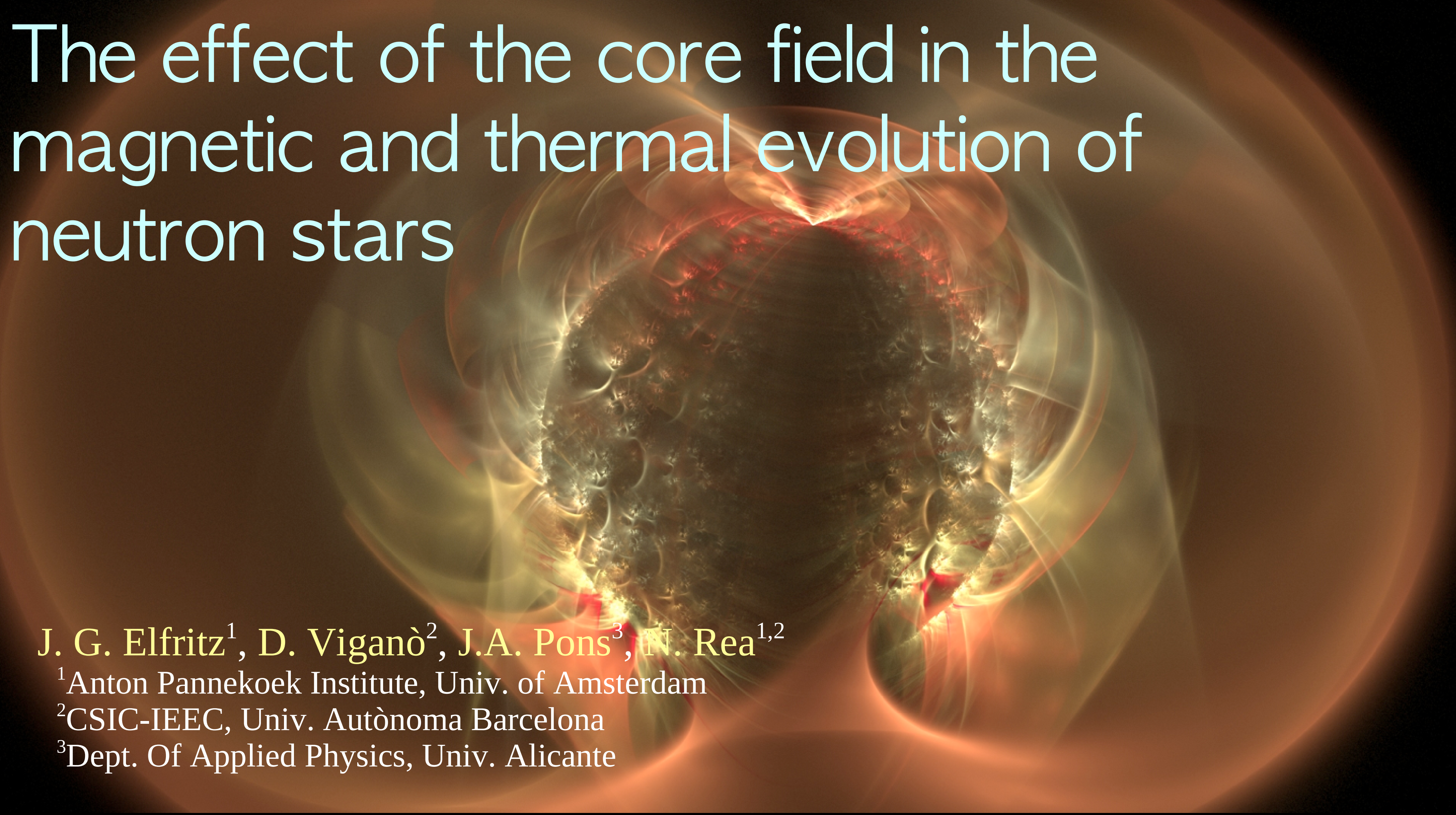

The effect of the core field in the magnetic and thermal evolution of neutron stars

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NewCompStar Annual Meeting
Budapest, Hungary
June 2015

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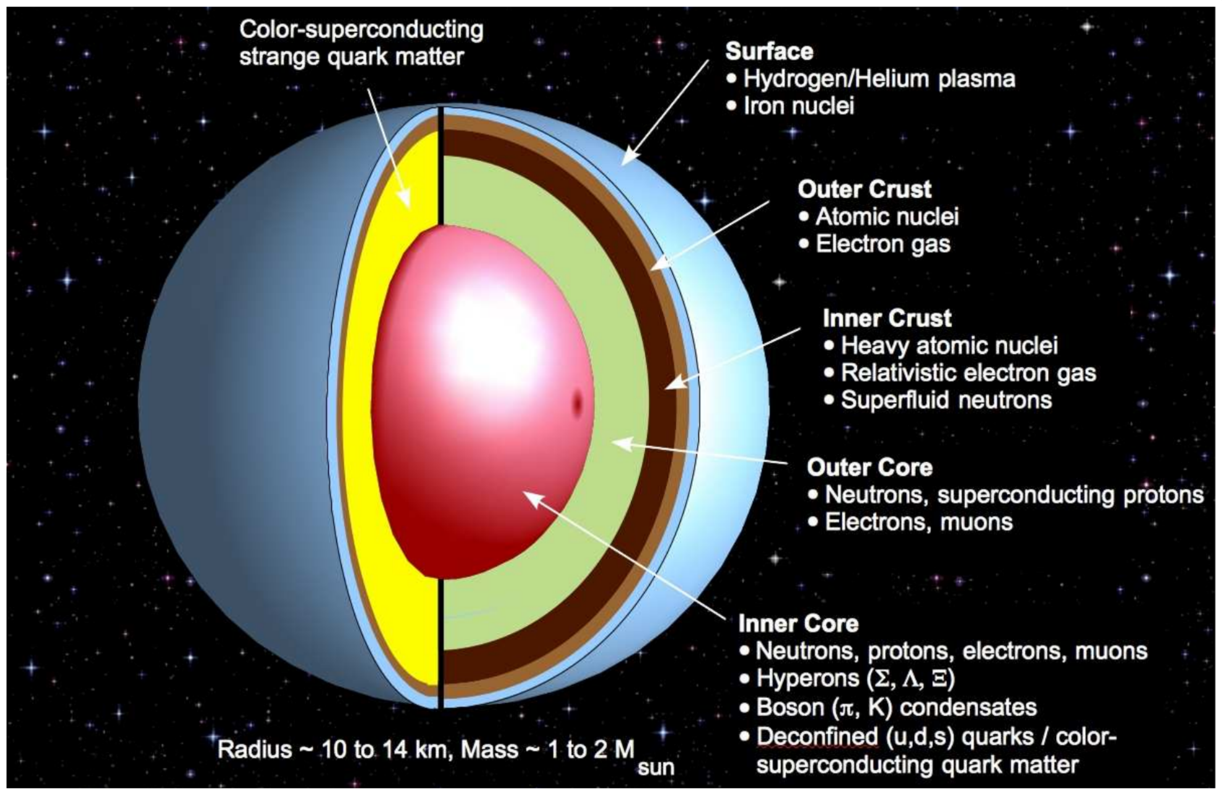
Physical Motivation: Neutron star (NS) primer

