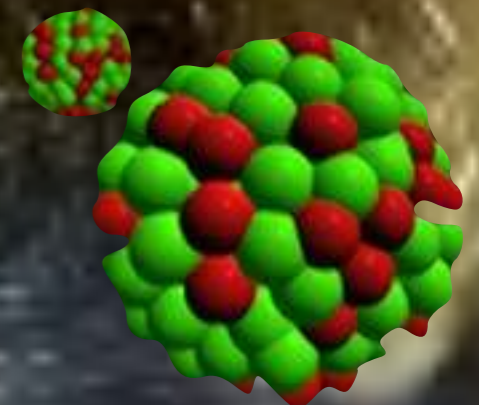
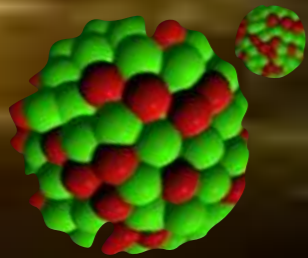
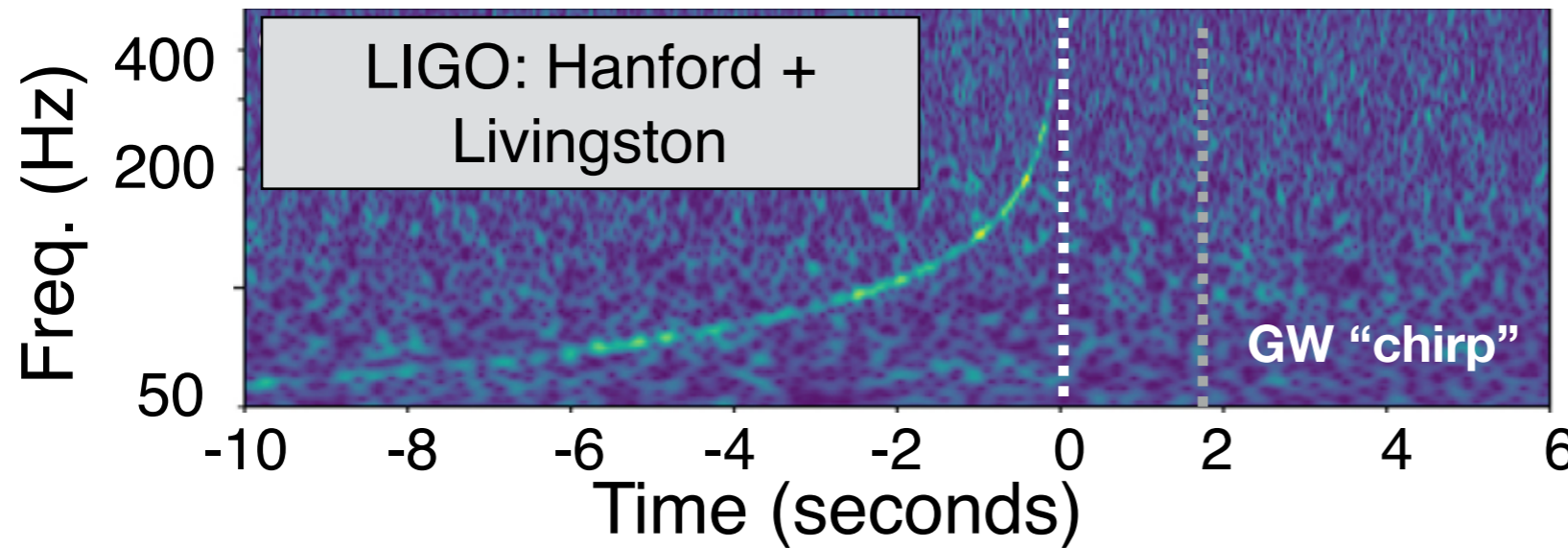


# Diagnosing Nuclear Synthesis from Kilonova Light Curves

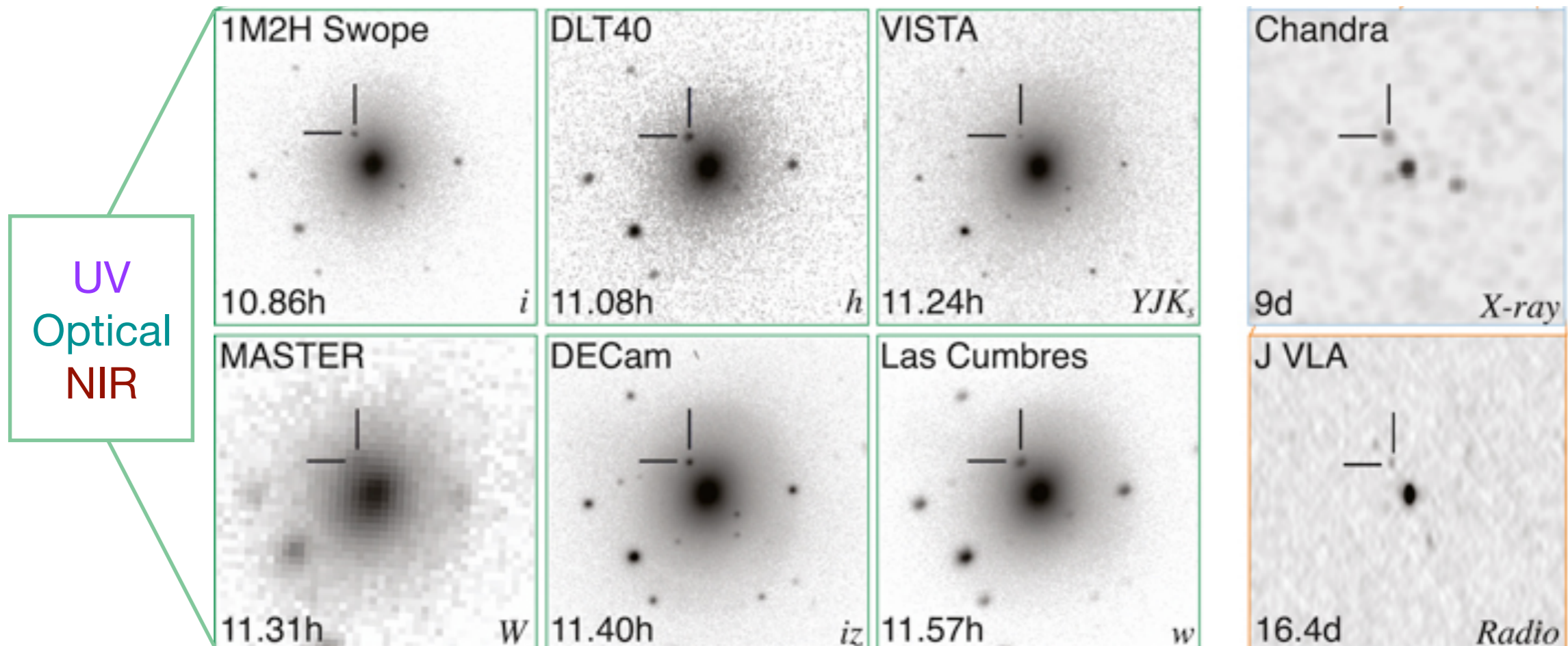
Jennifer Barnes  
Columbia University



# GW170817: the first neutron star merger



A gravitational wave signal with an electromagnetic counterpart detected from  $\gamma$ -ray to radio waves

