

# Optical/infrared Counterparts of Gravitational Wave Sources

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# Optical/infrared Counterparts of Gravitational Wave Sources

- Physics of kilonova
- Variety of kilonova

MT, Kato, Gaigalas et al. 2018, ApJ, 852, 109

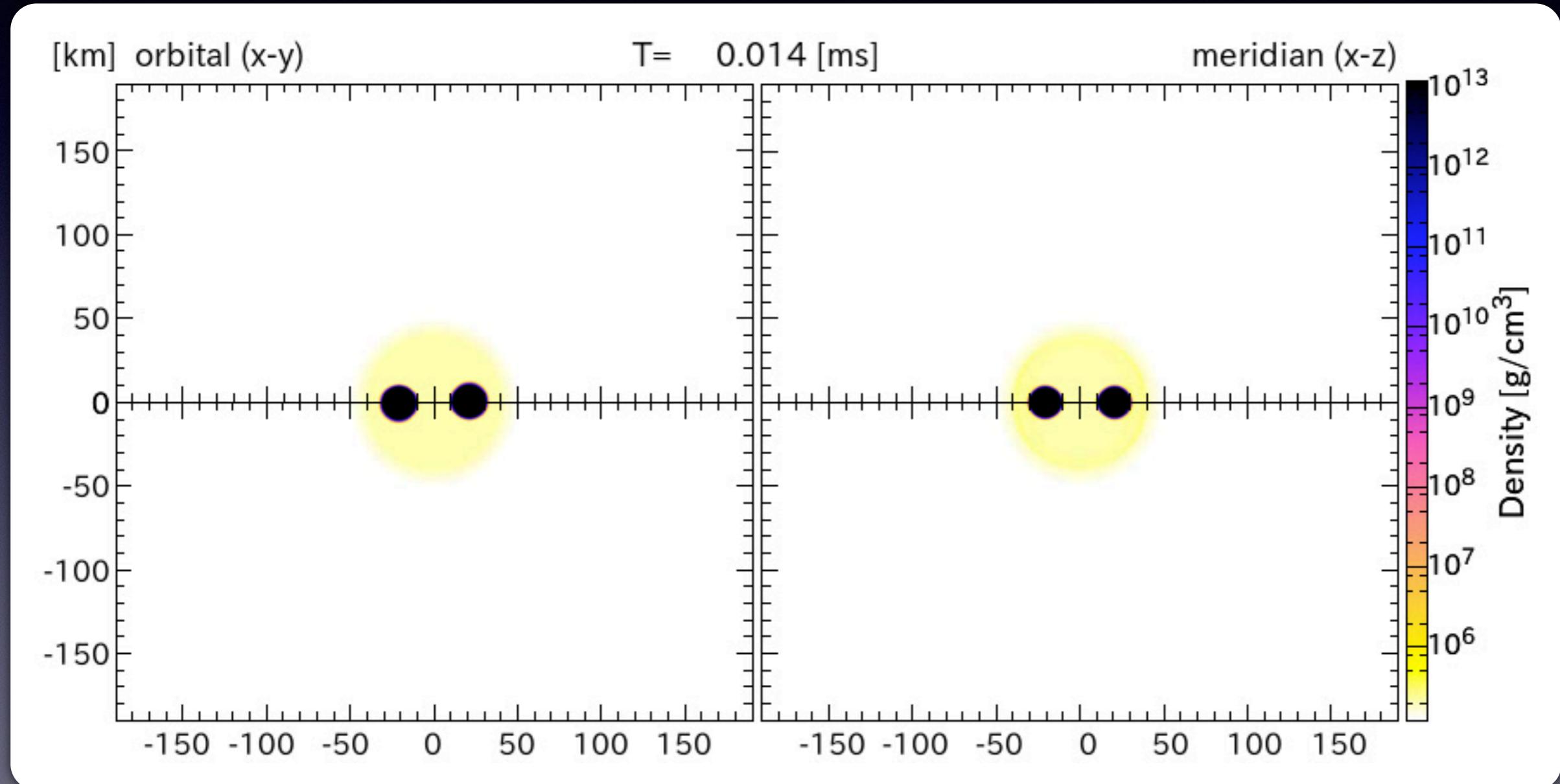
MT, Kato, Gaigalas, Kawaguchi 2019, arXiv:1906.08914

Neutron star merger => gravitational waves  
=> ejection of material

$10^{-3}$  - 1 sec

Top view

Side view

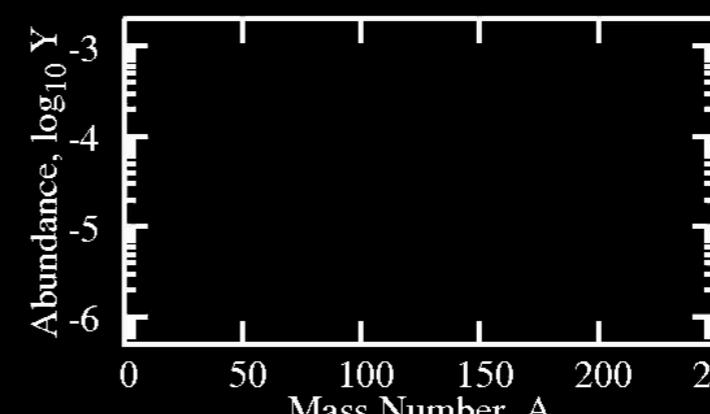
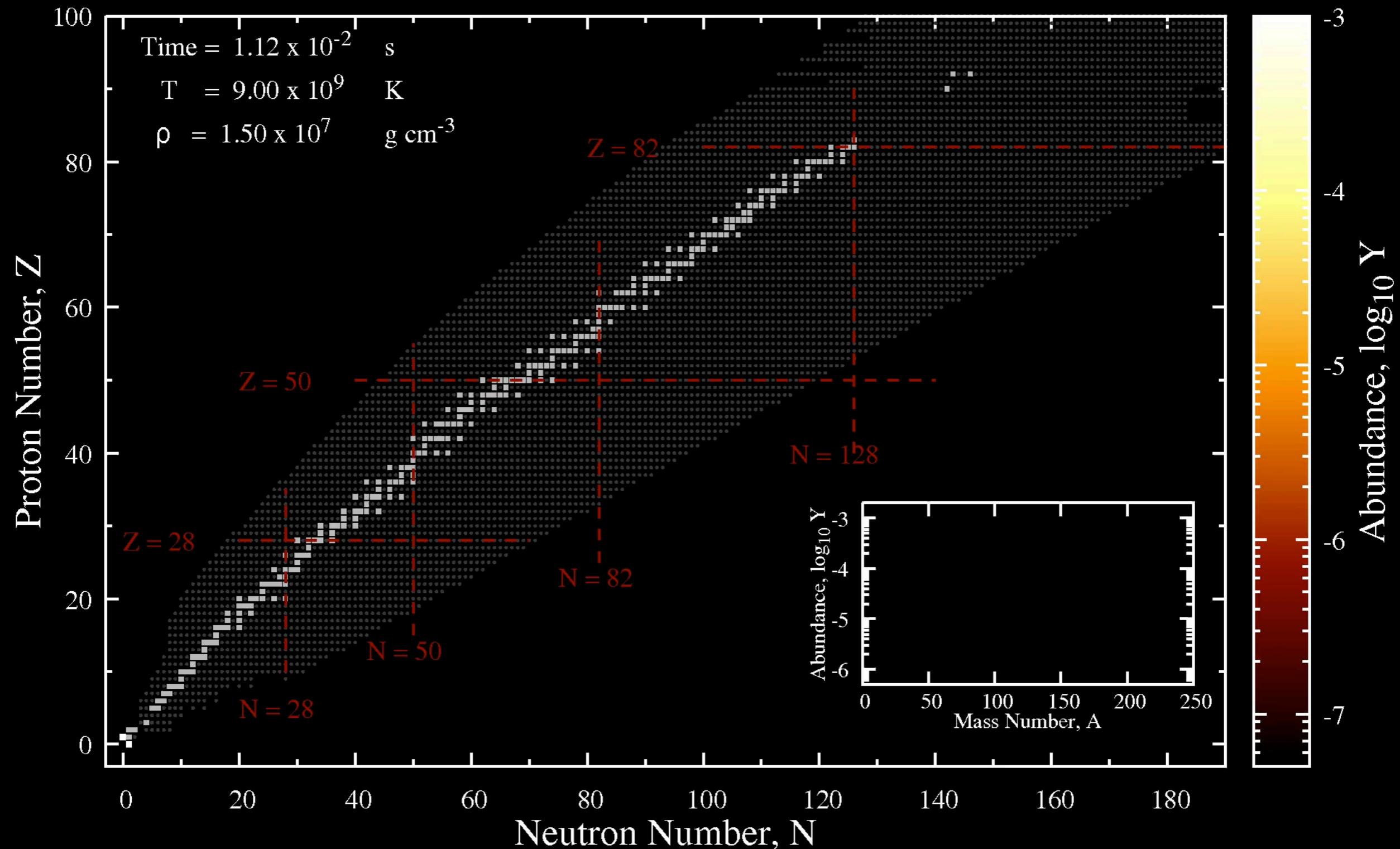


