



**Exploring the origin of heavy elements
with multimessenger astronomy**

マルチメッセンジャーで探る重元素の起源

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(C) Tohoku University

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Smaranika Banerjee (Stockholm U.), Kyohei Kawaguchi (AEI), Kenta Hotokezaka (U. Tokyo)

Exploring the origin of heavy elements with multimessenger astronomy

- Neutron star mergers, heavy elements, and kilonovae
- Decoding signals from kilonovae
- O4, O5, and beyond

The origin of elements in the Universe

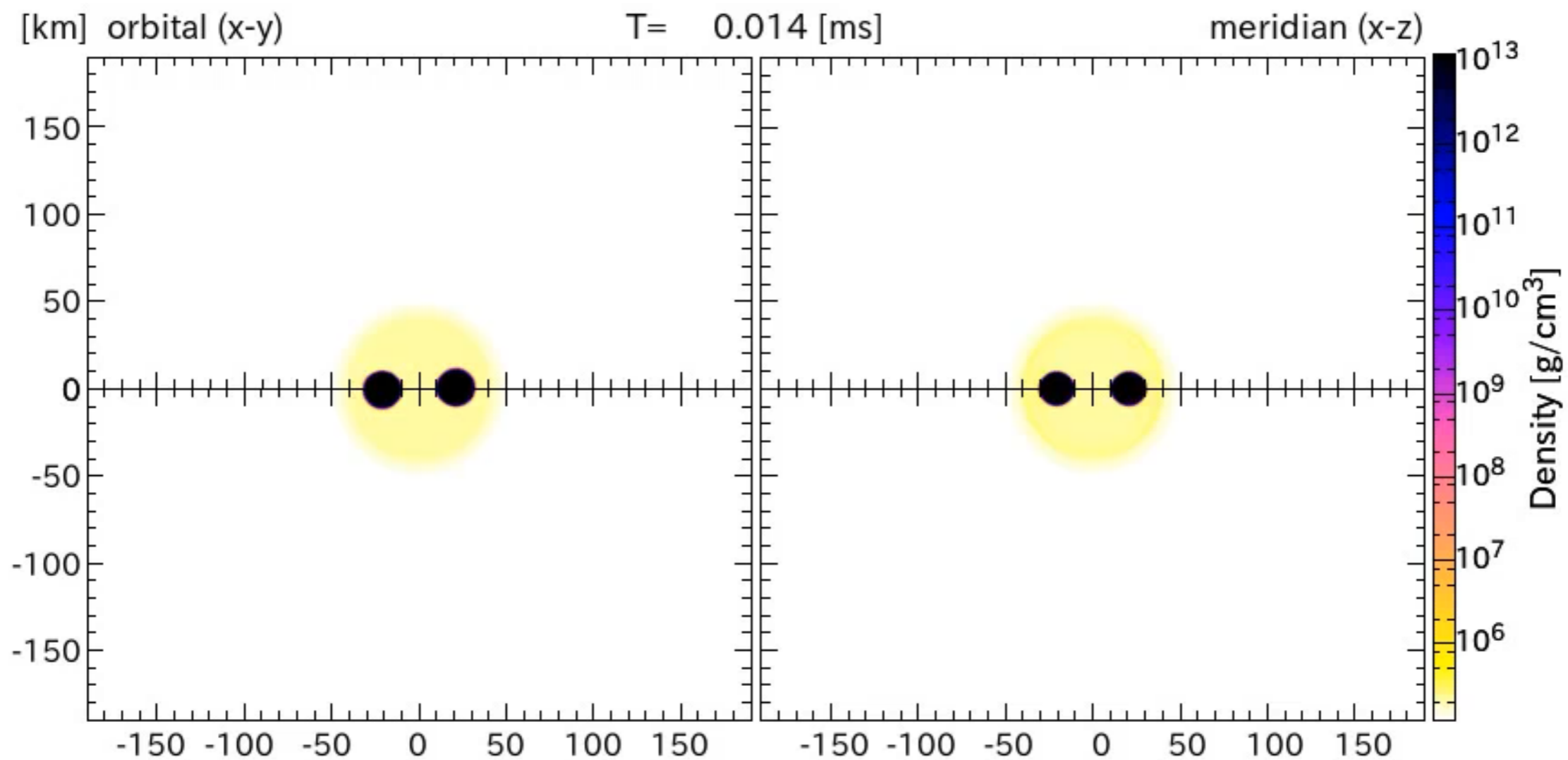
??

1 H	Big bang															2 He	
3 Li	4 Be	Platinum Gold										5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	Stars and supernovae										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	57~71 La-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	89~103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
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	71 Lu			
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	103 Lr			

Mass ejection from NS merger

Top view

Side view

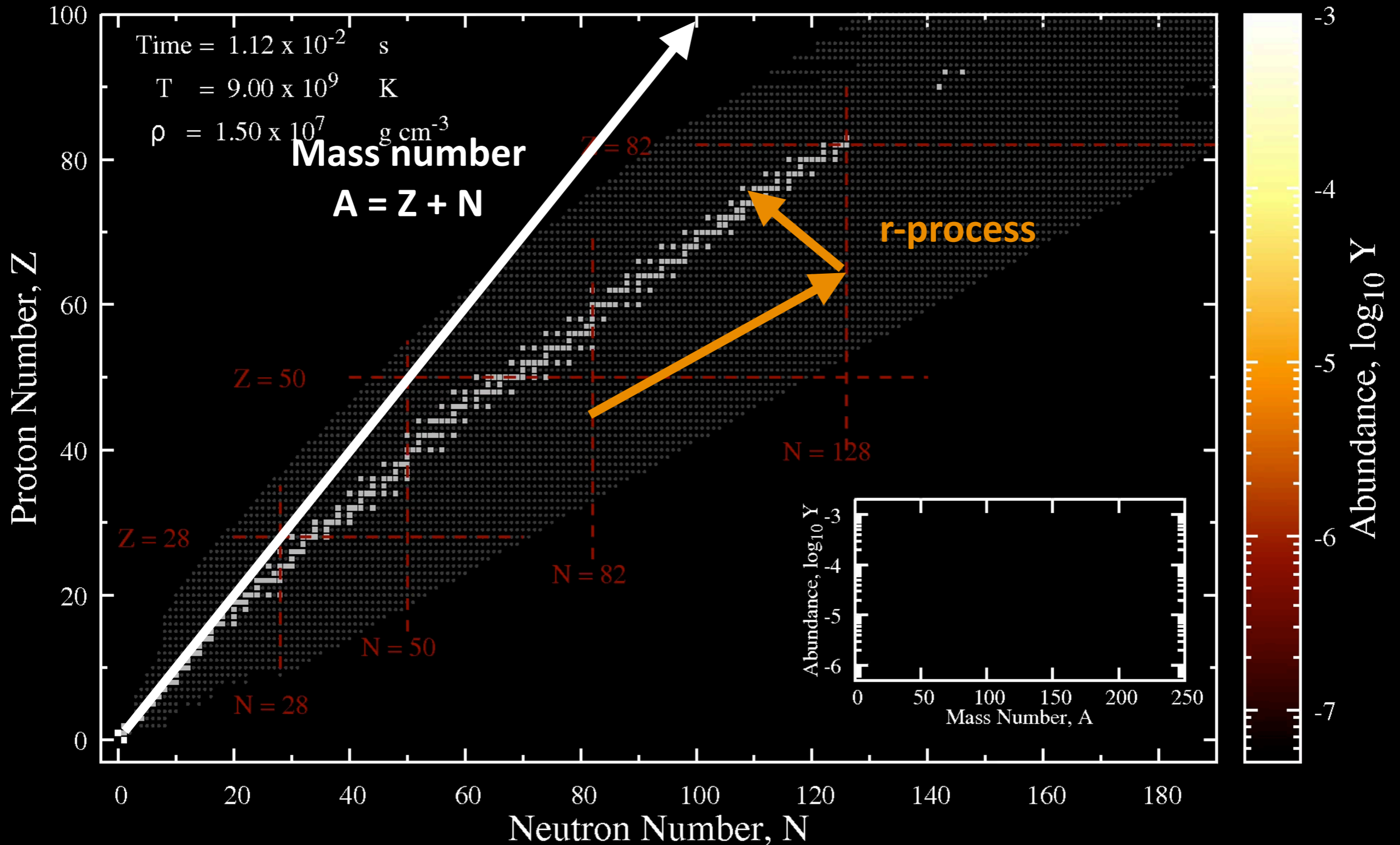


Sekiguchi+15, 16

$M \sim 10^{-3} - 10^{-2} M_{\text{sun}}$

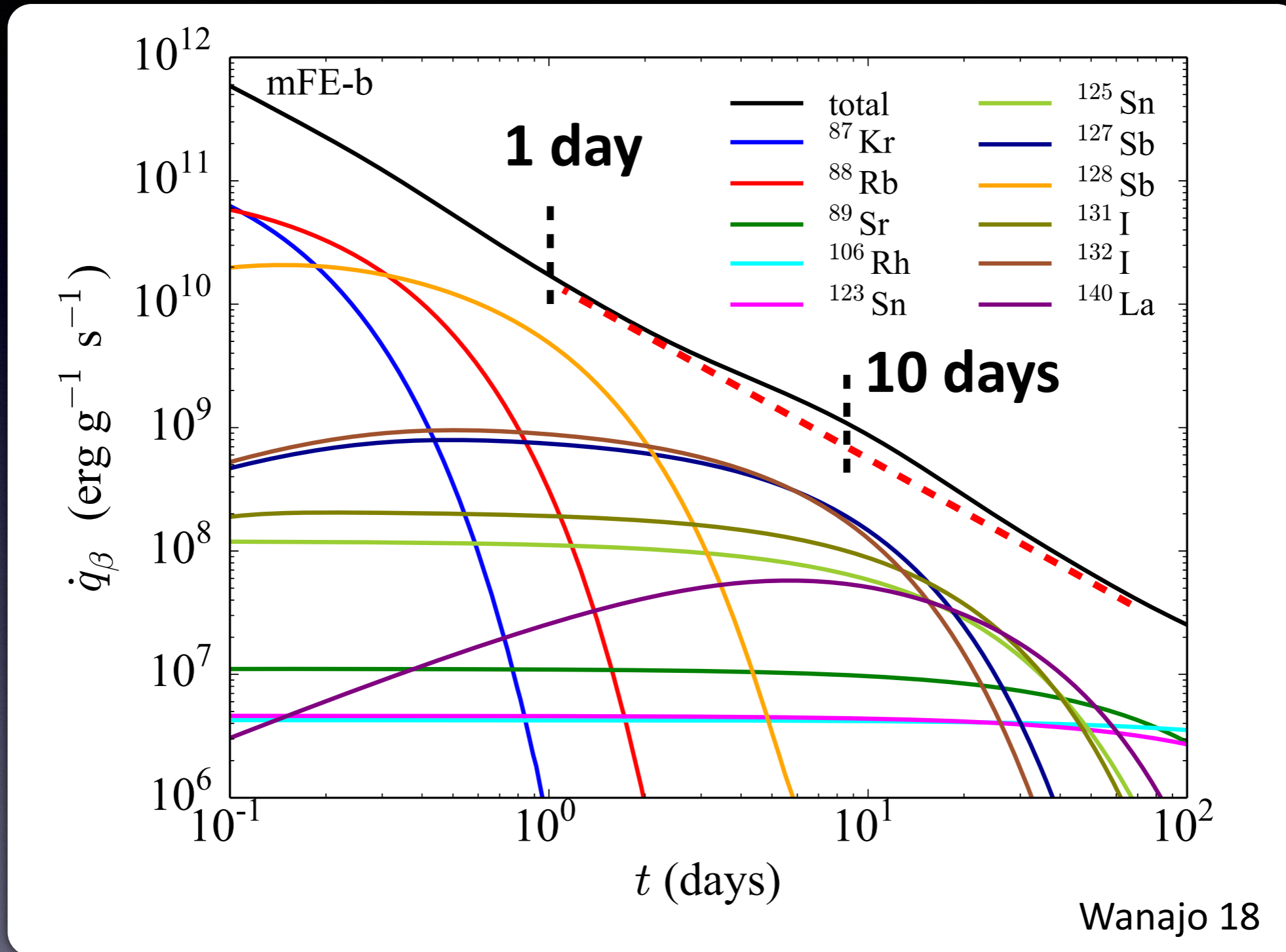
$v \sim 0.1 - 0.2 c$

r-process nucleosynthesis in NS merger



(C) Nobuya Nishimura

Radioactive decay luminosity (β -particles, γ -rays, neutrinos)



