Title: Consequences of Low Resolution and High Initial Magnetic Fields in Binary Neutron Star Merger Simulations

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Collection/Series: Magnetic Fields Around Compact Objects Workshop

Date: March 27, 2025 - 3:45 PM

URL: https://pirsa.org/25030145

Abstract:

Simulations of magnetized binary neutron star mergers often seed the interiors of the initial stars with unrealistically strong magnetic fields to overcome the suppression of small-scale turbulence by finite grid resolution and observe postmerger magnetic collimation and potential jet breakout. We present a curious numerical instability arising from low resolution (227 meters) and high initial dipolar fields ($E_{tot} = 5 \times 10^{49}$ ergs) observed when conducting BNS mergers in a full 3D domain. Initial poloidal structures of sufficient magnitude can linger within the merger remnant, even through the turbulent merger process. Differential rotation then winds these structures into two counterrotating torii separated by the x-y plane. Numerical diffusion inherent to the low resolution grid then causes counterrotating field lines to interact near the x-y plane, leading to spurious magnetic energy dissipation that feeds back into fluid motion. We discuss the consequences of this feedback, including a large circular drift of the merger remnant, and how increased resolution or grid symmetry can alleviate this issue.

Magnetized Hypermassive Neutron Stars:

Experiments with Numerical Effects

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Magnetic Fields Around Compact Objects Workshop 2025


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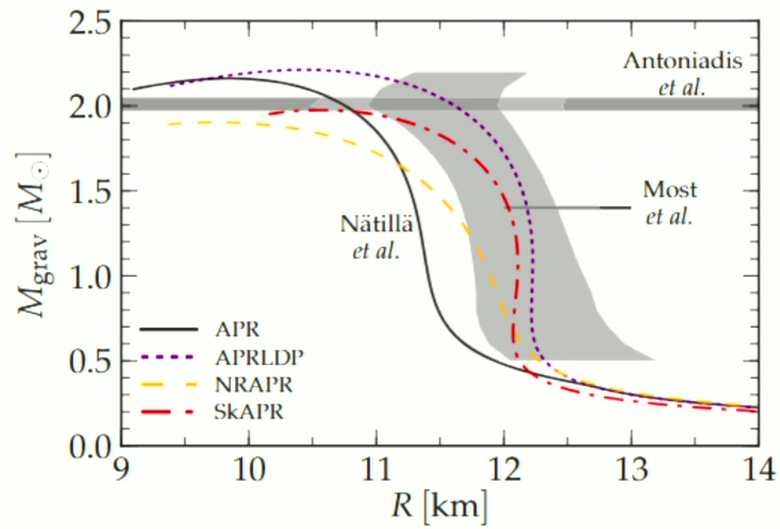
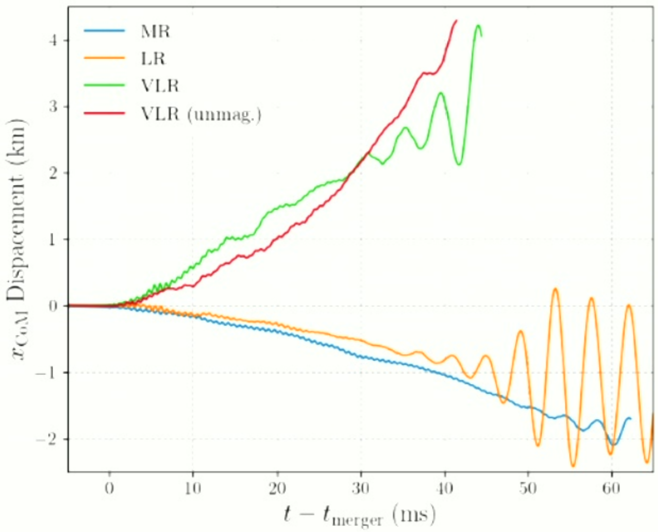
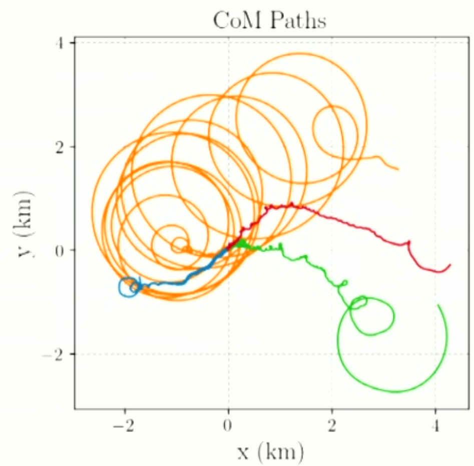
Simulation Overview

