Using statistical methods to determine the astrophysical origins of heavy nuclei

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TRIUMF Theory Group

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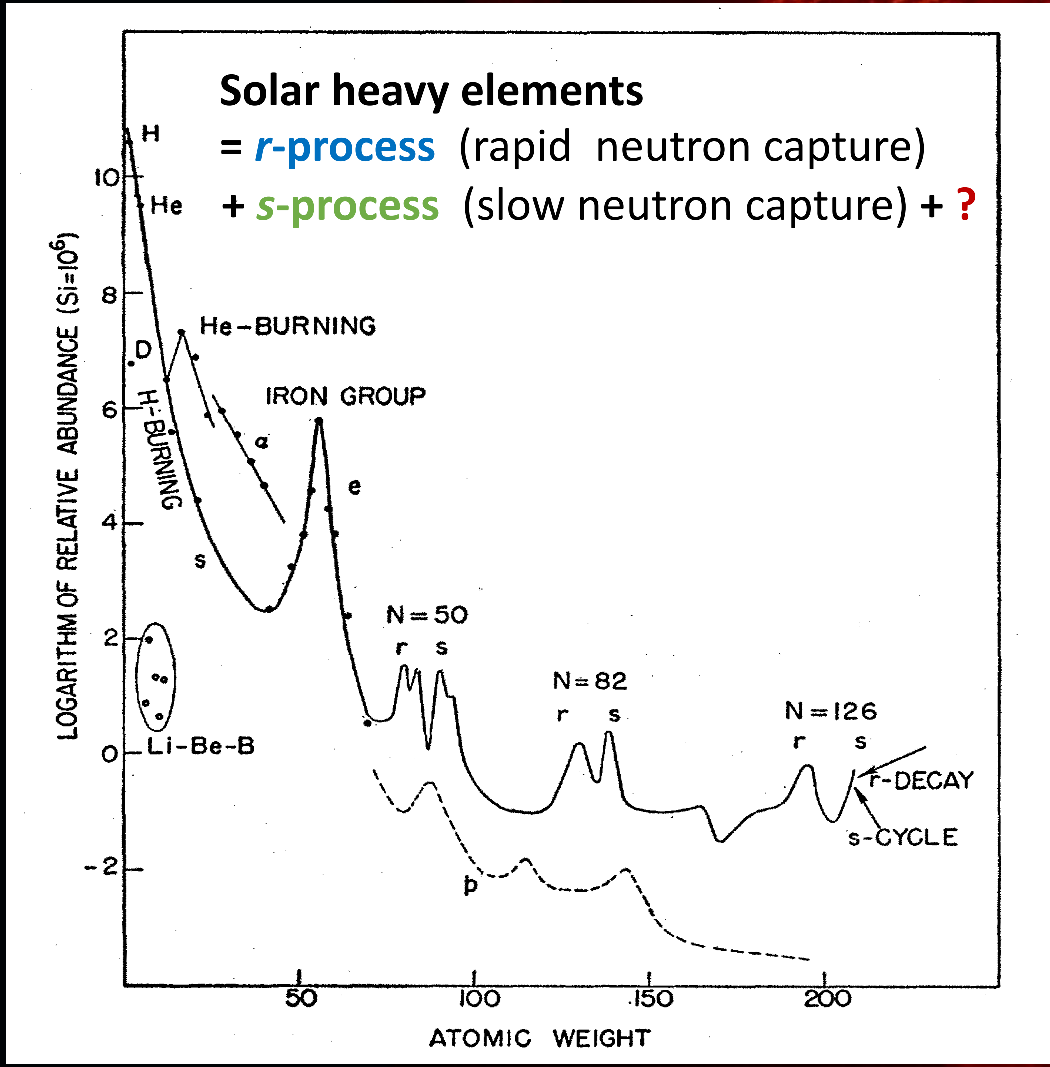
McMaster University
June 9, 2022

TRIUMF

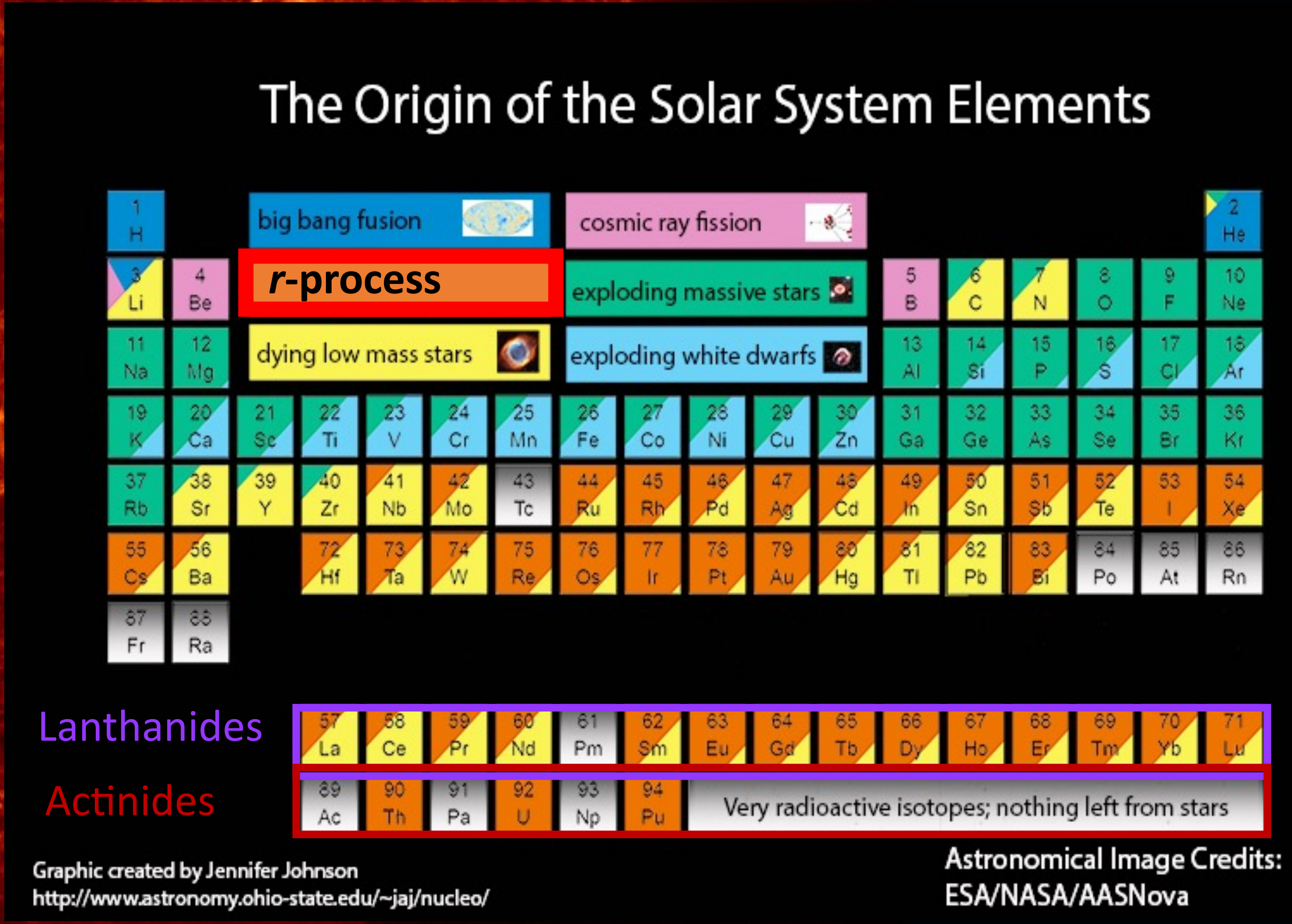
FRIB Theory Alliance

NSERC CRSNG

The solar composition can be decomposed into many processes → multiple nucleosynthesis sites enriched the solar system

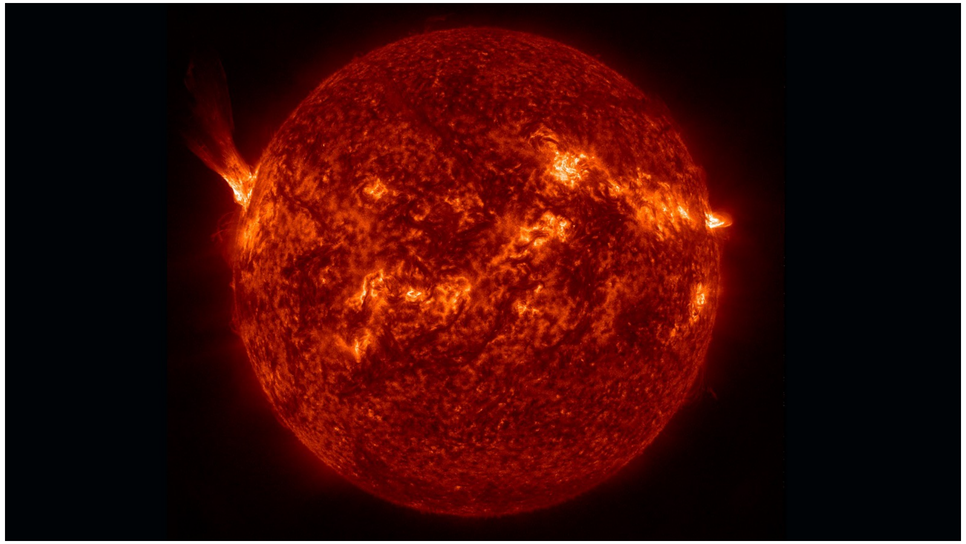


Burbidge, Burbidge, Fowler, and Hoyle (B²FH) (1957)

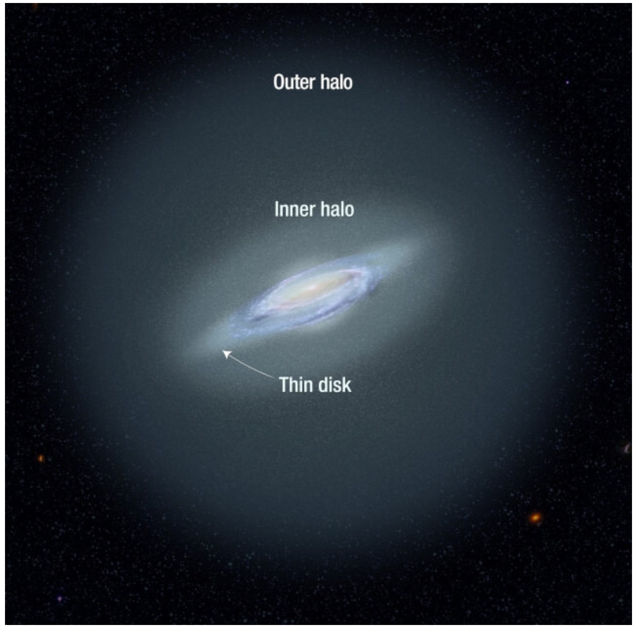


So many messengers

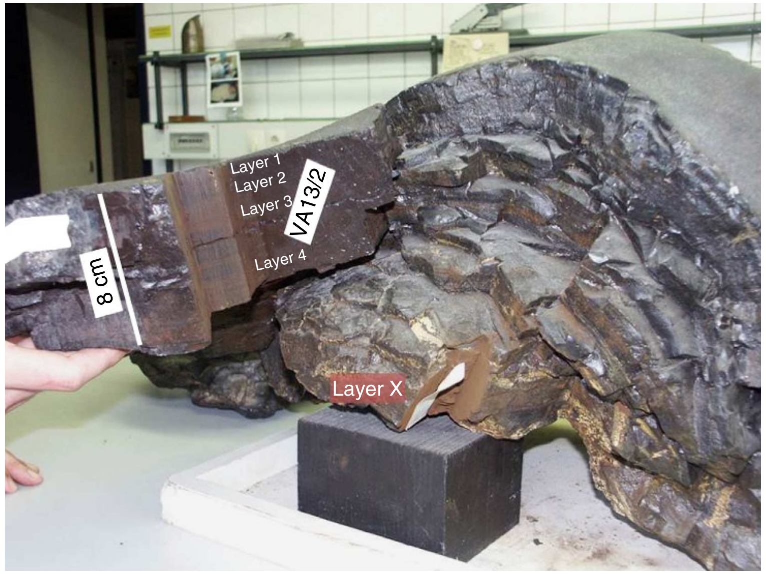
Our Sun



Stars in the Milky Way disk and halo

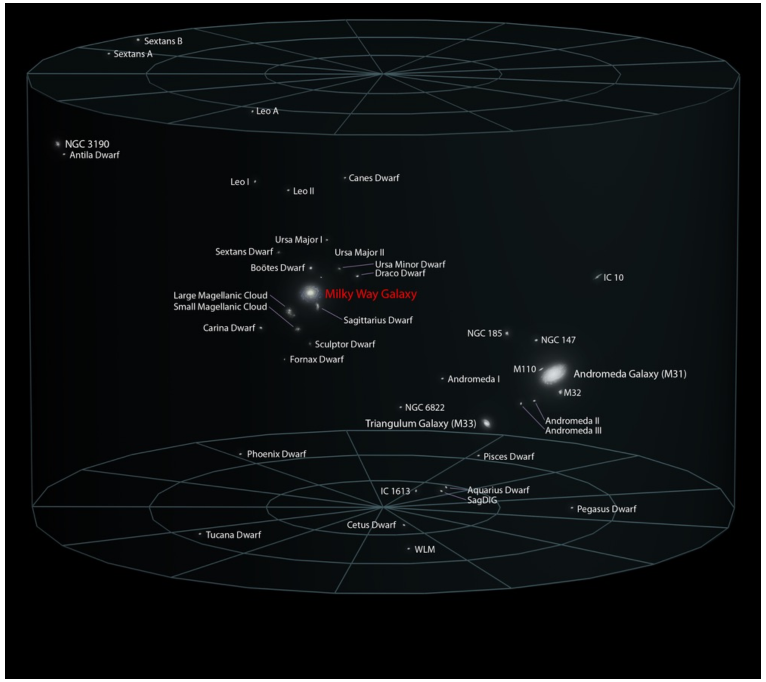


Deep-sea ocean crusts

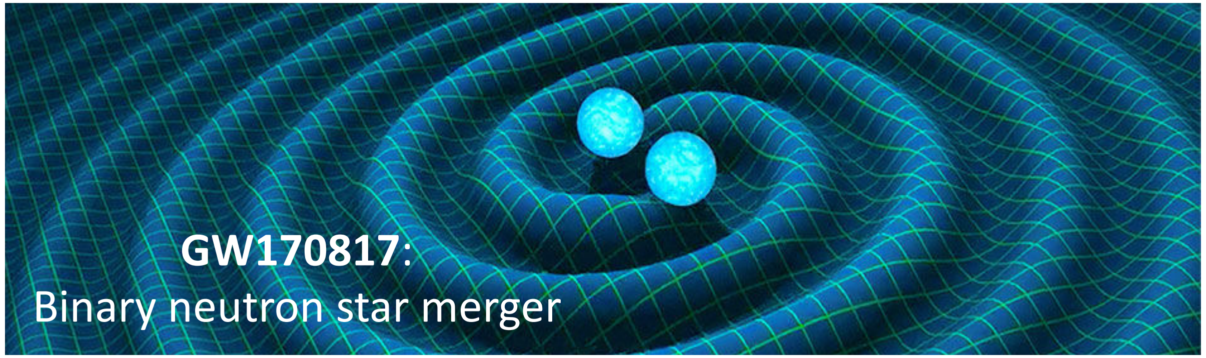


Meteorites

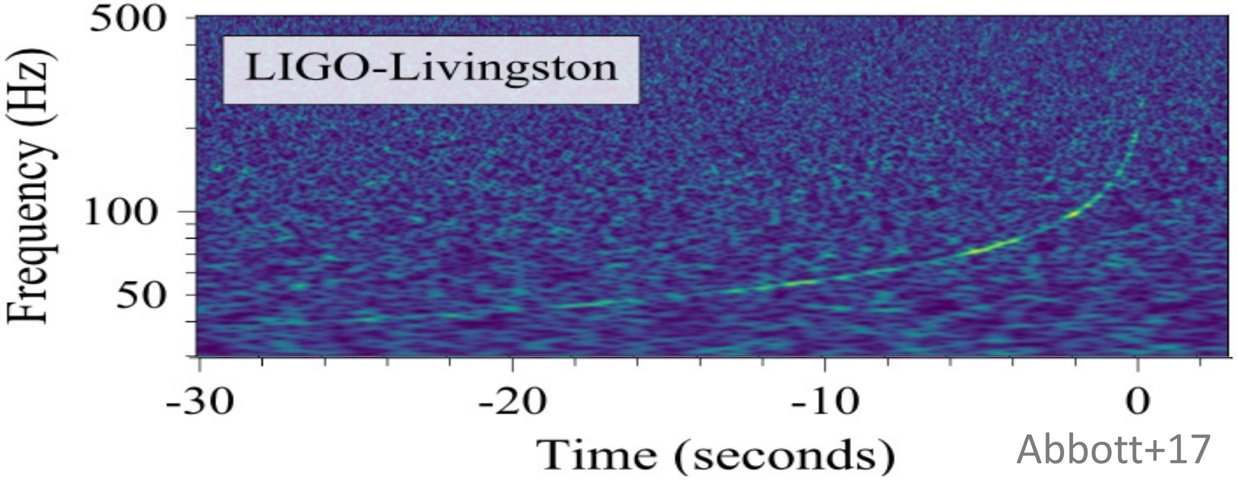
Stars in galaxies near the Milky Way



Multi-messenger single events



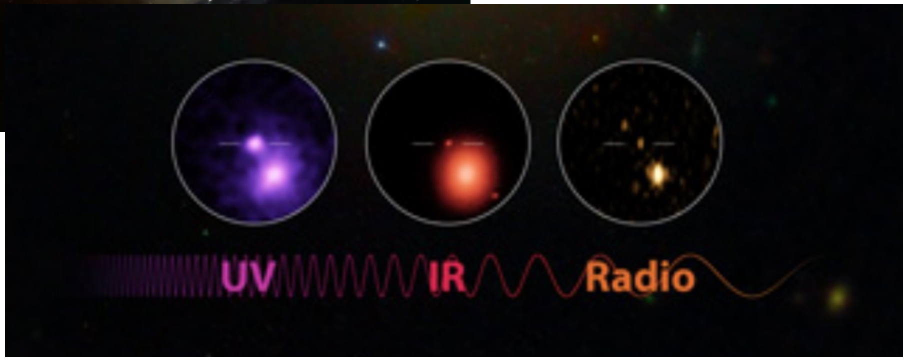
Gravitational Wave



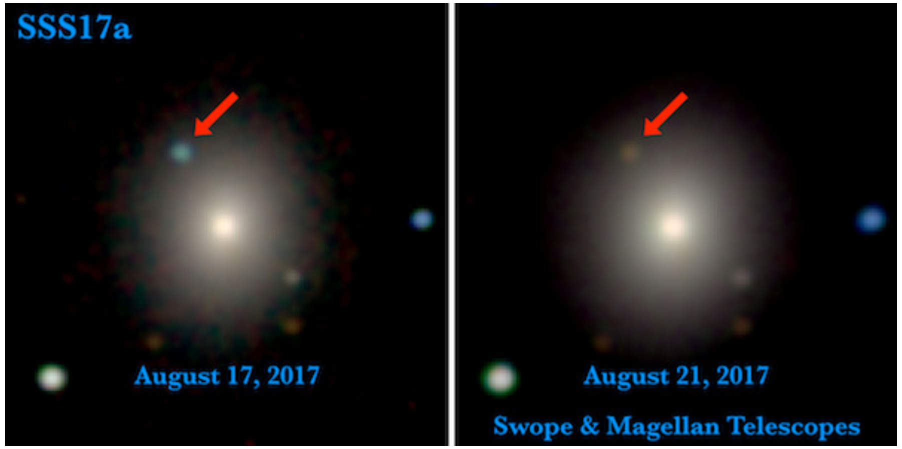
Abbott+17

NASA Goddard

UV (NASA Swift satellite)
IR (Gemini South telescope)
Radio (Very Large Array)
γ-ray, X-ray, and optical
also observed



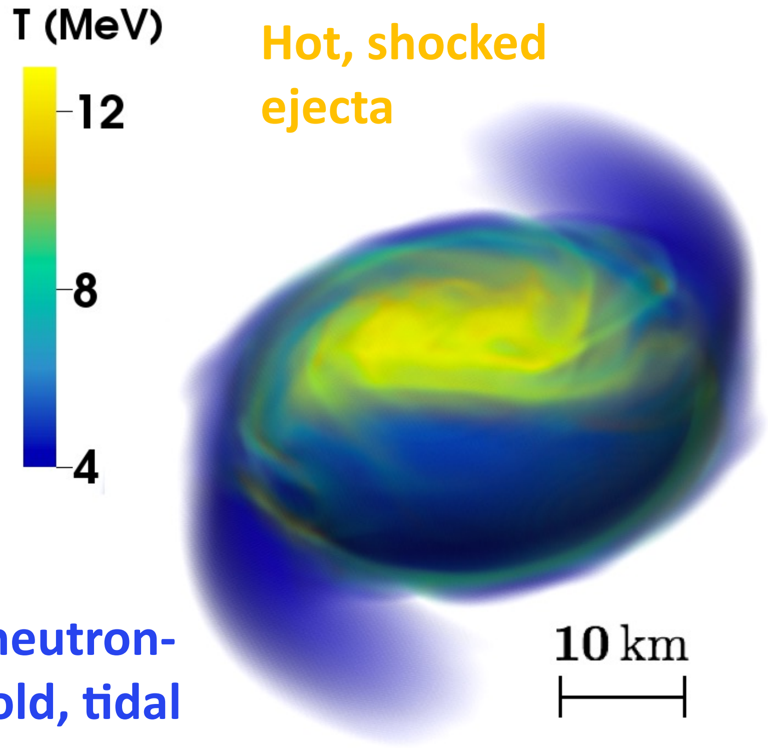
Hurt/Kasliwal/Hallinan, Evans, and the GROWTH collab.



