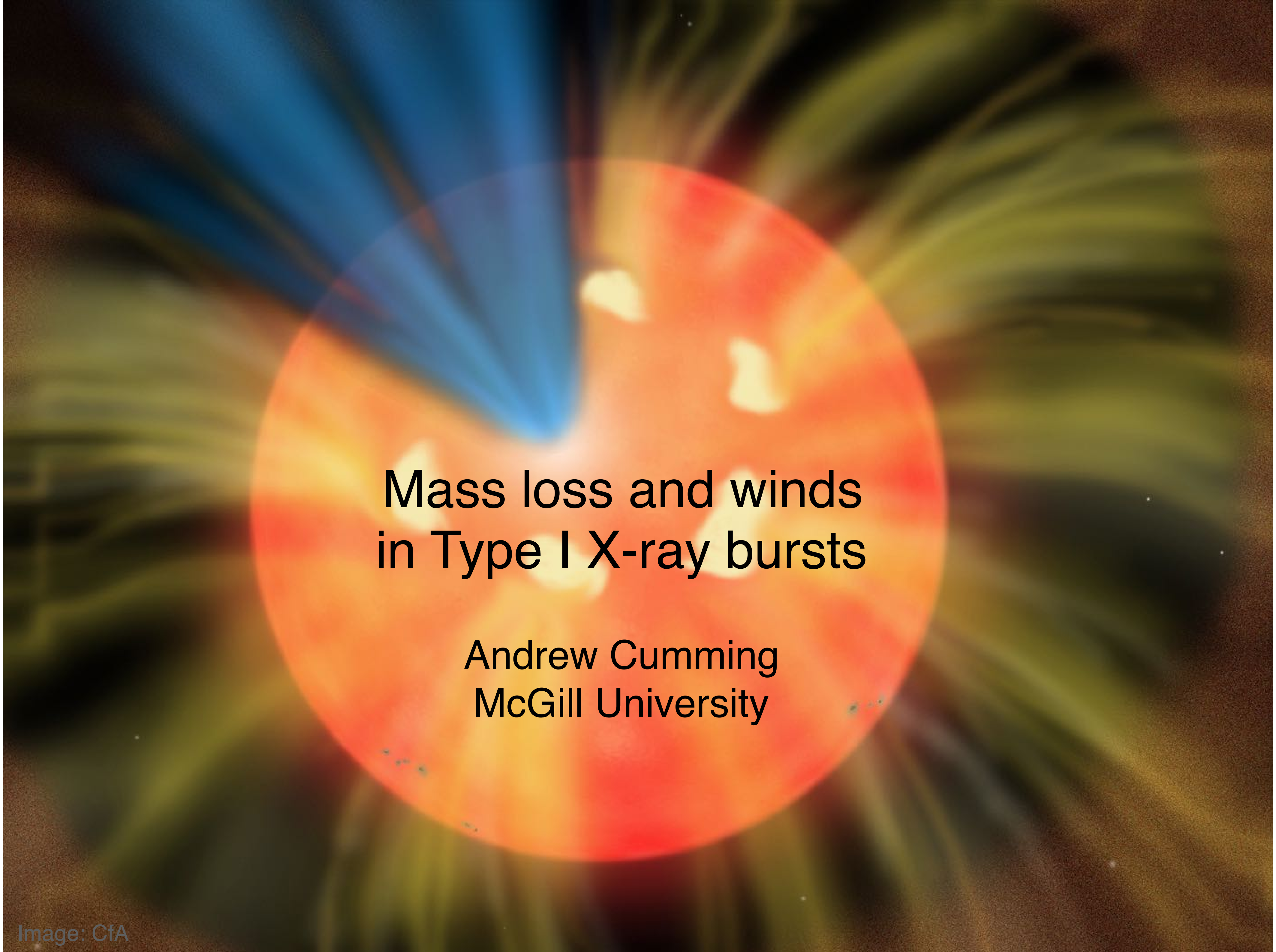

Mass loss and winds in Type I X-ray bursts

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McGill University

Image: CfA

Why think about mass loss?

It may not be obvious why we would worry about mass loss in Type I X-ray bursts since

$$E_{\mathrm{nuc}} \sim (1-5)\ \frac{\mathrm{MeV}}{\mathrm{nuc}} \ll \frac{GM}{R} \sim 200\ \frac{\mathrm{MeV}}{\mathrm{nuc}}$$

so can unbind at most ~1% of the accreted mass (we'll see later that ~0.1% more realistic)

but…

Why think about mass loss?

…it could have important implications:

- eject heavy elements made in the burst => nucleosynthesis

- absorption features from heavy elements at the photosphere

  —> measure redshift
  —> identify nuclear burning (rp-process) products
  —> test burst physics, reveals the composition layer by layer

- pollute the companion or disk?

  e.g. O, Ne in ultracompact X-ray binaries (Weinberg et al. 2006)

- a significant amount of the burst energy can go into ejecting mass
  => affects interpretation of burst energetics

Why now?

- lots of recent work on using photospheric radius expansion bursts to get **neutron star mass and radius constraints**

  van Paradijs (1979), Ozel et al., Steiner et al., Poutanen, Suleimanov et al.

  relies on understanding the evolution of the photosphere during the burst, in particular identifying “touchdown”

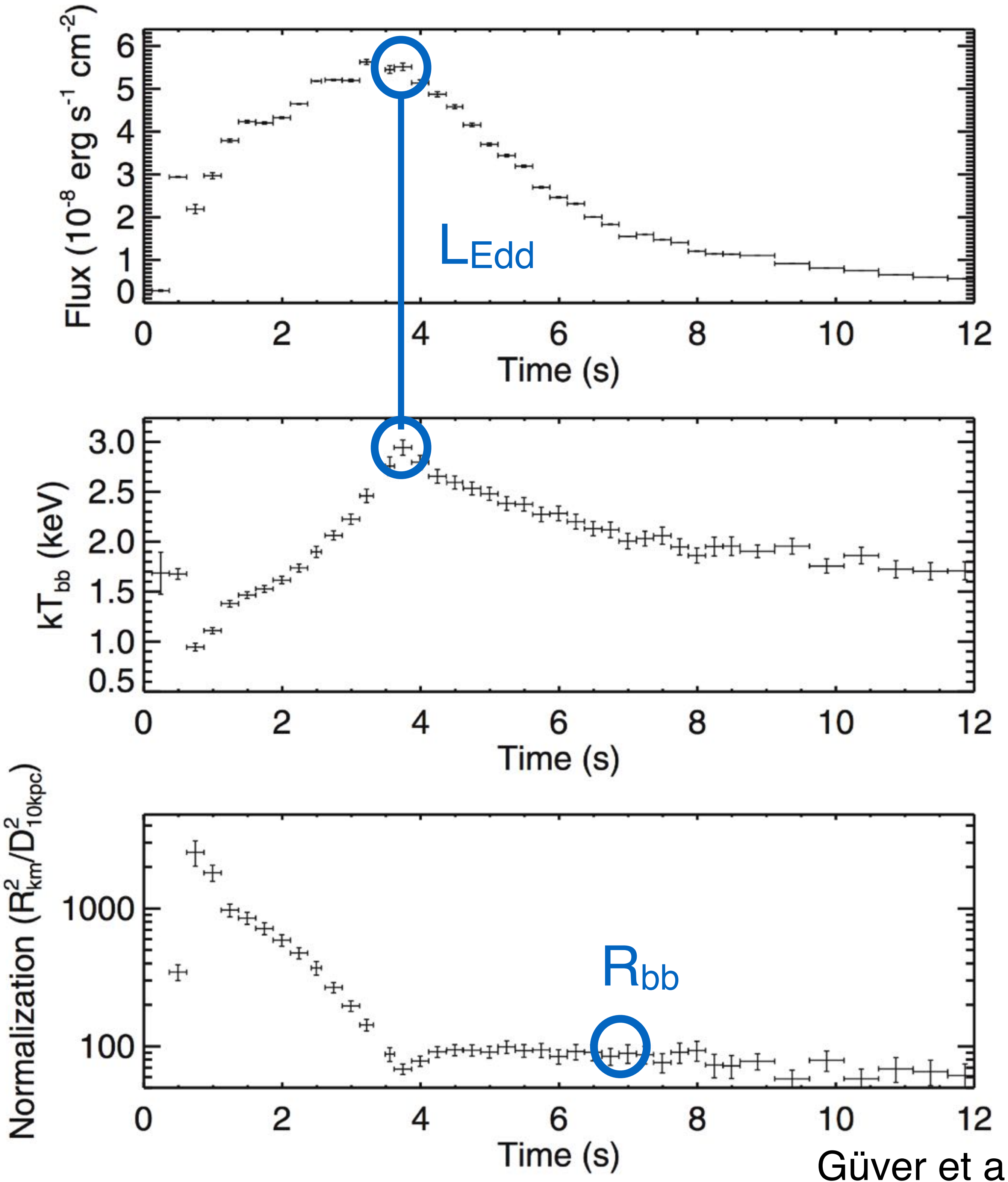
- **observational evidence for absorption edges**

  superexpansion bursts in ’t Zand & Weinberg (2010)
  HETE J1900 Kajava et al. (2017)
  Barriere et al. (2015) NUSTAR observations of GRS 1741.9-2853
  (5.5 keV absorption line @1.7 sigma)

- **long Type I X-ray bursts** (superbursts and intermediate duration bursts) with Eddington phases that last for minutes!

- **large observational databases** of PRE bursts to compare against

- new capability in **NICER** to study < 1 keV part of the X-ray spectrum => see expanded phases? Keek et al. (2018) burst from 4U 1820-30



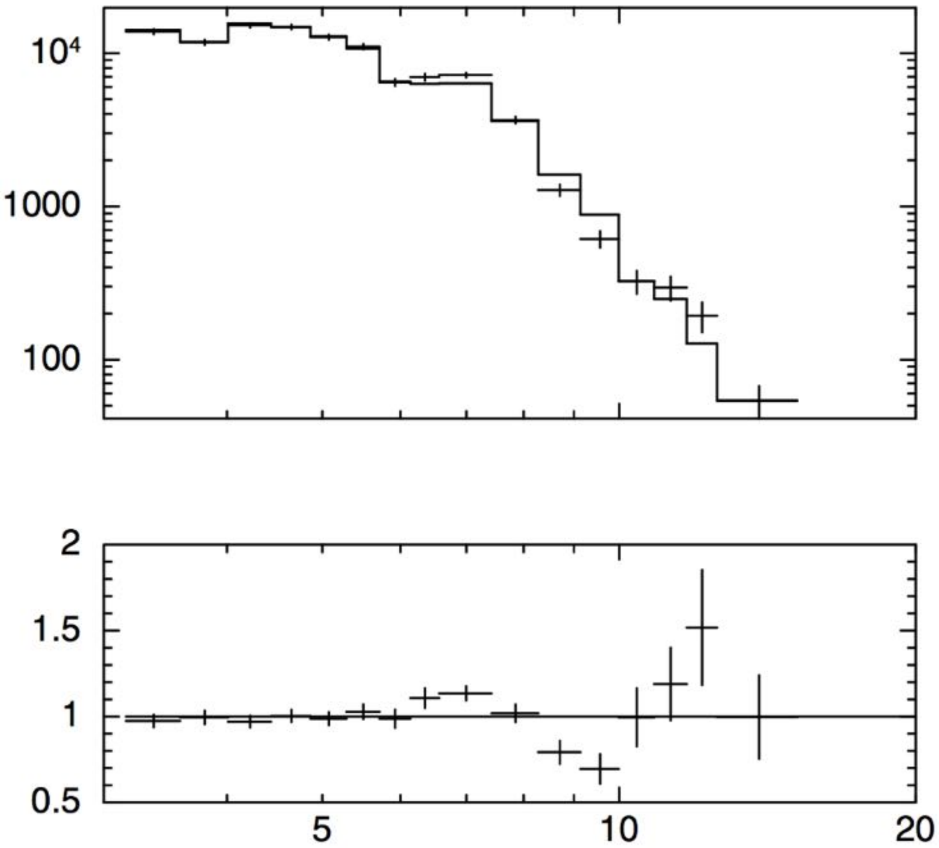
Güver et al. (2010)

+ distance
=> [M,R]

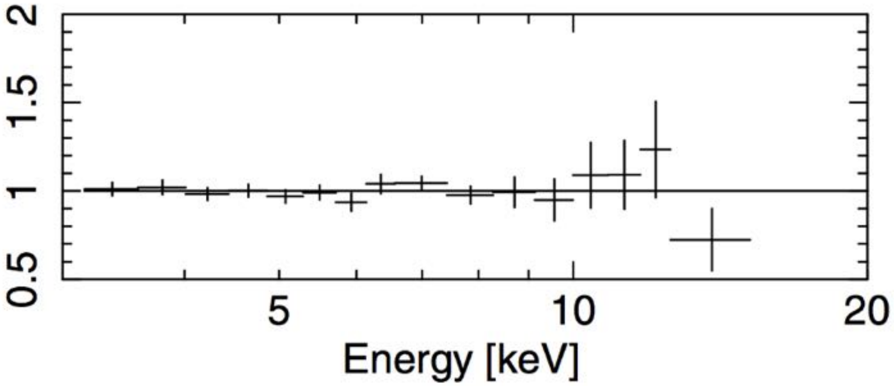
Need to understand:

- is the spectral shape changing in the way we expect in the tail?
- are we correctly identifying the touchdown point?
- choice of bursts (hard state or soft state?)

