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Gravitational waves from core-collapse SNe

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Work in progress in collaboration with:
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Ministero dell'Università e della Ricerca

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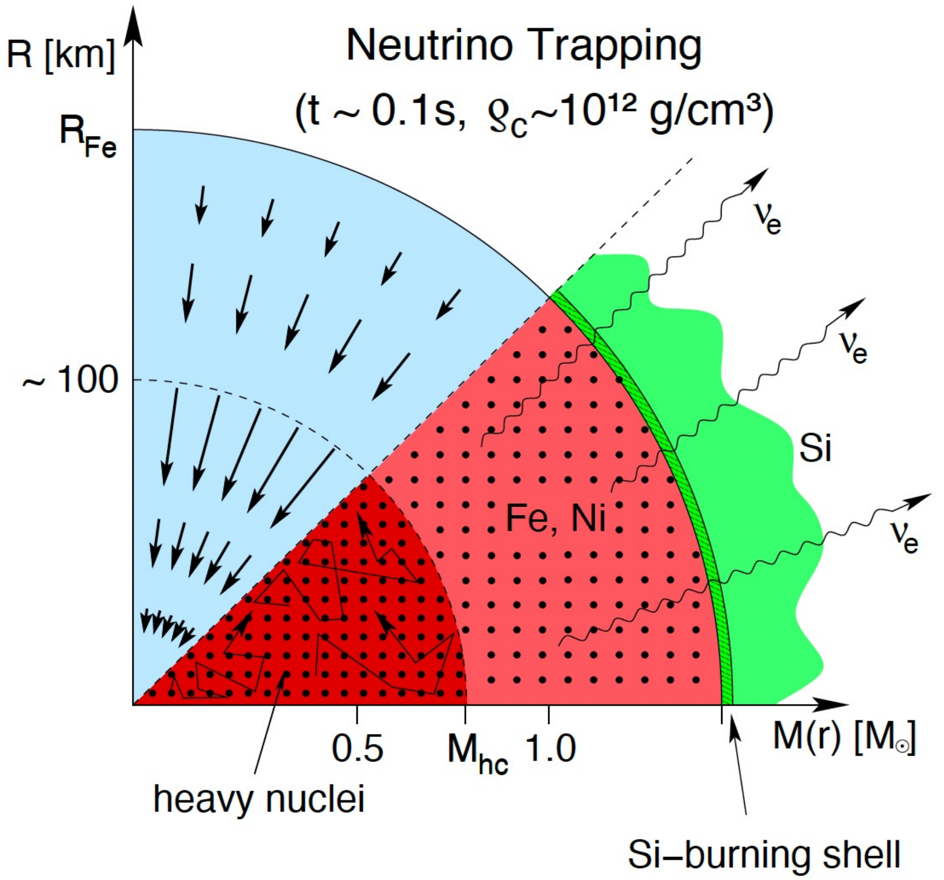
CC SNe: explosion mechanism

A core-collapse Supernova is the terminal phase of a massive star $[\mathrm{M} \geq 8\, M_{\odot}]$.

➢ Formation of a degenerate Iron core

⟶ e^{-}captures reduces electron degeneracy pressure



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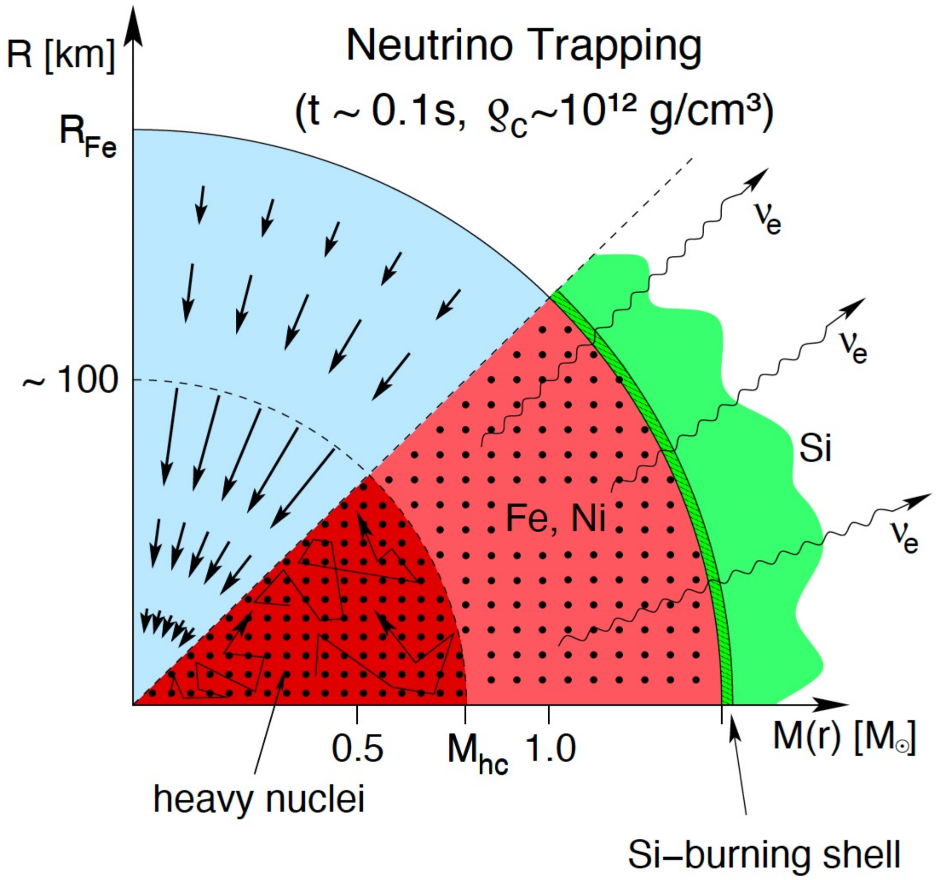
  - → Keeps going on until inner core becomes uncompressible ($\rho \sim 10^{14}\ \mathrm{g/cm^3}$)



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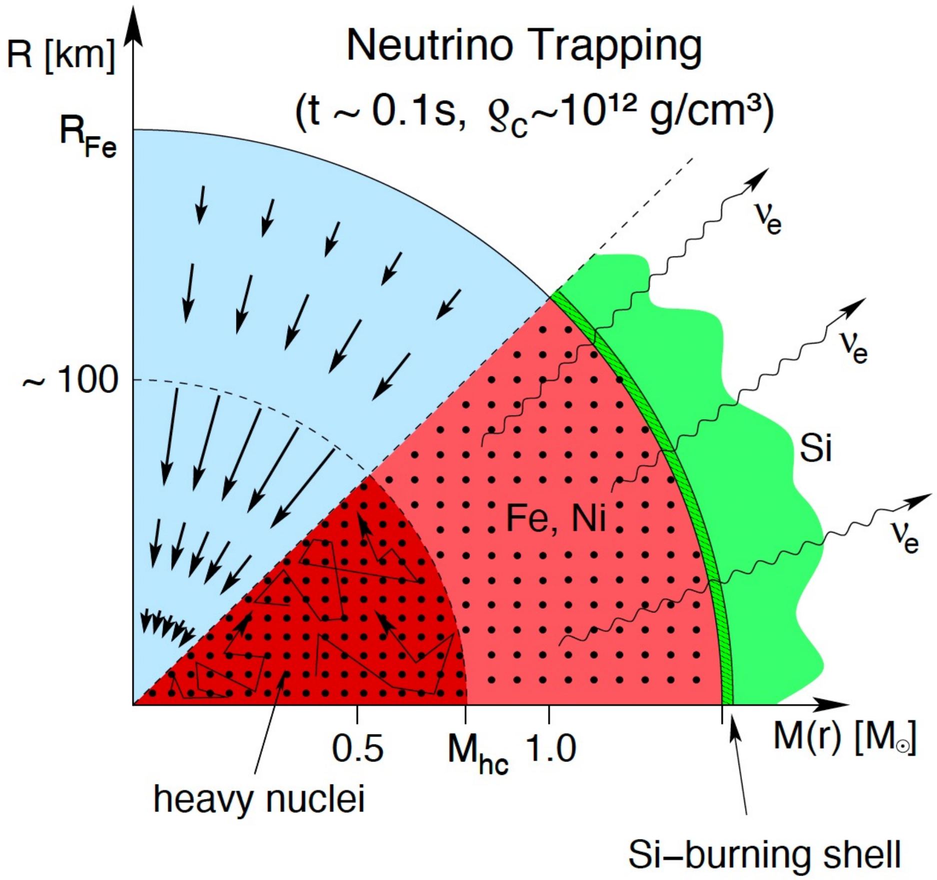
  - → e^- captures reduces electron degeneracy pressure
- Onset of the gravitational collapse
  - → Keeps going on until inner core becomes uncompressible ($\rho \sim 10^{14}\ \mathrm{g/cm^3}$)
- Core bounce and formation of a shock-wave
  - → Converts the implosion into an explosion



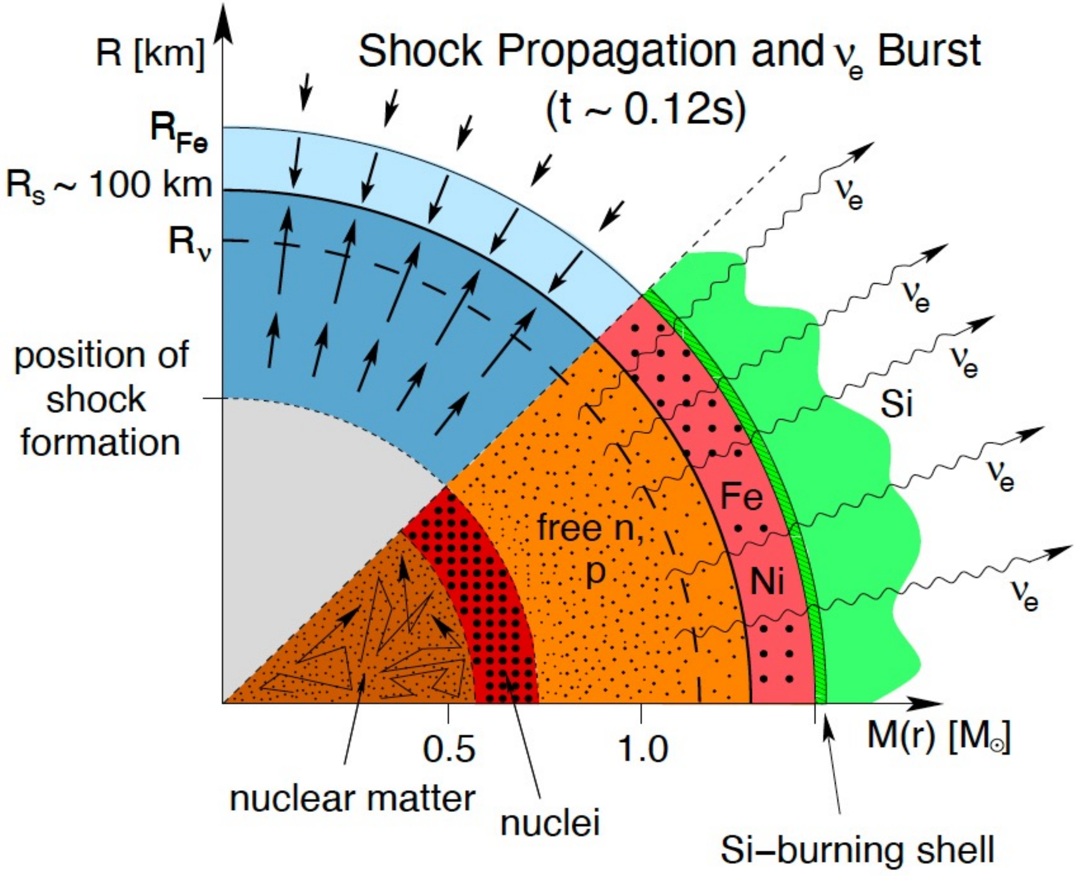
CC SNe: explosion mechanism

During shock-wave propagation

➢ Matter infalling (accretion) from above forms a PNS

⟶ $R \sim 10 - 30$ km, M $\sim 1.5\, M_\odot$

⟶ Cooling via neutrino emission of all species
$E \sim 10^{53}$ erg , $t \sim 10$ s.



