Super-Eddington Continuum-Driven Winds

may apply to

Luminous Blue Variables (LBVs)

Radiative force

$$\vec{g}_{rad} = \int_0 d\nu \, \kappa_\nu \langle \hat{n} \, I_\nu \rangle / c \qquad = \kappa F / c \quad \textbf{if } \kappa \textbf{ gray}$$

e.g., compare electron scattering force vs. gravity

$$\Gamma \equiv \frac{g_{el}}{g_{grav}} = \frac{\dfrac{L}{4\pi r^2 c} \dfrac{\sigma_{Th}}{\mu_e}}{\dfrac{GM}{r^2}} = \frac{\kappa_e L}{4\pi G M c}$$

- For sun, $\Gamma_\odot \sim 2 \times 10^{-5}$
- But for hot-stars with $L \sim 10^6 L_\odot$; $M = 10\text{-}50 \, M_\odot$

$$\Gamma \lesssim 1$$

Interior: Radiation Pressure

Radiative diffusion

$$\frac{dP_{rad}}{d\square} = F$$

Hydrostatic equilibrium

$$\frac{dP_{tot}}{d\square} = F_{crit}$$

$$\frac{P_{rad}}{P_{tot}} = \square \quad (\square >> 1)$$

$$\frac{P_{rad}}{P_{gas}} = \frac{\square}{1 \square \square} \square \square \square^{\square 1} \square$$