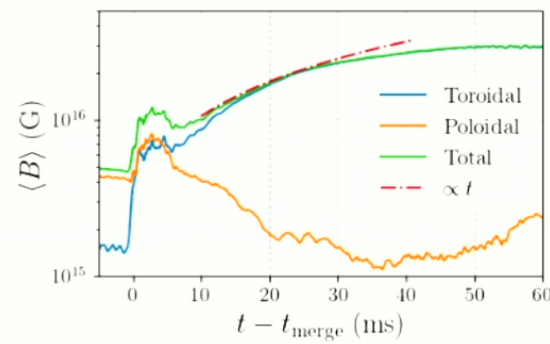
- `IllinoisGRMHD` *(Etienne et al. 2015, Werneck et al. 2023)* with APRLDP *(Akmal et al. 1998, Schneider et al. 2019)* tabulated EOS.
- Strong initial fields of $B_{max} = 6\times10^{16}$ G; $E_{mag} = 5\times10^{49}$ ergs.
- 3 Resolutions:
  - VLR: $\Delta x_{min} = 277$ m
  - LR: $\Delta x_{min} = 227$ m
  - MR: $\Delta x_{min} = 177$ m



Link with Resolution and Magnetic Fields



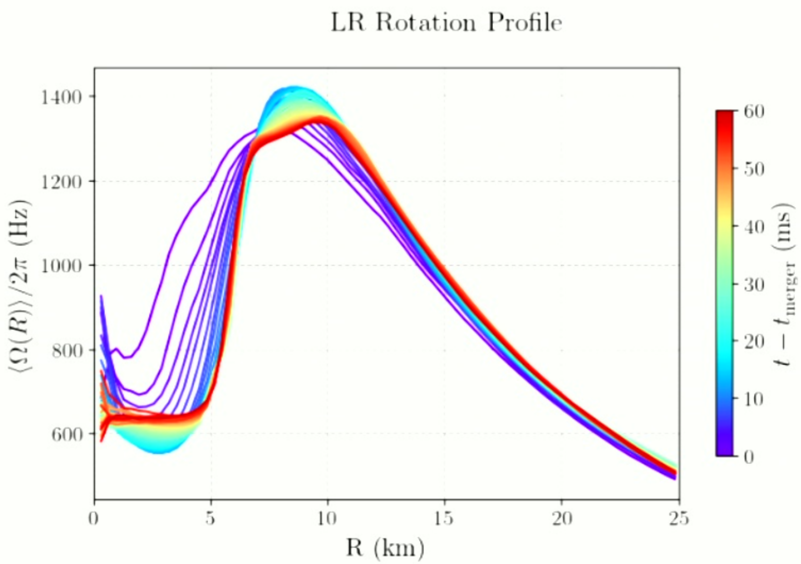


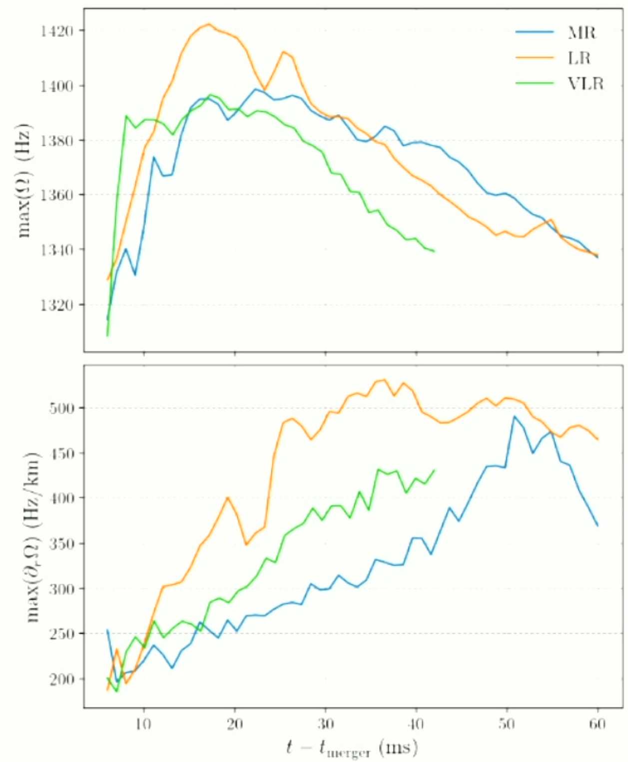


- Onset of "wobbling" also coincided with slower growth of E_{mag} often associated with magnetic braking *(e.g. Shapiro 2000, Duez et al. 2006)*.

