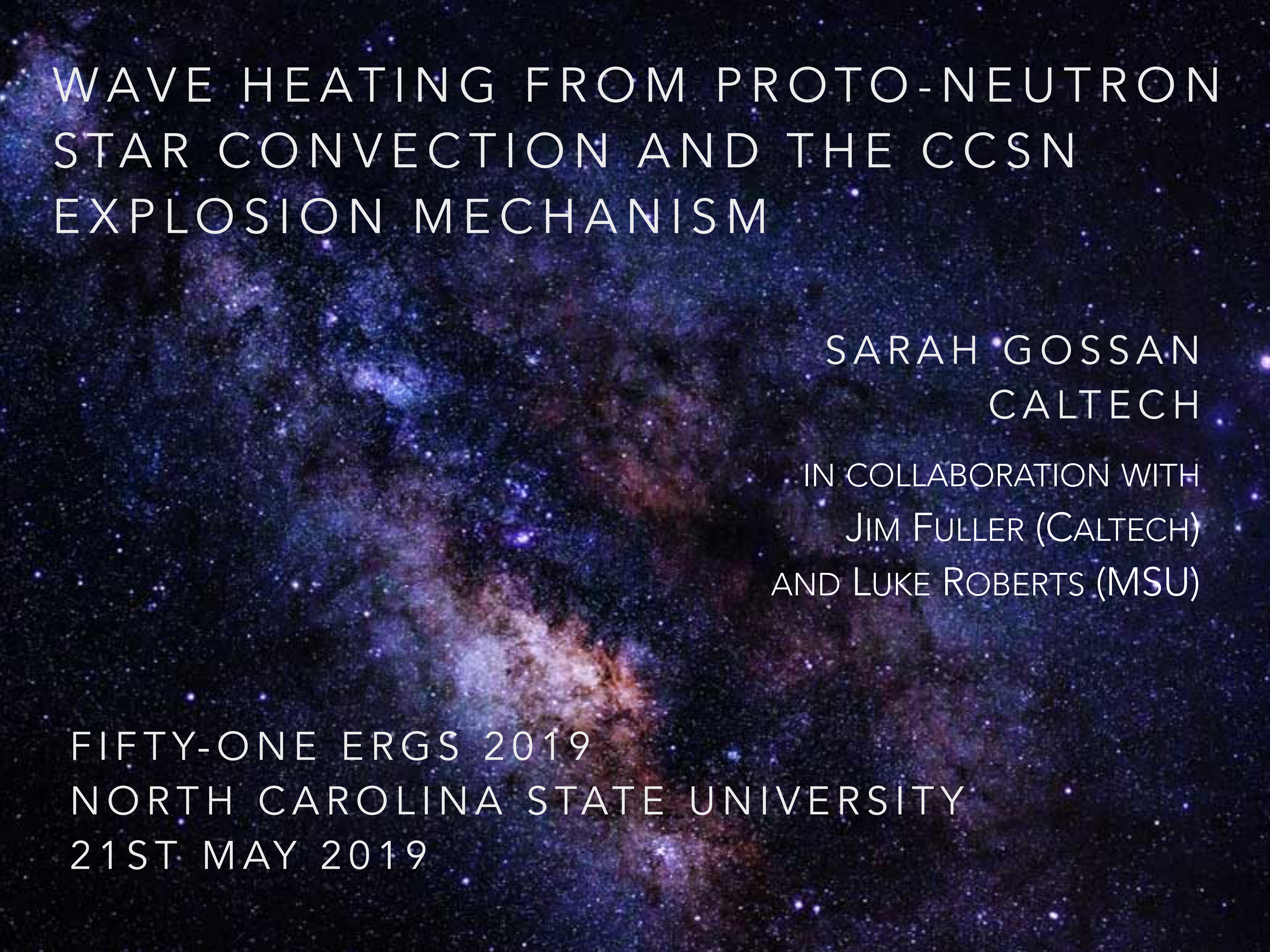

WAVE HEATING FROM PROTO-NEUTRON STAR CONVECTION AND THE CCSN EXPLOSION MECHANISM

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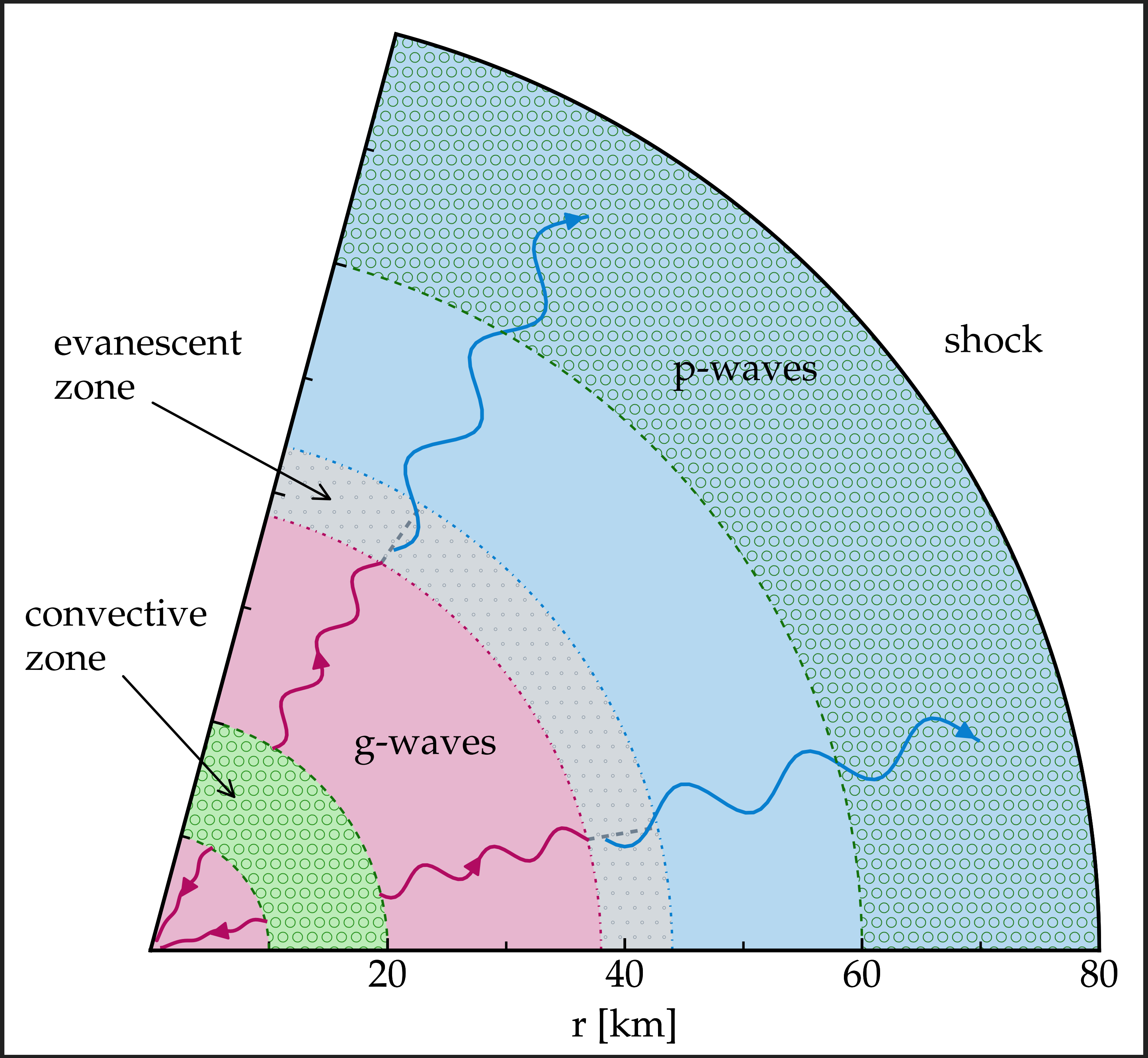
MOTIVATION — THE CCSN EXPLOSION PROBLEM

