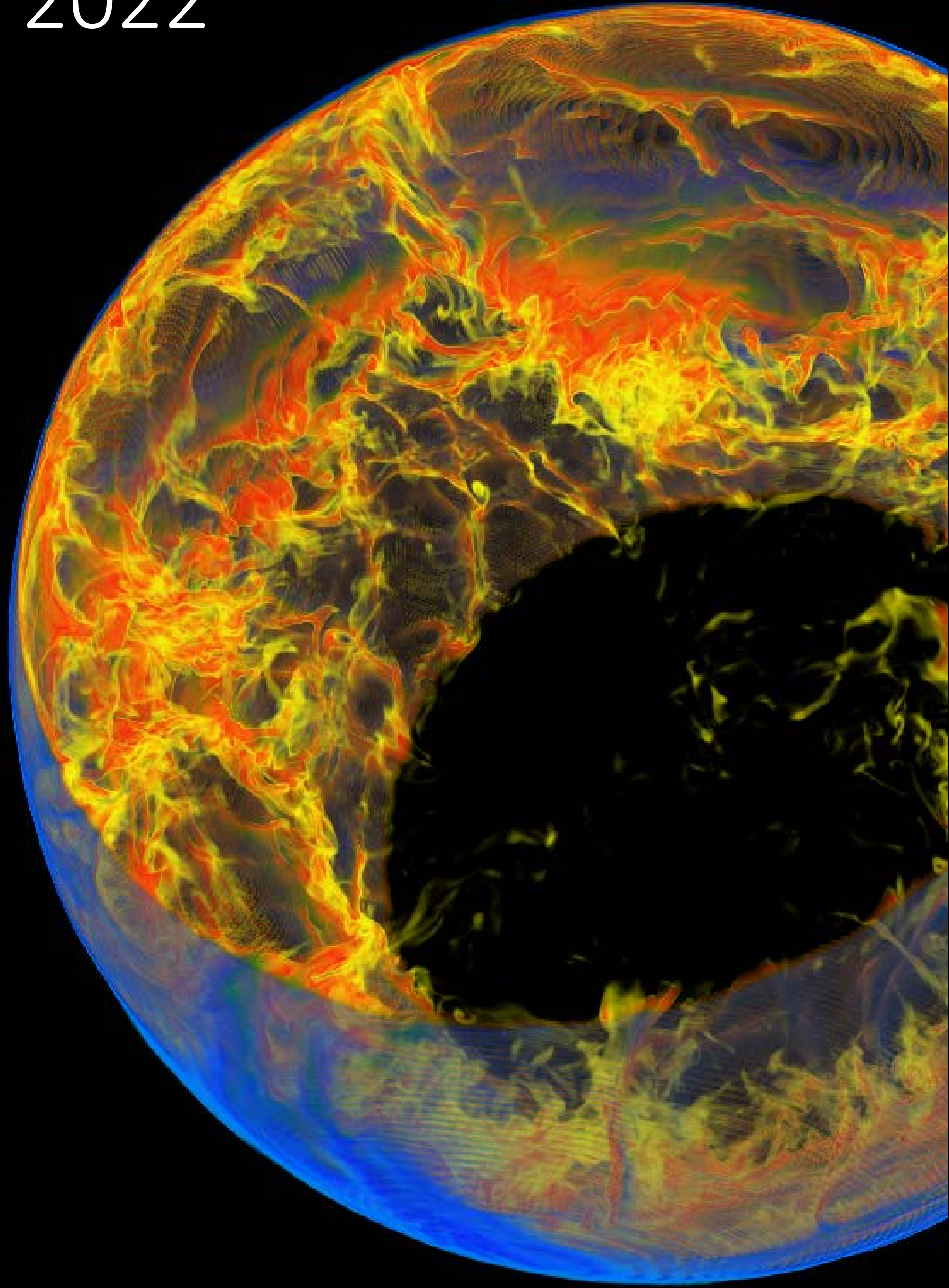
National Nuclear Physics Summer School 2022

Nuclear Astrophysics Lectures

Zach Meisel (Ohio University)

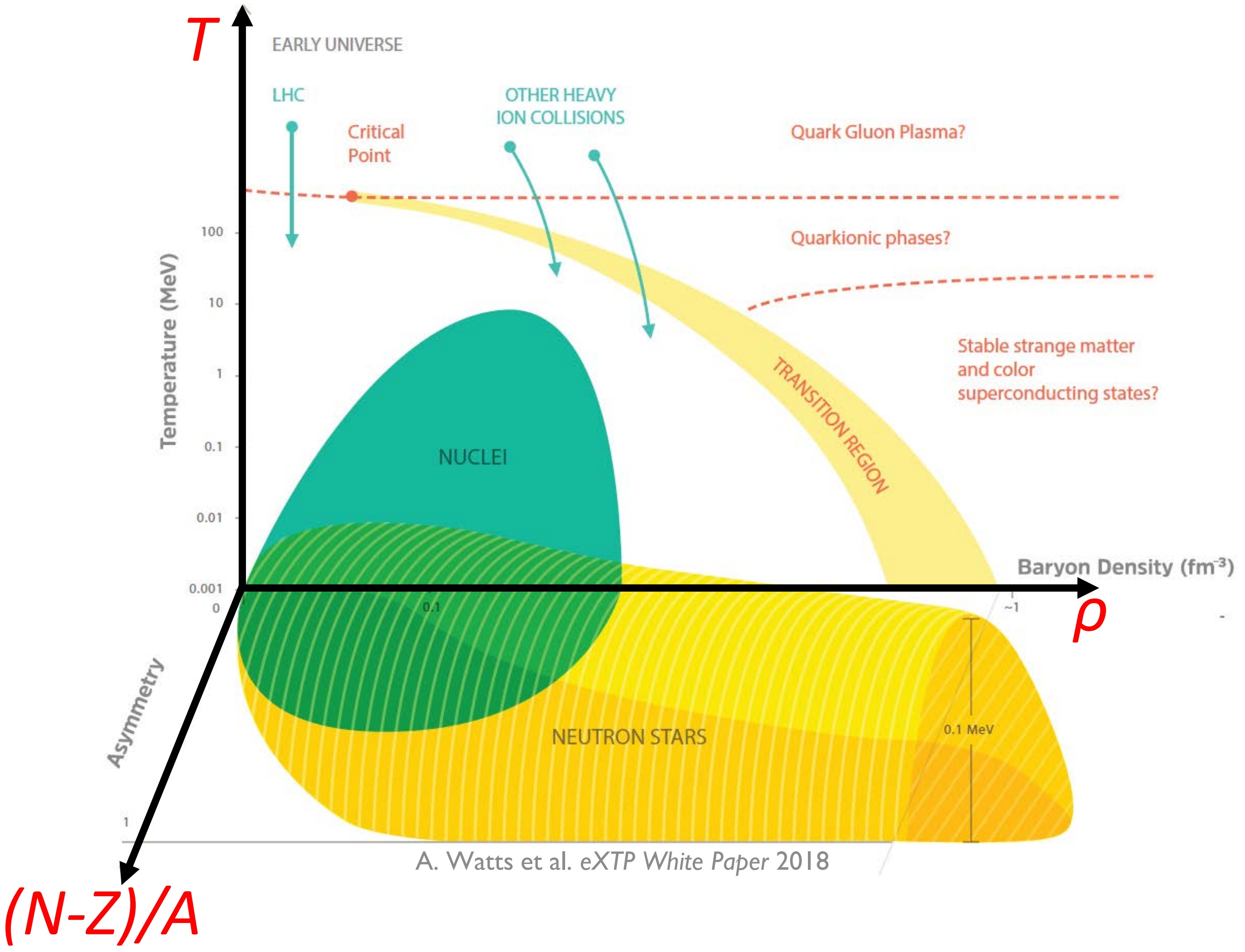
Lecture 1: Astrophysical Reaction Rates
Lecture 2: Nucleosynthesis
Lecture 3: Accreting Neutron stars



Lecture 3: Accreting Neutron Stars

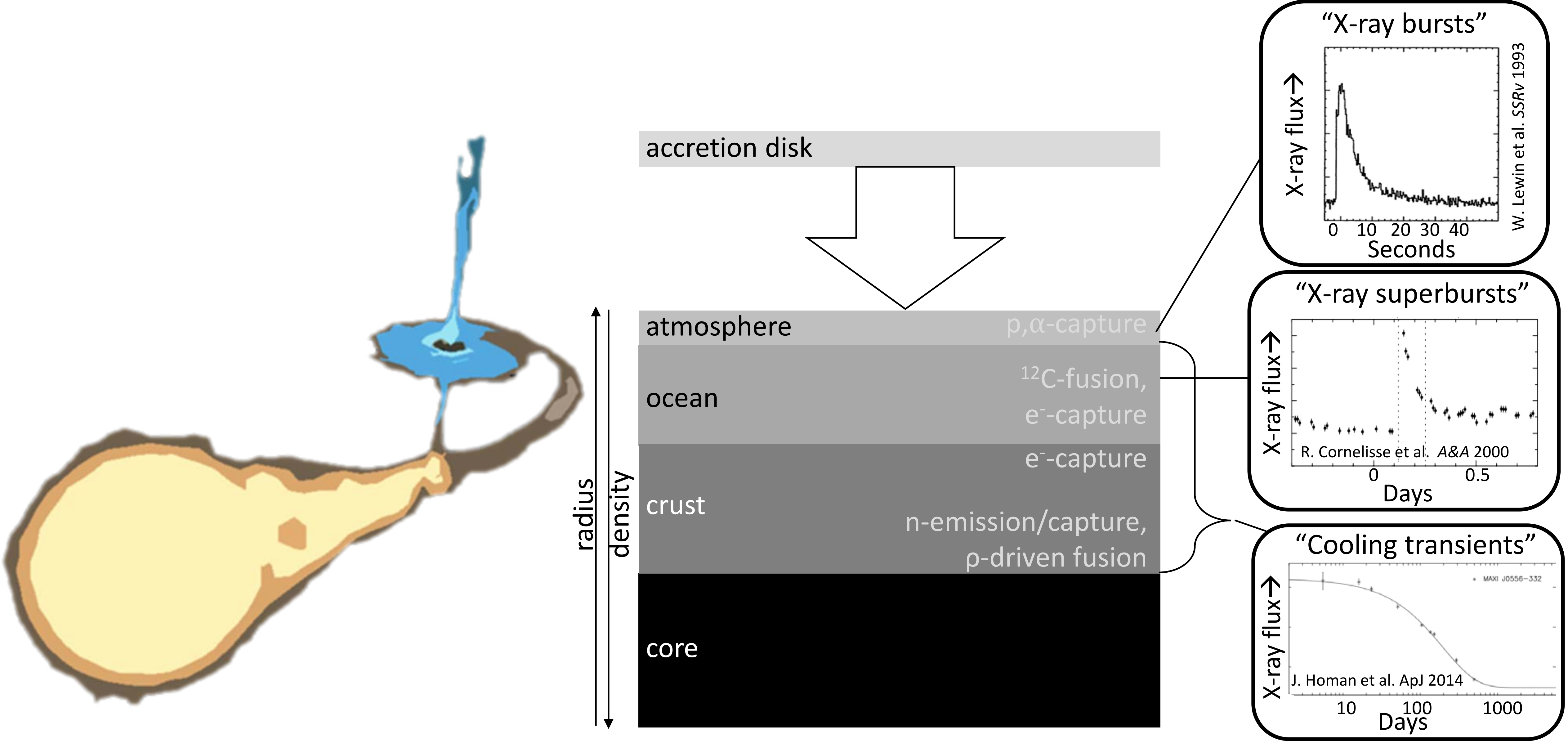
- Overview of the system
- Example: The ^{22}Mg branch-point
- XRB Connection to the NS Crust
- Crust Connection to Superbursts

Neutron stars provide unique access to high-density, low-temperature matter



A. Watts et al. *eXTP White Paper* 2018

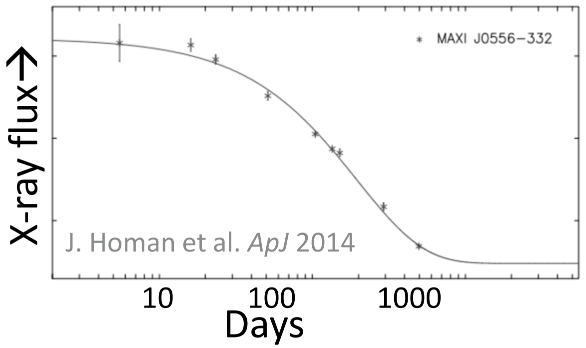
Accreting Neutron Stars: *Dense Matter Laboratories*



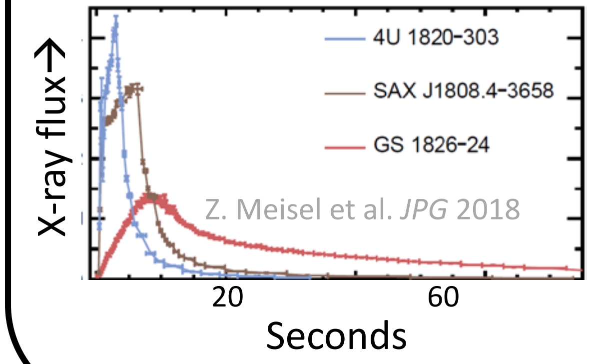
The approach to understanding dense matter behavior:

Observations

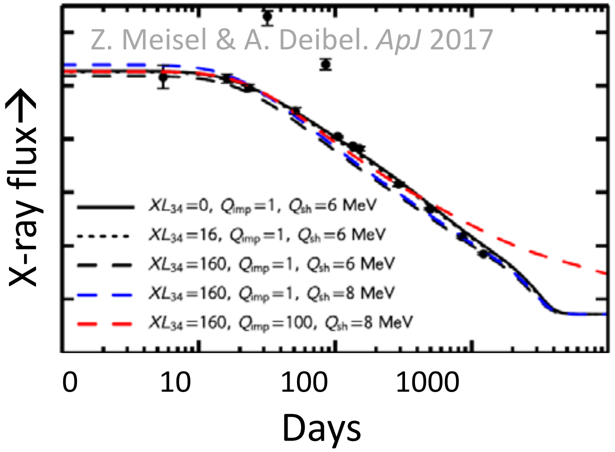
Cooling transients:

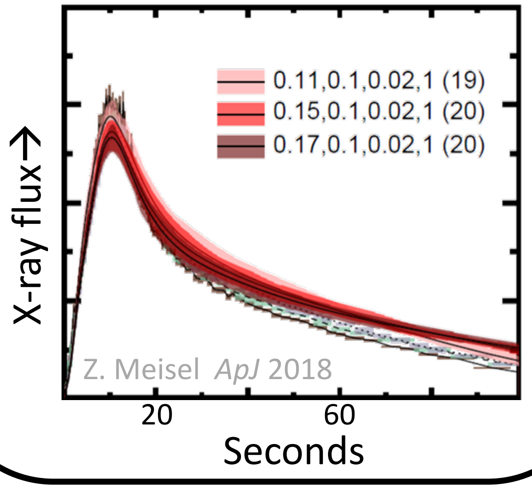


X-ray bursts:

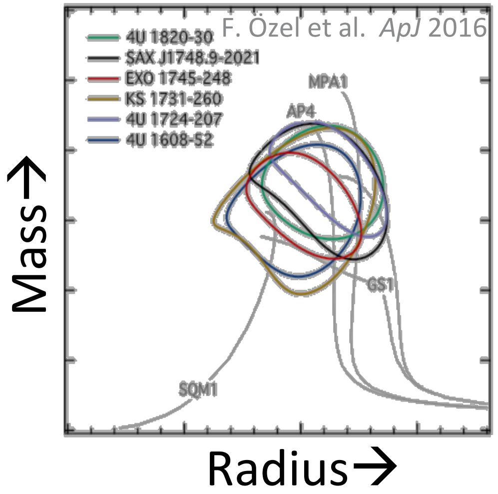


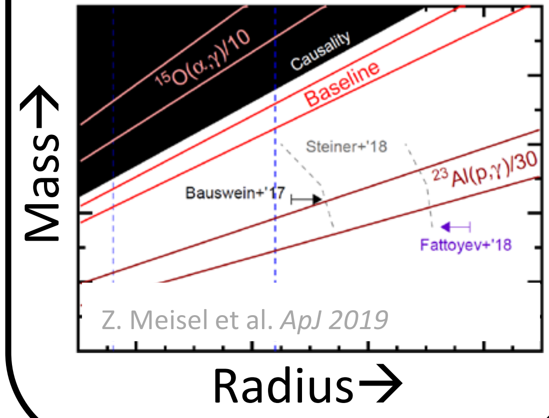
Models



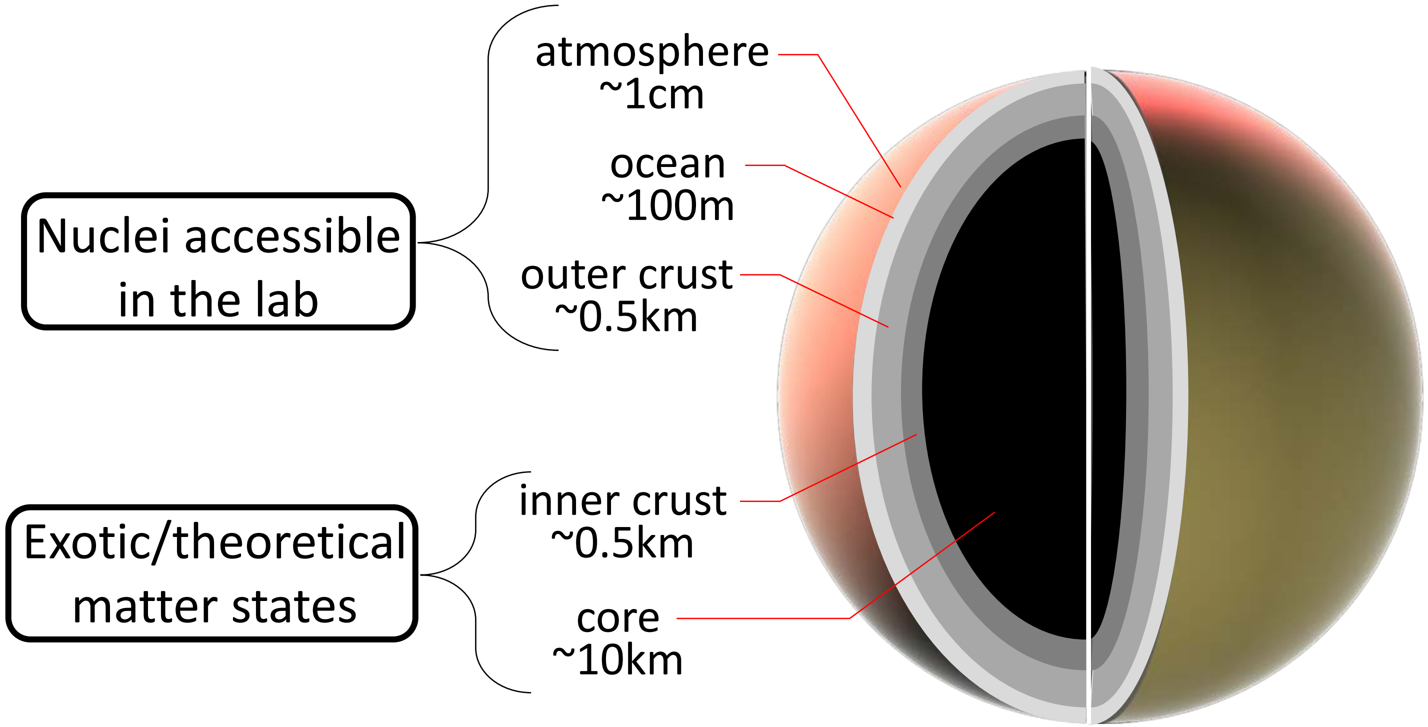


Insight into Nature

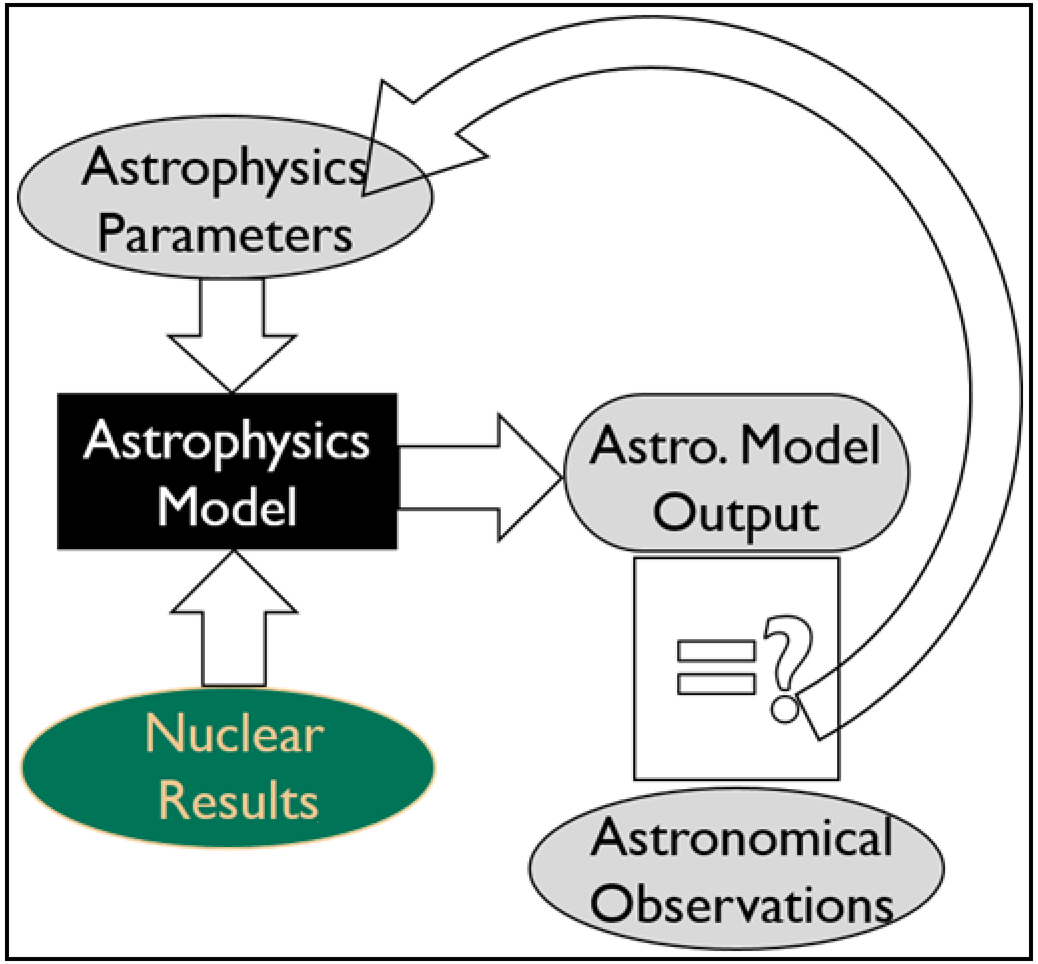




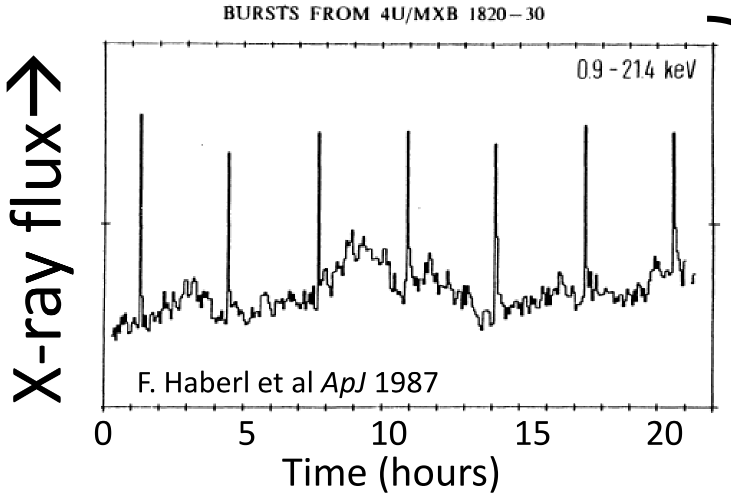
What does this have to do with nuclear physics?

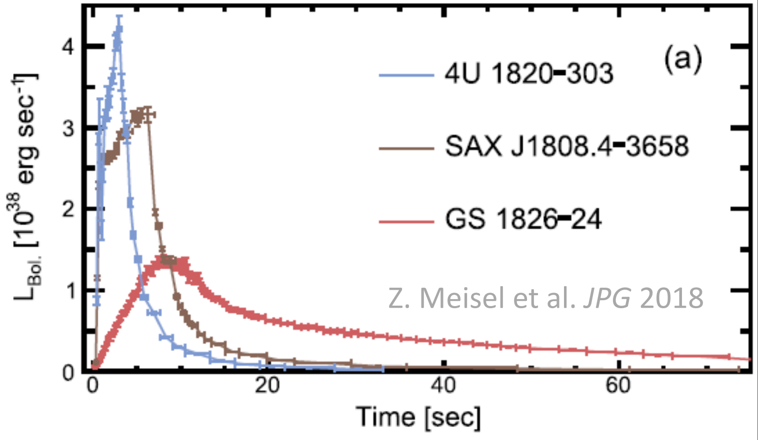


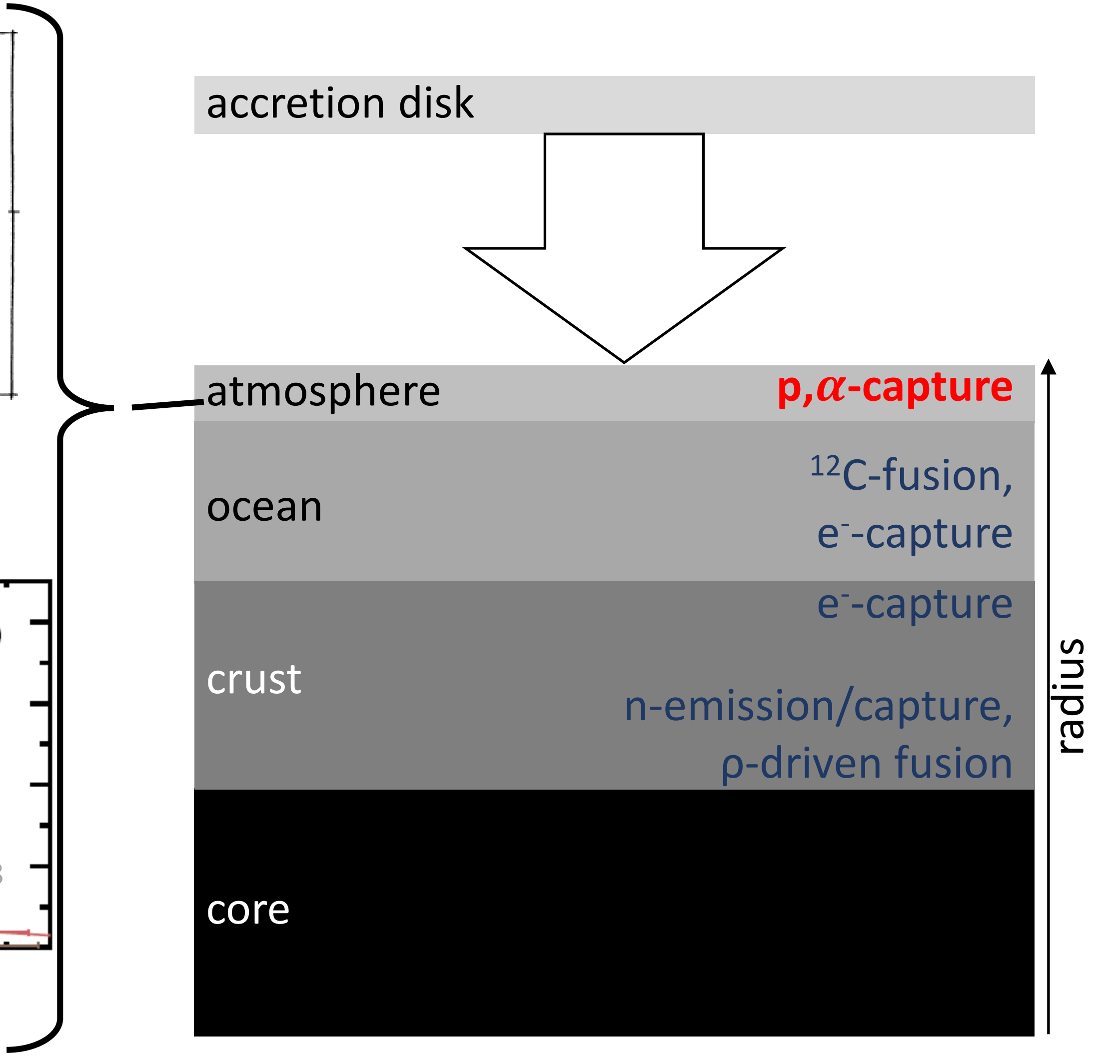
Nuclear Astrophysics Machine:

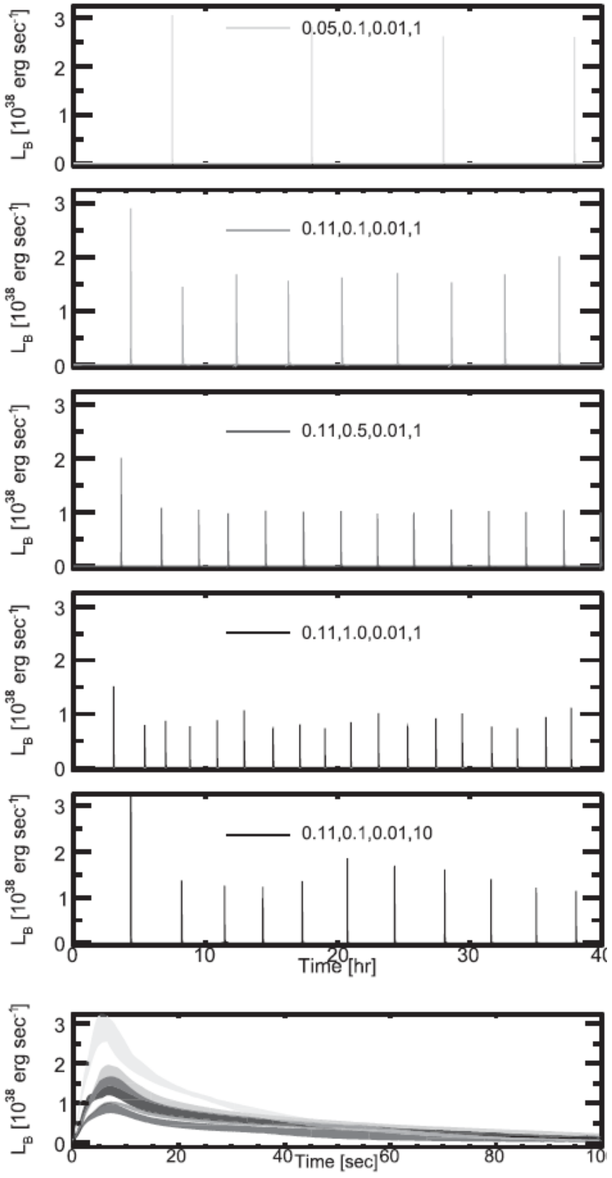


Type-I x-ray bursts:
hydrogen & helium burning on the neutron star surface





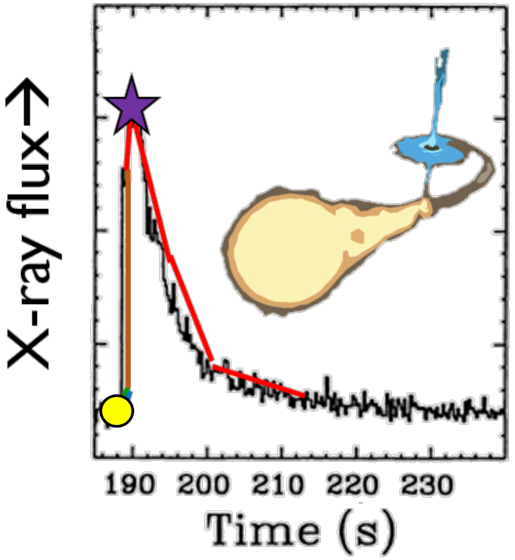


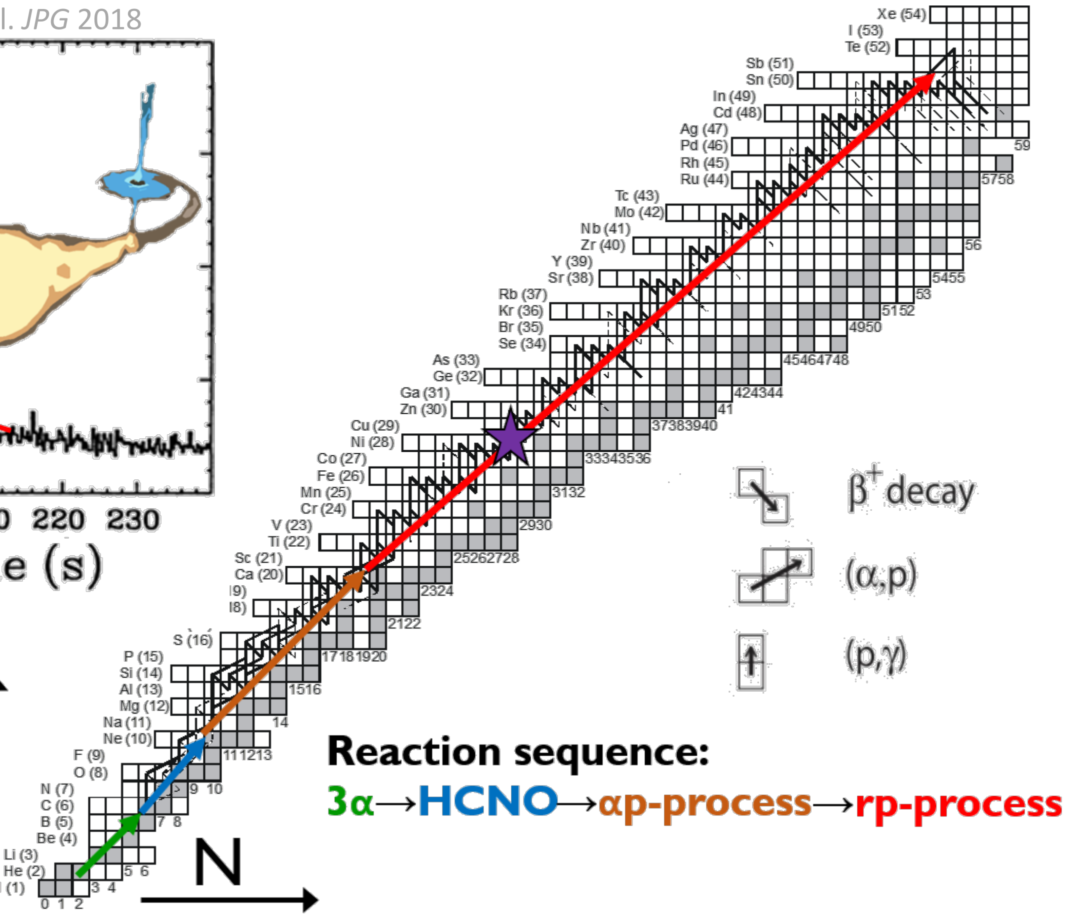


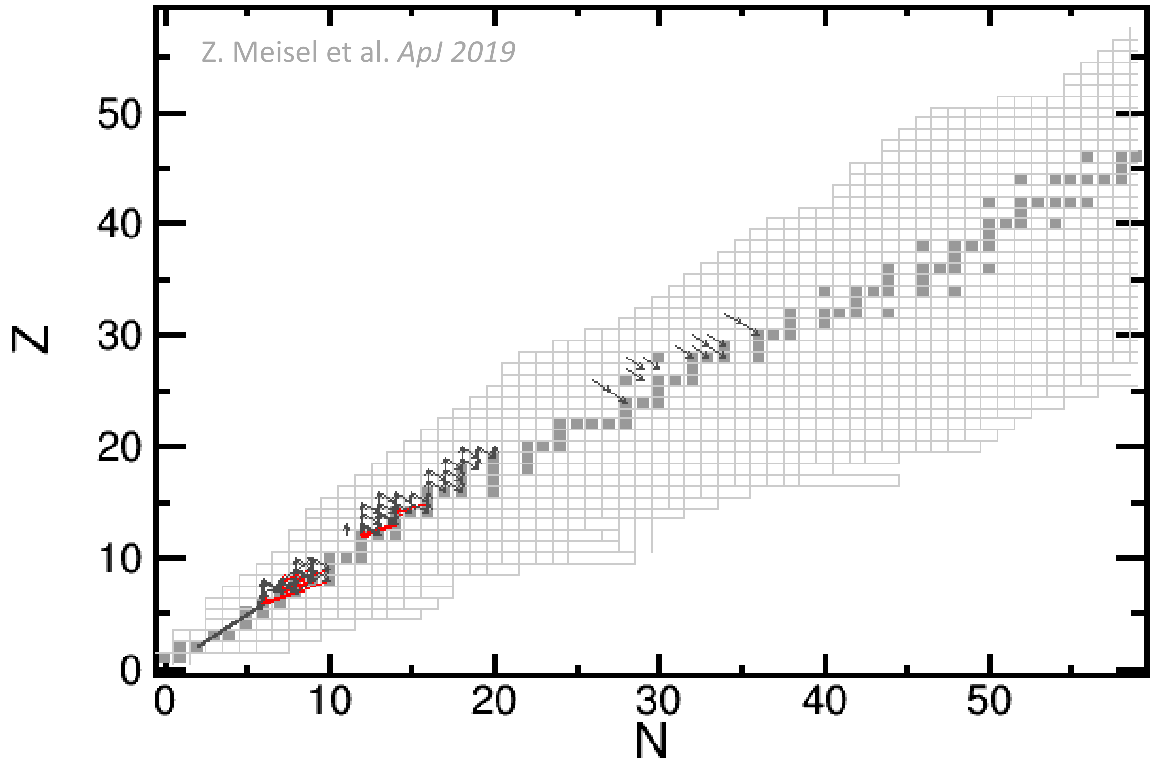
Z. Meisel *ApJ* 2018

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

Z. Meisel et al. *JPG* 2018



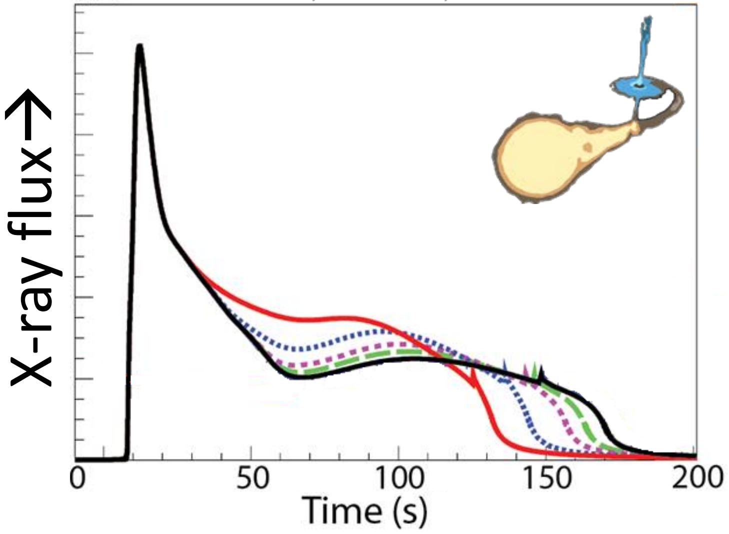




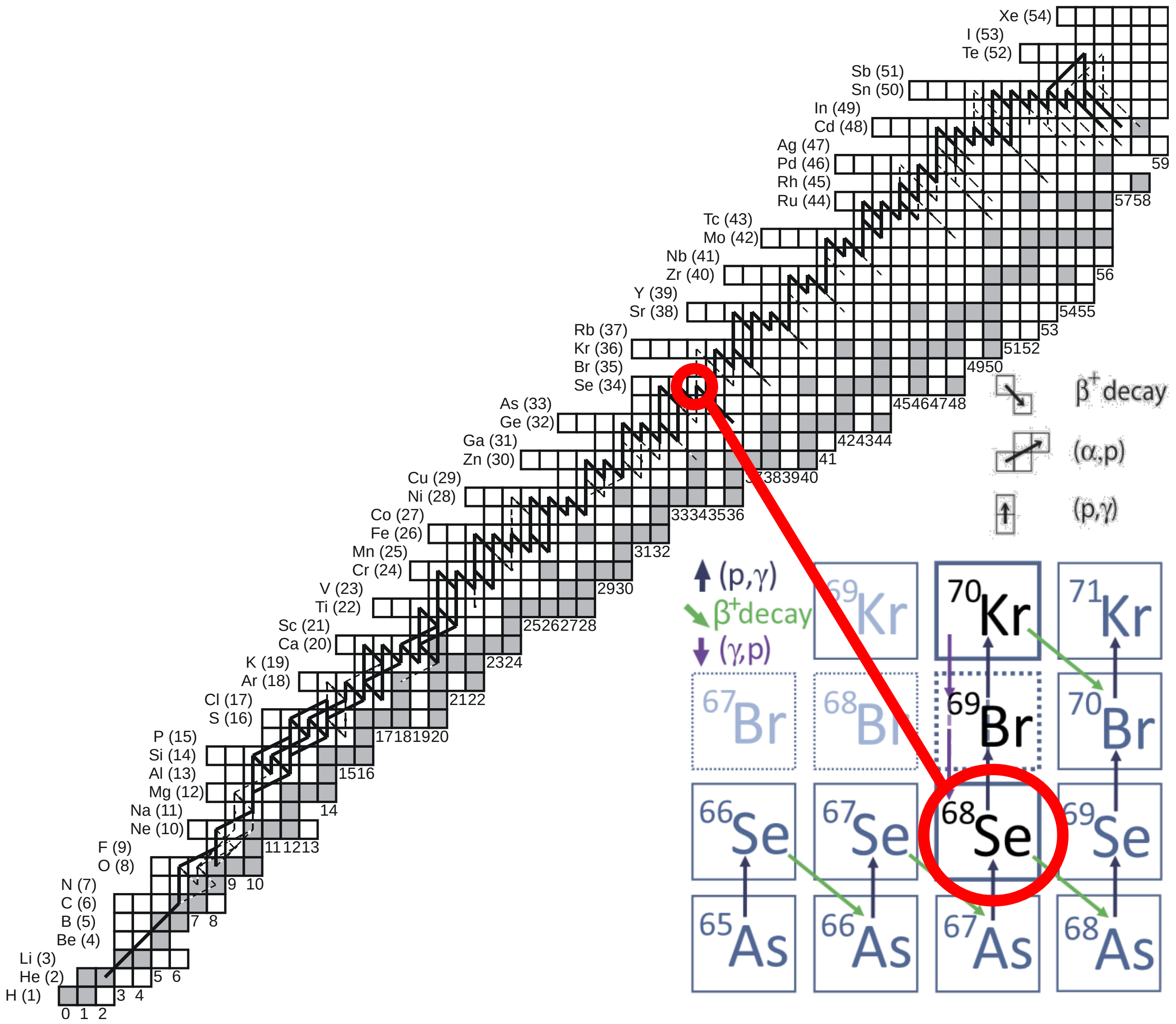
X-ray burst calculations are sensitive to nuclear physics

Model output:

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



Model:



rp-process reaction categories & rough locations

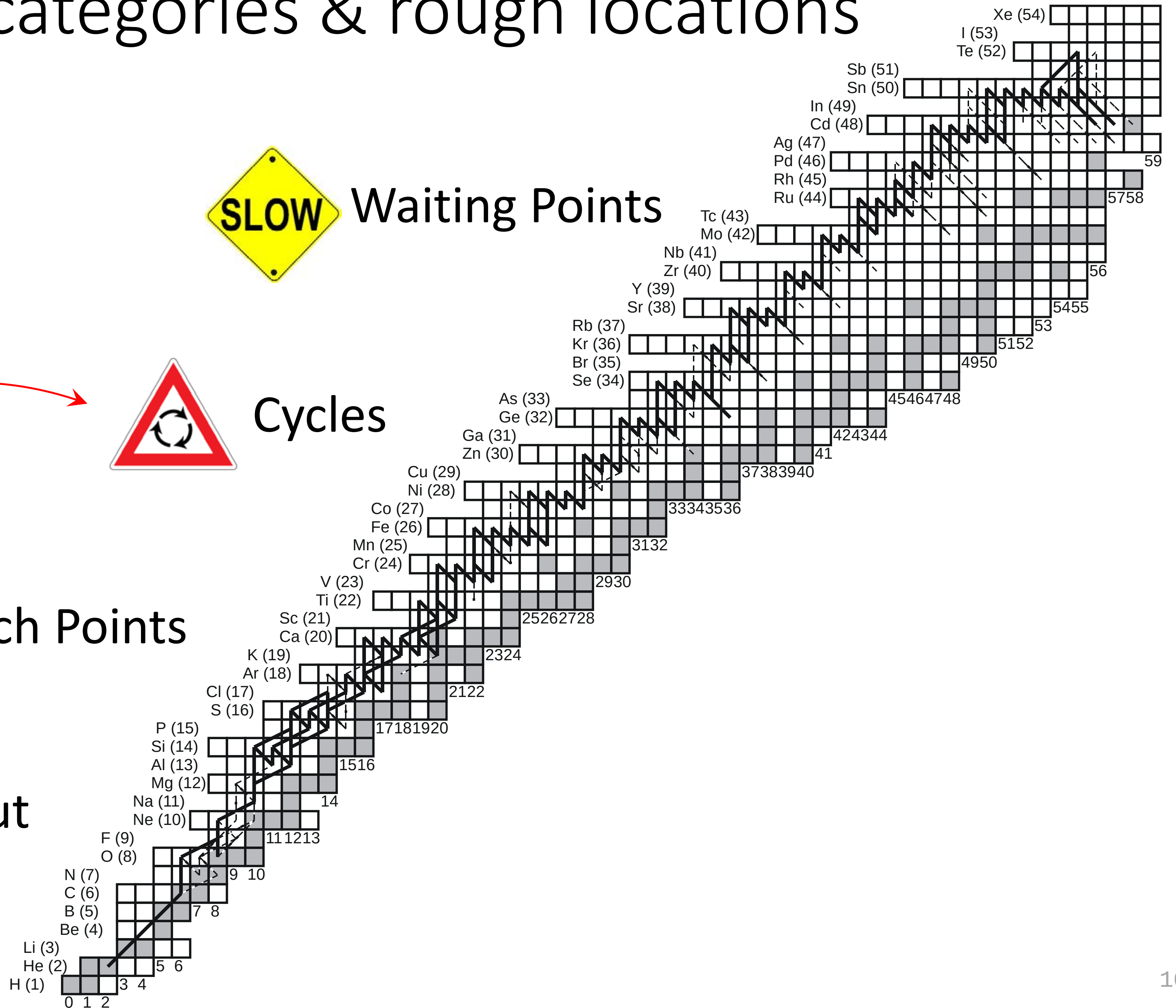
Waiting Points

often referred to as "waiting points" in the literature

Cycles

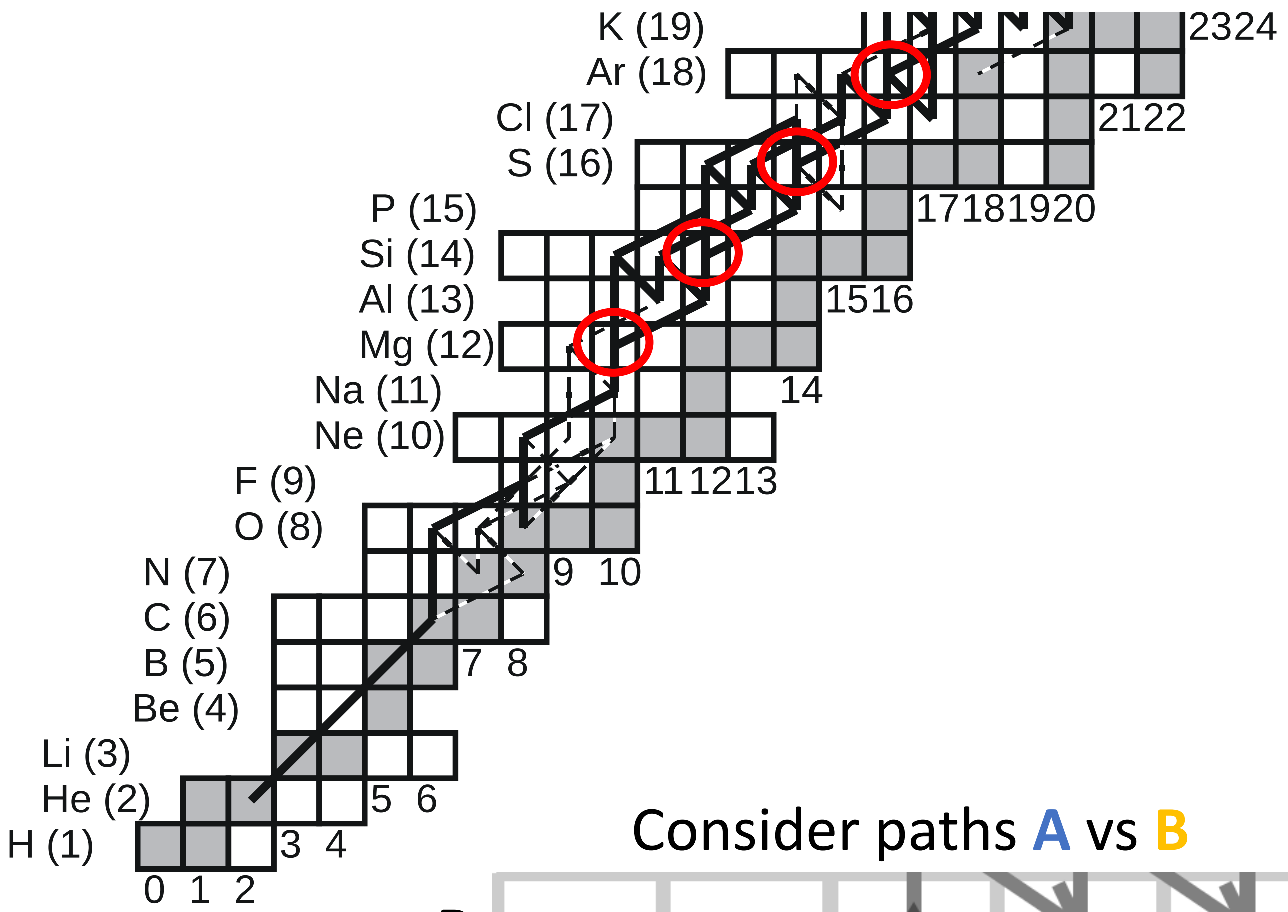
Branch Points

Ignition/Breakout

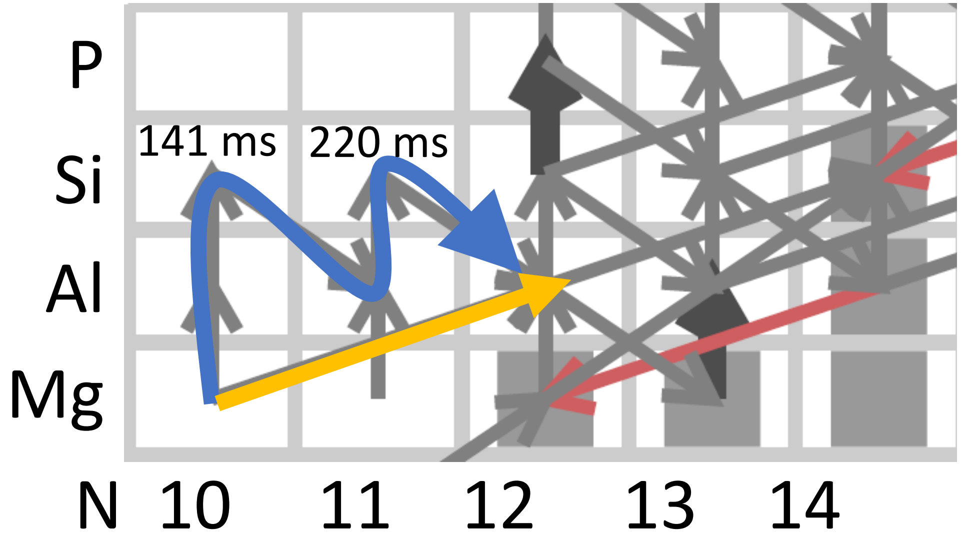


Branch Points

- 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. In particular, the (p,γ) rate above branch-point is critical.
  (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



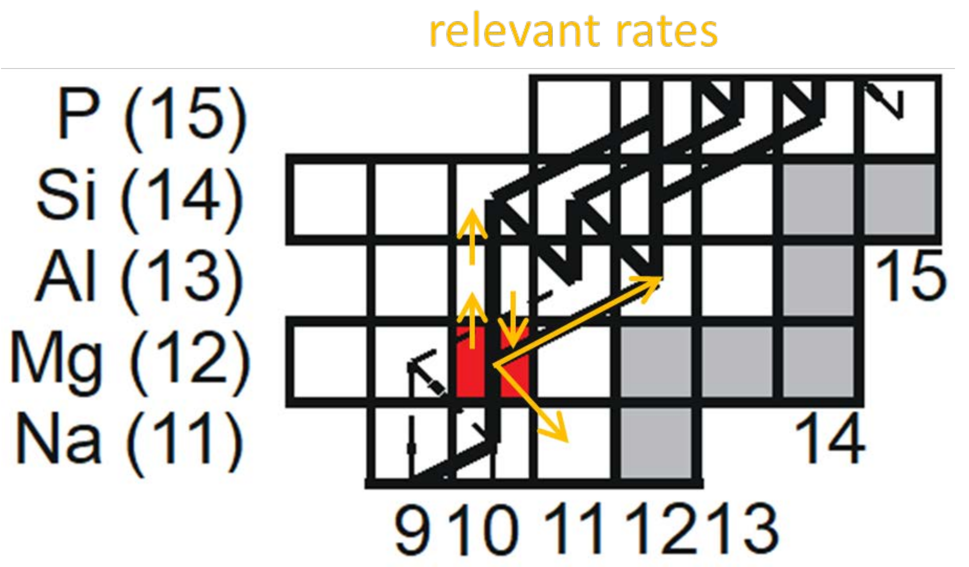
Consider paths A vs B



Example: ^{22}Mg waiting-point

- **Question of interest:**
  when does the αp-process, which impacts energy generation during the XRB rise, ensue?

- Note that the flow is pretty simple:
  just 3 pathways competing to destroy ^{22}Mg.
- So, we can assess the impact of modifying one of these rates by directly comparing rates.
- Decay rate per ^{22}Mg: $\lambda_\beta = \dfrac{\ln(2)}{t_{1/2}}$
- Strong rate per target nuclide: $\lambda_{\langle\sigma v\rangle} = \dfrac{X_{\text{fuel}}}{A_{\text{fuel}}}\rho N_A\langle\sigma v\rangle$
- Flow percentage: $F_i = 100\dfrac{\lambda_i}{\sum_j \lambda_j}$



The decay branch from ^{22}Mg is negligible for XRBs

- Decay rate: $\lambda_\beta = \frac{\ln(2)}{t_{1/2}}$
  - For ^{22}Mg, $t_{1/2} = 3.876\ s$ …this is the typical time for ^{22}Mg to decay
- Strong rate: $\lambda_{\langle\sigma v\rangle} = \frac{X_{\text{fuel}}}{A_{\text{fuel}}}\rho N_A \langle\sigma v\rangle$
  - For an example helium mass-fraction of $Y = 0.2$, density of 10^5 g/cm^3, and temperature of 1 GK, the timescale for α-capture by ^{22}Mg is
    $$1/\lambda \approx 1 \div \left(\frac{0.2}{4g/mol}\right)(10^6\ g/cm^3)(10^{-5}cm^3/mol \cdot s) = 2s$$
  - For a temperature of 1GK, reactions with a (p,γ) Q-value below 0.9 MeV are in $(p,\gamma)-(\gamma,p)$ equilibrium, via reciprocity [See Meisel+ JPG 2018, equation 9]. So we care about ^{23}Al(p,γ) capture on the equilibrium abundance of ^{23}Al. For an example hydrogen mass-fraction of $X = 0.03$, density of 10^6 g/cm^3, and temperature of 1 GK, the timescale for proton-capture by each ^{23}Al is
    $$1/\lambda \approx 1 \div \left(\frac{0.03}{1g/mol}\right)(10^6\ g/cm^3)(1cm^3/mol \cdot s) = 3 \times 10^{-5}s$$
- At higher temperatures, the (α,p) timescale will only get shorter and at lower temperatures, the (p, γ) timescale isn't as slow as the beta-decay until ~0.1GK (well below the XRB breakout temperature)

We need to consider equilibrium abundances

- The ratio of mass in ^{23}Al versus ^{22}Mg is set by the Saha equation
$$\frac{n_{Z,A}}{n_{Z+1,A+1}} \approx \frac{2}{n_p}\left(\frac{\mu_{\text{red}} k_B T}{2\pi\hbar^2}\right)^{3/2} \frac{g_{Z,A}}{g_{Z+1,A+1}} \exp\left(\frac{-Q_{p,\gamma}}{k_B T}\right)$$
- Assuming both are in the ground-state (which they will be for ~1GK), each $g_i = 1$
- However, the flow depends on the fraction of mass in the waiting-point or proton-capture daughter, not the ratio. So we need $\frac{N_{Z+1,A+1}}{N_{Z+1,A+1}+N_{Z,A}}$.
- This a common textbook problem in astrophysics for ionization fractions (See e.g. Ed Brown's "To Build A Star" problem 4.2).
To solve it, define $x = \frac{n_{Z+1,A+1}}{n_{Z+1,A+1}+n_{Z,A}} \equiv \frac{n_{Z+1,A+1}}{n}$, write out $\frac{(1-x)^2}{x}$, and note $1 - x = \frac{n_{Z,A}}{n}$. For a system of just the daughter $(Z+1, A+1)$, waiting-point (Z, A) and protons, then $n_{Z,A} = n_p$. So $\frac{(1-x)^2}{x} = \frac{n_{Z,A}^2}{n^2}\frac{n}{n_{Z+1,+A+1}} = \frac{n_{Z,A}^2}{n n_{Z+1,A+1}} = \frac{n_p n_{Z,A}}{n n_{Z+1,A+1}}$. The red bit is the Saha equation. So $\frac{(1-x)^2}{x} = \frac{n_p}{n}\frac{2}{n_p}\left(\frac{\mu_{\text{red}} k_B T}{2\pi\hbar^2}\right)^{3/2} \frac{g_{Z,A}}{g_{Z+1,A+1}} \exp\left(\frac{-Q_{p,\gamma}}{k_B T}\right)$. Solving for x, you get the fraction of mass in the waiting-point daughter, depending on the temperature & density.

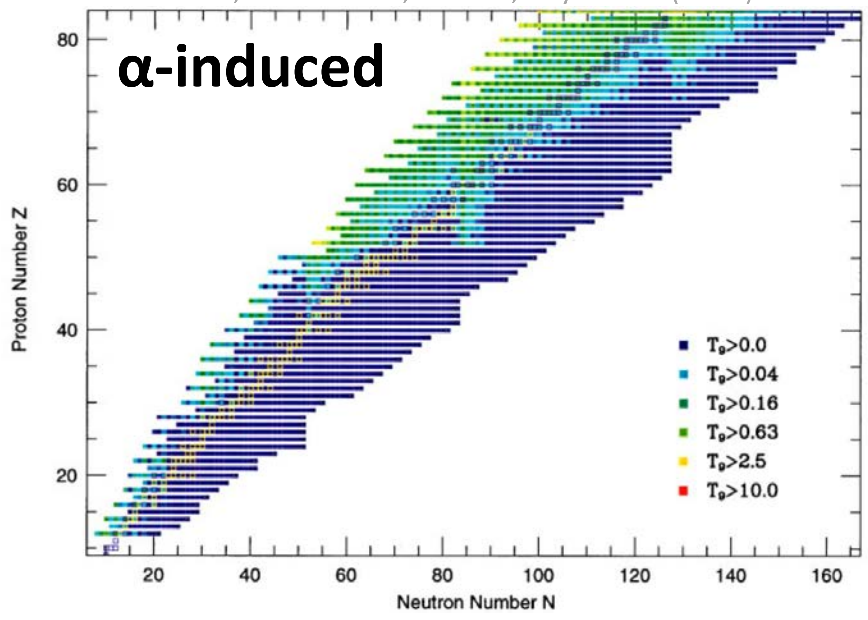
Waiting-point flow, accounting for equilibrium abundance

- The rates described earlier were *per target nucleus*, i.e. per ^{22}Mg or per ^{23}Al.
  However, the number of ^{22}Mg and ^{23}Al are related by equilibrium. We'll call a nucleus that is either ^{22}Mg or ^{23}Al and "equilibrium nucleus".
- The relevant rate for flow out of the waiting point is the *rate per equilibrium nucleus*.
  So we need to take our capture rates apply the fractions x and $1-x$, which we can call weighting factors W_i
- Then the rates per generic nucleus will be $\lambda_i = W_i \frac{X_{\text{fuel}}}{A_{\text{fuel}}} \rho N_A \langle \sigma v \rangle$, where the fuel is hydrogen for (p,γ) and helium for (α,p).
- The flow through the ^{22}Mg (α,p) branch is : $F_{\alpha,p} = 100 \frac{\lambda_{\alpha,p}}{\lambda_{\alpha,p}+\lambda_{p,\gamma}} \%$

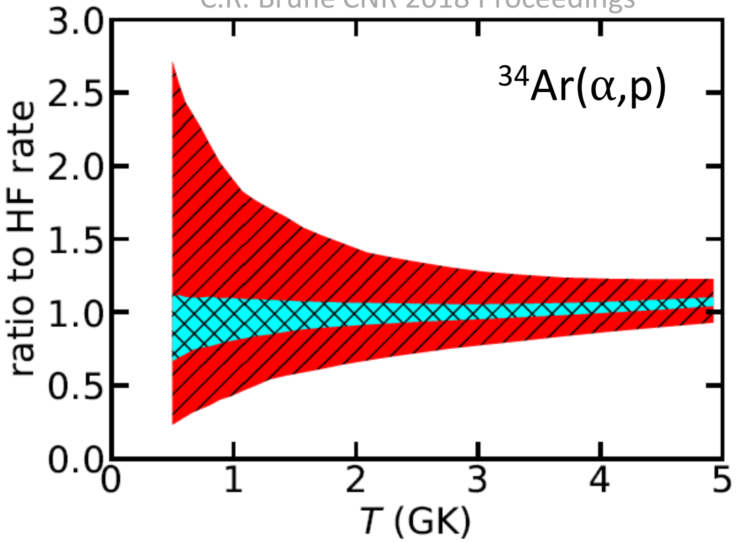
Aside: resonance vs statistical reaction rate estimates

- If we can't directly measure the cross-section in the energy window of interest (which is usually the case), we need to decide if we will treat the reaction in terms of individual resonances or as an ensemble of states that we will describe statistically
  - i.e. do we use the Narrow-Resonance (NR) or Hauser-Feshbach (HF) formalism?
  - NR: $N_A\langle\sigma v\rangle_{N\,res.} = \frac{1.54\times10^{11}}{\left(\frac{A_1A_2}{A_1+A_2}T_9\right)^{3/2}}\sum_{i=1}^{N}(\omega\gamma)_{R,i}\exp\left(-\frac{11.6045E_{R,i}}{T_9}\right)\frac{\mathrm{cm}^3}{\mathrm{mol\,s}}$
  - HF: $\sigma_{X(a,b)Y}^{HF} = \pi\left(\frac{\lambda}{\pi}\right)^2\sum_J\frac{2J+1}{(2J_a+1)(2J_X+1)}W_{ab}\frac{T_{aX}T_{bY}}{\sum_{chan}T_{chan}}$
- A heuristic is that if there are 10 astrophysically-relevant levels per MeV of excitation energy, then the Hauser-Feshbach formalism is valid
- The best is to check this with the statistical-resonance approach, statistically generating levels & level properties, calculating the NR rate and comparing to HF results

Rauscher, Thielemann, & Kratz, Phys.Rev.C (1997)

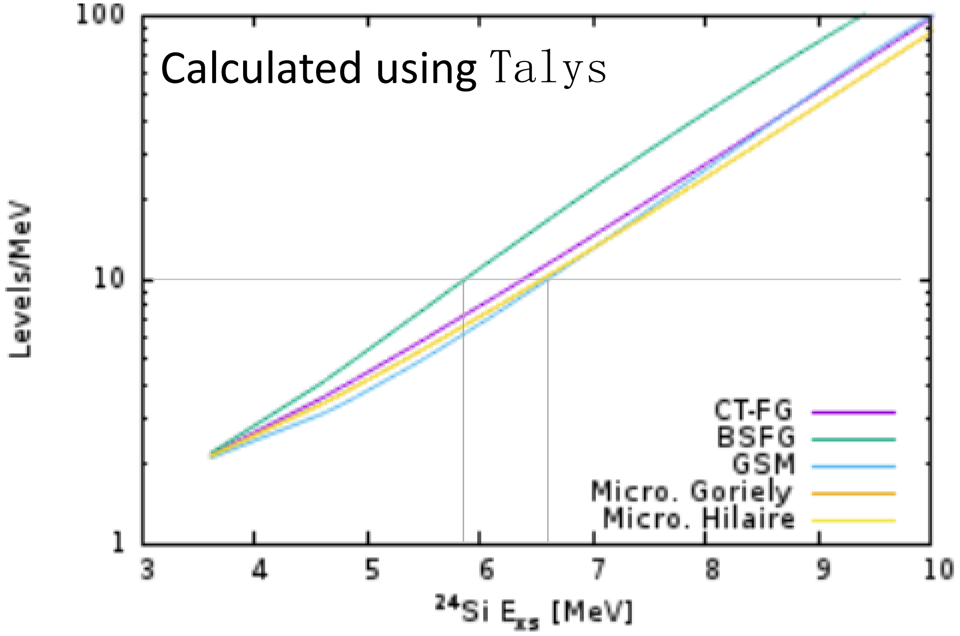


C.R. Brune CNR 2018 Proceedings



The $^{23}Al(p,\gamma)^{24}Si$ reaction rate

- What nuclear physics details do we need?
  - The ^{24}Si proton-separation energy is ~3.3MeV
  - For a peak XRB temperature of 1.5GK, the upper-end of the simple Gamow Window estimate is ~1.3 MeV
  - Therefore the relevant ^{24}Si states are from ~3.3 - 4.6 MeV. The level-density is anticipated to be low enough that the narrow resonance approximation should be used.
- Where do we get this data?
  - Nuclear mass measurements and spectroscopy can provide resonance energies: $E_r = Q - E_{xs}$, spectroscopy and transfer reactions can constrain J_i and the relevant Γ
  - However, only the 1st two excited states have been observed, so we need to rely on shell-model estimates for most state properties