Sekiguchi+15, 16

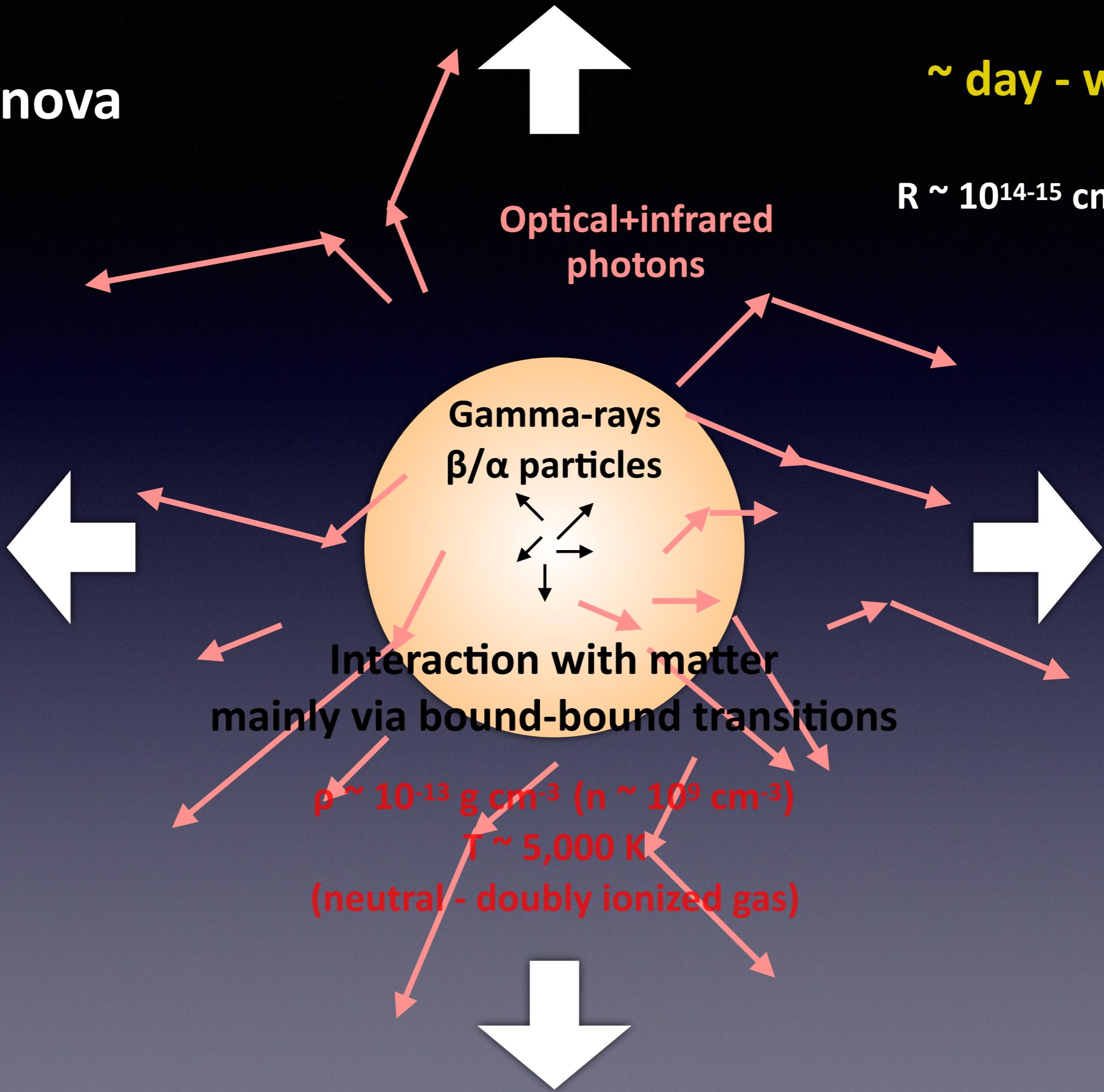
Mass  $\sim 10^{-3}$  -  $10^{-2}$  Msun   Velocity  $\sim 0.1$  -  $0.2$  c

