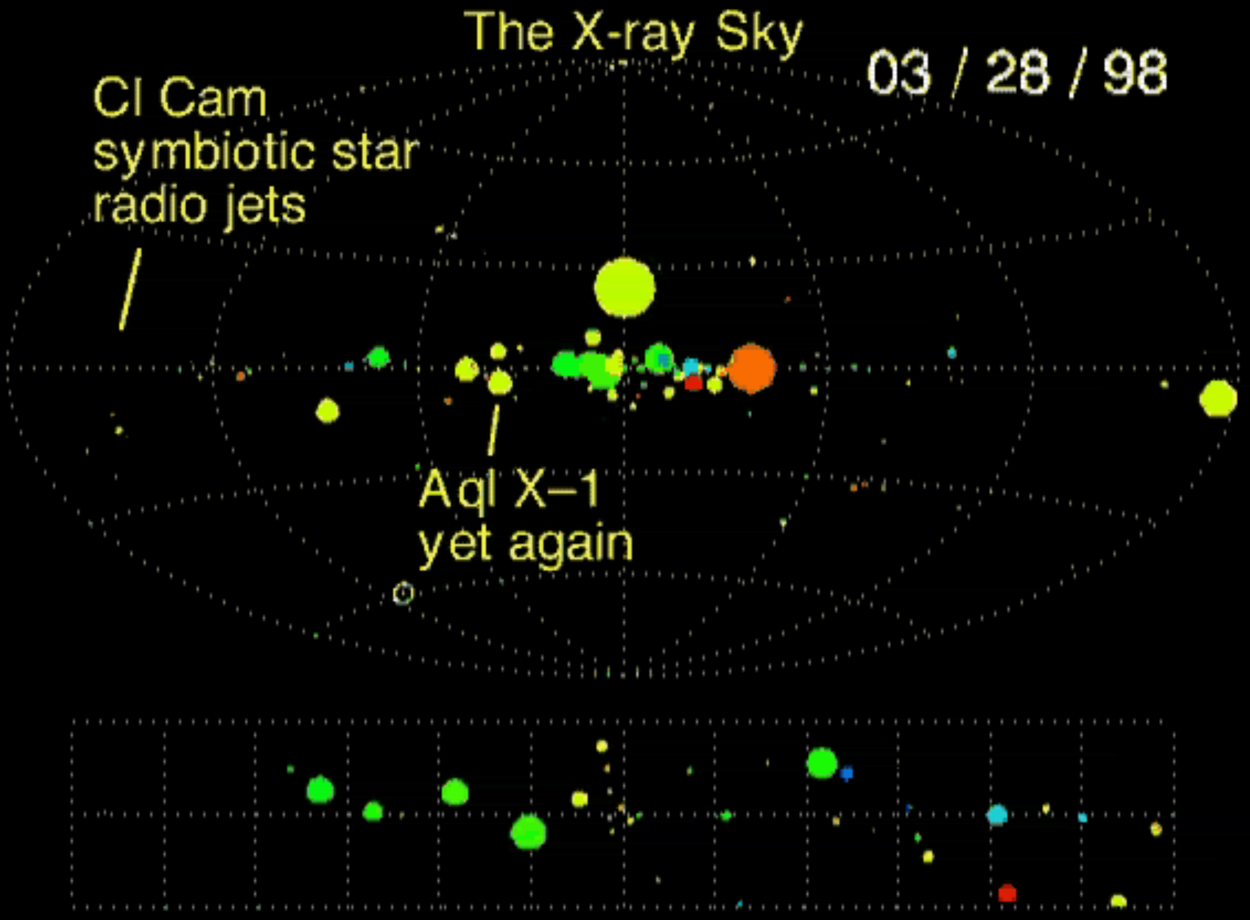
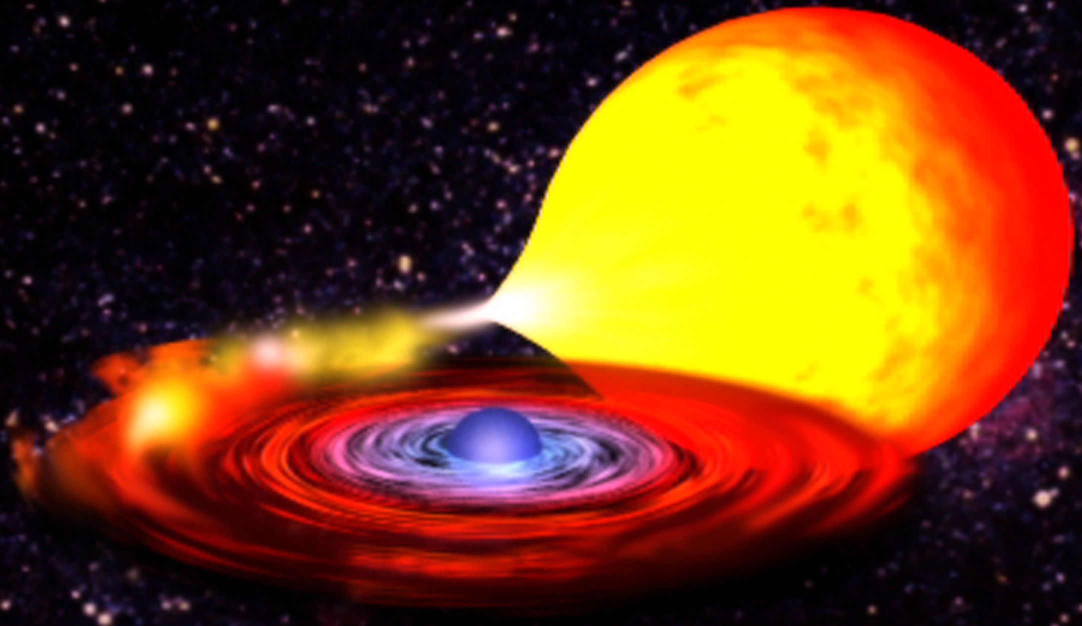
Custs of accreting neutron stars

H. Schatz
Michigan State University, NSCL & Joint Institute for Nuclear Astrophysics



D.A. Smith, M. Muno, A.M. Levine, R. Remillard, H. Bradt 2002 (RXTE All Sky Monitor)

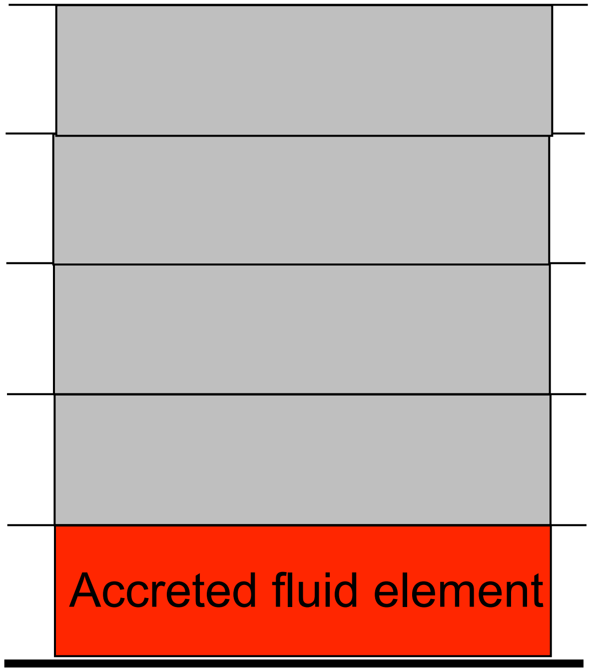
Accreting neutron stars



Many new observations with Chandra, XMM, RXTE
→ New, interesting phenomena (superbursts, …)
→ Constrain neutron star properties
(they get heavier, hotter, and spin faster than isolated NS)

Fate of matter accreted onto a neutron star

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



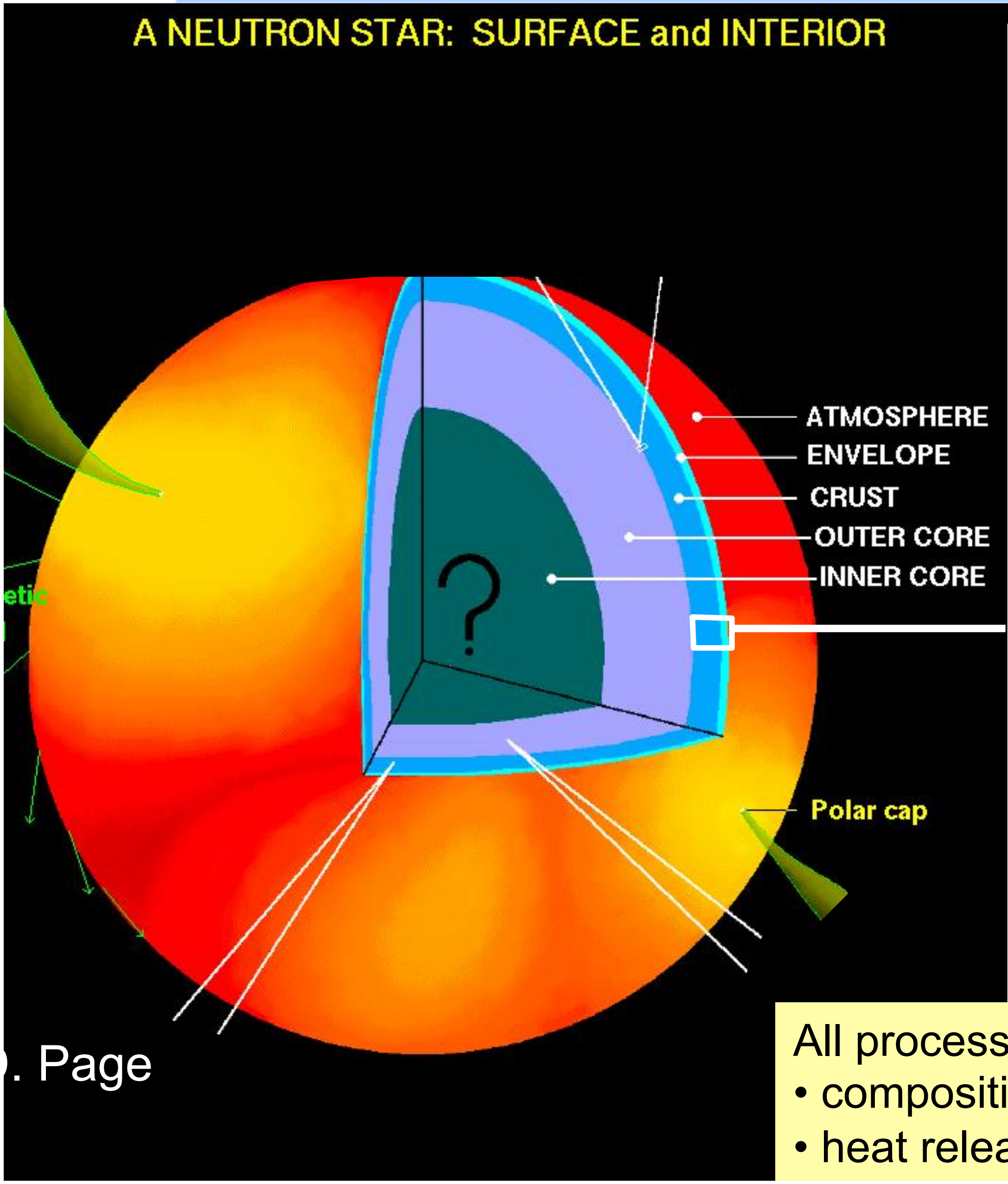
Neutron star surface

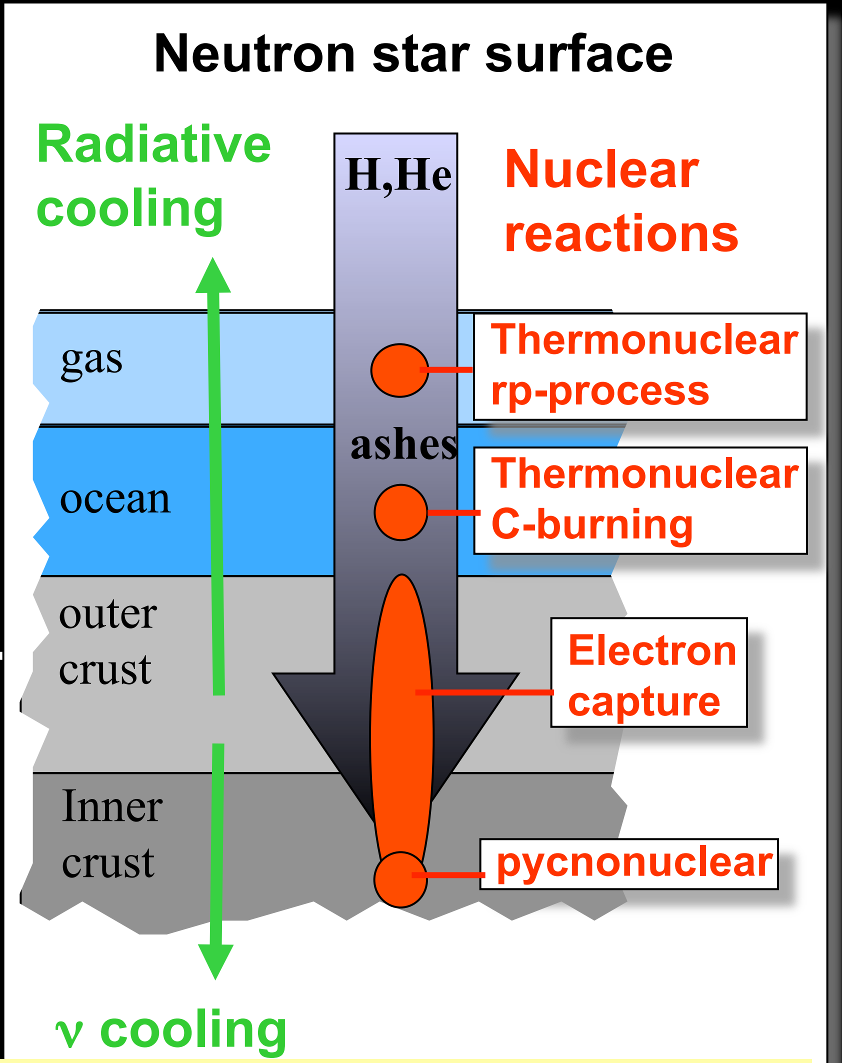
→ An accreted fluid element experiences contineously increasing pressure and density (after a day ~10^6 g/cm^3 – surface gravity is earth x10^{11})

→ is incorporated deeper and deeper into the neutron star "travels through neutron star crust"

→ "on the way" undergoes compositional changes through nuclear reactions

Surface of accreting neutron stars




Neutron star surface

Radiative cooling

H,He

Nuclear reactions

gas

ashes

ocean

outer crust

Inner crust

Thermonuclear rp-process

Thermonuclear C-burning

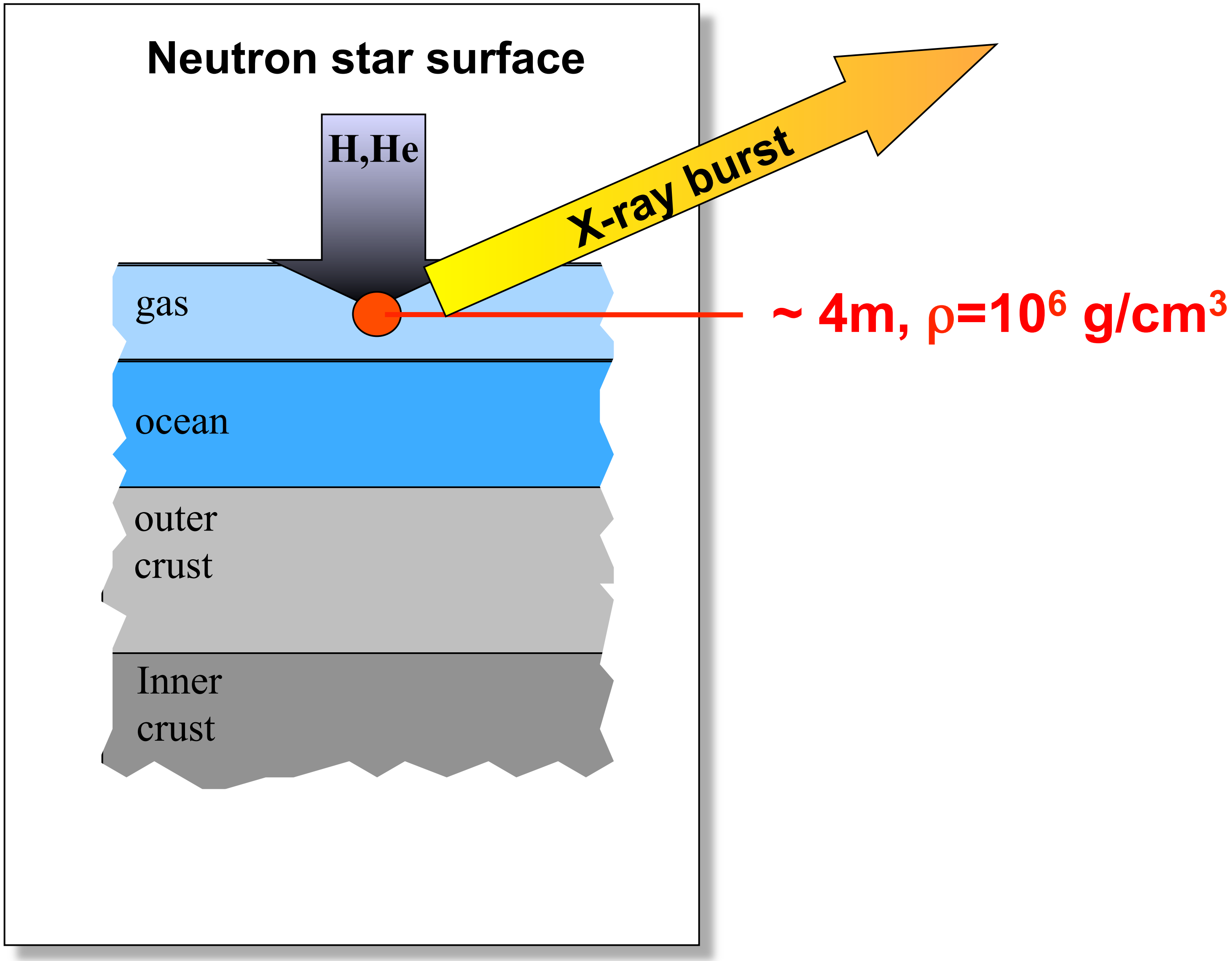
Electron capture

pycnonuclear

ν cooling

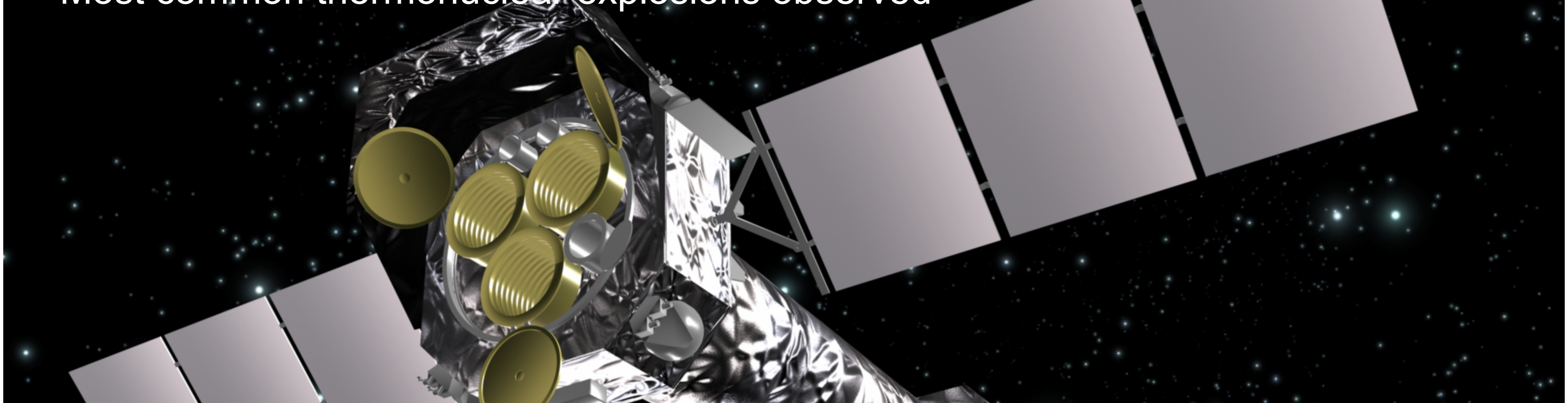
All processes are connected:
- composition (ashes = seed for next process)
- heat release → thermal conditions everywhere