Instability to strange mode pulsation

- Cox et al. 80’s; Glatzel et al. 90’s
- not related to □ or □ mech. (dynamical not thermal)
- favored when $P_{rad} > P_{gas}$ [□$_{Edd}$ > 1/2]
- lag of radiative diffusion, i.e. □P_{rad} lags □□$_{gas}$,

  so rad. does work on gas

Convective Instability

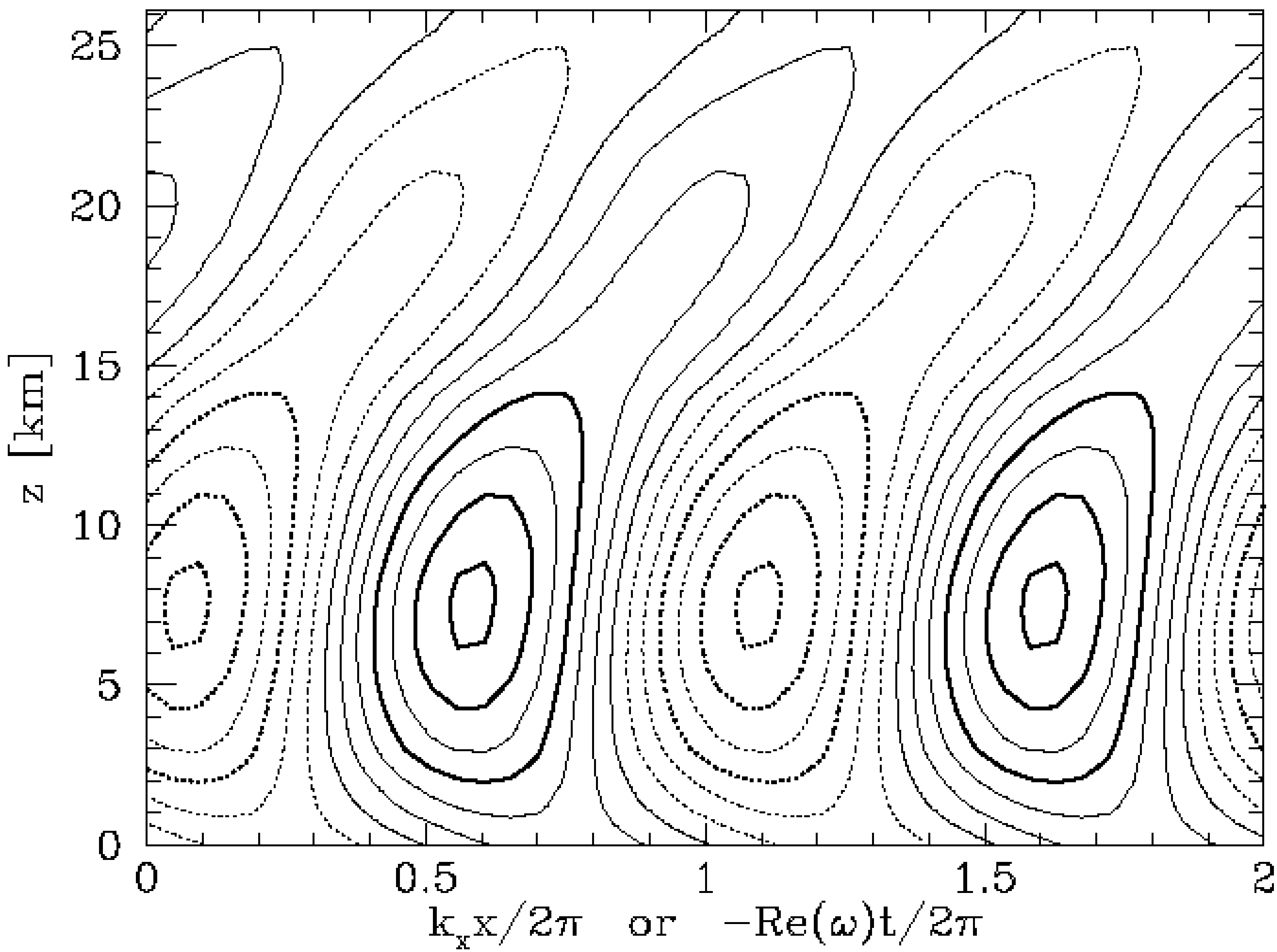
- **Classically expected in energy-generating core**
  - e.g., CNO burning => □~ $T^{10\text{-}20}$ => $dT/dr > dT/dr_{ad}$
- **But envelope also convective where □(r) > 1**
  - e.g., □Pup: $□_{*}$~1/2 => M(r) < M_{*}/2 convective!
- **For high density interior => convection efficient**
  - $L_{conv} > L_{rad}$ □ L_{crit} => $□_{rad}$ (r) < 1: hydrostatic equilibrium
- **Near surface, convection inefficient => super-Eddington**
  - but flow has $\dot{M} \sim L/a^2$
  - implies wind energy $\dot{M} v_{esc}^2 >> L$
  - would"tire" radiation, stagnate outflow
  - suggests highly structured, chaotic surface