1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

r-process sites in compact object mergers

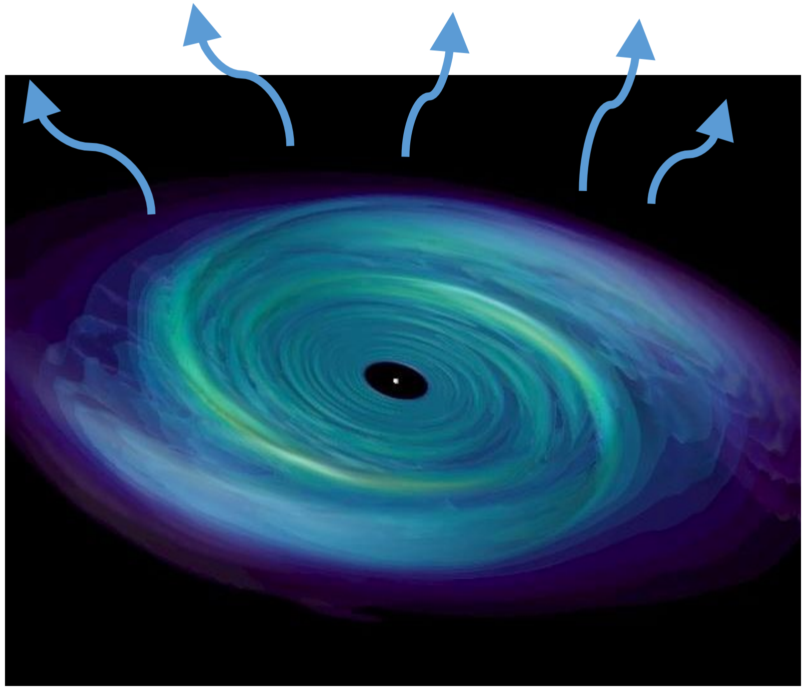
Dynamical ejecta



Foucart+16

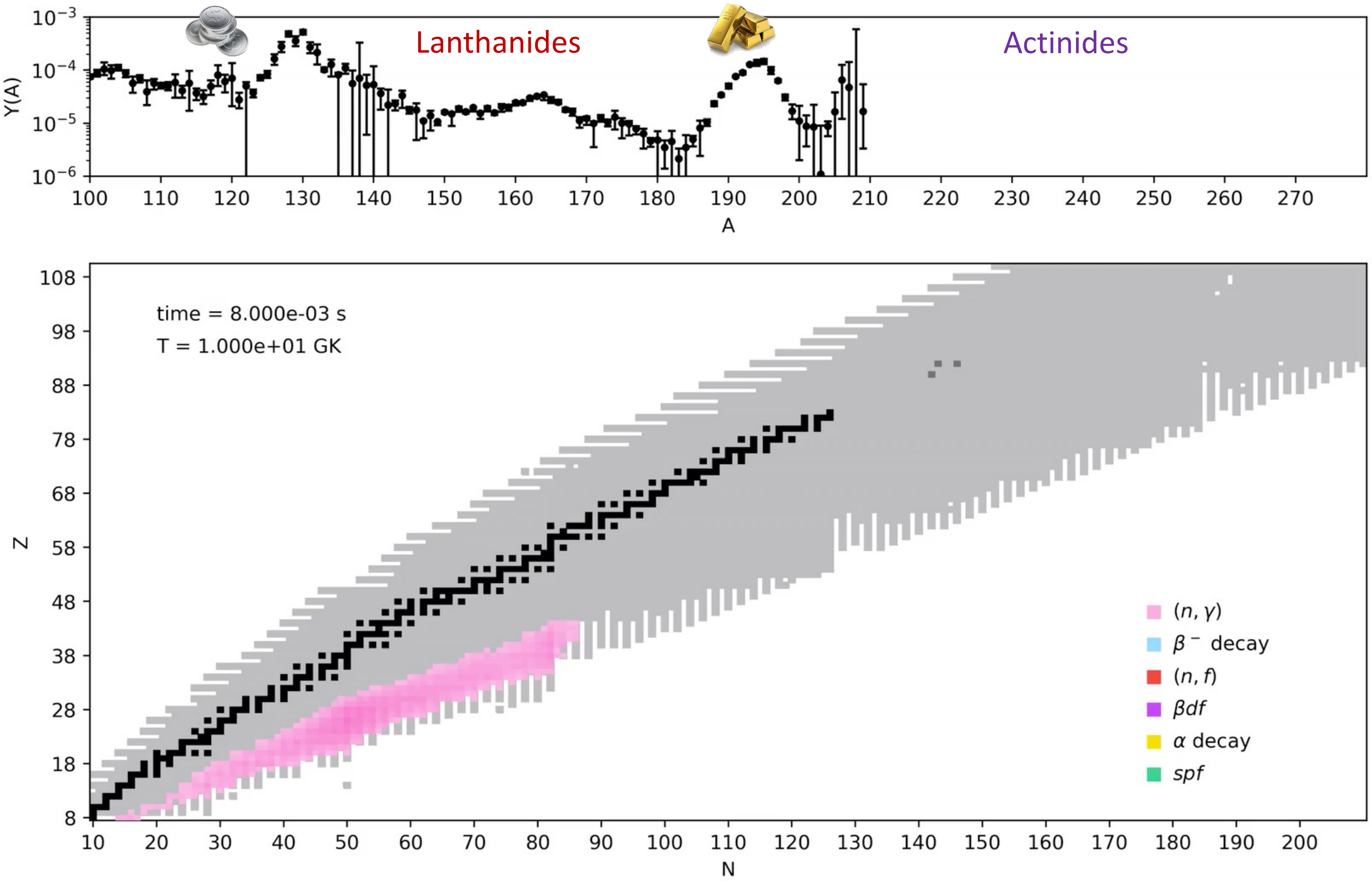
Accretion disk winds

(mass ejection mechanism and neutron richness varies)



Owen&Blondin 05

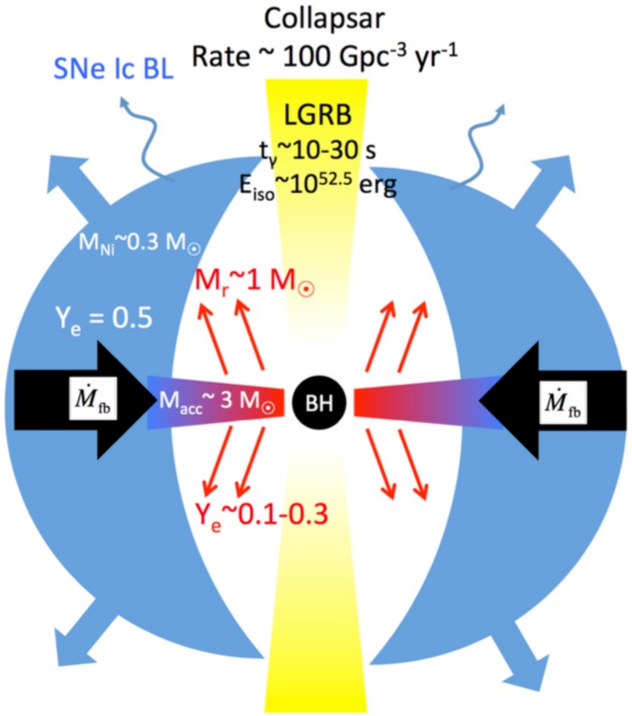
The *r* process in *very neutron-rich* conditions



Movie by
N. Vassh

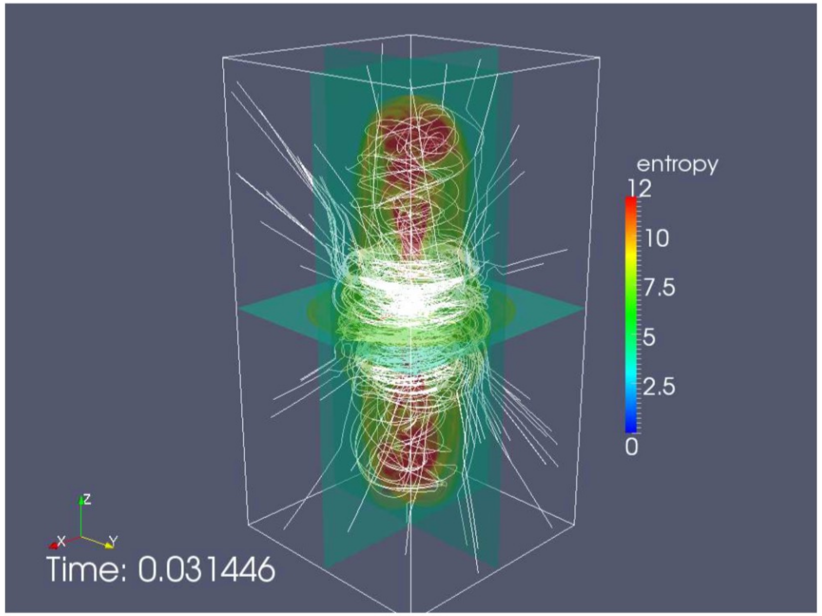
Some candidate sites for *r*-process element production

Collapsar disk winds



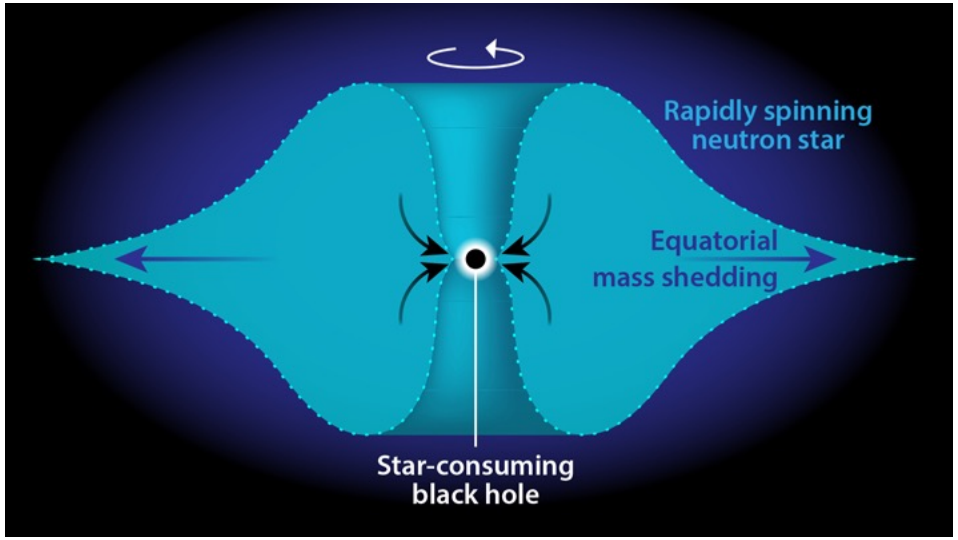
Siegel+18; see also McLaughlin&Surman 05, Miller+19

Magneto-rotationally driven (MHD) supernovae



Winteler+12; see also Mosta+17

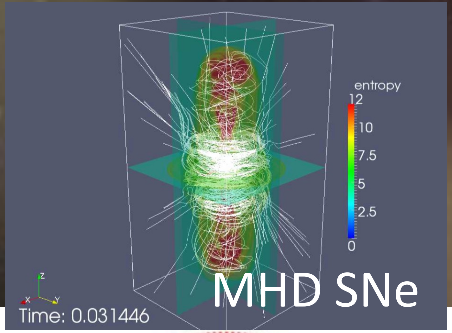
Primordial black hole + neutron star

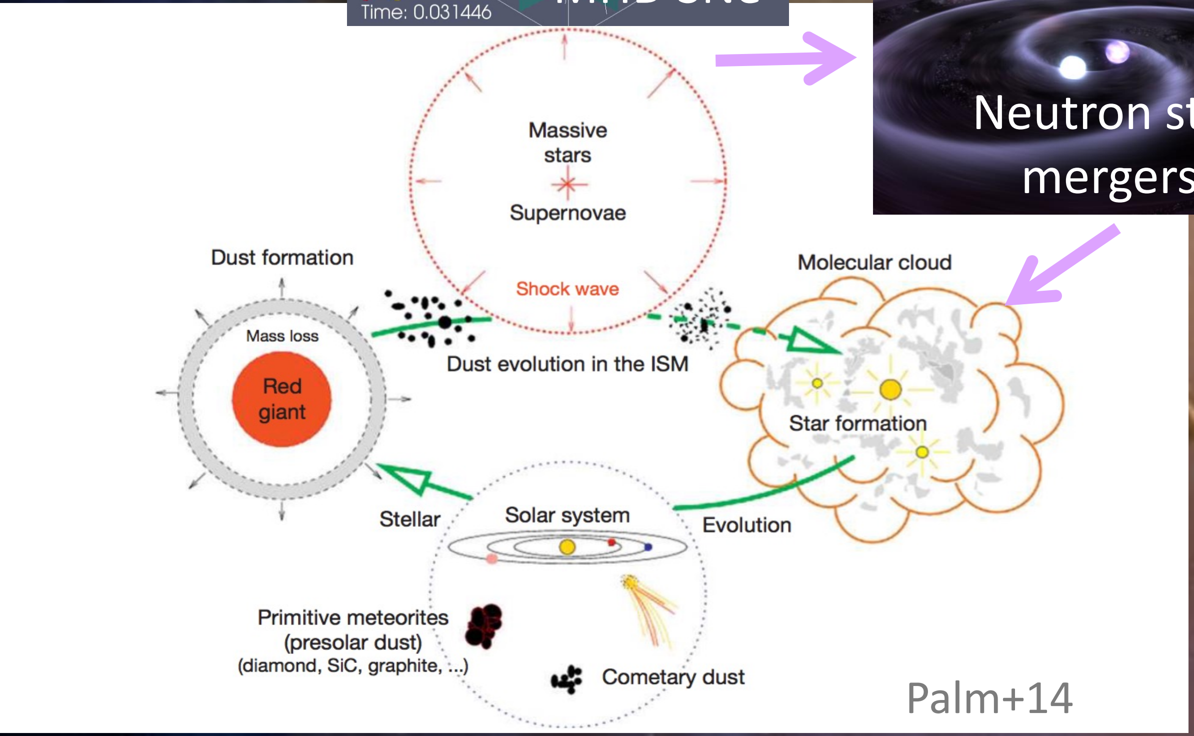


Credit: APS/Alan Stonebraker, via *Physics*

Fuller+17

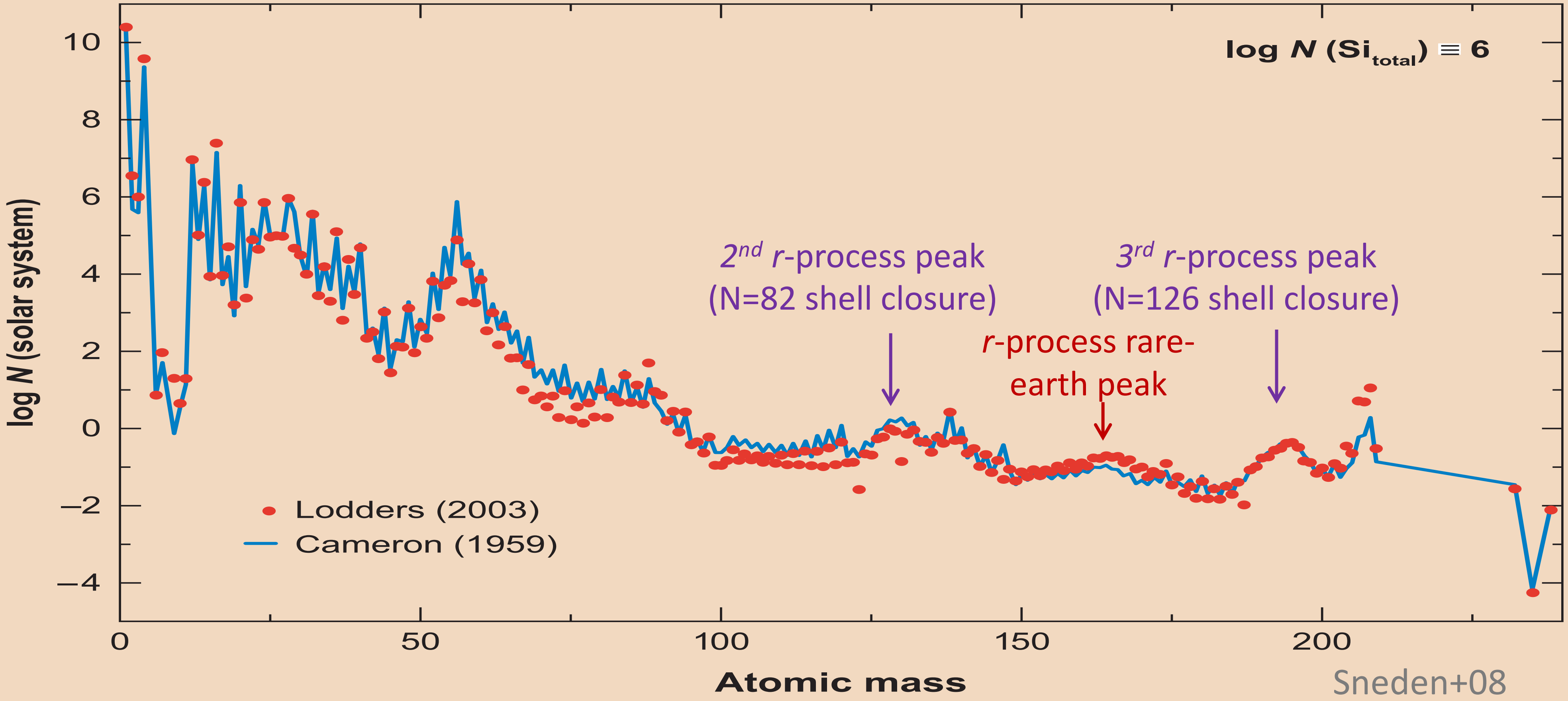
Which astrophysical sites produced the heavy isotopes in our solar system?





