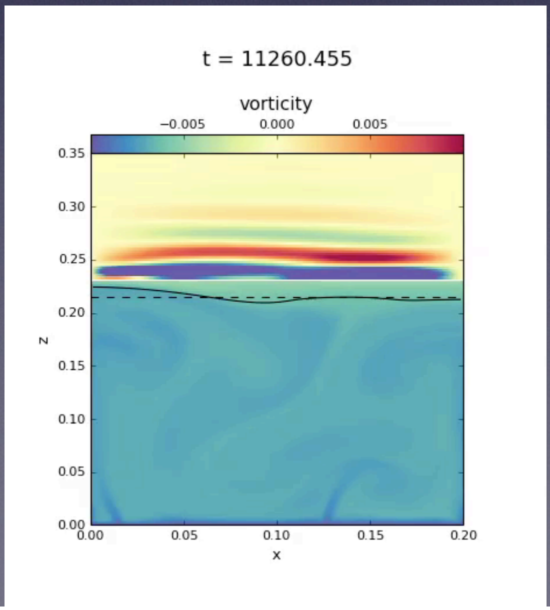
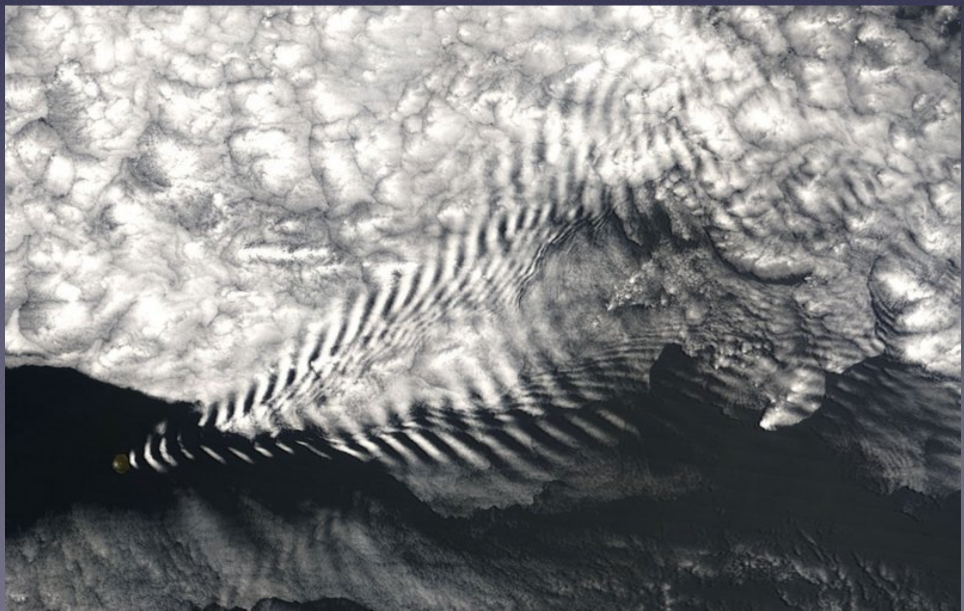
The Surprisingly Dynamic Last Years in the Lives of Massive Stars

Eliot Quataert
(UC Berkeley)

With: Josh Shiode, Daniel Lecoanet,
Jim Fuller, Hannah Klion, Matteo Cantiello





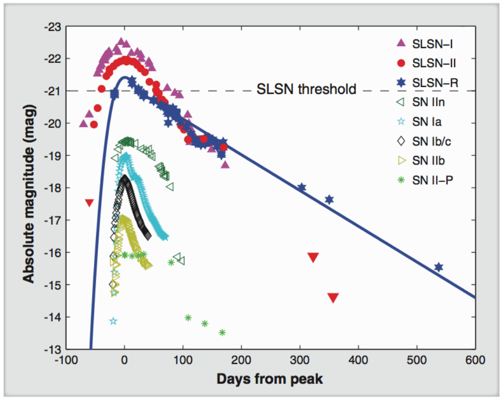
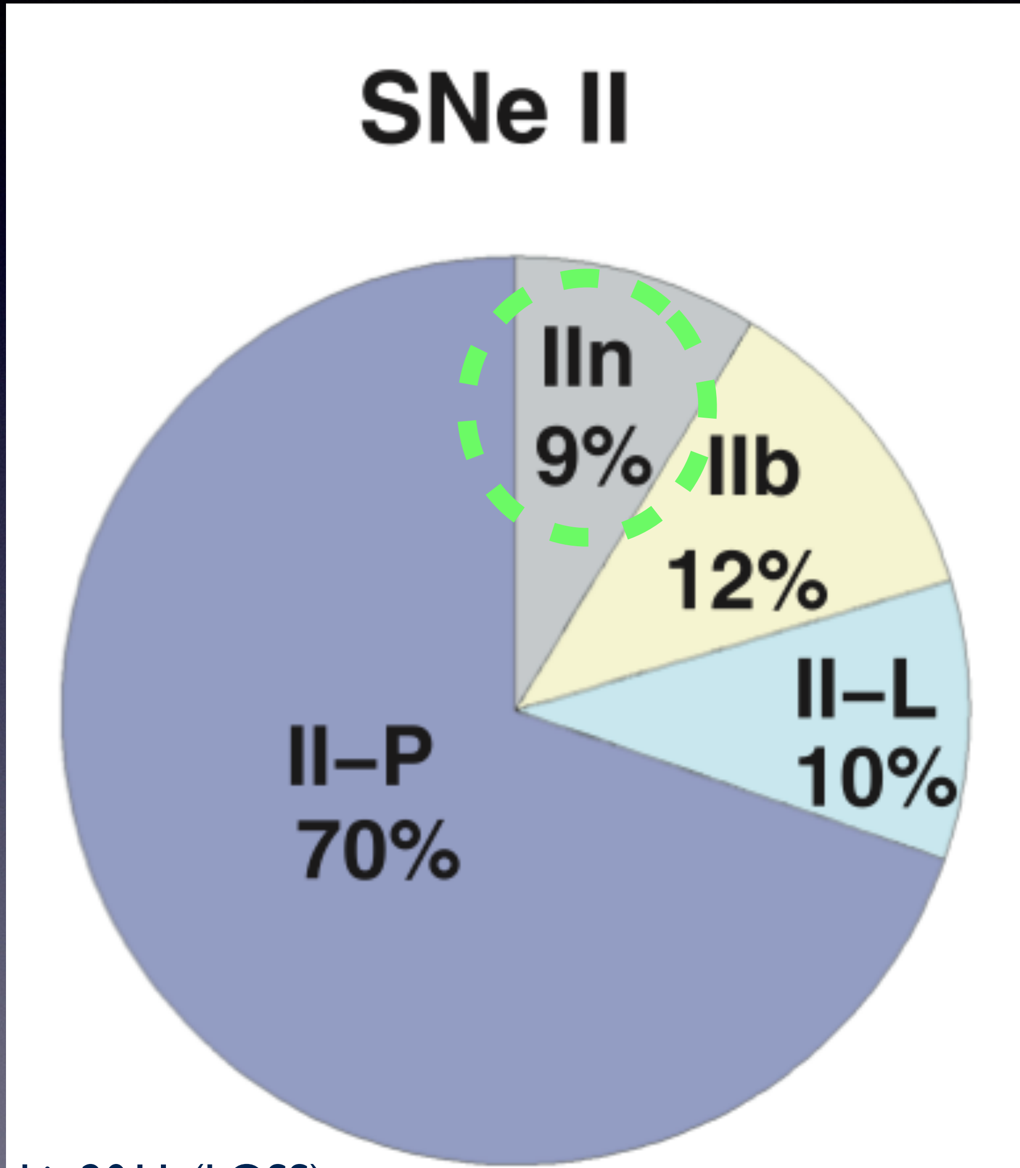


Fig. 1. The luminosity evolution (light curve) of supernovae. Common SN explosions reach peak luminosities of ~10^{43} ergs s^{-1} (absolute magnitude > –19.5). Superluminous SNe (SLSNe) reach luminosities that are greater by a factor of ~10. The prototypical events of the three SLSN classes—SLSN-I [PTF09cnd (*4*)], SLSN-II [SN 2006gy (*12*, *13*, *77*)], and SLSN-R [SN 2007bi (*7*)]—are compared with a normal type Ia SN (Nugent template), the type IIn SN 2005cl (*56*), the average type Ib/c light curve from (*65*), the type IIb SN 2011dh (*78*), and the prototypical type II-P SN 1999em (*79*). All data are in the observed *R* band (*80*).

Outline

- Observational Evidence for Extreme Mass Loss in the Last Few Years of the Lives of Massive Stars
- Late Stages of Massive Stellar Evolution
- Energy & Angular Momentum Transport by Convectively Excited Waves
    - Implications for Mass Loss & the Spins of Compact Objects

Core Collapse SNe



Li+2011 (LOSS)

Supernovae Powered by Interaction with Ambient Gas (Type IIn SNe)

- Interacting SNe: SN shock runs into dense wind at ~ $10^{2\text{-}3}$ AU and KE ⇒ thermal energy, radiation

Analogous to supernova remnant but interaction is much closer to the star with stellar wind not ISM

Supernovae Powered by Interaction with Ambient Gas (Type IIn SNe)

- Interacting SNe: SN shock runs into dense wind at ~ $10^{2\text{-}3}$ AU and KE ⇒ thermal energy, radiation

$$\tau_{diff} \sim \frac{R^2}{\ell_{mfp} c} \sim \tau_{exp} \sim \frac{R}{v_{sh}}$$

$$R \sim \left(\frac{M \kappa v_{sh}}{4c}\right)^{1/2} \sim 100\,\mathrm{AU}$$

R ~$10^{2\text{-}3}$ AU optimal for converting KE of shocked wind ⇒ radiation

Supernovae Powered by Interaction with Ambient Gas (Type IIn SNe)

- Interacting SNe: SN shock runs into dense wind at ~ $10^{2\text{-}3}$ AU and KE ⇒ thermal energy, radiation

- v_{wind} ~ 10^3 km/s & R ~ $10^{2\text{-}3}$ AU ⇒ interaction with mass lost in last ~ years of stellar evolution
  - Unique probe of massive stars just prior to core collapse

