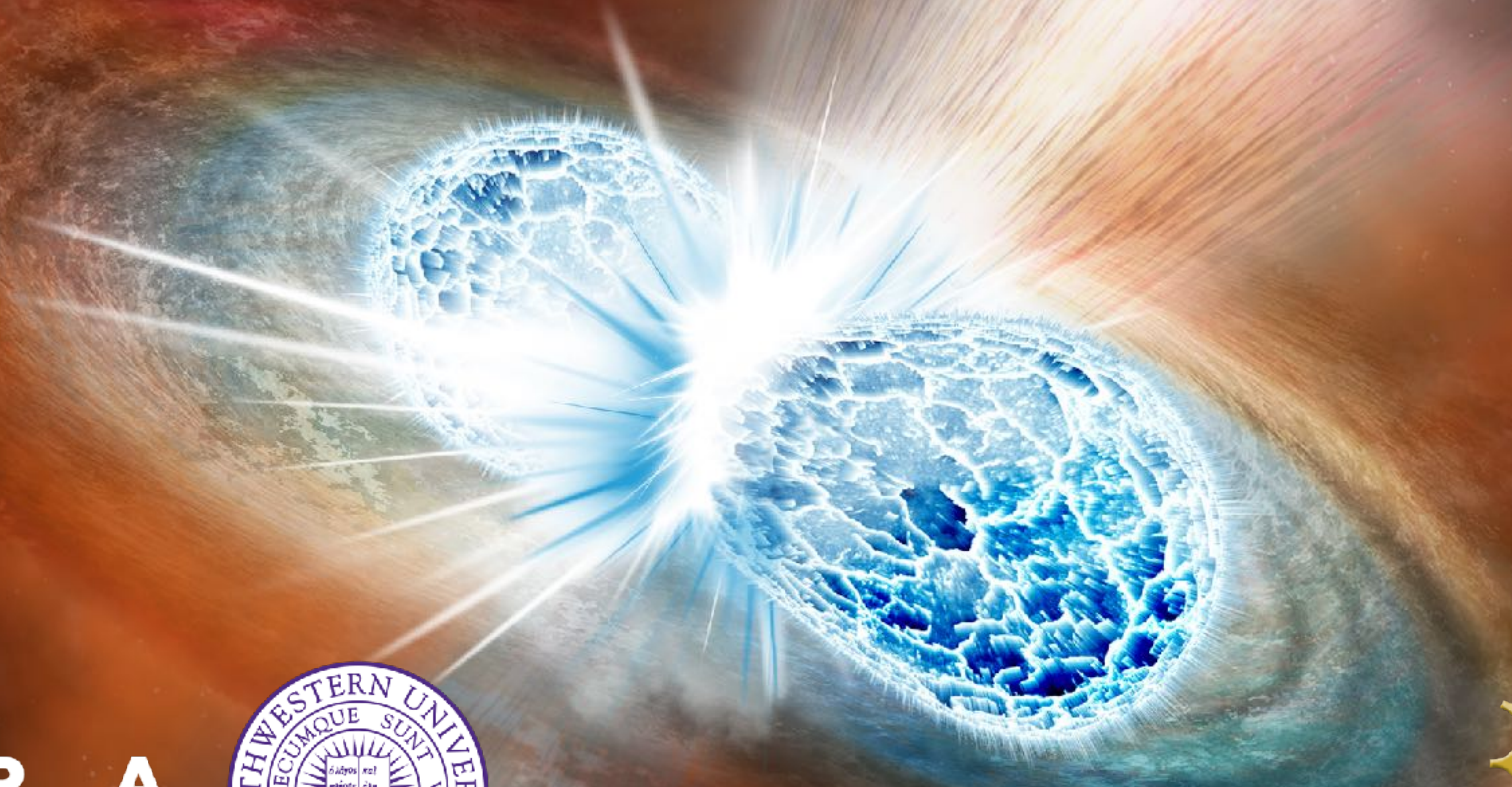
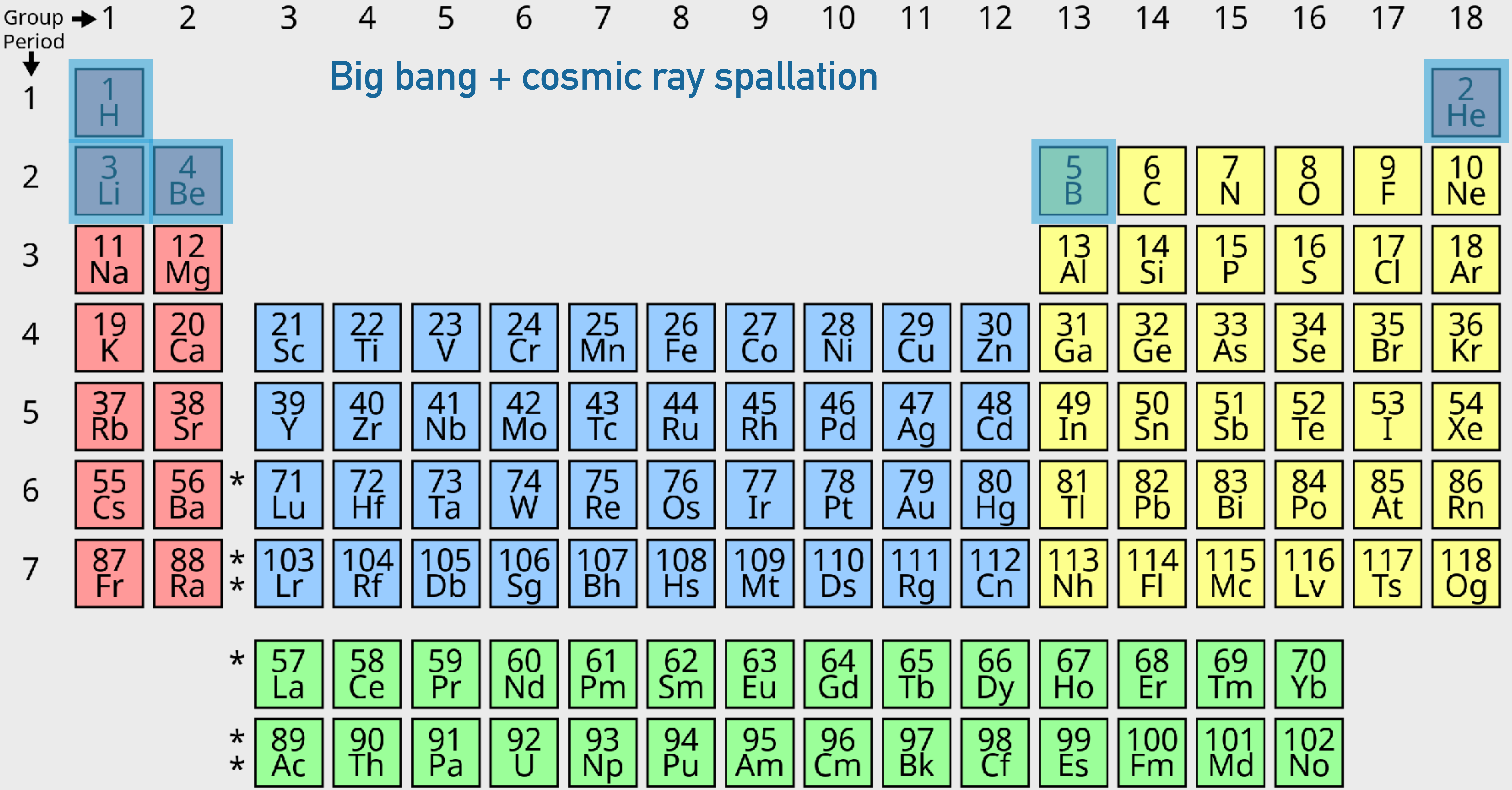
Uncovering neutron star mergers, heavy elements, and energetic explosions with multi-messenger astronomy

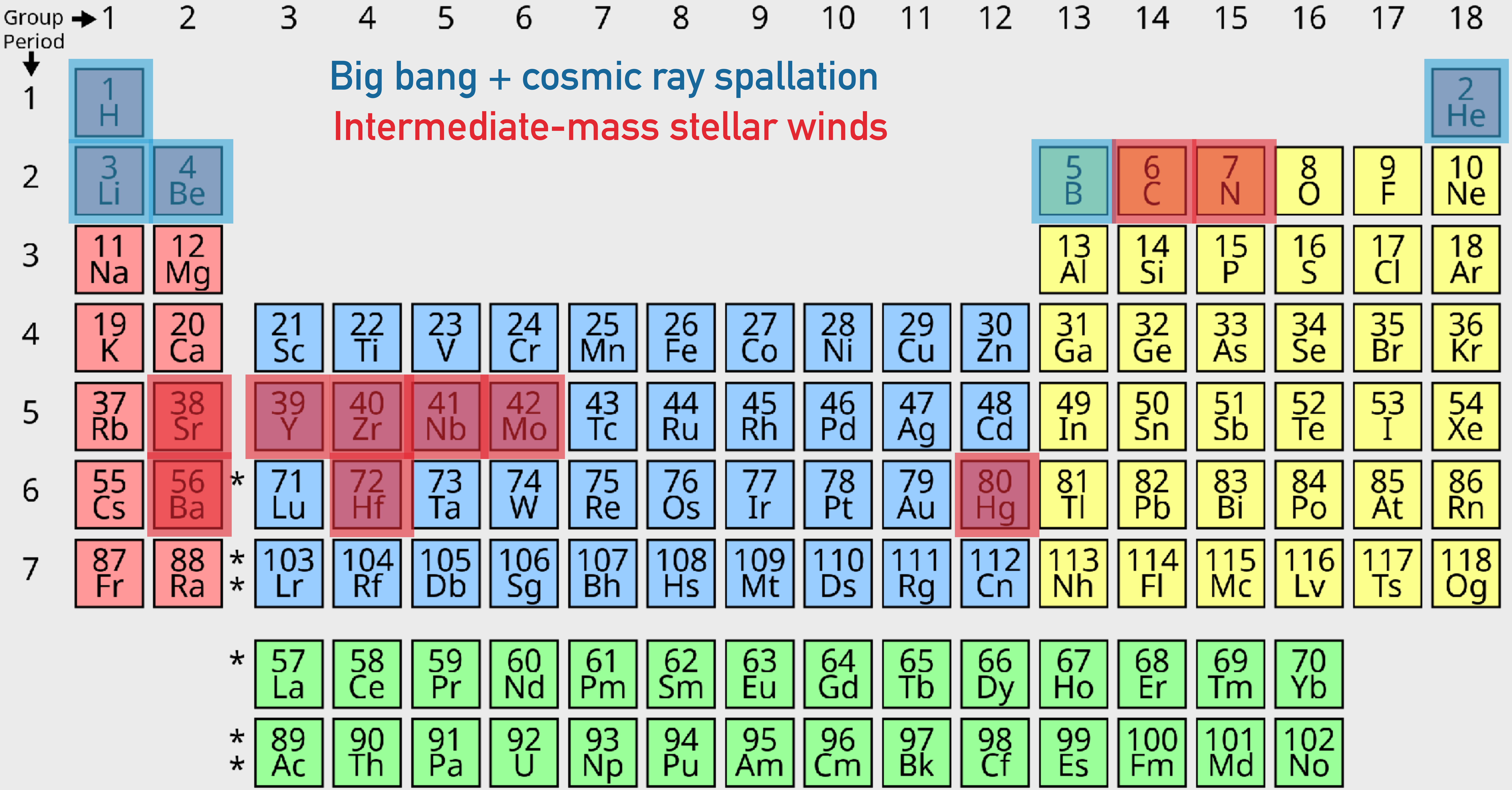
Charlie Kilpatrick
Northwestern University

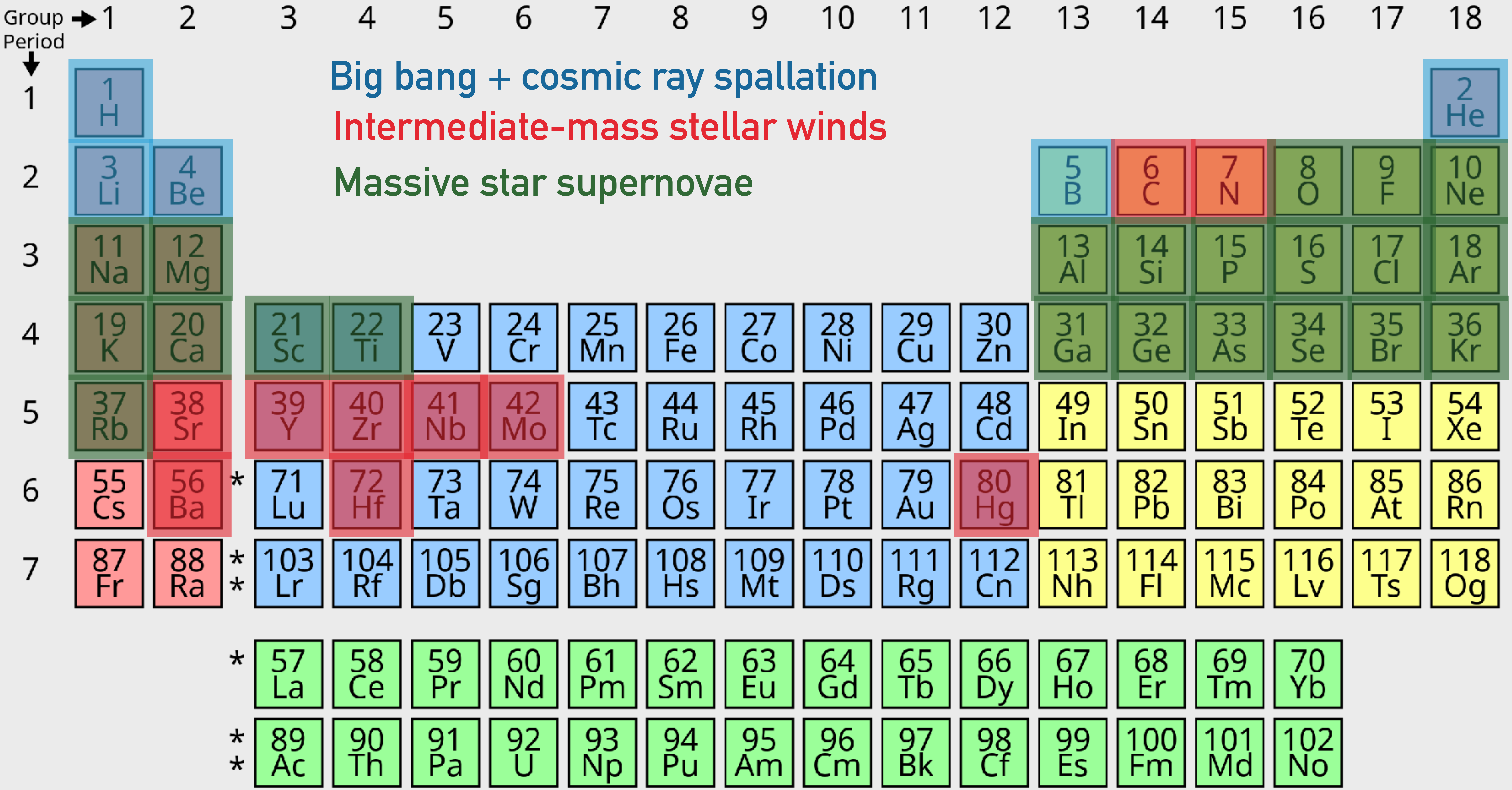


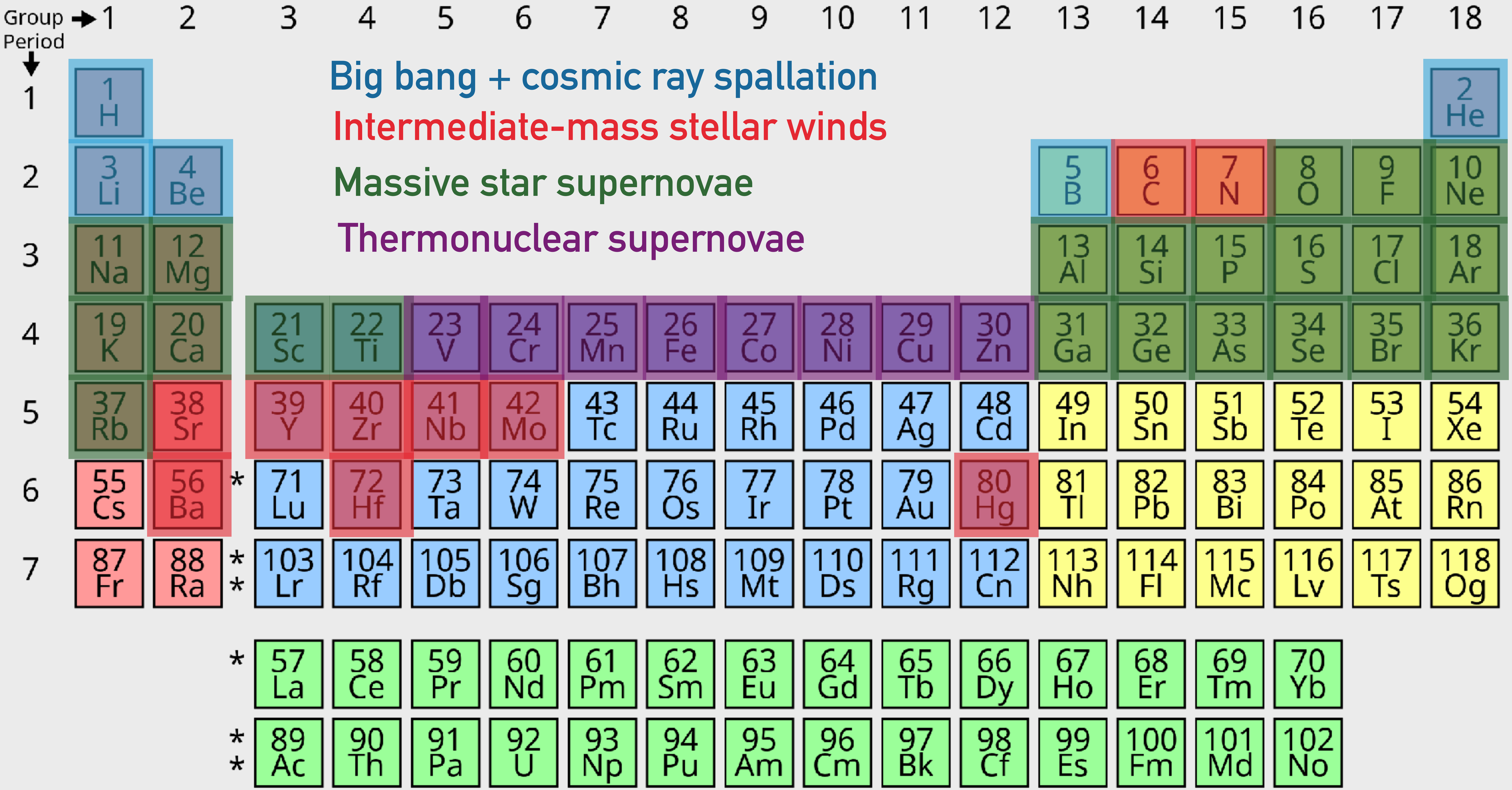
Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Big bang + cosmic ray spallation

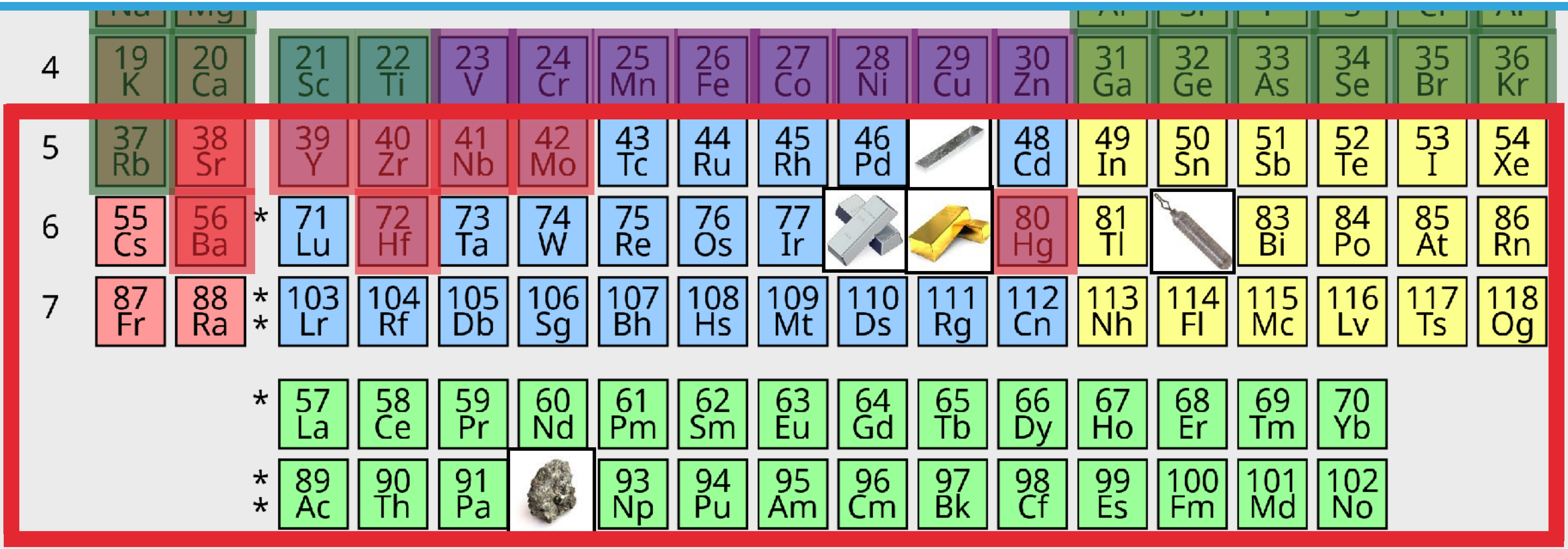


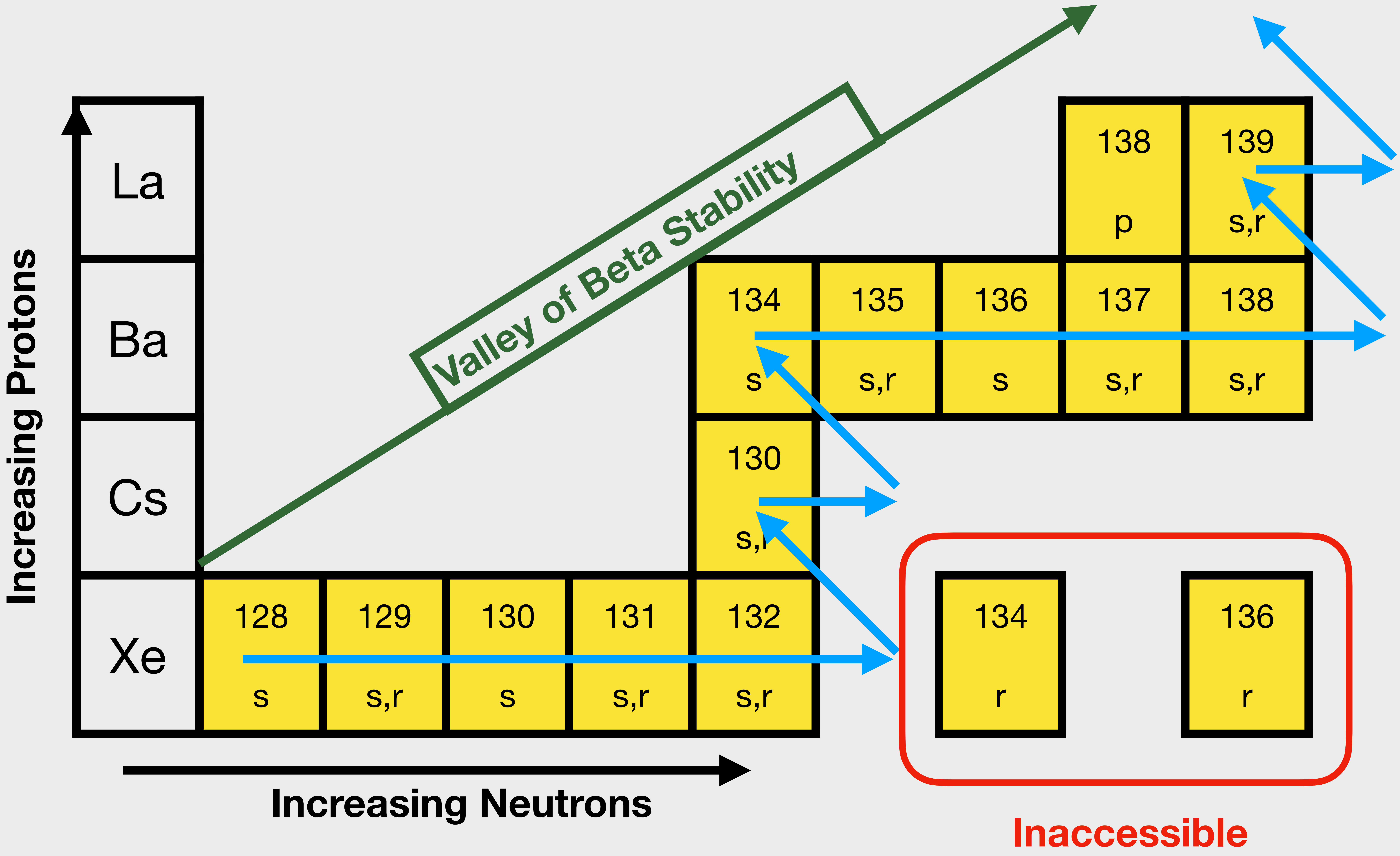

Group
Period
Big bang + cosmic ray spallation
Intermediate-mass stellar winds
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41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


Group
Period
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Big bang + cosmic ray spallation
Intermediate-mass stellar winds
Massive star supernovae
1 1 H 2 He
2 3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
3 11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
4 19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
5 37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
6 55 Cs 56 Ba * 71 Lu 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
7 87 Fr 88 Ra ** 103 Lr 104 Rf 105 Db 106 Sg 107 Bh 108 Hs 109 Mt 110 Ds 111 Rg 112 Cn 113 Nh 114 Fl 115 Mc 116 Lv 117 Ts 118 Og
* 57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb
** 89 Ac 90 Th 91 Pa 92 U 93 Np 94 Pu 95 Am 96 Cm 97 Bk 98 Cf 99 Es 100 Fm 101 Md 102 No


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

Where and how are the heaviest elements in the Universe (silver, platinum, gold, lead, uranium) synthesized?