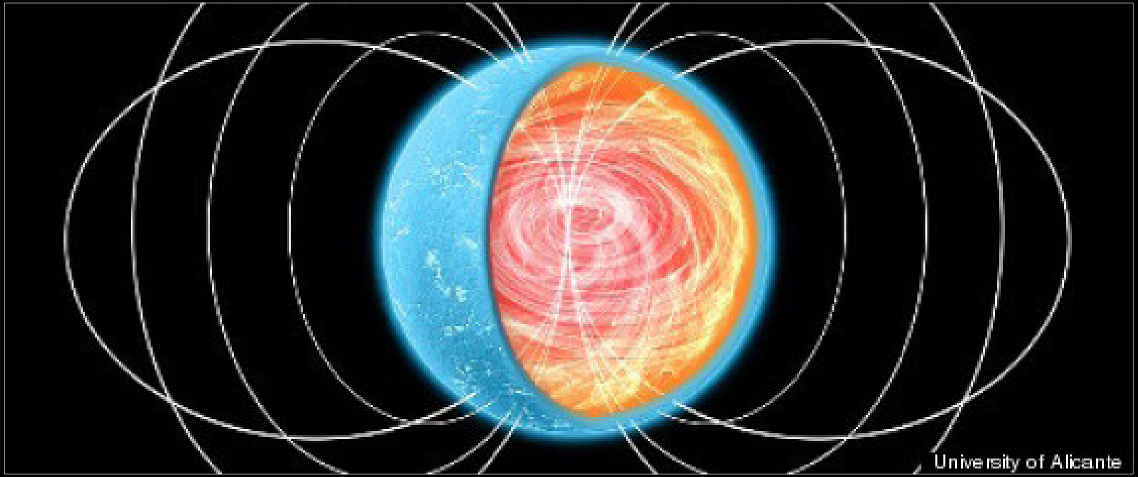
- NS evolutionary pathways strongly depend on magnetic morphology after crustal ion lattice crystallizes (Pons & Geppert (2007), Perna+ (2013))
- Initial conditions + crust−confined field sets the evolutionary stage (Viganò (2013))
- Mysteries remain over uncertain physics in the core



Courtesy Fridolin Weber

Physical Motivation: flux expulsion from NS cores

- Observations of ultramagnetic neutron stars (~ 10^{14} G)
  Mereghetti (2008), Rea & Esposito (2011)
- Could processes in the core be responsible?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- Alpha−dynamo (Goldreich & Reisenegger (1992)), Tayler−Spruit dynamo (Tayler 1973, Spruit 1999), post−infall driven convection (Obergaulinger+ 2014) could amplify field
- Our focus is on expulsion of strong core magnetic fields

Overview of driving mechanisms

- **Fluxoid buoyancy**: bulk radial fluxtube drift (Muslimov & Tsygan (1985), Baym & Pethick (1975))

  $\vec{f}_b = -\frac{\mathscr{E}_f}{c_s^2}\vec{g}$

- **Electron drag**: scattering of degenerate electron gas from core fluxtubes (Alpar+ (1984))

  $\vec{f}_D = -\frac{hn_p}{2}\mathscr{R}_p\vec{u}$

- **Magnus force**: redistribution to perpendicular flow (Jones (1987))

  $\vec{f}_M = -\frac{hn_p}{2}\left(\vec{u}\times\hat{b}\right)$

- **Fieldline tension**: Alfvenic relaxation (Harvey+ (1986), Konenkov & Geppert (2000), Glampedakis+ (2011))

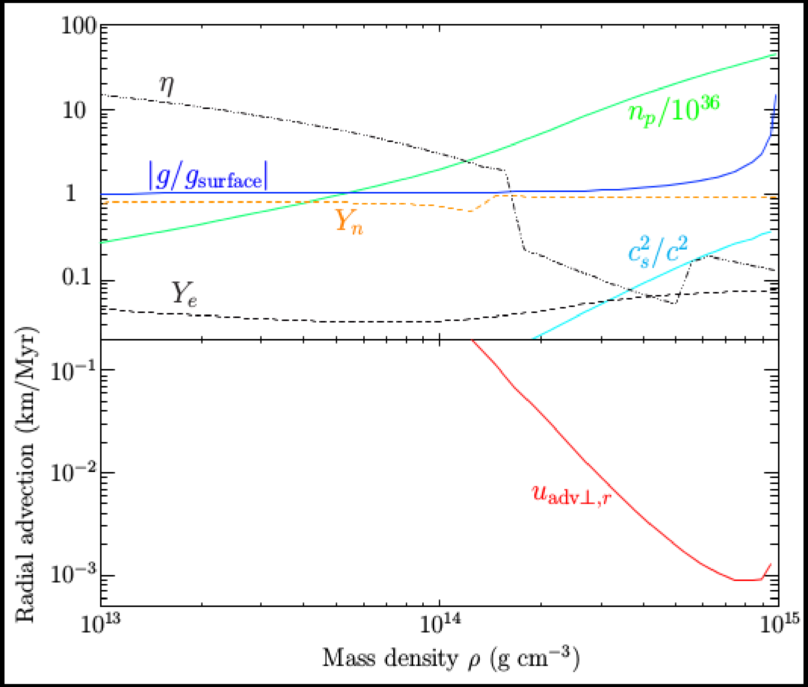
  $\vec{f}_T = \mathscr{E}_f\left(\hat{b}\cdot\vec{\nabla}\right)\hat{b}$

Generalized advective eMHD prescription

- Field−parallel components do not contribute to expulsion
- Bulk advection velocity is derived from combination of forces:

$$\vec{u}_\perp = \frac{1}{1+\mathscr{R}_p^2}\left[\mathscr{R}_p \vec{V}_\perp + \hat{b}\times\vec{V}\right]$$

$$V_\perp = \frac{2\varepsilon_f}{h n_p}\left[-\hat{b}\times\left(\left(\vec{\nabla}+c_s^{-2}\vec{g}\right)\times\hat{b}\right)\right]$$