E_x (MeV)	J	l	C^2S	Γ_γ (eV)	Γ_p (eV)
3.449(5)	2	0	0.7(4)	1.9×10^{-2}	1.0×10^{-4}
		2	0.002(1)		
		2	0.3(2)		
3.471(6)	0	2	0.8(4)	1.6×10^{-3}	6.2×10^{-5}
4.256(150)*	3	0	0.59	1.3×10^{-2}	9.0×10^{3}
		2	0.17		
5.353(150)*	3	0	0.0012	2.8×10^{-2}	3.6×10^{3}
		2	0.11		
5.504(150)*	2	0	0.044	2.2×10^{-1}	2.8×10^{4}
		2	0.068		
5.564(150)*	4	2	0.048	2.2×10^{-2}	2.2×10^{3}
6.004(150)*	4	2	0.28	6.5×10^{-3}	2.8×10^{4}
6.056(150)*	0	2	0.053	3.4×10^{-3}	5.6×10^{3}
6.072(150)*	2	0	0.012	5.0×10^{-2}	2.4×10^{4}
		2	0.093		

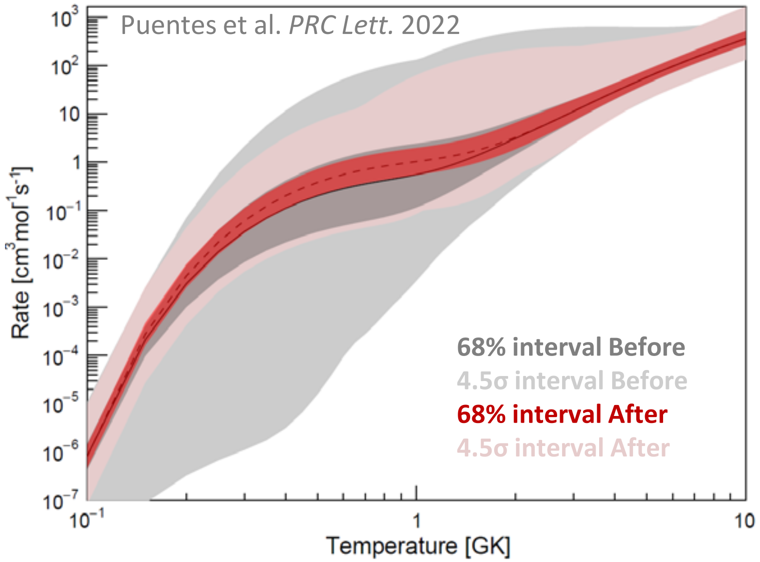
Puentes et al. *PRC Lett.* 2022

Aside: reaction rate uncertainty bands

- Your answer is only as good as your error bar.
- You can Monte Carlo the resonant rate parameters to get uncertainties
  - Normal distribution for masses, excitation energies, and channel radii
  - Log-normal distribution for spectroscopic factors
- Complications:
  - The resonance parameters are not independent! E.g. changing the mass changes the partial widths for the resonance
  - Factor uncertainties are usually more appropriate for theoretical estimates (e.g. x2 for shell-model spectroscopic factors)
- See papers associated with STARLIB (https://starlib.github.io/Rate-Library/) for how to do this and/or use the STARLIB rate library itself

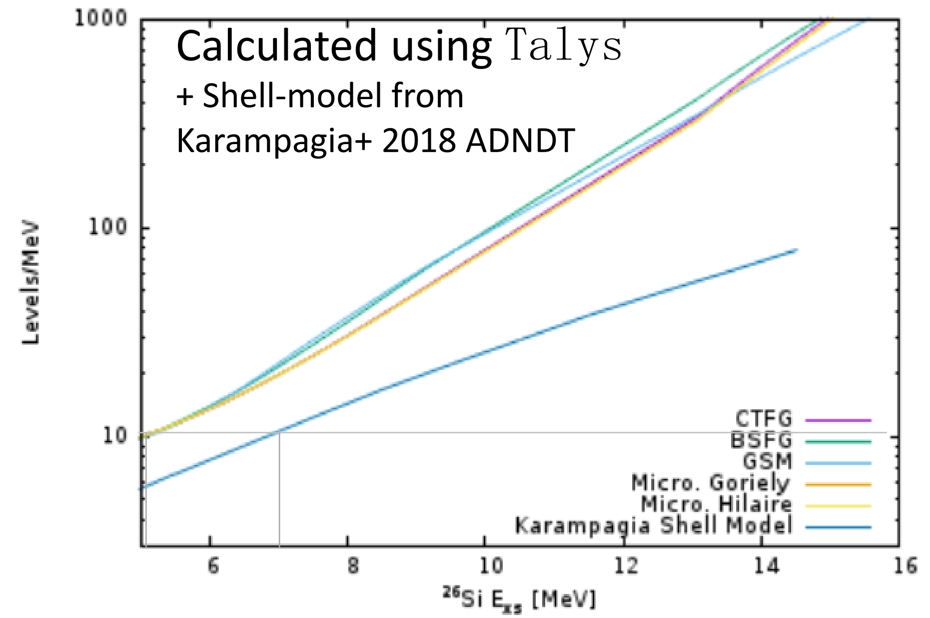
Procedure for you to squint at later:

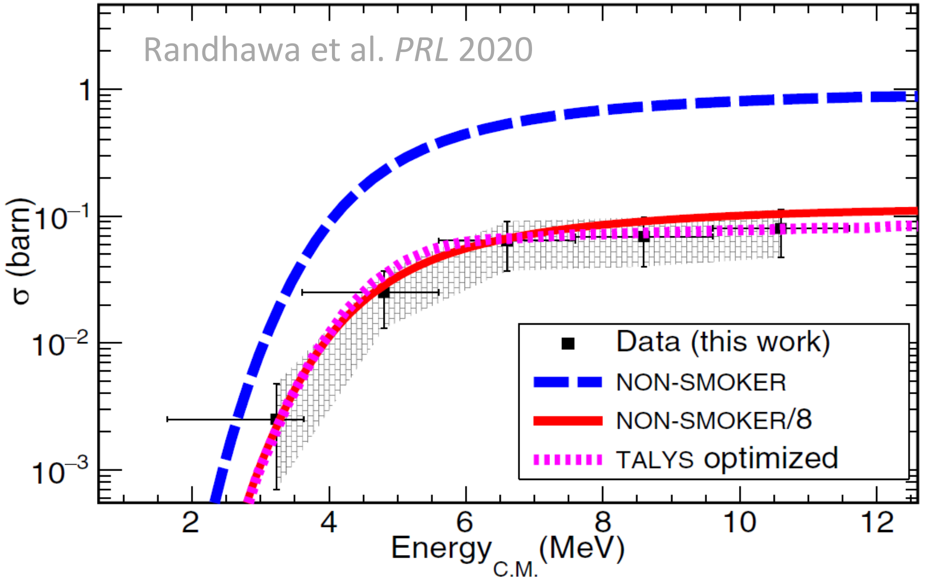
- For each MC iteration:
  1. MC mass within Gaussian uncertainty.
  2. MC channel radius within Gaussian uncertainty.
  3. For each level,
     1. MC each width within lognormal distribution
     2. MC excitation energy within gaussian uncertainty
     3. Scale proton width due to penetrability based on adjusted mass + adjusted excitation energy
     4. Calculate new resonance strength based on new proton & gamma-widths
  4. For DC component,
     1. MC each spectroscopic factor within lognormal distribution
     2. Scale each spectroscopic factor based on original S(E0)
     3. Combine to total S(E0)
  5. Calculate resonant rates in a temperature loop
  6. Sum resonant rates & DC rate for each temperature
- After all MC iterations,
  1. For each temperature, count from bottom to find 16% of iterations (for 68% contour), 50% of iterations (for mid-rate), and 84% of iterations (for 68% contour)



The ^{22}Mg(α,p) reaction rate

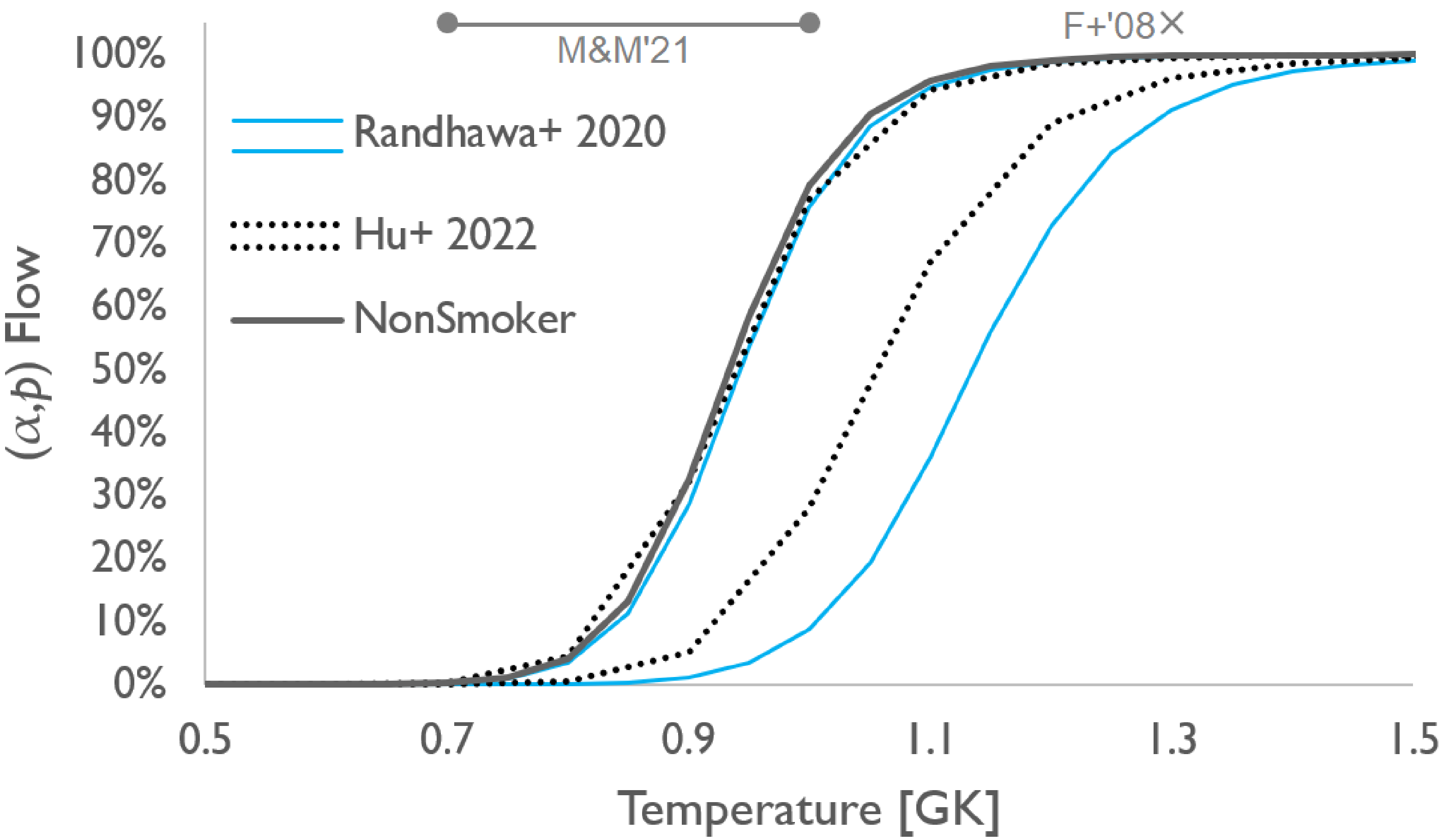
- What nuclear physics details do we need?
  - The ^{26}Si α-separation energy is ~9.2 MeV
  - For a peak XRB temperature of 1.5GK, the upper-end of the simple Gamow Window estimate is ~ 2.6MeV
  - Therefore the relevant ^{26}Si states are from ~9.2-11.8 MeV. The level-density is anticipated to be high enough that the Hauser-Feshbach formalism can be used.
- Where do we get this data?
  - Directly measured cross sections at higher energies can be extrapolated to lower energies using HF (ideally the statistical resonance method would be used)
  - Various HF inputs can be used to fit to the data. In this case, $T_p \approx \sum_{chan} T_{chan}$, so the α-optical potential is more or less all that matters (recall $\sigma^{HF}_{X(a,b)Y} \propto \sum_J \frac{T_\alpha T_p}{\sum_{chan} T_{chan}}$)
- Note that nothing forbids you from trying to do spectroscopy for all of the relevant levels, but at some point you'll miss important levels and will underestimate the reaction rate





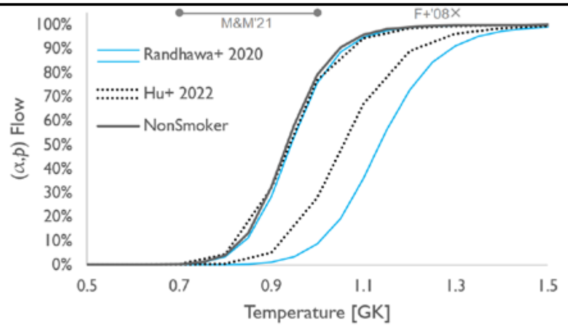
Finally, we get the (α,p) flow at ^{22}Mg

- Can see at which temperature the (α,p) process "turns on". i.e. when is the flow above some threshold
- Needed to select ignition conditions from multi-zone models (e.g. Merz & Meisel MNRAS 2021 and Fisker et al. ApJS 2008)

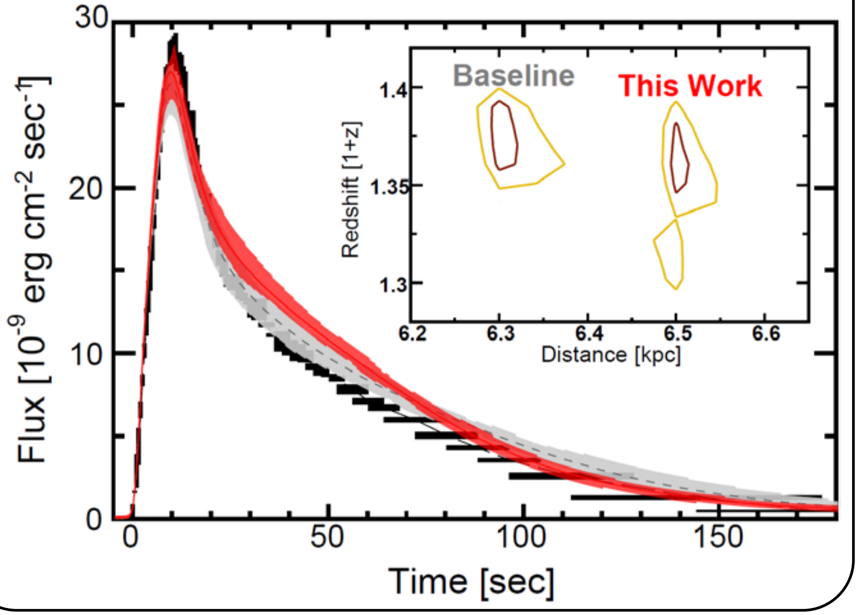


^{22}Mg(α,p) impact across model types

"Analytic Flow":
Calculate reaction rate competition for fixed conditions.
(See e.g. Puentes+ *PRCL* 2022)



"Multizone model":
1D model with full reaction network coupled to hydrodynamic evolution, e.g. using the [code MESA]
(See e.g. Randhawa *PRL* 2020)



"Post-processing":
Follow reaction network over pre-defined temperature & density trajectory, e.g. using the [CINA code]
(See e.g. Parikh+ *ApJS* 2008)