Pre SN Mass Loss Rate Can be Estimated From Observations

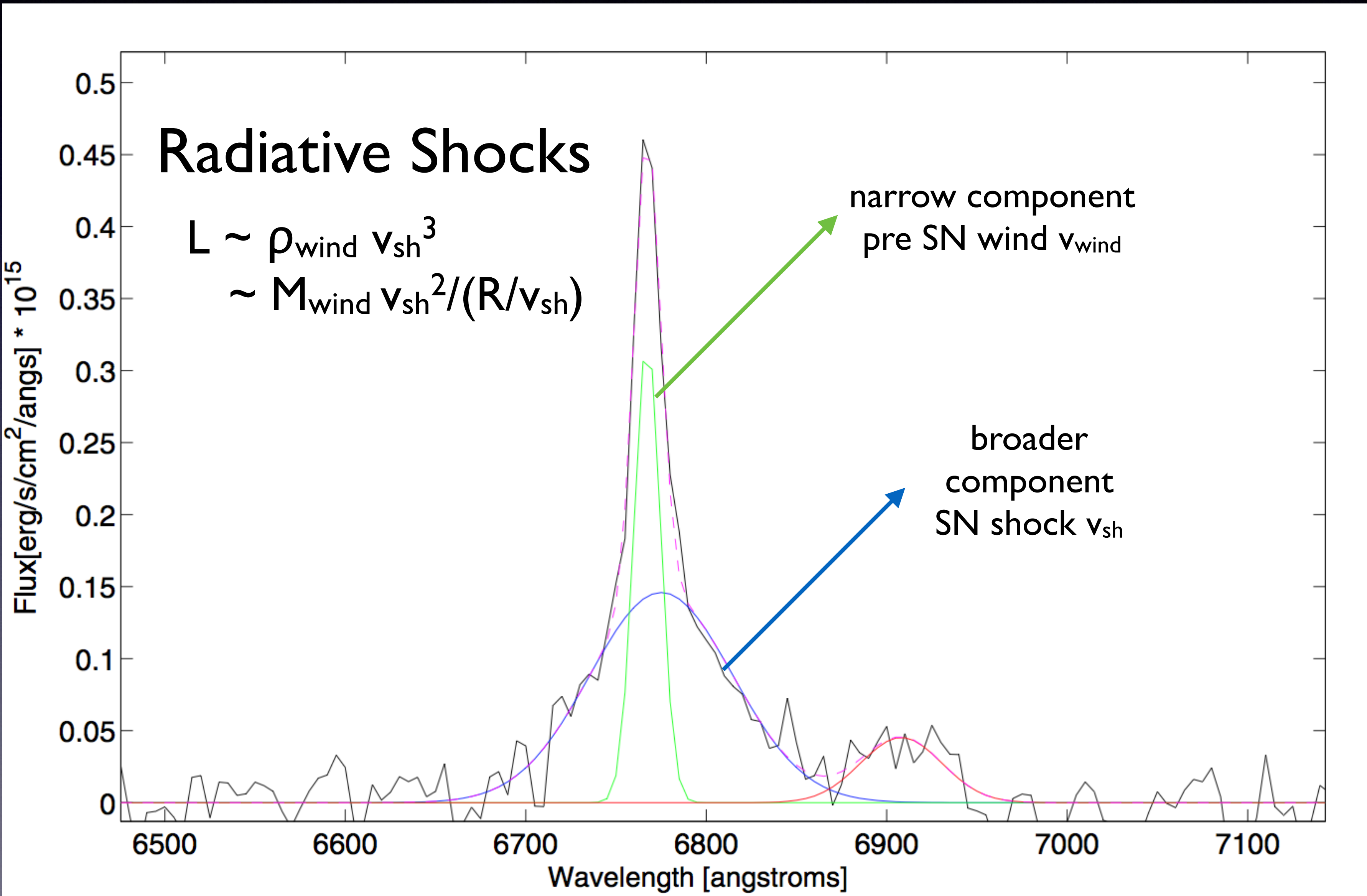
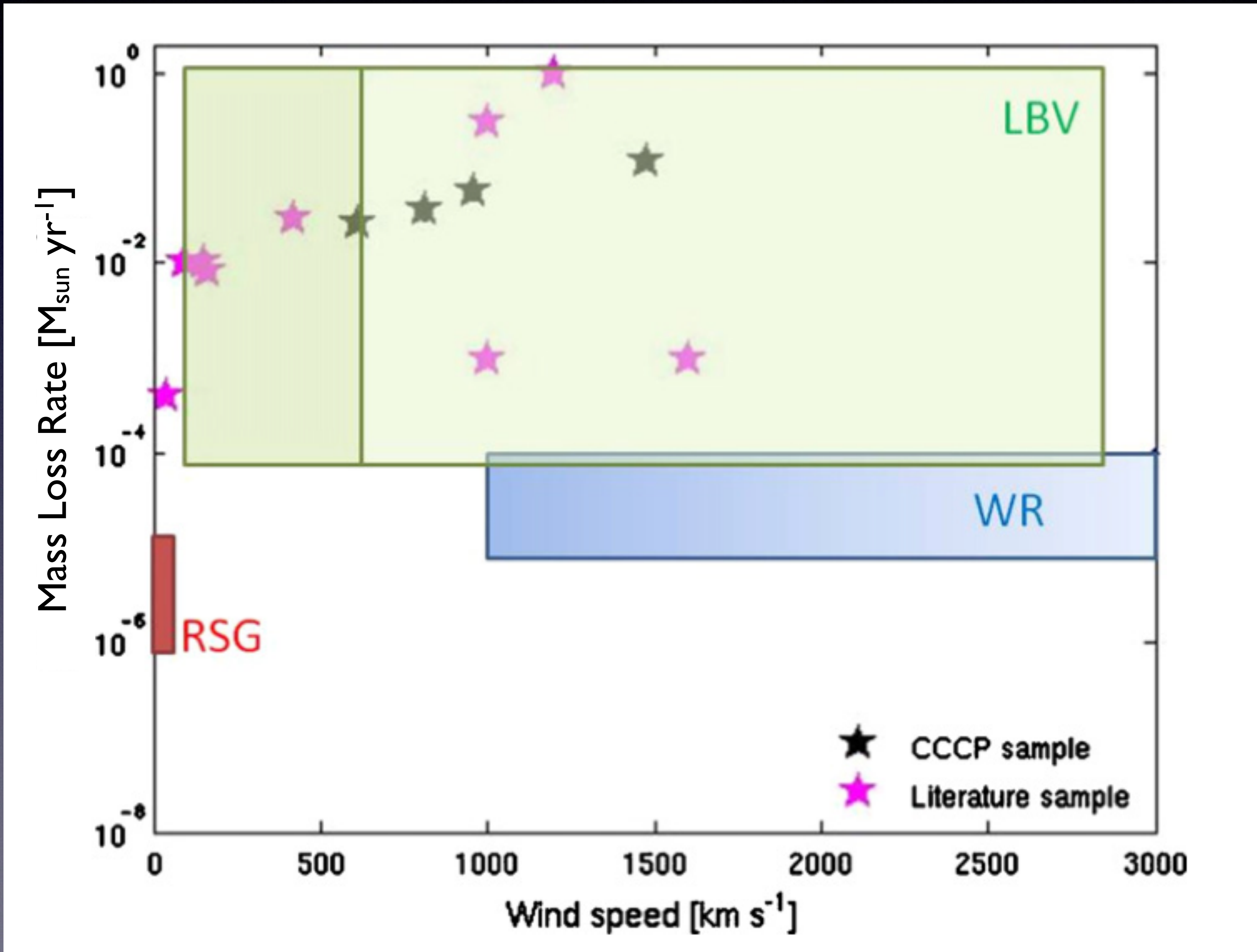


Figure 13. Decomposition of the Hα feature in the 2005 April 30 spectrum of SN 2005bx.

Kiewe+2012

Pre SN Mass Loss Rate Can be Estimated From Observations



Kiewe+2012

Superluminous SNe

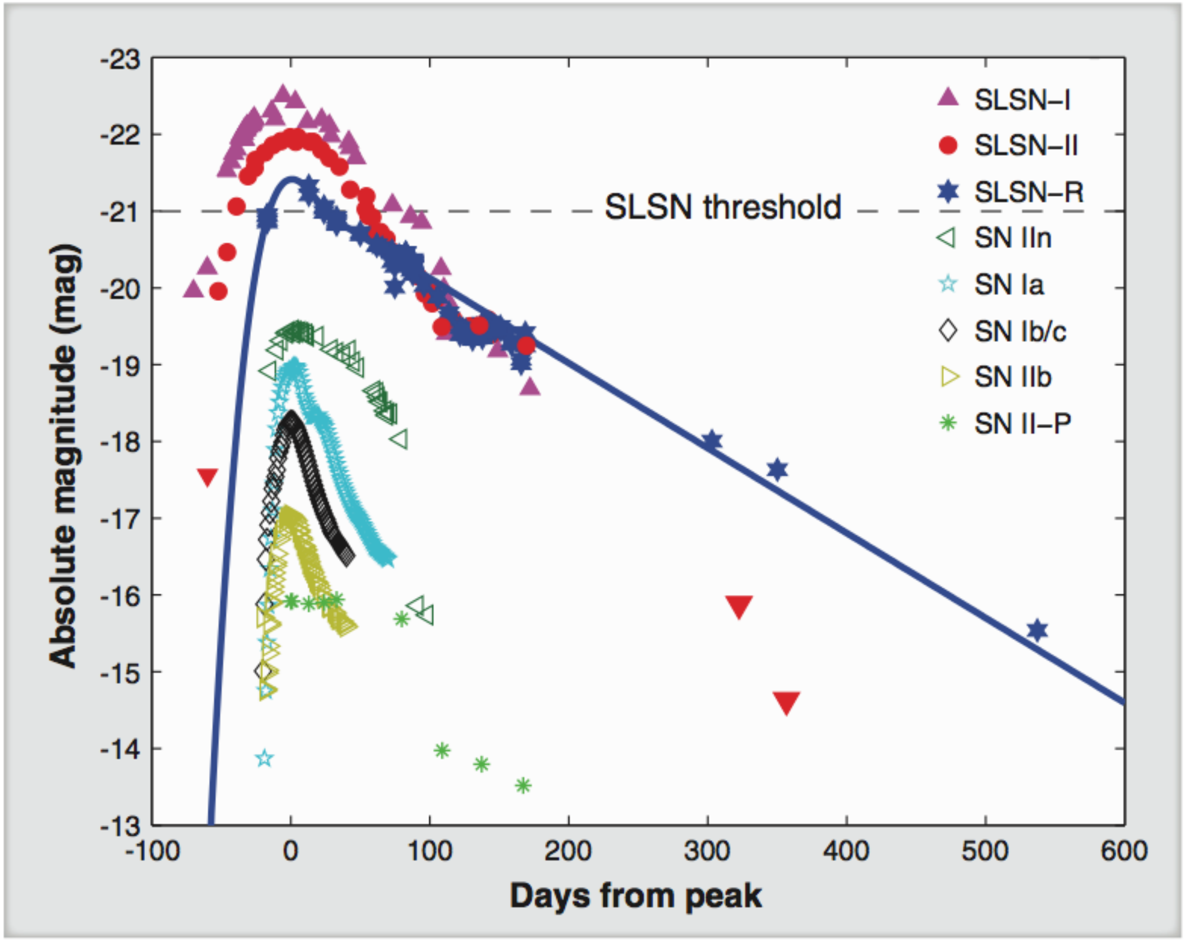
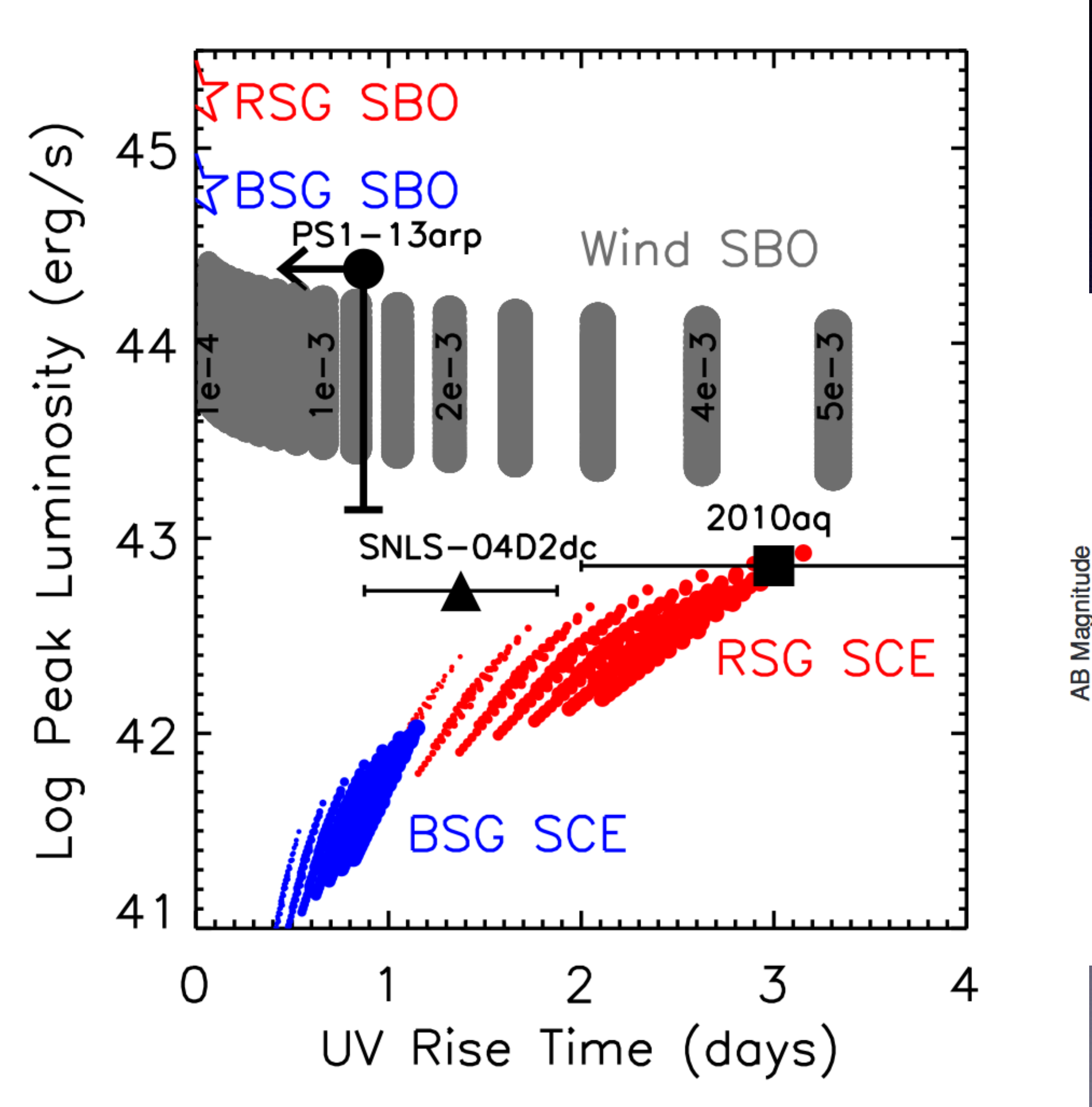