4U 0614+09 at 2.5 s / Black body + reflection fit

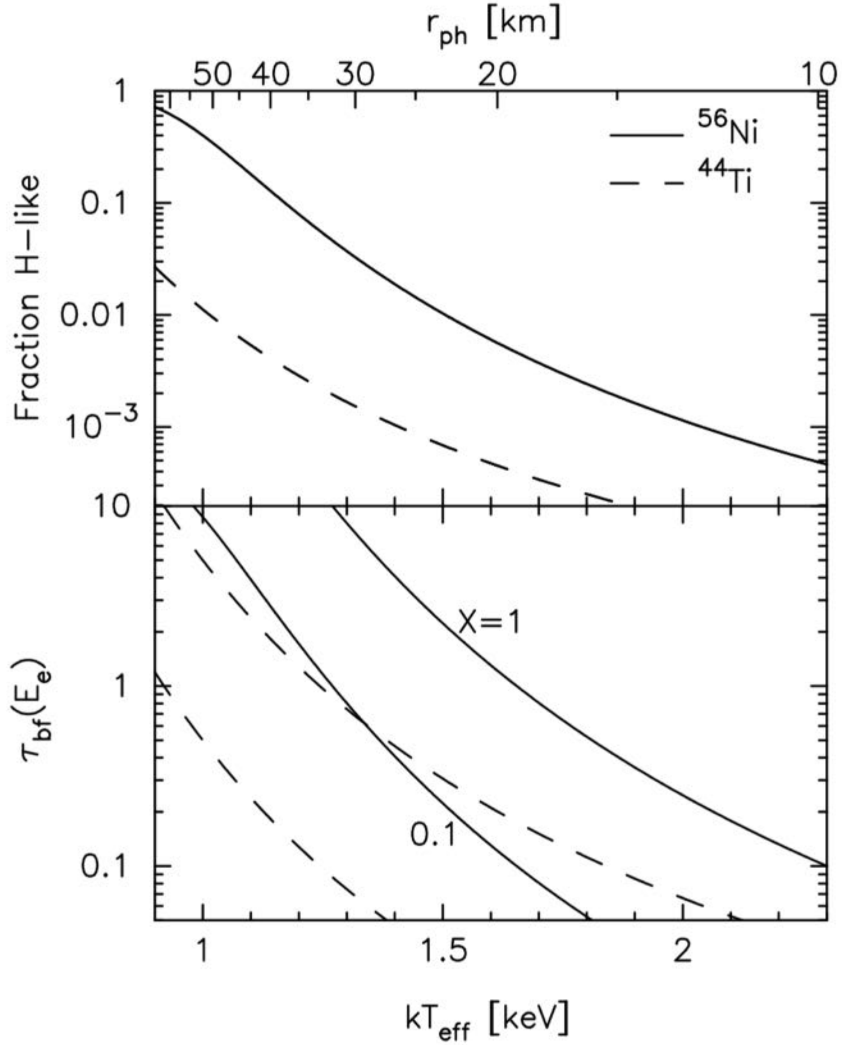


4U 0614+09 at 2.5 s / Fit with edge included

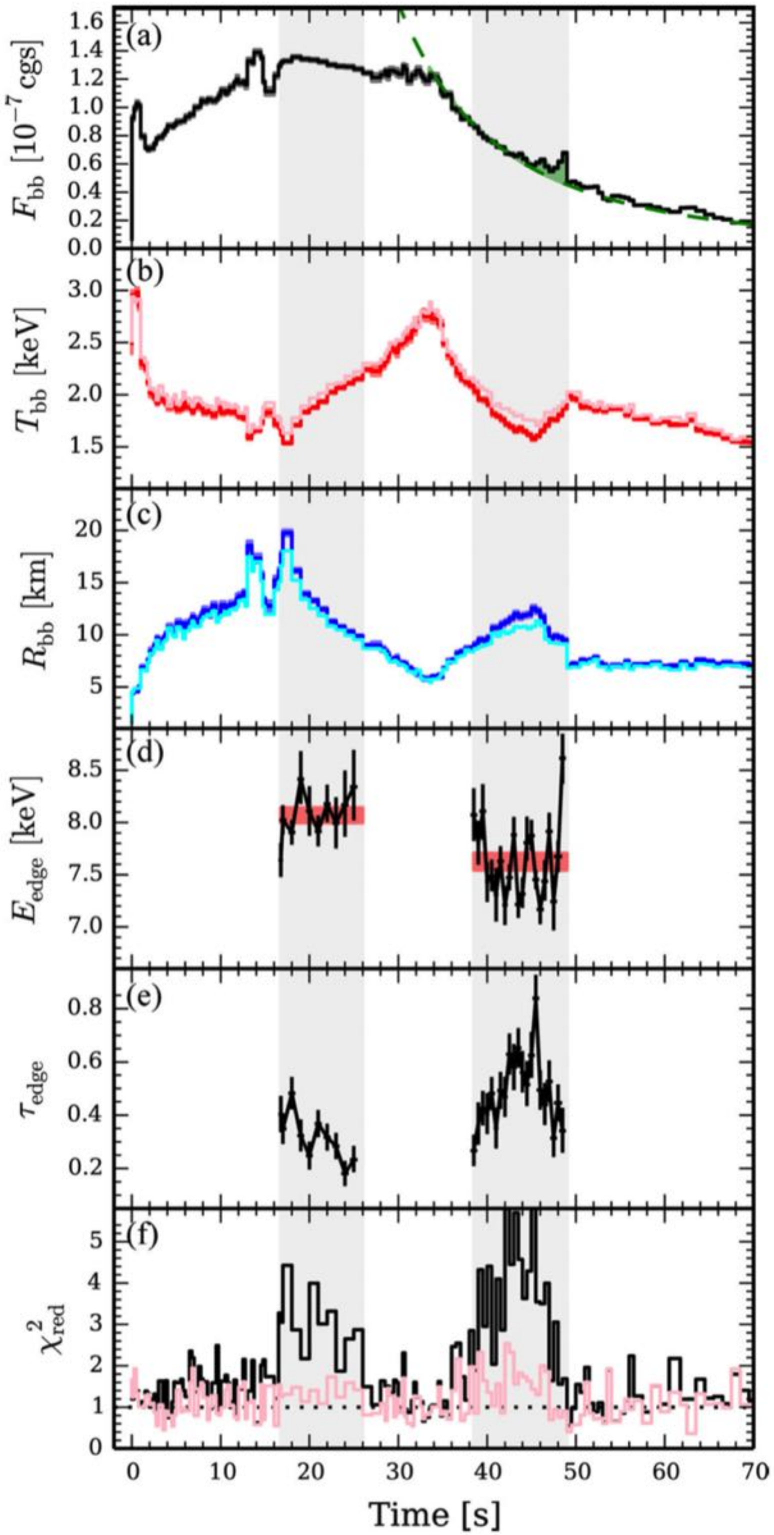


in ’t Zand & Weinberg (2010)

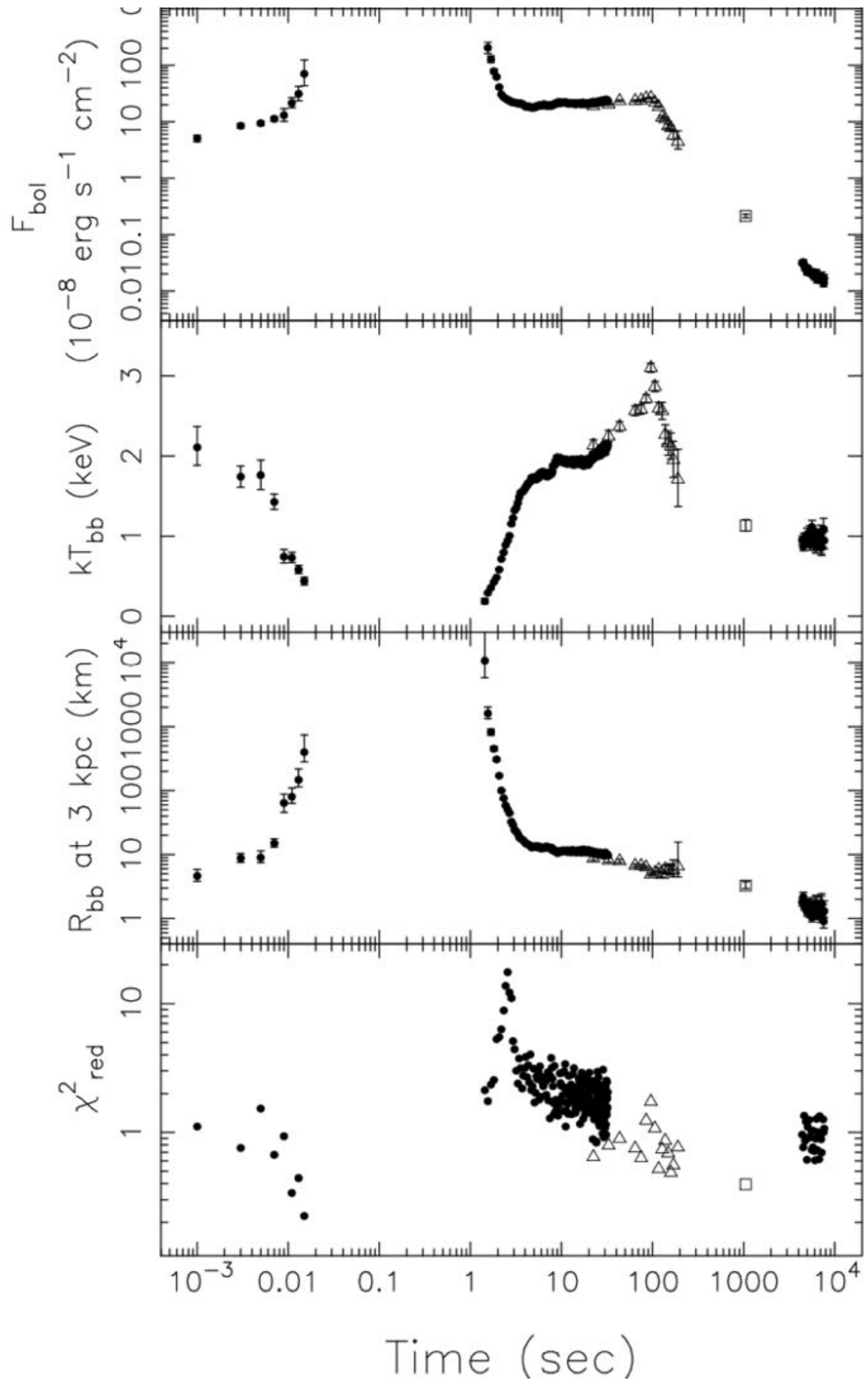
strong absorption edges in two “superexpansion” bursts



