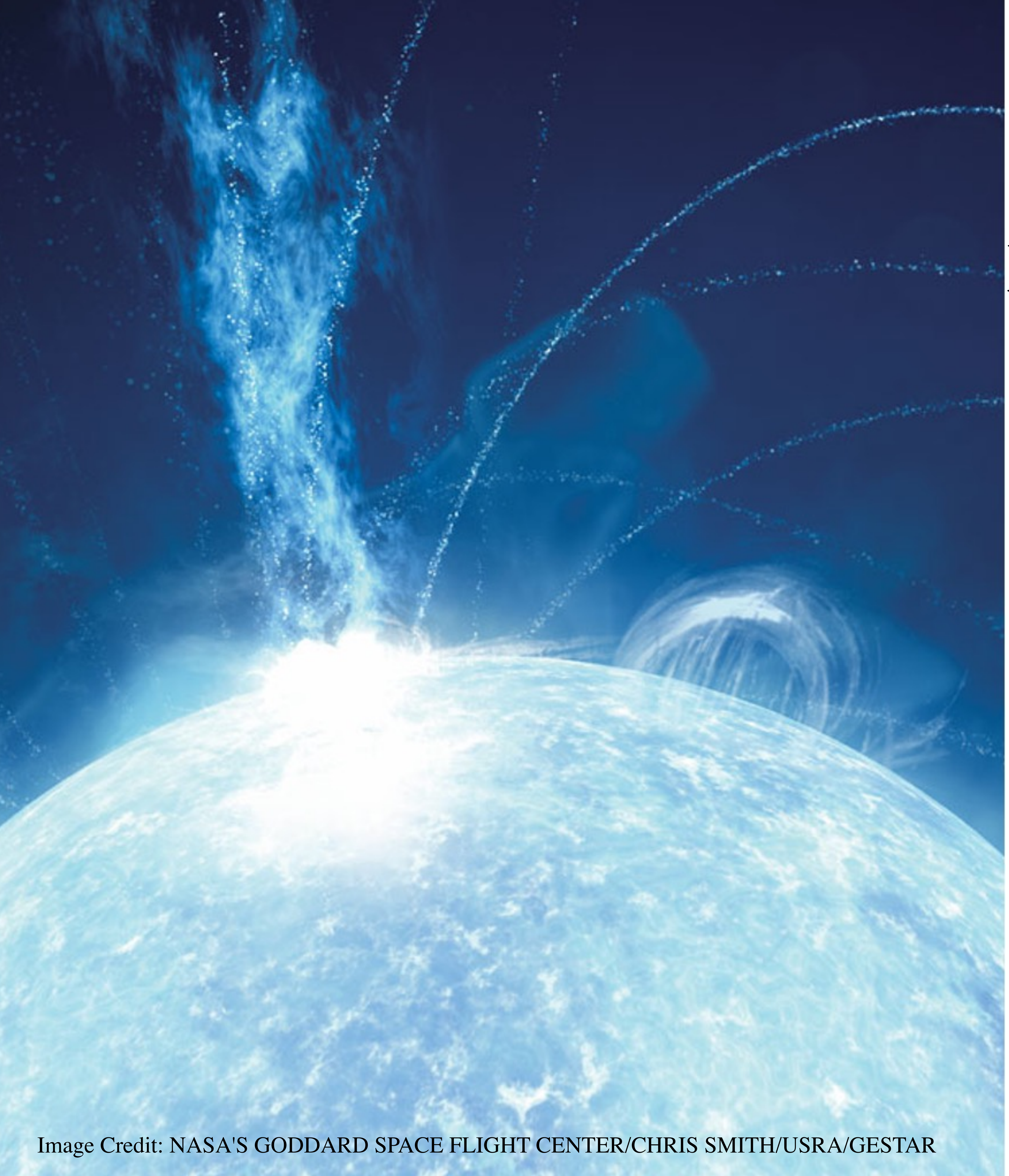


Image Credit: NASA'S GODDARD SPACE FLIGHT CENTER/CHRIS SMITH/USRA/GESTAR

Axion electrodynamics in dense neutron star matter

Filippo Anzuini

arXiv:2211.10863

THE UNIVERSITY OF MELBOURNE

MONASH University

OzGrav

In collaboration with J. A. Pons, A. Gómez-Bañón, P. D. Lasky, F. Bianchini and A. Melatos

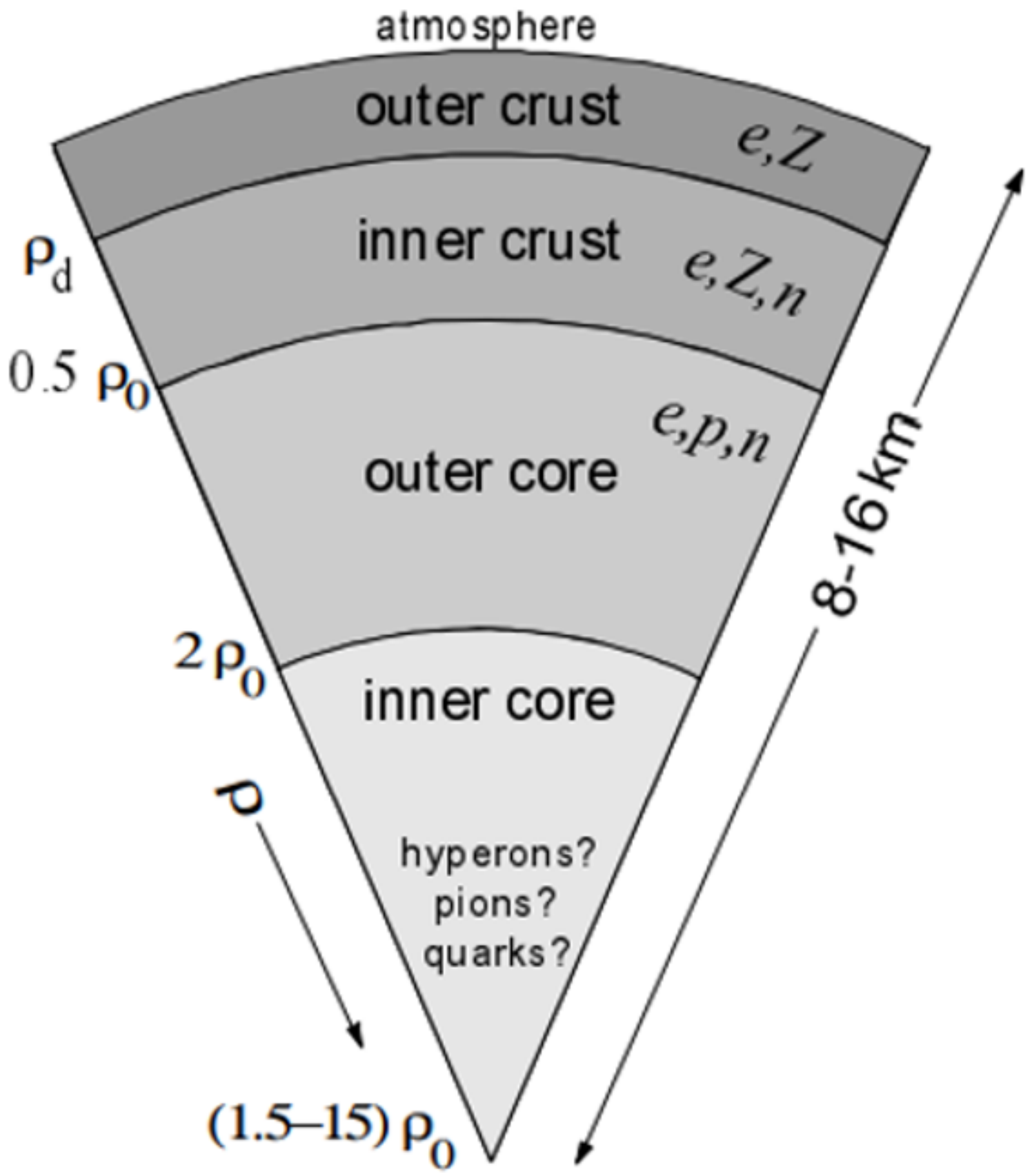
The Dark Side of the Universe, Sydney, 8 Dec 2022

