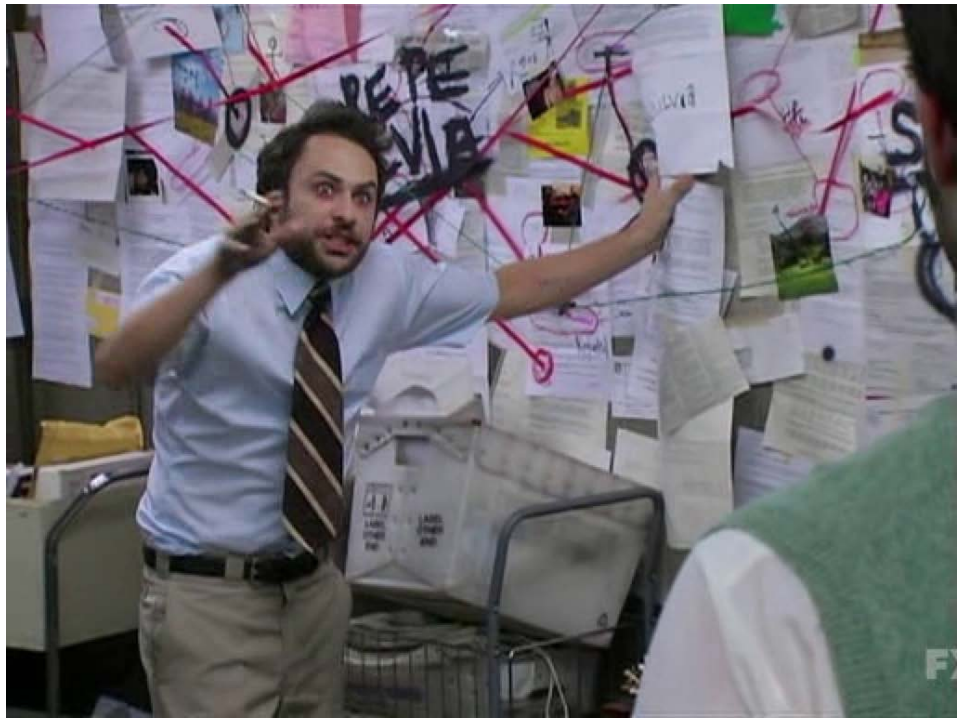
“Connecting Neutron Star Observables and Nuclear Reaction Studies”



Zach Meisel

OU Nuclear Theory Group Pow-wow

February 2019

Game Plan:

Content:

- Motivate NS connection to nuclear physics
- Surface burning processes
- Ocean & outer crust processes
- Inner crust reactions

(almost) all the gory details

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **45** (2018) 093001 (53pp) https://doi.org/10.1088/1361-6471/aad171

Topical Review

Nuclear physics of the outer layers of accreting neutron stars

Zach Meisel[1,6], Alex Deibel[2], Laurens Keek[3], Peter Shternin[4] and Justin Elfritz[5]

Structure:

- ~2 lecture/discussion sessions
  - *Interrupt whenever you want*
- Experiment & theory peppered throughout
- Typical order per topic:
  - Astro environment
  - Nuclear reactions that matter
  - How these reactions are determined

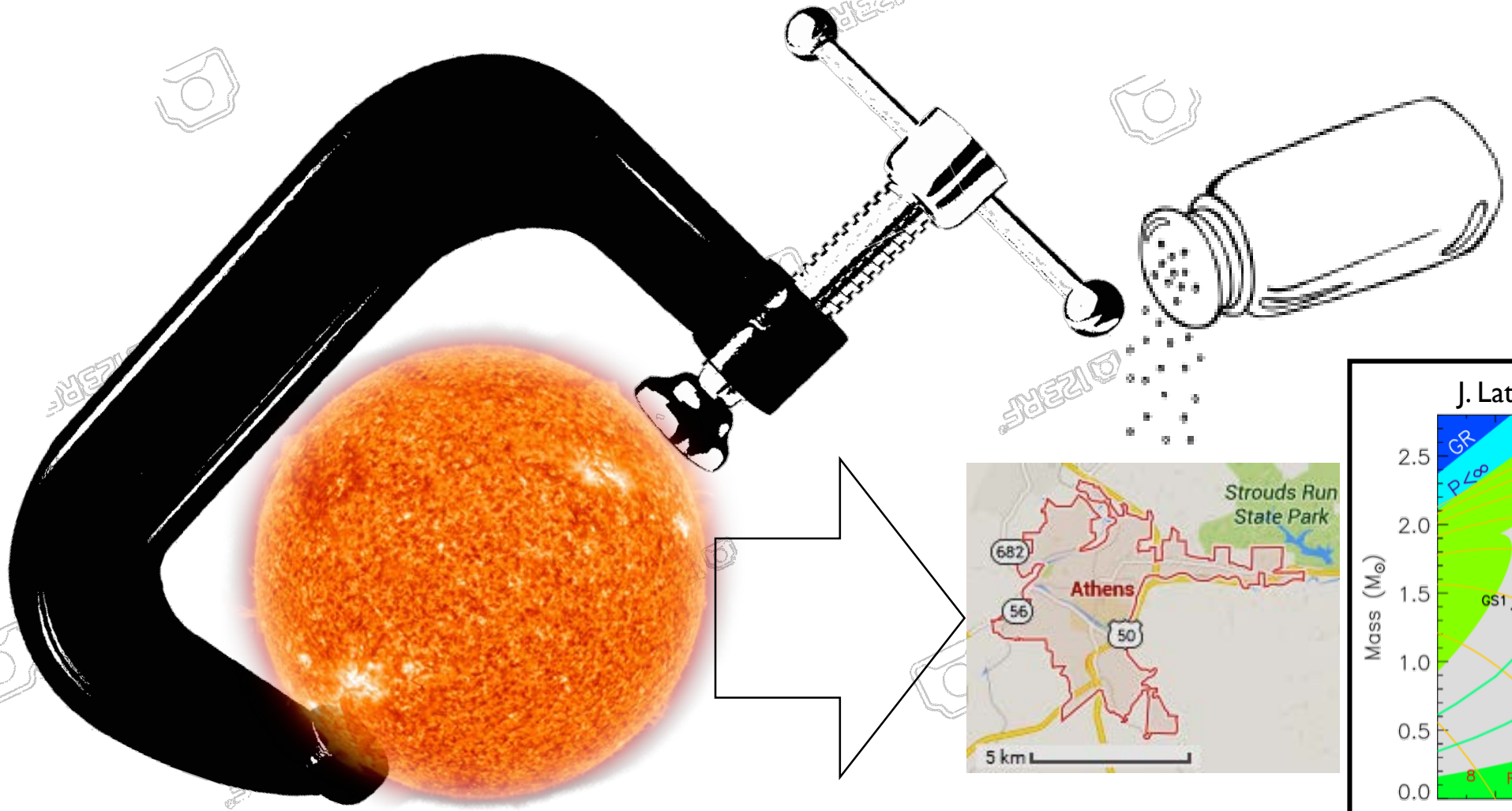
(almost) all the basic nuclear physics

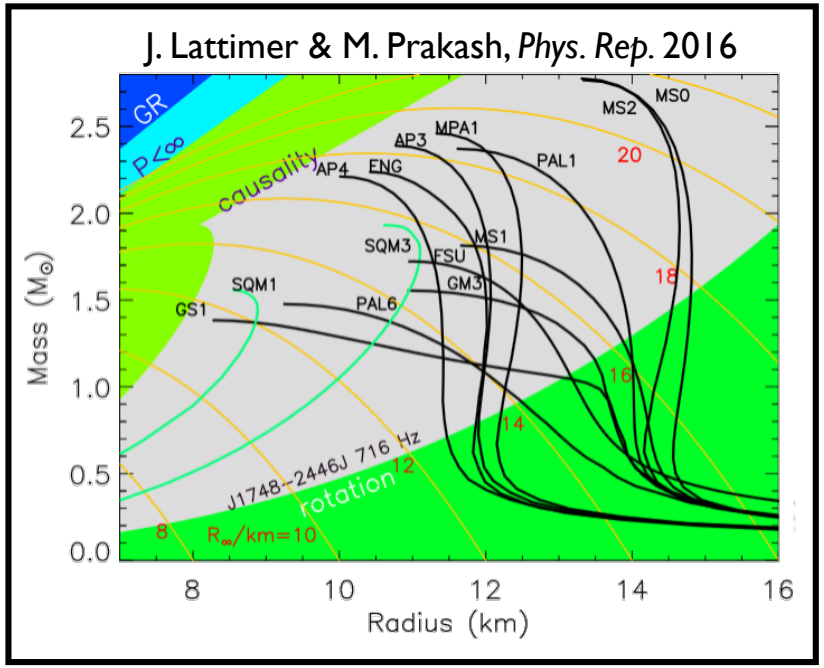
inpp.ohio.edu/~meisel/PHYS7501/Schedule.html

PHYS 7501 — Overview | Materials | Academic Honesty

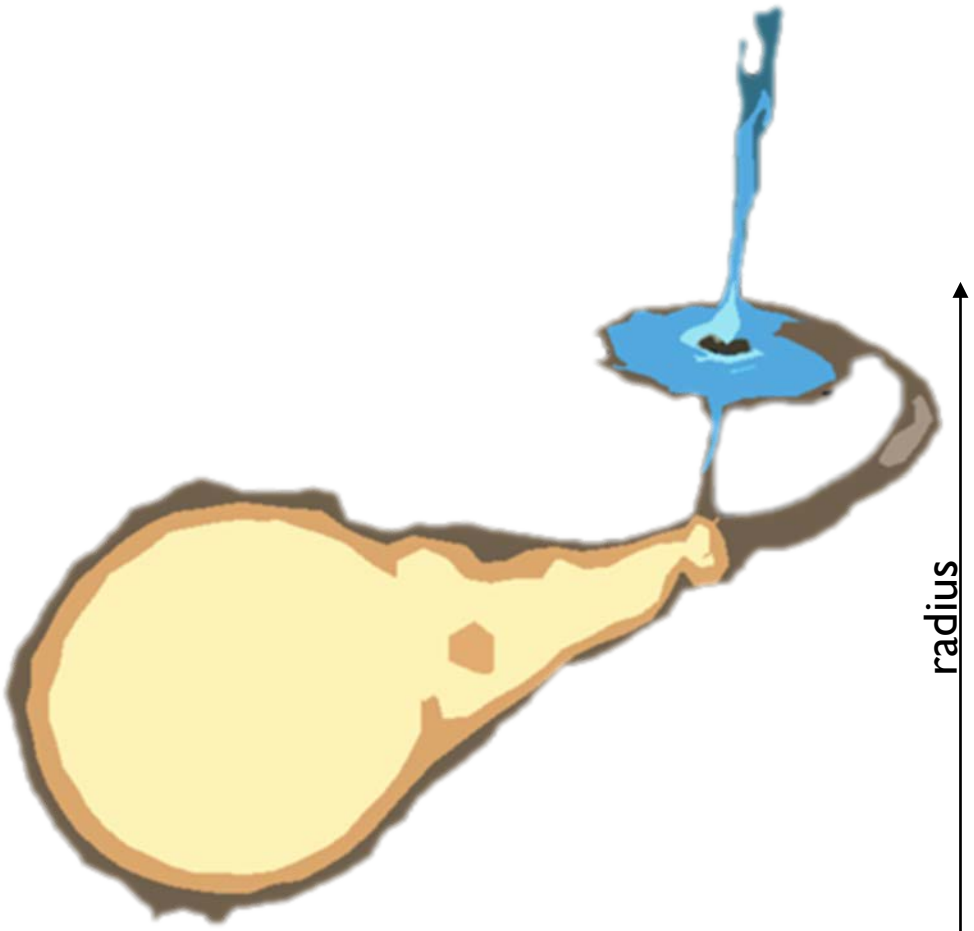
Date	Lecture Topic	Material Due
Tue. Aug. 29	Nuclear Properties	GA1
Thu. Aug. 31	Nuclear Phenomenology	GA2
Tue. Sep. 5	Nuclear Structure 1	GA3
Thu. Sep. 7	Nuclear Structure 2	HW1, GA4
Tue. Sep. 12	Nuclear Structure 3	GA5
Thu. Sep. 14	Radioactive Decay	GA6
~~Tue. Sep. 19~~ Fri. Sep. 15	Alpha Decay	GA7
~~Thu. Sep. 21~~ Mon. Sep. 25	Beta Decay	HW2, GA8
Tue. Sep. 26	Gamma Decay	Review Topic, GA9
~~Thu. Sep. 28~~	Fission	GA10
Tue. Oct. 3	Nucleon-nucleon Potential	GA11
Thu. Oct. 5	Review of Section 1	HW3
~~Tue. Oct. 10~~	**No Class**, Fall Reading Day	
Thu. Oct. 12	Midterm Exam	Exam, HW4
Tue. Oct. 17	Ab Initio Theory Discussion: Paper 1, Paper 2	
Thu. Oct. 19	Shell Model	
Tue. Oct. 24	Nuclear Reactions	GA12
~~Thu. Oct. 26~~ Wed. Oct. 25	Scattering	GA13
Tue. Oct. 31	Direct Reactions	GA14
Thu. Nov. 2	Resonant Reactions	GA15
Tue. Nov. 7	Statistical Reactions	HW5, GA16, Review Outline
Thu. Nov. 9	Other Reactions	
Tue. Nov. 14	Astrophysical Reaction Rates	GA17
Thu. Nov. 16	Nucleosynthesis	HW6, GA18
~~Tue. Nov. 21~~ Fri. Nov. 17	Experimental Techniques	GA19
~~Thu. Nov. 23~~	**No Class**, Thanksgiving Break	
Tue. Nov. 28	Nuclear Applications	GA20
Thu. Nov. 30	Review of Section 2	
Tue. Dec. 5	Final Presentations 1	HW7, Presentation Slides, Review Paper

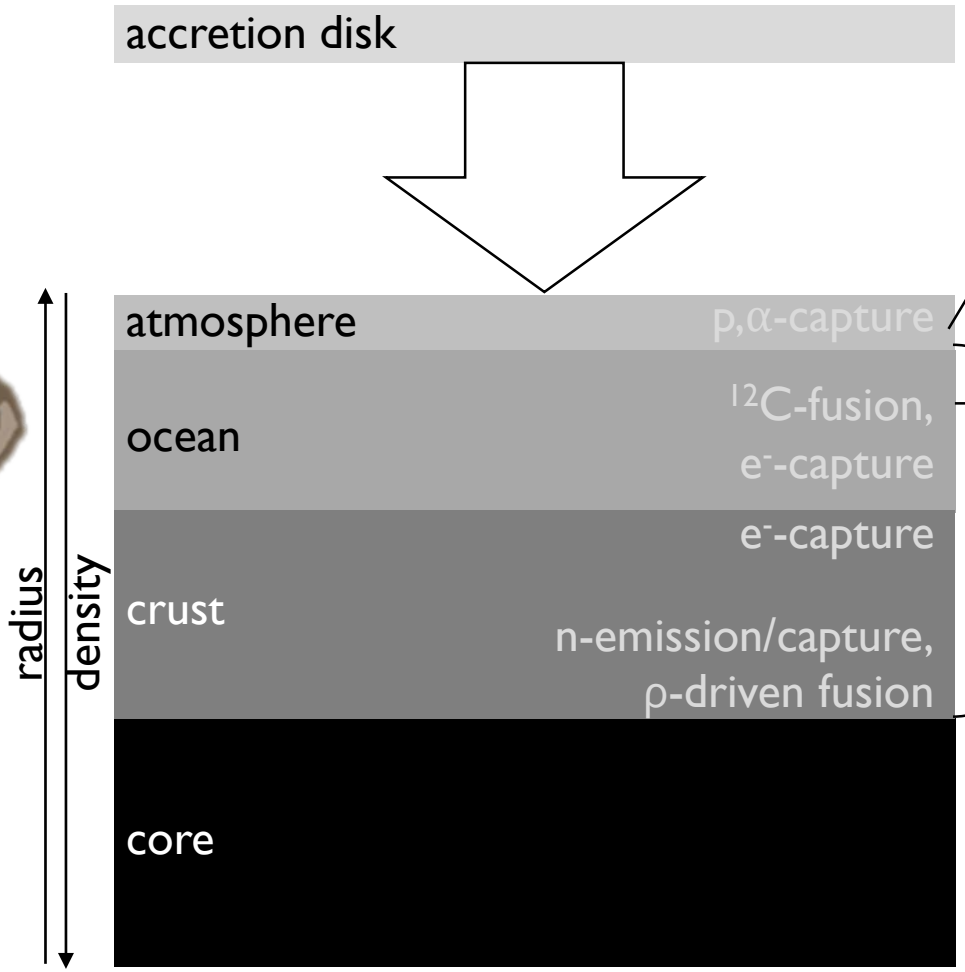
How do very high-density, “low” temperature objects behave?

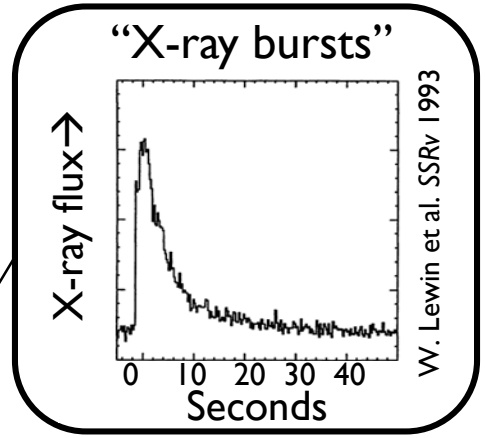


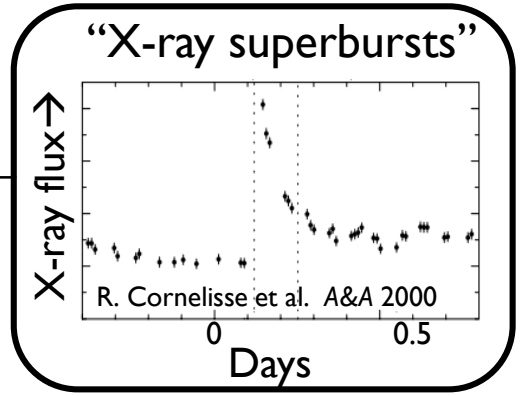


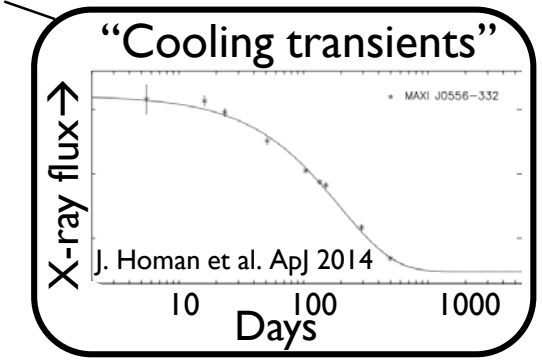
Accreting Neutron Stars: *Dense Matter Laboratories*







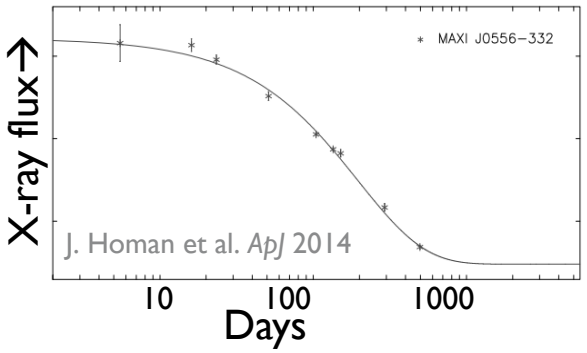




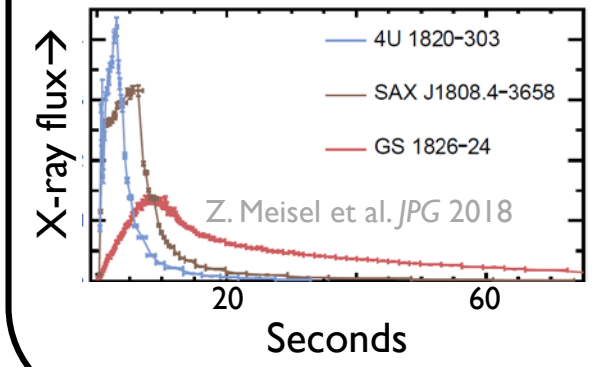
The approach to understanding dense matter behavior:

Observations

Cooling transients:



X-ray bursts:



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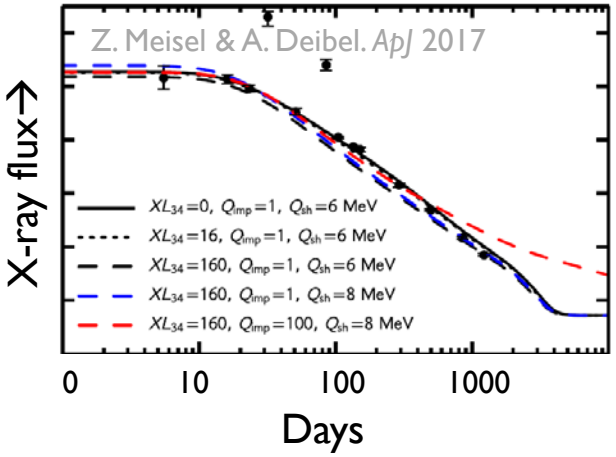
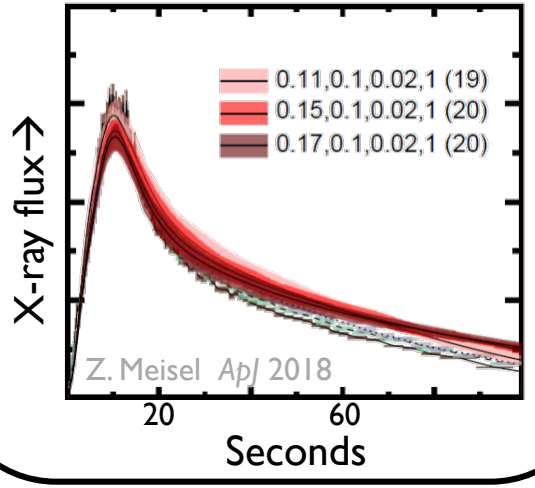
Models





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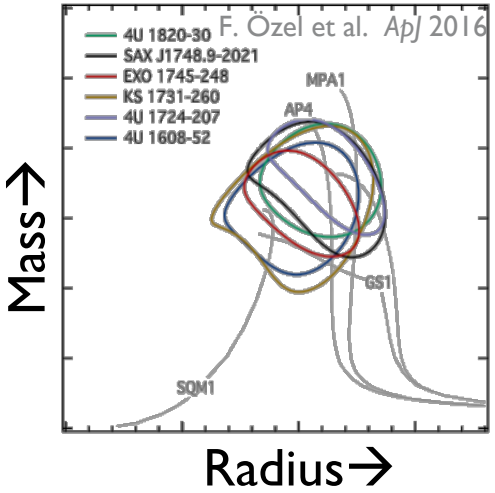
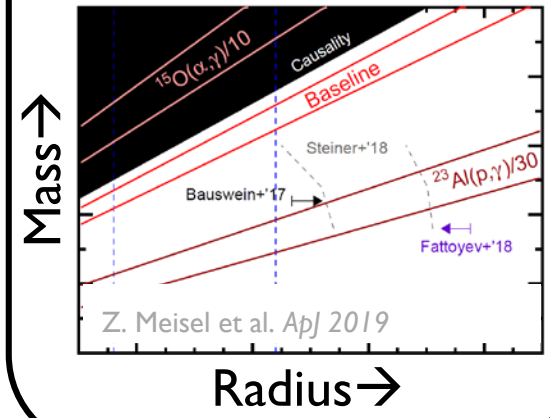
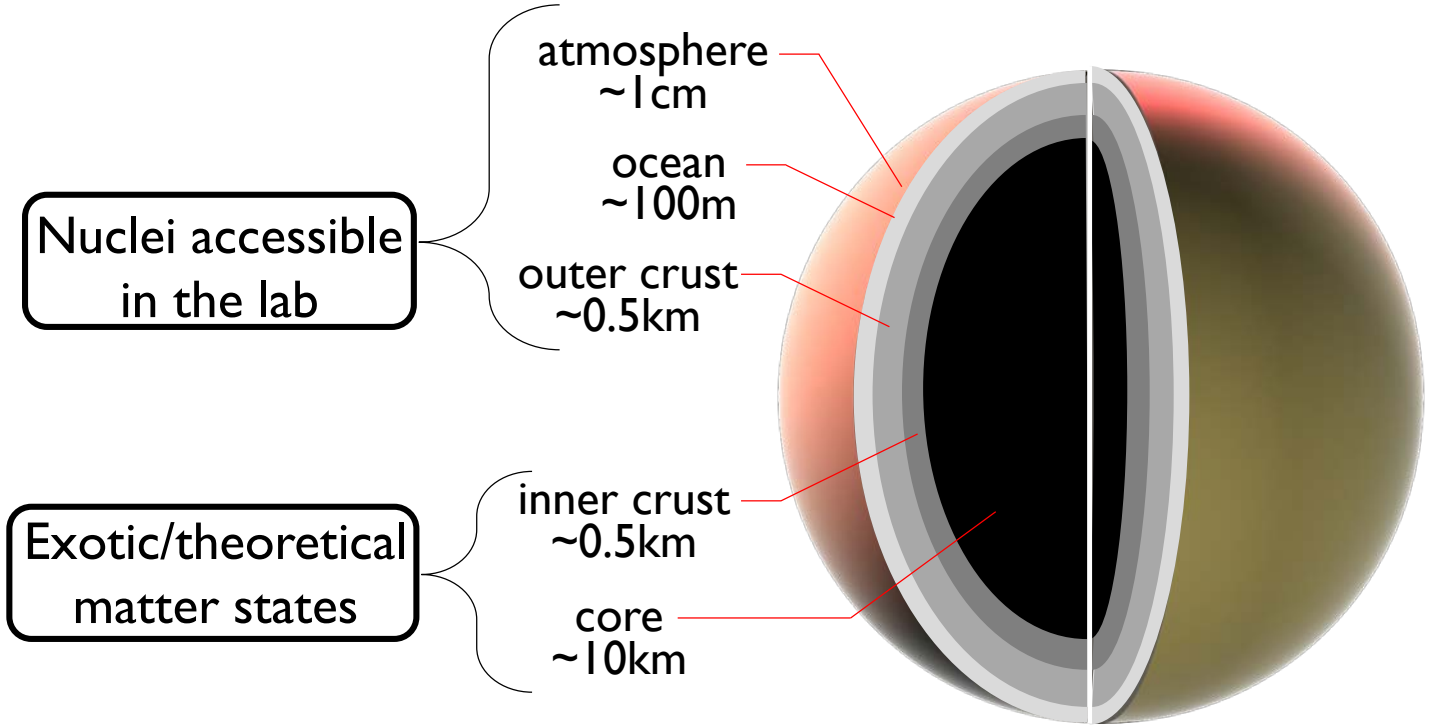
Insight into Nature

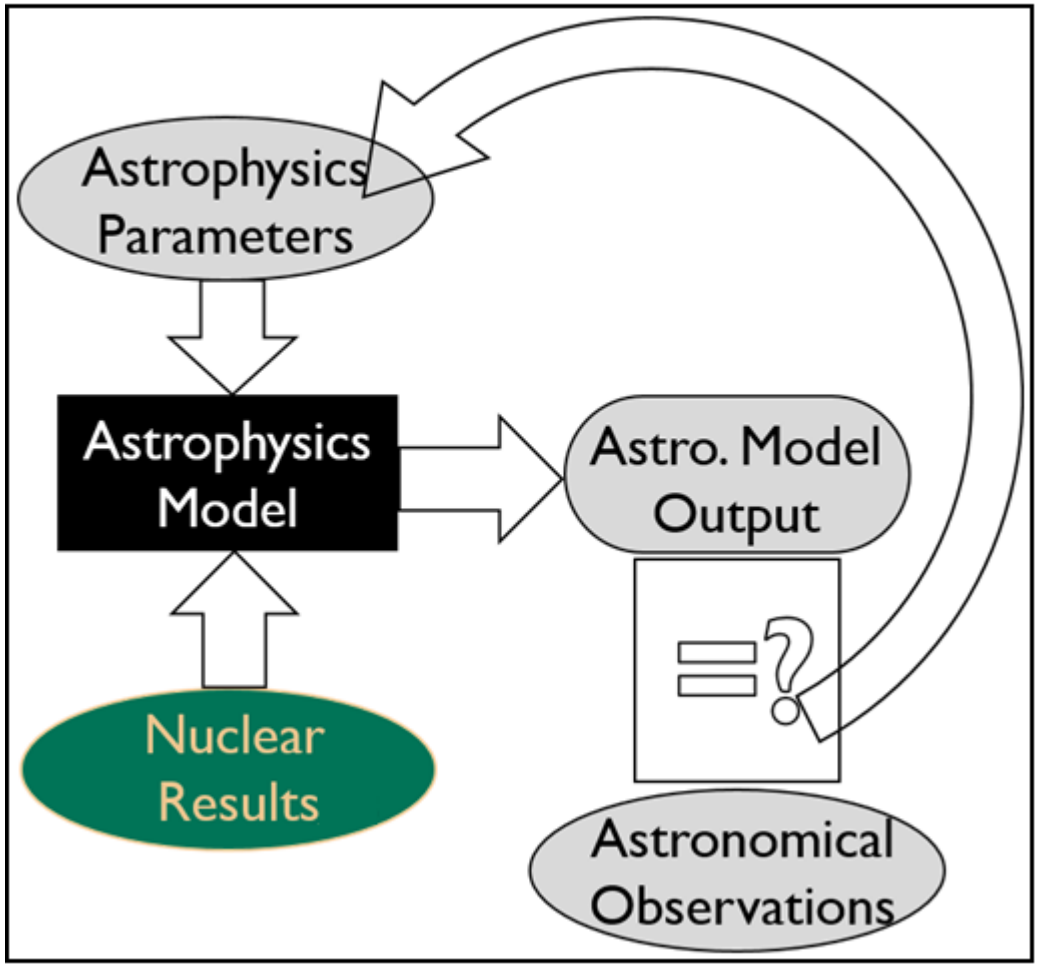




What does this have to do with nuclear physics?



Nuclear Astrophysics Machine:

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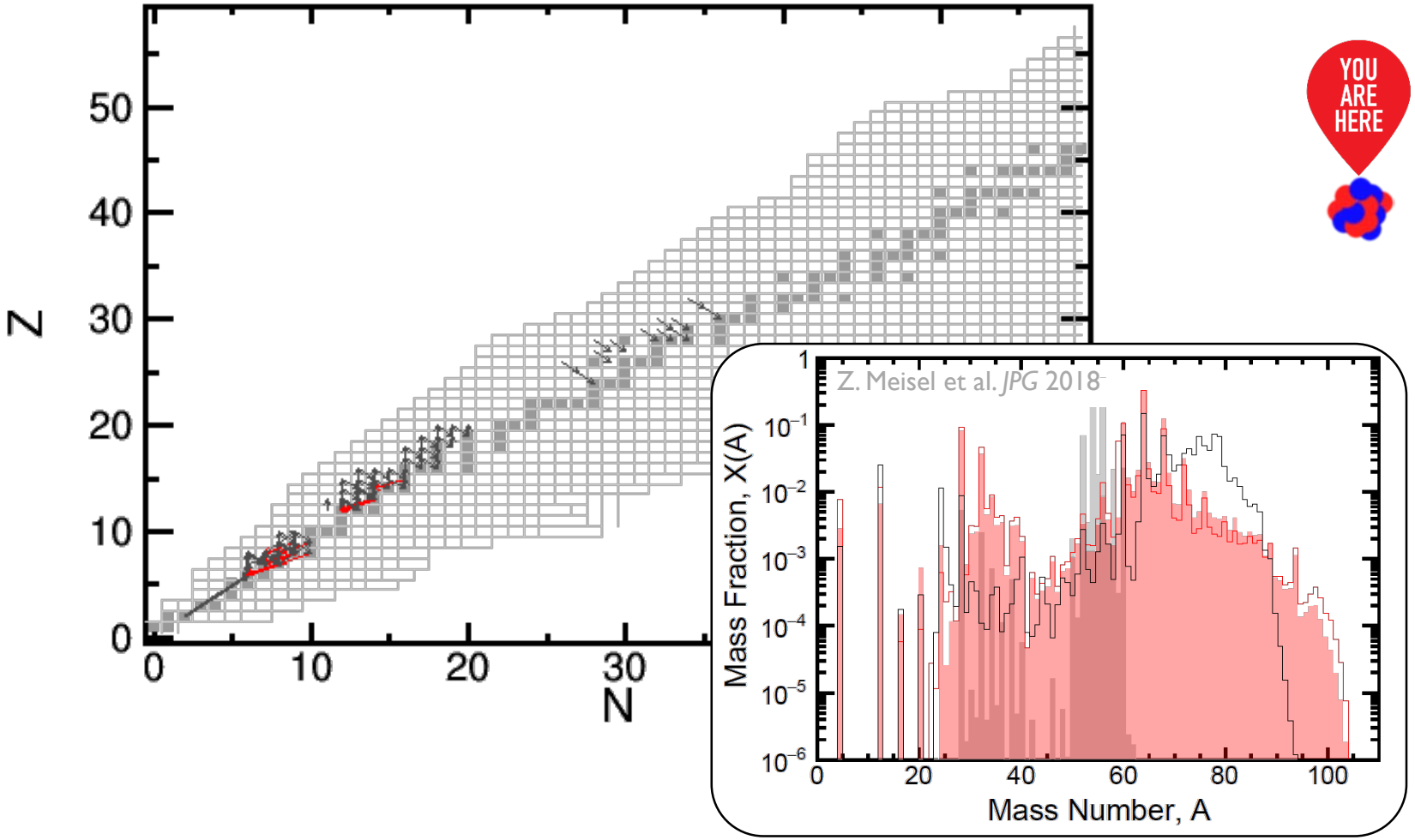
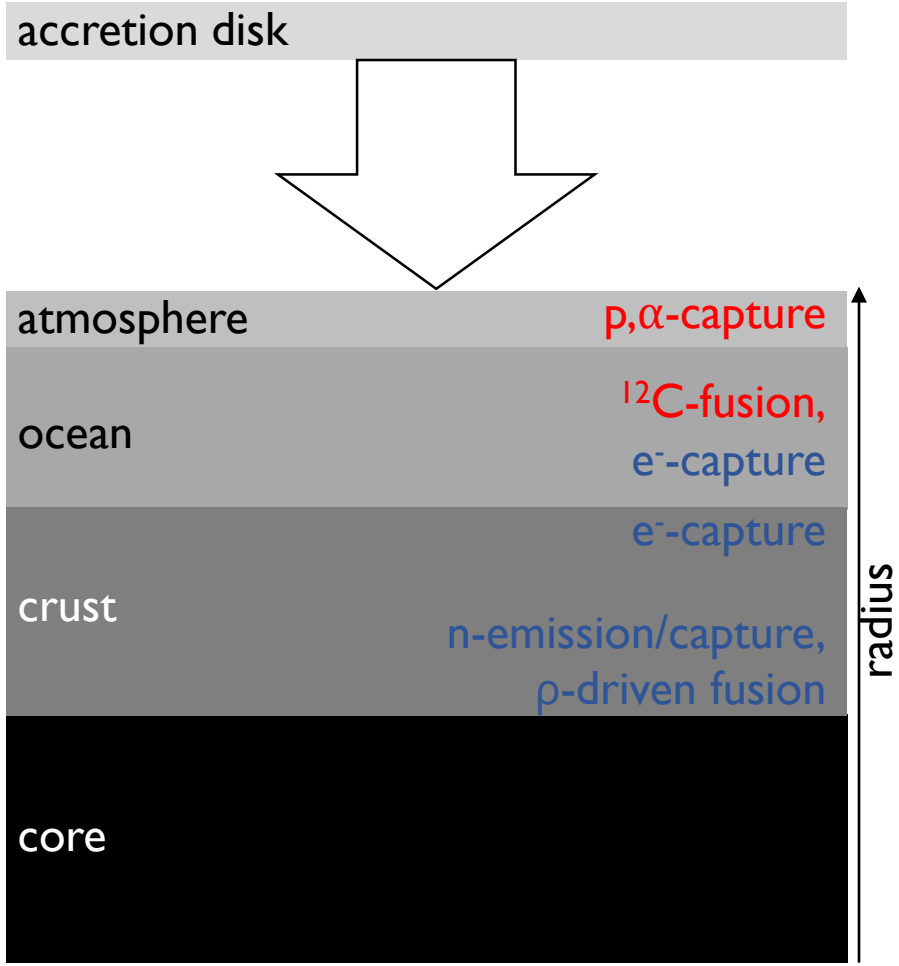
The journey of a nucleus in a neutron star

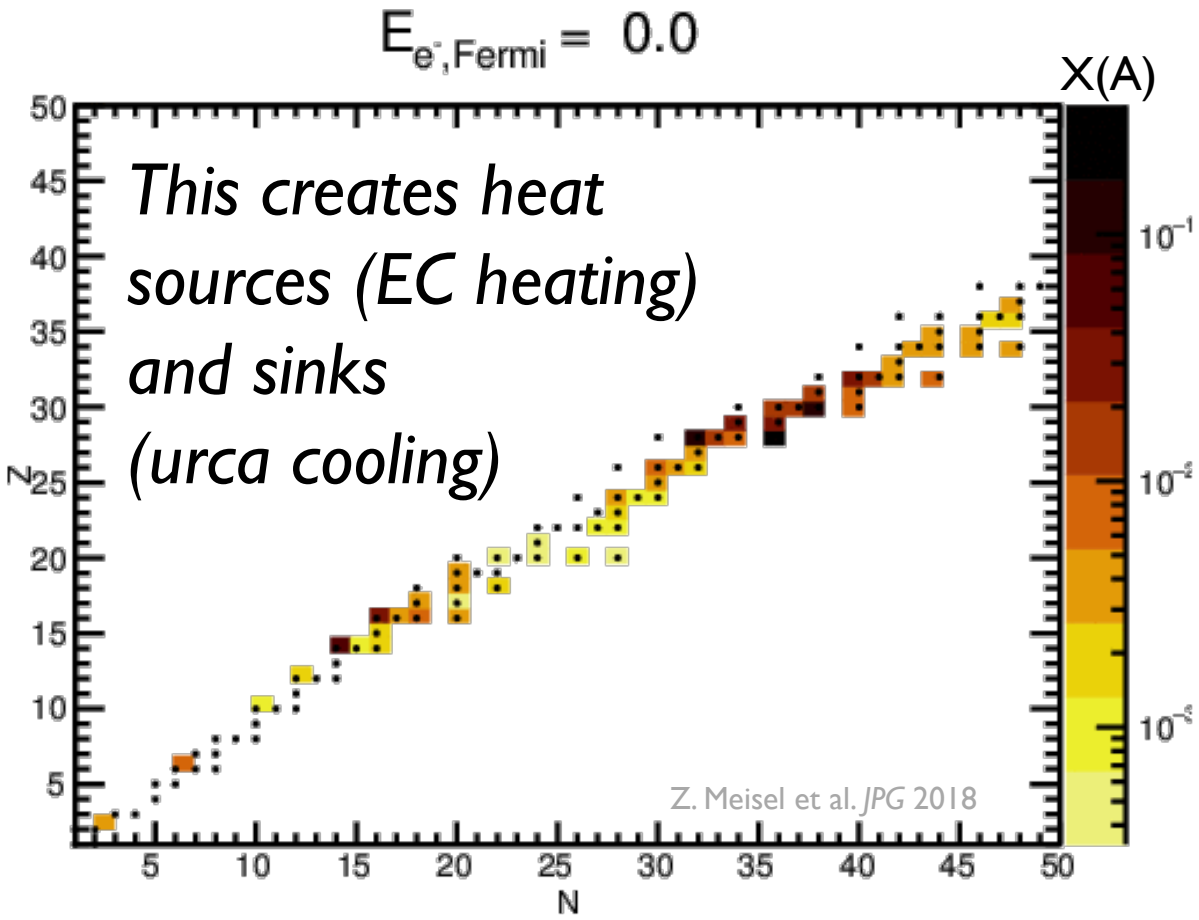
1. Production from H, He, C burning



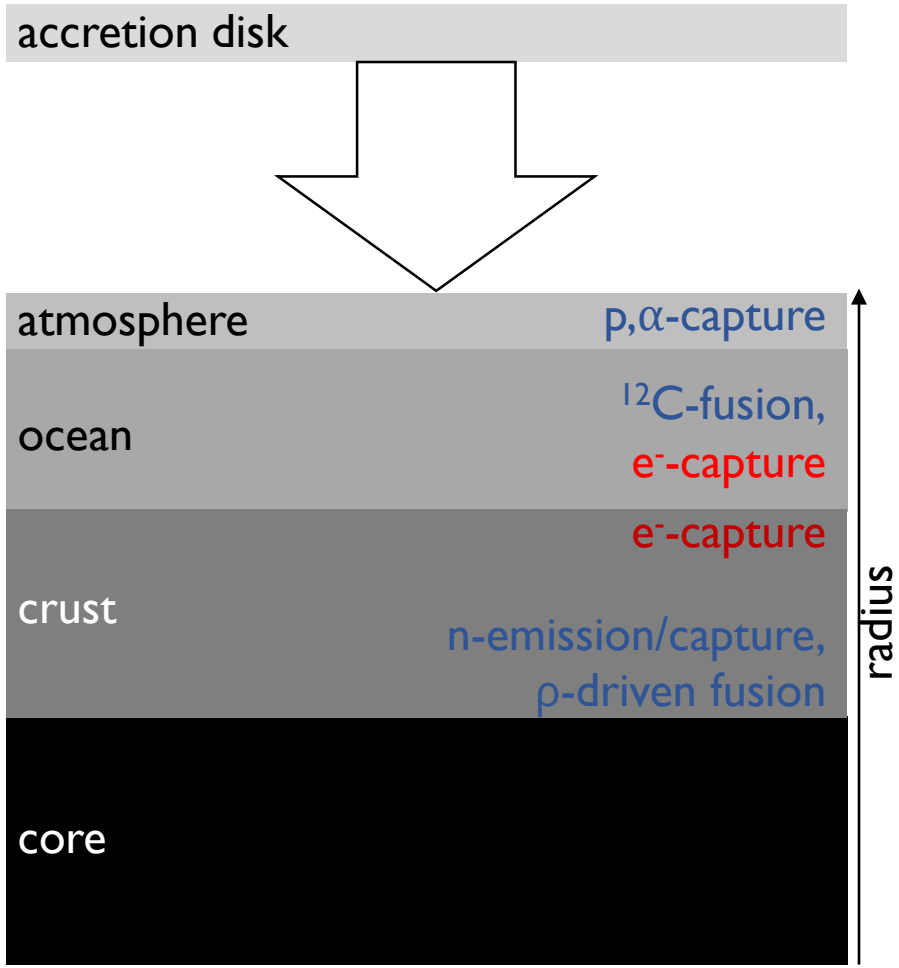


The journey of a nucleus in a neutron star

2. Burial and electron-capture



This creates heat sources (EC heating) and sinks (urca cooling)

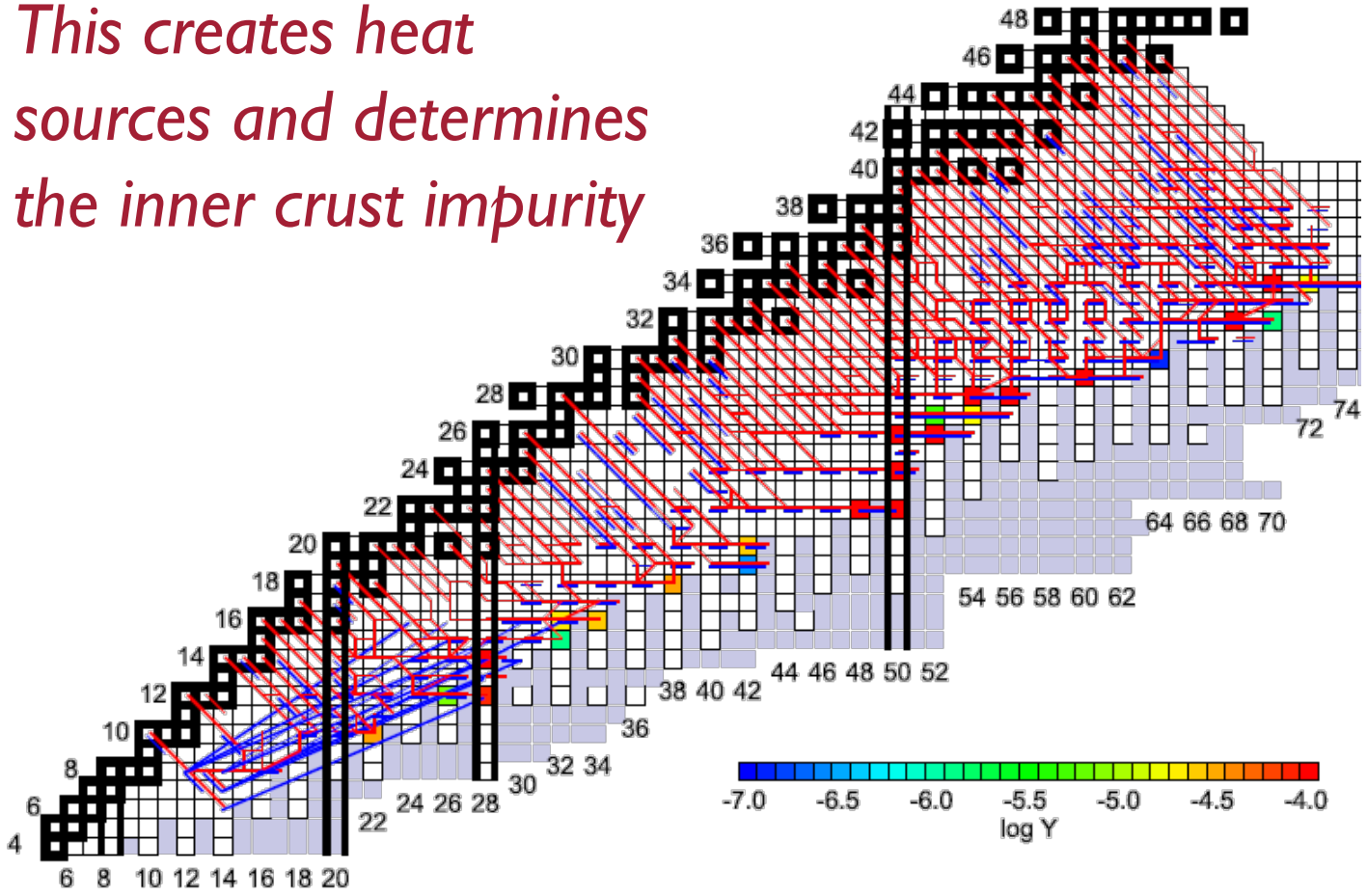


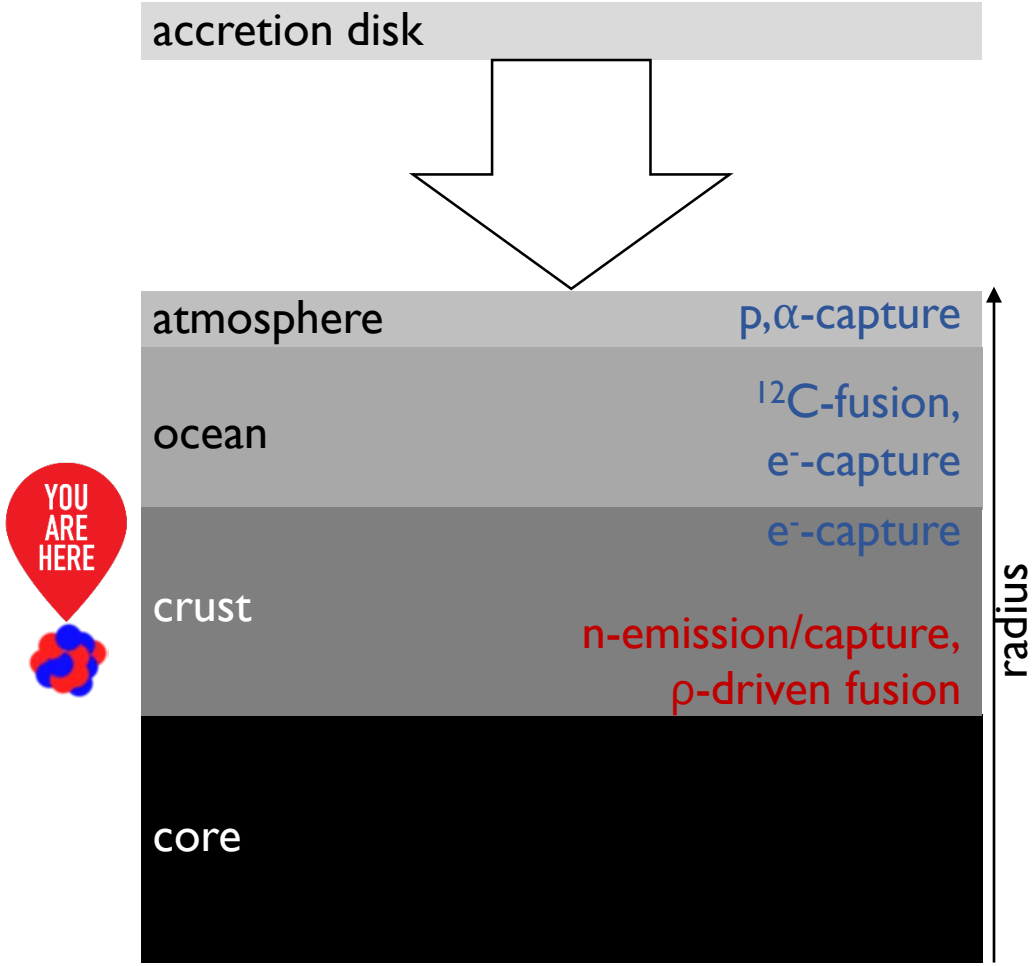
The journey of a nucleus in a neutron star

3. Fusion and disintegration

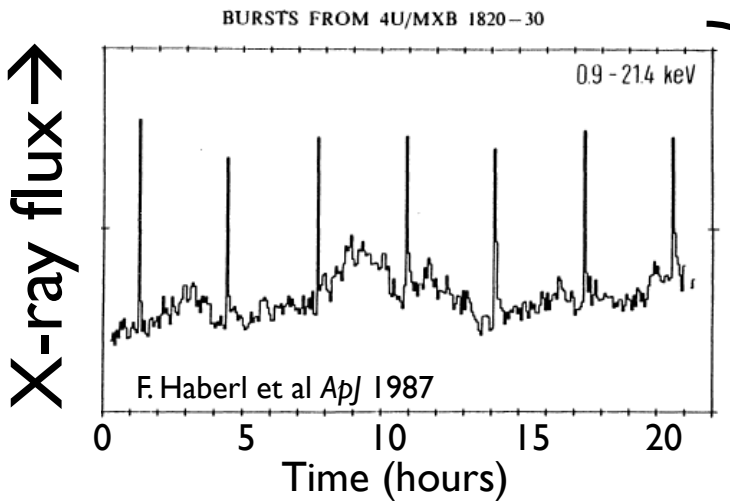
This creates heat sources and determines the inner crust impurity

