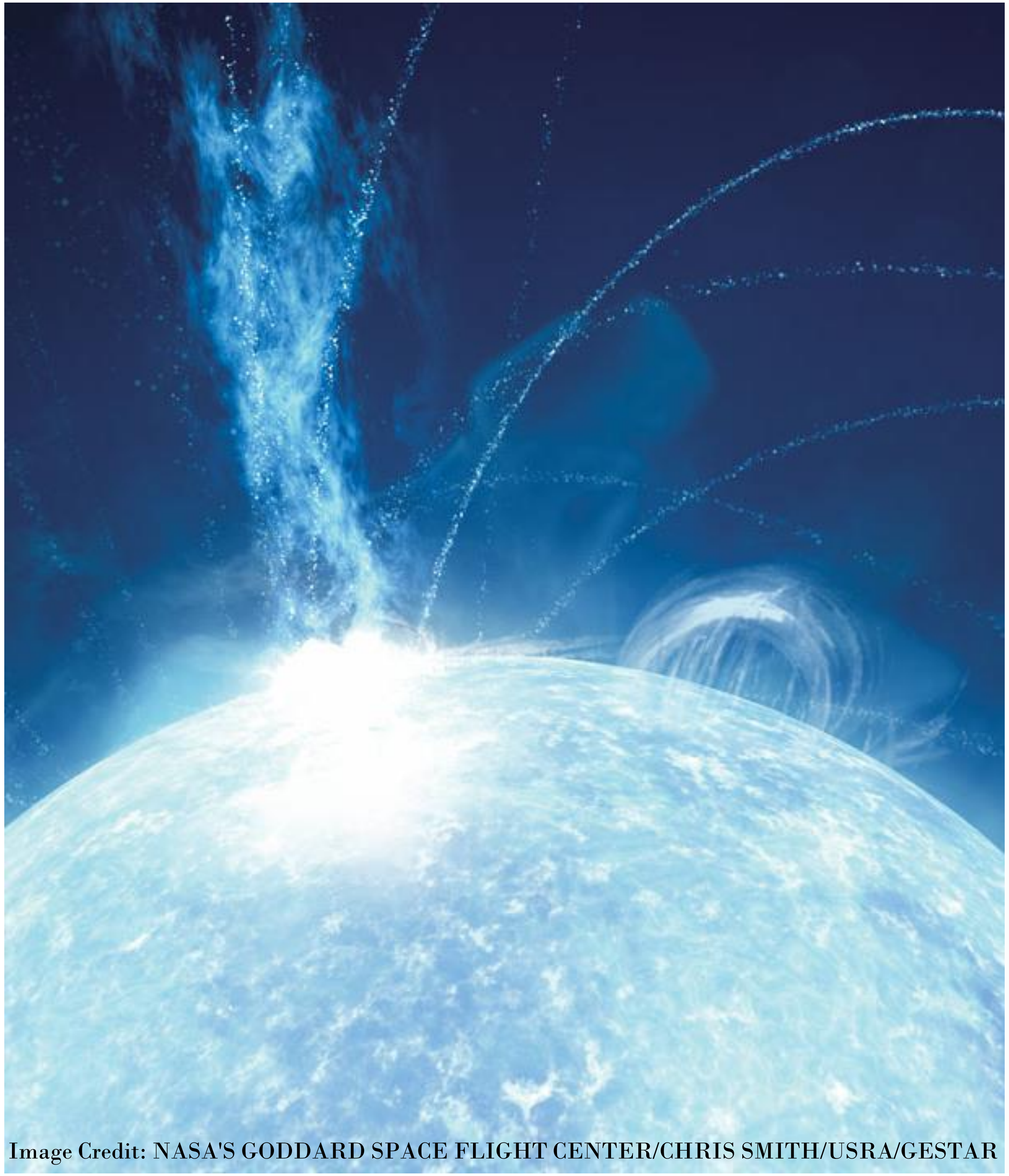

Axion phenomenology in dense, magnetized NS matter

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OzGrav

In collaboration with J. A. Pons (U. of Alicante), A. Gomez-Bañón (U. of Alicante), P. D. Lasky (Monash U.), F. Bianchini (Stanford U.), A. Melatos (U. of Melbourne)

IPMU, APEC seminar, 30 Sept 2022

Axions

- Axions are light bosons introduced to solve the "strong CP problem"
- Plausible candidates for dark matter
- Phenomenology: expected to be rich, but nothing observed yet.
- Coupling to photons (via EM fields). We can probe new phenomenology with available data of cooling NSs!

[1] R. D. Peccei and H. R. Quinn, CP conservation in the presence of pseudoparticles, Phys. Rev. Lett. 38, 1440 (1977)

Structure of the talk

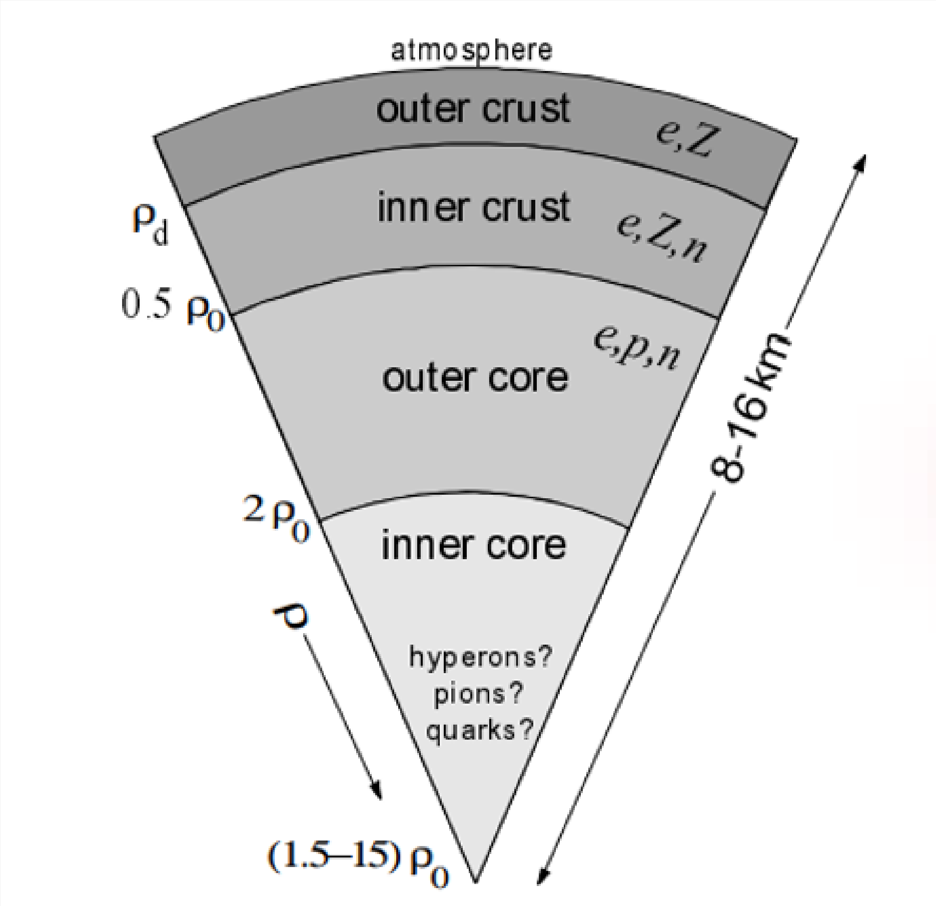
Finite density corrections to axion potential