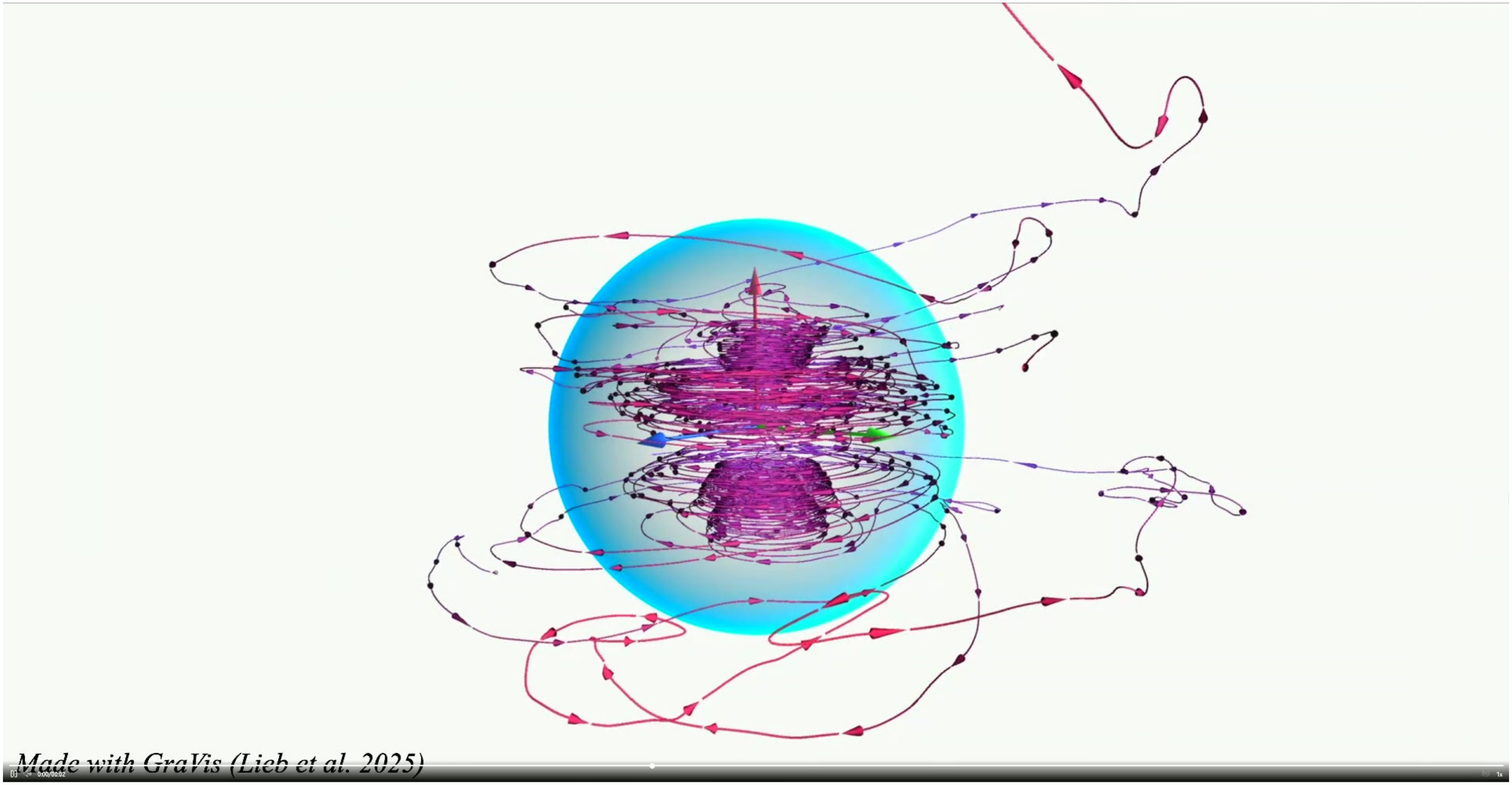
Link with Differential Rotation

- Sharp changes in profile correlate with CoM wobbling.
- Peak in rotation profile caves in.