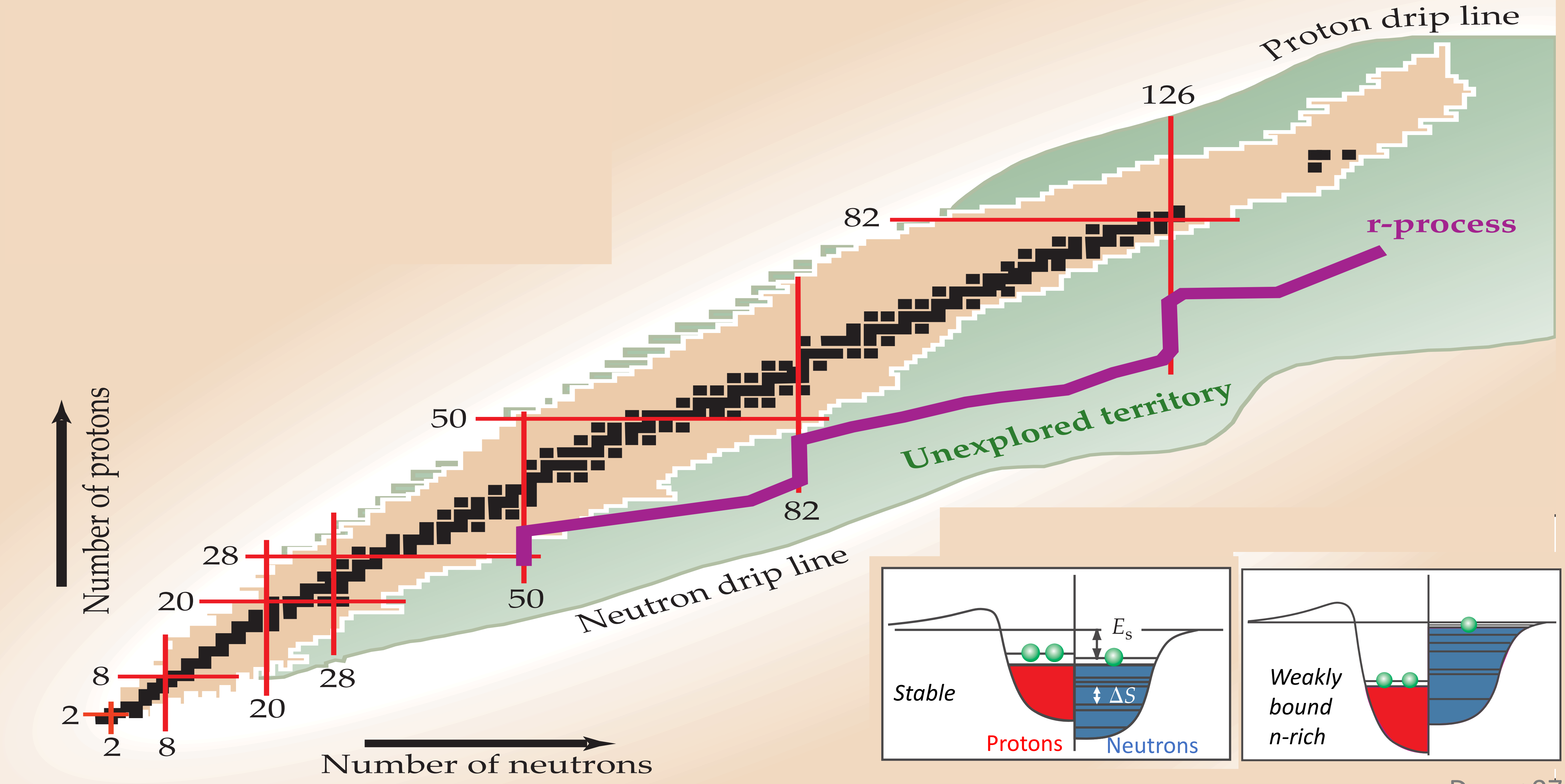
Palm+14

Solar abundances and nuclear structure



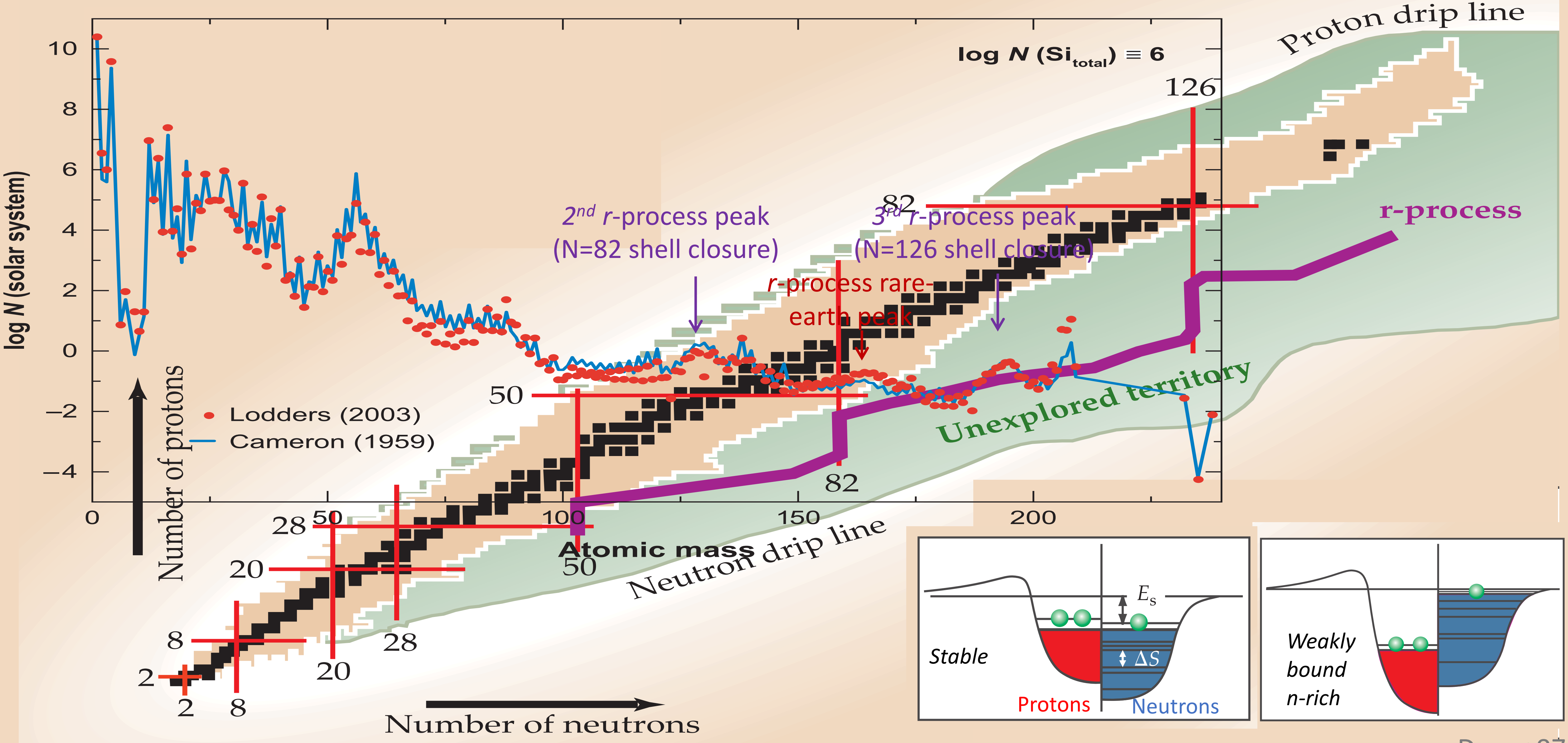
Sneden+08

Solar abundances and nuclear structure



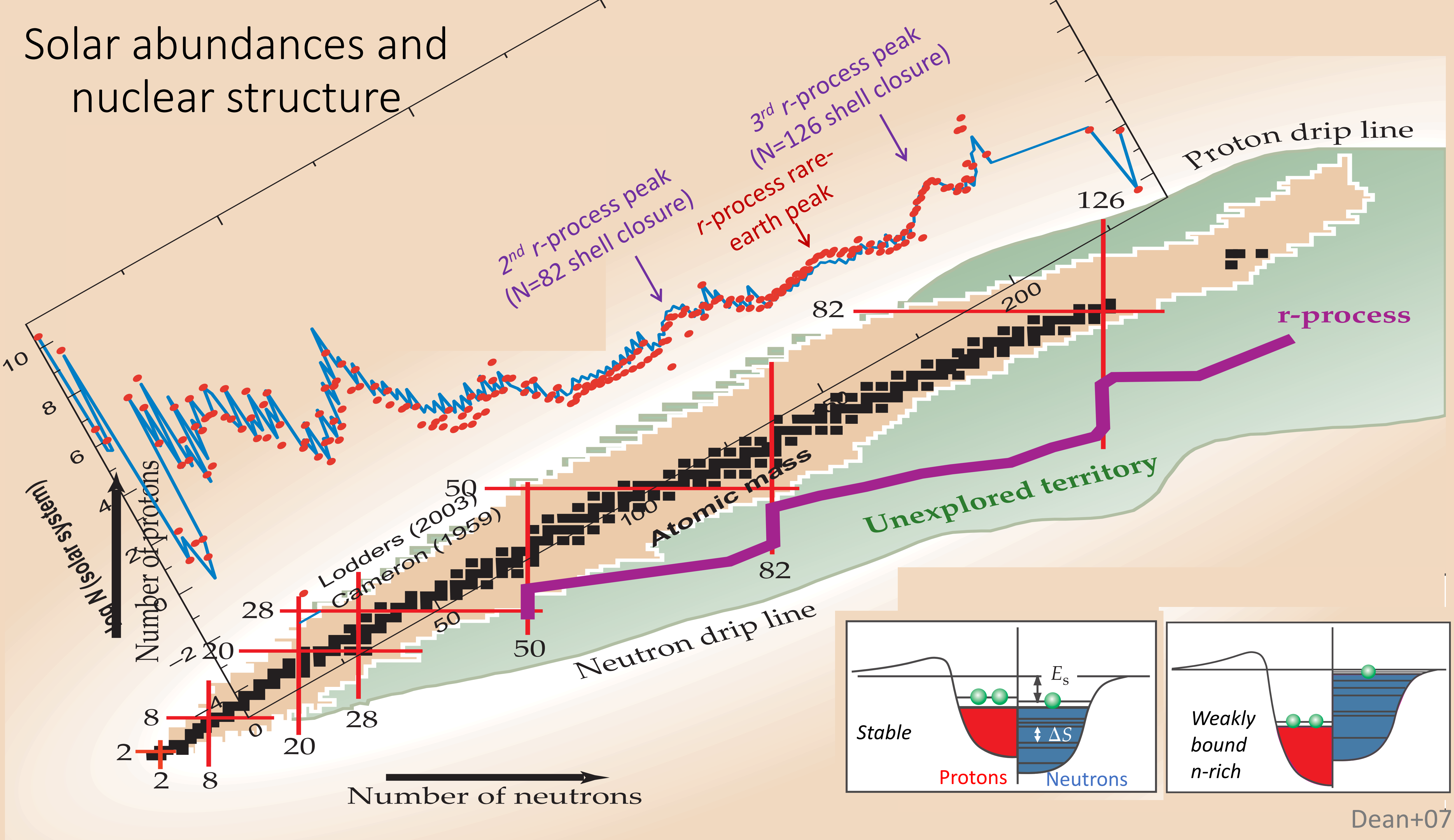
Dean+07

Solar abundances and nuclear structure



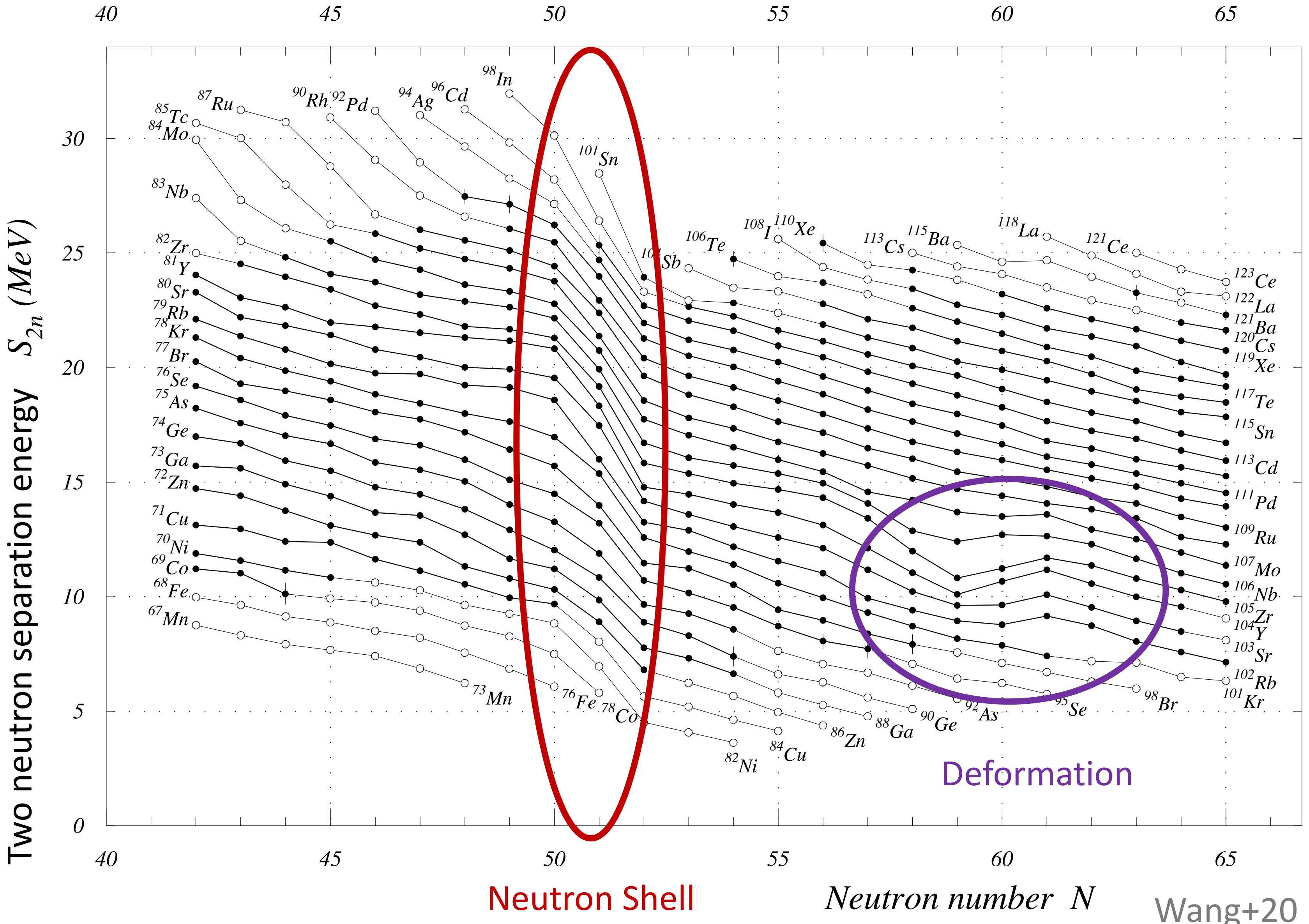
Dean+07

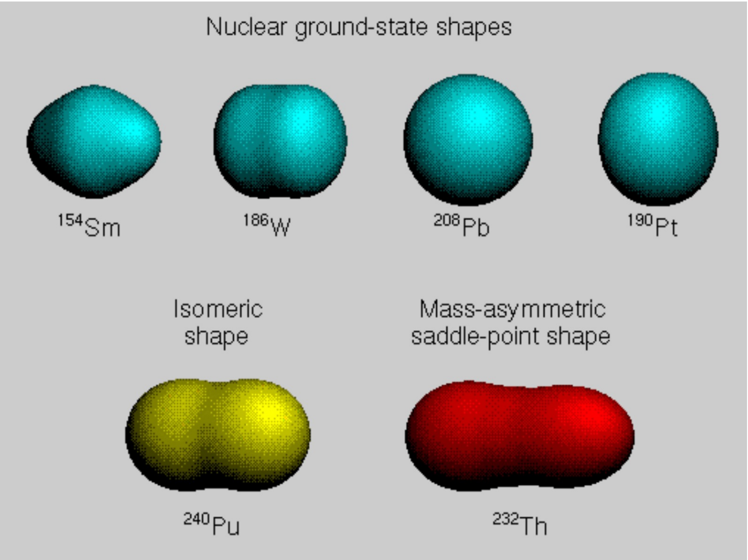
Solar abundances and nuclear structure



Dean+07

Mass trends and nuclear structure





Wang+20
(AME2020 Mass Evaluation)

