Wave-Driven Mass Loss

A mechanism for late-stage stellar eruptions

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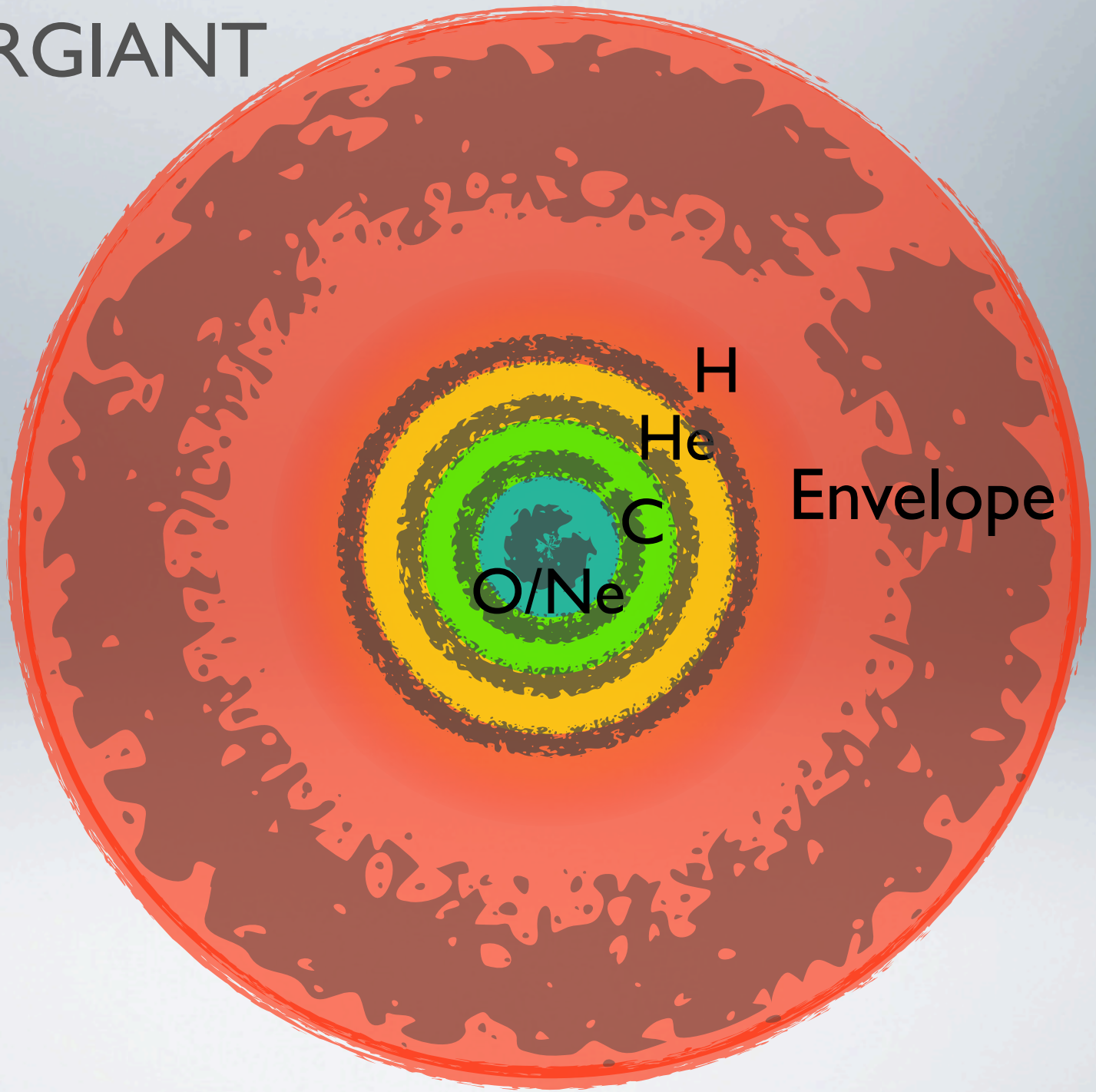
In a 25 $M_\odot$ star...

