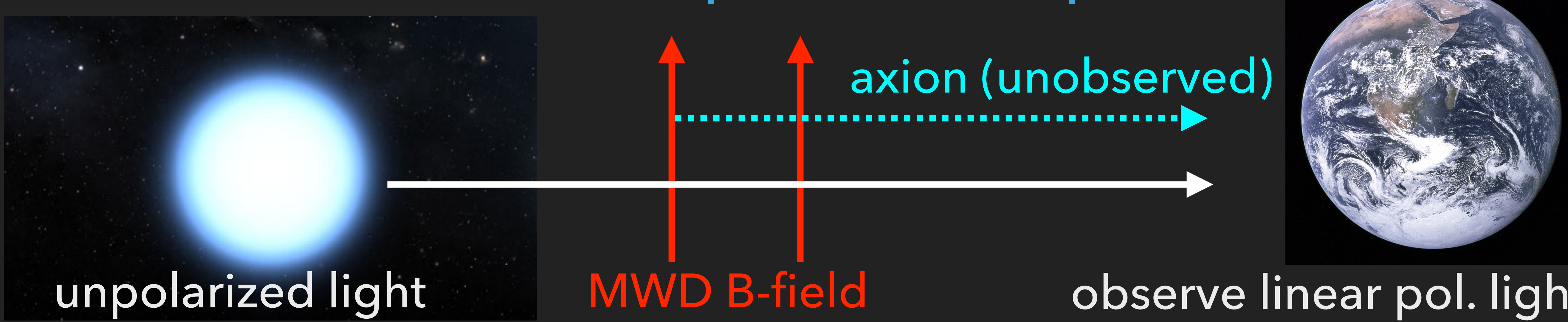
**Upper limit on the axion-photon coupling from magnetic white dwarf polarization**

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

2203.04319



# Axion contribution to optical MWD polarization



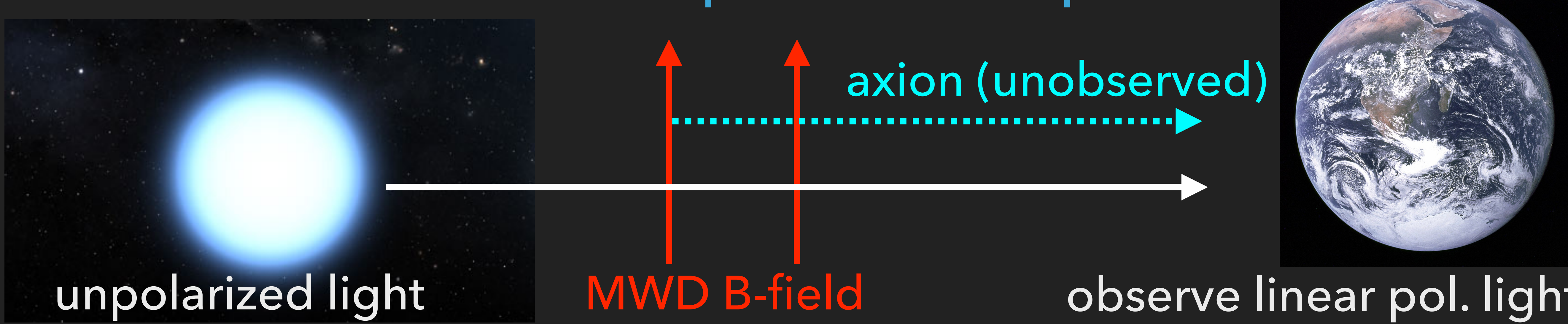

$$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4} = g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$

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

only convert photons
polarized along B-field

basic idea: Gill, Heyl 2011

# Axion contribution to optical MWD polarization




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

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

not important at optical frequencies

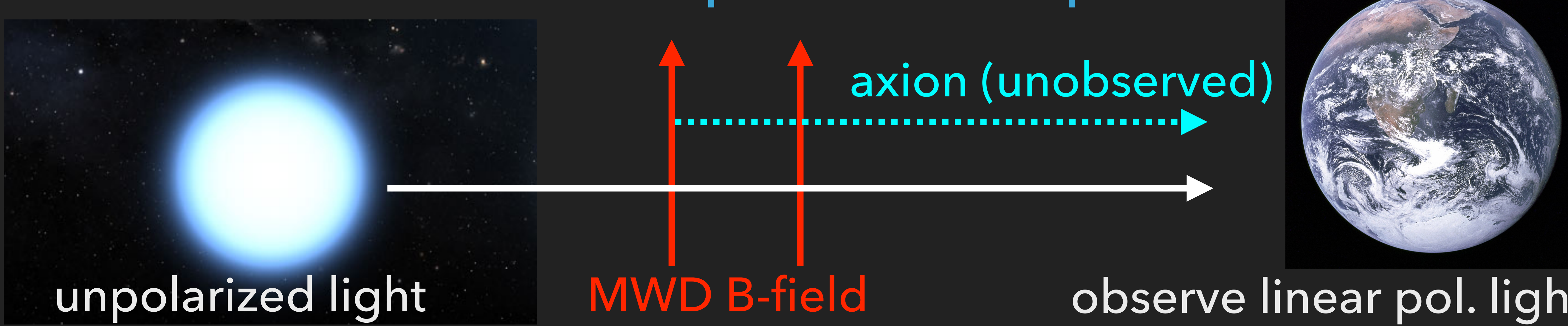
$$P_L \sim 1 - p_{\gamma\to\gamma} \sim 10^{-2} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_0}{1000\,\mathrm{MG}}\right)^2 \left(\frac{R_{\mathrm{WD}}}{0.01\ \mathrm{R}_\odot}\right)^2$$

polarization fraction

many MWD polarizations at this level

true at optical frequencies but not X-ray!

# Axion contribution to optical MWD polarization




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

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

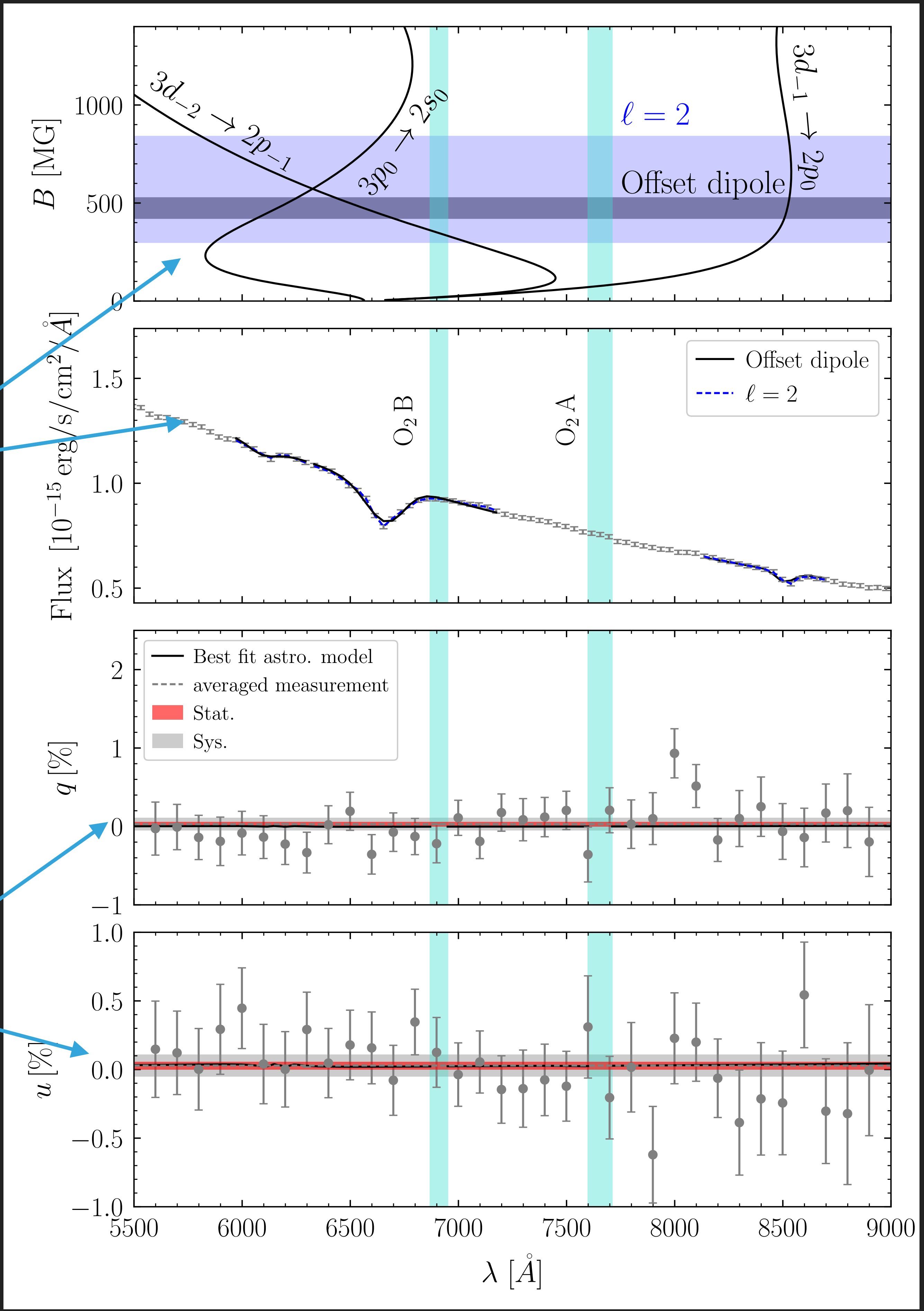
$$P_L \sim 1 - p_{\gamma\to\gamma} \sim 10^{-2} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\,{\rm GeV}^{-1}}\right)^2 \left(\frac{B_0}{1000\,{\rm MG}}\right)^2 \left(\frac{R_{\rm WD}}{0.01\ {\rm R}_\odot}\right)^2$$

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

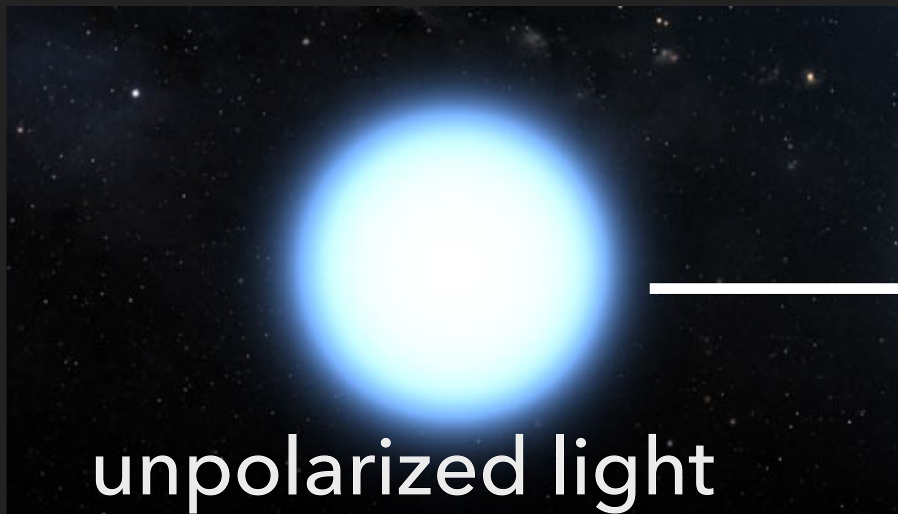
# Collected dedicated data at Keck (Hawaii) and Lick (California)

Intensity has spectral dips -> Zeeman effect -> B-field measurement

No linear polarization



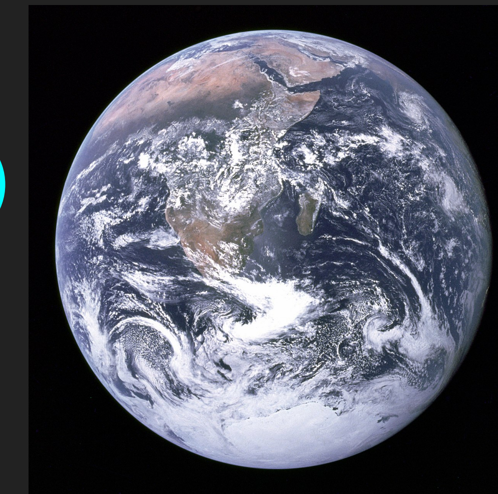
# MWD Polarization Results



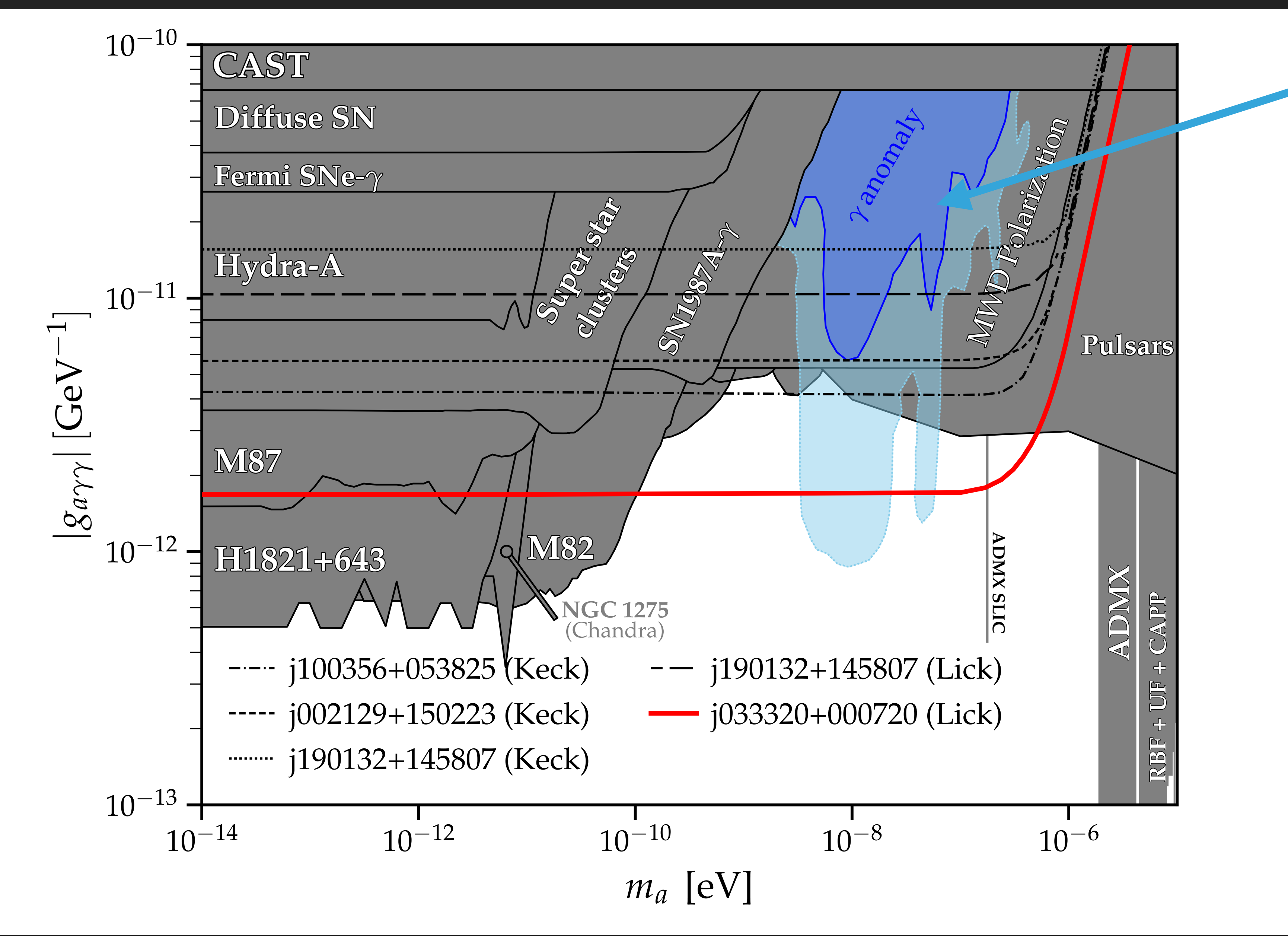
unpolarized light

MWD B-field

axion (unobserved)



