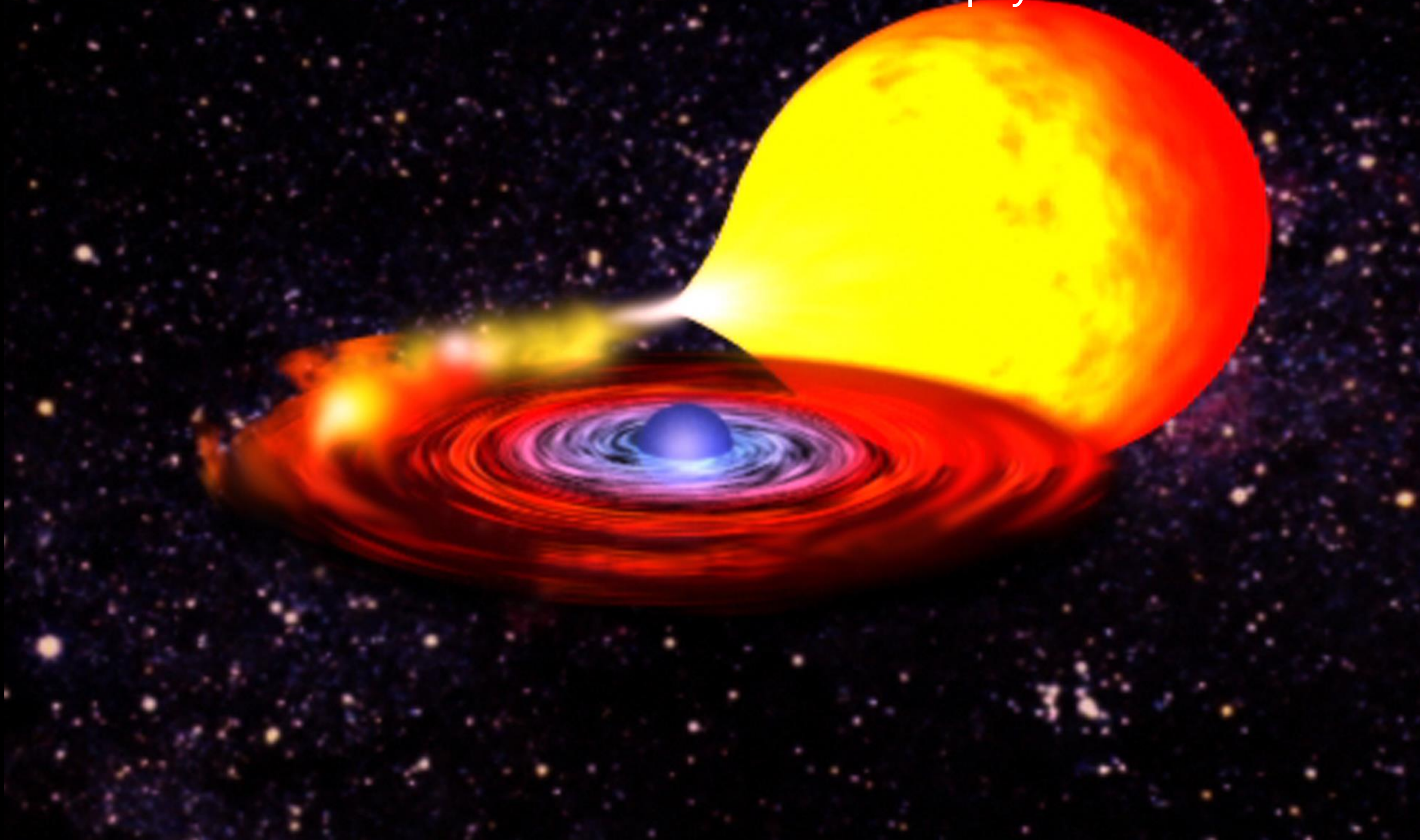
Rare Isotopes are
Heating and Cooling the Crust of Accreting Neutron Stars
and what rare isotope facilities can do about it …

H. Schatz
Michigan State University
National Superconducting Cyclotron Laboratory
Joint Institute for Nuclear Astrophysics

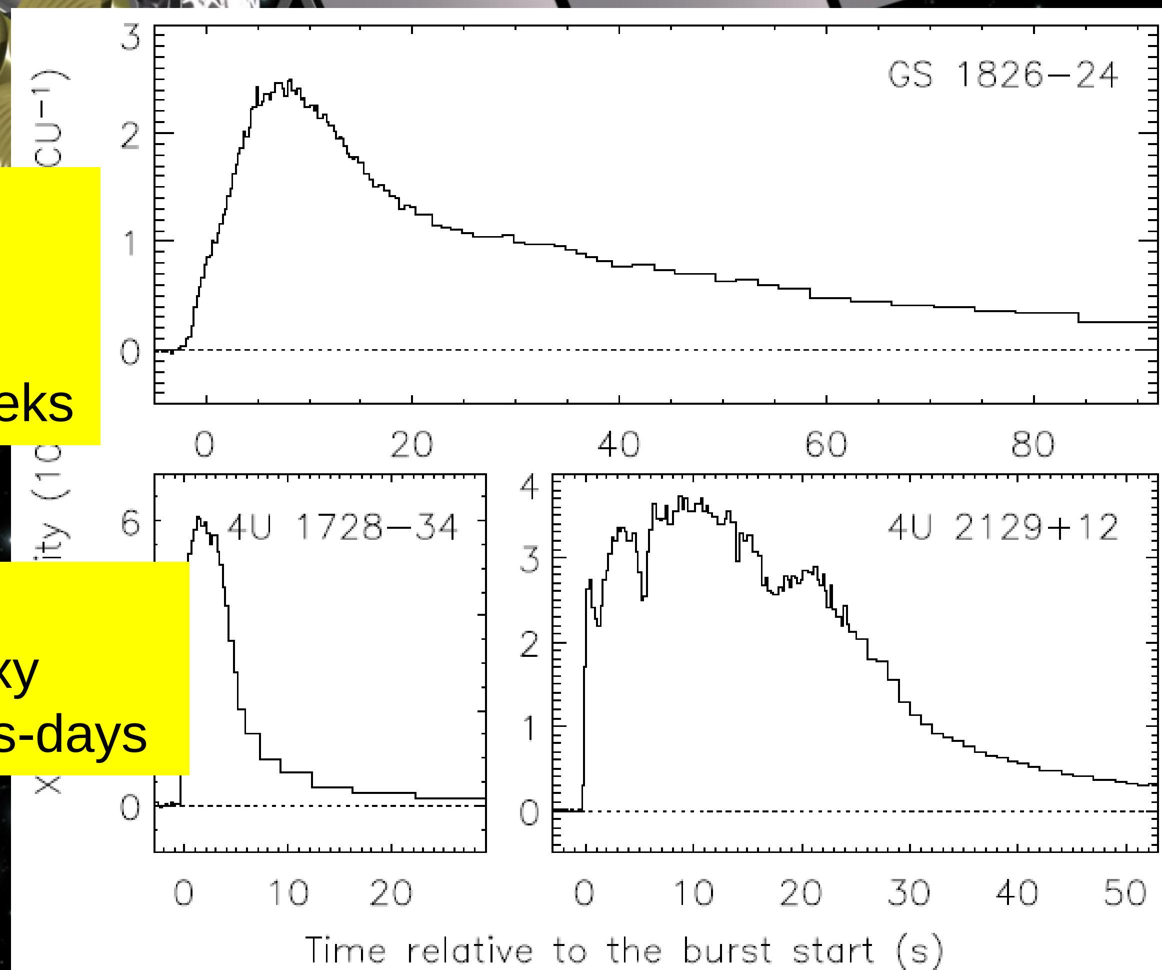


X-ray bursts

Most common thermonuclear explosions observed

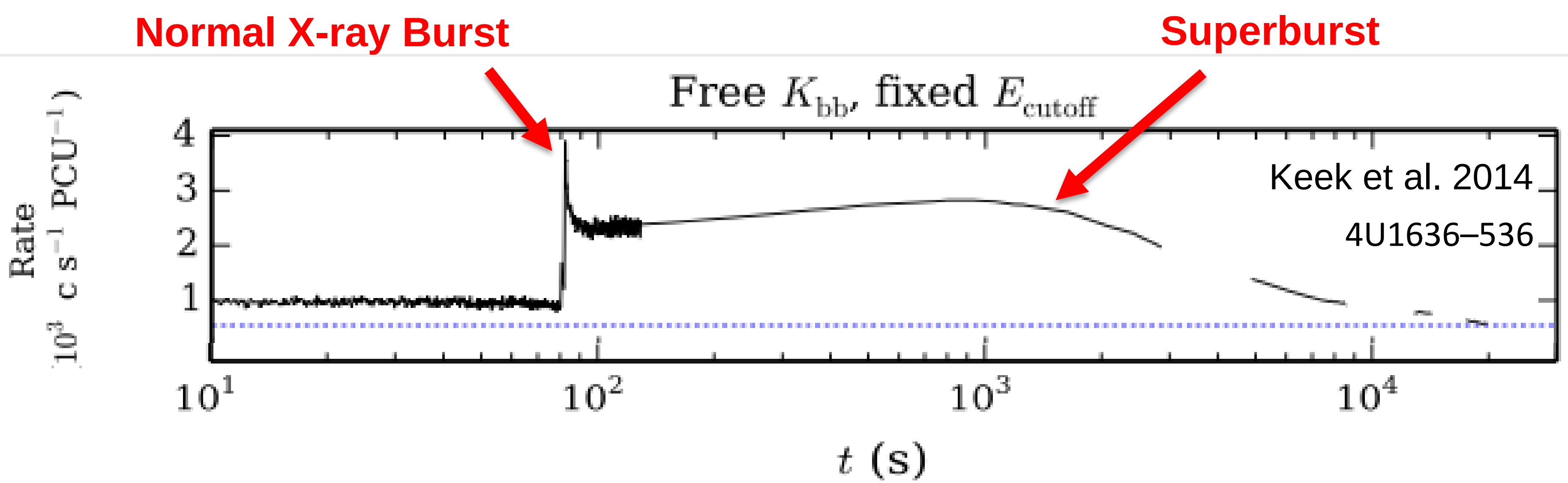
Bright:
Releases in 10s
as much energy
as the sun in a few weeks

