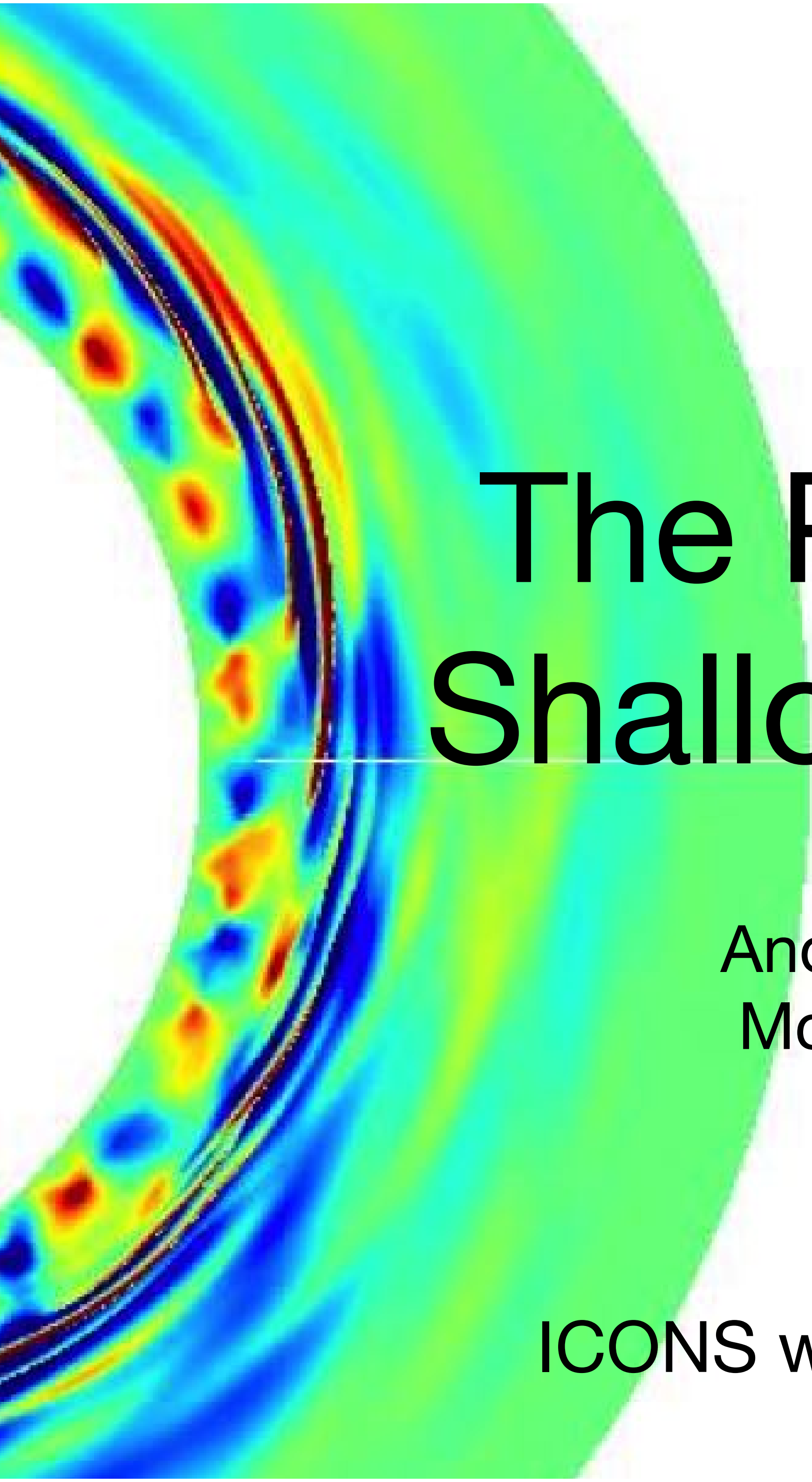

# The Physics of Shallow Heating

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ICONS workshop April 2019

# This talk

**Motivation:** The source of shallow heating is a major unsolved problem: unknown extra parameter in cooling curve fits (often dominates deep heating!); also crucial for nuclear burning

**Outline:**

- **Evidence for shallow heating**: crust cooling, long Type I X-ray bursts

- Different **energy sources** in the outer layers of accreting neutron stars - what shallow heating probably is not, and what it might be

- **Discussion points:** Theory to-do list and what we can look for observationally

# Early-time cooling curves imply a hot outer crust with an inwards heat flux

1. Observed effective temperature tells us the crust temperature

$$T_{\rm crust} \approx 2 \times 10^8\ {\rm K} \left(\frac{T_{\rm eff}}{100\ {\rm eV}}\right)^{1.82}$$

Gudmundsson et al. (1982)

2. Thermal timescale for outer crust

$$\tau \approx 10\ {\rm days} \left(\frac{\rho}{10^{10}\ {\rm g\ cm^{-3}}}\right)$$

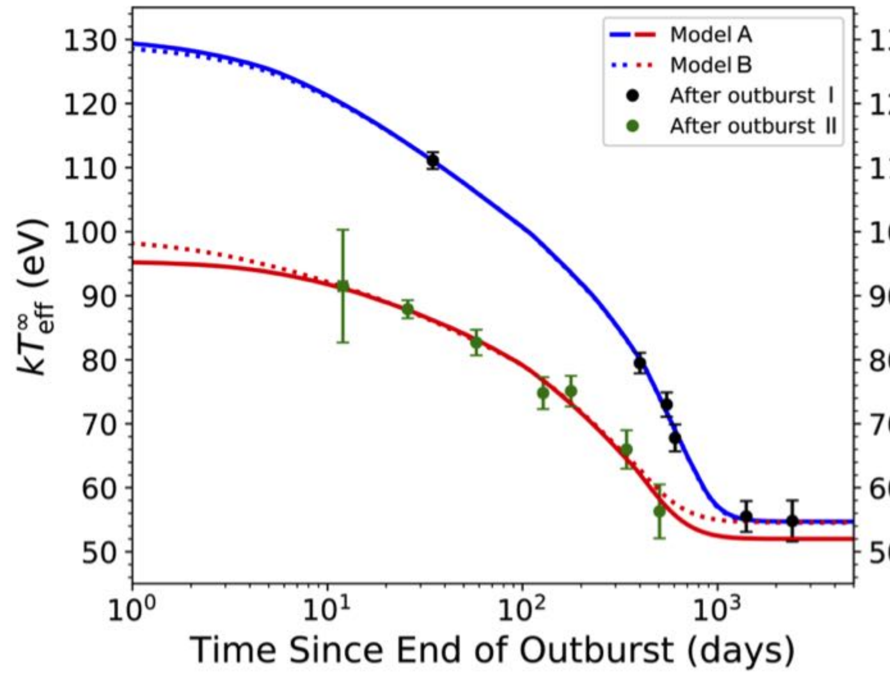
Brown & Cumming (2009 eq. 9); Deibel et al. (2015 eq. 1)

3. The lightcurve slope measures the temperature gradient and therefore heat flux

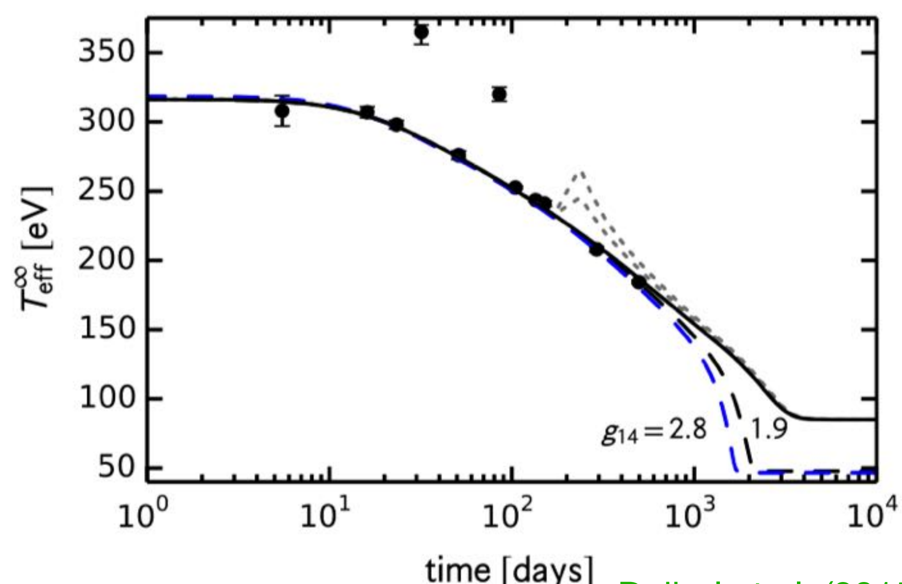
$$\frac{d\ln T_{\rm eff}^\infty}{d\ln t} = \left(\frac{d\ln T_{\rm eff}^\infty}{d\ln T}\right)\left(\frac{d\ln T}{d\ln y}\right)\left(\frac{d\ln y}{d\ln \tau}\right)$$
$$= 0.03\left(\frac{F}{10^{21}\ {\rm erg\ s^{-1}\ cm^{-2}}}\right)$$

Brown & Cumming (2009)

