Gravitational wave signal of protoneutron star convection

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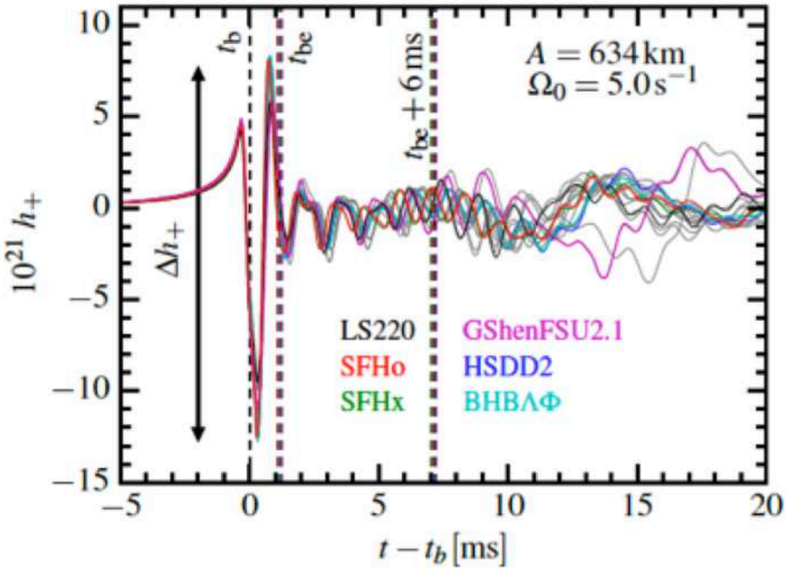
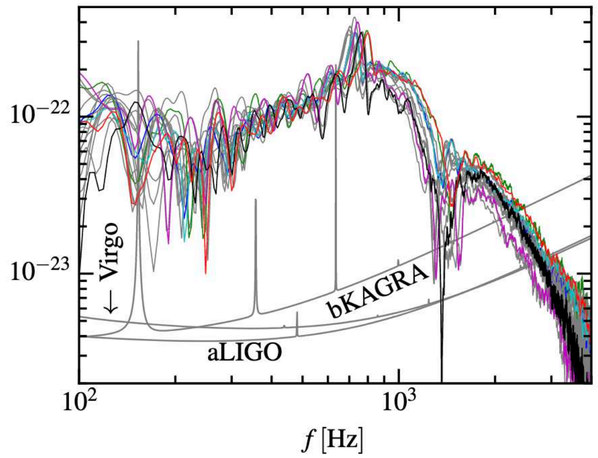
GW signal of CCSN

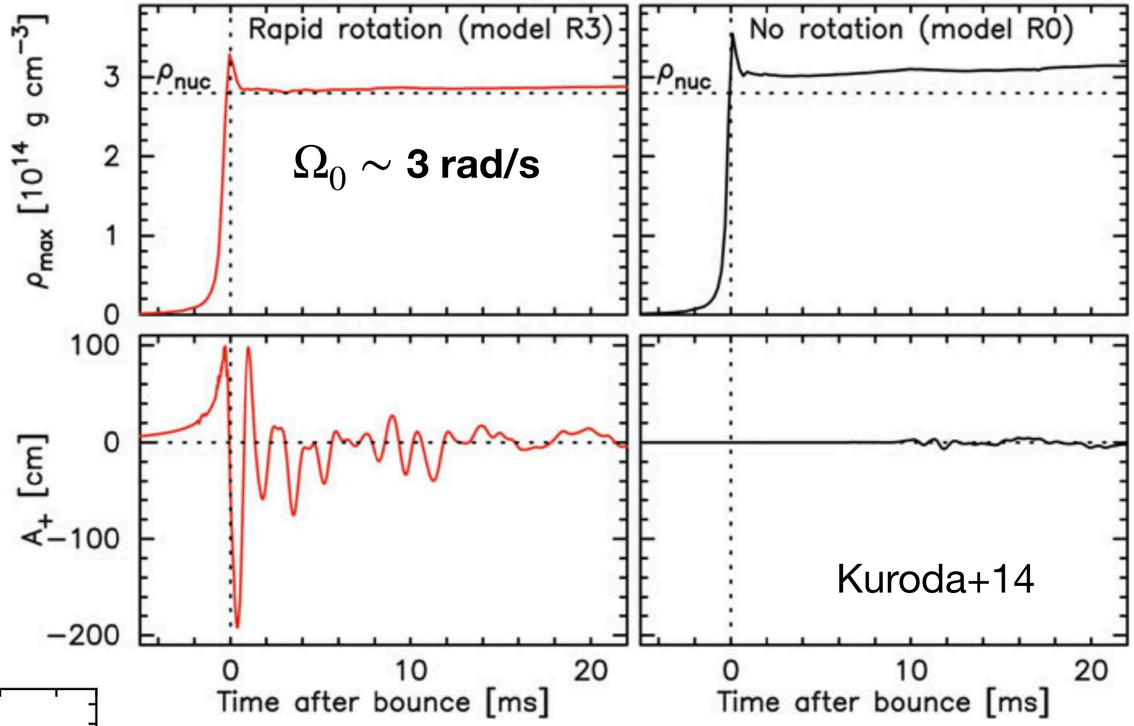
Bounce signal:

- only fast rotating models
- Δt ~ 5 ms
- f ~ 600-900 Hz
- h ~10^{-21} @ 10 kpc

Richers et al 2017





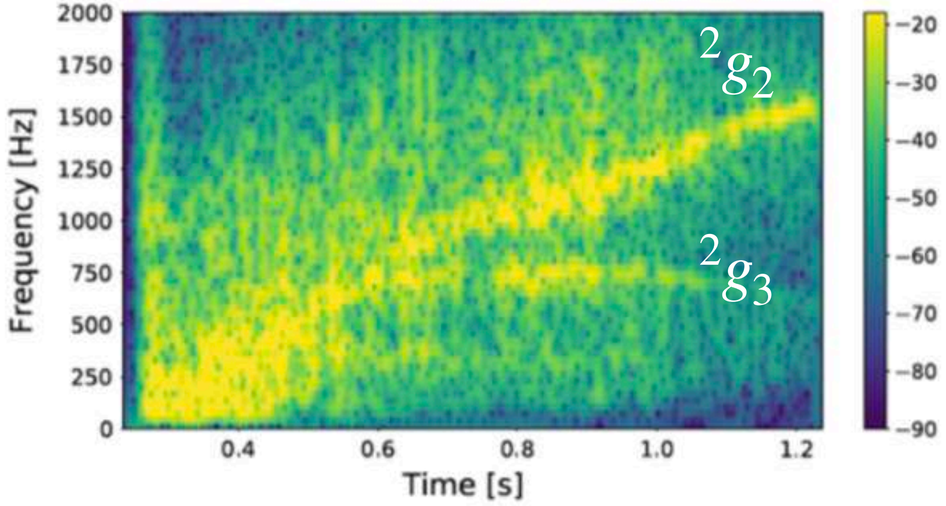


Postbounce signal : non-axisymmetric instabilities

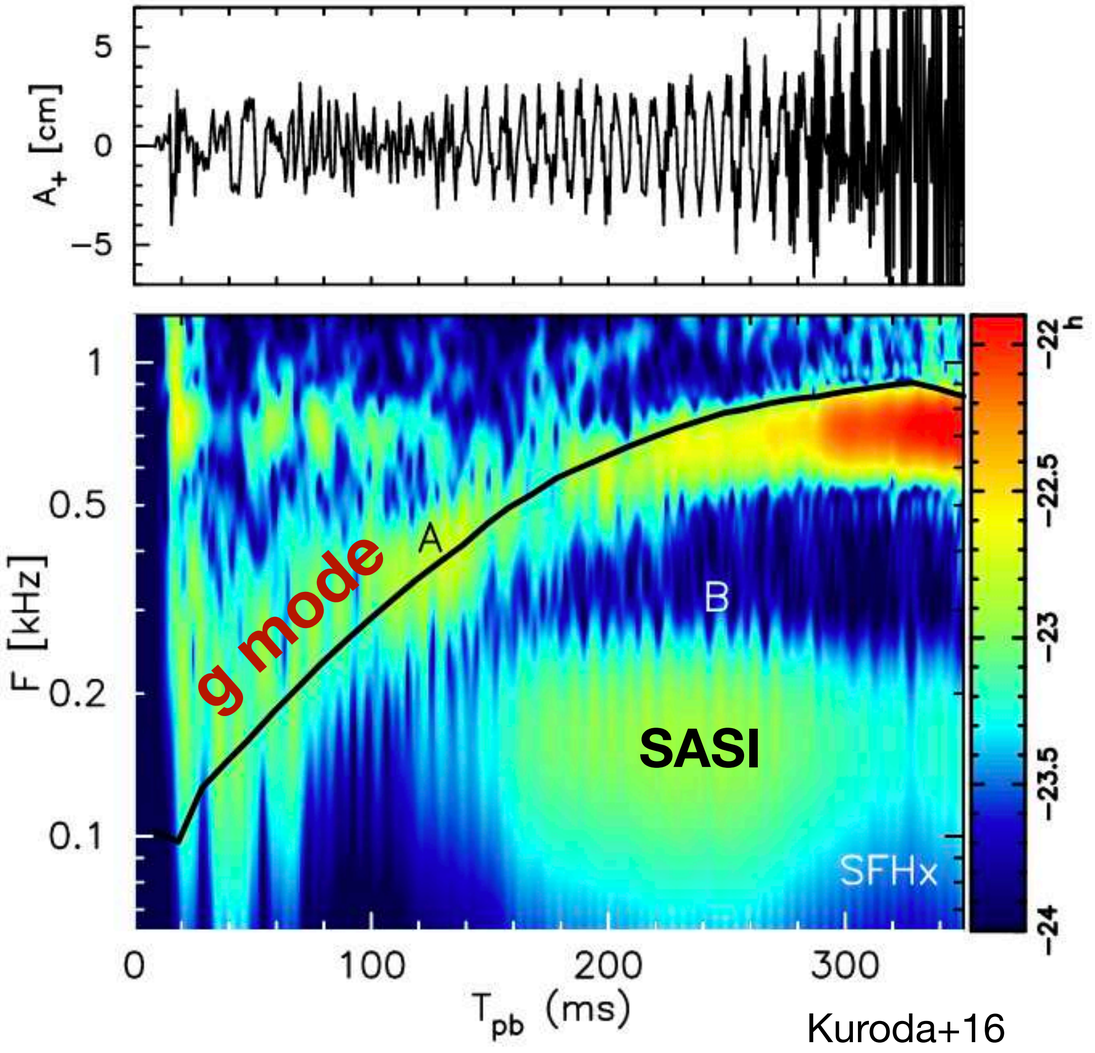
Post-bounce "SN" signal:

- g-modes, SASI, convection
- Δt ~ 0.1-1- s
- f ~ 50-2000 Hz
- h ~10^{-23}-10^{-22}@ 10 kpc