Large value of $\frac{a}{f_a}$

Our result: altered NS magnetic evolution, incompatibility with NSs thermal luminosity data

Bounds on how big $\frac{a}{f_a}$ can be from axion electrodynamics

NS structure and cooling



Cooling: neutrinos from crust+ core and photon emission

Image credit: [2] Yakovlev D. G., Levenfish K. P., Shibanov Y. A., 1999, Physics Uspekhi, 42, 737

Axion potential

In vacuo

$$V_0(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$

Minimum for $a = 0$

$+ \; f_a \gtrsim 10^8 \mathrm{GeV}$

[3] G. G. di Cortona, E. Hardy, J. P. Vega, and G. Villadoro, The QCD axion, precisely, Journal of High Energy Physics 2016, 34 (2016)
[4] K. Hamaguchi, N. Nagata, K. Yanagi, and J. Zheng, Limit on the axion decay constant from the cooling neutron star in Cassiopeia A, Phys. Rev. D 98, 103015 (2018)

Axion potential

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In medio

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

→ Minimum for

$$\frac{a}{f_a} \approx \pi$$

[5] A. Hook and J. Huang, Probing axions with neutron star inspirals and other stellar processes, Journal of High Energy Physics 2018, 36 (2018)
[6] R. Balkin, J. Serra, K. Springmann, and A. Weiler, The QCD axion at finite density, Journal of High Energy Physics 2020, 221 (2020)

Axion potential

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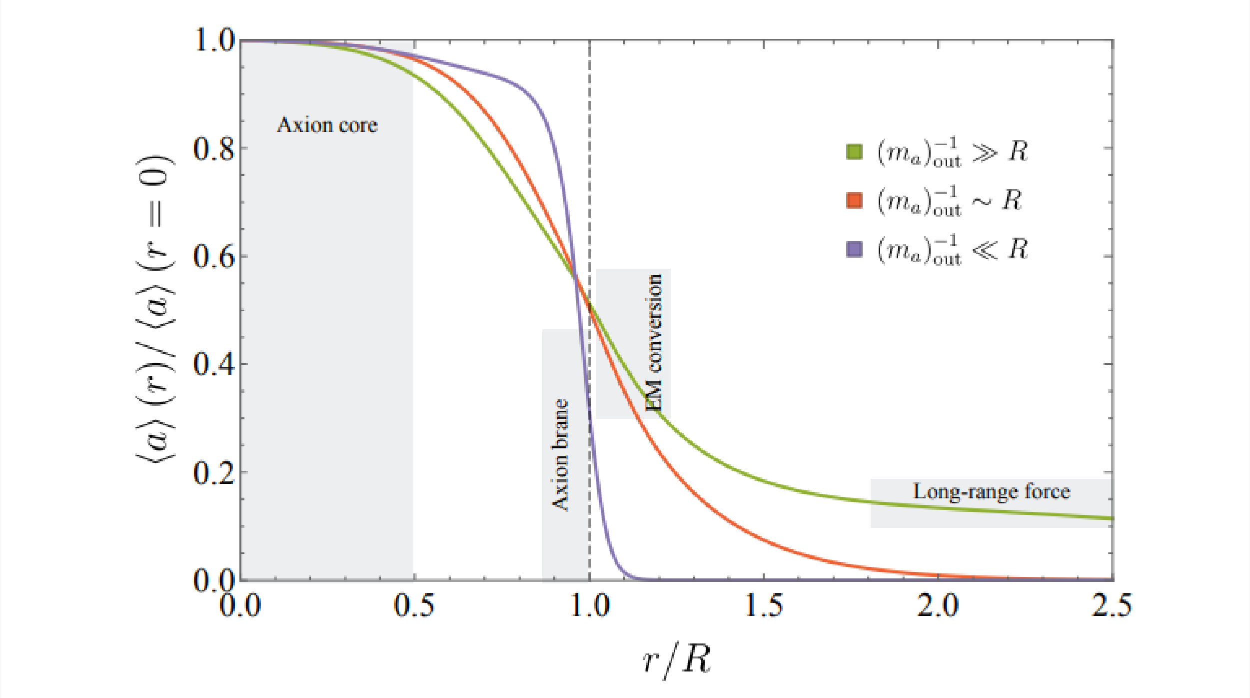
More possibilities considered in the literature

[5] A. Hook and J. Huang, Probing axions with neutron star inspirals and other stellar processes, Journal of High Energy Physics 2018, 36 (2018)

[6] R. Balkin, J. Serra, K. Springmann, and A. Weiler, The QCD axion at finite density, Journal of High Energy Physics 2020, 221 (2020)

Axion "sourcing"



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

with $m_a \propto \dfrac{1}{f_a}$

But… such shift of the axion field causes several problems, if axions couple to photons!