observe linear pol. light

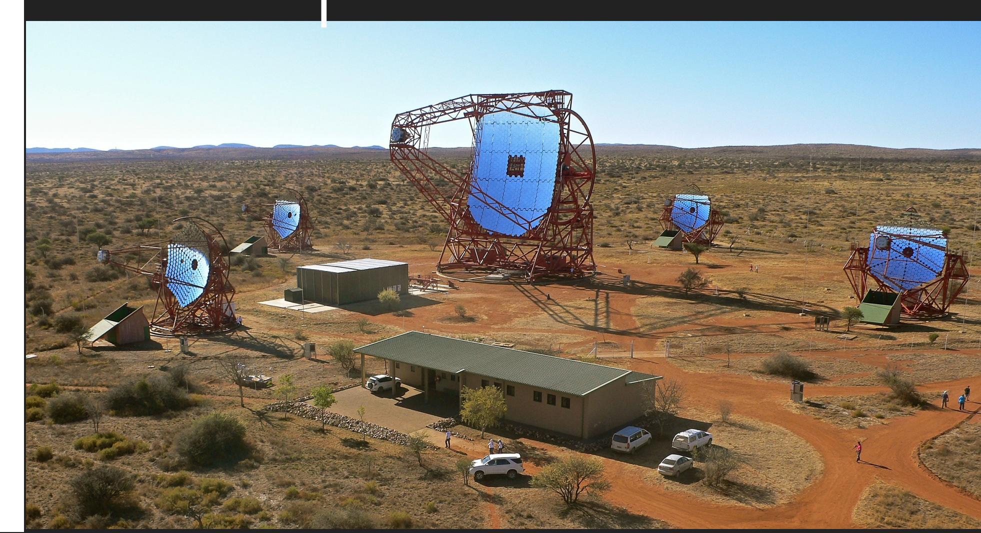



**gamma-ray transparency anomaly: Meyer et al. 2013, +**

**AGN**

**photons absorbed on EBL**

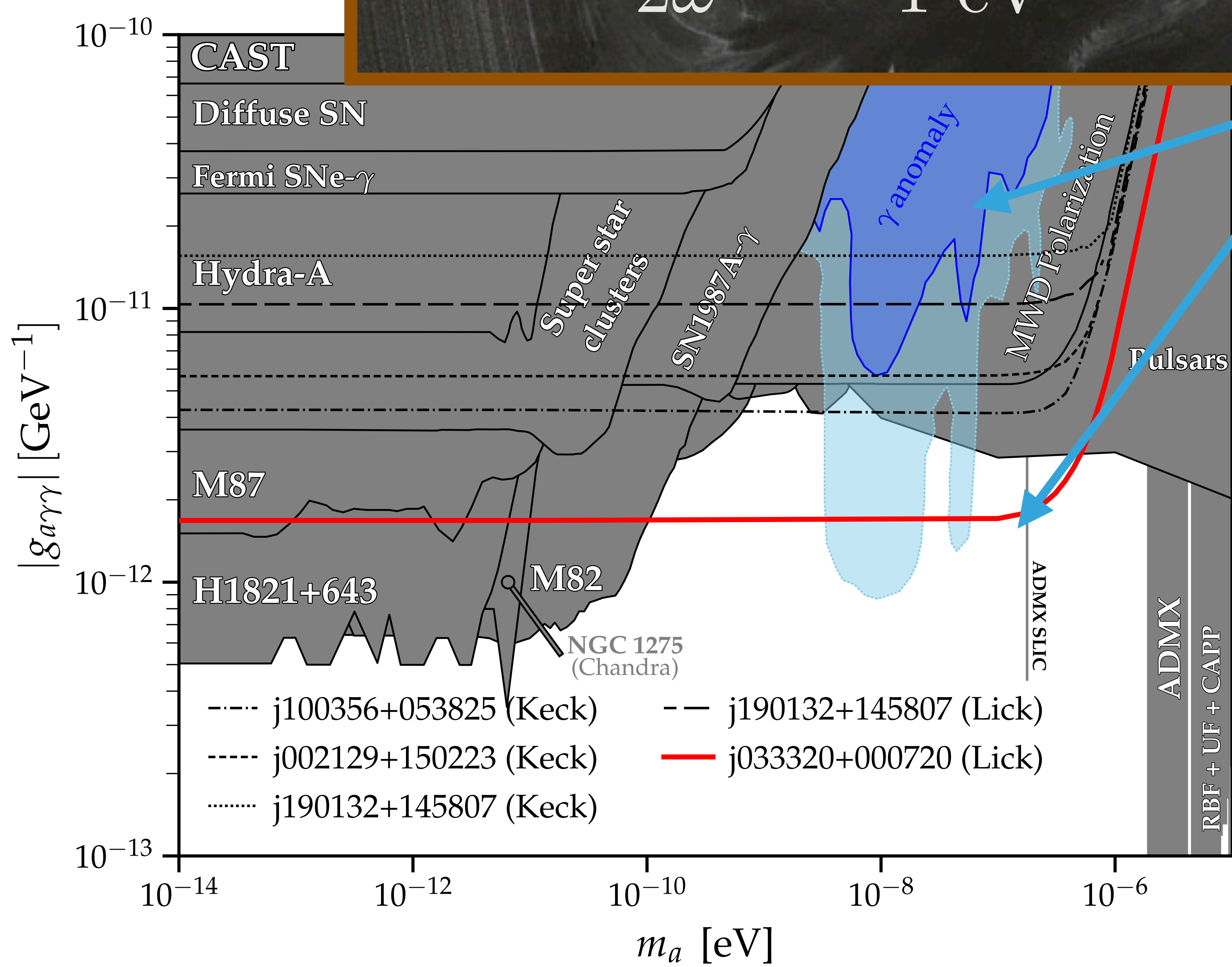
**conversion to and back from axions increase prop length**



# MWD Polarization Results


## mass dependence: photon-axion dispersion relations

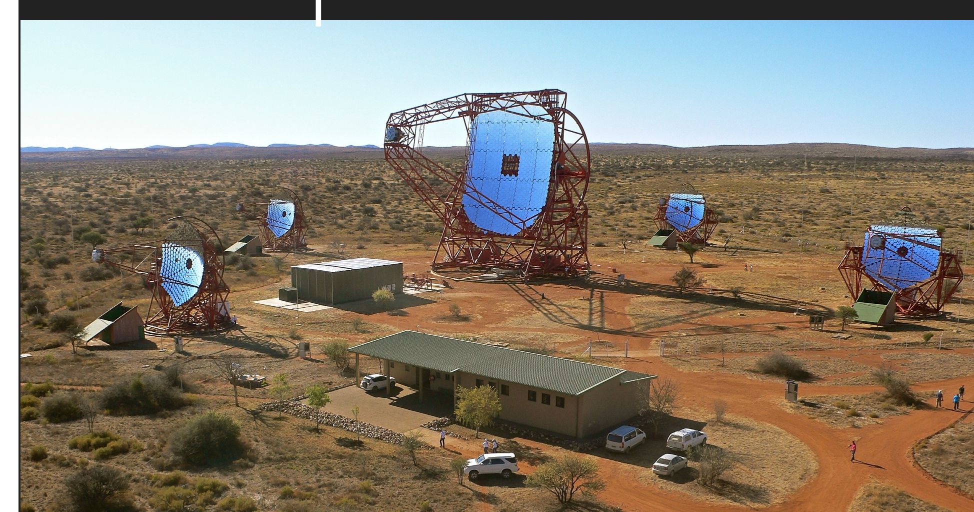
$$\delta k\, L \approx \frac{m_a^2}{2\omega} L \sim \frac{m_a^2}{1\ \mathrm{eV}} 0.01\ R_\odot \sim \left(\frac{m_a}{2\times 10^{-7}\ \mathrm{eV}}\right)^2 > 1$$




**AGN**

**photons absorbed on EBL**

**conversion to and back from axions increase prop length**



# Main Goal Today: Supernovae are axion laboratories

PHYSICAL REVIEW LETTERS **133,** 211002 (2024)

**Supernova Axions Convert to Gamma Rays in Magnetic Fields of Progenitor Stars**

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*Berkeley Center for Theoretical Physics, University of California, Berkeley, California 94720, USA*
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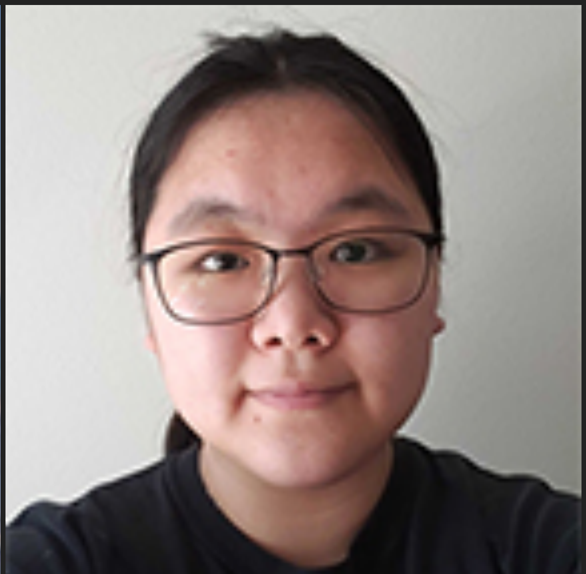
Claudio (postdoc)

Yujin (student)

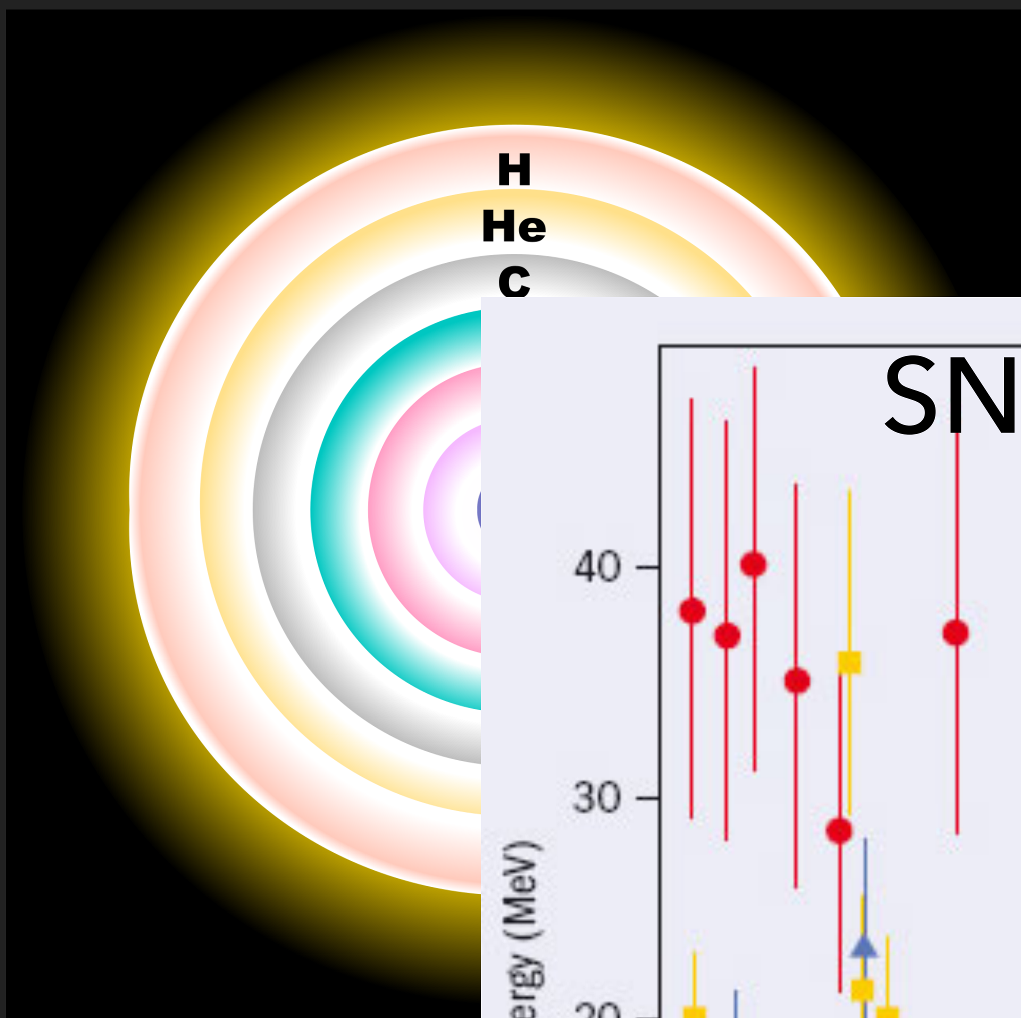


Inbar (postdoc)

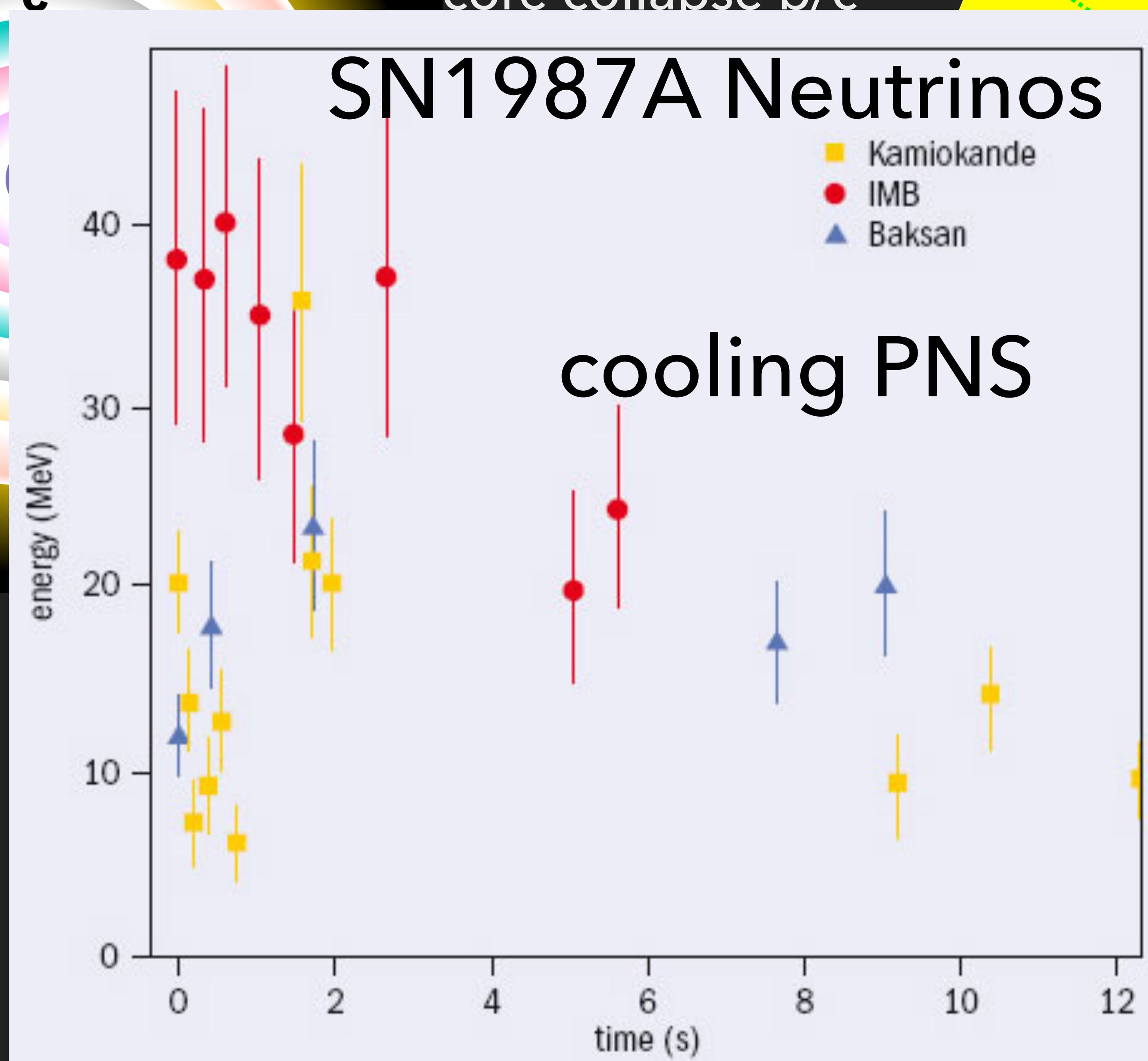
# Neutrinos produced from cooling proto-NS in SN1987A