Torres-Forné et al 2019



$\propto M_{PNS}/R_{PNS}^2$

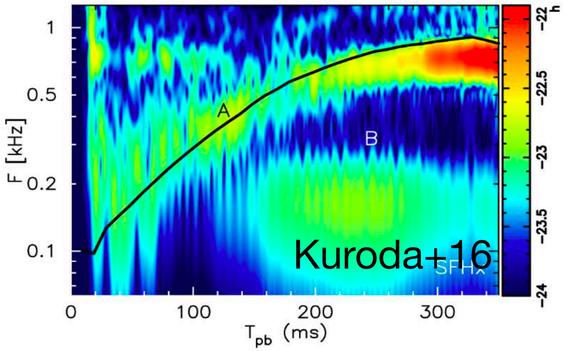


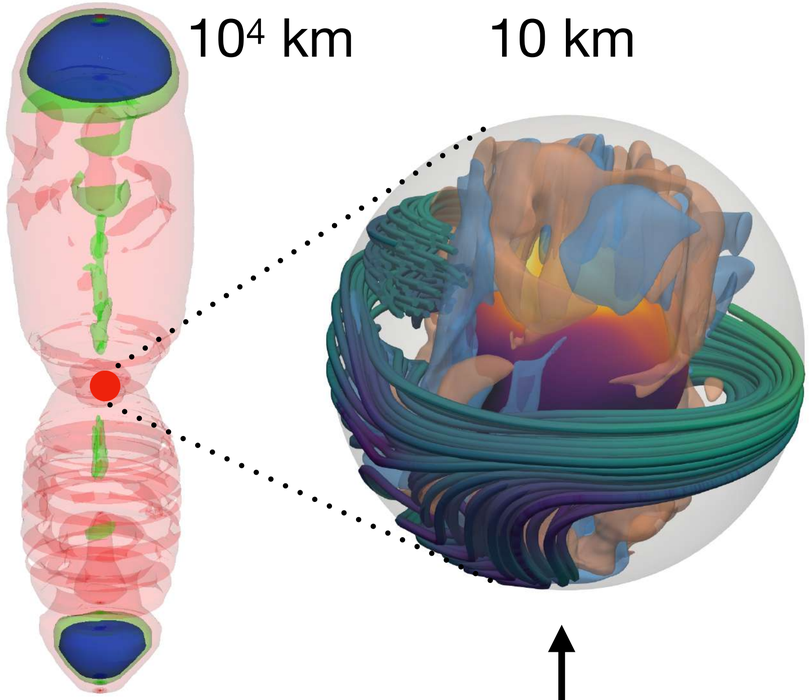
Kuroda+16

PNS convection signal ?

CCSN simulations

- Nucleosynthesis
- Multi-messenger observables





Bugli+21

3D-MHD PNS models

Study magnetar formation

- Fine characterisation of dynamo processes and large scale field generation
- Extensive parameter studies
- Derivation of physics informed scaling laws

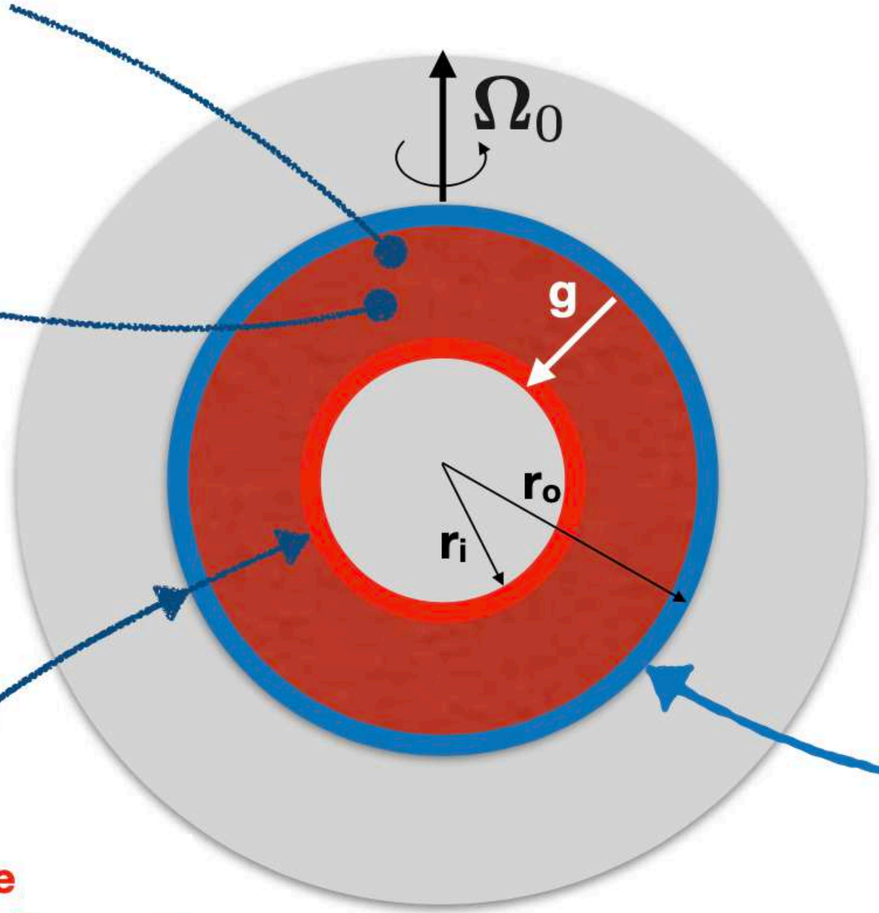
GW PNS convection signal ?

3D modelling with the MagIC code

Taken from 1D CCSN

Input:
- Temperature profile
- Density profile

Transport coefficients:
- Kinematic viscosity ν
- Thermal diffusivity κ
- Magnetic diffusivity η



Hypothesis:
- Spherical geometry
- Adiabatic stratification
- Low Mach convection

- 2nd order diffusion approximation for the neutrino transport
- Electrical conductivity of degenerate, relativistic electrons

- Orders of magnitude

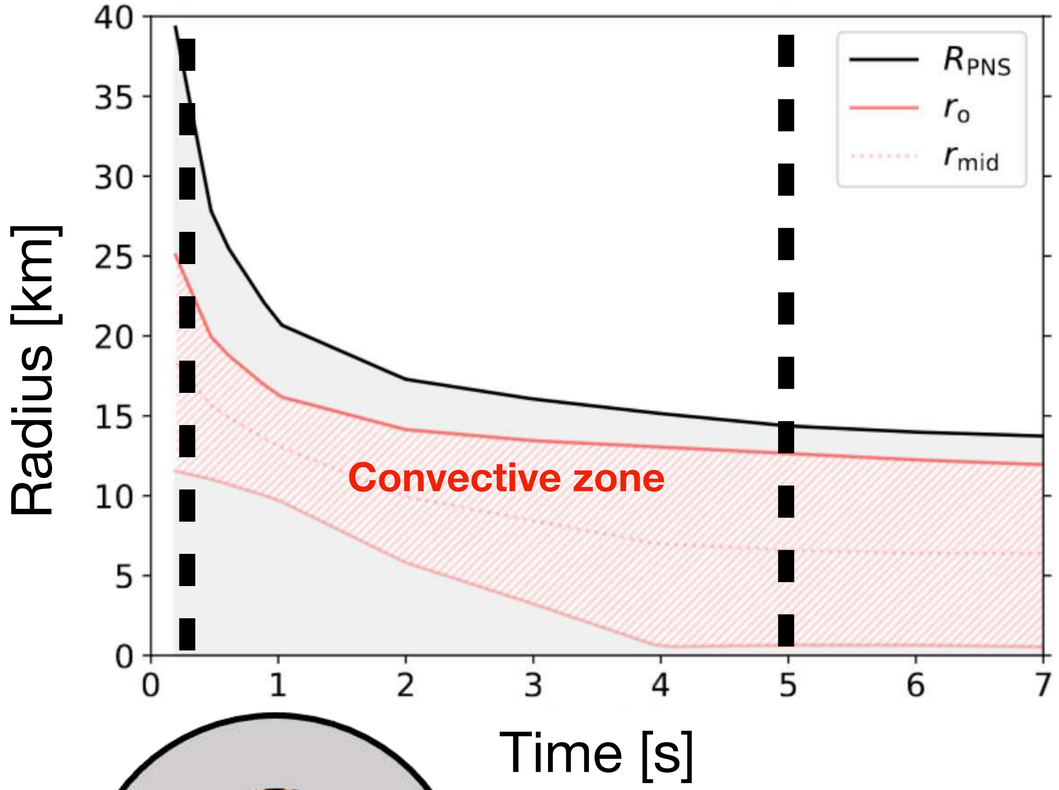
$$\begin{cases} \Phi_o \sim 10^{52}\,\mathrm{erg/s} \\ r_o \sim 25\,\mathrm{km} \\ T_o \sim 10^{11}\,\mathrm{K} \\ \varrho_o \sim 10^{13}\,\mathrm{g/cm^3} \\ \nu_o \sim 10^{10}\,\mathrm{cm^2/s} \\ \kappa_o \sim 10^{12}\,\mathrm{cm^2/s} \\ \eta_o \sim 10^{-3}\,\mathrm{cm^2/s} \end{cases}$$

MagIC

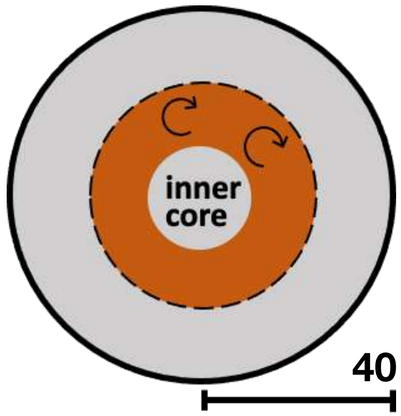
github.com/magic-sph/magic

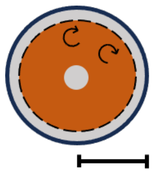
Boundary conditions:
- Mechanical: stress-free
- Thermal: fixed entropy flux
- Magnetic: perfect conductor ($B_{//}$)