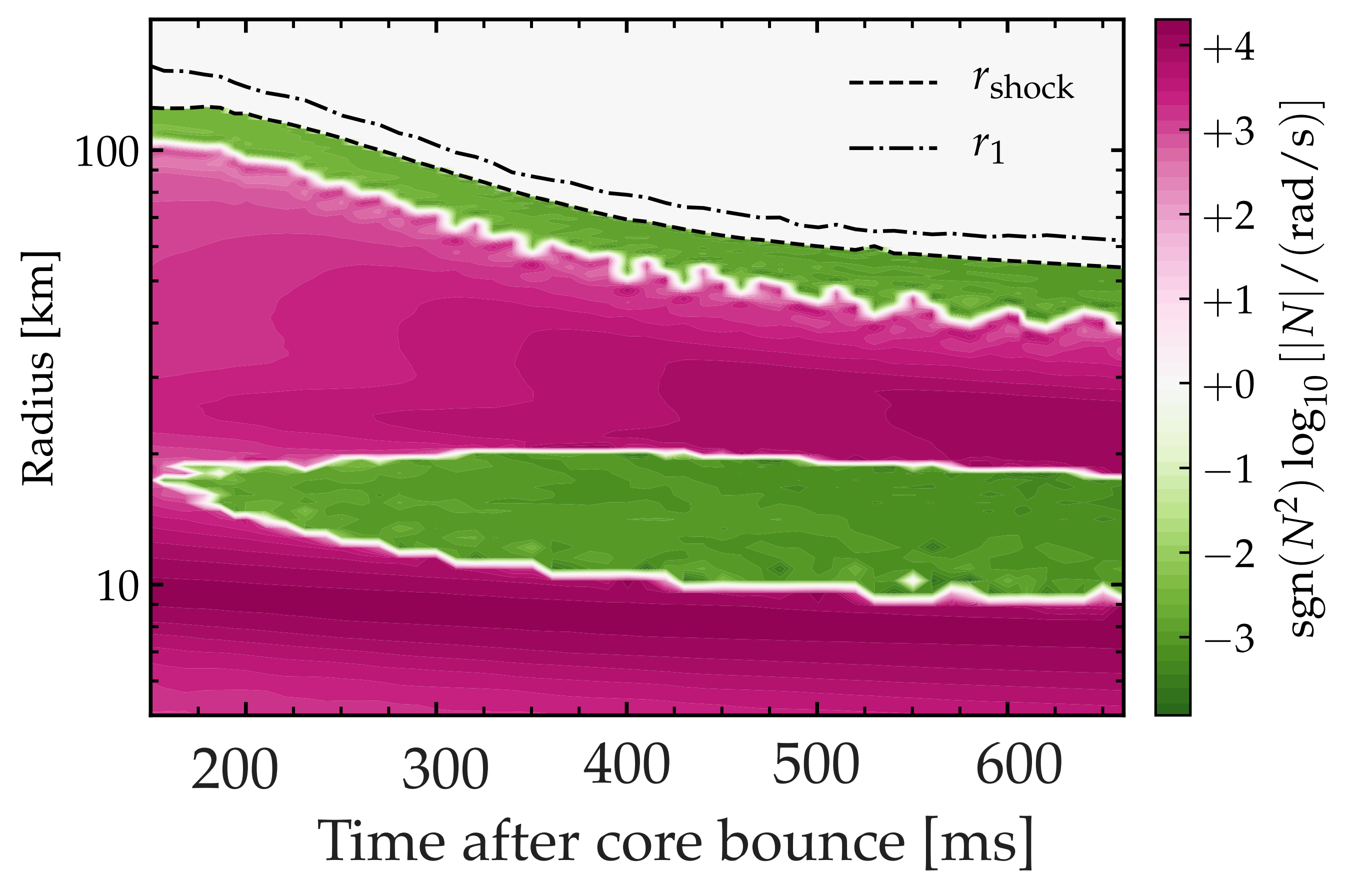
- ★ Why do so many simulations fail to explode?
  - ★ Many simulations lie near bifurcation between failed and successful explosions
  - ★ Don't have unlimited computational resources — need to implement approximations for source physics
  - ★ Proto-neutron star (PNS) hydrodynamics often not resolved — unclear how this affects the `explodability' of progenitors
  - ★ What are we missing?

BASIC IDEA

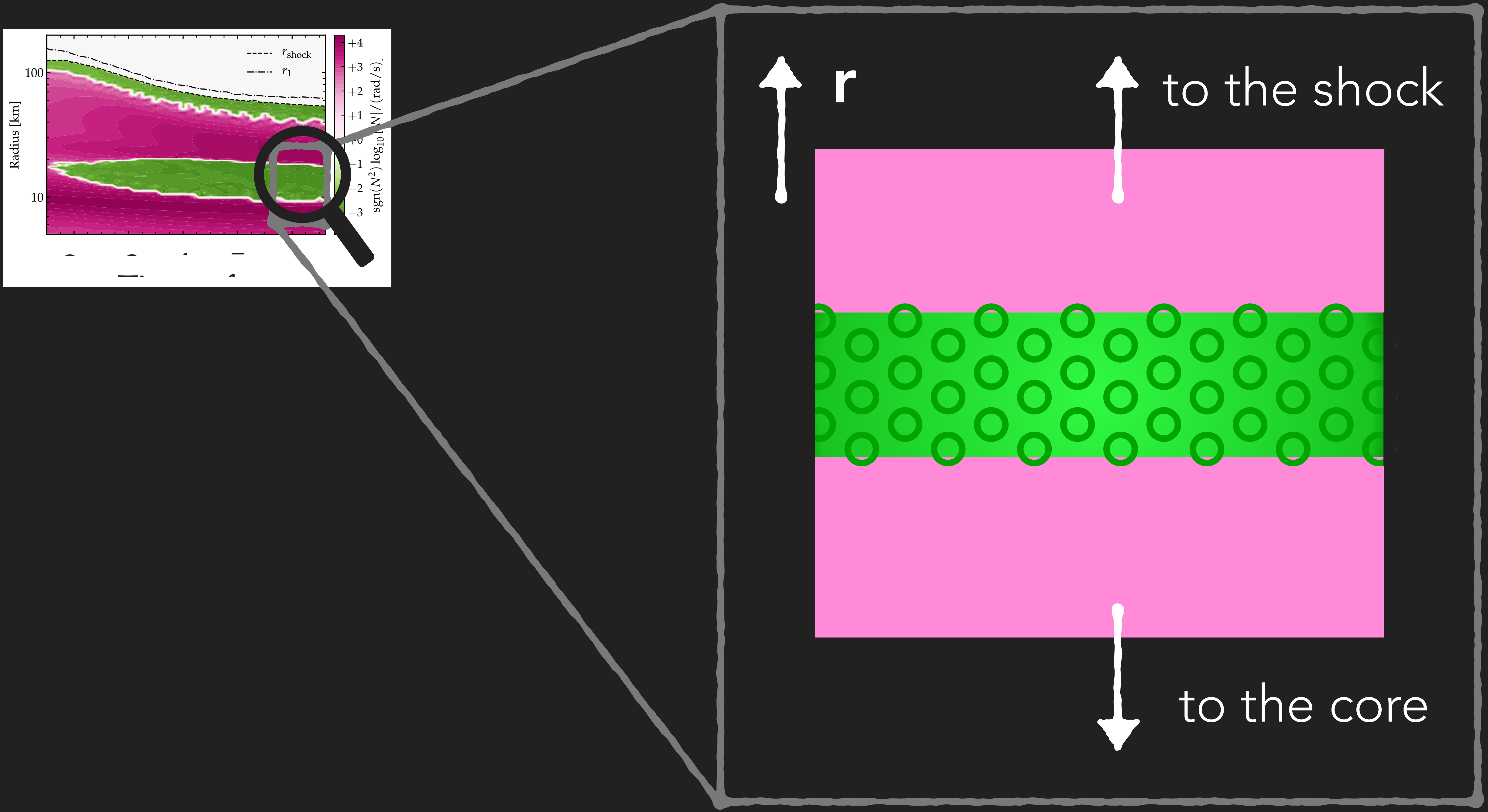

evanescent zone
shock
p-waves
convective zone
g-waves
20
40
60
80
r [km]

PNS CONVECTION

- ★ Use 1D simulations with M1 neutrino transport and mixing-length treatment of convection to follow evolution during first ~1s post-bounce
- ★ Distinguish between convective and radiative zones using buoyancy frequency