# r-process in NS merger

n-capture:  $\sim 1$  sec  
Decay: sec - days - weeks

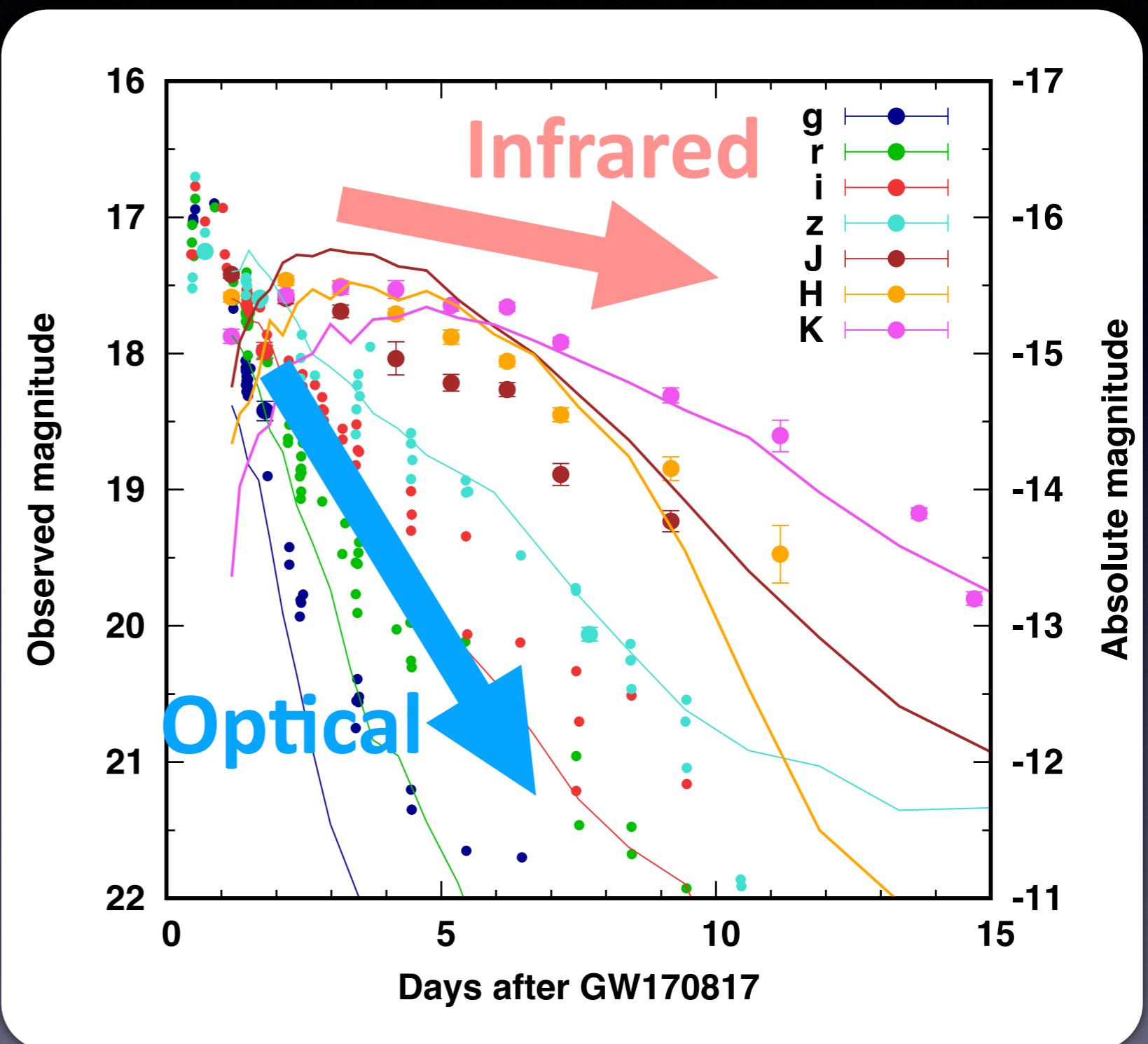


# Kilonova



# GW170817: optical/infrared light curves

Arcavi+17, Cowperthwaite+17,  
Diaz+17, Drout+17, Evans+17,  
Kasliwal+17, Pian+17,  
Smartt+17, Tanvir+17, Troja+17,  
Utsumi, MT+17, Valenti+17



$M(\text{r-process}) \sim 0.03\text{-}0.05 \text{ Msun}$

$$\lambda = \frac{hc}{\Delta E}$$

open s shell

1	H
3	4
Li	Be

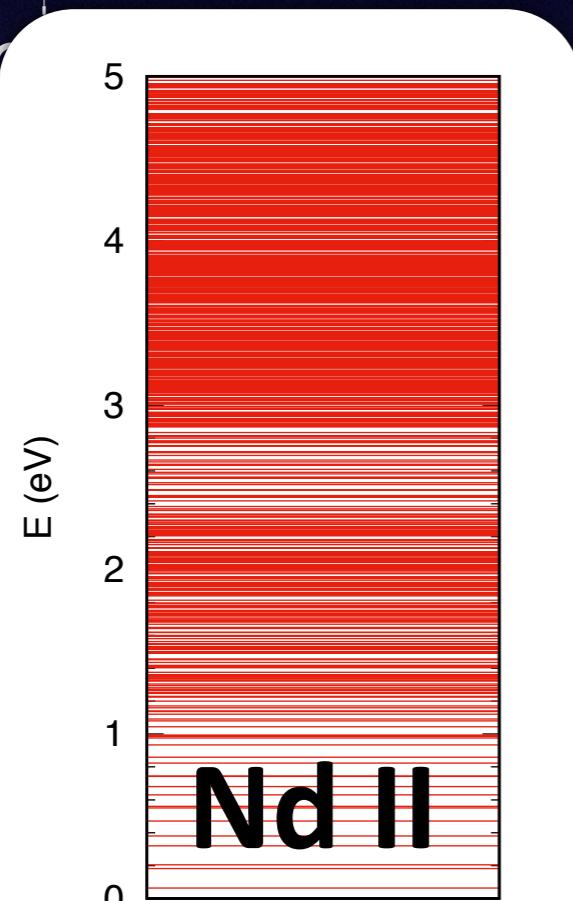
11	12
Na	Mg
19	20

K	Ca
37	38

Rb	Sr
55	56

Cs	Ba
87	88

Fr	Ra
89	90

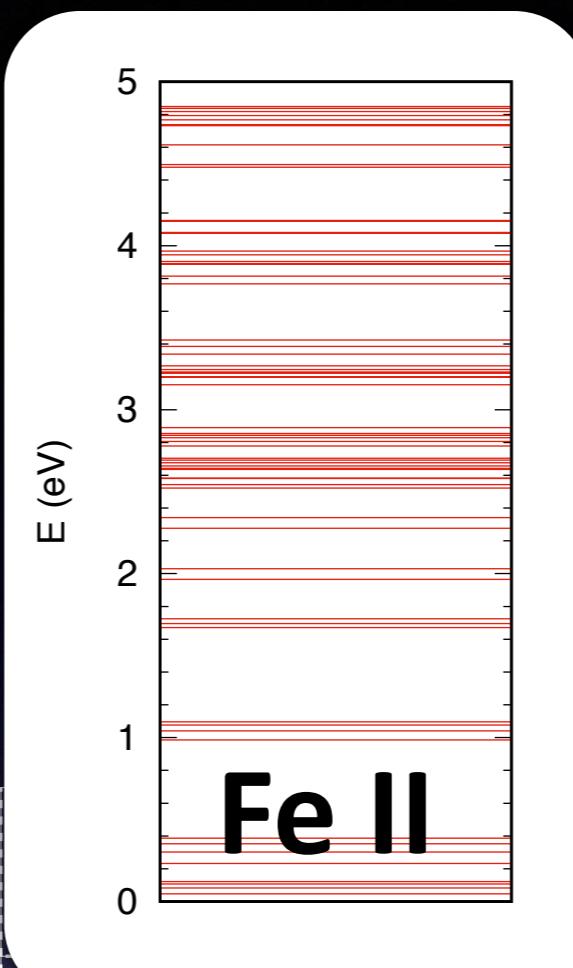


open d-shell

25	26	27
Mn	Fe	Co
43	44	45
Tc	Ru	Rh
75	76	77
Re	Os	Ir
107	108	109
Bh	Hs	Mt

60	61	62	63	64	65	66	67	68	69	70	71
Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
89	90	91	92	93	94	95	96	97	98	99	100
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm
101	102	103									
Md	No	Lr									

