GW170817: Optical/infrared Observations and Kilonovae

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(2018年9月10-13日@国立天文台) **TENNET: 16174**

電磁波各波長・重力波・ニュートリノ・宇宙線の
基礎的な検出原理、稼働装置、将来計画などを横断的に学ぶ

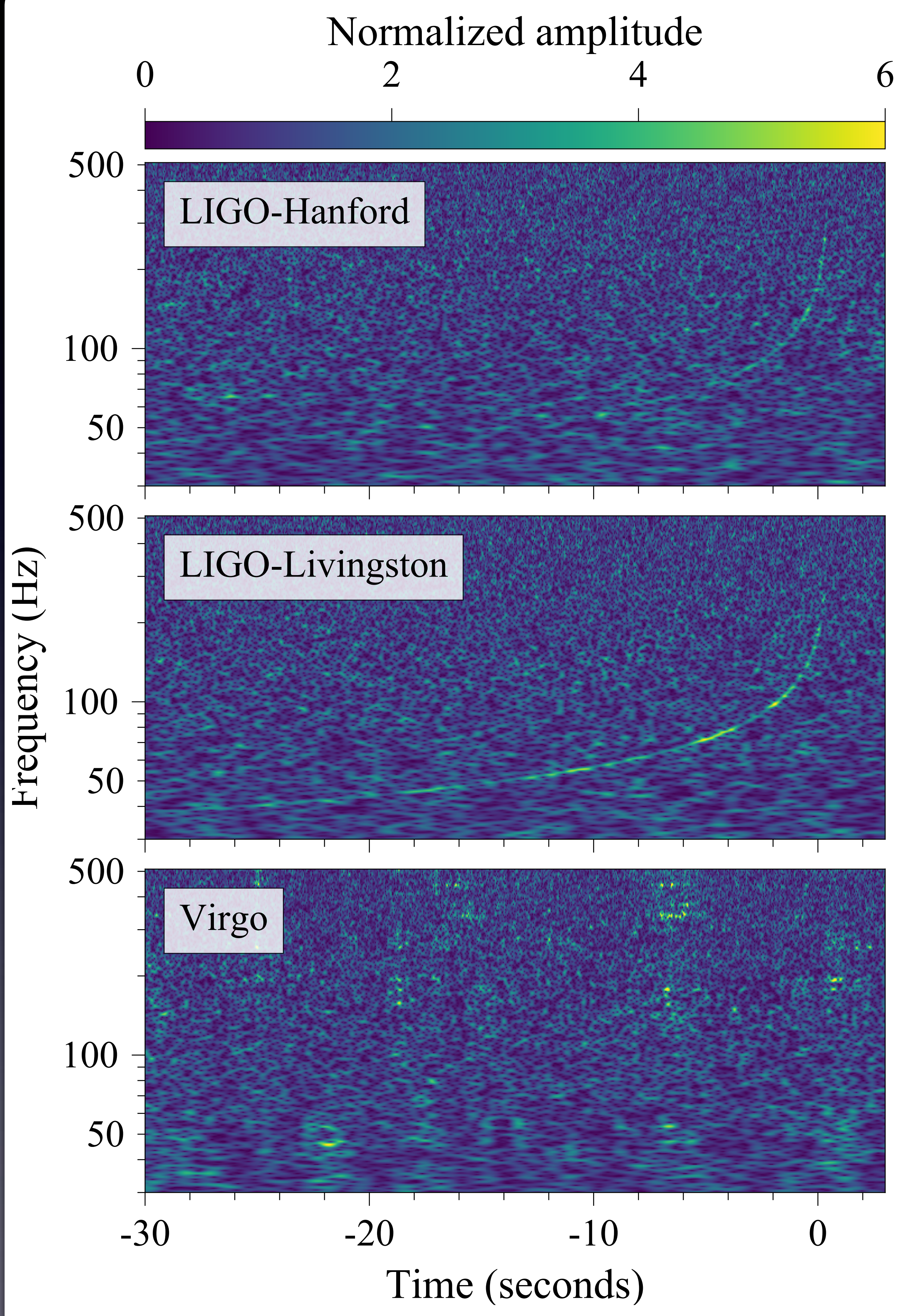
- ニュートリノ天文学 (吉田 滋さん, 2コマ)
- 重力波天文学 (麻生 洋一さん、久徳 浩太郎さん)
- 宇宙線天文学 (多米田 裕一郎さん)
- ガンマ線天文学 (水野 恒史さん, 2コマ)
- X線天文学 (馬場 彩さん, 2コマ)
- 光赤外線天文学 (松田 有一さん)
- 電波天文学 (秦 和弘さん)

GW170817: Optical/infrared Observations and Kilonovae

- GW170817: multi-messenger observations
- Kilonova and the origin of heavy elements
- Future prospects

2017 Aug 17

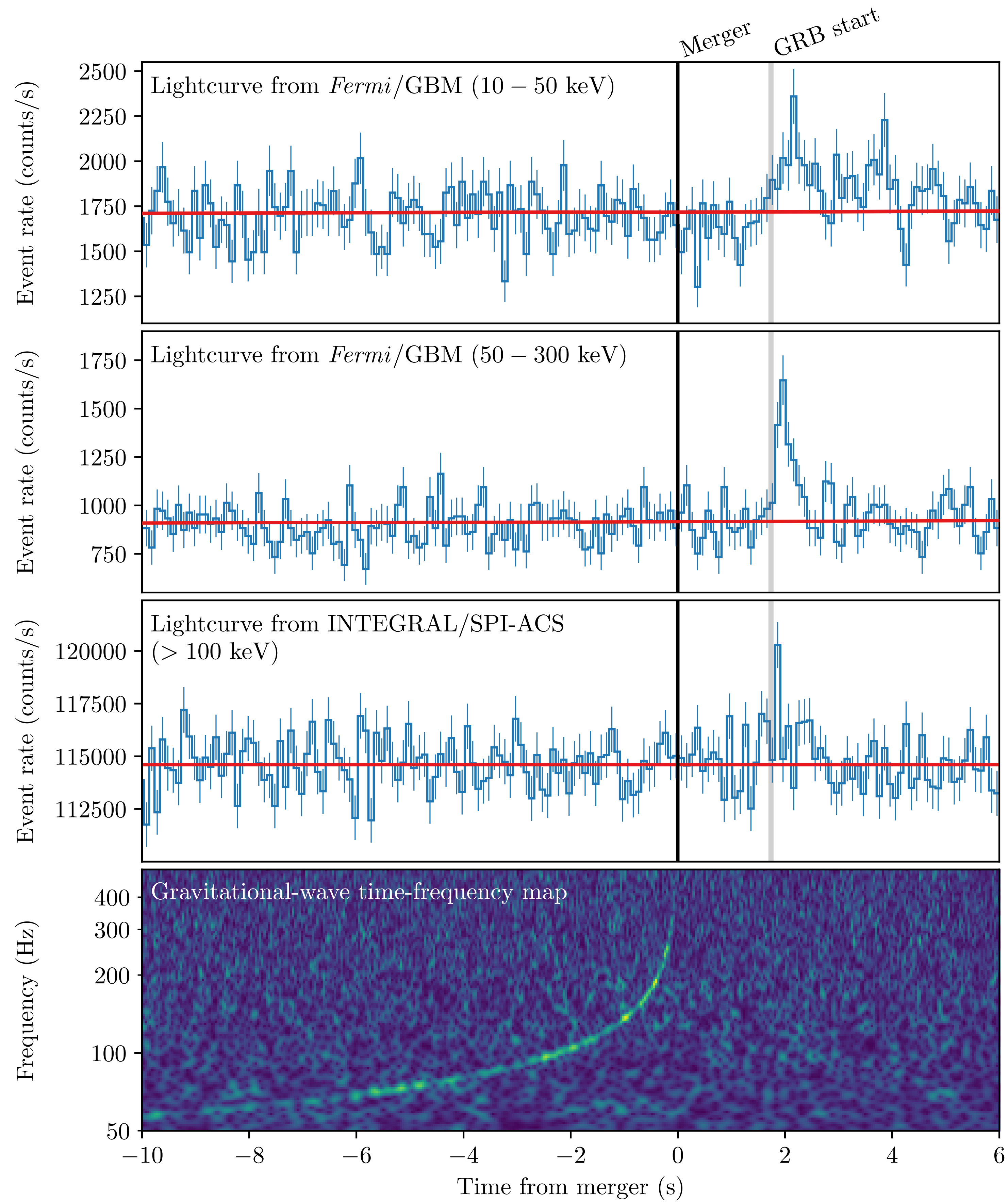
GW170817:
The first detection of GWs from a NS merger