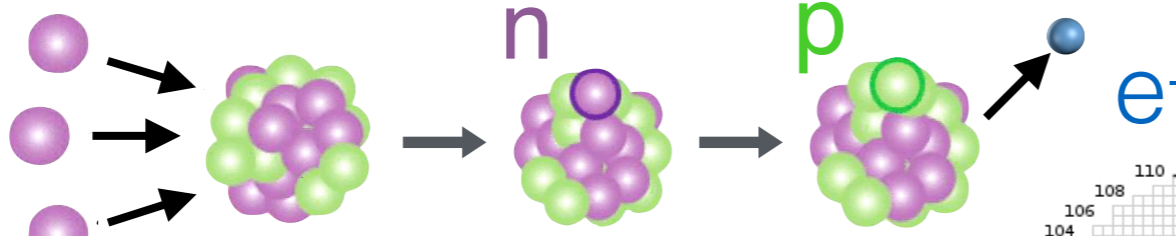


ad. from ALV + EM Partners 17

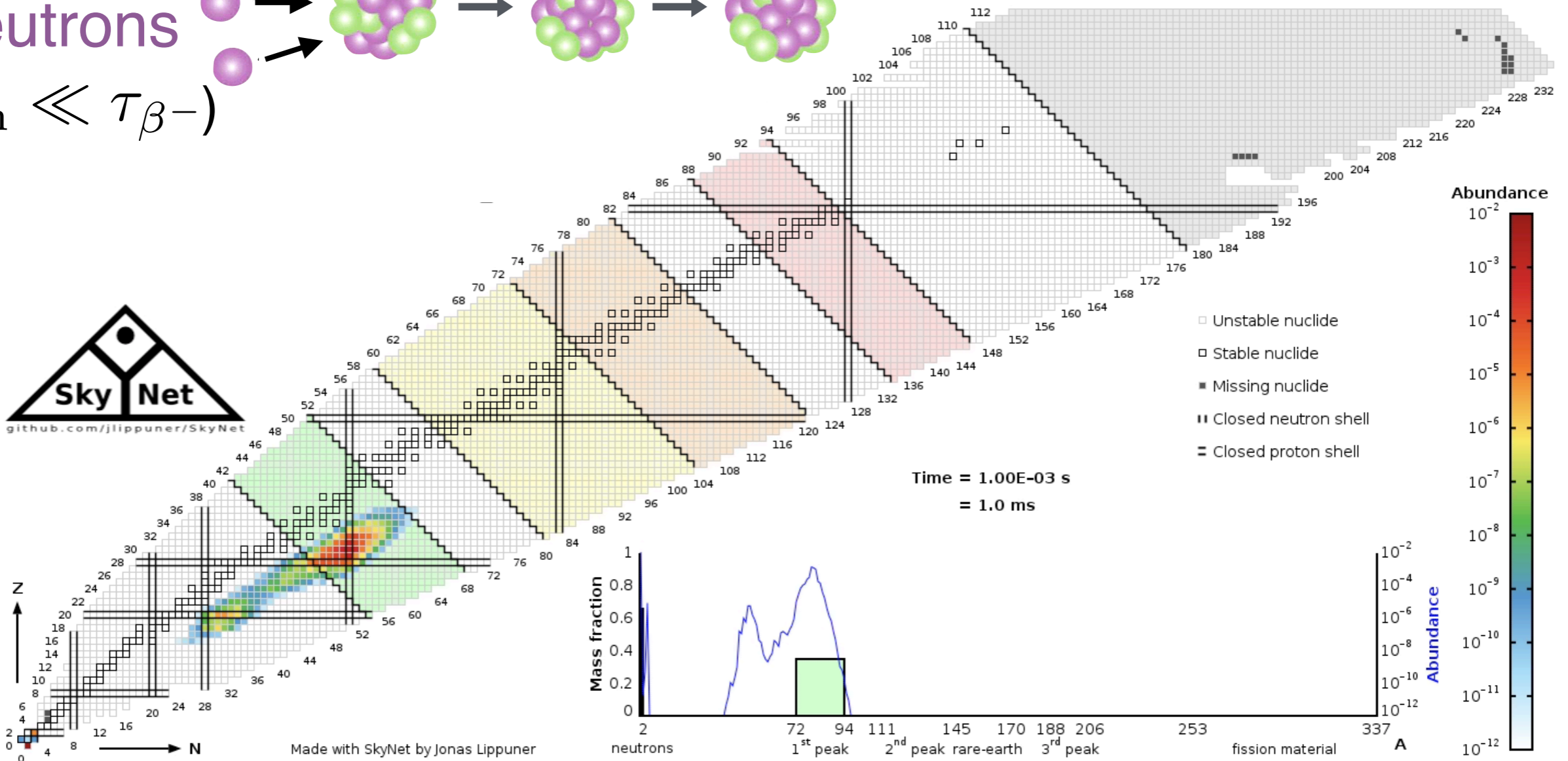
# The thermal (UVOIR) emission\* is powered by radioactivity

