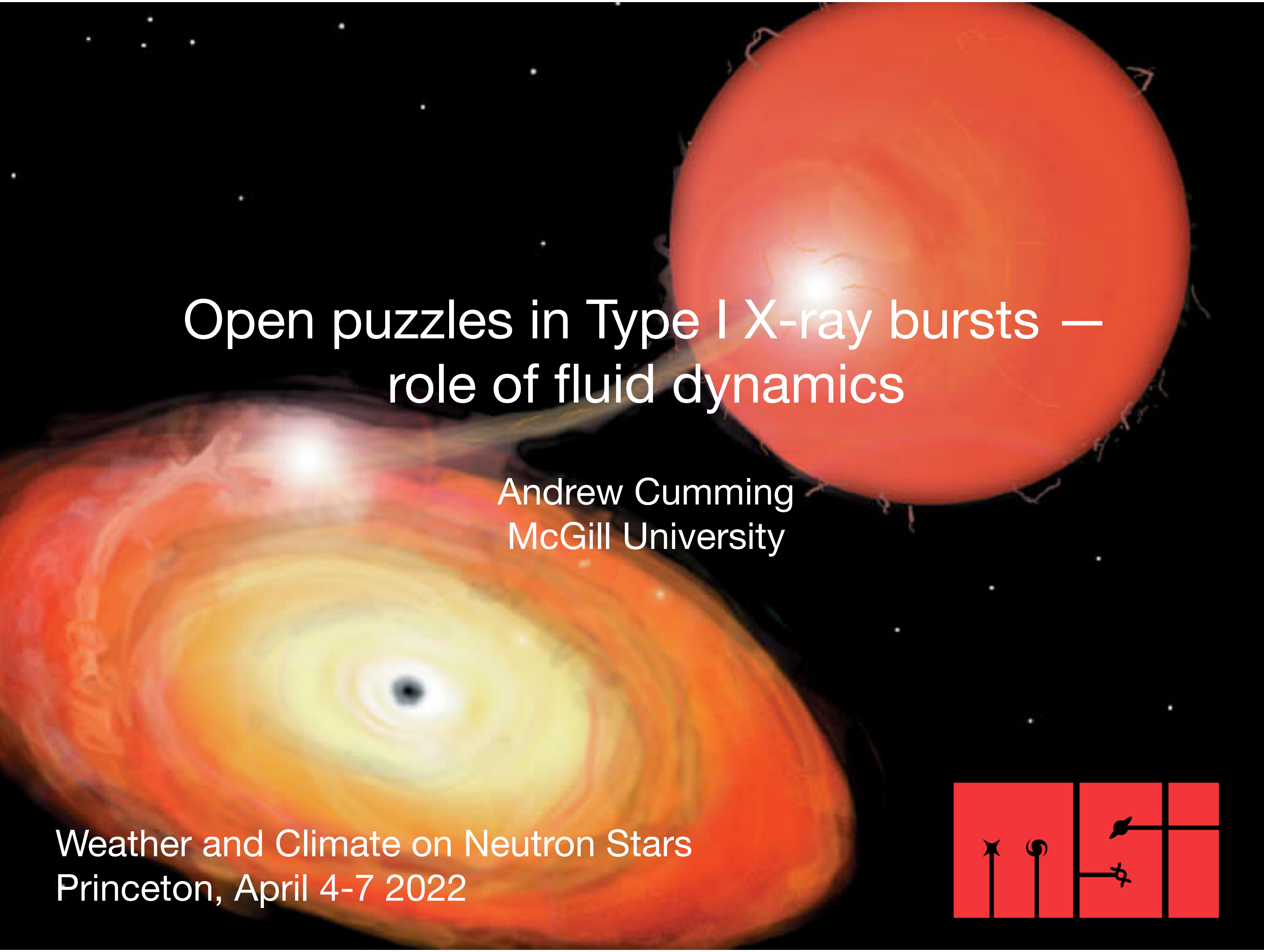

Open puzzles in Type I X-ray bursts — role of fluid dynamics

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McGill University

Weather and Climate on Neutron Stars
Princeton, April 4-7 2022

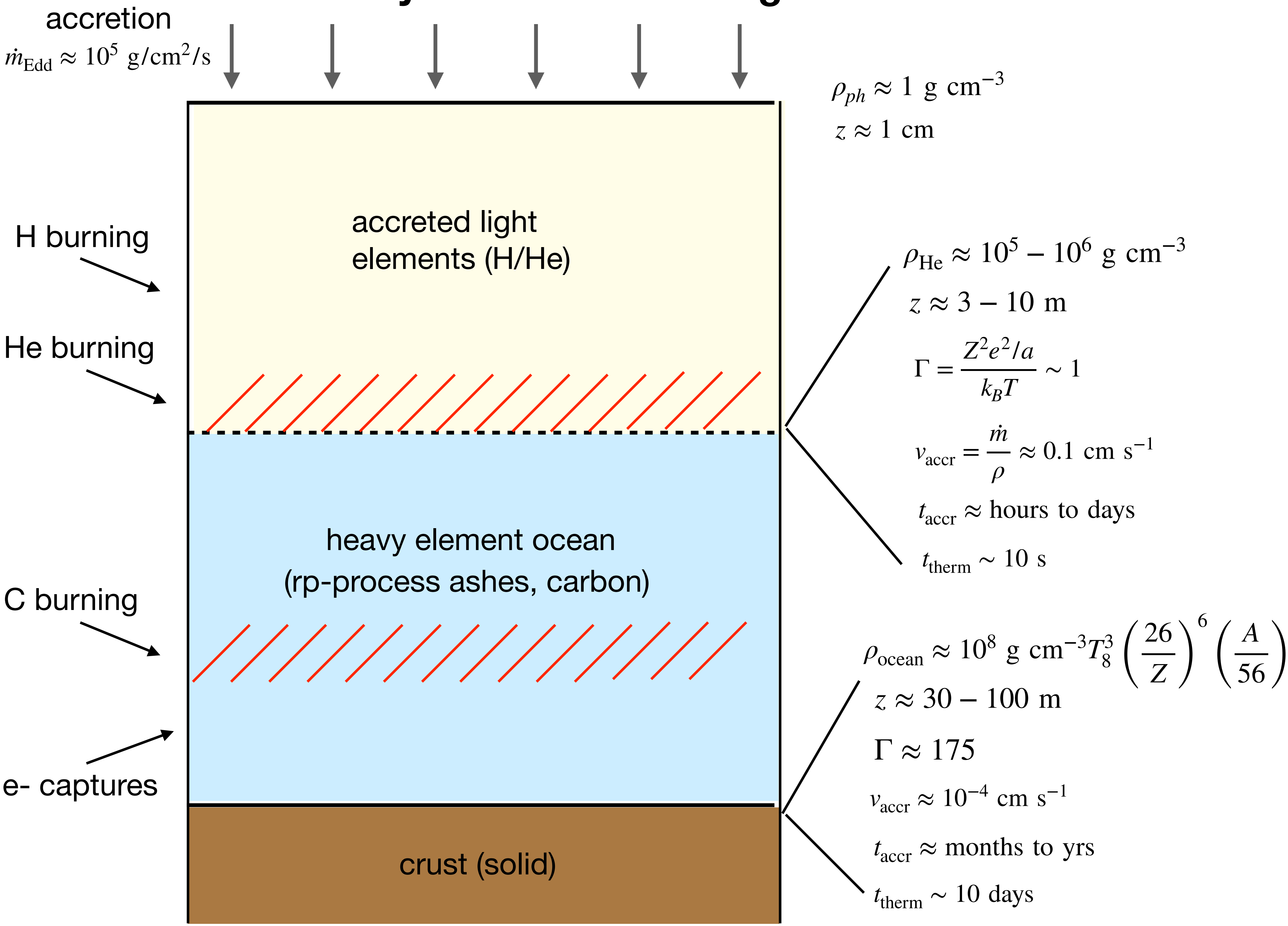
This talk

- Usually when we think of “weather and climate” in accreting neutron stars, we think of burst oscillations (see Anna Watts’ talk)
- In this talk, discuss some other examples where fluid dynamics plays a role in the evolution of the outer layers of accreting neutron stars, and in particular likely has implications for observations

- “Weather” also plays a role in the accumulation phases between bursts, and on longer timescales in the ocean

Four examples:
1. The role of convection in bursts
2. Compositionally-driven convection in NS oceans
3. Shallow heating
4. Spreading of accreted material