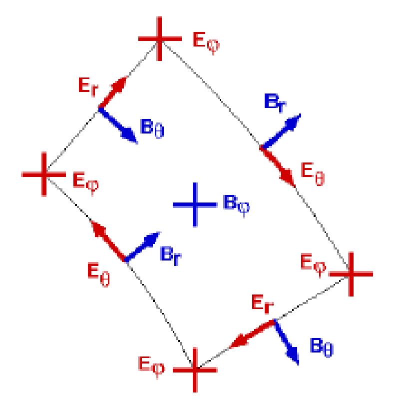
Principle EOS parameters

Upper analytic limit on radial fluxtube drift

Magneto−thermal numerical model

- Relativistic 2D model with azimuthal symmetry

  Pons & Geppert (2007), Aguilera (2008), Vigano+ (2011-2014)


Vigano+ (2012)

- Coupled magnetic and thermal time−advance
- Staggered numerical grid
- Hall induction equation with advection (shock−capturing)

$$\partial_t \vec{B} = -\vec{\nabla}\times\left[\eta\vec{\nabla}\times\left(e^{\nu}\vec{B}\right)\right] + \vec{\nabla}\times\left[e^{\nu}\vec{u}_{\rm adv}\times\vec{B}\right] - \vec{\nabla}\times\left[f_H\left(\vec{\nabla}\times(e^{\nu}\vec{B})\right)\times\vec{B}\right]$$

Ohmic and stratification

Advection

Hall and stratification

- Temperature evolution equation

$$c_v e^{\nu}\partial_t T - \vec{\nabla}\cdot\left[e^{\nu}\hat{\kappa}\cdot\vec{\nabla}\left(e^{\nu}T\right)\right] = e^{2\nu}\sum_i Q_i$$

Neutrino cooling,
Joule heating,
advective heating

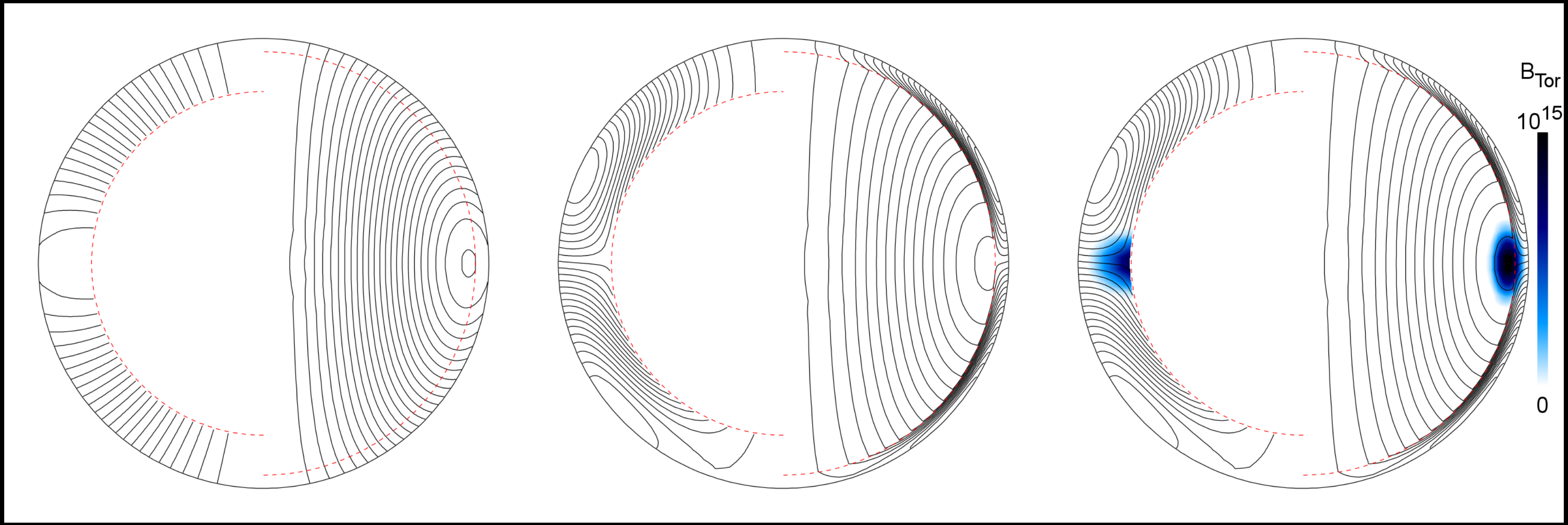
Simulation parameters

- 50 x 50 cells in radius and polar angle (hi-res in crust)
- Skyrme-type EOS from BPS (Baym+(1971), Douchin & Haensel (2001))
- Parametric study with varying impurity (Pons+(2013))
- 100 kyr investigations of three standard initial magnetic field prescriptions