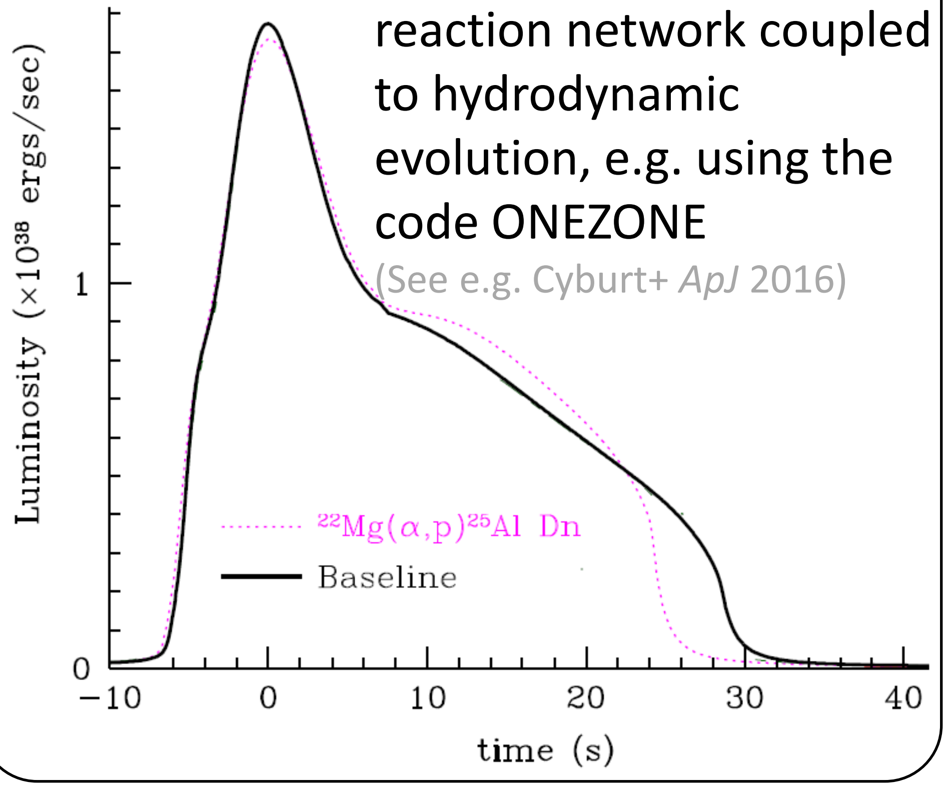
Final Abundance Ratios, $X_i/X_{i,\mathrm{std}}$, for Model F08 (Fisker et al. 2008) Resulting from Reaction-Rate Variations by a Factor of 10 (Up and Down)

Reaction	Isotope	10	0.1
^{22}Mg$(\alpha, p)^{25}$Al	^{25}Mg	...	8.81
	^{27}Al	...	2.23

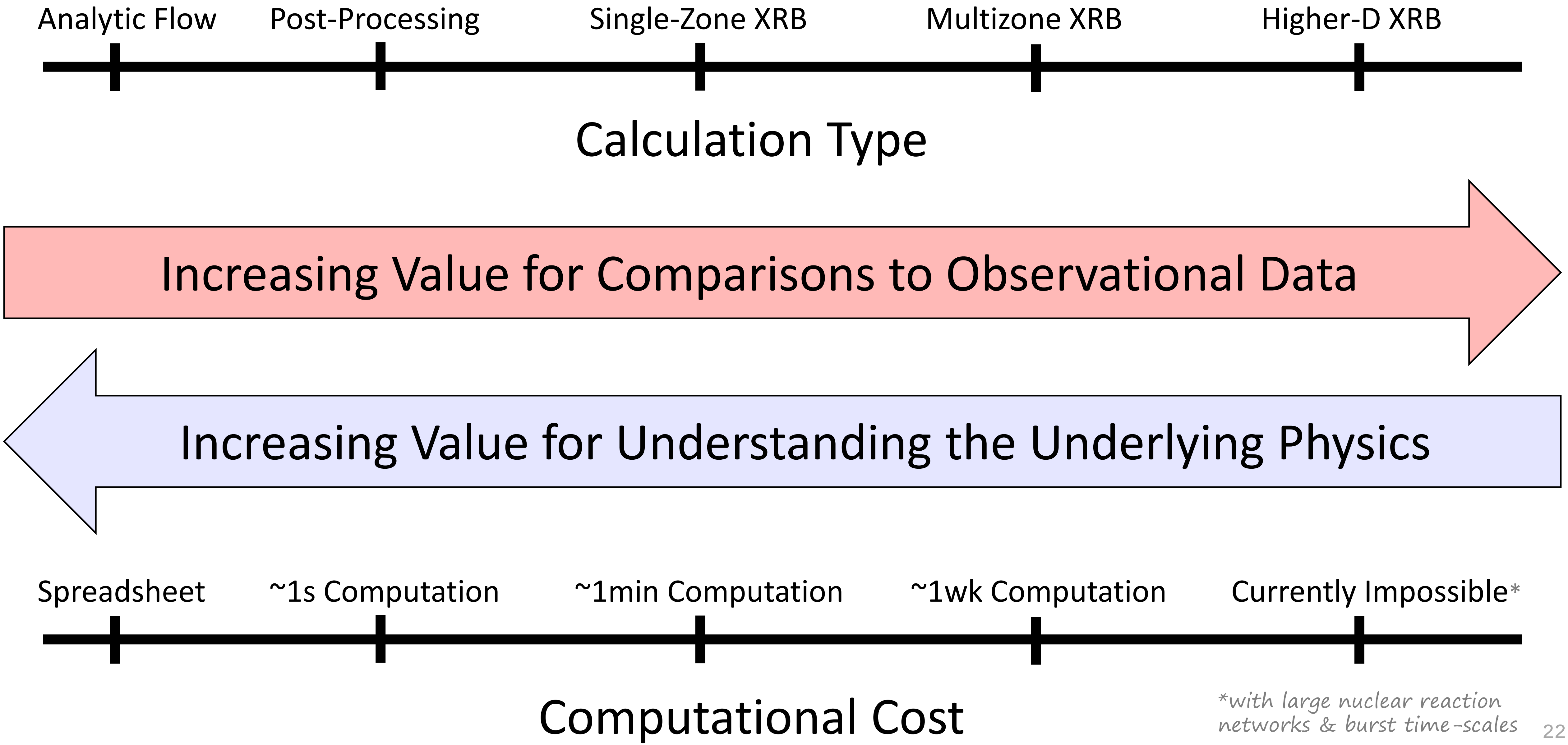
Nuclear Processes Affecting the Total Energy Output by More than 5% and at Least One Isotope

Reaction	Models Affected
^{22}Mg$(\alpha, p)^{25}$Al	F08

"Single-zone model":
0D model with full reaction network coupled to hydrodynamic evolution, e.g. using the code ONEZONE
(See e.g. Cyburt+ *ApJ* 2016)



Aside: the hierarchy of nuclear astrophysical models



*with large nuclear reaction networks & burst time-scales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JOURNEY TO THE CENTER OF THE
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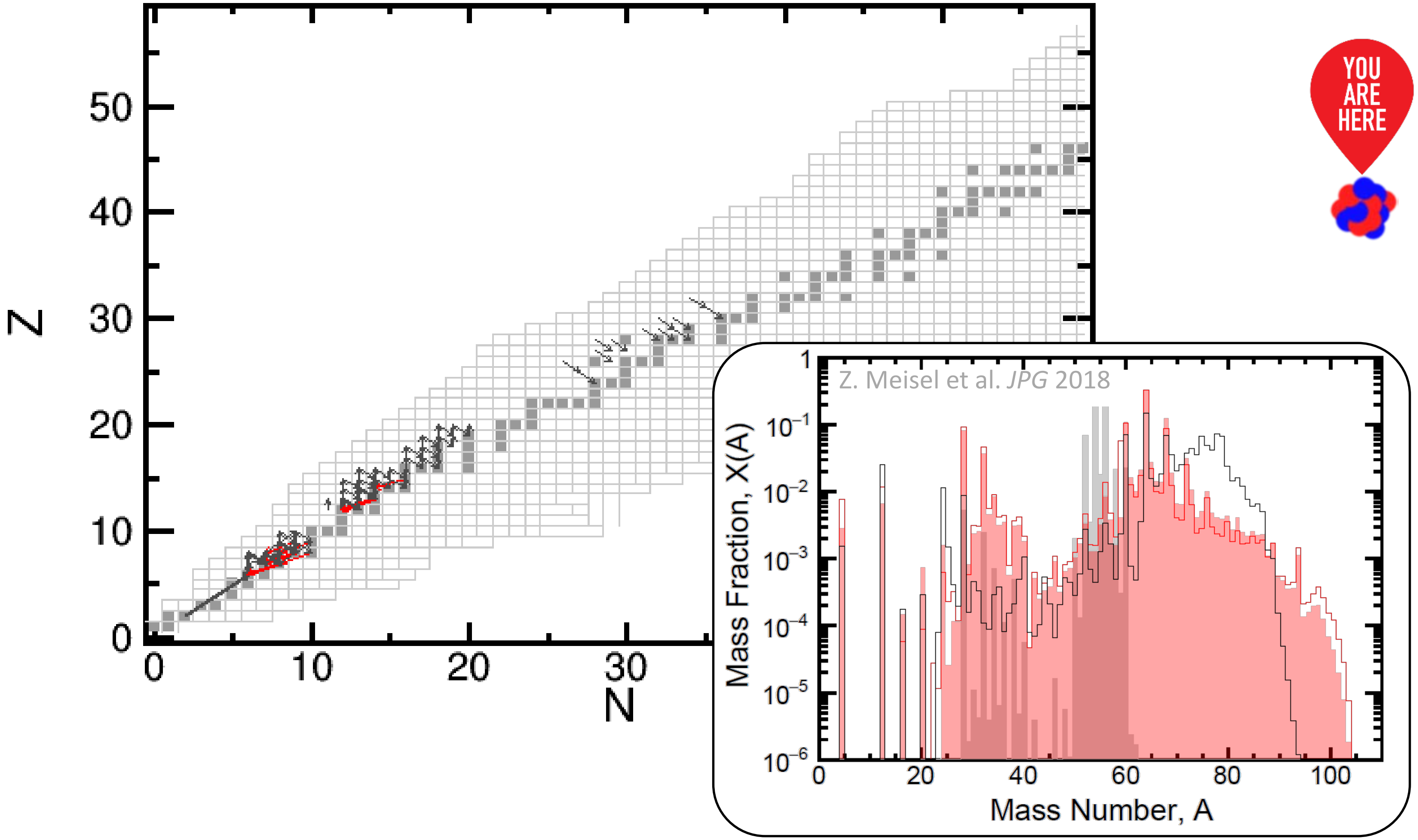
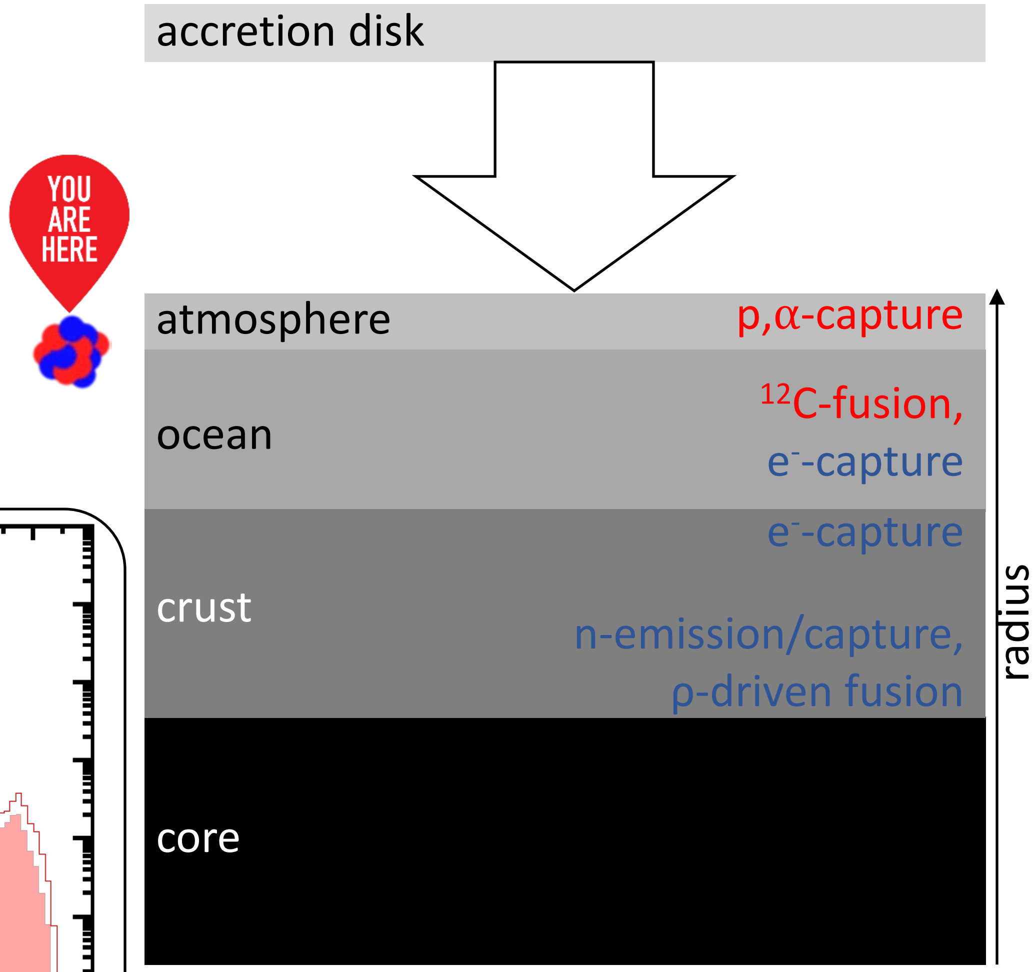
WALTER REISCH and
CHARLES BRACKETT