LIGO Scientific Collaboration
and Virgo Collaboration, 2017, PRL

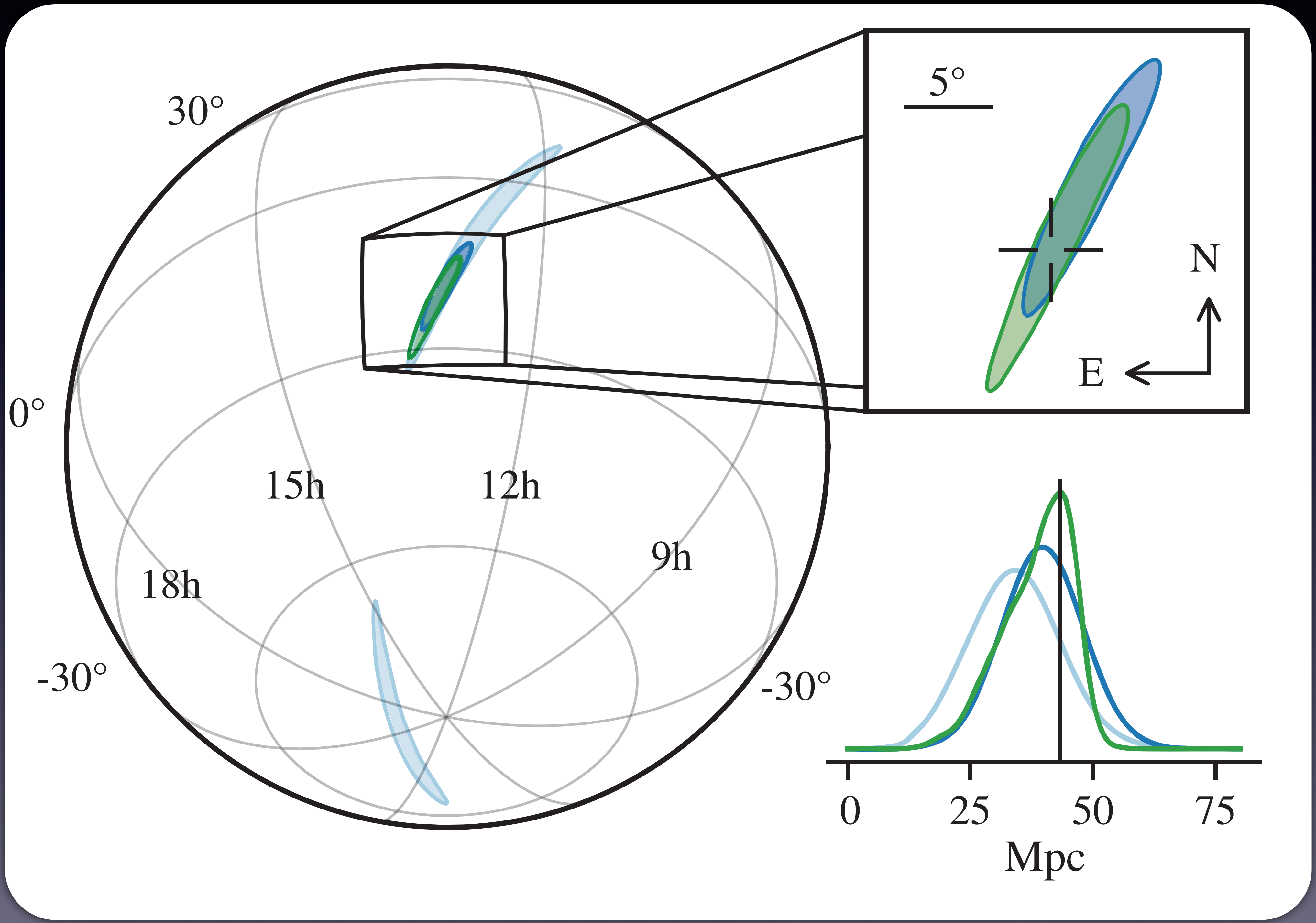
Gamma-ray
Fermi & INTEGRAL

~2 sec after the merger

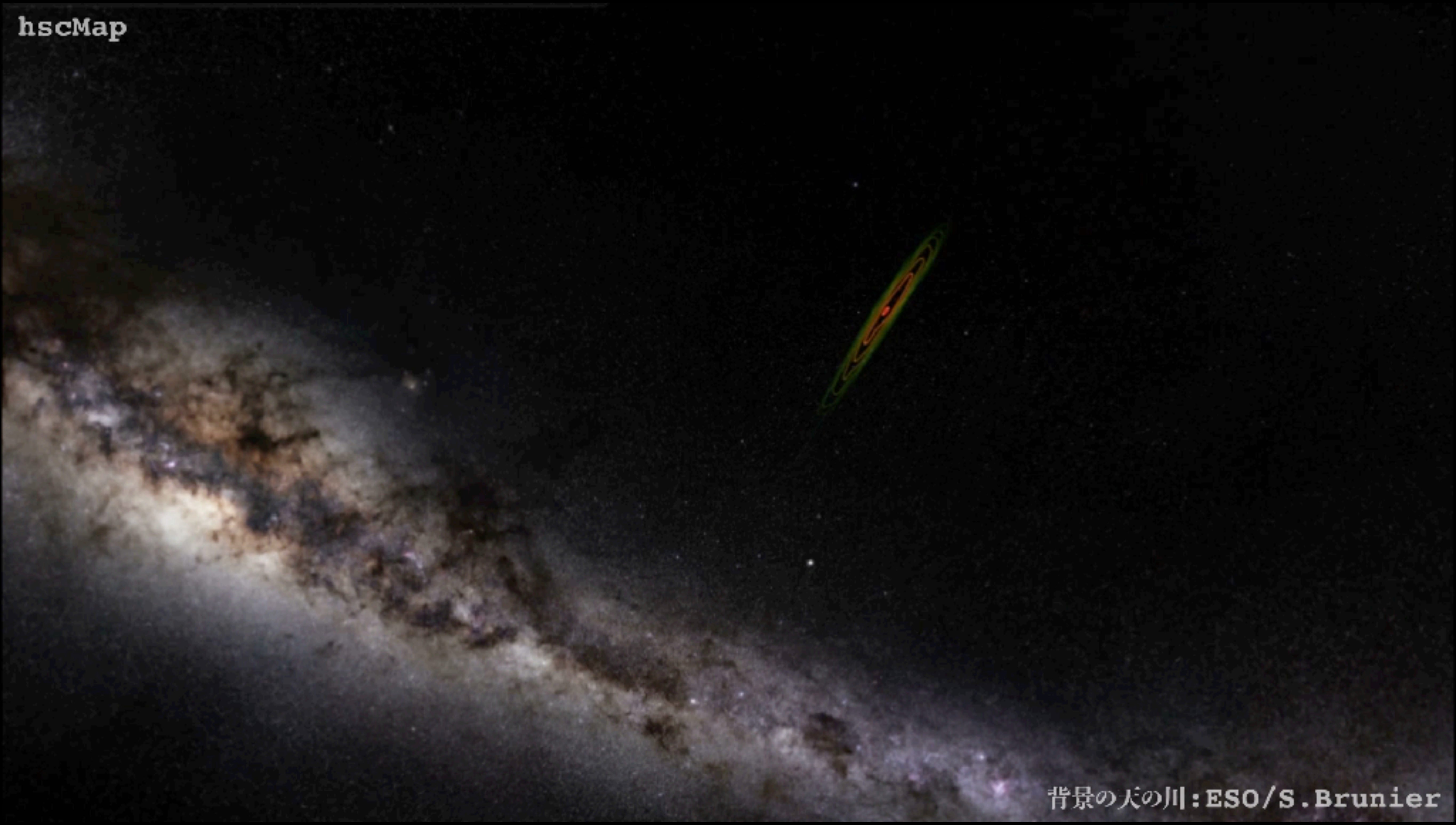


LIGO Scientific Collaboration
and Virgo Collaboration, 2017, ApJ

Skymap from 3 detectors (LIGO x 2 + Virgo)
==> 30 deg² (~40 Mpc)



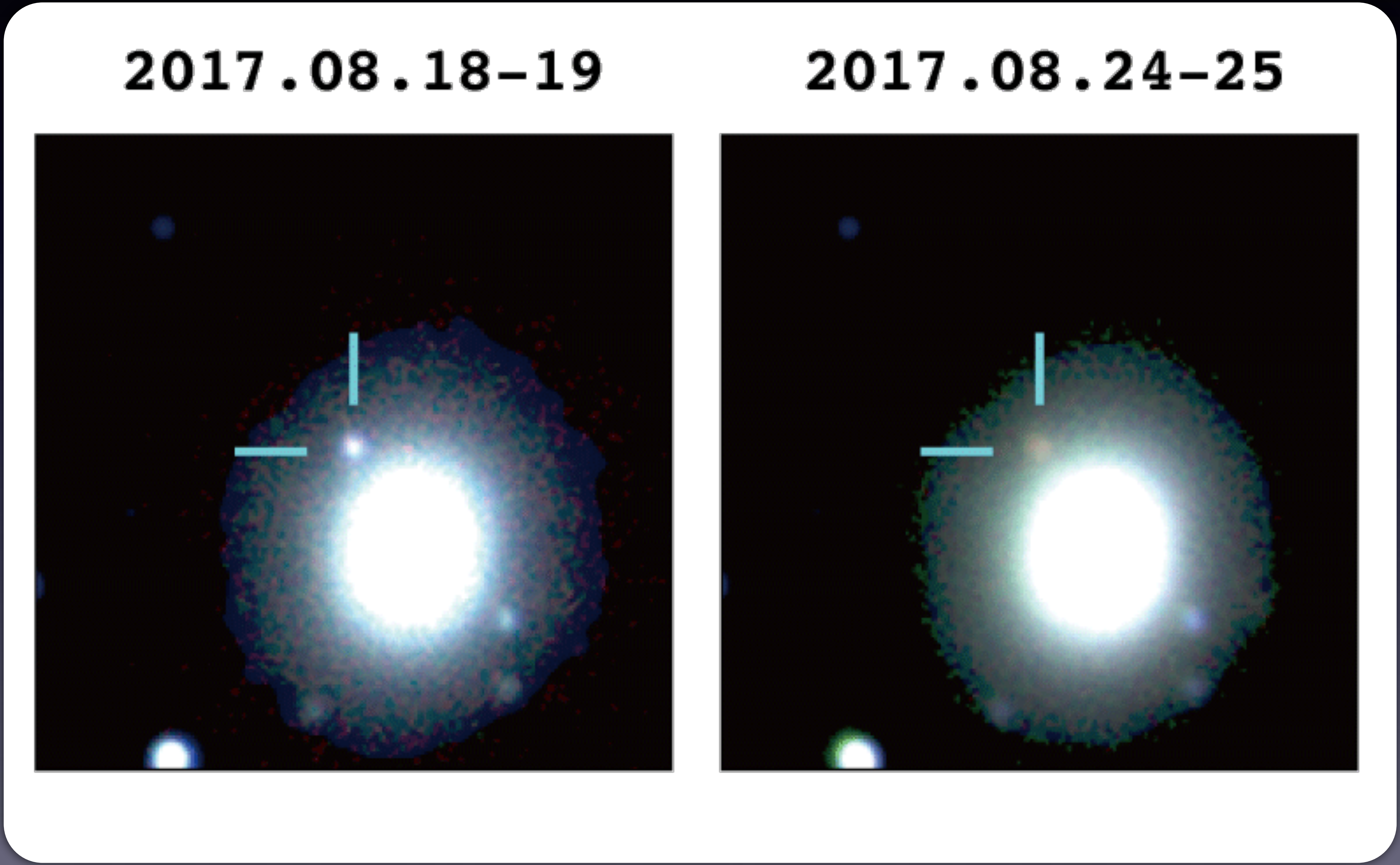
LIGO Scientific Collaboration and Virgo Collaboration, 2017



(C) Michitaro Koike (NAOJ/HSC)

Electromagnetic counterpart of GW170817 @ 40 Mpc

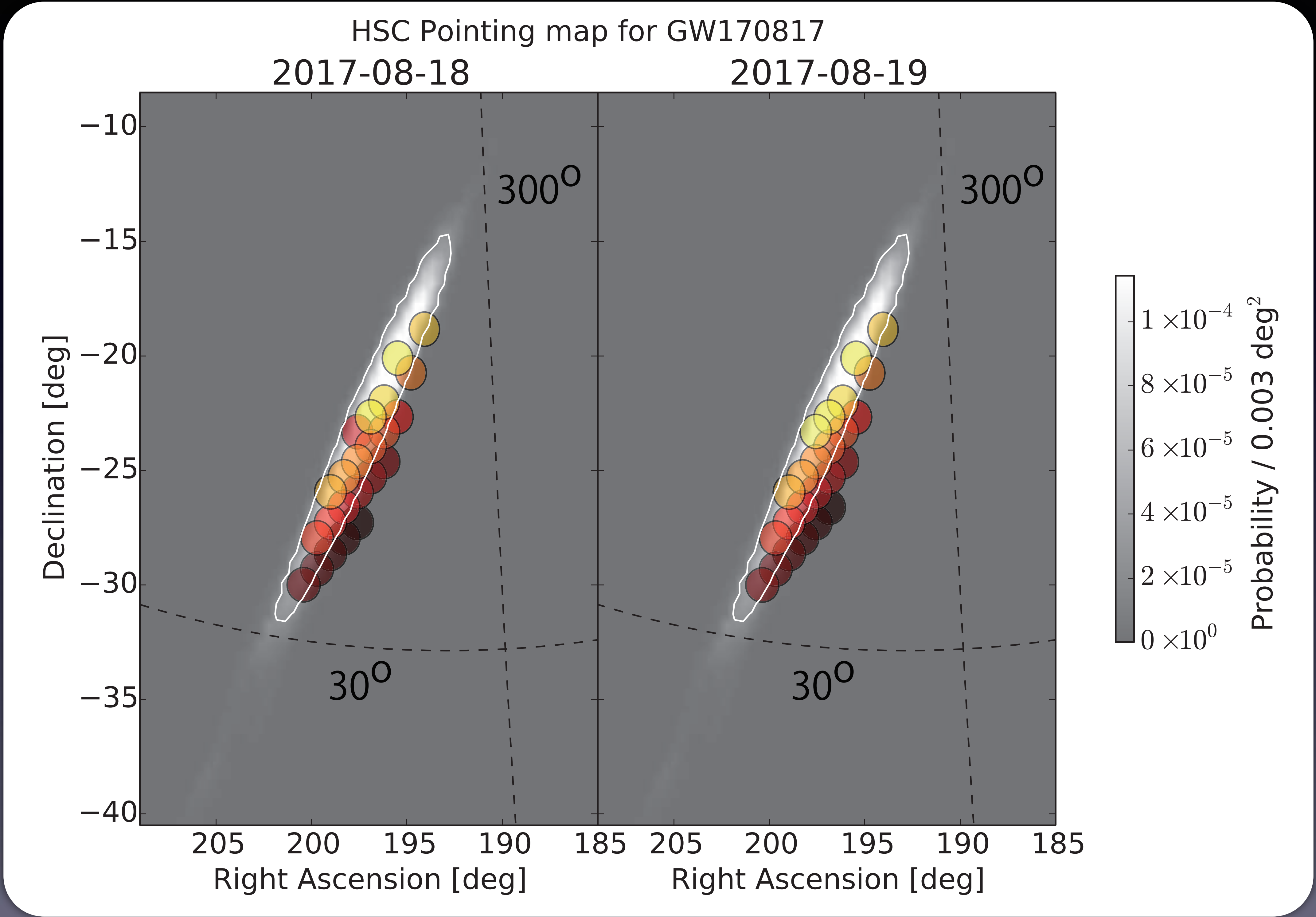
J-GEM: Japanese collaboration for Gravitational-wave
Electro-Magnetic follow-up (PI: Michitoshi Yoshida)



Subaru/HSC z +IRSF/SIRIUS H, Ks

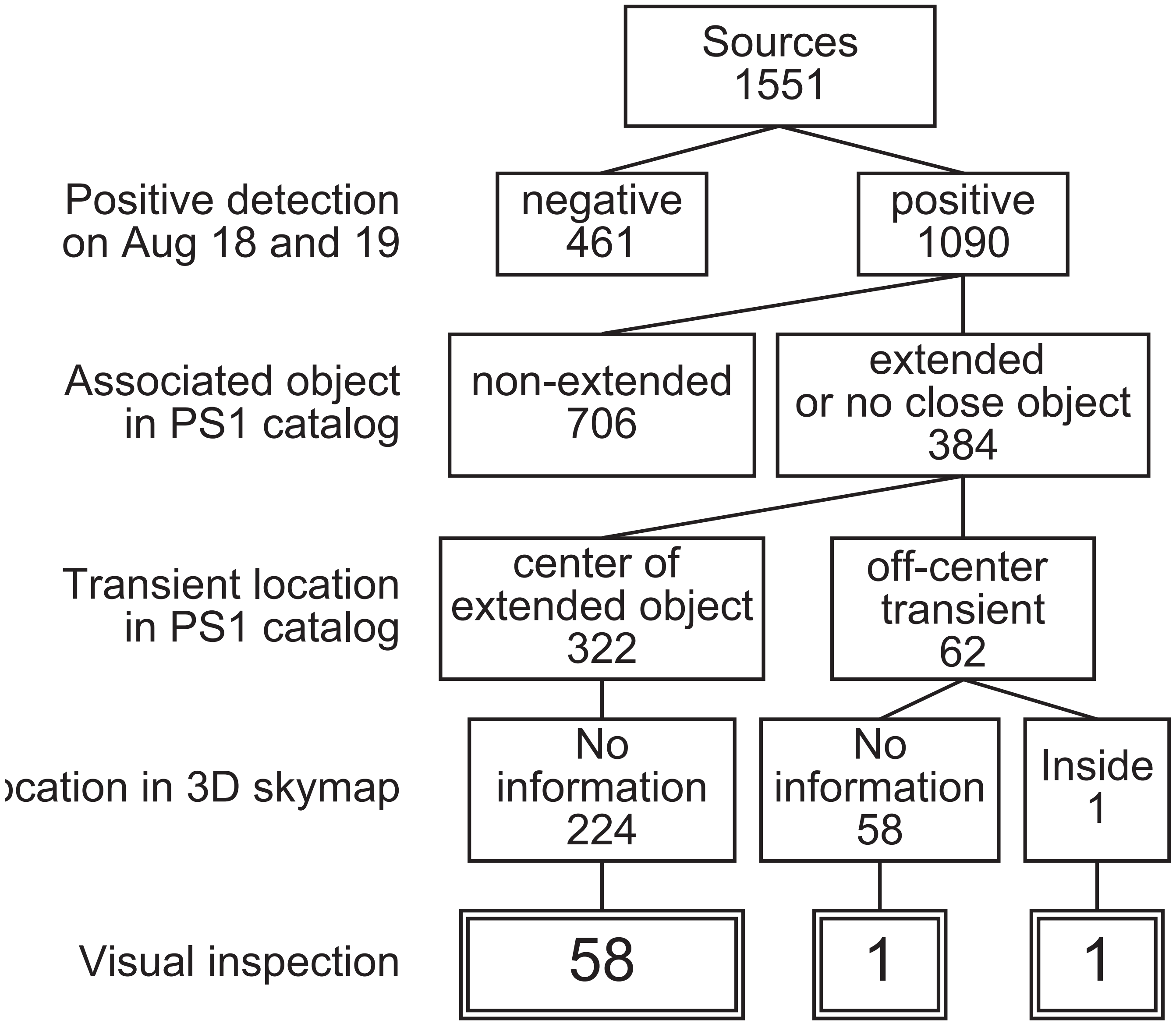
(Utsumi, MT et al. 2017, PASJ)

