GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Institute of Space Sciences

CSIC IEEC

MAGNESIA erc

3D magnetothermal evolution of neutron stars with the new finite volume code MATINS

Stefano Ascenzi (GSSI)

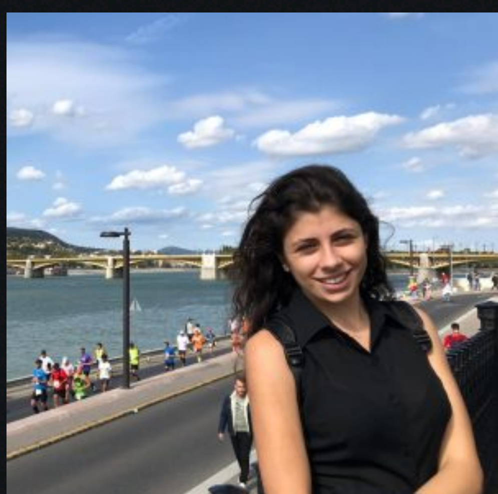
Collaborators: D. Viganò, C. Dehman, J. A. Pons, N. Rea, R. Perna, Davide De Grandis

Image credits: NASA's Goddard Space Flight Center/ Chris Smith

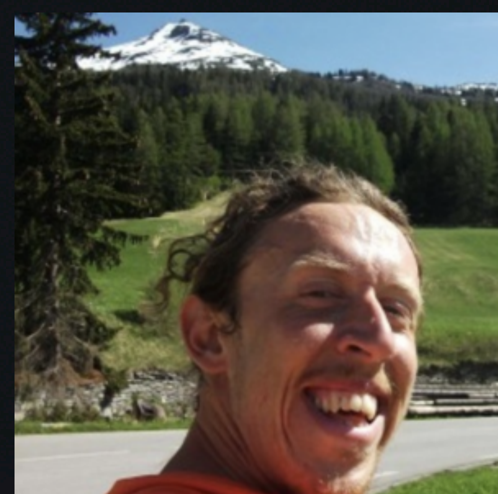
IReNA-INT Joint Workshop, Seattle, 12th Dec 2024

MATINS

MAgneto-**T**hermal evolution
of **I**solated **N**eutron **S**tars



Clara Dehman
(University of Alicante)



Daniele Viganò
(ICE-CSIC)

Jose Pons
(University of Alicante)

Nanda Rea
MAGNESIA PI (ICE-CSIC)

MAGNESIA

erc

Motivation

Magneto-thermal evolutionary models are able to account for the phenomenological diversity of different classes of neutron stars and link them within a unified evolutionary path

The Hall instability is expected to give rise to 3D modes, even for axisymmetric initial conditions

The 3D evolution leads to the formation of hot-spots on the stellar surface that can account for the pulsed fraction observed in some sources (see e.g. Igoshev+2021)

Magneto-Thermal Evolution

Ohmic dissipation

Hall drift

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

Coupling

$$\int_V c_v \frac{\partial (e^{\nu} T)}{\partial t} dV + \int_{\partial V} e^{2\nu} \mathbf{F} \cdot d\mathbf{A} = \int_V e^{2\nu} \dot{\epsilon} \, dV$$

Variation of temperature within a volume

Flux of heat through the volume boundary

Sources (sinks): heat generated (lost) within the volume

Source Term

$$\dot{\epsilon} = \frac{\|\mathbf{J}\|^2}{\sigma} - \dot{\epsilon}_\nu - \dot{\epsilon}_{BB}$$

Ohmic dissipation

Neutrino Cooling

Photon cooling (surface)

Heat Flux

$$e^{\nu(r)}\mathbf{F} = -\,k_\perp\Big[\underbrace{\nabla\tilde{T}} + \underbrace{(\omega_B\tau_0)^2(\mathbf{b}\cdot\nabla\tilde{T})\mathbf{b}} + \underbrace{(\omega_B\tau_0)(\mathbf{b}\times\nabla\tilde{T})}\Big]$$

Parallel to the temperature gradient

Parallel to the magnetic field

Hall term (orthogonal to the temperature gradient and the magnetic field)

$$\frac{k_\parallel}{k_\perp} \simeq 1 + (\omega_B\tau_0)^2$$

Solving the Heat Diffusion Equation

$$\int_V c_v \frac{\partial(e^{\nu}T)}{\partial t} dV + \int_{\partial V} e^{2\nu}\mathbf{F}\cdot d\mathbf{A} = \int_V e^{2\nu}\dot{\epsilon}\, dV$$

Discretization

$$V^{i,j,k}\frac{c_{v;i,j,k}}{\Delta t}(\tilde{T}^{n+1}_{i,j,k} - \tilde{T}^{n}_{i,j,k}) + \Phi_{i,j,k}(e^{2\nu_i}\mathbf{F}_{i,j,k}) = V^{i,j,k}e^{2\nu_i}\dot{\epsilon}_{i,j,k}$$

Implicit Scheme

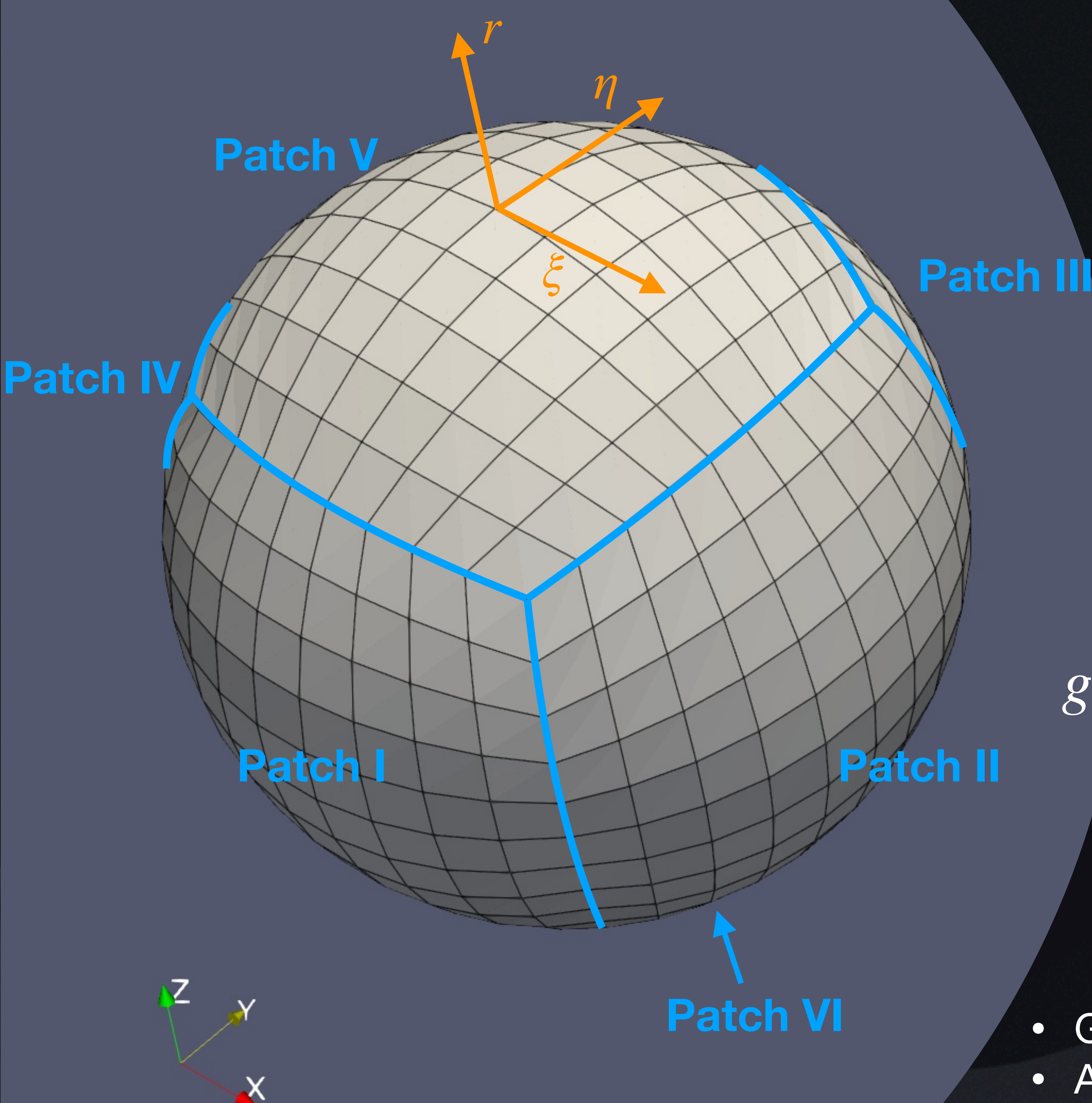
$$\hat{M}^s_l\ \tilde{T}^{n+1}_s = v(\tilde{T}^n_l)$$

$$\tilde{T}^{n+1}_s = (\hat{M}^{-1})^s_l\ v(\tilde{T}^n_\alpha)$$

LAPACK library

Grid: Cubed Sphere

(Ronchi+ 1996)



Desirable Features:

- Radial Coordinate (r)
- Non-singular

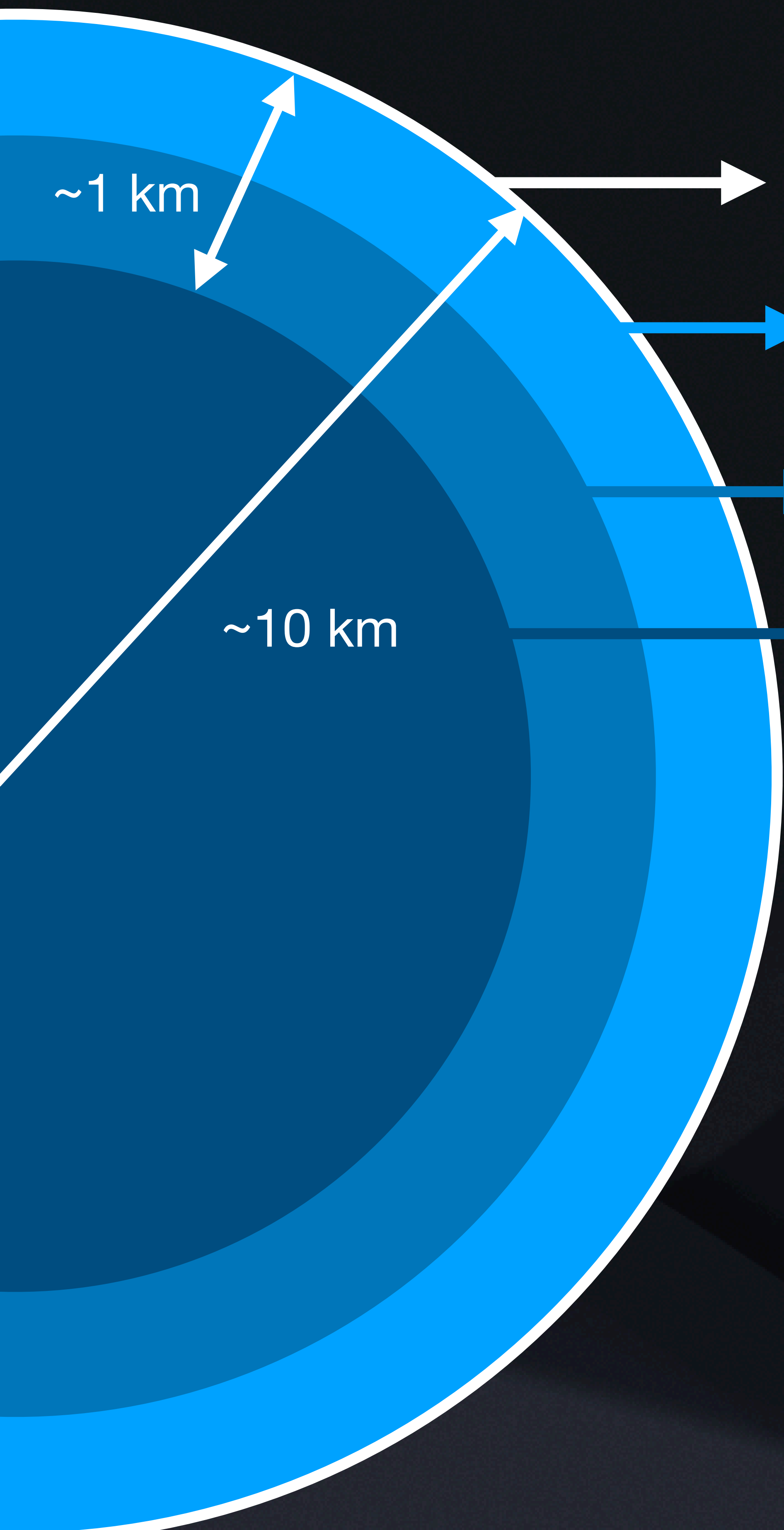
Non-orthogonal coordinate system

$$g_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\frac{X(\xi)Y(\eta)}{C(\xi)D(\eta)} \\ 0 & -\frac{X(\xi)Y(\eta)}{C(\xi)D(\eta)} & 1 \end{pmatrix}$$

Already used in:

- GR codes (e.g. Fragile+2008)
- Atmospheric codes (eg. GEOS-Chem; http://acmg.seas.harvard.edu/geos/)
- MHD codes (eg. Koldoba+2002)

Neutron Star structure

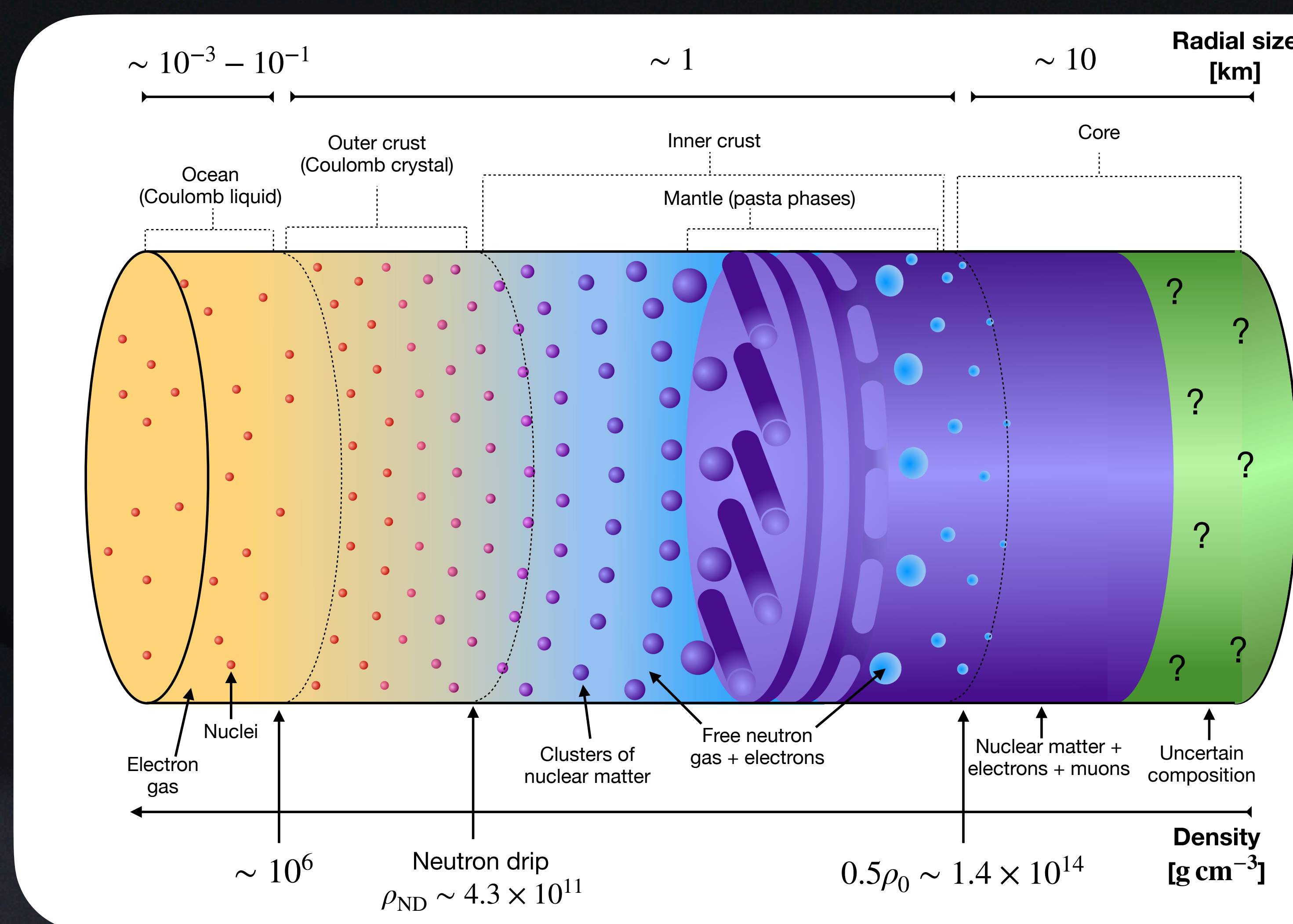


Ocean: ~ 1-100 m, liquid, light or heavy nuclei

Outer Crust: Coulomb lattice of heavy nuclei + relativistic degenerate electrons

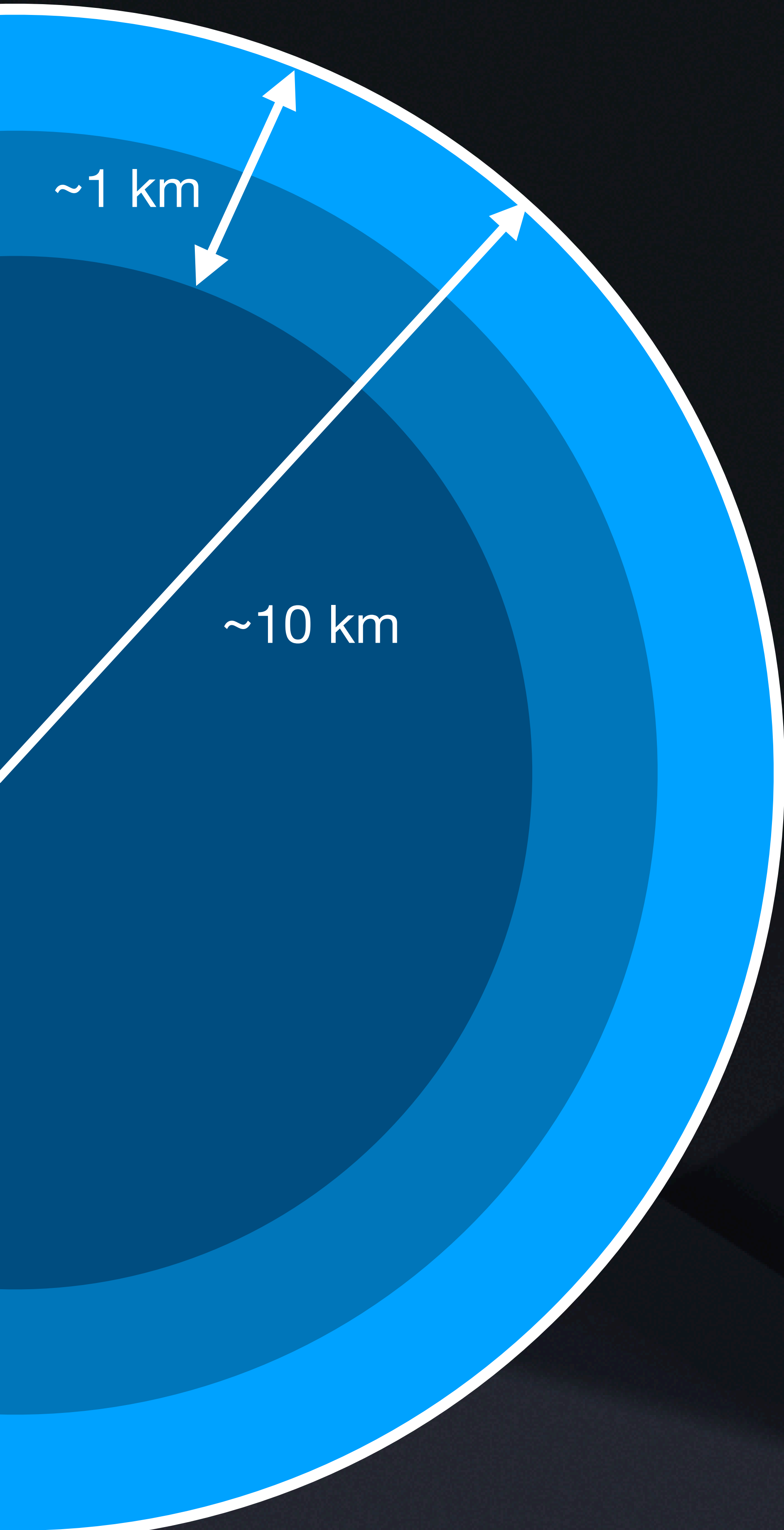
Inner Crust: neutrons start to drip out from nuclei

Core: neutron and proton superfluids, hyperons (?), quark-gluon plasma (?), pion condensate (?)