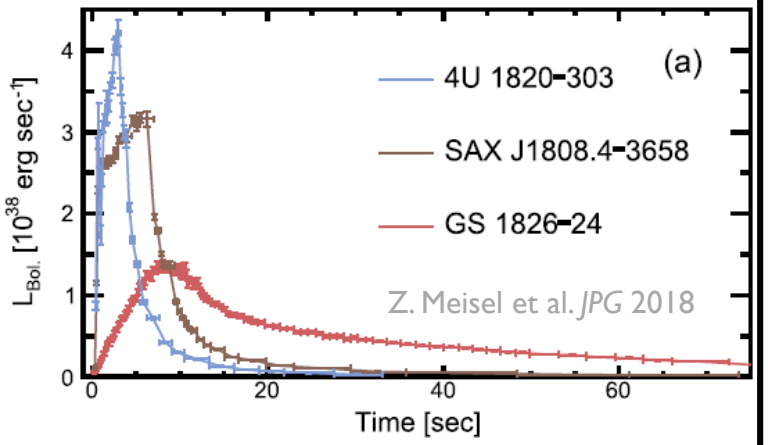
R. Lau et al. *ApJ* 2018

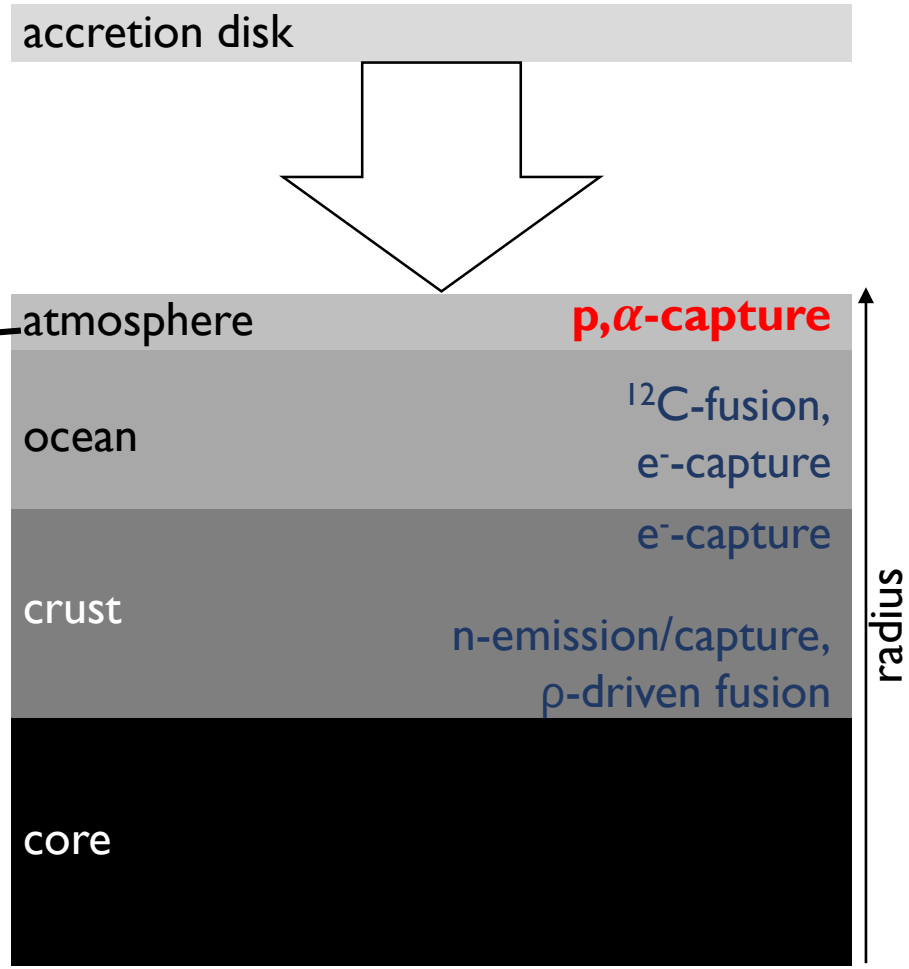


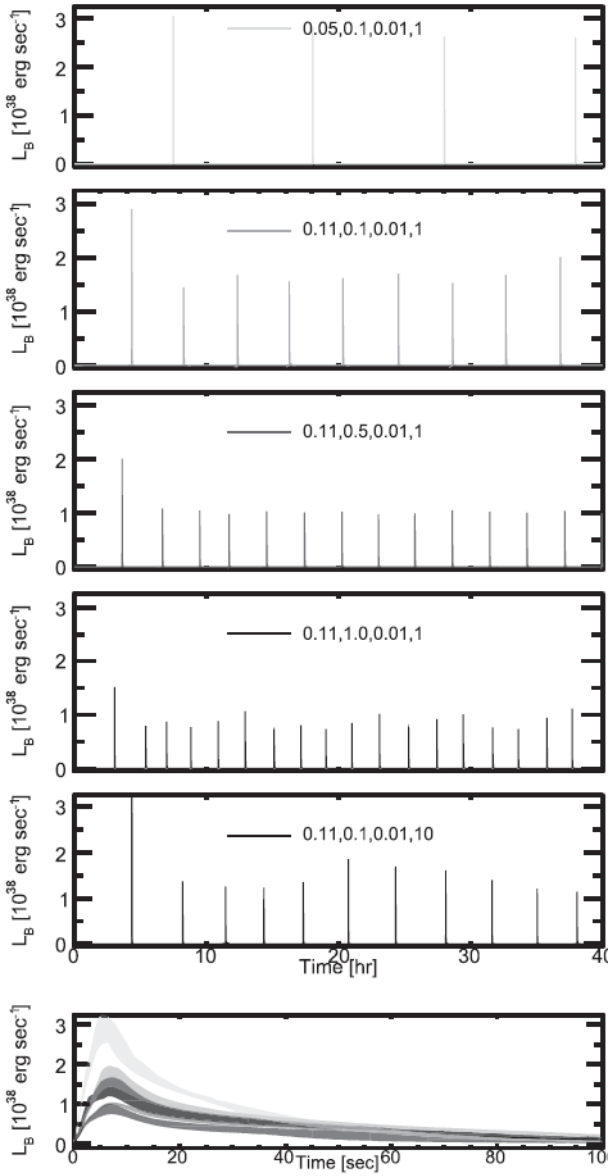


Type-I x-ray bursts: hydrogen & helium burning on the neutron star surface



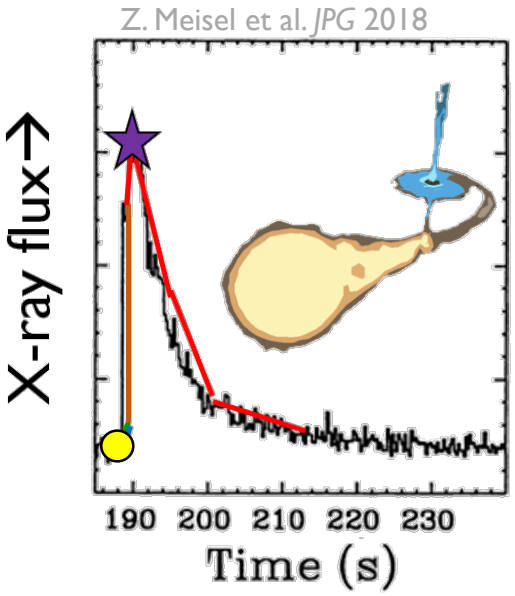


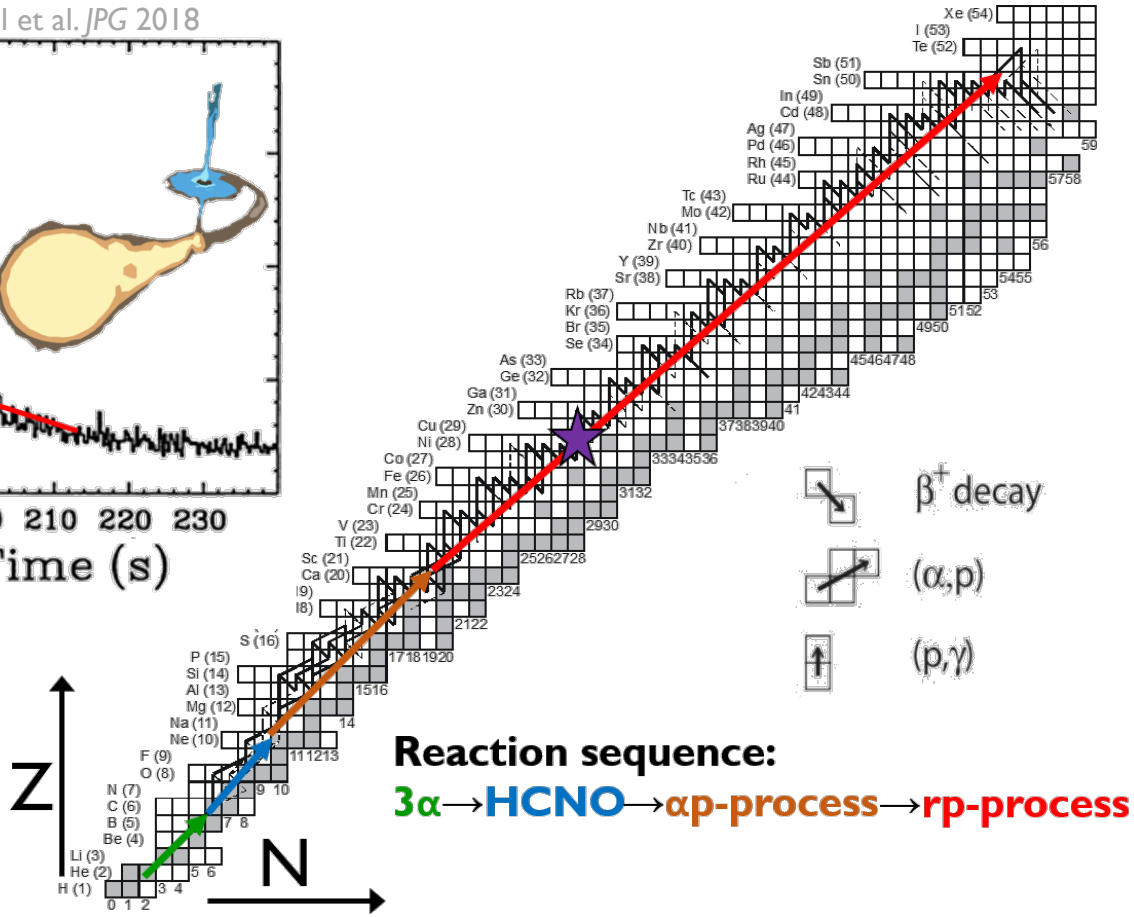




Z. Meisel *ApJ* 2018

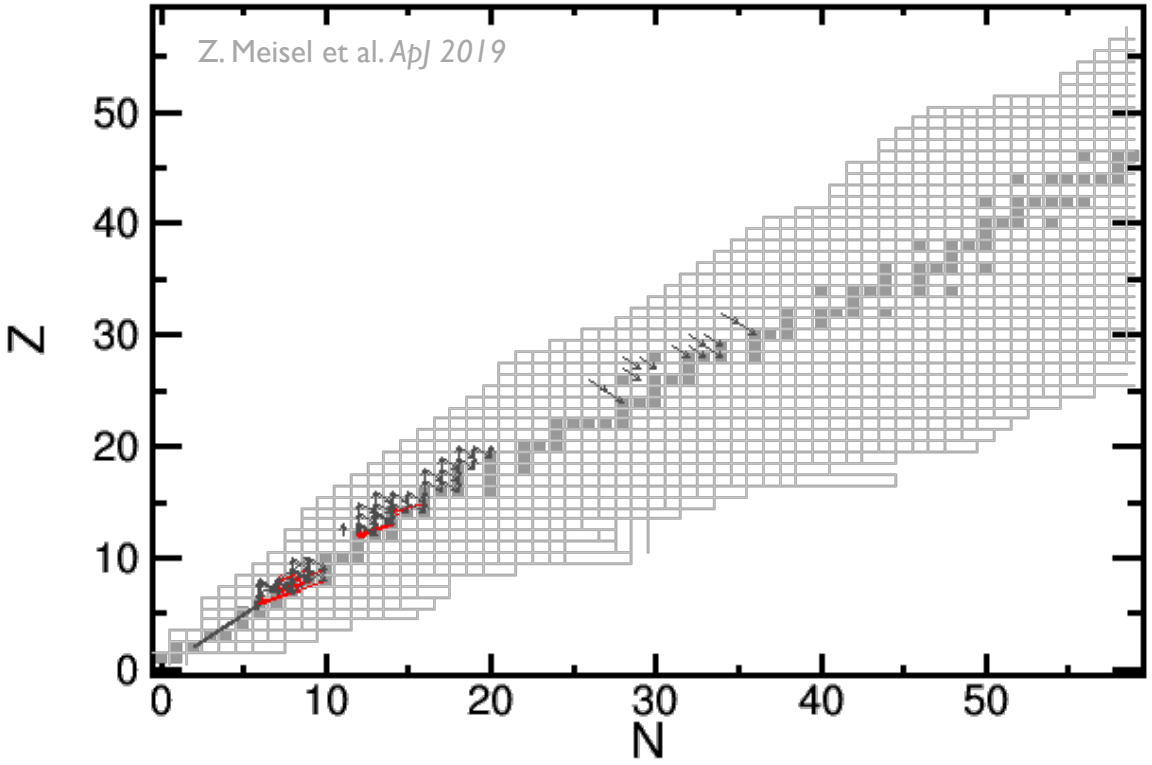
The rapid proton-capture (*rp*)-*process*: hydrogen & helium burning on the neutron star surface





Reaction sequence:

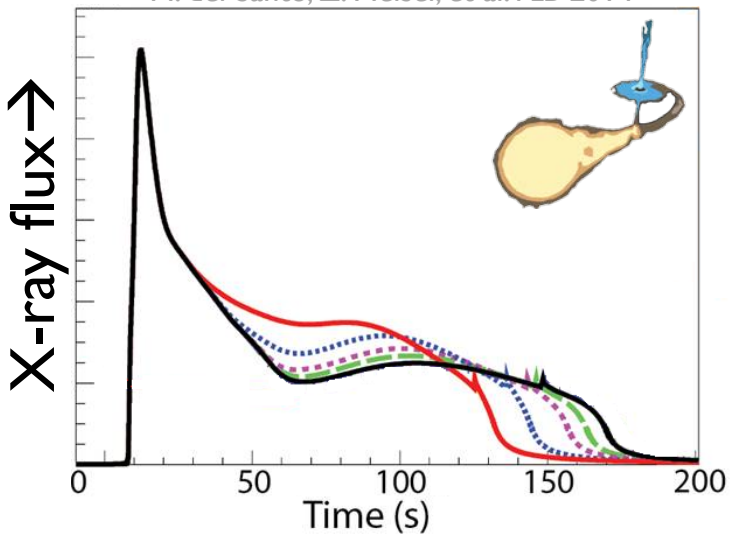
3α→HCNO→αp-process→rp-process



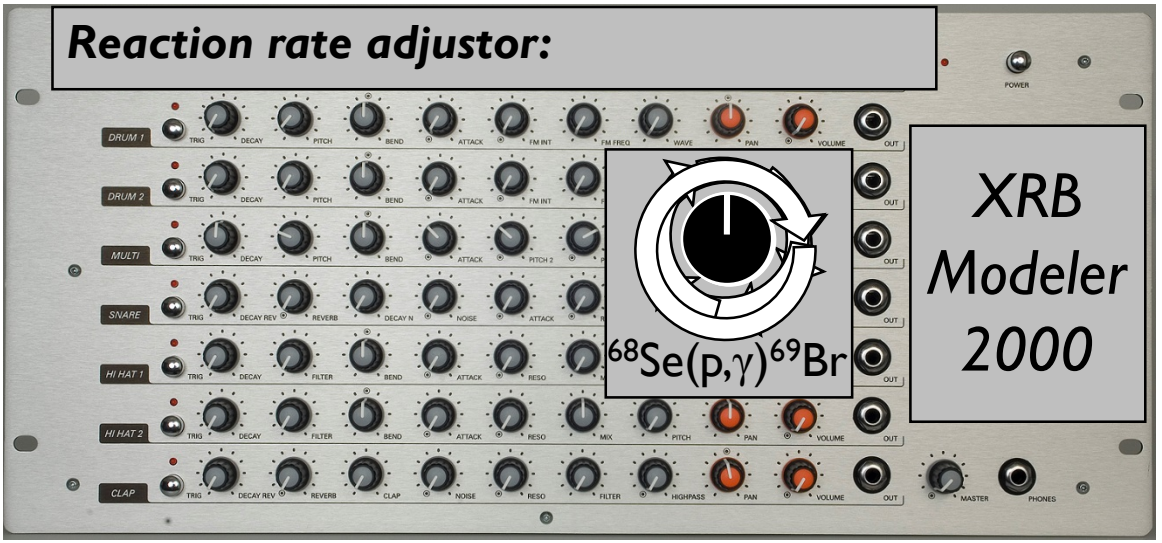
X-ray burst calculations are sensitive to nuclear physics

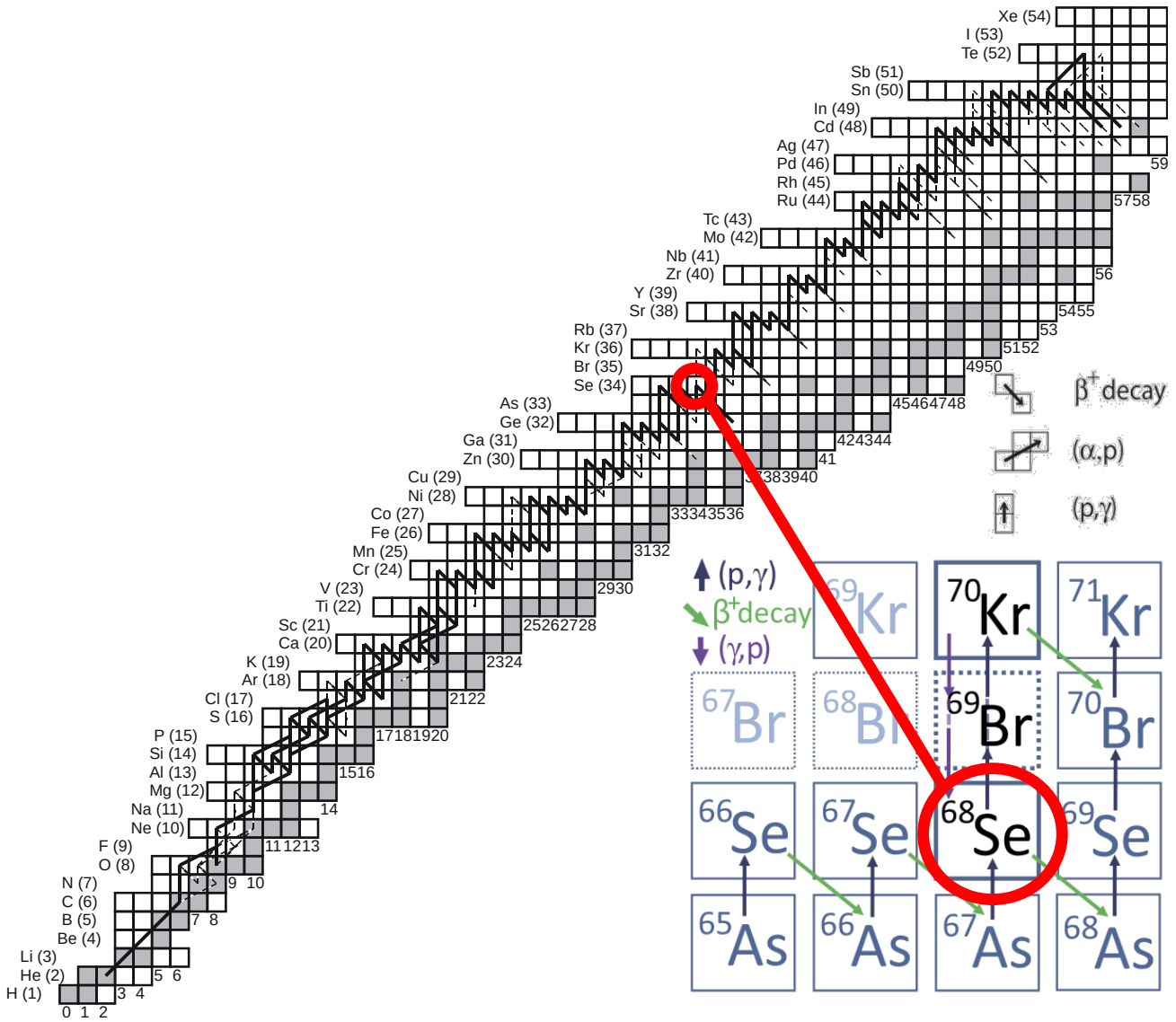
Model output:

M. del Santo, Z. Meisel, et al. *PLB* 2014

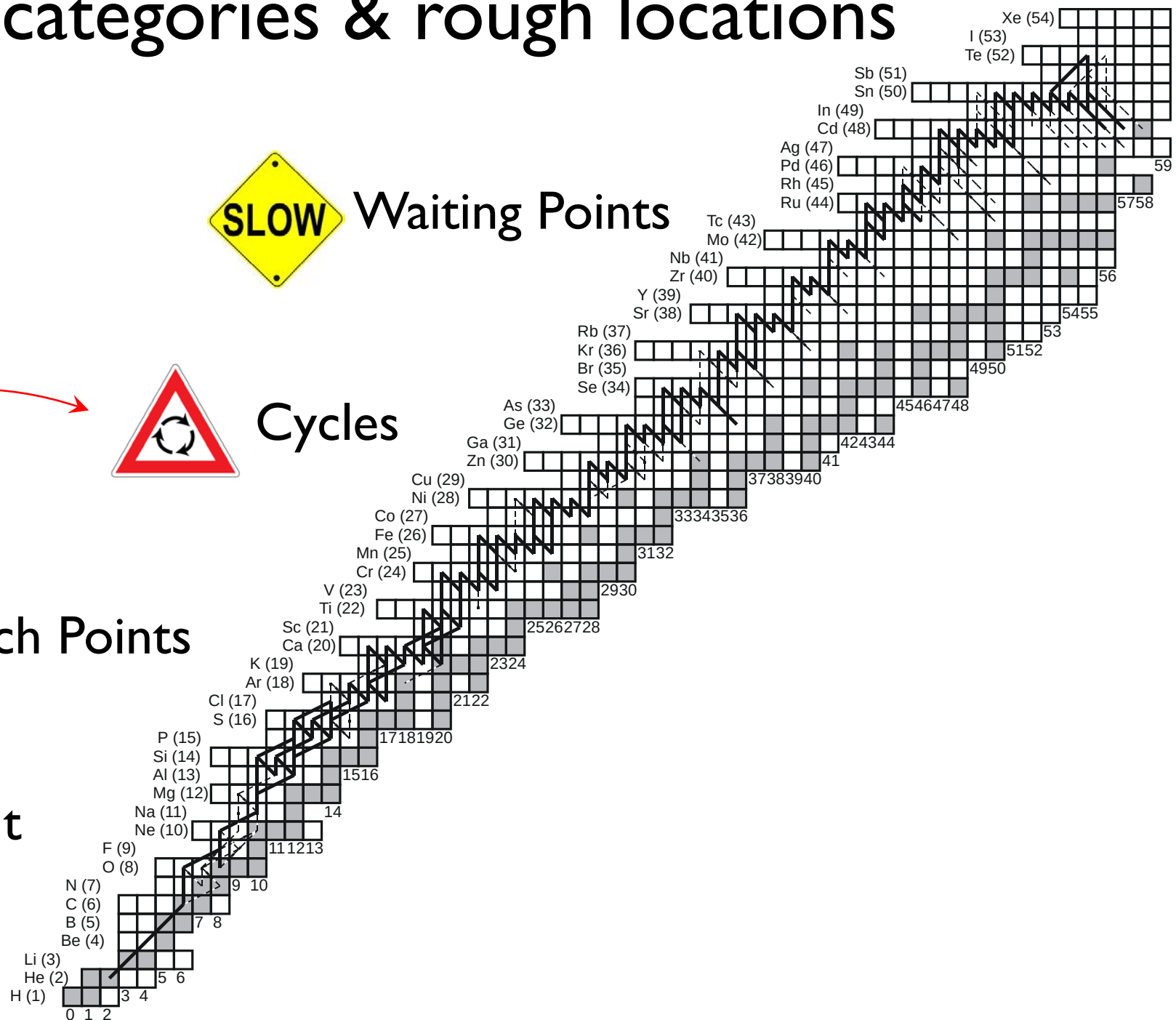


Model:





rp-process reaction categories & rough locations



Waiting Points

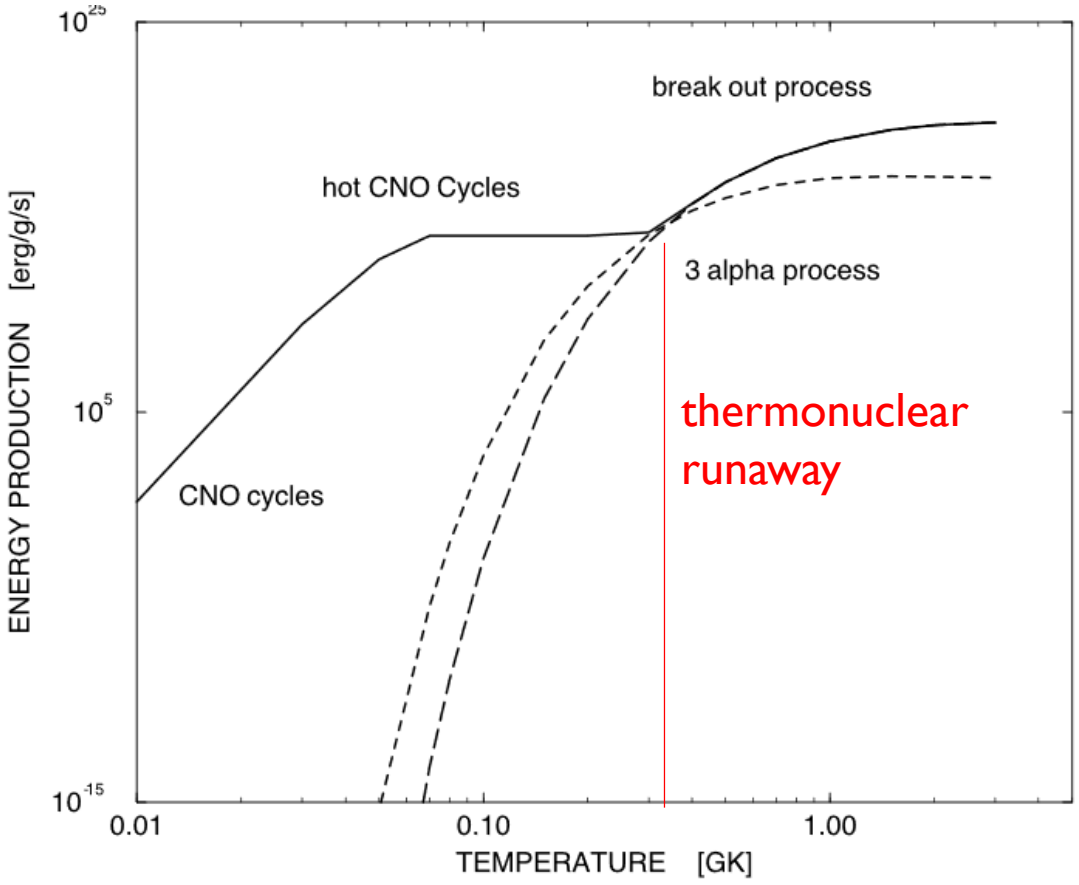
often referred to as "waiting points" in the literature

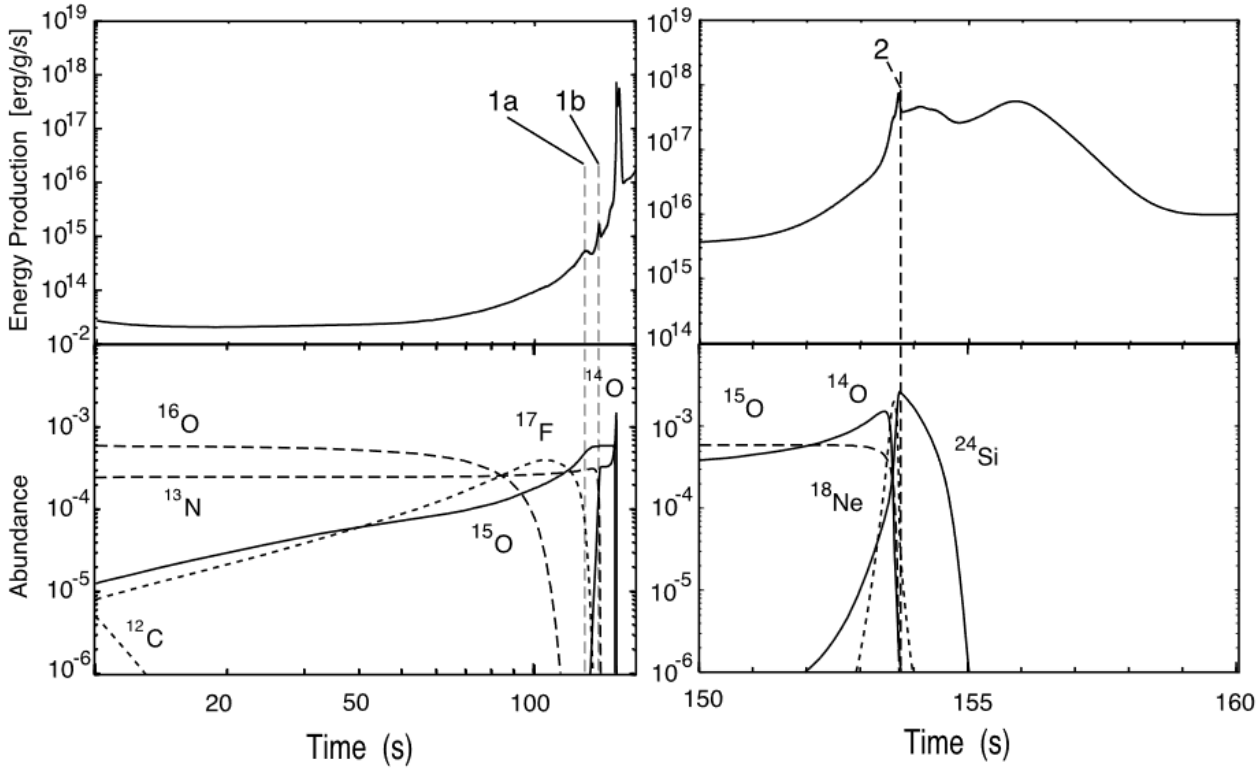
Cycles

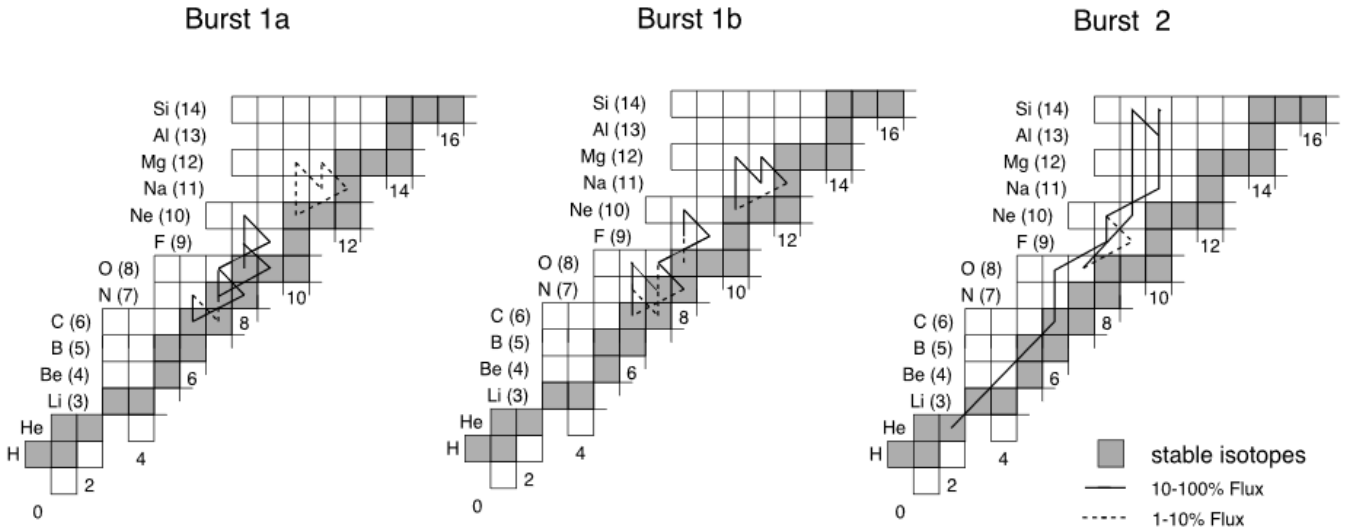
Branch Points

Ignition/Breakout

Ignition/Breakout







Wiescher, Görres, & Schatz *JPG*1999

Ignition/Breakout

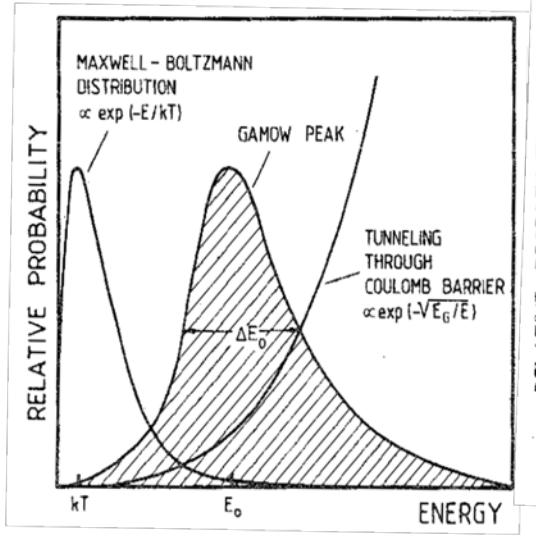
- Key reactions: $3\alpha \rightarrow {}^{12}C$, ${}^{14}O(\alpha,p){}^{17}F$, ${}^{18}Ne(\alpha,p){}^{21}Na$, and ${}^{15}O(\alpha,\gamma){}^{19}Ne$
- All are resonant reaction rates, so the question boils down to how well do we know the structure (excitation energies and partial widths) of the compound nucleus for each reaction
- Using units of MeV for $E_{R,i}$ and $(\omega\gamma)_{R,i}$ and amu for A_i,

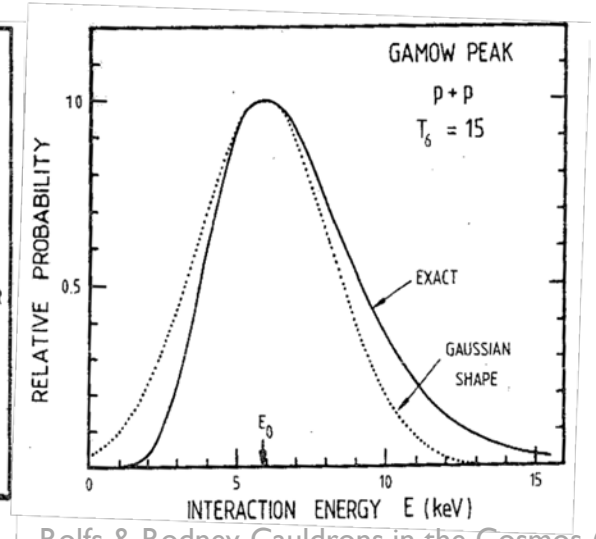
$$N_A\langle\sigma v\rangle_{N\,res.} = \frac{1.54\times10^{11}}{\left(\frac{A_1A_2}{A_1+A_2}T_9\right)^{3/2}}\sum_{i=1}^{N}(\omega\gamma)_{R,i}\exp\left(-\frac{11.6045E_{R,i}}{T_9}\right)\frac{\mathrm{cm}^3}{\mathrm{mol\ s}}$$

*technically only for narrow resonances so the 3α reaction is a bit more complicated

where $\omega = \frac{2J+1}{(2J_a+1)(2J_X+1)}$ and $\gamma = \frac{\Gamma_{aX}\Gamma_{bY}}{\Gamma}$

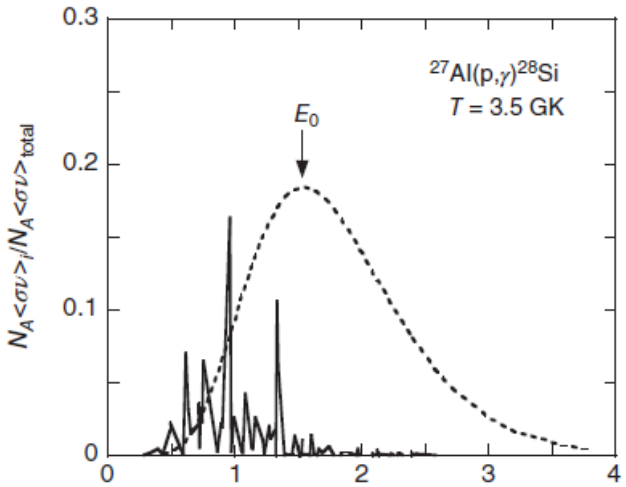
- We look for resonances near the Gamow window: $E_G = 0.122\left(Z_1^2Z_2^2\frac{A_1A_2}{(A_1+A_2)}T_9^2\right)^{1/3}$ MeV , $\Delta_G = 4\sqrt{\frac{E_Gk_BT}{3}}$ MeV





Rolfs & Rodney, Cauldrons in the Cosmos (1988)

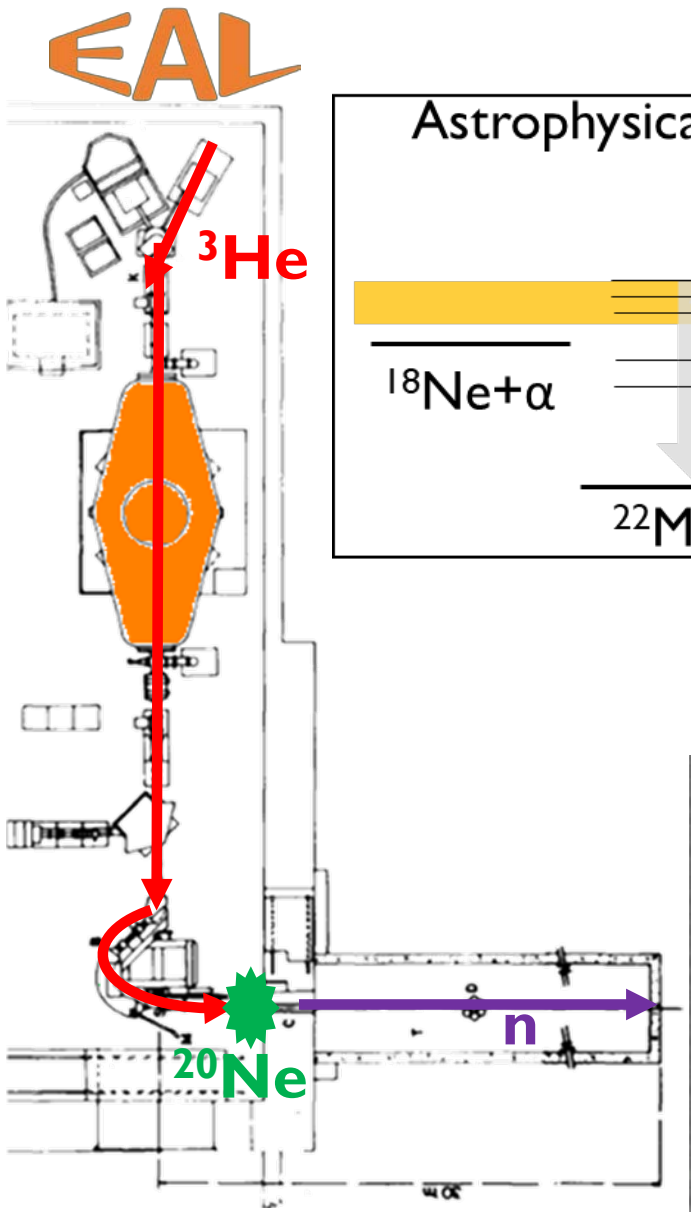
Gamow window estimate is approximate.
Have to calculate actual contributions to the rate:

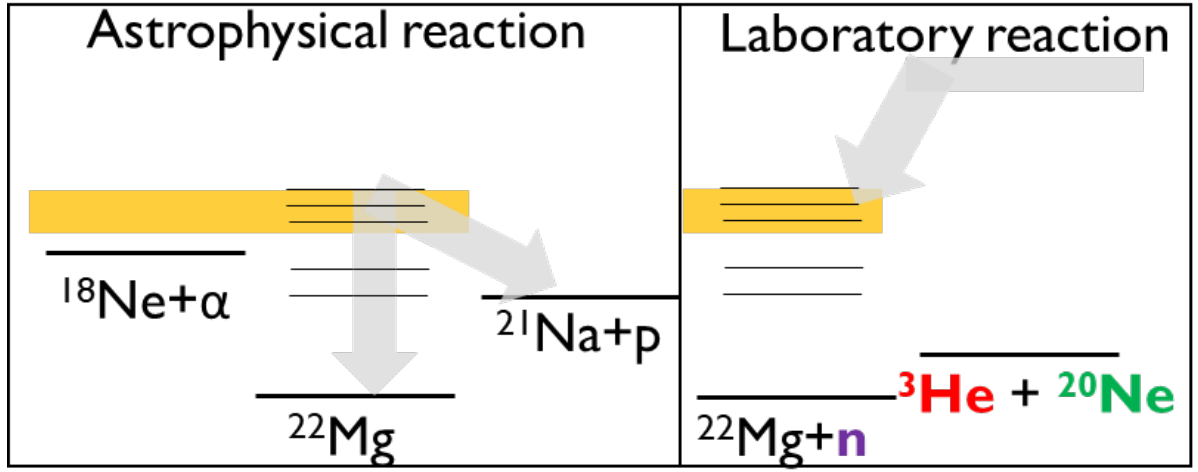


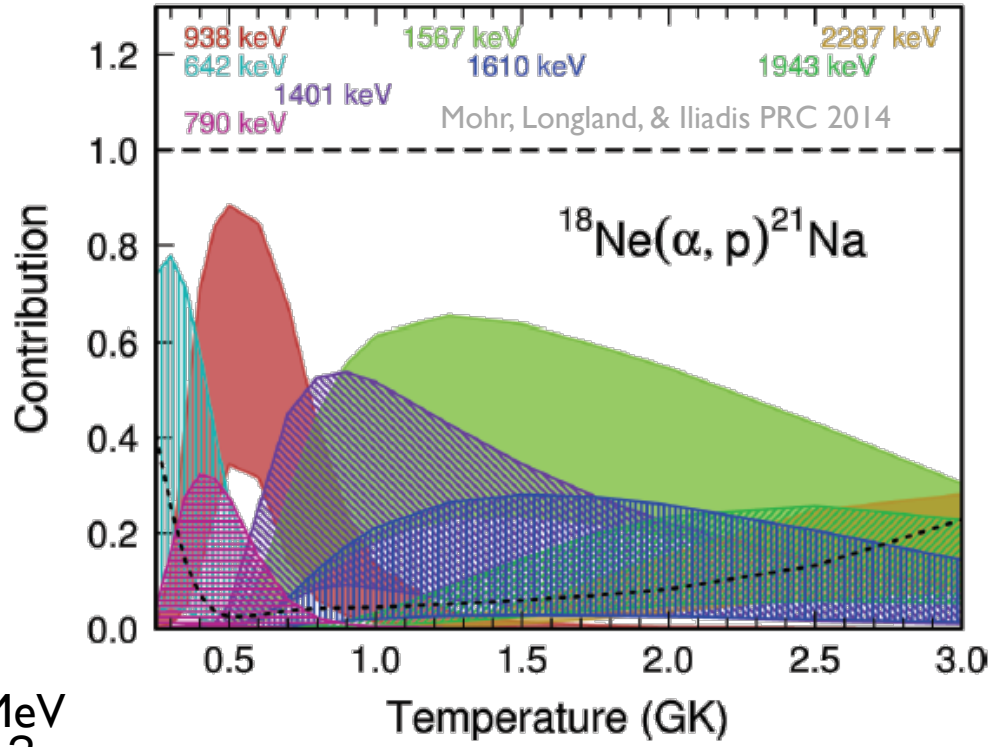
Iliadis, Nuclear Physics of Stars (2007)

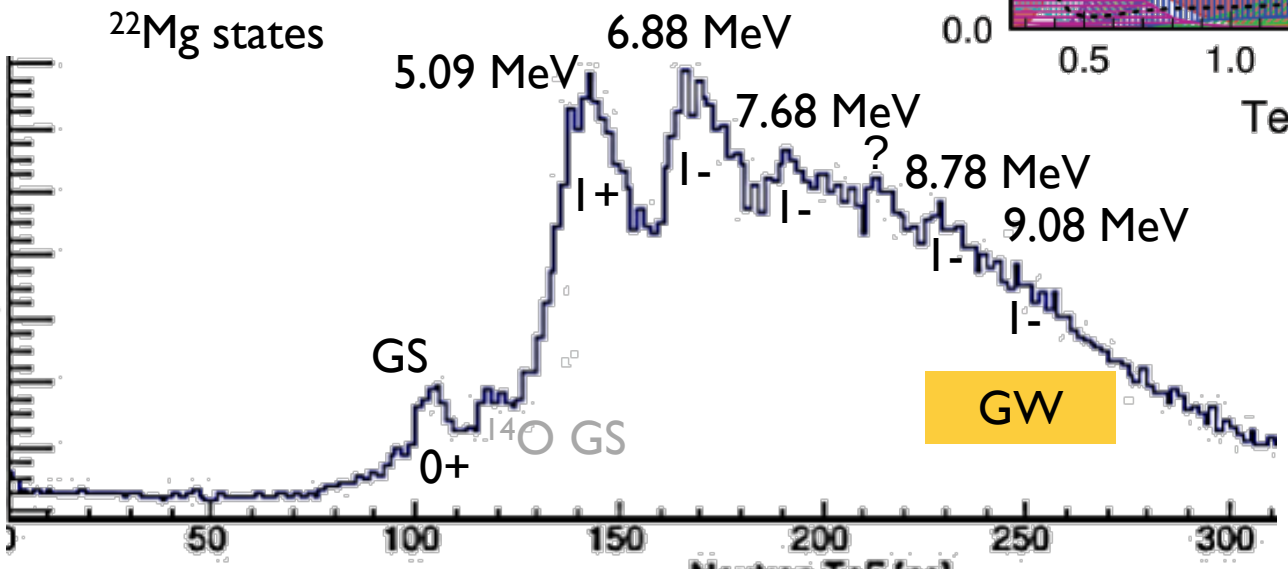
Ignition/Breakout: *Example of $^{18}Ne(\alpha,p)^{21}Na$*

Controversy: Is there another state near the 938keV resonance?



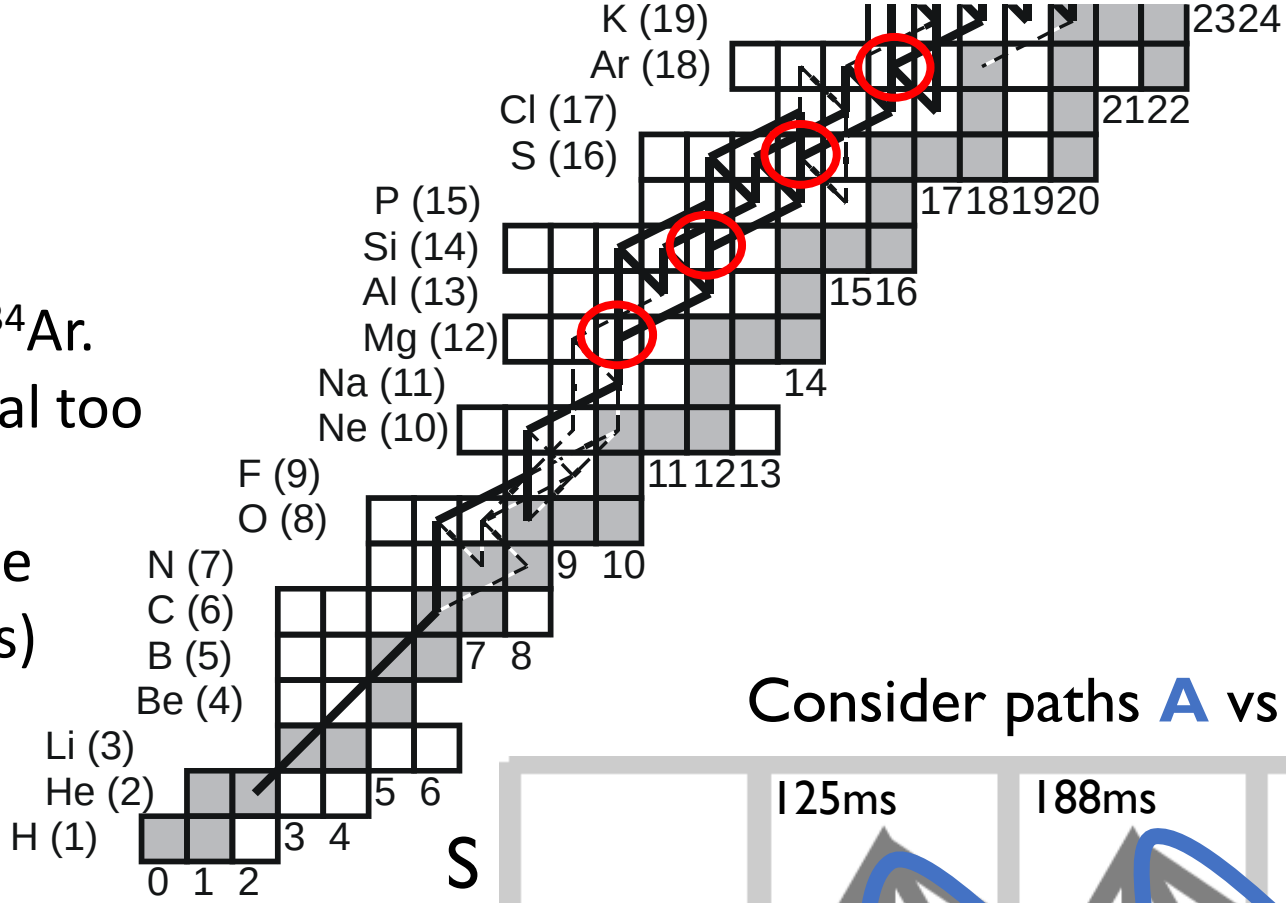




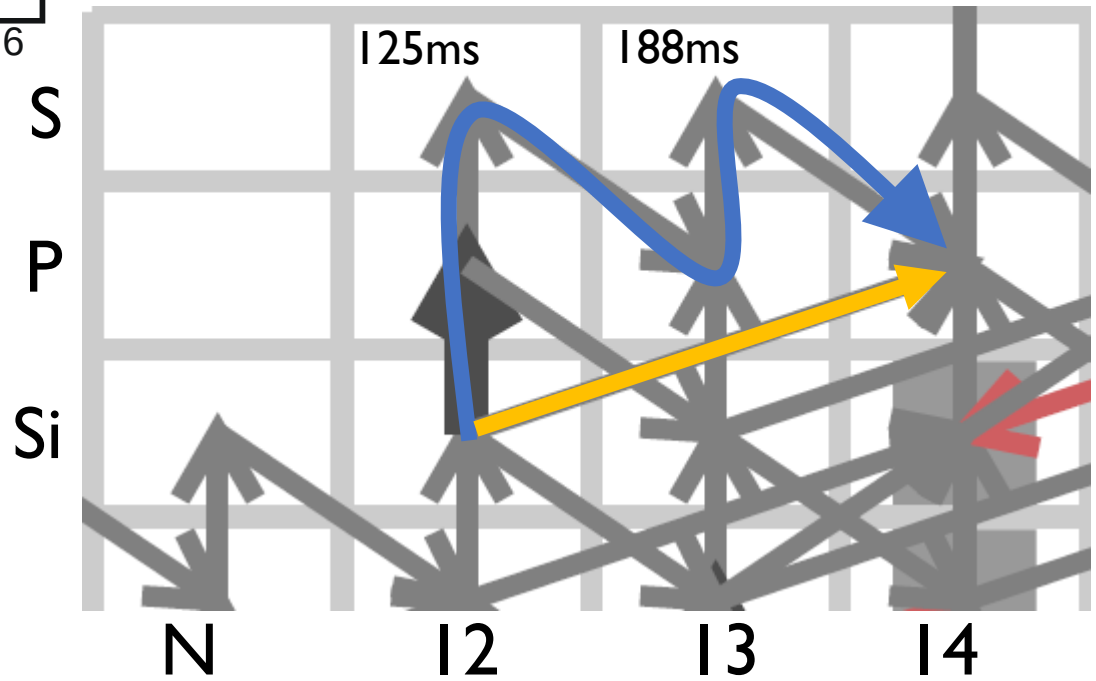


Branch Points

- Competition between (α,p) and (p,γ) reactions can lead to quite different network flow for ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar. (p,γ) rate above branch-point is critical too (e.g. ^{23}Al(p,γ) for ^{22}Mg branch-point)
- (p,γ) uncertainty from structure of the compound nucleus (levels and widths)
- (α,p) uncertainty from nuclear level densities and α-optical potentials

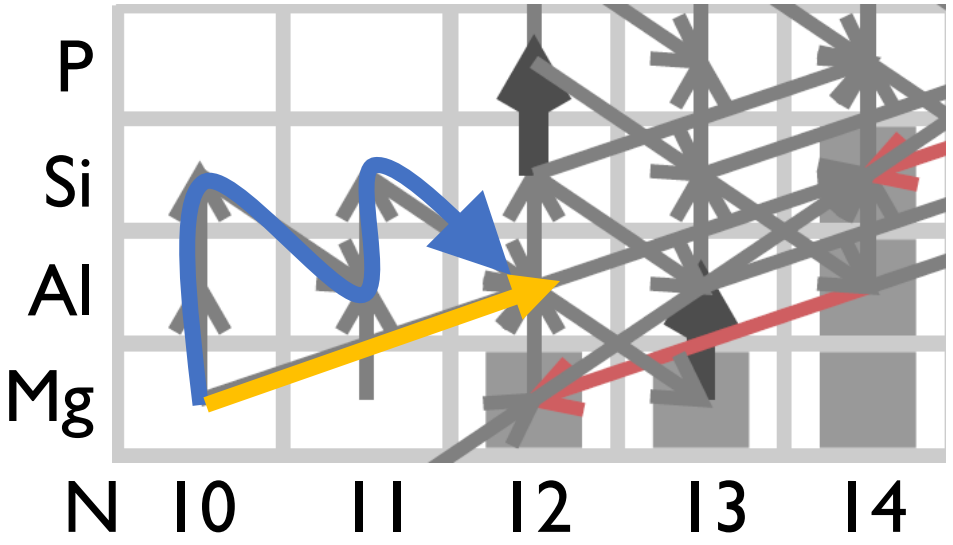


Consider paths **A** vs **B**



Branch Points

Consider paths **A** vs **B**



- Most interesting cases here are:
  ^{22}Mg(α,p), where the **LD and αOMP for ^{26}Si are needed**
  and
  ^{23}Al(p,γ), though this case was just constrained by experiment

- For populating a high-LD region, use the statistical formalism. Calculate cross section via Hauser-Feshbach method:
  - $\sigma^{HF}_{X(a,b)Y} = \pi \left(\frac{\lambda}{\pi}\right)^2 \sum_J \frac{2J+1}{(2J_a+1)(2J_X+1)} W_{ab} \frac{T_{aX} T_{bY}}{\sum_{chan} T_{chan}}$,
    where T_i are transmission coefficients and W_{ab} is a width-fluctuation correction factor
  - W_{ab} is a small correction that enhances elastic scattering b/c the incoming and outgoing T are correlated
  - Get T_i for particles from optical model potentials. For γ-rays, need γ-strength function.
  - Level density ρ comes in because T_i are sum over all final states:

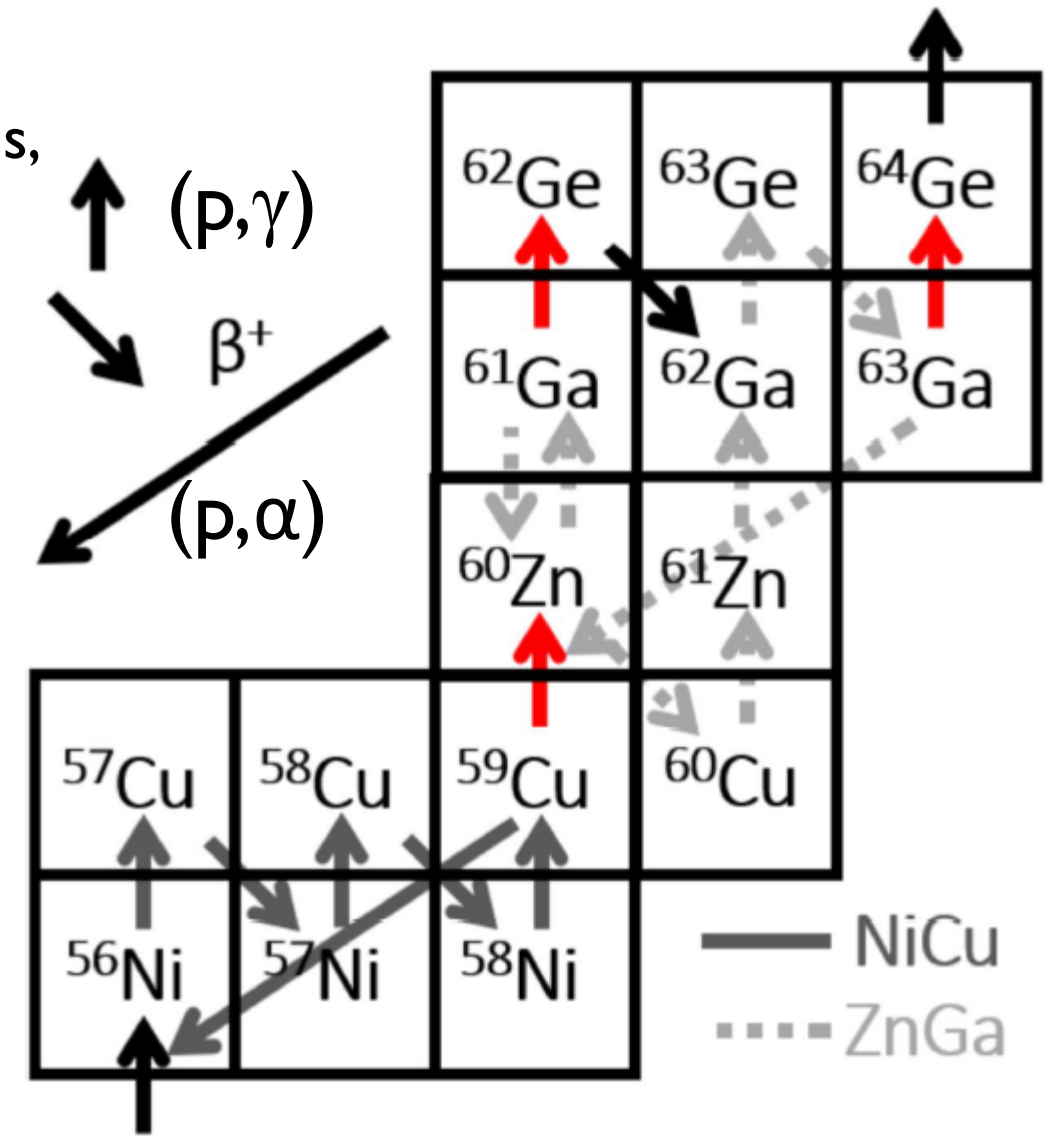
$$T(U,J,\pi) = \sum_{b'} \left(\sum_k T_{b'}(U,J,\pi,E_k,I_k,\pi_k) + \sum_{I'\pi'} \int_{E_c}^{U-B_{b'}} dE'\, T_{b'}(U,J,\pi,E',I',\pi')\, \rho_{b'}(E',I',\pi') \right)$$

