

AXION PHENOMENOLOGY IN MAGNETIZED NEUTRON STARS

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ARXIV:2211.10863



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MELBOURNE



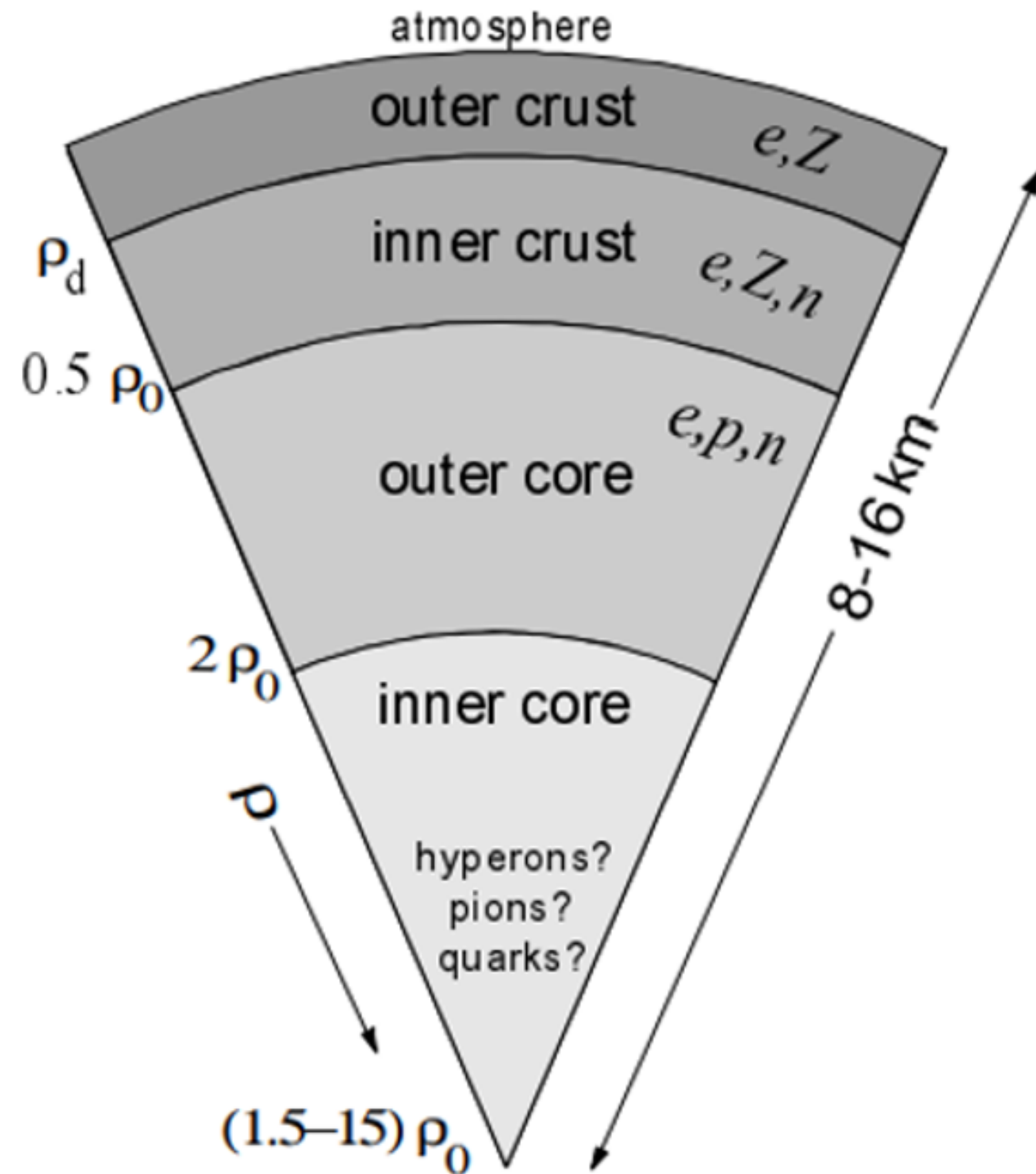
IN COLLABORATION WITH J. A. PONS, A. GÓMEZ-BAÑÓN,
P. D. LASKY, F. BIANCHINI AND A. MELATOS

AXIONS

- AXIONS WERE ORIGINALLY INTRODUCED TO SOLVE THE STRONG-CP PROBLEM [1]
- PLAUSIBLE CANDIDATES FOR DARK MATTER
- EXPECTED TO HAVE RICH PHENOMENOLOGY, BUT NOTHING OBSERVED YET
- BOOST AXION PHENOMENOLOGY WITH ELECTRODYNAMICS IN DENSE MATTER

[1] R. D. PECCEI AND H. R. QUINN, CP CONSERVATION IN THE PRESENCE OF PSEUDOPARTICLES, PHYS. REV. LETT. 38, 1440 (1977)

NSs



- **STRONG MAGNETIC FIELDS**

$$B_0 \in [10^8, 10^{15}] \text{ G}$$

CP-VIOLATING COUPLINGS IN NSs

ALP EQUATION OF MOTION [2]

$$\square a + (m_a)^2 a = \frac{g_{a\gamma}}{4\pi} \mathbf{E} \cdot \mathbf{B} - \sum_{j=p,n} \left(\bar{g}_{aj} \langle \bar{\psi}_j \psi_j \rangle + g_{aj} \langle i \bar{\psi}_j \gamma^5 \psi_j \rangle \right)$$

GM1A EoS [3] + WEAK INITIAL MAGNETIC FIELDS

$$\square a + (m_a)^2 a = -\bar{g}_{aN} \rho_S$$

[2] I. G. IRASTORZA AND J. REDONDO, PROGRESS IN PARTICLE AND NUCLEAR PHYSICS 102, 89 (2018)

[3] GUSAKOV M. E., HAENSEL P., KANTOR E. M., 2014, MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY, 439, 318