Frequent:
~ 100 systems in Galaxy
recurrence times: hours-days



XMM Newton

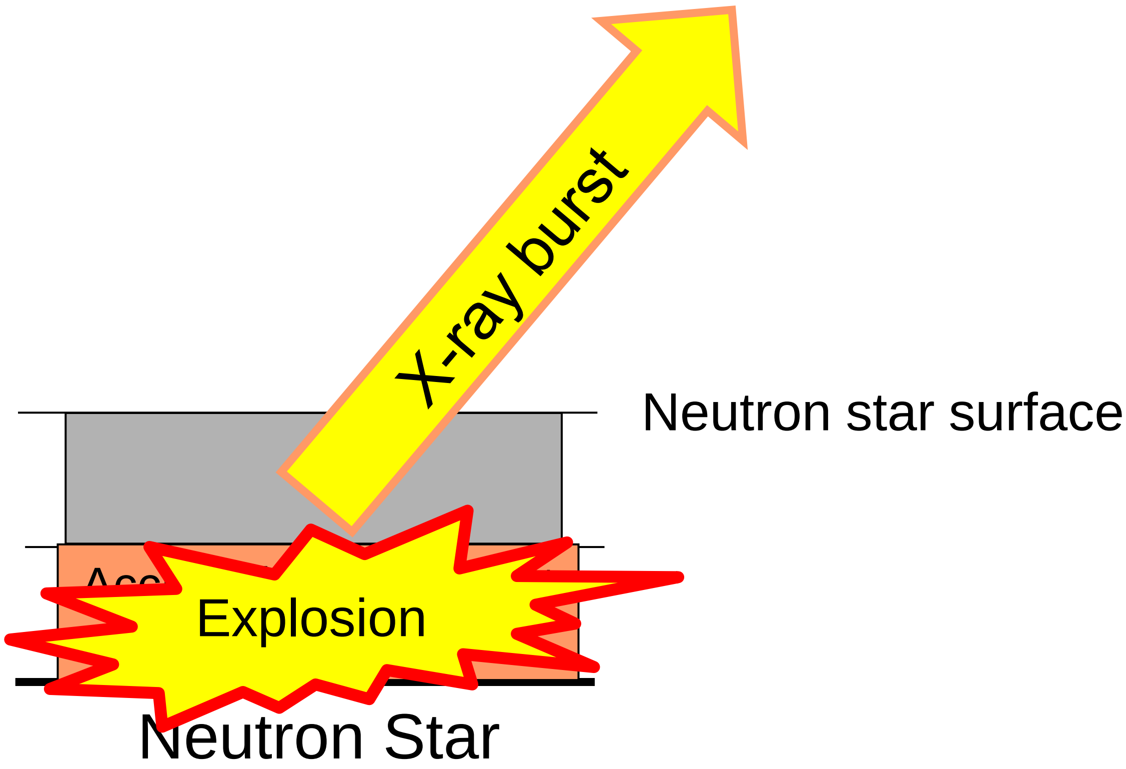
Occasionally Superbursts Occur



~22 superbursts bursts from 13 sources
recurrence time 1-2 years

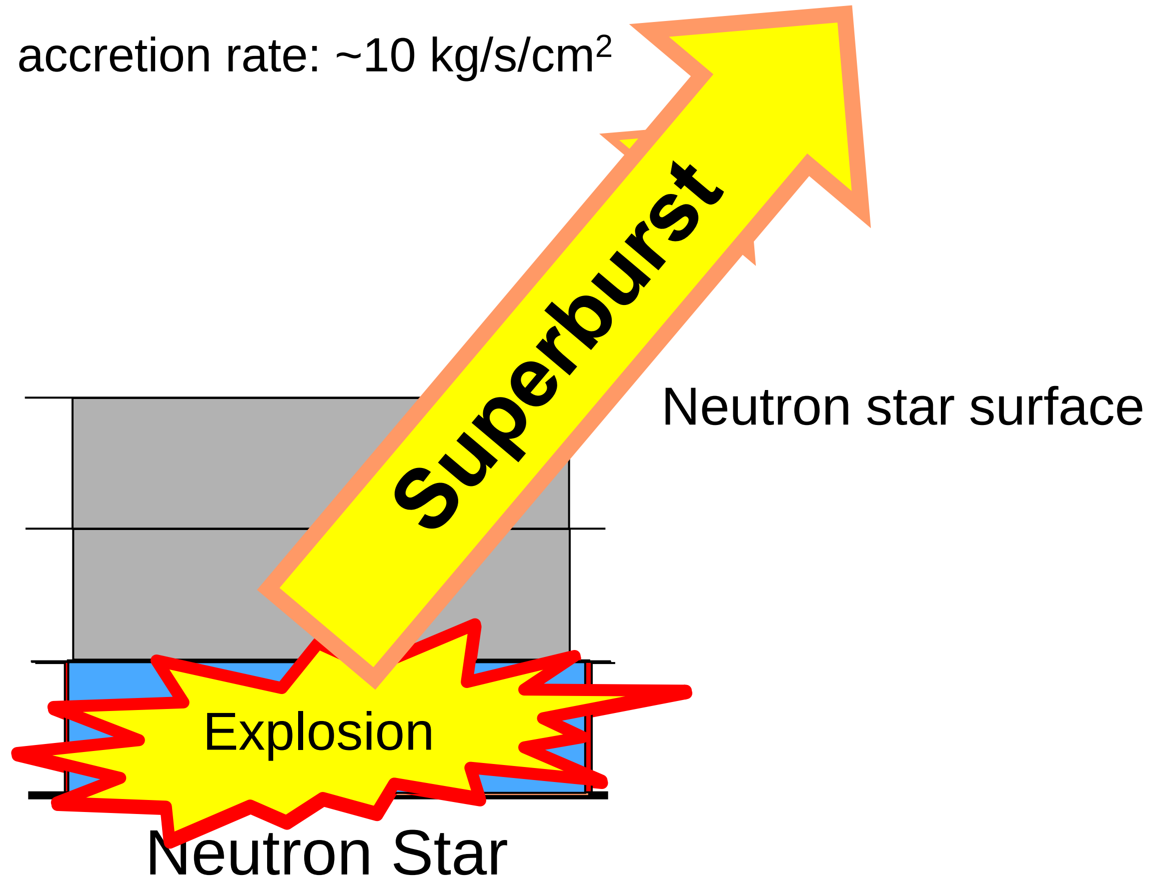
Fate of matter accreted onto a neutron star

accretion rate: ~10 kg/s/cm^2



This talk: continue to follow fate of fluid element
Remember: time = depth

Fate of matter accreted onto a neutron star

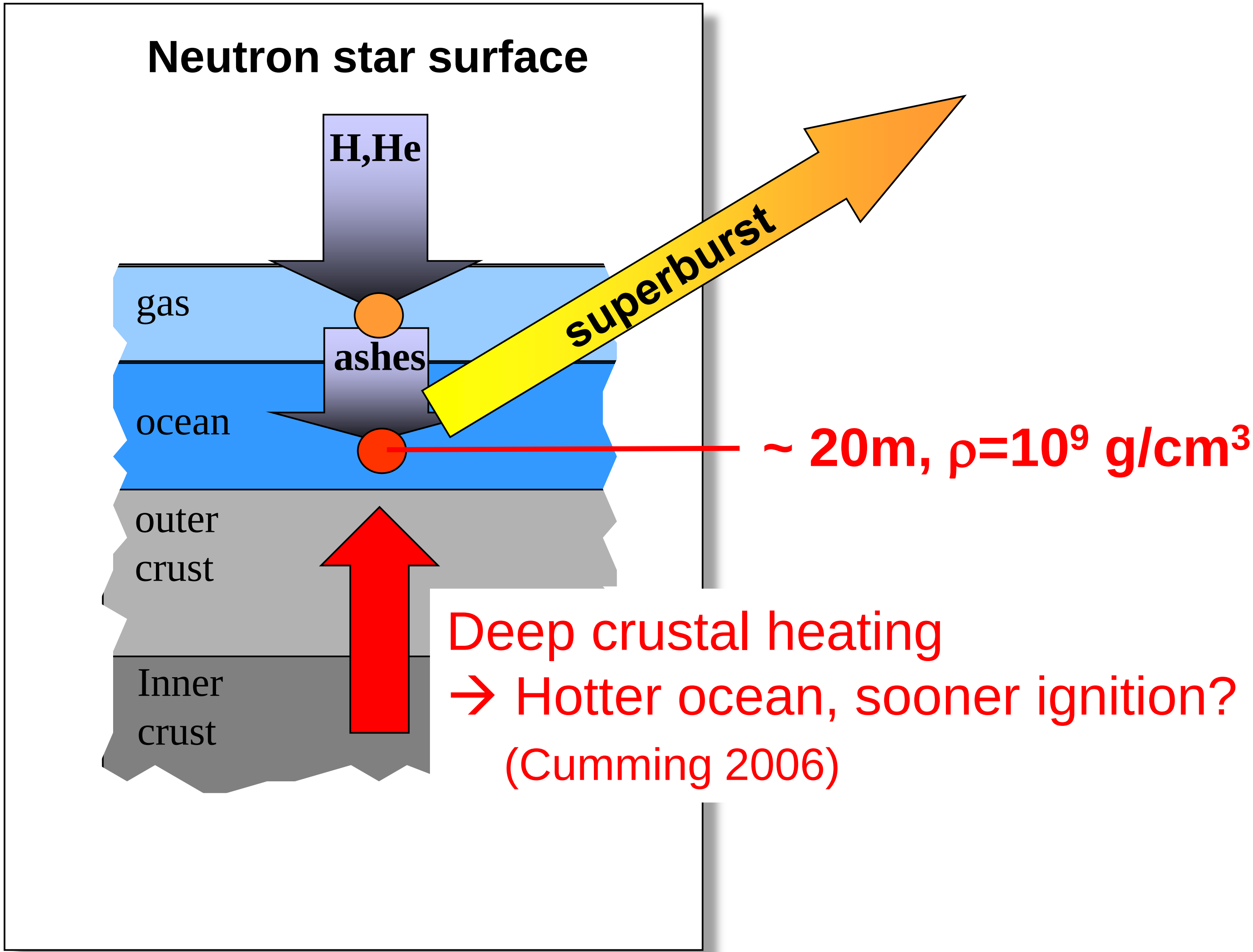


Carbon ignition model works (Cumming and Bildsten 2001, Strohmayer and Brown 2002)