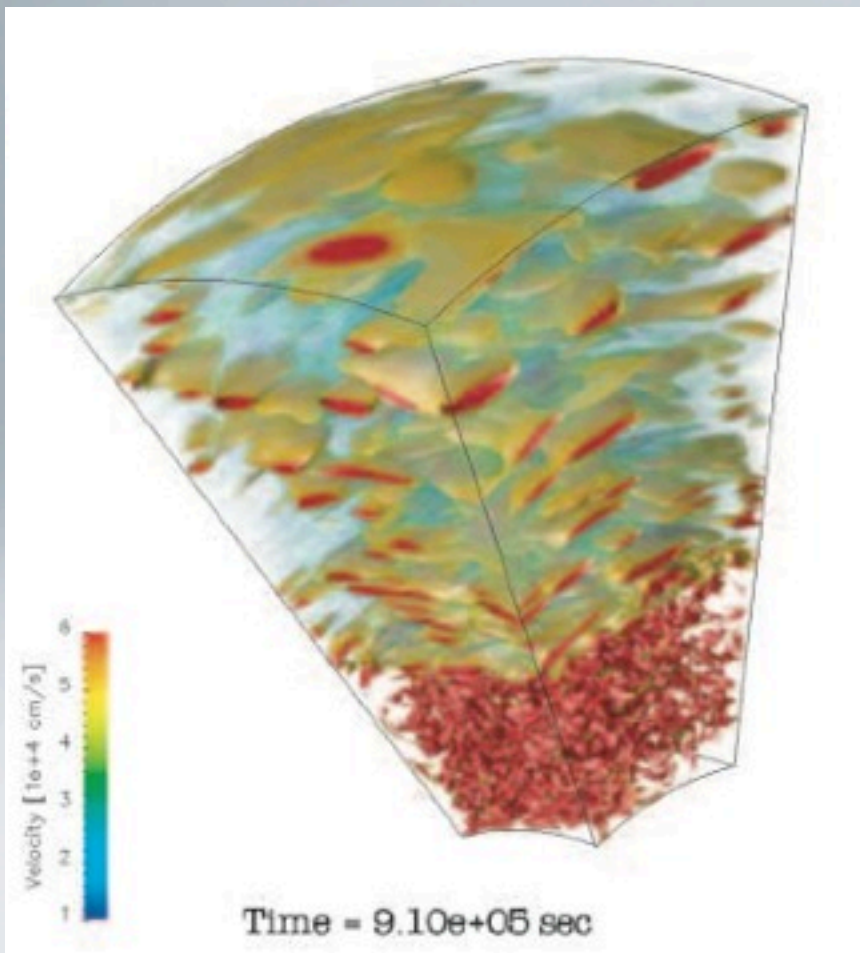
Stage	Duration (t_{nuc})	L_{fusion} ($L_\odot$)	Mach ($\mathcal{M}_{conv}$)	τ_c (s)
Carbon	$\sim 10^3$ yr	$\sim 10^6$	~ 0.003	$\sim 10^{4.5}$
Neon	~ 1 yr	$\sim 10^9$	~ 0.01	$\sim 10^3$
Oxygen	~ 1 yr	$\sim 10^{10}$	~ 0.02	$\sim 10^3$
Silicon	~ 1 day	$\sim 10^{12}$	~ 0.05	$\sim 10^2$

from Quataert & Shiode 2012,
after Woosley, Heger & Weaver 2002

Red Supergiant



(Stochastic) Convective Excitation



Meakin & Arnett 2007

$$L_{\rm conv} \sim 4\pi r^2 \rho v_{\rm conv}^3$$

$$\mathcal{M} \equiv \frac{v_{\rm conv}}{c_{\rm sound}}$$

$$\dot{E}_{\rm g\,modes} \sim \mathcal{M}\,{\rm L}_{\rm conv}$$

$$\ell_{\rm exc} \sim \frac{r}{H} \qquad \omega_{\rm exc} \sim \frac{v_{\rm conv}}{H}$$

