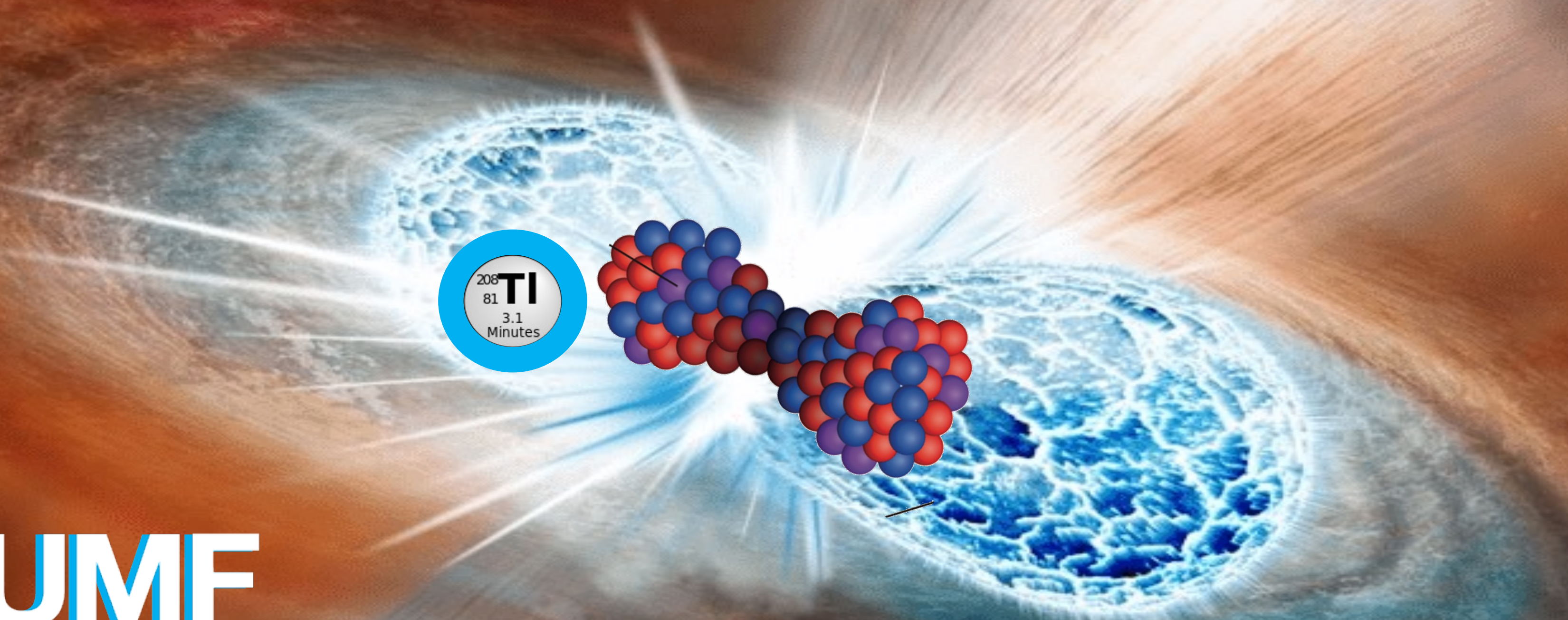
Illuminating astrophysical actinide production using MeV gamma-rays and metal-poor stars



TRIUMF

FRIB Theory Alliance

NSERC CRSNG

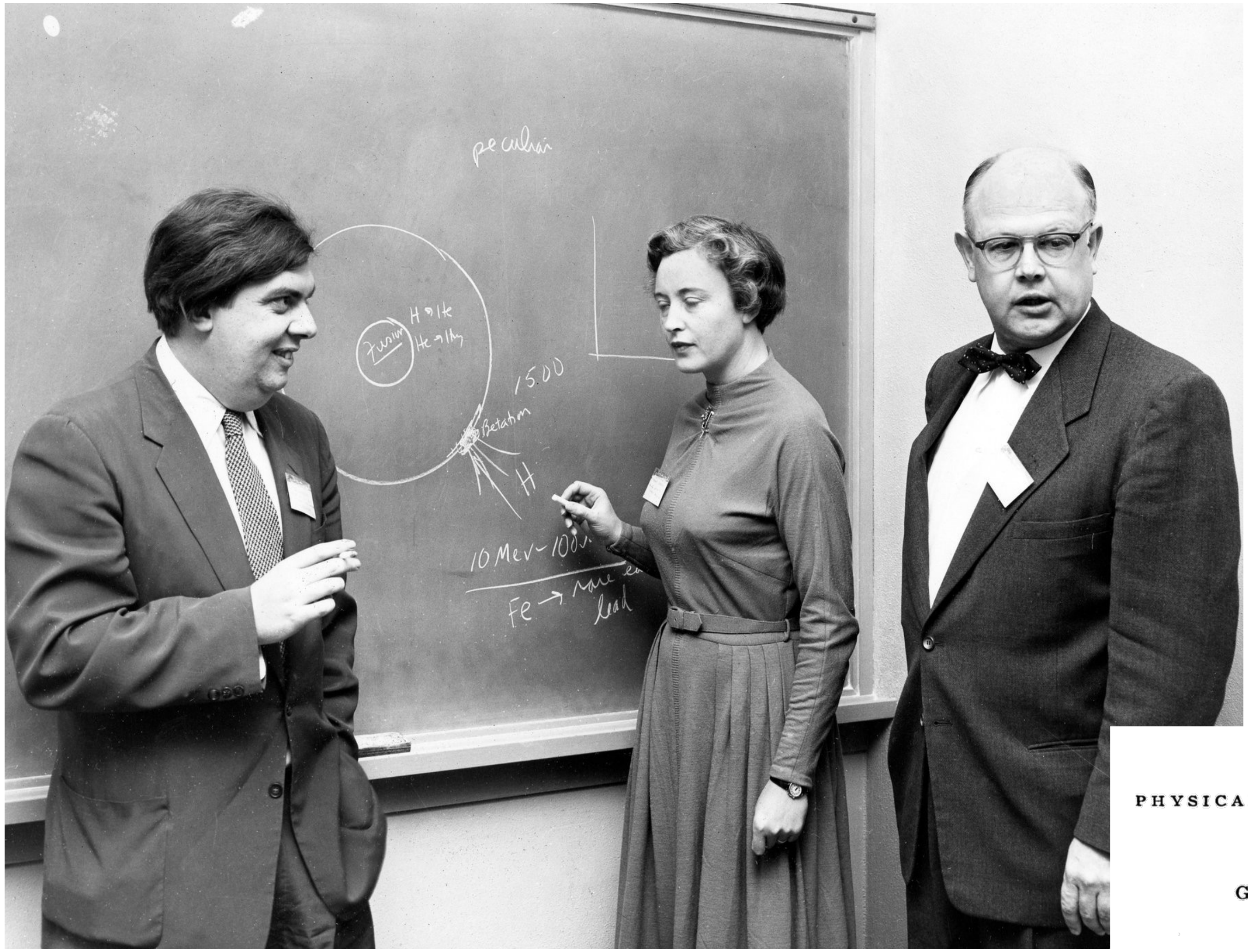
Nicole Vassh

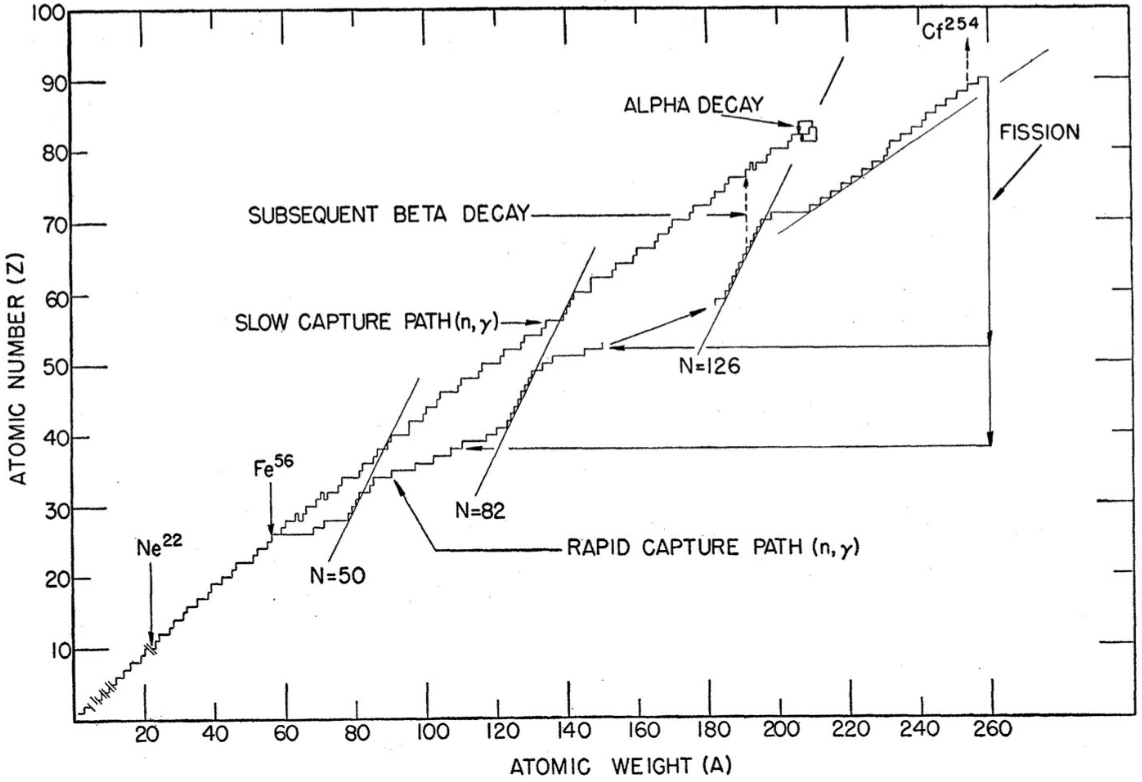
TRIUMF Theory Group

CaNPAN Jam

May 3, 2024

Production of fissioning nuclei in astrophysics?





Burbidge, Burbidge, Fowler and Hoyle
B^2FH (1957)

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*

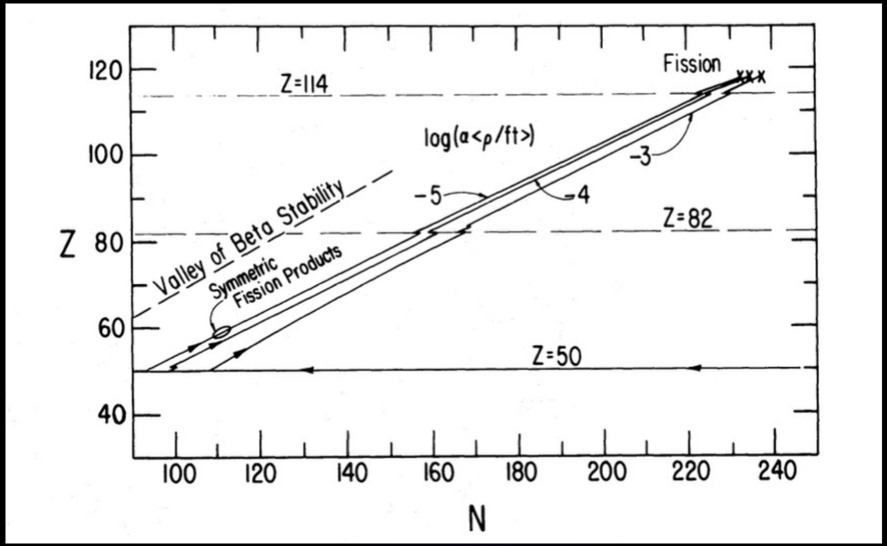
AND

E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

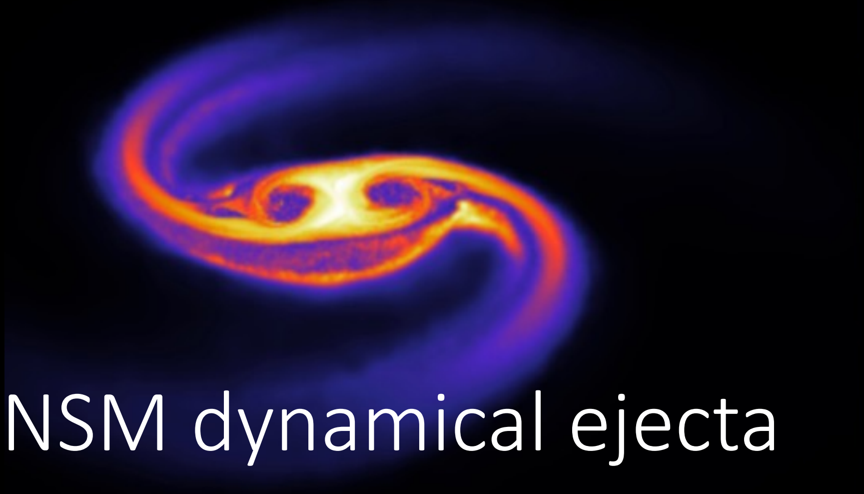
It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.

Production of fissioning nuclei in astrophysics?



Neutron-rich ejecta from neutron star mergers > 40 years ago

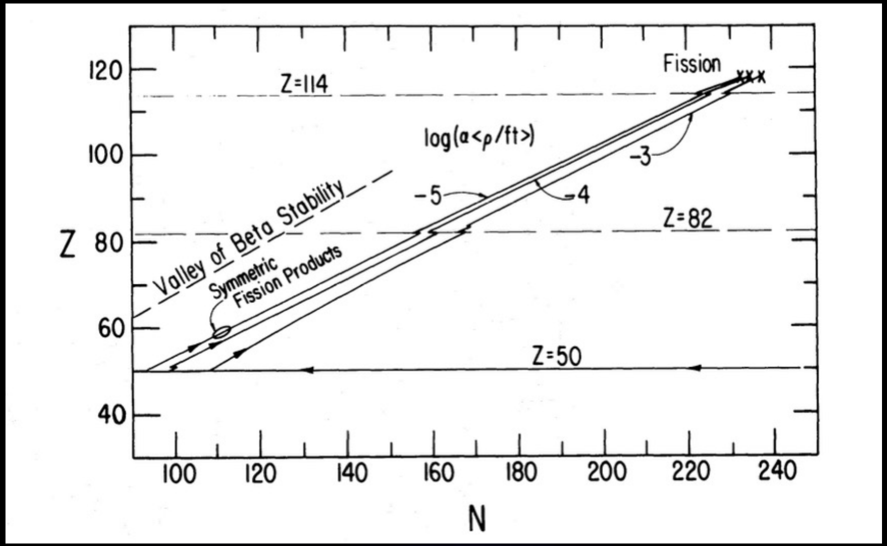
Lattimer&Schramm (1974), Lattimer+ (1977): initially cold, expanding neutron star matter → fission cycling *r* process + superheavy elements



NSM dynamical ejecta

Rosswog+13
See also Radice+19, Perego+19, Wanajo+14, Bovard+17 Vincent+19, Foucart+20….

Production of fissioning nuclei in astrophysics?



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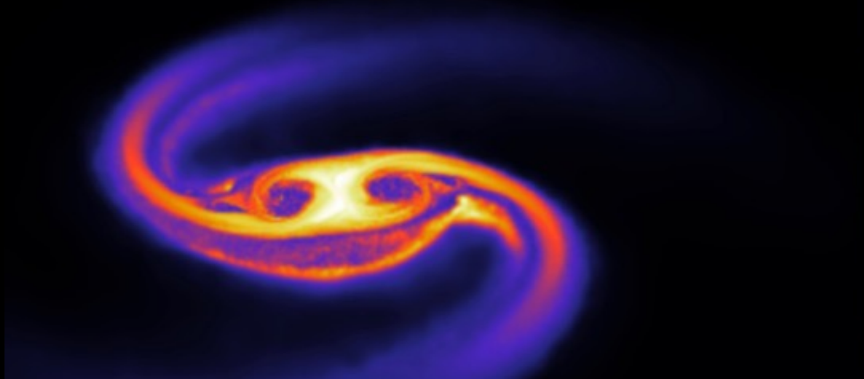
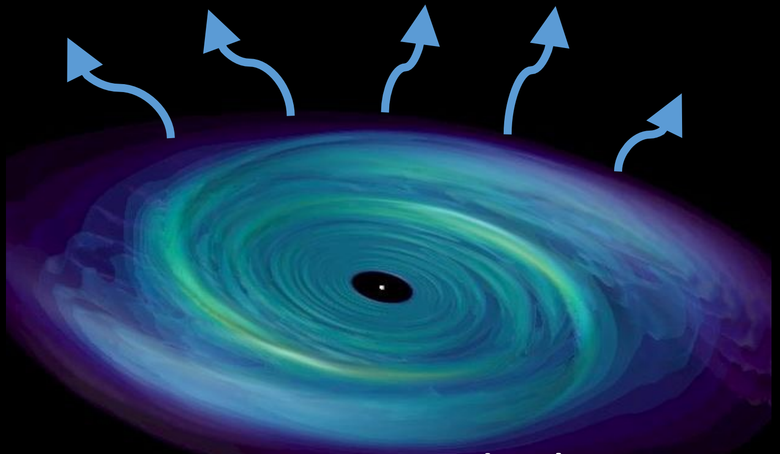




NSM dynamical ejecta

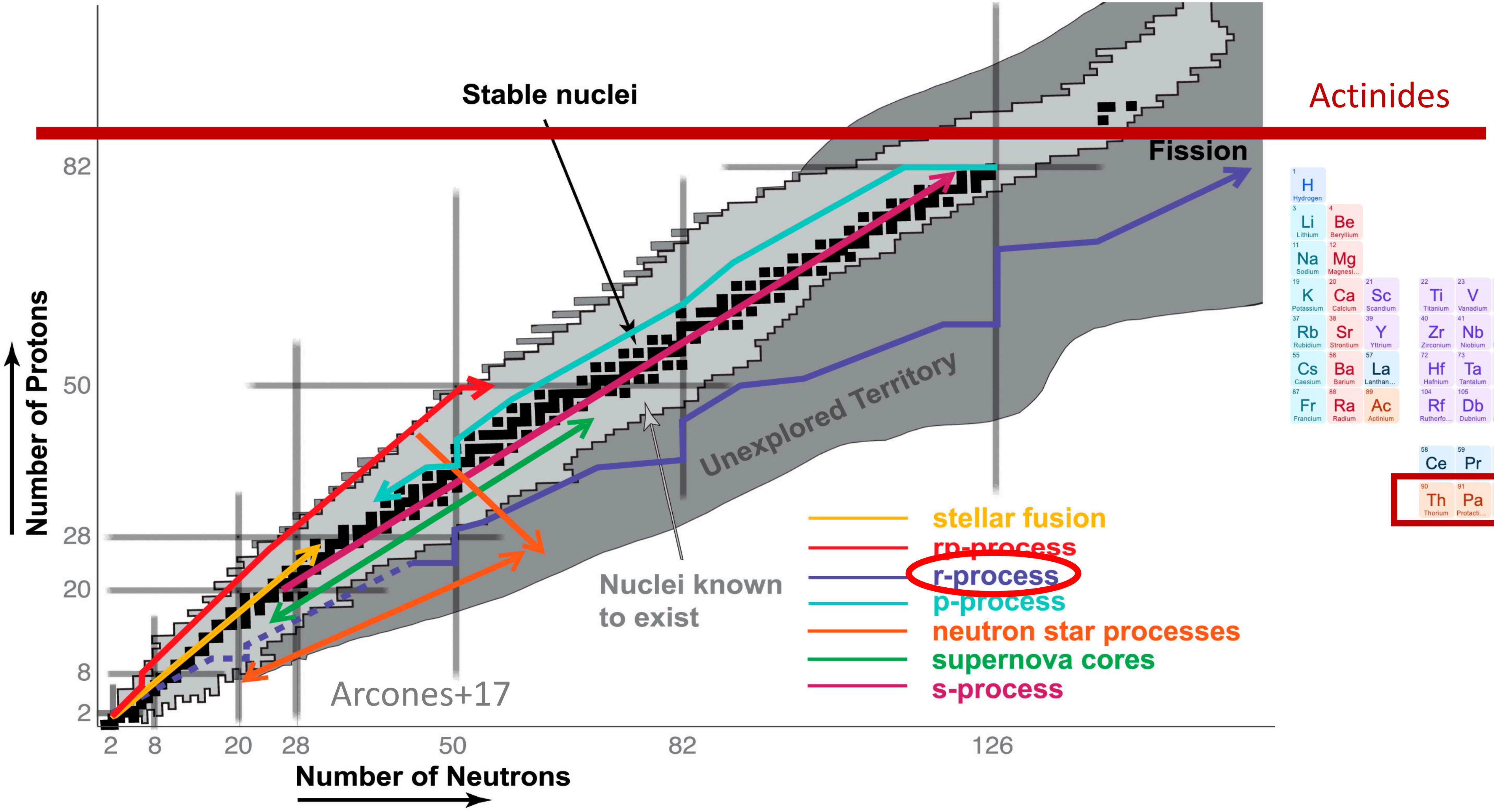
Rosswog+13
See also Radice+19, Perego+19, Wanajo+14, Bovard+17 Vincent+19, Foucart+20….