The journey of a nucleus in a neutron star

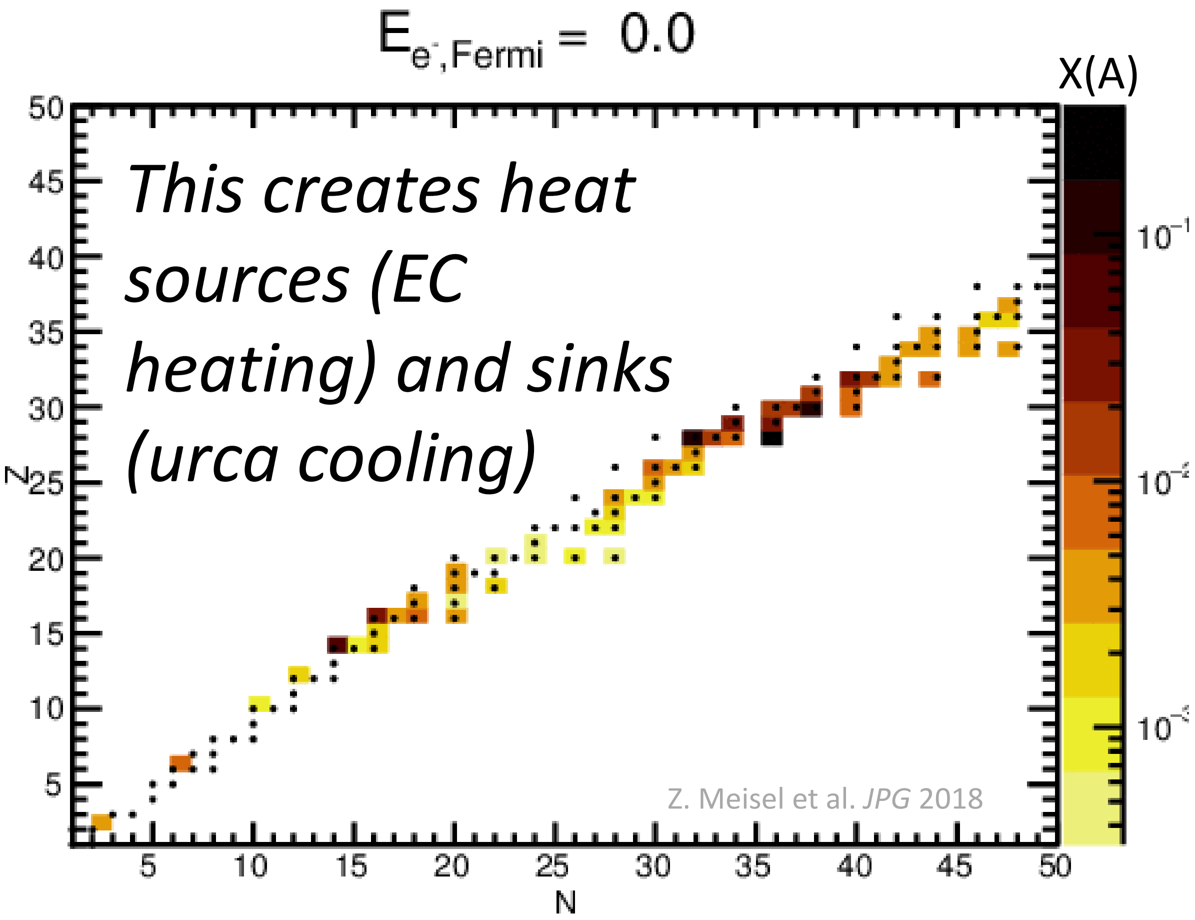
1. Production from H, He, C burning



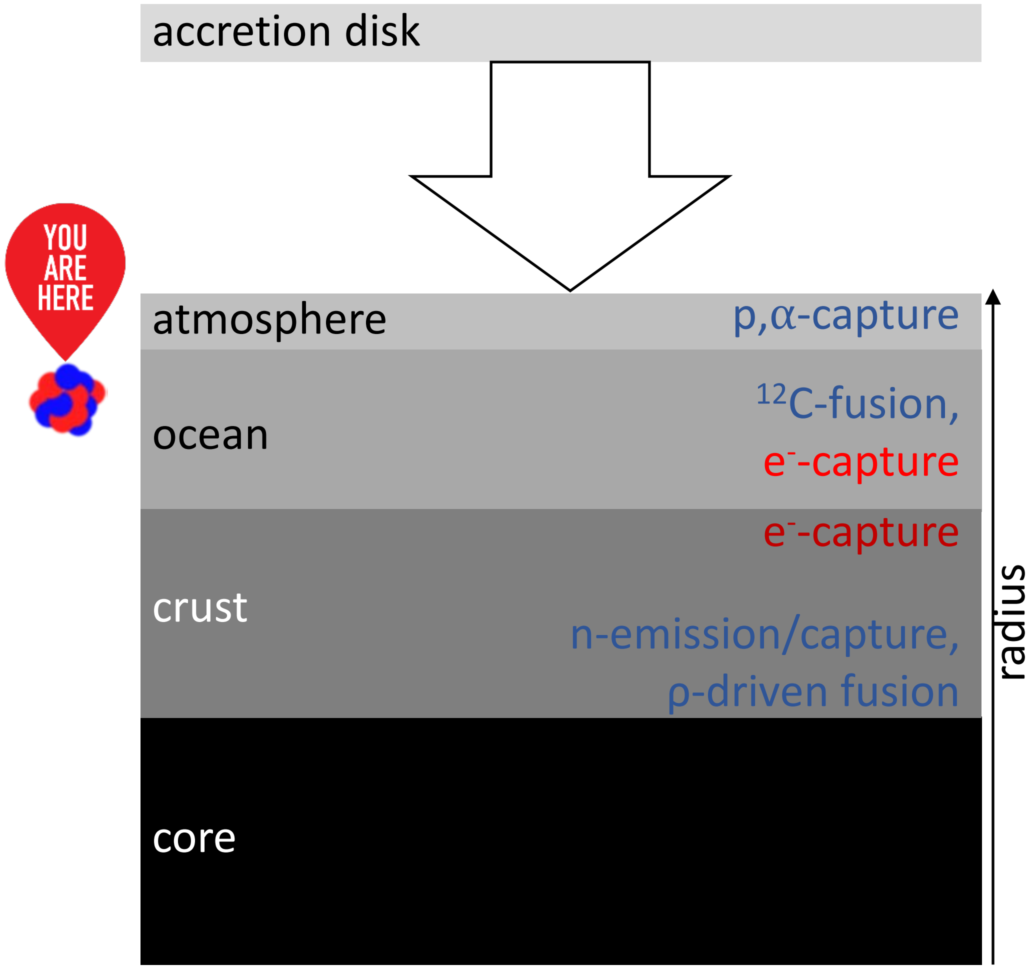


The journey of a nucleus in a neutron star

2. Burial and electron-capture



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

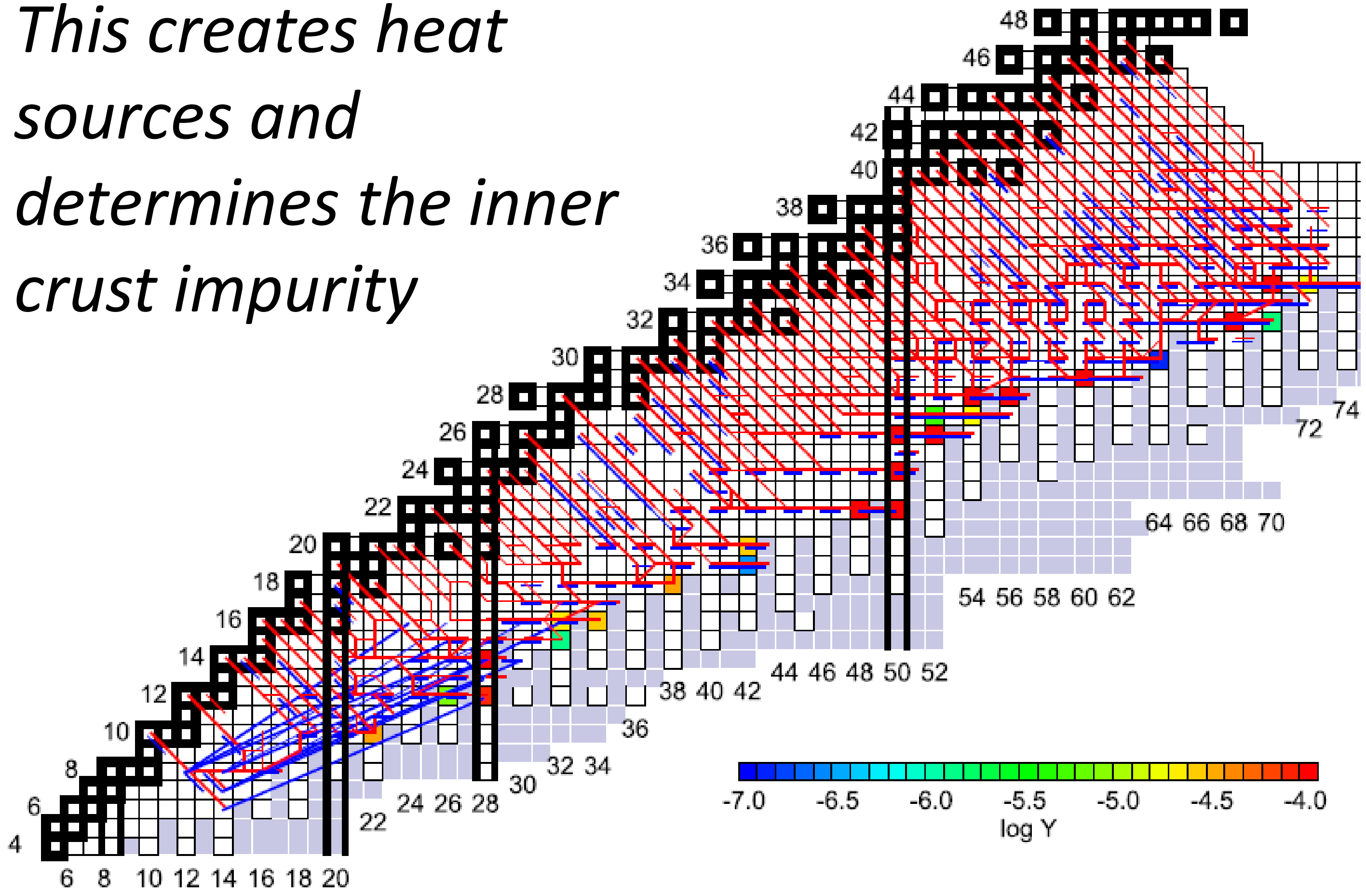


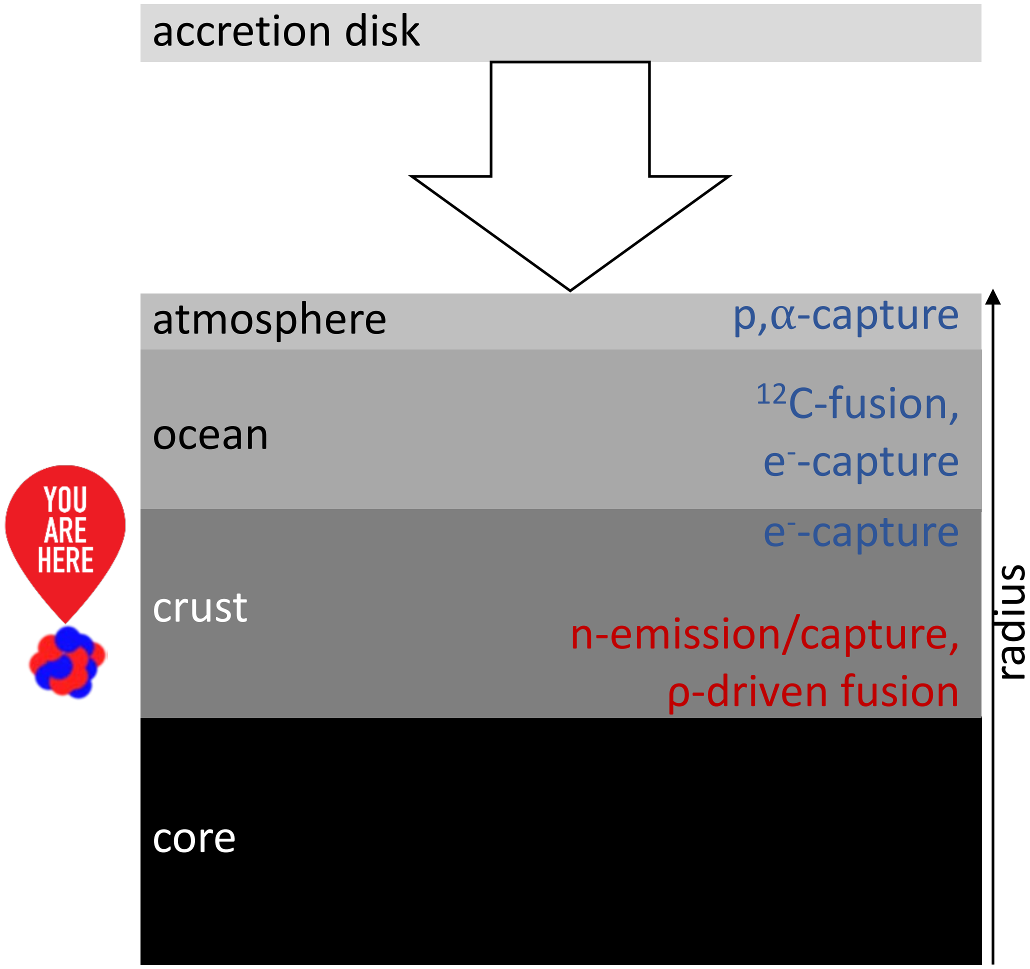
The journey of a nucleus in a neutron star

3. Fusion and disintegration

This creates heat sources and determines the inner crust impurity

R. Lau et al. *ApJ* 2018





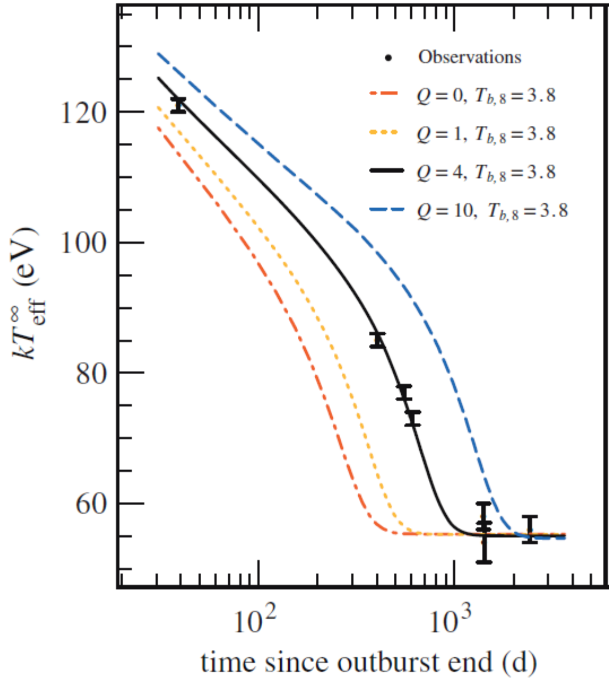
Surface burning impacts the crust

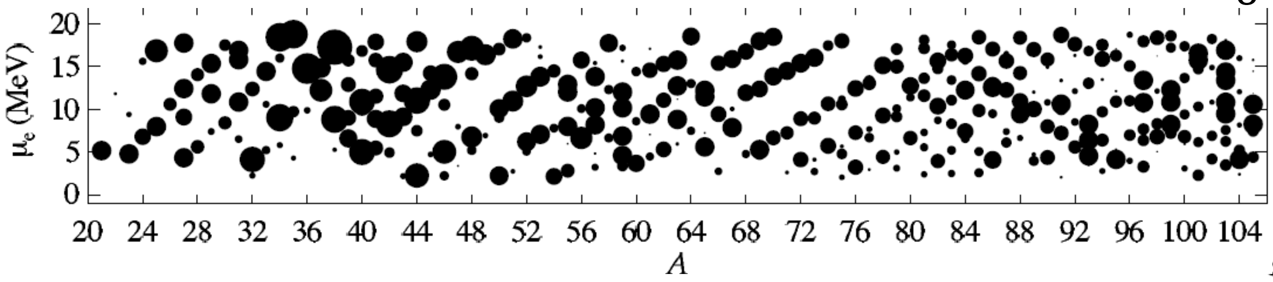
- The impurity parameter influences the crust thermal conductivity, which is important for crust cooling models
  - $Q_{imp} \equiv \frac{1}{n_{ion}} \sum_j n_j \left(Z_j - \langle Z \rangle\right)^2$
- Electron-capture heating, which is mostly relevant for even-A species,
  - $E_{heat} = \eta(|Q_{EC}(Z,A)| - |Q_{EC}(Z-1,A)| - E_{xs}) + E_{xs}$, where $\frac{1}{6} \lesssim \eta \lesssim \frac{1}{4}$

XRB from Meisel+ *ApJ* 2019

Rate Variation	Q_{imp}
Baseline	12.9
^{59}Cu(p,α) x100	14.5
^{59}Cu(p,γ) /100	14.4
^{61}Ga(p,γ) /100	15.5

Brown & Cumming *ApJ* 2009

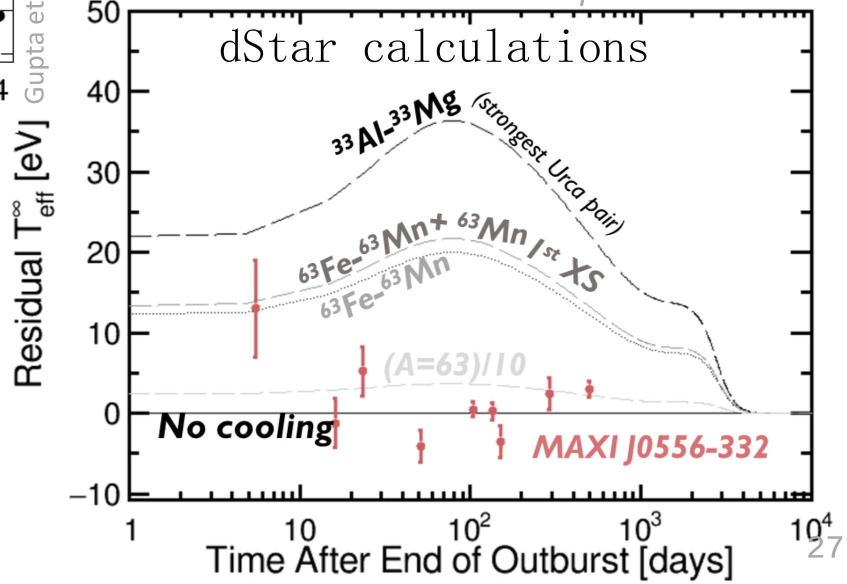




Gupta et al. *ApJ* 2007

- Urca cooling, which is mostly relevant for odd-A species,
  - $L_\nu \approx L_{34} X T_9^5 (2/g_{14}) R_{10}^2$ erg s^{-1}, where $L_{34} = 0.87 \left(\frac{10^6 s}{ft}\right)\left(\frac{56}{A}\right)\left(\frac{Q_{EC}}{4\ \text{MeV}}\right)^5 \left(\frac{\langle F \rangle^*}{0.5}\right)$

