Experimental Nuclear Astrophysics

Exotic Beam Summer School 2026

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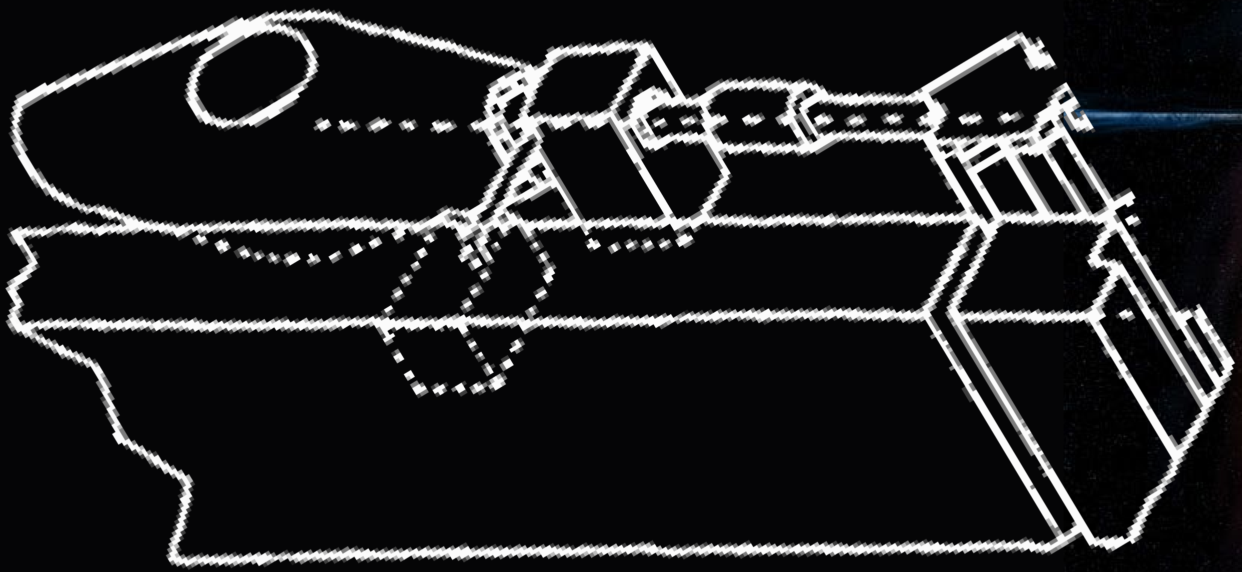
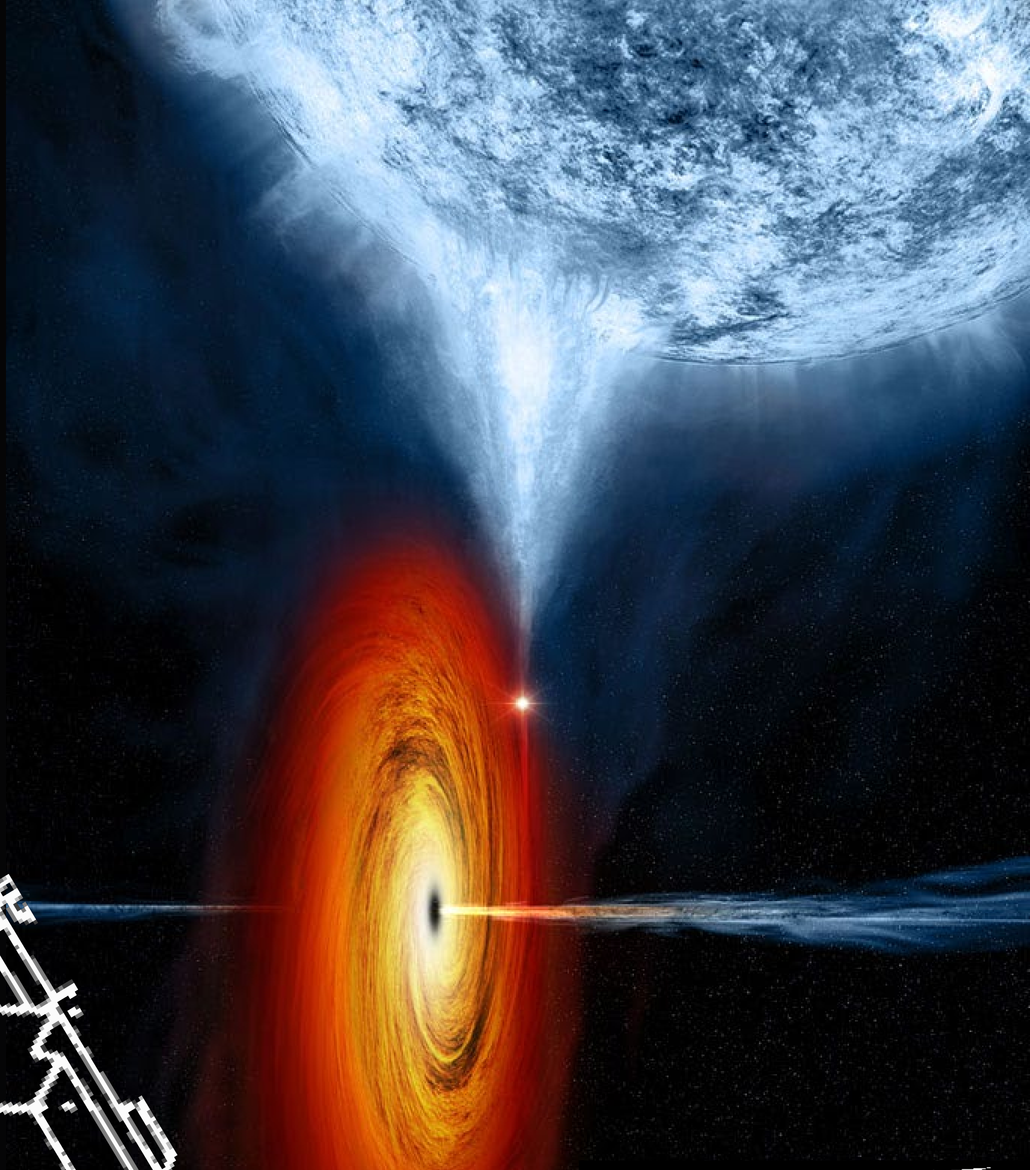
*Temu Wei Jia Ong





NSSC

NNSA

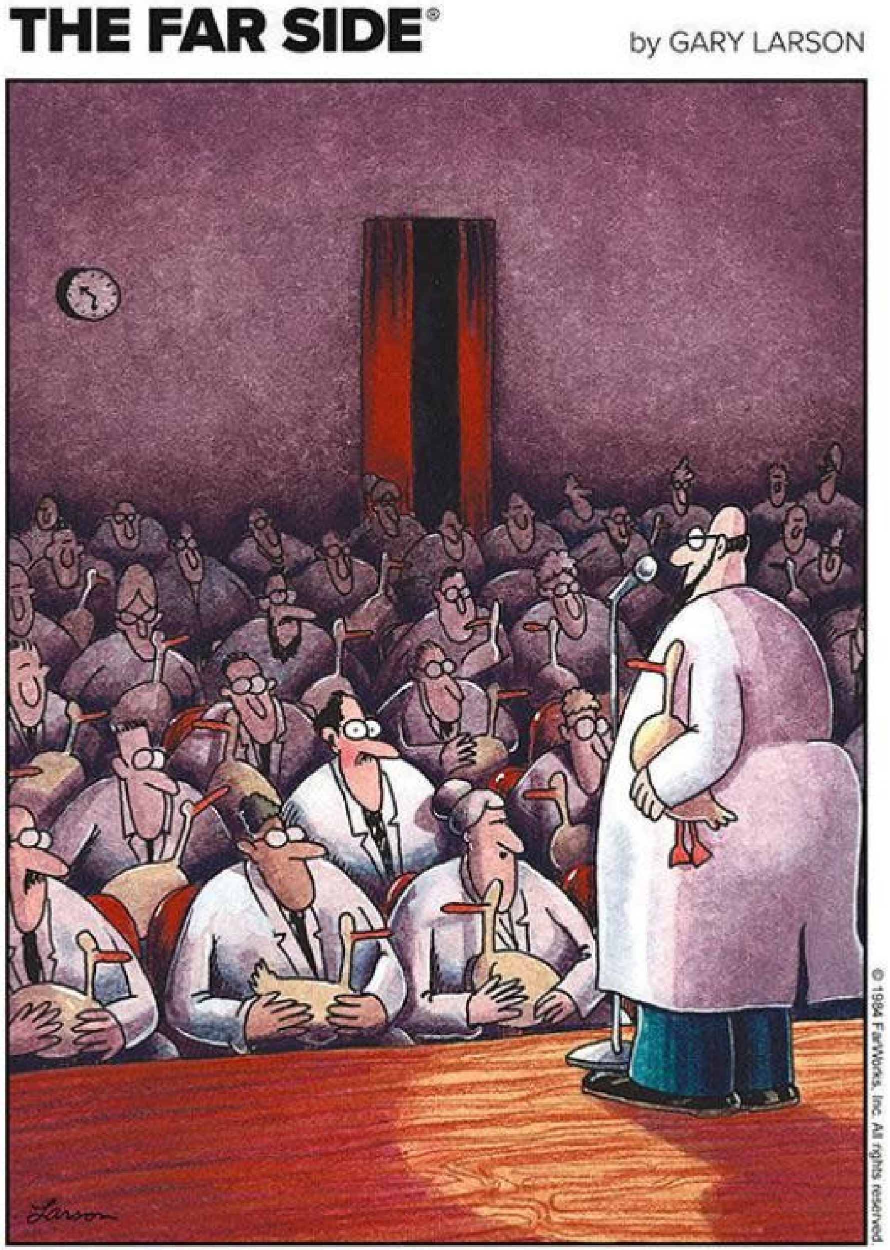
Department of Energy · United States of America

AFIT

Air Force Institute of Technology

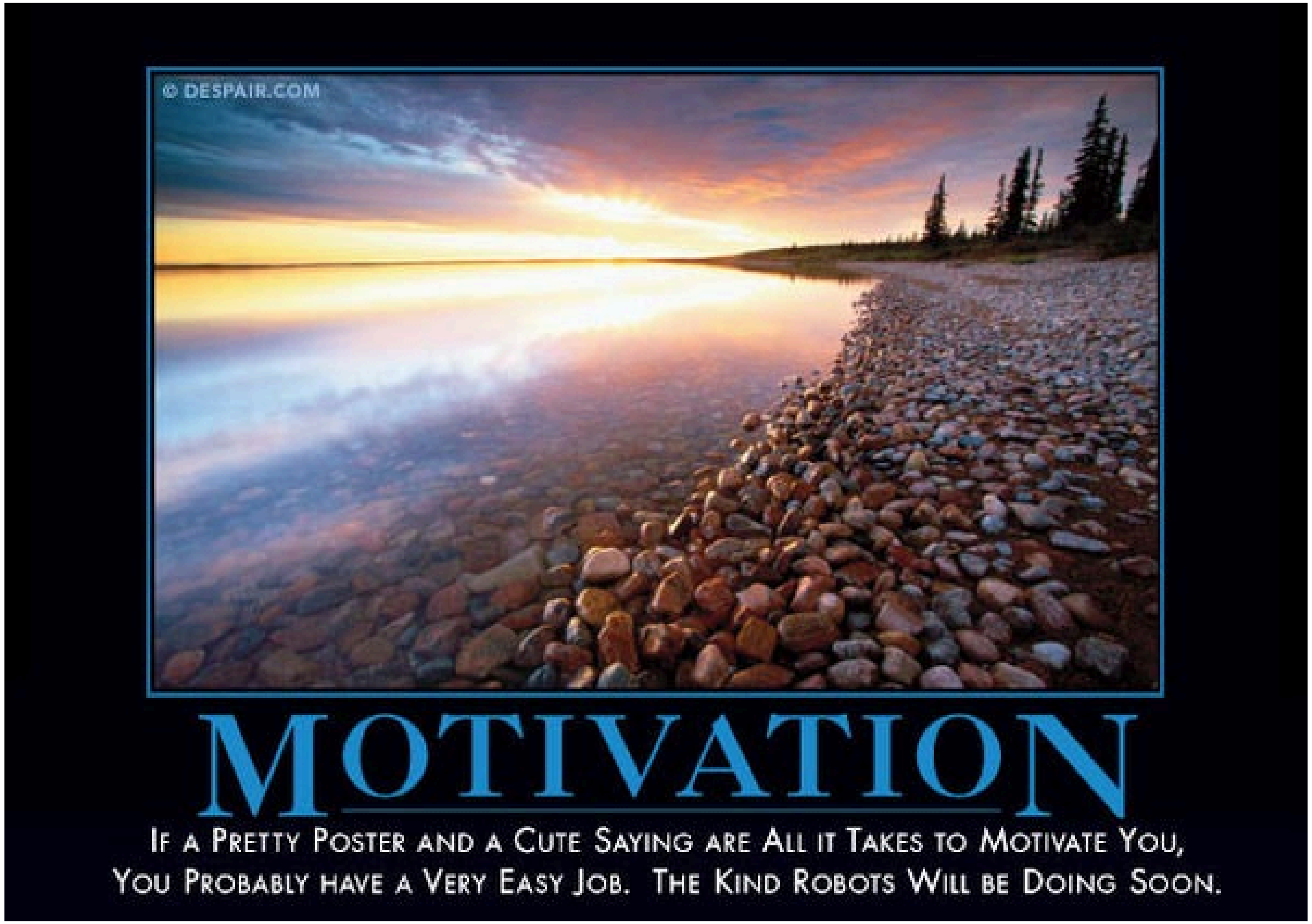
Lecture Plan

- Motivation and Context
- Methods and Examples
- Not-so-exotic Beams
- Details for Afficionados
- Tying into Astrophysics



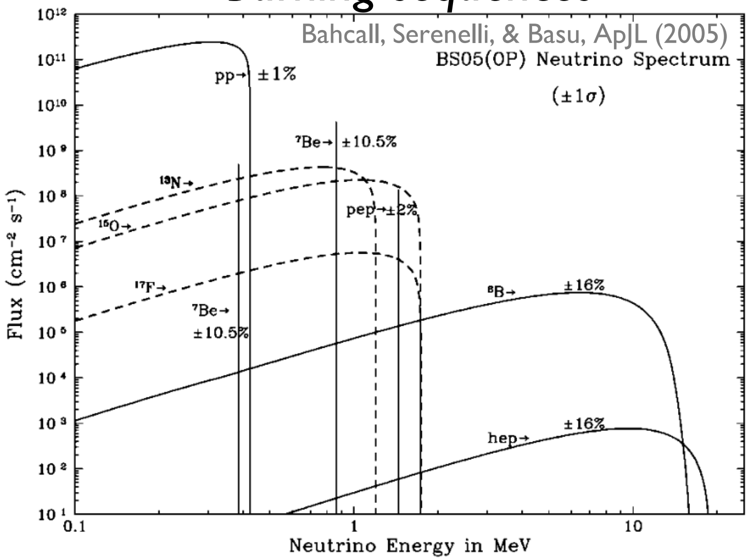
Suddenly, Professor Liebowitz realizes he has come to the seminar without his duck.

Motivation and Context

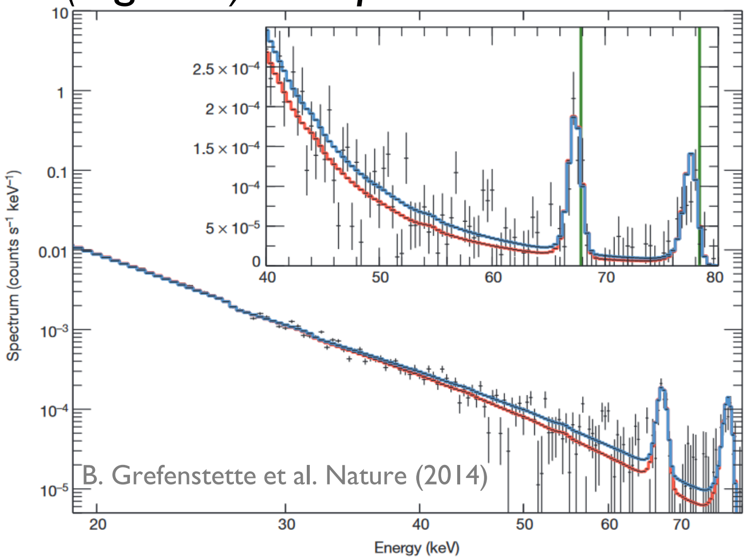


Some Evidence for Recent Nuclear Reactions in Space

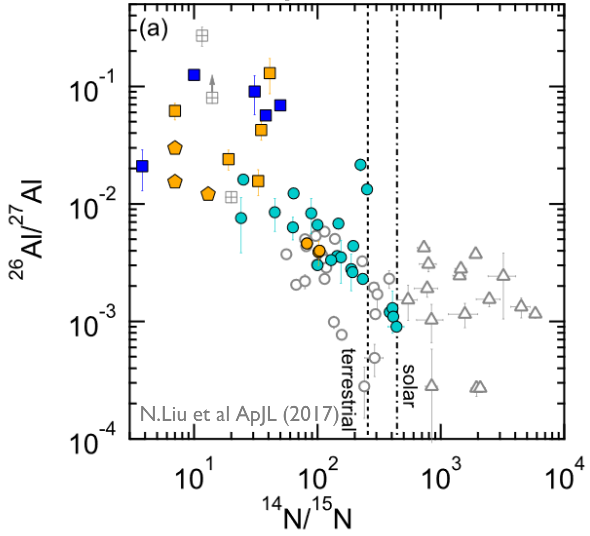
Solar ν attributable to hydrogen burning sequences



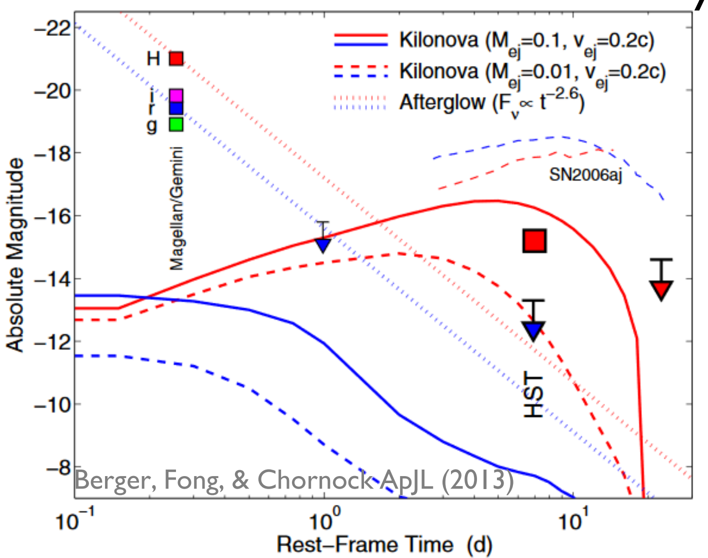
γ-rays of short-lived isotopes (e.g. ^{44}Ti) in supernova remnants



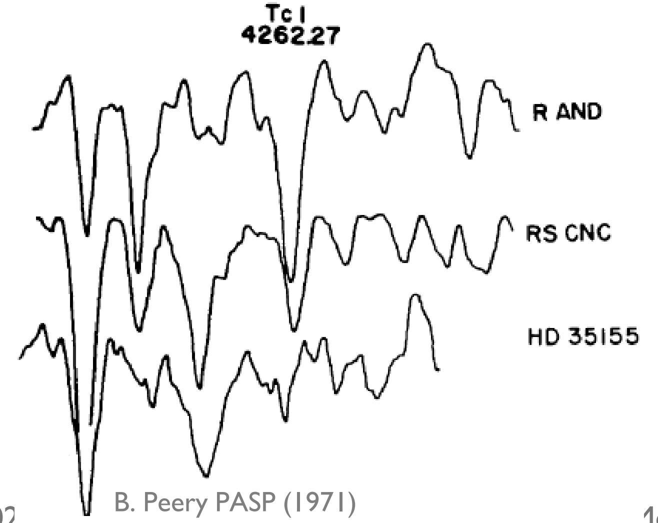
Anomalous isotopic ratios in meteoritic "pre-solar" dust grains



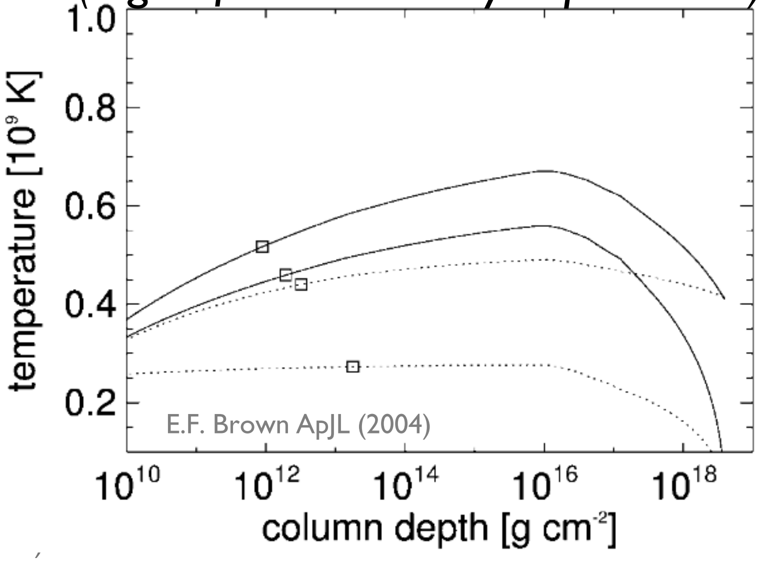
Neutron star merger afterglow associated with radioactive decay



Radioactive elements (e.g. Tc) in stellar spectra



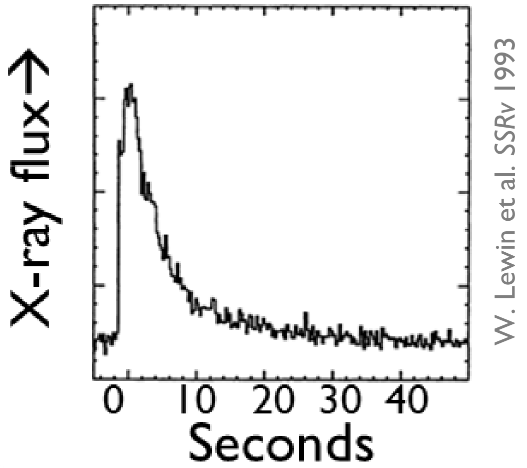
Match in energetics (e.g. C-fusion in X-ray superbursts)

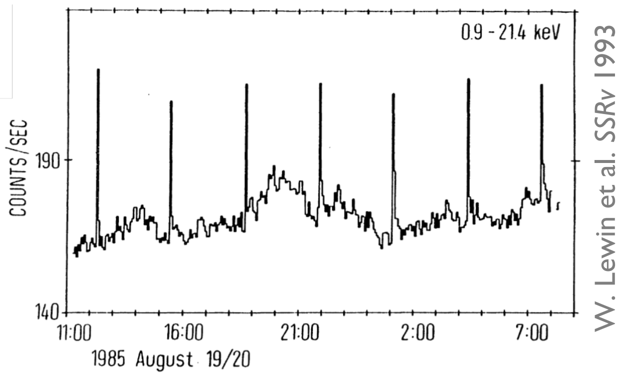


Astrophysics Model Calculations Tell Us What to Measure

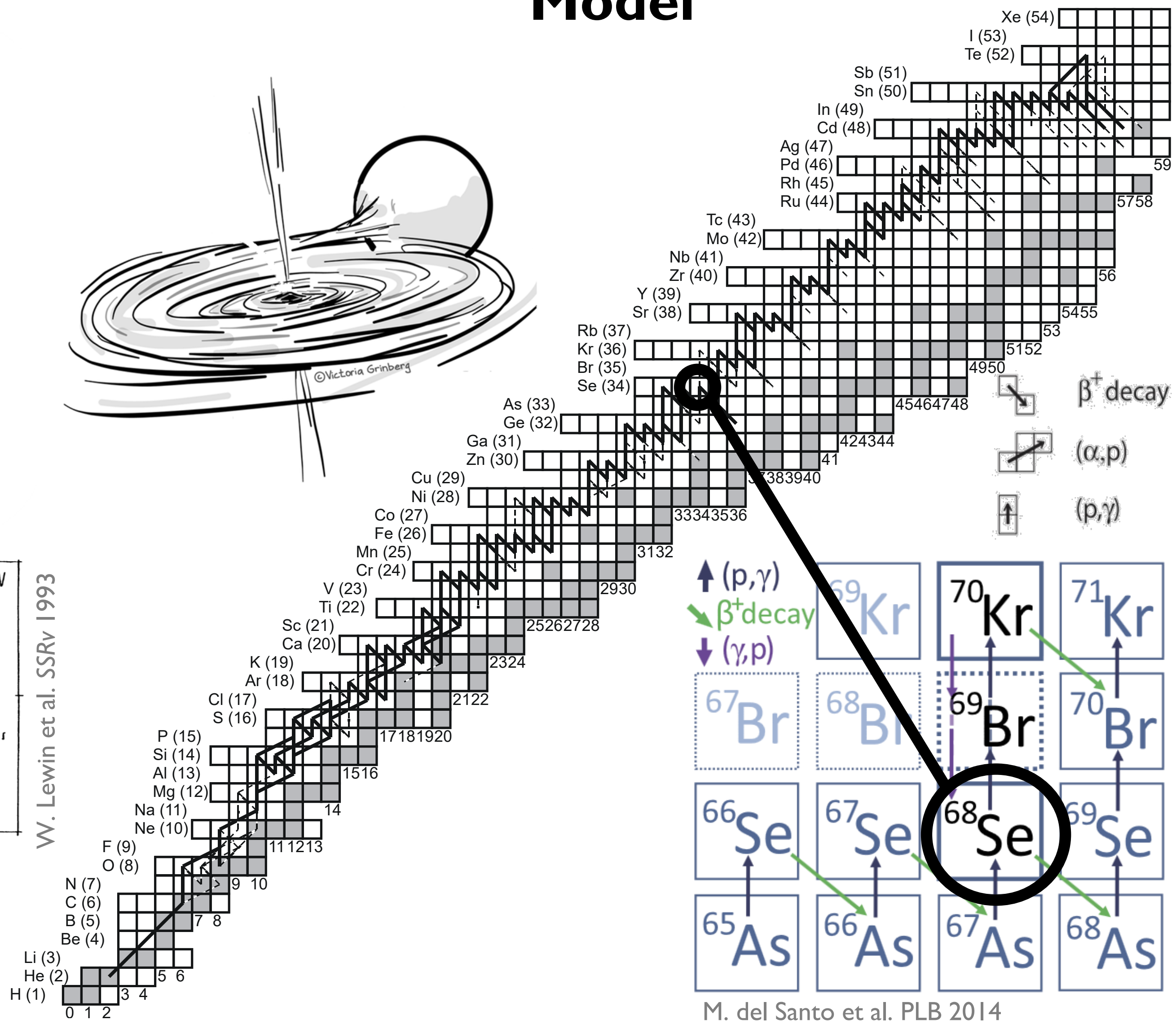
Phenomenon

"X-ray bursts"