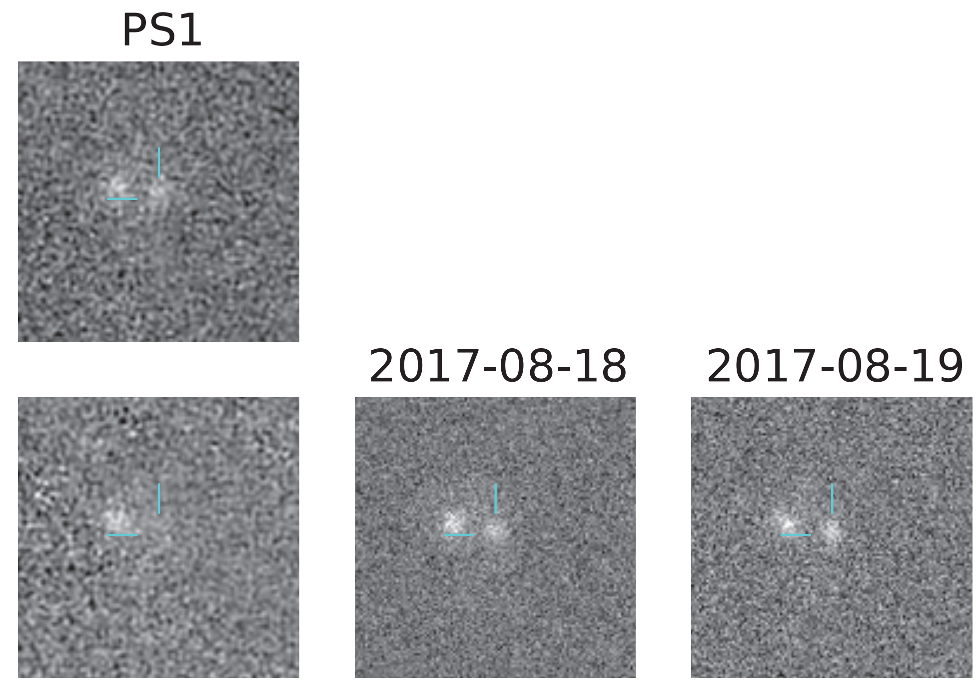
Survey with Subaru/HSC



Tominaga, MT et al. 2018, PASJ in press, arXiv:1710.05865

DECam: Soares-Santos et al. 2017





Remaining 59 objects
(58 center, 1 offset)

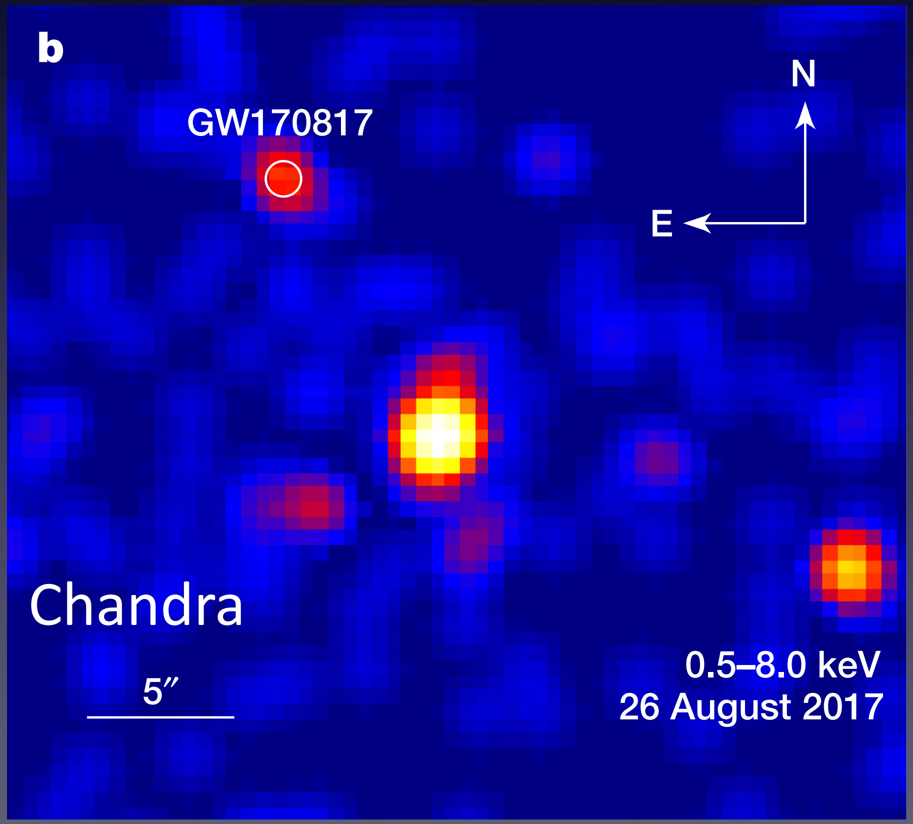
Tominaga, MT et al. 2018,
PASJ in press, arXiv:1710.05865

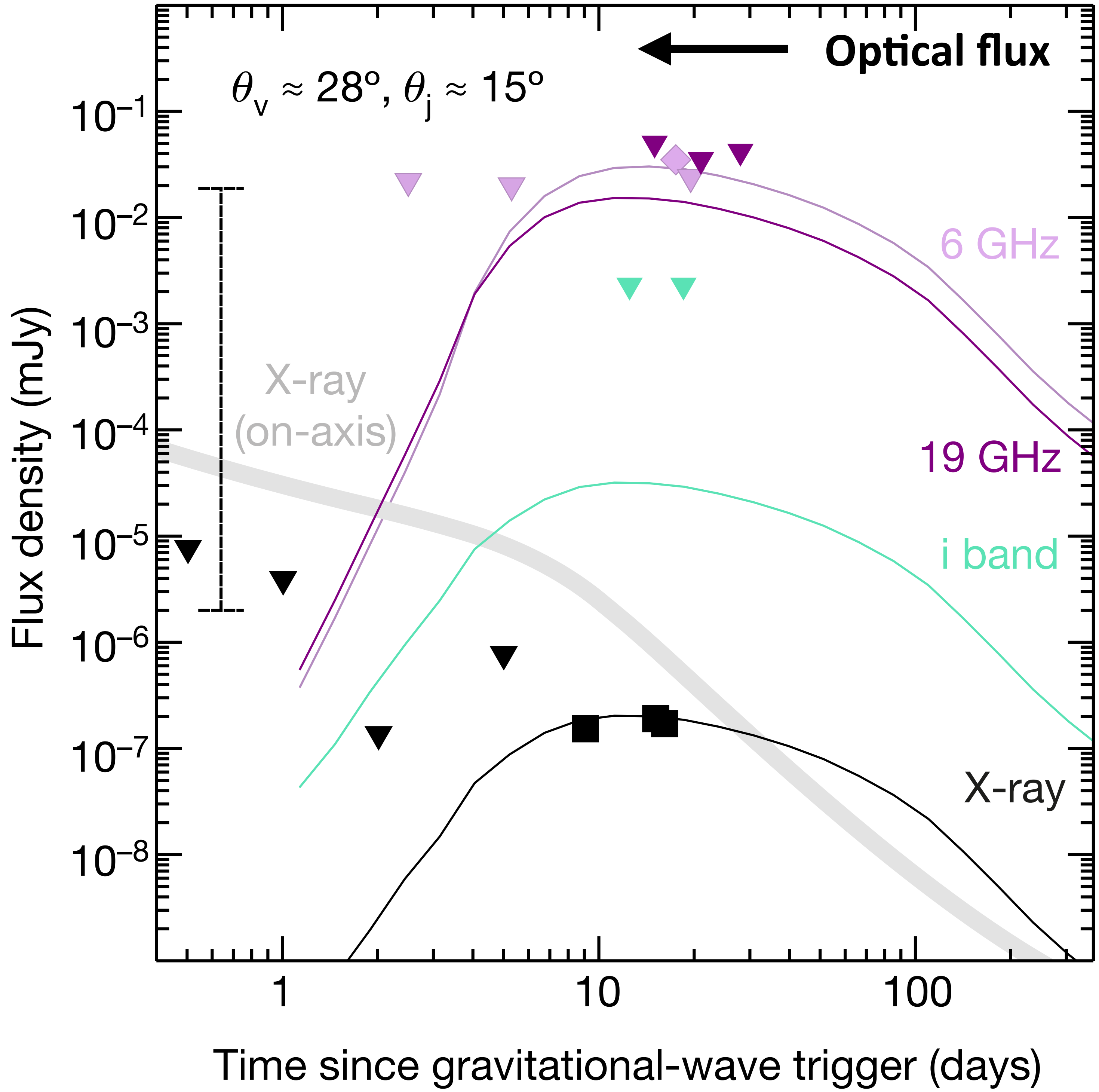
Probability to be inside of 3D map
= 9.3×10^{-5}

(Faint end of luminosity function)

That of NGC4993
= 0.64

X-ray and radio @ ~10 days





Troja+17

Electromagnetic signature from compact binary merger (NS-NS or BH-NS)