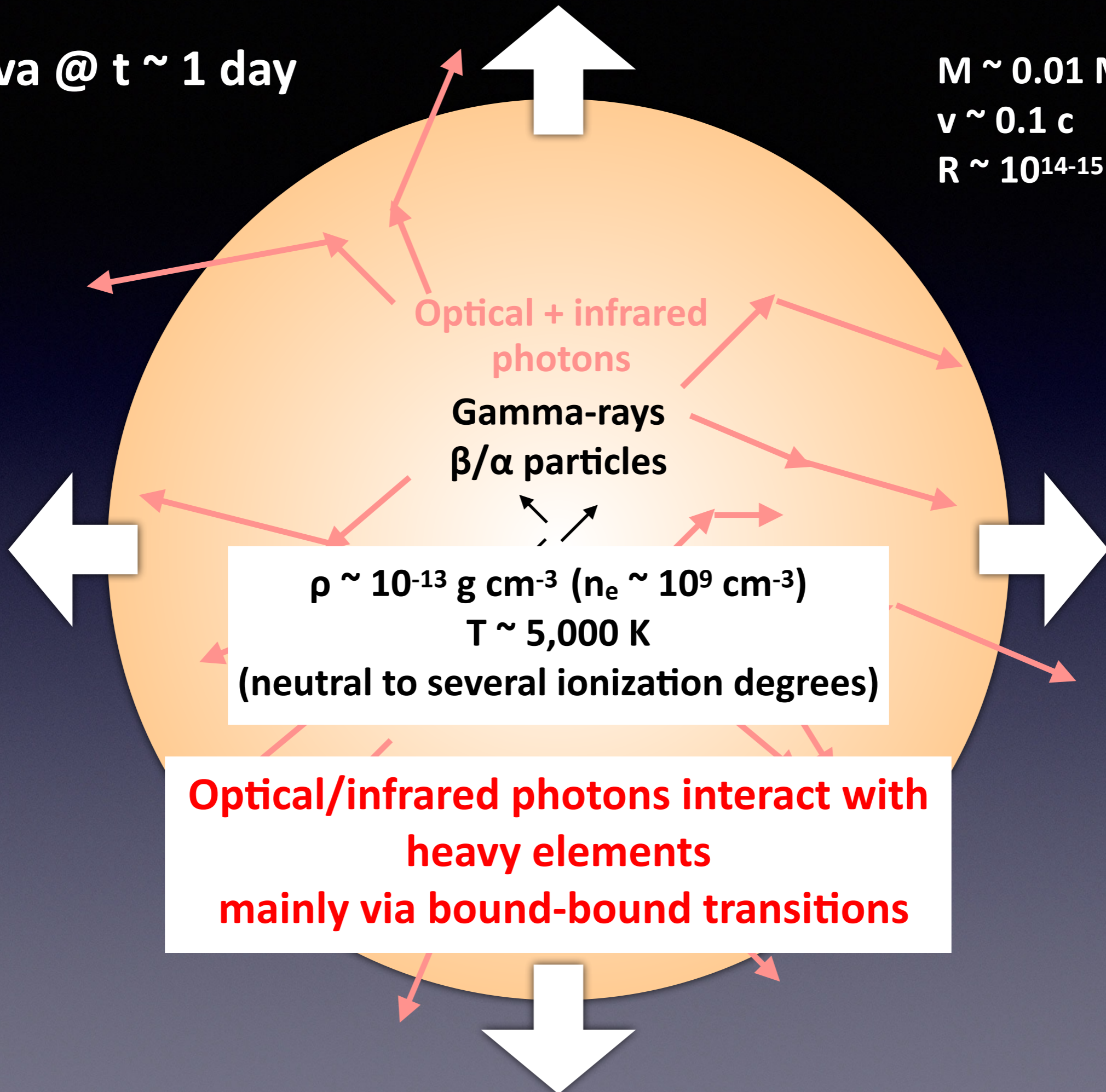
Wanajo 18

$$q \sim 2 \times 10^{10} t_{\text{day}}^{-1.3} \text{ erg s}^{-1} \text{ g}^{-1}$$

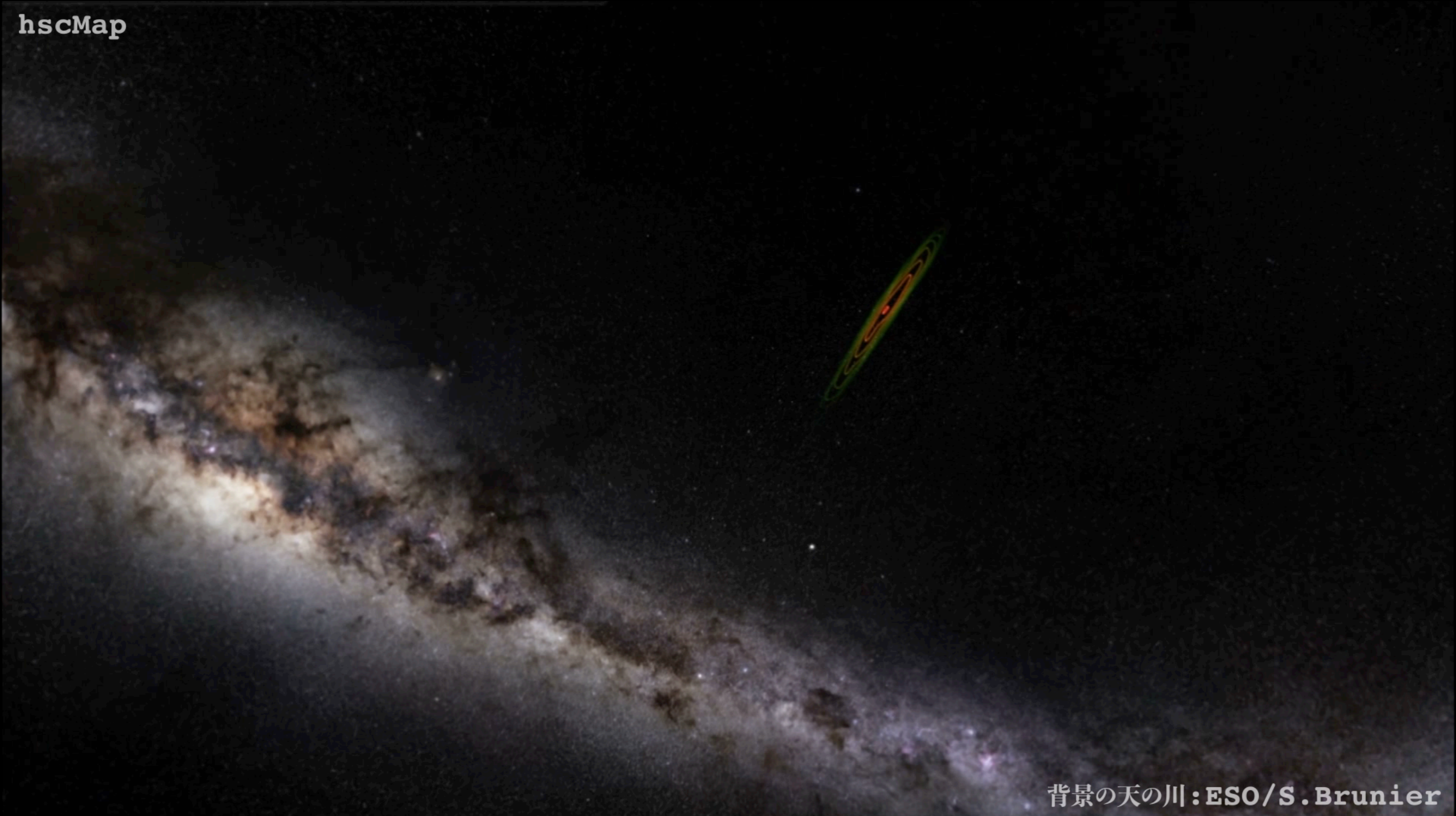
Metzger+10
Lippuner+15
Hotokezaka+16, 17

Kilonova @ $t \sim 1$ day

$M \sim 0.01 M_{\text{sun}}$
 $v \sim 0.1 c$
 $R \sim 10^{14-15} \text{ cm}$



Optical counterpart of GW170817



What can we learn from observations of kilonova?