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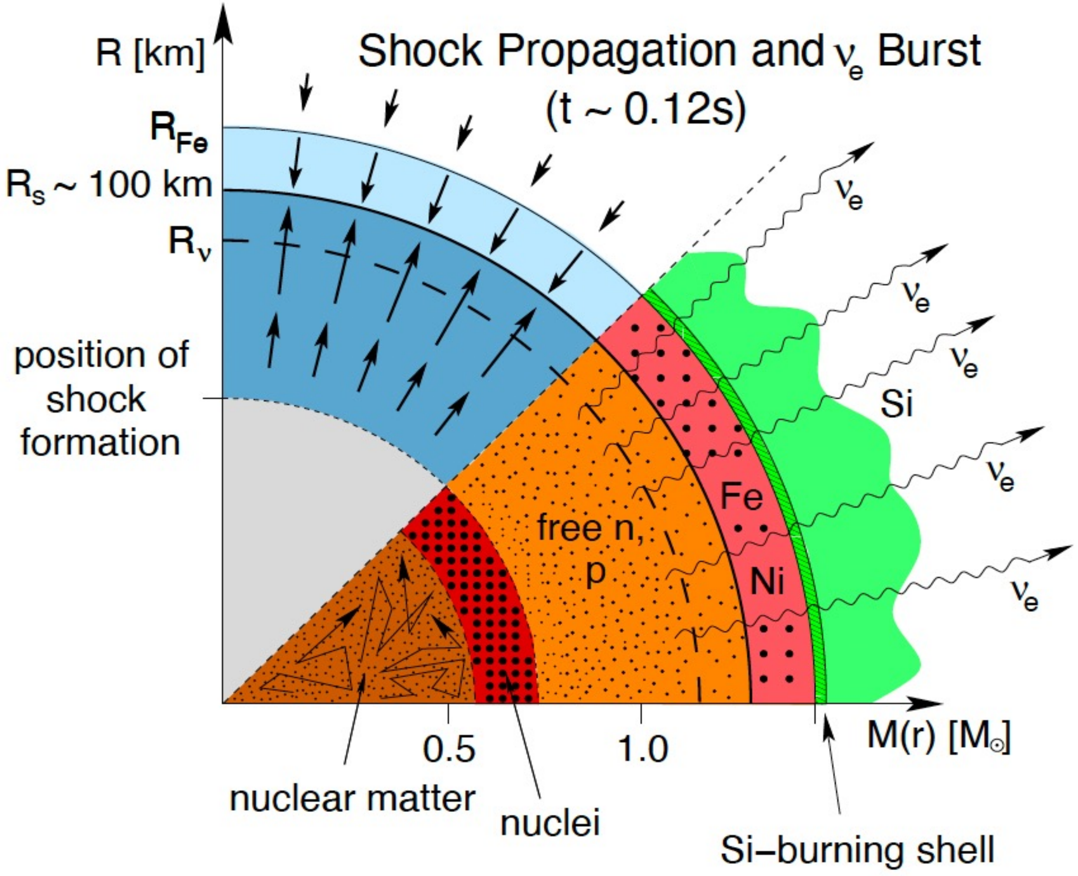
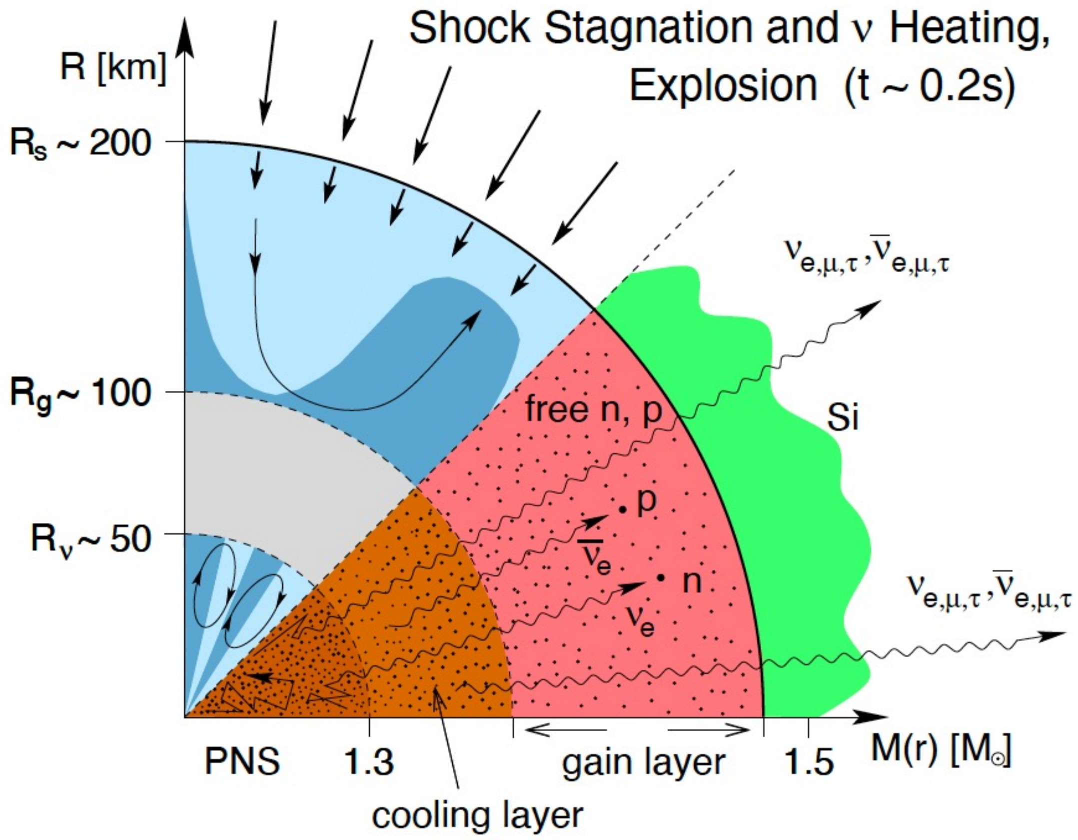
- The shock-wave loses energy dissociating heavy nuclei.
  - → Shock stalls at $R_s \sim 100$ km.



CC SNe: explosion mechanism

- Neutrinos deposit energy behind the shock front (ν- heating)



CC SNe: explosion mechanism

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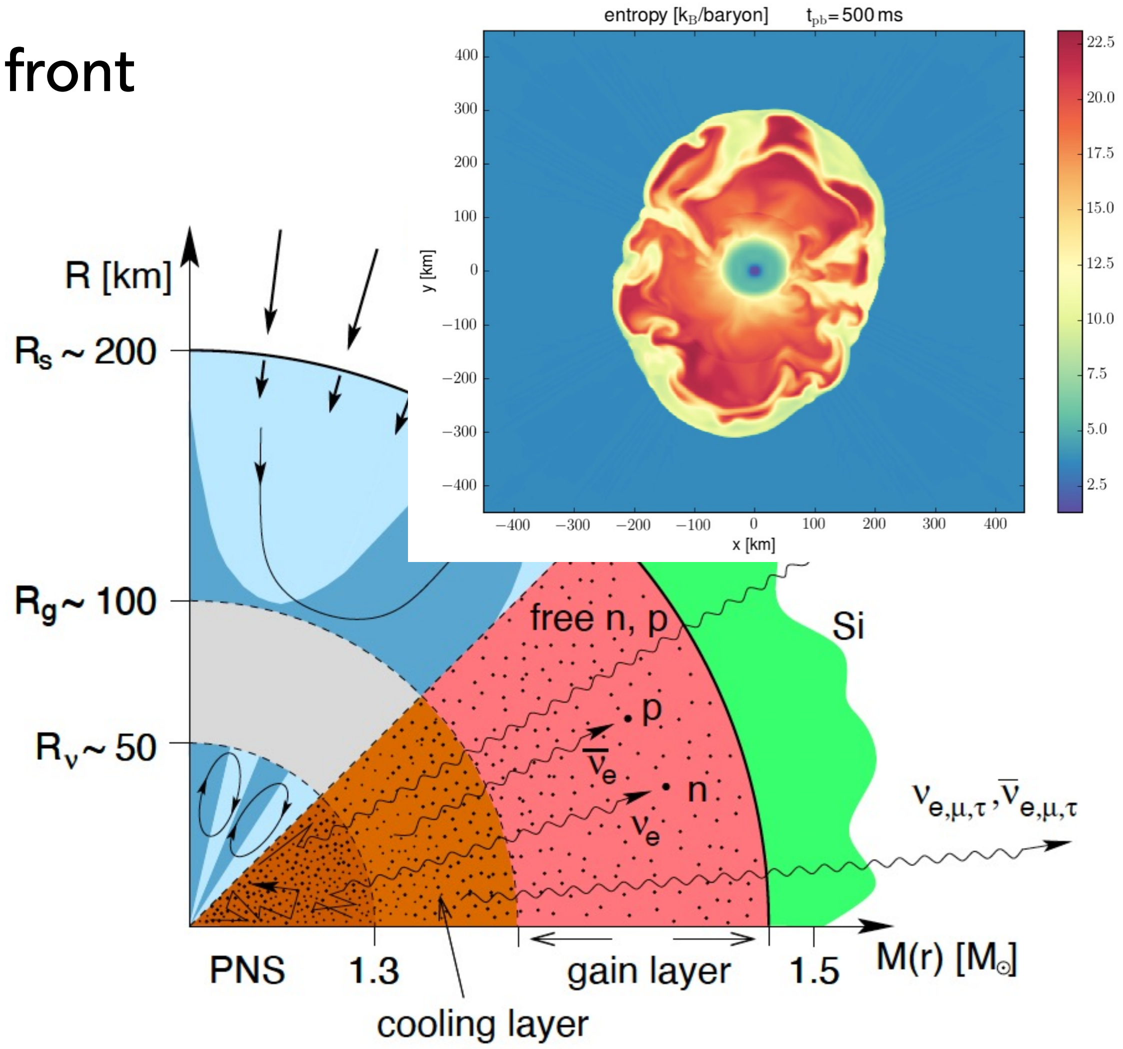
- Neutrinos heat high-entropy material at the PNS surface

→ Post-shock convection



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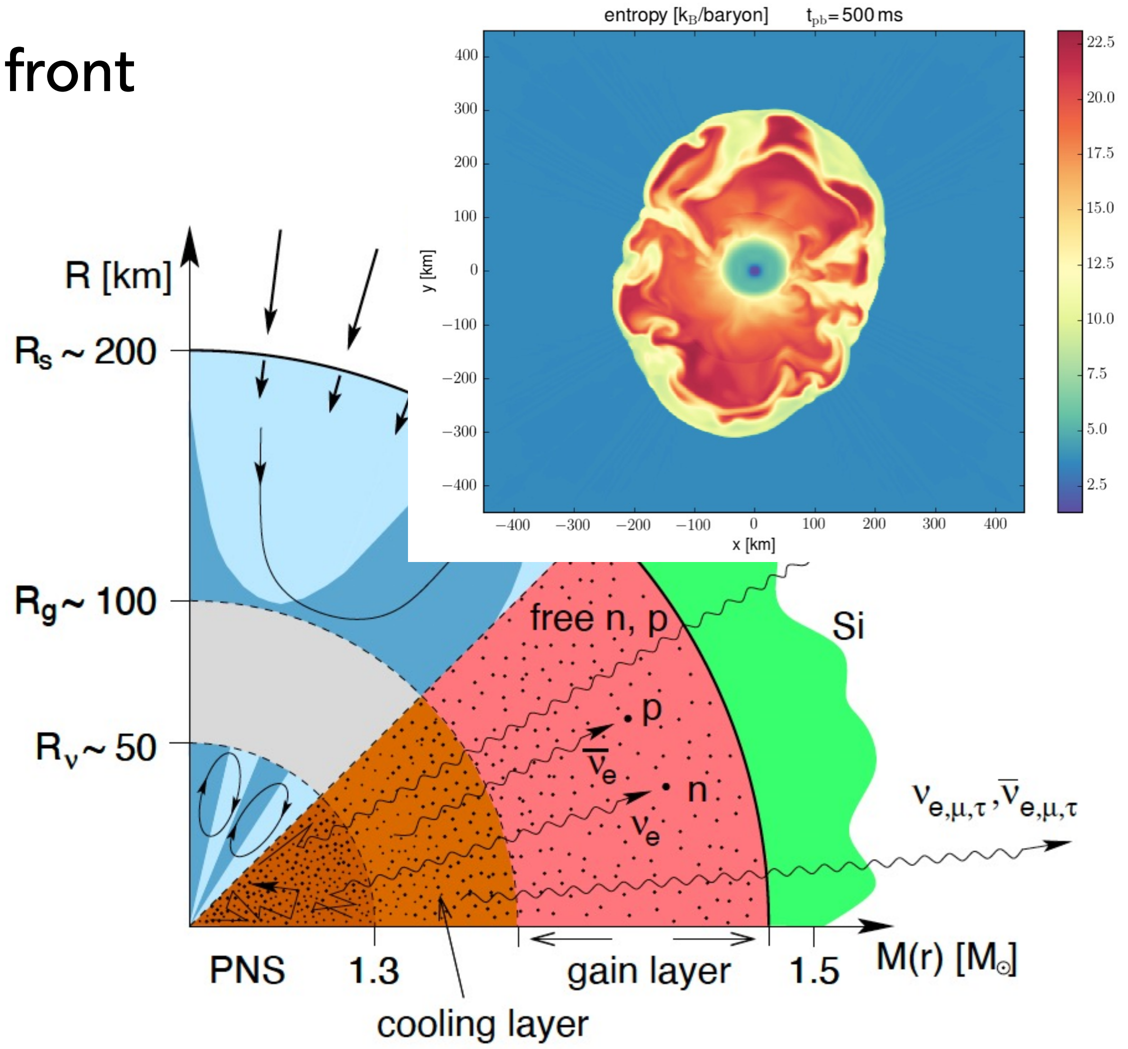
⟶ Post-shock convection