CP-VIOLATING COUPLINGS IN NSs

- ALP EQUATION OF MOTION

$$\square a + (m_a)^2 a = -\bar{g}_{aN} \rho_S$$

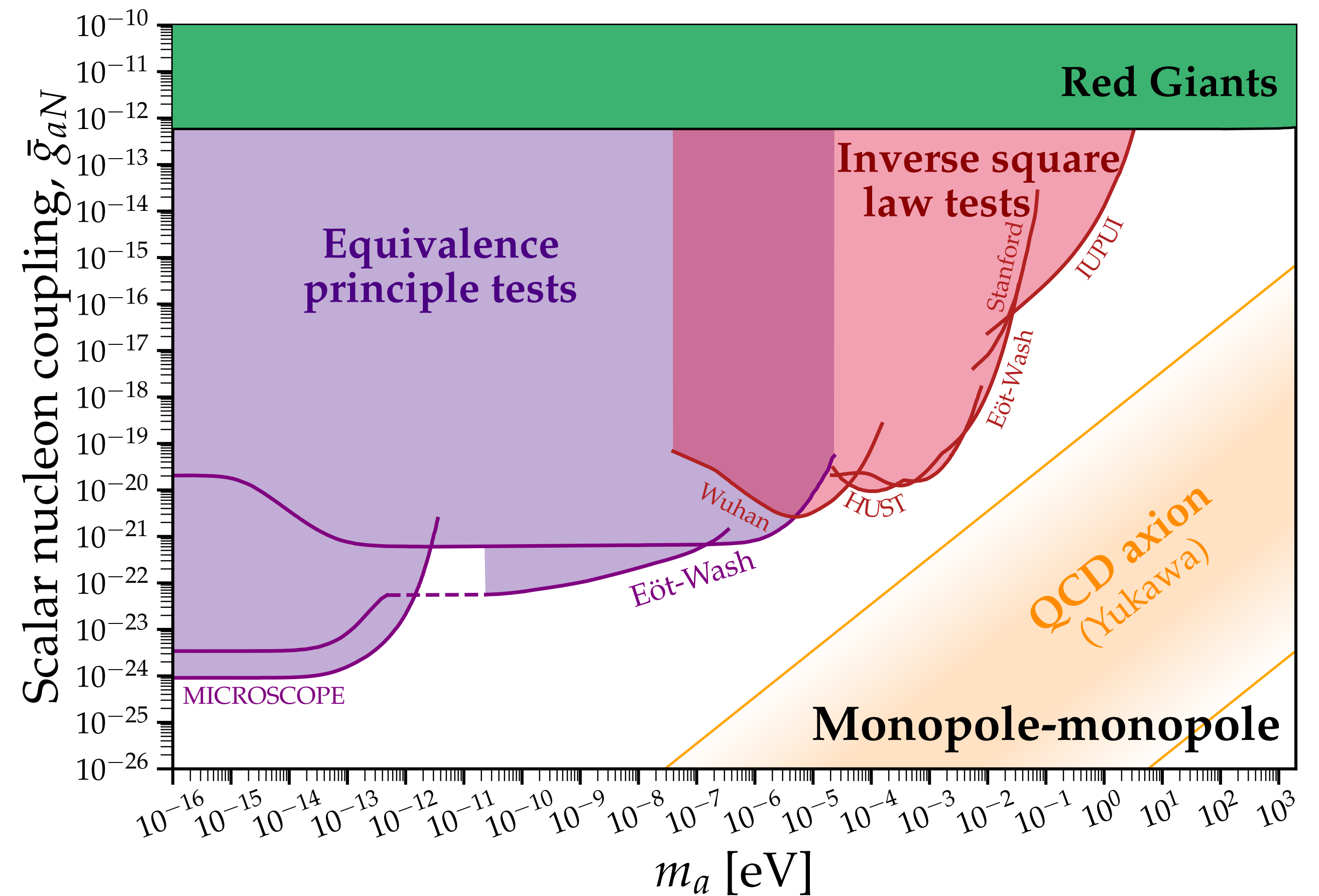
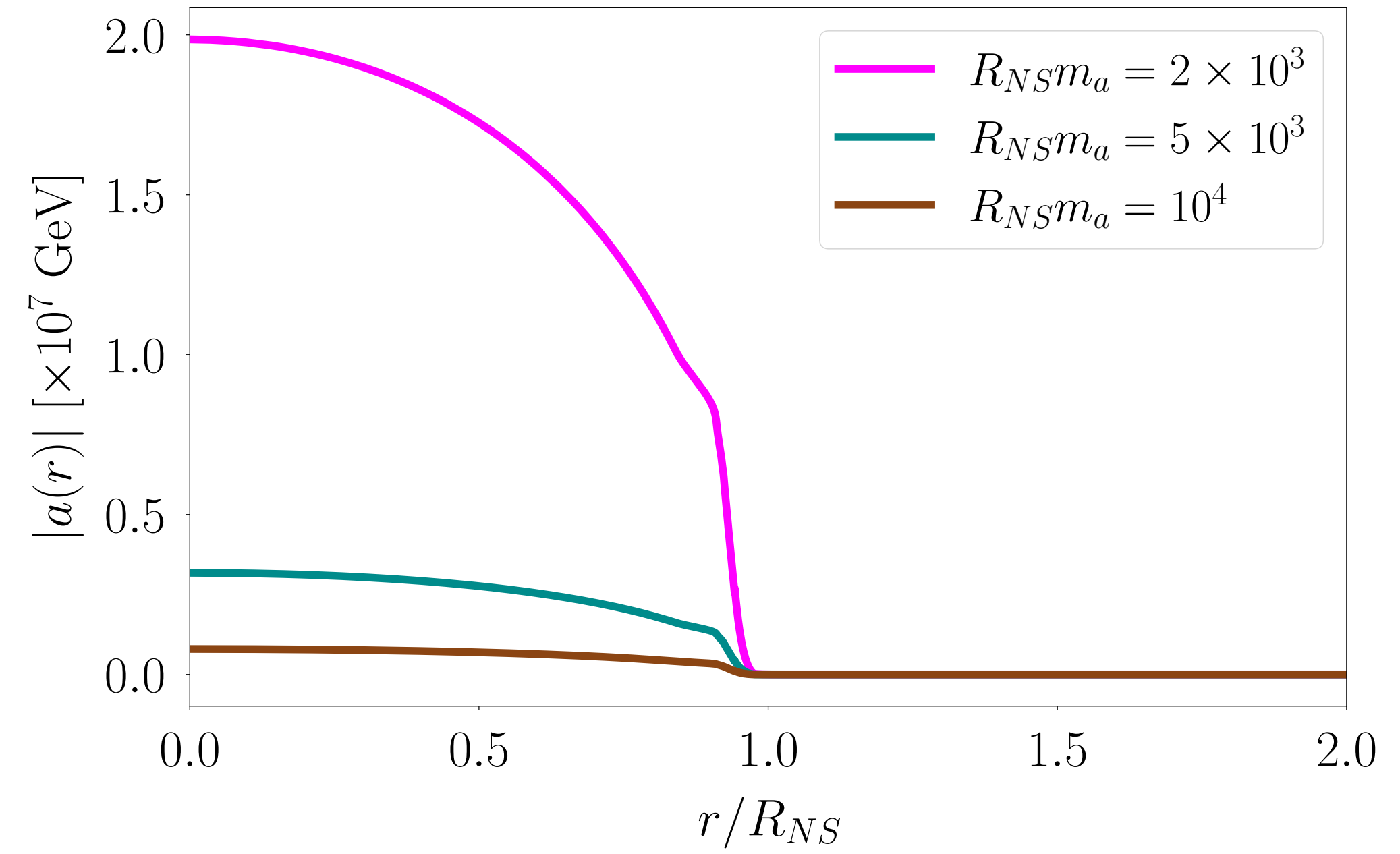
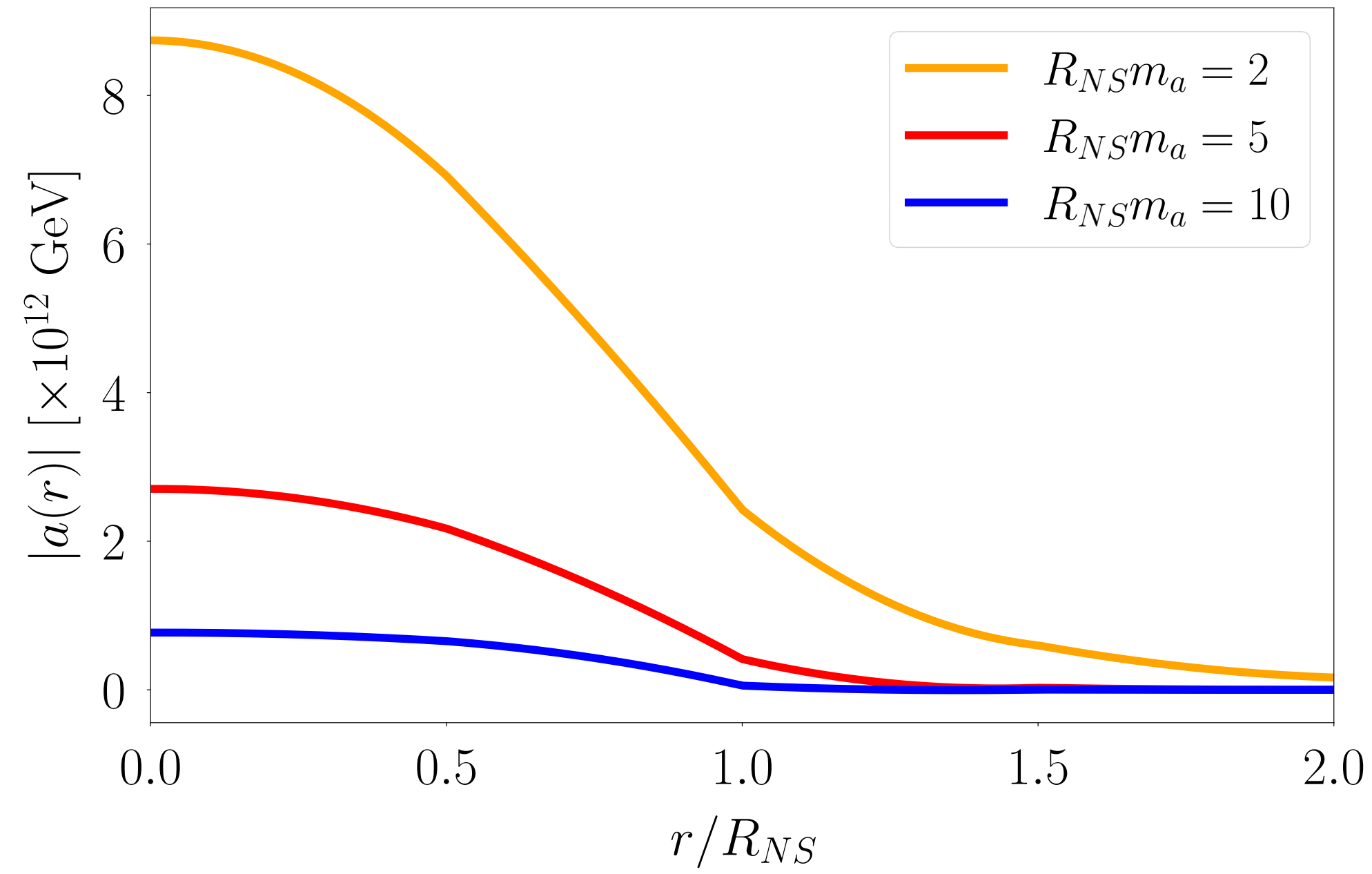


