

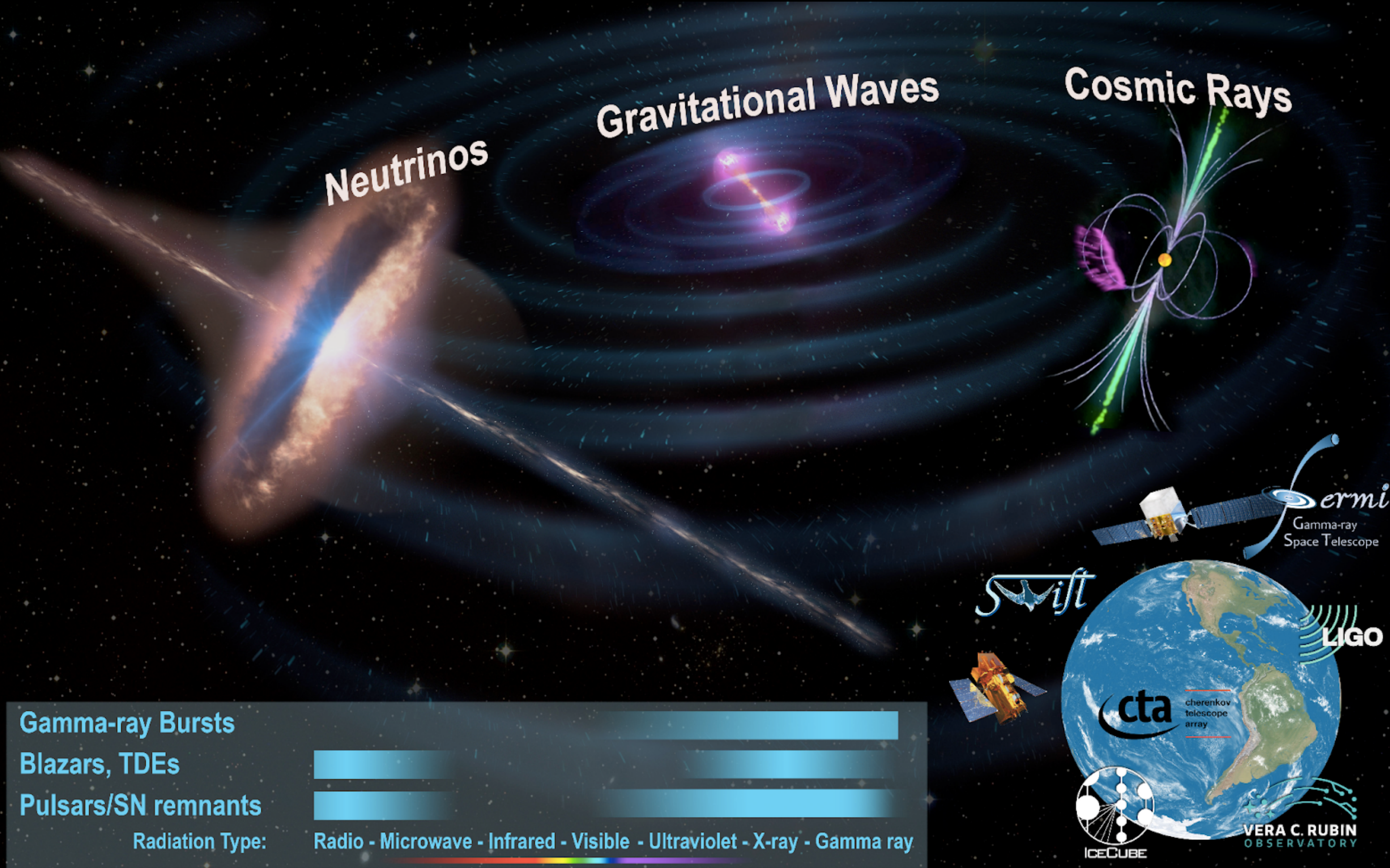
IMPACT OF MAGNETIC FIELD TOPOLOGY ON ELECTROMAGNETIC AND GRAVITATIONAL WAVES FROM BINARY NEUTRON STAR MERGERS

INÊS RAINHO
UNIVERSITAT DE VALÈNCIA

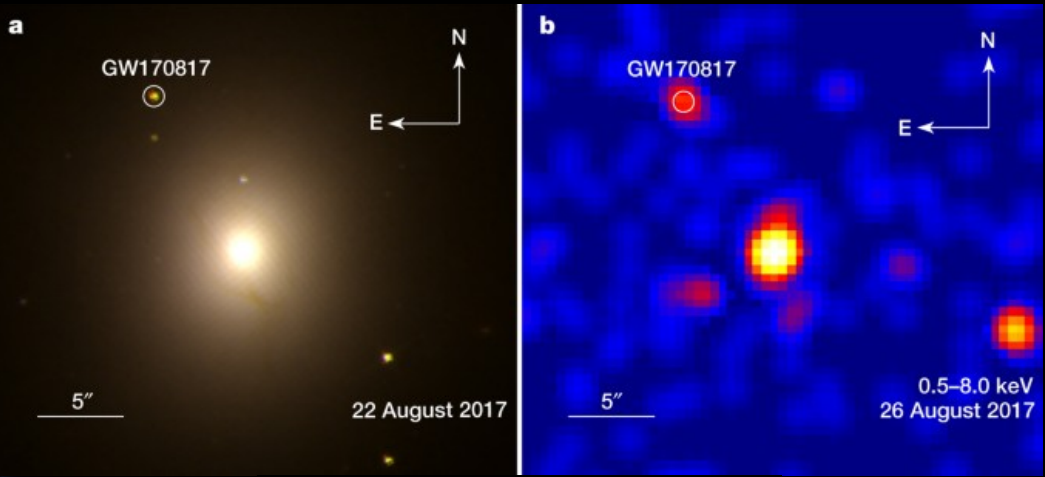
IN COLLABORATION WITH JAMIE BAMBER, DAVIDE GUERRA, MIQUEL MIRAVET-TENÉS, MILTON RUIZ, ANTONIOS TSOKAROS, STUART L. SHAPIRO

OBSERVING THE UNIVERSE

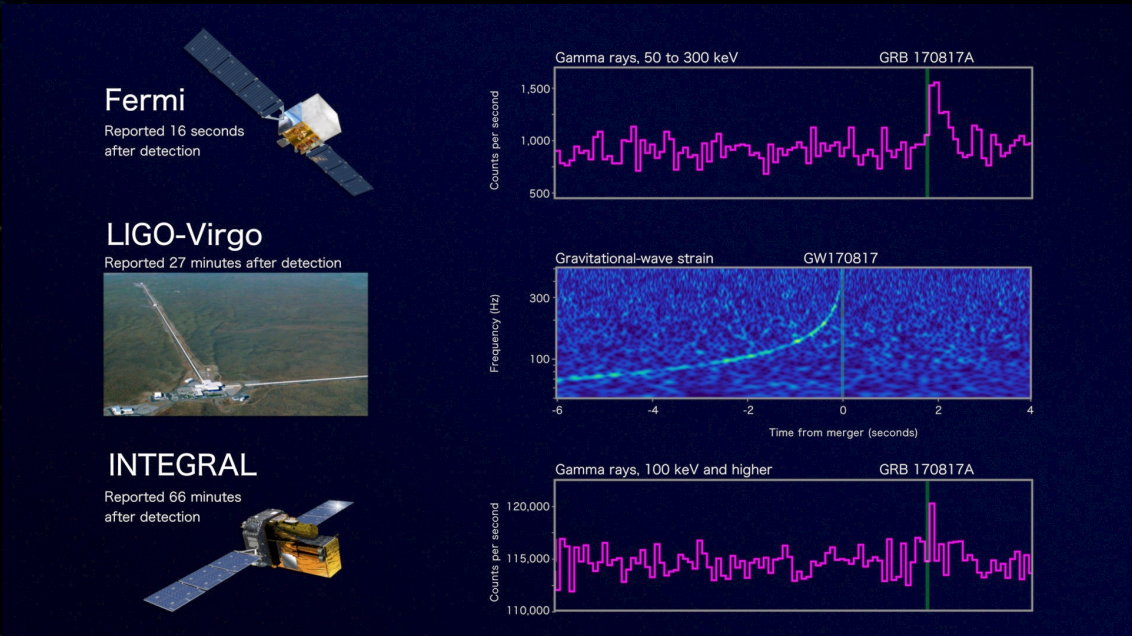
GRAVITATIONAL AND ELECTROMAGNETIC SIGNALS



GW170817



Troja E. et al., Nature 551, 71-74 (2017)



NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

NEUTRON STARS' MAGNETIC FIELDS

- Typically, **purely poloidal** fields are considered

NICER
observations
J0030+0451

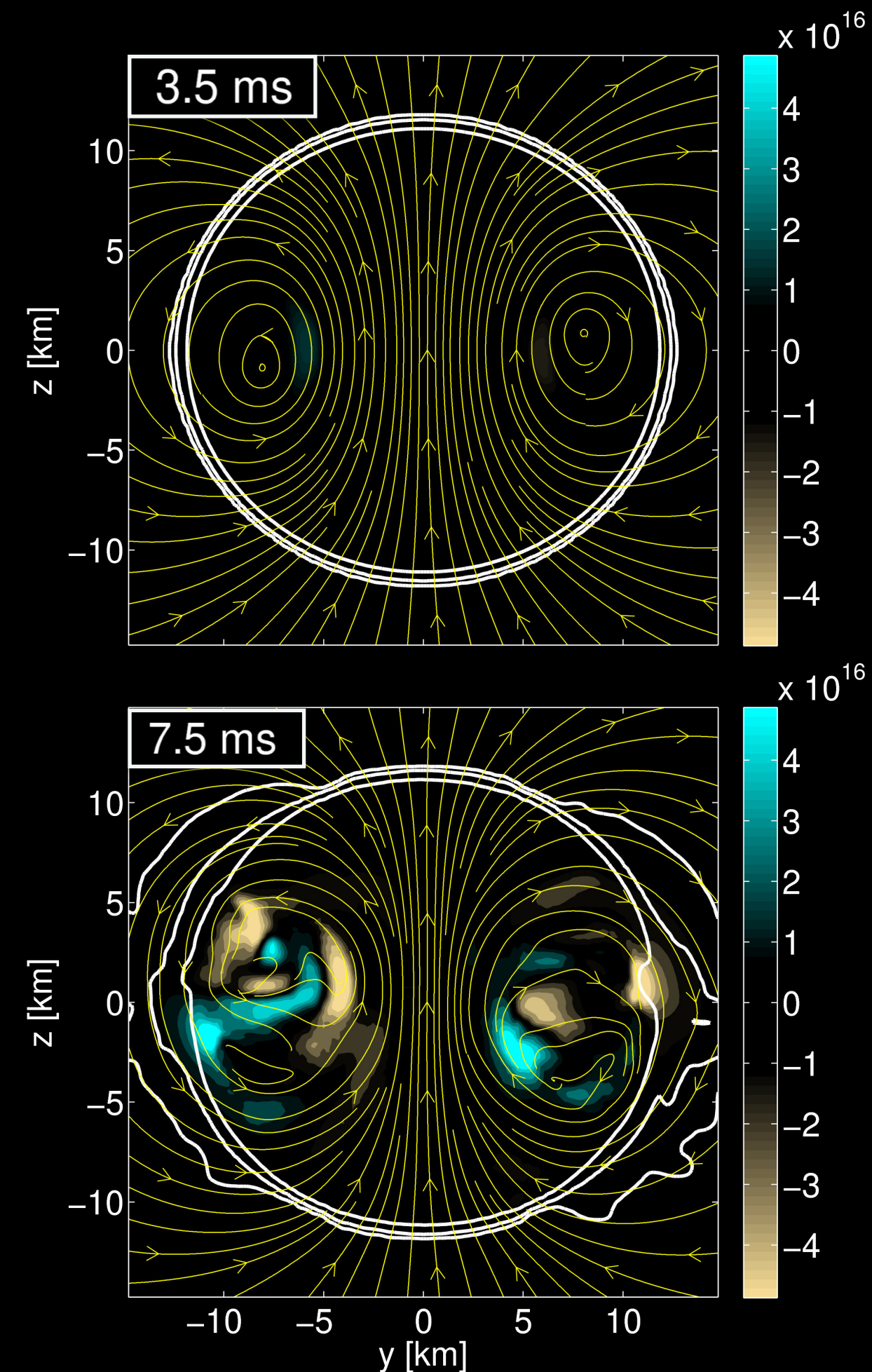


NASA's Goddard Space Flight Center

- 2/3 hot spots only in the southern hemisphere

⇒ non-dipolar magnetic field!

PURELY
POLOIDAL
FIELDS ARE
NOT STABLE...