- X-ray/gamma-ray

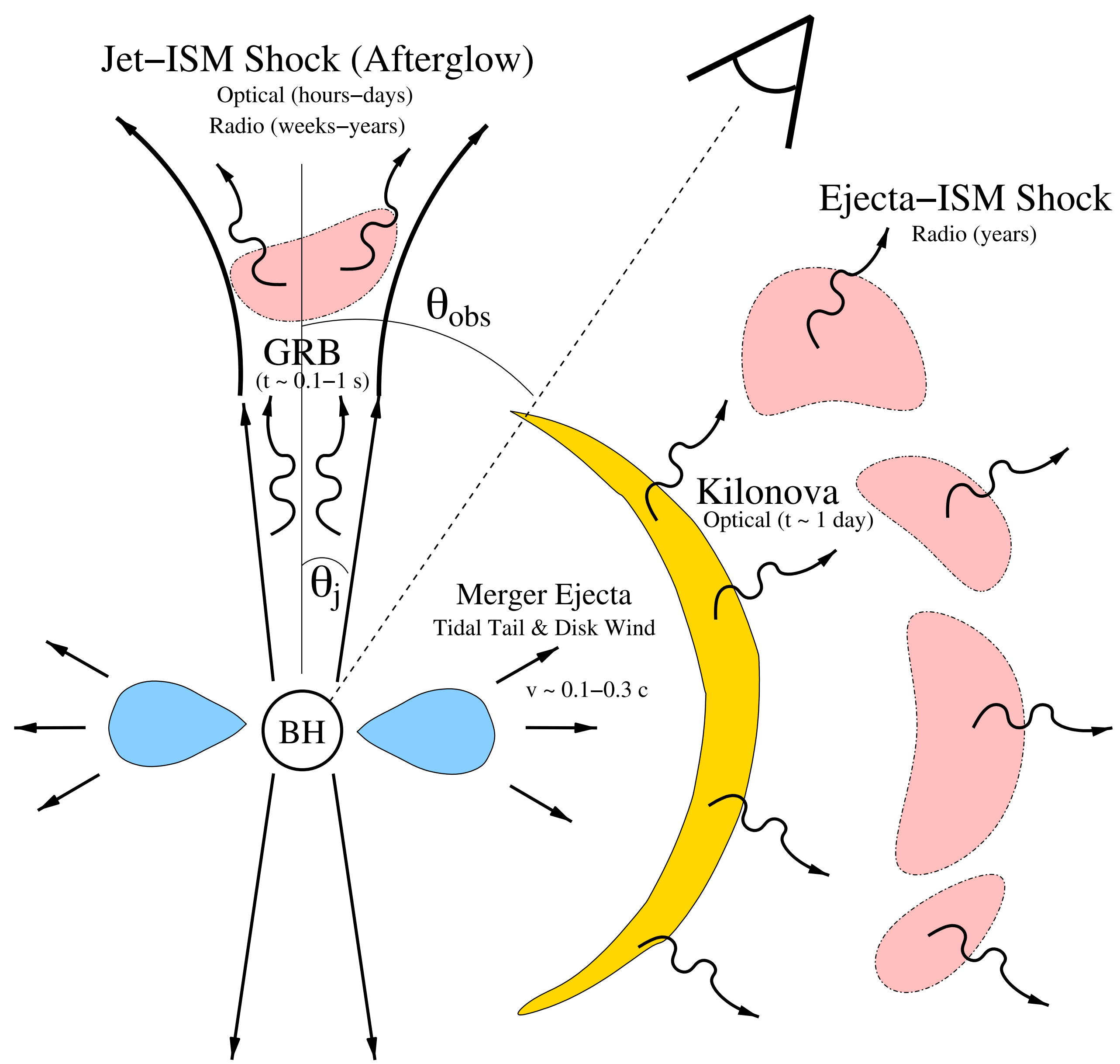
  Short GRB: strongly beamed

- Radio
  - Delayed by years
  - Emission from jet can come earlier

- Optical/NIR

  Delayed by only ~ 1 week

  Isotropic



Metzger & Berger 2012, ApJ 746, 48

Summary of multi-messenger observations

Abbott+17

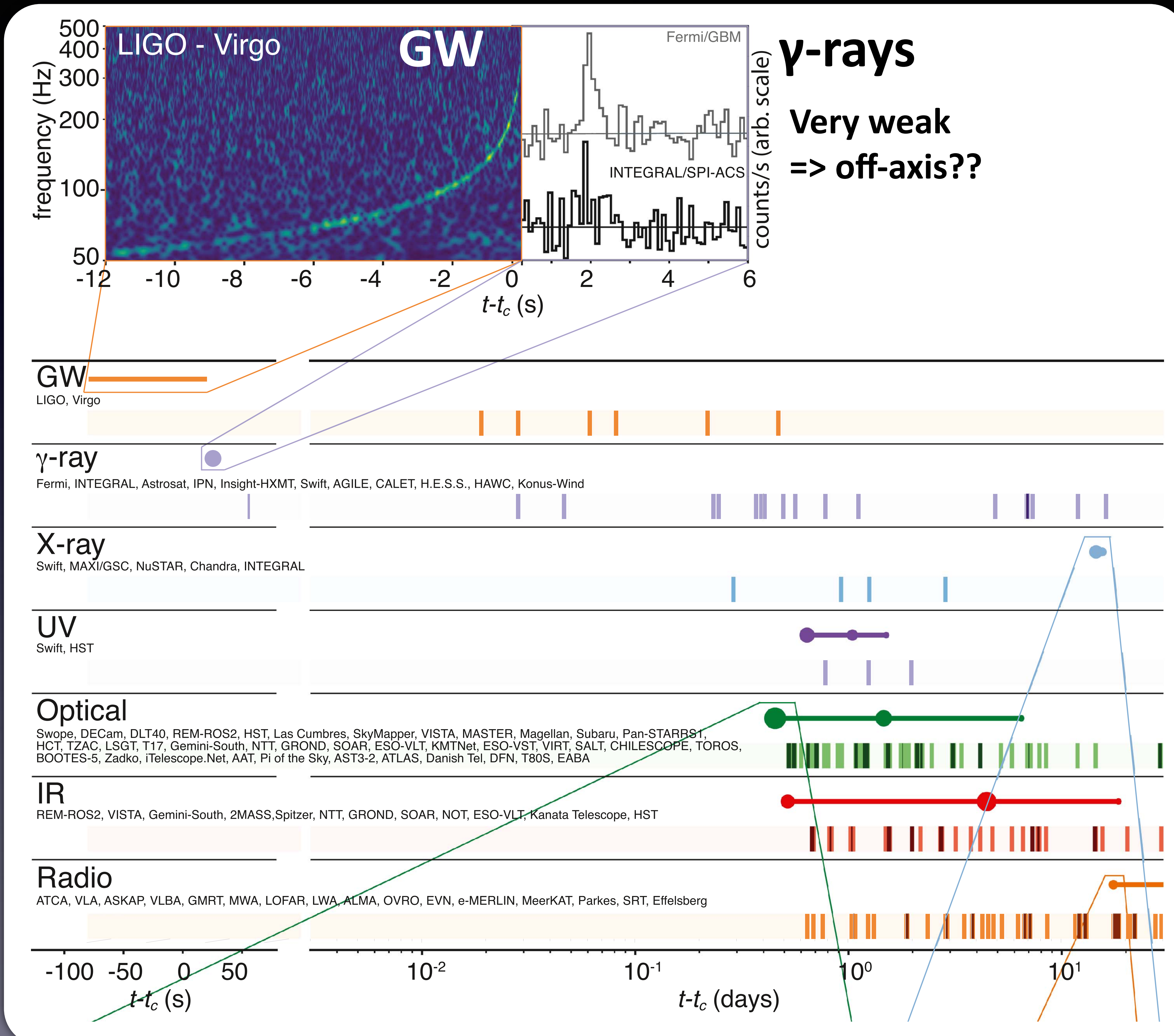
GRB

X-ray

Blue kilonova

Red kilonova

Radio



γ-rays

Very weak
=> off-axis??

What we learn from multi-messenger astronomy

- **Hubble constant**
  - GW => luminosity distance, EM => redshift
  - $H_0 = 70^{+12}_{-8}$ km s^{-1} Mpc^{-1}
- **Speed of GW**
  - Gamma-rays arrived 1.7 s after the merger (after 130 M light year race => 4×10^{15} s)
- **Physics of neutron star**
  - R ~< 14 km (for 1.4 Msun NS)
- **Jet formation/propagation in the merger**
  - ~2 sec?
- **Origin of heavy elements**

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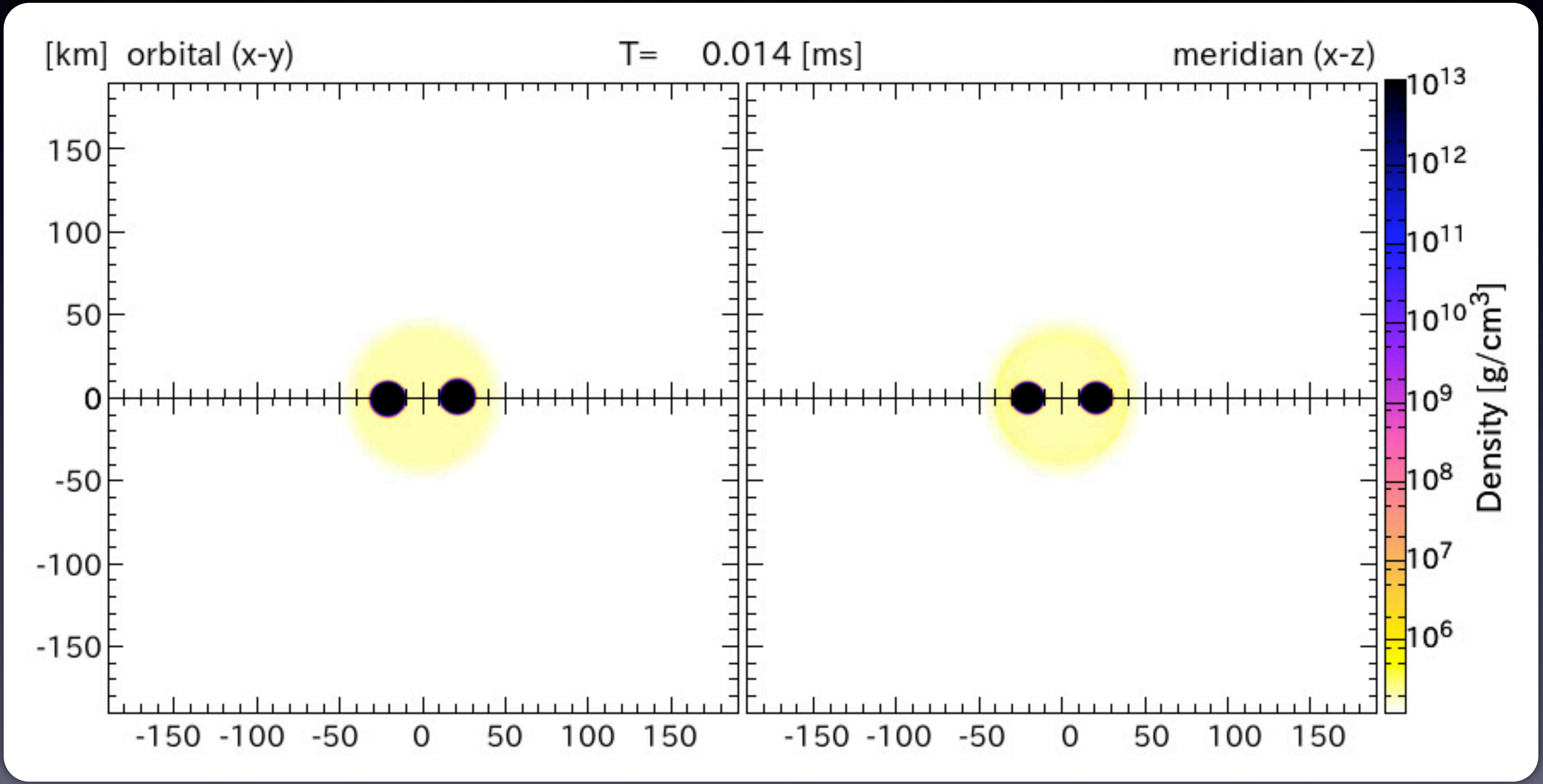
Mass ejection from NS merger