Protoneutron star structure

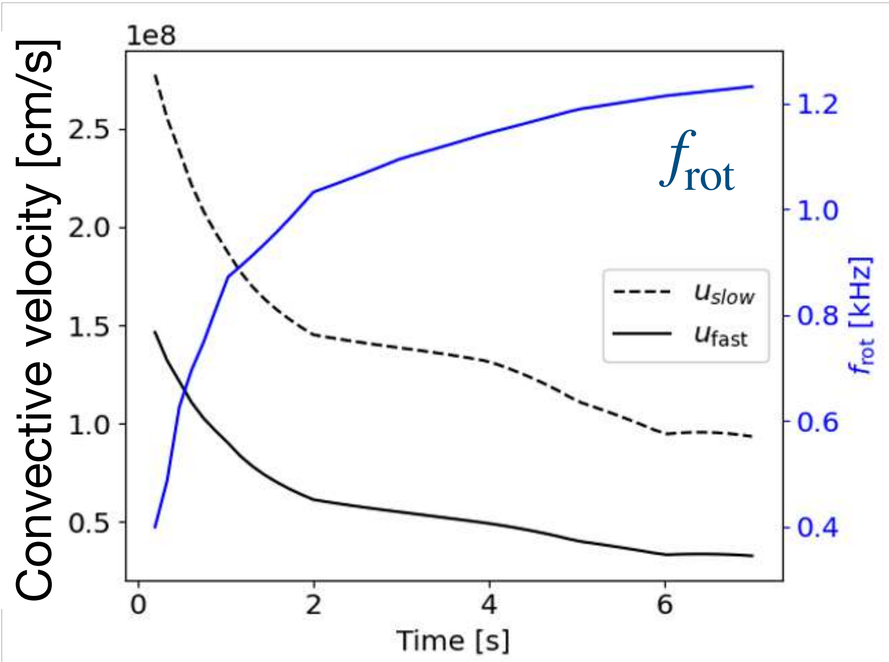


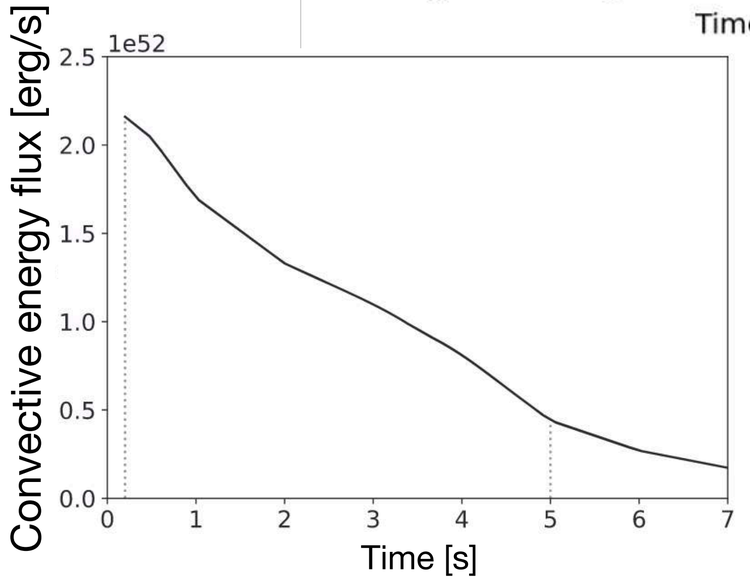
Early time



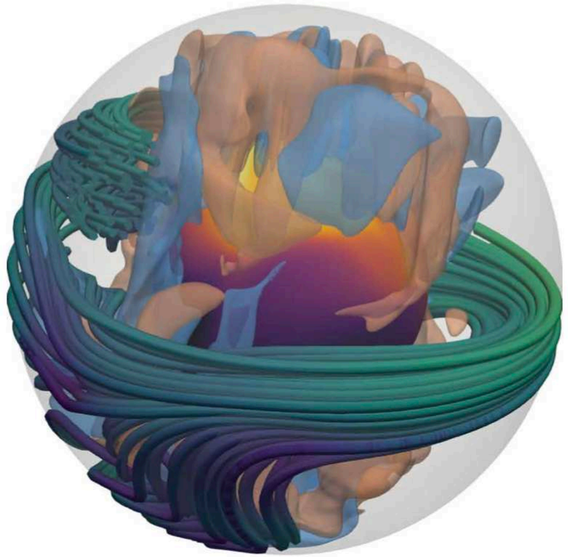


Late time

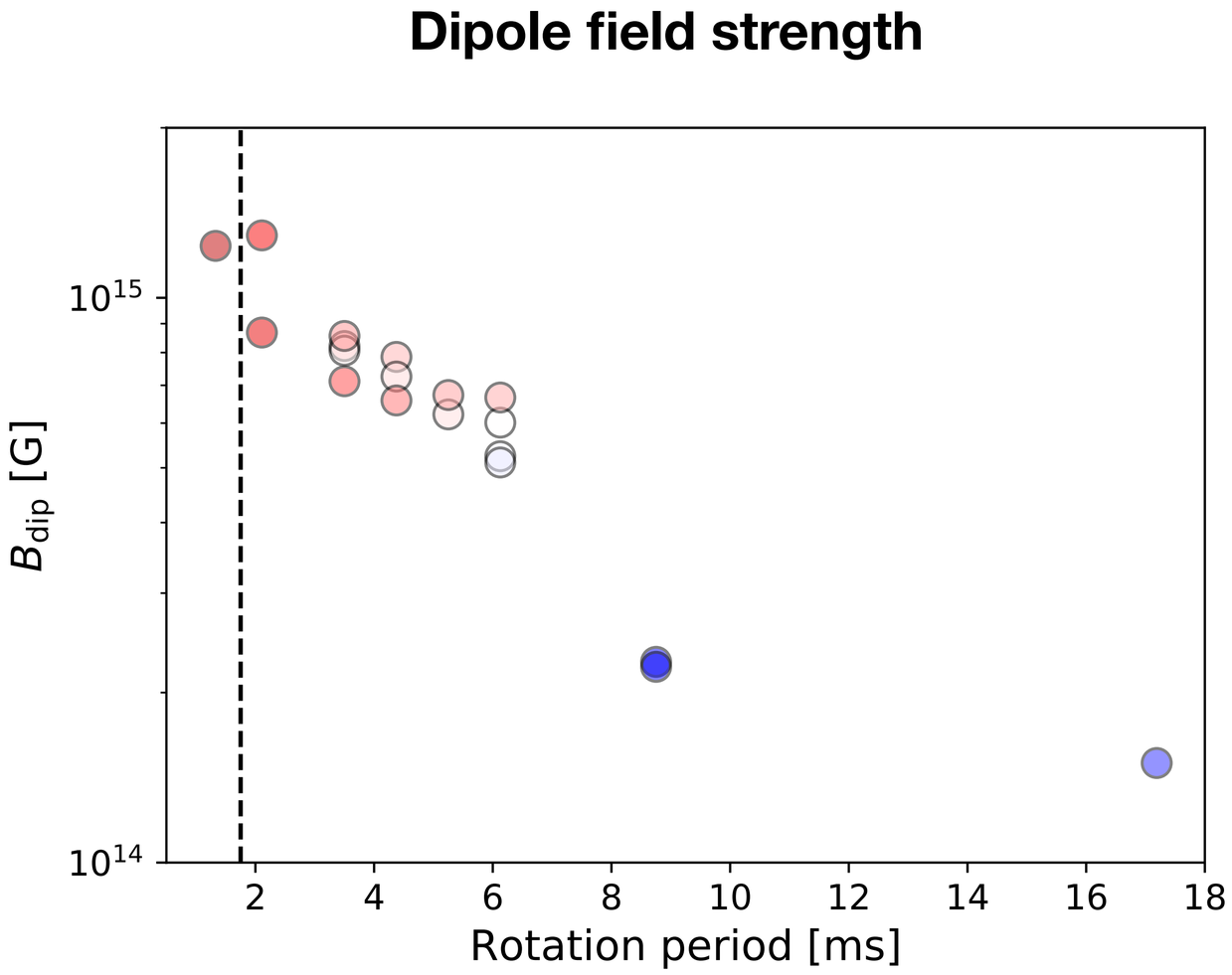


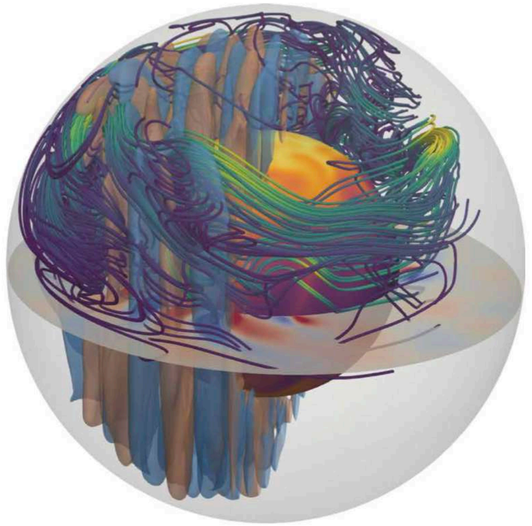


PNS convective dynamos



Strong field dynamo

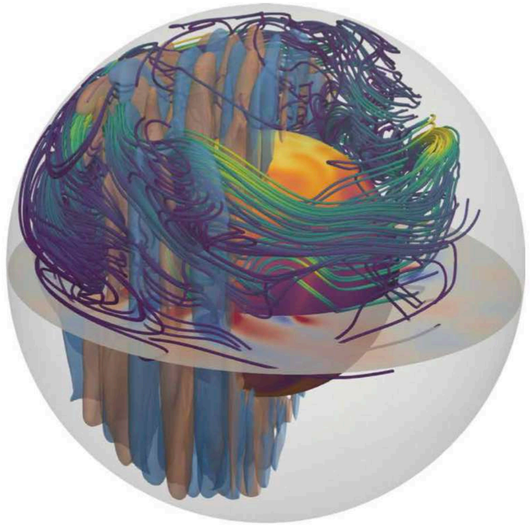




Raynaud+20

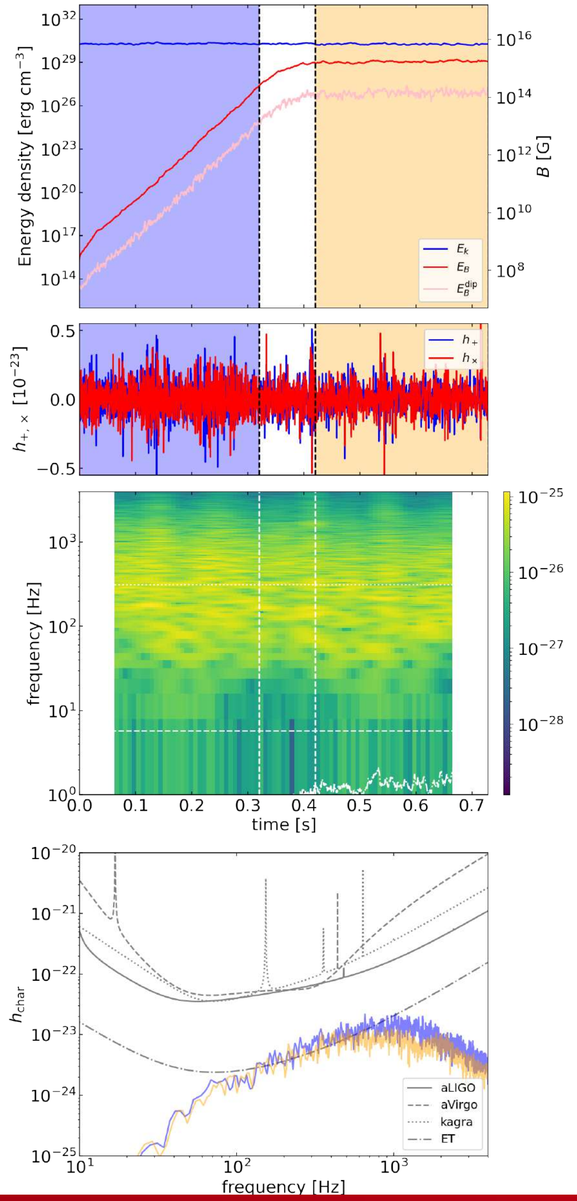
GW counterpart of PNS convective dynamos