Riccardo Cioffi (2014)

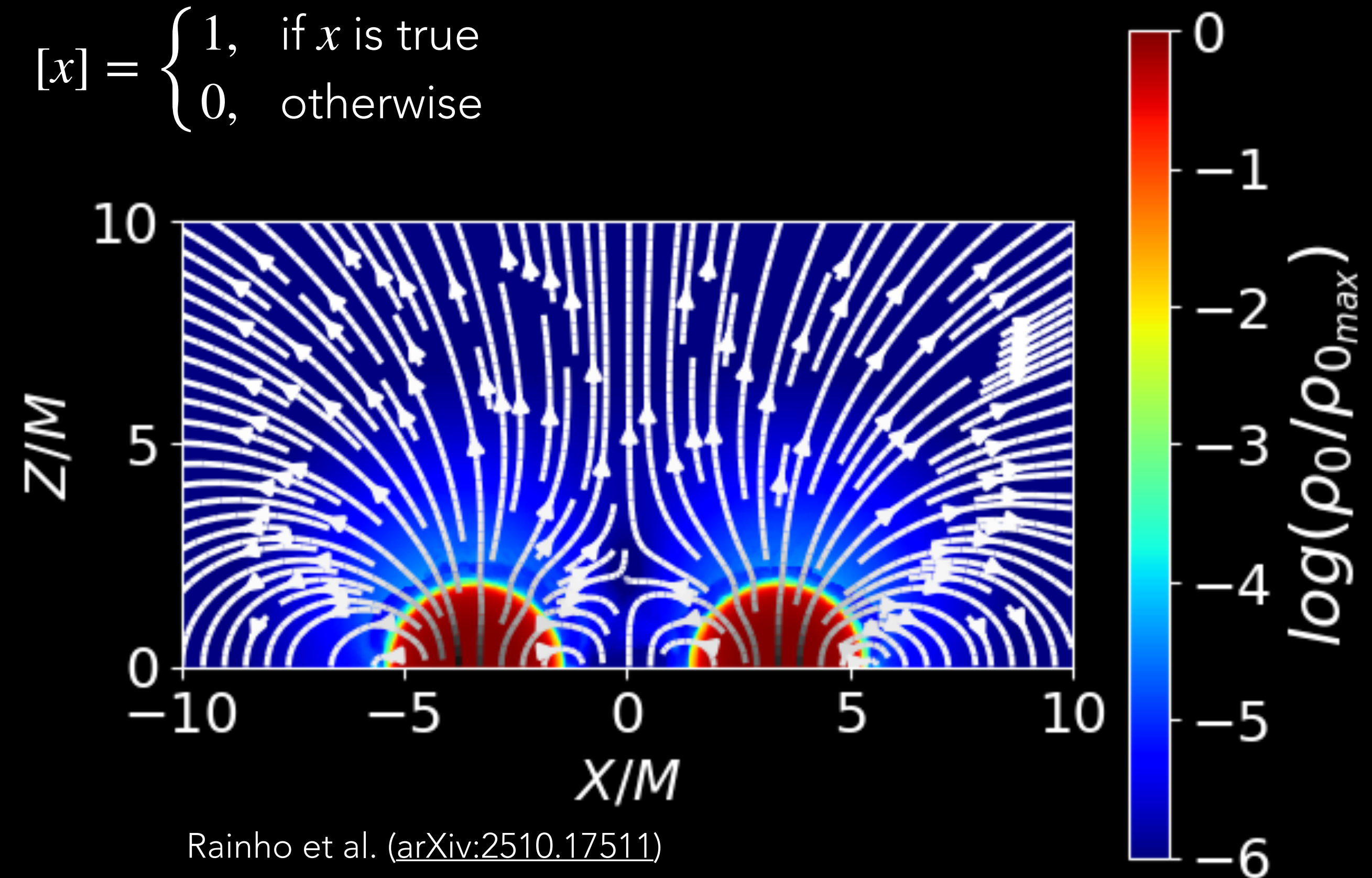
MAGNETIC FIELD MODELS

More general scenario with exterior dipole

$$\mathbf{A} = a_T \mathbf{A}_T [r < R_{NS}] + (1 - a_T) \mathbf{A}_P$$

$$[x] = \begin{cases} 1, & \text{if } x \text{ is true} \\ 0, & \text{otherwise} \end{cases}$$

- $a_T = 0 \rightarrow$ purely poloidal (P)



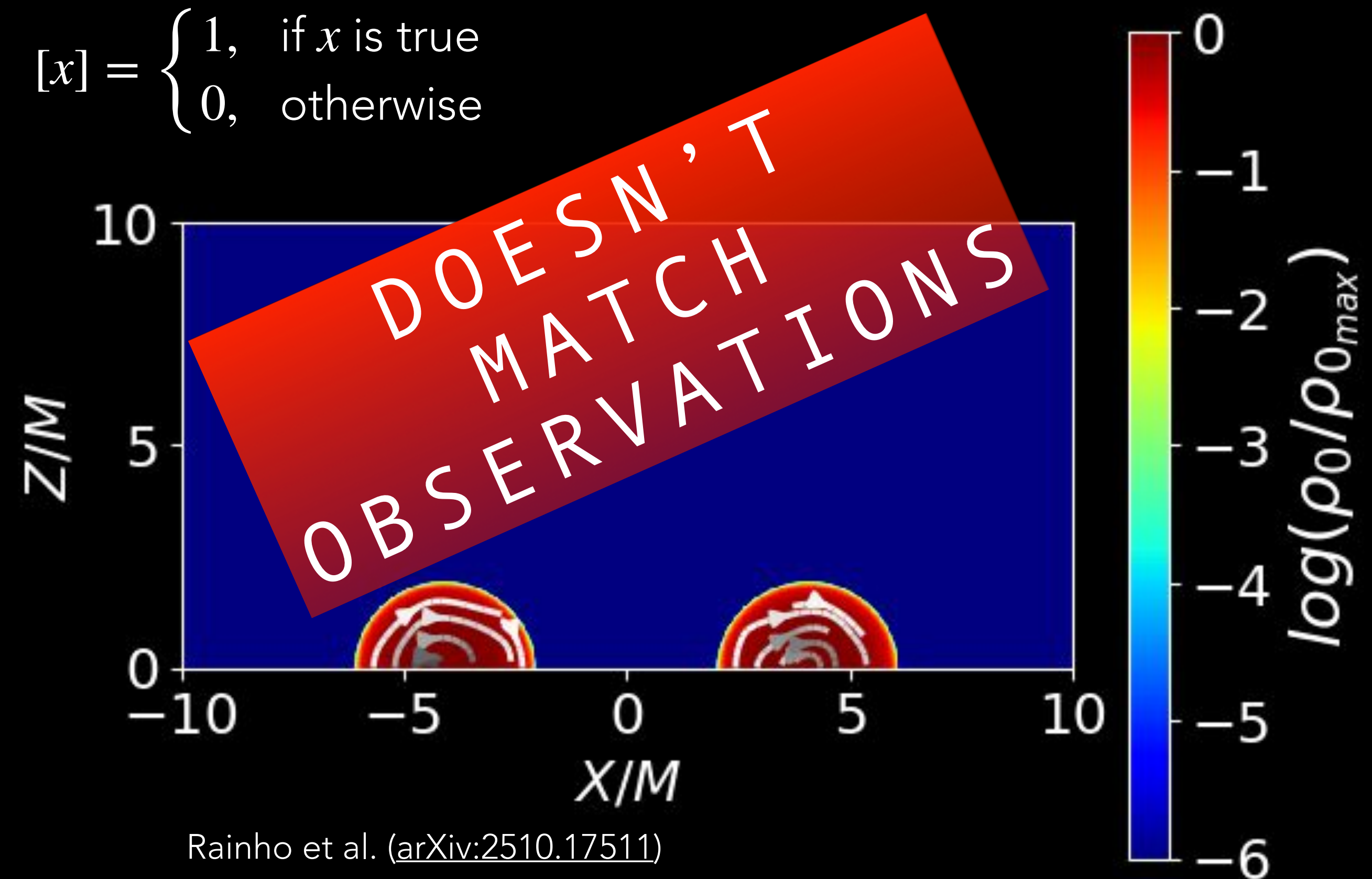
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- $a_T = 0 \rightarrow$ purely poloidal (P)
- $a_T = 1 \rightarrow$ no exterior component

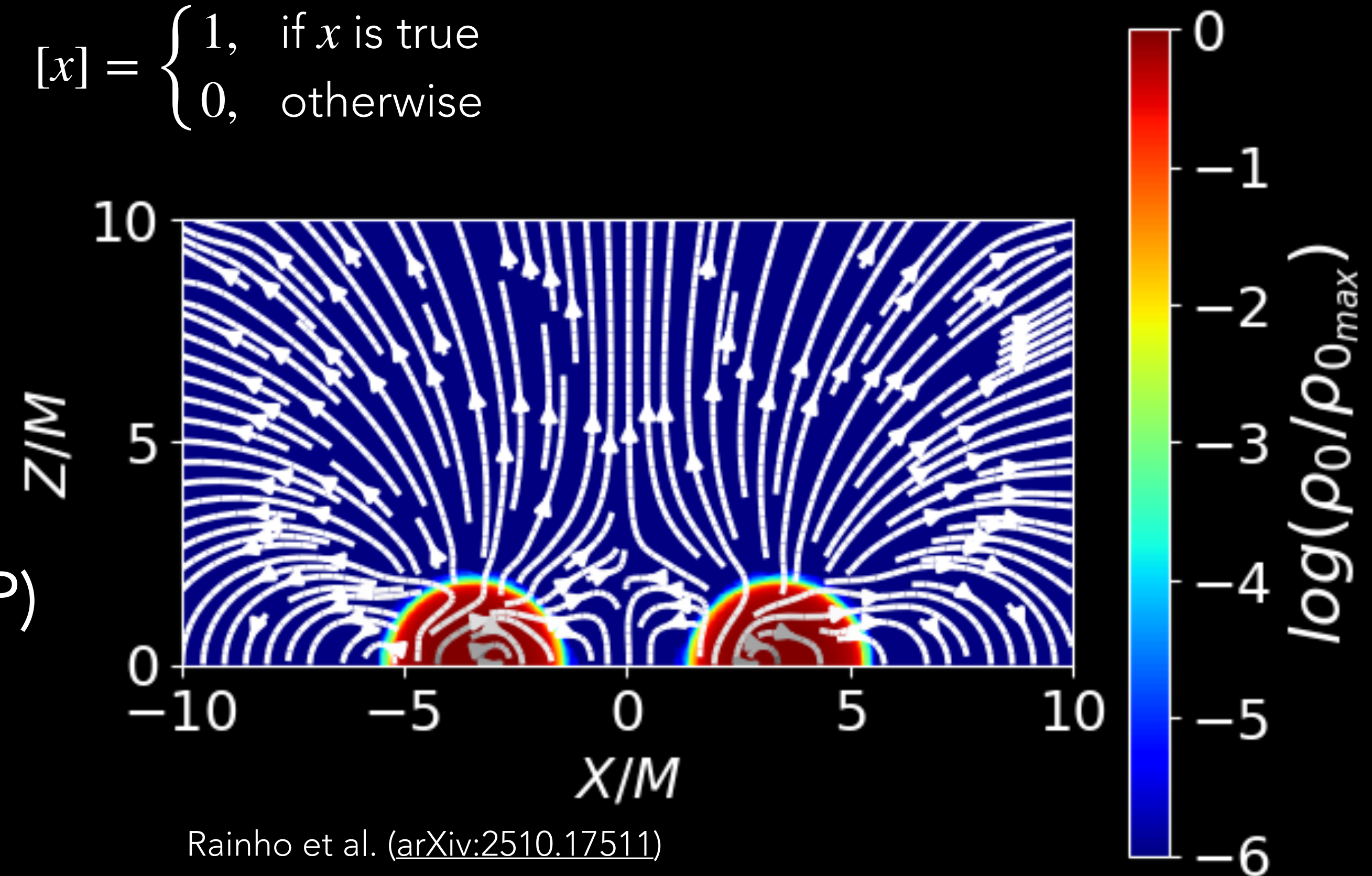


MAGNETIC FIELD MODELS

More general scenario with exterior dipole

$$\mathbf{A} = a_T \mathbf{A}_T [r < R_{NS}] + (1 - a_T) \mathbf{A}_P \quad [x] = \begin{cases} 1, & \text{if } x \text{ is true} \\ 0, & \text{otherwise} \end{cases}$$

- $a_T = 0 \rightarrow$ purely poloidal (P)
- $a_T = 1 \rightarrow$ no exterior component
- $a_T = 0.5 \rightarrow$ linear superposition (SP)



MAGNETIC FIELD MODELS

More general scenario with exterior dipole

TO COMPARE THE DIFFERENT CONFIGURATIONS, SET

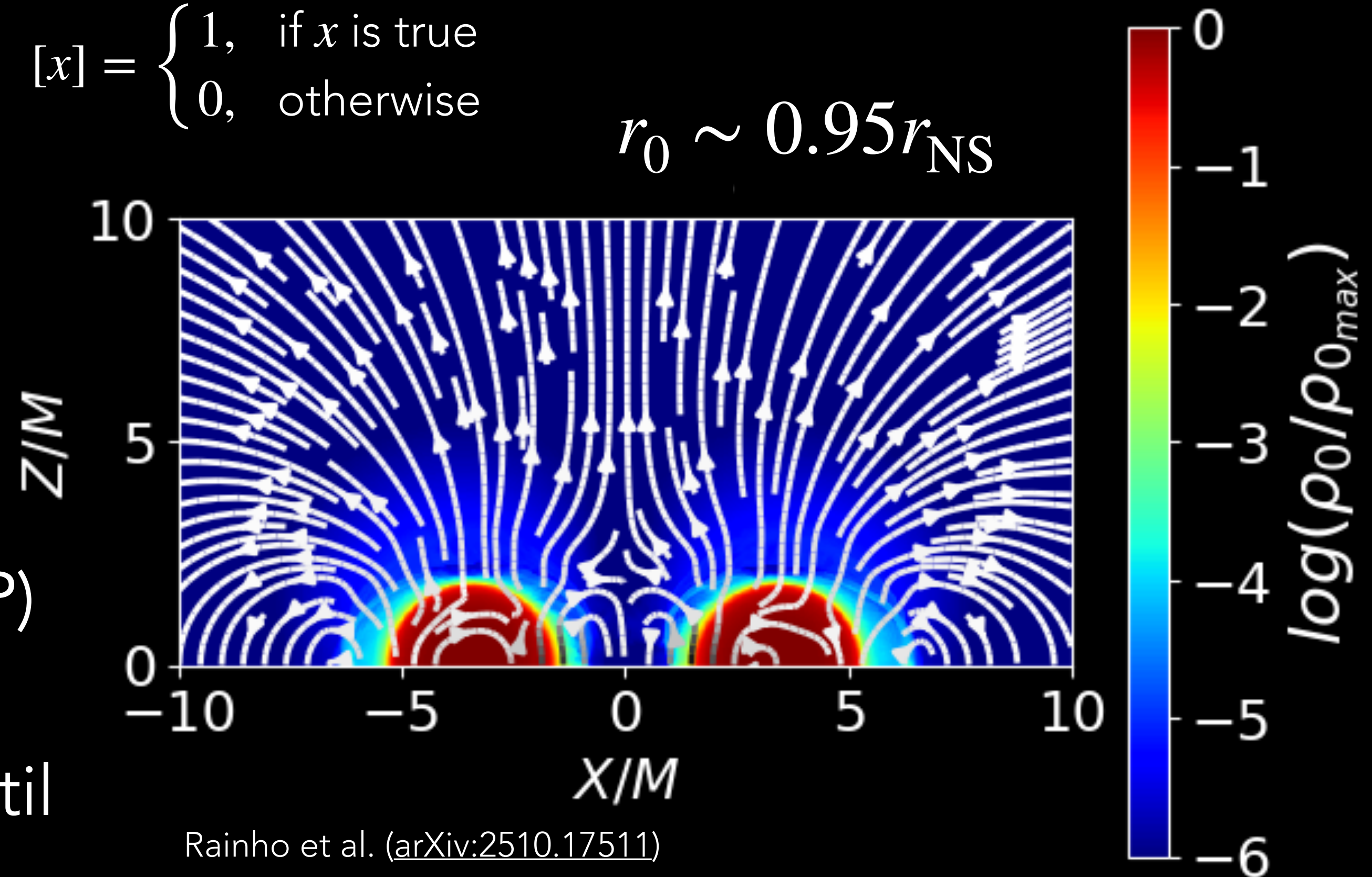
$$\beta^{-1} \equiv \frac{P_{\text{mag}}}{P_{\text{gas}}} = 0.003125$$

$$\mathbf{A} = a_T \mathbf{A}_T[r < R_{\text{NS}}] + (1 - a_T) \mathbf{A}_P$$

$$[x] = \begin{cases} 1, & \text{if } x \text{ is true} \\ 0, & \text{otherwise} \end{cases}$$