Observed decline in Teff over first few months
=> inwards directed flux of
0.5-1 MeV/nuc @$10^{17}$ g/s ~$10^{22}$ erg/cm$^2$/s




Parikh et al. (2019)




Deibel et al. (2015)

# Deep crustal heating is not enough to explain the properties of long Type I X-ray bursts

- The outwards heat flux from the crust determines ignition conditions for H-poor fuel

  e.g. He accretors: intermediate bursts
  H accretors: superbursts

  Fujimoto et al. (1987), Brown (2004)

- Superburst ignition $y \sim 10^{12}\ \mathrm{g\ cm^{-2}}$, $\rho \sim 10^{8} - 10^{9}\ \mathrm{g\ cm^{-3}}$

  requires $Q_b \approx 0.25\ \frac{\mathrm{MeV}}{\mathrm{nuc}} \left( \frac{\dot{M}}{0.3\dot{M}_{\mathrm{Edd}}} \right)$

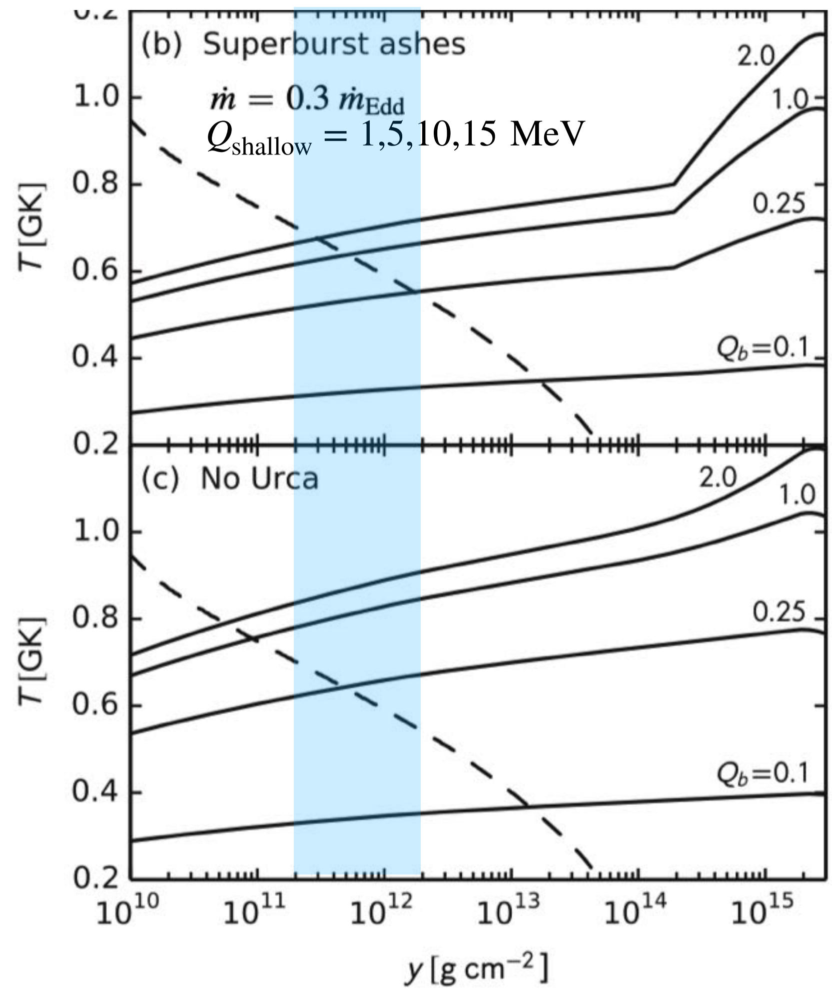
  Cumming et al. (2006)

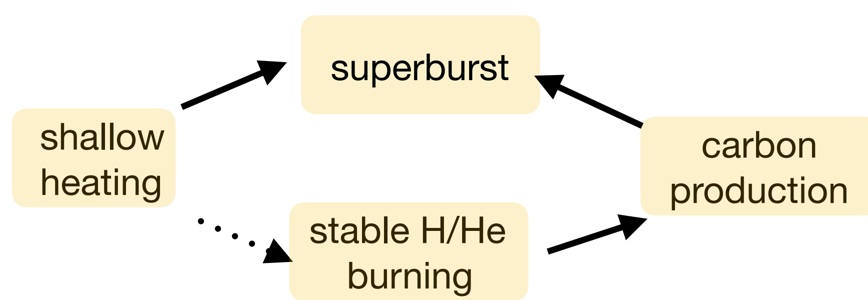
  URCA cooling in the ocean can require even more outwards flux Deibel et al. (2016)

- Superbursters show periods of steady H/He burning which may be required to produce enough $^{12}C$

  in 't Zand et al. (2003); Schatz et al. (2003)

Deibel et al. (2016)



# The shallow heat source has to turn on and off quickly

- The heat flux inferred from X-ray burst or superburst ignition is >> the quiescent flux  Galloway & Cumming (2006)

e.g. KS 1731-260  $L_q < 10^{33}\ \mathrm{erg\ s^{-1}} \Rightarrow Q_b < 0.02\ \mathrm{MeV} @ 10^{17}\ \mathrm{g\ s^{-1}}$

~ 30 times smaller flux in quiescence than when accreting

e.g. SAX J1808 fits to recurrence times of X-ray bursts

$\Rightarrow Q_b \approx 0.3\ \mathrm{MeV} \Rightarrow L \approx 2\times 10^{34}\ \mathrm{erg\ s^{-1}}$

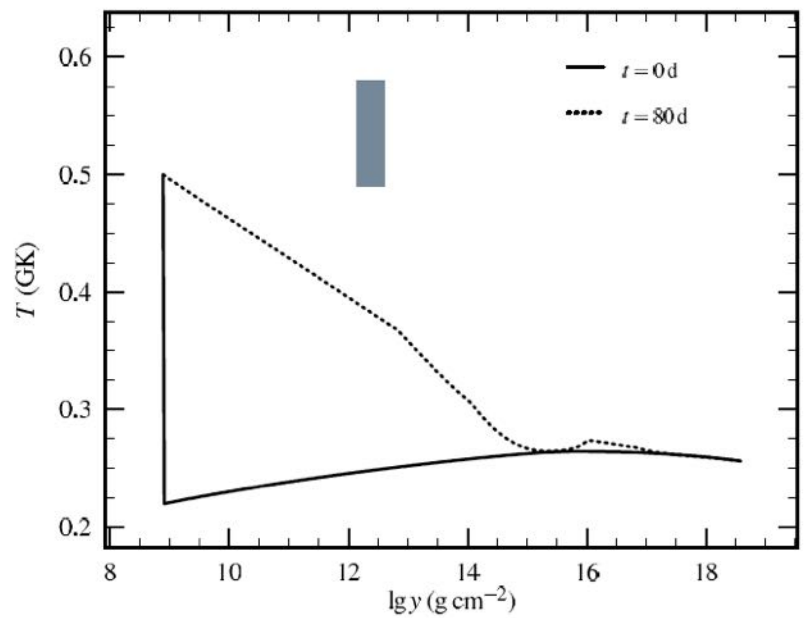
> 1000 times larger than the flux in quiescence!

- Superbursts in transients:
  4U 1608-52 after 55 days of accretion
  Keek et al. (2008)

  EXO 1745-248 before the outburst started

  Altamirano et al. (2012)

- Cooling is observed after short outbursts
  e.g. Terzan 5 11Hz pulsar shows cooling after 11 week outburst  Degenaar et al. (2013)




Keek et al. (2008)

# The shallow heating strength can be similar or different between outbursts

- MAXI J0556-332: extremely strong heating in first outburst, but much smaller in second and third (smaller) outbursts

Parikh et al. (2017)