Top view **Side view**



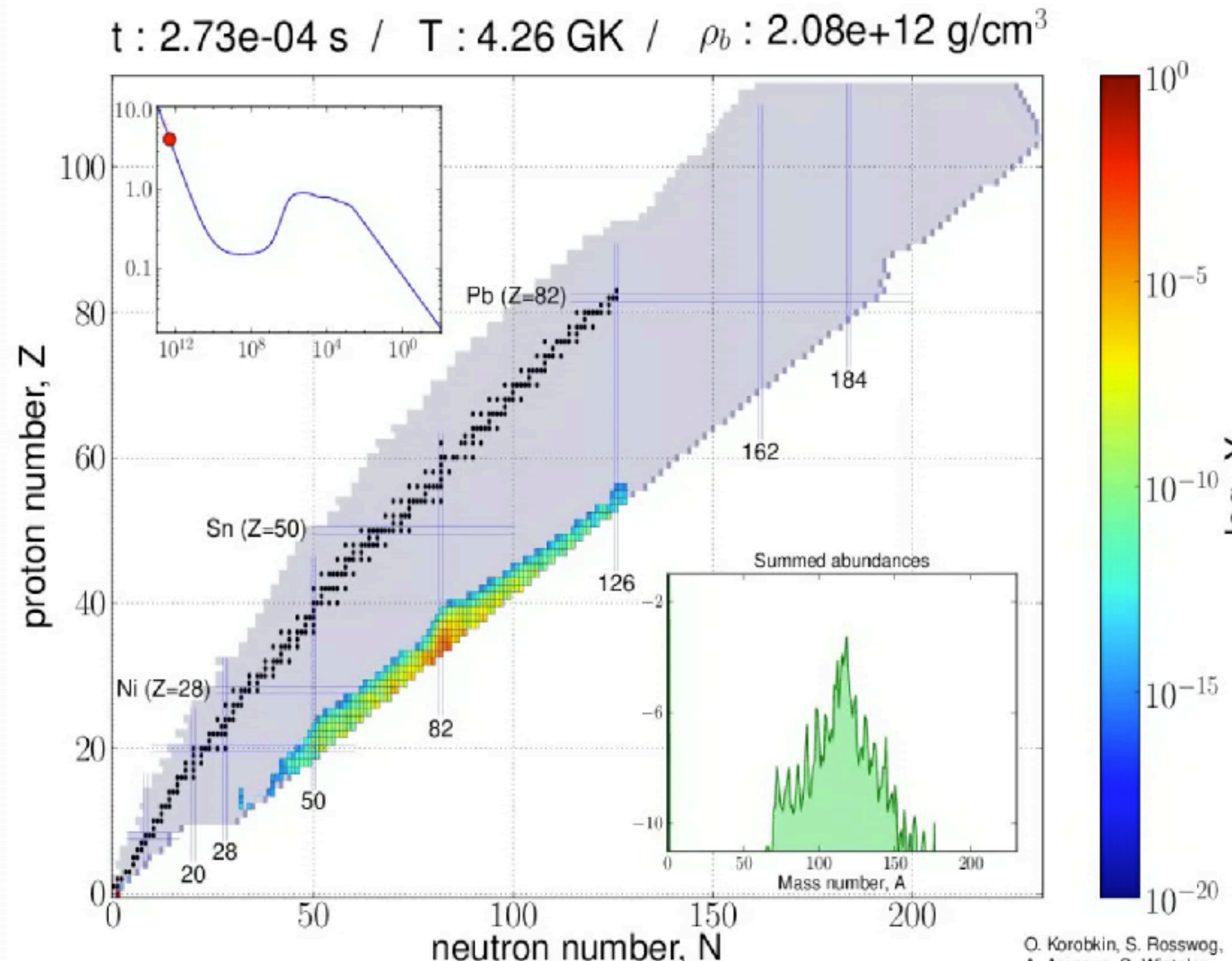
Sekiguchi+15, 16

- Tidal disruption
- Shock heating

M ~ 10^{-3} - 10^{-2} Msun

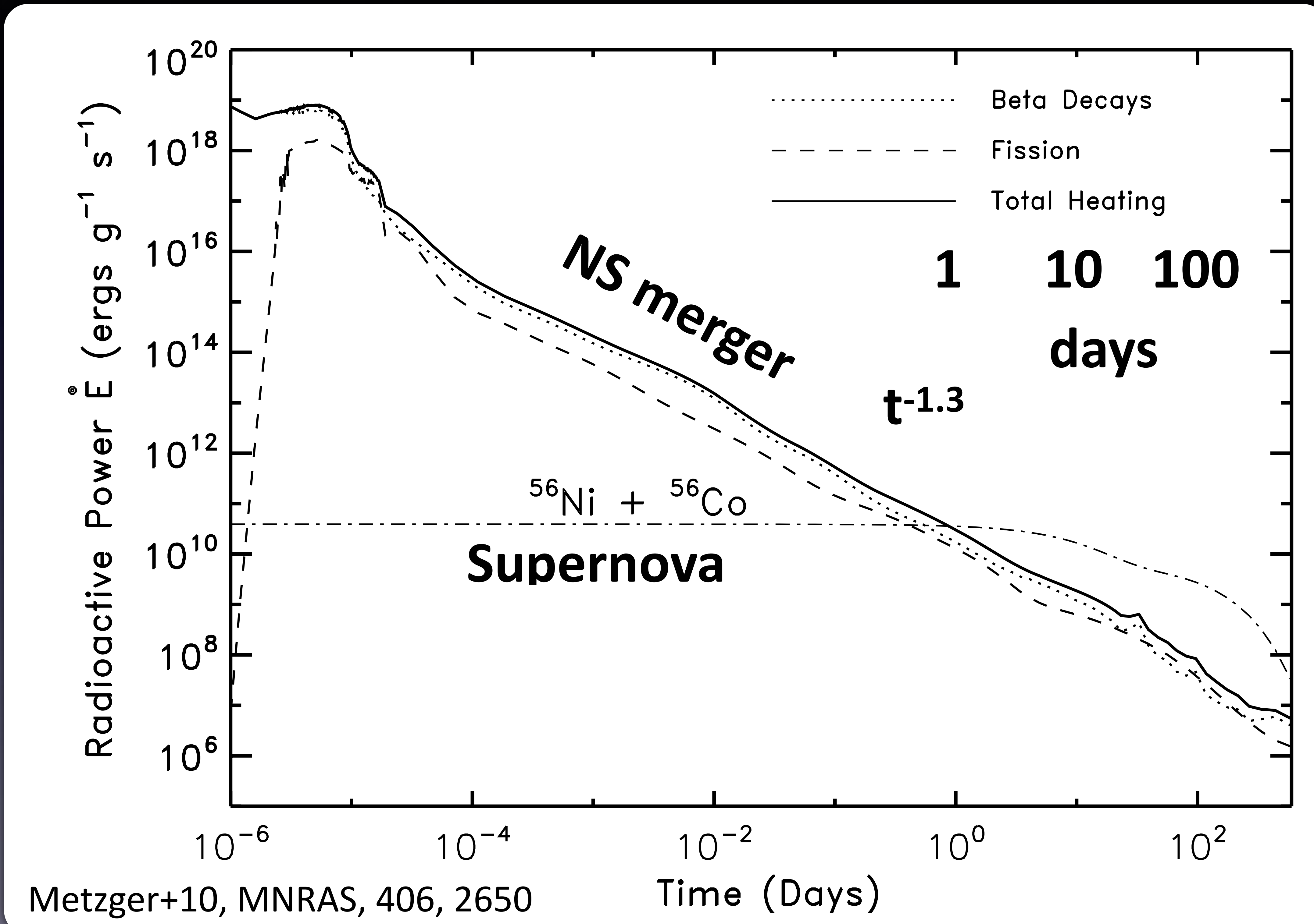
v ~ 0.1 - 0.2 c

r-process nucleosynthesis in NS merger



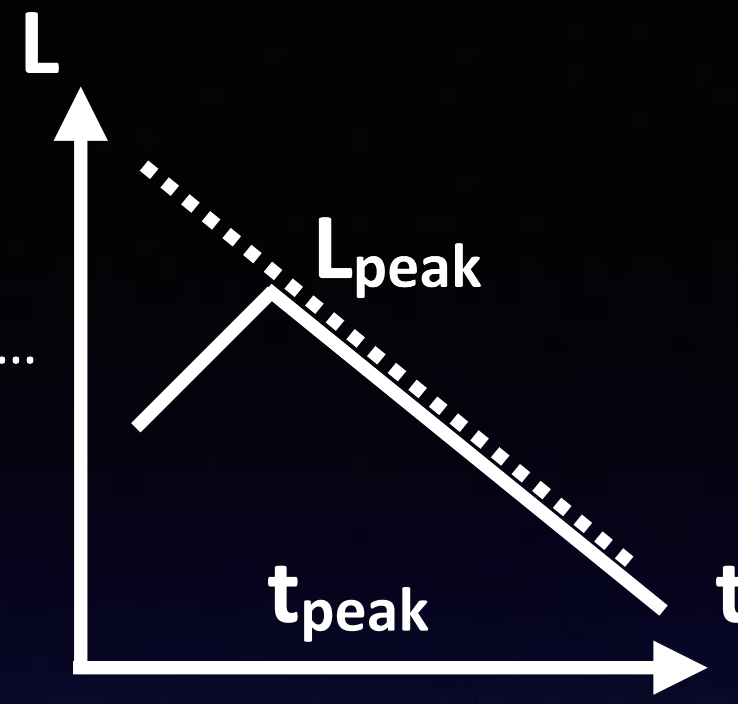
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

Radioactive energy => optical emission



“Kilonova/Macronova"

Initial works: Li & Paczynski 98, Kulkarni 05, Metzger+10, Goriely+11, …
High opacity: Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13, …



Timescale

$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$

$$\simeq 8.4 \text{ days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}$$

bound-bound transitions of heavy elements

Luminosity

$$L_{\rm peak} = L_{\rm dep}(t_{\rm peak})$$

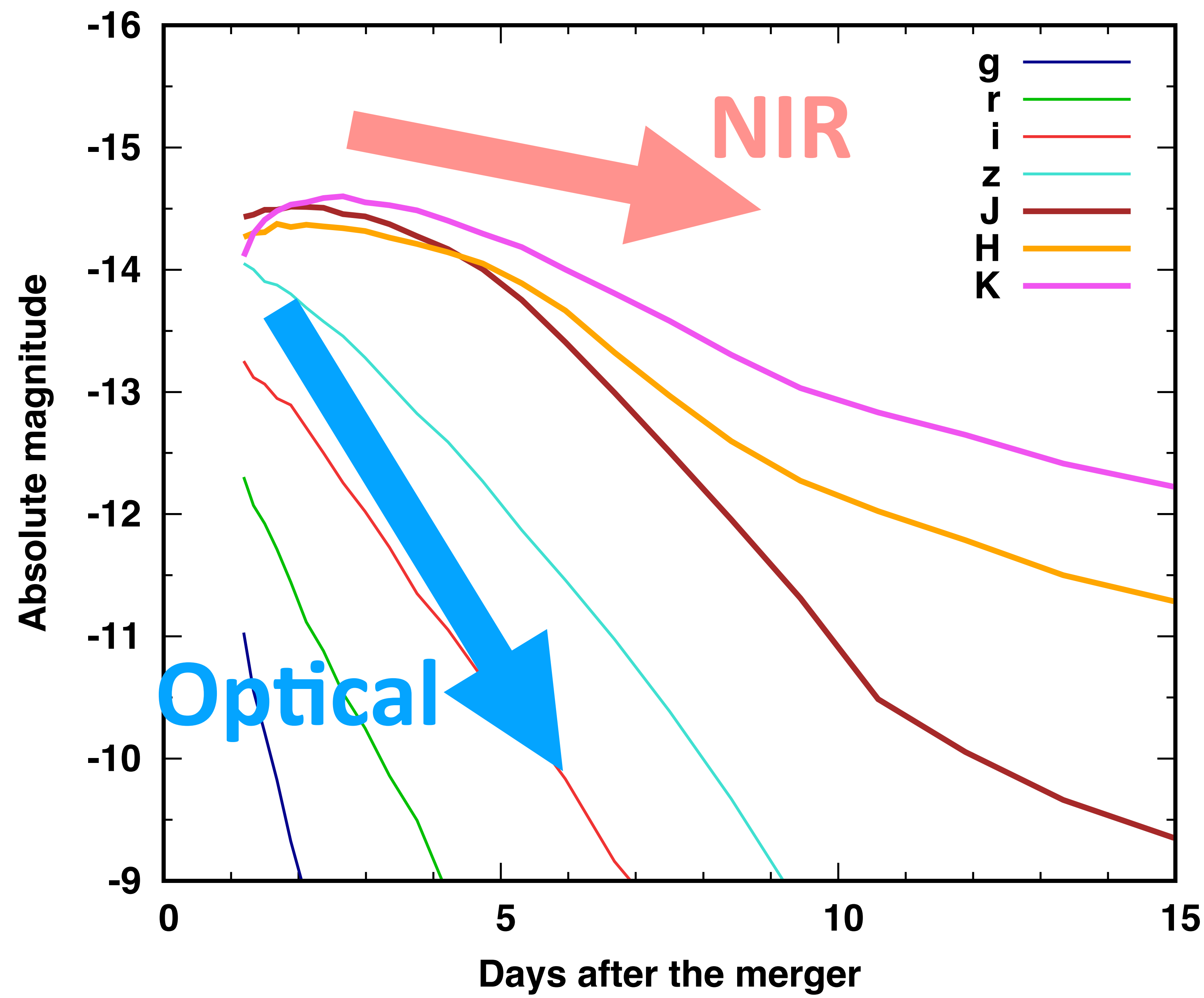
$$\simeq 1.3 \times 10^{40} \text{ erg s}^{-1} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{-0.65}$$