Problems:

- Not enough carbon produced in X-ray bursts
  (phase separation? Horowitz et al. 2007, Medin&Cumming 2011)
- Model recurrence time is 10-100 yr instead of 0.9-2 yr

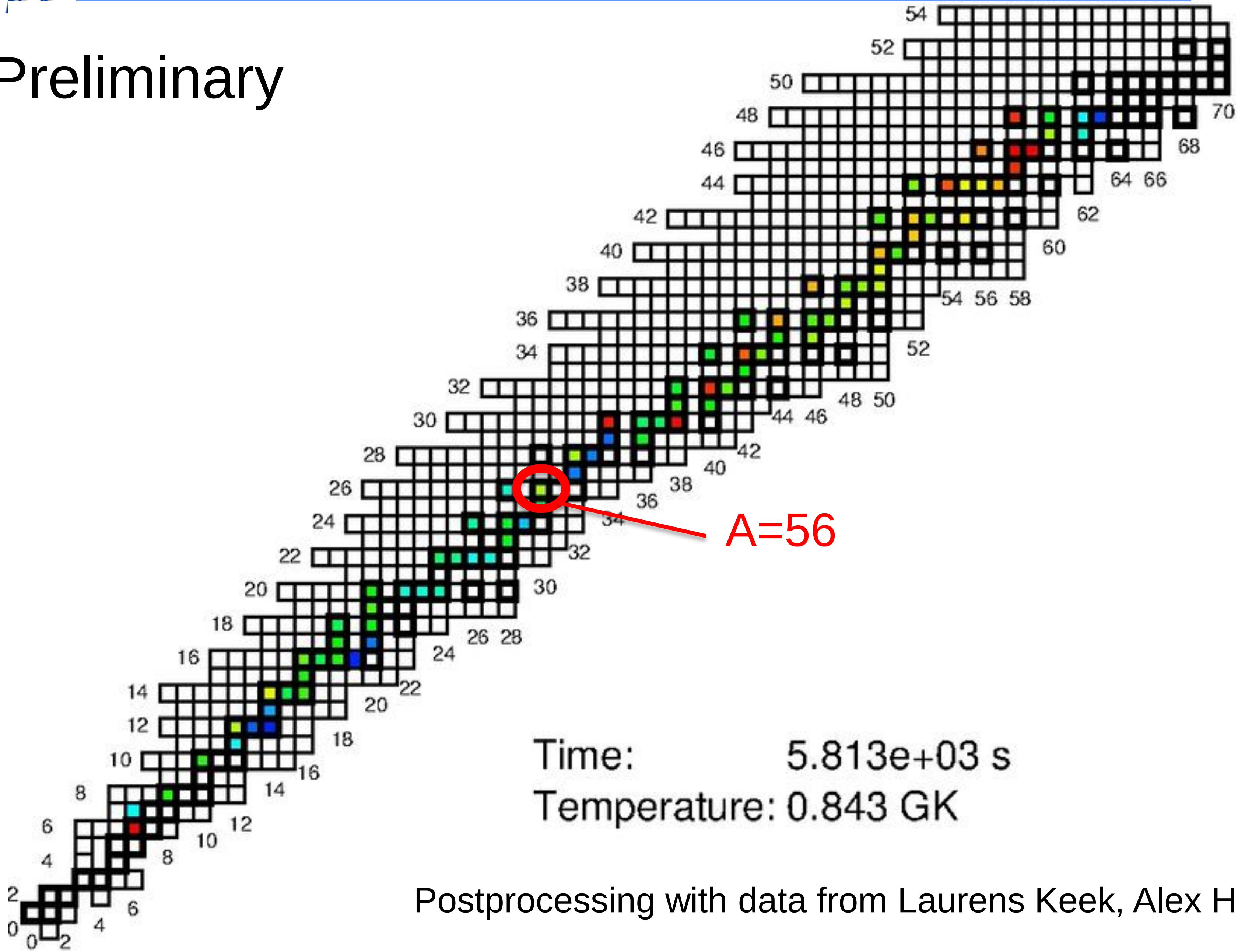
How can we make the ocean hotter?



Deep crustal heating
→ Hotter ocean, sooner ignition?
(Cumming 2006)

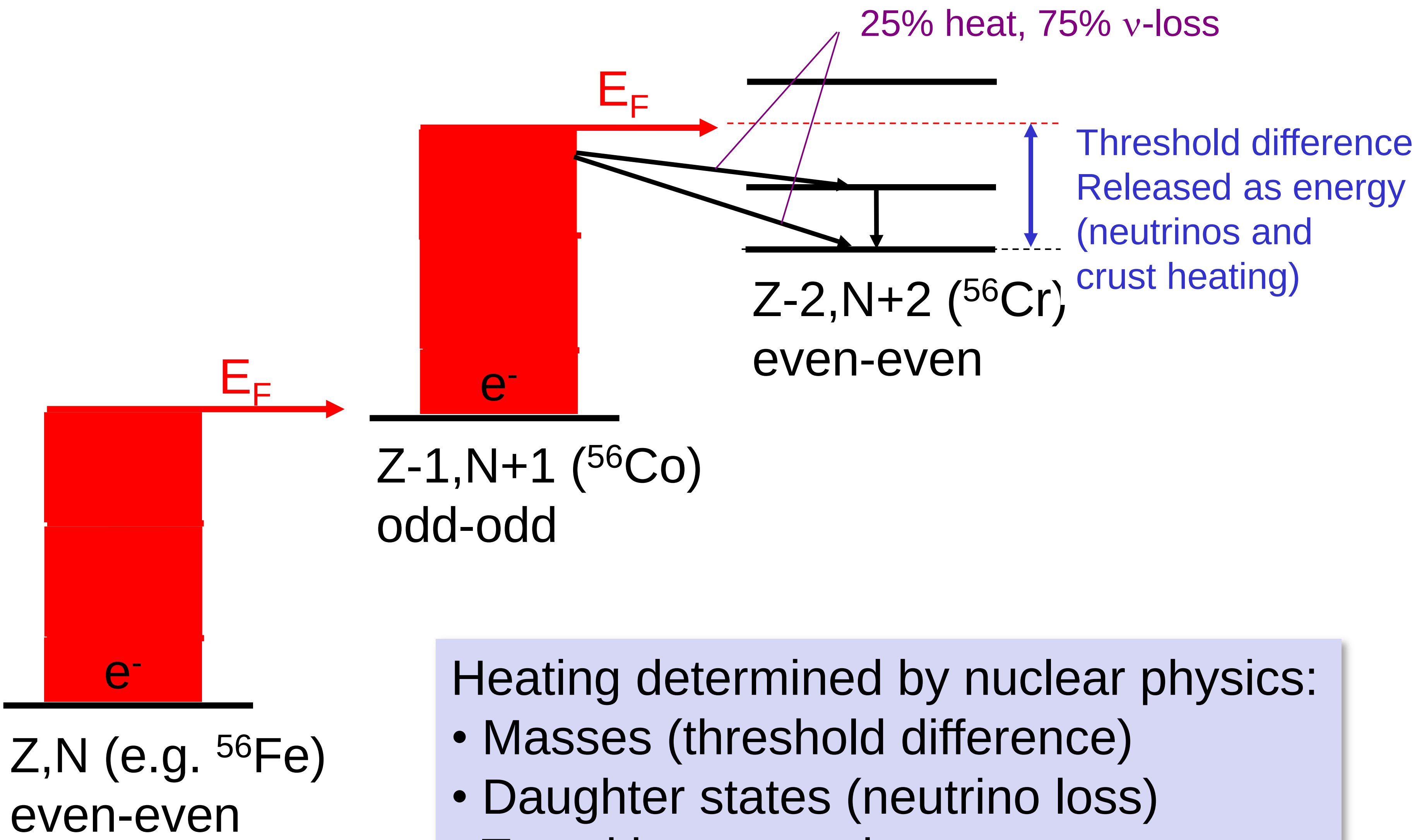
Nuclear processes during superburst

Preliminary



Postprocessing with data from Laurens Keek, Alex Heger

Crustal heating by pairing



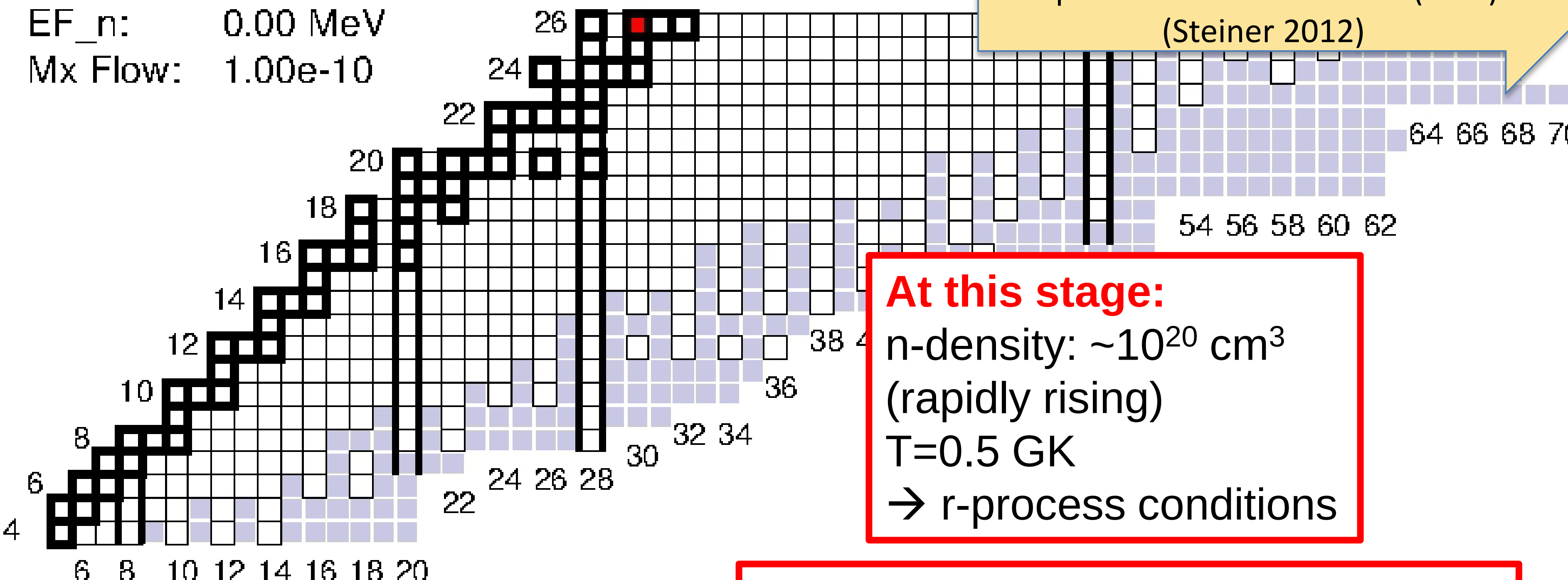
Heating determined by nuclear physics:
- Masses (threshold difference)
- Daughter states (neutrino loss)
- Transition strengths