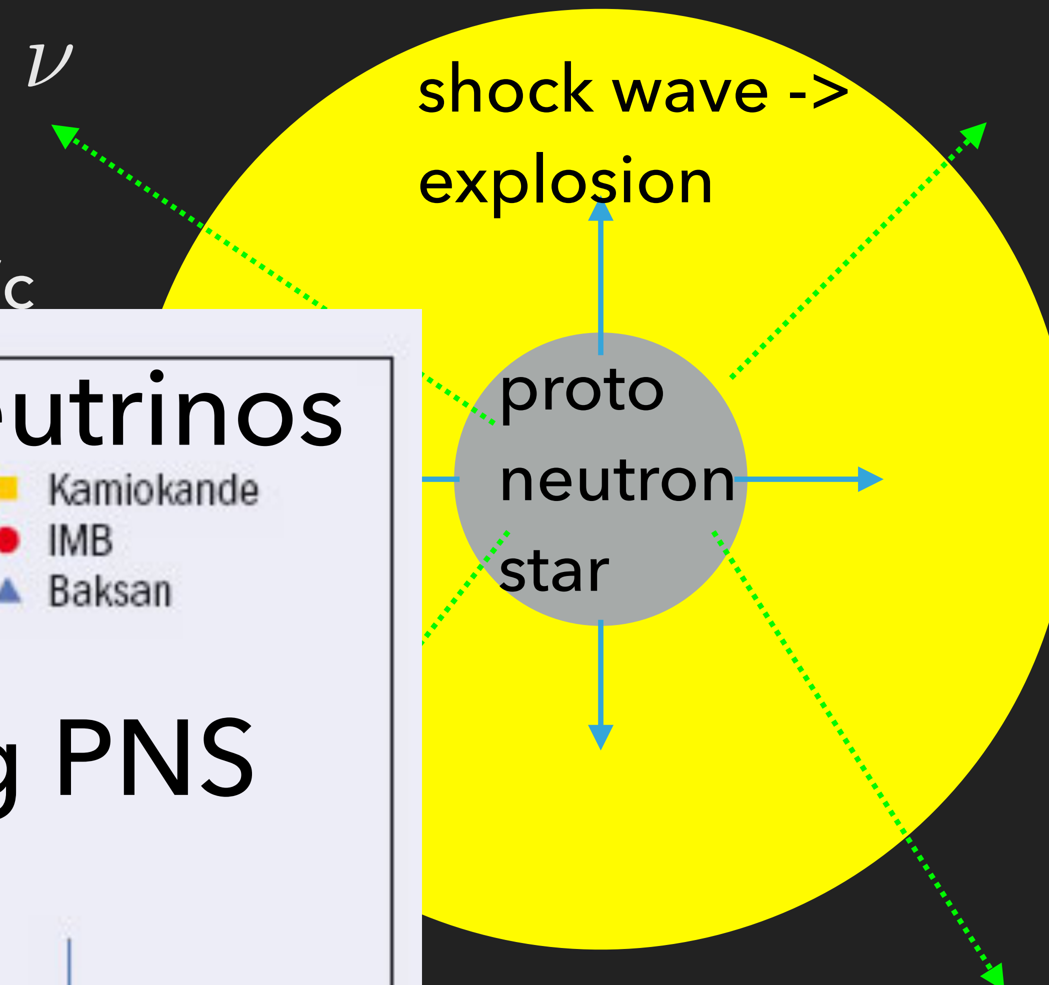
## Type II supernova

neutrinos escape (and heat) –> SN1987A neutrino signal



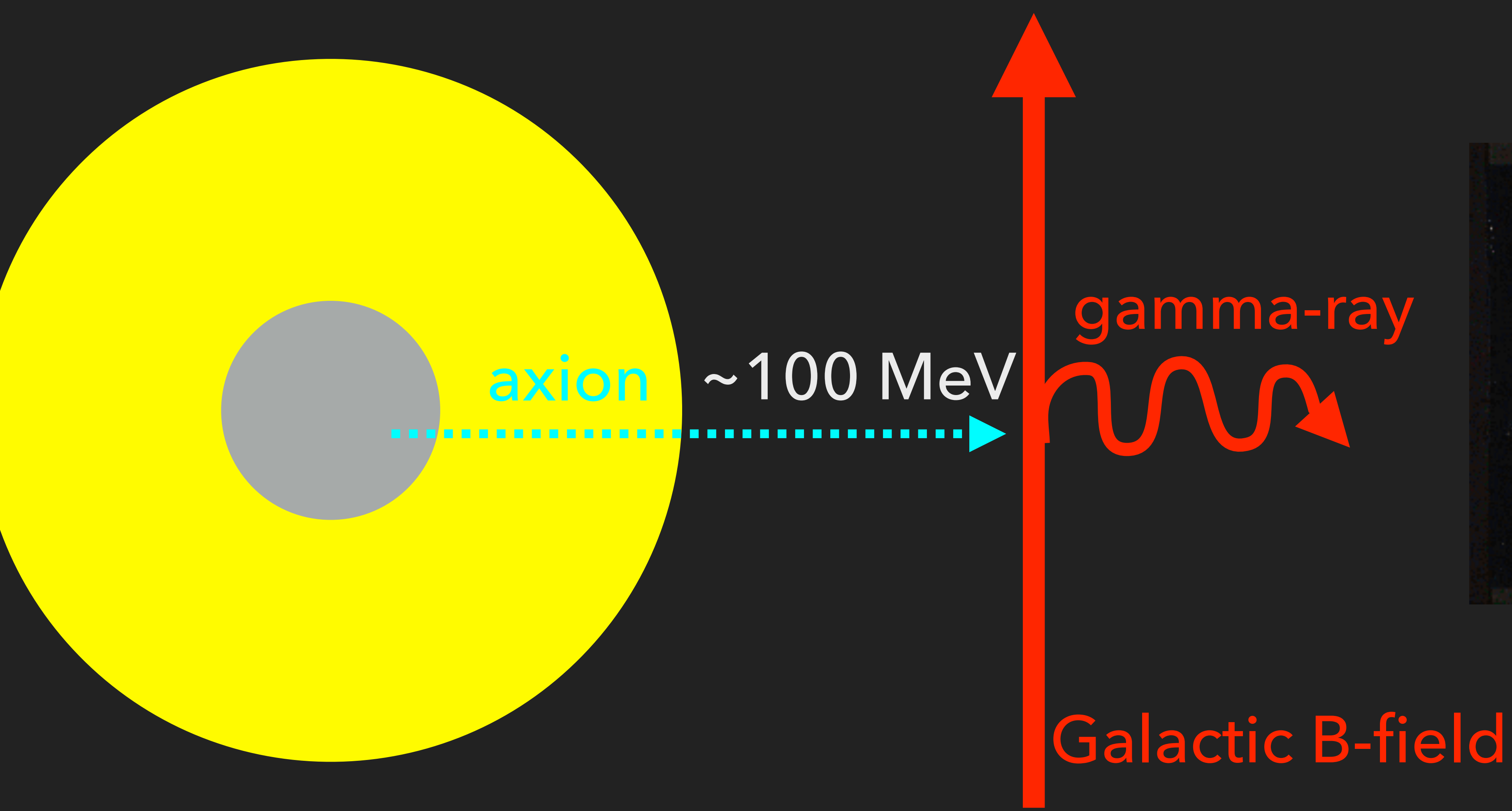

core collapse b/c



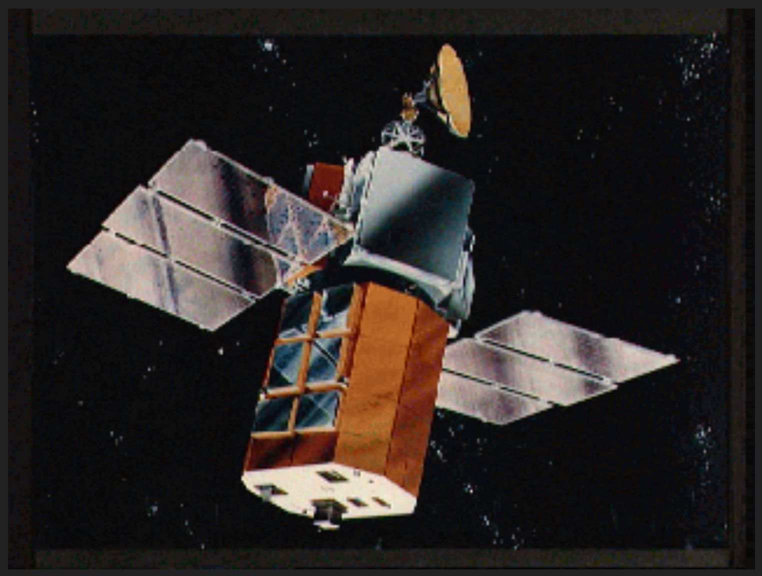



# Old idea: gamma-rays from conversion Galactic field

SN1987A: in the LMC at d ~ 50 Mpc



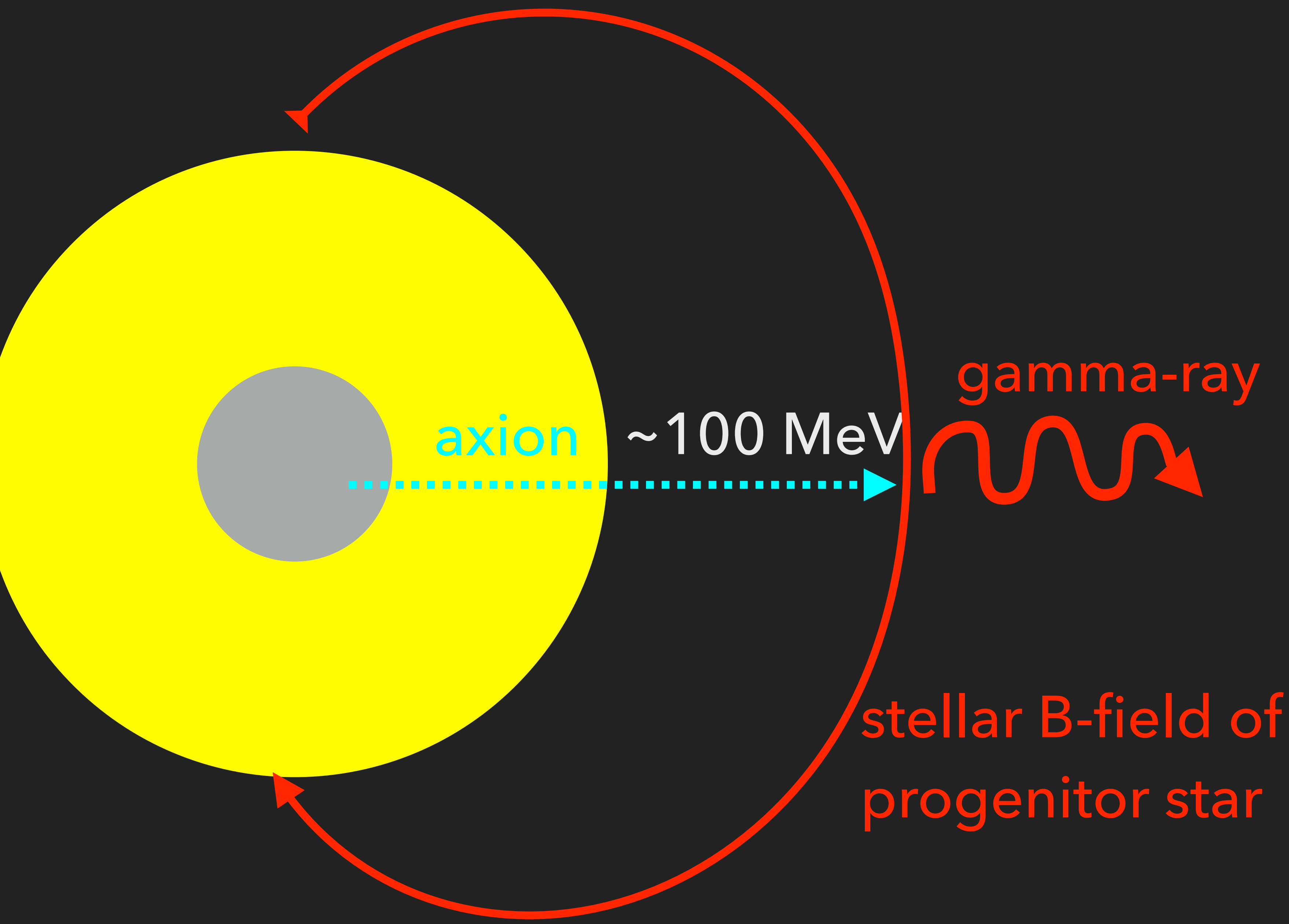

solar maximum mission



# 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

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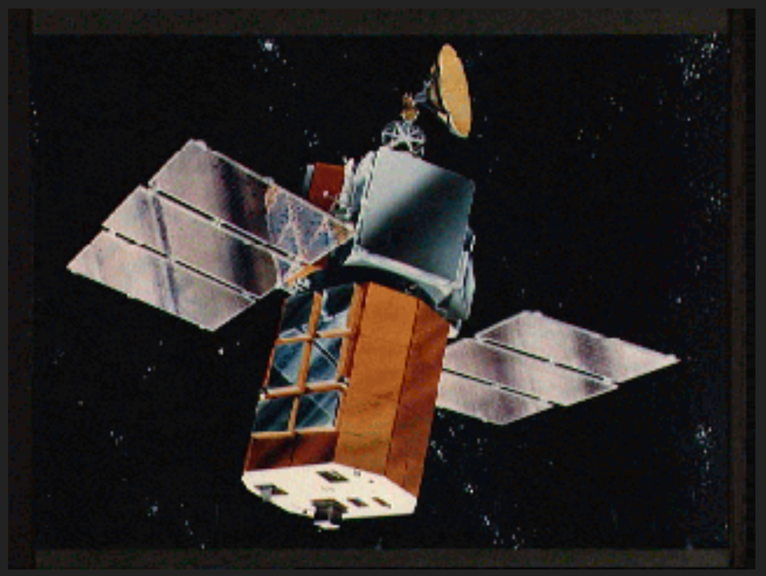
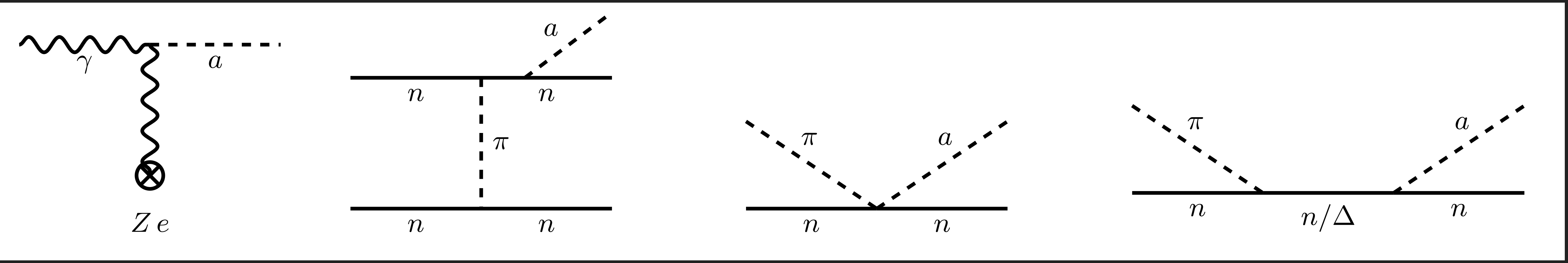
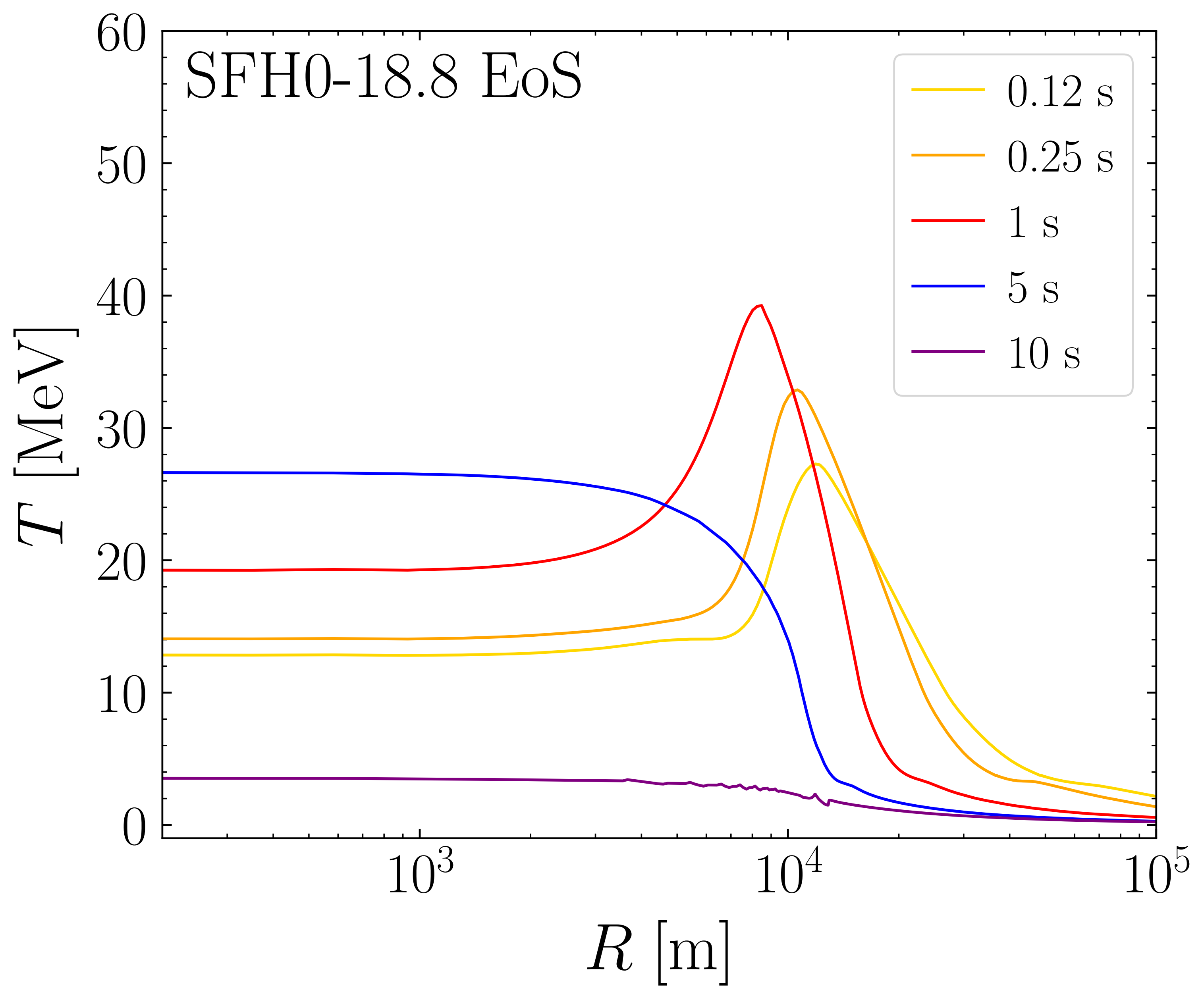