Core-extended

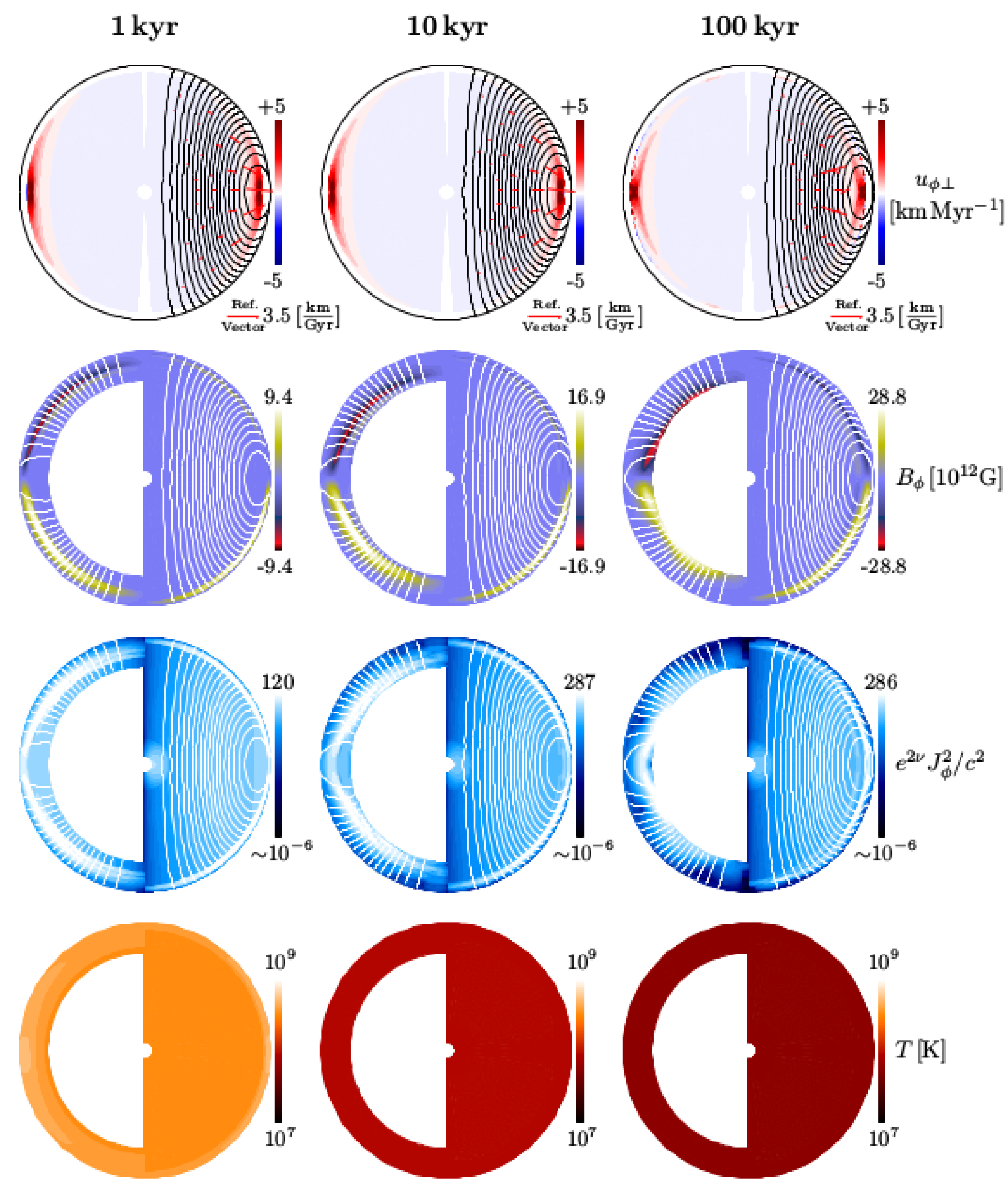
Hybrid poloidal

Hybrid toroidal



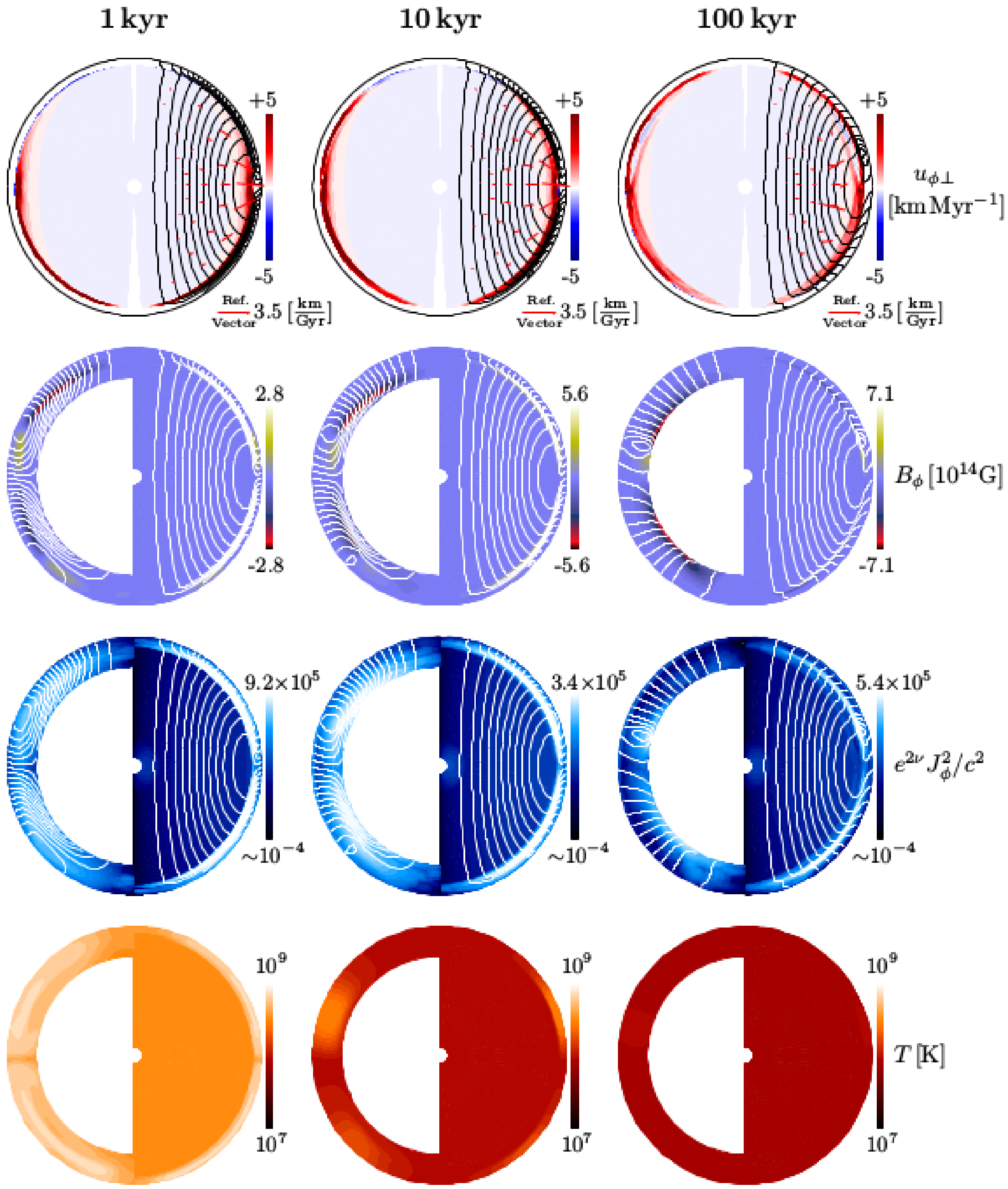
Results: core-extended fields

- Core field is static
- Crustal stratification drives field to interface
- Azimuthal advection much stronger than poloidal components
- Isothermal cooling