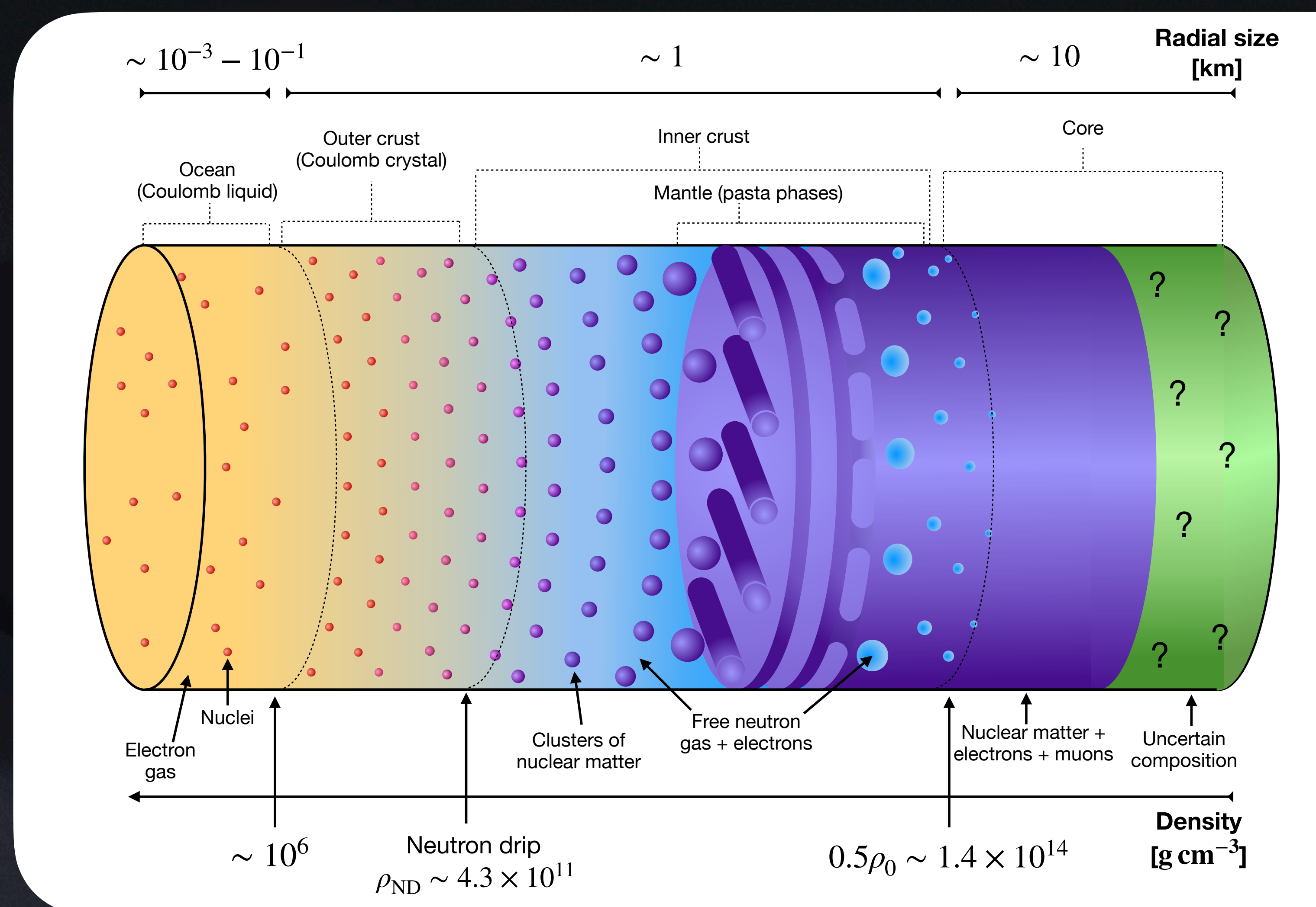
SA, Graber & Rea 2024

Neutron Star structure in MATINS



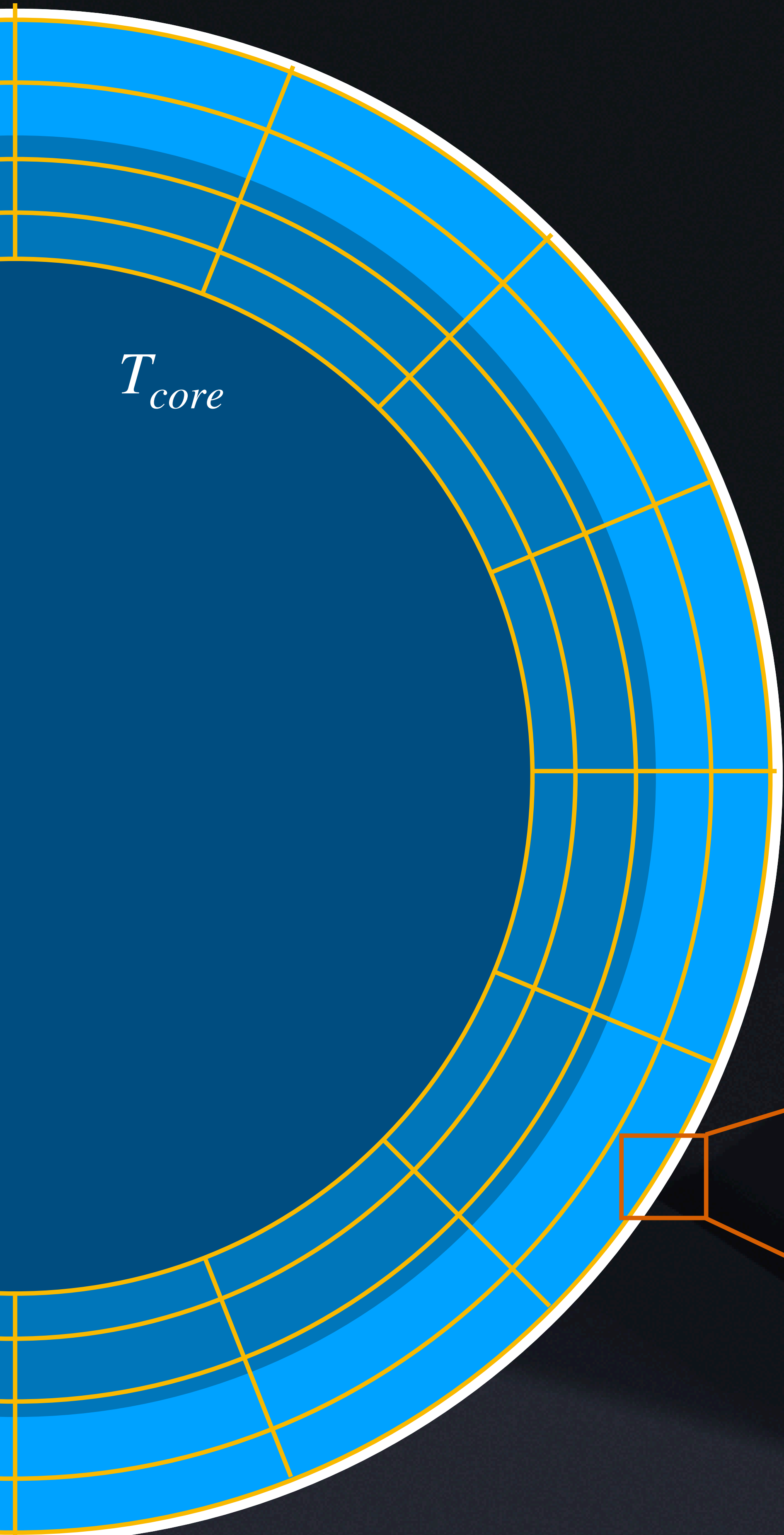
- Structure computed exploiting **different EOSs available** in the public **CompOSE database** (https://compose.obspm.fr/)

- **Microphysics** $(c_v, \dot{\epsilon}_\nu \, \hat{k})$ computed exporting the public code by Pothekin (http://www.ioffe.ru/astro/conduct/)