Light curves

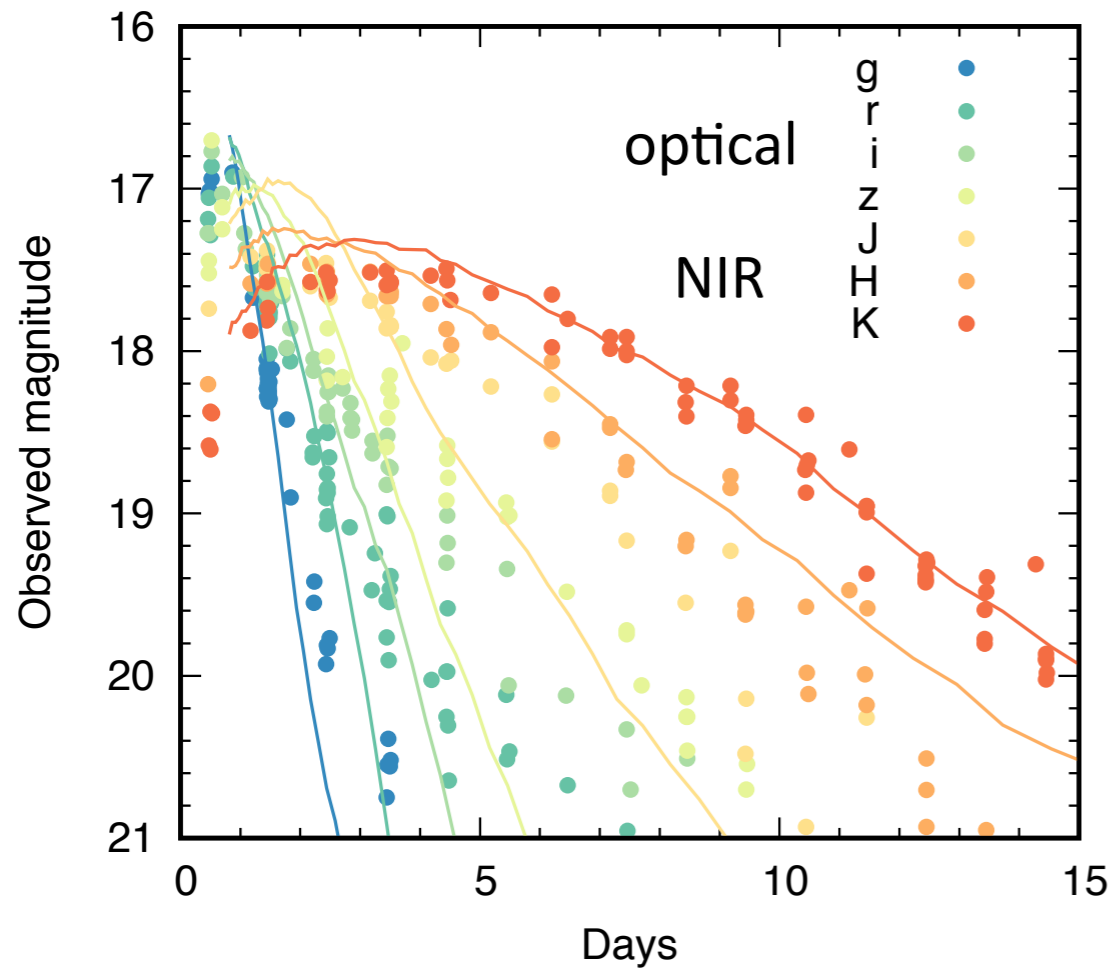


Figure from Kawaguchi+2018, 2020

Ejected mass and
(rough) composition

Spectra

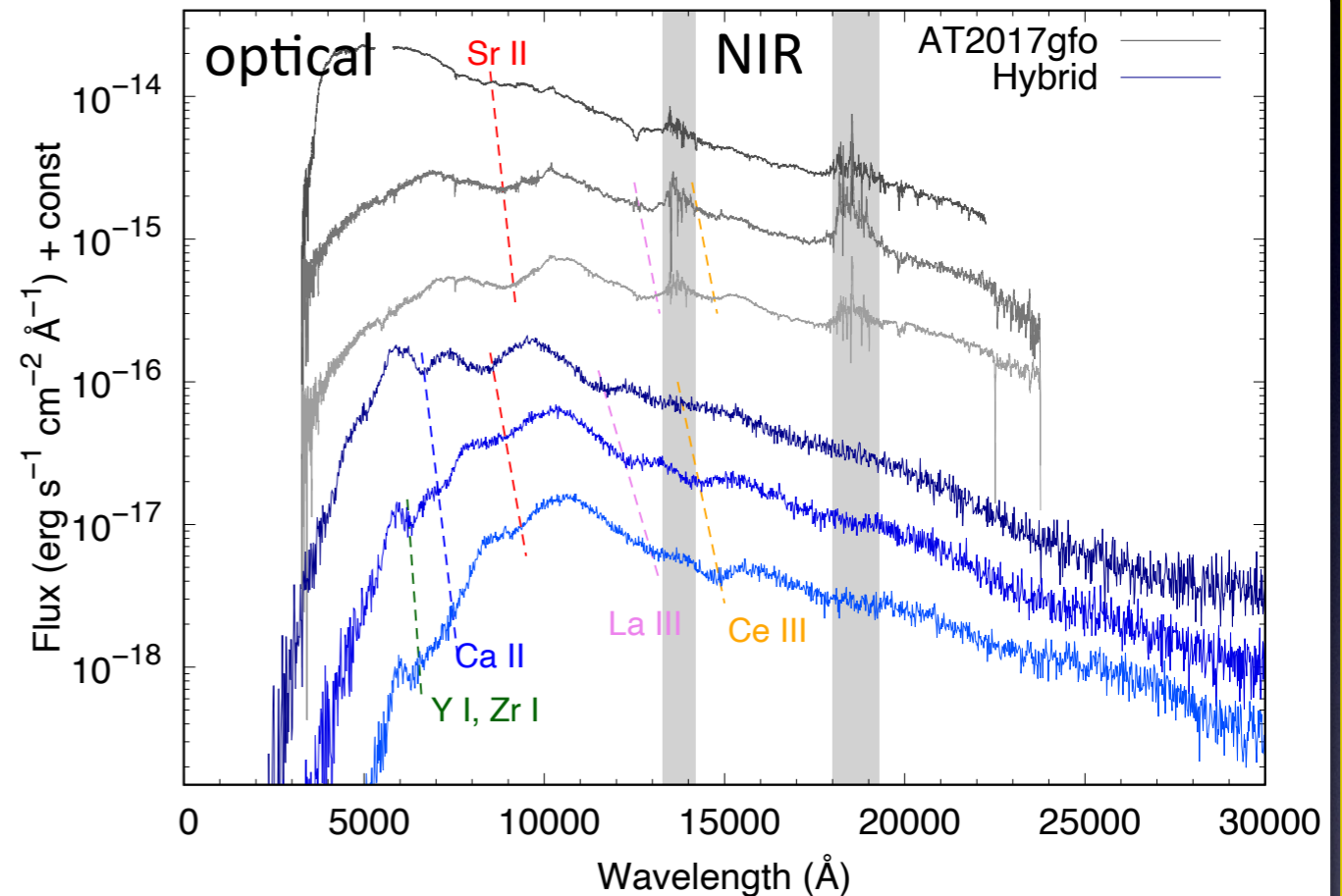


Figure from Domoto+2021, 2022

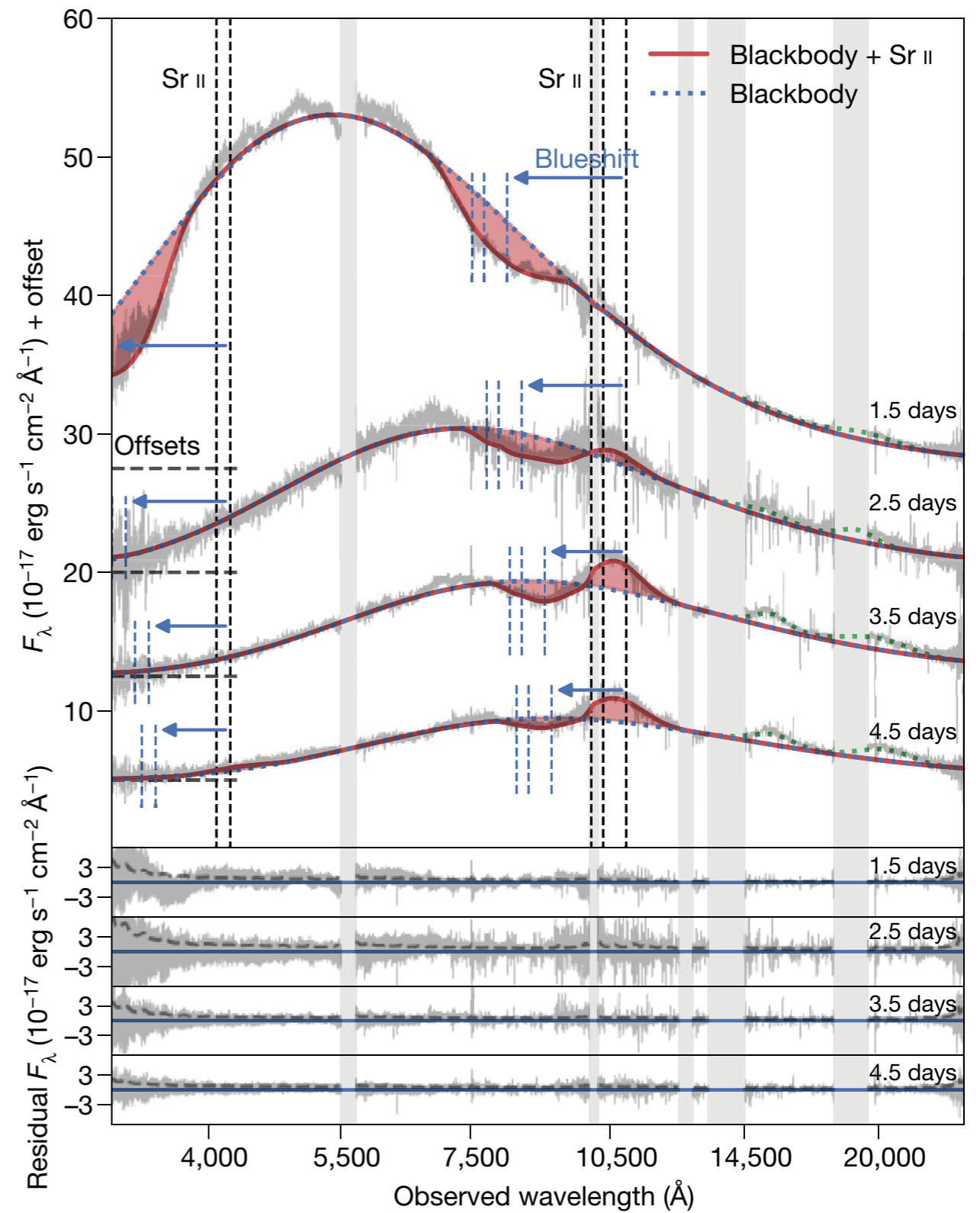
Detailed composition

Origin of r-process elements
Physics of neutron star mergers

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- Decoding signals from kilonovae
- O4, O5, and beyond

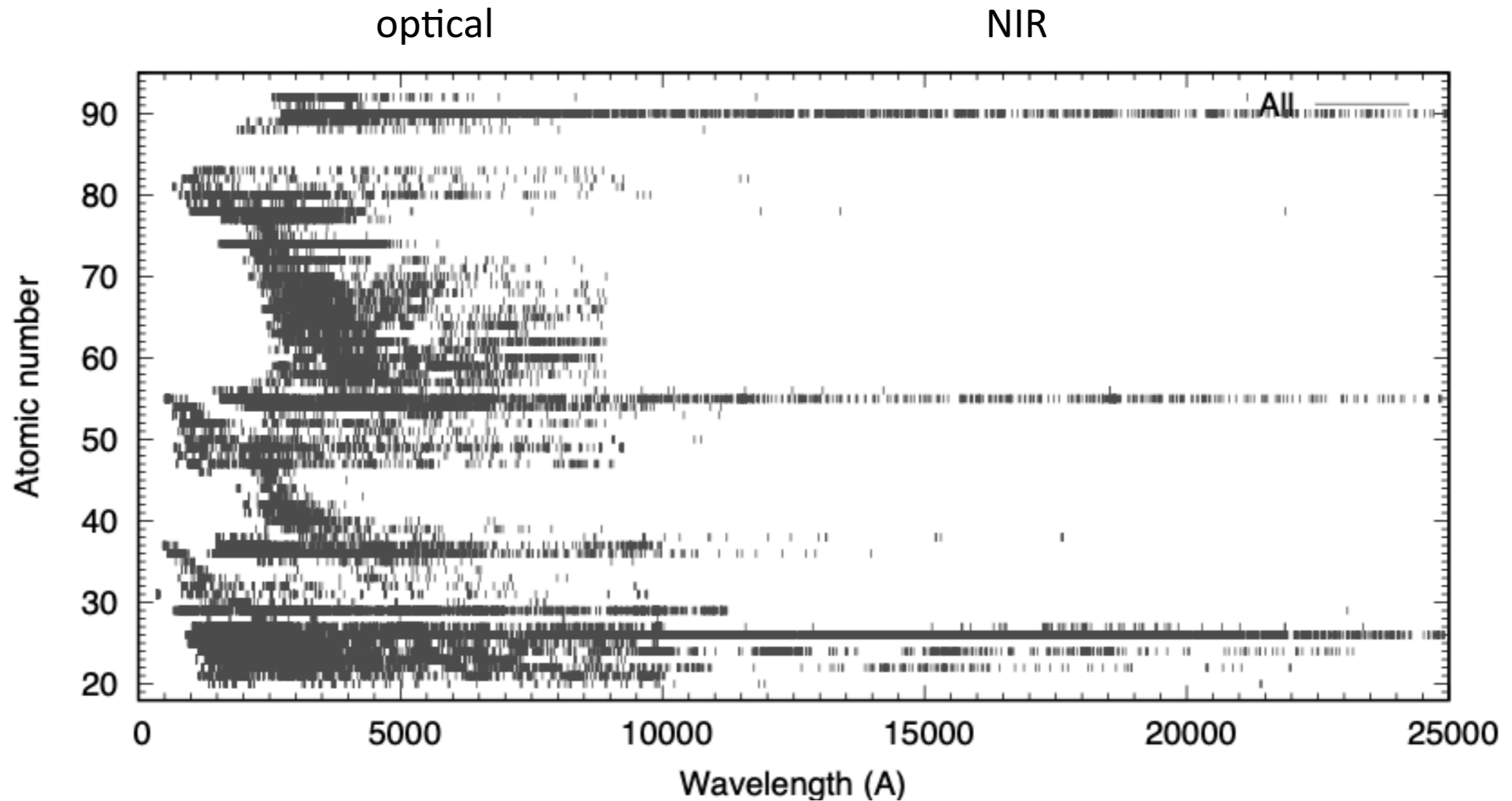
Identification of Sr II (Z=38)