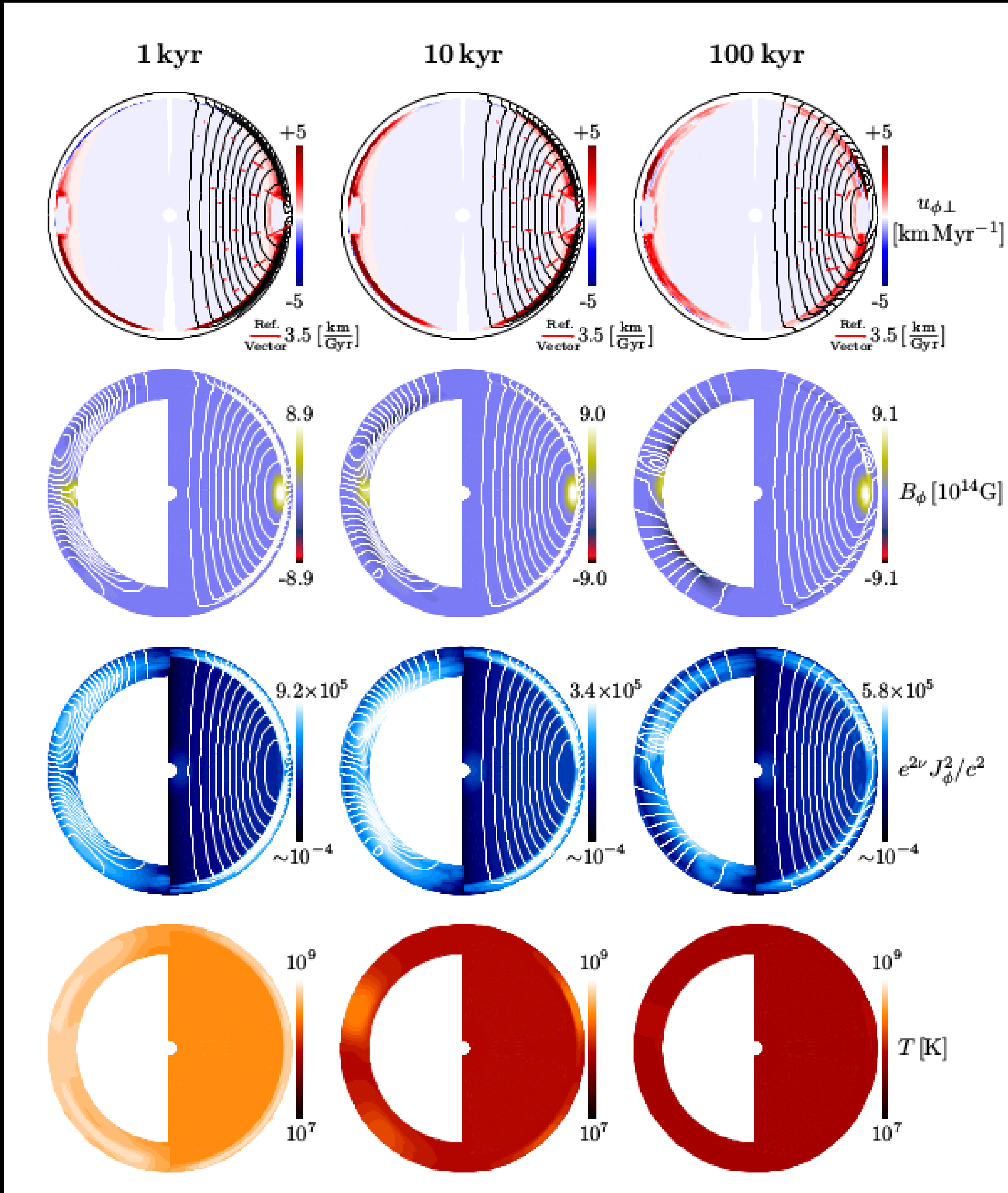
Results: hybrid poloidal fields

- Hall decay in crust much faster than any expulsion
- Nonlinear interaction at interface → submergence
- Joule-dominated
- Isothermal cooling (no diffusion)



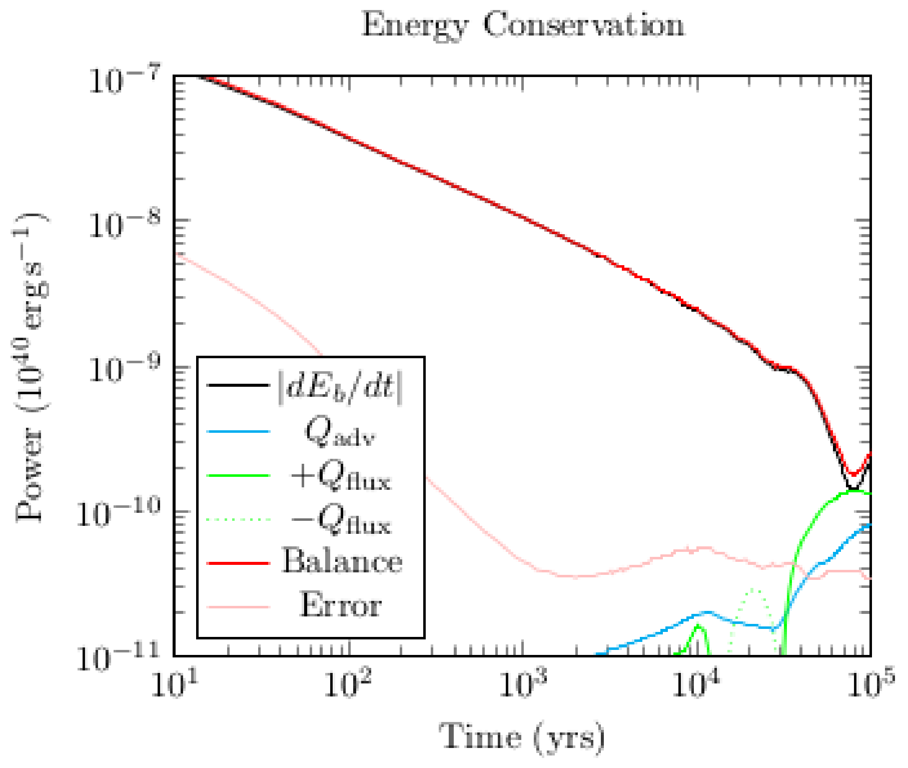
Results: hybrid toroidal fields

- Presence of toroidal field has negligible effect
- Joule-dominated
- Standard cooling



Instantaneous power: core-extended

- Negligible expulsion until 40 kyrs
- Advective heating becomes efficient by 100 kyrs
- Joule heating dominates