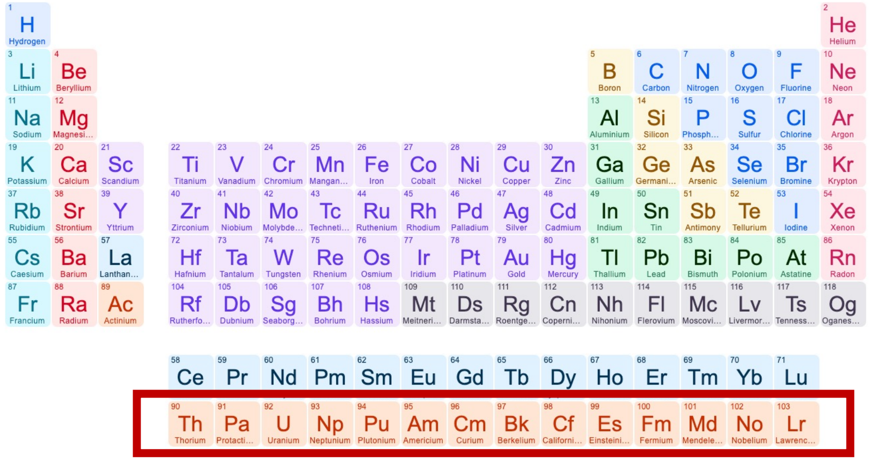
Post-merger disk ejecta

Owen&Blondin 05
See also Just+16, Miller+19, Most+21, Sprouse+23, Fernandez+23…

Production of fissioning nuclei in astrophysics?

* Our Sun and other stars: U-238
* Deep sea ocean crusts: Pu-244
* Meteorites: Cm-247





Fission in astrophysical environments

Incident neutron strikes

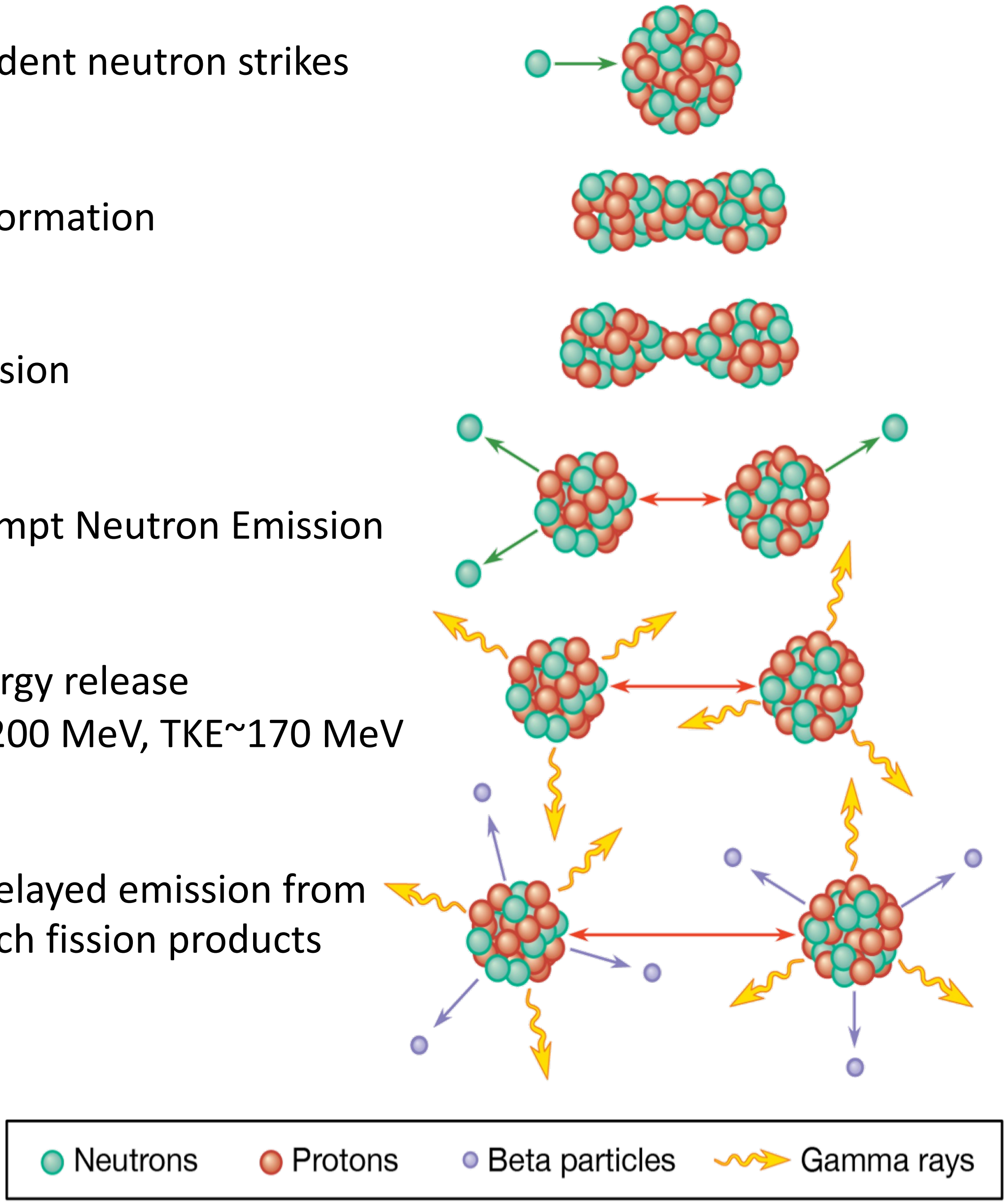
Deformation

Scission

Prompt Neutron Emission

Energy release
Q~200 MeV, TKE~170 MeV

β-delayed emission from
n-rich fission products



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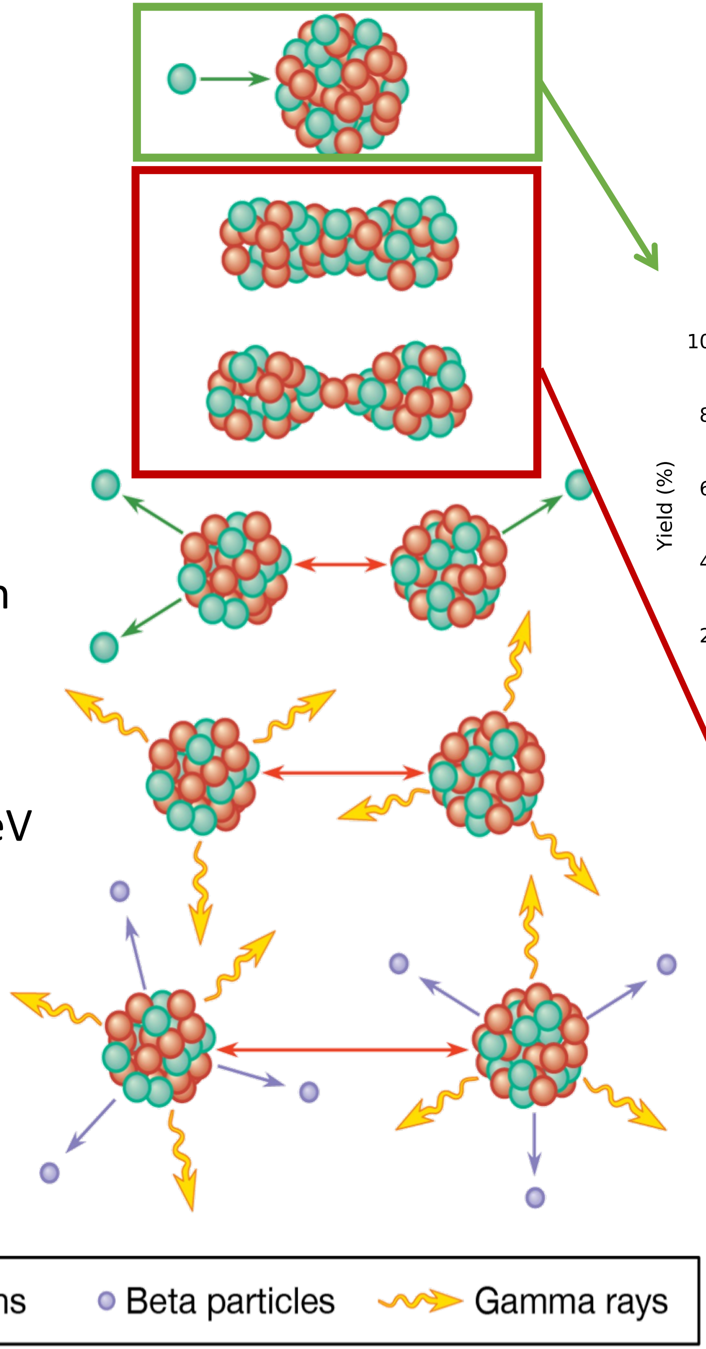
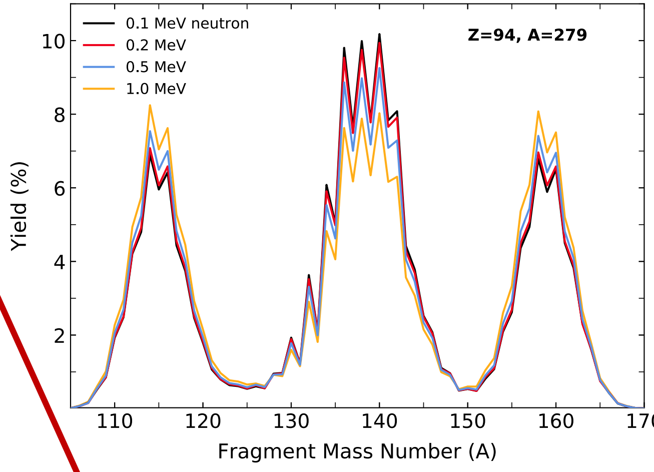
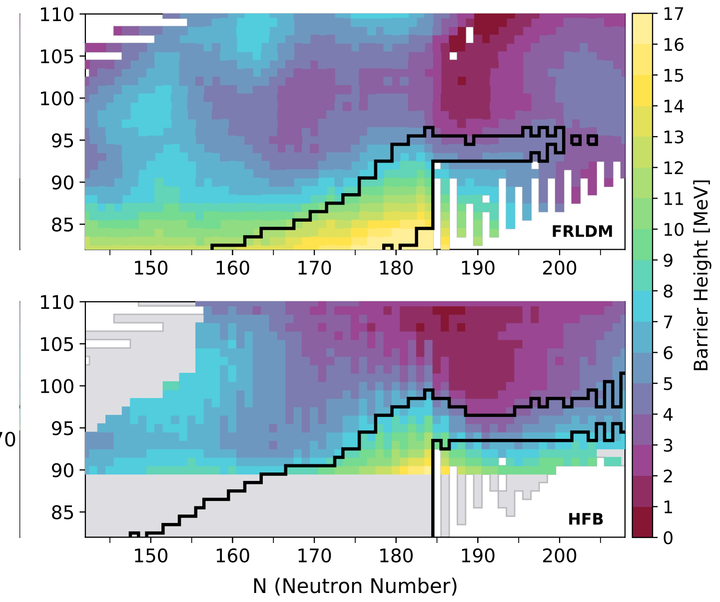
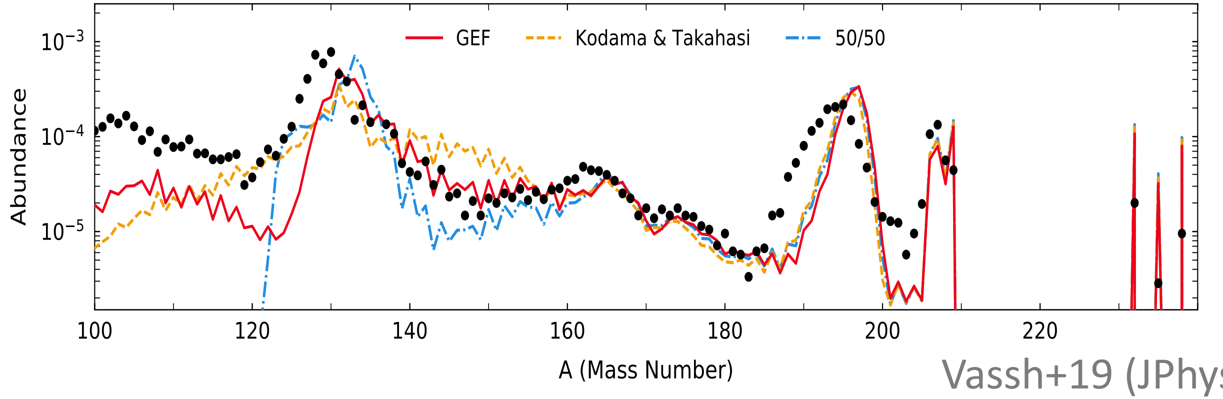


Fission yields and **rates** depend on incident energy and barrier height ((n,f), βdf, sf distinct)





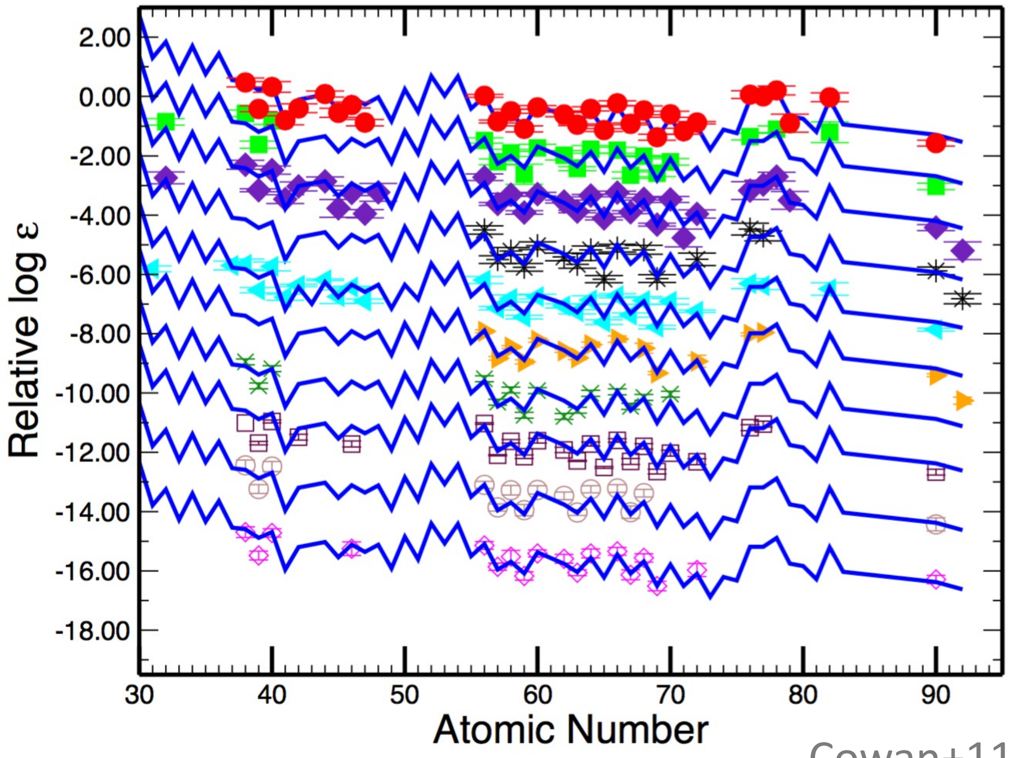
Predicted abundance dependence on yield model



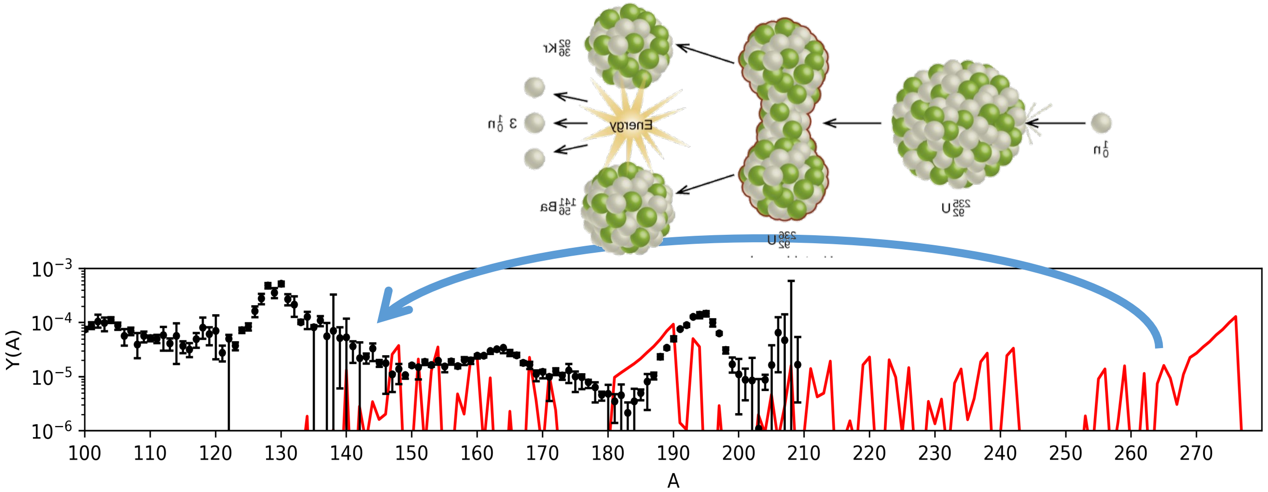
Vassh+19 (JPhysG)

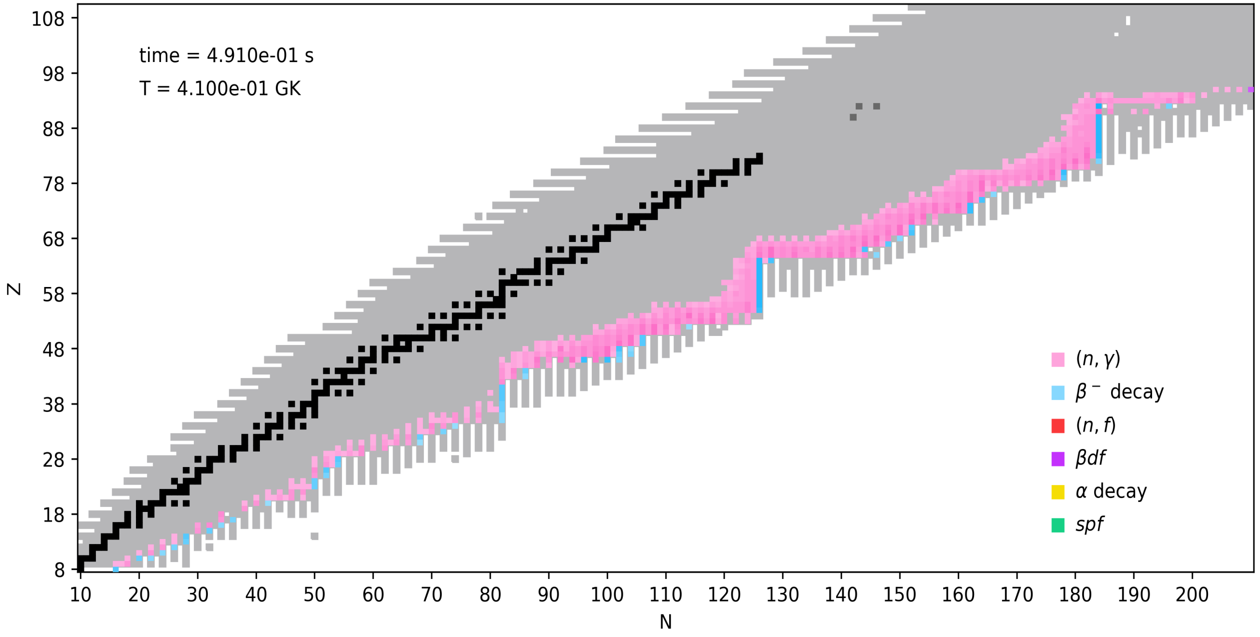
“Universality” or “robustness” of *r*-process abundances

10 *r*-process rich halo stars compared to solar: similar lanthanide abundance ratios



Cowan+11



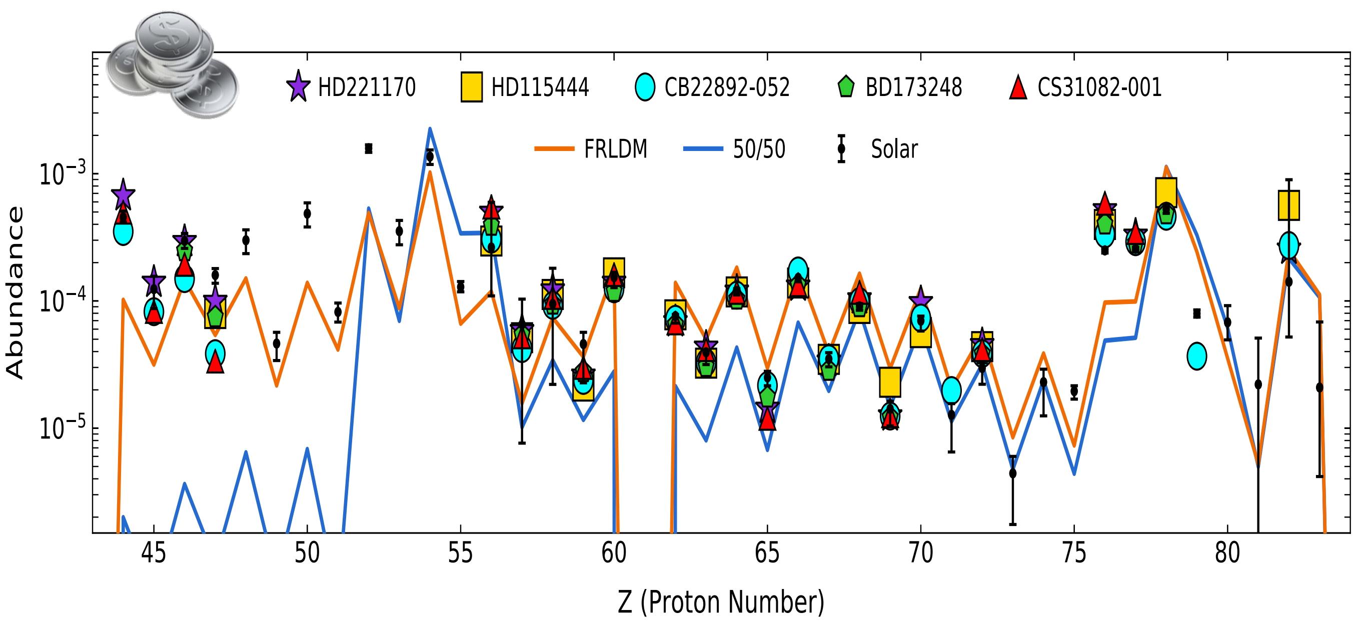


Fission cycling to “wash away” initial conditions and stabilize abundances?