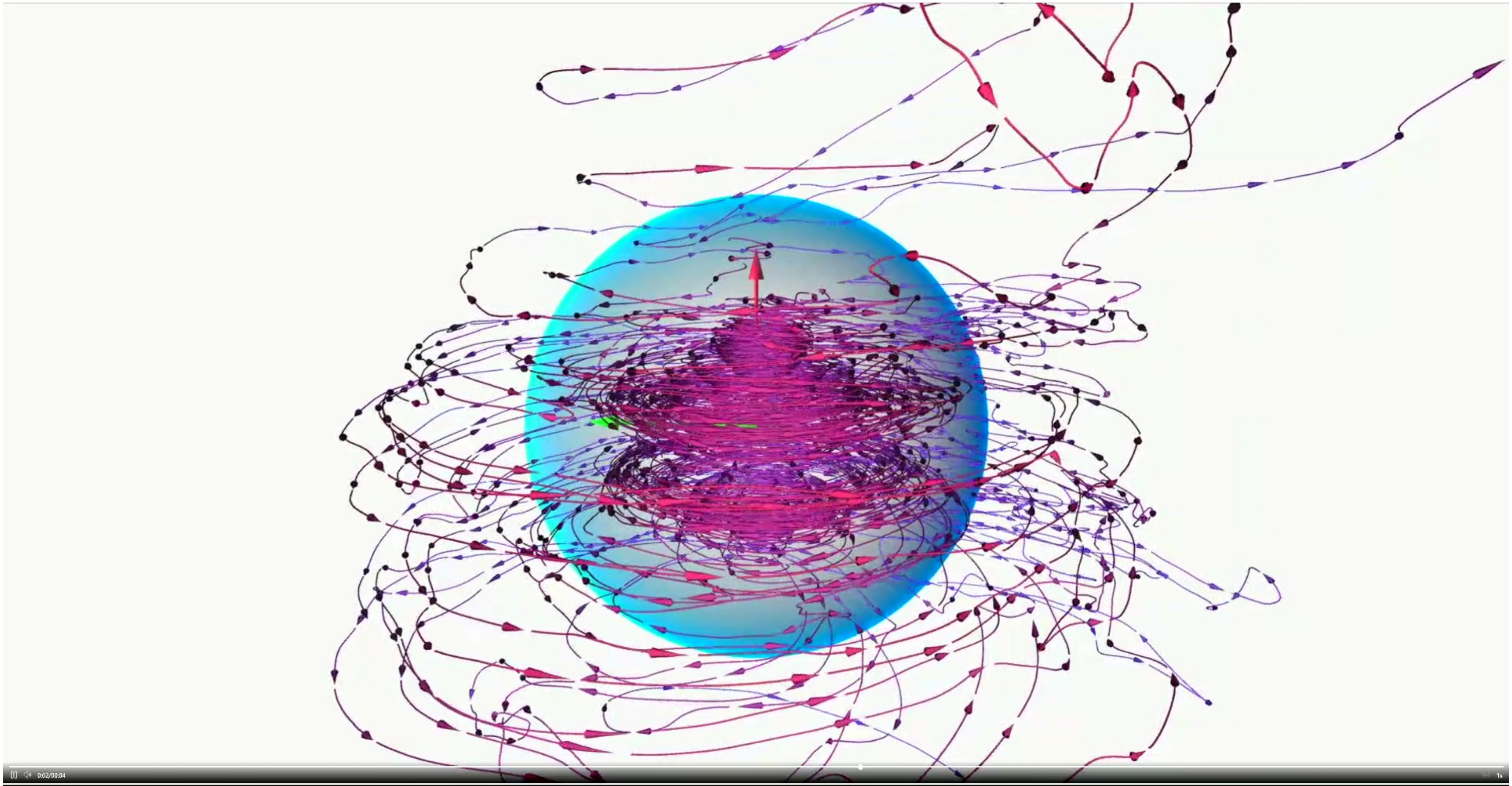




Link with Magnetic Field Structure



Made with GraVis (Lieb et al. 2025)