WAVE GENERATION

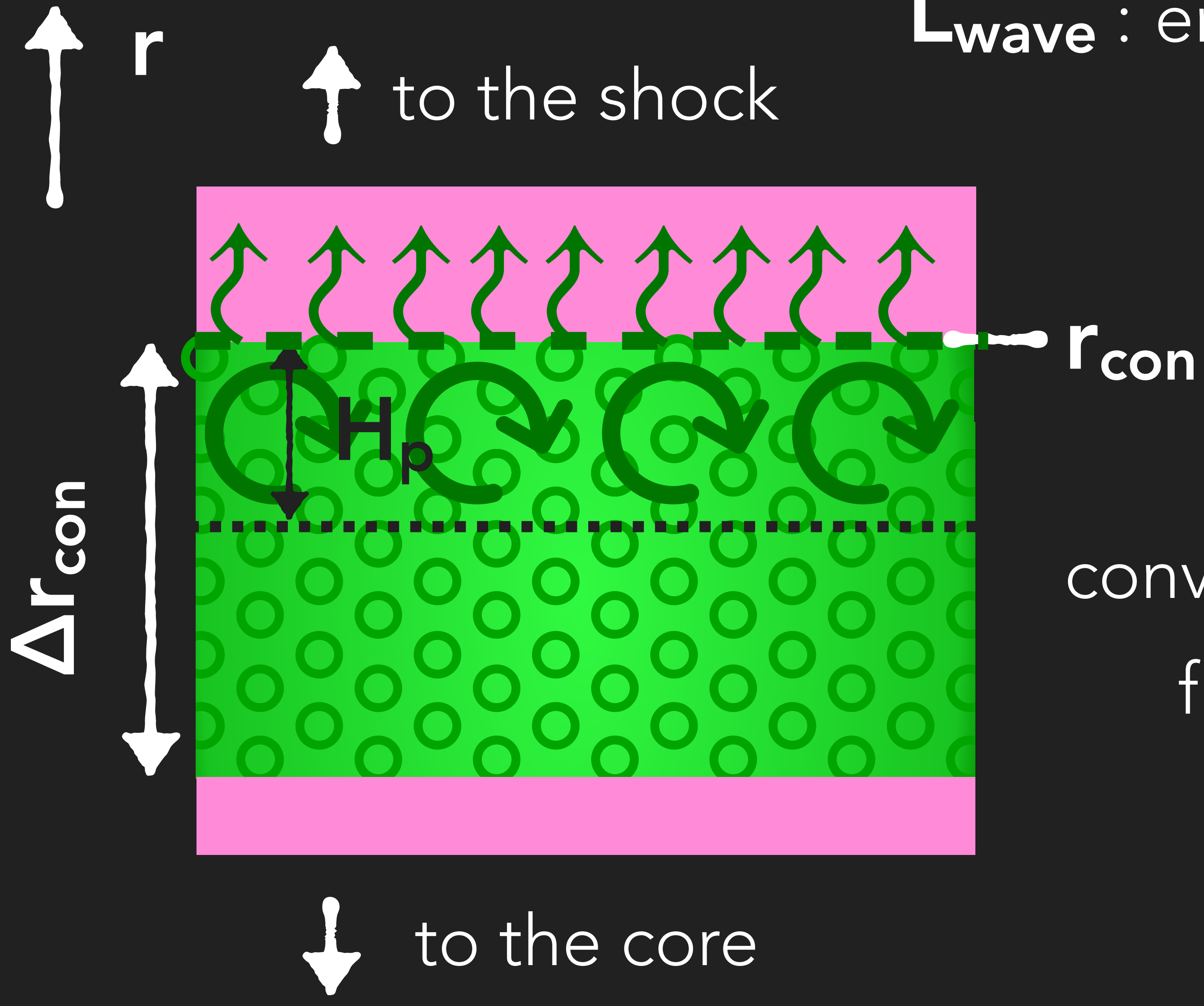


r

to the shock

to the core

WAVE GENERATION



r

to the shock

Δr_{con}

H_p

r_{con}

to the core

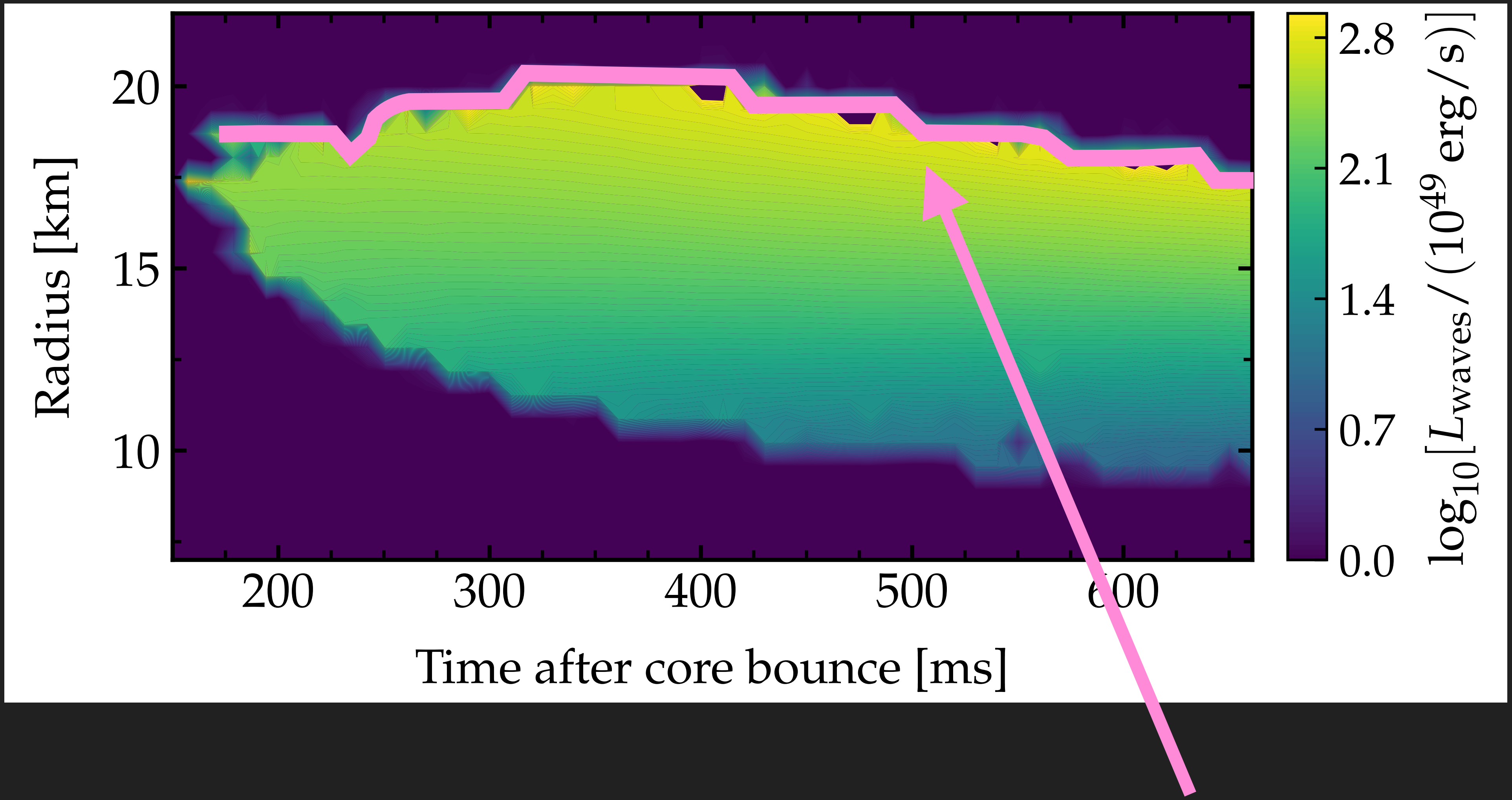
L_{wave} : energy flux in waves outgoing at r_{con}

$$L_{wave} \sim L_{con}\ M_{con}$$

convective energy flux at r_{con}

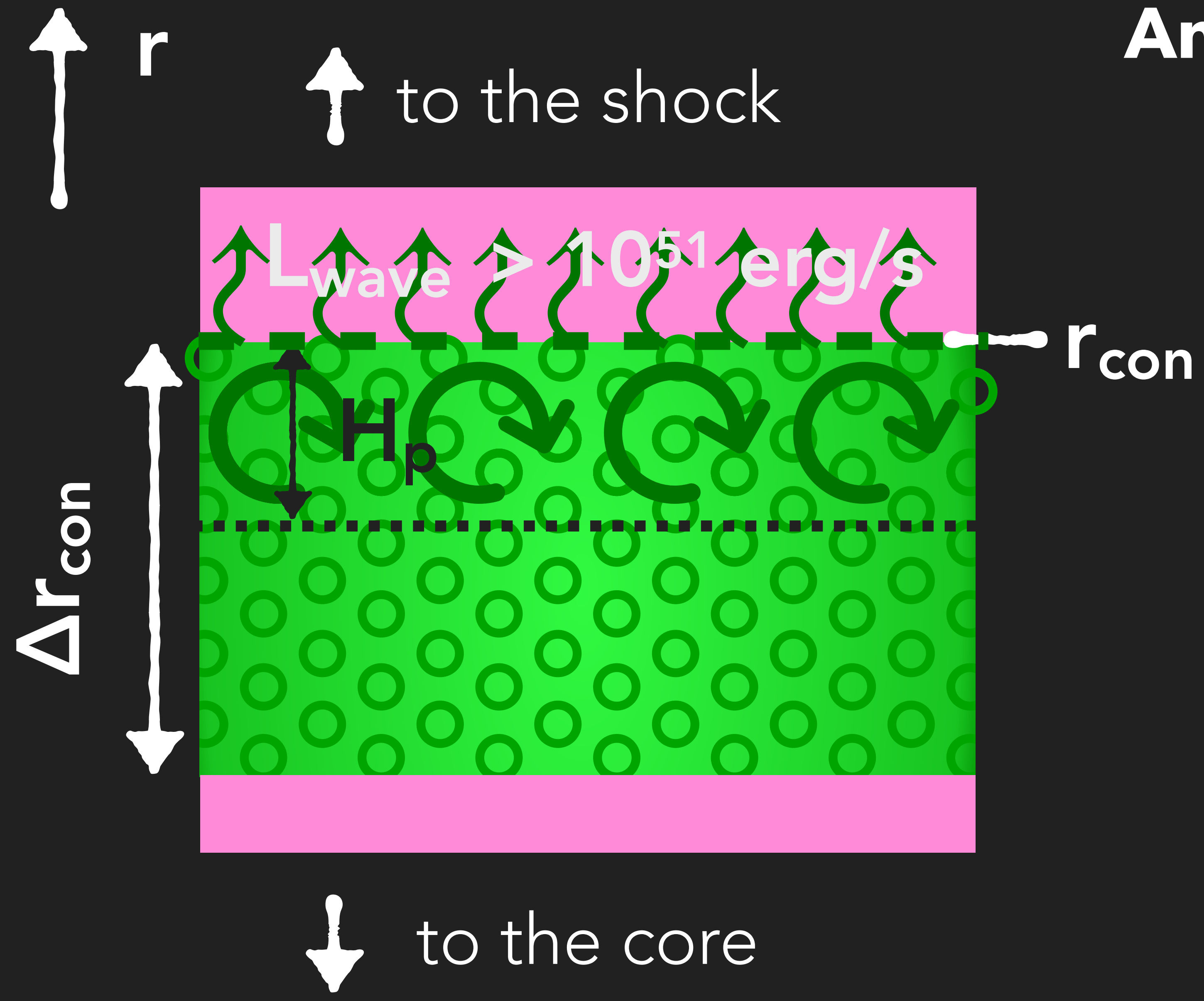
mach number $M_{con} = v_{con} / c_s$ at r_{con}