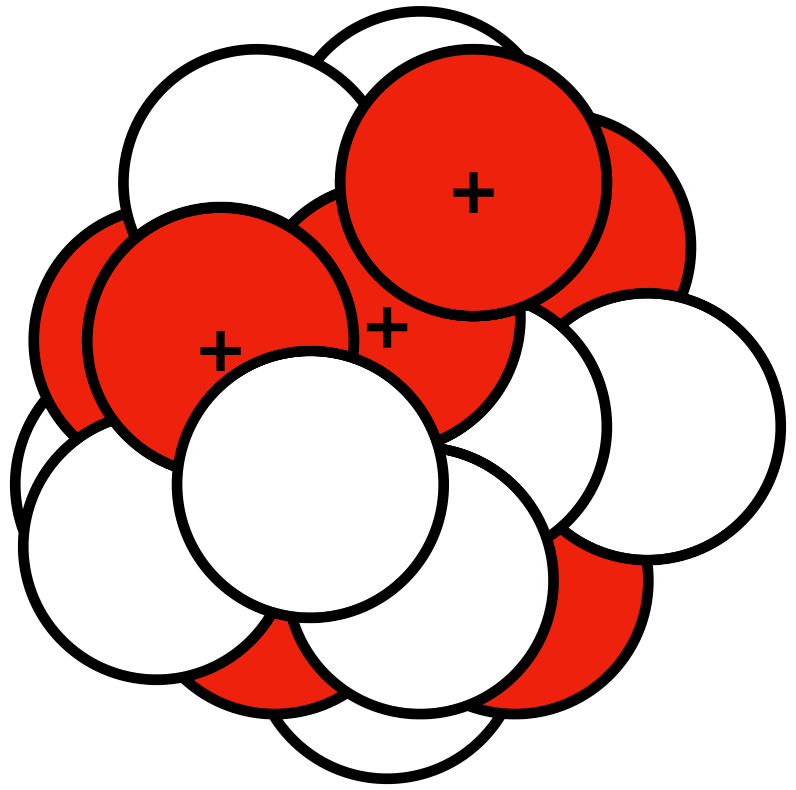




Increasing Protons
La
Ba
Cs
Xe
Valley of Beta Stability
138
p
139
s,r
134
s
135
s,r
136
s
137
s,r
138
s,r
130
s,r
128
s
129
s,r
130
s
131
s,r
132
s,r
134
r
136
r
Inaccessible
Increasing Neutrons

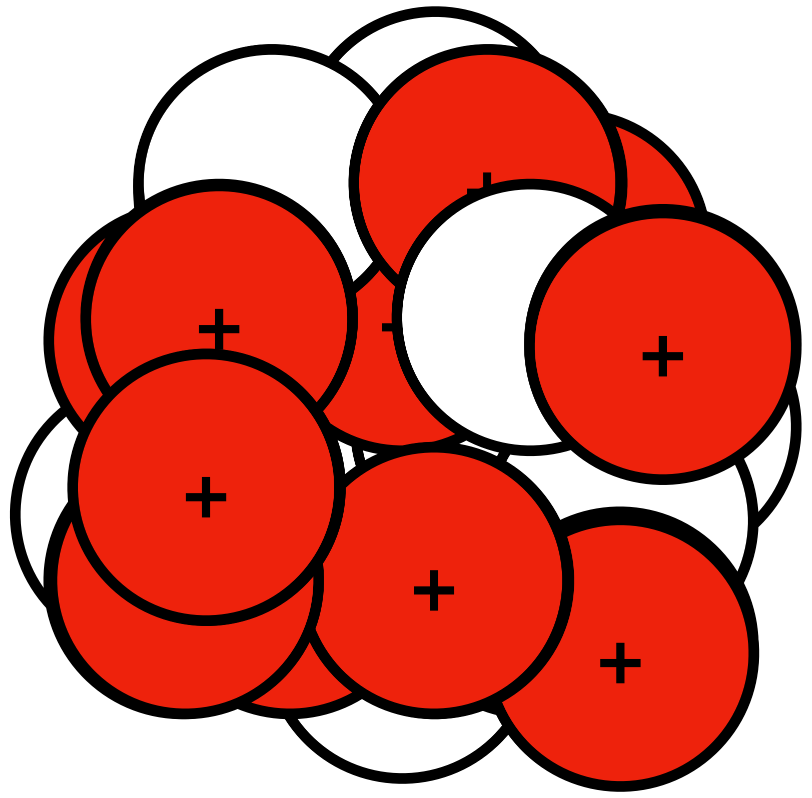
Slow neutron capture
s-process

$$\tau_\beta \ll \tau_n$$



Rapid neutron capture
r-process

$$\tau_\beta \gg \tau_n$$



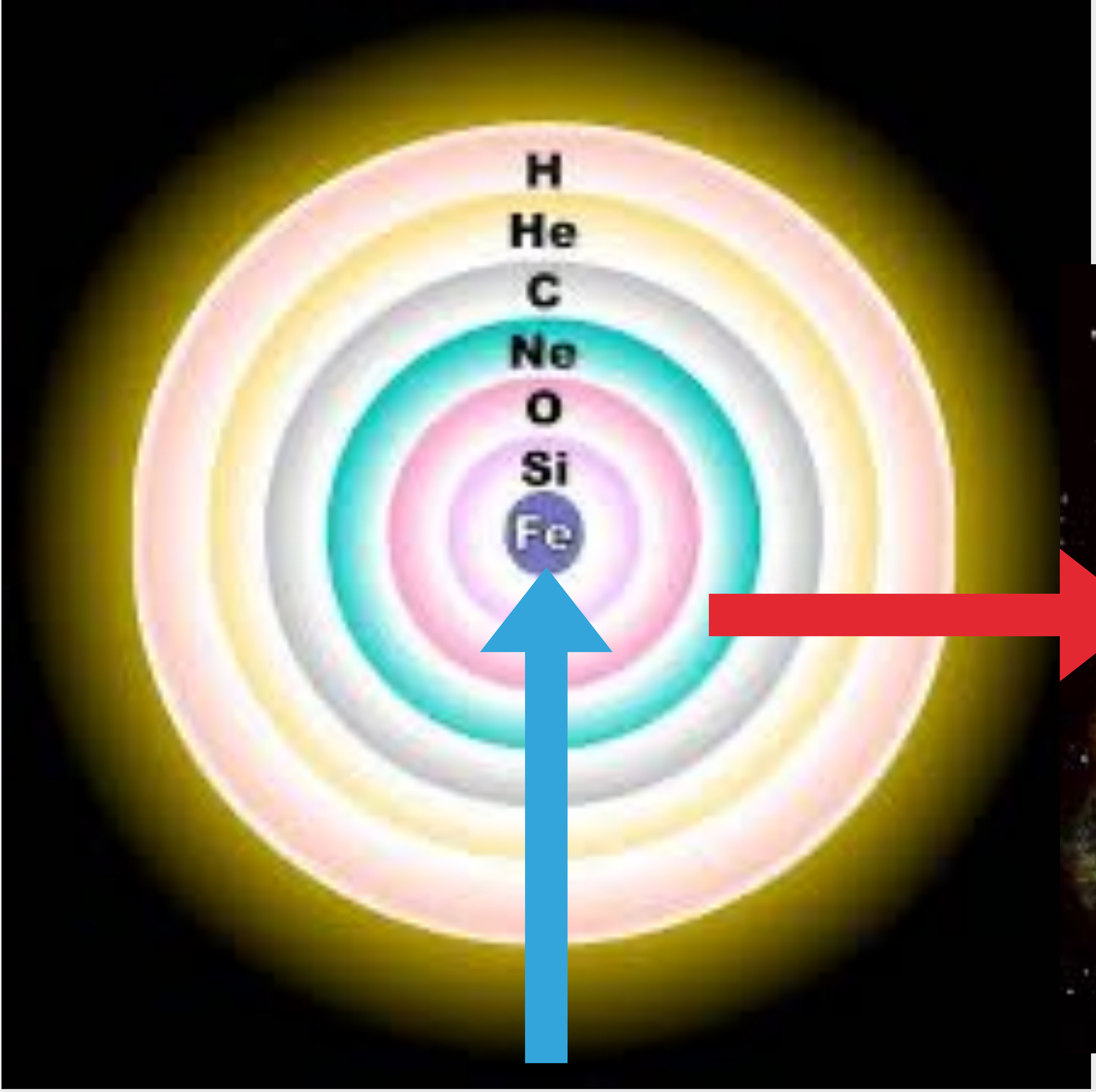
Synthesis of the Elements in Stars (1957; B^2FH)

Margaret Burbidge

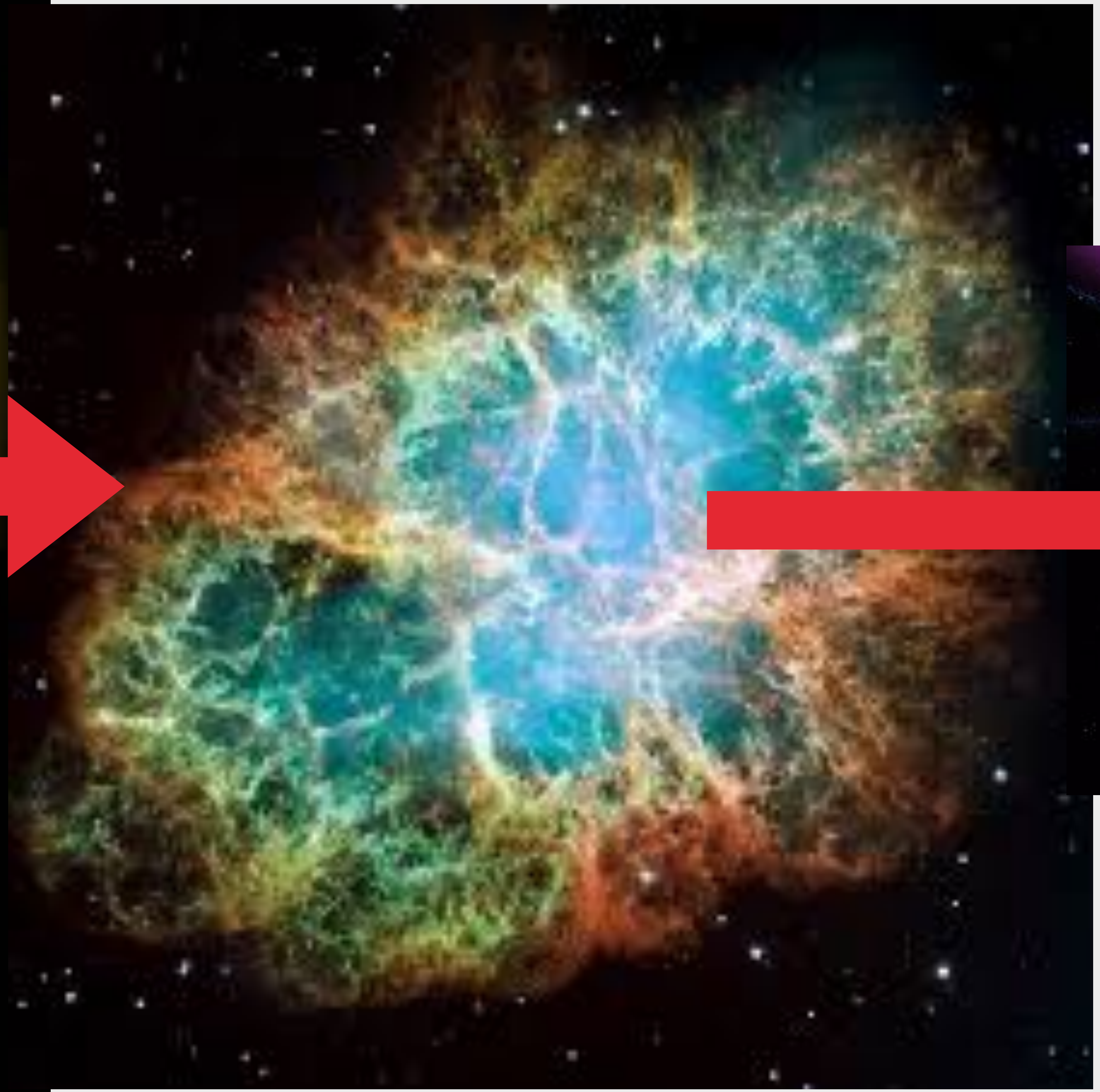
if a situation could arise in which some of the outer core material has been converted to isotopes in the iron peak by the equilibrium process (Sec. IV) while the inner core material has evolved to its last equilibrium configuration consisting of a pure neutron core, an instability in which the neutrons were mixed into the iron would result in the production of the *r*-process

r-process happens when neutron-rich cores of stars are torn apart

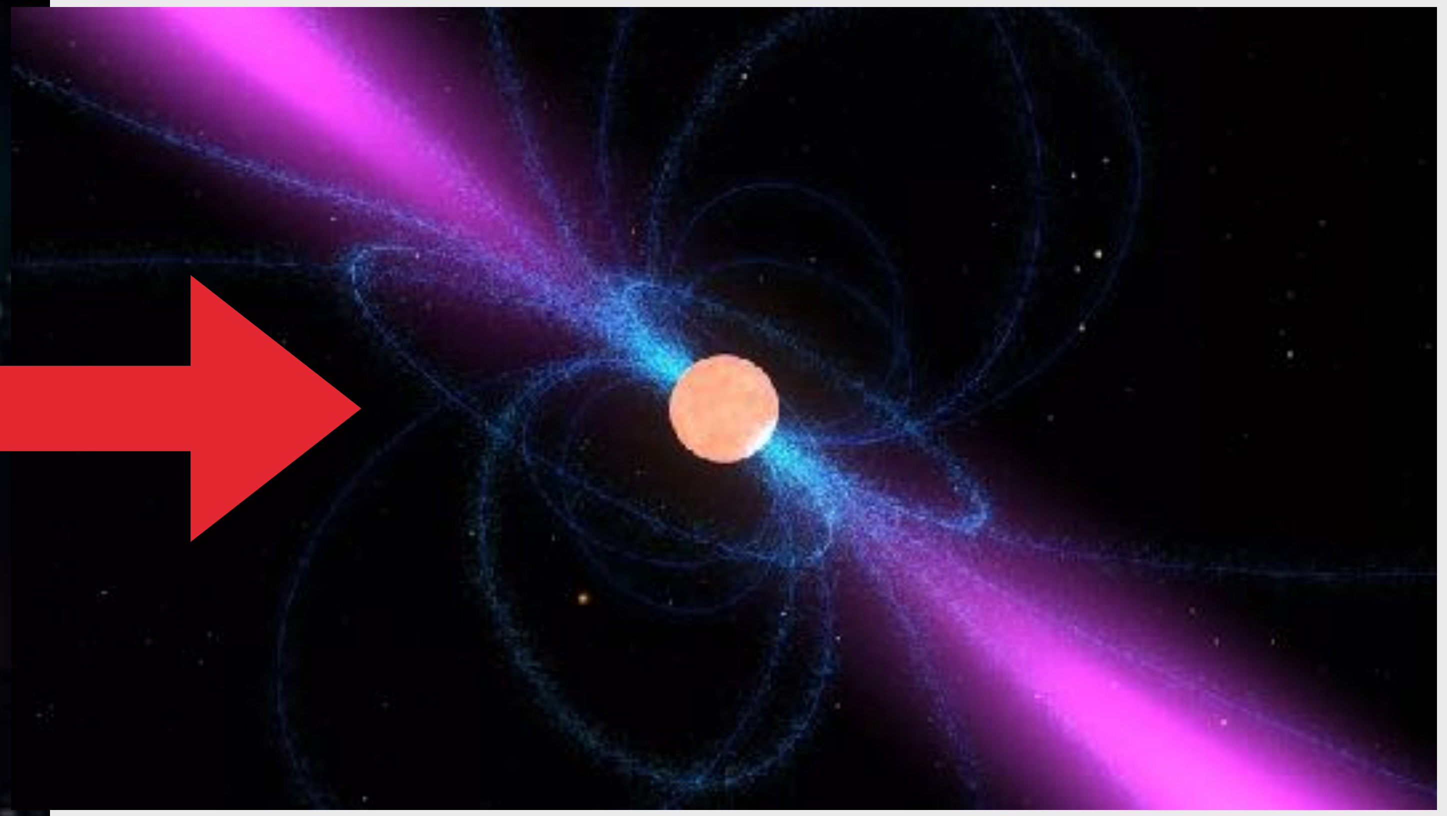
What is the observational signature?



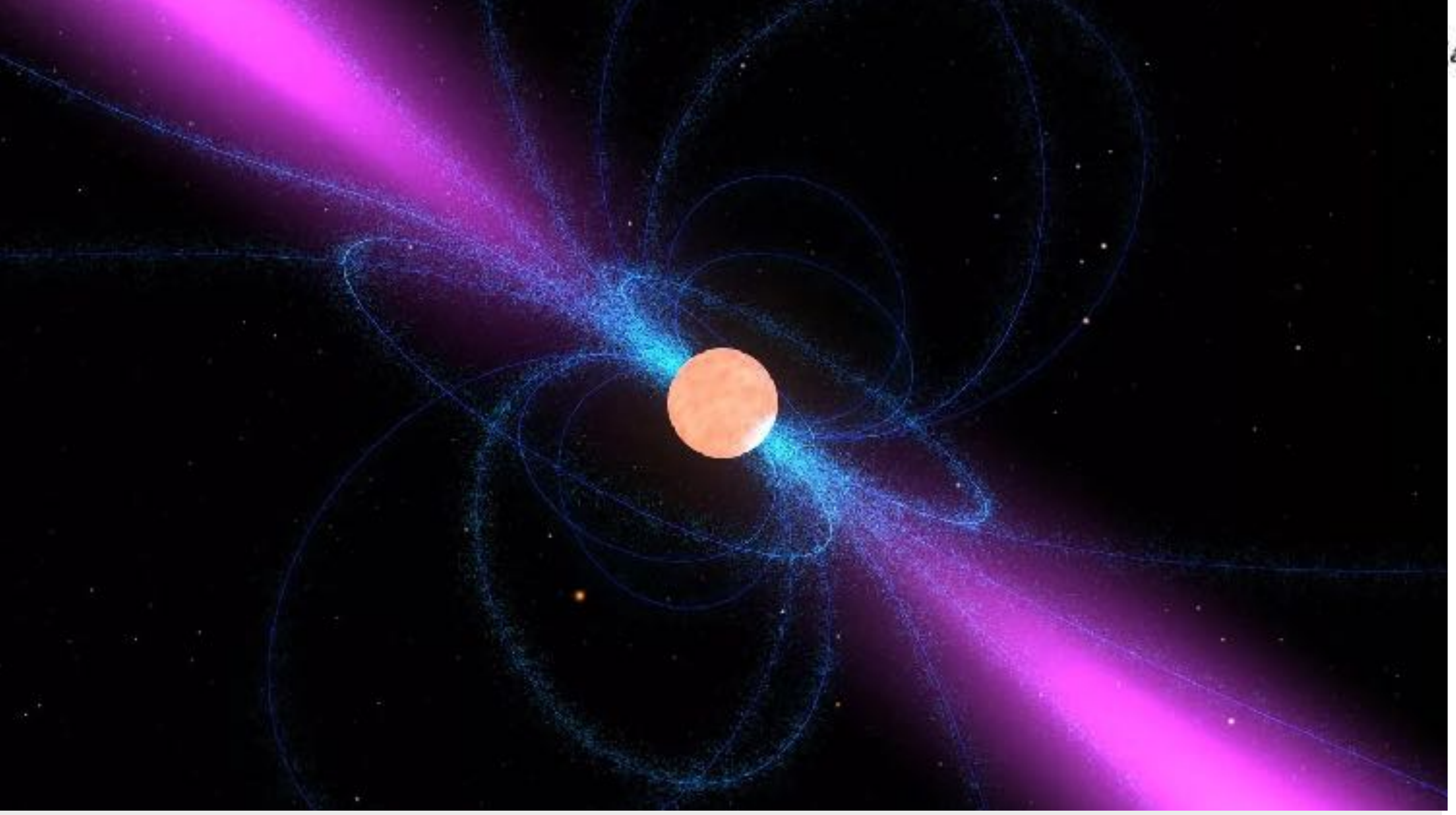
Proto-neutron star
core of massive star

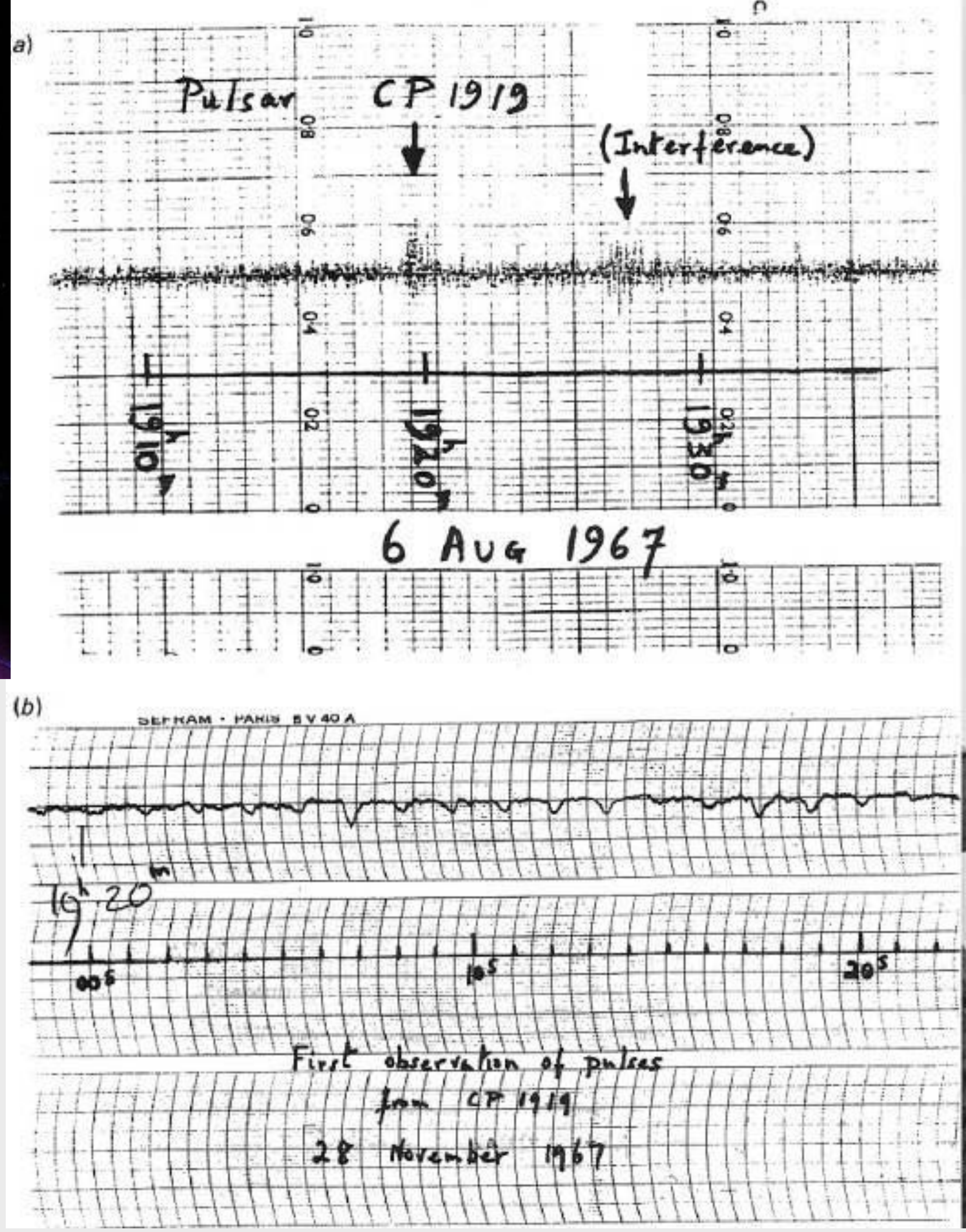


Supernova
explosion



A bare
neutron star





Jocelyn Bell Burnell, 1967

$$1\ \text{ms} \times c \rightarrow$$

$$R < 300\ \text{km}$$

Discovery of pulsars with repeating, millisecond timescale, coherent radio emission confirms existence of neutron stars


VLM
M
K
GFA
B
early B
O
Duchene & Kraus (2013)
Sana et al. (2014)
GRAVITY collaboration: Martina Karl et al. (2018)
Bordier et al. (2022)
Guo et al. (2022)
Multiplicity fraction (%)
100
80
60
40
20
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Mass of primary star ($M_\odot$)


VLM
M
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100
80
60
40
20
Multiplicity fraction (%)
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Mass of primary star ($M_\odot$)
Binary neutron stars

Major Science Questions

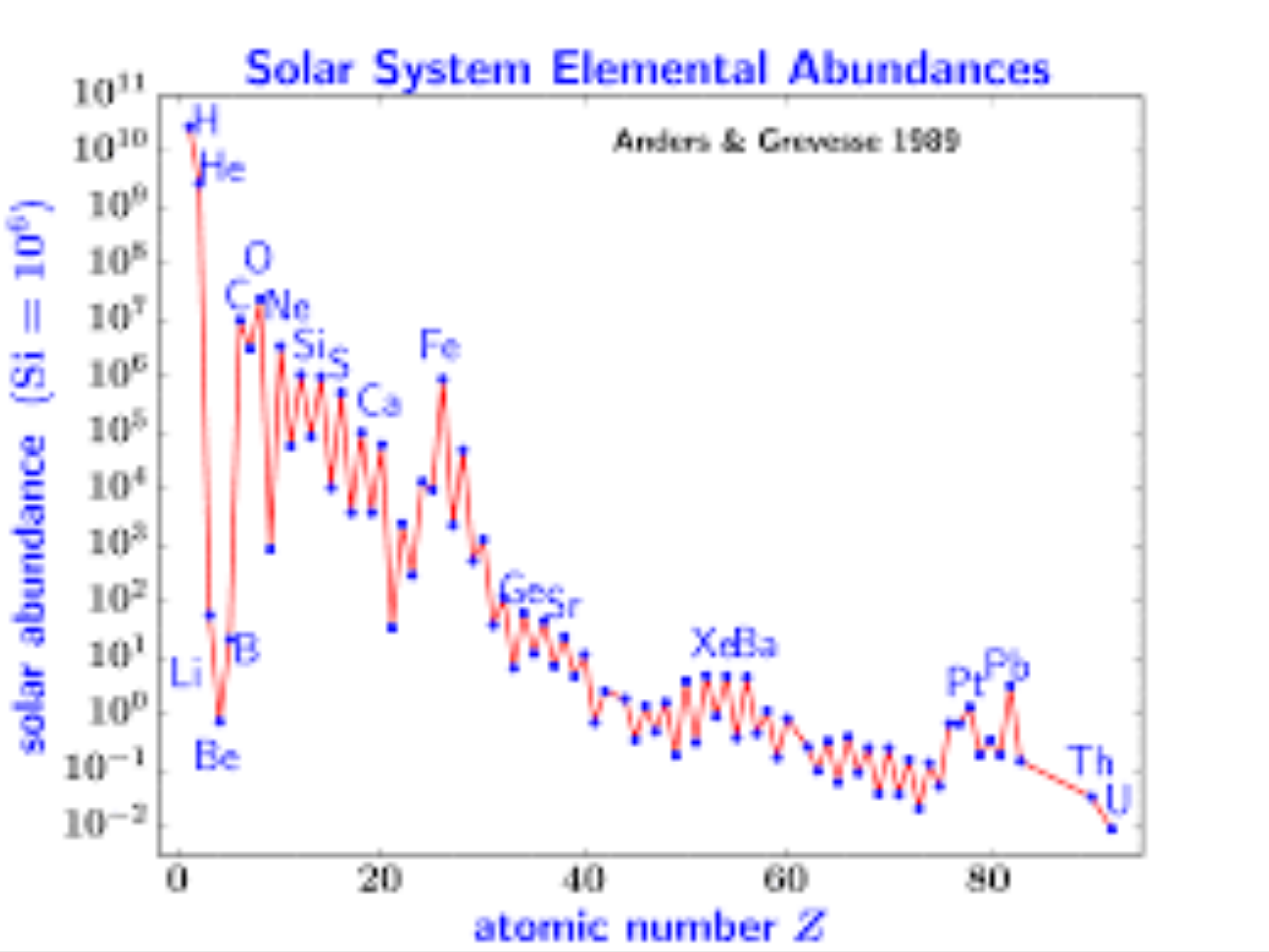
What are the observable signatures of r-process from neutron stars and how to distinguish them from other astrophysical phenomena?