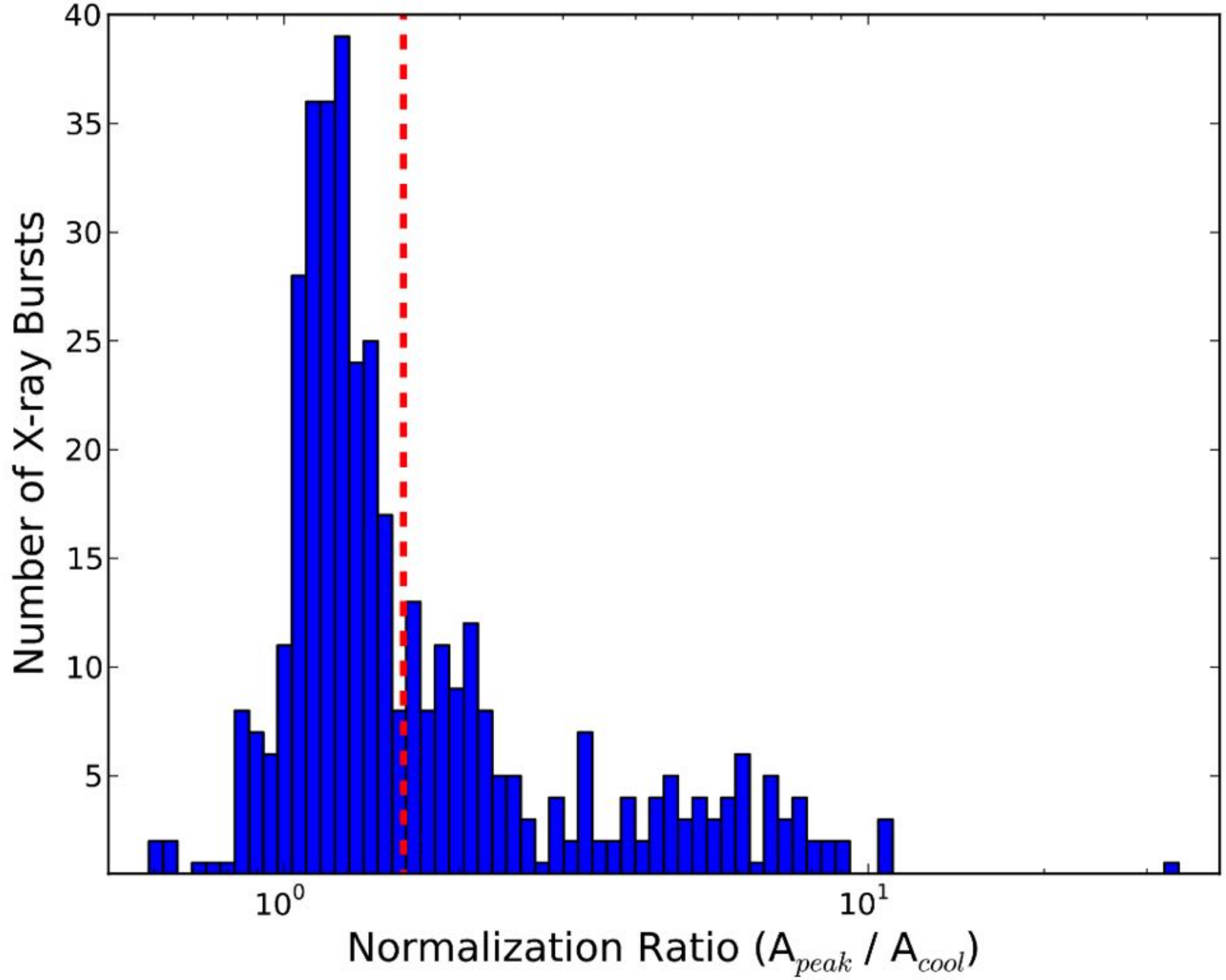
Need large mass fraction of Ni



Kajava et al. (2017)
Most energetic burst from
HETE J1900.1-2455



4U 0614+091 Kuulkers et al. (2010)



Güver, Özel, Psaltis (2012)

In most bursts, expansions are << 100km

- are we seeing expanded atmospheres?
- truncation of winds by heavy elements? (in 't Zand & Weinberg 2010)
- color correction?

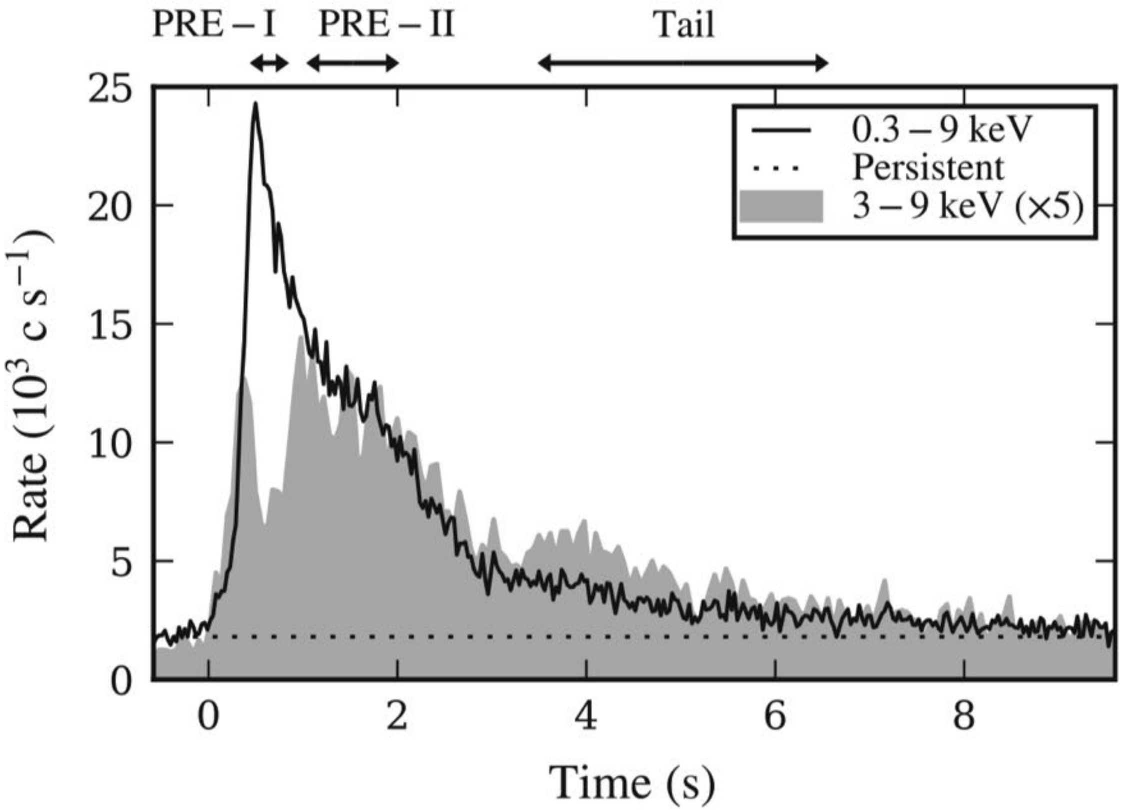


Figure 1. Photon count rate as a function of time in the 0.3–9 keV passband at 30 ms resolution. The top of the shaded region marks the 3–9 keV count rate for comparison (scaled by a factor of 5). The dotted line indicates the persistent count rate measured at the end of the observation. On top, three time intervals are indicated for spectroscopy (Figure 2).

Keek et al. (2018) NICER observations of 4U 1820-30

This talk

- how mass loss works
- heavy element transport by convection

Where next: coupled burst and wind calculations

- mass loss in cooling models and comparison with superexpansion bursts
- first results from MESA

How mass loss works

- key thing is the suppression of electron scattering opacity at high temperature

$$\kappa_e = 0.2 \times \left[1 + \left(\frac{T}{4.5 \times 10^8}\right)^{0.86}\right]^{-1}$$

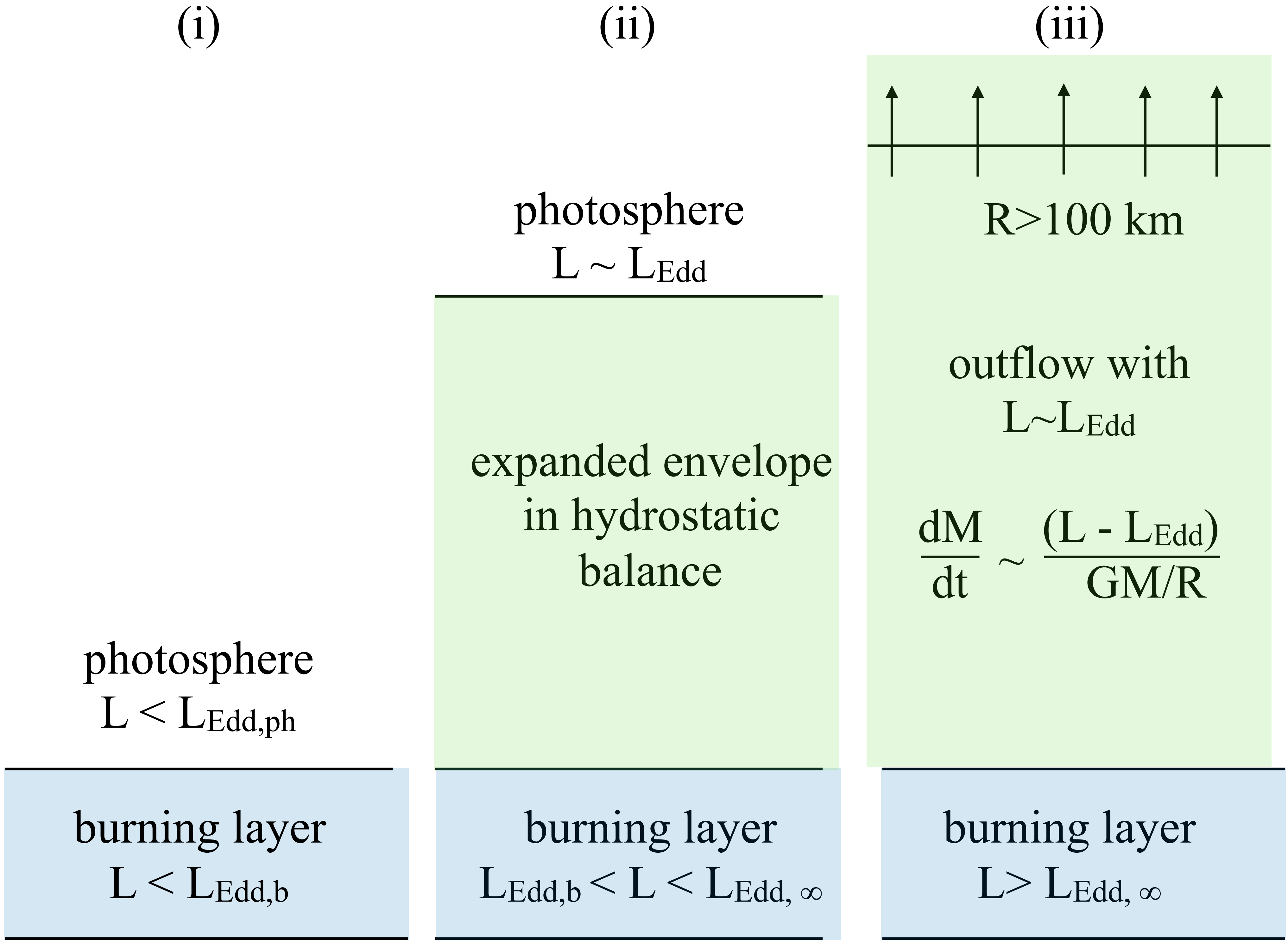
Paczynski (1983)

=> $\dfrac{L}{L_{\rm Edd}} \propto \kappa$ increases outwards

=> can be sub-Eddington in the burning layer, but super-Eddington at the photosphere

- GR has the same effect: $F_{\rm Edd} = \dfrac{cg}{\kappa}$ => $L_{\rm Edd} = \dfrac{4\pi GMc}{\kappa}(1+z)$

$$\frac{L}{L_{\rm Edd}} \propto \frac{(1+z)}{(1+z)^2} \propto \frac{1}{1+z}$$ increases outwards