Joss, Salpeter Ostriker 1973

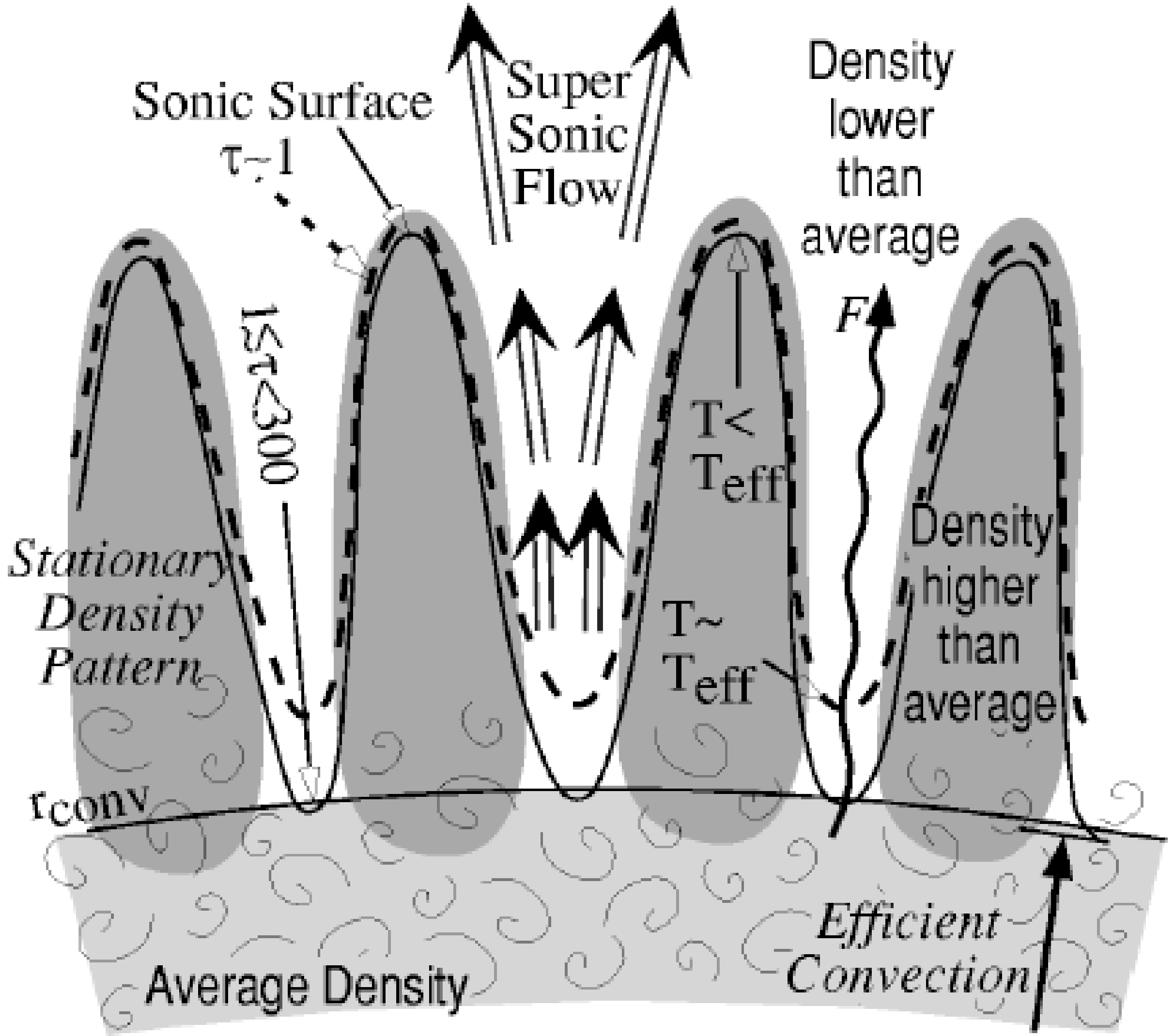
Instability of Thompson Atmosphere

- Spiegel 1968, 1999; Shaviv 2000
- simple $\square_{es}$; no ionization ; $\square_{*} \leq 1$.
- Basic idea: $\mathbf{P_{rad} > P_{gas}}$ => light fluid supports heavy
- Suggests buoyancy of "photon bubbles"
- Detailed stability analyses more complex
  - Key is again lag of rad. diff. vs. dynamical compression
  - Shaviv finds instability at $k_h \sim 2\square/H$

Propagating radiative instability

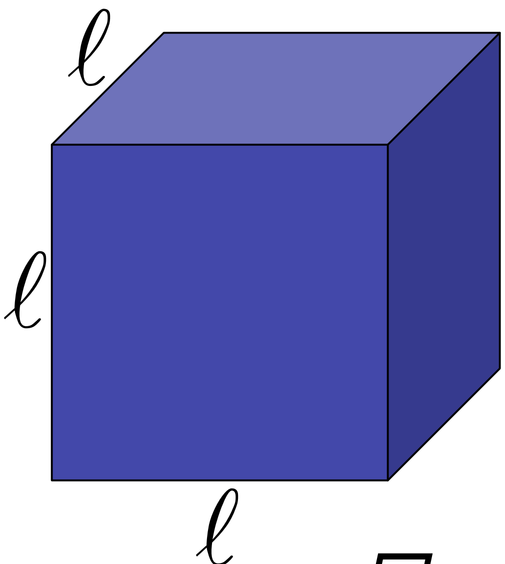


Shaviv 2001



Sonic Surface
τ~1
Super
Sonic
Flow
Density
lower
than
average
1≤τ<300
F
T<
Teff
Stationary
Density
Pattern
Density
higher
than
average
T~
Teff
rconv
Efficient
Convection
Average Density

Effective Opacity for "Cubic Blob"