open f shell



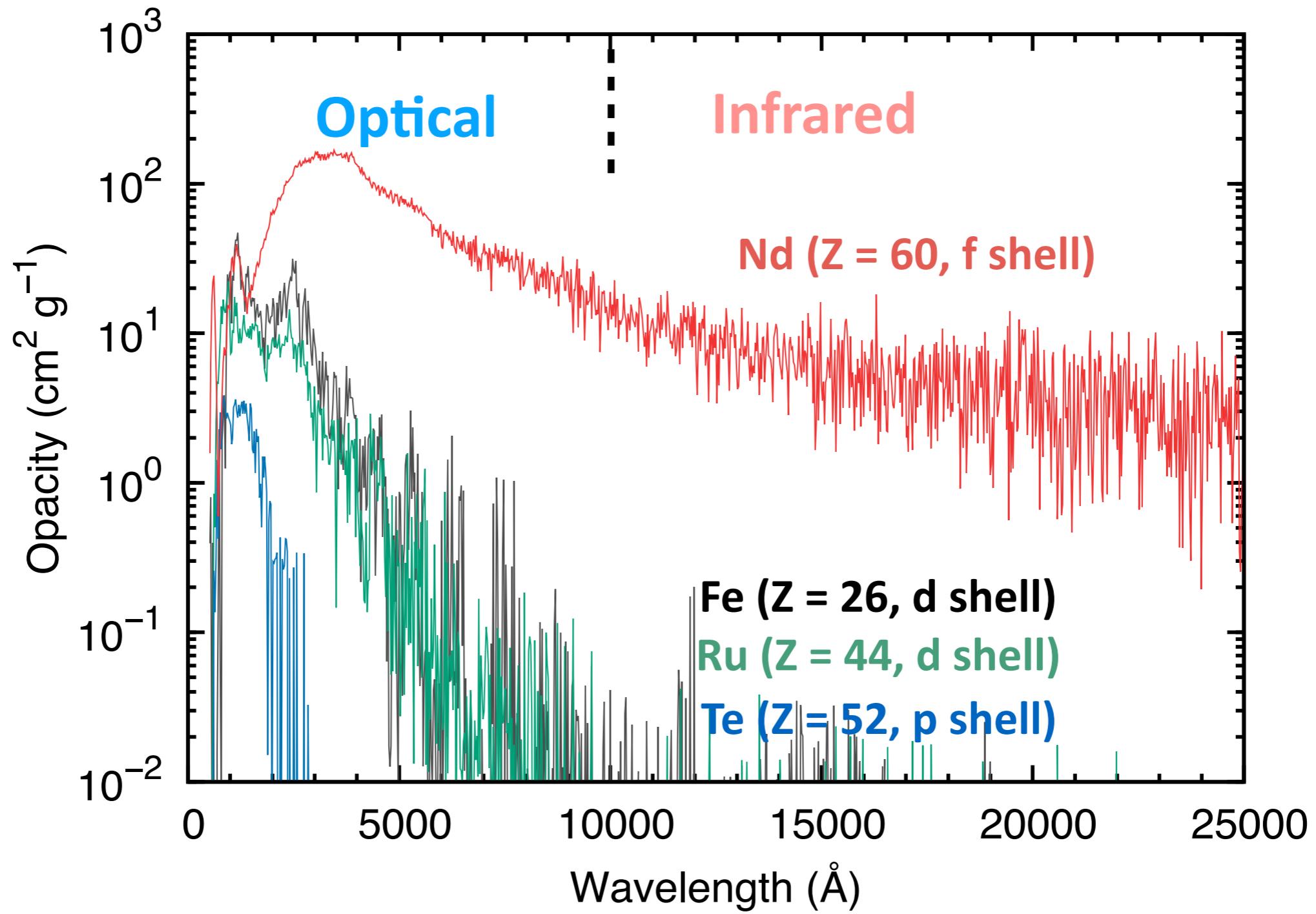
open p-shell

6	7	8	9	10
C	N	O	F	Ne
14	15	16	17	18
Si	P	S	Cl	Ar
32	33	34	35	36

50	51	52	53	54
In	Sn	Sb	Te	I
84	85	86	84	85
Po	At	Rn	Po	At
116	117	118	116	117
Lv	Ts	Og	Lv	Ts