- Dynamical deformation of the shock surface

⟶ Standing accretion shock instabilities (SASI)



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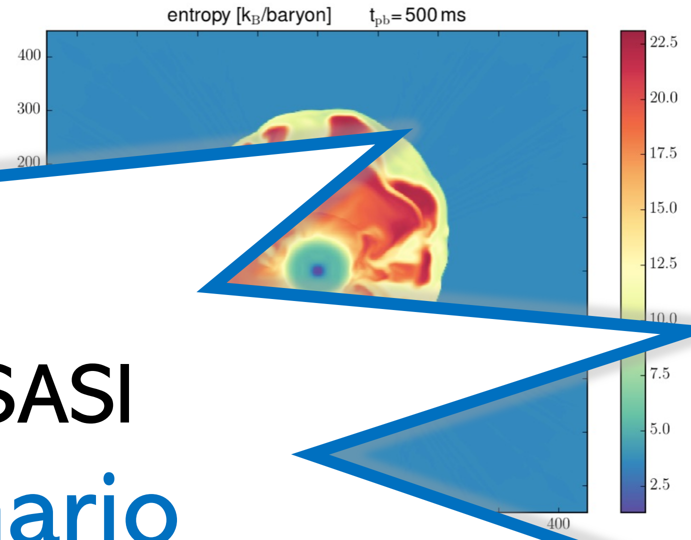

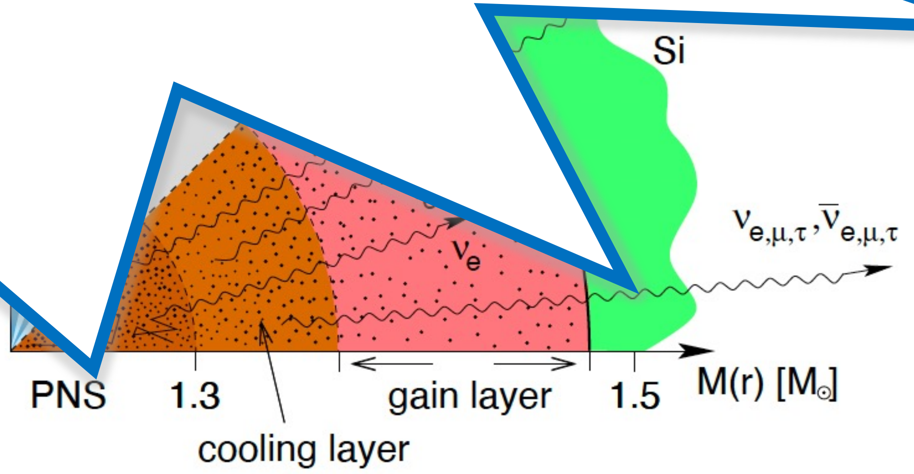

ν-heating +

post shock convection and SASI

Delayed Explosion Scenario

CC SNe: 3D simulations

Need for 3D SN simulations by Garching group [Max Planck Insitute for astrophysics].

- Based on the neutrino-hydrodynamics code PROMETHEUS-VERTEX *[Ramp & Janka, Astron. Astrophy. 396 (2002); Buras et al., A&A 447 (2006); Bollig et al., Phys.Rev.Lett.* 119 (2017)]

➤ s12.28

- $M_{\rm prog} = 12.28\ M_{\odot}$, $M_{\rm PNS} = 1.55\ M_{\odot}$
- 3D progenitor
- Successfull explosion
- Sampling rate $\Delta t = 0.2$ ms
- SFHo EOS *[Hempel & Schaffner-Bielic, NuPhA, 837 (2010)]*

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Anisotropic energy emission and mass flows are source of GWs

$$h_{ij} \propto \frac{G}{r} \ddot{Q}_{ij}$$

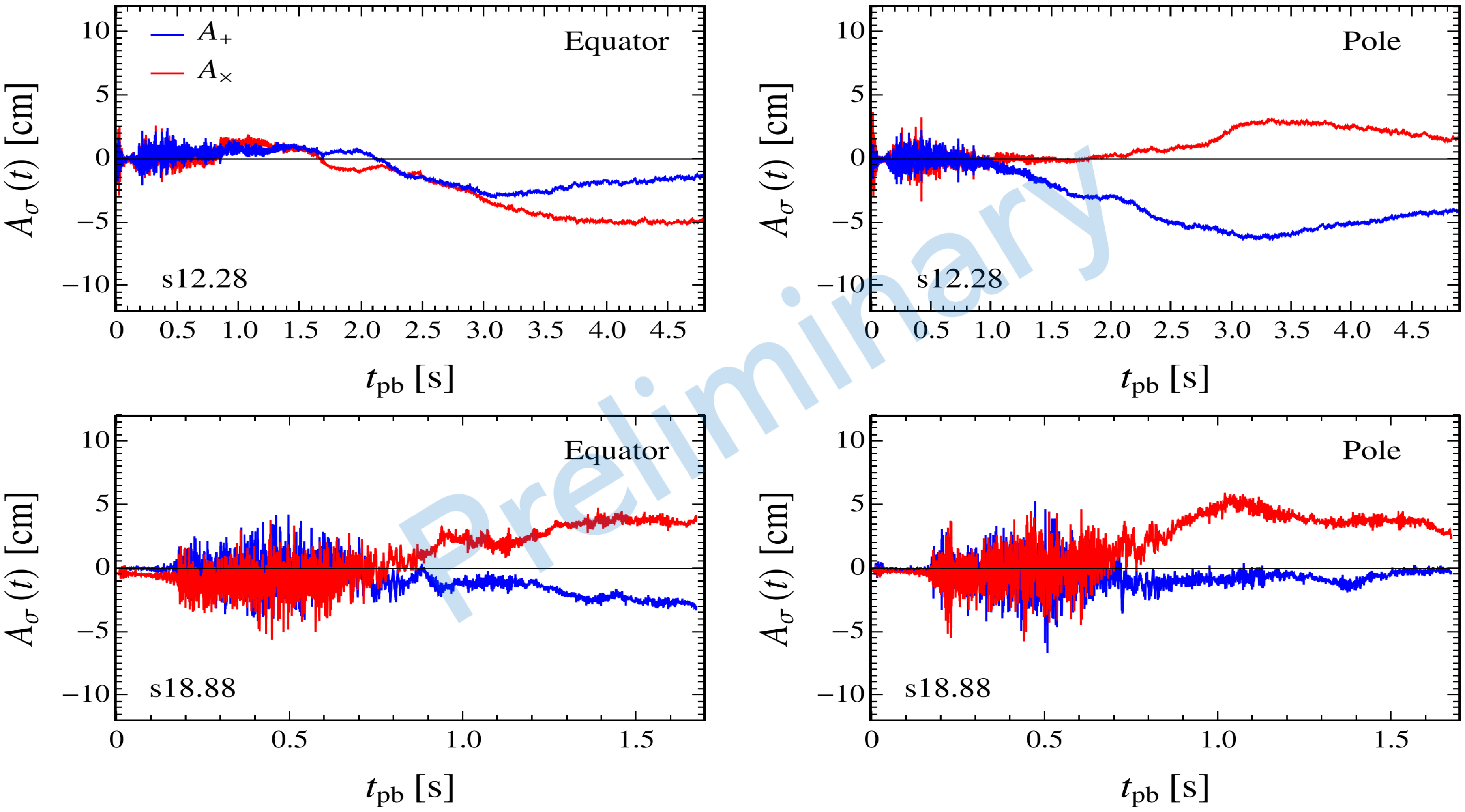
→ Quadrupole momentum tensor

GWs from hydro instabilities

$$\ddot{Q}_{ij} = \int d^3x\, \rho\, (2v_i v_j - x_i \partial_j \phi_{\rm eff} - x_j \partial_i \phi_{\rm eff})$$

$$A_+ = r\, h_+ = \ddot{Q}_{\theta\theta} - \ddot{Q}_{\phi\phi}$$

$$A_\times = r\, h_\times = 2\, \ddot{Q}_{\theta\phi}$$



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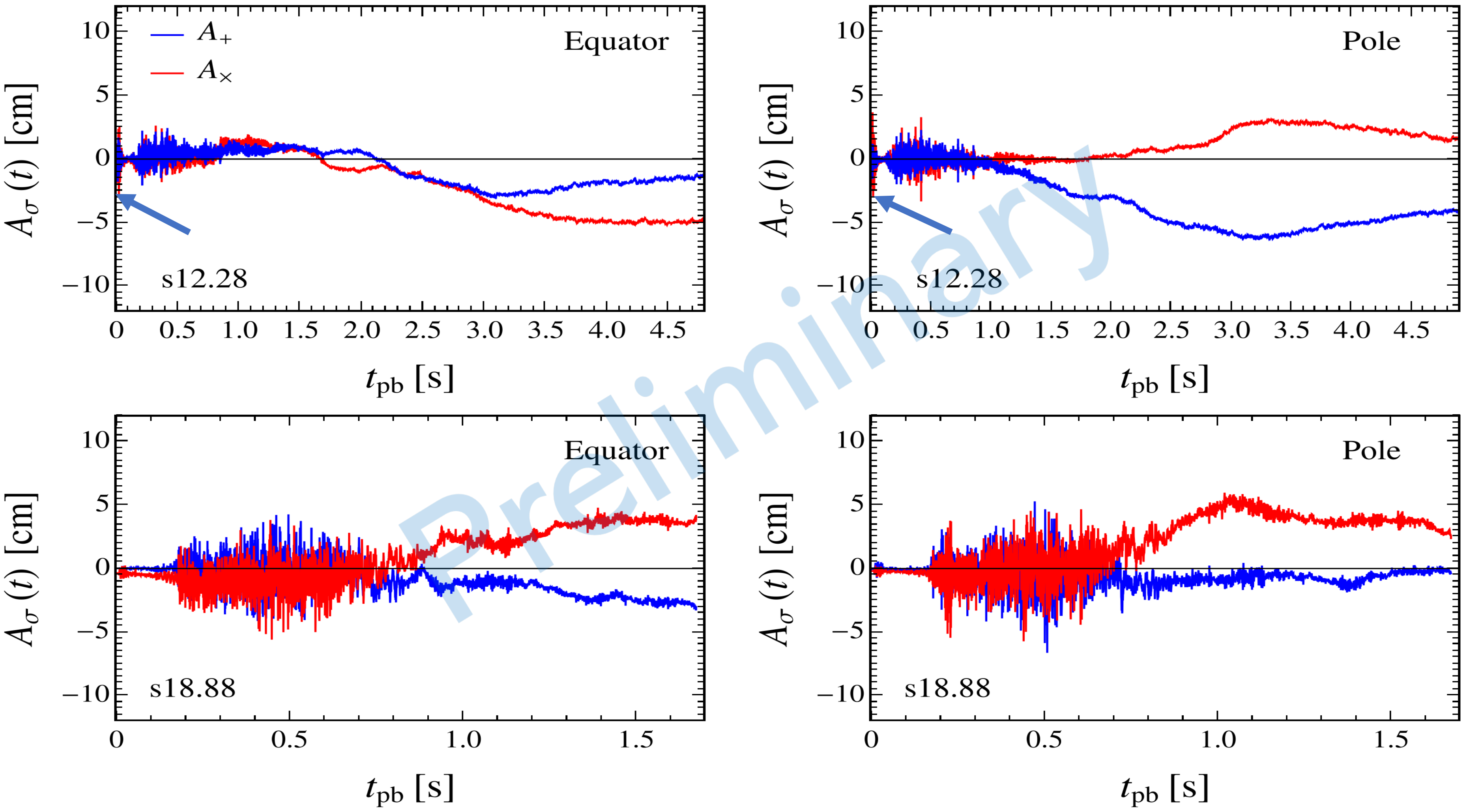