Crust processes: Electron capture and neutron emission

Masses: FRDM
Electron capture/β-decay: QRPA (P. Möller, S. Gupta)
Neutron capture: TALYS,
degeneracy and plasma corrections (Shternin et al. 2012)
(Caballero, Beard et al. in prep)
Fusion reactions: Beard, Gasques,Yakovlev et al.

Time:	4.525e+08 s
Temp:	0.50 GK
Density:	3.43e+09 g/cm^3
Yn:	0.00e+00
EF_e:	5.54 MeV
EF_n:	0.00 MeV
Mx Flow:	1.00e-10

Equilibrium nucleus: N=82 (^{120}Sr)
(Steiner 2012)



At this stage:
n-density: ~10^{20} cm^3
(rapidly rising)
T=0.5 GK
→ r-process conditions

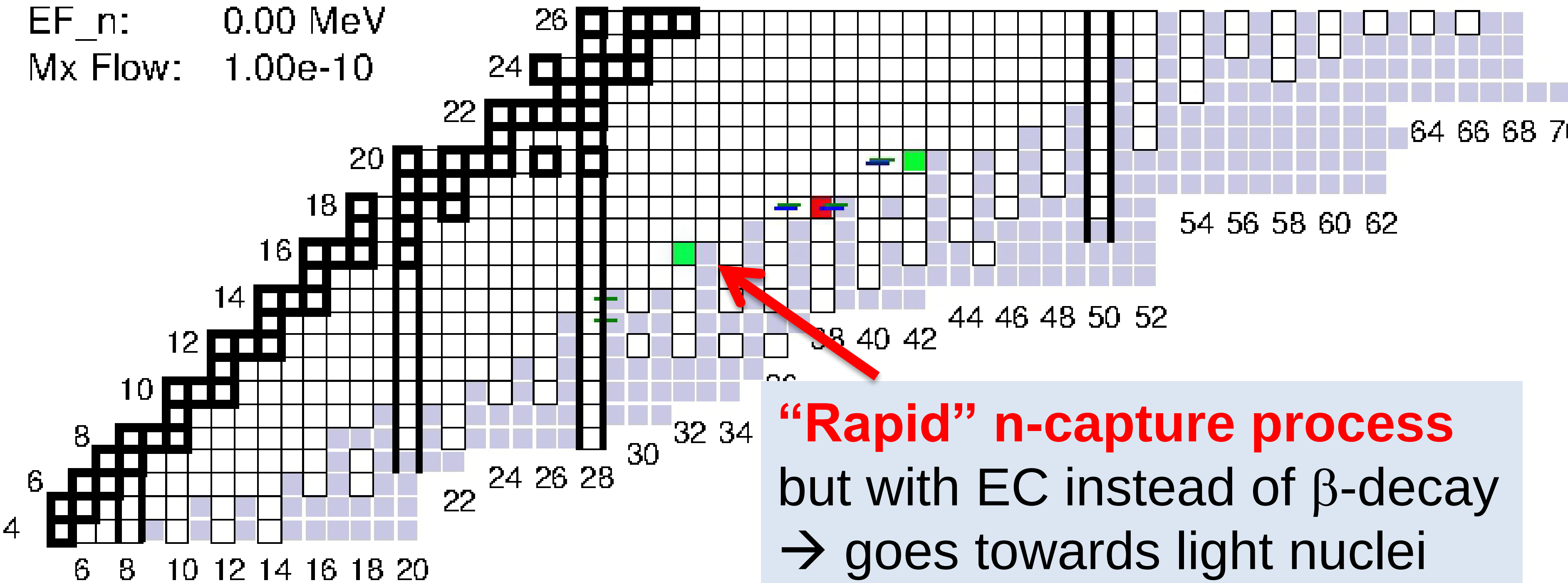
BUT electron Fermi energy is high
→ e-capture competes with n-capture
→ Who wins?

EC, (n,γ)
β-decay, (γ,n), fusion

Crust processes: Electron capture and neutron emission

Masses: FRDM
Electron capture/β-decay: QRPA (P. Möller, S. Gupta)
Neutron capture: TALYS,
degeneracy and plasma corrections (Shternin et al. 2012)

Time: 1.698e+11 s
Temp: 0.51 GK
Density: 4.18e+11 g/cm^3
Yn: 5.97e-16
EF_e: 25.93 MeV
EF_n: 0.00 MeV
Mx Flow: 1.00e-10



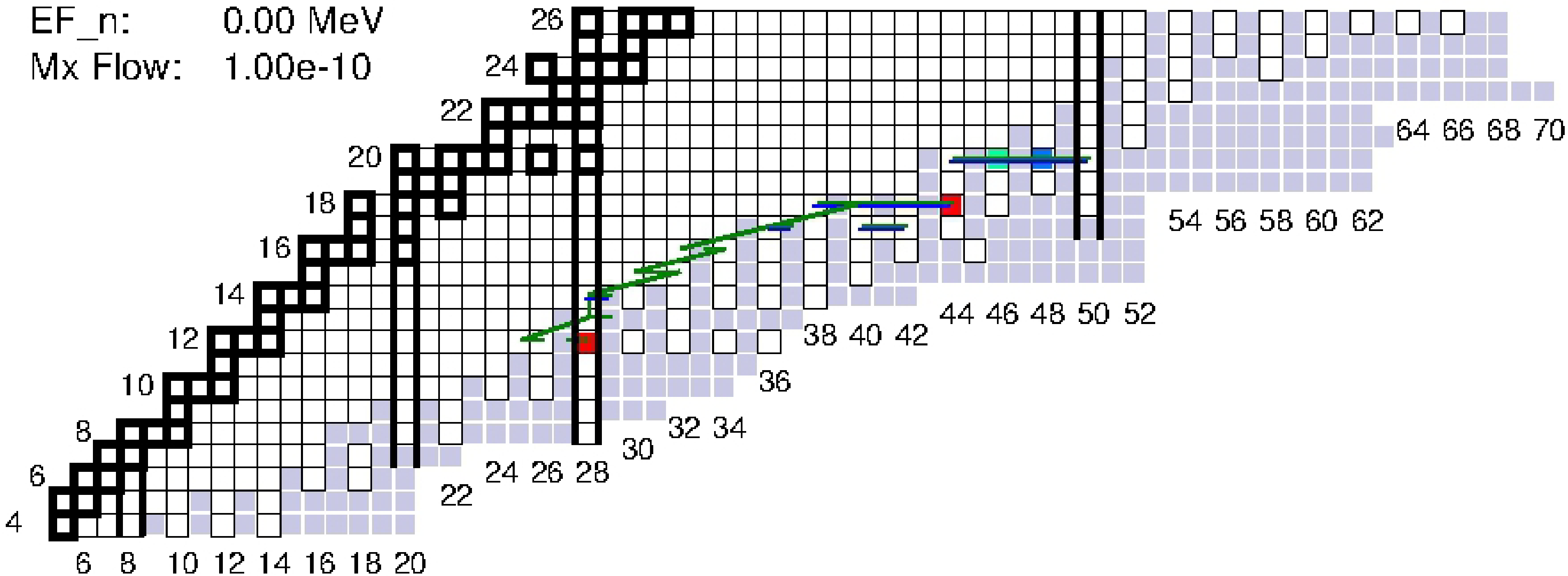
"Rapid" n-capture process
but with EC instead of β-decay
→ goes towards light nuclei

EC, (n,γ)
β-decay, (γ,n), fusion

Crust processes: Electron capture and neutron emission

Masses: FRDM
Electron capture/β-decay: QRPA (P. Möller, S. Gupta)
Neutron capture: TALYS,
degeneracy and plasma corrections (Shternin et al. 2012)

Time:	3.199e+11 s
Temp:	0.50 GK
Density:	7.38e+11 g/cm^3
Yn:	1.35e-06
EF_e:	30.45 MeV
EF_n:	0.00 MeV
Mx Flow:	1.00e-10