Goldreich & Kumar 1990;
Lecoanet & Quataert in prep

Energetics in Last Year

$$L_{\rm surf} \sim L_{\rm Edd}$$

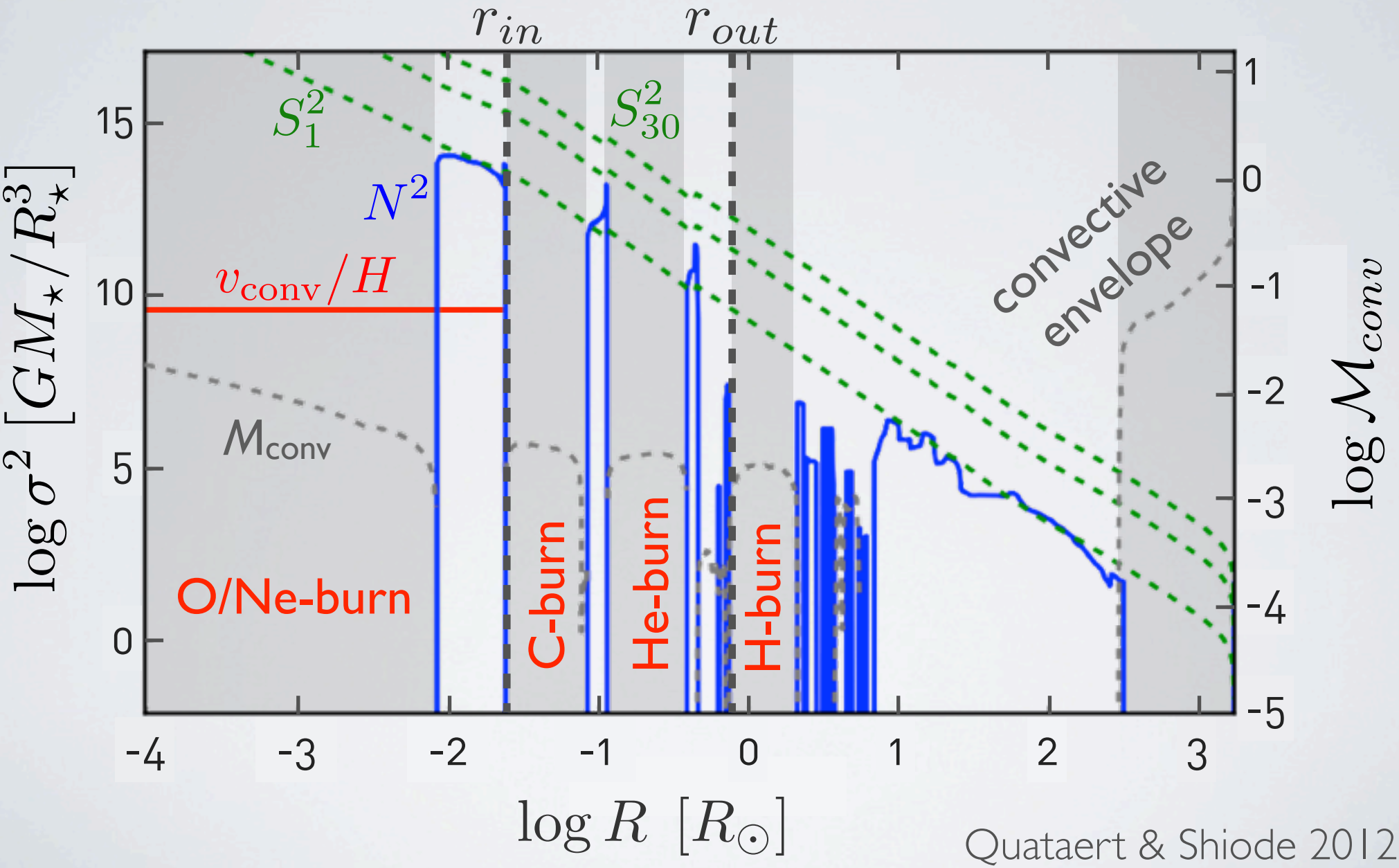
$$L_{\rm nuc} \sim 10^5 L_{\rm surf}$$

$$L_{\rm conv} \sim L_{\rm nuc}$$

$$\mathcal{M}_{\rm conv} \sim 10^{-2} - 10^{-1}$$

