Exposing the astrophysical conditions of *r*-process events through observable signatures of lanthanide and actinide production

FIRE

Fission In R-process Elements

JINA-CEE

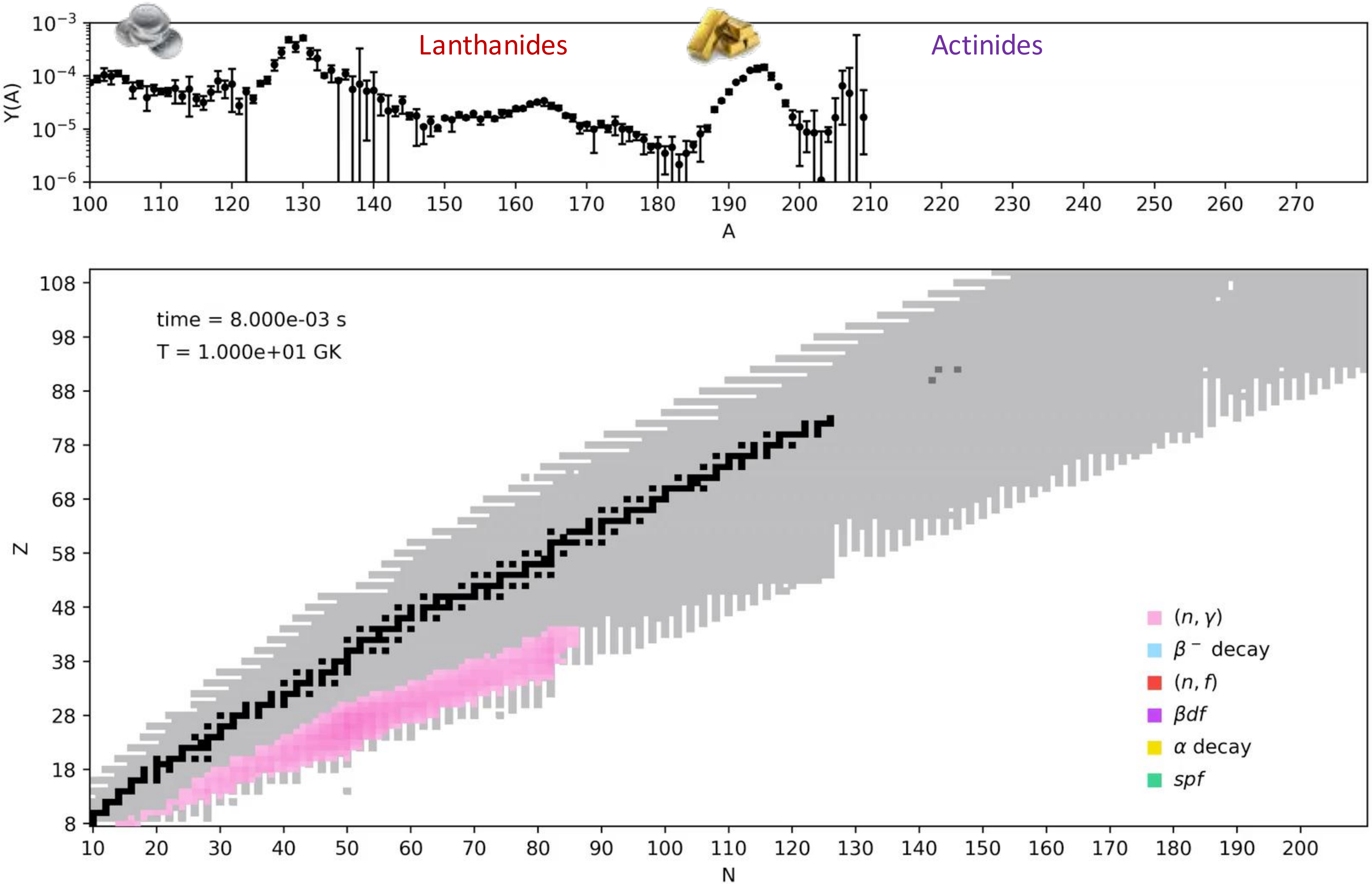
Nicole Vassh

University of Notre Dame

N3AS Online Seminar,

Live from home

June 2, 2020

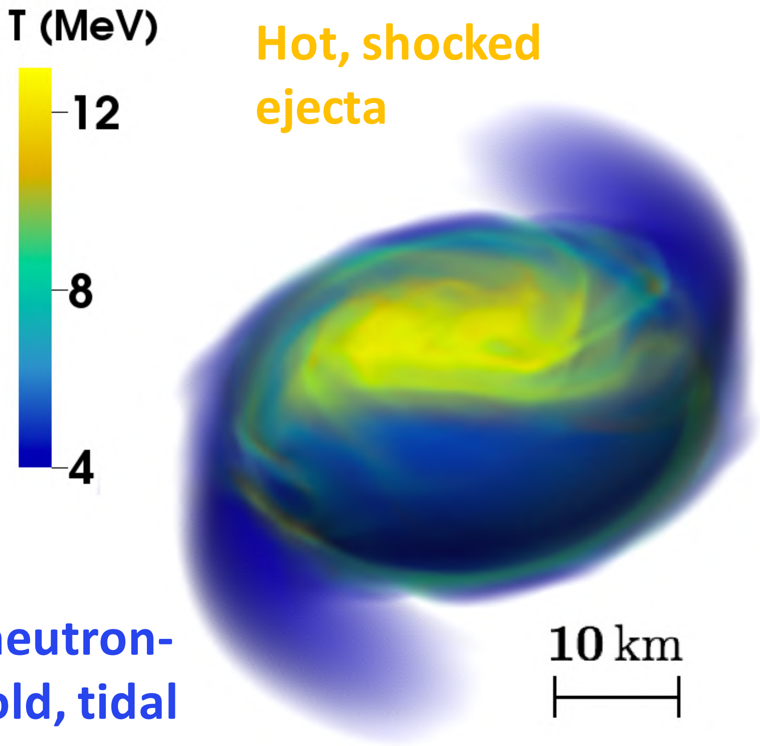


Movie by
N. Vassh

r-process sites in compact object mergers

Dynamical ejecta

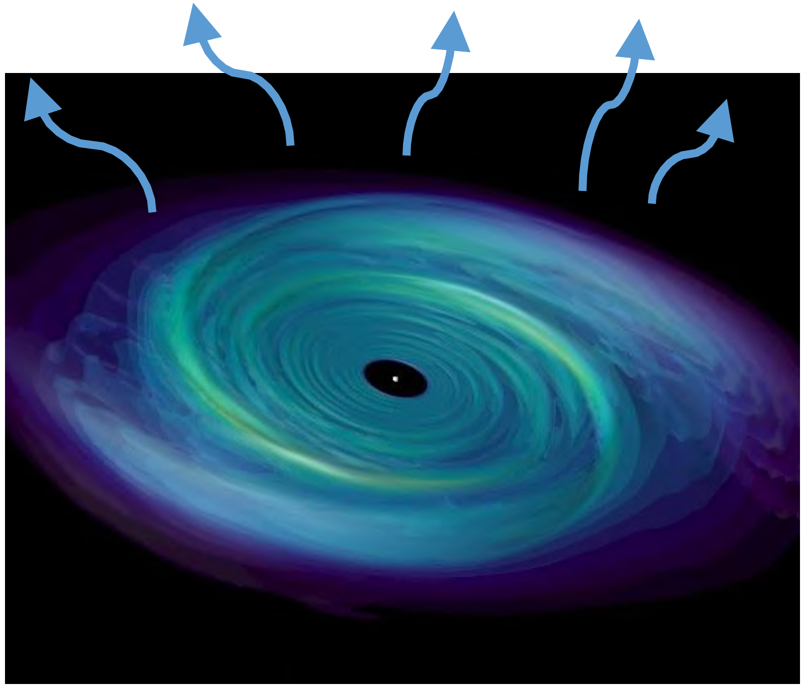
Hot, shocked ejecta



Very neutron-rich cold, tidal ejecta

Foucart *et al* (2016)

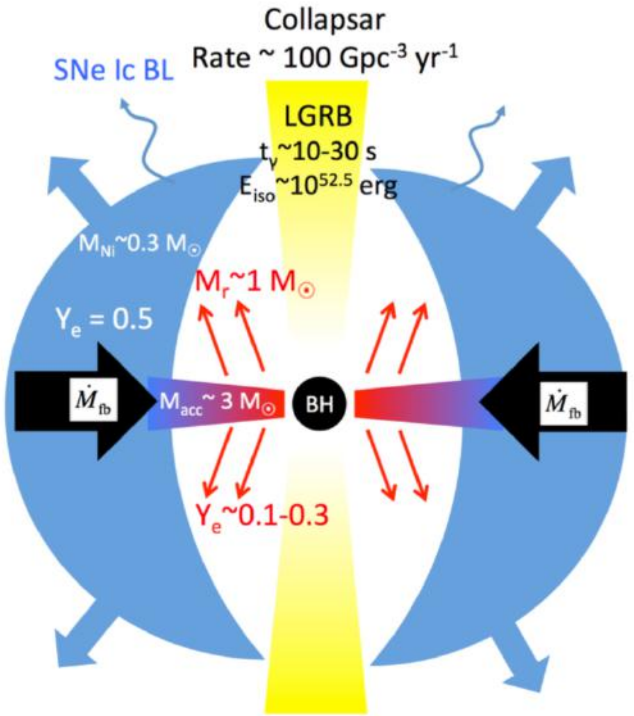
Accretion disk winds – exact driving mechanism and neutron richness varies



Owen and Blondin (2005)

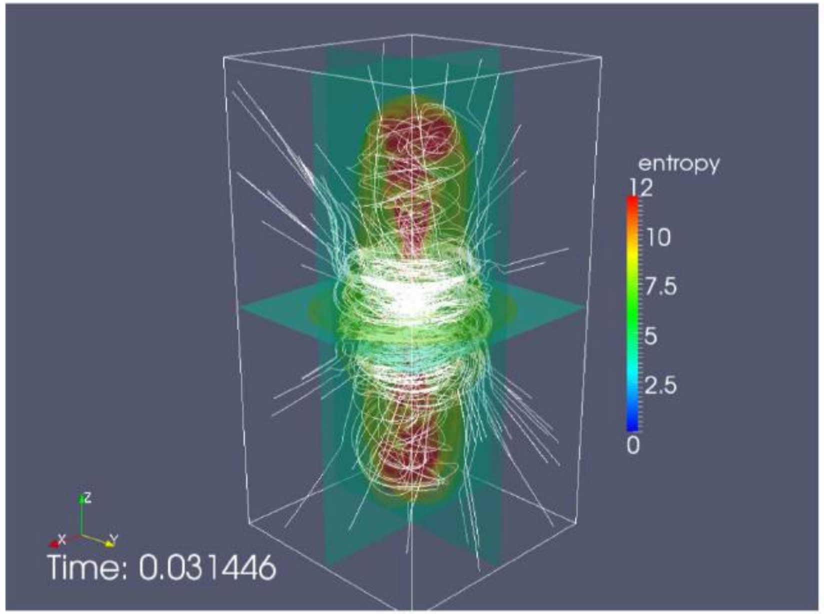
Possible sources of heavy *r*-process elements

Collapsar disk winds



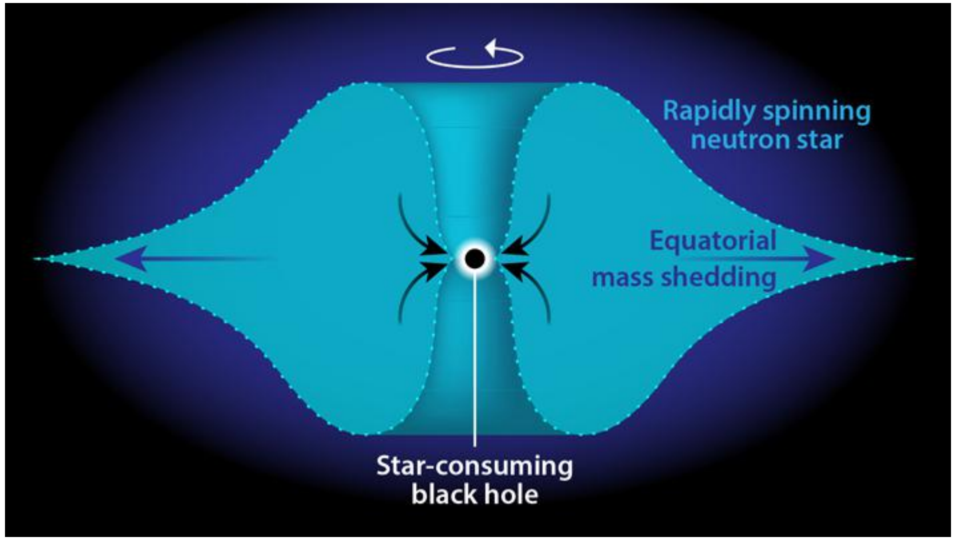
Siegel, Barnes, and Metzger (2018); also McLaughlin and Surman (2005), Miller *et al* (2019)

Magneto-rotationally driven (MHD) supernovae



Winteler *et al* (2012); also Mosta *et al* (2017)

Primordial black hole + neutron star

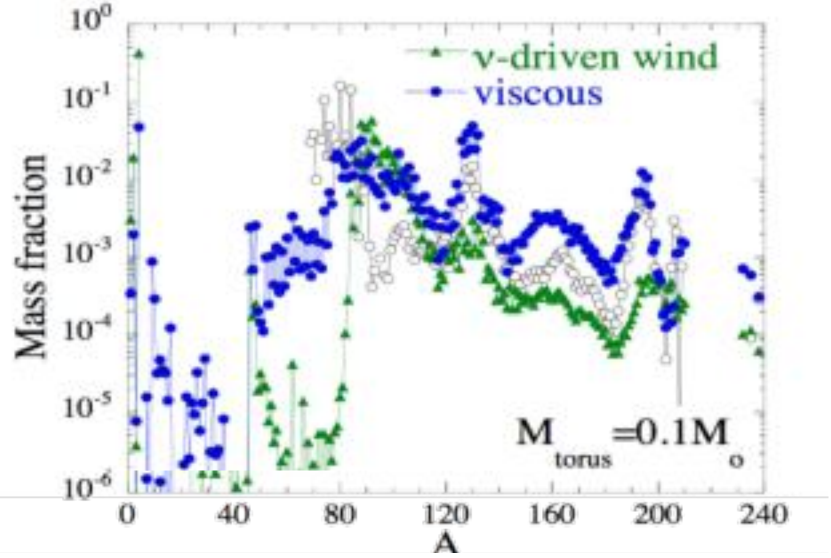


Credit: APS/Alan Stonebraker, via *Physics*

Fuller, Kusenko, and Takhistov (2017)

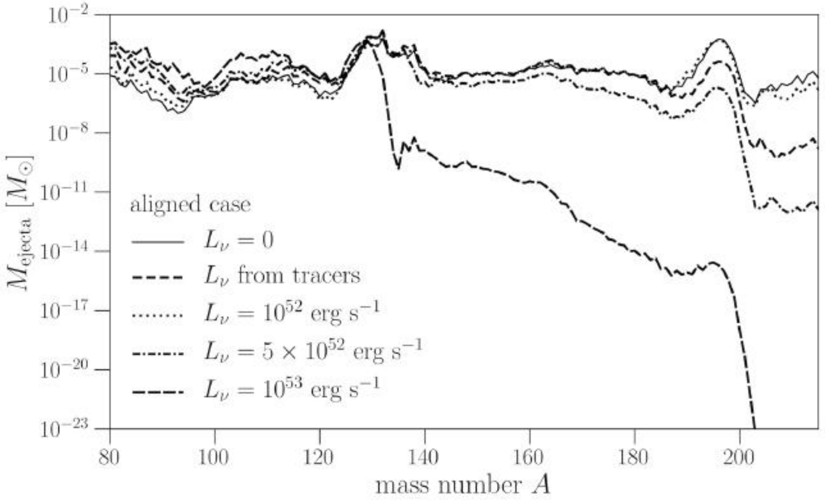
Example of astrophysical uncertainties in *r*-process sites: neutrino treatments

Accretion disk ejecta



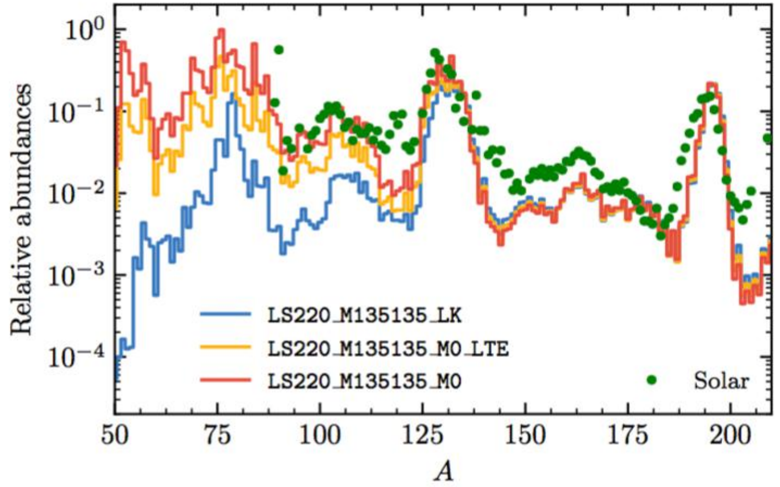
Just *et al* (2016)

