Harmonically Forced and Synchronized Dynamos: Theory and Experiments

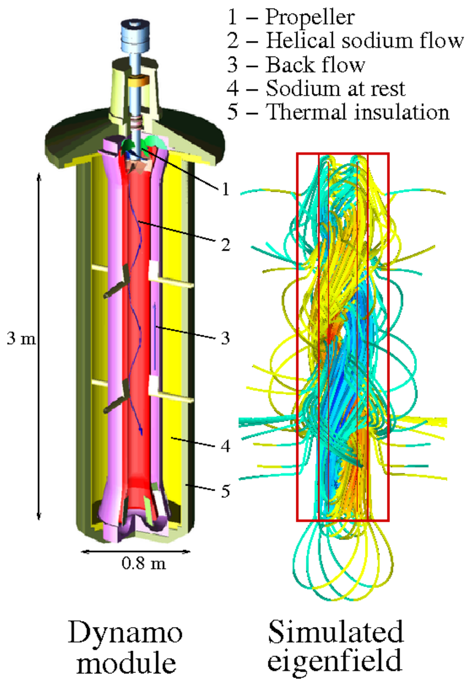
Frank Stefani

with thanks to
Sven Eckert, Gunter Gerbeth, André Giesecke, Gerrit Horstmann, Laurène Jouve, Peter Jüstel, Martins Klevs, George Mamatsashvili, Sebastian Röhrborn, Tobias Vogt, Tom Weier, Thomas Wondrak…

RTI2025, Los Angeles, January 27-31, 2025

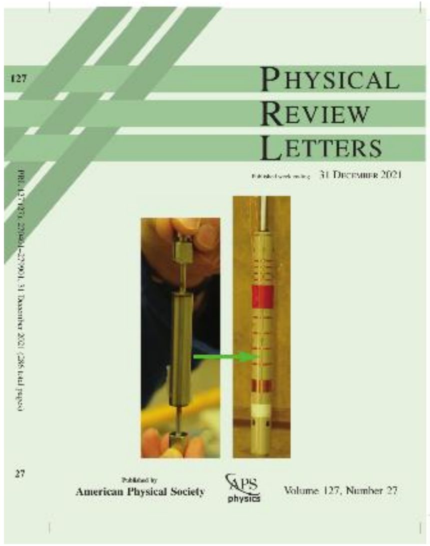
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

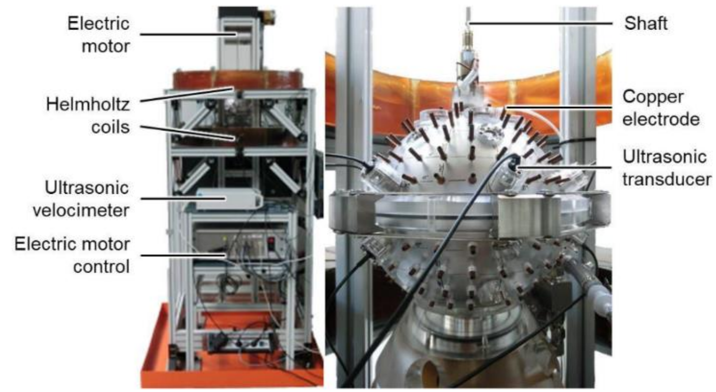
One can do decent (magneto-)hydrodynamics ignoring ΔT…



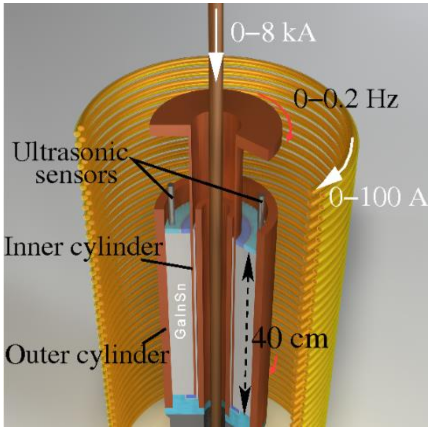
Dynamos

Alfvén waves at $c_s=v_a$

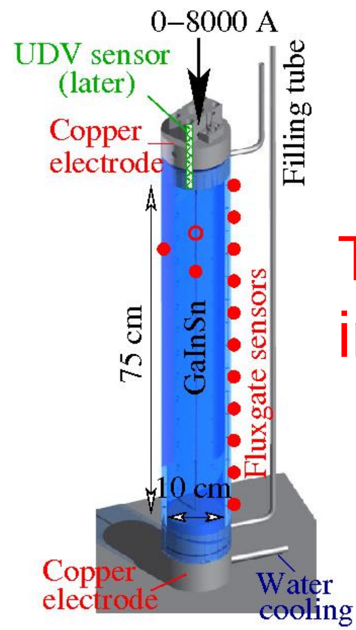




Magnetized spherical Couette flow

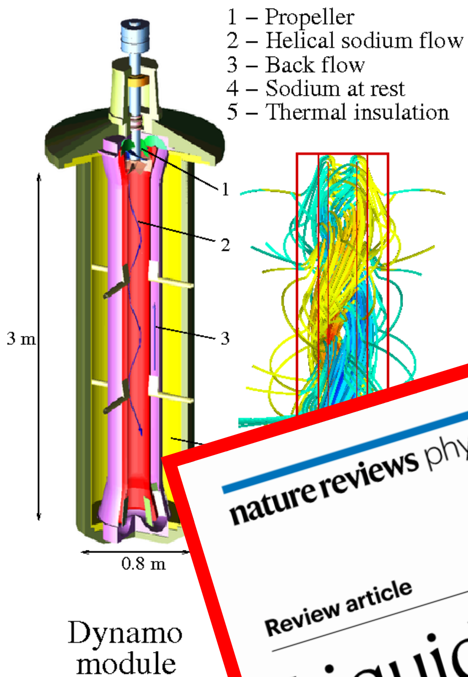


Helical and azimuthal magnetorotational instability (HMRI, AMRI)



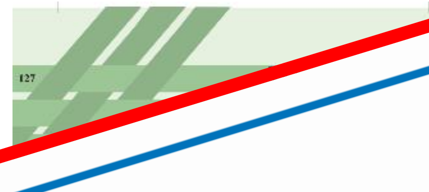
Tayler instability

One can do decent (magneto-)hydrodynamics ignoring ΔT…



Dyna

Alfvén waves at $c_s=v_a$



pherical

nature reviews physics

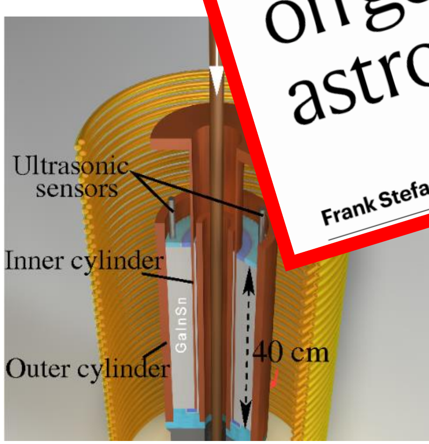
https://doi.org/10.1038/s42254-024-00724-1

Check for updates

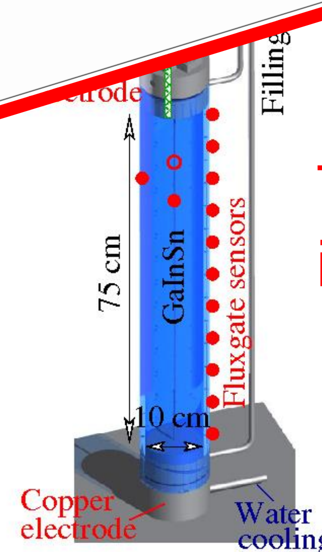
Review article

Liquid-metal experiments on geophysical and astrophysical phenomena

Frank Stefani



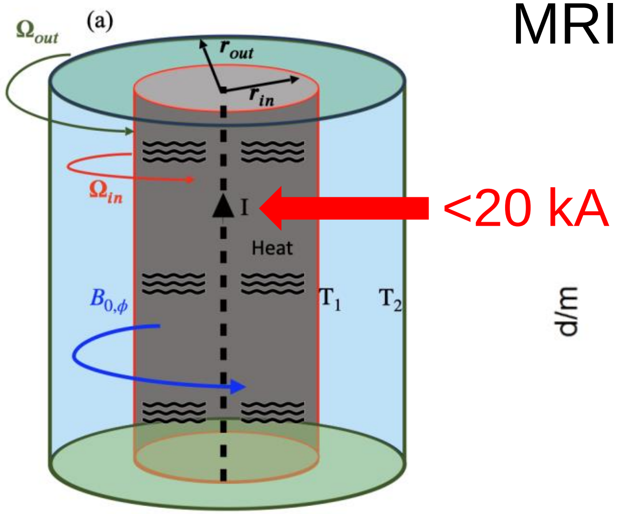
zimuthal magnetorotational instability (HMRI, AMRI)



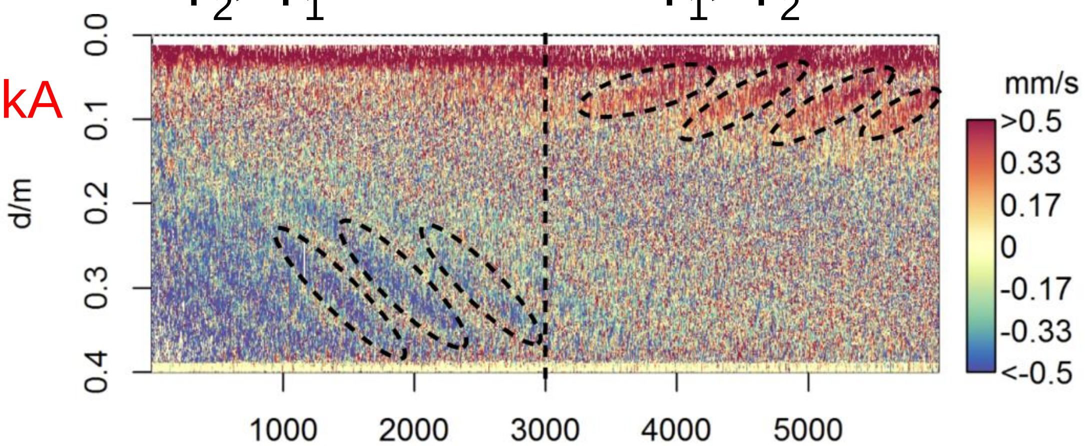
Tayler instability

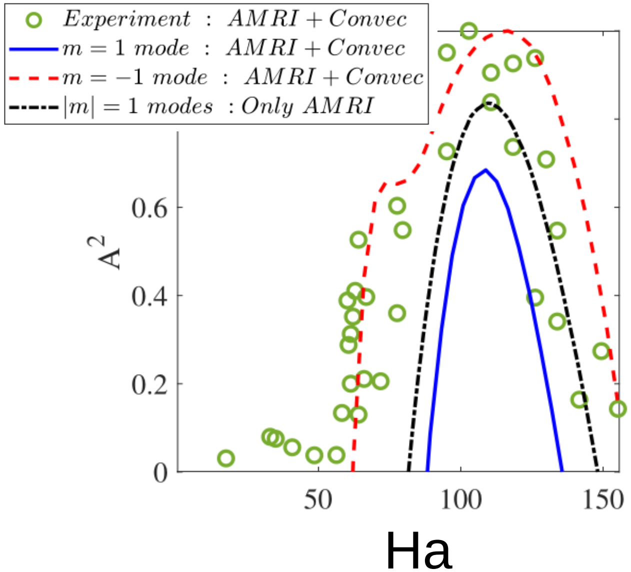
HZDR

…but sometimes ΔT reappears quite unexpectedly…

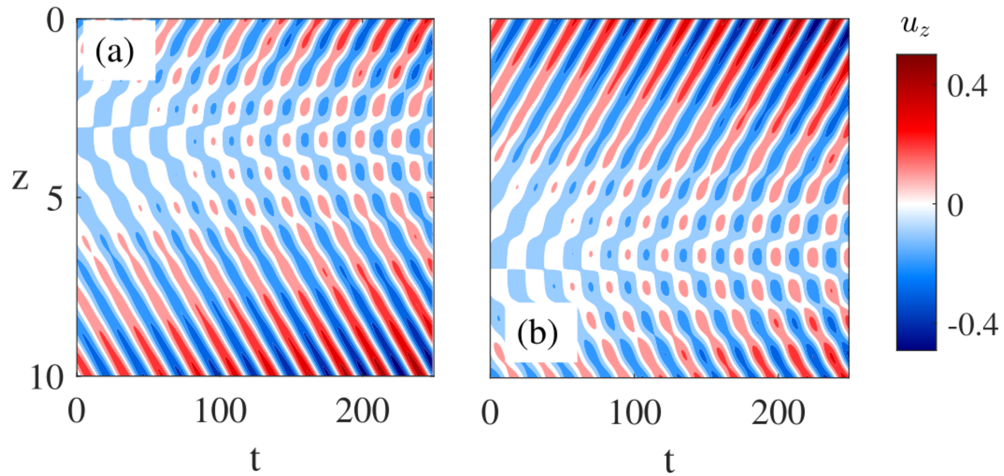


MRI Experiment with changing radial heat flux





Simulation



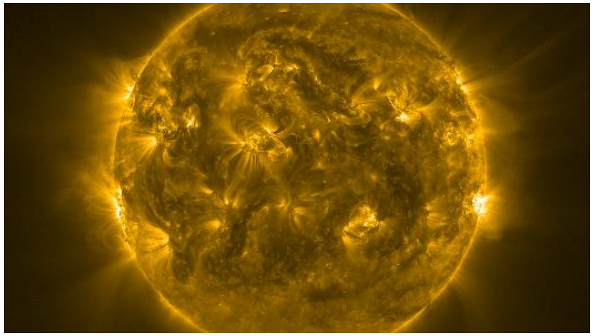
Mishra et al., J. Fluid Mech. 992, R1 (2024): **One-winged butterflies**: mode selection for AMRI

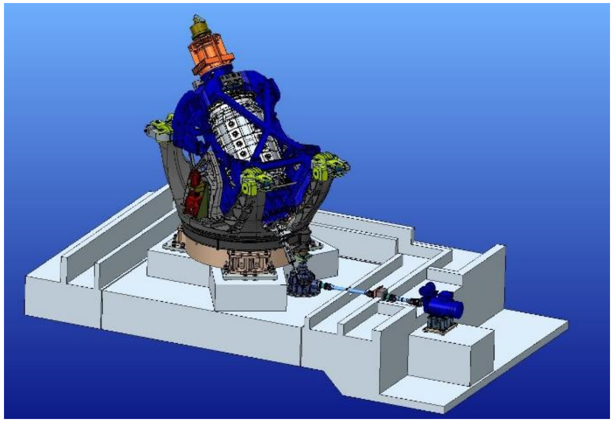
Schedule

- Magnetic tomography
  for liquid-metal convection
- Helicity oscillations

- Problem? What problem…?
- Rieger
- Schwabe/Hale
- Suess-de Vries (+Gleissberg)
- Bimodal sunspot distribution
- Wrap-up

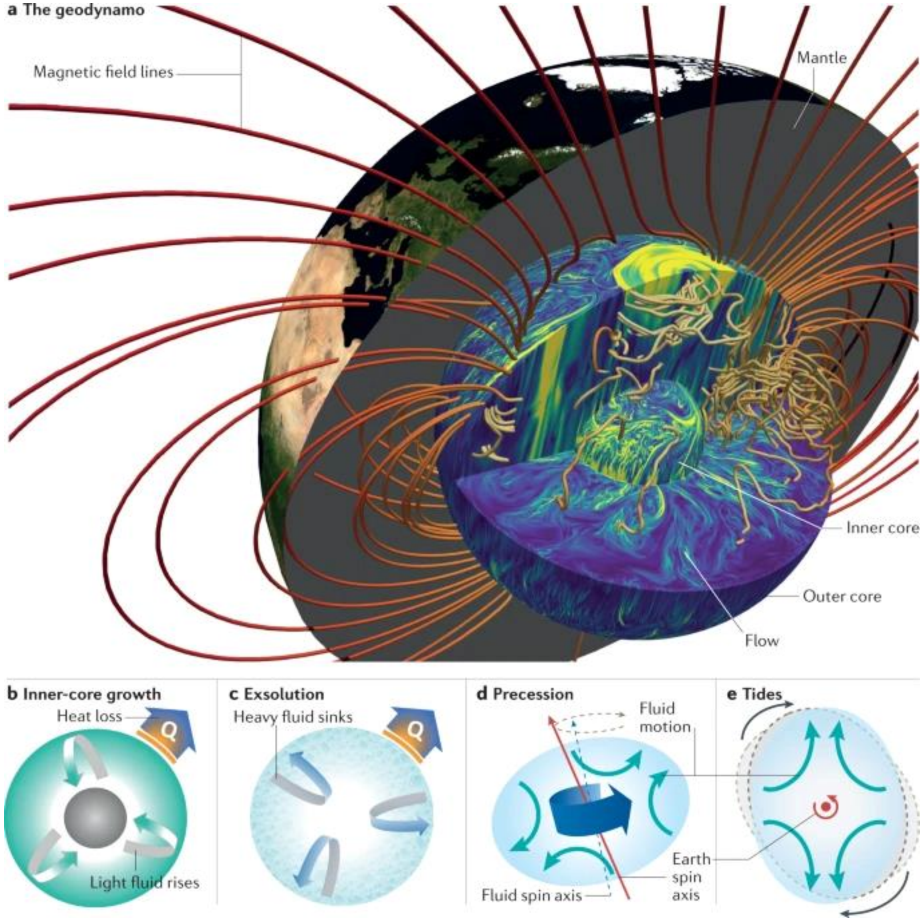
- Milankovic cycles
- The DRESDYN precession experiment





Precession, tides, et cetera: Great reviews

M. Le Bars, D. Cébron, P. Le Gals: Flows driven by libration, precession, and tides. Annu. Rev. Fluid Mech. 47 (2015)



Michael Le Bar’s talk this morning

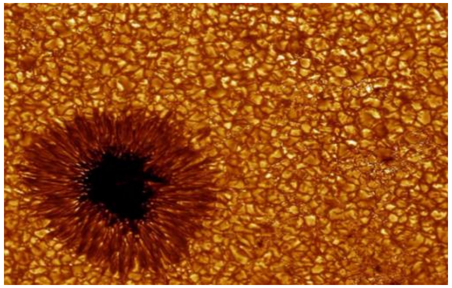
M. Landeau, A. Fournier, H.-C. Nataf, D. Cébron, N. Schaeffer: Sustaining Earth’s magnetic dynamo. Nature Rev. Earth Environ. 3 (2022), 255

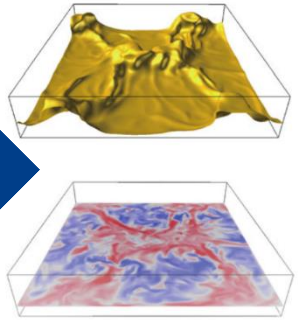
DRESDEN concept HZDR

Liquid metal convection

Convection at small Prandtl numbers → Liquid metals

Turbulent superstructures in shallow geometry (Γ>1)



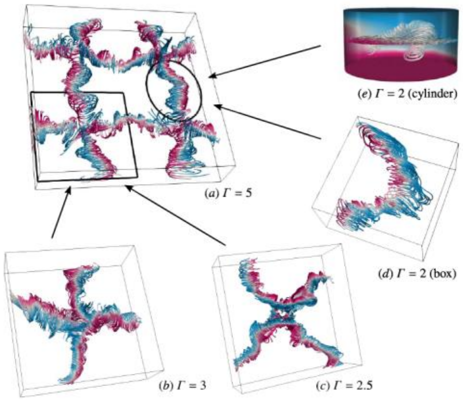


Akashi et al., J. Fluid Mech. 932, A27 (2022)

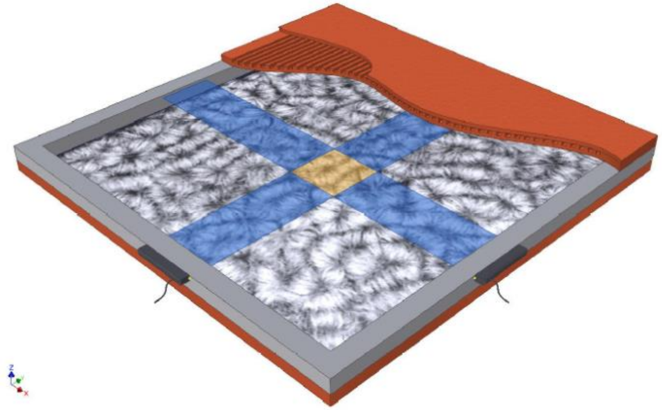
Jump rope vortex, detected first in…

Vogt et al., PNAS 115, 12674 (2018)

…turns out to be a **universal feature**



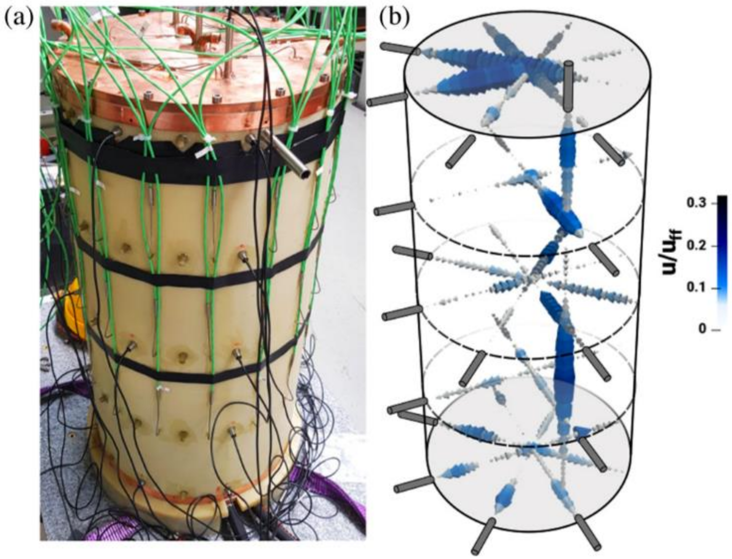
New experiment with Γ=25



Tobias Vogt

DRESDEN concept HZDR

Convection at Γ=0.5

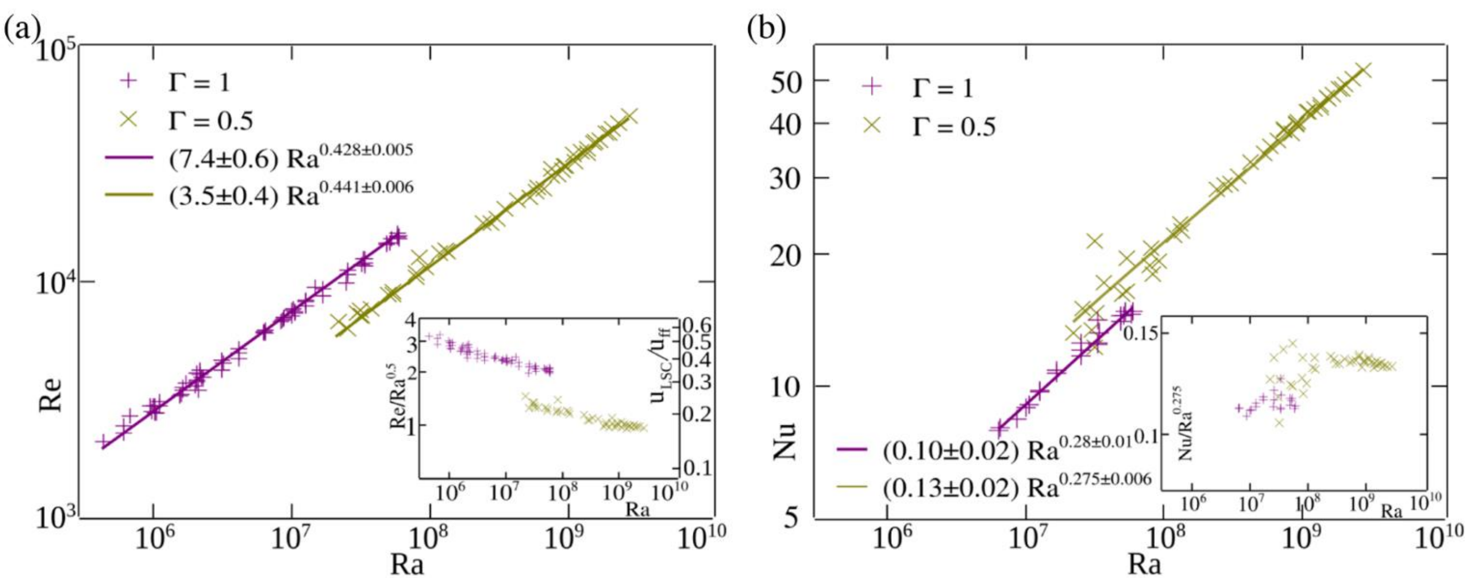


GaInSn (Pr~0.03)

H=2D=640 mm

$2\times10^7 \leq Ra \leq 5\times10^9$

17 UDV sensors

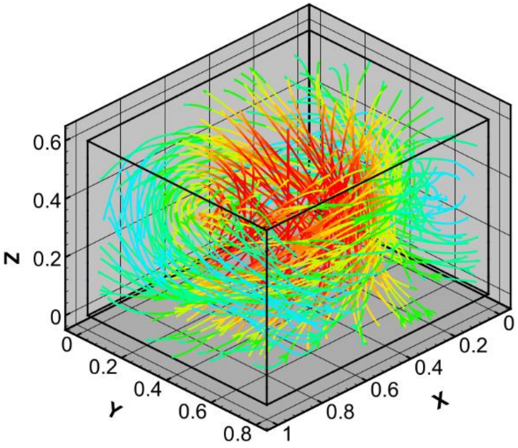


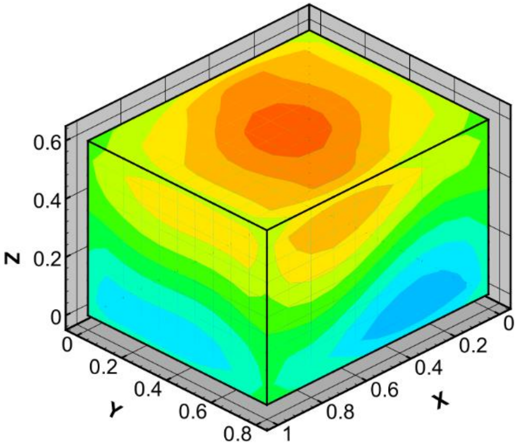
F. Schindler et al., PRL **128**, 164501 (2022); **131**, 159901 (2023)

From the integral equation approach for dynamos…

$$\mathbf{B}(\mathbf{r}) = \frac{\sigma\mu_0}{4\pi}\int_D \frac{\left(\mathbf{u}(\mathbf{r}')\times\mathbf{B}(\mathbf{r}')\right)\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}\,dV' + \frac{\sigma\mu_0}{4\pi}\oiint_S \varphi(\mathbf{s}')\,\frac{\mathbf{r}-\mathbf{s}'}{|\mathbf{r}-\mathbf{s}'|^3}\times\mathbf{n}(\mathbf{s}')\,dS'$$

$$\varphi(\mathbf{s}) = \frac{1}{2\pi}\int_D \frac{\left(\mathbf{u}(\mathbf{r}')\times\mathbf{B}(\mathbf{r}')\right)\cdot(\mathbf{s}-\mathbf{r}')}{|\mathbf{s}-\mathbf{r}'|^3}\,dV' - \frac{1}{2\pi}\oiint_S \varphi(\mathbf{s}')\,\frac{\mathbf{s}-\mathbf{s}'}{|\mathbf{s}-\mathbf{s}'|^3}\cdot\mathbf{n}(\mathbf{s}')\,dS'$$





F.S., G. Gerbeth, K.-H. Rädler, Astron. Nachr. 321 (2000), 65-73

M. Xu, F.S., G. Gerbeth, Phys. Rev. E 70 (2004), 056305

….to Contactless Inductive Flow Tomography (CIFT)

$$\mathbf{b}(\mathbf{r}) = \frac{\sigma\mu_0}{4\pi}\int_D \frac{(\mathbf{u}(\mathbf{r}')\times\mathbf{B}_0(\mathbf{r}'))\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}\,dV' + \frac{\sigma\mu_0}{4\pi}\oiint_S \varphi(\mathbf{s}')\,\frac{\mathbf{r}-\mathbf{s}'}{|\mathbf{r}-\mathbf{s}'|^3}\times\mathbf{n}(\mathbf{s}')\,dS'$$

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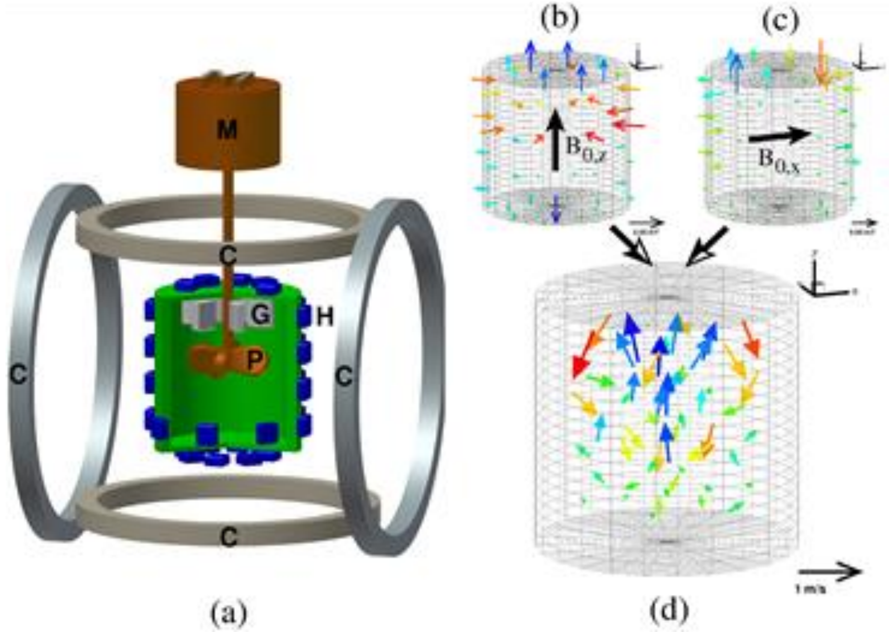


Inferring the *inducing* velocity **u** from the *induced* magnetic fields **b** for one or various applied fields $\mathbf{B}_0$

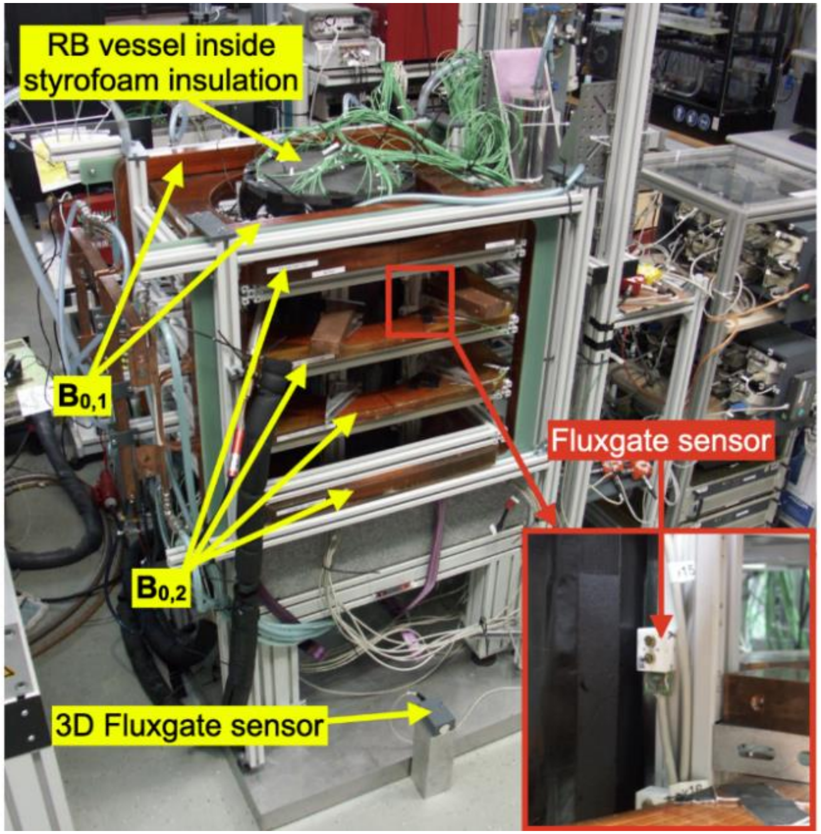
F.S., G. Gerbeth, Inverse Probl. 15 (1999), 771; 16 (2000),1

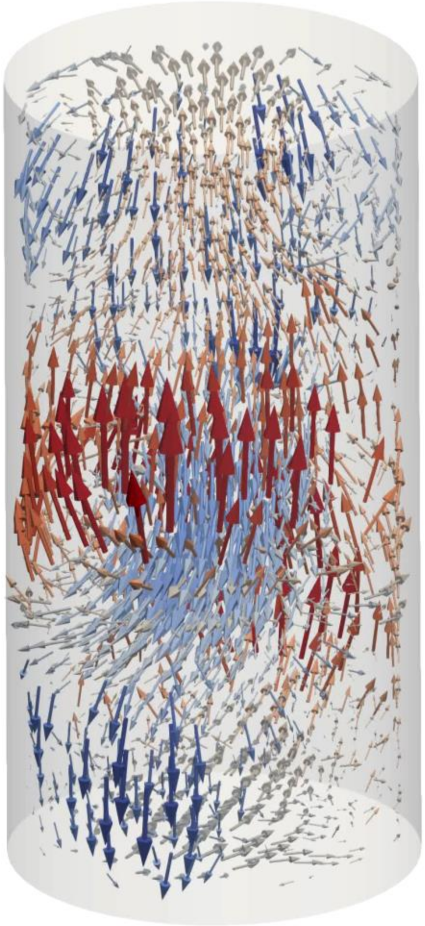
F.S., T. Gundrum, G. Gerbeth, Rev. E 70 (2004), 056306