Available atomic data

Data from the NIST ASD

Transitions with known wavelengths



Accurate transition data are highly incomplete (in particular NIR)

Atomic calculations for kilonova

Kasen+13: Sn II, Ce II-III, Nd I-IV, Os II (Autostructure)

Fontes+17: Ce I-IV, Nd I-IV, Sm I-IV, U I-IV (LANL Suite)

Wollaeger+18: Se, Br, Zr, Pd, Te (LANL Suite)

MT+18: Se I-III, Ru I-III, Te I-III, Nd I-III, Er I-III (HULLAC, GRASP)

Kasen+17, Fontes+20: Lanthanides (I-V)

MT+20: $Z = 26-88$ (I-IV, HULLAC)

Fontes+22: Actinides (I-IV)

s shell

p-shell

d-shell

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	57~71 La-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	89~103 Ac-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	71 Lu
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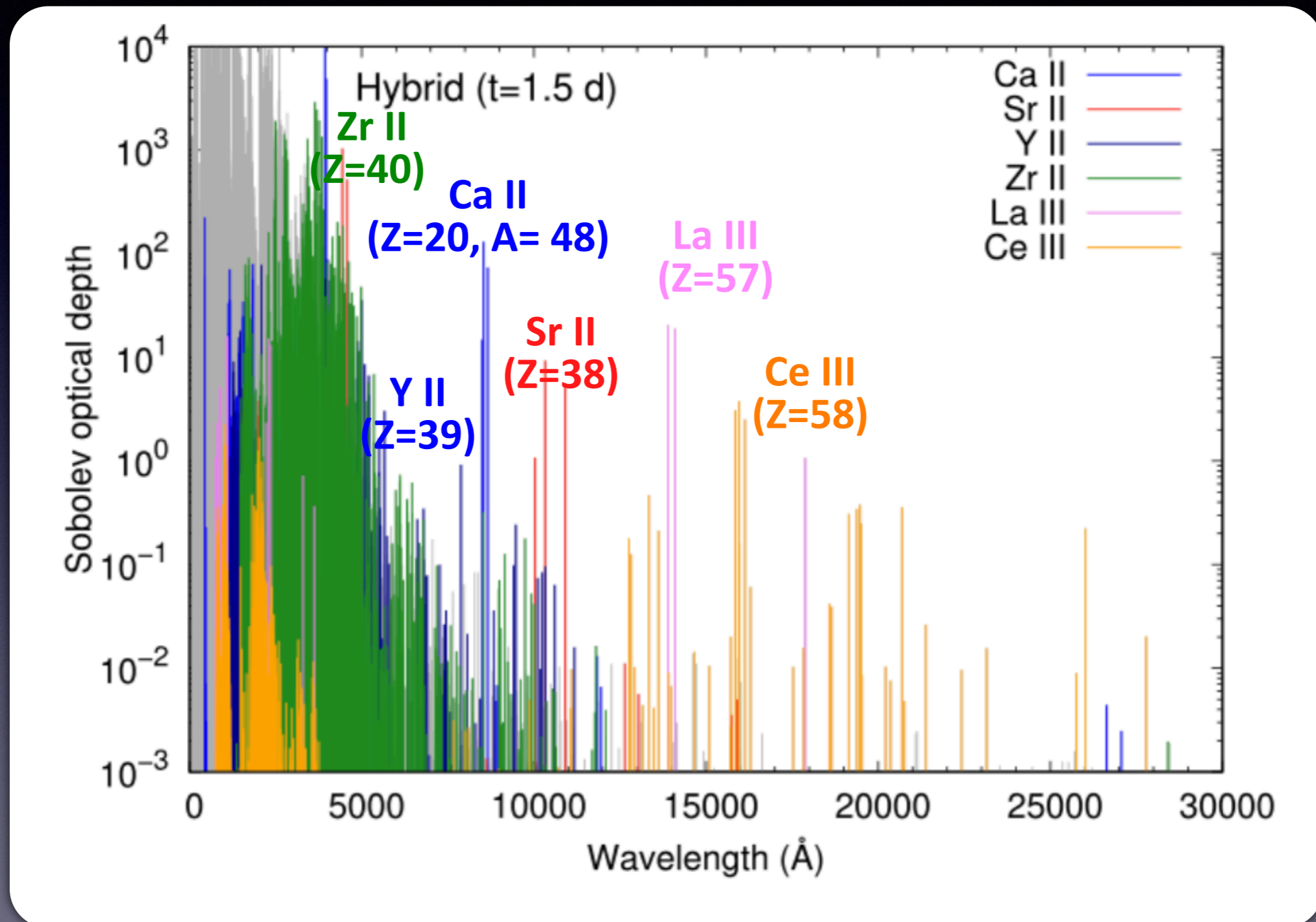
f shell

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	103 Lr
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Important elements for spectral features

Domoto+22

Complete theoretical atomic data + **Accurate** data for important elements

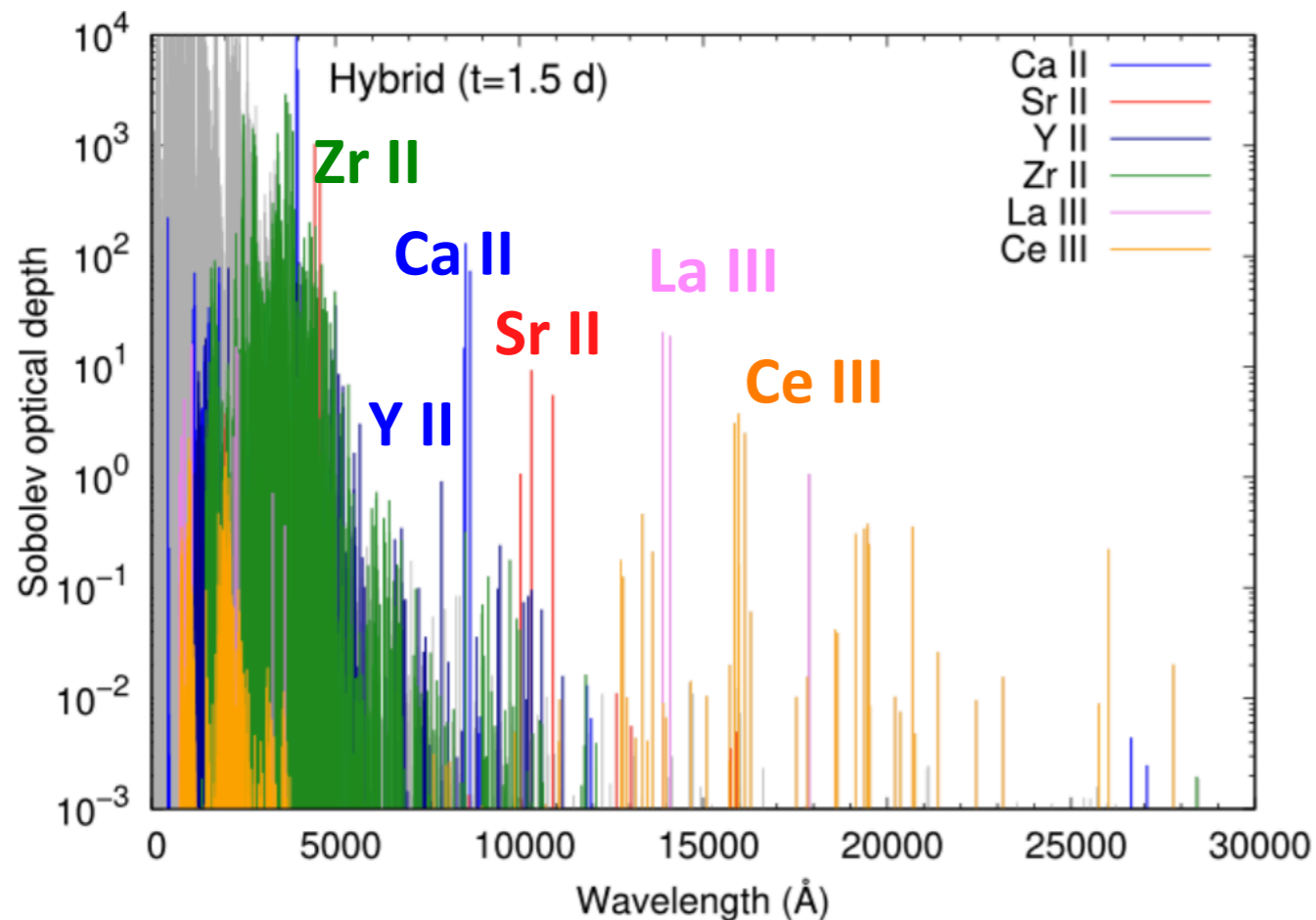


Relatively small number of elements are important

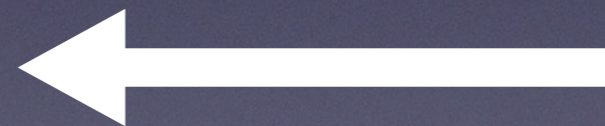
Important elements for spectral features

Domoto+22

$$\tau_l = \frac{\pi e^2}{m_e c} n_{i,j} t \lambda_l f_l \frac{g_k}{g_0} e^{-\frac{E_k}{kT}}$$



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

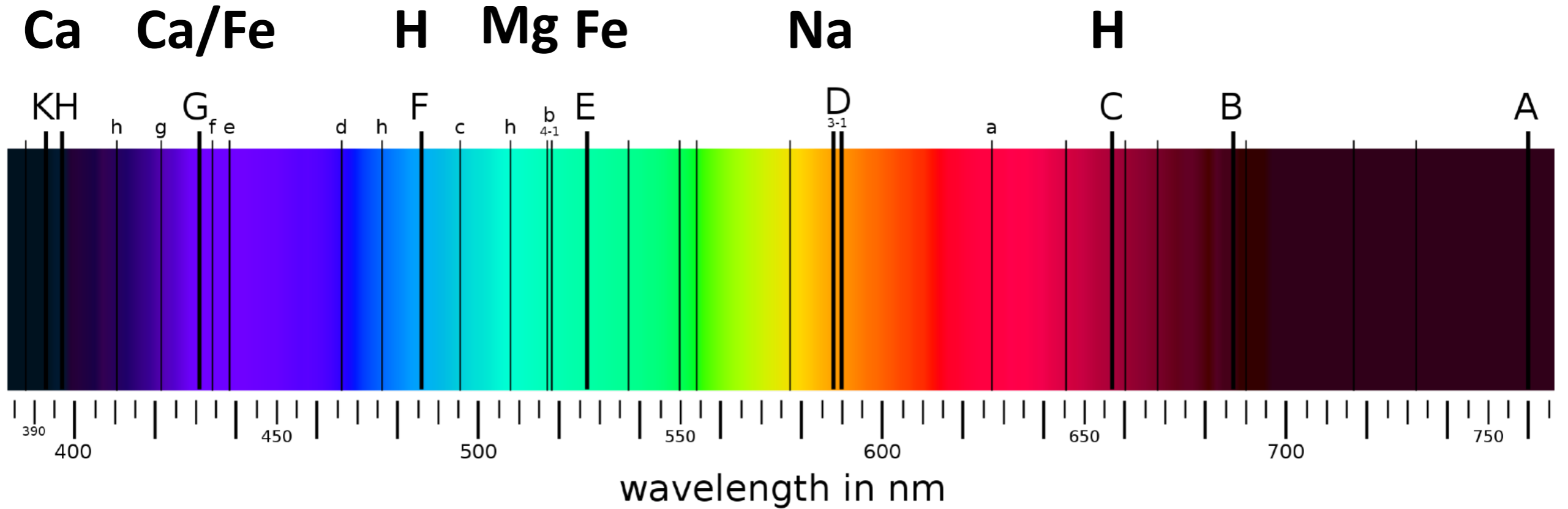


Elements with

- low-lying energy levels (higher population)
- relatively simple structure = small number of transitions
= high transition probability (sum rule)