[6] R. Balkin, J. Serra, K. Springmann, and A. Weiler, The QCD axion at finite density, Journal of High Energy Physics 2020, 221 (2020)

Coupling to photons

Modified induction equation:

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

ohmic dissipation

Hall drift

Axion dynamo!!
(conversion of axion potential energy in mag. energy)

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

Phenomenology in NSs

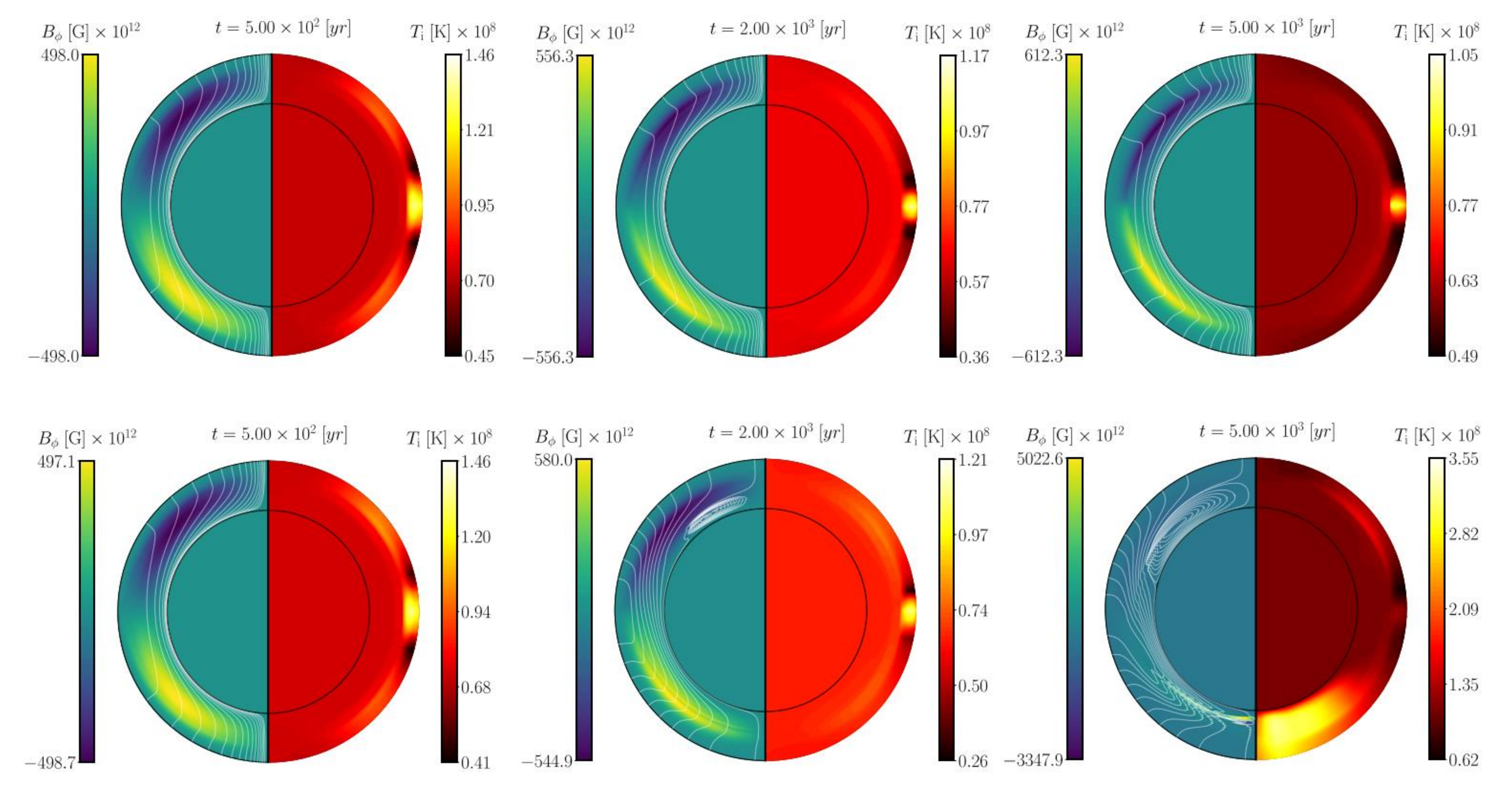
Two effects to look for:

- Magnetic field evolution due to dynamo (not really a direct observable)
- Joule heating rate: warms up the star and increases the redshifted thermal luminosity L_γ