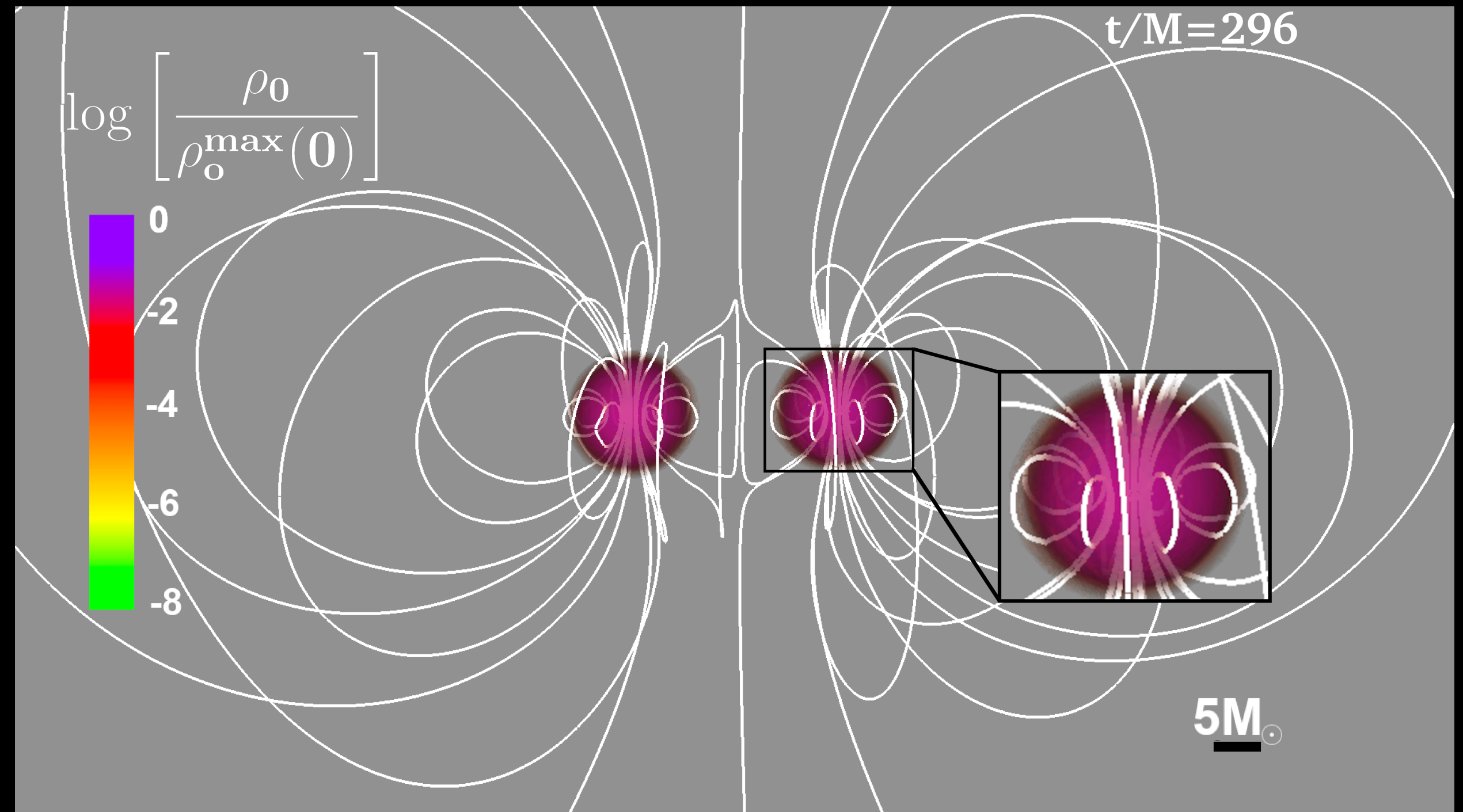
$$r_0 \sim 0.95 r_{\text{NS}}$$

- $a_T = 0 \rightarrow$ purely poloidal (P)
- $a_T = 1 \rightarrow$ no exterior component
- $a_T = 0.5 \rightarrow$ linear superposition (SP)
- $a_T = e^{-\left(\frac{r}{r_0}\right)^{2p}} \rightarrow$ "tilted" toroidal until $\sim r_0$ (τ_{r_0})



NUMERICAL SETUP FOR GRMHD SIMULATIONS

- Initial data from **COCAL**
 - **EOS**: SLy and WFF1
- **Illinois GRMHD** code
 - BSSN formulation + puncture gauge conditions
- Ideal MHD



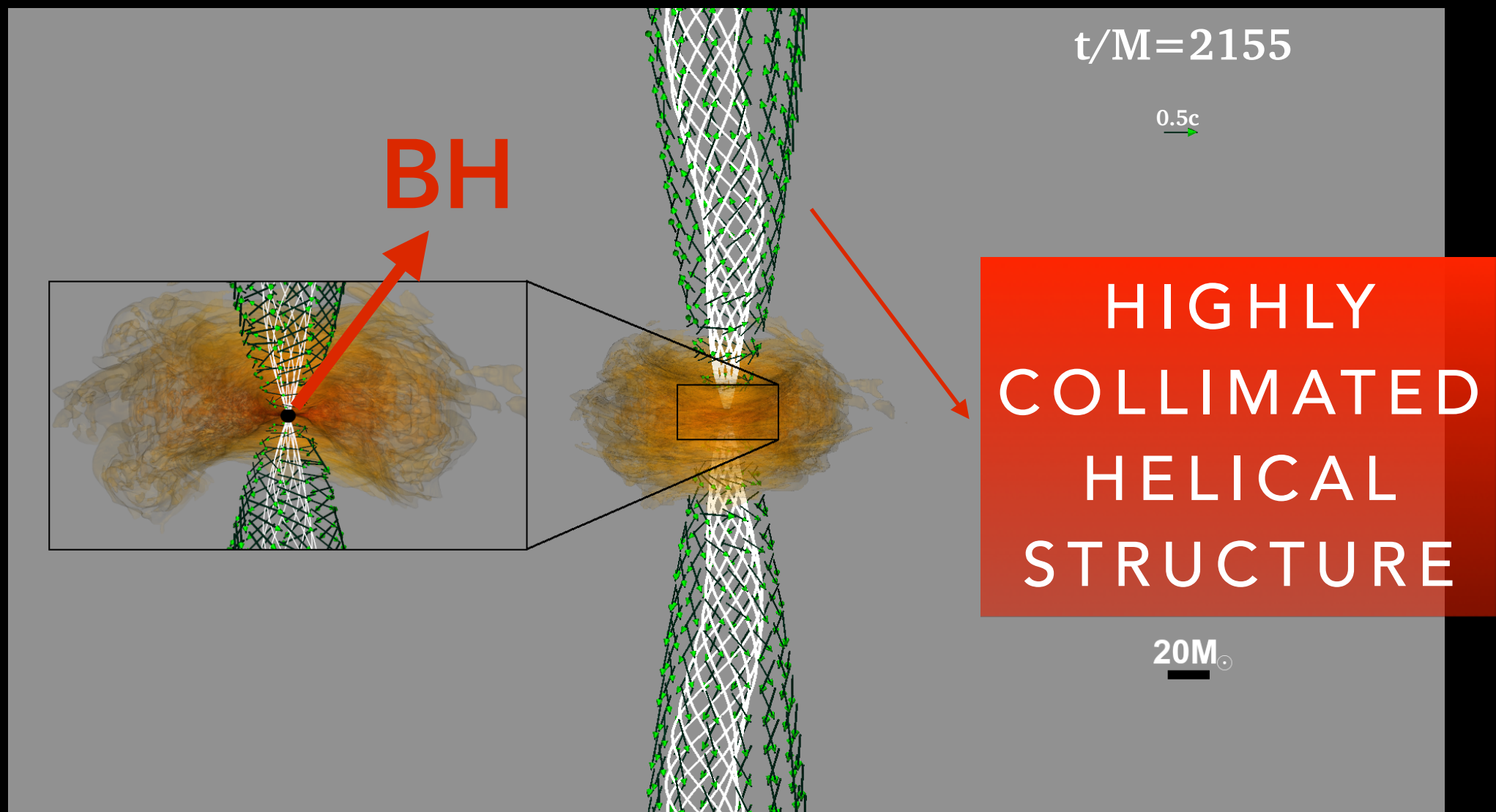
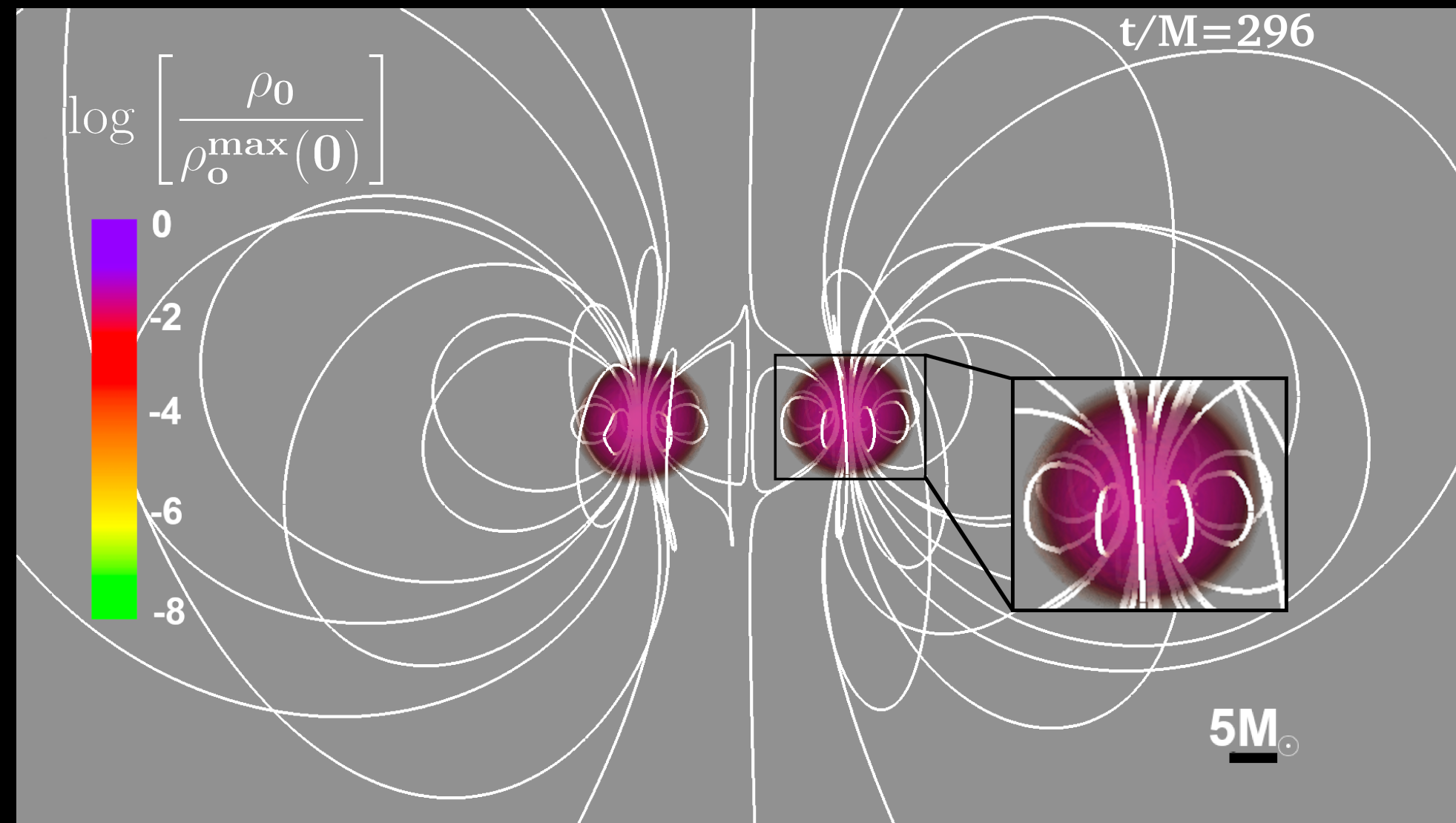
Rainho et al. ([arXiv:2510.17511](https://arxiv.org/abs/2510.17511))