\* “kilonova”

free neutrons  
 $(\tau_n \ll \tau_{\beta^-})$



More protons



courtesy J. Lippuner

More neutrons

# *R*-process nucleosynthesis can produce ~50% of nuclei heavier than Fe

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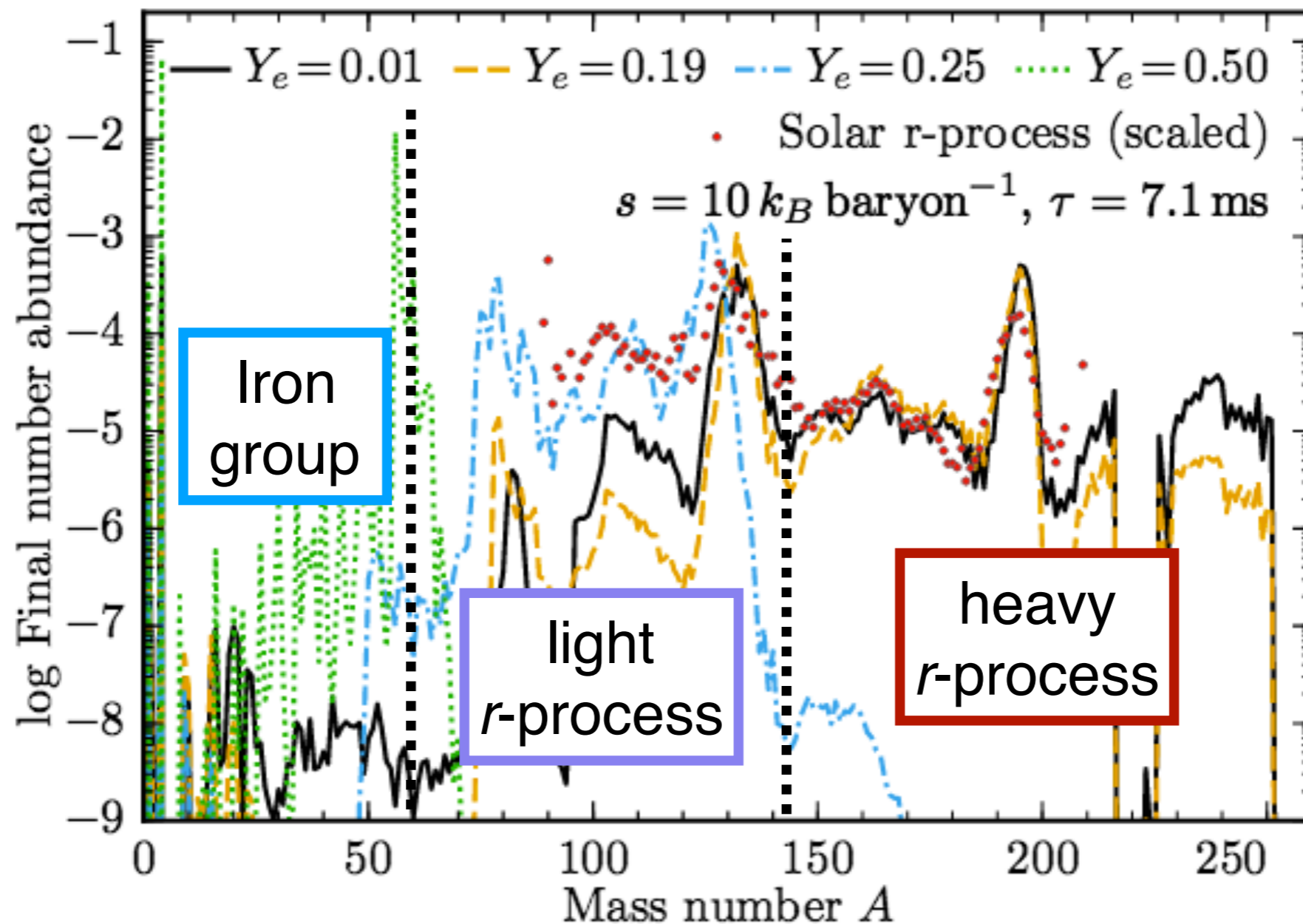
Elements made by  
the *r*-process

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86	
Fr 87	Ra 88	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	
		Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103	

# Can...but doesn't have to

The outcome of the  $r$ -process is highly variable, and we (currently) have only crude diagnostics for the composition

## I. Variability

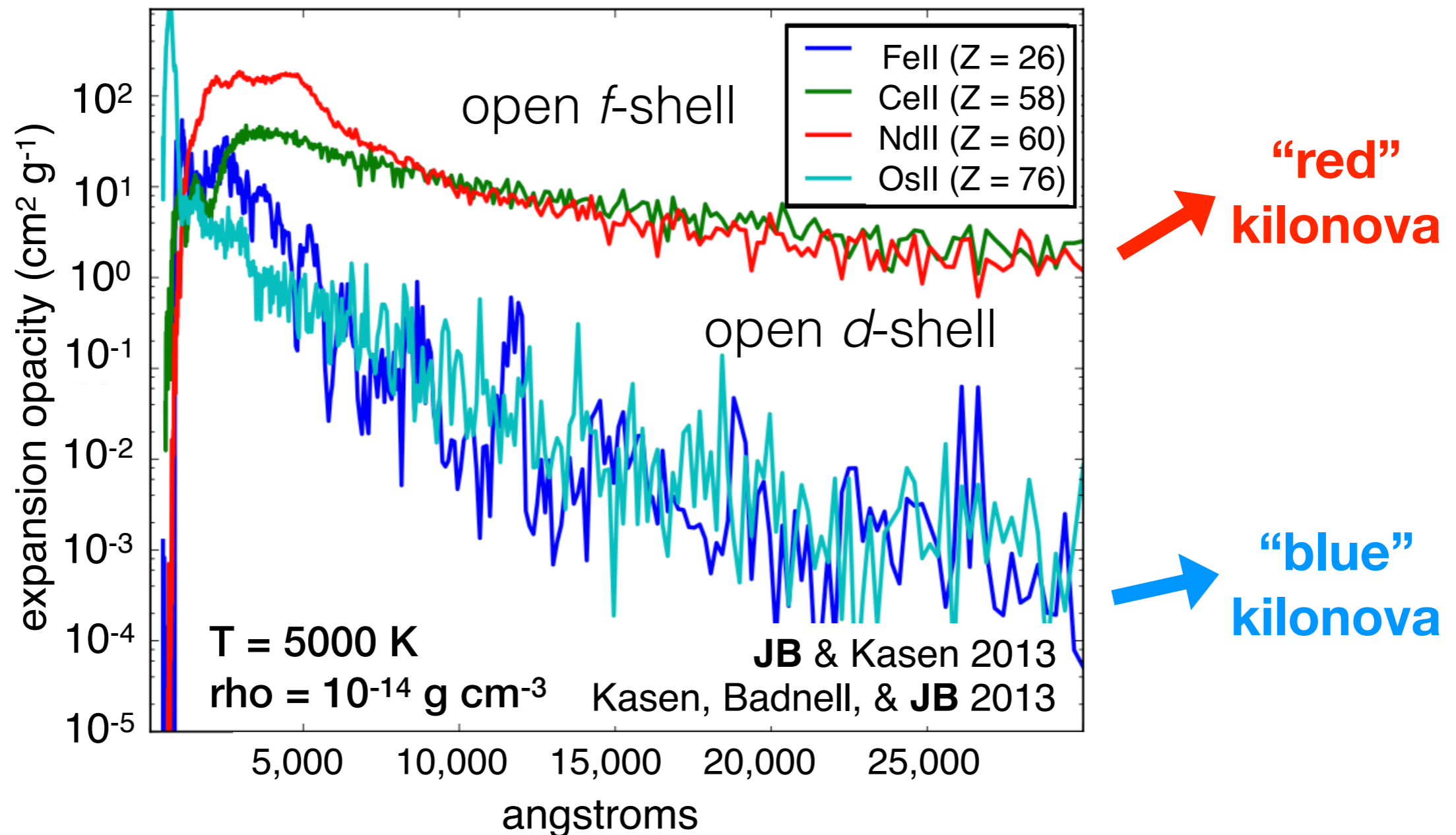


$$Y_e = \frac{p}{p + n}$$

# Can...but doesn't have to

The outcome of the  $r$ -process is highly variable, and we (currently) have only crude diagnostics for the composition