**Table 2**
Shallow Heating Parameters from NSCool

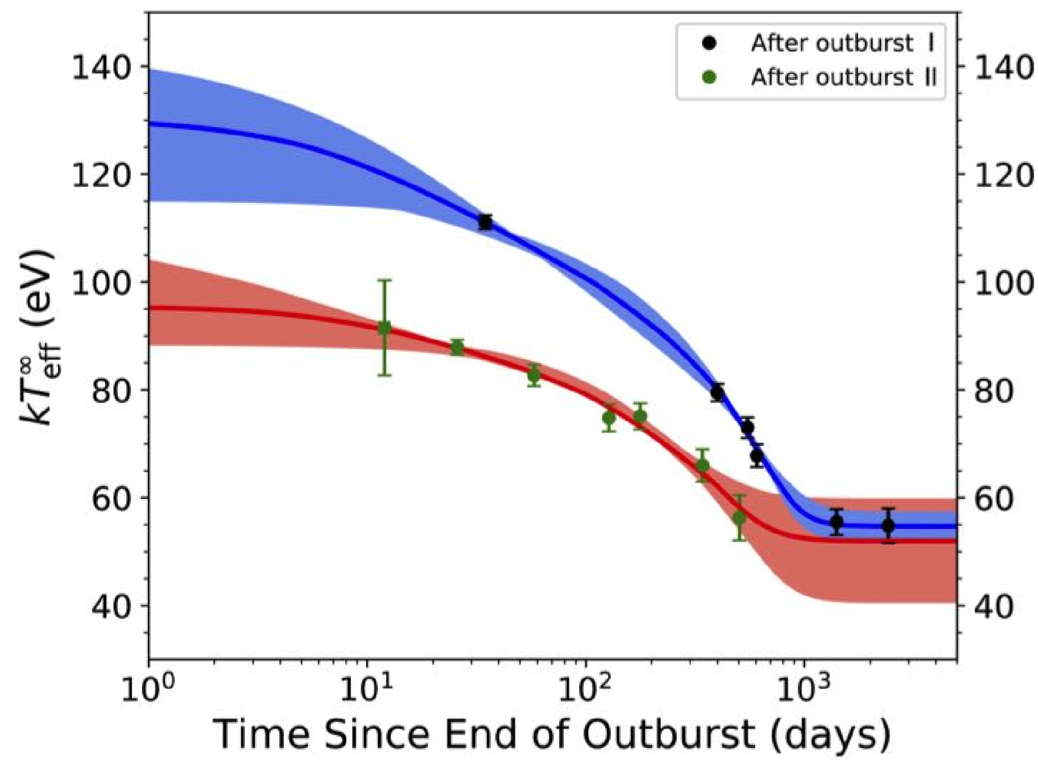
| Outburst | $Q_{sh}$ (MeV nucleon$^{-1}$) | $\rho_{sh}$ ($\times 10^9$ g cm$^{-3}$) |
|---|---|---|
| I | $17.0^{+2.2}_{-0.7}$ | $5.3^{+0.2}_{-0.5}$ |
| II[a] | 0 | ... |
| | $2.2 \pm 0.7$ | $33.5 \pm 0.8$ |
| III | $0.33 \pm 0.03$ | $1.6 \pm 1.3$ |

XTE J1701-462 had very similar outbursts properties to MAXI J0556 outburst I, but much smaller shallow heating!

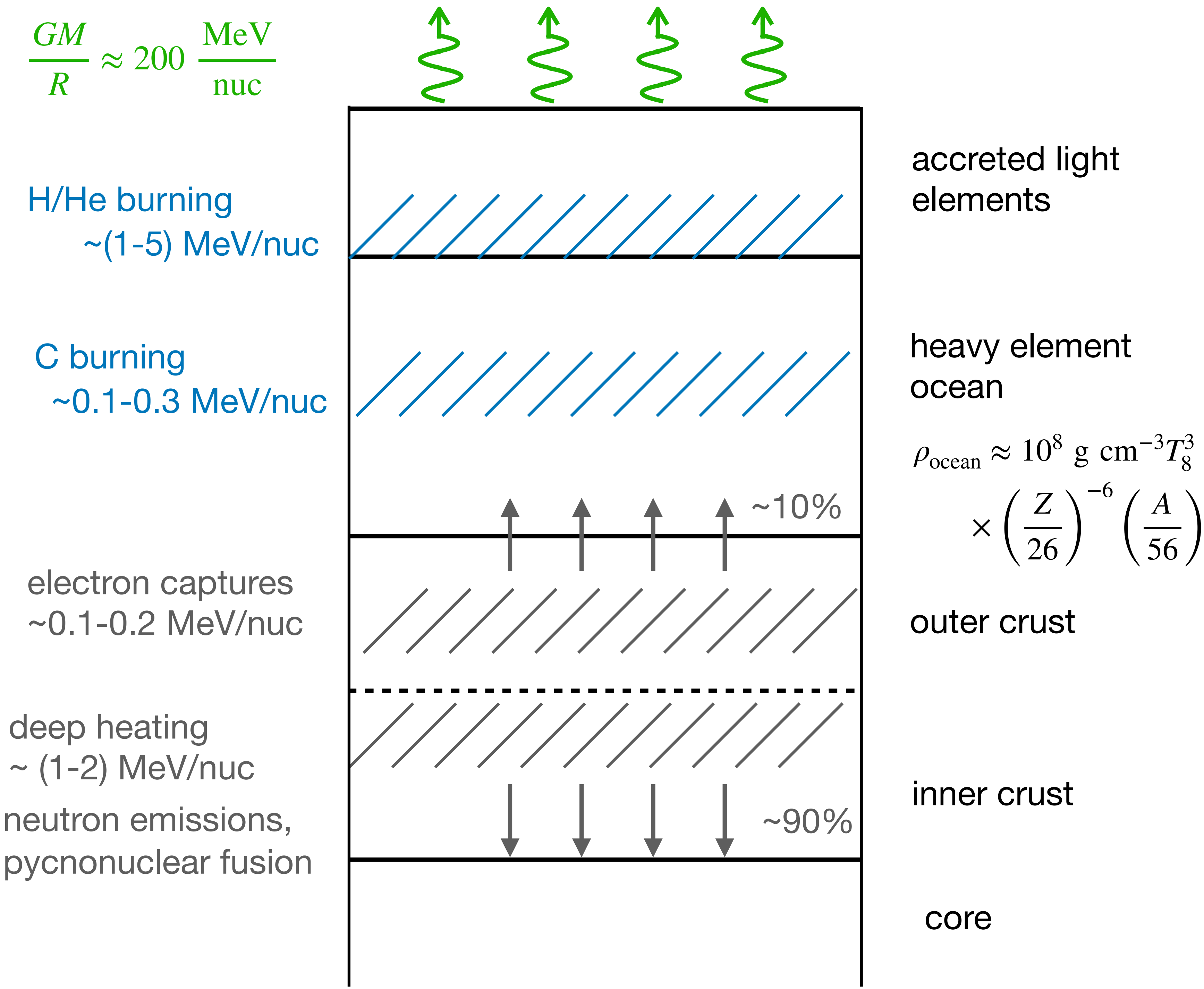
Page & Reddy (2013)

- New outburst of MXB 1659-29: same heating predicts the observed decline!

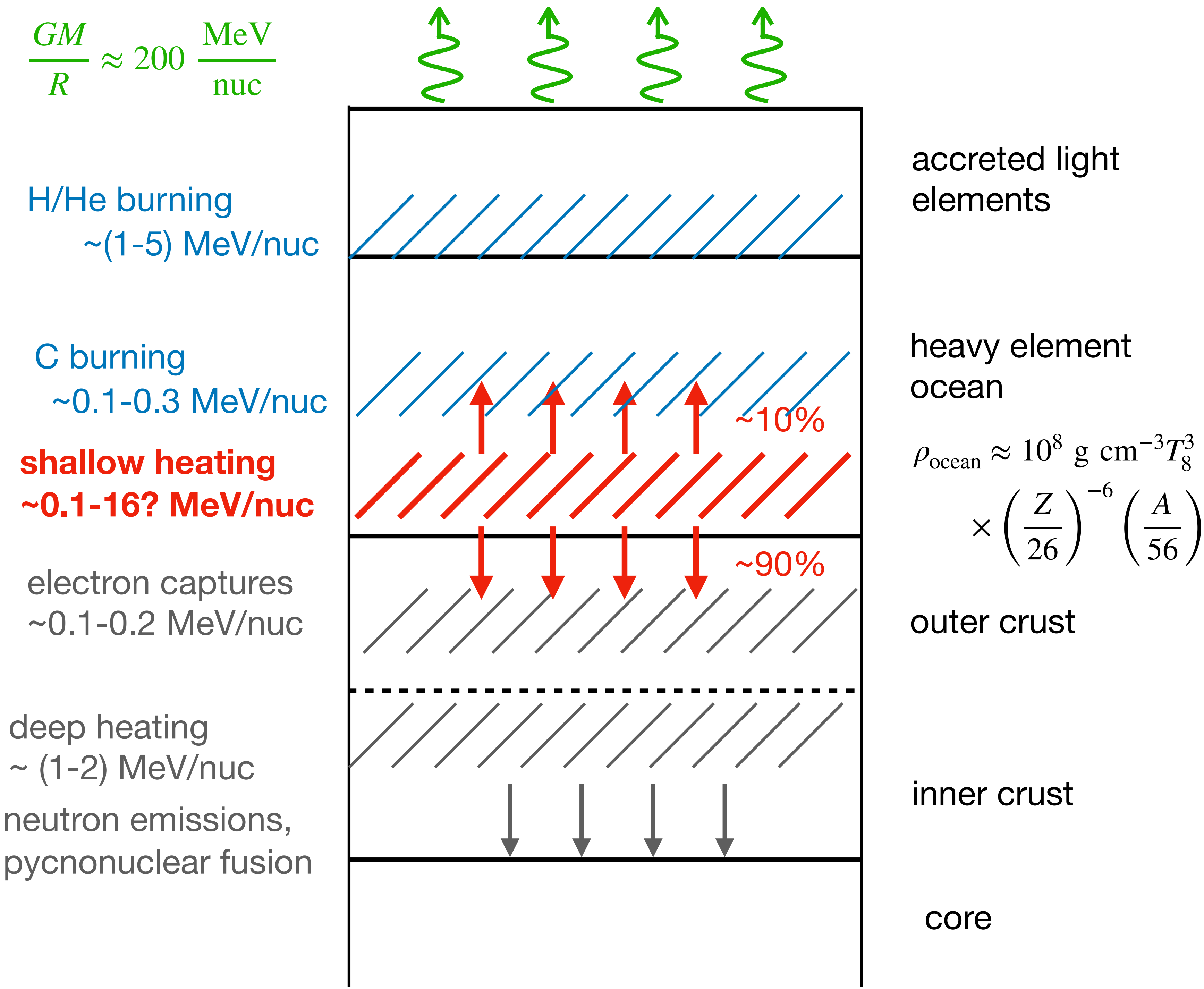
Parikh et al. (2019)