(i)
(ii)
(iii)
R>100 km
photosphere
L ~ LEdd
outflow with
L~LEdd
expanded envelope
in hydrostatic
balance
dM/dt ~ (L - LEdd)/(GM/R)
photosphere
L < LEdd,ph
burning layer
L < LEdd,b
burning layer
LEdd,b < L < LEdd, ∞
burning layer
L> LEdd, ∞

Models of PRE burst winds

wind speed $v_r \sim 0.01c$ => $r_{\rm phot}/v_r \lesssim 1$ s

motivates quasi-steady approach

optically thick wind, Newtonian gravity:

$$\dot{M} = 4\pi r^2 \rho u = \text{constant}$$

$$u\frac{du}{dr} + \frac{1}{\rho}\frac{dP}{dr} + \frac{GM}{r^2} = 0$$

$$L + \dot{M}\left(\frac{u^2}{2} + w - \frac{GM}{r}\right) = \dot{E} = \text{constant}$$

$$L = -\frac{16\pi r^2 acT^3}{3\kappa\rho}\frac{dT}{dr} \qquad w = \frac{5}{2}\frac{k_B T}{\mu m_p} + \frac{4aT^4}{3\rho}$$

Models of PRE burst winds

	Optically thick?	Newtonian?	Steady?	H/He only?
Ebisuzaki et al. (1983), , Kato (1983), Quinn & Paczynski (1985)	Y	Y	Y	Y
Paczynski & Prosynski (1986)	Y	N	Y	Y
Joss & Melia (1987)	N	Y	Y	Y
Nobili, Turolla, Lapidus (1994)	N	N	Y	Y
Yu & Weinberg (2018)	Y	Y	N	N

Paczynski & Anderson (1986) extended atmospheres in GR

Spectra of expansion phase: Titarchuk (1994), Shaposhnikov & Titarchuk (2002)

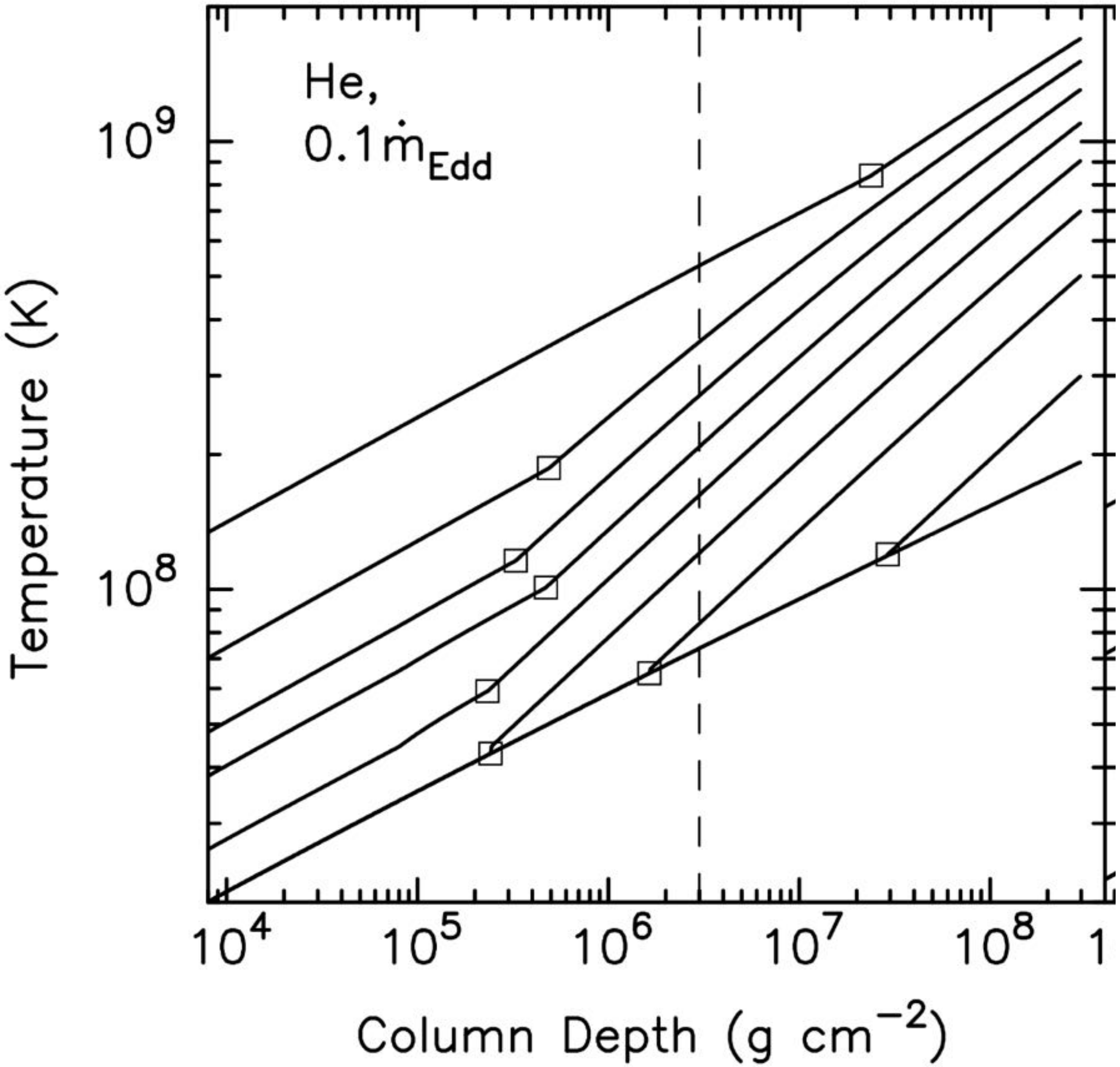
How far out can convection transport heavy elements?

- Joss (1976) pointed out that the convection zone cannot reach the photosphere (entropy of burned material < entropy of photosphere)

$$P_{\rm conv} \approx P_b \left(\frac{T_{\rm eff}}{T_b}\right)^{5/2} \sim 10^3 \ {\rm g\ cm^{-2}}$$

- Hanawa & Sugimoto (1982) realized that the convection zone extends until the thermal time matches the growth time

$$t_{\rm therm} = \frac{3\kappa y^2 c_P}{4acT^3} = 10^{-3}\ {\rm s}\ \frac{y_5^2}{T_8^3}\left(\frac{\kappa}{0.1}\right)$$



Weinberg, Bildsten & Schatz (2006)

Hanawa & Sugimoto (1982)

Compare the rate of change of entropy in the convection zone an radiative zones:

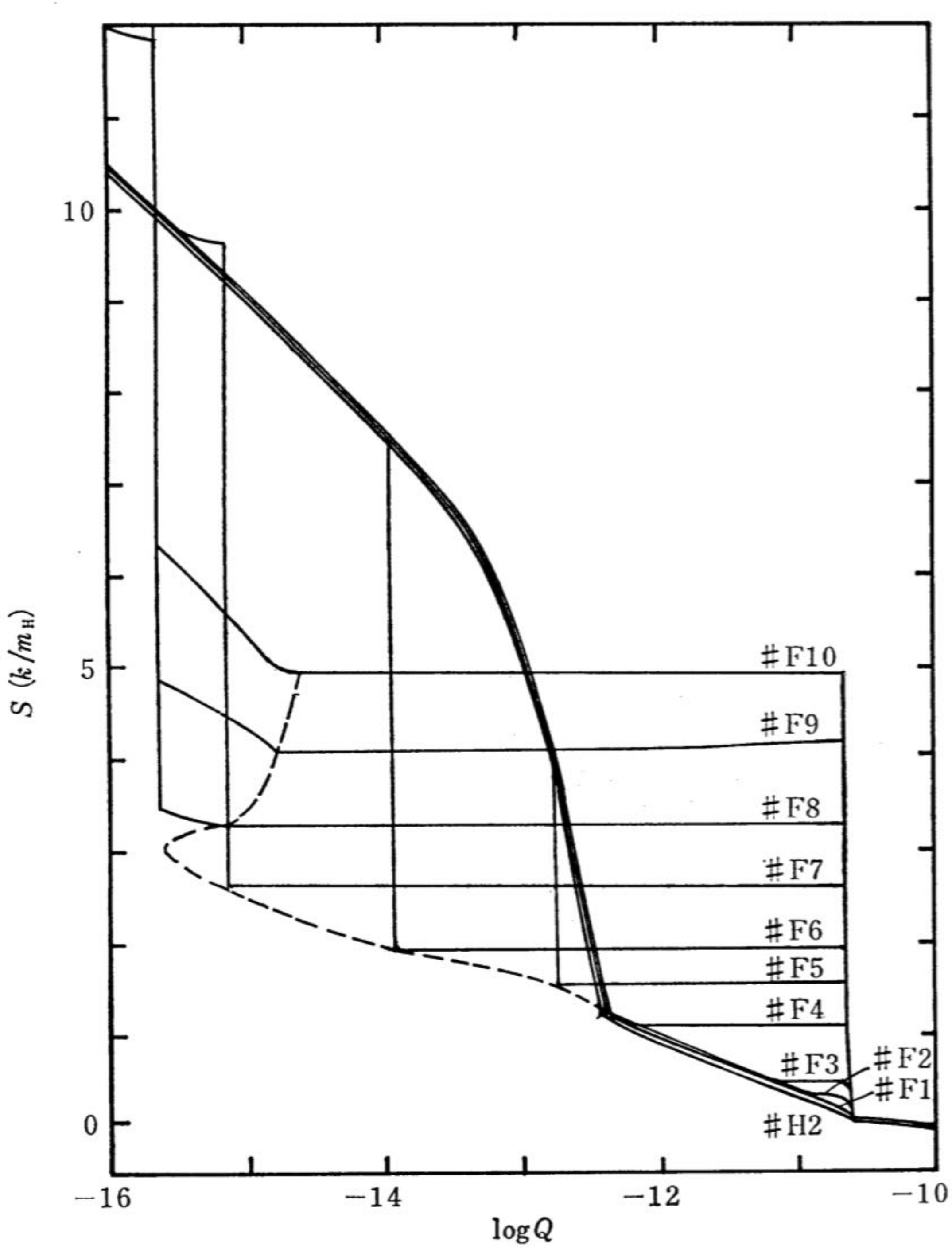
$$\left(\frac{ds}{dt}\right)_{\rm conv} \approx L_{\rm nuc} \Big/ \int_{\rm conv} dm\, T$$

$$\left(\frac{ds}{dt}\right)_{\rm rad} \approx L_{\rm rad} \Big/ \int_{\rm rad} dm\, T$$

=> $$\frac{L_{\rm rad}}{y_{\rm conv} T_{\rm rad}} \approx \frac{L_{\rm nuc}}{y_b T_b}$$