# Proto Neutron Stars from SN also produce axions

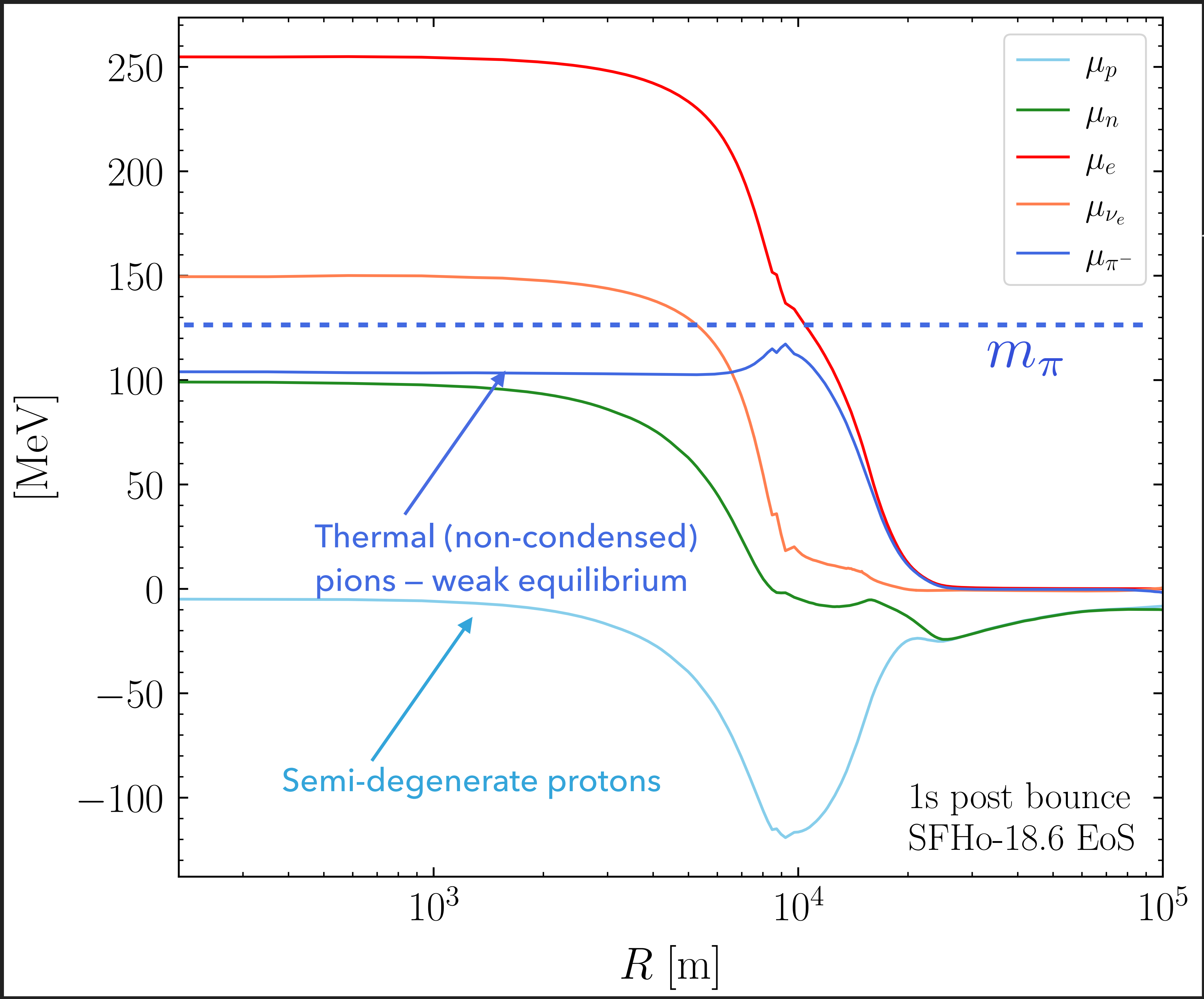



(Loop-induced production from nucleons important for ALPs)




Simulations from the Garching Core-Collapse Supernova archive

# Nontrivial populations of thermal protons, neutrons, pions




Weak equilibrium

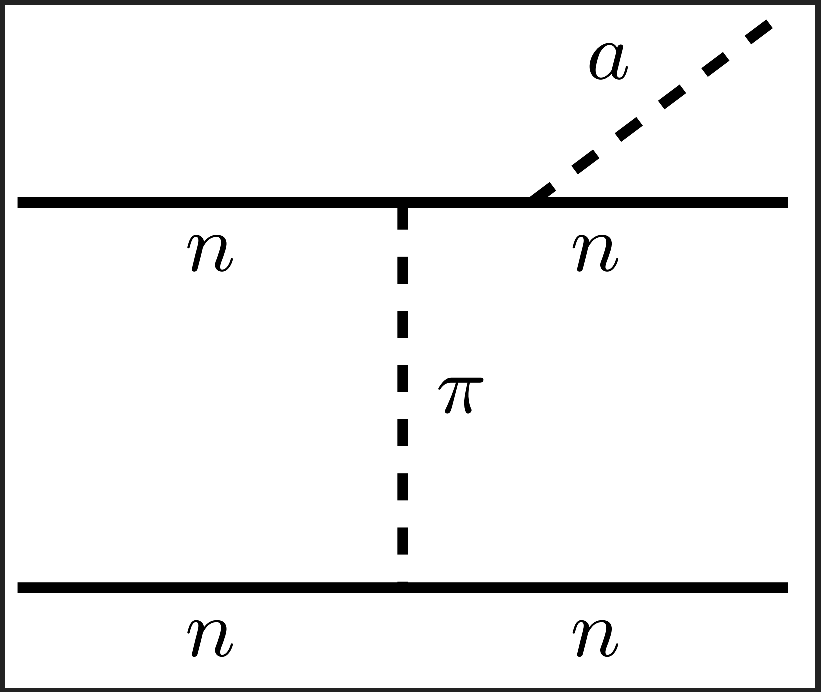
$$p + e^- \leftrightarrow n + \nu_e$$

$$n \leftrightarrow p + \pi^-$$

↓

$$\mu_{\pi^-} = \mu_e - \mu_{\nu_e}$$

# Axion production rates: neutron bremsstrahlung (example)




$$\mathcal{L} \supset \frac{C_{aNN}}{2f_a}\partial_\mu a\bar{N}\gamma^\mu\gamma^5 N$$

KSVZ (no tree-level quark coupling)

$$C_{aNN} \sim 0.02$$

ALP: no axion-gluon or tree-level quark

$$C_{aNN} \sim 10^{-4}$$

$$\frac{dN_a}{dt} \sim R^3 \frac{dn_a}{dt}$$

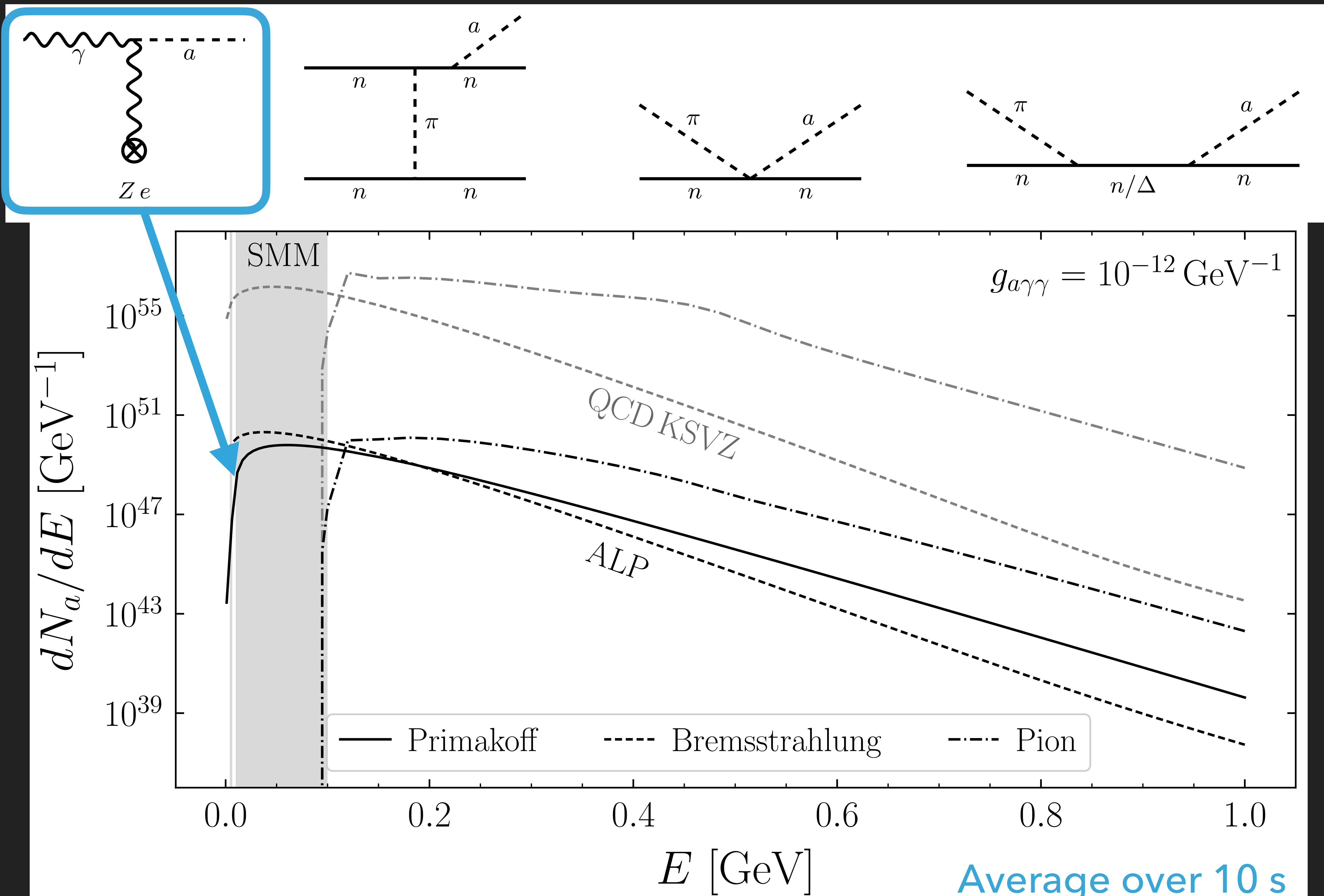
$$\frac{dn_a}{dt} \sim \frac{C_{aNN}^2}{f_a^2}\frac{p_f^4}{m_n^4}T^5$$

← Fermi suppression

$$\longrightarrow \frac{dN_a}{dt} \sim 10^{55}\,\frac{1}{\mathrm{s}}\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)^2$$

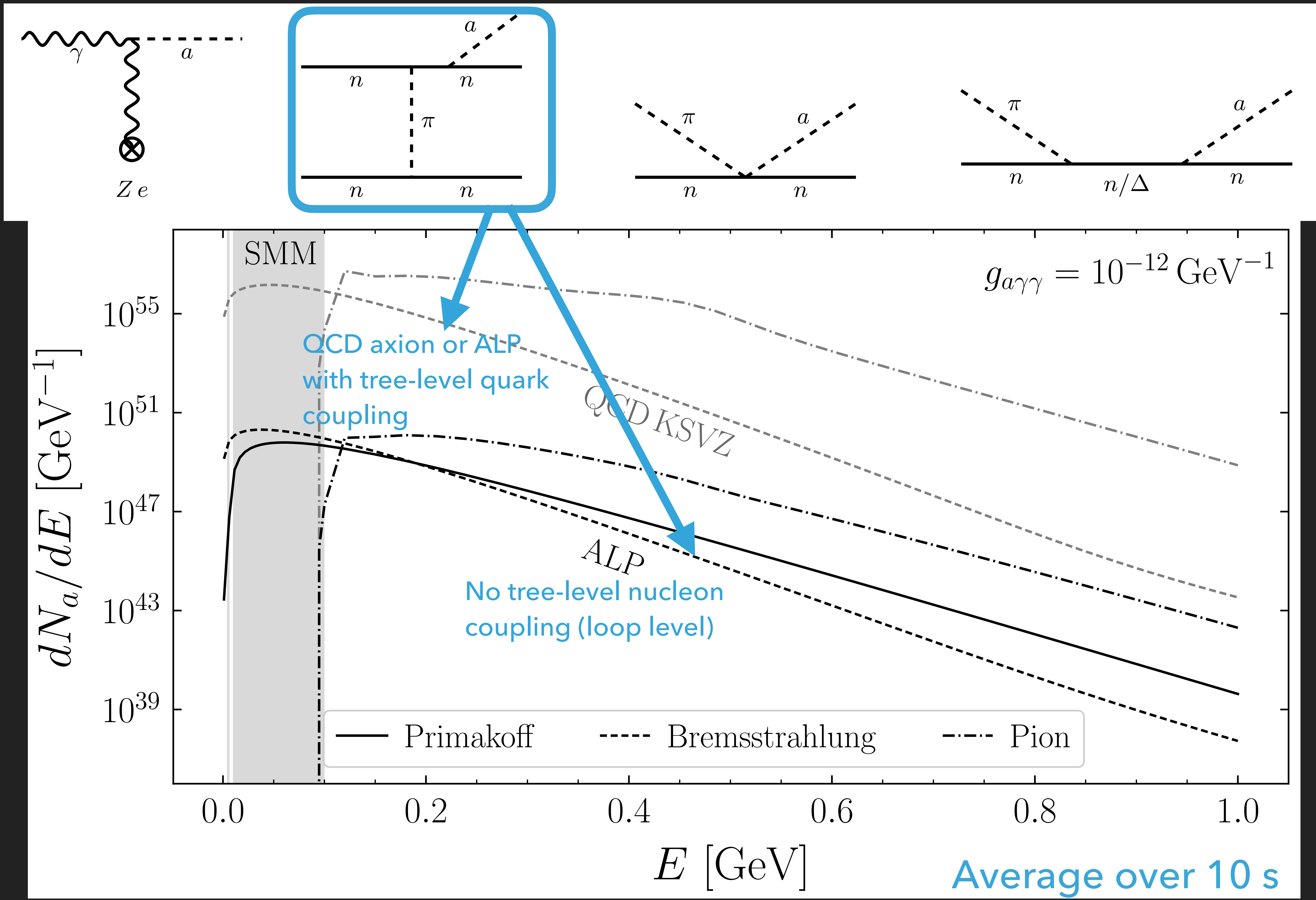
(KSVZ at ~1s after explosion)