WAVE GENERATION



$L_{\rm wave}$ > many 10^{51} erg/s emitted here through end of simulation

PROPERTIES OF EXCITED WAVES

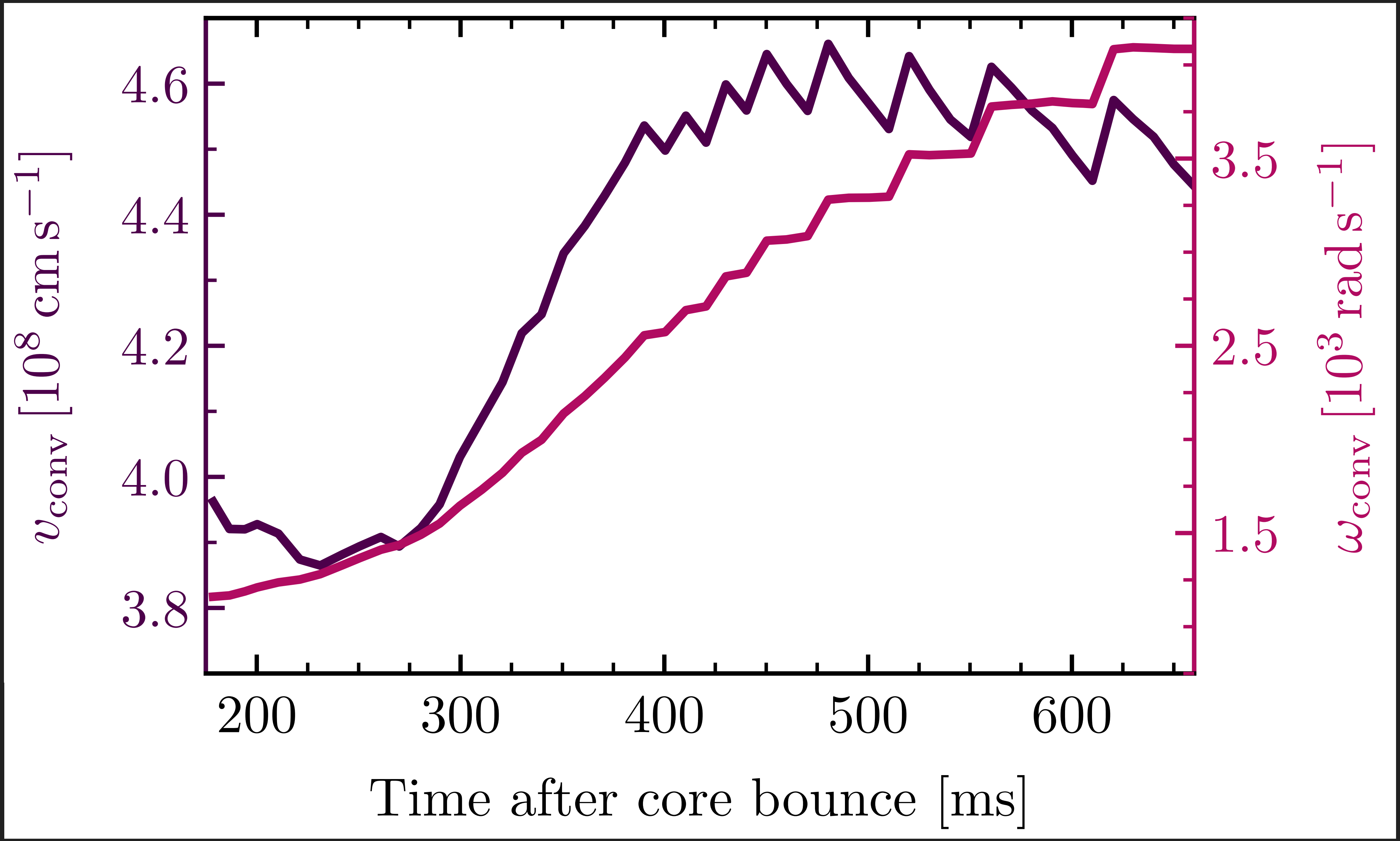


Angular spectrum unknown

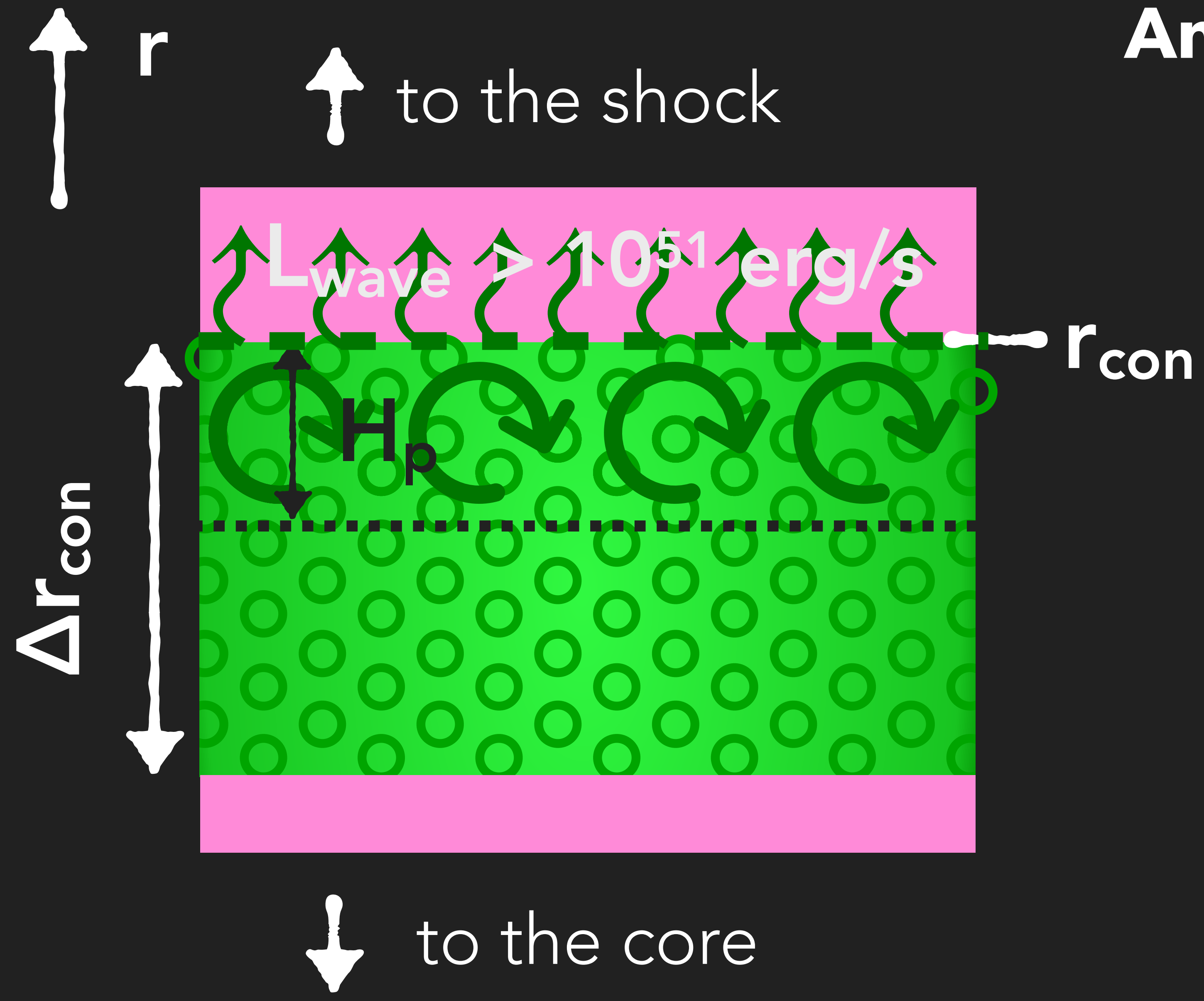
but a good place to start is the convective turnover frequency $\boldsymbol{\omega_{con}}$

$$\boxed{\omega_{con} = \frac{\pi\, v_{con}}{2\, H_p}}$$

CONVECTIVE TURNOVER FREQUENCY



PROPERTIES OF EXCITED WAVES



Angular spectrum unknown

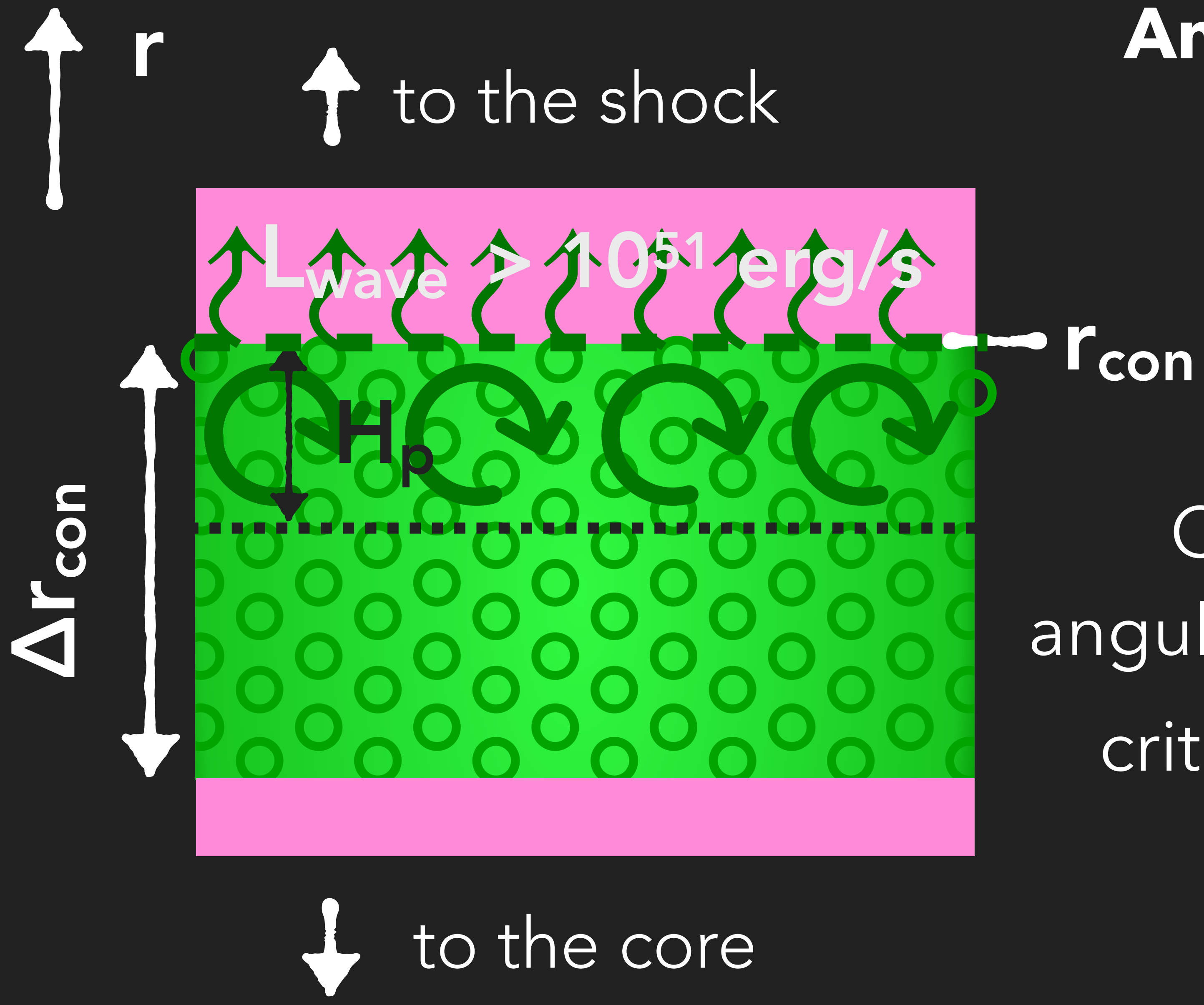
but a good place to start is the convective turnover frequency **ω_{con}**