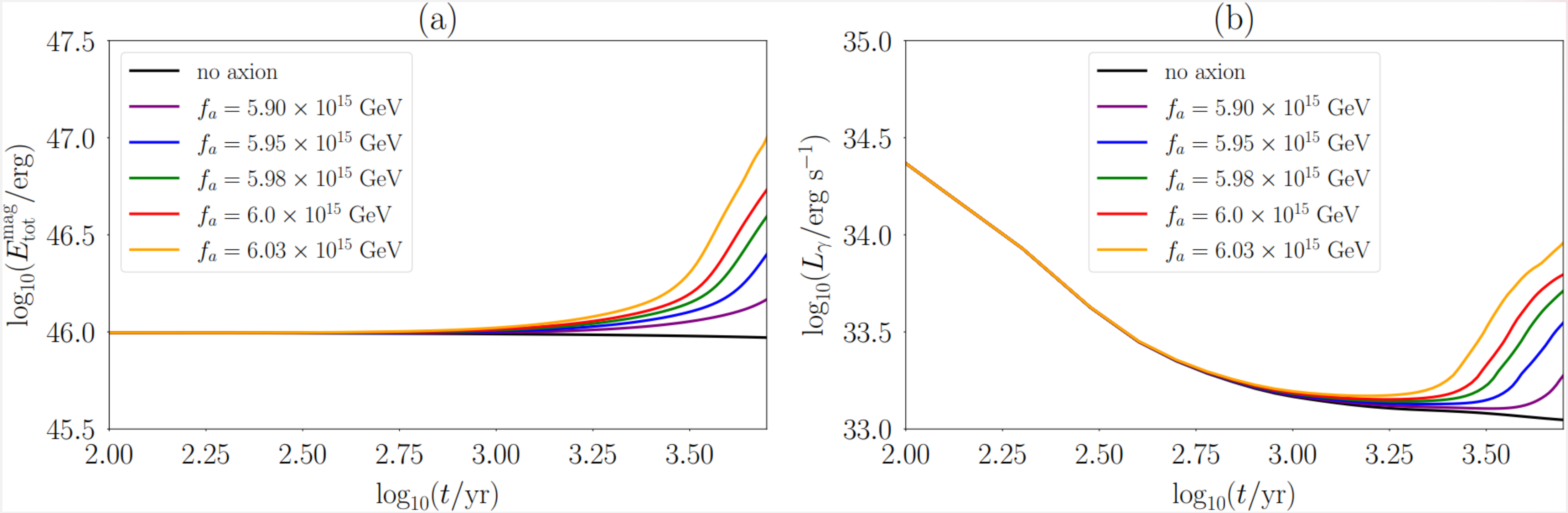
$$Q_{\rm J} = \frac{J^2}{\sigma_e}$$

[8] Vigano D., Garcia-Garcia A., Pons J. A., Dehman C., Graber V., 2021, Comput. Phys. Commun., 265, 108001

Magnetic dynamo

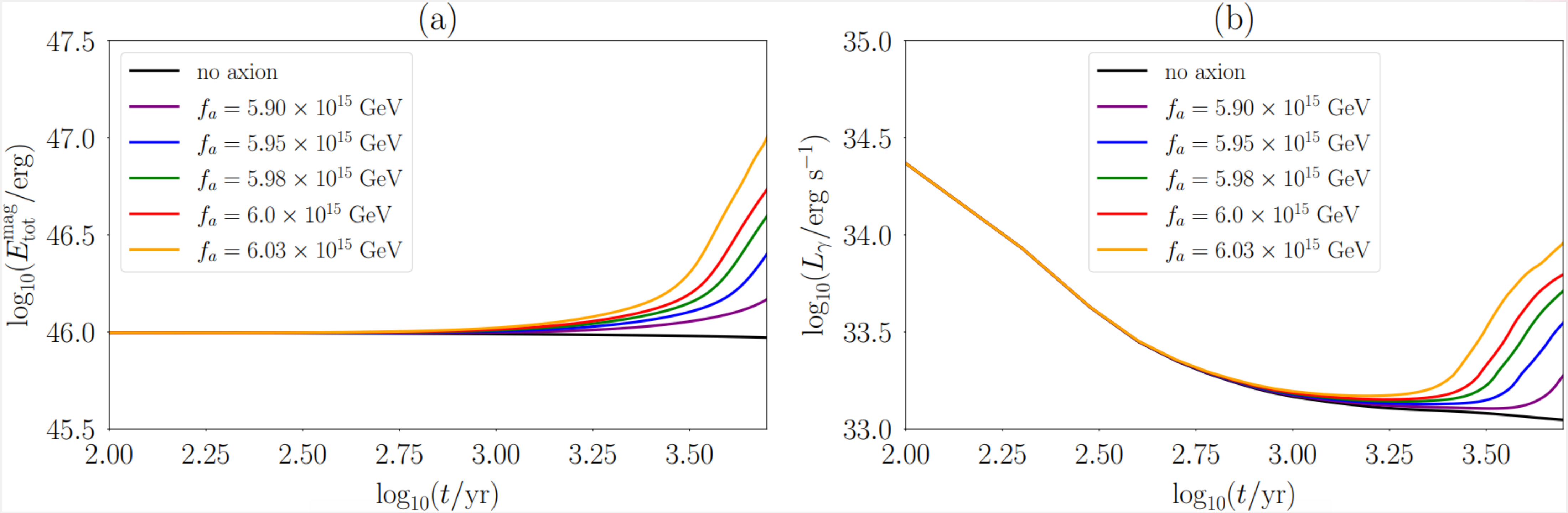


Magnetic dynamo



If f_a grows, so does $g_{a\gamma}a$ → Dynamo more efficient!

