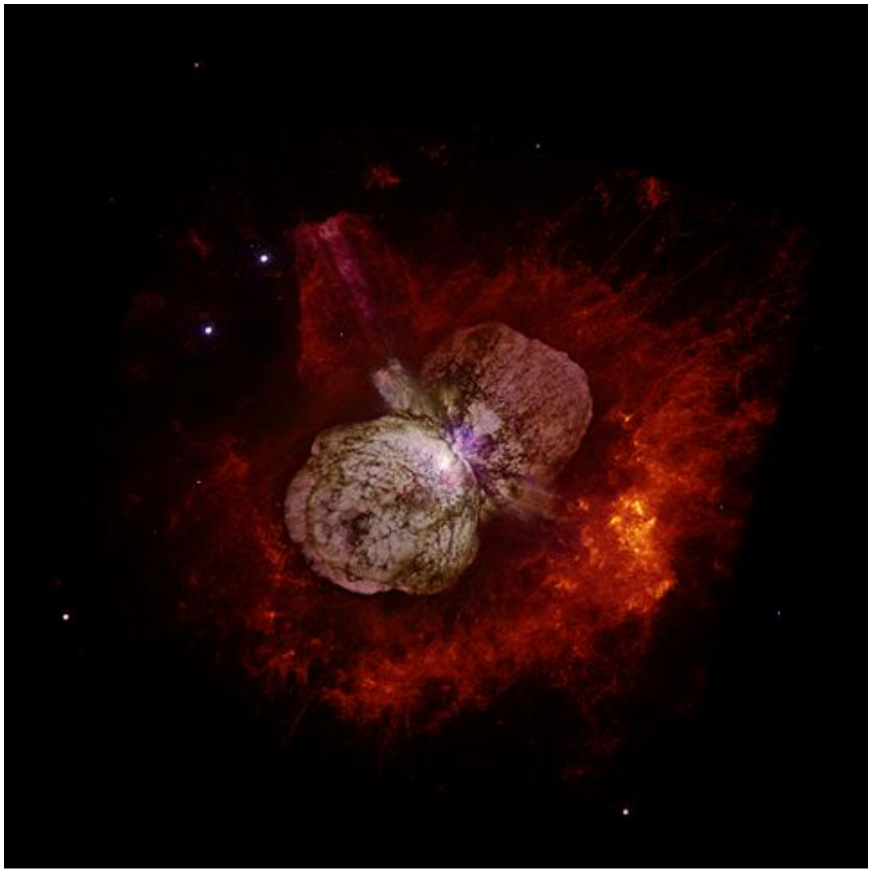
Instability Considerations for Massive Star Eruptions



Joyce Ann Guzik

Los Alamos National Laboratory

Massive Star Workshop

St. Paul, Minnesota

30 September – 3 October, 2012

References for work presented here

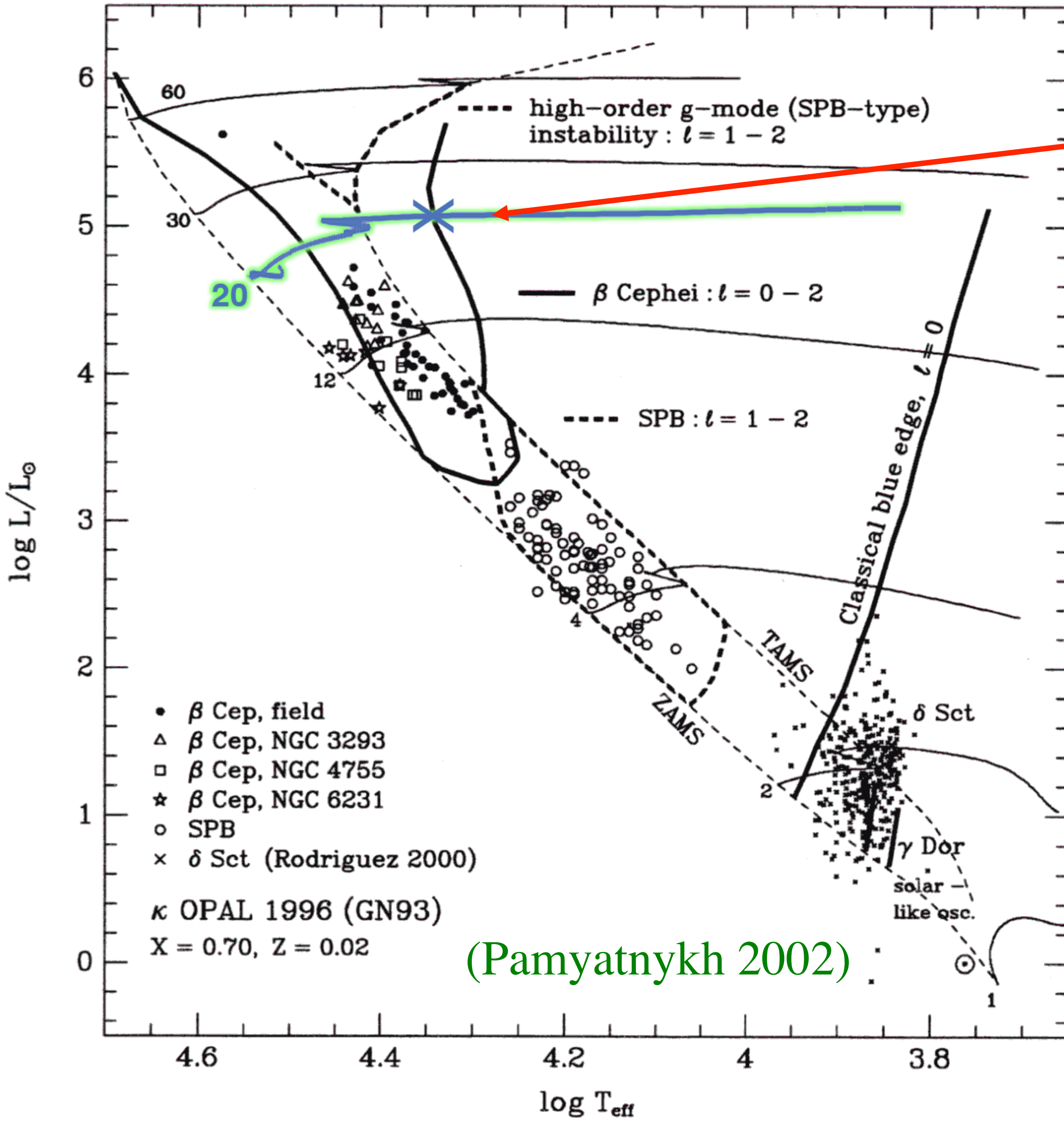
Los Alamos work 1993 – 2012 summarized in Astronomical Review (in press)