# Energy sources in an accreting neutron star



# Energy sources in an accreting neutron star



# Low density nuclear reactions

See Meisel et al. (2018) for a review

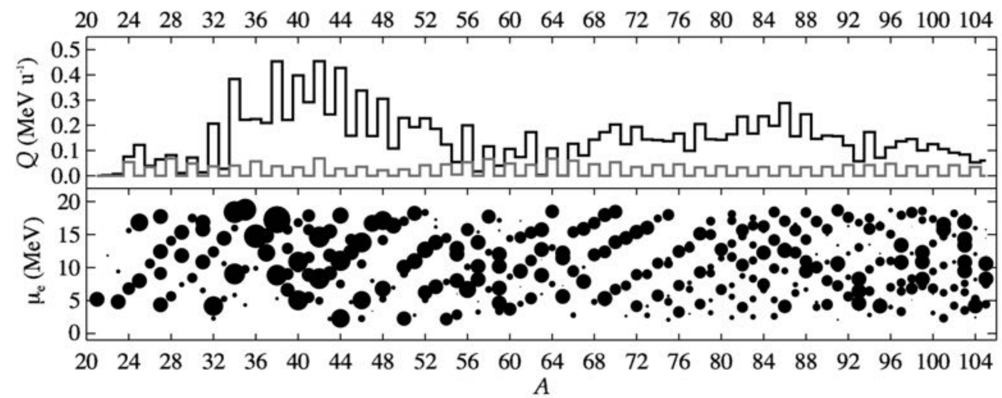
- **Electron captures** in the outer crust

$$Q \lesssim 0.3 - 0.5 \text{ MeV}$$

captures into excited states
=> less energy loss to neutrinos

Gupta et al. (2007)

pairing energy => even-even to odd-odd nucleus gives ~ 22 MeV /$A^{3/2}$



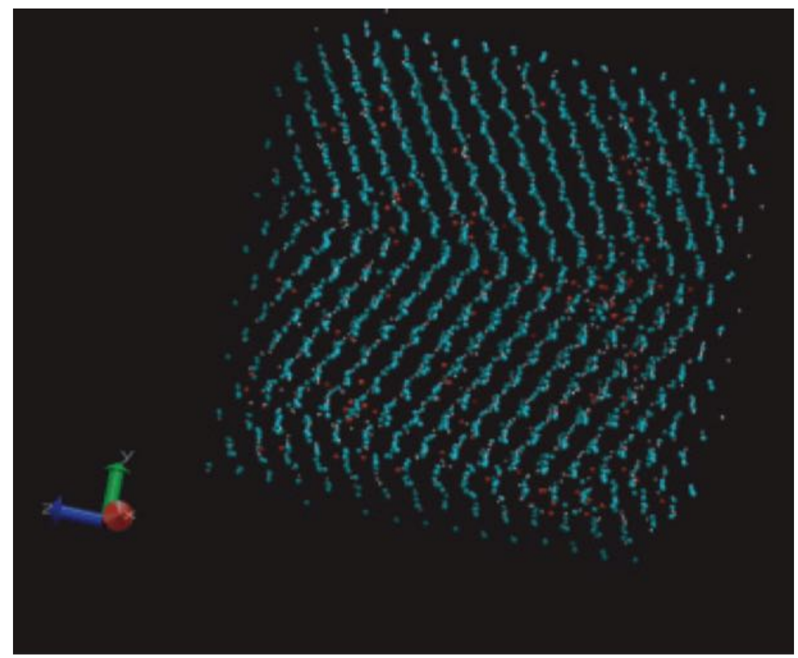

- Low density **fusion** reaction

$^{24}O + ^{24}O$ Q = 0.52 MeV

$$\rho \sim 10^{11} \text{ g cm}^{-3}$$

oxygen ions in interstitial sites

Horowitz et al. (2008)



Horowitz et al. (2008)

- **URCA cooling** reactions associated with odd-A nuclei => neutrino *cooling*

Schatz et al. (2014), Deibel et al. (2015, 2016)

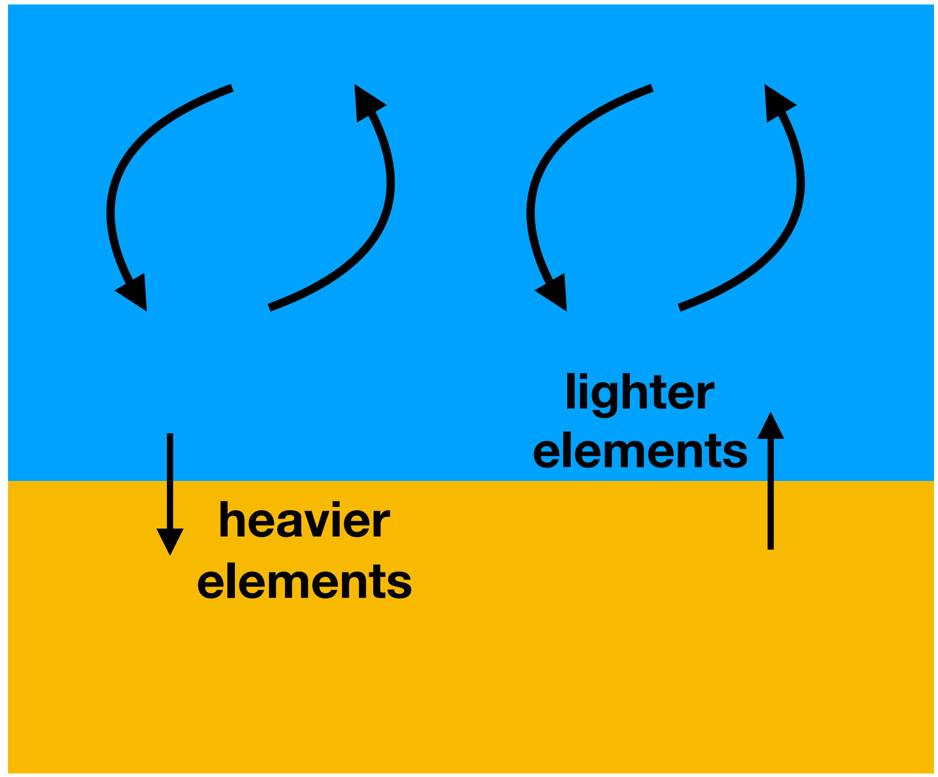
- **neutron transfer** reactions involving odd-A nuclei in outer crust Chugunov (2019)

# Chemical separation changes heat transport in the ocean

**composition flux** $F_X \uparrow$

**heat flux** $F \downarrow$

$$\frac{F}{c_P T} = -\left(\frac{\chi_X}{\chi_T}\right)\frac{F_X}{X}$$




**ocean floor**

$$\rho_{\rm ocean} \approx 10^8 \text{ g cm}^{-3} T_8^3 \times \left(\frac{Z}{26}\right)^{-6}\left(\frac{A}{56}\right)$$

for steady accretion,  the effective heating is

$$\frac{F}{\dot{m}} \approx 0.01 \frac{E_F}{m_p}\frac{\Delta X}{X} \qquad \Rightarrow Q \lesssim 0.2 \text{ MeV}$$

$$E_F = 5.1 \text{ MeV } \rho_9^{1/3} Y_e^{1/3}$$

Medin & Cumming (2011)

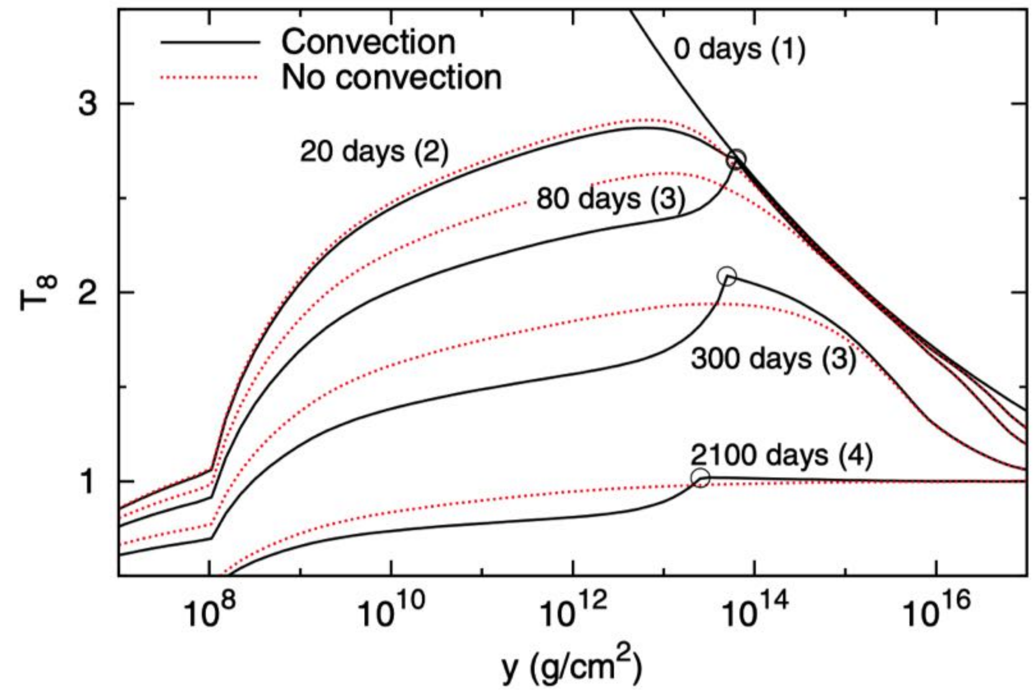
Horowitz et al. (2009), Medin & Cumming (2011, 2014, 2015), Mckinven et al. (2016), Caplan et al. (2018)