$\omega_{wave} \sim \omega_{con}$

Goldreich & Kumar (1990)
Lecoanet & Quataert (2013)

$\omega_{wave} \sim$ few 10^3 rad/s

PROPERTIES OF EXCITED WAVES



Angular spectrum unknown

Assuming $\omega_{wave} \sim \omega_{con}$

GK1990, LQ2013

$\omega_{wave} \sim$ few 10^3 rad/s

Consider flat spectrum over angular wave modes up to some critical angular wavenumber l_c

$$l_c = \frac{r_{con}}{\Delta r_{con}} \sim 3$$

PROPERTIES OF EXCITED WAVES

tl;dl[1] summary

Total luminosity in excited waves	$L_{\mathrm{wave}} \sim$ many 10^{51} erg/s
Angular frequency of excited waves	$\omega_{\mathrm{wave}} \sim \omega_{\mathrm{con}}$ $\sim$ few 10^{3} rad/s
Critical angular wavenumber	$l_c \sim 3$
Luminosity per excited wave mode	$L_{\mathrm{wave},\,l} \sim 10^{51}$ erg/s

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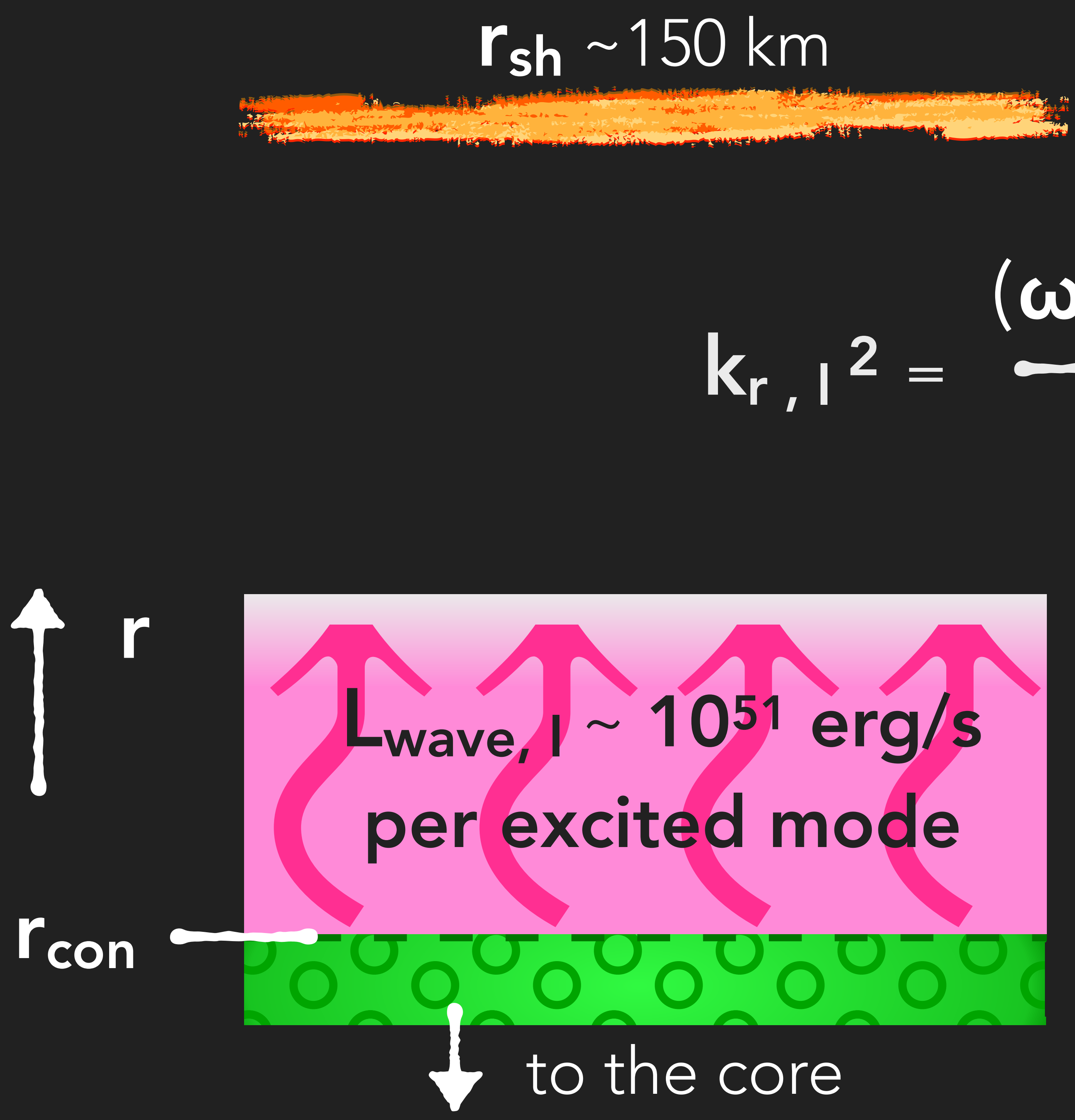
[1] (too long, didn't listen)

WAVE PROPAGATION



r_{sh} ~150 km

r

$L_{wave,\,l} \sim 10^{51}$ erg/s per excited mode

r_{con}

to the core

radial wavevector $k_{r\,,\,l}$

$$k_{r\,,\,l}^{\;2} = \frac{(\omega_{wave}^{2} - |N^{2}|)\,(\omega_{wave}^{2} - L_{l}^{2})}{\omega_{wave}^{2}\, c_{s}^{2}}$$