*assuming 50% thermalization

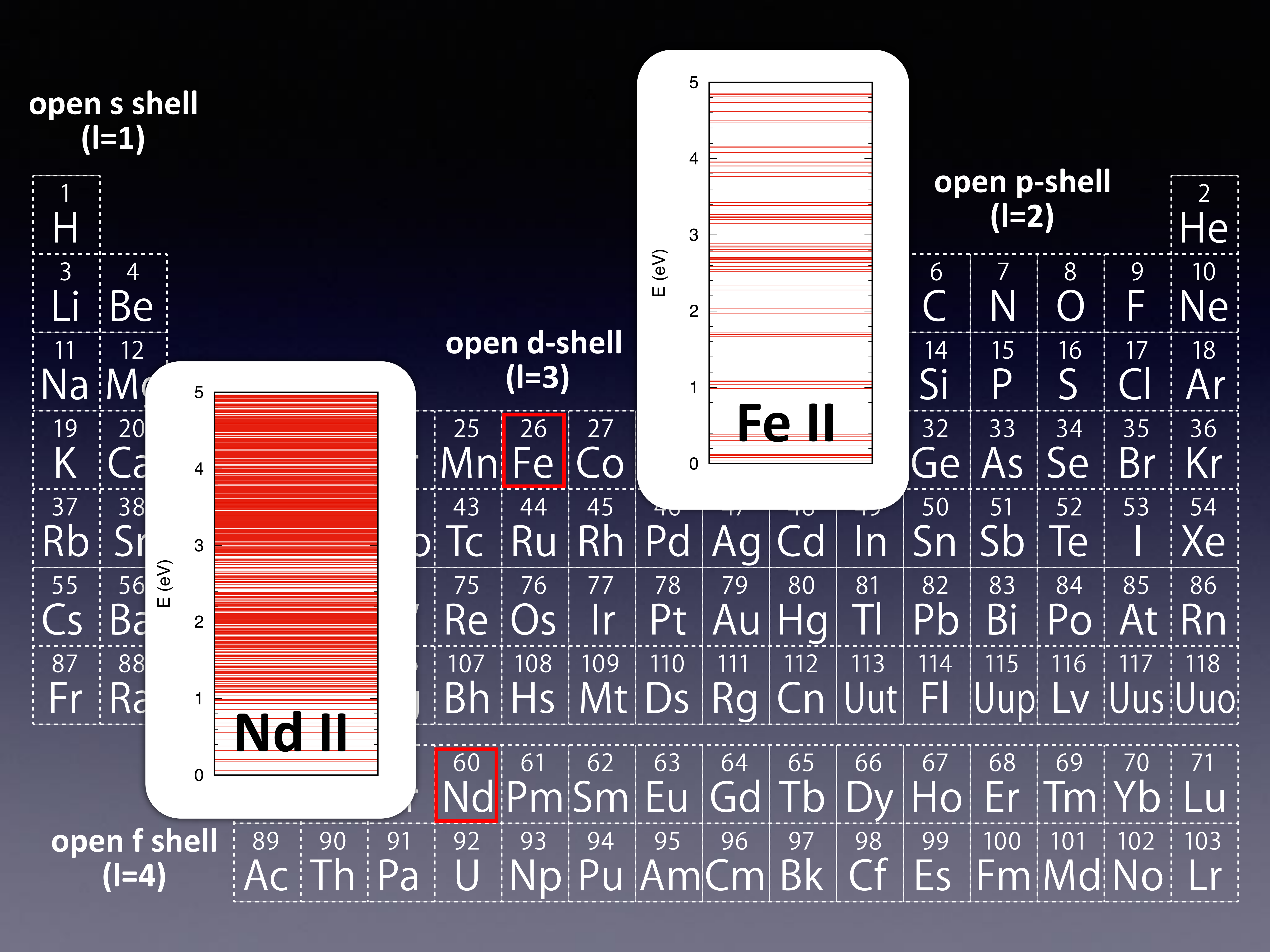
Light curves of kilonova

MT & Hotokezaka 13, MT+14,

$L \sim 10^{40}$-10^{41} erg s^{-1}
t ~ weeks
NIR > Optical

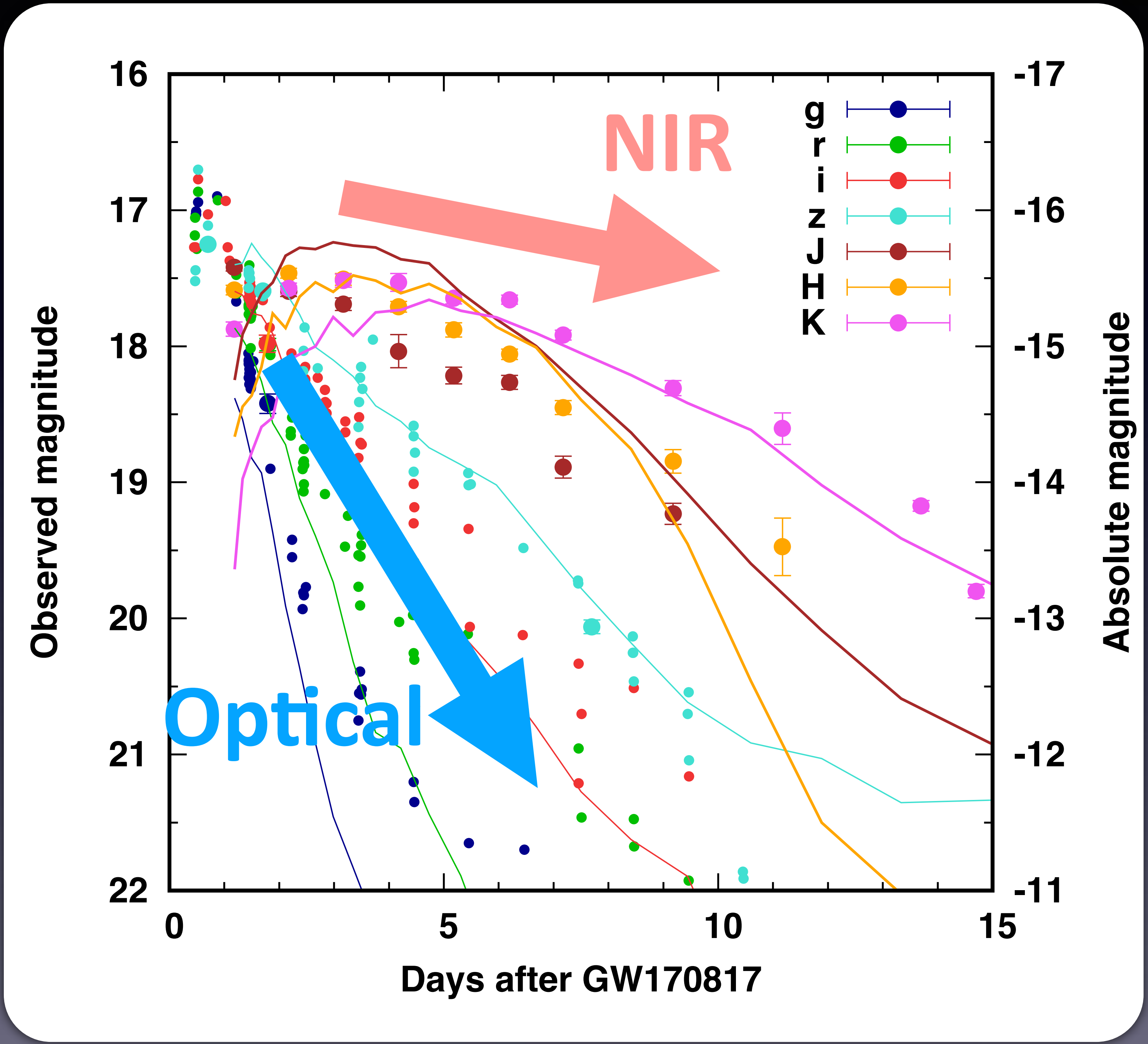


Model: MT+17a


open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
1 H
2 He
3 Li
4 Be
6 C
7 N
8 O
9 F
10 Ne
11 Na
12
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20
25 Mn
26 Fe
27 Co
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38
43 Tc
44 Ru
45 Rh
Pd
Ag
Cd
In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56
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
107 Bh
108 Hs
109 Mt
110 Ds
111 Rg
112 Cn
113 Uut
114 Fl
115 Uup
116 Lv
117 Uus
118 Uuo
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
E (eV)
0
1
2
3
4
5
Fe II
E (eV)
0
1
2
3
4
5
Nd II

GW170817: light curves

- Brightness
- Timescale
- SED



Model: MT+17b

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

Clear signature of lanthanide production!!
Ejecta mass ~0.03 Msun

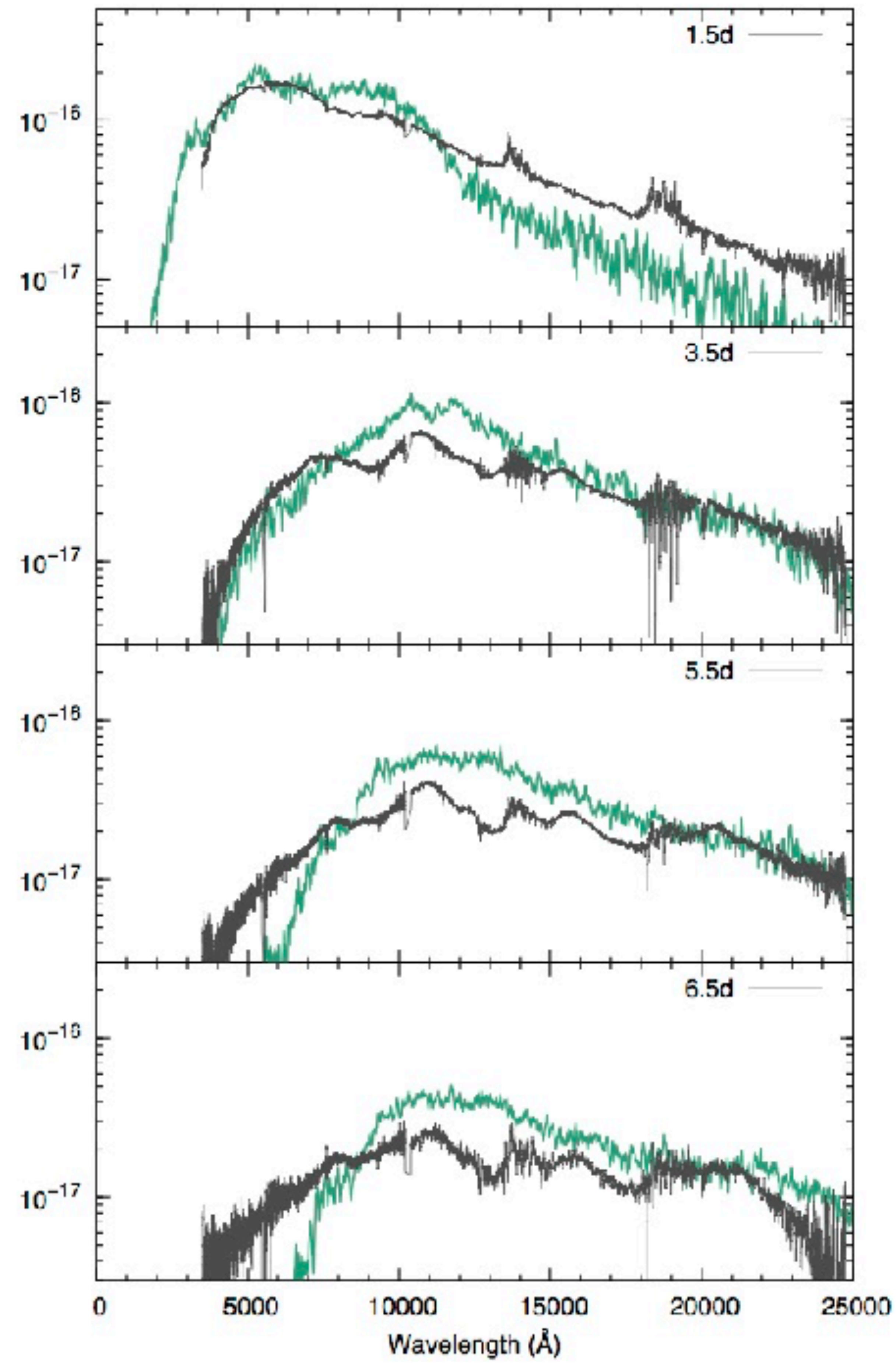
GW170817: Spectra

- Smooth spectra

Smoking gun!!