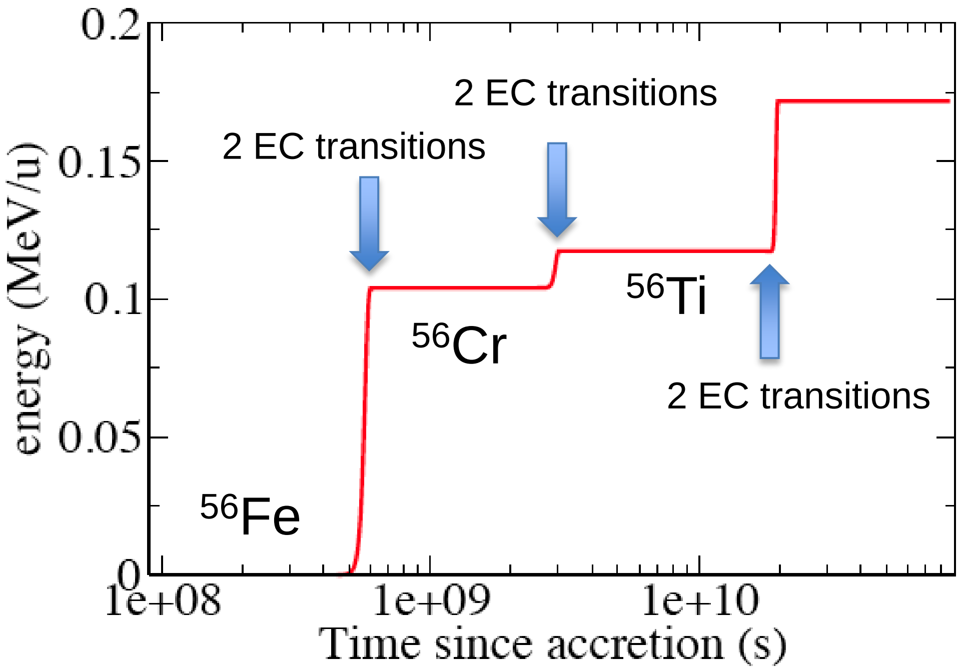
EC, (n,γ)

β-decay, (γ,n), fusion

A=56 material in the crust

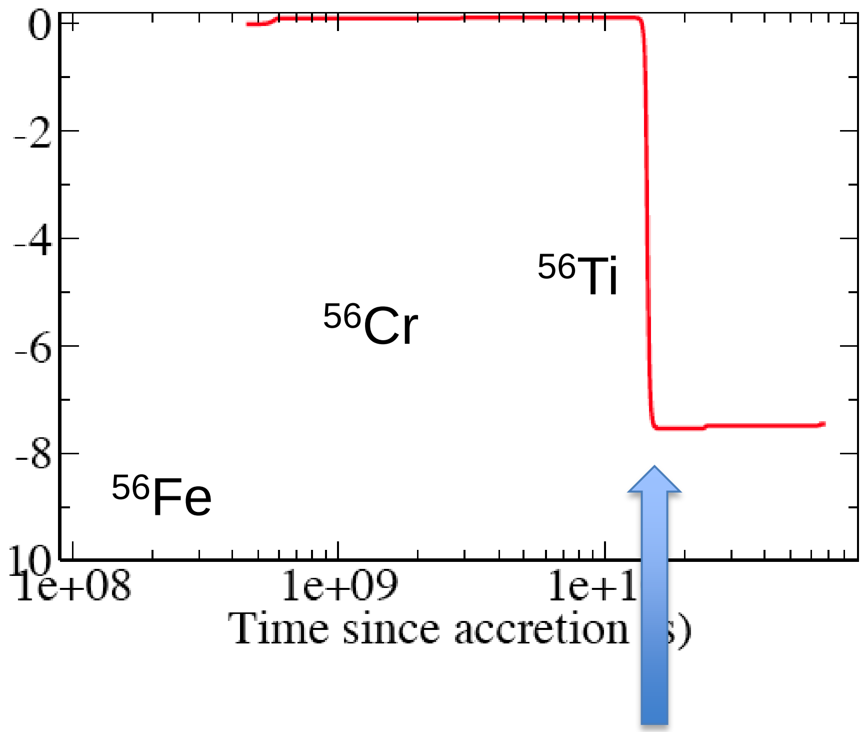
FRDM mass model

Time integrated energy release:



(Gupta, Möller, Kratz et al. 2007)

HFB-21 mass model

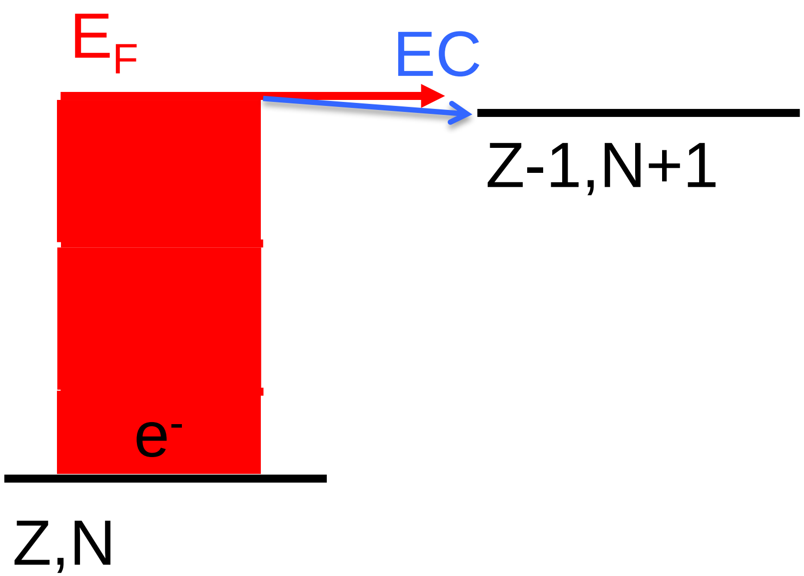


T=0.5 GK

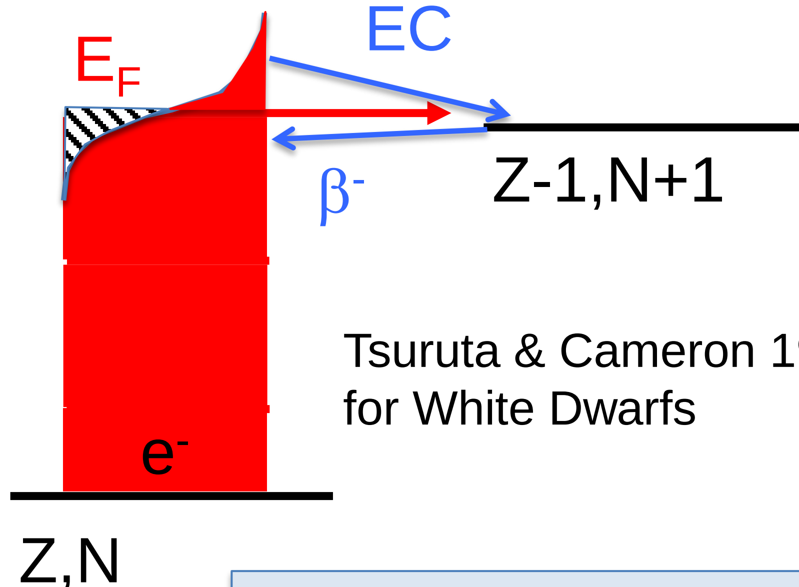
Massive cooling ???

Nuclear Urca process

Zero temperature



finite temperature



Tsuruta & Cameron 1962
for White Dwarfs

$$(Z,N) + e^- \rightarrow (Z-1,N+1) + \nu_e$$

$$(Z-1,N+1) \rightarrow (Z,N) + e^- + \bar{\nu}_e$$

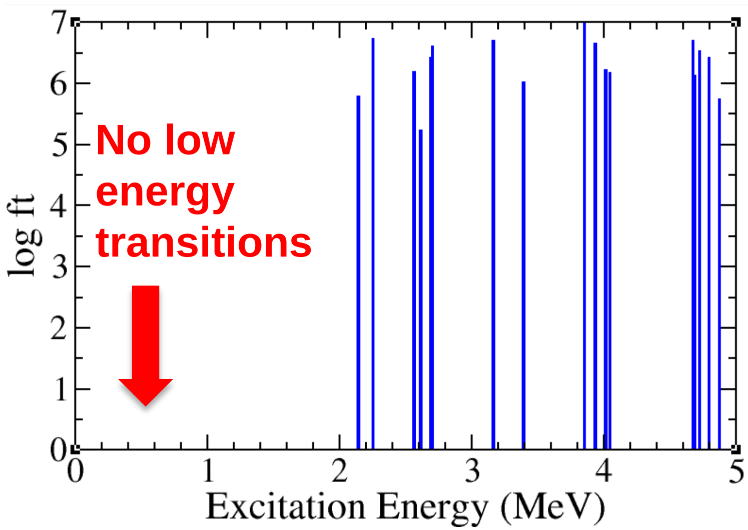
Urca process with nuclei
in thin layer (~1m) at compositional boundary

Occurs only if

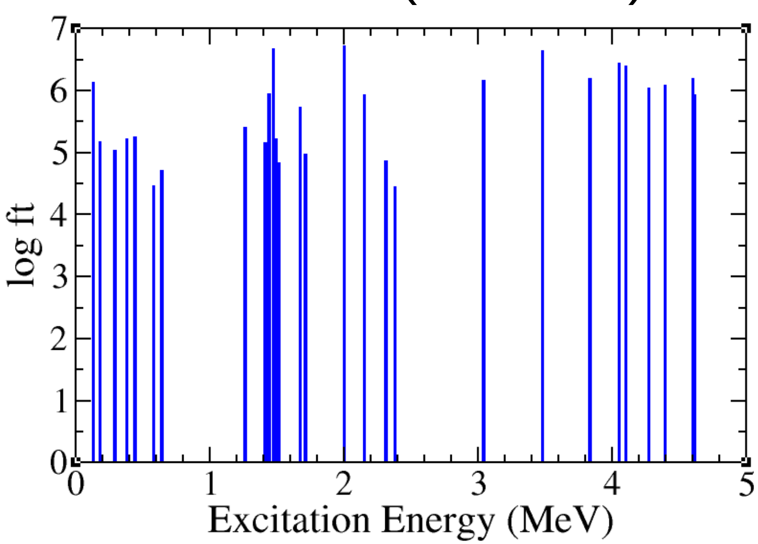
- Low lying transition
- Next EC blocked
  → masses