ELECTROMAGNETIC SIGNALS: INCIPIENT JET

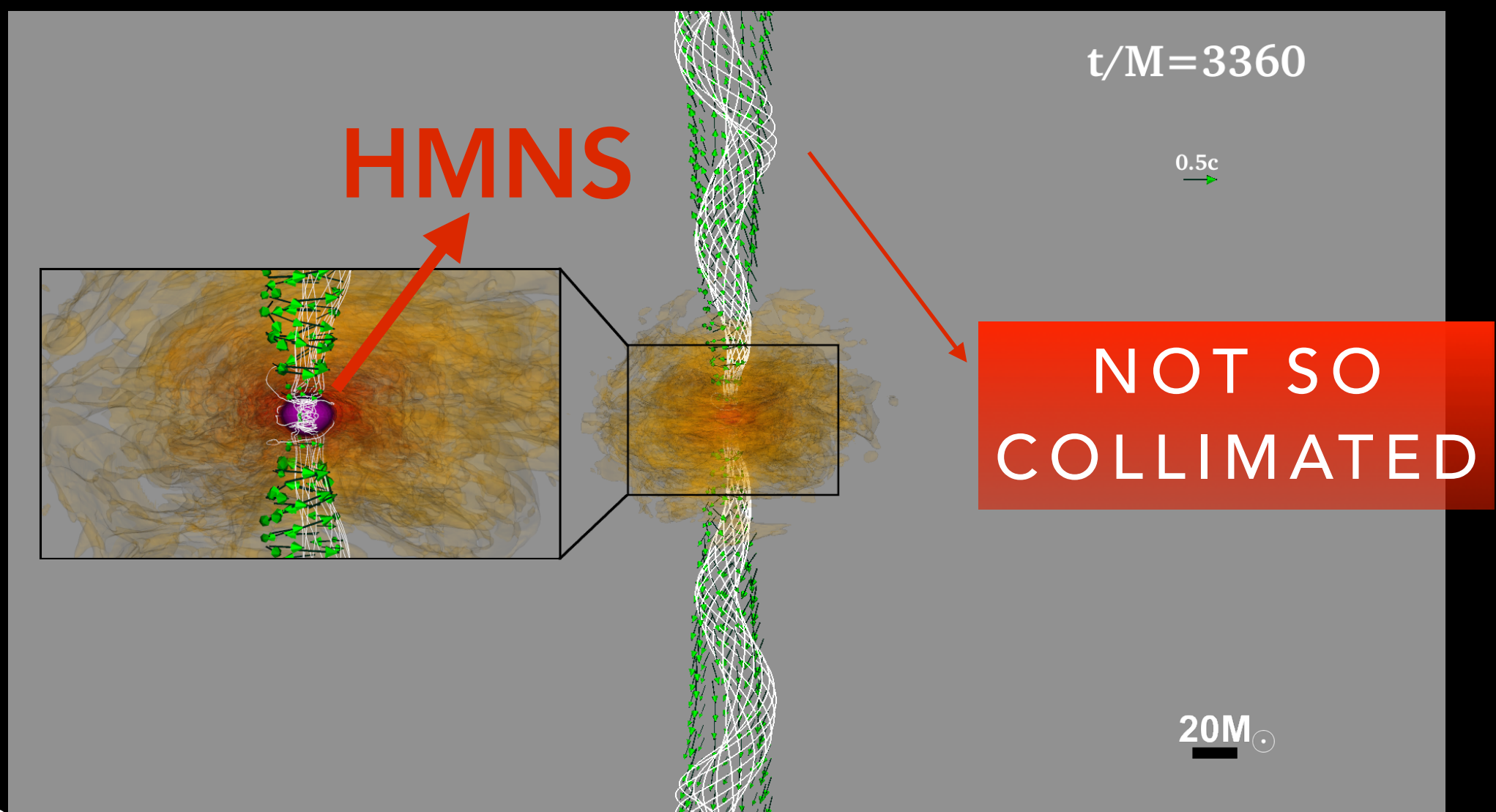
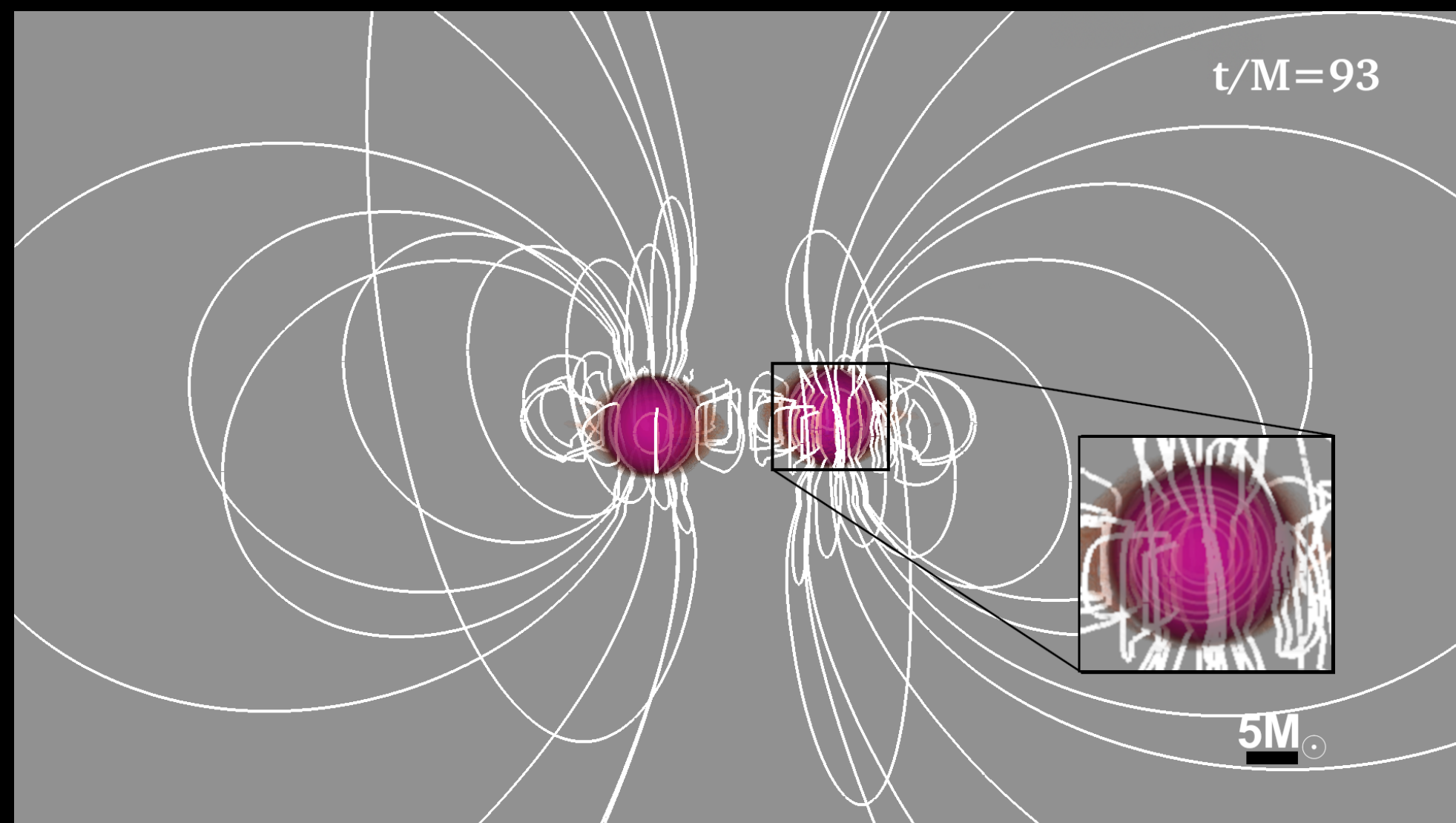
SLy