IMAGE CREDIT: C. O'HARE, CA JOHARE/AXIONLIMITS: AXIONLIMITS,
[HTTPS:// CAJOHARE.GITHUB.IO/AXIONLIMITS/](https://cajohare.github.io/axionlimits/) (2020)

[4] C. A. J. O'HARE AND E. VITAGLIANO, PHYS. REV. D 102, 115026 (2020)

ALPs IN NSs



$$2.9 \times 10^{-11} \lesssim m_a/\text{eV} \lesssim 1.5 \times 10^{-10}$$

$$2.9 \times 10^{-8} \lesssim m_a/\text{eV} \lesssim 1.5 \times 10^{-7}$$

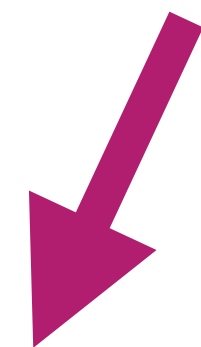
$$\bar{g}_{aN} = 10^{-23}$$

ONE ORDER OF MAGNITUDE SMALLER THAN LAB CONSTRAINTS!

AXION ELECTRODYNAMICS

MODIFIED INDUCTION EQUATION [5]:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left[\eta \nabla \times (e^\nu \mathbf{B}) + f_H [\nabla \times (e^\nu \mathbf{B})] \times \mathbf{B} - g_{a\gamma} c a e^\nu \mathbf{B} \right]$$



OHMIC DISSIPATION



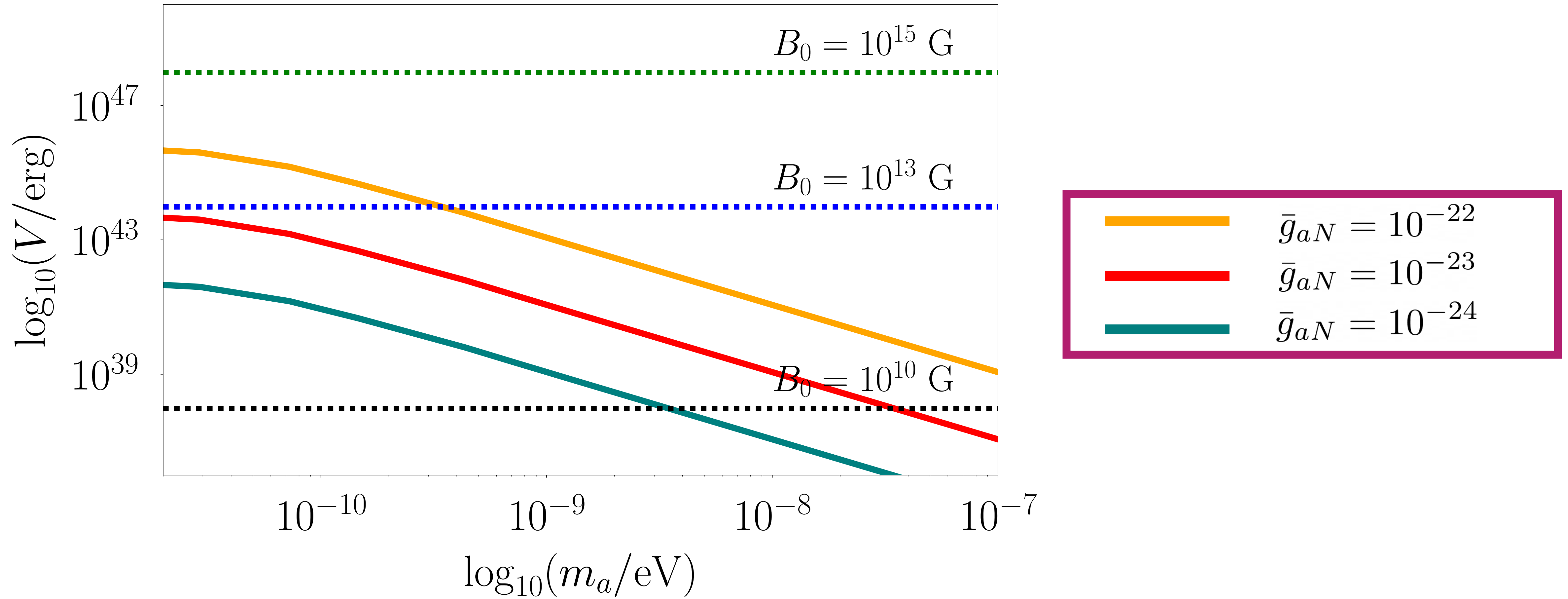
HALL DRIFT



DYNAMO

[5] L. VISINELLI, AXION-ELECTROMAGNETIC WAVES, MODERN PHYSICS LETTERS A 28, 1350162 (2013)