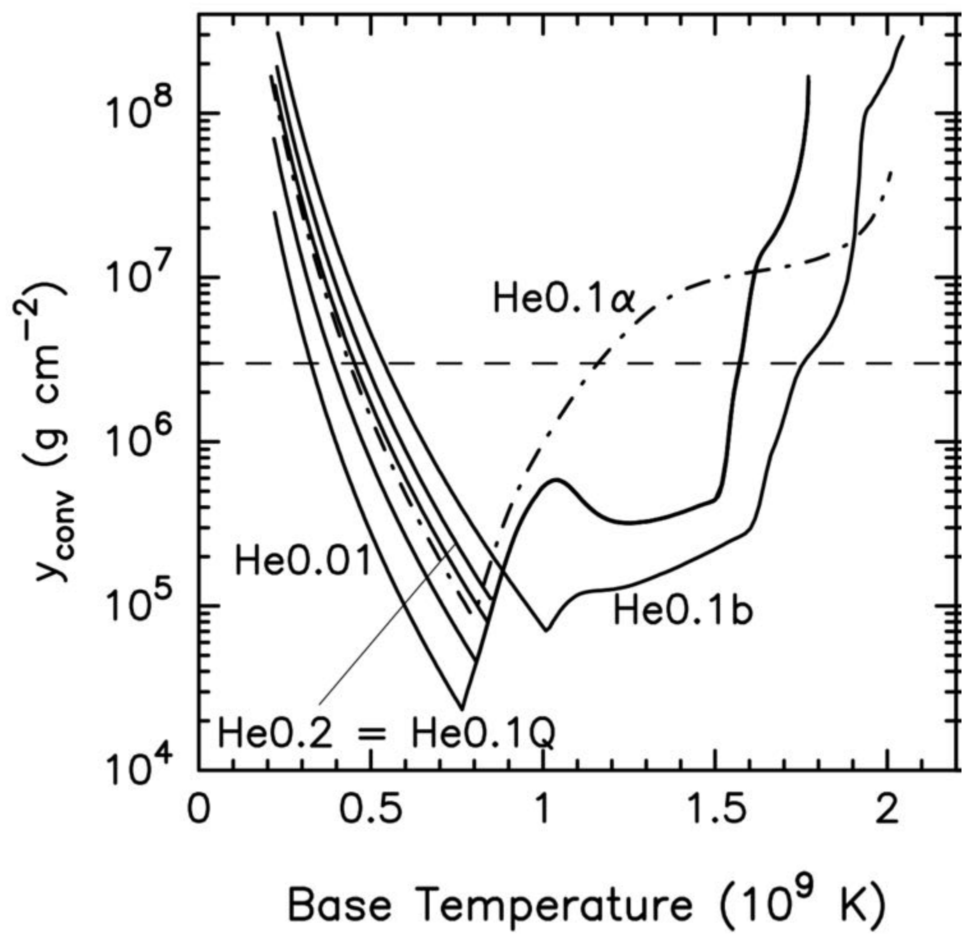
But $$T_{\rm conv} = T_b \left(\frac{y_{\rm conv}}{y_b}\right)^{\nabla_{ad}}$$

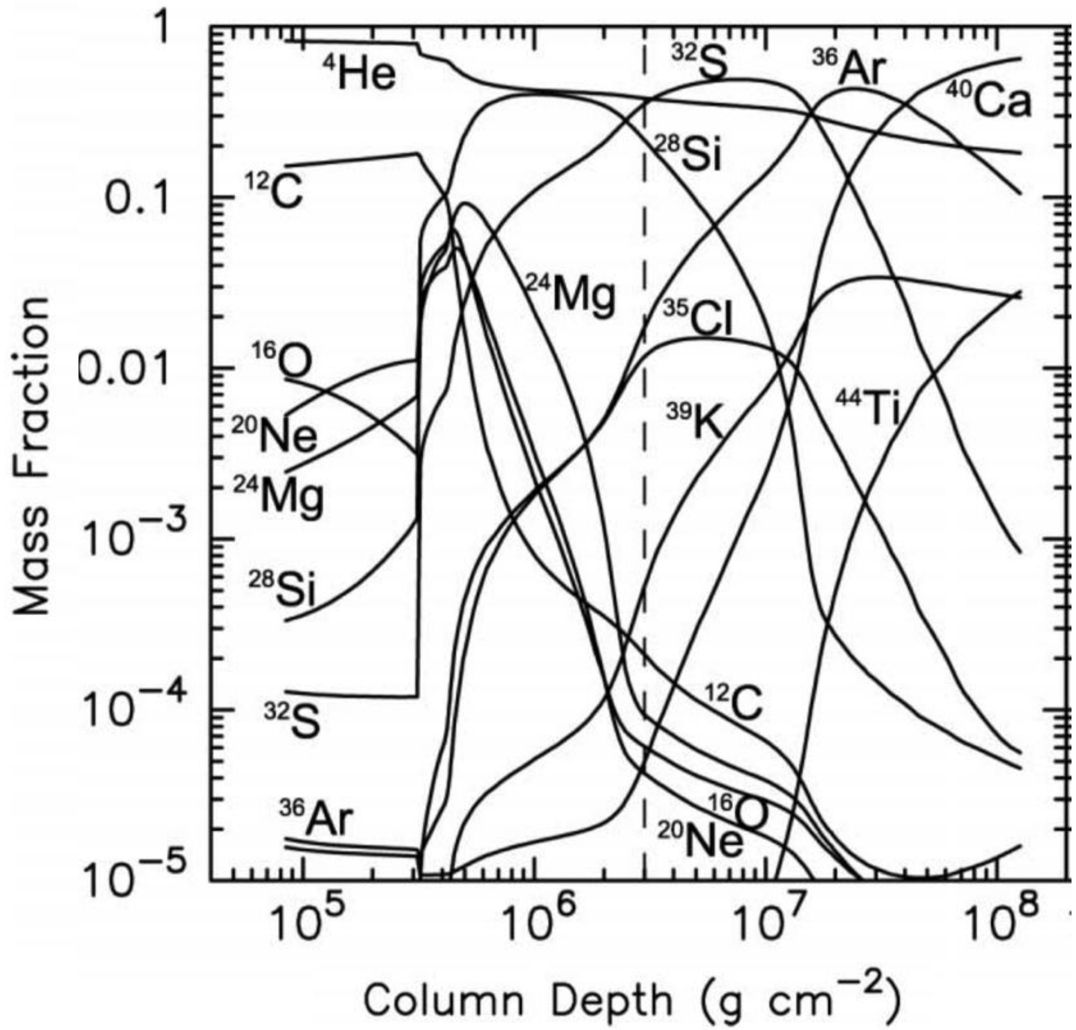
=> $$\boxed{\frac{y_{\rm conv}}{y_b} \approx \left(\frac{L_{\rm rad}}{L_{\rm nuc}}\right)^{\frac{1}{1+\nabla_{ad}}}}$$



Growth of the convection zone including nuclear reactions

Weinberg, Bildsten & Schatz (2006)





Next step: Coupled burst and wind calculations

Three approaches:

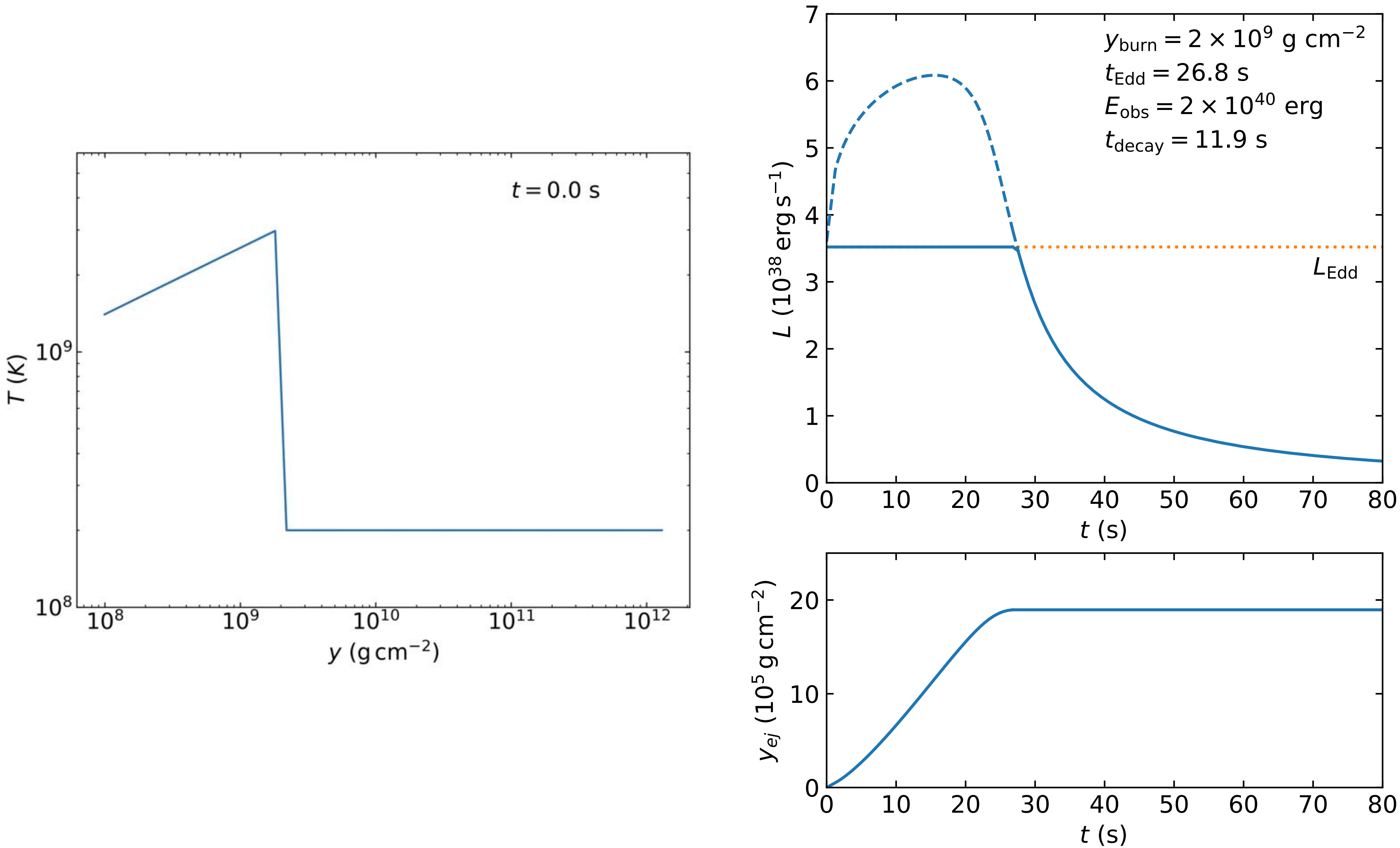
- **include mass loss due to the super-Eddington wind**
  - place the top of the grid deep enough so that radiation pressure sub-dominant / luminosity is < Eddington
  - the mass loss rate is set by comparing the luminosity at the top of the grid with the Eddington luminosity at infinity
  - can follow composition being ejected over time

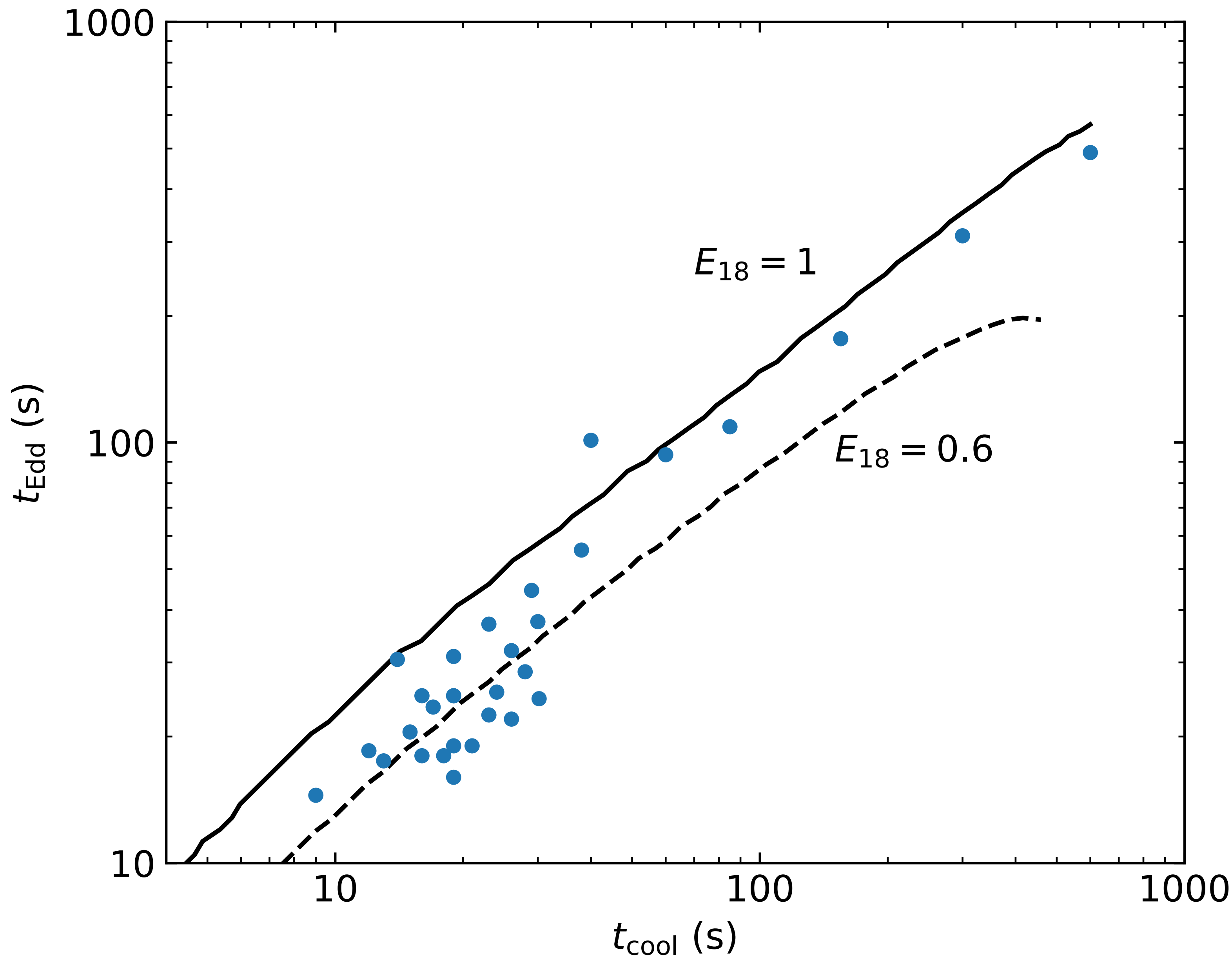
- **use steady-state wind models as an outer boundary condition for the stellar evolution code**
  - locate the grid outer boundary below the depth where wind is generated ($v>0$)
  - can predict e.g. photospheric radius as a function of time
  - might want to compute on the fly to use correct composition