Pulsations and Hydrodynamics of Luminous Blue Variable Stars J.A. Guzik & C. Lovekin

http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-12-22779

See also poster by Lovekin & Guzik

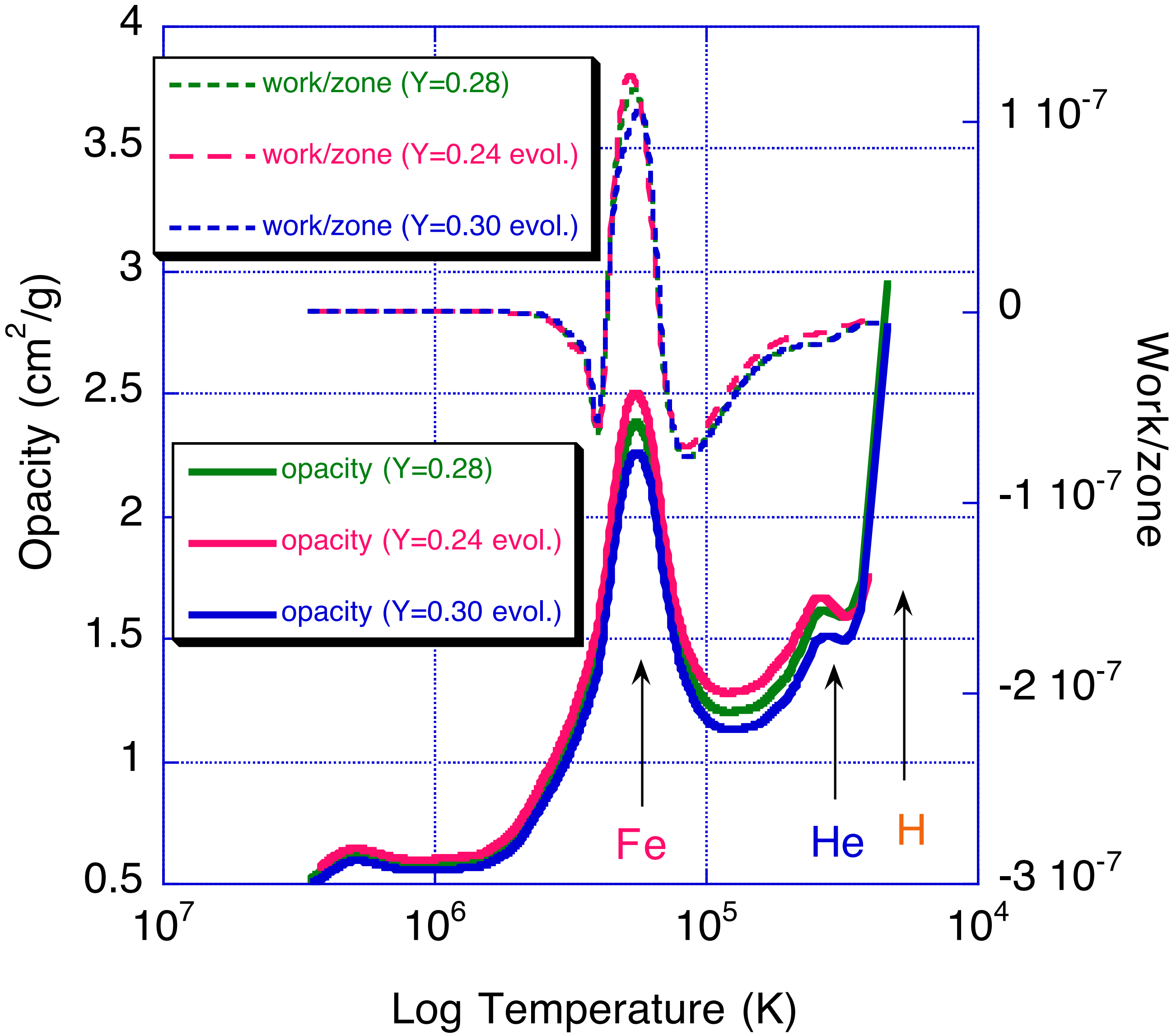
β Cephei and SPB stars in the H-R Diagram



Our evolution track with Iben code for (X, Y, Z = 0.70, 0.28, 0.02), X marks ~22,000 K models we studied

20 M_{sun} model radius increases from 6 R_{sun} on ZAMS to 15 R_{sun} before 'blue hook' to 23 R_{sun} after 'blue hook'

Pulsations driven by Fe-group element ionization opacity bump at about 200,000 K



20 M$_{sun}$
22,139 K

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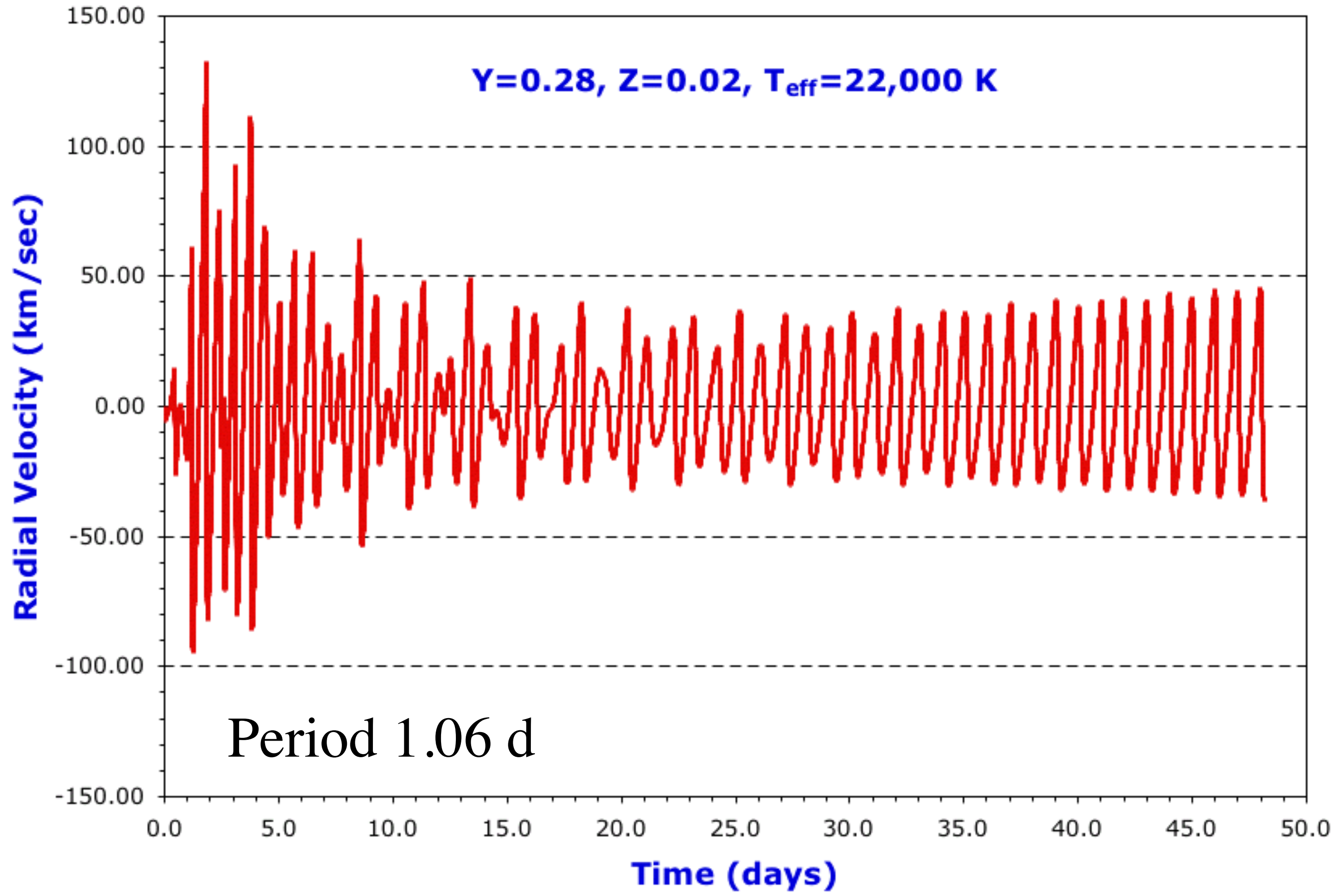
Nonlinear hydrodynamic simulations show radial pulsations