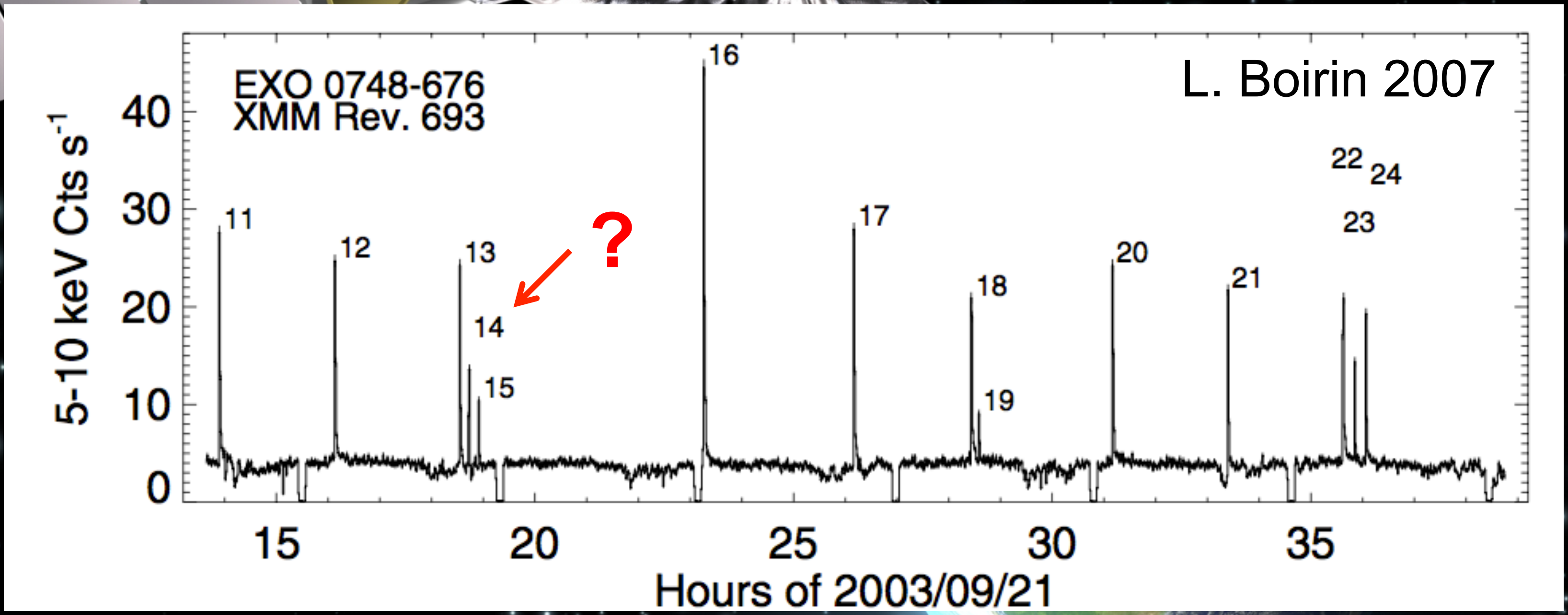
Step 1: Thermonuclear burning in atmosphere



X-ray bursts

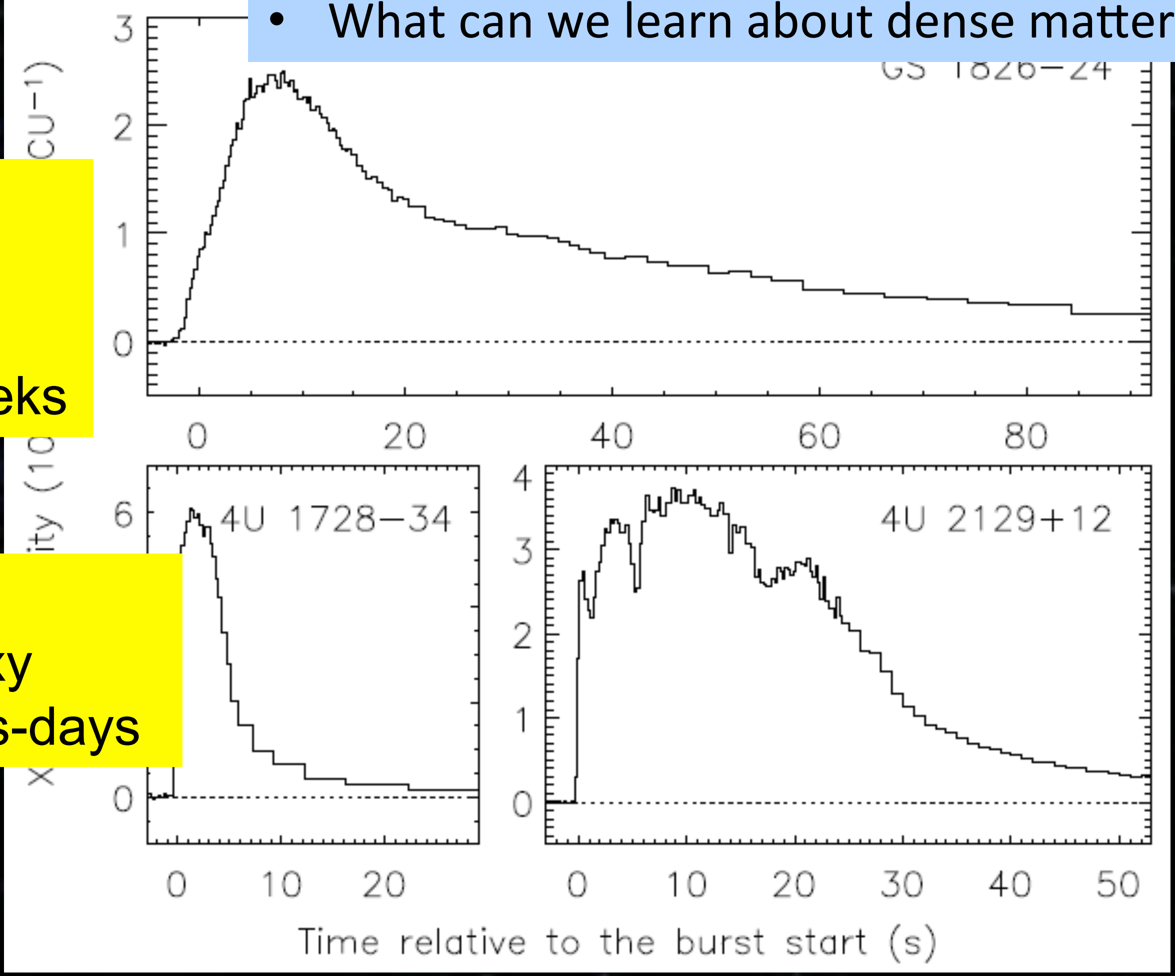
Most common thermonuclear explosions observed





Questions:

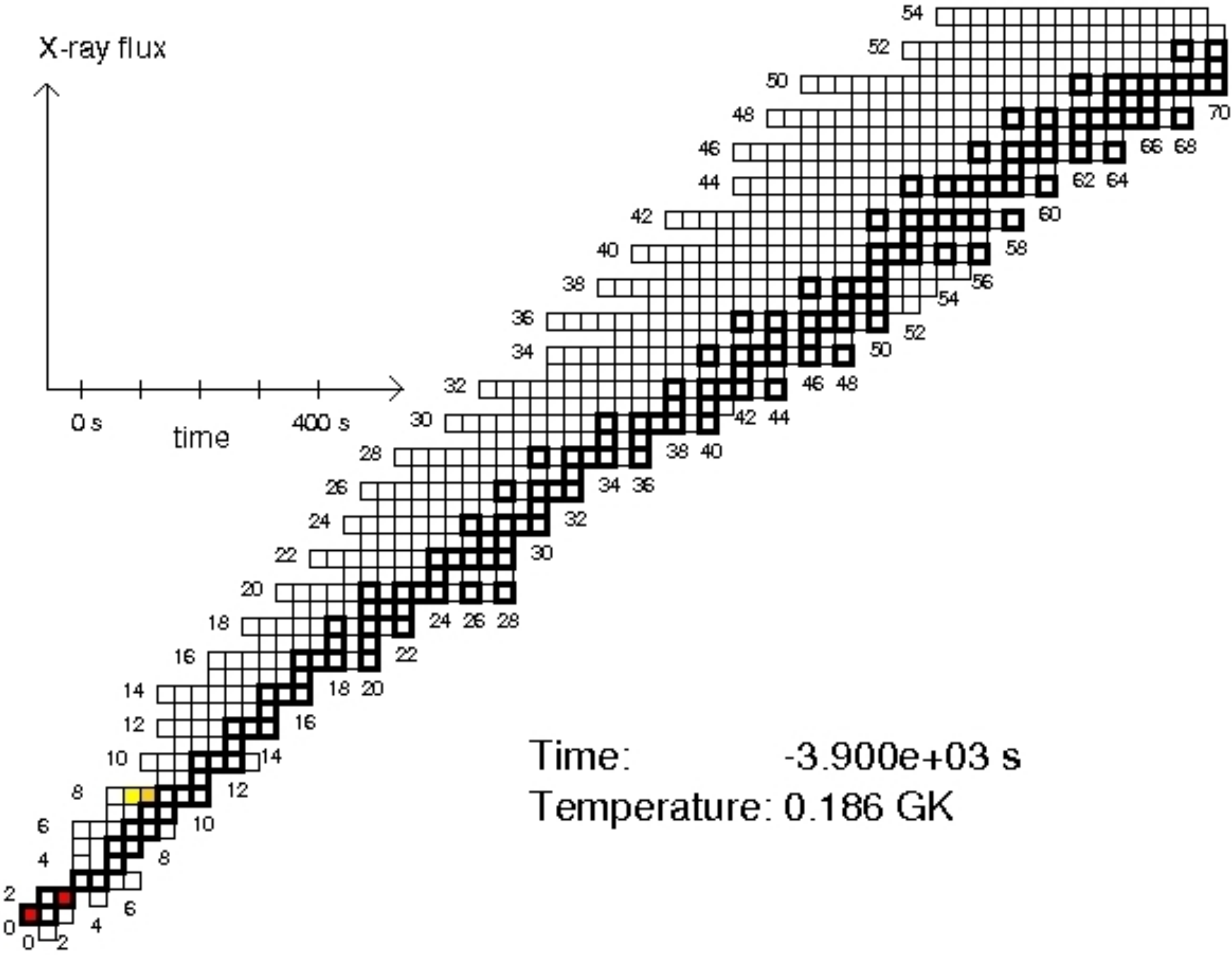
- Why all these different bursts?
- Why do many behave so puzzling?
- Origin of Superbursts, Oscillations, ….
- What can we learn about neutron stars?
- What can we learn about dense matter?



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

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

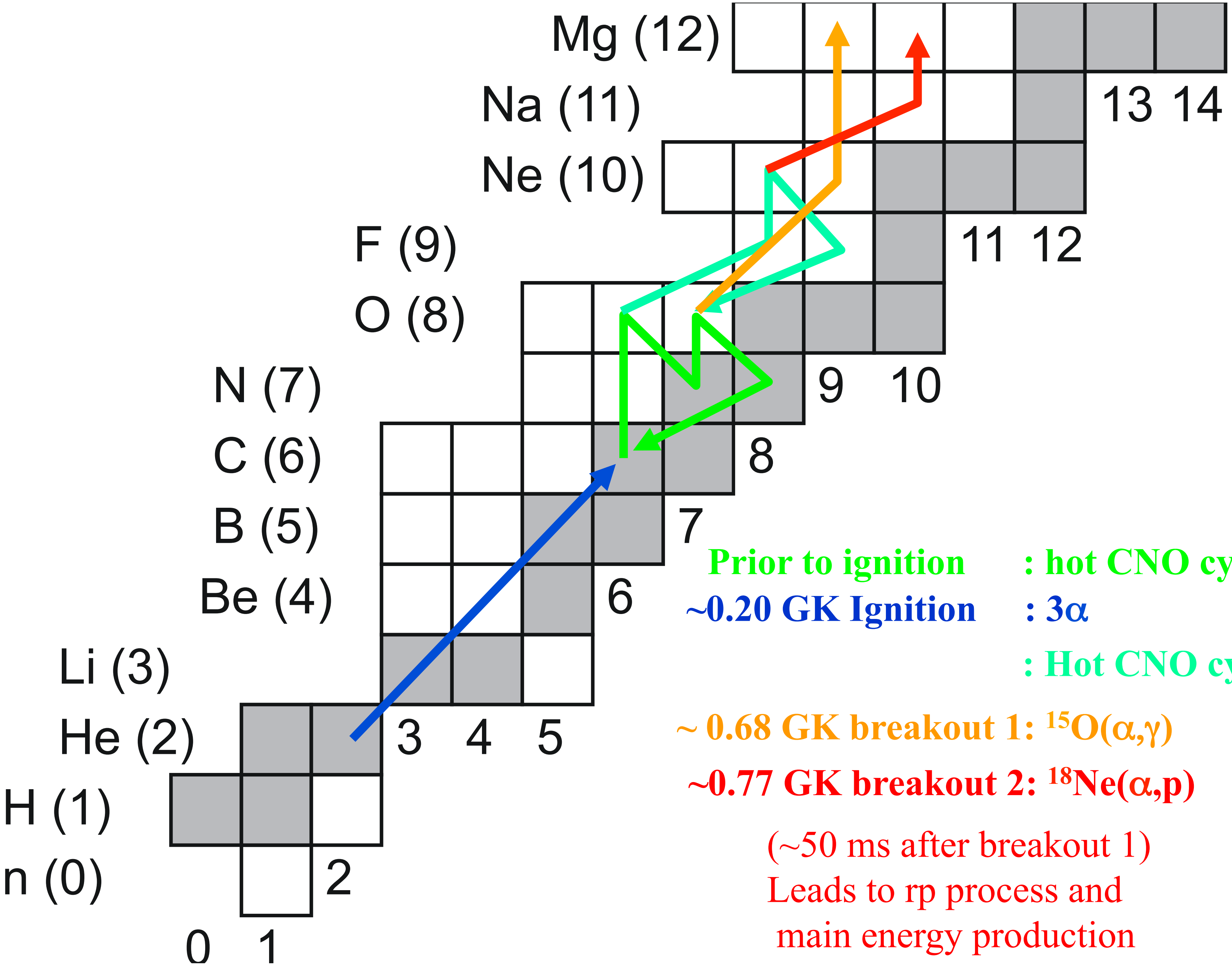
Type I bursts: thermonuclear – how can we tell?



Deepest zone of first burst (model zM of Woosley et al. 2007)

Model by Heger, Woosley et al.; Similar to other groups: Fisker et al. and Jordi et al.