- **extend the grid outwards and follow the time-dependent burning layer and wind simultaneously**

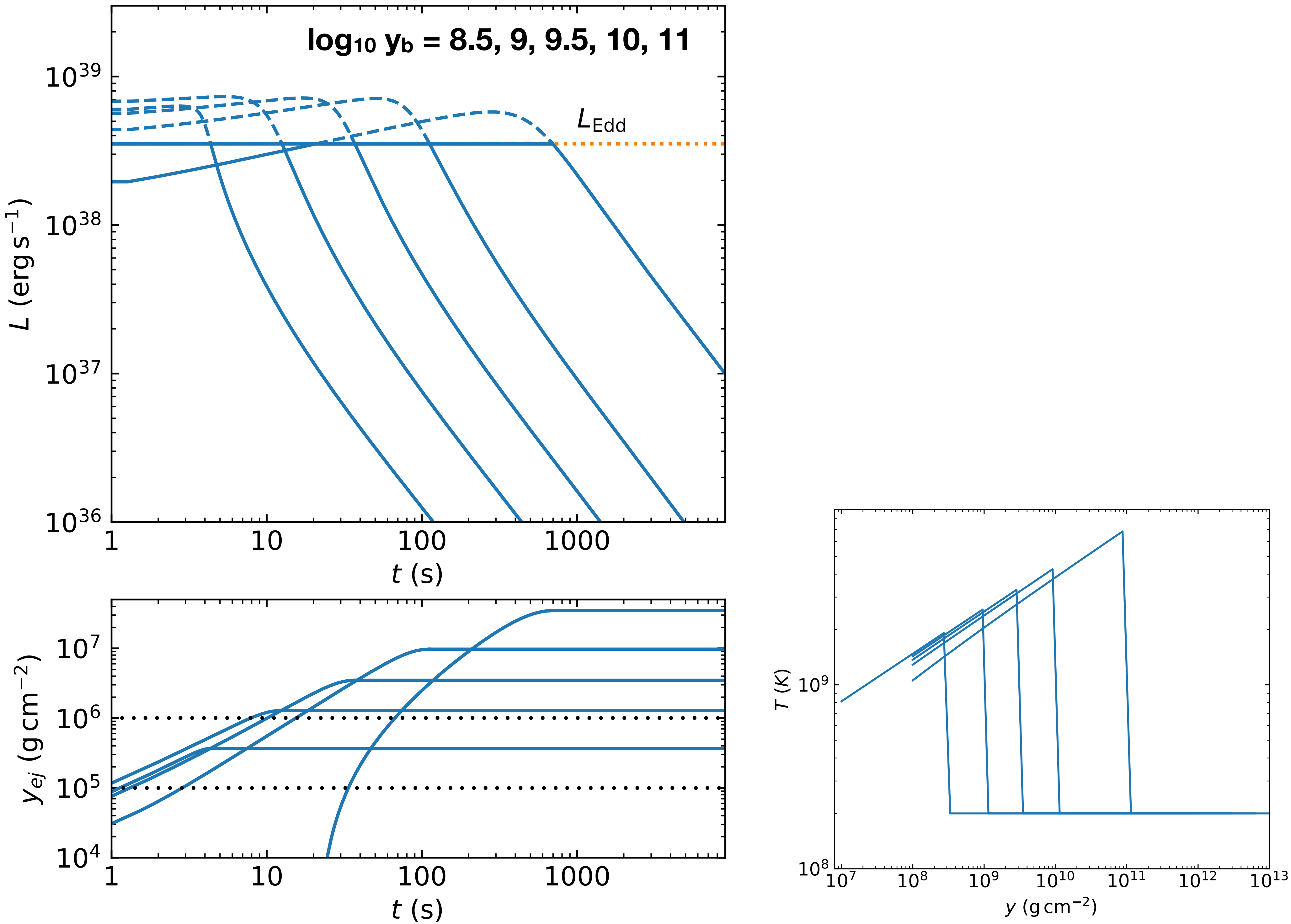
see the paper by Yu & Weinberg (2018) that just came out!

Cooling models for He flashes: heat the layer at the beginning and let it cool

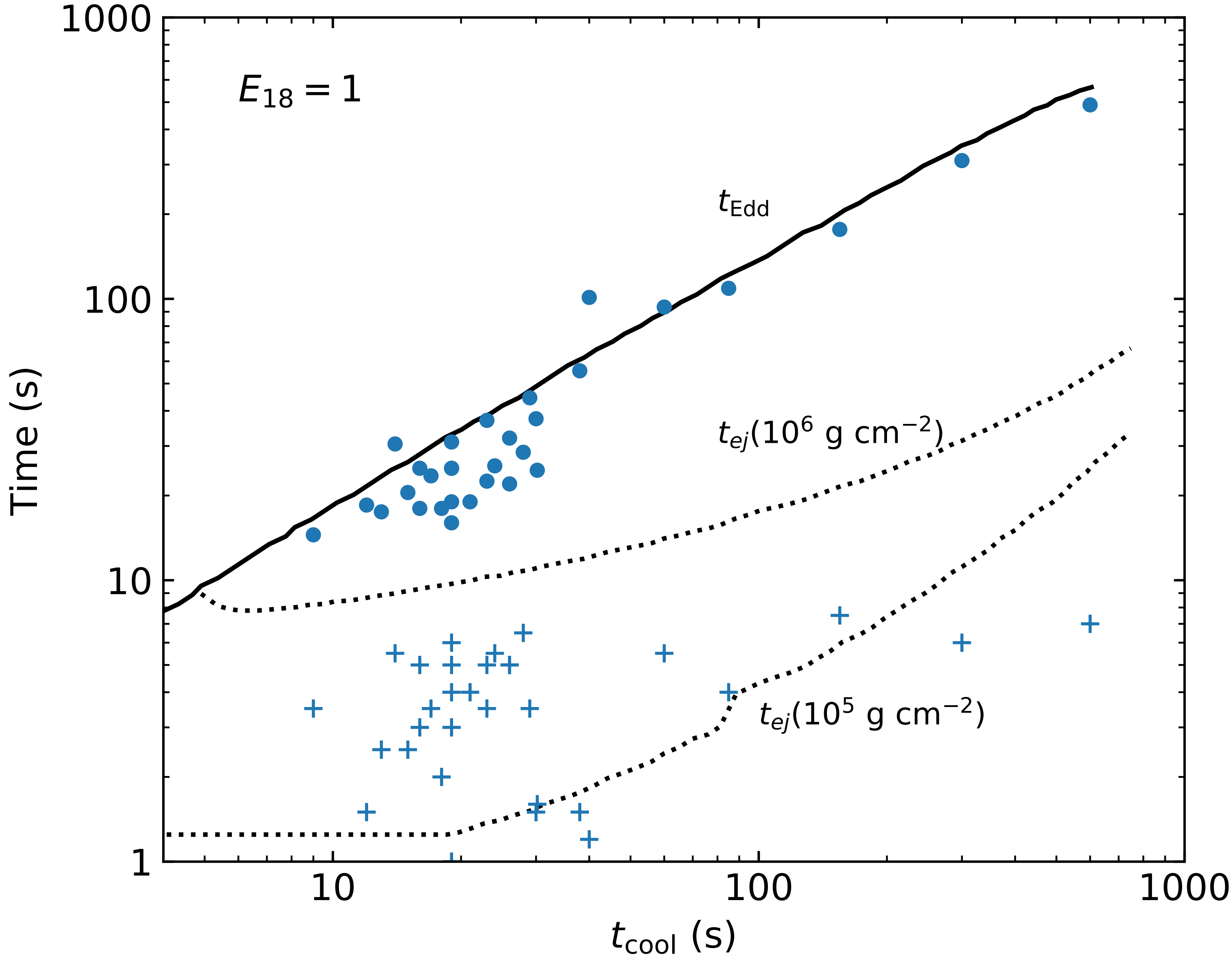




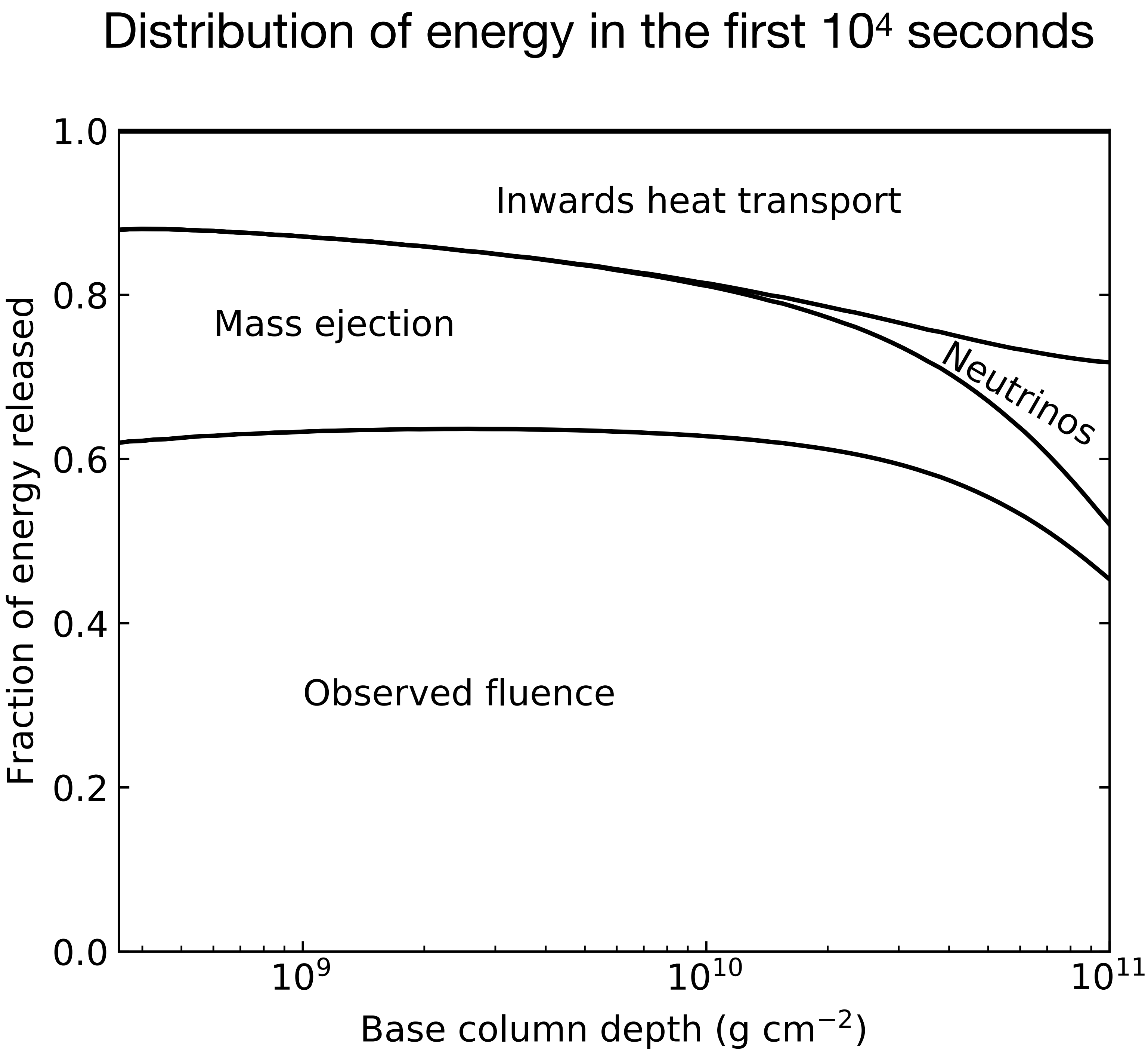
data from in’t Zand & Weinberg (2006)



log10 yb = 8.5, 9, 9.5, 10, 11
L_Edd
L (erg s^-1)
t (s)
y_ej (g cm^-2)
T (K)
y (g cm^-2)