SA, Graber & Rea 2024

MATINS Computational Domain



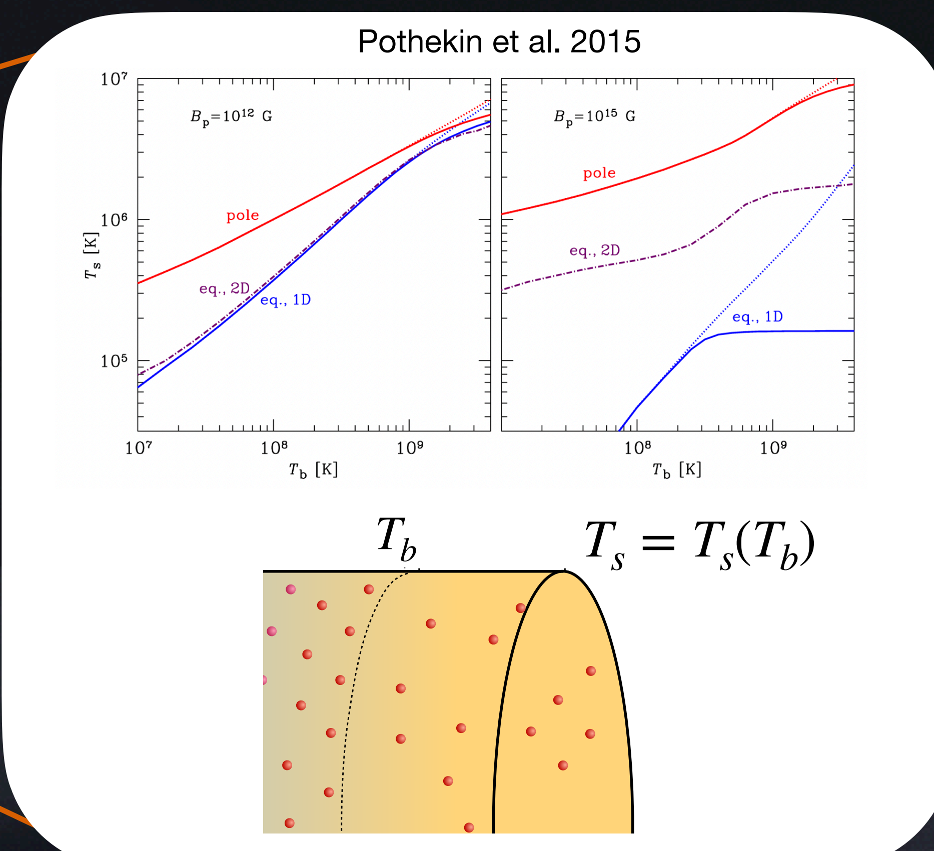
- Crust ✓
- Core (1 zone) ✓
- Envelope ✗

Internal Boundary

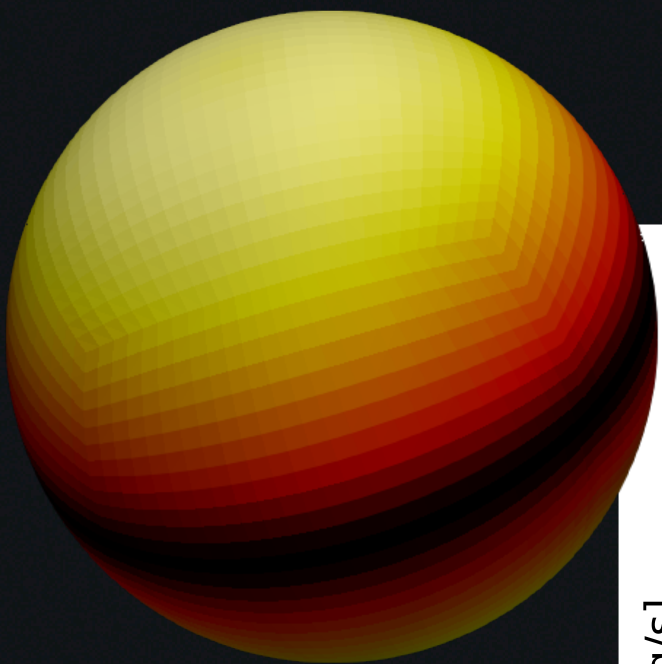
$$\frac{dT_{core}}{dt} = \left\langle \frac{e^{2\nu}\dot{\epsilon}_\nu(T_{core})}{c_v(T_{core})} \right\rangle$$