$$\Longrightarrow \dot{E}_{\rm g\ modes} \gg L_{\rm surf}$$

RED SUPERGIANT



Quataert & Shiode 2012

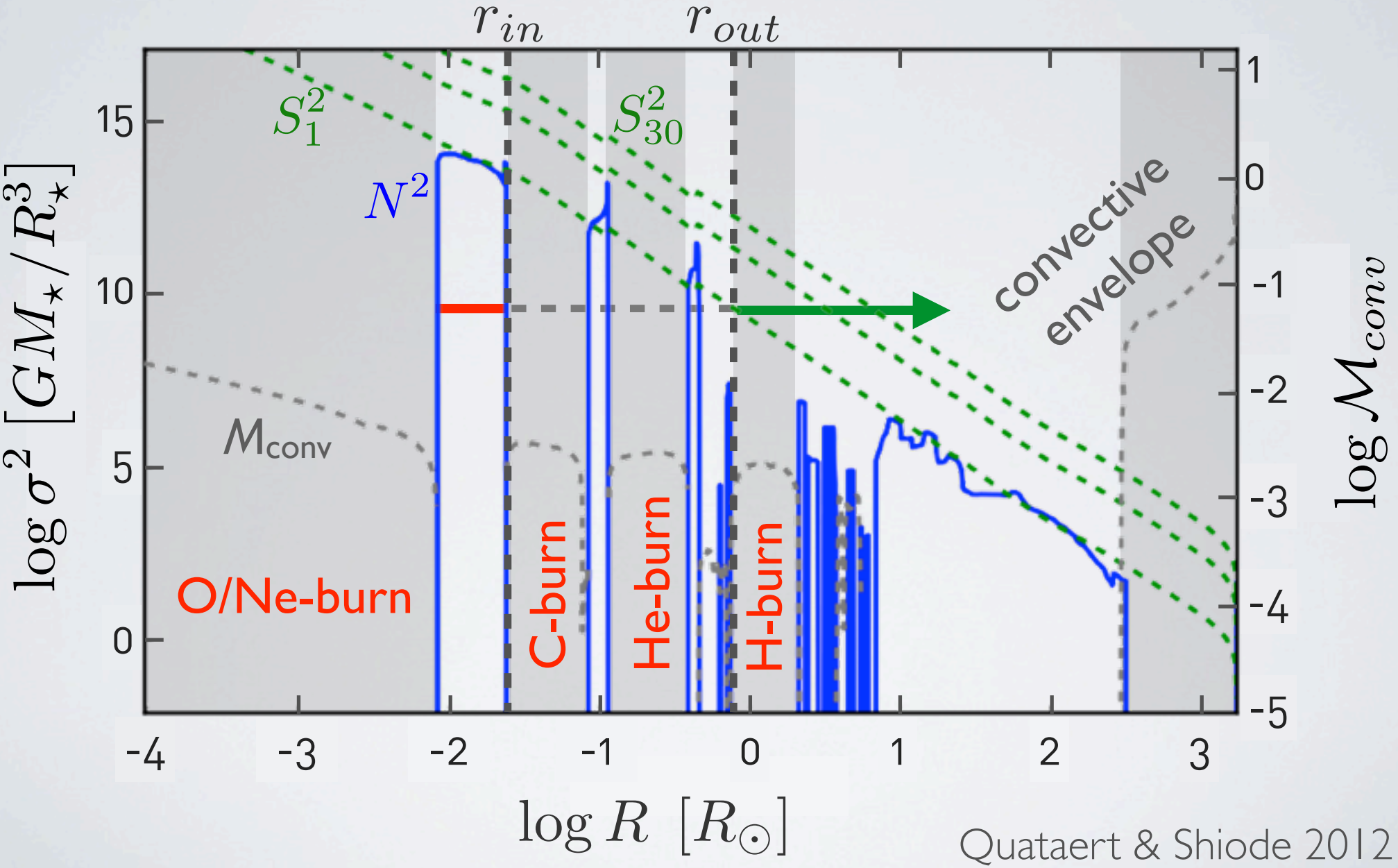
WHAT HAPPENS TO WAVES?

- Can.....
  - "Break", if $k_r \xi_r \sim \Lambda^{3/2} \left(\frac{N}{\omega}\right)^{3/2} \left(\frac{F_{\rm wave}}{\rho r^3 \omega^3}\right)^{1/2} \gtrsim 1,$