- Prompt post-bounce convection

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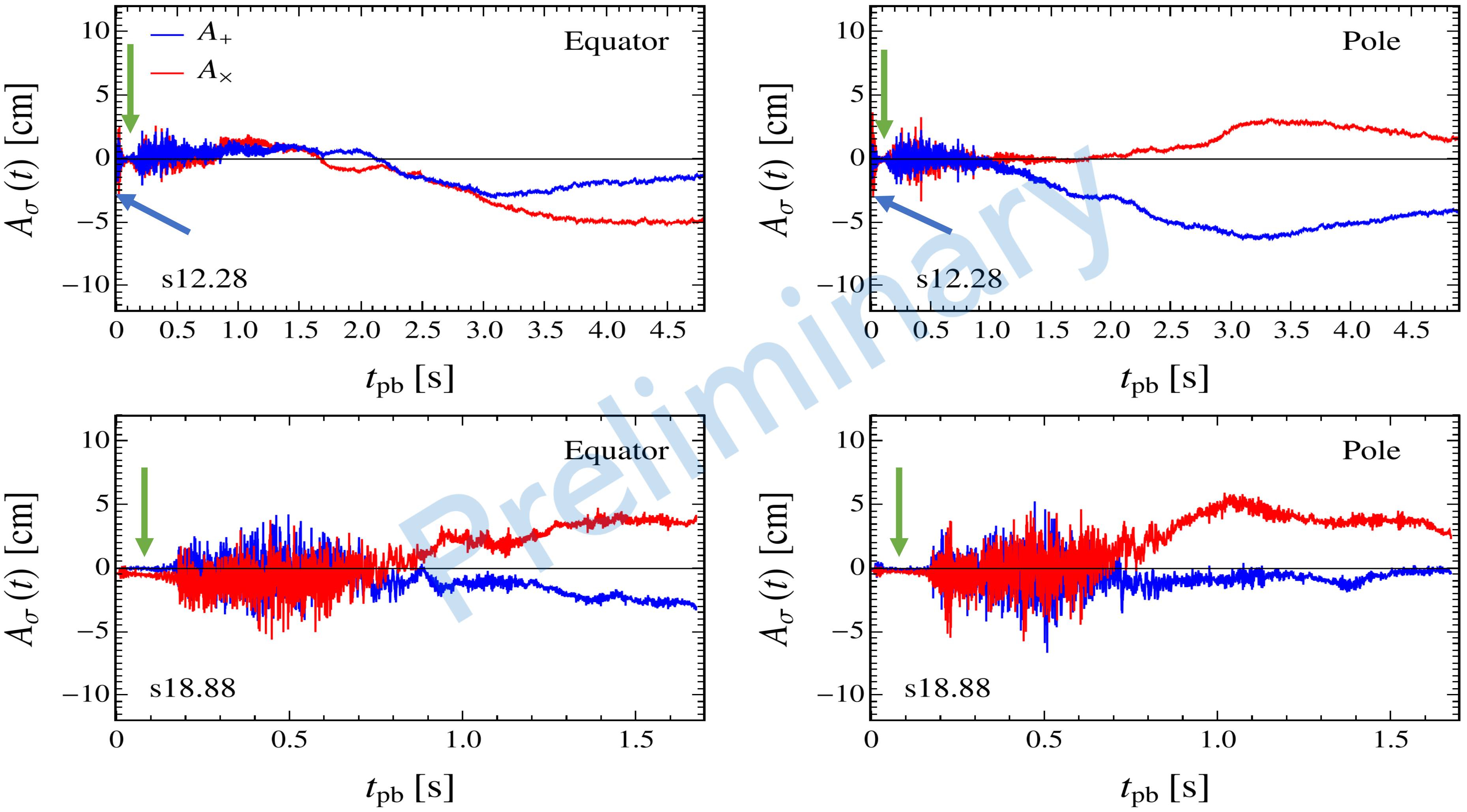

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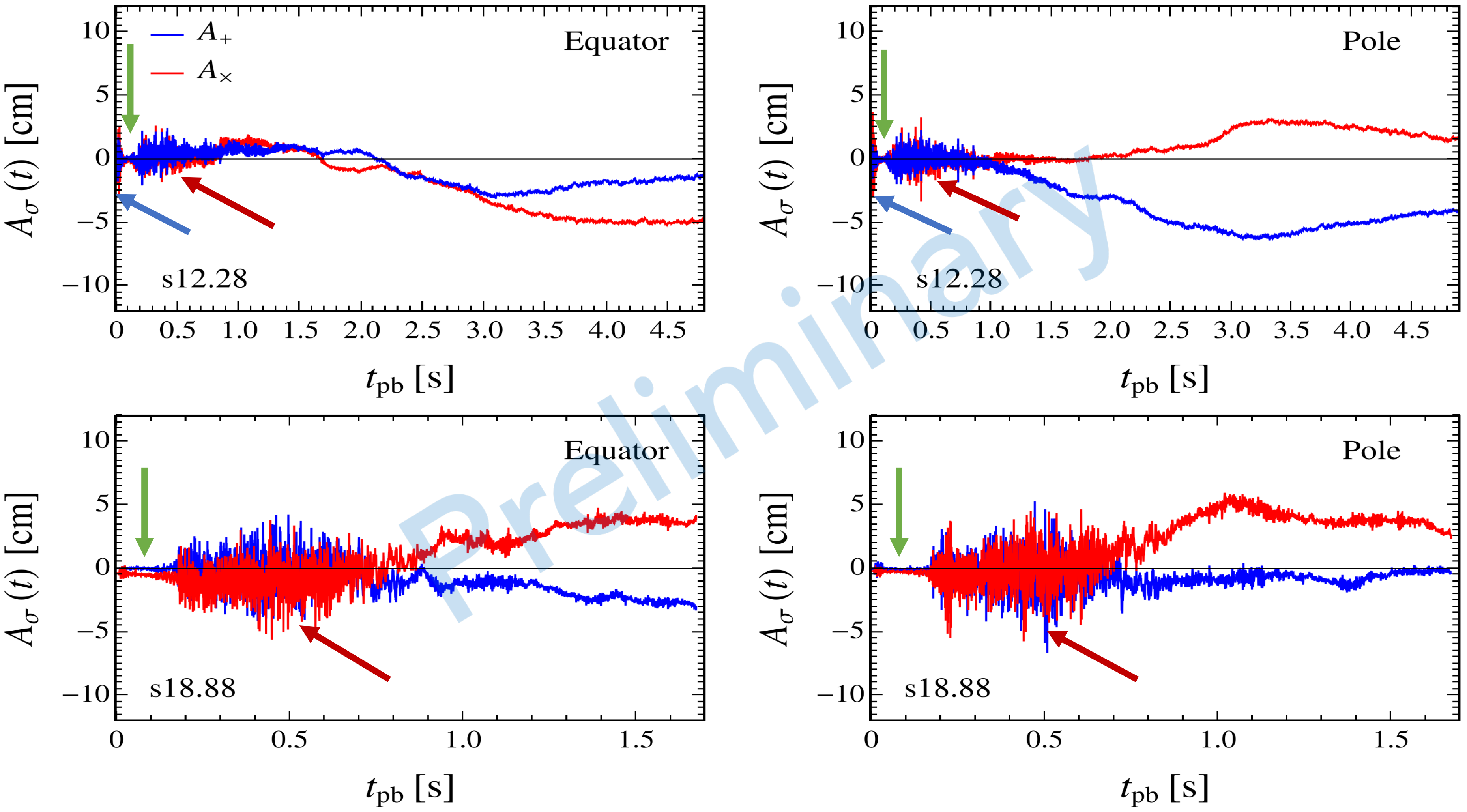

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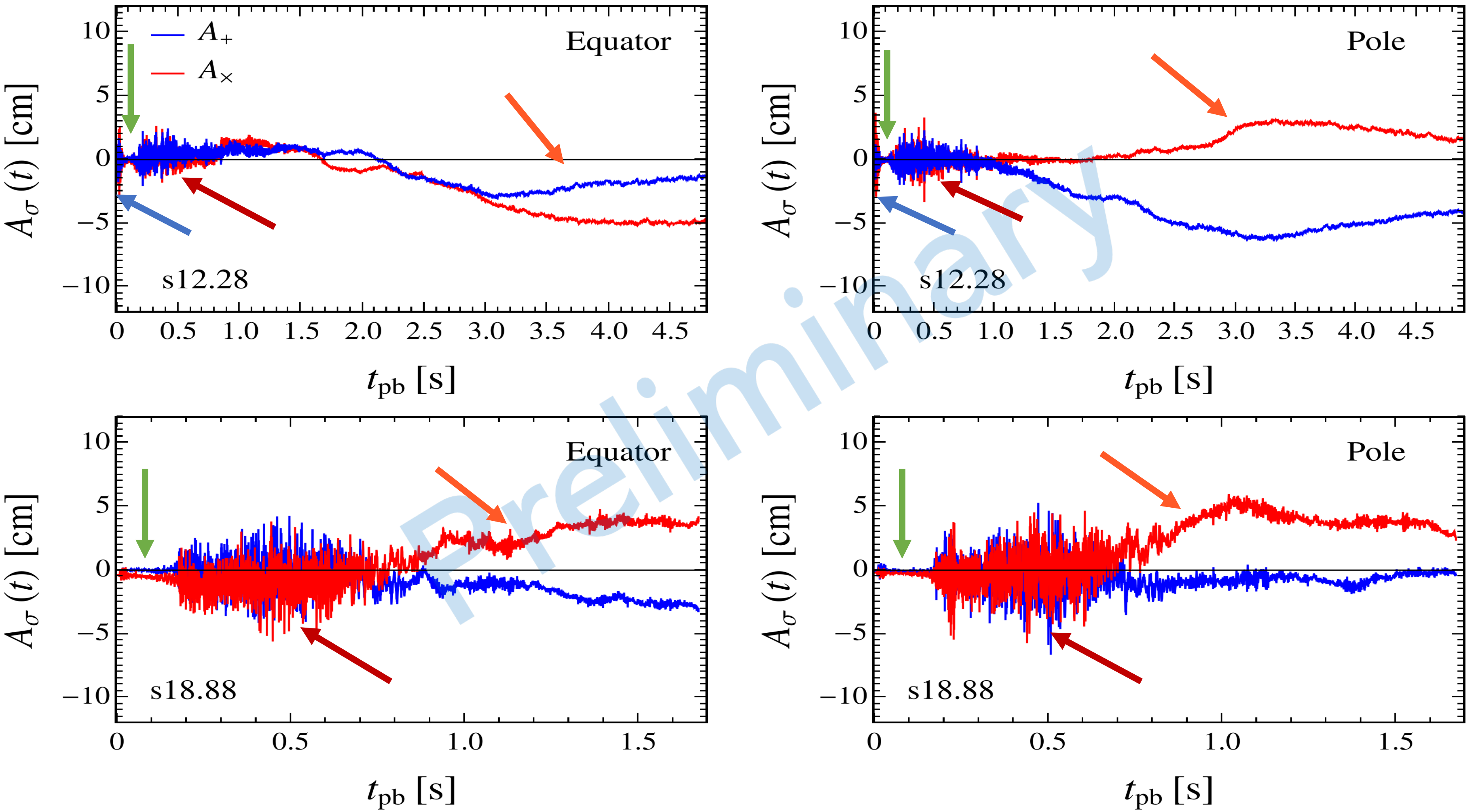

- Prompt post-bounce convection
- Quiescent phase (50-200 ms)
- Post-shock convection and SASI (200-700 ms)
- Anisotropic shock expansion (≳1 s)

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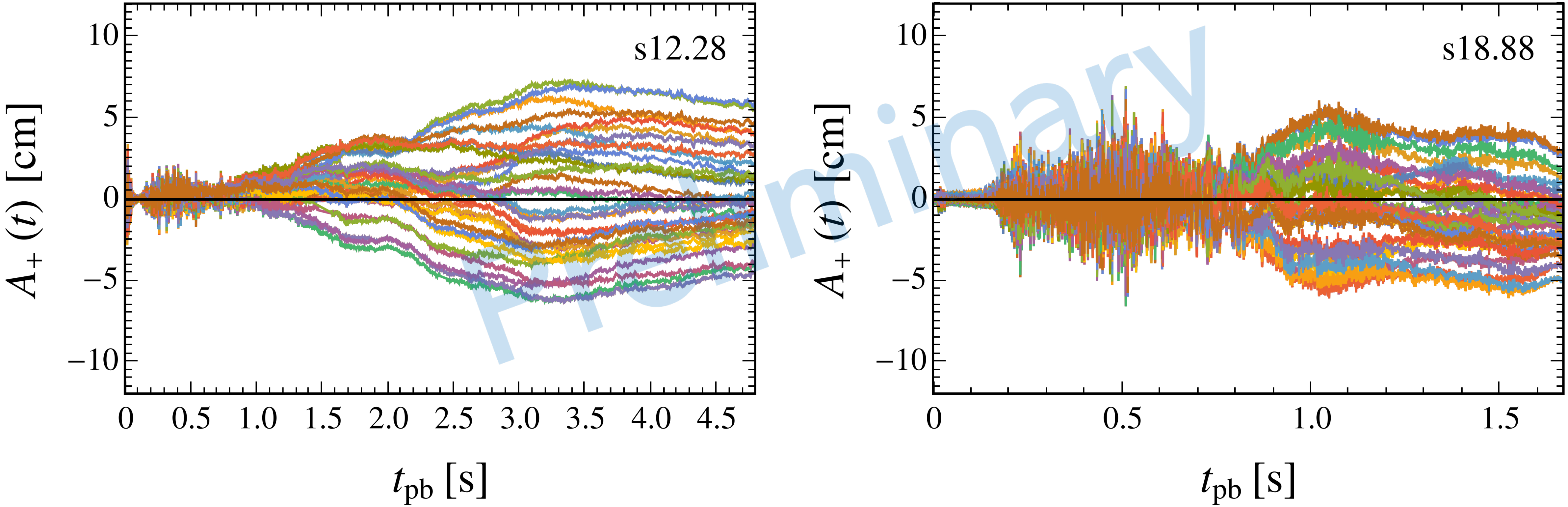
Strong dependency on the different viewing angles! (see also *[Vartanyan et al., Mon.Not.Roy.Astron.Soc. 489 (2019) 2]*)