Spotlight on the impact of nuclear masses

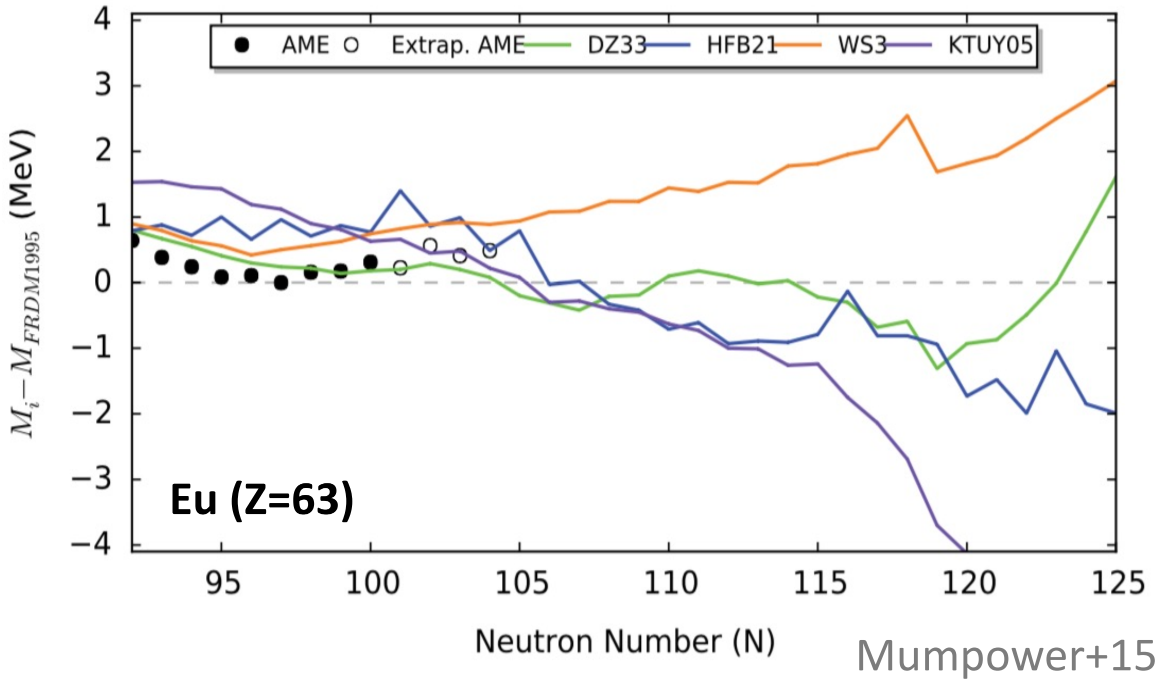
Masses determine key quantities that go into calculating capture and decay rates; for instance:

Neutron capture rates depend on the one neutron separation energy:

$$S_n(Z, A+1) = M_{Z,A} + M_n - M_{Z,A+1}$$

β^--decay rates depend on the Q-value:

$$Q_{\beta^-} = (M_{\text{parent}} - M_{\text{daughter}})c^2$$



Mumpower+15

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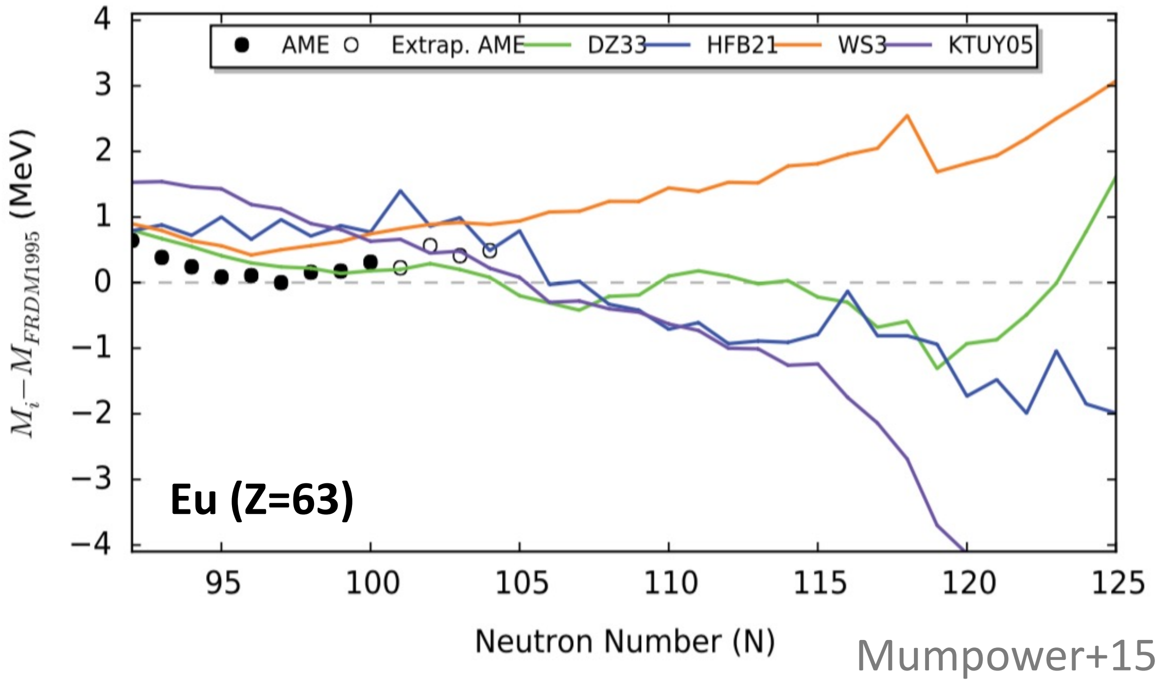
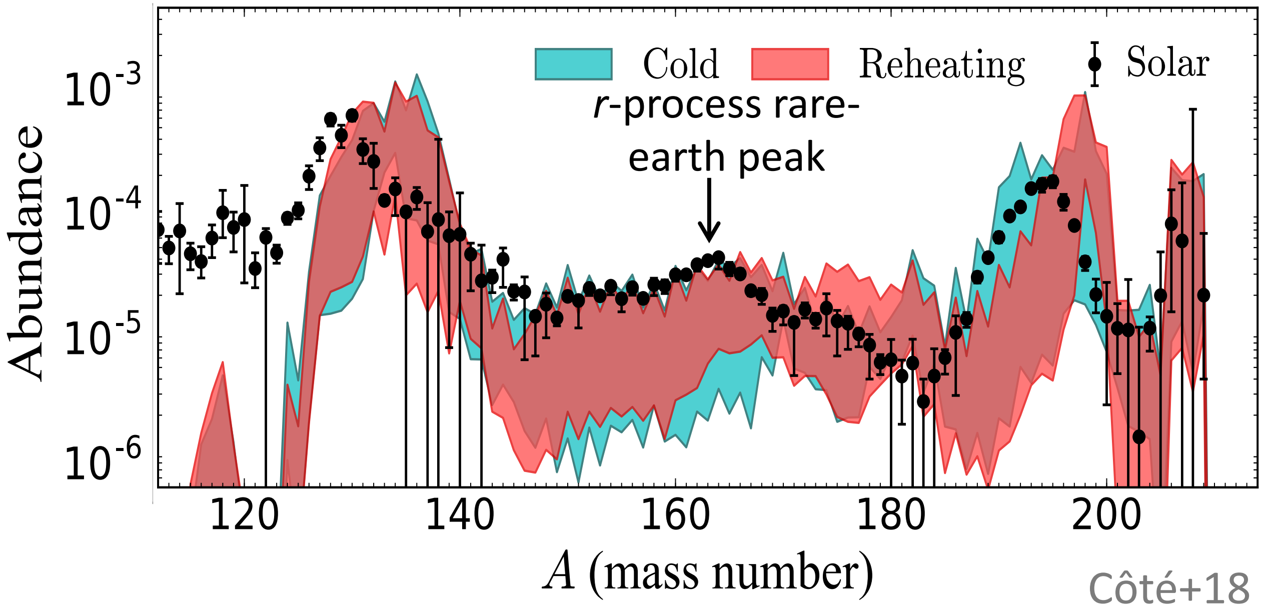


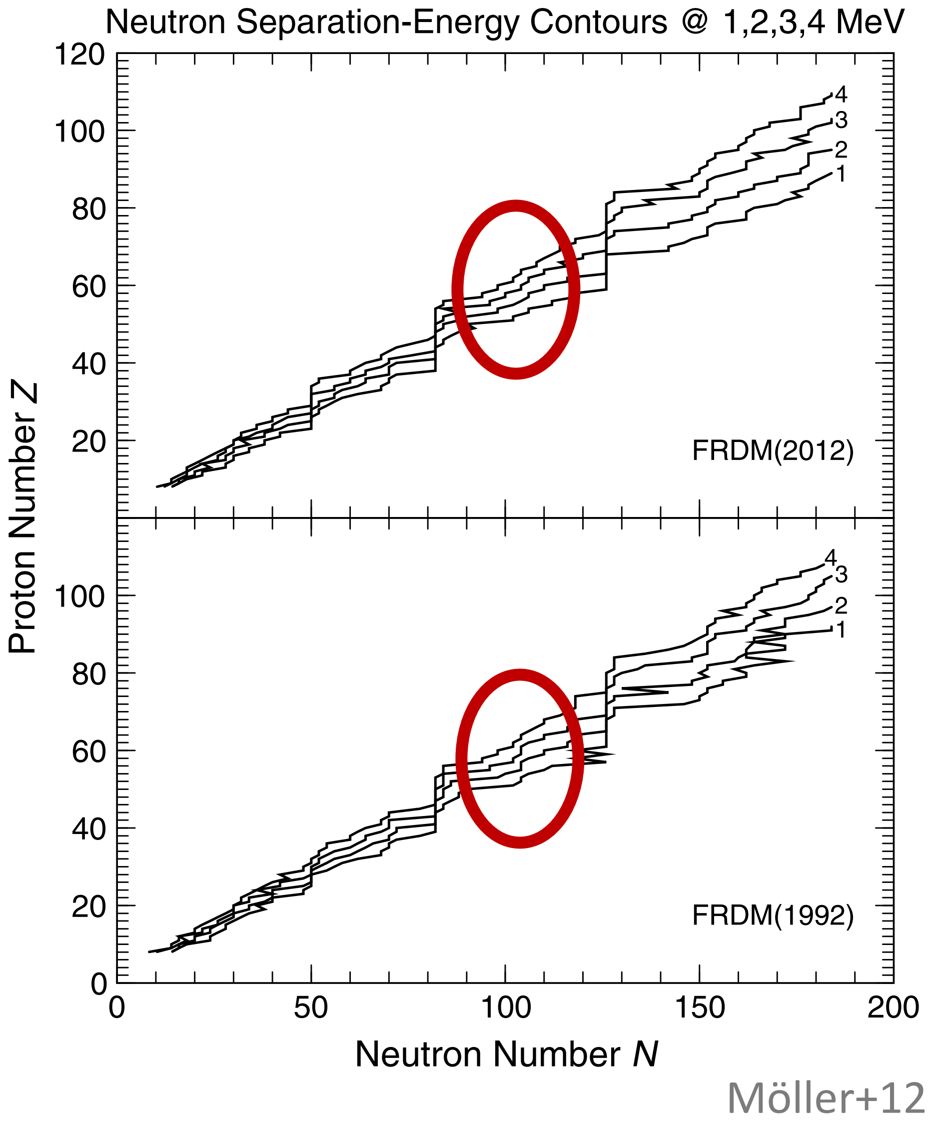
Mumpower+15

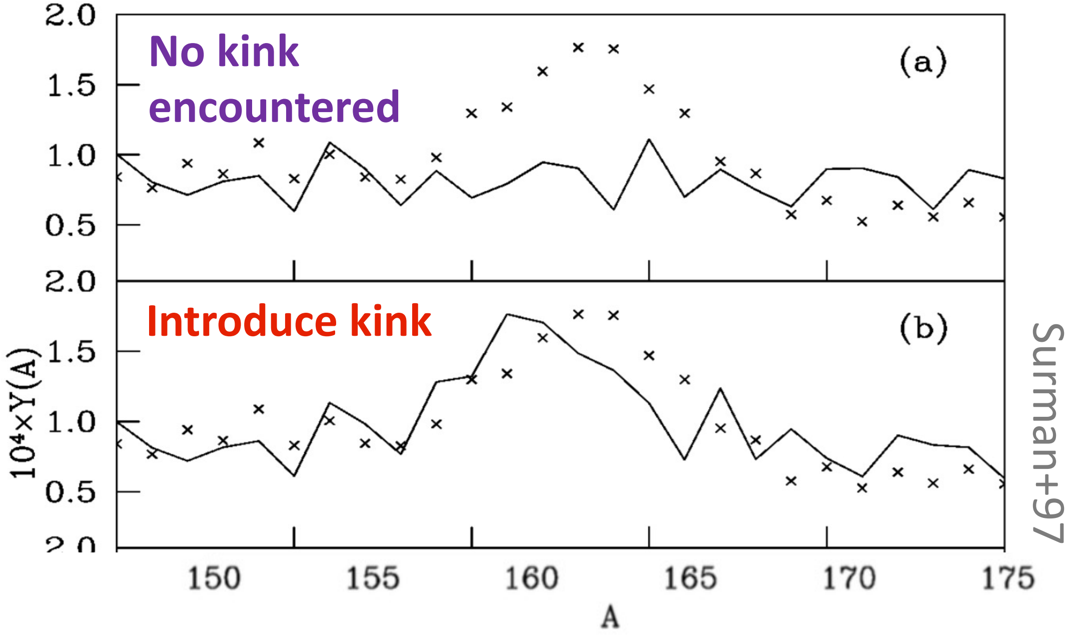
Abundance range from 10 mass models



Côté+18

A nuclear feature in the rare-earths and peak formation





(n,γ) ⇄ (γ,n) equilibrium: $\frac{Y(Z,N+1)}{Y(Z,N)} \sim e^{S_n(Z,N+1)/k_BT}$

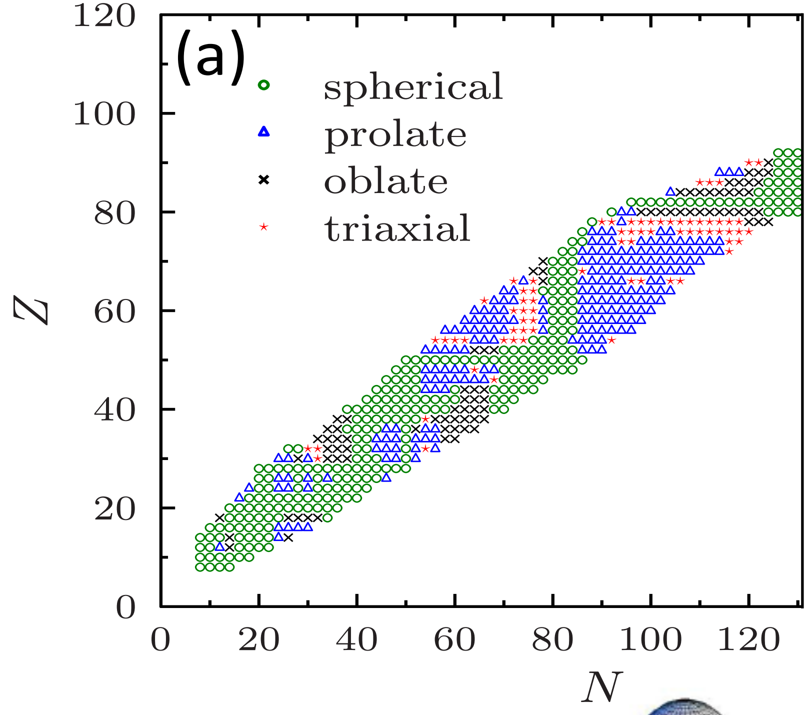
↓

the *r*-process path (location of the max abundance for all isotopic chains) tends to lie along contours of constant S_n

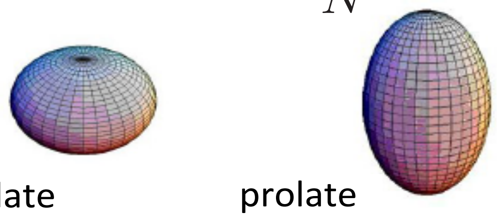
↓

When nuclei encounter a 'kink' in the *r*-process path, a local pileup occurs and abundance peaks form