- Integrate cross section for thermonuclear reaction rate:

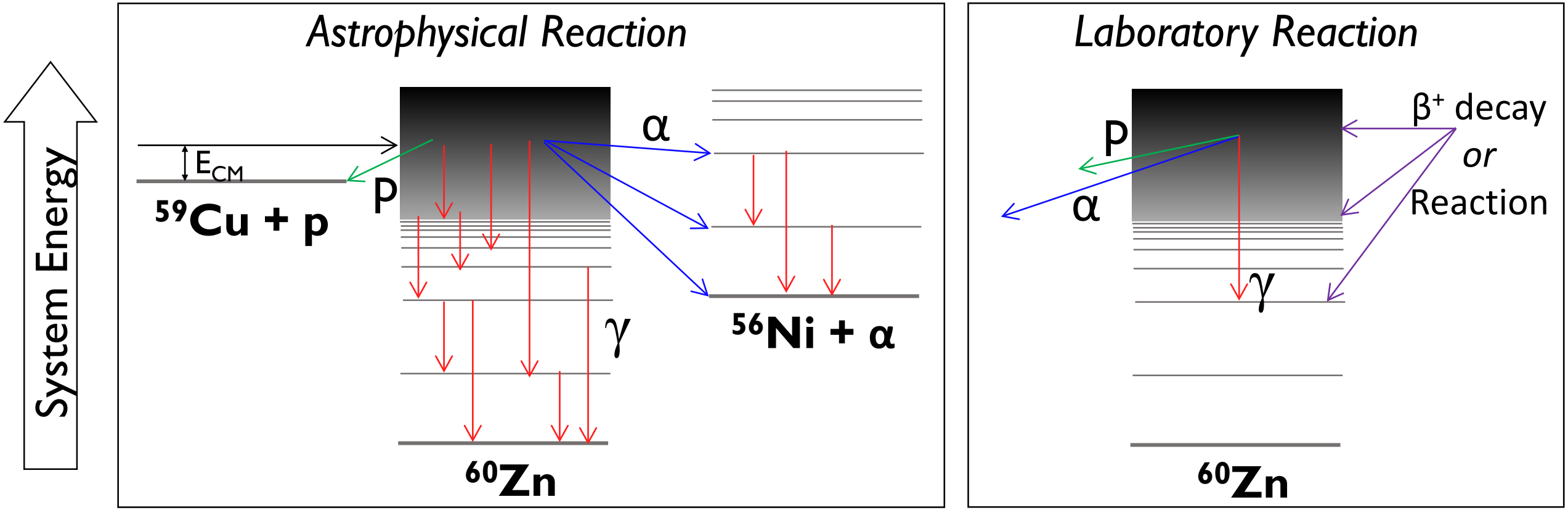
$$\sqrt{\frac{8}{\pi\mu}} \frac{1}{(k_B T)^{3/2}} \int_0^\infty \sigma_{12}(E) E \exp\left(-\frac{E}{k_B T}\right) dE$$

Cycles

- When S_α is lower than S_p in a compound nucleus, (p,γ) and (p,α) compete
- (p,α) stalls energy generation and introduces α back into the system
- Need LD and γSF for ^{60}Zn and ^{64}Ge



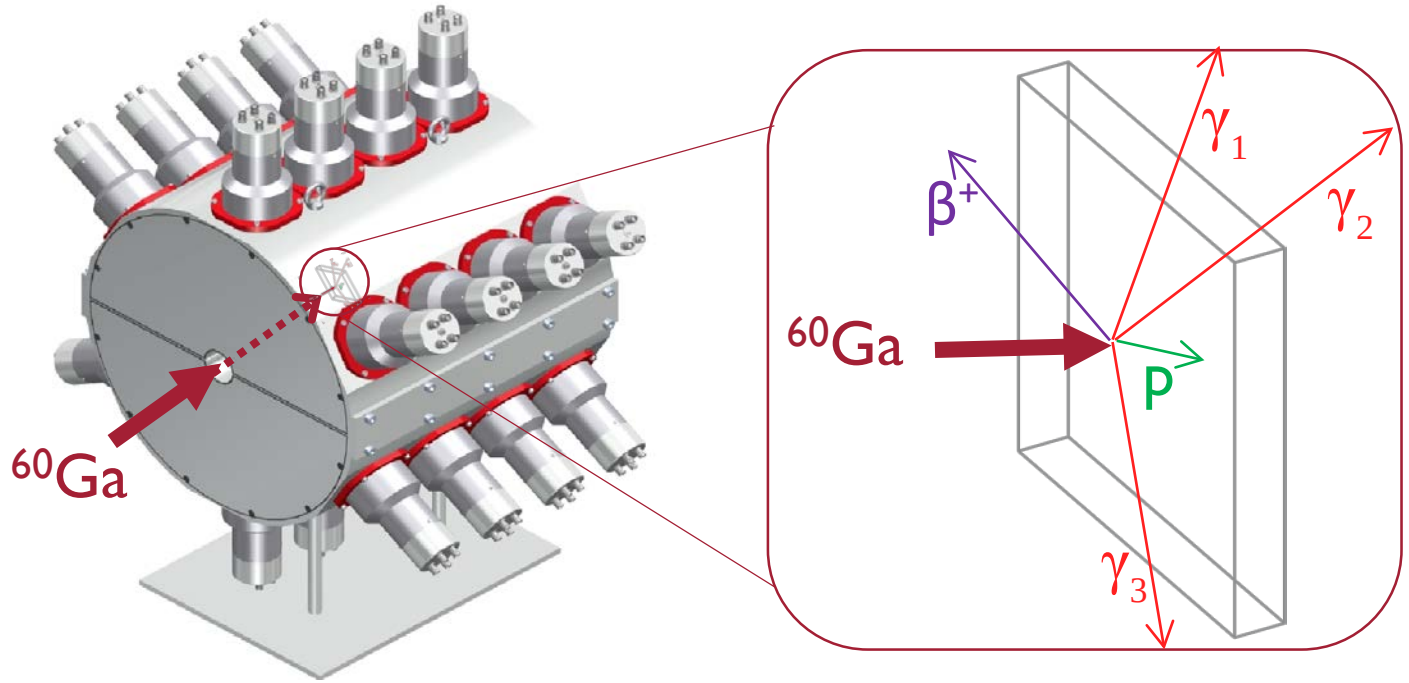
Cycles: *Example of* $^{59}Cu(p,\gamma)^{60}Zn$

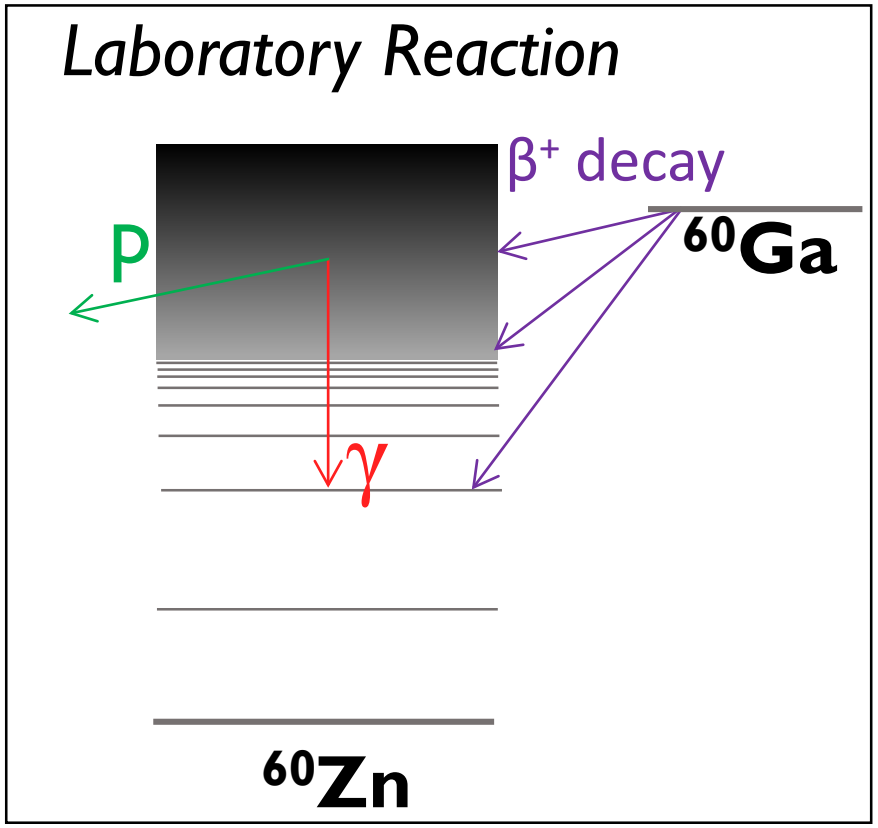


For statistical reactions, want the probability to transmit particles/photons in/out of the nucleus (particle optical potentials and γ strength functions) *and* the number of states to transmit to/from (nuclear level densities)

Cycles: *Example of* $^{59}Cu(p,\gamma)^{60}Zn$

The β-Oslo Technique @ NSCL/FRIB:





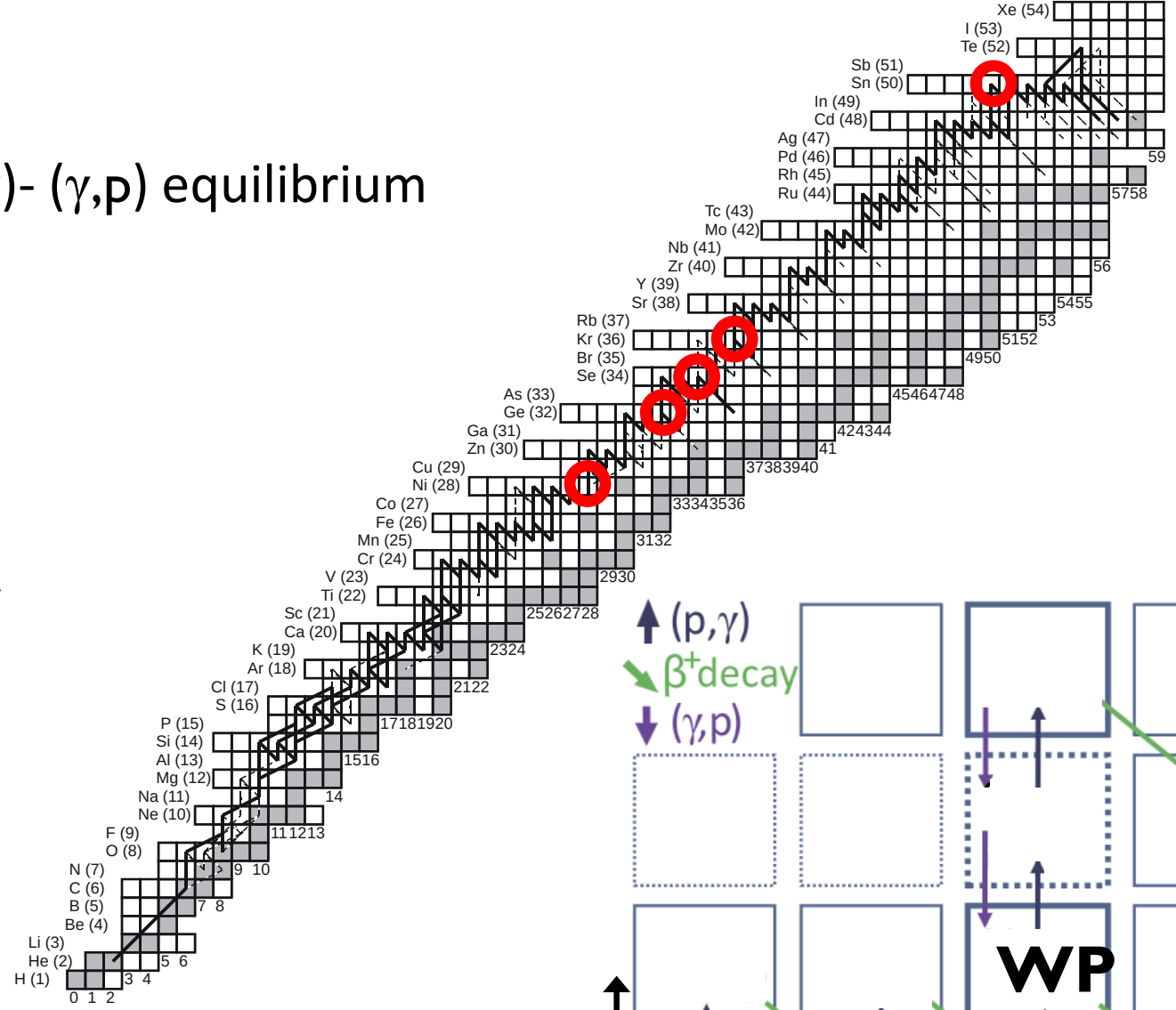
$$P(E_\gamma, E_x) = \rho(E_x - E_\gamma)T(E_\gamma)$$

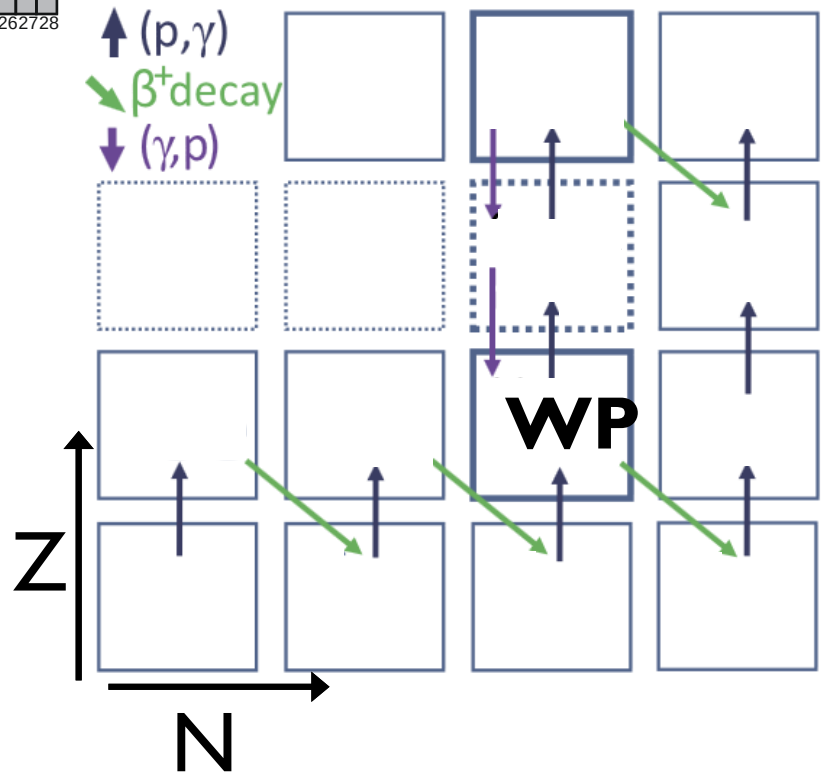
The β-Oslo technique determines the level density and γ-strength function needed for the statistical reaction rate.

This first application (April 2019) including proton-decay will simultaneously determine the proton optical potential.

Waiting points

- Stuck waiting for β-decay because (p,γ)- (γ,p) equilibrium at ^{56}Ni, ^{64}Ge, ^{68}Se, ^{72}Kr, ^{100}Sn
- Caused by:
  - low (p,γ) Q-value
  - long half-life (~seconds)
- Also impacted by p,γ rate on waiting-point proton-capture daughter





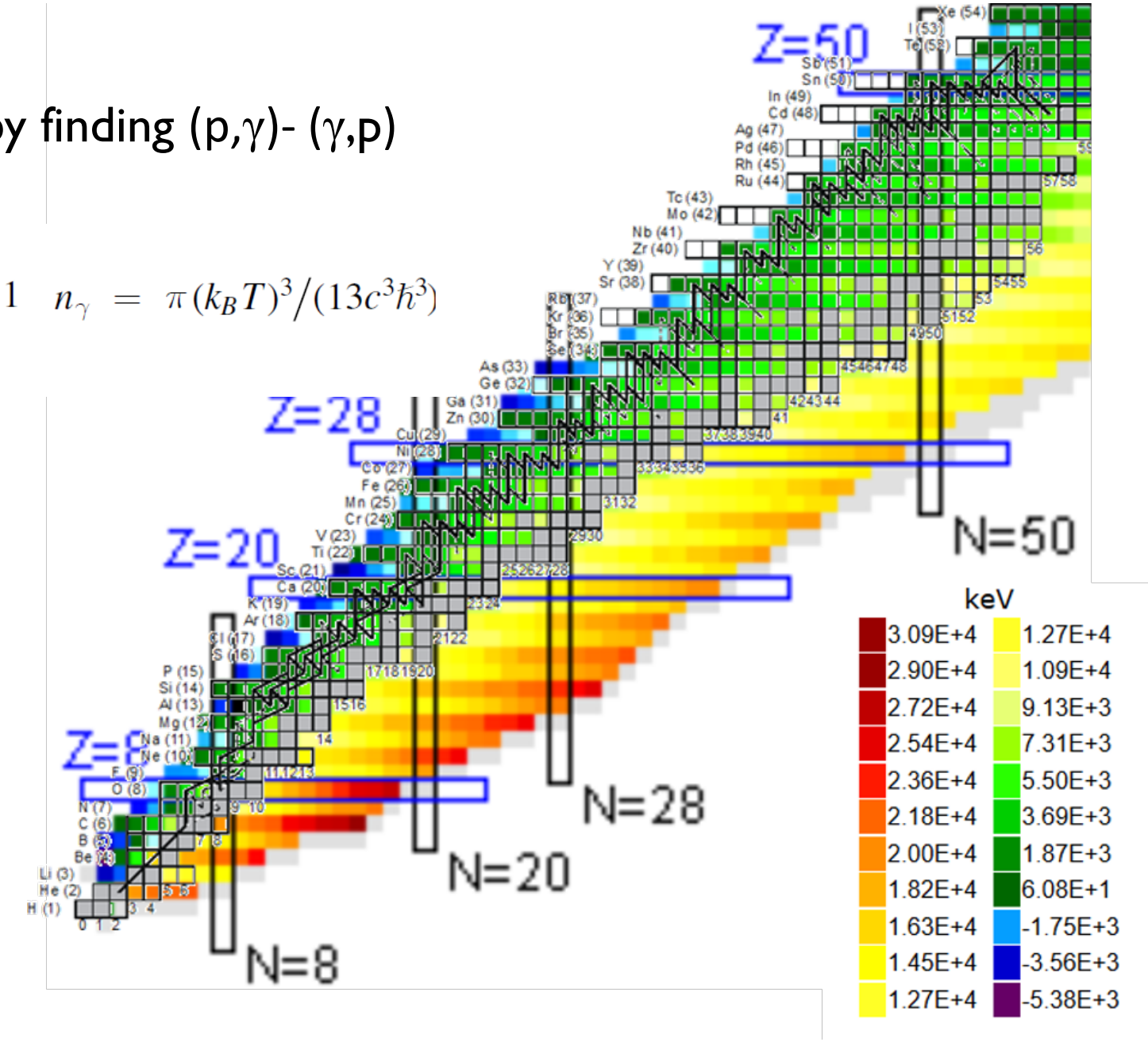
Waiting points

- The path of the rp-process is dictated by finding (p,γ)- (γ,p) equilibrium nucleus

$$\frac{\lambda_{\gamma,\mathrm{p}}}{\lambda_{\mathrm{p},\gamma}} = \frac{n_{\mathrm{p}}}{n_\gamma}\left(\frac{\mu_{\mathrm{red}}c^2}{k_{\mathrm{B}}T}\right)^{3/2}\exp\left(-\frac{Q_{\mathrm{p},\gamma}}{k_{\mathrm{B}}T}\right) \gtrsim 1, \quad \mu_{\mathrm{red}} \approx 1 \quad n_\gamma = \pi(k_B T)^3/(13c^3\hbar^3)$$

For $\rho \sim 10^6 \frac{\mathrm{g}}{\mathrm{cm}^3}$, $X(H) \sim 0.7$, and $T \sim 1\mathrm{GK}$, this turns out to be $S_p \sim 1\mathrm{MeV}$

- So, waiting points have $S_p \sim 1$MeV and >second half-lives

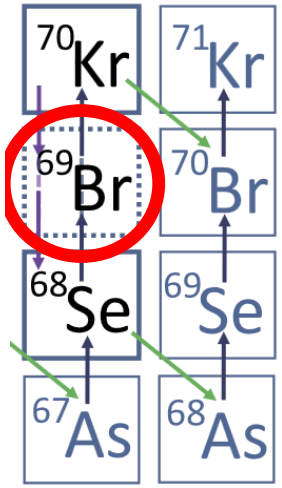


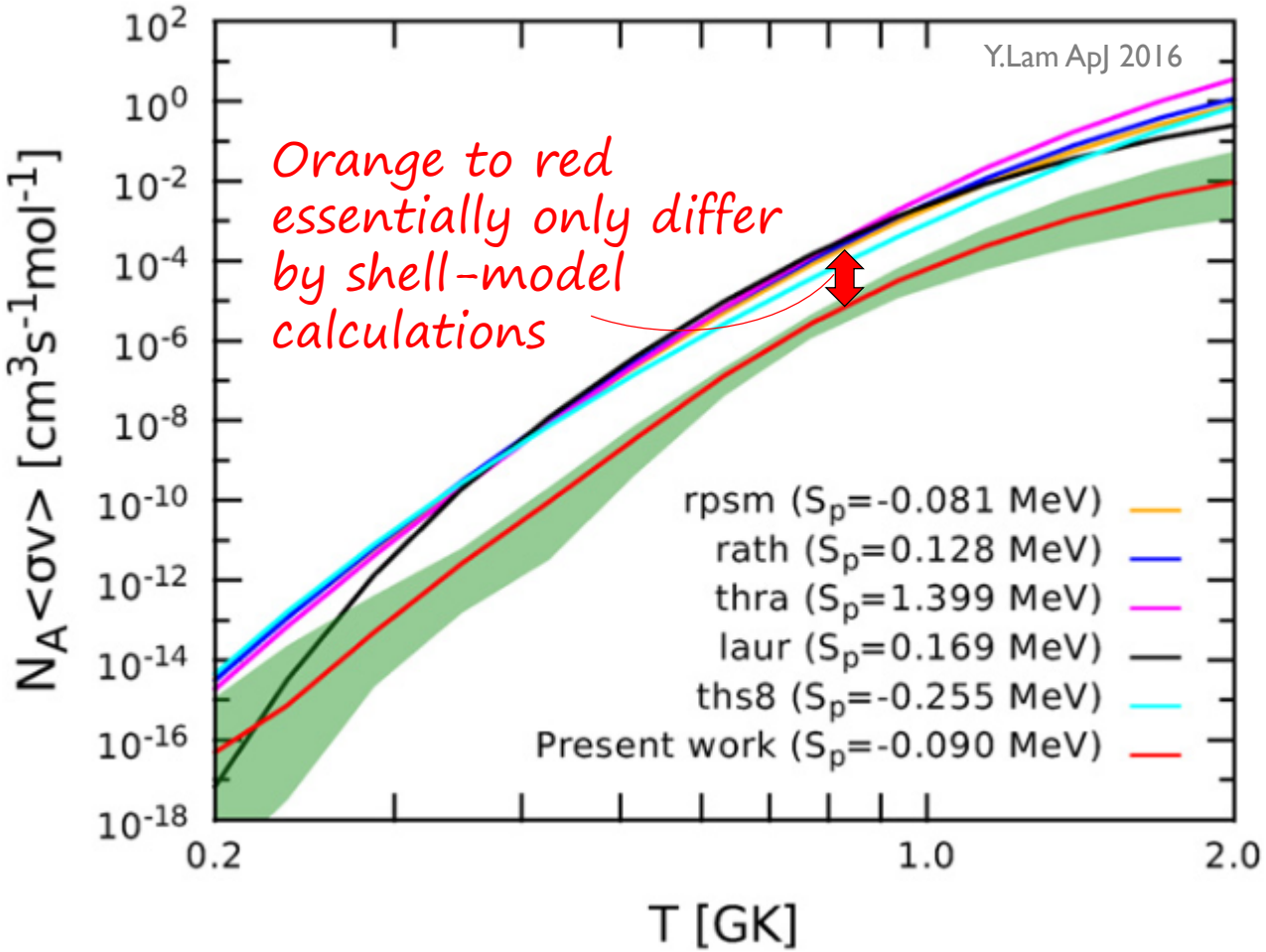
Waiting points

- Completely dominated by reaction Q-value

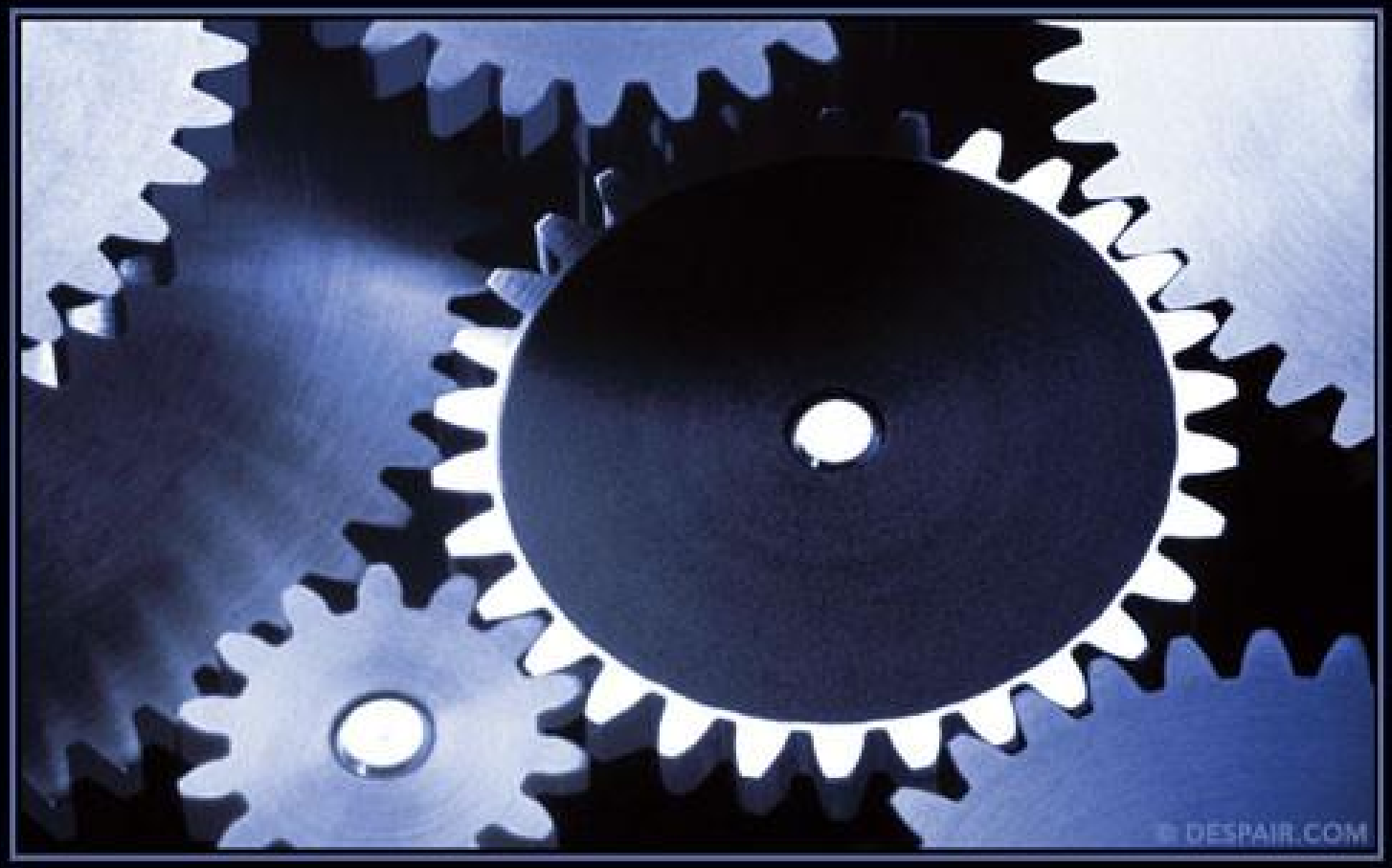
$$\frac{\lambda_{\gamma,\mathrm{p}}}{\lambda_{\mathrm{p},\gamma}} = \frac{n_{\mathrm{p}}}{n_{\gamma}}\left(\frac{\mu_{\mathrm{red}}c^2}{k_{\mathrm{B}}T}\right)^{3/2}\exp\left(-\frac{Q_{\mathrm{p},\gamma}}{k_{\mathrm{B}}T}\right) \gtrsim 1$$

- Need precise masses and excitation energies
- Major outstanding uncertainties:
  ^{65}As and ^{66}Se masses, ^{57}Zn βp-branching





How do we know which *rp*-process reactions matter?

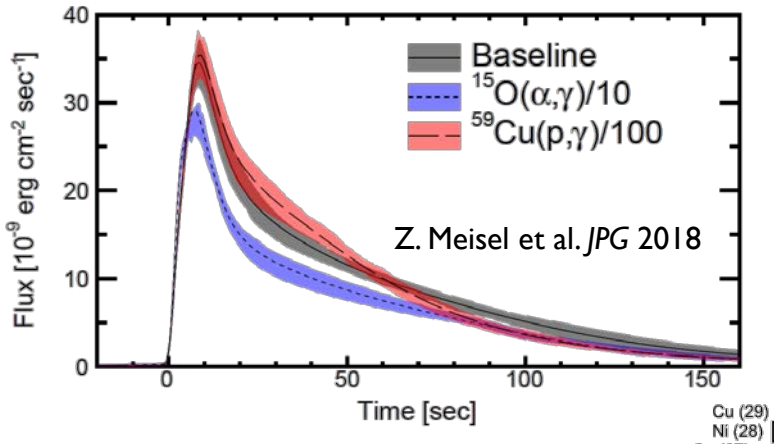


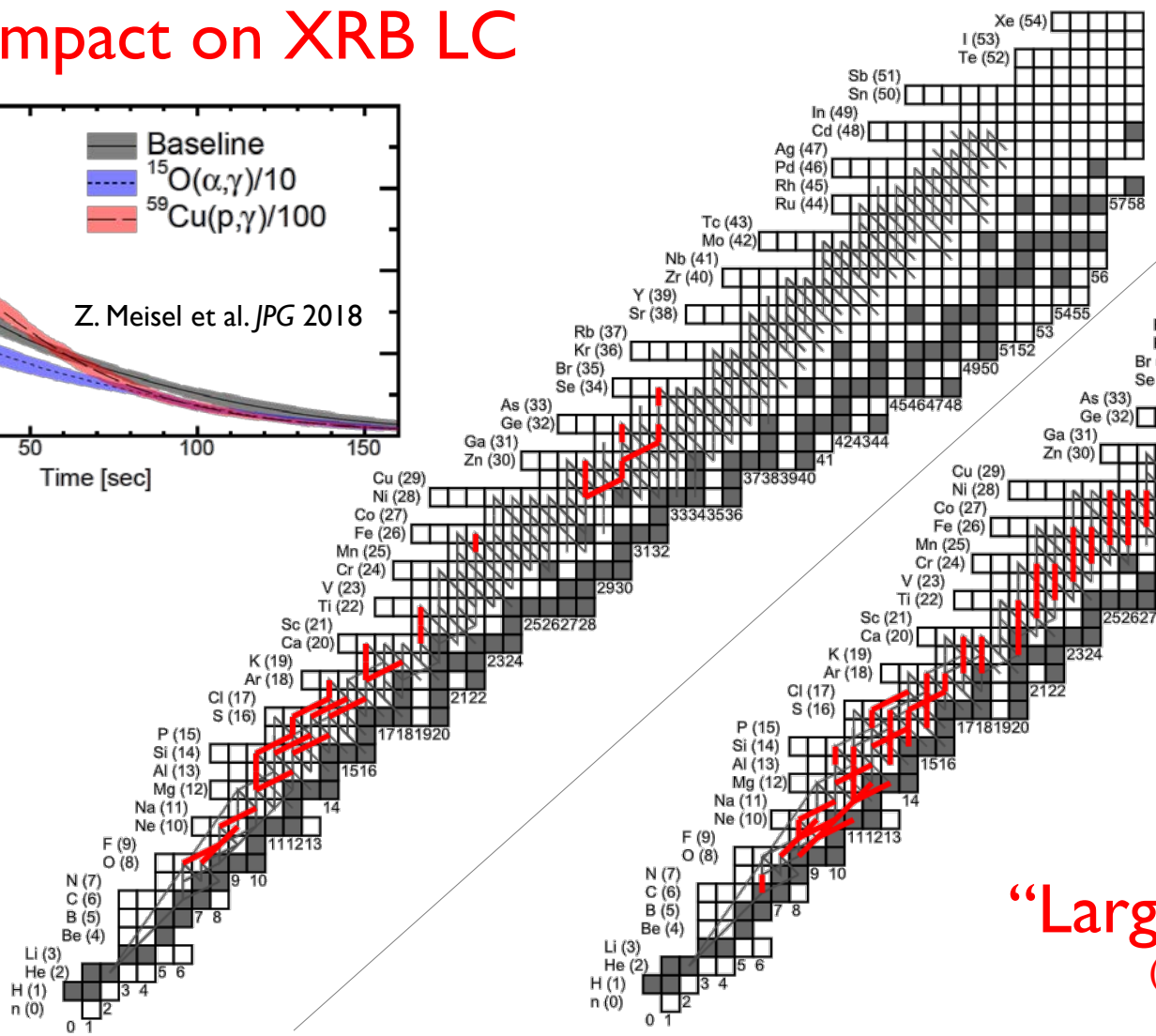
WORTH

JUST BECAUSE YOU'RE NECESSARY DOESN'T MEAN YOU'RE IMPORTANT.

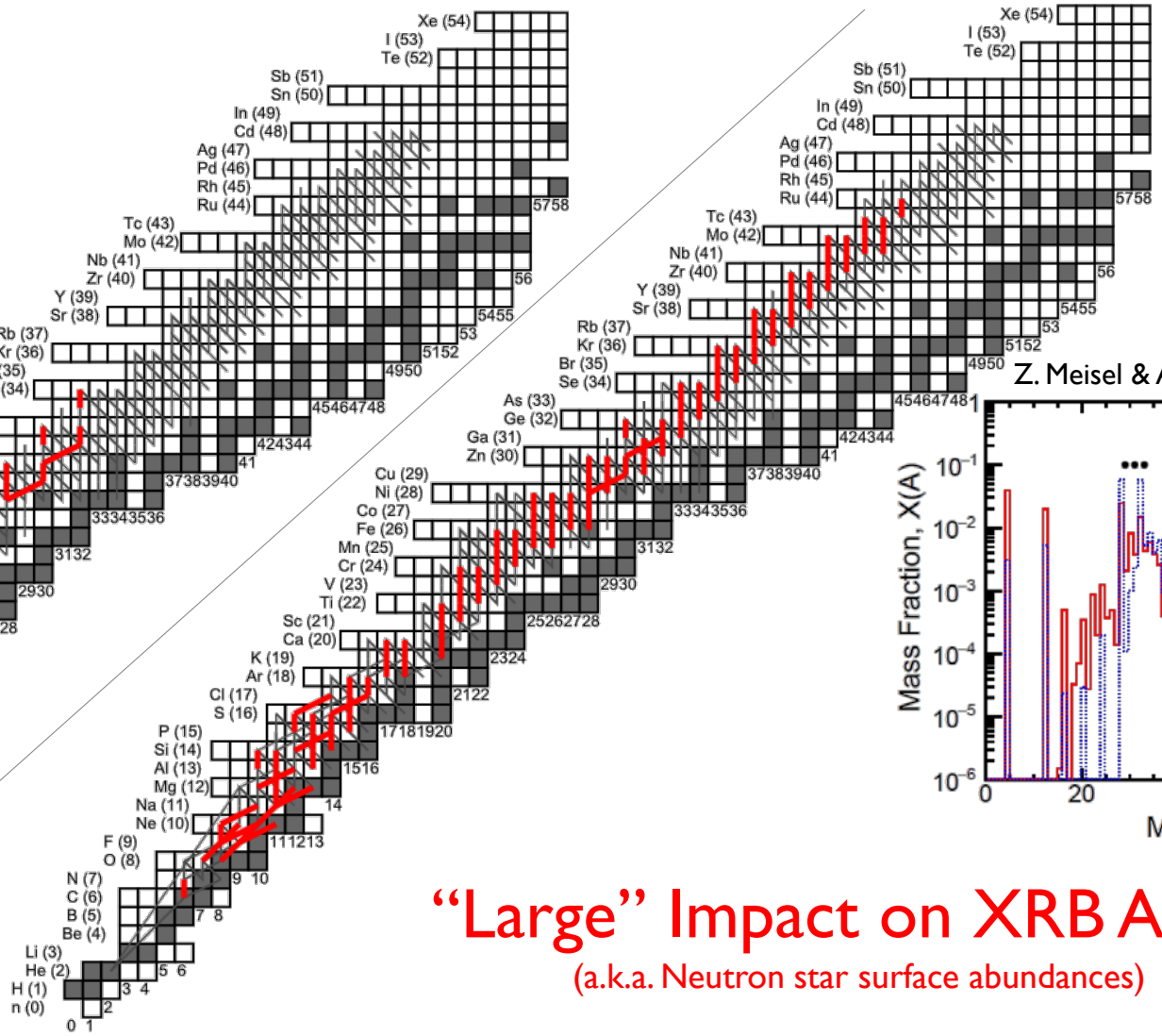
Sensitivity studies: brute-force ways to see what matters

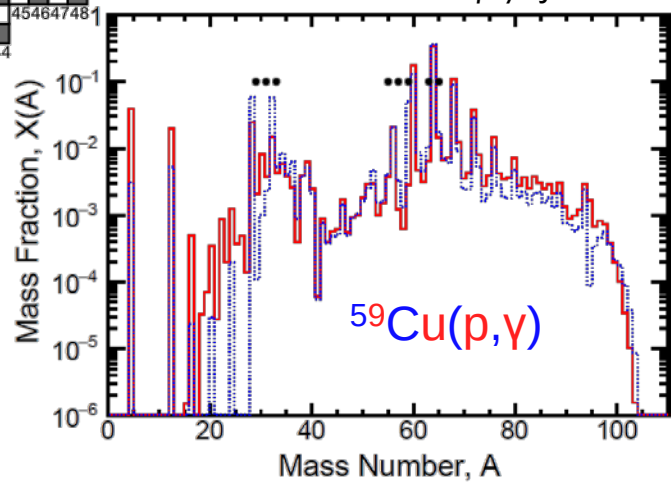
"Large" Impact on XRB LC





R. Cyburt et al. *ApJ 2016*



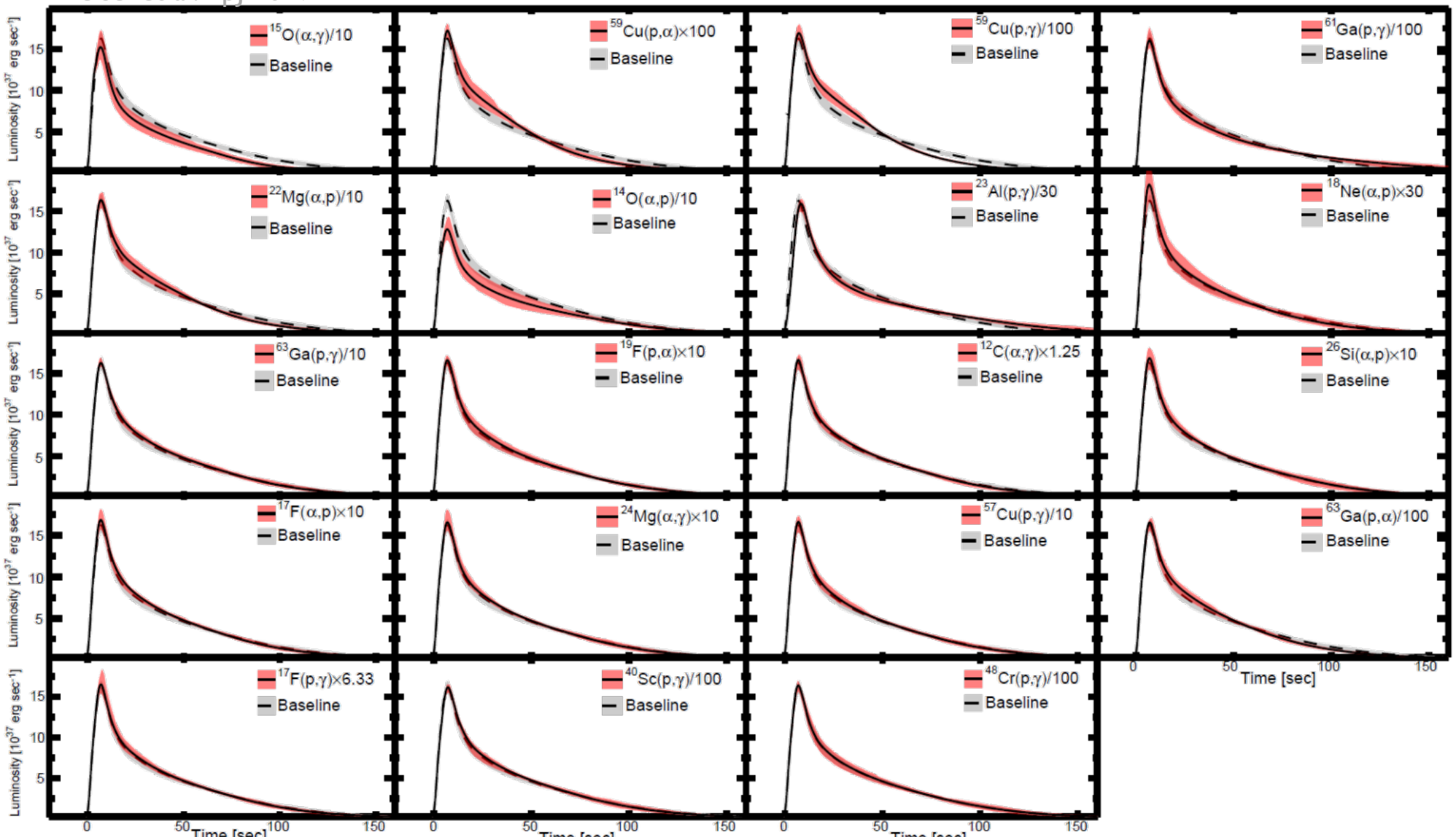


"Large" Impact on XRB Ashes

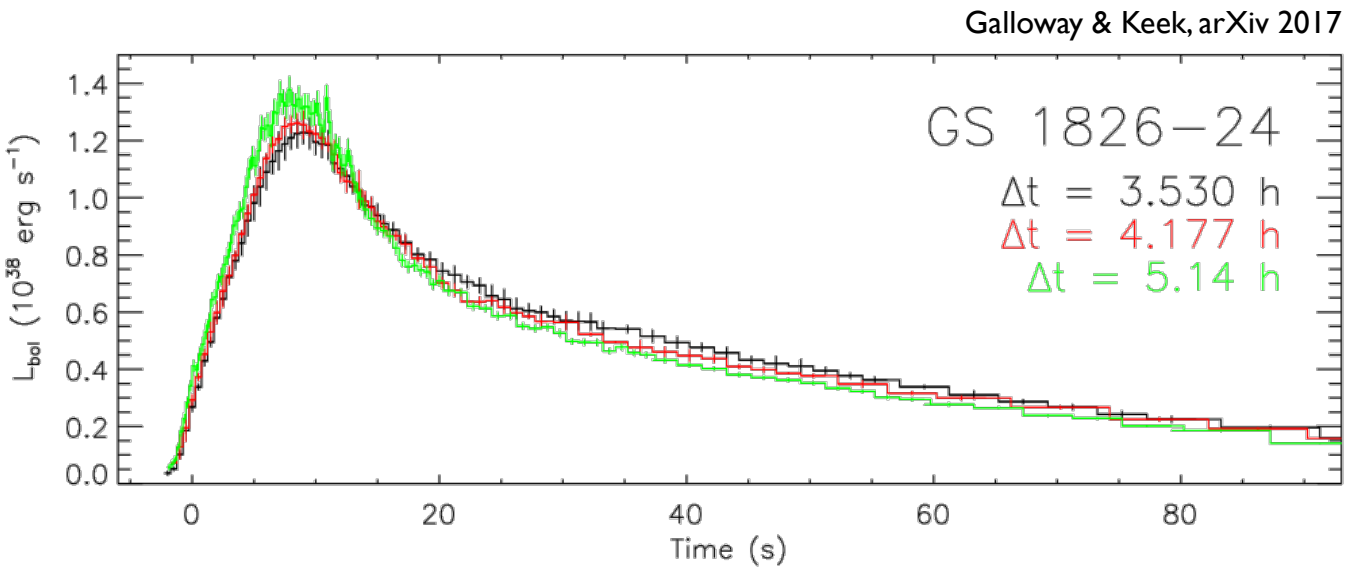
(a.k.a. Neutron star surface abundances)

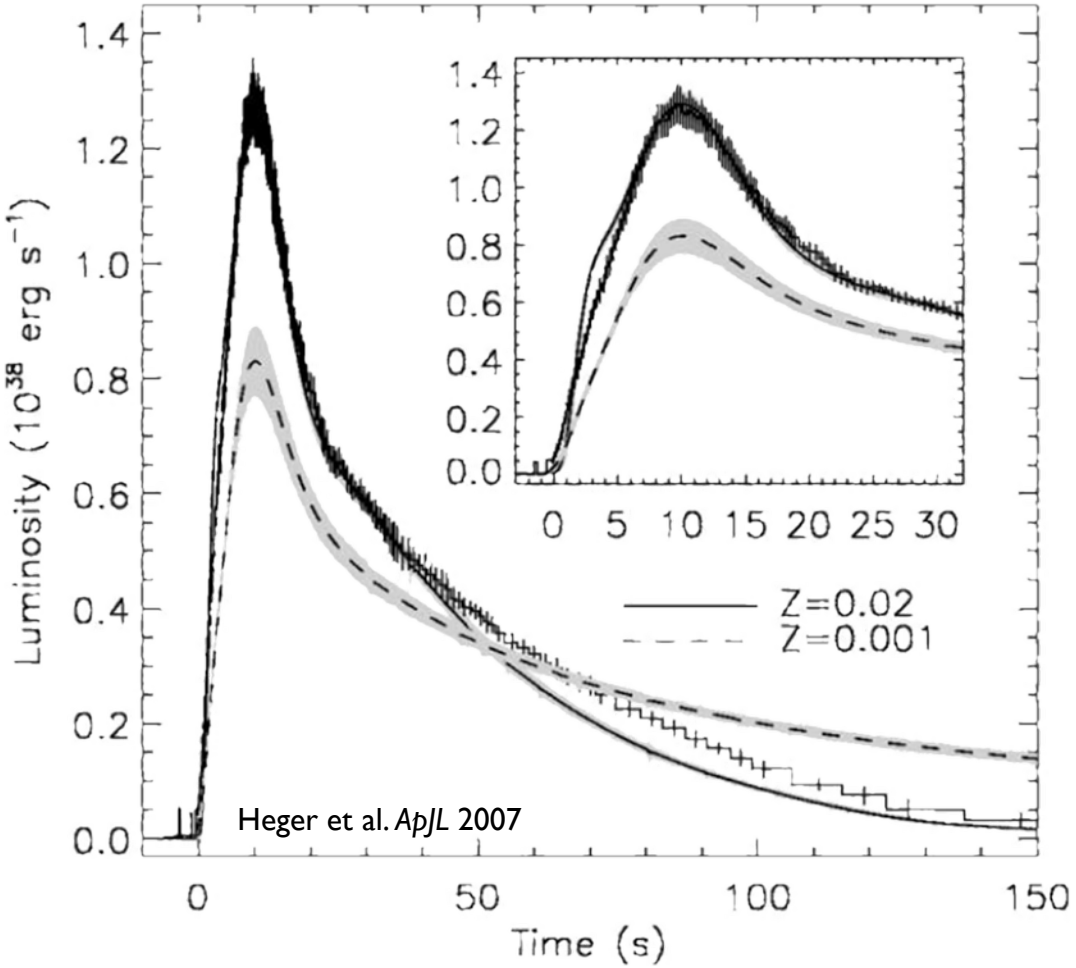
The impact of rate variations doesn't look very impressive. Are we sure they matter?

Meisel et al. ApJ 2019



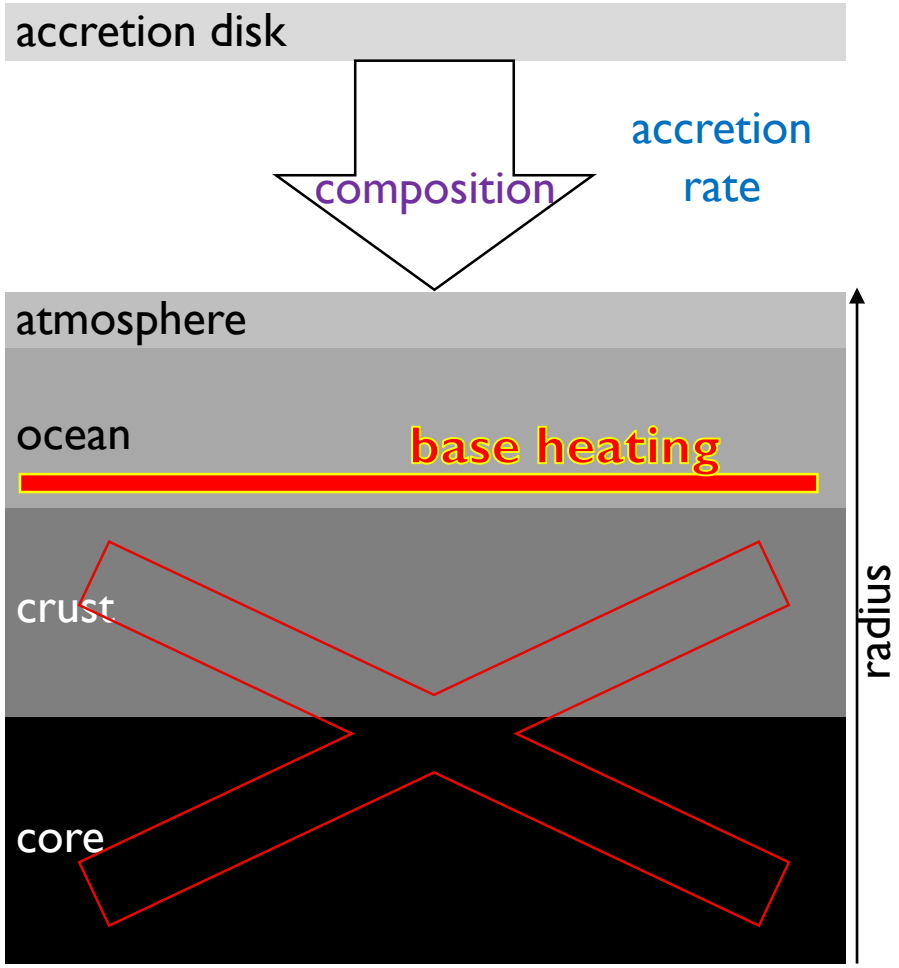
Consider the Clock Burster, GS 1826-24



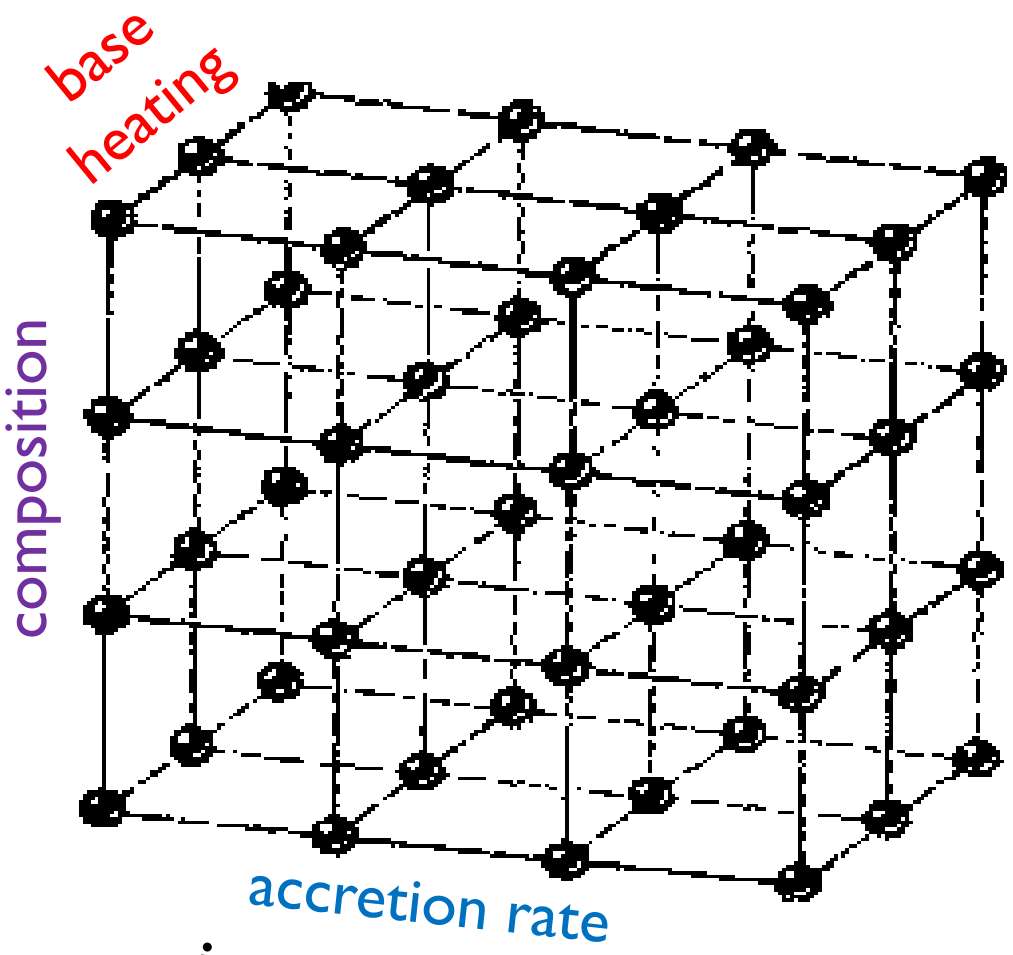


Do reaction rate sensitivities matter for modeling this source?