69	70	71
Tm	Yb	Lu
101	102	103
Md	No	Lr

# Opacity calculations for NS merger



# Status of atomic calculations for kilonova

**open s shell**

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

Fontes+17: Ce I-IV, Nd I-IV, Sm I-IV, U I-IV

Wollaeger+17: Se, Br, Zr, Pd, Te

MT+18: Se I-III, Ru I-III, Te I-III, Nd I-III, Er I-III

Kasen+17: all lanthanides

**MT+19: all r-process elements**

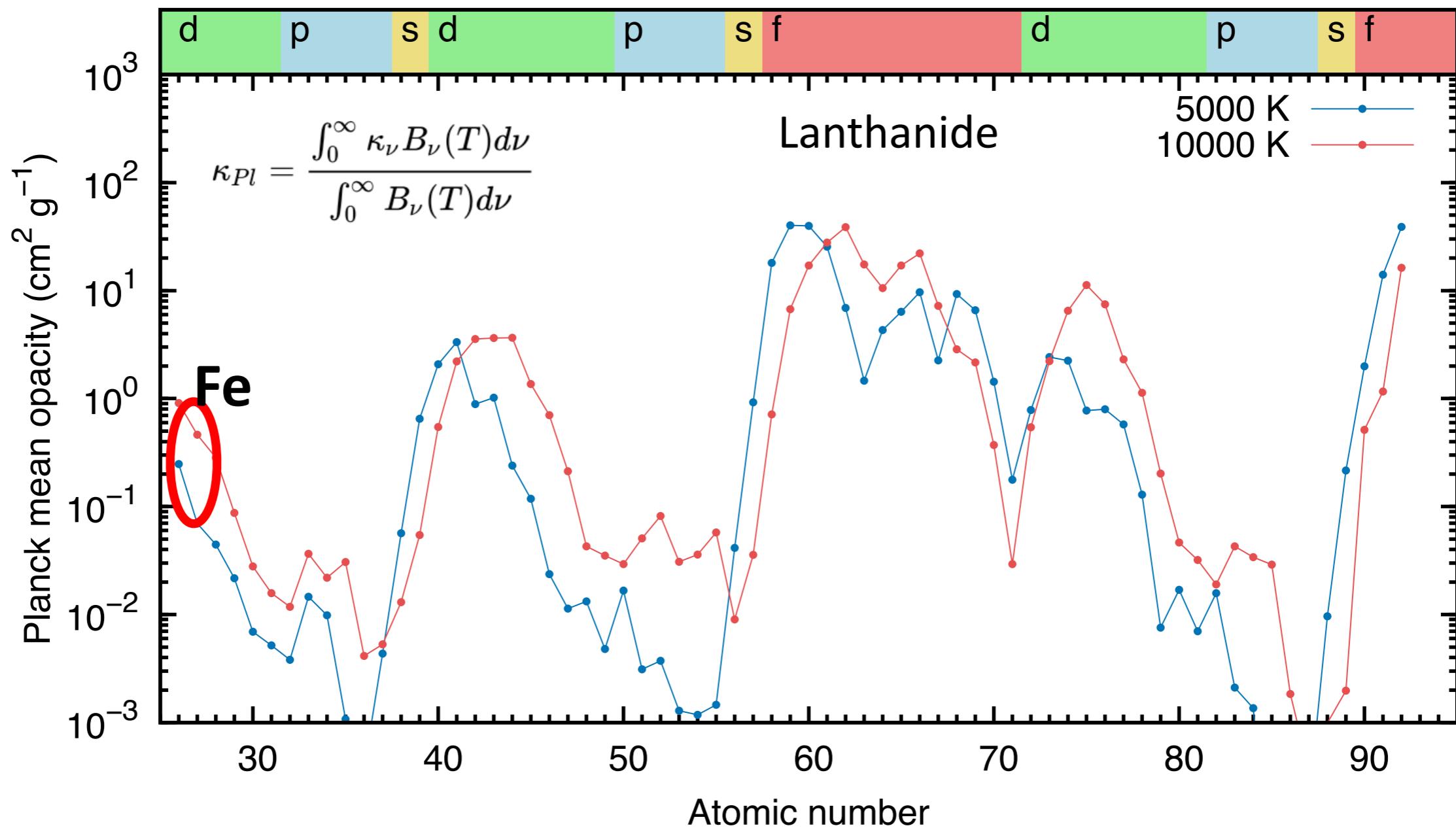
**open p-shell**

1	H																			2
3		4																		He
Li	Be																			
11	12																			
Na	Mg																			
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	Nh	Fl	Mc	Lv	Ts	Og			

**open f shell**

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				

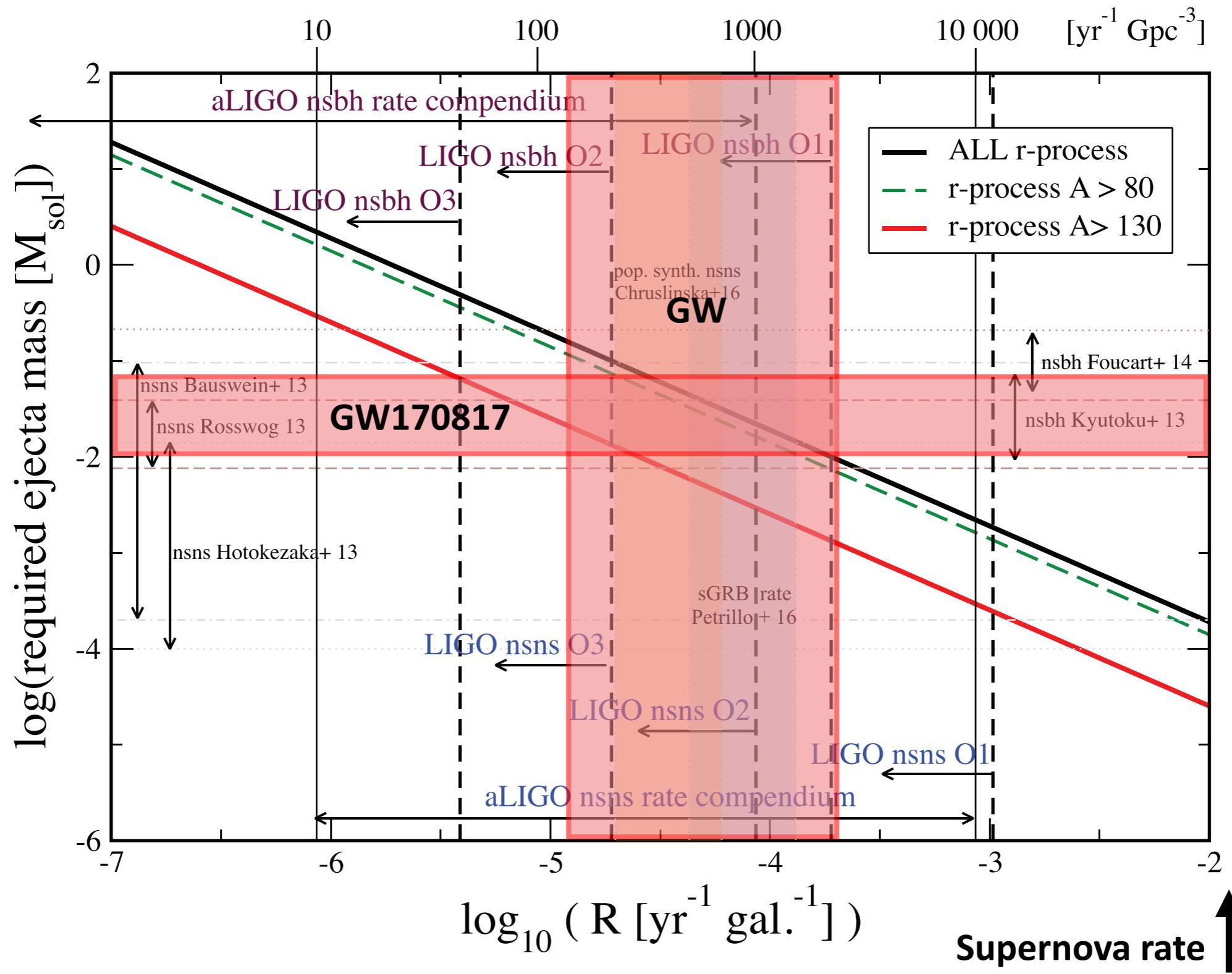
# Element dependence



Depends not only on elements  
but also on T and  $\rho$  (which evolve with time)