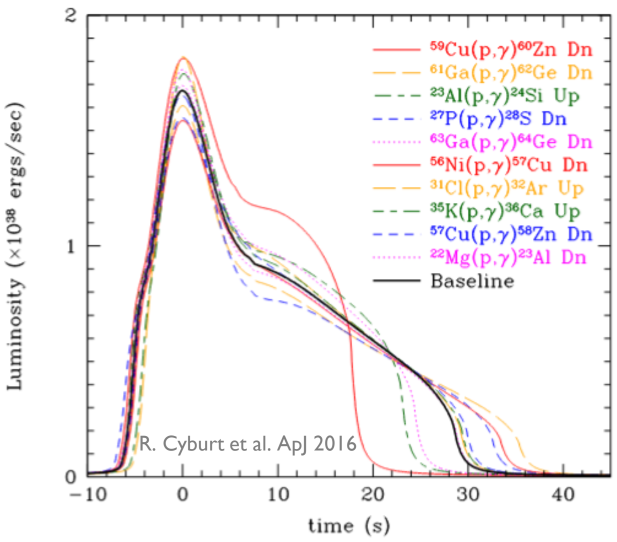


Model



H. Schatz et al. ApJ 1999

Sensitivity

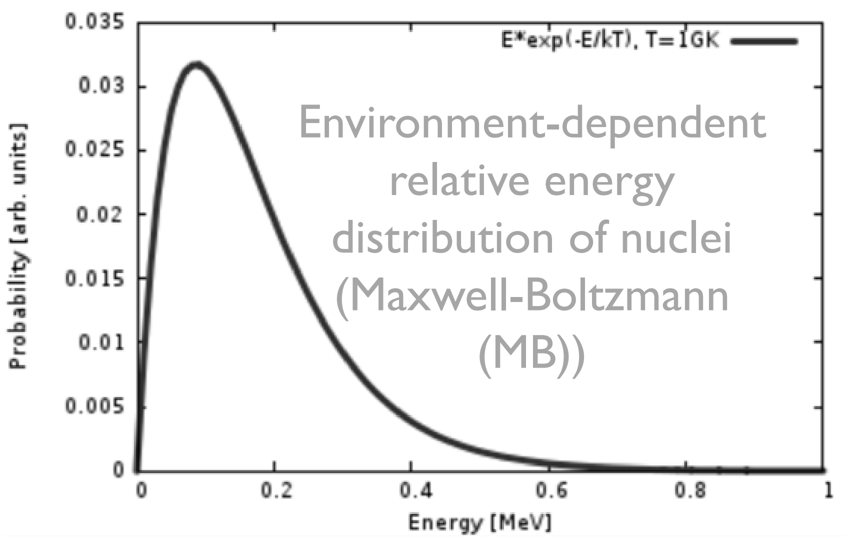


Learn important nuclear quantities ***and*** the relevant environment conditions.

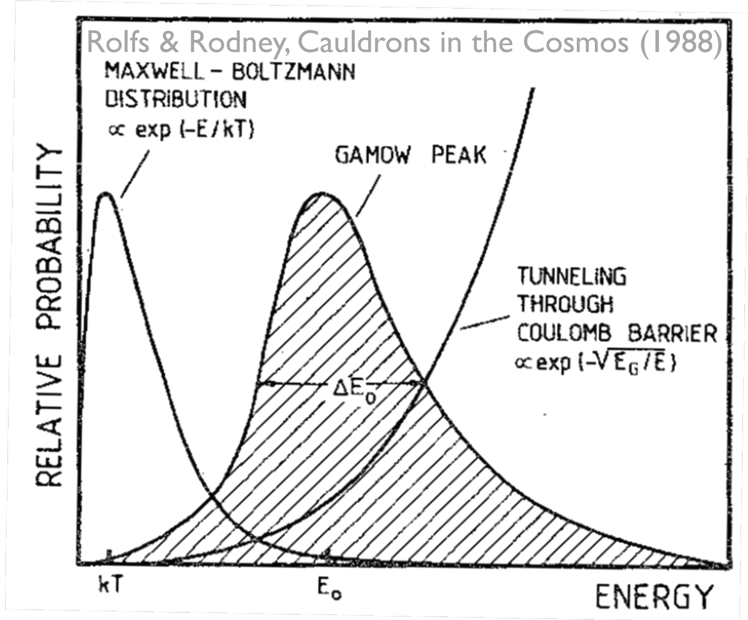
Fundamentally, We Want Nuclear Reaction and Decay Rates

- The nuclear reaction rate is described in general by:
  - $\langle \sigma v \rangle_{12} = \sqrt{\frac{8}{\pi\mu}} \frac{1}{(k_B T)^{3/2}} \int_0^\infty \sigma_{12}(E) E \exp\left(-\frac{E}{k_B T}\right) dE$

Nuclear reaction cross section for species 1+2



- We only need the cross section at astrophysically-relevant energies
  - For charged particles, this is the Gamow window, $E_G \pm \Delta_G$. If we pretend $\sigma_{12}(E)$ is primarily characterized by the Coulomb barrier and convolve this with the MB-distribution:
    - $E_G = 0.122\left(Z_1^2 Z_2^2 \frac{A_1 A_2}{(A_1+A_2)} T_9^2\right)^{1/3}$ MeV, $\Delta_G = 4\sqrt{\frac{E_G k_B T}{3}}$ MeV
    - *This fails at >GK temperatures. Best to just evaluate the peak of the integrand!*
  - For neutrons, we care about energies near the mode of the MB-distribution: $KE_{neutron} = k_B T$
    - Pro-tip: $11.6045 * E_{MeV} = T_9$

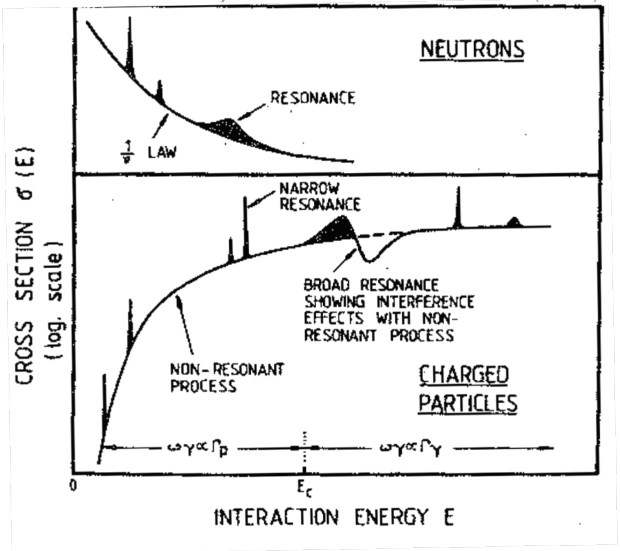


Fundamentally, We Want Nuclear Reaction and Decay Rates

- If the reaction rate is mostly due to a handful of resonances, our lives aren't necessarily any easier, but they are different:
  - $N_A\langle\sigma v\rangle_{N\,res.} = \frac{1.54\times10^{11}}{\left(\frac{A_1A_2}{A_1+A_2}T_9\right)^{3/2}}\sum_{i=1}^{N}(\omega\gamma)_{R,i}\exp\left(-\frac{11.6045E_{R,i}}{T_9}\right)\frac{\mathrm{cm}^3}{\mathrm{mol\ s}}$

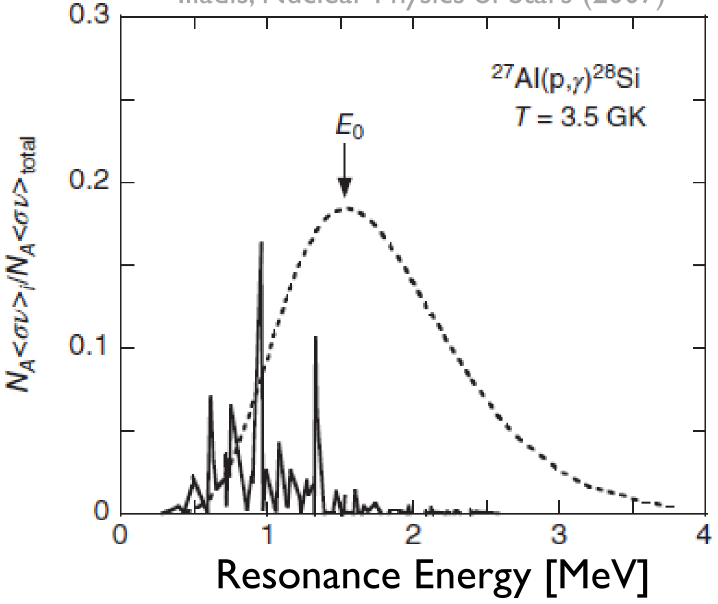
Strength and Energy of Resonance #i for 1+2

Rolfs & Rodney, Cauldrons in the Cosmos (1988)



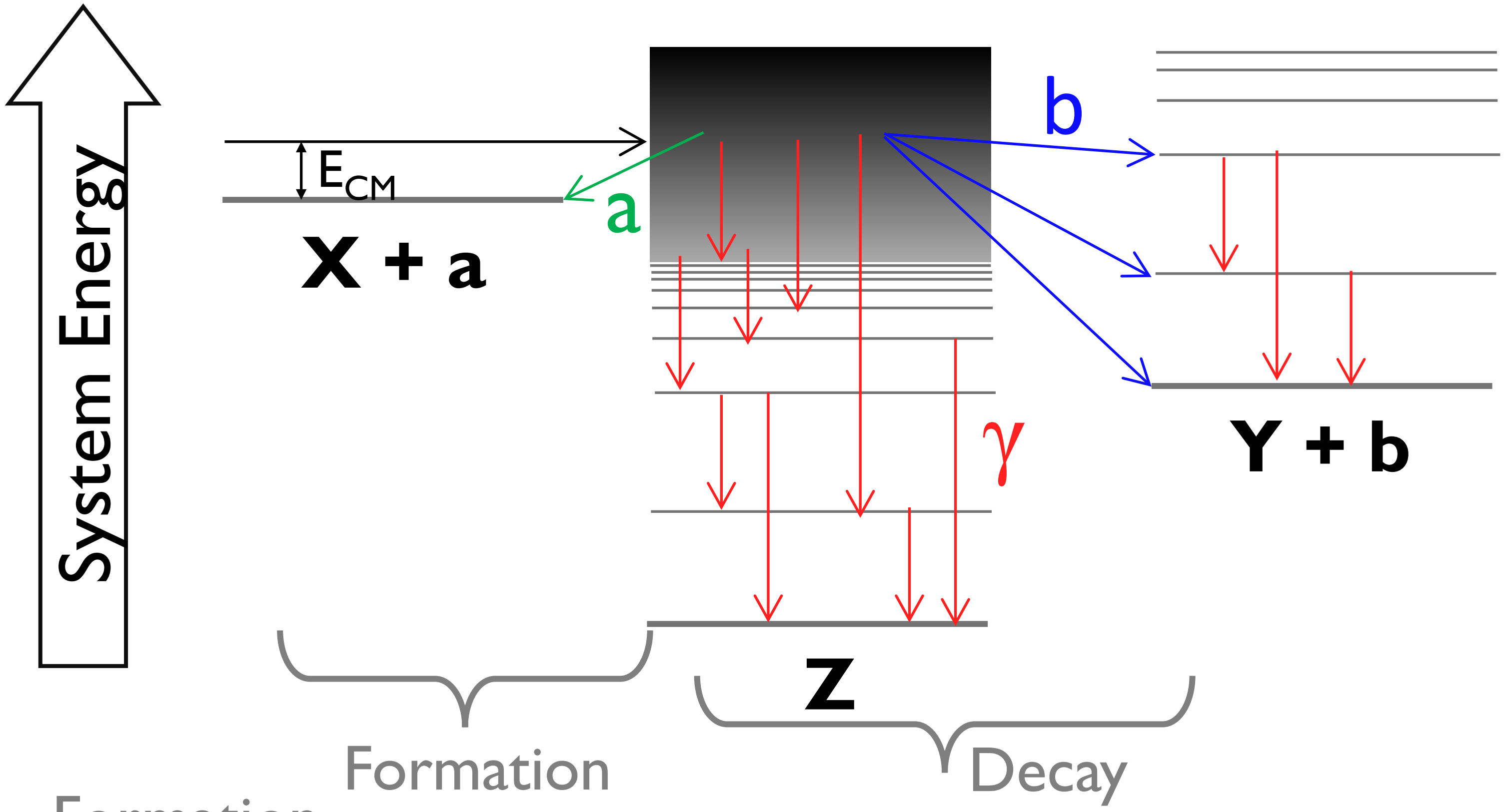
- Note that key resonance energies are only loosely related to the Gamow window (which assumes a smooth σ)
- If we can't measure $(\omega\gamma)_R$, we can constrain its ingredient
  - $(\omega\gamma)_R = \frac{2J_R+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_{12}\Gamma_{34}}{\Gamma}$
    - J_i : Spins of the Resonance-state, 1, and 2
    - Γ_{12} : Entrance width (1 fuses with 2)
    - Γ_{34} : Partial exit width (R decays into 3+4)
    - Γ : Total decay width (R decays into anything)

Iliadis, Nuclear Physics of Stars (2007)



Fundamentally, We Want Nuclear Reaction and Decay Rates

- If the reaction rate is due to lots of resonances, we again have a new problem
- We shift to indirect determination of the cross section by adopting the Hauser-Feshbach (HF) formalism and determining the HF-ingredients



$$\sigma^{HF}_{X(a,b)Y} = \overbrace{\boxed{\pi \left(\frac{\lambda}{\pi}\right)^2 \sum_J \frac{2J+1}{(2J_a+1)(2J_X+1)} W_{ab}}}^{\text{Formation}} \underbrace{\frac{T_{aX} T_{bY}}{\sum_{chan} T_{chan}}}_{\text{Decay}}$$

T from Level densities, Optical potentials, & Strength functions

Fundamentally, We Want Nuclear Reaction and Decay Rates

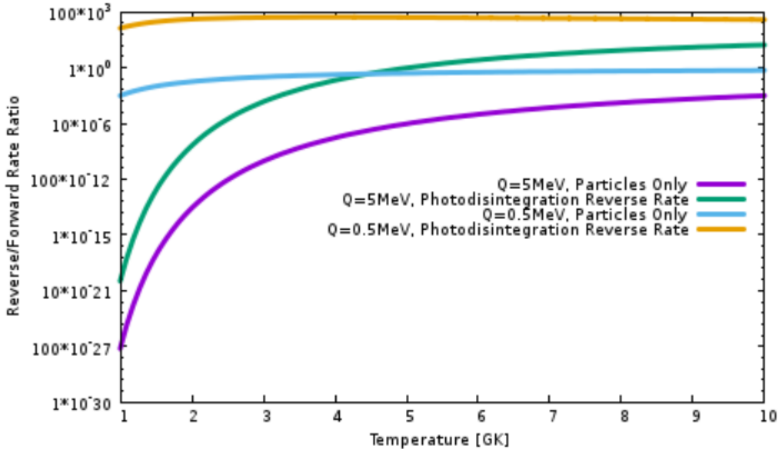
- Many weak decay rates are (mostly) just determined by the half-life: $\lambda = \frac{\ln(2)}{t_{1/2}}$
- However, electron-capture (EC) can play a prominent role, especially in electron-degenerate environments.
  Then we consider the more messy details: $\lambda = \frac{\ln(2)}{t_{1/2}} = \frac{G_F^2 m_e^5 c^4}{2\pi^3 \hbar^7} \left|M_{fi}\right|^2 f(Z_d, Q)$,
  where $f(Z_d, Q)$ is the dimensionless Fermi integral and so $ft = \frac{2\ln(2)\pi^3\hbar^7}{G_F^2 m_e^5 c^4} \frac{1}{\left|M_{fi}\right|^2}$
- The goal is then to constrain the comparative half-life ft
- For EC reactions in relatively stable degenerate environments, an interesting phenomenon known as Urca cycling can occur. In that case, the neutrino luminosity, $L_\nu \propto \frac{Q^5 T^5}{ft'}$, where $ft' = \frac{ft_{EC} + ft_\beta}{2}$, and $\frac{(ft)_\beta}{2J_\beta + 1} = \frac{(ft)_{EC}}{2J_{EC} + 1}$

Many Times, You Actually Just Want the Q-value

- For nuclear reaction rates at high temperatures, the (endothermic) reverse rate competes with the (exothermic) forward rate
  - so $\frac{\langle\sigma v\rangle_{34}}{\langle\sigma v\rangle_{12}} = \frac{(2J_1+1)(2J_2+1)}{(2J_3+1)(2J_4+1)} \frac{(1+\delta_{34})}{(1+\delta_{12})} \left(\frac{\mu_{12}}{\mu_{34}}\right)^{3/2} \exp\left(-\frac{Q_{12}}{k_B T}\right)$

    or $\frac{\langle\sigma v\rangle_{3\gamma}}{\langle\sigma v\rangle_{12}} \approx \left(\frac{\mu_{12}c^2}{k_B T}\right)^{\frac{3}{2}} \exp\left(-\frac{Q_{12}}{k_B T}\right)$

    via "detailed balance"

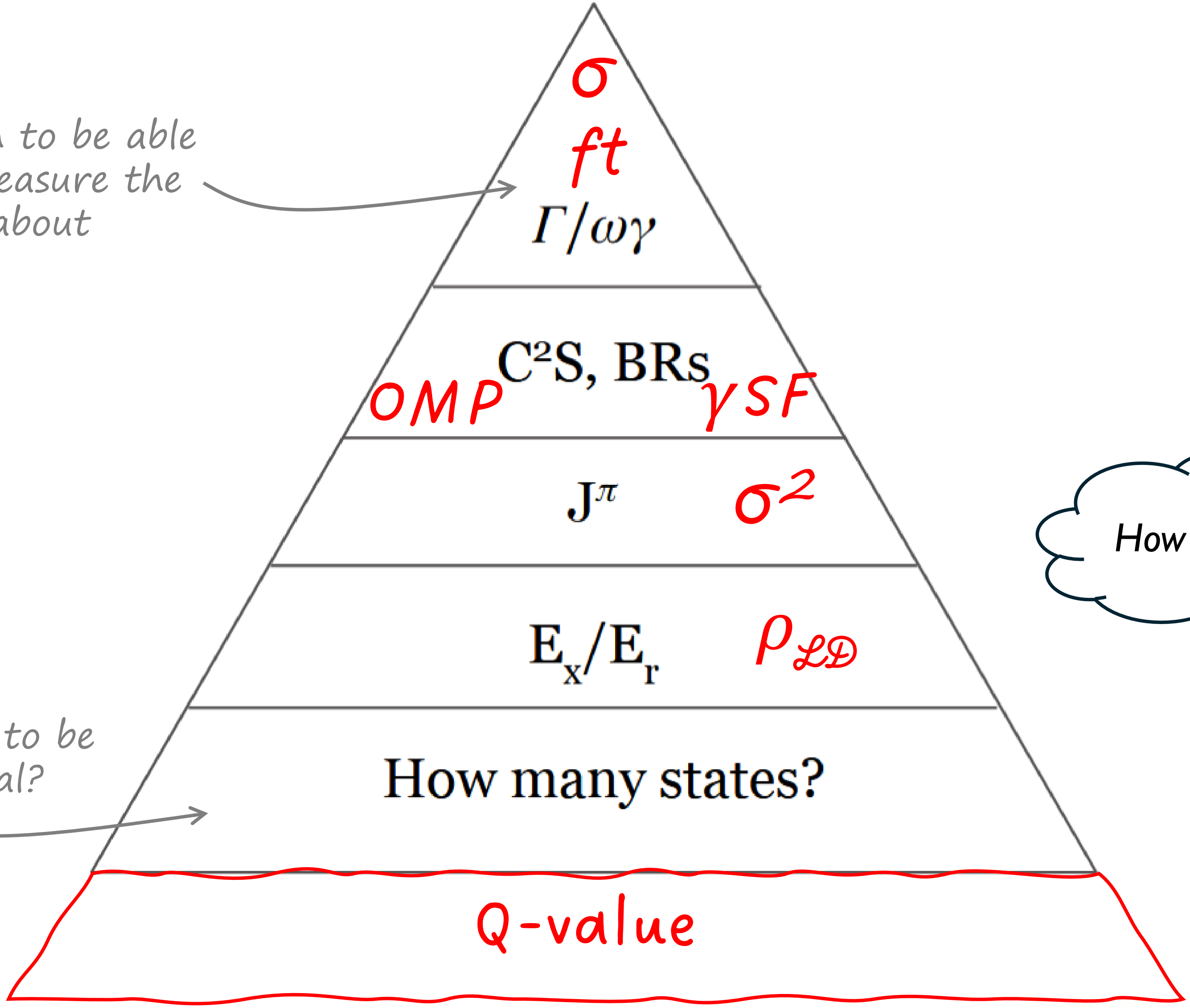


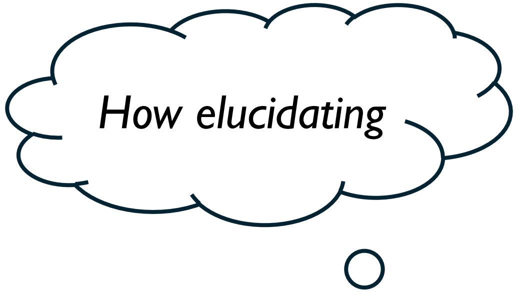
- Above the equilibrium temperature, relative abundances are set by the reaction Q-value (a.k.a. separation energy)
- At high-enough temperatures, this applies to the ~whole nuclear landscape, and is called Nuclear Statistical Equilibrium (NSE). At cooler temperatures, this applies to groups of nuclides, and is called Quasi-Statistical Equilibrium (QSE).
- This is why the rp-process and r-process march along ~constant S_p and S_n, respectively

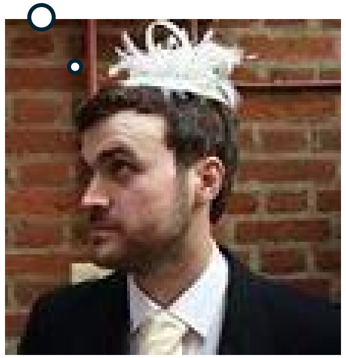
Adsley's Hierarchy of Needs (for Experimental Nuclear Astrophysicists)

If I'm lucky enough to be able to just directly measure the thing I care about

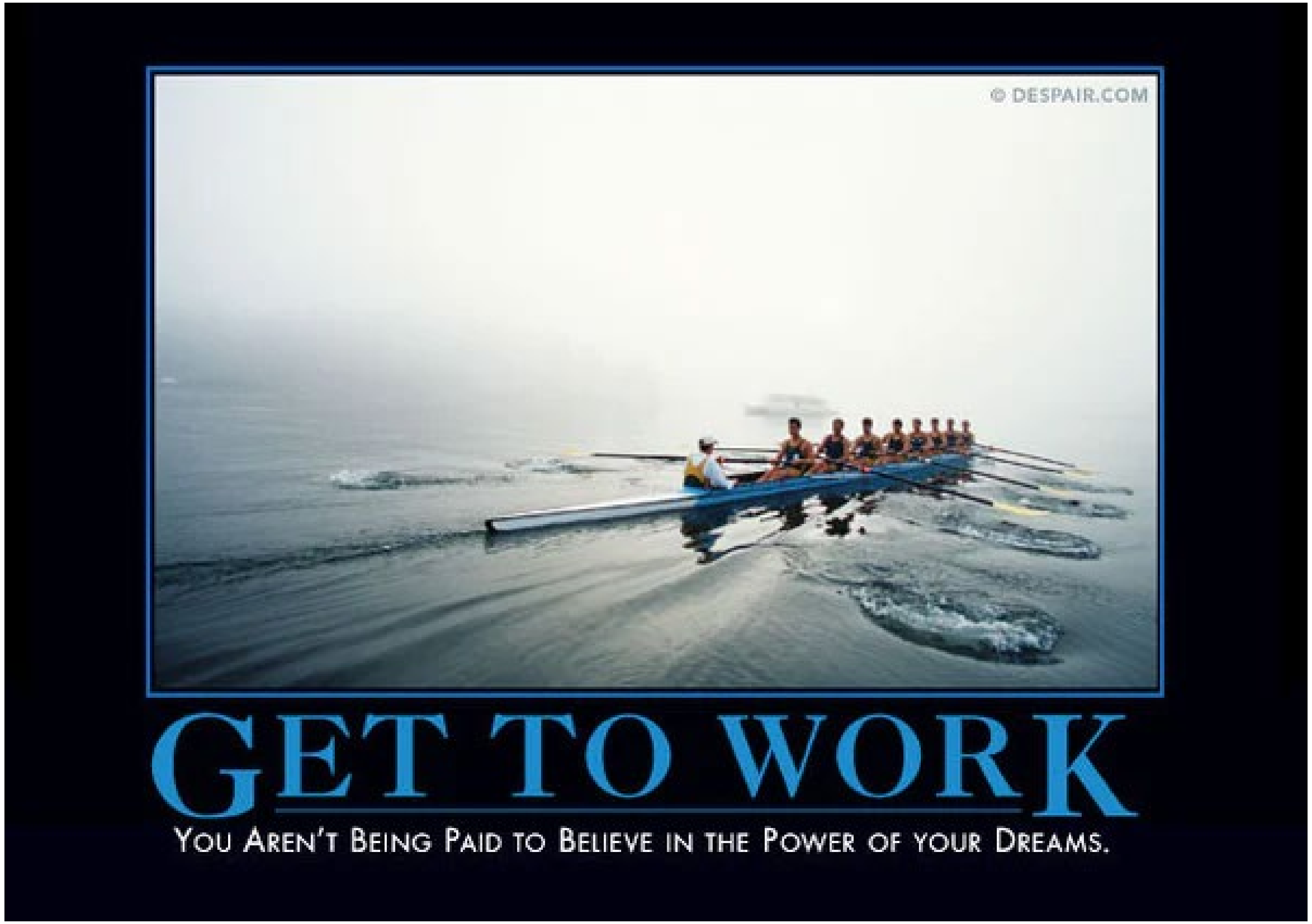
Is the treatment going to be resonant or statistical?