What new surveys are needed to find these signatures, and how can they best be designed to understand r-process bearing transients?

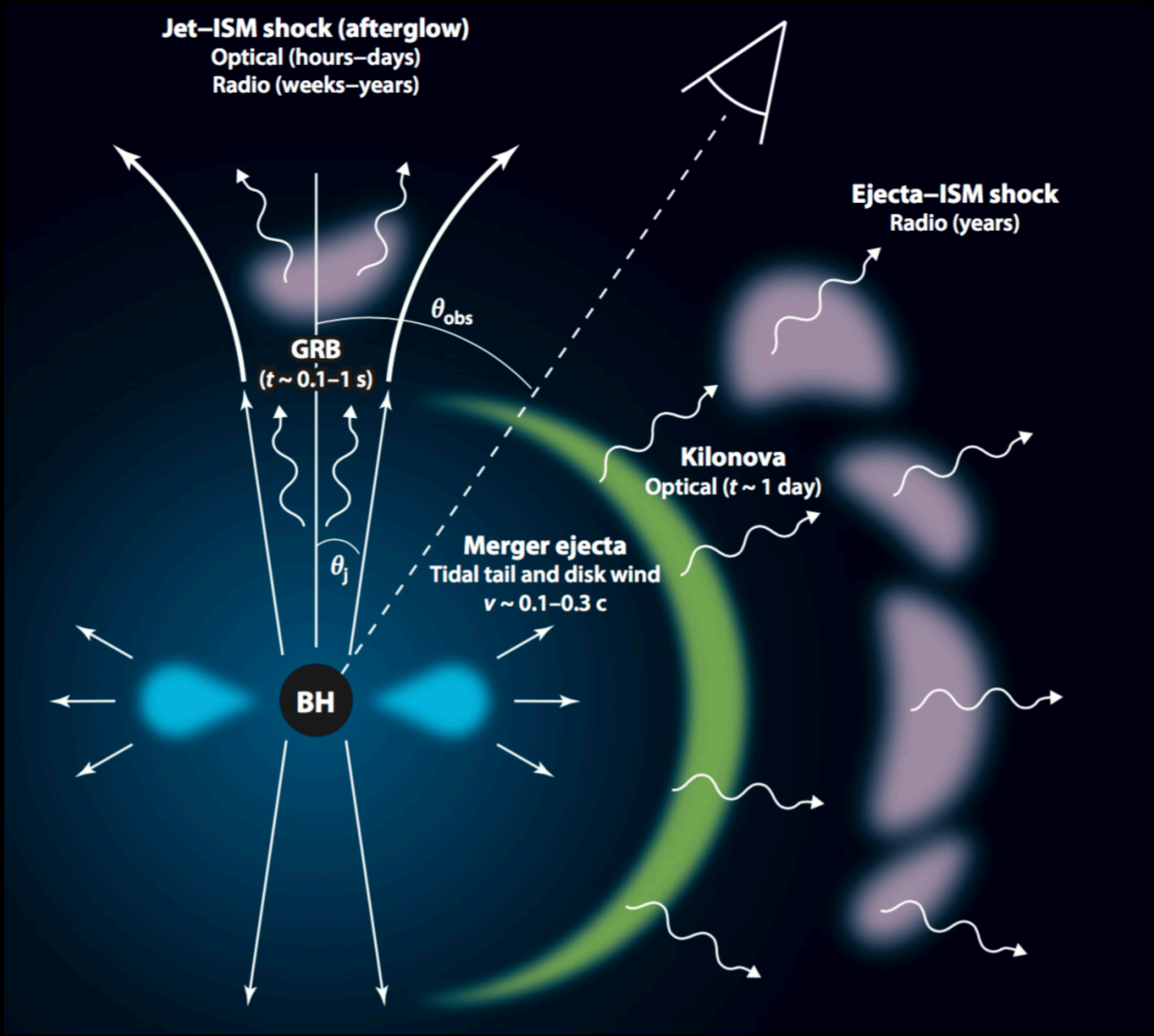
What is the prospect of isolating r-process production via large populations?

What are the observable signatures of r-process from neutron stars and how to distinguish them from other astrophysical phenomena?

Can they produce the heaviest elements?



Is there a distribution of yields from astrophysical sources of the r-process?

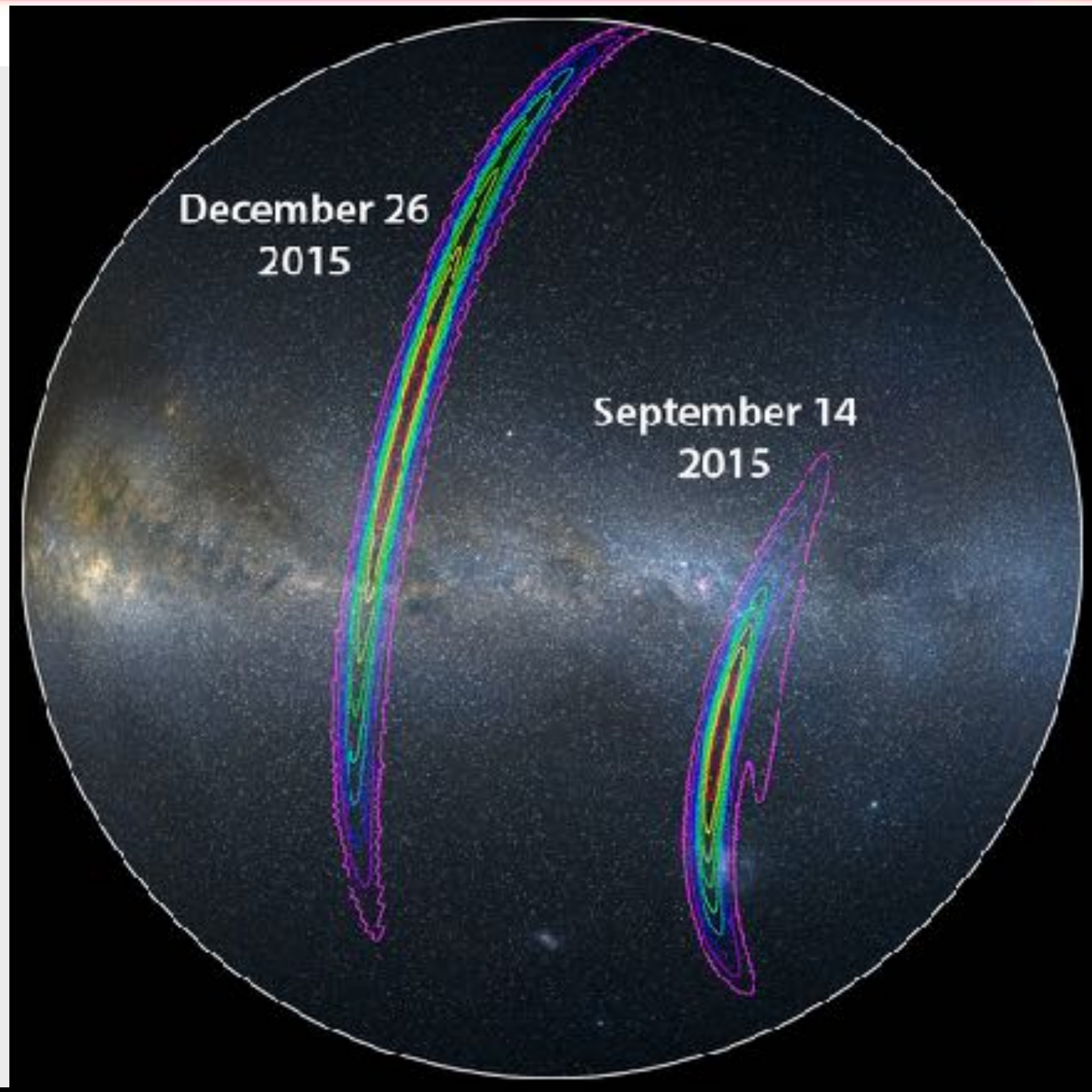


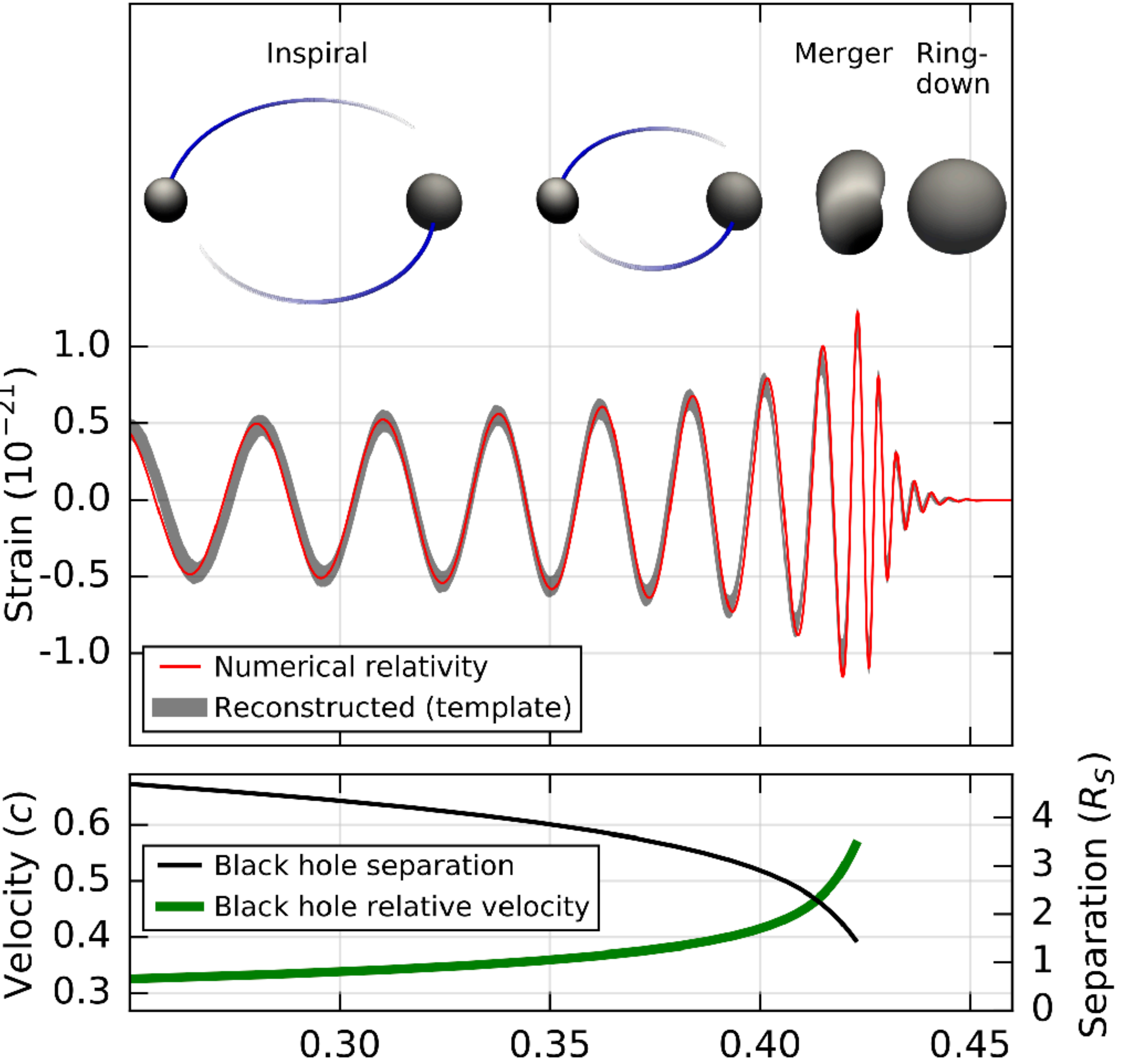
Metzger+2019

Advanced LIGO Interferometer

Credit: Caltech/LIGO

LIGO enabled searches for black hole and neutron star mergers, for the first time triggered on the gravitational signature of two compact objects





Abbott+2016

Template matching provides the source type by mass

Scale of the strain signal indicates the distance to the source

Time at which the signal peaks in frequency is the point of merger

Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of a possible gravitational-wave counterpart

1 message

LIGO/Virgo Circulars <lvccirc@capella2.gsfc.nasa.gov> Thu, Aug 17, 2017 at 6:24 AM

TITLE: GCN CIRCULAR
NUMBER: 21505
SUBJECT: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of a possible gravitational-wave counterpart
DATE: 17/08/17 13:21:42 GMT
FROM: Reed Clasey Essick at MIT <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary identification of a GW candidate associated with the time of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.

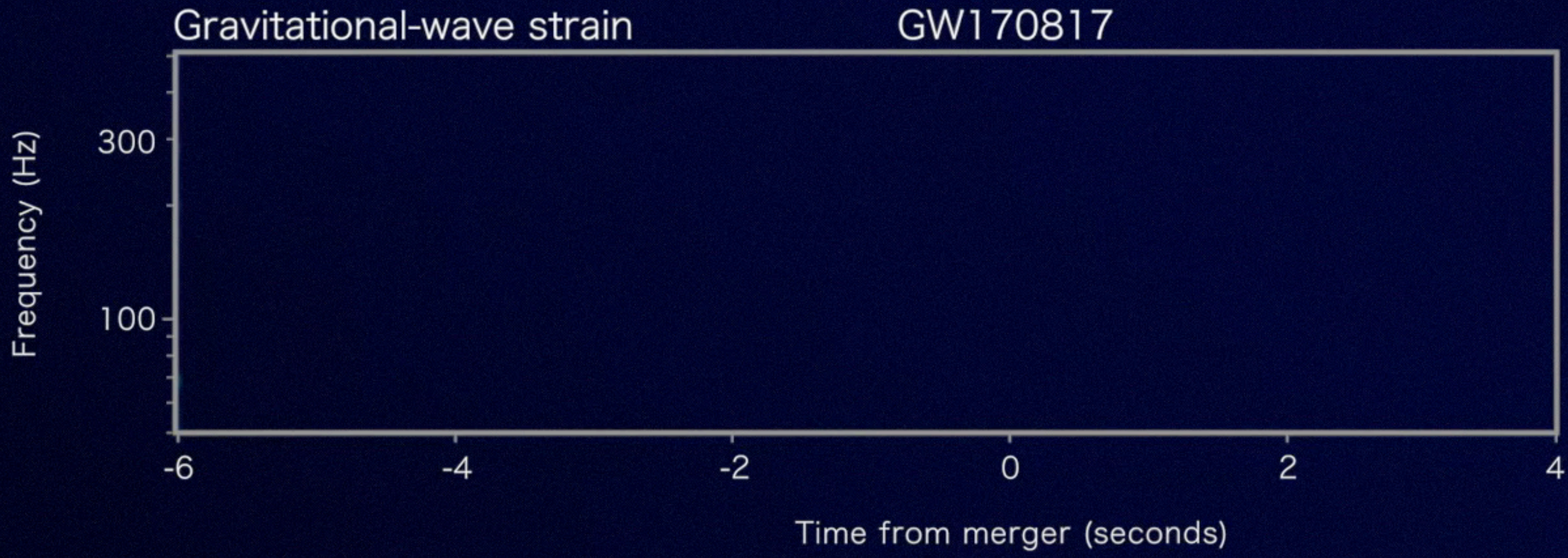
The candidate is consistent with a neutron star binary coalescence with False Alarm Rate of ~1/10,000 years.

An offline analysis is ongoing. Any significant updates will be provided by a new Circular.

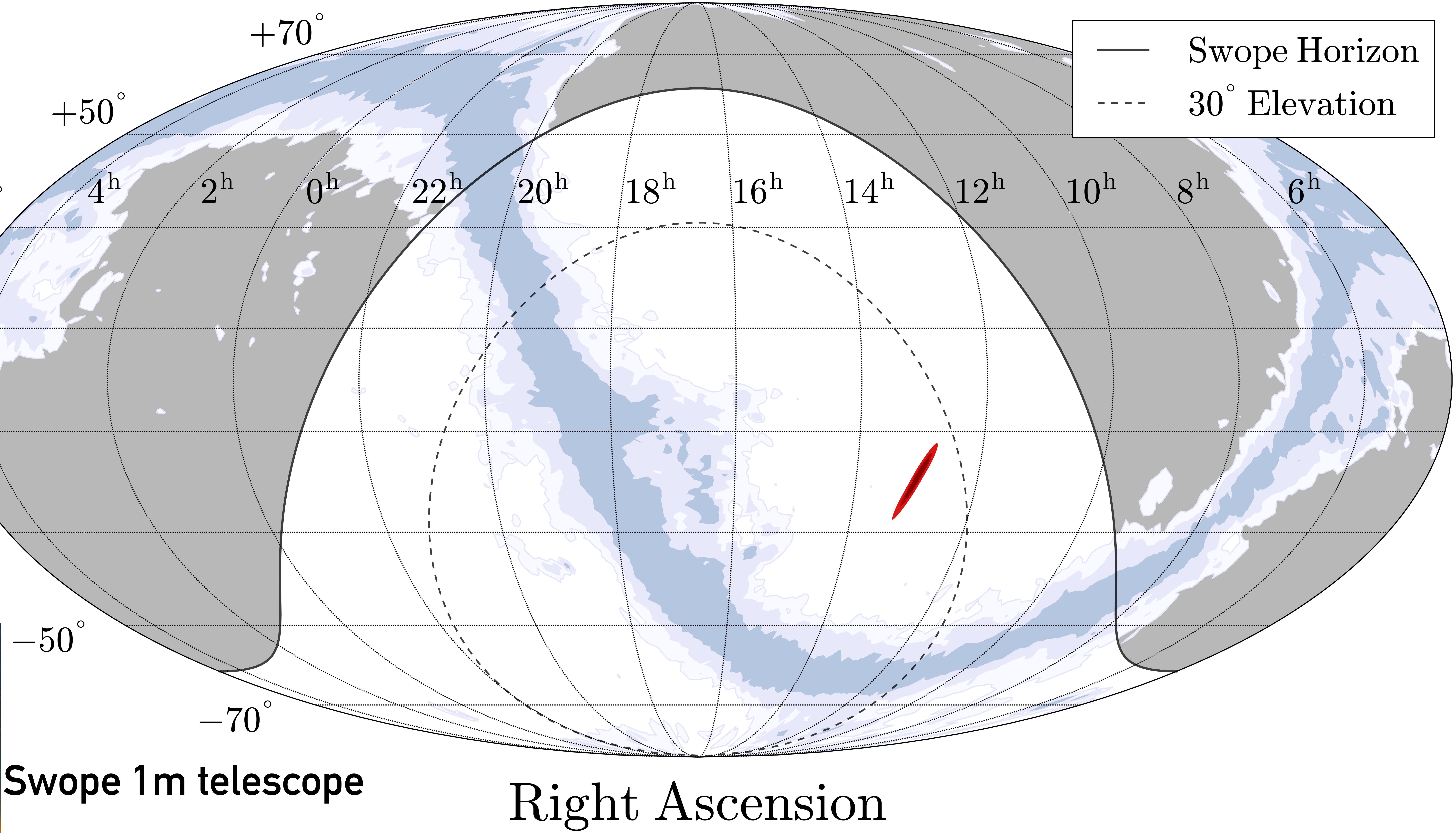
A 1.5+1.3 $M_\odot$ neutron star merger at 40 Mpc

Fermi

LIGO

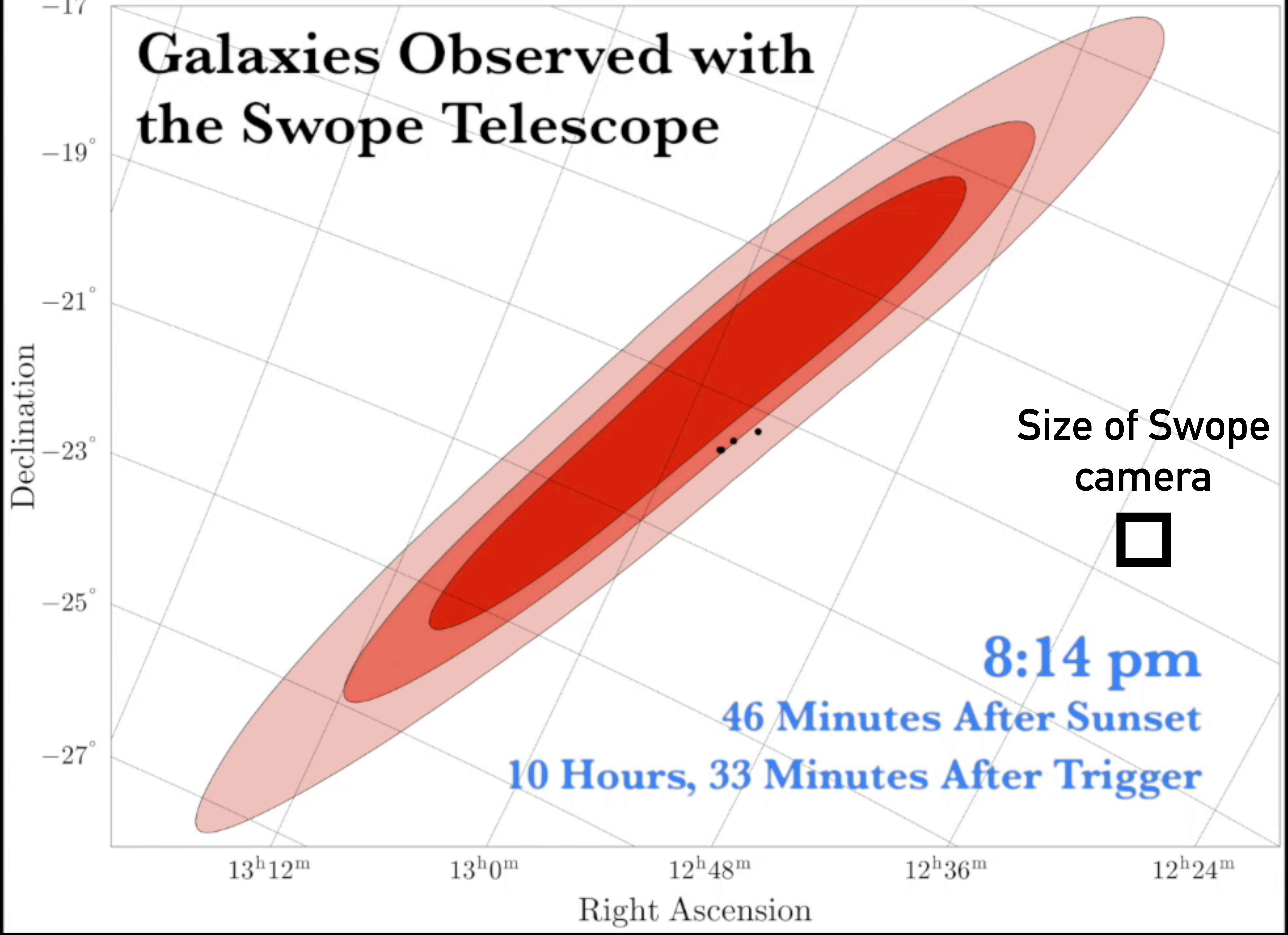



GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)