Fig. 1. The luminosity evolution (light curve) of supernovae. Common SN explosions reach peak luminosities of ~10^{43} ergs s^{-1} (absolute magnitude > –19.5). Superluminous SNe (SLSNe) reach luminosities that are greater by a factor of ~10. The prototypical events of the three SLSN classes—SLSN-I [PTF09cnd (*4*)], SLSN-II [SN 2006gy (*12*, *13*, *77*)], and SLSN-R [SN 2007bi (*7*)]—are compared with a normal type Ia SN (Nugent template), the type IIn SN 2005cl (*56*), the average type Ib/c light curve from (*65*), the type IIb SN 2011dh (*78*), and the prototypical type II-P SN 1999em (*79*). All data are in the observed *R* band (*80*).

can have E radiated
~ 10^{51} ergs ~ $E_{kinetic}$

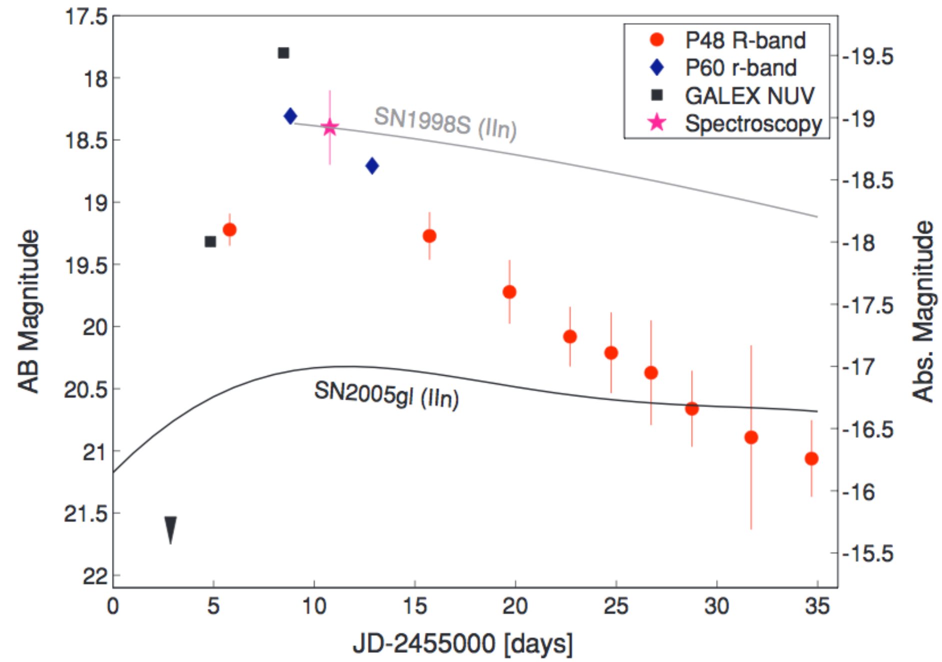
one type is
interaction with
particularly large mass
ejection ~ M_{sun}
prior to core collapse

Shock Breakout in a Wind



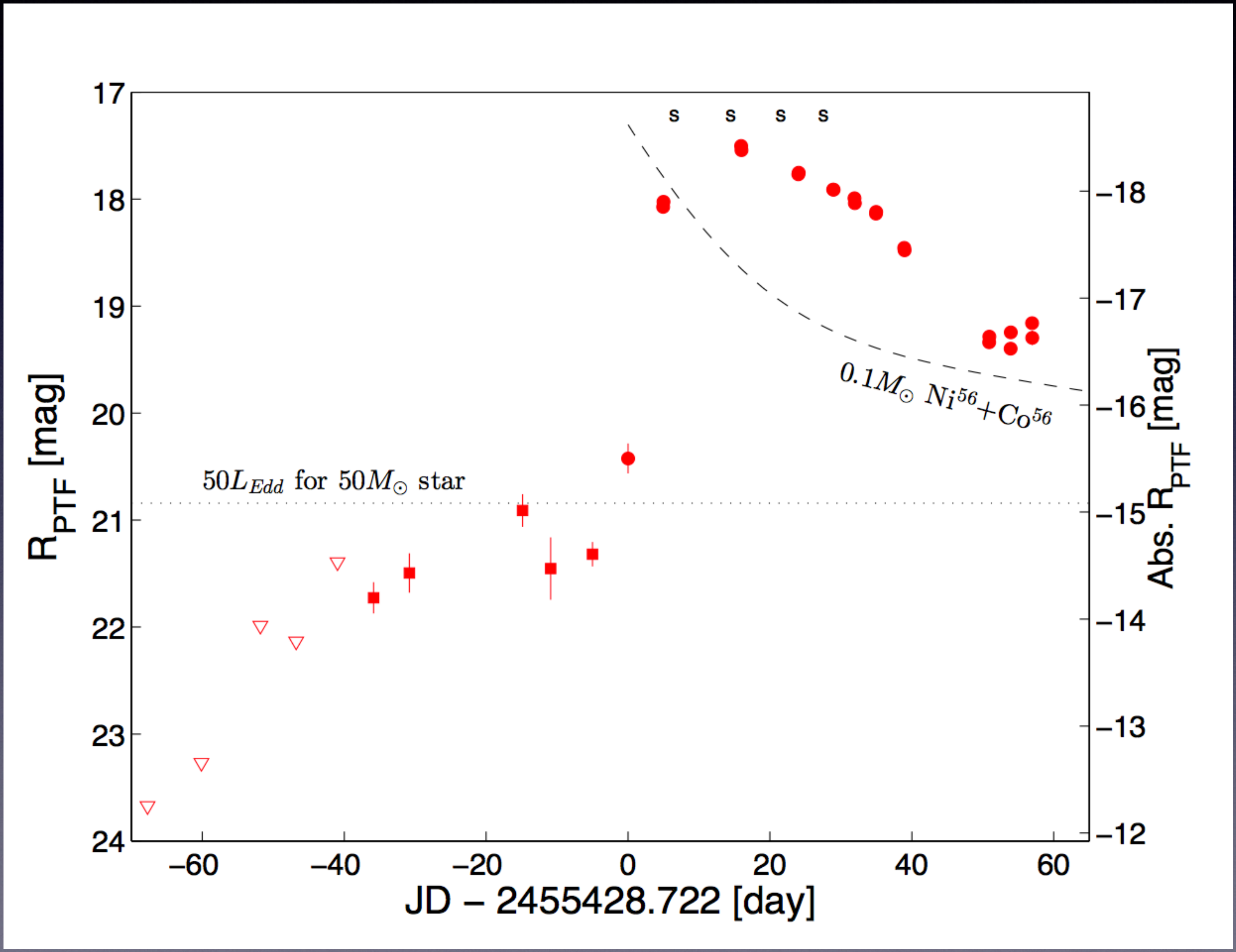
Gezari+ 2015

Large $\dot{M}_{wind}$ prolongs shock breakout signature



Ofek+2010 infer $\dot{M}_{wind} \sim 0.1\ M_{\odot}\,yr^{-1}$

Pre-SN Outbursts



Ofek+2014

My foray into sophisticated data science

- ΔM up to $\sim M_{sun} \Rightarrow \Delta M/M \sim 10^{-4} - 10^{-2}$
- $\Delta t \sim$ yrs $\Rightarrow \Delta t/t_{lifetime} \sim 10^{-7}$
- Large $\dot{M}$ inferred in few % of SNe $\Rightarrow$

  (though super-luminous SNe are rarer $\sim 10^{-4}$ SN rate)
- Suggests something unusual physically connected to late stages of massive stellar evolution