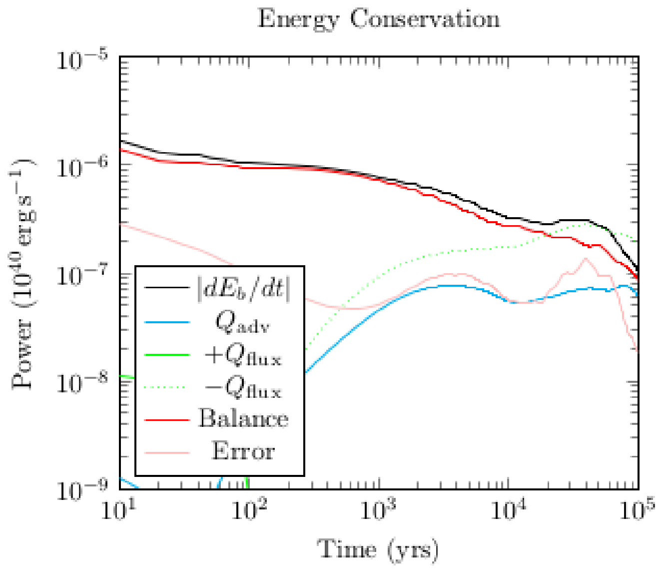


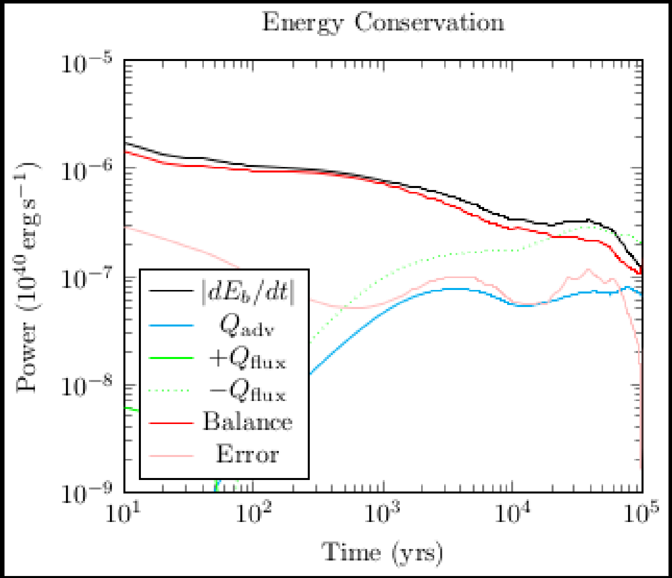
Energy conservation: hybrid cases

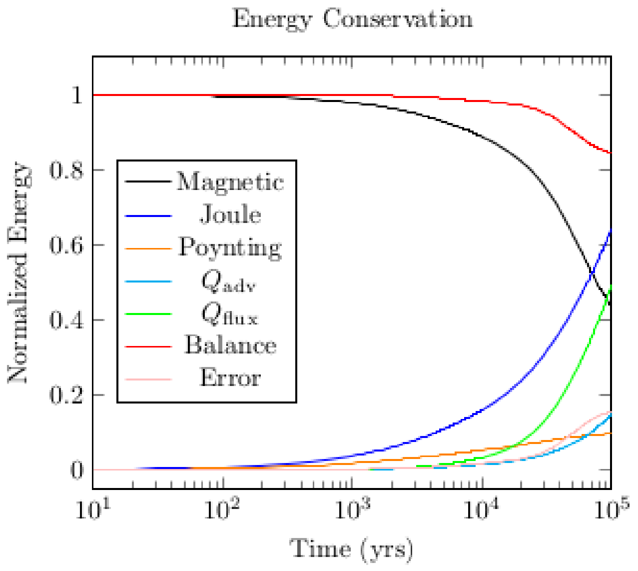
- Strong crust−confined fields are buried into the outer core
- Submergence rate is comparable to field decay rate
- Higher numerical error due to strong gradients at interface
- Joule dissipation dominant, but weak in NS core