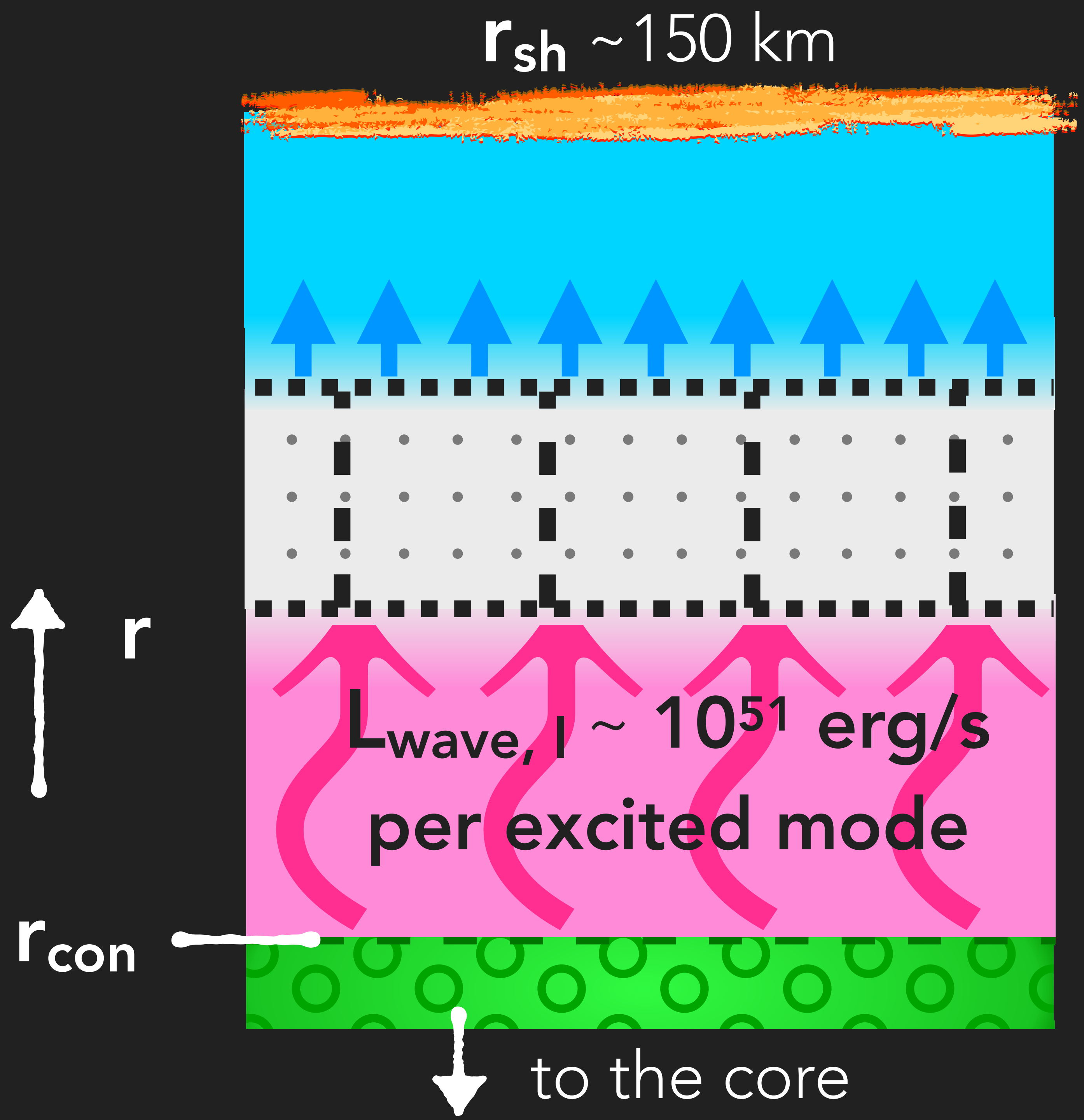
buoyancy frequency

Lamb frequency

$$L_{l}^{2} = \frac{l\,(l+1)\,c_{s}^{2}}{r^{2}}$$

waves can propagate where $k_{r\,,\,l}^{\;2} > 0$

WAVE PROPAGATION



Fraction $T_l^{\,2}$ of incident wave flux transmitted in acoustic waves where

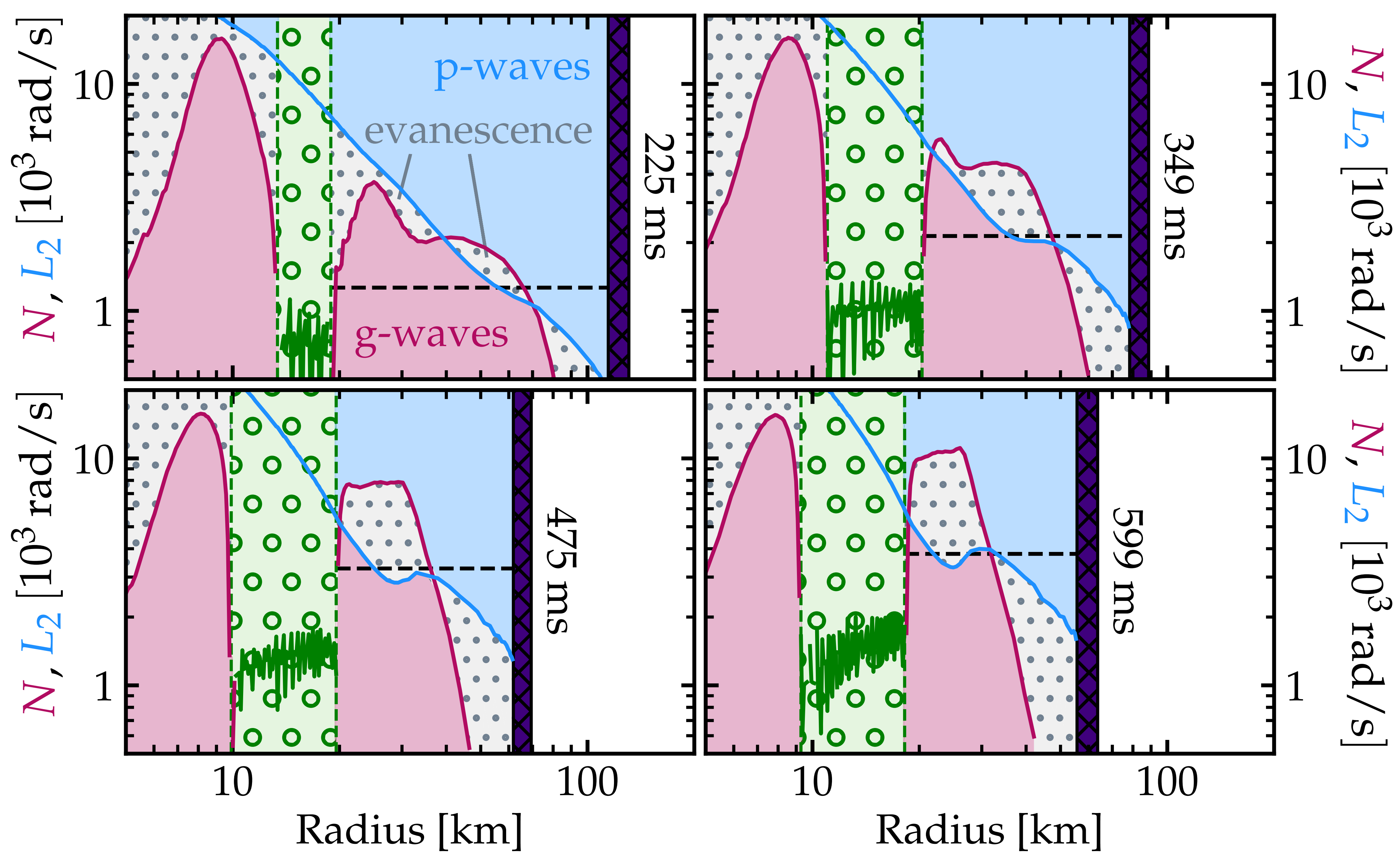
$$\omega_{wave} > |N| \,,\; L_{\,l = 1, \ldots, lc}$$