Thermal Balance in Stars

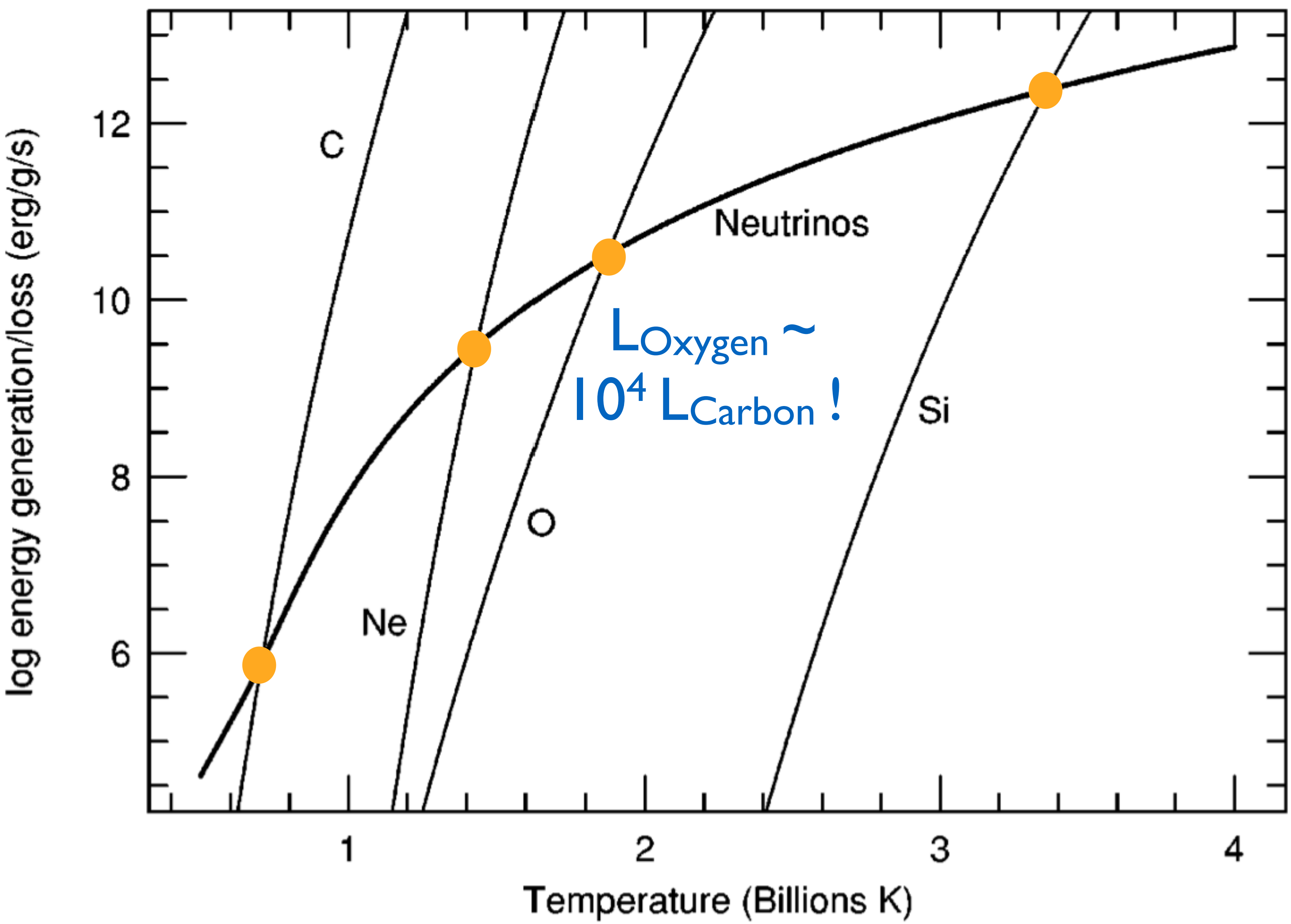
- Main sequence & low mass stellar evolution

$$L_{fusion} \sim L_{rad} + L_{conv}$$

- Late Stages of Massive Stellar Evolution
  - Temp for C fusion → thermal neutrino cooling important

$$\boxed{L_{fusion} \sim L_{neutrino}}$$

Woosley, Heger, and Weaver: Evolution and explosion of massive stars



Thermal Balance in Stars

- Main sequence & low mass stellar evolution

$$L_{fusion} \sim L_{rad} + L_{conv}$$

- Late Stages of Massive Stellar Evolution
  - Temp for C fusion → thermal neutrino cooling important

$$\boxed{L_{fusion} \sim L_{neutrino} >> L_{Edd}}$$

  - large L_{fusion} accelerates stellar evolution

Late Stages of Massive Stellar Evolution

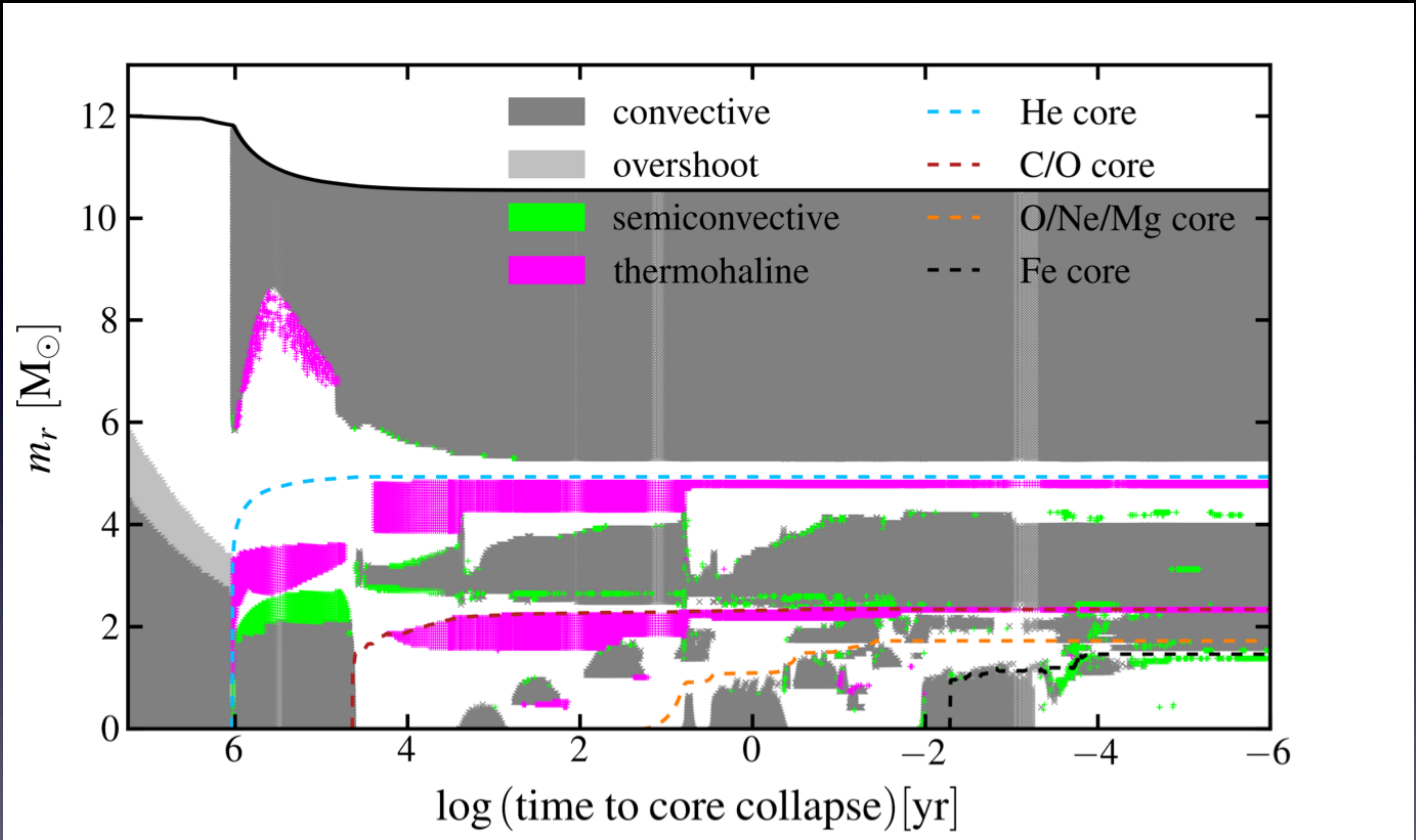
25 M_{sun} (MS lifetime ~ 10^7 yrs)

Stage	Duration (t_{nuc})	L_{fusion} ($L_\odot$)
Carbon	$\sim 10^3$ yr	$\sim 10^6$
Neon	~ 1 yr	$\sim 10^9$
Oxygen	~ 1 yr	$\sim 10^{10}$
Silicon	~ 1 d	$\sim 10^{12}$

Late stage mass loss tied to C, Ne, O, & Si fusion stages of stellar evolution

Preferential Mass Loss in the Years Prior to Core Collapse

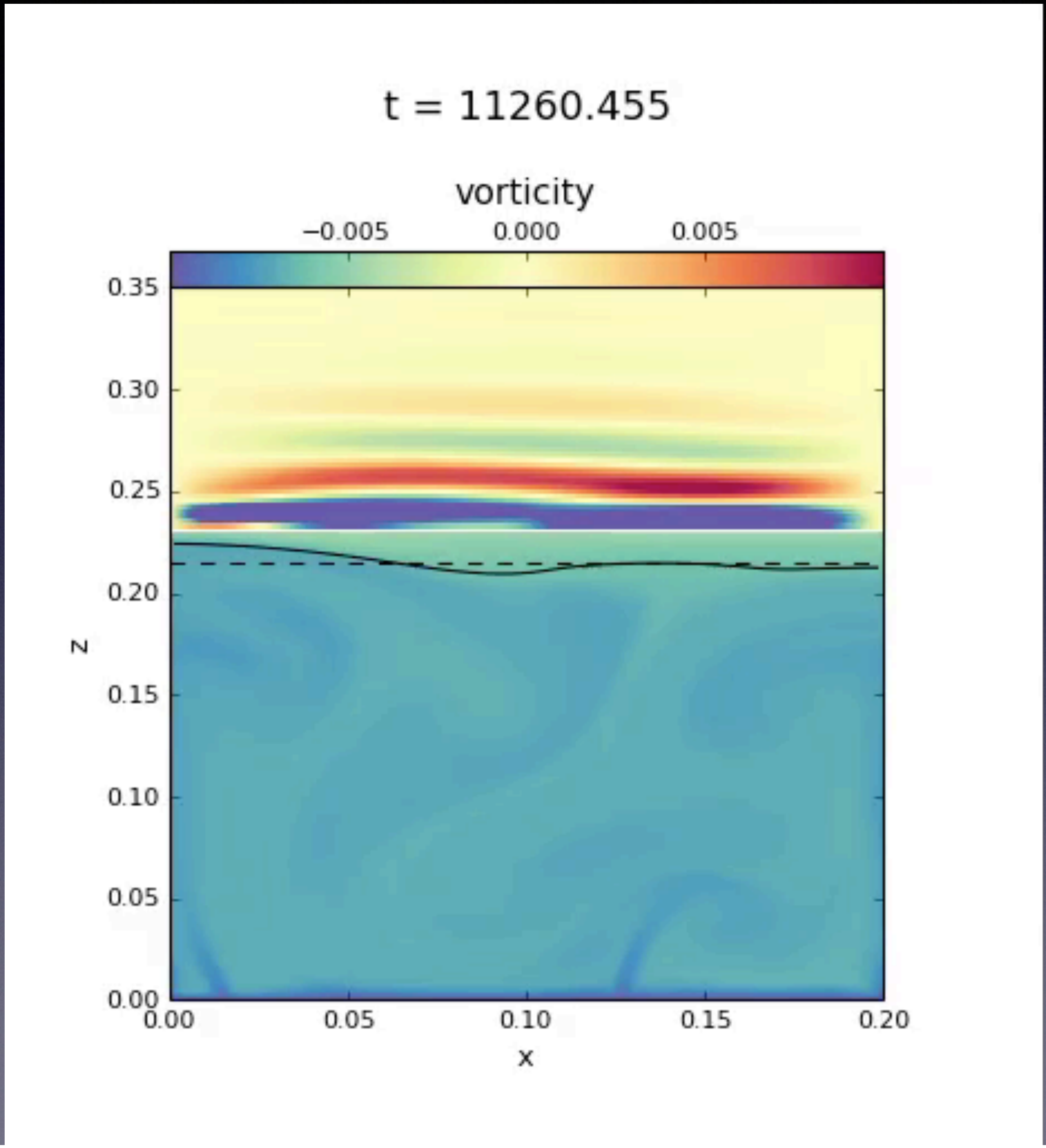
- Binaries. e.g., Common Envelope Evolution with BH/NS that Ejects Mass & triggers Core Collapse (Chevalier 2012)
- Tap into Core Fusion Energy to Power Outflow
  - wave-driven mass loss (Quataert & Shiode 2012)



$L_{fusion} >> L_{Edd}$ in last ~ years

$L_{fusion} \neq L_{\nu}$ everywhere $\Rightarrow$ convection w/ $L_{conv} >> L_{Edd}$