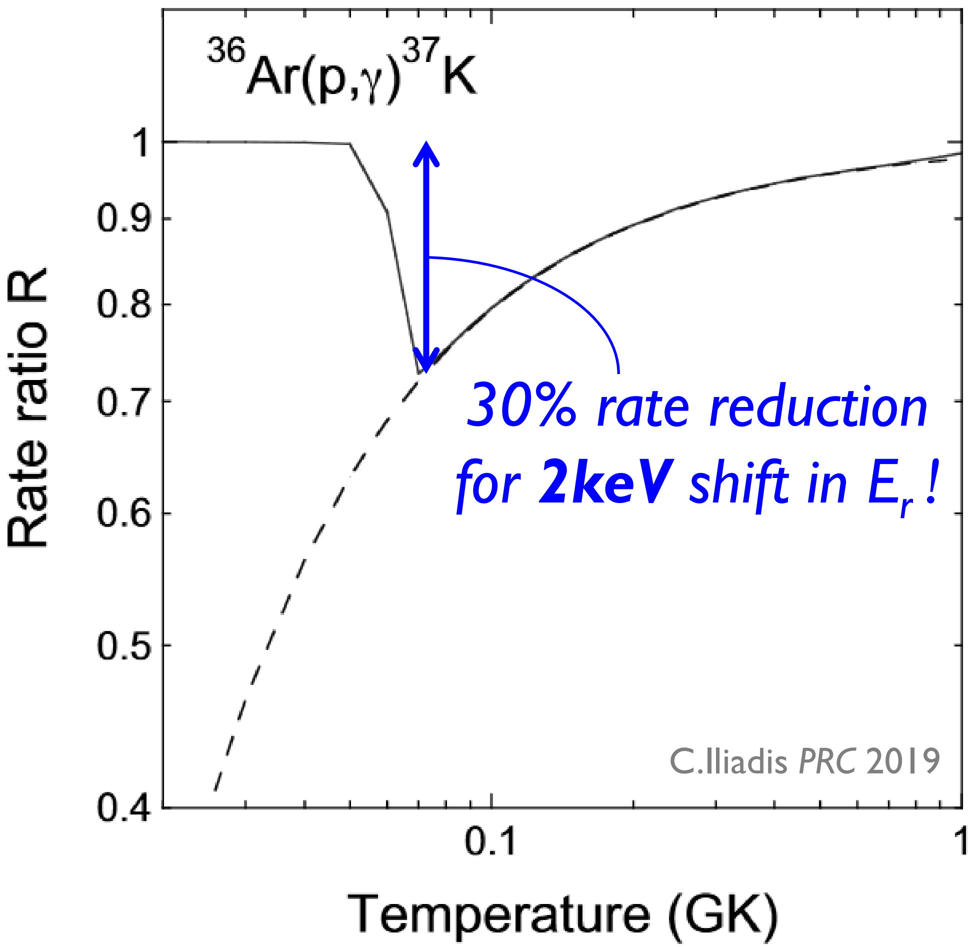




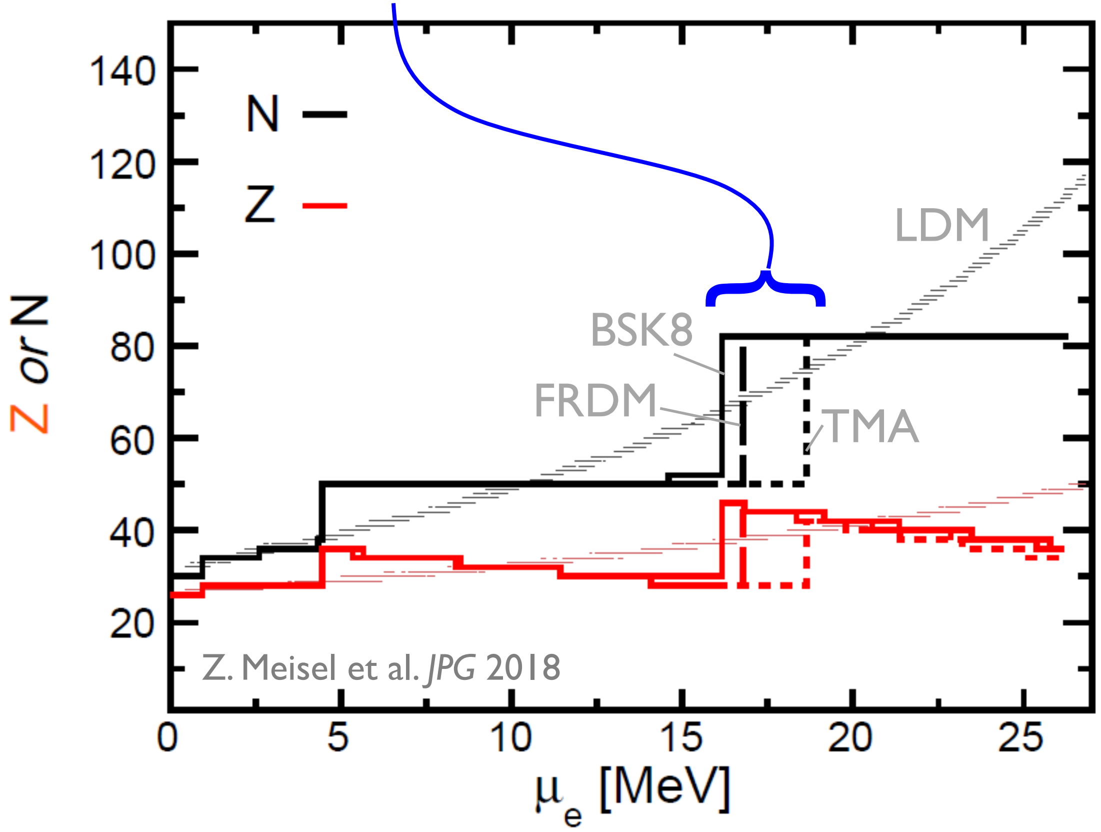
Methods and Examples



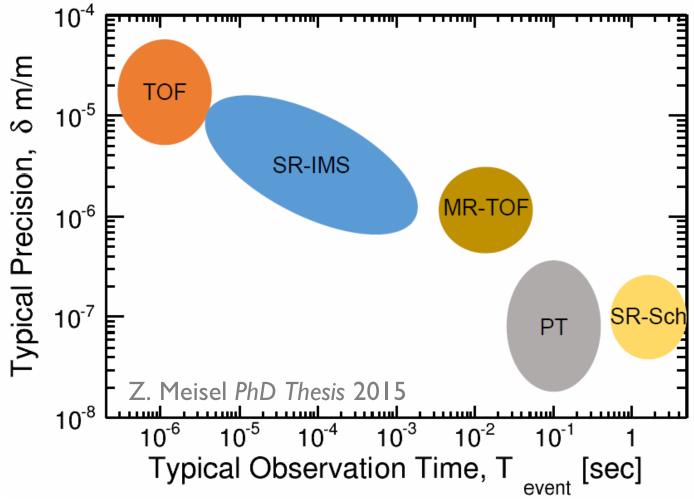
Nuclear Masses for Astrophysics:
Required precision depends on context



~MeV *changes needed for significant neutron star structure modification*

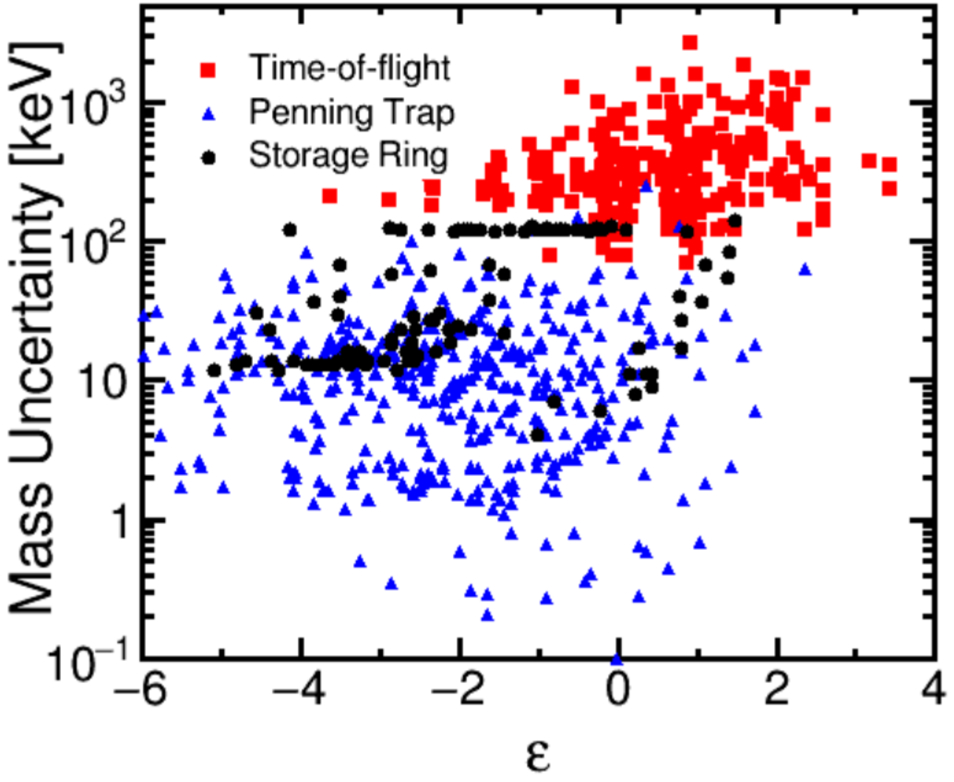


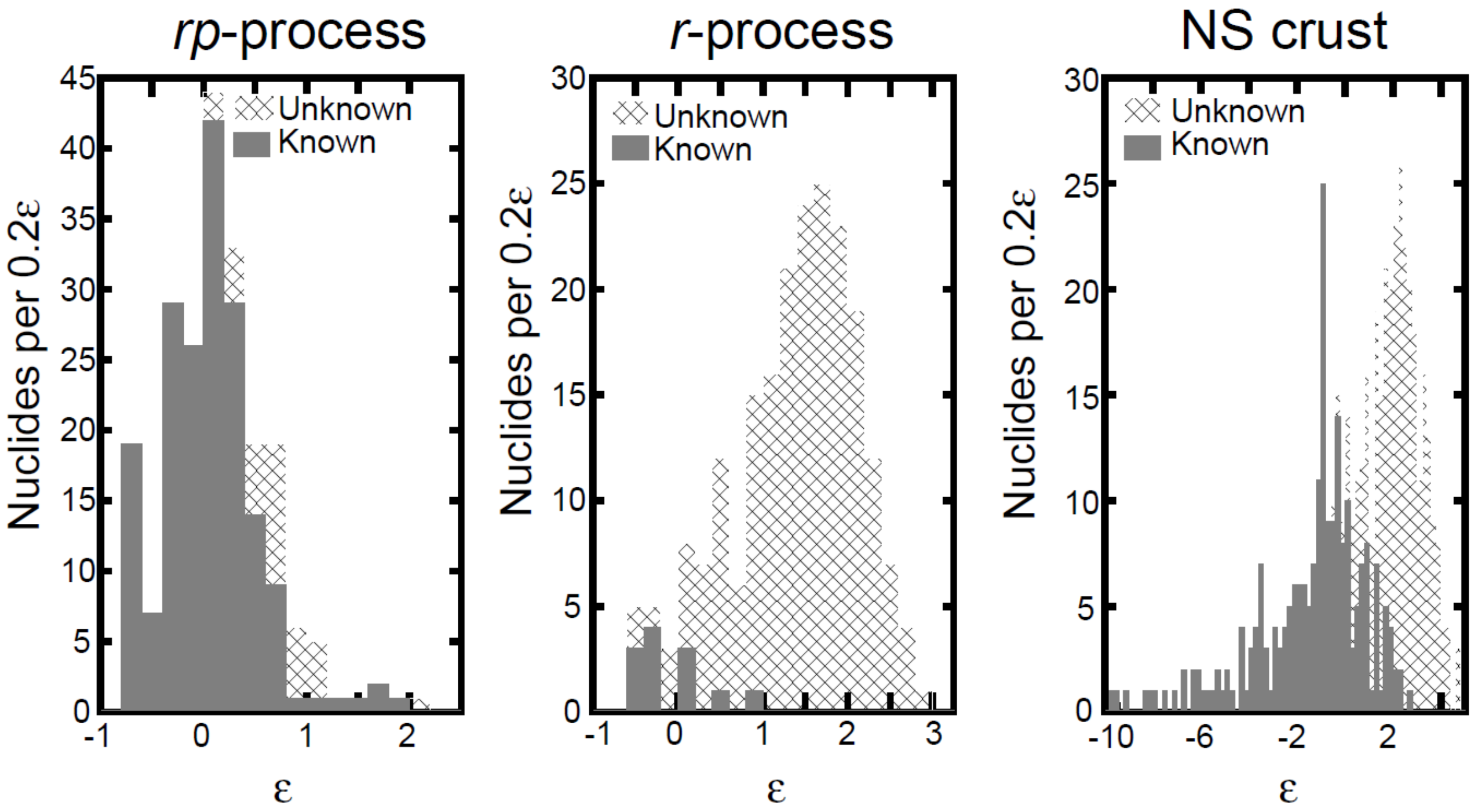
Nuclear Masses for Astrophysics:
Achievable precision depends on technique



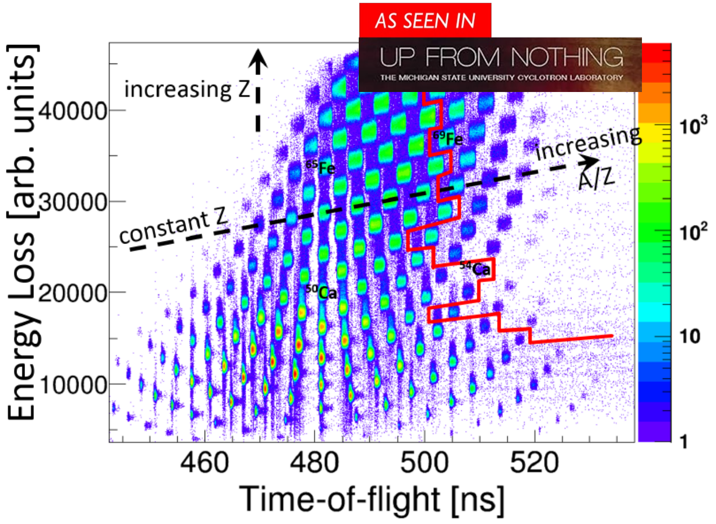
Define "exoticity": $\varepsilon = \log_{10}\left|\frac{\Delta N_{\mathrm{stab.}}}{t_{1/2}(\Delta N_{\mathrm{drip}}+1)}\right|$

Meisel & George *IJMS* 2013



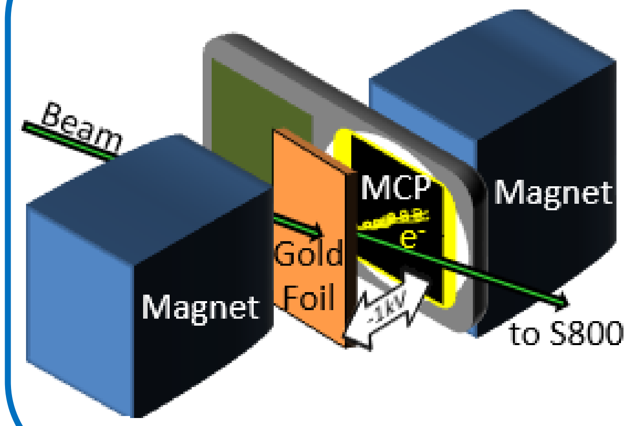


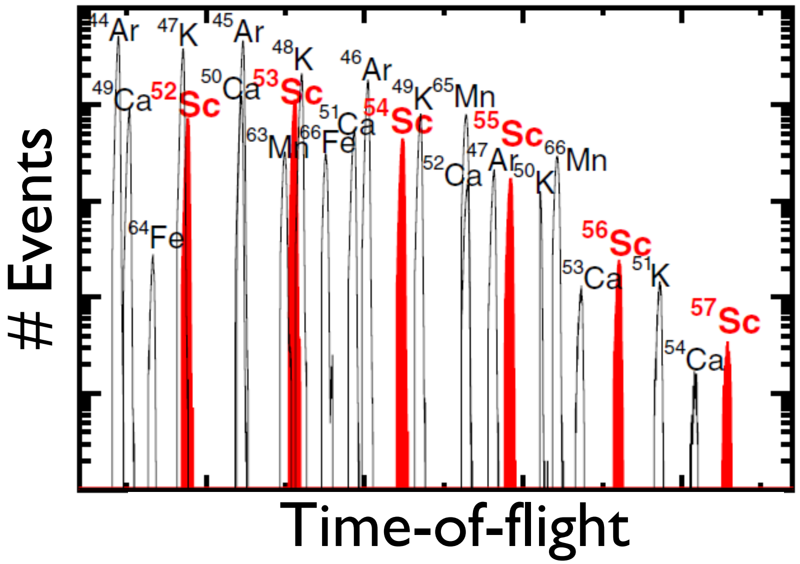
Nuclear Masses for Astrophysics: *Low-precision, high-exoticity*

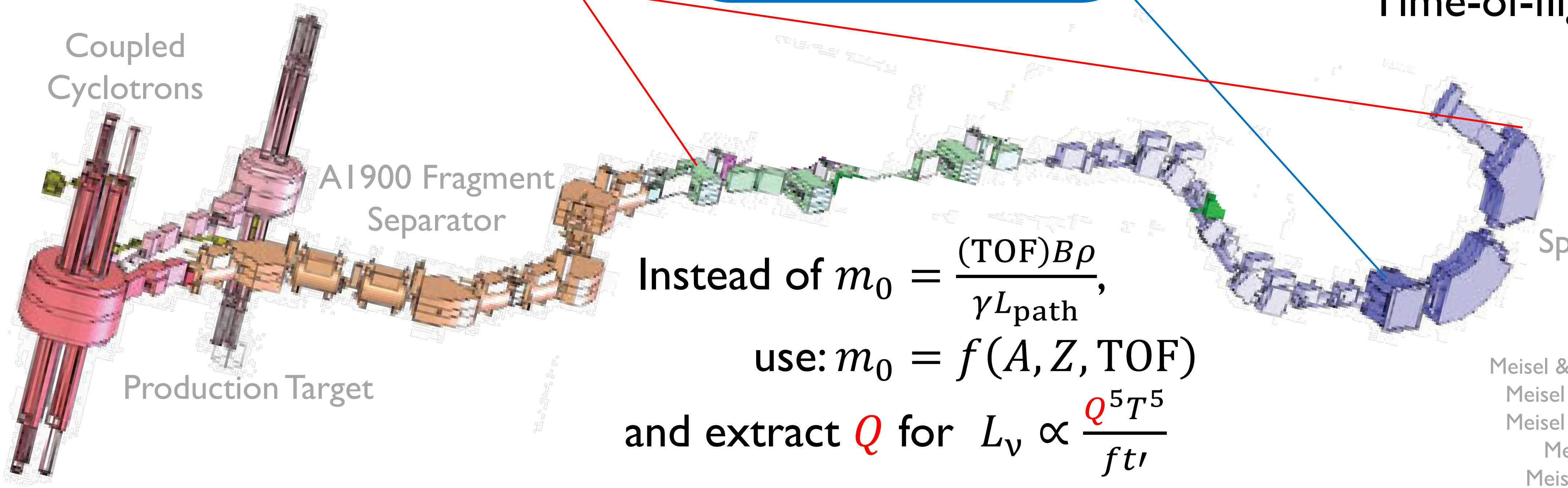


Timing measurement

Momentum measurement







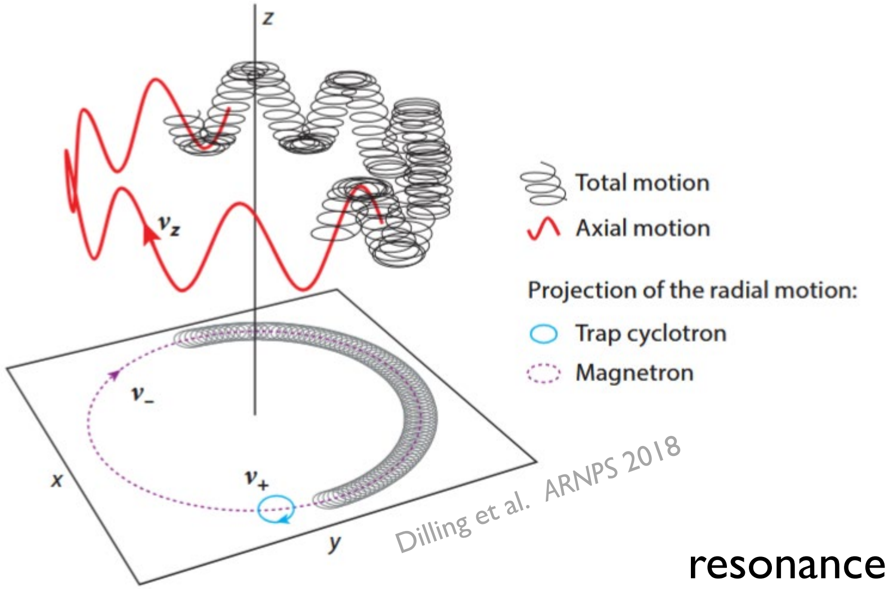
Instead of $m_0 = \frac{(\mathrm{TOF})B\rho}{\gamma L_{\mathrm{path}}}$,

use: $m_0 = f(A, Z, \mathrm{TOF})$

and extract Q for $L_\nu \propto \frac{Q^5 T^5}{ft\prime}$

Meisel & George *IJMS* 2013
Meisel et al. *PRL* 114 2015
Meisel et al. *PRL* 115 2015
Meisel et al. *PRC* 2016
Meisel et al. PRCL 2020

Nuclear Masses for Astrophysics: *High-precision, lower-exoticity*

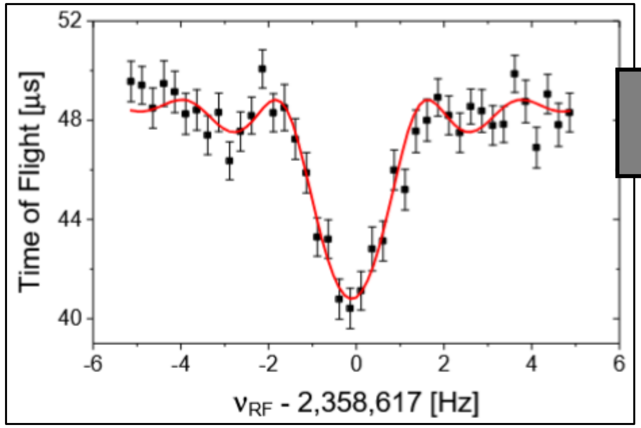


Dilling et al. *ARNPS* 2018

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Can extract Q and therefore $E_{R,i}$