MESA calculations performed for a grid of conditions

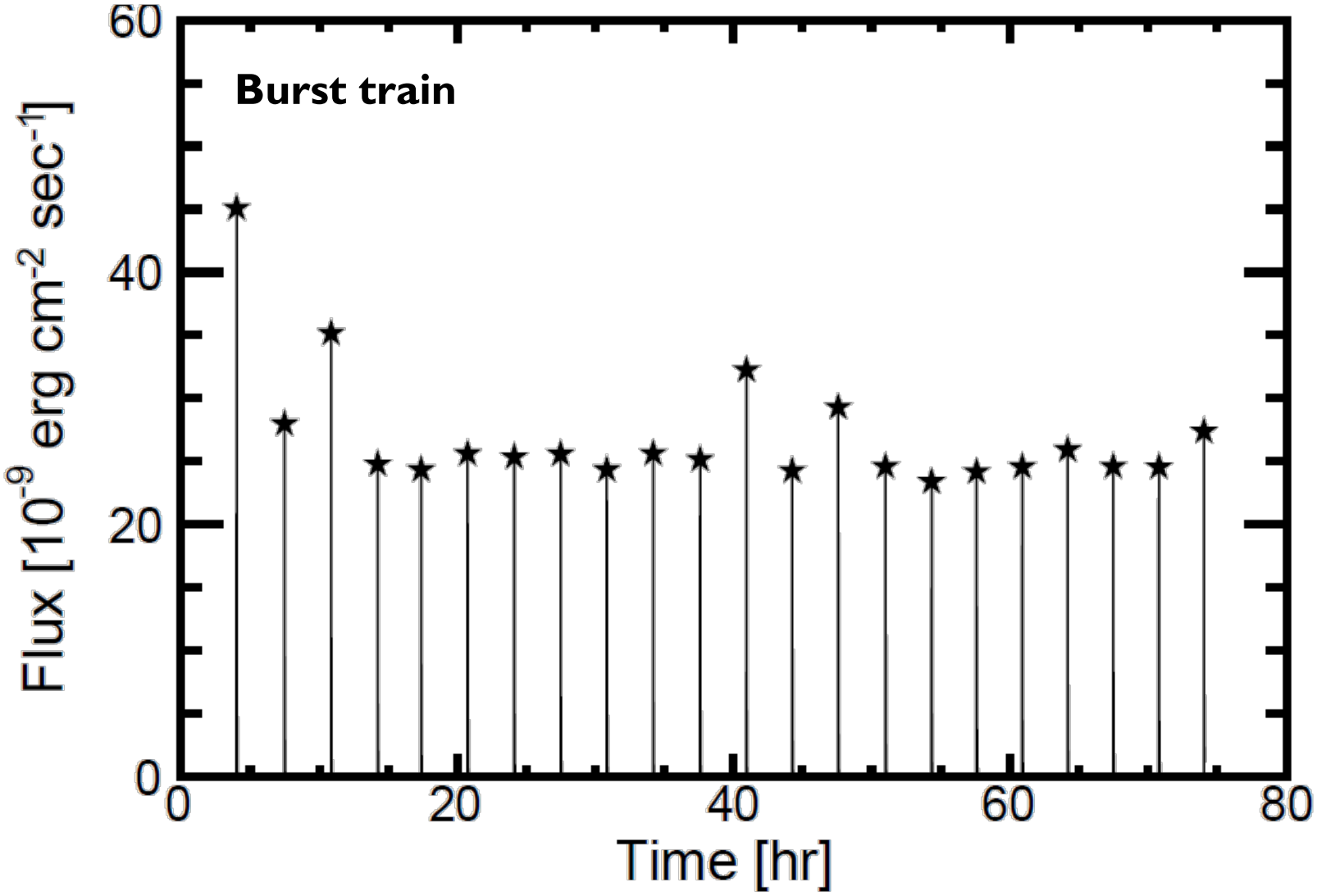


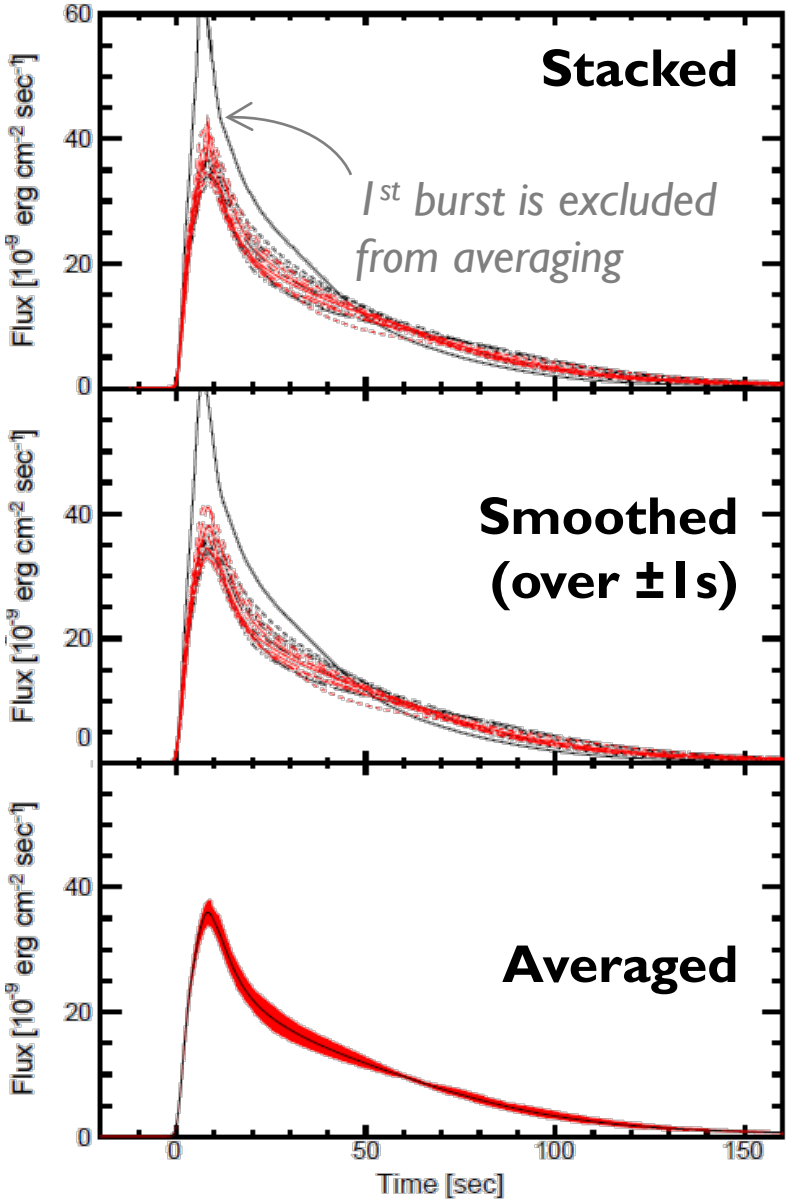
*the models are one-dimensional



in sets of three,
to match the observed ratio

MESA output processing: *stacking, smoothing, & averaging*

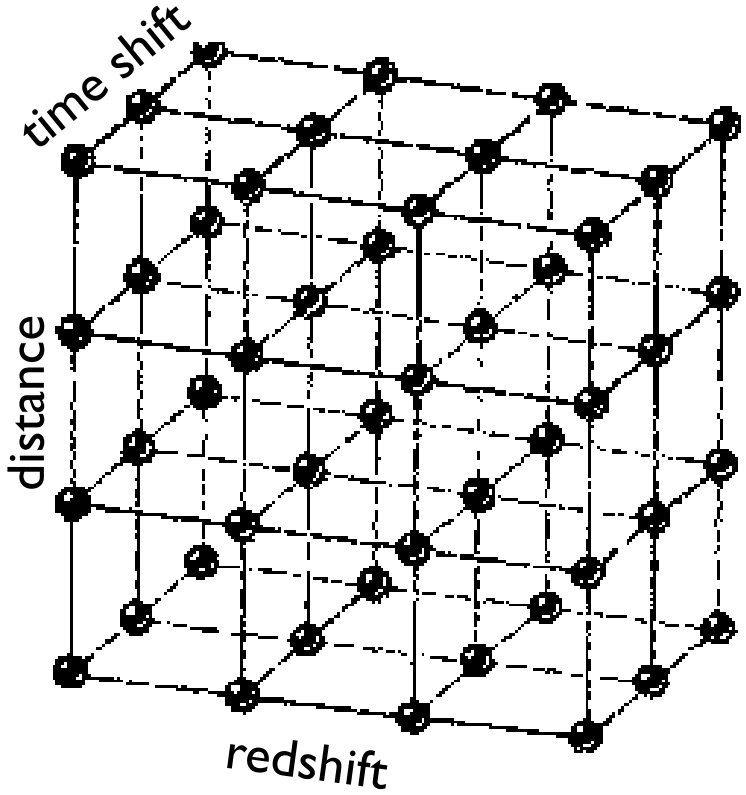




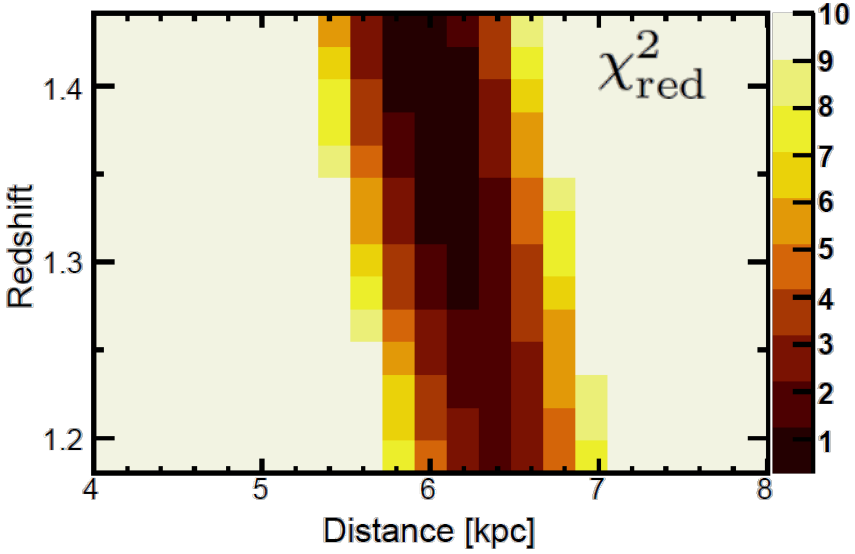
Meisel *ApJ* 2018

Model-observation comparisons were performed for the year 1998, 2000, 2007 burst epochs, for a grid of *z* and *d*

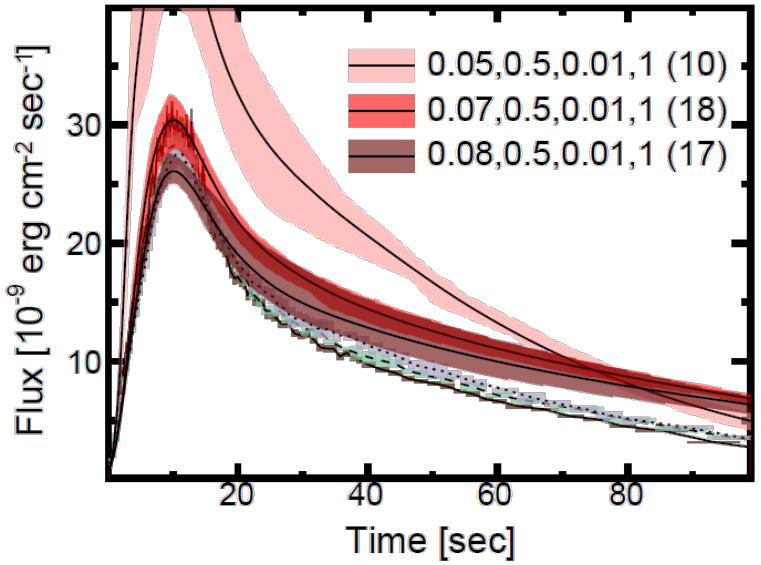
For highest $\dot{M}$ in a triplet, compared light curve to 2007 epoch at each point in a grid of modifications:



For highest $\dot{M}$ in a triplet, found the best-fit (1+z) and $d\xi_b^{1/2}$, for an arbitrary time shift:



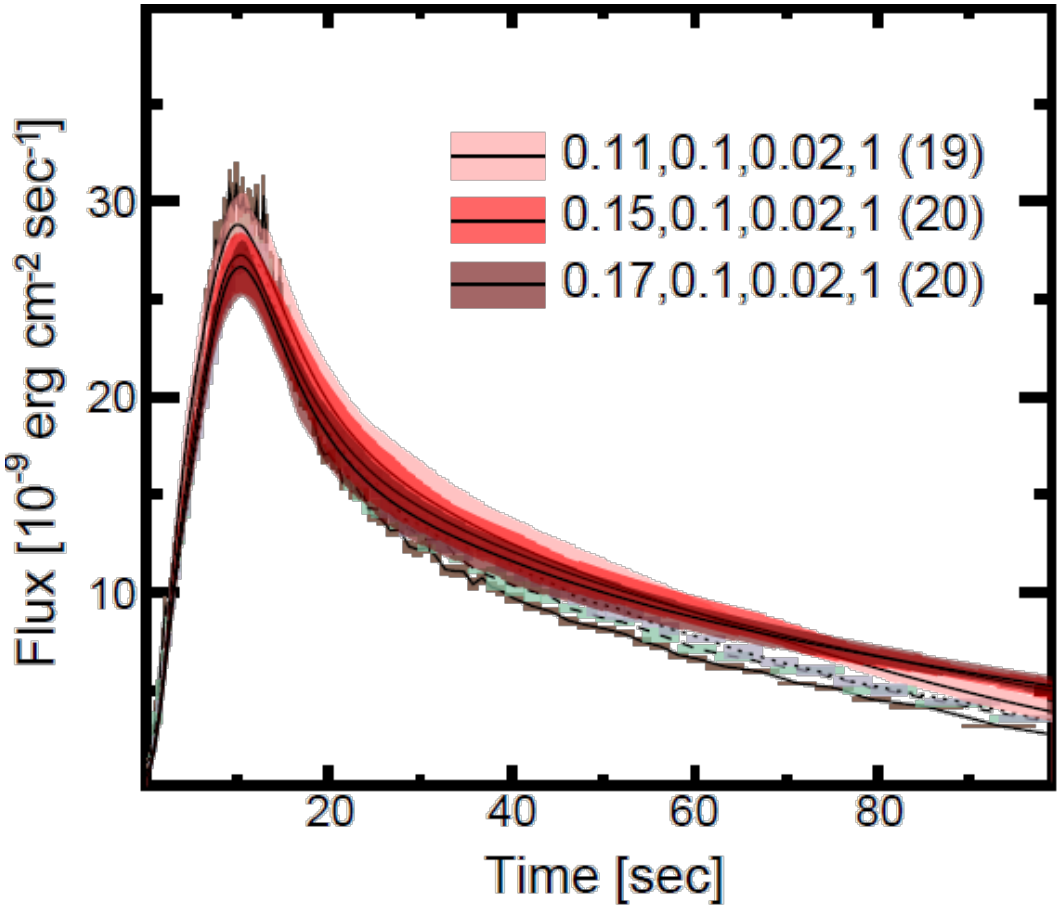
Applied the best-fit (1+z) and $d\xi_b^{1/2}$ from the highest $\dot{M}$ in a triplet, and an arbitrary time shift, to LCs from all three $\dot{M}$:

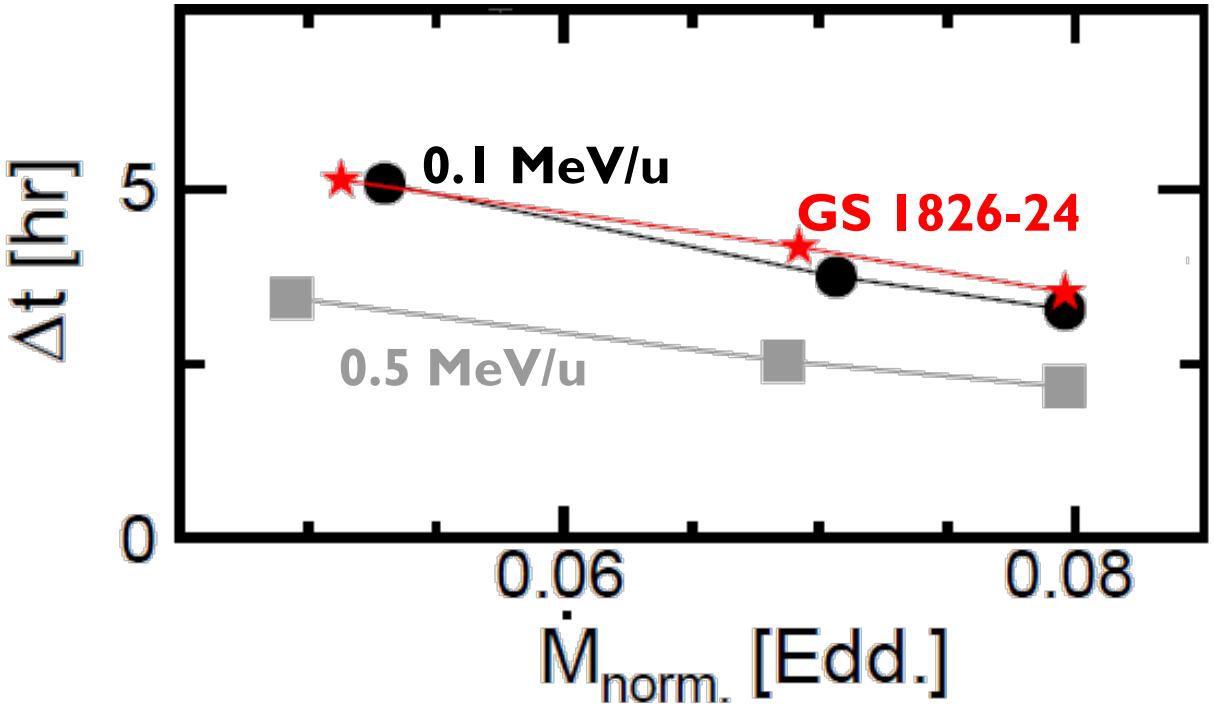


$$F(t) = L(t)/[4\pi\xi_b(1+z)d^2]$$
$$t = t_0[1+z]$$

Meisel *ApJ* 2018

The clock-burster was reproduced, with stringent constraints on the astrophysical conditions

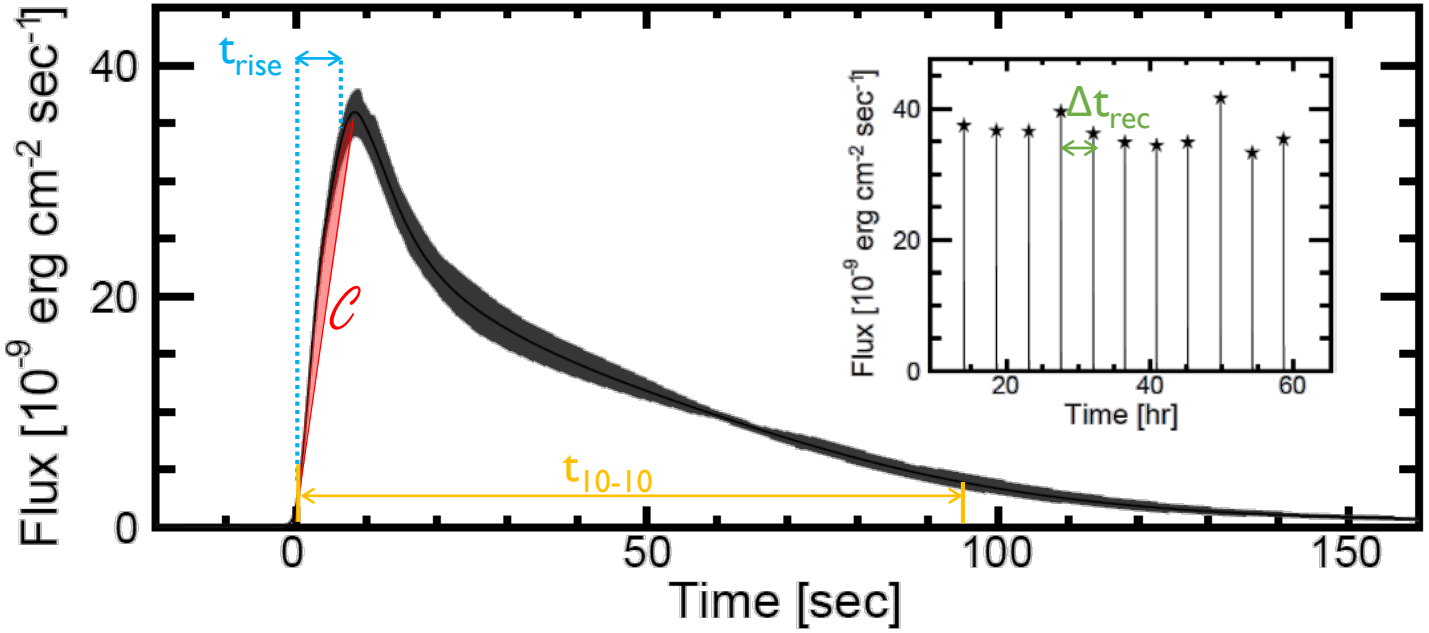


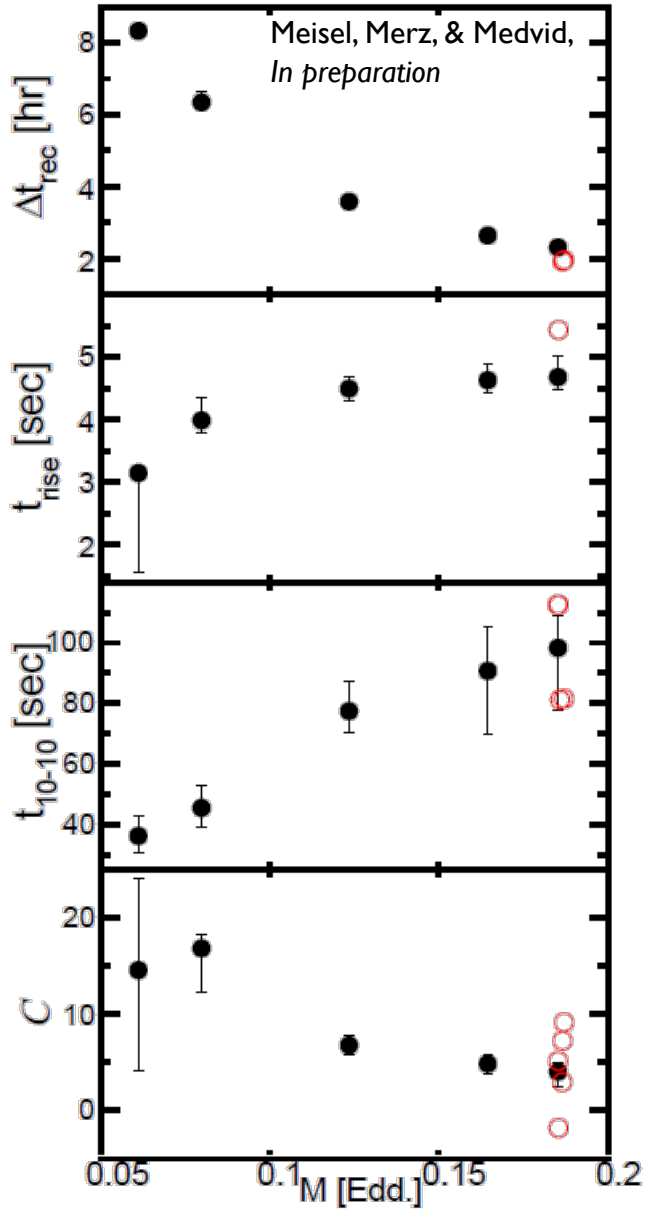


Meisel *ApJ* 2018

Were these results sensitive to nuclear physics uncertainties?

Yes, *but* the impacts are not great enough to significantly change the best-fit astrophysical conditions.



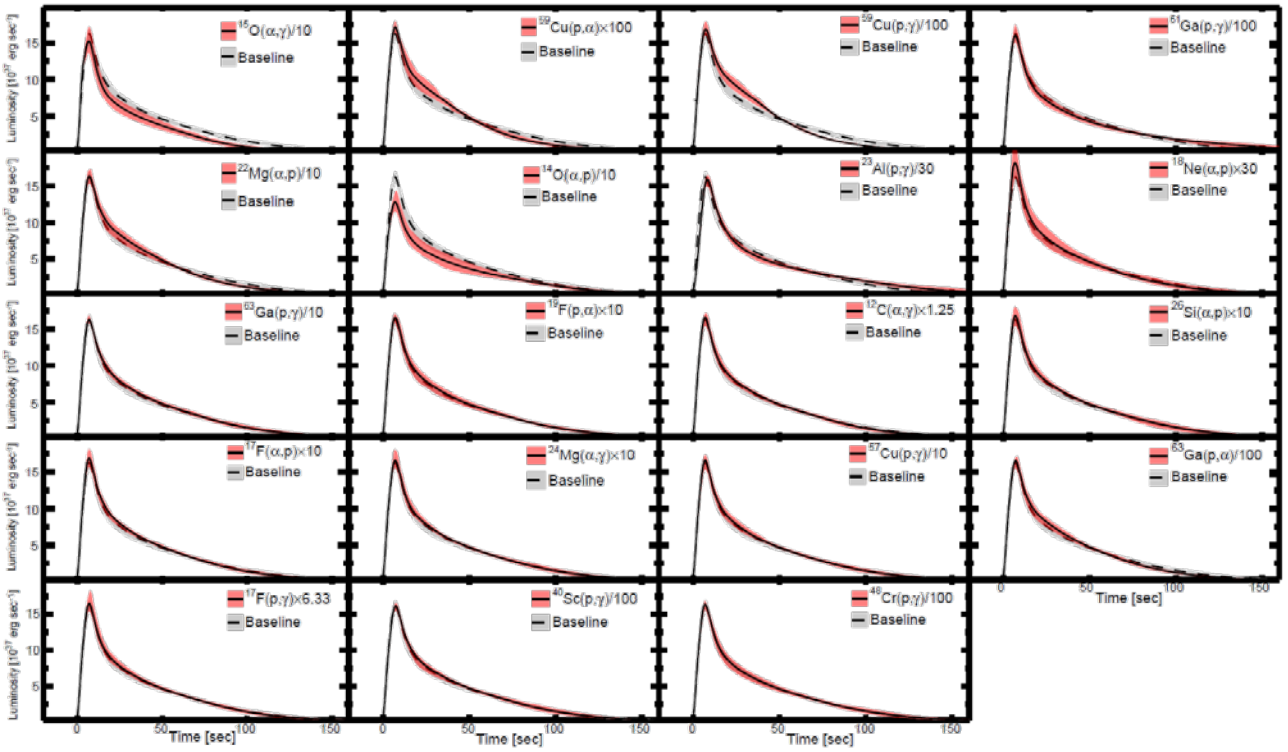


This is great! Otherwise we would need to do a recursive study of nuclear physics sensitivities.

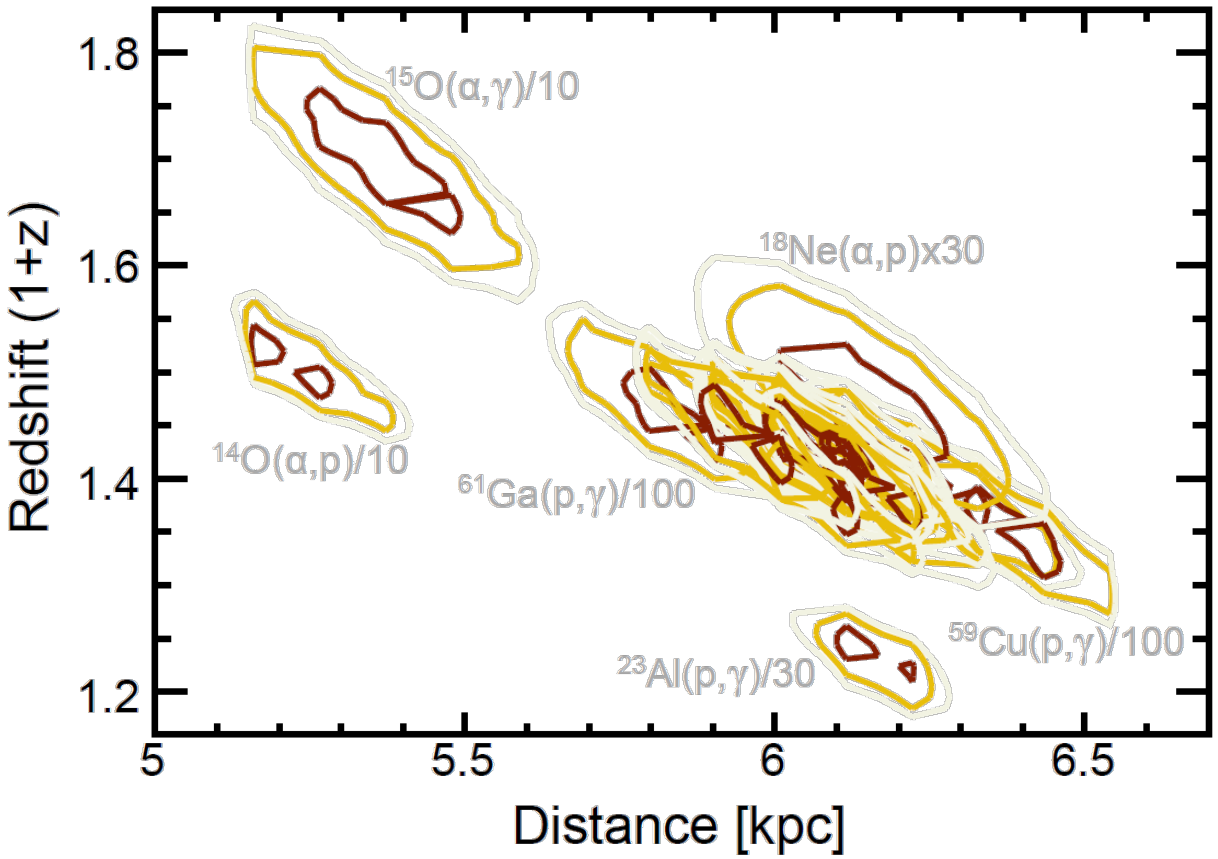
The natural question is whether the impact of nuclear uncertainties matter anyway.

Do the nuclear physics sensitivities matter? **Yes.**

Consider variations of the significant reaction rate uncertainties identified in Cyburt et al. 2016…

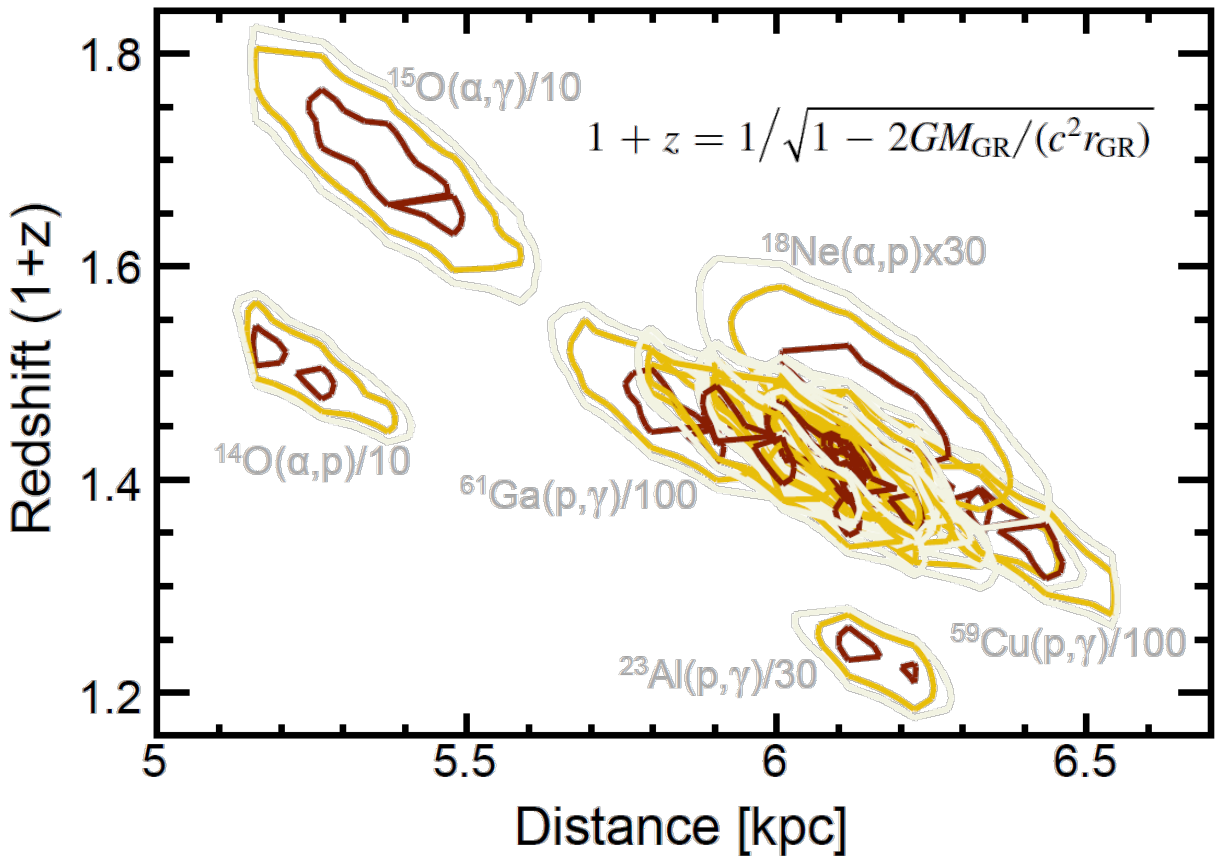


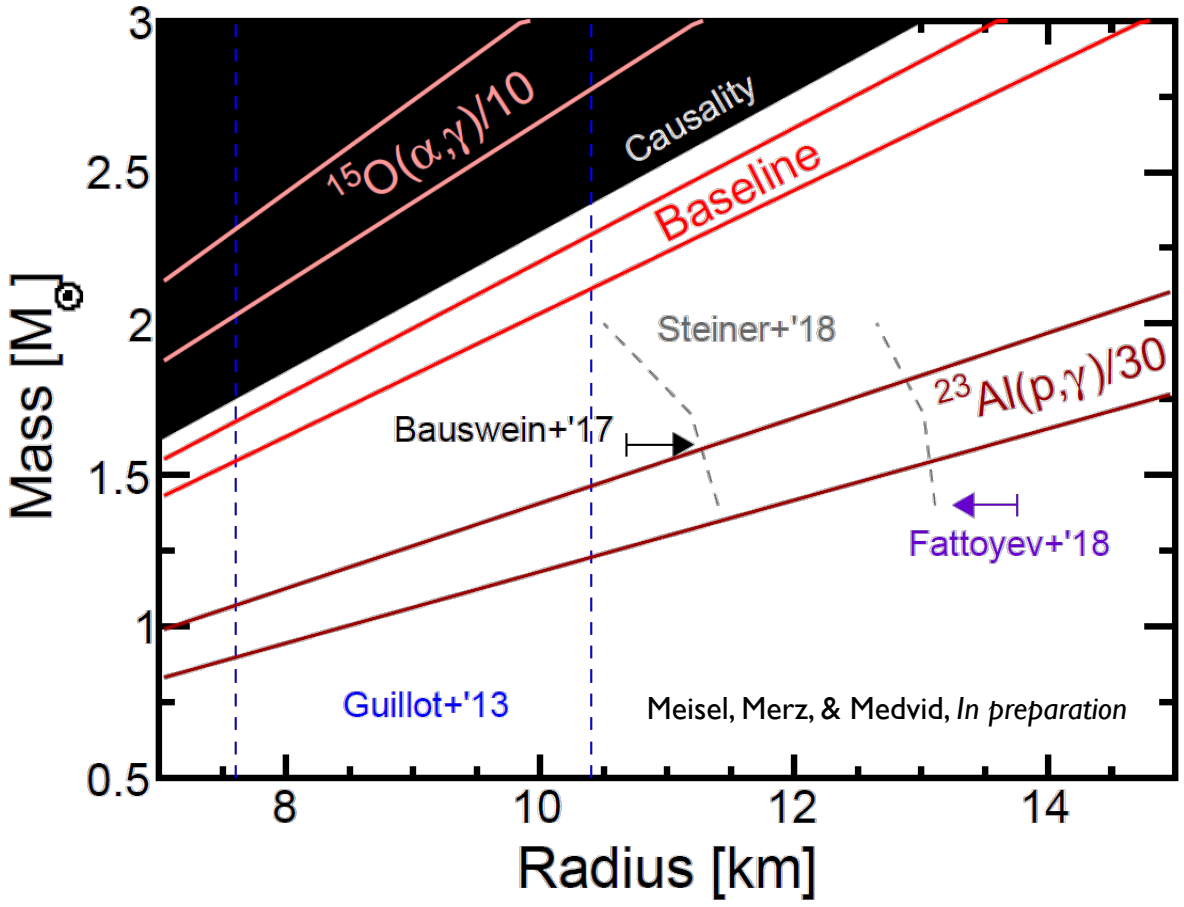
… and re-do the fit to the GS 1826-24 light curve



Meisel, Merz, & Medvid, *In preparation*

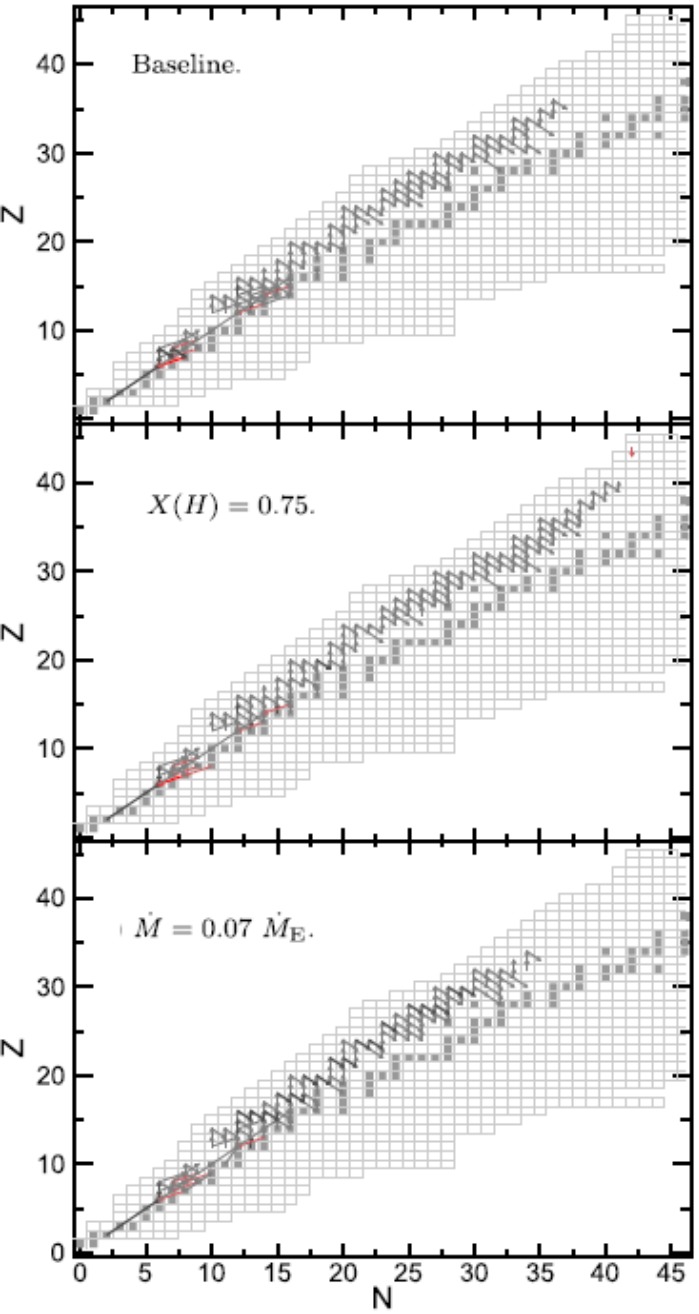
Reaction rate uncertainties lead to redshift uncertainties, which in-turn lead to uncertainties on the NS mass-radius

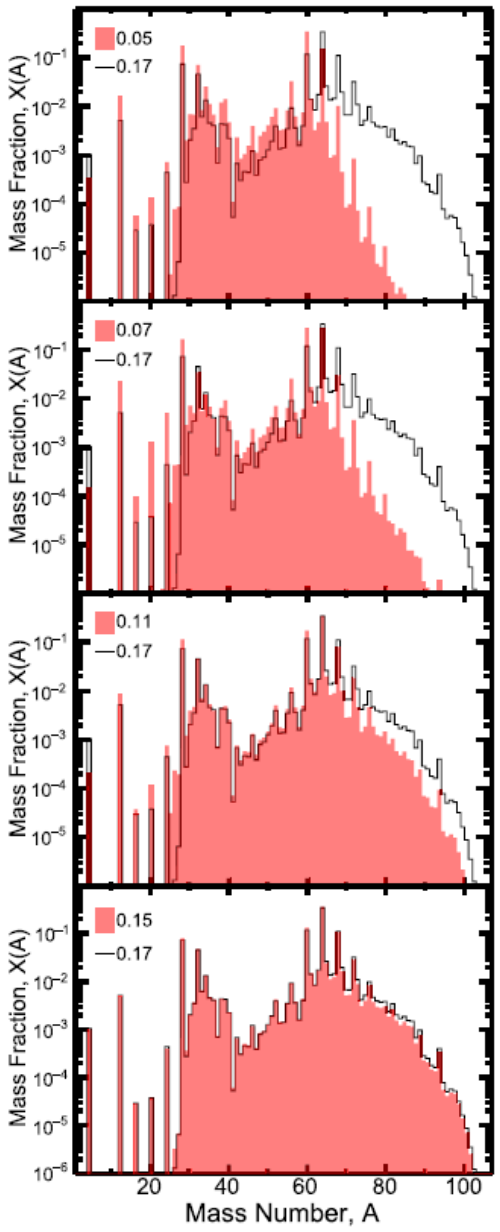




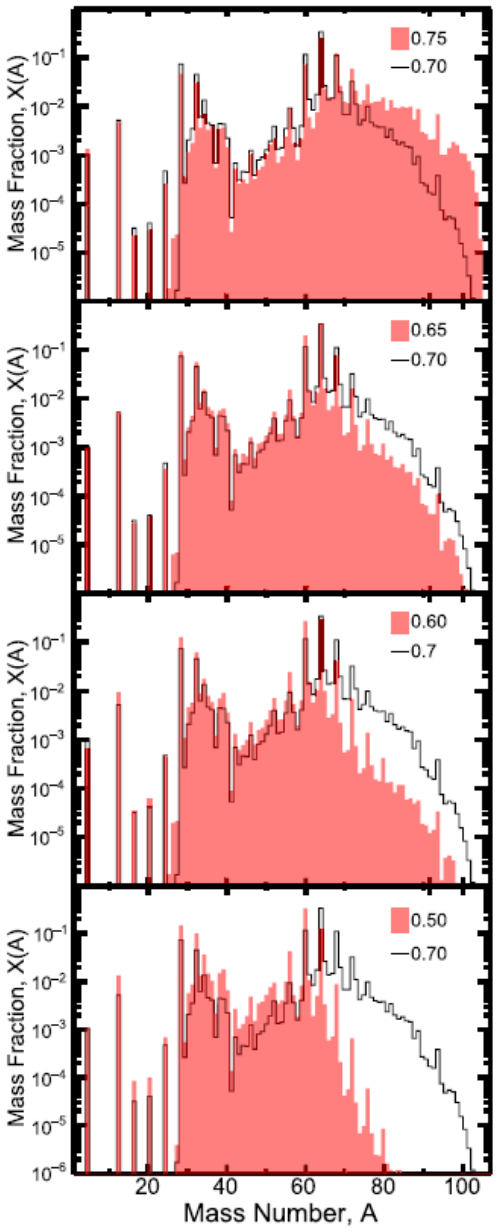
From a positive perspective,
if we reduce these reaction rate uncertainties, we have a new mass-radius constraint.

Note: "Important" rates may be different for different conditions



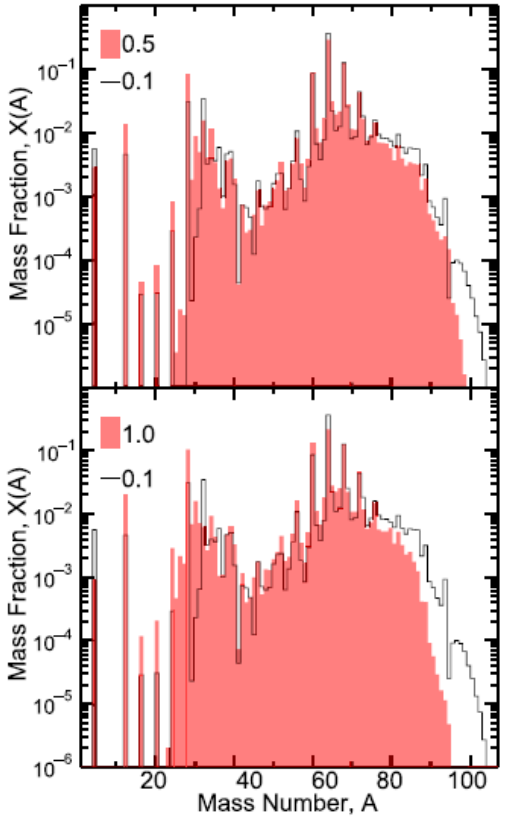


(a) Varying $\dot{M}$.



(b) Varying $X(H)$.

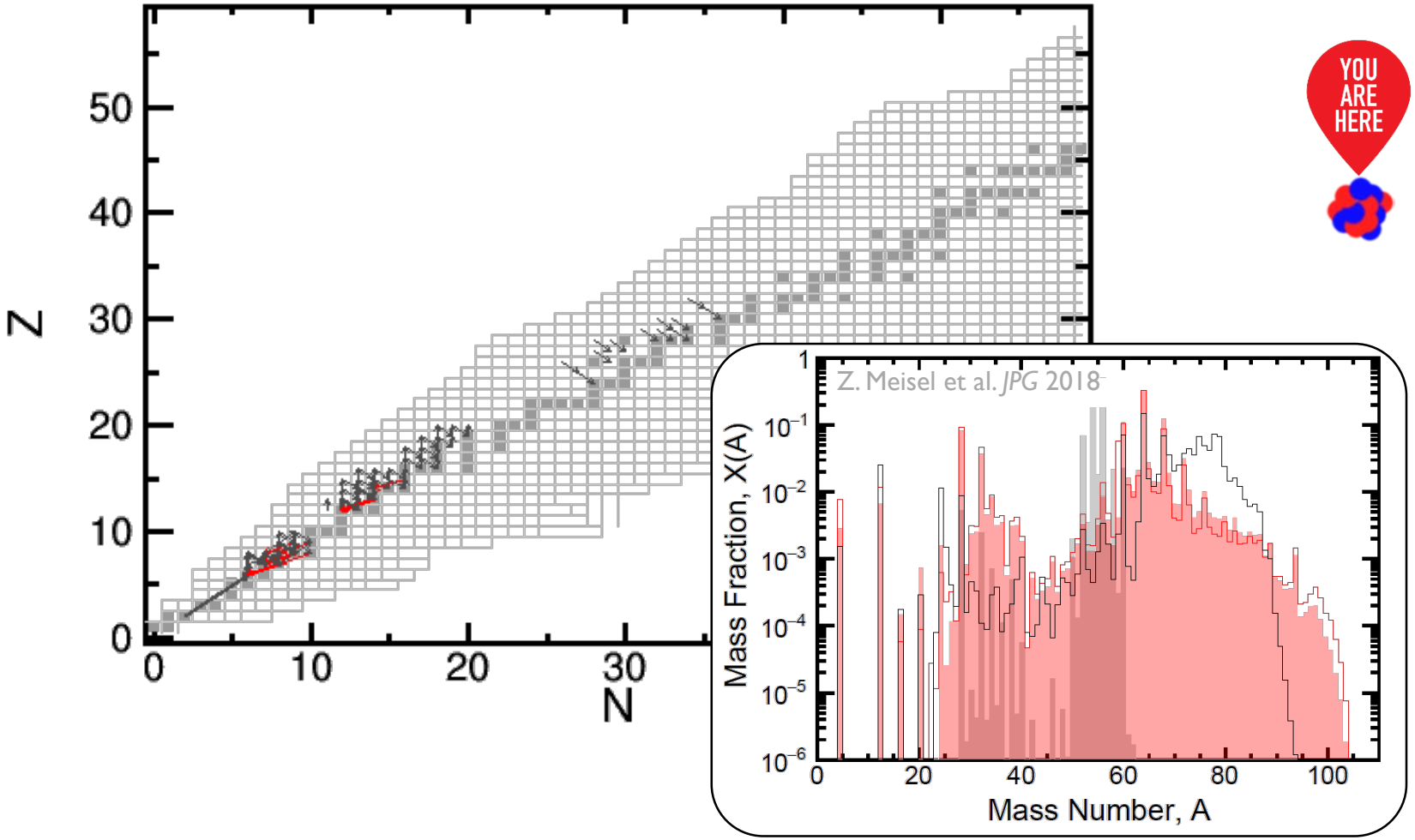
Meisel et al. ApJ 2019

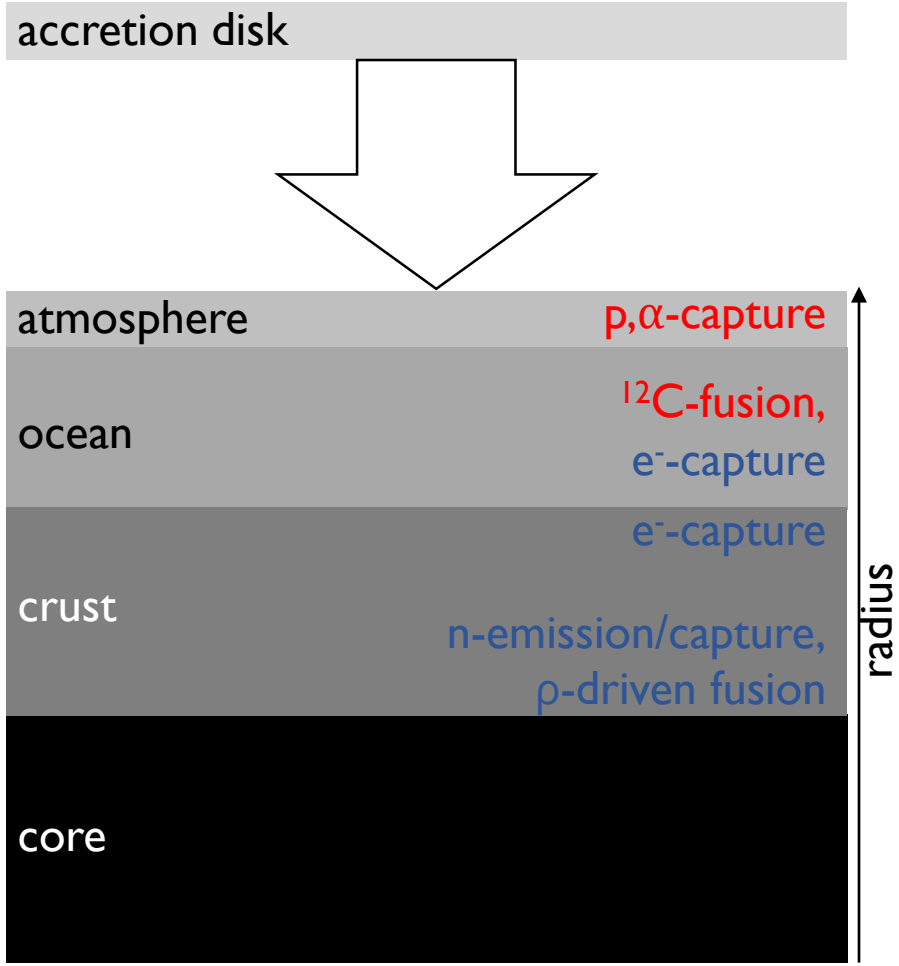


(c) Varying Q_b with $Z = 0.01$.