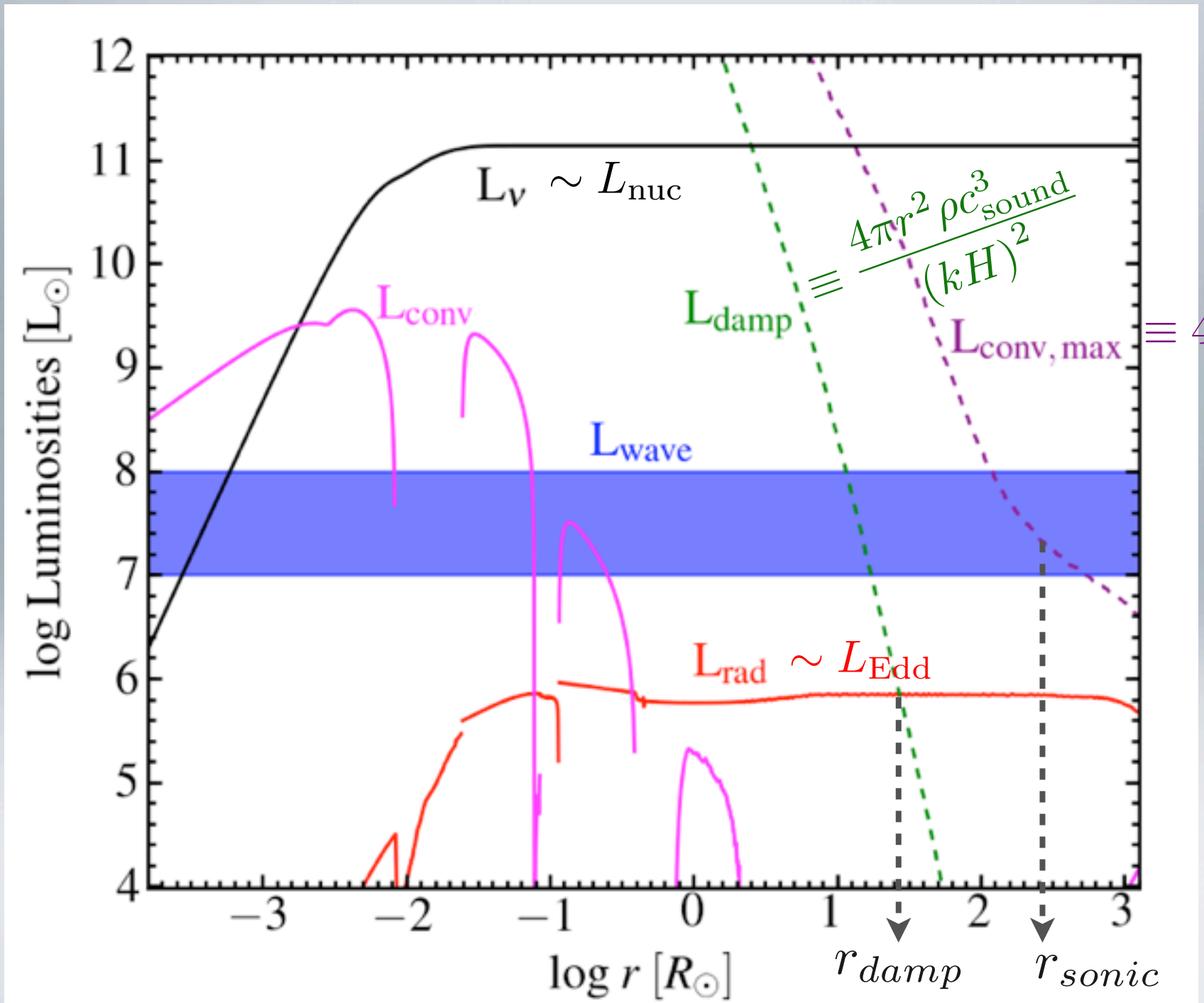
    $\Lambda^2 = \ell(\ell+1)$
  - Damp by neutrino emission, in time $t_\nu \sim 0.01\, t_{\rm nuclear}$
  - Tunnel to envelope and propagate as p-mode, if

$$t_{\rm leak} \sim \frac{r_{in}}{v_{\rm group}} \left(\frac{r_{out}}{r_{in}}\right)^{2\Lambda} < t_\nu$$

RED SUPERGIANT



Quataert & Shiode 2012



Shiode & Quataert 2012

Conclusion

- Convection excites super-Eddington wave luminosity at late burning stages (O-burning & beyond)
- Waves can tunnel to envelope and deposit energy
- Implied mass-loss rates of $\lesssim 1 \mathrm{M}_\odot\,\mathrm{yr}^{-1}$
- Mass-loss inducing or not, implications for stellar evolution are potentially exciting
  - 1-D simulations with MESA are forthcoming