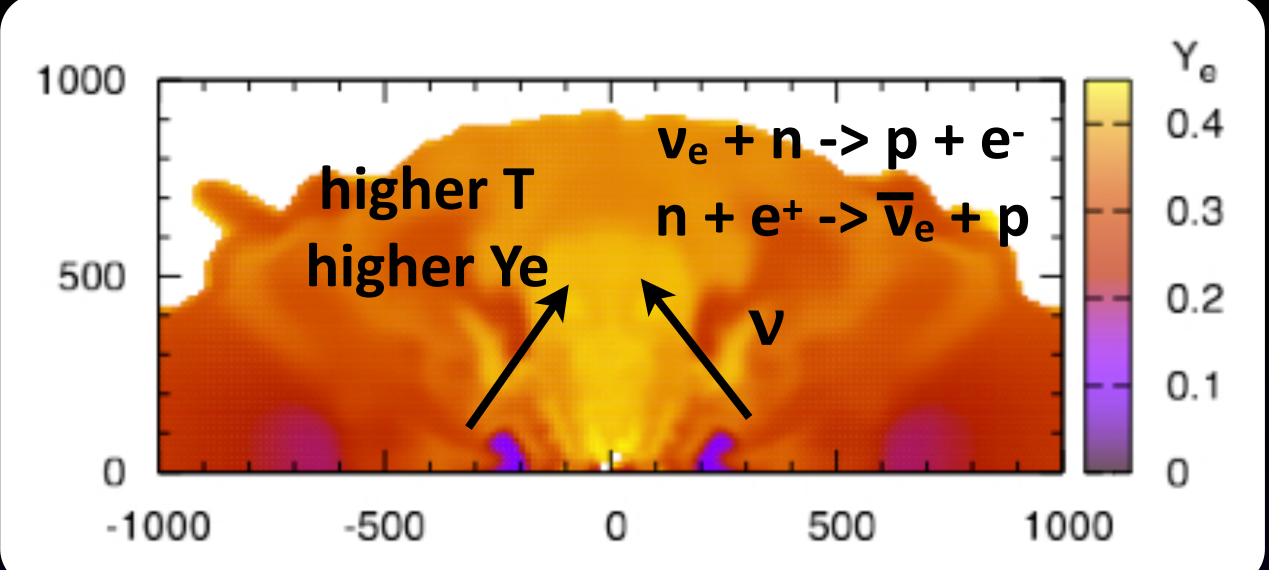
Spectra taken w/ VLT/X-shooter

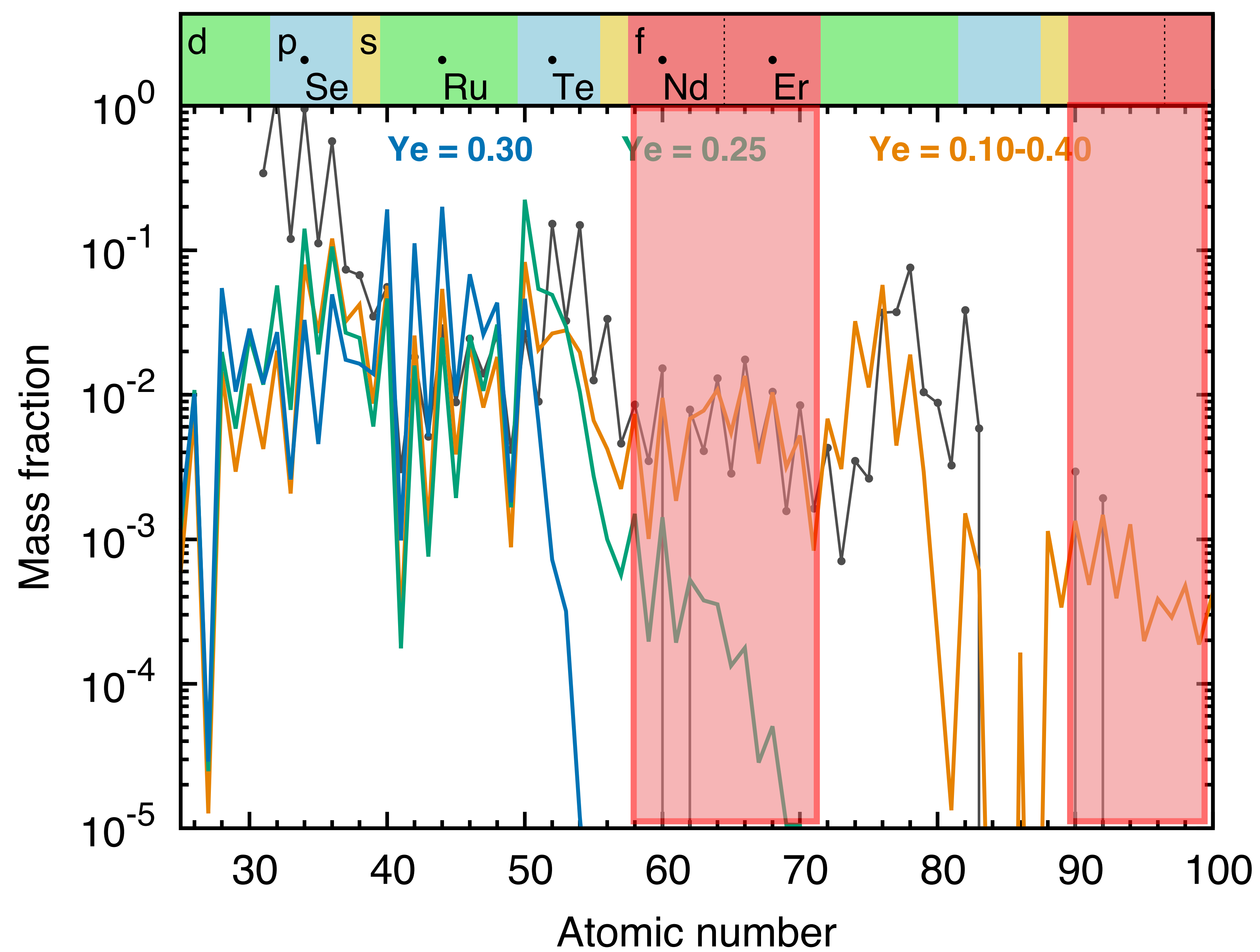
Data: Pian+2017
Model: MT+2017



$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

- Low Ye => stronger r-process
- Neutrino absorption increases Ye



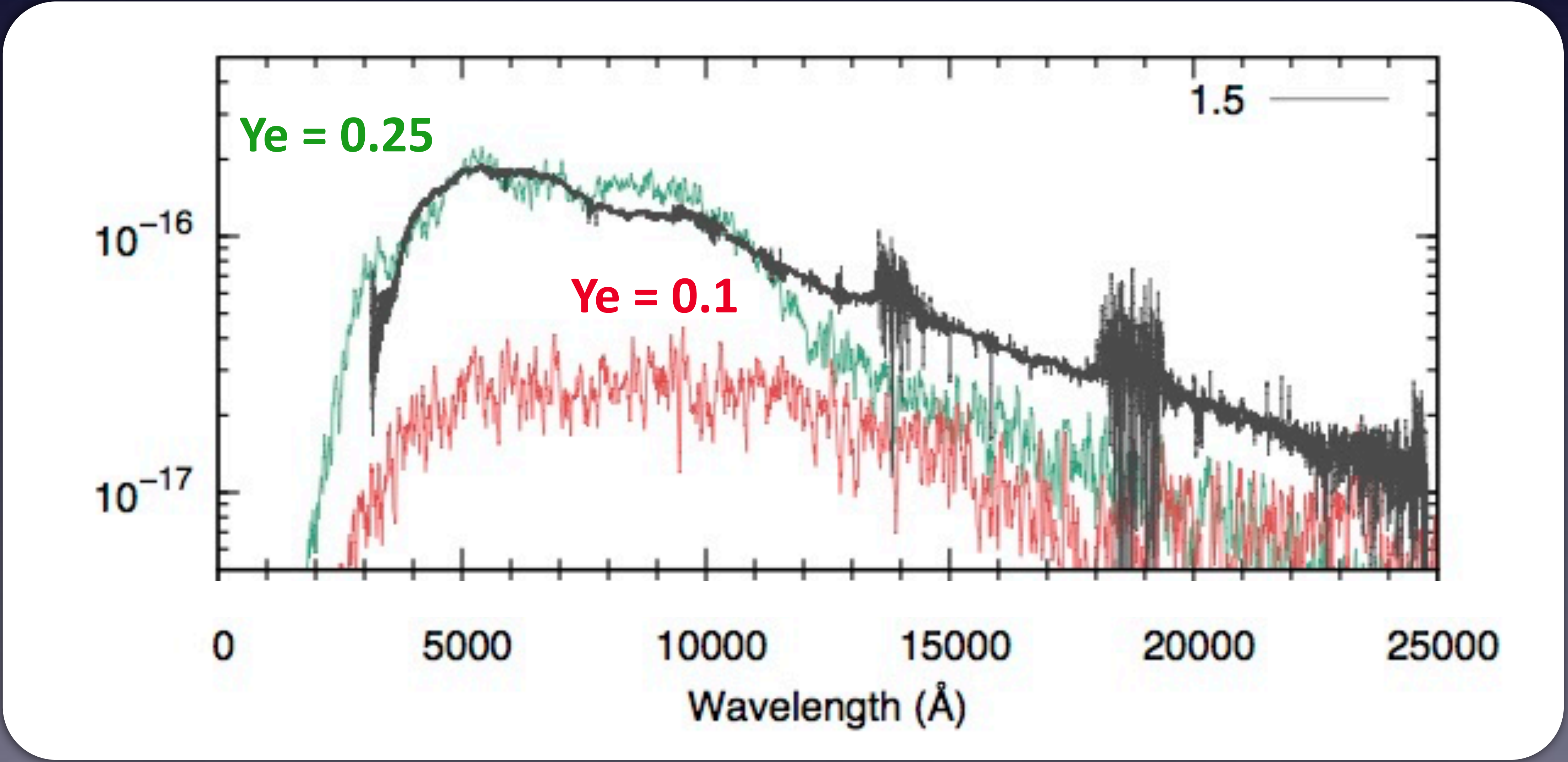


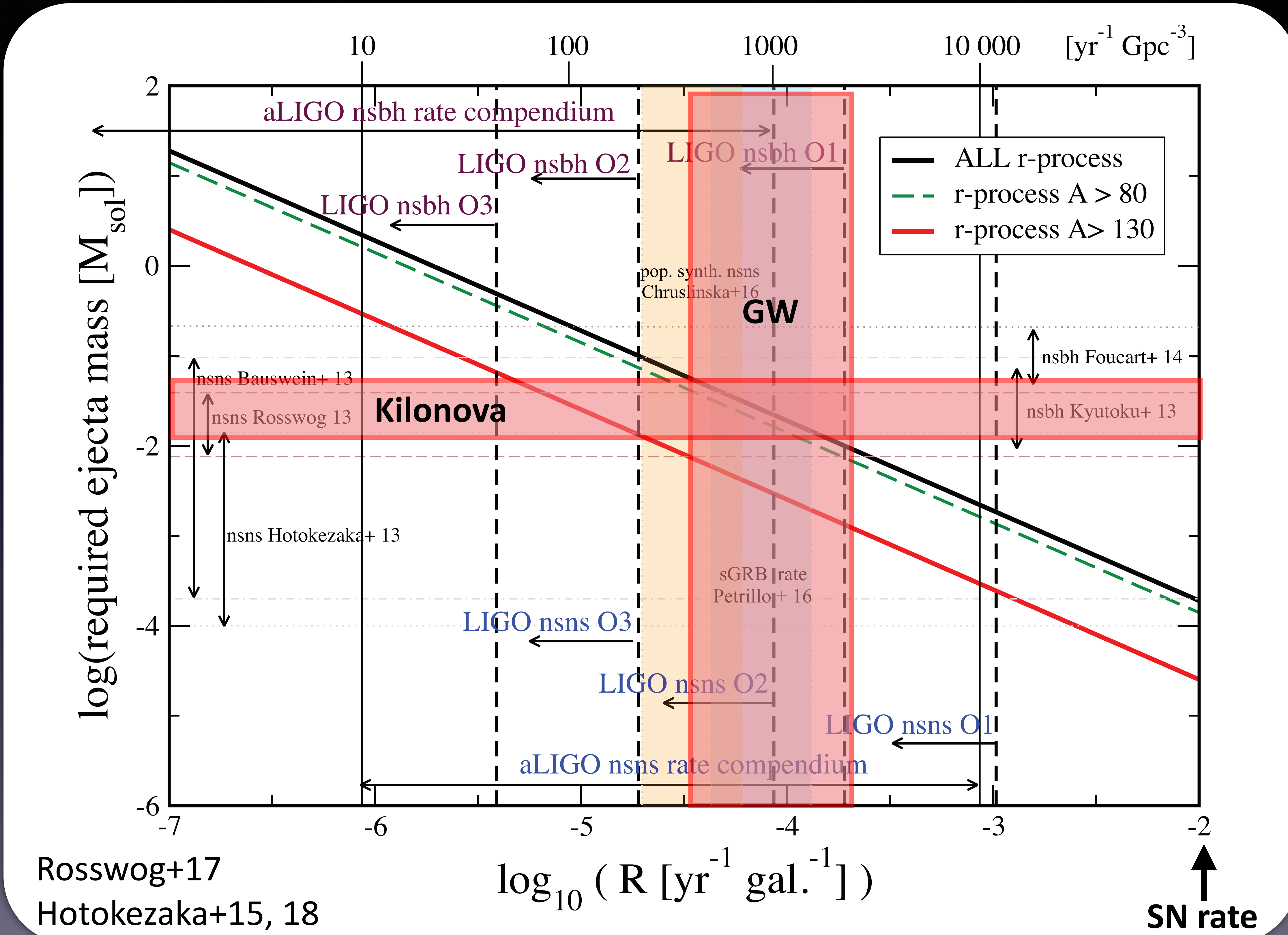
Presence of "blue" kilonova

Cowperthwaite et al. 2017;
Drout et al. 2017; Nicholl et al. 2017;
Villar et al. 2017

=> wide range of r-process elements

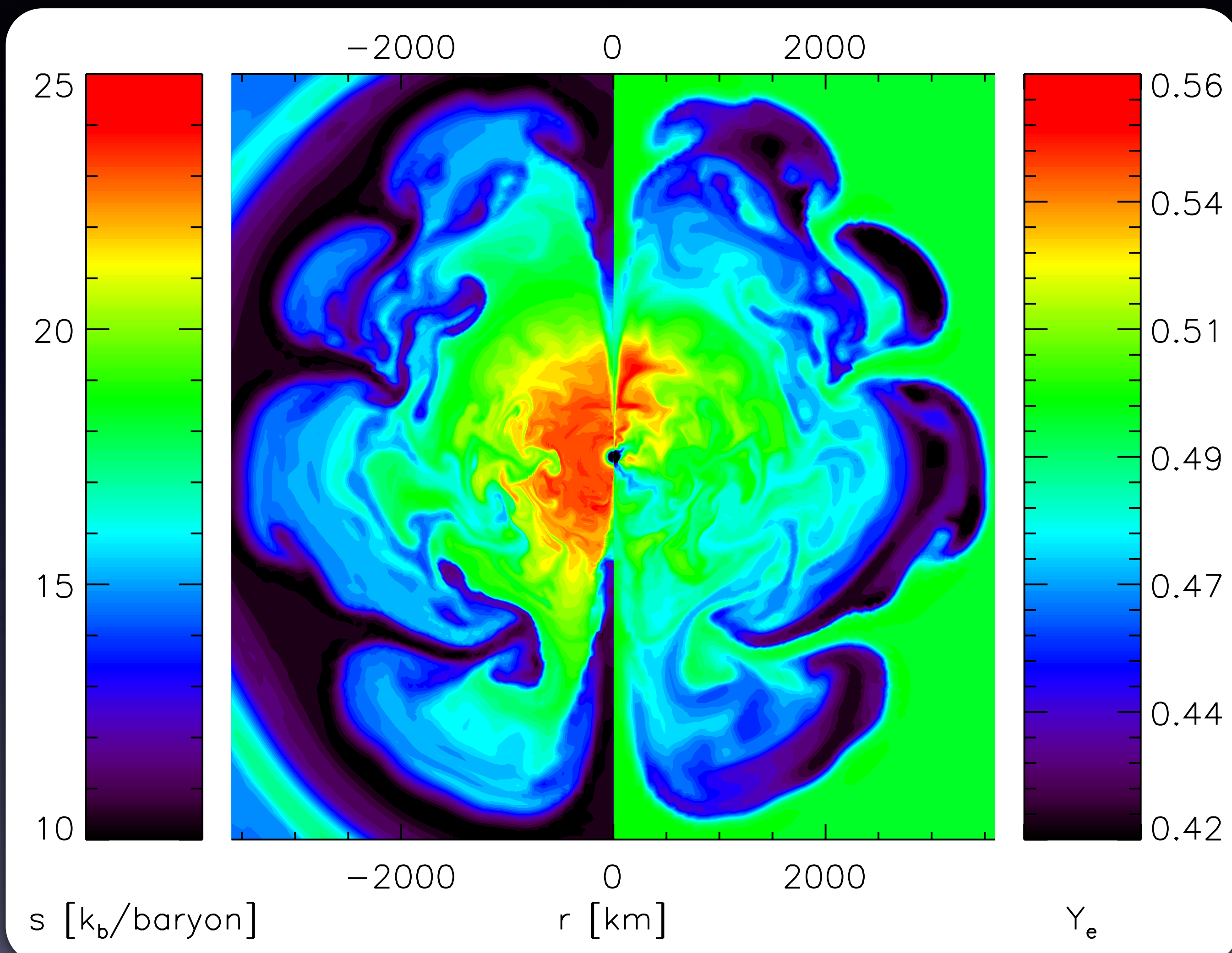
MT+2017





CAVEATS: abundance ratios are not well constrained

r-process nucleosynthesis in core-collapse supernovae



Wanajo+11, Wanajo 14

$$\nu_e + n \rightarrow p + e^-$$

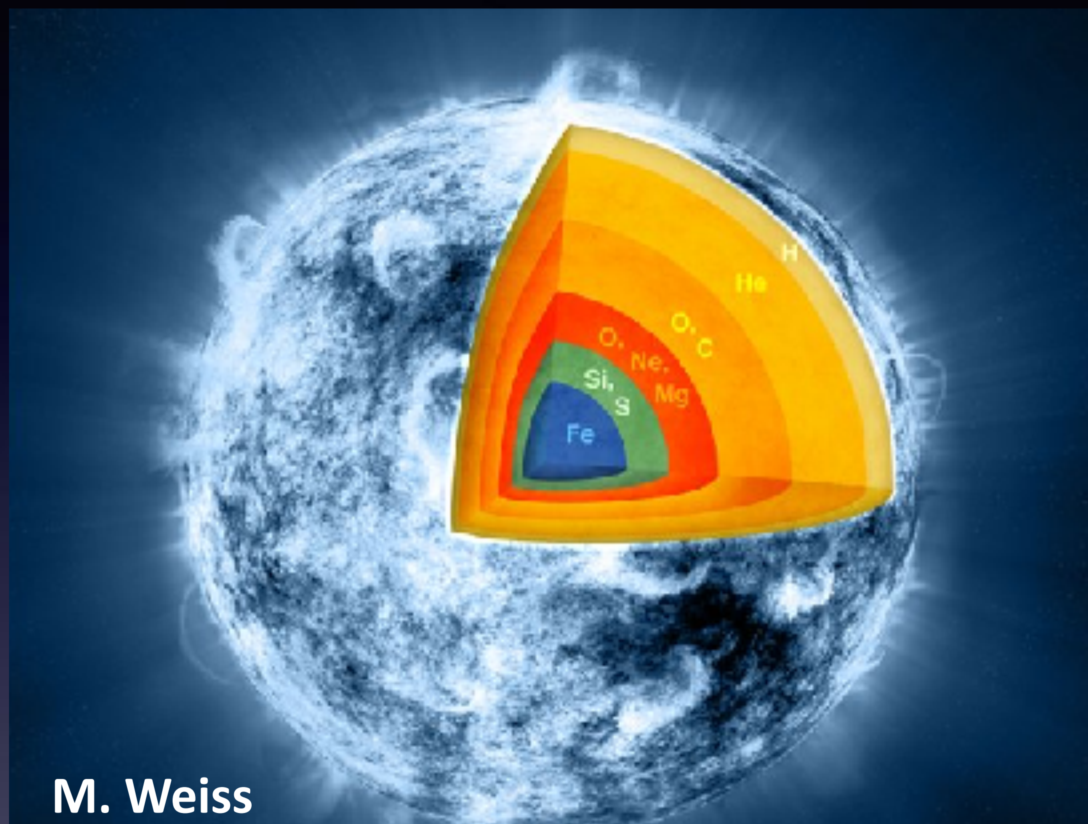
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Difficult to produce r-process elements in normal (neutrino-driven) core-collapse supernova