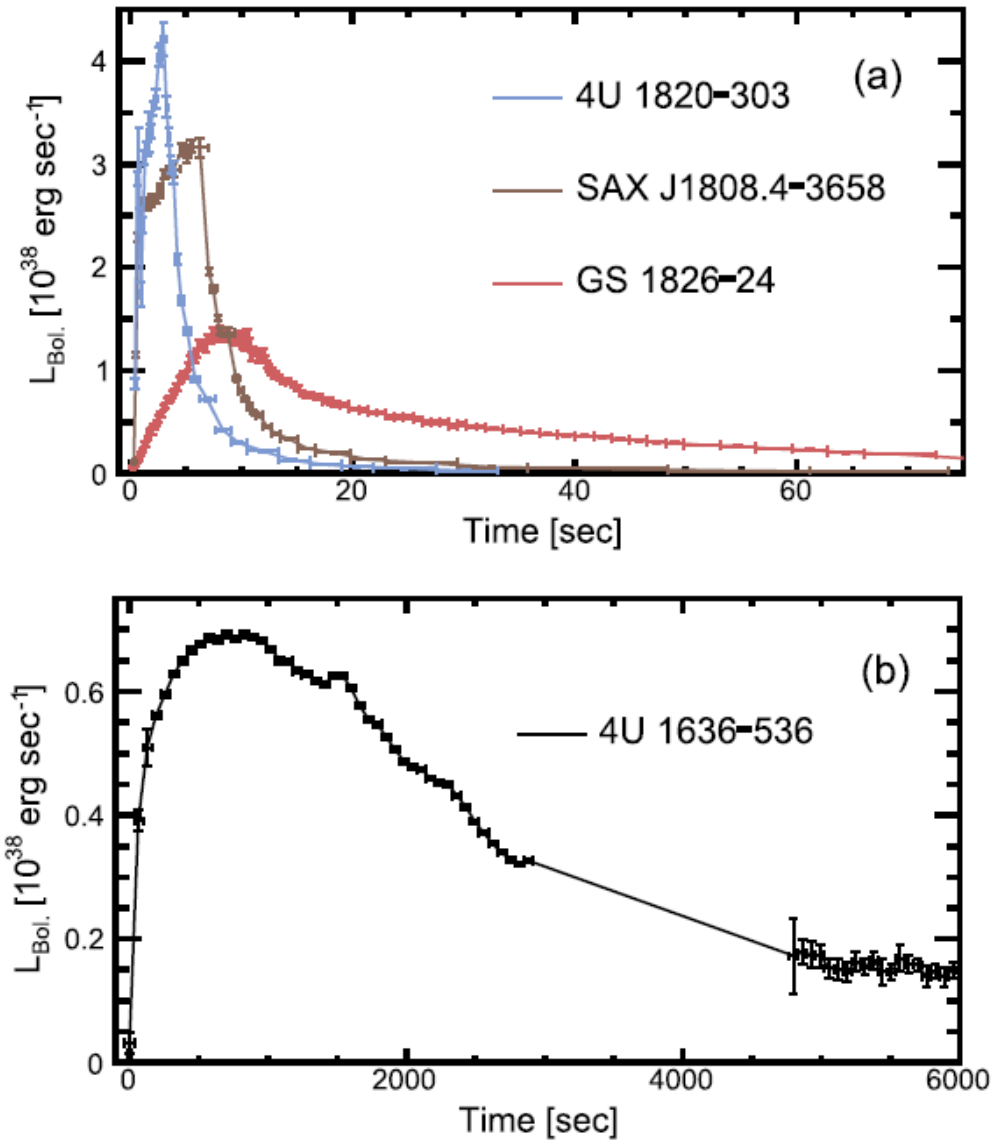
The journey of a nucleus in a neutron star

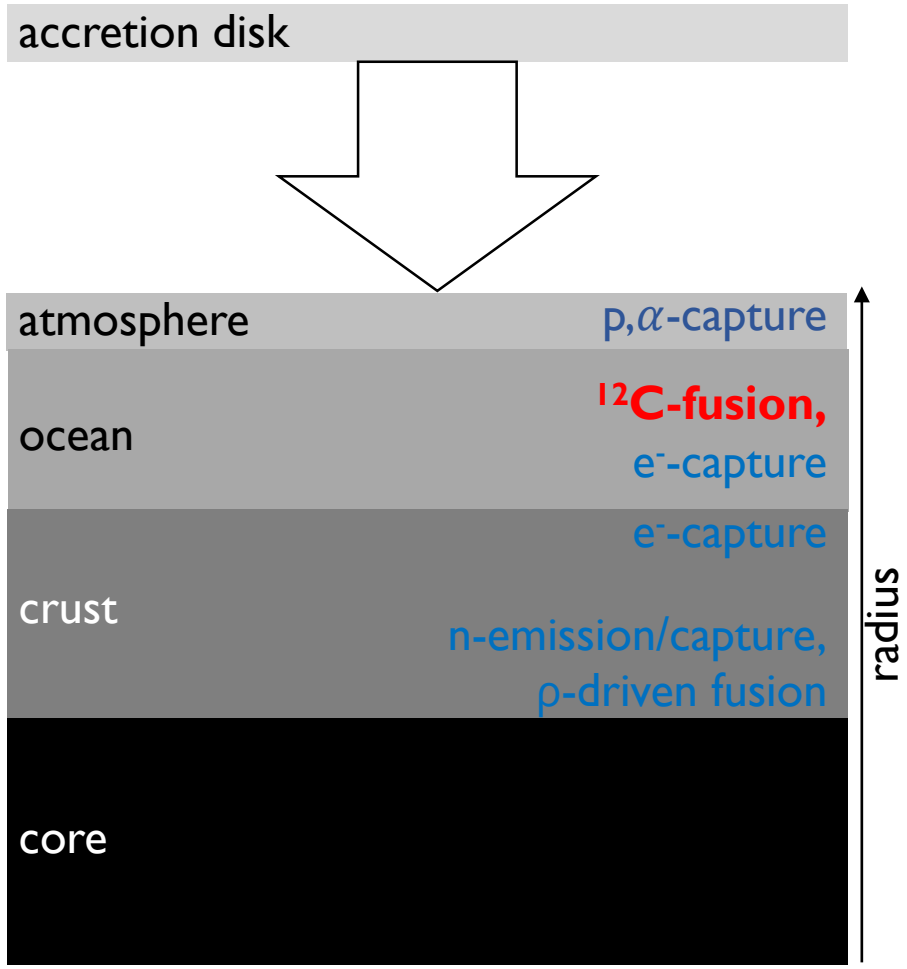
1. Production from H, He, C burning





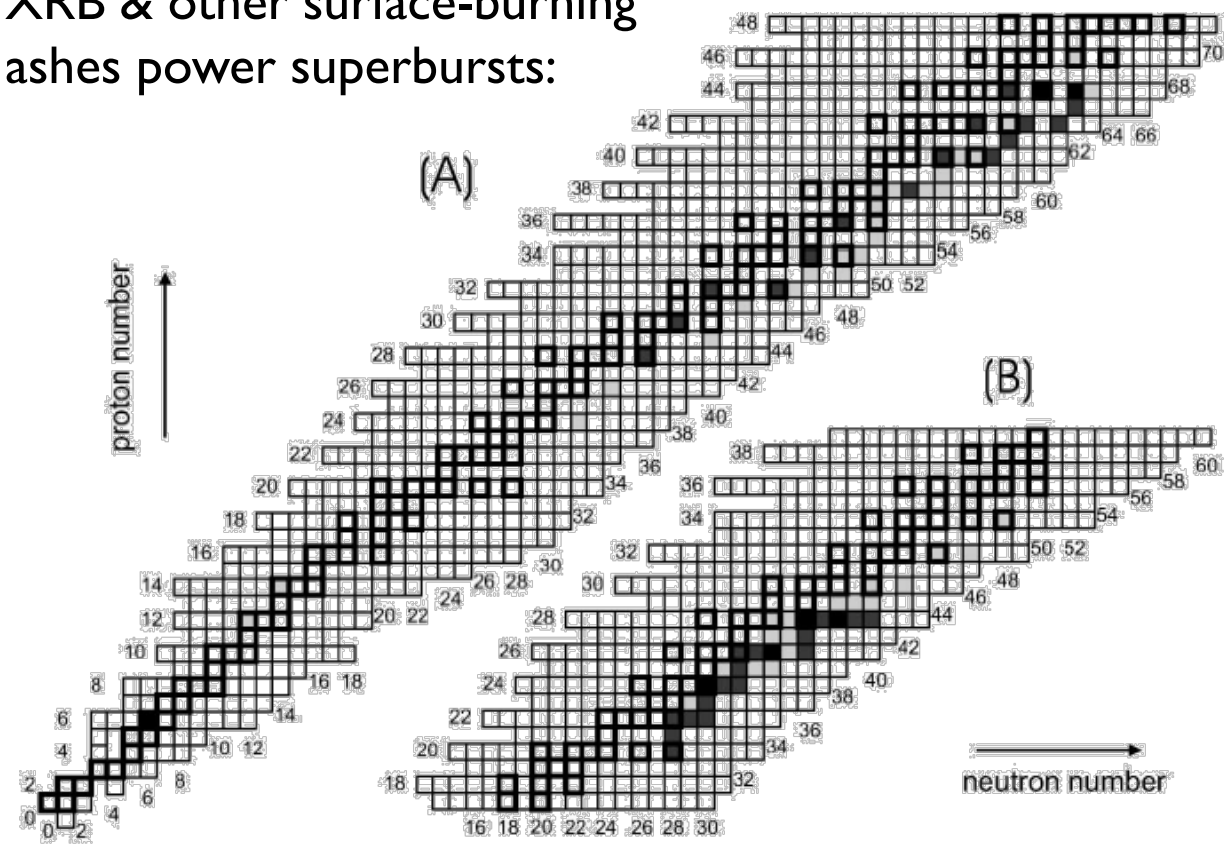
X-ray superbursts:
Carbon burning and photodisintegration in the ocean

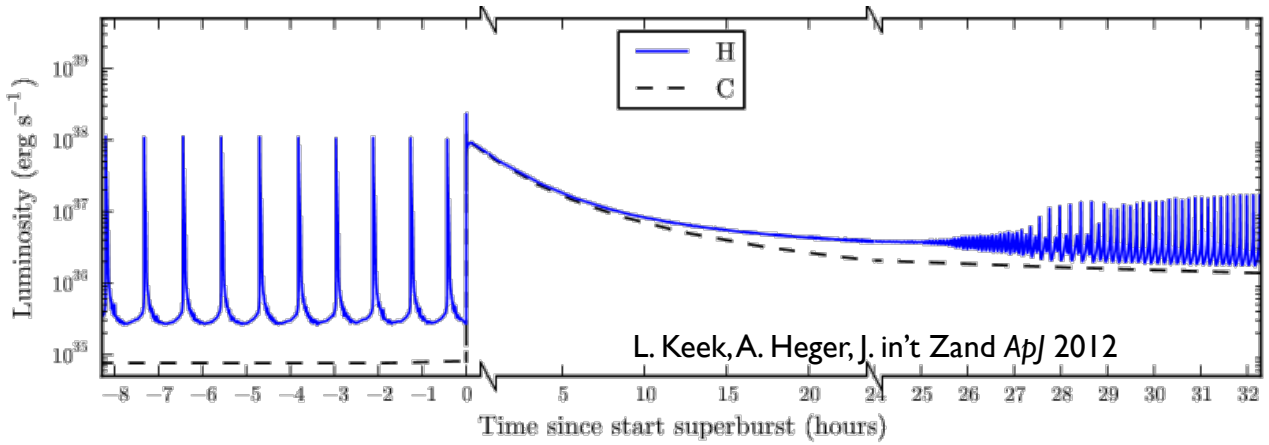




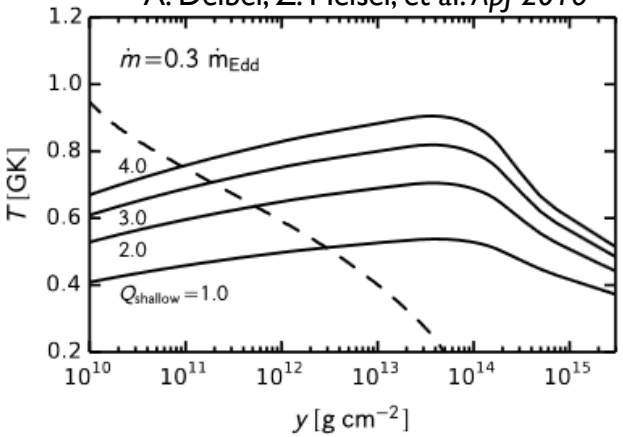
X-ray superbursts:
Carbon burning and photodisintegration in the ocean

XRB & other surface-burning ashes power superbursts:





A. Deibel, Z. Meisel, et al. *ApJ 2016*



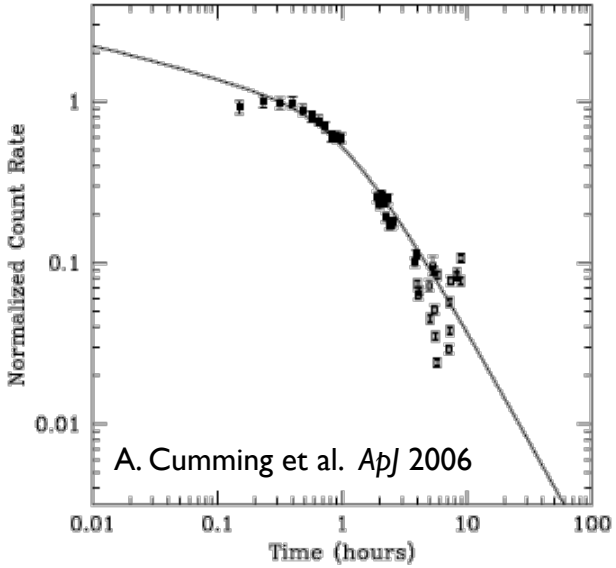
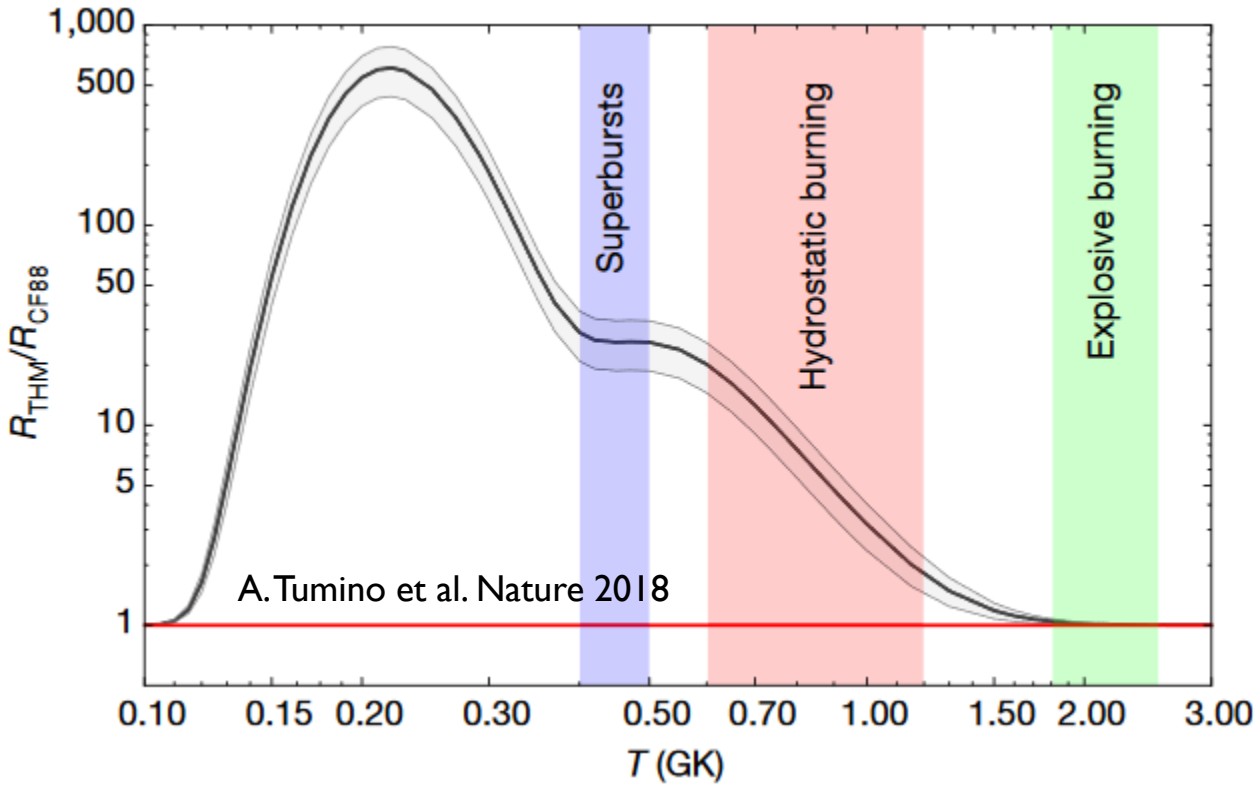


FIG. 9.—Fitted light curve for Ser X-1.

Model C-ignition depth is ~10X deeper than the fit C-ignition depth.

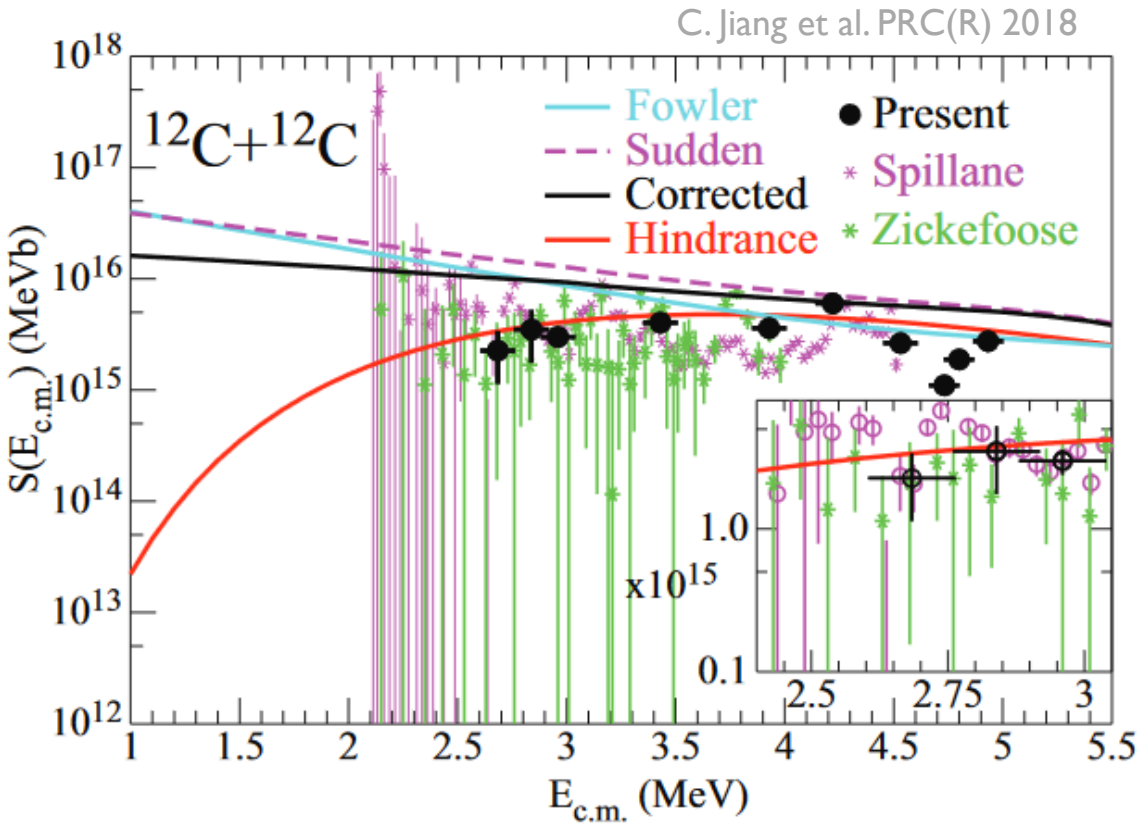
$^{12}C+^{12}C$ fusion: enhanced or suppressed?

From R-matrix fit to different reaction accessing the same compound nucleus (trojan horse method)



*They fit their data using unphysical J^{π}

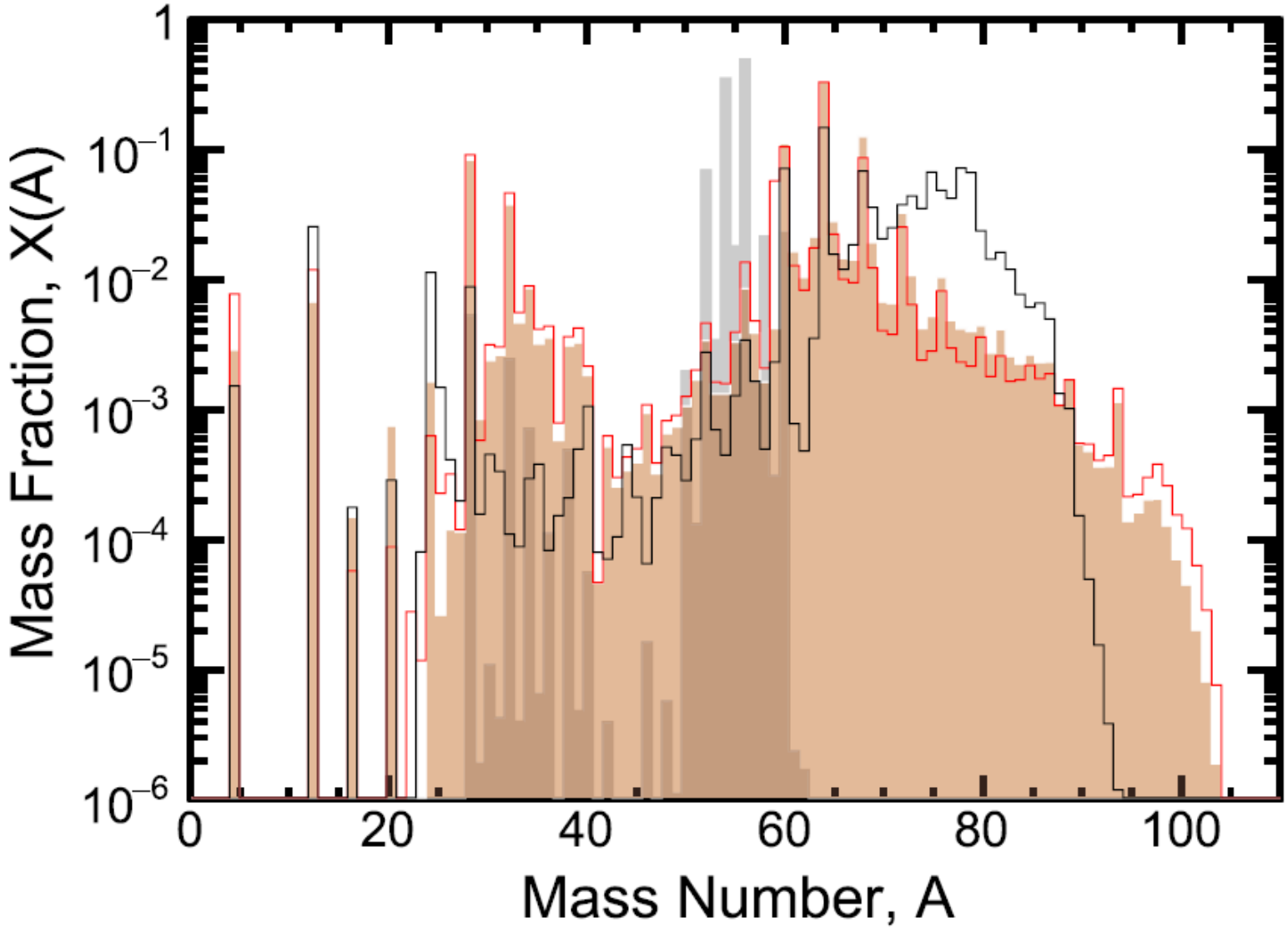
From direct measurements



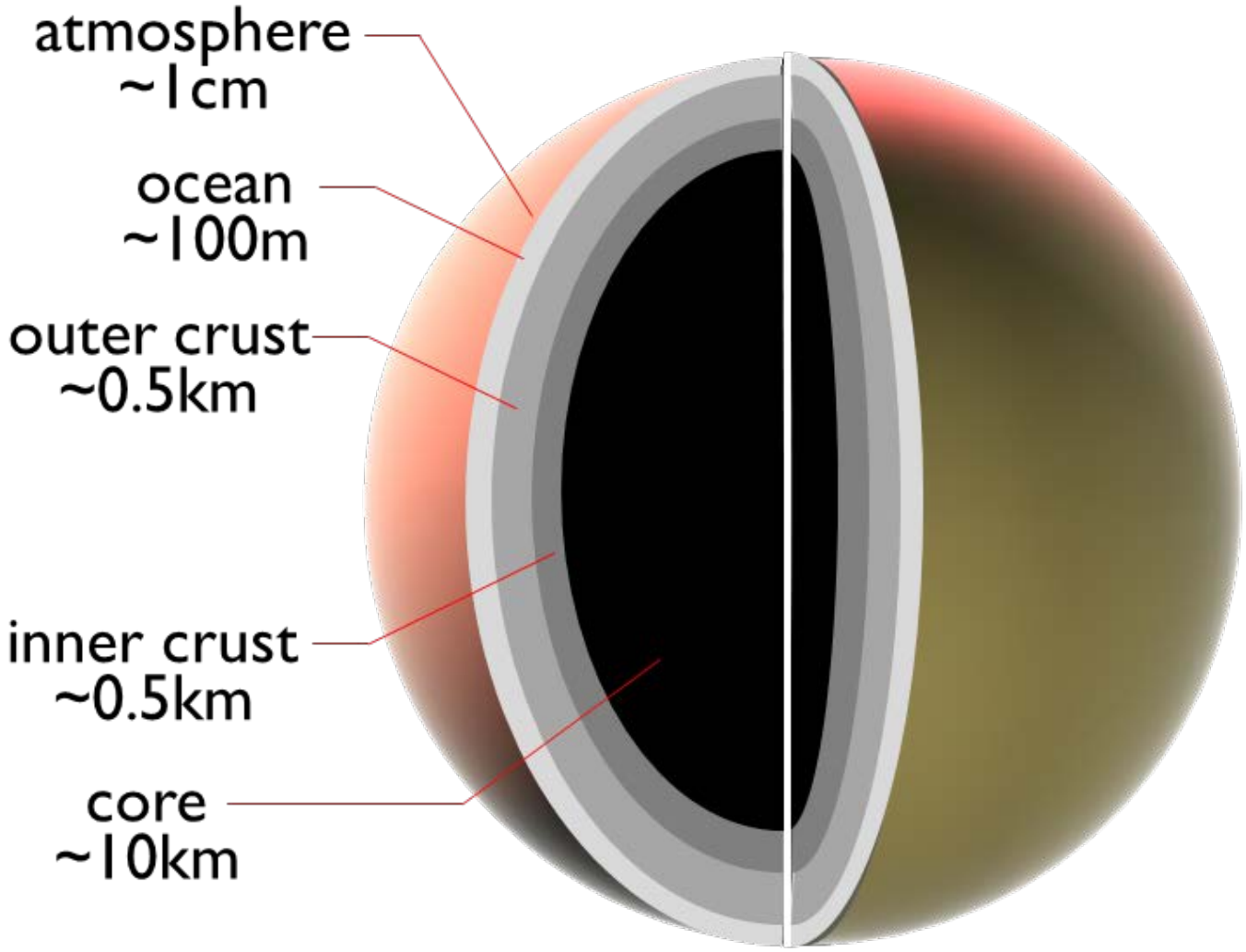
*Their theory comparisons are out-of-the-box, except "hindrance" model is fit

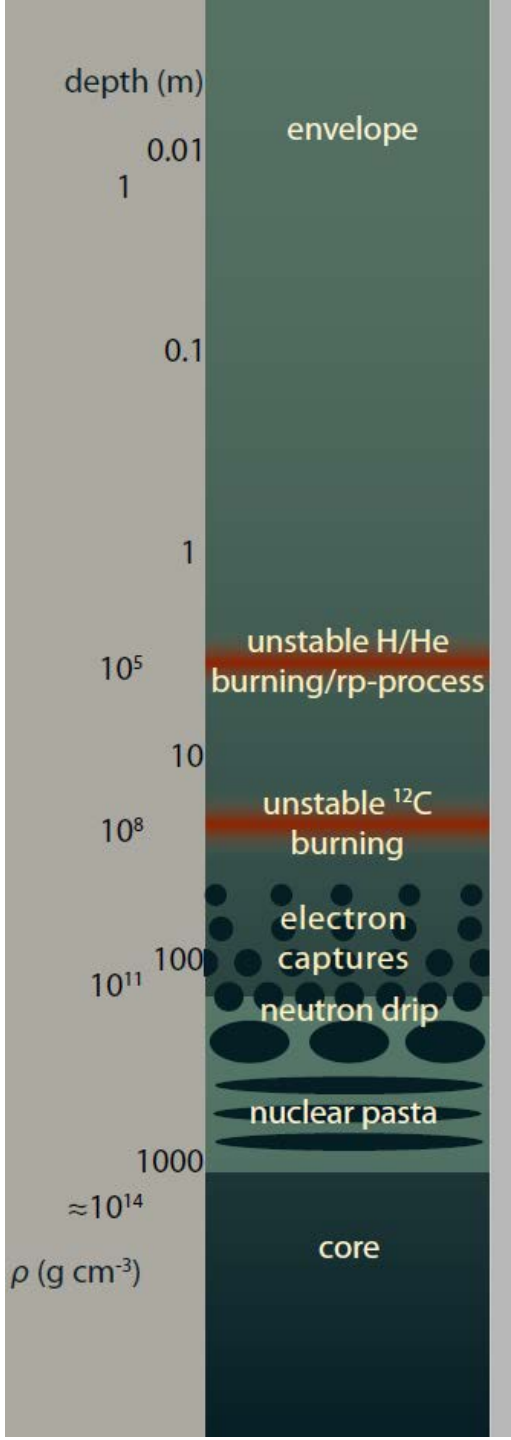
*R.Cooper et al. ApJ 2009 showed factor of ~25 could resolve superburst ignition problem

Various surface burning processes lead to very different ash distributions

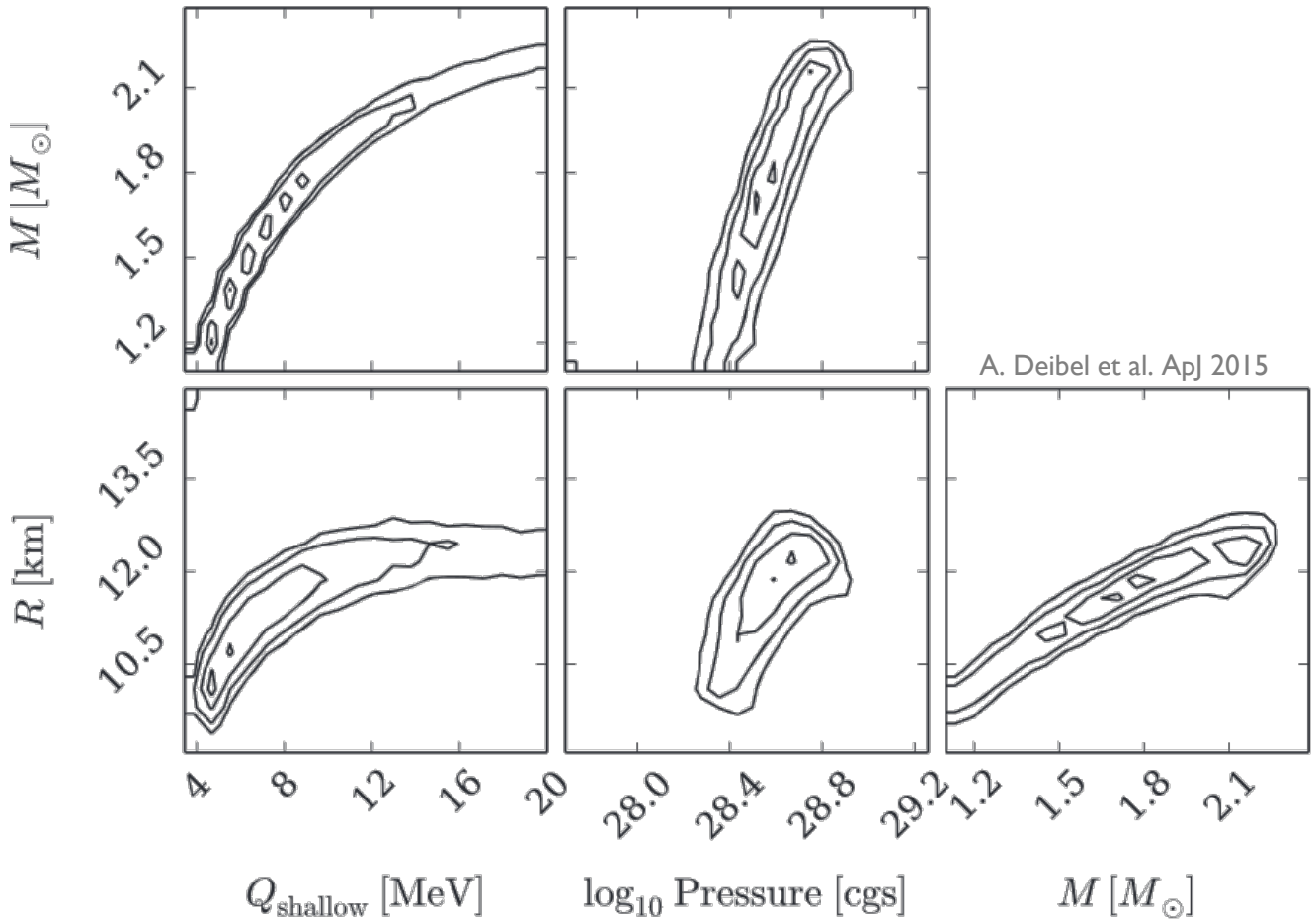


Going lower: into the crust

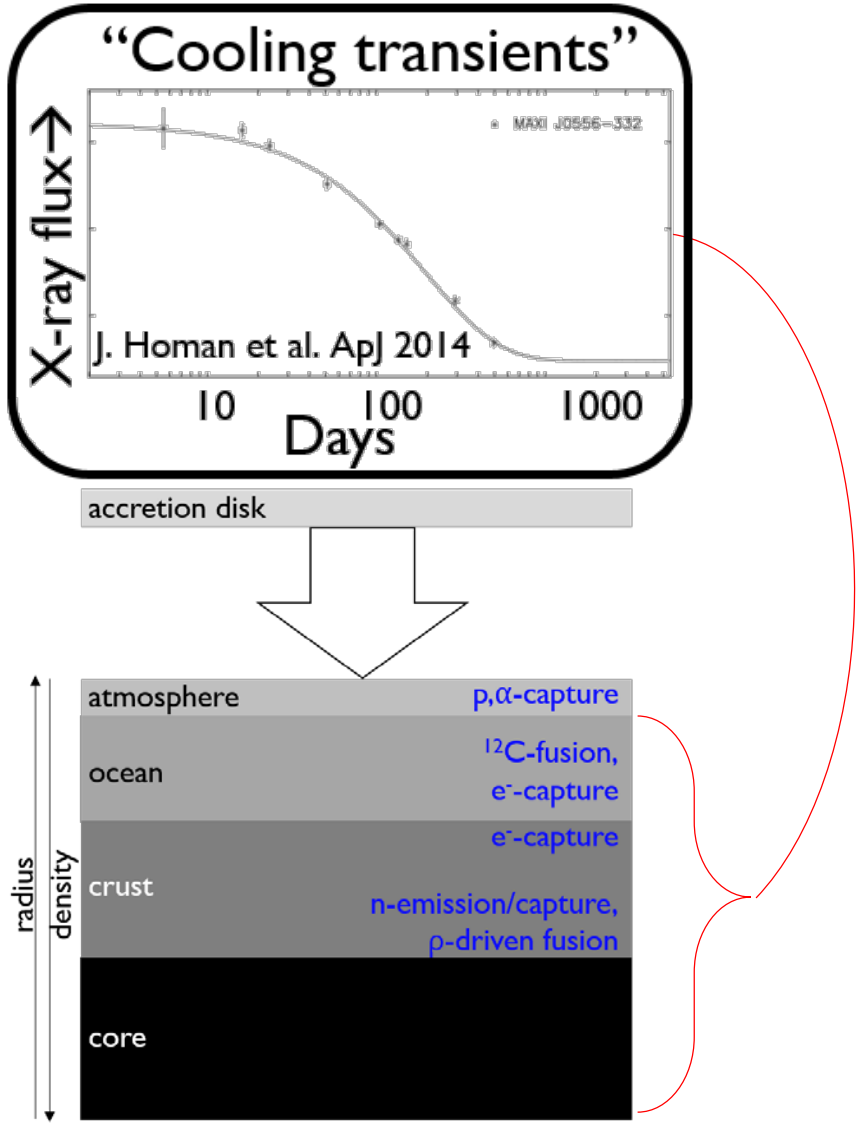




Cooling transients are sensitive to NS composition & thermal structure



A. Deibel et al. ApJ 2015



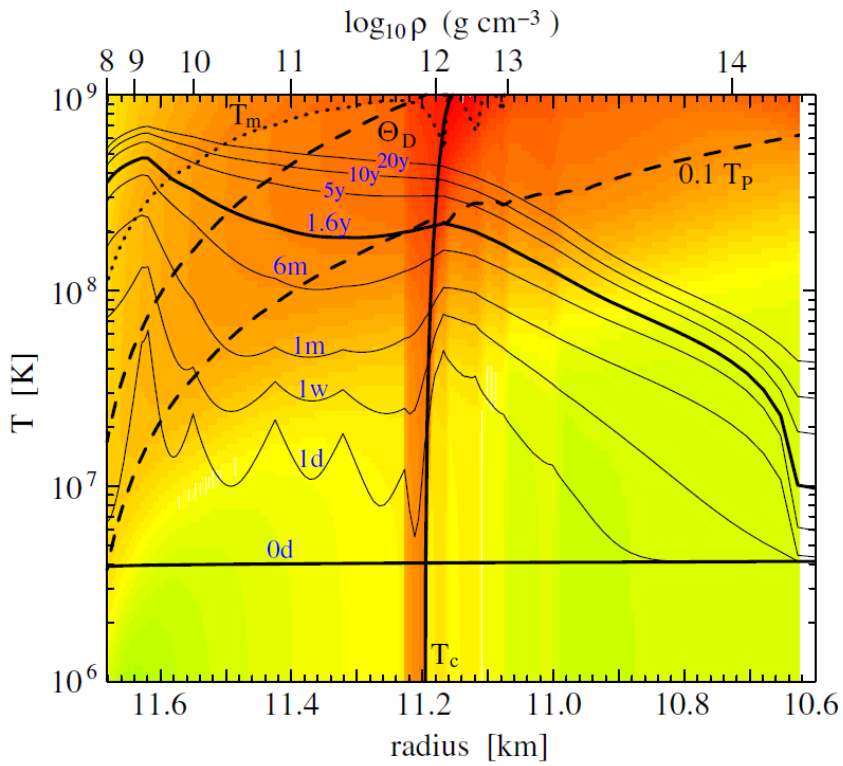
Cooling transients are sensitive to NS composition & thermal structure

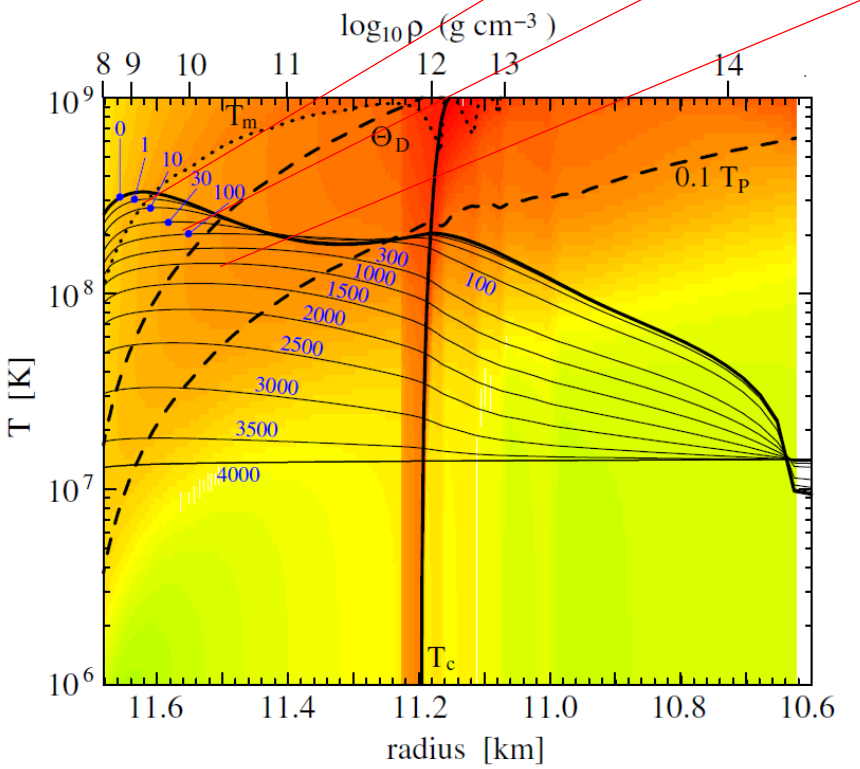
- Crust thermally relaxes:
  solving thermal diffusion results in a thermal timescale

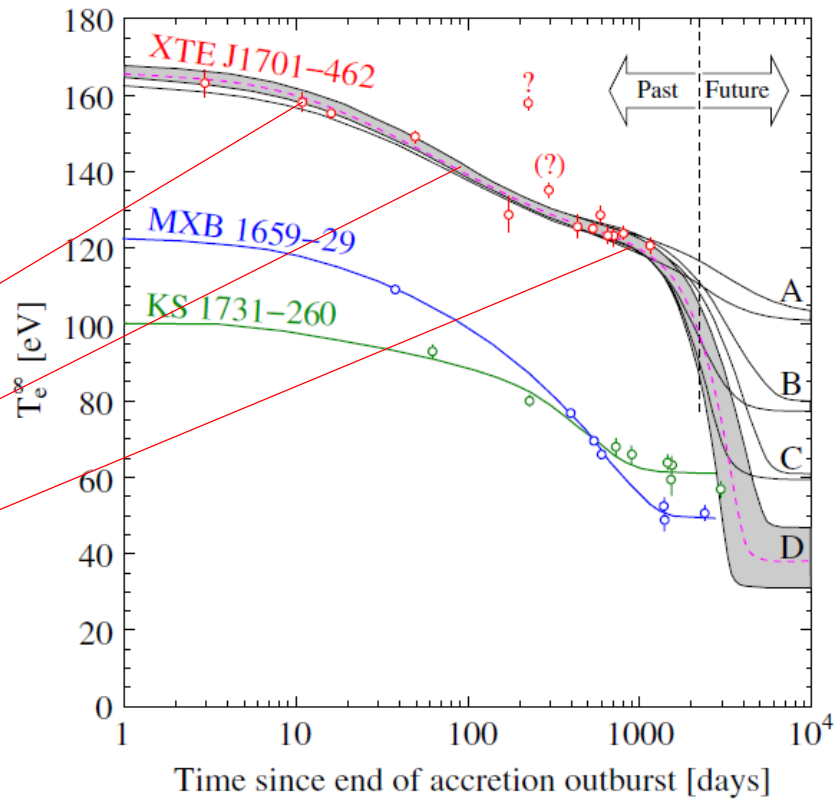
$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T)$$

$$\tau = ((1+z)/4)\left(\int_0^y \sqrt{c_p/(\rho K)}\,dy'\right)^2$$

$$K \propto Q_{\rm imp}$$







See outer-crust at ~100 days
See inner crust at ~1000 days
See core at ~4000 days

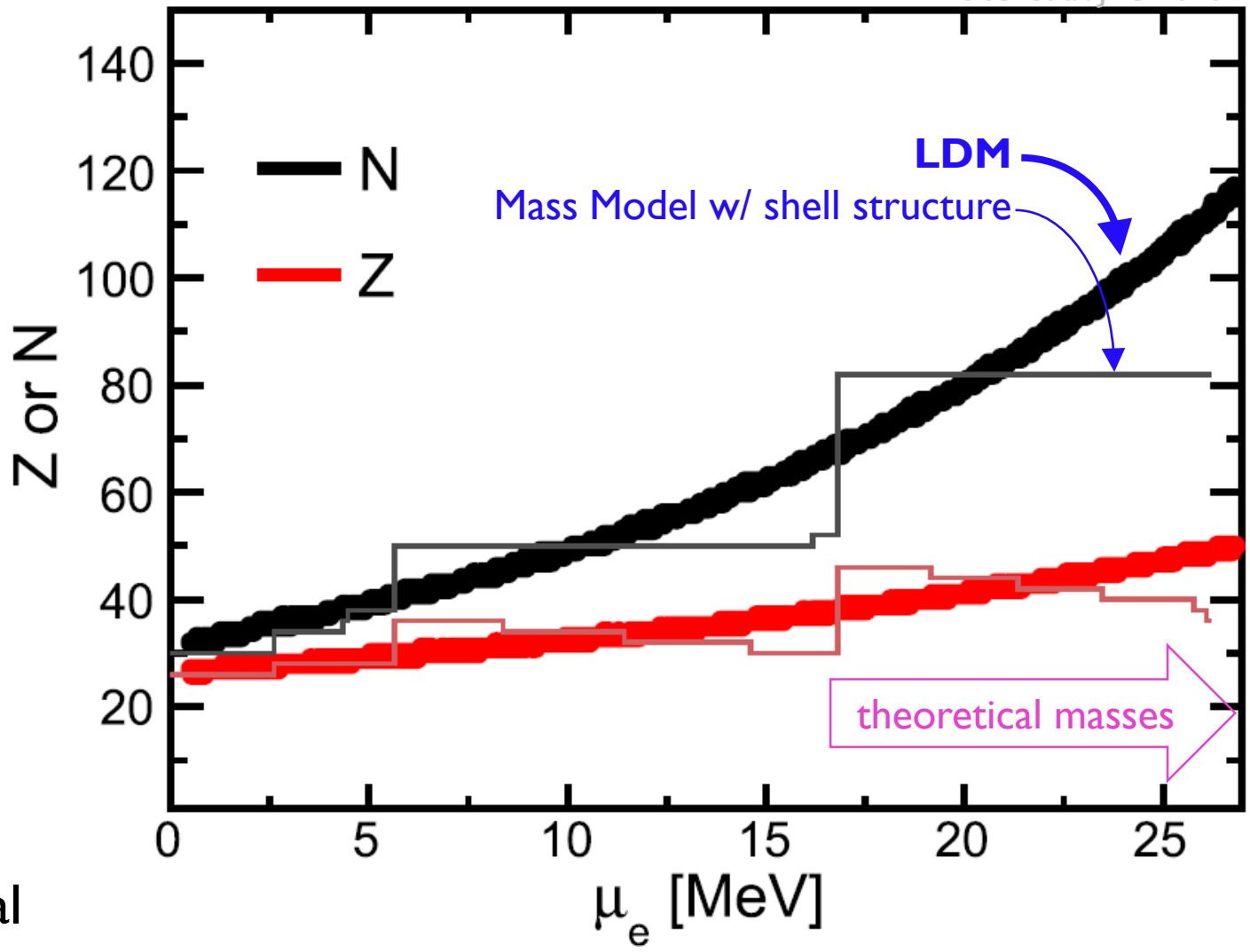
First, consider the non-accreted crust

- Assuming a long cooling time, achieve T=0 thermodynamic equilibrium
- Minimize energy: $E_{total}/A = E_{nuclear}/A + E_{e\text{-}gas}/A + E_{lattice}/A$
- For LDM & BCC lattice:

$$E_{\text{total}}(A, Z, \mu_e)/A = m_{\text{p}}c^2 Y_e + m_{\text{n}}c^2(1 - Y_e) - a_v + \frac{a_s}{A^{1/3}} + a_c A^{2/3} Y_e^2 + a_a(1 - 2Y_e)^2 + \frac{3}{4} Y_e \mu_e - C_\ell A^{2/3} Y_e^{5/3} \mu_e,$$

- For inner crust, add neutron gas, modify LDM for compressibility, & choose a local Z-density to define "clusters"

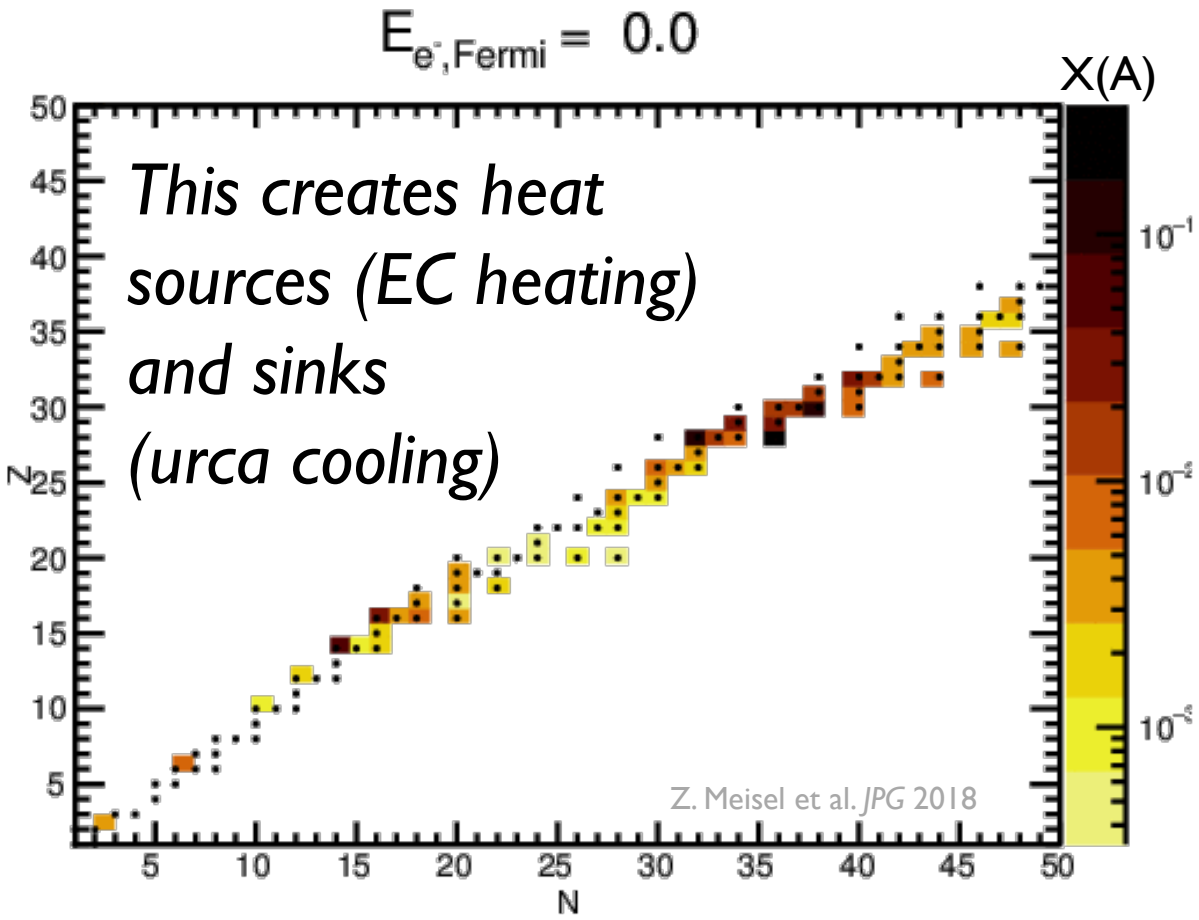
Meisel et al. JPG 2018



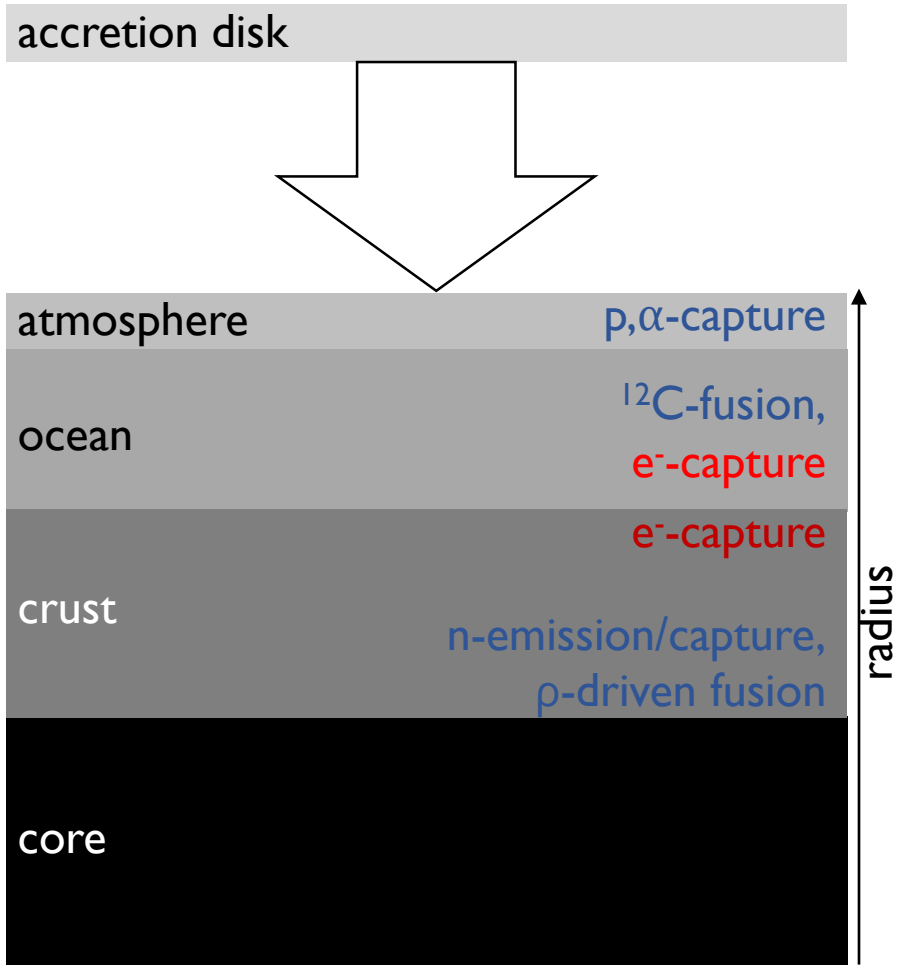
What if N=82 disappears?