Supplemental Slides

Observational context

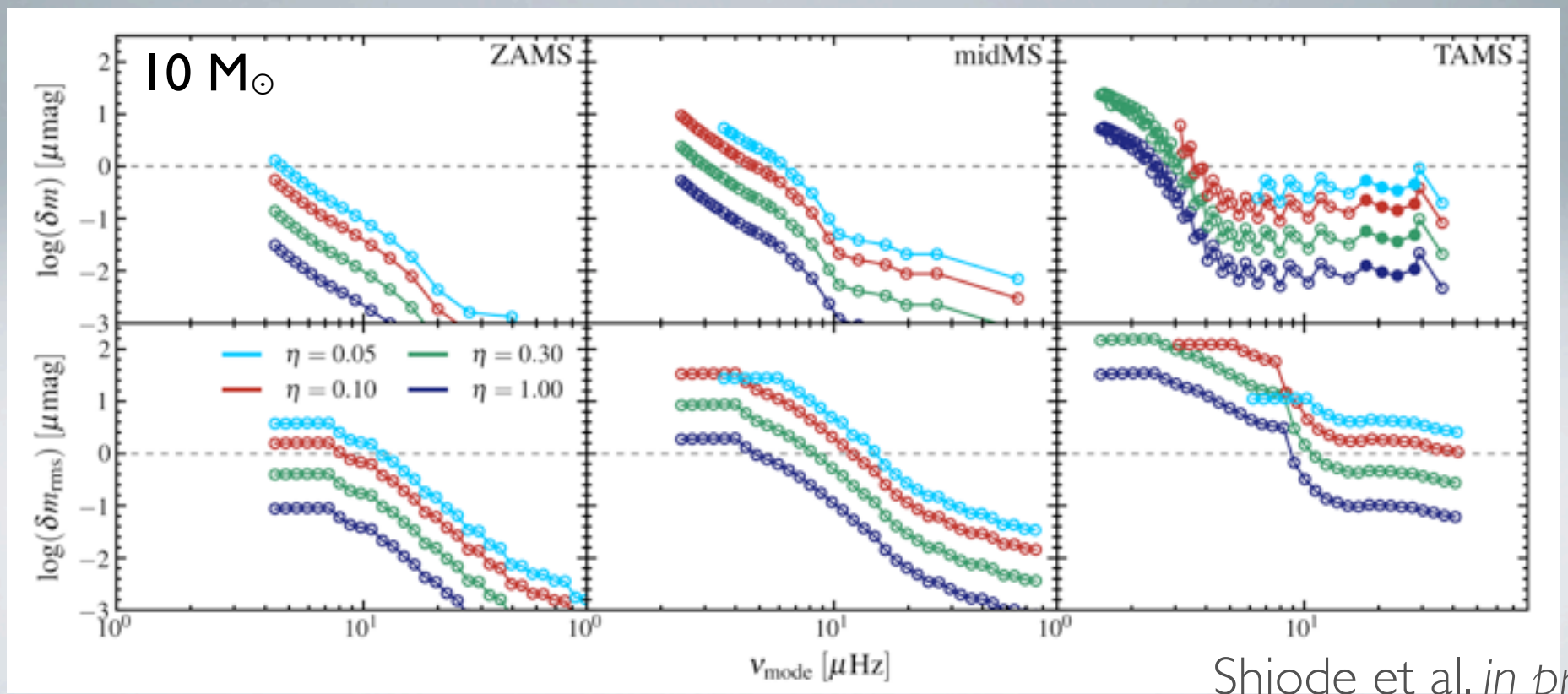
Probing convective excitation

Simulations??

PROBING THE EXCITATION SPECTRUM

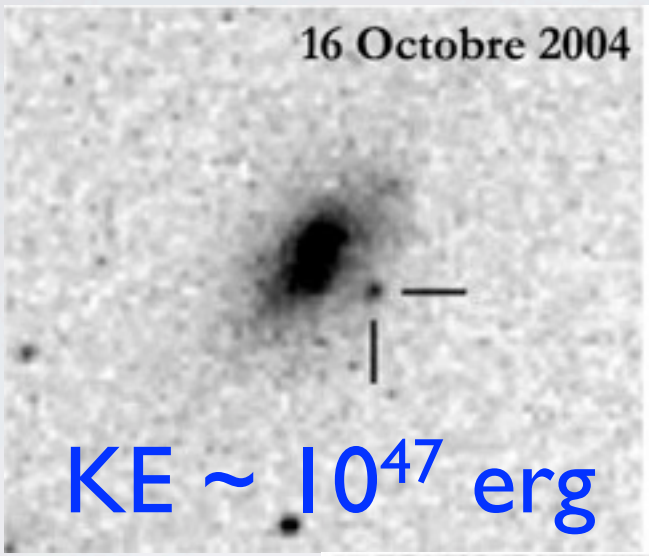
$$\frac{d\dot{E}_{\rm g\,modes}}{d\ln\omega\, d\ln\ell} \sim \mathcal{M}_{\rm conv}\, \mathrm{L}_{\rm conv} \left(\frac{\omega}{\omega_{\rm conv}}\right)^{-13/2} \left(\frac{\ell}{r/H}\right)^{4} \exp\left[-\left(\frac{\ell}{\ell_{\rm max}}\right)^{2}\right]$$

$$\text{for } \omega \geq \omega_{\rm conv} \equiv v_{\rm conv}/H, \;\; \ell \geq 1, \;\; \text{with } \ell_{\rm max} \equiv (r/H)\,(\omega/\omega_{\rm conv})^{3/2}$$