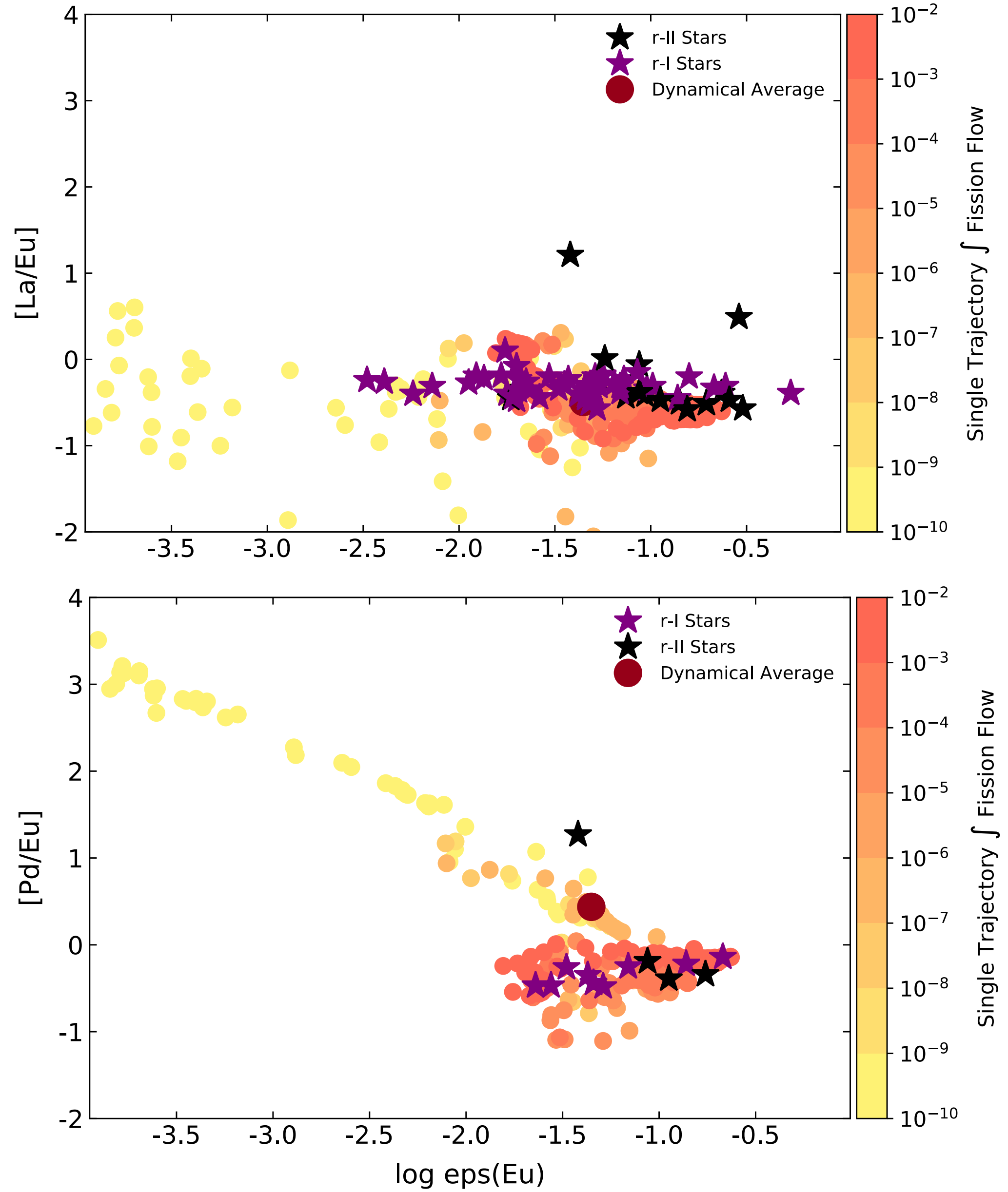
“Universality” or “robustness” of *r*-process abundances

10 *r*-process rich halo stars compared to solar:
similar lanthanide abundance ratios

and light precious metal (Ag,Pd)

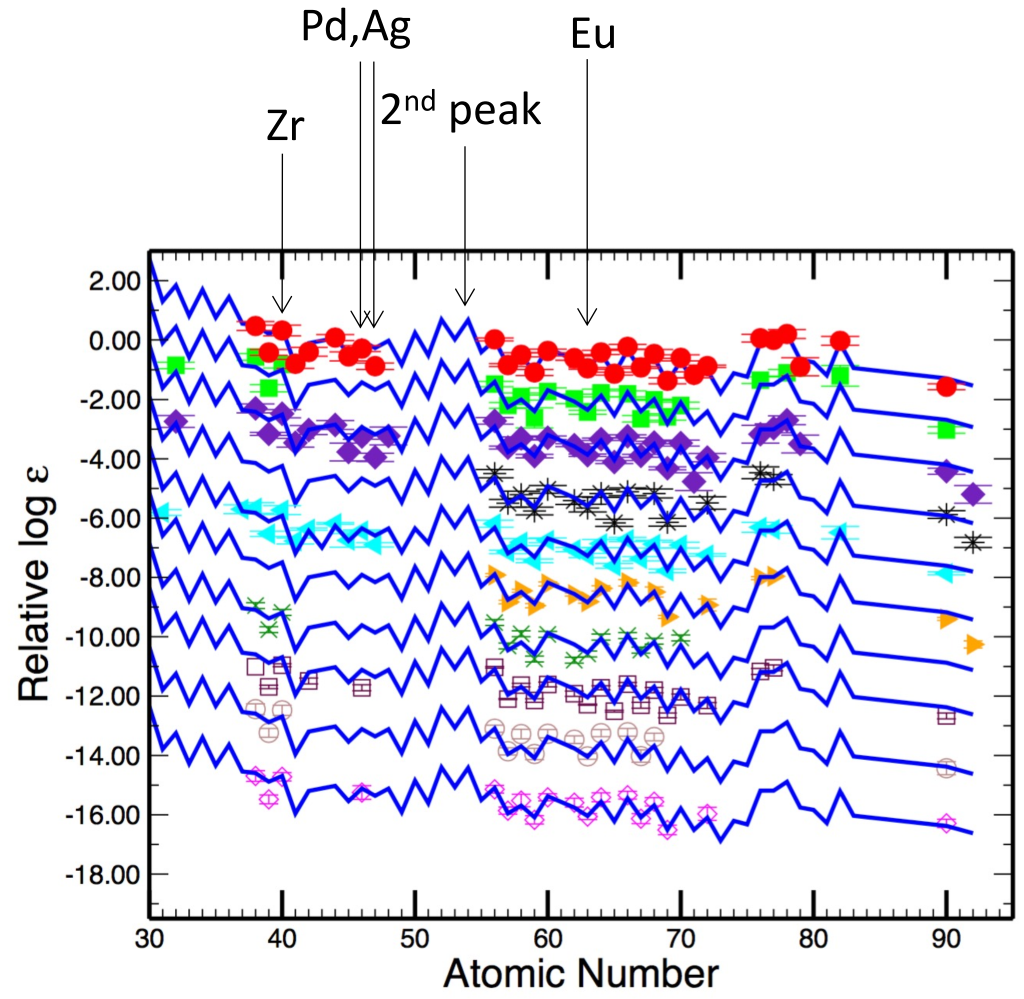


1.2-1.4 $M_\odot$ NSM dynamical ejecta
(hydro simulation Rosswog+13)
with theoretical fission yields from LANL (Mumpower+20)



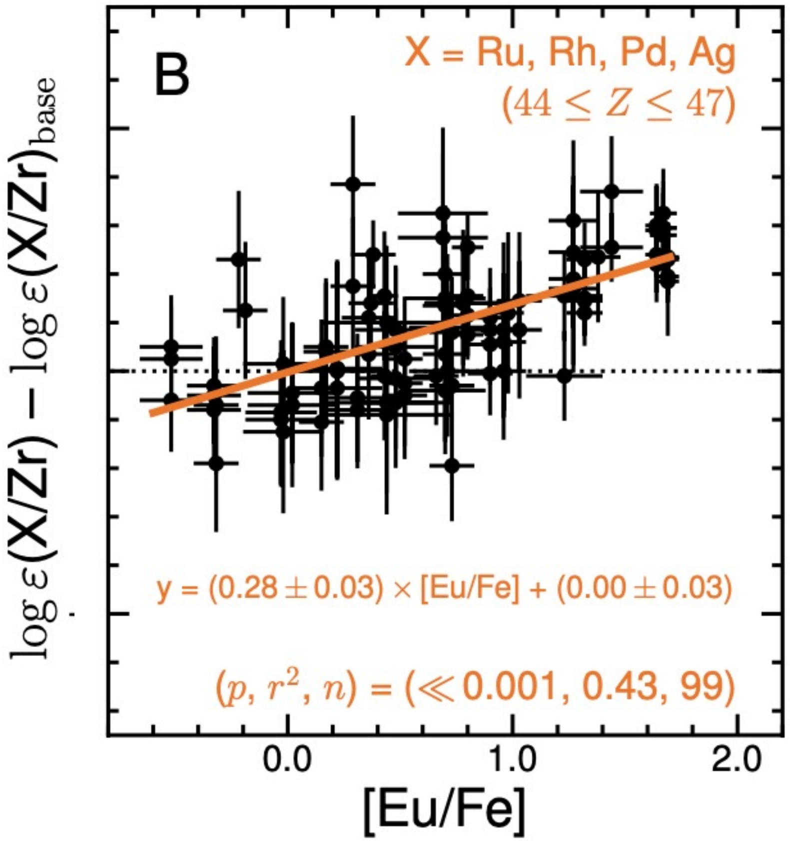
Vassh+20 (ApJ 896, 28)

Looking at a larger sample of stars: evidence of fission fragments



Cowan+11

Ag (stable isotopes A=107,109), Eu (isotopes A=151,153) correlated through fission → *r*-process reach A>260



Roederer, Vassh+23 (Science 382 (6675))

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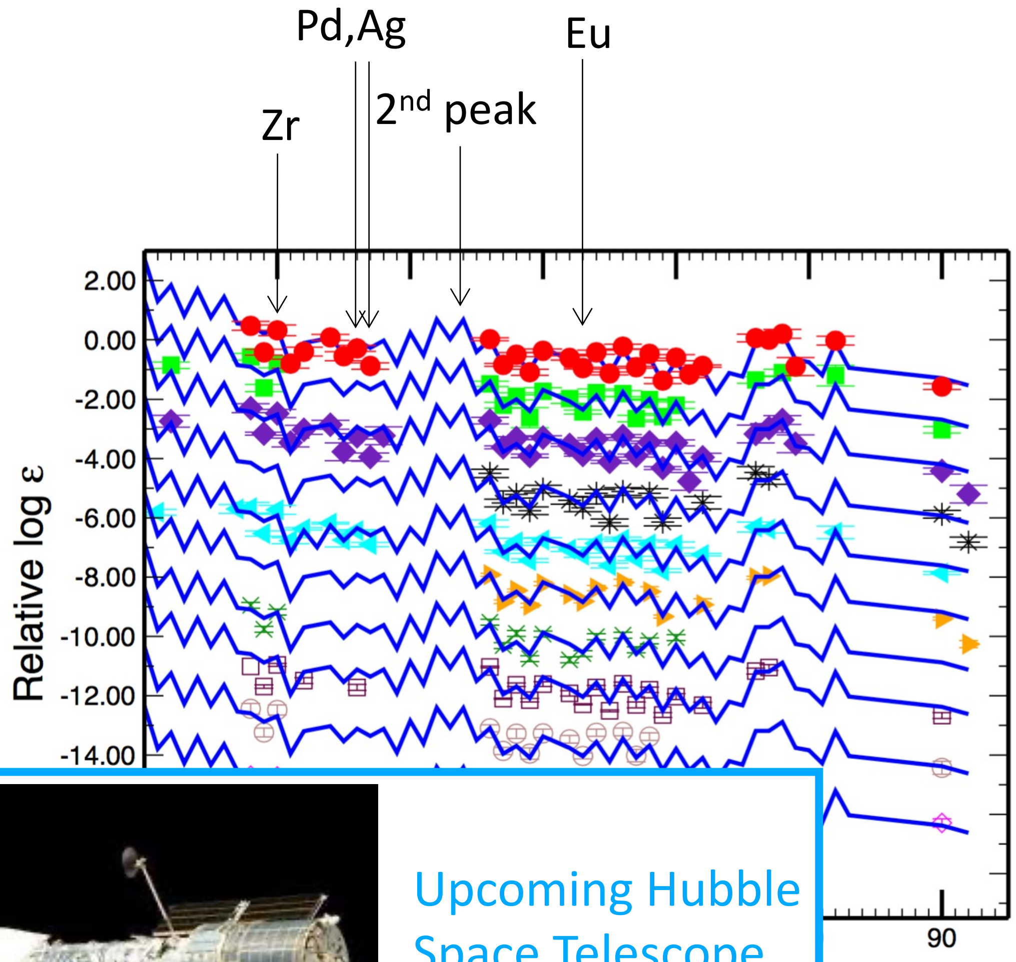

Upcoming Hubble Space Telescope Observations (Cd, Z=48)

Cowan+11

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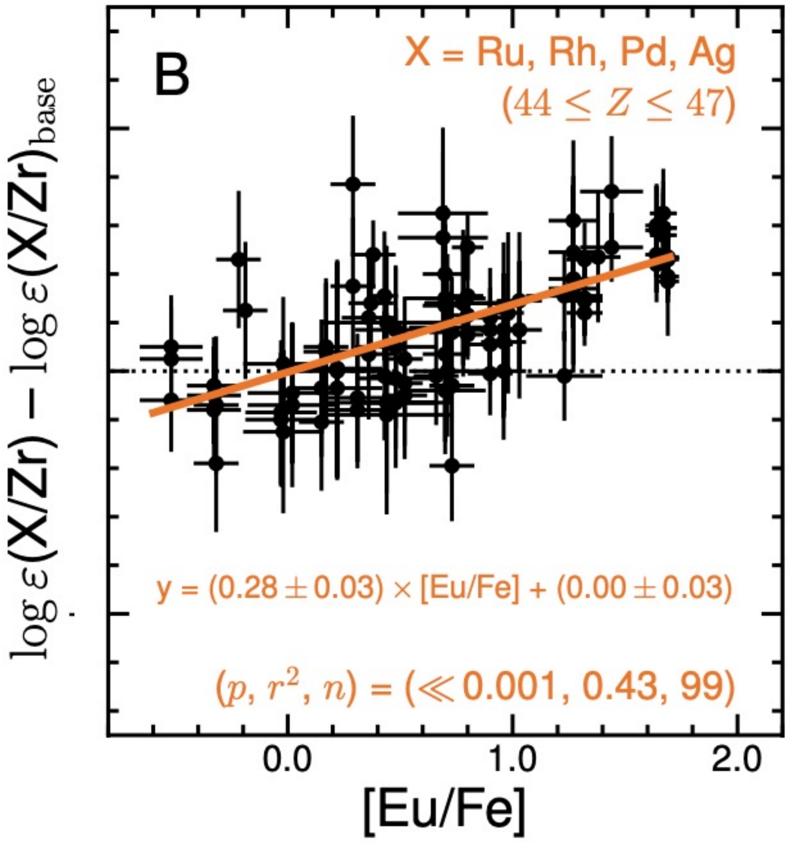

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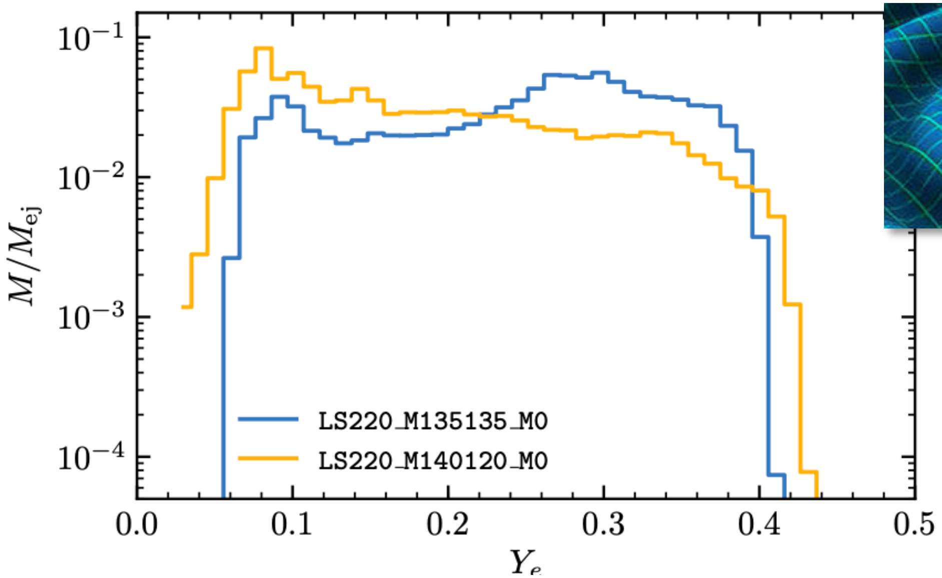
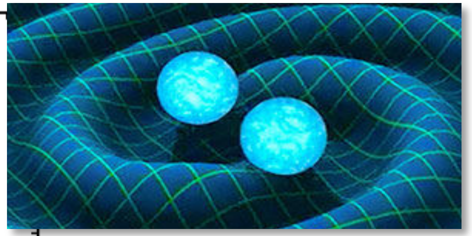
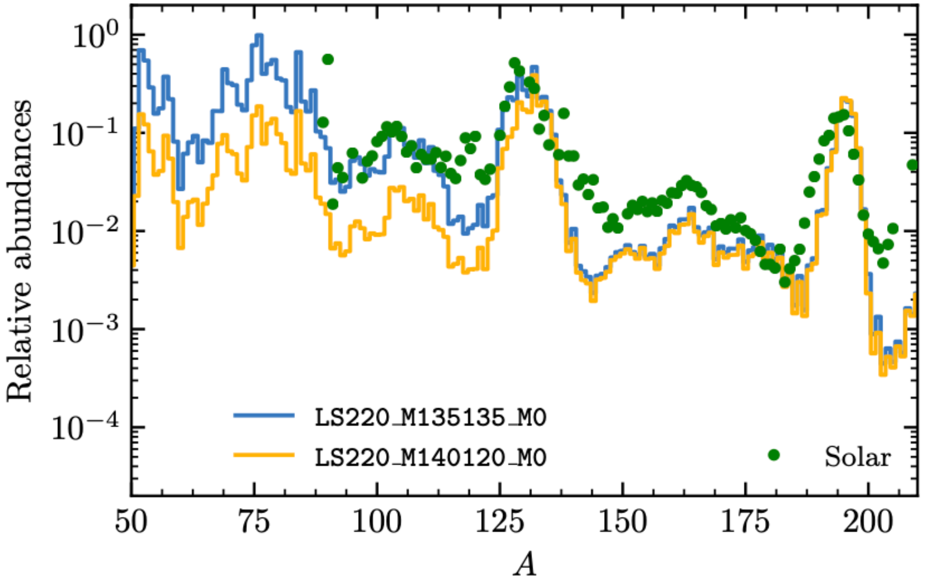
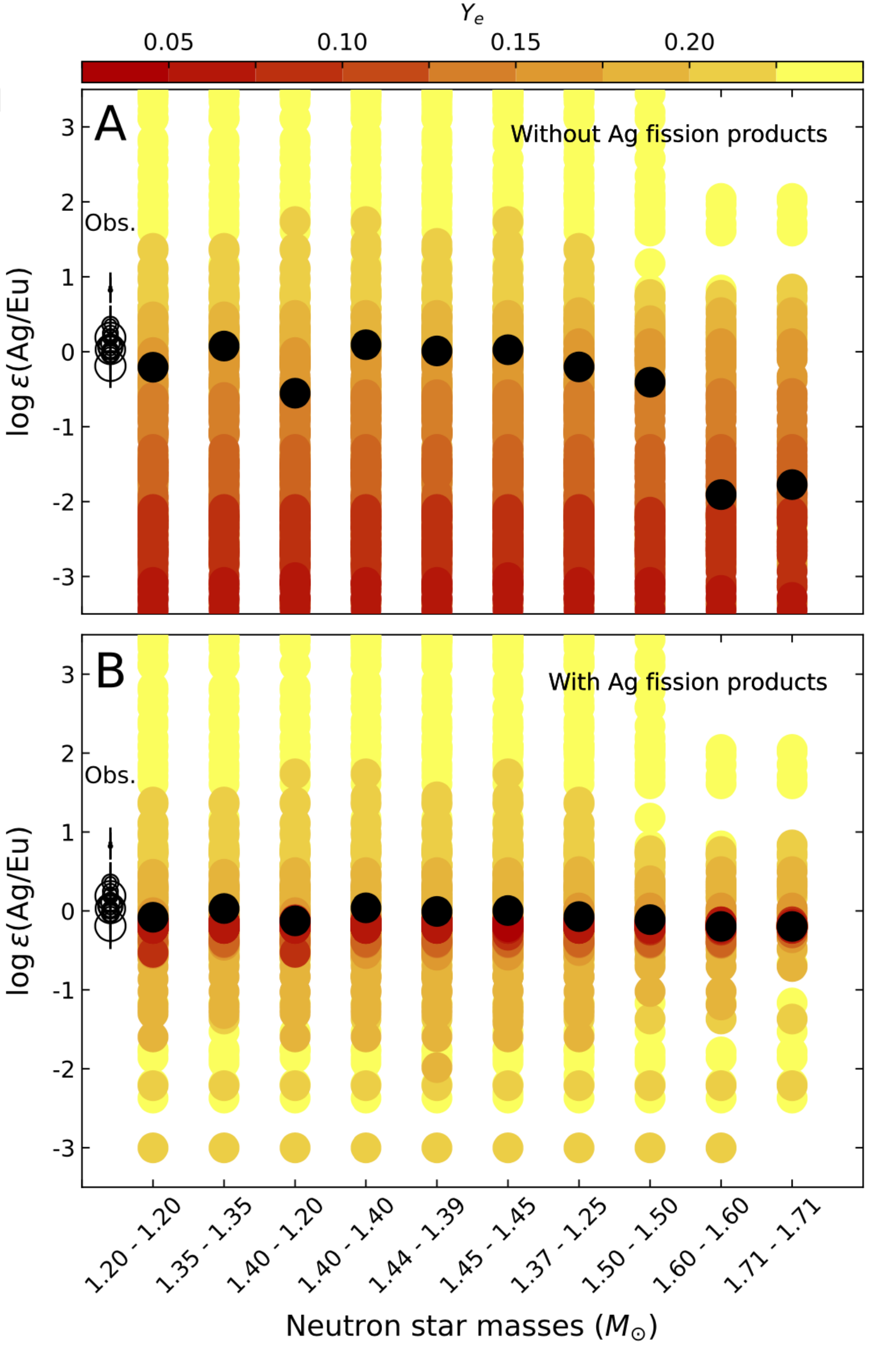
Why consistent ratios of Ag, Eu point to fission