Before

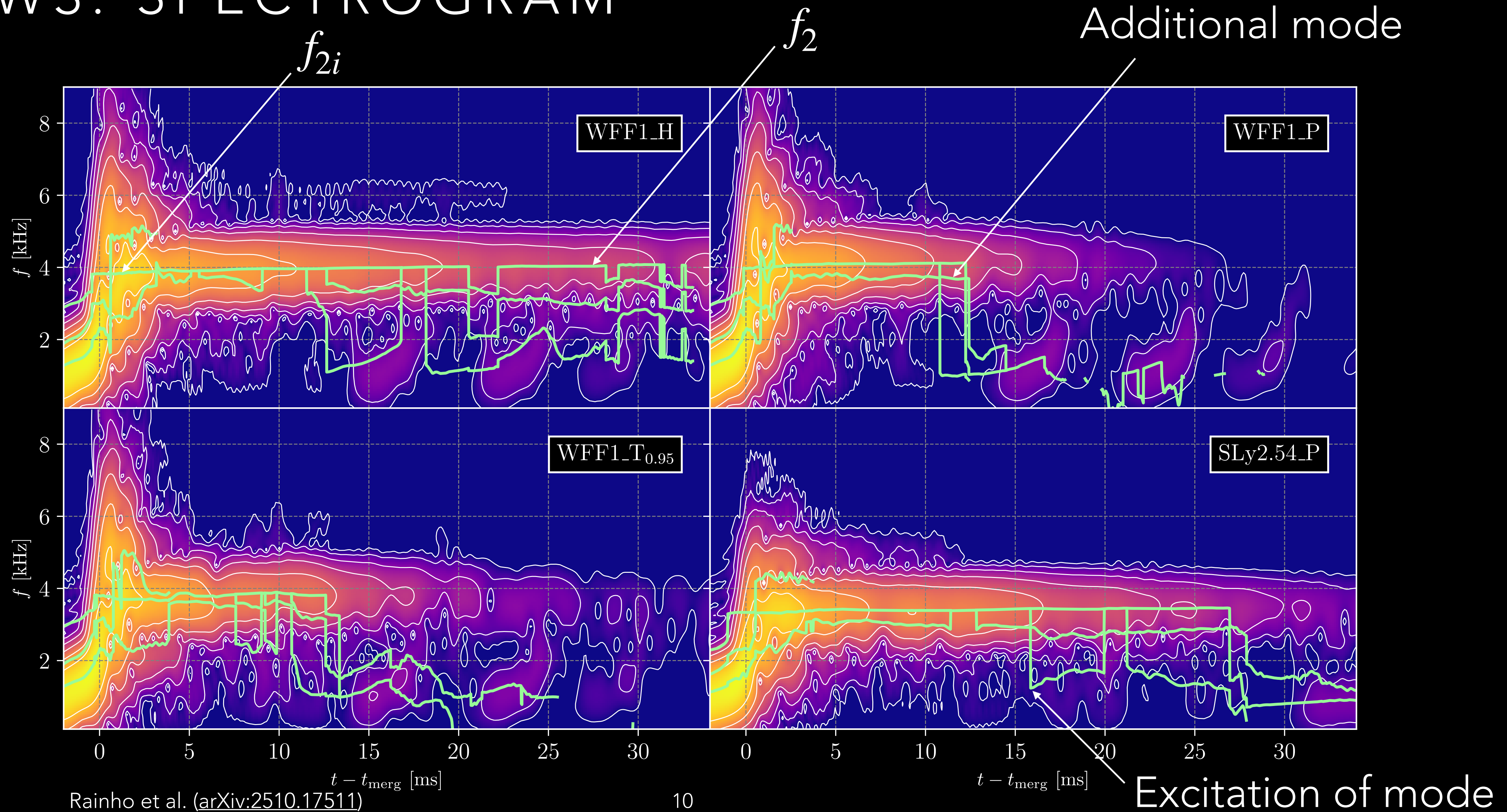
After



WFF1



GWS: SPECTROGRAM



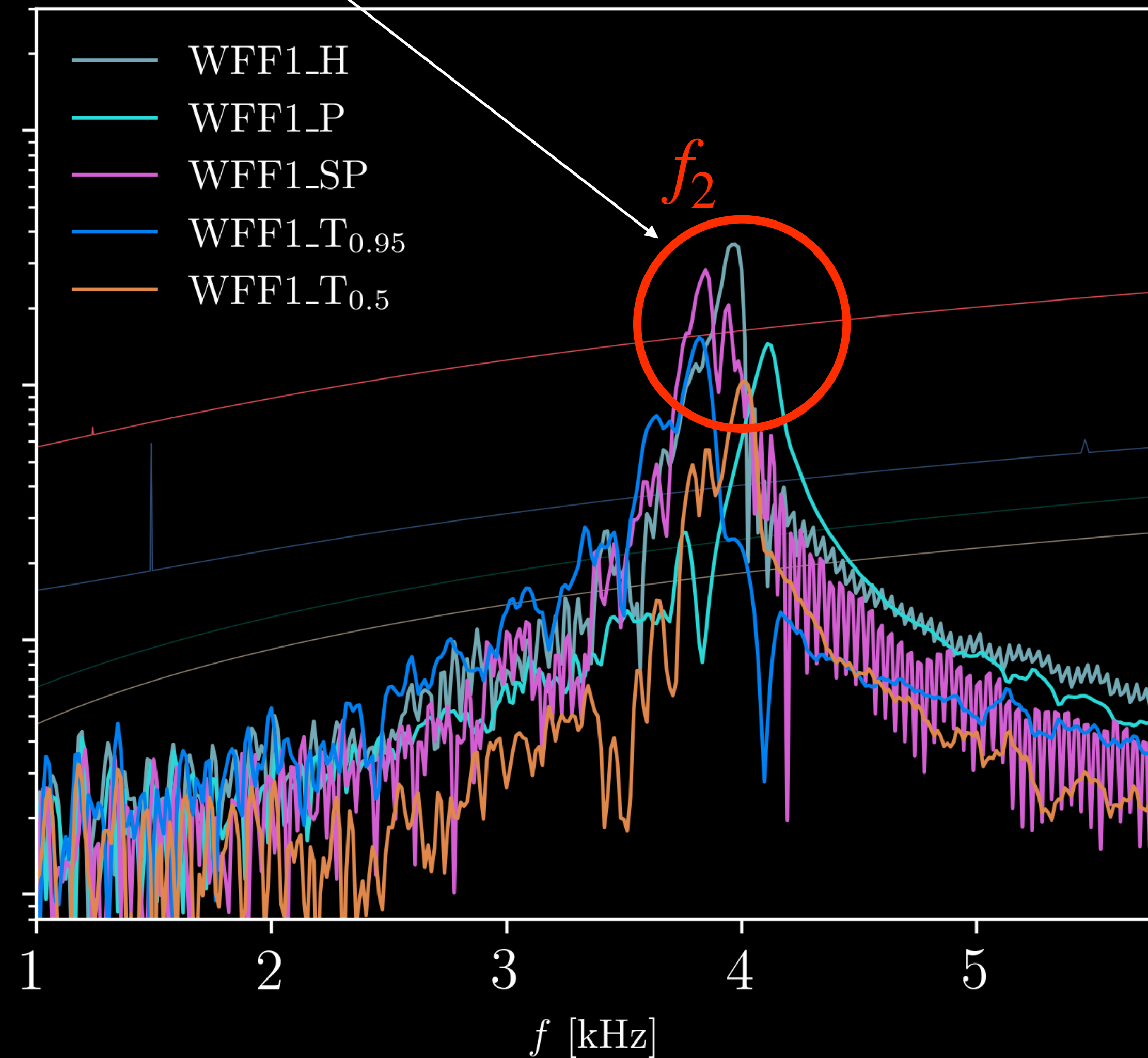
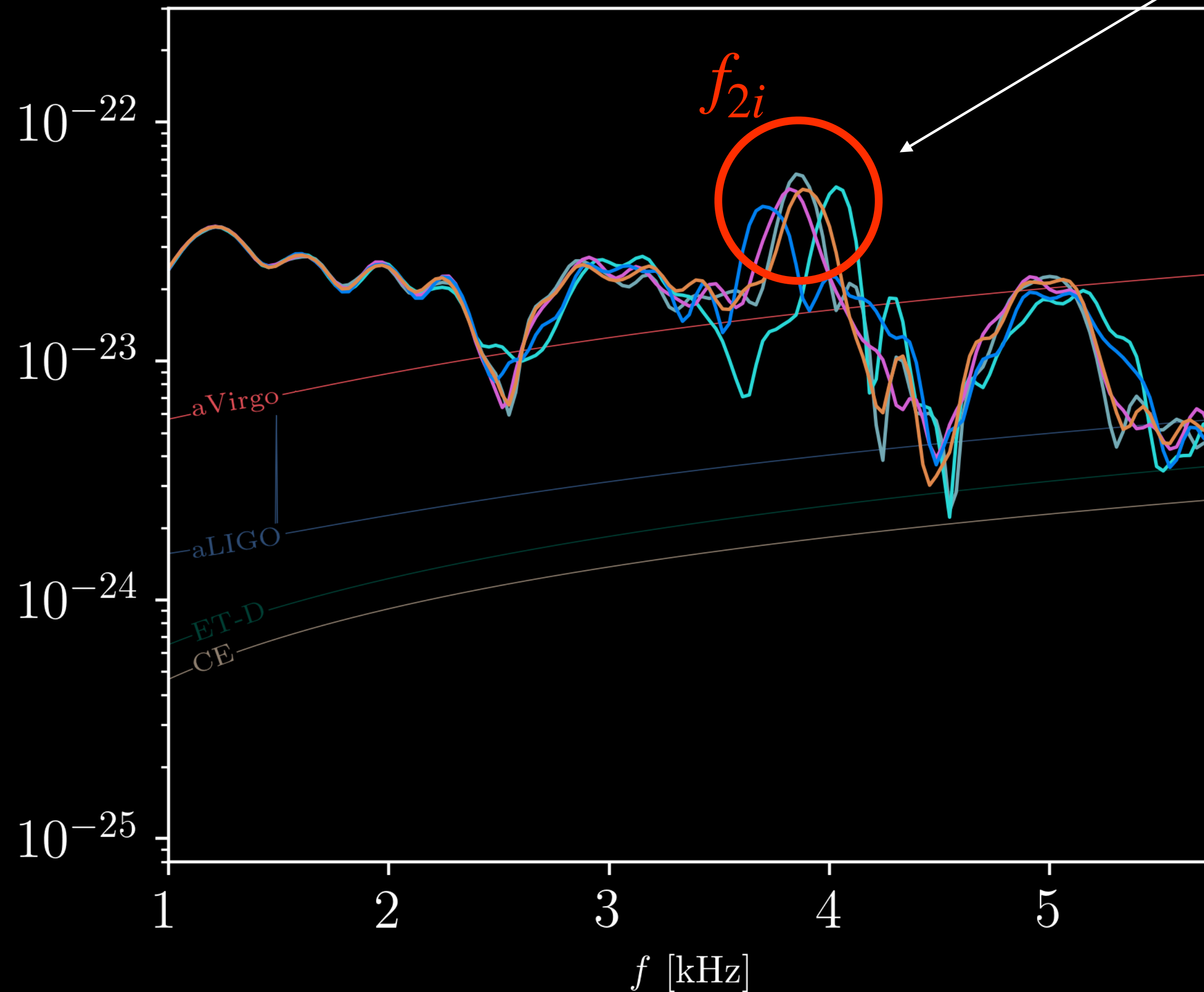
GWS: FREQUENCY SHIFT

SHIFT IN THE
PEAK FREQUENCY!

-5ms up to 6ms

6ms up to 30ms

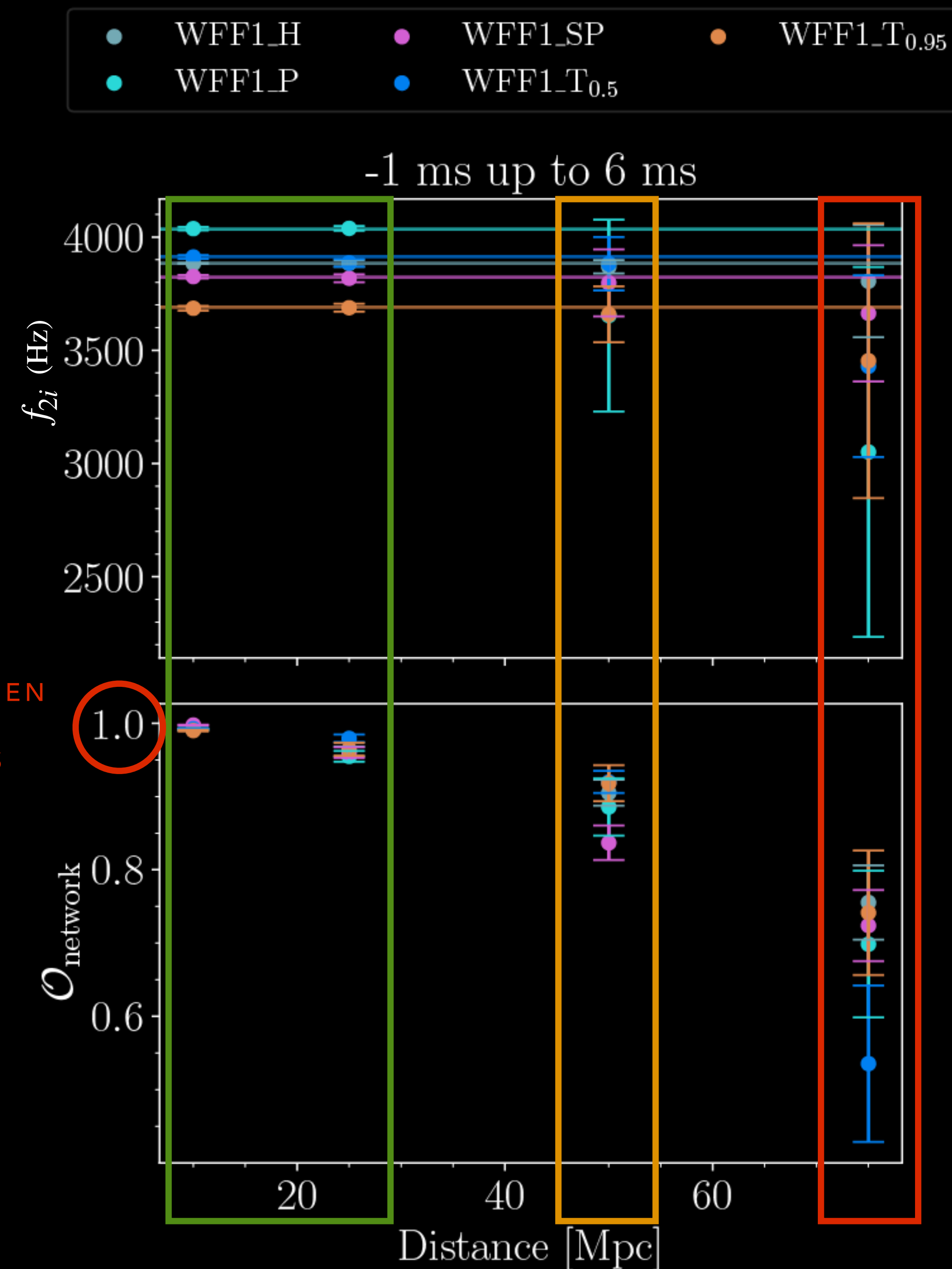
$2\tilde{h}\sqrt{f} \text{ (Hz}^{-1/2}\text{) @50 Mpc}$



GWS: DETECTABILITY OF THE SHIFT

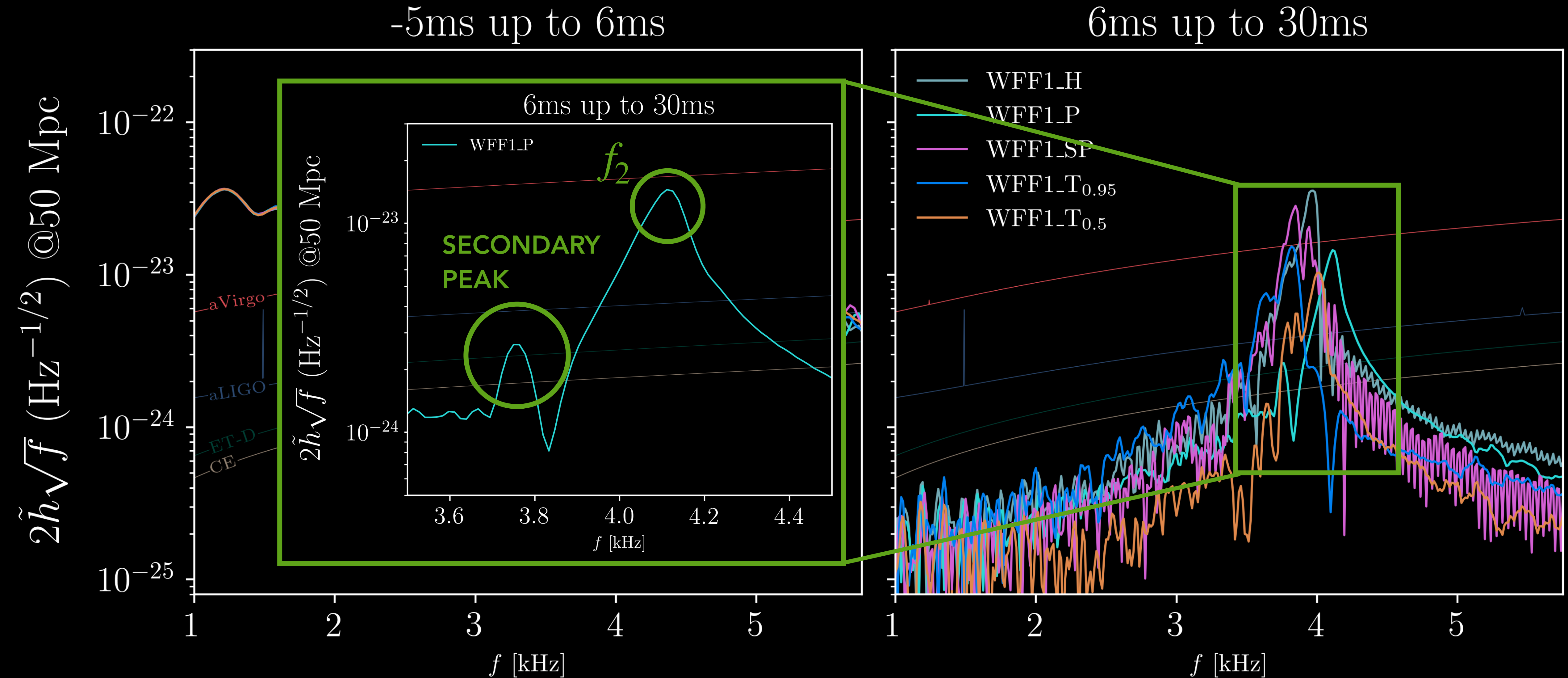
- *BayesWave* algorithm [N. J. Cornish and T. B. Littenberg, 2015]
- Third-generation detector Einstein Telescope
- Optimal sky location and inclination
- Distinguishable up to ~ 50 Mpc