The journey of a nucleus in a neutron star

2. Burial and electron-capture



This creates heat sources (EC heating) and sinks (urca cooling)



Surface ashes set the composition for most of the outer crust

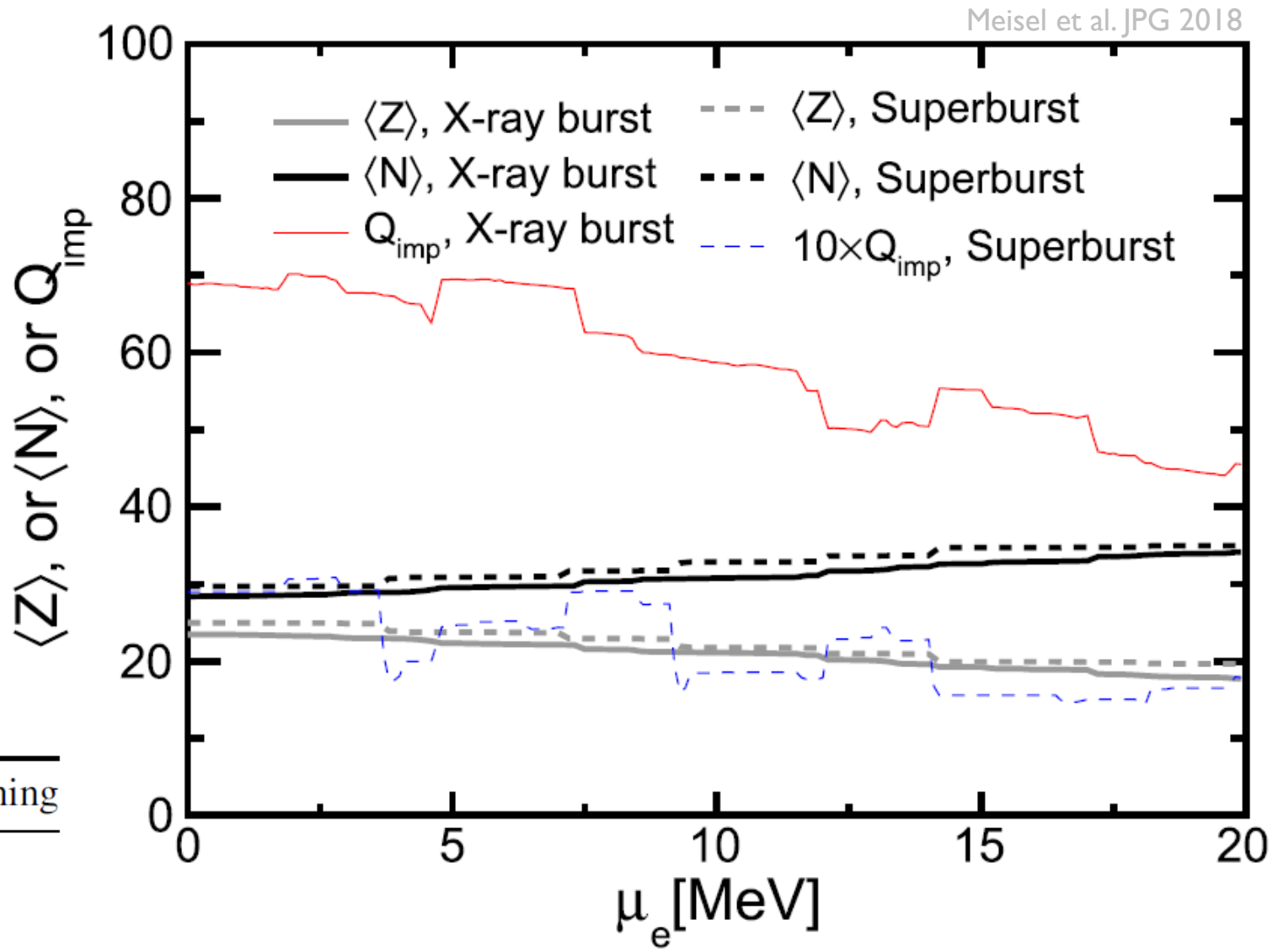
- Interesting quantity is Q_{imp}, the variance of the charge distribution

$$Q_{\rm imp} \equiv \frac{1}{n_{\rm ion}} \sum_j n_j (Z_j - \langle Z \rangle)^2$$

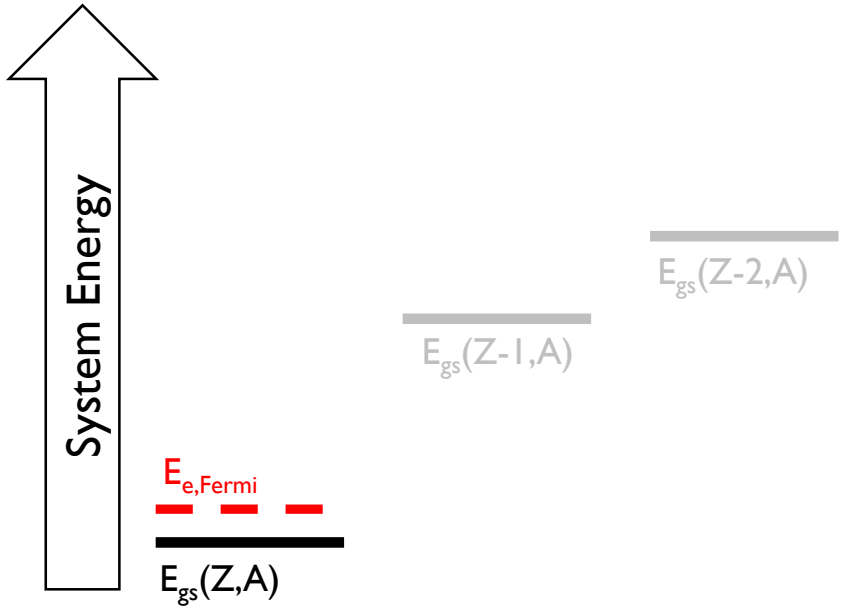
- Sets ion-impurity scattering (dominates thermal conductivity for lower T and/or deeper layers)

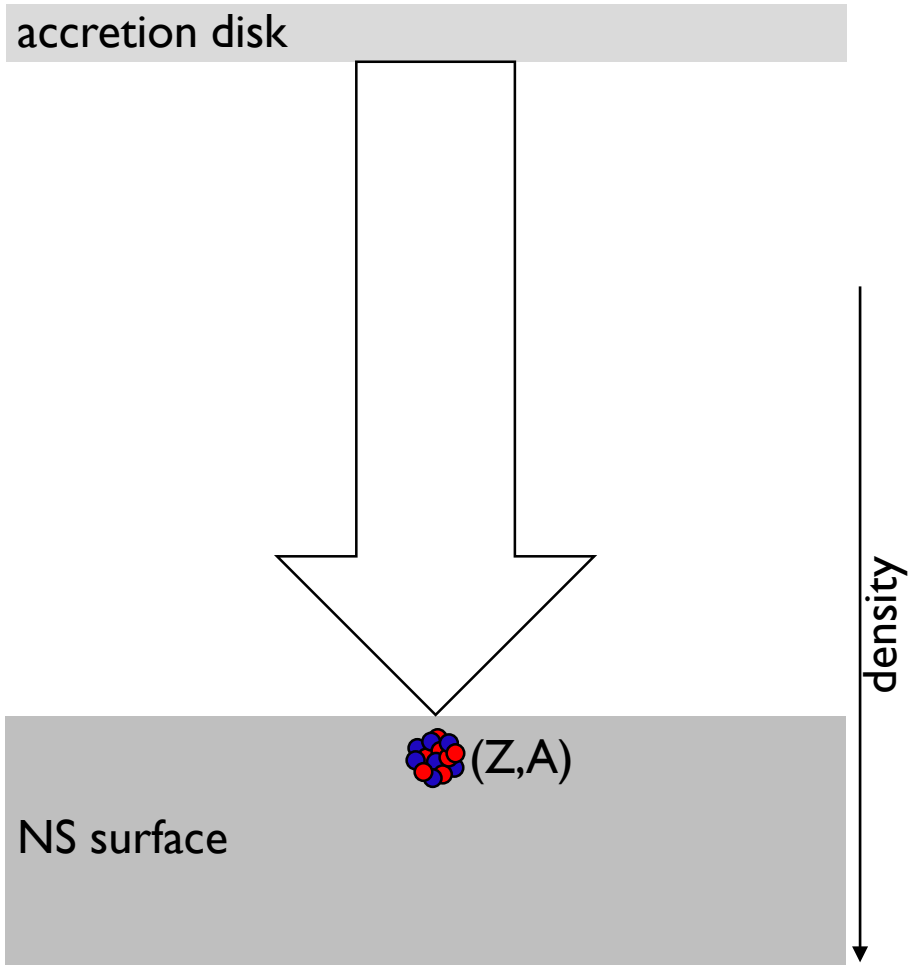
- At the surface:

Quantity	x-ray burst	Superburst	Stable burning
$\langle Z \rangle$	24	25	26
$\langle A \rangle$	52	55	60
$Q_{\rm imp}$	69	3	101

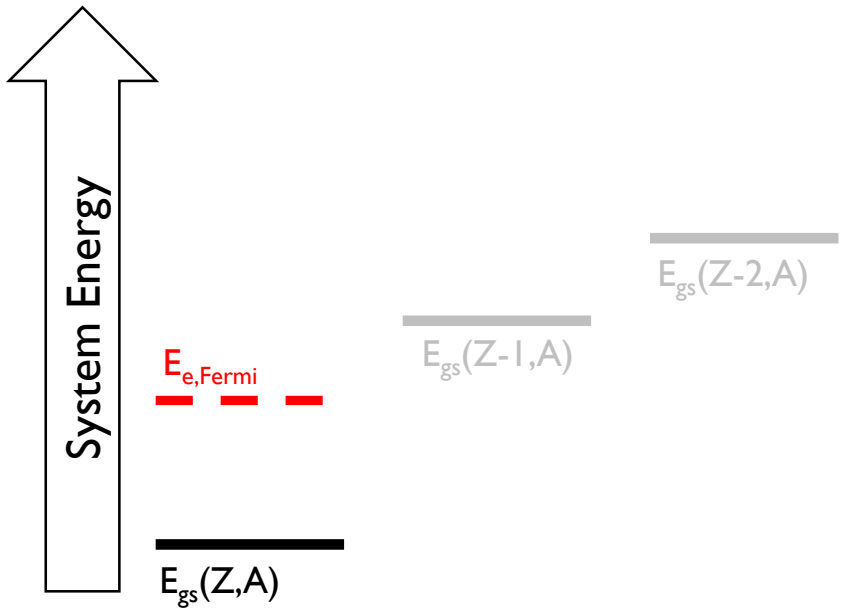


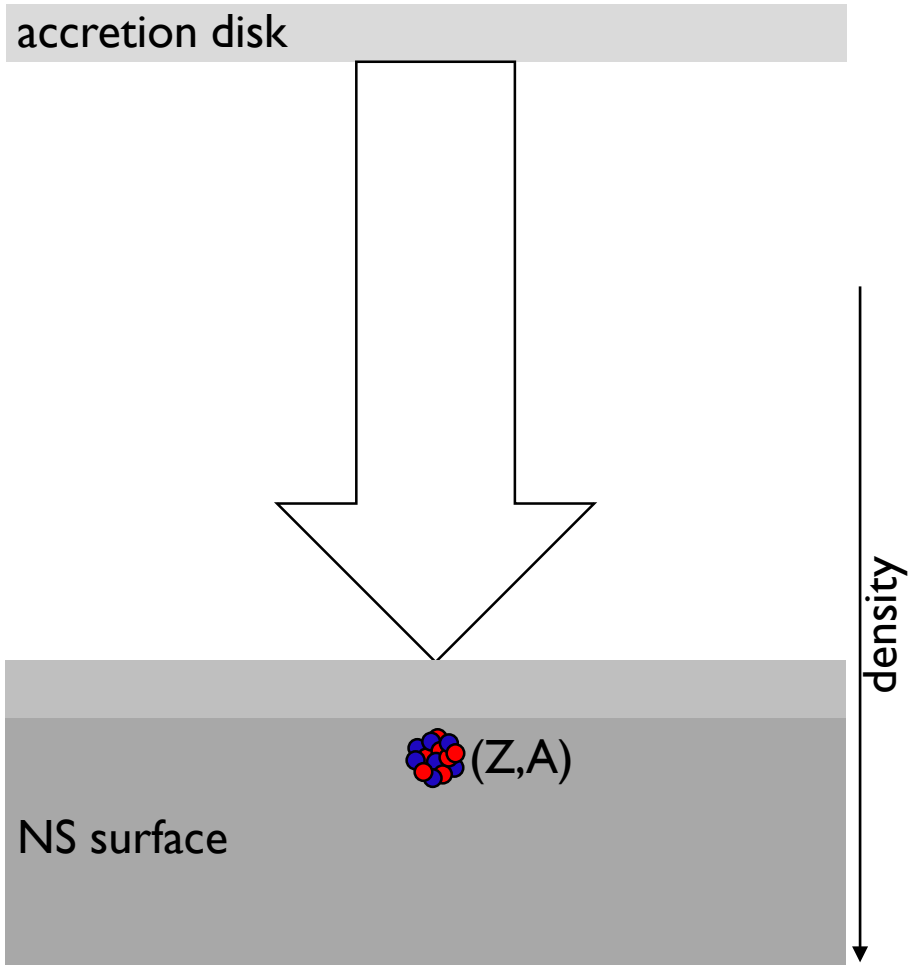
Buried nuclei undergo electron capture in the degenerate electron gas



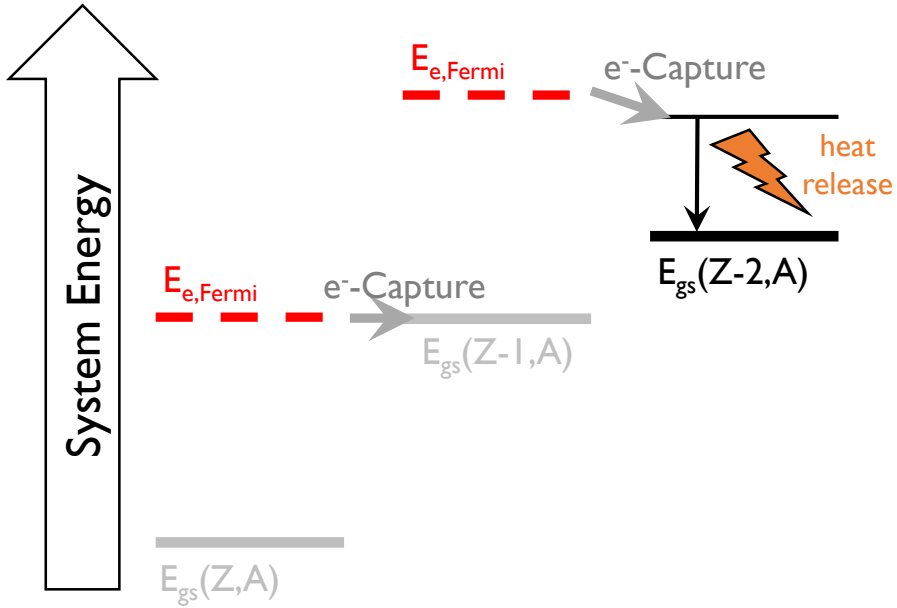


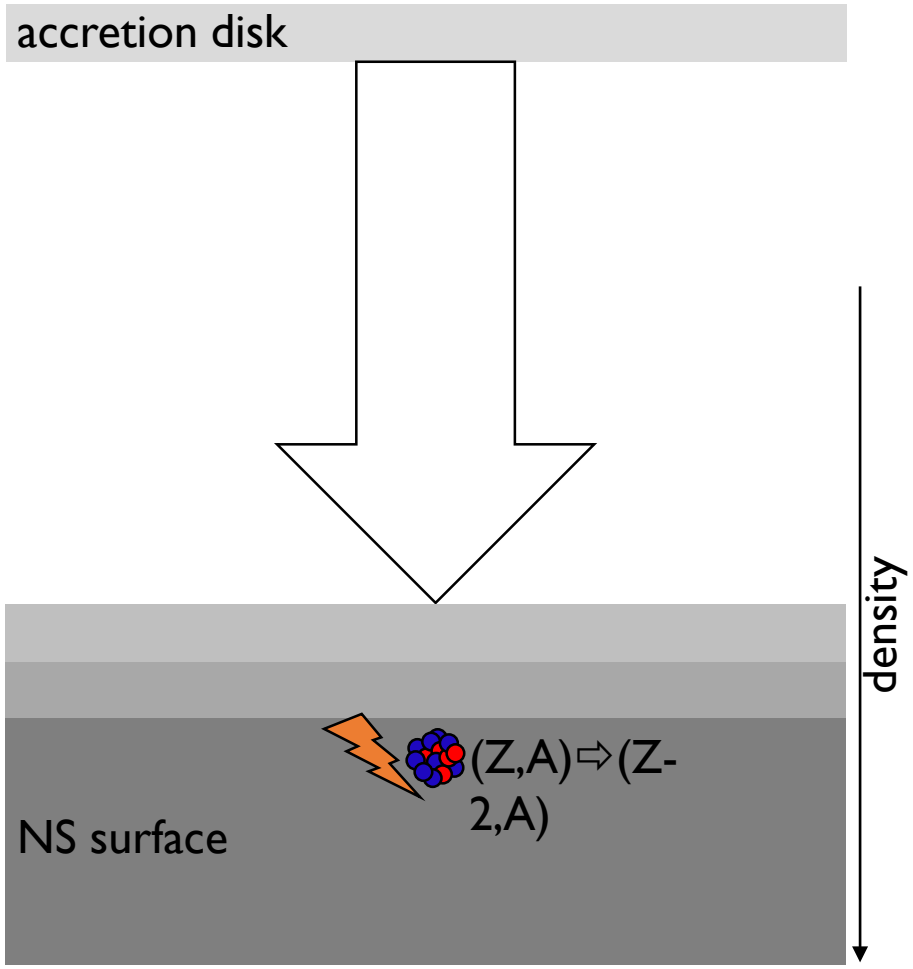
Buried nuclei undergo electron capture in the degenerate electron gas



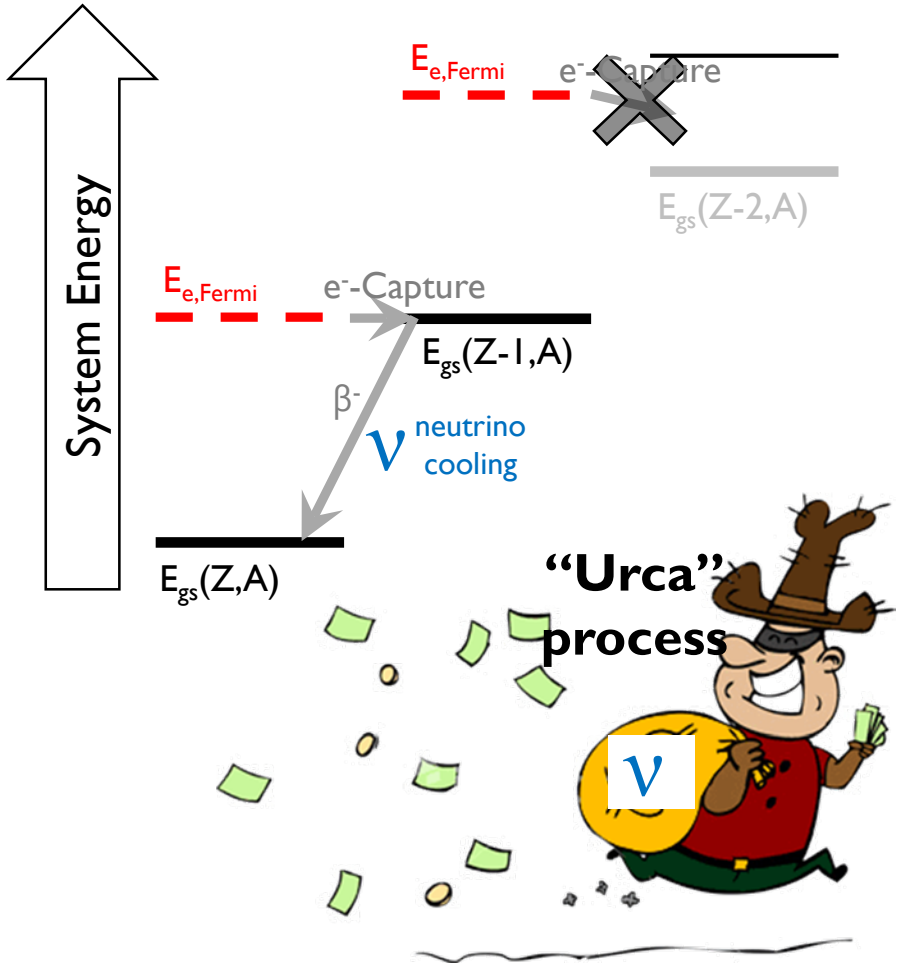


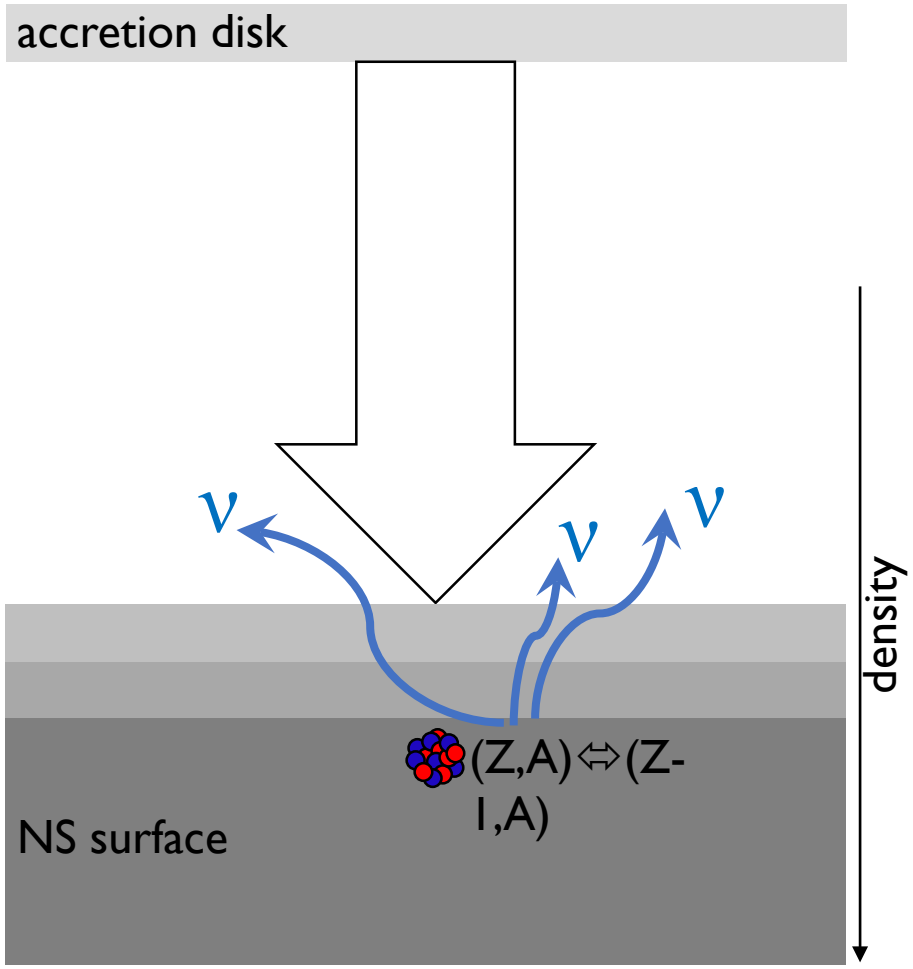
Buried nuclei undergo electron-capture, *causing heat release*



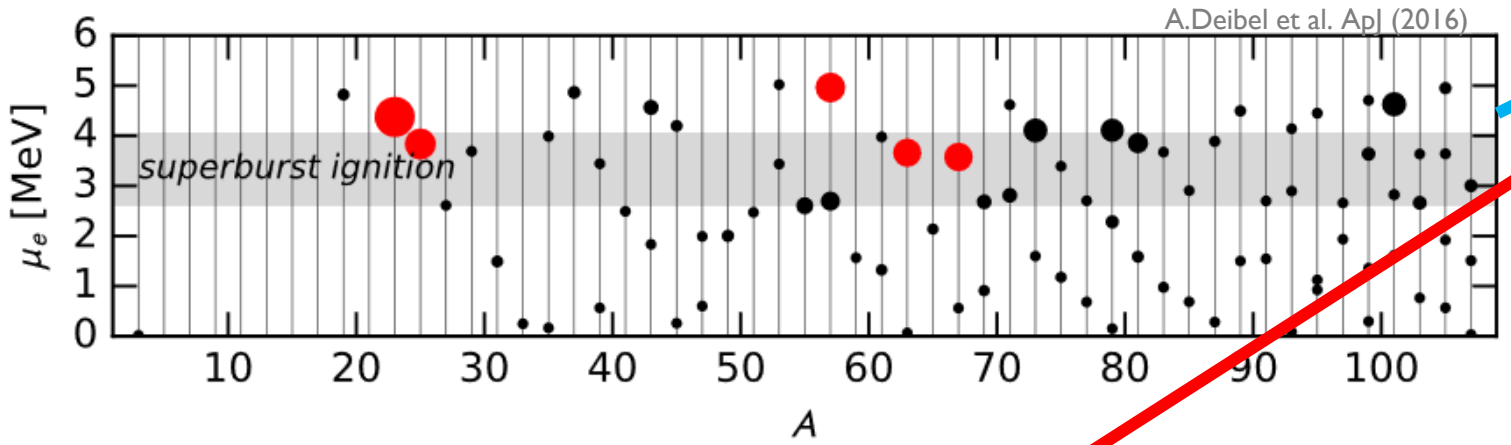


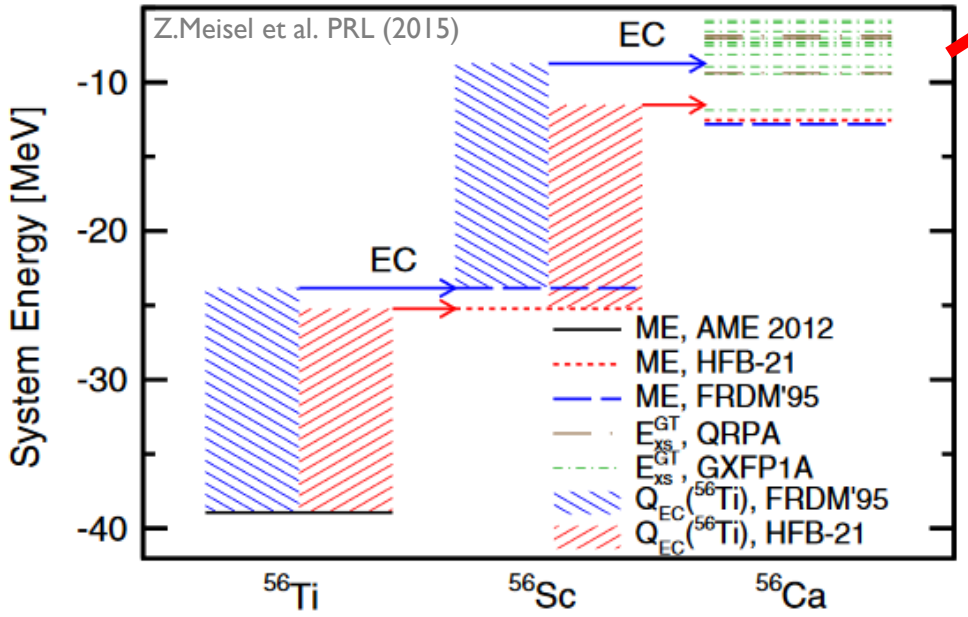
Buried nuclei undergo electron-capture, OR *cooling*

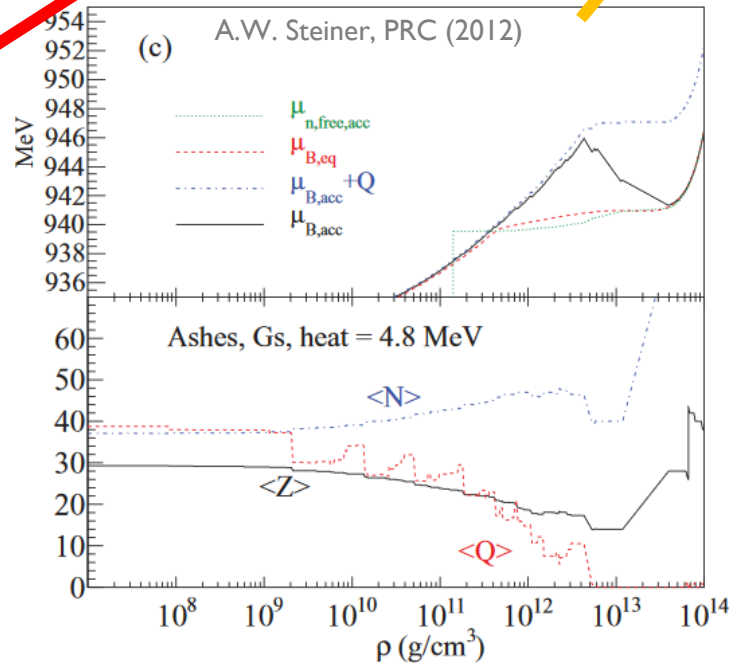


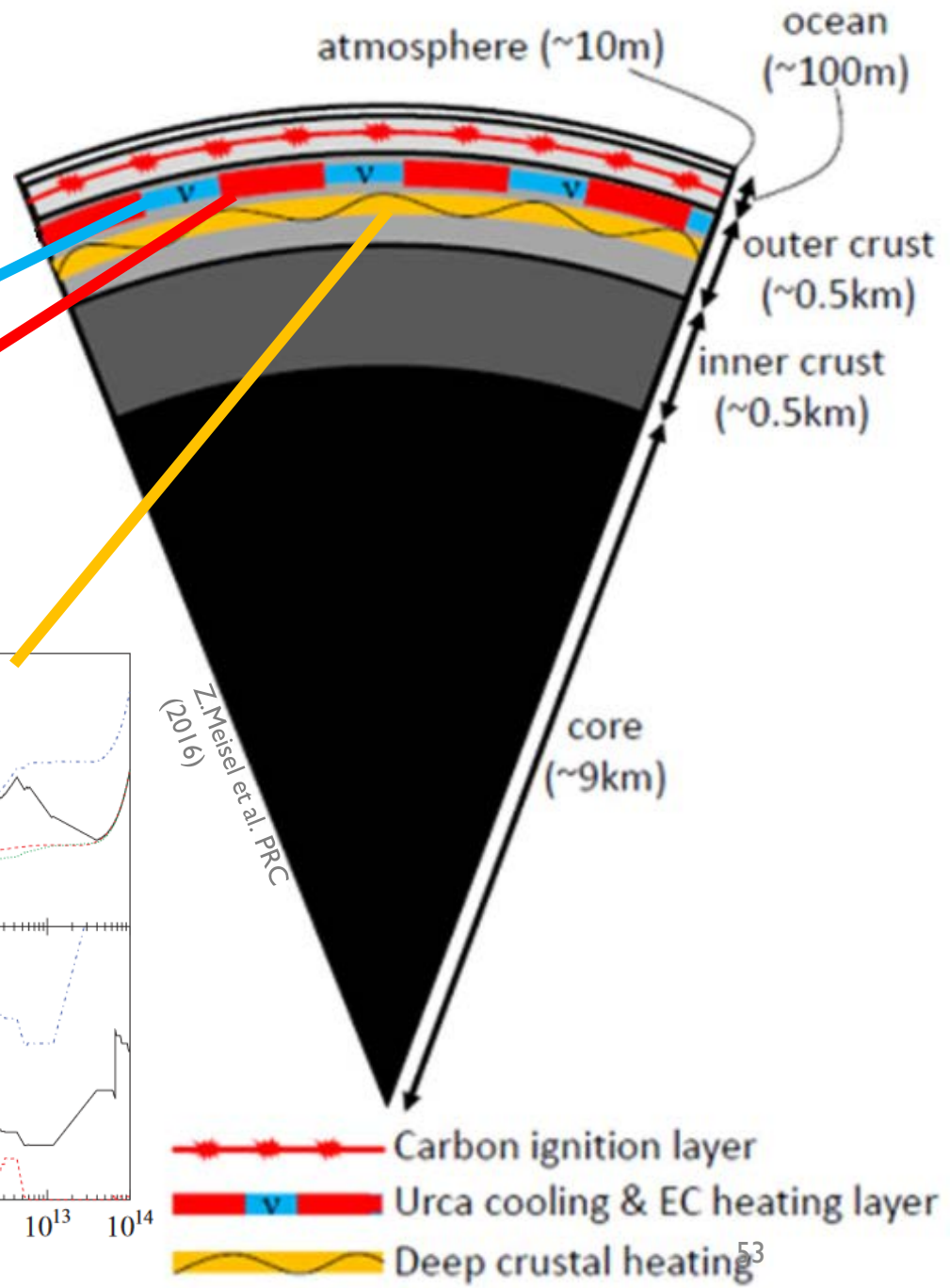


The neutron star crust is peppered with local heat sources & sinks



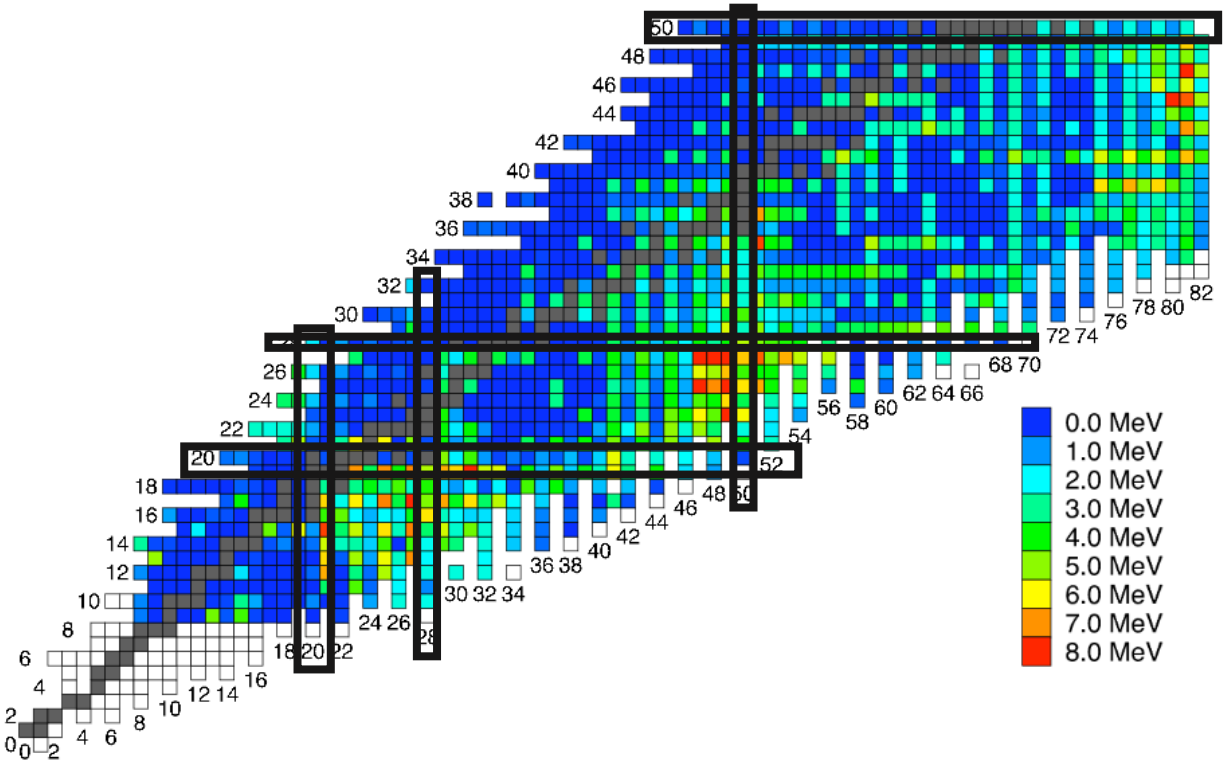






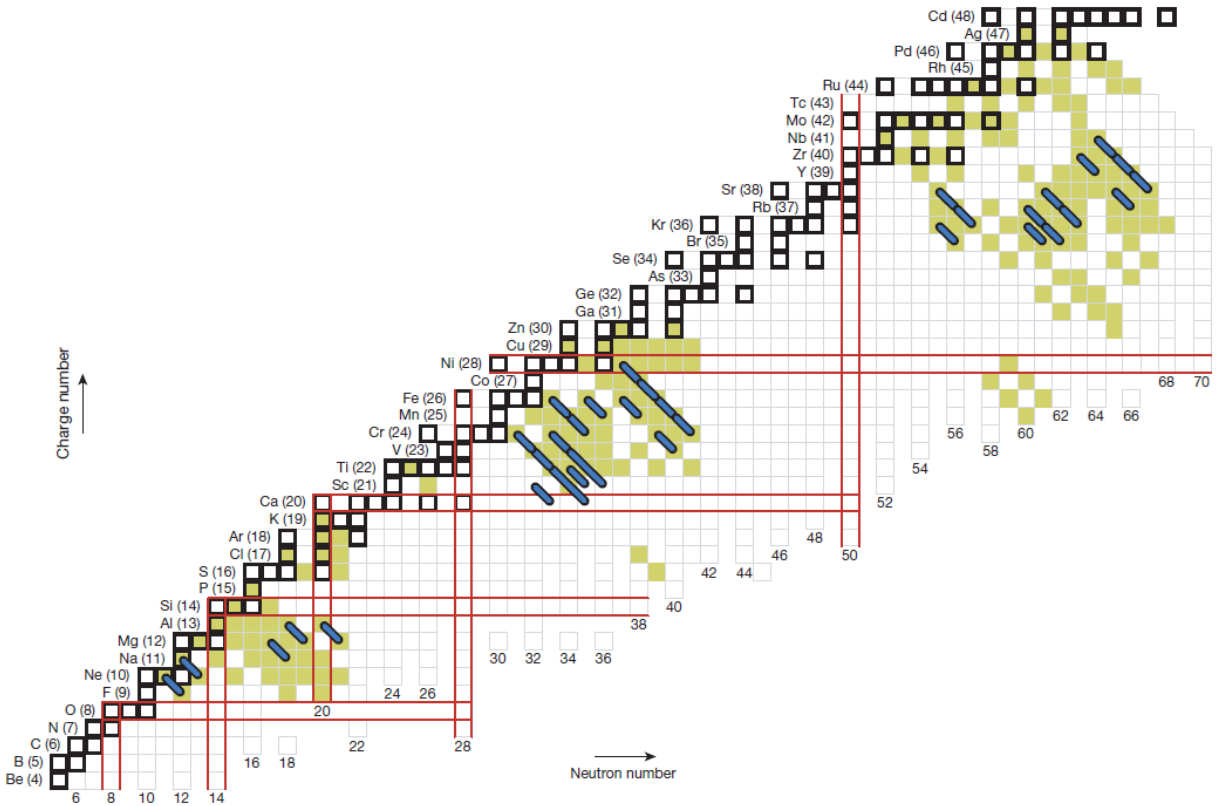
Mass surface sets global systematics of heating & cooling

Maximum possible E release per EC



S.S. Gupta et al. ApJ 2007

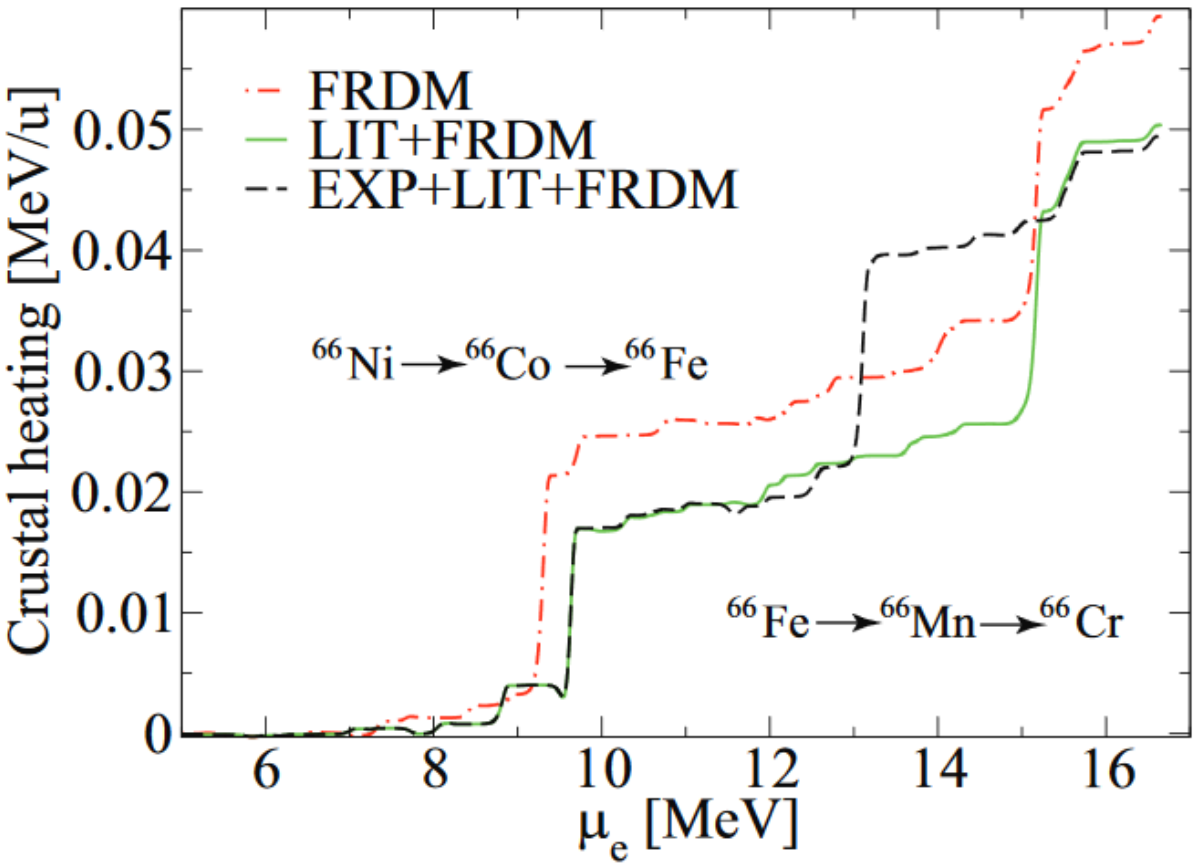
Urca cooling & deformation

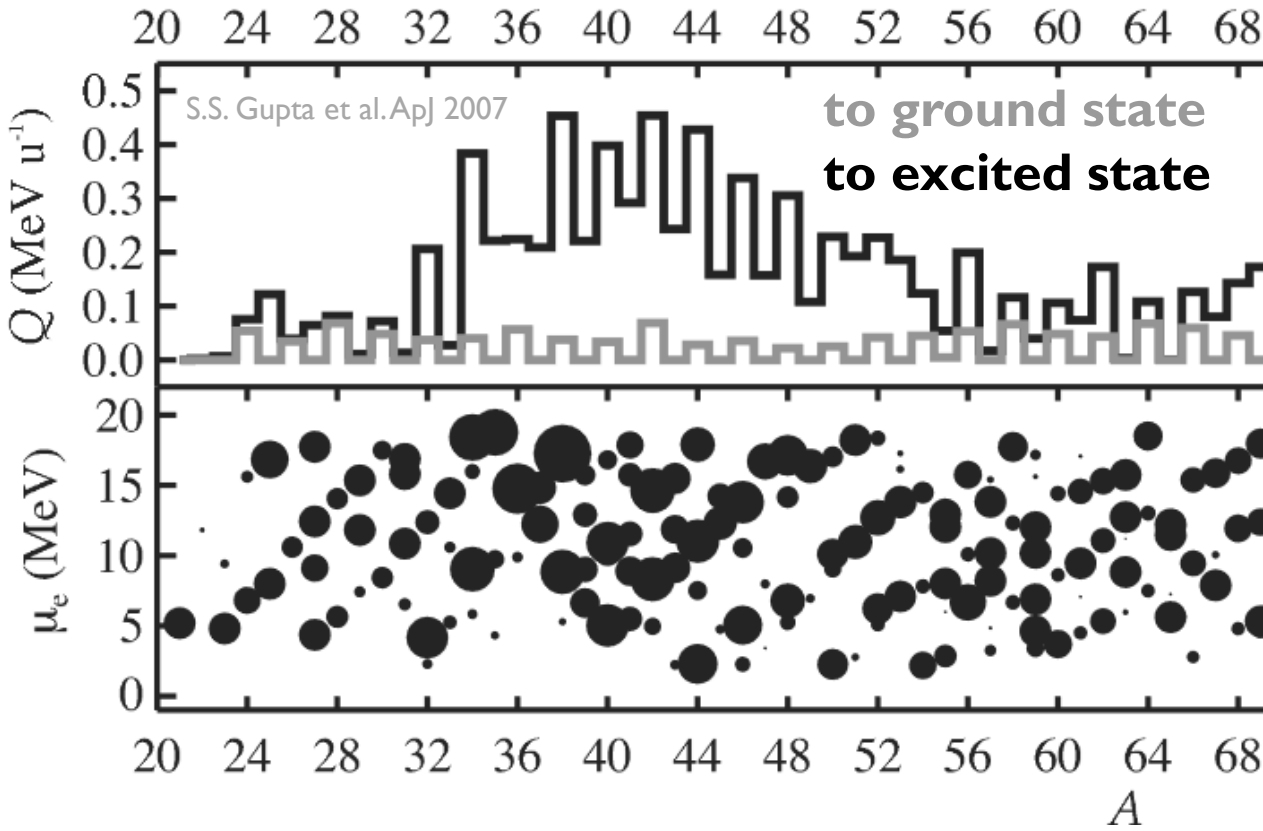


H. Schatz et al. Nature 2014

Heating depth & strength due to nuclear masses & J^{π}_{xs}

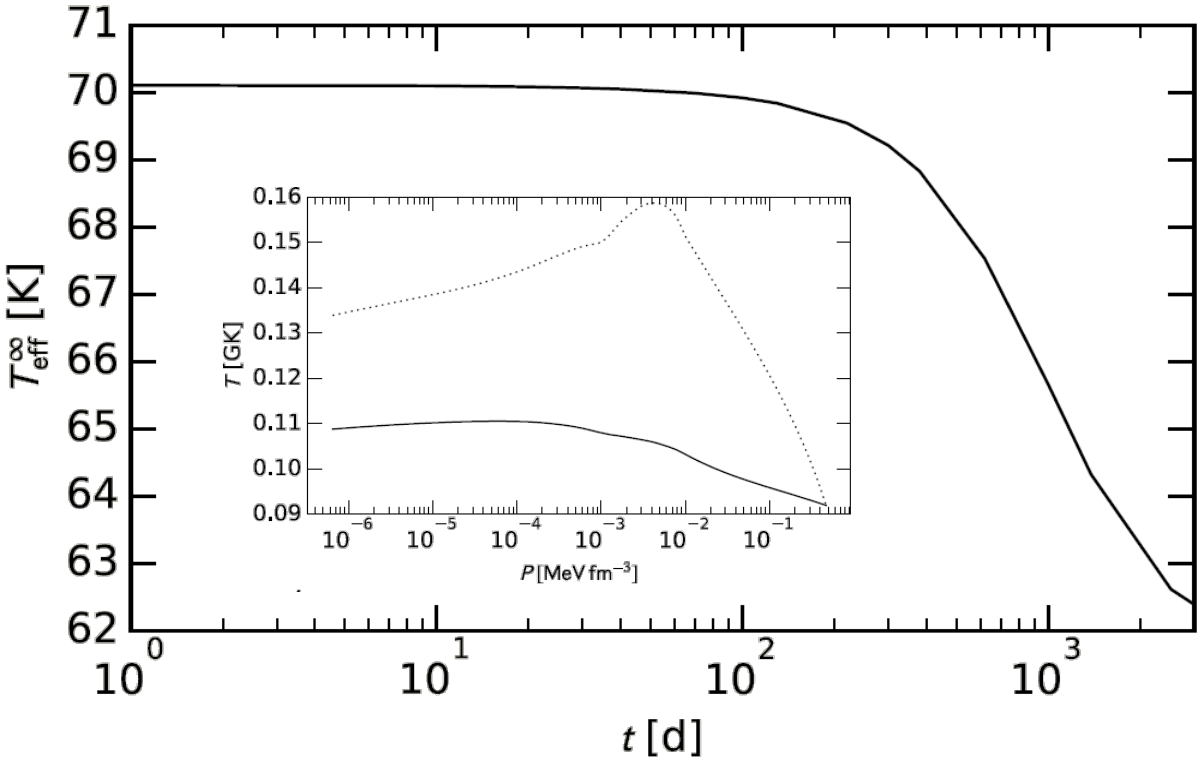
A. Estrade et al. PRL 2011



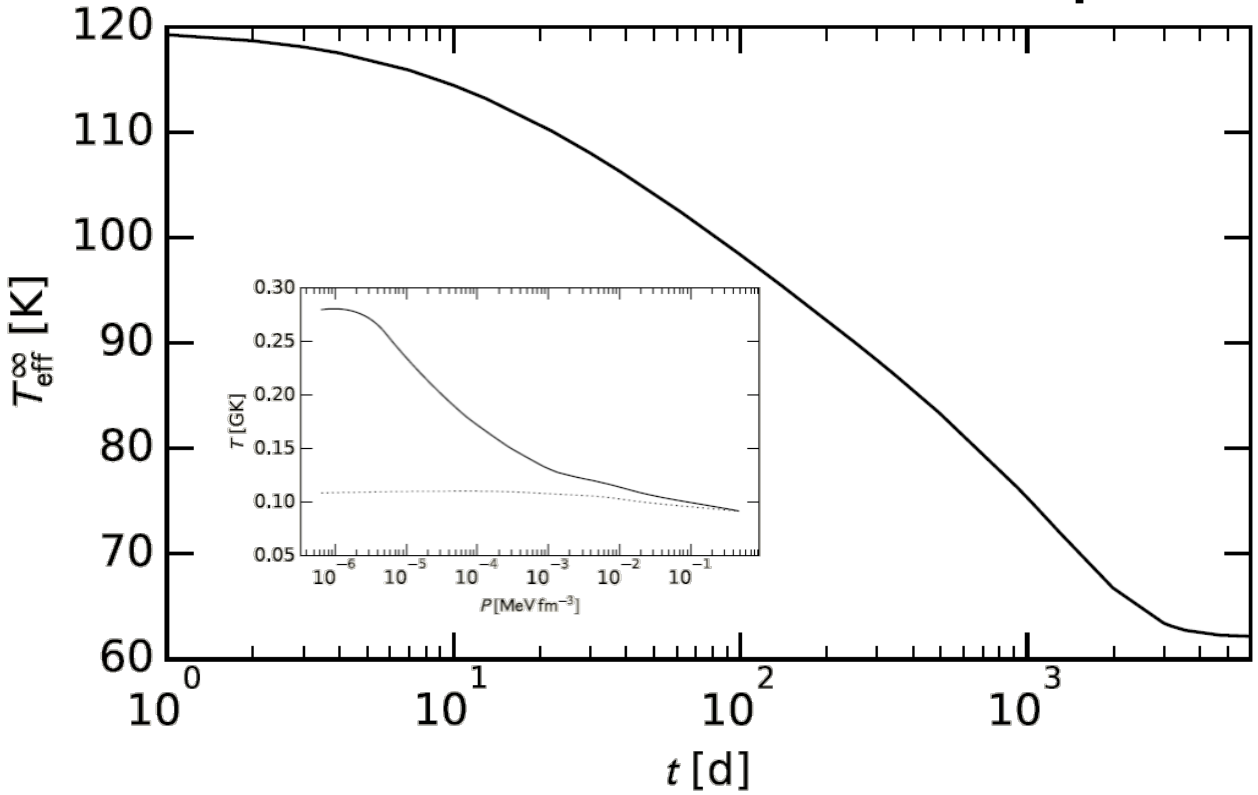


Including EC heating transforms the transient light curve

Only deep crustal heating



…+ heat at shallower depths

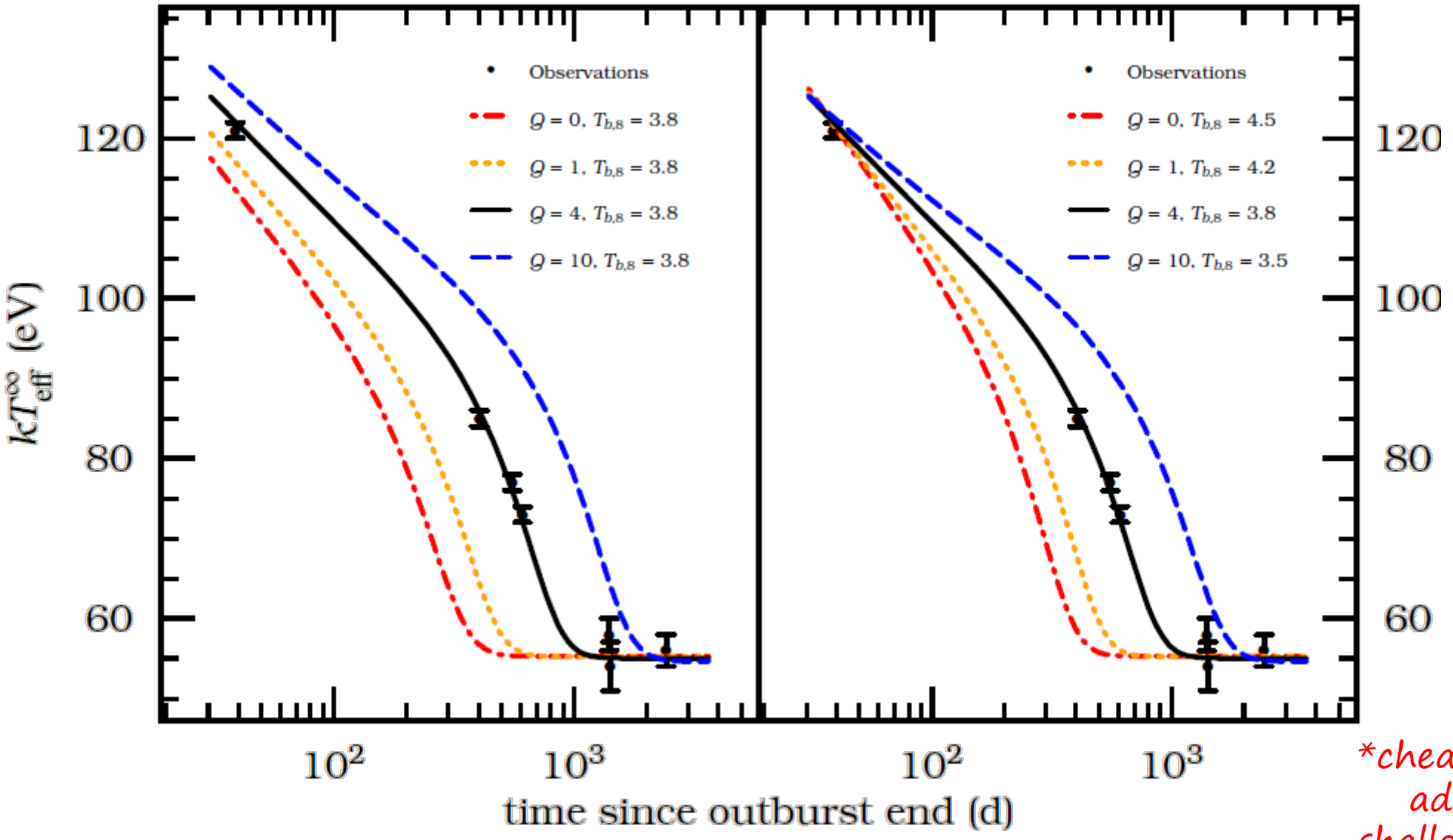


E. F. Brown

Can then reproduce transient light curves

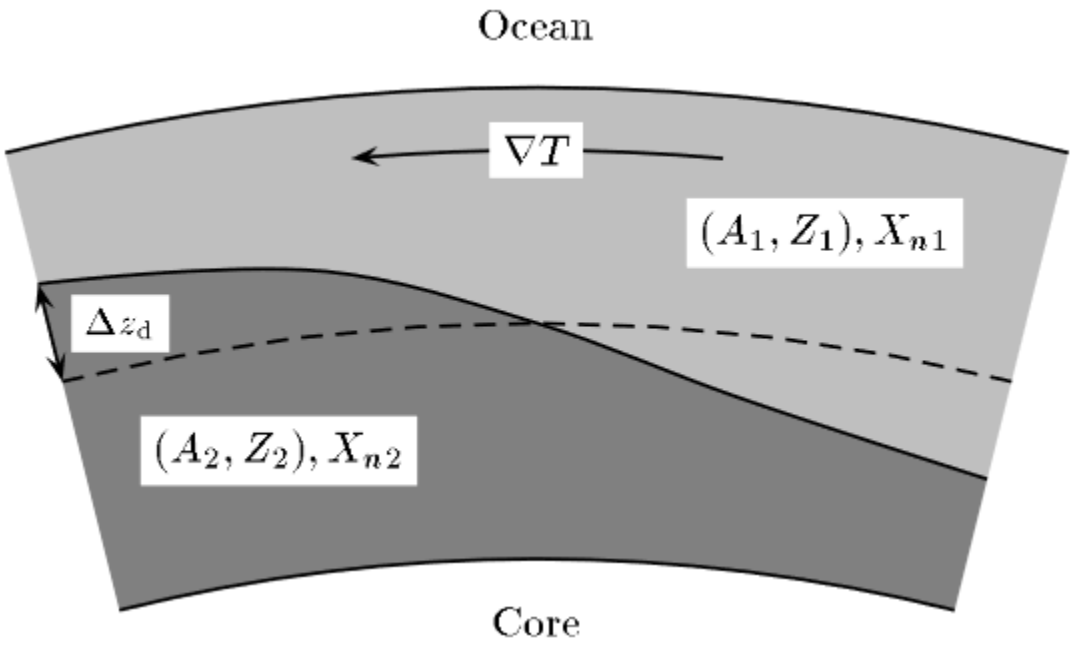
…& find the crust seems to be pretty pure

Brown & Cumming ApJ 2009



*cheating a bit: add extra shallow heating

What if accretion isn't uniform? Get nonuniform heating



Ushomirsky et al. MNRAS 2000

$$\dot{E}_{\rm GW} = 2\pi\nu N_{\rm GW} = -\frac{32}{5}\frac{G(2\pi\nu)^6(I\varepsilon)^2}{c^5}$$

$$\varepsilon \approx 1.7\times10^{-9}\frac{\Upsilon}{Z}\frac{\delta T}{10^7\ {\rm K}}\frac{2.44}{g_{14}}\left(\frac{R}{10\ {\rm km}}\right)^4 I_{45}^{-1}\left(\frac{|Q_{\rm EC}|}{30\ {\rm MeV}}\right)^3$$

This is one possibility for the slightly faster-than-expected spin down of PSR J1023+0038
(27% faster than expected from measured radio emission)

PRL **119,** 161103 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

Are Gravitational Waves Spinning Down PSR J1023+0038?