Remember Simon Cabanes' talk yesterday

Convection at Γ=0.5

Collaps of large-scale coherent flow





Chaotic transitions between single, double, and triple rolls

T. Wondrak et al., J. Fluid Mech. **974**, A48 (2023)

R. Mitra et al., Flow Meas. Instr. **100**, 102709 (2024)

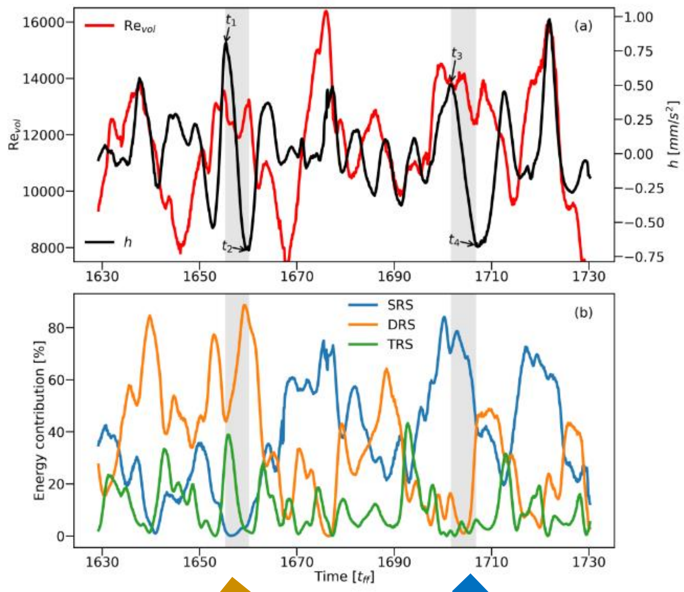
Application of **Contactless Inductive Flow Tomography** for flow reconstruction using 6x7=42 fluxgate sensors

DRESDEN concept HZDR

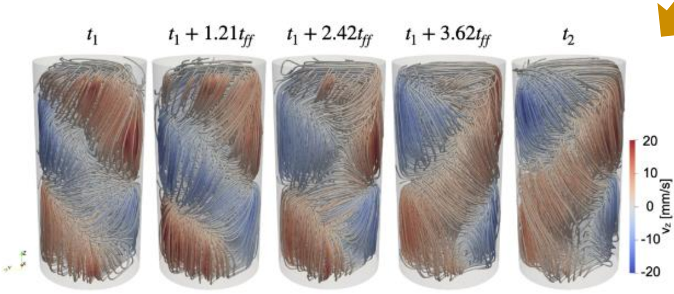
Oscillations of helicity

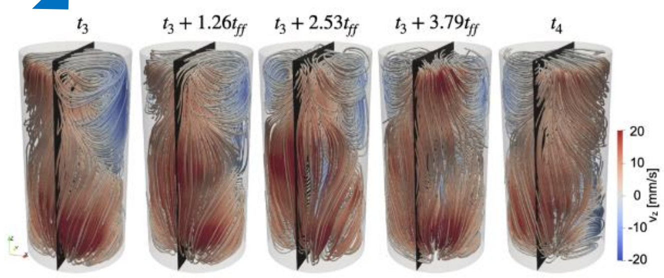
Helicity density:

h=**u**• rot **u**



Chaotic transitions between single, double, and triple rolls



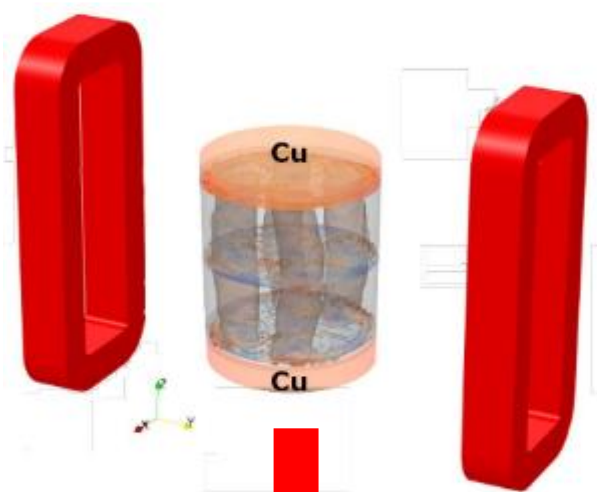


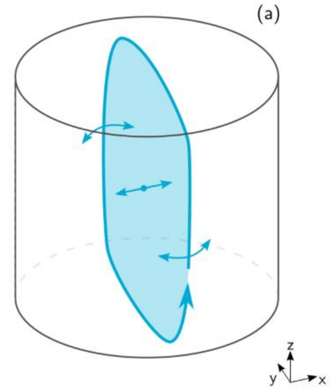
Helicity oscillations (with nearly no energy change) occur for Double Roll Structure and Single Roll Structure

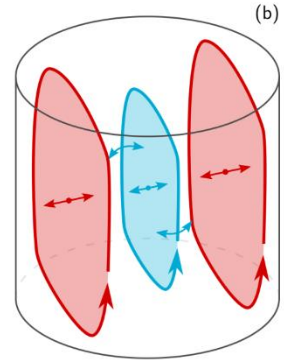
R. Mitra et al., Phys. Fluids 36, 066611(2024)

Helicity synchronization in a Rayleigh-Bénard flow

Goal: **resonant excitation of the helicity** of the sloshing m=1 mode (single roll structure) by a **tide-like** (m=2) electromagnetic force



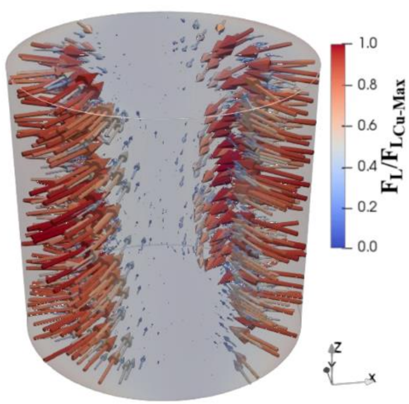


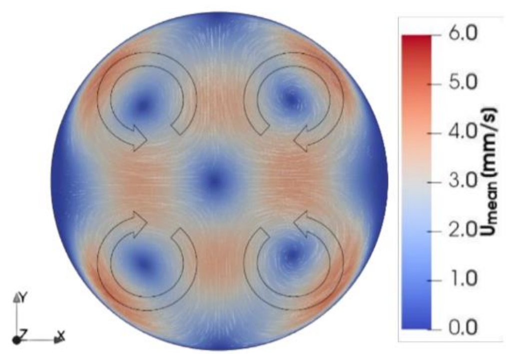


LSC with torsional and sloshing motion

Synchronized helicity

Tide-like force





Four-roll structure

P. Jüstel et al., Phys. Fluids 34, 104115 (2022)

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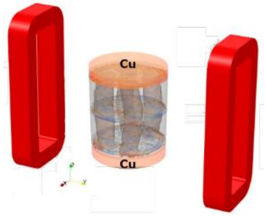
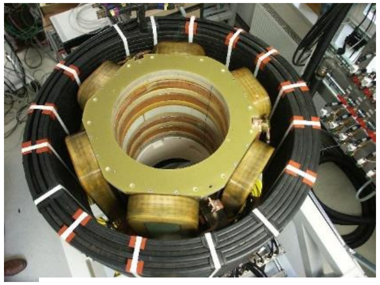
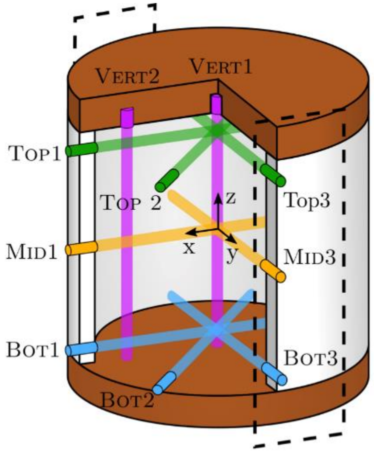
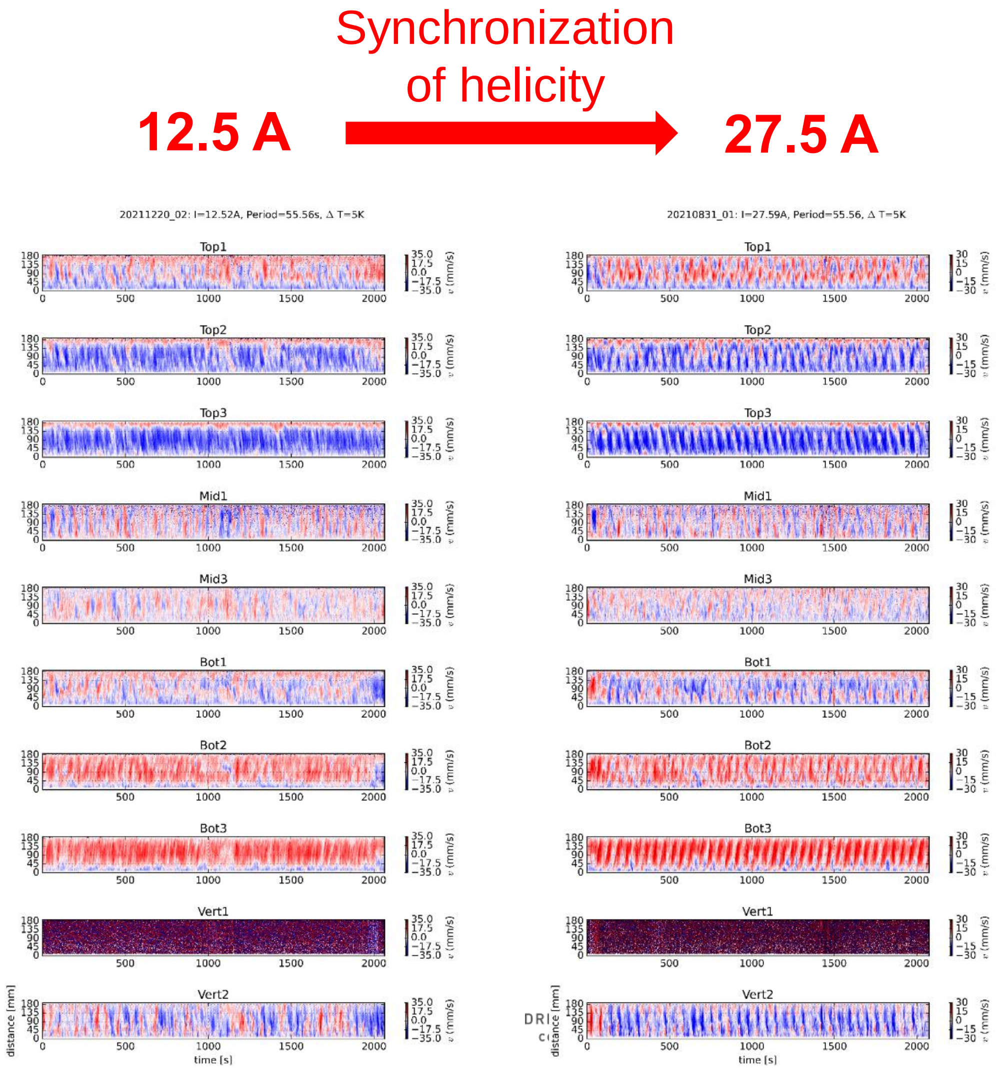
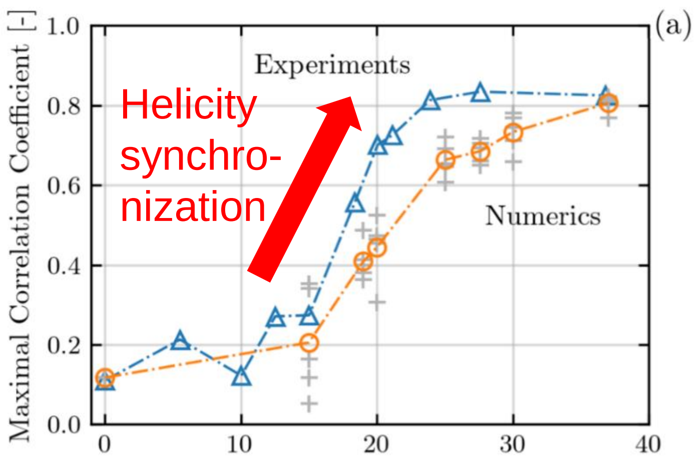










Jüstel et al., Phys. Fluids 34, 104115 (2022)

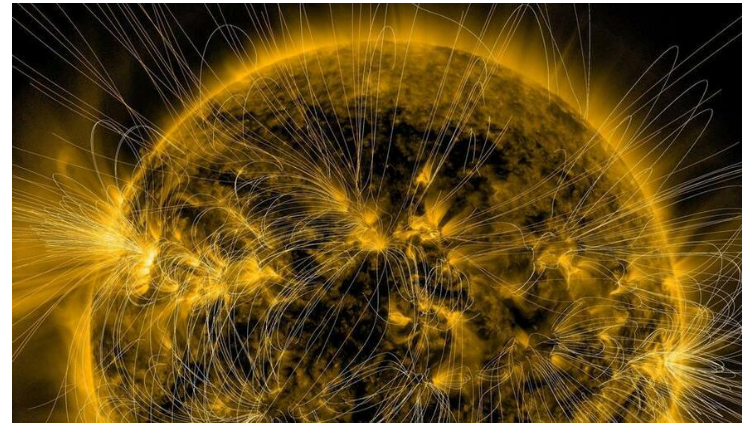
The solar dynamo

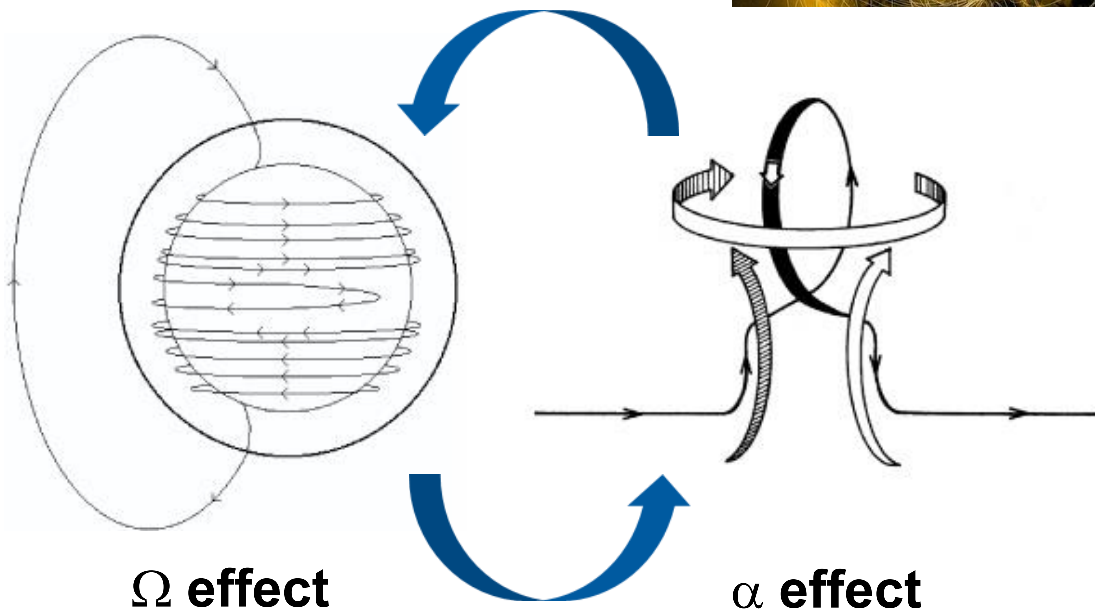
Problem? What Problem…?

The solar dynamo: Basics

Any solar dynamo needs:

- some Ω effect to wind up toroidal field from poloidal field
- some α effect to regenerate poloidal field from toroidal field





Ω effect **α effect**

Parker, Astrophys J. 122, 293 (1955)

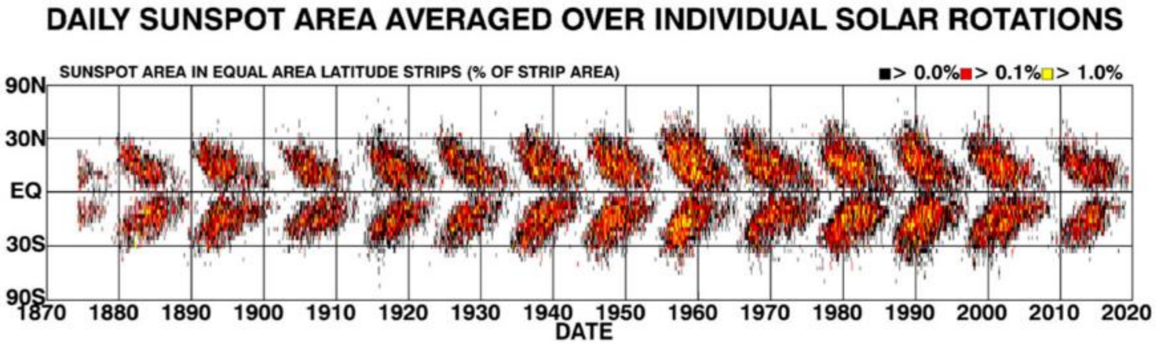
Remember Nick Featherstone's talk on Wednesday

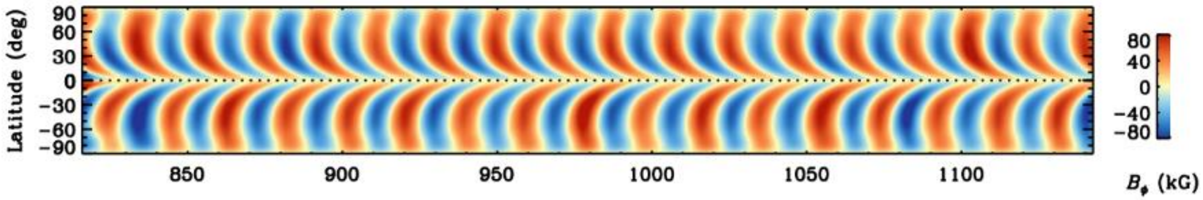
The solar dynamo: conventional wisdom

With appropriate models, e.g. Babcock-Leighton (including meridional circulation), and some parameter fitting, one “readily” obtains

- a reasonable period of the Hale cycle (22 years)
- a reasonable shape of the butterfly diagram of sunspots

http://www.solarcyclescience.com/solarcycle.html





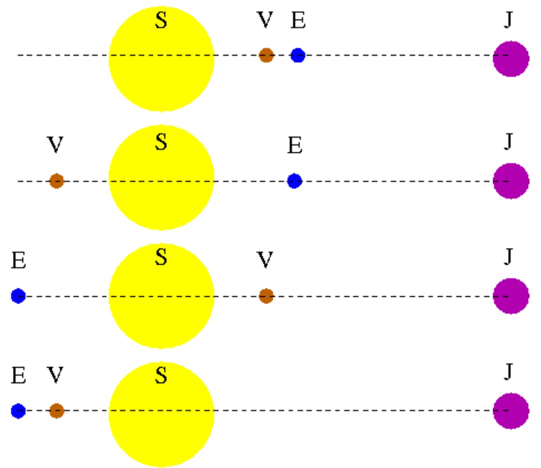
Karak, B.B., Miesch, M., ApJ 847 (2017), 69

DRESDEN concept

HZDR

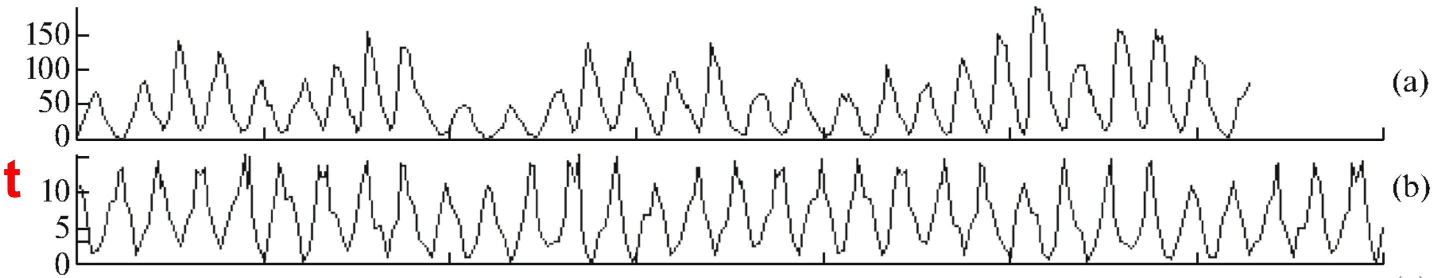
First indication for phase stability and clocking

Conspicuous parallelity of the solar Schwabe cycle with 11.07-yr spring-tide period of the tidally dominant Venus-Earth-Jupiter system (despite weak tidal forces → 1 mm tidal height!)

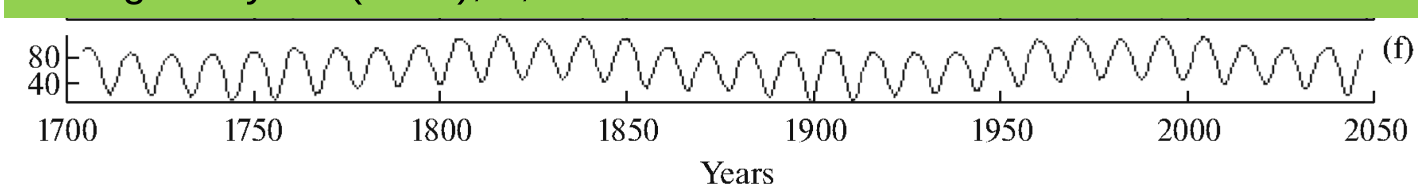


Sunspots

VEJ alignment index

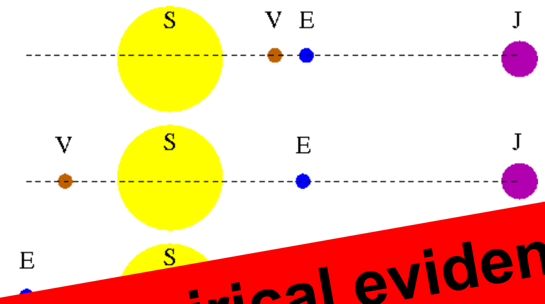


Bollinger, Proc. Okla. Acad. Sci. 33 (1952), 307; Takahashi, Solar. Phys. 3 (1968), 598; Wood, Nature 240 (1972), 91; **Wilson, Pattern Recogn. Phys. 1 (2013),** 147; Okhlopkov, Mosc. U. Bull. Phys. B. 69 (2014), 257; **Okhlopkov, Mosc. U. Bull. Phys. B. 71 (2016),** 444; Scafetta, Pattern Recogn. Phys. 2 (2014), 1; Vos et al. 2004



First indication for phase stability and clocking

Conspicious parallelity of the solar Schwabe cycle with 11.07-yr spring-tide period of the tidally dominant Venus-Earth-Jupiter system (despite weak tidal forces → 1 mm tidal height!)



Heavy discussion about empirical evidence of phase stability (and synchronization)

Dicke 1978, Schove 1983, F.S. et al. 2016, 2019, 2022

Nataf 2022, Weisshaar et al. 2023

Scafetta 2023, F.S. et al. 2023

Sunspots

VEJ alignment index

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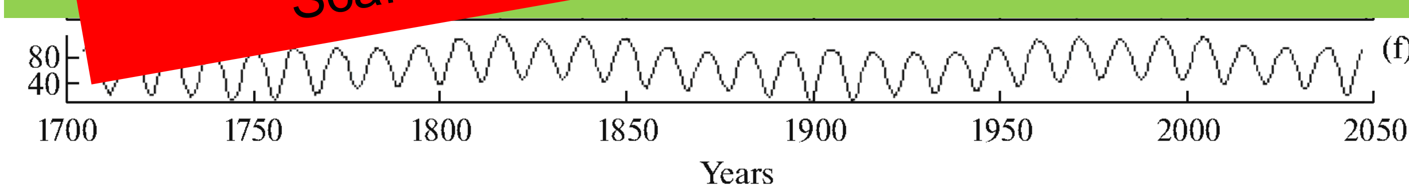
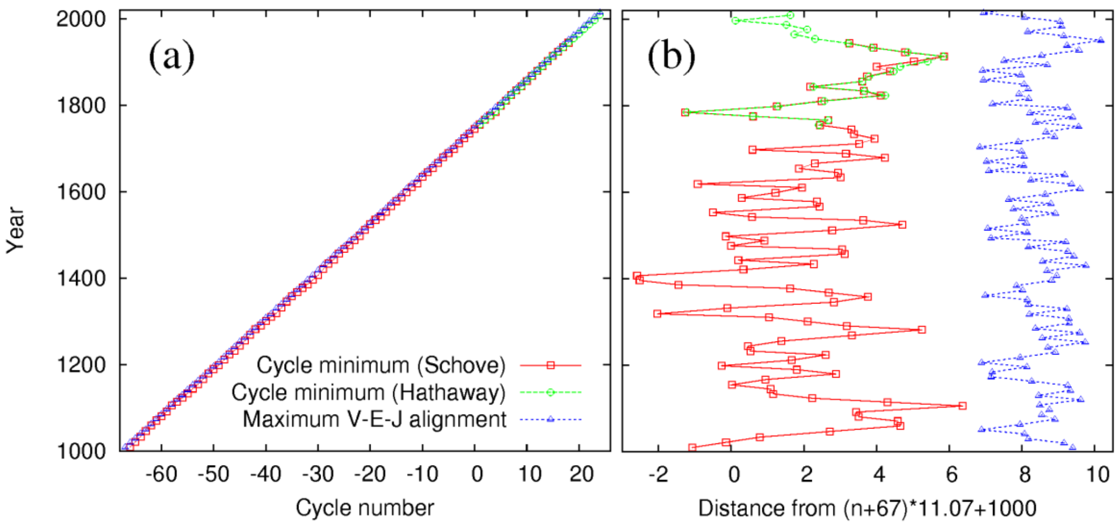
(2014), 257;
), 444; Scafetta, Pattern
e et al. 2004



First indication for phase stability and clocking



Residuals

Schove, D.J.: J. Geophys. Res. 60 (1955), 127; Hathaway, D.H., Liv. Rev. Sol. Phys. 7 (2010)

Strong indication for a clocked process, in contrast to a random walk process

F. S. et al., Solar Physics 294 (2019)

Schove's data (derived mainly from aurorae borealis) are often criticized ("9 per century rule")

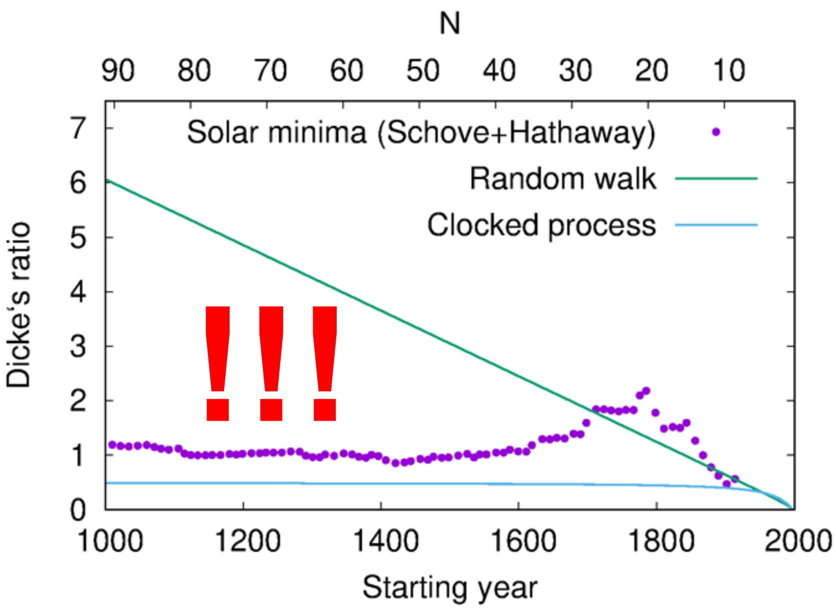
I. Usoskin, Living Rev. Sol. Phys. 14, 3 (2017); H.-C. Nataf, Solar Physics 297 (2022), 107

However: ^{10}Be and ^{14}C data give similar cycles.

F. S. et al., Astron. Nachr. 341 (2020), 600

DRESDEN concept HZDR

Dicke´s ratio in dependence on the number N of cycles



Distinction between random walk (RW) and clocked process (CP) for the instants y_n of sunspot maxima/minima

Residuals: $\delta y_n = y_n - y_0 - p(n-1)$, with p being the mean cycle period

A telling measure for discriminating between RW und CP is DICKE´s RATIO between the variance of δy_n and the variance of $(\delta y_n - \delta y_{n-1})$

	RATIO	Limes N→ infinity
Random walk	$(N+1)(N^2-1)/(3(5N^2+6N-3))$	N/15
Clocked process	$(N^2-1)/(2(N^2+2N+3))$	1/2

Dicke, R.H., Nature 276 (1978), 676

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Phase stability of the Schwabe cycle: the state of the debatte

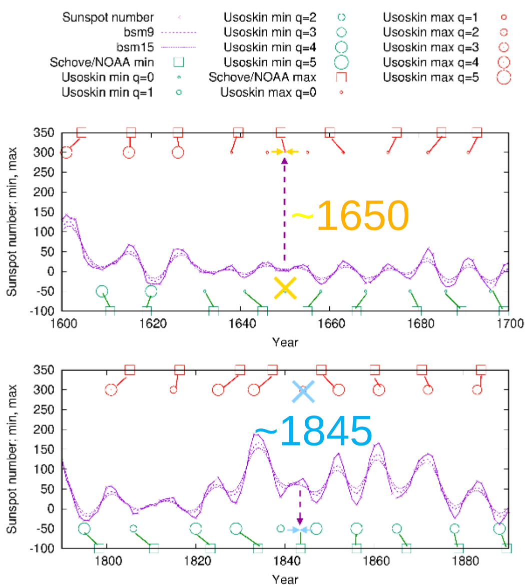
F.S. et al., Solar Physics 294 (2019) — Criticized by → Nataf, Solar Physics 297 (2022), 107

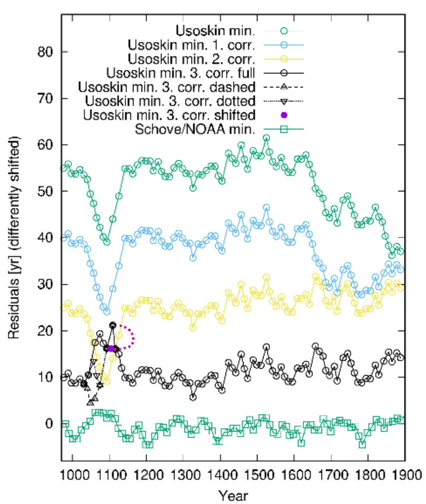
Nataf, Solar Physics 297 (2022), 107 — Criticized by ↓ Scafetta, Solar Physics 298 (2023), 24

Scafetta, Solar Physics 298 (2023), 24 — answer → Nataf, Solar Physics 298 (2023), 33

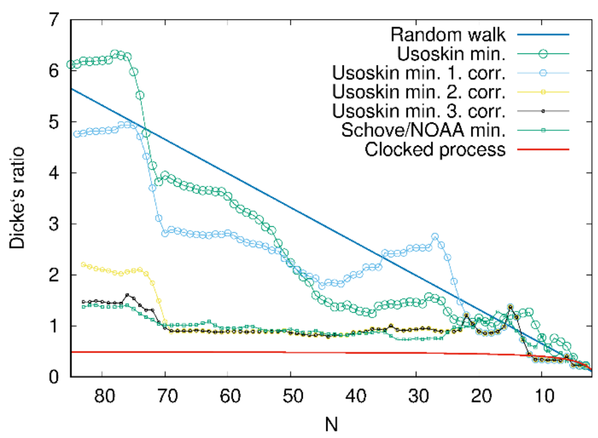
Weisshaar et al., A&A 671 (2023), A87: **No evidence for synchronization of the solar cycle by a “clock”** — Criticized by → F.S., J. Beer, Weier, **No evidence for absence of solar dynamo synchro-nization,** promptly rejected by Editor of A&A → Solar Physics 298, 83 (2023)

^{14}C-Data: two very plausible corrections → clocked process down to AD 1140





Residuals



Dicke-Ratio

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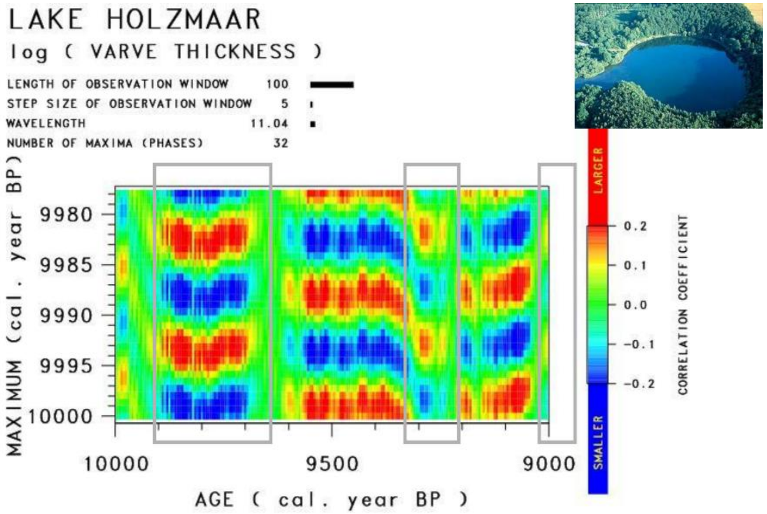
Second indication for phase stability and clocking

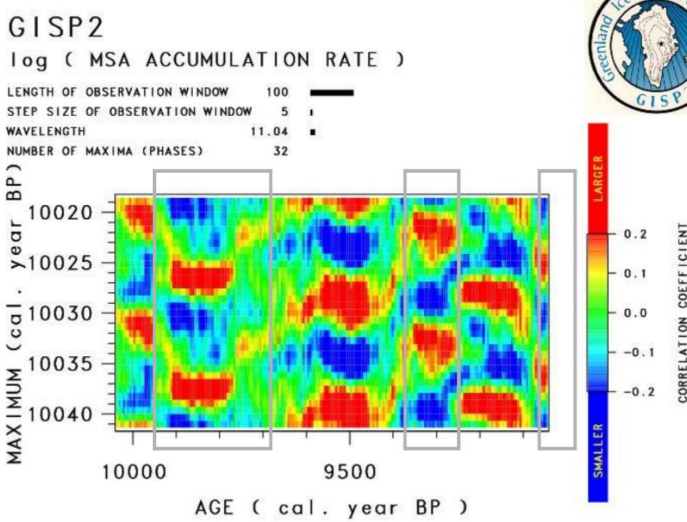
Phase diagrams for algae data from lake Holzmaar und algae-produced Methanesulfonate (MSA) in Greenland ice core GISP2 show 11.04-years cycle with very similar band structures.