PERFECT MATCH BETWEEN
INJECTED AND
RECOVERED SIGNALS



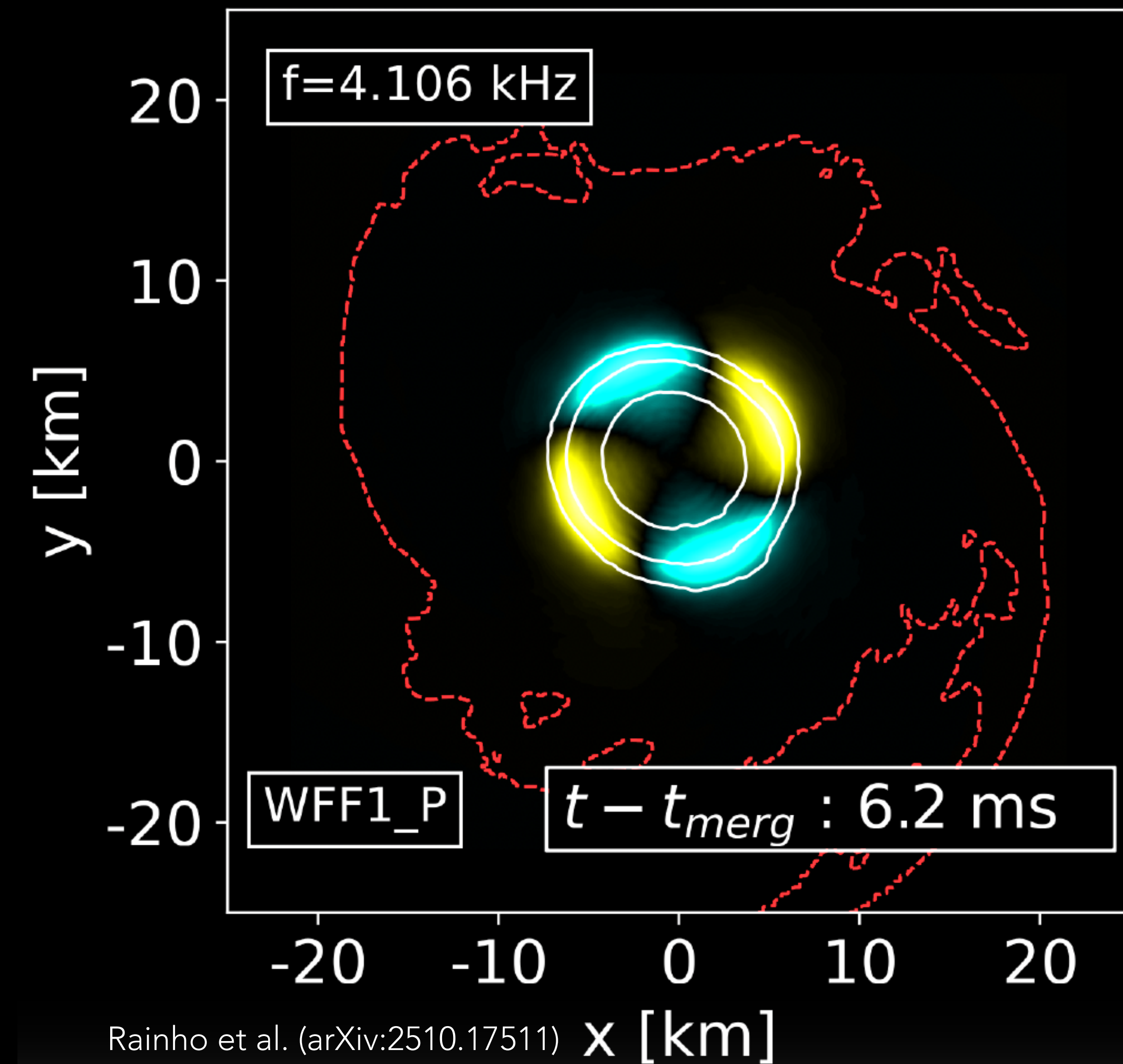
Rainho et al. (arXiv:2510.17511)

GWS: ADDITIONAL MODE



GWS: DENSITY EIGENFUNCTIONS

$m=2$

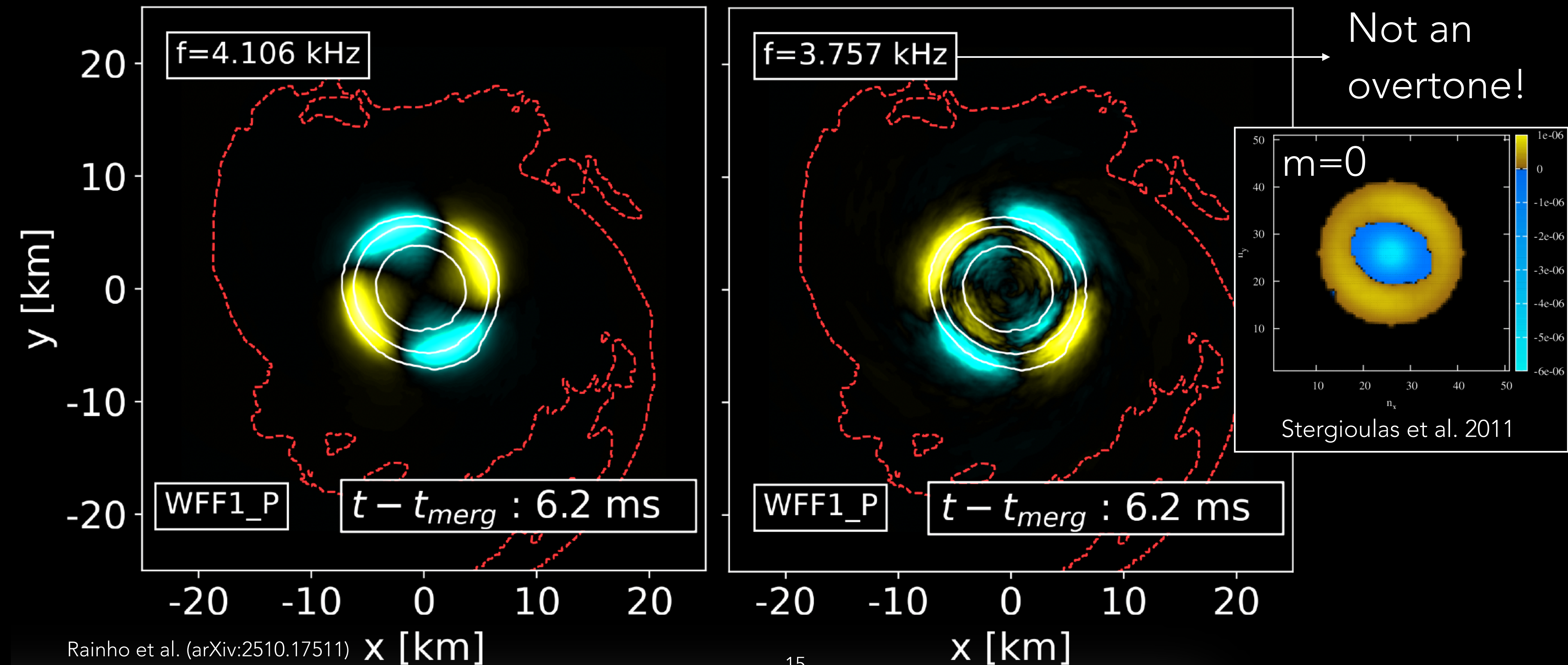


GWS: DENSITY EIGENFUNCTIONS

$m=2$

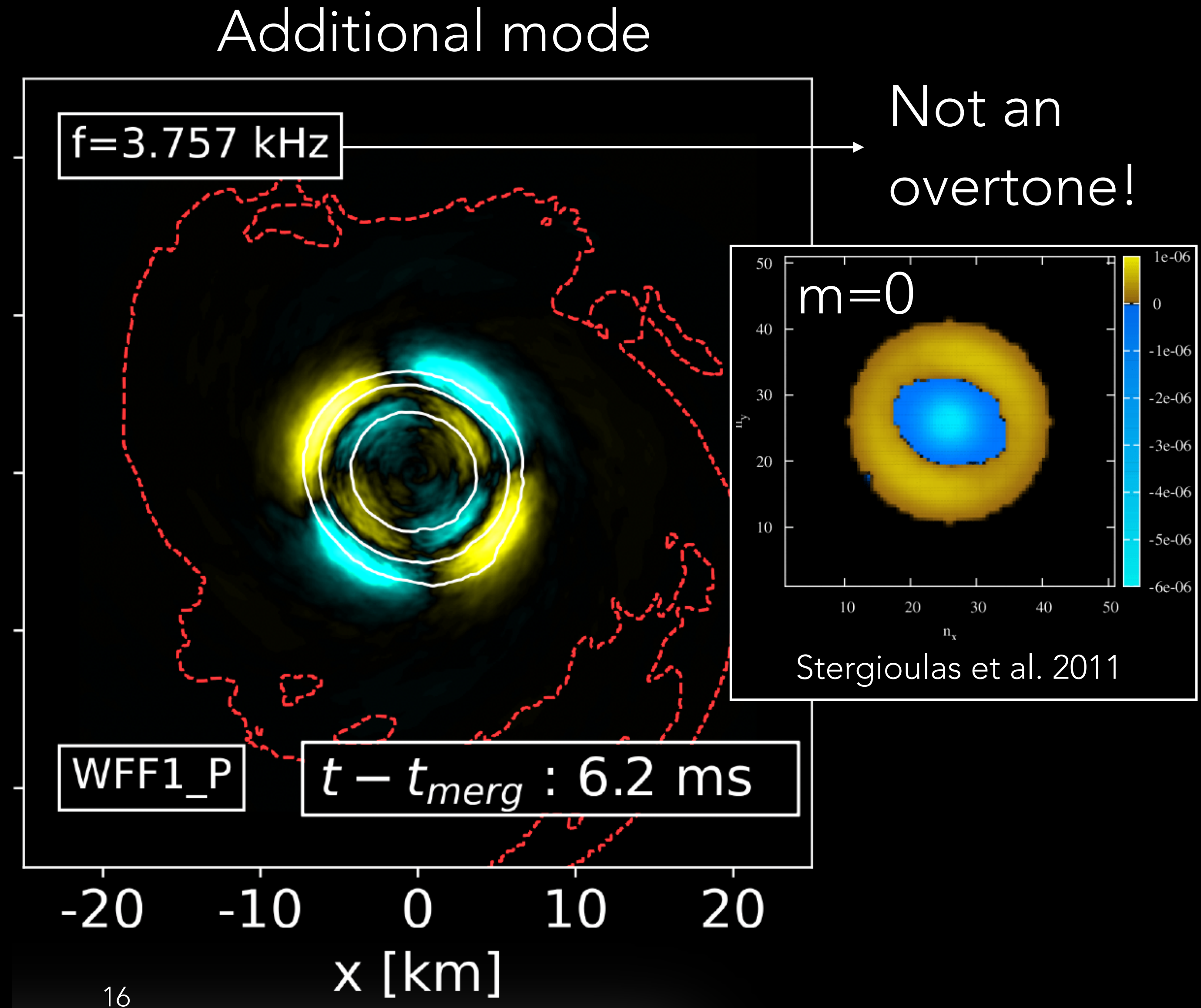
Additional mode

Not an
overtone!



GWS: DENSITY EIGENFUNCTIONS

- The additional mode observed is a **non-linear coupling** of the **$m=0$** and **$m=2$** modes

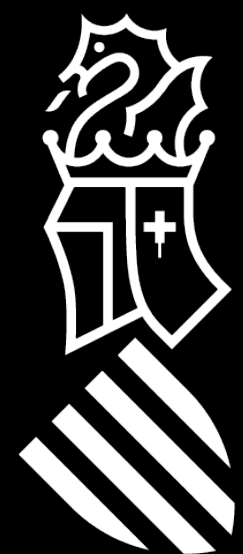


CONCLUSIONS

- **Poloidal field inside important** to the formation of an incipient jet.
- Different magnetic fields lead to a **shift in the GWs' peak**.
- Some **GW peaks might be distinguishable** by future detectors for closer events.
- Hot rings correlate with regions of convective stability

Thank you!

ianrain@uv.es



GENERALITAT
VALENCIANA



VNIVERSITAT
DE VALÈNCIA



BACKUP SLIDES

VECTOR POTENTIAL EXPRESSIONS

- $\mathbf{A} = (1 - a_T) \mathbf{A_P} + a_T \mathbf{A_T}$
- $\mathbf{A_P} = \frac{\pi \varpi^2 I_P r_P^2}{(r_P^2 + r^2)^{3/2}} \left[1 + \frac{15 r_P^2 (r_P^2 + \varpi^2)}{8 (r_P^2 + r^2)^2} \right] \hat{\mathbf{e}}_\phi$
- $\mathbf{A_T} = 2 I_T \log \left(\frac{2 r_T}{\varpi^2} \right) \max(P - P_{\text{cut}}, 0)^{n_b} \hat{\mathbf{e}}_y$