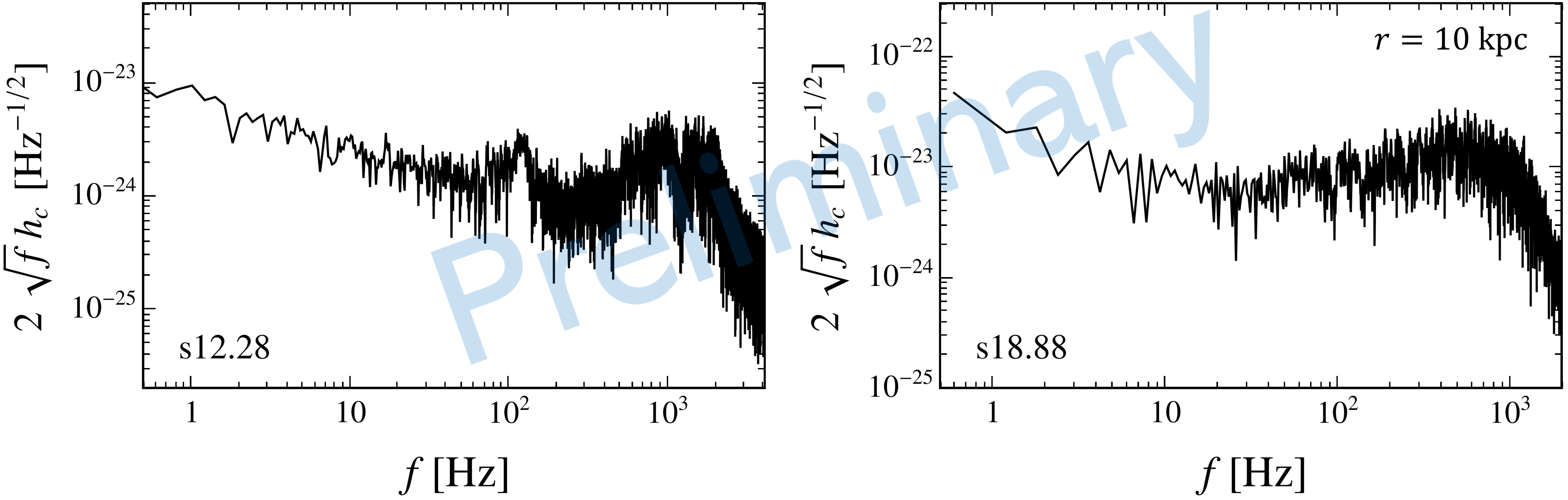


GWs from hydro instabilities

For the analysis in the frequency domain, we define the characteristic strain

$$h_c(f) = \sqrt{0.5(|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2)}$$

- Most of the power concentrated at $f \sim \mathcal{O}(1)\ \mathrm{kHz}$
- Memory contribution at $f \sim 1 - 10\ \mathrm{Hz}$



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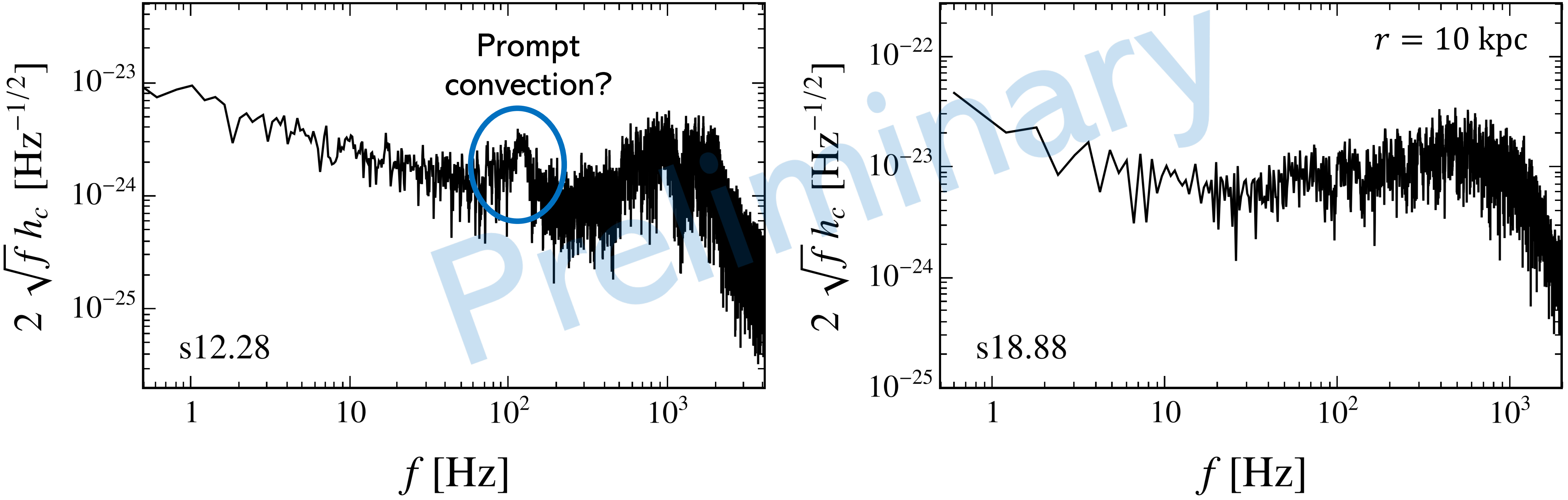

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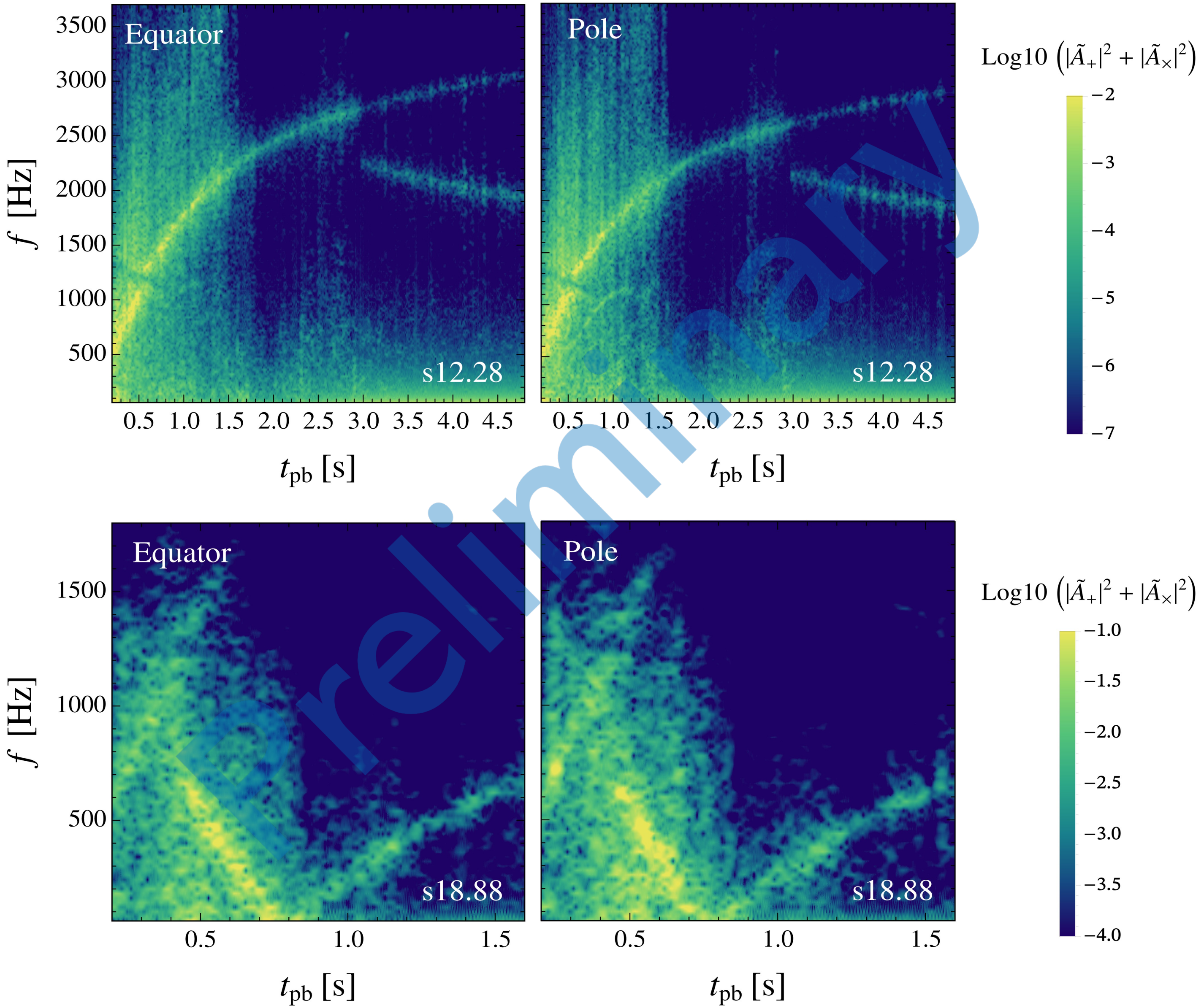
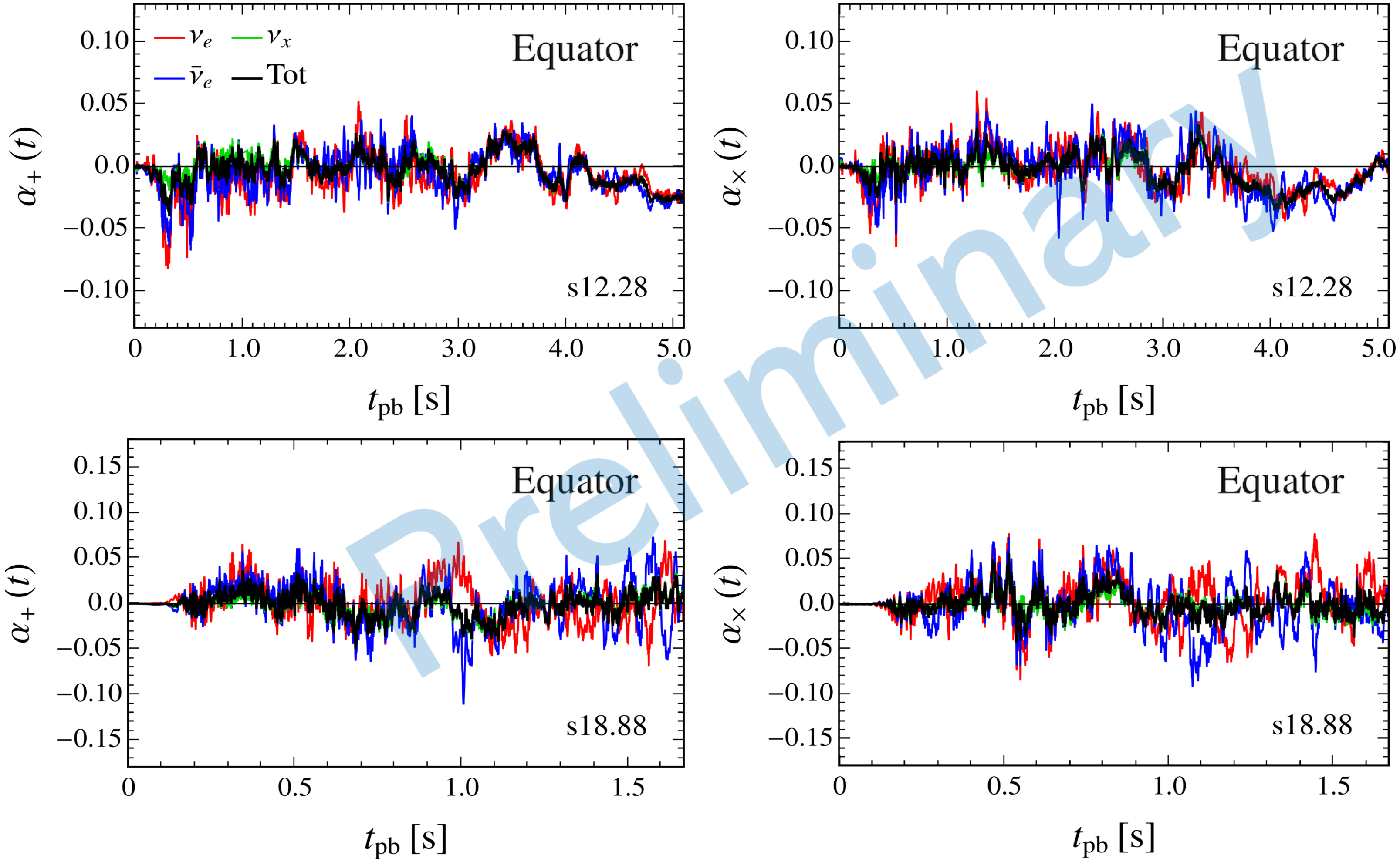