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

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

Image credit: Yakovlev D. G., Levenfish K. P., Shibanov Y. A., 1999, Physics Uspekhi, 42, 737

CP-violating couplings in NSs

ALP equation of motion [2]

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

GM1A EoS [3] + weak initial magnetic fields

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

[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

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

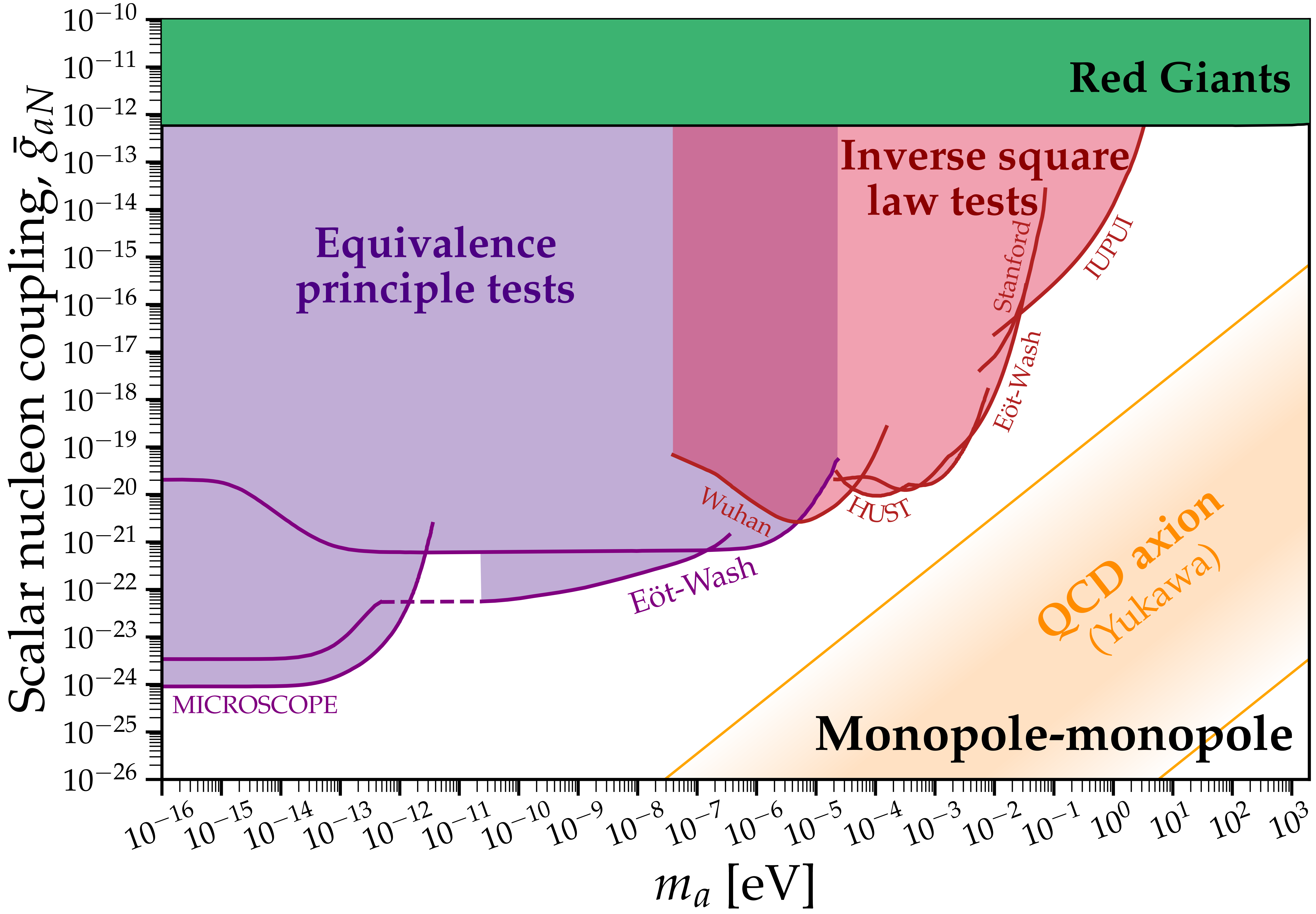
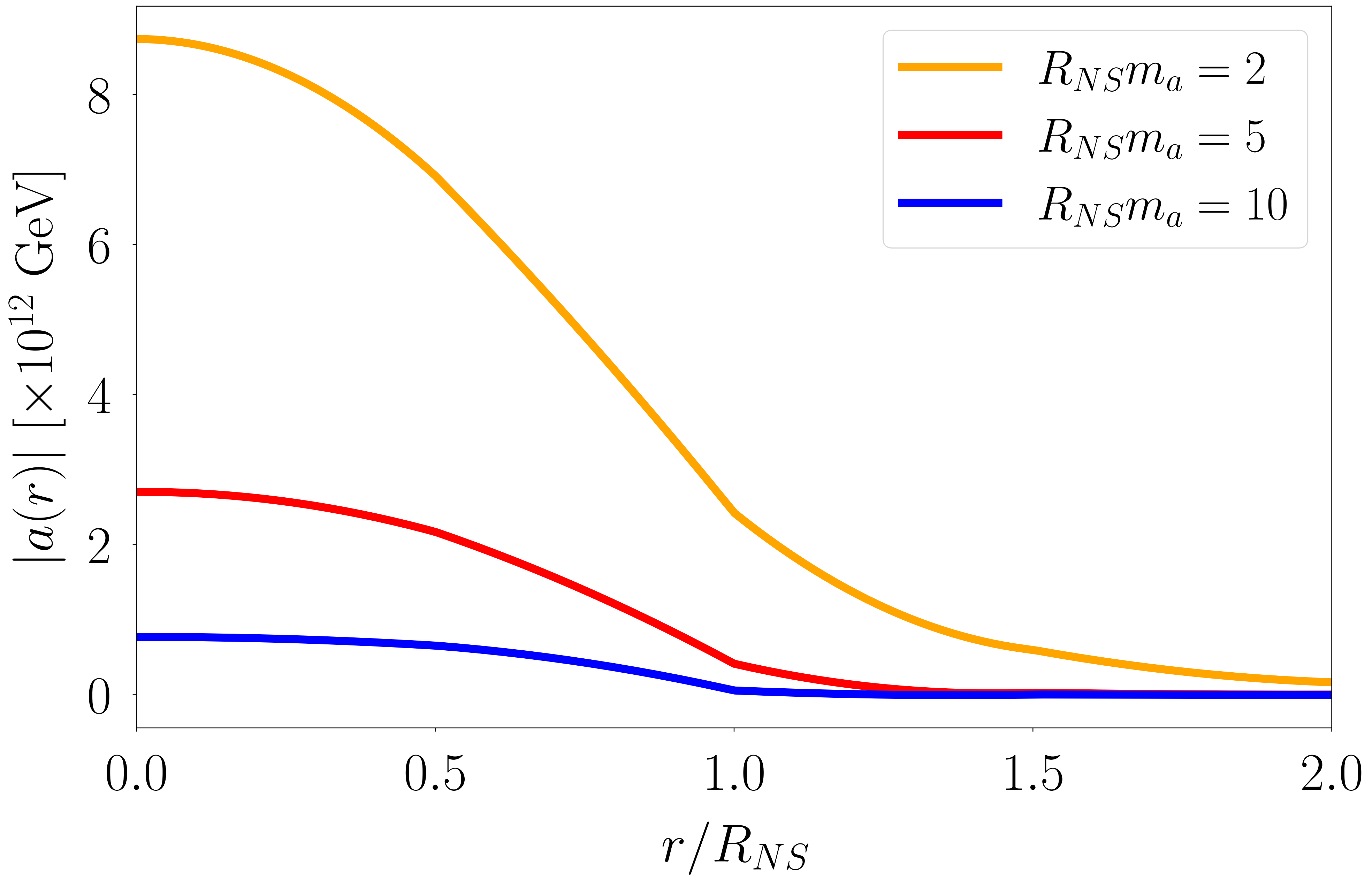
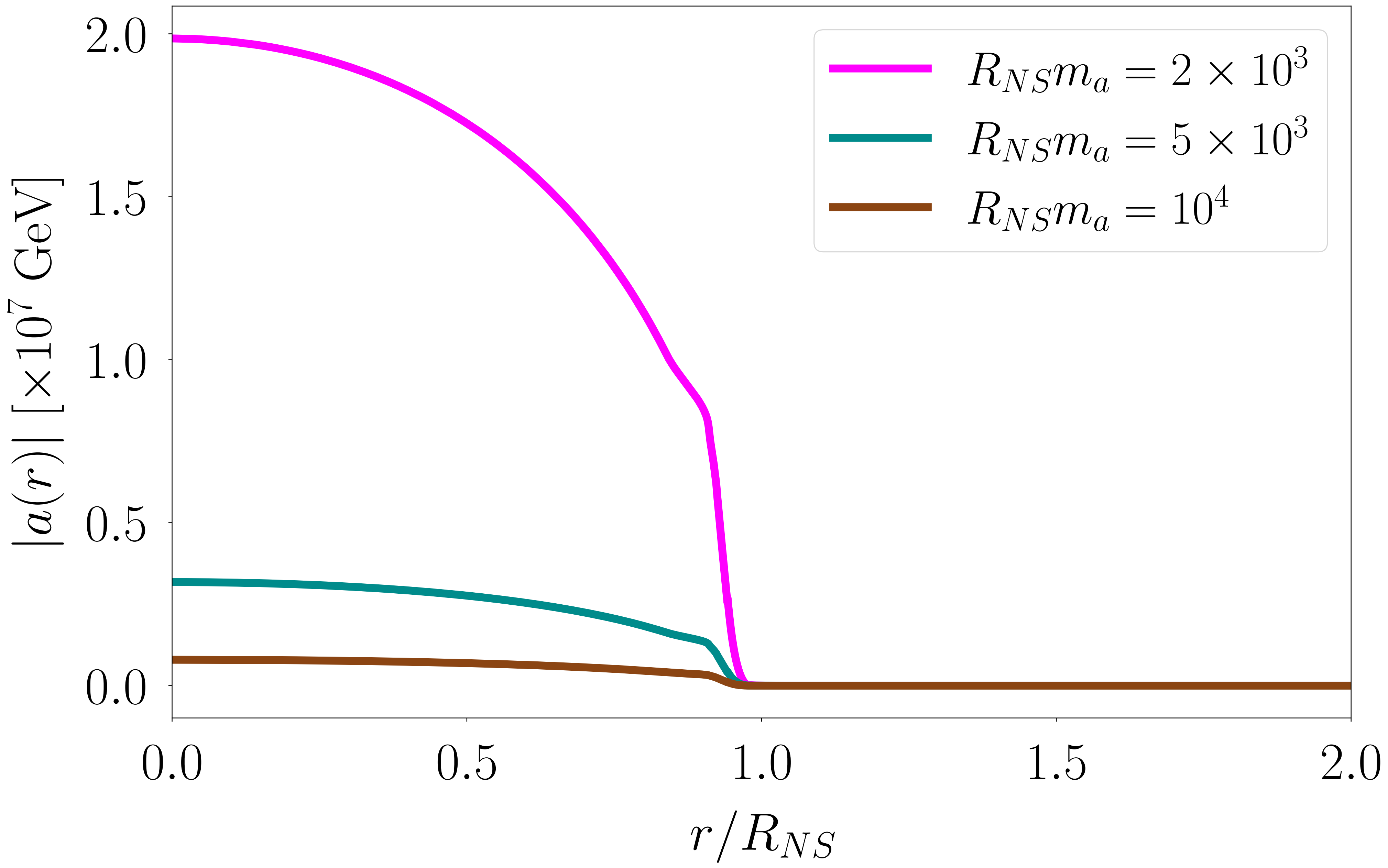