Convective Excitation of Waves

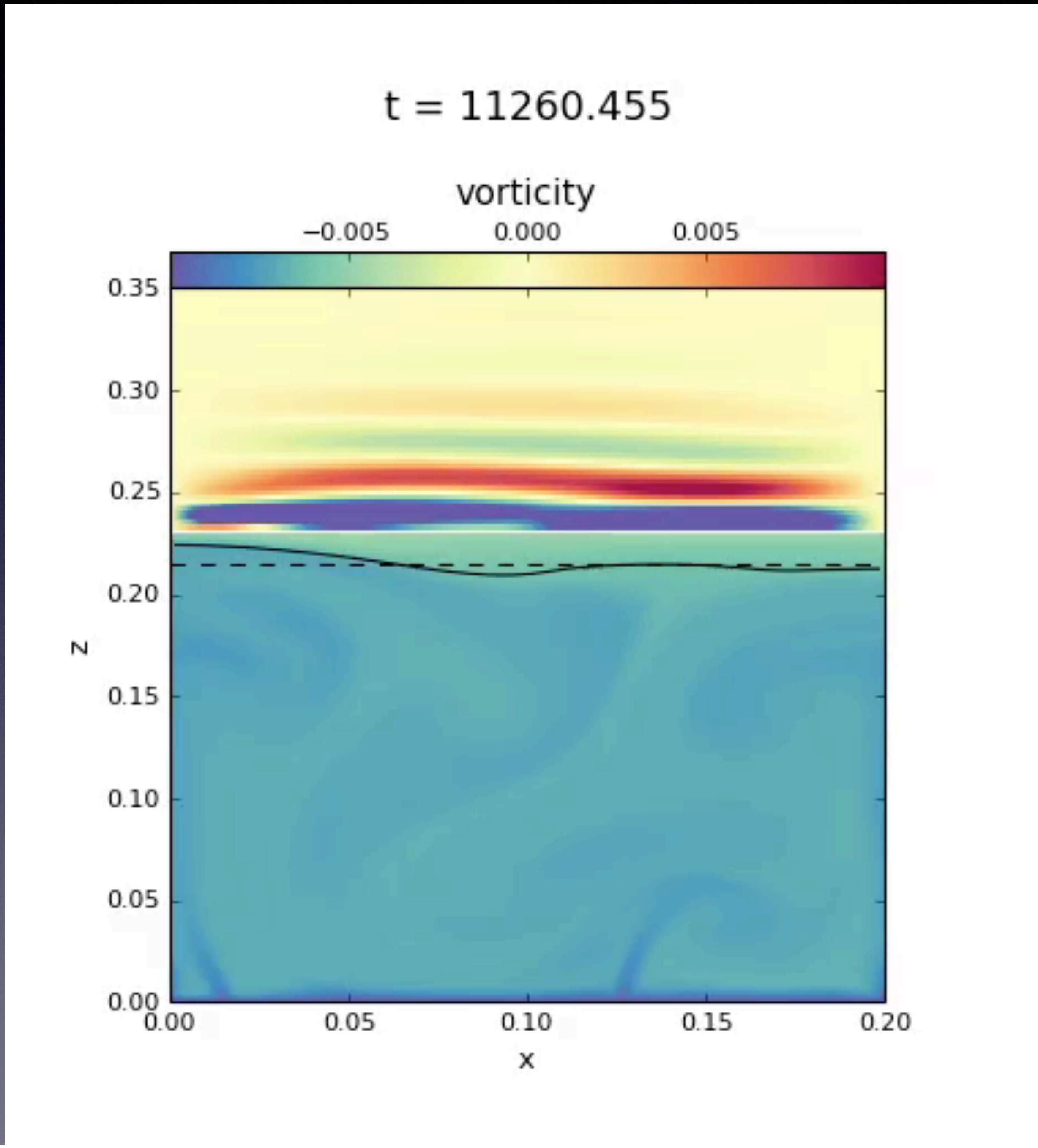


radiative zone with waves excited by convection

convection zone

Daniel Lecoanet

Convective Excitation of Waves



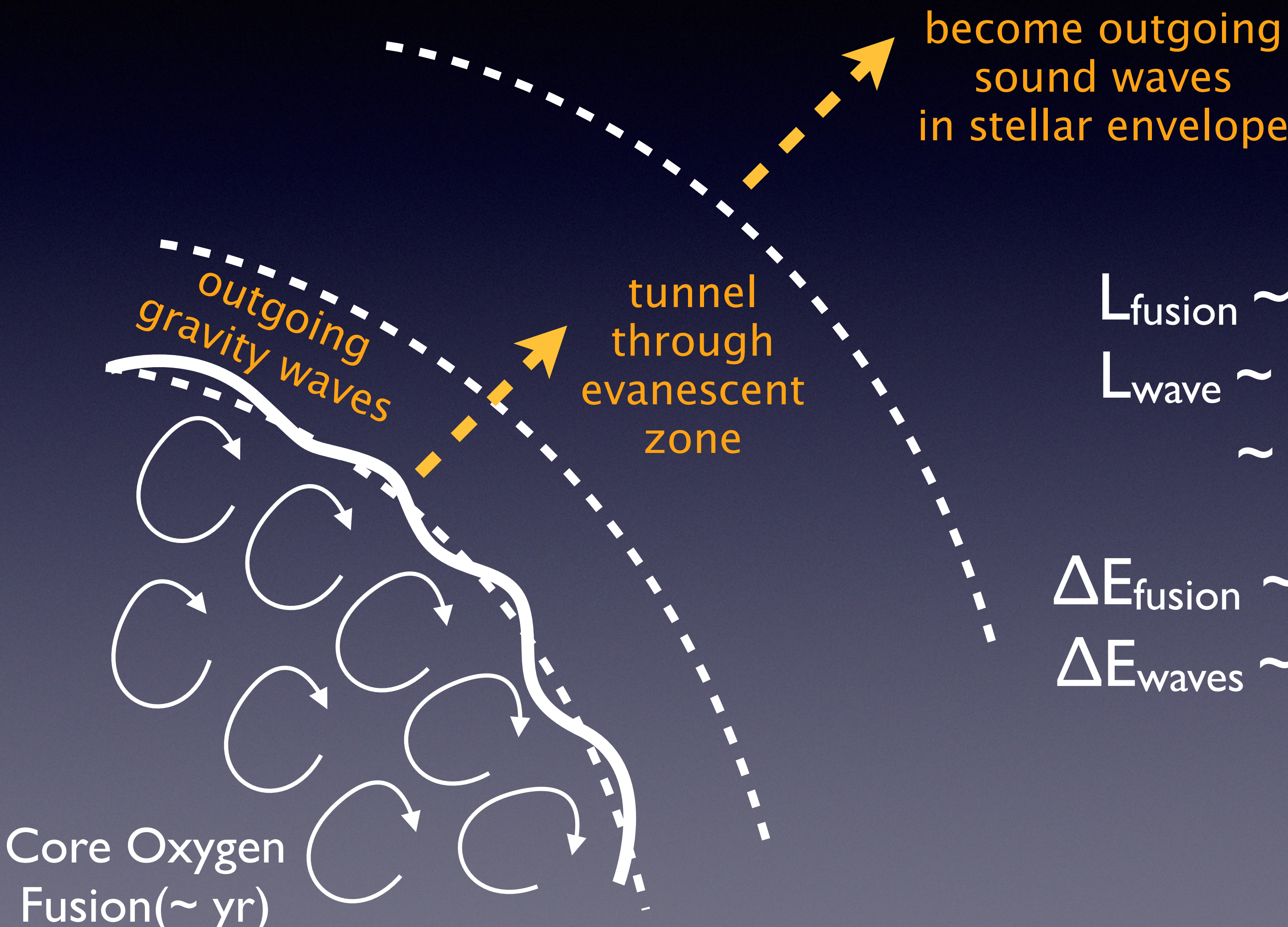
Daniel Lecoanet

Internal Gravity Waves

$\mathcal{M} = v_c/c_s$
(conv. Mach #)