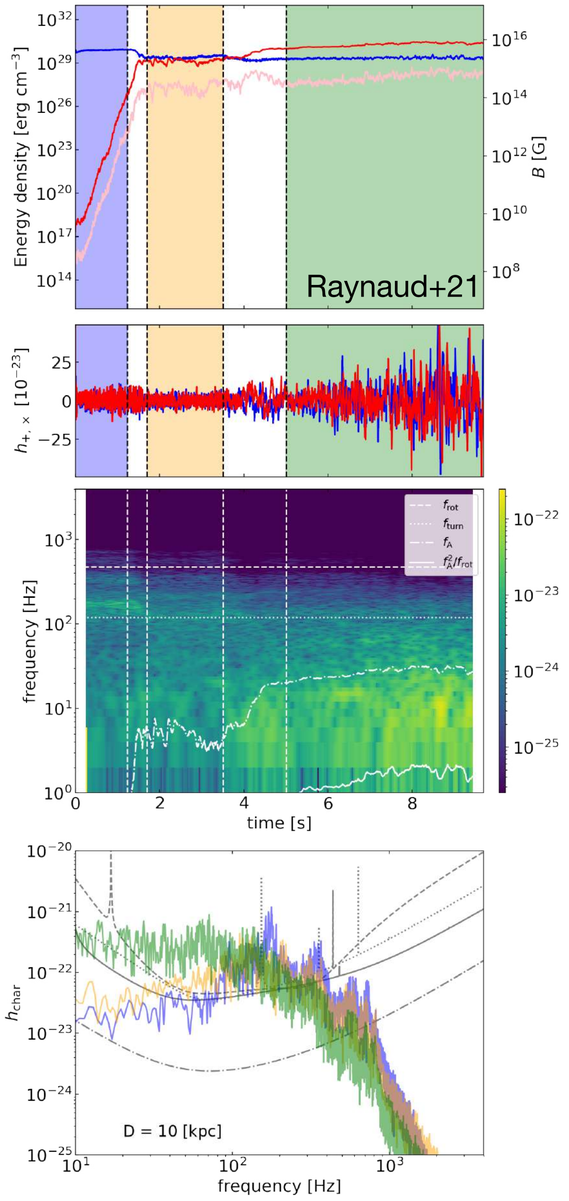
$P = 175$ ms



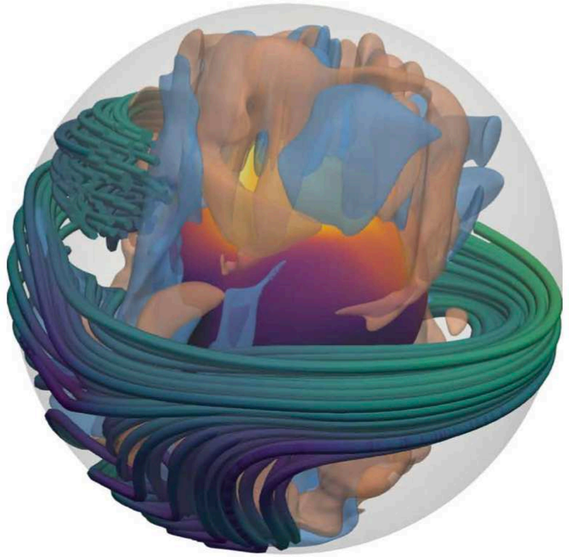
~ "$\alpha\Omega$" dynamo

$$\frac{E_B}{E_{\rm kin}} \lesssim 1$$





$P = 2.1$ ms



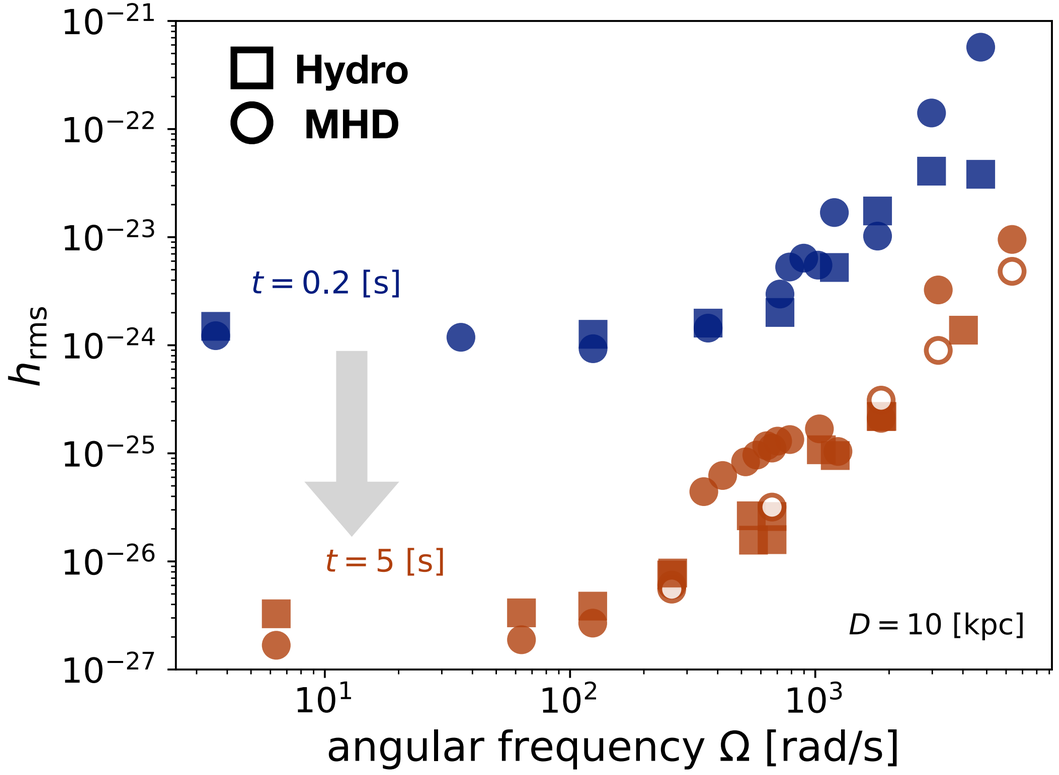
Strong field dynamo

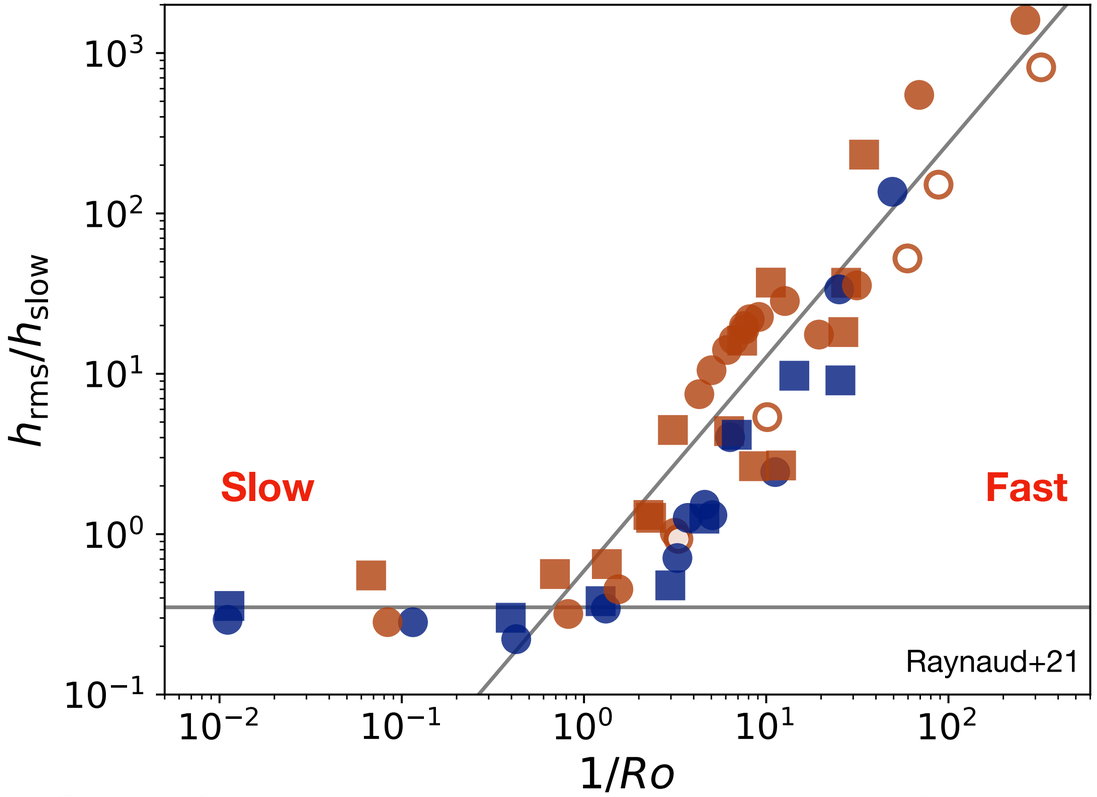
$$\frac{E_B}{E_{\rm kin}} \propto \left(\frac{U}{\Omega d}\right)^{-1} \equiv Ro^{-1} \gg 1$$