Model initiated in fundamental mode with radial velocity amplitude 5 km/sec.



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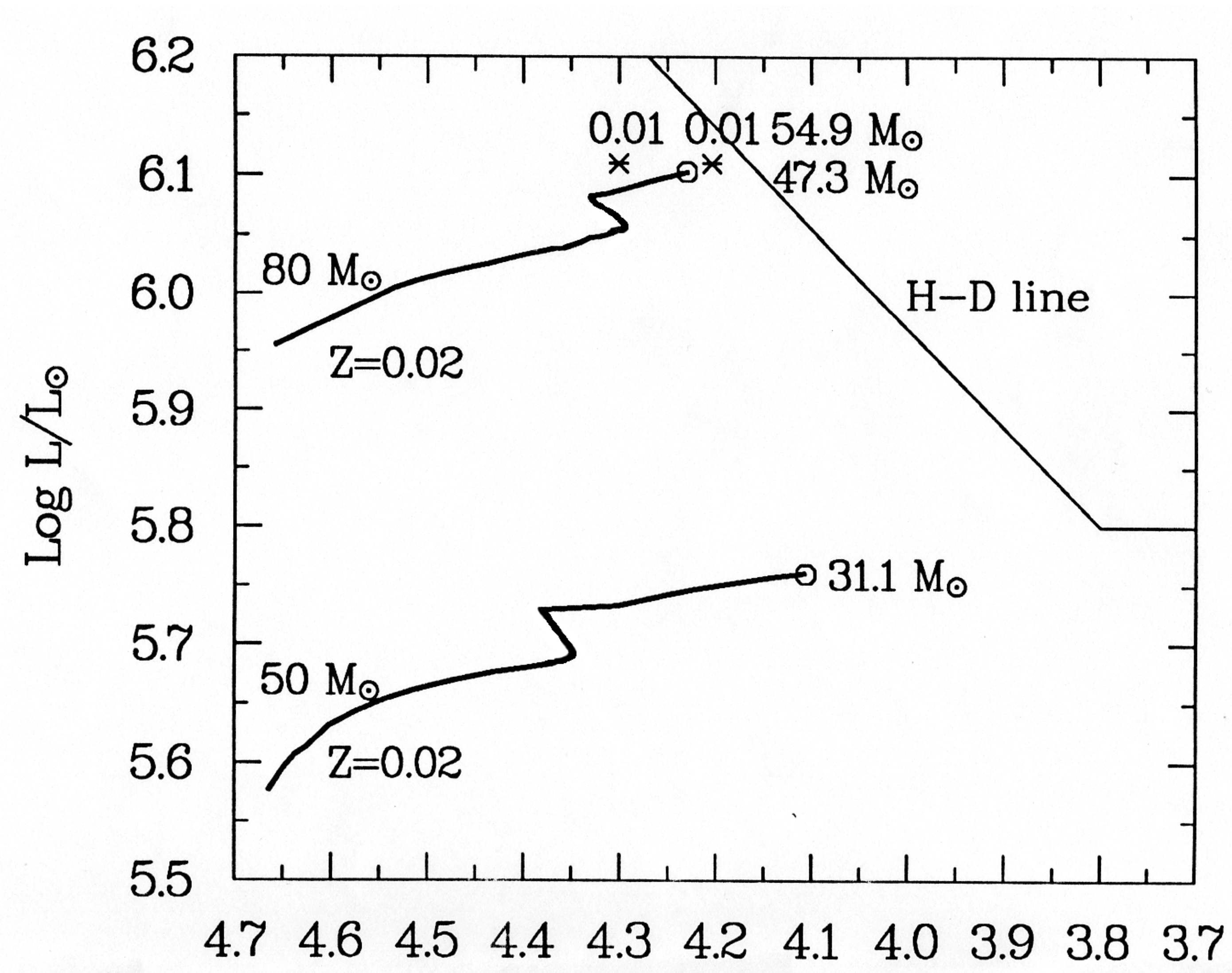
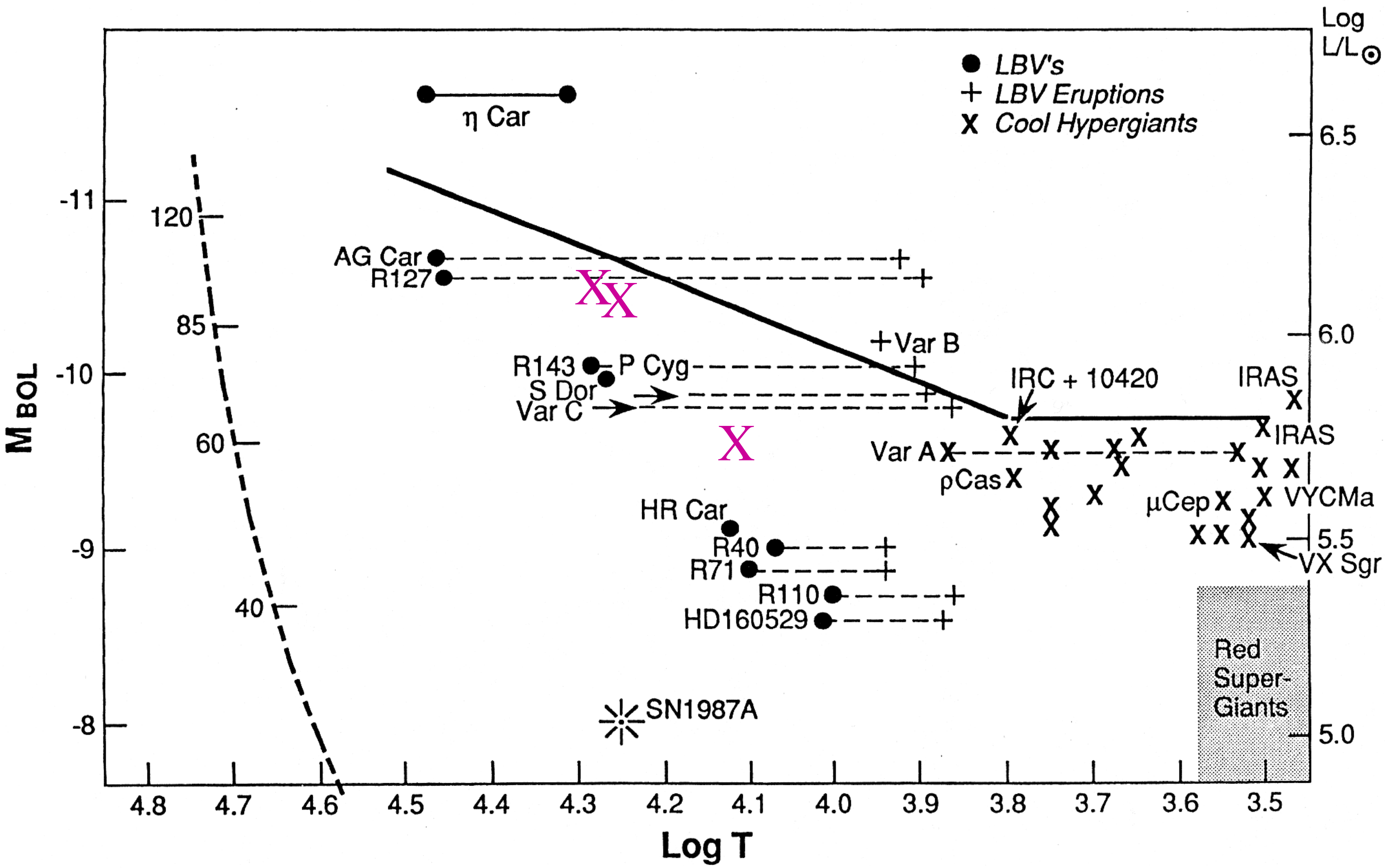
Evolution tracks of 80 and 50 M_{sun} models with mass loss