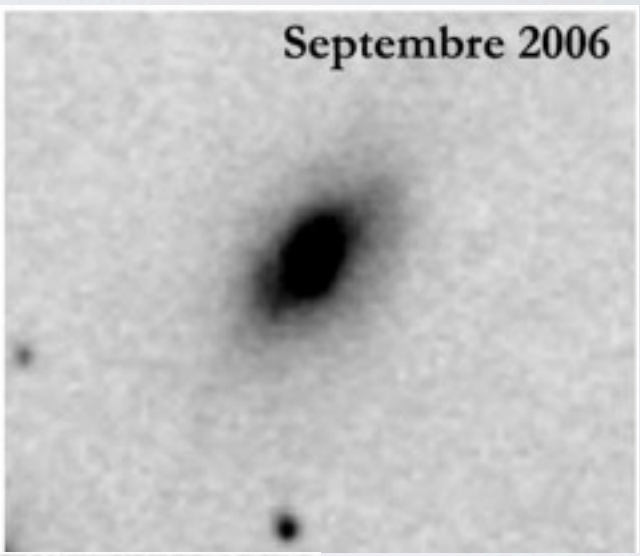


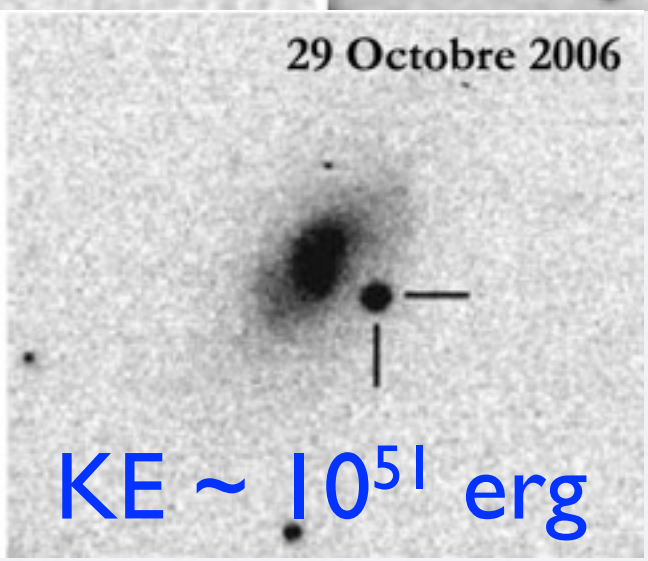
Shiode et al. *in prep*

SN 2006jc: Precursor Event



KE ~ 10^{47} erg



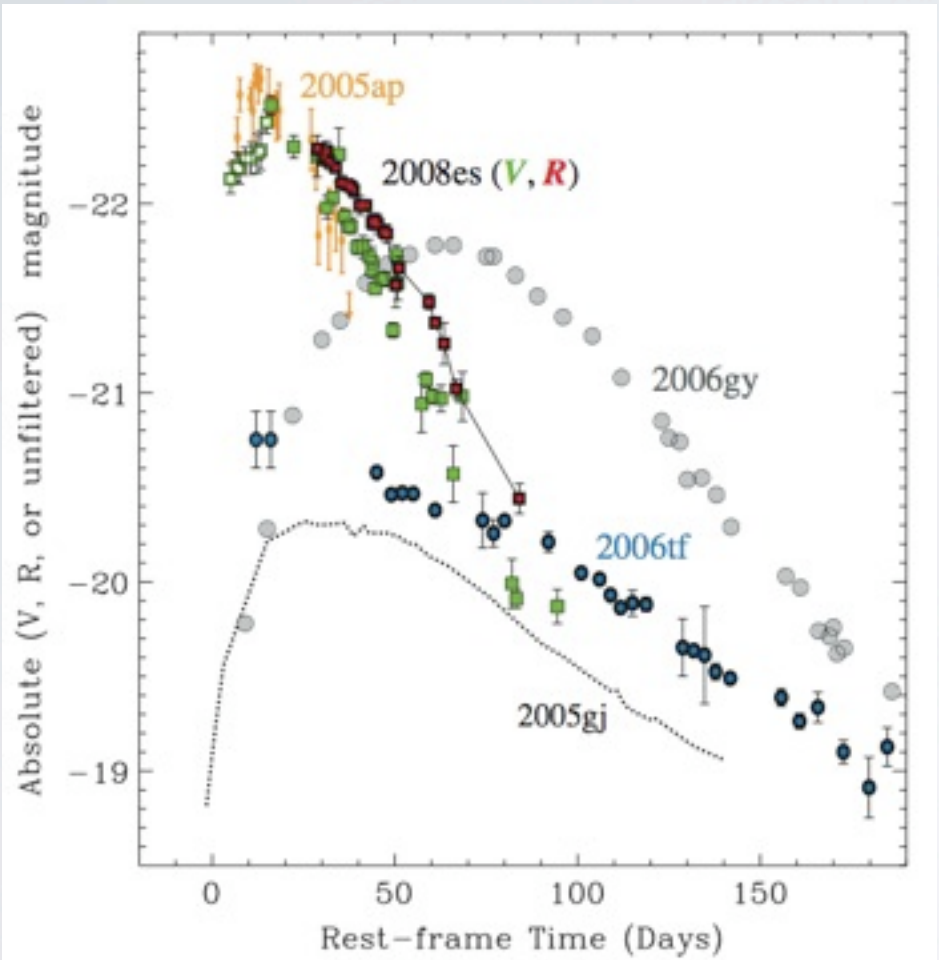