# Proto Neutron Stars from SN also produce axions




Average over 10 s

# Proto Neutron Stars from SN also produce axions



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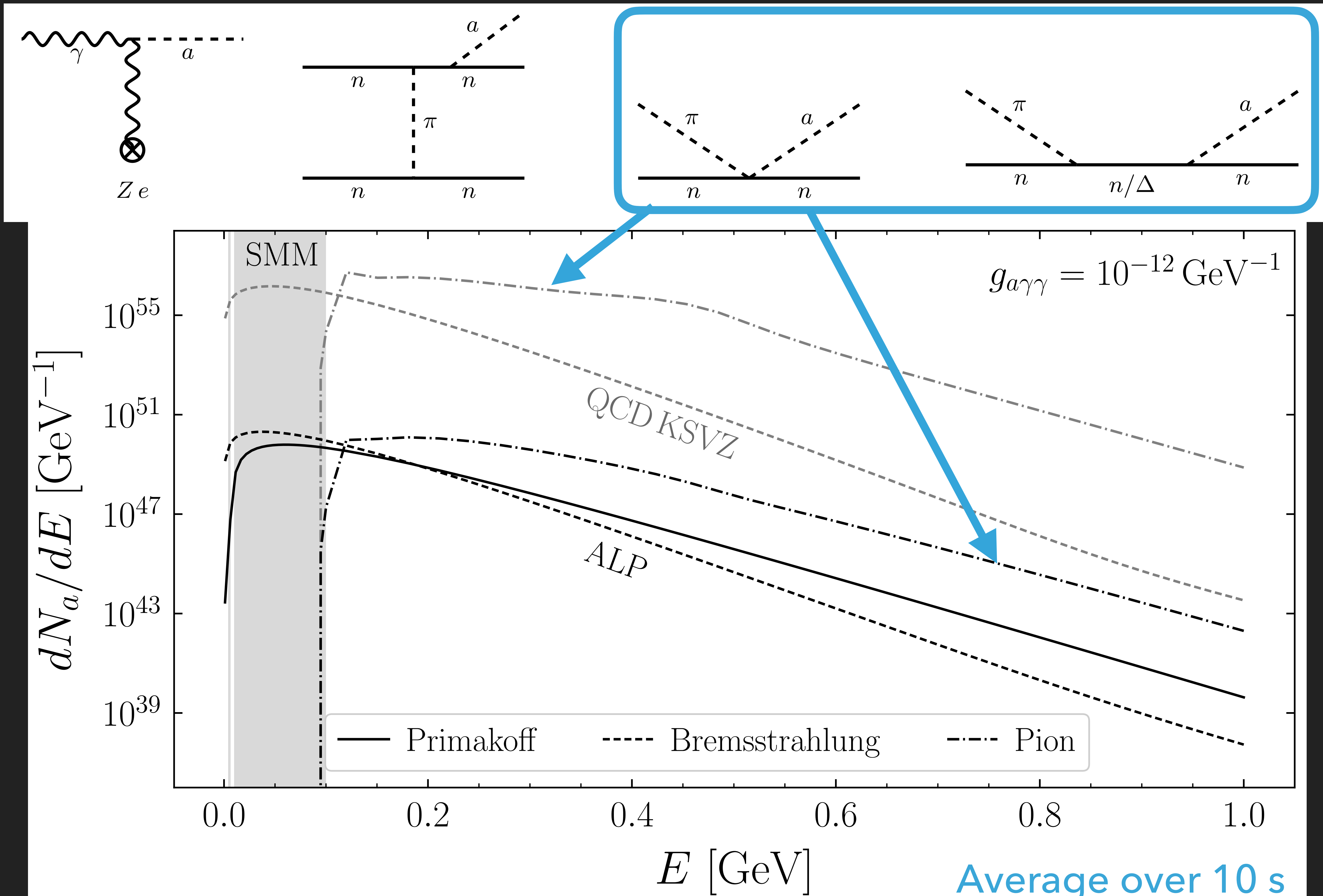
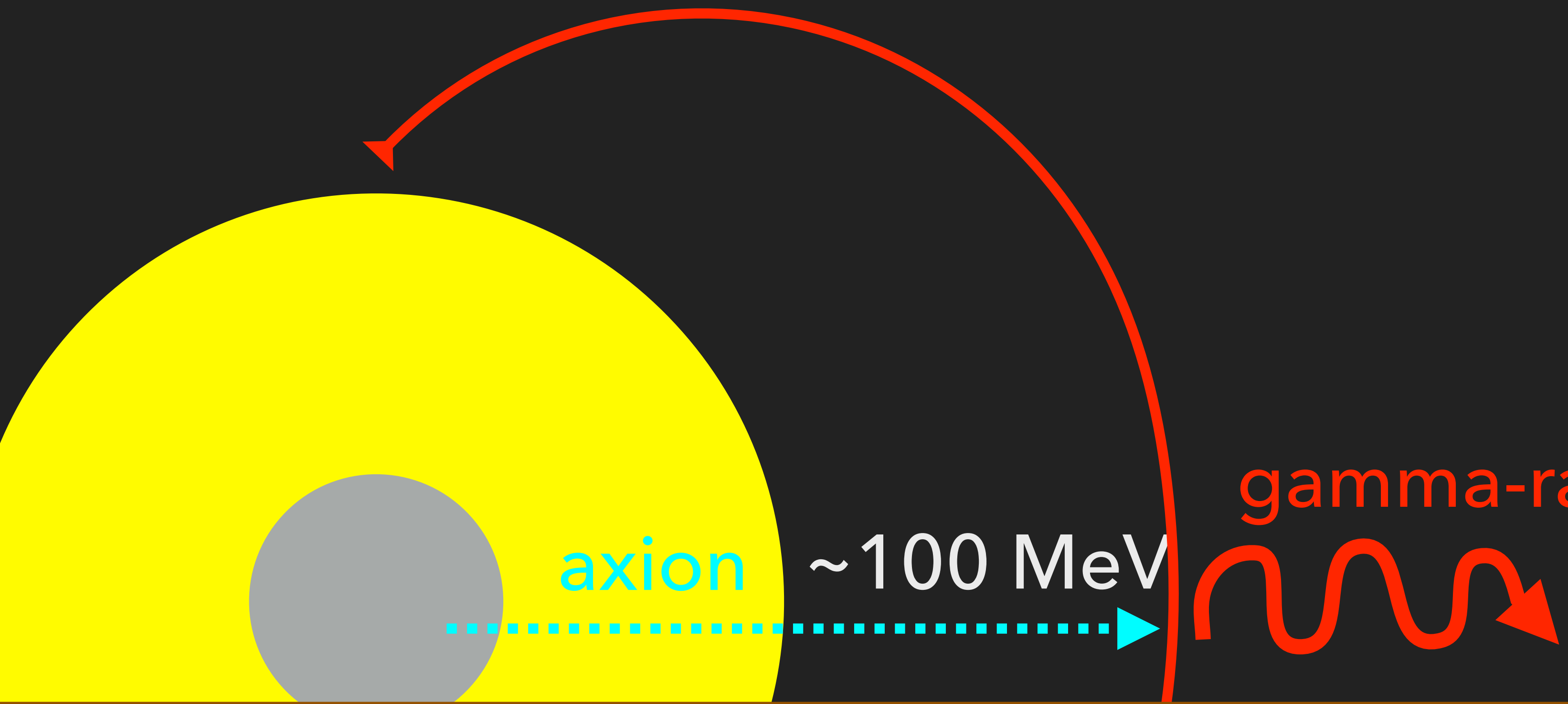



Average over 10 s

# Axions convert to gamma-rays on magnetic fields




solar maximum mission

**SN1987A progenitor: Sk -69 202**

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

**Galactic Magnetic field**

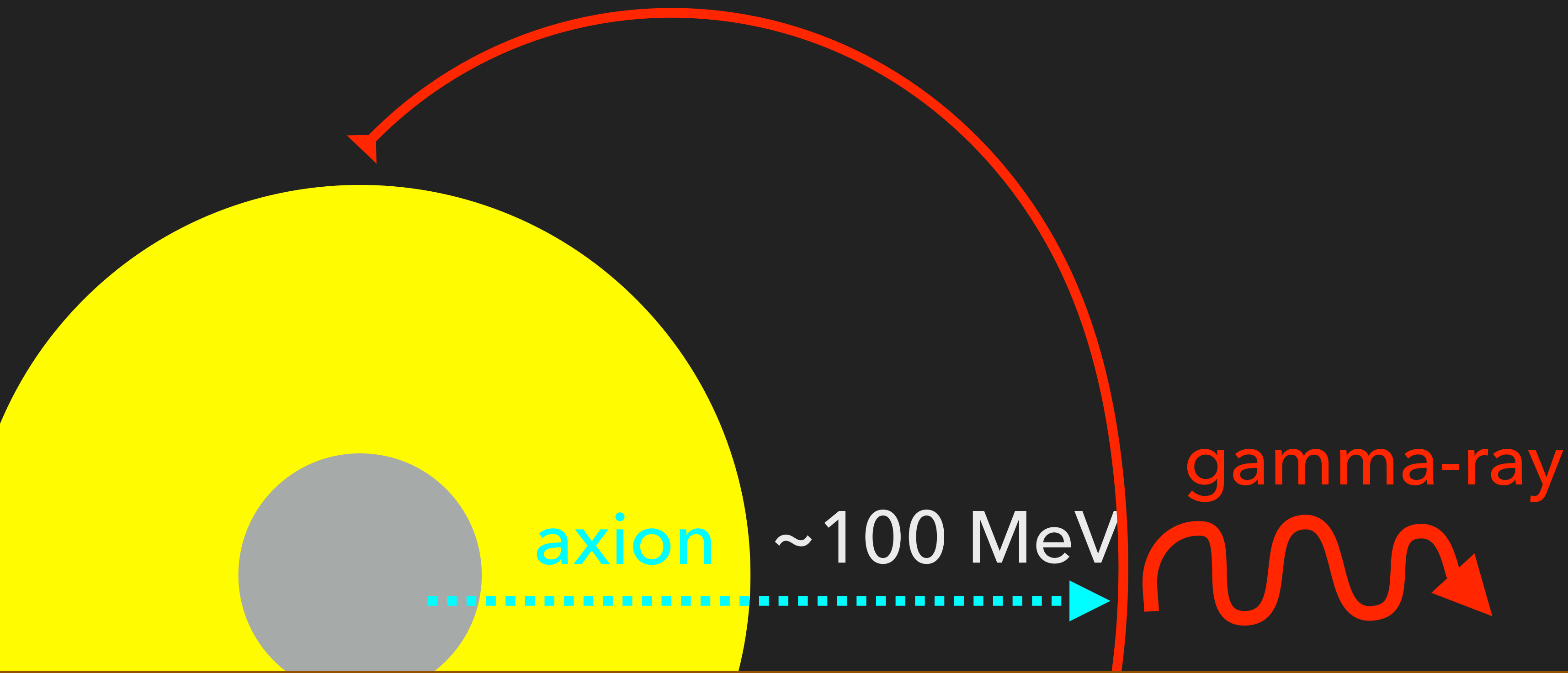
1. ordered + random fields
2. $L \sim \mathrm{kpc}$
3. $B \sim \mu G$

**Axion-photon conversion probability:**

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

⟵ For both!!

# Axion and photons must remain in phase to convert

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**SN1987A progenitor: Sk -69 202**

1. Blue Supergiant
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3. B ~ 1 kG

**progenitor conversion probability:**

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

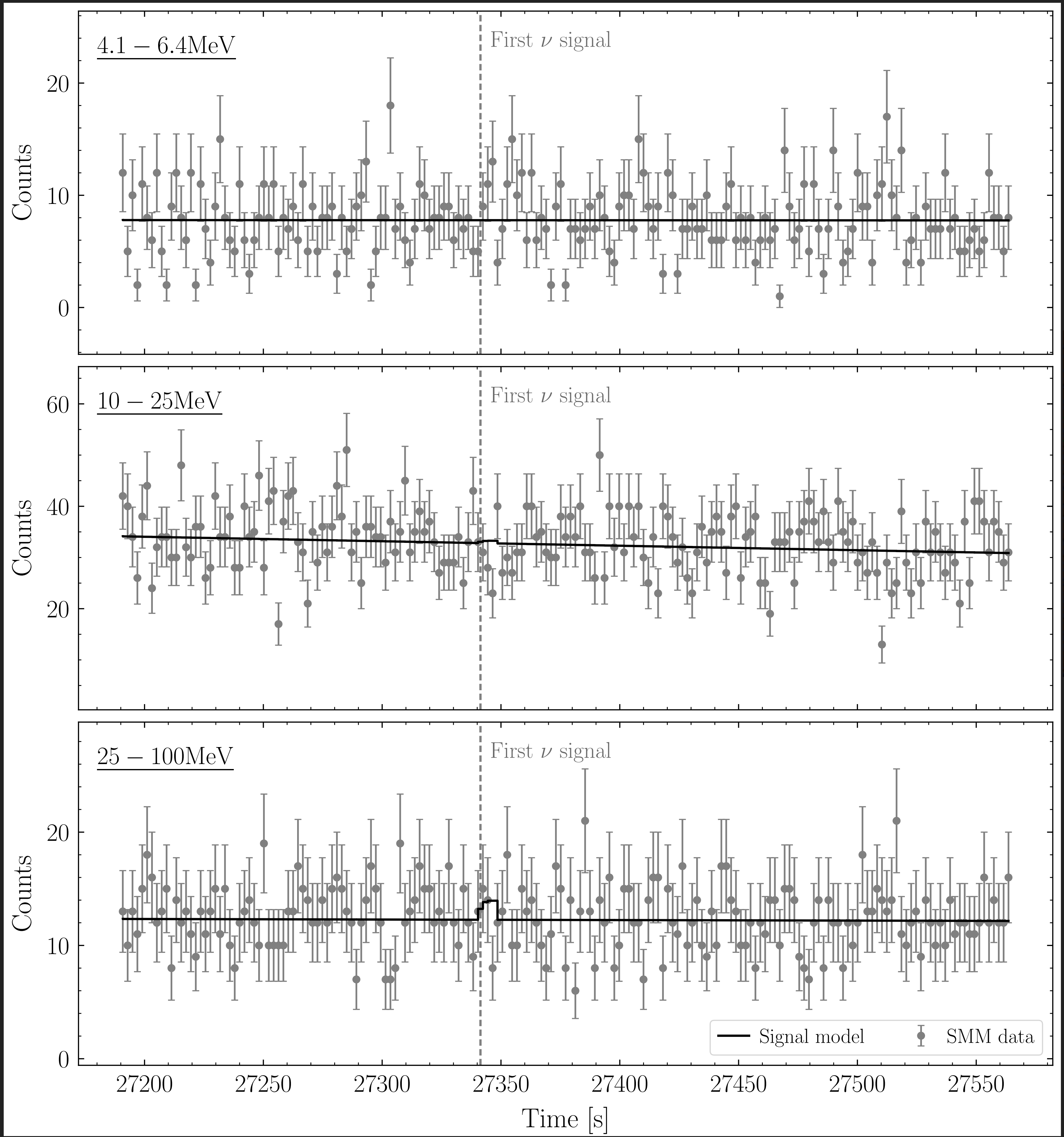
$$\sim 10^{-5} \left( \frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}} \right)^2$$

Matches Galactic conversion prob.!