Bands are separated by apparent 5.5-years-phase jumps, resulting from nonlinear transfer function (due to optimality condition of algae growth)

Strong evidence for a 11.04(?)-years-cycle, that was phase-stable over 1000 years!

H. Vos et al., in "Climate in Historical Times: Towards a Synthesis of Holocene Proxy Data and Climate Models", GKSS School of Environmental Research, p. 293 (2004)

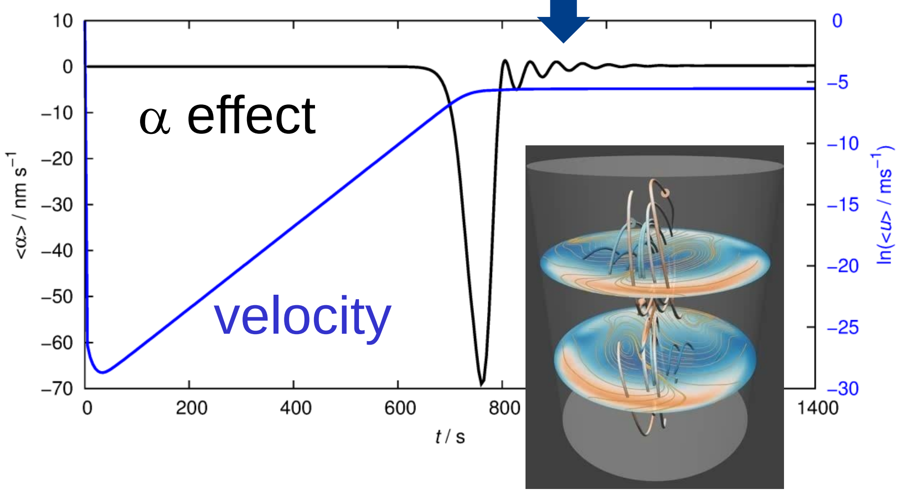


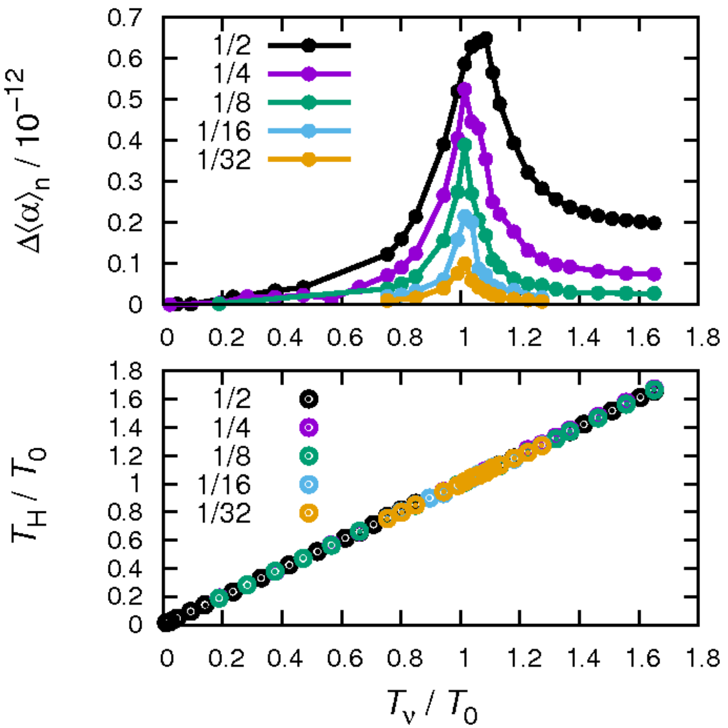


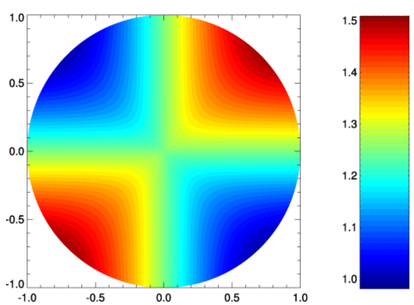
F. S. et al., Astron. Nachr. 341 (2020), 600

Original idea: tidal forces might synchronize α to 11.07 years

Current driven Tayler instability (with azimuthal wave number m=1) tends to undergo intrinsic helicity oscillations…







…which can be easily synchronized by tidal (m=2) perturbations (of the VEJ-system)

N. Weber et al., NJP 17 (2015), 113013; F. S. et al., Solar Phys. 291 (2016), 2197; Solar Physics 294 (2019), 60

A simple ODE model of a synchronized dynamo

$$\dot{A}(t) = \alpha(t)B(t) - \tau^{-1}A(t)$$

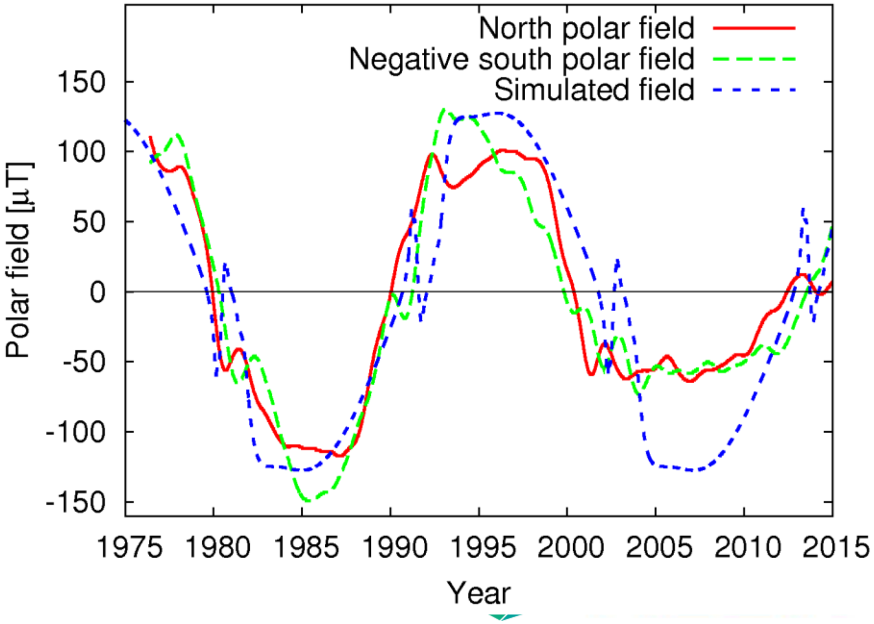
$$\dot{B}(t) = \omega A(t) - \tau^{-1}B(t)$$

$$\alpha(t) = \frac{c}{1+gB^2(t)} + \frac{pB^2(t)}{1+hB^4(t)}\sin(2\pi t/T_\nu)$$

Oscillatory α term with period of 11.07 years and resonant dependence on the field strength

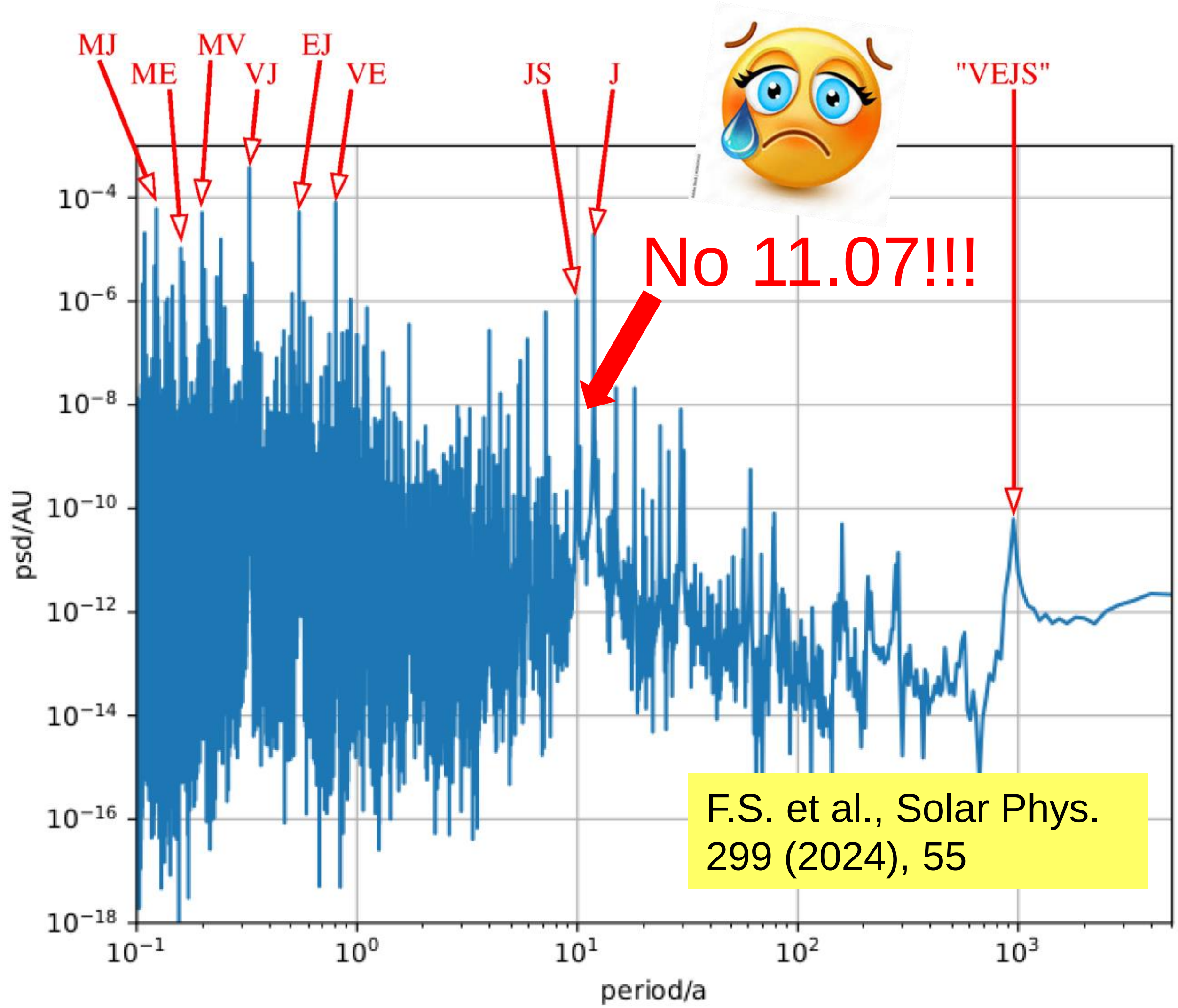
Constant α term with quenching

…parametric resonance yields a 22.14 years solar cycle!



F.S. et al, Solar Phys. 291 (2016), 2197

However: No 11.07-yr peak in the spectrum of tidal potential…



H.-C. Nataf, Solar Phys. 297, 107 (2022),
R.G. Cionco et al., Solar Phys. 298, 70 (2023)

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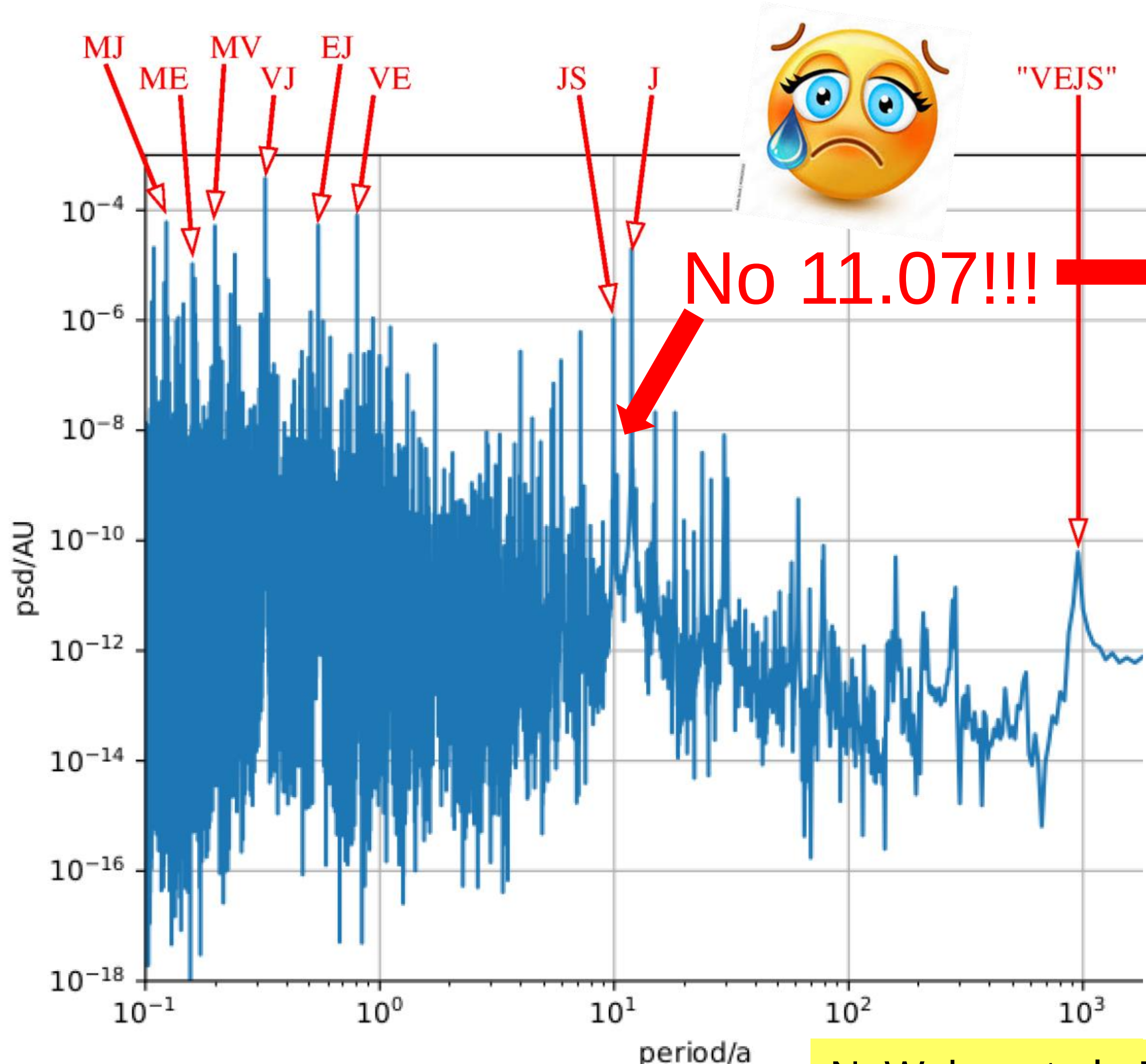
However: No 11.07-yr peak in the spectrum of tidal potential…



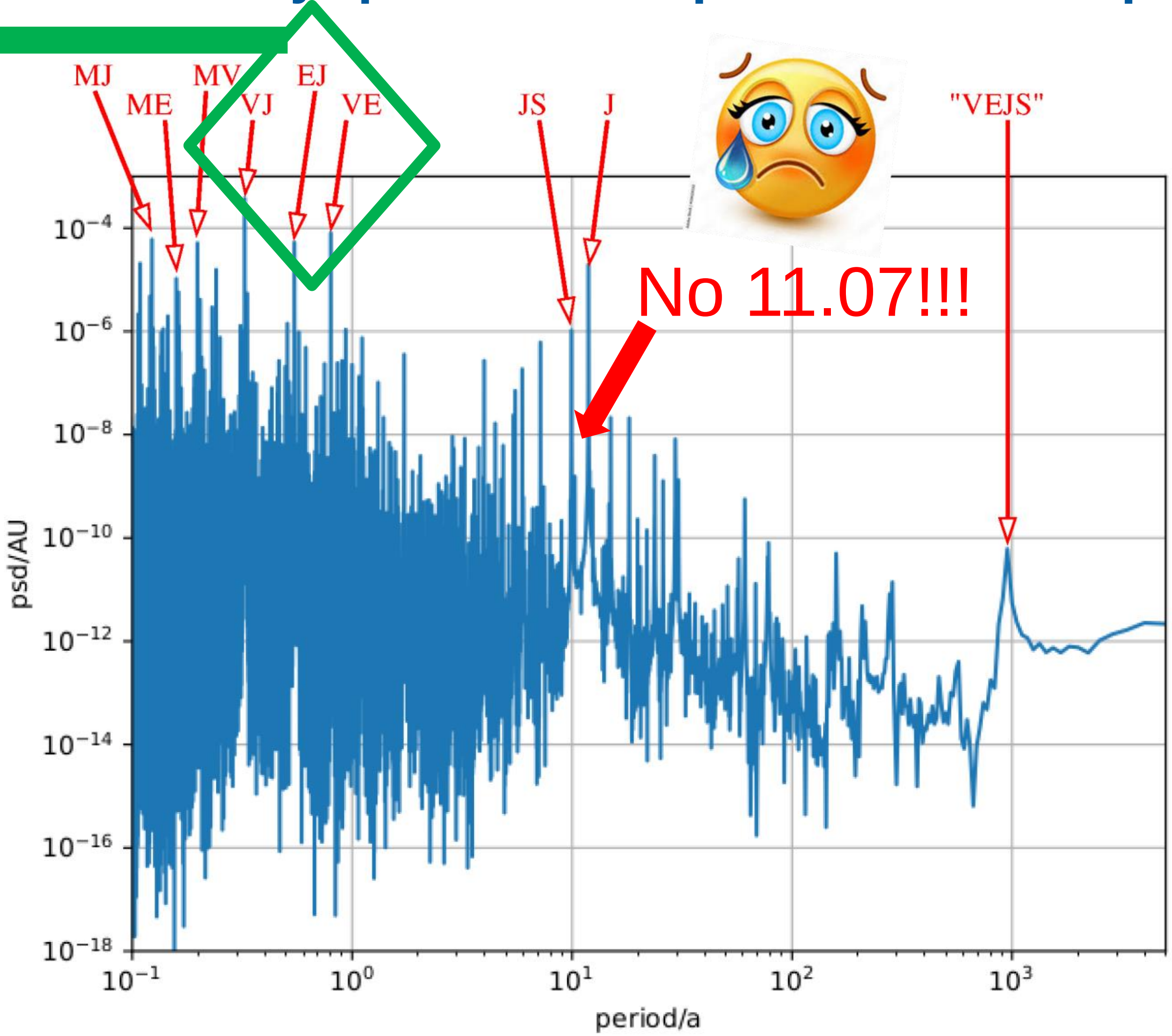
This puts into question the entire concept of **direct helicity synchronization** (e.g., of the Tayler instability) by tidal forces as previously developed in…

H.-C. Nataf, Solar Phys. 297, 107 (2022),
R.G. Cionco et al., Solar Phys. 298, 70 (2023)

N. Weber et al., New J. Phys 17, 113013 (2015); F. Stefani et al. Solar Phys. 291 (2016), 294 (2019), 296 (2021)

However: No 11.07-yr peak in the spectrum of tidal potential…

So, let's first focus on those periods



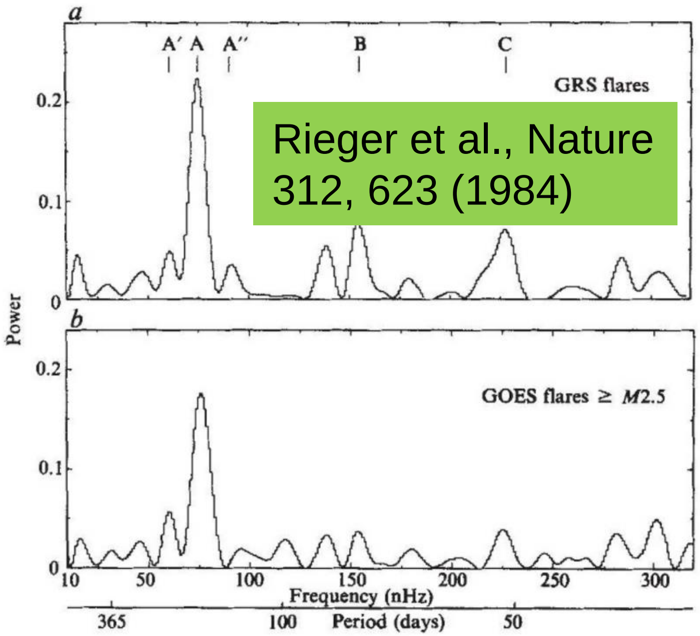
H-.C. Nataf, Solar Phys. 297, 107 (2022),
R.G. Cionco et al., Solar Phys. 298, 70 (2023)

DRESDEN concept

HZDR

Rieger

Rieger and Rieger-type periods



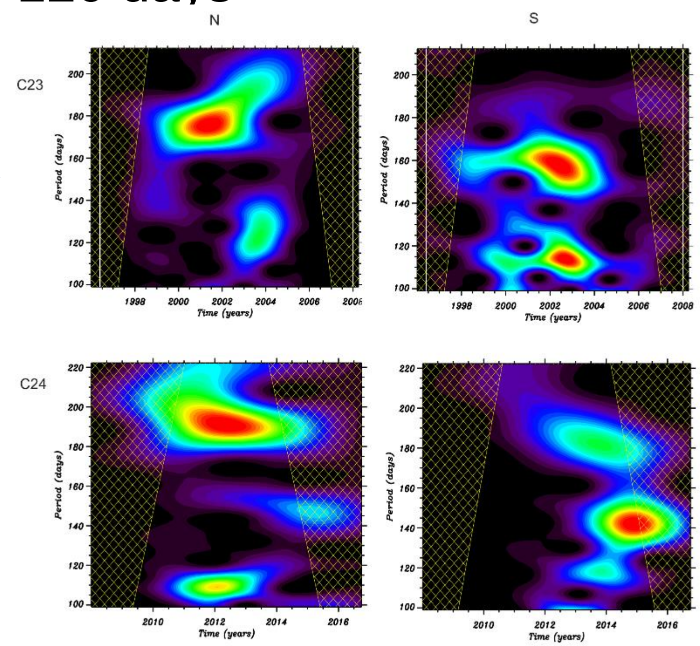
Rieger et al., Nature 312, 623 (1984)

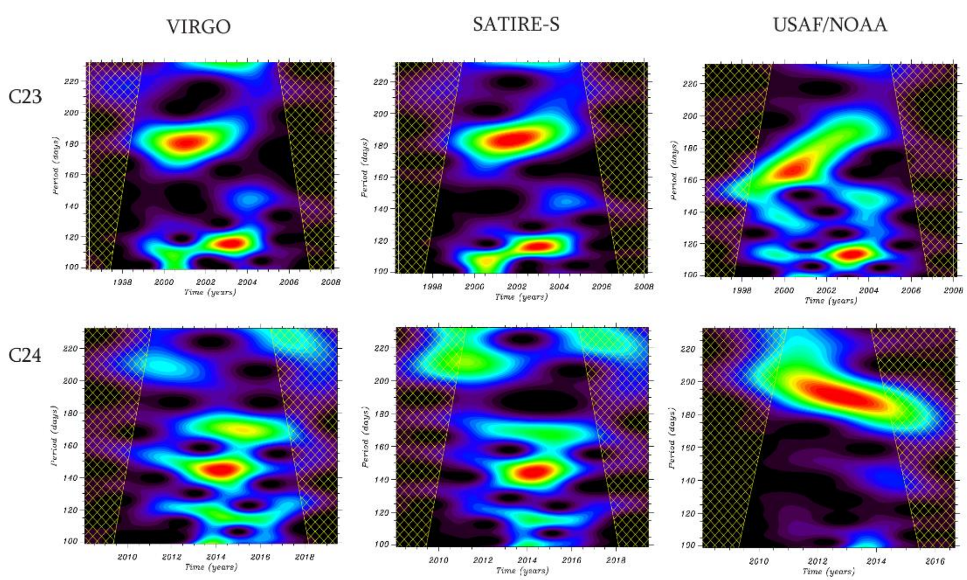
Originally: 154 days

A 154-day periodicity in the occurrence of hard solar flares?

E. Rieger*, G. H. Share†, D. J. Forrest†, G. Kanbach*, C. Reppin* & E. L. Chupp‡

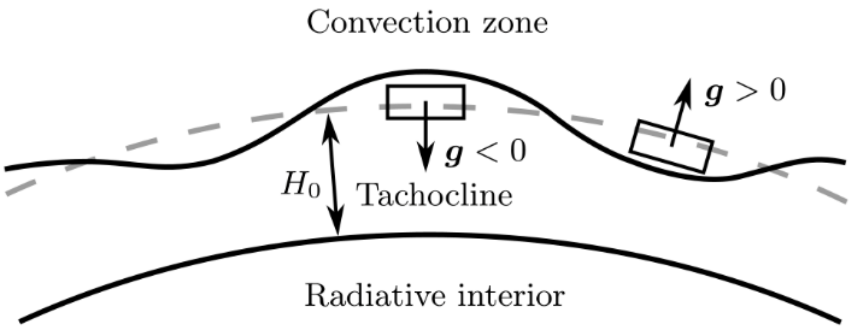
Meanwhile: also periods close to 190 and 120 days



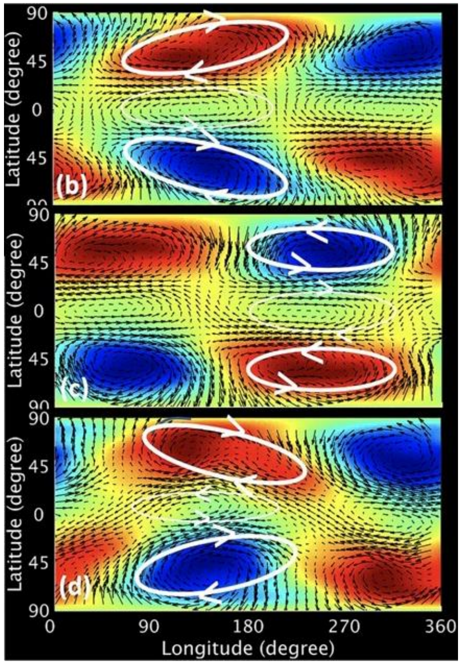


E. Gurgenashvili et al., A&A 653, A146 (2021)

New ansatz: Tidal synchronization of magneto-Rossby waves



magneto-Rossby waves



Shallow water approximation with azimuthal magnetic field under the influence of tidal forces, using some (not well-known) wave damping factor λ

M. Dikpati, S.W. McIntosh, Space Weather 18 (2020), e2018SW002109

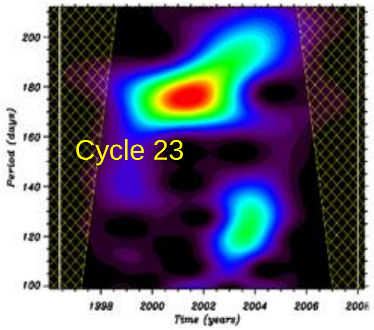
G. Horstmann et al., Astrophys. J. 944 (2023), 48

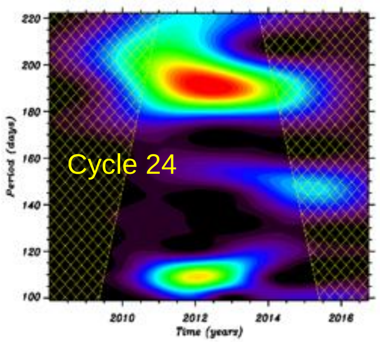
New ansatz: Tidal synchronization of magneto-Rossby waves

$$\Box_{v_A}^2 v - C_0^2 \Box_{v_A} \Delta v + f_0^2 \frac{\partial^2 v}{\partial t^2} - C_0^2 \beta \frac{\partial}{\partial x}\frac{\partial v}{\partial t} + 2\lambda \frac{\partial}{\partial t}\Box_{v_A} v - \lambda C_0^2 \Delta \frac{\partial v}{\partial t} + \lambda^2 \frac{\partial^2 v}{\partial t^2} = f_0 \frac{\partial}{\partial x}\frac{\partial^2 V}{\partial t^2} - \lambda \frac{\partial}{\partial y}\frac{\partial^2 V}{\partial t^2} - \frac{\partial}{\partial t}\frac{\partial}{\partial y}\Box_{v_A} V$$

$$= \left[f_0 \Omega + 2\Omega^2 - \frac{2 v_A^2}{R_0^2} + \frac{2 f_0 \Omega}{R_0} y \right] \frac{4K\Omega}{R_0} \sin\left(\frac{2x}{R_0} - 2\Omega t \right) + \frac{4K\lambda\Omega^2}{R_0} \cos\left(\frac{2x}{R_0} - 2\Omega t \right)$$