Be careful about interpretations with constant opacities

# Constraints from the total amount in our Galaxy



Rosswog+17, Hotokezaka+15, 18

# Optical/infrared Counterparts of Gravitational Wave Sources

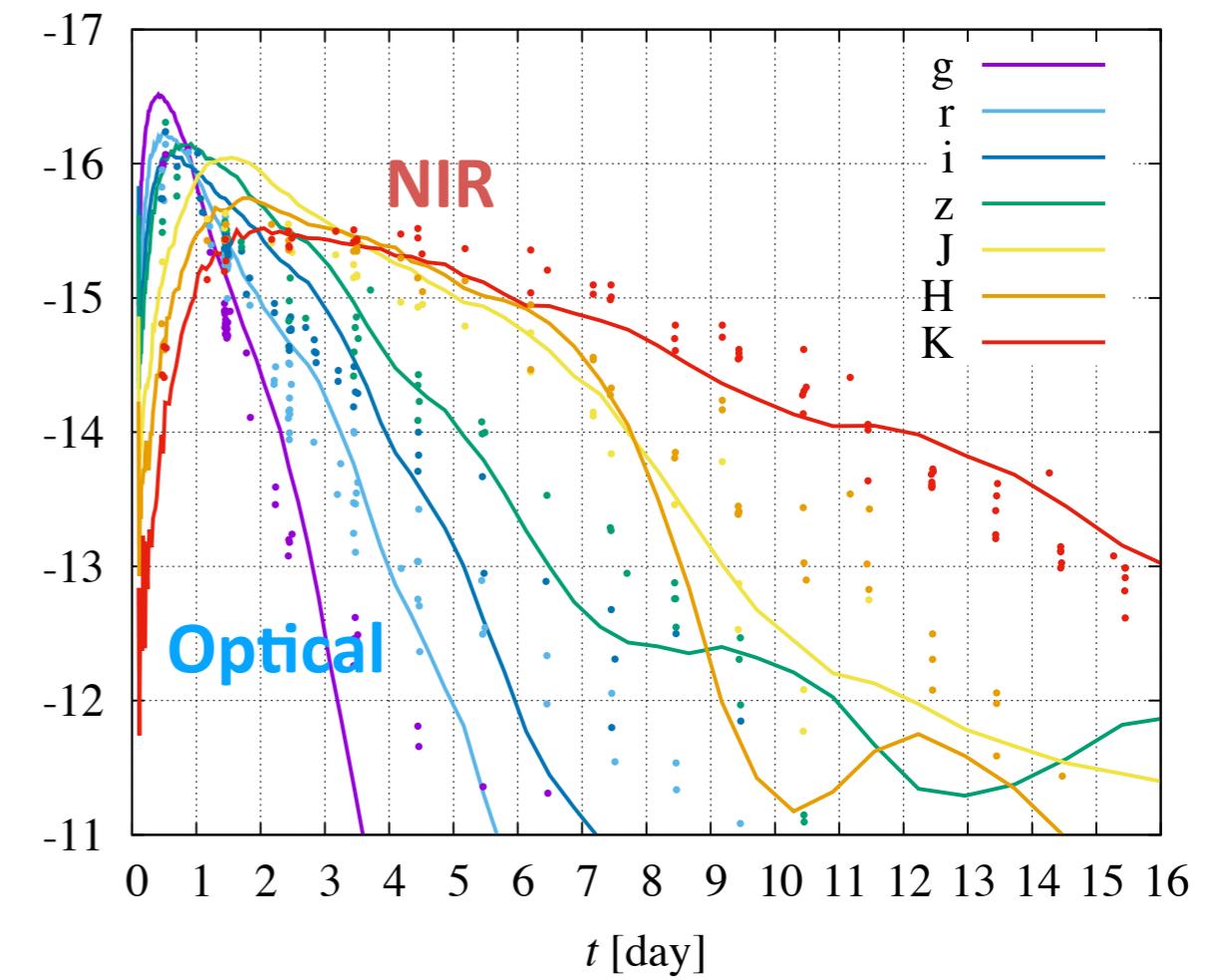
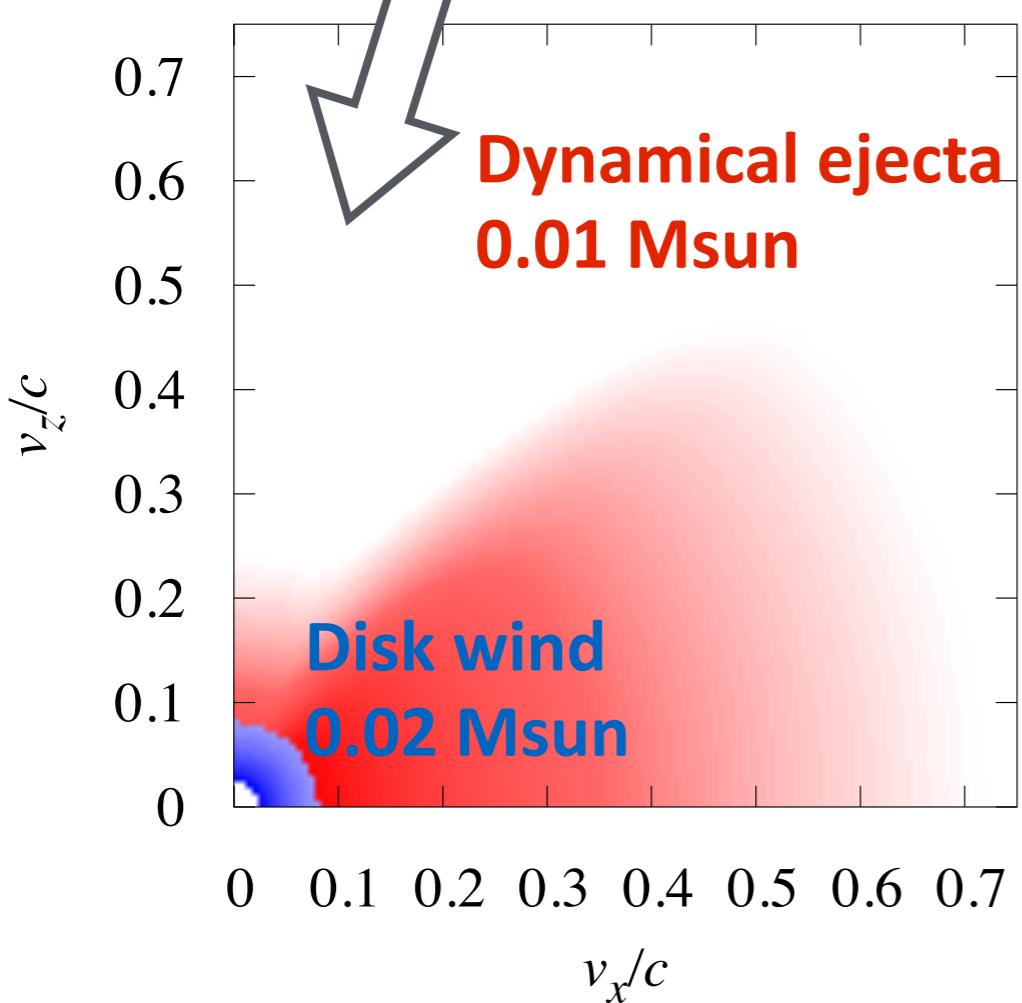
- Physics of kilonova
- Variety of kilonova