$$B_{\rm dip} \sim 10^{15}\,{\rm G}$$
$$B_{\rm tor} \sim 10^{16}\,{\rm G}$$

Raynaud+20

Amplitude scaling



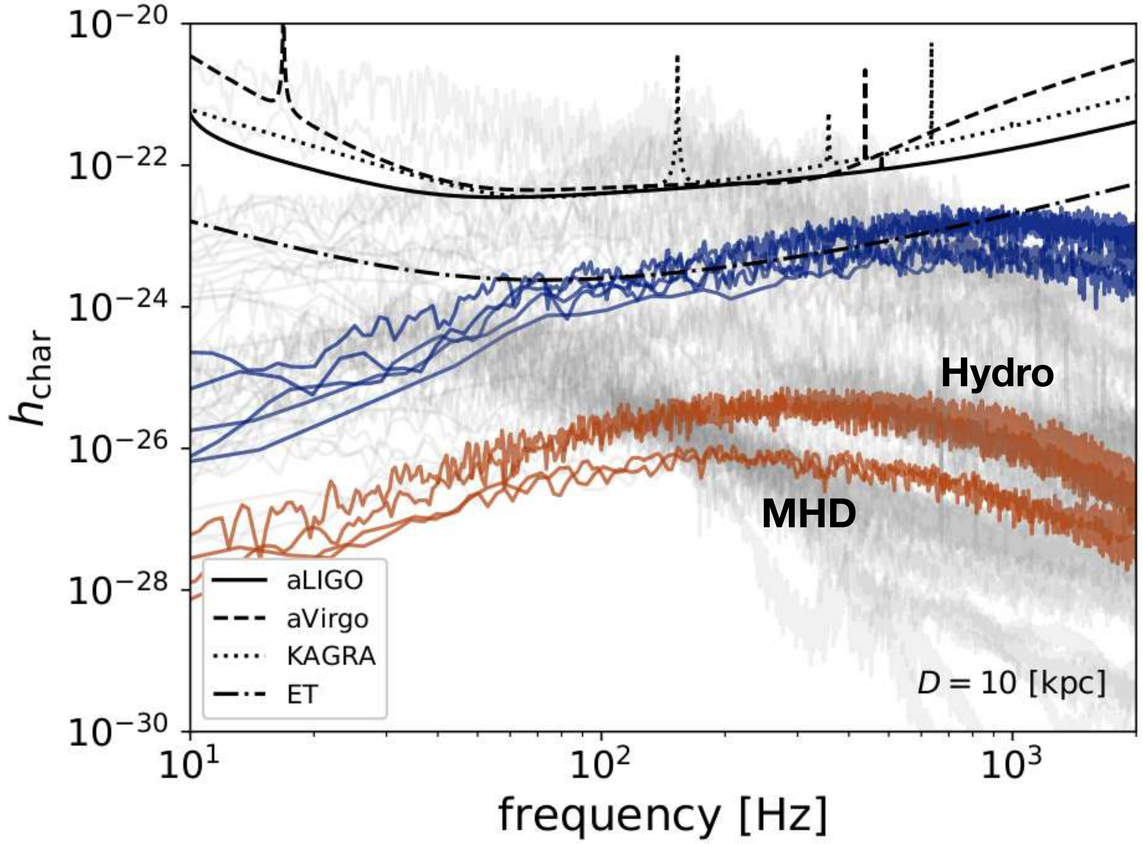


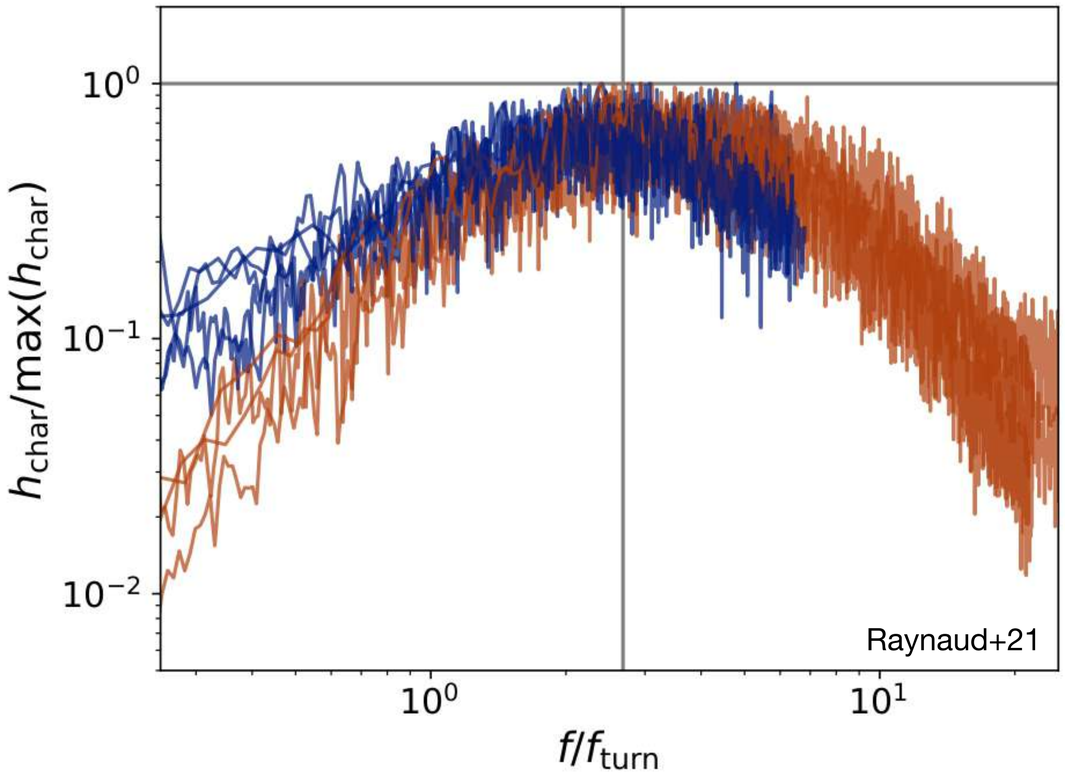
State-of-the-art rotating convection scalings (Aurnou+20)

- **Slow rotation:** $f_{\rm turn} \gg f_{\rm rot} \iff Ro \gg 1$
- **Fast rotation:** $f_{\rm turn} \ll f_{\rm rot} \iff Ro \ll 1$

with the Rossby number $Ro \equiv \dfrac{U}{\Omega d} \equiv \dfrac{f_{\rm turn}}{f_{\rm rot}}$