ESTIMATED ENERGY BUDGET FOR THE DYNAMO



DENSITY CORRECTIONS TO AXION POTENTIAL

$$a(r) \approx \begin{cases} \pm \pi f_a & r \leq r_{\text{crit}} \\ \pm \pi f_a \frac{r_{\text{crit}}}{r} e^{-m_a(r-r_{\text{crit}})} & r > r_{\text{crit}} \end{cases} .$$

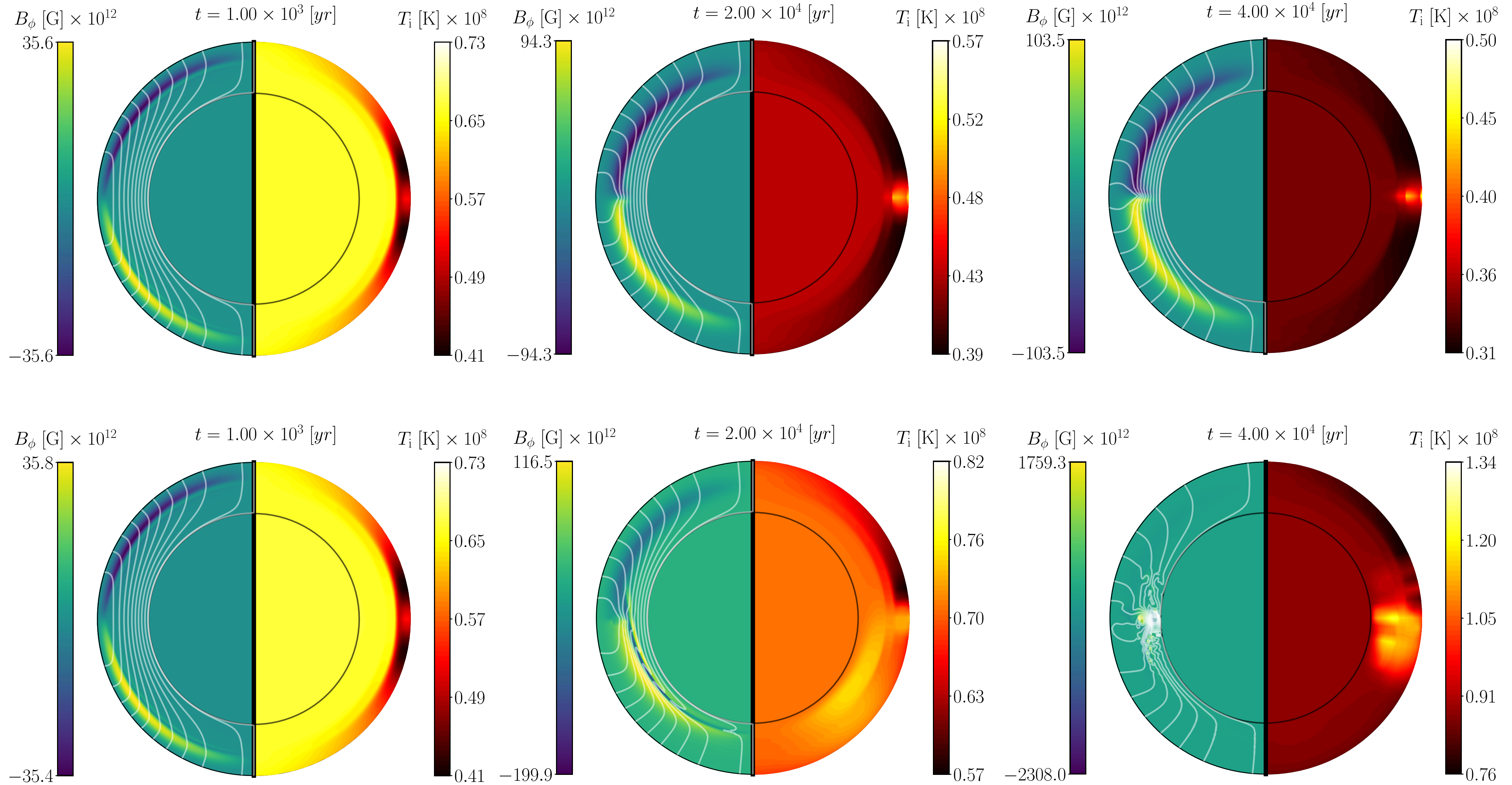
FINITE DENSITY CORRECTIONS
(SEVERAL POSSIBILITIES IN THE LITERATURE)

$$V(a) \approx \left(1 - \frac{\sigma_N n_N}{m_\pi^2 f_\pi^2} \right) V_0(a)$$

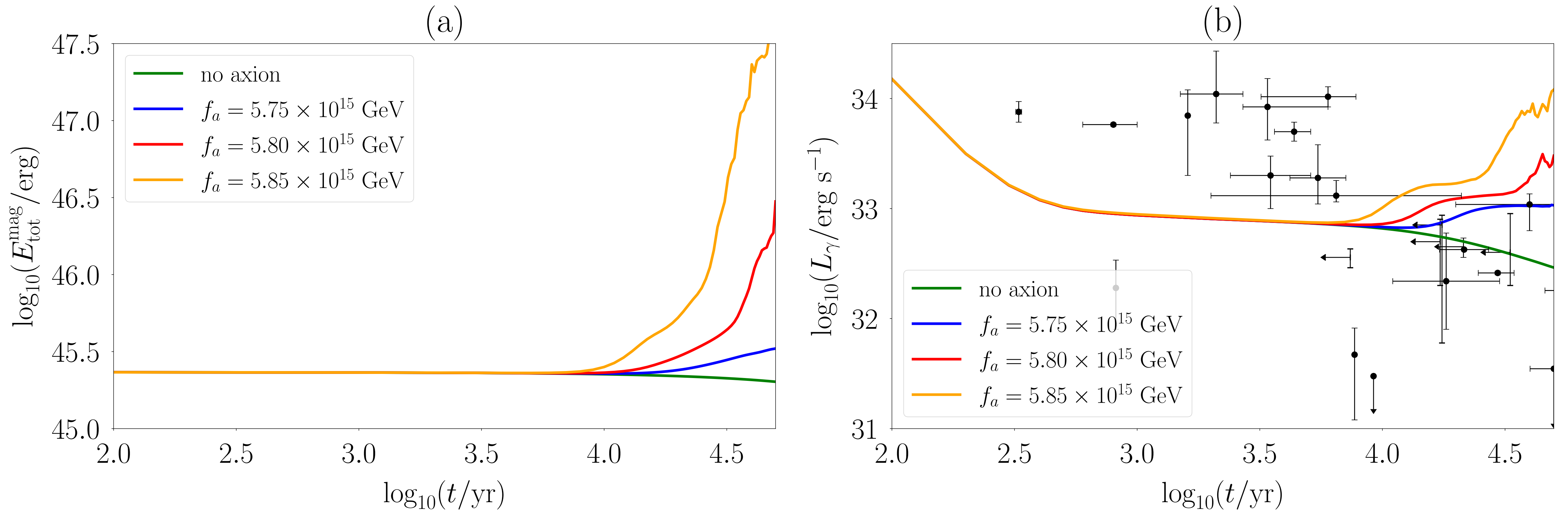
[6] A. HOOK AND J. HUANG, JOURNAL OF HIGH ENERGY PHYSICS 2018, 36 (2018)