Kawaguchi, Shibata, MT 2018, ApJ, 865, L21

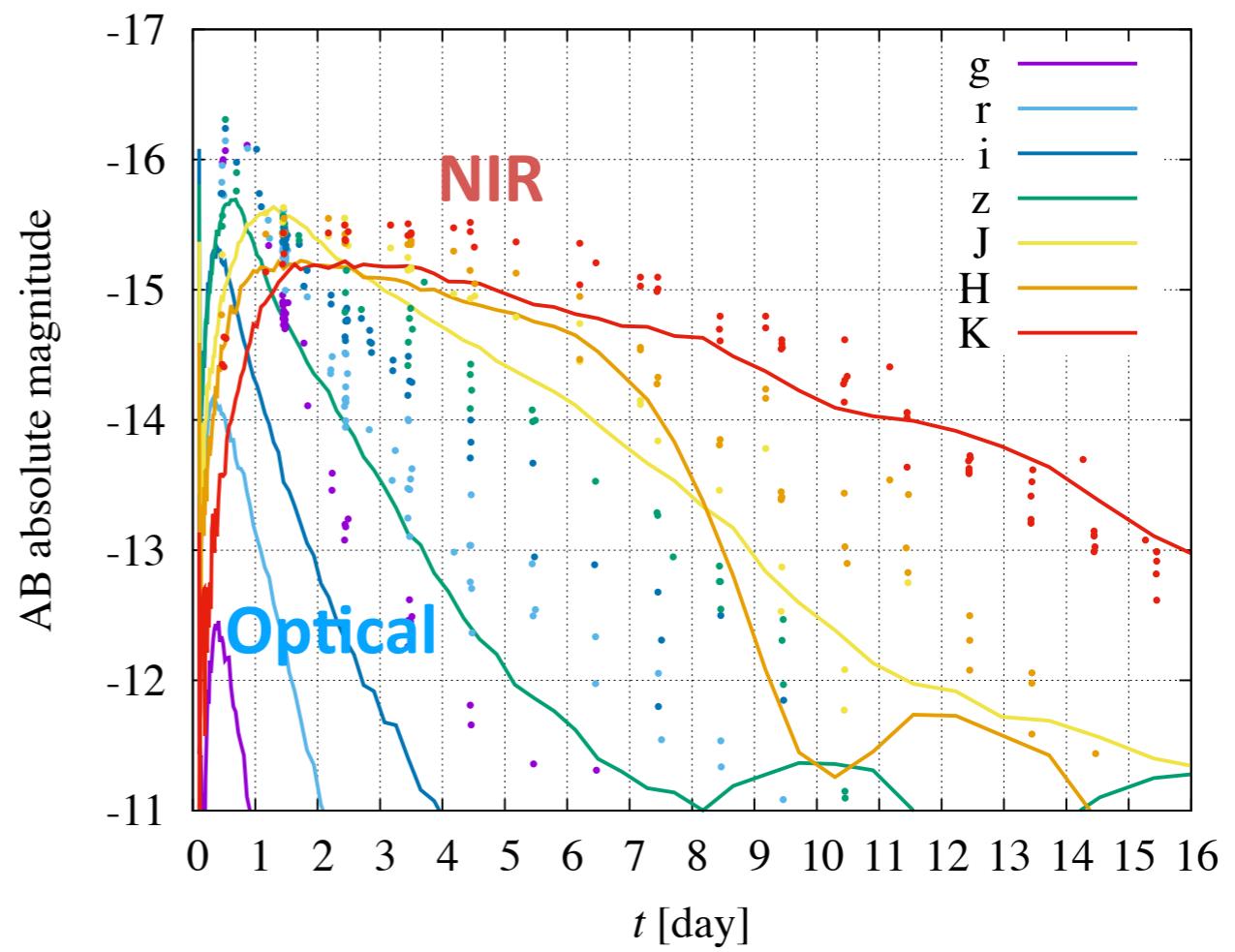
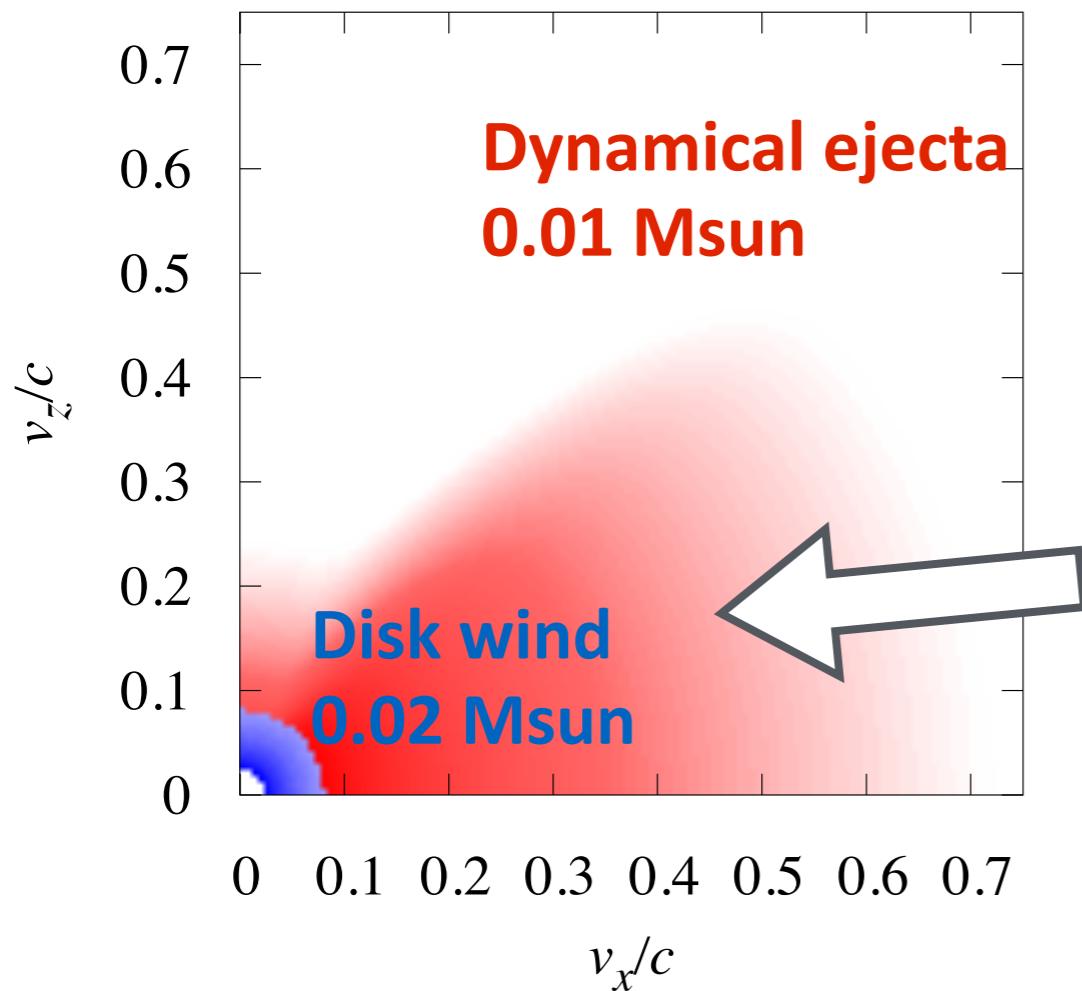
Kawaguchi, Shibata, MT 2019, arXiv:1908.05815

# (1) Viewing angle

GW170817 ( $\sim 30$  deg)