Burst Ignition:



Prior to ignition : hot CNO cycle

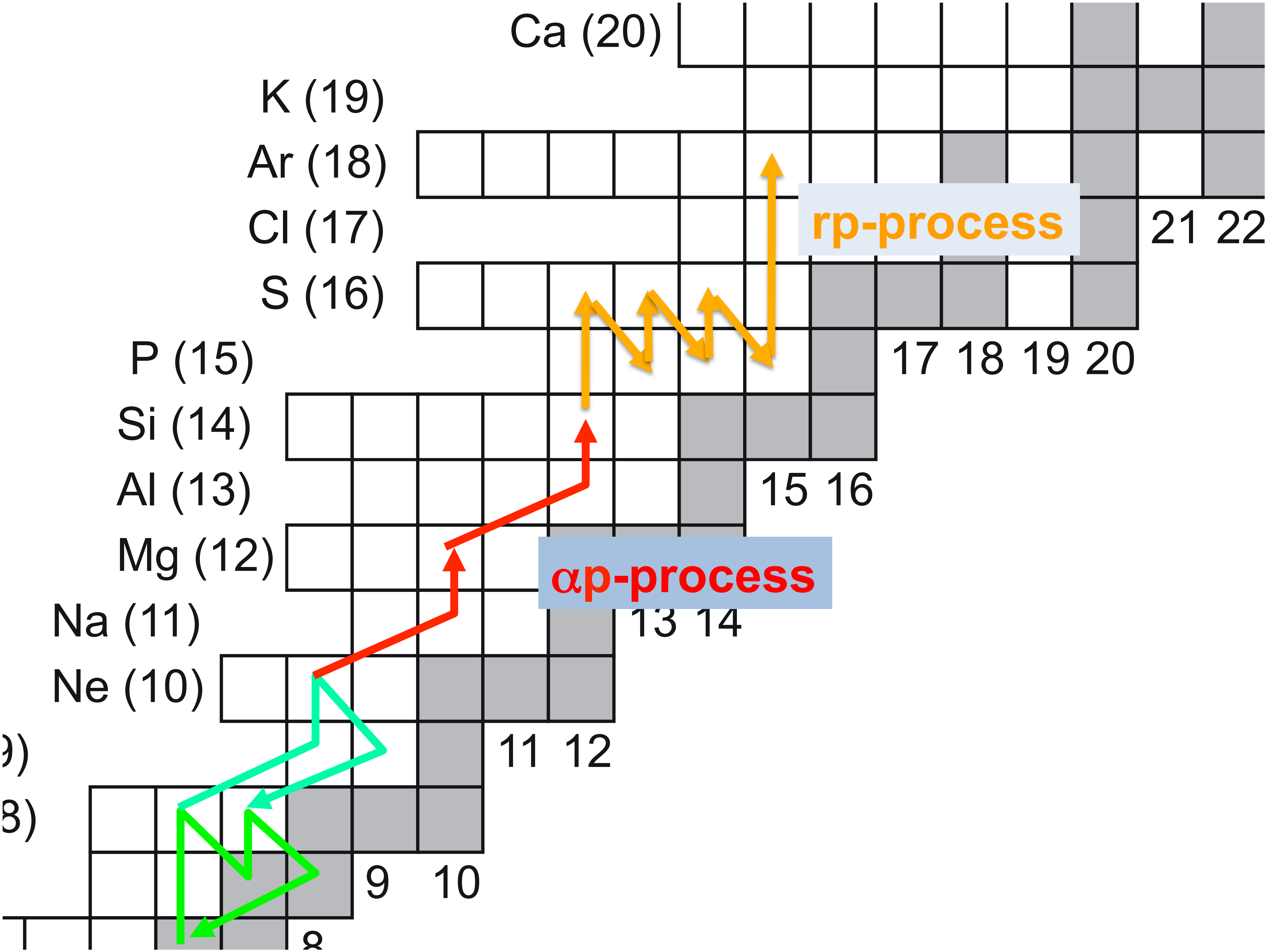
~0.20 GK Ignition : 3α

: Hot CNO cycle II

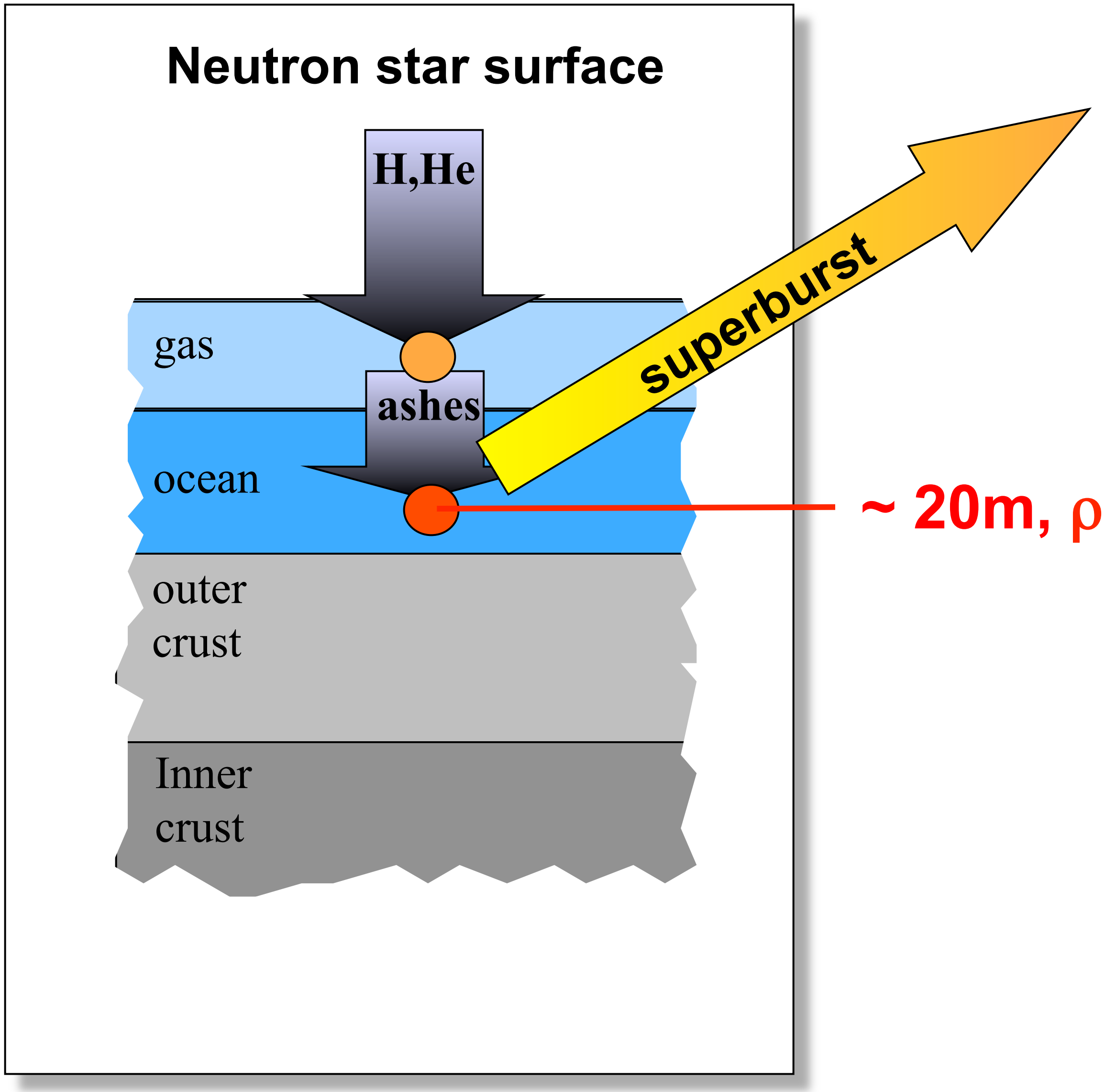
~ 0.68 GK breakout 1: ^{15}O(α,γ)

~0.77 GK breakout 2: ^{18}Ne(α,p)

(~50 ms after breakout 1)
Leads to rp process and
main energy production


Ca (20)
K (19)
Ar (18)
Cl (17)
S (16)
P (15)
Si (14)
Al (13)
Mg (12)
Na (11)
Ne (10)
9)
8)
rp-process
αp-process
21 22
17 18 19 20
15 16
13 14
11 12
9 10
8

Step 2: Deep ocean burning: Superbursts

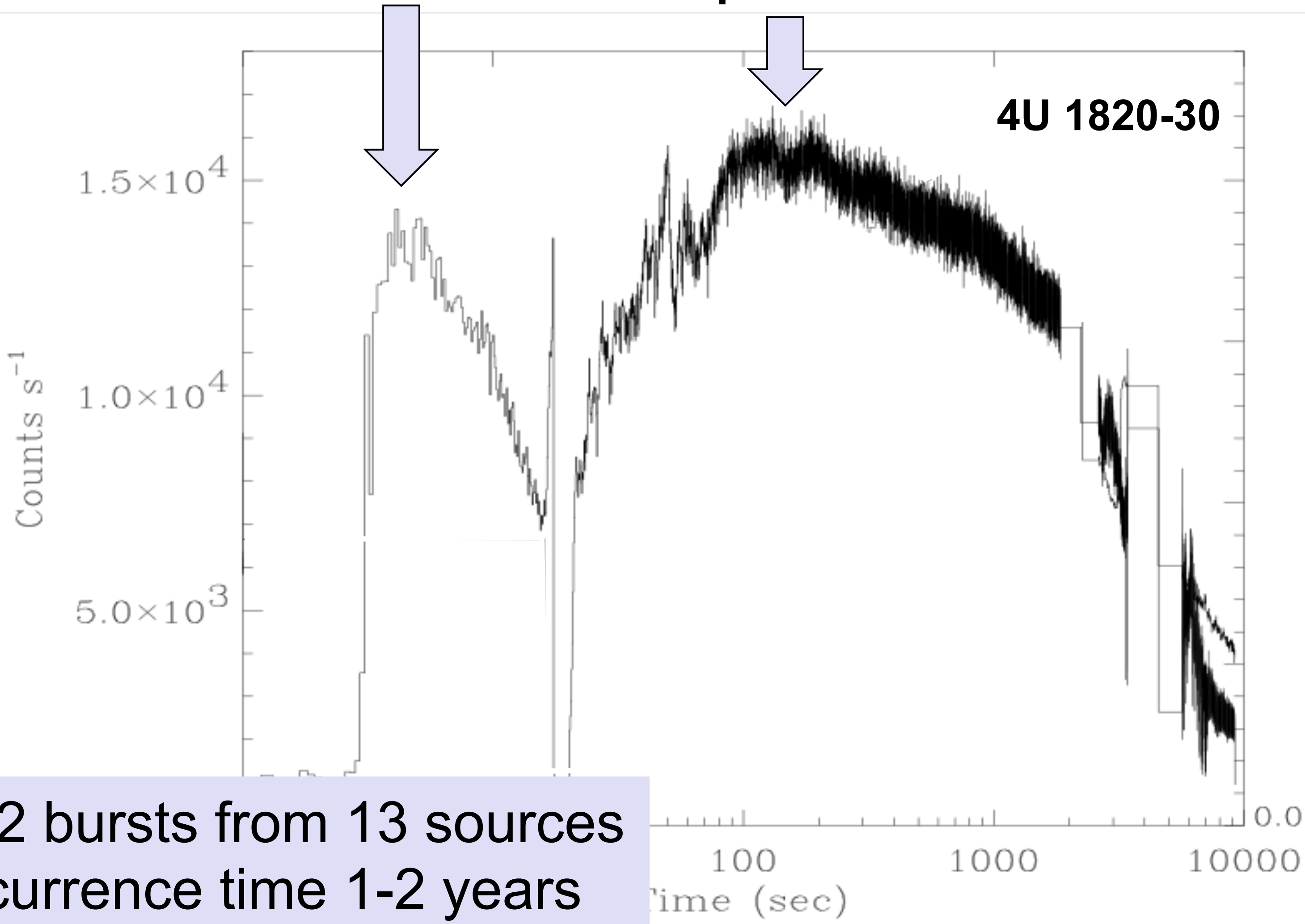


~ 20m, $\rho=10^9$ g/cm^3

Observed: Superbursts

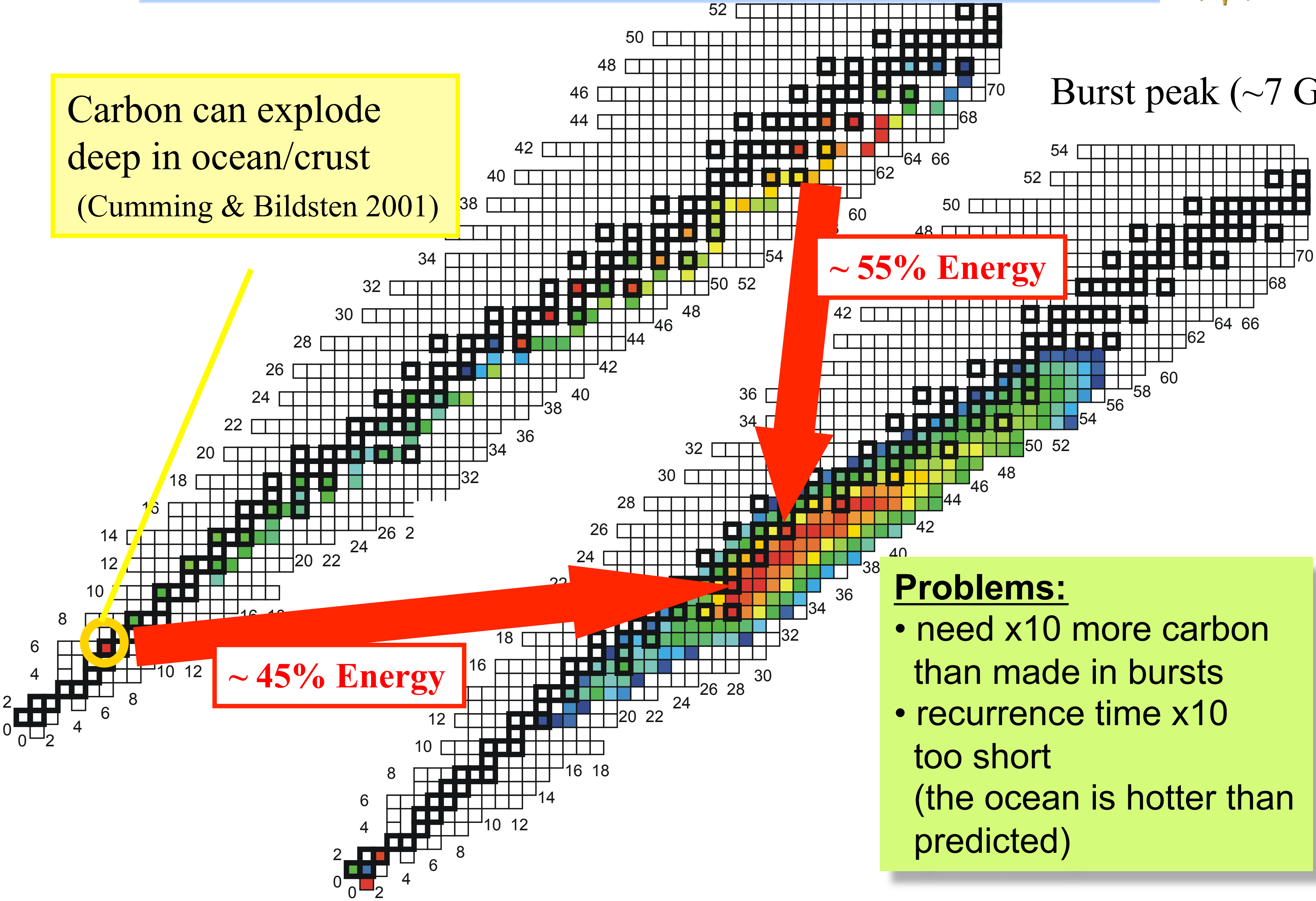
Progenitor

Superburst



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

Ashes to ashes – the origin of superbursts ?



Carbon can explode deep in ocean/crust

(Cumming & Bildsten 2001)

Burst peak (~7 GK)

~ 55% Energy

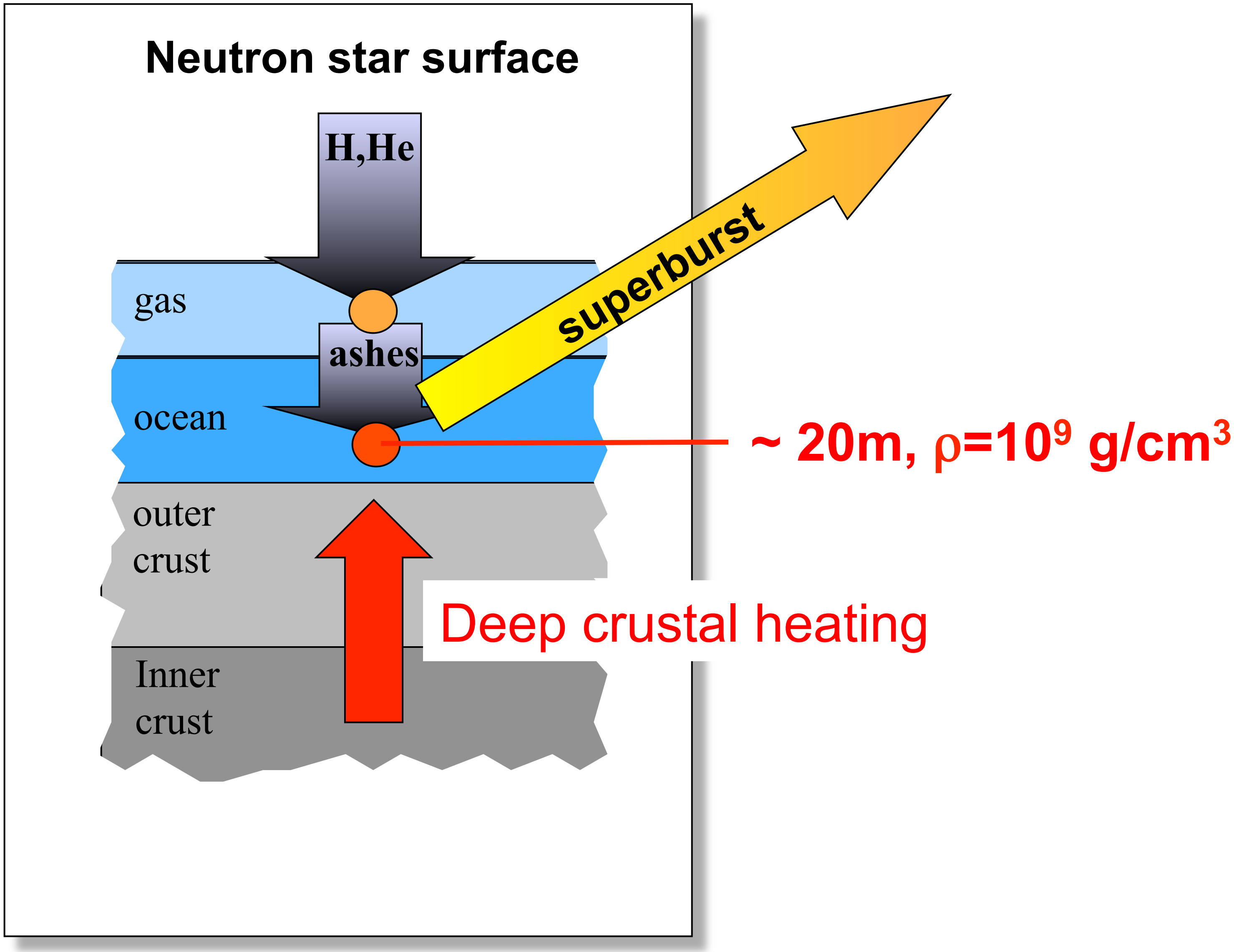
~ 45% Energy

Problems:

- need x10 more carbon than made in bursts
- recurrence time x10 too short (the ocean is hotter than predicted)

(Schatz, Bildsten, Cumming, ApJ Lett. 583(2003)L87

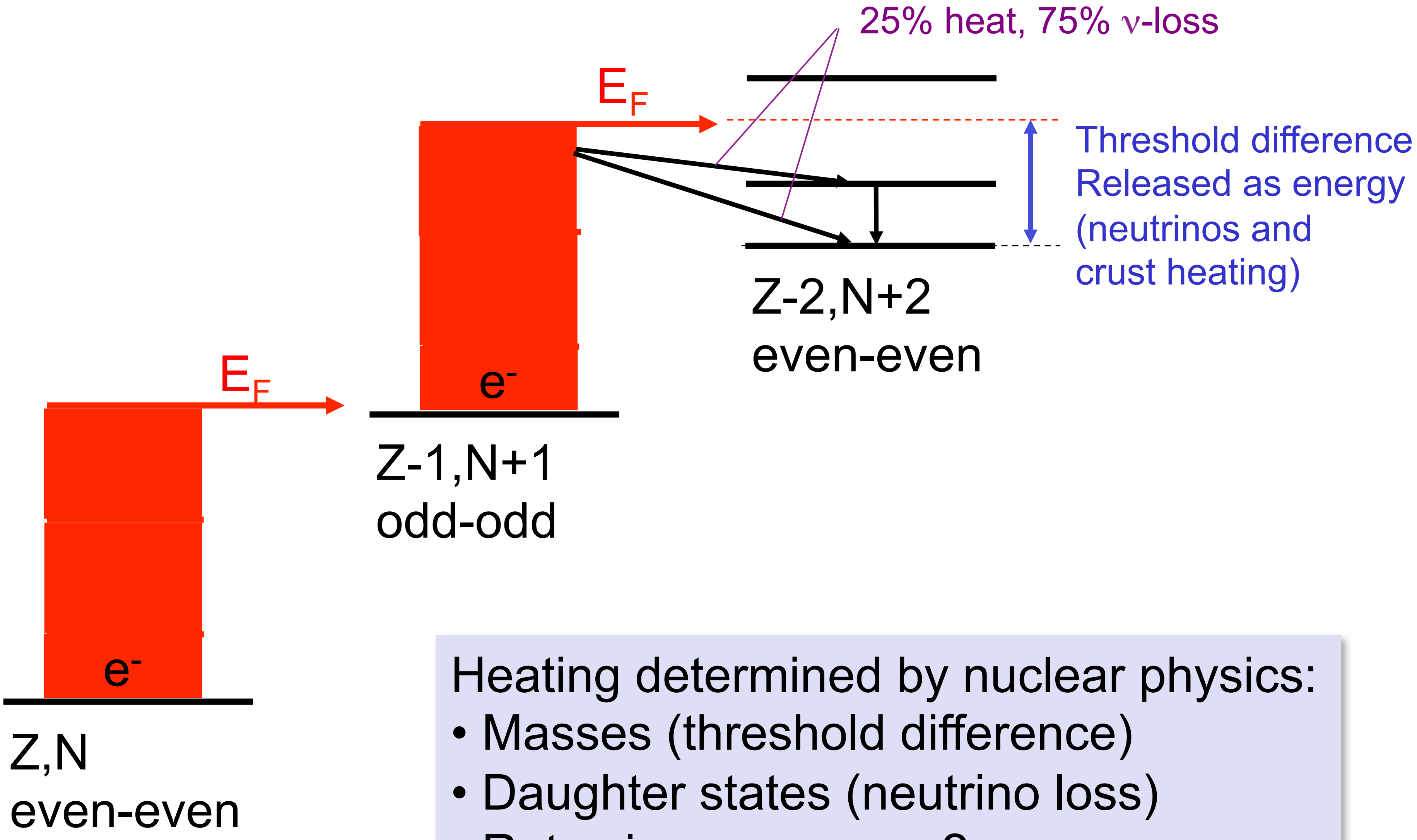
How can we make the ocean hotter?



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

Deep crustal heating

Crustal heating by pairing



25% heat, 75% ν-loss

E_F

Threshold difference
Released as energy
(neutrinos and
crust heating)

E_F

e^-

Z-2,N+2
even-even

e^-

Z-1,N+1
odd-odd

Z,N
even-even

Heating determined by nuclear physics:

- Masses (threshold difference)
- Daughter states (neutrino loss)
- Rates in some cases?

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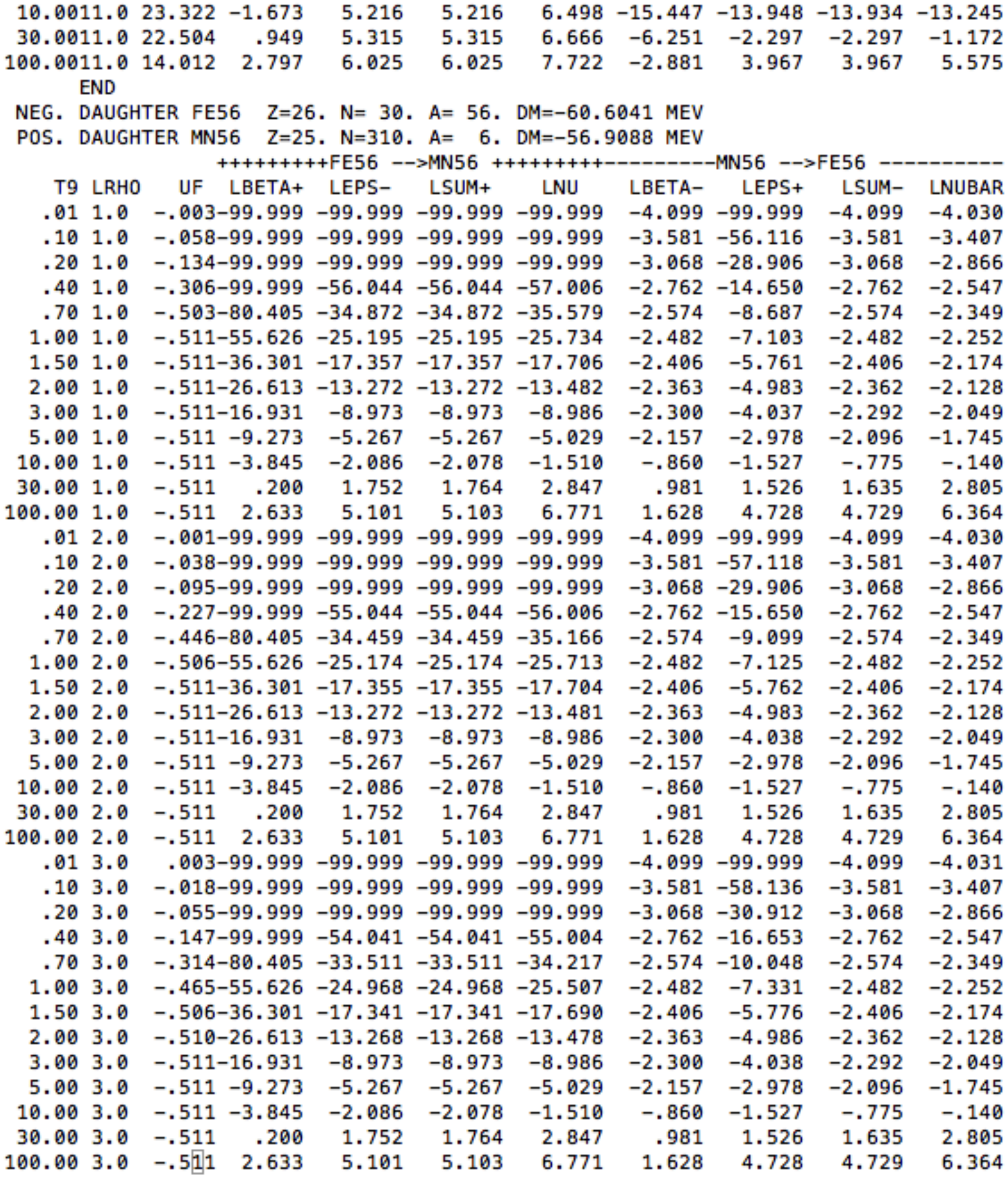

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 10.0011.0 23.322 -1.673   5.216   5.216   6.498 -15.447 -13.948 -13.934 -13.245
 30.0011.0 22.504   .949   5.315   5.315   6.666  -6.251  -2.297  -2.297  -1.172
100.0011.0 14.012  2.797   6.025   6.025   7.722  -2.881   3.967   3.967   5.575
      END
 NEG. DAUGHTER FE56  Z=26. N= 30. A= 56. DM=-60.6041 MEV
 POS. DAUGHTER MN56  Z=25. N=310. A=  6. DM=-56.9088 MEV
                 +++++++++FE56 -->MN56 +++++++++---------MN56 -->FE56 ----------
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   .10 1.0  -.058-99.999 -99.999 -99.999 -99.999  -3.581 -56.116  -3.581  -3.407
   .20 1.0  -.134-99.999 -99.999 -99.999 -99.999  -3.068 -28.906  -3.068  -2.866
   .40 1.0  -.306-99.999 -56.044 -56.044 -57.006  -2.762 -14.650  -2.762  -2.547
   .70 1.0  -.503-80.405 -34.872 -34.872 -35.579  -2.574  -8.687  -2.574  -2.349
  1.00 1.0  -.511-55.626 -25.195 -25.195 -25.734  -2.482  -7.103  -2.482  -2.252
  1.50 1.0  -.511-36.301 -17.357 -17.357 -17.706  -2.406  -5.761  -2.406  -2.174
  2.00 1.0  -.511-26.613 -13.272 -13.272 -13.482  -2.363  -4.983  -2.362  -2.128
  3.00 1.0  -.511-16.931  -8.973  -8.973  -8.986  -2.300  -4.037  -2.292  -2.049
  5.00 1.0  -.511 -9.273  -5.267  -5.267  -5.029  -2.157  -2.978  -2.096  -1.745
 10.00 1.0  -.511 -3.845  -2.086  -2.078  -1.510   -.860  -1.527   -.775   -.140
 30.00 1.0  -.511   .200   1.752   1.764   2.847    .981   1.526   1.635   2.805
100.00 1.0  -.511  2.633   5.101   5.103   6.771   1.628   4.728   4.729   6.364
   .01 2.0  -.001-99.999 -99.999 -99.999 -99.999  -4.099 -99.999  -4.099  -4.030
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   .40 2.0  -.227-99.999 -55.044 -55.044 -56.006  -2.762 -15.650  -2.762  -2.547
   .70 2.0  -.446-80.405 -34.459 -34.459 -35.166  -2.574  -9.099  -2.574  -2.349
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  1.50 2.0  -.511-36.301 -17.355 -17.355 -17.704  -2.406  -5.762  -2.406  -2.174
  2.00 2.0  -.511-26.613 -13.272 -13.272 -13.481  -2.363  -4.983  -2.362  -2.128
  3.00 2.0  -.511-16.931  -8.973  -8.973  -8.986  -2.300  -4.038  -2.292  -2.049
  5.00 2.0  -.511 -9.273  -5.267  -5.267  -5.029  -2.157  -2.978  -2.096  -1.745
 10.00 2.0  -.511 -3.845  -2.086  -2.078  -1.510   -.860  -1.527   -.775   -.140
 30.00 2.0  -.511   .200   1.752   1.764   2.847    .981   1.526   1.635   2.805
100.00 2.0  -.511  2.633   5.101   5.103   6.771   1.628   4.728   4.729   6.364
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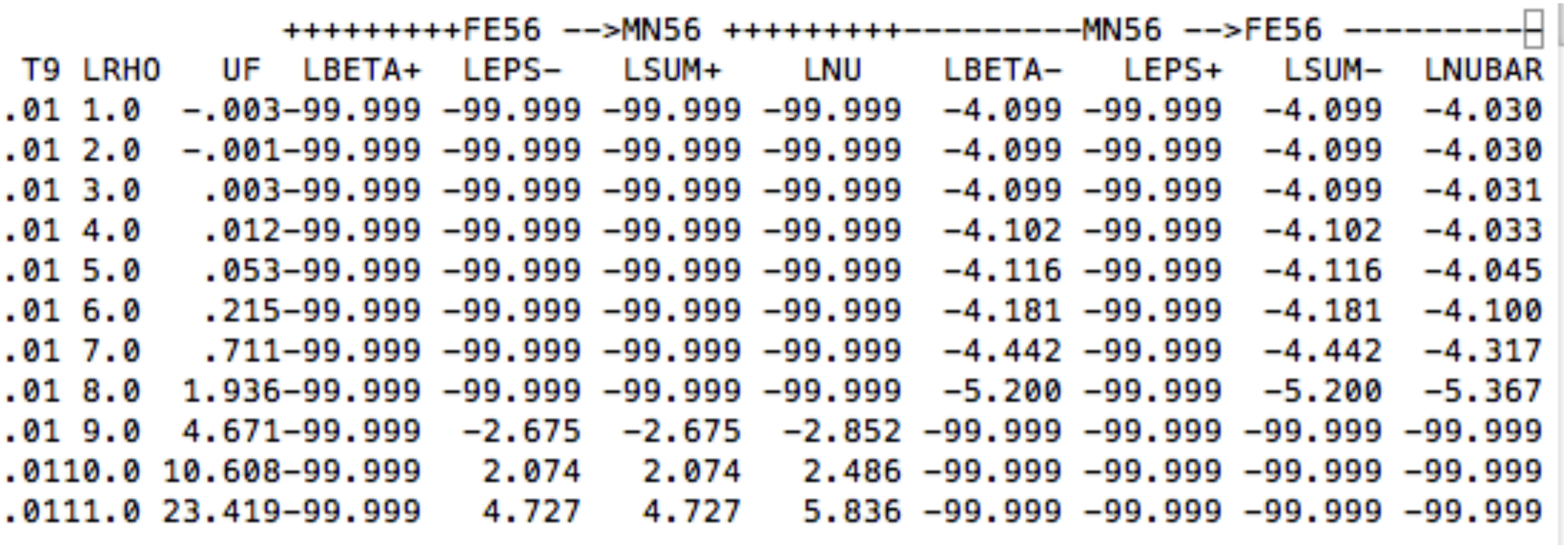
   .10 3.0  -.018-99.999 -99.999 -99.999 -99.999  -3.581 -58.136  -3.581  -3.407
   .20 3.0  -.055-99.999 -99.999 -99.999 -99.999  -3.068 -30.912  -3.068  -2.866
   .40 3.0  -.147-99.999 -54.041 -54.041 -55.004  -2.762 -16.653  -2.762  -2.547
   .70 3.0  -.314-80.405 -33.511 -33.511 -34.217  -2.574 -10.048  -2.574  -2.349
  1.00 3.0  -.465-55.626 -24.968 -24.968 -25.507  -2.482  -7.331  -2.482  -2.252
  1.50 3.0  -.506-36.301 -17.341 -17.341 -17.690  -2.406  -5.776  -2.406  -2.174
  2.00 3.0  -.510-26.613 -13.268 -13.268 -13.478  -2.363  -4.986  -2.362  -2.128
  3.00 3.0  -.511-16.931  -8.973  -8.973  -8.986  -2.300  -4.038  -2.292  -2.049
  5.00 3.0  -.511 -9.273  -5.267  -5.267  -5.029  -2.157  -2.978  -2.096  -1.745
 10.00 3.0  -.511 -3.845  -2.086  -2.078  -1.510   -.860  -1.527   -.775   -.140
 30.00 3.0  -.511   .200   1.752   1.764   2.847    .981   1.526   1.635   2.805
100.00 3.0  -.511  2.633   5.101   5.103   6.771   1.628   4.728   4.729   6.364
```

Xnet: File ffnu

Regrouped for same low temperature (cut and paste)