Solar spectrum

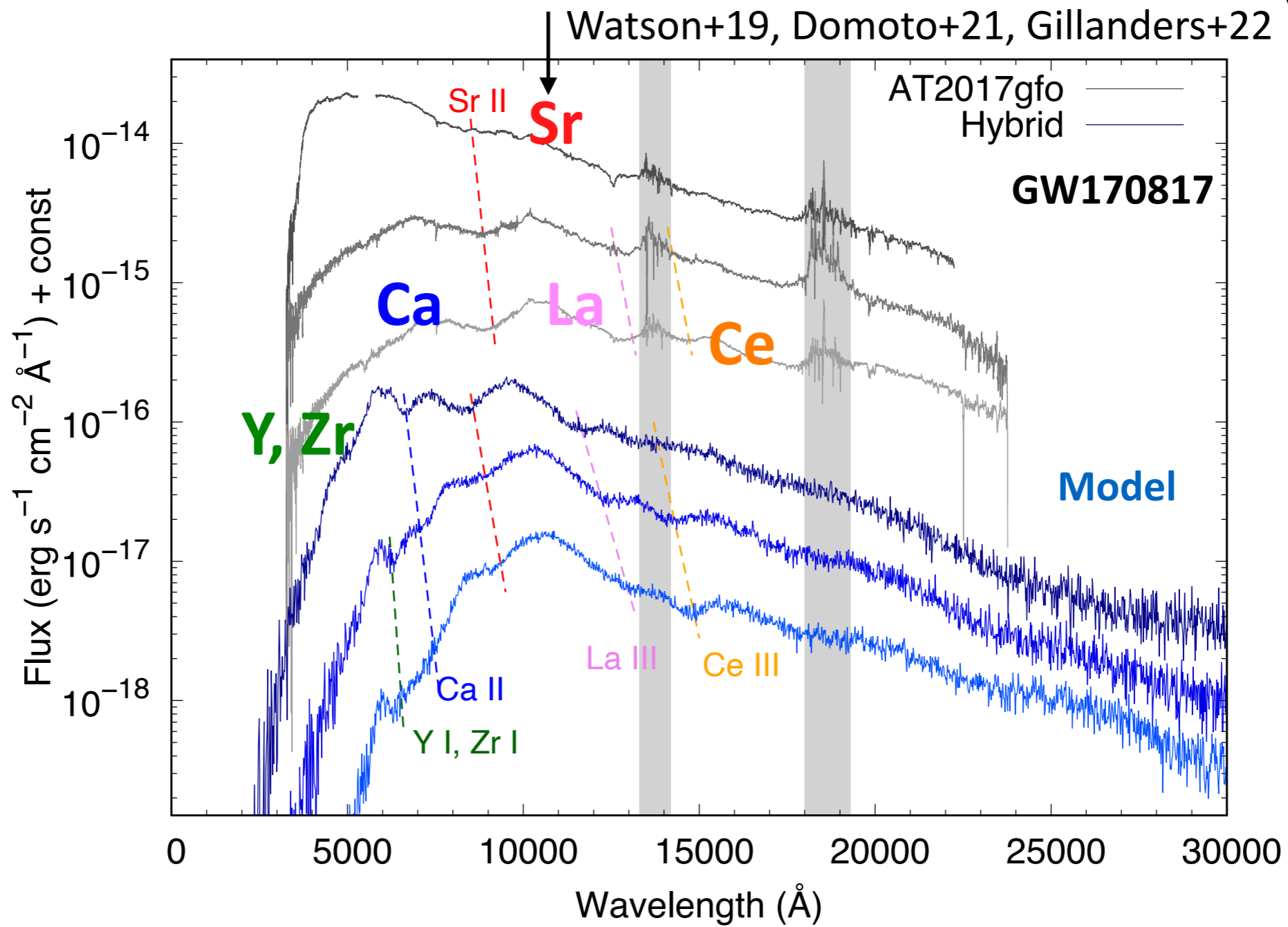
https://en.wikipedia.org/wiki/Fraunhofer_lines



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<table border="1"> <tbody> <tr> <td>57 La</td> <td>58 Ce</td> <td>59 Pr</td> <td>60 Nd</td> <td>61 Pm</td> <td>62 Sm</td> <td>63 Eu</td> <td>64 Gd</td> <td>65 Tb</td> <td>66 Dy</td> <td>67 Ho</td> <td>68 Er</td> <td>69 Tm</td> <td>70 Yb</td> <td>71 Lu</td> </tr> <tr> <td>89 Ac</td> <td>90 Th</td> <td>91 Pa</td> <td>92 U</td> <td>93 Np</td> <td>94 Pu</td> <td>95 Am</td> <td>96 Cm</td> <td>97 Bk</td> <td>98 Cf</td> <td>99 Es</td> <td>100 Fm</td> <td>101 Md</td> <td>102 No</td> <td>103 Lr</td> </tr> </tbody> </table>																		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	71 Lu	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	103 Lr
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Identification of La III (Z=57) and Ce III (Z=58) in NIR spectra

Domoto+22



$$X(\text{Ca}) < 10^{-5}$$

$$X(\text{Sr}) \sim 10^{-2}$$

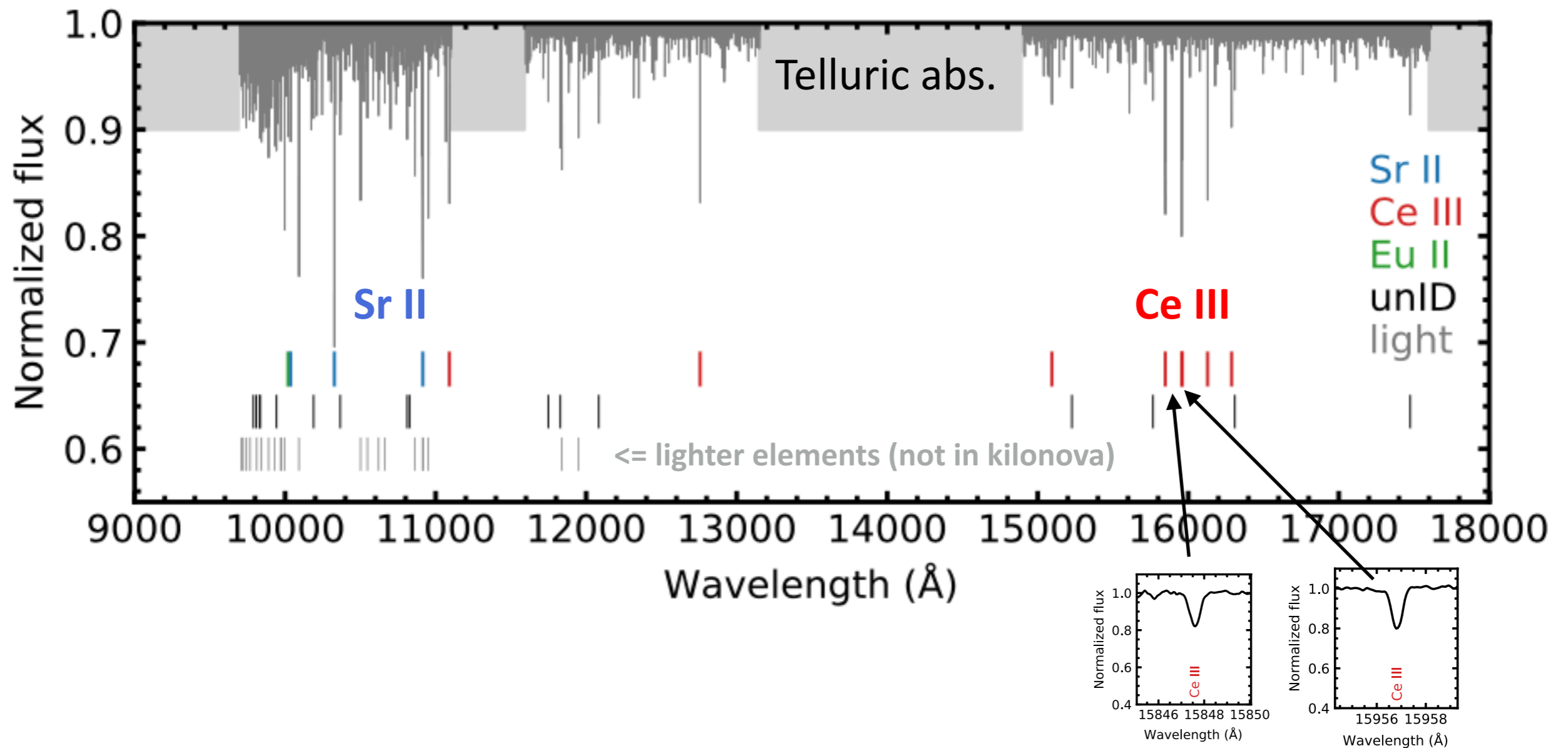
$$X(\text{La}) > 10^{-6}$$

$$X(\text{Ce}) \sim 10^{-4}$$

Test with the spectrum of a chemically peculiar star (= metal rich plasma!)