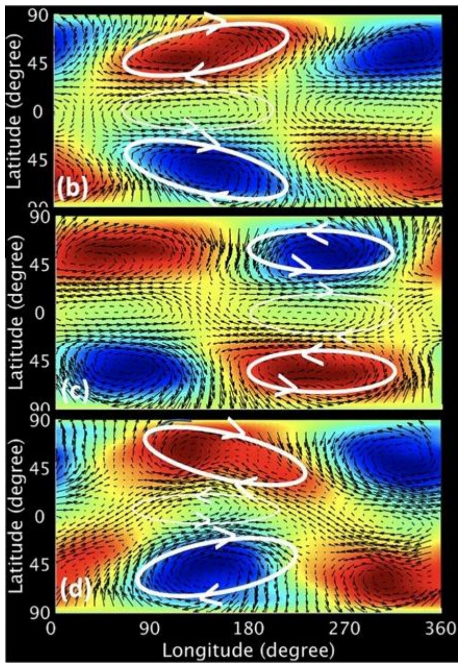
Rieger-type periods





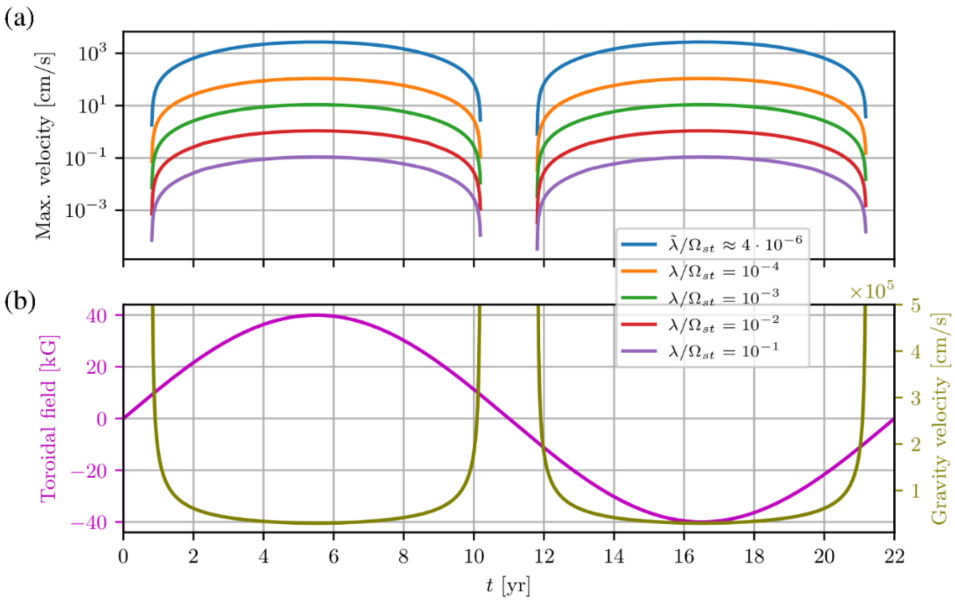
E. Gurgenashvili et al., A&A 653, A146 (2021)

magneto-Rossby waves



M. Dikpati, S.W. McIntosh, Space Weather 18 (2020), e2018SW002109

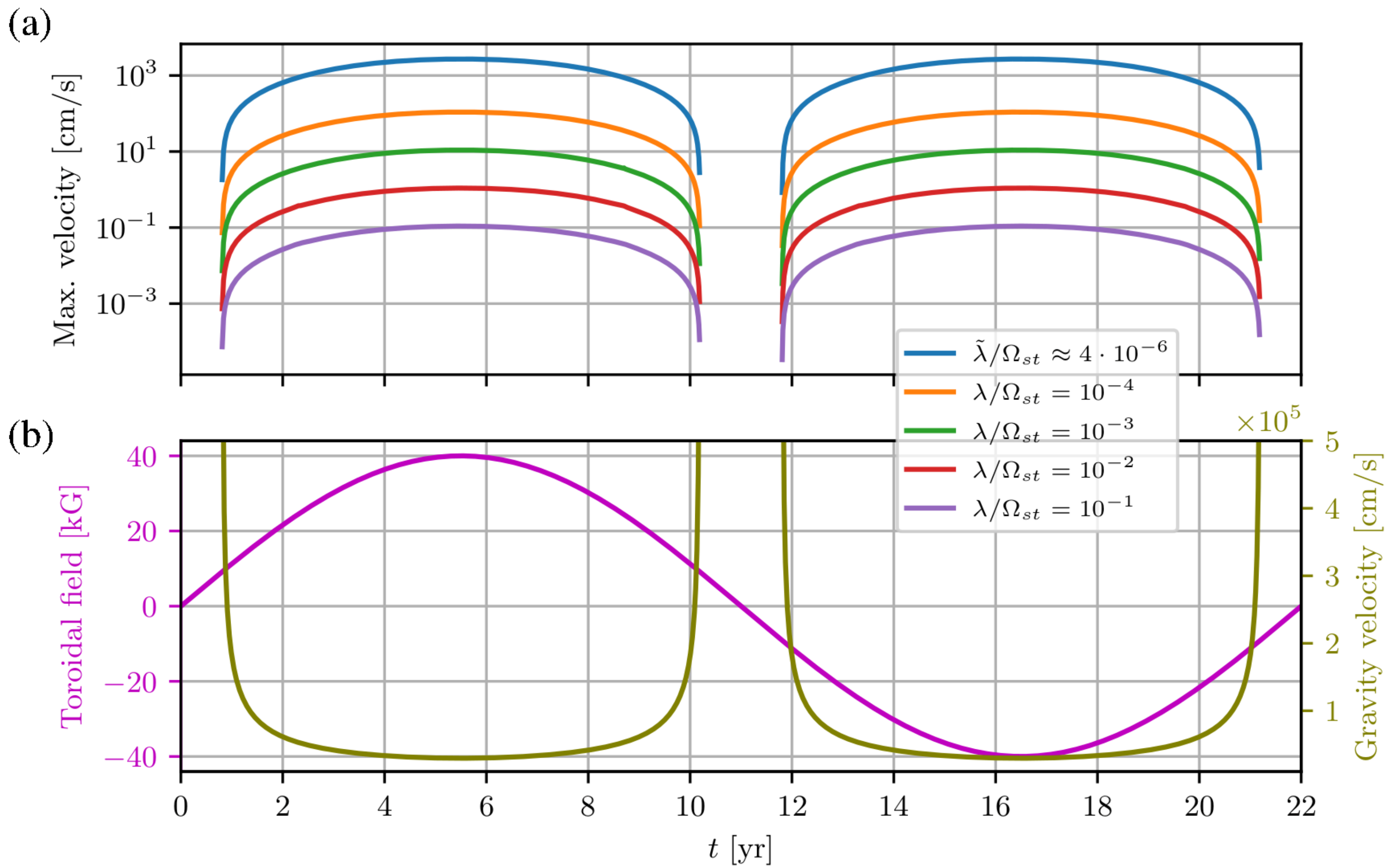
Analytical solution



Example: Venus-Jupiter spring tide, period 118 days; wave **velocities of up to 1-100 m/s are possible** for realistic tides

G. Horstmann et al., Astrophys. J. 944 (2023), 48; F.S. et al., Solar Phys. 299 (2024), 55

λ-dependent reaction on the 118-day spring tide of Venus-Jupiter

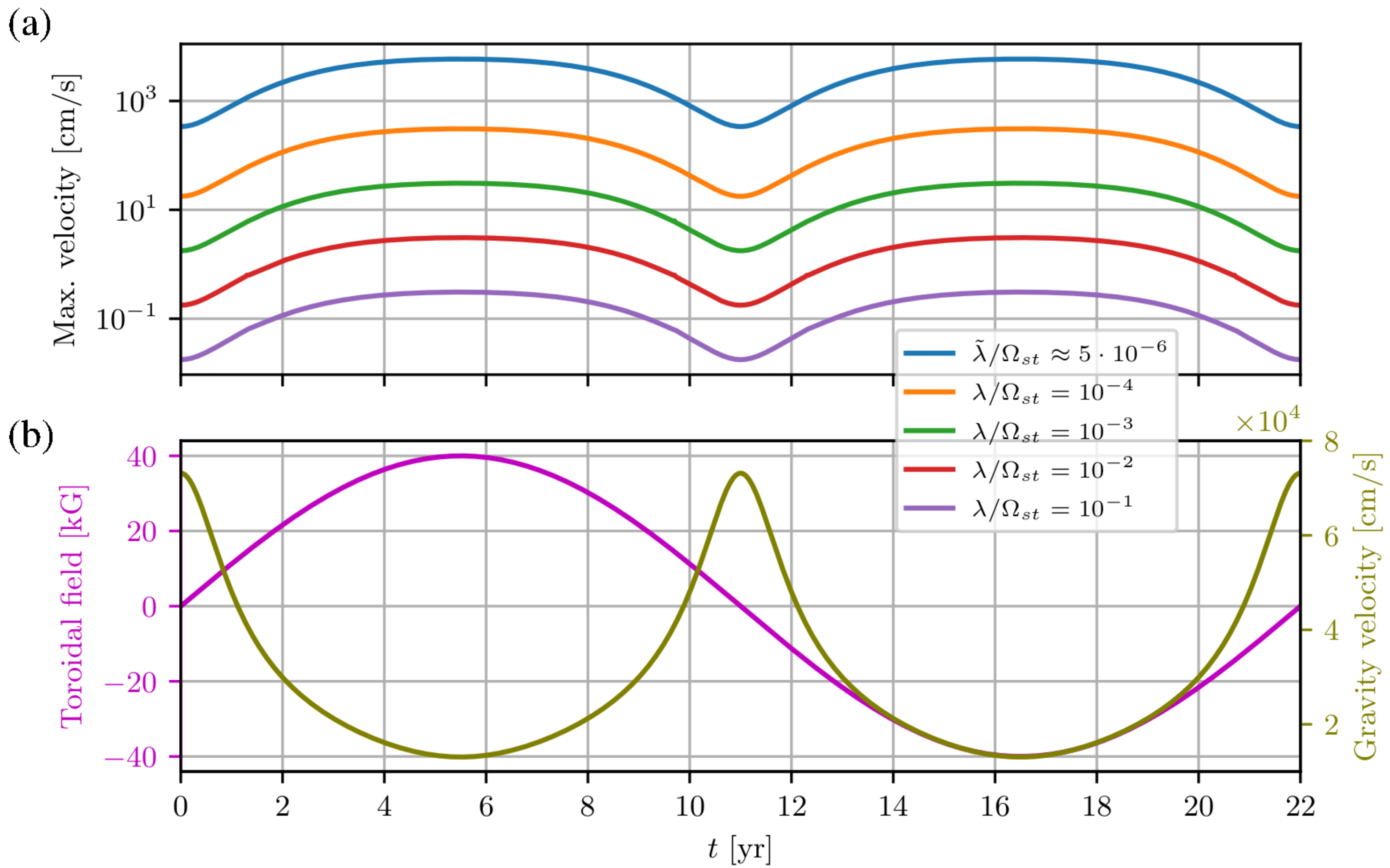


Simplified assumption:

$$V = K\left(\frac{1}{2} + \frac{y}{R_0}\right)\left[1 + \cos\left(\frac{2x}{R_0} + \Omega_{\rm st} t\right)\right]$$

F.S. et al., Solar Phys. 299 (2024), 55

λ-dependent reaction on the 199-day spring tide of Earth-Jupiter



Simplified assumption: $V = K\left(\frac{1}{2} + \frac{y}{R_0}\right)\left[1 + \cos\left(\frac{2x}{R_0} + \Omega_{\rm st} t\right)\right]$

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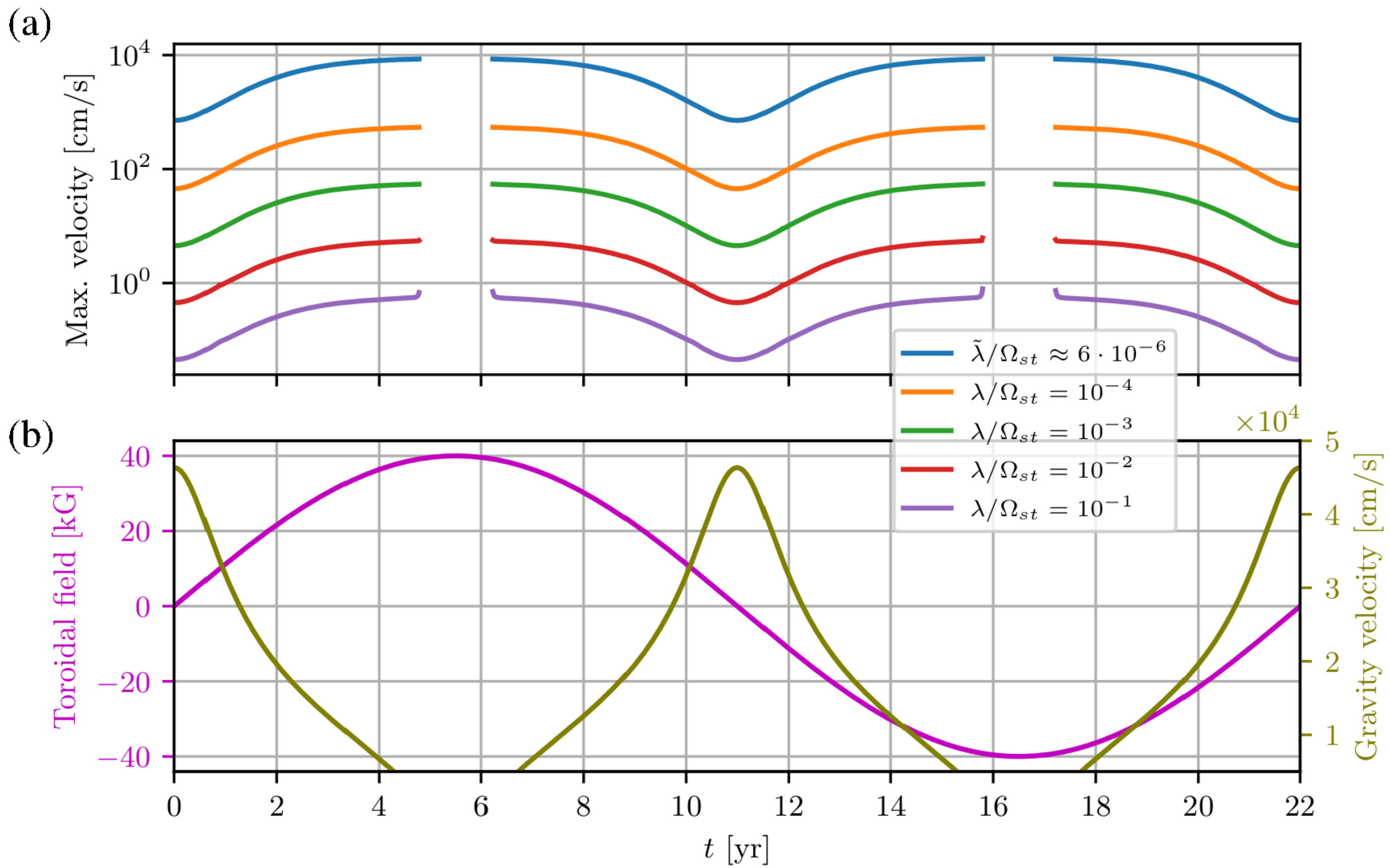
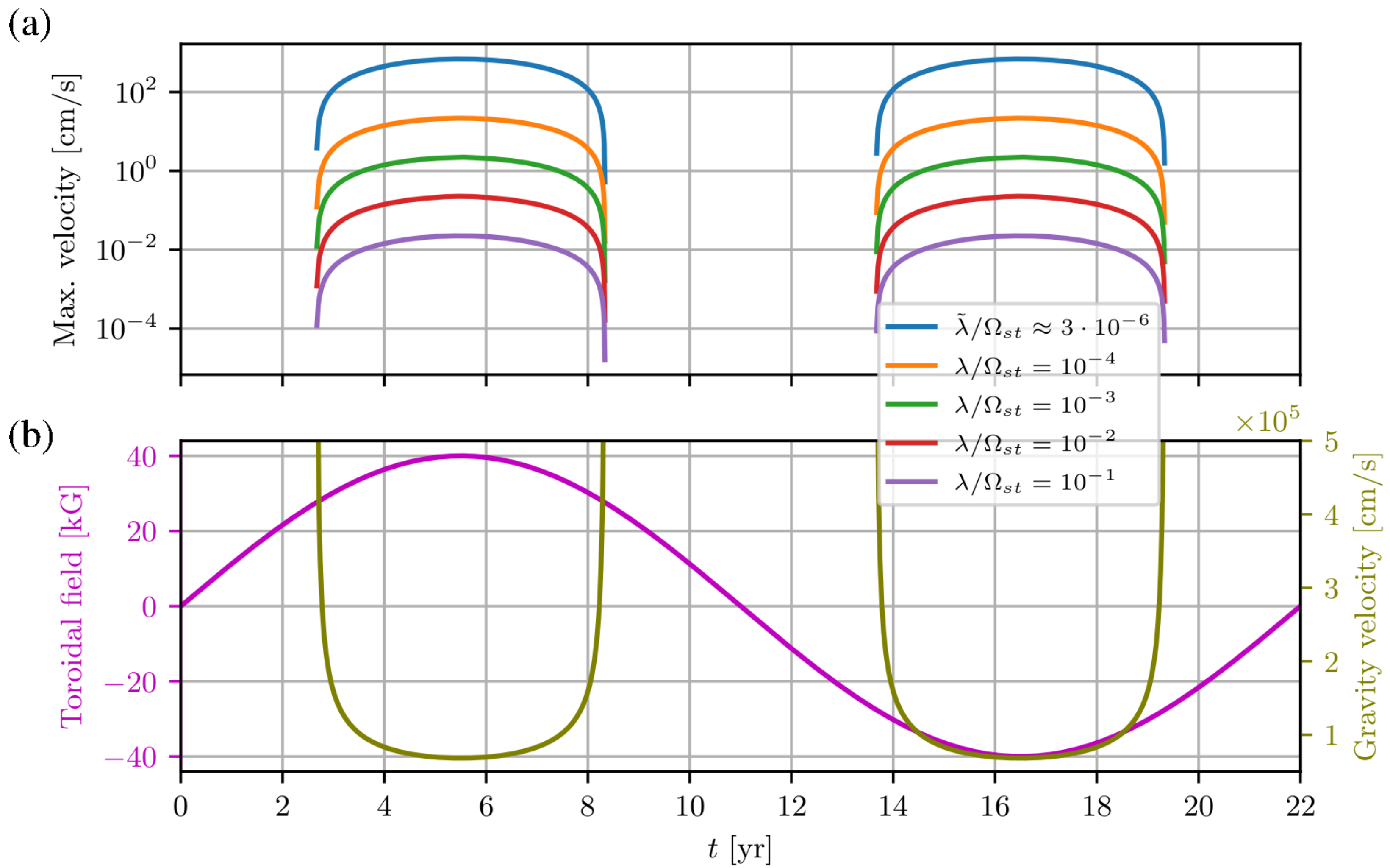
λ-dependent reaction on the 292-day spring tide of Earth-Venus



Simplified assumption: $$V = K\left(\frac{1}{2}+\frac{y}{R_0}\right)\left[1+\cos\left(\frac{2x}{R_0}+\Omega_{st}t\right)\right]$$

What about Mercury? 72-day spring tide of Mercury-Venus



Simplified assumption:

$$V = K\left(\frac{1}{2}+\frac{y}{R_0}\right)\left[1+\cos\left(\frac{2x}{R_0}+\Omega_{\rm st}t\right)\right]$$

Schwabe/Hale

Where does the 11.07-yr come from? The formal answer…

N. Scafetta, Front. Astron. Space 9, 937930 (2022)

$$P_{\mathrm{VEJ}} = \frac{1}{2}\left[\frac{3}{P_{\mathrm{V}}} - \frac{5}{P_{\mathrm{E}}} + \frac{2}{P_{\mathrm{J}}}\right]^{-1}$$

with P_V = 224.701 days, P_E = 365.256 days, P_J = 4332.589 days

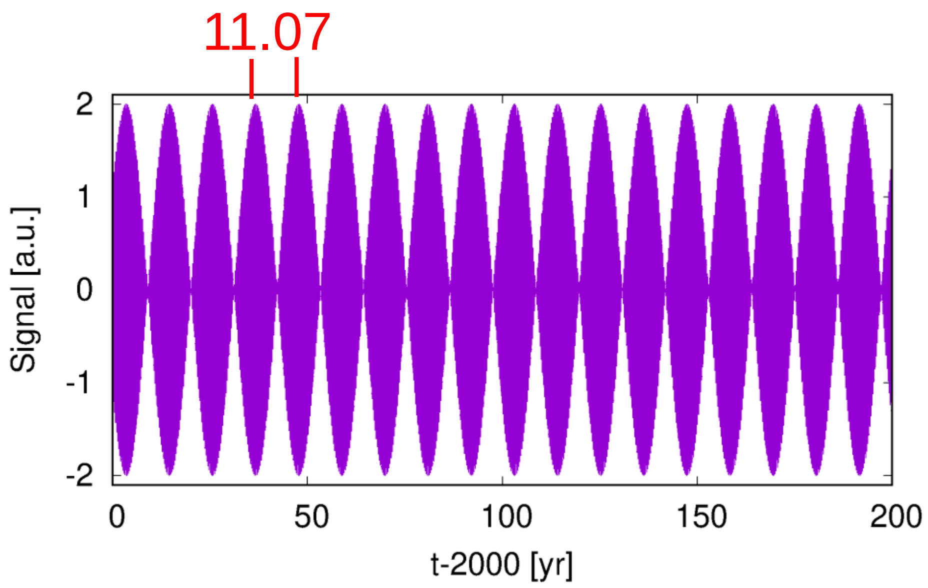
Applying (3,−5, 2) =3(1,−1, 0) − 2(0, 1, − 1)

we get

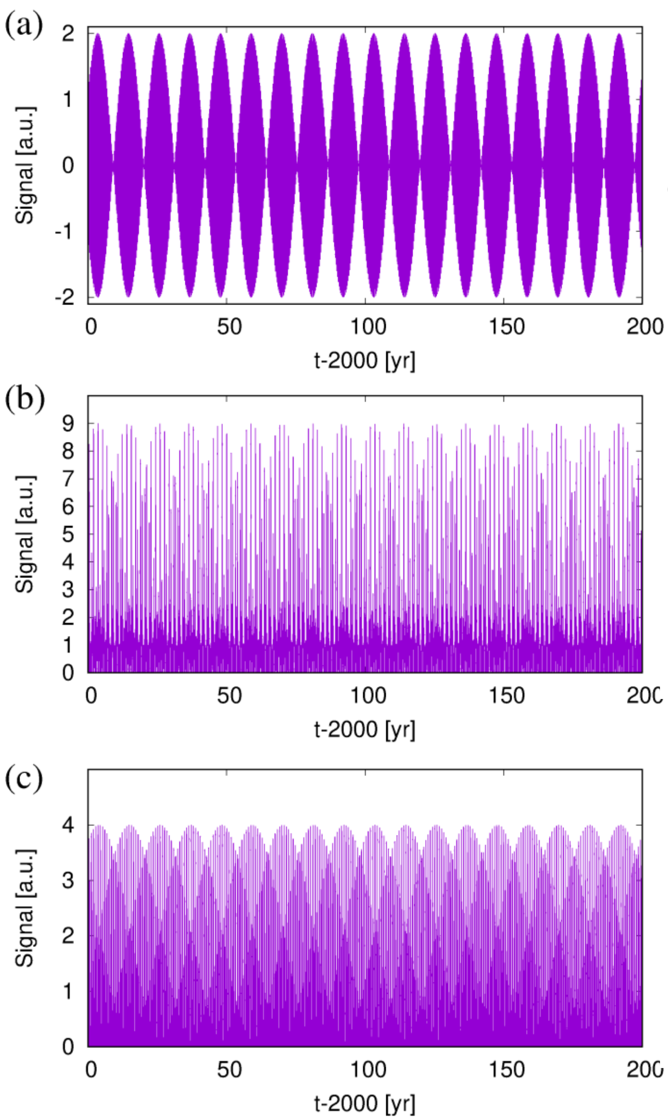
$$s(t) = \cos\left(2\pi \cdot 2 \cdot \frac{t - t_{\mathrm{EJ}}}{0.5 \cdot P_{\mathrm{EJ}}}\right) + \cos\left(2\pi \cdot 3 \cdot \frac{t - t_{\mathrm{VE}}}{0.5 \cdot P_{\mathrm{VE}}}\right)$$

Combination of the second harmonics of the Earth-Jupiter spring tide and the third harmonics of the Venus-Earth spring tide…

But why should that be of any physical relevance?



Where does the 11.07-yr come from? From math to physics



$$s(t) = \cos\left(2\pi \cdot 2 \cdot \frac{t - t_{\mathrm{EJ}}}{0.5 \cdot P_{\mathrm{EJ}}}\right) + \cos\left(2\pi \cdot 3 \cdot \frac{t - t_{\mathrm{VE}}}{0.5 \cdot P_{\mathrm{VE}}}\right)$$

Presumably, the dynamo relevant effect of the waves (helicity, zonal flows) will be a quadratic functional. Most simply:

$$s(t) = \left[\cos\left(2\pi \cdot \frac{t - t_{\mathrm{VJ}}}{0.5 \cdot P_{\mathrm{VJ}}}\right) + \cos\left(2\pi \cdot \frac{t - t_{\mathrm{EJ}}}{0.5 \cdot P_{\mathrm{EJ}}}\right) + \cos\left(2\pi \cdot \frac{t - t_{\mathrm{VE}}}{0.5 \cdot P_{\mathrm{VE}}}\right)\right]^2$$

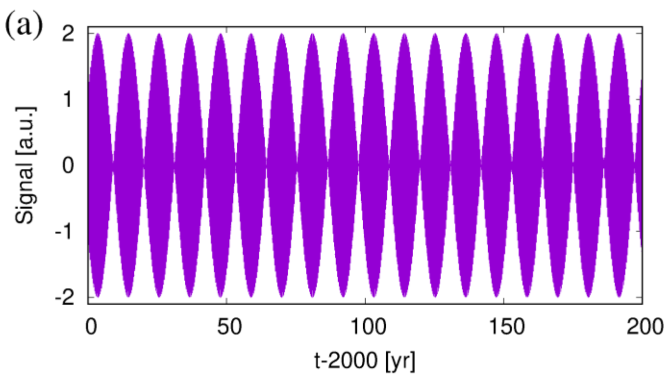
Even if assuming a too high field…

$$s(t) = \left[\cos\left(2\pi \cdot \frac{t - t_{\mathrm{VJ}}}{0.5 \cdot P_{\mathrm{VJ}}}\right) + \cos\left(2\pi \cdot \frac{t - t_{\mathrm{EJ}}}{0.5 \cdot P_{\mathrm{EJ}}}\right) + \cos\left(2\pi \cdot \frac{t - t_{\mathrm{VE}}}{0.5 \cdot P_{\mathrm{VE}}}\right)\right]^2$$

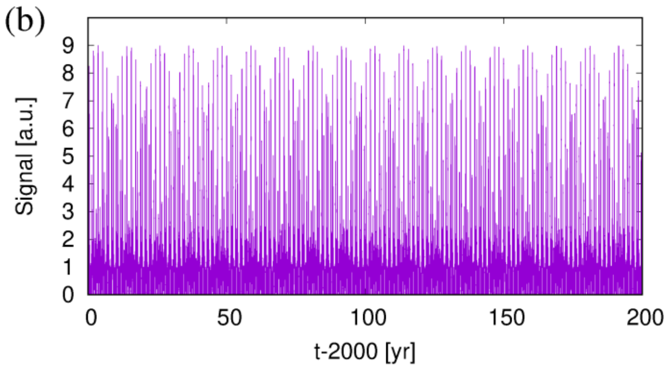
DRESDEN concept

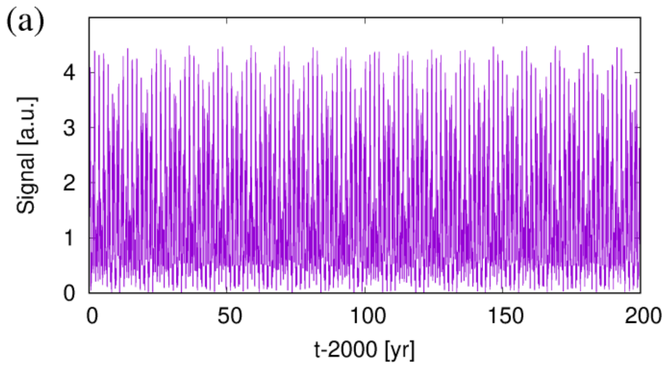
HZDR

Where does the 11.07-yr come from? Axi-symmetric part



$$S(t) = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \left[\cos\left(2\pi\cdot\frac{t-t_{\mathrm{VJ}}}{0.5\cdot P_{\mathrm{VJ}}}+2\varphi\right)+\cos\left(2\pi\cdot\frac{t-t_{\mathrm{EJ}}}{0.5\cdot P_{\mathrm{EJ}}}+2\varphi\right) + \cos\left(2\pi\cdot\frac{t-t_{\mathrm{VE}}}{0.5\cdot P_{\mathrm{VE}}}+2\varphi\right)\right]^2$$

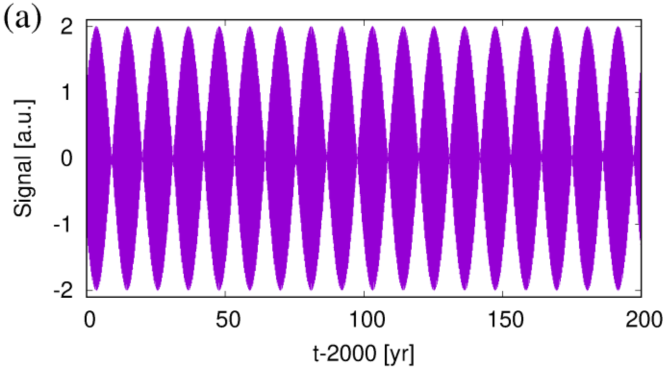




With all 3 waves: 11.07-yr remains!

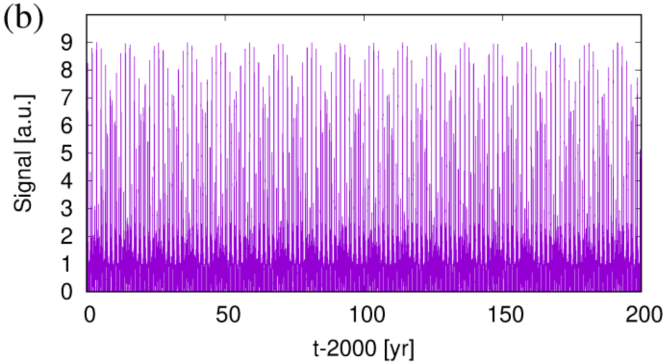
Where does the 11.07-yr come from? Axi-symmetric part

(a)

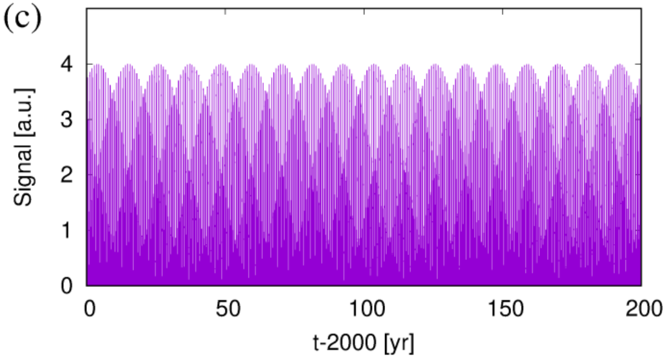


$$S(t) = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \left[\cos\left(2\pi\cdot\frac{t-t_{\mathrm{VJ}}}{0.5\cdot P_{\mathrm{VJ}}}+2\varphi\right)+\cos\left(2\pi\cdot\frac{t-t_{\mathrm{EJ}}}{0.5\cdot P_{\mathrm{EJ}}}+2\varphi\right) + \cos\left(2\pi\cdot\frac{t-t_{\mathrm{VE}}}{0.5\cdot P_{\mathrm{VE}}}+2\varphi\right)\right]^2$$

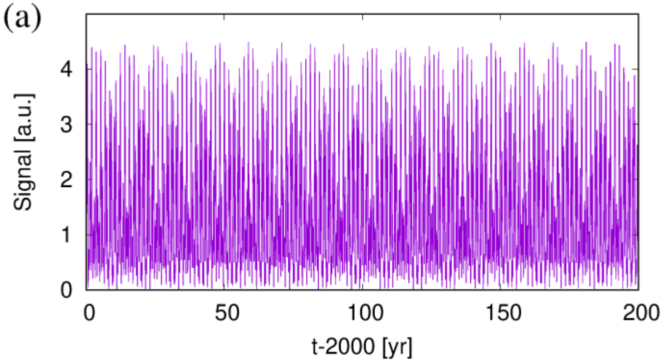
(b)



(c)

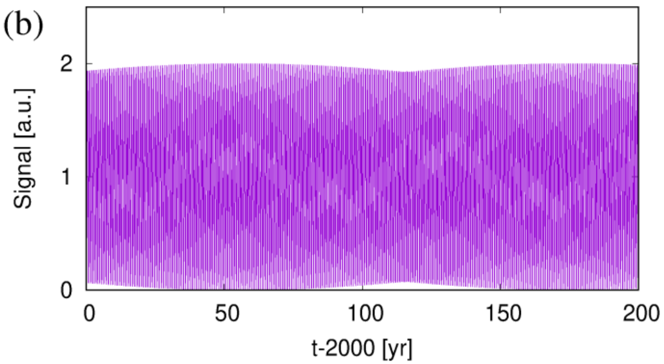


(a)



With all 3 waves: 11.07-yr remains!