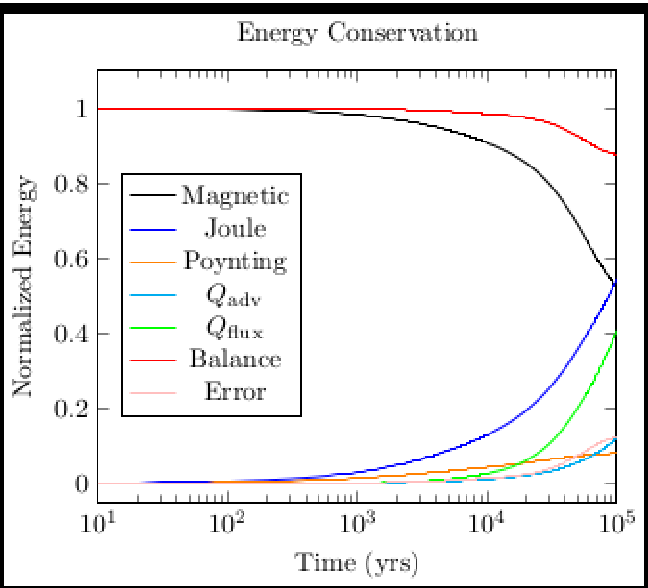
Hybrid poloidal

Hybrid toroidal



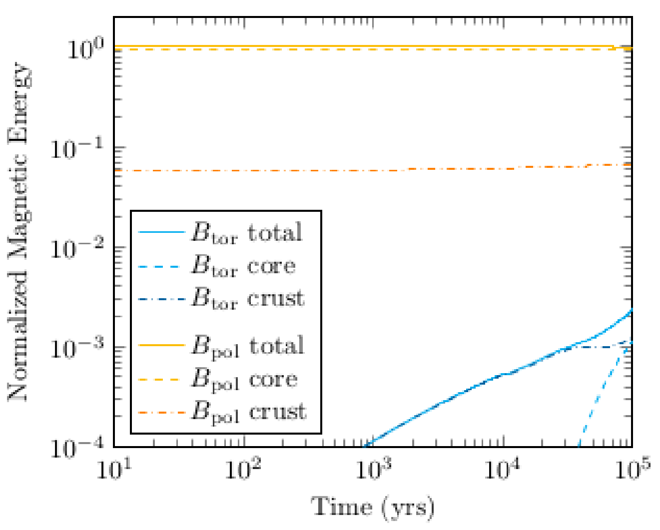


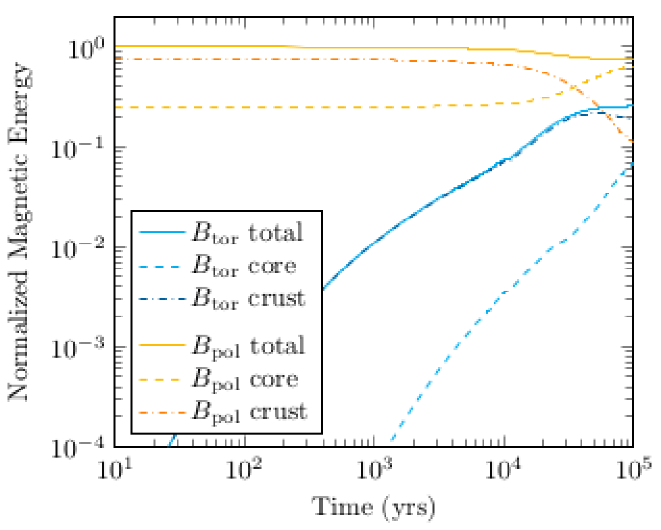


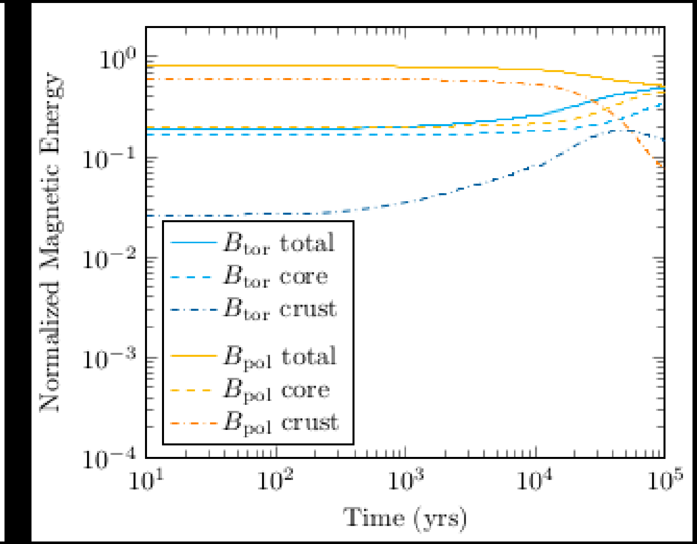


Bulk magnetic energy transport

- Standard Hall cascade in crust (~10 kyrs)
- Advective induction of toroidal component in core


Core−extended


Hybrid
poloidal

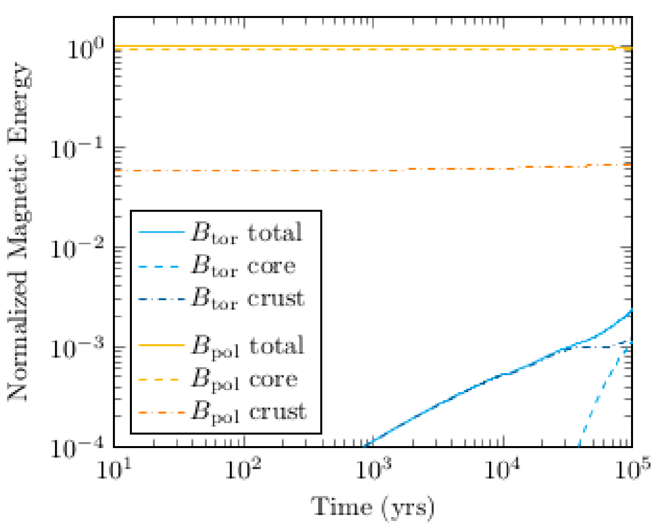

Hybrid
toroidal

- Weak enhancement of poloidal crust field
- Negligible growth of toroidal component in core

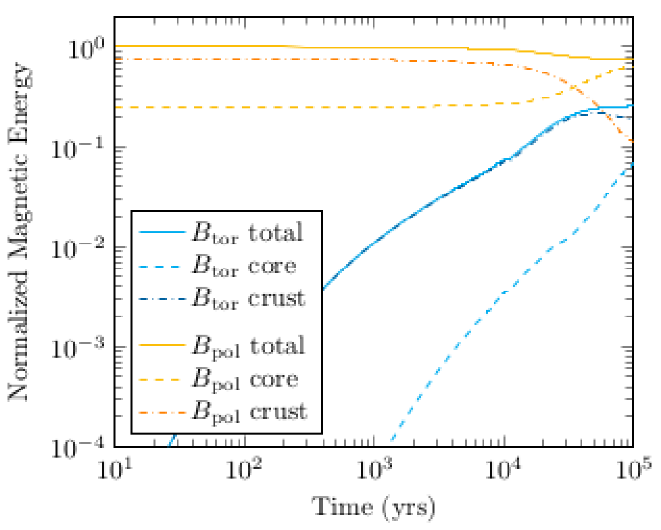
Bulk magnetic energy transport

- Standard Hall cascade in crust (~10 kyrs)
- Advective induction of toroidal component in core

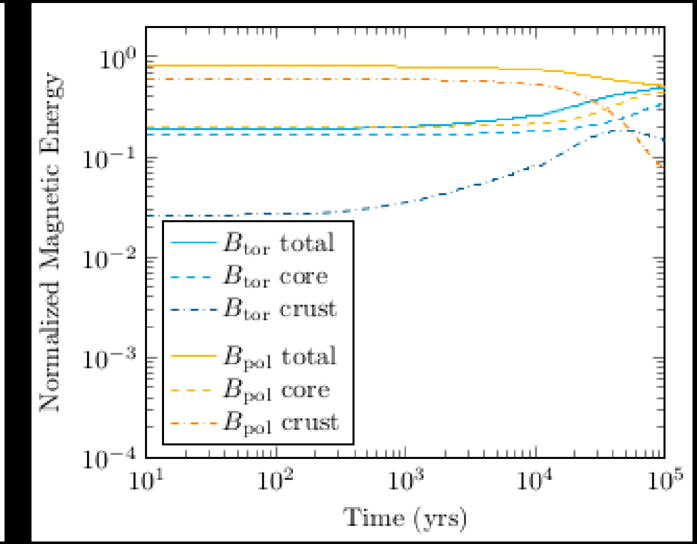
Core−extended



Hybrid
poloidal



Hybrid
toroidal

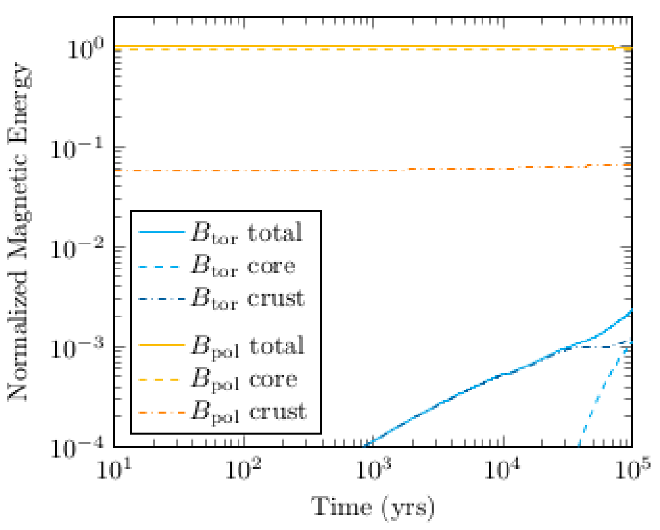


- Poloidal → Toroidal coupling in crust (Hall)
- Submerging field becomes poloidal in core
- Possible steady state beyond 100 kyrs