Tanaka, Domoto, Aoki et al. 2023

Subaru/IRD (R ~ 70,000)

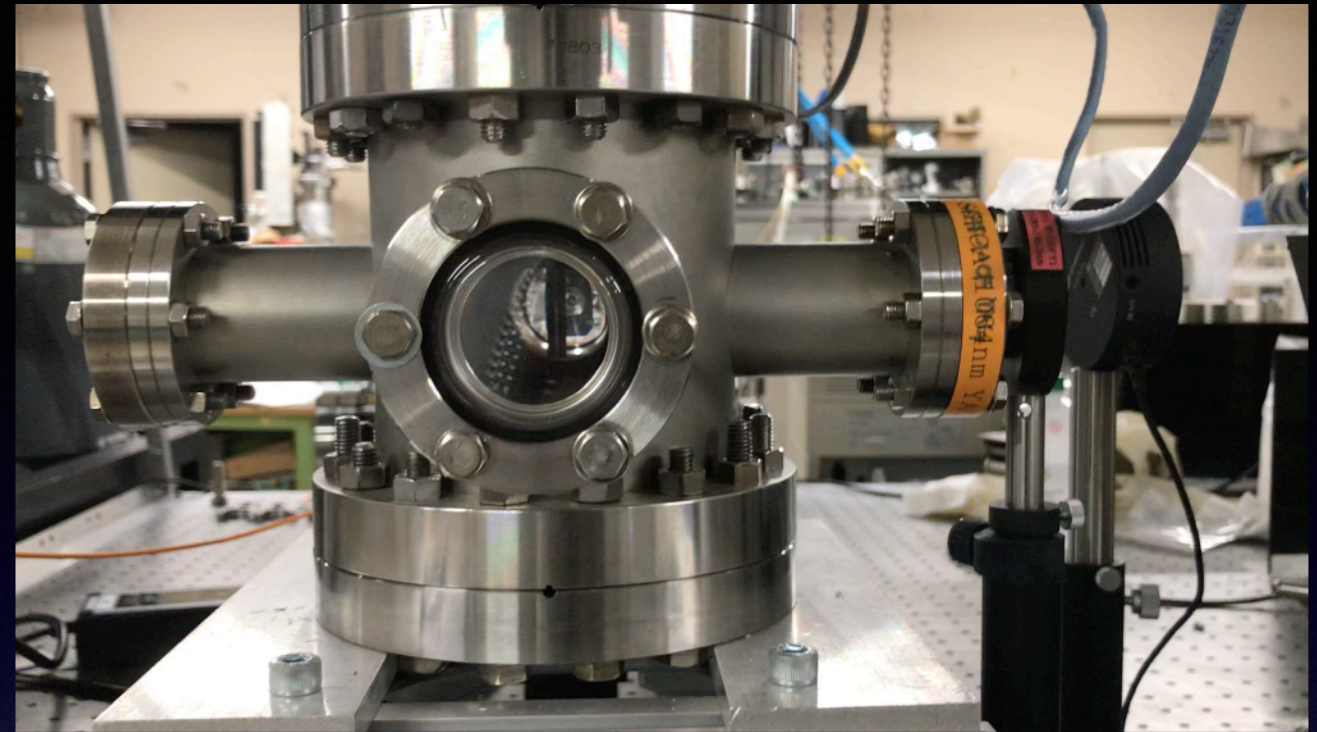


Strongest lines = Ce III, Sr II

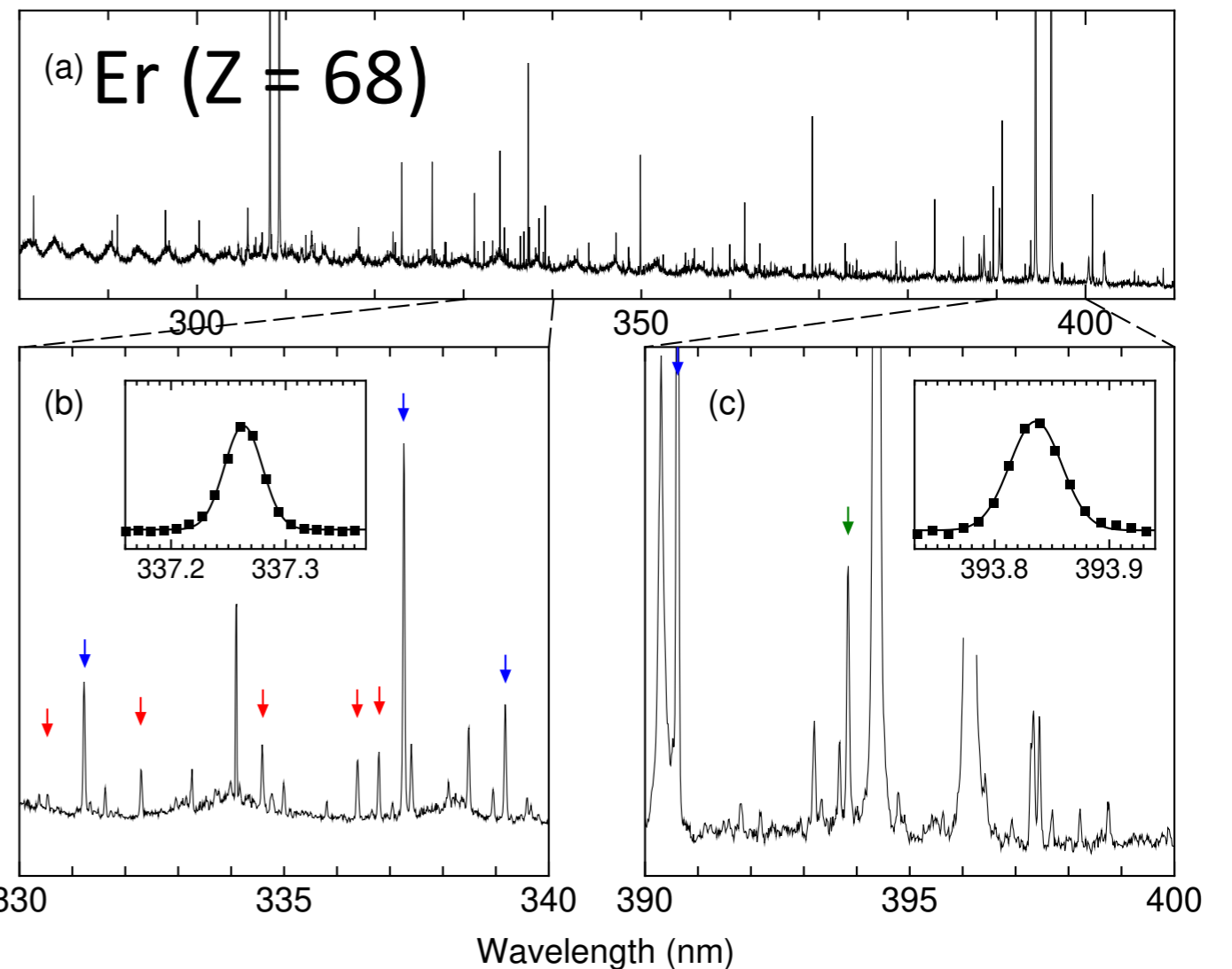
No other comparably strong lines = Uniqueness!

Lab measurements for transition probabilities

Laser induced breakdown
spectroscopy ($R \sim 10,000$ in optical)



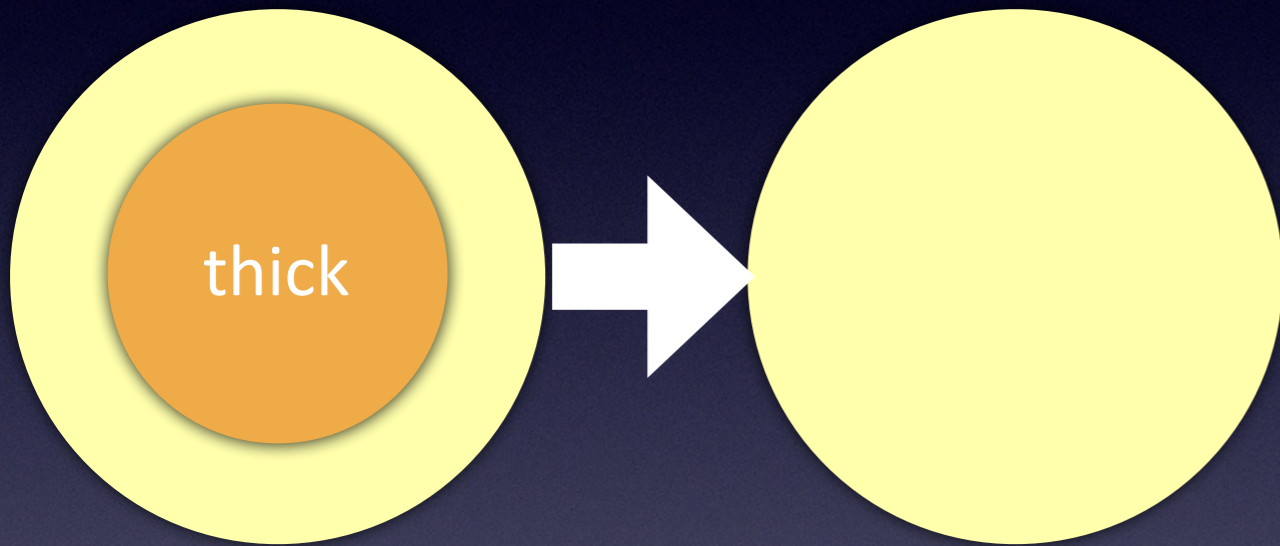
Measurements of Ce and La
in optical
=> extension to NIR (2024)



Emission line of Te III (Z=52) at late phase (inner ejecta)

Early phase
(absorption line)

Late phase
(emission line)