(b)



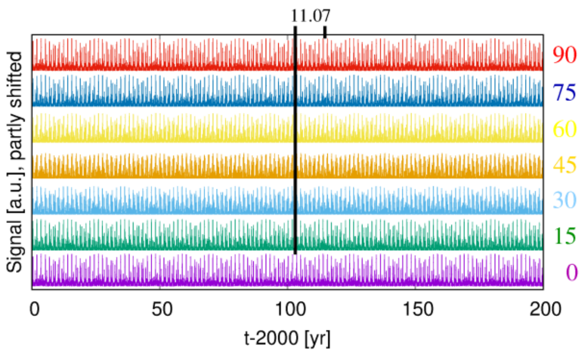
With one wave skipped: 11.07-yr disappears

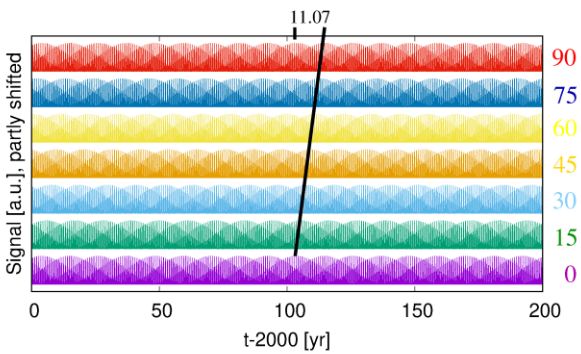
Where does the 11.07-yr come from? Axi-symmetric part

The role of Scafetta's "orbital invariance"

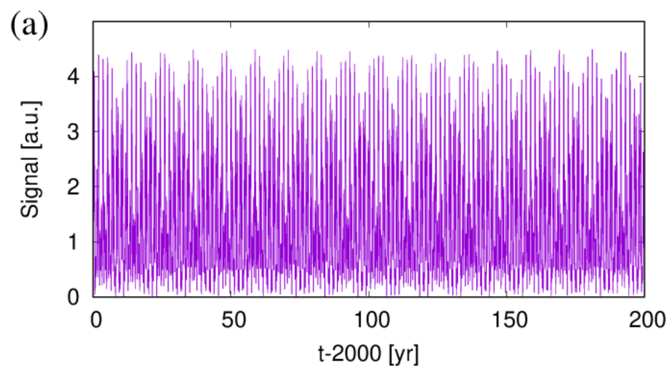
$$S(t) = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \left[\cos\left(2\pi\cdot\frac{t-t_{\rm VJ}}{0.5\cdot P_{\rm VJ}}+2\varphi\right)+\cos\left(2\pi\cdot\frac{t-t_{\rm EJ}}{0.5\cdot P_{\rm EJ}}+2\varphi\right) + \cos\left(2\pi\cdot\frac{t-t_{\rm VE}}{0.5\cdot P_{\rm VE}}+2\varphi\right)\right]^2$$

Beat maximum occurs independently of φ

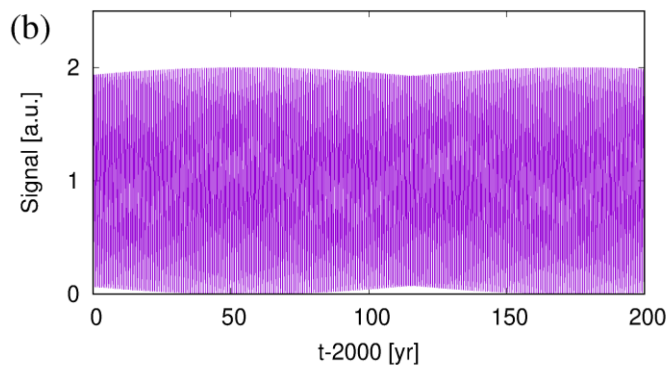




Beat maximum shifts with φ



With all 3 waves: 11.07-yr remains



With one wave skipped: 11.07-yr disappears

DRESDEN concept HZDR

A „realistic“ 2D α–Ω-dynamo model with meridional circulation…

$$\frac{\partial B}{\partial t} = \tilde{\eta} D^2 B + \frac{1}{s}\frac{\partial (sB)}{\partial r}\frac{\partial \tilde{\eta}}{\partial r} - R_\mathrm{m} s \boldsymbol{u}_\mathrm{p} \cdot \nabla \left(\frac{B}{s}\right) + C_\Omega s (\nabla \times (A \boldsymbol{e}_\phi)) \cdot \nabla \Omega \,,$$

$$\frac{\partial A}{\partial t} = \tilde{\eta} D^2 A - \frac{R_\mathrm{m}}{s} \boldsymbol{u}_\mathrm{p} \cdot \nabla (sA) + C_\alpha^\mathrm{c} \alpha^\mathrm{c} B + C_\alpha^\mathrm{p} \alpha^\mathrm{p} B \,,$$

$$C_\Omega = \Omega_\mathrm{eq} \mathrm{R}_\odot^2 / \eta_\mathrm{t} \,,$$

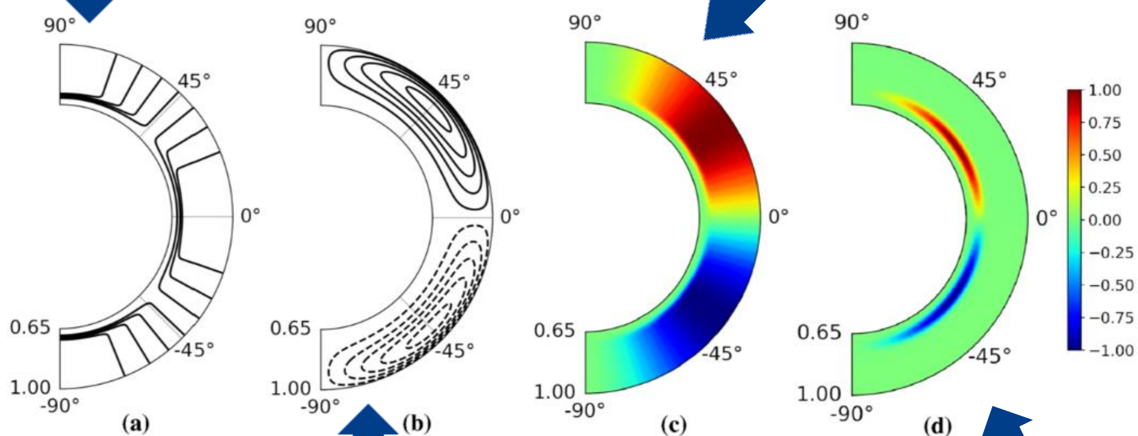
$$R_\mathrm{m} = u_0 \mathrm{R}_\odot / \eta_\mathrm{t} \,,$$

$$C_\alpha^\mathrm{c} = \alpha_\mathrm{max}^\mathrm{c} \mathrm{R}_\odot / \eta_\mathrm{t} \,,$$

$$C_\alpha^\mathrm{p} = \alpha_\mathrm{max}^\mathrm{p} \mathrm{R}_\odot / \eta_\mathrm{t} \,.$$

$$\Omega(r,\Theta) = C_\Omega \left\{ \Omega_\mathrm{c} + \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{r - r_\mathrm{c}}{d}\right)\right](1 - \Omega_\mathrm{c} - c_2 \cos^2\Theta) \right\}$$

$$\alpha^\mathrm{c}(r,\Theta,t) = C_\alpha^\mathrm{c} \frac{3\sqrt{3}}{4} \sin^2\Theta \cos\Theta \left[1 + \mathrm{erf}\left(\frac{r - r_\mathrm{c}}{d}\right)\right]\left[1 + \frac{|\boldsymbol{B}(r,\Theta,t)|^2}{B_0^2}\right]^{-1}$$



$$\alpha = \alpha^\mathrm{c} + \alpha^\mathrm{p}$$

Assumed to result from wave helicity

$$\boldsymbol{u}_\mathrm{p} = \nabla \times (\psi(r,\Theta)\boldsymbol{e}_\phi)$$

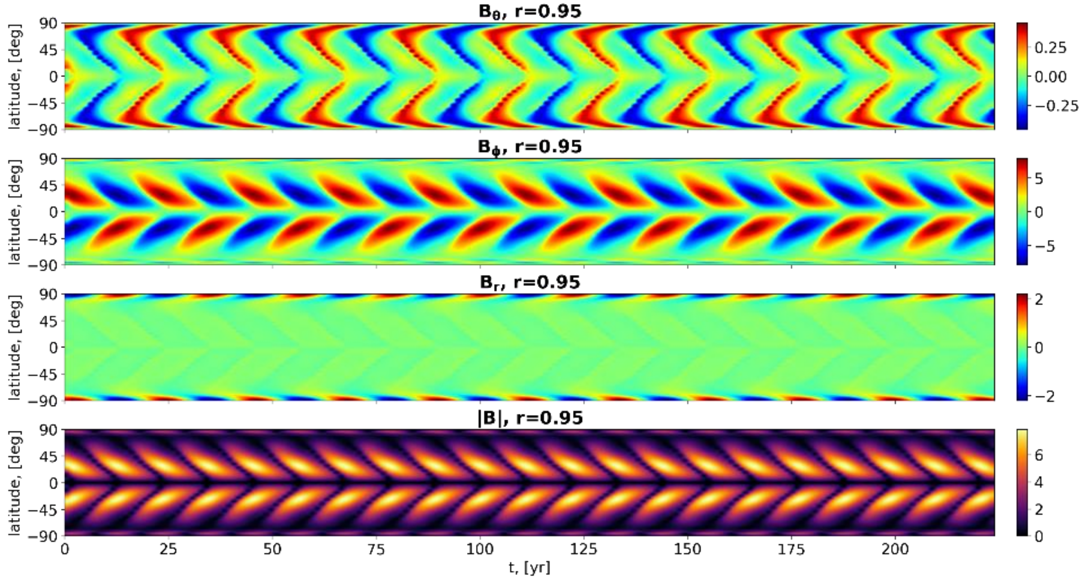
$$\psi(r,\Theta) = R_\mathrm{m} \left\{ -\frac{2}{\pi}\frac{(r - r_\mathrm{b})^2}{(1 - r_\mathrm{b})} \sin\left(\pi \frac{r - r_\mathrm{b}}{1 - r_\mathrm{b}}\right) \cos\Theta \sin\Theta \right\}$$

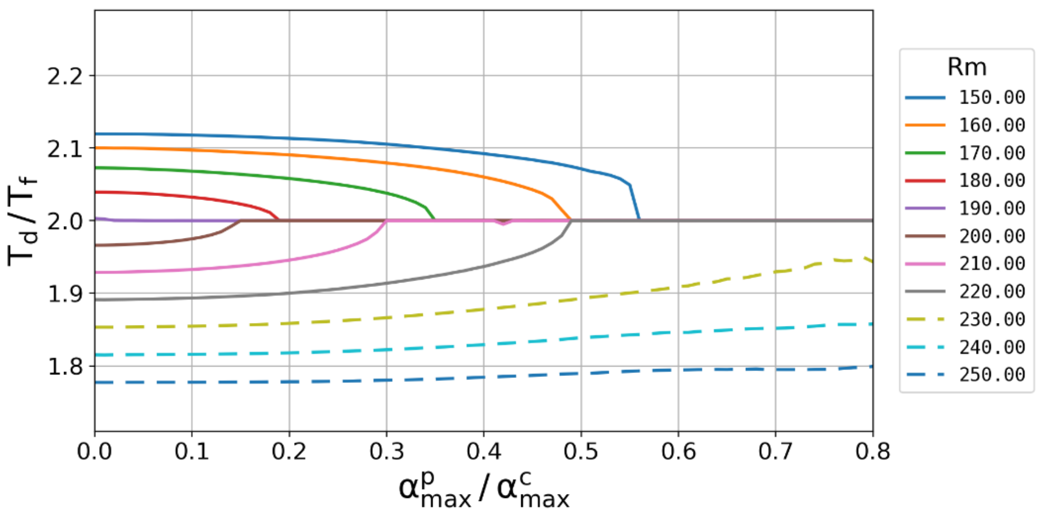
$$\alpha^\mathrm{p}(r,\Theta,t) = C_\alpha^\mathrm{p} \frac{1}{\sqrt{2}} \sin^2\Theta \cos\Theta \left[1 + \mathrm{erf}\left(\frac{r - r_\mathrm{c}}{d}\right)\right]\left[1 - \mathrm{erf}\left(\frac{r - r_\mathrm{d}}{d}\right)\right] \times \frac{2|\boldsymbol{B}(r,\Theta,t)|^2}{1 + |\boldsymbol{B}(r,\Theta,t)|^4} \sin(2\pi t / T_\mathrm{f}) \,,$$

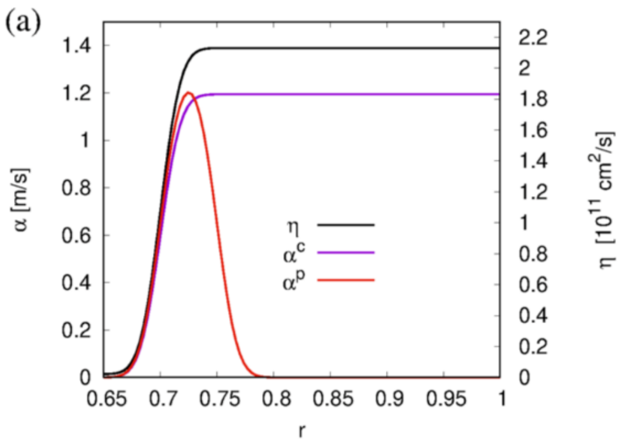
11.07 yr

M. Klevs, F. Stefani., L. Jouve, Solar Phys. 298, 90 (2023)

…shows again a nice parametric resonance







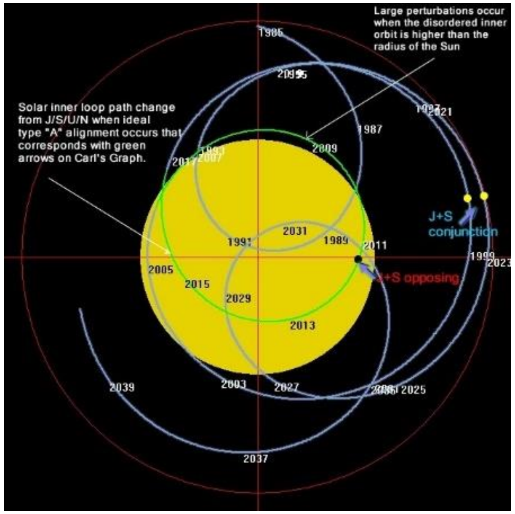
Much higher conductivity in the tachocline than in the convection zone

For a reasonable value α_0=1.3 m/s, we need just **~dm/s** for the synchronized α to entrain the entire dynamo

DRESDEN concept HZDR

Suess-de Vries (+Gleissberg)

How to explain Suess/de Vries (~200 yr) and Gleissberg (~90 yr)

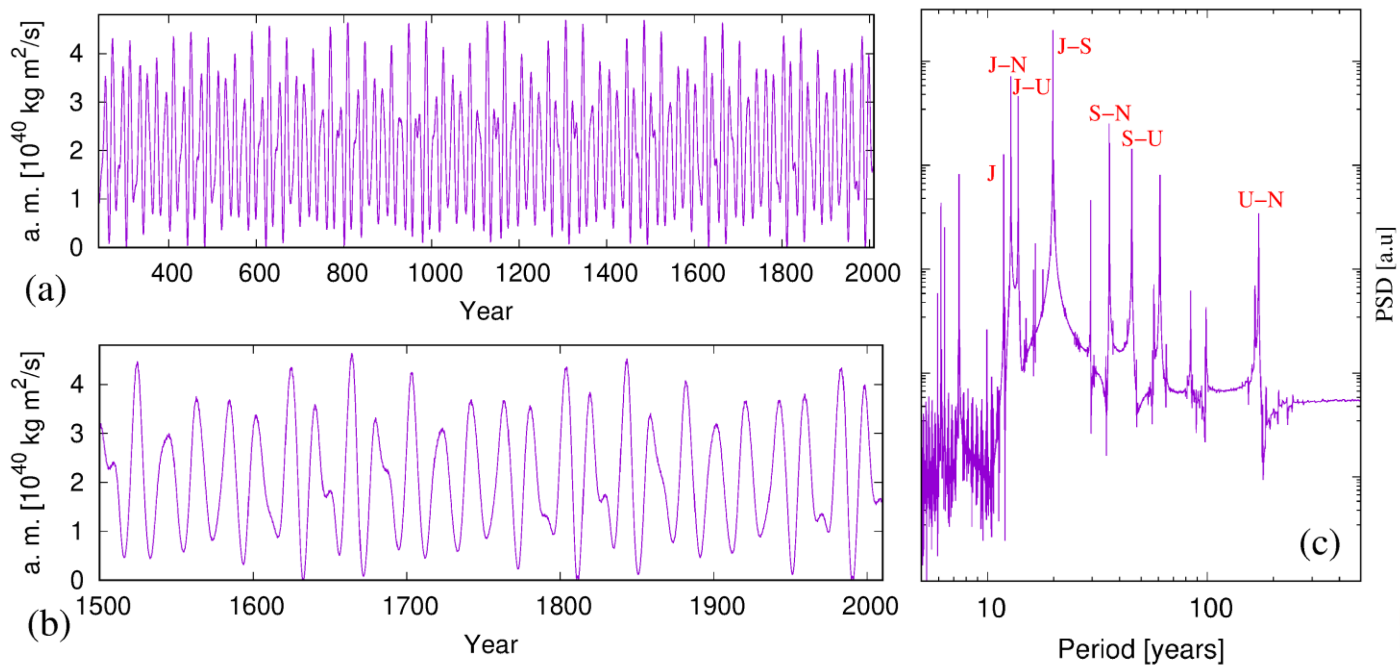


Sun around barycenter of the solar system…Spin-orbit coupling not perfectly understood yet! → 19.86 years

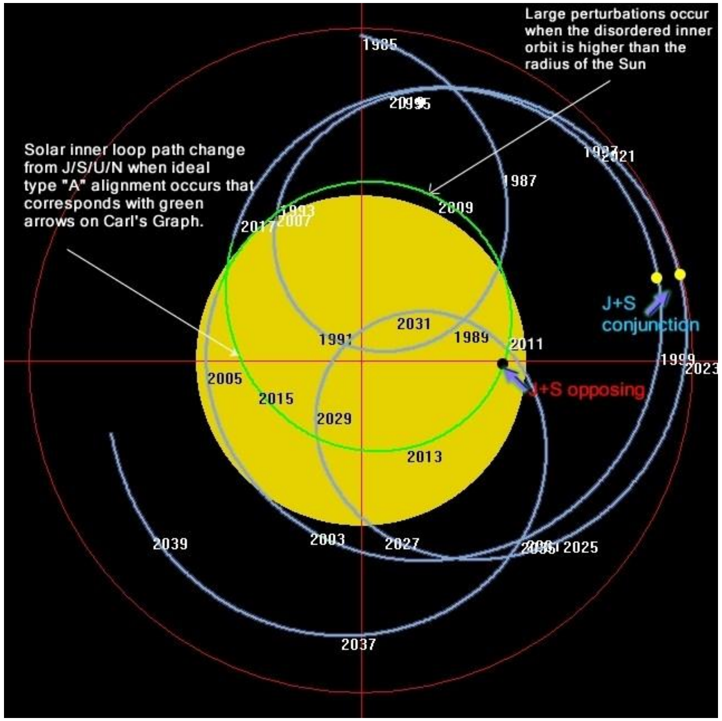
Wilson, Pattern Recogn. Phys. 1 (2013), 147; Solheim, Pattern. Recogn. Phys. 1 (2013), 159; Sharp, Int. J. Astron. Astrophys. 3 (2013), 260; **J. Shirley, arXiv:2309.13076**

F.S. et al., Solar Physics 296, 88 (2021)

Orbital angular momentum



Suess/de Vries cycle: A beat period between 22.14 and 19.86 yr ?



Tidal forcing → 22.14 years

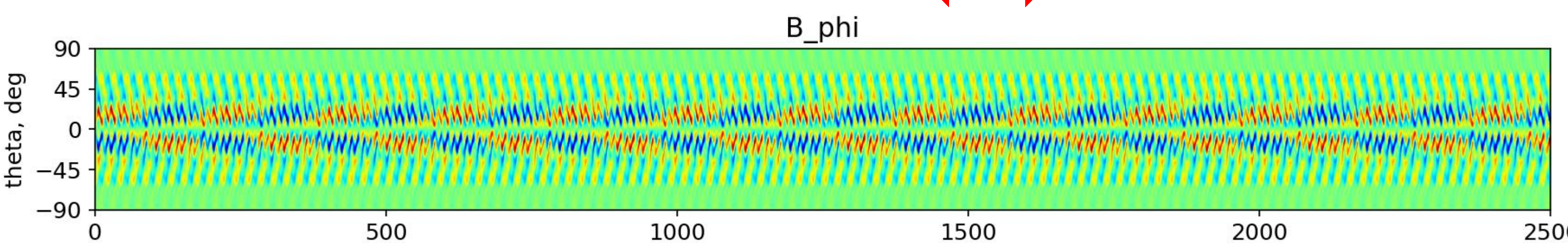
Sun around barycenter → 19.86 years

(with unclear spin-orbit Coupling)

Beat period: <u>193 years</u>

19.86 x 22.14/(22.14-19.86)

193 years: Suess-de Vries cycle



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HZDR

A little regression to an 1D α–Ω-model (with periodic α term):

$$\frac{\partial B(\theta,t)}{\partial t} = \omega(\theta,t)\frac{\partial A(\theta,t)}{\partial \theta} - \frac{\partial^2 B(\theta,t)}{\partial \theta^2} - \kappa B^3(\theta,t)$$

$$\frac{\partial A(\theta,t)}{\partial t} = \alpha(\theta,t)B(\theta,t) - \frac{\partial^2 A(\theta,t)}{\partial \theta^2},$$

Loss parameter with angular momentum periodicity ~19.86 yr

$$\omega(\theta,t) = \omega_0(1 - 0.939 - 0.136\cos^2(\theta) - 0.1457\cos^4(\theta))\sin(\theta)\,,$$

$$\alpha(\theta,t) = \alpha^p(\theta,t) + \alpha^c(\theta,t)$$

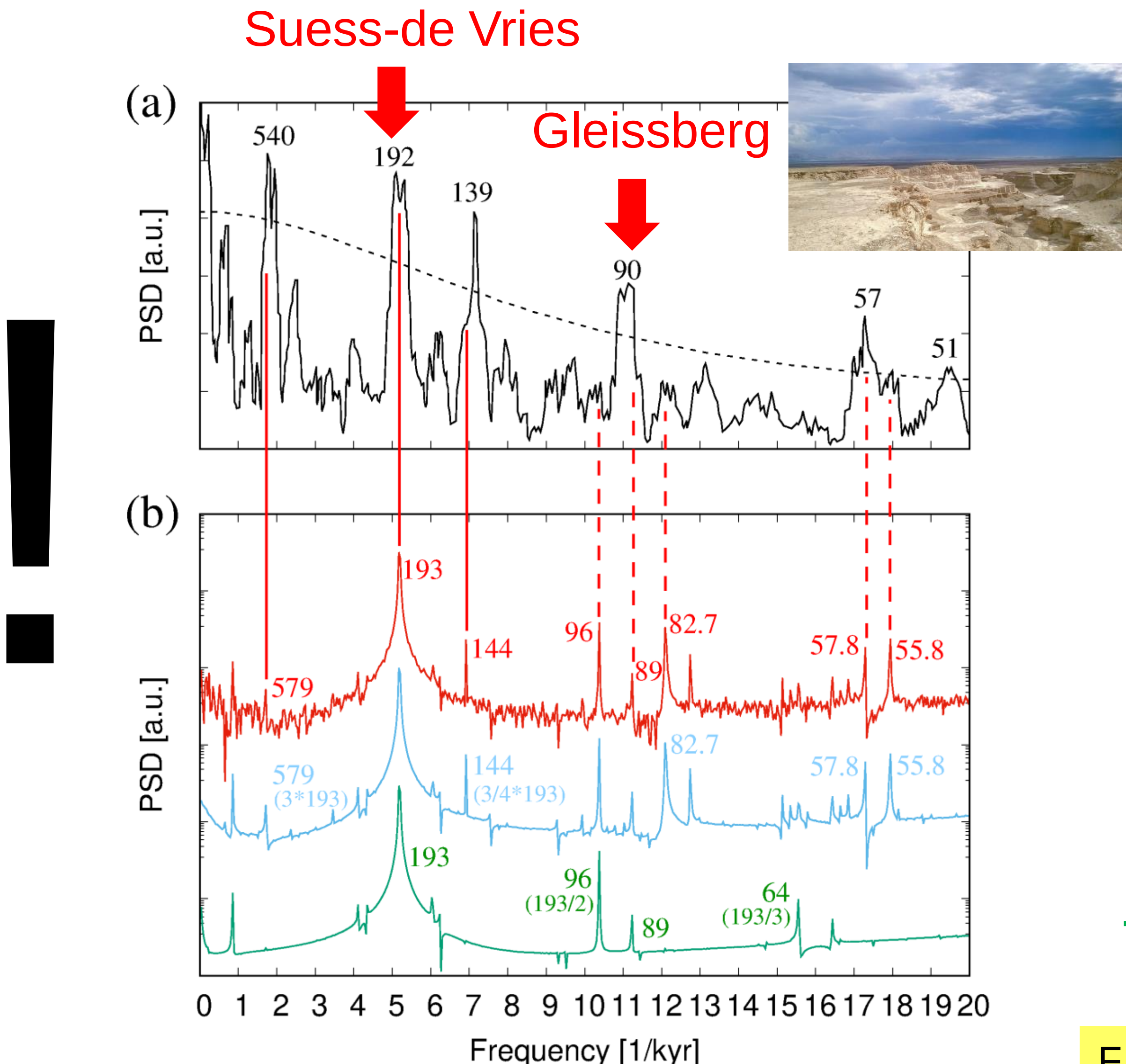
$$\alpha^p(\theta,t) = \alpha_0^p \sin(2\pi t/11.07)\mathrm{sgn}(90^\circ - \theta)\frac{B^2(\theta,t)}{(1 + q_\alpha^p B^4(\theta,t))} \text{ for } 55^\circ < \theta < 125^\circ$$

$$\alpha^c(\theta,t) = \alpha_0^c\big(1 + \xi(t)\big)\sin(2\theta)/\big(1 + q_\alpha^c B^2(\theta,t)\big)$$

Noise with strength D

F.S. et al., Solar Physics 294 (2019), 60,
Solar Physics 296, 88 (2021)

Comparison: numerical results - sediment data (Lake Lisan)



Yearly sediment thicknesses over 8500 years (climate archive)

S. Prasad et al., Geology 32, 581 (2004)

1D α–Ω-dynamo model

…with some noise

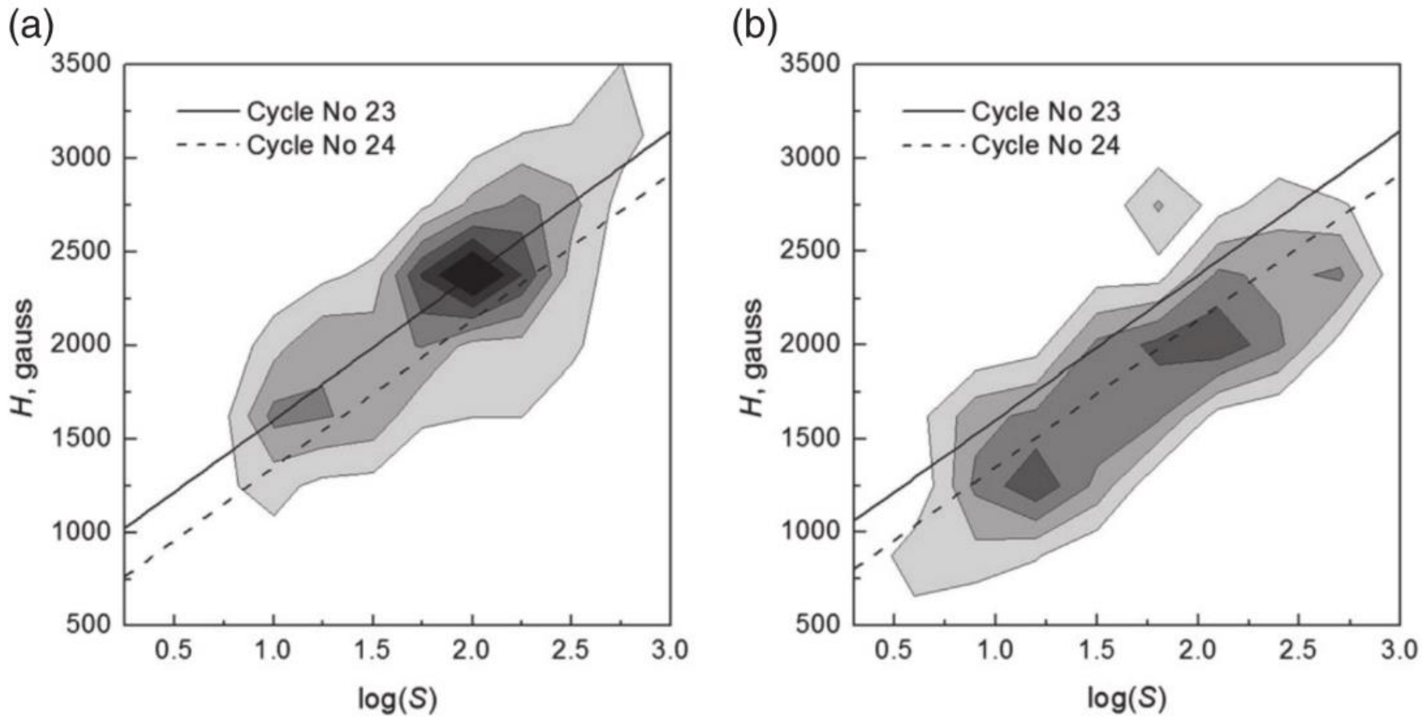
…all planets

…only Jupiter and Saturn

F.S. et al., Solar Physics 296, 88 (2021); 299 (2024), 55

Bimodal sunspot distribution

Bimodal sunspot distribution

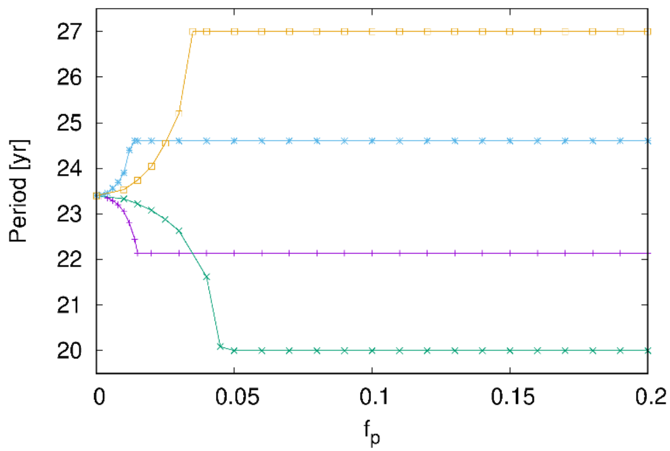


Y. A. Nagovitsyn, A. A. Pevtsov, A. A. Osipova, Astron. Nachr. 338, 26 (2017)

One possible explanation is related to the relative importance of diffusion and advection in the upper and bottom parts of the solar convection zone.