Magnetic dynamo

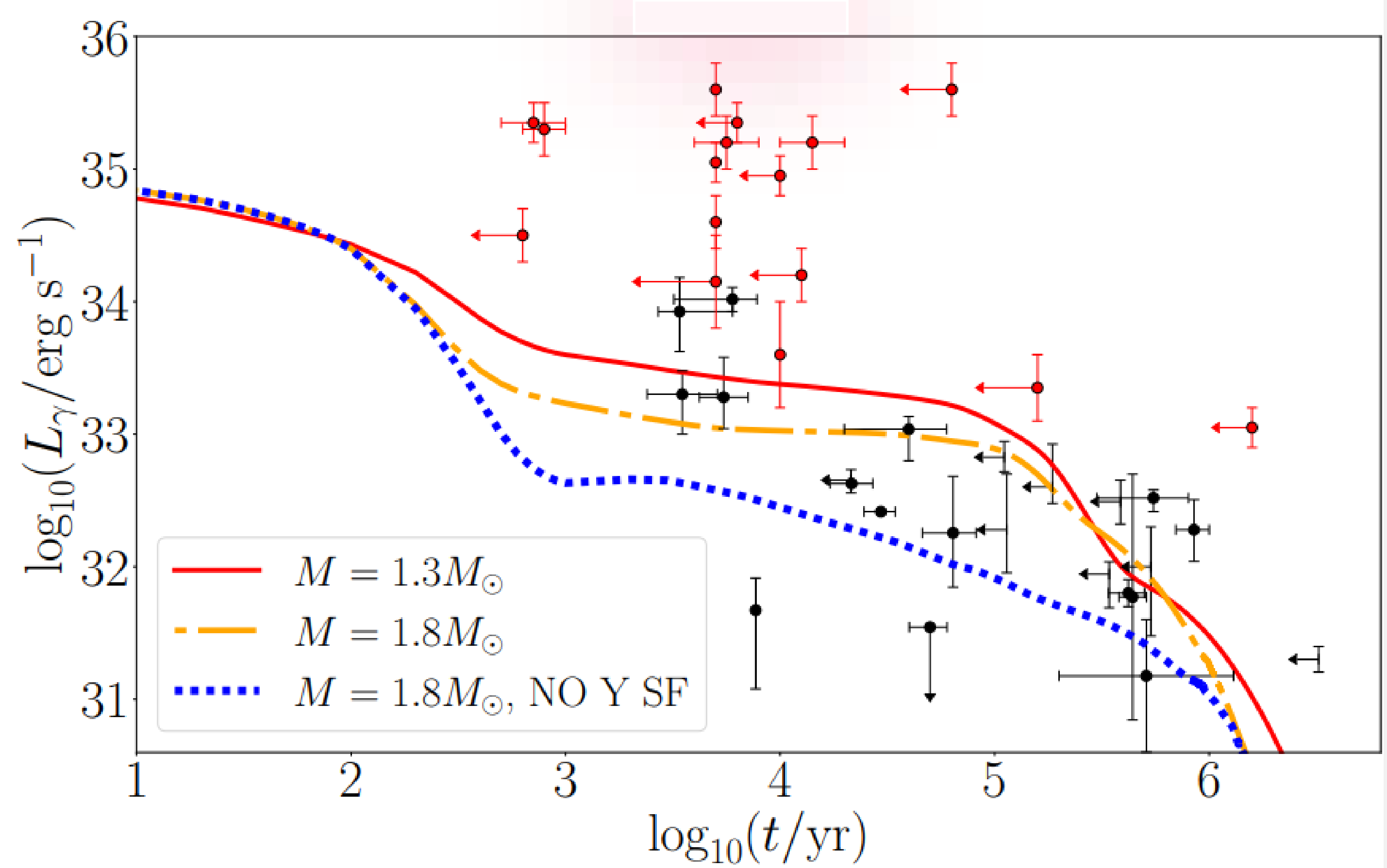


Huge problems!

All NSs would evolve into magnetars!

All NSs would get hotter and brighter as they age!

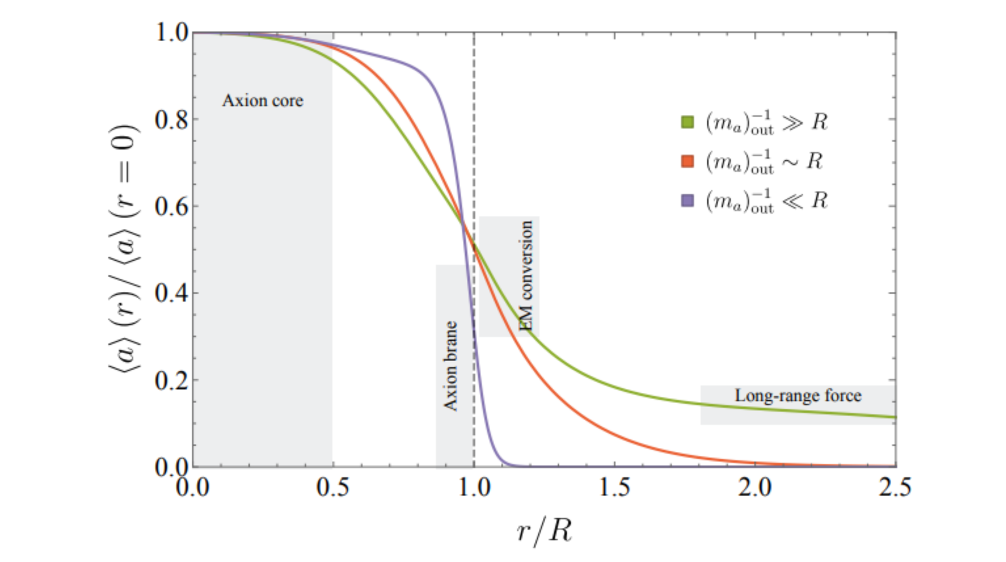
Available NS data



[9] F. Anzuini, A. Melatos, C. Dehman, D. Viganò and J. A. Pons, 2022, Thermal luminosity degeneracy of magnetized neutron stars with and without hyperon cores, Monthly Notices of the Royal Astronomical Society, (arXiv:2205.14793).

Solutions

- Bounds on the axion parameter space. For crust-confined fields $g_{a\gamma}a \ll 10^{-15}$ ... but in the core $g_{a\gamma}a \approx 10^{-3}$!!!



[6] R. Balkin, J. Serra, K. Springmann, and A. Weiler, The QCD axion at finite density, Journal of High Energy Physics 2020, 221 (2020)

Solutions

- Bounds on the axion parameter space. For crust-confined fields $g_{a\gamma}a \ll 10^{-15}$. But in the core $g_{a\gamma}a \approx 10^{-3}$!!!

- Additional terms in Maxwell equations?

- NSs do not source axions with $\frac{a}{f_a} \approx \pi$, or axions do not couple with photons (or neither of them!)

Conclusions and outlook

- To kill the axion dynamo:
  - (i) axion field confined to the core
  - (ii) NSs do not source axions with $\frac{a}{f_a} \approx \pi$
  - (iii) No coupling to photons
- Are there standard ways to "source" axions? Yes, and with $\frac{a}{f_a} \ll 1$!
- Is it the same for other light bosons?
- Reverse engineering: to prevent the axion-dynamo, we can place constraints on dense matter EoS