MHD SNe

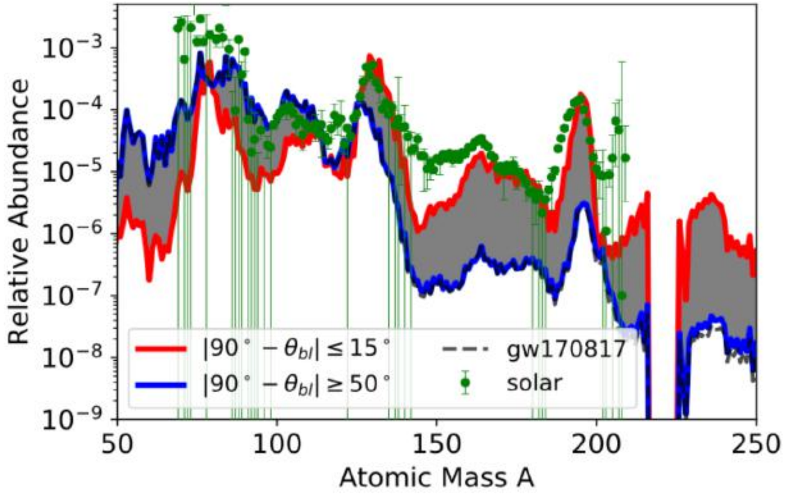


Halevi and Mosta (2018)

Merger dynamical ejecta

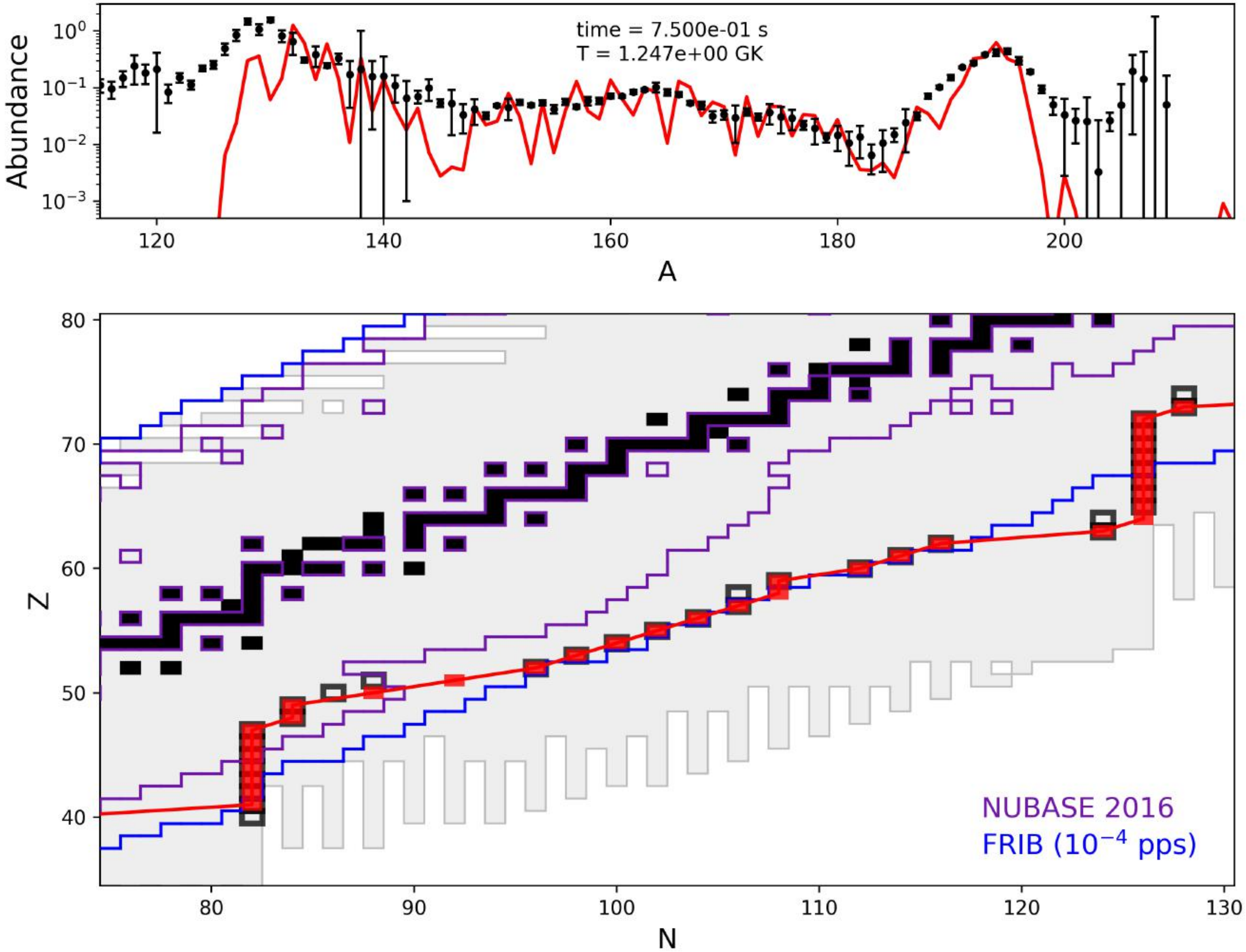


Radice *et al* (2019); see also Perego *et al* (2019)



Miller *et al* (2019)

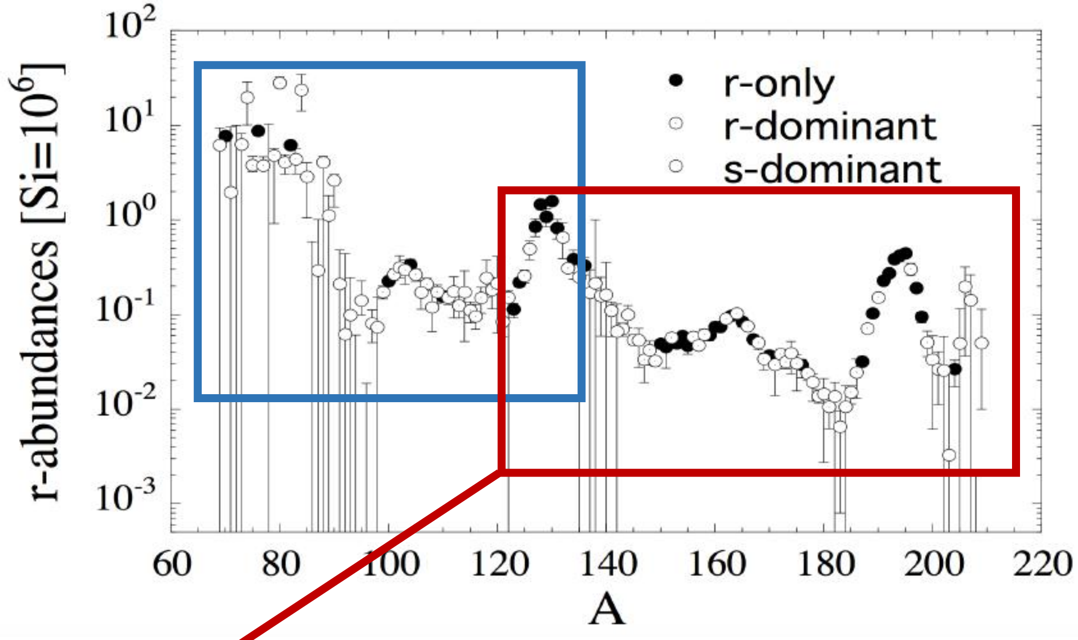
FRIB reach in key regions impacting the evolution of *r*-process abundances



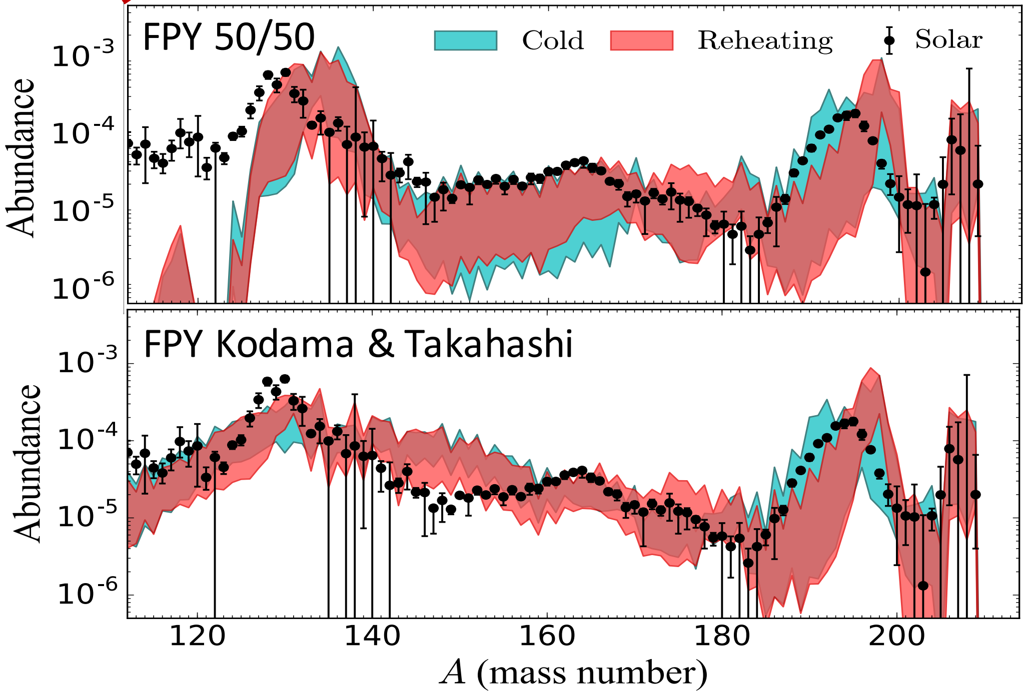
Movie by
N. Vassh

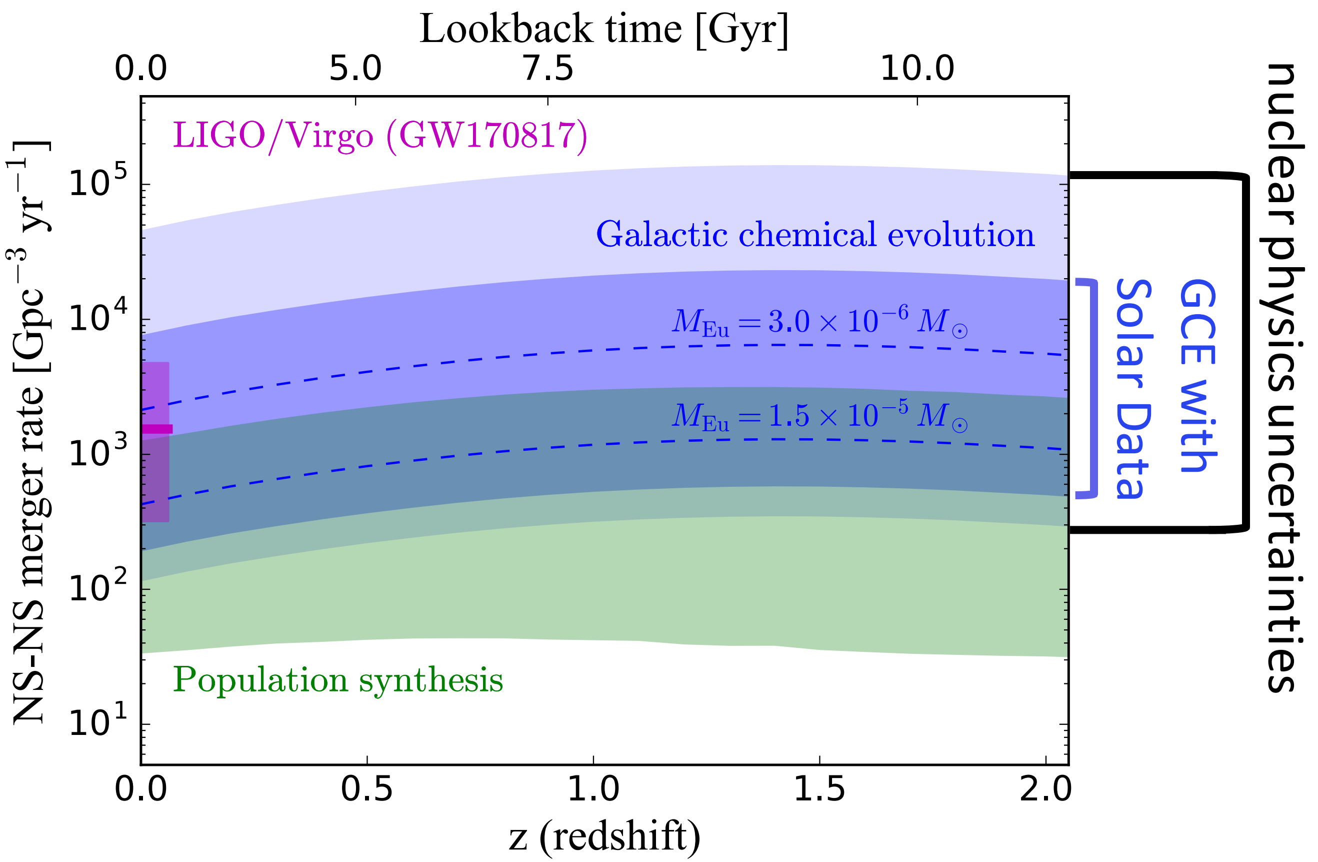
Connecting nuclear physics, lanthanide production, and *r*-process conditions

Uncertainties in GW170817 lanthanide production from nuclear physics



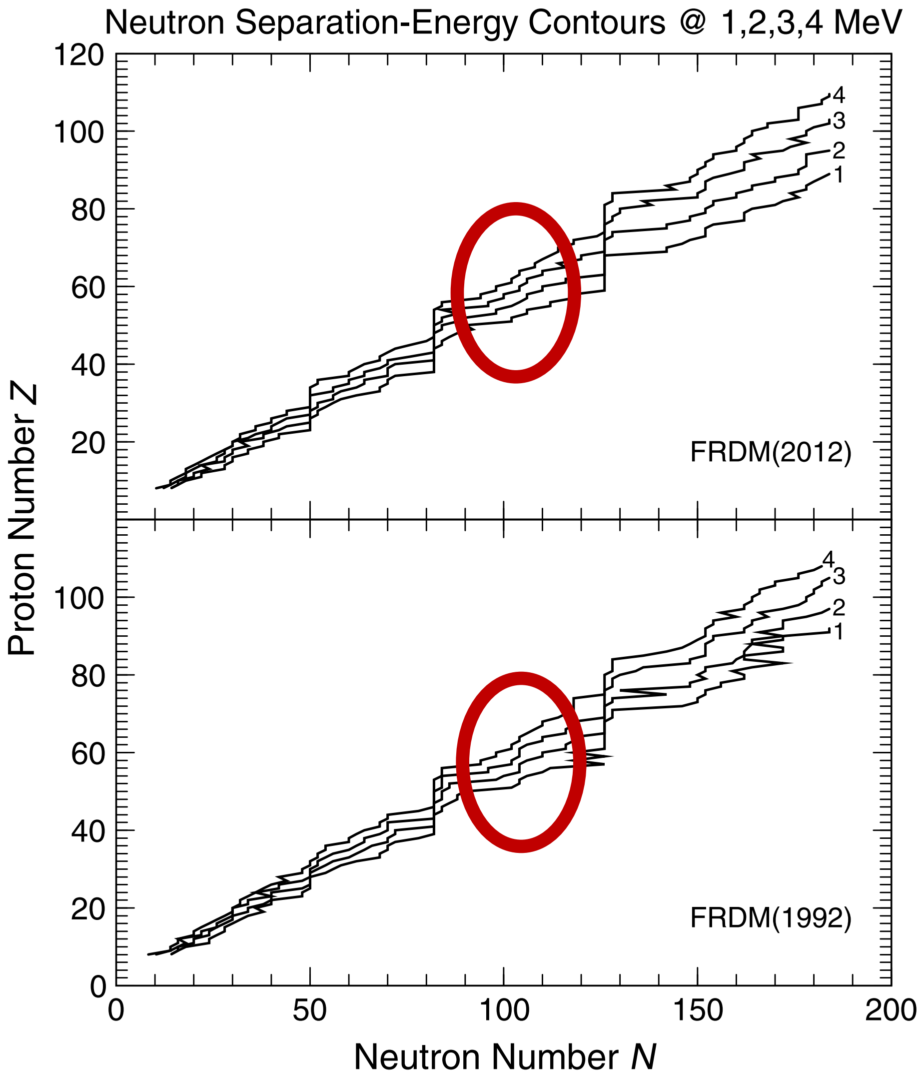
Bands from 10 mass models



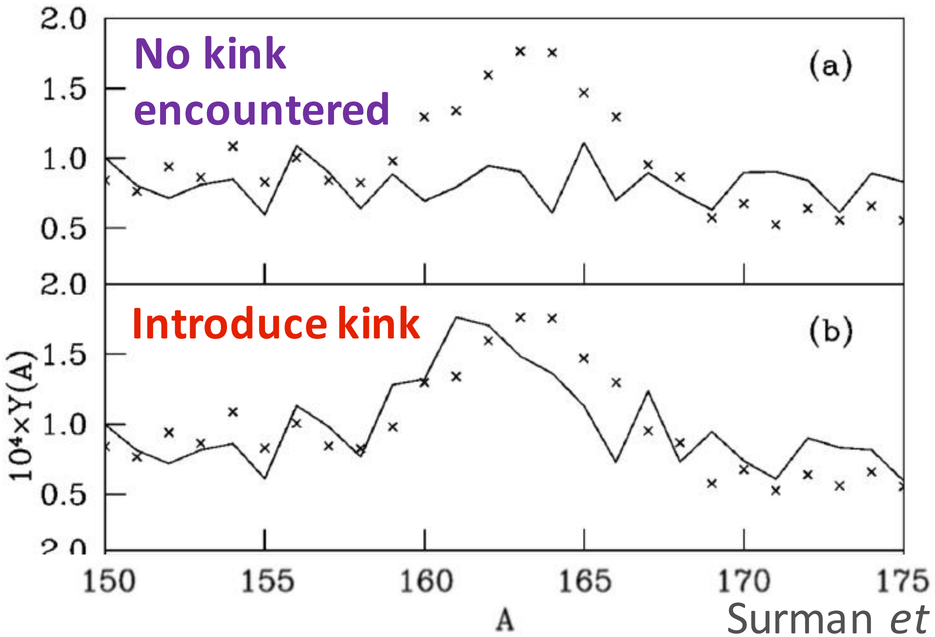


Côté, Fryer, Belczynski, Korobkin, Chruślińska, Vassh, Mumpower, Lippuner, Sprouse, Surman and Wollaeger (ApJ 855, 2, 2018)