^{61}Zn mass

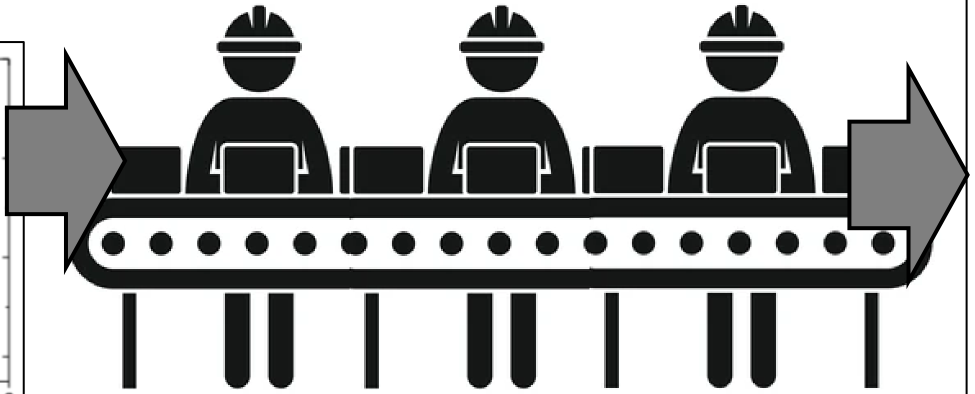


Meisel et al. *PRC* 2022

resonance properties ($E_{R,i}$)

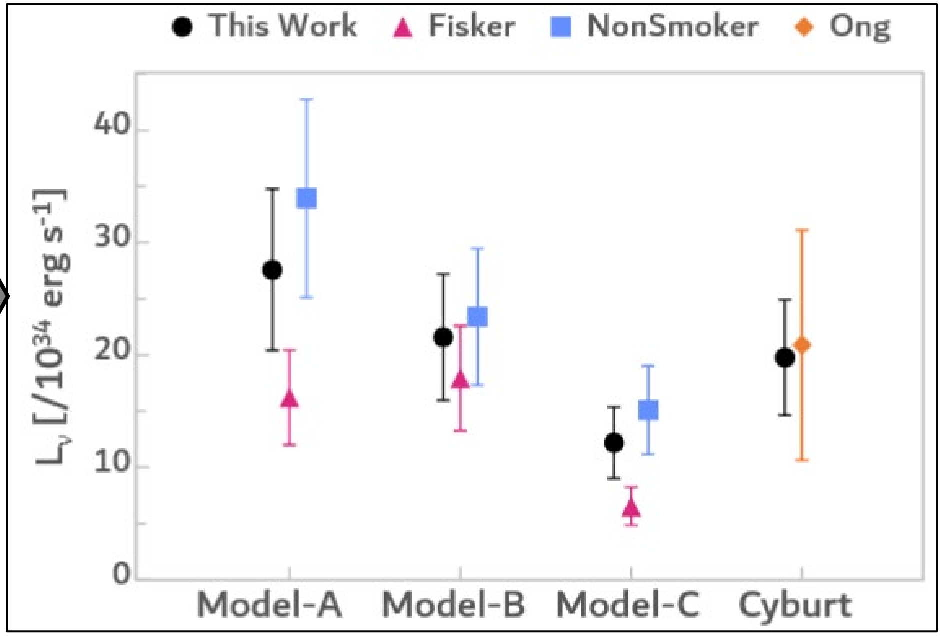
reaction rate

XRB calcs of rp-process ashes



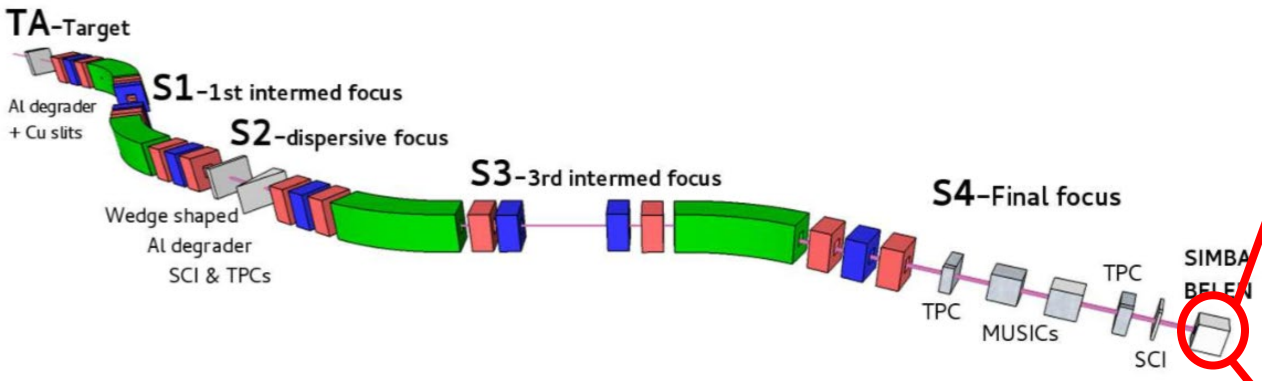
$$N_A\langle\sigma v\rangle \propto \sum_{i=1}^{N}(\omega\gamma)_{R,i}\exp\left(-\frac{11.6045E_{R,i}}{T_9}\right)$$

NS Crust Urca luminosity

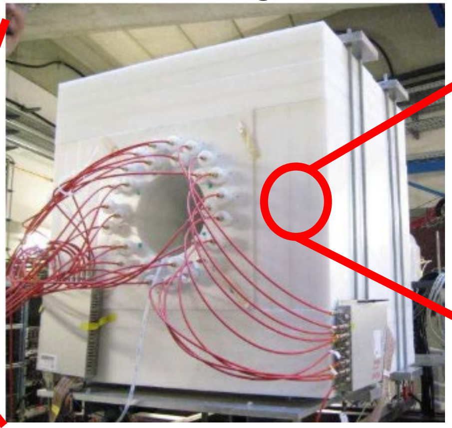


Meisel et al. *PRC* 2022

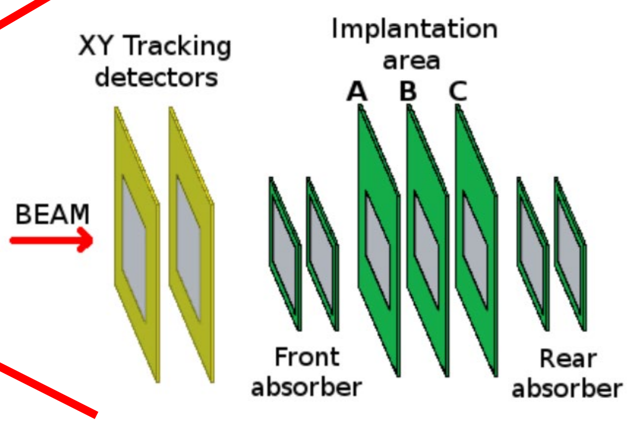
Radioactive Decays for Half-Lives and Branchings



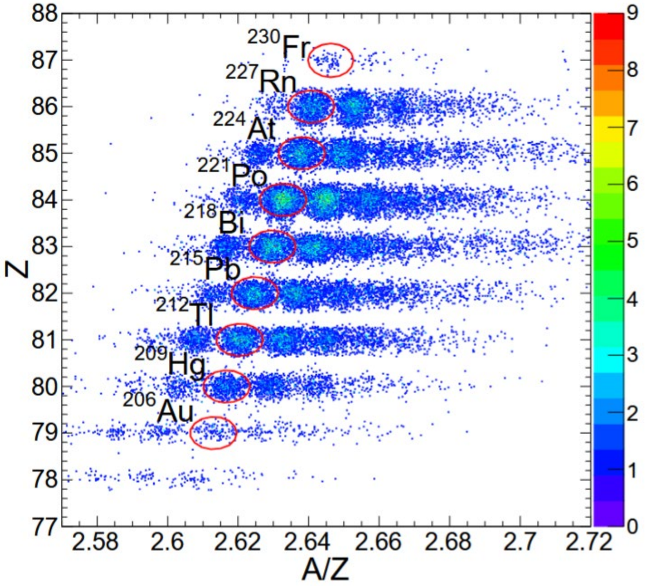
Neutron Long-counter



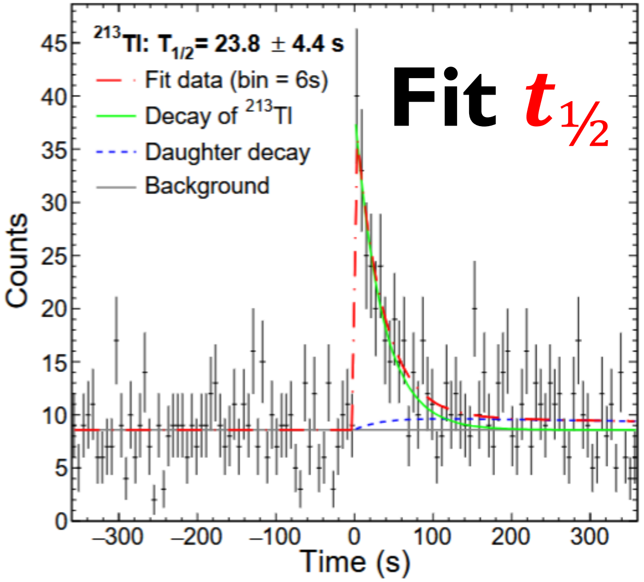
Implantation Si-Stack



ID particle with TOF-ΔE combo.

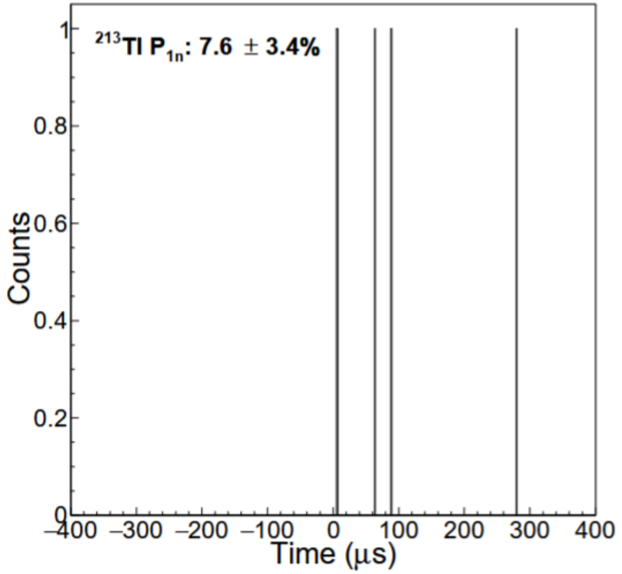


Gate on space & time following implant, look for low-E deposition from β



Fit $t_{1/2}$

For valid decays, look for neutrons within thermalization time, P_n

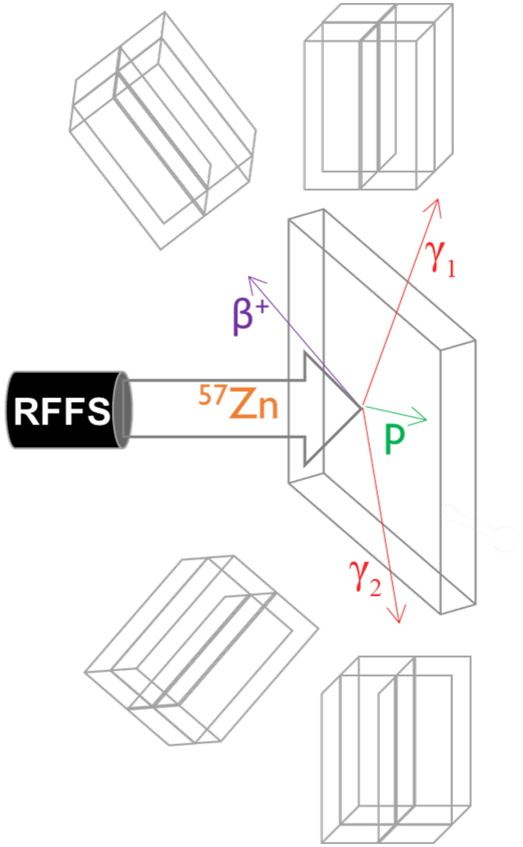


Implement λ into reaction network calculations (e.g. r-process nucleosynthesis)

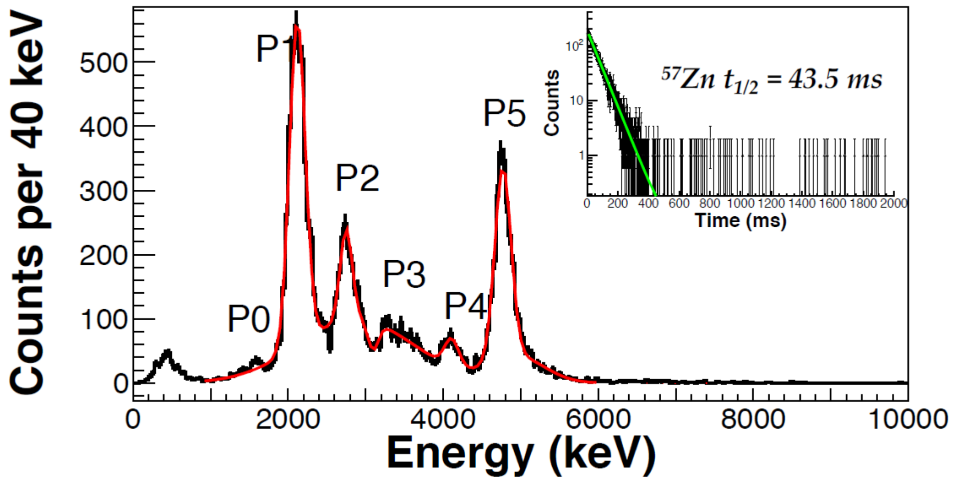
R. Caballero-Folch et al. PRC 2017

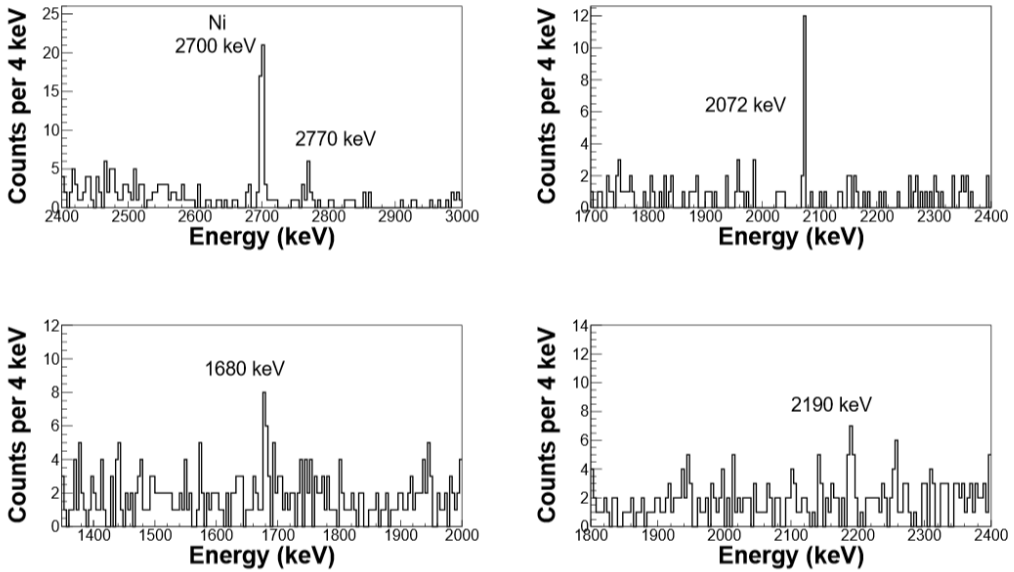
Radioactive Decays for Spectroscopy

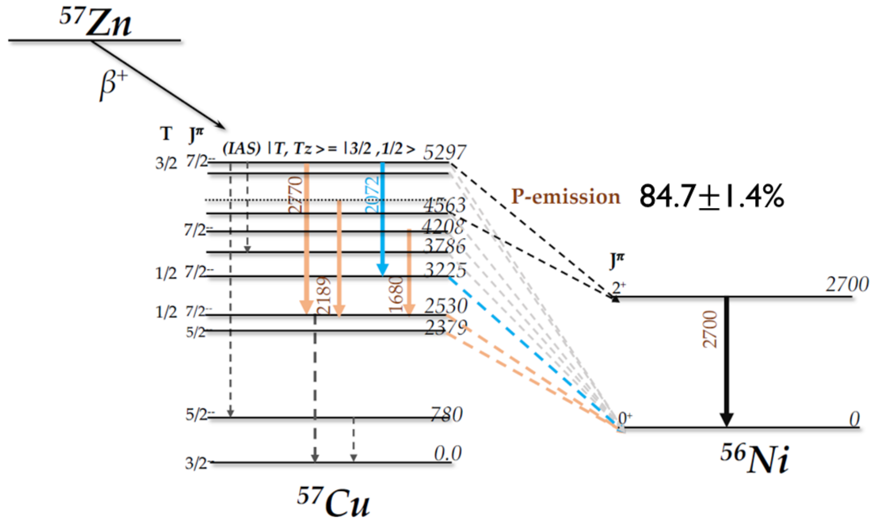
Measure β-γ, β-*p*, and β-*p*-γ *correlations to reconstruct* ^{57}*Cu structure, determining* $E_{R,i}$ *and* P_{β}



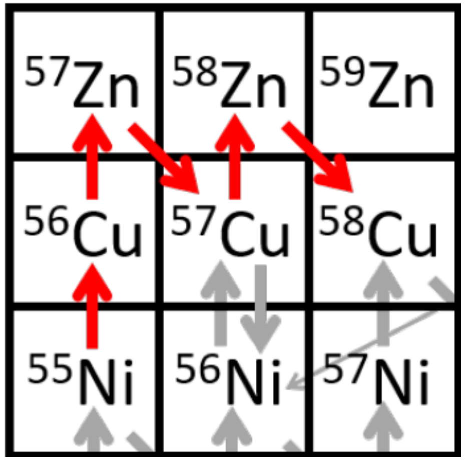
M. Saxena et al. *PLB* 2022







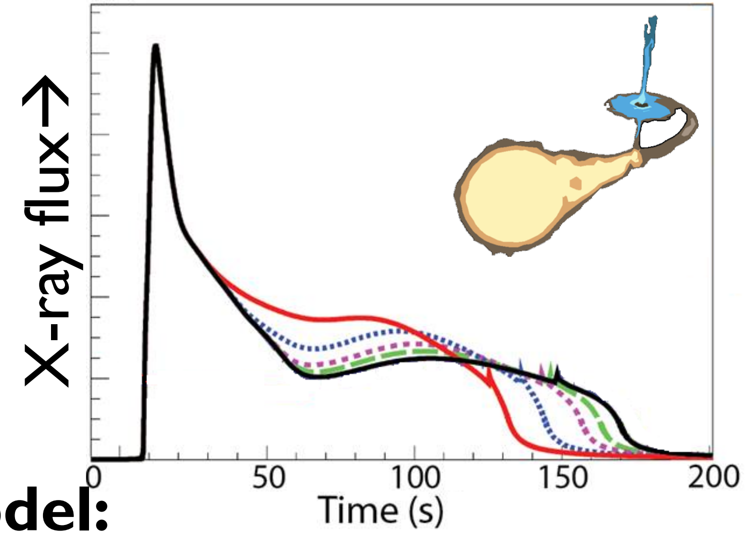
Constrain XRB ^{56}Ni bypass



Radioactive Decays for Masses

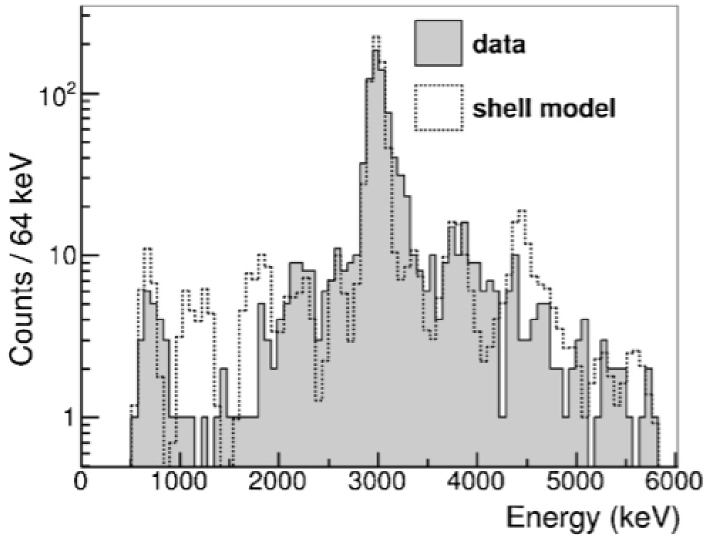
Mass rules everything around me. -Method Man
(if he were a nuclear astrophysicist)

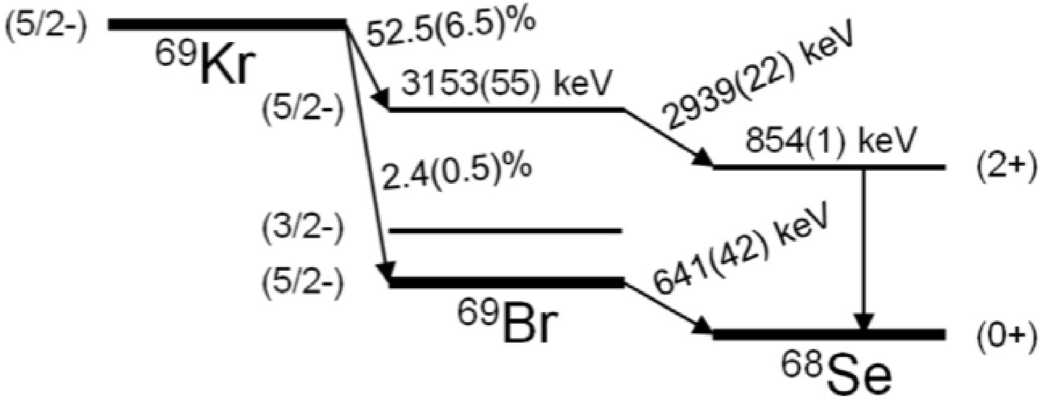
XRB Model output:



XRB Model:

Determine Q-value, setting (p,γ)-(γ,p) equilibrium, by finding the lowest-E β-delayed protons



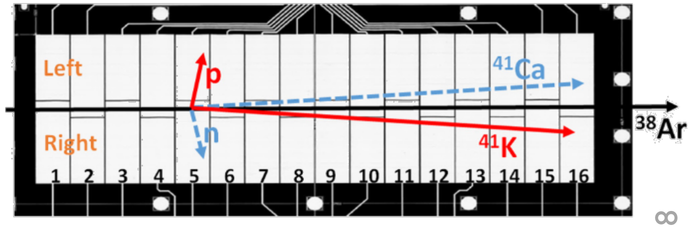


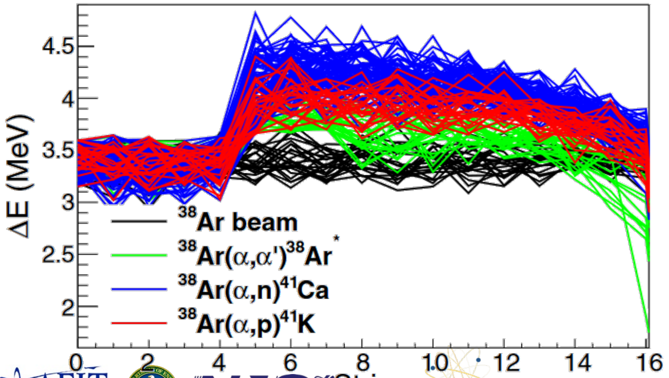
M. del Santo,, et al. *PLB* 2014

Cross Sections with Exotic Beams

- The concept is simple: count what goes in, what it can hit, and what comes out
  - For a thin-target set-up: $\sigma = \frac{Y}{n_a} = \frac{N_{out}}{I_{in} t n_a} = \frac{N_{detected}}{\varepsilon I_{in} t n_a} =$… *usually complicated set of things you actually measured*
- In practice, challenges come from low-intensity poorly-controlled beams and significant backgrounds (including beam-induced)
- The best-bet is to detect the recoil (and possibly coincident radiation)