$$T_l^{\,2} = -2 \int dr \,|\, k_{r\,,\,l} \,|$$

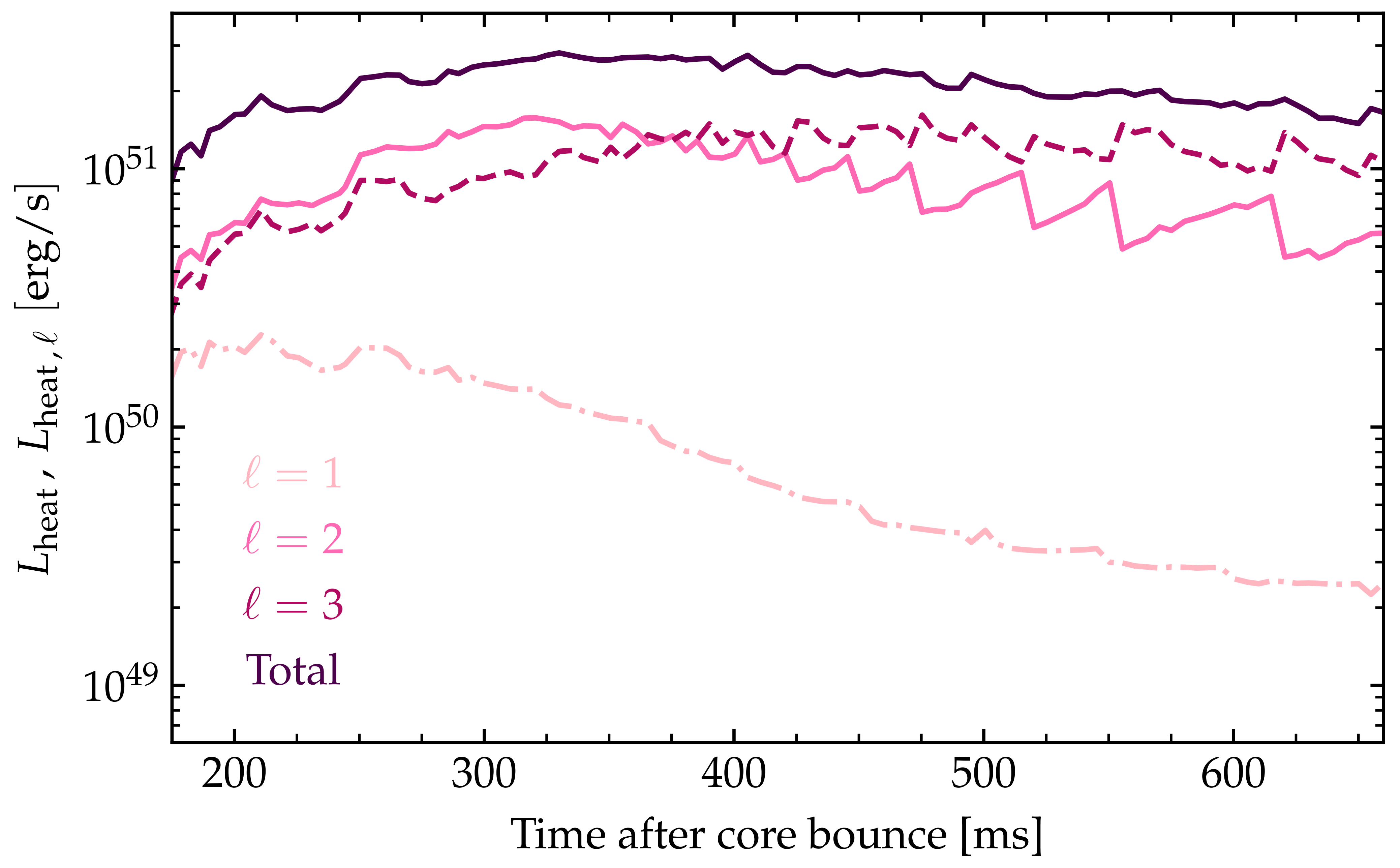
Total heating rate L_{heat}

$$L_{heat} = \sum_{l = 1, \ldots, l_c} L_{wave,\,l} \, T_l^{\,2}$$

WAVE PROPAGATION



WAVE HEATING RATES



LIMITATIONS

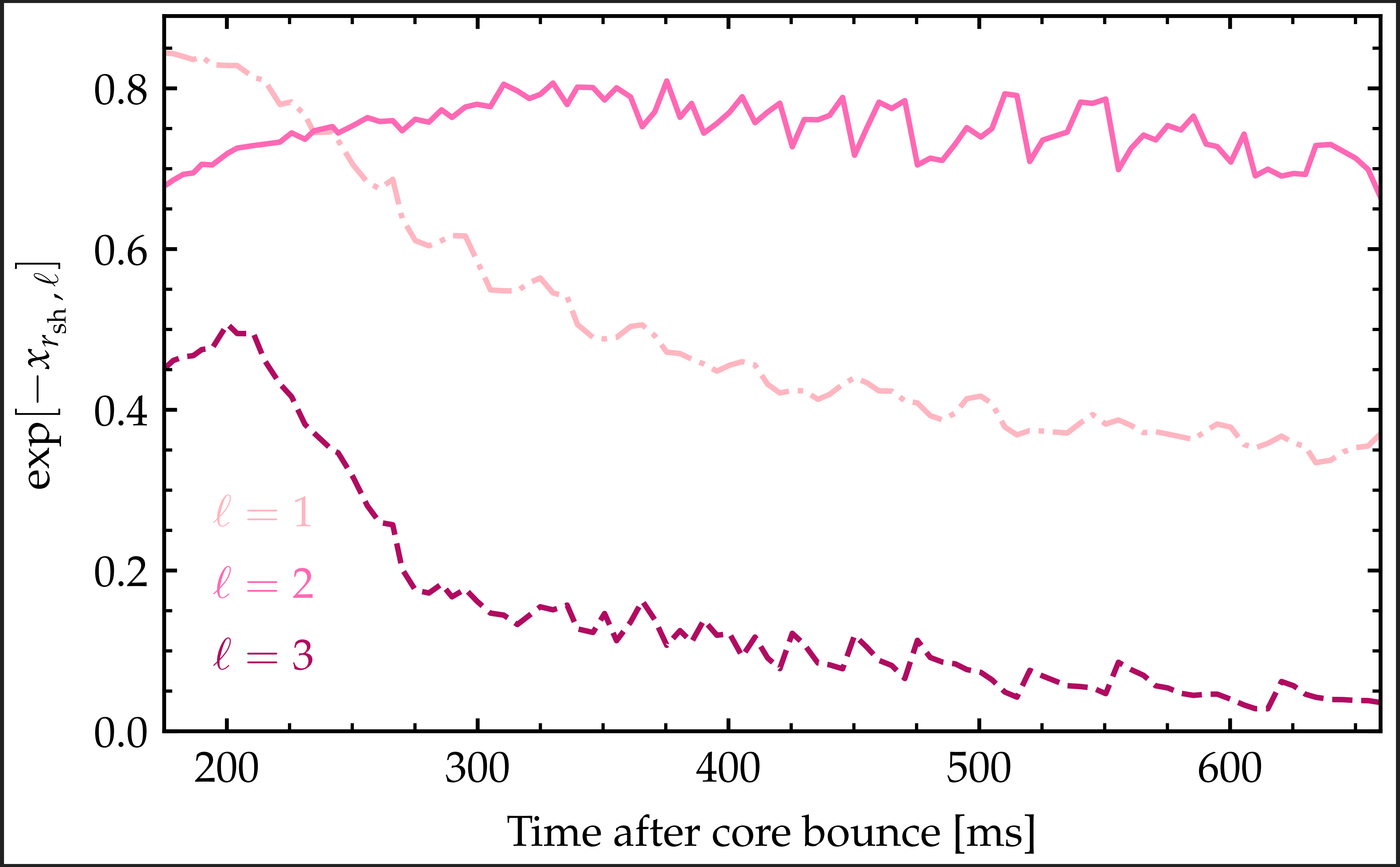
(1) Uncertainty in the excited wave spectrum

(2) Assumption of linear wave dynamics

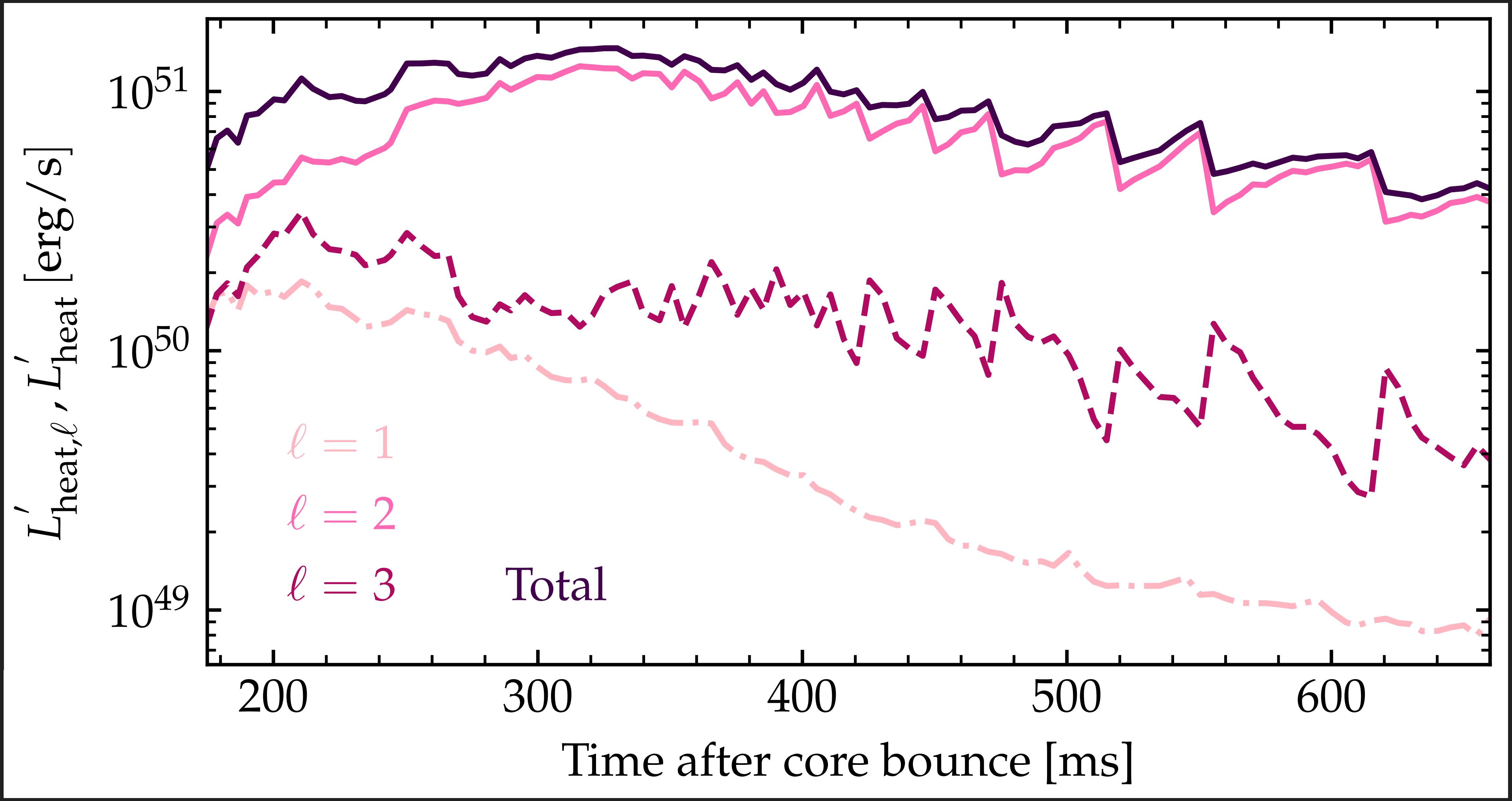
(3) Wave damping ignored

(4) Our simulations don’t explode!