Swope 1m telescope

Las Campanas, Chile



Galaxies Observed with the Swope Telescope
Size of Swope camera
8:14 pm
46 Minutes After Sunset
10 Hours, 33 Minutes After Trigger
Declination
−17°
−19°
−21°
−23°
−25°
−27°
Right Ascension
13h12m
13h0m
12h48m
12h36m
12h24m

Difference Imaging

Digital image subtraction allows
automatic identification of transients

Discovery of the optical counterpart to GW170817

Dave Coulter

TITLE: GCN CIRCULAR
NUMBER: 21529
SUBJECT: LIGO/Virgo G298048: Potential optical counterpart discovered by Swope telescope
DATE: 17/08/18 01:05:23 GMT
FROM: Edo Berger at Harvard U <eberger@cfa.harvard.edu>

D. A. Coulter, C. D. Kilpatrick, M. R. Siebert, R. J. Foley (UCSC), B. J. Shappee, M. R. Drout, J. S. Simon, A. L. Piro (Carnegie), and A. Rest (STScI)

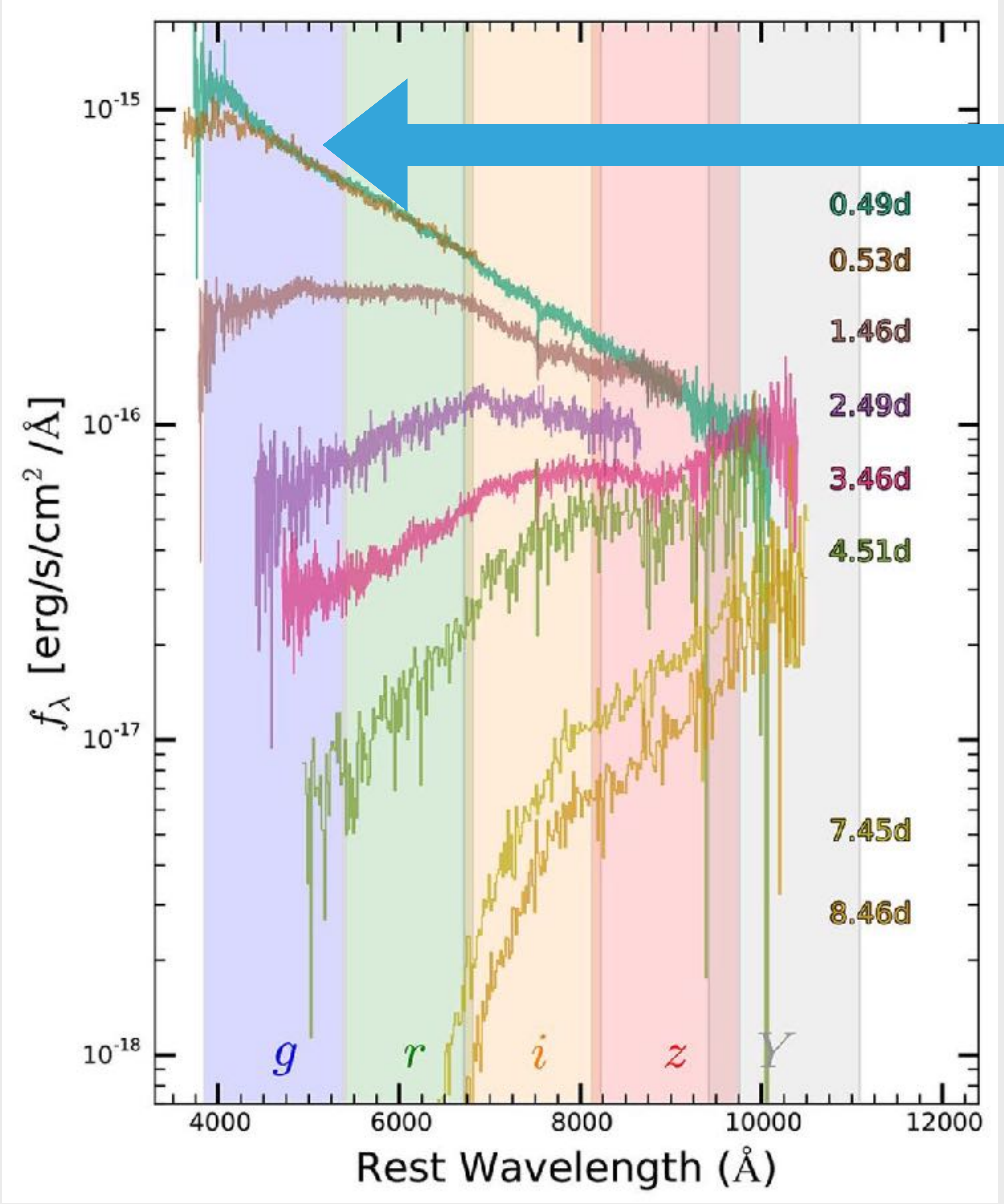
report on behalf of the One-Meter Two-Hemisphere (1M2H) collaboration:

On 2017 Aug 18 UT in the process of observing several galaxies coincident with the highest-likelihood localization region for the LIGO/Virgo G298048 trigger (LVC GCNs 21509, 21513) with the 1-m Swope telescope at Las Campanas Observatory, we detect a source 5.3¿ E and 8.8¿ N of NGC 4993, an S0 galaxy in the NGC 4993 / ESO 508-G018 group at a distance of ~40 Mpc (Tully-Fisher distance to the group; Freedman et al., ApJ, 553, 47, 2001).
The object is:

SSS17a 13:09:48.089 -23:22:53.35

How can we separate the gold from iron and rocks?

Light curve properties of kilonovae

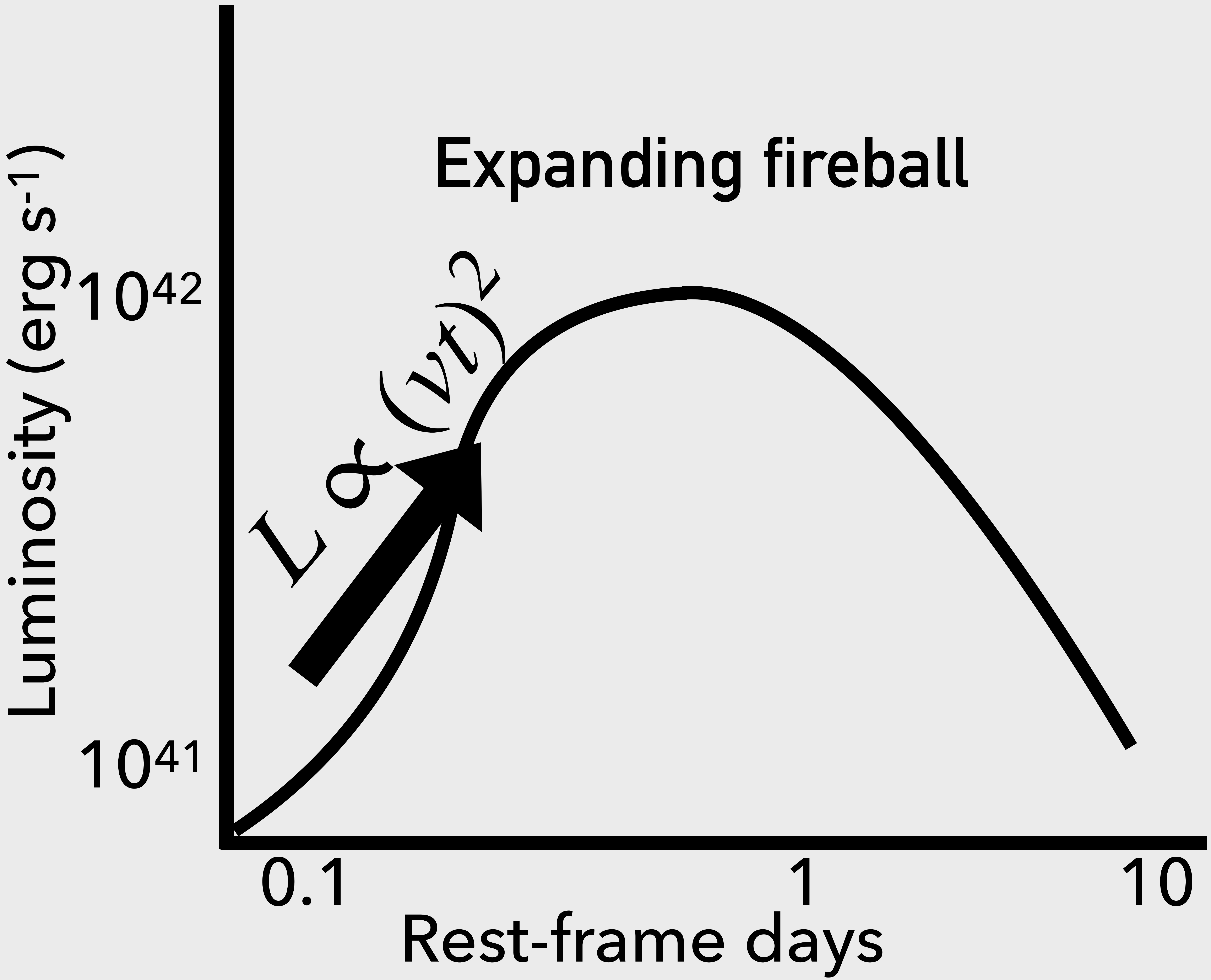


What was the origin of this extremely blue component?

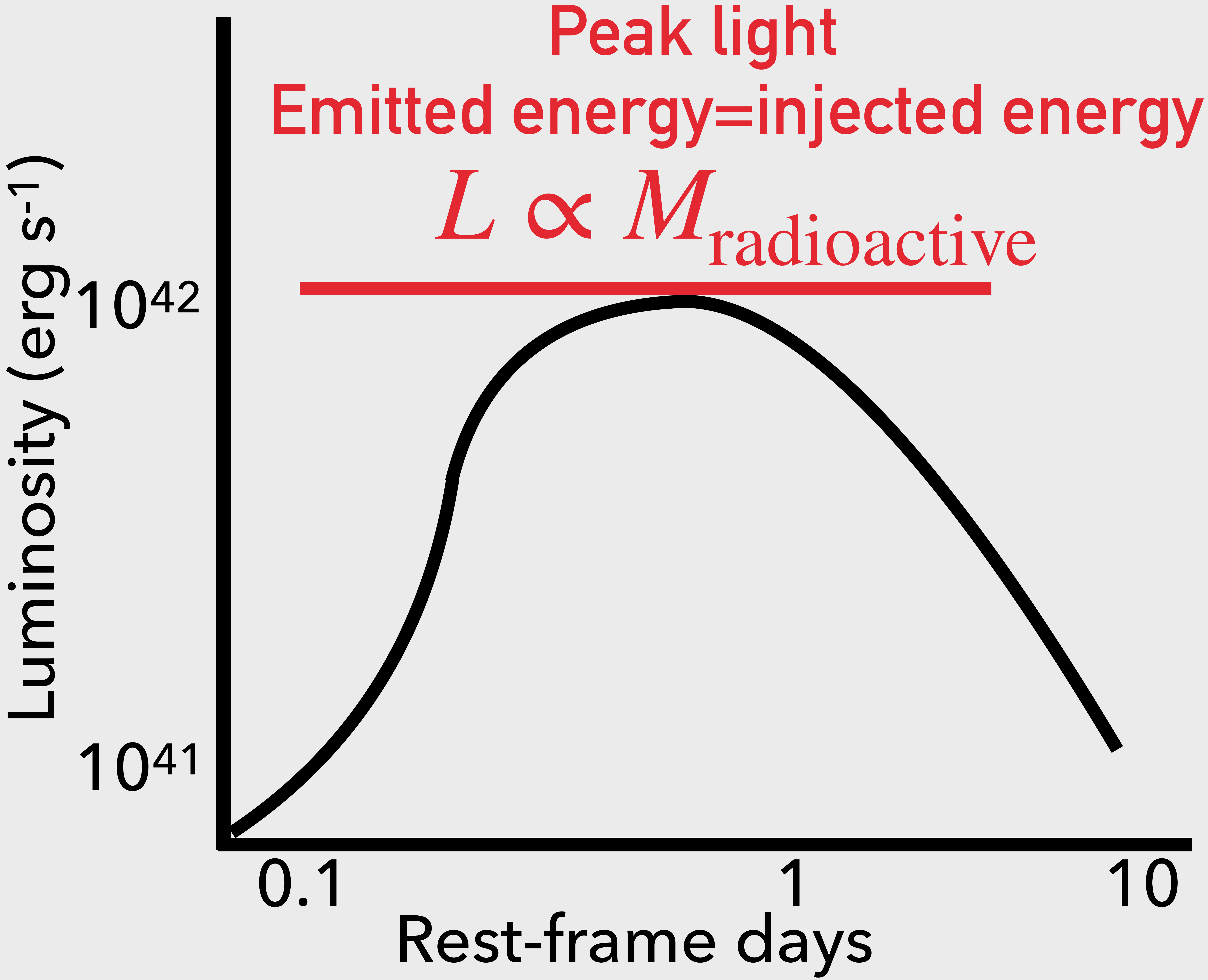
The peak of the energy distribution shifted beyond 9000 Å in <5 days

Kilpatrick+2017

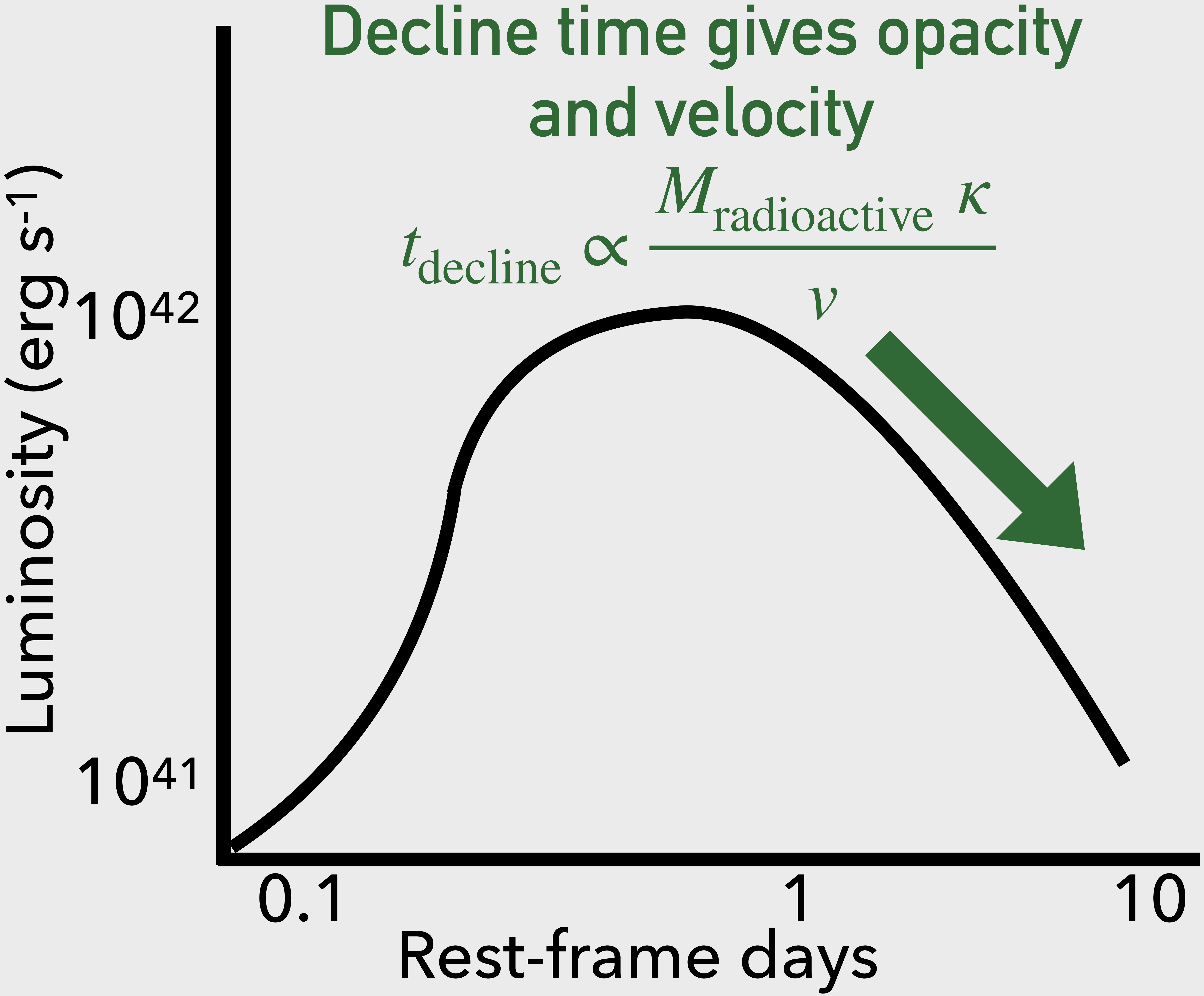
Light curve properties of kilonovae: Arnett's law



Light curve properties of kilonovae: Arnett's law



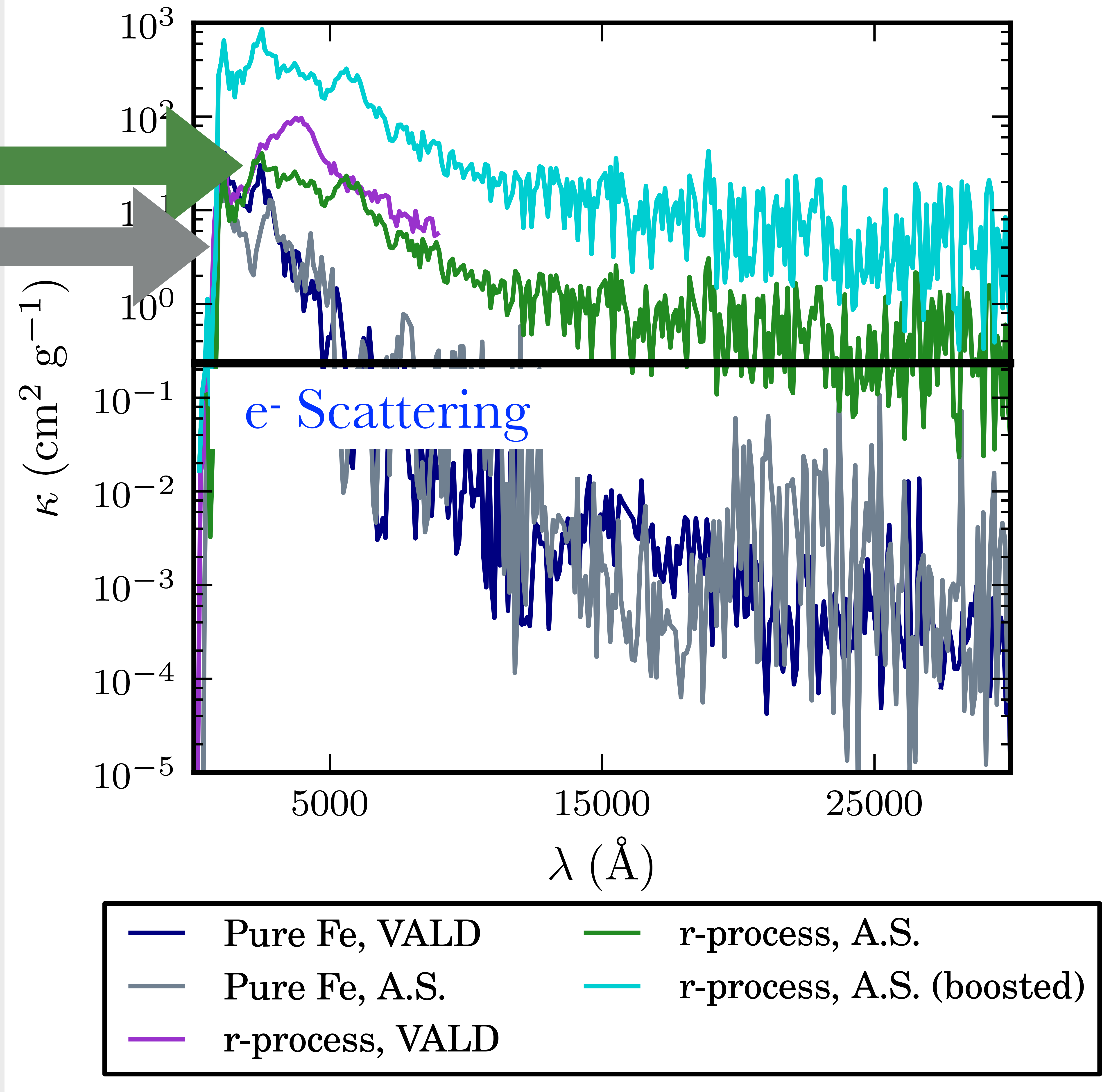
Light curve properties of kilonovae: Arnett's law



Spectral properties of r-process transients

r-process opacities (5-10 cm^2 g^{-1})

Iron-like opacities (~1 cm^2 g^{-1})



A cataclysmic explosion involving the neutron-rich core of a massive star will be extremely red

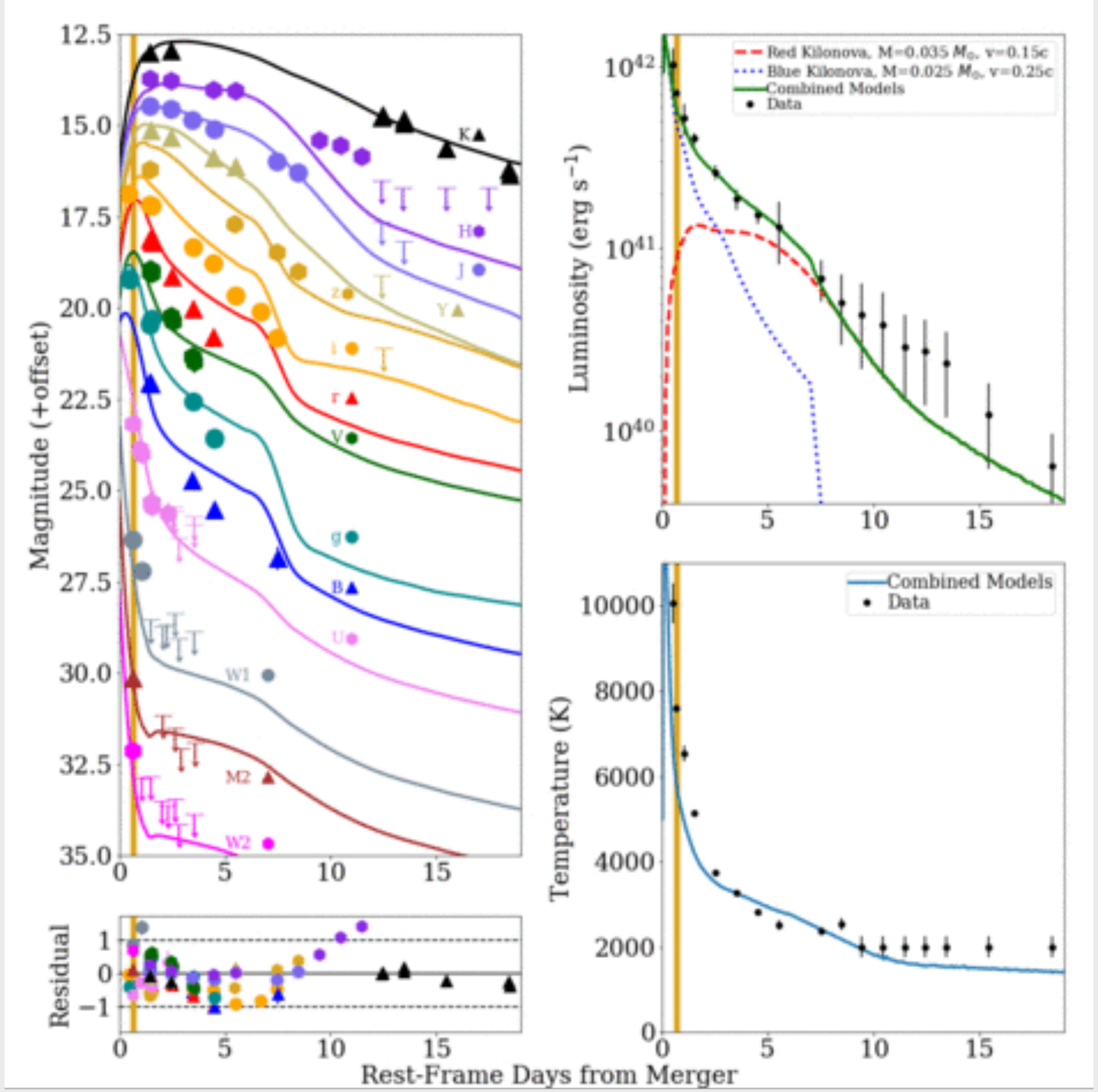
Light curve properties of kilonovae: Arnett's law

"Blue" kilonova:

$\kappa = 1 \text{ cm}^2 \text{ g}^{-1}$, 0.025 M$_\odot$

"Red" kilonova:

$\kappa = 5 - 10 \text{ cm}^2 \text{ g}^{-1}$, 0.035 M$_\odot$



Kilpatrick et al. 2017

Galactic Enrichment

Net r-Process Yield

$$R_{MW} = 25\ \mathrm{Myr}^{-1}$$

$$t_{\mathrm{H}} \approx 10^{10}\ \mathrm{yr}$$

$$R_{MW} \times t_{\mathrm{H}} \times M_{\mathrm{r-process}} \approx 10^{4}\ \mathrm{M}_{\odot} \approx X_{\mathrm{r-process}} \times M_{G}$$

$$M_{\mathrm{r-process}} \approx 0.04\ M_{\odot}$$

Galactic r-Process Mass Inventory

$$X_{\mathrm{r-process}} \approx 10^{-7}$$

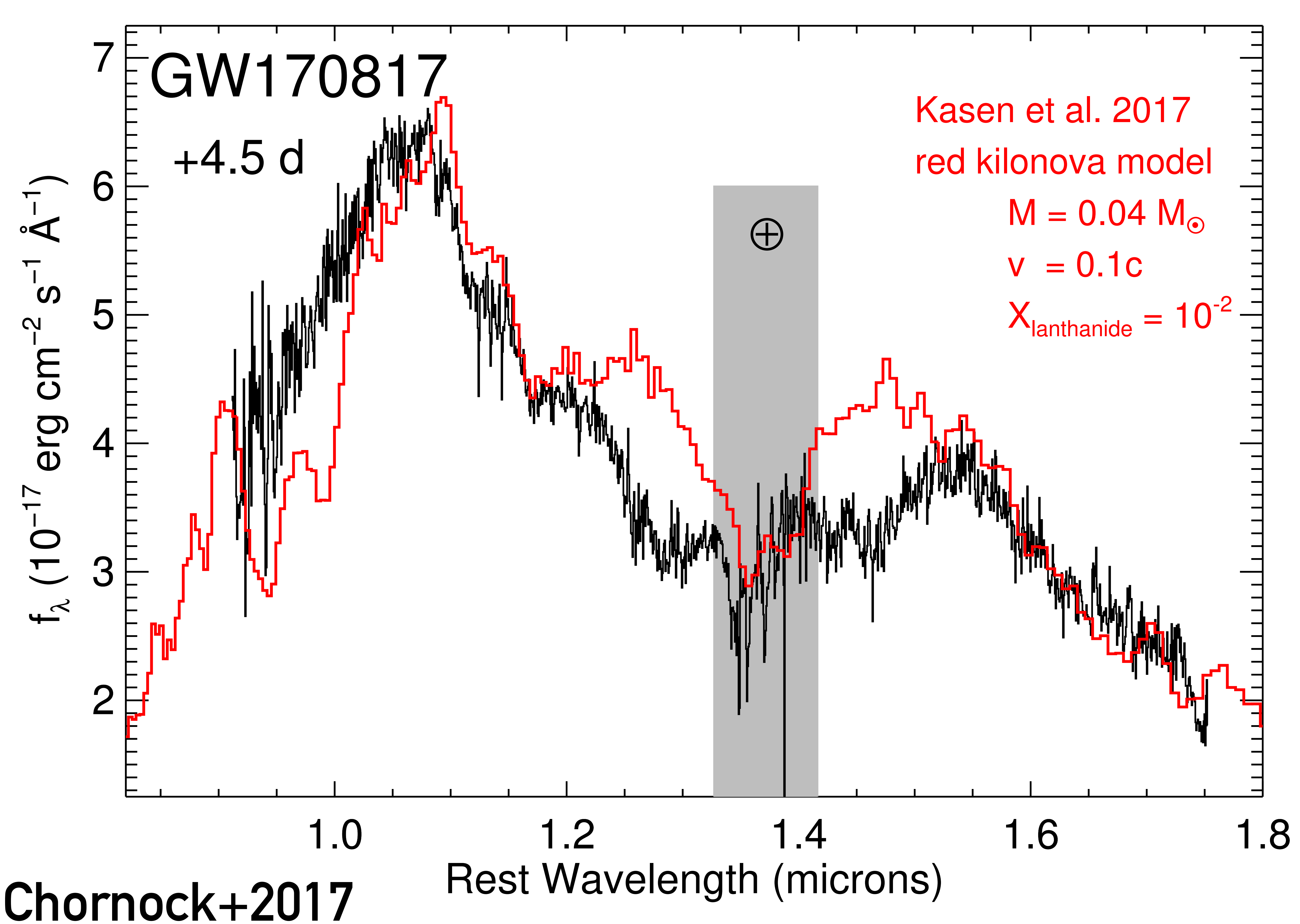
$$M_{G} \approx 10^{11}\ \mathrm{M}_{\odot}$$

Kilpatrick et al. 2017

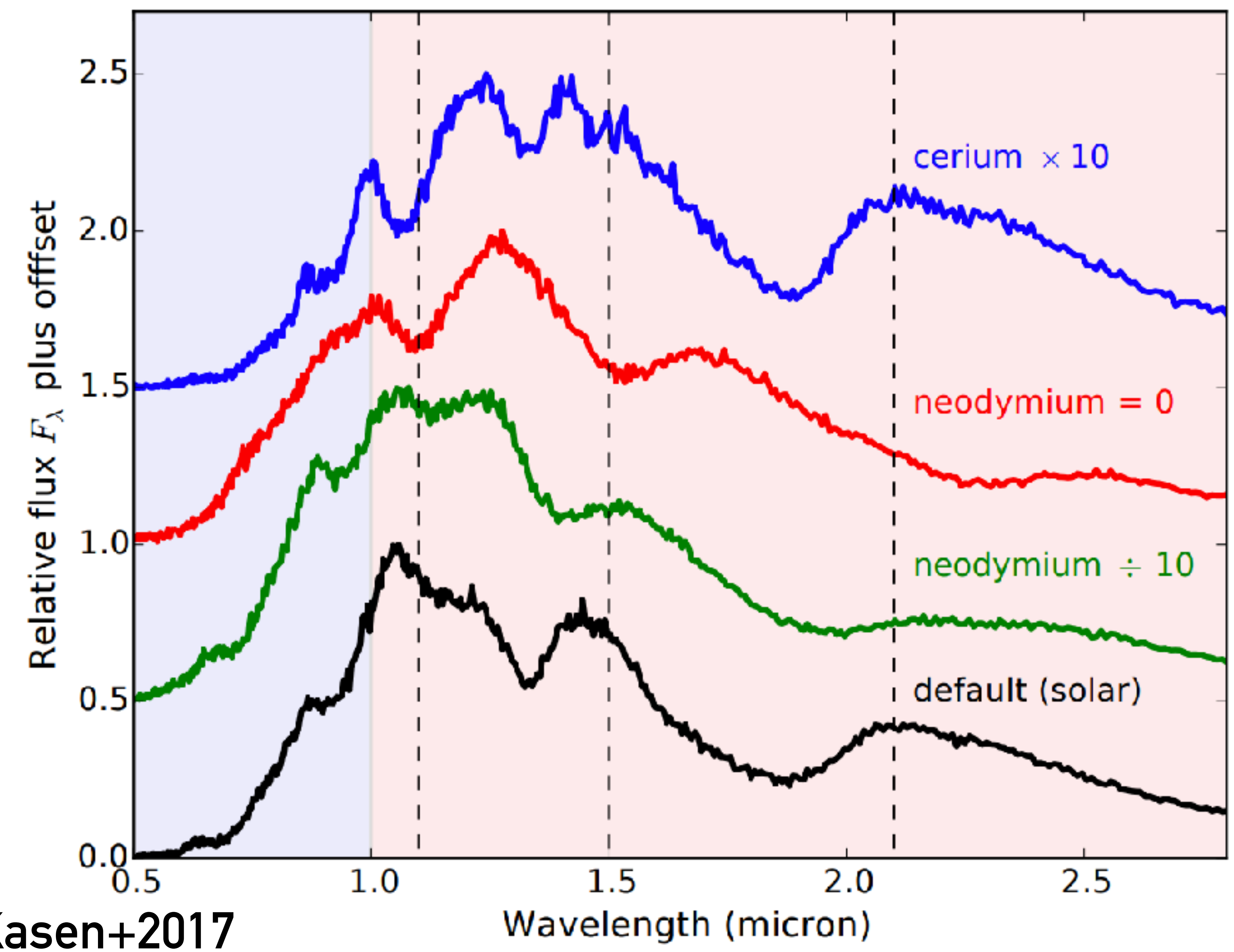
Remaining open questions...

What specific r-process elements were produced? Is there a diversity in these abundances? Spectral "features" do not correspond to any one r-process species.

Searches and spectral coverage in the infrared is essential!



Chornock+2017



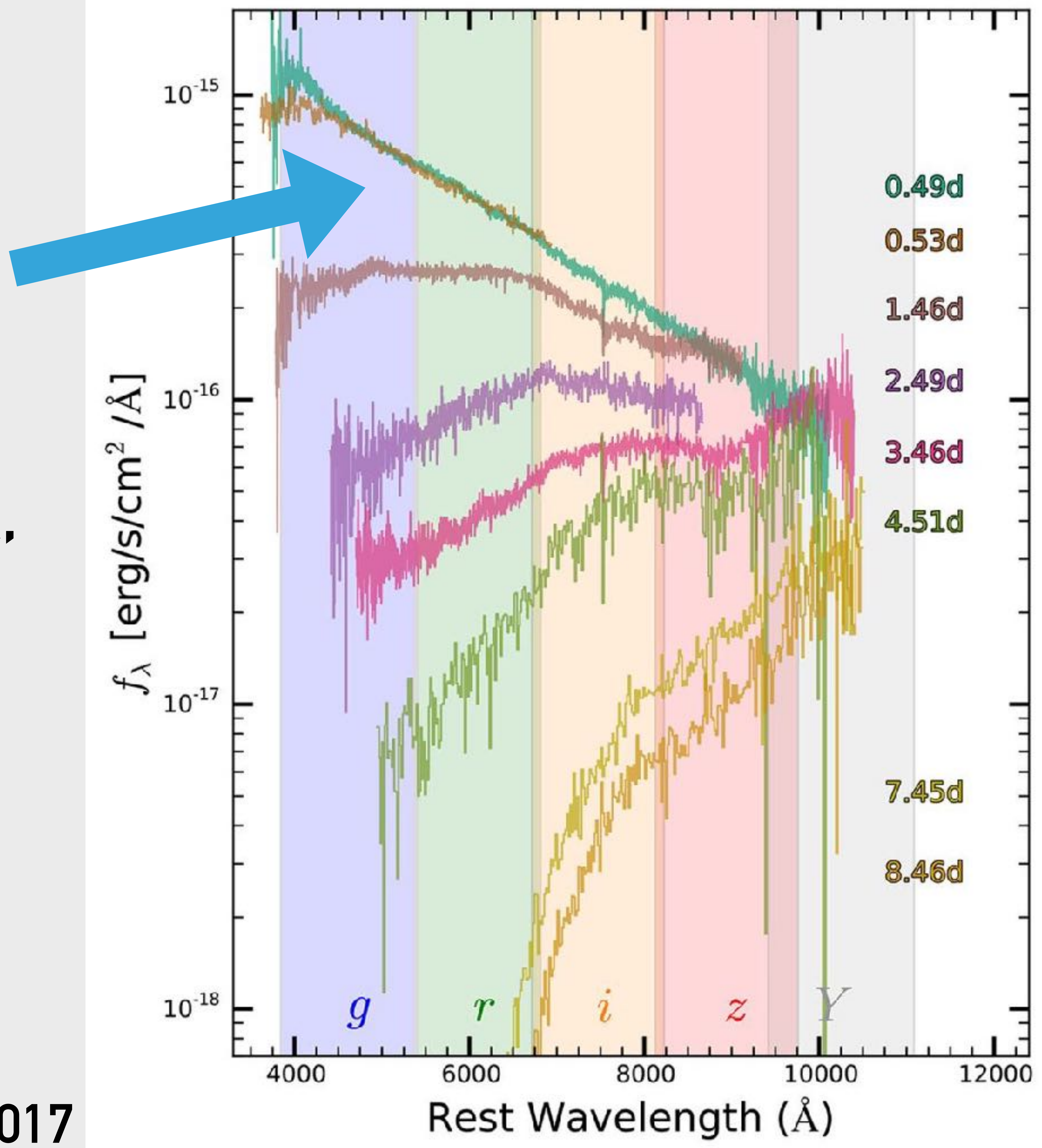
Kasen+2017

Remaining open questions…

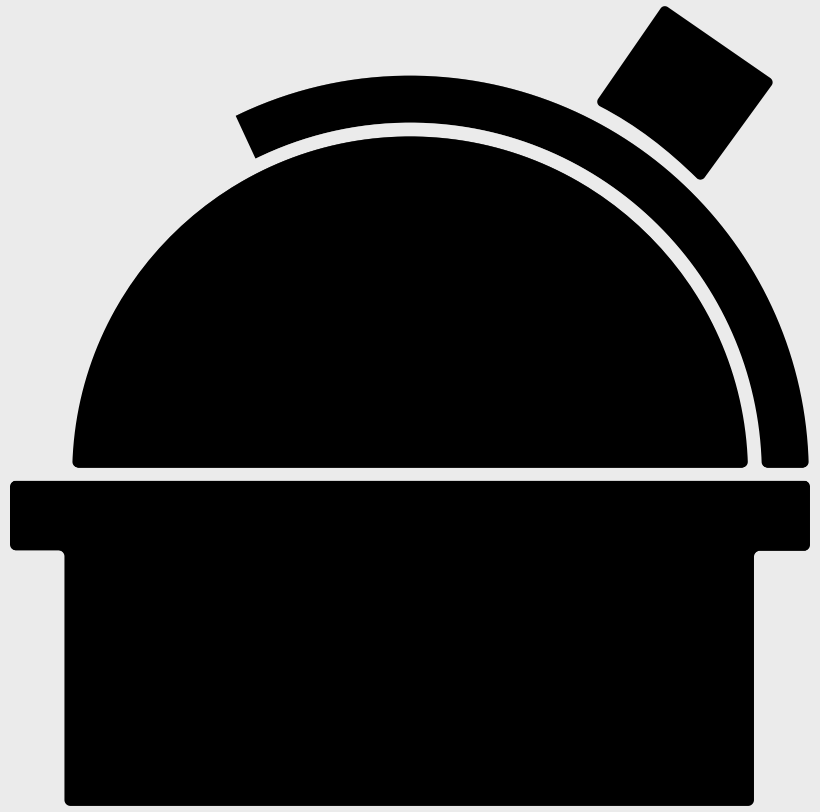
What gave rise to the blue emission and low opacity ejecta?

Low r-process abundances, a shock, non-thermal emission, magnetar-powered emission?

Rapid observations and coverage in the ultraviolet are needed

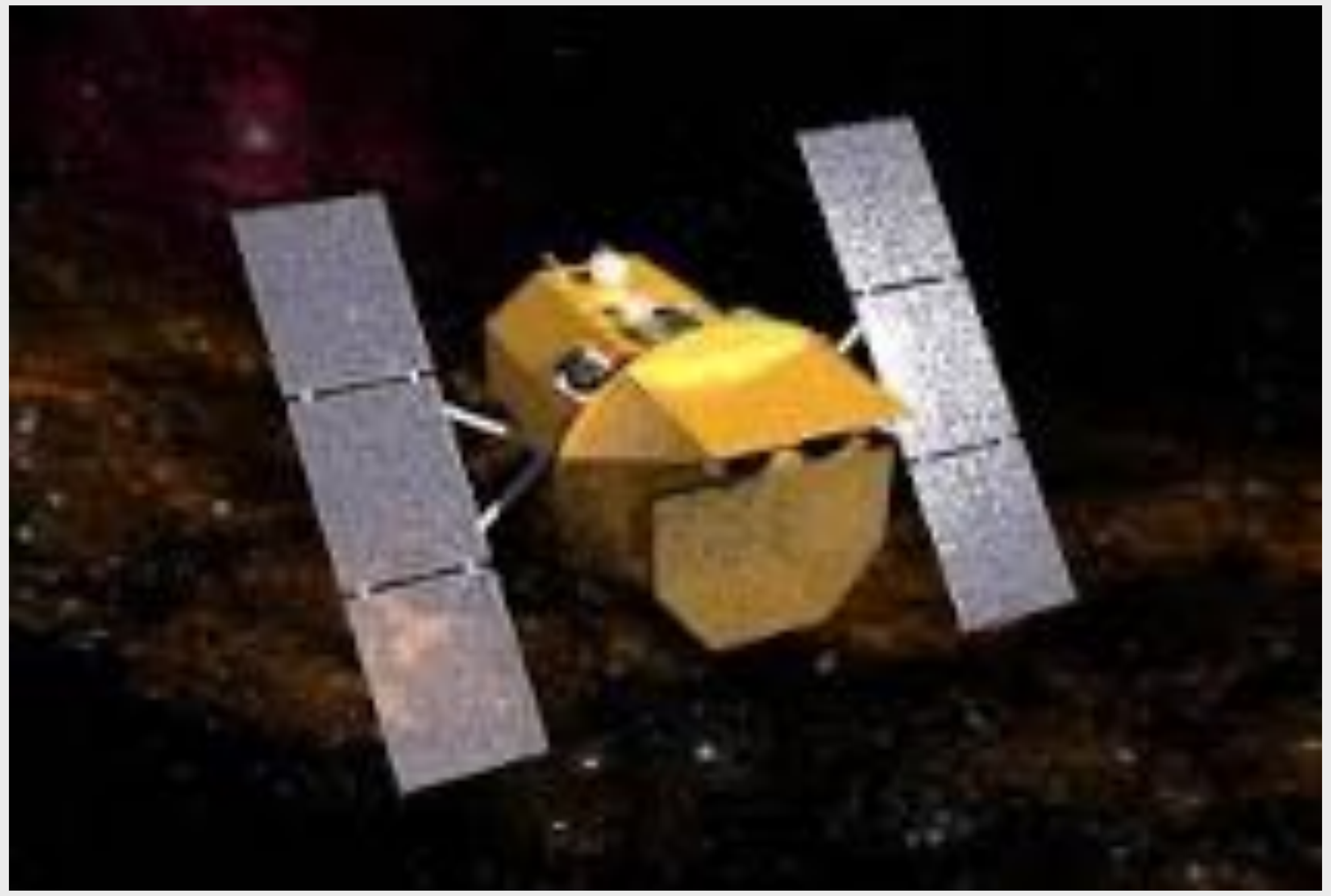


Kilpatrick+2017



What new surveys are needed to find these signatures, and how can they best be designed to understand r-process bearing transients?

Challenges of optical/infrared surveys



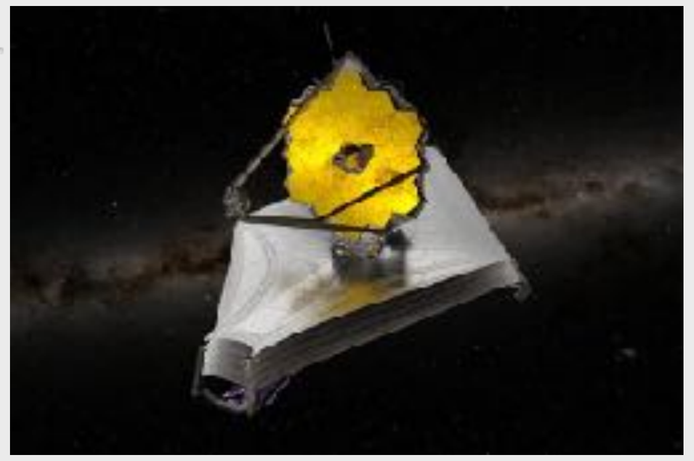
Strategies for rapid follow up

A distributed, global and space-based network

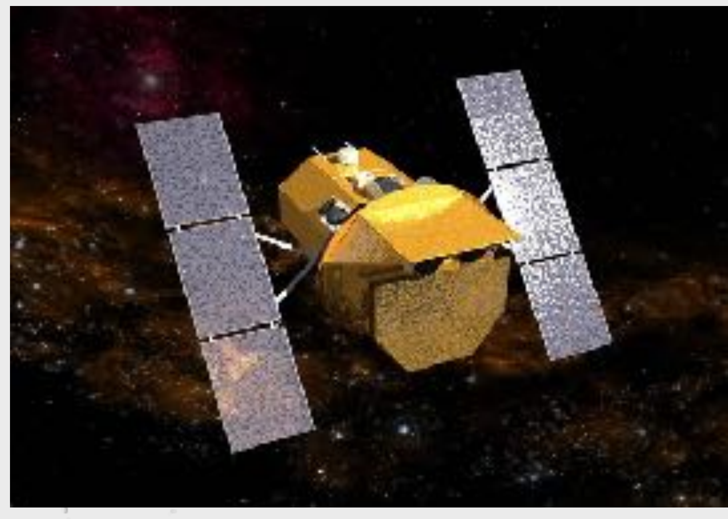
Operating during O3-O4: A worldwide network of 0.7-1.5m ground-based telescopes covering gamma-ray to radio wavelengths