Image credit: C. O'Hare, ca johare/axionlimits: Axionlimits, https:// cajohare.github.io/AxionLimits/ (2020)

[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

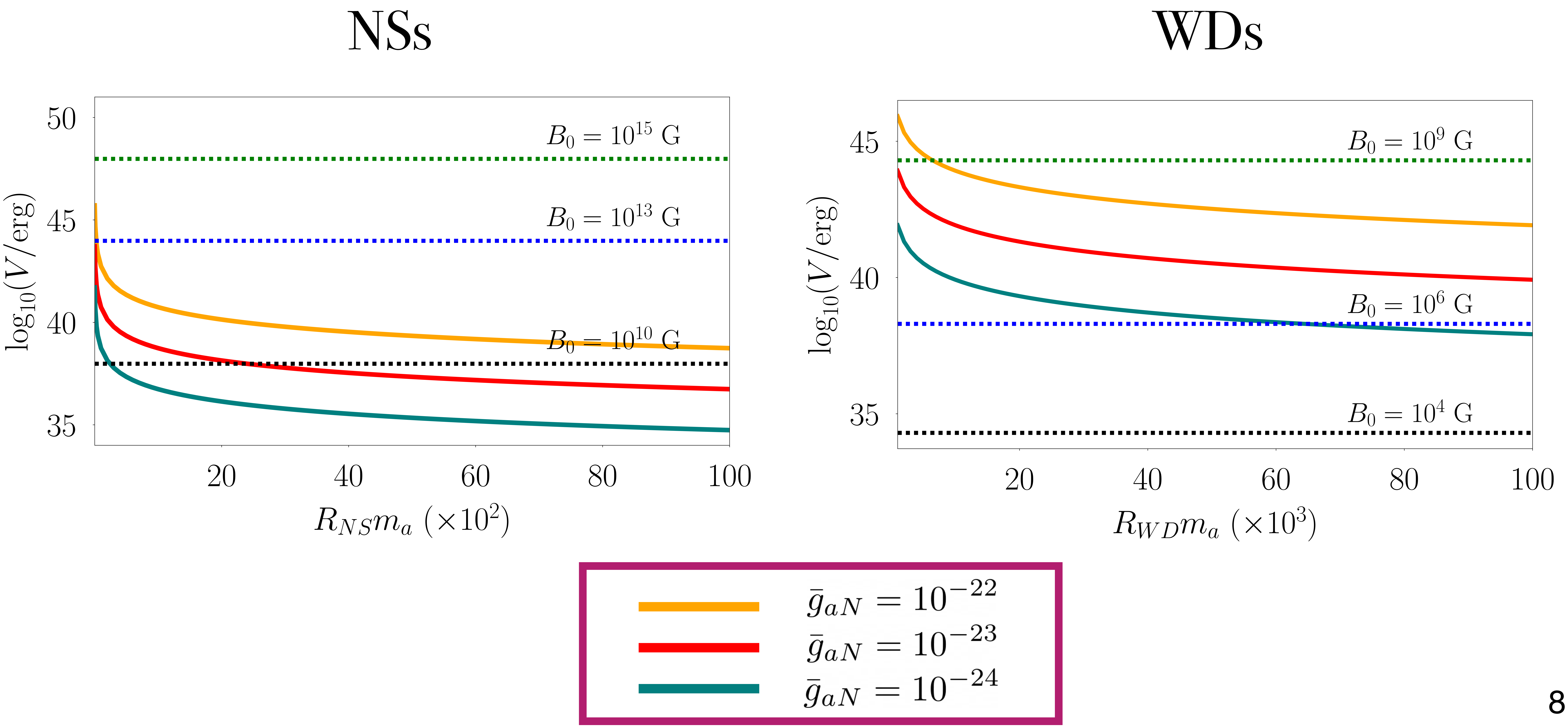
Modified induction equation [5]:

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

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

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

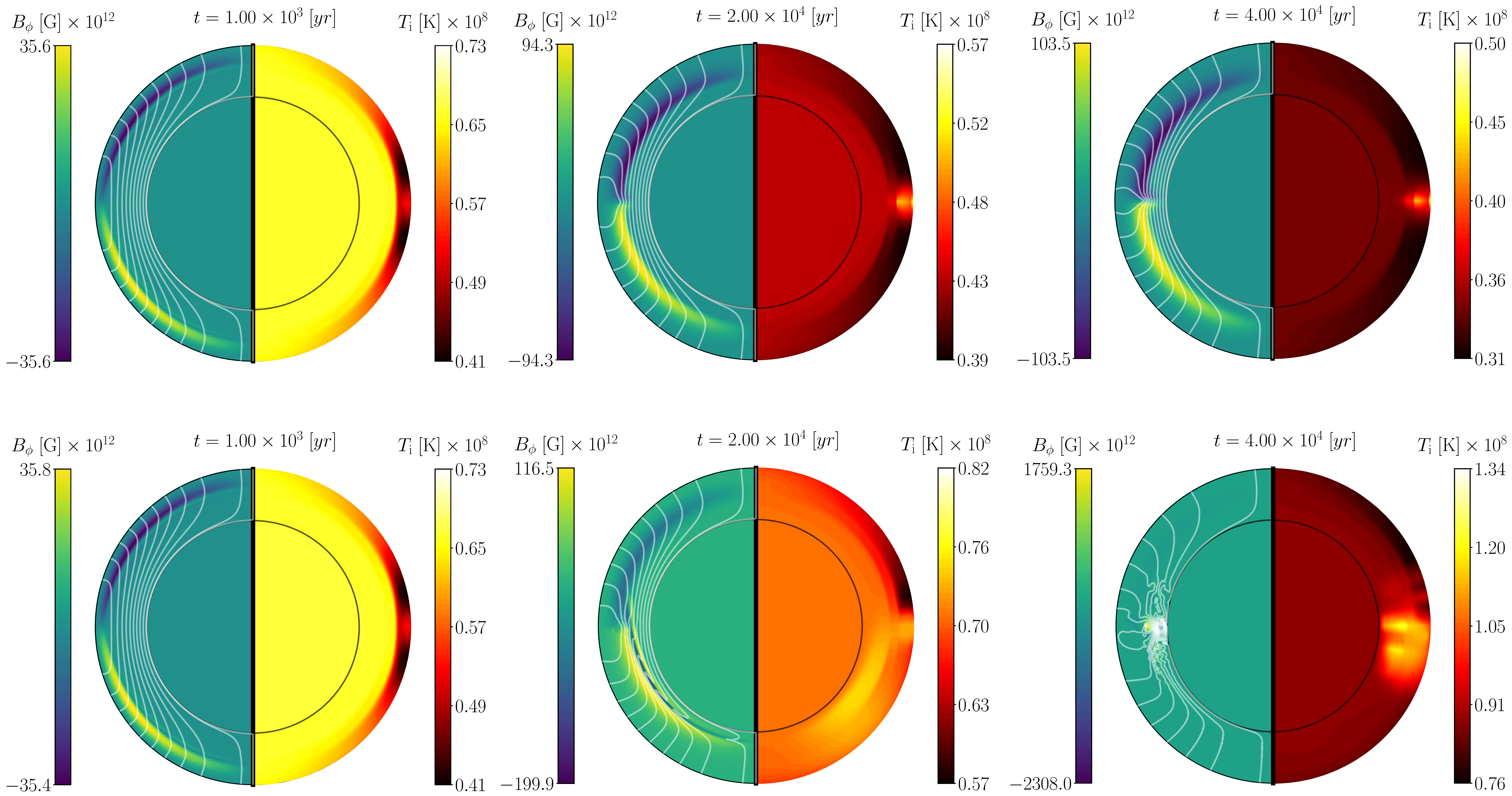
Finite density corrections
(several possibilities in the literature)

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

[6] A. Hook and J. Huang, Journal of High Energy Physics 2018, 36 (2018)

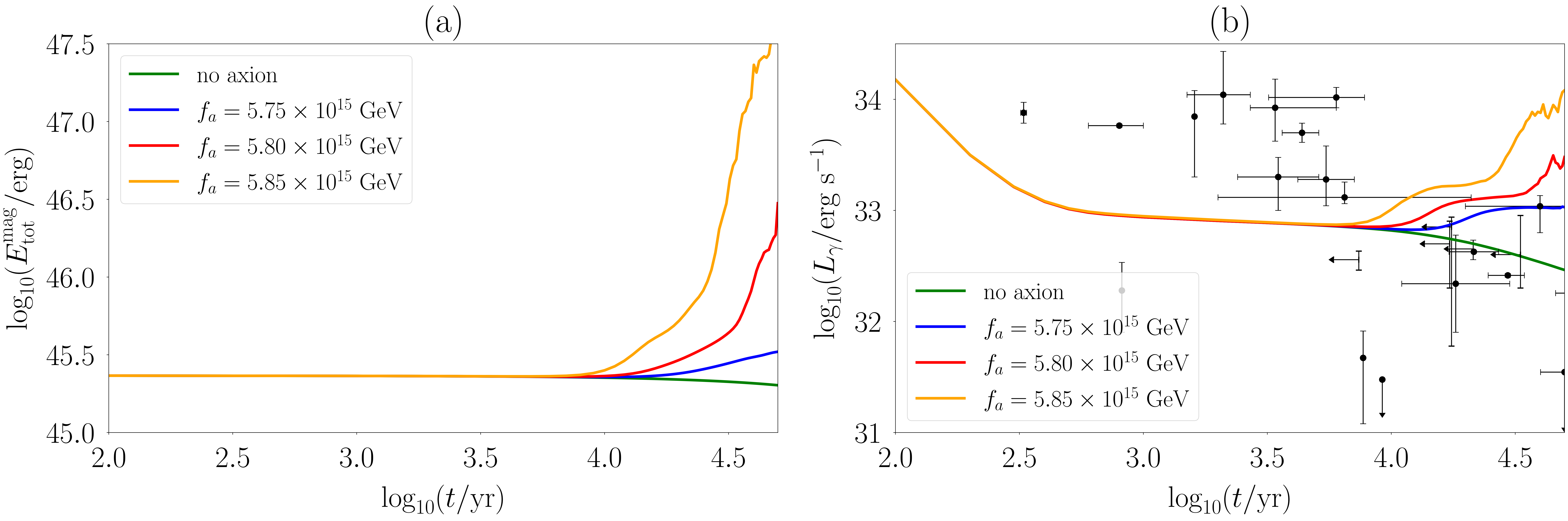
[7] R. Balkin, J. Serra, K. Springmann, and A. Weiler, Journal of High Energy Physics 2020, 221 (2020)

Magneto-thermal evolution



[8] F. Anzuini, J. A. Pons, A. Gómez-Bañón, P. D. Lasky, F. Bianchini, and A. Melatos. Magnetic dynamo caused by axions in neutron stars, 2022, arXiv:2211.10863