$$\Sigma_{eff} \approx \ell^2\,[1 - e^{-\tau_b}]$$

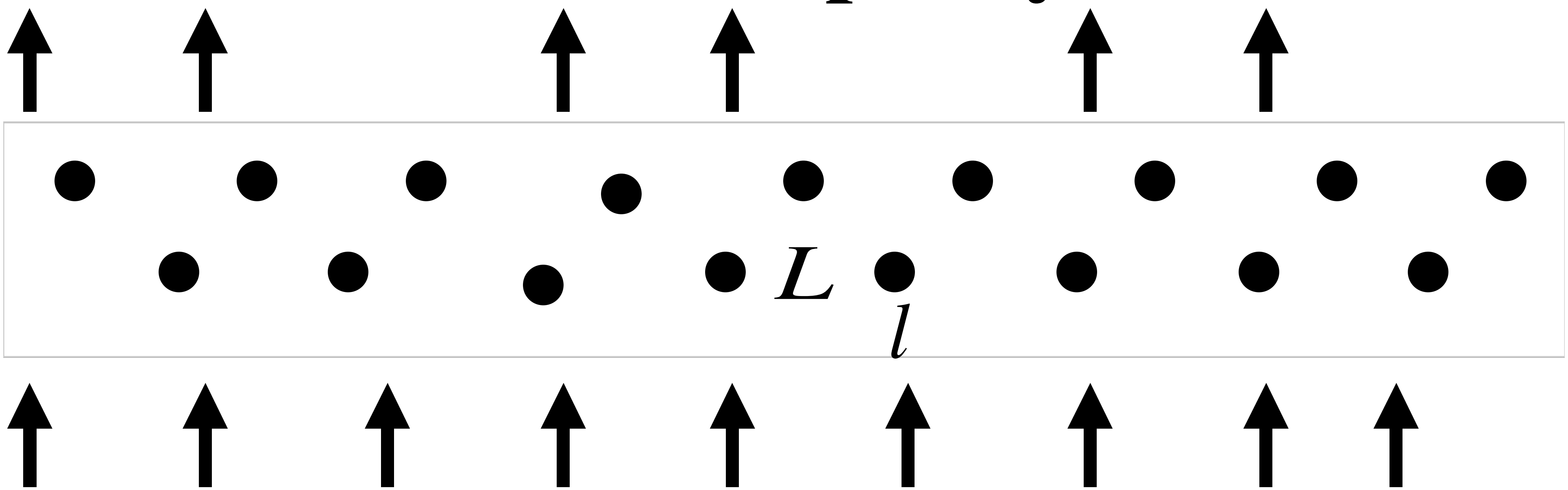
$$\tau_b \equiv \kappa\rho_b \ell$$

$$\kappa_{eff} \equiv \frac{\Sigma_{eff}}{m_b} = \frac{\ell^2\,[1 - e^{-\tau_b}]}{\rho_b \ell^3} = \kappa\,\frac{1 - e^{-\tau_b}}{\tau_b}$$

$$\approx \kappa \qquad ; \tau_b << 1$$

$$\approx \kappa/\tau_b = \ell^2/m_b \quad ; \tau_b >> 1$$

Porous opacity



$$\square_b = \square\square_b l = \square\square\frac{L^3}{l^2} \equiv \frac{\square}{\square_*}$$

$$\square_b >> 1; \quad \square_{eff} = \frac{l^2}{m_b} = \frac{\square}{\square_b} = \square\frac{\square_*}{\square}$$

Super-Eddington Wind

Shaviv 98-02

Driven by continuum opacity in a porous medium when $\square_{*} > 1$

$$\square_{eff}(r) = \square_{*} \frac{\square_{*}}{\square(r)}$$

- Critical density $\square_{c} = \square_{*}\ \square_{*}$

$$\dot{M} = 4\square R_{*}^{2} \square_{*} \square_{*} a$$

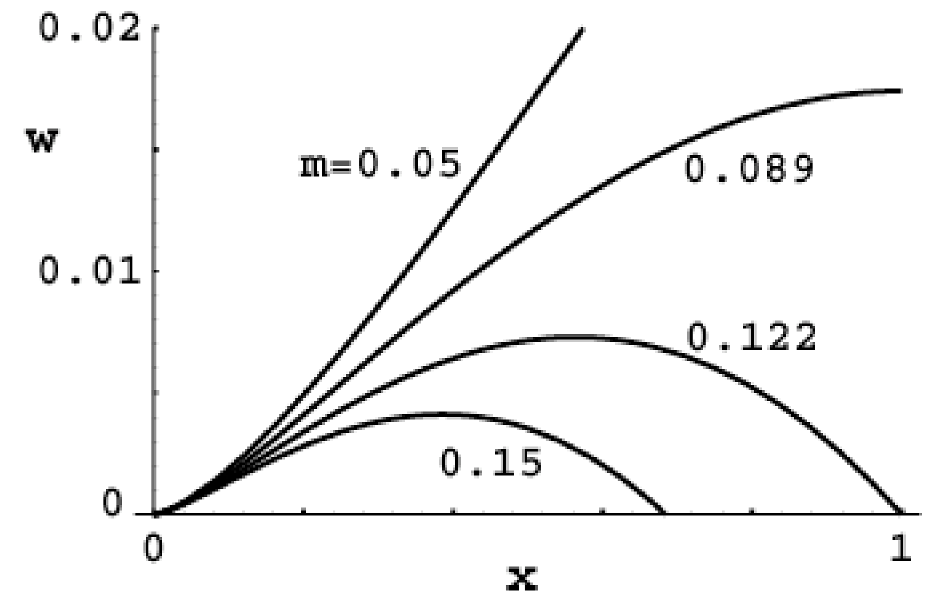
Stagnation of photon-tired outflow

$$v\frac{dv}{dr} \approx -\frac{GM_*(1-\Gamma(r))}{r^2} \quad ; \quad r \geq R_*.$$

$$L = L_* - \dot{M}\left[\frac{v^2}{2} + \frac{GM_*}{R_*} - \frac{GM_*}{r}\right].$$

$$w \equiv v^2 R_*/2GM_* \; ; \quad x \equiv 1 - R_*/r,$$

$$m \equiv \frac{\dot{M}GM_*}{L_* R_*} \approx 10^{-2}\,\frac{\dot{M}_{-4}V_{1000}^2}{L_6},$$



Shaviv & Owocki, in prep.