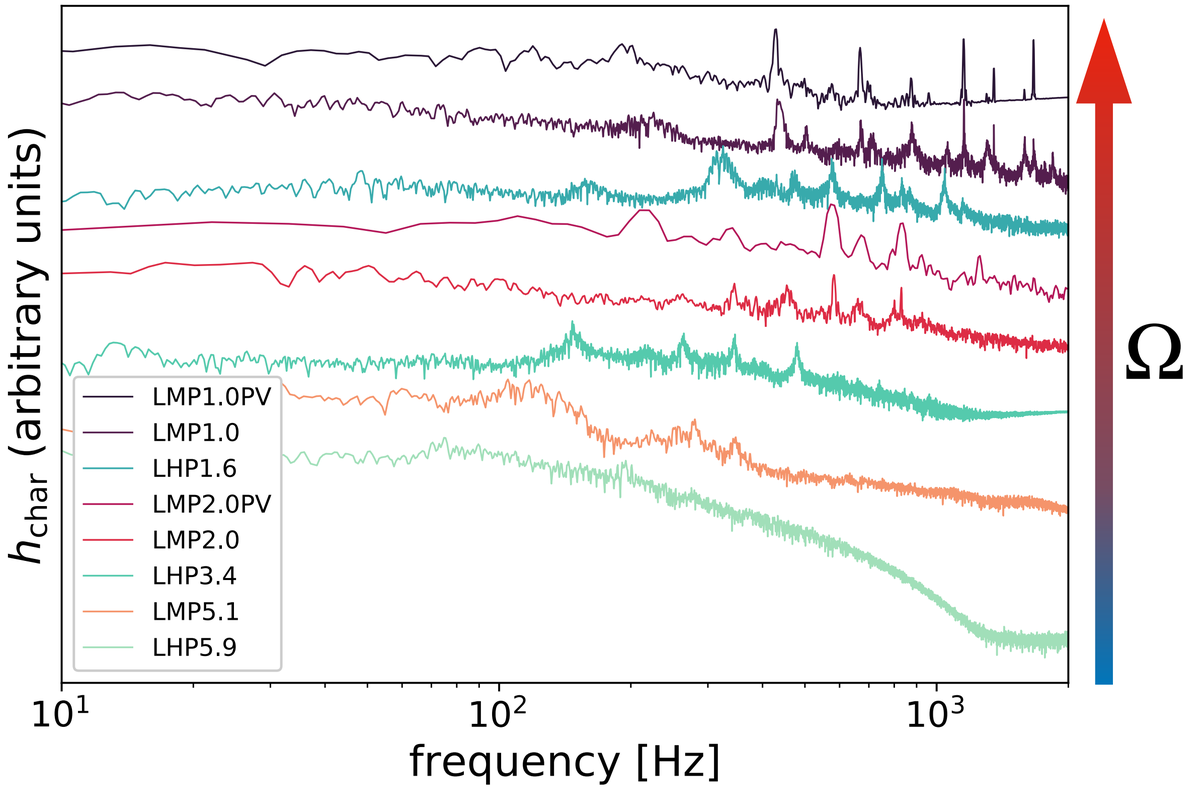
Frequency scaling: slow rotation

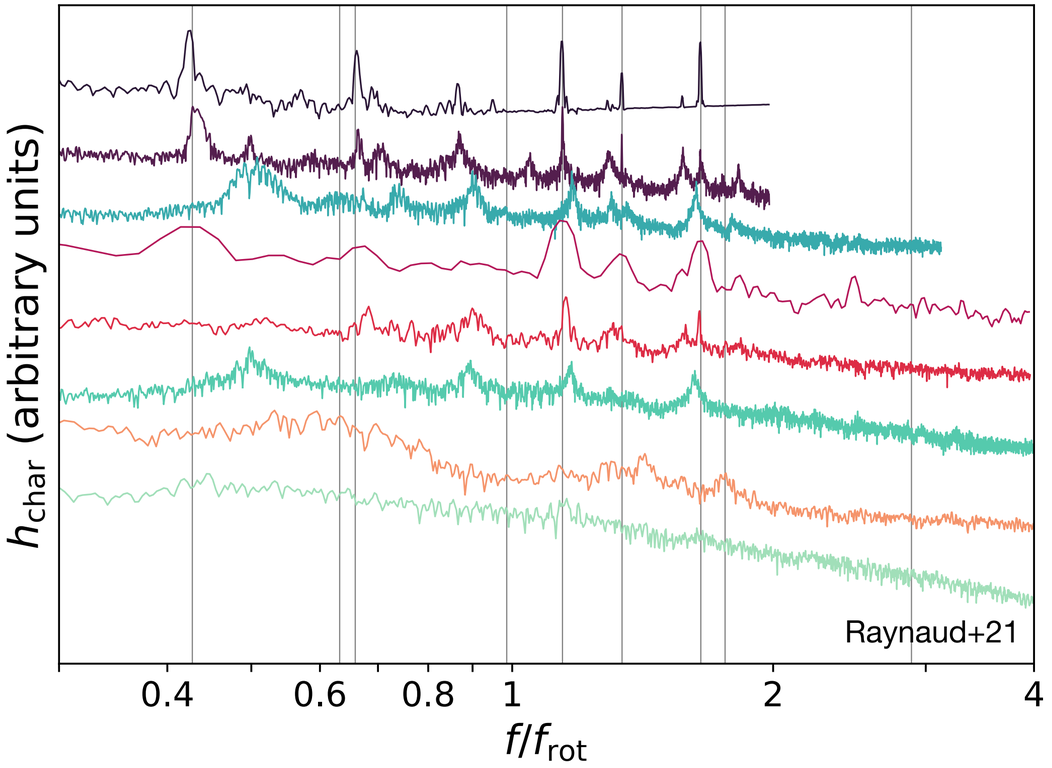




$$f_{\rm max} \propto f_{\rm turn} \equiv u_{\rm rms}/d$$

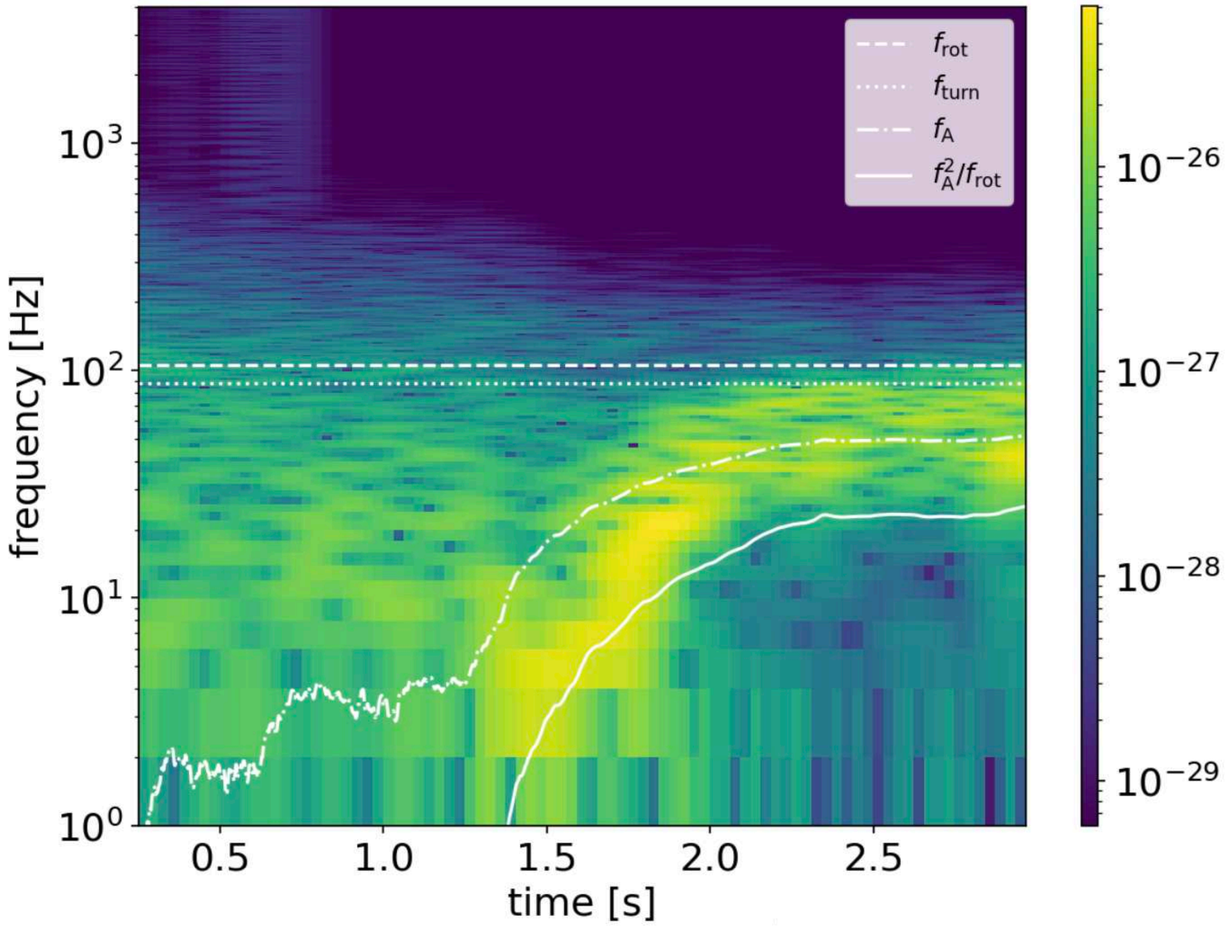
Frequency scaling: fast rotation

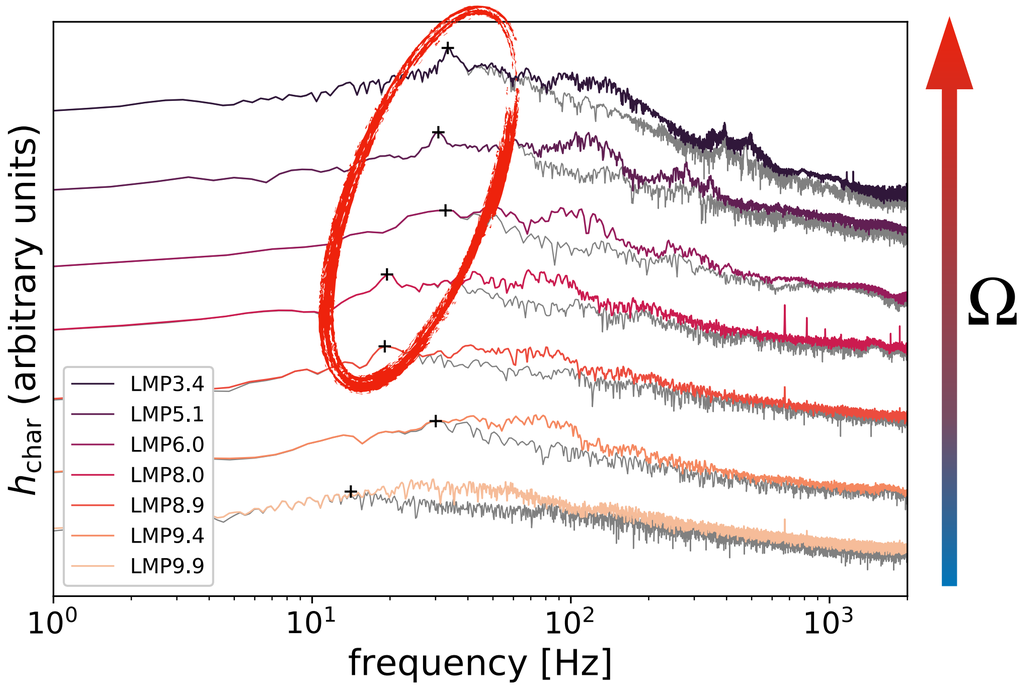




Inertial modes $f_{peaks} \propto f_{rot}$

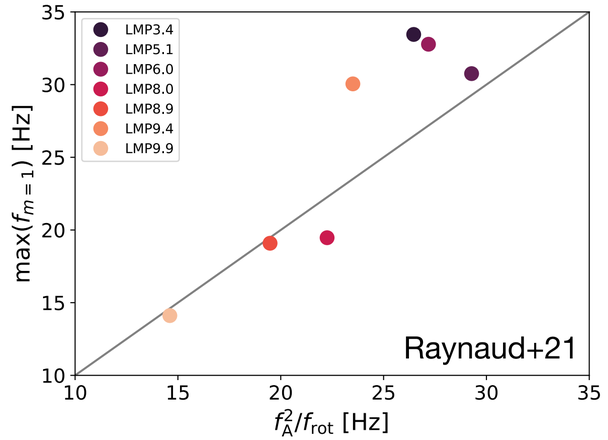
Strong field dynamo growth





Rossby $m = 1$ mode modified by magnetic effects

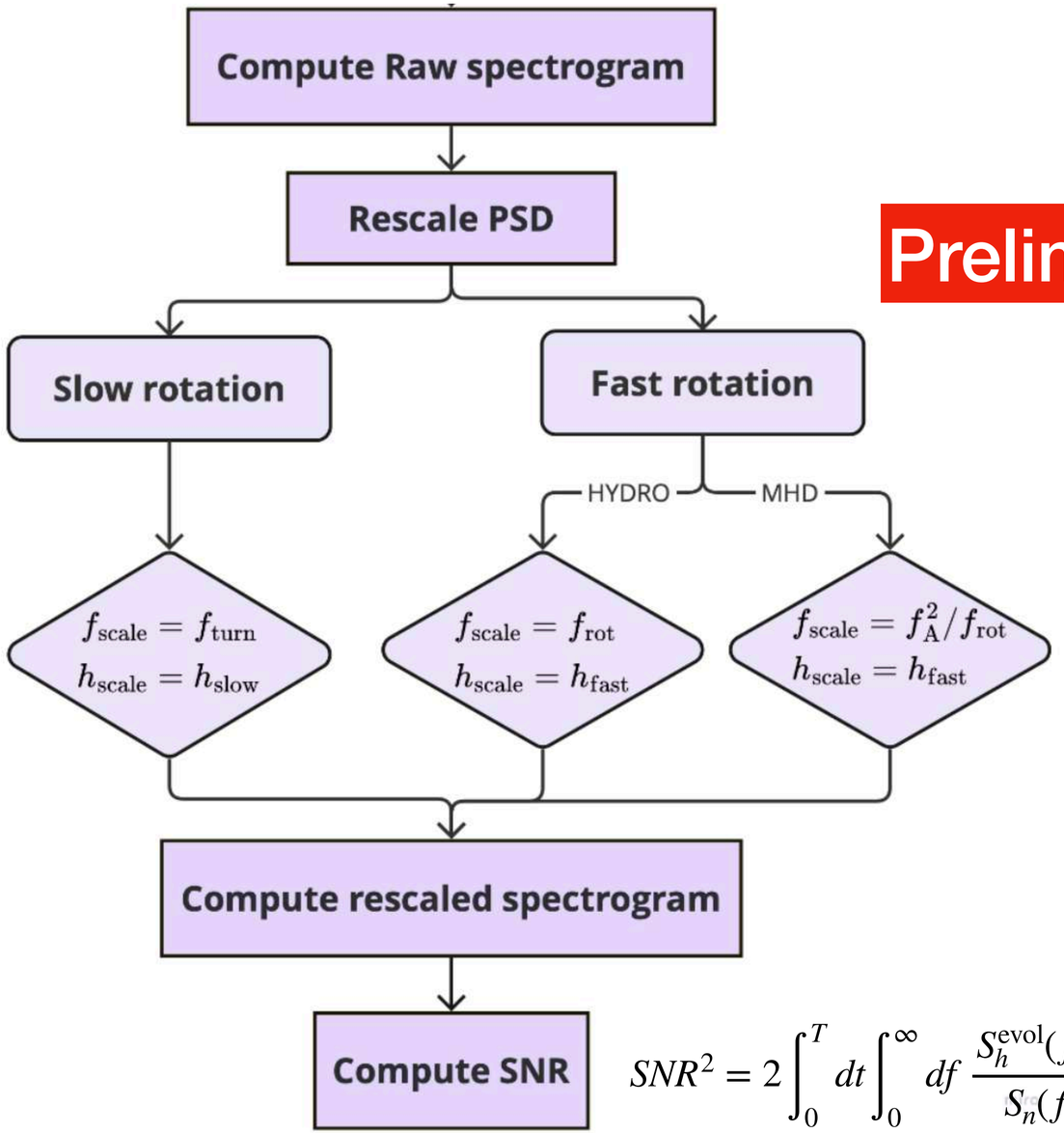
$$f \propto f_A^2/f_{\rm rot}$$



Detectability ?