K Georgieva, ISRN Astronomy and Astrophysics 2011, A437838 (2011)

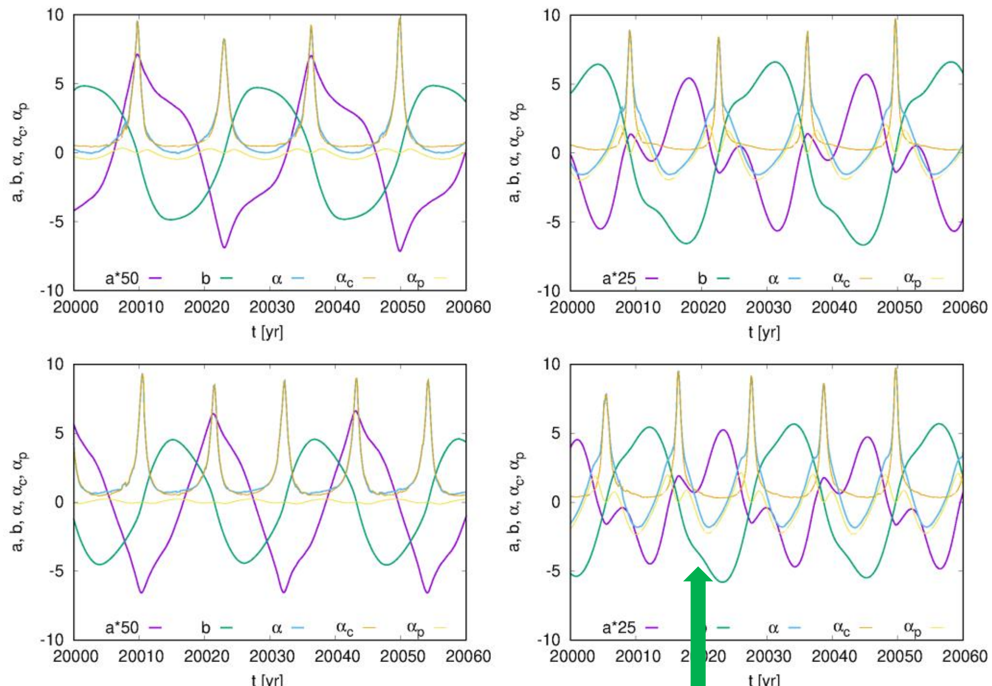
Bimodal sunspot distribution: natural feature of synchronization



Parametric resonance for various (real and hypothetical) forcing frequencies

At synchronization

At f_p=0.17



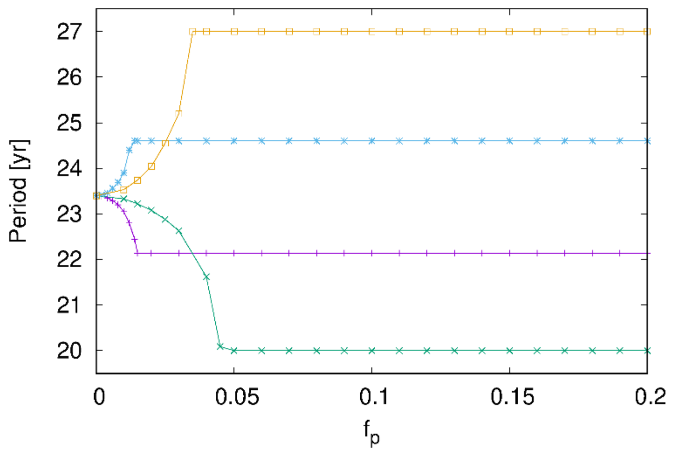
Only very weak α_p needed for synchronization

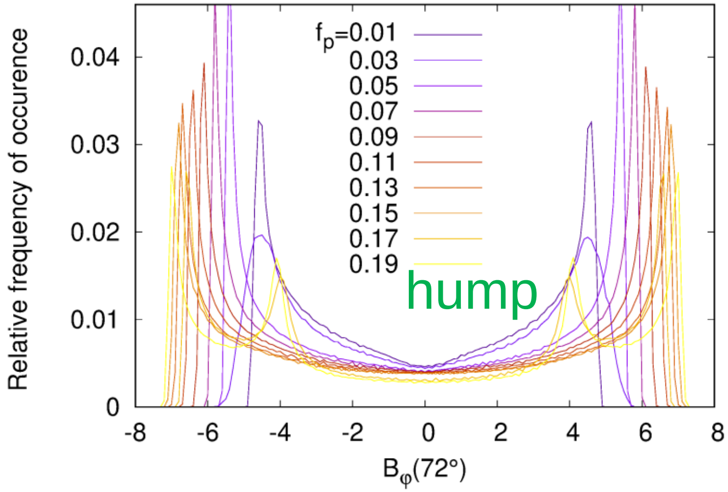
A hump emerges for higher α_p

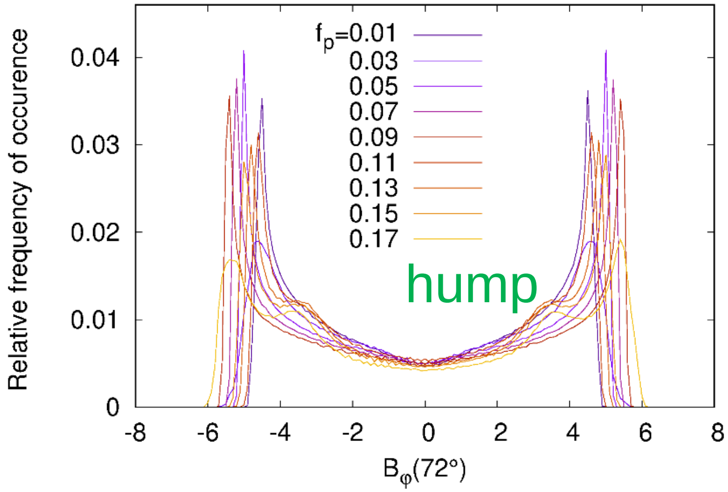
DRESDEN concept

HZDR

Bimodal sunspot distribution: natural feature of synchronization

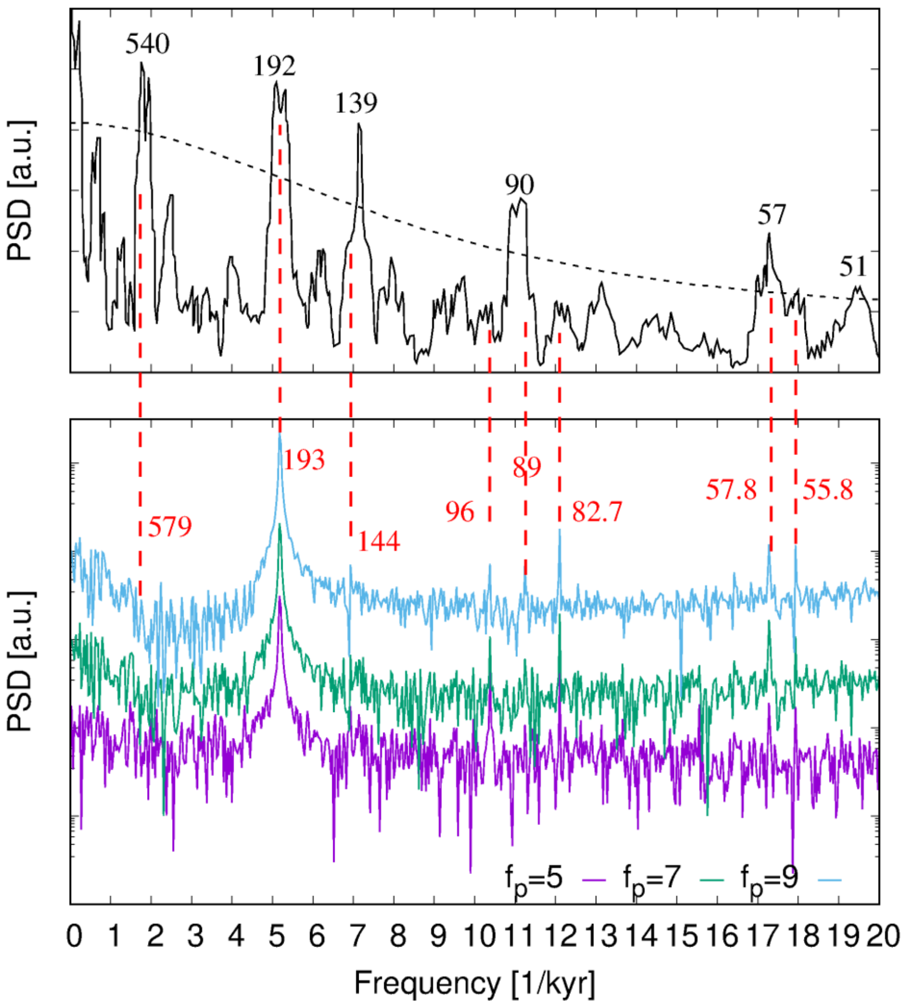




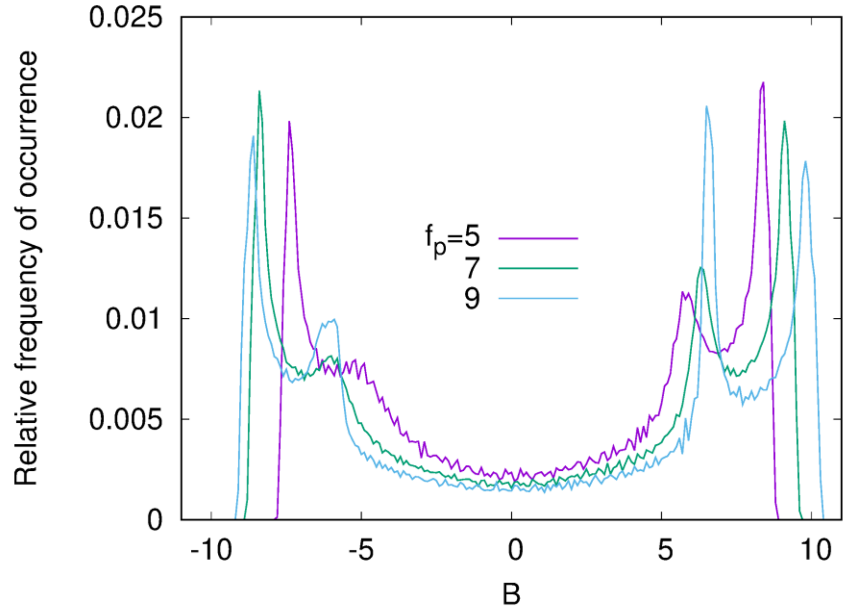


Parametric resonance for various (real and hypothetical) forcing frequencies

Bimodal sunspot distribution: natural feature of synchronization

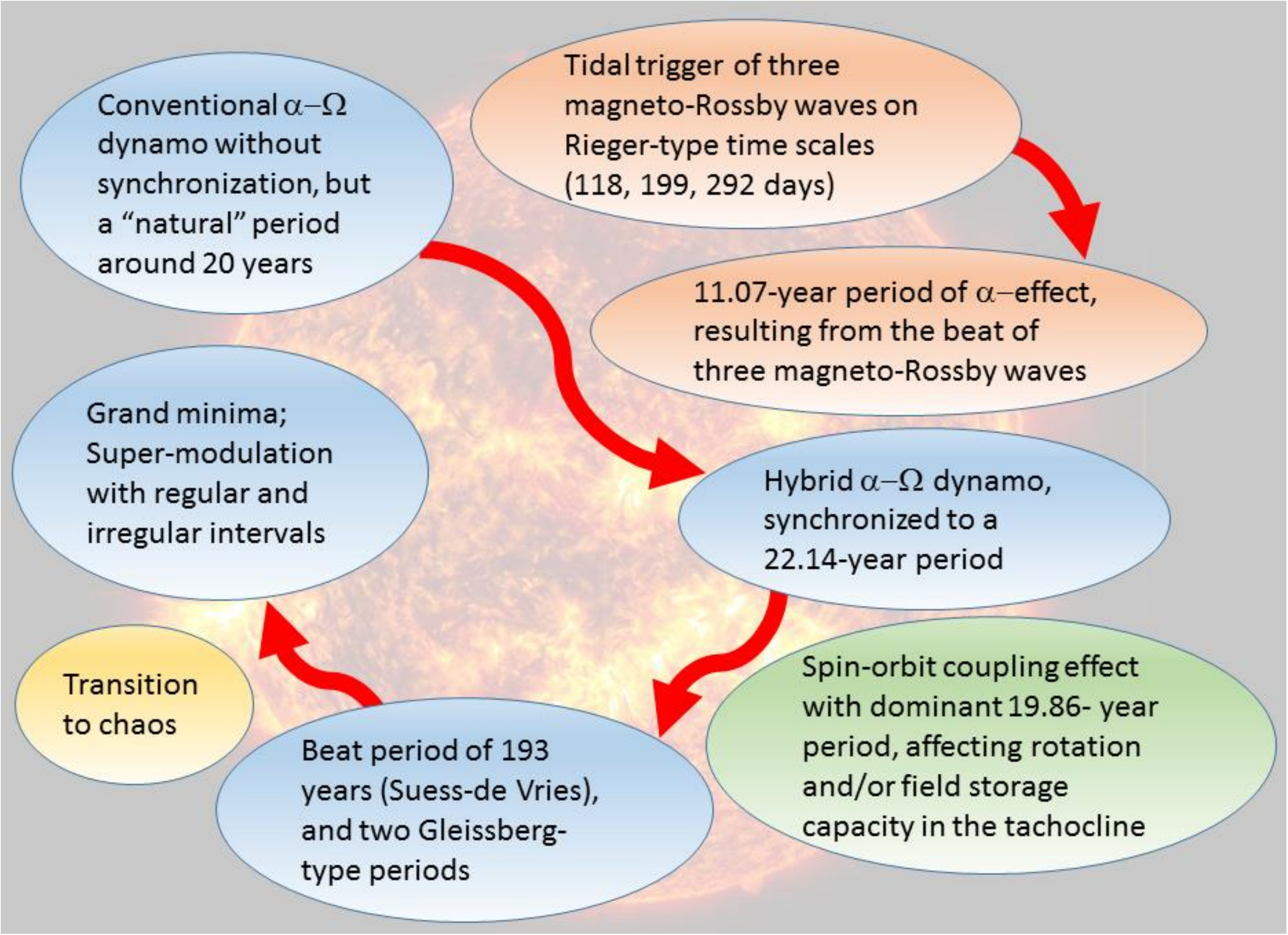


Other parameters (more consistent with previous results): The hump remains a very stable feature



Wrap-up

Summary



Conventional α–Ω dynamo without synchronization, but a "natural" period around 20 years
Tidal trigger of three magneto-Rossby waves on Rieger-type time scales (118, 199, 292 days)
11.07-year period of α–effect, resulting from the beat of three magneto-Rossby waves
Grand minima; Super-modulation with regular and irregular intervals
Hybrid α–Ω dynamo, synchronized to a 22.14-year period
Transition to chaos
Spin-orbit coupling effect with dominant 19.86- year period, affecting rotation and/or field storage capacity in the tachocline
Beat period of 193 years (Suess-de Vries), and two Gleissberg-type periods

Summary

- General principle: Energy is „harvested“ on the shortest possible time-scales

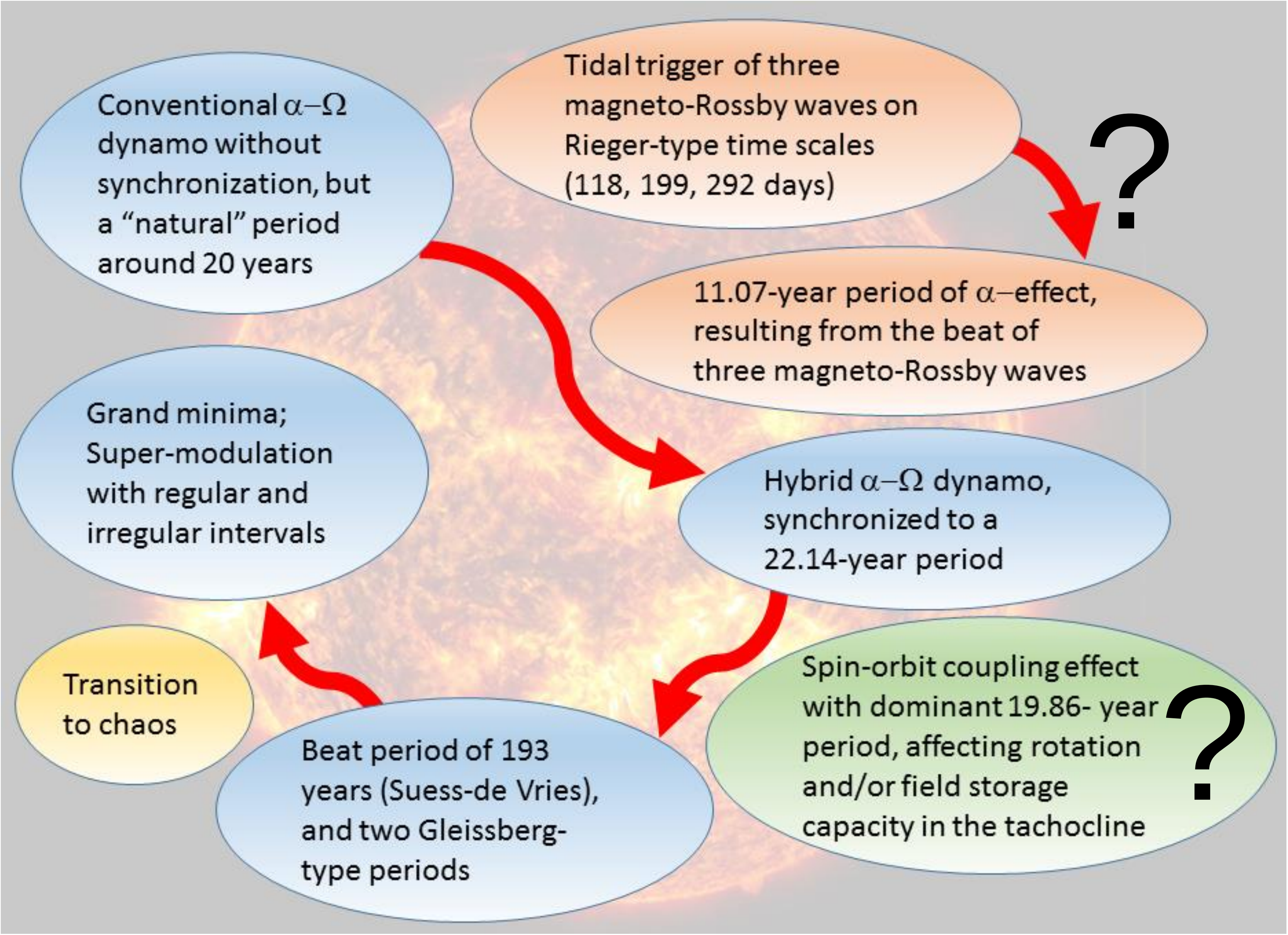
- Various dynamo periods emerge as beat periods
- Three tidally triggered magneto-Rossby waves on Rieger-type time-scale → Schwabe/Hale
- Hale+Barycentric motion → Suess-de Vries (+Gleissberg)

- **Self-consistency**: The sharp Suess-de Vries peak at 193 years could hardly be explained without phase-stability of the primary Hale cycle at 22.14 years

- Bimodal sunspot distribution ← natural feature of synchronization

DRESDEN concept HZDR

Summary and open problems



Open questions and next steps

- Are the observed magneto-Rossby waves indeed tidally triggered: m=2 ?, periods?
- Better estimation of the damping parameter λ
- Detailed computation of the nonlinear terms (e.g., for helicity and α, or nonlinear tachocline oscillations)

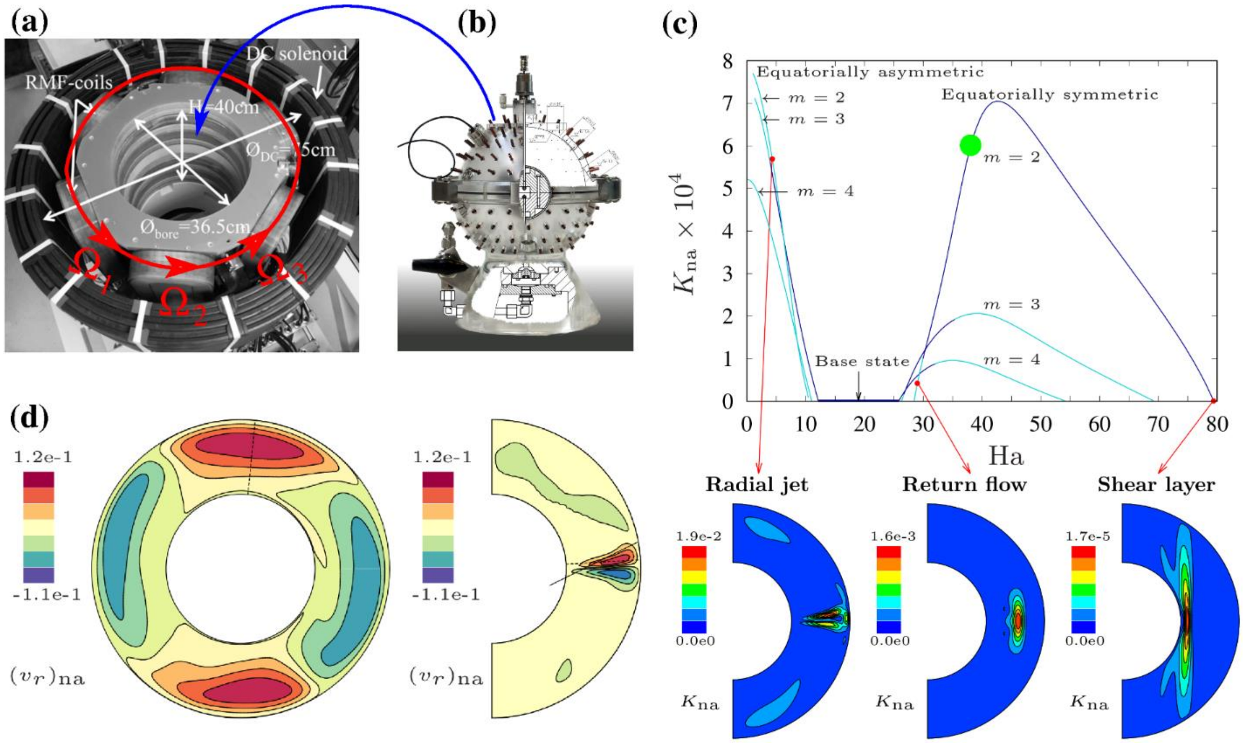
R. Avalos-Zuniga, K.-H. Rädler, GAFD 103, 375 (2009)

- Understand the spin-orbit coupling from barycentric motion, and its influence on the solar dynamo

J. Shirley, arXiv:2309.13076

- Perhaps stochastic resonance for 2318-yr?

Our plan for an experiment with tidal excitation of three waves



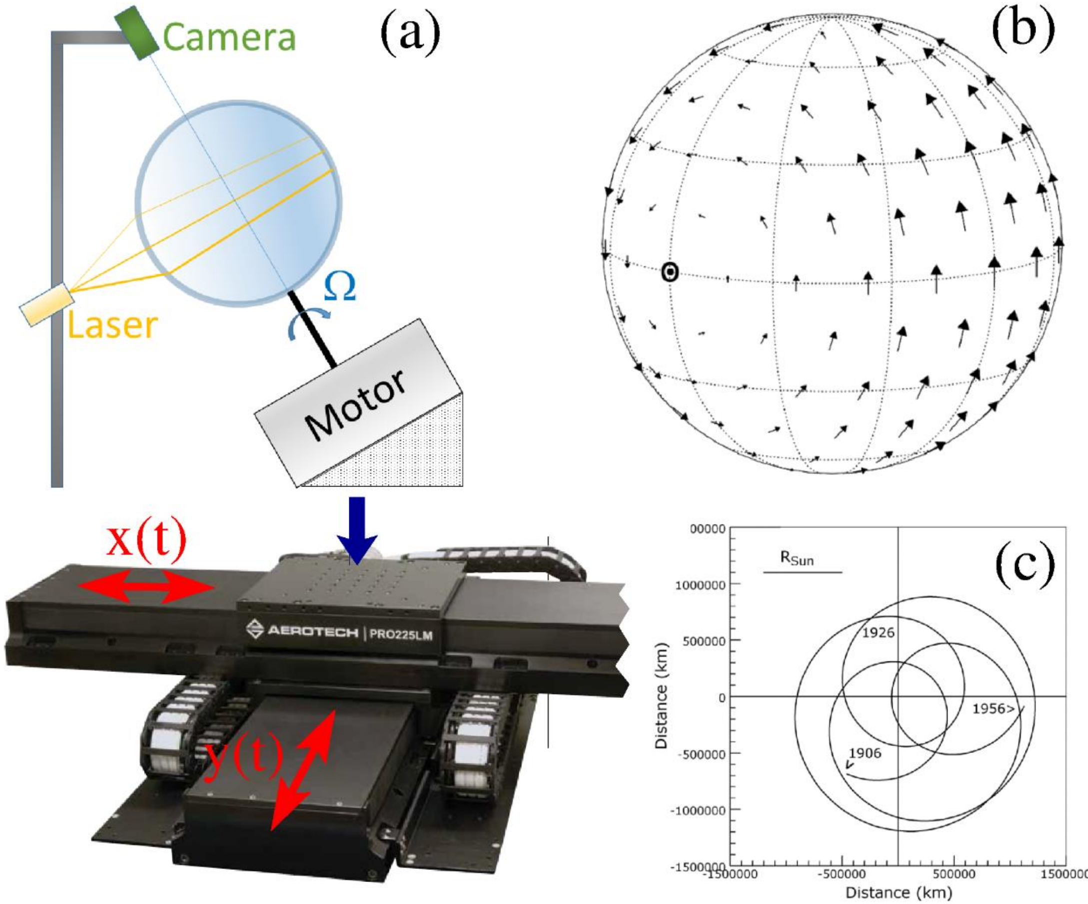
Jüstel et al., Phys. Fluids 34, 104115 (2022)

Ogbonna et al., Phys. Fluids 32, 124119 (2020)

Excitation of three waves with azimuthal wave number m=2 (c,d) in a magnetized spherical Couette flow HEDGEHOG (b) by tide-like forces generated in the MultiMag facility (a)

Study of beat period in the emerging zonal flow (and the α-Effect)

Our plan for an experiment on spin-orbit coupling



Rosette-shaped barycentric motion (c) and inclined rotation axis lead to spin-orbit coupling

Emerging torque has typical m=1 structure (b) well known from precession

J. Shirley, Planet. Space Sci. 141, 1 (2017), 1339

Theory is yet underexplored, parameters still to be constrained by observation
→ Improved theory + experiment (a)

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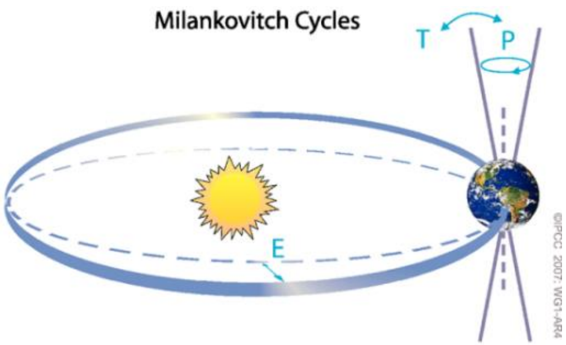
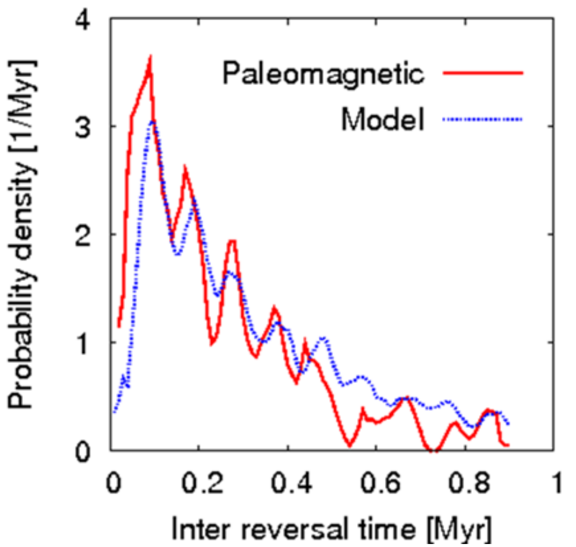
Milankovic cycles

Role of mechanical forcings for the geodynamo (Milankovic cycles)

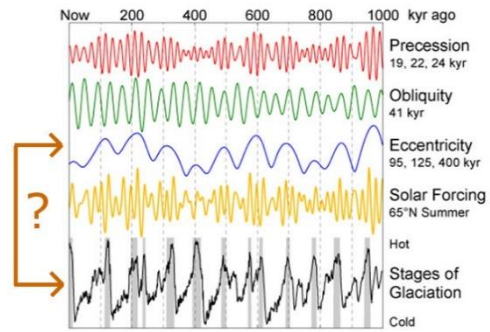
Strong indication for influence of variations of Earth´s orbit parameters (precession, obliquity, excentricity) on the statistics of the geodynamo





Probability density of inter-reversal times shows maxima at multiples of the Milankovic cycle of Earth‘s orbit eccentricity (95 ka)

Connection with climate??



Consolini, De Michelis, Phys. Rev. Lett. 90 (2003), 058503

Stochastic resonance

Changing moment of inertia when a 120 m water column is concentrated in ice sheets

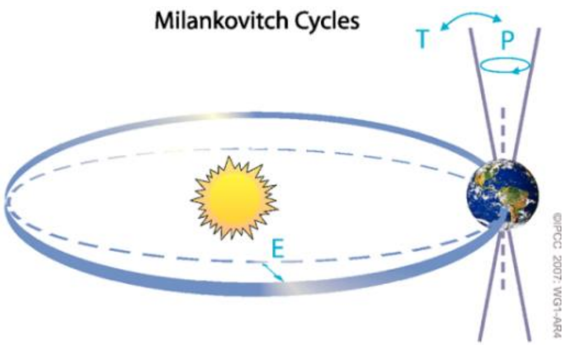
→ Change of Earth´s rotation period

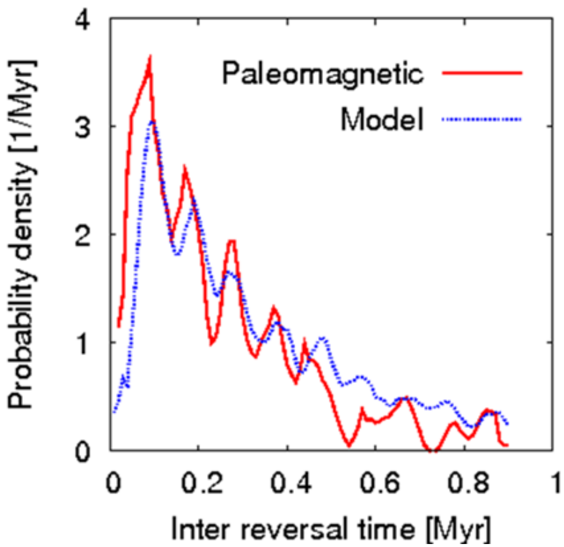
→ Influence on geodynamo

C.S.M. Doake: A possible effect of ice ages on the Earth’s magnetic field, Nature 267 (1977), 415

Role of mechanical forcings for the geodynamo (Milankovic cycles)

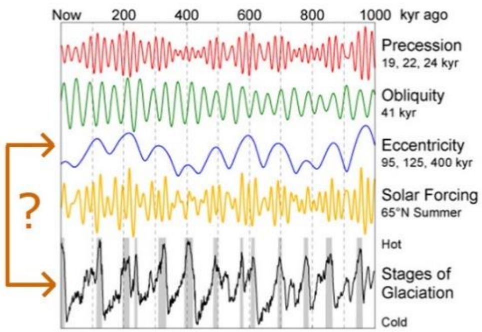
Strong indication for influence of variations of Earth´s orbit parameters (precession, obliquity, excentricity) on the statistics of the geodynamo





Probability density of inter-reversal times shows maxima at multiples of the Milankovic cycle of Earth's orbit eccentricity (95 ka)

Connection with climate??



Consolini, De Michelis, Phys. Rev. Lett. 90 (2003), 058503

Stochastic resonance

Alternative: Effect of eccentric Kepler orbits

→ **Fluid instabilities in ellipsoids**

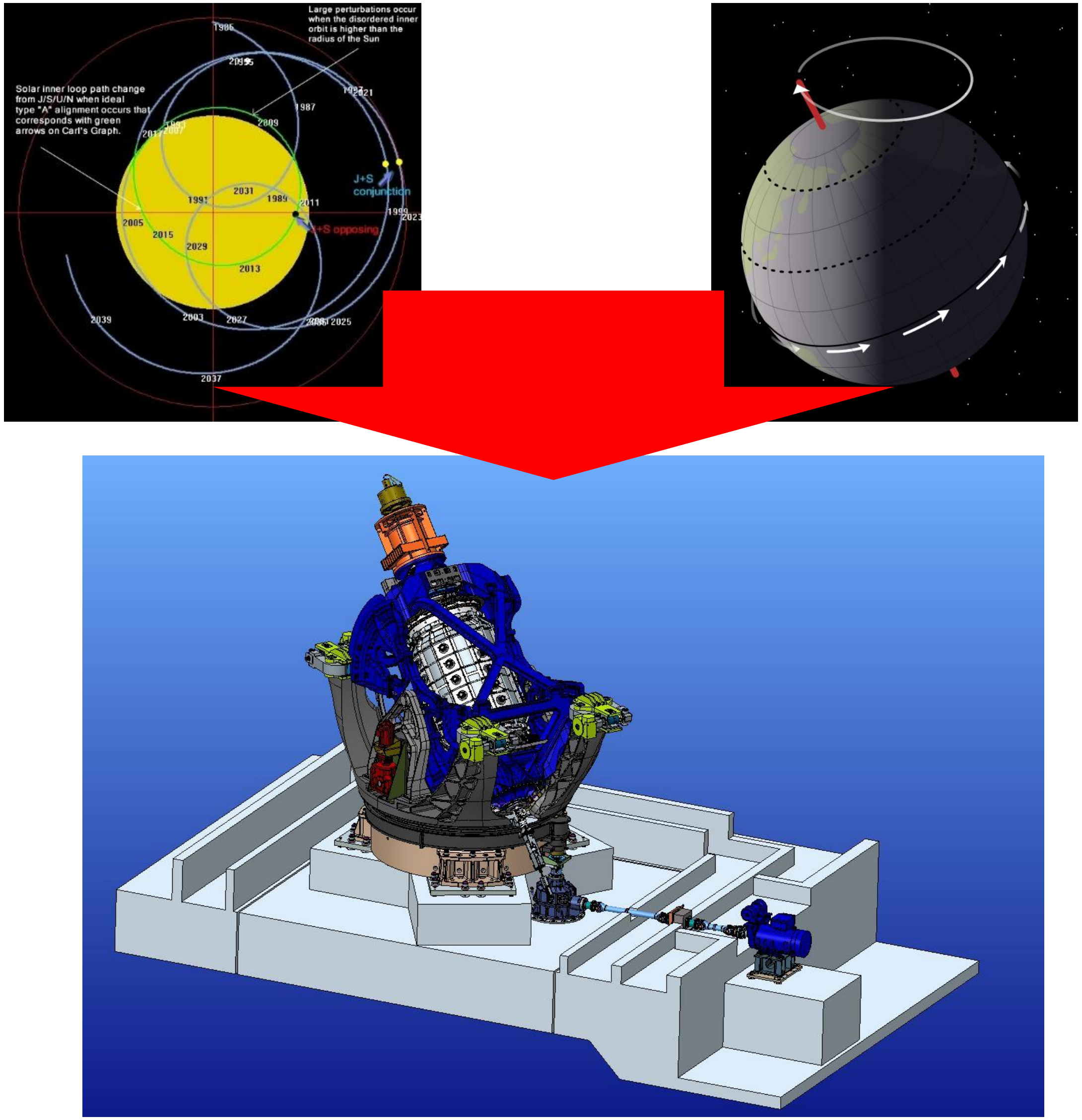
→ **Orbit-spin coupling for the case of tilted rotation axis**

Vidal and Cebron, JFM 833 (2017), 469;

Shirley and Mischna, Planet. Space Science 139 (2017), 3; Shirley, arXiv:2309.13076