KE ~ 10^{51} erg

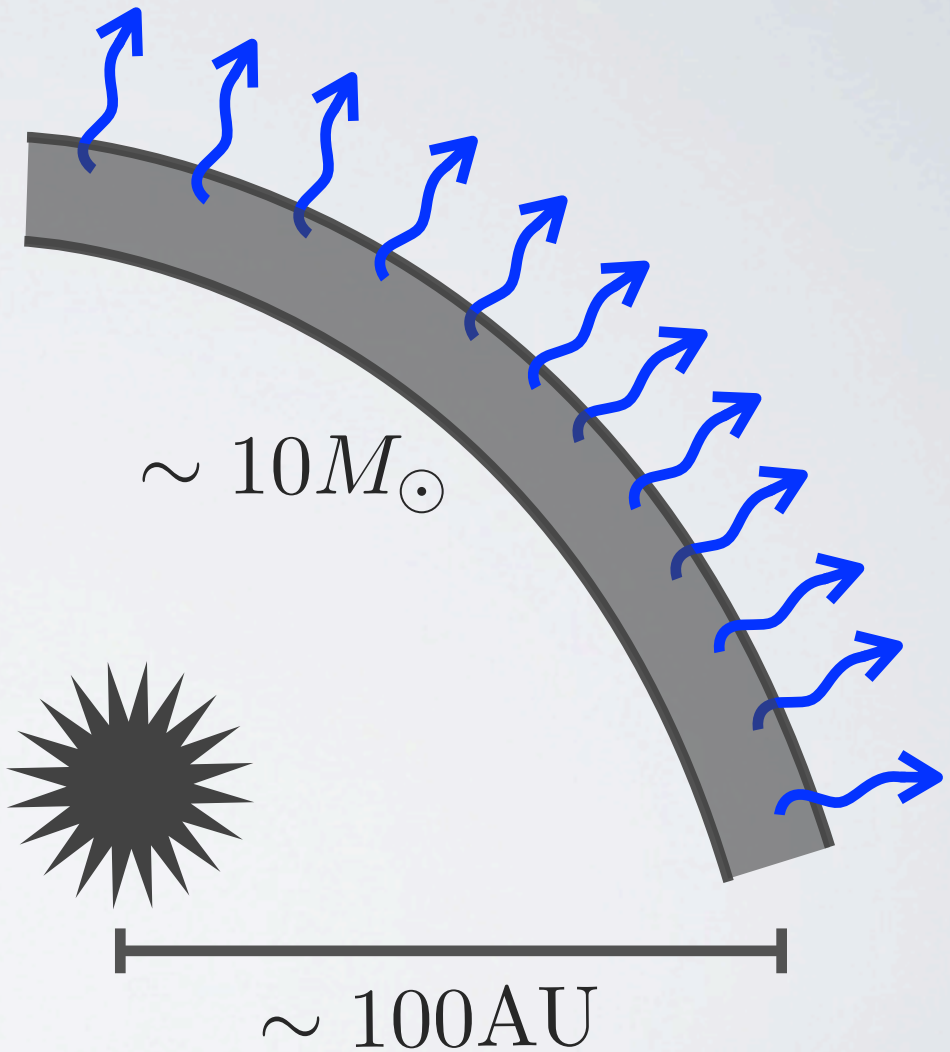
Eruption
2 years
pre-SN

images: Pastorello et al. 2007

INTERACTING SNE



Miller et al. 2009



e.g., 2006gy