Outer layers of an accreting neutron star



accretion

$\dot{m}_{\rm Edd} \approx 10^5$ g/cm^2/s

H burning

He burning

C burning

e- captures

accreted light elements (H/He)

heavy element ocean (rp-process ashes, carbon)

crust (solid)

$\rho_{ph} \approx 1$ g cm^{-3}

$z \approx 1$ cm

$\rho_{\rm He} \approx 10^5 - 10^6$ g cm^{-3}

$z \approx 3 - 10$ m

$$\Gamma = \frac{Z^2e^2/a}{k_BT} \sim 1$$

$$v_{\rm accr} = \frac{\dot{m}}{\rho} \approx 0.1 \text{ cm s}^{-1}$$

$t_{\rm accr} \approx$ hours to days

$t_{\rm therm} \sim 10$ s

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

$z \approx 30 - 100$ m

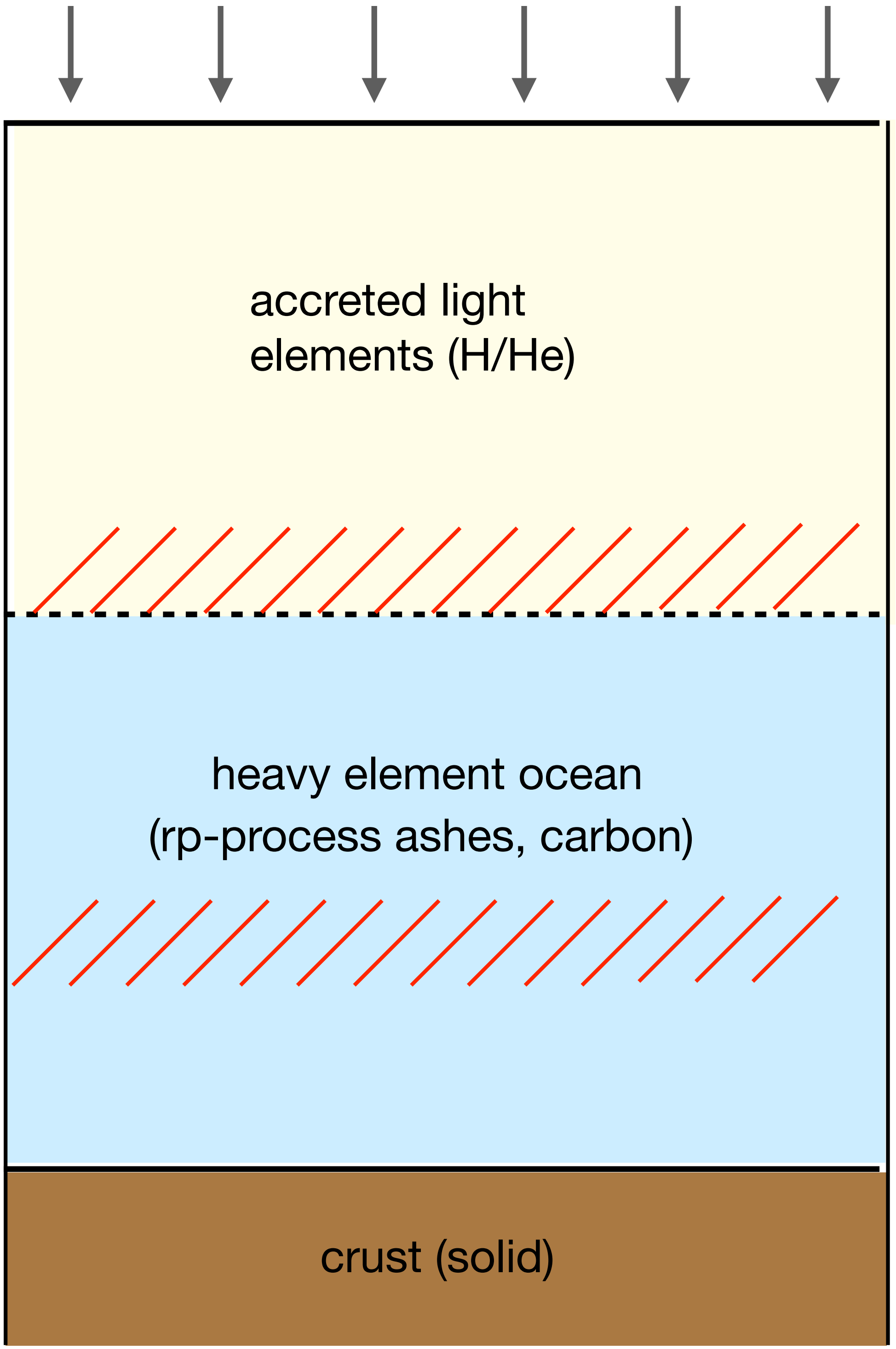
$\Gamma \approx 175$

$v_{\rm accr} \approx 10^{-4}$ cm s^{-1}

$t_{\rm accr} \approx$ months to yrs

$t_{\rm therm} \sim 10$ days

Outer layers of an accreting neutron star



Opportunities for dynamics even in the accumulation phases between bursts

- Incoming material is rotating rapidly
- Material preferentially accretes at equator (disk) or magnetic poles
- Drives circulation in the accumulating layer?

- H and/or He can burn stably between bursts
- “Marginally stable burning” (mHz QPOs)

- Heavy element composition laid down into the ocean likely changes on long timescales as accretion rates evolve

- Electron captures in the ocean could lead to solids forming => precipitation
- Chemical separation on freezing is likely: heavy elements preferentially incorporated into crust

1. Convection during the Type I X-ray burst - importance and observational consequences

- Convection occurs during the initial phases of bursts (<1s) when the thermonuclear runaway starts and nuclear energy release is rapid — by the time we see photons, the convection is usually over

- It can bring freshly-made heavy elements to a low enough density that they can be ejected in a wind Weinberg et al. (2006)

- In the case where the ignition happens in a pure He layer, convection brings the burning products up into the H-shell, leading to additional nuclear energy release Woosley et al. (2003)

- For deep ignition of carbon, the burning timescale is << convective turnover time (“flame”). The temperature profile left behind by the combustion front determines the shape of the superburst lightcurve

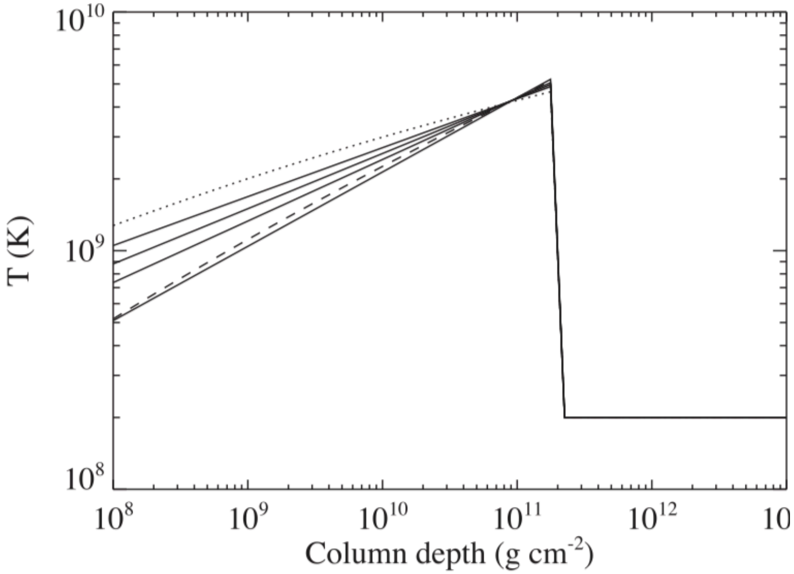
  Keek et al. (2015)