- Large power at low frequency for s12.28 just after core bounce.
- "Haze" of different modes at $t_{pb} \in [0.2, 1]s$
- Rising of a dominant PNS oscillation mode at late times
- Matter memory effect at late times
- Aliasing artifacts at $f \gtrsim f_s/2$

GWs from neutrino emission

Anisotropy parameter $\alpha_S(t,\alpha,\beta) = \frac{1}{\Lambda(t)} \int_{4\pi} d\Omega' \, W_S(\Omega',\alpha,\beta) \frac{d\Lambda}{d\Omega'}(\Omega',t)$ *[Müller et al., A&A, 537, A63 (2012)]*



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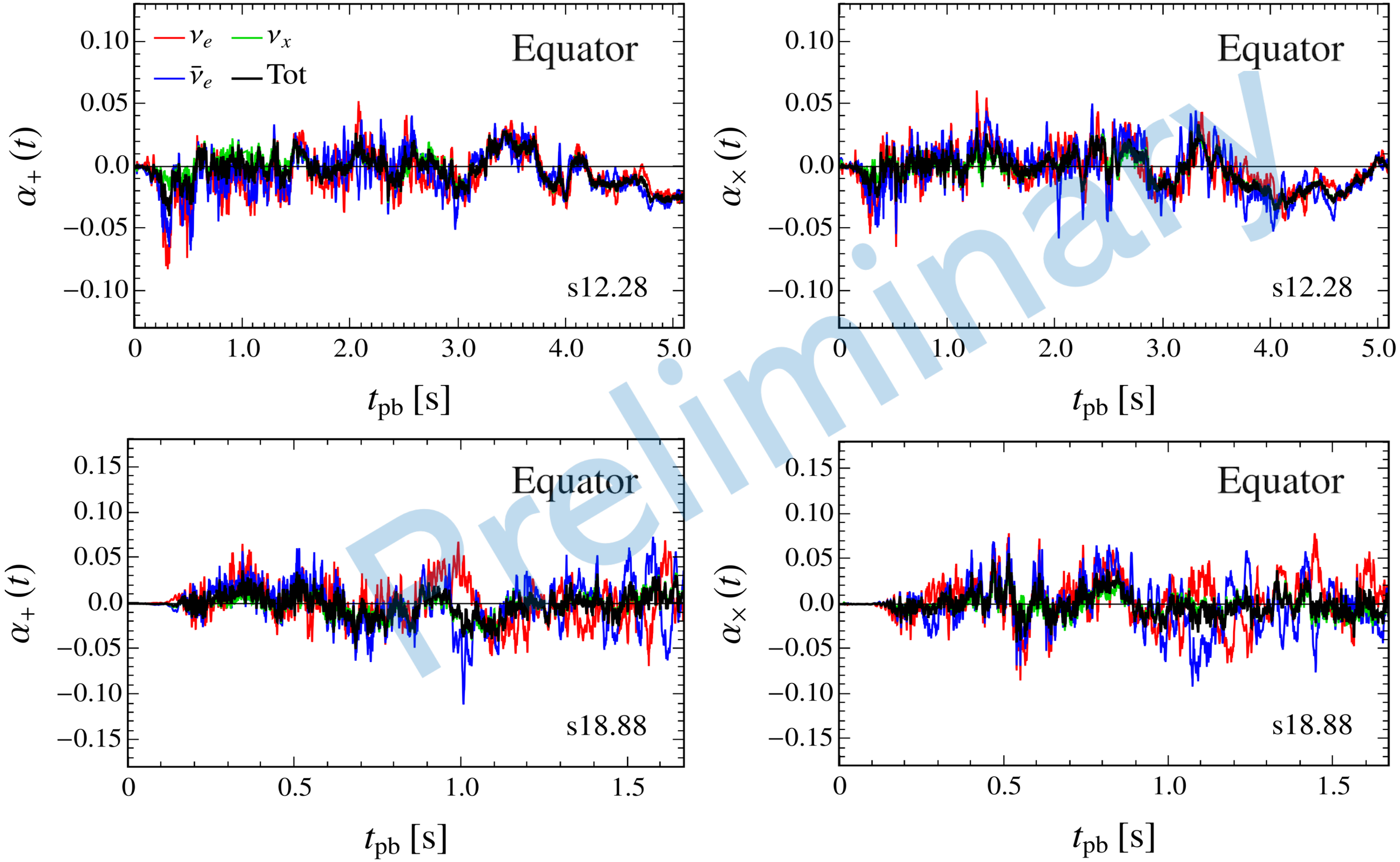
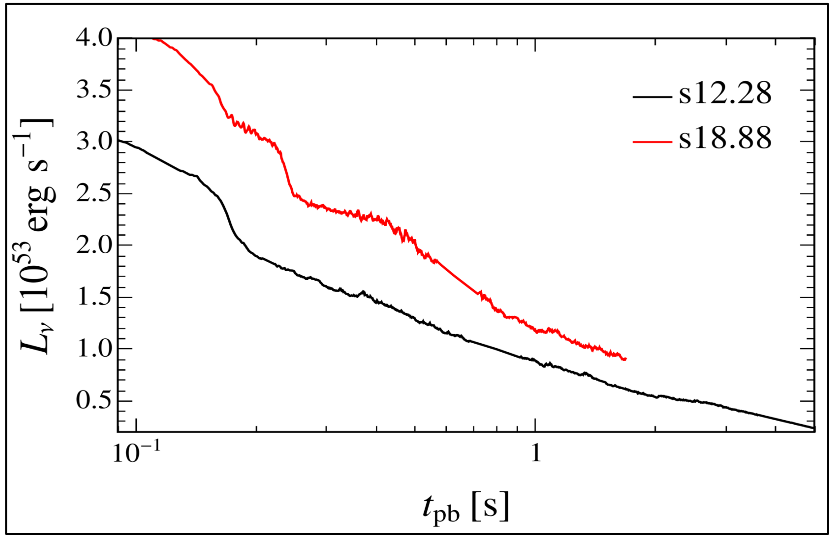
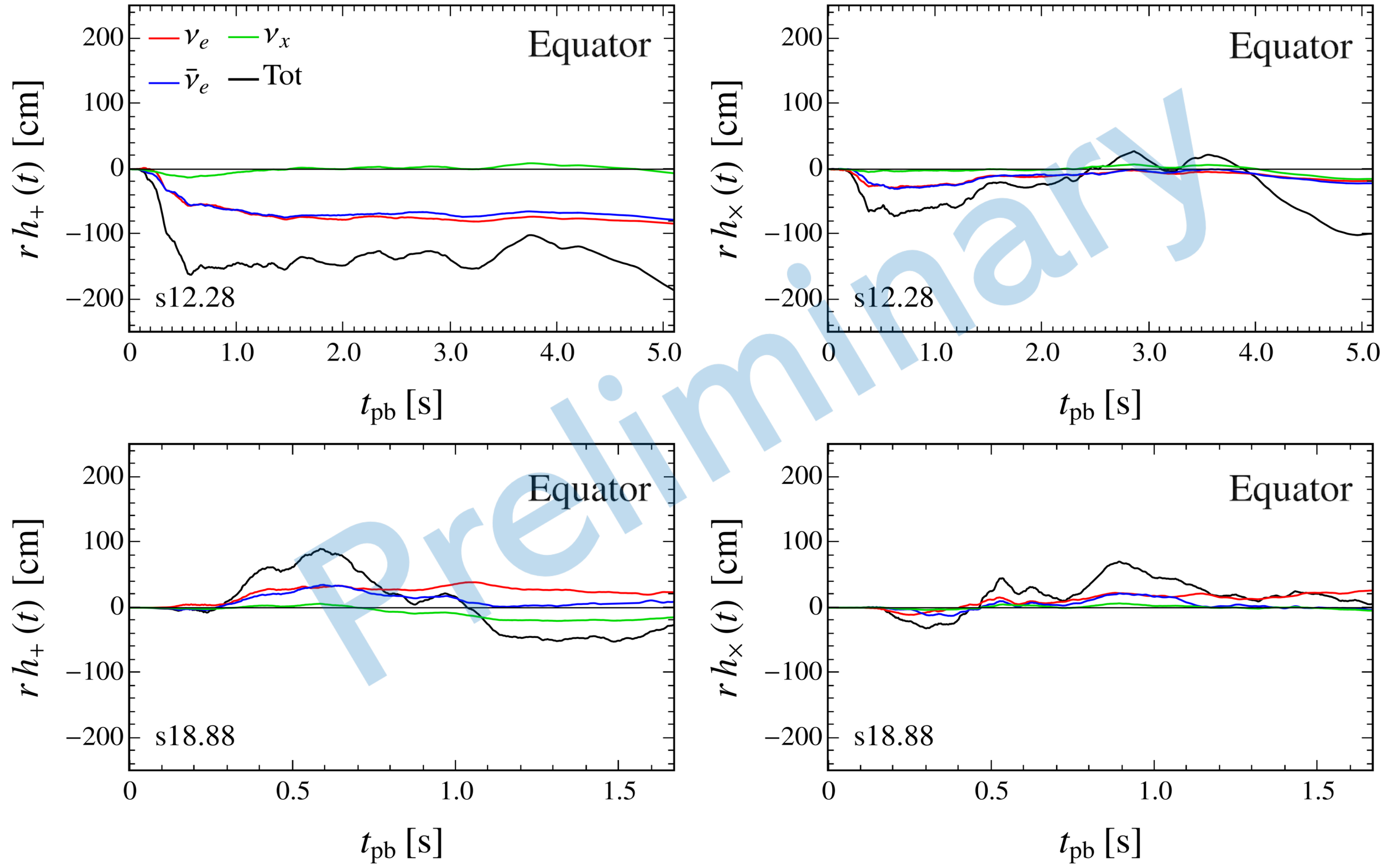


- Nearly isotropic emission at $t_{pb} < 0.1$ s
- SASI and post shock convection power highly time-dependent anisotropic emission $t_{pb} \gtrsim 0.2$ s



GWs from neutrino emission

GW strain $$h_S(t,\alpha,\beta) = \frac{2G}{rc^4}\int_0^t dt'\, L_\nu(t')\,\alpha_S(t',\alpha,\beta)$$ *[Müller et al., A&A, 537, A63 (2012)]*



- Amplitudes grow over $\Delta t \sim 0.3 - 0.5$ s, when large scale accretion builds up
- Long late-time memory effects
- Larger strains than matter component