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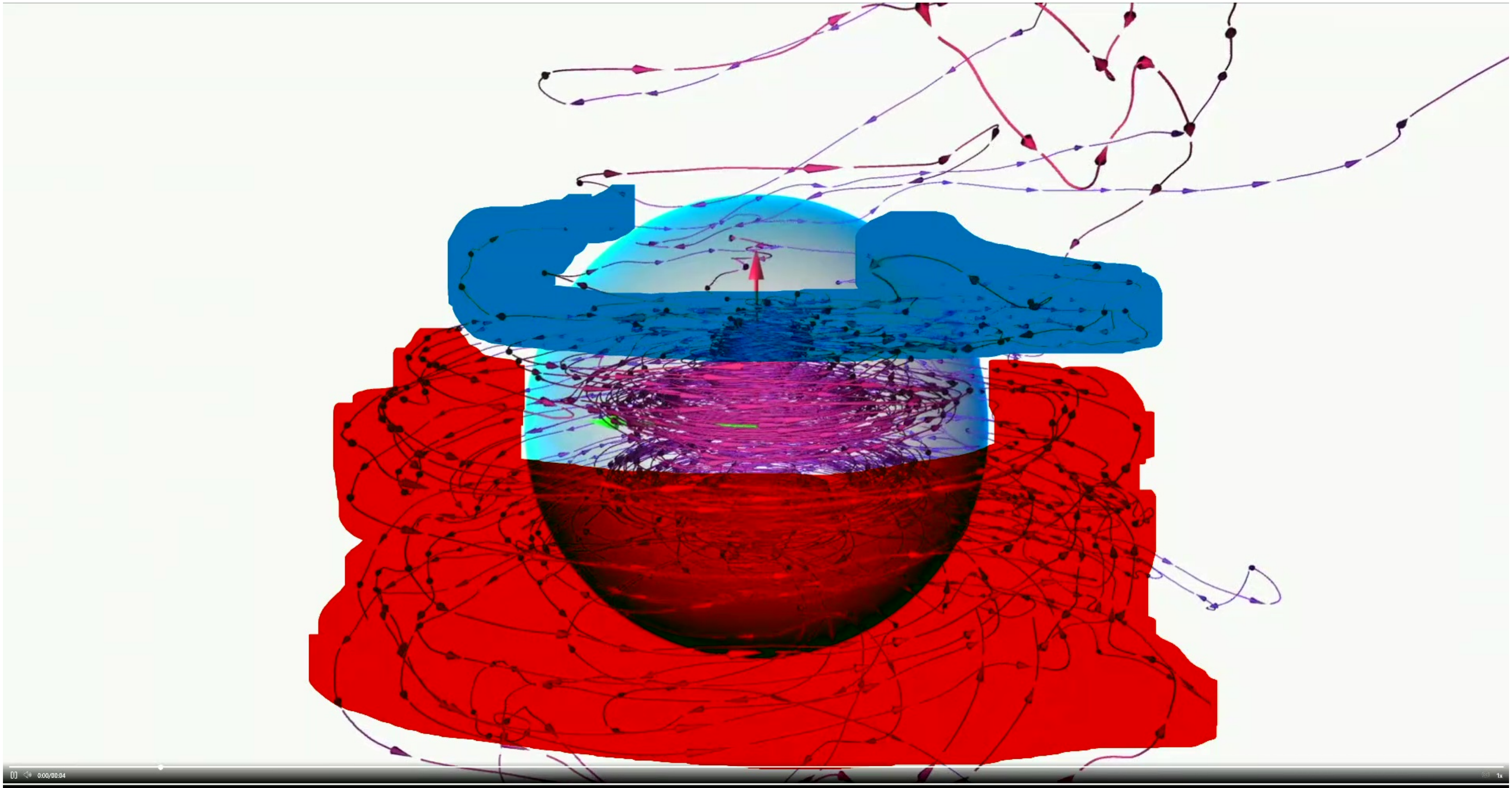

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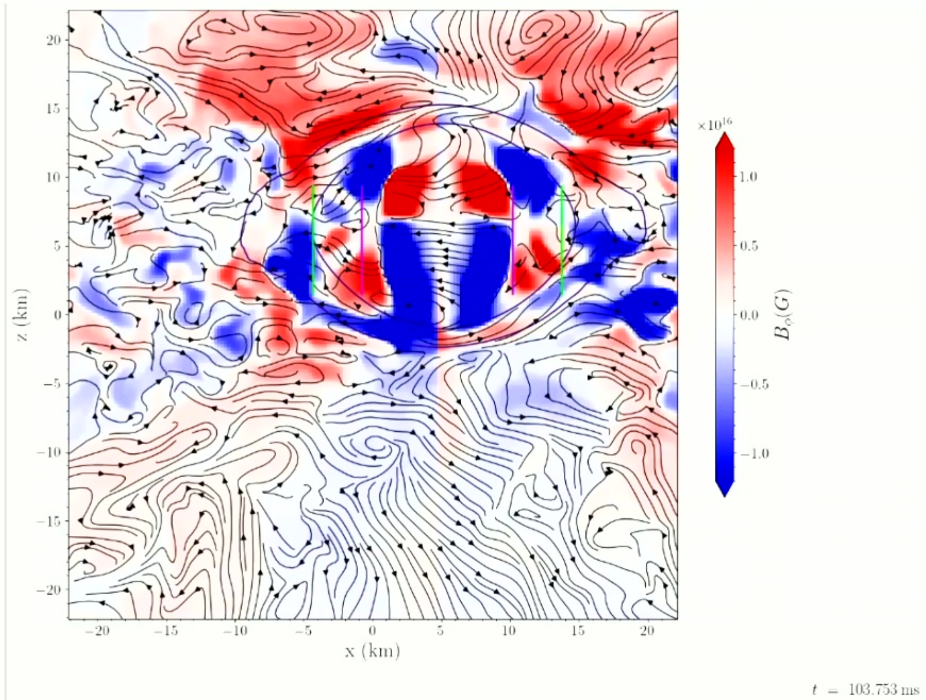
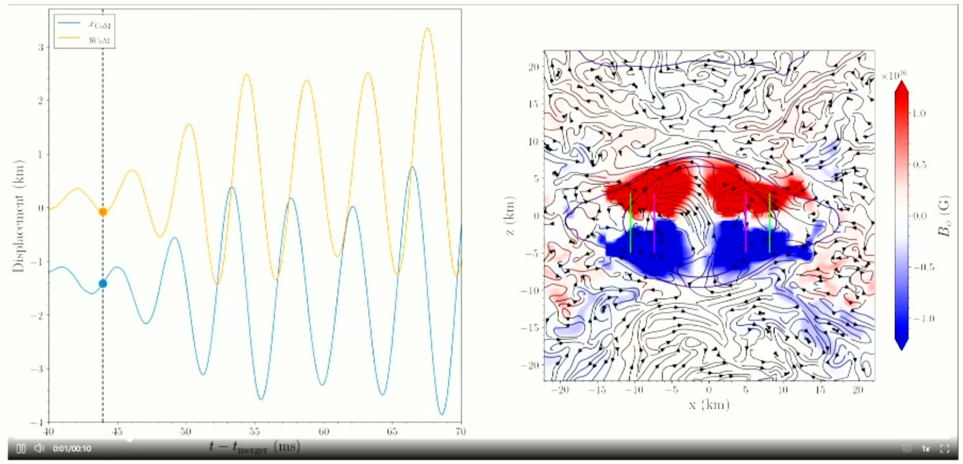
Link with Magnetic Field Structure