Location of hydro models on HR diagram



HR Diagram from Humphreys & Davidson 1994

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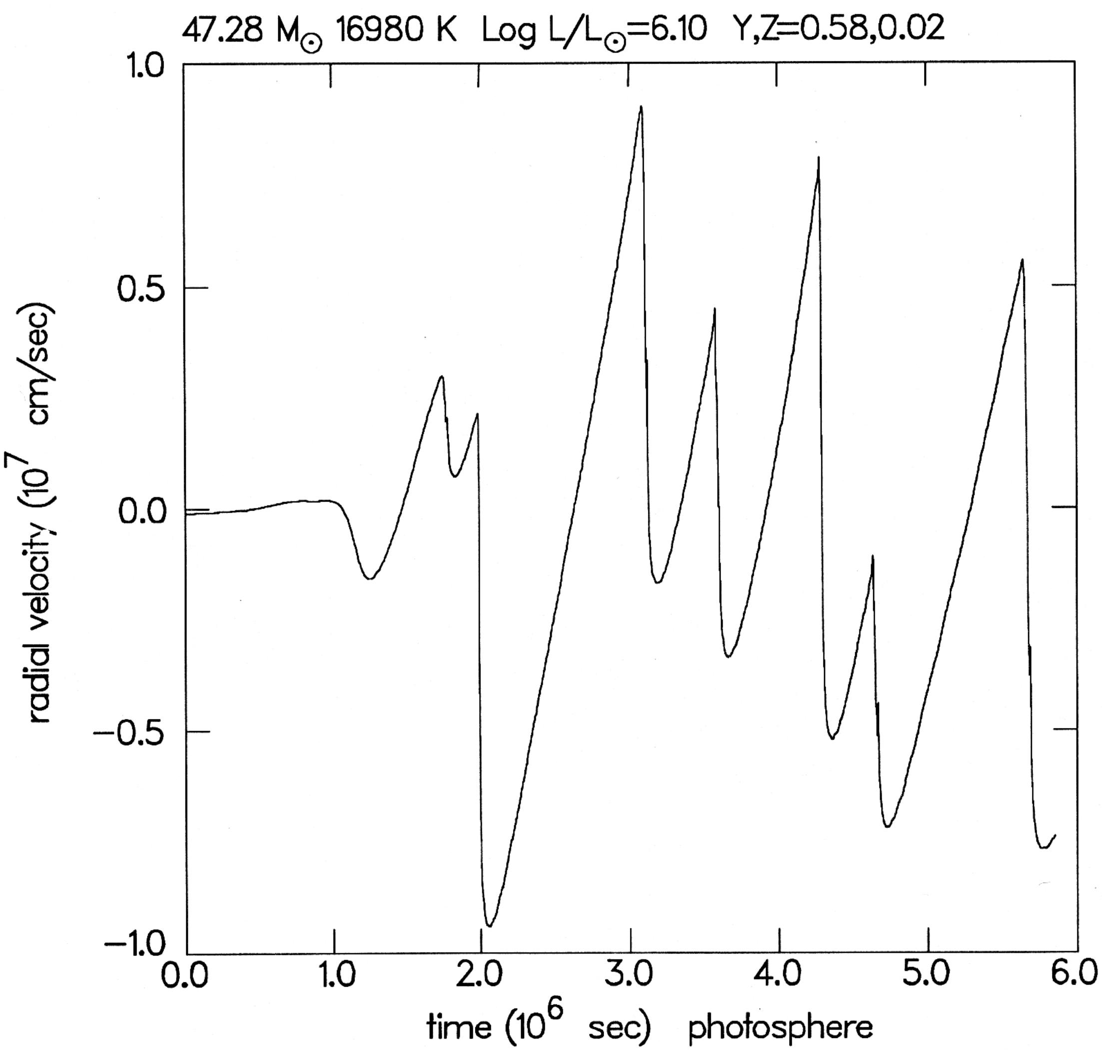
Model pulsates for surface Y=0.58