Radice+19 merger dynamical ejecta: 1.35-1.35 vs. 1.2-1.4 $M_{\odot}$









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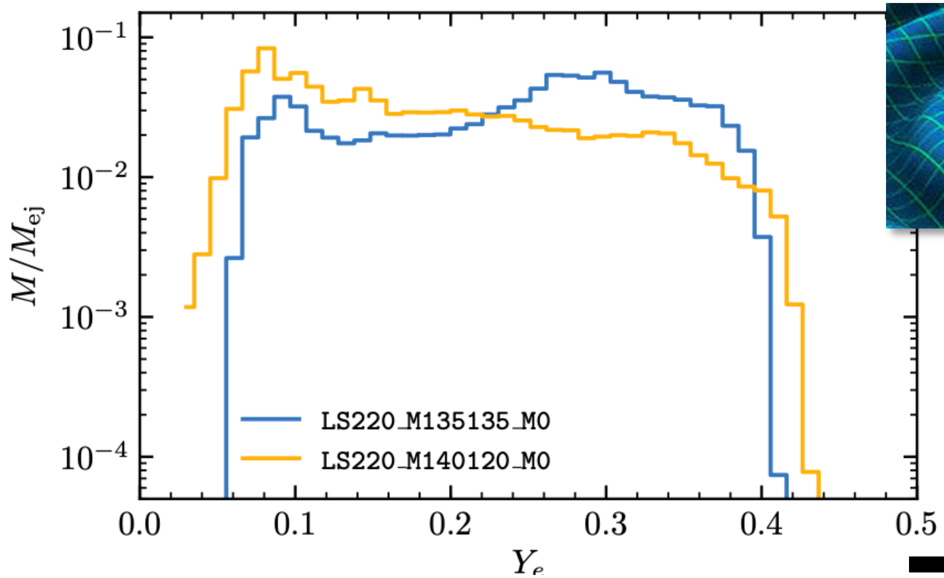
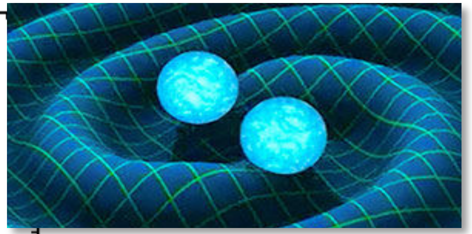
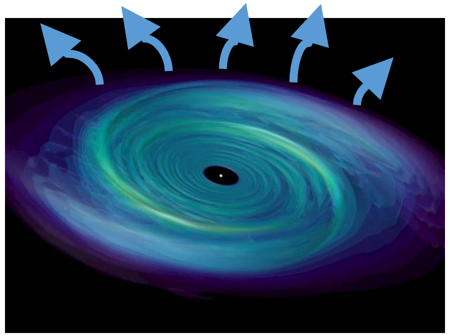
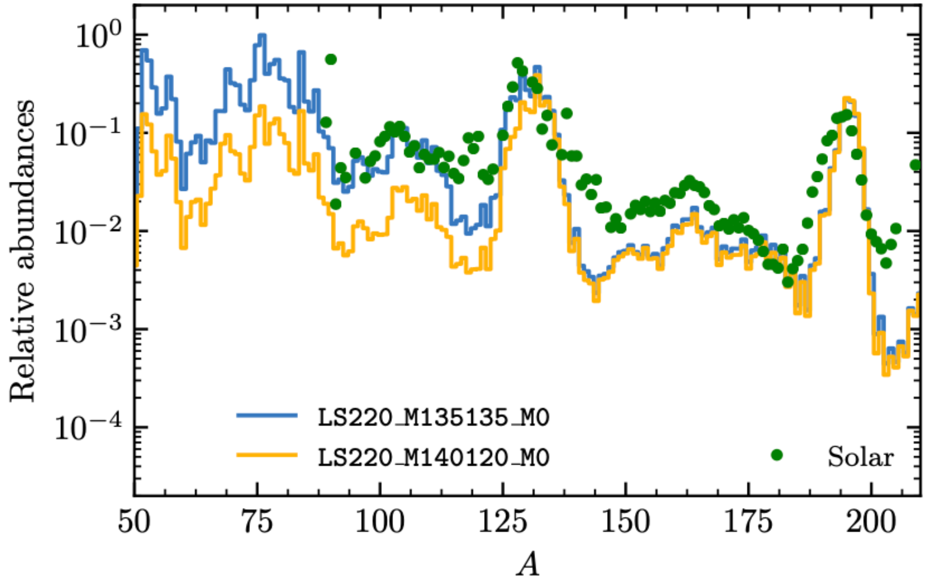
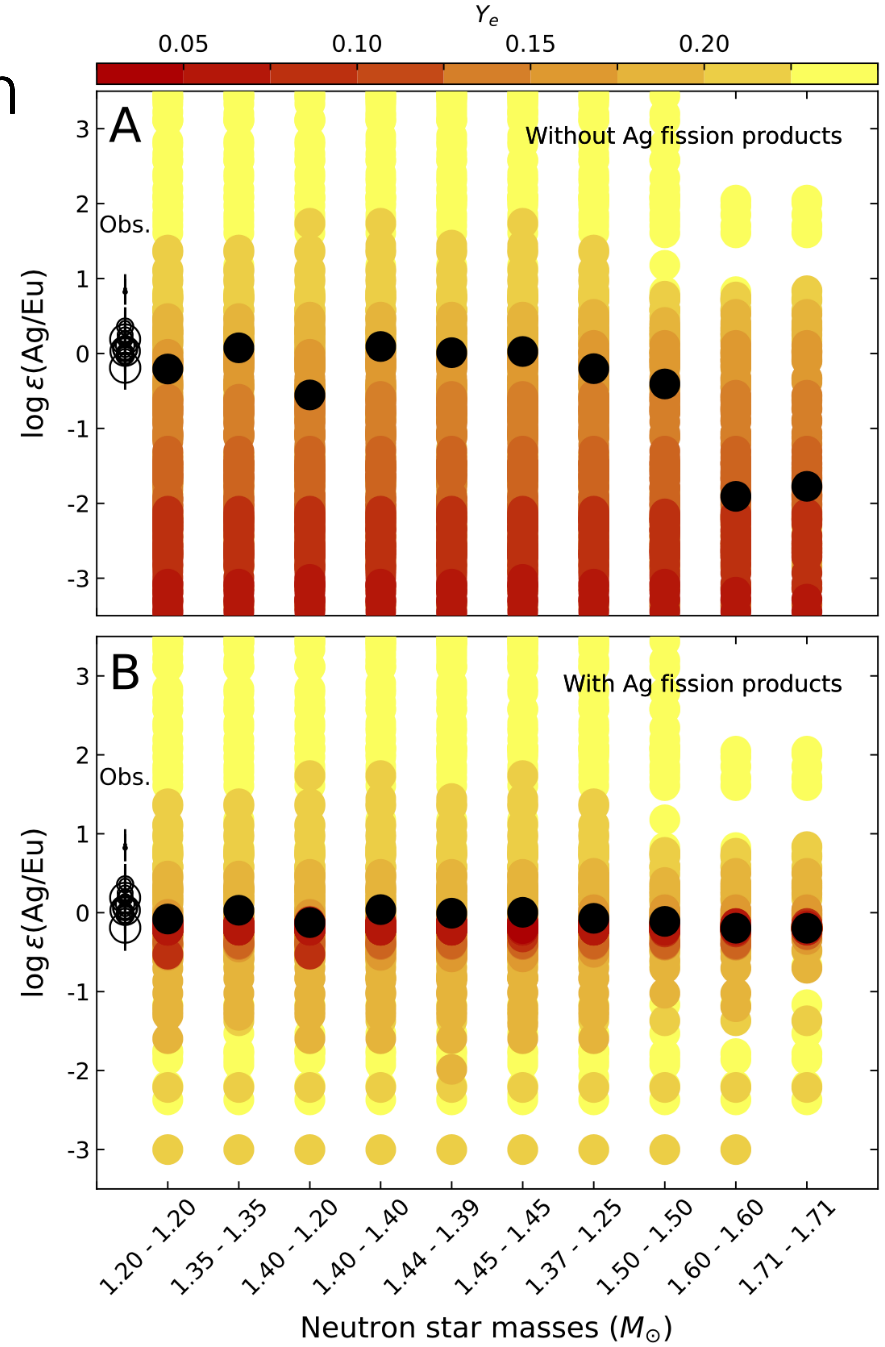




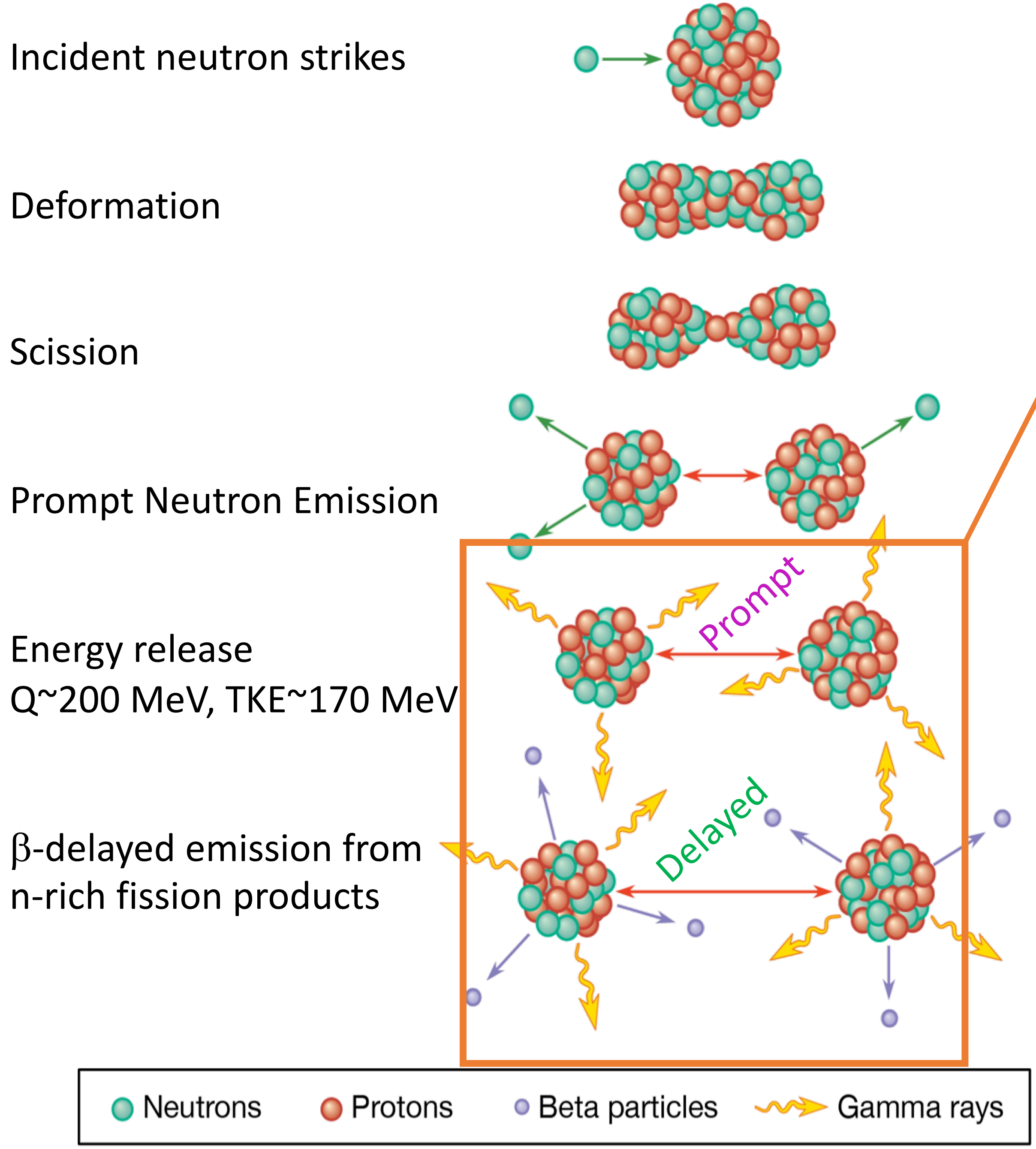




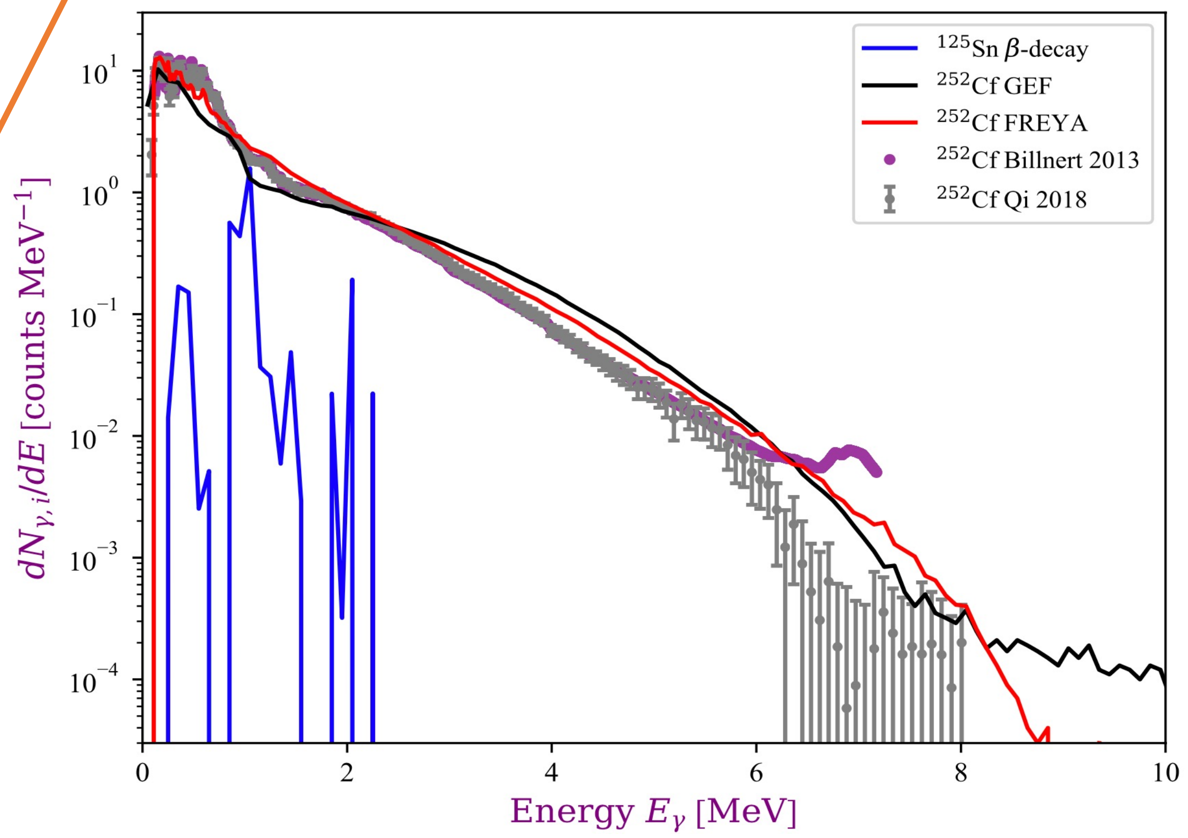


Roederer, Vassh+23 (Science 382 (6675))

Fission in astrophysical environments

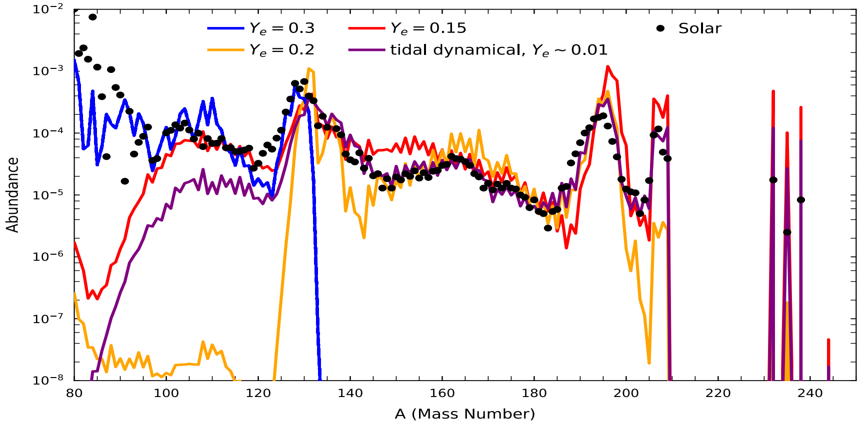


Gammas > 3.5 MeV: signature of prompt and delayed **fission gammas** in an astrophysical event!