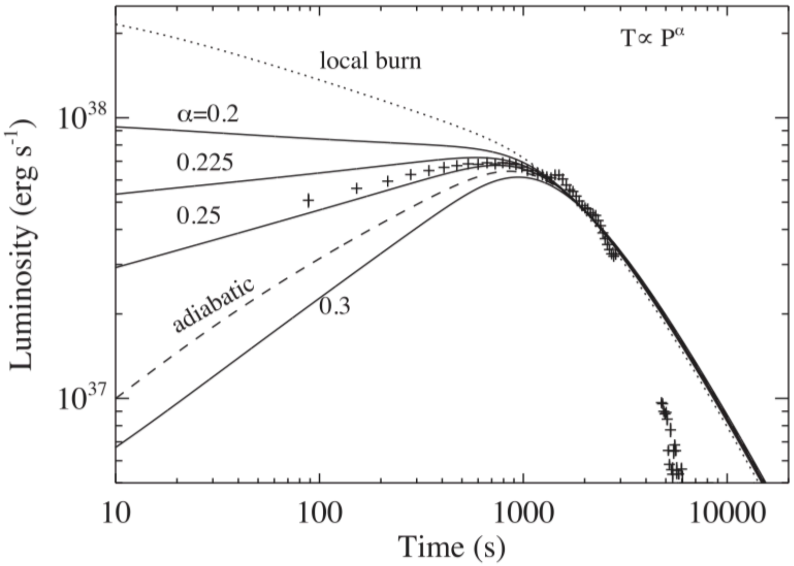
- In PRE bursts, the composition profile left behind by convection influences the burst lightcurve Guichandut et al. (2022)

The superburst light curve shape reflects the temperature profile left behind by the carbon burning flame

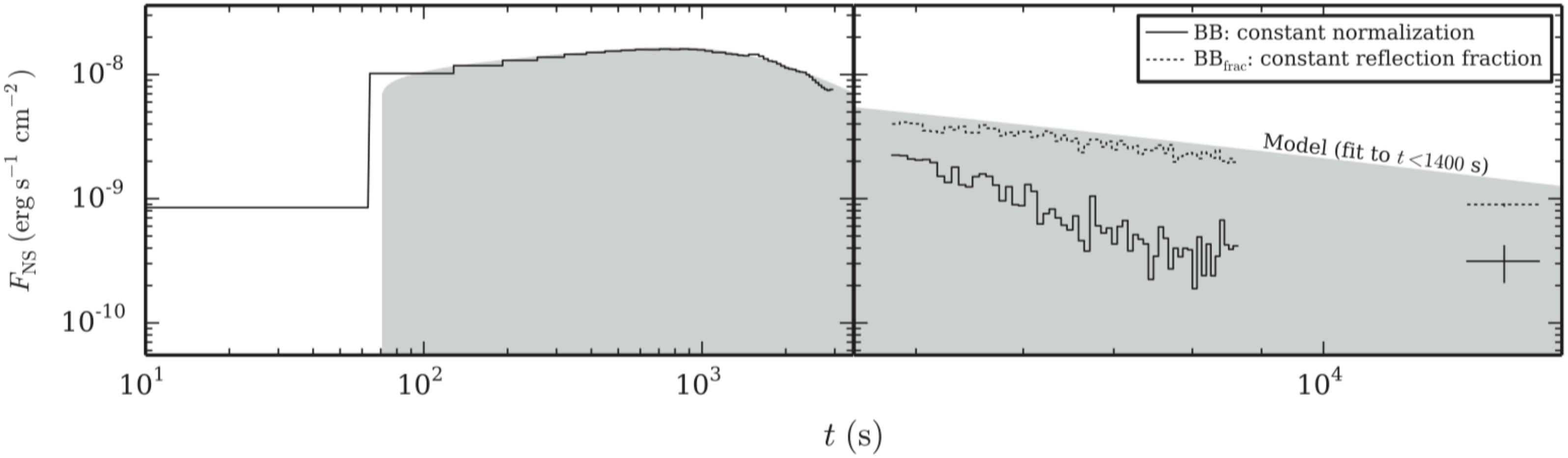
Keek et al. (2015)

- Different temperature profiles lead to different shapes for the superburst rise





- Simplest models (local burning in place or adiabatic) don't fit the data



A NICER burst from SAX J1808.4-3658

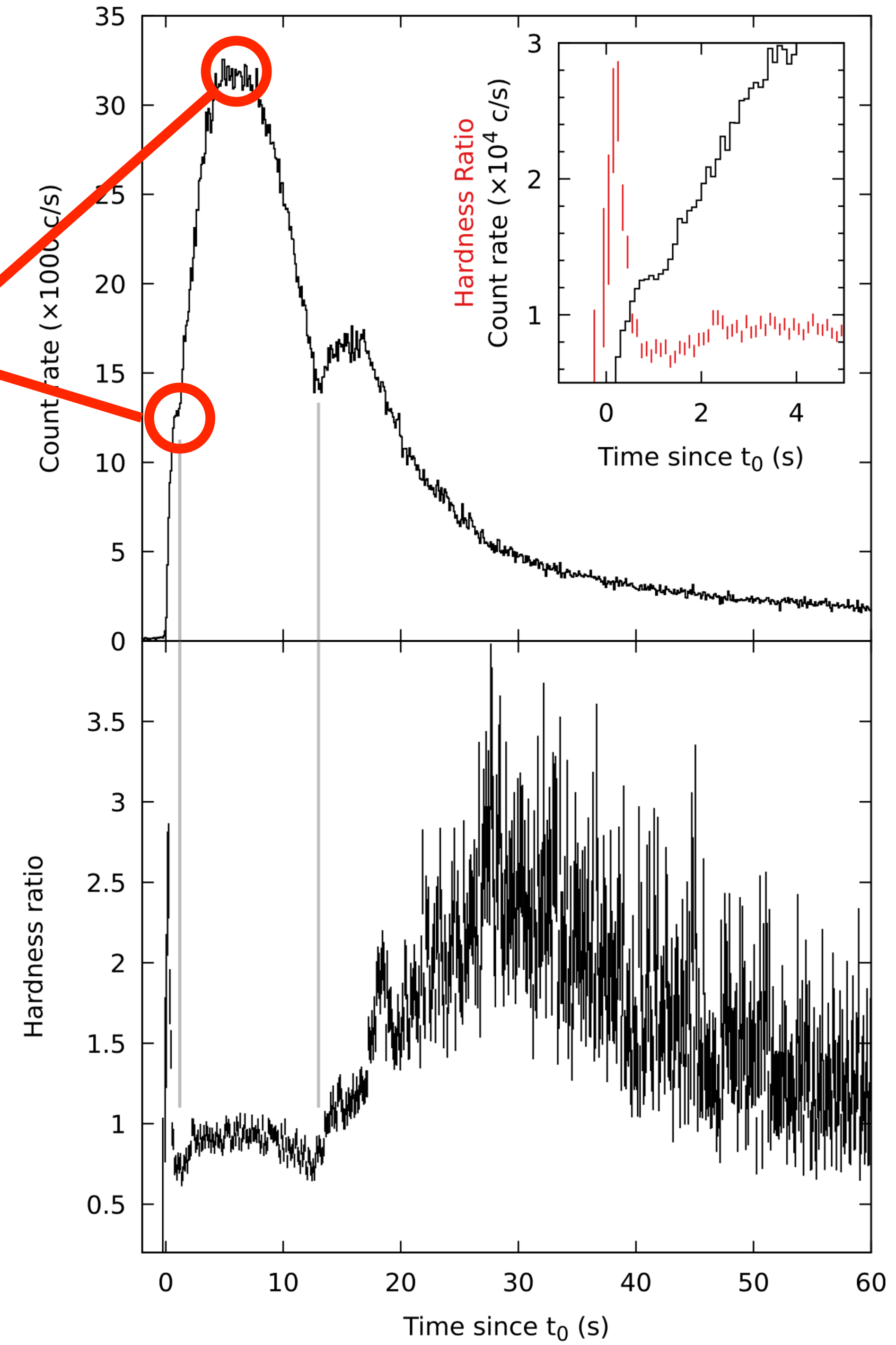
- Bright PRE burst during the 2019 outburst
- Luminosity “pauses” during the rise
- Ratio between the “pause” luminosity and the peak is ~1.7, consistent with the ratio between solar and pure He Eddington luminosities

$$L_{\rm Edd} = \frac{4\pi GMc}{\kappa_T} \approx \frac{3.5\times 10^{38}\ {\rm erg\ s^{-1}}}{1+X}$$

- Suggests that we are first seeing the solar Eddington, then the pure He Eddington once the H-rich layer is ejected

- Seems reasonable since at these accretion rates, H depletes before He ignition, leaving a H-rich layer on top of a pure He layer (Galloway et al. 2006)
- Similar idea had been suggested for 4U 1636-53 based on bimodal distribution of peak luminosities (Sugimoto et al. 1984)

- Early papers looking into H ejection used steady-state models (Taniguchi & Hanawa 1985; Kato 1986). Time-dependent calculations have not been done.