M_{init} = 80 Msun
M_{final} = 47.28 Msun

Amplitude ~100 km/sec

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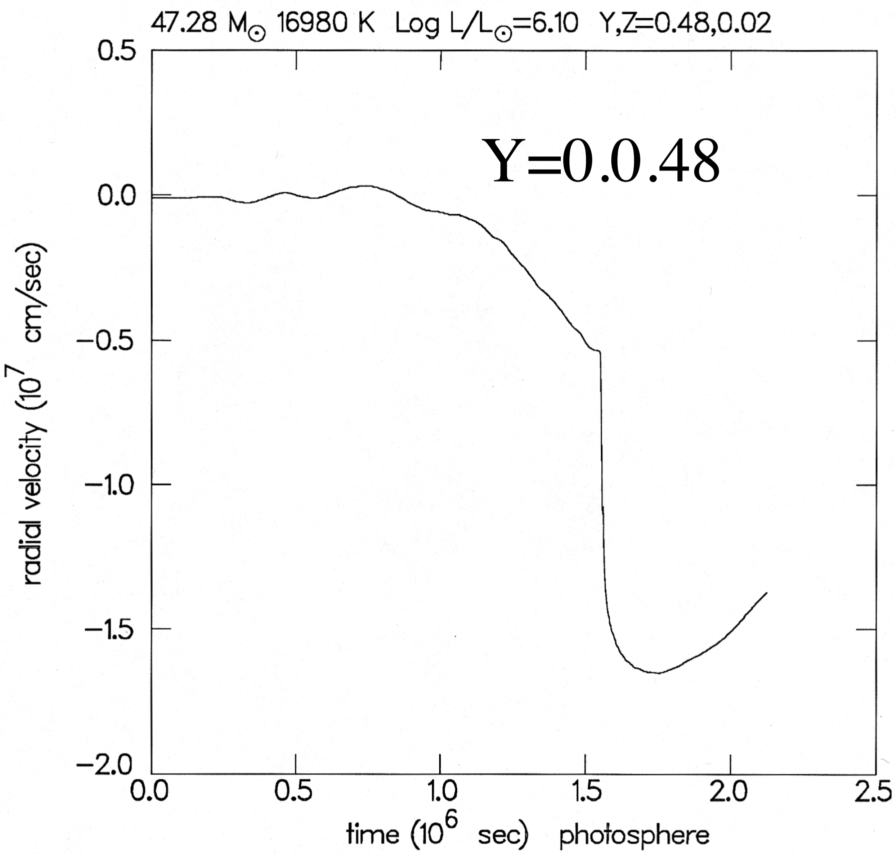
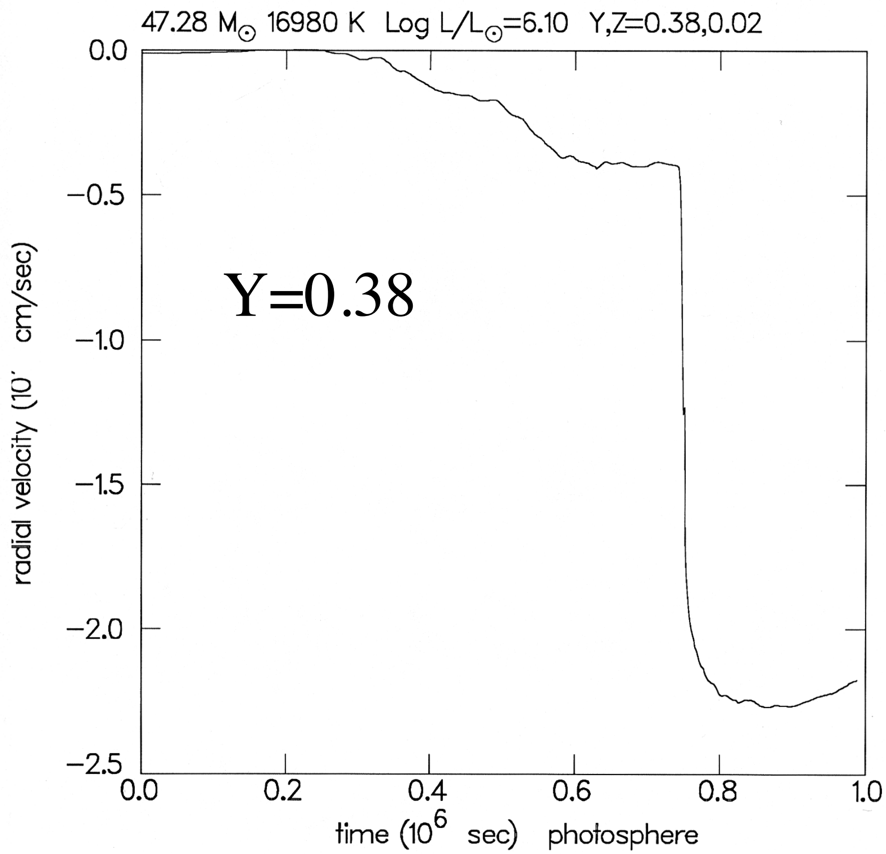
For Y=0.38 and 0.48, models shows large abrupt increase in outward radial velocity





Time-dependent convection and the Eddington limit

•Models show "outbursts" when the ***radiative luminosity*** of ***deep envelope zones*** near pulsation driving region (T>100,000 K) exceeds the ***Eddington luminosity*** for some portion of a pulsation cycle.

Eddington Luminosity = $4\pi GMc/\kappa$

•At this limit, the force due to radiation pressure outward exceeds the force due to gravity.

•In a static non-pulsating model, convection turns on to transport the required luminosity, so the model avoids exceeding the Eddington limit.

•However, in a pulsating model, convection takes some time to turn on during pulsation cycle, so the Eddington limit is periodically exceeded.