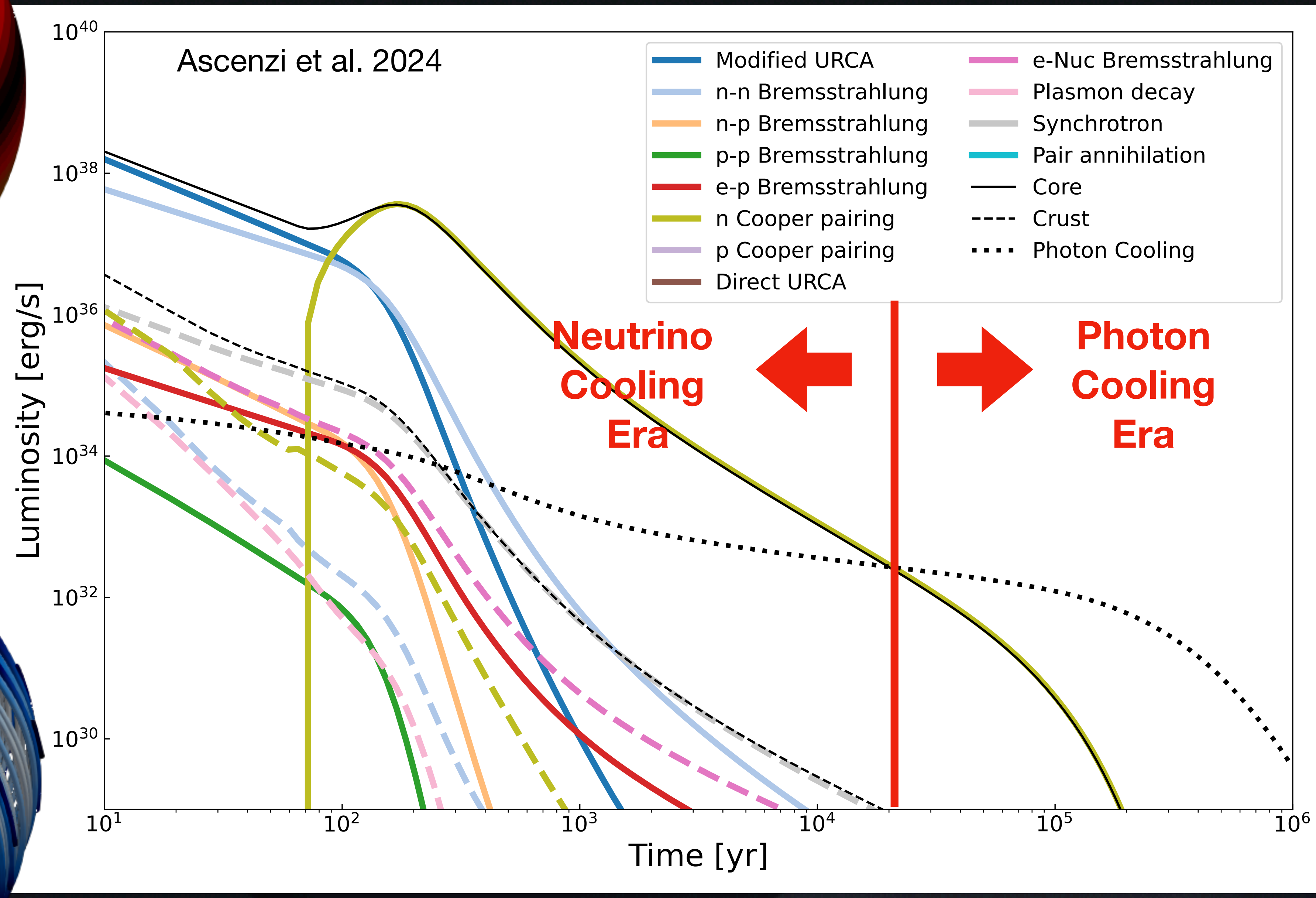
External Boundary

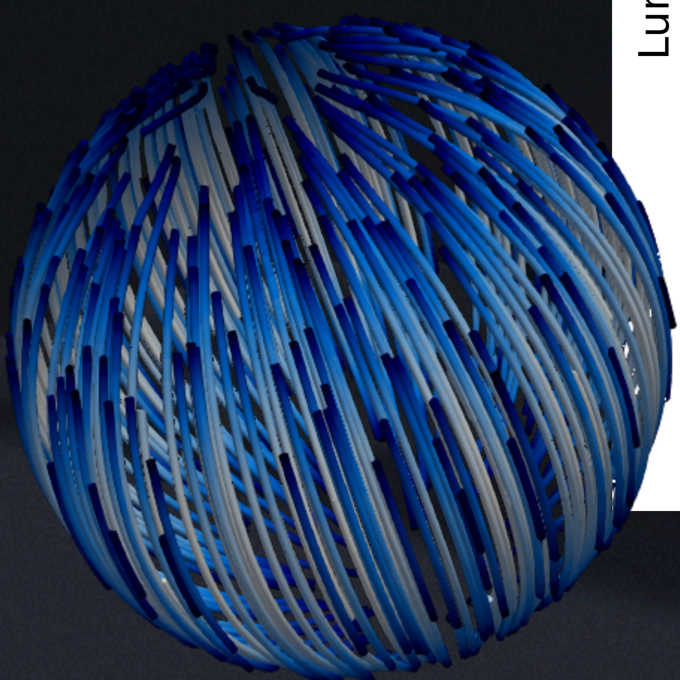
$$F_b = F_r \propto T_s^4$$



An axisymmetric test run: Dipolar Poloidal non-evolving Field

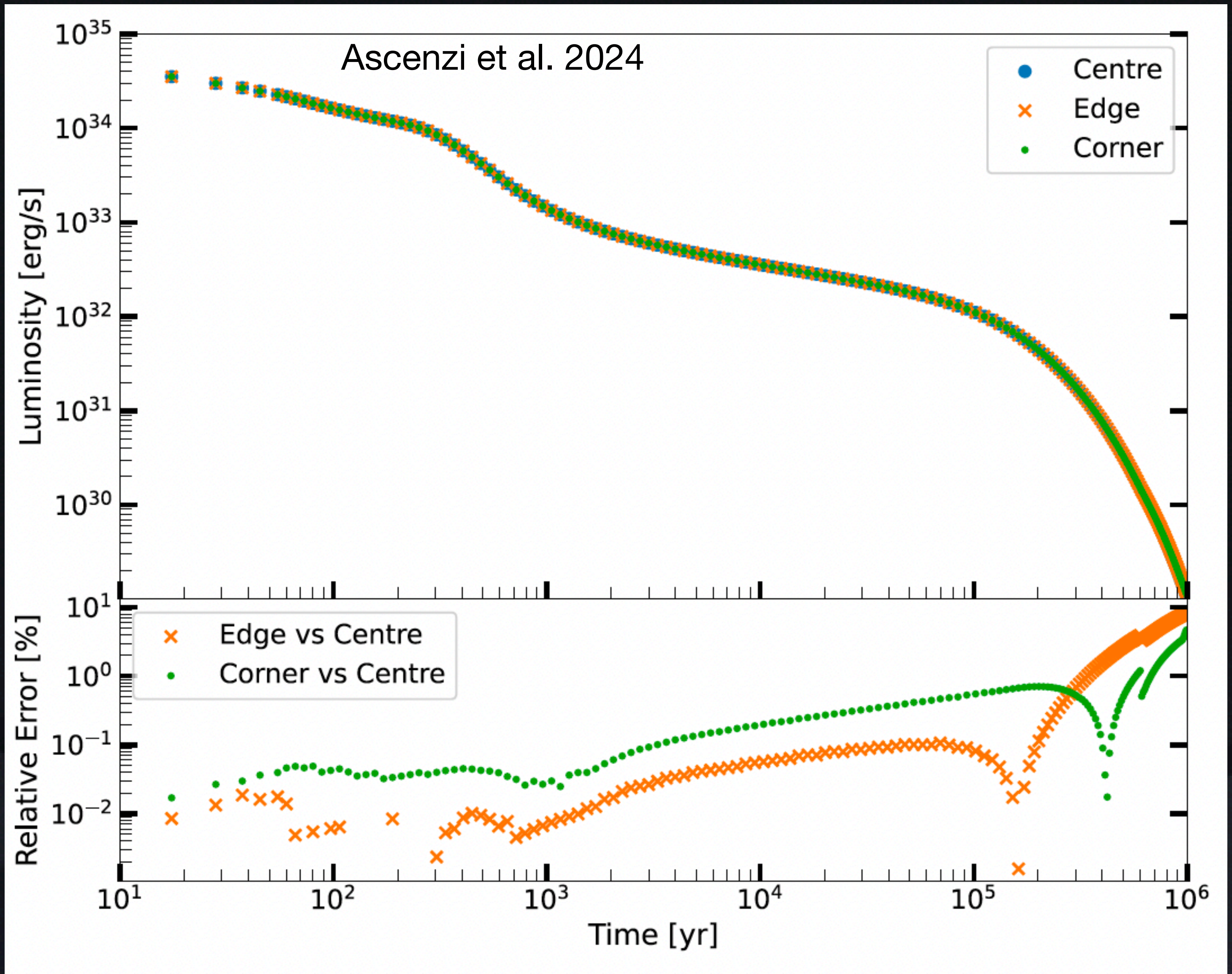






EOS: SLy4

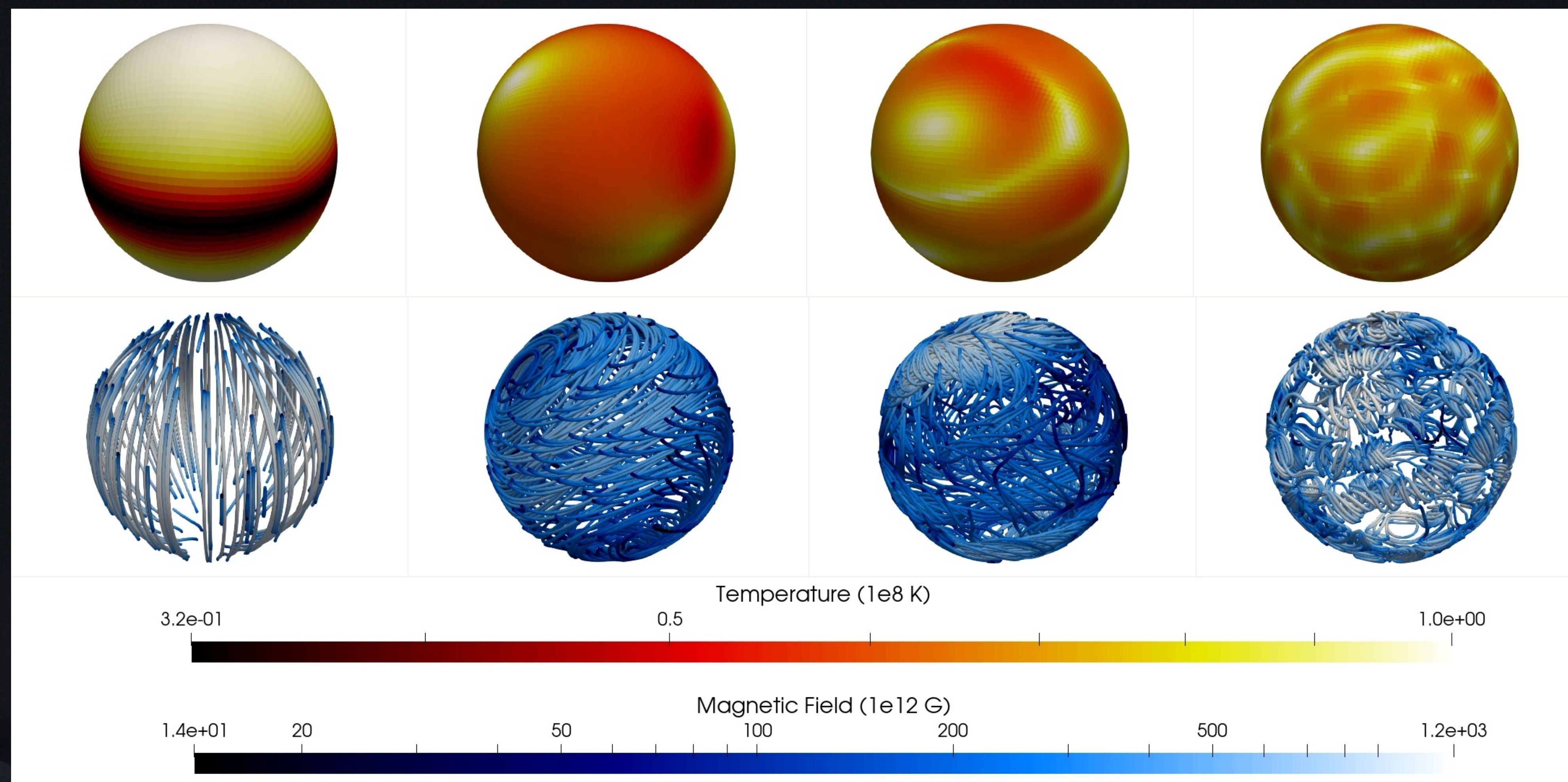
An axisymmetric test run: Dipolar Poloidal non-evolving Field