OBSERVABLE EFFECT



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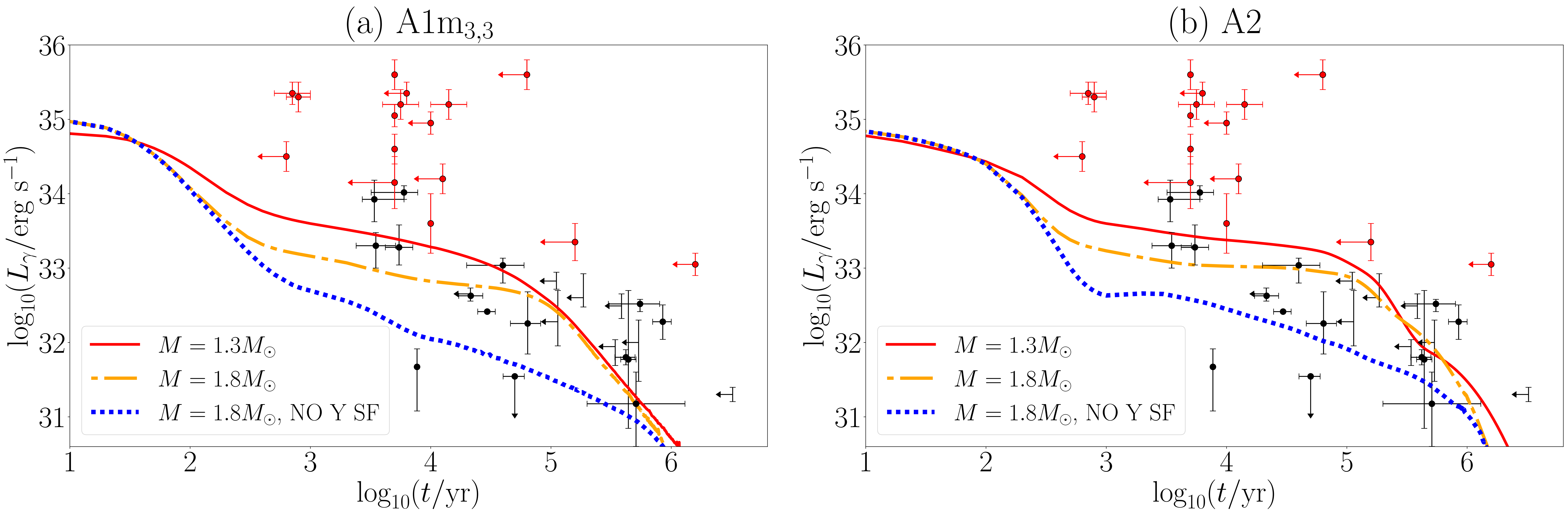
Cooling without axions



[9] F. Anzuini, A. Melatos, C. Dehman, D. Viganò, and J. A. Pons, Thermal luminosity degeneracy of magnetized neutron stars with and without hyperon cores, MNRAS, 515, 3014 (2022)

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

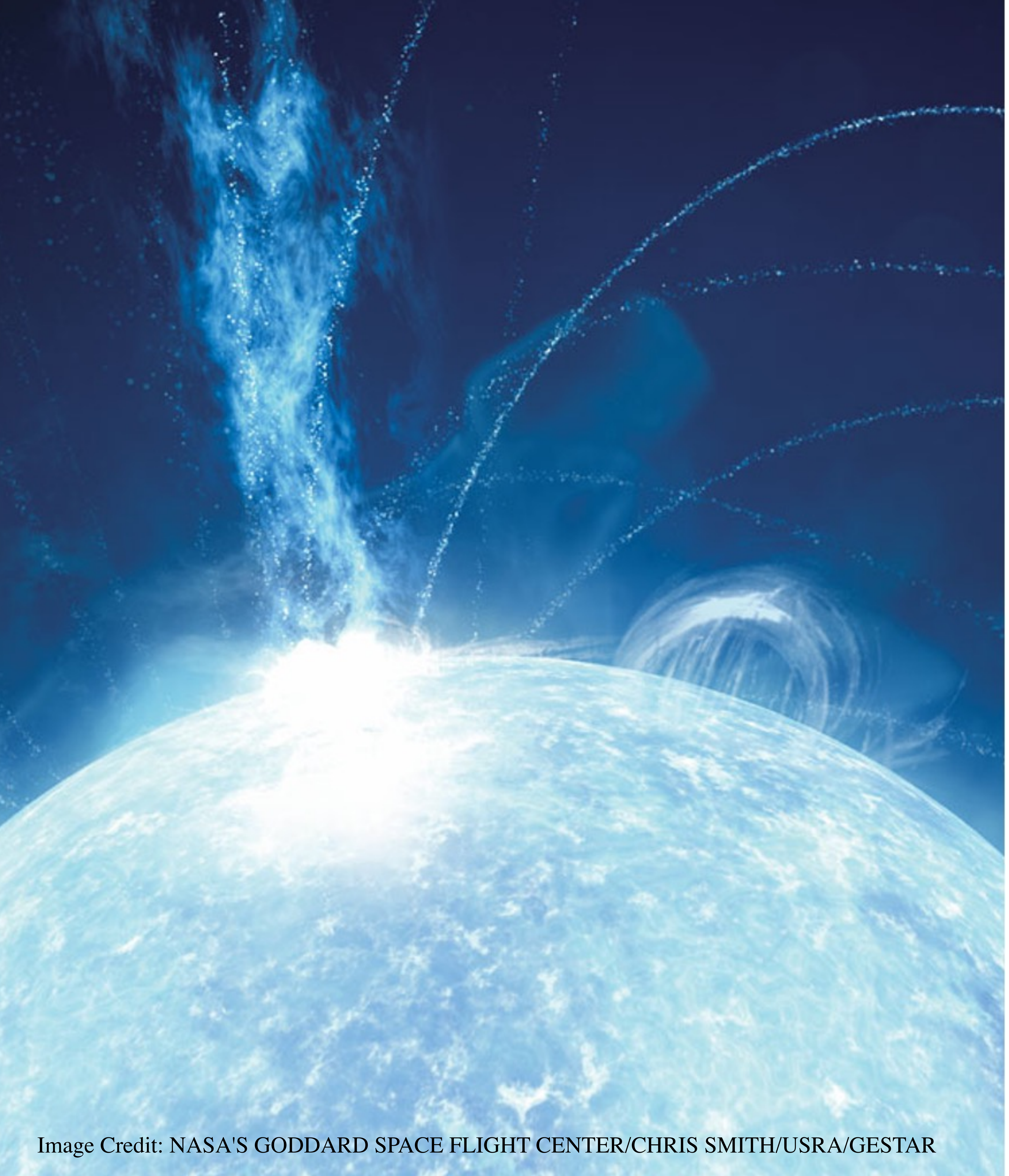
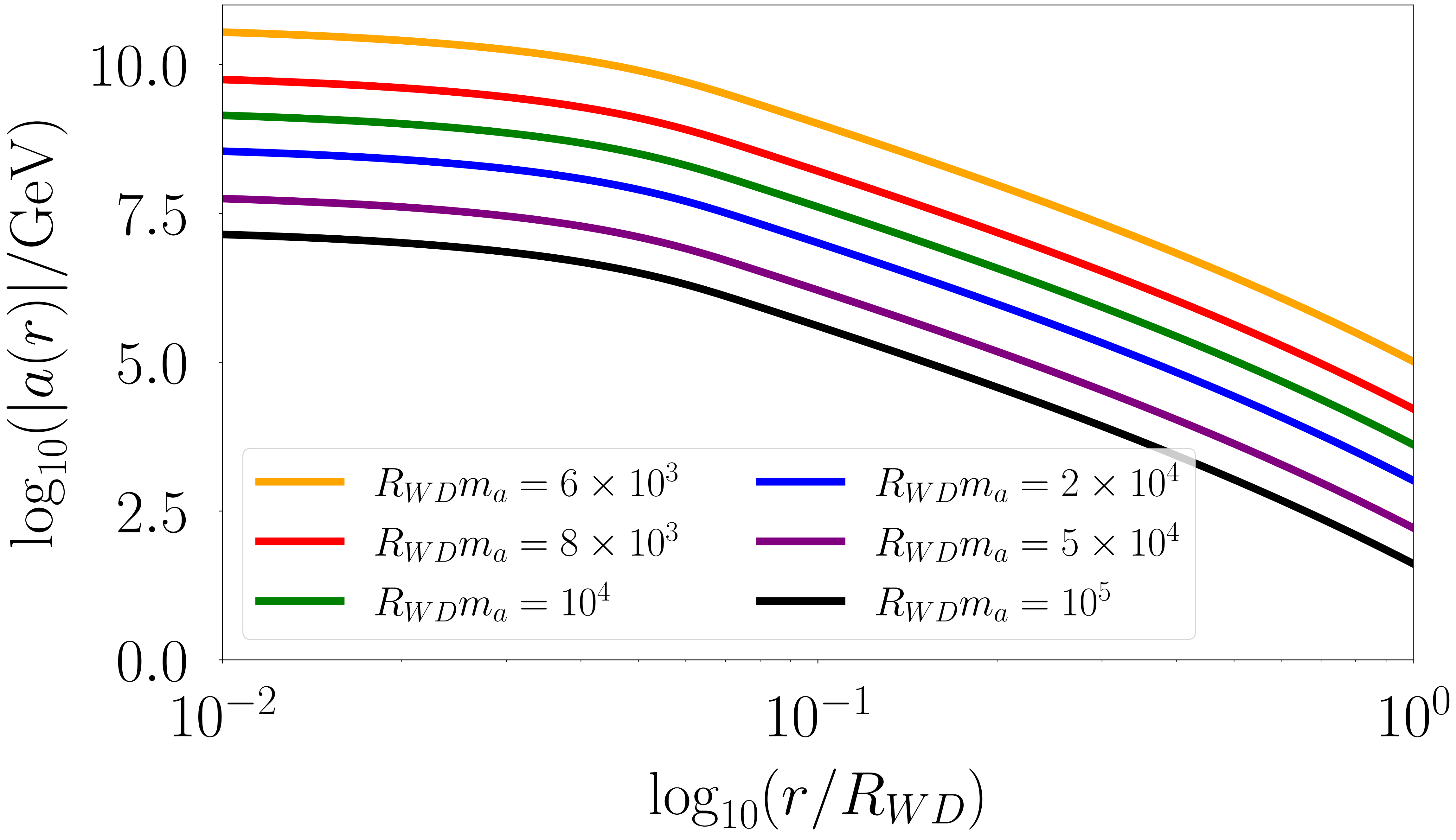