Predictions for a nuclear deformation in the rare-earths

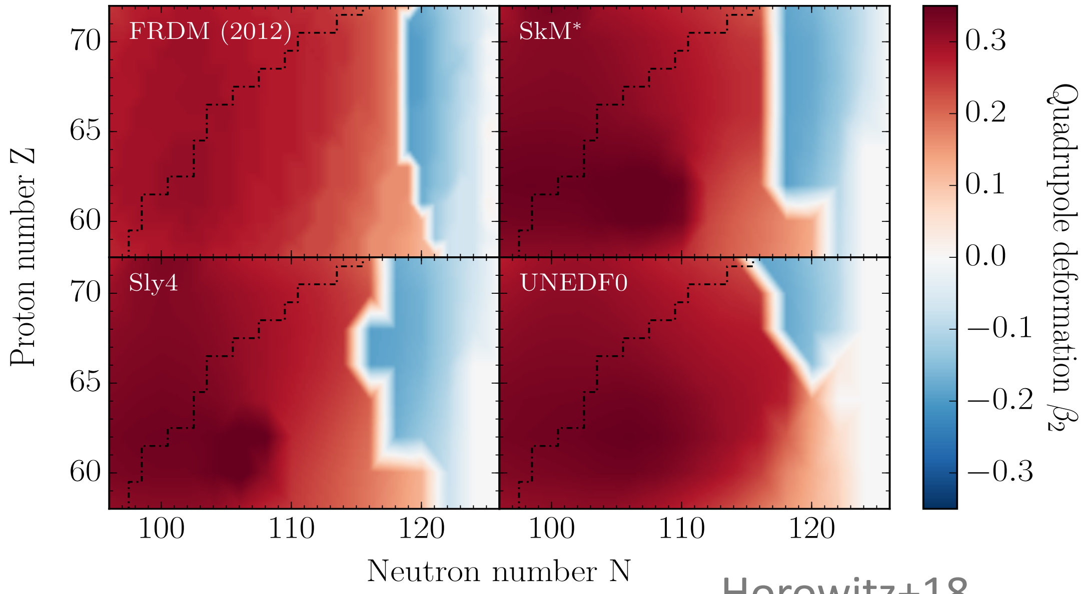


Lacroix+15

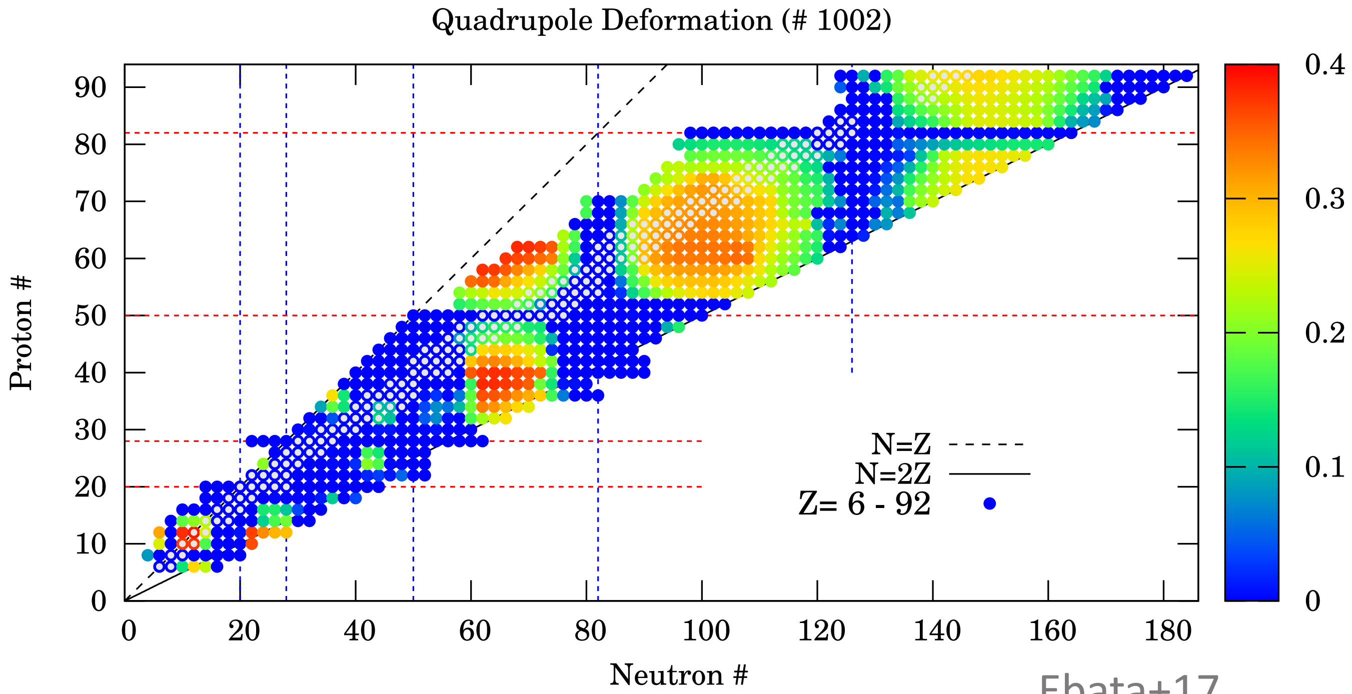


oblate

prolate

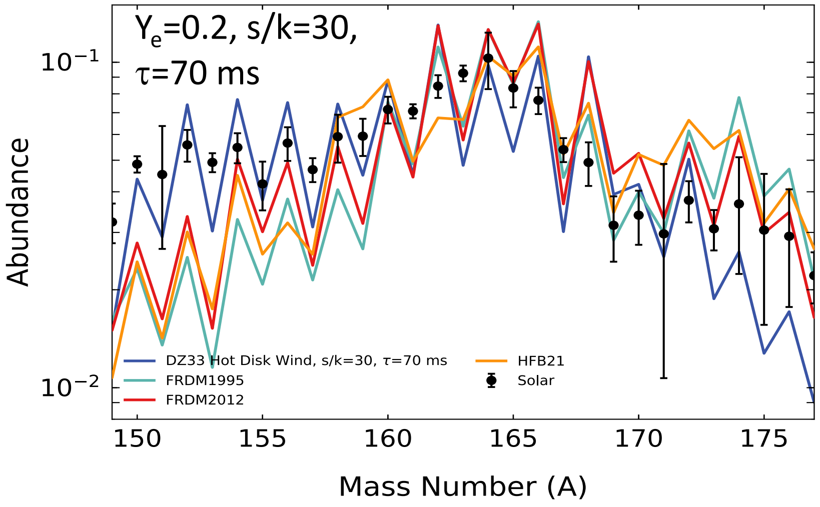


Horowitz+18

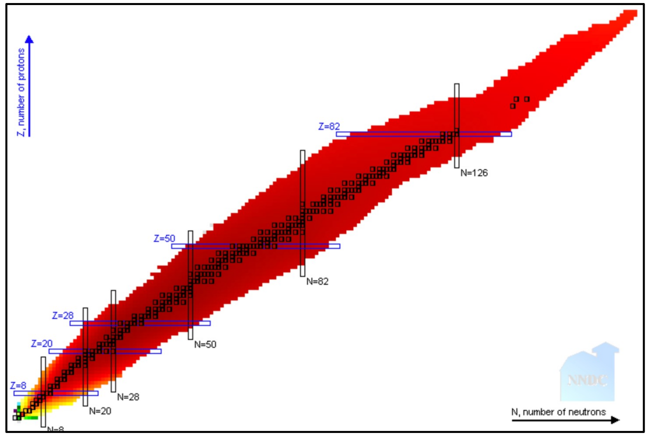


Ebata+17

A statistical approach to exploit the interplay between nuclear properties and astrophysical outcomes

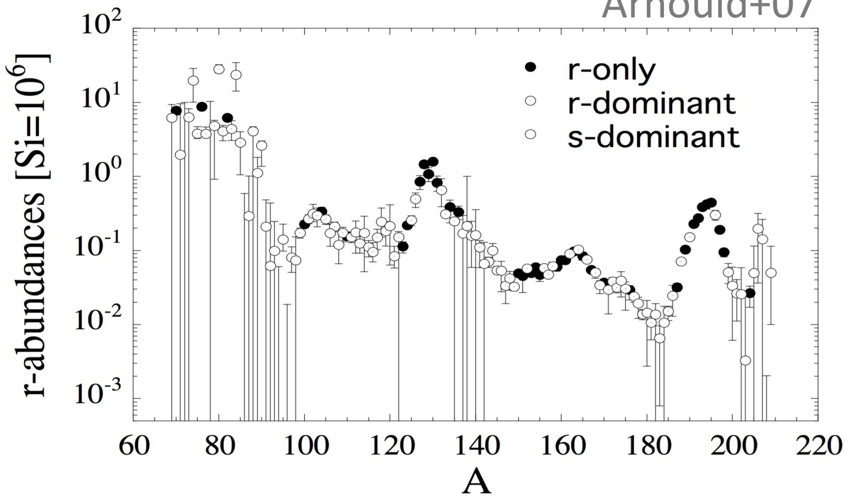


Nuclear masses are key inputs for reaction and decay rates

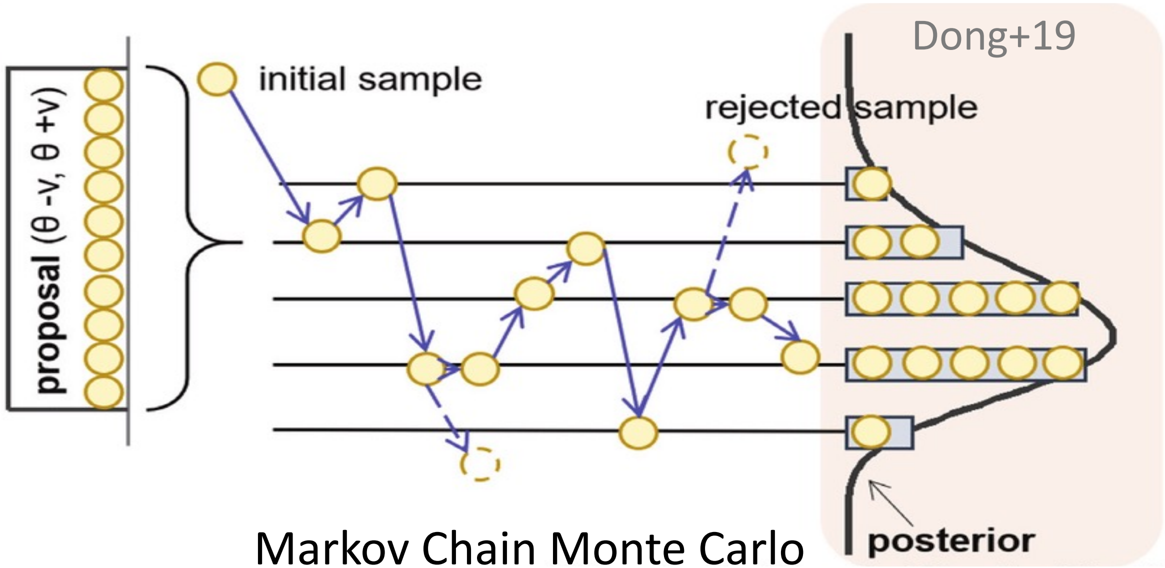


We have mass data to inform us but don't yet know masses of some important neutron-rich nuclei

Arnould+07



Nuclear structure (shell closures, deformation…) affects abundances



Markov Chain Monte Carlo

Markov Chain Monte Carlo (MCMC) procedure

- Monte Carlo mass corrections

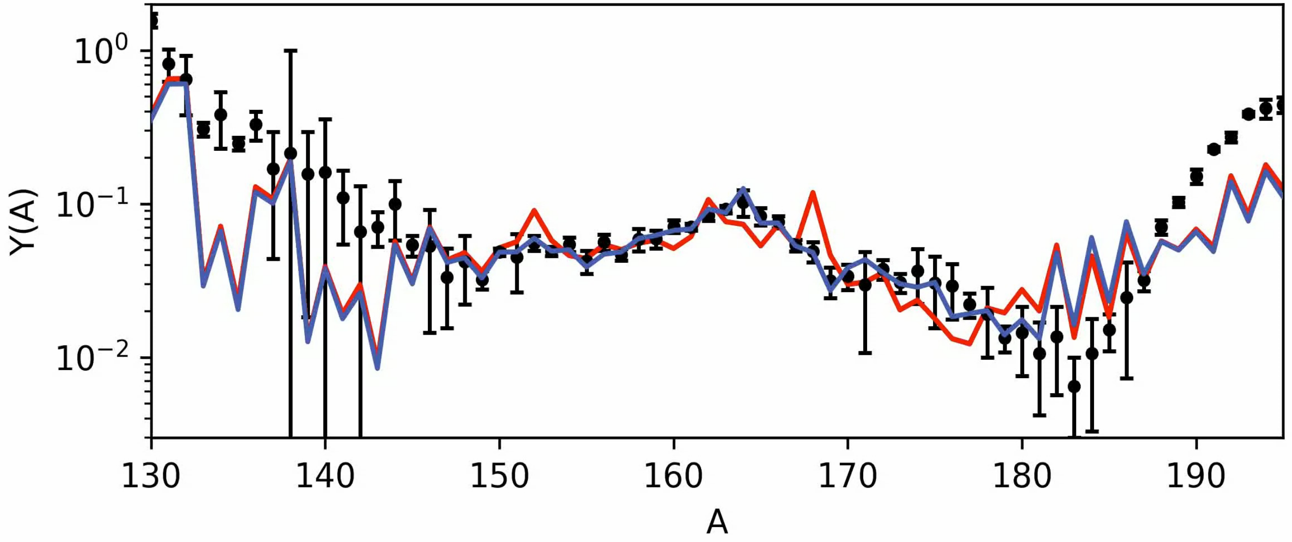
$$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

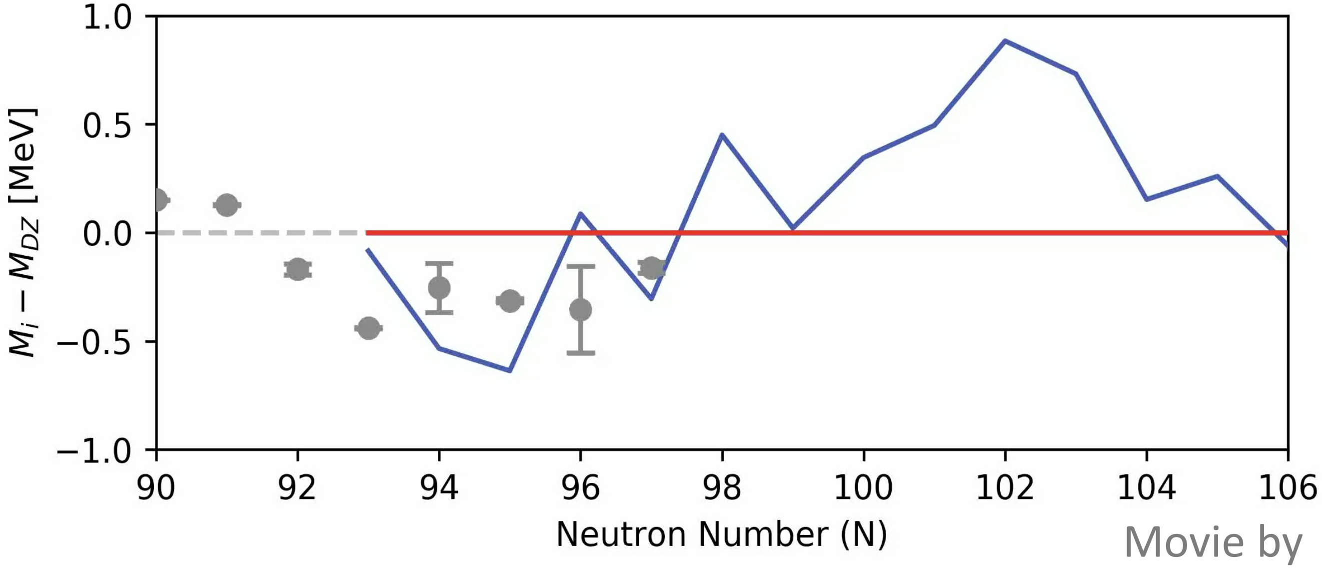
- Calculate: $\sigma^2_{\text{rms}}(M_{\text{AME12}}, M) \leq \sigma^2_{\text{rms}}(M_{\text{AME12}}, M_{DZ})$
- Calculate:

$$D_n(Z,A) = (-1)^{A-Z+1}\left(S_n(Z,A+1) - S_n(Z,A)\right) > 0$$

- Update nuclear quantities and rates
- Perform nucleosynthesis calculation
- Calculate $\chi^2 = \sum_{A=150}^{180} \frac{\left(Y_{\odot,r}(A) - Y(A)\right)^2}{\Delta Y(A)^2}$
- Update parameters OR revert to last success

$$\mathcal{L}(\text{m}) = \exp\left(-\frac{\chi^2(\text{m})}{2}\right) \longrightarrow \alpha(\text{m}) = \frac{\mathcal{L}(\text{m})}{\mathcal{L}(\text{m}-1)}$$

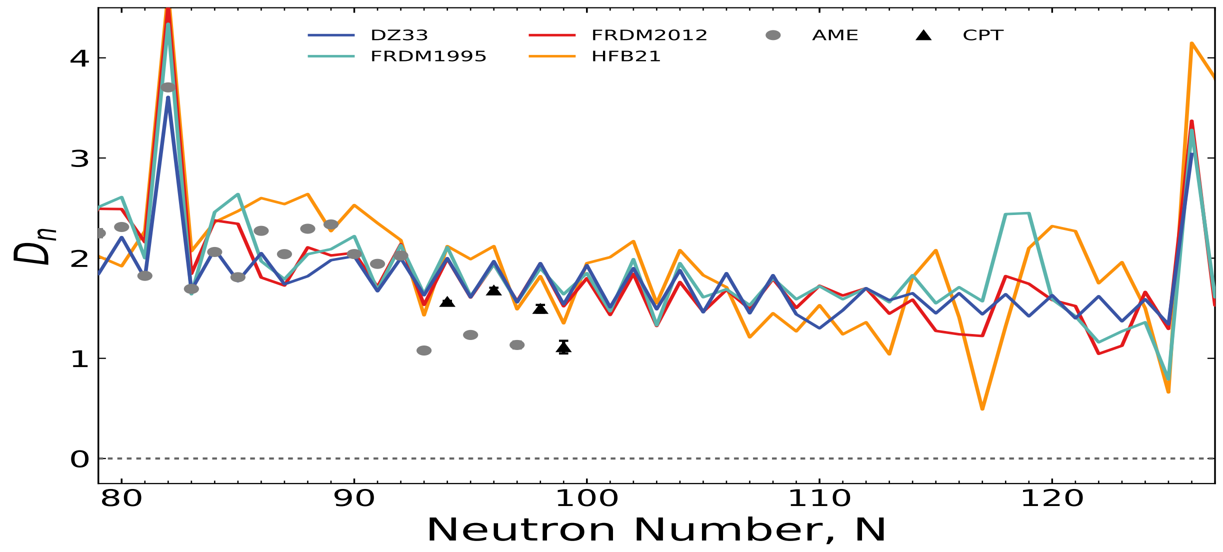




Movie by N. Vassh

Black – solar abundance data
Grey – AME 2012 data
Red – values at current step
Blue – best step of entire run

Applying physical constraints



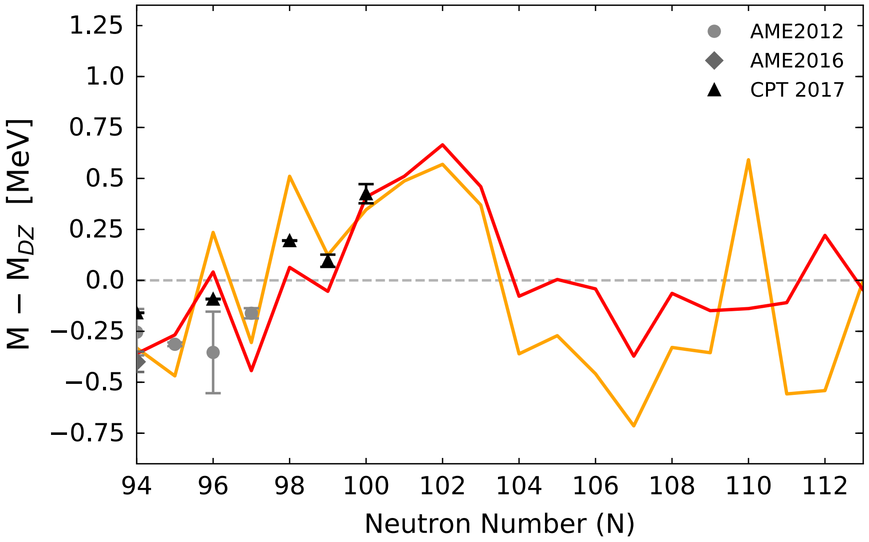
The one neutron pairing metric:

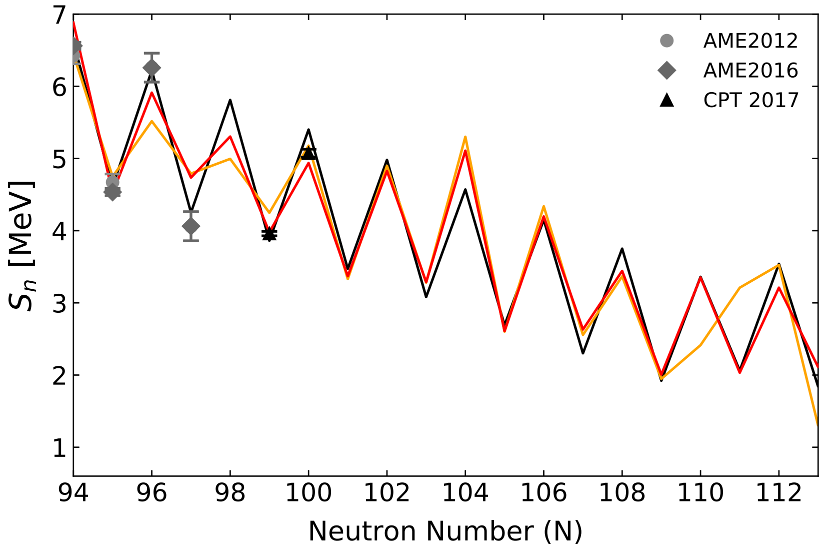
$$D_n(Z,A) = (-1)^{A-Z+1}\left(S_n(Z,A+1) - S_n(Z,A)\right)$$