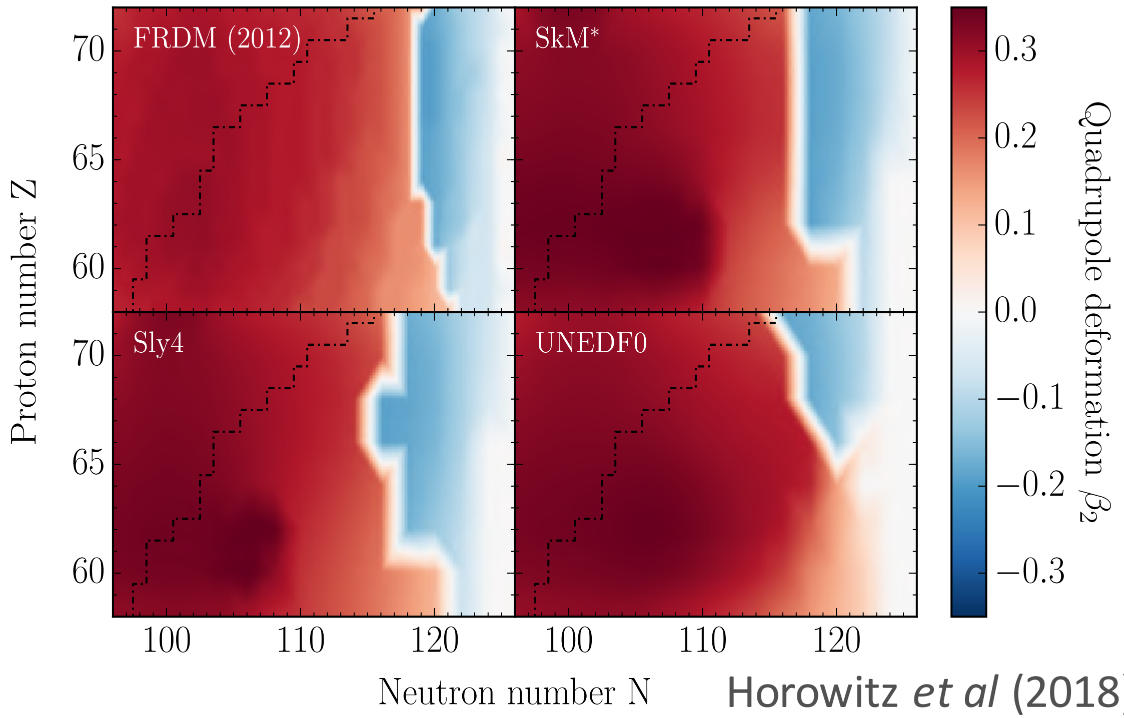
Predicted deformation in the rare-earths and peak formation



Möller *et al* (2012)



Surman *et al* (1997)



Horowitz *et al* (2018)

MCMC procedure

- Monte Carlo mass corrections

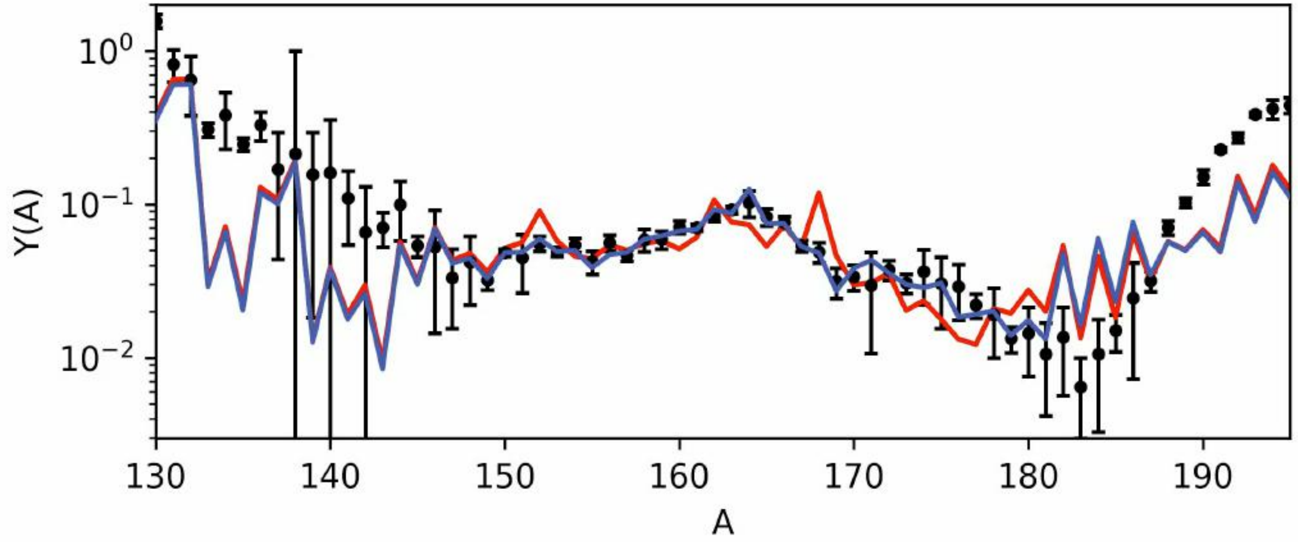
  $$M(Z,N) = M_{DZ}(Z,N) + a_N e^{-(Z-C)^2/2f}$$

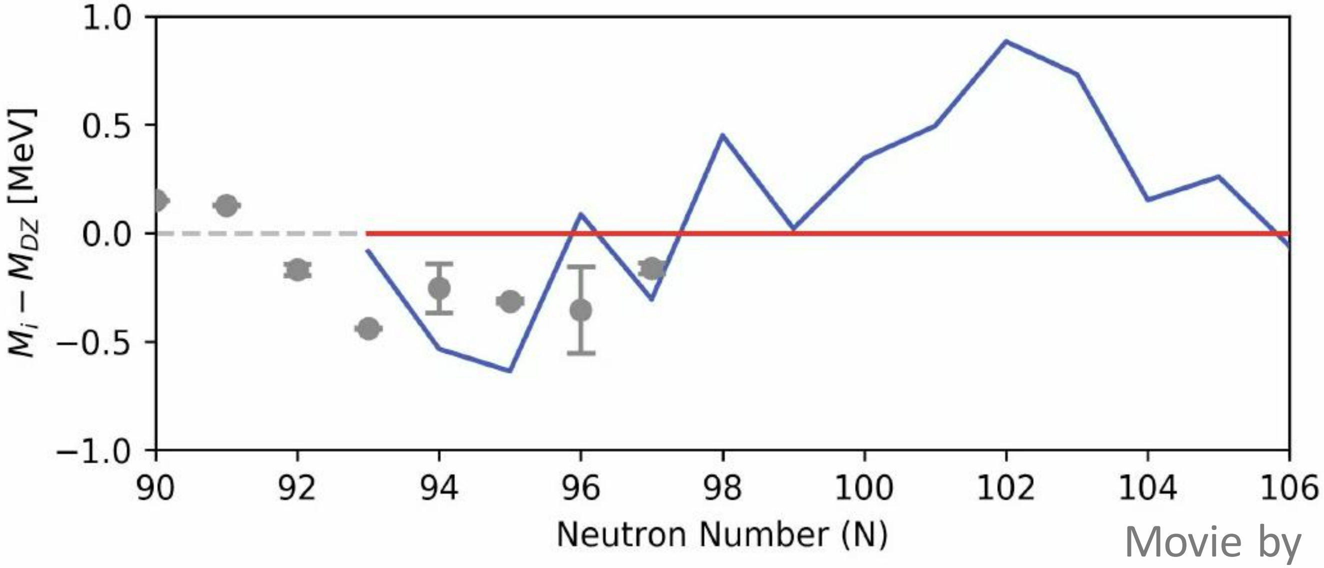
- Check: $\sigma^2_{\mathrm{rms}}(M_{\mathrm{AME12}}, M) \leq \sigma^2_{\mathrm{rms}}(M_{\mathrm{AME12}}, M_{DZ})$
- Check:

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

- 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

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



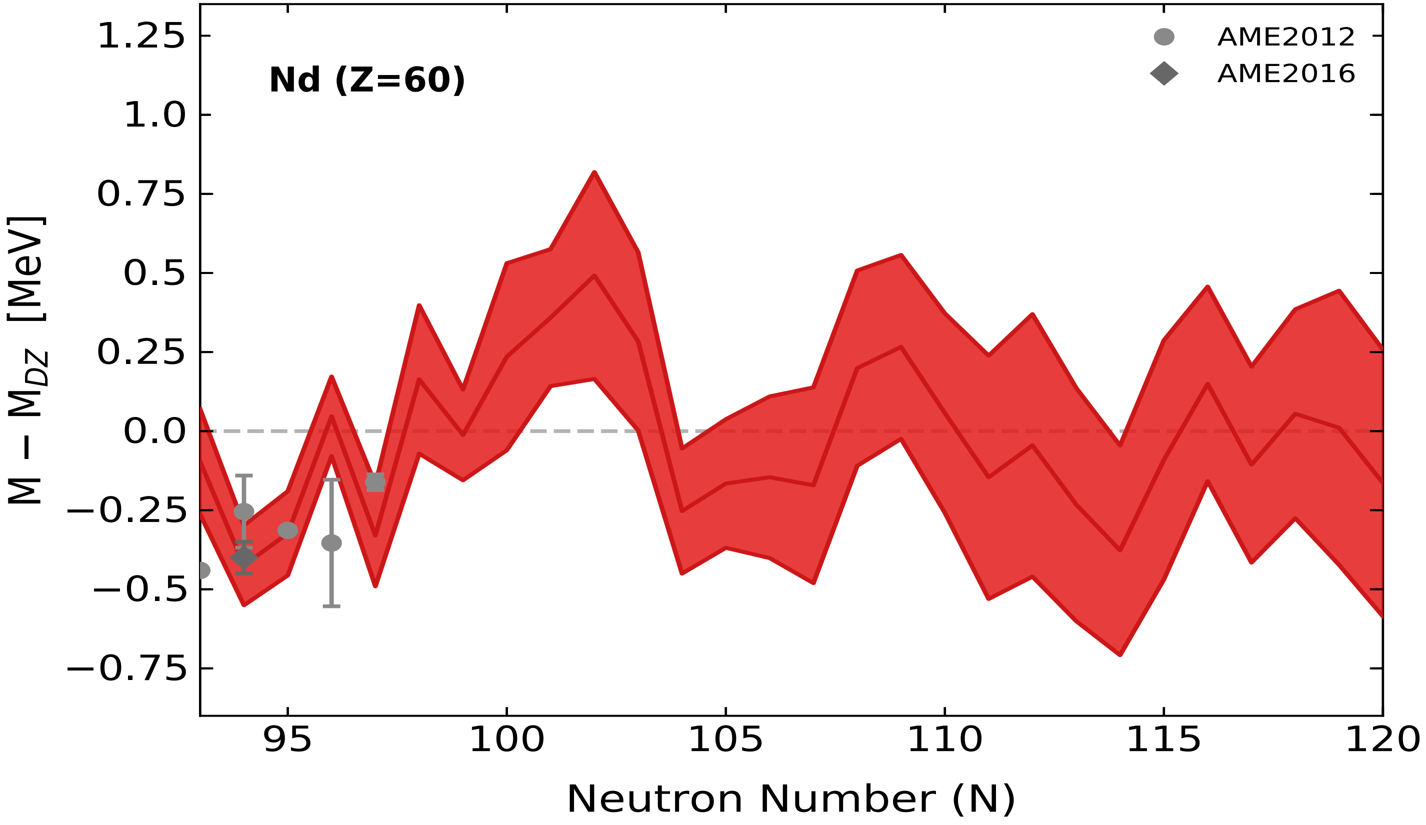


Movie by N. Vassh

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

Results

- Astrophysical trajectory: hot, low entropy outflow (as can be found in an NSM accretion disk) (s/k=30, τ=70 ms, Y_e=0.2)
- 50 parallel, independent MCMC runs; Average run χ^2~23



Argonne NATIONAL LABORATORY

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Orford, Vassh, *et al*
(Phys. Rev. Lett. 120, 262702, 2018));
Vassh *et al* (in prep., 2020)

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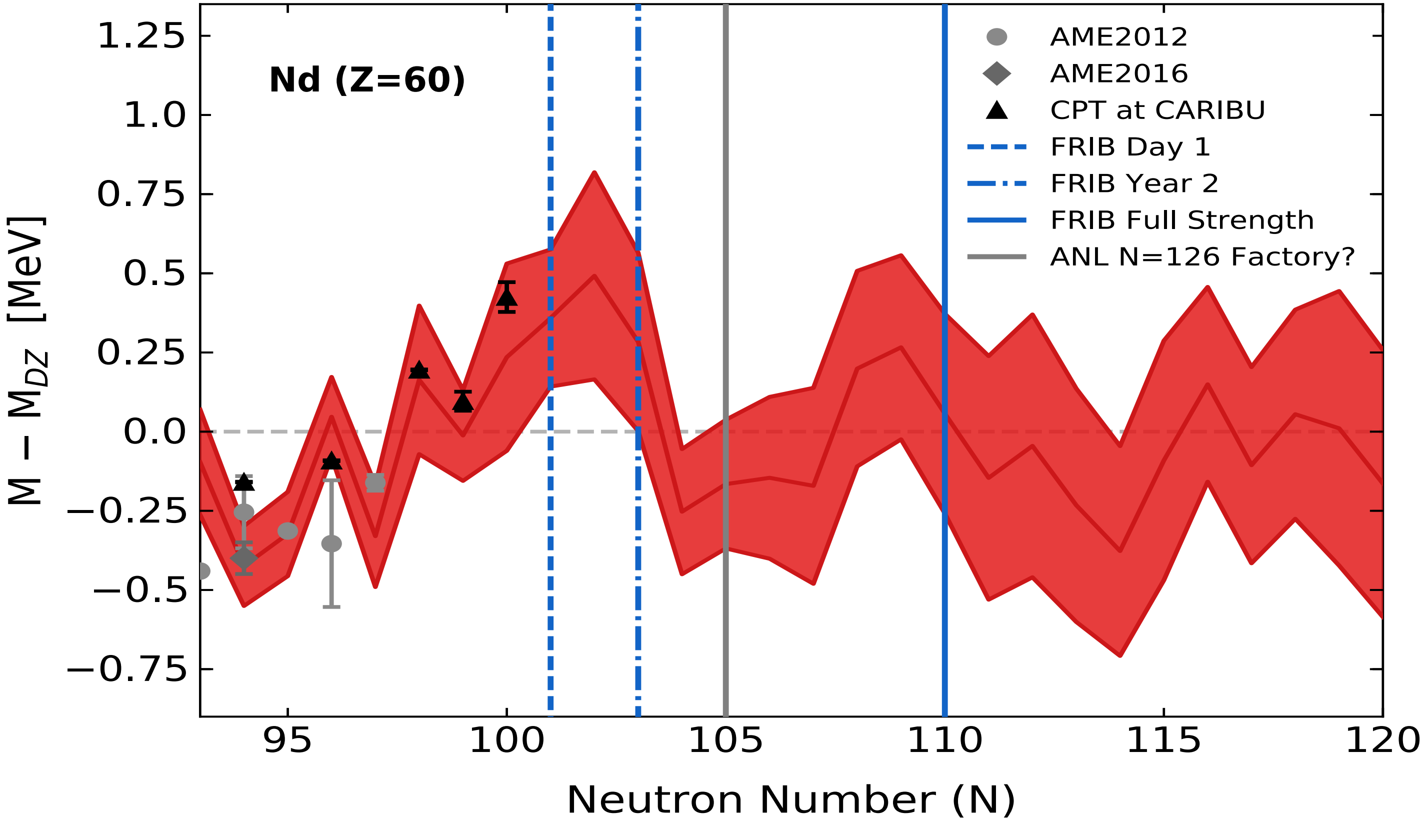