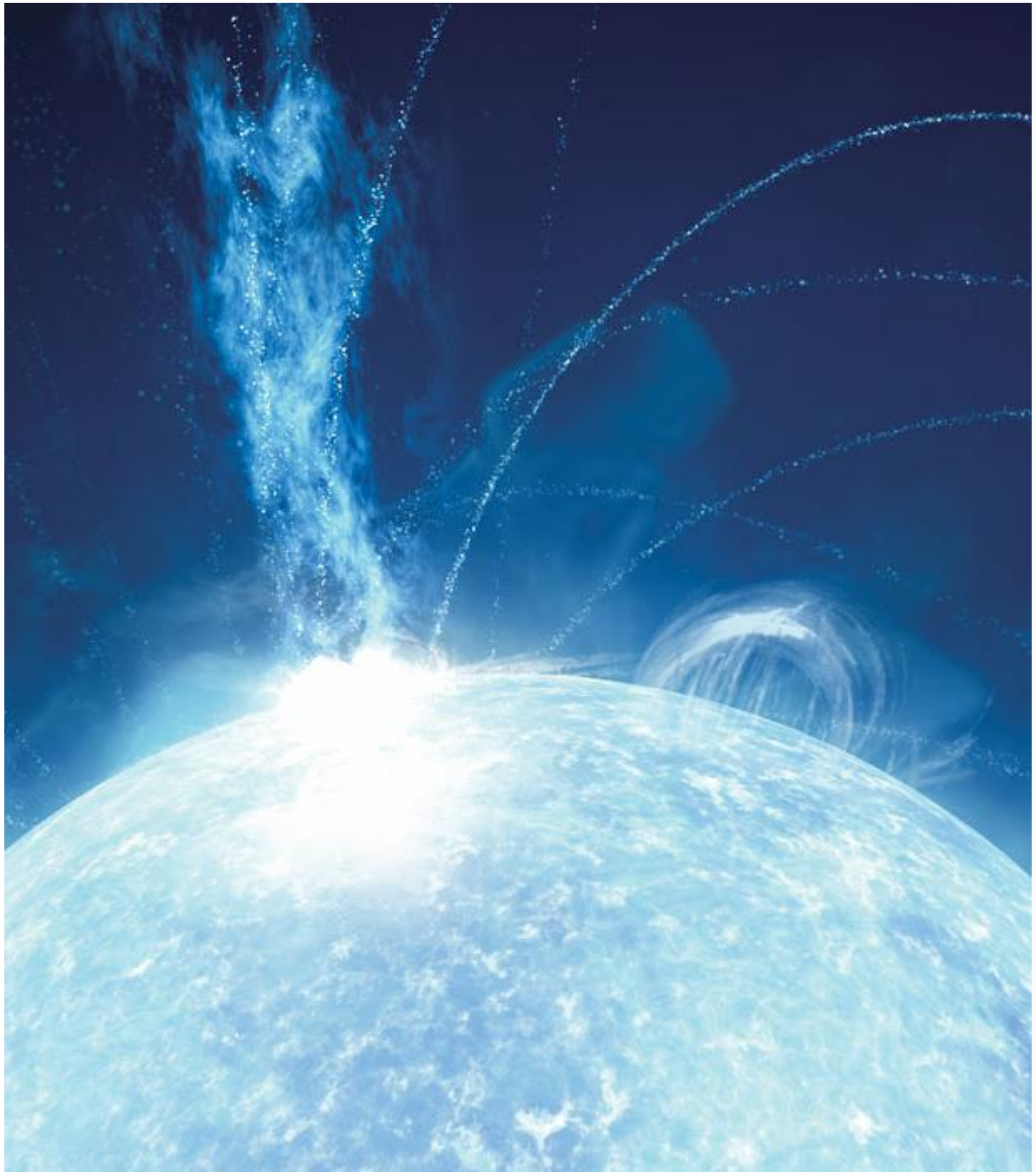


Image Credit: NASA'S GODDARD SPACE FLIGHT CENTER/CHRIS SMITH/USRA/GESTAR

THANK YOU!

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filippo.anzuini@gmail.com (better this one!)

Modified Maxwell's equations

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

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

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

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

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

"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.

At first order in $g_{a\gamma}$

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

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

⬇

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

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

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

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

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

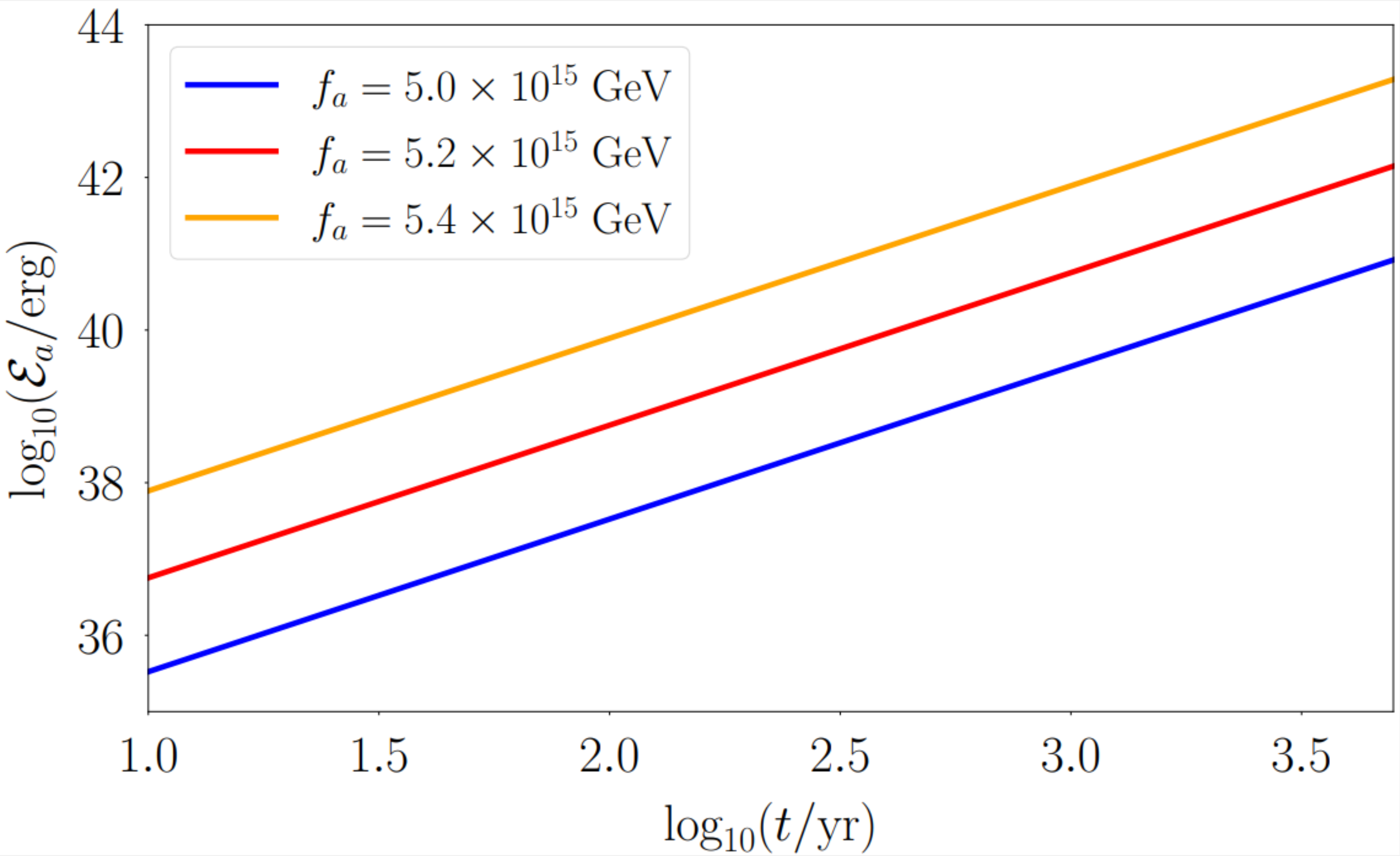
"Standard" axion-Maxwell Eqs.