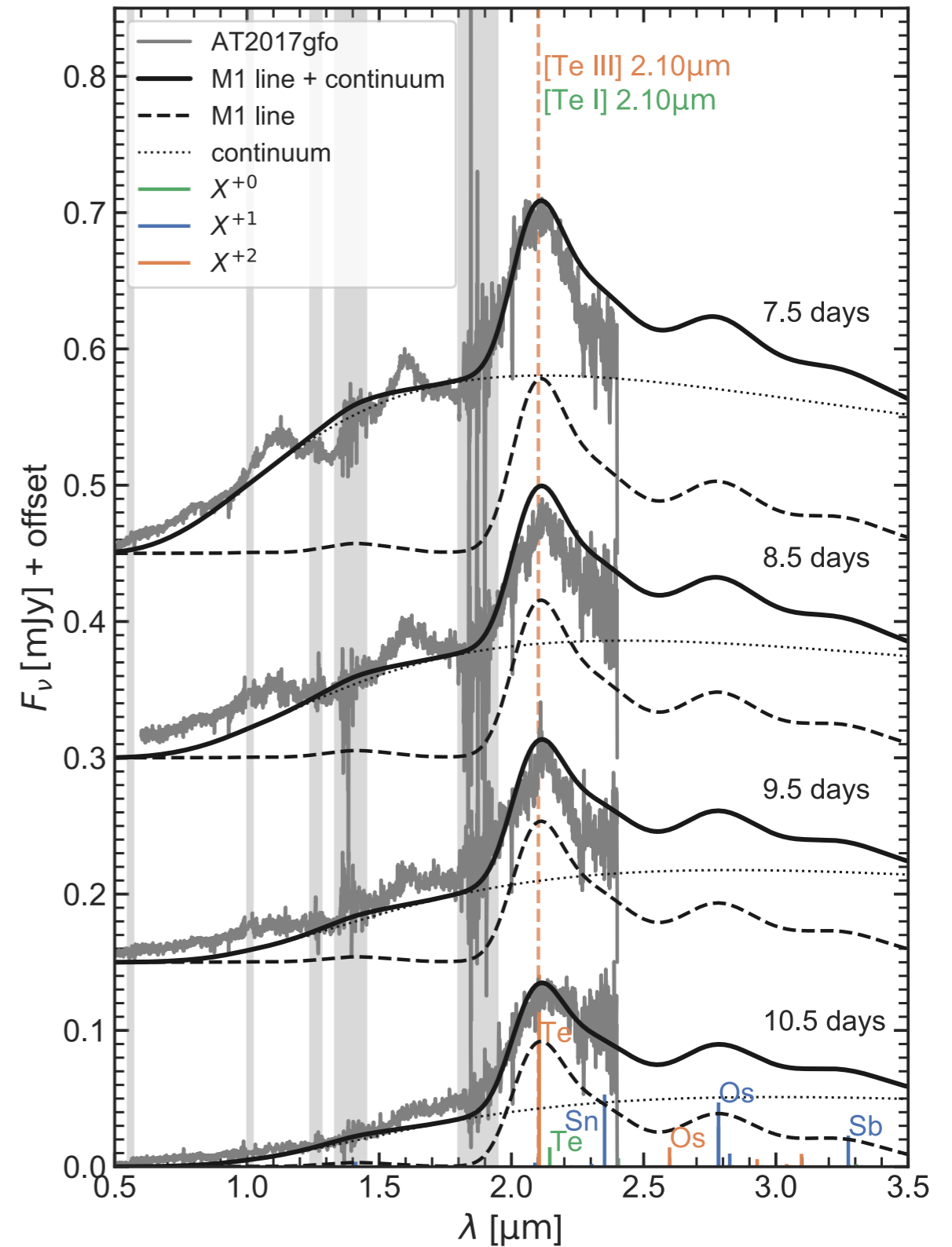


$M(\text{Te III}) \sim 10^{-3} M_{\text{sun}}$ at $v < 0.07 c$

\Rightarrow

$M(\text{Te}) \sim 3 \times 10^{-3} M_{\text{sun}}$

$X(\text{Te}) \sim 10^{-2}$



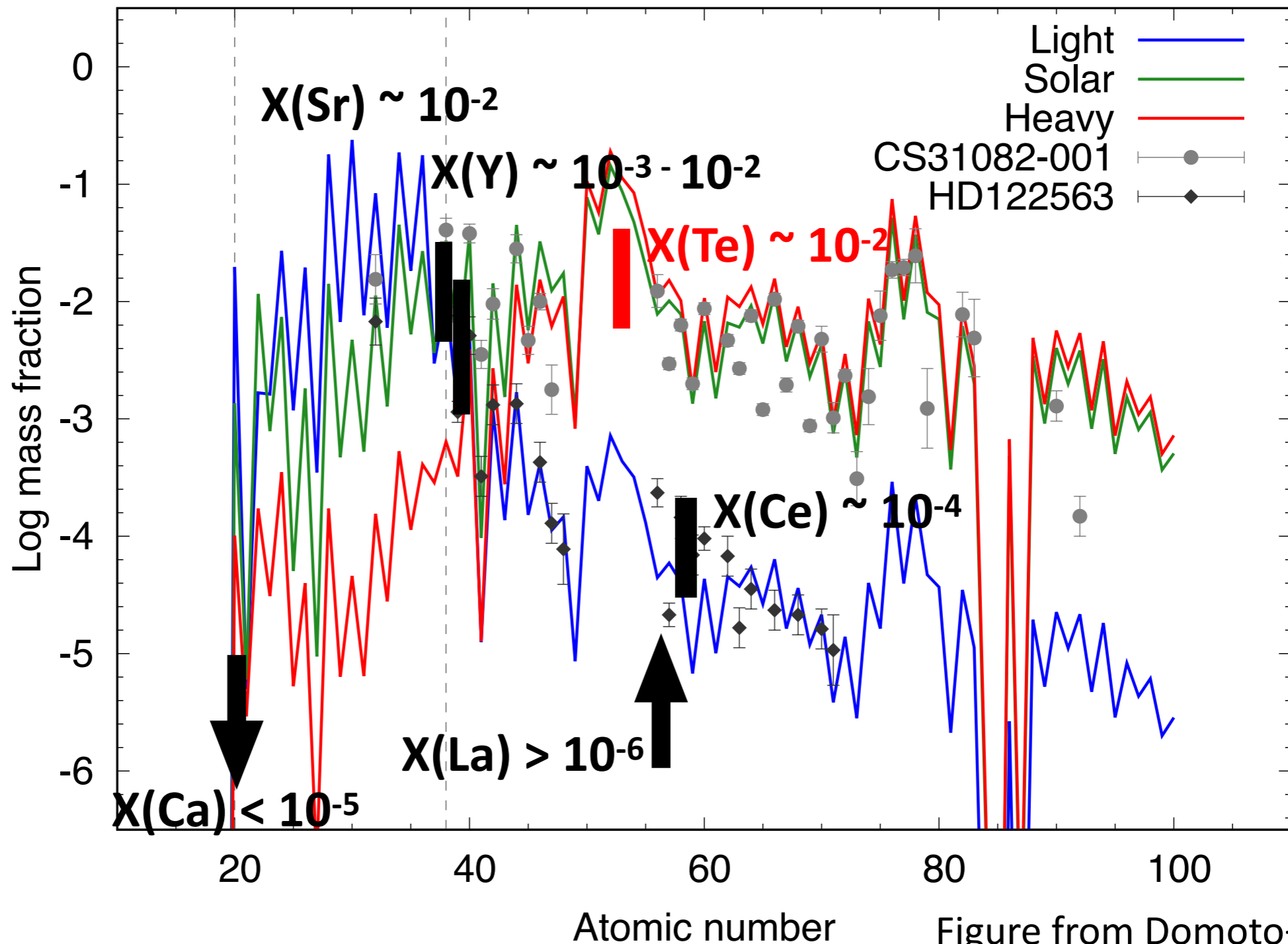
Hotokezaka, MT+ 23

Also seen in GRB 230307A (Levan+23, Gillanders+23)

Constraints on the nucleosynthesis so far

Sr, Ca: Domoto+21, La, Ce: Domoto+22, He: Tarumi+23, Y: Sneppen+23, Te: Hotokezaka+23

$X(\text{He})$
 $\sim 10^{-3}$



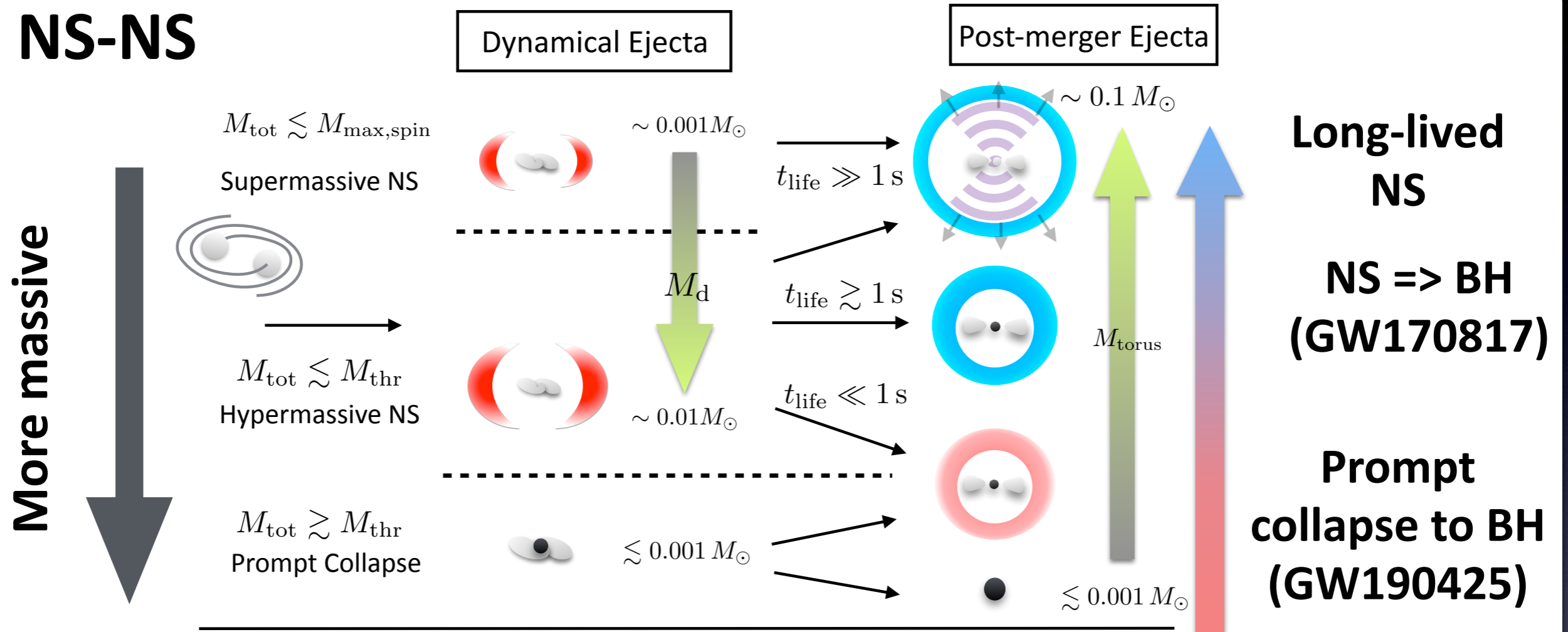
Unique constraints also on the physics of NS mergers

Exploring the origin of heavy elements with multimessenger astronomy

- Neutron star mergers, heavy elements, and kilonovae
- Decoding signals from kilonovae
- 04, 05, and beyond