[7] R. BALKIN, J. SERRA, K. SPRINGMANN, AND A. WEILER, JOURNAL OF HIGH ENERGY PHYSICS 2020, 221 (2020)

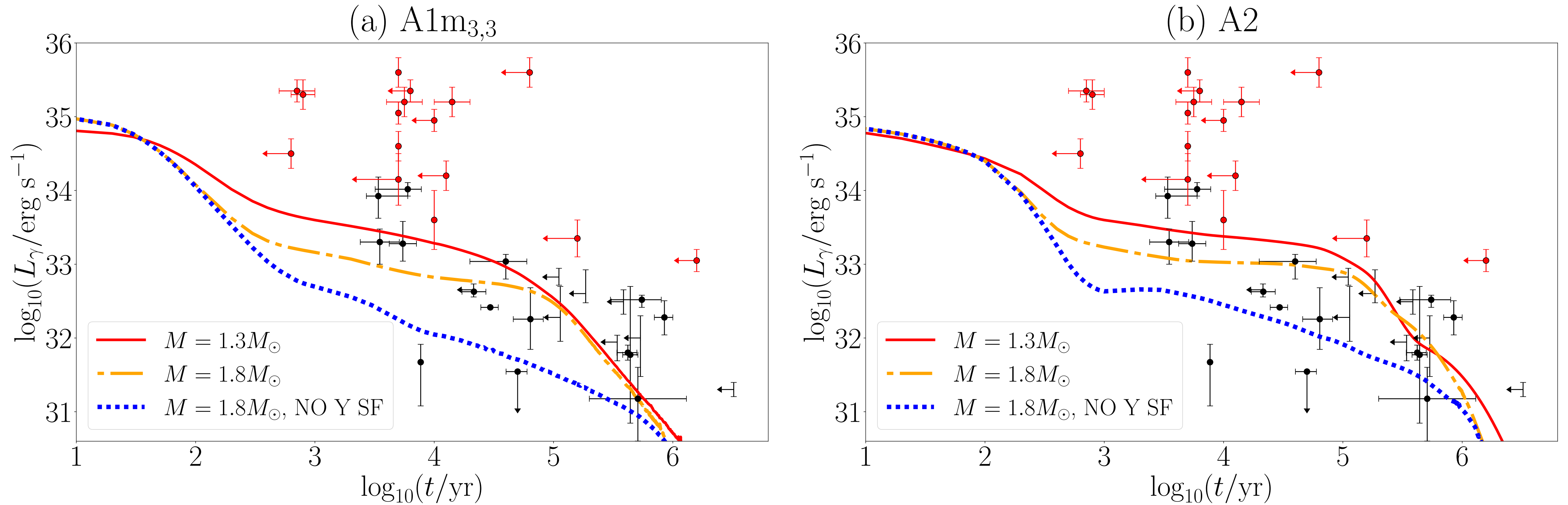
MAGNETO-THERMAL EVOLUTION



OBSERVABLE EFFECT



COOLING WITHOUT AXIONS



CONCLUSION

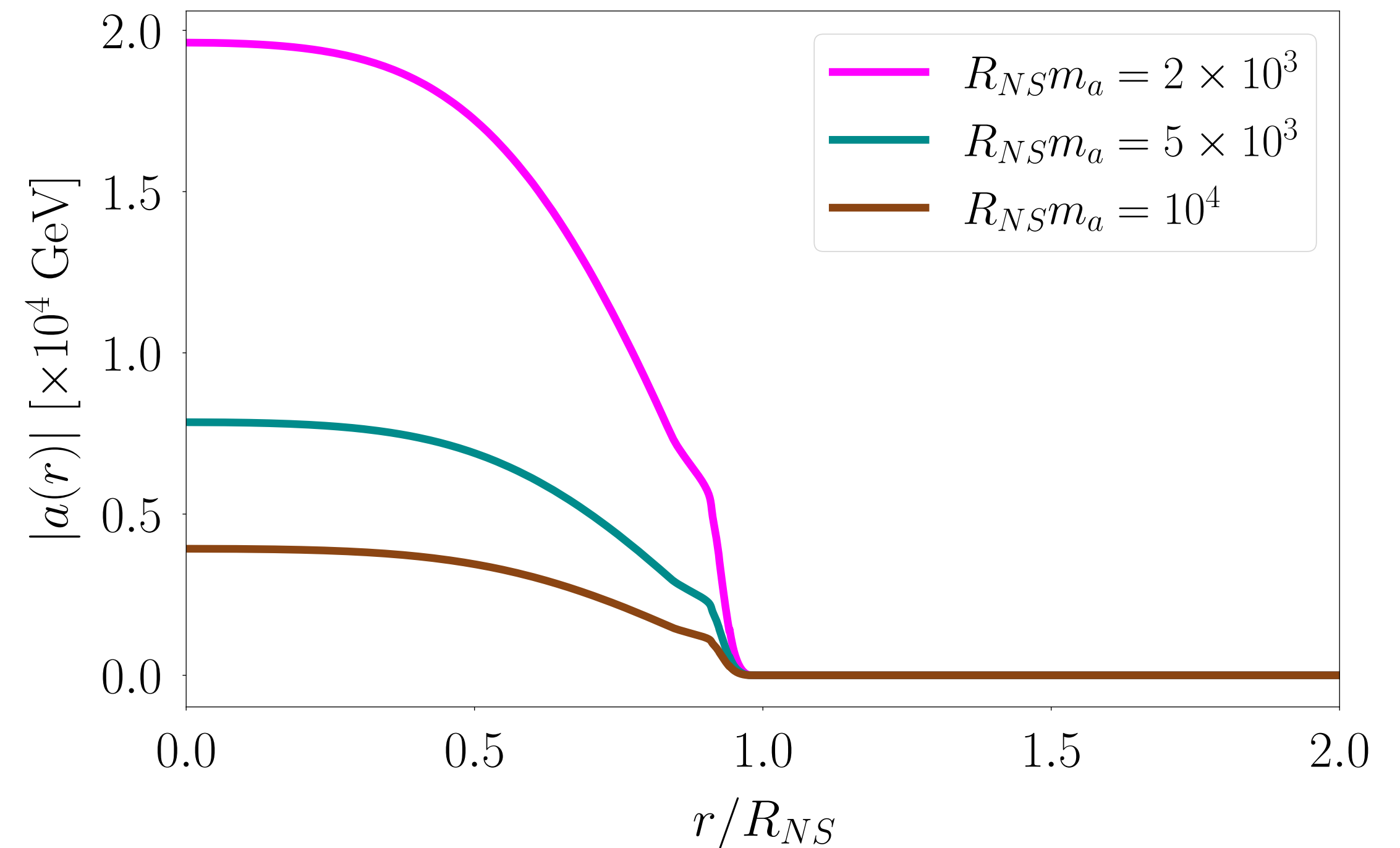
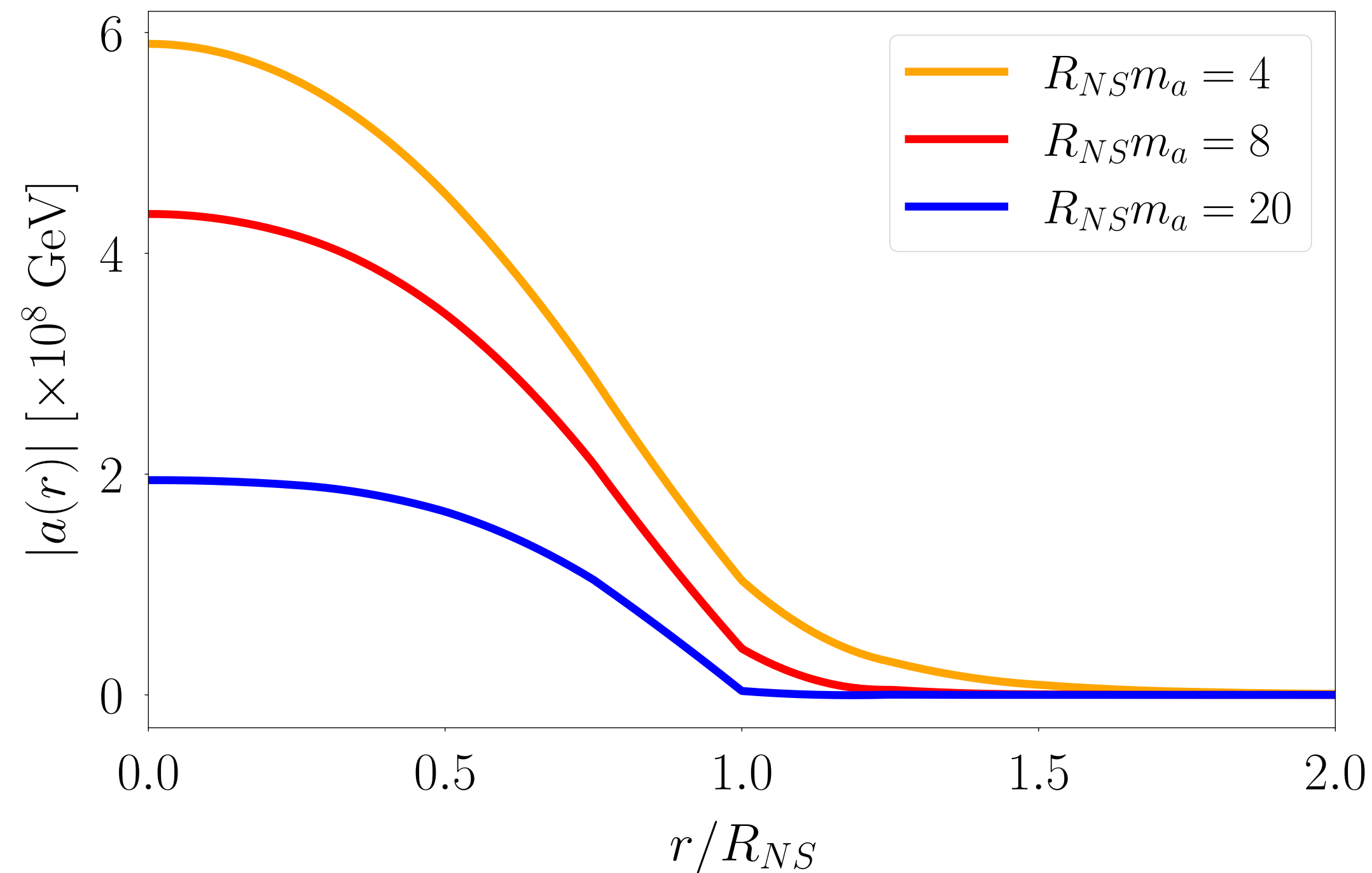
- AXION ELECTRODYNAMICS IN DENSE MATTER CAN BE USED TO CONSTRAIN AXION COUPLINGS AND TO TEST PROPOSED MODELS
- BOUNDS ON AXION-NUCLEON CP-VIOLATING COUPLINGS

OUTLOOK

- EXTENSION TO CP-CONSERVING COUPLINGS
- MAGNETO-THERMAL SIMULATIONS FOR WDs

THANK YOU!

QCD AXION IN NSs



$$10^{-29} \left(\frac{10^9 \text{ GeV}}{f_a} \right) \lesssim \bar{g}_{aN} \lesssim 10^{-21} \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$