# Signature of chemical separation at early times during cooling

- After an outburst, the ocean refreezes as the star cools down

$$F_{\rm conv} \approx -10^{25}\,{\rm erg\,cm^{-2}s^{-1}}\,y_{14}^{5/4}\left(\frac{\partial t/\partial \ln X}{10\,{\rm days}}\right)^{-1}$$

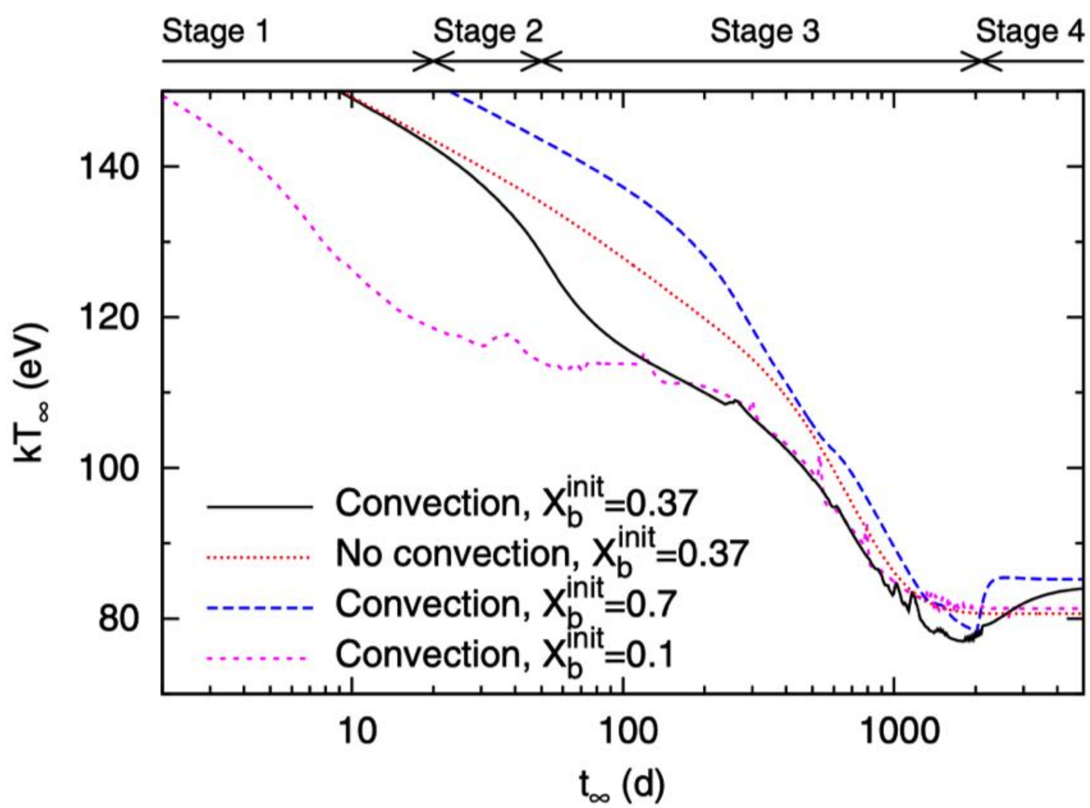
Medin & Cumming (2014)




- Inwards heat flux acts as "latent heat"; ocean cools rapidly; large portions of the ocean can freeze and unfreeze; eventually returns to the "standard" cooling curve

- Rapid redistribution of light elements during ocean freezing: could affect the $T_{\rm eff}$-$T_{\rm b}$ relation

- Potentially complicates interpretation of early time data (e.g. to measure shallow heating)



# Shear heating

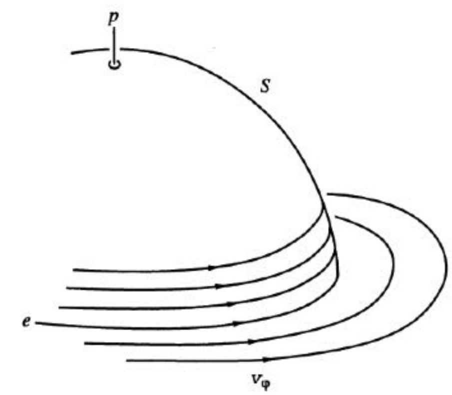
- How does matter accreting through a disk join the star and spread over the stellar surface?

- Kinetic energy of incoming matter

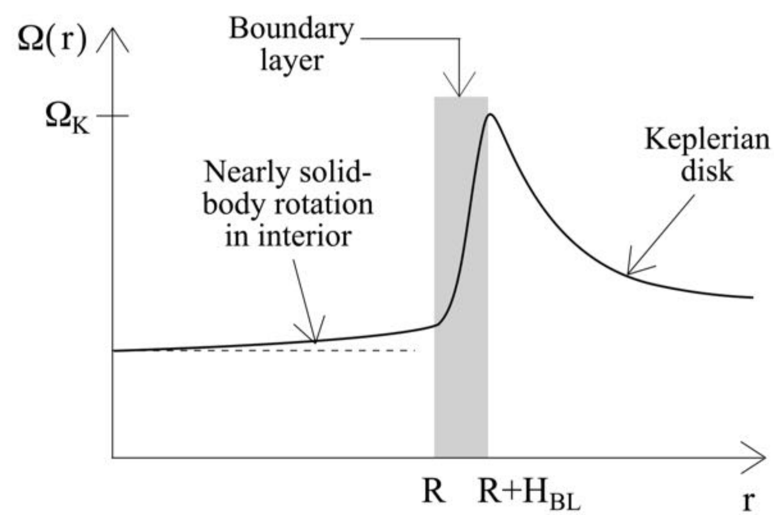
$$\frac{1}{2}v_K^2 = \frac{GM}{2R} \approx 100 \ \frac{\text{MeV}}{\text{nuc}}$$

1-10% of this would be enough to explain the shallow heating we see

- Studies of how matter spreads suggest it happens at low density
- Wave transport could perhaps deposit energy deep




Inogamov & Sunyaev (1999)



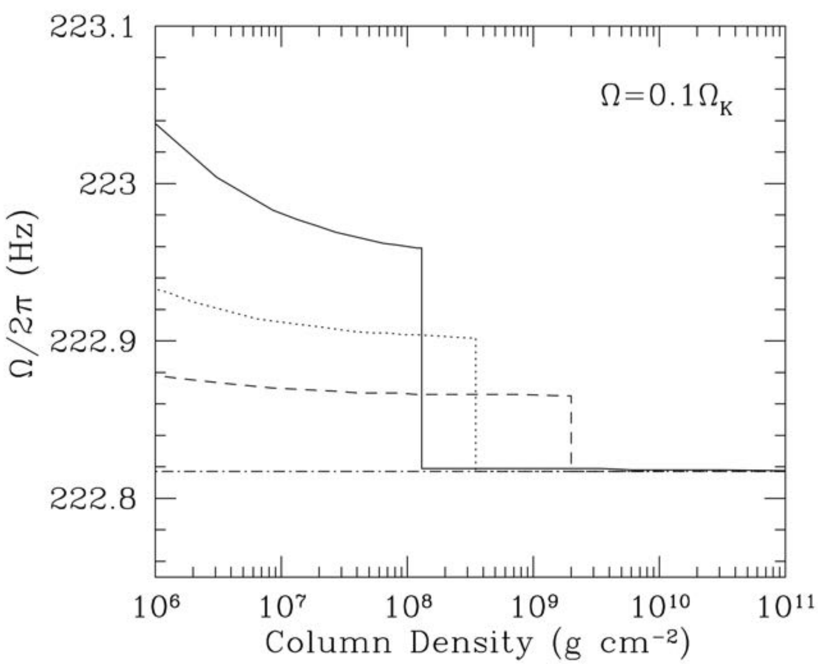

Piro & Bildsten (2007)