Ion Chambers (e.g. MUSIC) are challenged by rate & ΔZ-resolution

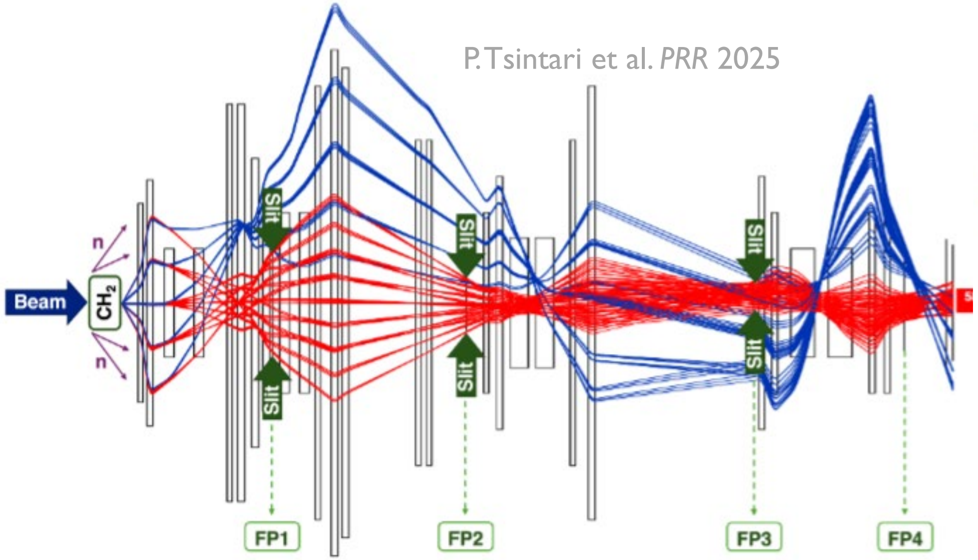


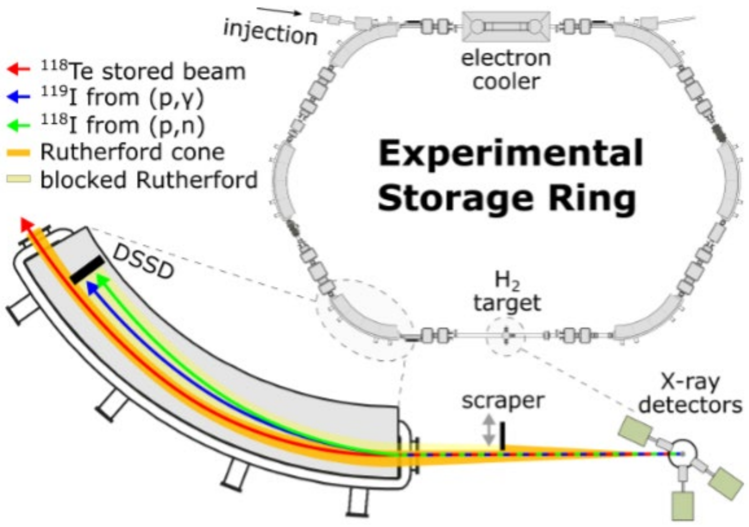


R. Talwar et al. *PRC* 2018

Recoil Separators (e.g. SECAR) and storage rings (e.g. CRYRING) are challenged by recoil acceptance and complicated backgrounds

P. Tsintari et al. *PRR* 2025

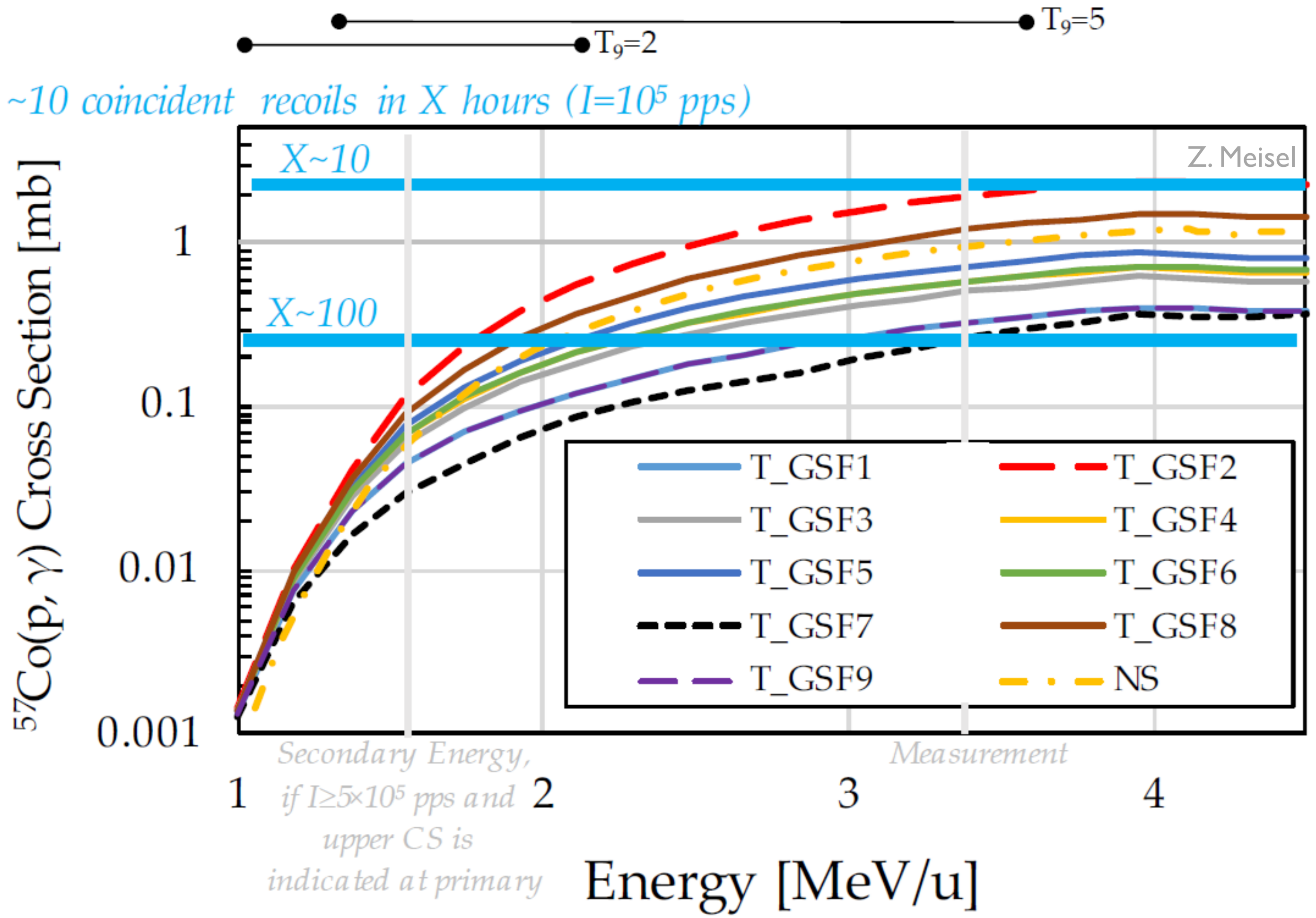




S.F. Dellmann et al. *PRL* 2025

Using Cross Sections from Exotic Beam Measurements

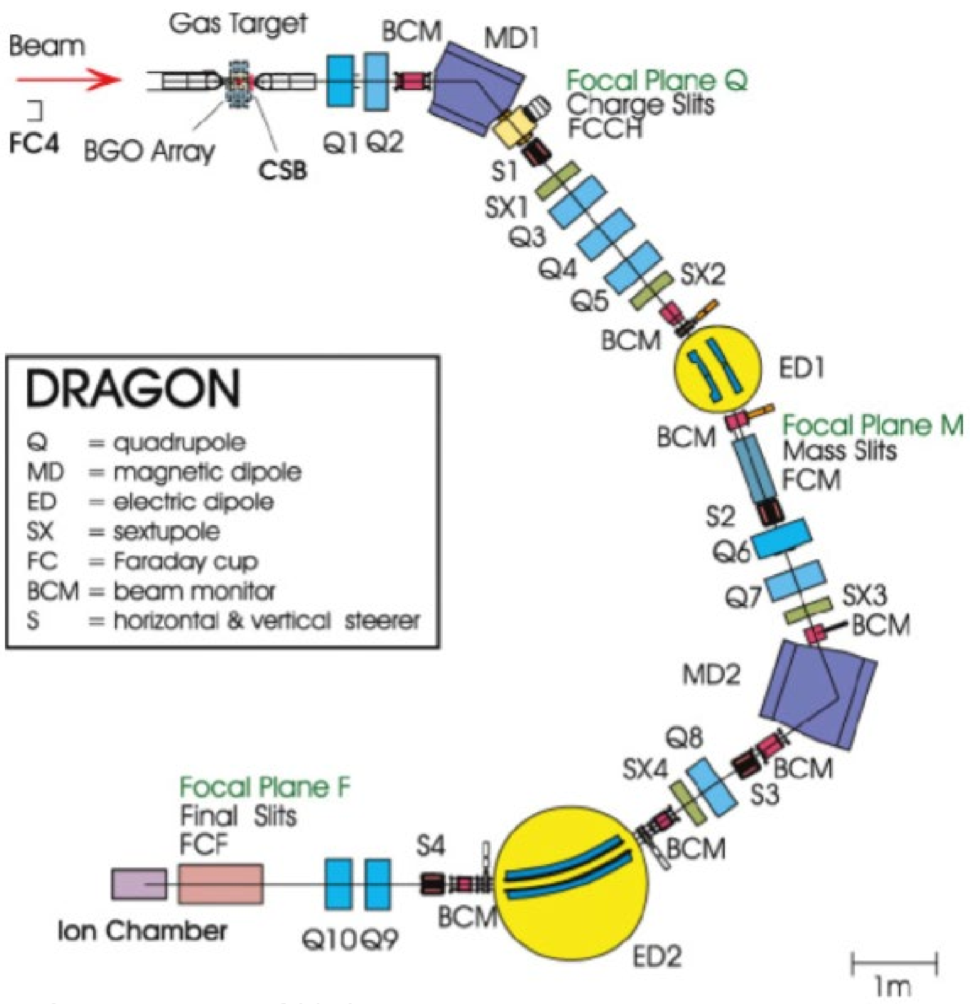
- Life is hard and astrophysical reaction yields are low…



… so usually extrapolation to lower energies is required …and everyone agrees on exactly how that is best done

For current RIB facilities, direct cross section measurements can be possible for CCSN, but only the extreme high-*T* range of XRBs. Increasing intensities are bringing more conditions into reach.

Direct Measurement of Resonance Strengths



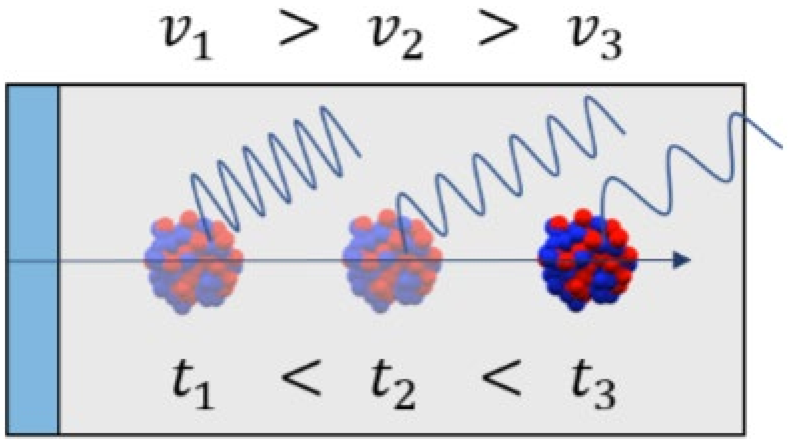
D. Connolly et al. *PRC* 2018

1. Tune the beam energy such that energy-loss in the target scans the resonance
   (you need to know $E_{R,i}$ beforehand!)
2. Measure the number of recoils in the final focal plane and the beam intensity (e.g. via scattering) to get the yield:
   $$Y = N_{rec}/(N_b \eta_{total})$$
3. Determine all of the efficiencies, transmission factors, and live times that go into the total efficiency:
   $$\eta_{total} = f_q T_{sep} T_{MCP} \eta_{MCP} \eta_{IC} f_{live}$$
   (…this is the hard part)
4. So long as $\Delta E_{target} > \Gamma_{res}$, $\omega\gamma \propto Y$
5. ~~Profit.~~ Calculate $N_A \langle \sigma v \rangle$

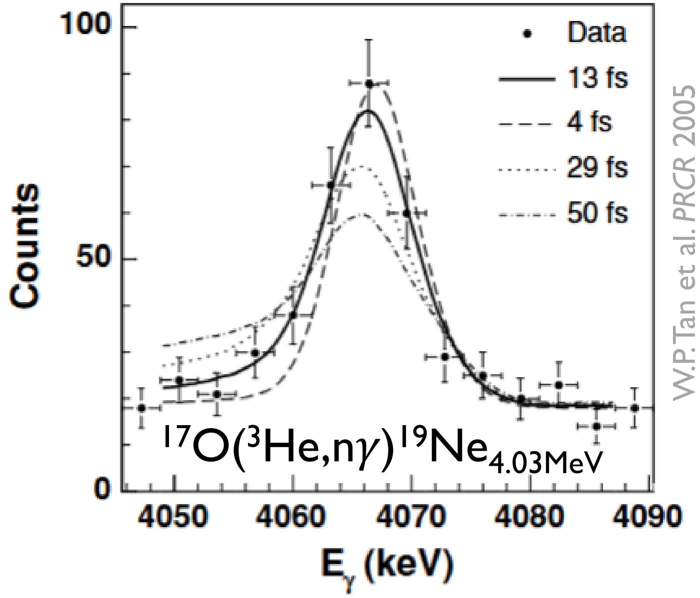
Resonance Strength Components: *Direct determination of Partial Widths*

$$(\omega\gamma)_R = \frac{2J_R + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\Gamma_{12}\Gamma_{34}}{\Gamma}$$

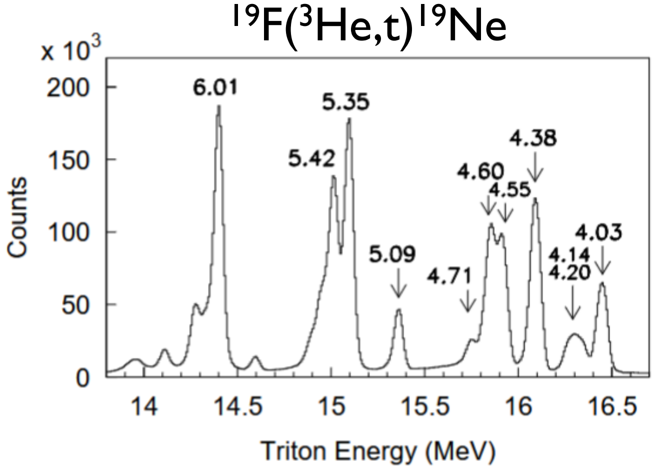
- $\Gamma \propto \tau^{-1}$, thus excited state decay half-lives are great if we can get them.
- e.g.* the doppler-shift attenuation method for Γ_γ,
- or transfer reaction + decay branchings for $\frac{\Gamma_\alpha}{\Gamma}$
  (though note if $\Gamma \approx \Gamma_\alpha + \Gamma_\gamma$ and $\Gamma_\alpha \ll \Gamma_\gamma$, then $\omega\gamma \propto \Gamma_\alpha$)
- Here, for the holy-grail of X-ray bursters, ^{15}O(α,γ)^{19}Ne

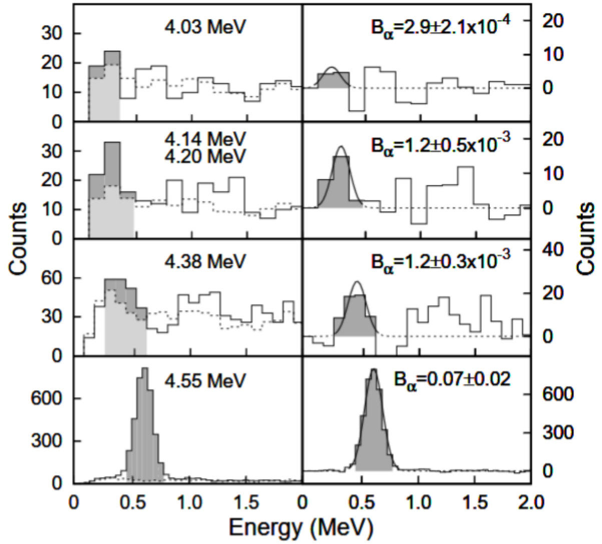


S. Prill et al. *JPhysConfSer* 2020



W.P.Tan et al. *PRCR* 2005





W.P.Tan et al. *PRL* 2007

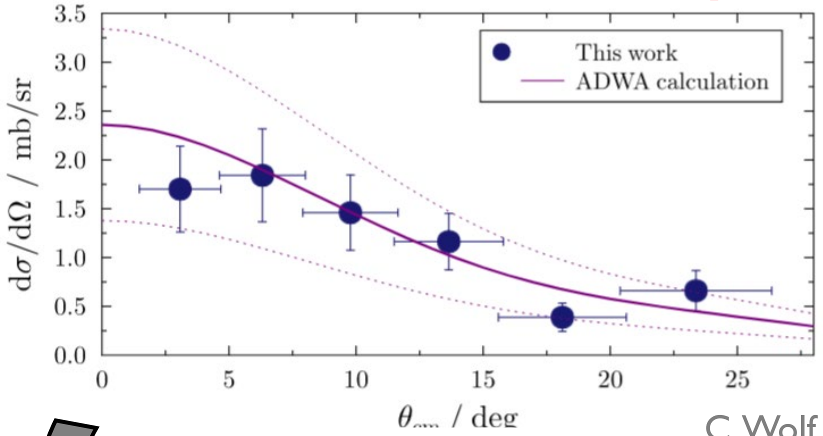
*Stable beam examples, but can be done in inverse kinematics

Resonance Strength Components: *Indirect determination of Partial Widths*

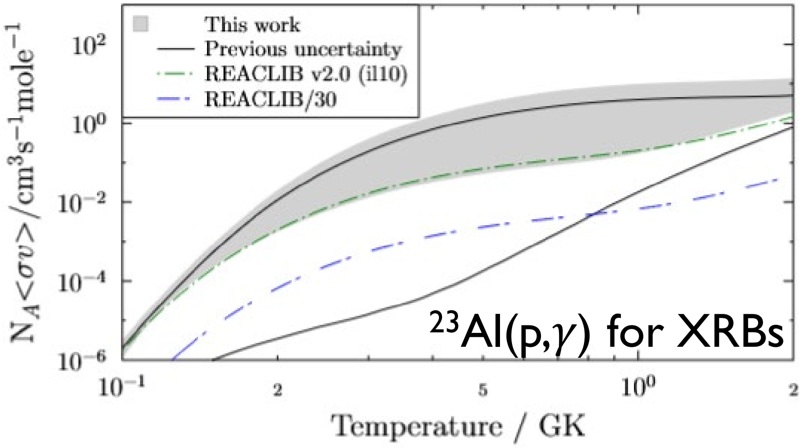
$$(\omega\gamma)_R = \frac{2J_R+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_{12}\Gamma_{34}}{\Gamma}$$

- Various bits of sorcery exist to extract widths from nuclear reaction analyses, typically involving a healthy dose of theory

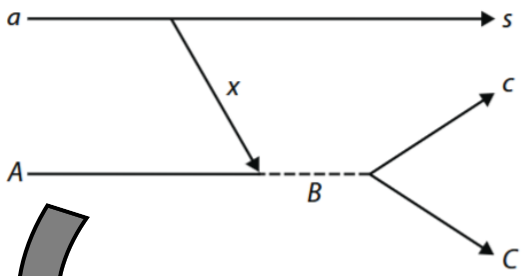
e.g. $d\sigma/d\Omega \longrightarrow C^2S \longrightarrow \Gamma_p$



C. Wolf et al. *PRL* 2019

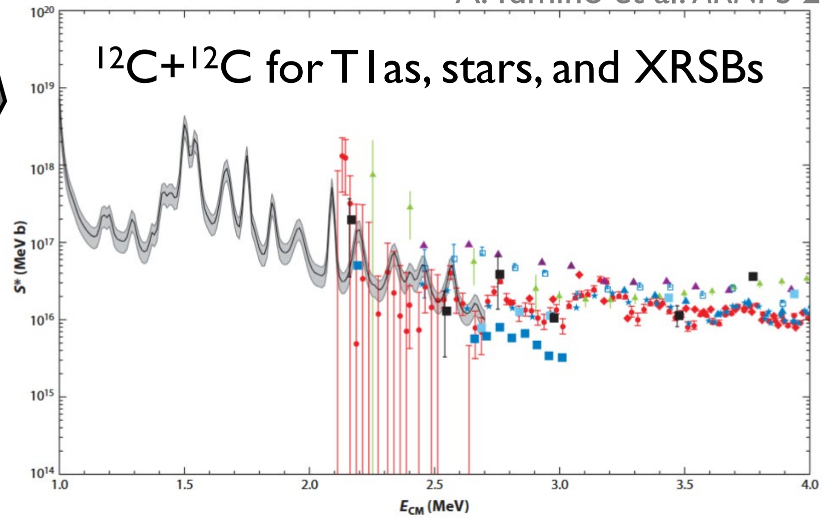


e.g. Trojan horse method



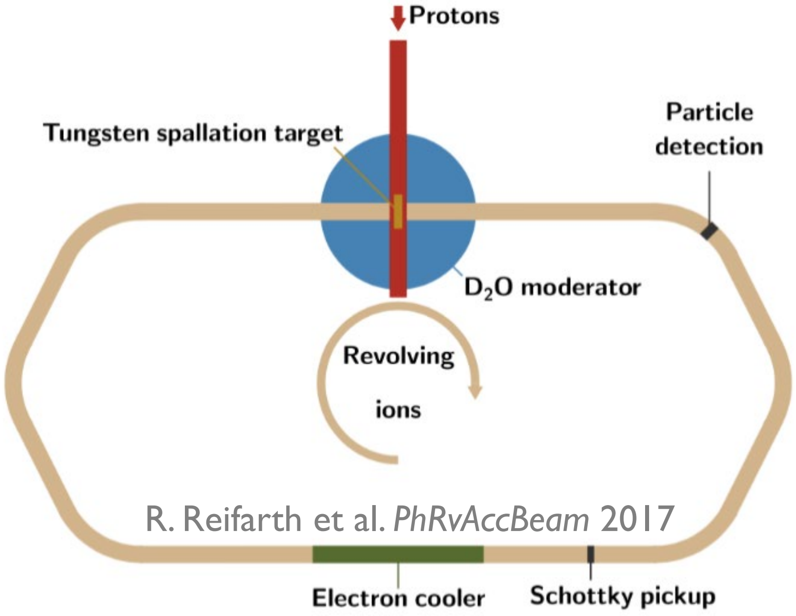
…to mimic A+x ⟶C+c

A. Tumino et al. *ARNPS* 2018

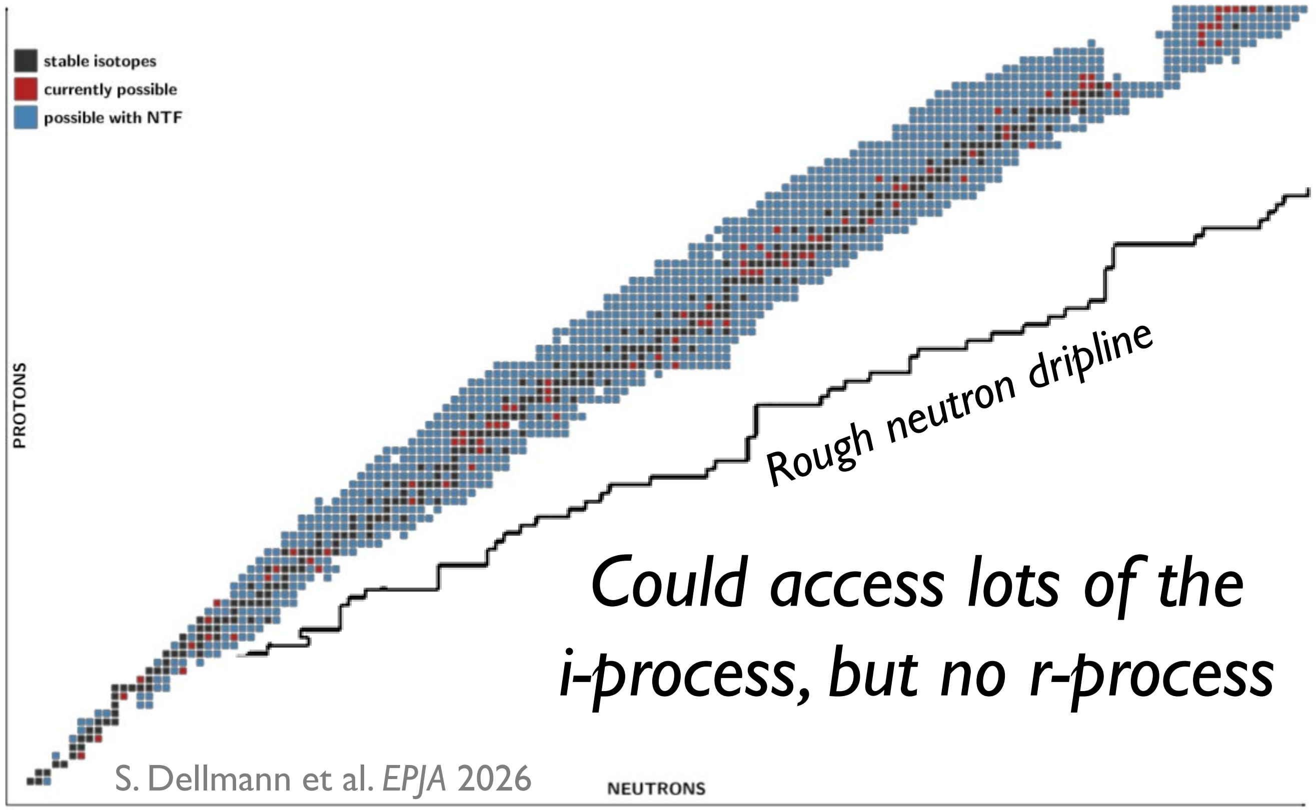


Neutron Captures on Exotic Nuclides

- Neutrons are particularly problematic for direct measurements because they don't make a great target …and to-date haven't made a target at all
- The neutron-target concept aims to pass a radioactive beam through a cloud of thermalized neutrons, ideally recycling the beam via a storage ring
- Even if successful, lots of inaccessible space on the nuclear landscape