```
              +++++++++FE56 -->MN56 +++++++++---------MN56 -->FE56 ---------
 T9 LRHO    UF  LBETA+  LEPS-   LSUM+    LNU    LBETA-   LEPS+   LSUM-   LNUBAR
.01 1.0  -.003-99.999 -99.999 -99.999 -99.999  -4.099 -99.999  -4.099  -4.030
.01 2.0  -.001-99.999 -99.999 -99.999 -99.999  -4.099 -99.999  -4.099  -4.030
.01 3.0   .003-99.999 -99.999 -99.999 -99.999  -4.099 -99.999  -4.099  -4.031
.01 4.0   .012-99.999 -99.999 -99.999 -99.999  -4.102 -99.999  -4.102  -4.033
.01 5.0   .053-99.999 -99.999 -99.999 -99.999  -4.116 -99.999  -4.116  -4.045
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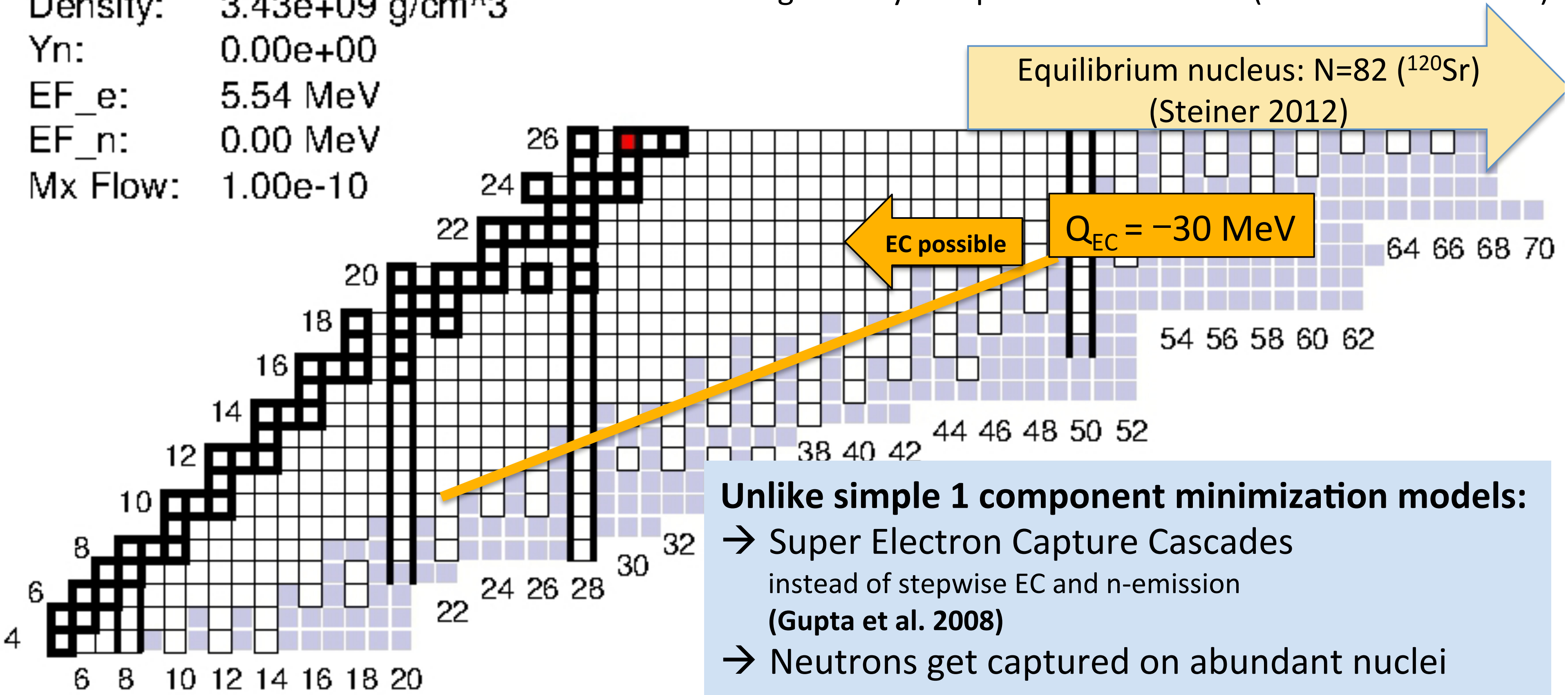
.01 8.0  1.936-99.999 -99.999 -99.999 -99.999  -5.200 -99.999  -5.200  -5.367
.01 9.0  4.671-99.999  -2.675  -2.675  -2.852 -99.999 -99.999 -99.999 -99.999
.0110.0 10.608-99.999   2.074   2.074   2.486 -99.999 -99.999 -99.999 -99.999
.0111.0 23.419-99.999   4.727   4.727   5.836 -99.999 -99.999 -99.999 -99.999
```

Crust processes: Electron capture and neutron emission

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

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)

EC possible

$Q_{EC} = -30$ MeV

Unlike simple 1 component minimization models:

→ Super Electron Capture Cascades
instead of stepwise EC and n-emission
(Gupta et al. 2008)

→ Neutrons get captured on abundant nuclei
path splits, multi isotope composition

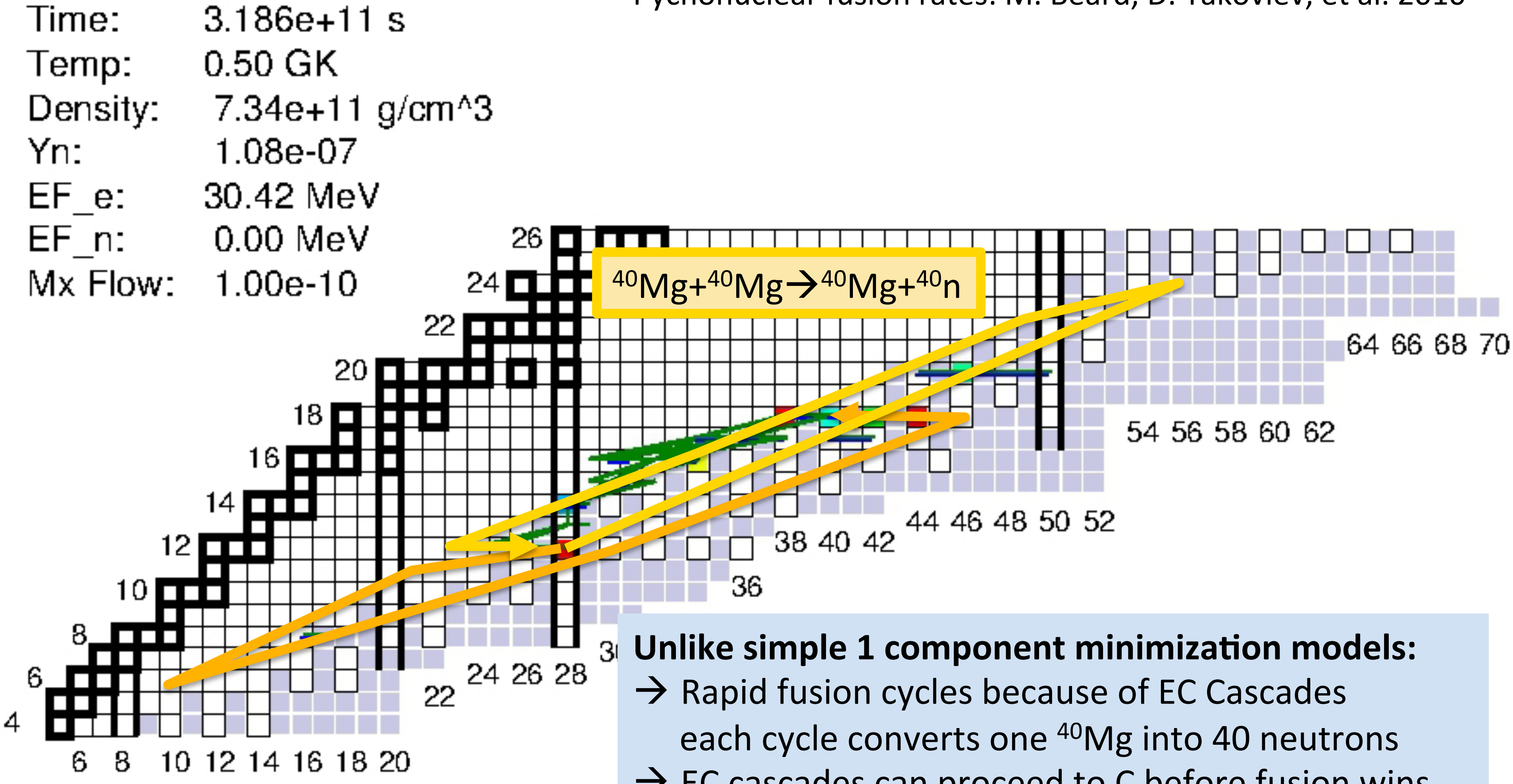
→ No path to equilibrium (Jones 2005)

EC, (n,γ)

β-decay, (γ,n), fusion

Crust processes: Pycnonuclear fusion cycles

Pycnonuclear fusion rates: M. Beard, D. Yakovlev, et al. 2010