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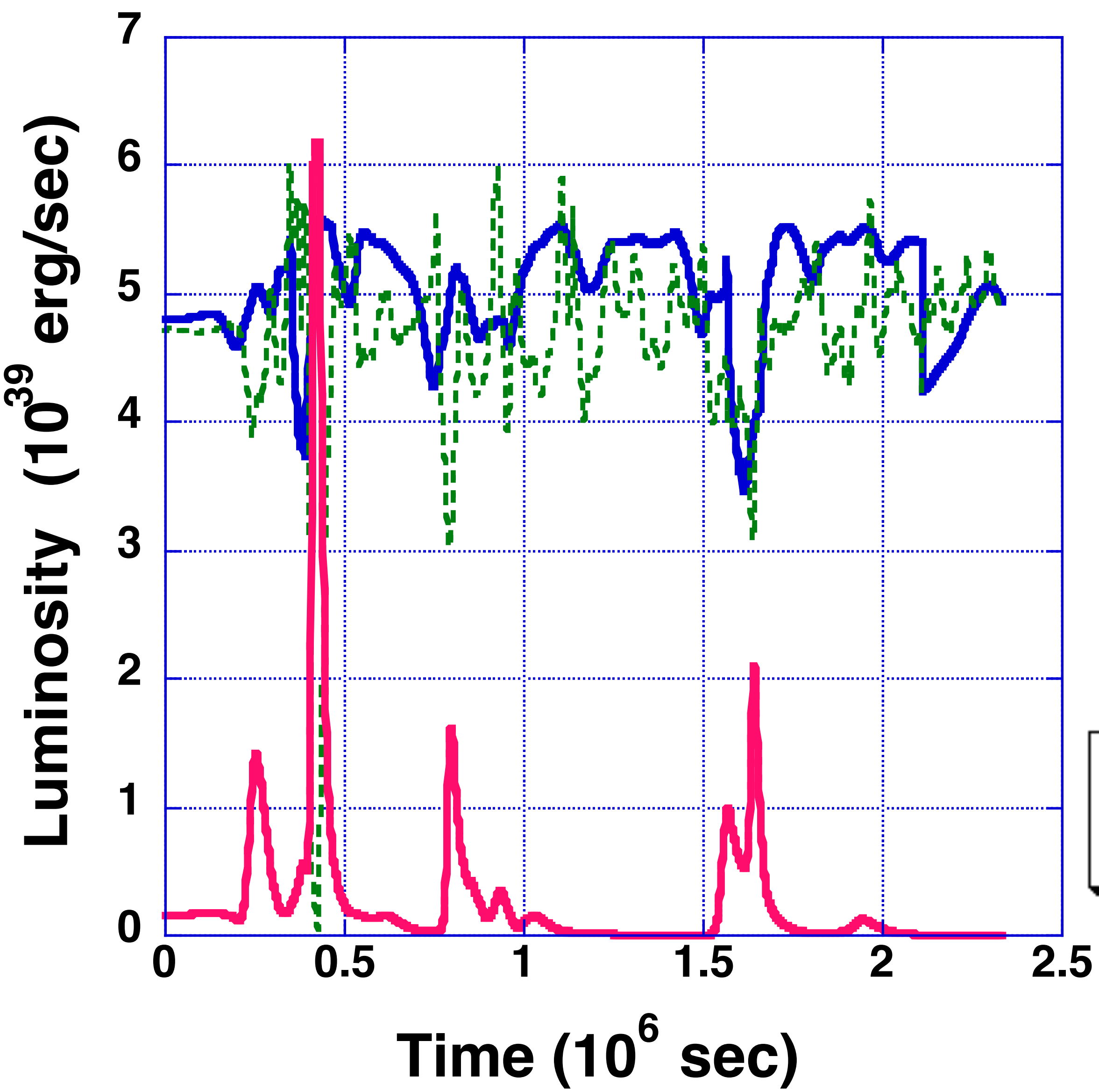
Due to lag in convective luminosity increase during pulsations, deep layers can exceed L_{edd}



47 solar masses,
T_{eff} = 16,980 K
zone 25/60

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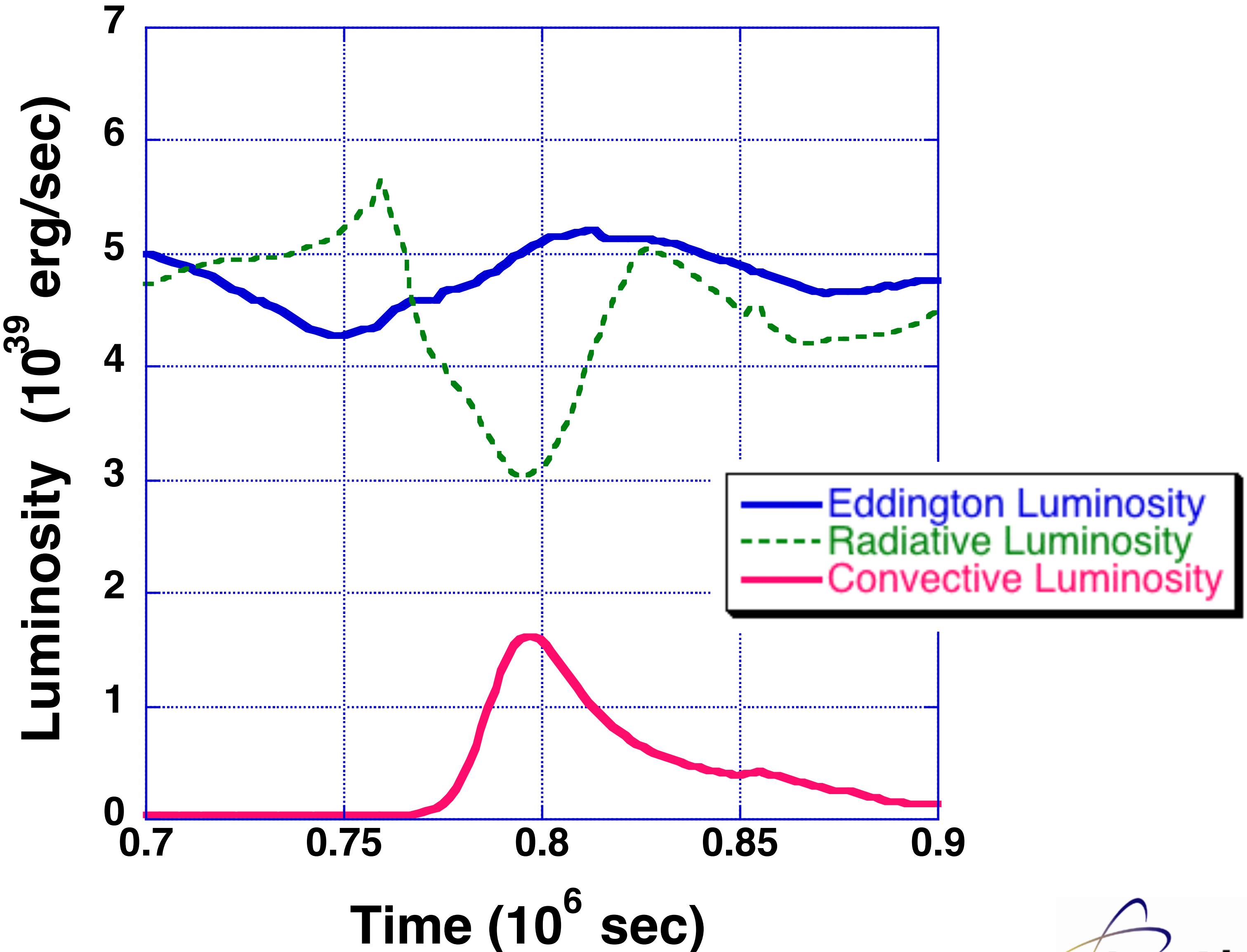
Radiative luminosity exceeds L_{edd} until convection turns on to transport some luminosity