## II. Diagnostics



# Did the NS merger really synthesize the full range of r-process elements?

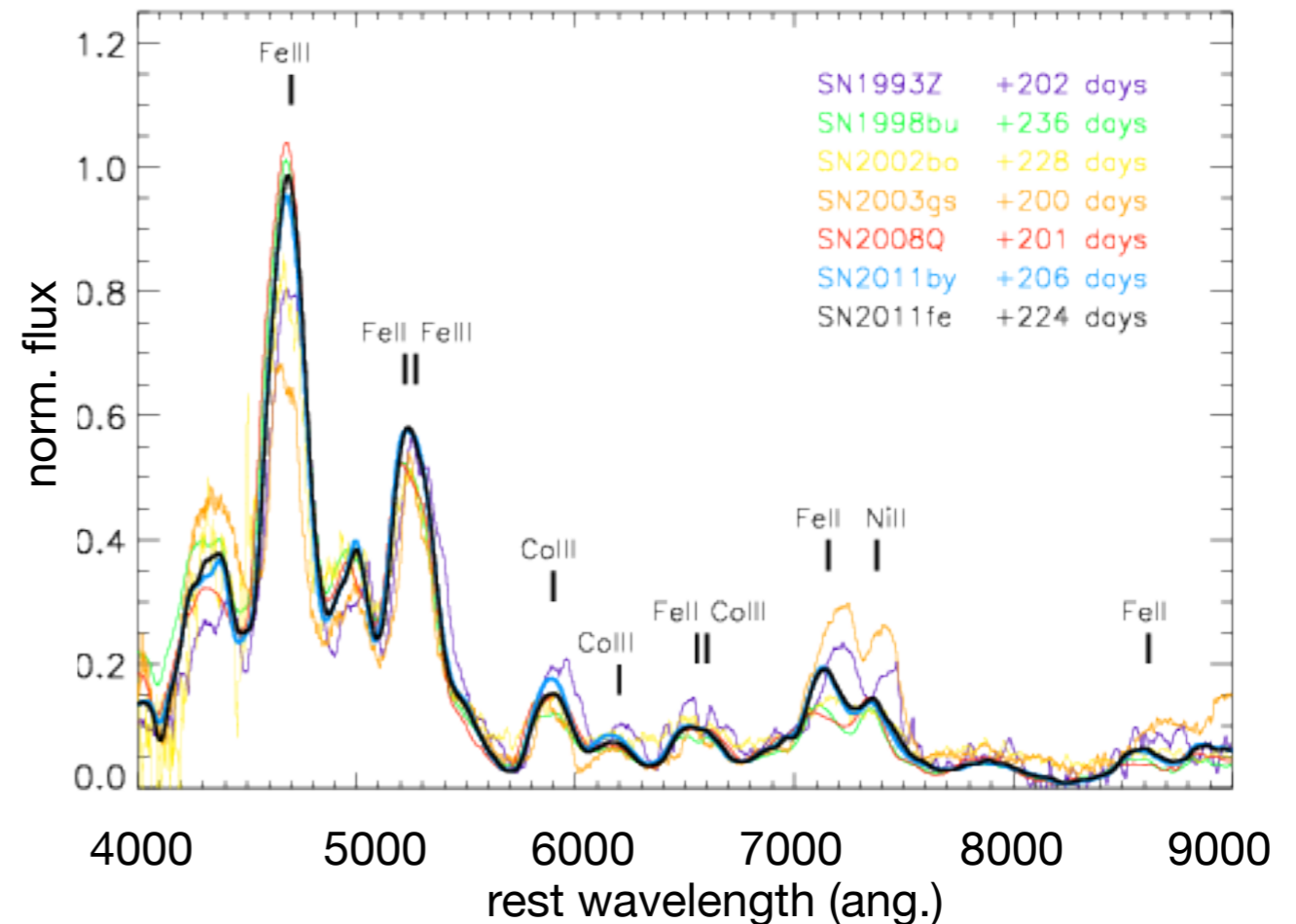
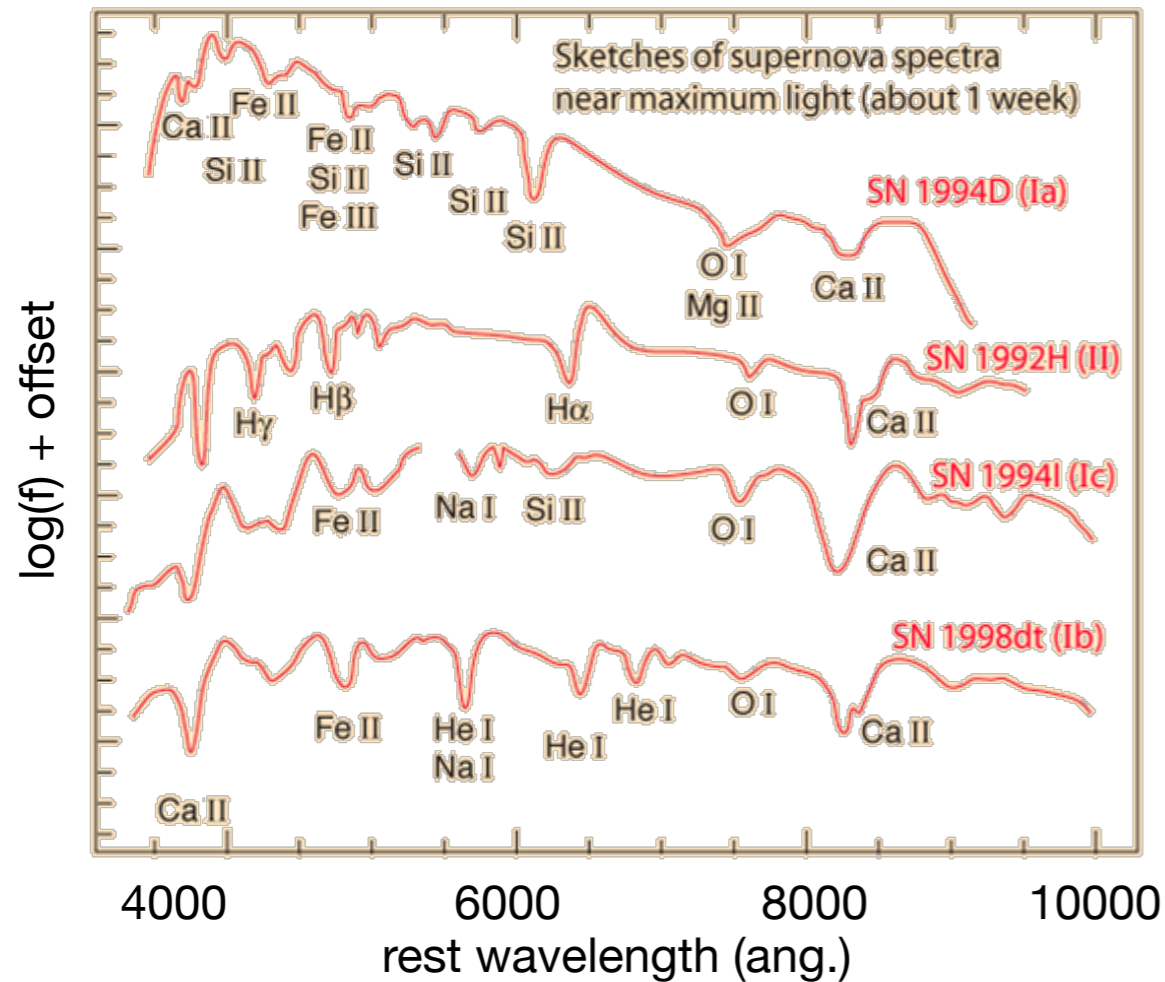
Elements made by the *r*-process