- Magnetic braking generates counterrotating "channels" in problematic areas on equatorial plane:
  - Outside $\max(\Omega)$
  - Between $\max(\Omega)$ and $\max(\partial_r \Omega)$
- Growth of channels slower in MR case.



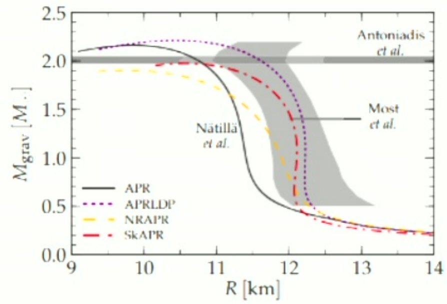
Link with Magnetic Field Structure

- Magnetic braking generates counterrotating "channels" in problematic areas on equatorial plane:
  - Between $\max(\Omega)$ and $\max(\partial_r \Omega)$
  - Outside $\max(\Omega)$
- Growth of channels slower in MR case.
- "Channel" strength and location roughly correlate with CoM motion, but source of $\sim 4-5$ ms period unclear.
  - Alfvén timescale $t_A \approx R\sqrt{\frac{M}{2E_{mag}}} = 4.8$ ms *(Lasky et al. 2011)*.

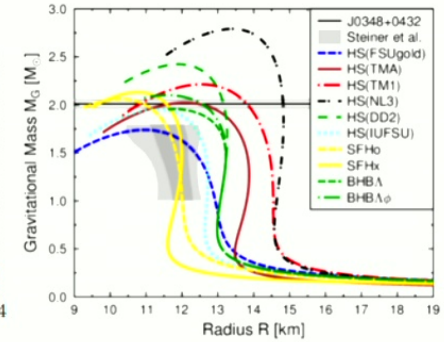


RNS Model

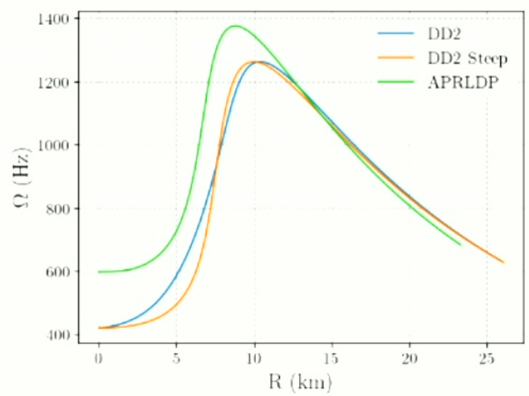
- Toy model: set HMNS rotation profile and seed with 10^{50} erg internal poloidal field to recreate strong velocity and B^i gradients.
- Improved `Hydro_RNSID` thorn *(Cassing and Rezzolla 2024)* sets realistic postmerger profiles *(Uryu et al. 2017)*.
- 3 Tests at VLR:
  - DD2 EOS, Ω profile matching simulation from *Cassing and Rezzolla 2024.*
  - APRLDP EOS, Ω profile matching MR BNS.
  - DD2 EOS, prescribing steeper Ω profile by hand to match APRLDP case.