Chandra

VLA

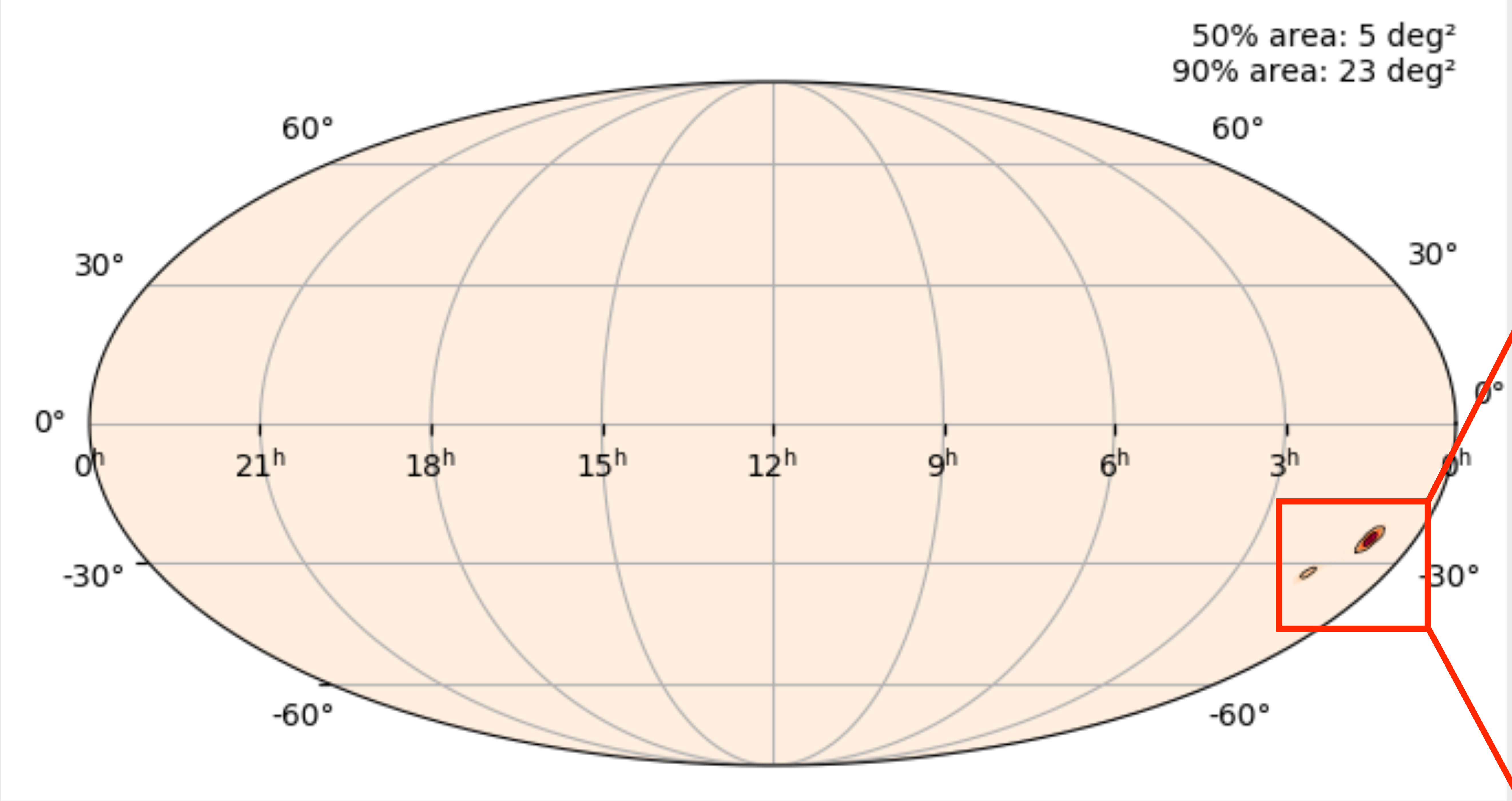


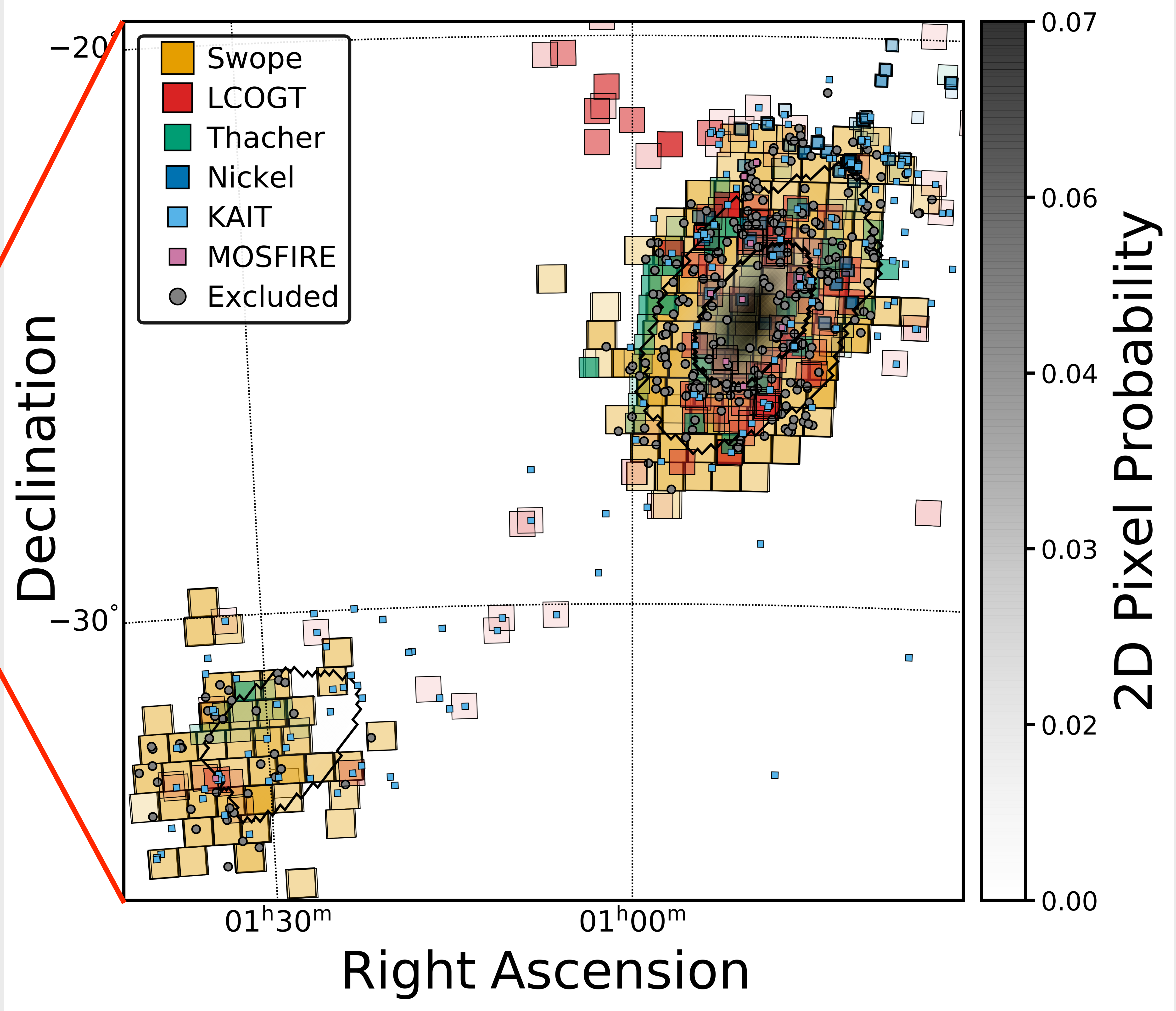
JWST



Swift

Black Hole/Neutron Star Merger GW190814



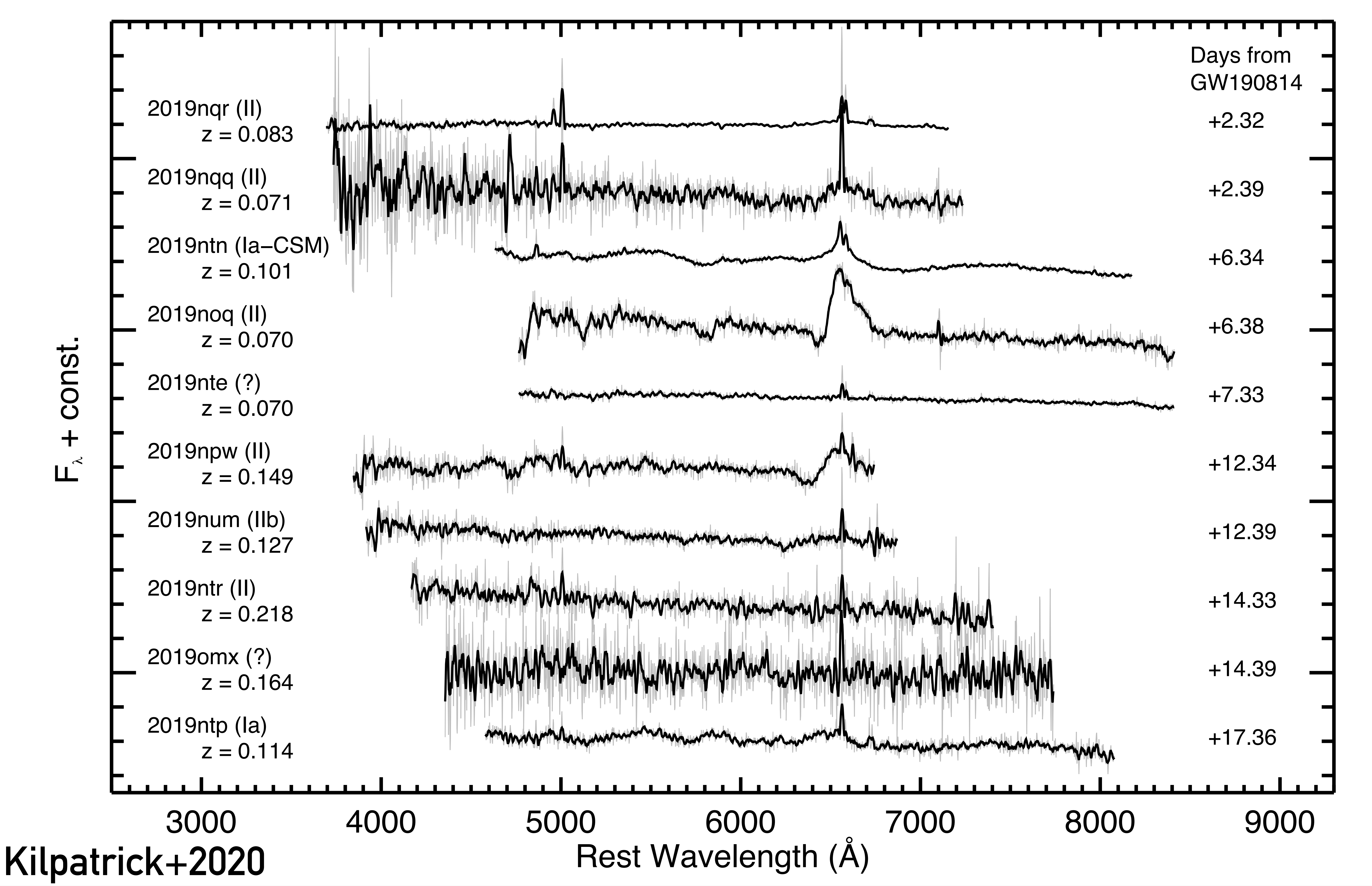


A 23.2 + 2.6 $M_\odot$ black hole and neutron star(?) merger

Best localized GW event yet: extremely promising for search and follow up!

Kilpatrick et al. 2021

GW190814 candidate vetting: follow-up data



No valid candidates after vetting 189 transients discovered <2 weeks from merger, including 46 spectra of transients and their host galaxies

Black Hole/Neutron Star Merger GW190814

$$r_{\rm tidal} \approx \left(\frac{M_{BH}}{M_{NS}}\right)^{1/3} R_{NS}$$

$$r_{\rm ISCO} = \frac{6GM_{BH}}{c^2}$$

$$\frac{r_{\rm tidal}}{r_{\rm ISCO}} \propto M_{BH}^{-2/3} M_{NS}^{-1/3} R_{NS} > 1$$

Condition to produce a kilonova - requires a low-mass black hole or stiff equation of state

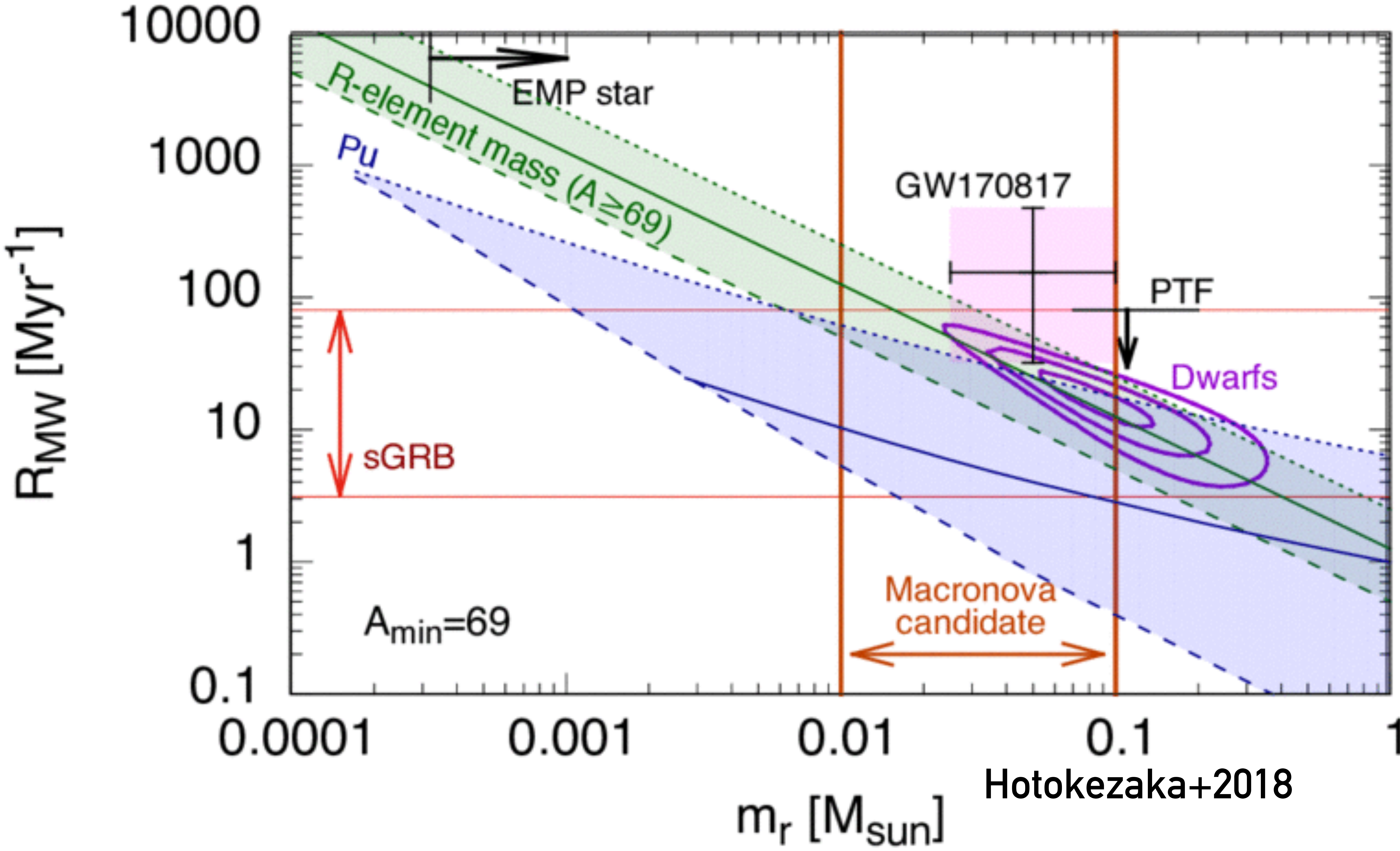
Ejecta spirals into black hole, Kyutoku et al. 2015

Few NS mergers during O3-O4

O2 rates: 320-4740 Gpc^{-3} yr^{-1} (Abbott+2017)

O3 rates: 13-1900 Gpc^{-3} yr^{-1} (LVK/GWTC-3+2021)

O4 rates: 7.6-250 Gpc^{-3} yr^{-1} (LVK/GWTC-4+2025) - !!!

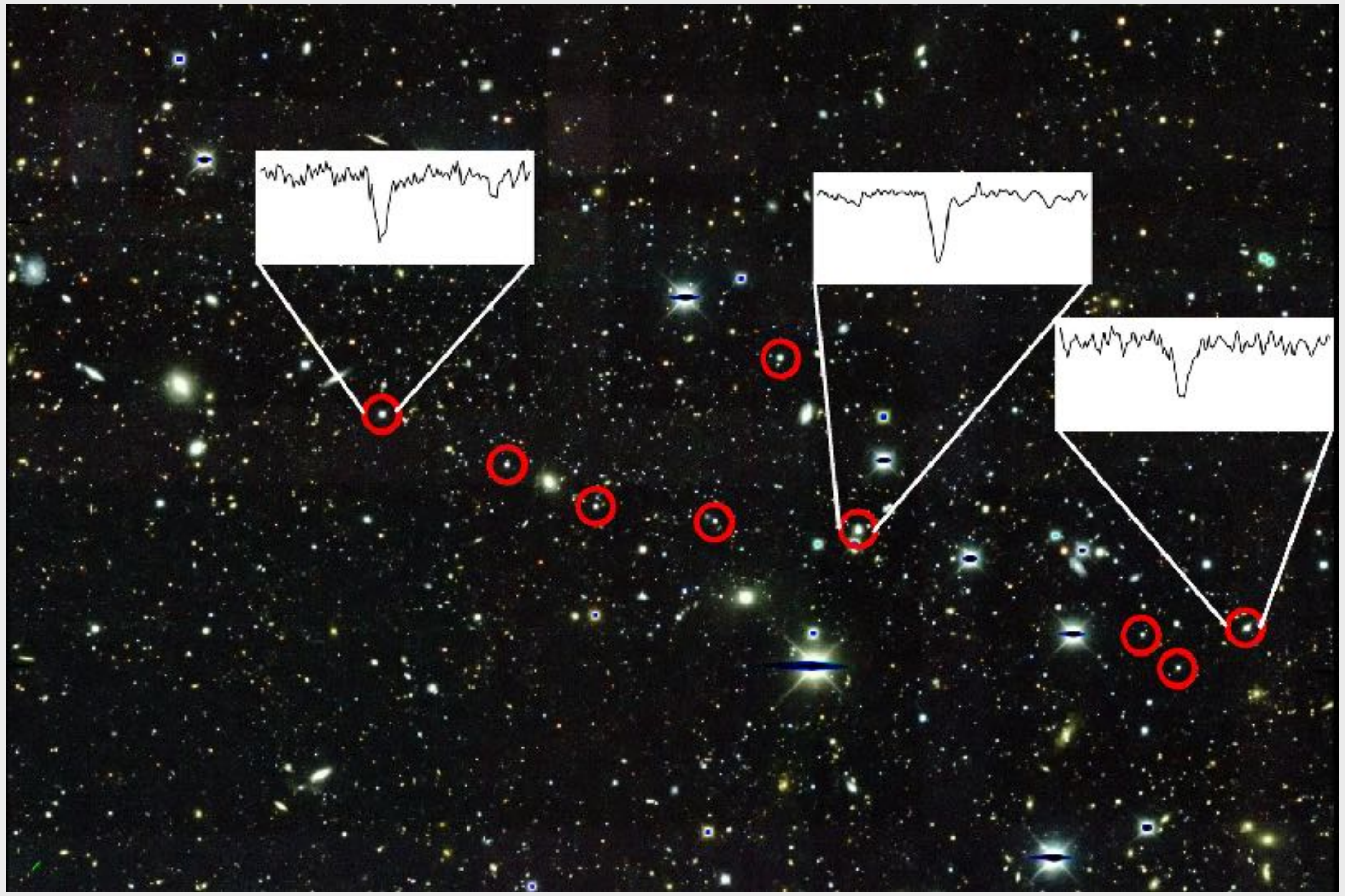


Hotokezaka+2018

Have we unsolved the r-process problem?

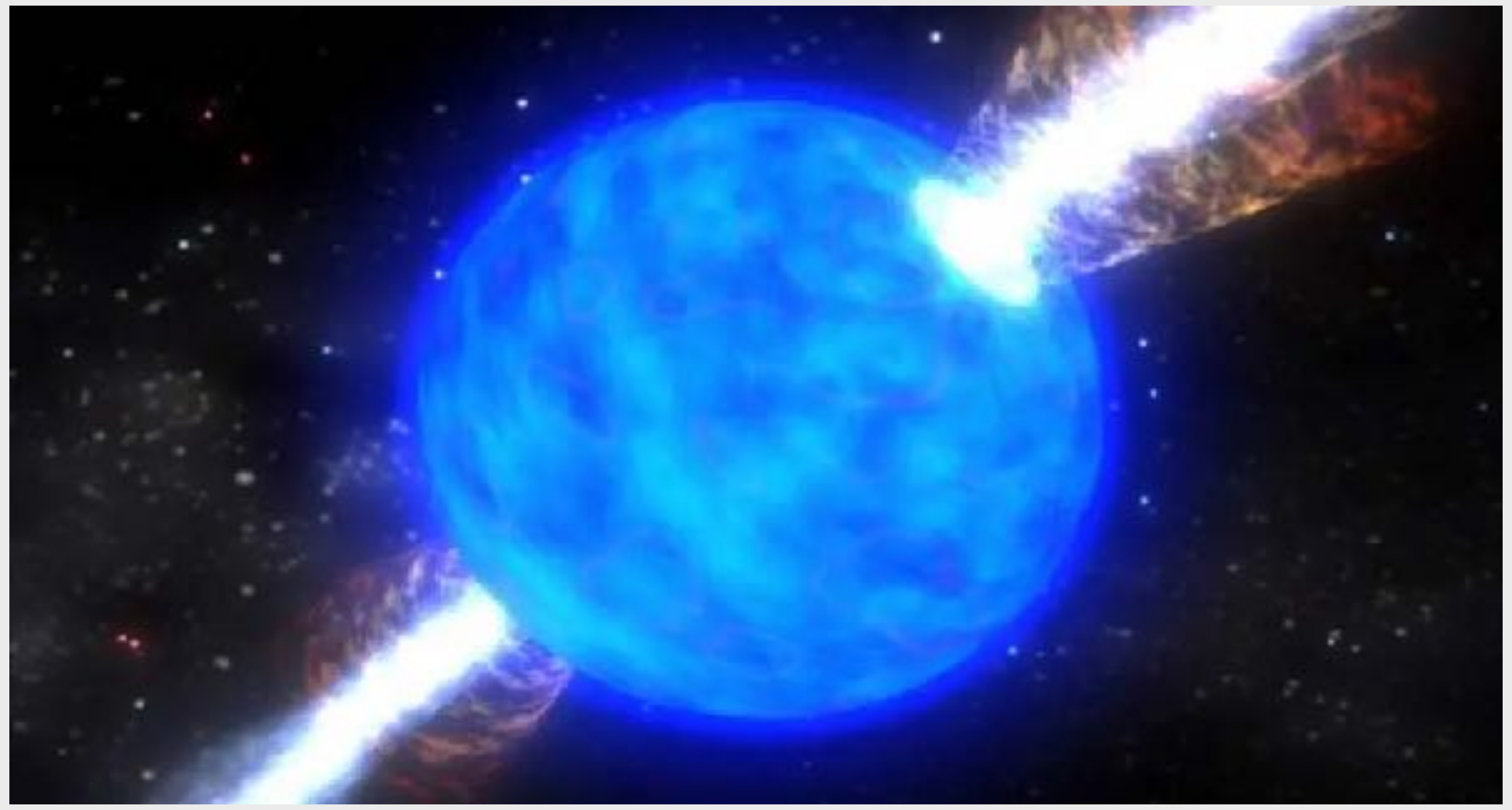
We may need new sources of the r-process, particularly those that can produce elements quickly

Where did all of the r-process go?

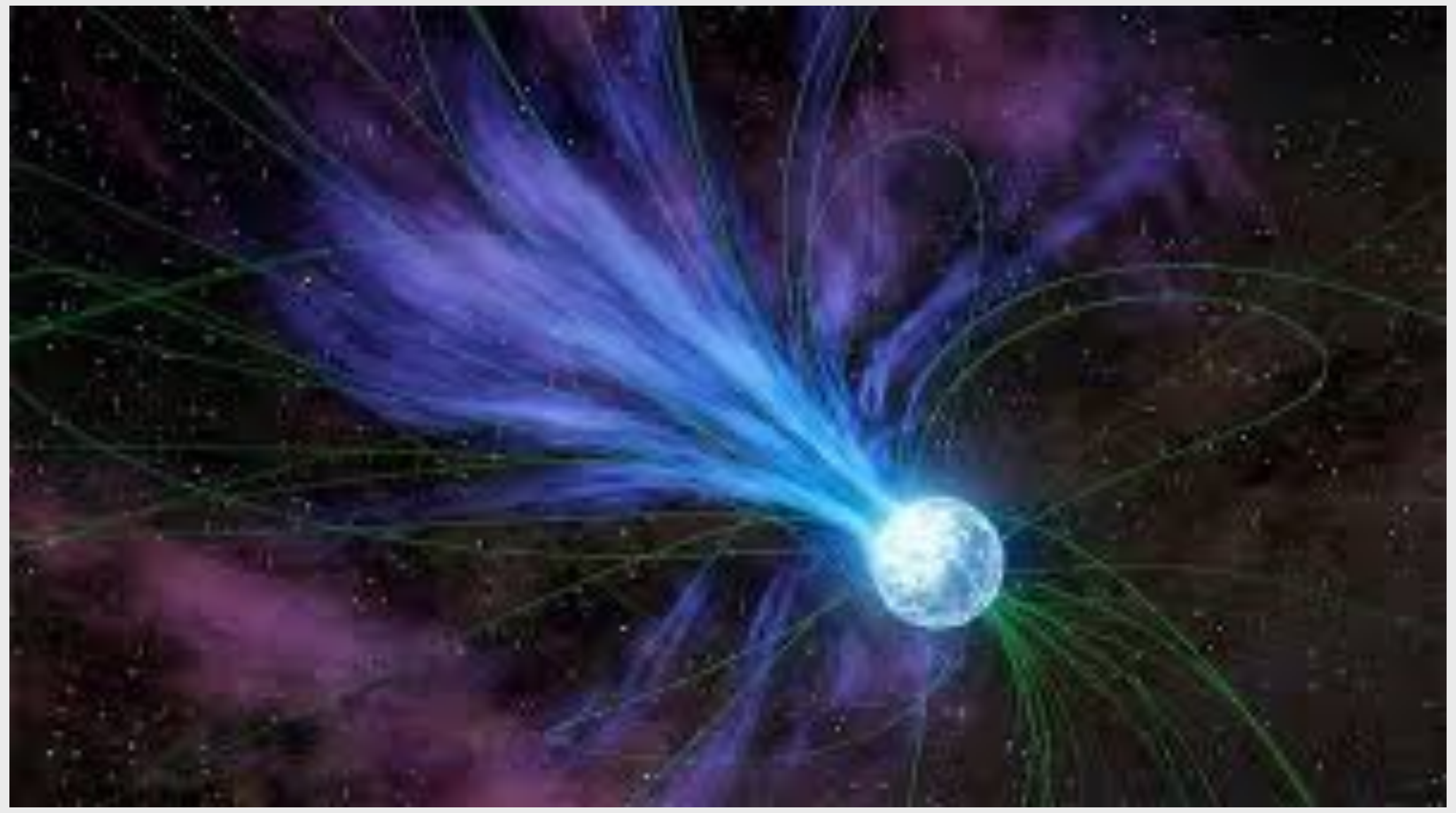


Reticulum II, Ji+2018

r-process in low-metallicity dwarf galaxies requires an early Universe source of material



Collapsars - massive star explosions that can form a low metallicity, Siegel+2019



Magnetar flares - eruptions from magnetized neutron stars, Patel+2025

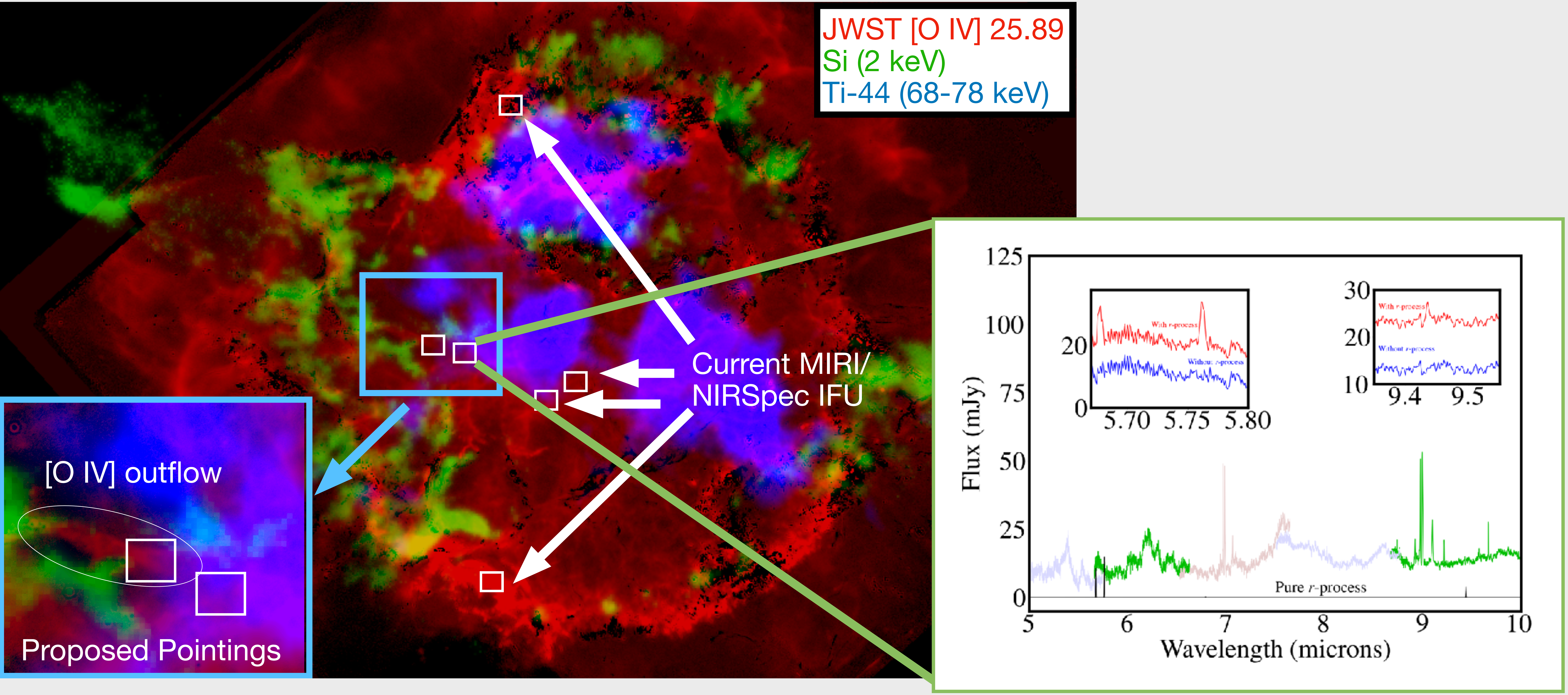
Where did all of the r-process go?

Normal supernova explosions:

- We know they occur very early in the Universe (z=5; Coulter+2026)
- They host neutron stars (Chakrabarty+2001)
- They occur at >1,000x the rate of neutron star mergers (LVK+2025)

Milisavljevic+2024

Where did all of the r-process go?