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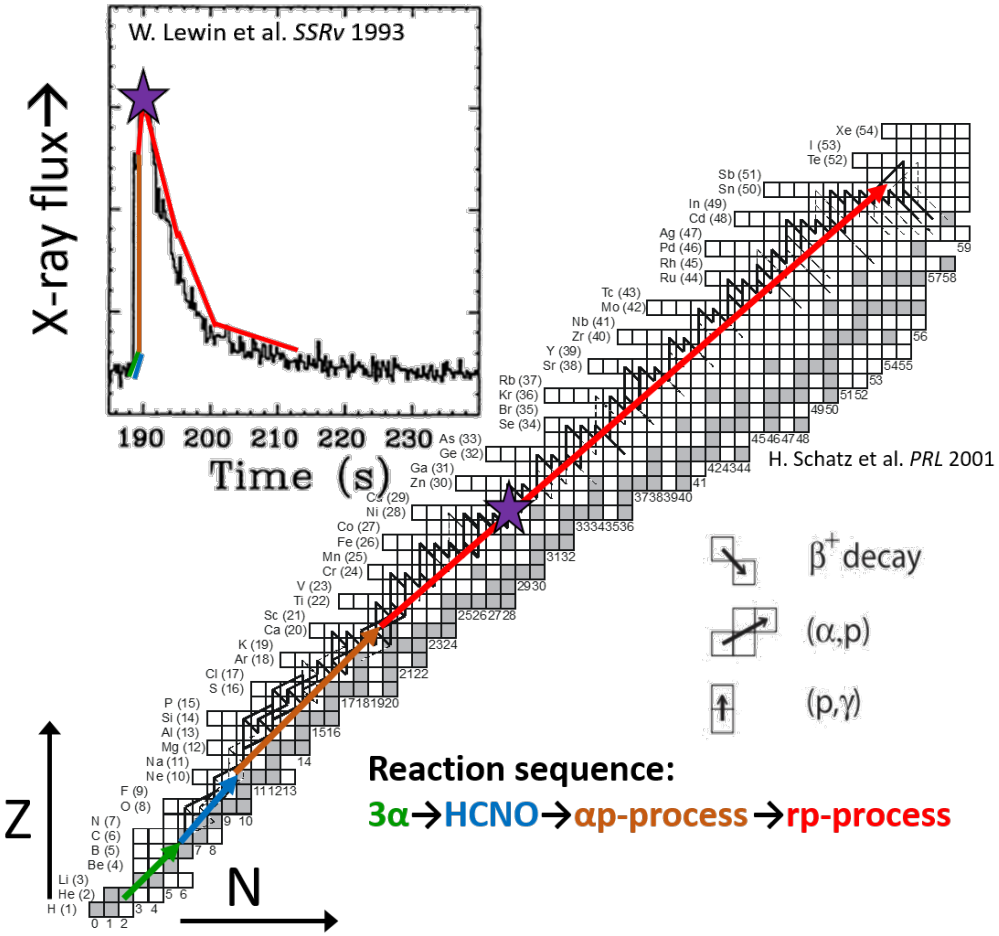
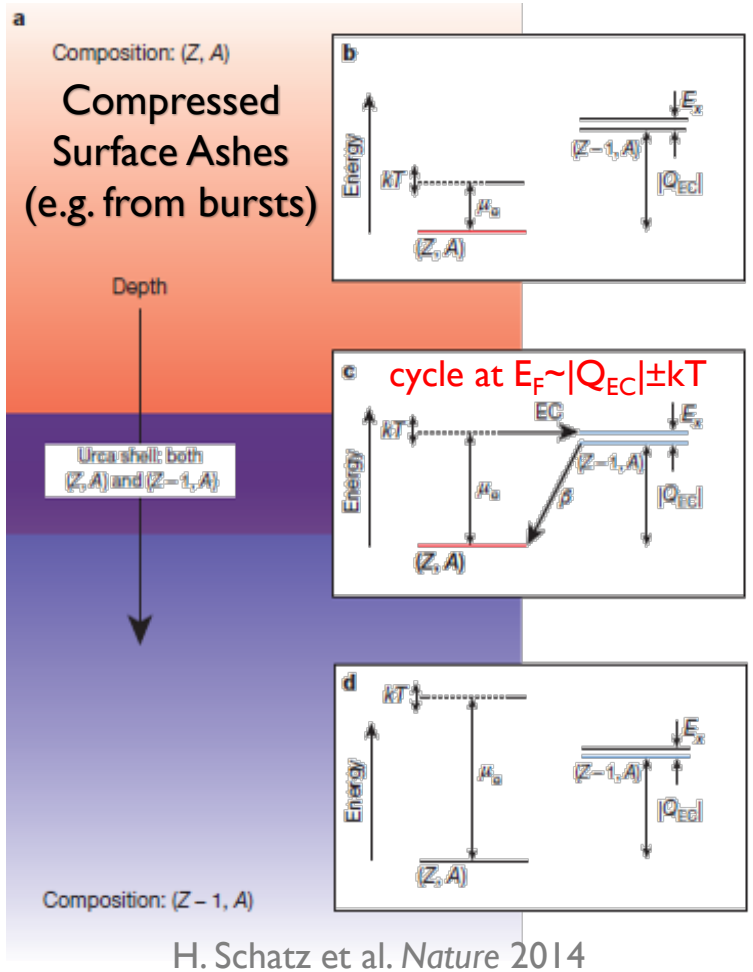
Leiden Observatory, Leiden University, Neils Bohrweg 2, 2333 CA Leiden, The Netherlands
and ASTRON, The Netherlands Institute for Radio Astronomy, Postbus 2, 7900 AA Dwingeloo, The Netherlands
(Received 24 March 2017; published 17 October 2017)

Urca Cooling: Possible thermal barriers in the NS outer layers

Surface burning ashes enrich the neutron star ocean & crust:

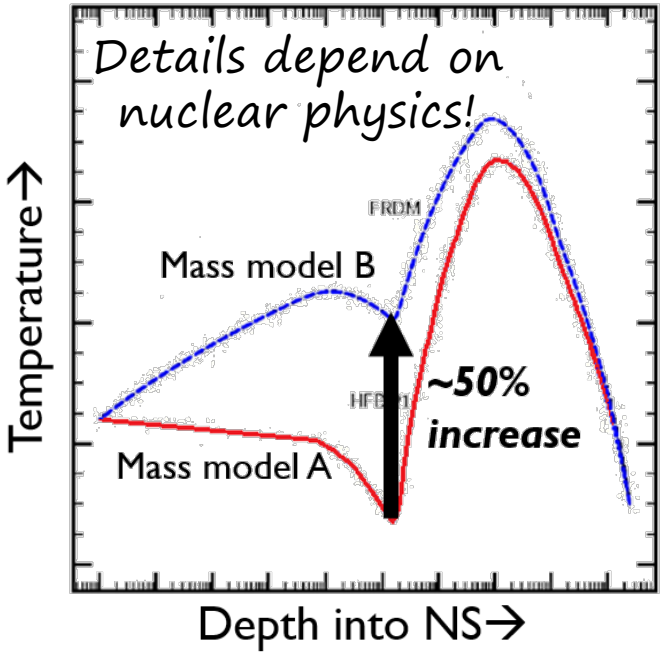


Ashes can undergo EC/β⁻-decay cycling, leading to strong ν-cooling:

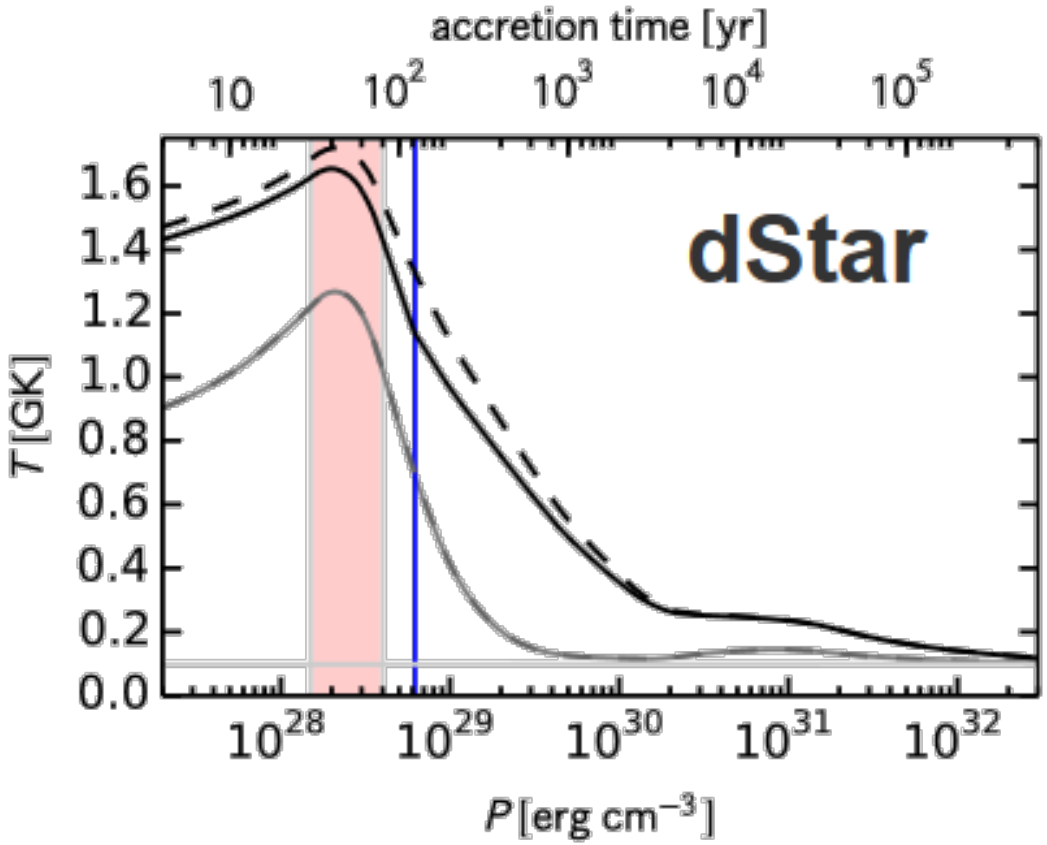


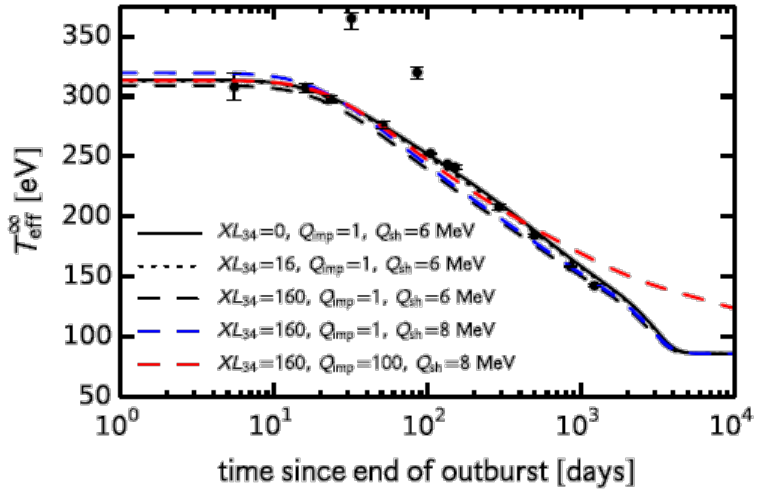
H. Schatz et al. *Nature* 2014

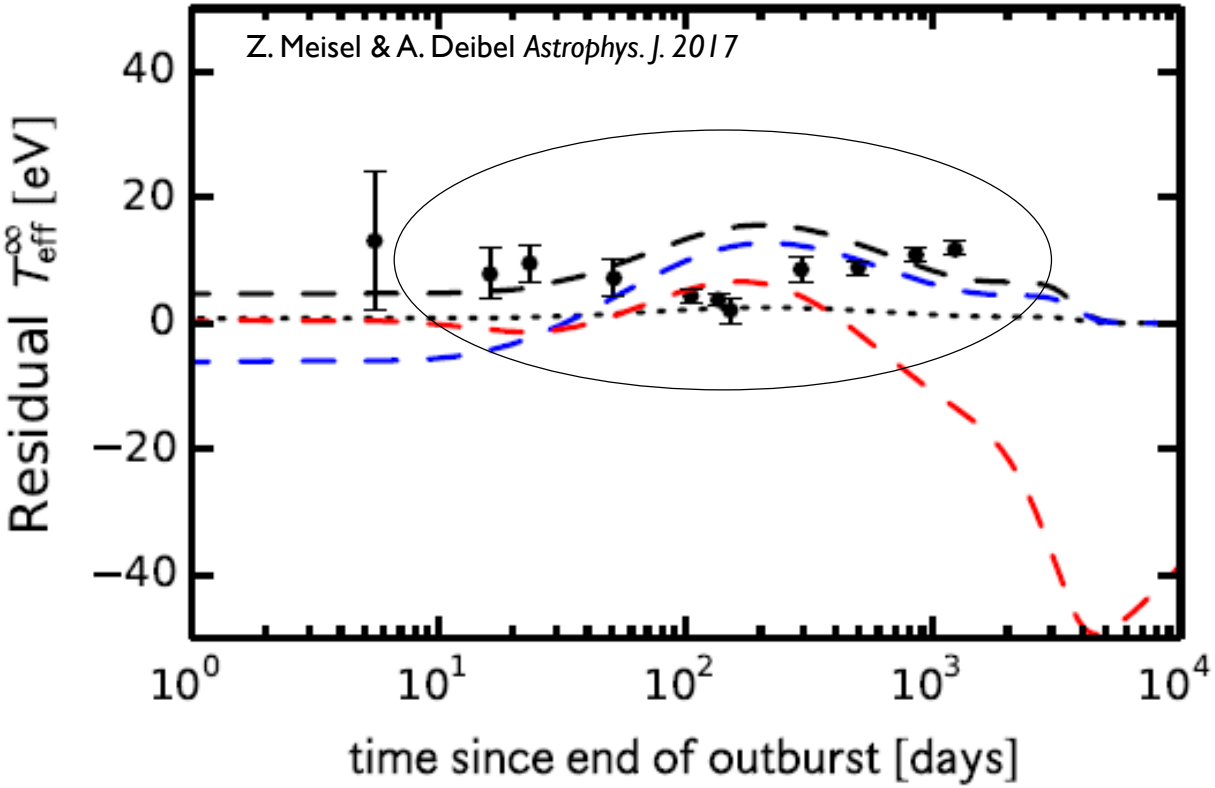
This "Urca" cooling can substantially alter the accreted crust thermal profile:



Urca cooling has a unique signature in cooling transients, indicative of past surface nuclear burning

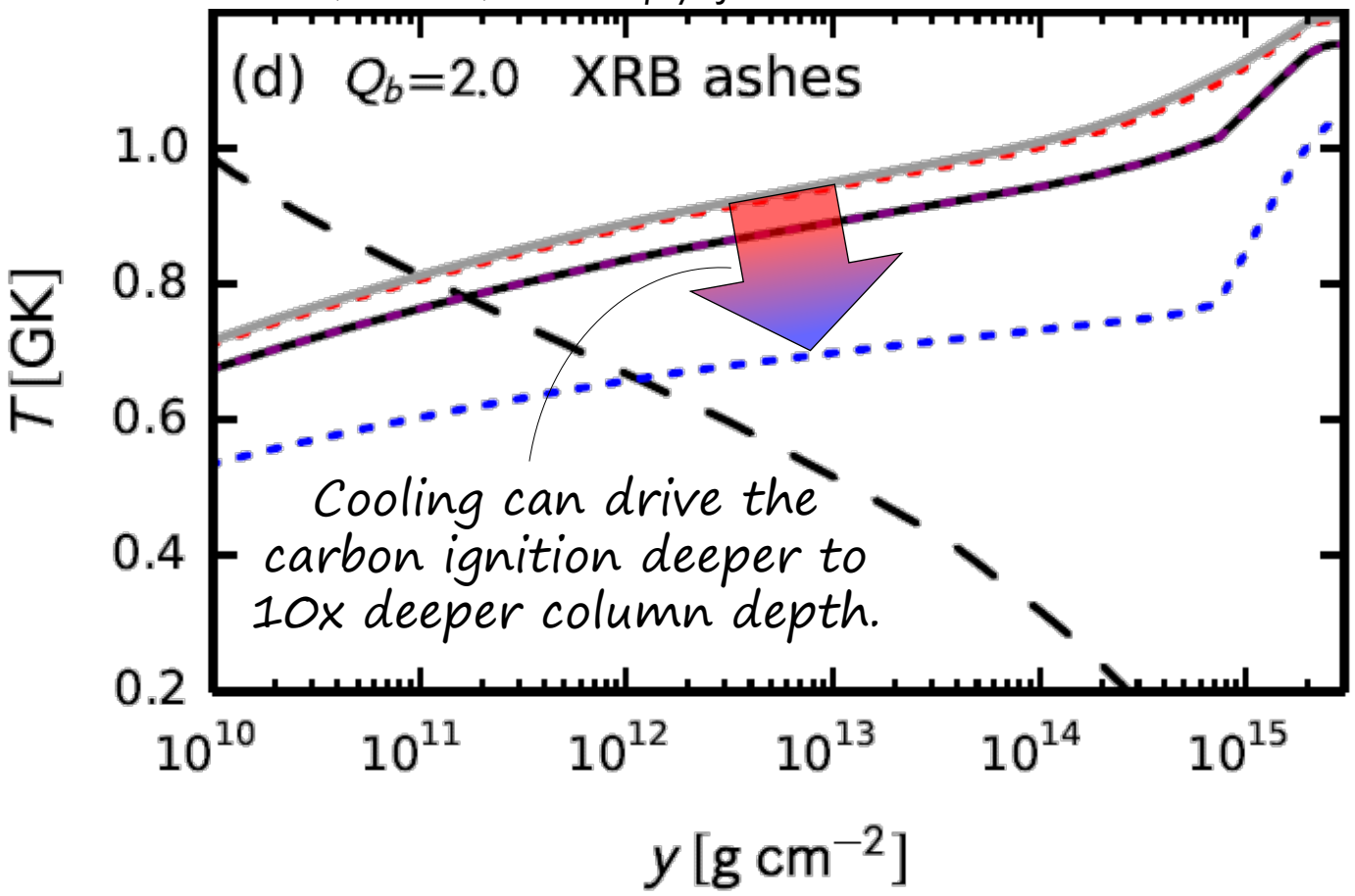


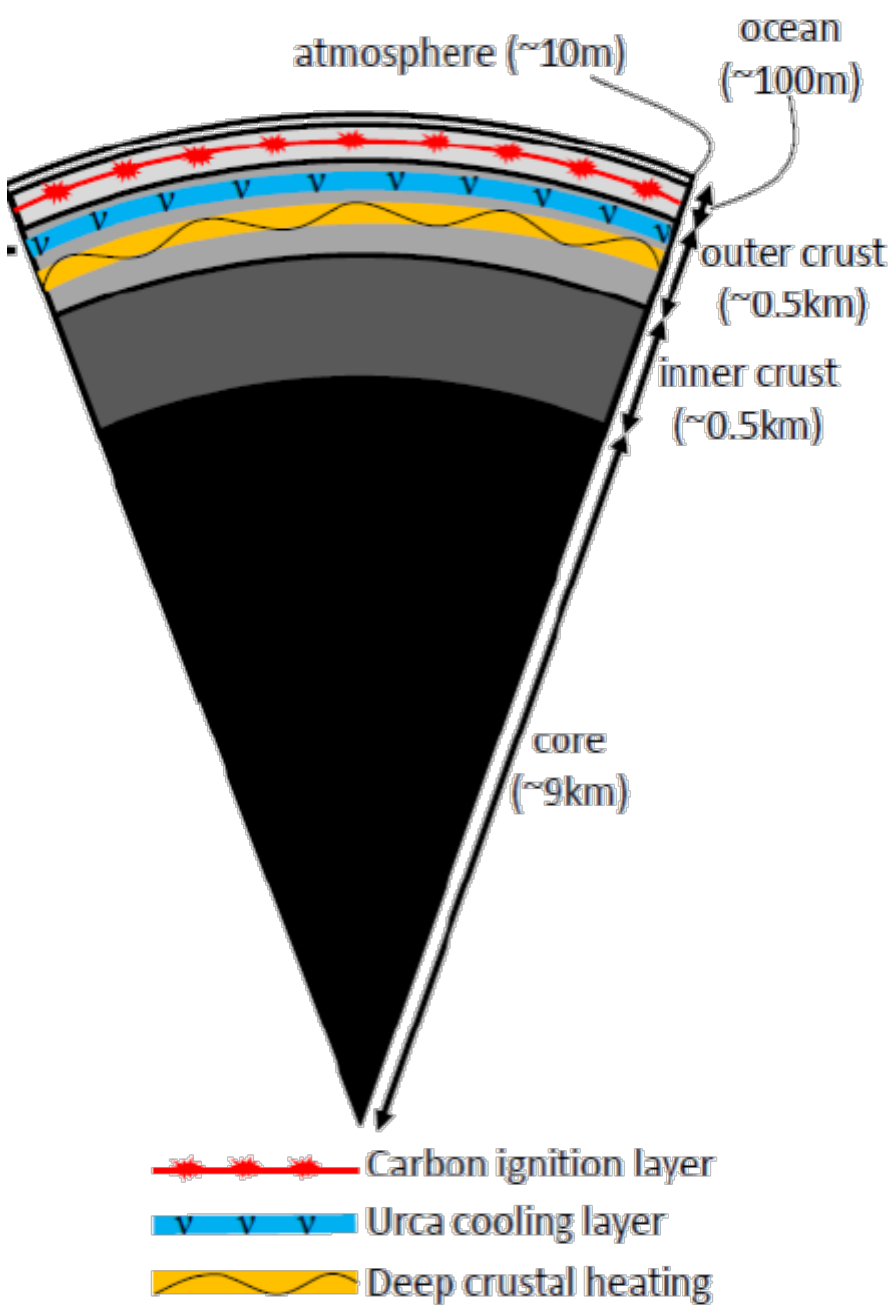




Urca cooling may impact X-ray superburst ignition

A. Deibel, Z. Meisel, et al. *Astrophys. J. 2016*





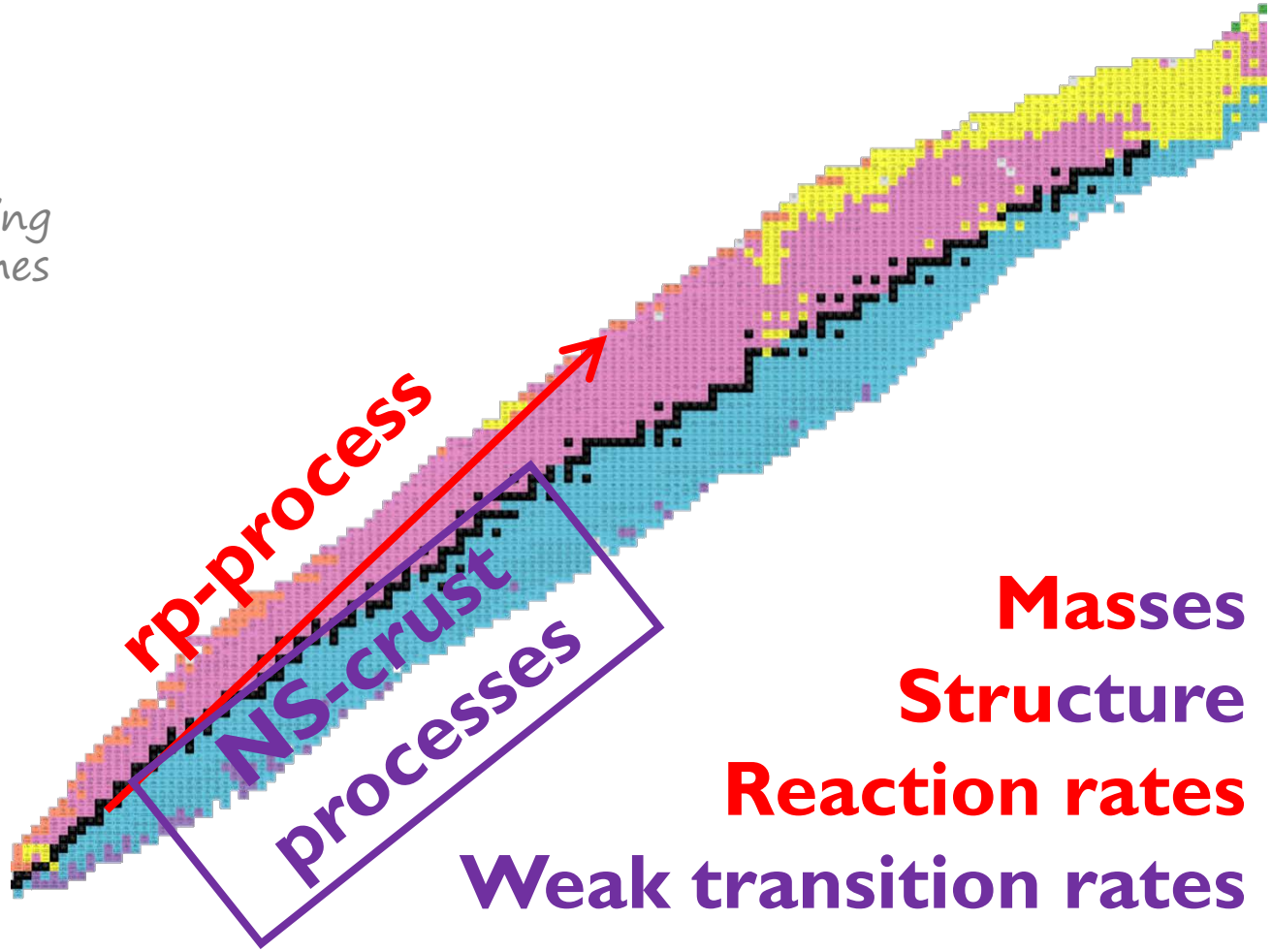
Urca cooling strengths depend sensitively on nuclear physics

Surface burning (e.g. XRB) ashes

$$L_\nu \approx L_{34} \times 10^{34}\ \mathrm{erg\ s^{-1}}\, X T_9^5 \left(\frac{g_{14}}{2}\right)^{-1} R_{10}^2,$$

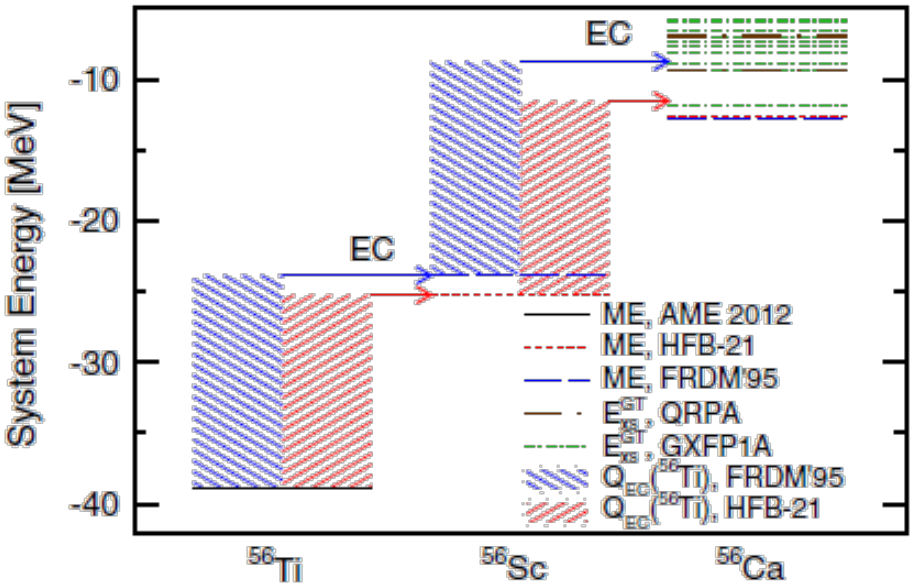
$$L_{34} = 0.87 \left(\frac{10^6\ \mathrm{s}}{ft}\right)\left(\frac{56}{A}\right)\left(\frac{Q_{\mathrm{EC}}}{4\ \mathrm{MeV}}\right)^5 \left(\frac{\langle F\rangle^*}{0.5}\right)$$

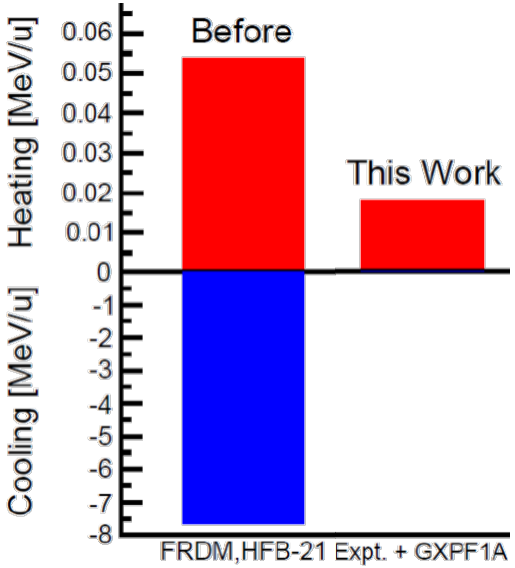
Intrinsic nuclear properties

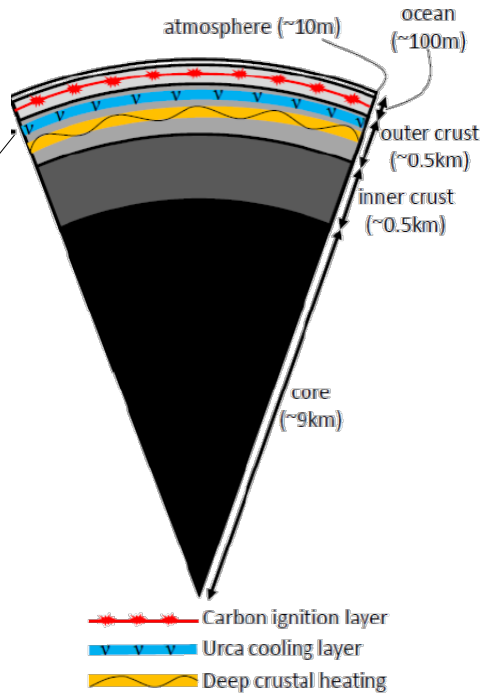


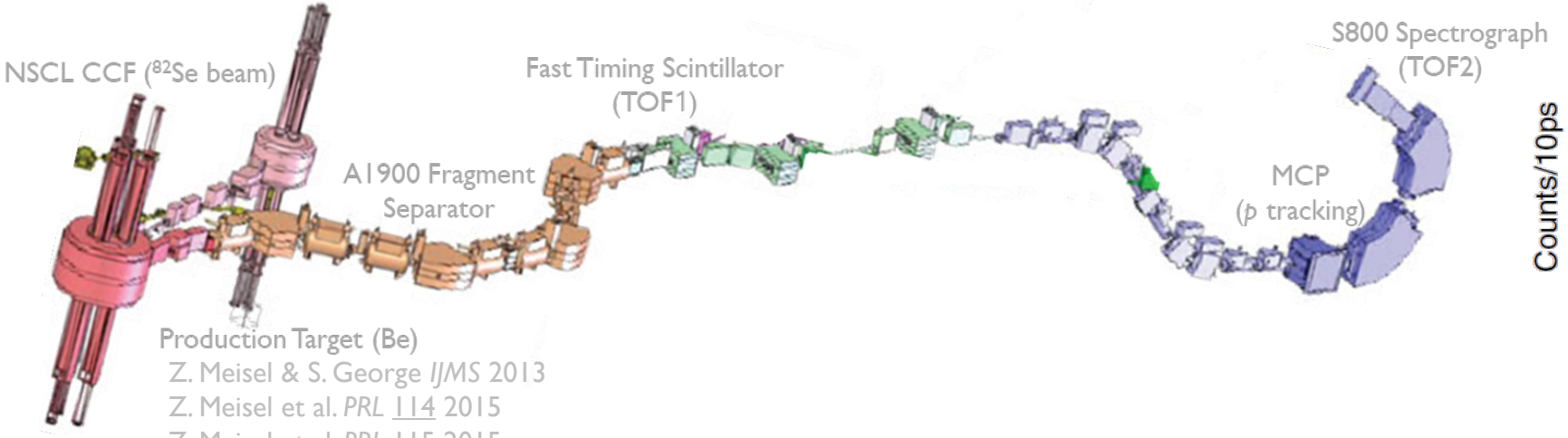
Masses
Structure
Reaction rates
Weak transition rates

Mass Impact Example: ^{56}Ti-^{56}Sc-^{56}Ca

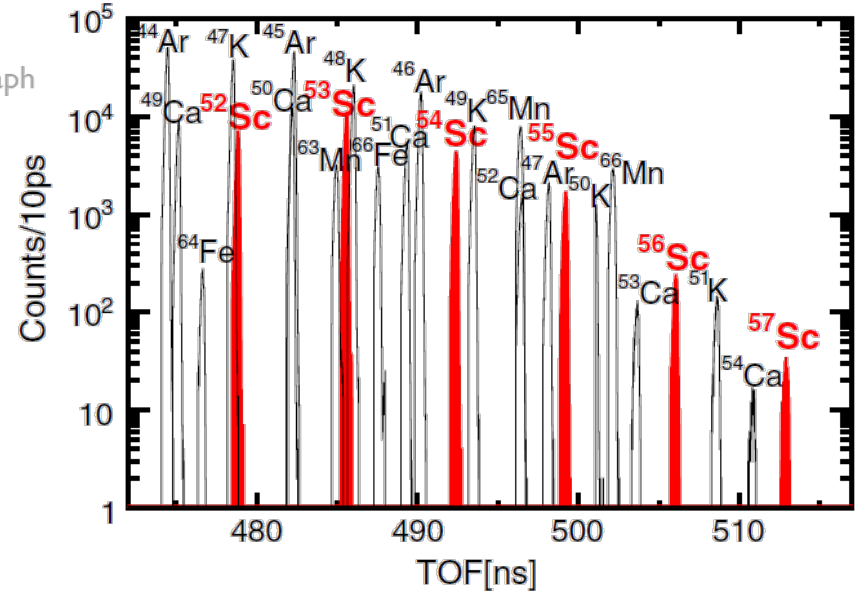








Z. Meisel & S. George *IJMS* 2013
Z. Meisel et al. *PRL* 114 2015
Z. Meisel et al. *PRL* 115 2015
Z. Meisel et al. *PRC* 2016
Z. Meisel et al. *In Preparation*



The cycling rate is set by the weak rate

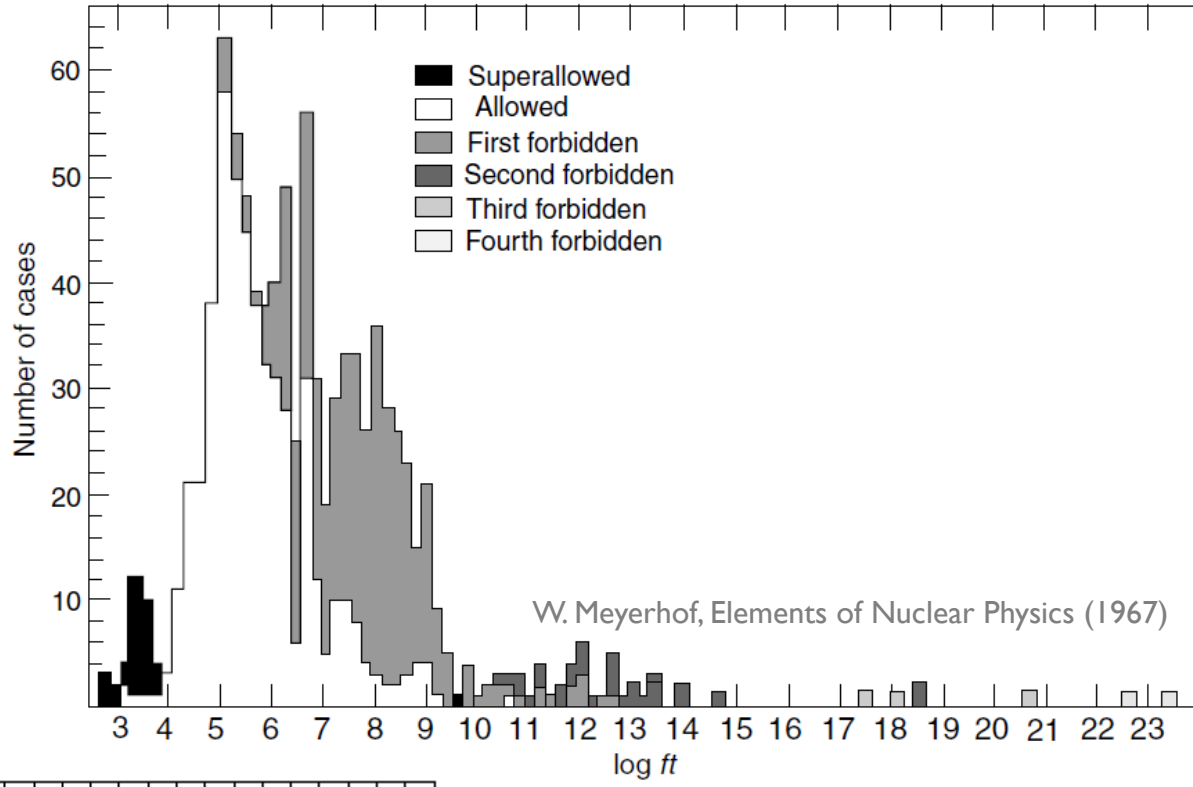
- Get weak rate from wavefunction overlap & phase space integral:
  - $\lambda = \frac{G_F^2 m_e^5 c^4}{2\pi^3 \hbar^7} \left|M_{fi}\right|^2 f(Z_d, Q) = \frac{\ln(2)}{t_{1/2}}$
  - Rephrase as the comparative half-life, *ft*,

$$ft = \frac{2\ln(2)\pi^3\hbar^7}{G_F^2 m_e^5 c^4} \frac{1}{\left|M_{fi}\right|^2}$$

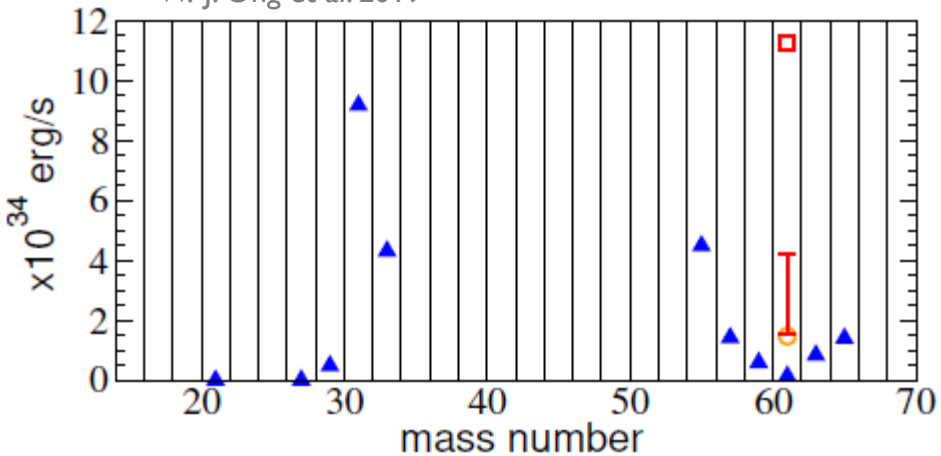
- Need Q-value, half-life, & branching ratio
  - or measure J^π and estimate *ft* from $\Delta J^{\Delta\pi}$
  - or calculate ψ-overlap

- ft in L_ν is $\frac{ft_\beta + ft_{EC}}{2}$

L_ν only depends linearly on ft, but ft can span orders of magnitude



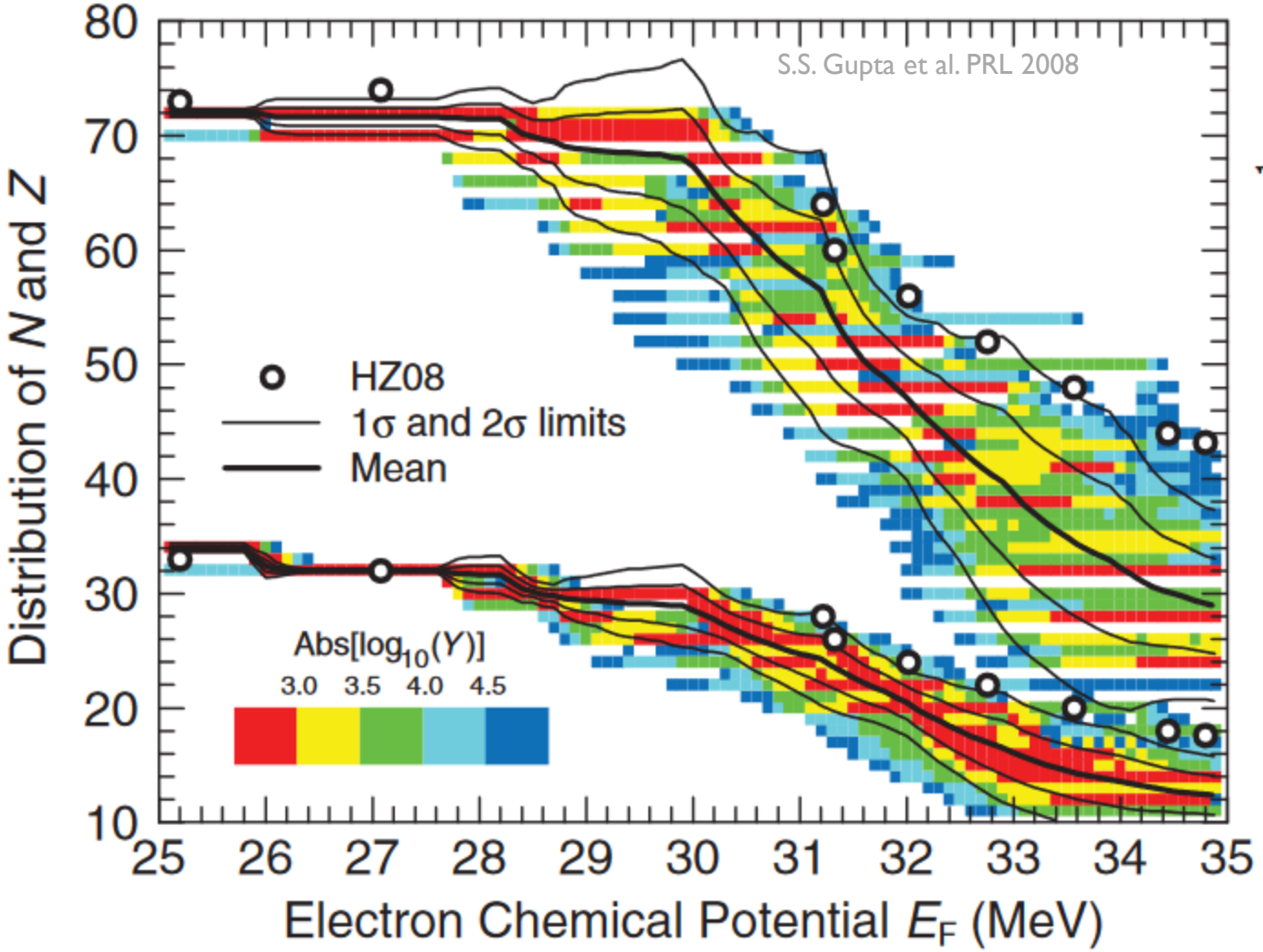
W.-J. Ong et al. 2019



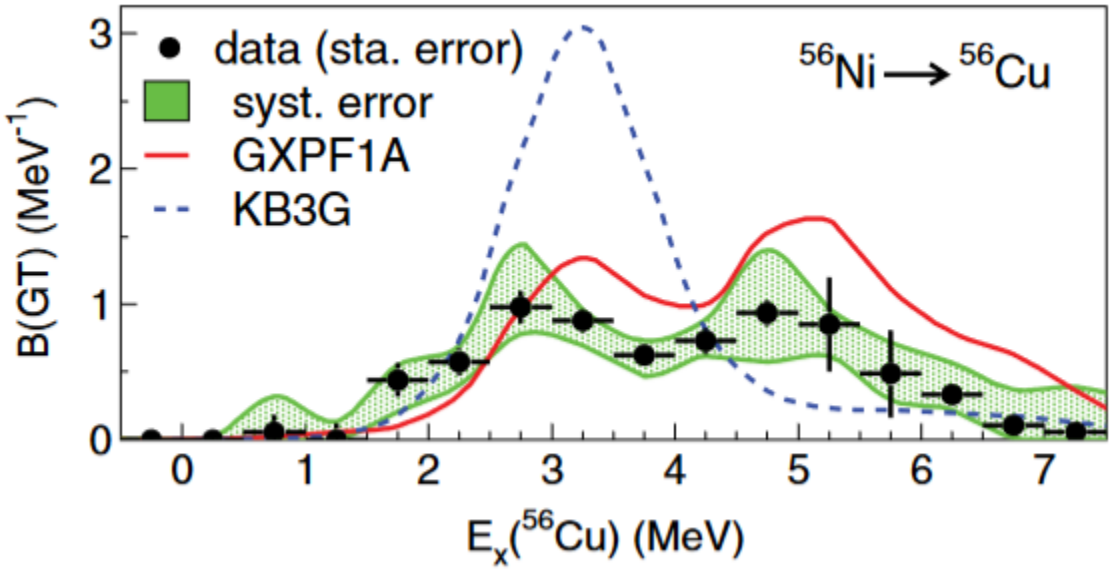
EC near neutron drip (S_n=0) broadens abundance distribution

emitted n can be captured or just contribute to n-gas

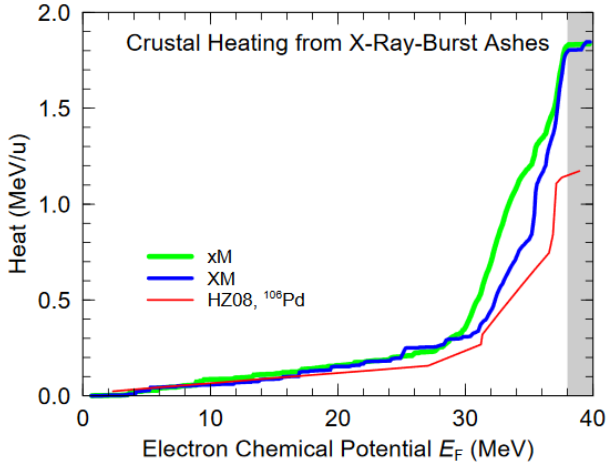
EC into excited states must be calculated, unless charge-exchange measurements are possible



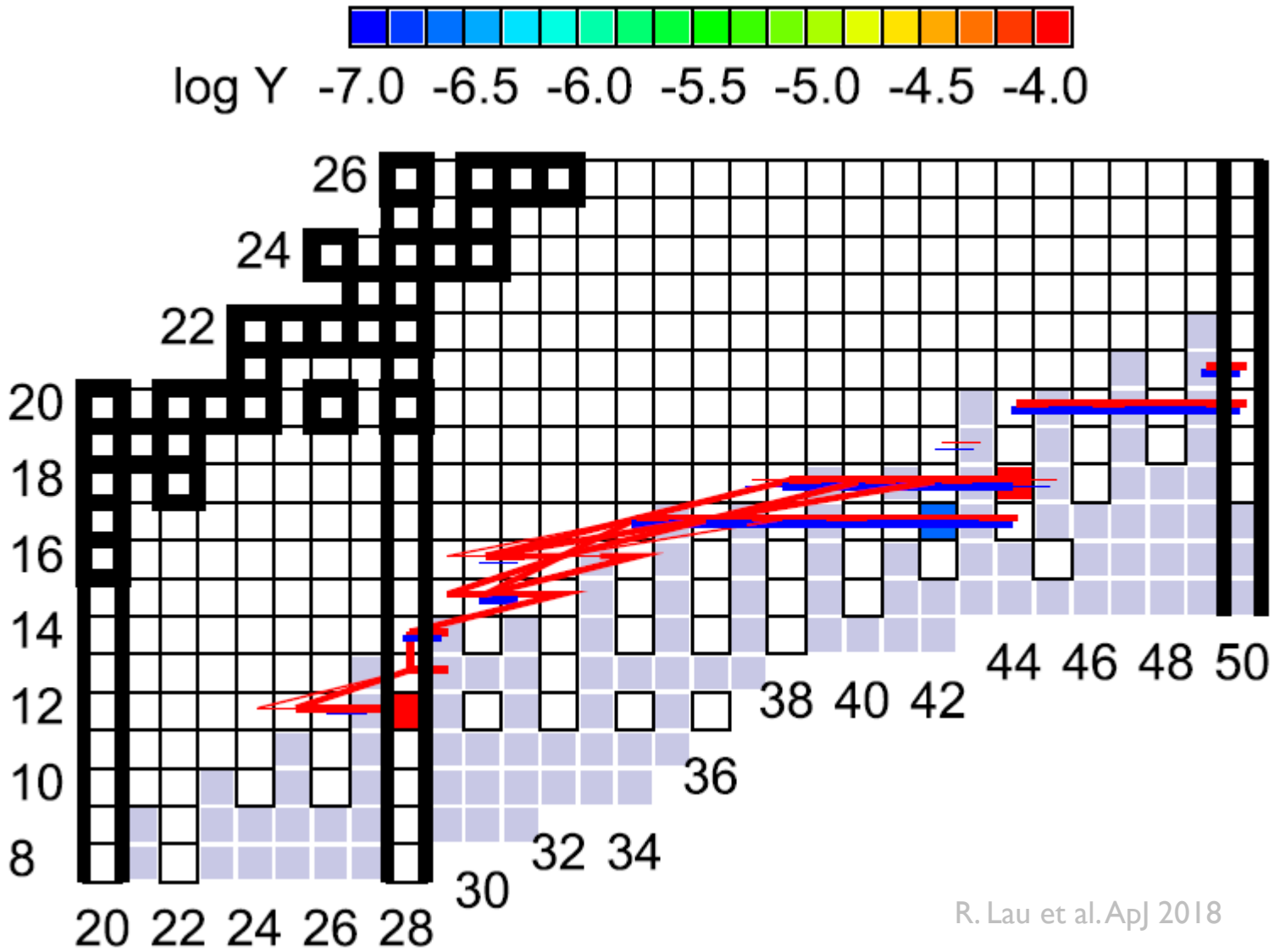
M. Sasano et al. PRL (2011)



n-drip sets-in around ~20-40MeV for nuclei in surface burning ashes



Superthreshold (EC,*x*n) Cascades (SECs) find equilibrium



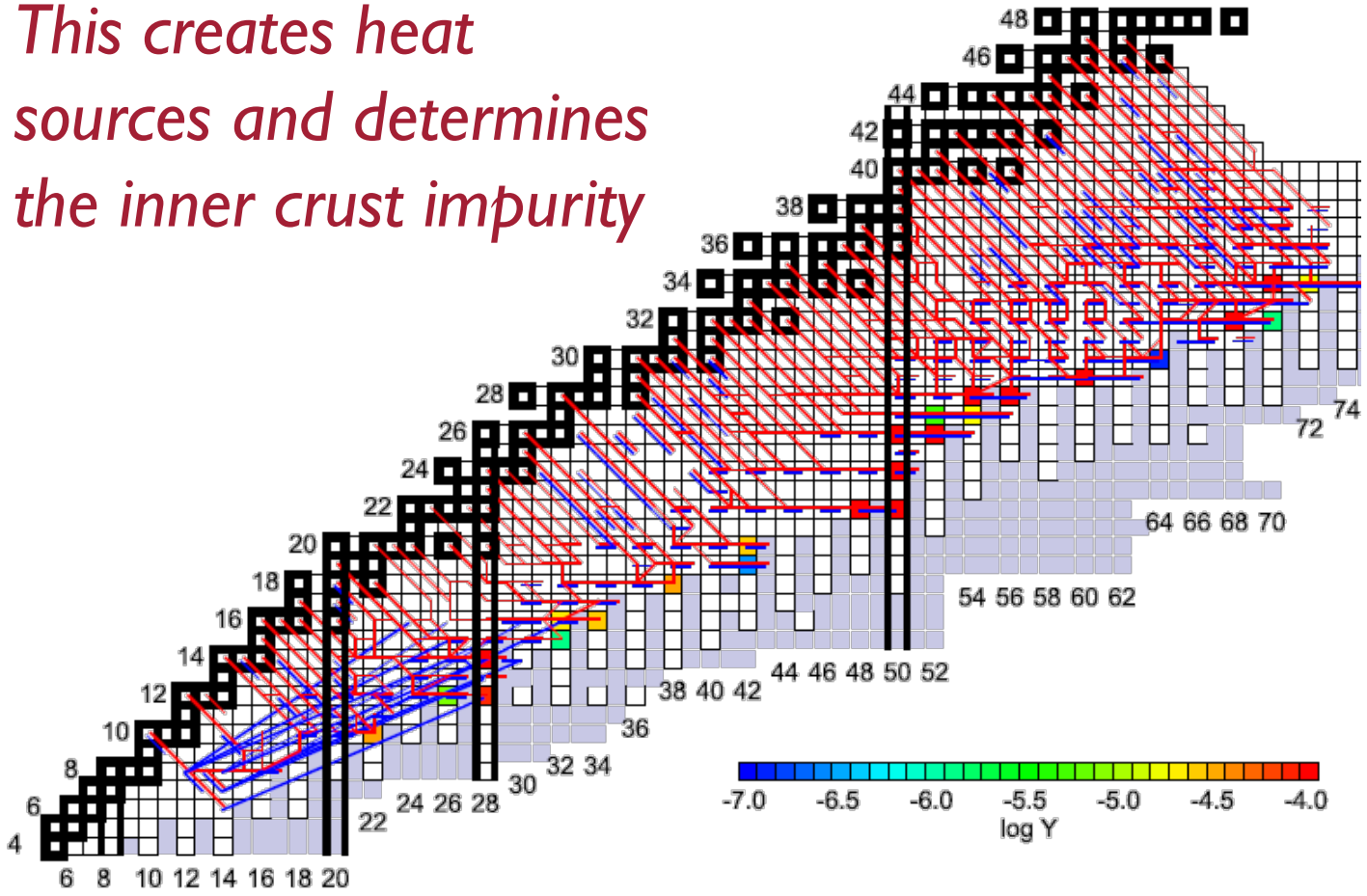
R. Lau et al. ApJ 2018

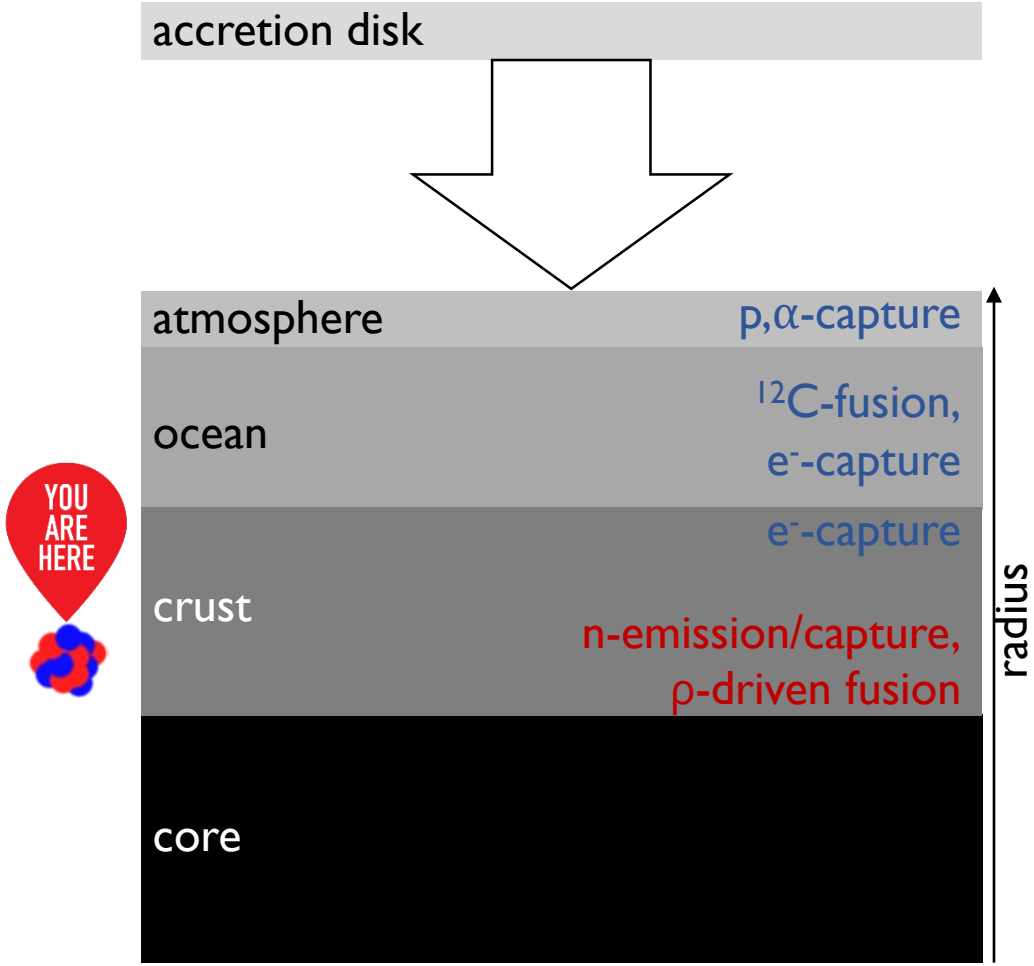
The journey of a nucleus in a neutron star