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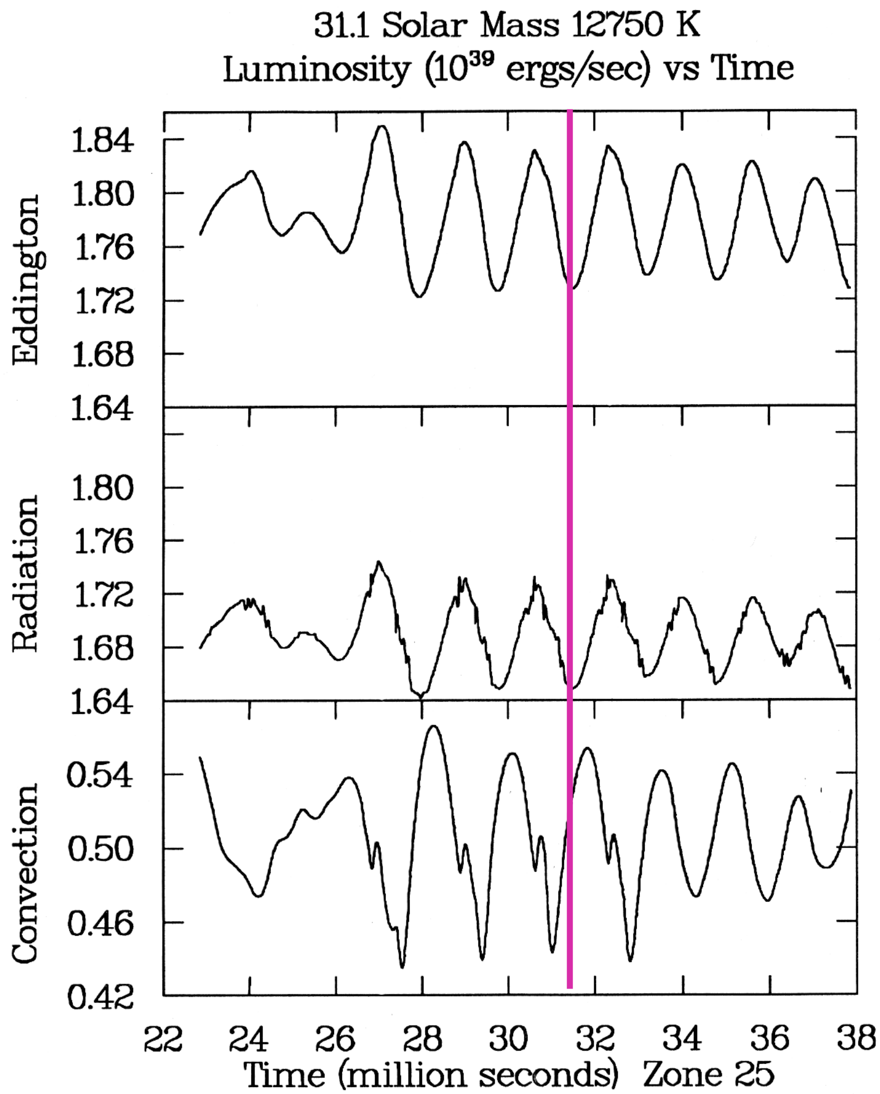
Convective luminosity increase can lag radiative luminosity decrease



Even though for 31 M_{sun} model radiative luminosity is below Eddington luminosity, this model illustrates clearly the lag of convective luminosity increase as radiative luminosity decreases

Summary of hydro model results

For high-mass models near the H-D limit:

•Pulsations grow to large amplitudes (> 100 km/sec)
•Pulsation periods and amplitudes are similar to LBV microvariations (5 to 50 days, ~0.1 mag)

•When deeper (adiabatic) regions of the envelope exceed L_{Edd}, an "outburst" occurs:

The radial velocity at the photosphere remains negative, and the radii of outer zones monotonically increase during several pulsation cycles

•An increase in envelope helium abundance lowers the opacity in driving regions and limits the pulsation amplitudes, putting an end to the "outbursts"

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Winds or eruptions?

•We have shown only that pulsations can trigger instability, and cause the outer layers of the star to move outward.

•Perhaps pulsation initiates flow, and shocks and line-driven wind accelerate it (Bjorkman 1999).

•Our envelope models encompass only ~10^{-4} solar masses, whereas in observed outbursts much more mass can be lost.

•Considering pulsation period and recovery time, winds produce at most 4 x 10^{-3} M_{sun}/year (10^{-4} M_{sun} every ~10 days) Including rotation may increase mass loss.

•Also, the calculated "outbursts" are generated within a few pulsation cycles (< 1 year) beginning from a near-static configuration, whereas the observed time between major outbursts is years or decades.

We have outlined a mechanism for pulsation-driven mass loss, modulated by the buildup of pulsation amplitude, rather than a mechanism for the rare giant eruptions

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Requirements for giant eruption mechanism

For giant eruptions like those of η Car and P Cyg,

Need a mechanism that:

1) **Ejects a large amount of mass, so origin must be deep-seated**

Envelope has 95% of stellar radius but only contains 10^{-4} M_{sun}

η Car lost ~20 M_{sun} over ~ 20 years (~1 M_{sun}/year)

2) ***Turns on*** suddenly, and then (perhaps after a bounce/rebound) ***turns off*** for hundreds or thousands of years

3) **Generates large amount of energy** (>10^{49} ergs)

Large luminosity, M_{BOL} increase during outbursts

Need energy to lift mass out of deep potential well

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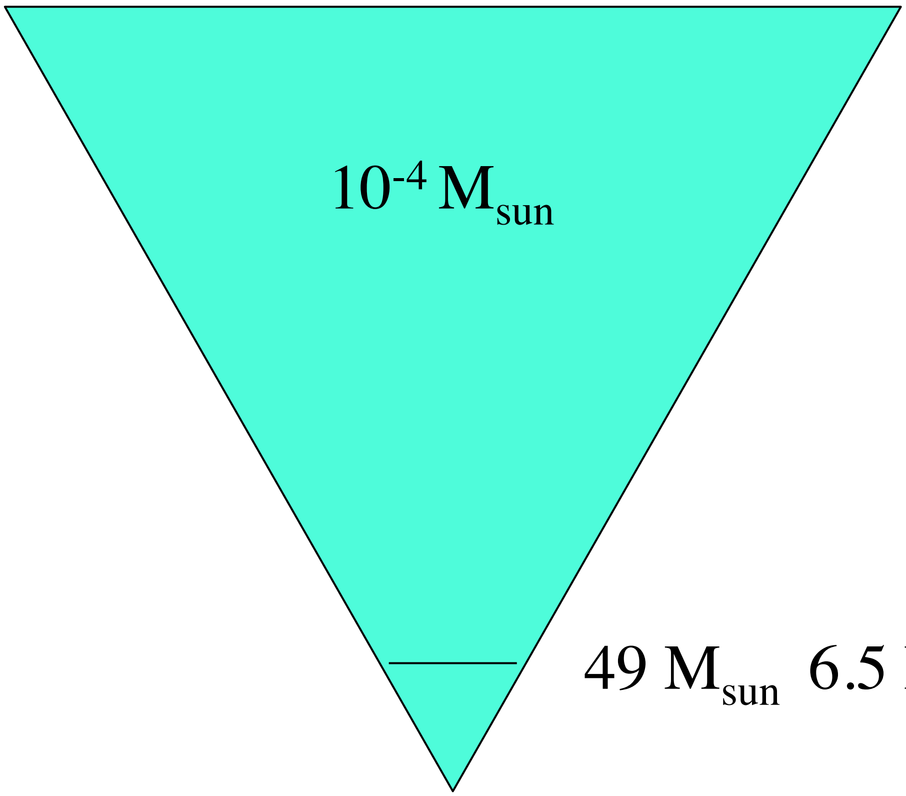
A mechanism releasing solar masses of material must be deep-seated