INITIAL DATA

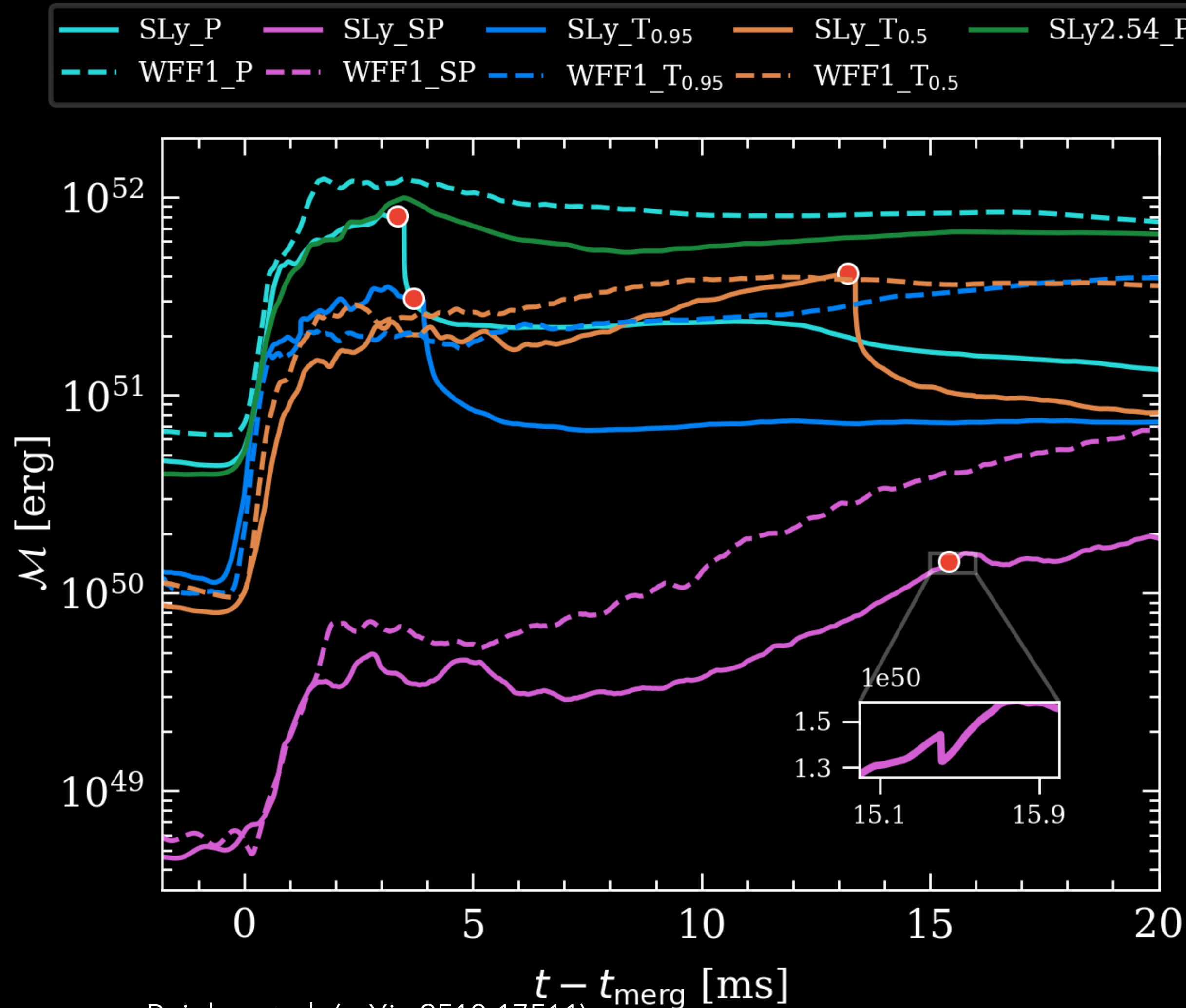
EOS	$M_0[M_\odot]$	$R_x[\text{km}]$	$\mathcal{C}$	Λ	$M[M_\odot]$	$M\Omega$
SLy	3.04	9.05	0.17	353	2.70	0.030
SLy2.54	2.83	9.25	0.16	498	2.54	0.029
WFF1	2.95	7.86	0.19	232	2.60	0.037

RESOLUTION

EOS	Grid hierarchy [†]	Max. resolution	N_{NS}
SLy	$3024.03 \text{ km}/2^{n-1}$	95 m	91
SLy2.54	$5748 \text{ km}/2^{n-1}$	90 m	102
WFF1	$2646.03 \text{ km}/2^{n-1}$	86 m	91

[†] n denotes the level number.

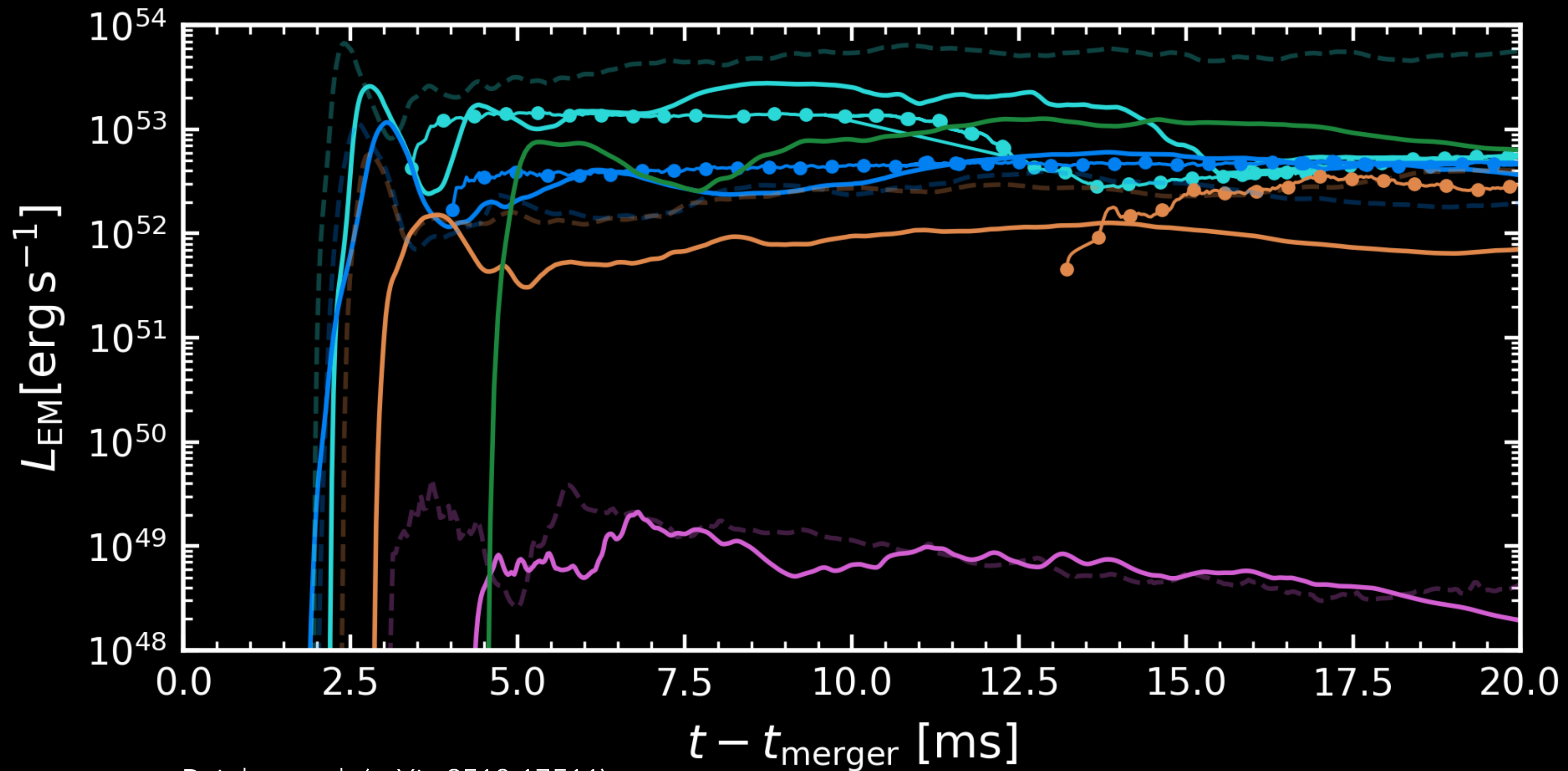
ELECTROMAGNETIC ENERGY



Rainho et al. (arXiv:2510.17511)

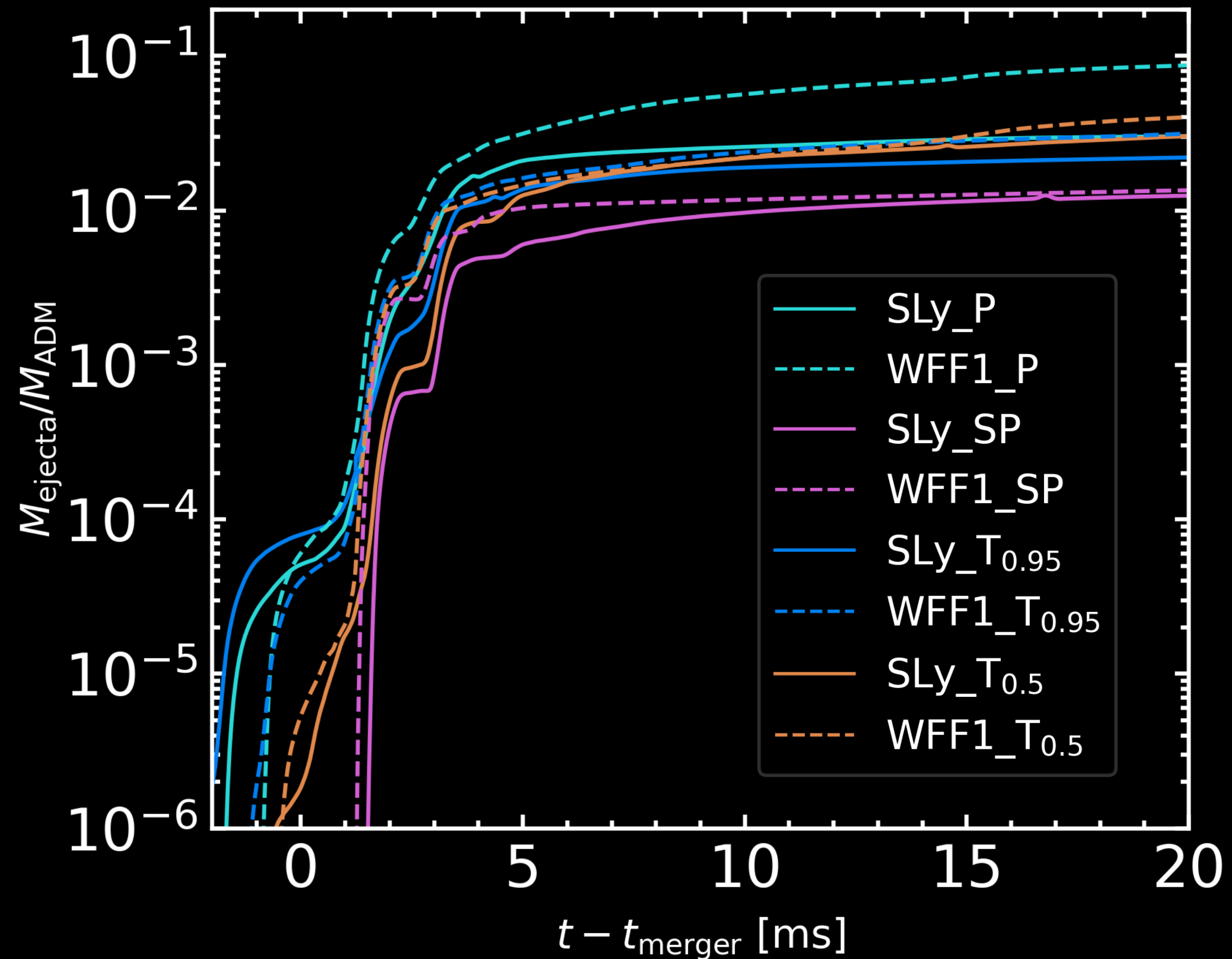
Case	$\mathcal{M}$ [erg]	B[G]
SLy_P	$10^{50.66}$	$10^{16.23}$
SLy2.54_P	$10^{50.61}$	$10^{16.20}$
SLy_SP	$10^{48.72}$	$10^{15.26}$
SLy_T _{0.95}	$10^{50.53}$	$10^{16.17}$
SLy_T _{0.5}	$10^{49.96}$	$10^{15.88}$
WFF1_P	$10^{50.82}$	$10^{16.41}$
WFF1_SP	$10^{48.86}$	$10^{15.43}$
WFF1_T _{0.95}	$10^{50.39}$	$10^{16.19}$
WFF1_T _{0.5}	$10^{50.05}$	$10^{16.02}$

ELECTROMAGNETIC LUMINOSITY



Rainho et al. ([arXiv:2510.17511](https://arxiv.org/abs/2510.17511))