Wang,Vassh+20 (ApJ Letters 903, L3)

Fission in astrophysical environments



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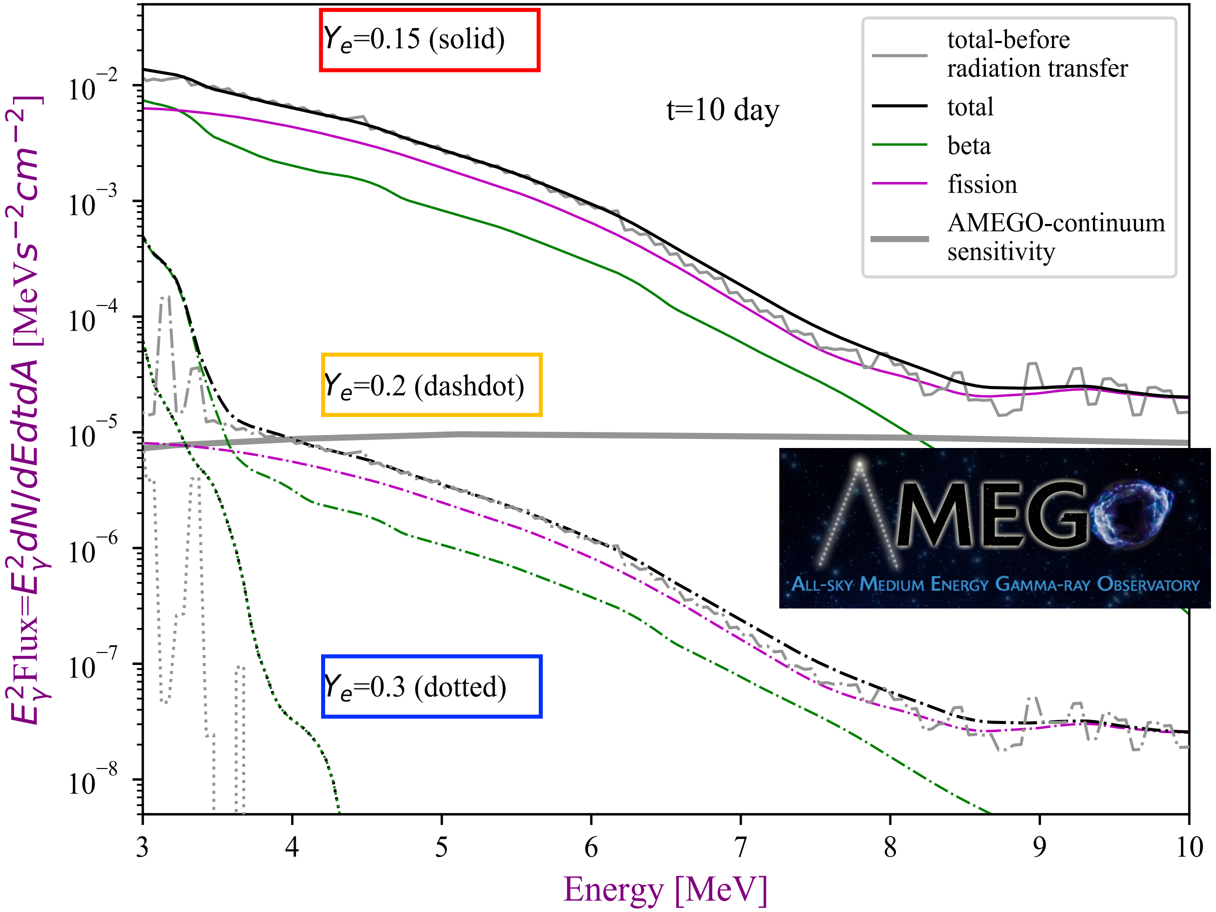
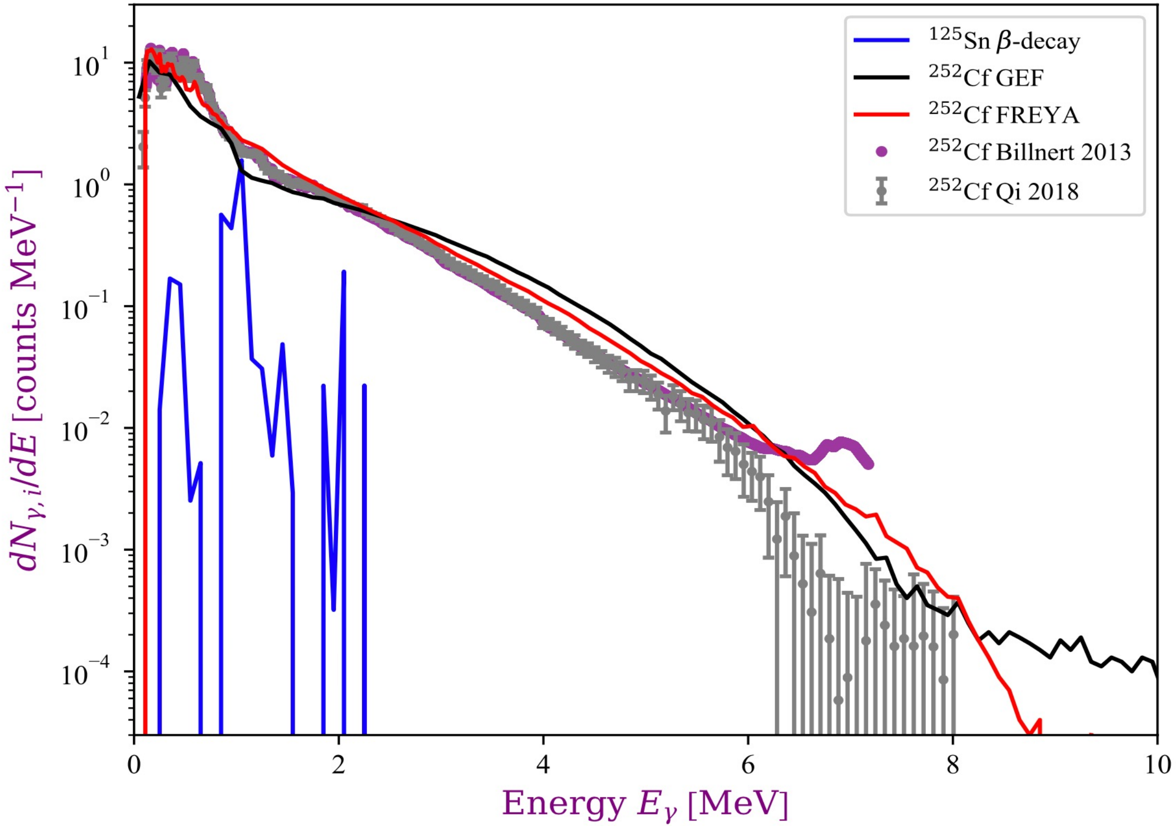


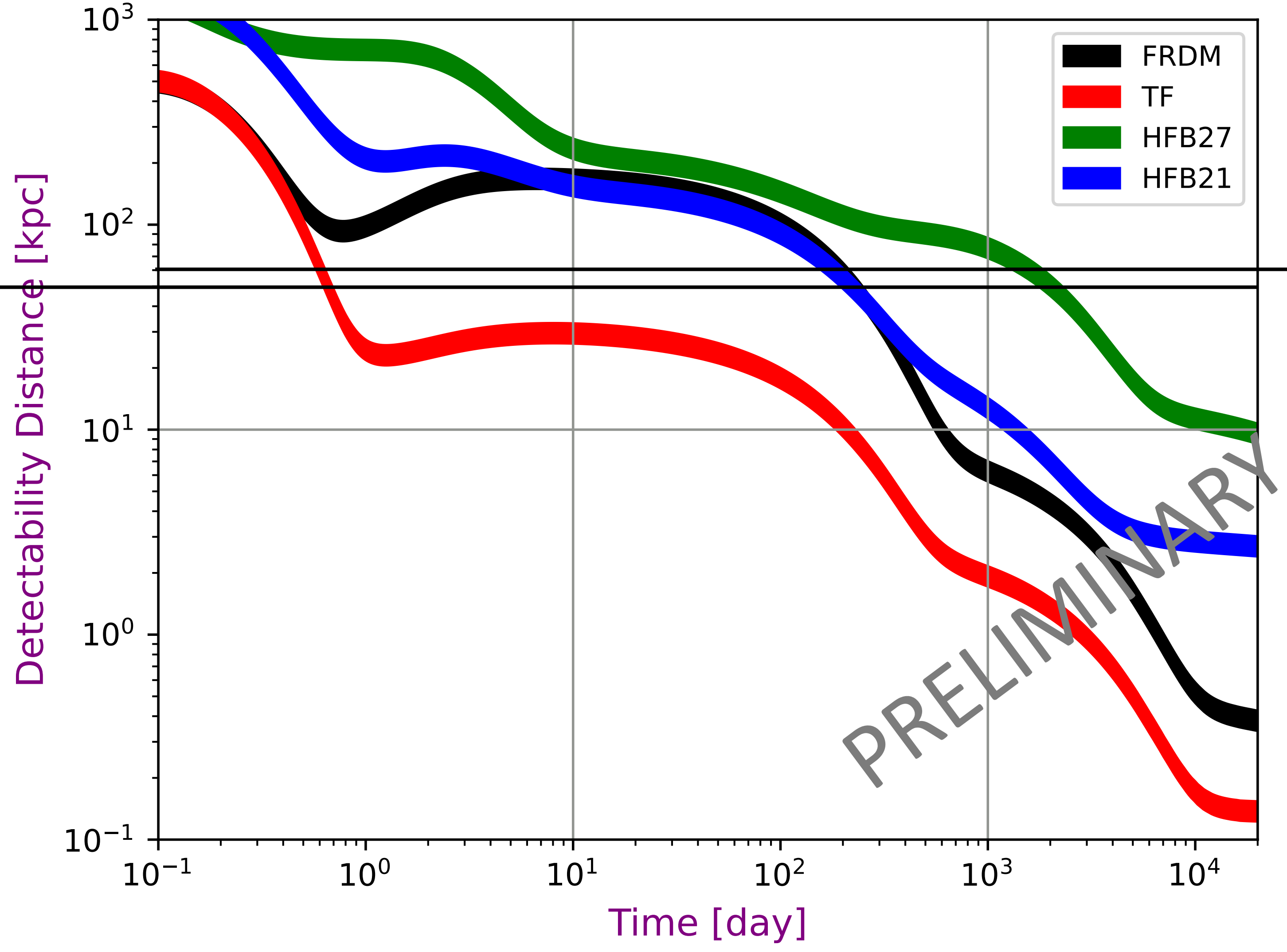


Wang,Vassh+20 (ApJ Letters 903, L3)

Detectability of fission gammas (>3.5 MeV) with the AMEGO telescope:

predicted detectability distance depends on nuclear model

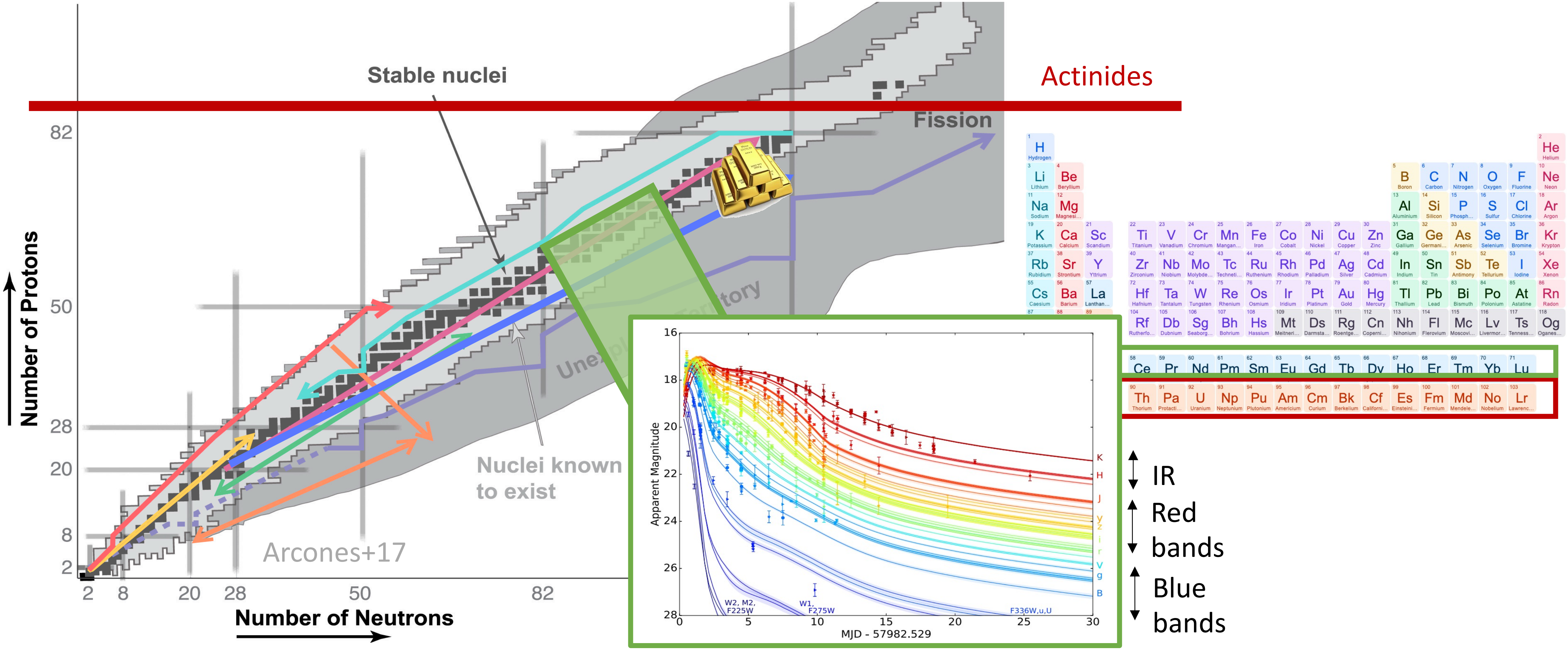
Large Magellanic Cloud (50 kpc)



Wang, Vassh+24 (in prep)

Small Magellanic Cloud (60 kpc)

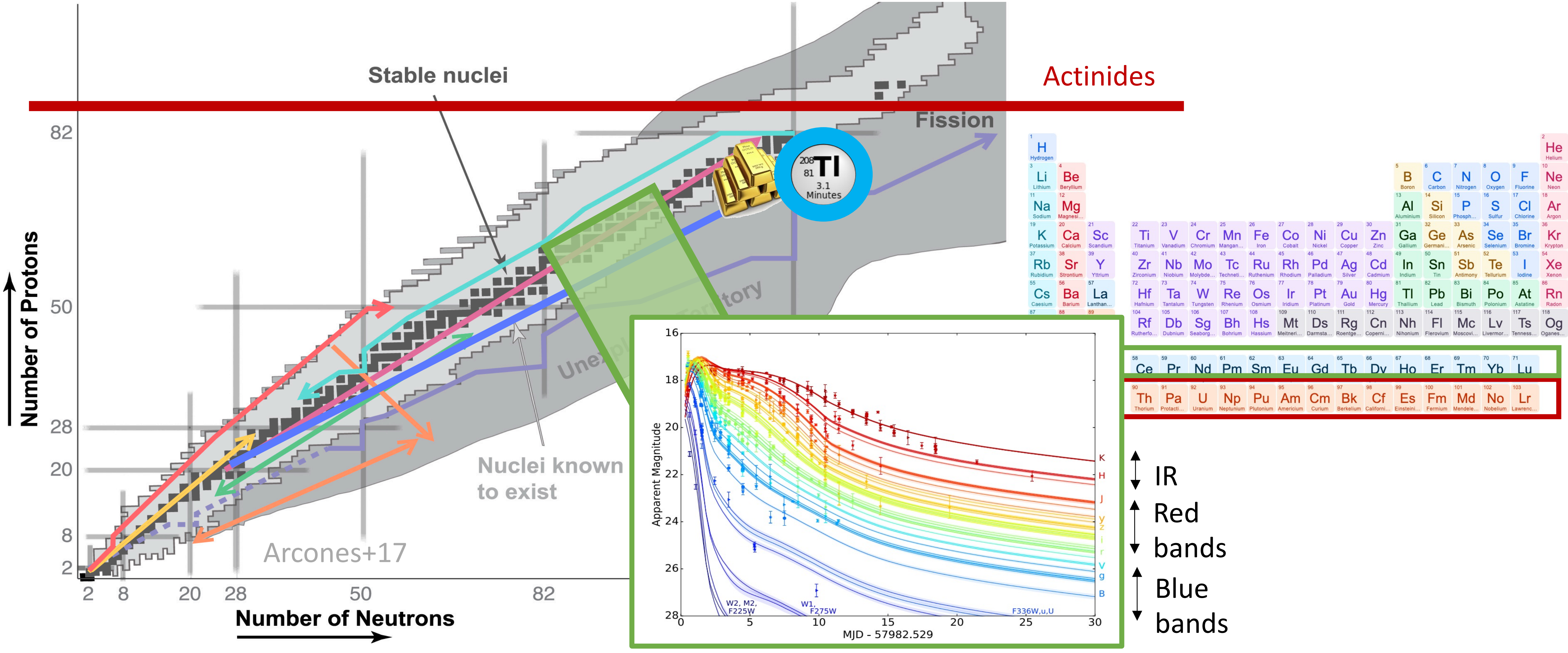
Production of fissioning nuclei in astrophysics?



Villar+17; see also Cowperthwaite+17

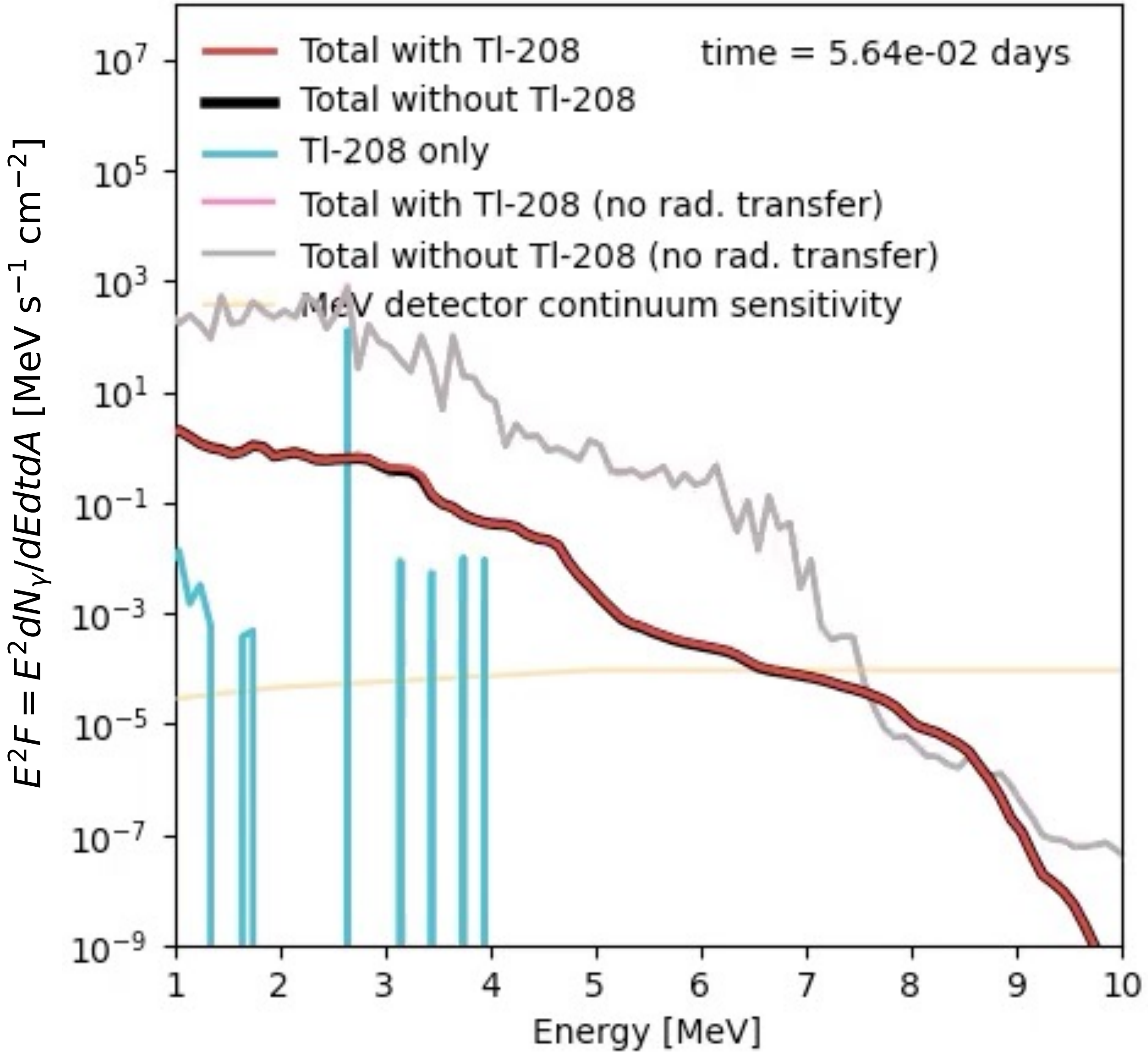
Production of fissioning nuclei in astrophysics?