Proposed observations to isolate a new site of r-process in Cas A

What is the prospect of isolating r-process production via large populations?

Multi-messenger infrastructure with:

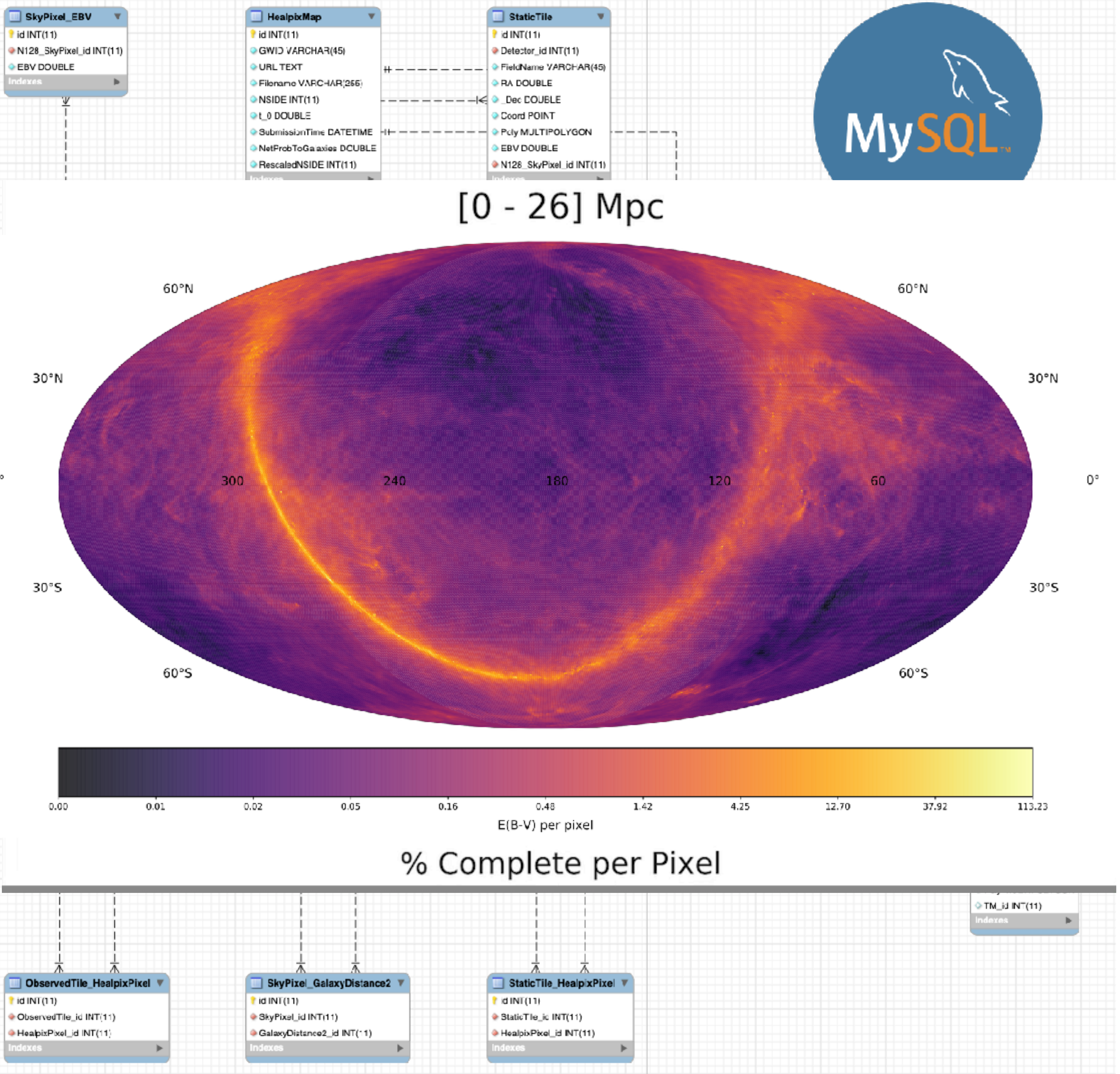
Teglon

TROVE

Detection threshold for binary neutron star merger

More detectors = better localization

Teglon



- Converts GLADE to a queryable database format
- Calculates 3D spatially varying catalog completeness
- Models HEALPix data format
- Supports ingesting a variety of value-added geospatial data

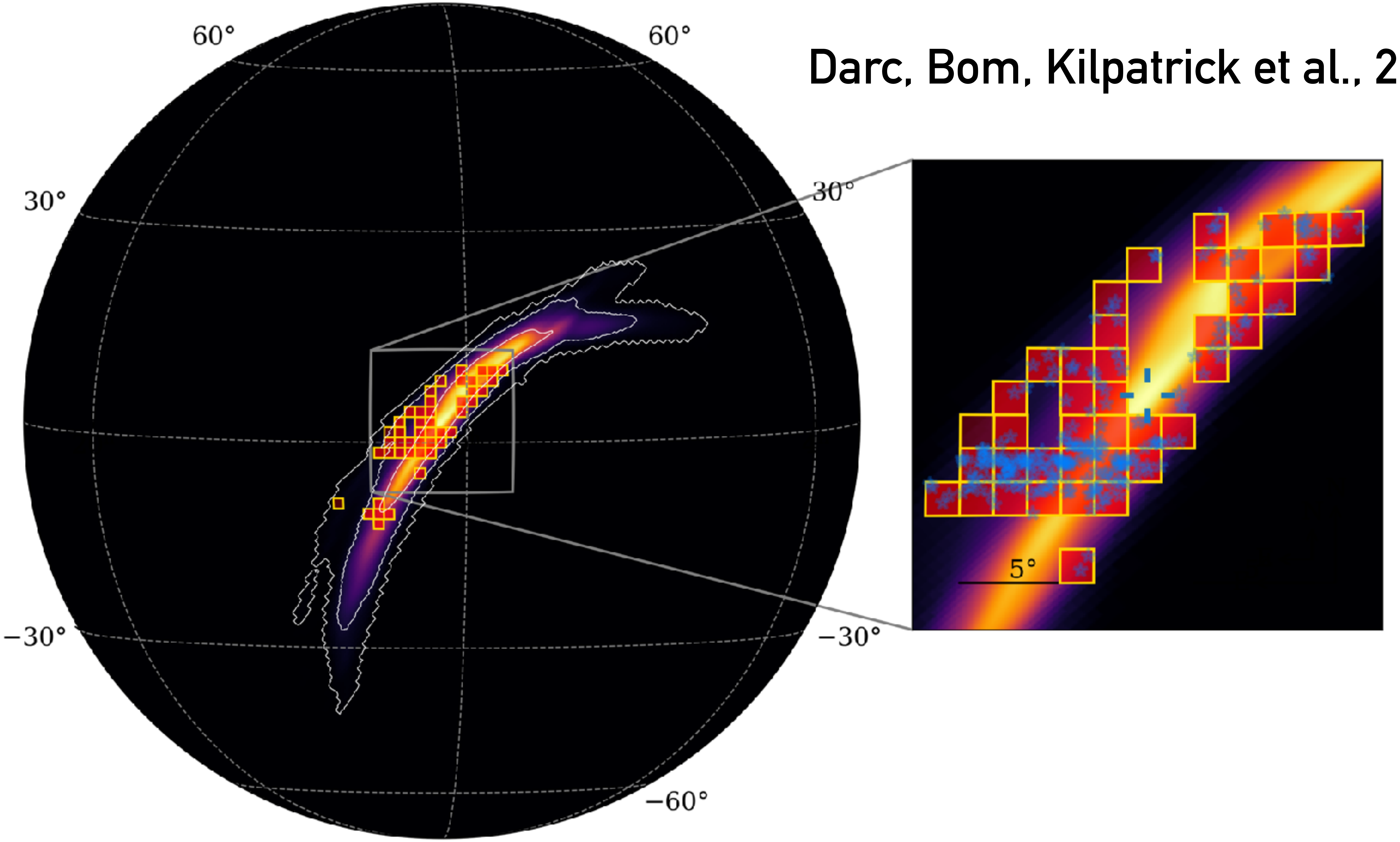
https://github.com/gw-commons

Kilpatrick, Coulter, et al. 2021

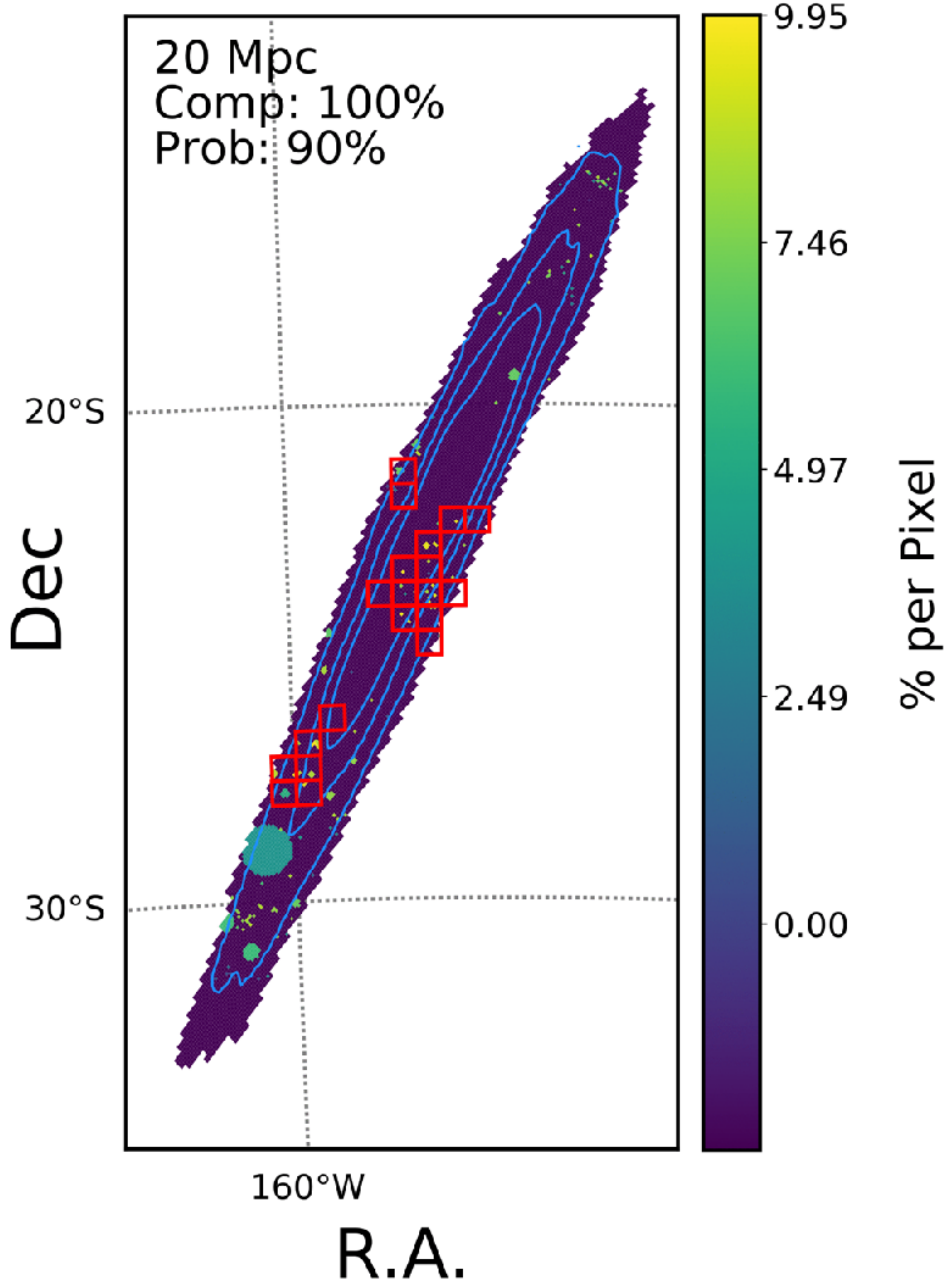
Coulter, Kilpatrick et al., 2025

Darc, Bom, Kilpatrick et al., 2025

Darc, Bom, Kilpatrick et al., 2025



Any spatially-varying metric (in 2D or 3D) can be optimized on sky, crossmatched to other catalogs/maps, and used to generate an observing plan



20 Mpc
Comp: 100%
Prob: 90%
20°S
30°S
160°W
Dec
R.A.
9.95
7.46
4.97
2.49
0.00
% per Pixel

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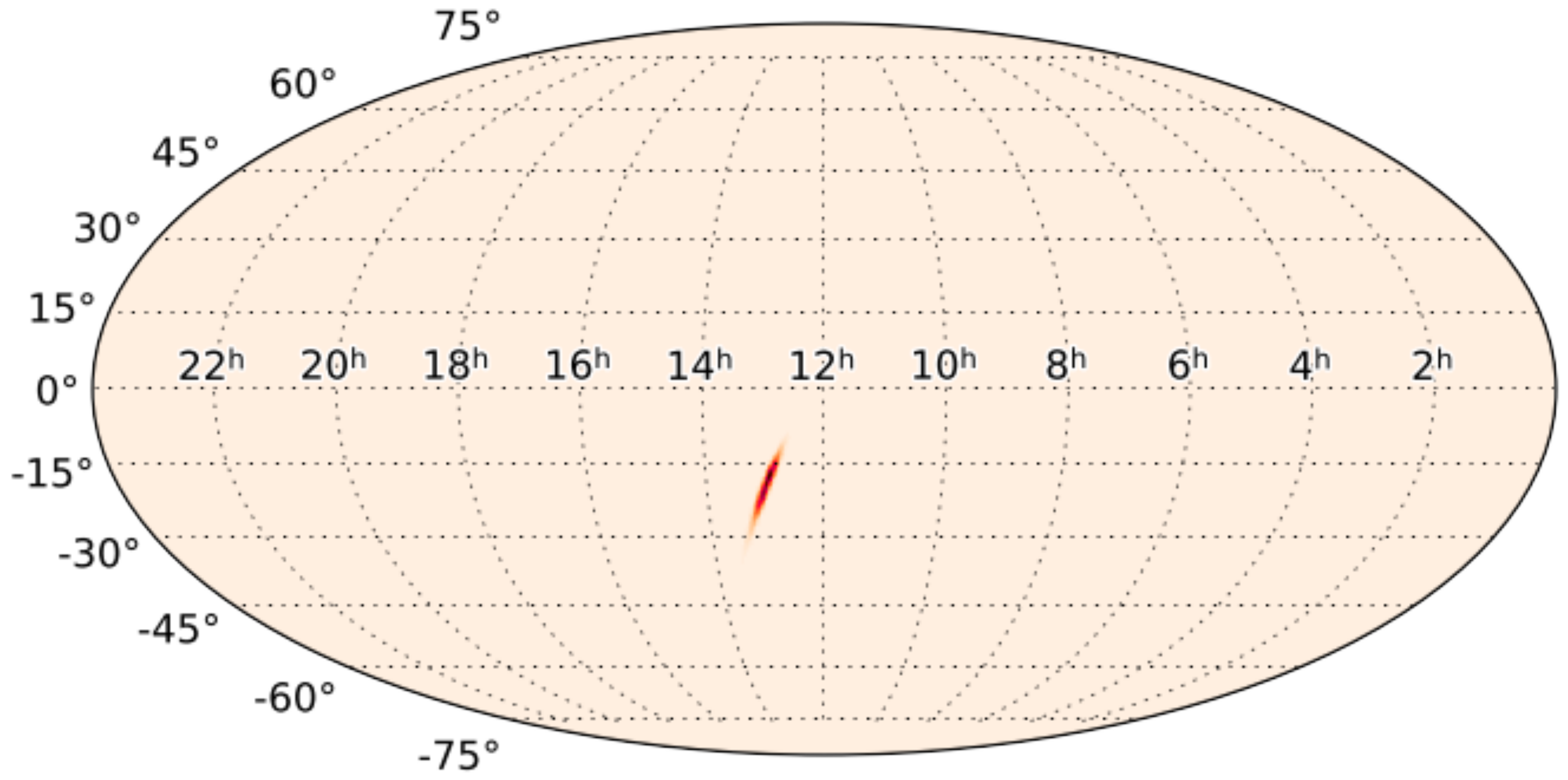
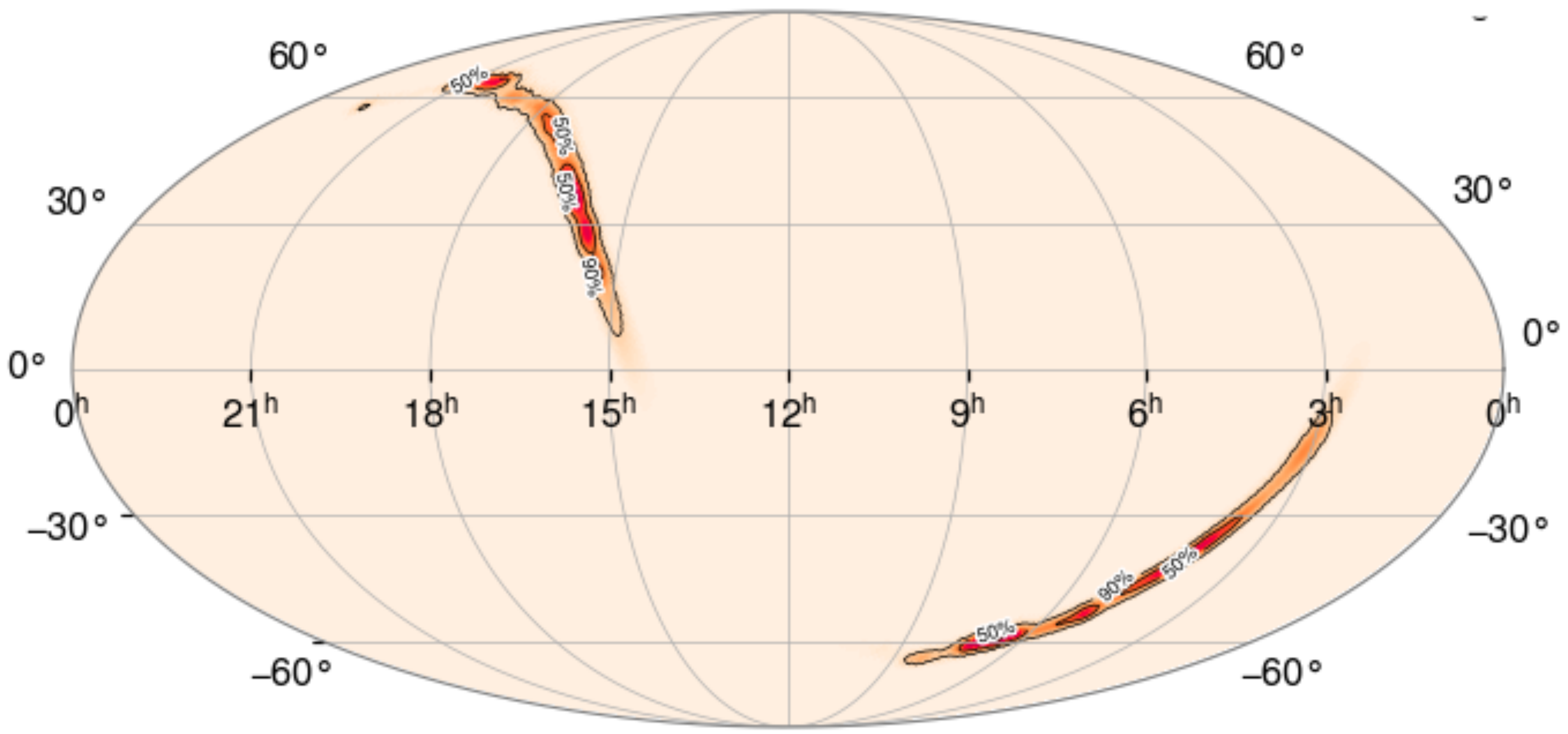
The Localization Process is ***HARD!***

2D Localization: Multiple detector events - especially with Virgo - helps a lot



GW170817: ~30 deg^2

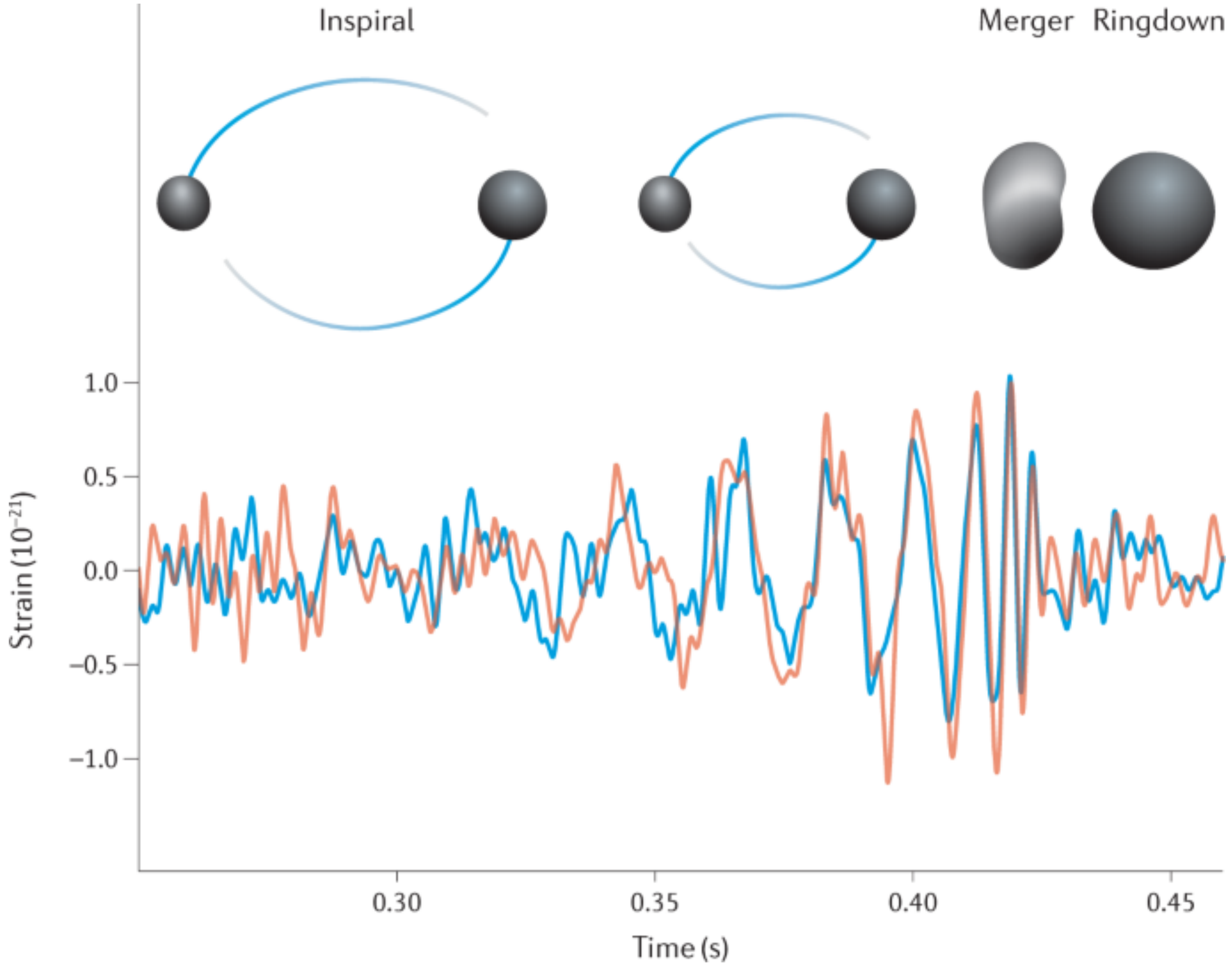
Credit: LIGO/Virgo; Abbott+2017

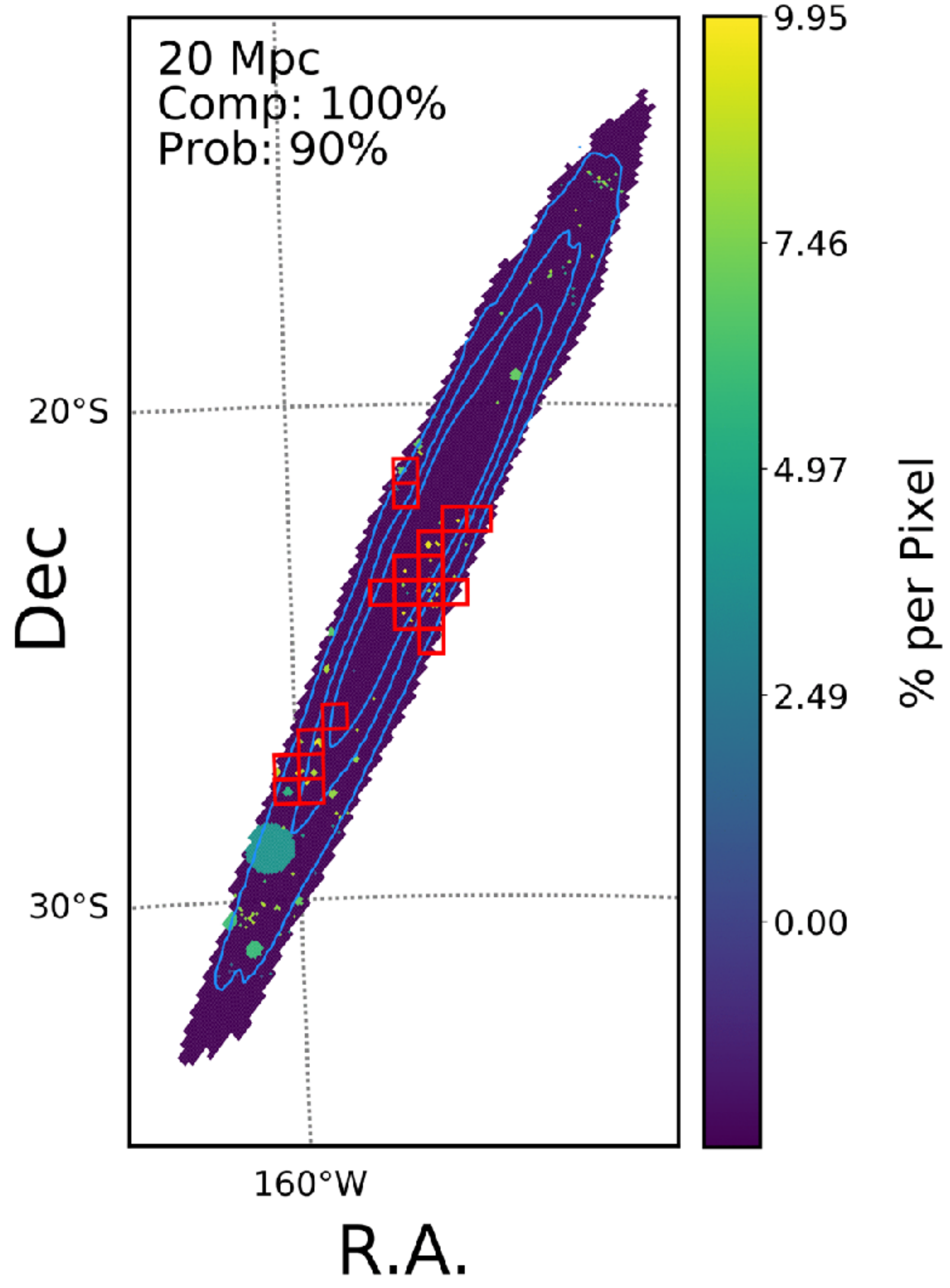


S250818k: ~800 deg^2

Credit: LVK; GraceDB

The Localization Process is ***HARD!***





GW170817: ~40 Mpc

Matching GW distance to galaxies gives us candidate hosts (assuming galaxy catalogs are complete)