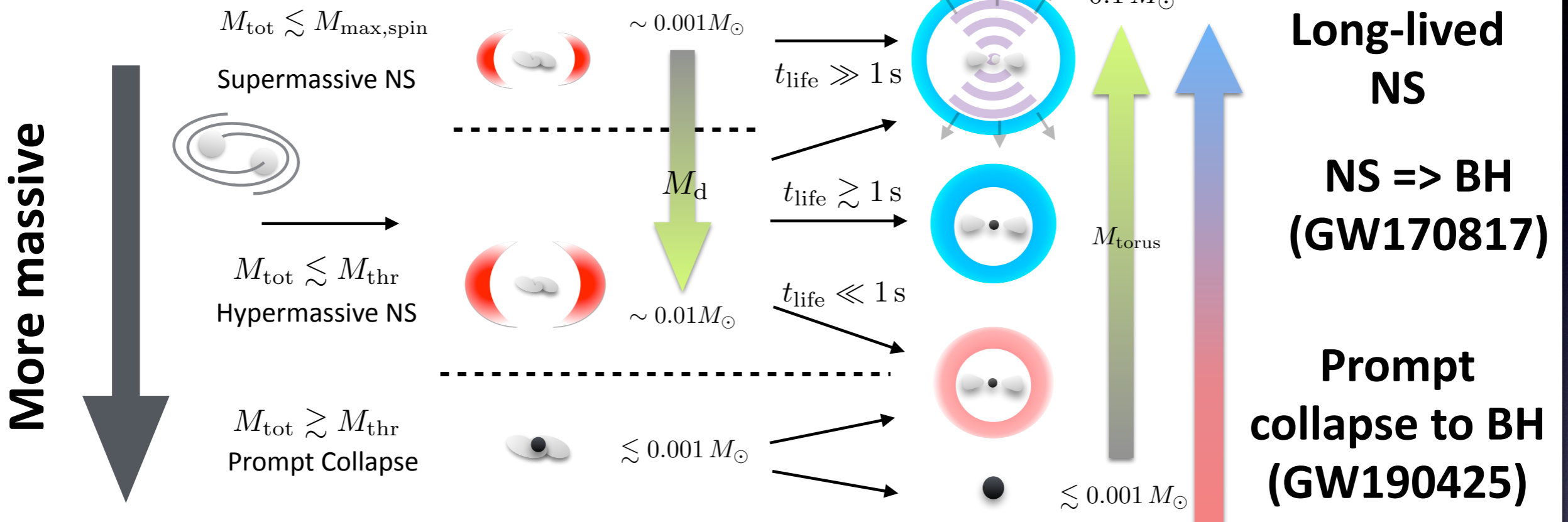
Diversity of neutron star mergers

NS-NS

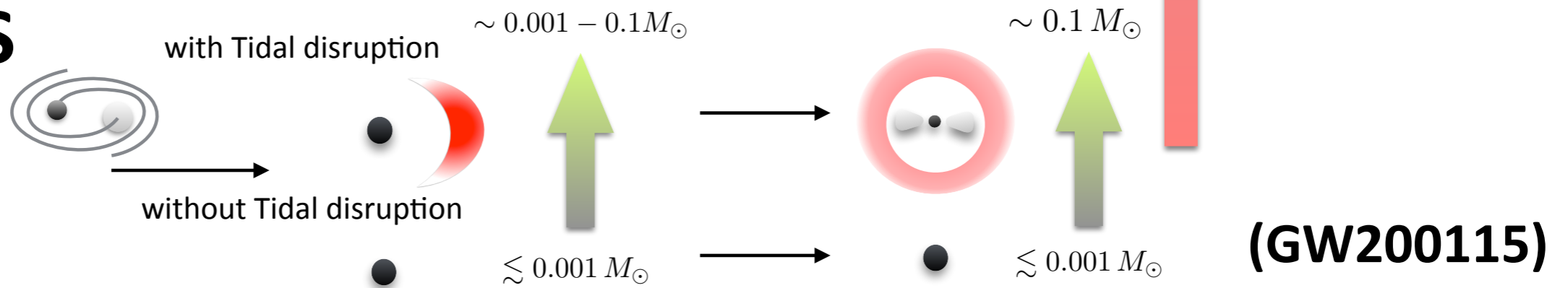


Diversity of neutron star mergers

NS-NS



BH-NS



**Event rate of NS mergers at < 40 Mpc
~ 1 event in 30 years
(see Asano-san's talk)**

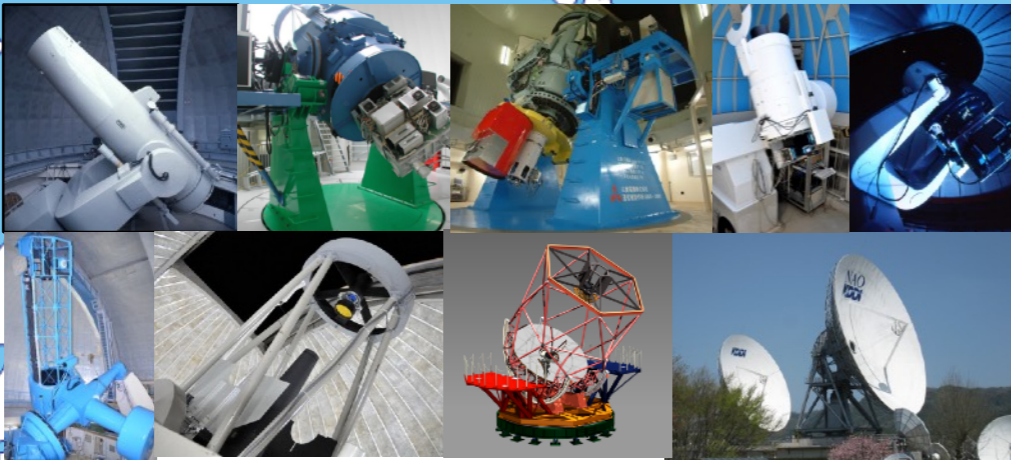
Need to observe NS merger events at larger distances!

$d = 100$ Mpc \Rightarrow volume $\times 10$ (1 event in 3 yr)

$d = 200$ Mpc \Rightarrow volume $\times 100$ (1 event in 0.3 yr)

Optical/IR follow-up observations

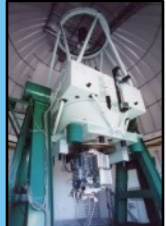
J-GEM: Japanese Collaboration for Gravitational Wave ElectroMagnetic Wave Follow-up



- Kiso Schmidt telescope (1.05m, Tokyo)
- /● Kanata telescope (1.5m, Hiroshima)
- Nayuta telescope (2m, Hyogo)
- MITSuME telescope (0.5m, Titech , NAOJ)
- OAO-WFC(0.91m, NAOJ)
- Seimei telescope (3.8m, Kyoto)
- 32m radio telescope (Yamaguchi)



○ HinOTORI (0,5m, Hiroshima)@China



● IRSF telescope (1.4m,Nagoya)@South Africa



○/● Subaru (8.2m, NAOJ)@Hawaii



● TAO (6m, Tokyo)
□ ASTE (10m, NAOJ) @Chile

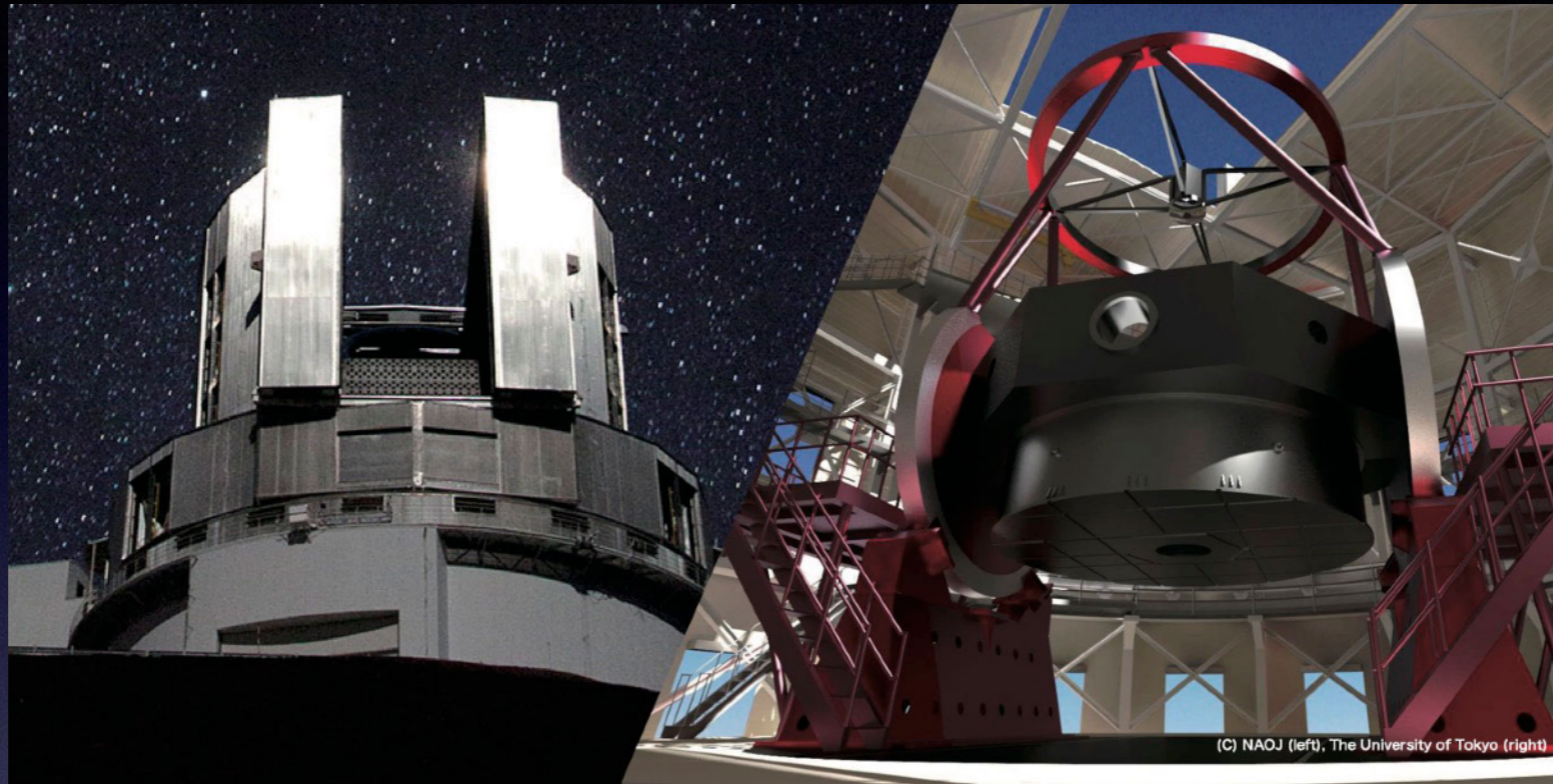


○ MOA-II (1.8m), B&C (0.61m)
(Nagoya)@New Zealand

Upgrades for spectroscopic observations

Subaru (north)

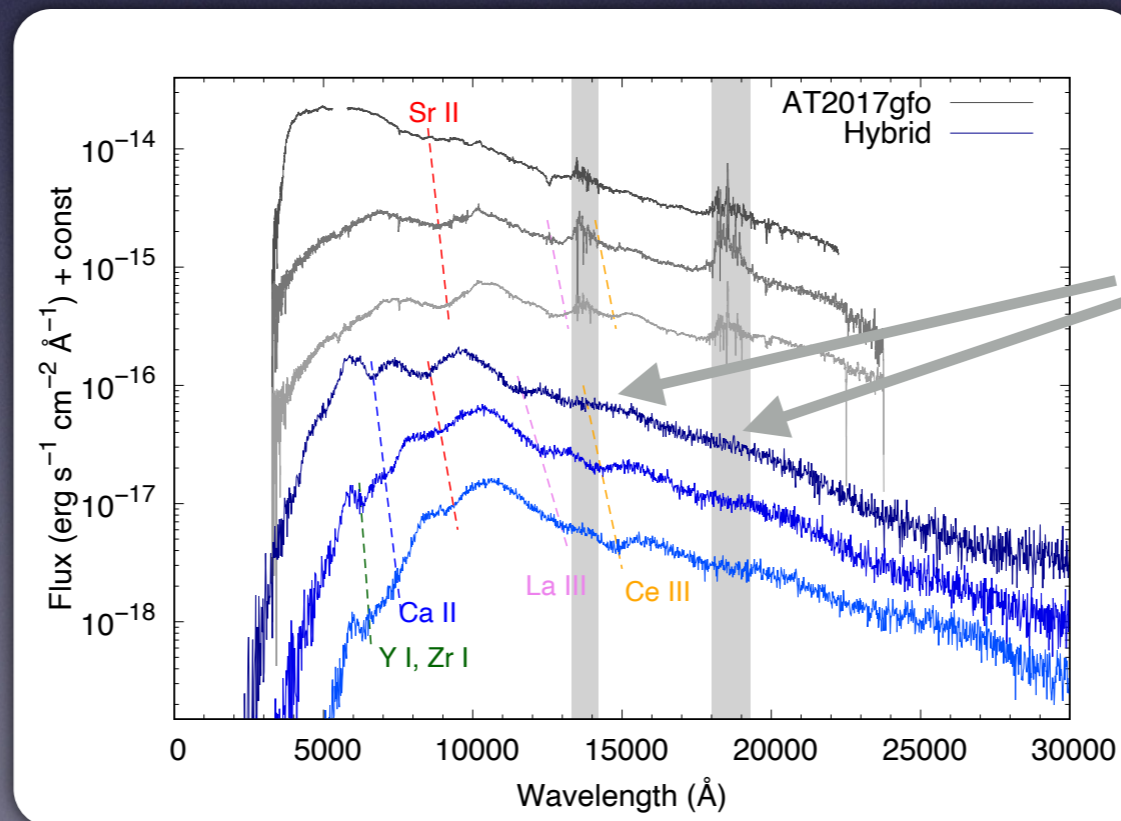
TAO (south)



(C) NAOJ/U. Tokyo

NINJA

High sensitivity observations with (laser tomography) adaptive optics => fainter objects



SWIMS

Continuous spectra opening the atmospheric windows (5500 m altitude!)

Summary

- **Multimessenger observations of NS mergers**
 - Kilonovae: probe of heavy element nucleosynthesis
 - Progress in decoding spectral features of kilonovae
 - Sr II (or He I), Ce III, La III, Y II, Te III have been suggested (more works in progress)
- **Future**
 - More events with different masses and different line of sights
=> Comprehensive pictures of NS mergers
 - Optical/IR follow-up: upgrades for spectroscopic facilities