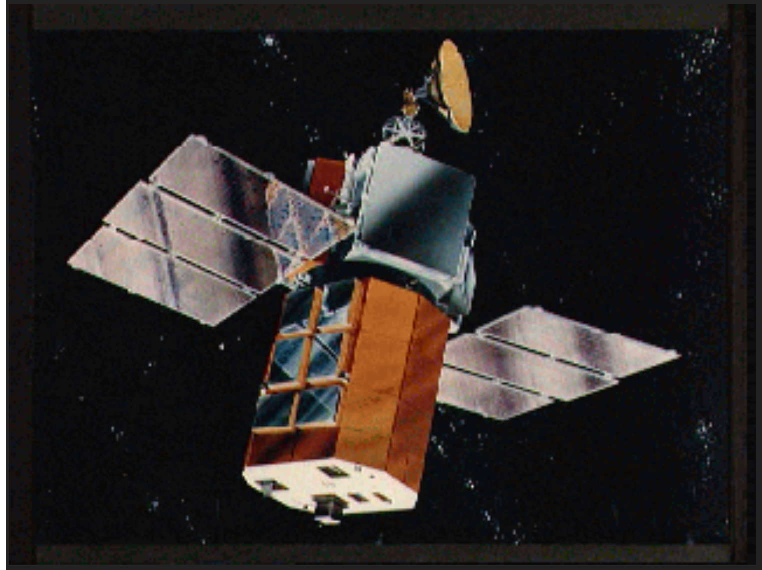
**when does mass-dependence come in?**

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

# SMM did not see a gamma-ray burst from SN1987A

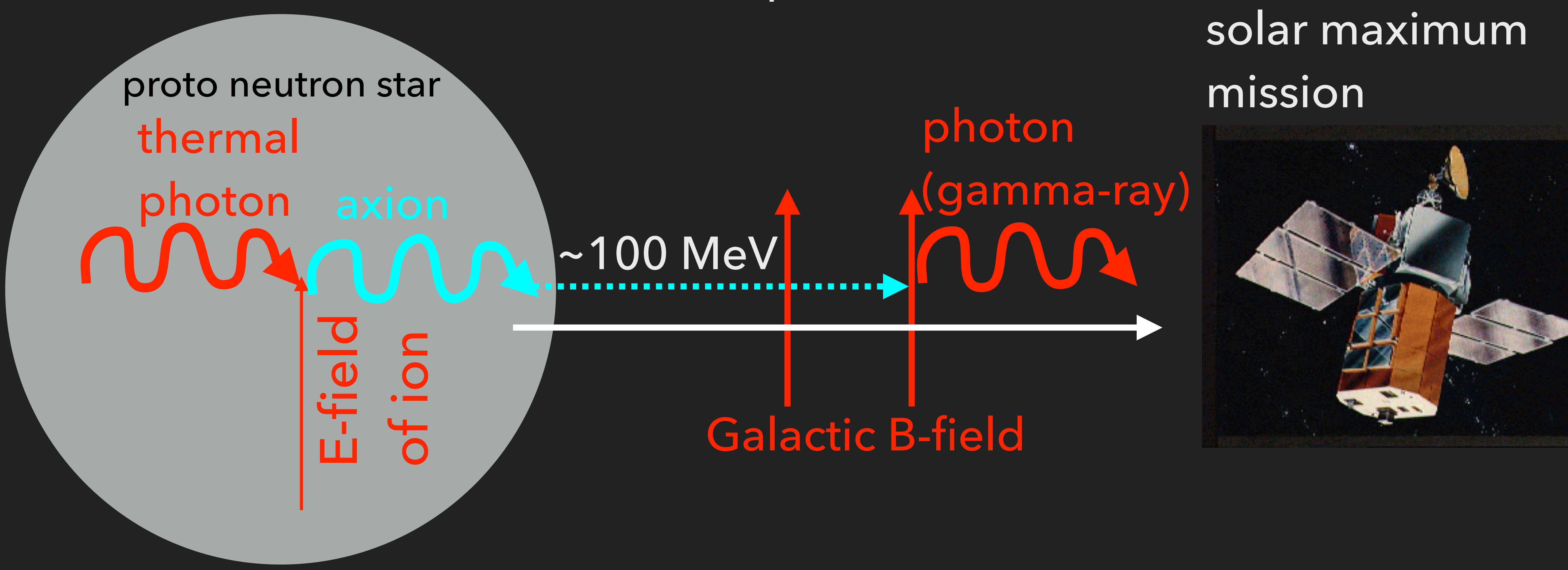



solar maximum mission



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

SN1987A: in the LMC at d ~ 50 Mpc



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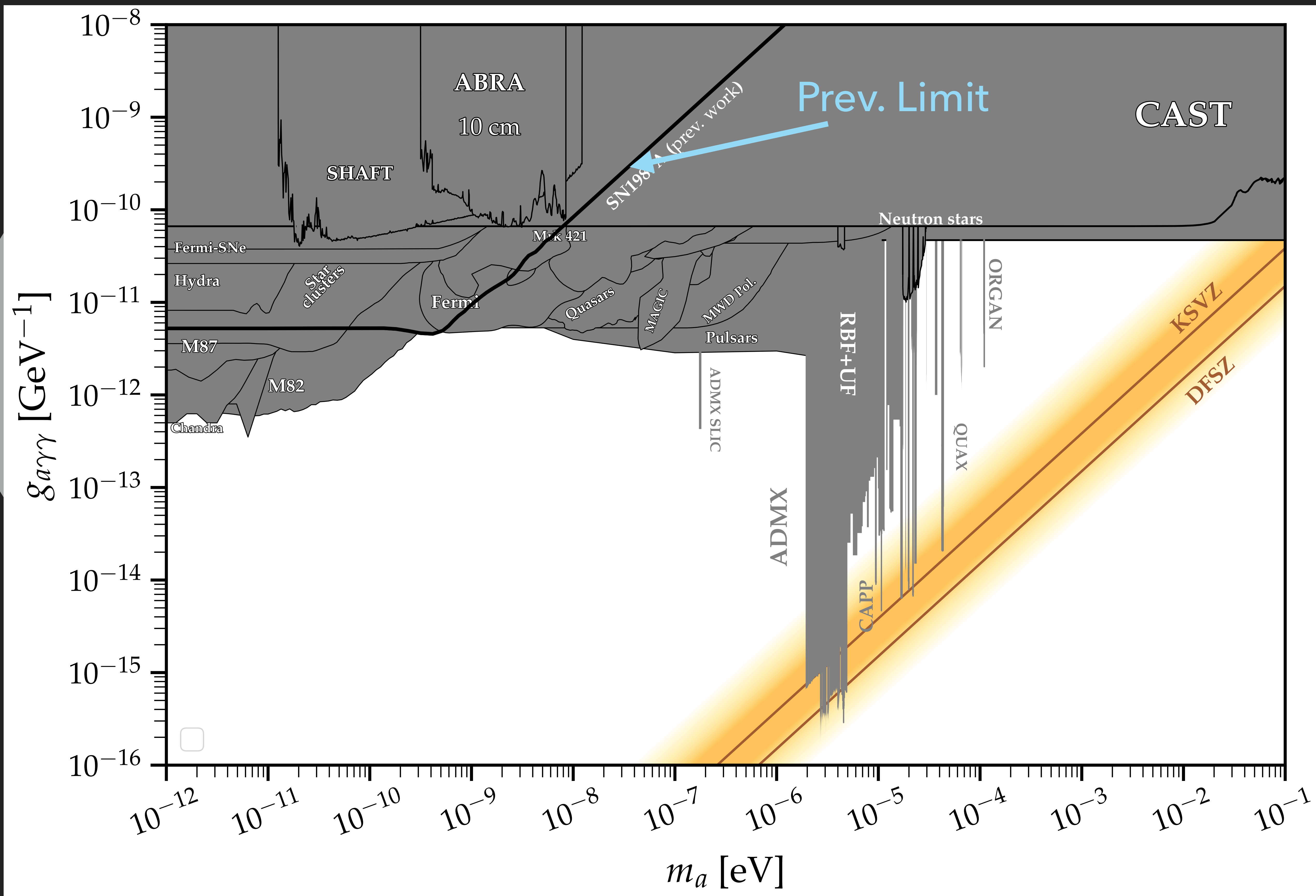
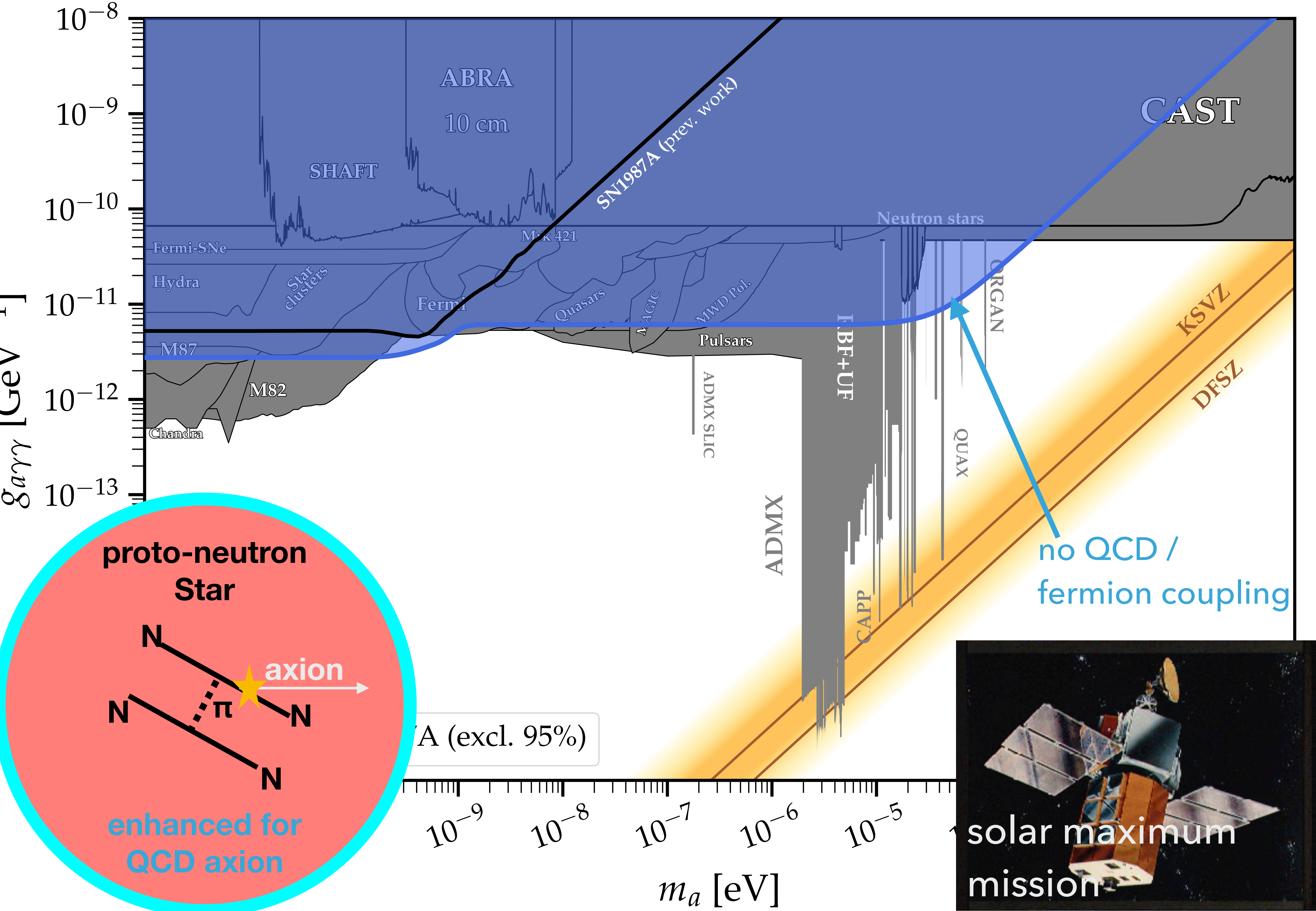
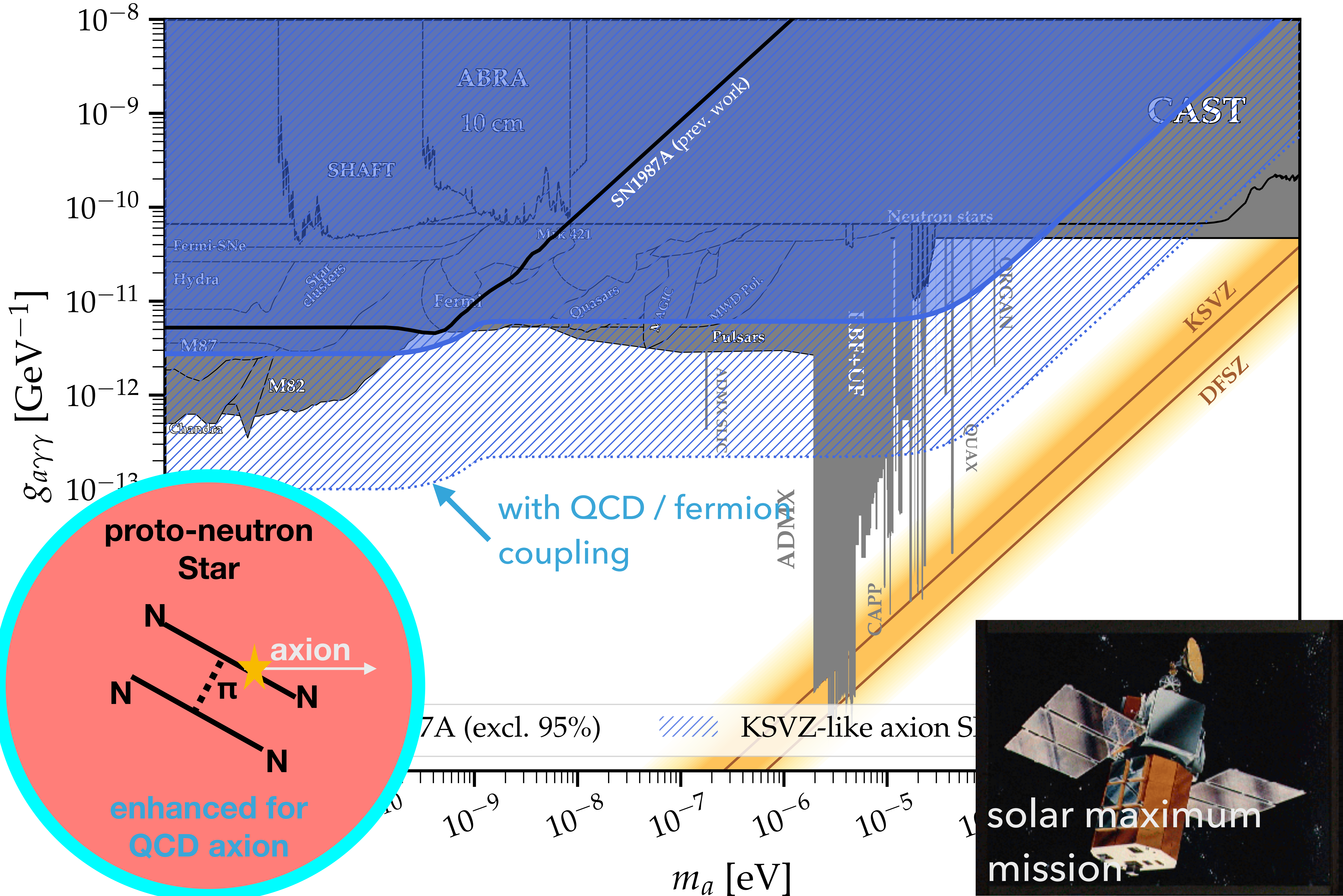


# New Idea: gamma-rays from SN1987A progenitor B-field



# 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?

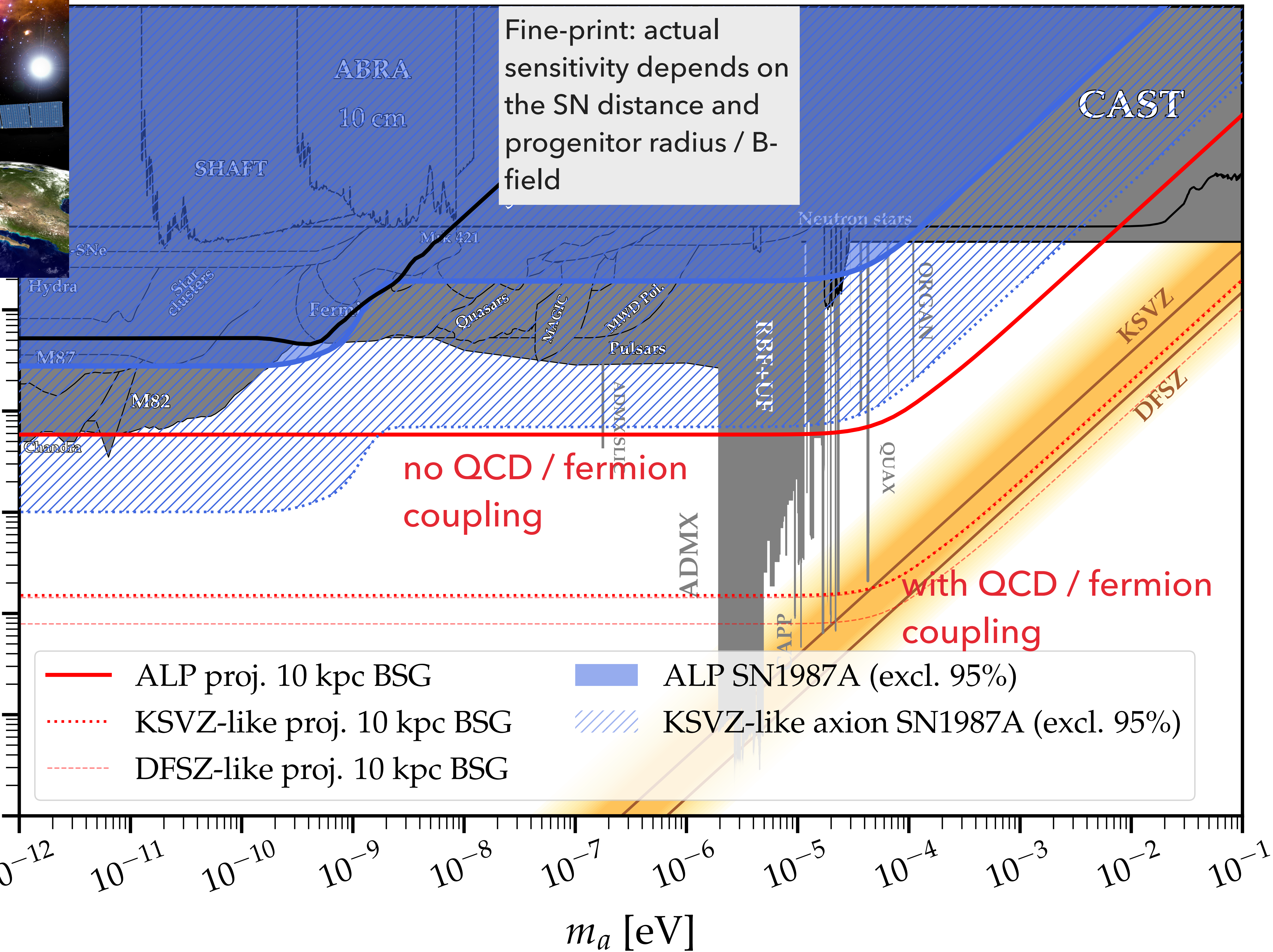
Answer: likely nothing!