Non- axisymmetric runs with non-evolving field

Temperature

Magnetic Field



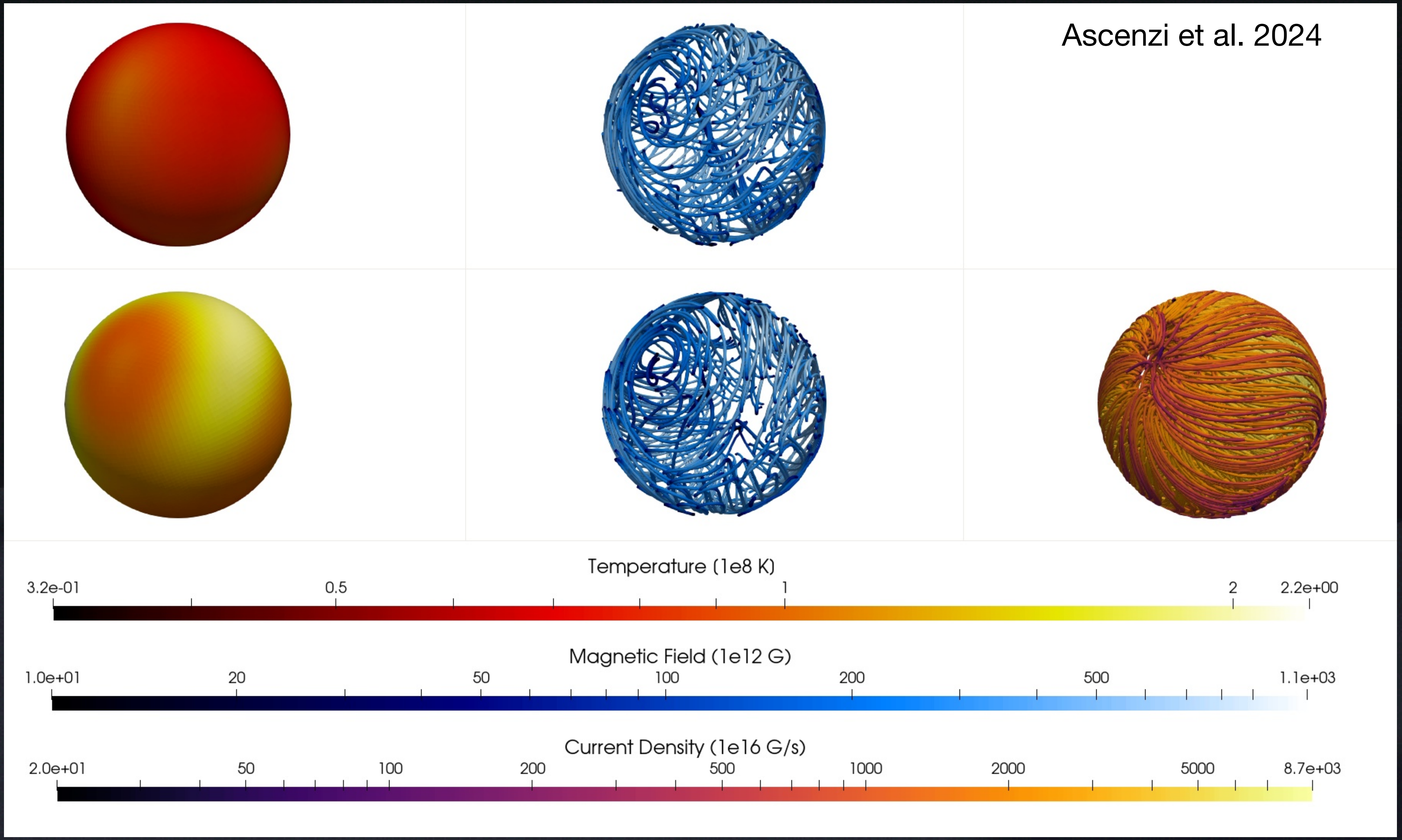
Ascenzi et al. 2024

A non- axisymmetric run with magnetic field evolution

Temperature

Magnetic Field

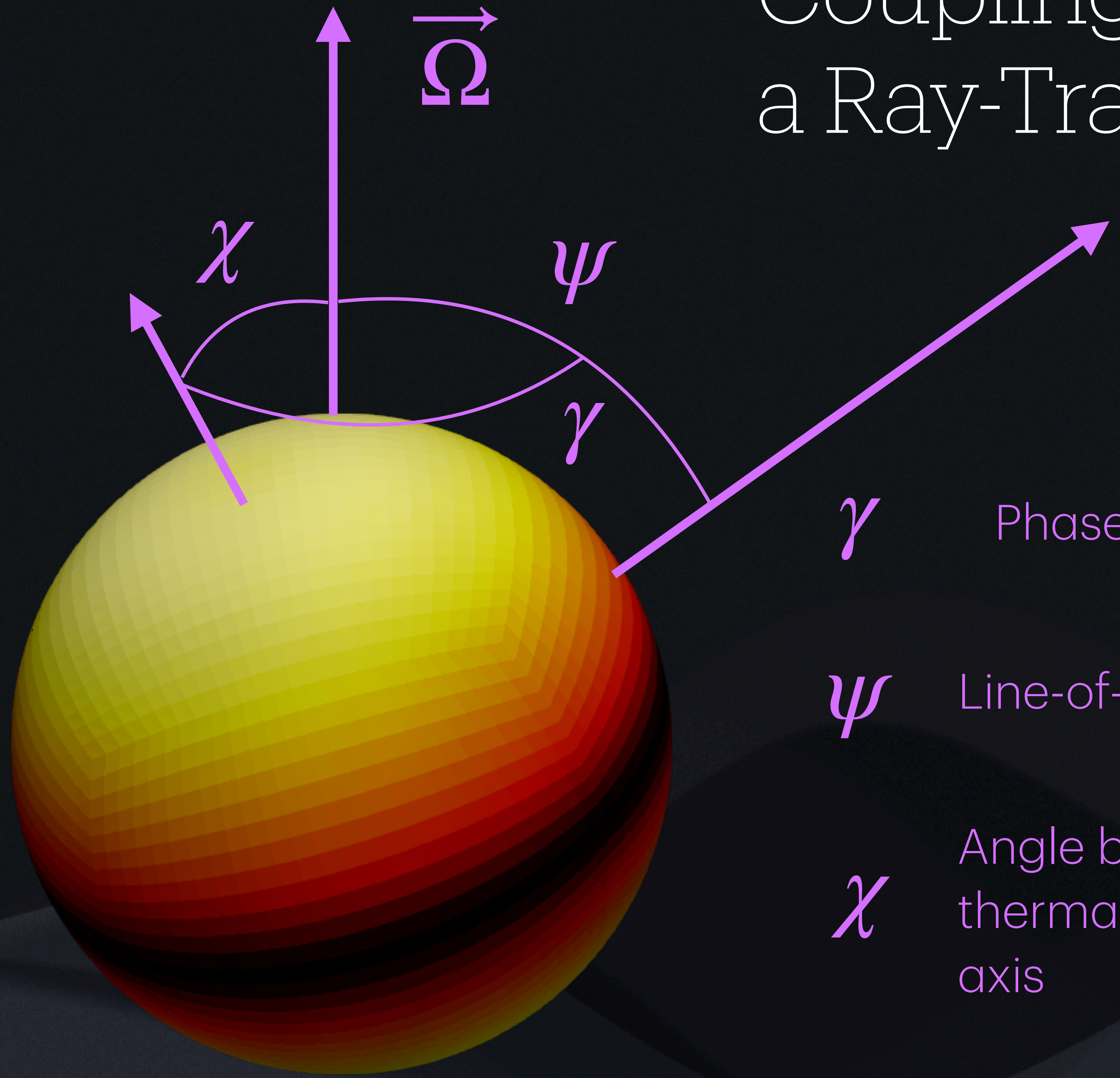
Electric current density



Non-evolving B-field

Evolving B-field

Coupling MATINS with a Ray-Tracing code



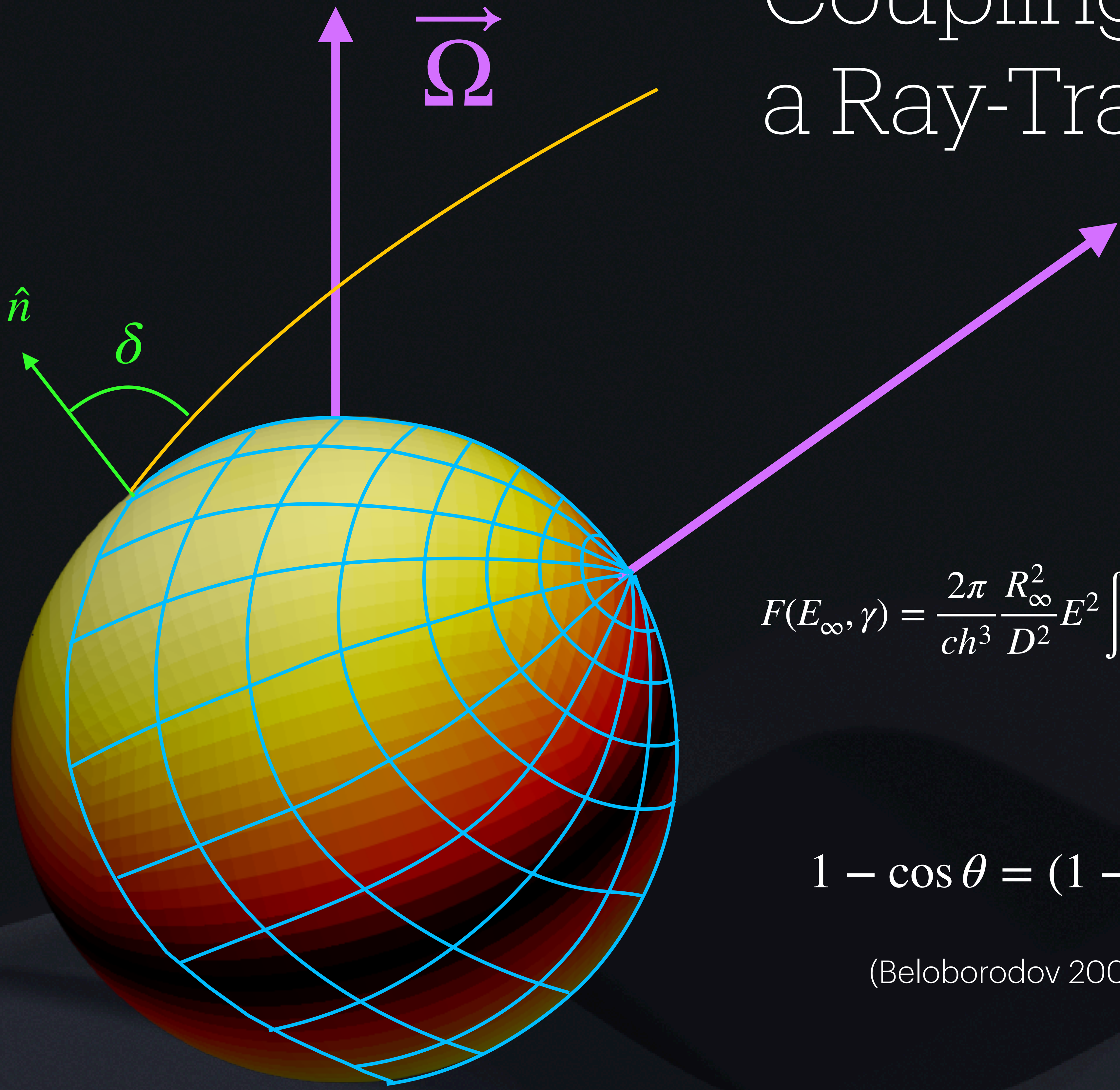
In collaboration with Rosalba Perna (Stony Brook University)