$\dot{E}_{waves} \gtrsim \mathcal{M}\, L_{conv}$

$\omega \sim v_c/H$



$L_{fusion} \sim 10^{10}\, L_\odot$

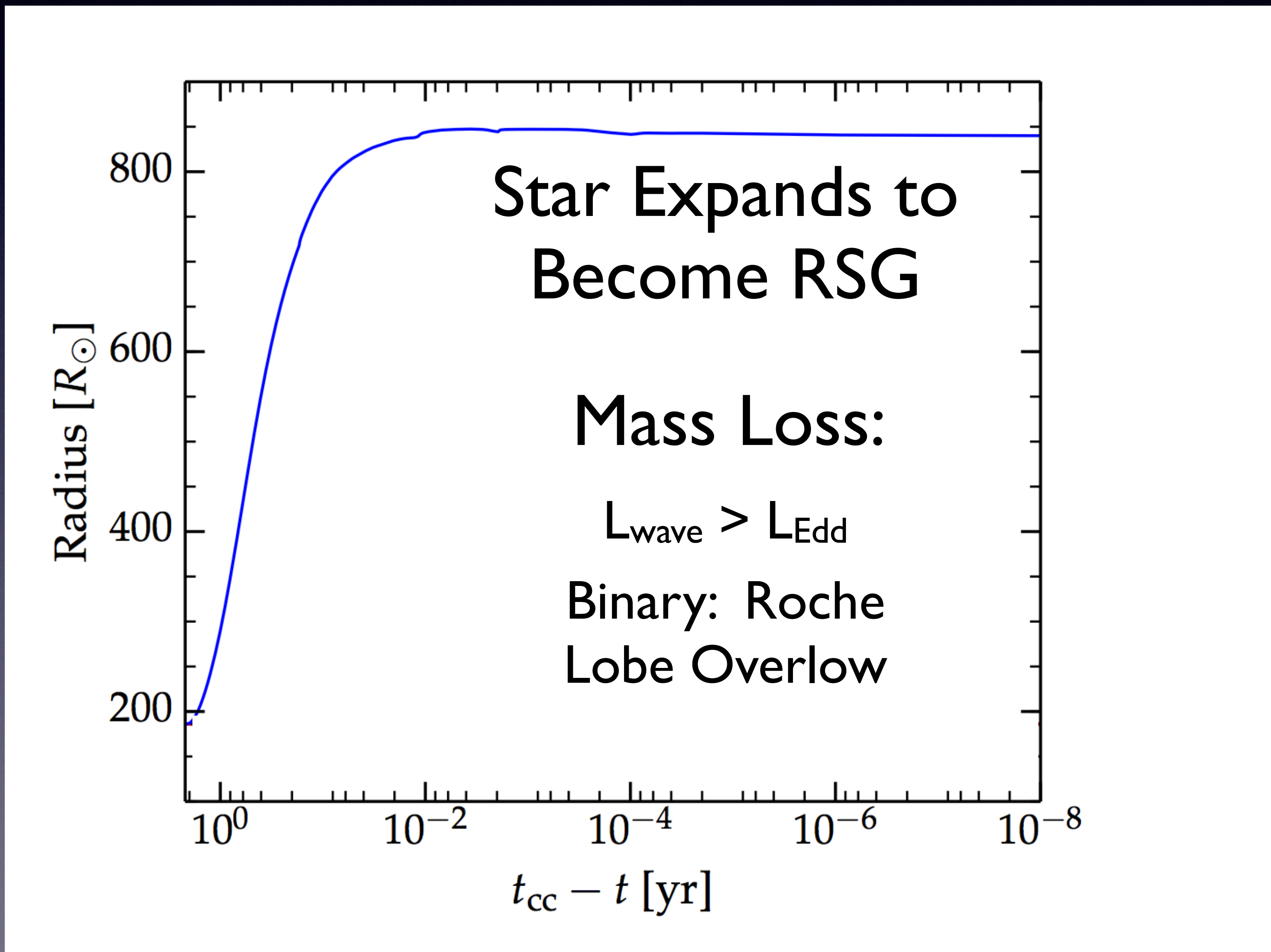
$L_{wave} \sim 10^{7.5}\, L_\odot$

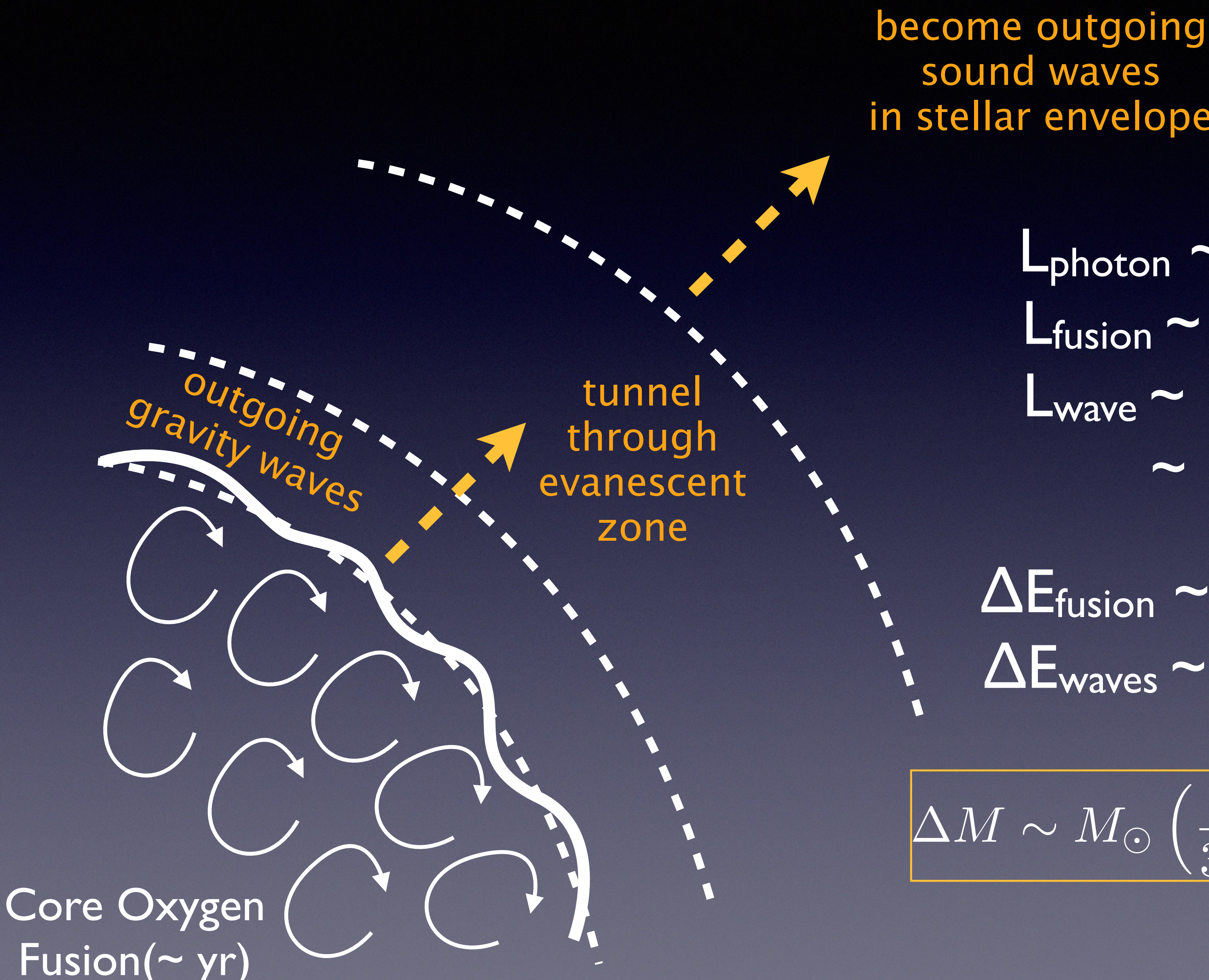
$\sim 100\, L_{EDD}$

$\Delta E_{fusion} \sim 10^{51}$ ergs

$\Delta E_{waves} \sim 10^{48}$ ergs

MESA Models with Super-Eddington Energy Deposition in Stellar Envelope





$L_{photon} \sim 10^5\, L_\odot$

$L_{fusion} \sim 10^{10}\, L_\odot$

$L_{wave} \sim 10^{7.5}\, L_\odot$

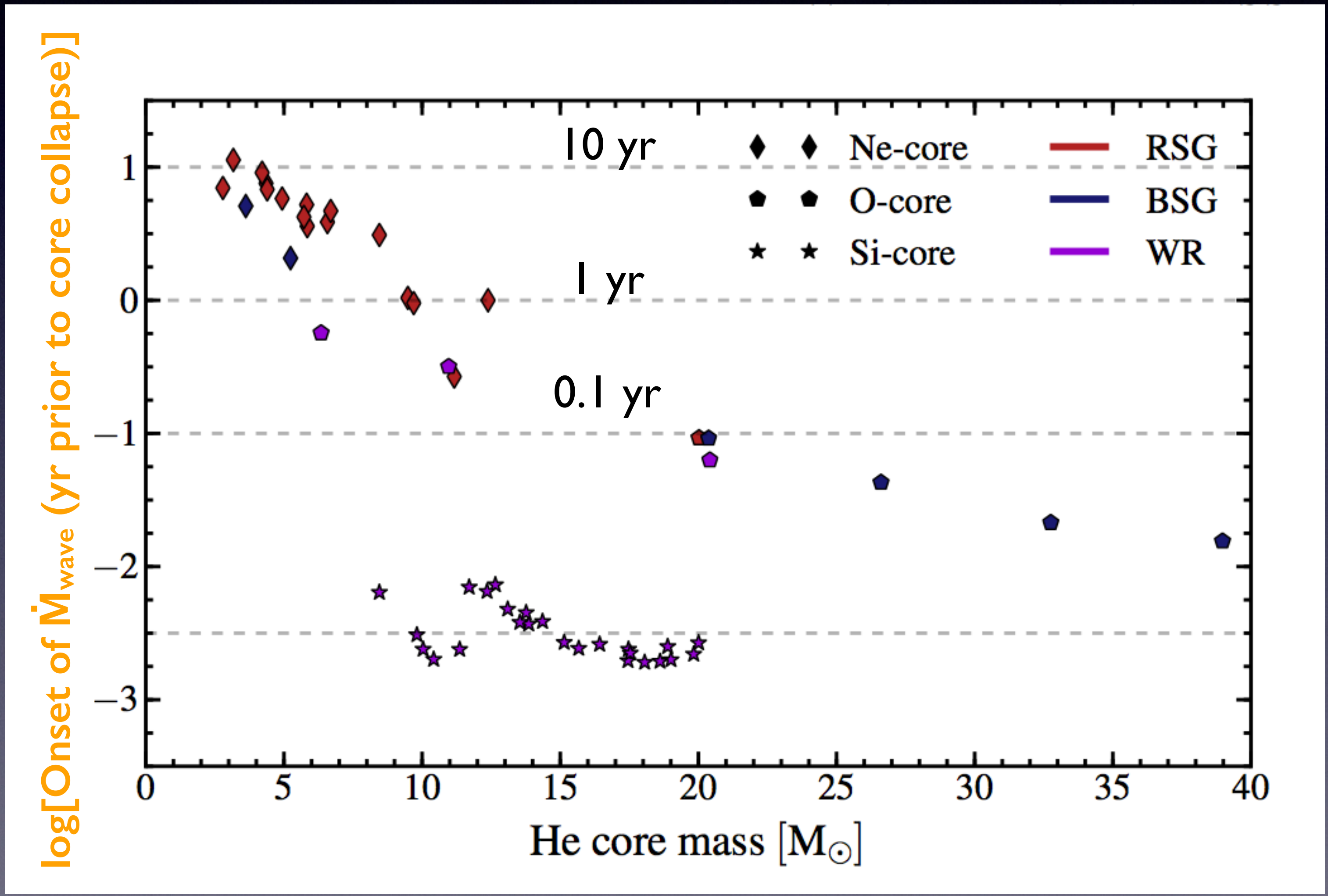
$\sim 100\, L_{EDD}$

$\Delta E_{fusion} \sim 10^{51}$ ergs

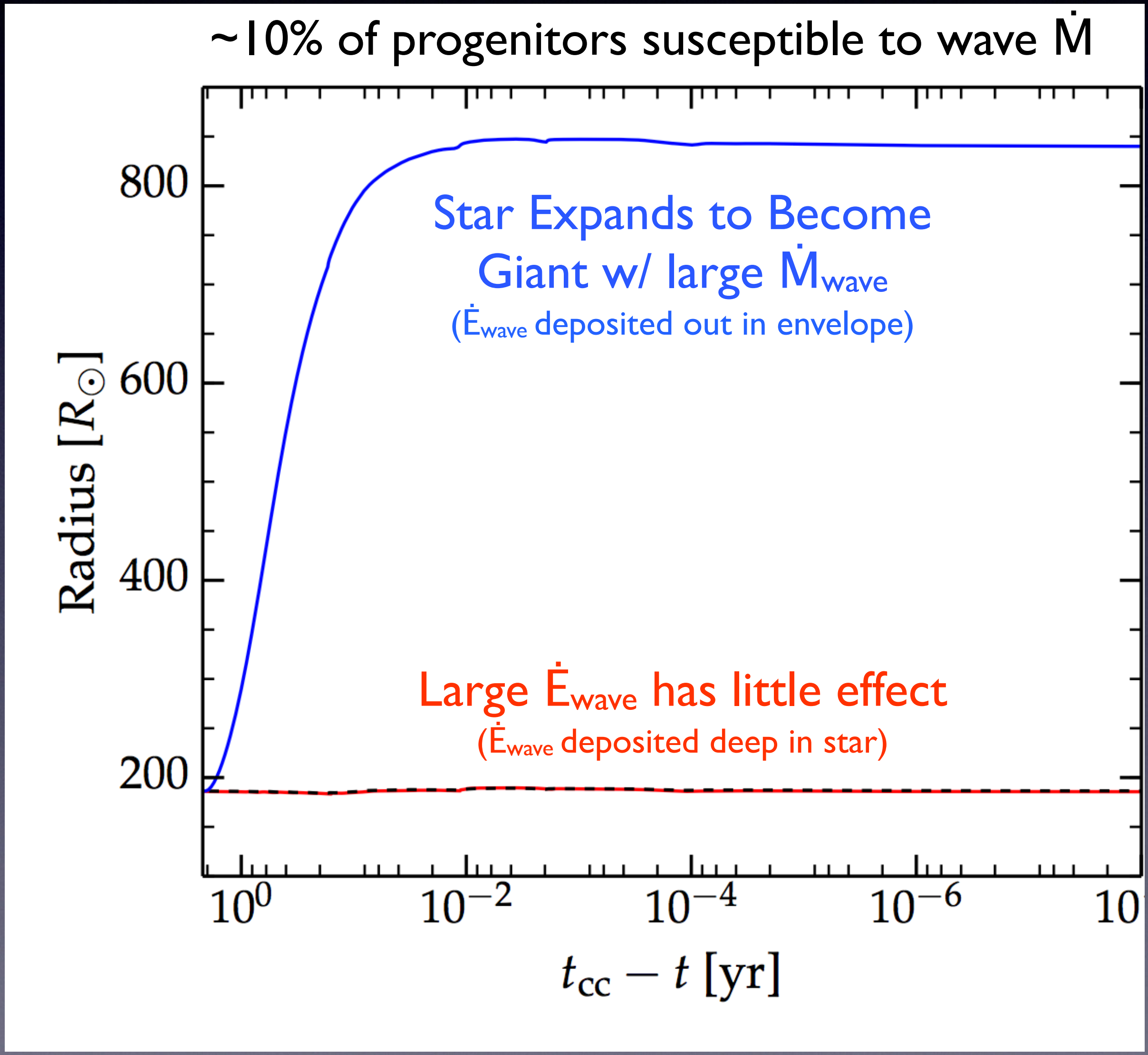