R. Reifarth et al. *PhRvAccBeam* 2017

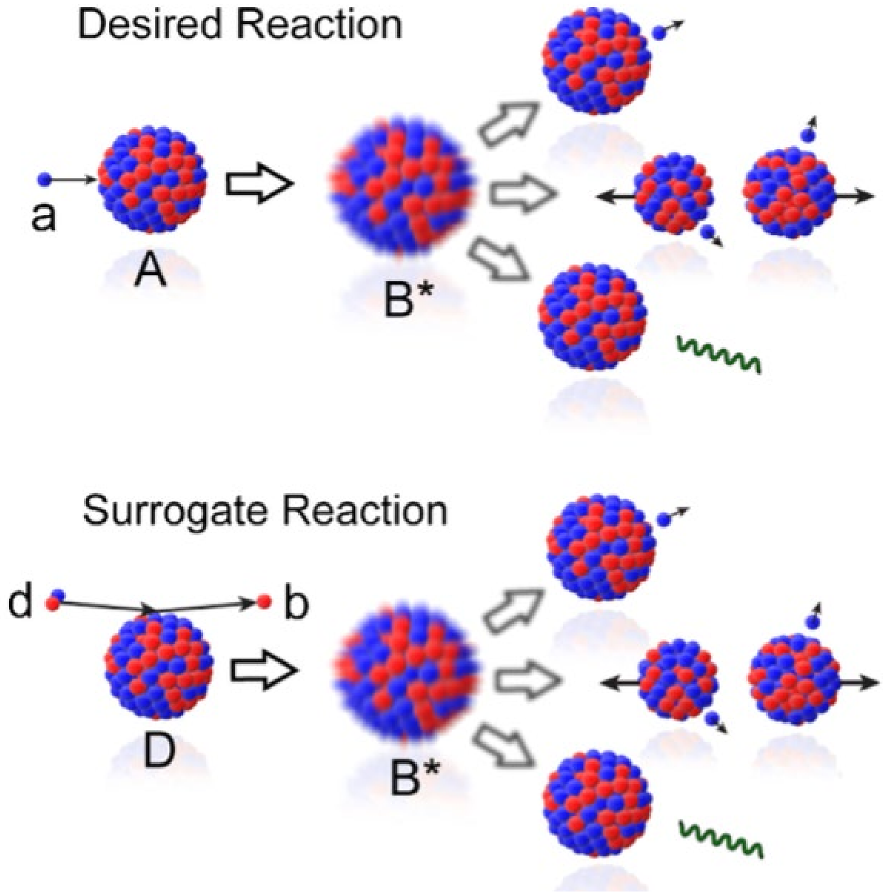


S. Dellmann et al. *EPJA* 2026

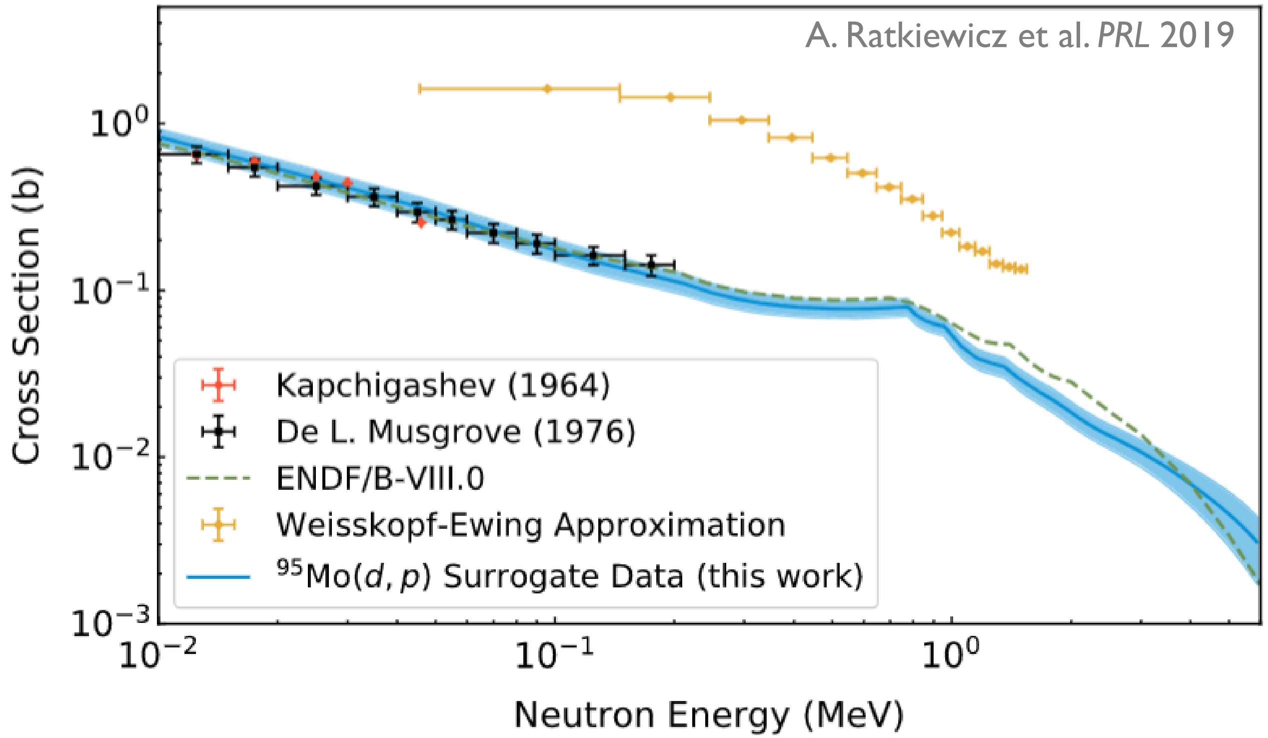
Could access lots of the i-process, but no r-process

Surrogate Neutron Captures on Exotic Nuclides

- We can mimic (n,γ) on very exotic nuclides via (d,pγ), if we assume we've formed the same compound nuclear state (which, via "amnesia" shouldn't care how its formed)
- In practice, this requires some theory gymnastics, but seems to get the job done

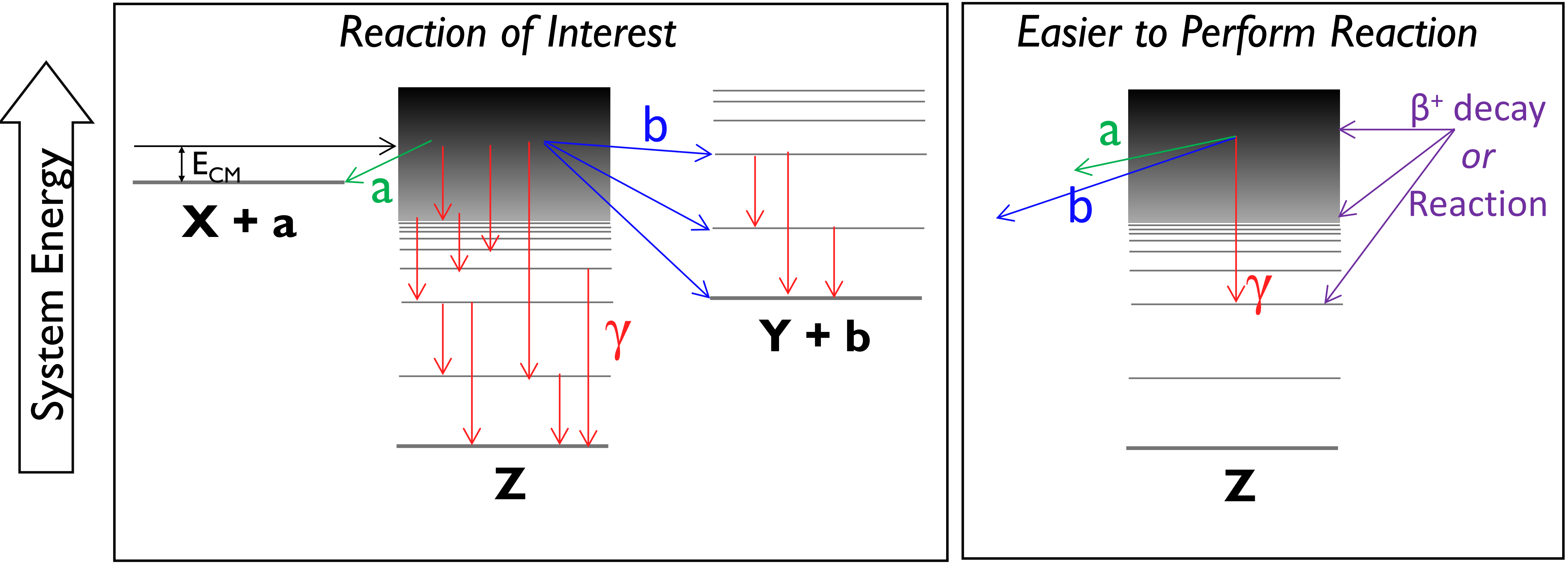


J. Escher et al. *RMP* 2012



Data to Constrain Neutron Captures on Exotic Nuclides

- When the compound nucleus level-density is high-enough, "amnesia" tells us that its enough to determine the ingredients of a Hauser-Feshbach calculation and then calculate the cross section (and reaction rate)

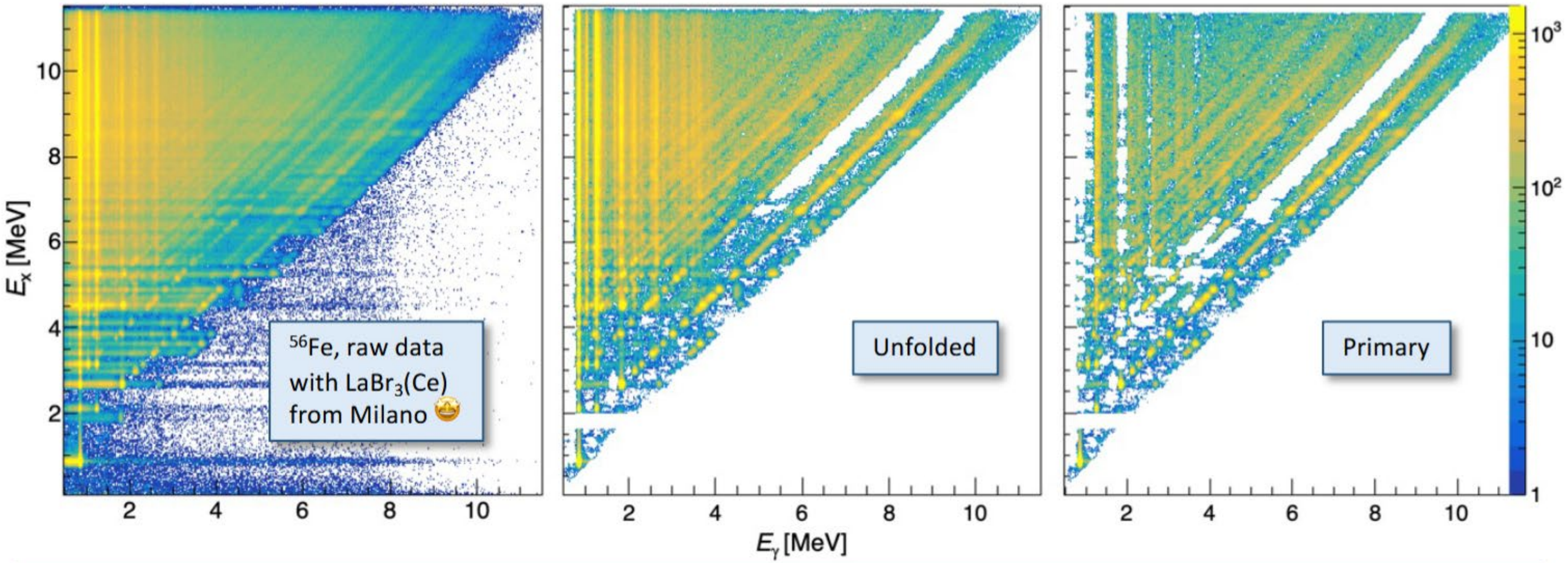


Measurements to Constrain Neutron Captures on Exotic Nuclides

- For exotic beams, a tool of choice is the Oslo method

Courtesy of A.C. Larsen

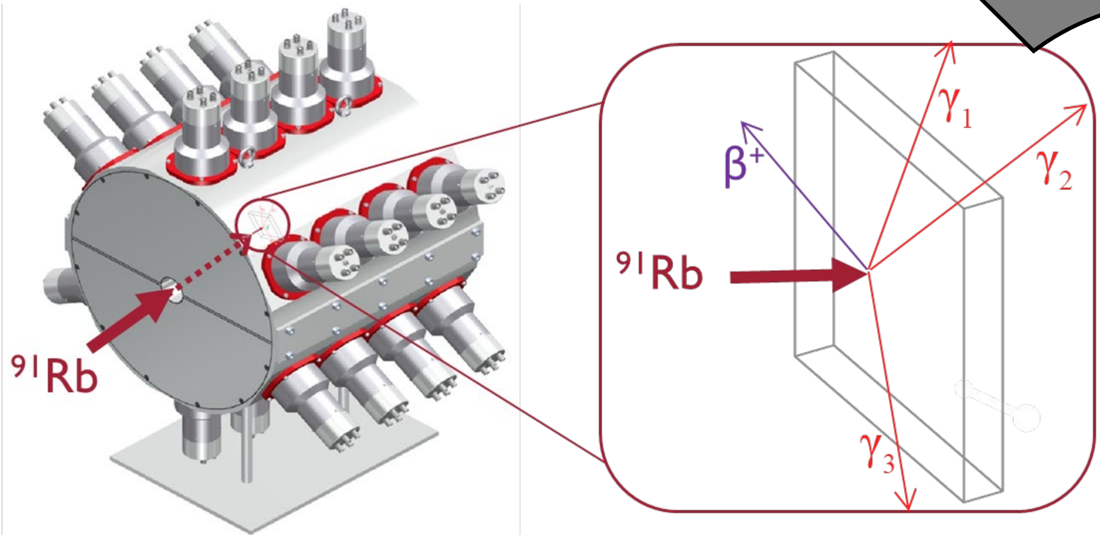
[Data from Larsen et al., PRL **111**, 242504 (2013)
and J.Phys.G: Nucl. Part. Phys. 44, 064005 (2017)]



0. Get yourself an ($E\gamma$,E_x) matrix (>20 000 coincidences)
1. Correct for the γ-detector response [Guttormsen et al., NIM A 374, 371 (1996)]
2. Extract *distribution of* primary γs for each E_x [Guttormsen et al., NIM A 255, 518 (1987)]
3. Obtain level density and γ-strength from primary γ rays [Schiller et al., NIM A 447, 498 (2000)]
4. Normalize & evaluate systematic errors [Schiller et al., NIM A 447, 498 (2000), Larsen *et al.*, PRC **83**, 034315 (2011)]

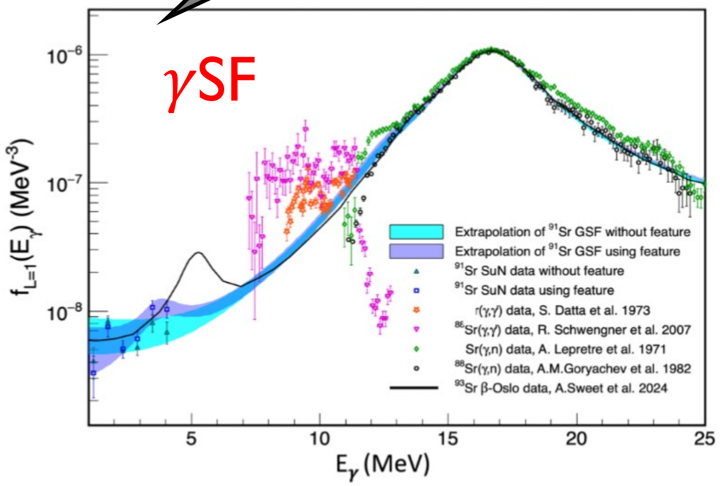
Measurements to Constrain Neutron Captures on Exotic Nuclides

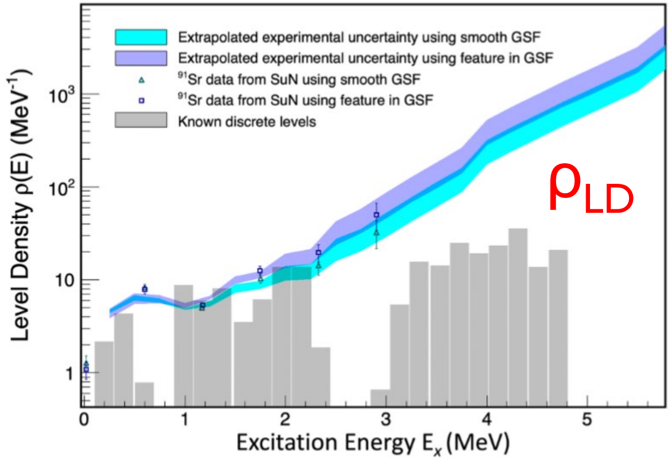
- For exotic beams, a tool of choice is the Oslo method, which can be enacted via β-decay or inverse kinematics. The key is to get E_x and E_γ.
- The main sticking point is usually normalization, which often requires theory



A. Simon et al. *NIMA* 2013

B. Greaves et al. *PRC* 2025





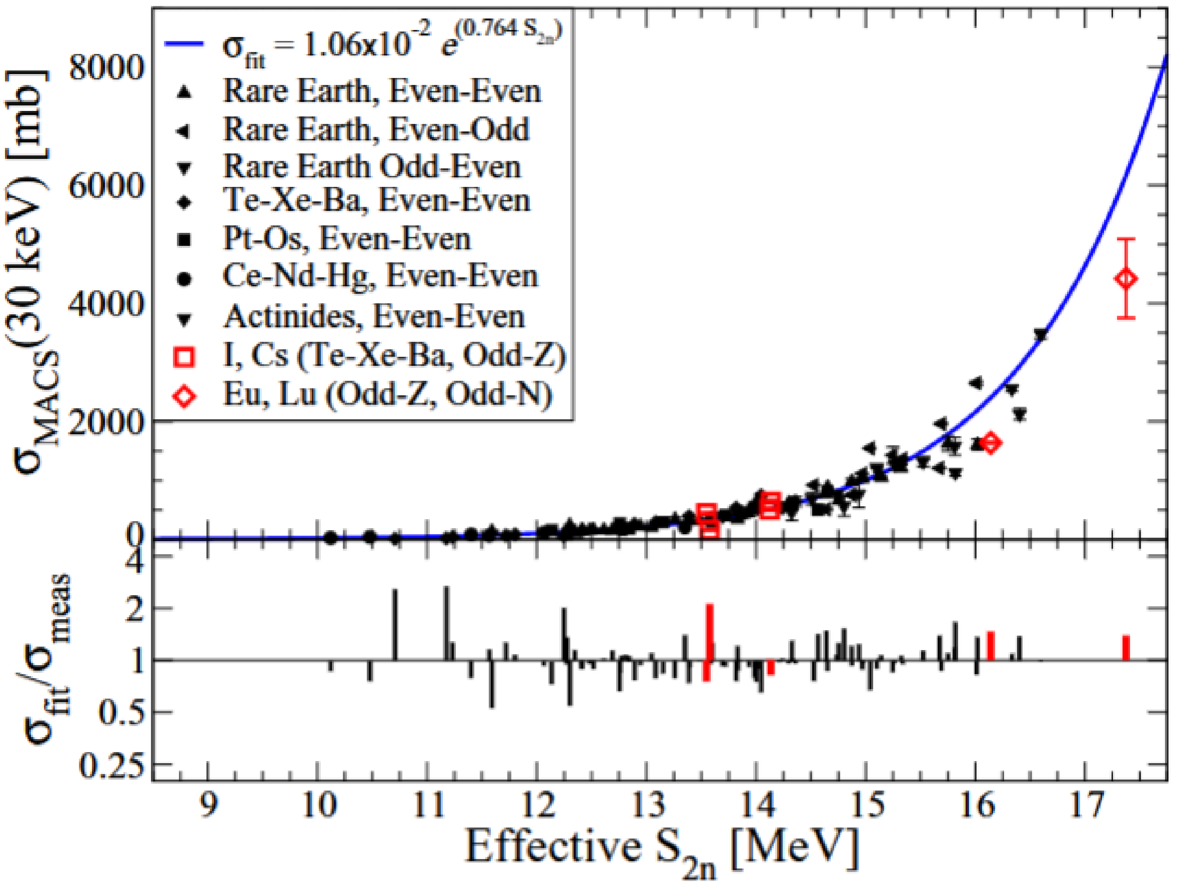
$T \longrightarrow \sigma$

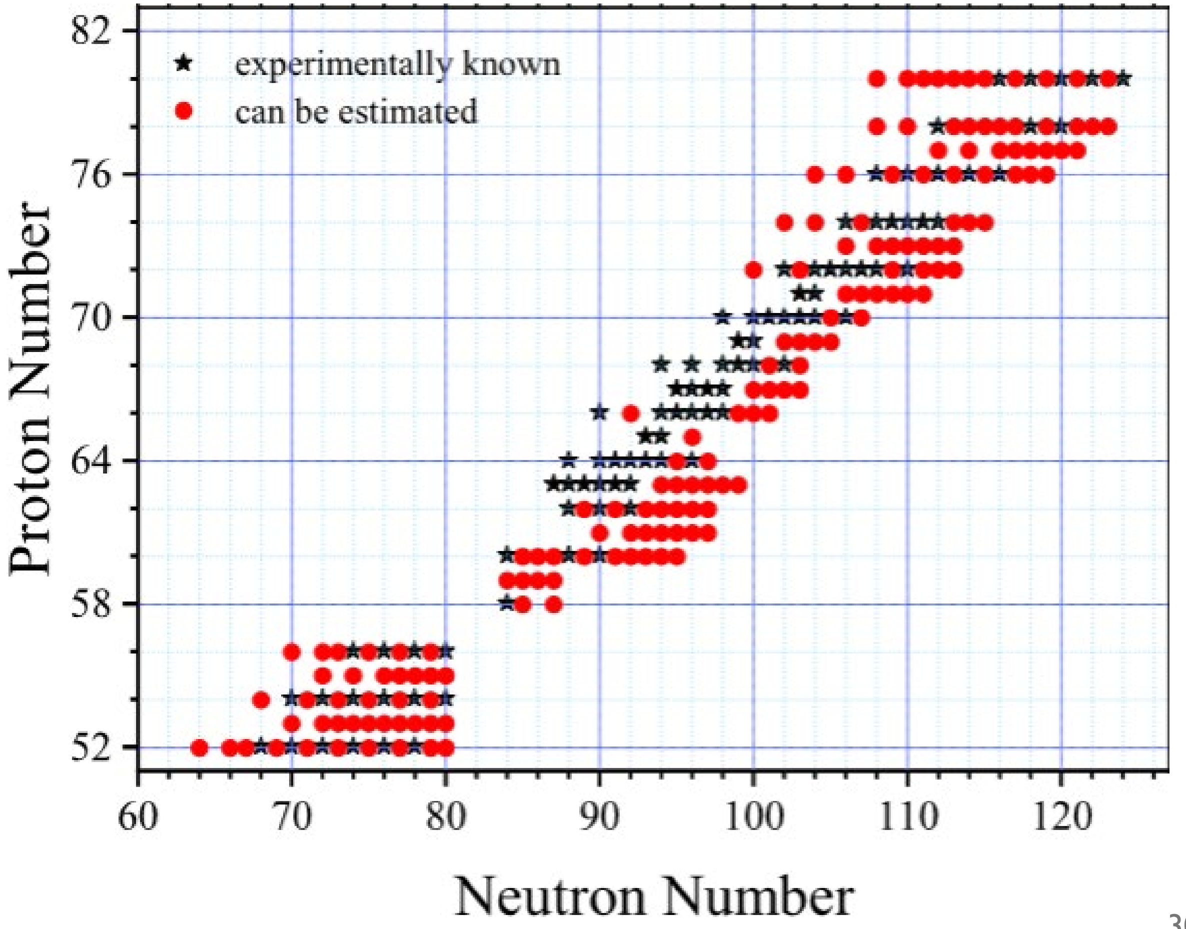
…please don't call this "indirect measurement of a reaction cross section".
It's constraining ingredients of a reaction cross section calculation. Good stuff, but not the same thing!

Psych! Masses strike again for Neutron Captures on Exotic Nuclides

- For heavy neutron-rich nuclides (specifically A≳110), there is a tight correlation between the 5-100 keV Maxwellian-averaged cross section (MACS) σ_{MACS} and the two-neutron separation energy, $S_{2n}(Z,N) = ME(Z,N-2) + 2 * ME(n) - ME(Z,N)$

Couture, Casten, & Cakirli *PRC* 2021





Not-so-exotic Beams

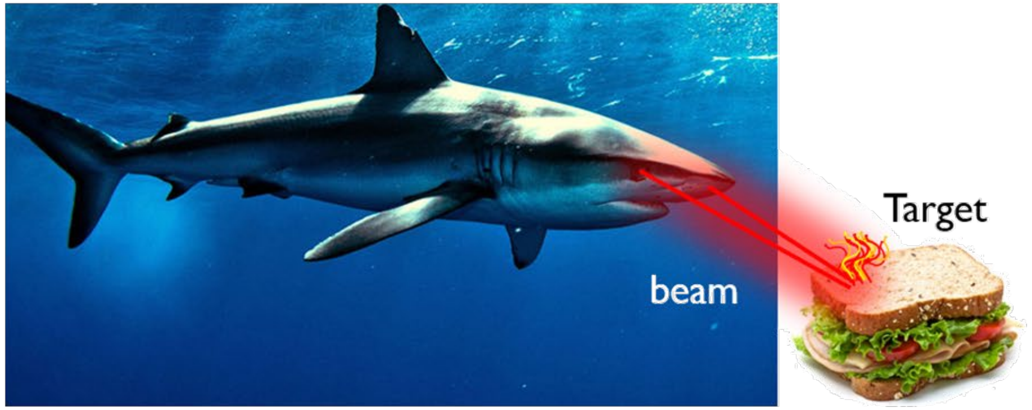
AI (Gemini) generated …because I'm hip, with the times, and bad at finding photos of a trusty old sedan next to a supercar.