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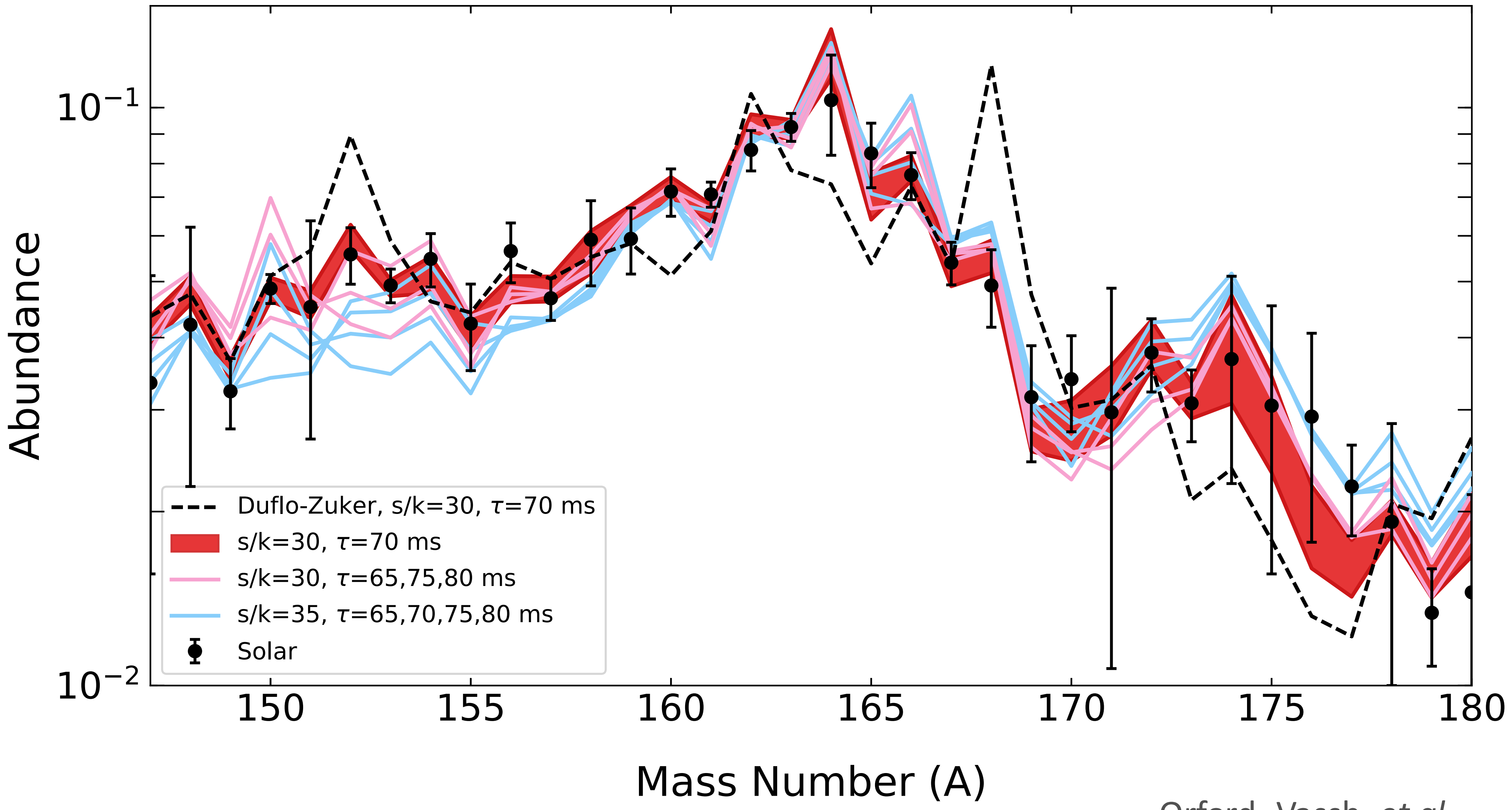
Orford, Vassh, *et al* (Phys. Rev. Lett. 120, 262702, 2018));
Vassh *et al* (in prep., 2020)

Peak formation in winds with *similar* astrophysical conditions

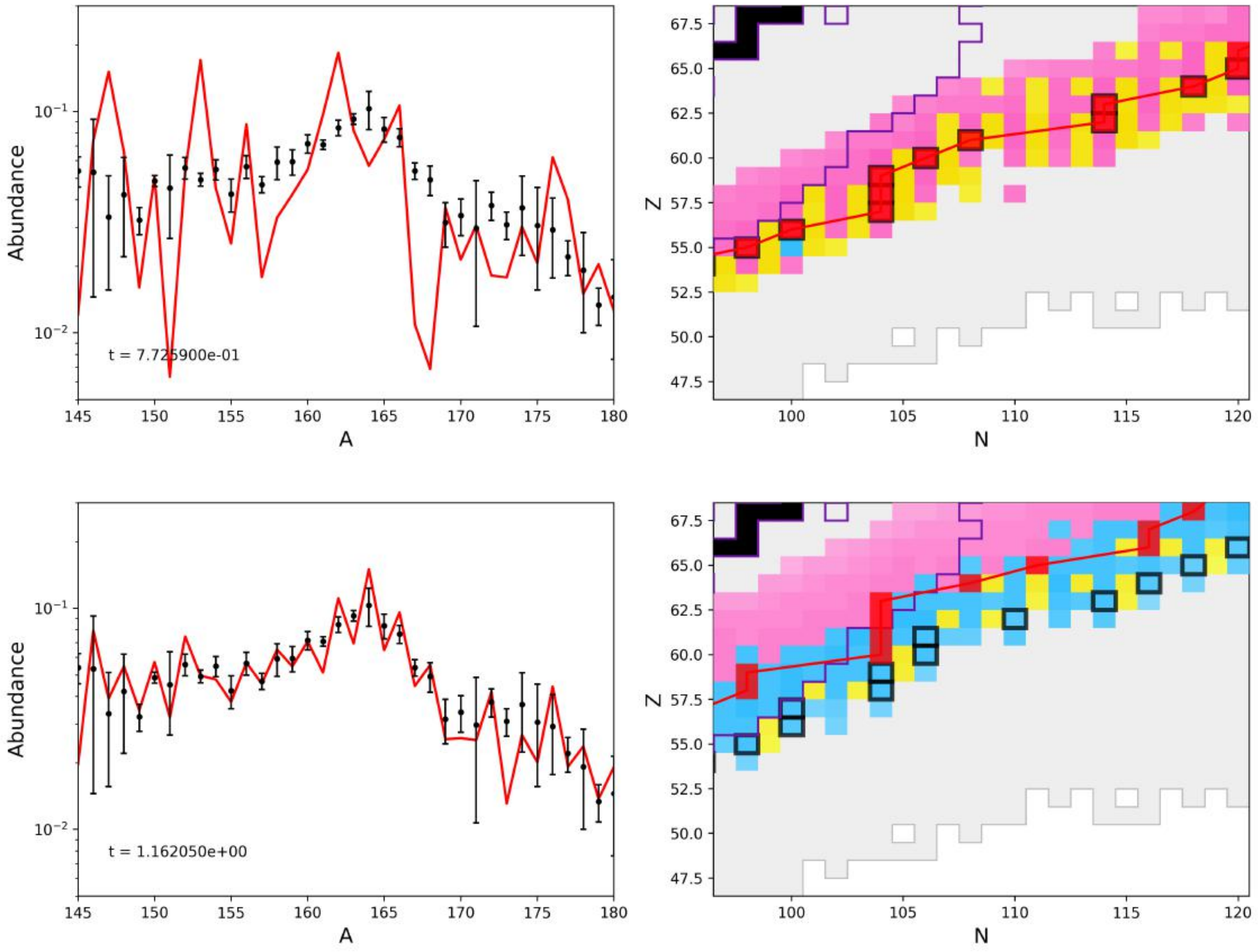


Orford, Vassh, *et al*
(Phys. Rev. Lett. 120, 262702, 2018))

Peak formation example: hot dynamics

Early time

Later time



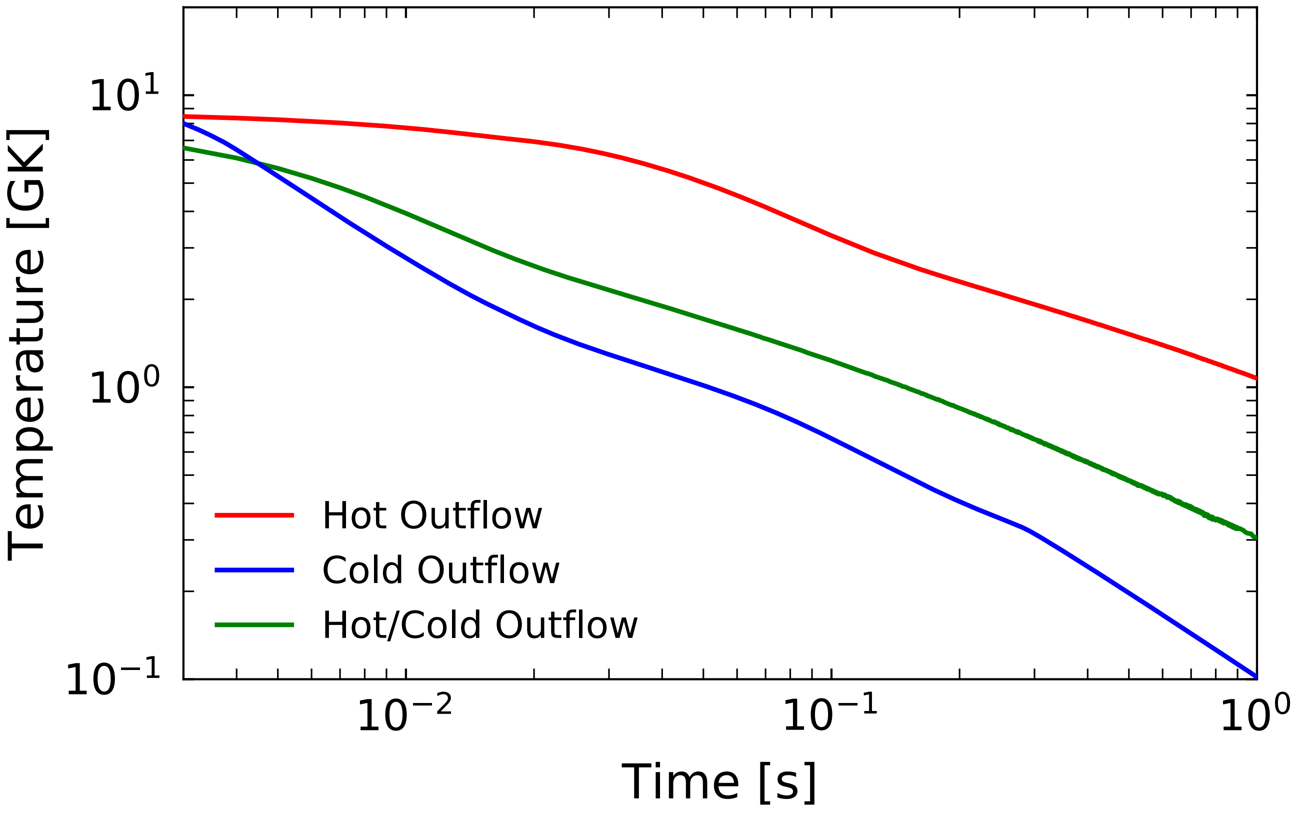
neutron capture photodissociation β-decay

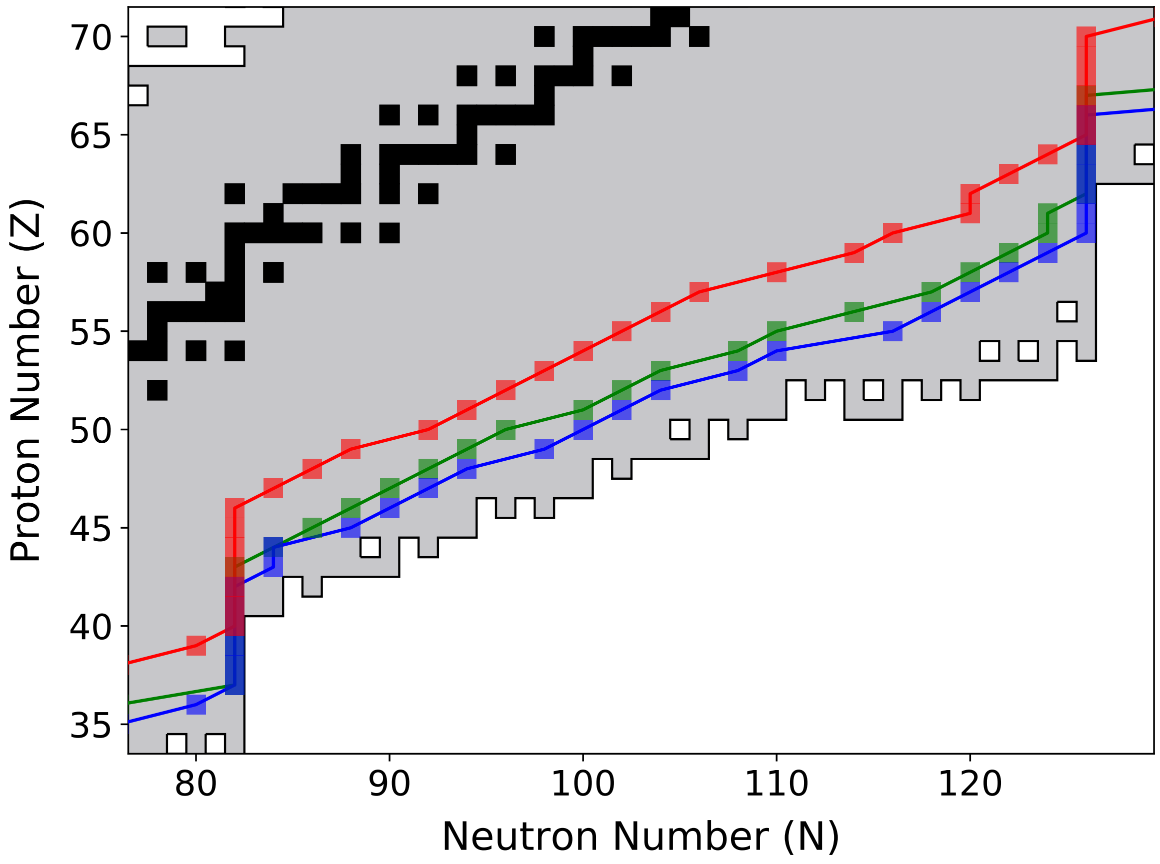
(n,γ) equilibrium (dependent on S_n) most abundant nuclei

(colored by the dominant reaction/decay channel at the time)

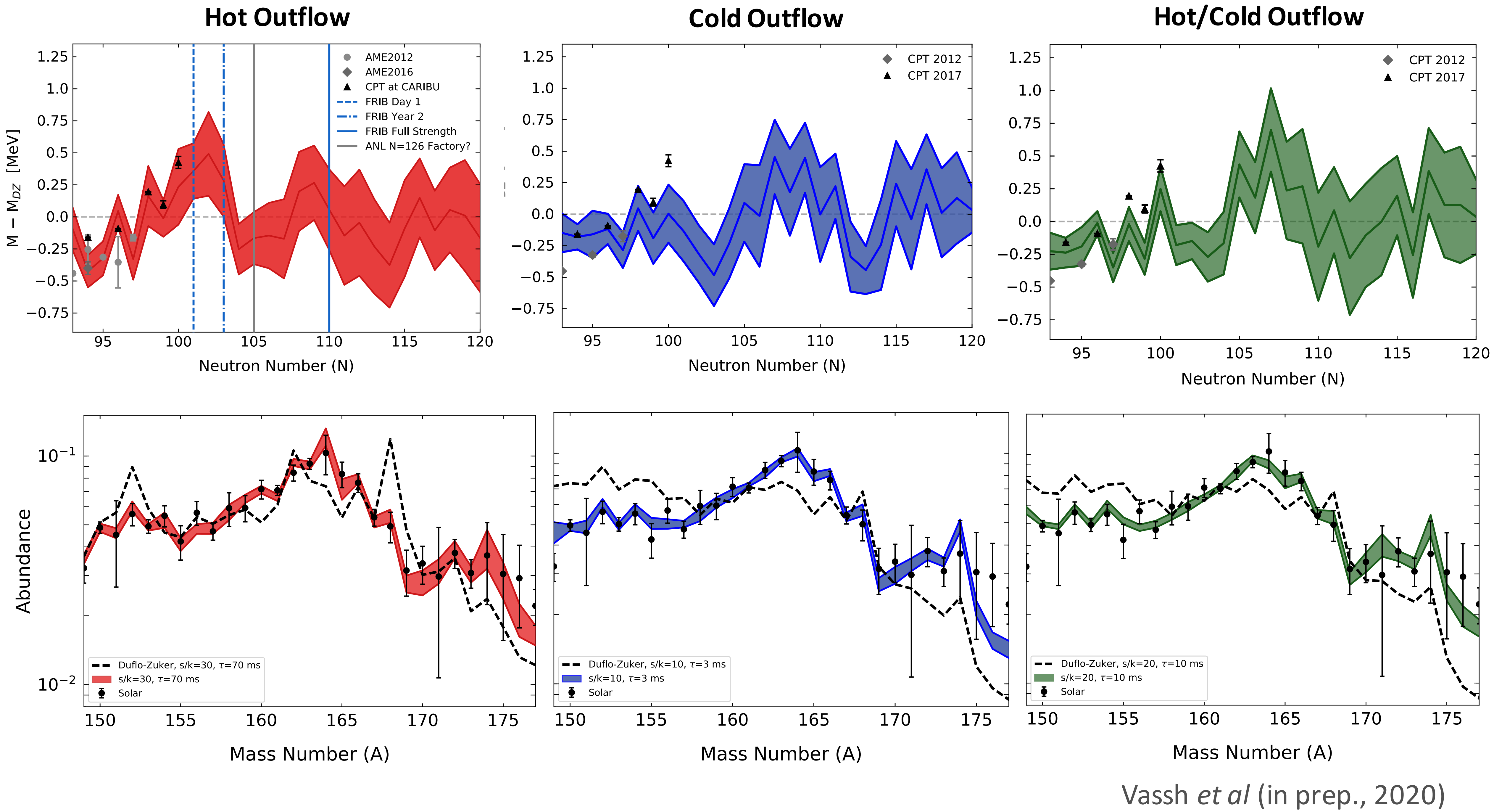
Vassh *et al* (in preparation)