$\Delta E_{waves} \sim 10^{48}$ ergs

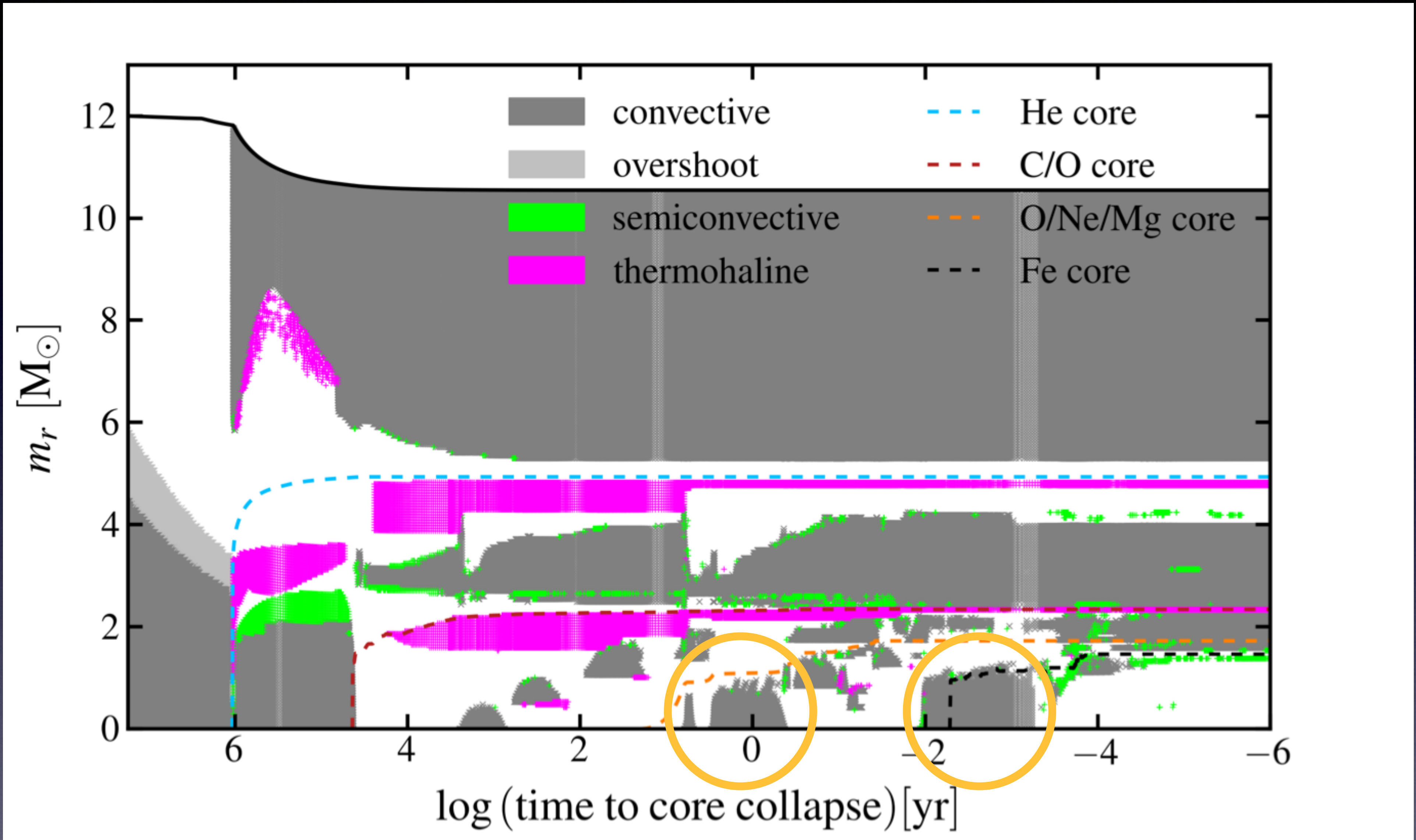
$$\boxed{\Delta M \sim M_\odot \left(\frac{v_{\rm wind}}{300\ {\rm km\,s^{-1}}}\right)^{-2}}$$

Variation in Wave-Driven Mass Loss with Progenitor

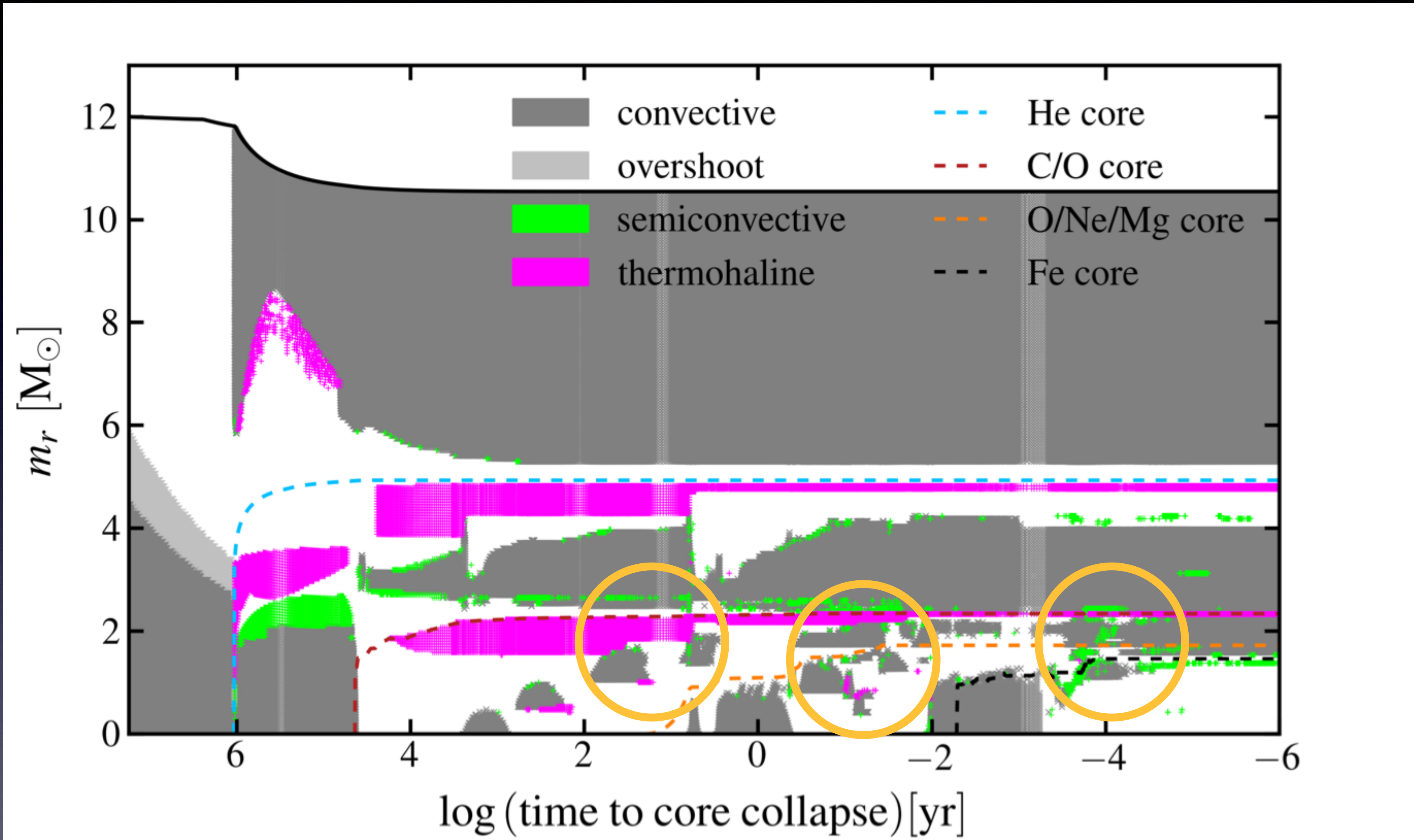


Variation in Wave-Driven Mass Loss with Progenitor





Core Fusion: Waves Propagate into Envelope



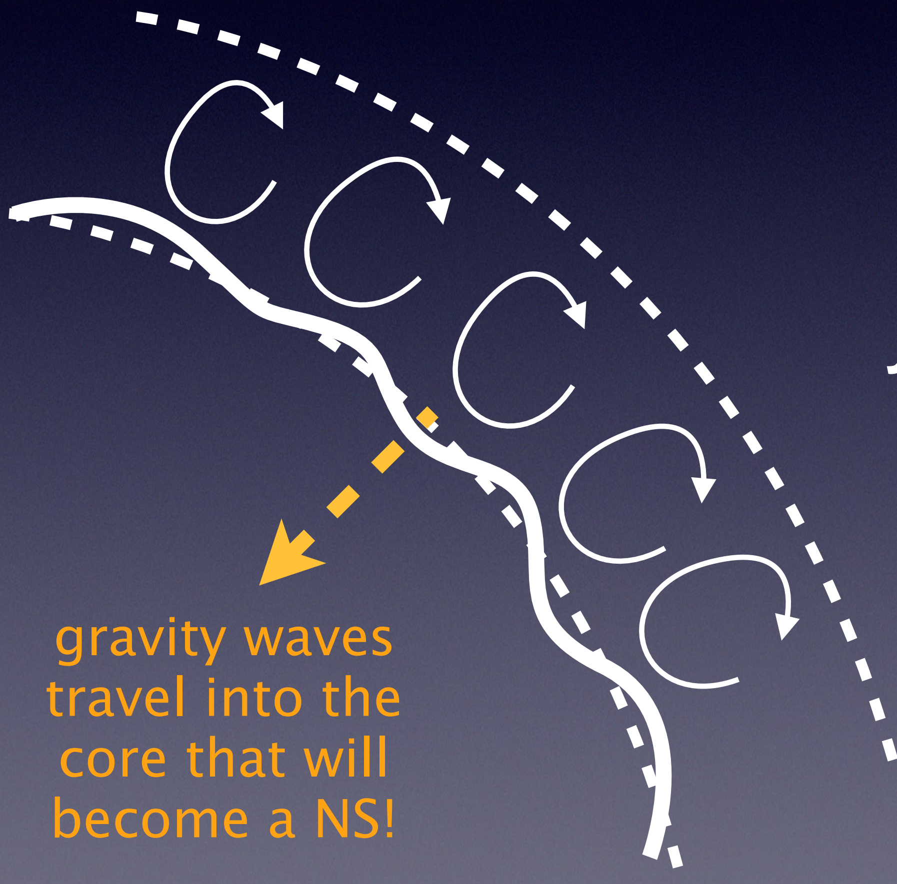
Shell Fusion: Waves Propagate into Envelope & Core

Effect of Waves on the Spin of the Stellar Core

(Fuller + 2015)

Internal Gravity Waves

$$\dot{J} = \frac{m\dot{E}}{\omega}$$



gravity waves travel into the core that will become a NS!