Image Credit: NASA'S GODDARD SPACE FLIGHT CENTER/CHRIS SMITH/USRA/GESTAR

THANK YOU!

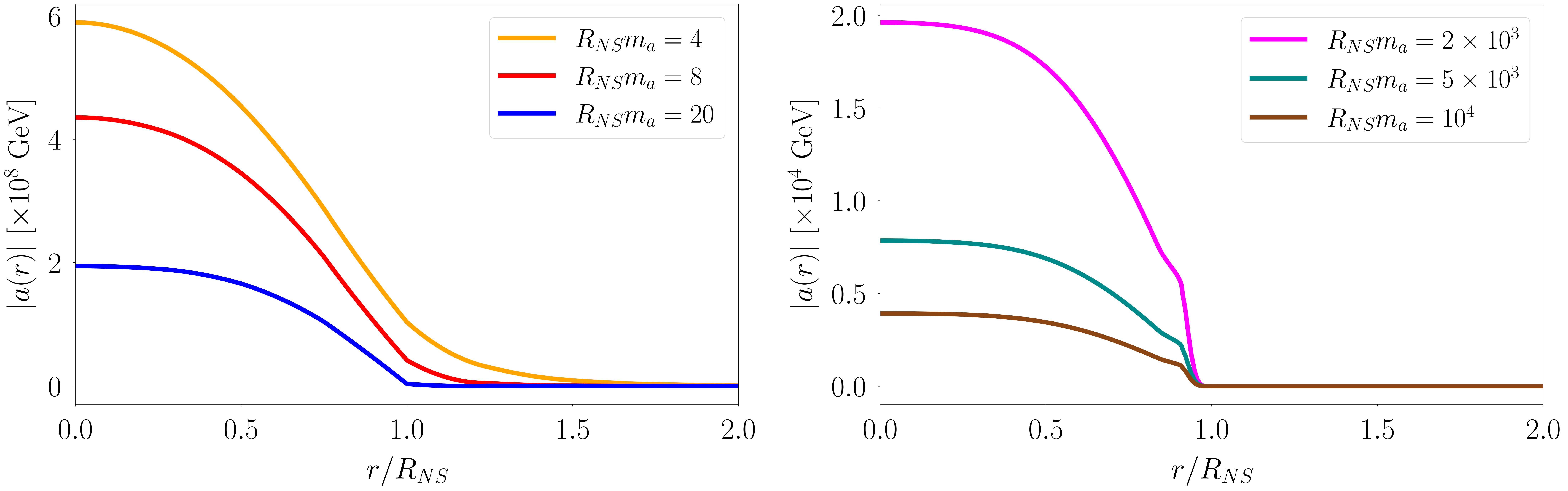
ALPs in WDs



$$1.5\times10^{-10}\lesssim m_a/\mathrm{eV}\lesssim 2.5\times10^{-9}$$

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

QCD AXION IN NSs



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

$f_a = 10^{17}$ GeV

$f_a = 5\times10^{16}$ GeV

$f_a = 2\times10^{16}$ GeV

$f_a = 2\times10^{14}$ GeV

$f_a = 8\times10^{13}$ GeV

$f_a = 4\times10^{13}$ GeV

[4] C. A. J. O'Hare and E. Vitagliano, Cornering the axion with CP-violating interactions, Phys. Rev. D 102, 115026 (2020)

AXION-MAXWELL EQS.

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

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

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

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

[5] L. Visinelli, Axion-Electromagnetic Waves, Modern Physics Letters A 28, 1350162 (2013)

AXION ELECTRODYNAMICS

Modified induction equation [5]:

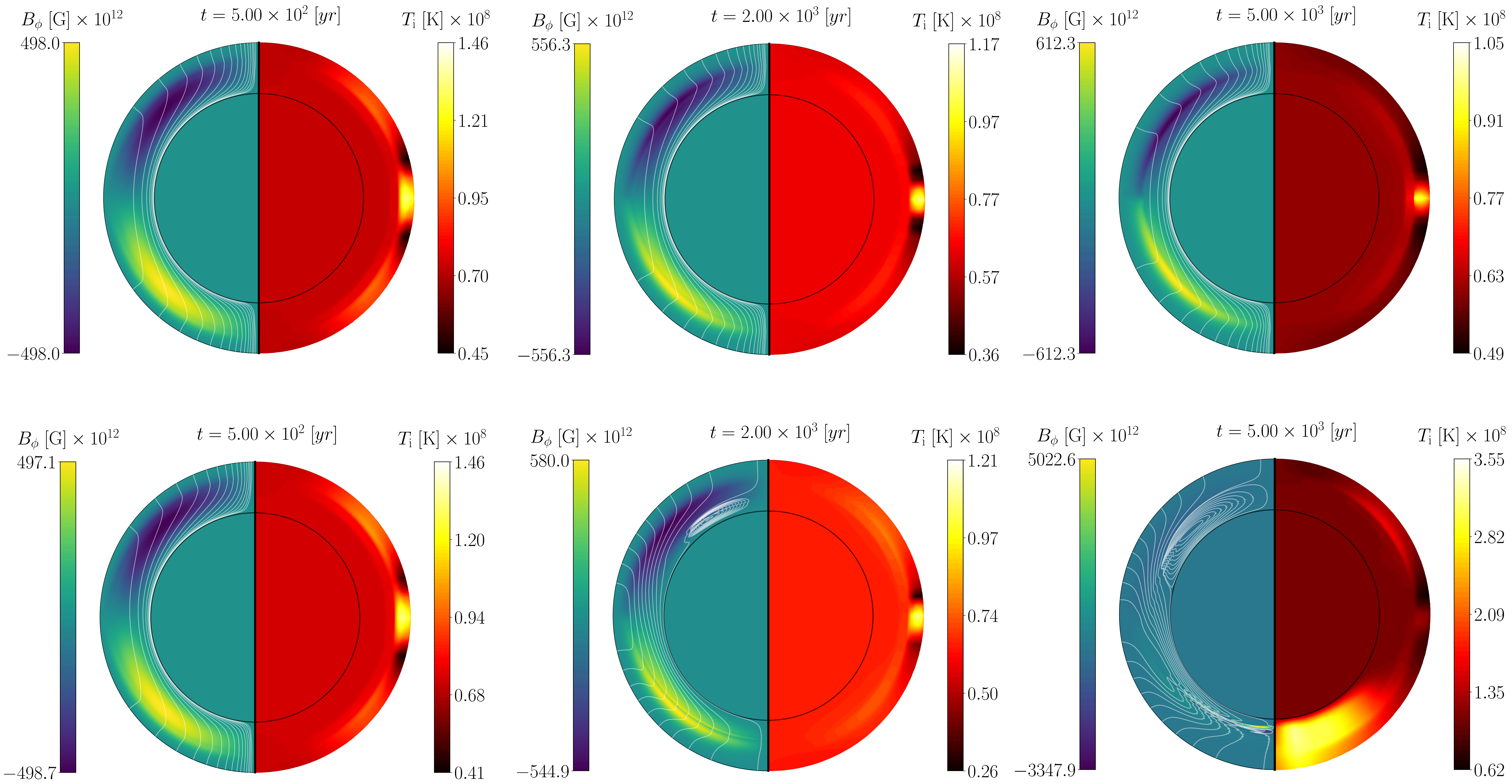
$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \left[\eta \boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B}) + f_H [\boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B})] \times \boldsymbol{B} - g_{a\gamma} c a e^{\nu} \mathbf{B} \right]$$