Bult et al. (2019) ApJL

MESA simulations of burst winds

- We have been modelling bursts in the pure He ignition regime using MESA
- Follow the expansion and ejection by the wind using MESA's hydro capability (following Yu & Weinberg 2018 but with hydrogen included + update to latest MESA)
- Convection mixes the nuclear burning products out to column depths

$$y \sim 10^5 - 10^6 \text{ g cm}^{-2}$$

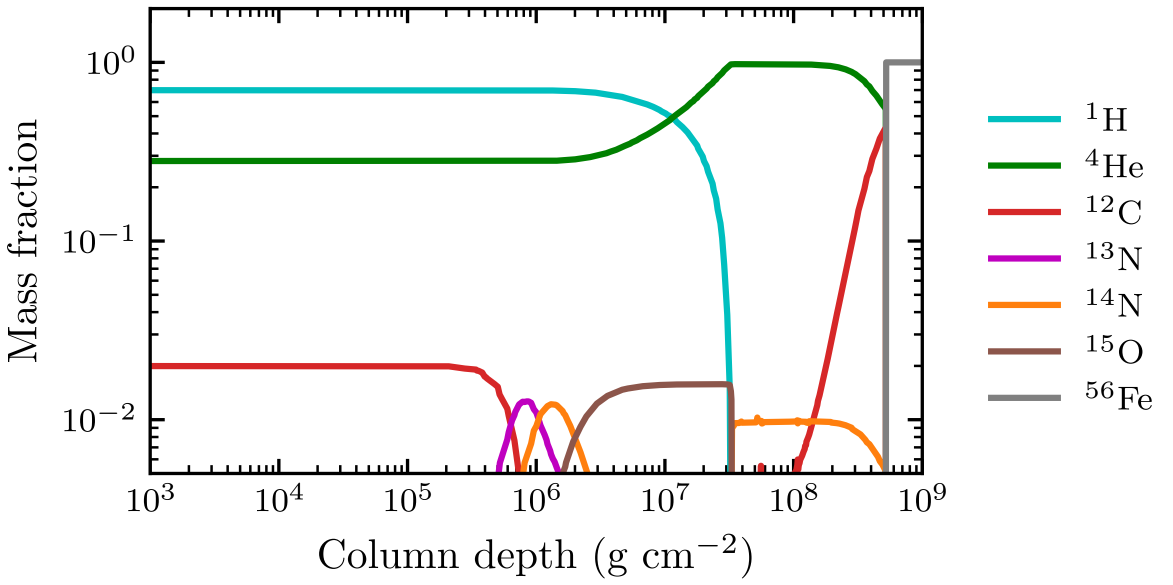
Comparable to mass ejected in a few seconds => heavy elements can be ejected

Weinberg et al. 2006

Simon Guichandut

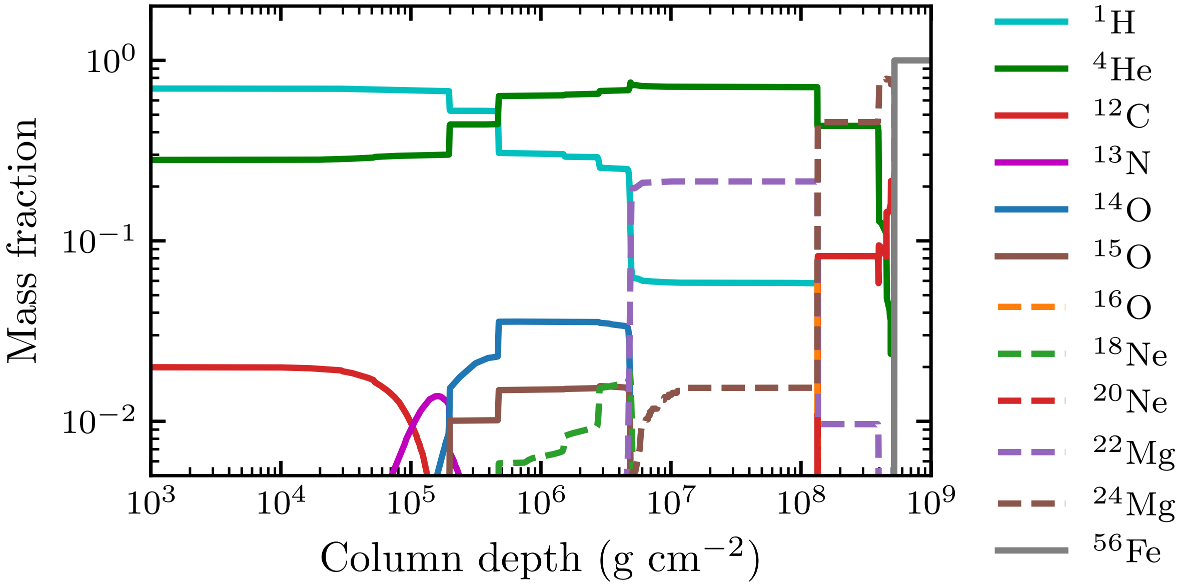
H depletion

Before ignition



Convection zone extent

After ignition



The peak luminosity tracks the H abundance profile

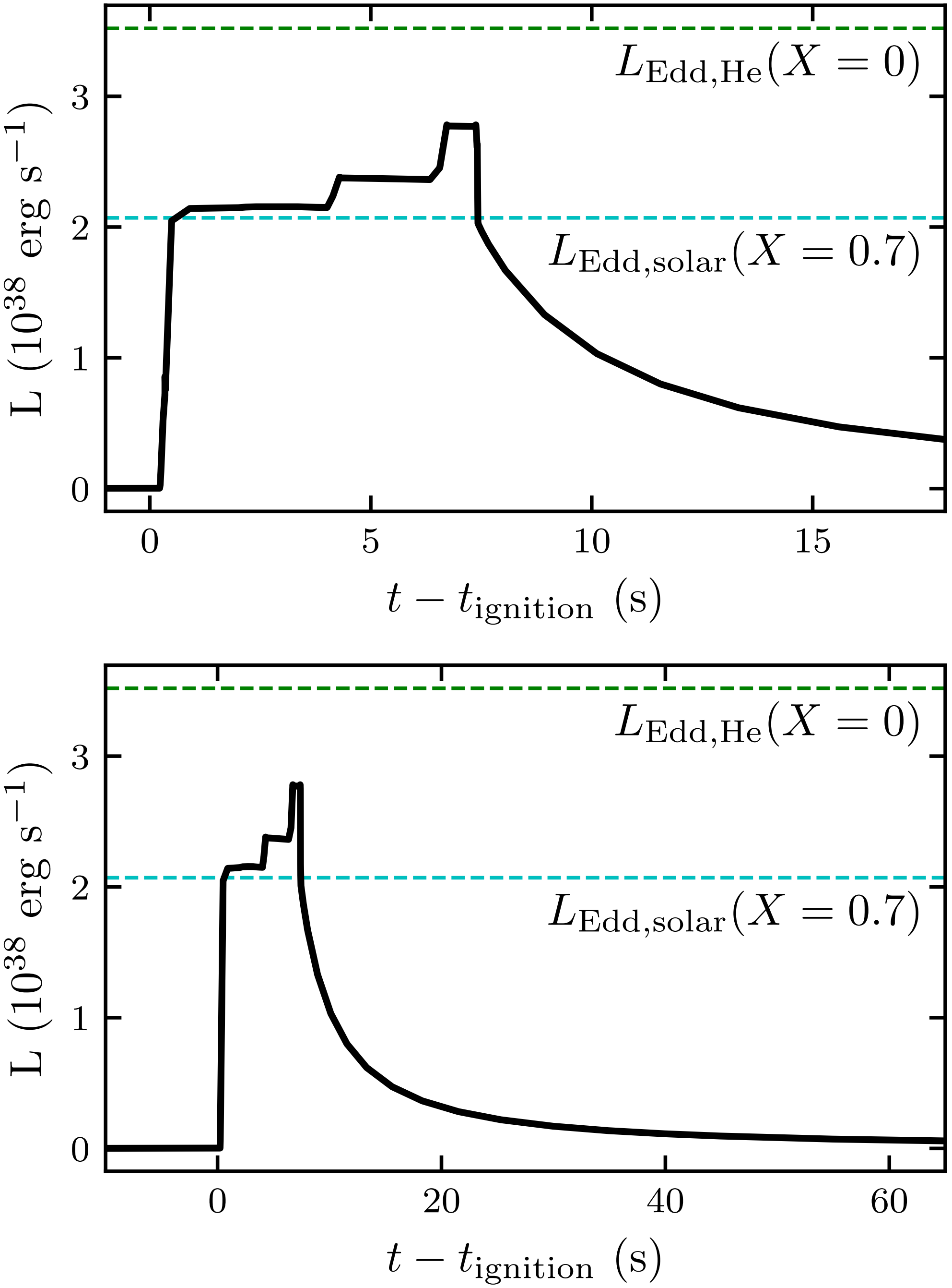
- Luminosity increases during the peak as the ejected material becomes less H-rich
- The models show discrete jumps in luminosity that correspond to jumps in the H mass fraction with depth (X~0.3, 0.5, 0.7)
- This model never reaches the pure He Eddington luminosity