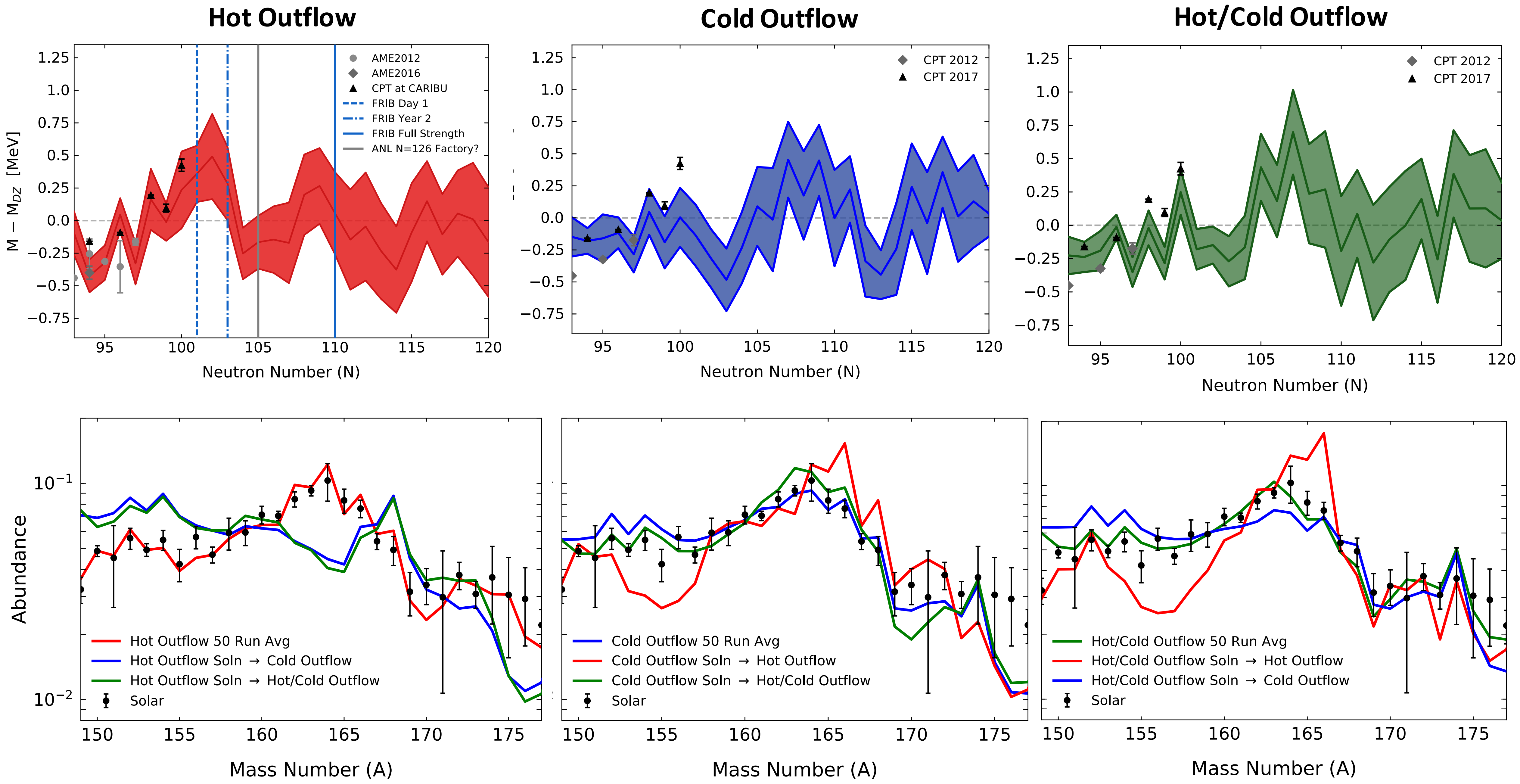
Peak formation in outflows with *distinct* astrophysical conditions





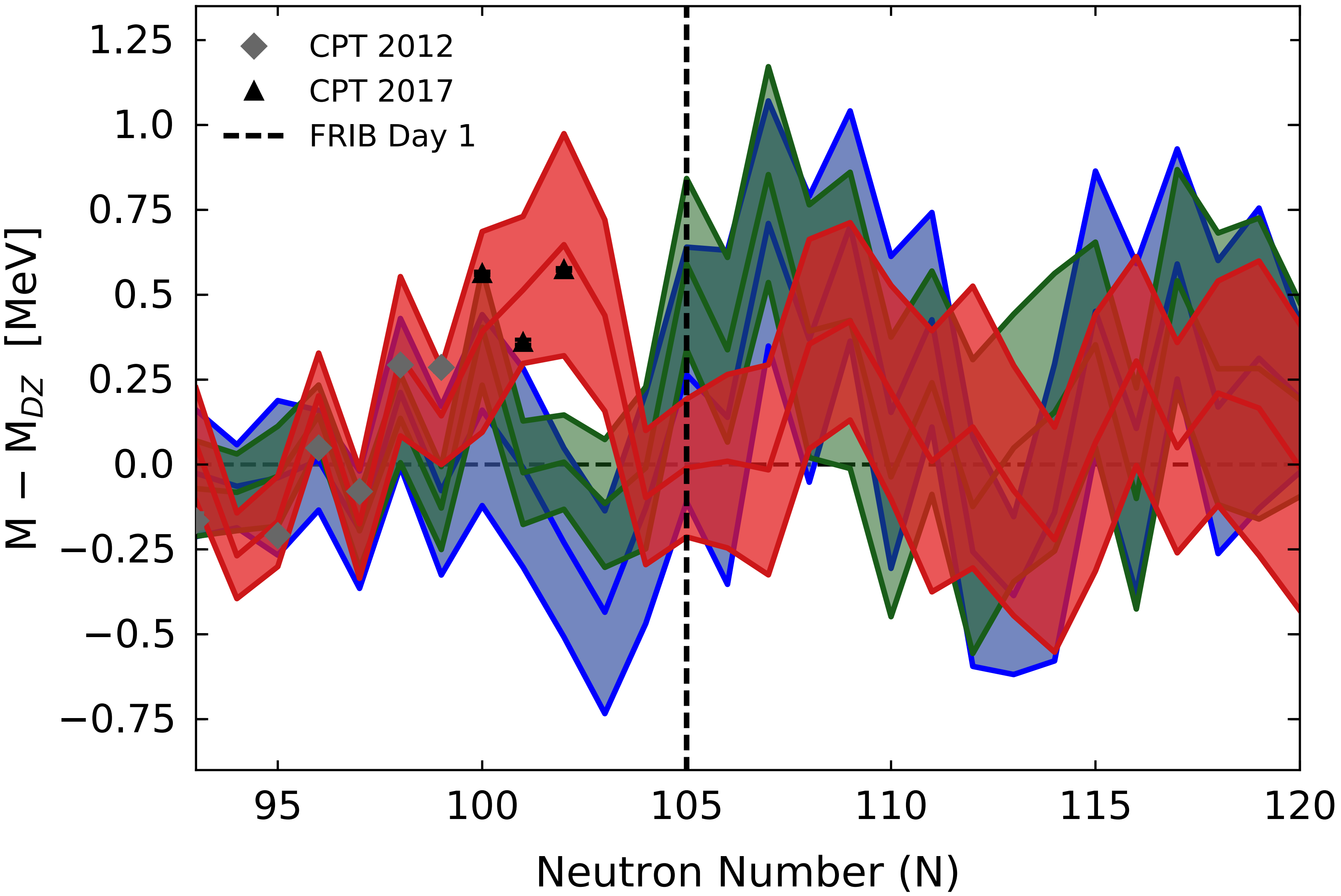
Vassh *et al* (in prep., 2020)


Hot Outflow
Cold Outflow
Hot/Cold Outflow
AME2012
AME2016
CPT at CARIBU
FRIB Day 1
FRIB Year 2
FRIB Full Strength
ANL N=126 Factory?
CPT 2012
CPT 2017
M − M_DZ [MeV]
Neutron Number (N)
Abundance
Mass Number (A)
Duflo-Zuker, s/k=30, τ=70 ms
s/k=30, τ=70 ms
Solar
Duflo-Zuker, s/k=10, τ=3 ms
s/k=10, τ=3 ms
Duflo-Zuker, s/k=20, τ=10 ms
s/k=20, τ=10 ms
Vassh et al (in prep., 2020)



Vassh *et al* (in prep., 2020)

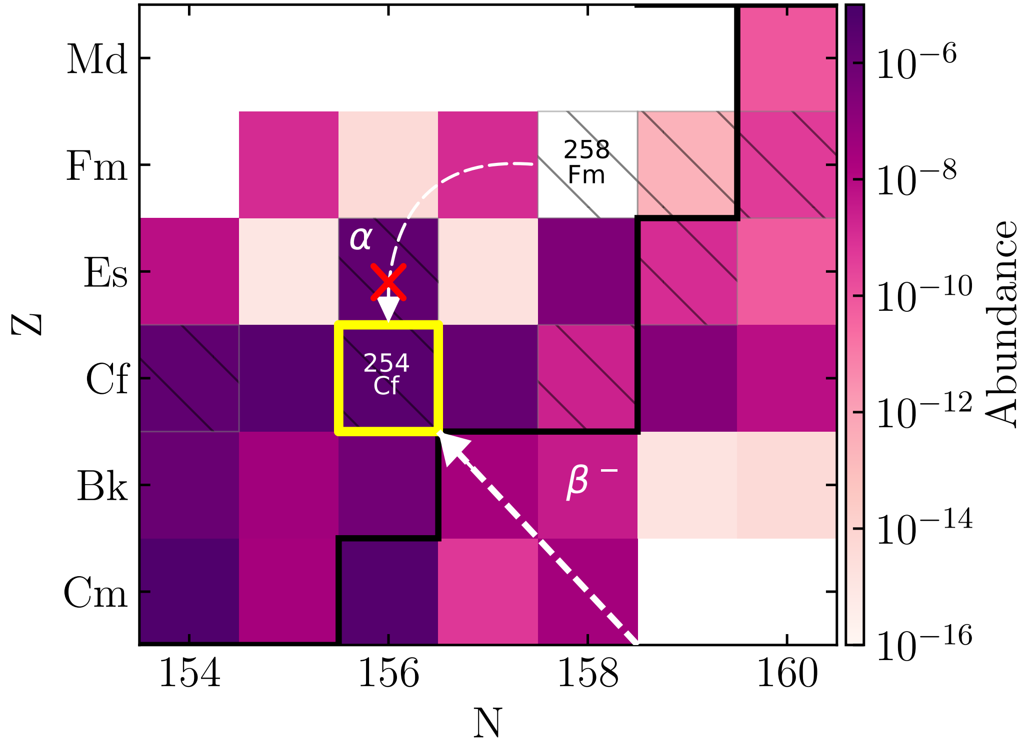
Comparing to the most neutron-rich measurements: Samarium

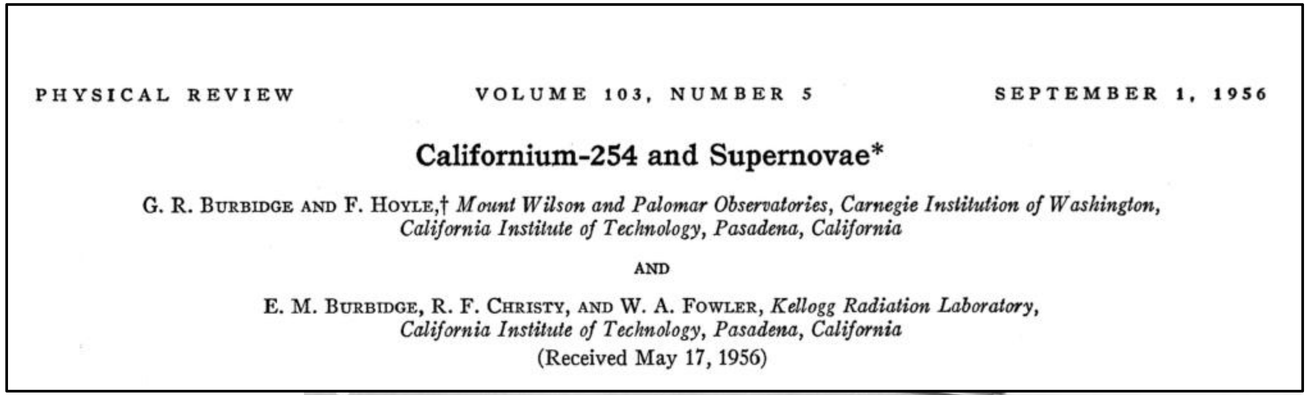


Vassh *et al* (in prep., 2020)

What are the heaviest nuclei reached in an astrophysical scenario?
Possible signatures of actinide production

Actinides in astrophysical environments?





PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

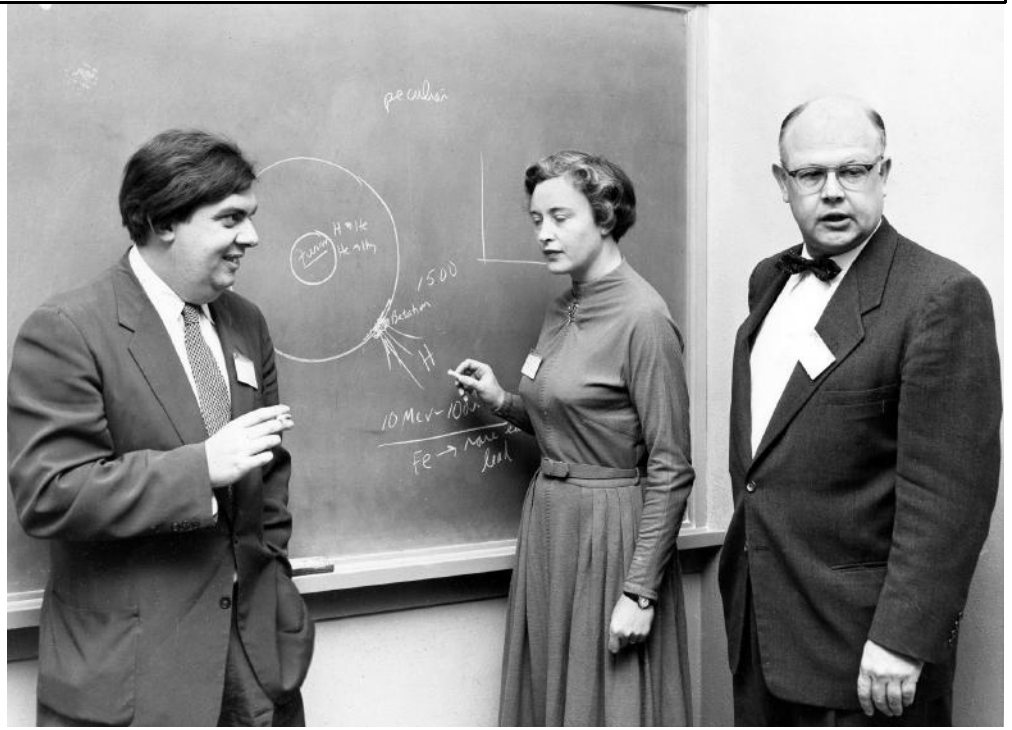
Californium-254 and Supernovae*

G. R. BURBIDGE AND F. HOYLE,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

E. M. BURBIDGE, R. F. CHRISTY, AND W. A. FOWLER, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

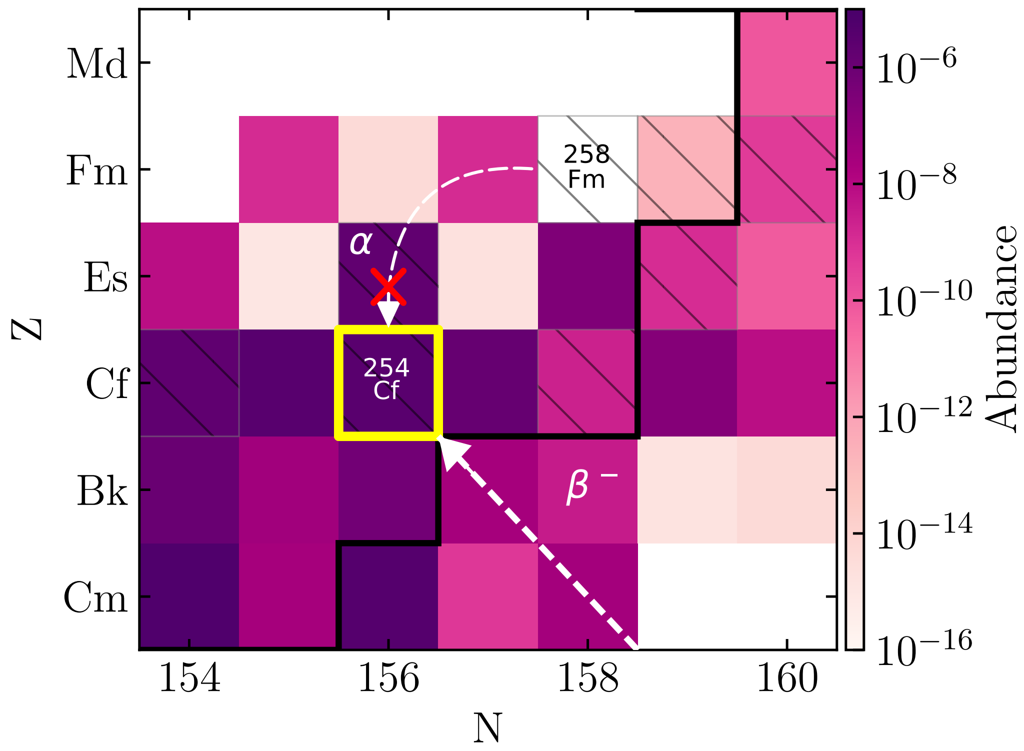


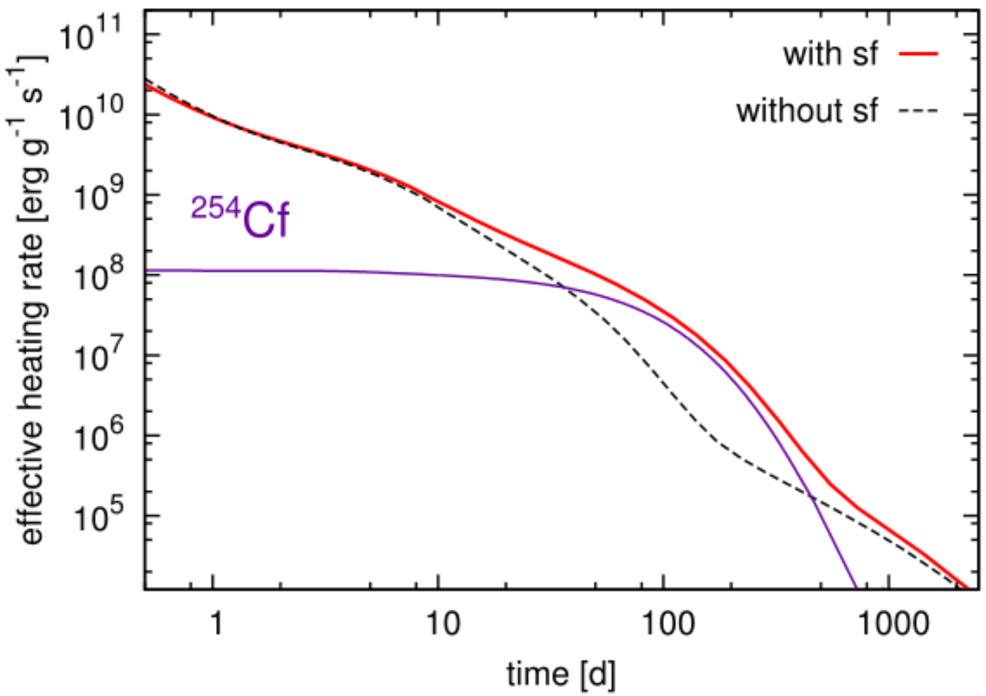
W. W. Girdner/Caltech Archives

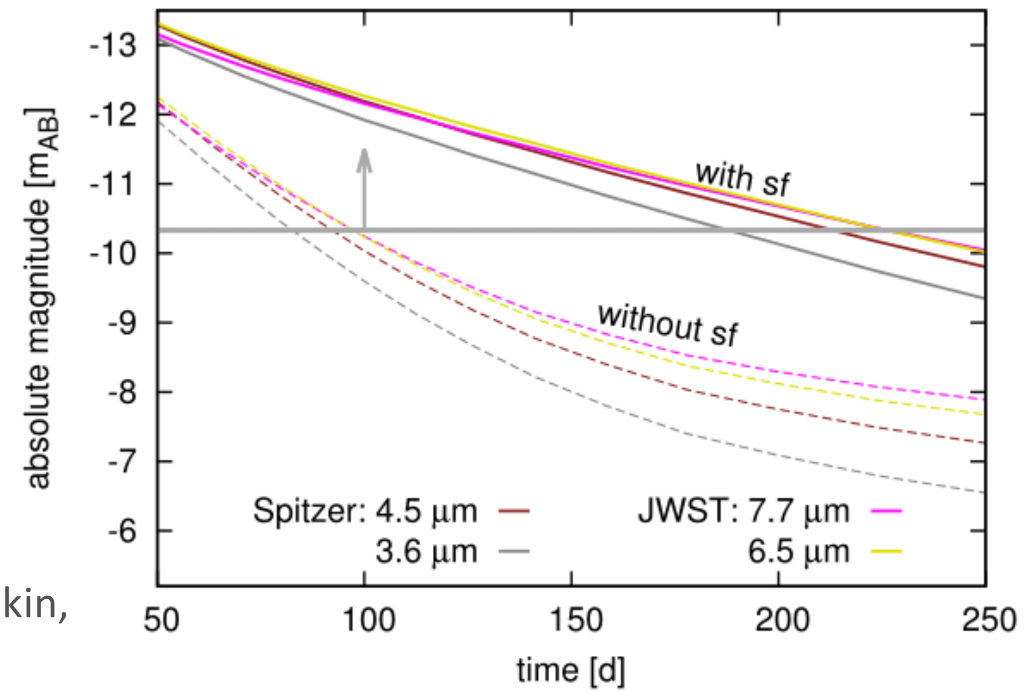
Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes (ApJL 863, L23, 2018)

*July 8 JINA online event:
"A Celebration of Margaret Burbidge"

Actinides in astrophysical environments?





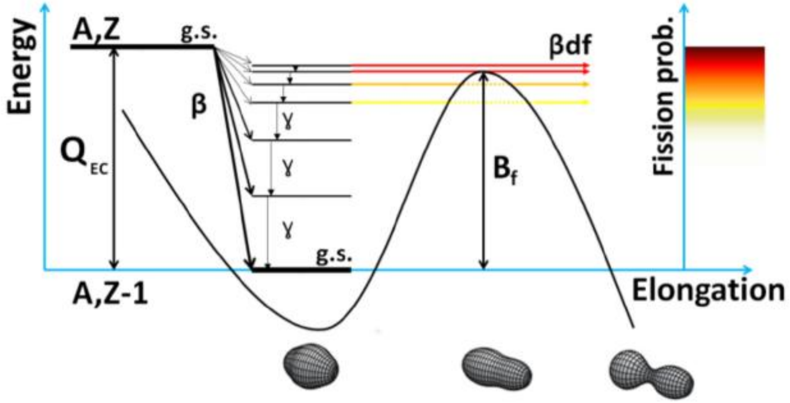


The spontaneous fission of ^{254}Cf can be a primary contributor to the nuclear heating affecting NSM light curves at late epochs

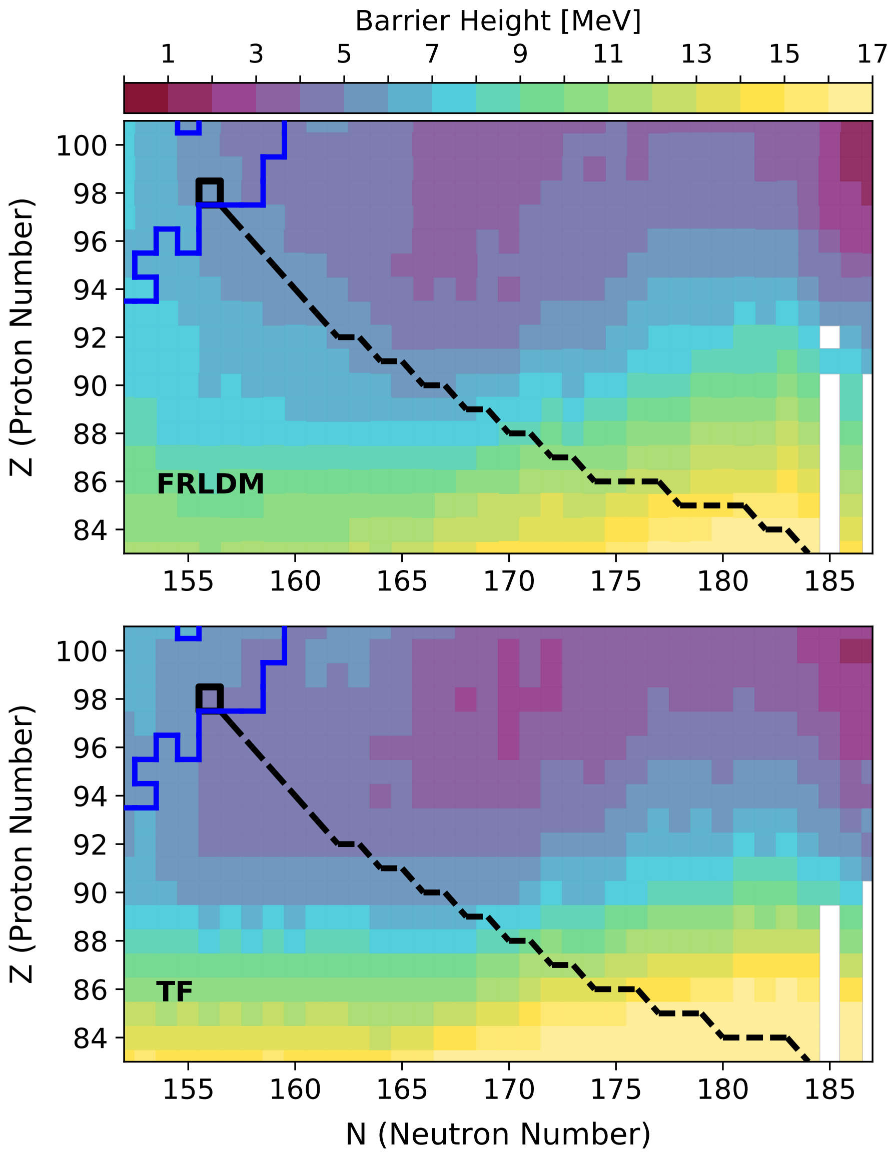
This species could make the difference between detection and no detection of NSMs for the James Webb Space Telescope

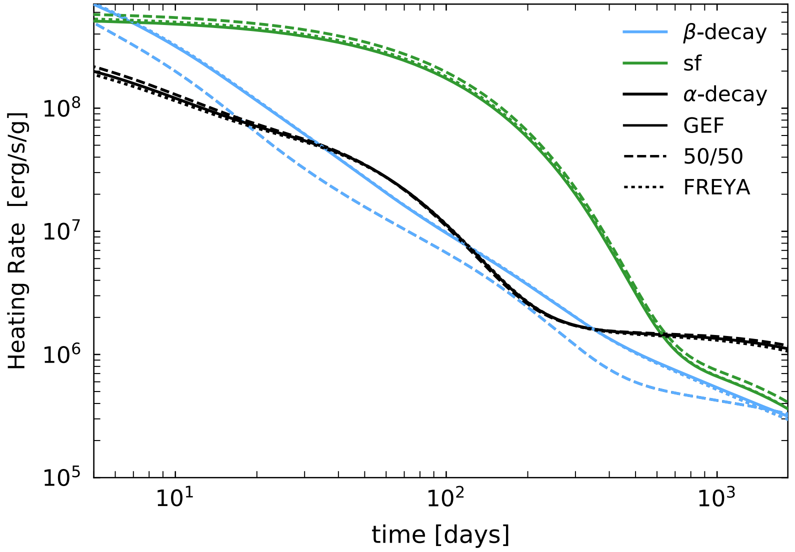
Zhu, Wollaeger, Vassh, Surman, Sprouse, Mumpower, Möller, McLaughlin, Korobkin, Kawano, Jaffke, Holmbeck, Fryer, Even, Couture, Barnes (ApJL 863, L23, 2018)

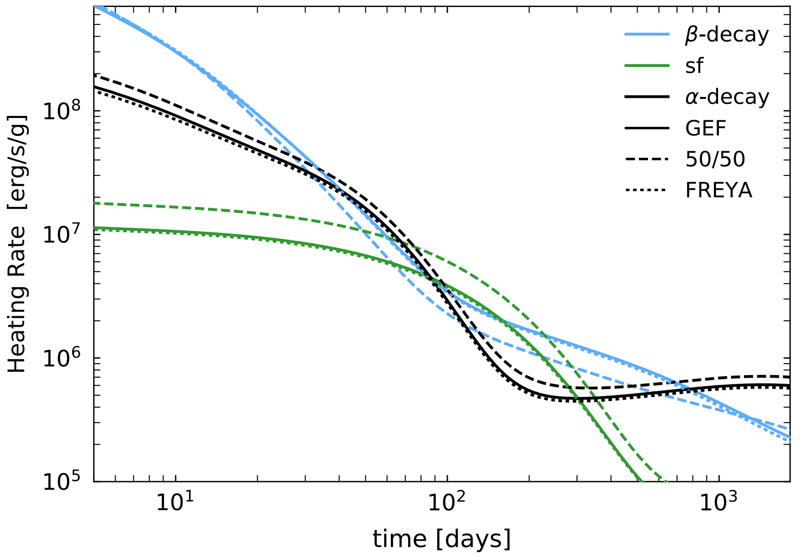
When is ^{254}Cf strongly populated?
Heavy element fission barriers in the *r* process



Andreyev, Nishio, and Schmidt (2018)



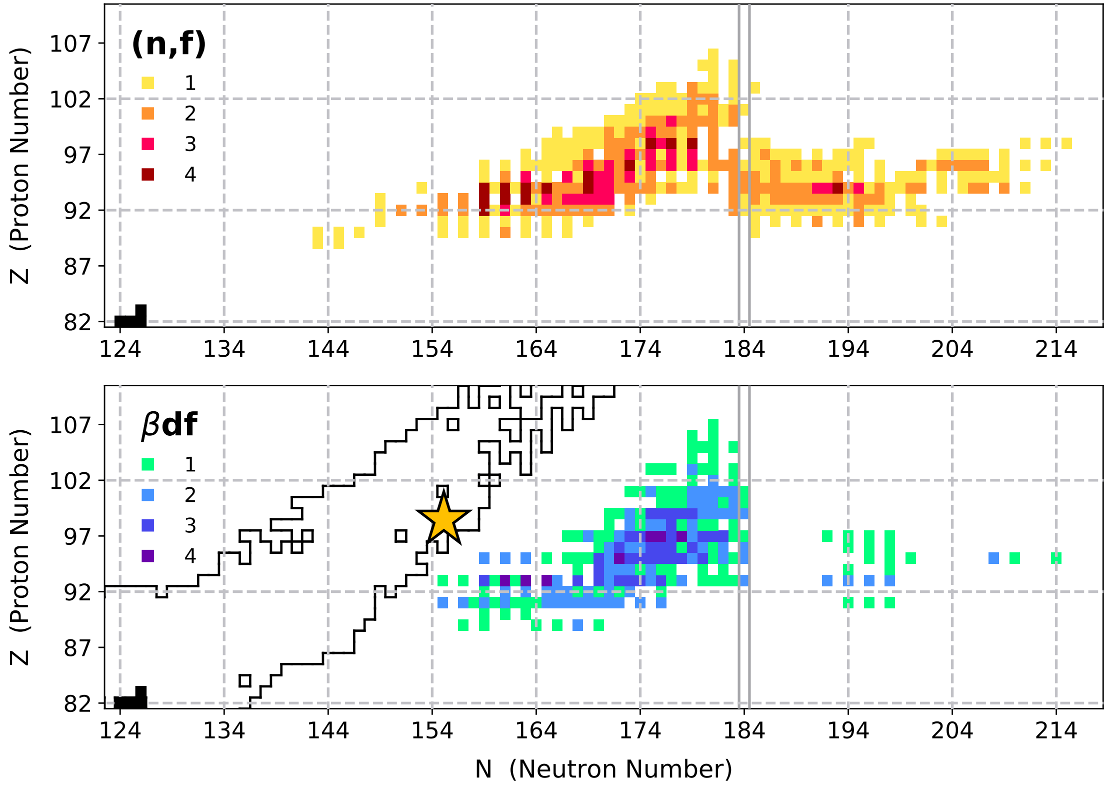




Vassh *et al* (J. Phys. G, 46, 065202, 2019, arXiv:1810.08133)

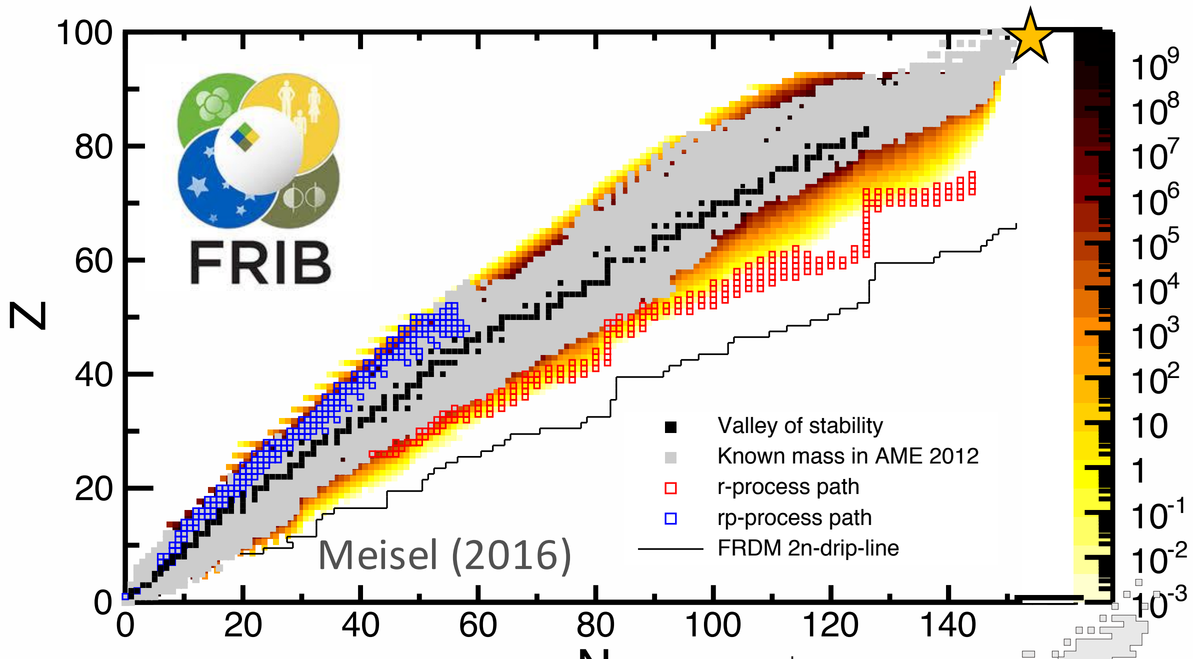
Will future rare-isotope beams reach key fissioning *r*-process nuclei?