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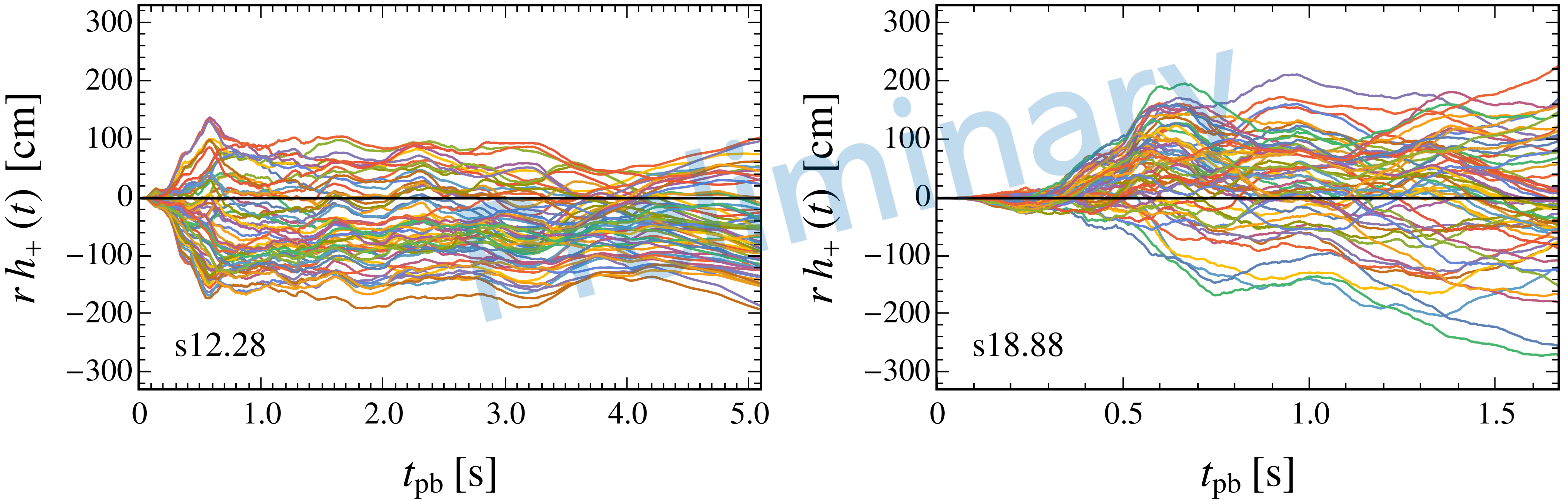
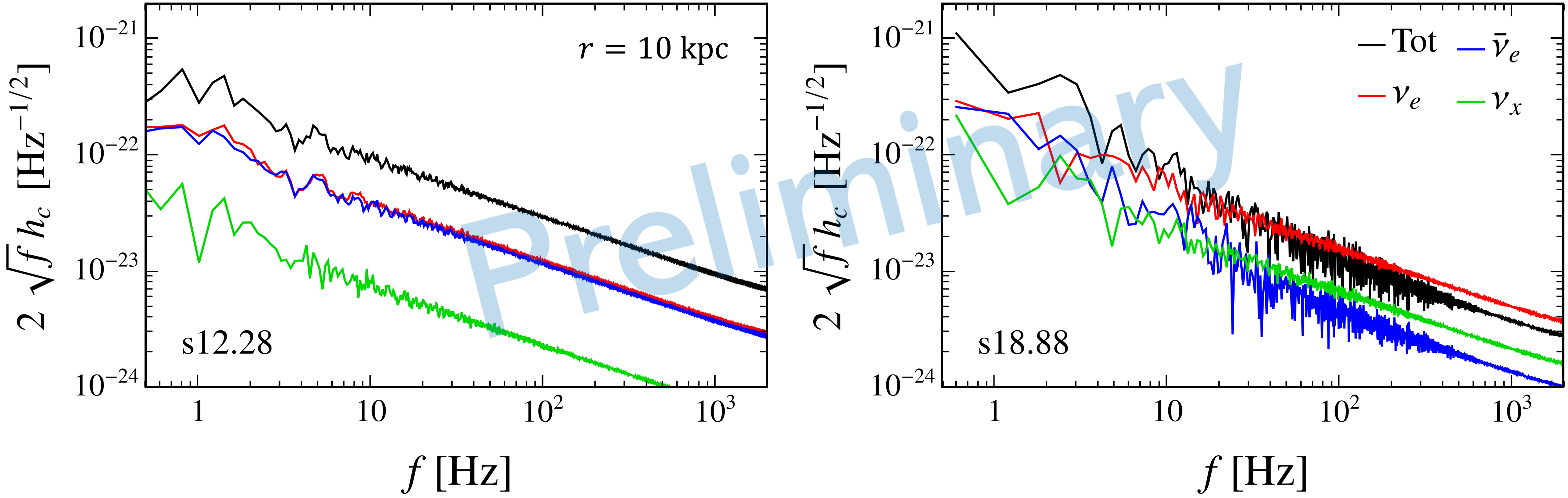


GWs from neutrino emission

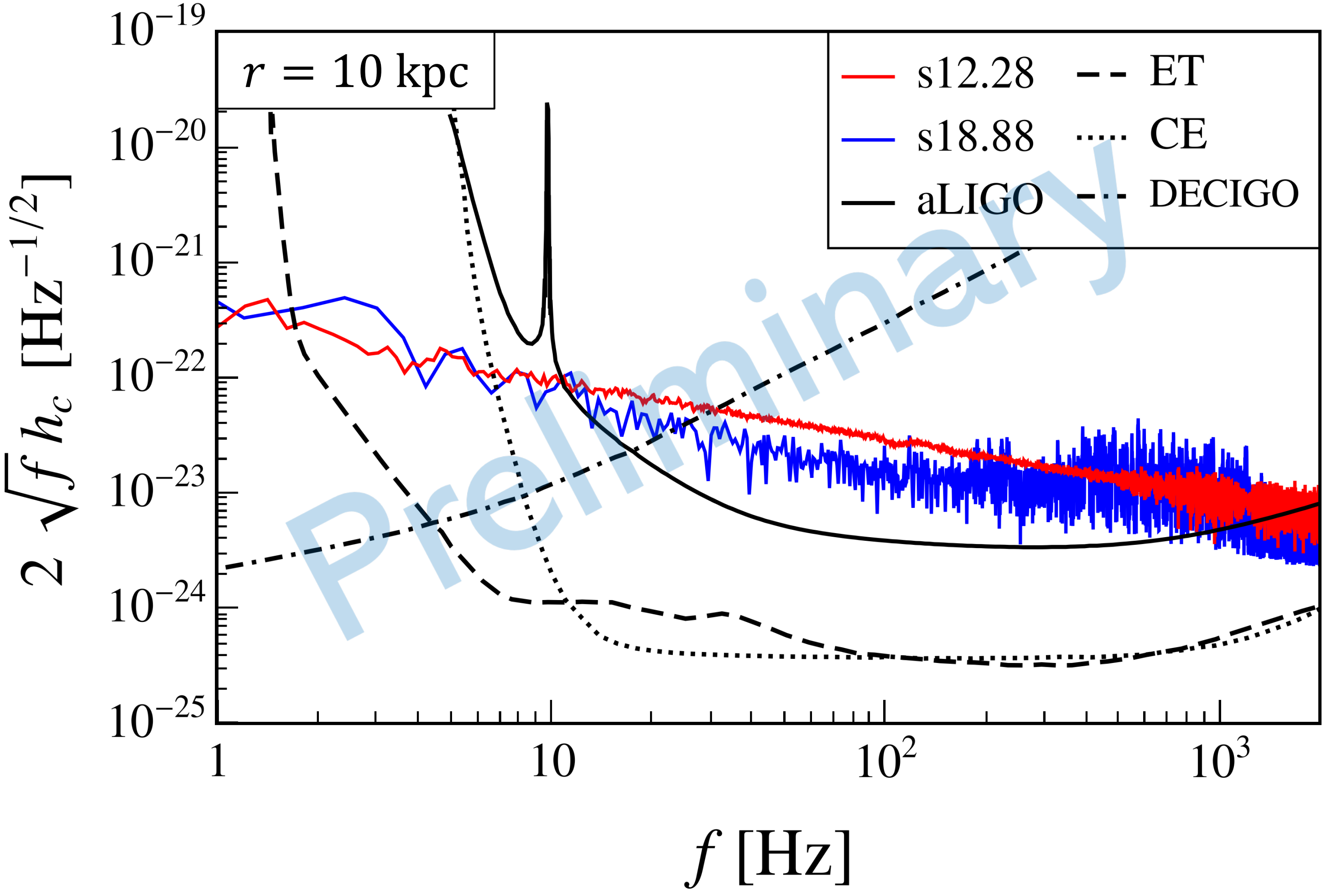
For the analysis in the frequency domain, we define the characteristic strain

$$h_c(f) = \sqrt{0.5(|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2)}$$

- Emission dominated by neutrino memory component at $\mathrm{f} \sim 1 - 10\ \mathrm{Hz}$
- Characteristic strain decays as $h_c \sim f^{-1}$ at higher frequencies

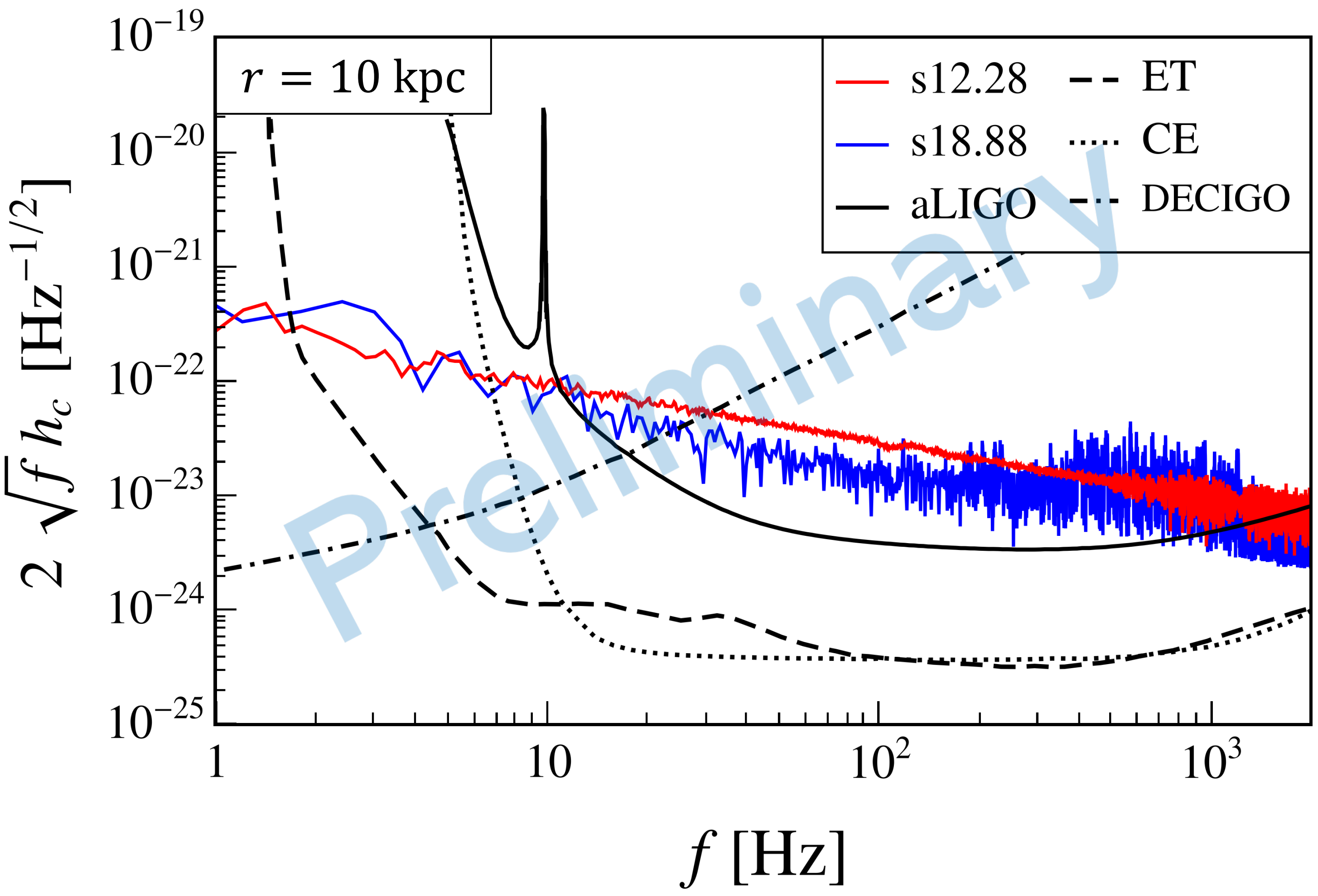


Detection prospects



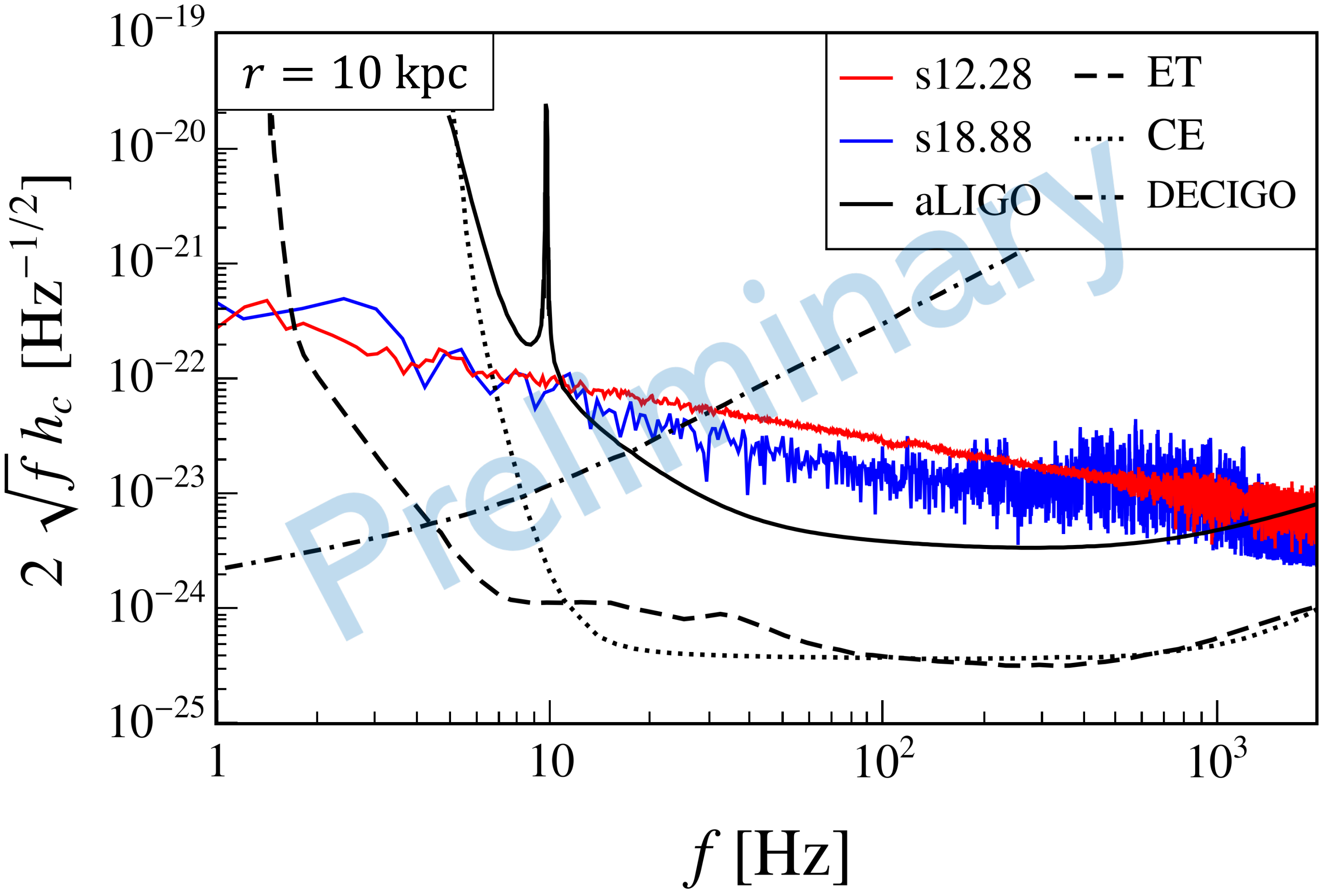
Detection prospects

- Current detectors like aLIGO able to capture high-frequency modes.