Take aways

- Treatment of convection (and convective-boundary mixing) matters for making accurate light curve predictions

- Additional nuclear burning induced as the convection zone penetrates into the H-rich layer (Woosley et al. 2003)

- Need to understand the time-dependent evolution of the convection zone with composition gradients (e.g. staircases)



Guichandut et al., in prep

2. Compositionally-driven convection in the ocean

- Natural to think of the neutron star ocean as being a quiescent environment: dense, slow accretion, high thermal conductivity

- In fact, we expect the ocean to be undergoing slow convection, driven by chemical separation at the ocean floor (and possible also mid-ocean) Horowitz et al. (2009)

Consequences:

- Mixes the composition of the ocean. This could be important for carbon ignition for example

- This compositionally-driven convection occurs in a thermally-stable environment => it transports heat inwards => can lead to observable signatures, in particular for crust cooling curves

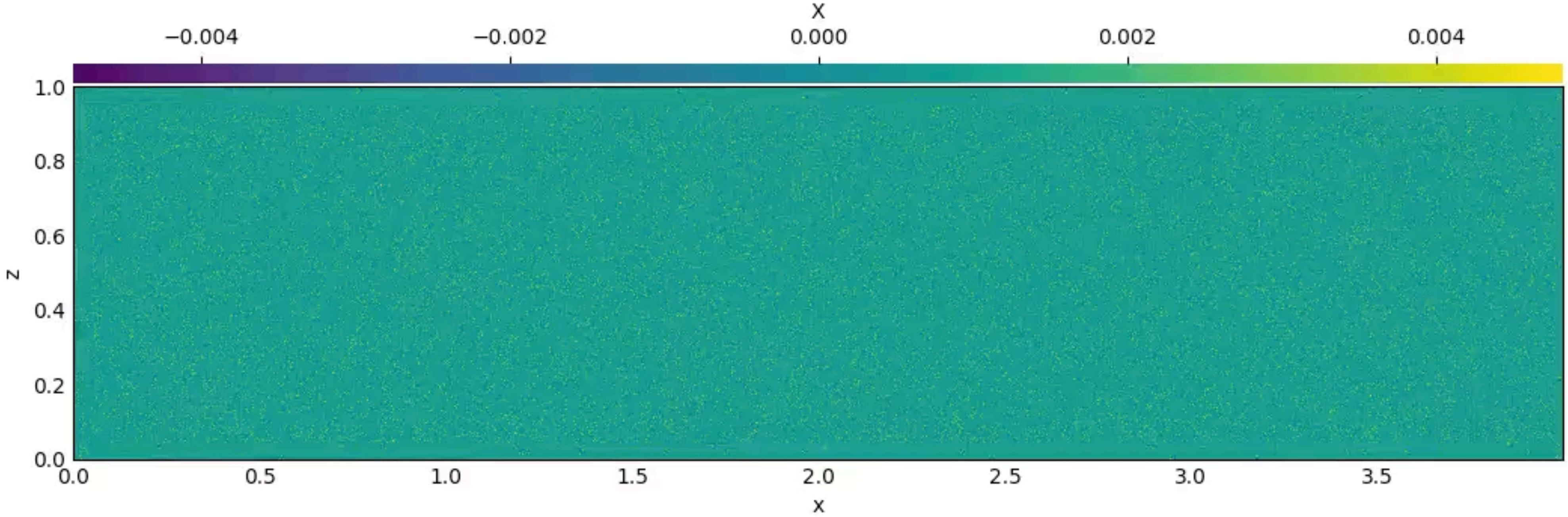
Rafael Fuentes

Compositionally-driven convection

- Bousinessq simulations using the Daedalus code (Pr=0.1)

composition
flux

0.000



composition
(blue=light, yellow=heavy)

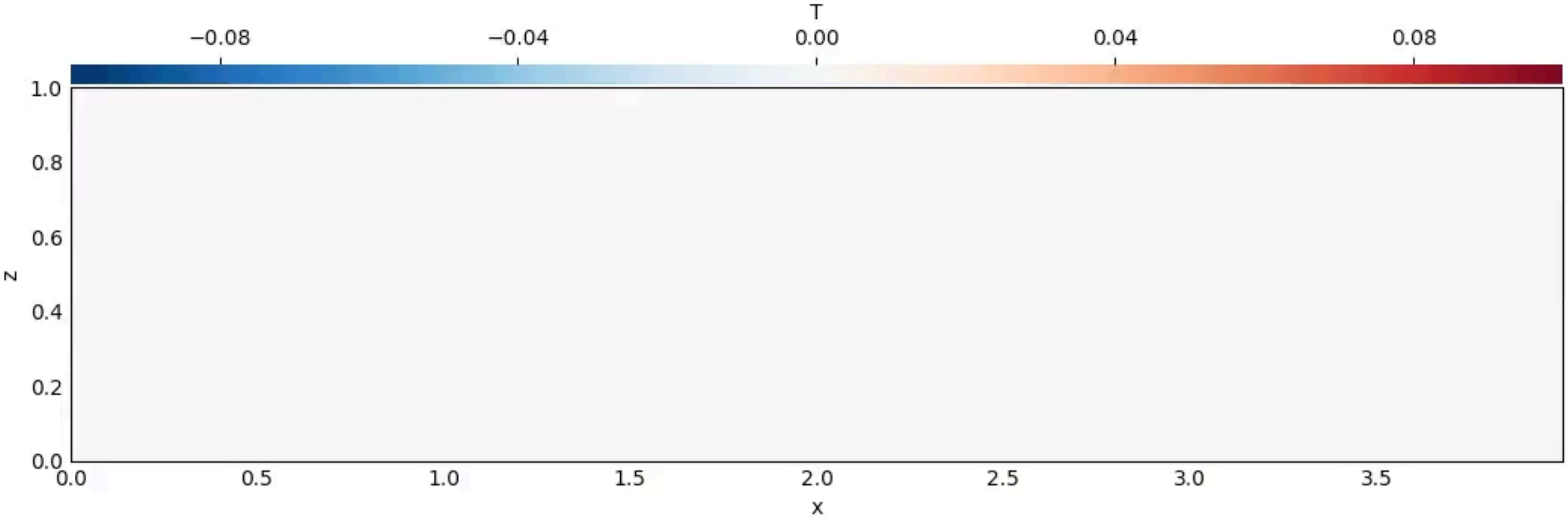
composition
flux

Compositionally-driven convection

temperature
(blue =cold, red=hot)