This is the *Exotic Beam* Summer School, but Not-so-exotic Beams are Still Essential

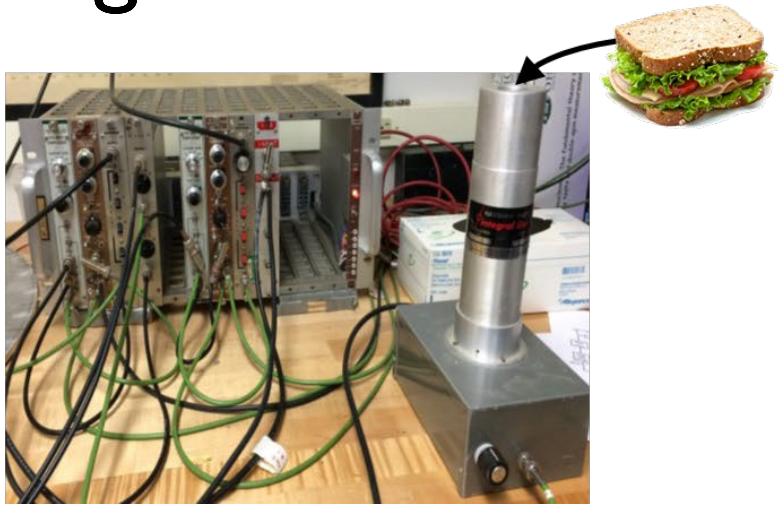
- When it comes down to it, stable beams are just plain better.
- You get much higher intensities, much more precise beam energies, and much smaller beam spots, for much cheaper.
- …with the pesky caveat that it only applies to stable isotopes
- In nuclear astrophysics, (probably) most stable-beam experiments involve directly impinging protons, deuterons, or α-particles on a target and either measuring the immediate (prompt) radiation or the (delayed) decay radiation from an activated target.
- However, many stable beam experiments use different (and often heavier) species to populate an exotic isotope off-stability
- Many techniques are similar to those described thus far, but others are possible. I'll mention a few that I think are particularly notable, but I'm sure I've missed more.

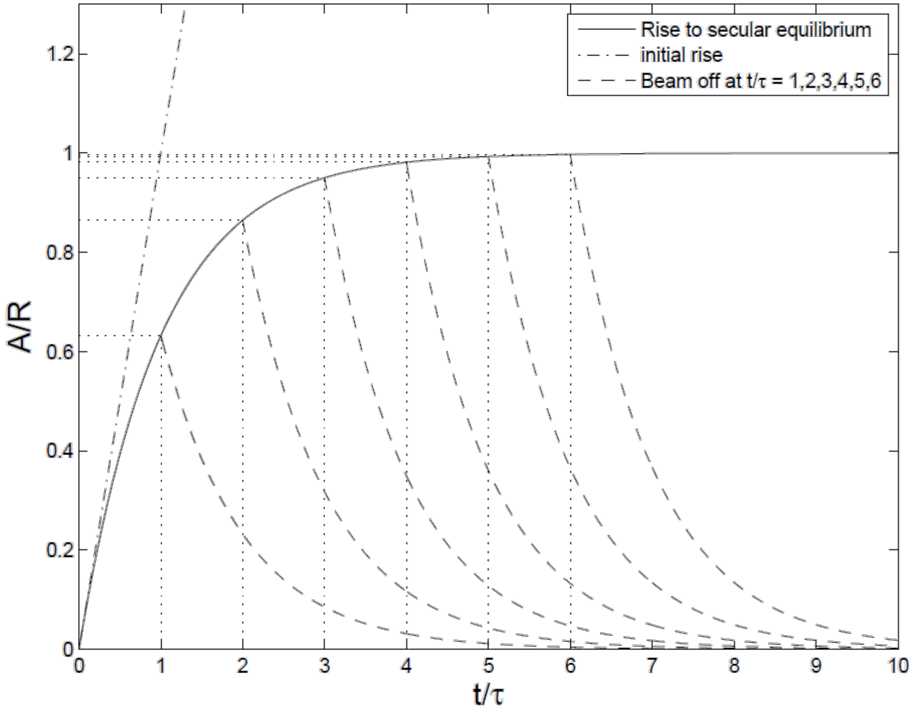
Activation is a Workhorse of Stable-target σ Measurements

(1)



(2)

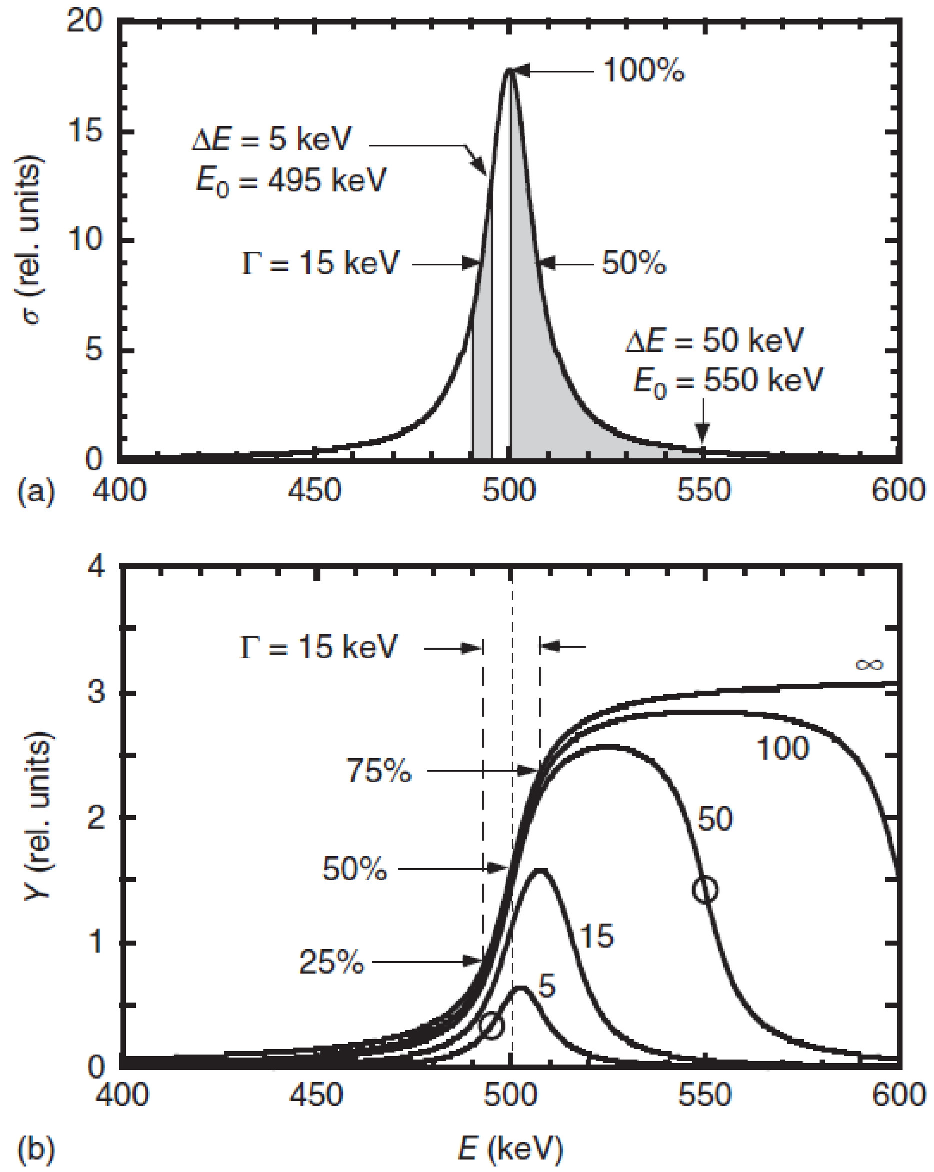




A. Bielajew, Intro. to Special Relativity,
Quantum Mechanics, and Nuclear Physics
For Nuclear Engineers 2014

$$\sigma_{12} = \frac{A_2(t_{post-irr})e^{-\lambda_2 t_{post-irr}}}{I_1 n_2 (1 - e^{-\lambda_2 t_{irr}})}$$

$\omega\gamma$ Can Be Measured *Really* Accurately with Resonance Scans



C. Iliadis, Nuclear Physics of Stars (2015)

- *All* you need is very precise control & diagnostics of your beam energy, excellent knowledge of the stopping-power (ε) of the beam in your target material, and a prompt-radiation detection system of very well known efficiency
- These are of course always easy conditions to obtain

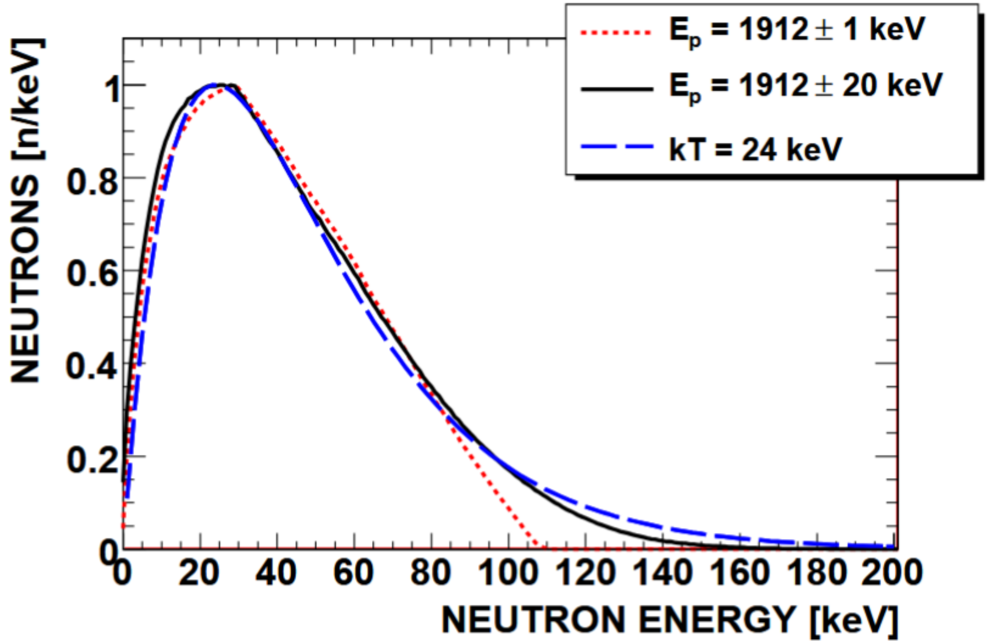
College Humor

$$Y_{max,\Delta E\rightarrow\infty} = \frac{\lambda_{R,i}^2 \omega\gamma_{R,i}}{2\varepsilon|_{E_{R,i}}}$$

$$E_{Y=½Y_{max,\Delta E\rightarrow\infty}} = E_{R,i}$$

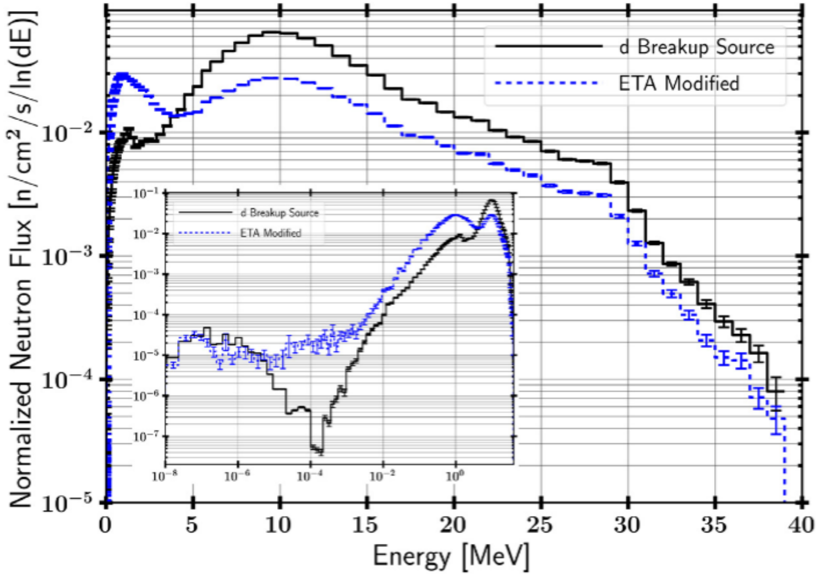
Neutron Beams are in the Liminal Space Between Exotic & Not

- Neutron beams are tough to wrangle because of the lack of charge and the nuclear-reaction origin of the beam
- Sometimes serendipity intervenes, like with ^{7}Li(p,n), where the neutron-spectrum from a ~1.9 MeV proton on ^{7}Li looks a lot like the s-process MB-distribution
- In principle, energy tuning assemblies could be used for nuclear astrophysics (e.g. for kilonovae), but in practice they've been limited to nuclear applications



R. Reifarth et al. *Nucl. Inst. Meth. A* 2009

J. Bevins et al. *Nuclear Instruments Methods A* 2019



Details for Afficionados

Office Space

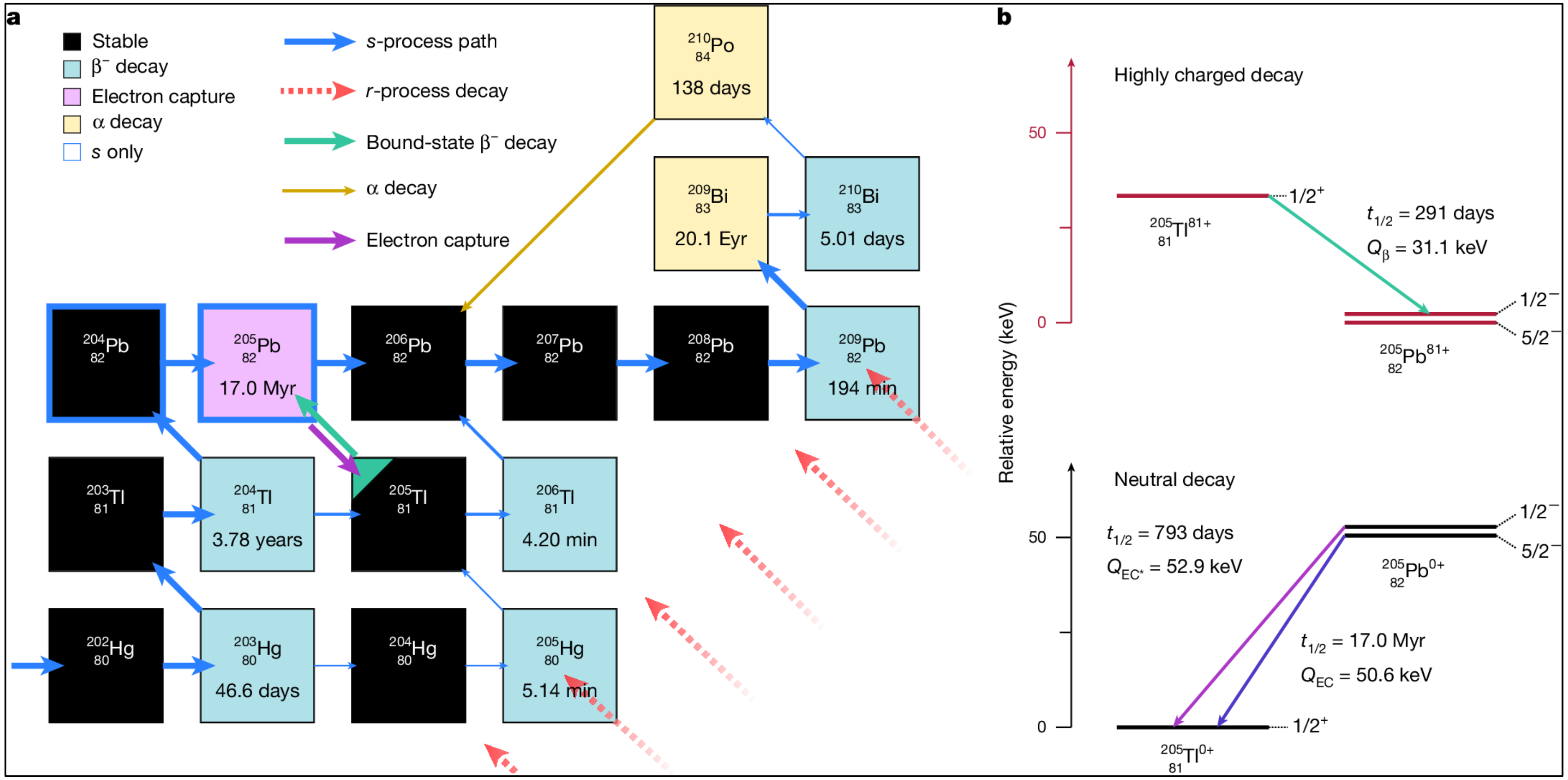
It Turns Out That the Laboratory isn't a Star

- Stars are plasmas and your set-up (probably) isn't
- Factors we may need to consider to turn your great measurement into a useful astrophysical rate are ionization/excitation and screening

The Brave Fighter of Sun Fighbird

Weak Rates Can Be Radically Altered at High-T and/or High-ρ

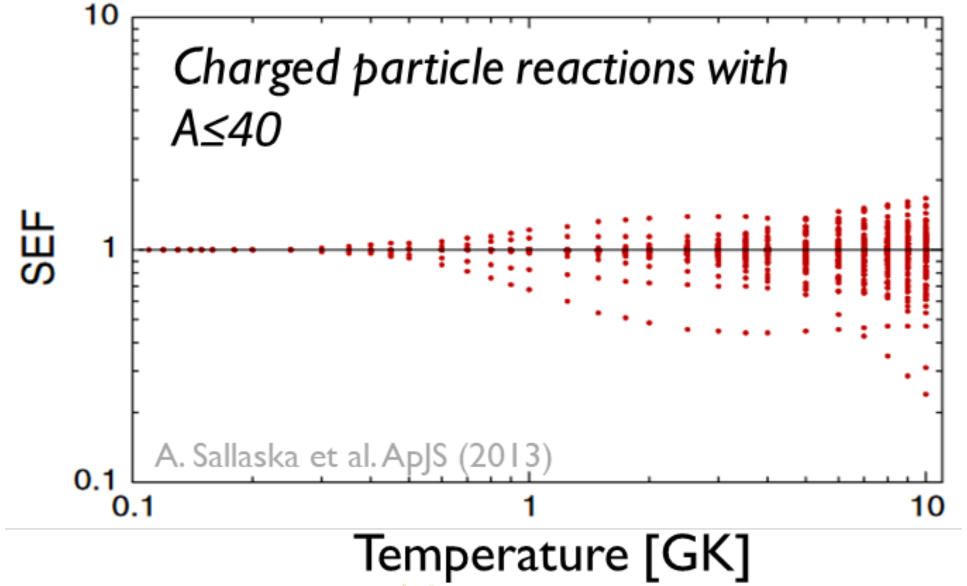
- Probably the most striking case is ^{205}Tl, where bound-state β-decay can proceed when ^{205}Tl is fully ionized.
- For many other cases, thermal population of excited states and partial ionizations can open-up new phase-space that dramatically enhance weak rates.
- Conversely, capture of atomic electrons isn't possible in fully-ionized conditions.



G. Leckenby et al. *Nature* 2024

Reaction Rates Can Be Altered by High-T

- Thermonuclear reaction rates can be substantially modified by the thermal population of the ground-state of the "target" nucleus.
- The ratio between the stellar and laboratory rate is known as the Stellar Enhancement Factor (SEF) [though the "enhancement" can be <1], which depends on the spin-distribution and level-density of the "target" nucleus
- Substantially-populated excited states with long lifetimes (compared to the problem timescale) must be tracked as separate nuclei and are known as *astromers*



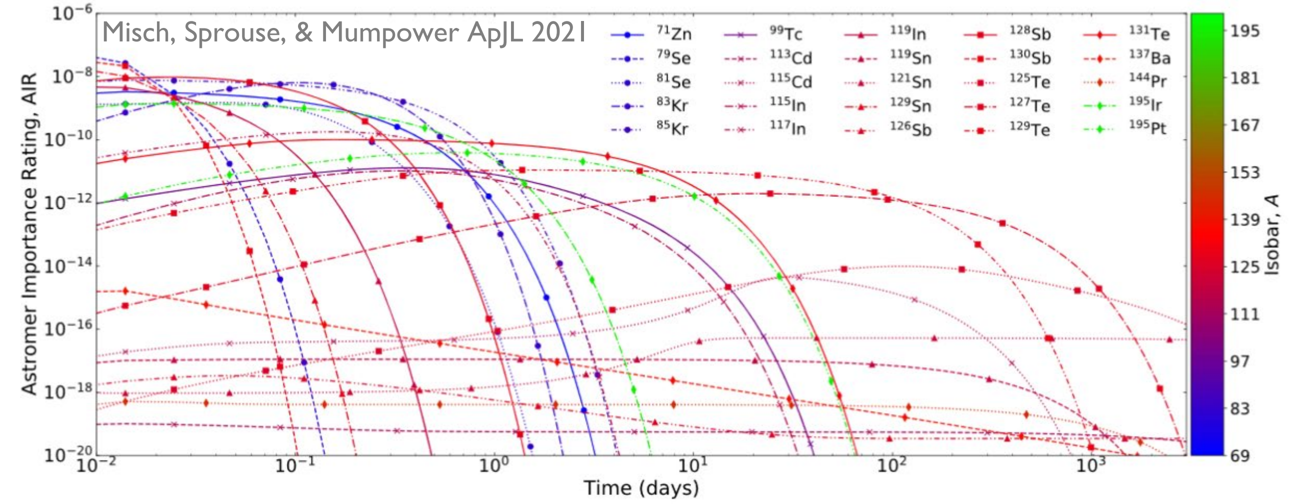
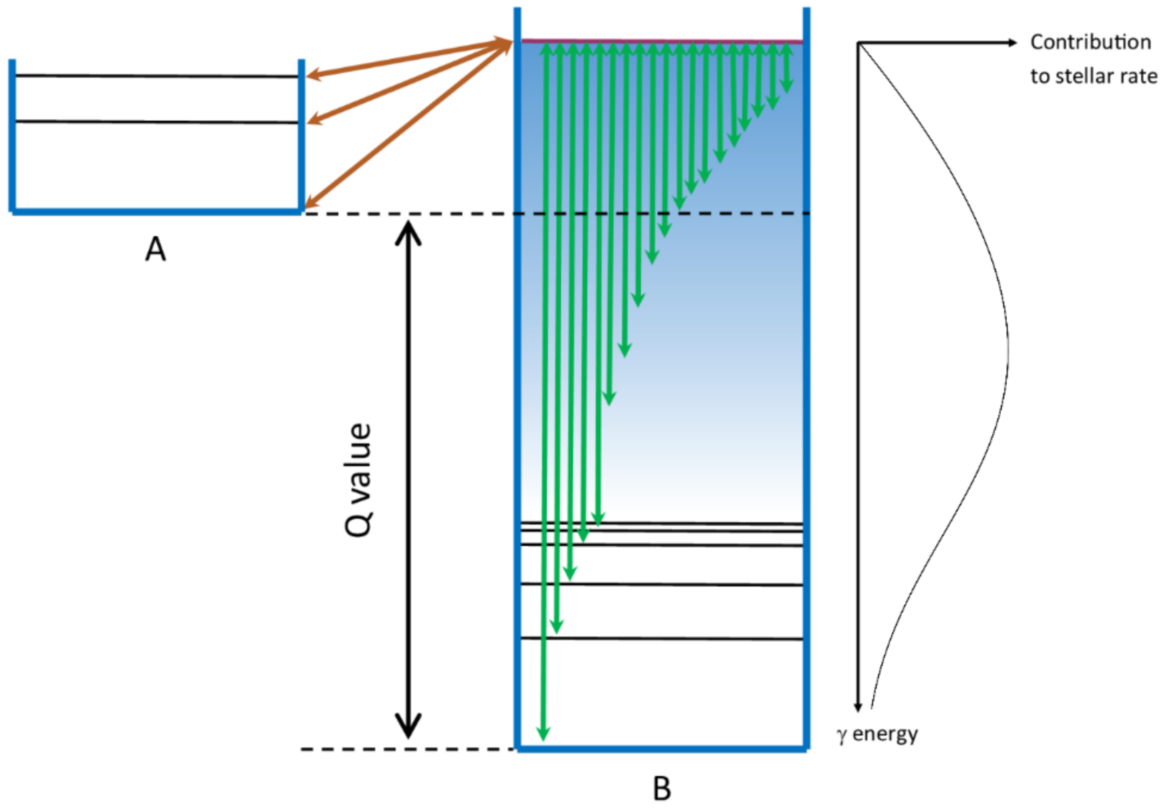


Figure 2. Influential *r*-process astromers ranked by their AIR. We show isotopes with AIR values that appear among the top five at some point in our simulation. Color indicates approximately the *r*-process abundance peak the nucleus resides in: first (blue), second (red), or third (green).