The periodic table shows elements made by the *r*-process highlighted in green. Elements Pt (78), Au (79), U (92), and Pu (94) are circled in red. A bracket on the left indicates that elements from La (57) to Lu (71) and Ac (89) to Lr (103) are also included in the *r*-process synthesis.

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86	
Fr 87	Ra 88	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	
		Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103	

# Tools for probing the composition

## I. Spectral features (in the photospheric or nebular phase)



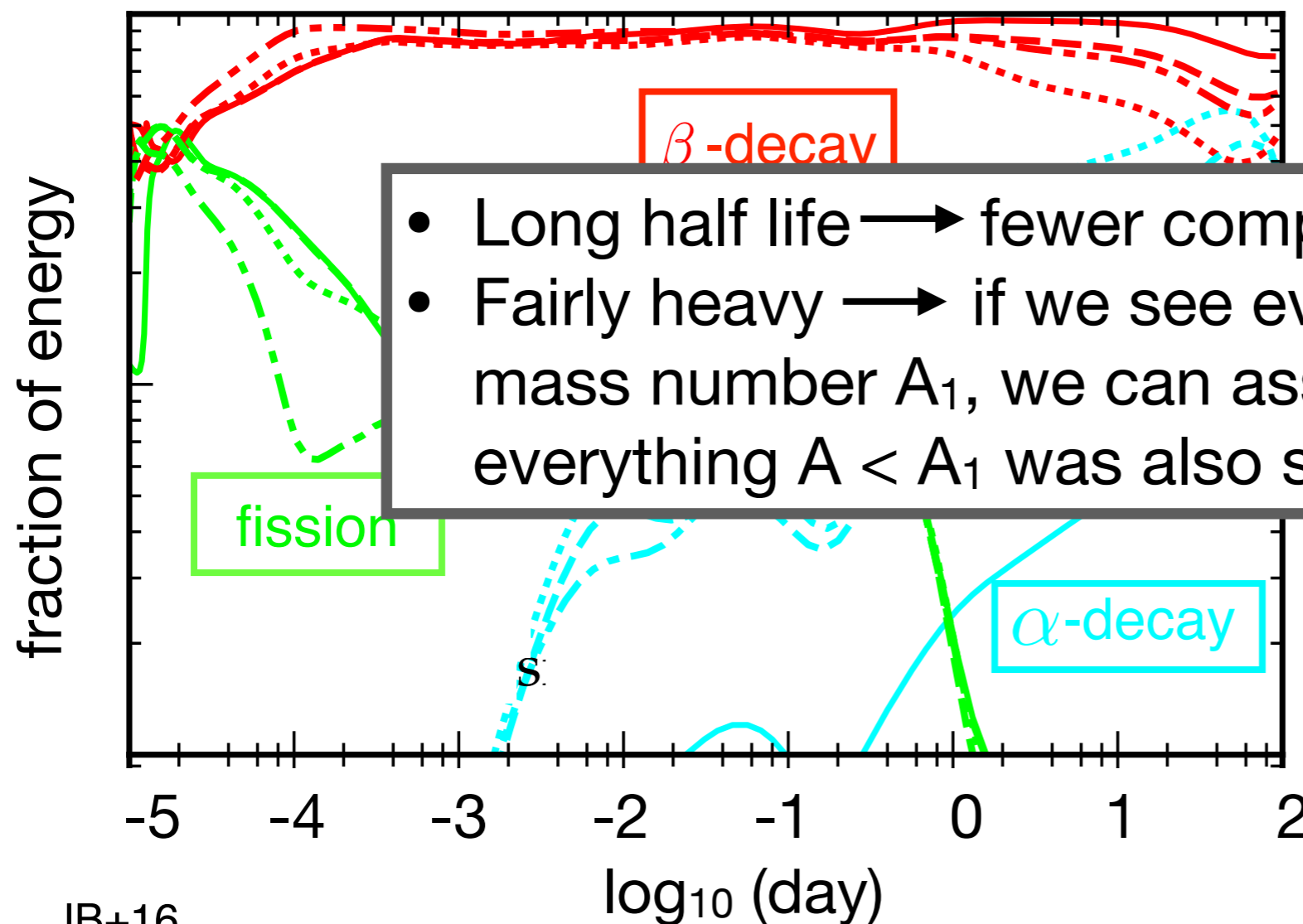
**Disclaimer:** this plots shows supernova spectra. We don't yet have the tools needed to do a similar analysis for kilonovae



# Tools for probing the composition

## II. Look for clues in the bolometric luminosity

**Basic idea:** Kilonovae are powered by the combined effects of many decays. If at some time one of these becomes dominant, it could change the shape of the bolometric light curve.