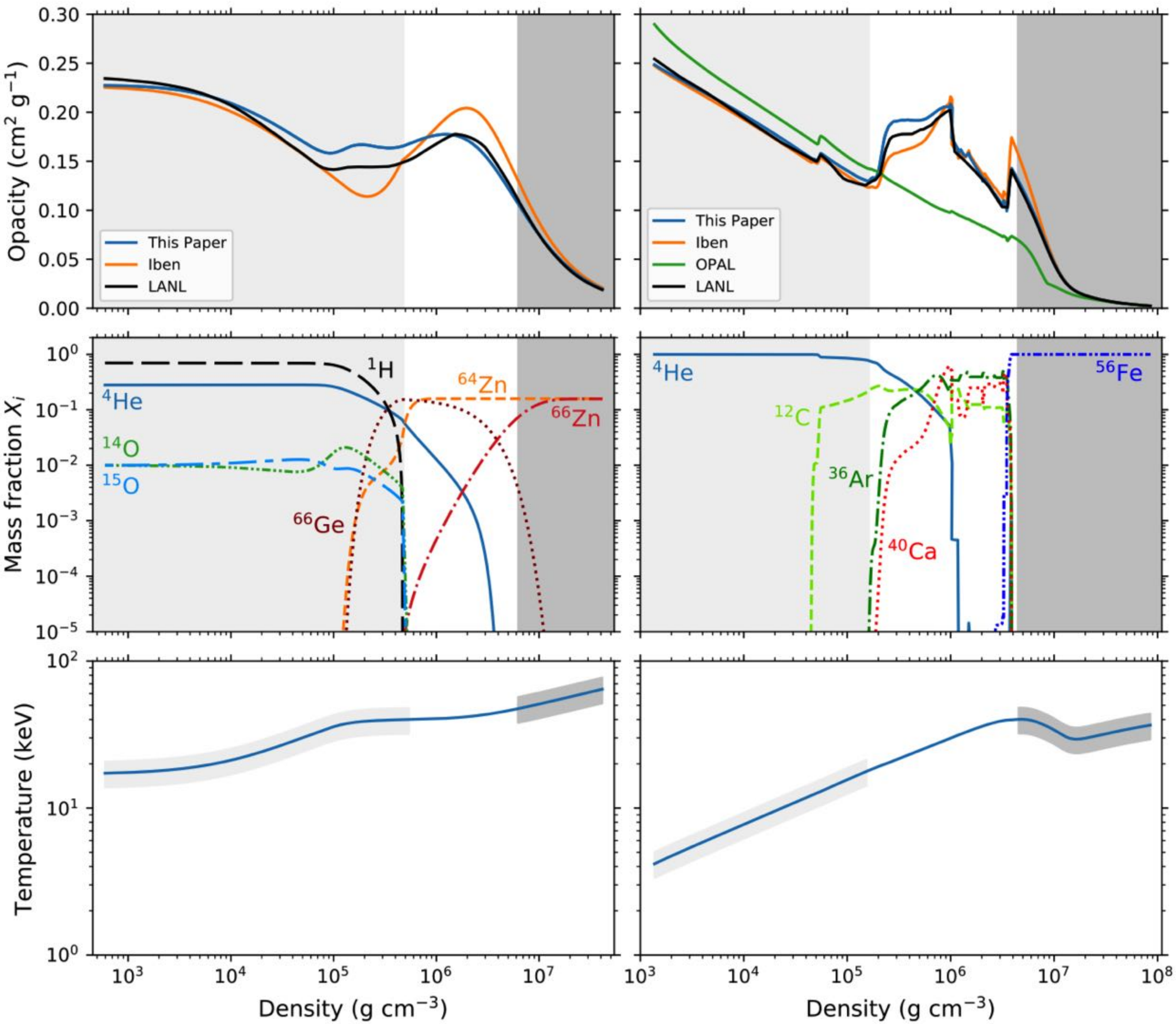
$E_{18} = 1$
$t_{\rm Edd}$
$t_{ej}(10^6$ g cm$^{-2})$
$t_{ej}(10^5$ g cm$^{-2})$
Time (s)
$t_{\rm cool}$ (s)
1000
100
10
1
10
100
1000



Distribution of energy in the first 10⁴ seconds
Inwards heat transport
Mass ejection
Neutrinos
Observed fluence
Fraction of energy released
Base column depth (g cm⁻²)
1.0
0.8
0.6
0.4
0.2
0.0
10^9
10^10
10^11

Opacities in Type I X-ray bursts

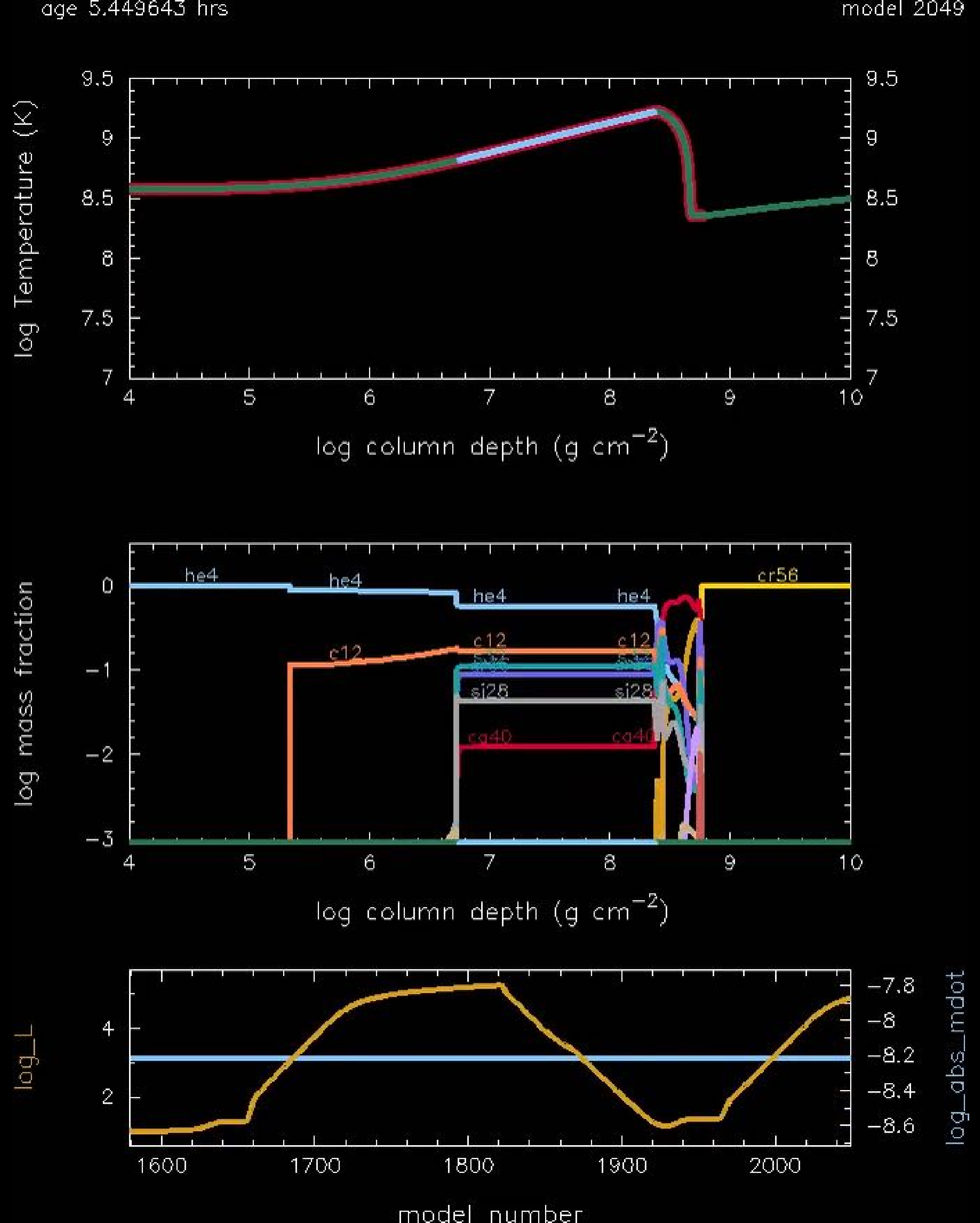
Pelletier et al. (2018) in prep



use LANL opacities to check and calibrate opacity prescriptions used in Type I X-ray burst models

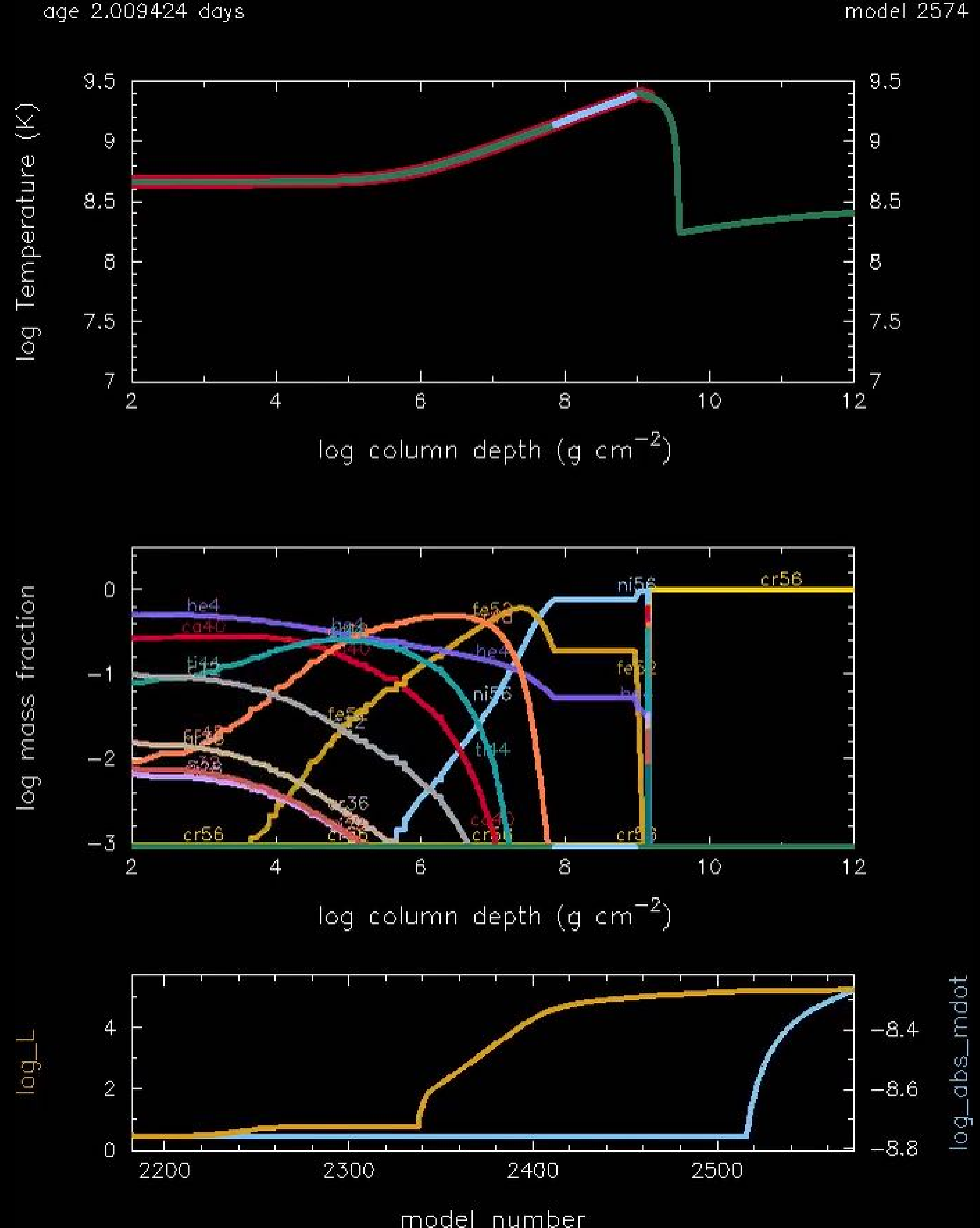
MESA uses OPAL - off by factor of 2 for heavy ashes