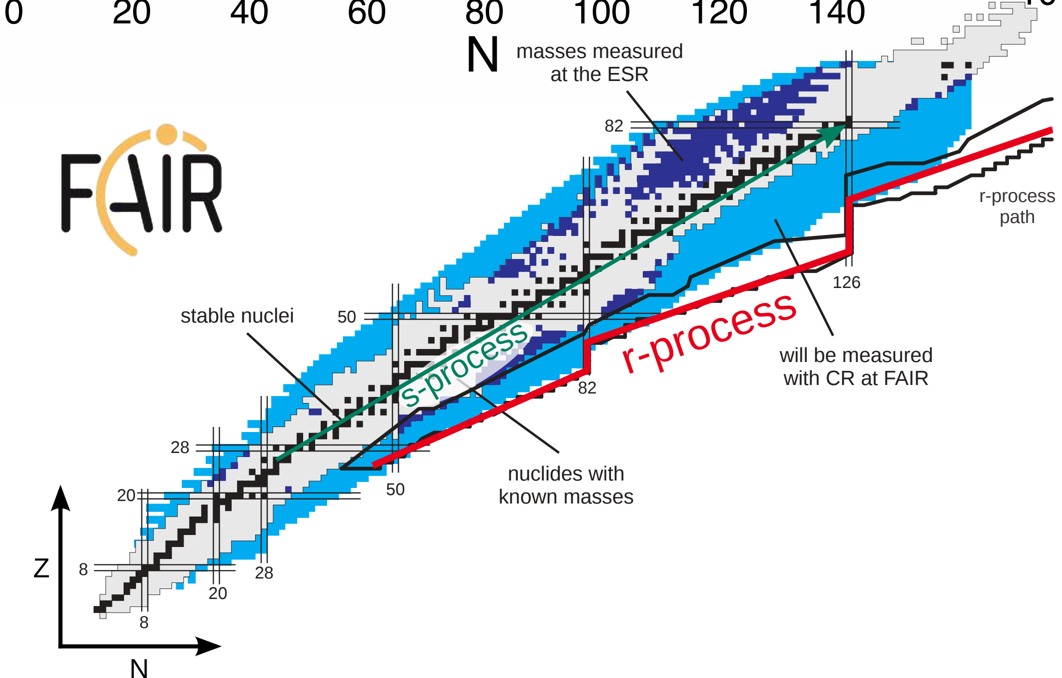
Nuclei with high fission flow when average over 30 dynamical ejecta trajectories from a NSM simulation given four mass/fission barrier models



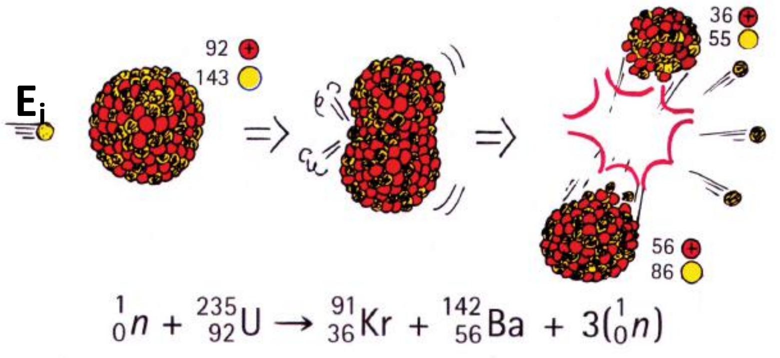
Vassh *et al* (J. Phys. G, 2019)

★ denotes location of ^{254}Cf

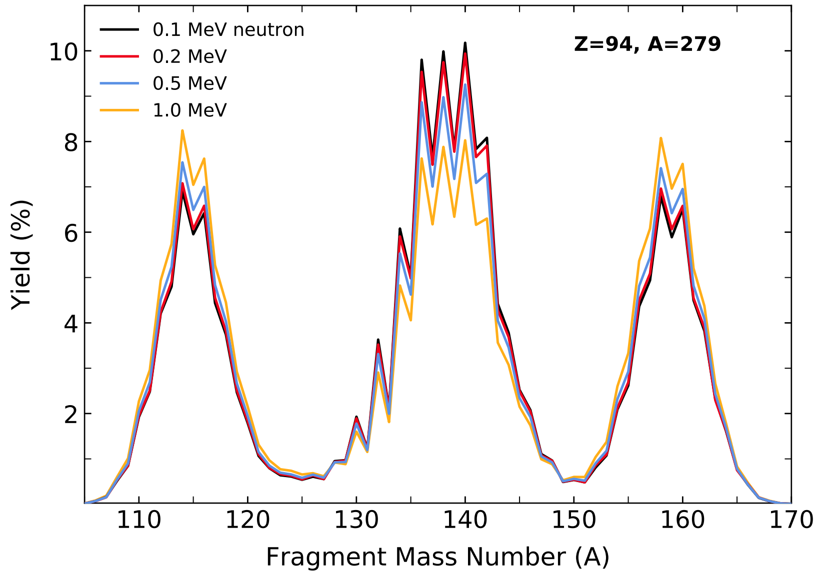


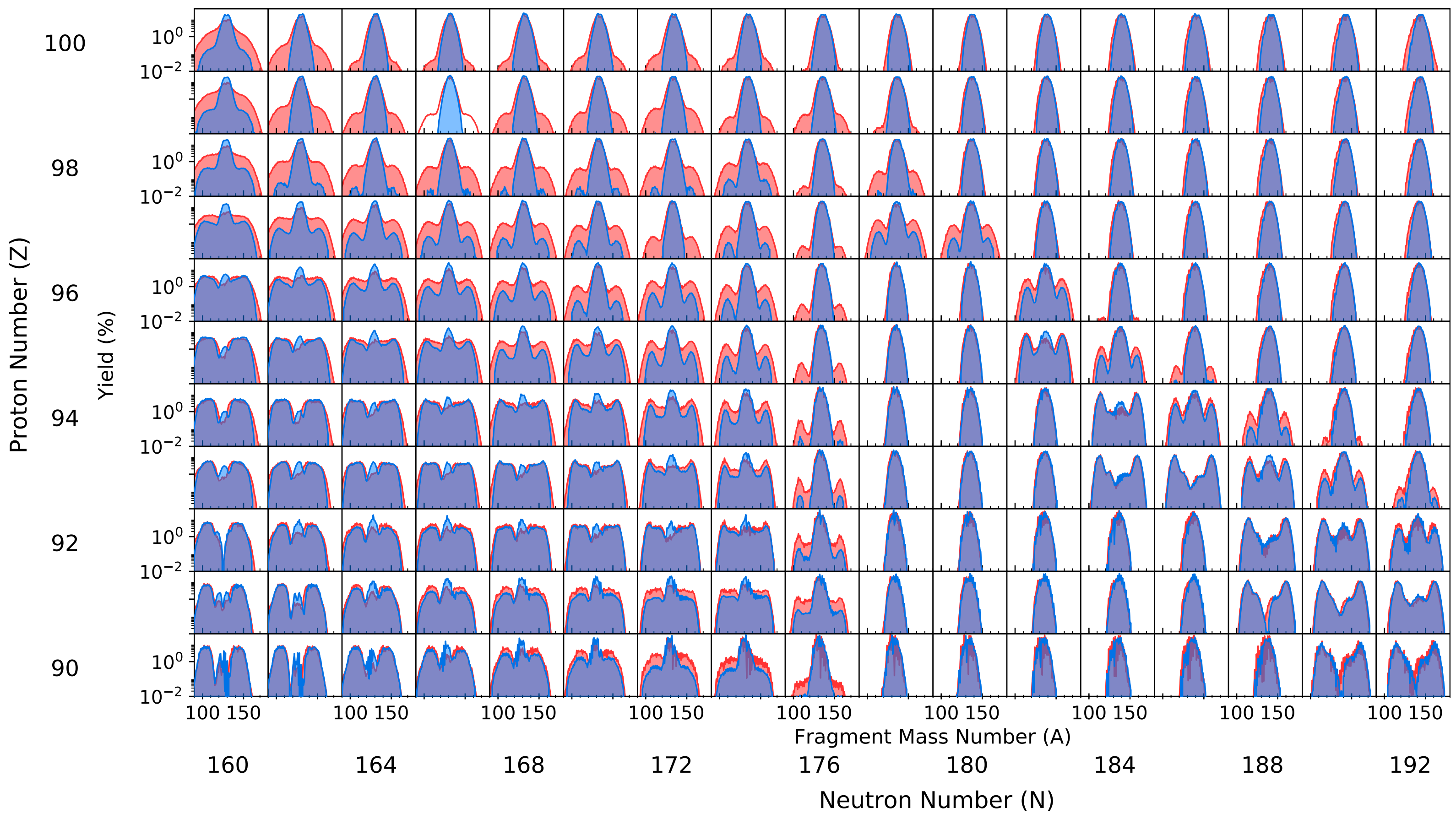


Excitation energy dependence:
distinct fission yields for β-delayed, neutron-induced and spontaneous fission



(n,f) yield dependent on E_i but temperature range of *r*-process sees yields at 0.1 MeV (~1 GK) sufficient

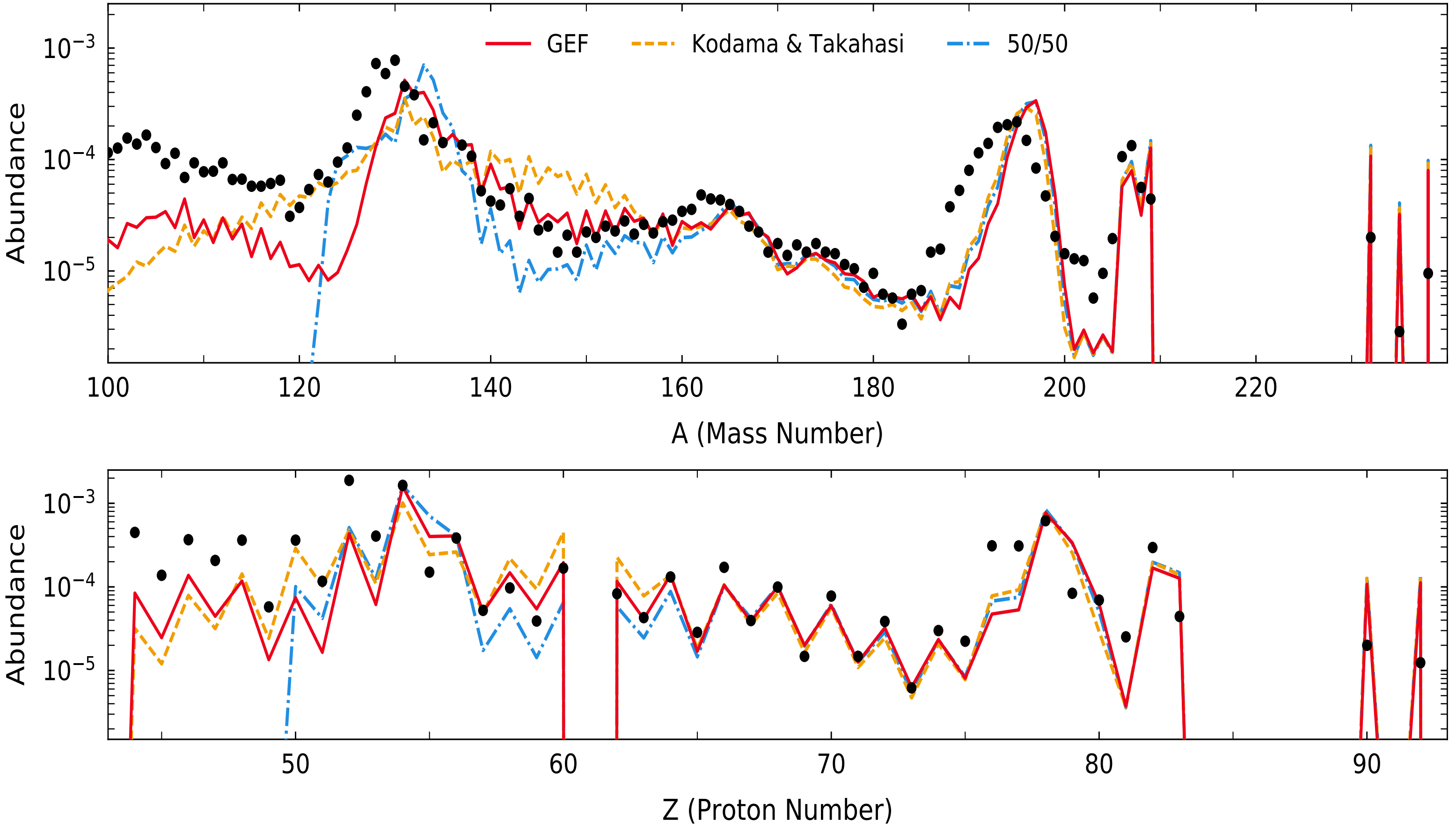




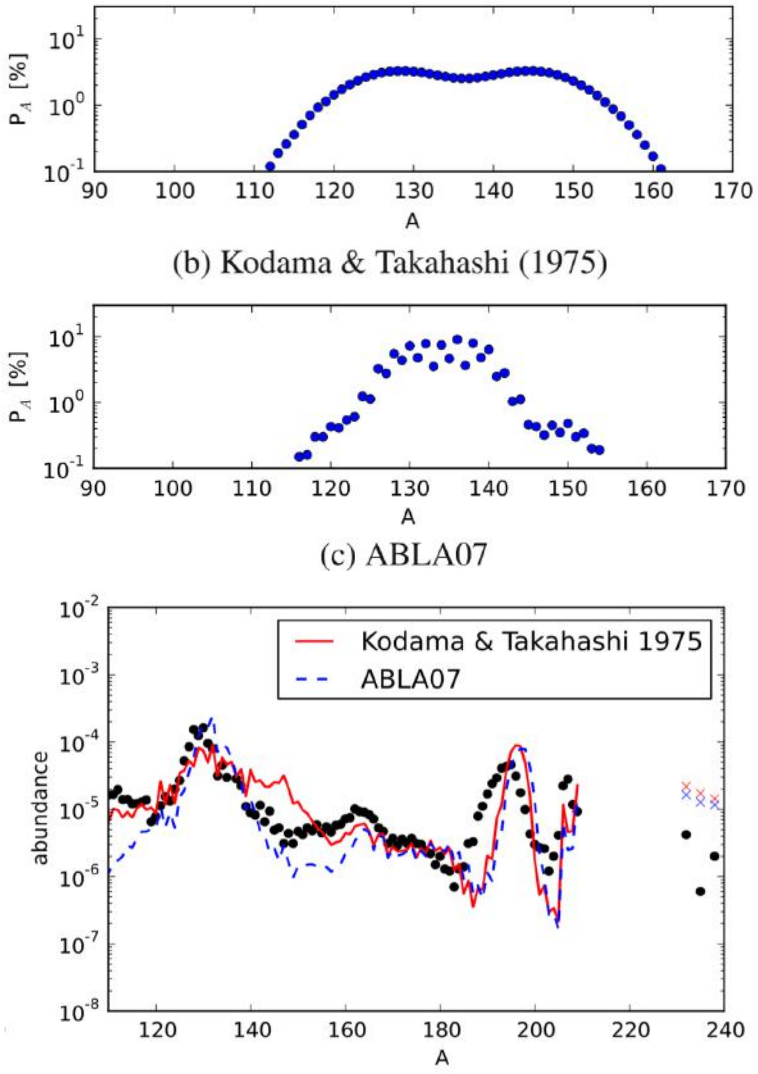
(n,f) yields with excitation energy $E_i + S_n$ differ from sf yields which have zero excitation energy (above from GEF 2016)

Vassh *et al* (J. Phys. G, 2019)

Dependence of lanthanide abundances on fission yields



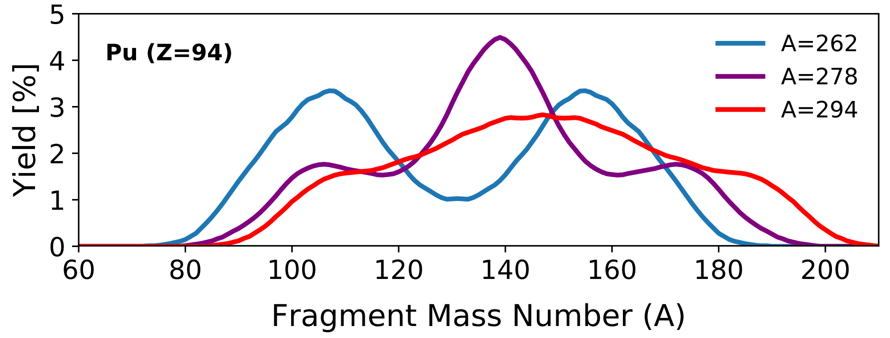
Vassh *et al* (J. Phys. G, 2019)