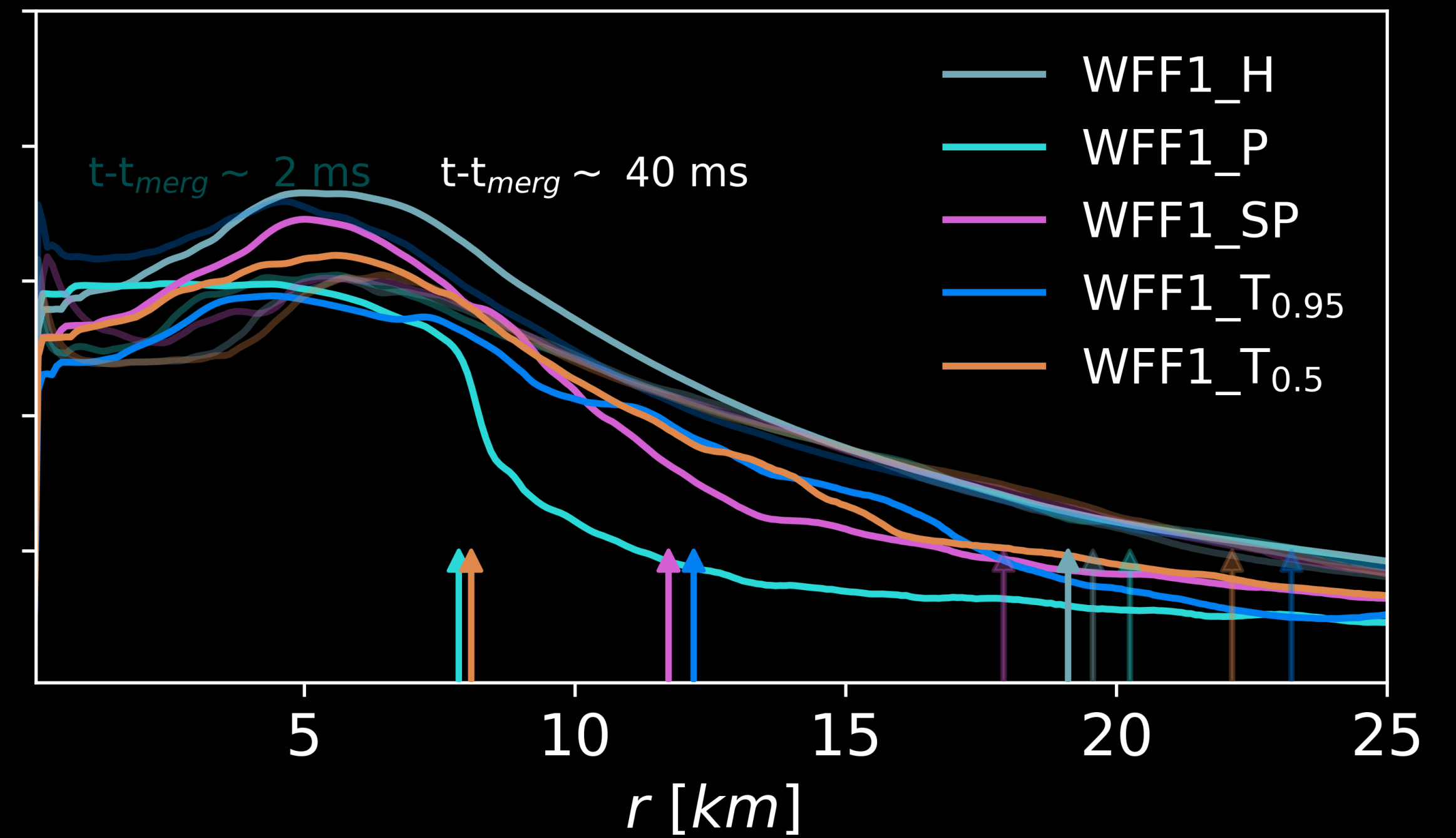
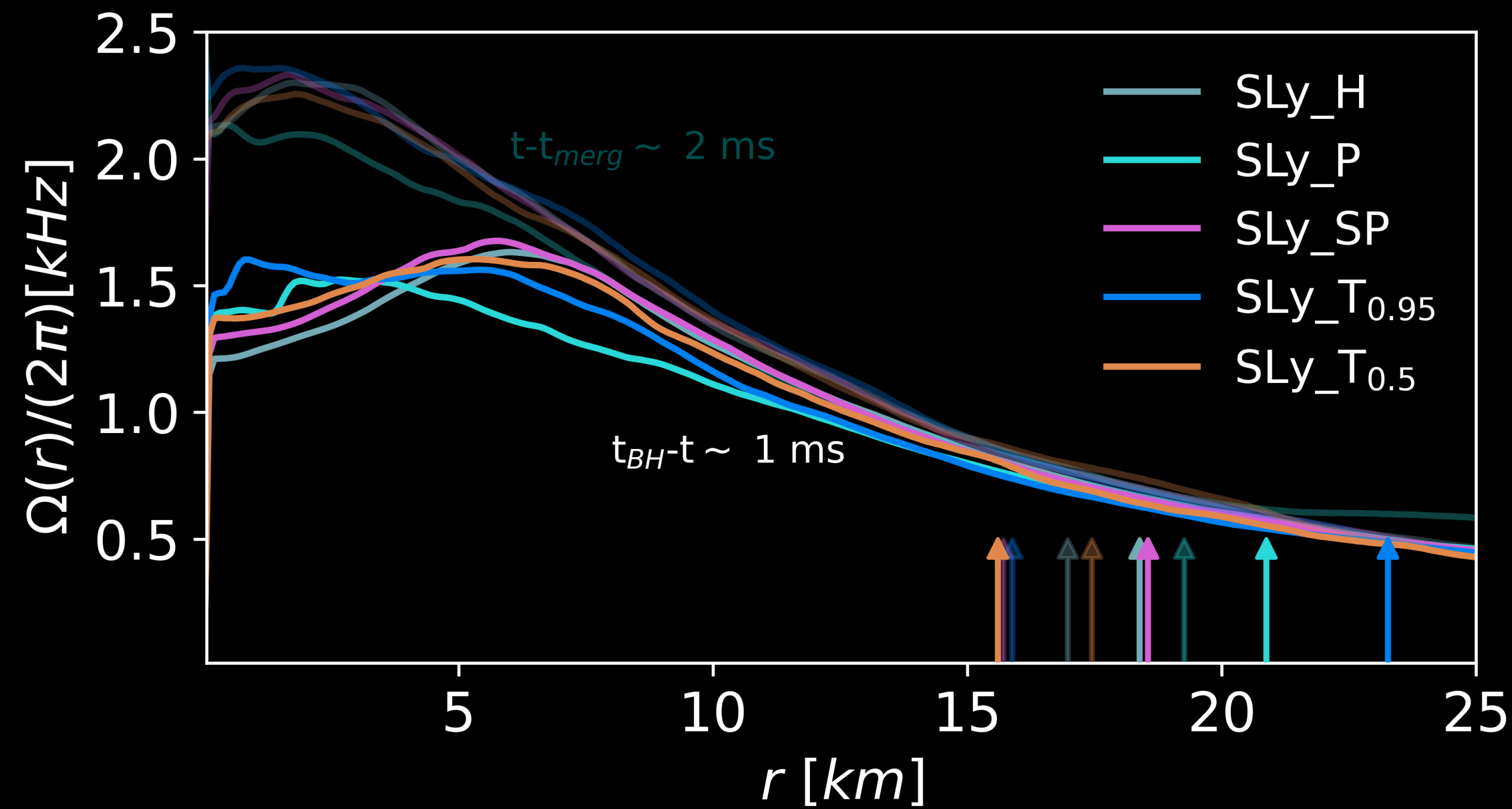
ELECTROMAGNETIC SIGNALS: EJECTA



Rainho et al. ([arXiv:2510.17511](https://arxiv.org/abs/2510.17511))

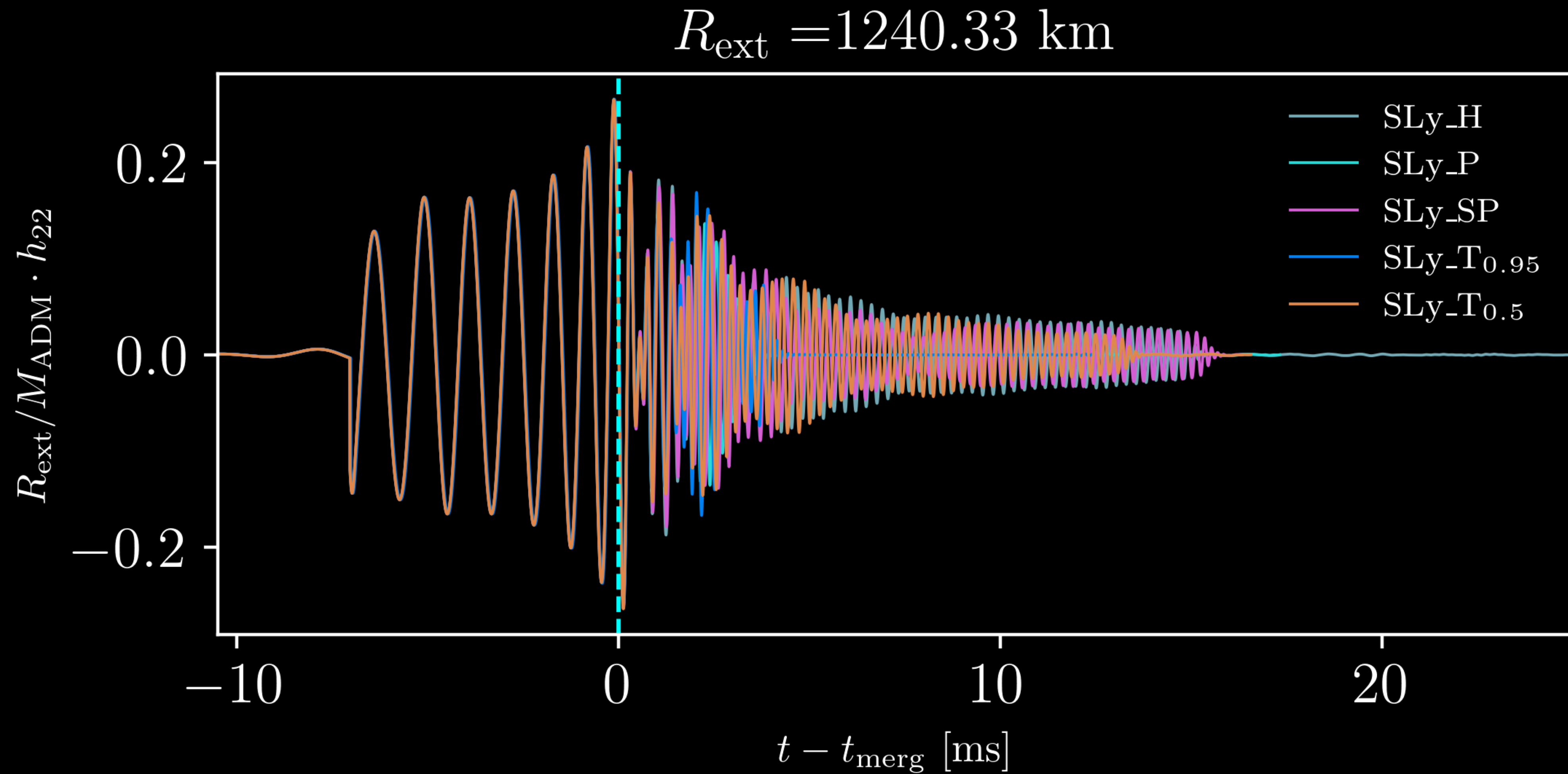
- At 20 ms after merger:
 $M_{\text{ejecta}}(\text{P}) > M_{\text{ejecta}}(\text{T}_{0.5}) > M_{\text{ejecta}}(\text{T}_{0.95}) > M_{\text{ejecta}}(\text{SP})$
- $M_{\text{ejecta}}(\text{WFF1}) > M_{\text{ejecta}}(\text{SLy})$

ROTATIONAL PROFILES



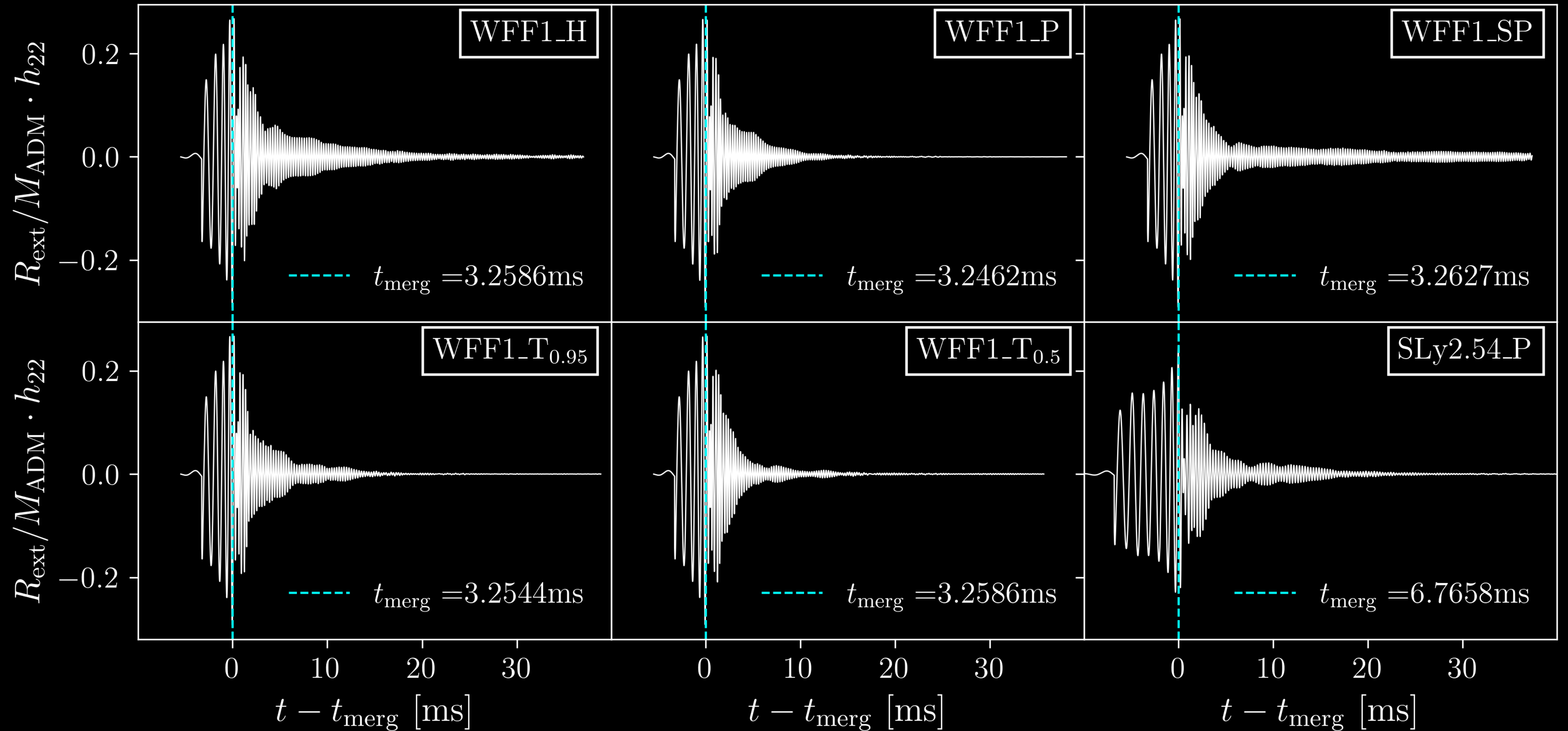
Rainho et al. ([arXiv:2510.17511](https://arxiv.org/abs/2510.17511))

WAVEFORMS (CASES THAT COLLAPSE)



Rainho et al. ([arXiv:2510.17511](https://arxiv.org/abs/2510.17511))

WAVEFORMS (CASES WITH LONGER LIVED REMNANTS)



EM SIGNALS: JETS CONSISTENT WITH SHORT GRB

- Larger poloidal component $\rightarrow$ cleaner/wider funnel
- Largest Lorentz factor for pure poloidal case
- No jet yet for SP
- $L_{\text{EM}} \sim 10^{51} - 10^{52} \text{ erg/s}$
- $M_{\text{ejecta}}(\text{P}) > M_{\text{ejecta}}(\text{T}_{0.5}) > M_{\text{ejecta}}(\text{T}_{0.95}) > M_{\text{ejecta}}(\text{SP})$