49 M_{sun} evolved model (after mass loss)



130 R_{sun}

49 M_{sun} 6.5 R_{sun}

Energy required to lift 1 M_{sun} material out of gravitational potential well: 3 x 10^{49} ergs

= amount of energy produced by 0.002 M_{sun} hydrogen (a few zones in H-burning shell region in calculation) converted to He

H-burning shell at 20 M_{sun}, 2 R_{sun}, 27 million K

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Proposed deep-seated mechanisms for instabilities

- Gravity-mode mixing in H-burning shell
- Epsilon mechanism (pulsation driving due to local nuclear energy generation)
- Tidal forcing/flexing effect of binary companion to initiate mixing episodes leading to nuclear burning

- Secular/thermal instability
  - Kelvin Helmholtz (thermal) timescale: $T = GM^2/LR$
  - Instead of normal pulsation analysis that searches for modes on dynamical timescale, find instead modes where star is in hydrostatic equilibrium, but is not in thermal equilibrium

- SASI instability as proposed for Type II supernovae

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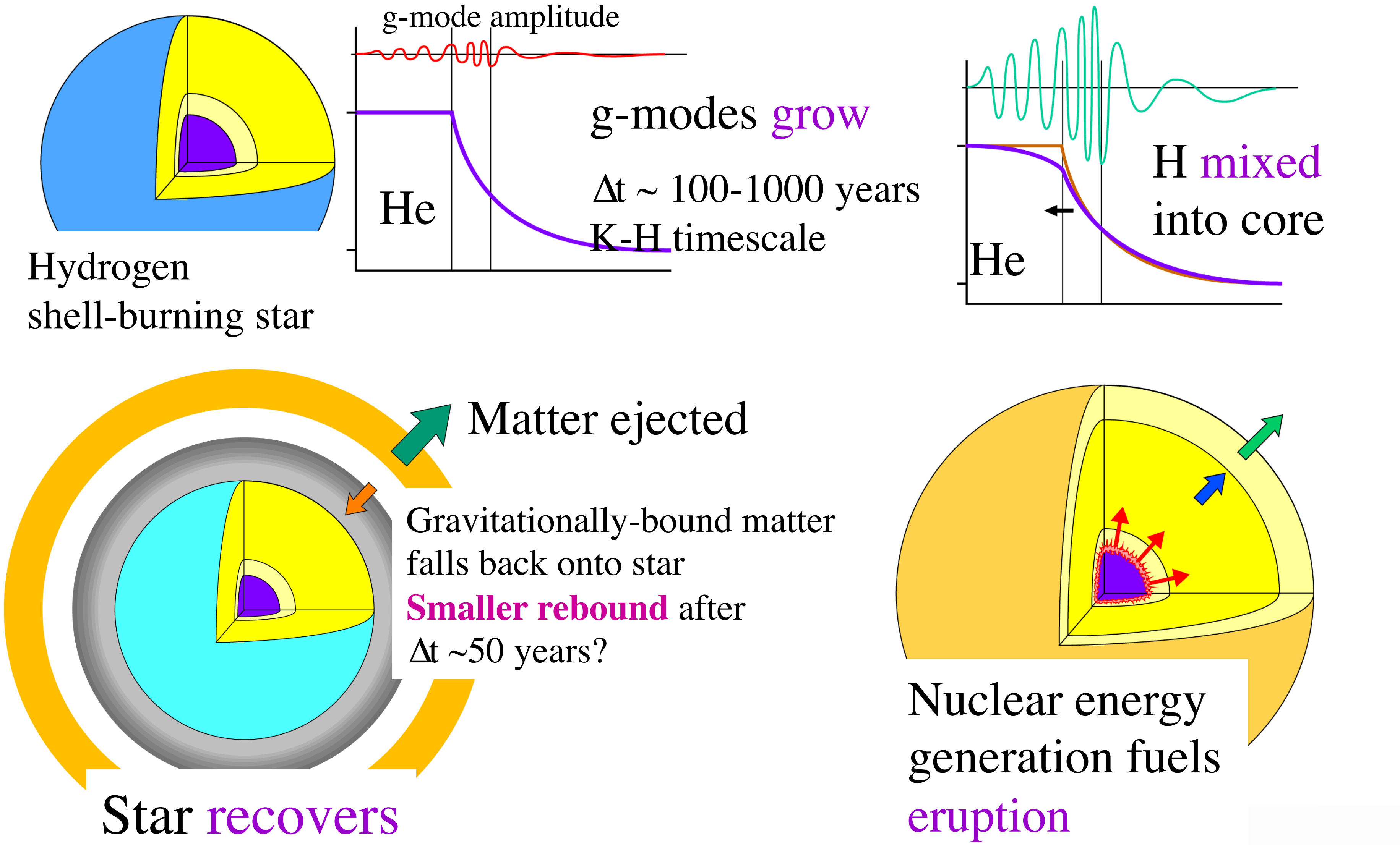
Example outburst mechanism: g-mode mixing in H-burning shell



Physics needed in codes

- Pulsation hydrodynamics (nonlinear)
- Nonradial as well as radial*
- Envelope/atmosphere included to follow dynamics, shocks/outbursts/ mass loss/infall and recovery
- Deep interior included to follow energy generation, produce or react to instabilities and mixing events
- Rotation (differential radially and azimuthally, angular momentum transport)*
- Convection (DNS, time dependent, non-local, overshooting)*
- Calculate p-modes (high amplitude near surface) and g-modes (interior)
- Tidal forcing/flexing, mass transfer from/to binary companion
- Beyond Lagrangian--adaptive grid or Eulerian

- Need to handle disparate time and spatial scales (evolution, thermal, dynamical, convective, pulsation, . . .)
- *2D or probably 3D required for nonlinear/nonradial, convection, rotation, tides, . .

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Which codes are available?

2D/3D evolution + hydro (include rotation, convection, or ability to deal with binary companion)

- Rotorc (Deupree), Djehuty (Dearborn), FLASH, Woodward code, Arnett codes

Planar 3D codes (e.g. Rage, and Stanford/NASA Ames code that can model layers in 3D, some with B fields)

1D hydro codes

- Dynstar (Ostlie) Lagrangian hydro code can't follow mass loss
- TITAN (Mihalas) Lagrangian adaptive grid
- Bowen code for Mira mass loss (doesn't follow pulsation driving region)

Wind-outflow modeling codes?

Supernova modeling codes?

Nonlinear plus nonradial pulsation codes?

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