↓

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

[5] L. Visinelli, Axion-Electromagnetic Waves, Modern Physics Letters A 28, 1350162 (2013)

Phenomenology



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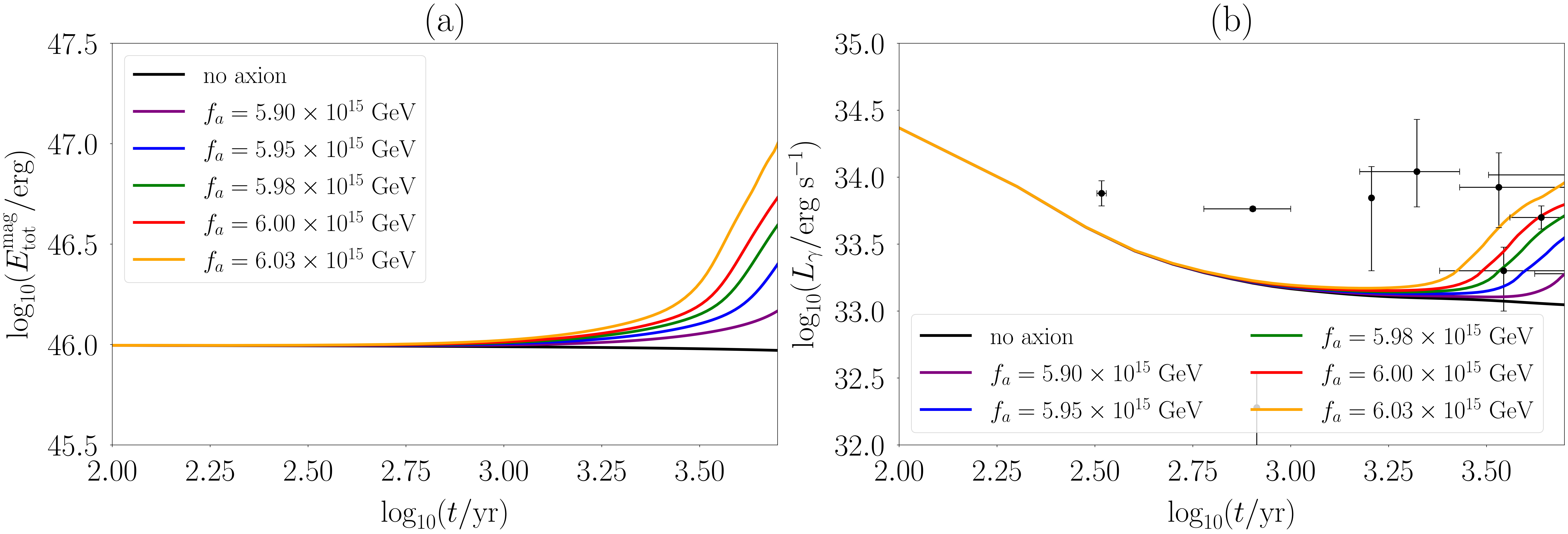
Observable effect



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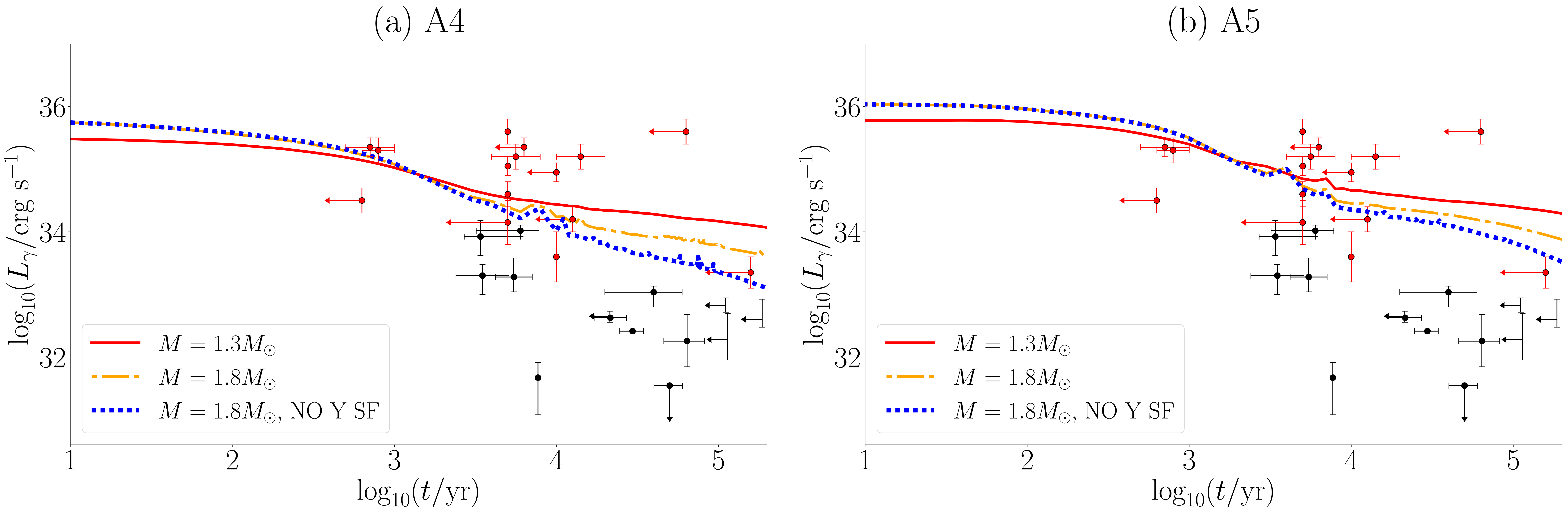

[9] F.Anzuini,A.Melatos,C.Dehman,D.Viganò, and J. A. Pons, Thermal luminosity degeneracy of magnetized neutron stars with and without hyperon cores, MNRAS, 515, 3014 (2022)

"Standard" axion-Maxwell eqs.

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

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

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

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

[10] Y. Kim, D. Kim, J. Jeong, J. Kim, Y. C. Shin, and Y. K. Semertzidis, Physics of the Dark Universe 26, 100362 (2019)

"Standard" axion-Maxwell eqs.

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

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

↓

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

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

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

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

[10] Y. Kim, D. Kim, J. Jeong, J. Kim, Y. C. Shin, and Y. K. Semertzidis, Physics of the Dark Universe 26, 100362 (2019)

“Standard” axion-Maxwell eqs.