Hypotheses

- From the 3D models
  - Self-similarity of the PSD
  - Frequency & amplitude scaling relations
- From the 1D model
  - PNS evolution from 0.2 s to 7 s
- Angular momentum conservation $\Longrightarrow$ $\Omega(t)$
- Asymptotic regimes :
  - Slow rotation ($Ro \gg 1$)
  - Fast rotation ($Ro \ll 1$)

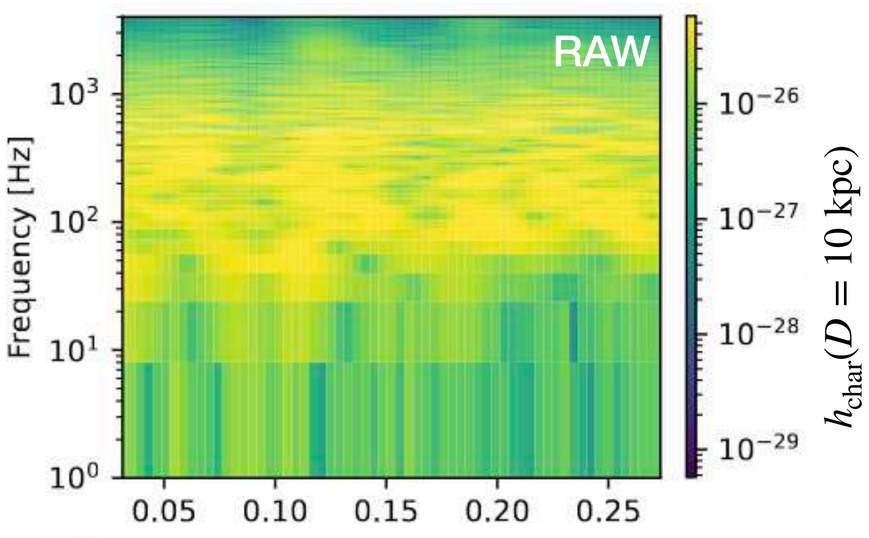


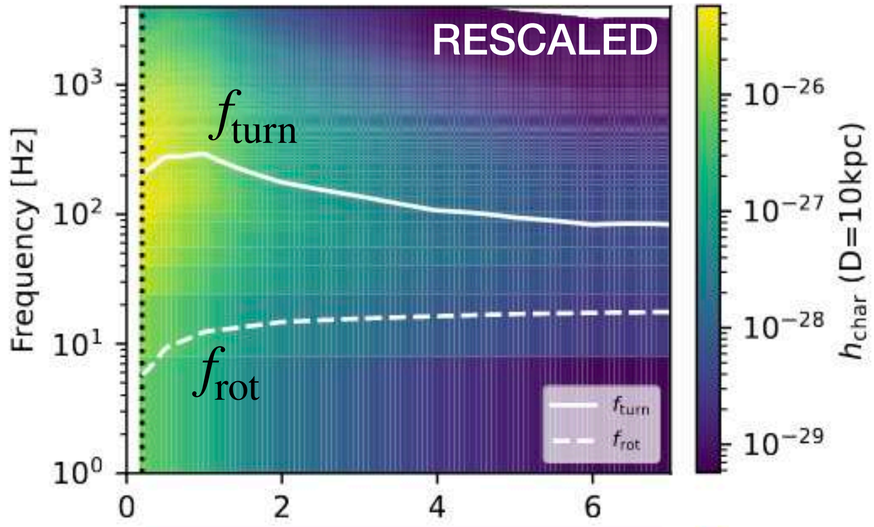
Preliminary !

$$SNR^2 = 2\int_0^T dt \int_0^\infty df \, \frac{S_h^{\rm evol}(f,t)}{S_n(f)} = \int_0^T \sigma(t) dt$$