```
Time:       3.186e+11 s
Temp:       0.50 GK
Density:     7.34e+11 g/cm^3
Yn:          1.08e-07
EF_e:       30.42 MeV
EF_n:        0.00 MeV
Mx Flow:     1.00e-10
```

$^{40}Mg + ^{40}Mg \rightarrow ^{40}Mg + ^{40}n$

Unlike simple 1 component minimization models:

→ Rapid fusion cycles because of EC Cascades each cycle converts one ^{40}Mg into 40 neutrons

→ EC cascades can proceed to C before fusion wins

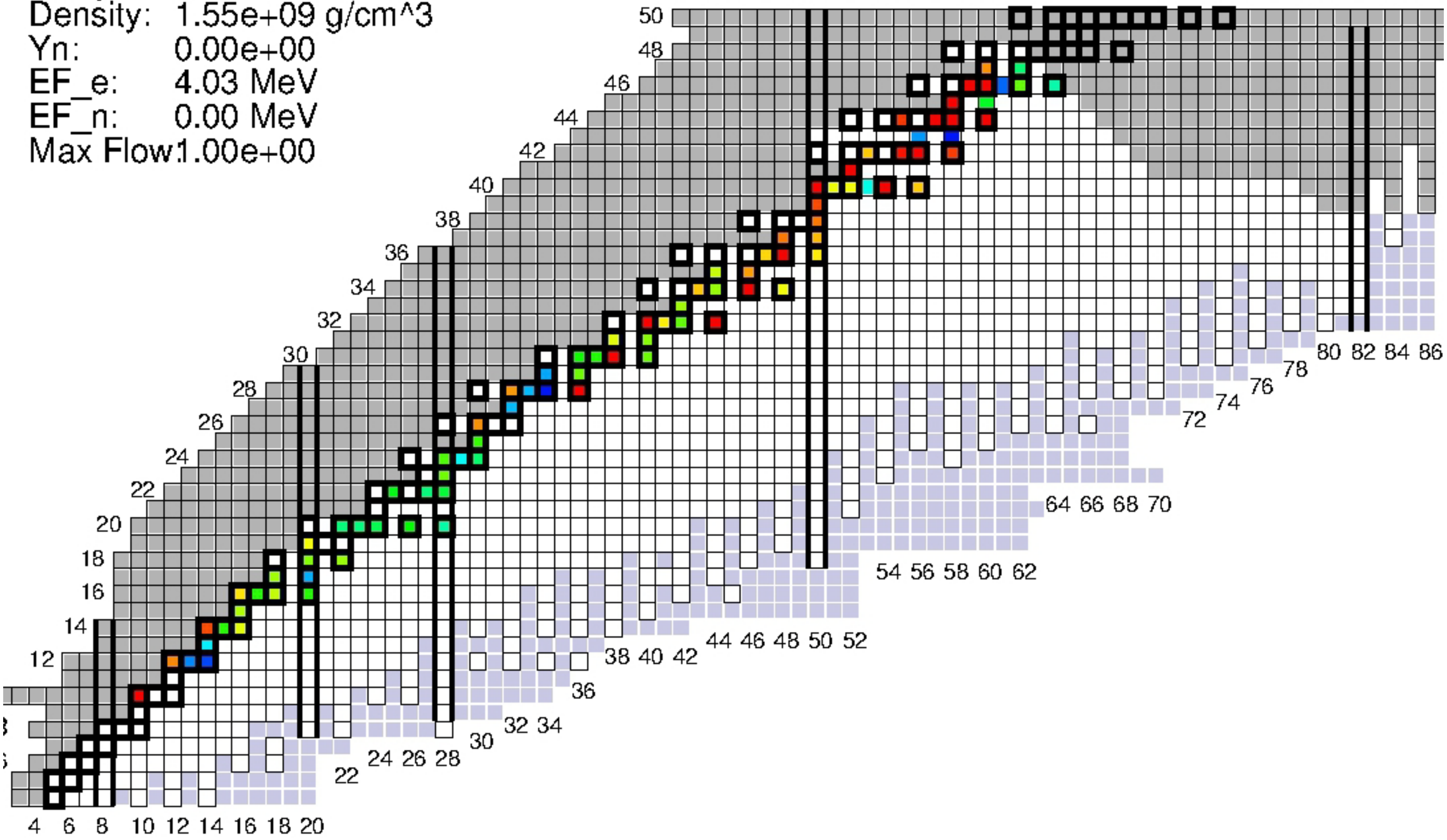
→ Multiple ion composition → many fusion reactions $^{40}Mg + ^{25}N$, $^{40}Mg + ^{40}Mg$, $^{40}Mg + ^{28}O$, $^{40}Mg + ^{20}C$, …

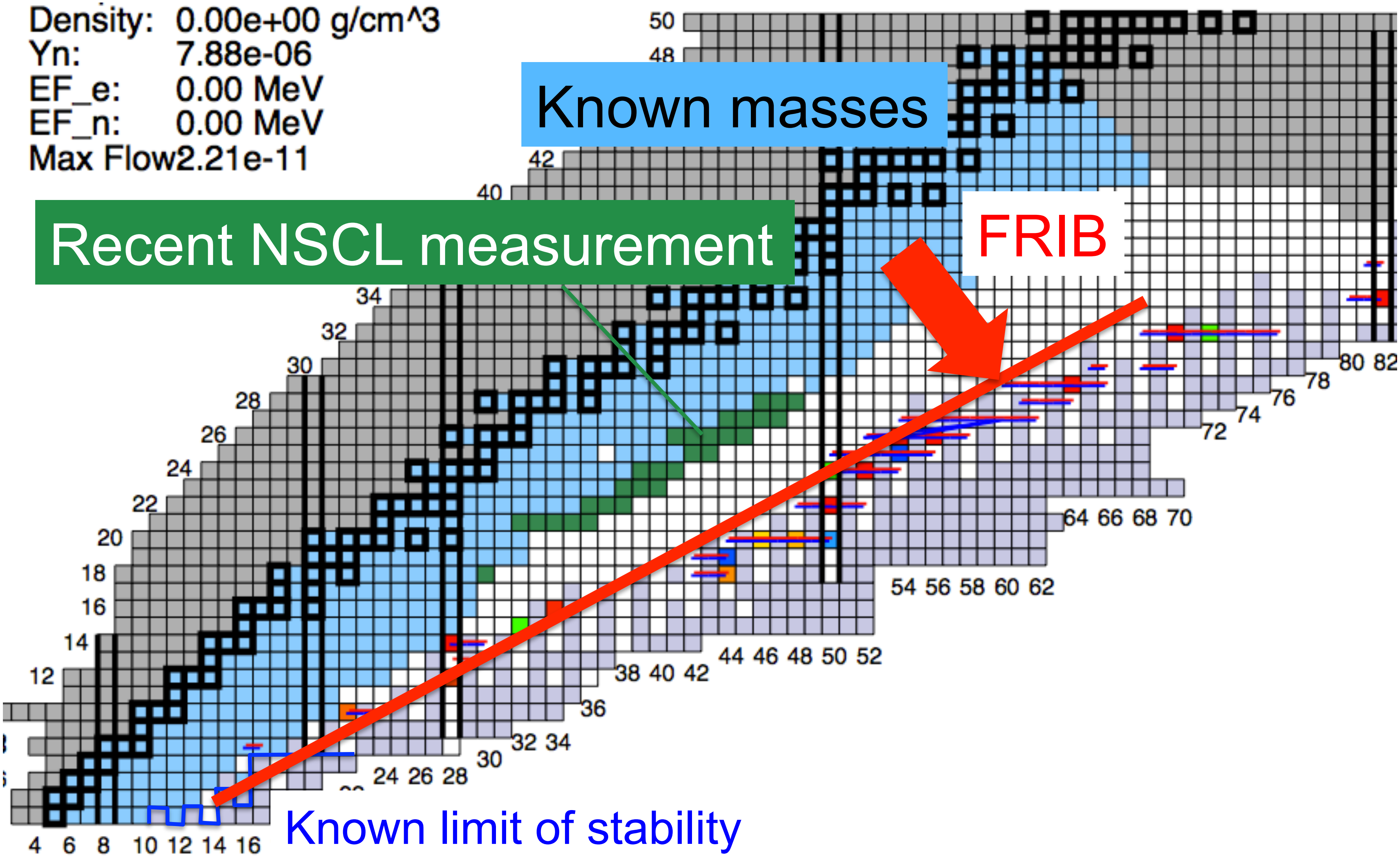
EC, (n,γ)

β-decay, (γ,n), fusion

Crust simulation for rp-process ashes from X-ray bursts

Time: 1.400e+08 s
Temp: 0.48 GK
Density: 1.55e+09 g/cm^3
Yn: 0.00e+00
EF_e: 4.03 MeV
EF_n: 0.00 MeV
Max Flow 1.00e+00





Known masses

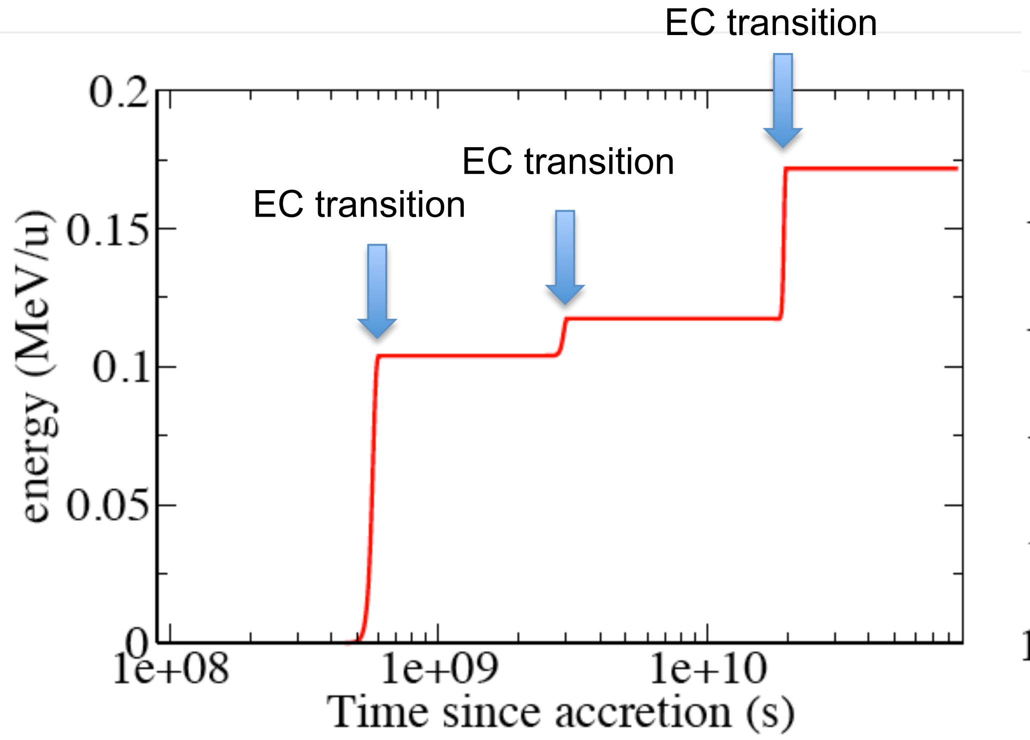
Recent NSCL measurement

FRIB

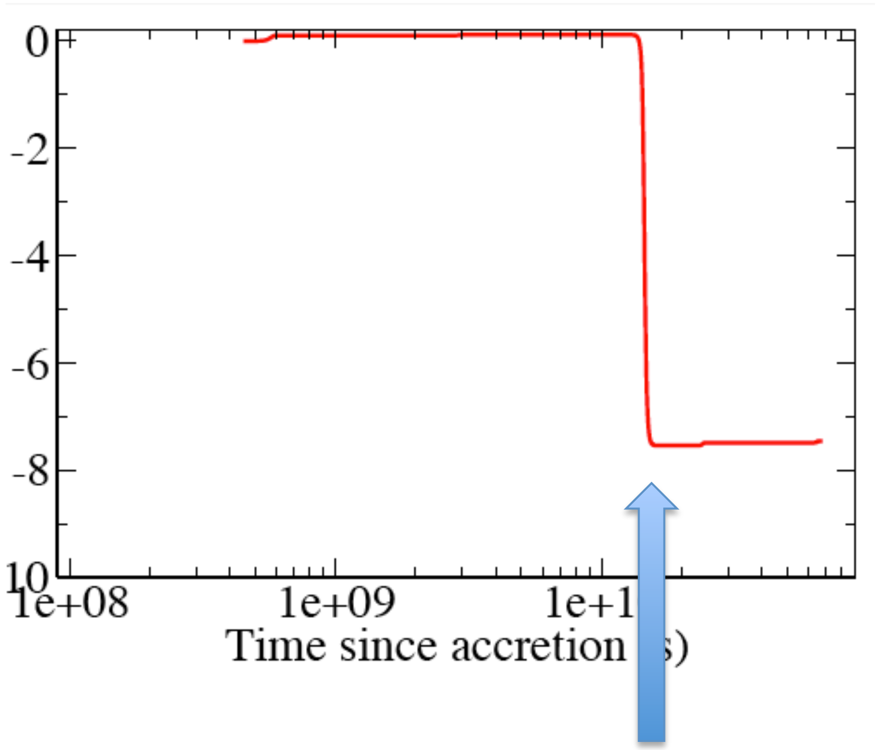
Known limit of stability

A=56 material in the crust

FRDM mass model



HFB-21 mass model

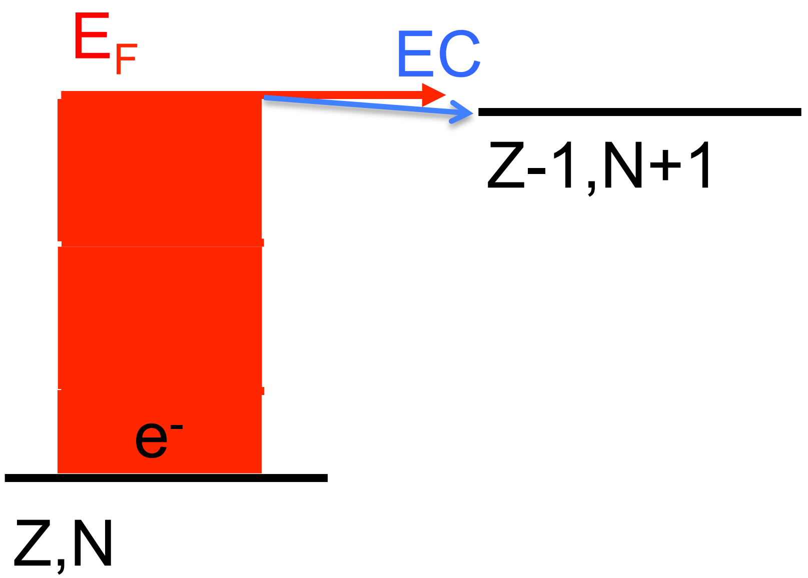


Massive cooling ???

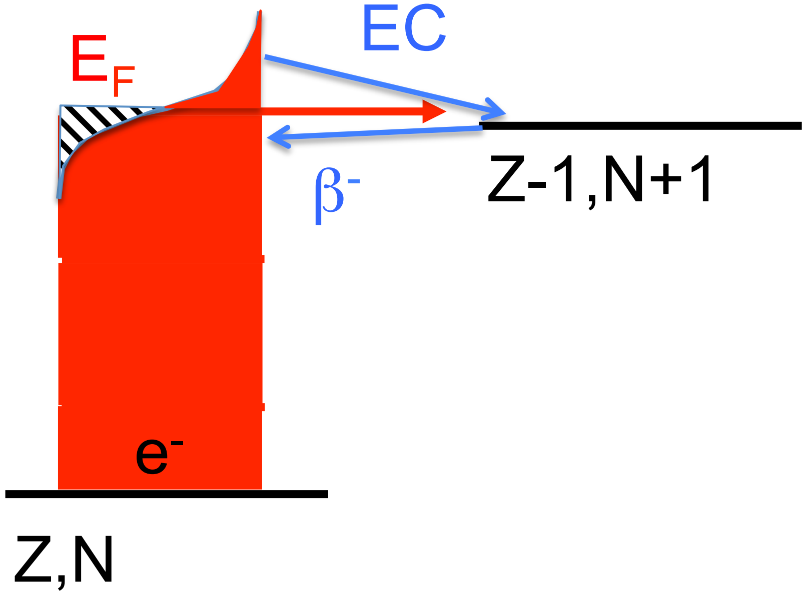
T=0.5 GK

Nuclear Urca process

Zero temperature



finite temperature



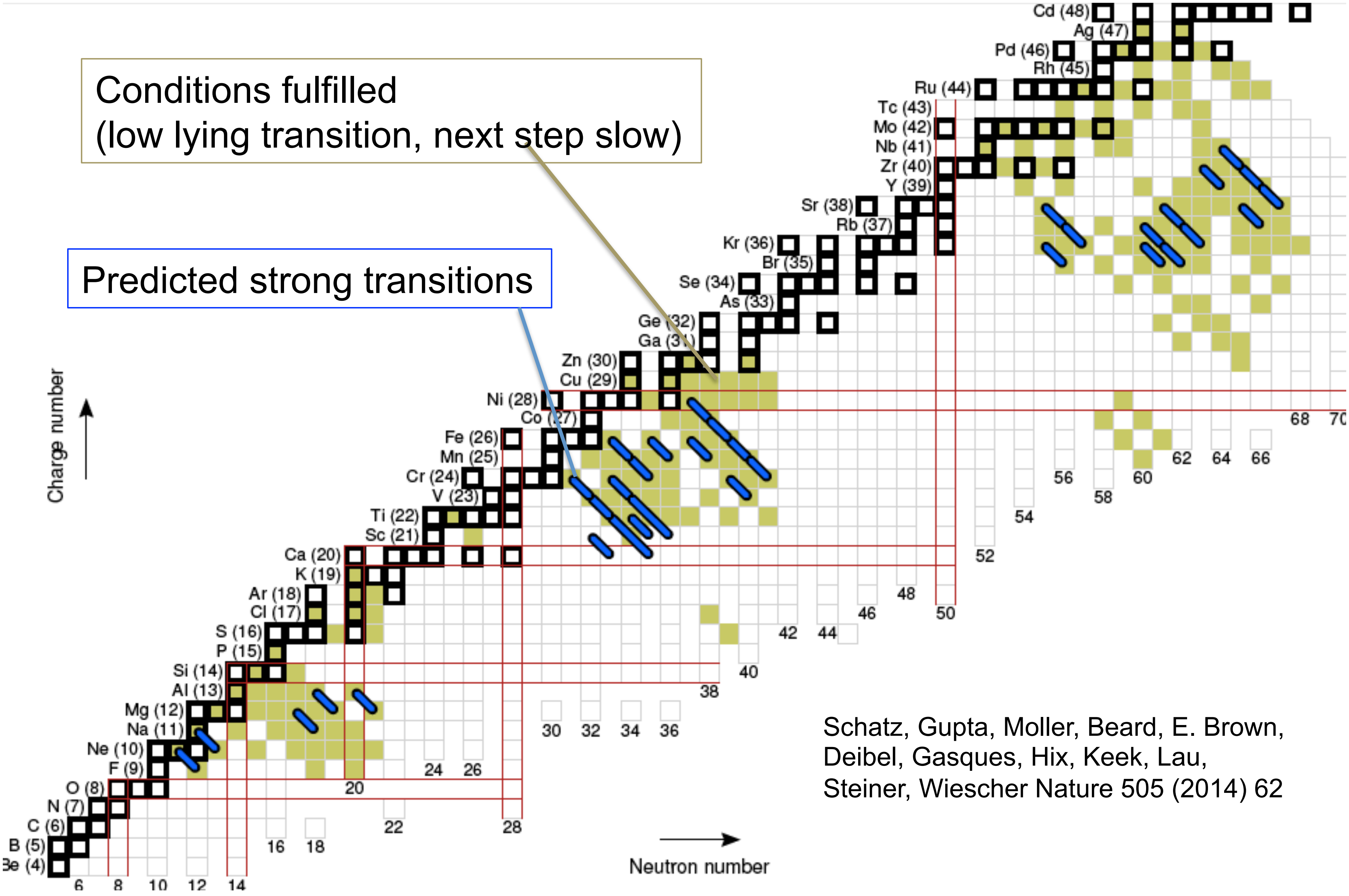
Tsuruta & Cameron 1962
for White Dwarfs

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

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