Yellow line: $f_a = 10^{17}$ GeV

Red line: $f_a = 5 \times 10^{16}$ GeV

Blue line: $f_a = 2 \times 10^{16}$ GeV

Magenta line: $f_a = 2 \times 10^{14}$ GeV

Teal line: $f_a = 8 \times 10^{13}$ GeV

Brown line: $f_a = 4 \times 10^{13}$ GeV

AXION-MAXWELL EQS.

$$\nabla \cdot (\mathbf{E} - g_{a\gamma} a \mathbf{B}) = 4\pi \rho_c$$

$$\nabla \times [e^\nu (\mathbf{B} + g_{a\gamma} a \mathbf{E})] = \frac{\partial (\mathbf{E} - g_{a\gamma} a \mathbf{B})}{c \partial t} + \frac{4\pi e^\nu}{c} \mathbf{J}$$

$$\nabla \cdot (\mathbf{B} + g_{a\gamma} a \mathbf{E}) = 0$$

$$\nabla \times [e^\nu (\mathbf{E} - g_{a\gamma} a \mathbf{B})] = -\frac{1}{c} \frac{\partial (\mathbf{B} + g_{a\gamma} a \mathbf{E})}{\partial t} .$$

AXION ELECTRODYNAMICS

MODIFIED INDUCTION EQUATION [5]:

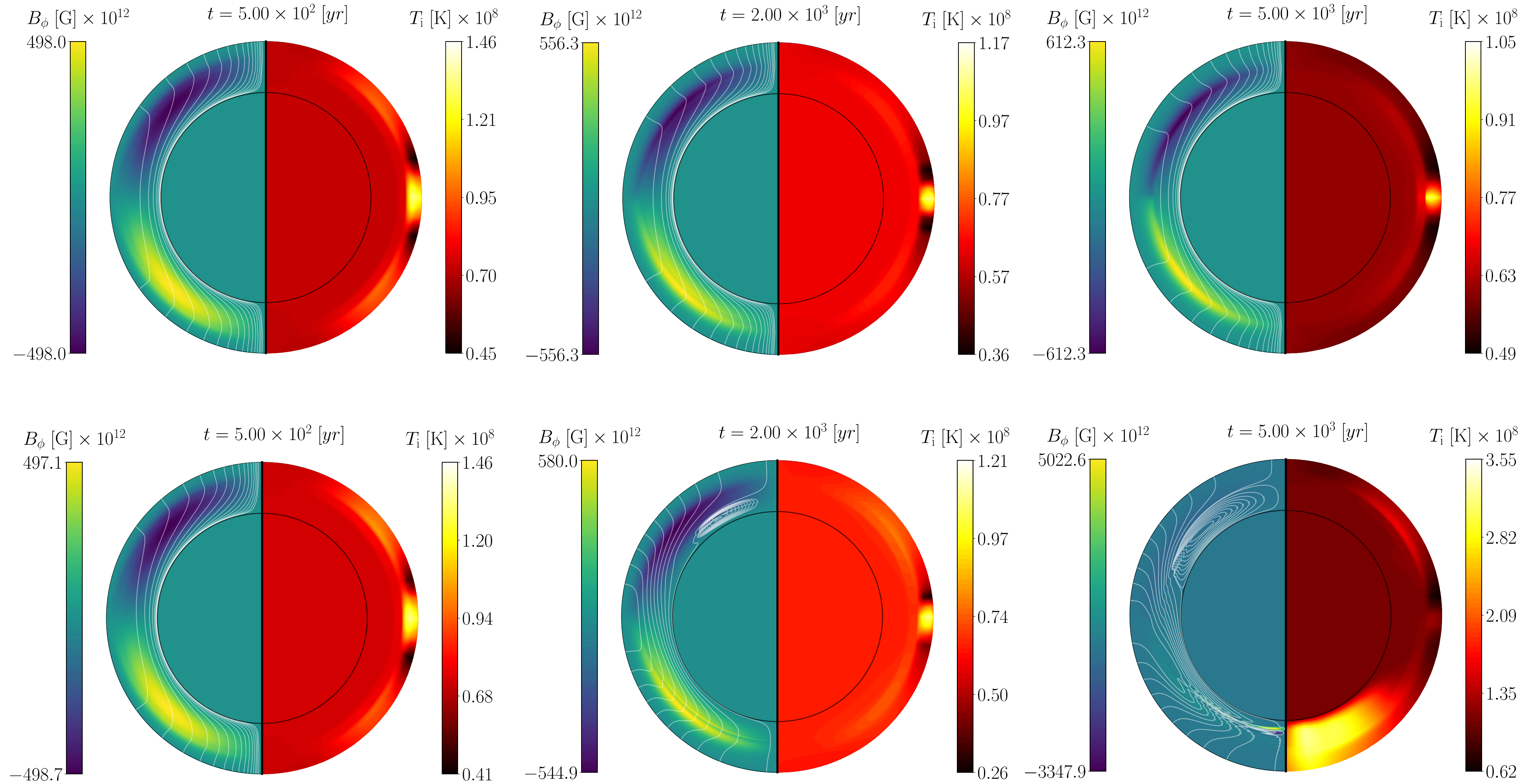
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left[\eta \nabla \times (e^\nu \mathbf{B}) + f_H [\nabla \times (e^\nu \mathbf{B})] \times \mathbf{B} - g_{a\gamma} c a e^\nu \mathbf{B} \right]$$



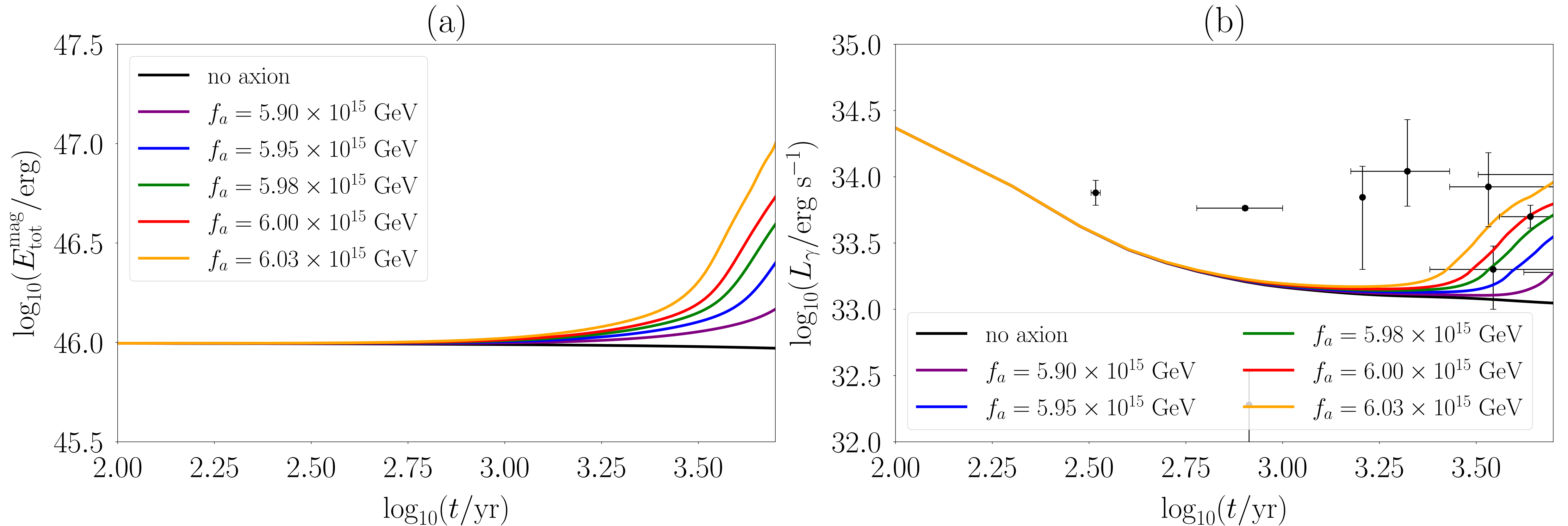
$$\frac{\partial B}{\partial t} \approx \frac{B}{\tau_{\text{dyn}}}$$

[5] L. VISINELLI, AXION-ELECTROMAGNETIC WAVES, MODERN PHYSICS LETTERS A 28, 1350162 (2013)

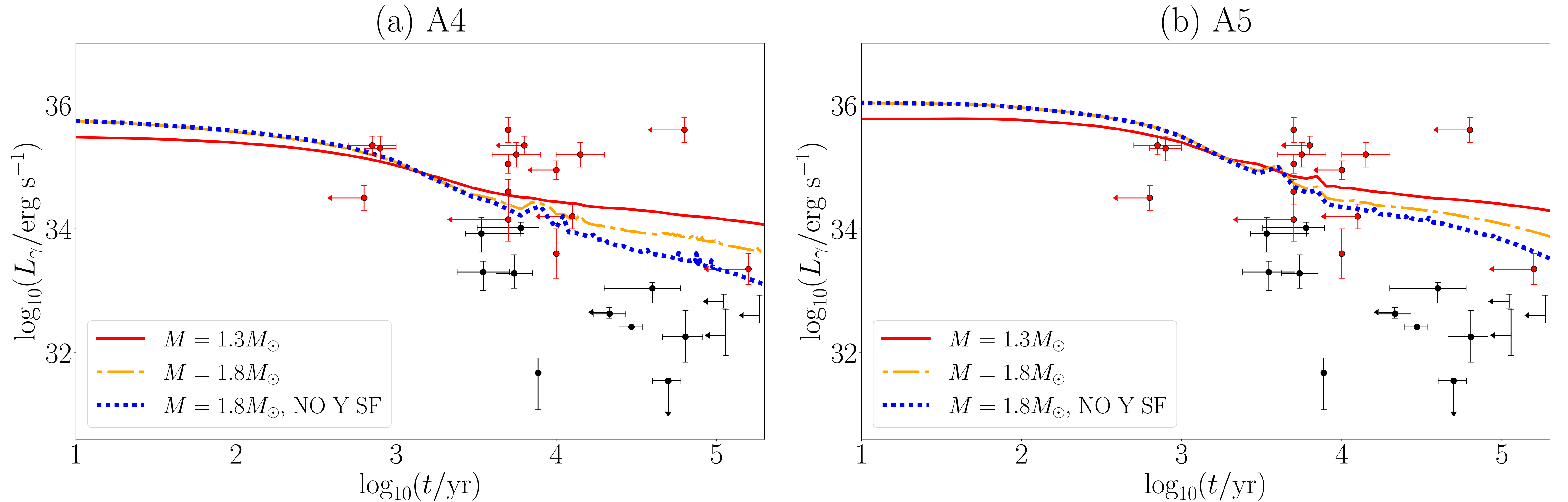
PHENOMENOLOGY



OBSERVABLE EFFECT



COOLING WITHOUT AXIONS



“STANDARD” AXION-MAXWELL EQS.