Shell C, O, Ne, Si Fusion

(~10 yr to ≲ day)

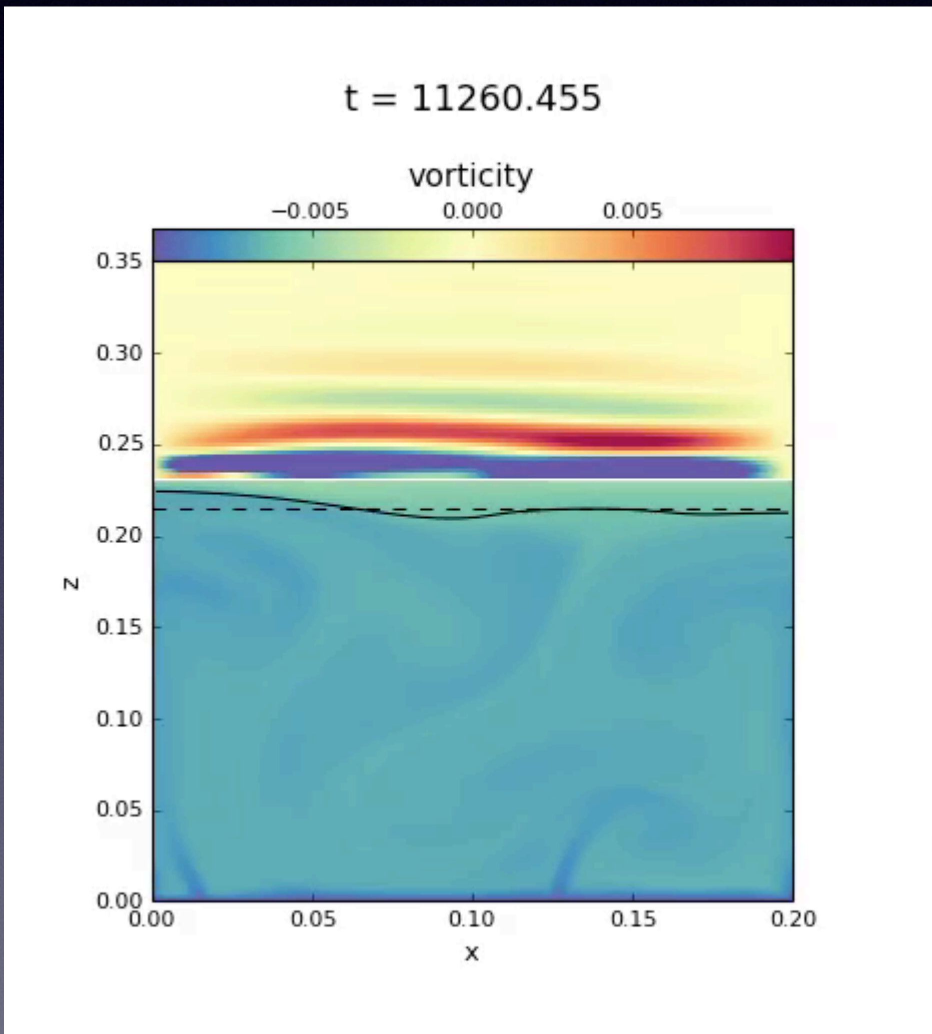
$J_{NS} \sim 10^{47}\,(P/0.1\ s)^{-1}\ g\ cm^2\ s$

J_{waves} (m > 0) $\sim 3\,10^{49}\ g\ cm^2\ s$ C shell fusion

$\sim 3\,10^{48}\ g\ cm^2\ s$ Si shell fusion

Waves Can Dramatically Modify Spin of the Resulting NS

What if the Fe Core is Very Slowly Rotating Prior to Core Collapse?



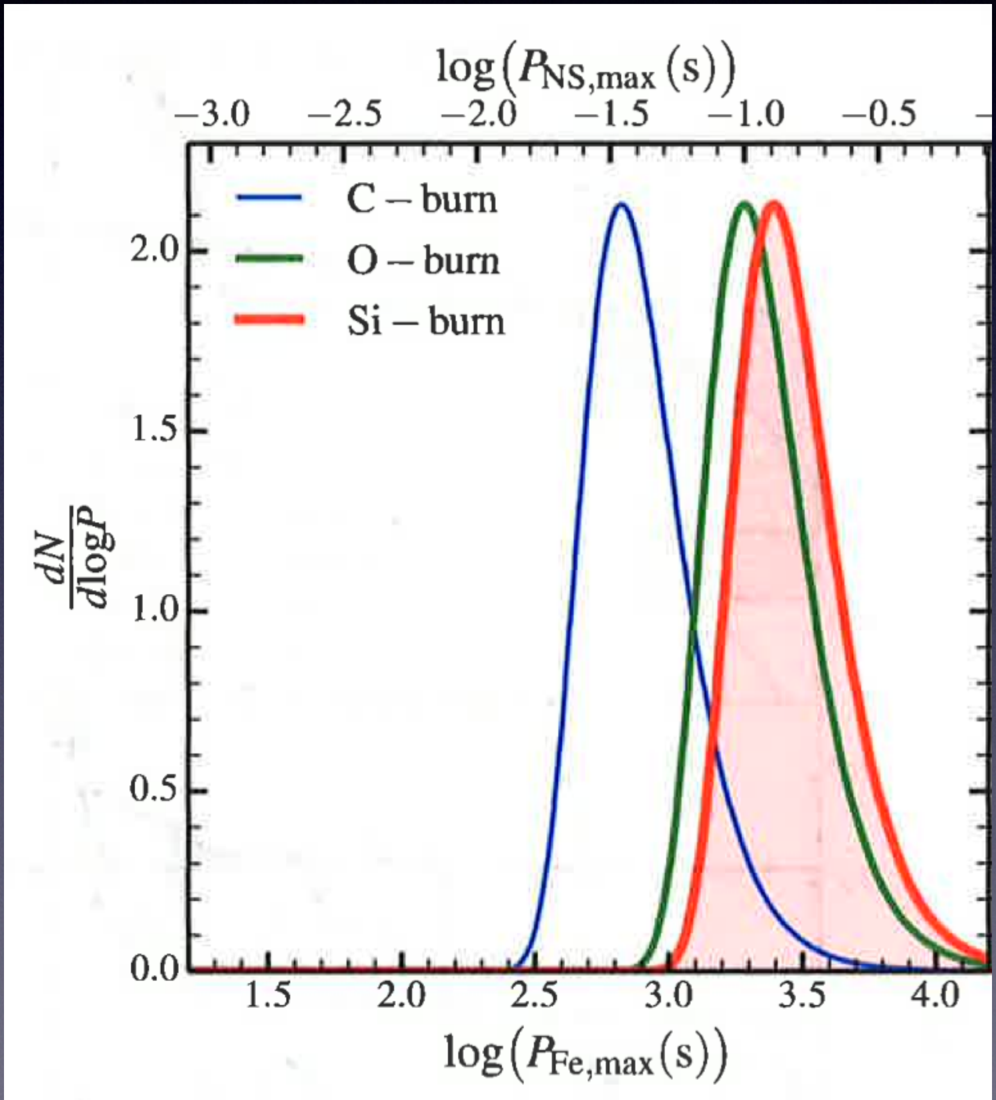
Core is Stochastically Spun Up by Waves from Si Shell Fusion

$$J_{\rm core} \sim \frac{J_{\rm waves}}{N_{\rm eddy}^{1/2}} \sim \frac{J_{\rm waves}}{(\omega_c T_{\rm shell})^{1/2}}$$

N_{eddy} ~ 300 (Si shell fusion)

(cf. N_{eddy} ~ 10^{11} for MS solar convection)

What if the Fe Core is Very Slowly Rotating Prior to Core Collapse?



Core is Stochastically Spun Up by Waves from Si Shell Fusion

$$J_{\rm core} \sim \frac{J_{\rm waves}}{N_{\rm eddy}^{1/2}} \sim \frac{J_{\rm waves}}{(\omega_c T_{\rm shell})^{1/2}}$$

$N_{\rm eddy}$ ~ 300 (Si shell fusion)

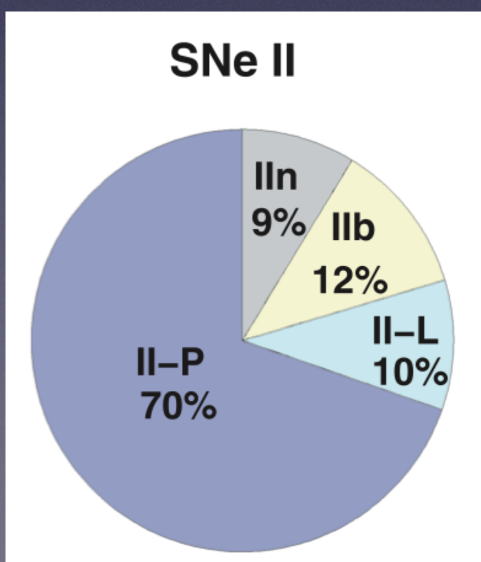
(cf. $N_{\rm eddy}$ ~ 10^{11} for MS solar convection)

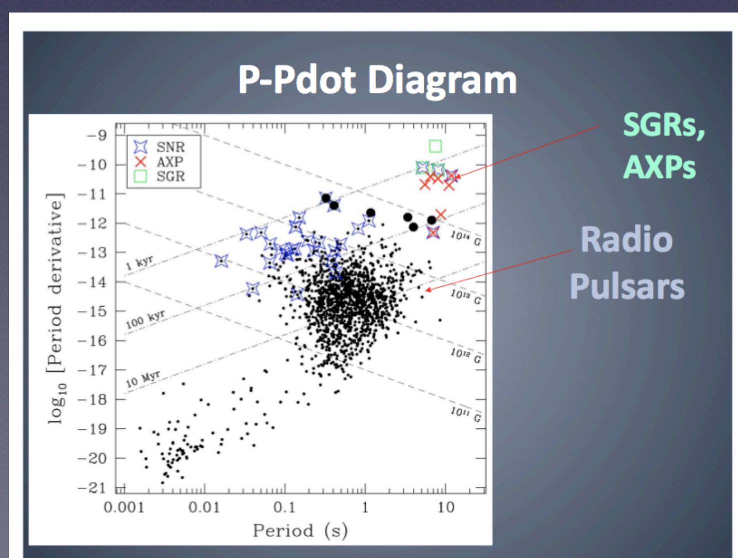
$\Rightarrow P_{\rm NS} \sim 0.1$ sec

~ estimated NS spin periods from population studies

Overview

- $L_{fusion} >> L_{Edd}$ in last ~ yr-decade of stellar evolution → vigorous convection and a super-Eddington wave flux
  - prodigious mass loss seen in circumstellar interaction and shock breakout from core-collapse SNe
  - reshapes the spin of the stellar core & plausibly explains the typical ~0.1 sec spin of radio pulsars





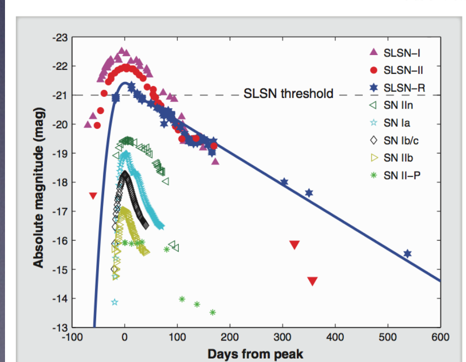


Fig. 1. The luminosity evolution (light curve) of supernovae. Common SN explosions reach peak luminosities of ~10^{43} ergs s^{-1} (absolute magnitude > –19.5). Super-luminous SNe (SLSNe) reach luminosities that are greater by a factor of ~10. The prototypical events of the three SLSN classes—SLSN-I [PTF09cnd (*4*)], SLSN-II [SN 2006gy (*12*, *13*, *77*)], and SLSN-R [SN 2007bi (*7*)]—are compared with a normal type Ia SN (Nugent template), the type IIn SN 2005cl (*56*), the average type Ib/c light curve from (*65*), the type IIb SN 2011dh (*78*), and the prototypical type II-P SN 1999em (*79*). All data are in the observed *R* band (*80*).