# (1) Viewing angle



- Optical emission can be suppressed by 1-2 mag (in r, i, and z-bands)
- Near-infrared is almost unaffected

## (2) Mass

**NS-NS**

More massive ↓

$$M_{\text{tot}} \lesssim M_{\text{max,spin}}$$

Supermassive NS



$$M_{\text{tot}} \lesssim M_{\text{thr}}$$

Hypermassive NS

$$M_{\text{tot}} \gtrsim M_{\text{thr}}$$

Prompt Collapse

Dynamical Ejecta



$$\sim 0.001 M_{\odot}$$



$$\sim 0.01 M_{\odot}$$
  
 $M_d$

$$\lesssim 0.001 M_{\odot}$$



Post-merger Ejecta

$$\sim 0.1 M_{\odot}$$



$$t_{\text{life}} \gg 1 \text{ s}$$

$$t_{\text{life}} \gtrsim 1 \text{ s}$$

$$t_{\text{life}} \ll 1 \text{ s}$$



$$M_{\text{torus}}$$

$$\lesssim 0.001 M_{\odot}$$

**Long-lived NS**

**NS => BH  
(GW170817)**

**Prompt  
collapse  
to BH**

## (2) Mass

**NS-NS**

More massive ↓

$$M_{\text{tot}} \lesssim M_{\text{max,spin}}$$

Supermassive NS



$$M_{\text{tot}} \lesssim M_{\text{thr}}$$

Hypermassive NS

$$M_{\text{tot}} \gtrsim M_{\text{thr}}$$

Prompt Collapse

Dynamical Ejecta



$$\sim 0.001 M_{\odot}$$



$$M_d \downarrow \sim 0.01 M_{\odot}$$

$$\lesssim 0.001 M_{\odot}$$

Post-merger Ejecta

$$\sim 0.1 M_{\odot}$$

$$t_{\text{life}} \gg 1 \text{ s}$$

$$t_{\text{life}} \gtrsim 1 \text{ s}$$

$$t_{\text{life}} \ll 1 \text{ s}$$

$$M_{\text{torus}}$$

$$\lesssim 0.001 M_{\odot}$$

**Long-lived NS**

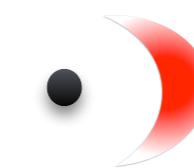
**NS => BH  
(GW170817)**

**BH-NS**

with Tidal disruption



without Tidal disruption



$$\sim 0.001 - 0.1 M_{\odot}$$

$$\lesssim 0.001 M_{\odot}$$

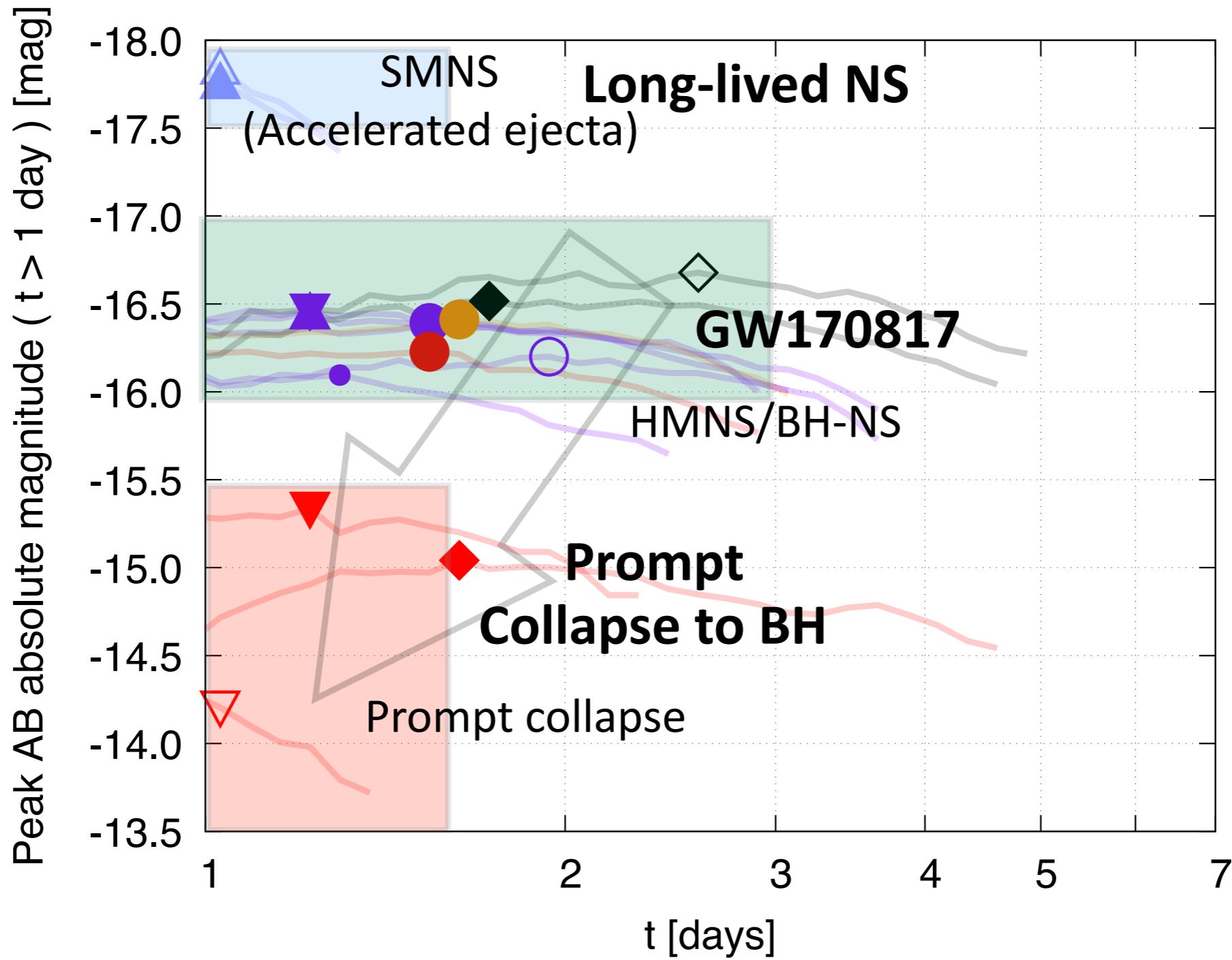
$$\sim 0.1 M_{\odot}$$

$$\lesssim 0.001 M_{\odot}$$

**Prompt collapse to BH**

**Bright only for low-mass or high-spin BH**

# Variety of kilonovae



GW => Mass (initial condition!)

Kilonova brightness/color/timescale => physics in NS merger

# Summary

- Physics of kilonova
  - Systematic opacity calculations for all the elements from Z=30 to 89 (I, II, III, IV)
  - More direct connection between NS mergers and kilonova
- Variety of kilonova
  - Viewing angle  
Optical: fainter for off-axis events (by 1-2 mag)  
Infrared: almost unchanged
  - Mass  
Less massive => long-lived NS => brighter by ~1 mag  
More massive => Prompt collapse to BH => fainter by 1-2 mag  
BH-NS => needs low-mass, spinning BH for kilonova