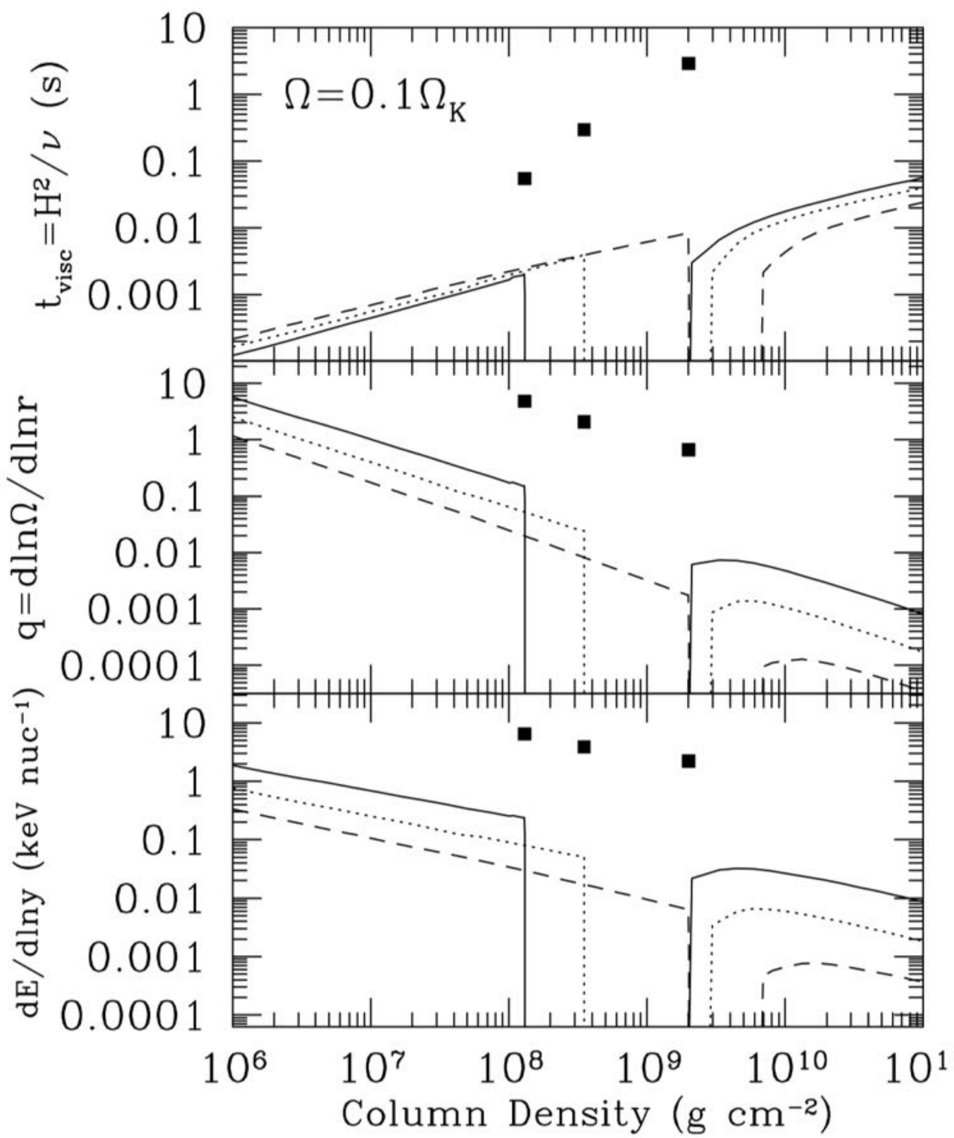
# How much shear is needed to carry the angular momentum into the star

- Angular momentum transport by hydrodynamic instabilities + Taylor-Spruit dynamo prescription

Piro & Bildsten (2007),
see also Fujimoto (1993)

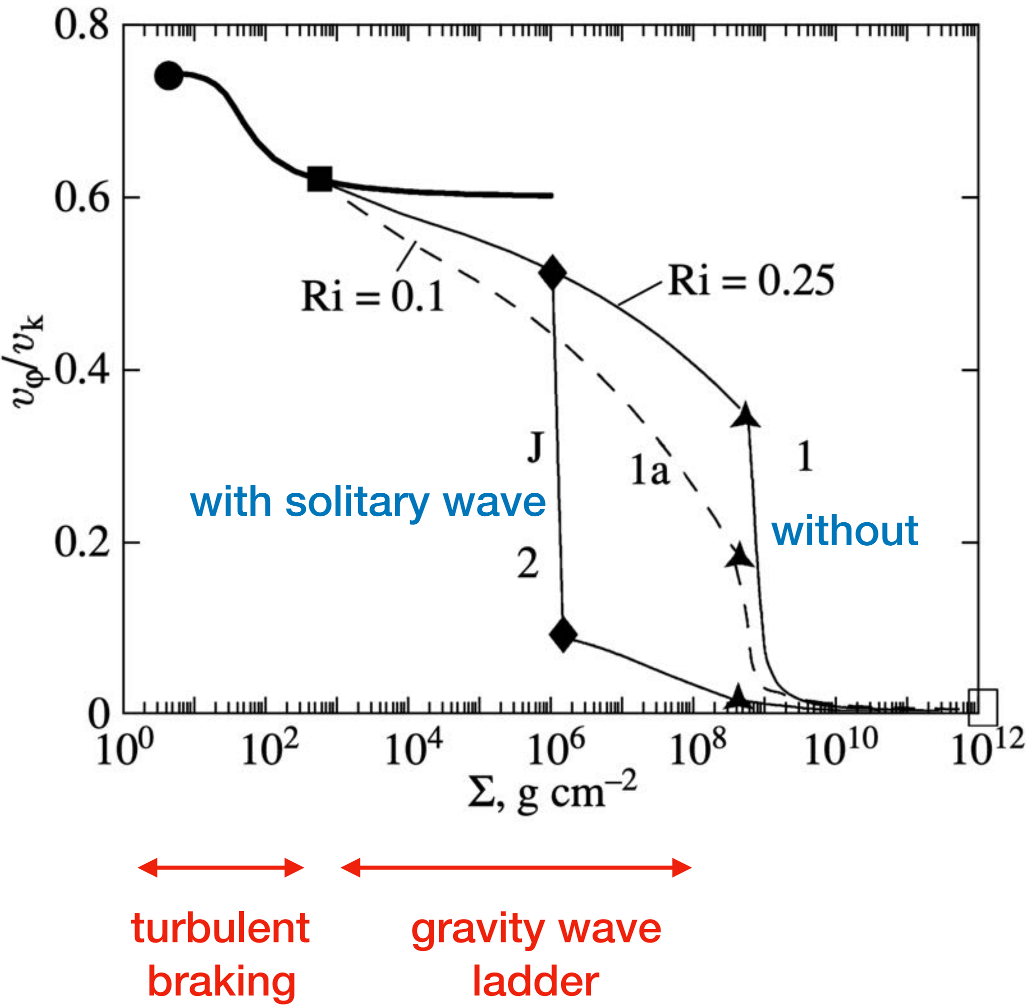
Accumulating layer is close to rigid rotaiton; very little viscous heating