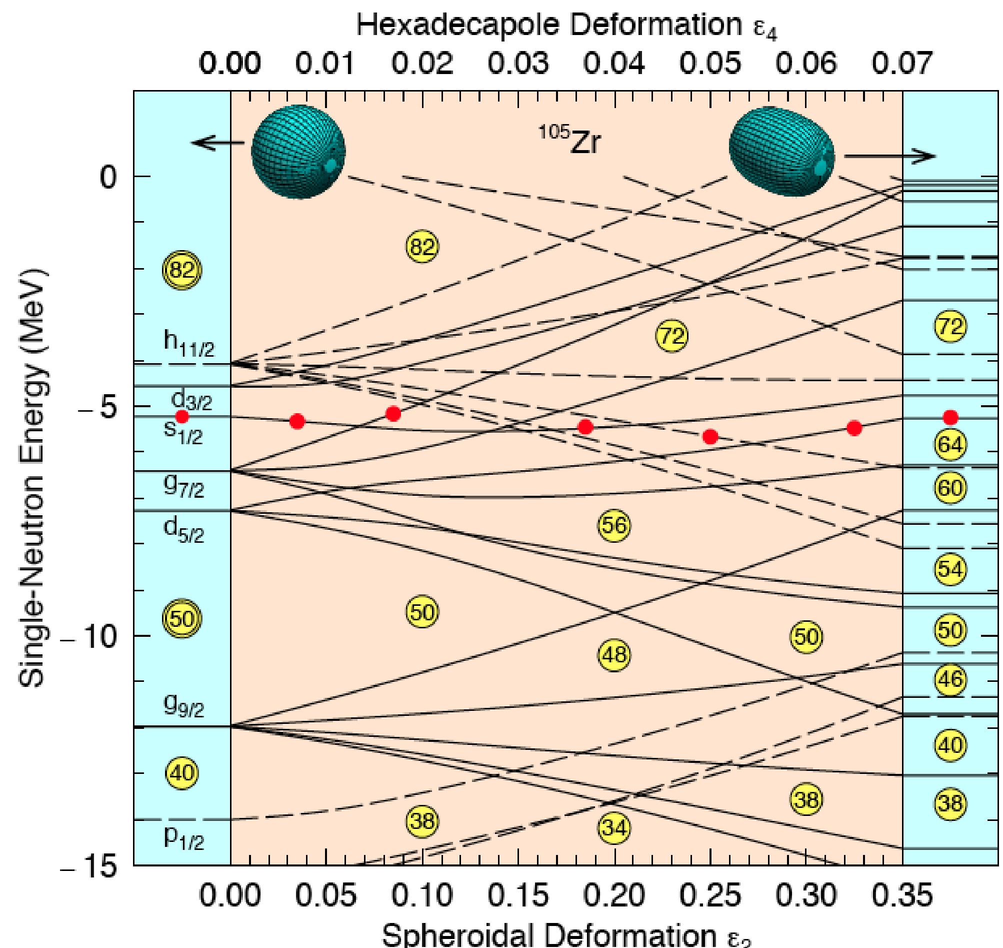
Strong dependence on nuclear structure

EC on ^{42}Si (closed shell)



EC on ^{58}Cr (mid shell)





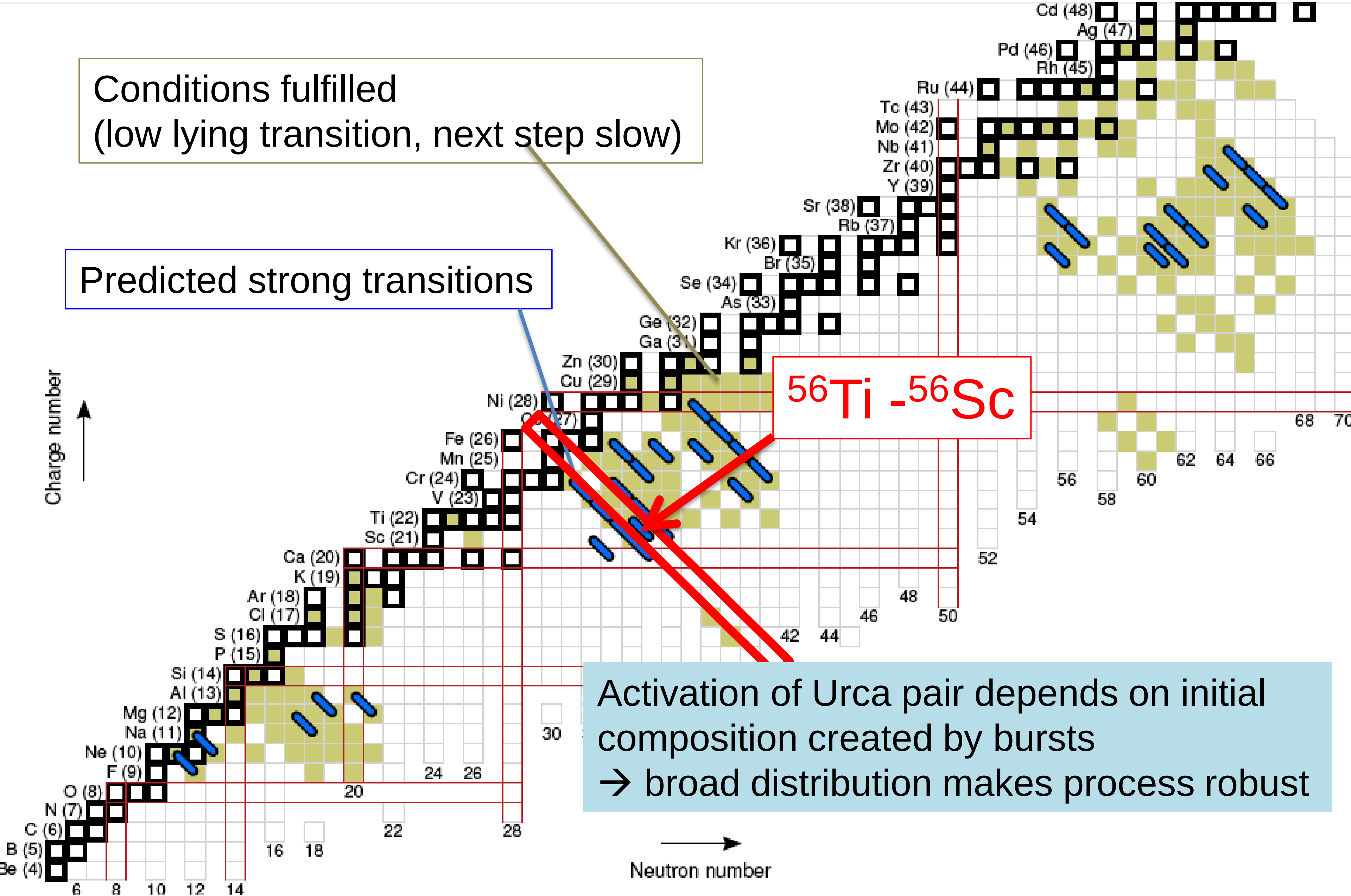
P. Moller

S. Gupta, P. Moller

Location of predicted cooling Urca pairs

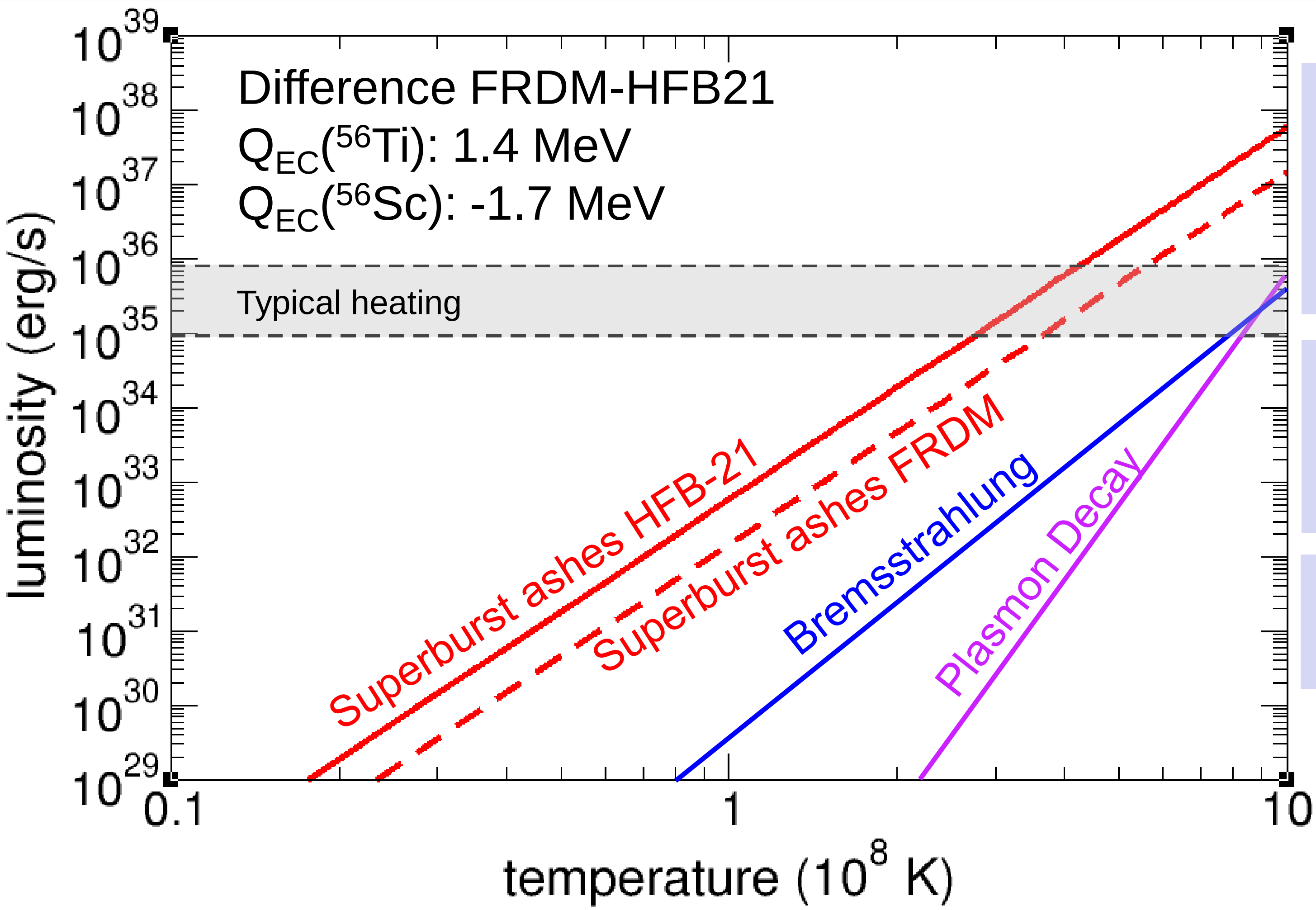
Conditions fulfilled
(low lying transition, next step slow)