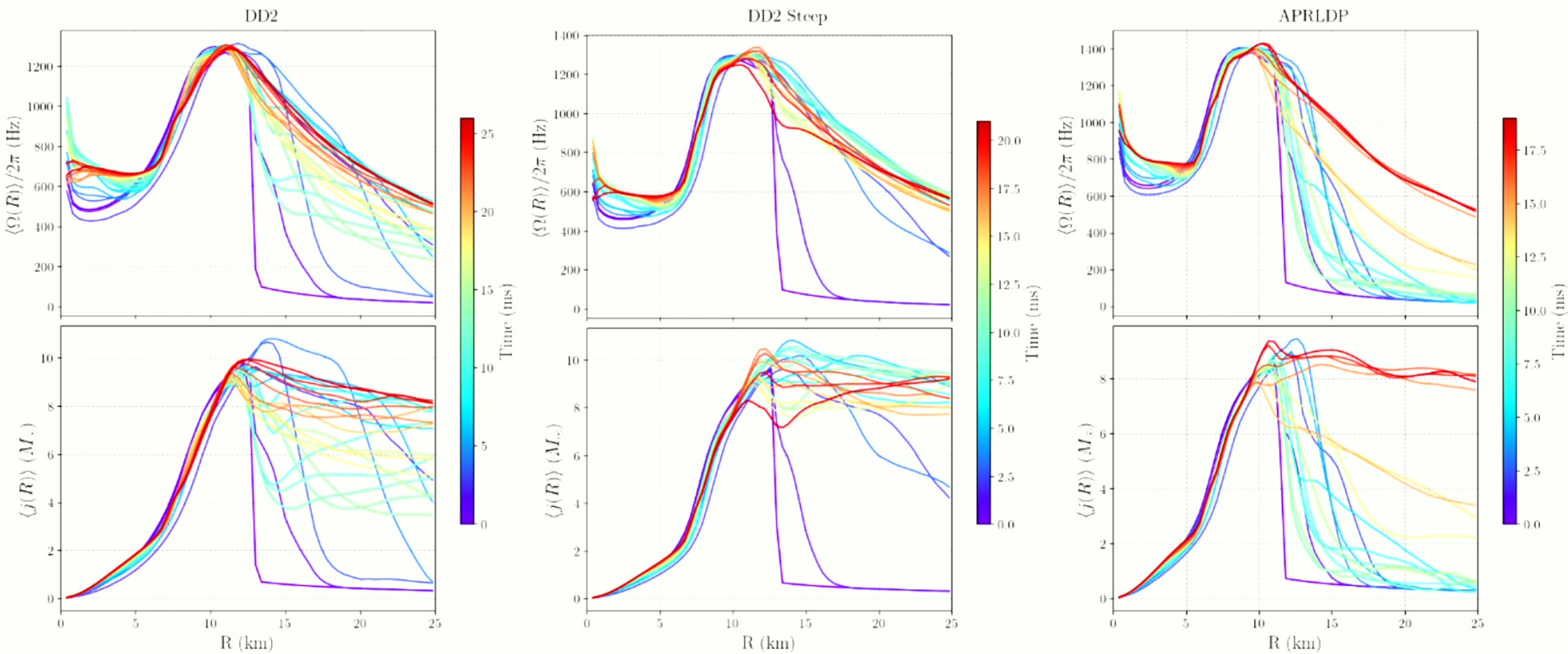
Schneider et al. 2019



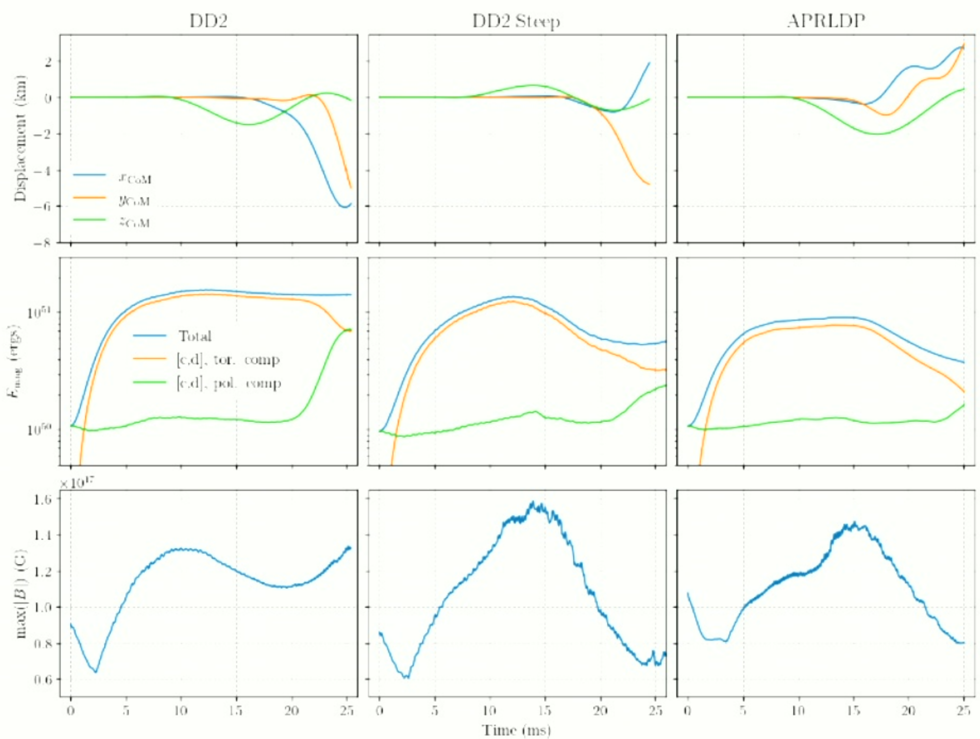
Hempel et al. 2012

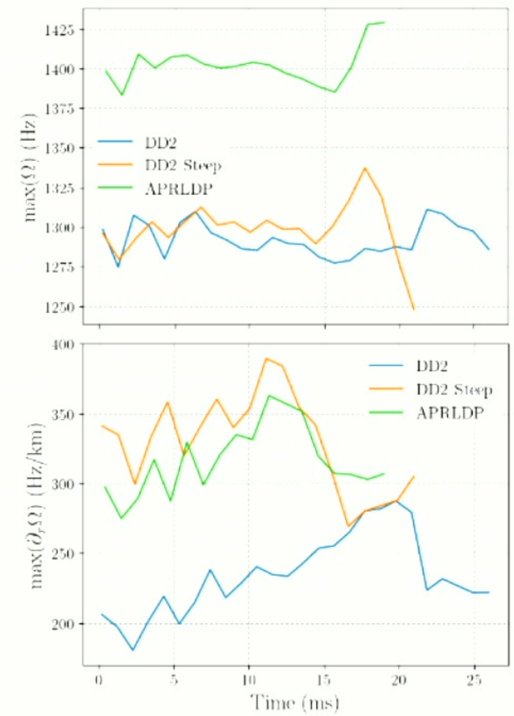


RNS Rotation Profiles

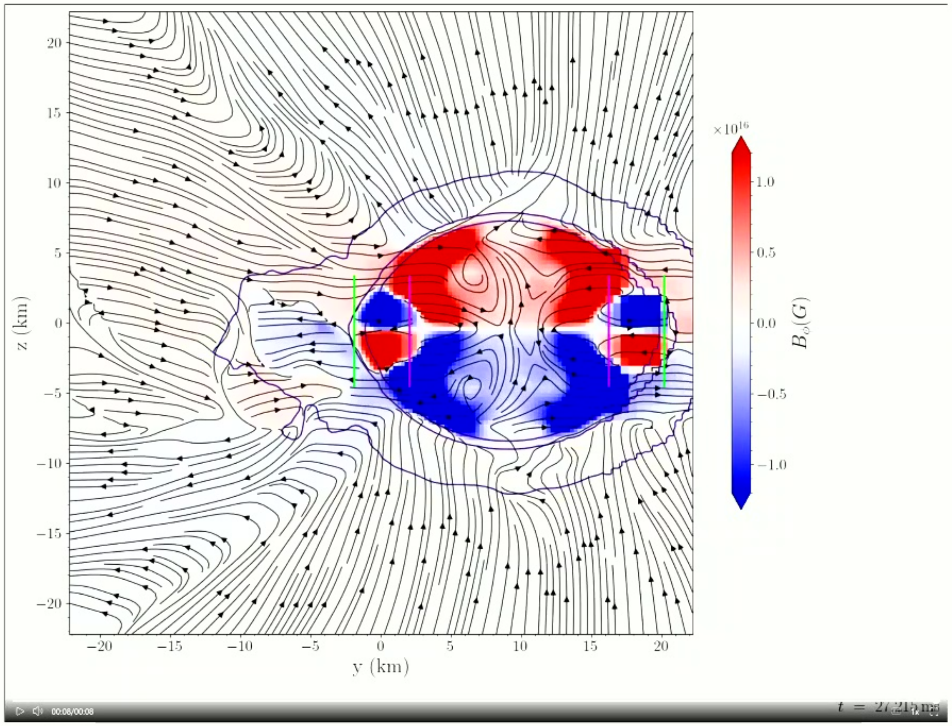


RNS Magnetic Fields





RNS Magnetic Fields



Conclusions and Future Work

- Particular combinations of numerical methods, magnetic field strengths, resolution, and/or EOS may be problematic.
- Apply lessons from RNS to BNS.
- Repeat RNS simulations at much higher resolution, compare evolution with uniform or j-constant rotation profiles *(e.g. Siegel et al. 2014, Siegel et al. 2017, Tsokaros et al. 2022)*, model dynamo/MRI activity in the remnant seen in high resolution simulations *(Kiuchi et al. 2024)*.

Thanks for listening!