A beacon of *in situ* lead production – Thallium-208's 2.6 MeV emission line



Villar+17; see also Cowperthwaite+17

r process in neutron star mergers: MeV gamma rays emitted from the β-decay of neutron-rich isotopes



Movie by
M. Larivière

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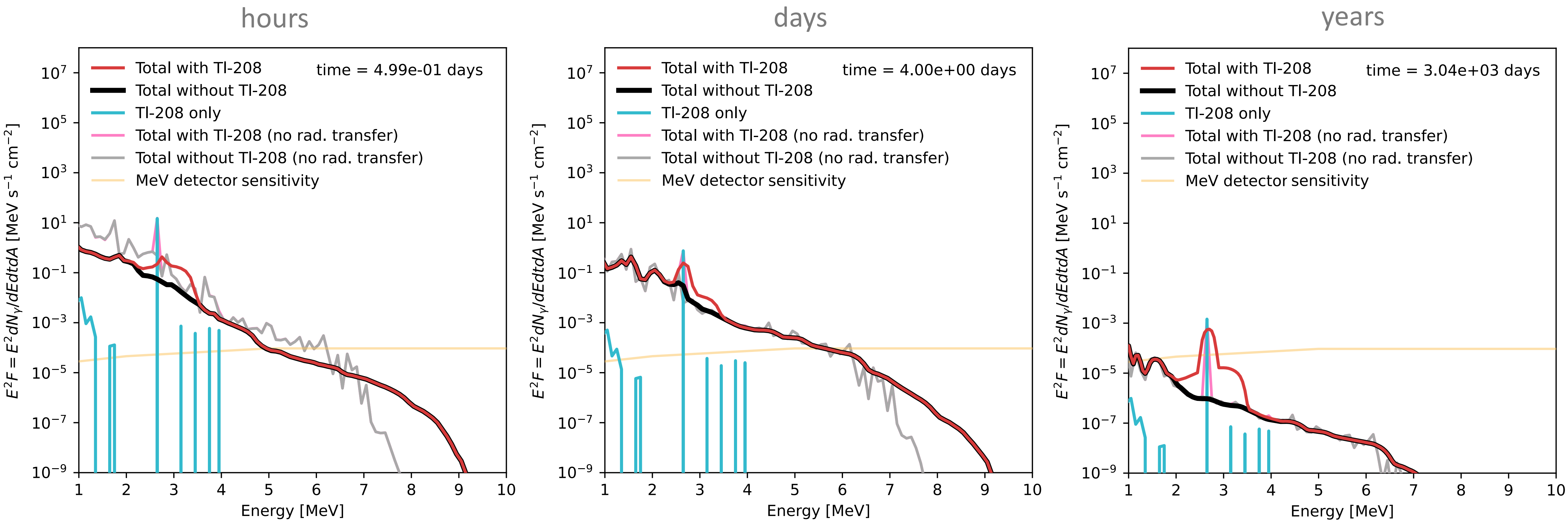
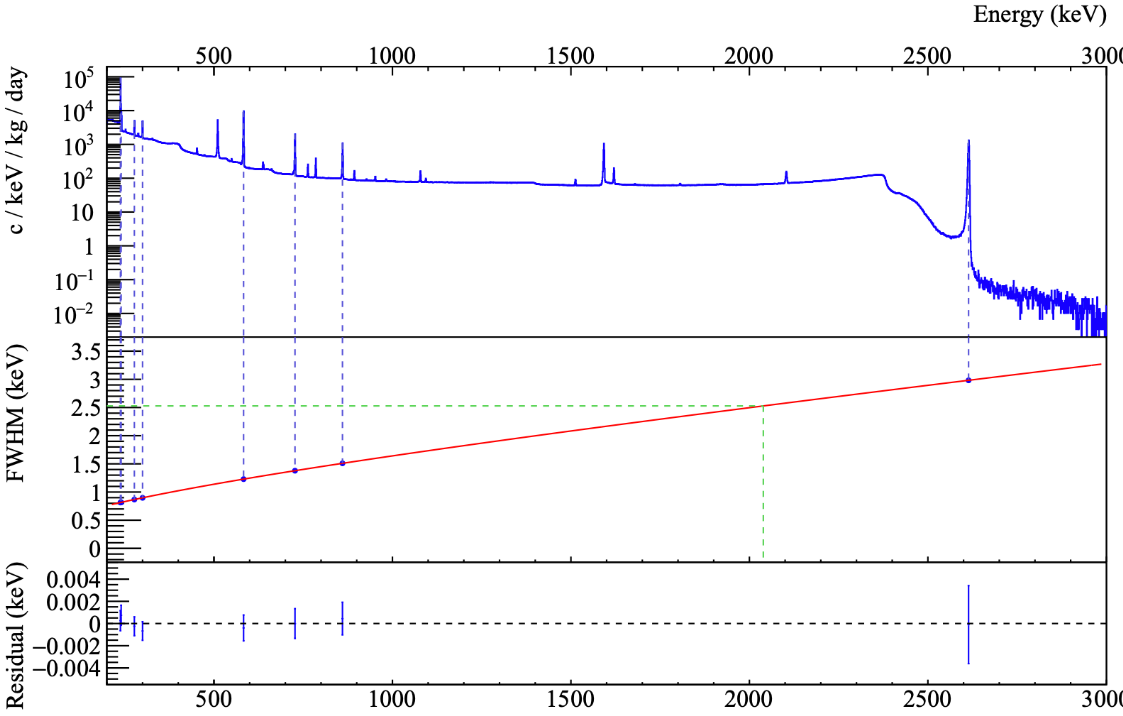


@ 10 kpc (Galactic)

Vassh, Wang, Larivière+24 (PRL 132, 052701)

The 2.6 MeV gamma-ray line of Tl-208 and the Th-232 decay chain



Alvis+19

Majorana demonstrator
(^{76}Ge neutrinoless double β-decay search)

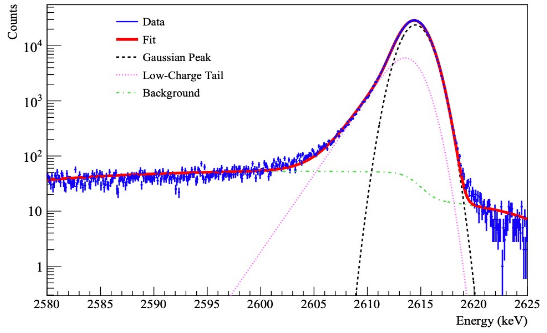
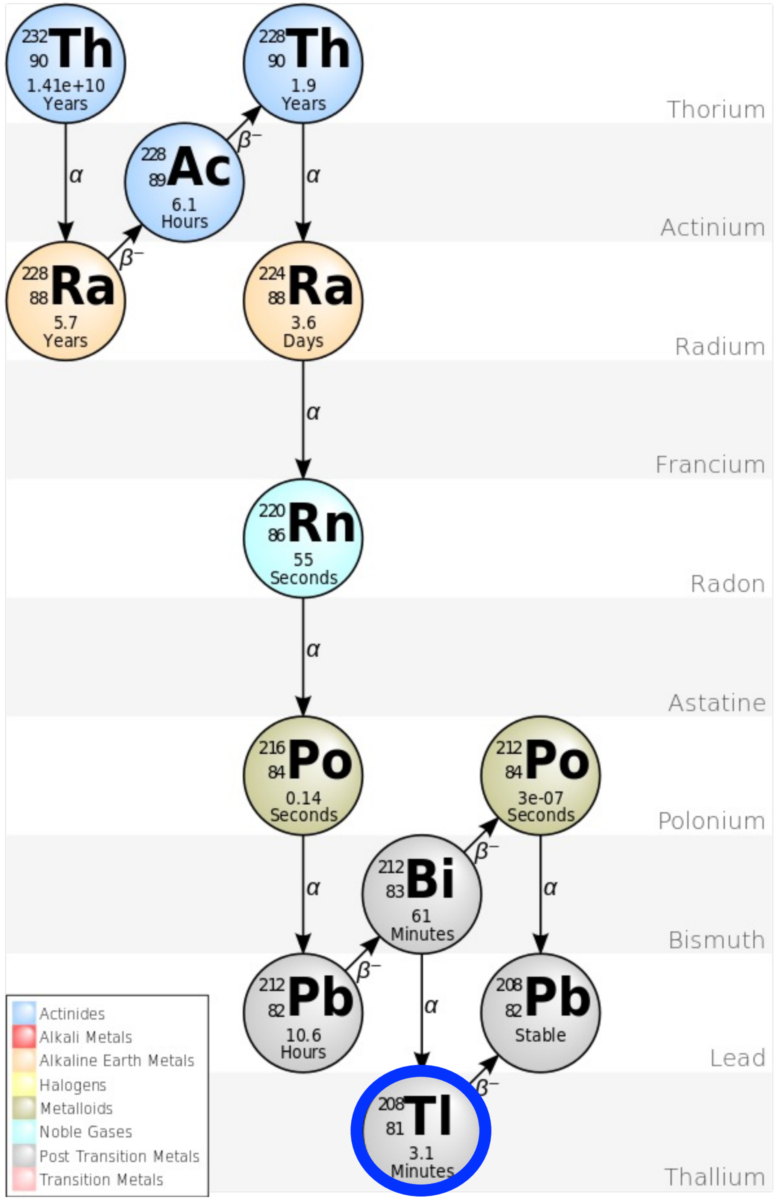
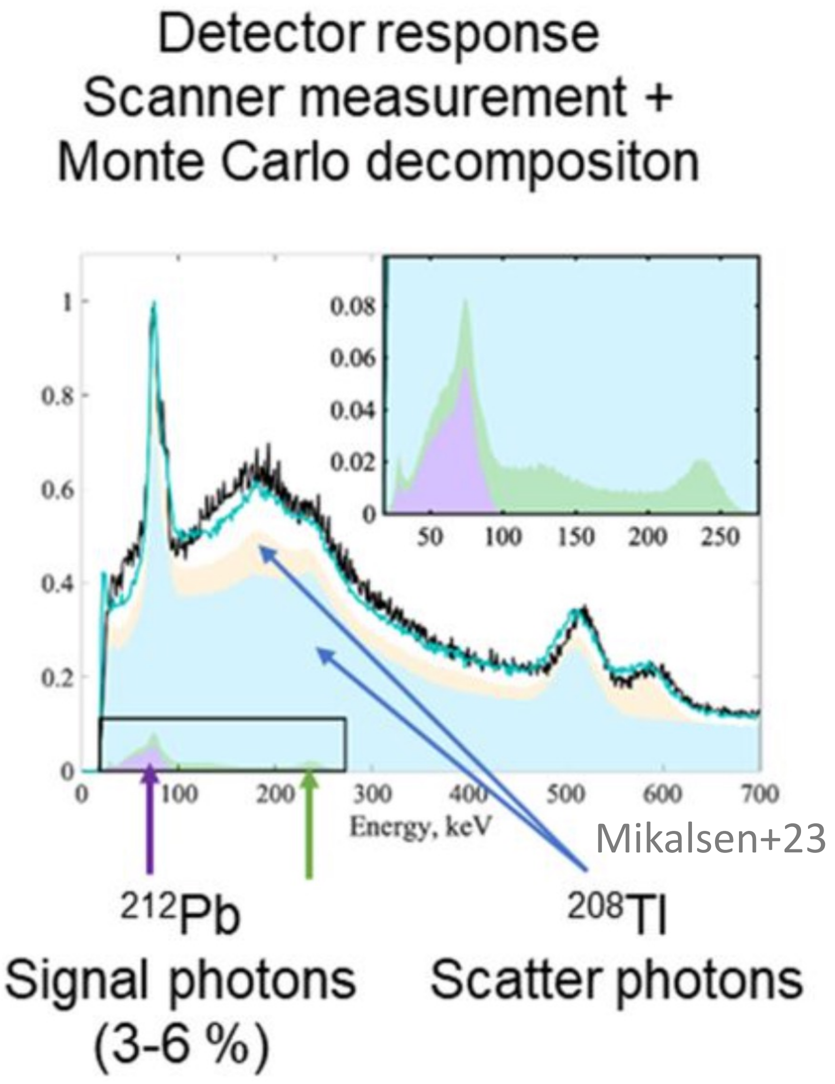


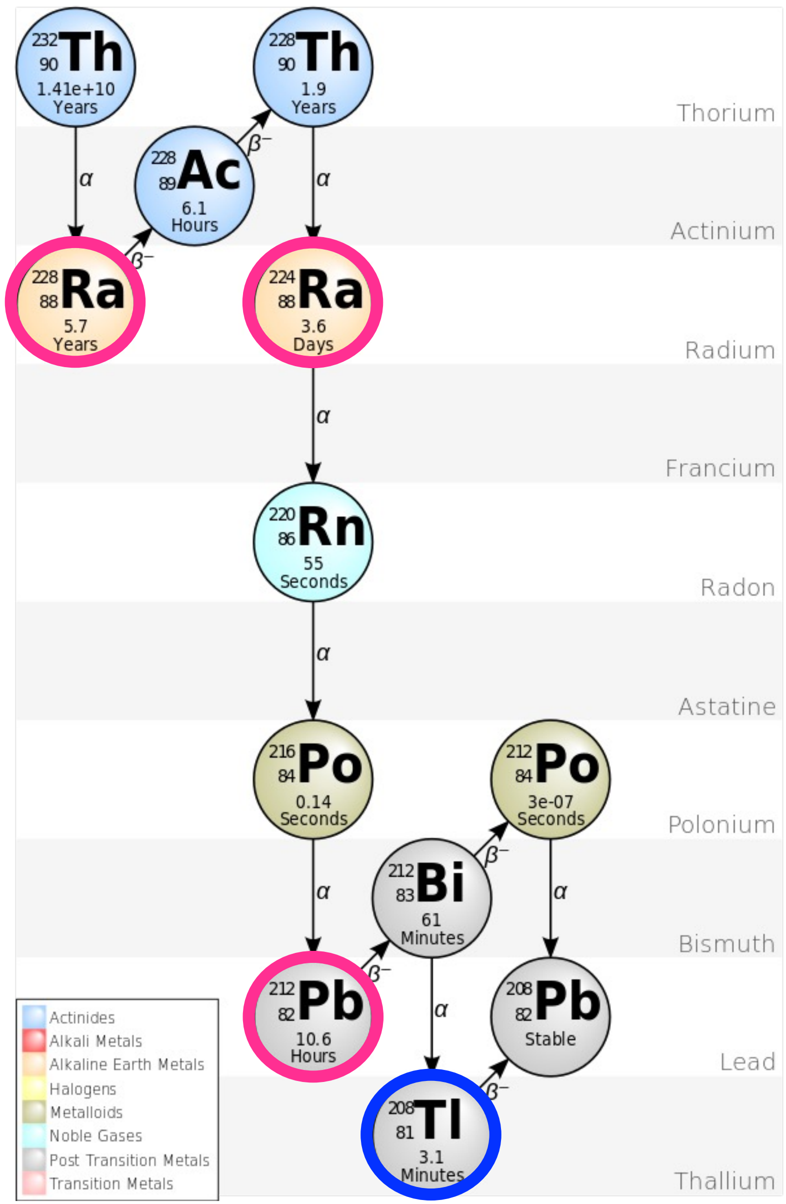
FIG. 3. Color online. The 2615 keV peak from ^{208}Tl in calibration data with all detectors combined is shown in the blue points with statistical error bars.



The 2.6 MeV gamma-ray line of Tl-208 and the Th-232 decay chain

Nuclear medicine:
Clinical imaging studies using ^{224}Ra α-particle therapy

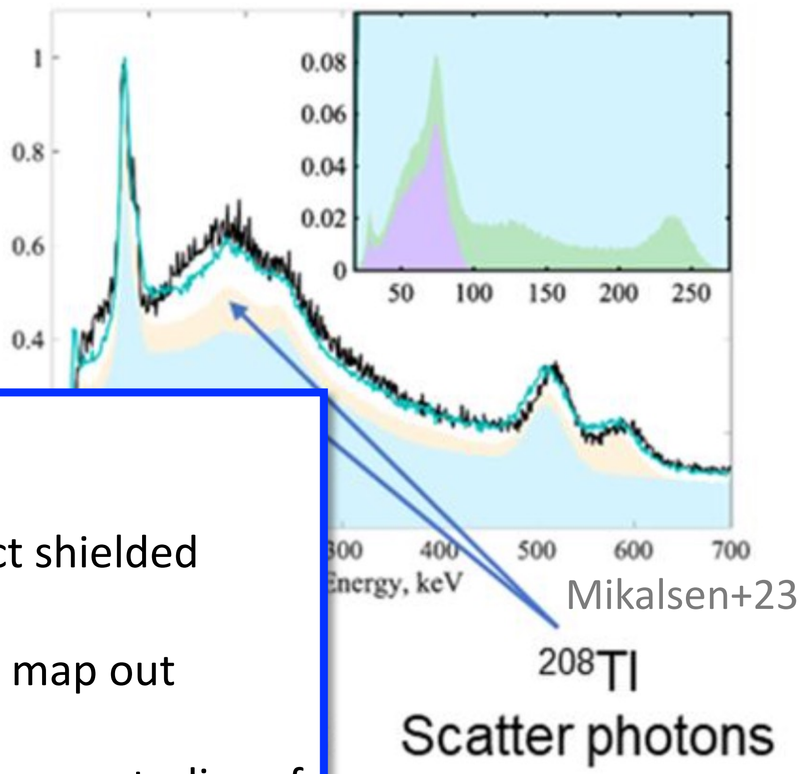




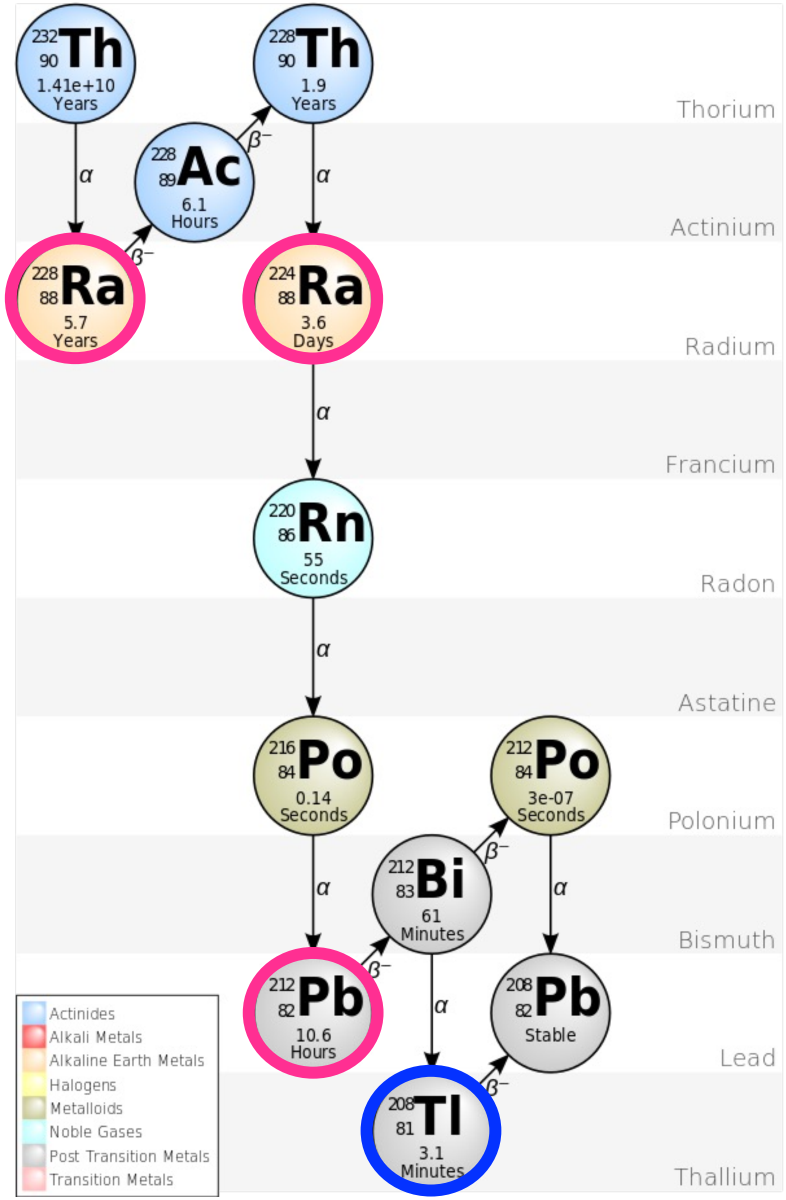
The 2.6 MeV gamma-ray line of Tl-208 and the Th-232 decay chain

Nuclear medicine:
Clinical imaging
studies using ^{224}Ra
α-particle therapy

Detector response
Scanner measurement +
Monte Carlo decompositon



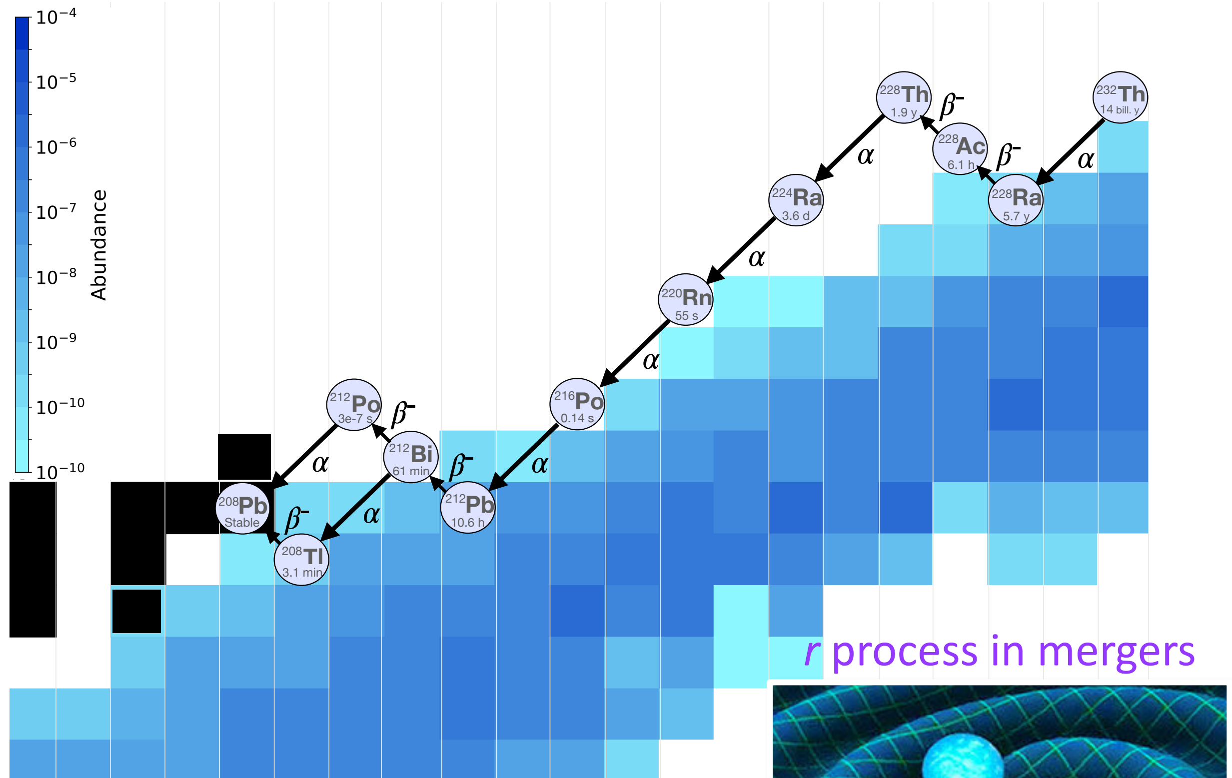
And many more! e.g.:
Exp. background: SNO+,
Nuclear safeguards: detect shielded enriched U-232,
Geology: aerial surveys to map out terrestrial Th,
Soil and Hydrological Sciences: studies of soil and water content….