Predicted strong transitions



Activation of Urca pair depends on initial composition created by bursts
→ broad distribution makes process robust

Crust Neutrino Cooling Processes



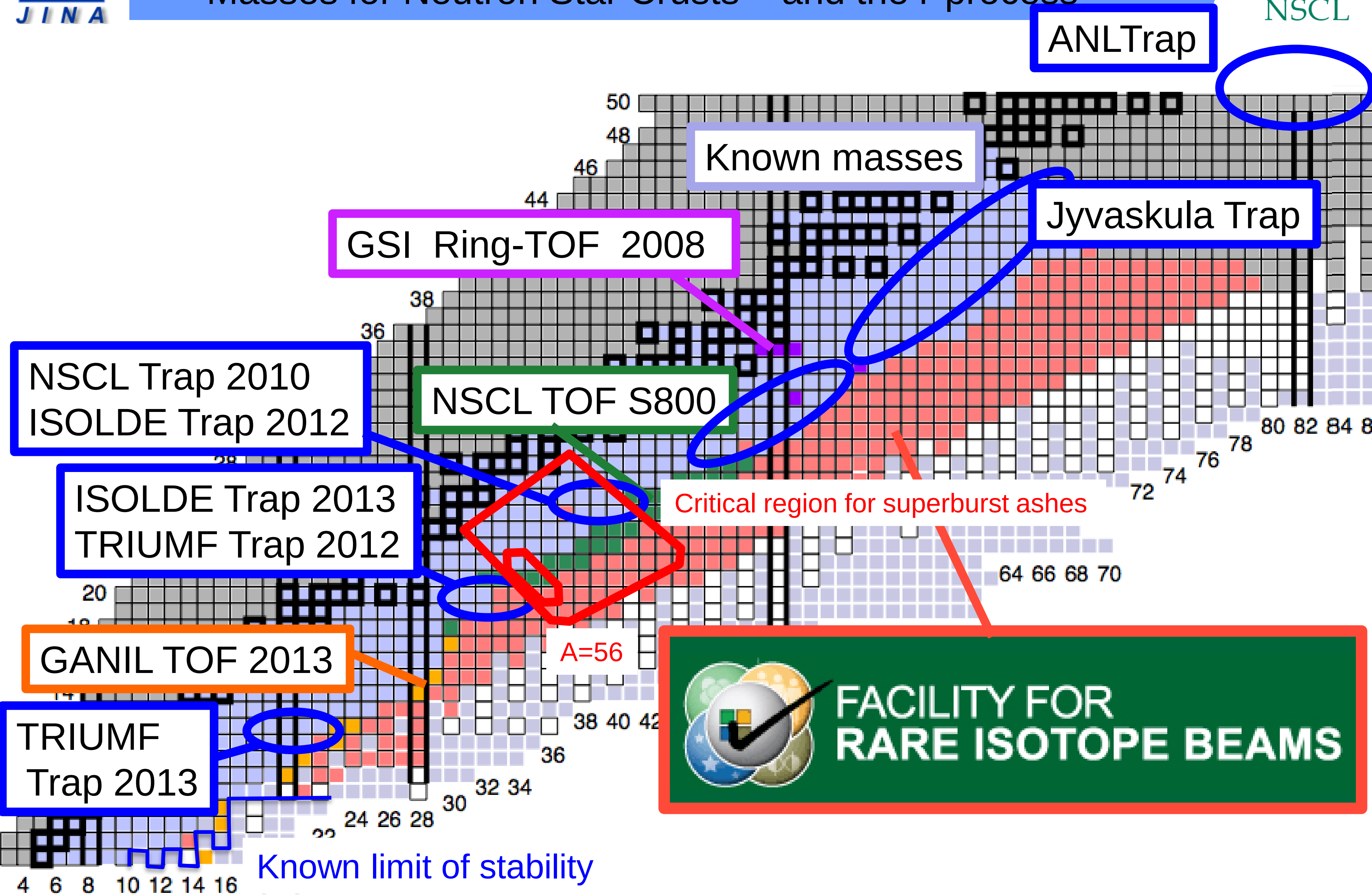
~T^5
→ Limits maximum temperature

→ robust effect despite nuclear uncertainties

→ Need better masses

H. Schatz, S. Gupta, P. Möller, M. Beard, E. F. Brown, A. T. Deibel, L. R. Gasques, W. R. Hix, L. Keek, R. Lau, A. W. Steiner & M. Wiescher Nature 505 (2014) 62

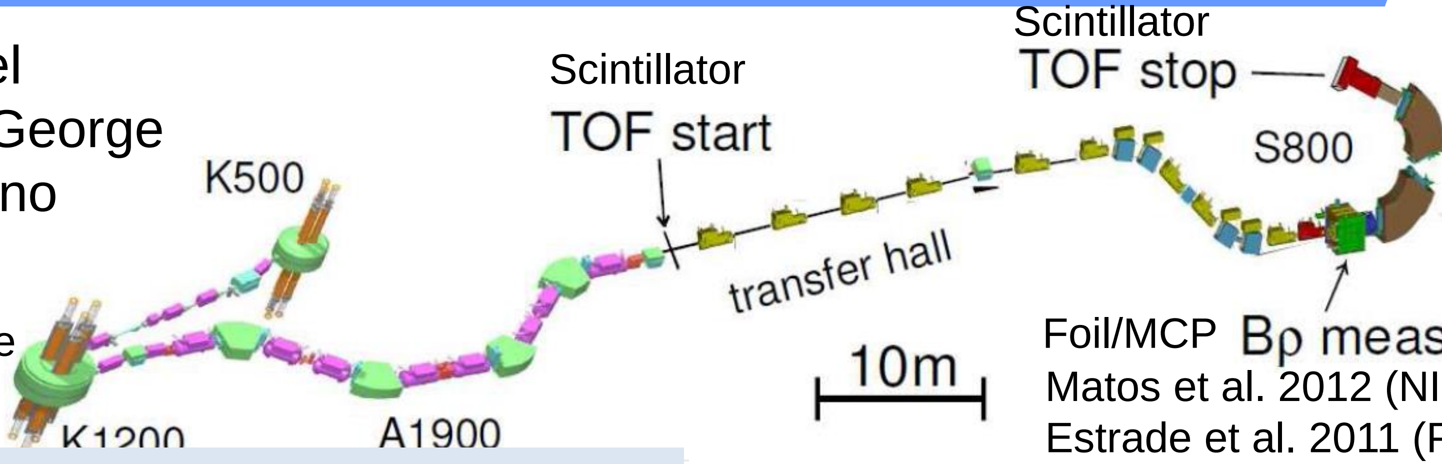
Masses for Neutron Star Crusts – and the r-process



Mass measurements of very neutron rich nuclei

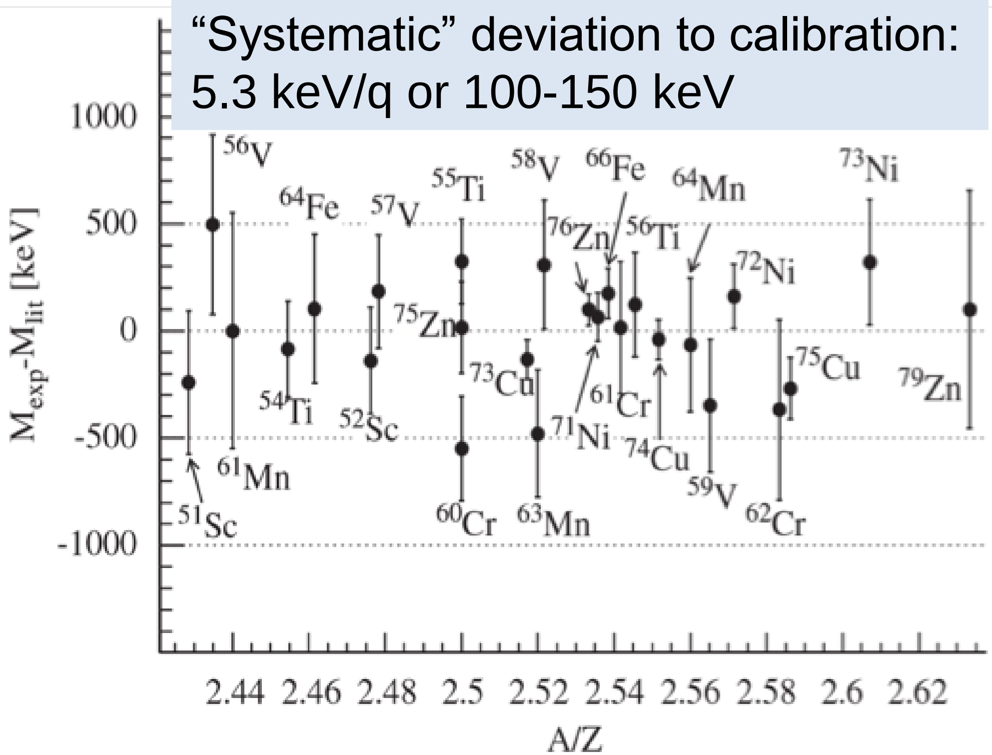
Zach Meisel
Sebastian George
Fiore Carpino