thermally-insulating boundaries

t =



composition
flux

Compositionally-driven convection

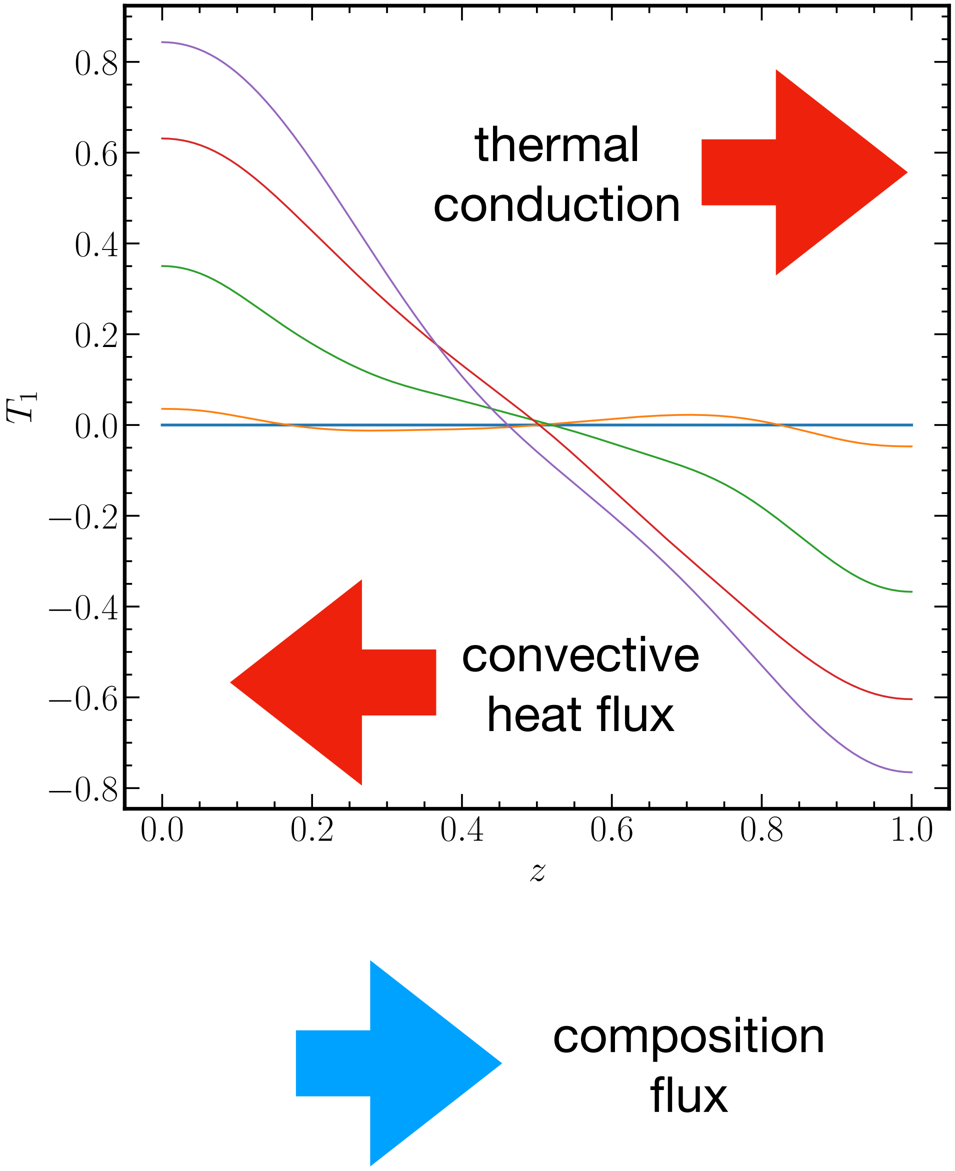
- Temperature profiles evolve to a steady-state

- Goal is to check mixing theory predictions when thermal diffusion time < convective turnover time

- thermal leakage from rising fluid elements changes heat transport and the gradients in the convection zone

- gradients adjust to

$$\nabla_X \approx \frac{\chi_T}{\chi_X}(\nabla - \nabla_{\mathrm{ad}})\left(\frac{\mathrm{Pe}}{9/2 + \mathrm{Pe}}\right)$$



thermal conduction

convective heat flux

composition flux

Chemical separation changes heat transport in the ocean

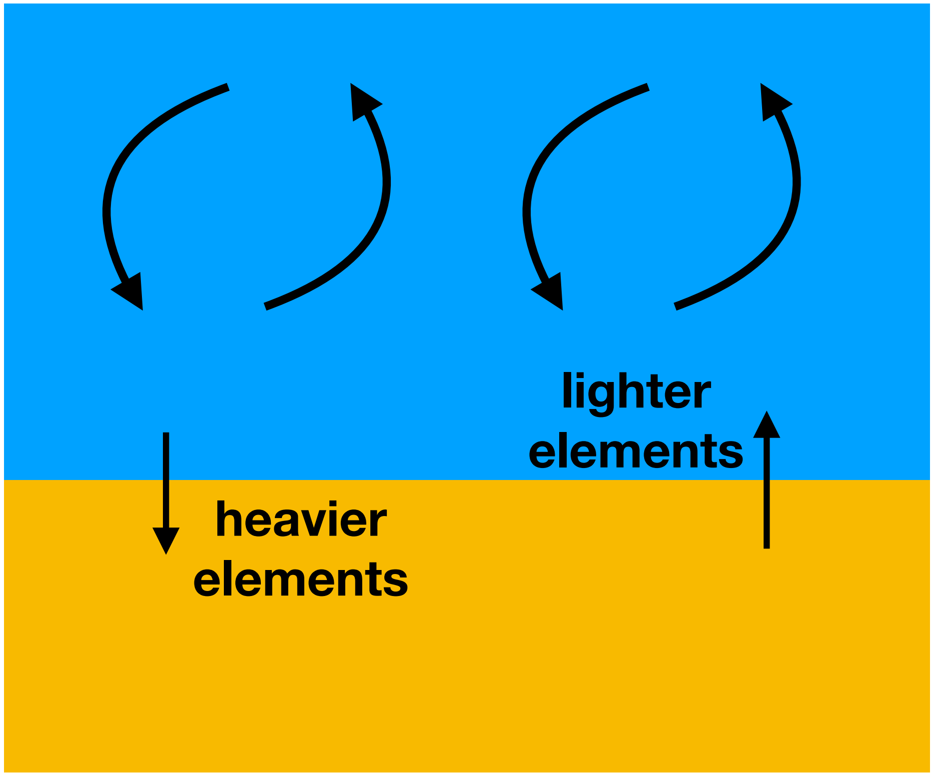
composition flux

$F_X \uparrow$

heat flux

$F \downarrow$

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



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

for steady accretion, the effective heating is

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

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

Medin & Cumming (2011)

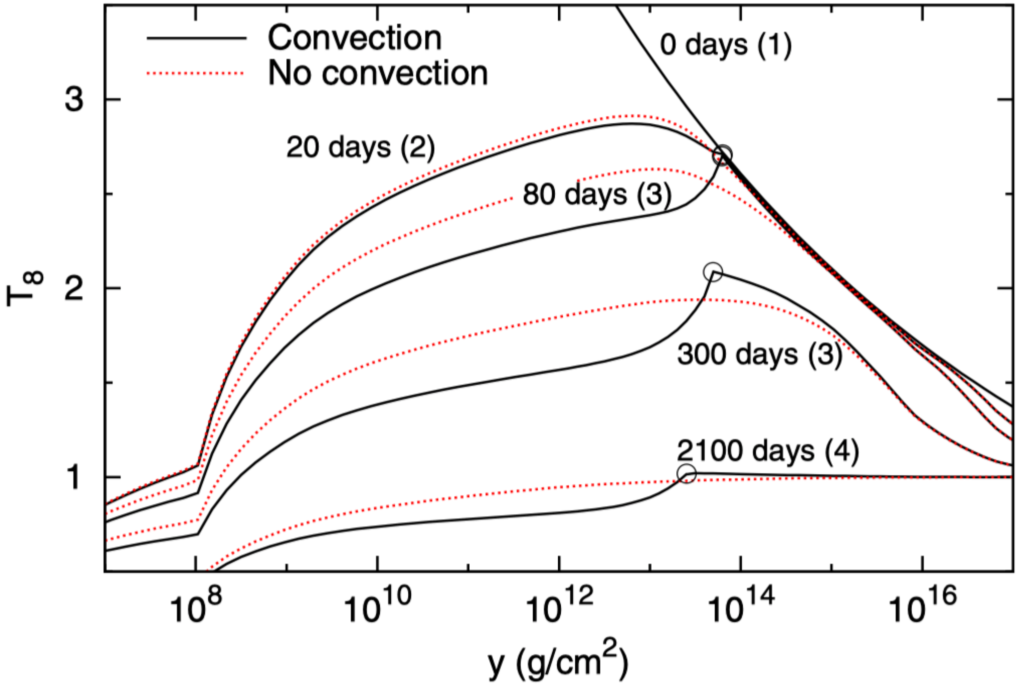
Horowitz et al. (2009), Medin & Cumming (2011, 2014, 2015), Mckinven et al. (2016), Caplan et al. (2018)