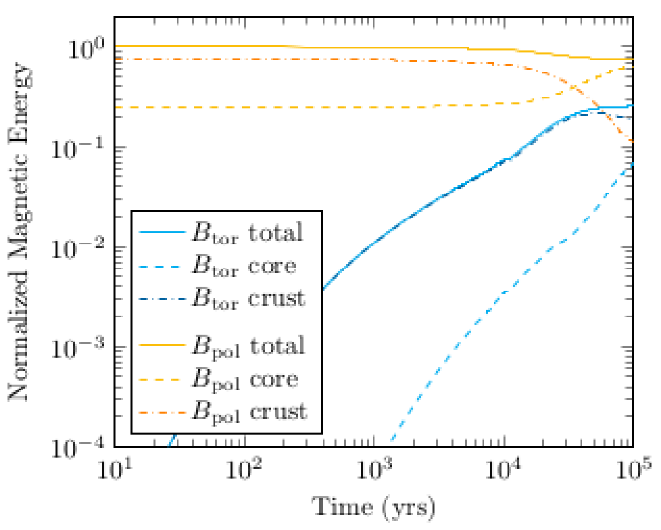
Bulk magnetic energy transport

- Standard Hall cascade in crust (~10 kyrs)
- Advective induction of toroidal component in core

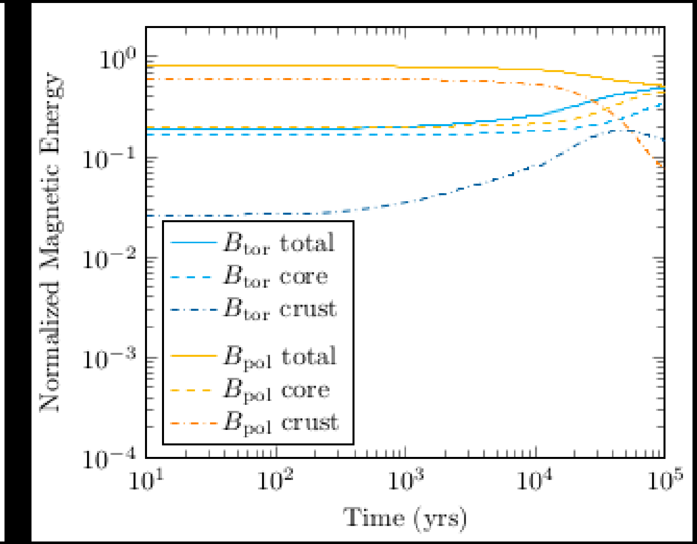
Core−extended



Hybrid poloidal

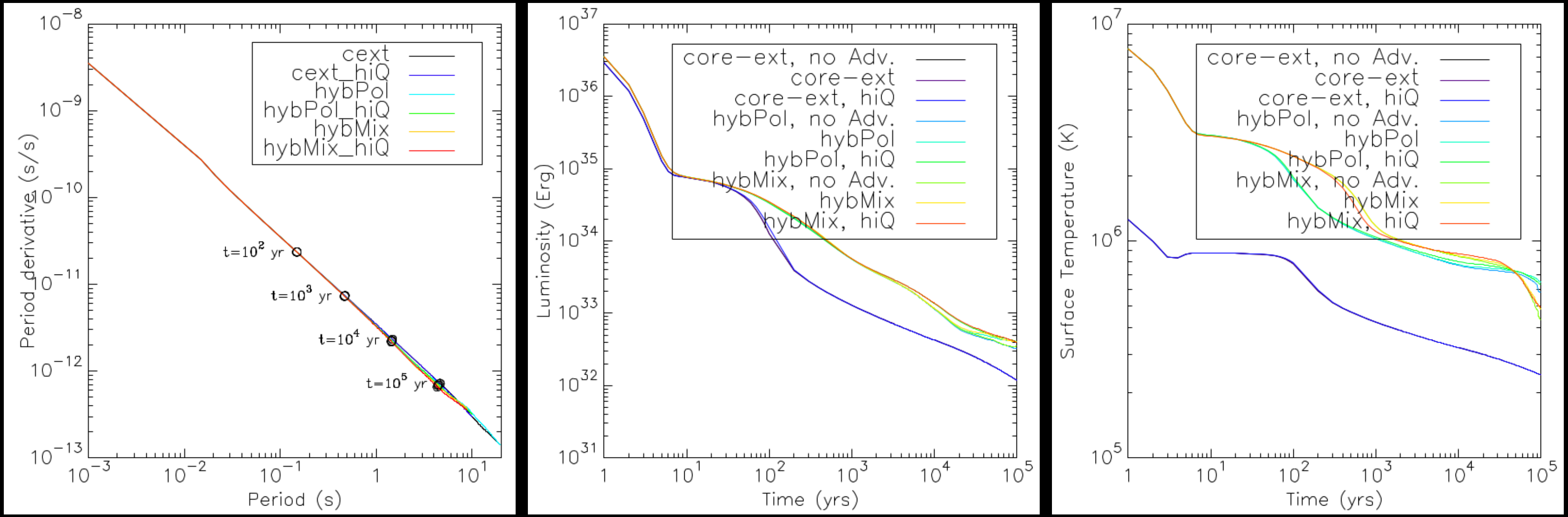


Hybrid toroidal



- Energy equipartition at 100 kyrs when initially strong toroidal component is imposed
- Core−dominated energy at 100 kyrs

Effects on observables



$$P\dot{P} = 3.5 \times 10^{-40} B_p^2 \qquad L = 2\pi \int_0^{\infty} \sigma_{SB} R_\infty^2 T_\infty^4 \sin\theta \, d\theta$$

- Presence of core field prevents characteristic knee in P−Pdot
- NS with core advection indistinguishable by advection−free NS

Summary

- Expulsion of core magnetic field does not affect observables in first 100kyrs
  - Realistic ICs predict weak net submergence of crust field
- Temperature evolution is insensitive to core dynamics
- Strong advection is confined to outer core
- Can neglect the core when testing cooling models against observations
- Microphysics at crust-core interface play important role
- Core field configuration at birth may be critical to future work