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

# Future supernova

But what if Fermi did catch the next Galactic SN?

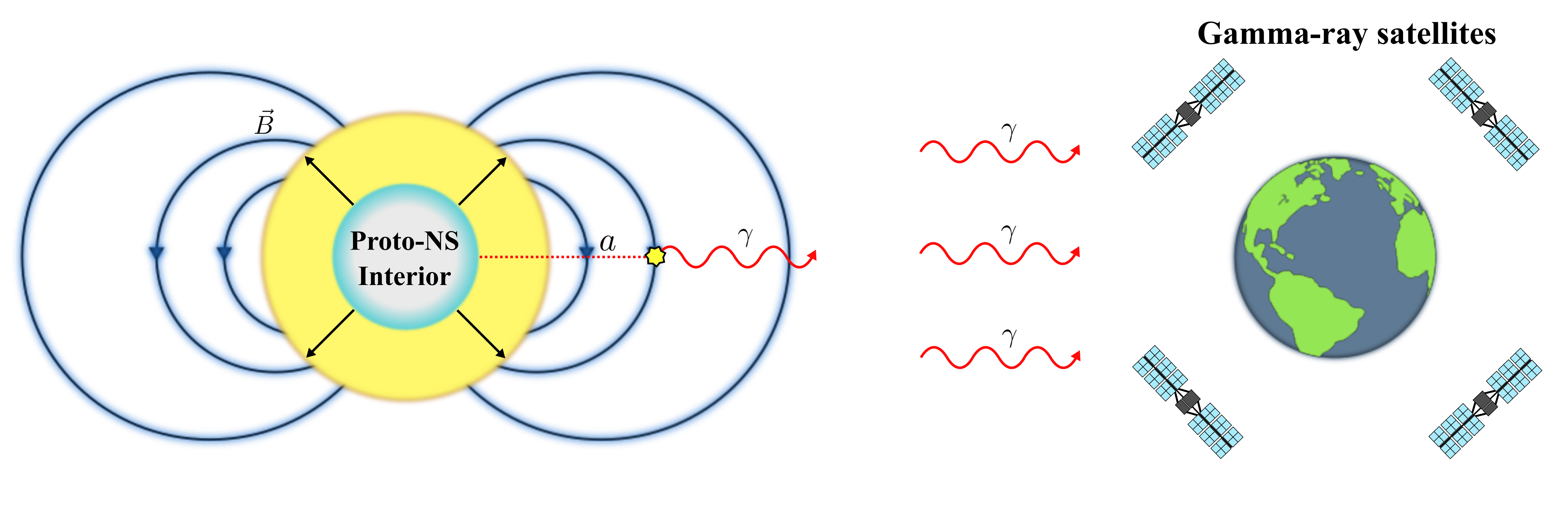
# Future supernova: axion signal with Fermi-LAT



# Future supernova

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

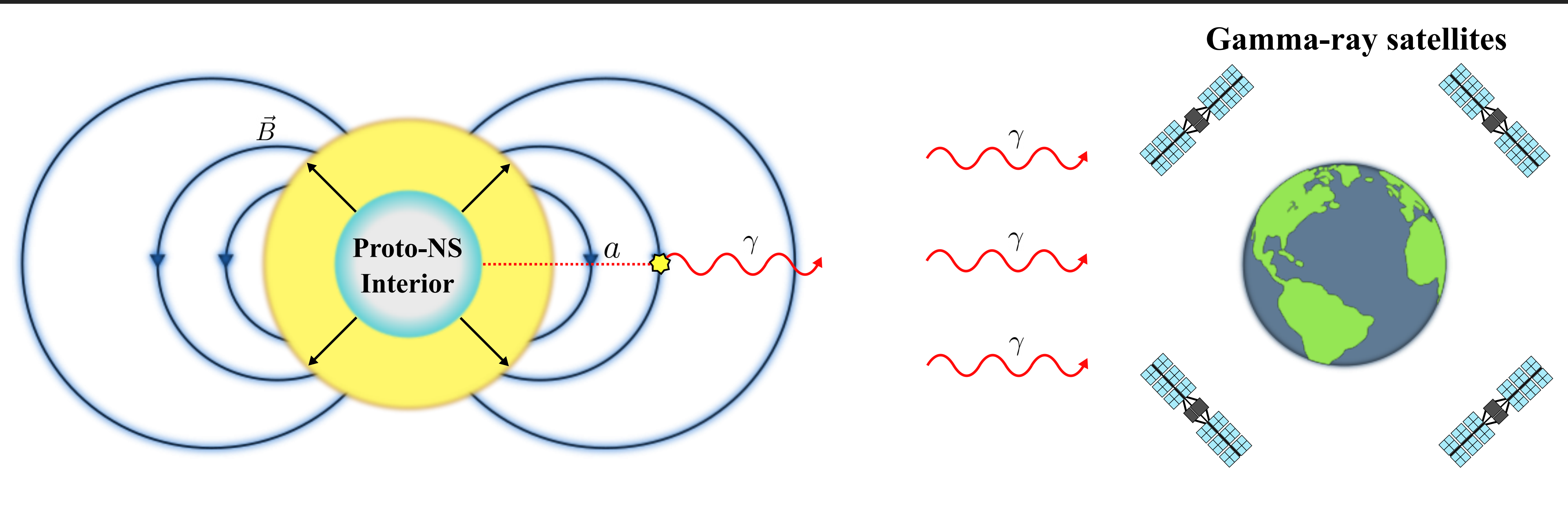
## **Proposal:** Full-Sky constellation of SmallSats for continuous, full-sky ~100 - 500 MeV gamma-ray detection

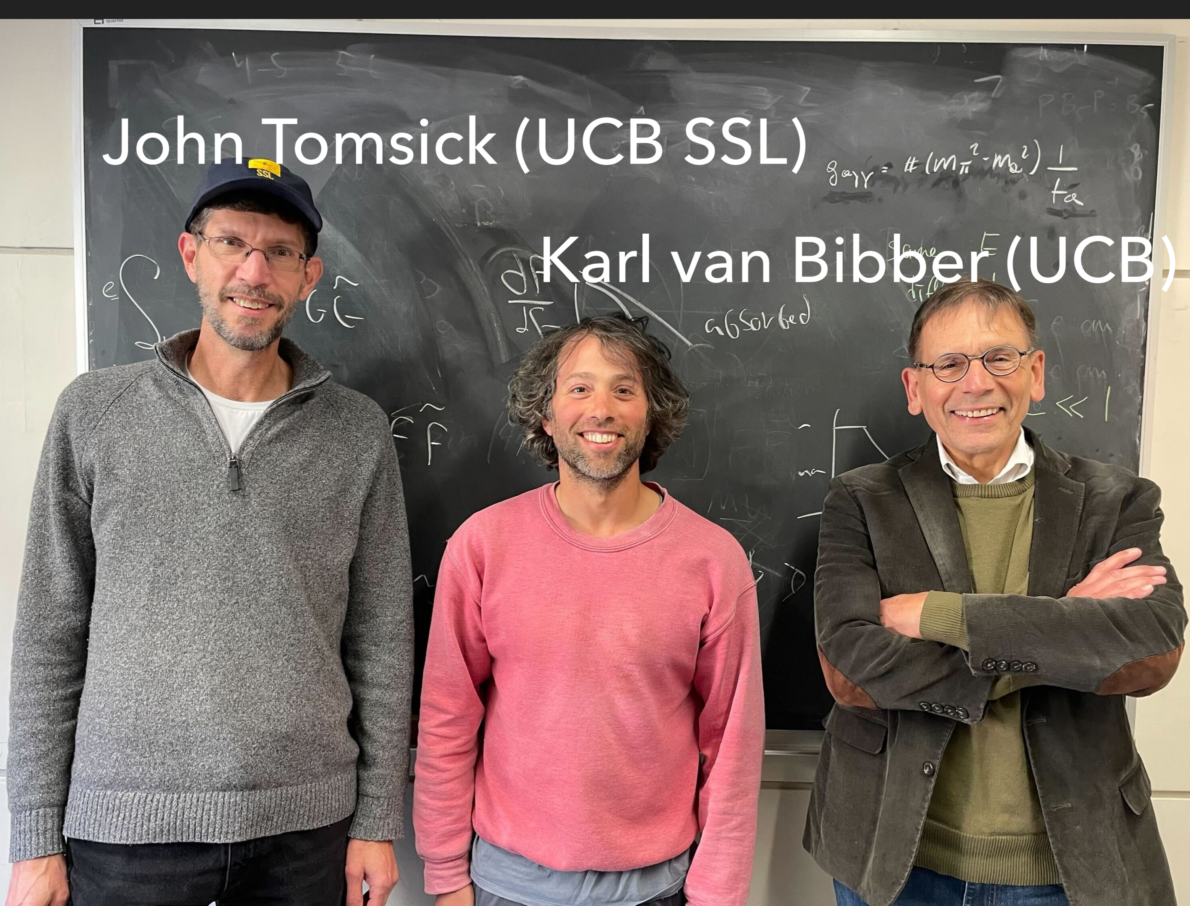



GALactic AXion Instrument for Supernova (GALAXIS)

***Exciting Update**: Received funding to build a prototype detector!*

# GALactic AXion Instrument for Supernova (GALAXIS)




1. Multiple 16U CubeSats (will construct 1 over next 3 years)
2. Alternating layers of converting and tracking scintillators
3. Read out by silicon photomultipliers
4. Will validate with radioactive sources + accelerator beams

## GALAXIS Science & Collaboration: Let's chat!

1. Dependence of axion signal on progenitor B-field?
2. Calculation of axion emissivity could be improved (pion condensate possible, ultra-high densities, 3d simulation, …)
3. What are other science targets for GALAXIS & how does that inform design?

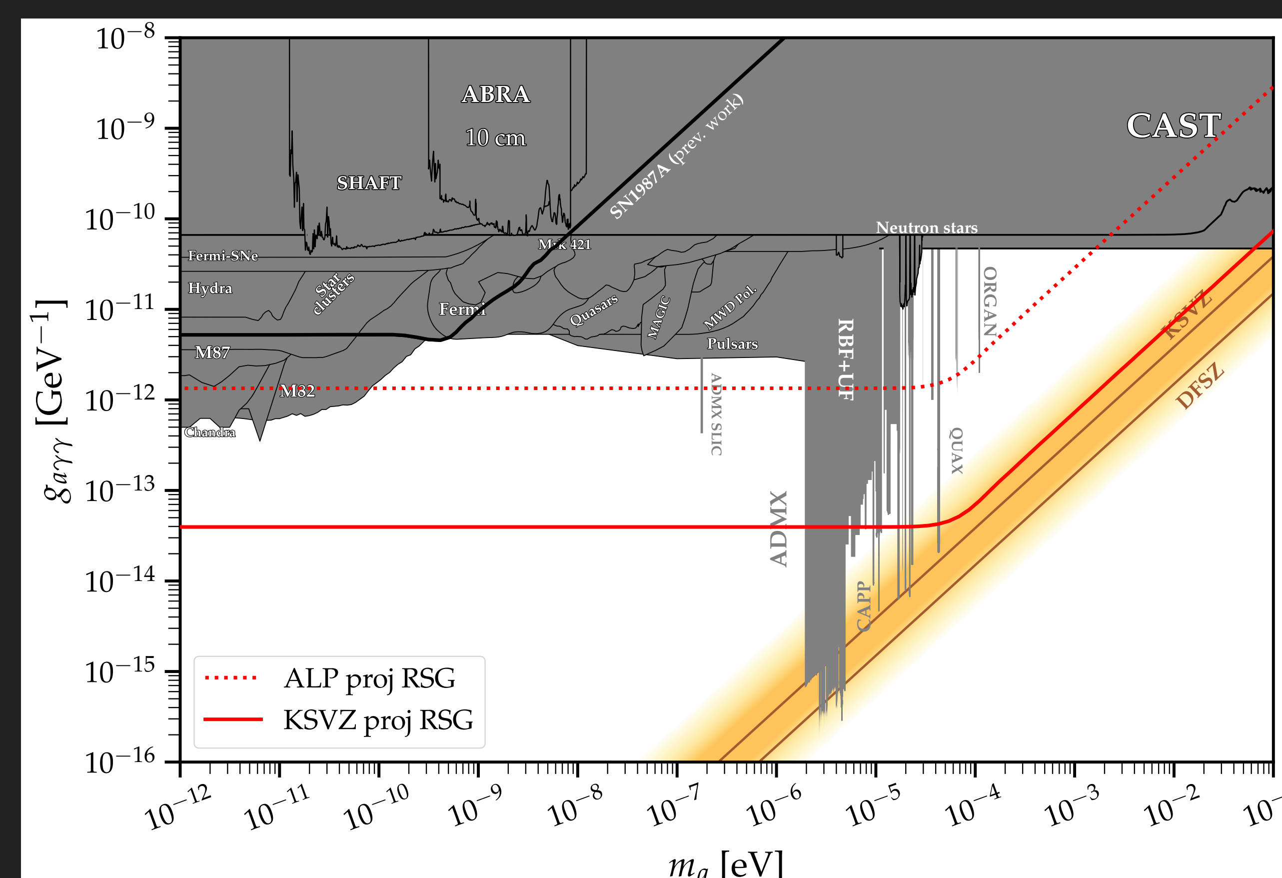
# Example of need for more work: progenitor field

## *SN1987A progenitor: BSG*

1. Strong dipole fields: B ~ 1 kG
2. Compact: R ~ 40 $R_s$

## *Most SN: RSG progenitors*

1. Weak dipole fields: B ~ kG
2. Large: R ~ 400 $R_s$
3. Turbulent fields from convection: B ~ 100 G, L ~ 40 $R_s$



# Heavy axions also exciting gamma-ray science from SN

## *Heavy axions coupling to QCD expected in string axiverse*

**Time-delayed gamma-ray signatures of heavy axions from core-collapse supernovae**


Joshua N. Benabou,[1,2] Claudio Andrea Manzari,[1,2] Yujin Park,[1,2]
Garima Prabhakar,[2] Benjamin R. Safdi,[1,2] and Inbar Savoray[1,2]

[1] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.*
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(Dated: December 19, 2024)
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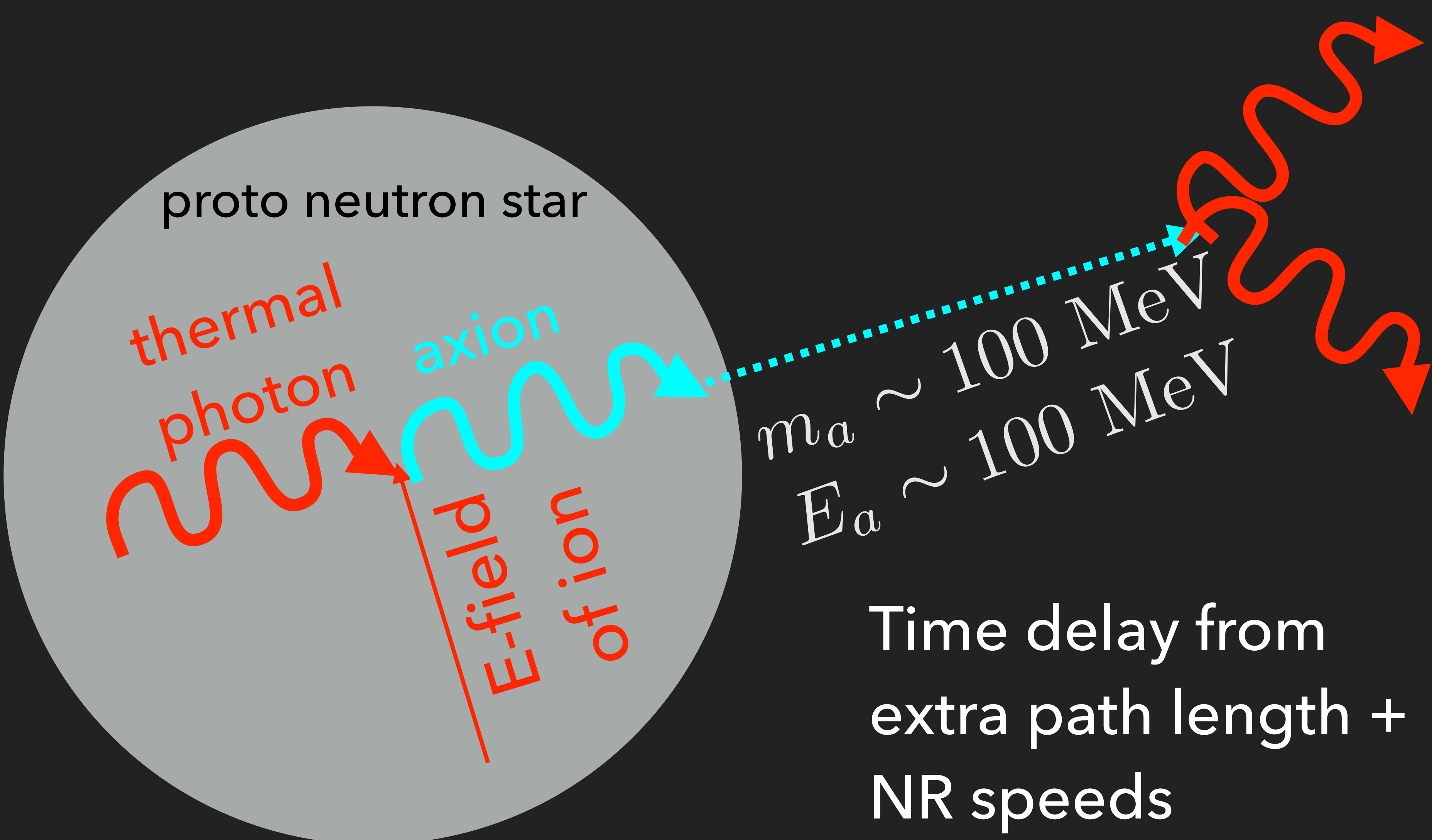


Time delay from extra path length + NR speeds

# Heavy axions also expected to couple to QCD

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

QCD axion and heavy ALPs only!