Signature of chemical separation at early times during cooling

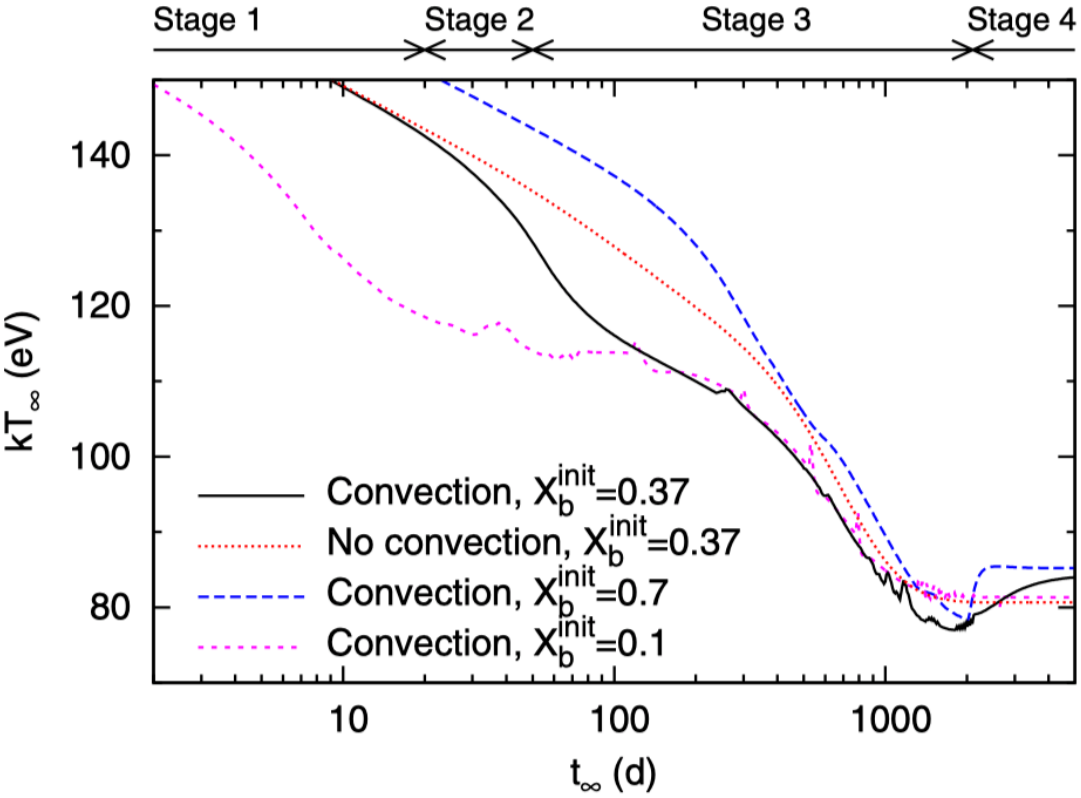
- After an outburst, the ocean refreezes as the star cools down

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

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_b relation
- Potentially complicates interpretation of early time data (e.g. to measure shallow heating)
- Late time (~1000s of days) increase in temperature? (Parikh et al. 2020)



3. Shallow heating

- Superburst models involving carbon ignition and cooling curves measured in quiescence both require a “shallow” heat source — densities are typically ~10^9 - 10^{10} g/cm^{3,} consistent with being in the ocean / outer crust

- Generally ~1 MeV per accreted nucleon, but may be ~10 MeV in one outburst from MAXI (see Dany Page’s talk)

- Physical mechanism is unknown. There is a lot of energy in the incoming accreted material if it can be deposited deep enough

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

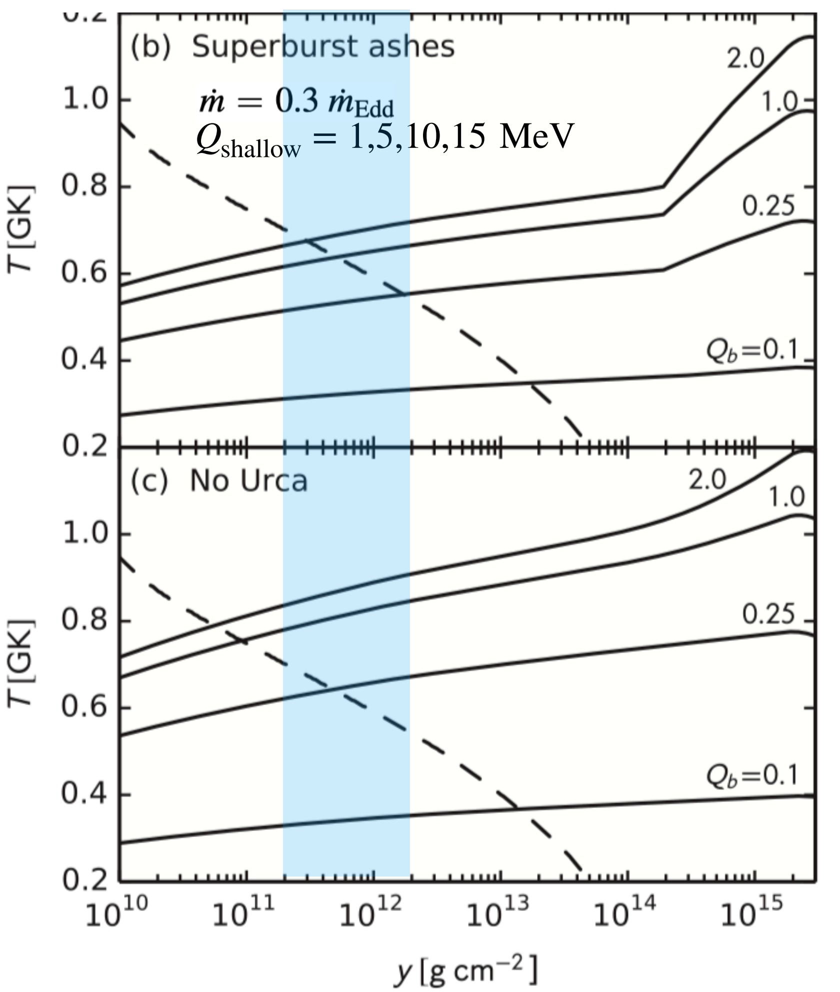
  Cumming et al. (2006)

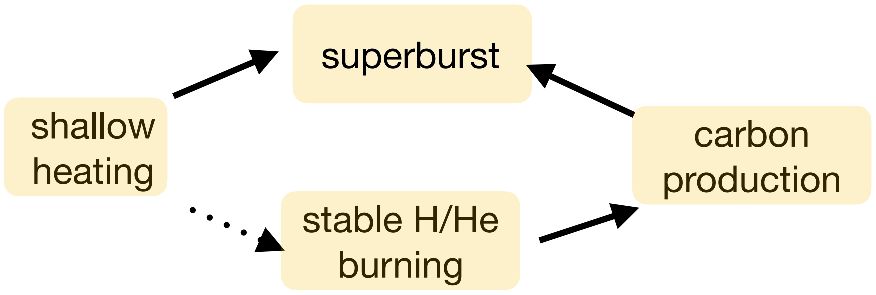
  URCA cooling in the ocean can require even more outwards flux Deibel et al. (2016)

- 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)





shallow heating

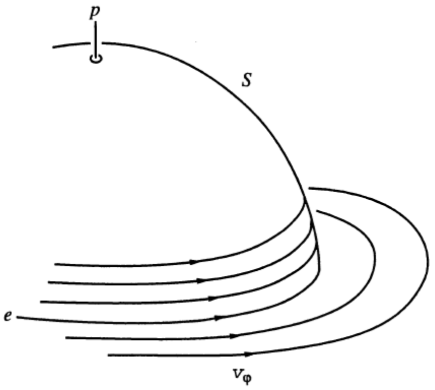
superburst

stable H/He burning

carbon production

Shear heating

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



Inogamov & Sunyaev (1999)

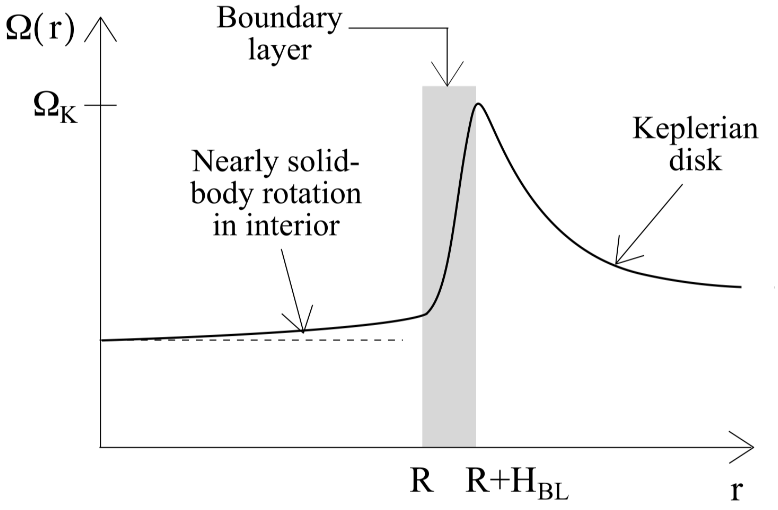
- Kinetic energy of incoming matter

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

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 with only a small viscous heating