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

↓

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

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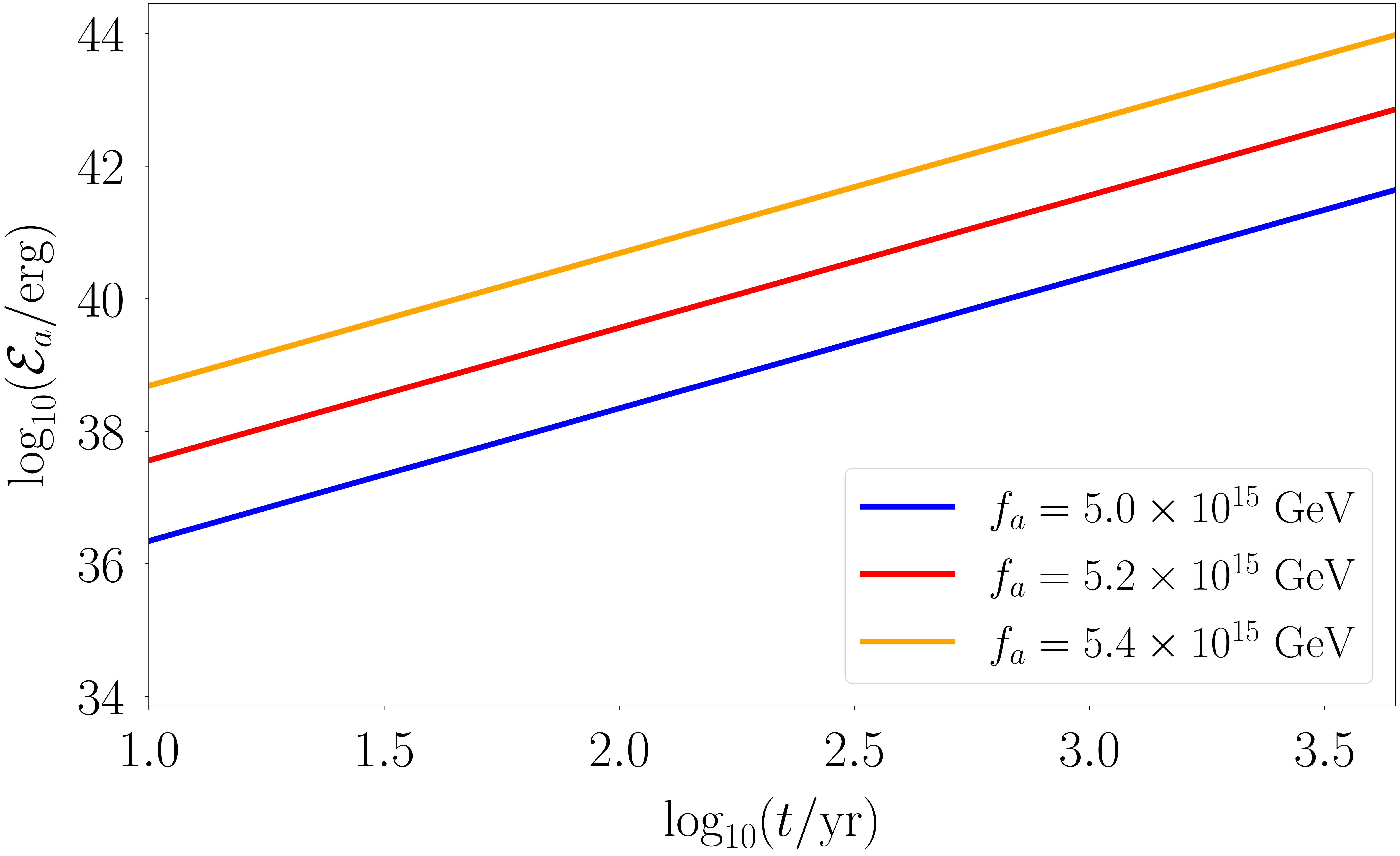

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Magneto-thermal evolution

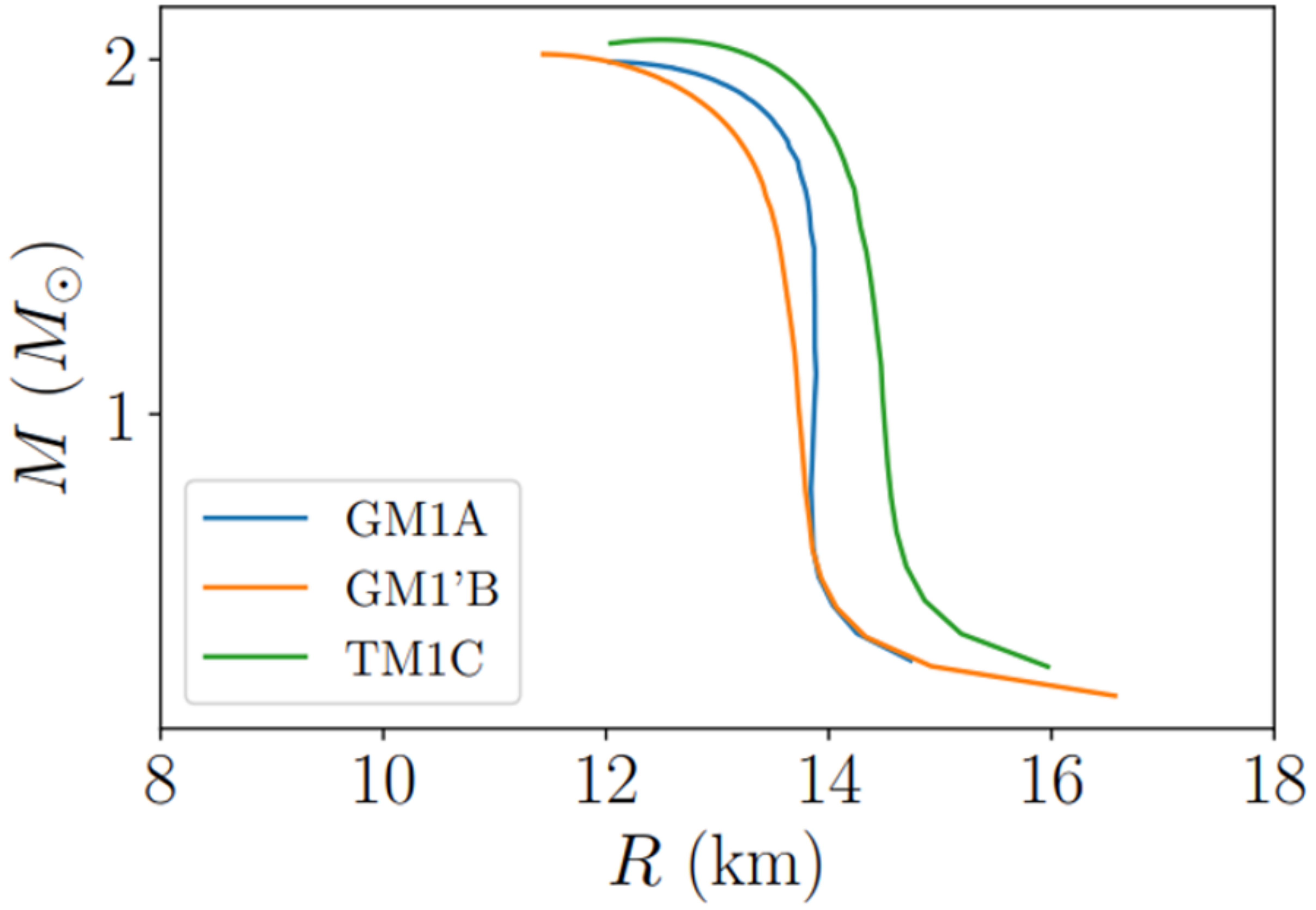
Heat diffusion equation

$$c_{\rm V} e^{\nu} \frac{\partial T}{\partial t} + \boldsymbol{\nabla} \cdot (e^{2\nu} \boldsymbol{F}) = e^{2\nu} (Q_{\rm J} - Q_{\nu})$$

Magnetic induction equation

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

NS equation of state



[3] Gusakov M. E., Haensel P., Kantor E. M., 2014, Monthly Notices of the Royal Astronomical Society, 439, 318