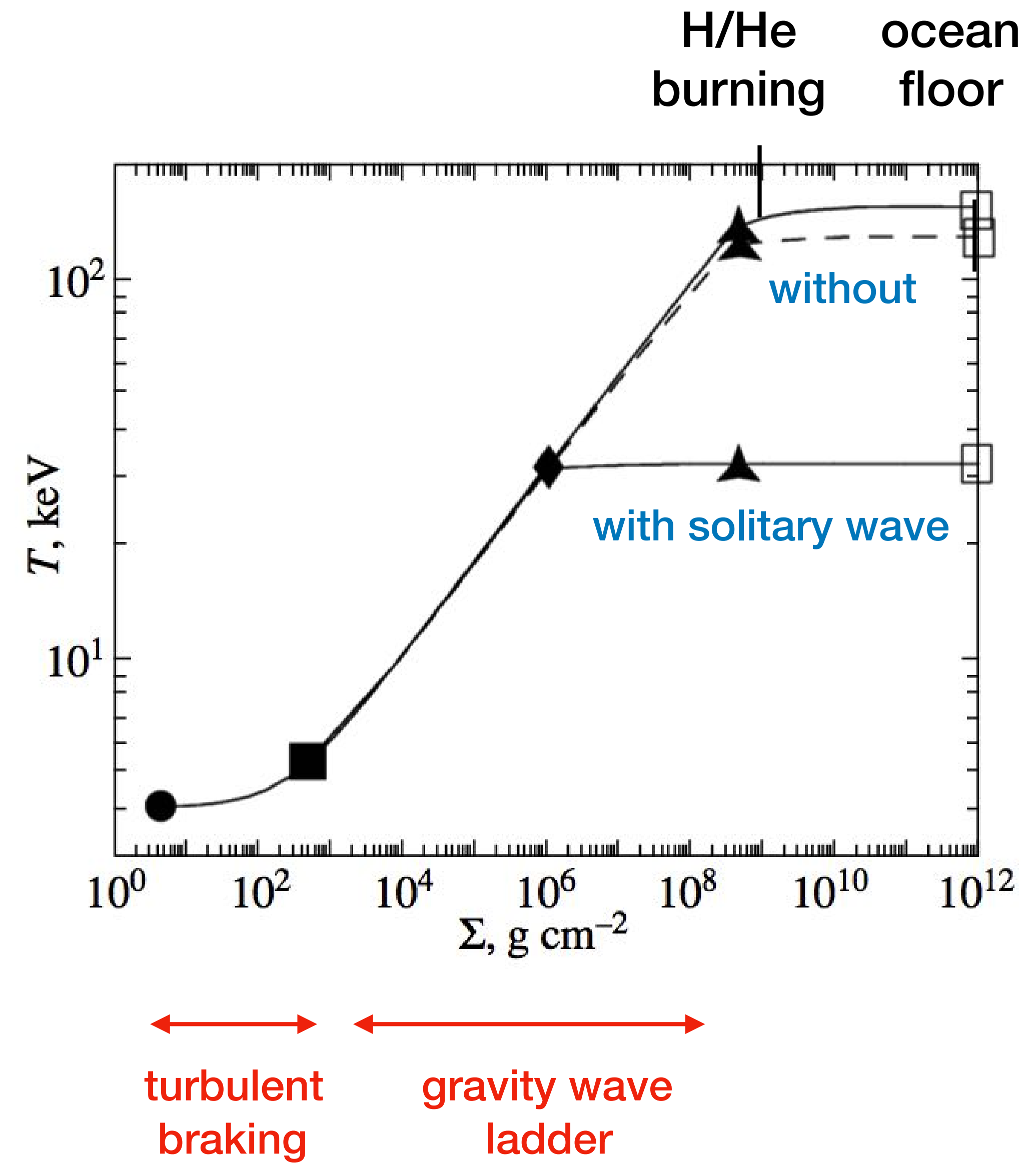


# Spread of matter over a neutron star surface

## Inogamov & Sunyaev (2010)



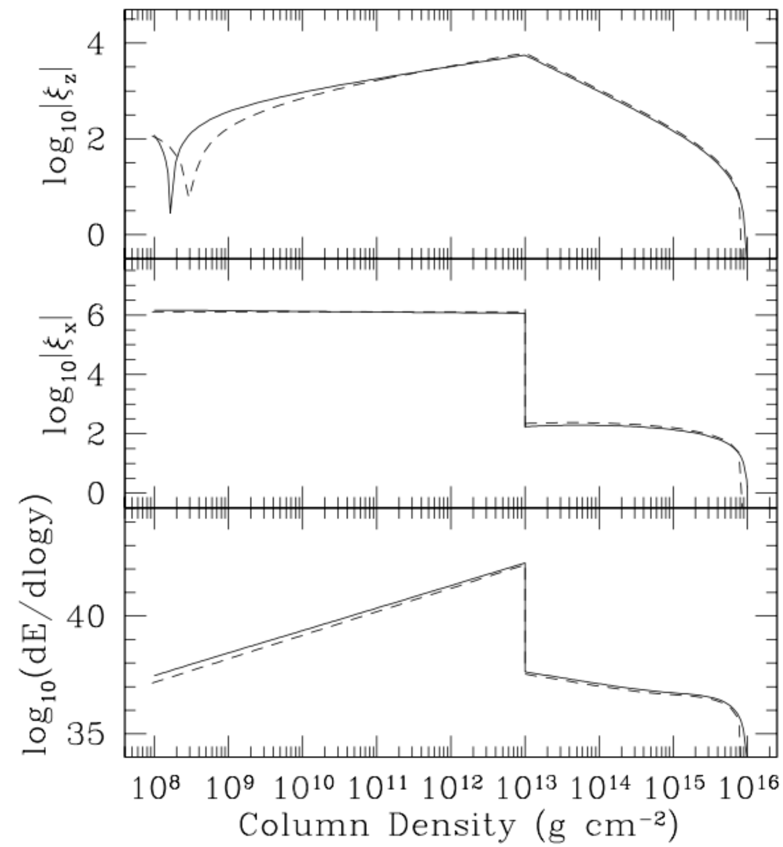




- Argued that the entire ocean can be spun up by gravity wave transport of angular momentum
- Leads to strong (10's of MeV) heating at depth; could be truncated by excitation of large solitary gravity wave

# Heating associated with the ocean-crust interface mode

- Crust-ocean interface mode involves horizontal motions of the entire ocean
- Boundary layer width: $\delta \sim \left(\frac{\nu}{\omega}\right)^{1/2}$

$$\frac{\delta}{H} = \left(\frac{\nu}{\omega H^2}\right)^{1/2} = \left(\frac{1}{\omega t_{\rm visc}}\right)^{1/2}$$
$$= 2.0 \times 10^{-6} \left(\frac{\omega/2\pi}{250\ {\rm Hz}}\right)^{-1/2} \left(\frac{A}{56}\right)^{-1/2} \rho_9^{-1/3}$$



Piro & Bildsten (2005)

- Viscous dissipation rate

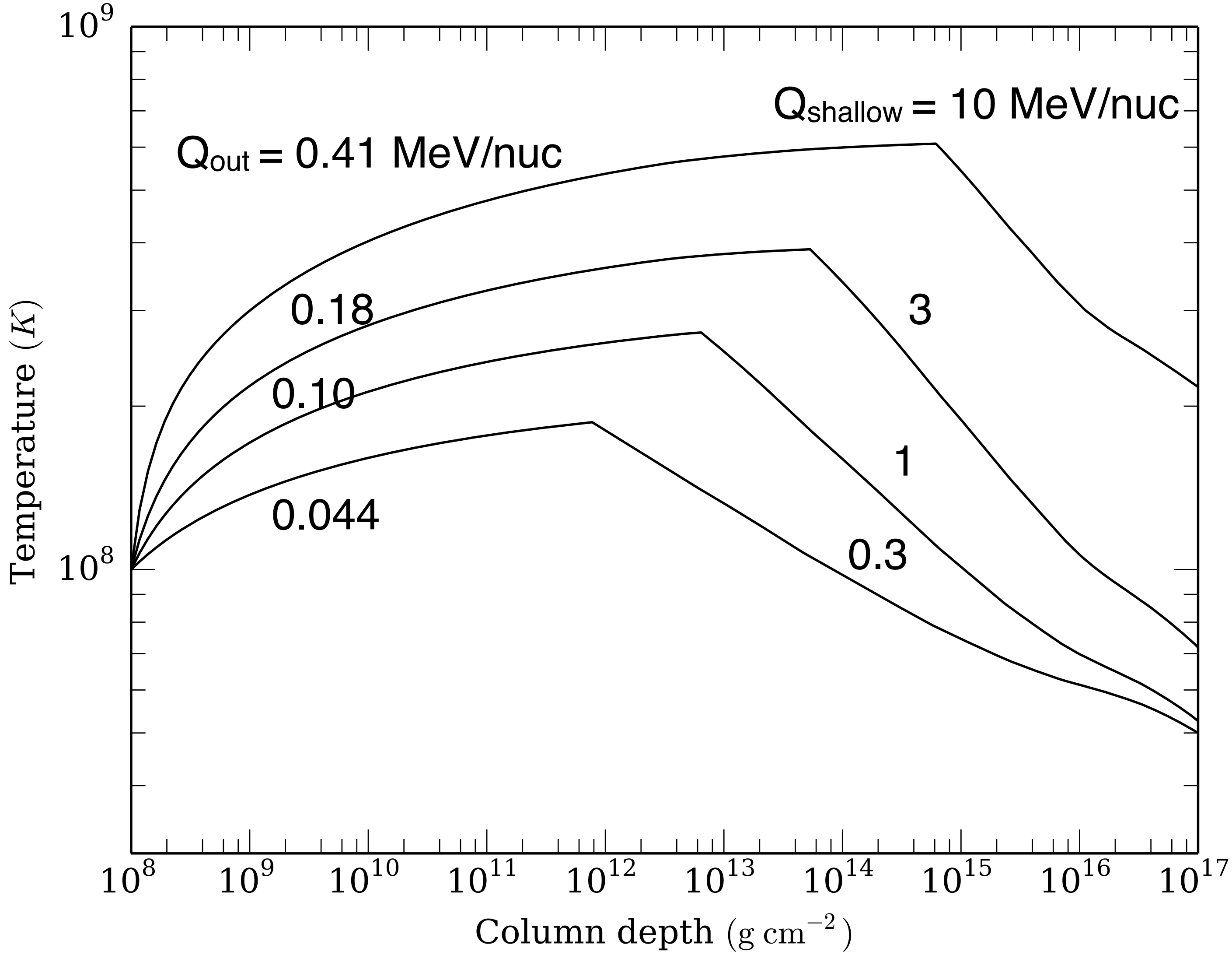
$$\eta \left(\frac{dU}{dz}\right)^2 \approx \eta \left(\frac{U}{\delta}\right)^2 \approx \rho\omega U^2$$