γ Phase angle

ψ Line-of-sight-rotational axis angle

χ Angle between a reference to thermal map and the rotational axis

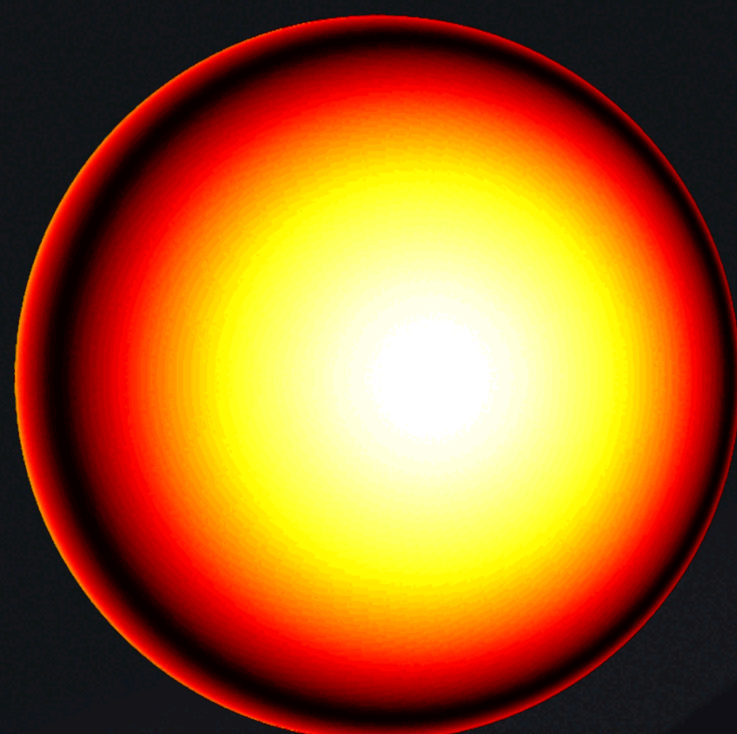
Coupling MATINS with a Ray-Tracing code

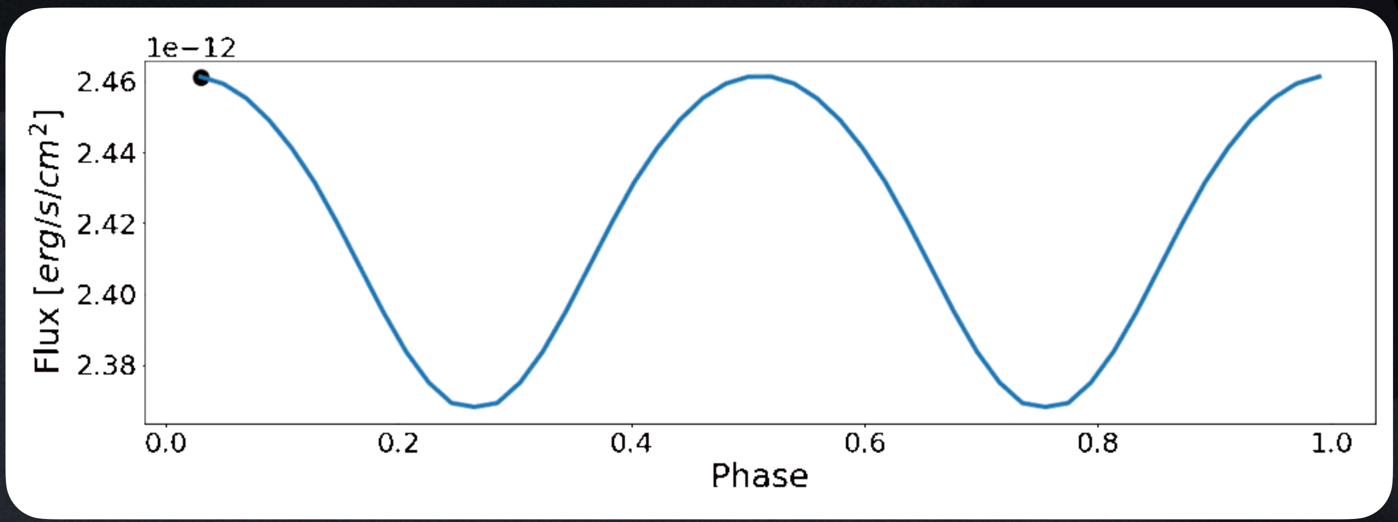


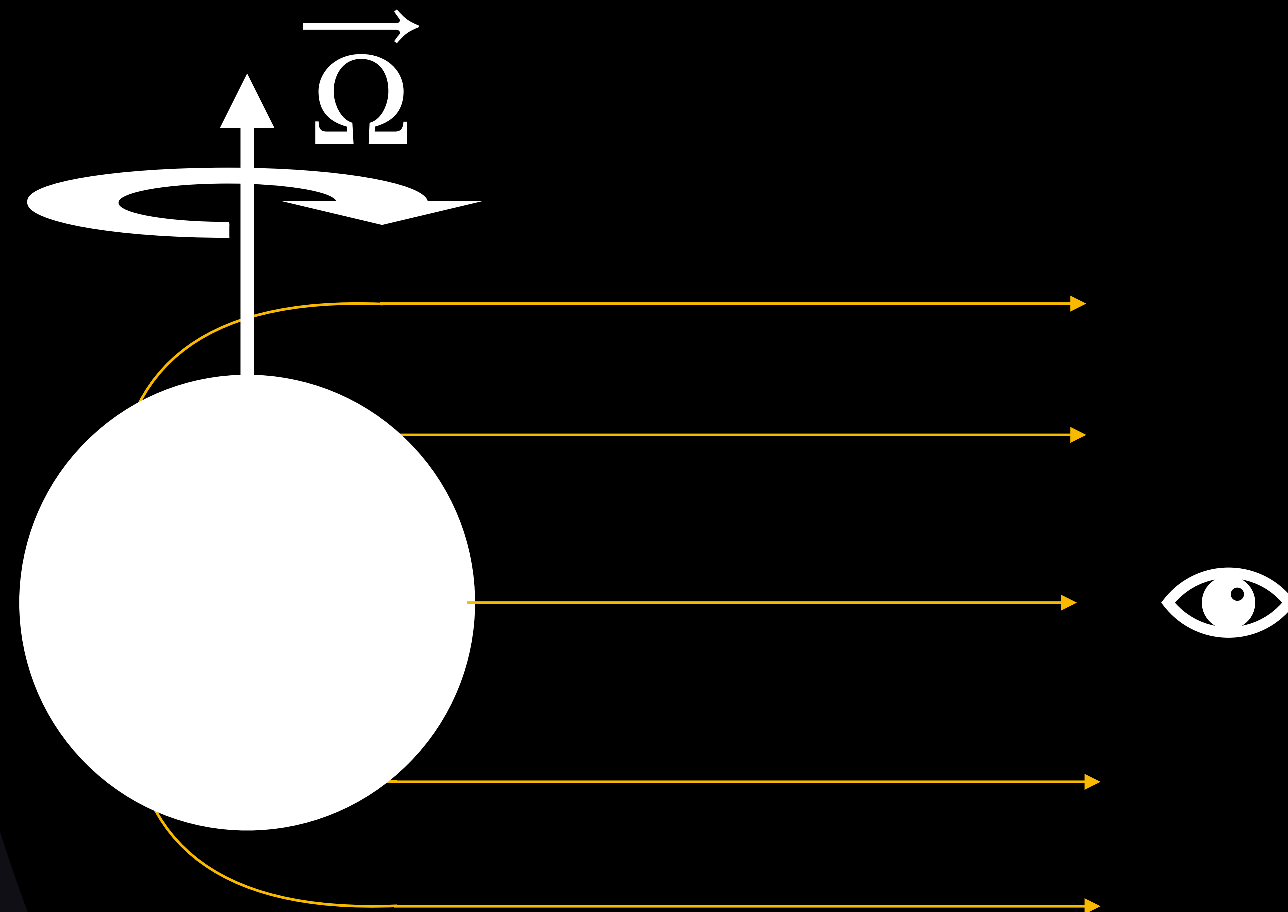
$$F(E_\infty, \gamma) = \frac{2\pi}{ch^3}\frac{R_\infty^2}{D^2}E^2\int_0^1 2\sin\,\delta d\sin\delta\int_0^{2\pi}\frac{d\phi}{2\pi}B_\nu[T_s(\theta(\delta),\phi),E]$$

$$1-\cos\theta = (1-\cos\delta)\left(1-\frac{R_s}{R}\right)^{-1}$$

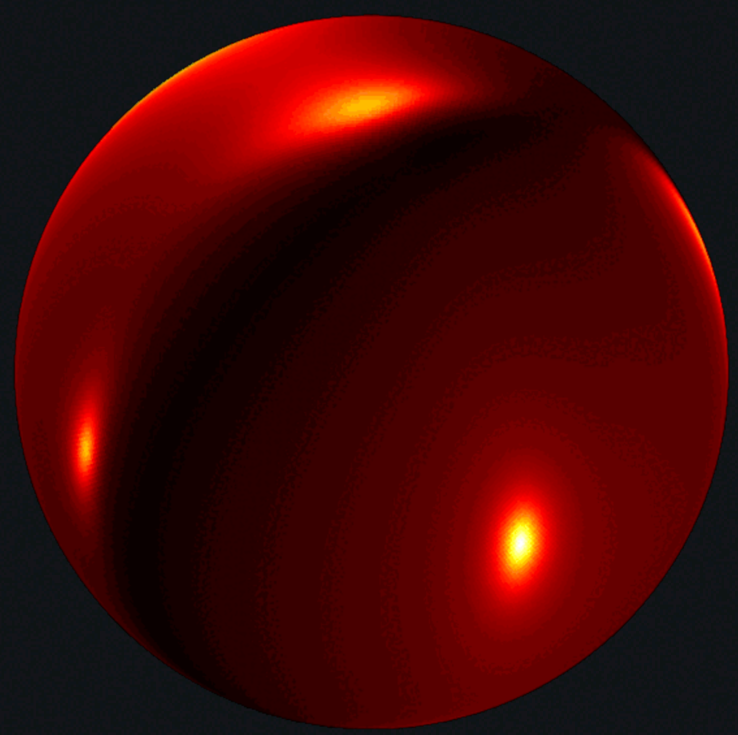
(Beloborodov 2002)