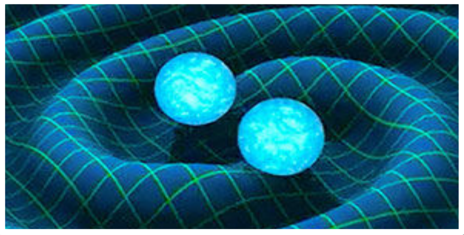
Thallium-208: a beacon of *in situ* neutron capture nucleosynthesis

Nicole Vassh,[1,*] Xilu Wang,[2,†] Maude Larivière,[1,3] Trevor Sprouse,[4,5] Matthew R. Mumpower,[4,5]
Rebecca Surman,[6] Zhenghai Liu,[7] Gail C. McLaughlin,[7] Pavel Denissenkov,[8,9,10] and Falk Herwig[8,9,10]

[1] *TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[2] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, People's Republic of China*
[3] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z1, Canada*



r process in mergers



Vassh, Wang, Larivière+24 (PRL 132, 052701)

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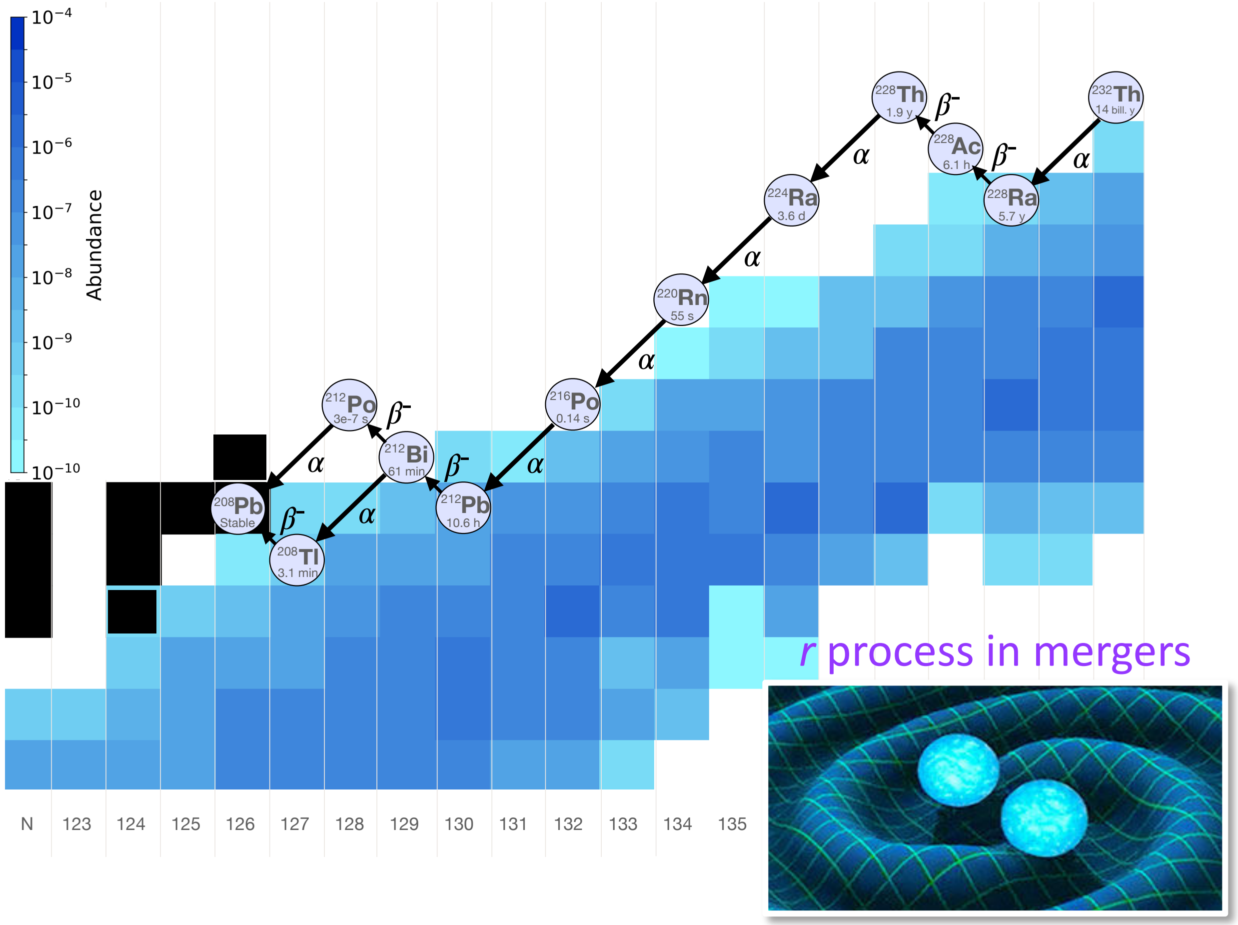
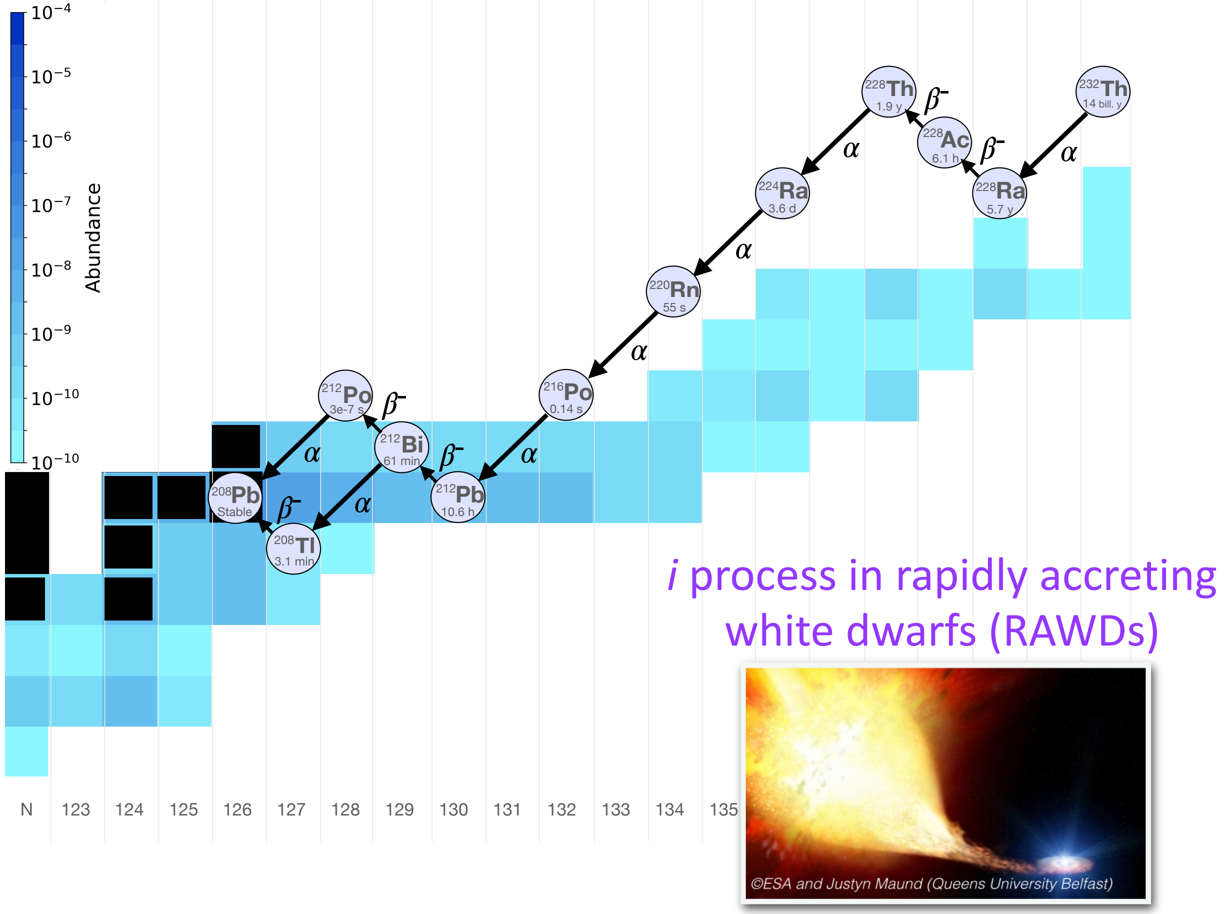
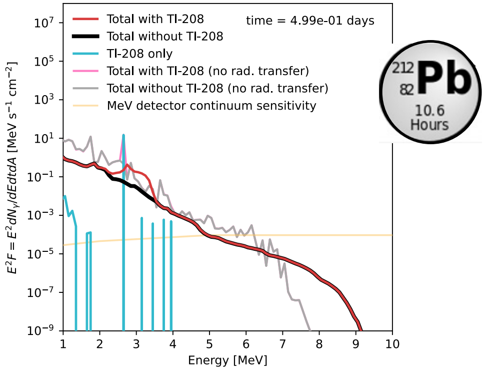
[2] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, 100049, People's Republic of China*
[3] *Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, V6T 1Z1, Canada*

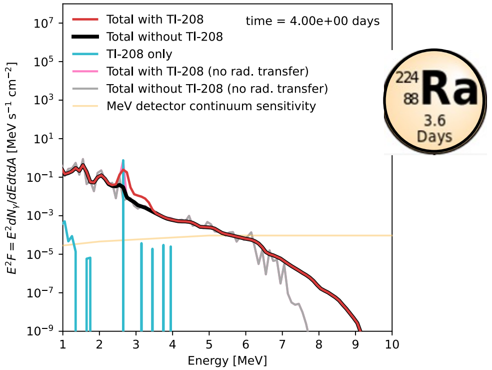


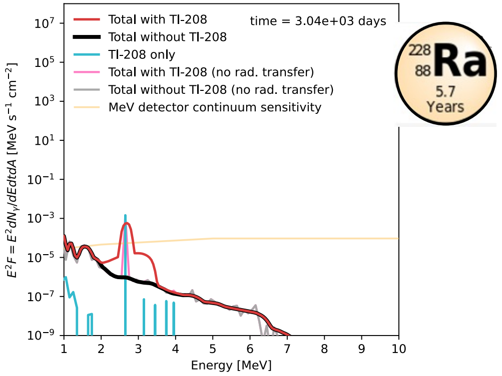


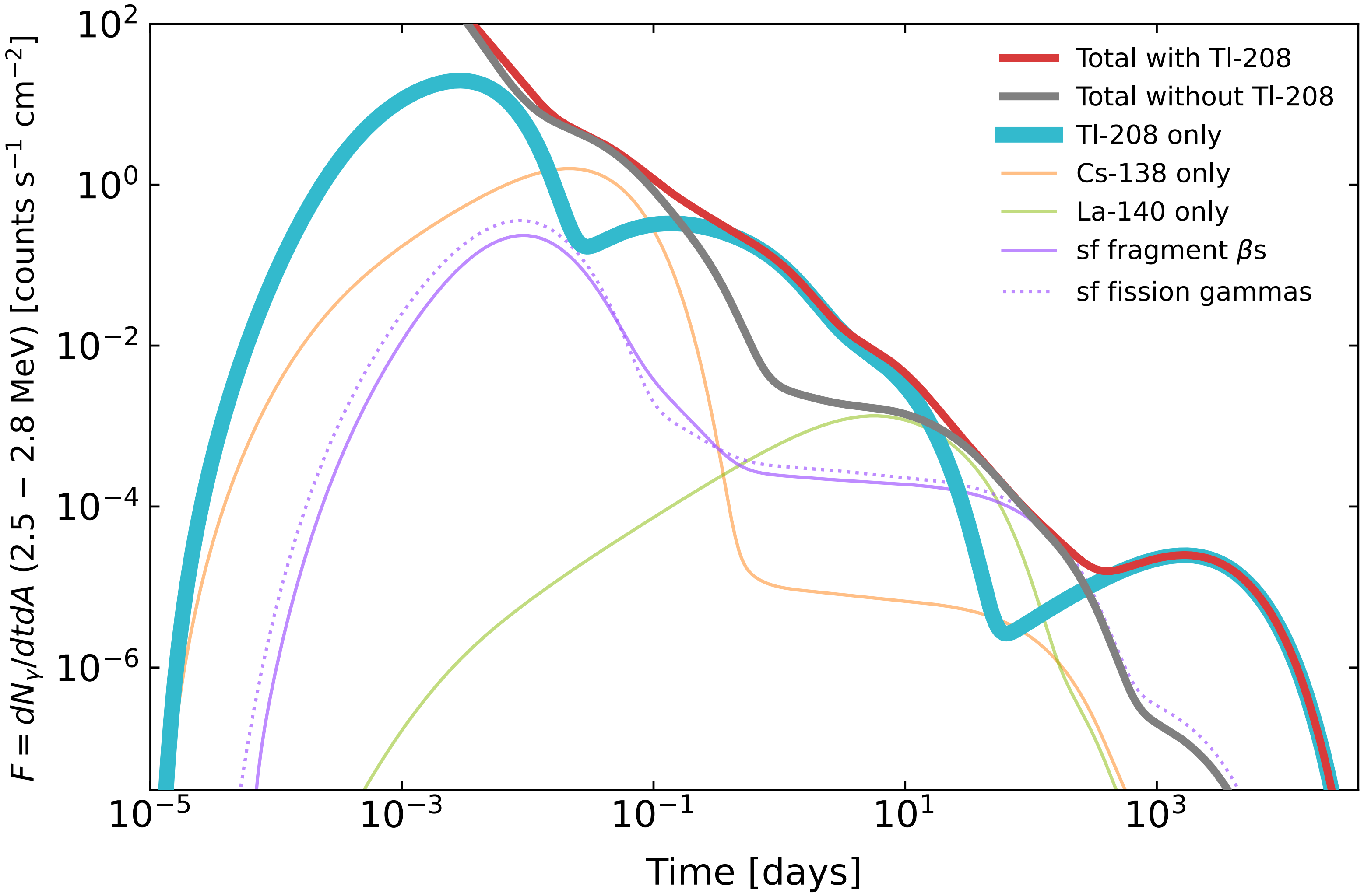
Vassh, Wang, Larivière+24 (PRL 132, 052701)

Comparison with other nuclei with decays emitting in the 2.5-2.8 MeV energy range



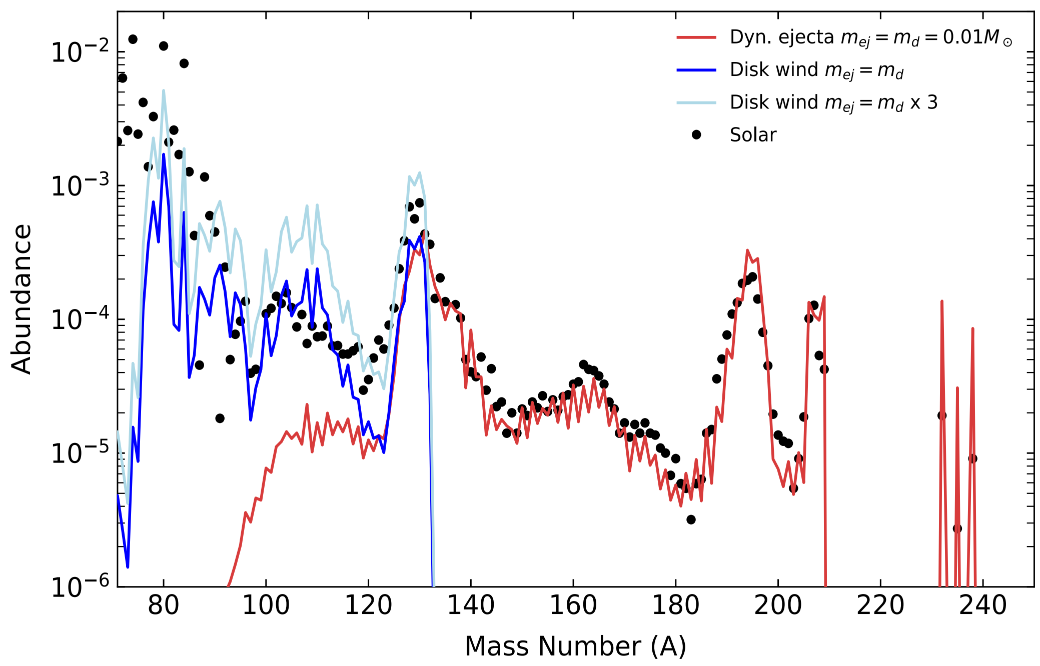


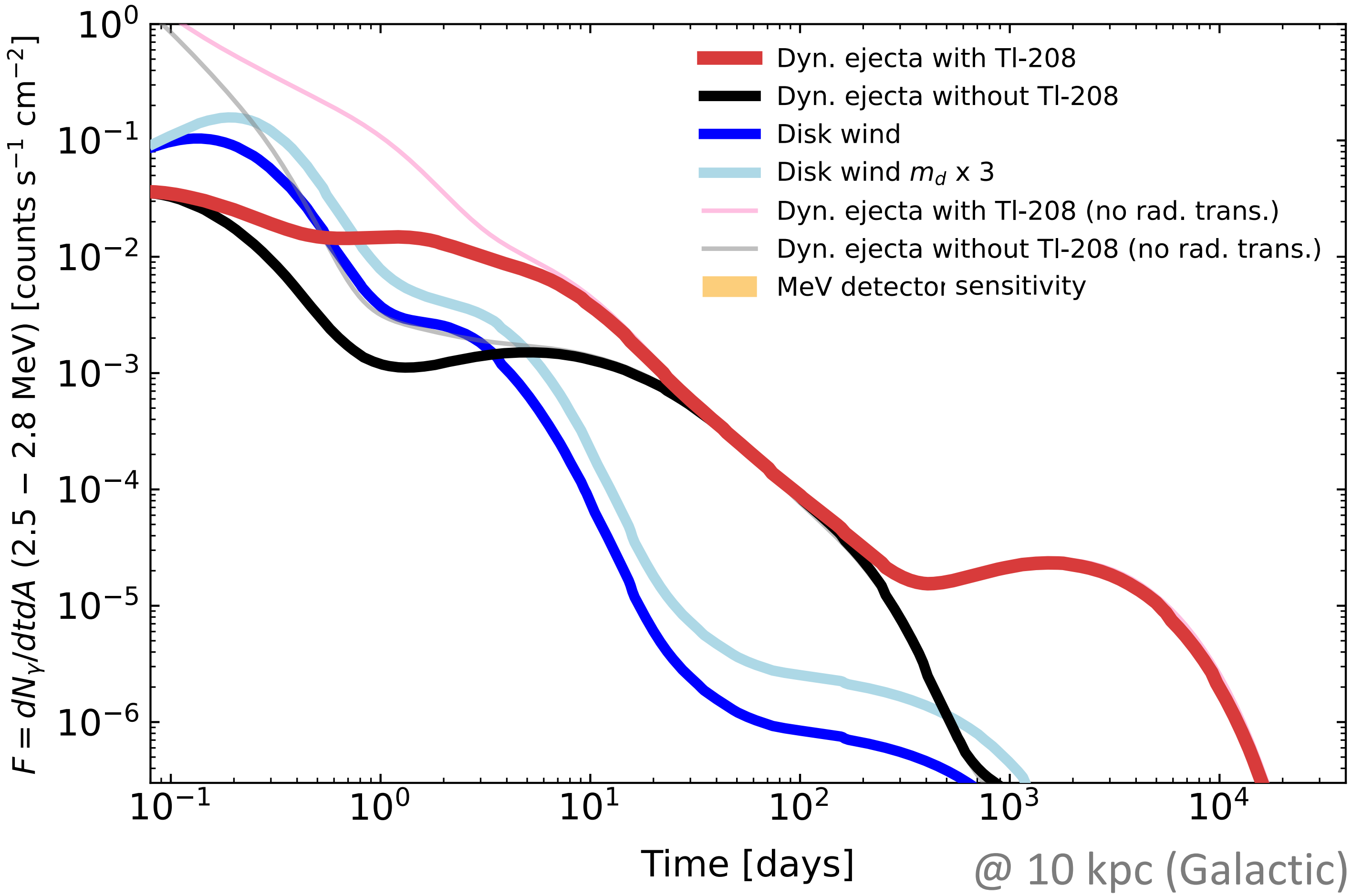




Vassh, Wang, Larivière+24 (PRL 132, 052701)