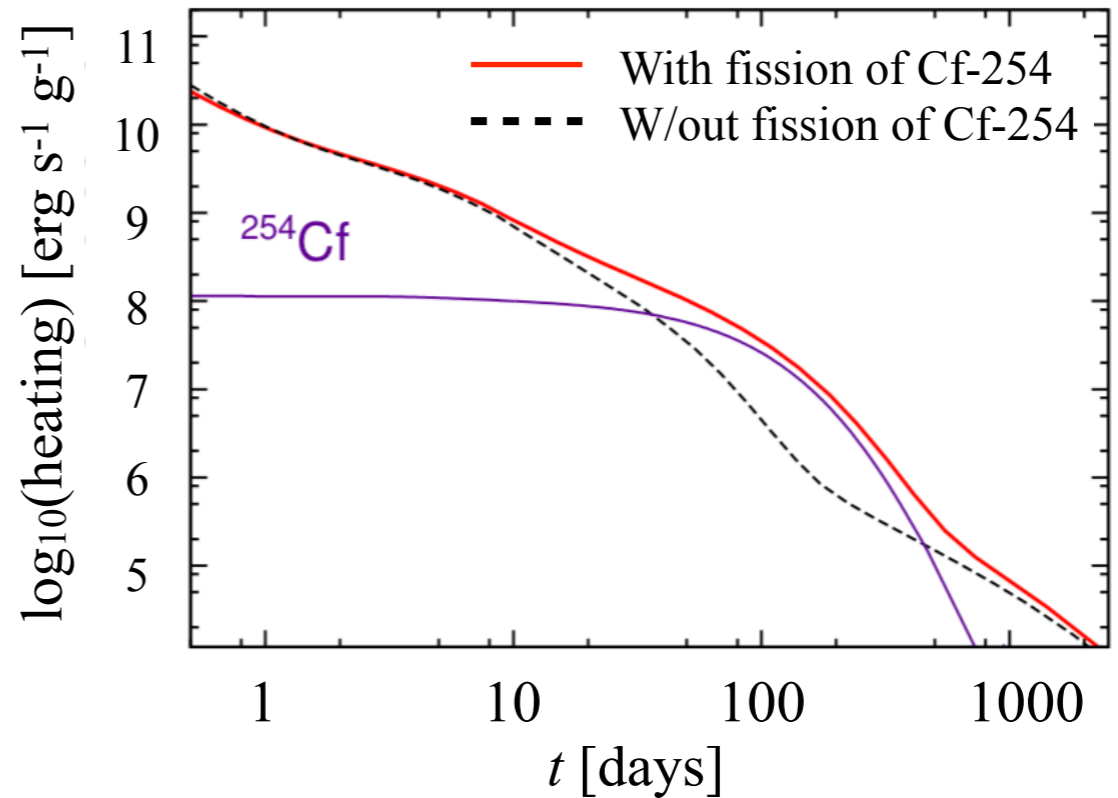
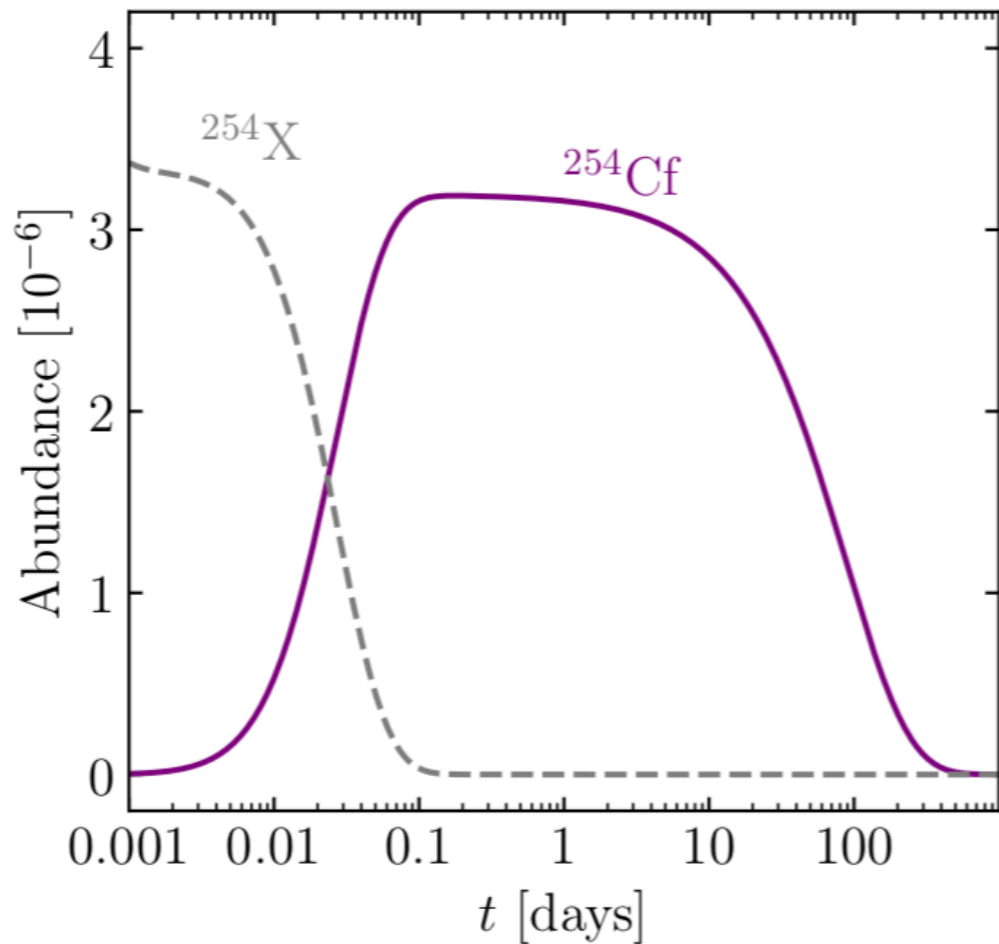


- Long half life  $\rightarrow$  fewer competing decays
- Fairly heavy  $\rightarrow$  if we see evidence of mass number  $A_1$ , we can assume that everything  $A < A_1$  was also synthesized