$$\nabla \cdot (\mathbf{E} - g_{a\gamma} a \mathbf{B}) = 4\pi \rho_c$$

$$\nabla \times \left[e^\nu (\mathbf{B} + g_{a\gamma} a \mathbf{E}) \right] = \frac{\partial (\mathbf{E} - g_{a\gamma} a \mathbf{B})}{c \partial t} + \frac{4\pi e^\nu}{c} \mathbf{J}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times (e^\nu \mathbf{E}) = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} .$$

“STANDARD” AXION-MAXWELL EQS.

$$\mathbf{E} \approx \mathbf{E}_0 + \mathbf{E}_a = \mathbf{E}_0 + g_{a\gamma} \mathbf{E}_1$$

$$\mathbf{B} \approx \mathbf{B}_0 + \mathbf{B}_a = \mathbf{B}_0 + g_{a\gamma} \mathbf{B}_1$$



$$\nabla \cdot (\mathbf{E}_a - g_{a\gamma} a \mathbf{B}_0) = 0$$

$$\nabla \times [e^\nu (\mathbf{B}_a + g_{a\gamma} a \mathbf{E}_0)] = \frac{\partial (\mathbf{E}_a - g_{a\gamma} a \mathbf{B}_0)}{c \partial t}$$

$$\nabla \cdot \mathbf{B}_a = 0$$

$$\nabla \times (e^\nu \mathbf{E}_a) = -\frac{1}{c} \frac{\partial \mathbf{B}_a}{\partial t}$$

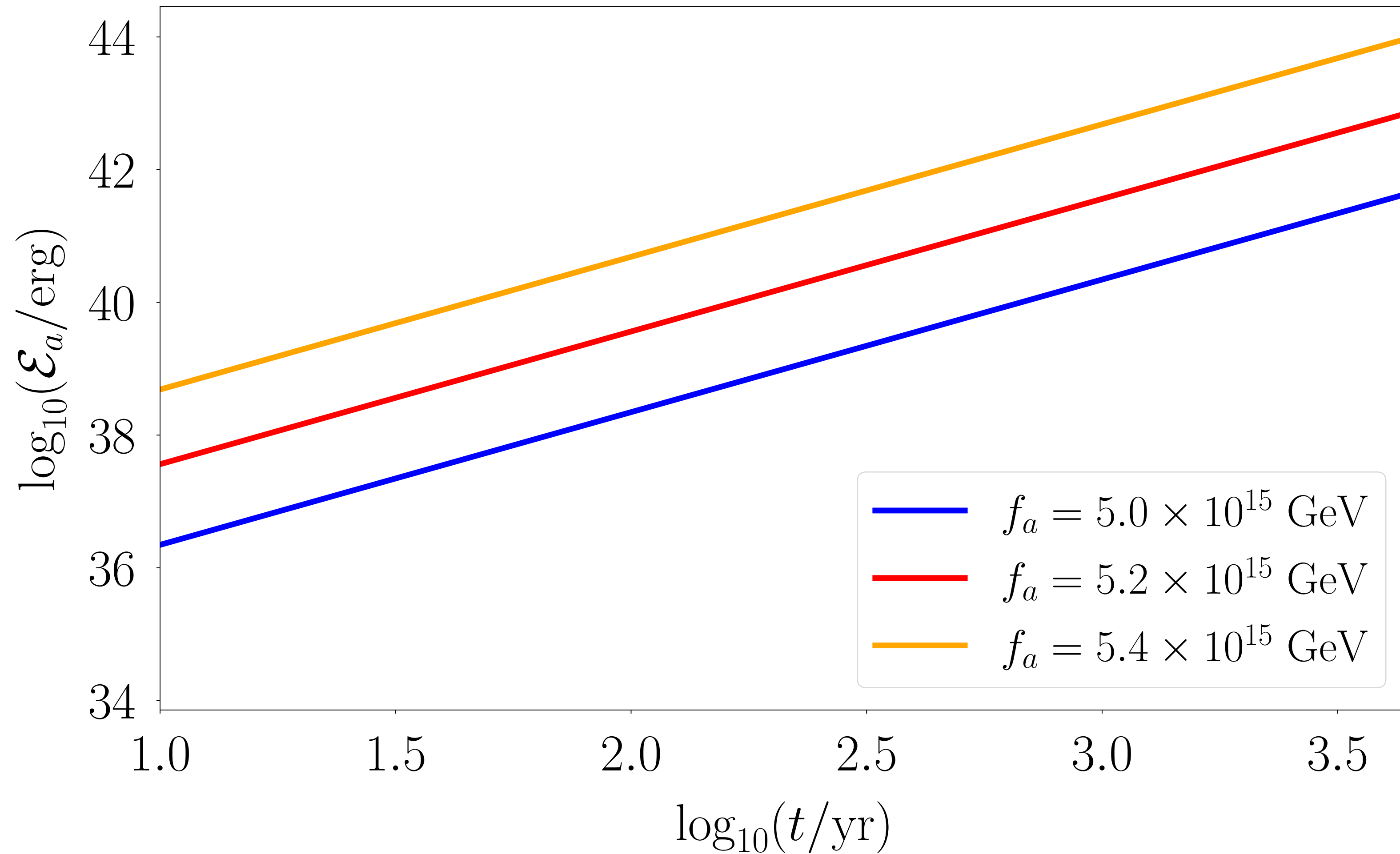
“STANDARD” AXION-MAXWELL EQS.

$$\nabla^2 \mathbf{E}_a = \frac{1}{c^2} \frac{\partial^2 (\mathbf{E}_a - g_{a\gamma} a \mathbf{B}_0)}{\partial t^2} + g_{a\gamma} \nabla [\nabla a \cdot \mathbf{B}_0] - \frac{g_{a\gamma}}{c} \nabla \times \frac{\partial (a \mathbf{E}_0)}{\partial t}$$



$$\mathbf{E}_a \propto g_{a\gamma} a \mathbf{B}_0$$

“STANDARD” AXION-MAXWELL EQS.



MAGNETO-THERMAL EVOLUTION

HEAT DIFFUSION EQUATION

$$c_V e^\nu \frac{\partial T}{\partial t} + \nabla \cdot (e^{2\nu} \mathbf{F}) = e^{2\nu} (Q_J - Q_\nu)$$

MAGNETIC INDUCTION EQUATION

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left[\frac{c^2}{4\pi\sigma_e} \nabla \times (e^\nu \mathbf{B}) + \frac{c}{4\pi en_e} [\nabla \times (e^\nu \mathbf{B})] \times \mathbf{B} \right]$$

NS EQUATION OF STATE