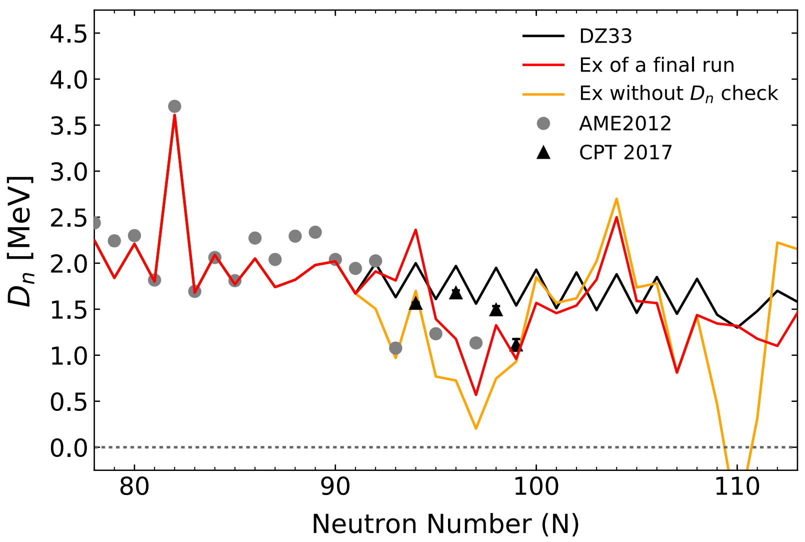
is worked into the likelihood function

$$\mathcal{L}(m) \sim \exp\left(-\frac{\chi^2(m)}{2}\right) \longrightarrow \mathcal{L}' = \mathcal{L}\theta(D_n(Z,A))$$

where $\theta = 1$ if $D_n(Z,A) > 0$ and $D_n(Z,A) < D_n(Z,Z+126)$







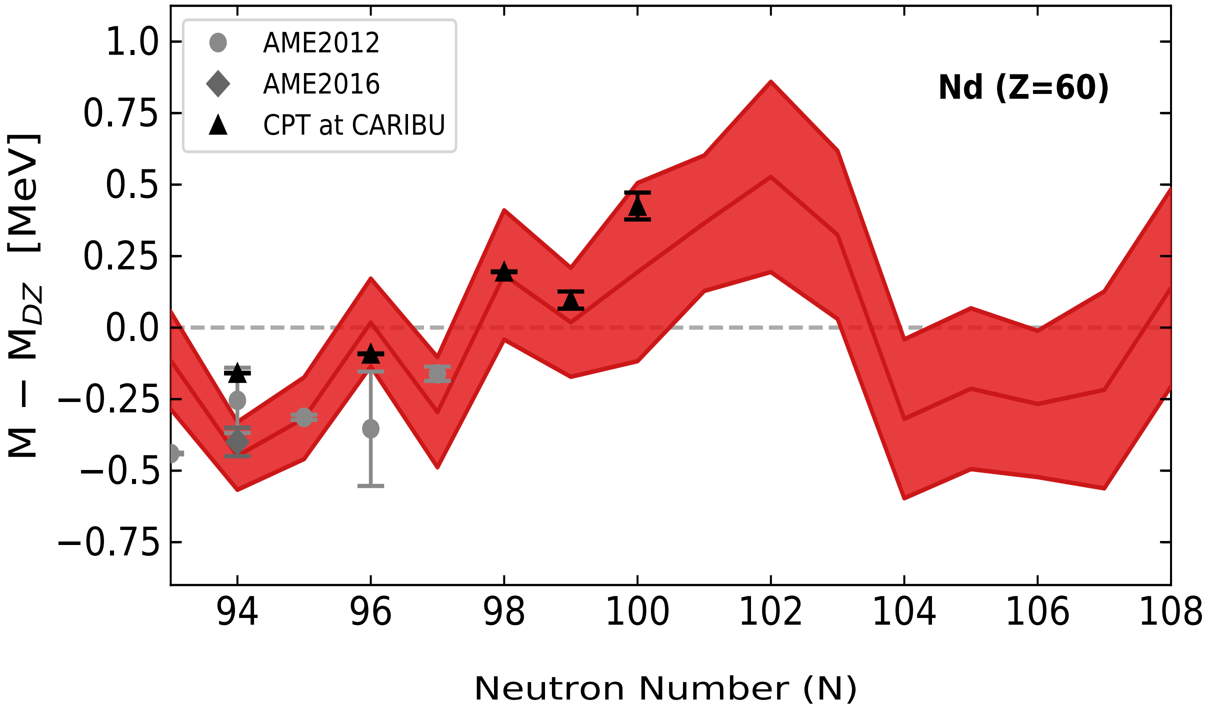
Vassh+21 (ApJ 907, 98)

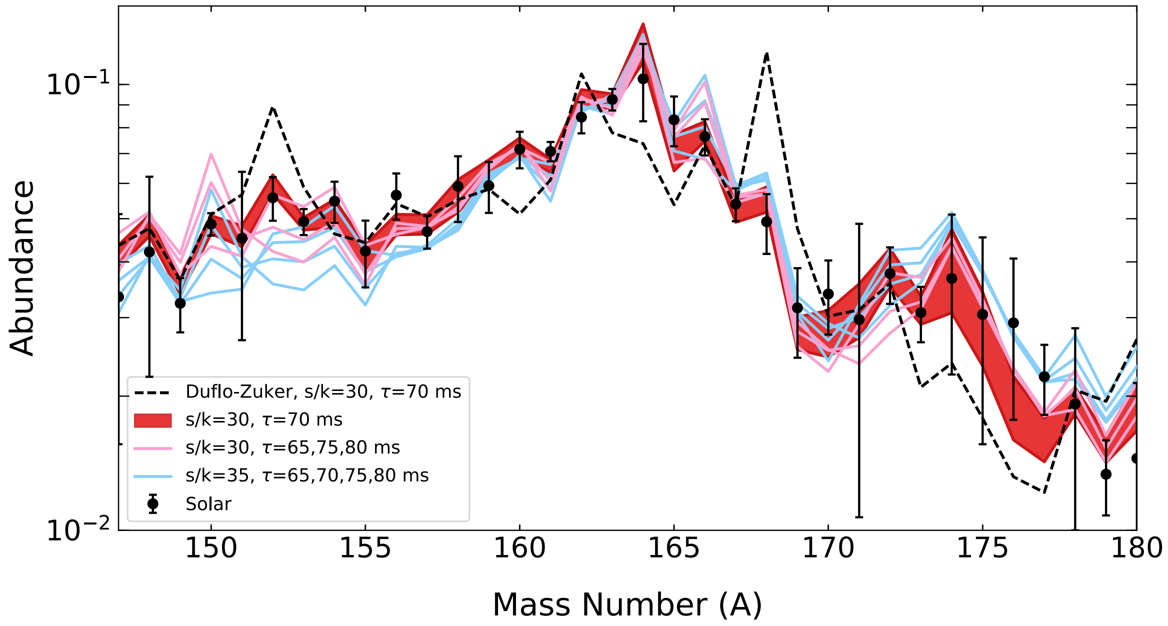
MCMC results:
rare-earth masses to form peak in hot and *similar* astrophysical conditions

- Astrophysical trajectory:
  hot, low entropy outflow as from a NSM accretion disk
  (s/k=30, τ=70 ms, Y_e=0.2)

- 50 parallel, independent MCMC runs

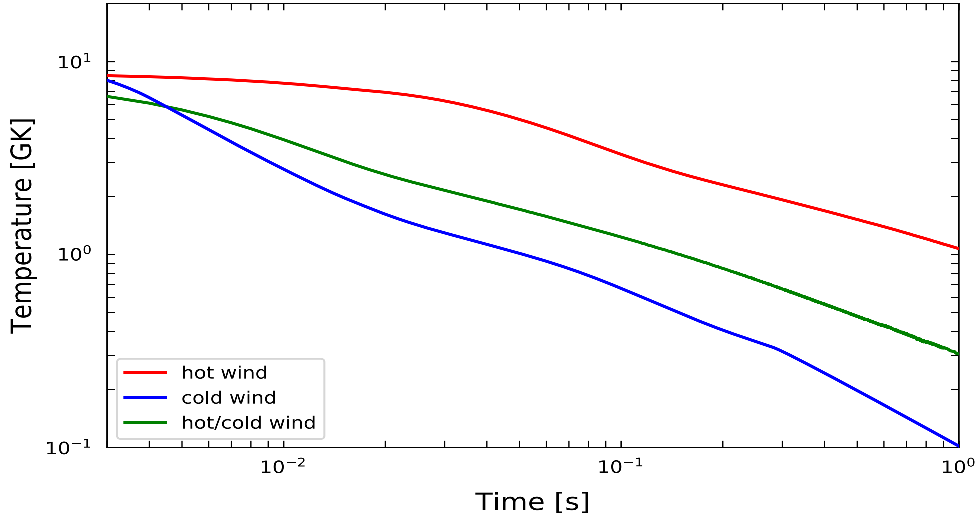
Orford,Vassh+18
(Phys. Rev. Lett. **120**, 262702 (2018))

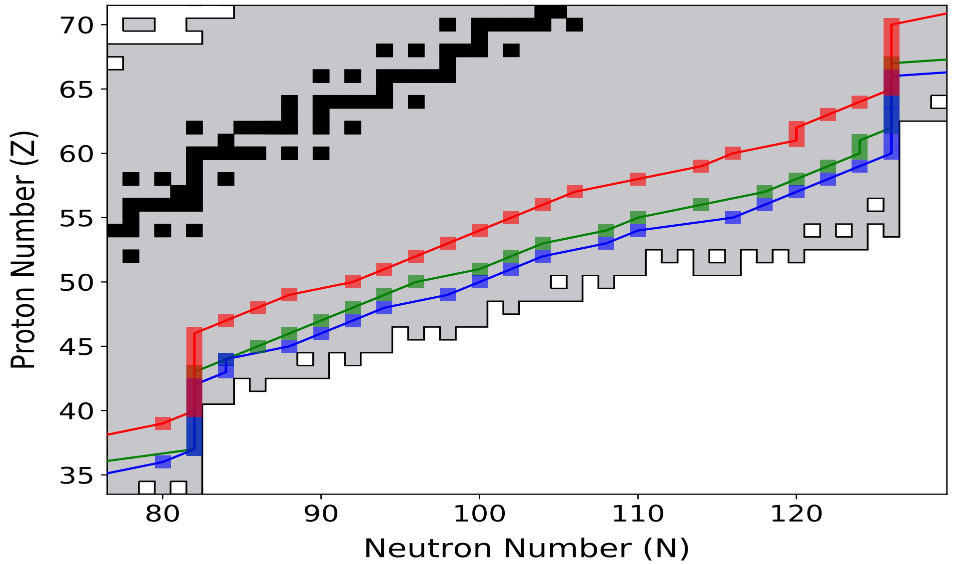




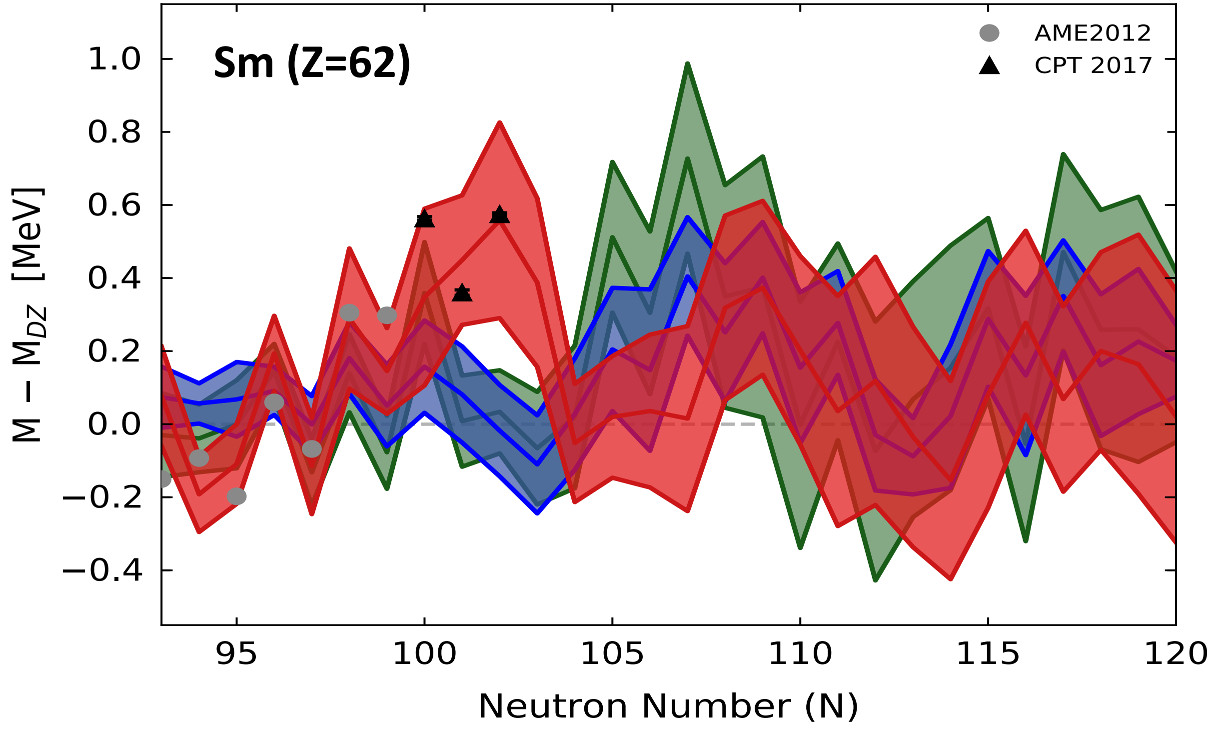
Ejecta Outflow Parameters

Outflow Type	Entropy (s/k_B)	Timescale (ms)	Y_e
Hot	30	70	0.2
Hot/cold	20	10	0.2
Cold	10	3	0.2





MCMC results in *moderately neutron-rich* astrophysical outflows

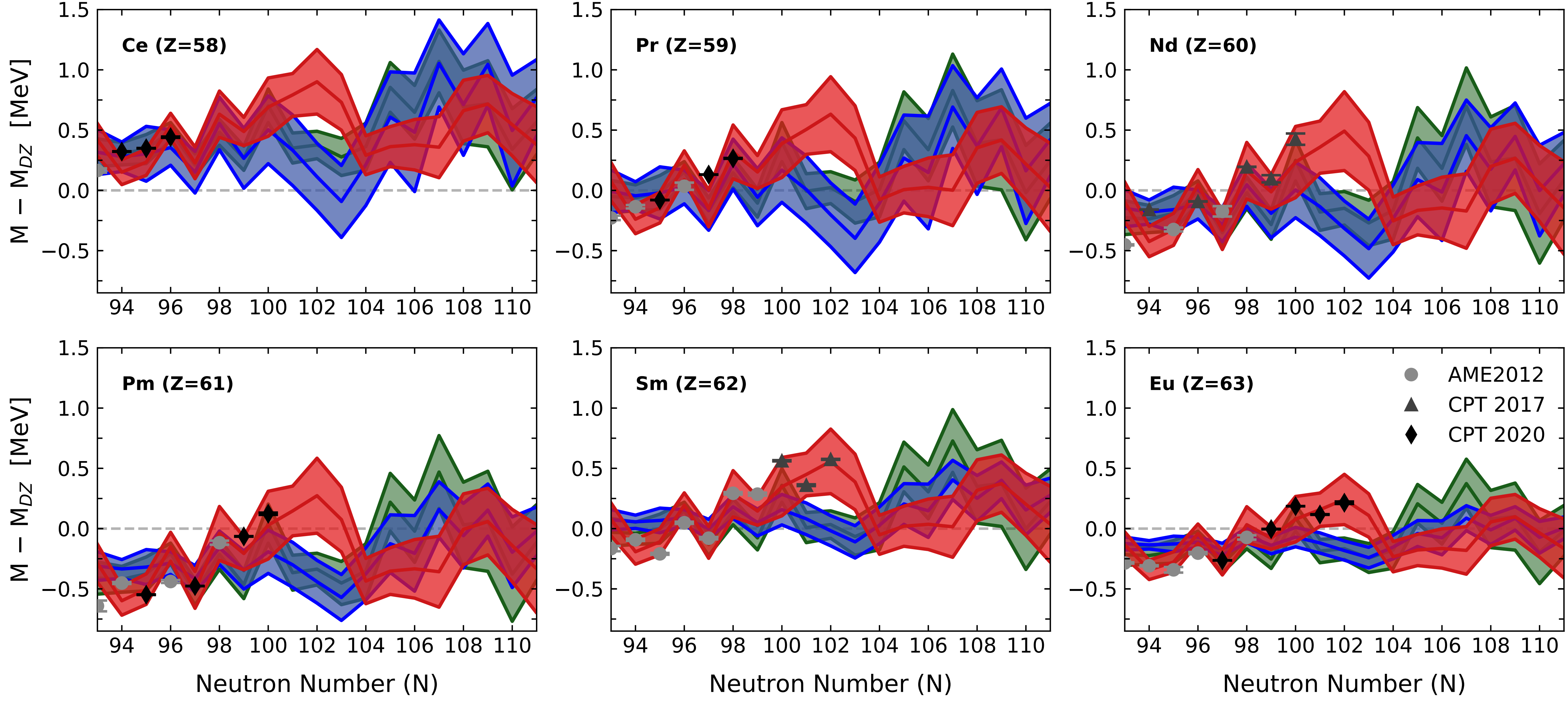


Neutron star merger accretion disk winds with:

Hot = extended (n,γ)⇆(γ,n) equilibrium

Cold = photodissociation falls out early

Vassh+21 (ApJ 907, 98)