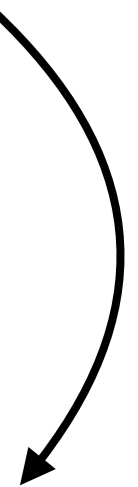
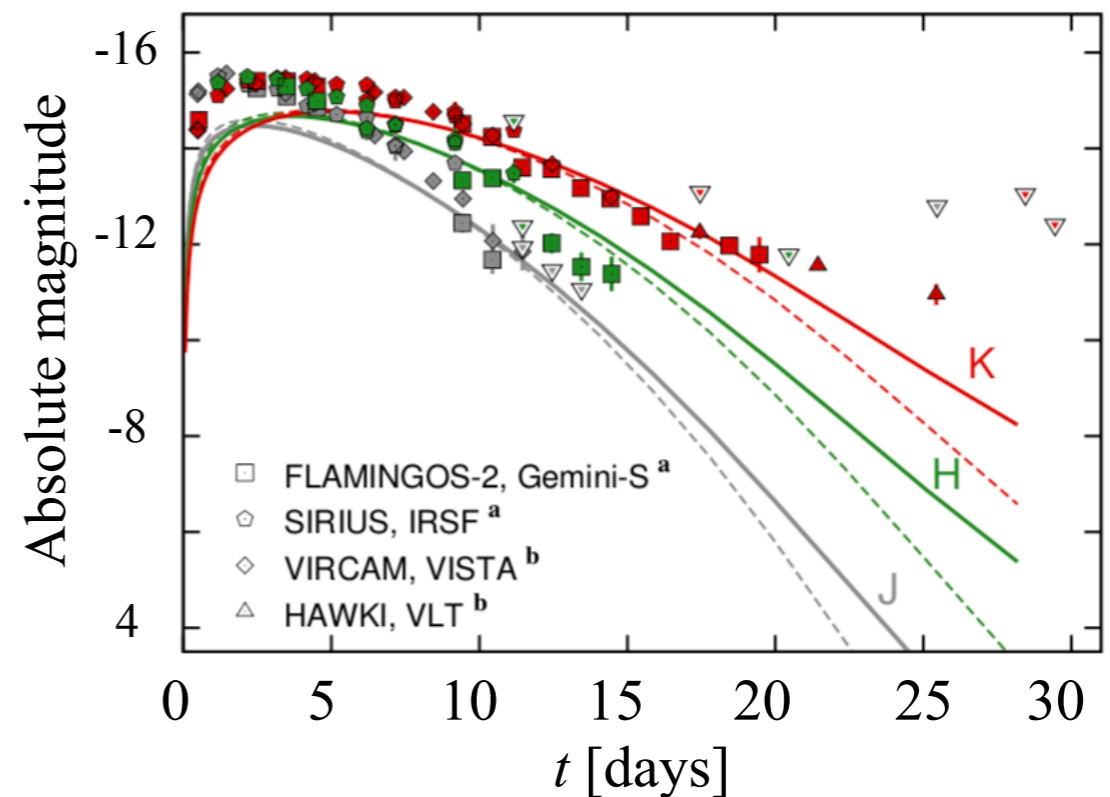
### Fission and alpha-decay

- Produce a lot of energy compared to beta-decay
- Don't follow power-law energy generation of beta-decay

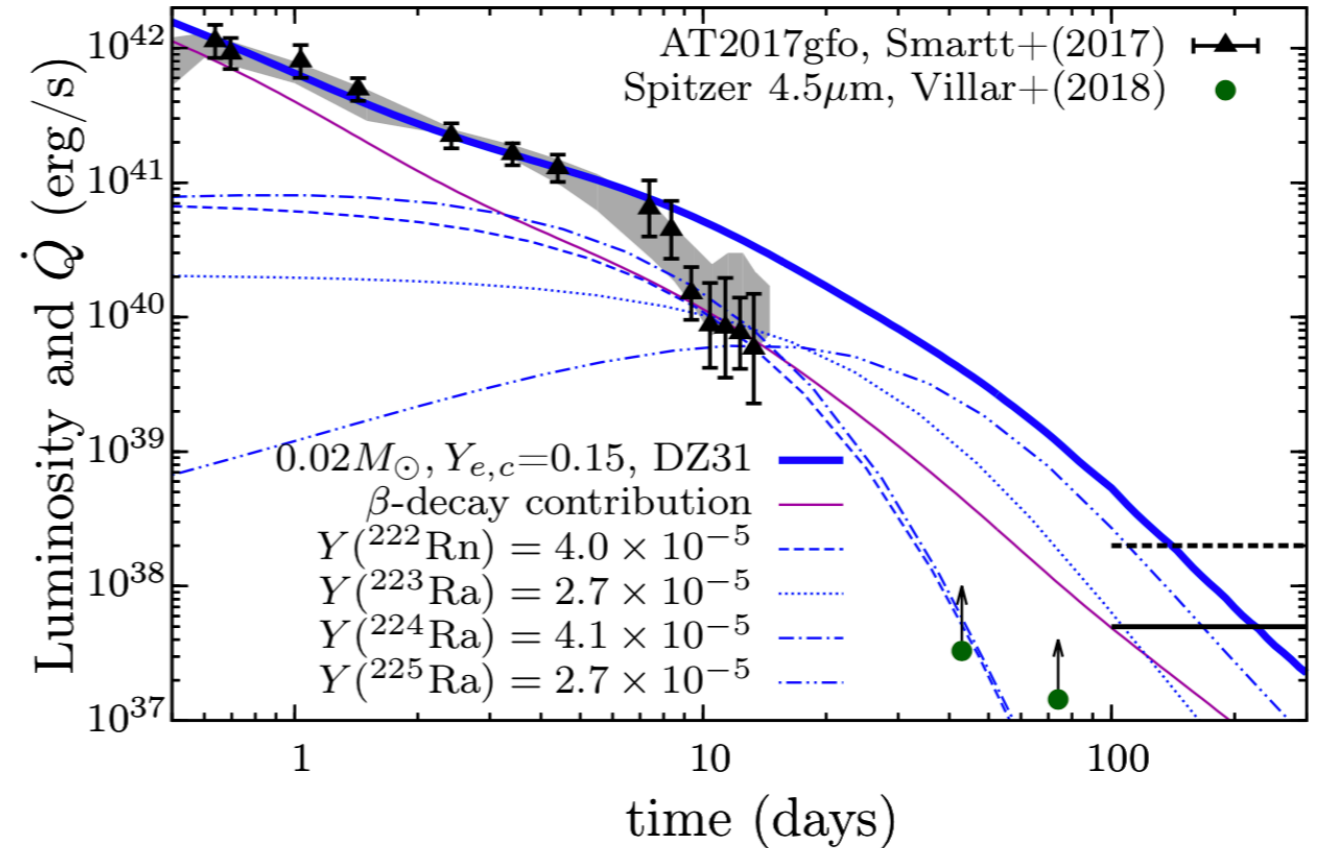
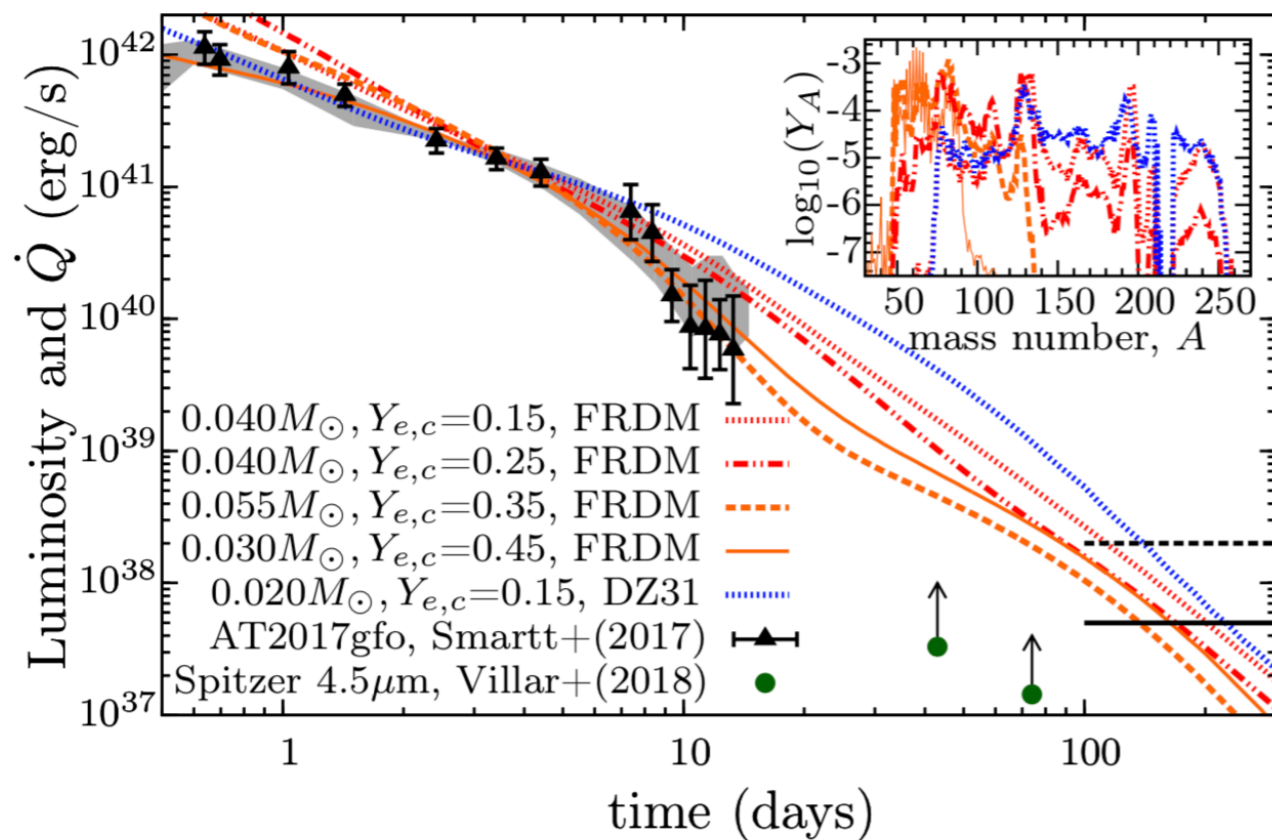
# Looking for Fission with Cf-254