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

Large!


Sring Axiverse: *heavy axions -> small cycles -> large instanton actions*

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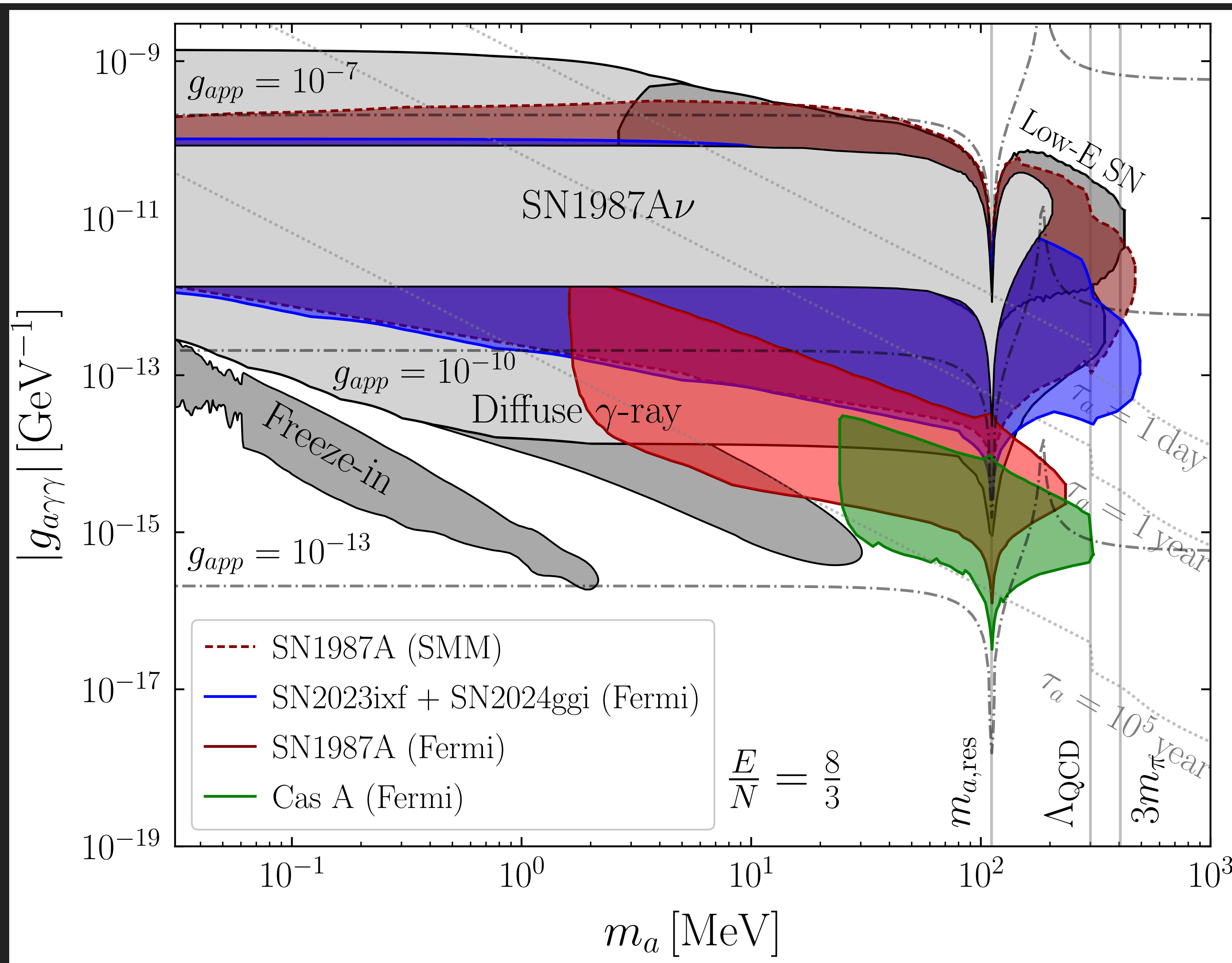

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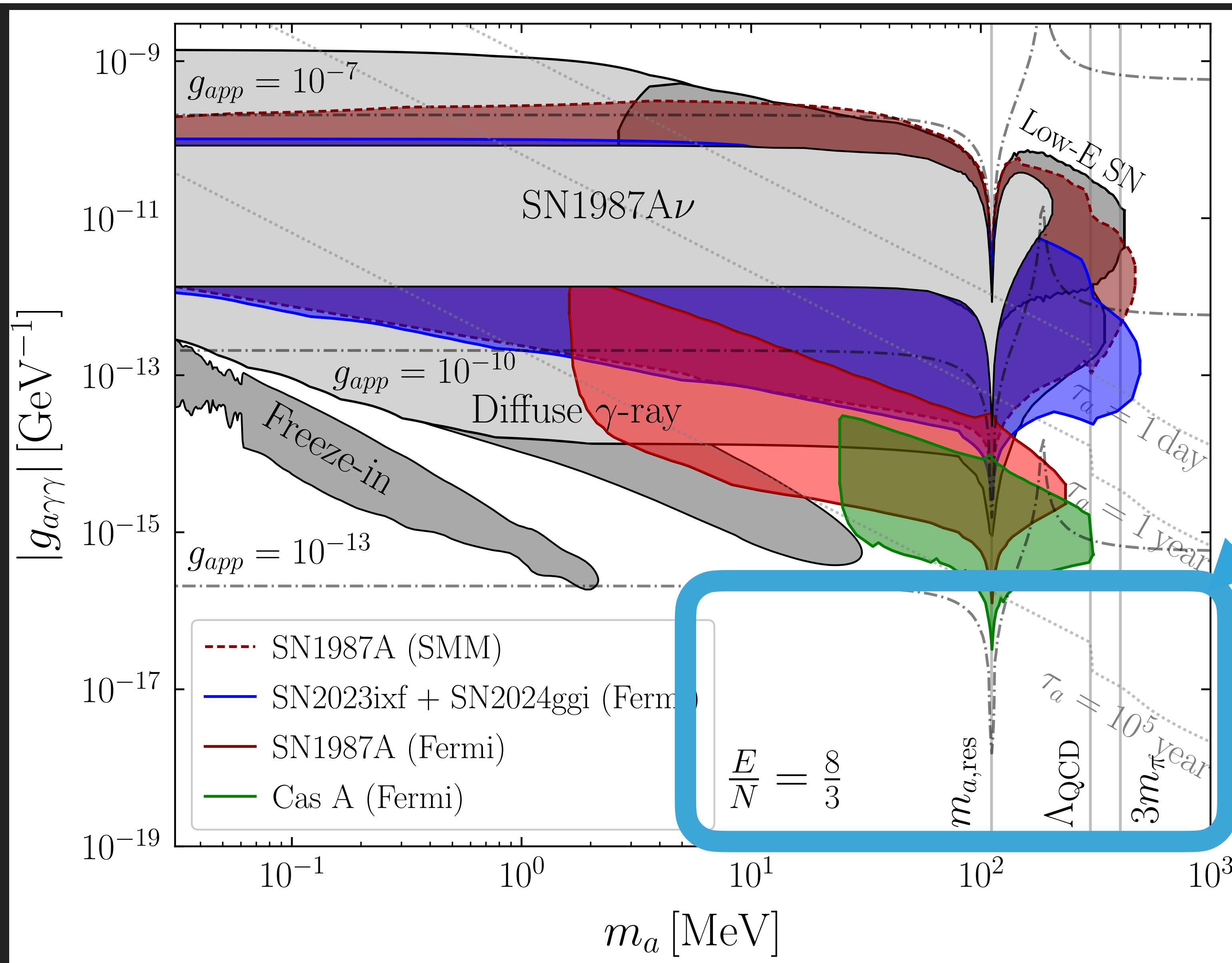
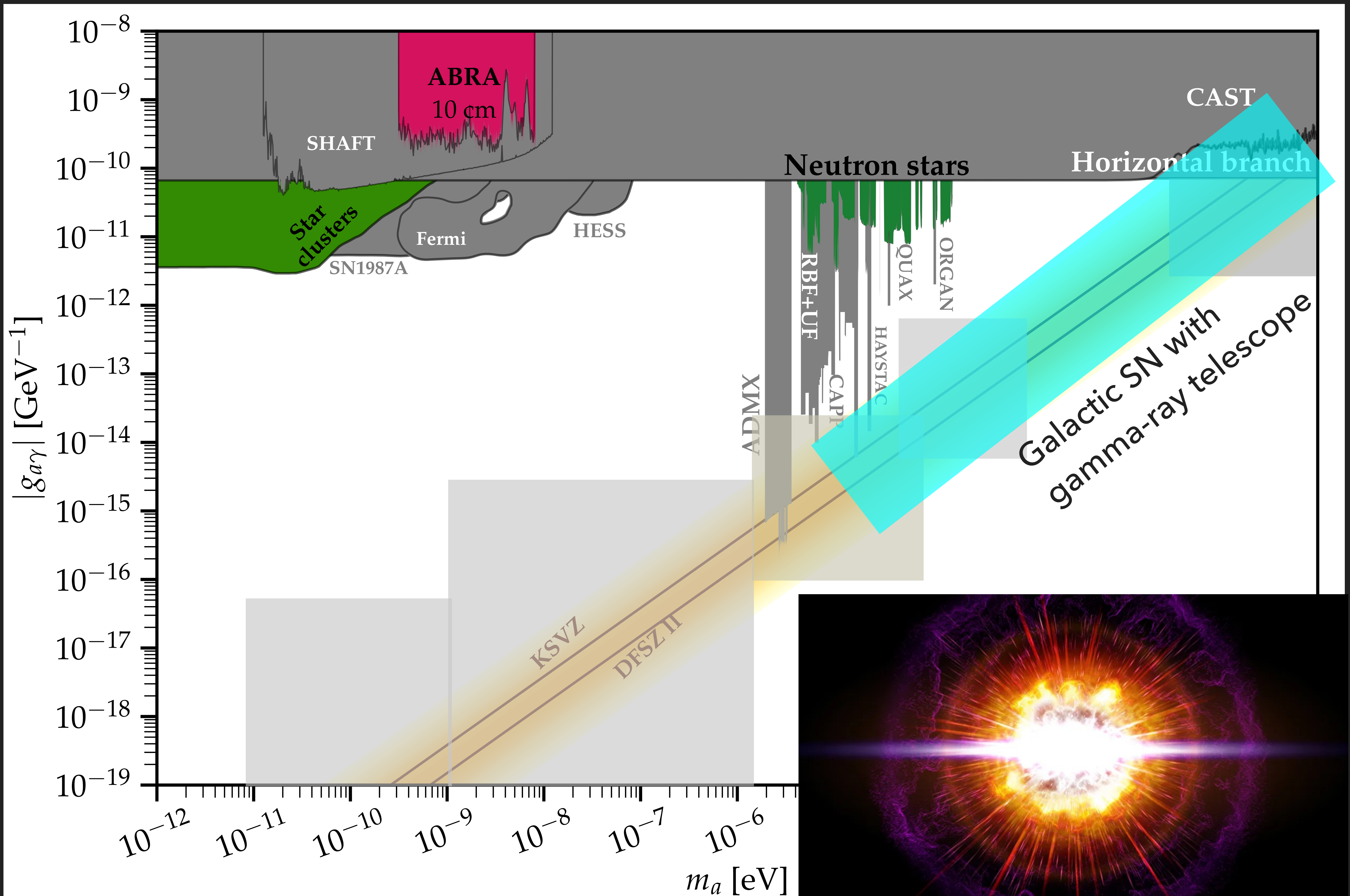



GUT scale decay constants: Next SN + GALAXIS

# Supernovae provide discovery path for QCD axion



# QUESTIONS?

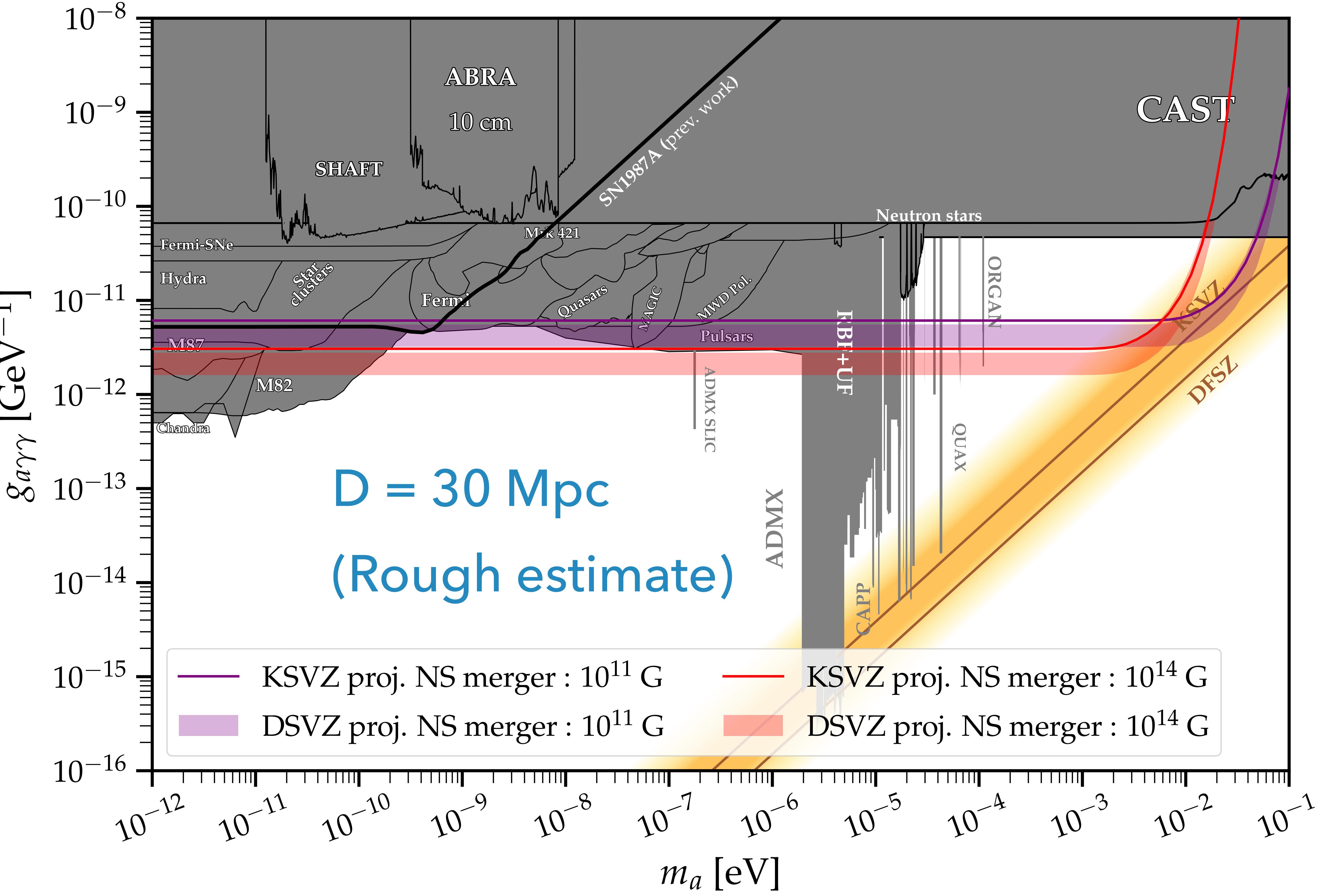
NASA

ALFRED P. SLOAN FOUNDATION

U.S. DEPARTMENT OF ENERGY

Office of Science

# Axions from NS-NS mergers may produce gamma rays



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

Fermi missed it!