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

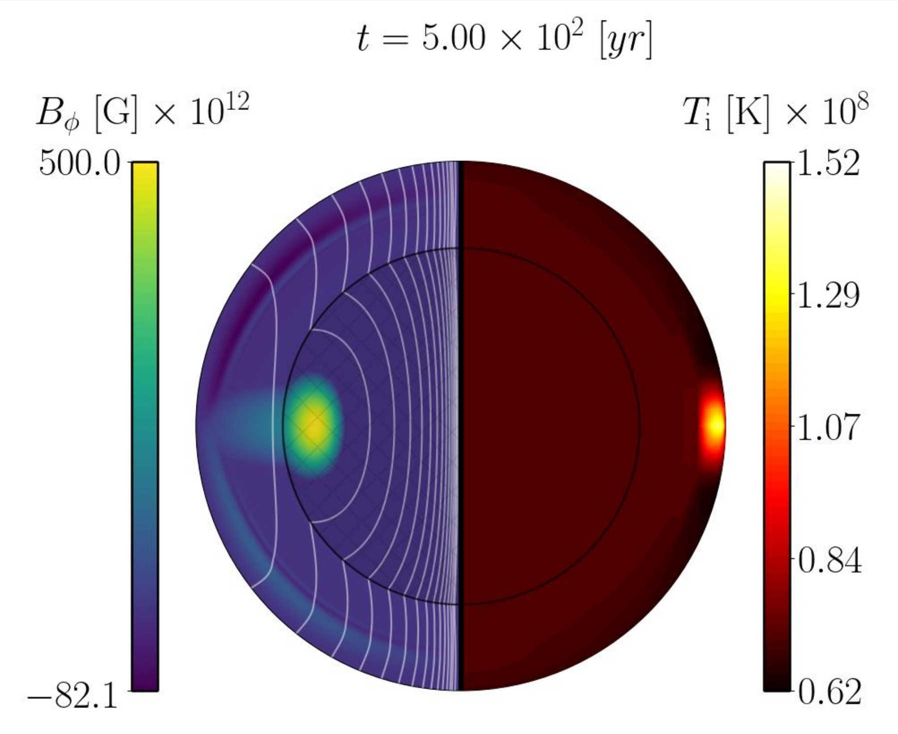
The solution is

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

“Standard” axion-Maxwell Eqs.



Core fields



[9] F. Anzuini, A. Melatos, C. Dehman, D. Viganò and J. A. Pons, 2022, Thermal luminosity degeneracy of magnetized neutron stars with and without hyperon cores, Monthly Notices of the Royal Astronomical Society, (arXiv:2205.14793).

Magneto-thermal evolution

- Heat diffusion equation

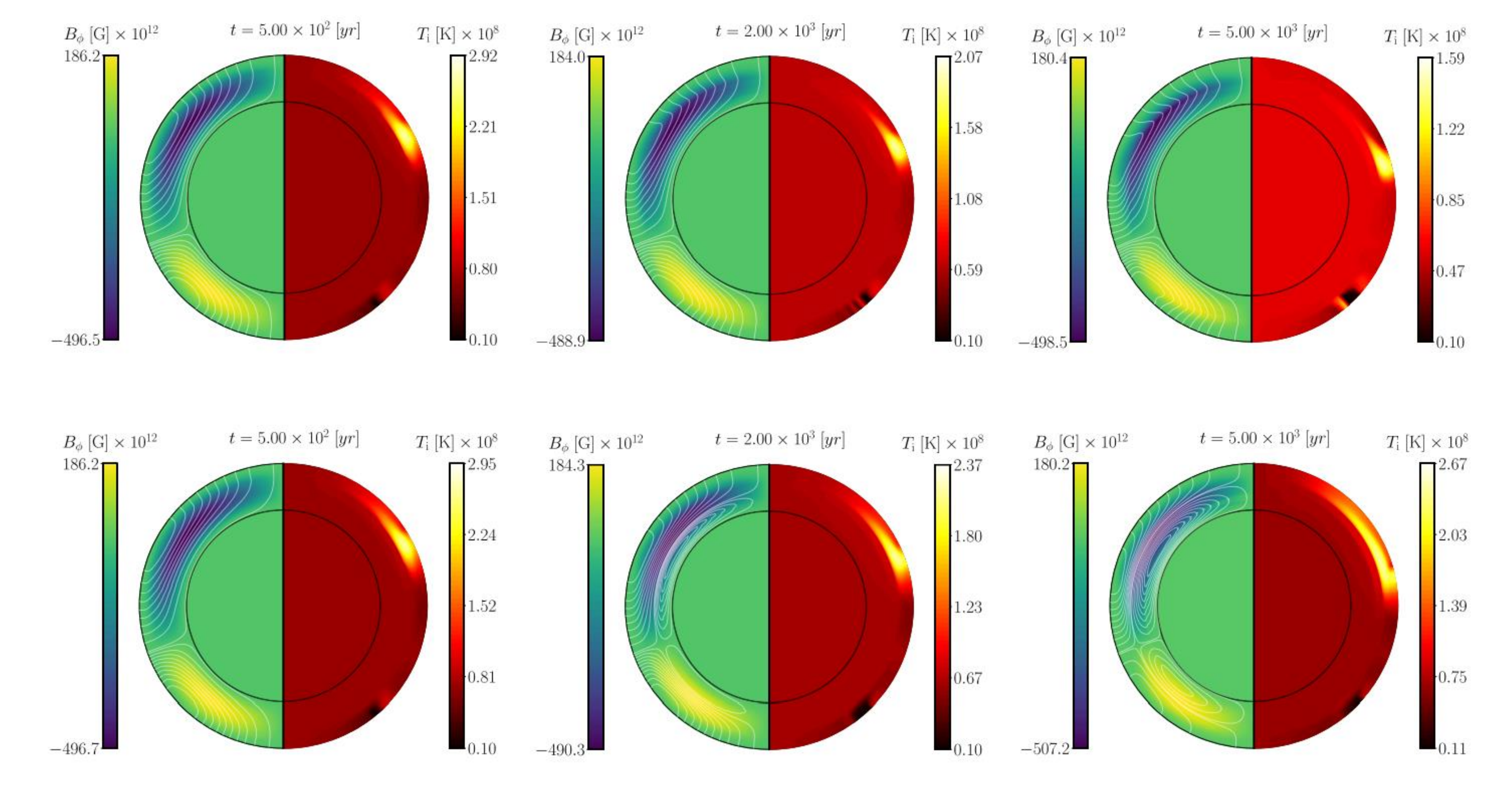
$$c_{\mathrm{V}} e^{\nu} \frac{\partial T}{\partial t} + \boldsymbol{\nabla} \cdot (e^{2\nu} \boldsymbol{F}) = e^{2\nu} (Q_{\mathrm{J}} - Q_{\nu})$$