Meisel & Deibel *ApJ* 2017

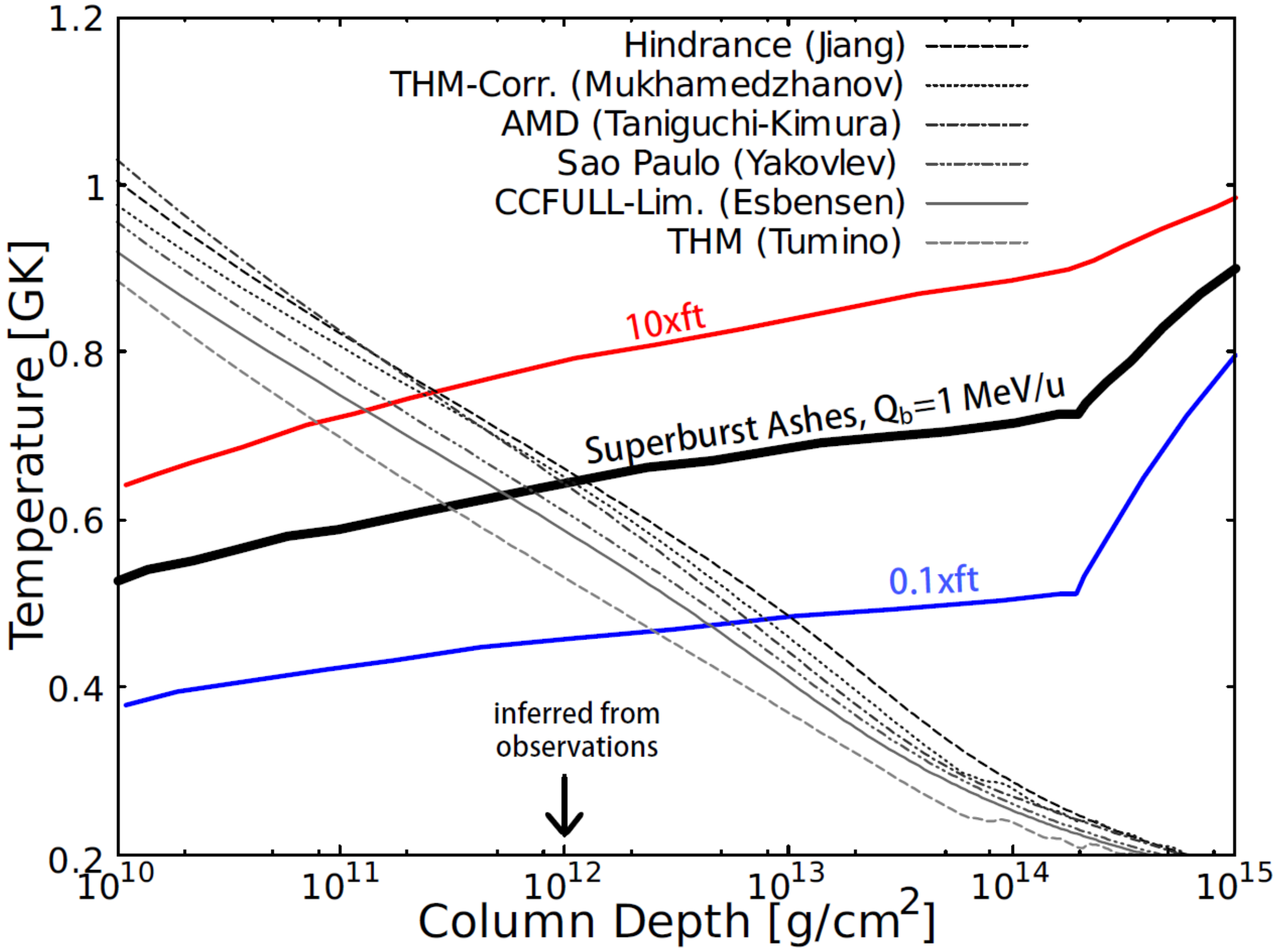


- For all of these, need to know surface-burning abundances, as well as properties of neutron-rich nuclei (masses, E_{xs}, ft-values)

Surface burning impacts the crust…*which impacts superbursts*

Deibel et al. *ApJ* 2016

- X-ray superbursts are ~100x more powerful than X-ray bursts and are most likely powered by carbon ignition.
- The inferred carbon ignition depth only matches modeled carbon ignition depths with extra "shallow heating" added (which is of as-yet unknown origin)
- The amount & location of shallow heating depends on other crust heating/cooling sources, as well as the crust thermal conductivity (i.e. impurity)

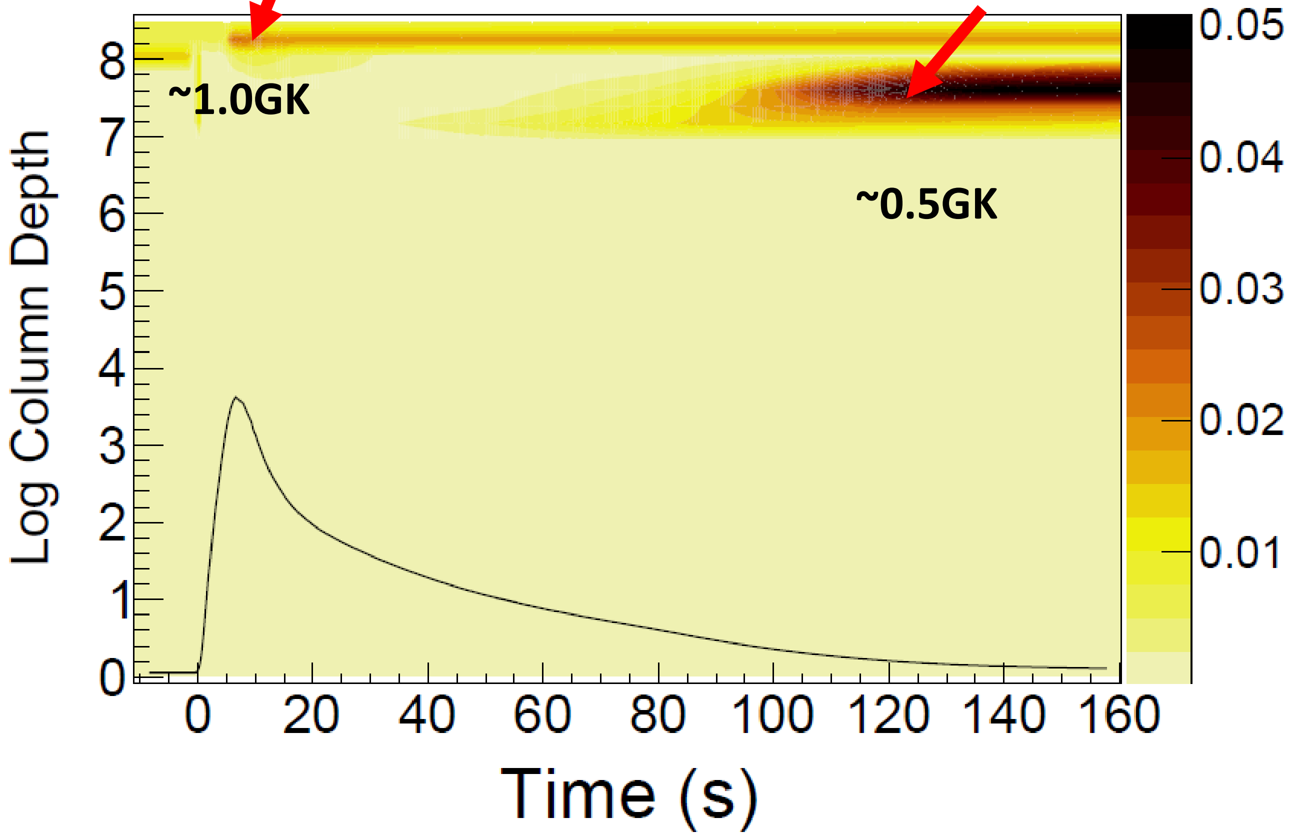


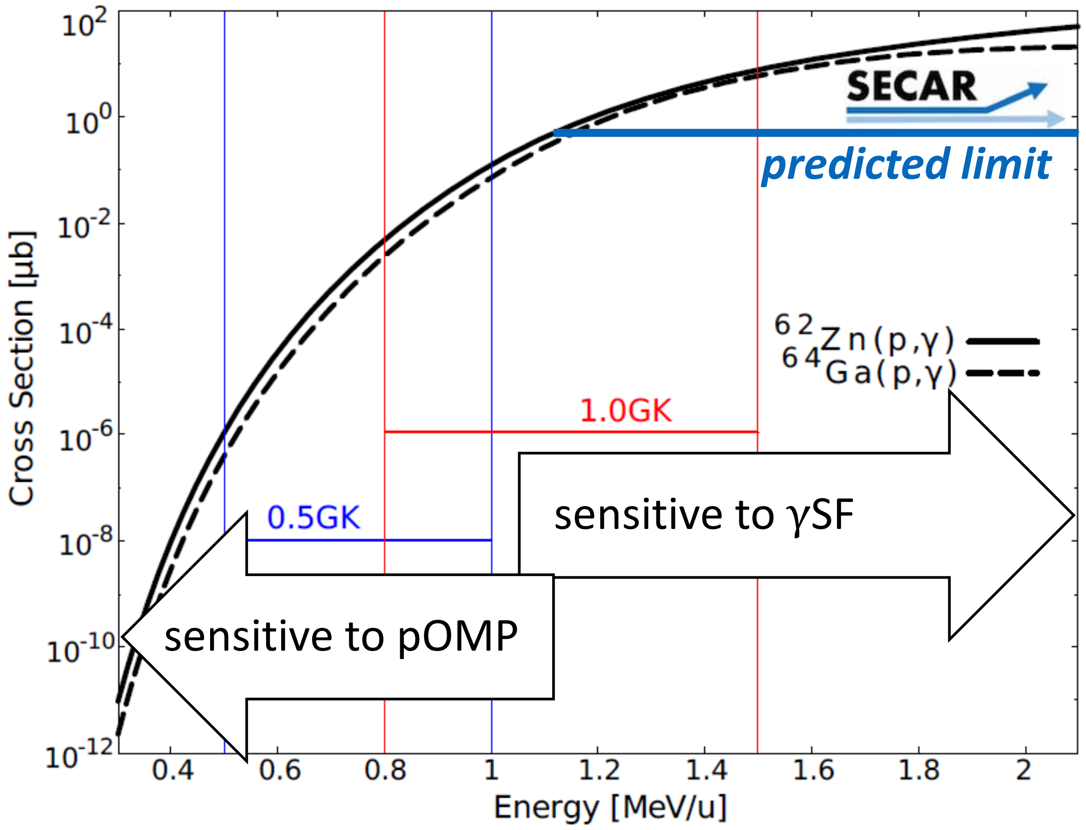
*This plot is for very deep "shallow" heating.
Otherwise, the urca cooling impact is much less important.

The relevant reaction rate uncertainties may be different for surface-burning than for the XRB light curve

Environment conditions during
the light curve impactaren't necessarily the same as
for the abundance impact.

For the cases below,
rather than a direct-capture measurement,
we need an indirect measurement
(and a specific kind!)

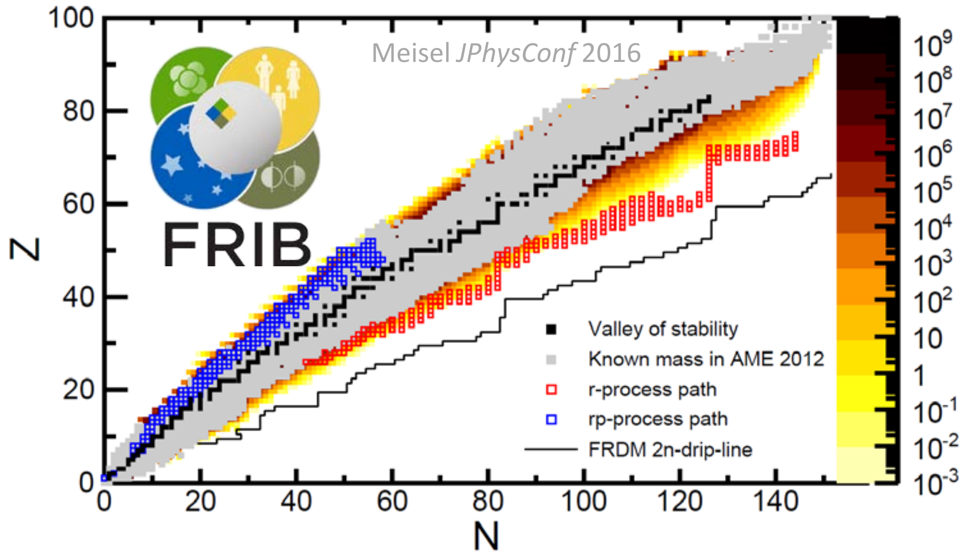


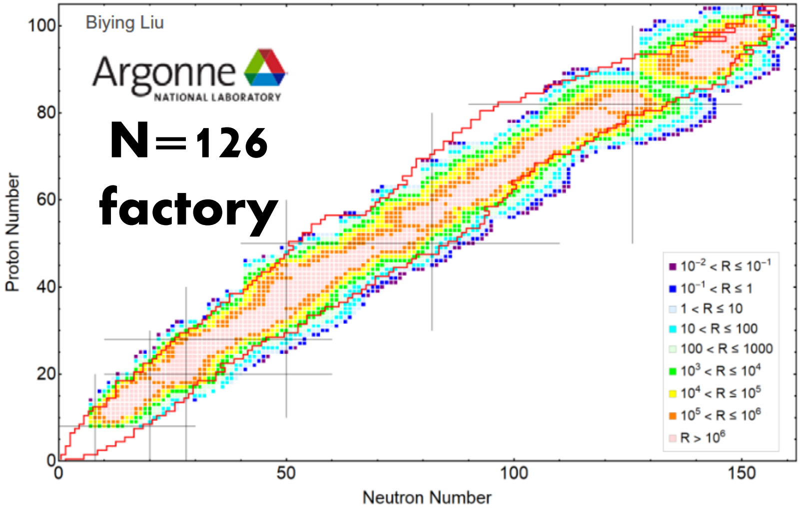


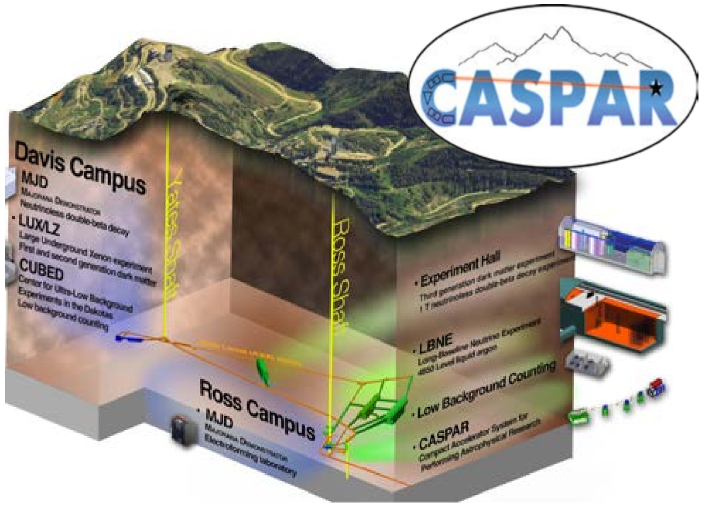
Merz & Meisel *MNRAS* 2021

Concluding Remarks:

This is a good time to be in nuclear astrophysics research







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COSI A Gamma-ray Space Explorer

IReNA

For a status update and summary of open questions see:

Horizons: Nuclear Astrophysics in the 2020s and Beyond

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Nuclear Astrophysics is a field at the intersection of nuclear physics and astrophysics, which seeks to understand the nuclear engines of astronomical objects and the origin of the chemical elements. This white paper summarizes progress and status of the field, the new open questions that have emerged, and the tremendous scientific opportunities that have opened up with major advances in capabilities across an ever growing number of disciplines and subfields that need to be integrated. We take a holistic view of the field discussing the unique challenges and opportunities in nuclear astrophysics in regards to science, diversity, education, and the interdisciplinarity and breadth of the field. Clearly nuclear astrophysics is a dynamic field with a bright future that is entering a new era of discovery opportunities.

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Further Reading

- Nuclear Physics of Stars (C. Iliadis)
- Cauldrons in the Cosmos (C. Rolfs & W. Rodney)
- Stellar Explosions (J. José)
- Lecture Materials on Nuclear Astrophysics (H. Schatz)
- Chapter 5: Stellar Astrophysics (E.F. Brown)
- Z. Meisel et al., J. Phys. G. (2018)
- D. Galloway & L. Keek, contribution to *Timing Neutron Stars* (2020)
- H. Schatz et al. Physics Reports (1998)
- JINA Horizons Whitepaper (2022)