3. Fusion and disintegration

This creates heat sources and determines the inner crust impurity

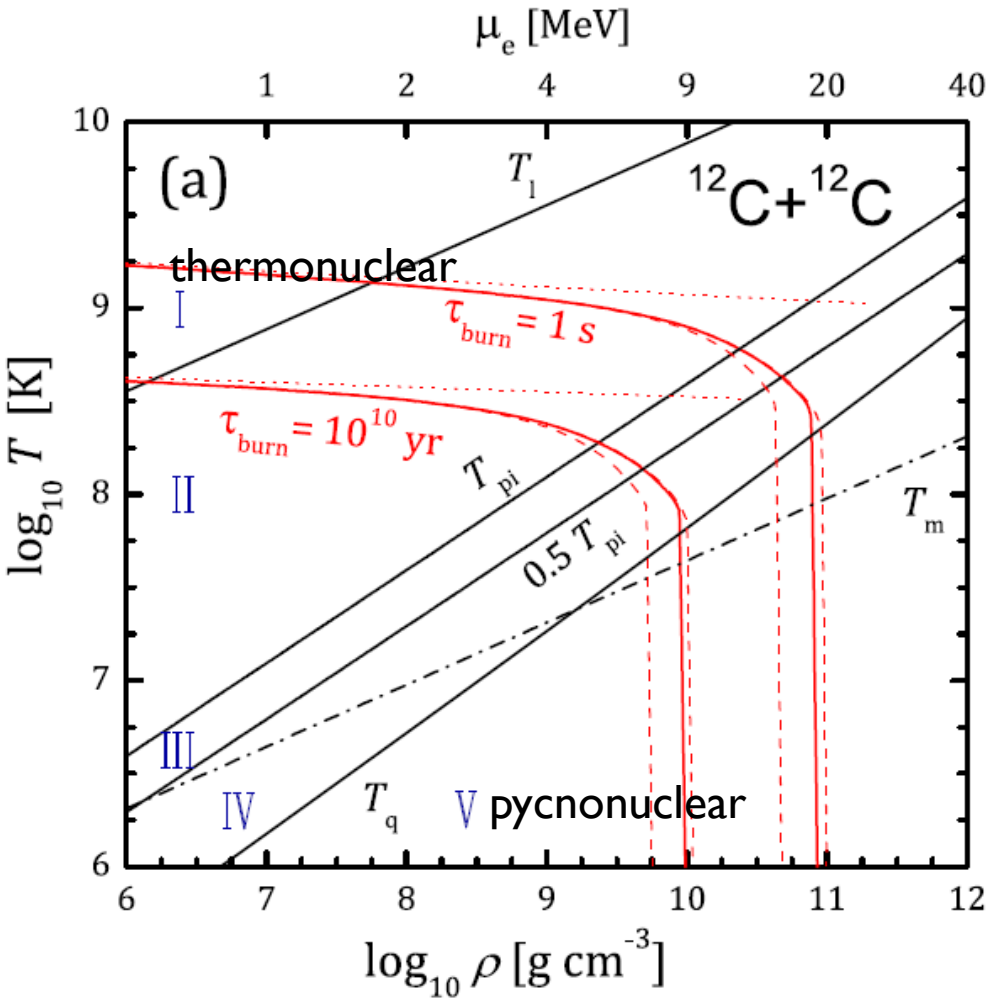
R. Lau et al. *ApJ* 2018

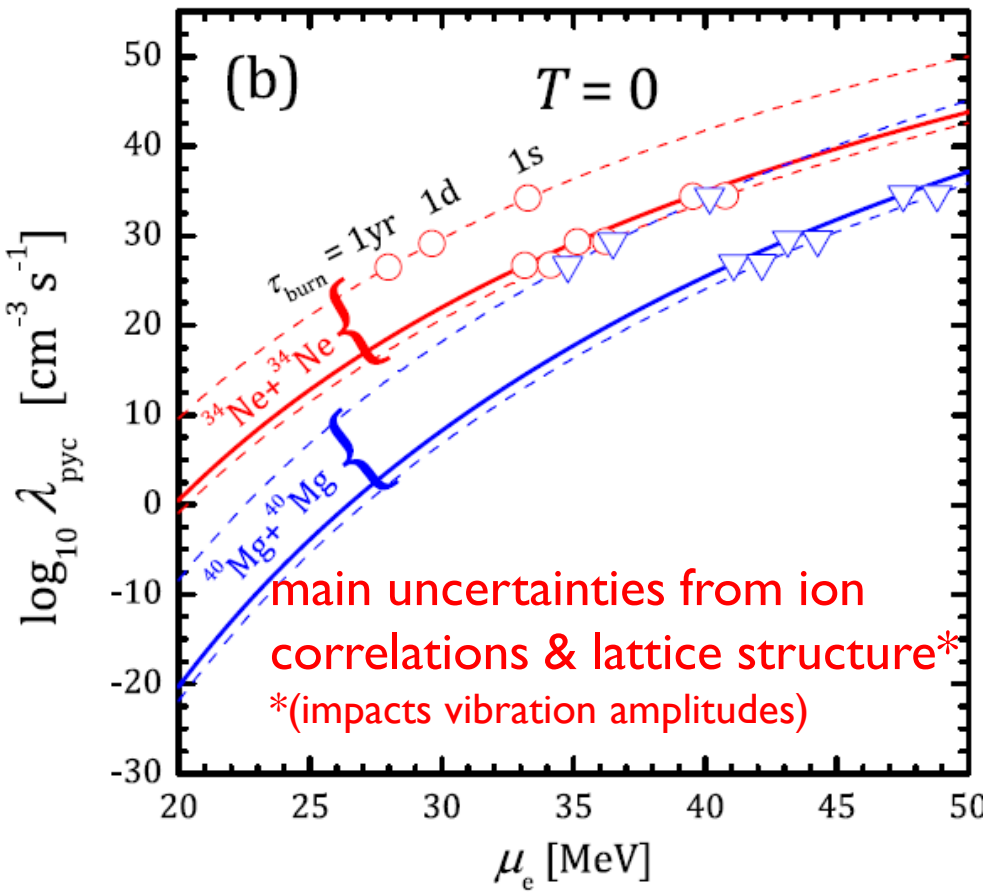




Pycnonuclear (density-driven) fusion

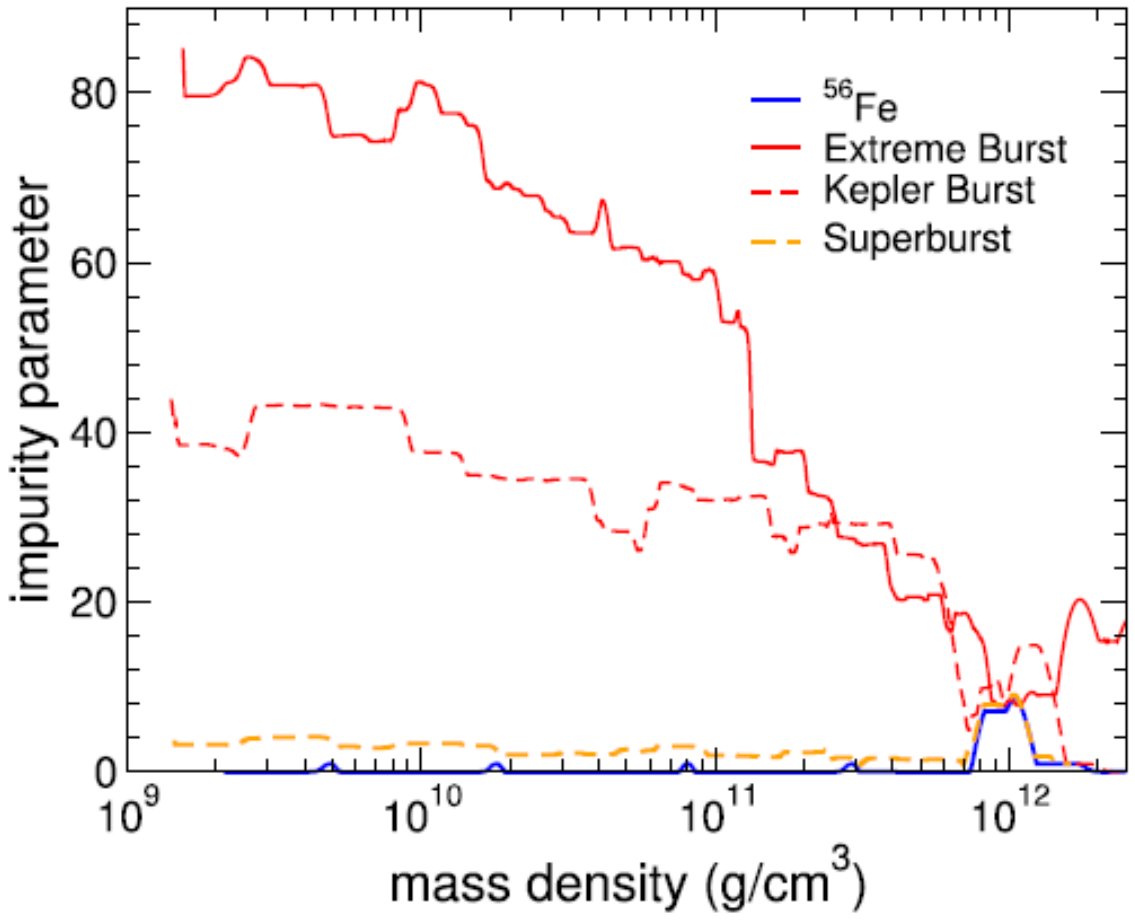
- Zero-point oscillation of nuclei around equilibrium positions enables nuclear fusion
- Rates span orders of magnitude & uncertainties are essentially decoupled from terrestrial nuclear physics input

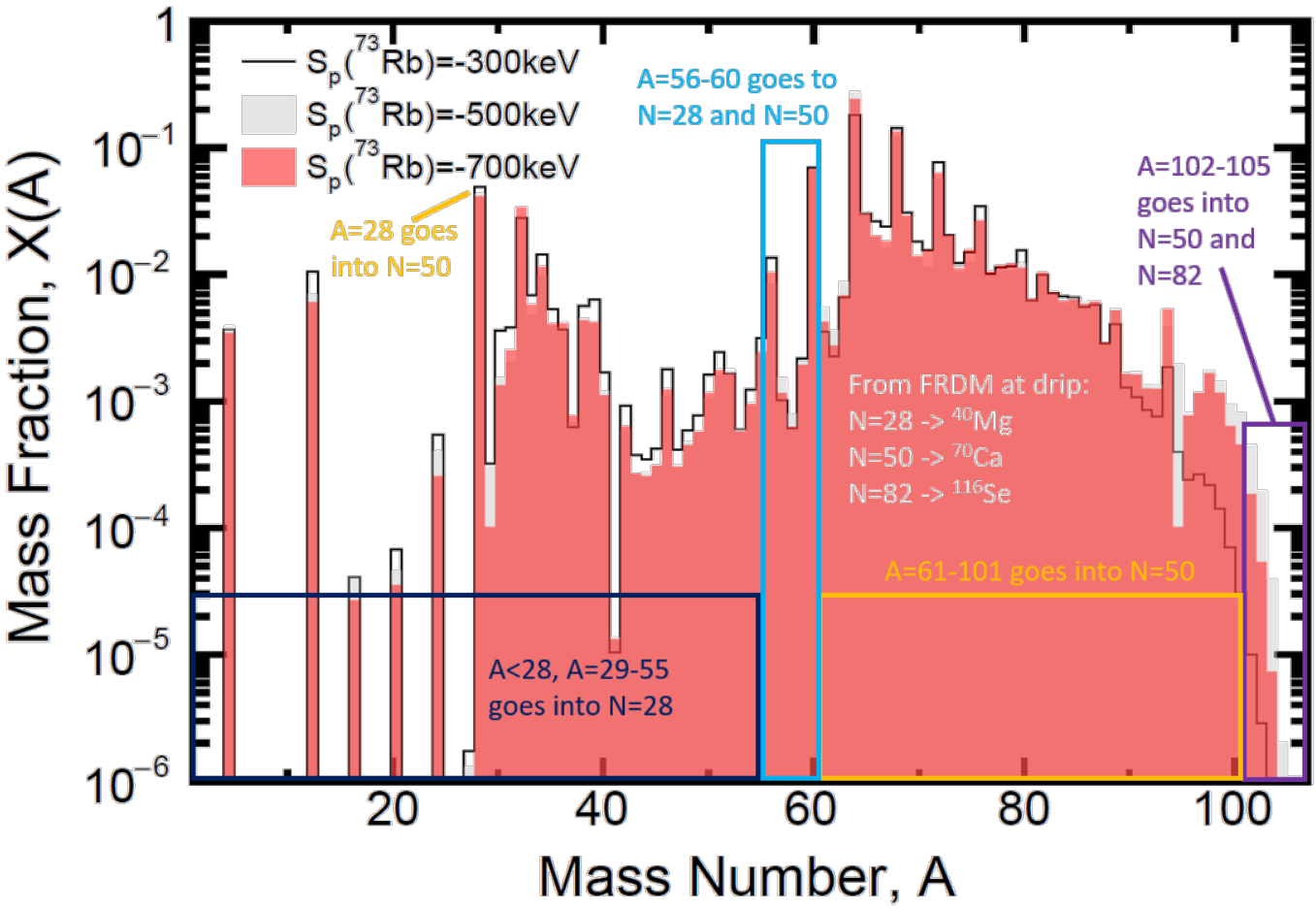




Pycnonuclear reactions purify the inner crust

R. Lau et al. ApJ 2018

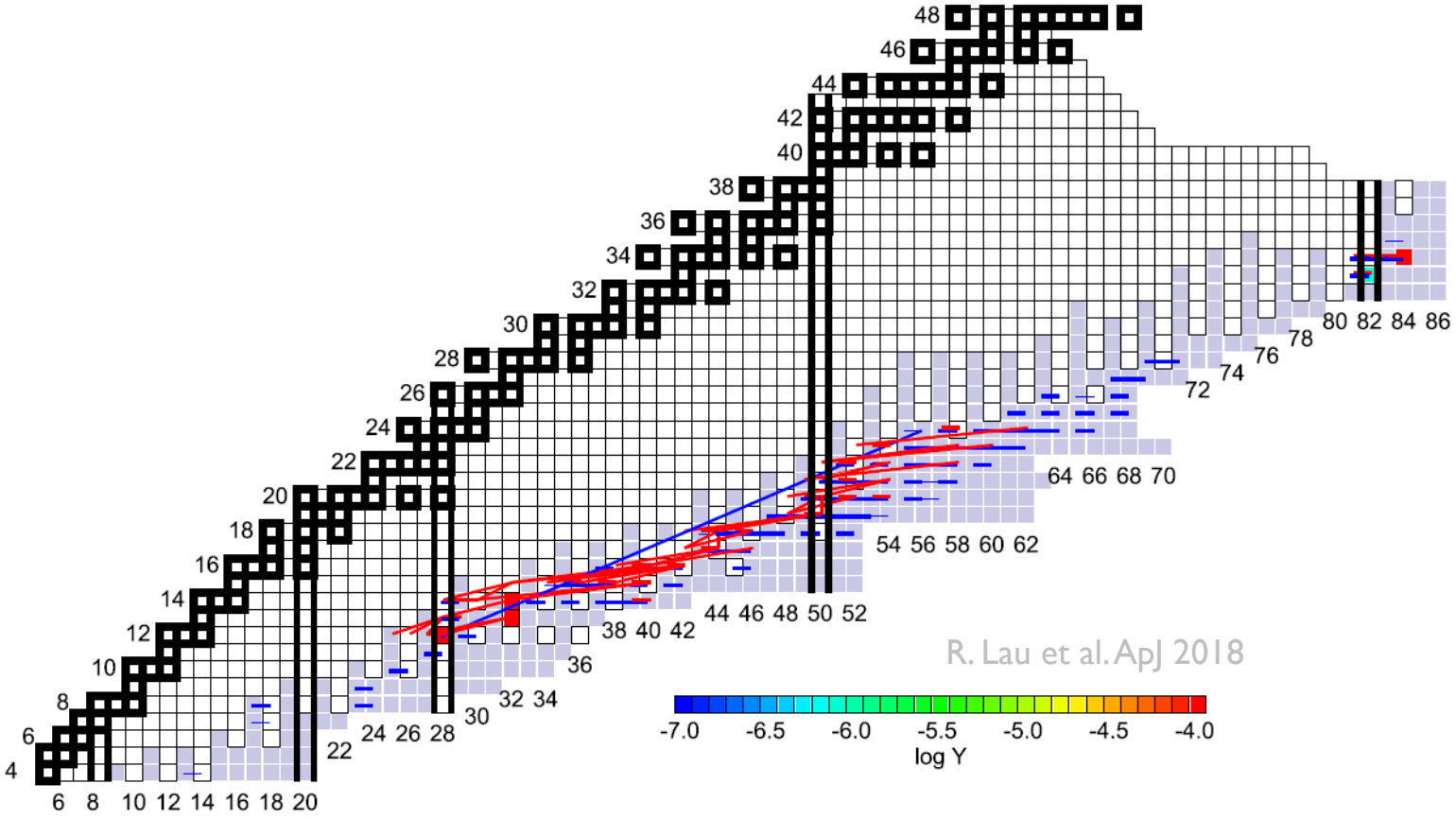


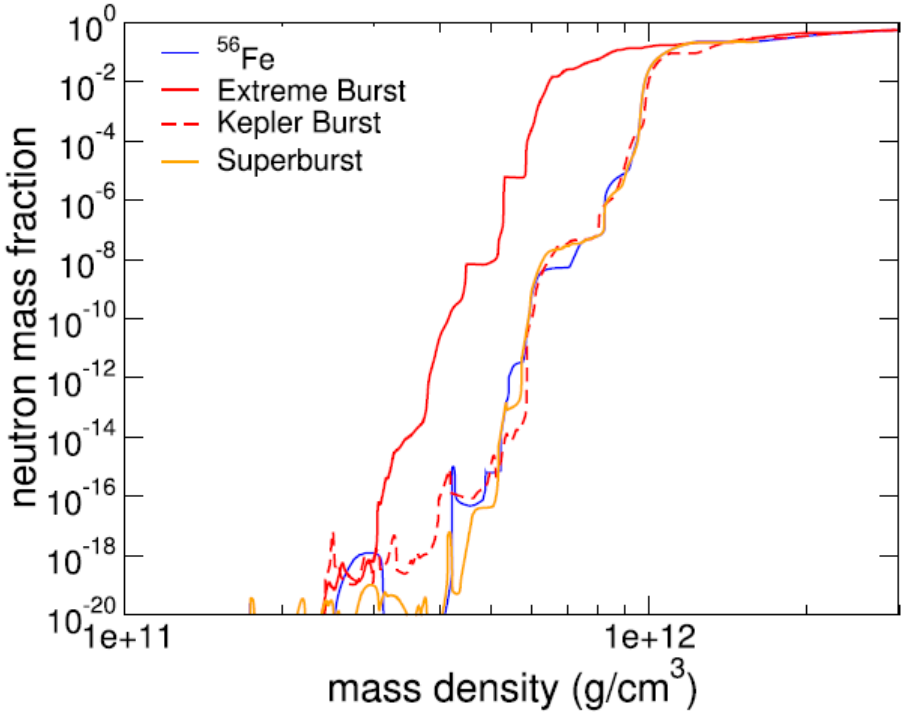


Meisel et al. ApJ 2019

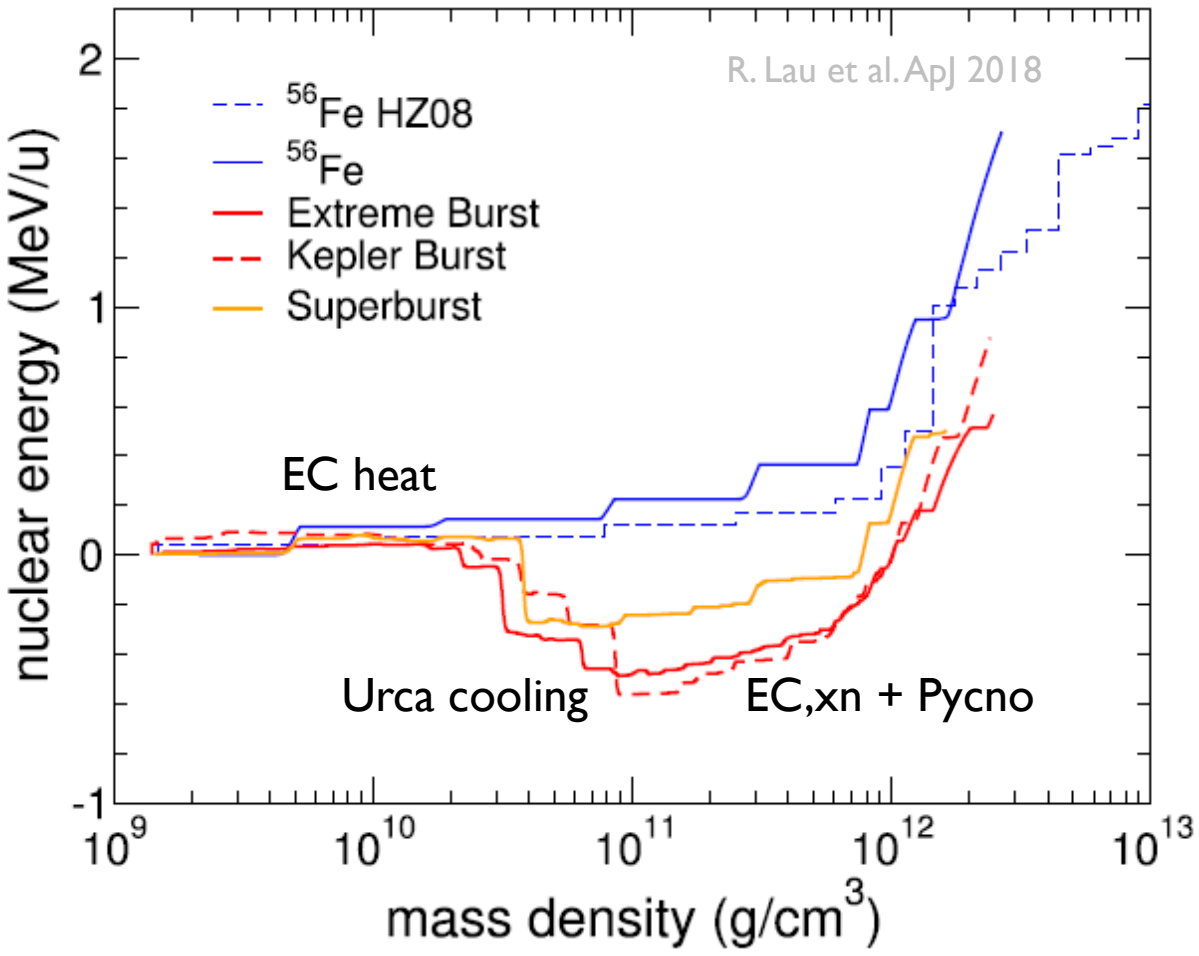
Q_{imp}^{inner}	13.0	15.7	15.9	14.4	13.4	11.2	11.5	13.5	10.1	13.0	15.1	15.9	15.7	14.7
Q_{imp}^{inner}	12.9	14.5	14.4	15.5	13.4	13.2	12.3	12.9	12.9	12.9	12.9	12.8	12.9	13.0

Ultimately, pycnonuclear reactions + SEC dissolve nuclei into neutrons

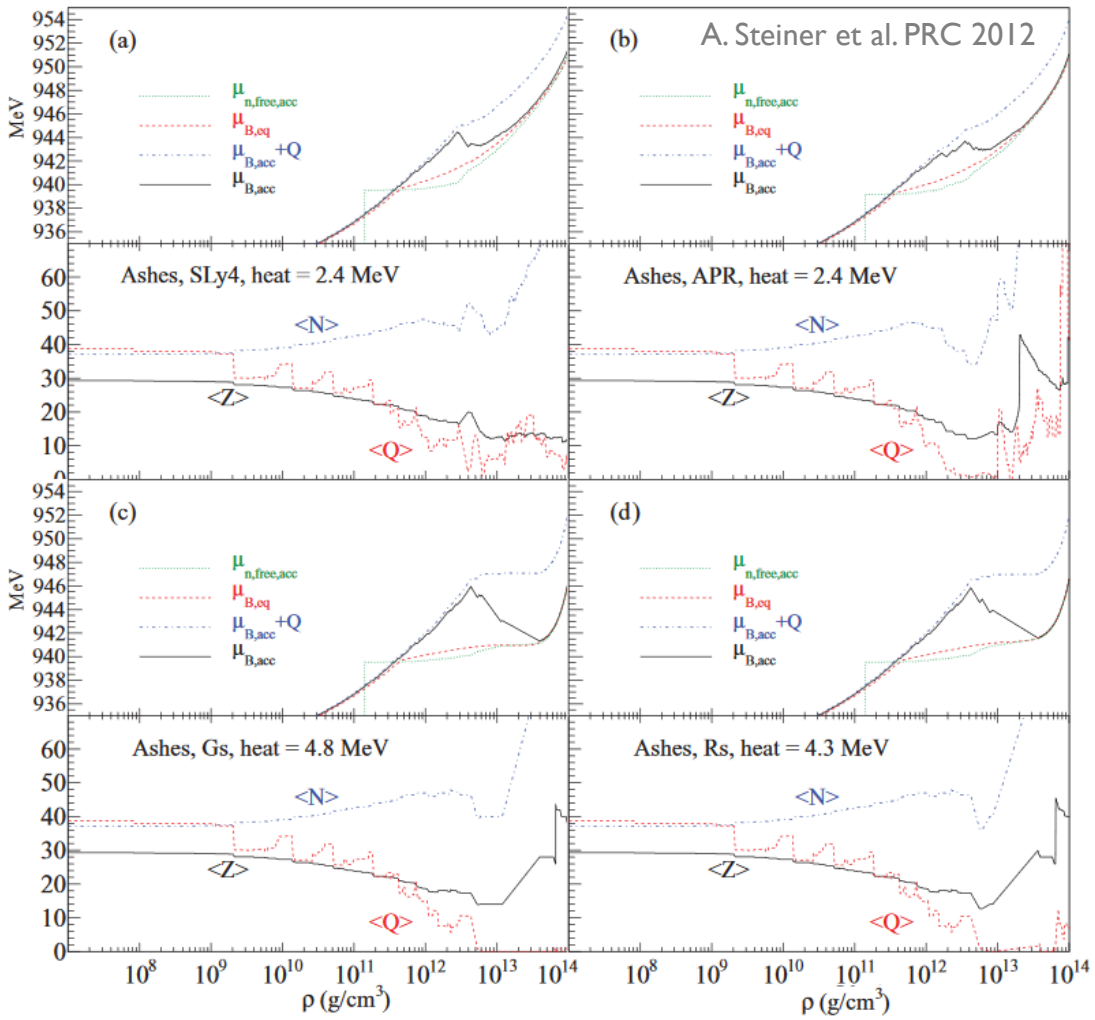




Wind up with similar heating independent of assumptions



~2-4 MeV/u total



*Distribution sets time for break in transient light curve, magnitude alters T-gradient & therefore cooling timescale

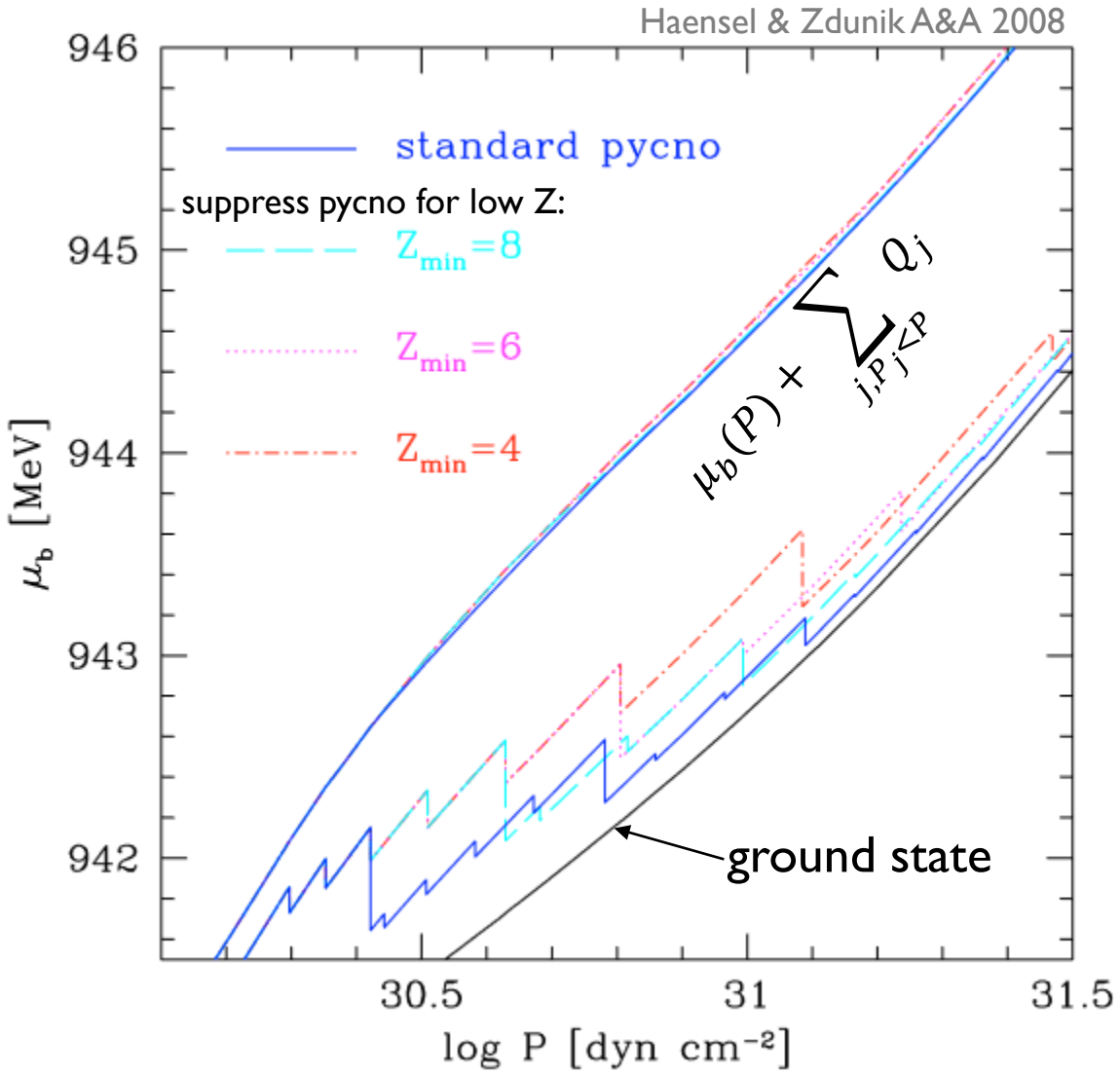
Surface composition driven to cold-catalyzed state

- Gibbs free-energy per nucleon (i.e. baryon chemical potential)

$$\mu_b(\mathrm{P}) = \frac{[\mathrm{BE(P)} + \mathrm{P}]}{n_b(P)}$$

approximating $T = 0$

- Minimizing μ_b winds up with the ground state of the crust at that pressure
- Non-catalyzed crust is a heat reservoir & crust reactions drive material to the ground state
- Initial μ_b are pretty similar because BE/A for most stable nuclei is about the same
- Total heating then mostly depends on the equilibrium composition at the crust-core transition, which mostly depends on the EoS (since EoS determines $P_{crust-core}(\rho_{crust-core})$



neutron-transfer: a new reaction mechanism for the crust

Concept: weakly bound neutron tunnels into nearby nucleus where it would be more bound

1. Assume Fermi's golden rule for the transition probability: $W = \frac{2\pi}{\hbar}|M|^2\rho \approx 10^{22}\left(\frac{M}{1\,\mathrm{MeV}}\right)^2 \frac{\rho}{1\,\mathrm{MeV}^{-1}}\,\mathrm{s}^{-1}$
2. Say the density of states is ~ ρ = 1MeV^{-1}
3. For the wavefunction overlap of the matrix element, assume they overlap in an asymptotic region described by:
4. Take the first-order result from the integral for the wave-function overlap:
5. Volume-average the transition probability, weighting by the density of correlated neutron donor & acceptor nuclei
6. Use previous approximations for the pair correlation function and use a saddle-point approximation for the integral to get an analytic form for the rate:

$$\Psi_\mathrm{a} \approx A_\mathrm{a}\frac{r_\mathrm{a}}{r'}\exp(-\kappa r')$$

$$M \approx \frac{3\hbar^2}{2m_\mathrm{n}}\frac{1}{\sqrt{r_\mathrm{d}r_\mathrm{a}}}\frac{\exp(-\kappa l)}{l}$$

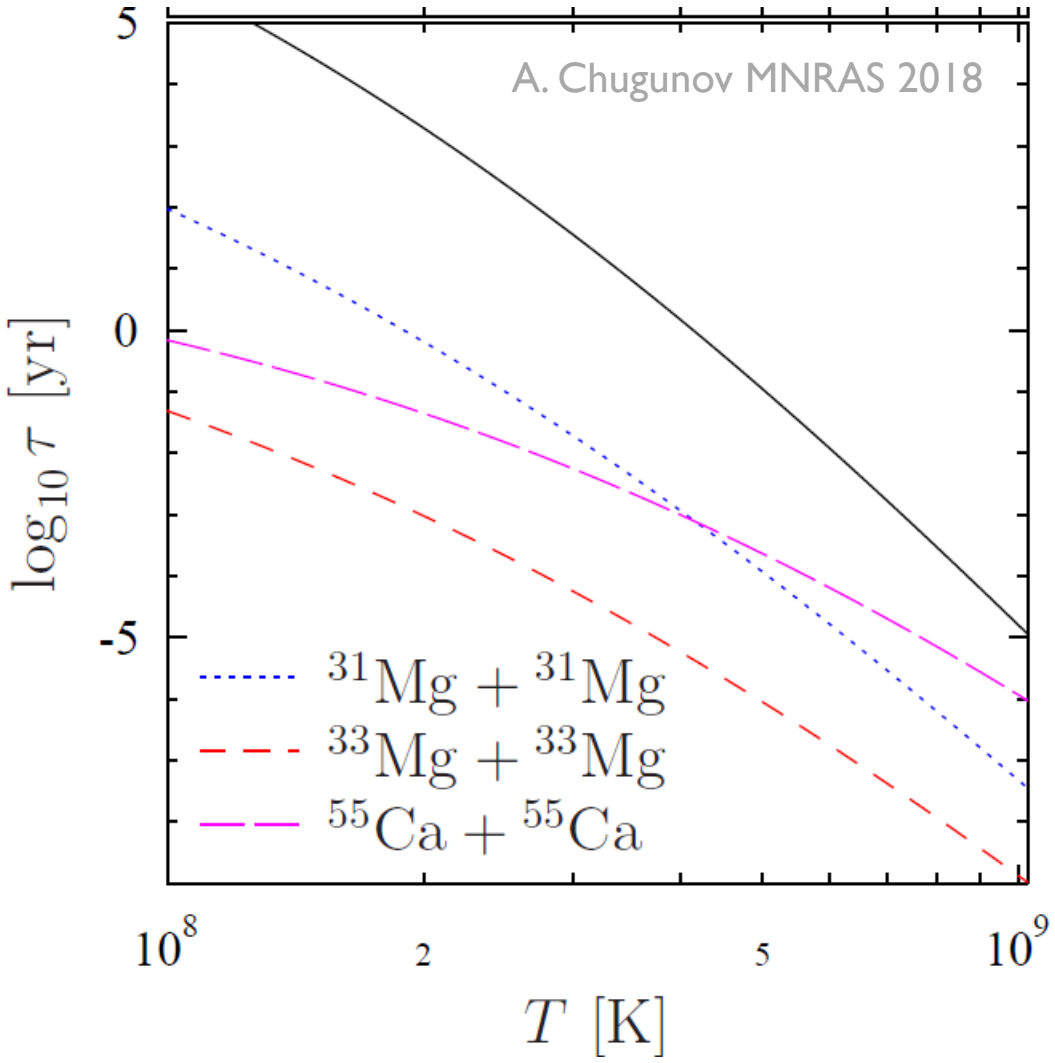
$$\lambda = \int W(\boldsymbol{l})\mathfrak{n}_\mathrm{a}(\boldsymbol{l})\mathrm{d}^3\boldsymbol{l}$$

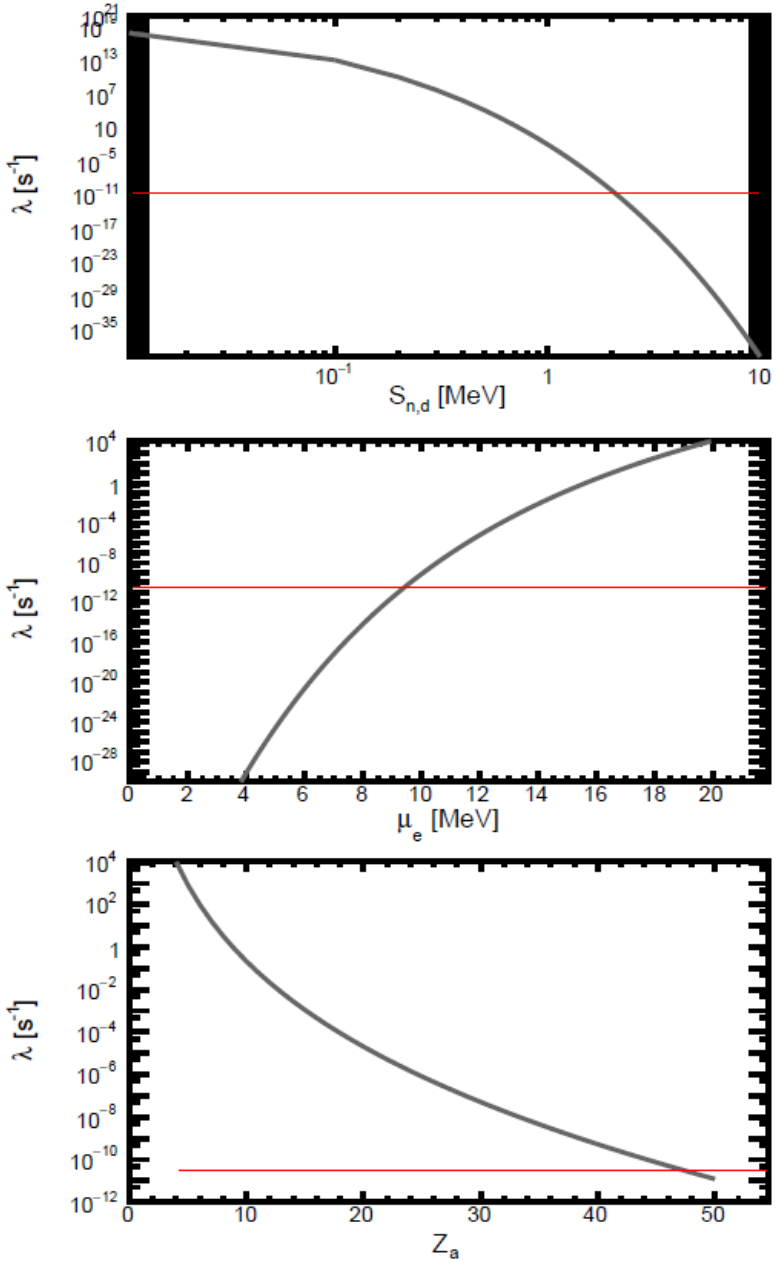
$$\mathfrak{n}_\mathrm{a}(l) = n_\mathrm{a}\,g_\mathrm{ad}(l)$$

$$\lambda = 4\pi n_\mathrm{a} l_\mathrm{pk}^3\sqrt{\frac{\pi l_\mathrm{pk}}{a_\mathrm{ad}\,\Gamma_\mathrm{ad}}}W(l_\mathrm{pk})g_\mathrm{ad}(l_\mathrm{pk})$$

A. Chugunov MNRAS 2018

(very approximate) neutron transfer reaction rates



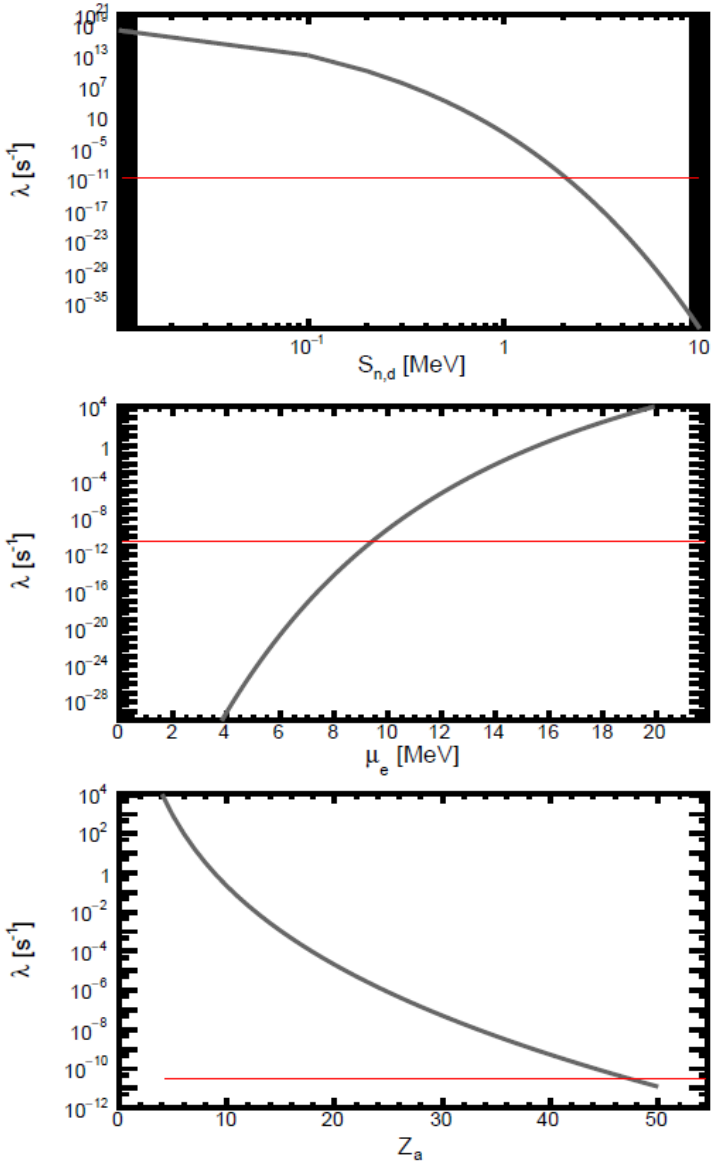


Fast enough to burn-out some urca nuclei in hours

Guess for the n-transfer impact

- Work is ongoing to assess the impact in a crust network calculation …but let's guess what will happen anyways
- Rates are fastest for low S_n donors (~< 3MeV)
  high Q_{EC}
  low-Z acceptors
- So, a few MeV from n-drip (where EC,xn might happen anyways), we might expect urca nuclides to donate their neutron to the highest X(A) low-Z nucleus (whatever A=28 is at that depth)
- That will re-shuffle odd-A abundances into A=29
- For Urca candidates, A=29 has one of the deepest capture depths (largest QEC) and has Sn>3MeV, …so this Urca cooling would be enhanced

Red line is typical accretion timescale for urca nucleus depths (at ~Eddington)

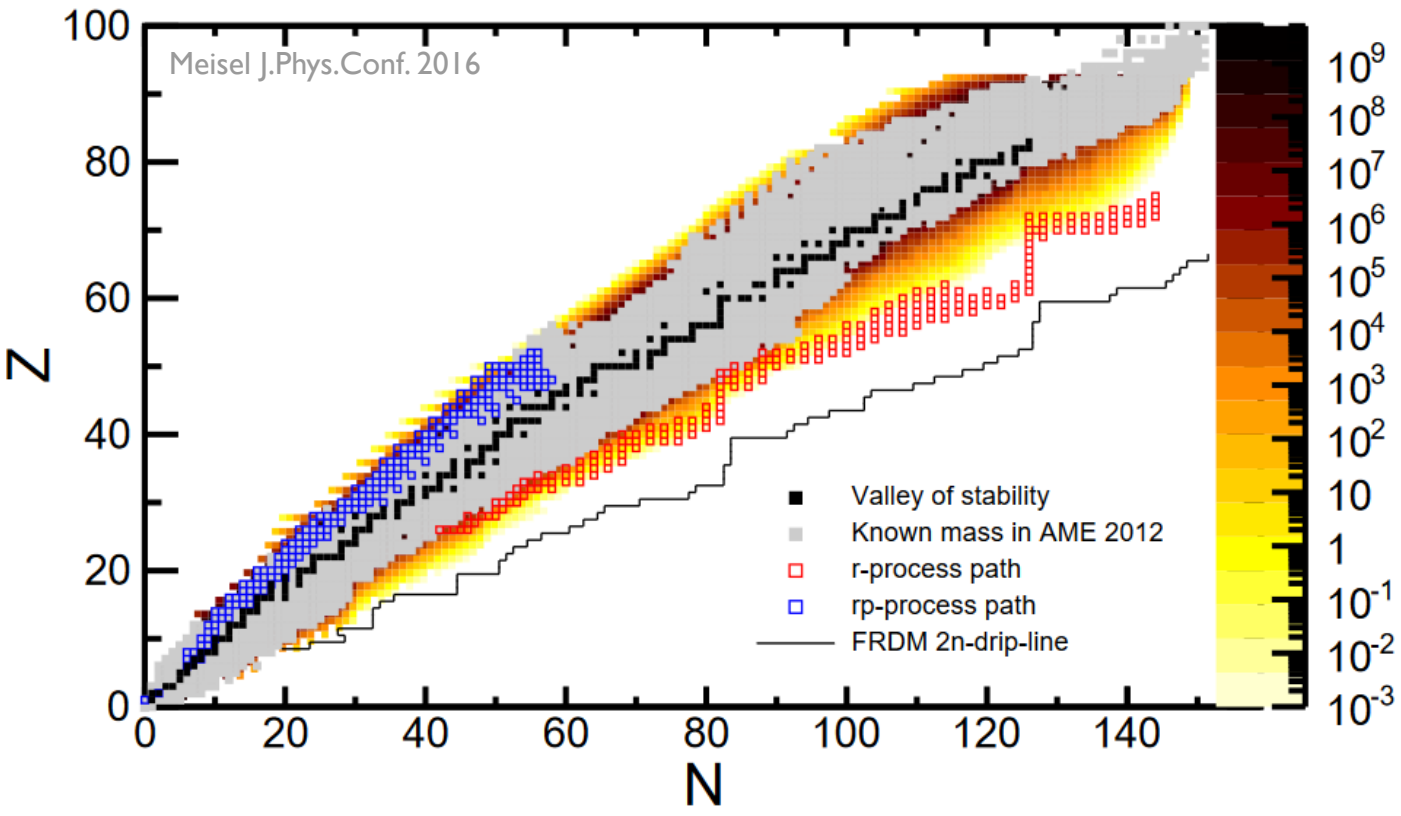


Meisel & Deibel ApJ 2017

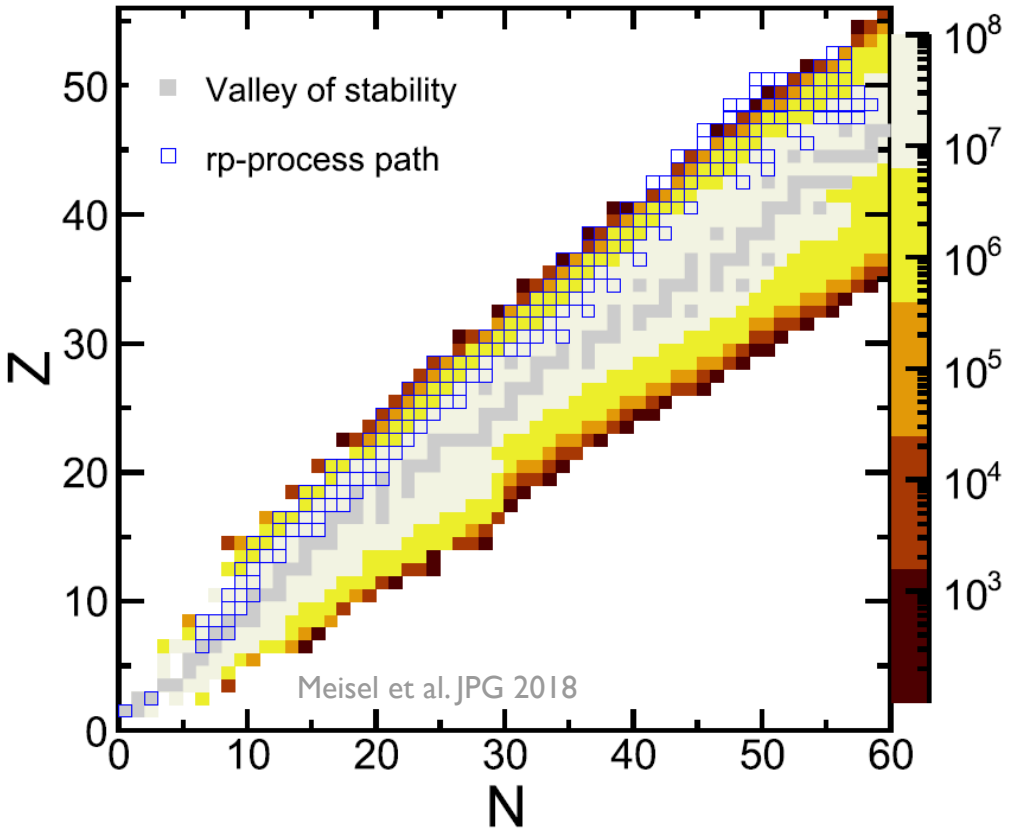
EC Parent	$\lvert Q_{EC}\rvert$ (MeV)
^{29}Mg	13.3
^{31}Al	11.8
^{33}Al	13.4
^{55}Sc	12.1
^{57}Cr	8.3
^{57}V	10.7
^{59}Mn	7.6
^{63}Cr	14.7
^{65}Fe	10.3
^{65}Mn	11.7

FRIB will drastically expand our experimental reach

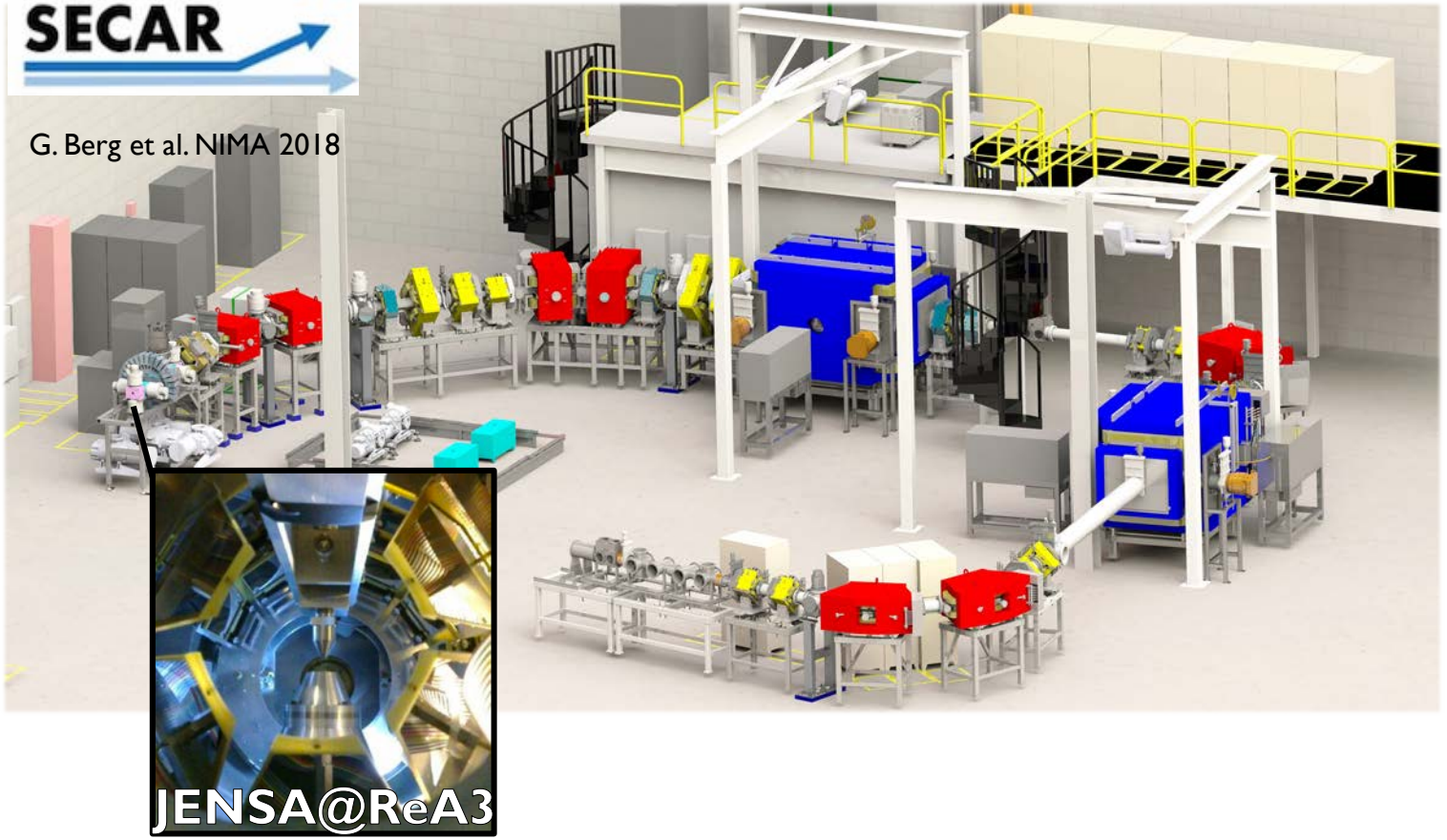
Fast beam rates in pps



Reaccelerated beam rates in pps



New tools at FRIB multiply the impact, e.g. SECAR



K. Schmidt et al. NIMA2018

Areas for improvement (in terms of nuclear physics)

- Targeted indirect measurements & calculations for key rp-process reaction rates
- Direct measurements of rp-process reaction rates
- Measurements of $^{12}C+^{12}C$ to lower energies
- N=82 evolution with decreasing Z
- Accurate electron-capture rate calculations
- Charge-exchange measurements off stability for electron-capture rates
- Measurement & calculation of structure of exotic nuclides (for EC and EC,xn)
- Less approximate estimates for neutron-transfer rates