Stellar γ-induced Rates aren't Much Like Laboratory Rates

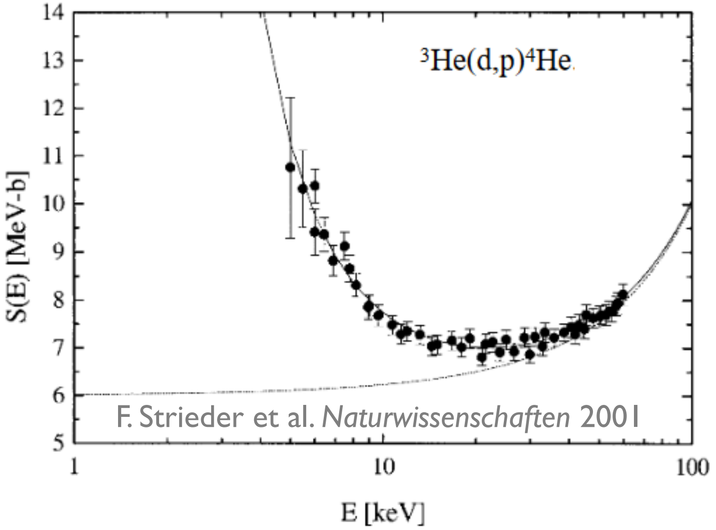
- Laboratory photodisintegration only takes place on the target's ground state.
- However, in the astrophysical environment reactions mostly proceed through photo-disintegration of excited states of the "target" nucleus.
- The best-bet is to measure the reverse reaction in the lab instead.
- Photonuclear reactions in the lab still useful, but to constrain statistical model inputs (γSF and ρ_{LD})



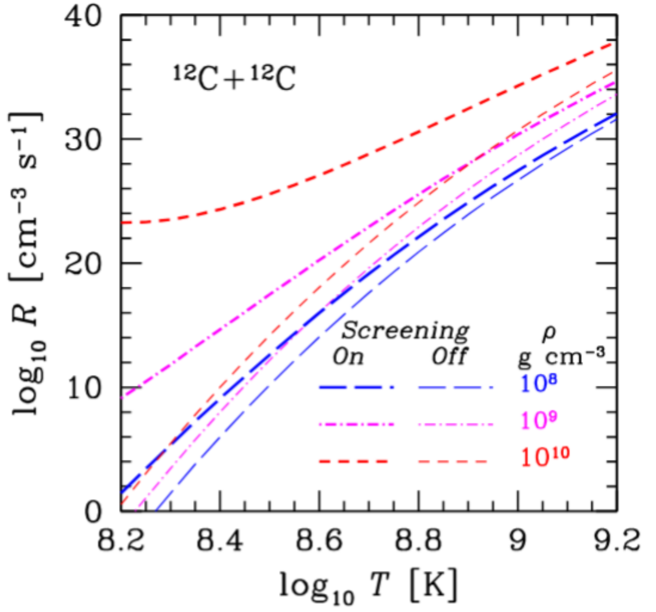
Rauscher *NucPhysNews* 2018

Screening Enhances Laboratory & Astrophysical Rates
…*but Not in the Same Way*

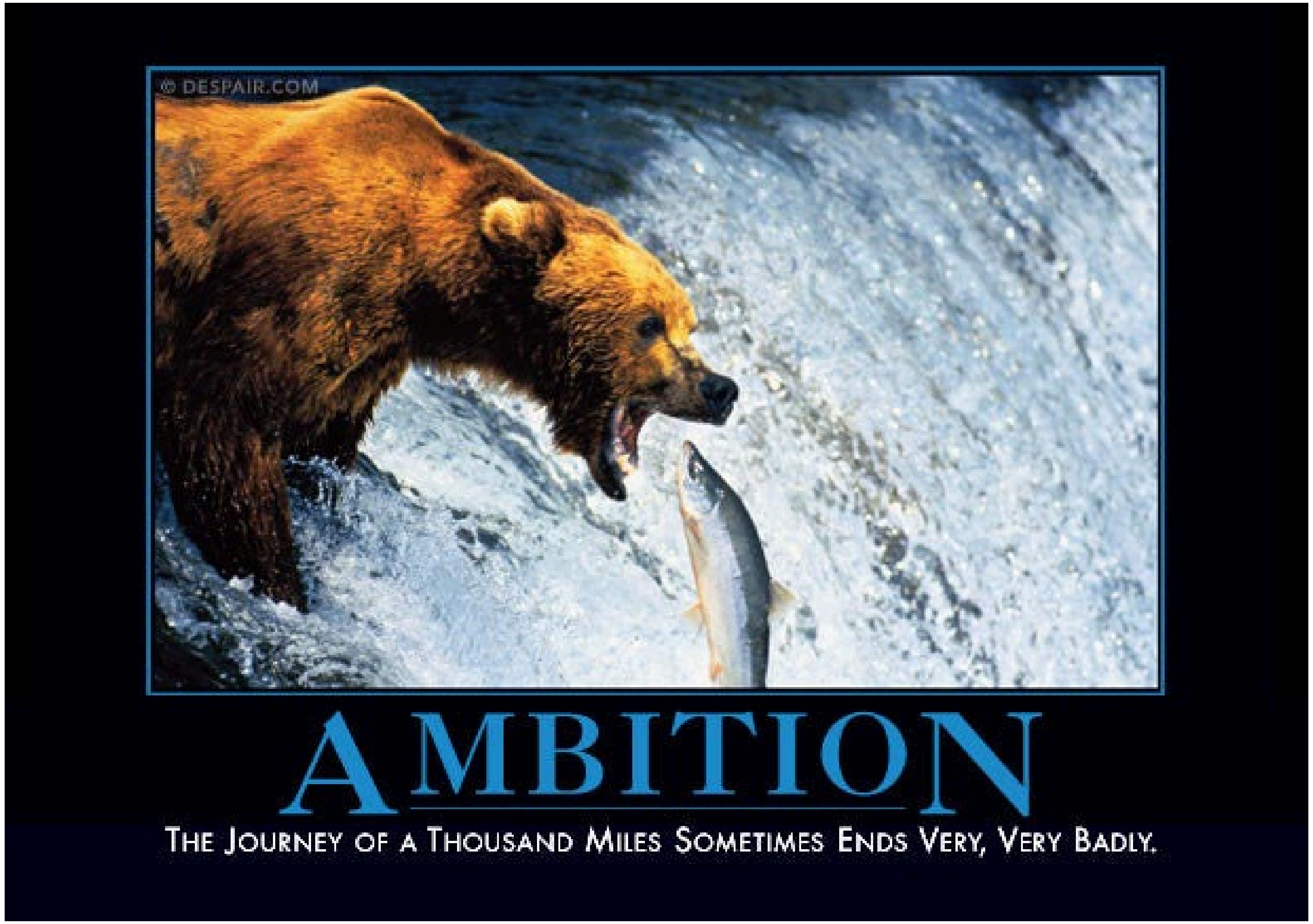
- At energies well below the Coulomb barrier, measurements show an enhancement in the cross section due to atomic electrons in the target screening the Coulomb potential
- The same type of effect is expected in astrophysical plasmas
  …but is quantitatively very different.
- Salpeter screening is usually assumed. It is pretty small (and roughly zero for resonances [Iliads *PRC* 2023]), so only relevant for very high-precision rates
  (e.g. solar fusion)
- At extreme densities, like in neutron-star inner crusts, screening becomes most of the ballgame



Kravchuk & Yakovlev *PRC* 2014



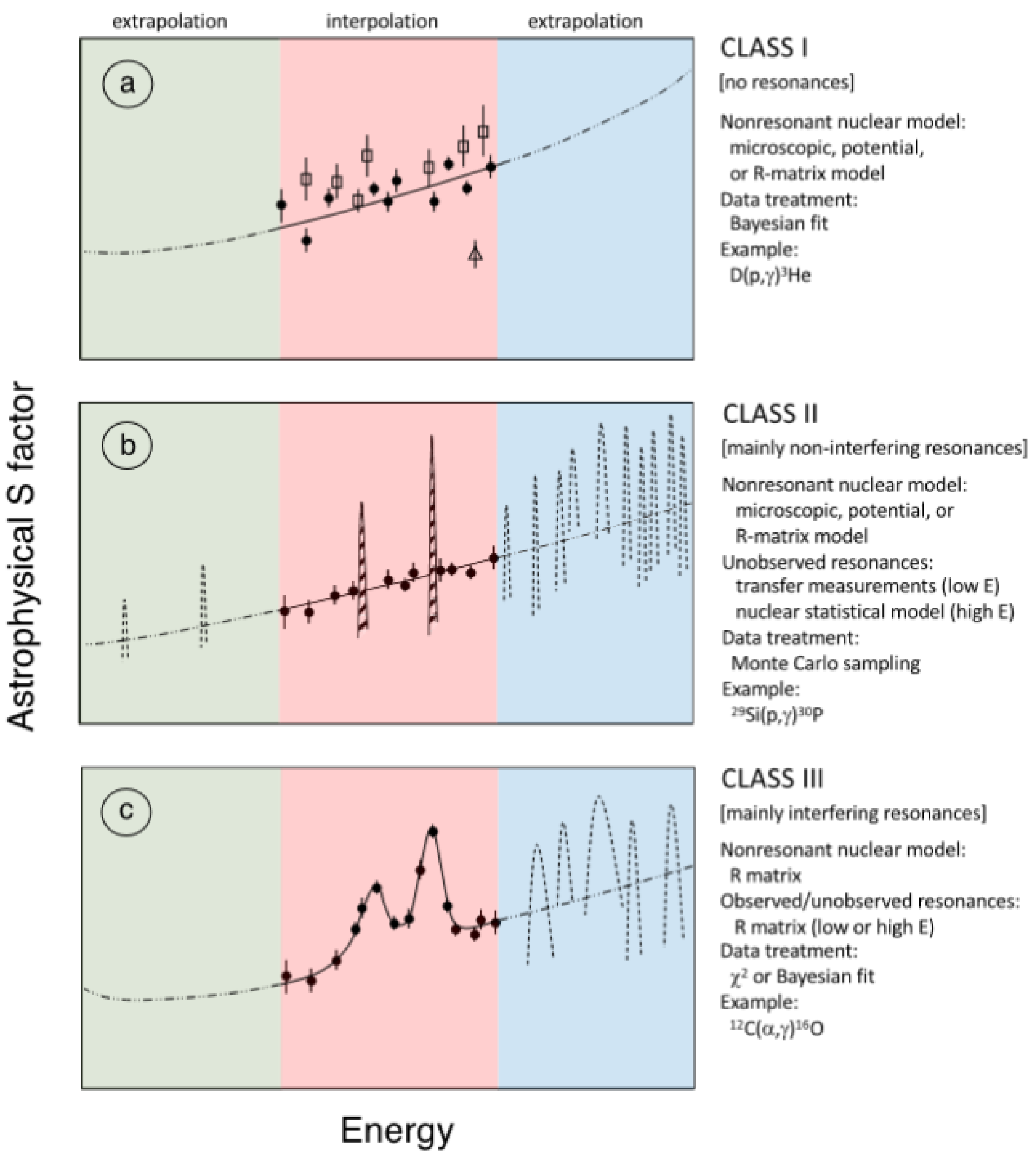
Tying into Astrophysics



Turning Data into a Rate

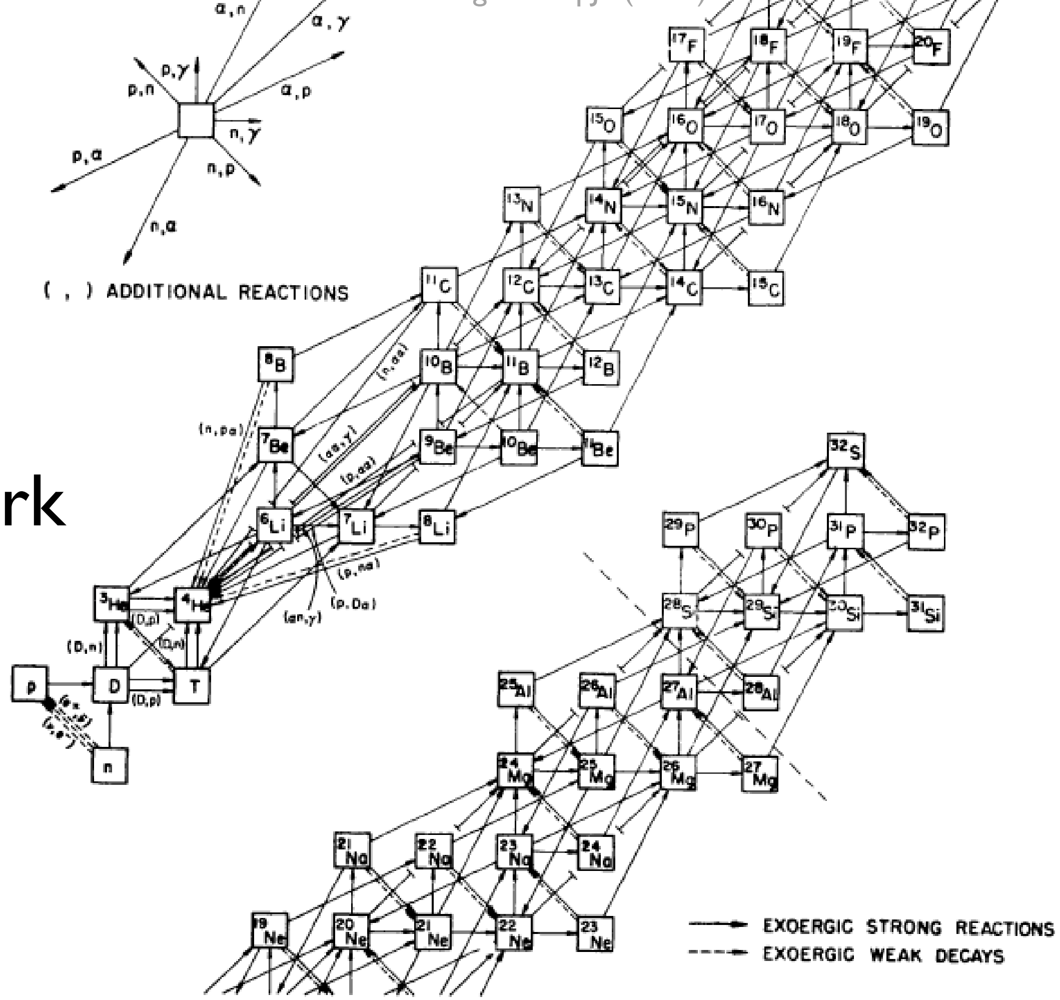
- Rate evaluations usually involve more than one measurement and almost always require some theory assumptions
- If you measured σ, you could use Rauscher's exp2rate.f90 code to get a rate,
- or, if you think your reaction is in the statistical regime, fit your cross section data with Talys and then use those Talys inputs to calculate an astrophysical rate
- Otherwise, buckle-up and cozy-up to ETR25 (C. Iliadis et al. *ApJS* 2026)

C. Iliadis et al. *ApJS* 2026



Reaction Networks

R.V.Wagoner ApJS (1969)



- Astrophysical environments typically contain many nuclei, each of which could in principle interact with the other
  (in practice usually only the photons and light projectiles matter)
- To see what happens, we need a reaction network
- The basic idea is to see how the abundance changes for each isotope at each step in time based on the production and destruction via all mechanisms and often to include the energy generation from said reactions
- For each species i,

$$\frac{dY_i}{dt} = \underbrace{\left[\sum_{j,k} Y_j Y_k \rho N_A \langle\sigma v\rangle_{jk\to i} + \sum_{l} \lambda_{l\to i} Y_l\right]}_{\text{Production}} - \underbrace{\left[\sum_{m} Y_i Y_m \rho N_A \langle\sigma v\rangle_{im\to any} + \sum_{n} \lambda_{i\to n} Y_l\right]}_{\text{Destruction}}$$

Astrophysics Models Provide Complementary Insight

Analytic Flow | Post-Processing | Single-Zone XRB | Multizone XRB | Higher-D XRB

Calculation Type

Increasing Value for Comparisons to Observational Data →

← Increasing Value for Understanding the Underlying Physics

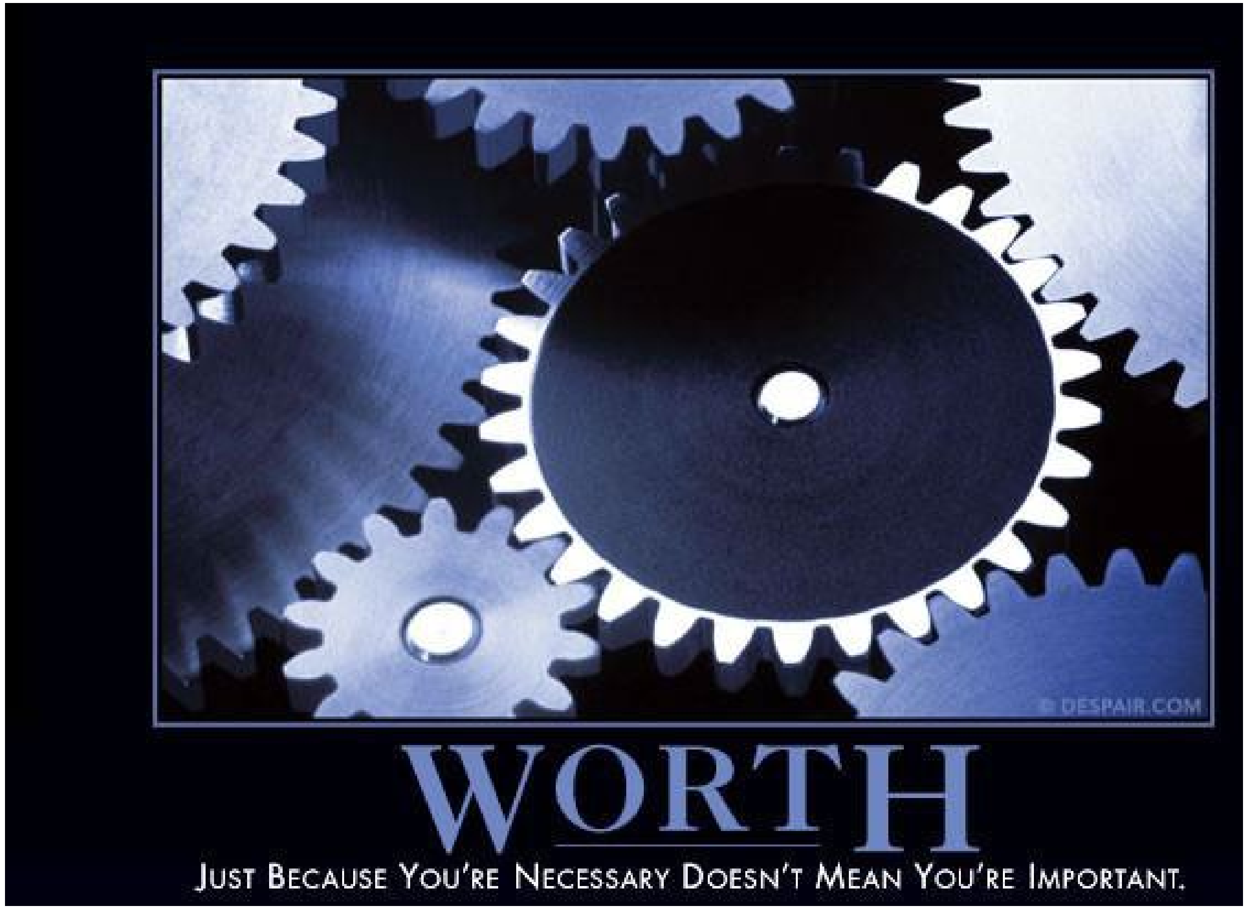
Spreadsheet | ~1s Computation | ~1min Computation | ~1wk Computation | Currently Impossible*

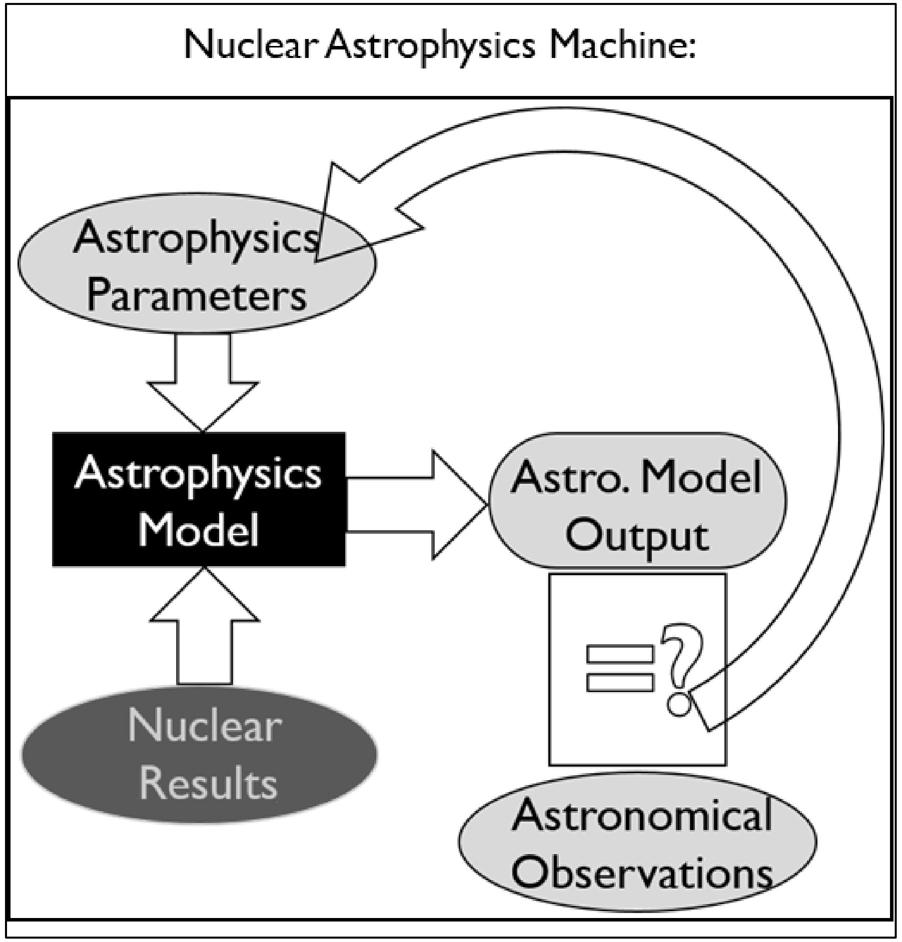
Computational Cost

*with large nuclear reaction networks & burst time-scales

Sensitivity Studies Provide Critical Guidance

- We can figure out what's worth measuring and how much good our measurement did by turning the nuclear data "knobs" on our model and assessing the impact ("sensitivity"). This should be iterative as we get more data.





Before Concluding, Appreciate all the Theory We Rely On

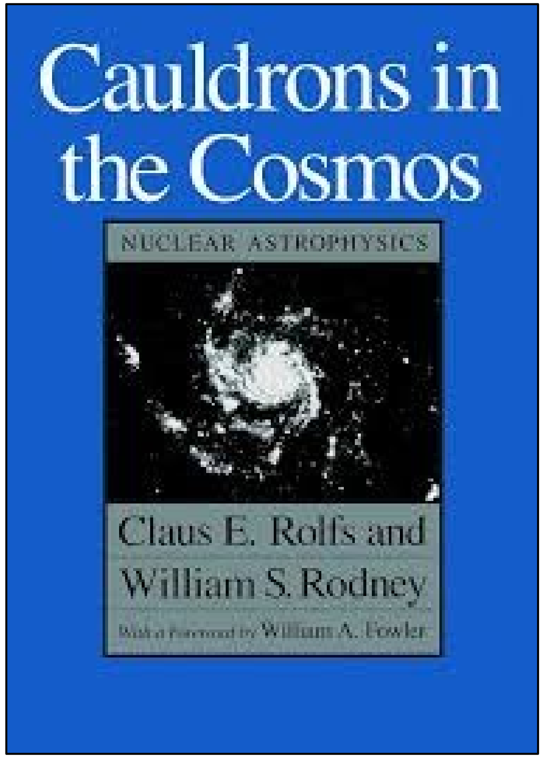
In homage to an apocryphal quote of Heisenberg:

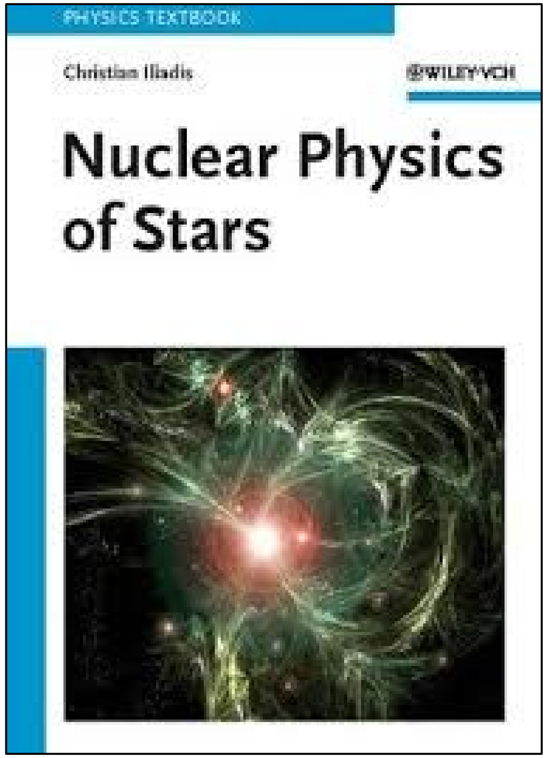
The first gulp from the glass of measurement will turn you into an experimentalist,
but at the bottom of the glass theory is waiting for you.

Thanks for your attention, here's some **Further Reading**

- If your interest is piqued, but you want to know where you can *really* learn about experimental nuclear astrophysics, consult the following:

Essential Texts:





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