0.2 Eddington
0.4 MeV/nuc



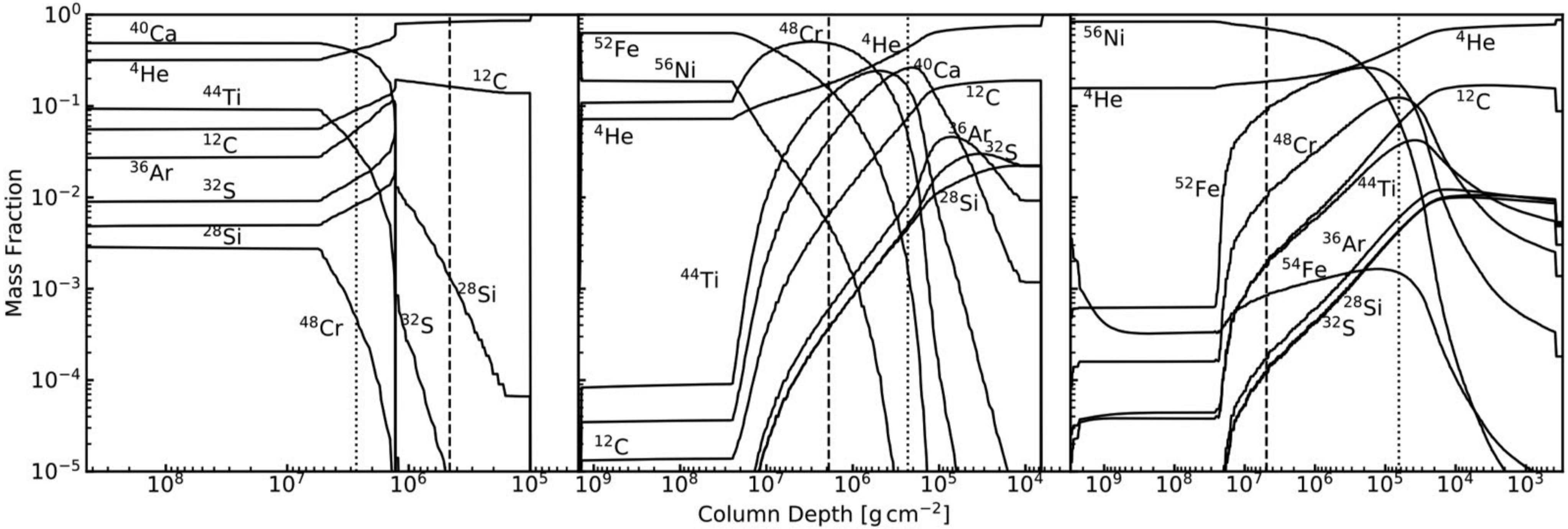
Simulations with MESA star, including prescription for super Eddington wind

0.1 Eddington
0.1 MeV/nuc



Simulations with MESA star, including prescription for super Eddington wind

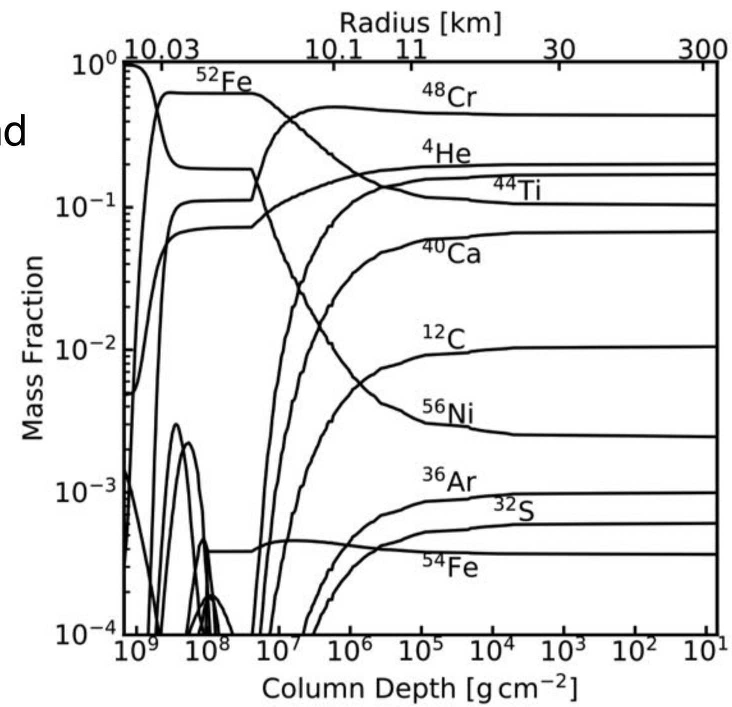
Yu & Weinberg (2018)



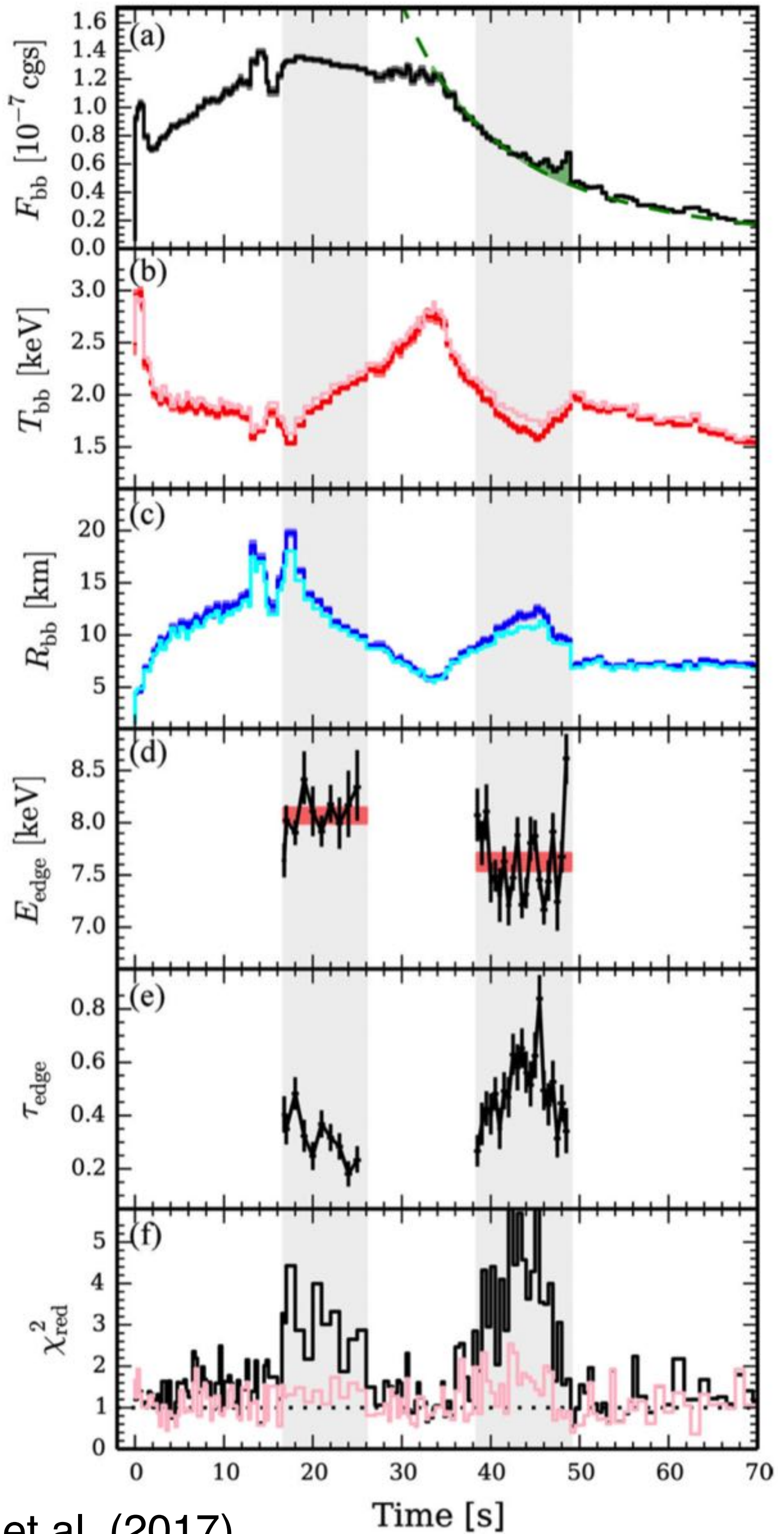
Run an X-ray burst calculation in MESA until $L=L_{Edd}$ at the upper boundary

then restart calculation with MESA's hydrodynamics turned on to follow the wind

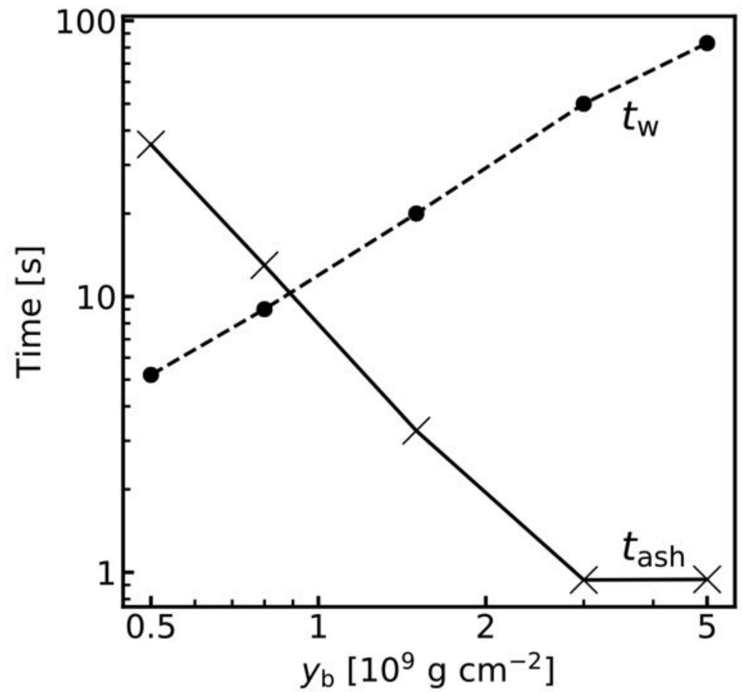
during wind phase



Absorption edges appear ~ 15 seconds into the 30 second Eddington phase



Kajava et al. (2017)



Yu & Weinberg (2018)

Conclusions

- photospheric radius expansion bursts with mass loss can tell us a lot about Type I X-ray burst physics, as the wind “peels away” the burning products laid down by convection

- more work needed to couple burst simulations with wind models

- even with existing models, there are more comparisons that we can do with data on PRE’s

- if you’re working with MESA, check radiative opacities for heavy elements

- open questions:
  - what effect do heavy elements have on the wind structure, spectrum
  - need predictions for specific elements, e.g. Fe-peak will take longer to emerge, will only be there for more energetic bursts
  - beyond 1D?
  - does the timing of the HETE J1900 observations make sense (edges seen ~ 1/2 through the Eddington phase)