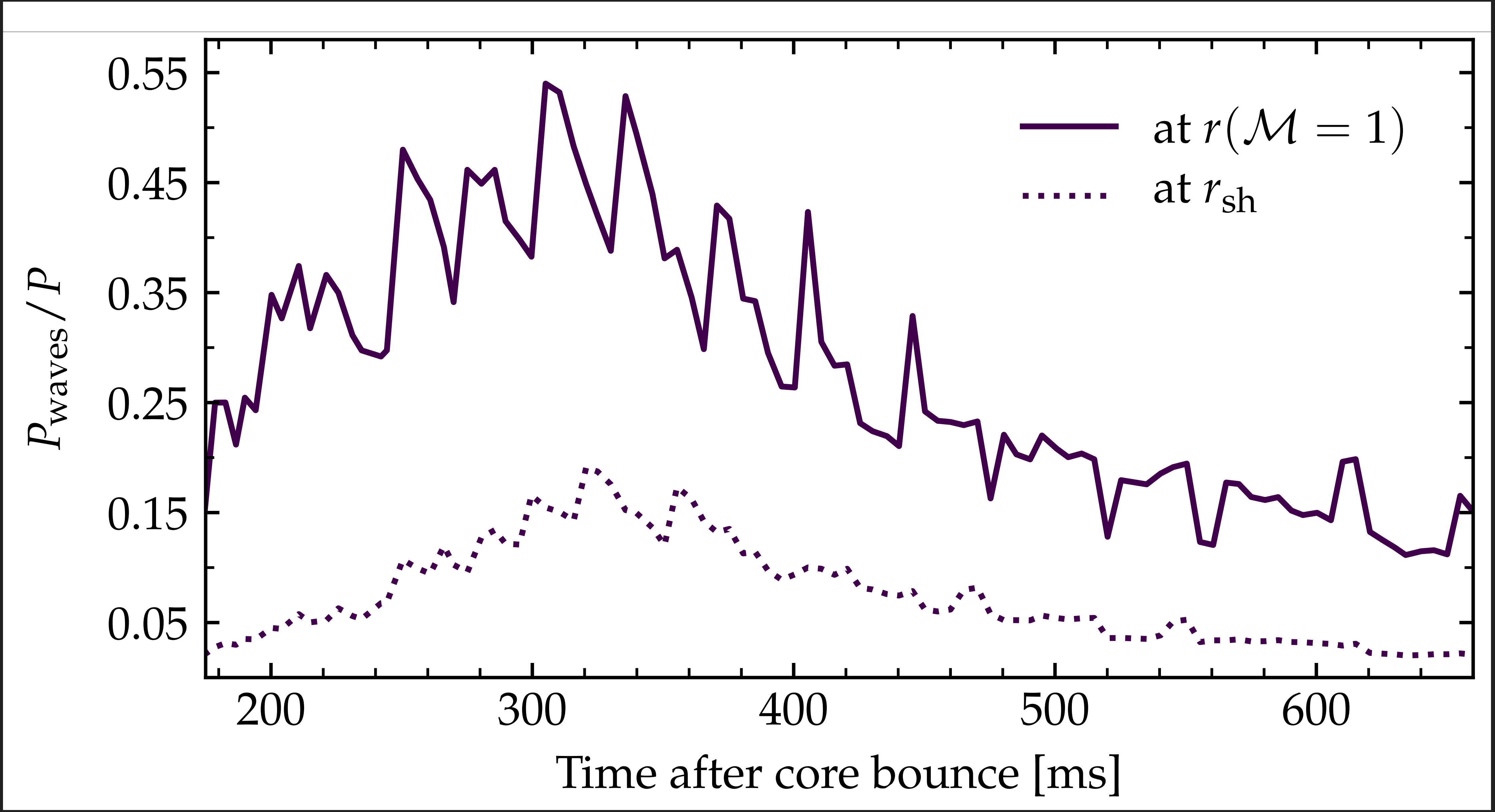
NEUTRINO DAMPING



CORRECTED HEATING RATES



WAVE PRESSURE BEHIND THE SHOCK



SUMMARY

★ Motivation: several state-of-the-art supernova simulations find progenitor models evolve close to weak successful explosion/ failed explosion boundary.

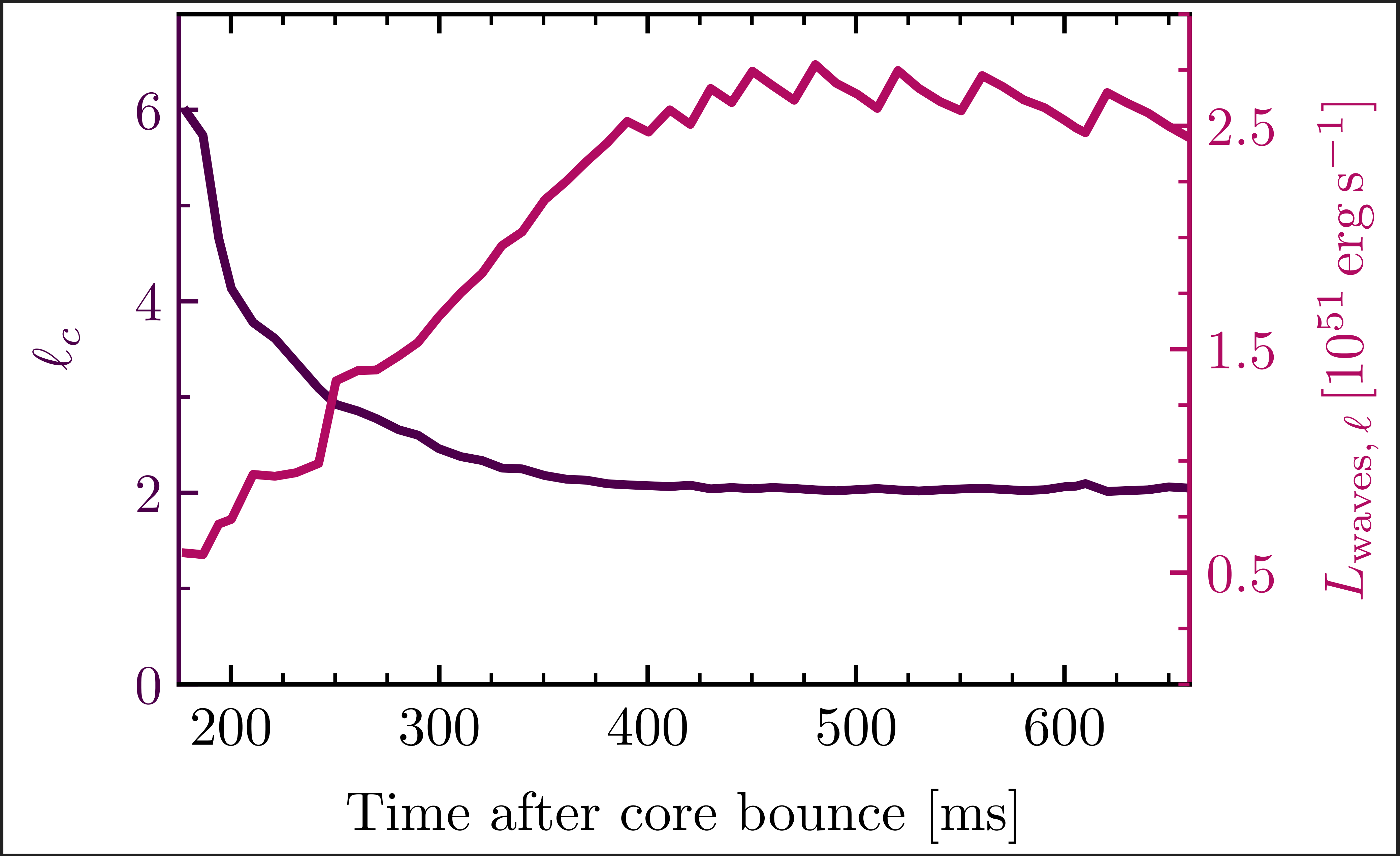
★ Proposal: effects of wave heating from PNS convection missed if simulation doesn't resolve PNS hydrodynamics — could this contribute to shock revival?

★ Results: find heating rates of several 10^{50} erg/s behind the stalled shock out to late times (~1s post-bounce).

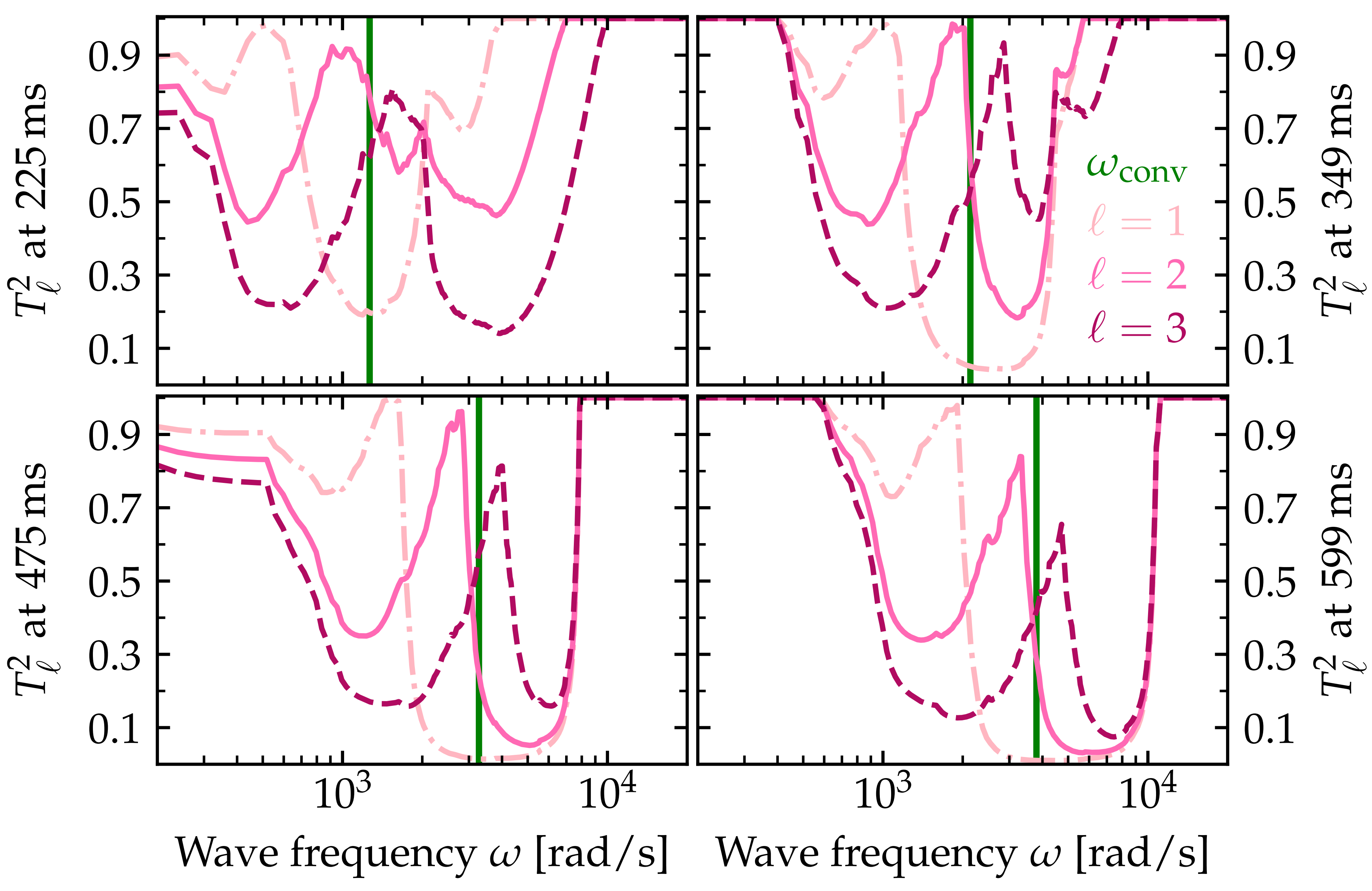
★ Conclusion: sub-dominant but impactful contribution to shock revival from wave heating from PNS convection — important to account for effects.

SUPPLEMENTARY SLIDES

EXCITED WAVE LUMINOSITY



FREQUENCY DEPENDENCE OF WAVE TRANSMISSION



WAVE NON-LINEARITY