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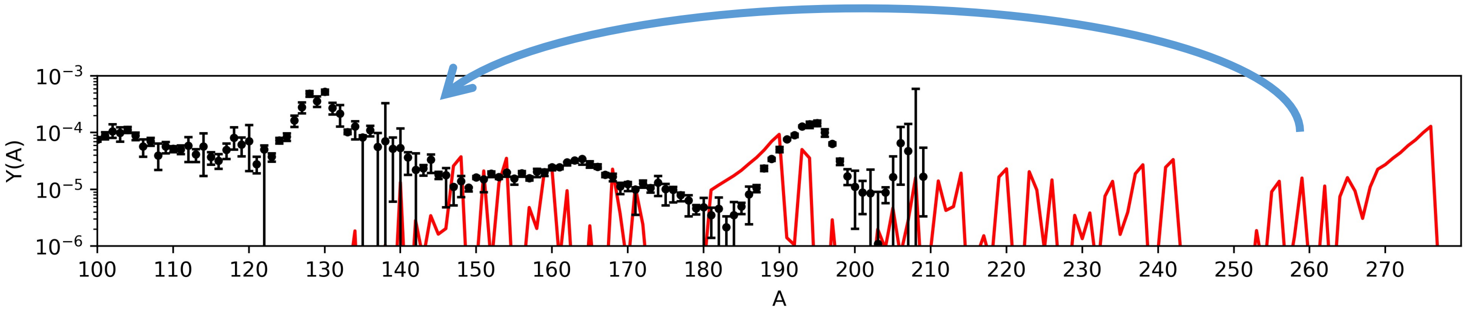
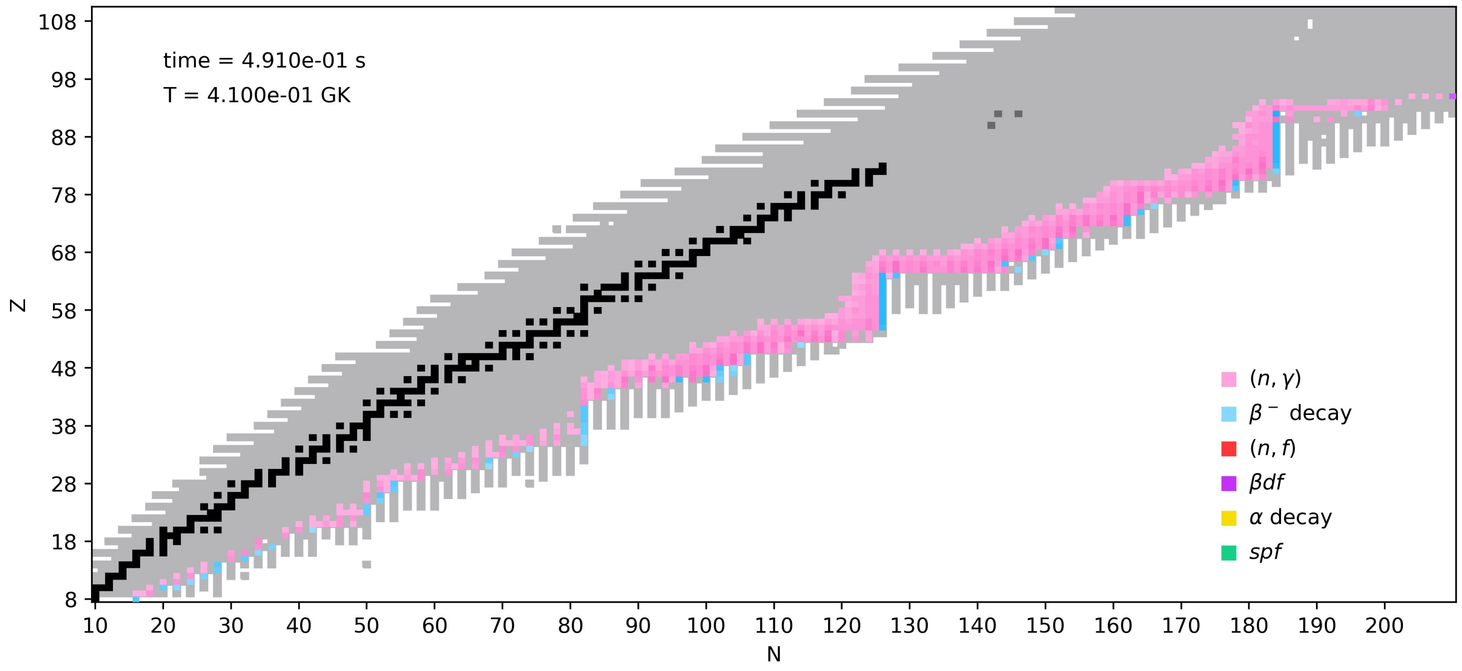
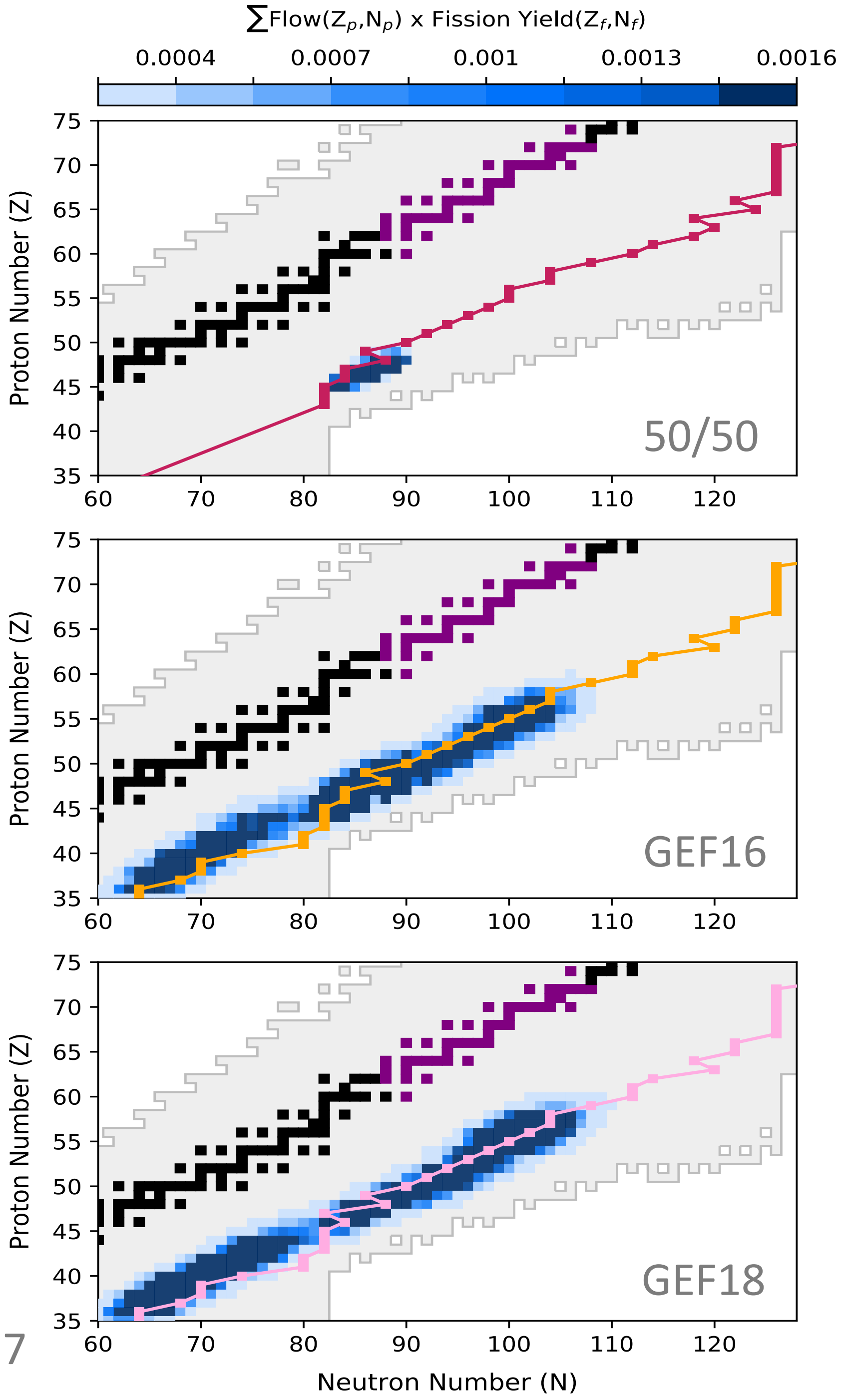
Orford,Vassh+22 (Phys. Rev. C Letter 105, L052802)

Potential complications in understanding rare-earth peak formation due to fission deposition