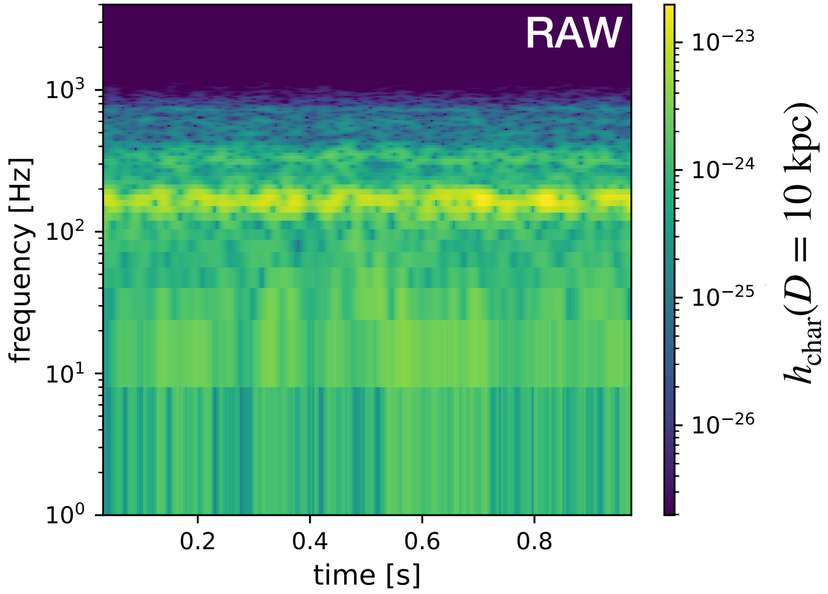
Synthetic spectrograms

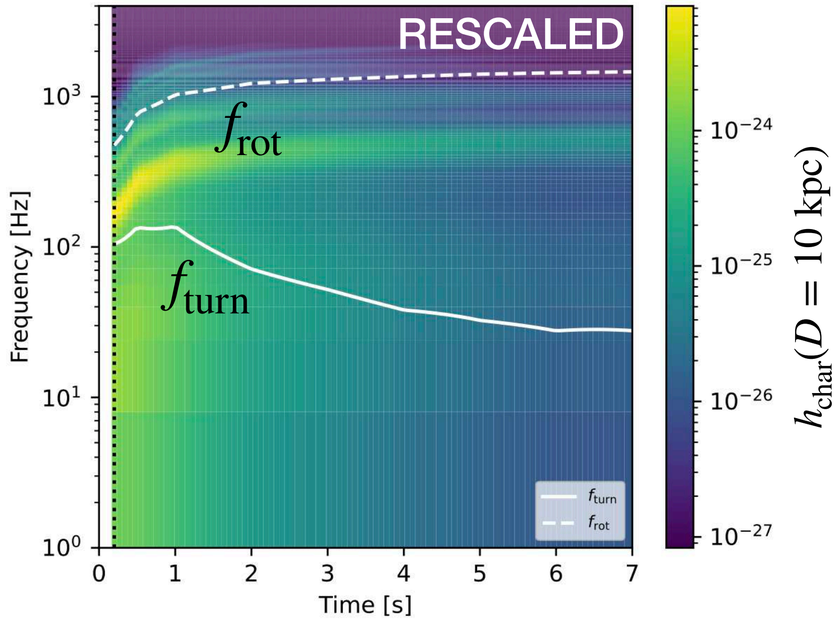
Slow rotation





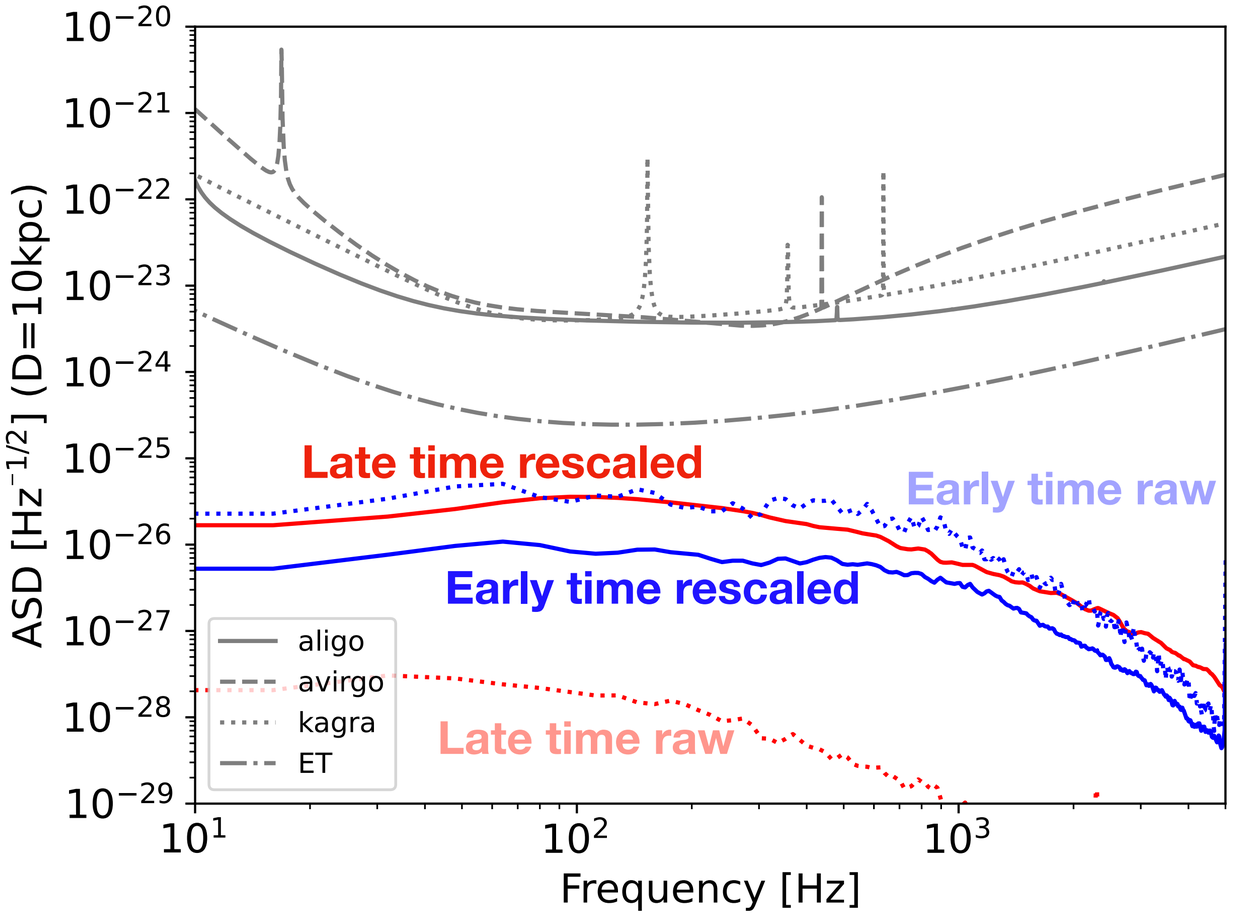
Fast rotation



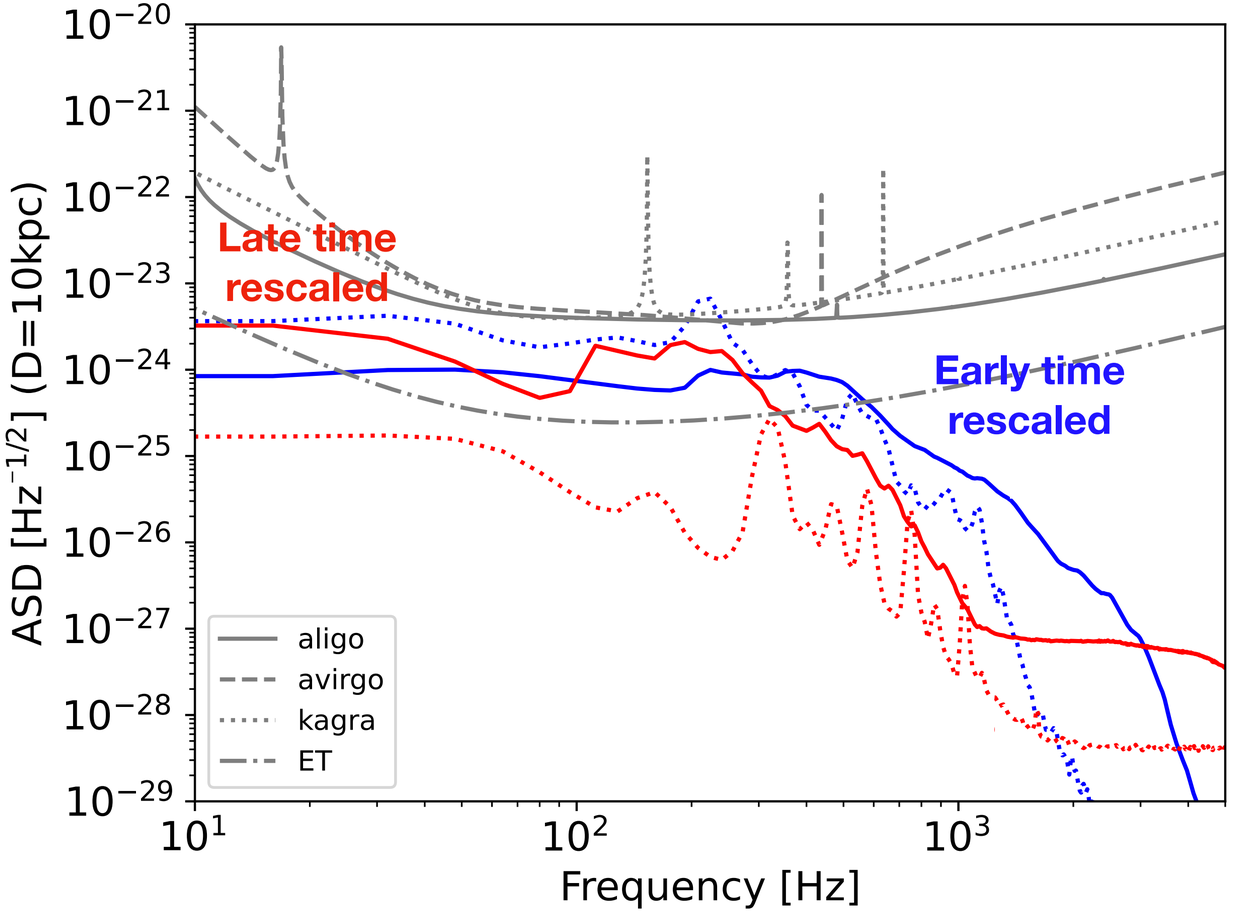


Rescaled spectra

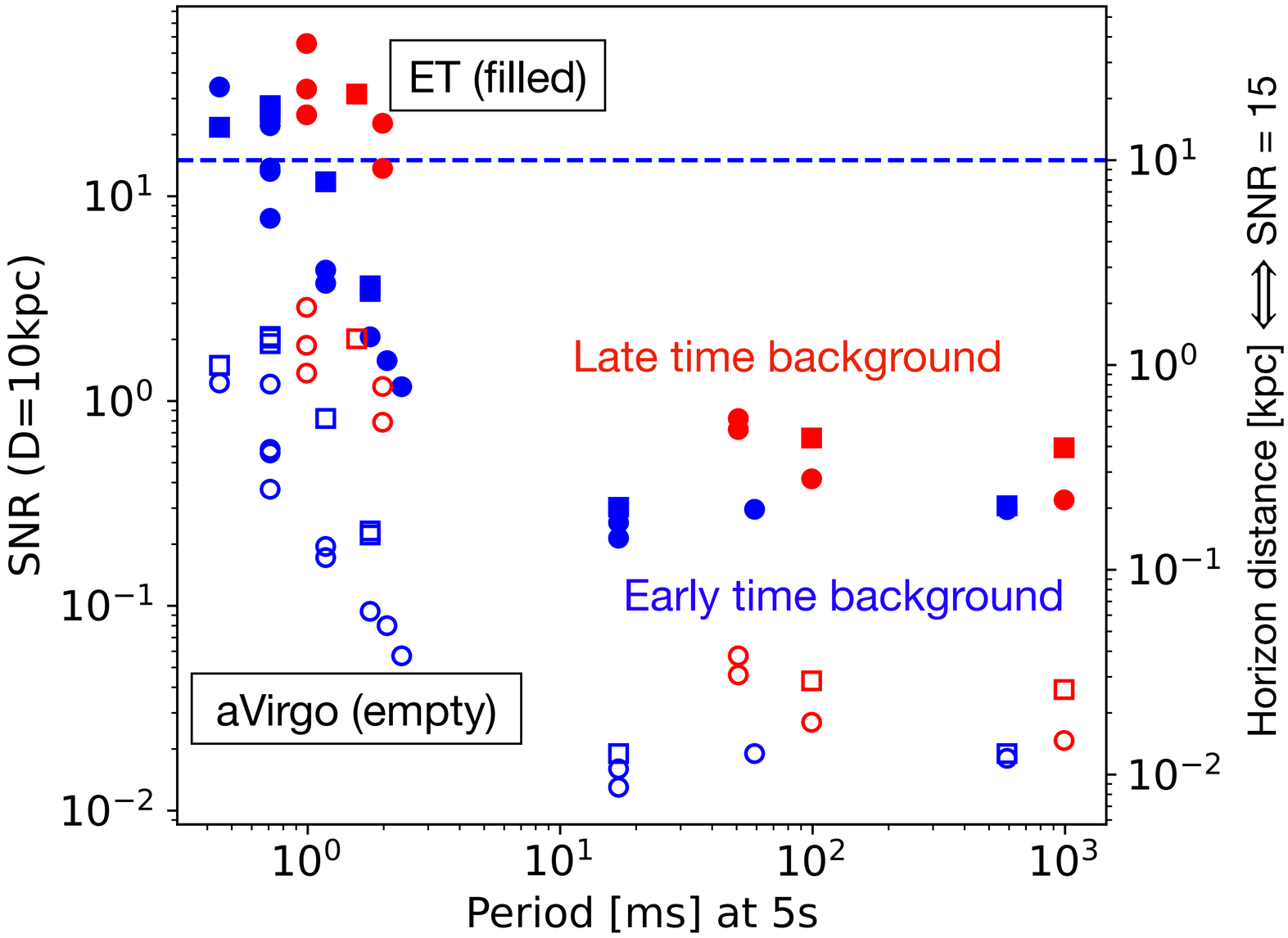
Slow rotation

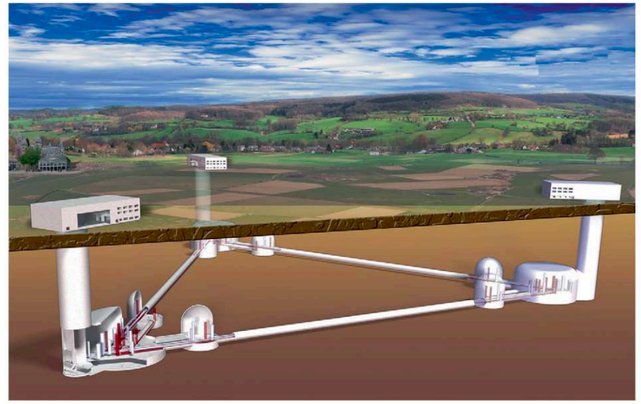


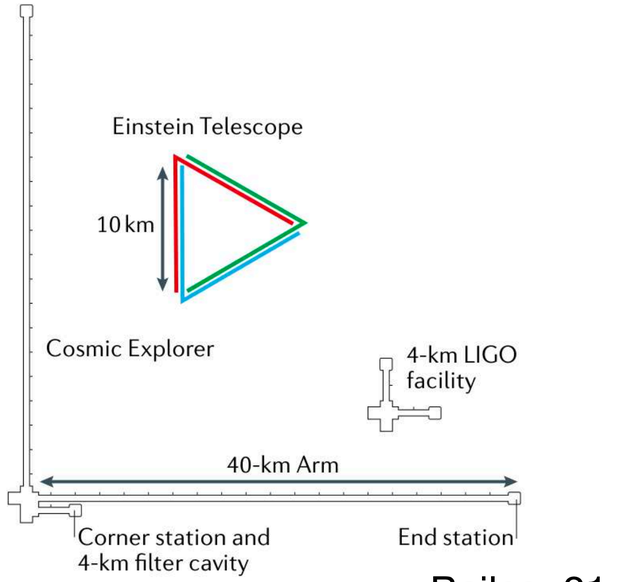
Fast rotation



SNR estimates







Bailes+21

Conclusion

Slow rotation $Ro \gg 1$

- Broad spectrum
- $f_{\max} \propto f_{\text{turn}}$
- Weak impact of magnetic field

- SNR ~ O(0.1) @ 10 kpc with ET

Fast rotation $Ro \ll 1$

- h_{rms} strongly increases
- Complex spectra with inertial modes
- Possibly low frequency, strong field dynamo signature

- SNR ~ O(10) @ 10 kpc with ET

Perspectives

- Coupling with a stable zone to study the excitation of g-modes by turbulent convection

- Characterization of the different PNS dynamo scenarios

References
Raynaud+20,21

Dynamo scenarios:
Barrère+22,23,24 (submitted)
Reboul-Salze+21,22