The DRESDYN Precession experiment

Precession driven DRESDYN dynamo: Two motivations

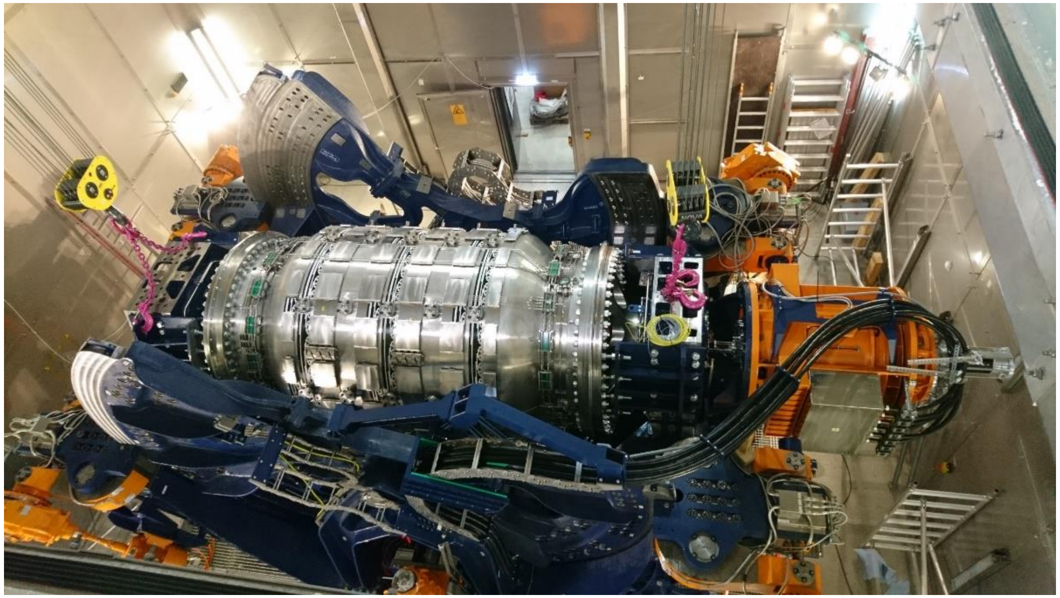


DRESDEN concept

HZDR

DREsden sodium facility for DYNamo and thermohydraulic studies

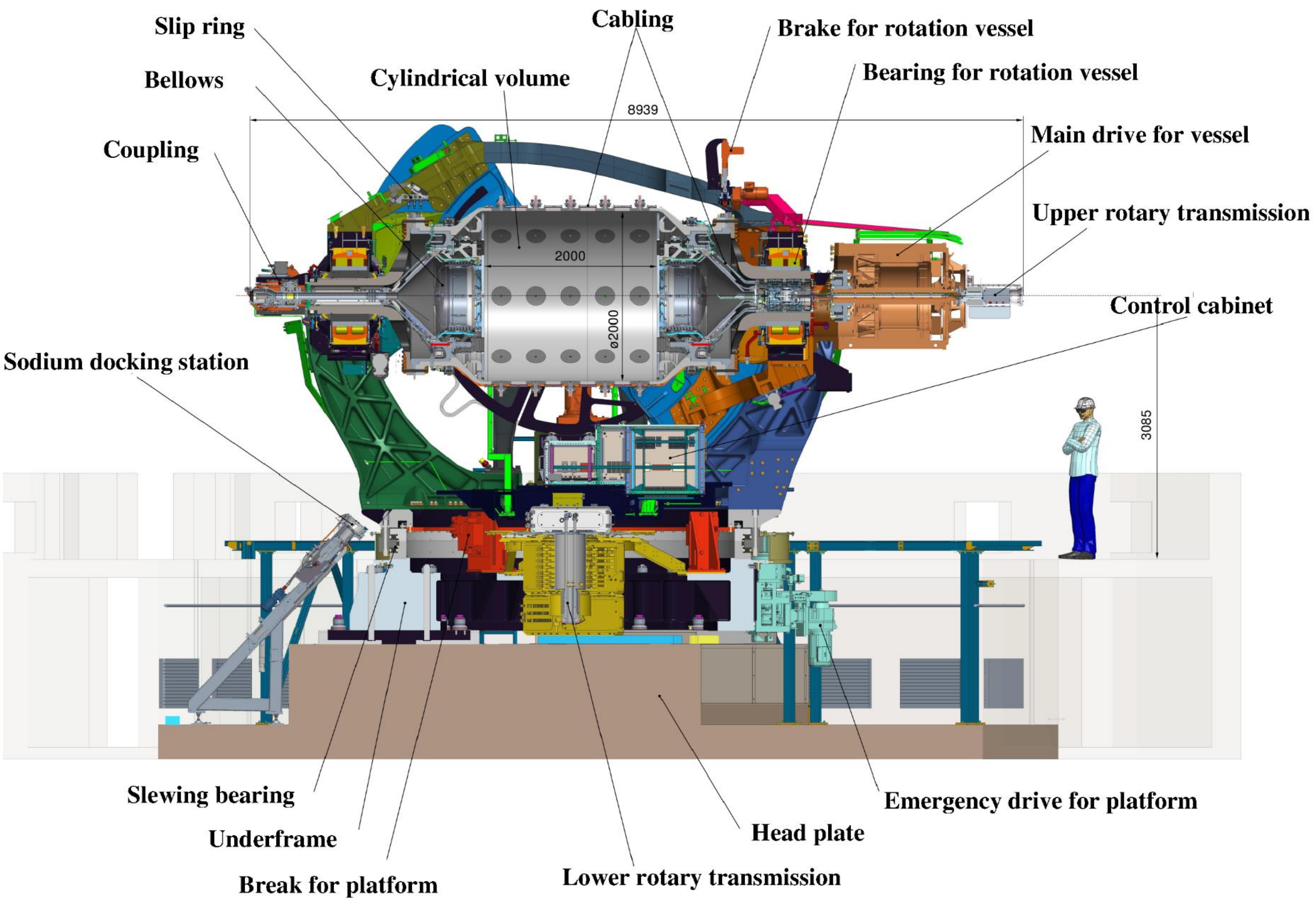
- DRESDYN building ~500 m^2
- Total sodium inventory: 12 tons
- Precession driven dynamo experiment with separate strong basement and containment for Argon flooding
- Large experimental hall for MRI/TI experiment, sodium loop, liquid metal batteries, Rayleigh-Bénard experiment



F.S. et al.: Magnetohydrodynamics 48 (2012), 103; 51 (2015), 275; GAFD (2018); C.R. Phys. (2024)

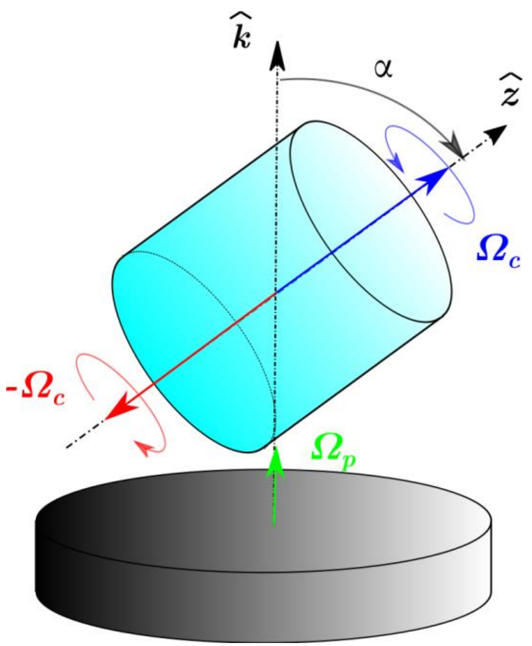
DRESDEN concept HZDR

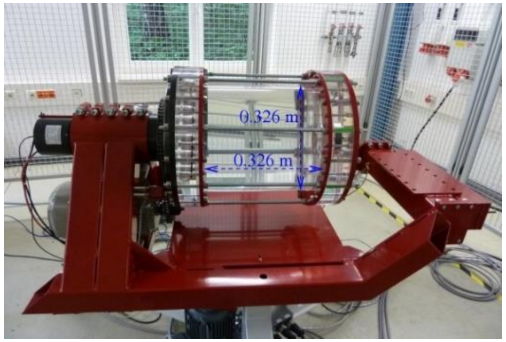
Precession driven dynamo within the DRESDYN project

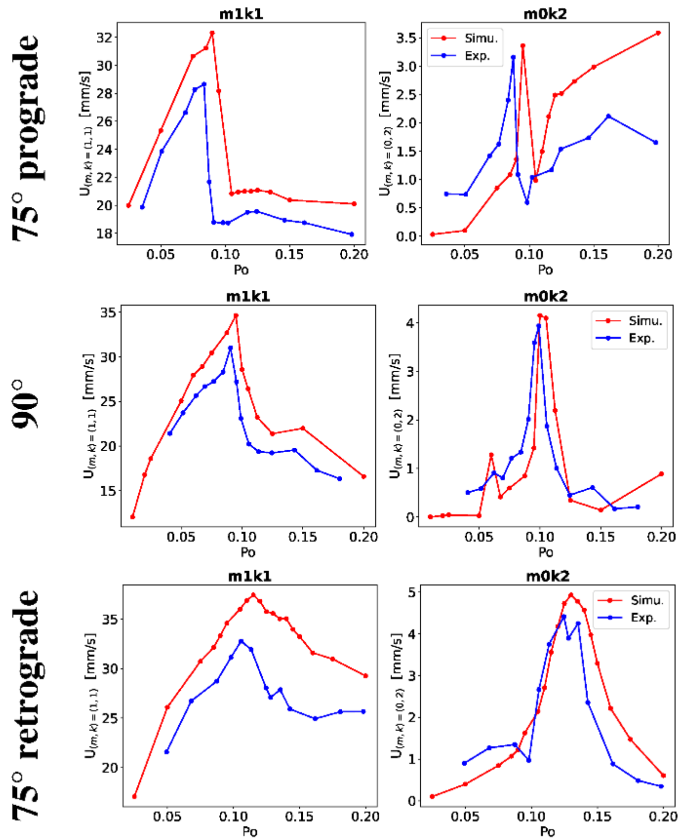


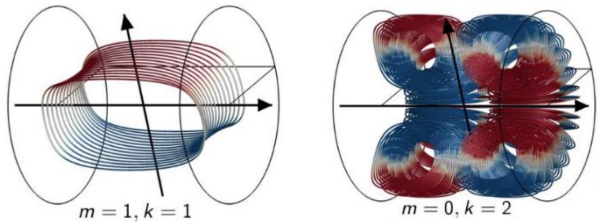
Precession driven dynamo: Prospects for self-excitation

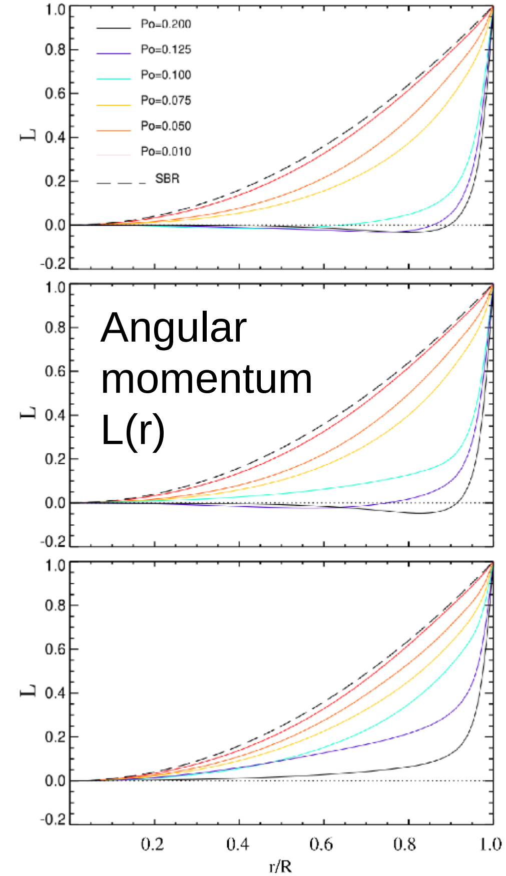
Good agreement of measured and simulated dynamo-relevant flow modes







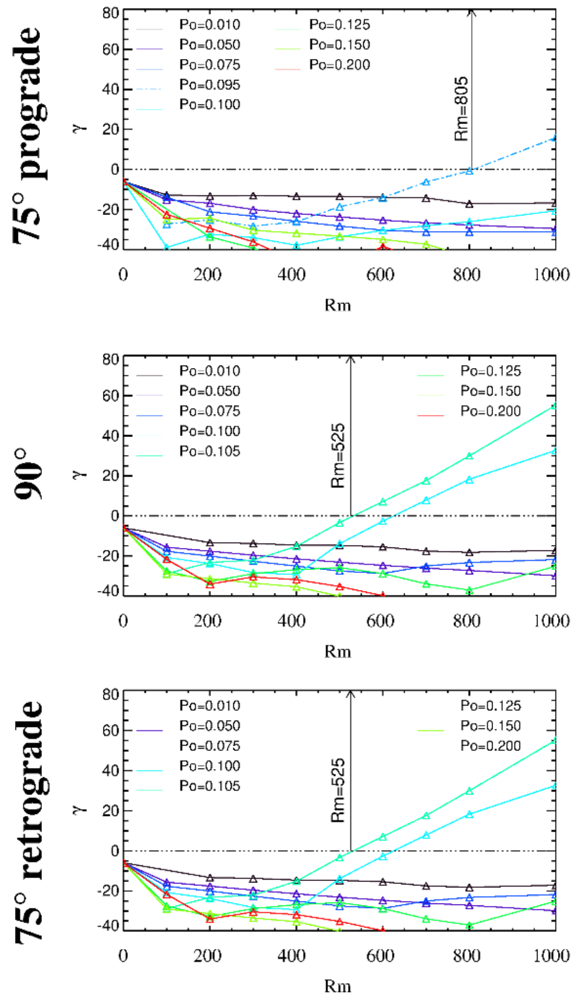


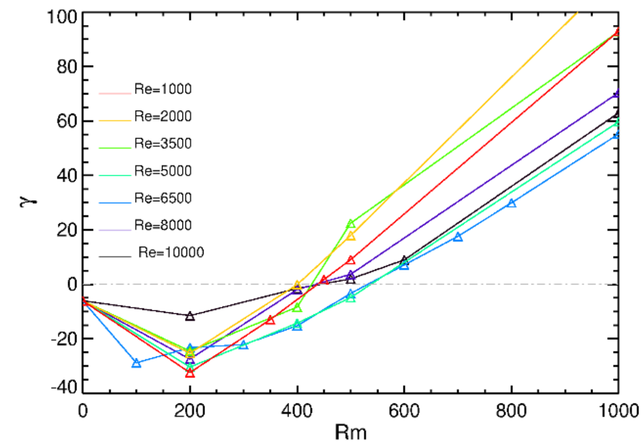


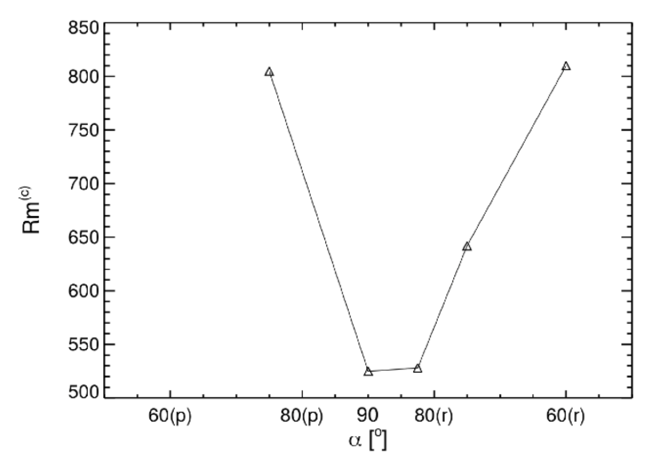
V. Kumar et al., Phys. Fluids 35 (2023), 014114; A. Giesecke et al. JFM 998, A30 (2024)

Precession driven dynamo: Prospects for self-excitation

In a narrow range of the precession ratio, **dynamo action is predicted for Rm~430** (Rm=700 is technically feasible)







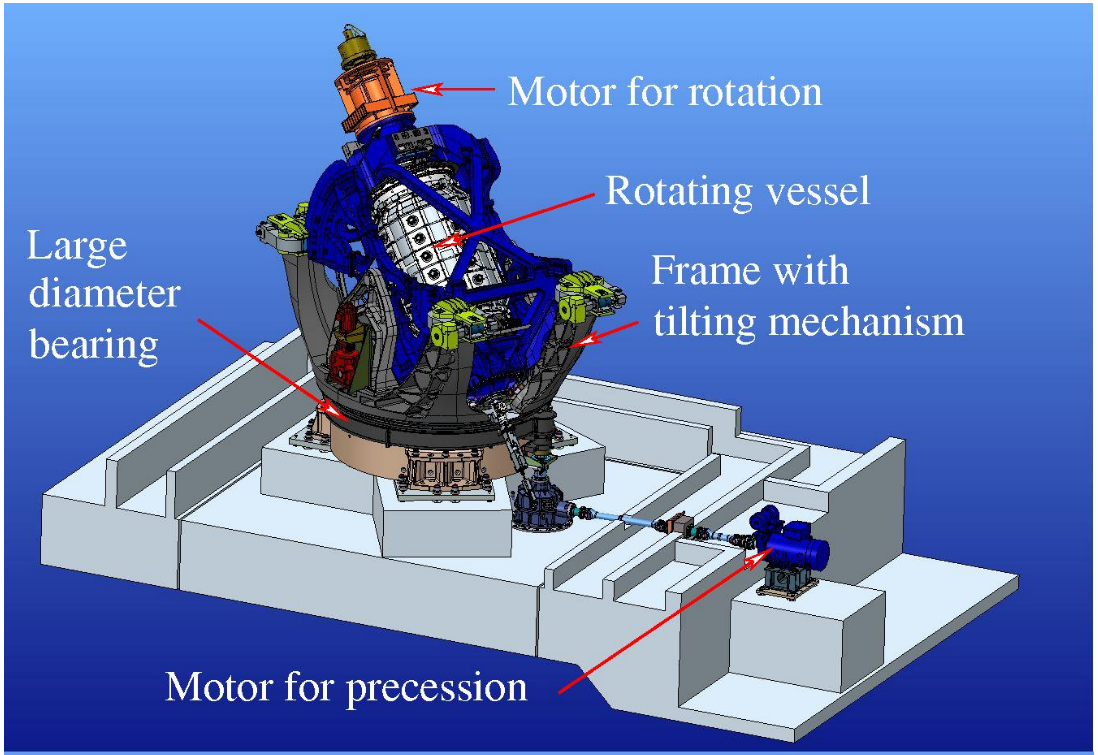
Giesecke et al., Phys. Rev. Lett. 120 (2018), 024502; Kumar et al., Phys. Fluids 35 (2023), 014114; Phys. Rev. E 109 (2024), 065101

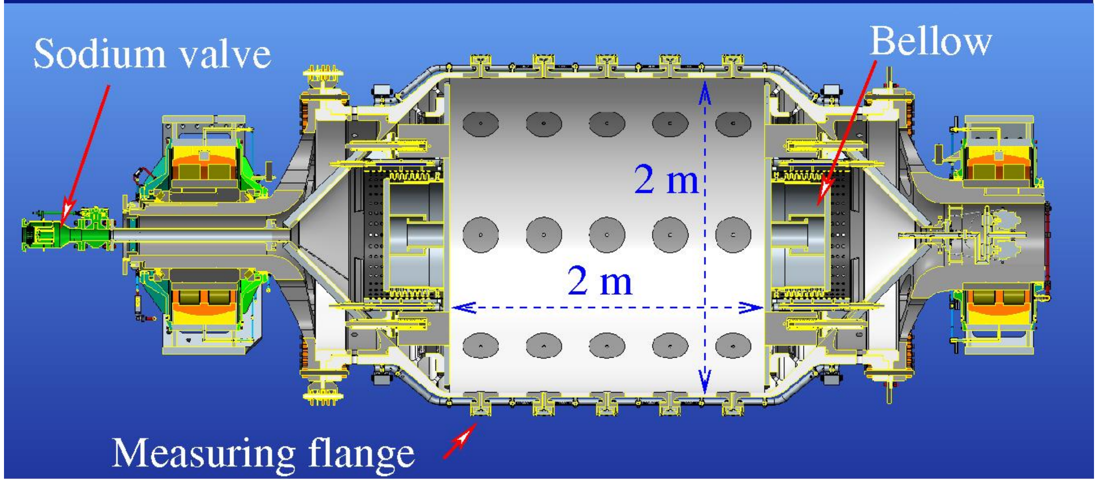
DRESDEN concept HZDR

Precession driven dynamo within the DRESDYN project

Key parameters:

- Cylinder with 2 m diameter and 2 m height, 8 tons of liquid sodium
- Cylinder rotation: 10 Hz (Ek~10^{-8}) will need ~ 1 MW motor power
- Turntable rotation: 1 Hz
- Magnetic Reynolds number ~ 700
- Gyroscopic torque onto the basement: 8 MNm !





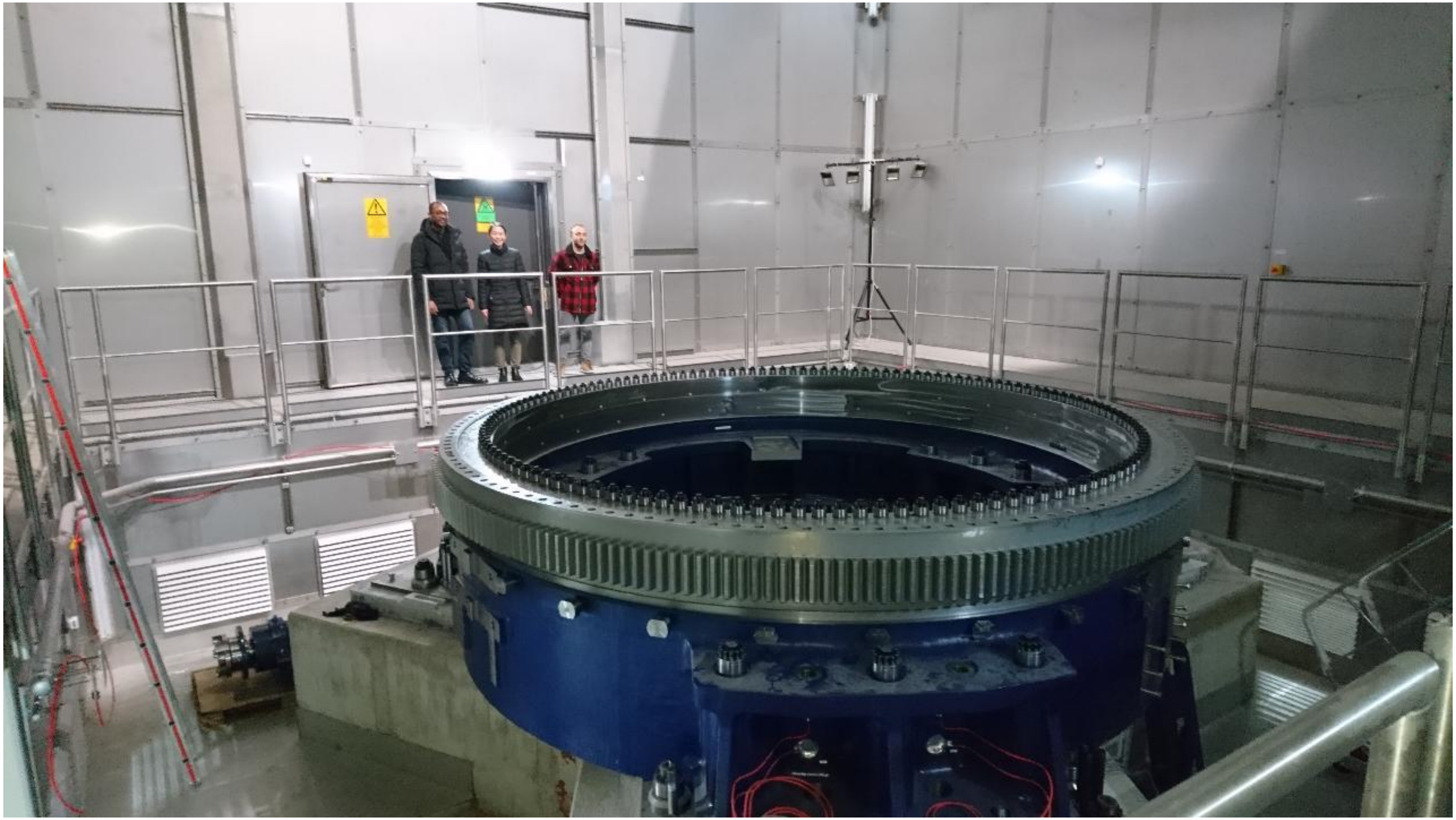
“Fundamental” problems due to huge gyroscopic torque

April 2013: drilling 7 holes (22 m deep)

July 2013: Constructing the ferroconcrete basement

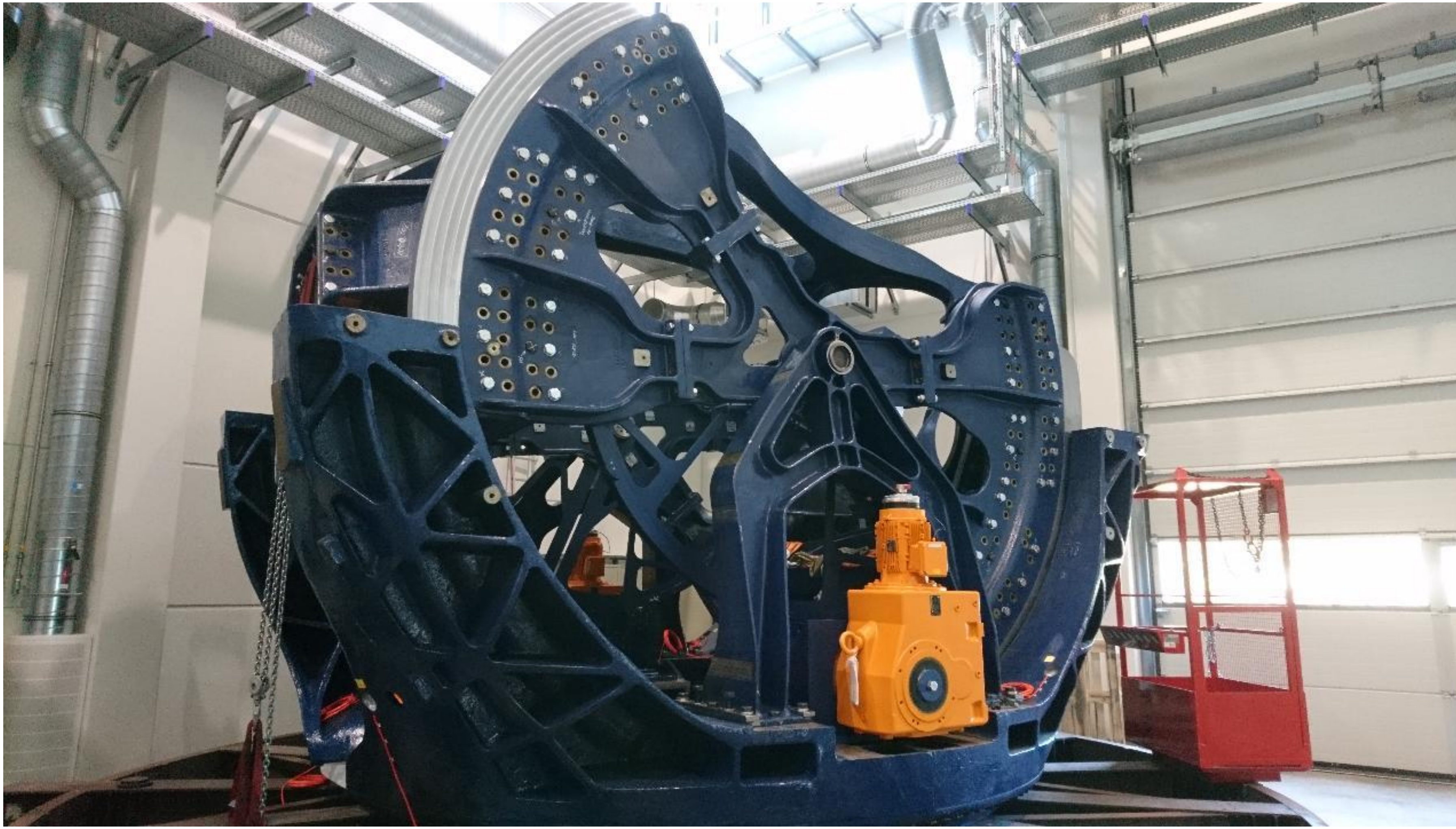
May 2015: The tripod for the dynamo within the containment (with stainless steel “wallpaper”)

Large ball bearing installed (12/2018)



Traverse and pylons (01/2019)

Test assembly of the tilting frame (07/2019)



DRESDEN concept

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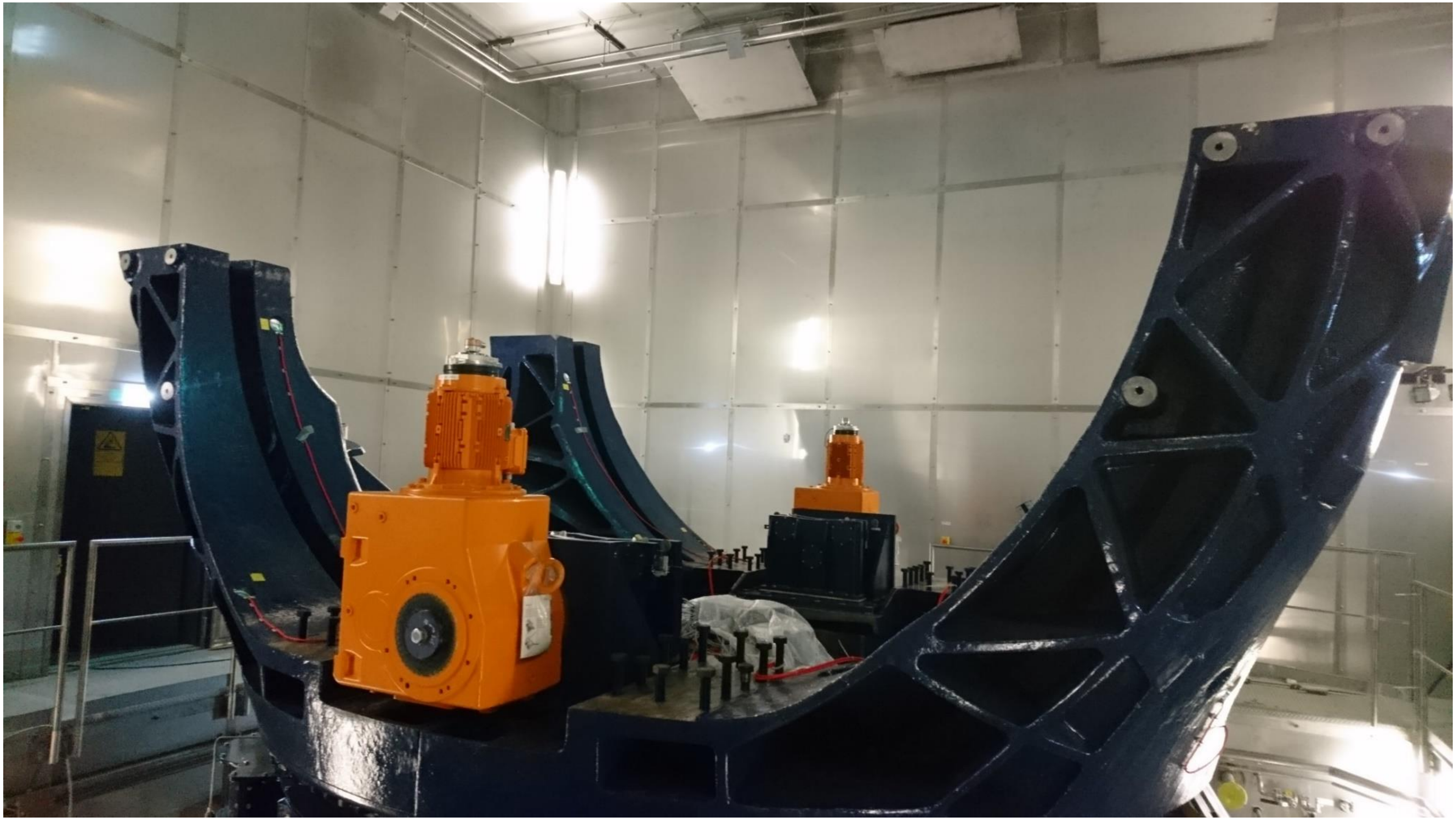
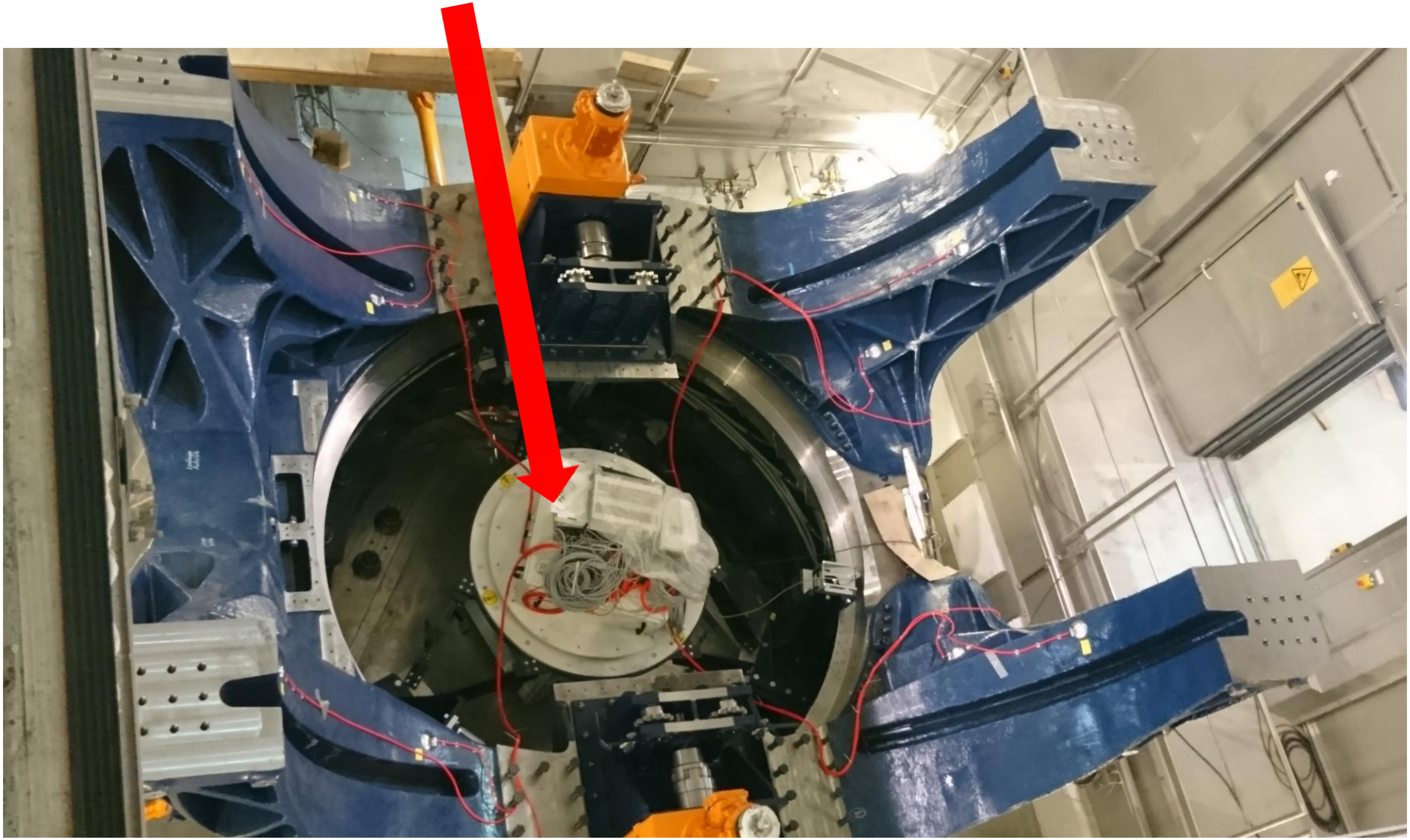
Pylons transferred to the containment (11/2019)