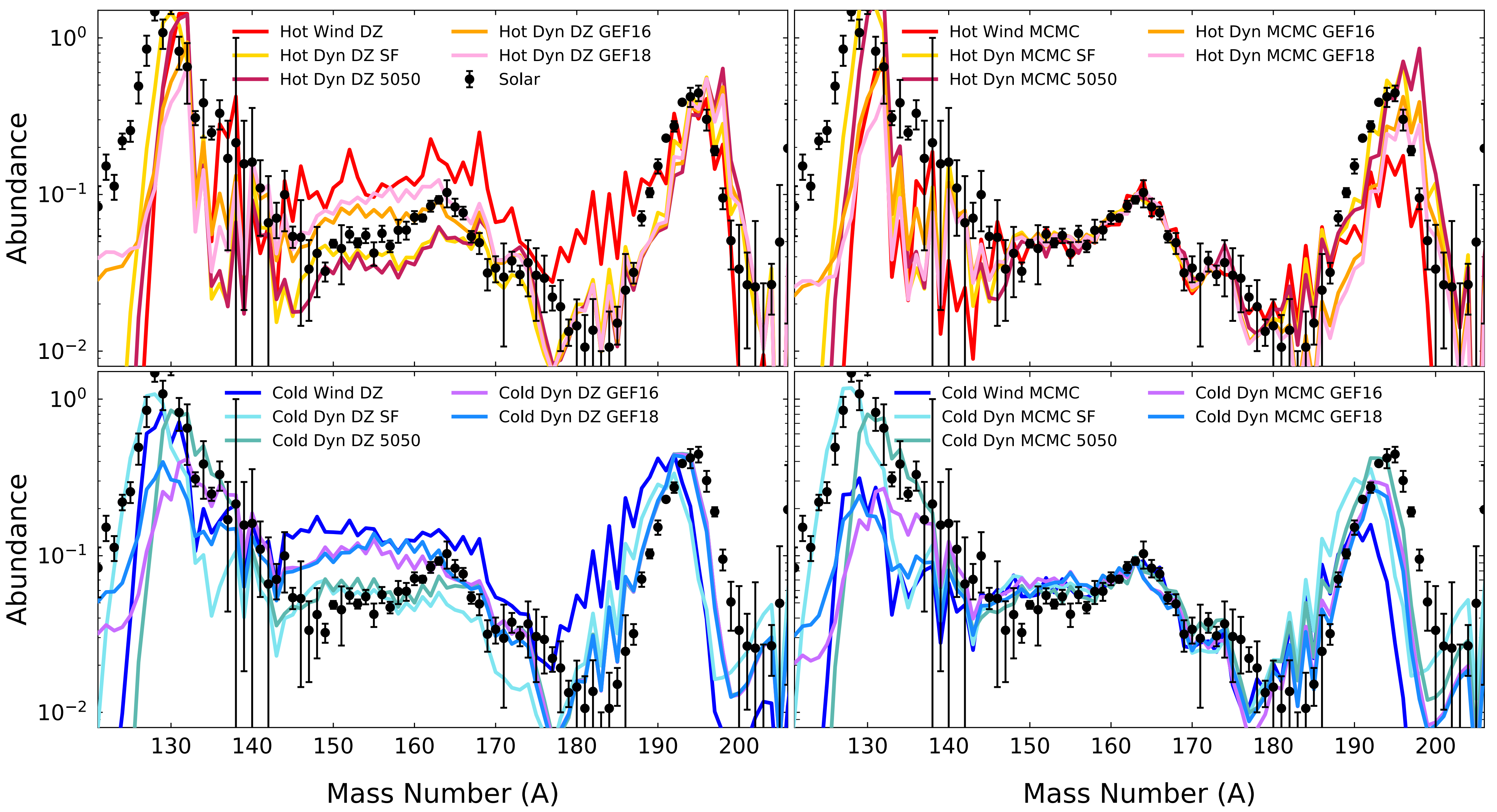






Vassh+22,
arXiv:2202.09437

MCMC results in *very neutron-rich* astrophysical outflows

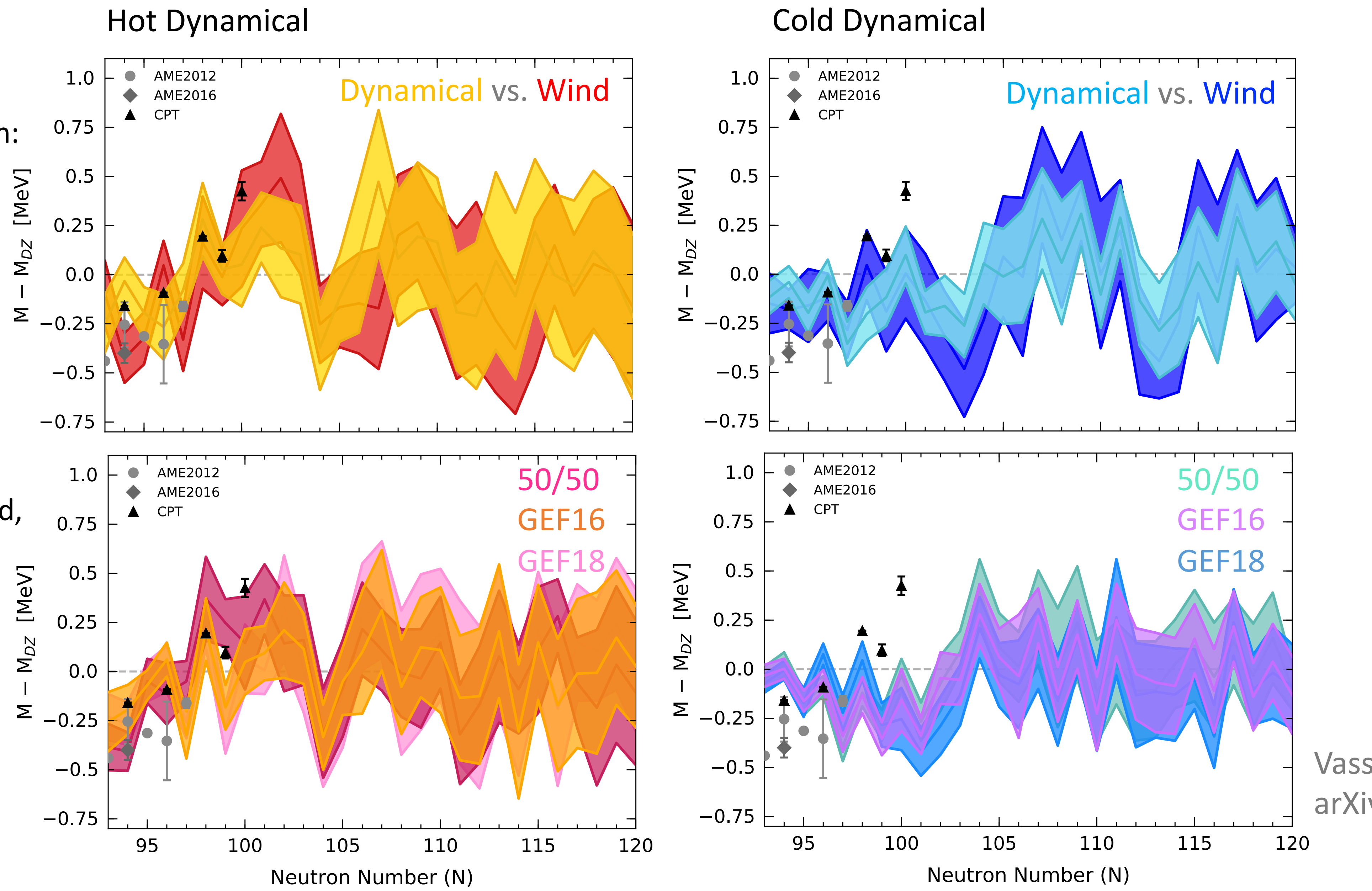


Vassh+22, arXiv:2202.09437

MCMC results in *very neutron-rich* astrophysical outflows

Simplified fission: 50/50 + instant SF at $A \geq 250$

Neutron-induced, beta-delayed and SF with FRLDM barriers



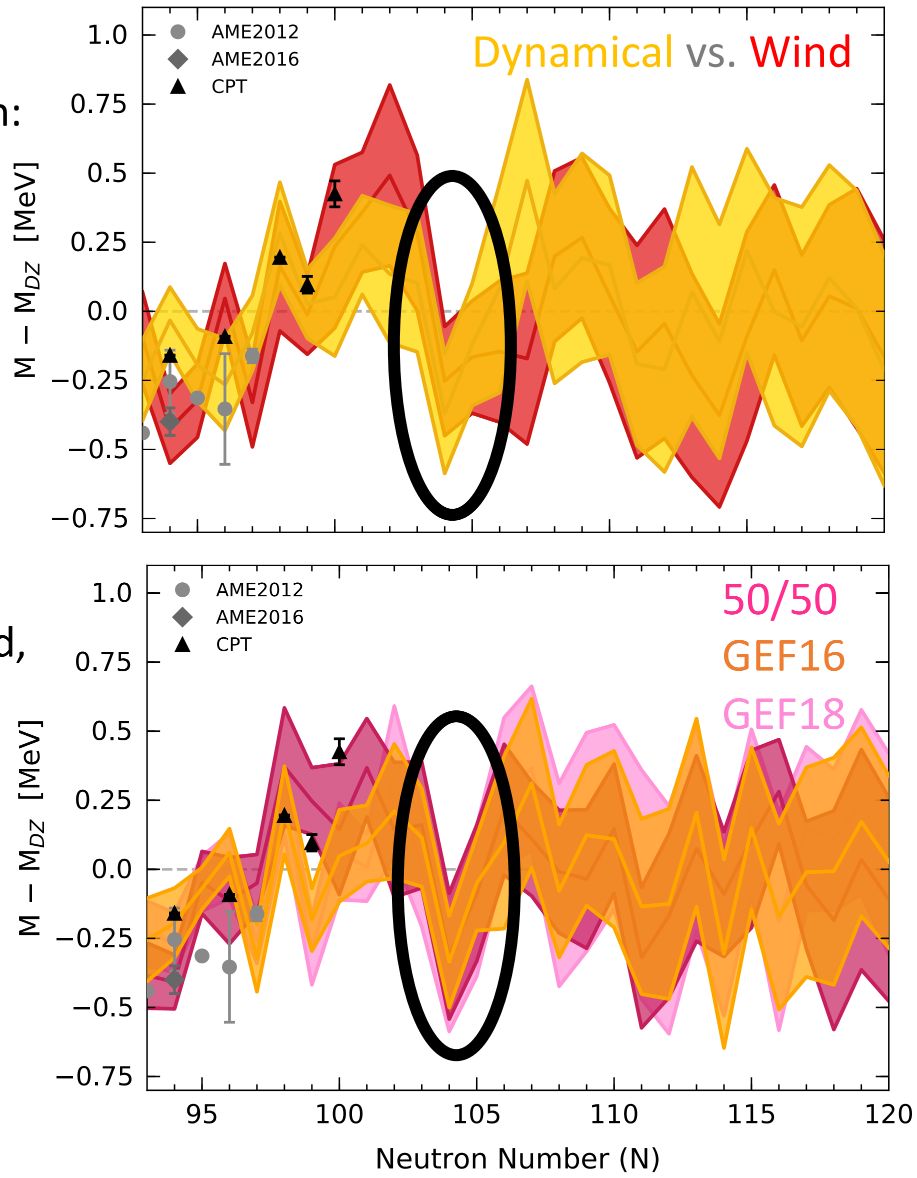
Vassh+22, arXiv:2202.09437

MCMC results in *very neutron-rich* astrophysical outflows

Hot Dynamical

Simplified fission: 50/50 + instant SF at $A \gtrsim 250$

Neutron-induced, beta-delayed and SF with FRLDM barriers

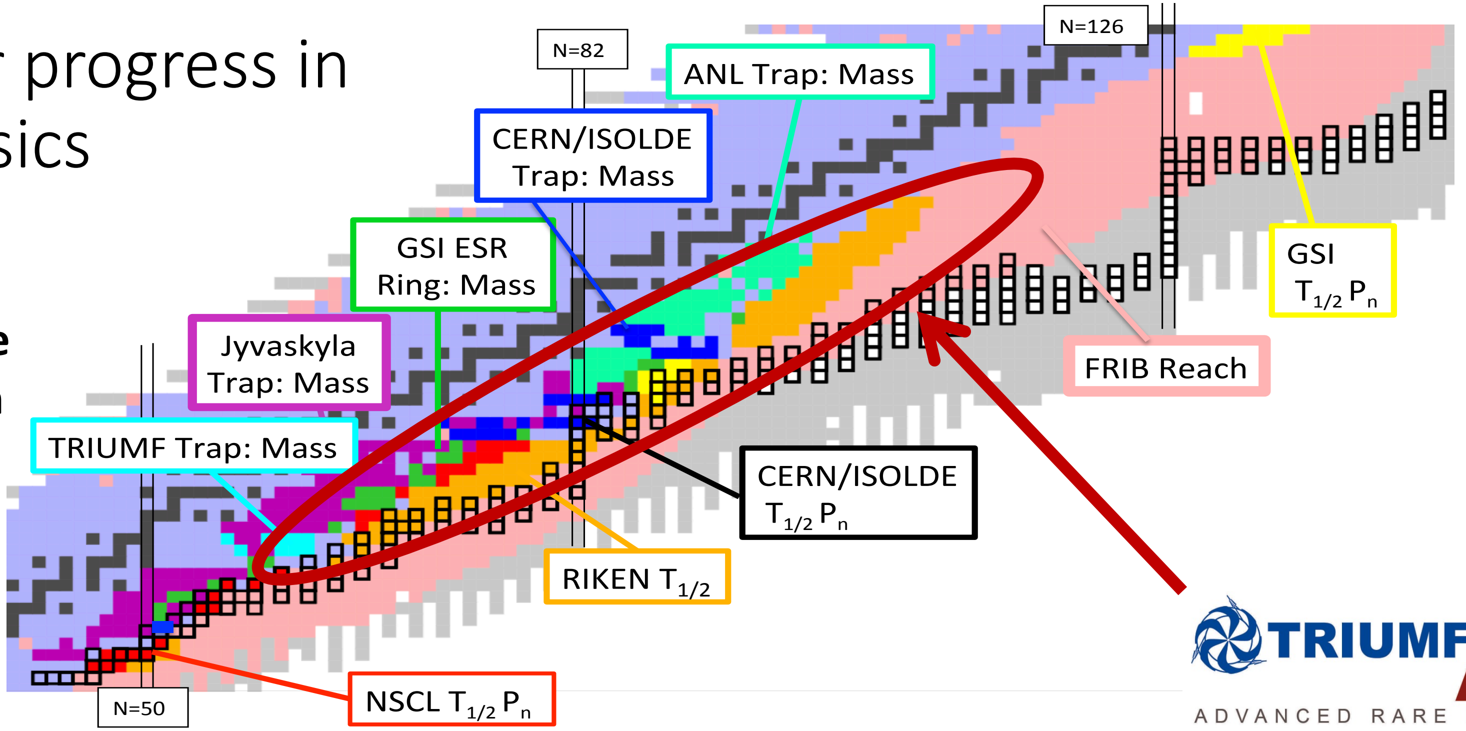


Despite outflows having distinct densities and n-richness, and even differing involvements from fission deposition, *we consistently find the need for a feature of enhanced stability at **N=104** for hot cases*

Vassh+22, arXiv:2202.09437

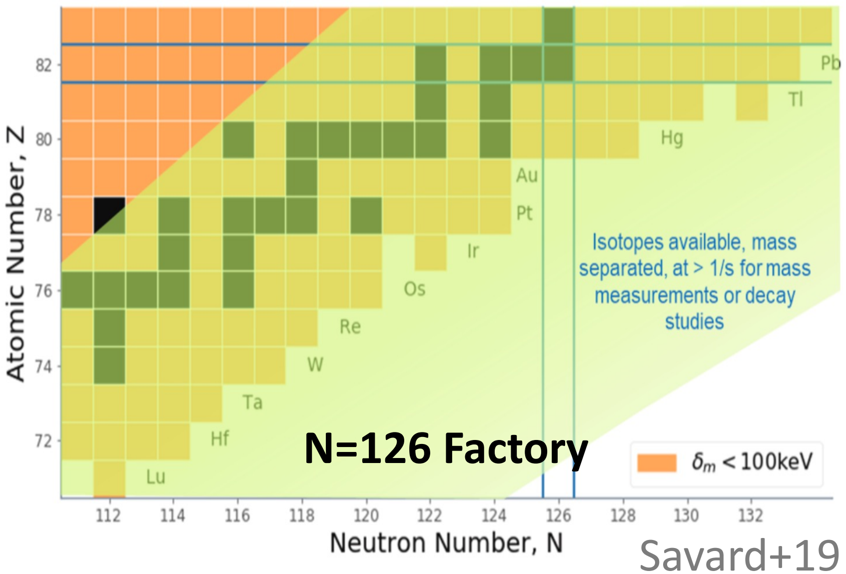
Opportunities for progress in nuclear astrophysics

Worldwide experimental campaigns to measure the properties of neutron-rich nuclei:
masses, half-lives, reaction rates…

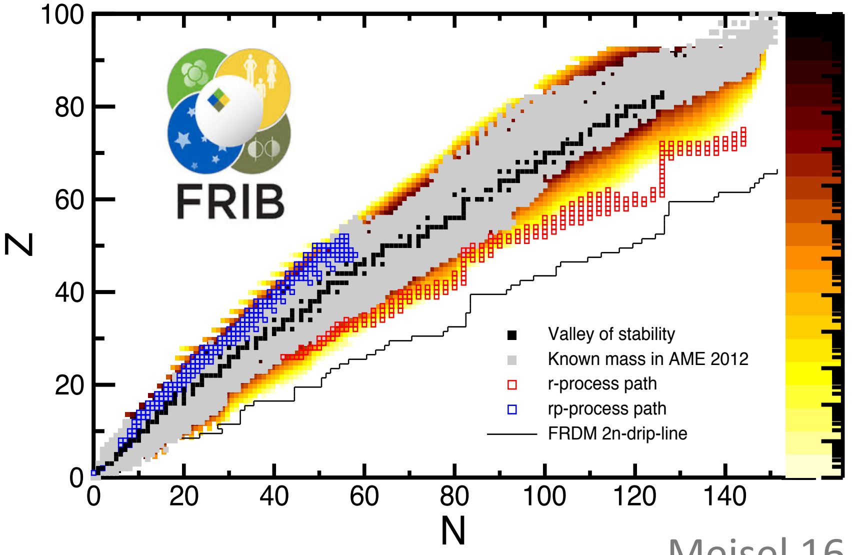


TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

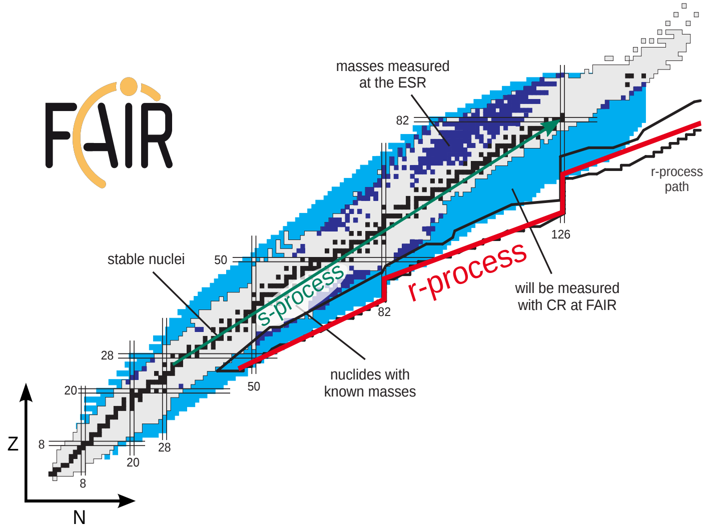
Horowitz+18



Savard+19



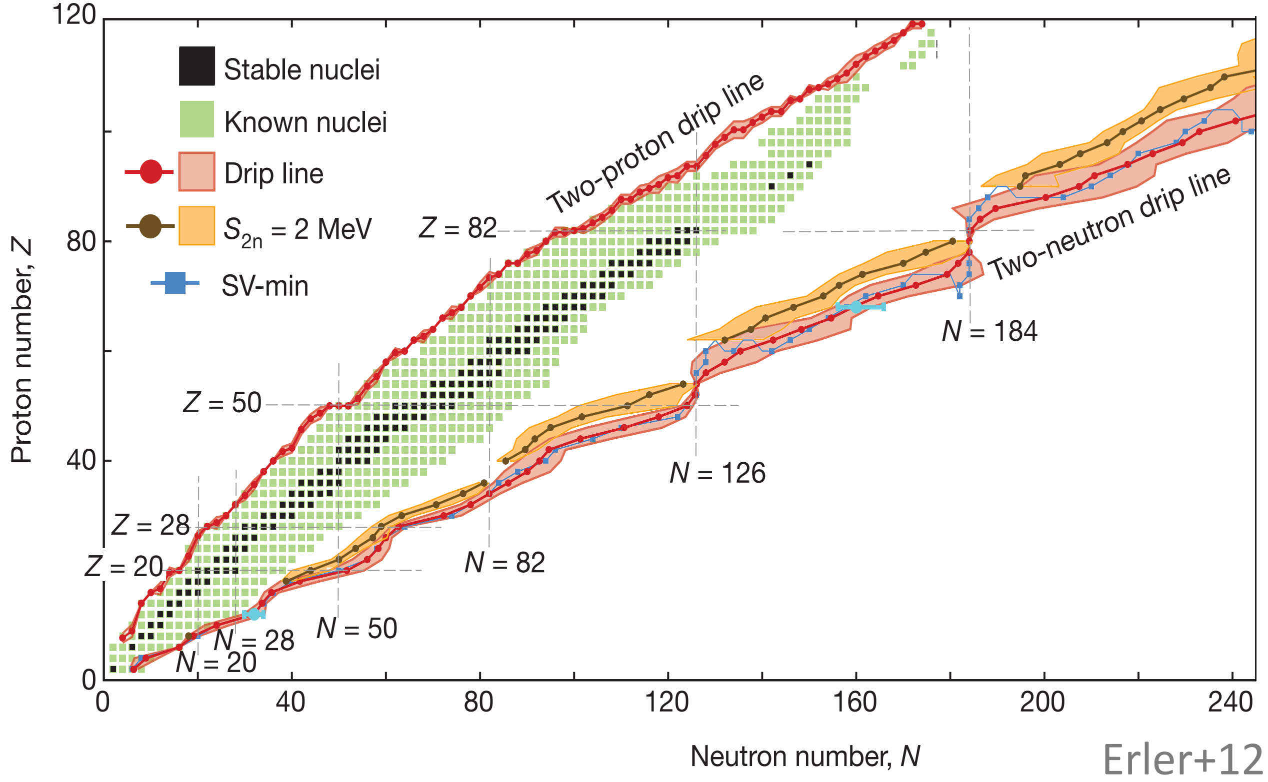
Meisel 16



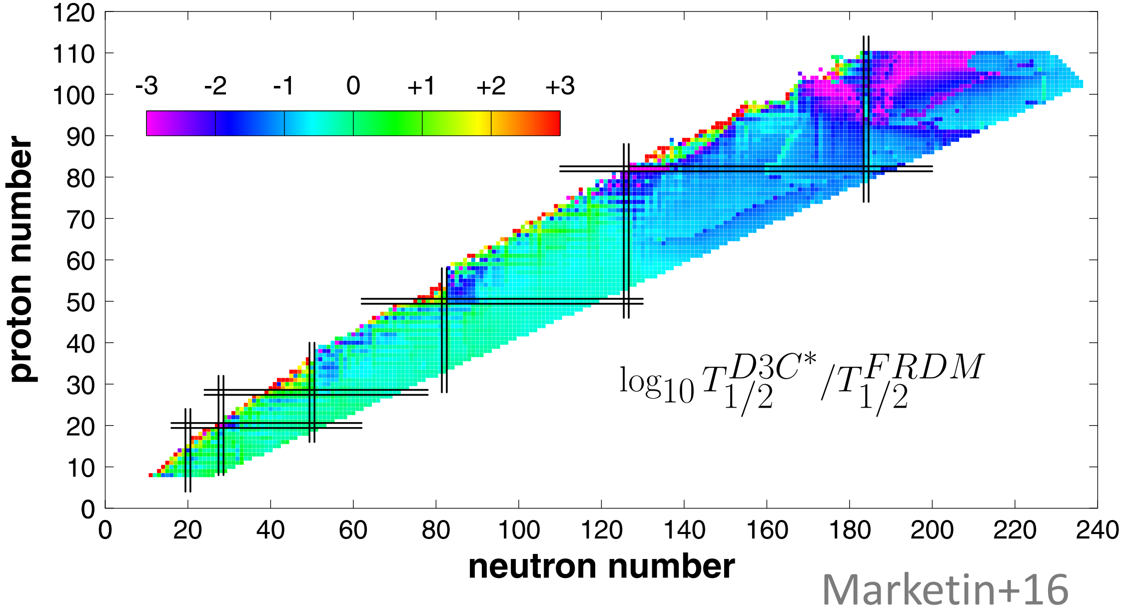
Opportunities for progress in nuclear astrophysics

Theory developments:
Structure theory (masses, deformation, level densities…), reaction theory (capture cross sections…), fission yields and rates, and β-decay rates….

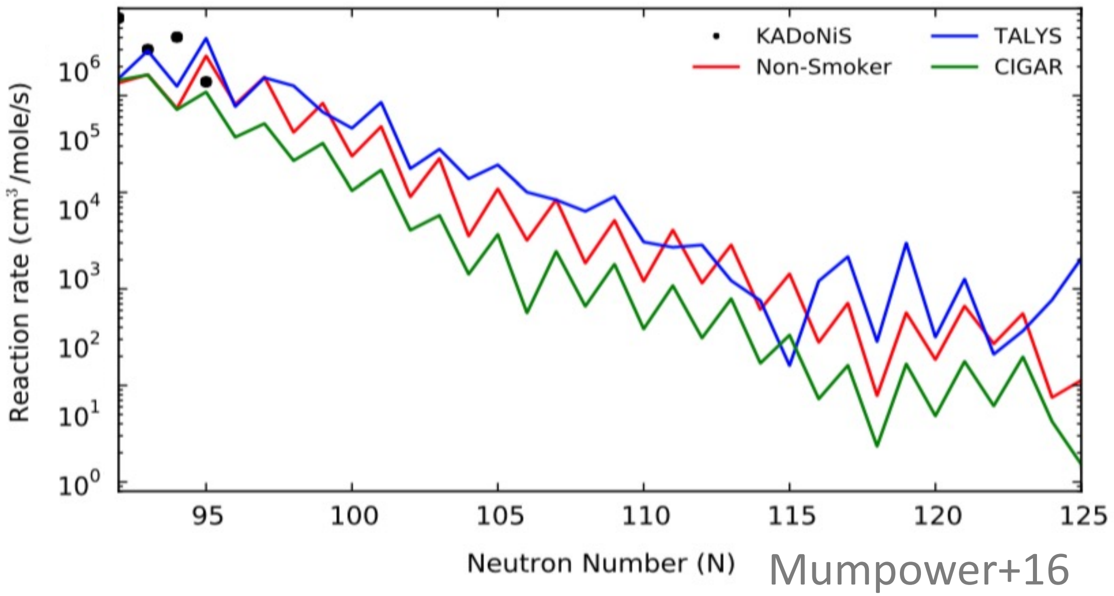
Modeling masses all the way to the dripline



β-decay calculations



Neutron capture models



Thank you! Merci!

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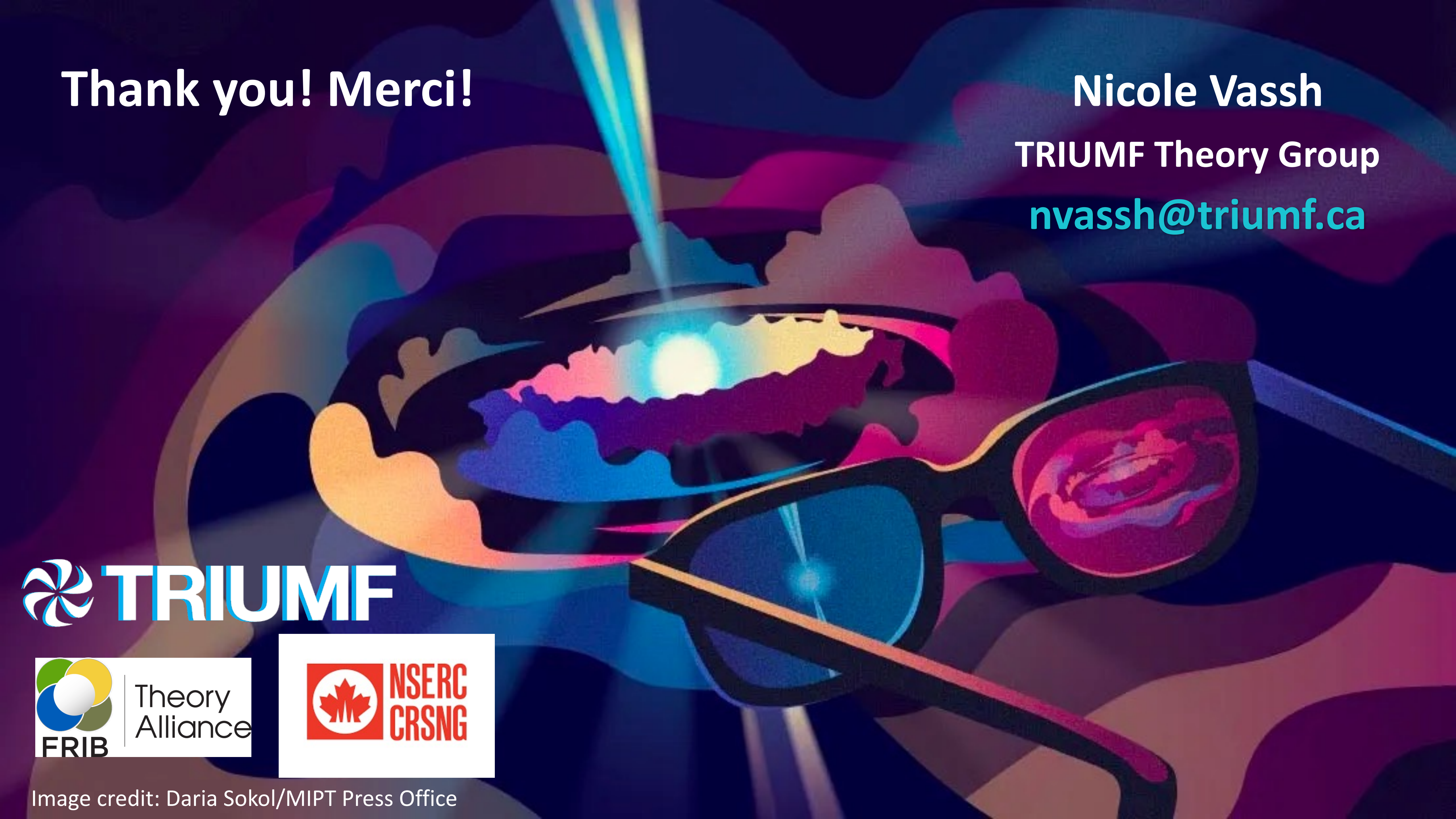

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