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

Location of predicted cooling Urca pairs



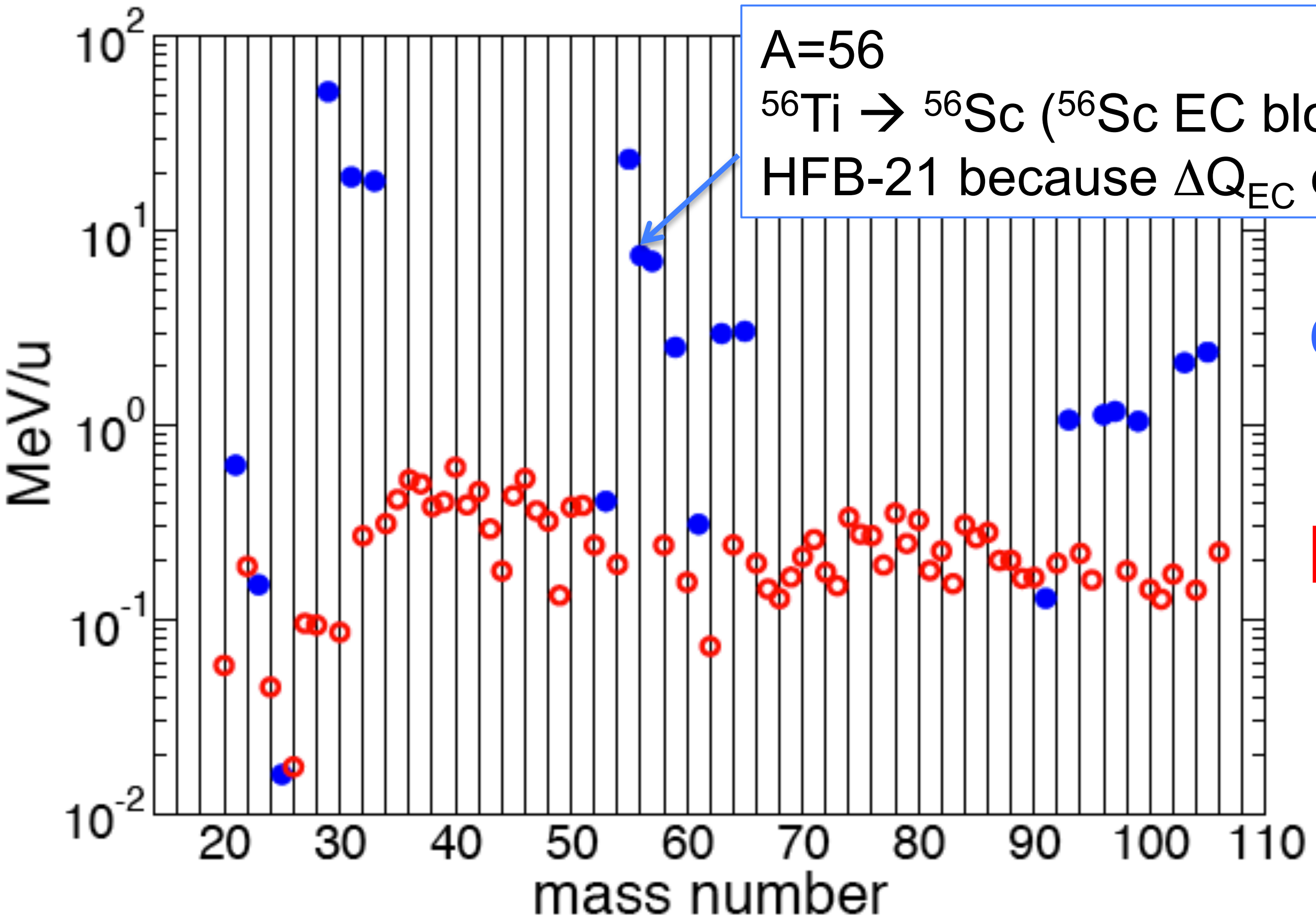
Conditions fulfilled
(low lying transition, next step slow)

Predicted strong transitions

Schatz, Gupta, Moller, Beard, E. Brown,
Deibel, Gasques, Hix, Keek, Lau,
Steiner, Wiescher Nature 505 (2014) 62

Heating or cooling depends on initial composition

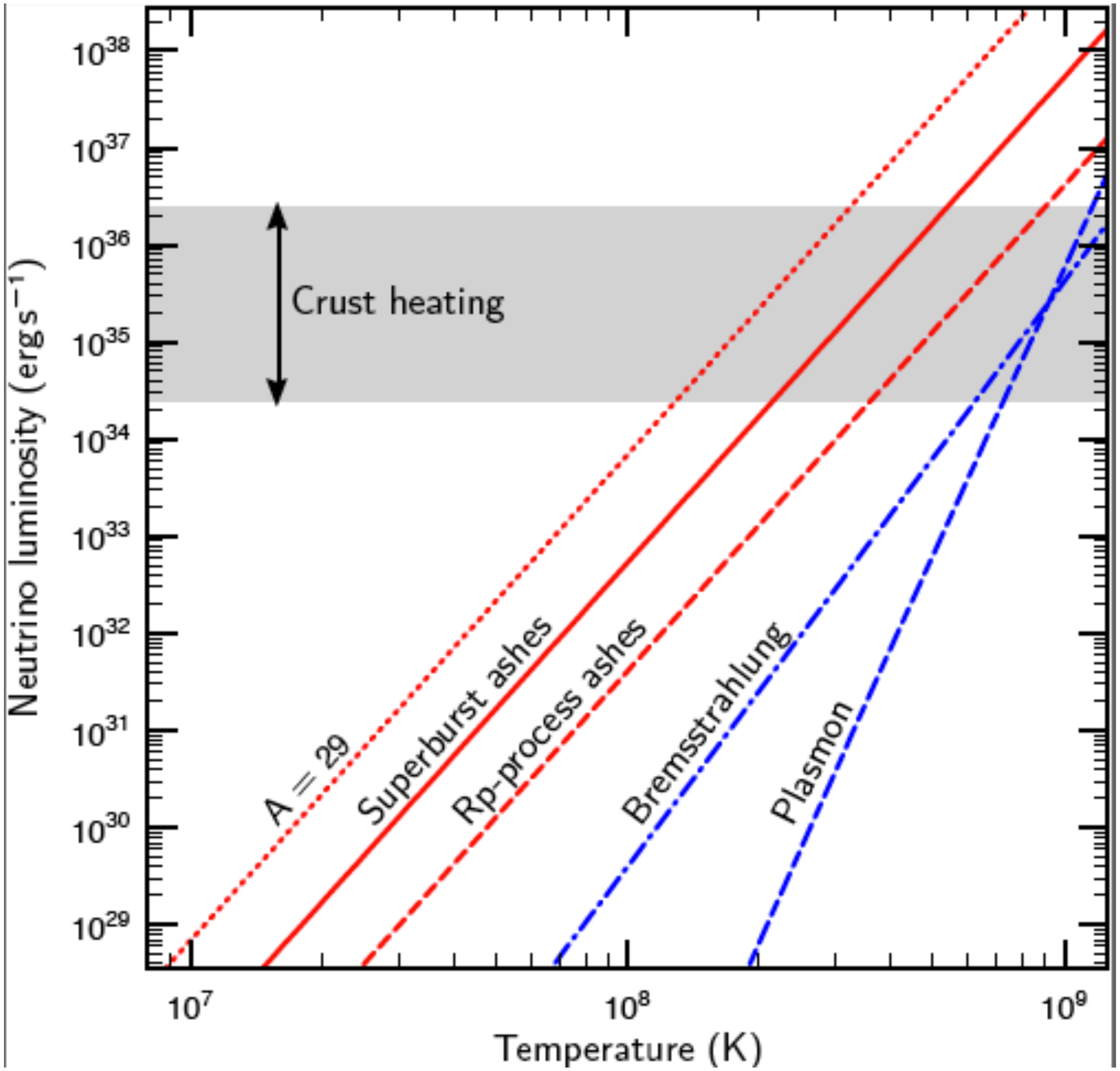
- need EC to low lying states (< kT) → deformation
- next EC needs to be blocked



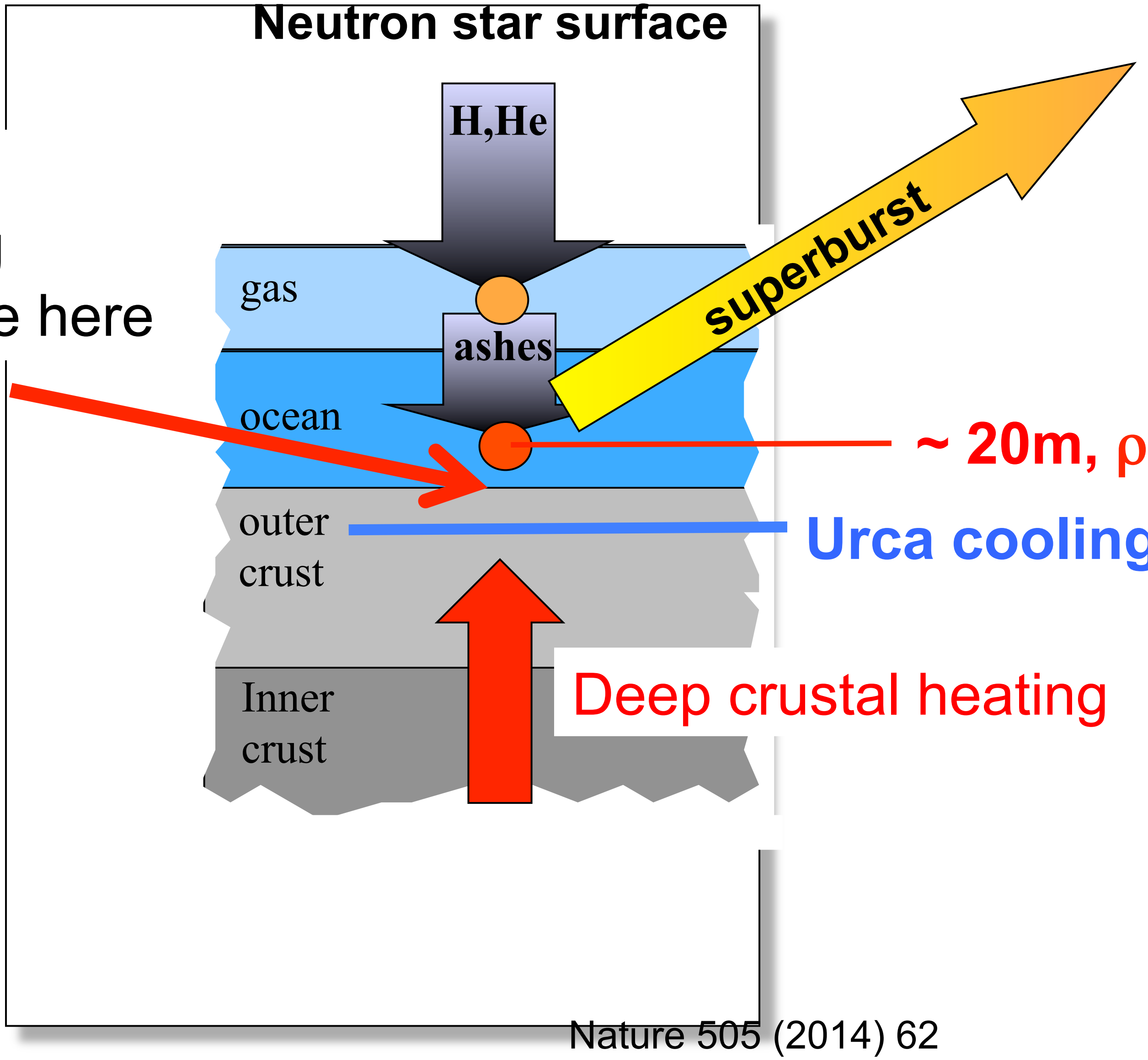
A=56
^{56}Ti → ^{56}Sc (^{56}Sc EC blocked in HFB-21 because ΔQ_{EC} only 1 MeV

cooling

heating


Neutrino luminosity (erg s⁻¹)
10³⁸
10³⁷
10³⁶
10³⁵
10³⁴
10³³
10³²
10³¹
10³⁰
10²⁹
Temperature (K)
10⁷
10⁸
10⁹
Crust heating
A = 29
Superburst ashes
Rp-process ashes
Bremsstrahlung
Plasmon

How can we make the ocean hotter?



Ocean heating must be here

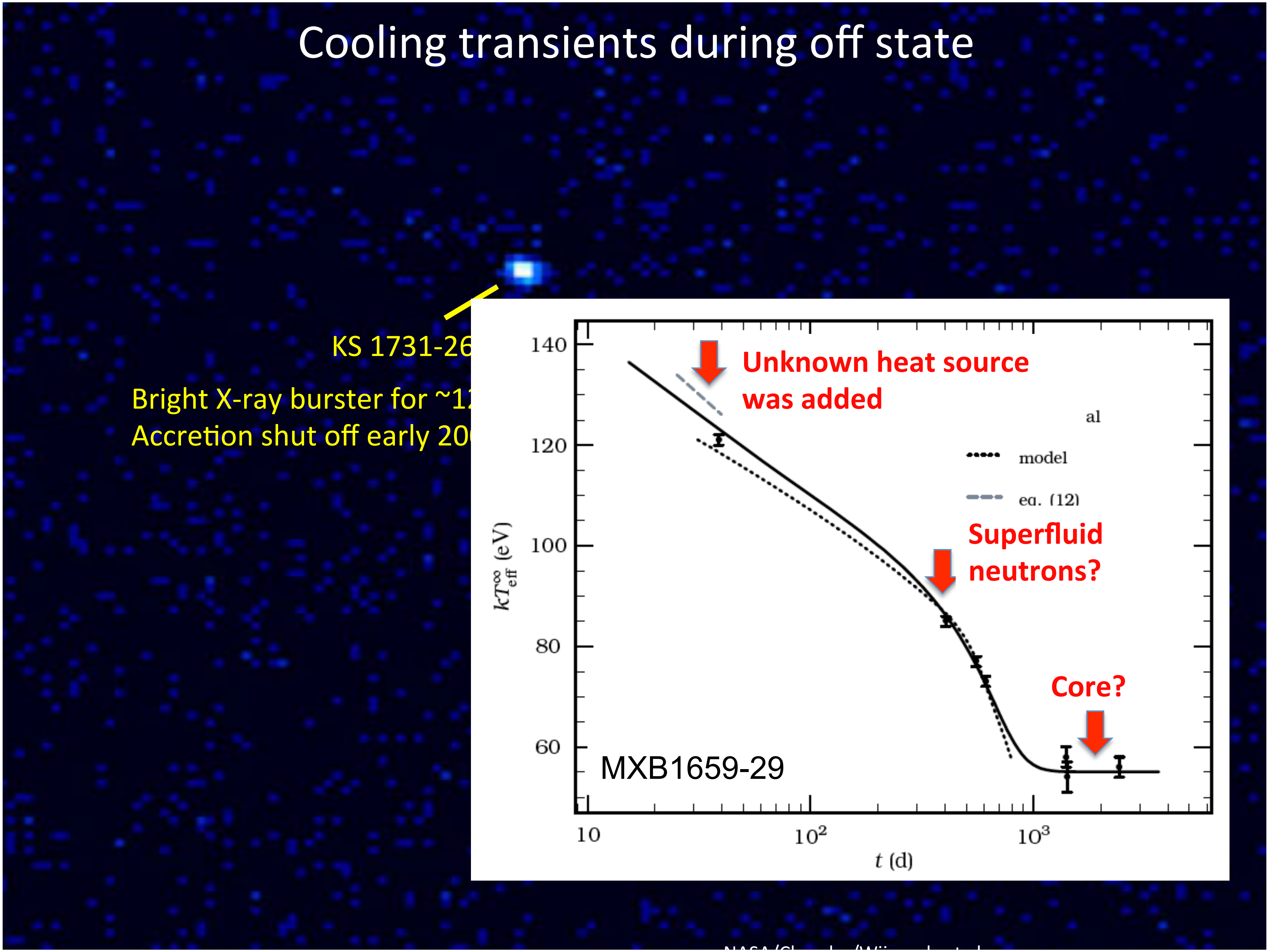
~ 20m, $\rho = 10^9$ g/cm^3

Urca cooling layer shield

Deep crustal heating

Nature 505 (2014) 62

Cooling transients during off state



KS 1731-26

Bright X-ray burster for ~12

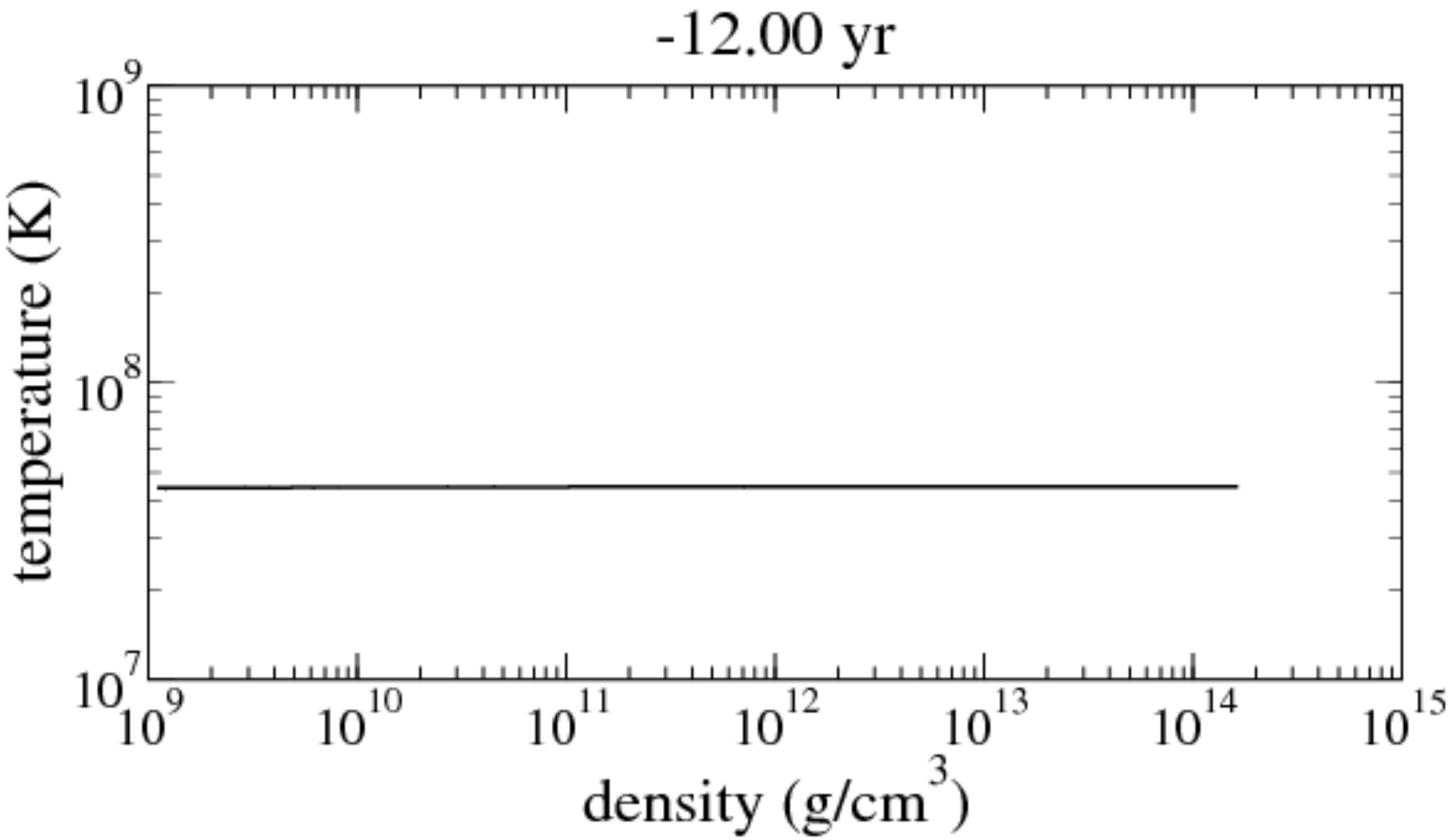
Accretion shut off early 20

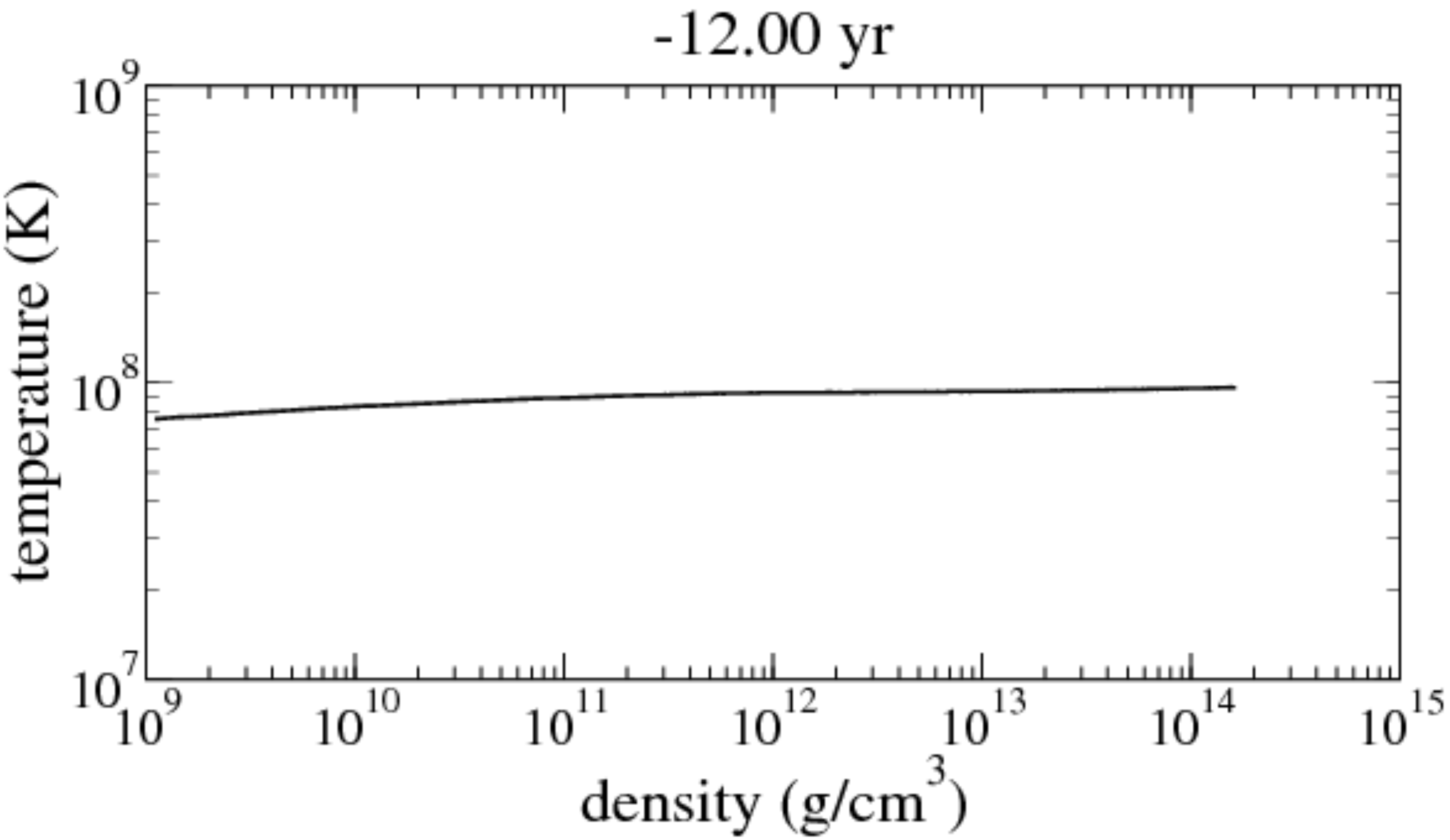
Unknown heat source was added

Superfluid neutrons?

Core?

NASA/Chandra/Wijnands et al.


-12.00 yr
10^9
10^8
10^7
temperature (K)
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
density (g/cm^3)