Cf-254 could serve as a late time ( $\tau_{1/2} = 60.5$ ) energy reservoir, brightening the light curve



# Looking for actinide fingerprints with alpha-decay

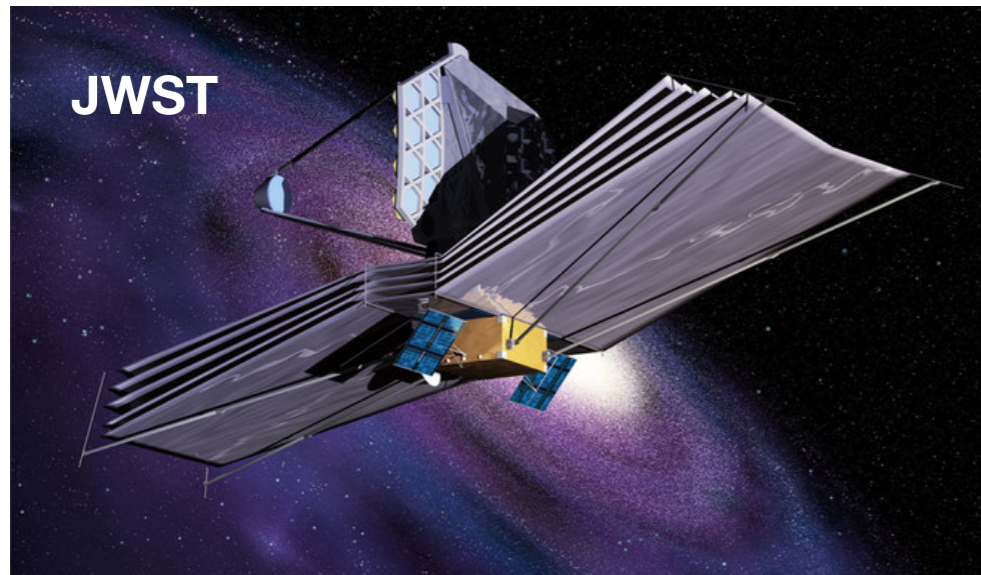


- Determine which sets of nuclear heating rates gives properties the are consistent with observed bolometric luminosities of AT2017gfo
- Perform a detailed study of late time heating, modeling heating by individual alpha-decay chains, to extrapolate bolometric luminosity to late times

# Challenges to measuring $L_{\text{bol}}$

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**Technical:** We need to make precision measurements at low luminosities



## James Webb Space Telescope:

- *NIR-cam* (0.6–4 $\mu\text{m}$ ): can detect  $L_{\text{NIR}} > 5 \times 10^{37} \text{ erg s}^{-1}$
- *Mid-Infrared Instrument* (5–14  $\mu\text{m}$ ): can detect  $L_{\text{MIR}} > 1 \times 10^{38} \text{ erg s}^{-1}$

**Theory/modeling:** How can we measure bolometric luminosity in the nebular phase?

- The blackbody assumption eventually breaks down
- We have very limited knowledge of the prominent emission features for *r*-process compositions
- Low densities may lead to inefficiencies in the reradiating of deposited energy (aka “freeze out”)