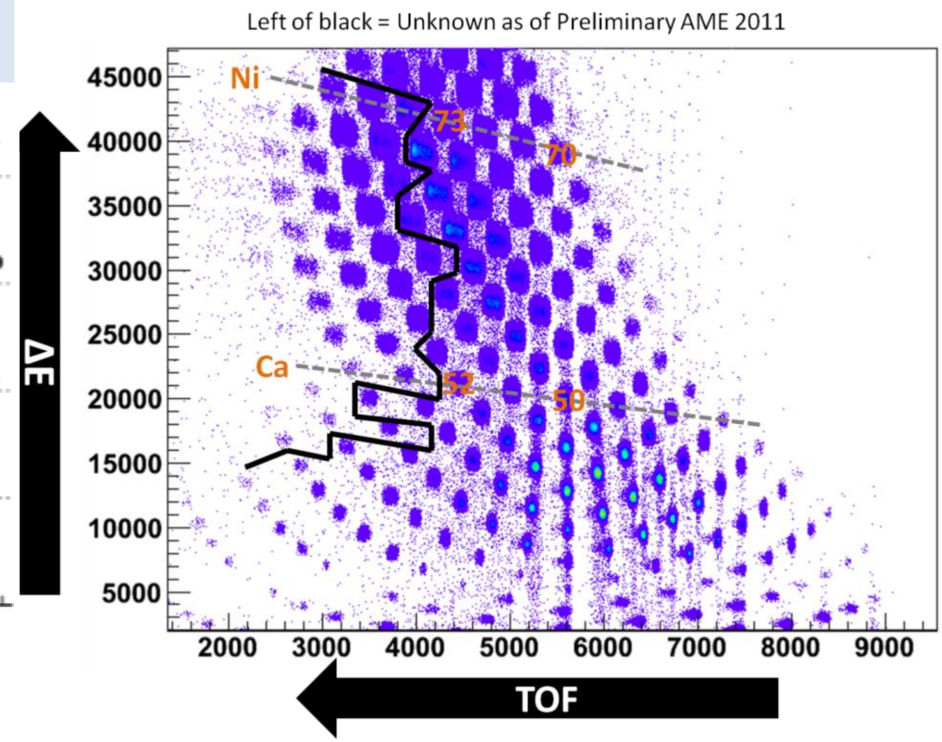
140 MeV/u ^{82}Se



Matos et al. 2012 (NIM)
Estrade et al. 2011 (PRL)

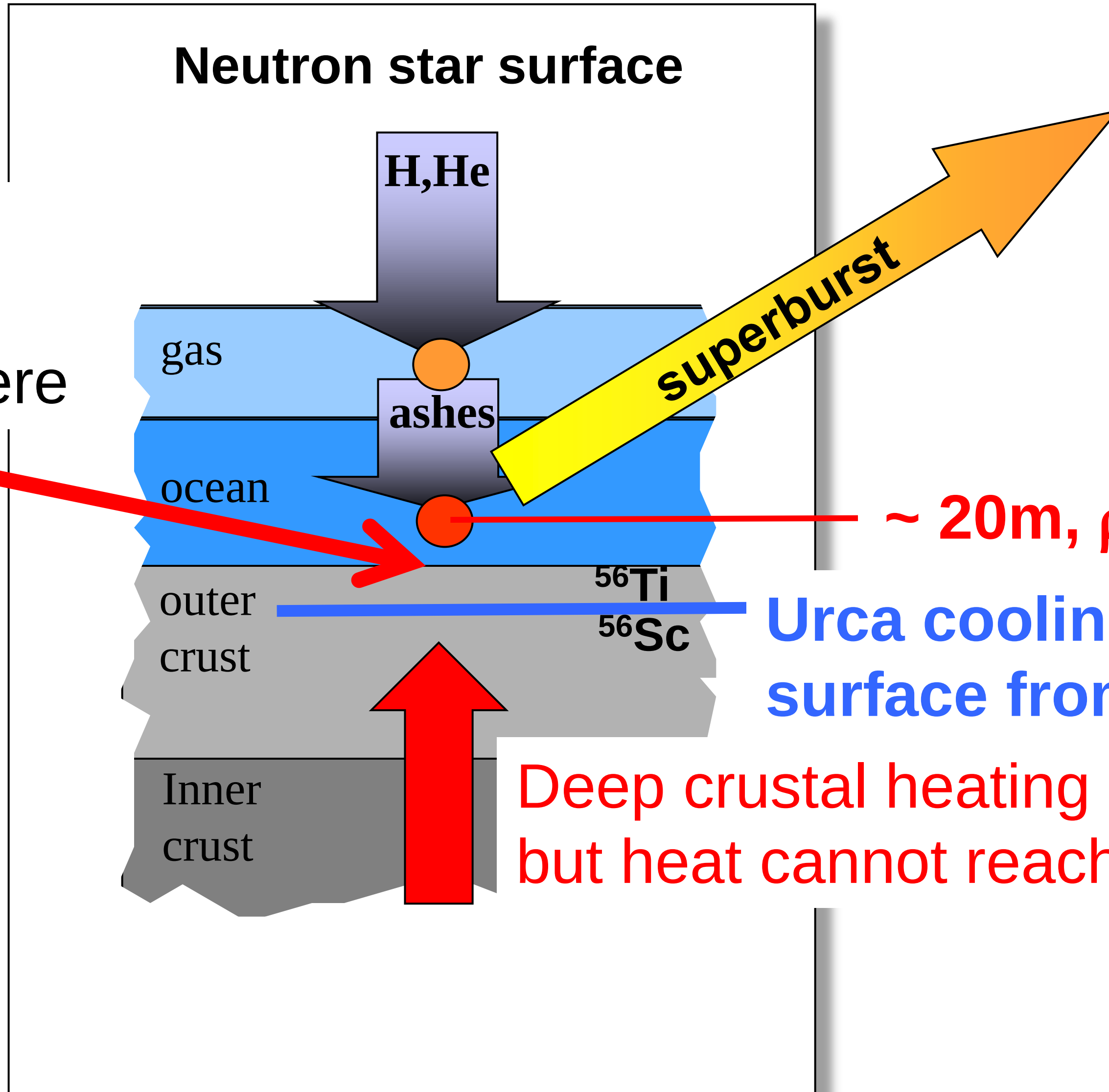
“Systematic” deviation to calibration:
5.3 keV/q or 100-150 keV





→ ~500 keV accuracy (~1:10⁵)

How can we make the ocean hotter?



Ocean heating must be here

~ 20m, $\rho=10^9$ g/cm^3

Urca cooling layer shield surface from heating

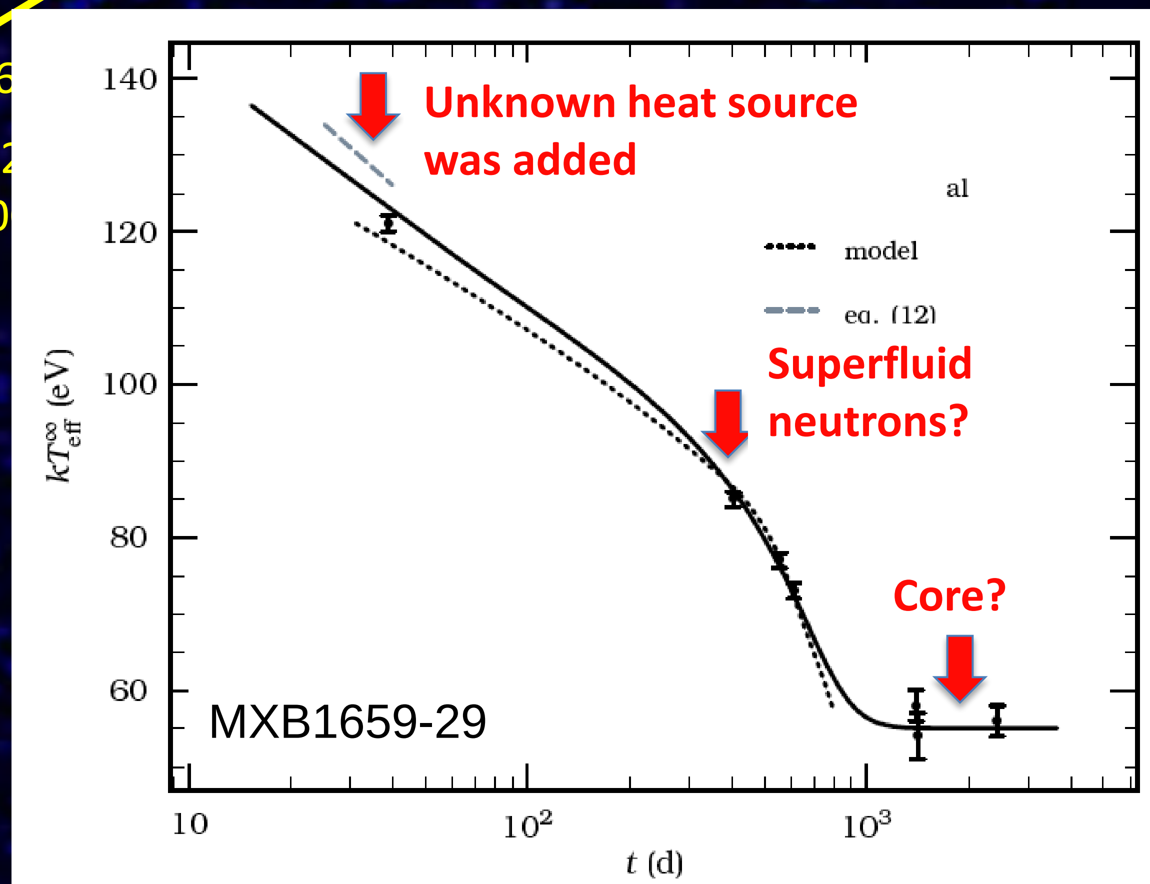
Deep crustal heating
but heat cannot reach surface

So why do we still care about deep crustal heating?
Transiently Accreting Neutron Stars

KS 1731-26

Bright X-ray burster for ~12

Accretion shut off early 20



NASA/Chandra/Wijnands et al.

Some Conclusions

- Nuclear processes with rare isotopes in the crust of accreting neutron stars can heat AND cool

- New Urca mechanism for cooling in neutron stars
  → Operates close to the surface
  → Indicates that solution to superburst problem
  requires an unknown very shallow heating mechanism
  → Limits overall maximum temperature the crust can be heated to

- Need more nuclear structure information from stability to drip line for A<110 to reliably predict effects:
  - Weak interaction strength
  - Masses
  - Fusion Reactions
  - Neutron Captures
  - Mapping of neutron drip line
  - Plus: Burst physics to get the initial composition right

- New RIB facilities can produce most crust nuclei and will have large impact