Comparison with other nuclei with decays emitting in the 2.5-2.8 MeV energy range

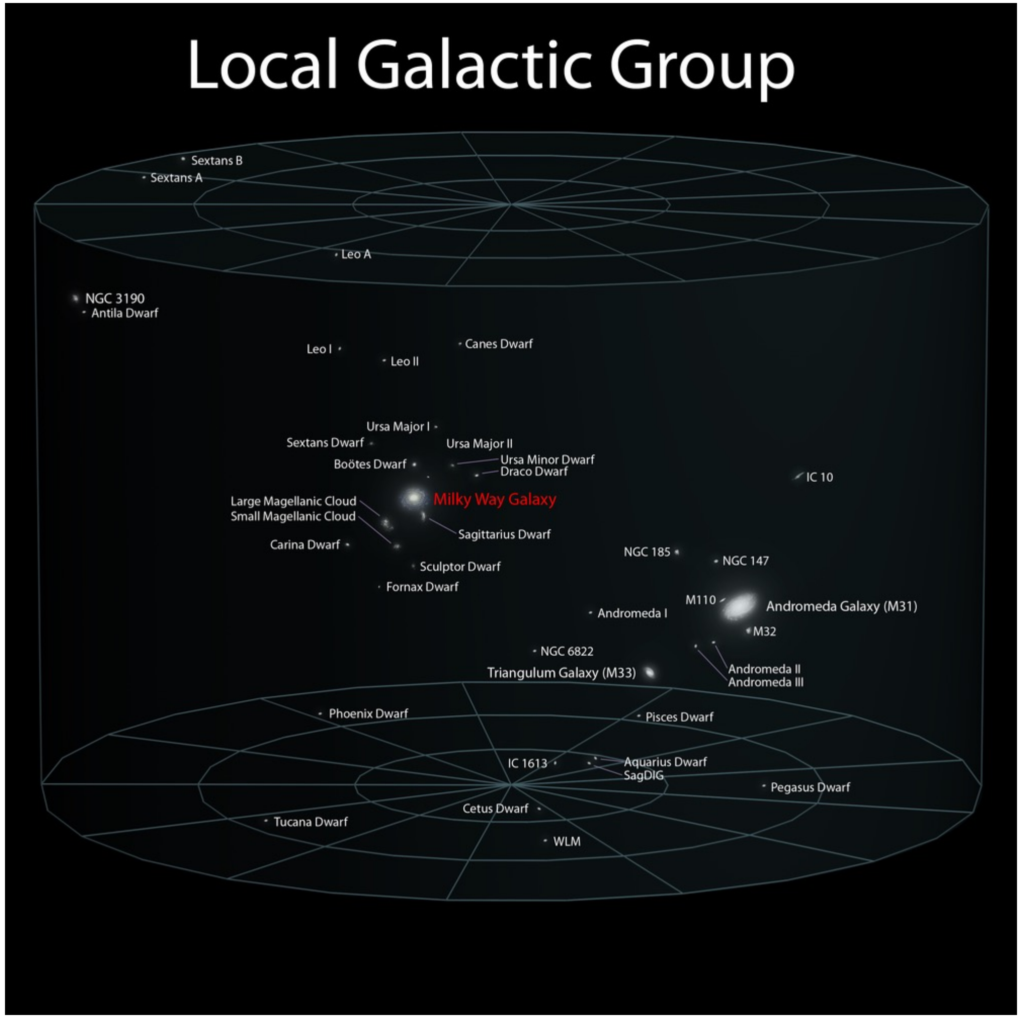


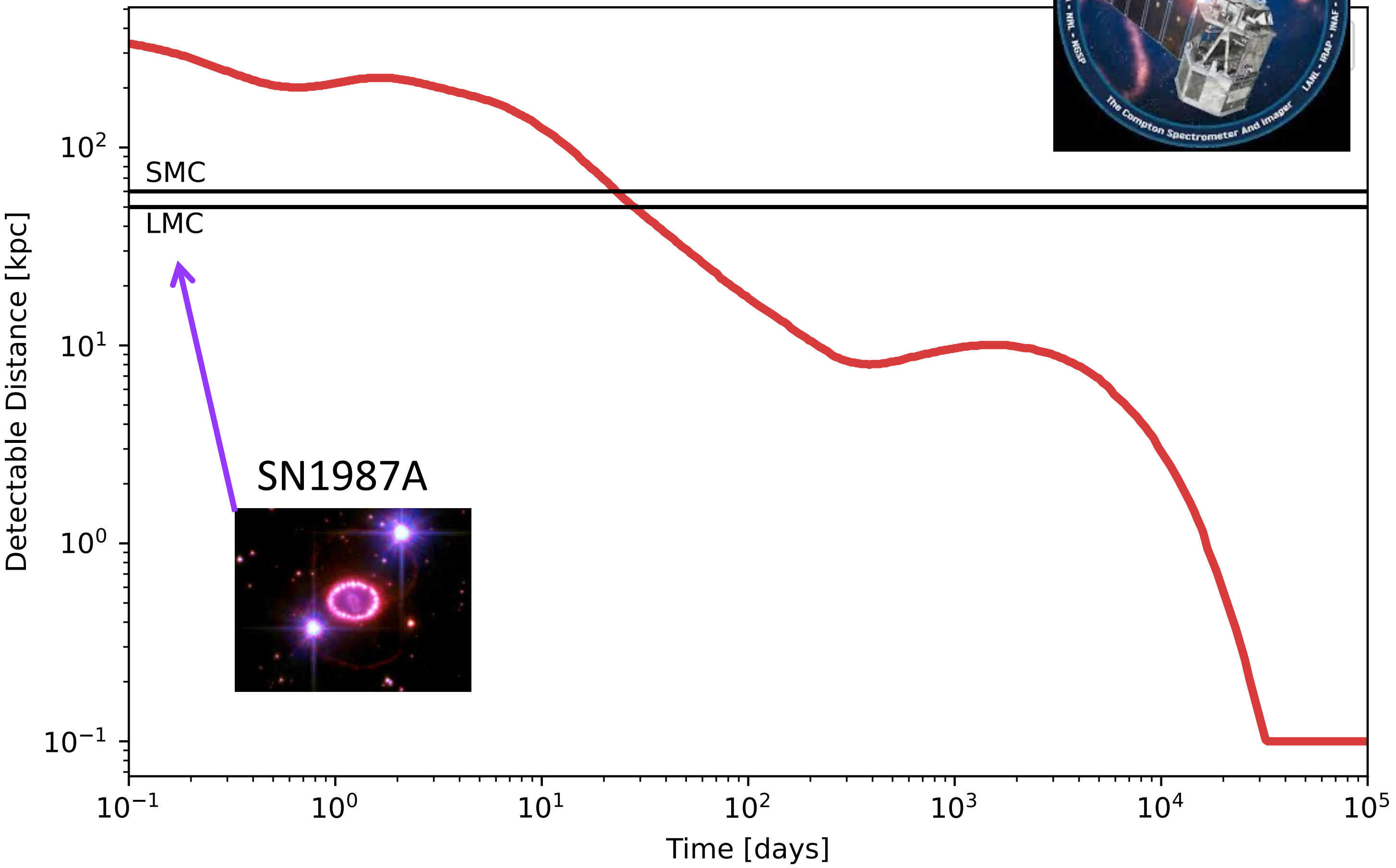


@ 10 kpc (Galactic)

Vassh, Wang, Larivière+24 (PRL 132, 052701)

From how far could we see a thallium signal given projected detector sensitivity?

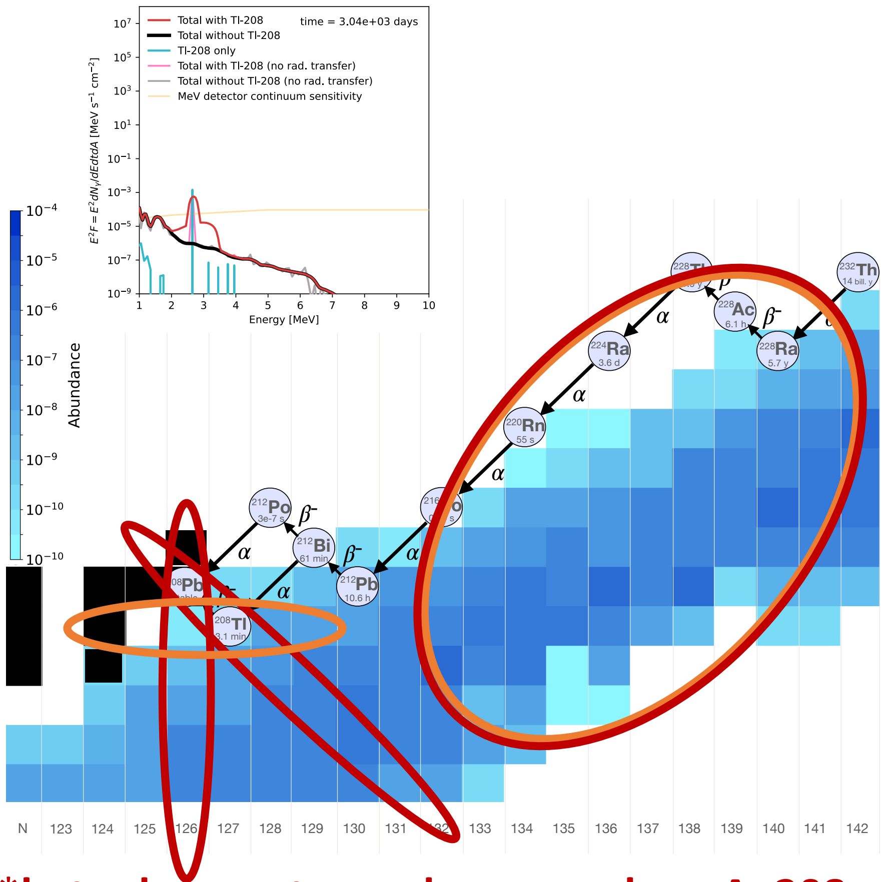


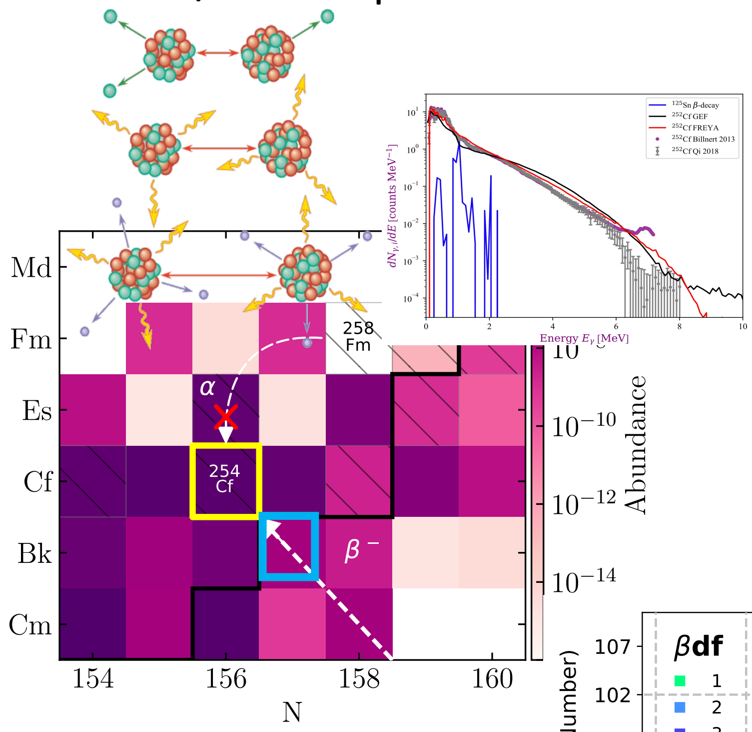


Courtesy of M. Larivière

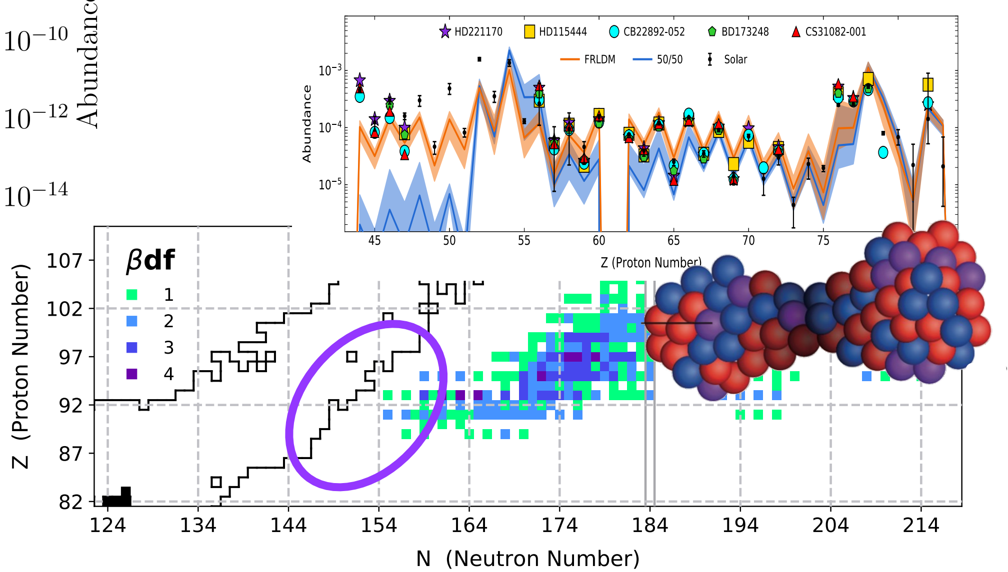
Vassh, Wang, Larivière+24 (PRL 132, 052701)

What can current and near future rare isotope beam facilities target in connection to actinide / lead production observables?





*half-lives and branching ratios of n-rich actinide decays (e.g. Bk-254)
*fission gamma spectra / beta-spectra of n-rich fission daughters



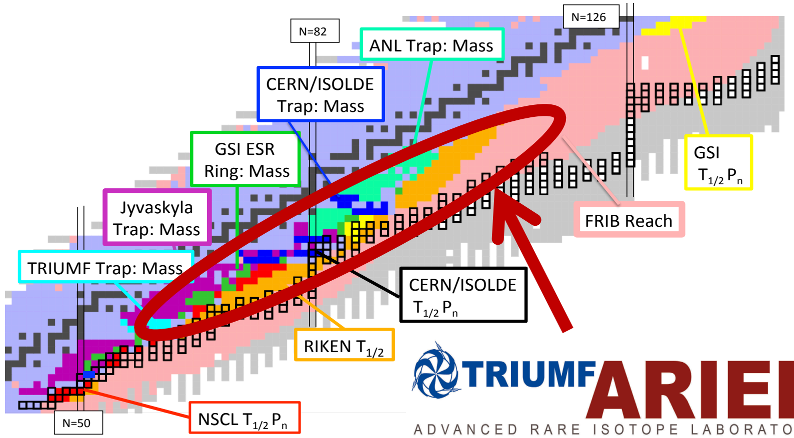
*beta-decay rates and masses along A=208 and N=126 which affect Tl, Ra production
*extend exp boundary for half-lives, branching ratios of A~224-228 elements feeding alpha-decaying species like Ra-224
*neutron capture rates for Tl-205-208

*fission barrier heights and branching ratios near Z=92, N=154 to begin constraining extrapolations and inform rate / yield predictions
*Masses of n-rich daughter products with A~140-160

An international and multi-disciplinary community is working to answer these questions

There are numerous groups worldwide doing calculations, measurements, and observations relevant for heavy element synthesis!

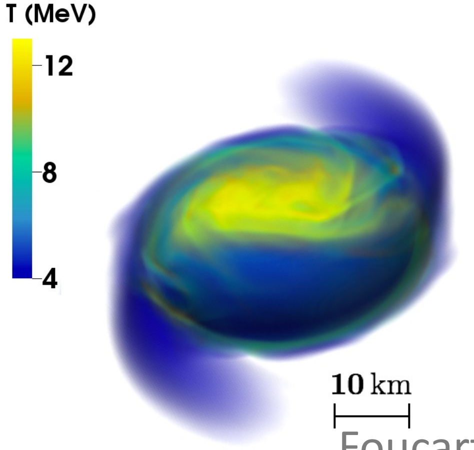
Experimental campaigns



TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY

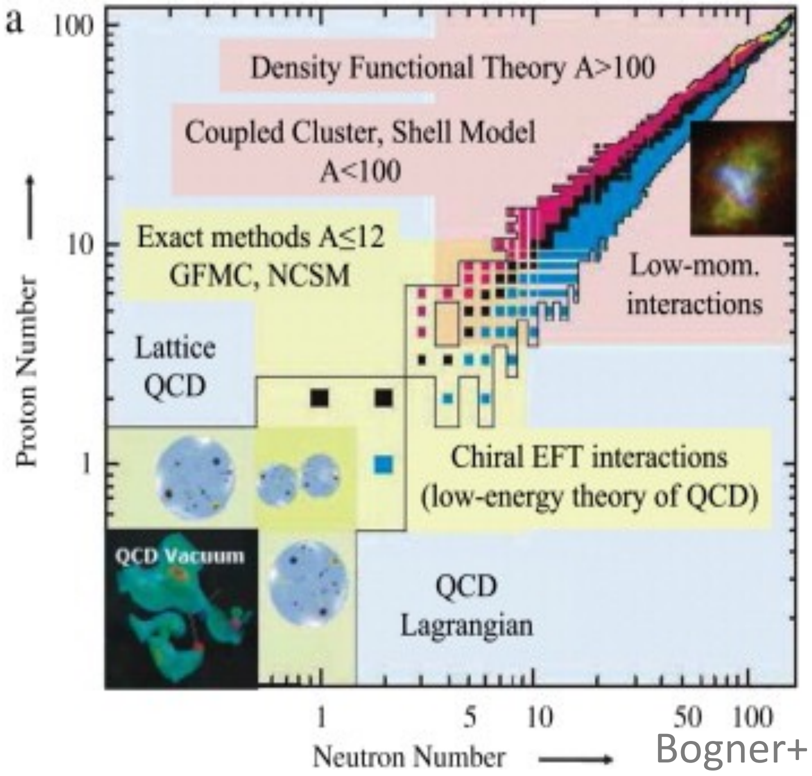
Horowitz+18

Advances in computational simulations



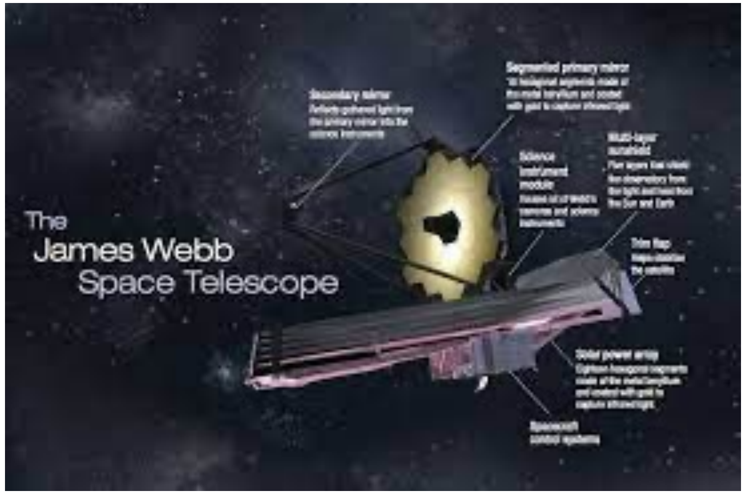
Foucart+16

Advances in nuclear theory



Bogner+

Observational campaigns



LIGO VIRGO