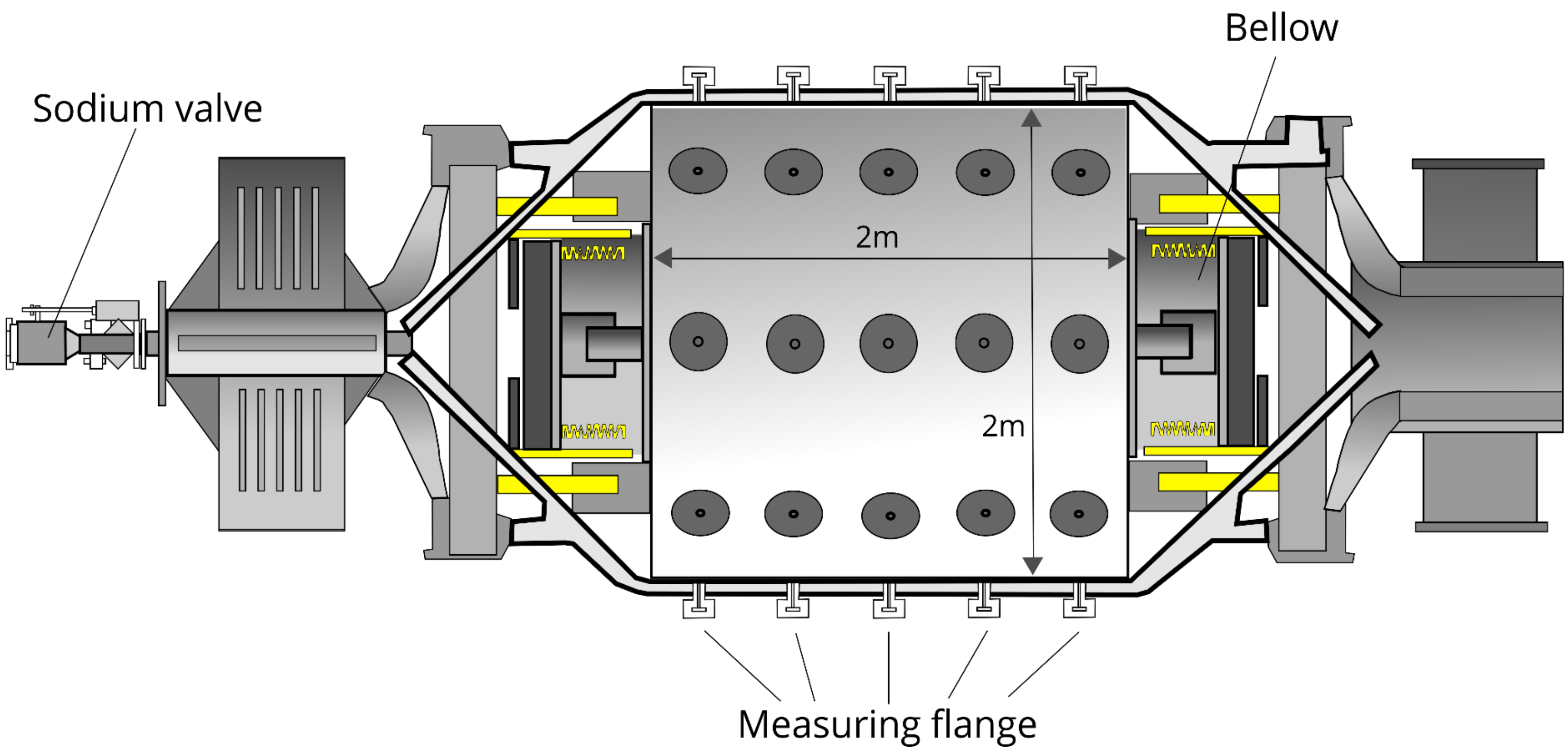
Pylons with central rotary connection (for 1 MW power and oil)



DRESDEN concept

HZDR

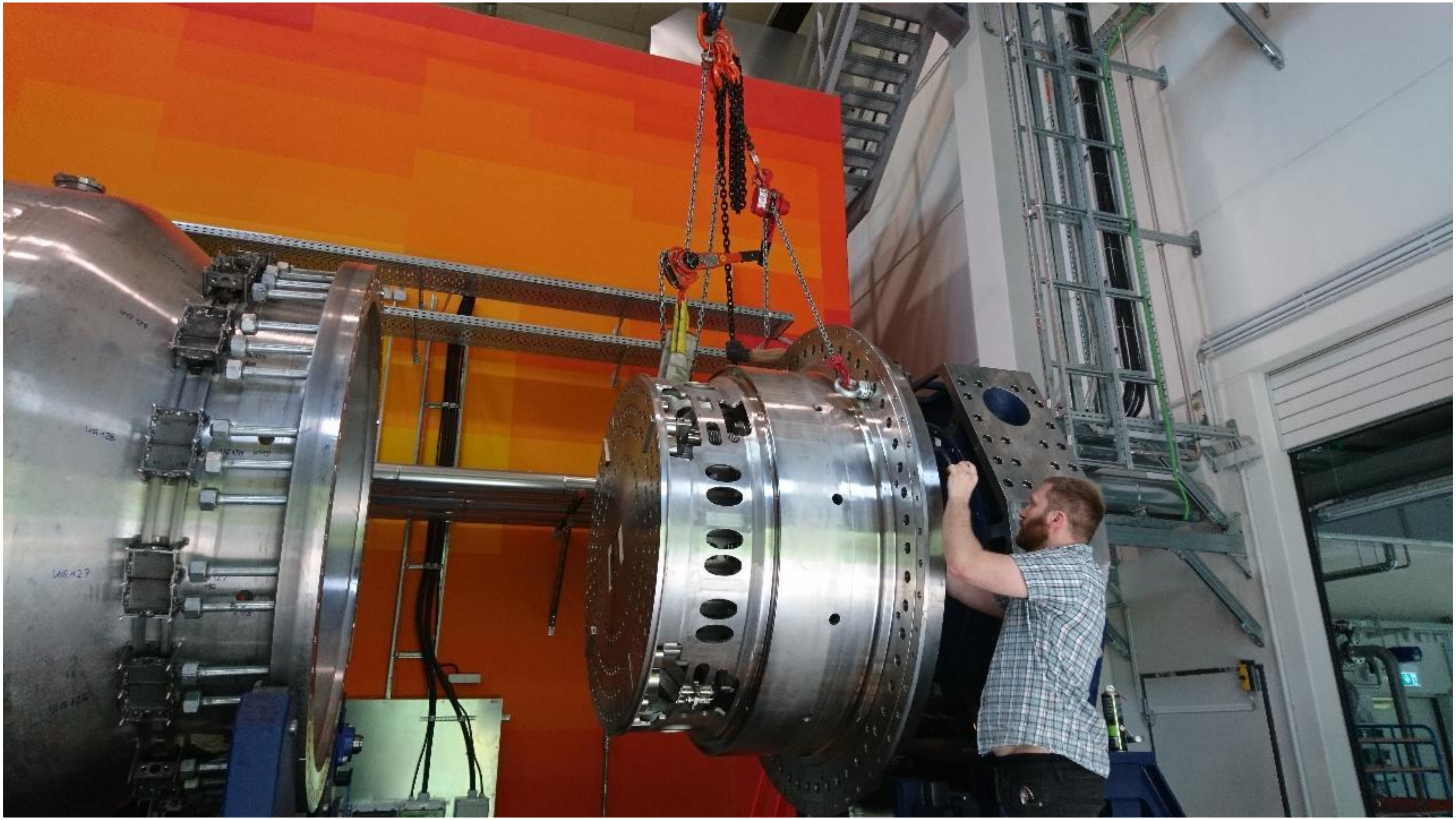
Rotation vessel with bearings



Pressure test (with 35 bar) of the rotation vessel (3/2019)

The vessel arrives at HZDR (July 3, 2020)

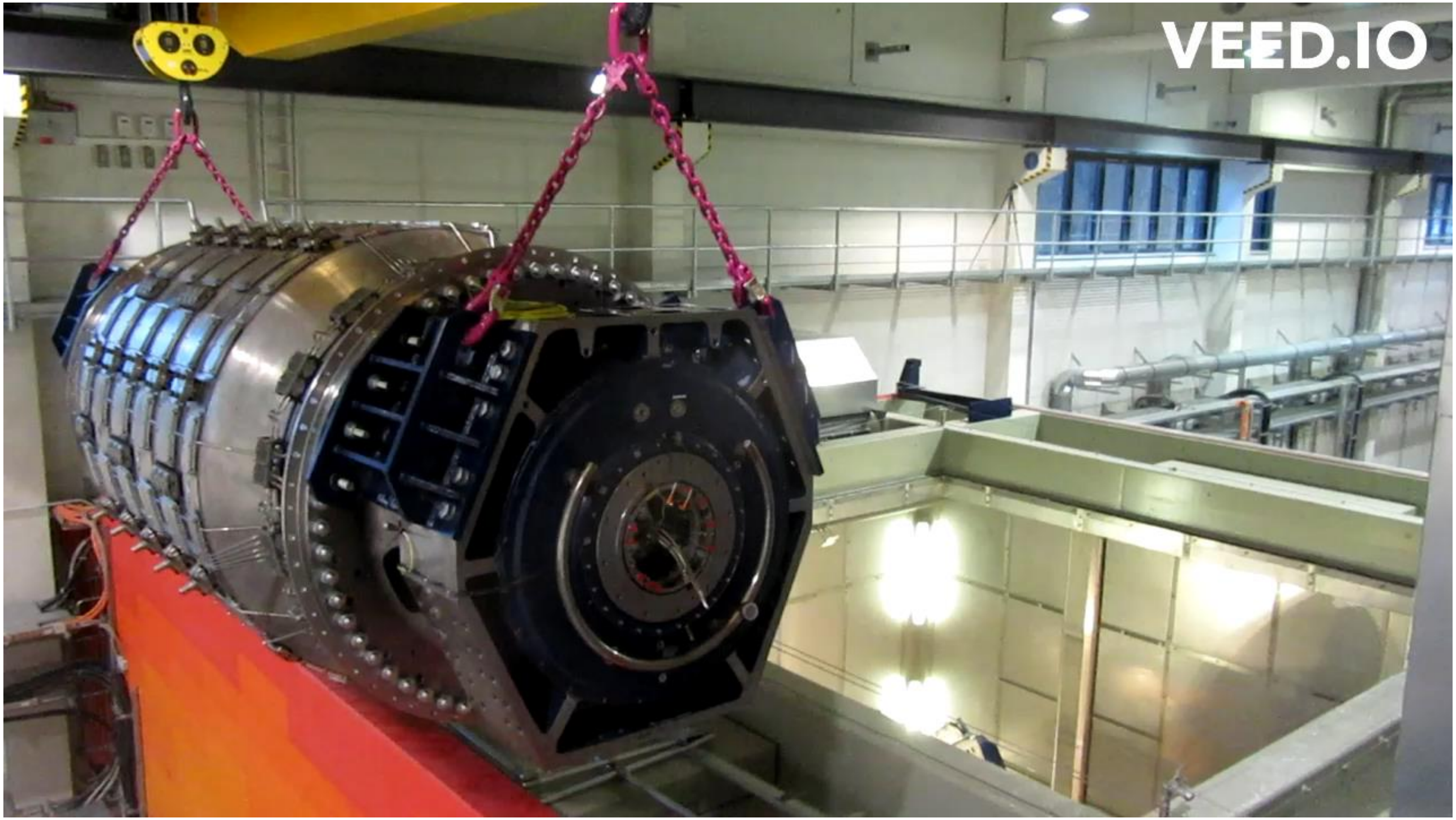
Assembly of the first conical end and the bearing (May 2022)



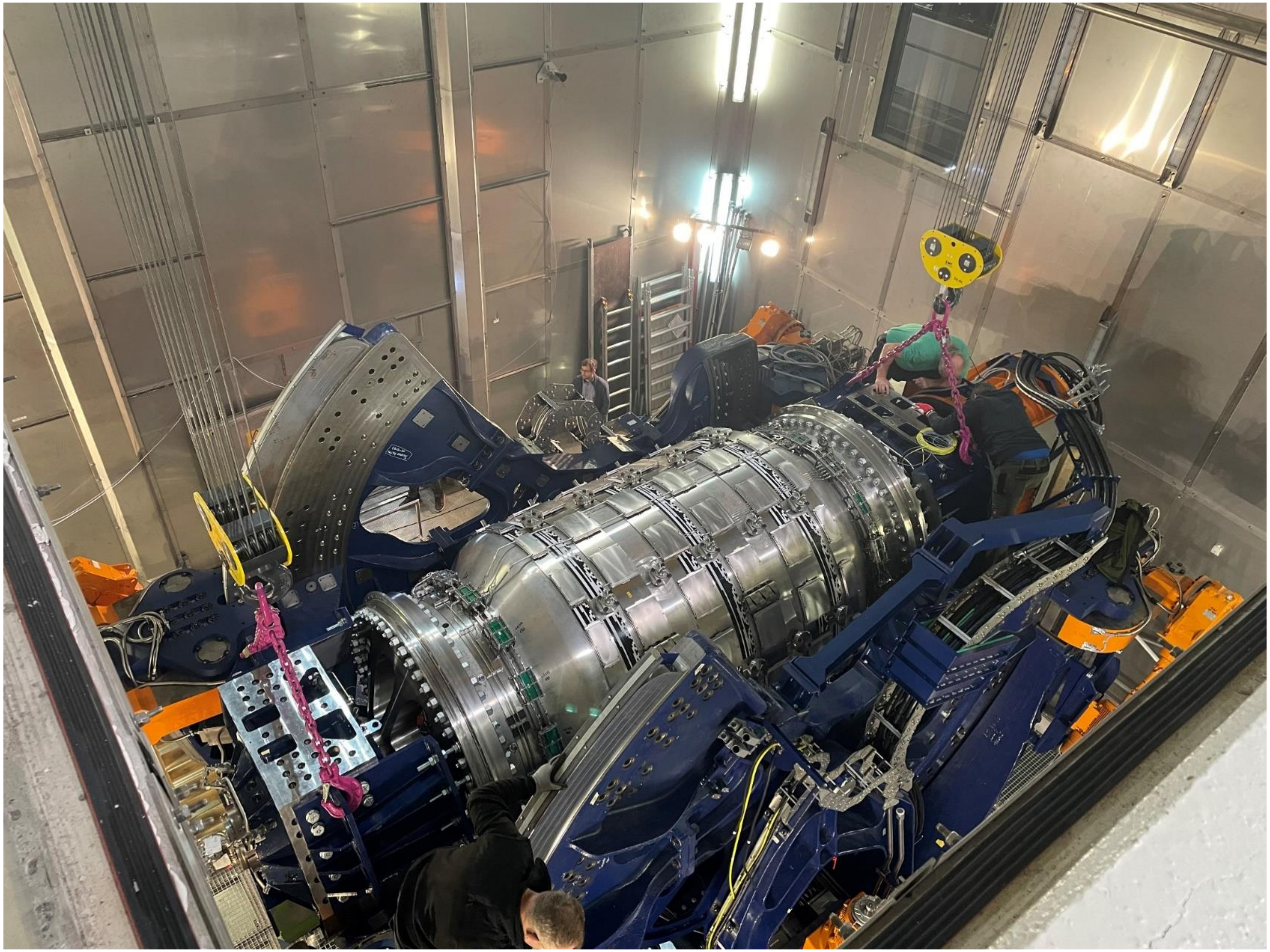
DRESDEN concept

HZDR

And then came January 17, 2024…



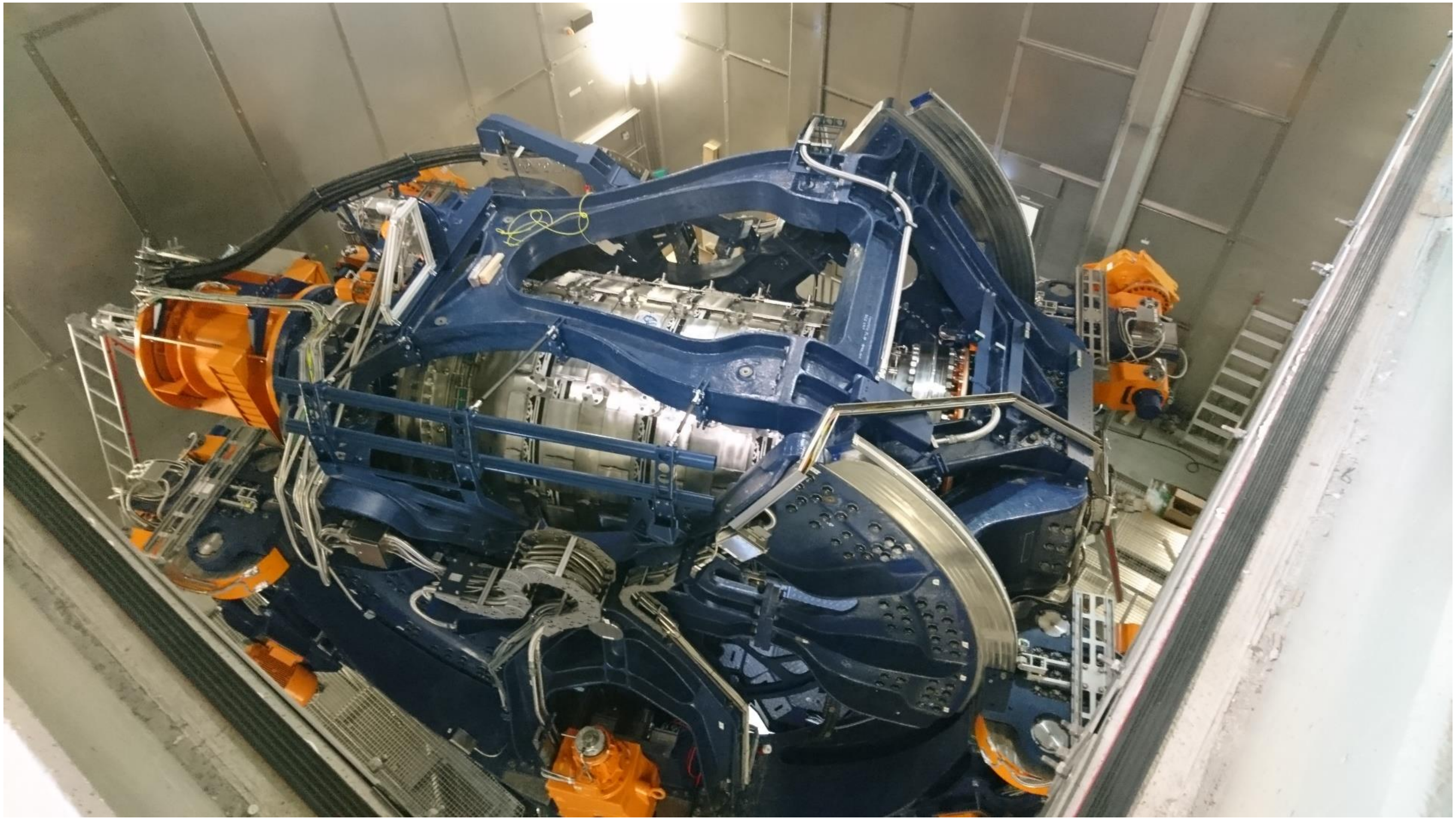
It's done!



DRESDEN concept

HZDR

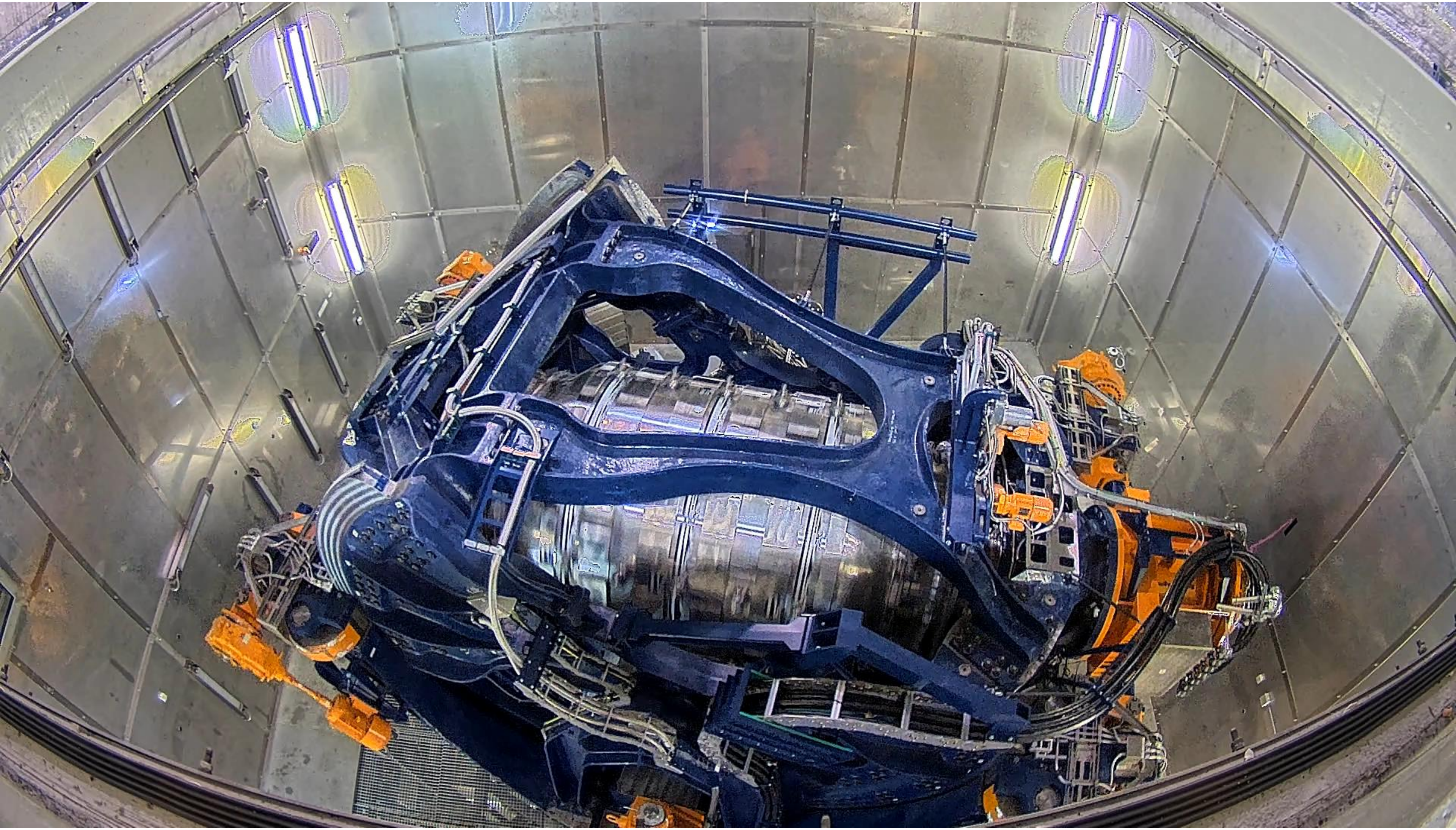
Ready to go…



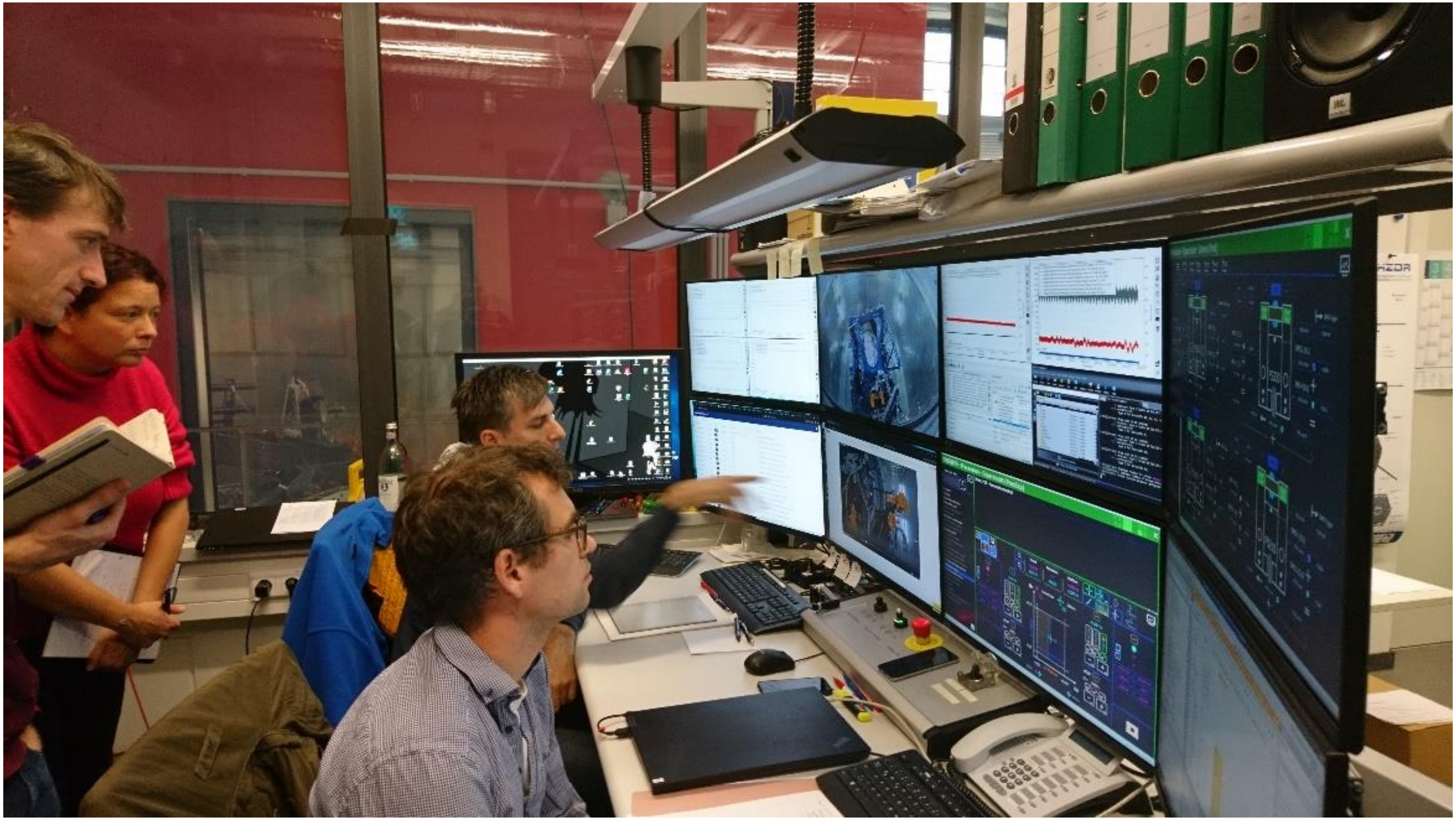
DRESDEN concept

HZDR

28. November 2024: The first water experiment (at 1 Hz)



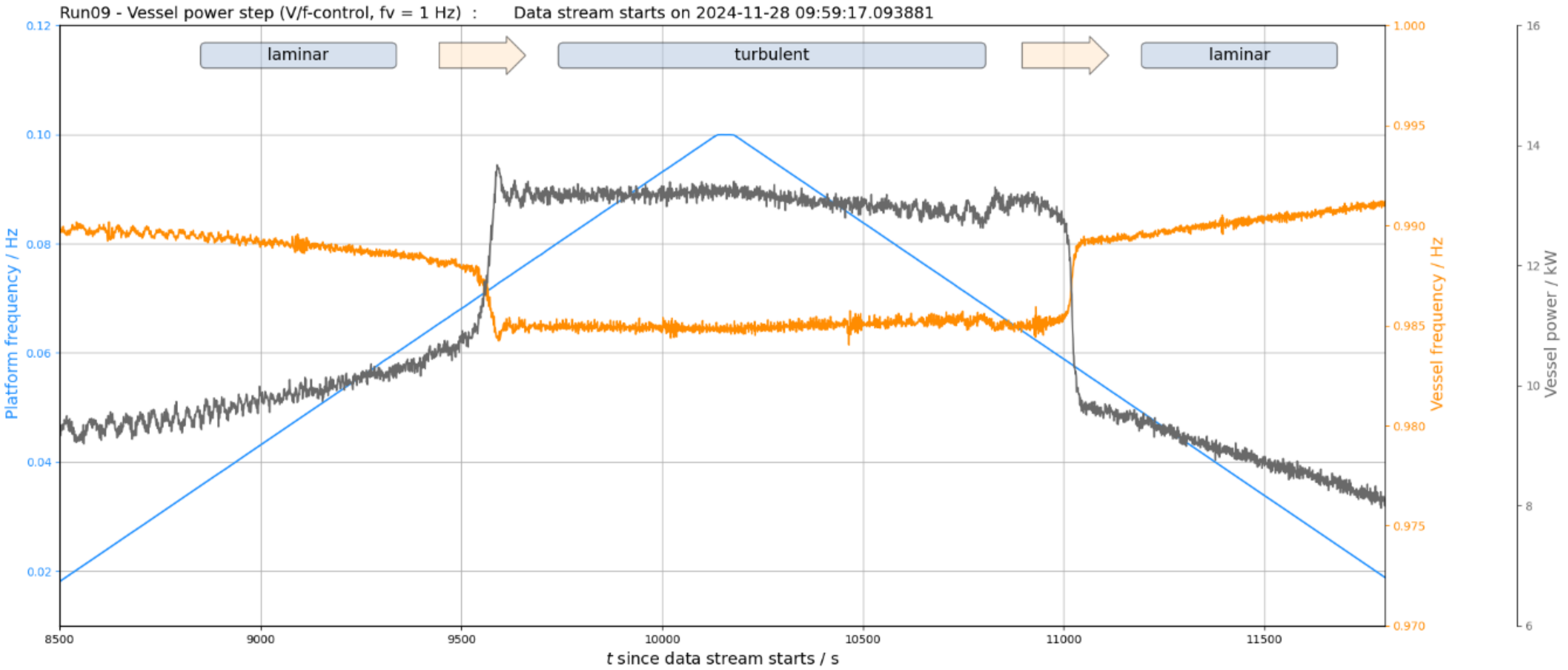
28. November 2024: The first water experiment (at 1 Hz)



DRESDEN concept

HZDR

28. November 2024: The first water experiment (at 1 Hz)



Transition laminar-turbulent observed at the expected precession ratio (with slight hysteris)

28. November 2024: The first water experiment (at 1 Hz)

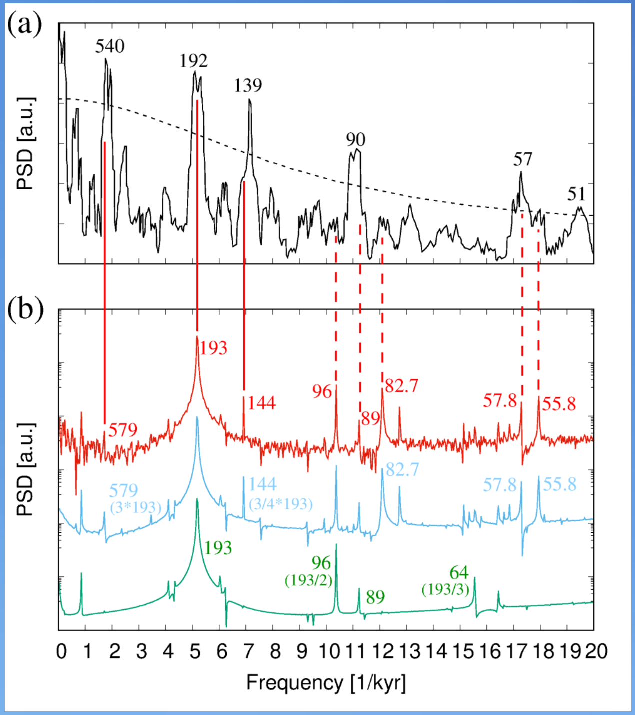
DRESDEN concept

HZDR

Oil leakage at one bearing → vessel must be taken out again

This will take another 8-10 weeks

Sodium system is ready…first runs hopefully in 2026



Thank you for your attention!