The Localization Process is ***HARD!***

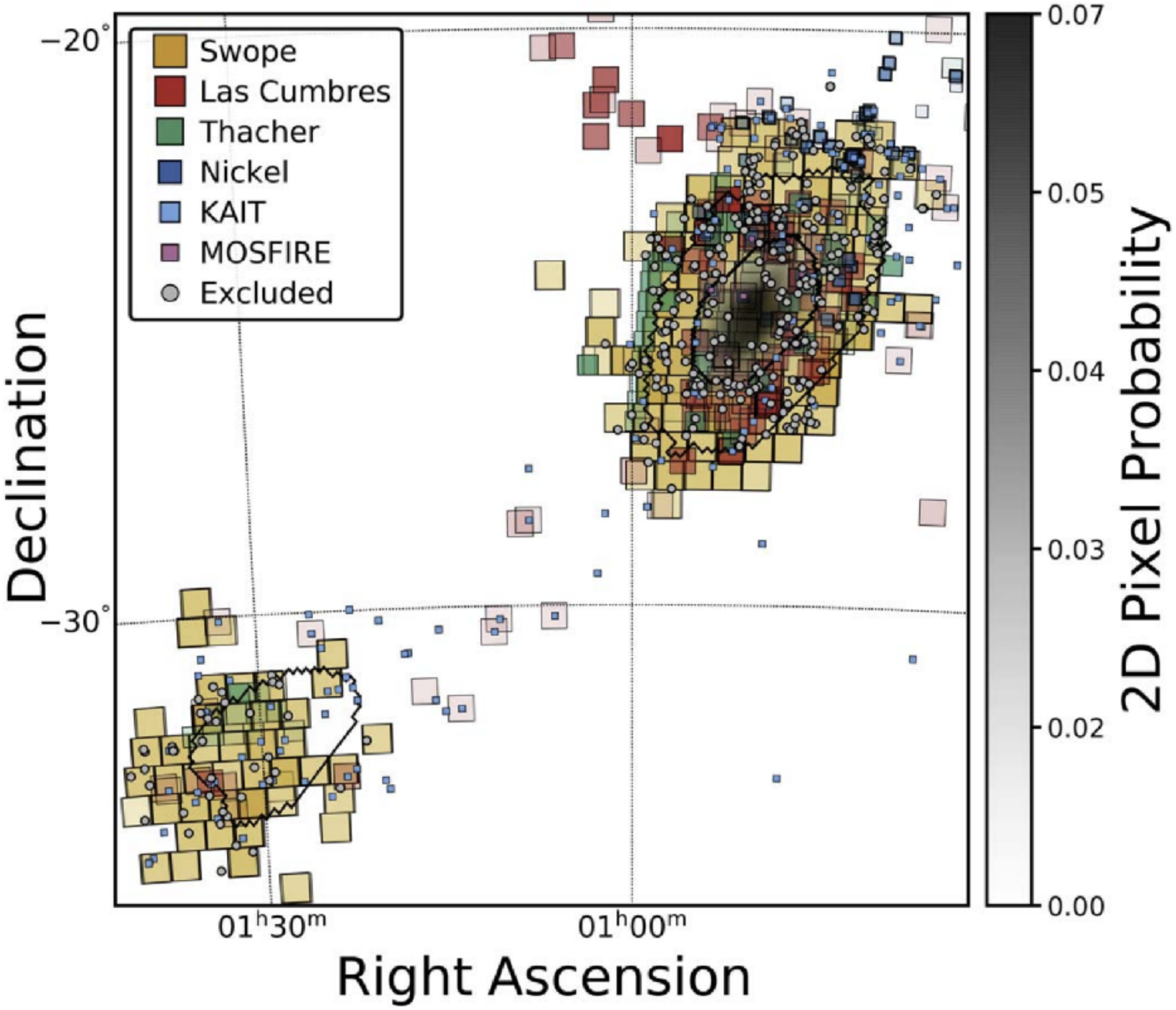
Distance Criterion: Are galaxies at the GW-predicted luminosity distance?

GW190814

189 candidates (e.g. Kilpatrick+2021)

~50% ruled out using distance criteria

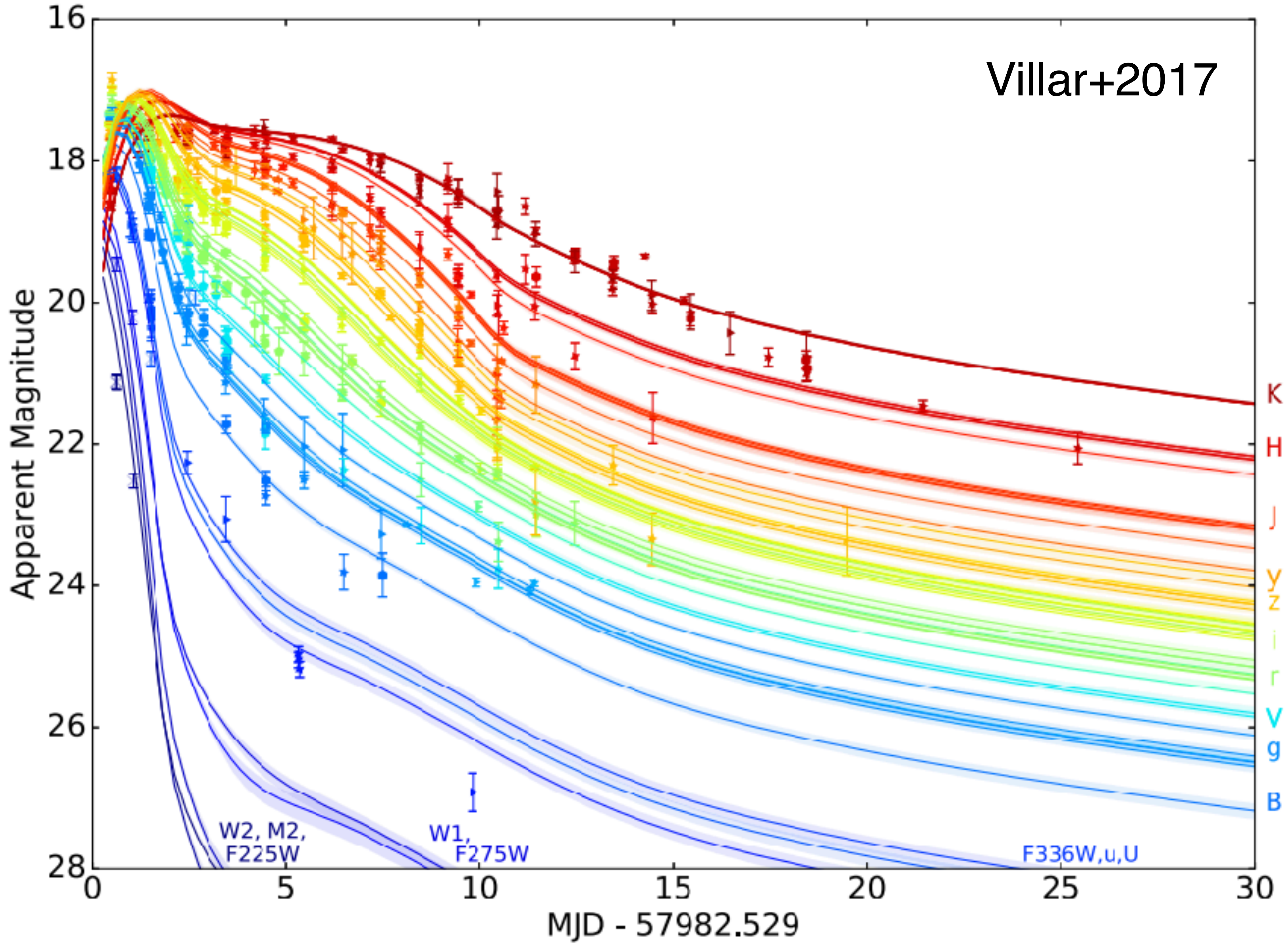
~2/3 of O3 GW candidate counterparts ruled out using real-time information (Rastinejad+2022)



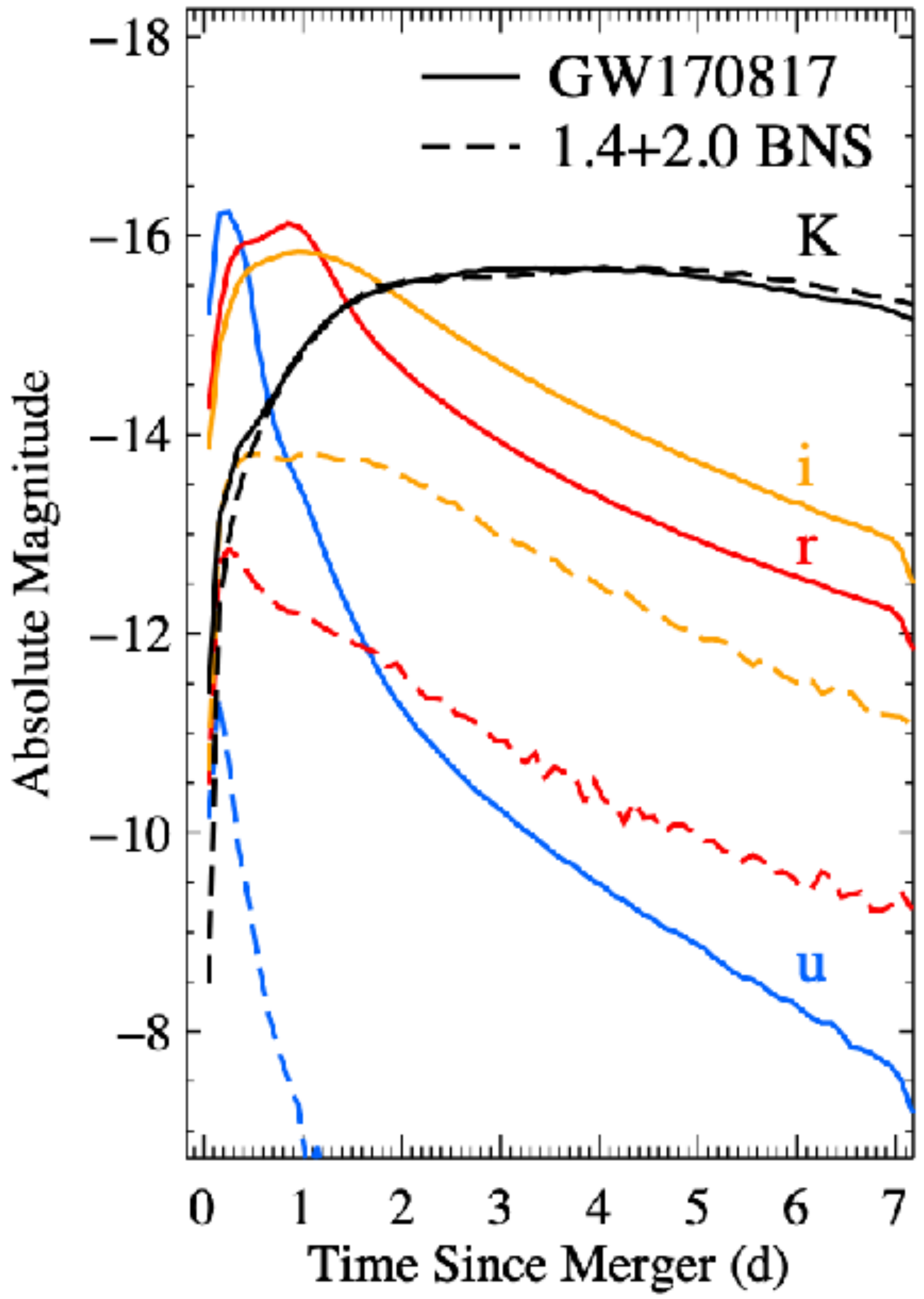
The Localization Process is ***HARD!***

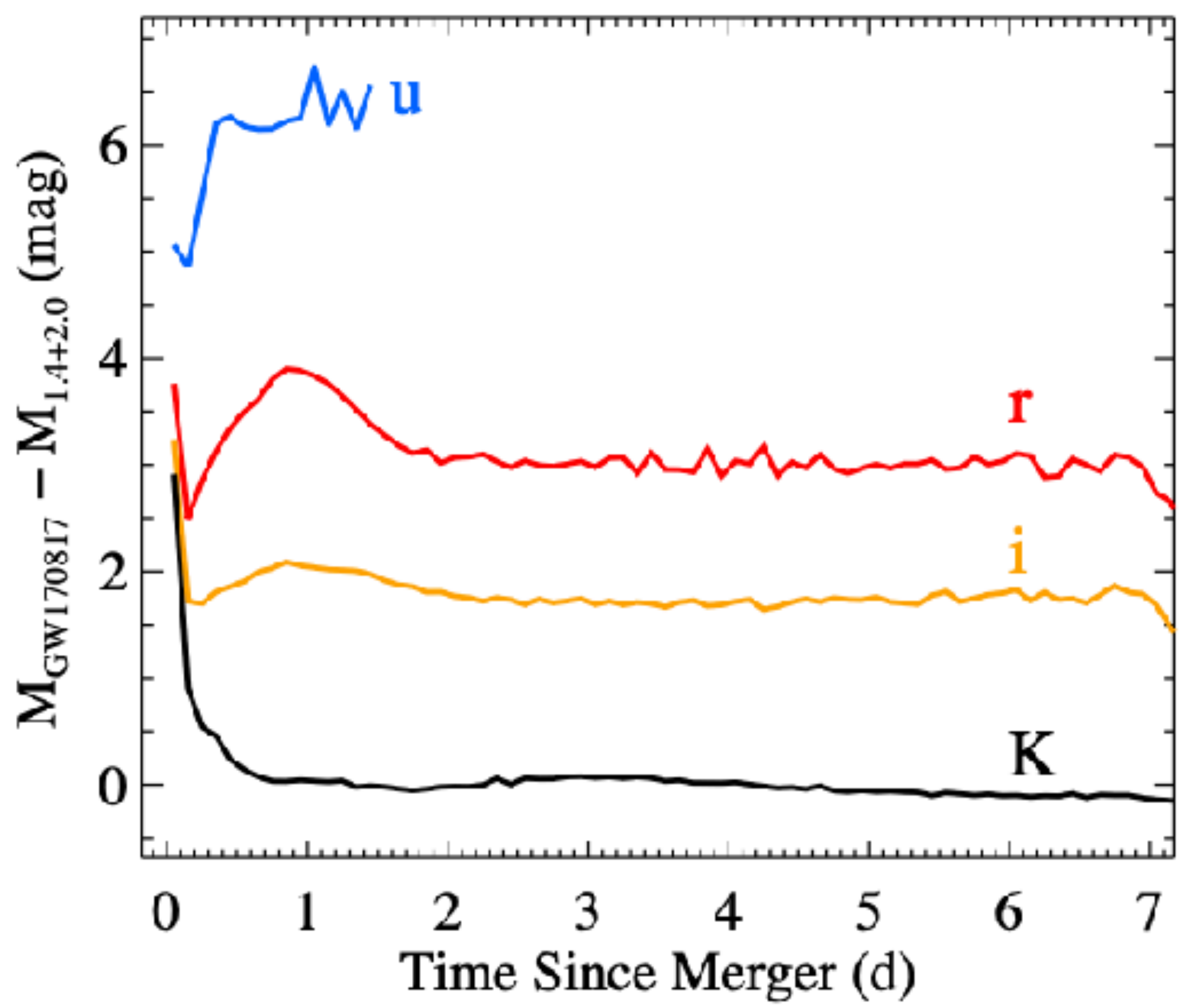
Photometric Information: What do GW counterparts look like?

We can find these transients with reasonable assumptions about NS mergers



GW170817 was surprisingly blue (Metzger+2014, Kasen+2015, Tanaka+2016 notwithstanding)

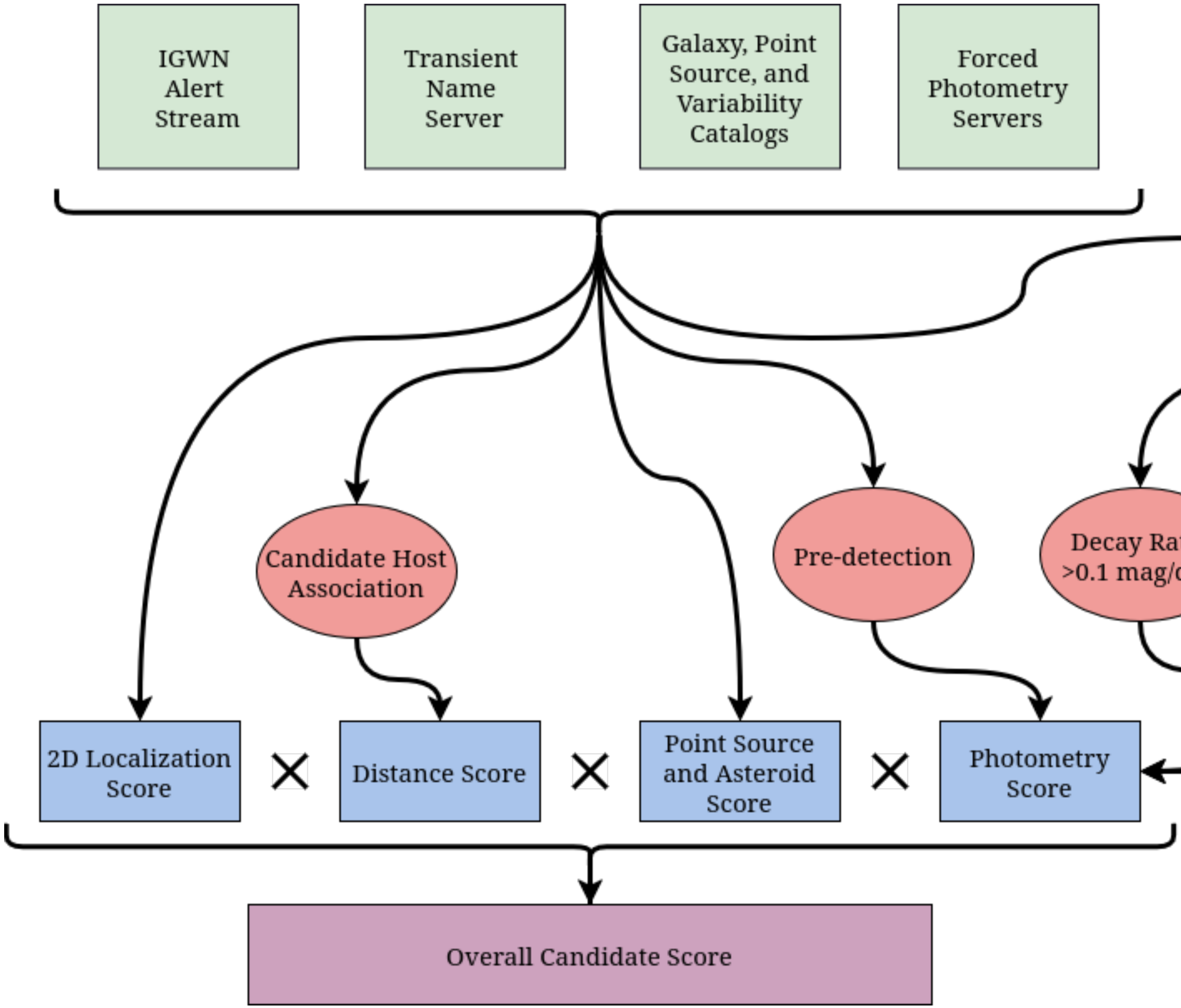




Foley, Coulter, Kilpatrick+2020

How much variance can there be as a function of GW-observable parameters?

The Tool for Rapid Object Vetting and Examination (TROVE) v0.1 GW Vetting Algorithm



Franz+2025, ApJL

TROVE v0.1 Web Interface

SN2025ulz

Classify | Edit | Share | Delete | Vet

Names	SN2025ulz	
	S250818k	
Coords.	15:51:54.201	+30:54:08.67
	237.975838	30.902408
Galactic	49.509535	50.630027
Ecliptic	225.504783	49.514382

Score Details

S250818k

2D Localization Score: 0.66

Point Source Score (1 or 0): 1

3D Association Score: 0.17

Maximum Luminosity: 4.89 x 10^{41} erg/s

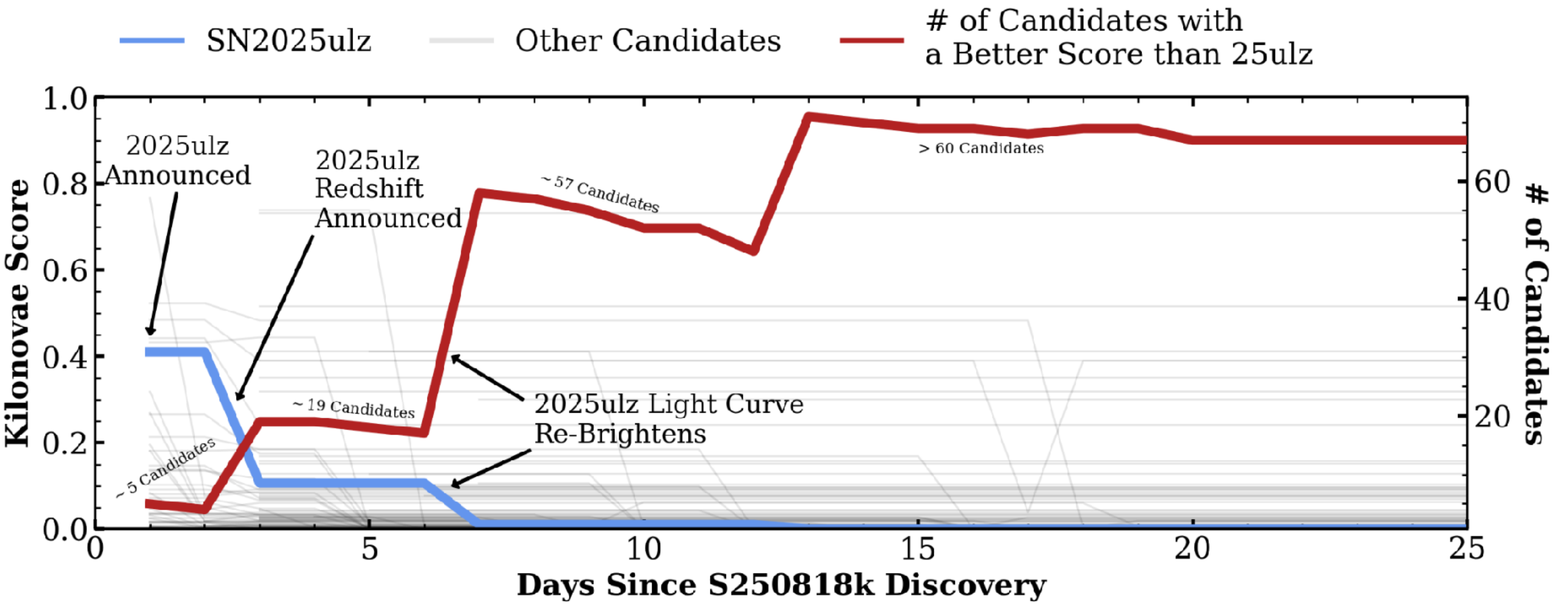
Time of Maximum Light Curve: 26.76 days

Light Curve Slope (positive is brightening): 3.01 mag/day

▸ Host Galaxies

▾ Photometry

Application to Transients in the S250818k Localization



Franz+2025

Look out for TROVE v1.0 by this fall - we will need beta testers!

TROVE Home Nonlocalized Events Targets Alerts Observations Data Users

Search by name

Congratulations!! Welcome to the TROVE!

Latest Comments

No comments yet.

Latest Targets

ID	Created
Please login to view or create targets.	

https://datatrove.as.arizona.edu

Summary

- In 2017, we isolated a source of the r-process, but many questions remain as to the exact elements, underlying physics, and exact rates of these events

- More recent GW observations suggests other sources of the r-process are needed, with many candidates but so far no conclusive results - collapsars, magnetar flares, and core-collapse supernovae are all promising candidates

- New tools and multi-messenger infrastructure are a promising way to optimize future follow up of all events, particular observing optimization with Teglon and analysis of electromagnetic counterparts with TROVE - expect to see TROVE v1.0 by this fall!