- Magnetic induction equation

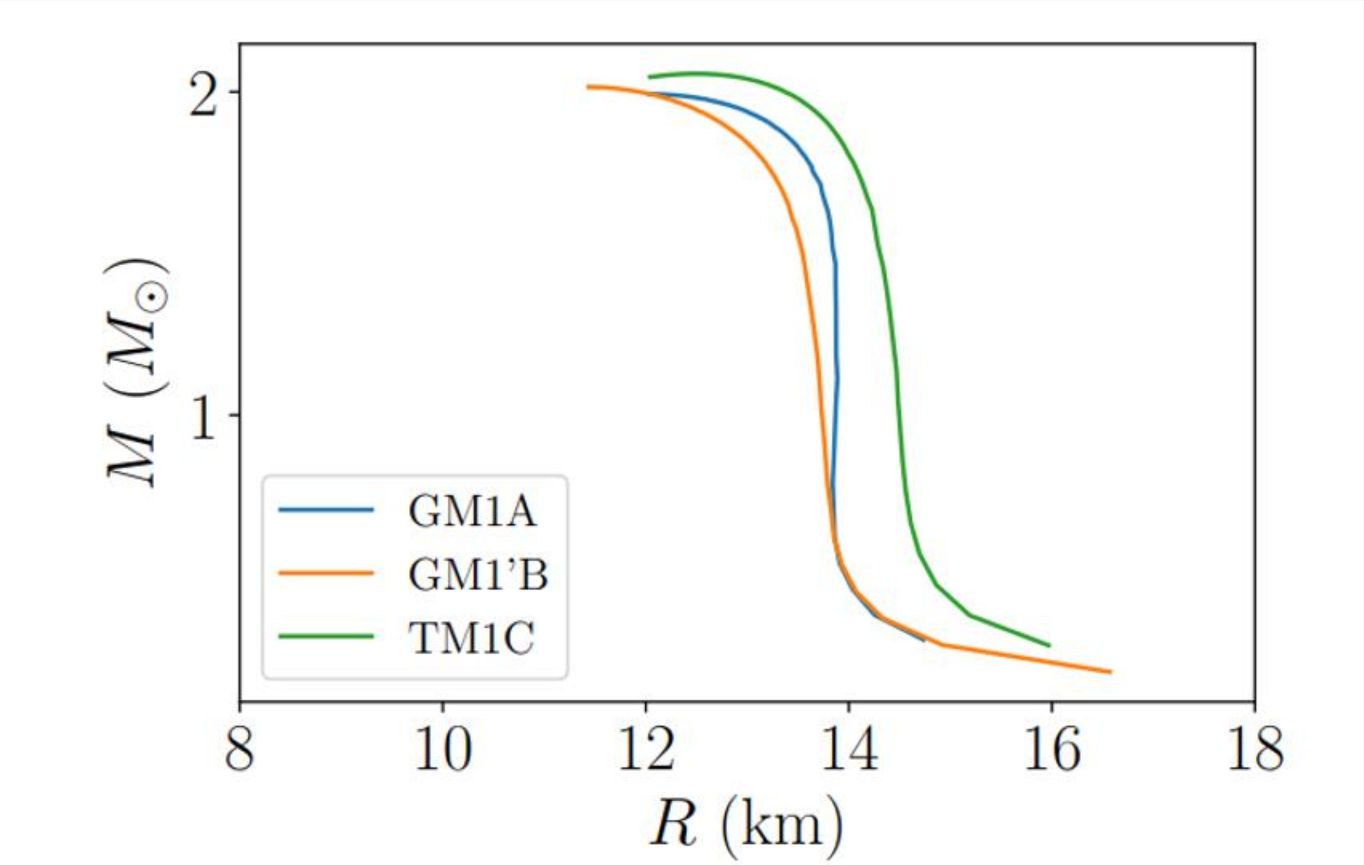
$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \left[\frac{c^2}{4\pi\sigma_e} \boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B}) + \frac{c}{4\pi e n_e} [\boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B})] \times \boldsymbol{B} \right]$$

[11] Pons J. A., Viganò D., 2019, Living Reviews in Computational Astrophysics, 5, 3
[8] Vigano D., Garcia-Garcia A., Pons J. A., Dehman C., Graber V., 2021, Comput. Phys. Commun., 265, 108001

Other magnetic topologies



Mass-Radius relation



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