=> $F = 1.8 \times 10^{22}\ {\rm erg\ cm^{-2}\ s^{-1}} \left(\frac{\alpha}{10^{-3}}\right)^2 \left(\frac{\omega/2\pi}{250\ {\rm Hz}}\right)^{5/2} \left(\frac{56}{A}\right)^{1/2}$

or ~ 2 MeV/nucleon at an accretion rate of 0.1 Eddington

Deibel & Cumming, in prep

# Thermal profiles with shallow heating at the ocean floor

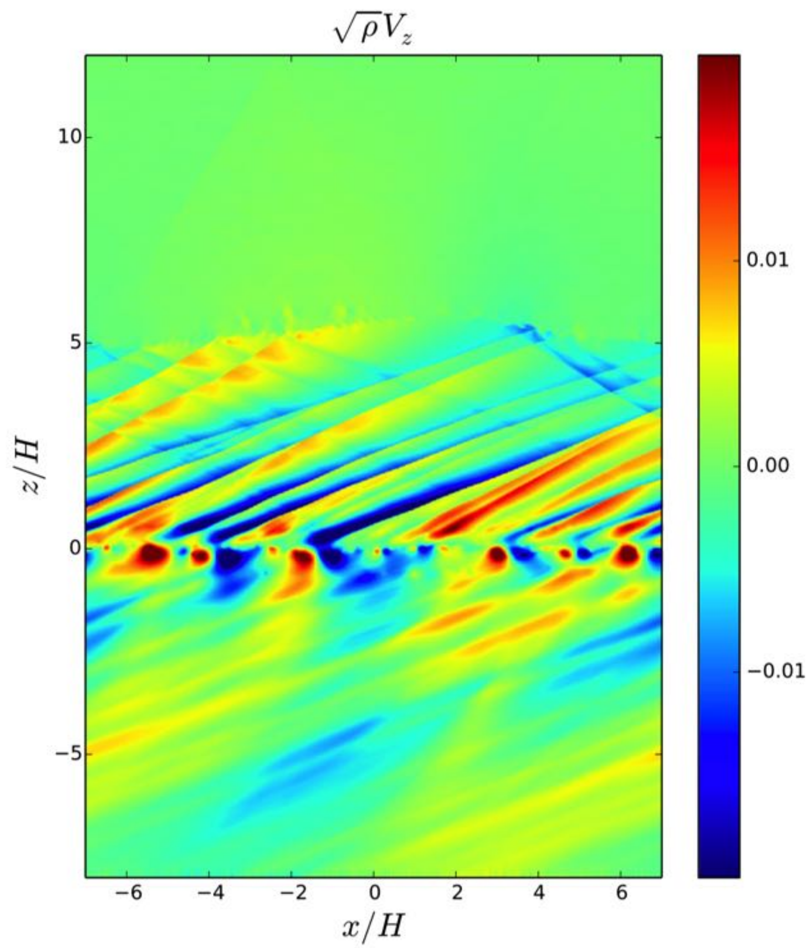



Increased shallow heating => deeper ocean => larger fraction of the heating goes inwards

Deibel & Cumming, in prep

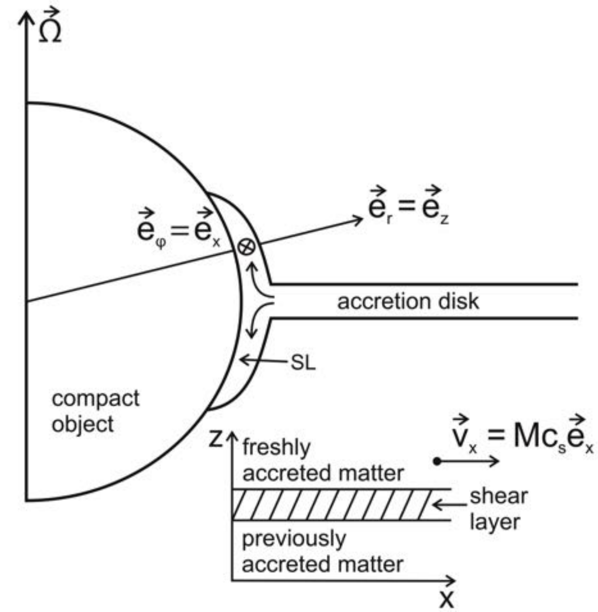
# Acoustic waves are excited in the accretion disk boundary layer

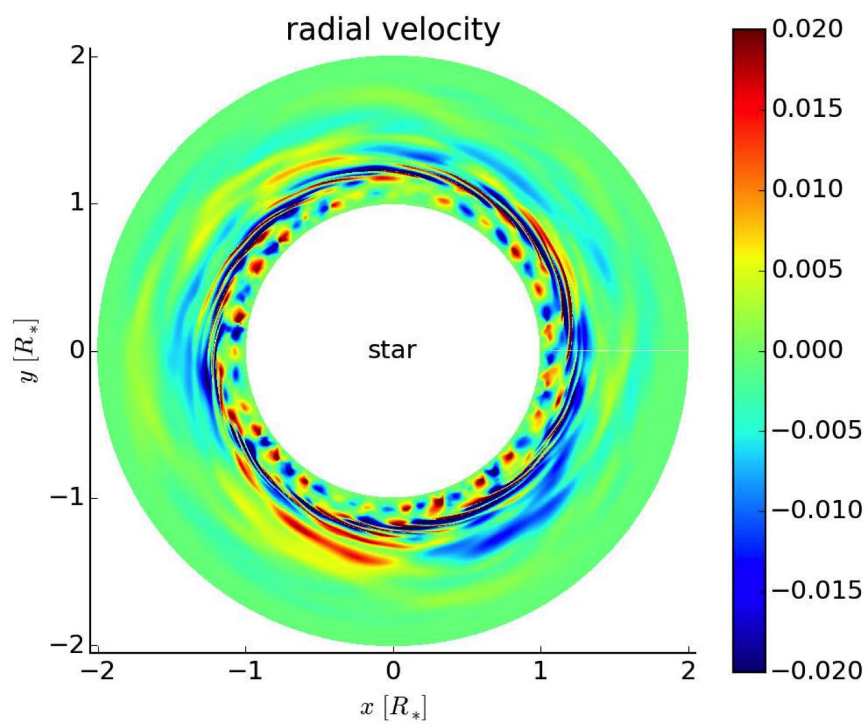
- Sonic instability excites acoustic waves in the boundary layer
- Play a key role in angular momentum transport in the boundary layer




Philippov & Rafikov (2016)

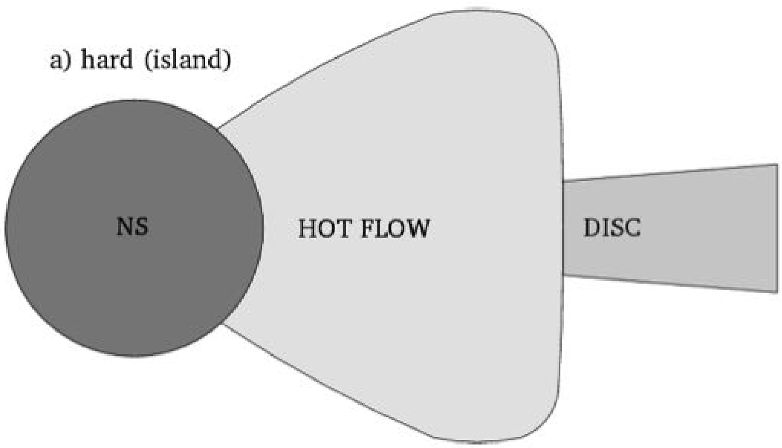
see also Belyaev et al. (2012, 2013)

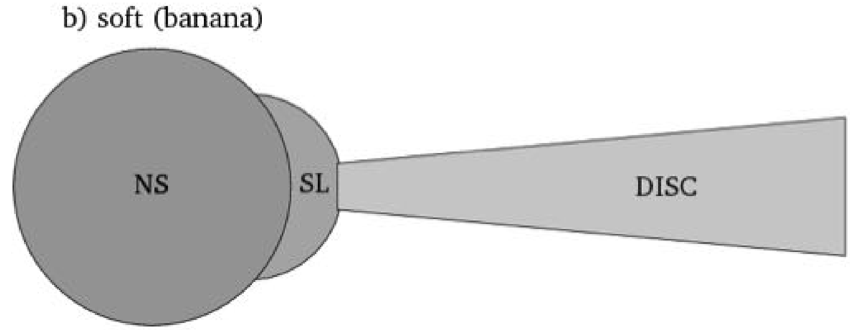



Hertfelder & Kley (2015)

# Nuclear Burning Phenomenology of Accreting Neutron Stars




regular bursting (mixed H/He, pure He ignition, pure He bursts)

significant color correction evolution during bursts

stable burning; irregular bursting

superbursts

mHz QPOs

burst oscillations

color correction almost constant during burst

**What role does shallow heating (and/or geometry) play in this?**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IS NOW IN THE SHALLOWS
THE
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# Shallow heating: Points for discussion

- **Plenty of energy in the shear between the star and accreted material.** We are used to thinking of the accretion energy being immediately radiated away; perhaps a small fraction (1-10%) is transported inwards.
- **Wave transport** could perhaps deposit energy deep; details (and predictability) not clear
- Timing: could respond quickly to changes in accretion rate; could be a lag
- Is disk accretion required? If so, would expect an association with the soft state (banana state)? Cooling is seen in the Terzan 5 11Hz X-ray pulsar.
- Similar outbursts but different shallow heating: perhaps the NS spin is different between sources?
- **Important to think about the connection with nuclear burning.** Examples: (1) with shallow heating as large as MAXI, H/He burning should be completely stable. (2) Shallow heating could help with carbon production (by stabilising H/He over part of the star) but at the same time has to allow carbon to burn unstably.