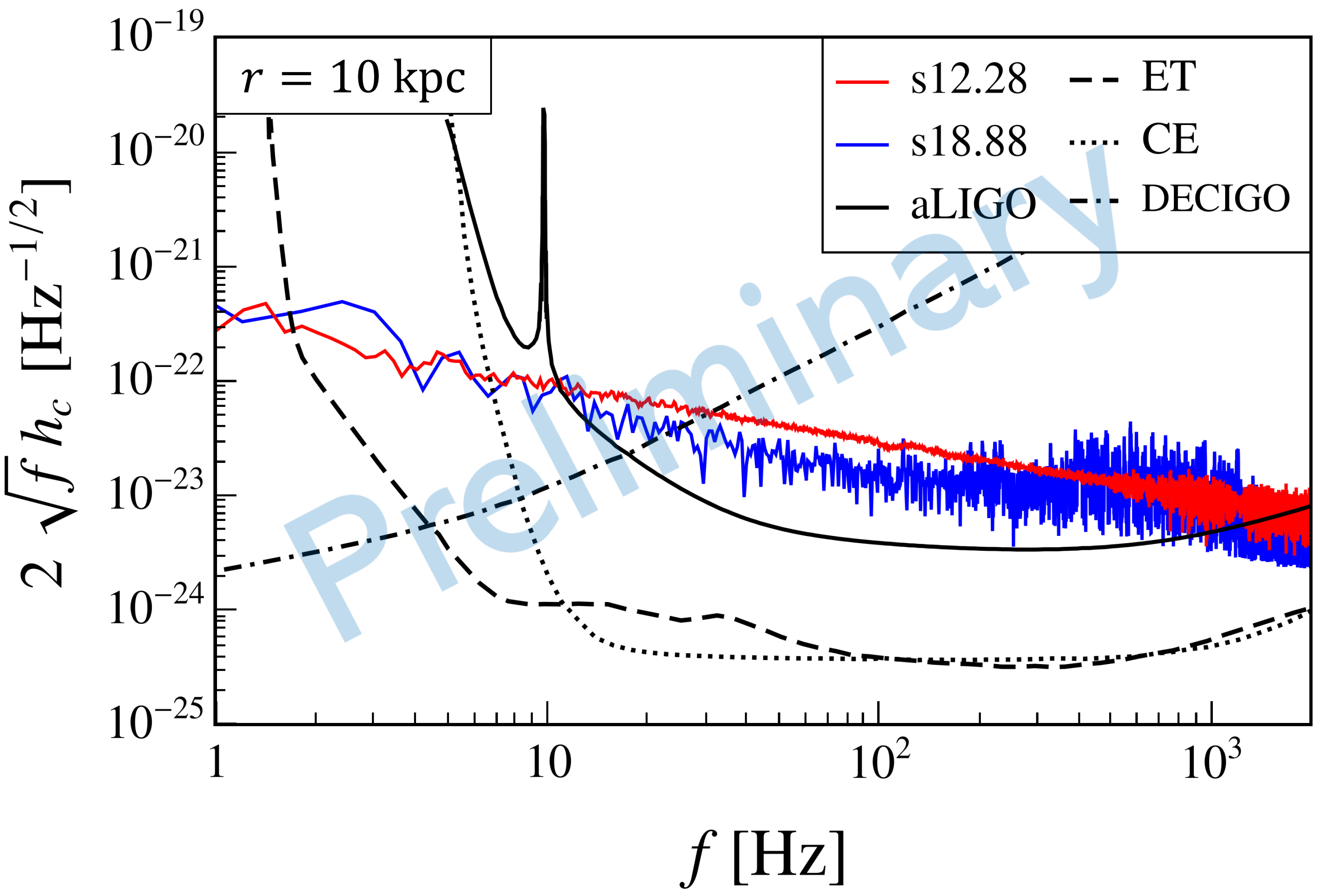
Detection prospects

- Current detectors like aLIGO able to capture high-frequency modes.
- Future detectors as ET and CE able to detect both neutrino and matter GWs



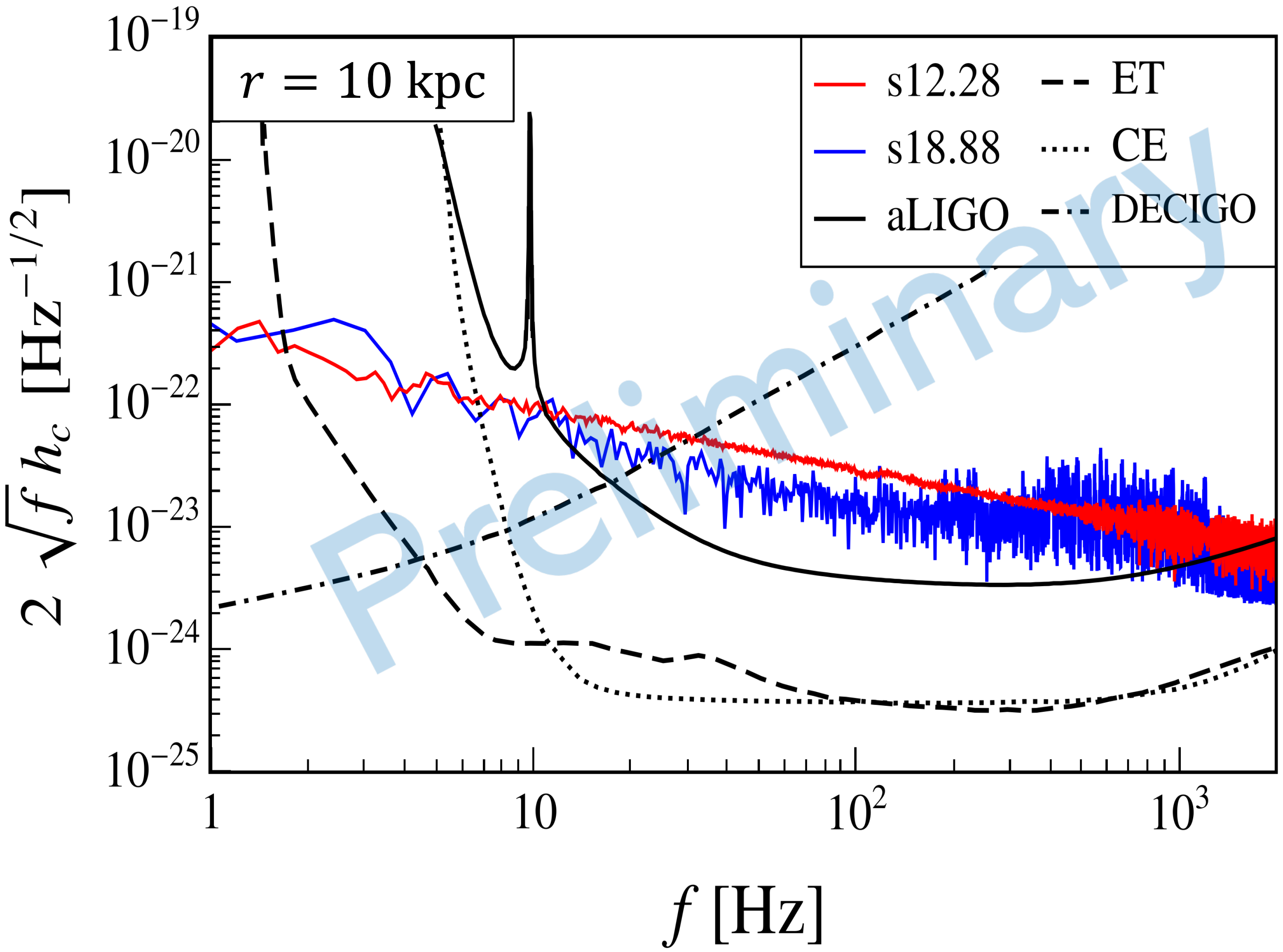
Detection prospects

- Current detectors like aLIGO able to capture high-frequency modes.
- Future detectors as ET and CE able to detect both neutrino and matter GWs
- DECIGO able to capture the full memory components



Summary and conclusions

- Anisotropic neutrino emission and mass flows are sources of GWs during cc SNe.
- GWs from hydro instabilities encode phases of SN explosion mechanism
- Neutrino memory GWs are related to highly time-dependent anisotropic emission
- Both matter and neutrino GWs from the next Galactic SN are in the reach of current and future GW detectors



Acknowledgements

- INFN
- PRIN 2022 “PANTHEON”

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Ministero dell'Università e della Ricerca
Italiadomani
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Angle-dependence of $\ddot{Q}_{ij}$

$$\ddot{Q}_{\theta\theta} = \left(\ddot{Q}_{xx}\cos^2\phi + \ddot{Q}_{yy}\sin^2\phi + 2\ddot{Q}_{xy}\sin\phi\cos\phi\right)\cos^2\theta + \ddot{Q}_{zz}\sin^2\theta - 2\left(\ddot{Q}_{xz}\cos\phi + \ddot{Q}_{yz}\sin\phi\right)\sin\theta\cos\theta$$

$$\ddot{Q}_{\phi\phi} = \ddot{Q}_{xx}\sin^2\phi + \ddot{Q}_{yy}\cos^2\phi - 2\ddot{Q}_{xy}\sin\phi\cos\phi\,,$$

$$\ddot{Q}_{\theta\phi} = (\ddot{Q}_{yy} - \ddot{Q}_{xx})\cos\theta\sin\phi\cos\phi + \ddot{Q}_{xy}\cos\theta(\cos^2\phi - \sin^2\phi) + \ddot{Q}_{xz}\sin\theta\sin\phi - \ddot{Q}_{yz}\sin\theta\cos\phi\,.$$

Angular weight functions

$$W_S(\theta', \phi', \alpha, \beta) = \frac{D_S(\theta', \phi', \alpha, \beta)}{N(\theta', \phi', \alpha, \beta)}$$

$$\begin{aligned} D_+ \;=\; & [1 + (\cos\phi' \cos\alpha + \sin\phi' \sin\alpha) \sin\theta' \sin\beta + \cos\theta' \\ & \cos\beta] \; \{[(\cos\phi' \cos\alpha + \sin\phi' \sin\alpha) \sin\theta' \cos\beta - \\ & \cos\theta' \sin\beta]^2 - \sin^2\theta' \, (\sin\phi' \cos\alpha - \cos\phi' \sin\alpha)^2\} \end{aligned}$$

$$\begin{aligned} D_\times \;=\; & [1 + (\cos\phi' \cos\alpha + \sin\phi' \sin\alpha) \sin\theta' \sin\beta + \cos\theta' \\ & \cos\beta] \; 2\, [(\cos\phi' \cos\alpha + \sin\phi' \sin\alpha) \sin\theta' \cos\beta - \\ & \cos\theta' \sin\beta] \; \sin\theta' \, (\sin\phi' \cos\alpha - \cos\phi' \sin\alpha) \; , \end{aligned}$$

$$\begin{aligned} N \;=\; & [(\cos\phi' \cos\alpha + \sin\phi' \sin\alpha) \sin\theta' \cos\beta \; - \; \cos\theta' \\ & \sin\beta]^2 + \sin^2\theta' \, (\sin\phi' \cos\alpha - \cos\phi' \sin\alpha)^2 \; . \end{aligned}$$

Gravitational wave energy