-12.00 yr
temperature (K)
density (g/cm^3)
10^7
10^8
10^9
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}

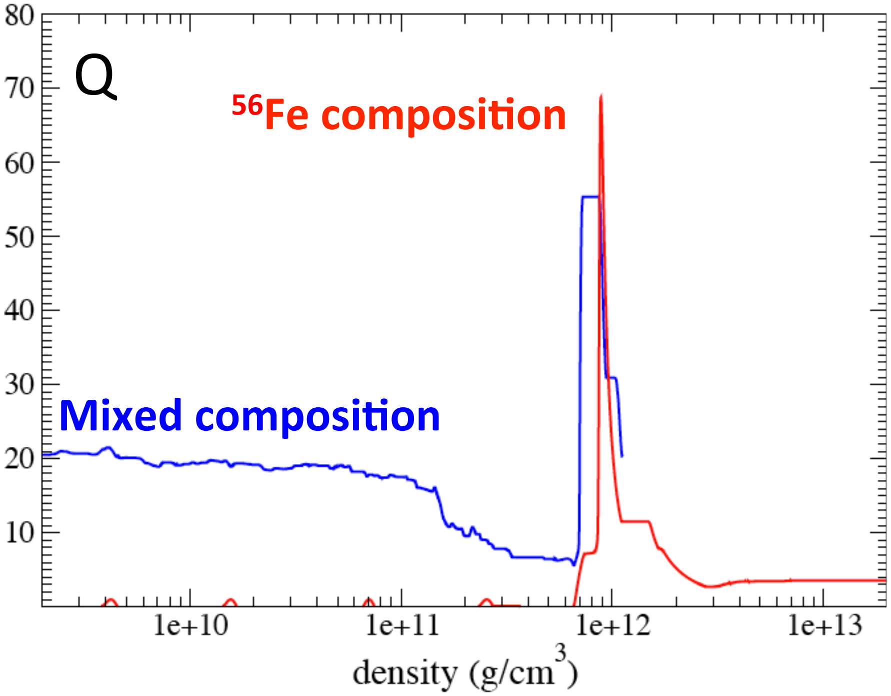
Impurity parameter

$$Q = \frac{\sum Y_i (Z_i - <Z>)^2}{\sum Y_i}$$

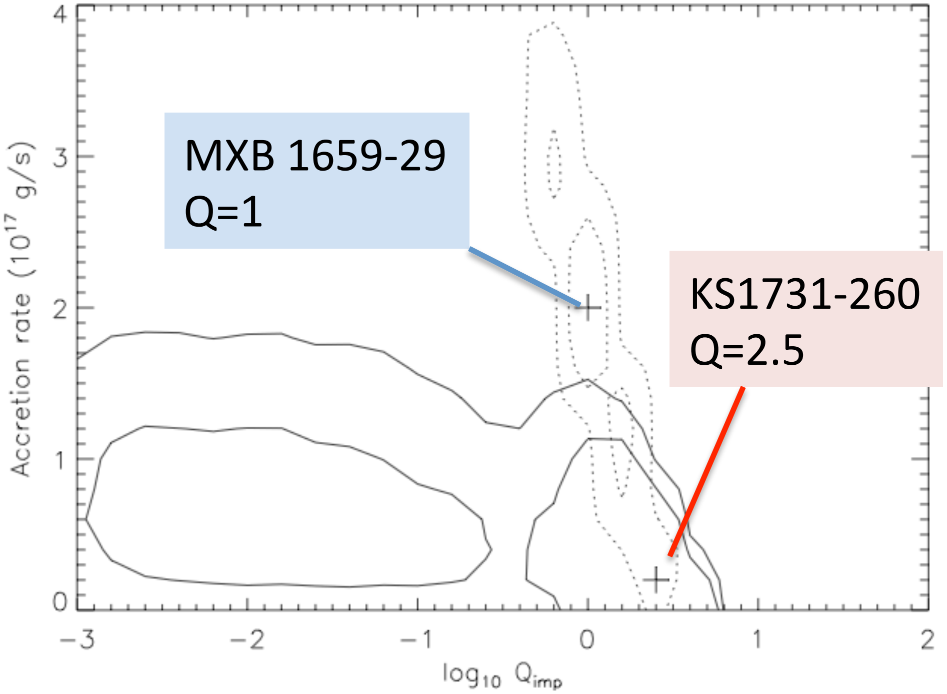
- Describes impurity of compsoition
- Affects thermal conductivity

- Significant deviations from zero for single initial species
- For mixed composition convergence to similar composition at ~10^{12} g/cm^3

Simulation



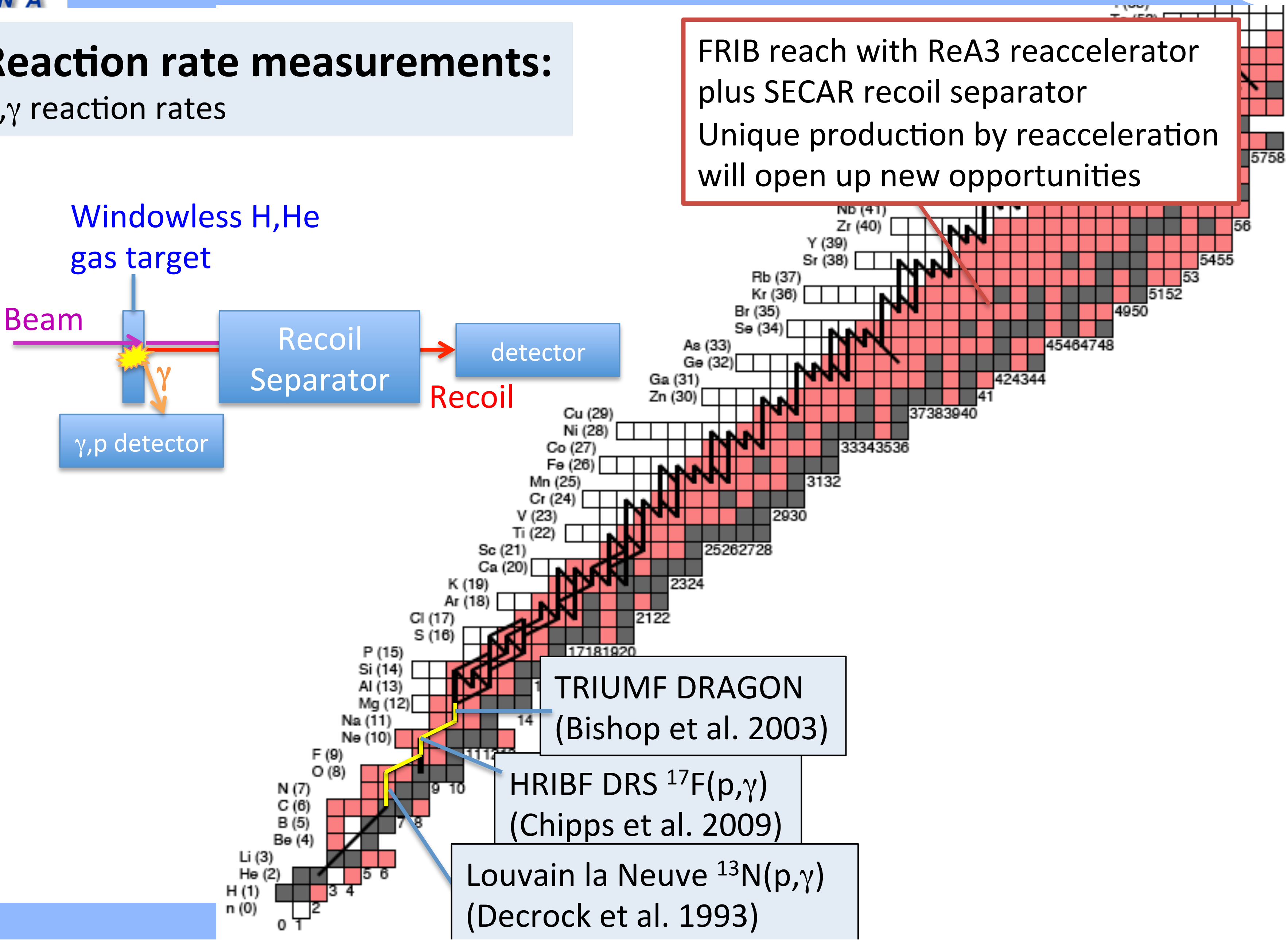
Observation



rp-process reaction rate measurements

Reaction rate measurements:

p,γ reaction rates



FRIB reach with ReA3 reaccelerator plus SECAR recoil separator

Unique production by reacceleration will open up new opportunities

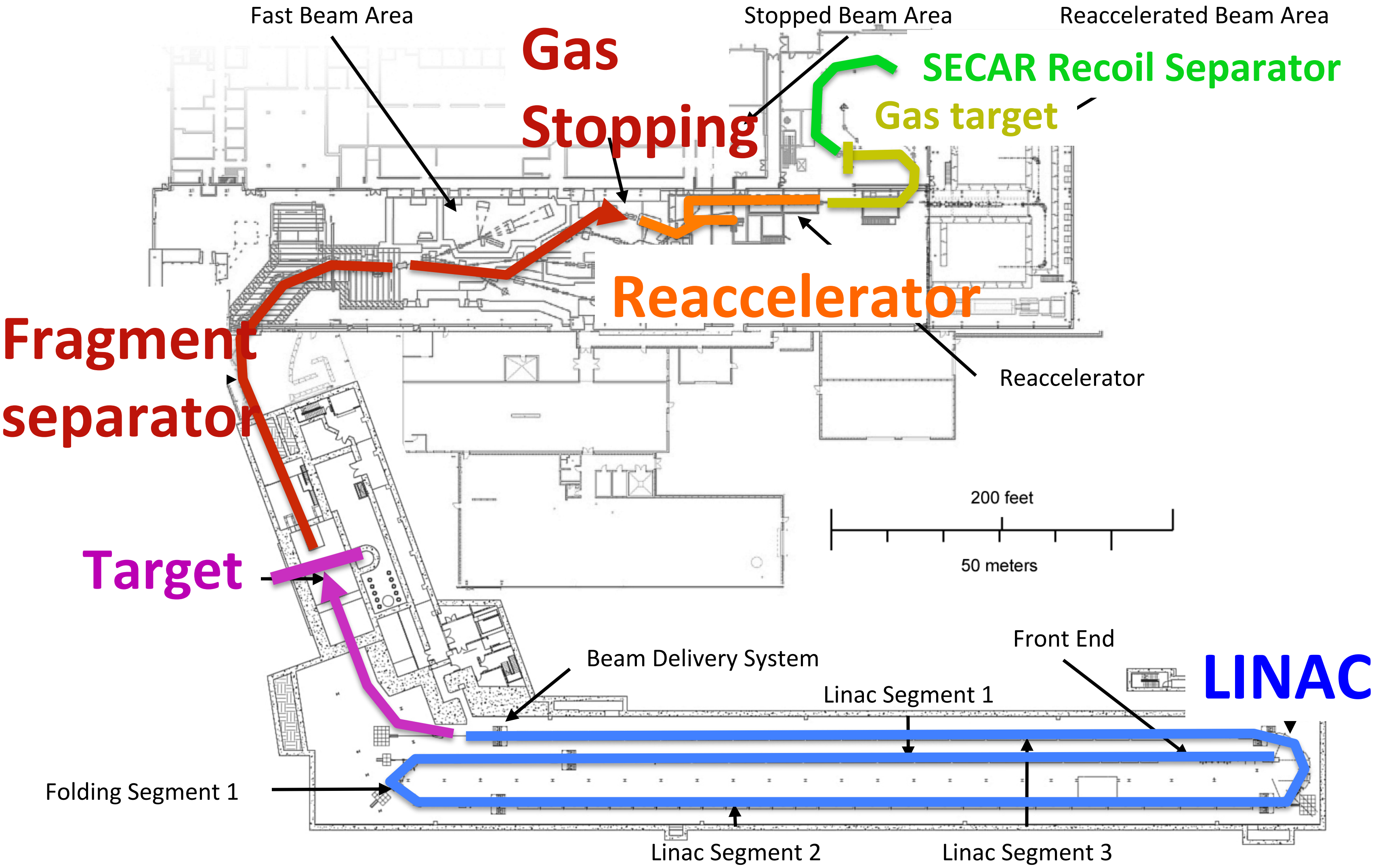
TRIUMF DRAGON (Bishop et al. 2003)

HRIBF DRS ^{17}F(p,γ) (Chipps et al. 2009)

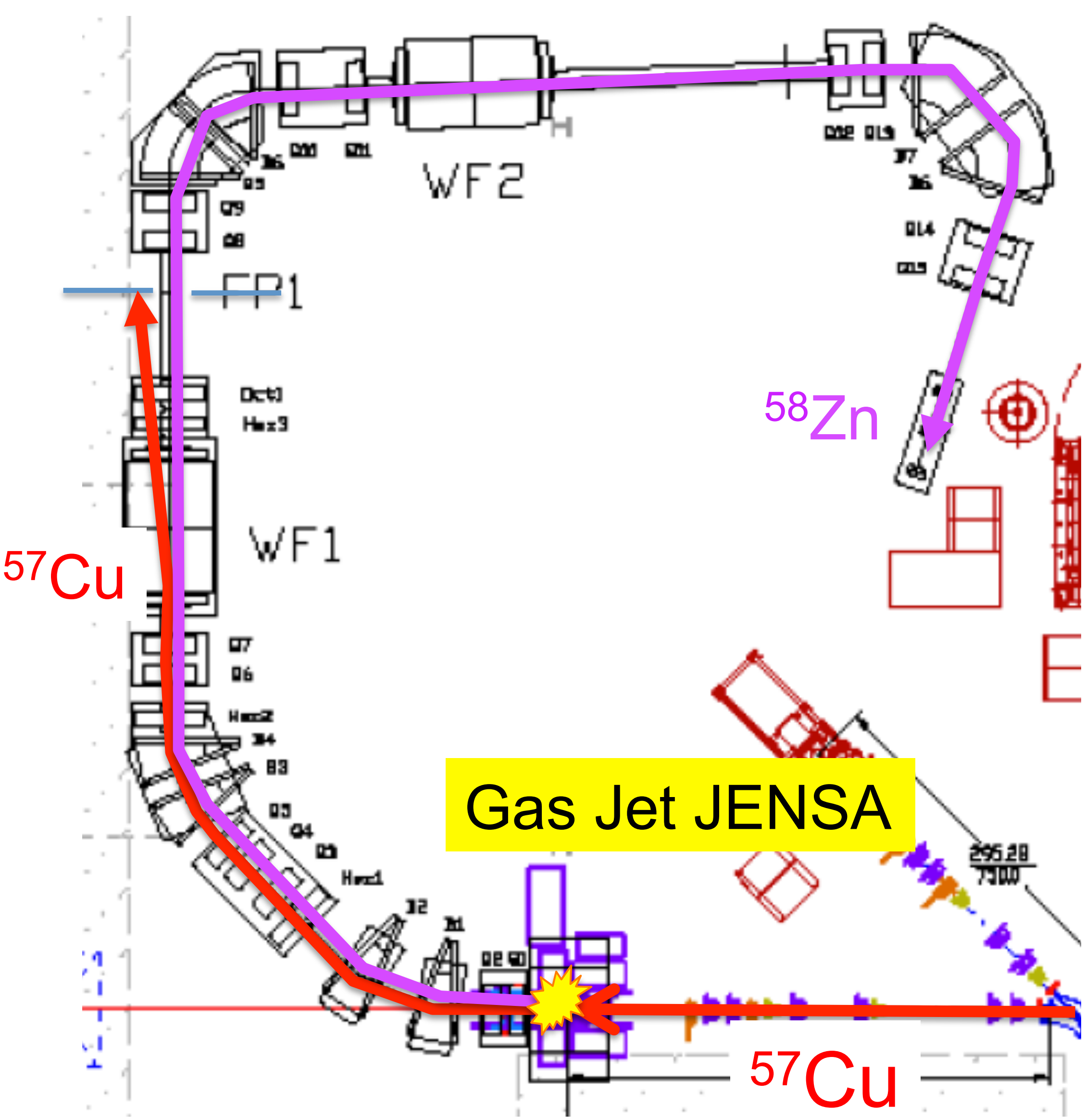
Louvain la Neuve ^{13}N(p,γ) (Decrock et al. 1993)

FRIB Layout

example: nuclear astrophysics experiment



SECAR Recoil Separator Project



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Pacific Northwest NATIONAL LABORATORY

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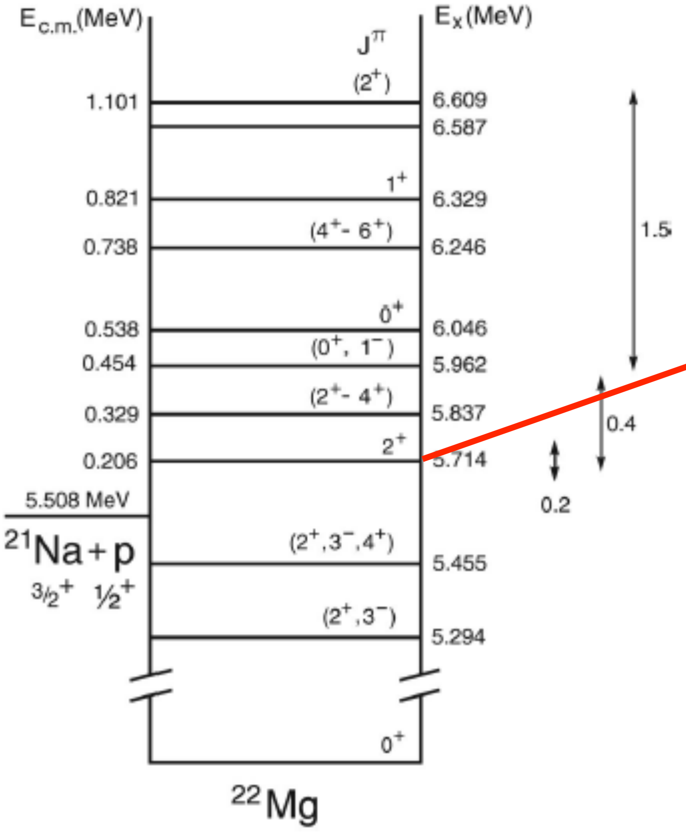
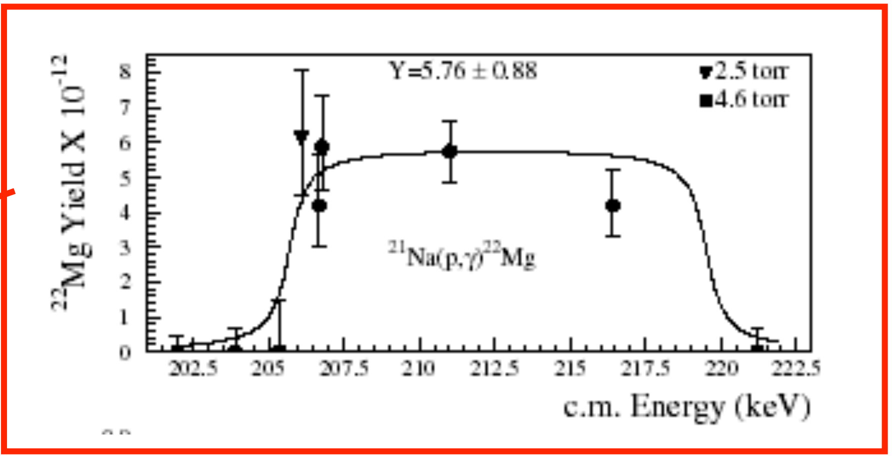
McMaster University

CMU CENTRAL MICHIGAN UNIVERSITY

Results



Result for 206 keV resonance:



S. Bishop et al. Phys. Rev. Lett. 90 (2003) 2501