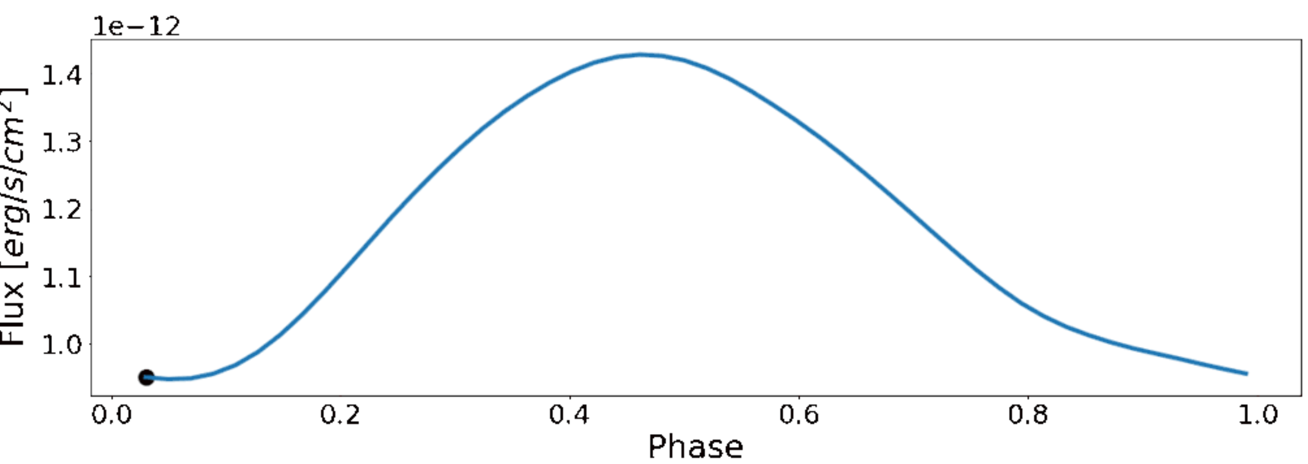



1e−12
2.46
2.44
2.42
2.40
2.38
Flux [erg/s/cm²]
0.0
0.2
0.4
0.6
0.8
1.0
Phase

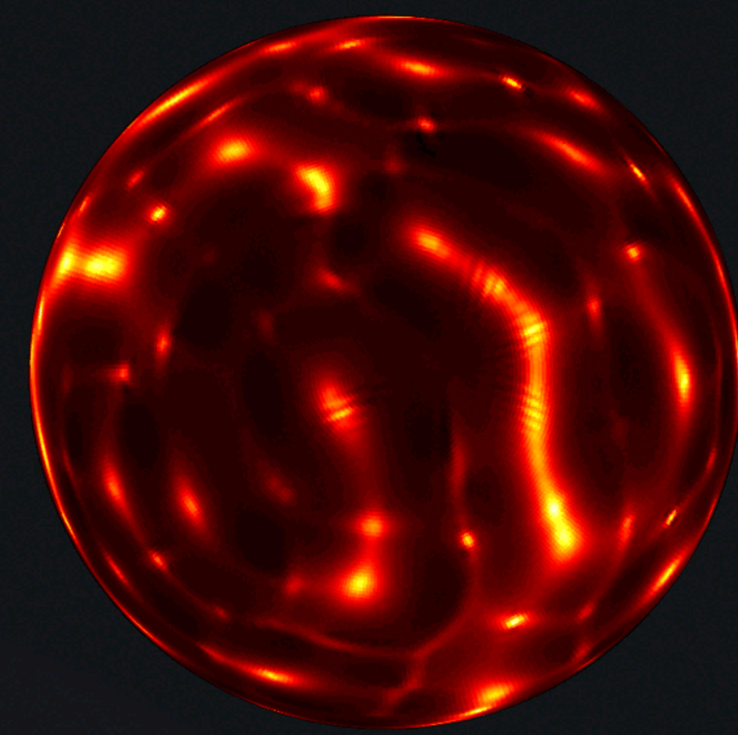

$\vec{\Omega}$

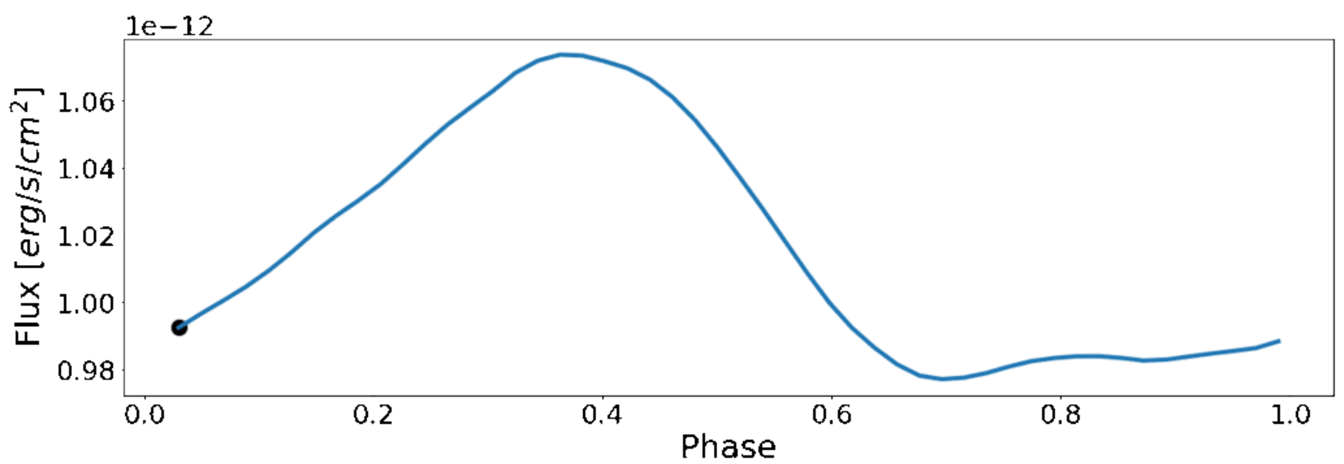
Pulsed Fraction $\sim 15\,\%$



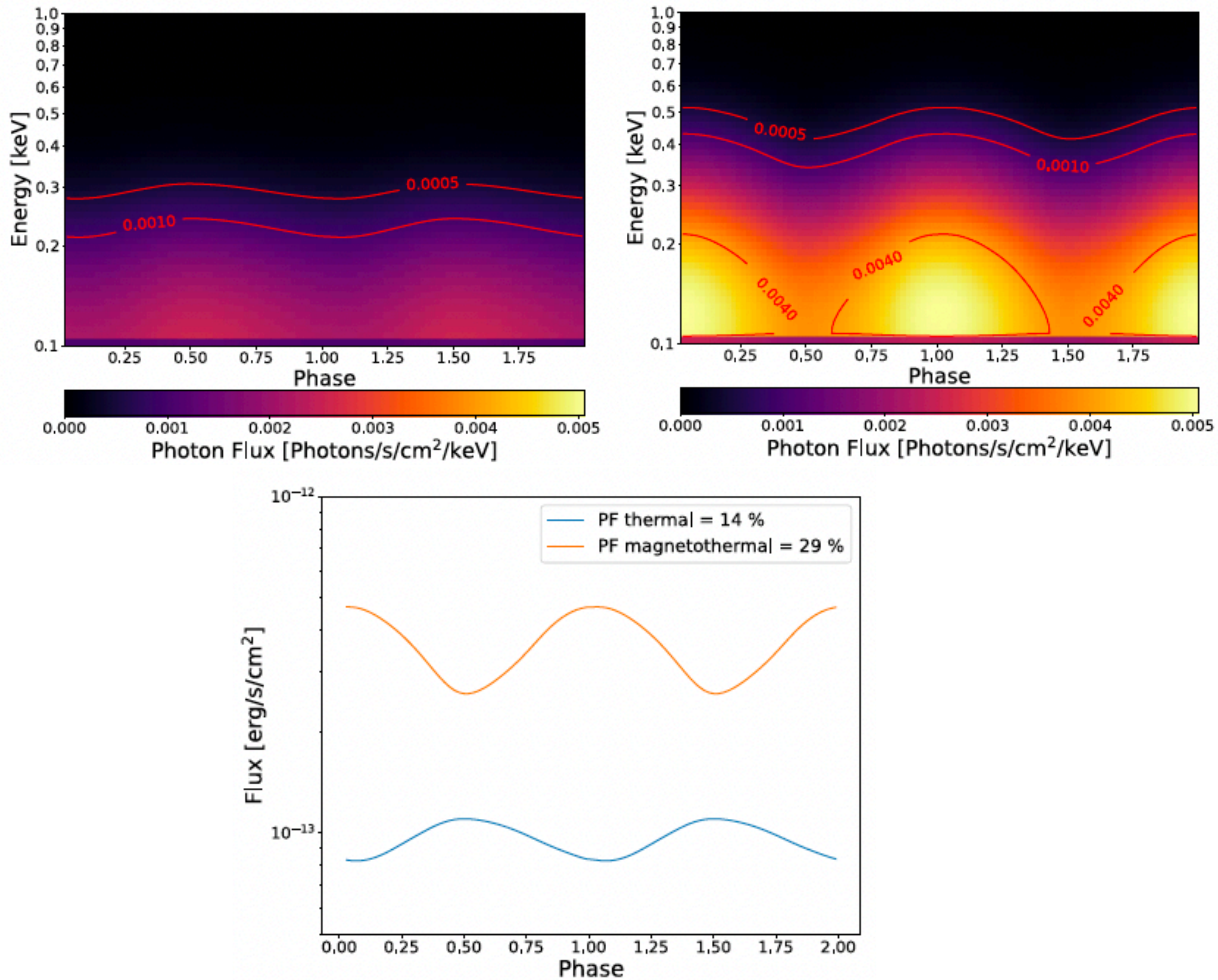


Pulsed Fraction $\sim 2\,\%$





Pulsed Profile: Magnetothermal vs Thermal



Summary

MATINS

MAgneto-**T**hermal evolution of **I**solated **N**eutron **S**tars

- We developed a finite volume magnetothermal code MATINS (Dehman+2022, Ascenzi+2024)
- 3D
- Cubed sphere grid (Ronchi+1996)
- Detailed numerical microphysics from Pothekin public code (http://www.ioffe.ru/astro/conduct/, see Pothekin+2015 for a review)
- Coupled ray-tracing code to link surface temperature maps with observed puled profile