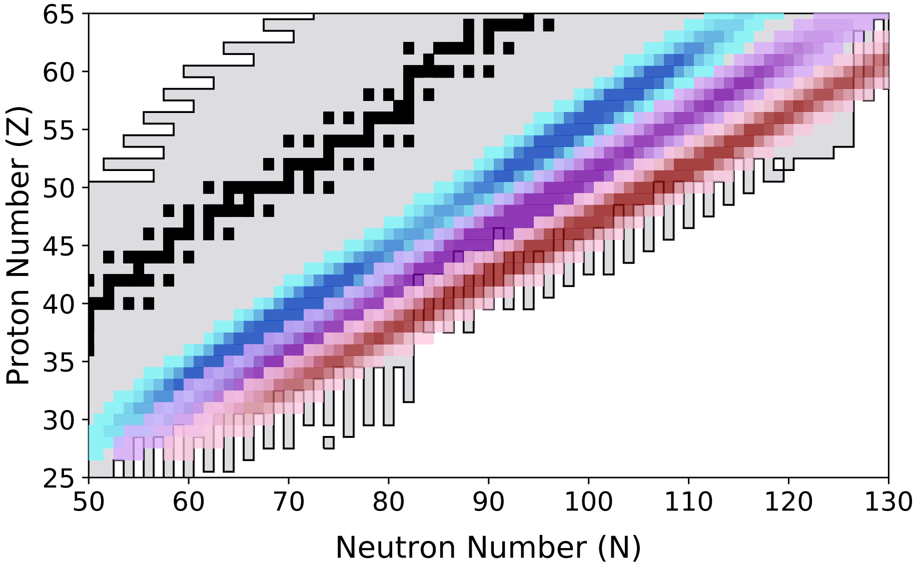


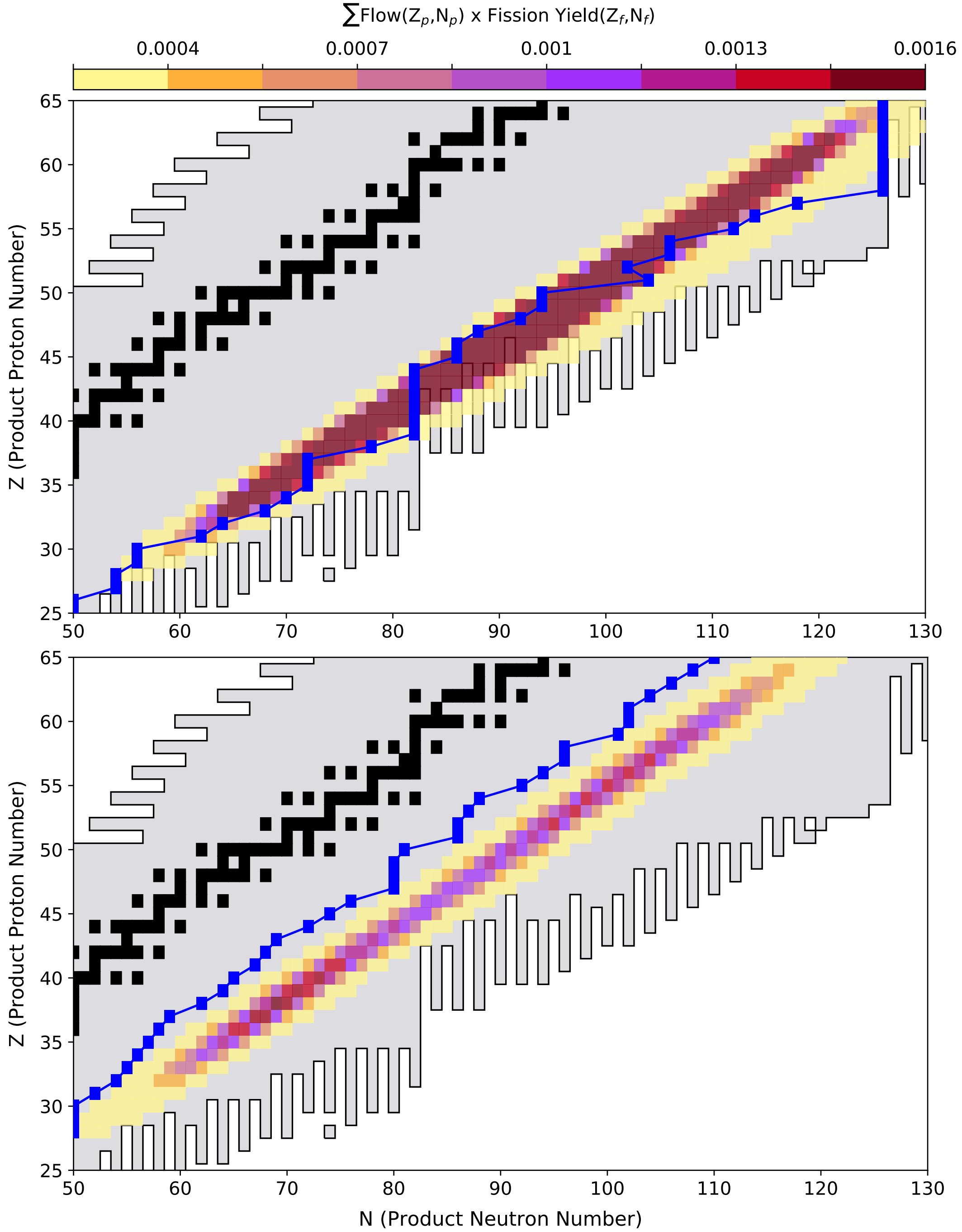
Eichler *et al* (2015)

Macroscopic-microscopic fission yields for neutron-rich nuclei in the *r*-process

FRLDM Yields from Mumpower *et al* (arXiv:1911.06344, 2019)

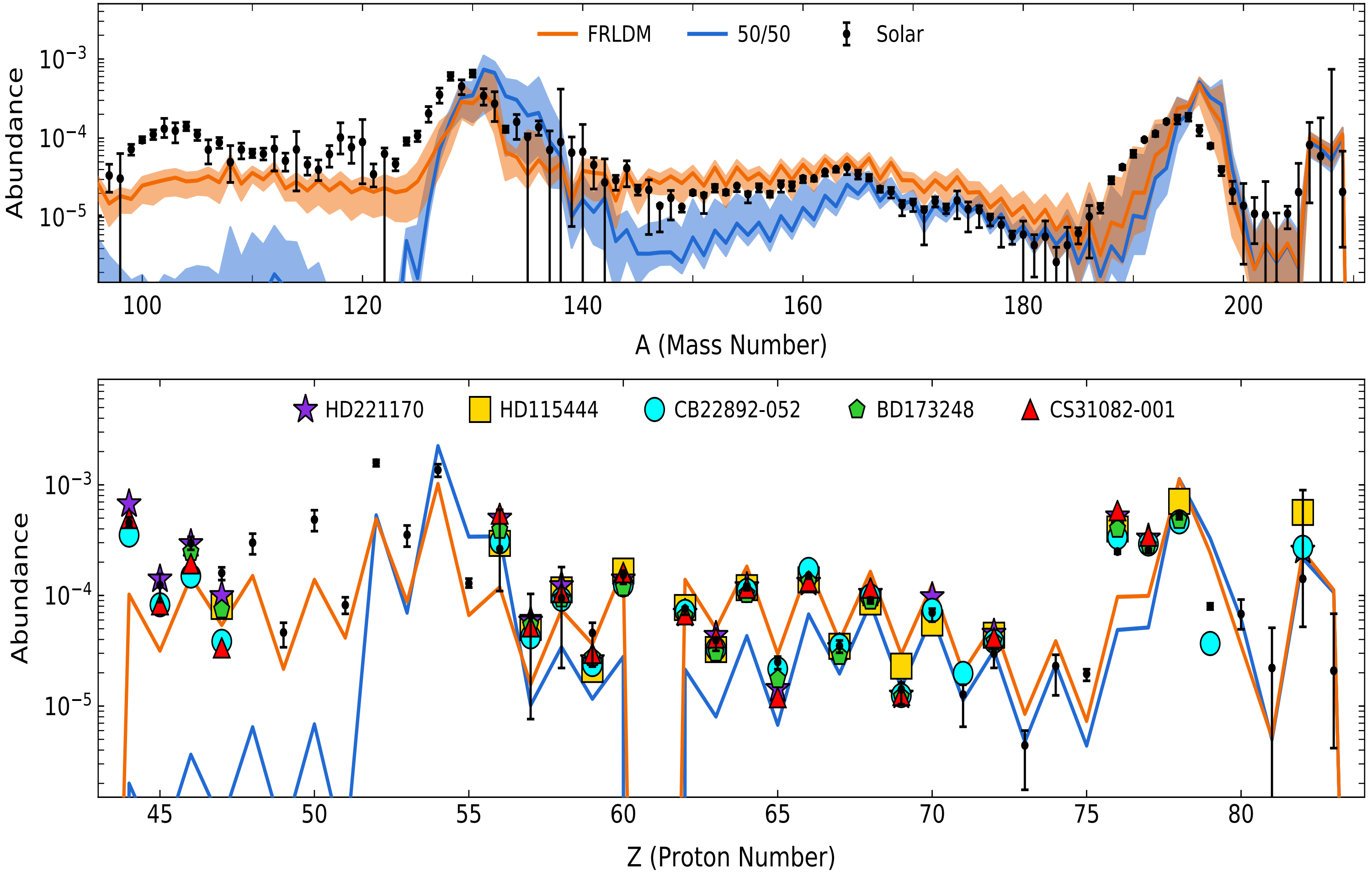






Vassh *et al* (accepted ApJ 2020, arXiv:1911.07766)

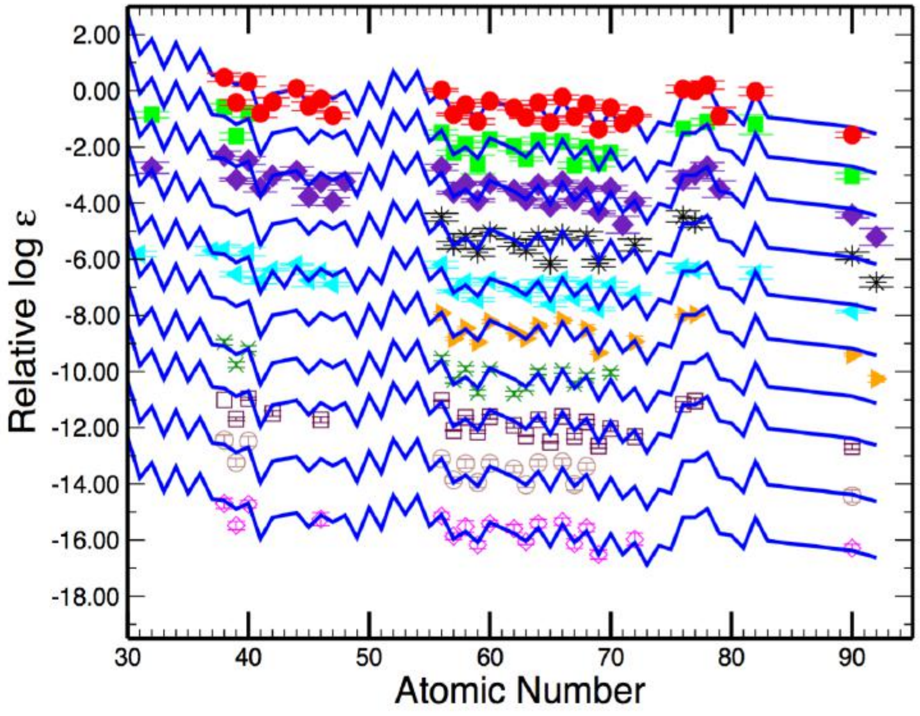
Fission deposition to explain robustness of observed elemental abundances?



1.2-1.4 M$_\odot$ NSM dynamical ejecta using Rosswog *et al* 2013 simulation conditions (very neutron-rich with robust fission)

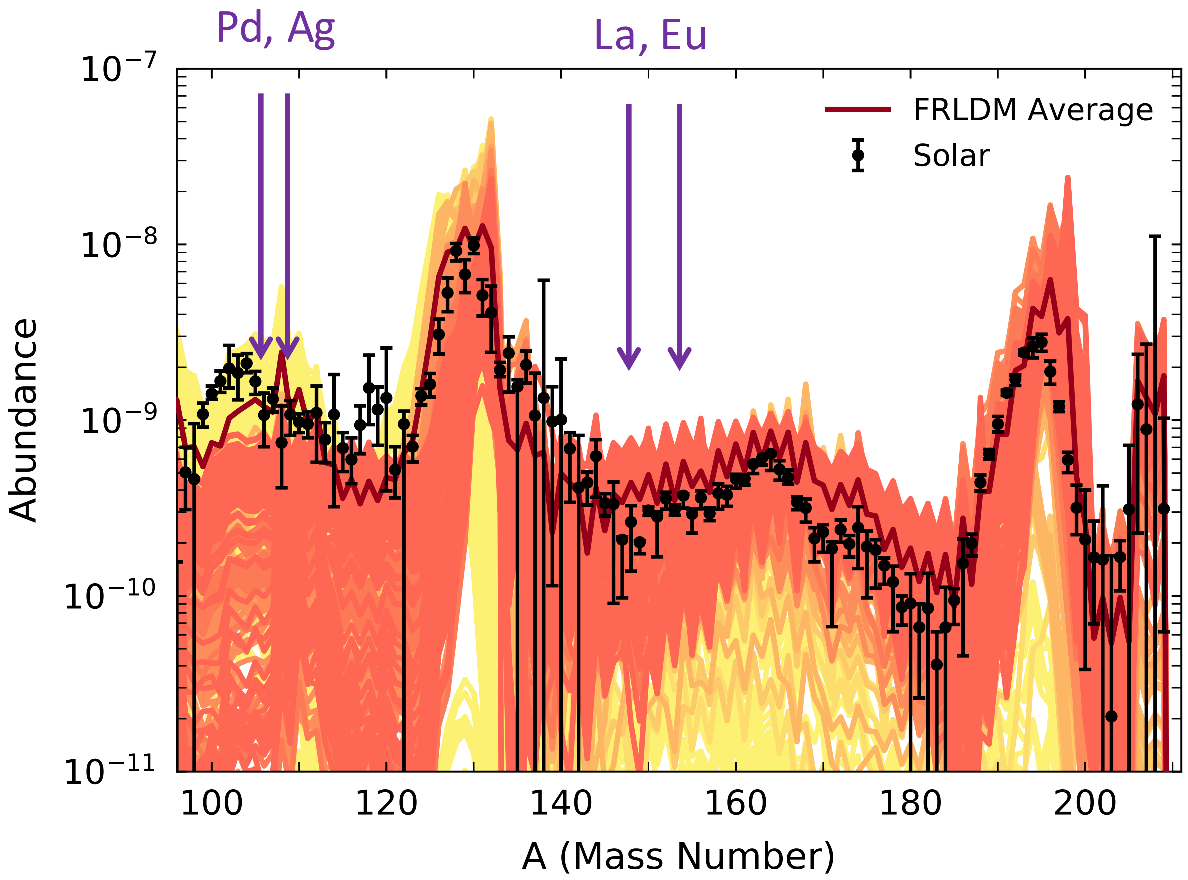
Vassh *et al* (accepted ApJ 2020, arXiv:1911.07766)

10 *r*-process rich halo stars compared to Solar

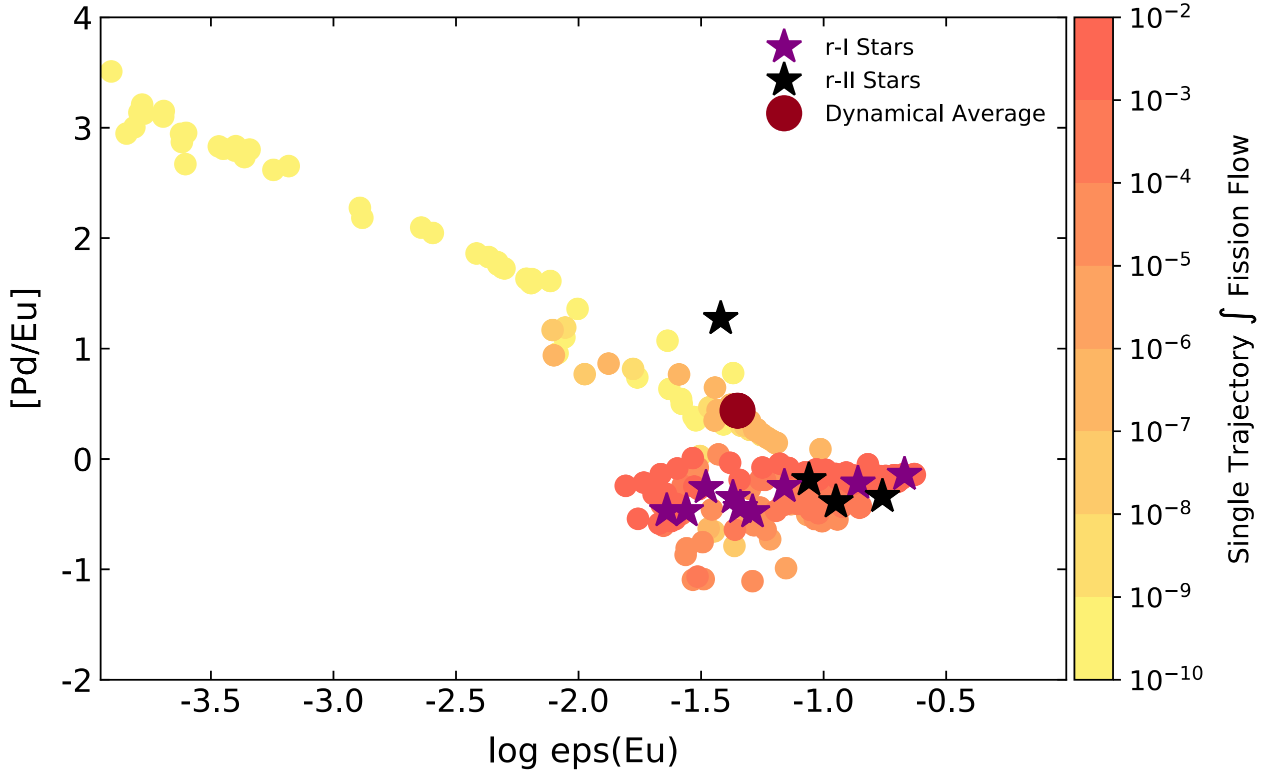


Cowan, Roederer, Sneden and Lawler (2011)

Fission deposition to explain robustness of observed elemental abundances?



1.2-1.4 $M_\odot$ NSM dynamical ejecta using simulation of Radice *et al* 2018 with M0 neutrino transport (broad range of conditions)



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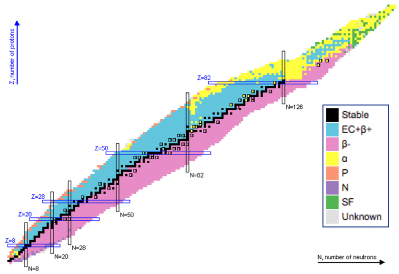
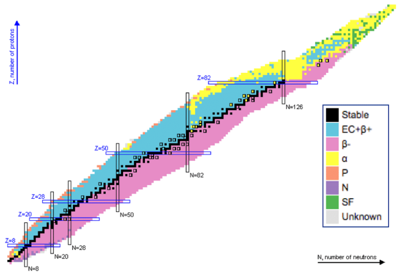


Nuclear physics uncertainties impact important open questions in *r*-process heavy element production

- Can mergers account for all the *r*-process material observed in the galaxy?
- Do mergers produce precious metals such as gold in sufficient amounts? Are actinides produced?
- At what site(s) and under what conditions does heavy element nucleosynthesis occur?
- What determines the relative ratios of lanthanides such as the rare-earth elements?



Nuclear physics uncertainties impact important open questions in *r*-process heavy element production

- Can mergers account for all the *r*-process material observed in the galaxy?
- Do mergers produce precious metals such as gold in sufficient amounts? Are actinides produced?
- At what site(s) and under what conditions does heavy element nucleosynthesis occur?
- What determines the relative ratios of lanthanides such as the rare-earth elements?