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



Piro & Bildsten (2007)

- Wave transport could perhaps deposit energy deep

e.g. gravity wave in ocean

Inogamov & Sunyaev (2010)

acoustic waves excited in disk boundary layer

Philippov & Rafikov (2016), Belyaev et al. (2012, 2013), Hertfelder & Kley (2015)

4. Global view of nuclear burning on accreting neutron stars

- Our basic picture of the outer layers of accreting NS has been remarkably successful in explaining new observed phenomena:
  - burst types
  - mHz QPOs
  - superbursts
  - burst oscillations
  - ten-minute recurrence time bursts

- But there are still many puzzles and details that don't make sense
  - the transition to stable burning happens at ~0.1 Edd instead of Edd
  - short intermittent helium flashes at high accretion rate
  - the relation between mHZ QPOs and bursts
  - how to make the carbon for superbursts
  - the spectral evolution during bursts depends on accretion state/rate

- Many of the behaviours that don't make sense are linked to the "banana" state in which the accretion disk is thought to extend inwards to the neutron star surface

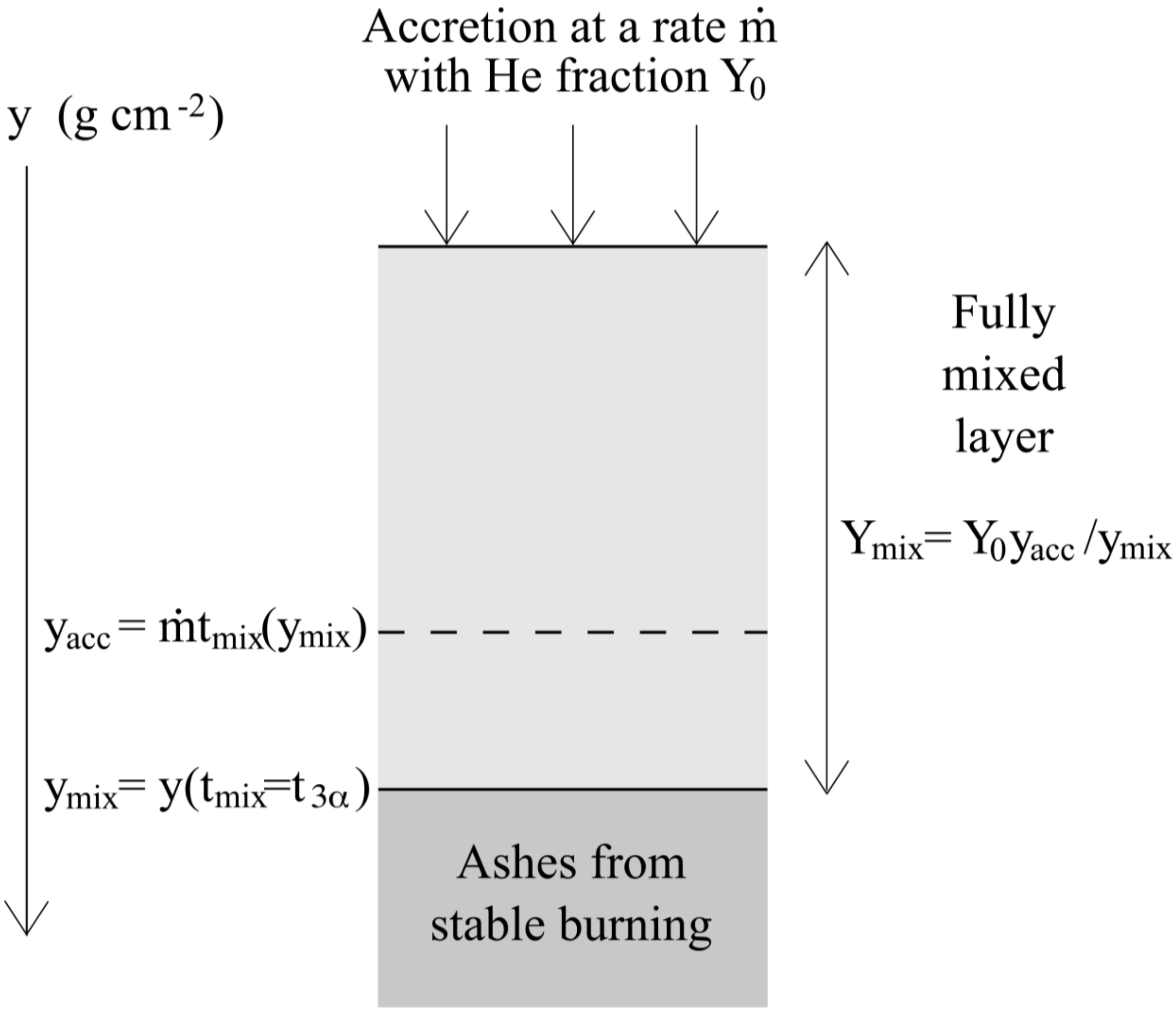
- Suggests that we need to think about how material spreads over the surface and/or comes into coronation with the star and how that interacts with nuclear burning

Turbulent mixing of accreted material

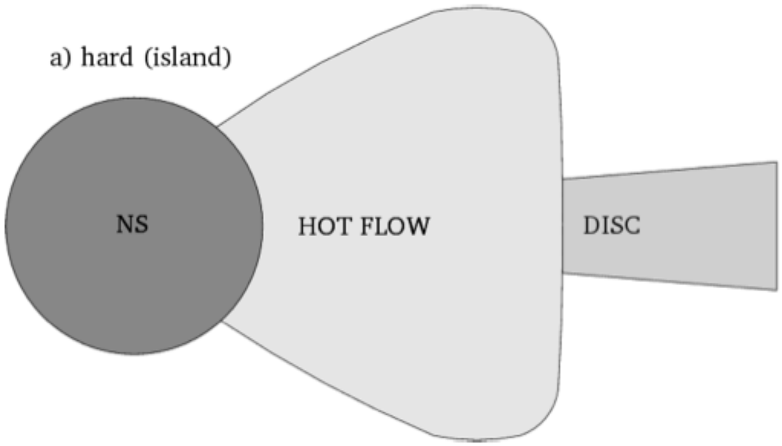
- Turbulent mixing of freshly accreted material opens up stable burning regime at low accretion rate

Piro & Bildsten (2007)

Keek et al. (2009)

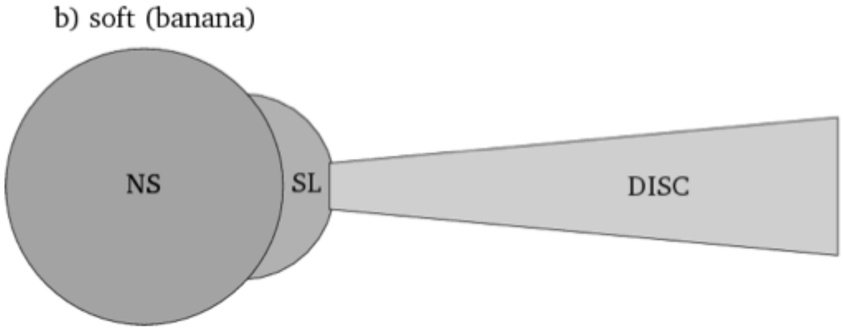


Nuclear Burning Phenomenology of Accreting Neutron Stars



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?

Summary

- Convection in the early stages of bursts can leave signatures in observations
- Need to understand convection + burning; composition profiles left behind; boundary layer mixing
- Superburst rise reflects the temperature profile left behind by the carbon flame
- First models of mass loss with H included => rising luminosity during burst peak reflects changing H abundance with depth

- Phase separation / electron captures in the ocean can drive convection/mixing
- Compositionally-driven convection transports heat inwards
- Mixes the composition in the ocean
- Can significantly delay freezing of the ocean after accretion outbursts

- Both long Type I X-ray bursts and crust cooling observations imply a source of “shallow heating”
- Plenty of energy in the incoming material if it can be deposited deep in the ocean
- Important to understand how the circulation of incoming material / transport of angular momentum affects the nuclear burning during the accumulation phase
- Missing piece of physics that can explain the global X-ray burst phenomenology?