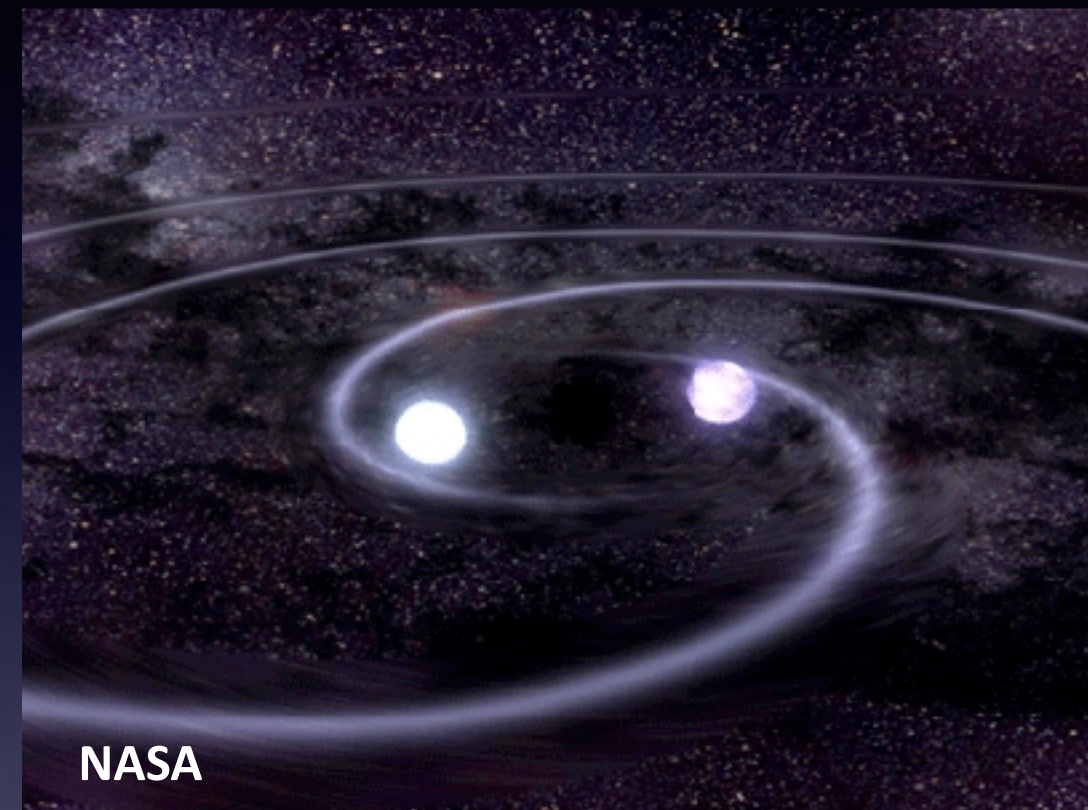
*** r-process in peculiar SNe is NOT excluded (e.g., magnetic field)**

Origin of r-process elements

Supernova



NS merger



Well known event rate

Robust r-process

Unknown event rate and ejection per event

Difficult to have r-process?

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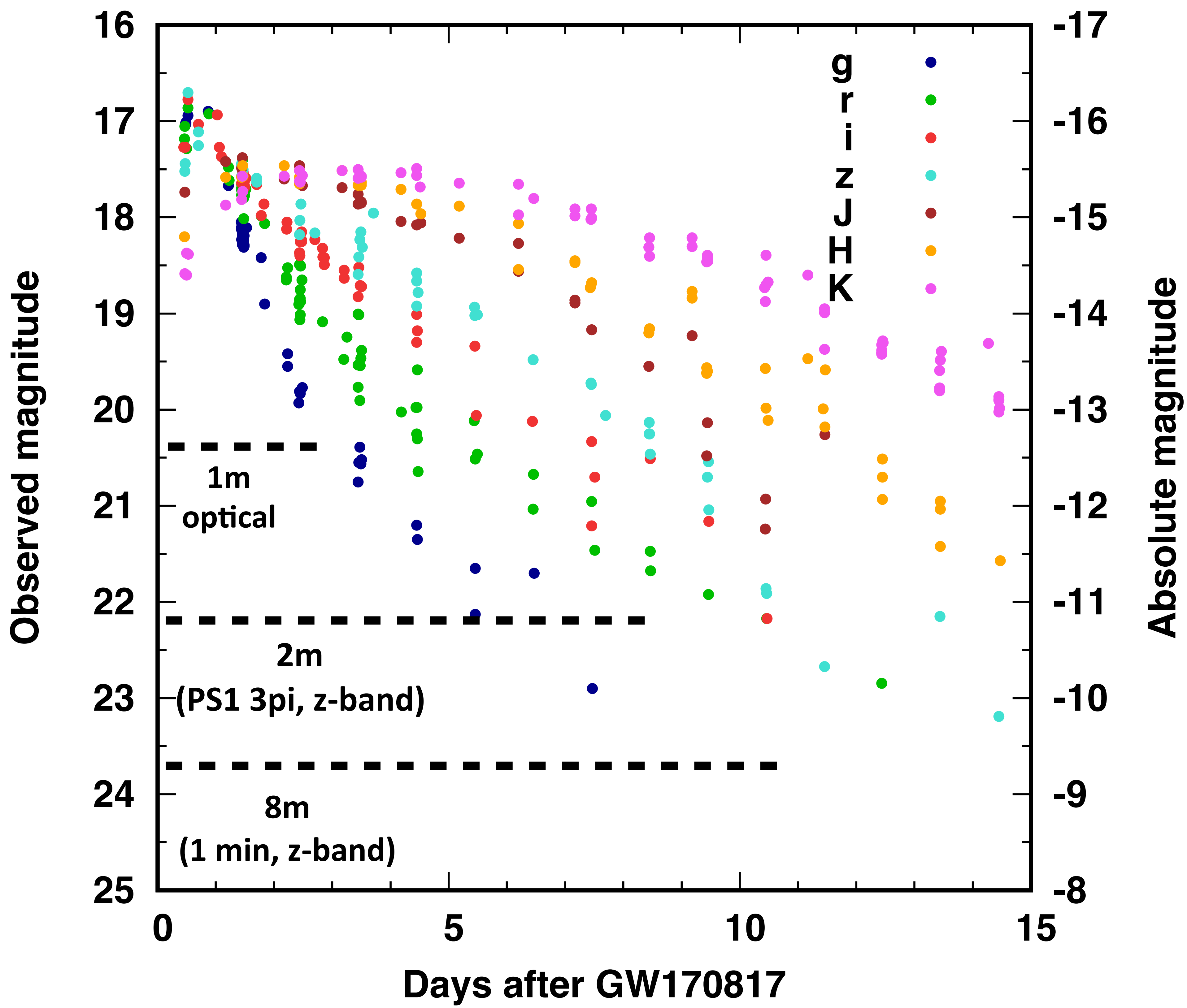
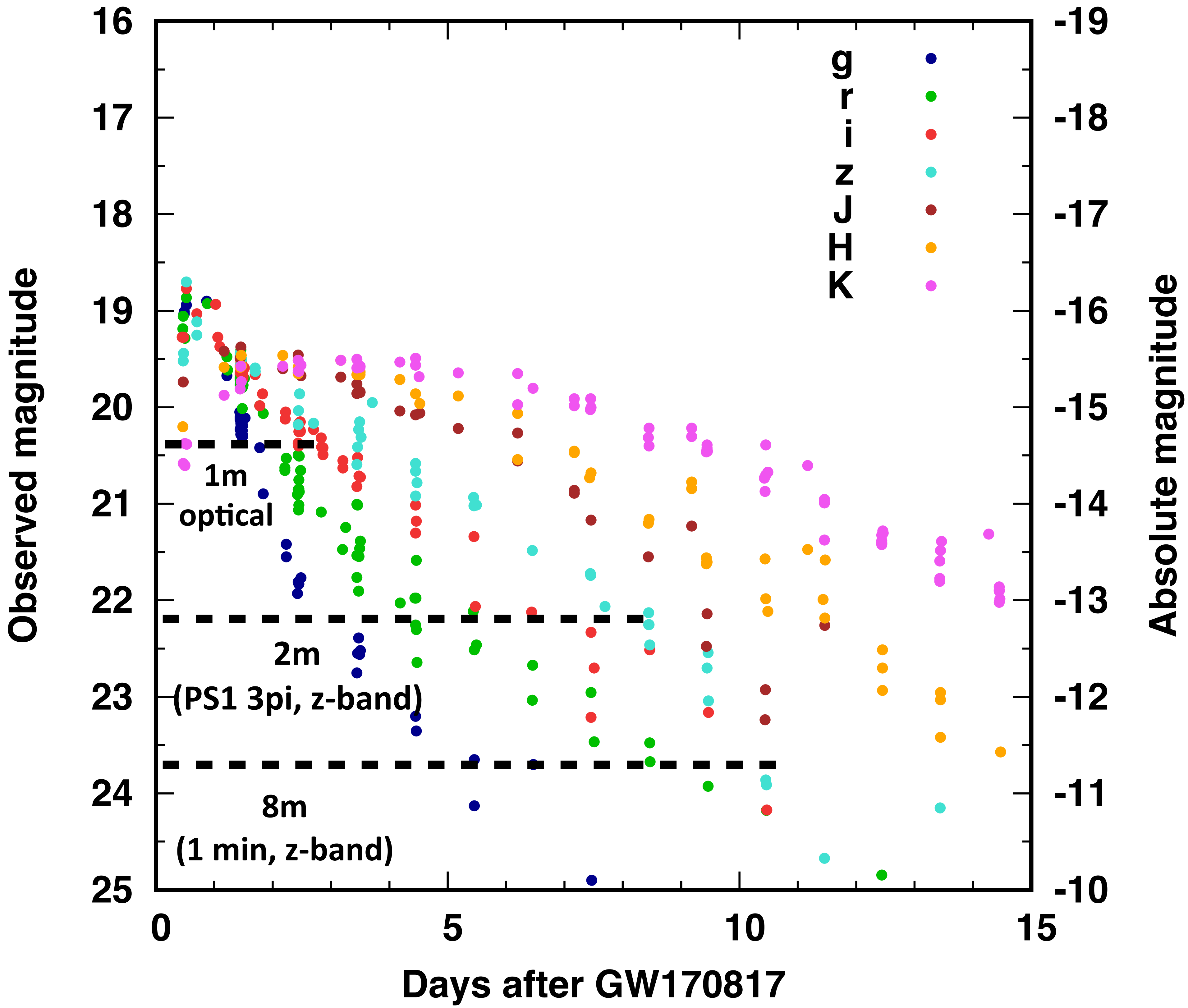
40 Mpc



Observed magnitude
16
17
18
19
20
21
22
23
24
25
Absolute magnitude
-17
-16
-15
-14
-13
-12
-11
-10
-9
-8
0
5
10
15
Days after GW170817
g
r
i
z
J
H
K
1m
optical
2m
(PS1 3pi, z-band)
8m
(1 min, z-band)

100 Mpc



16
17
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-19
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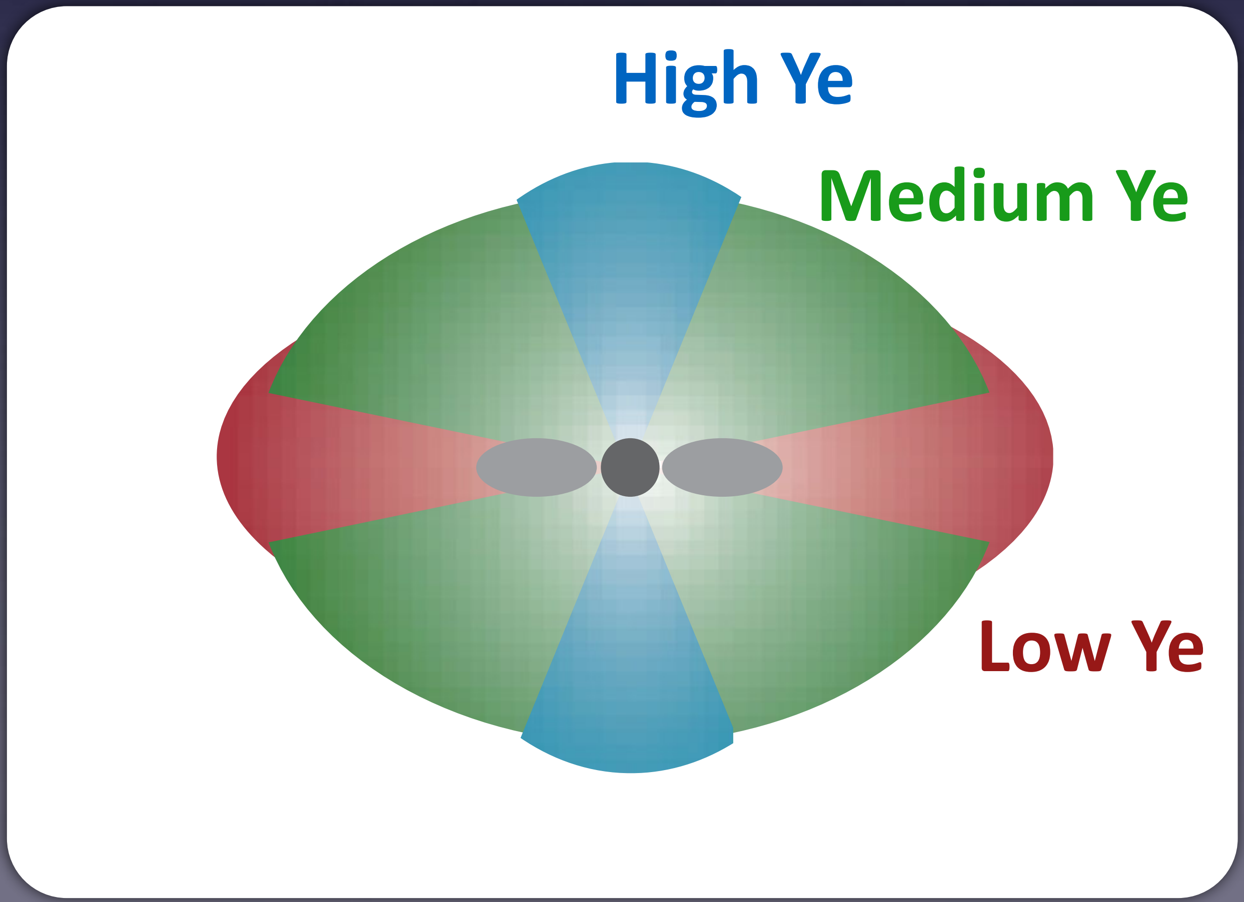
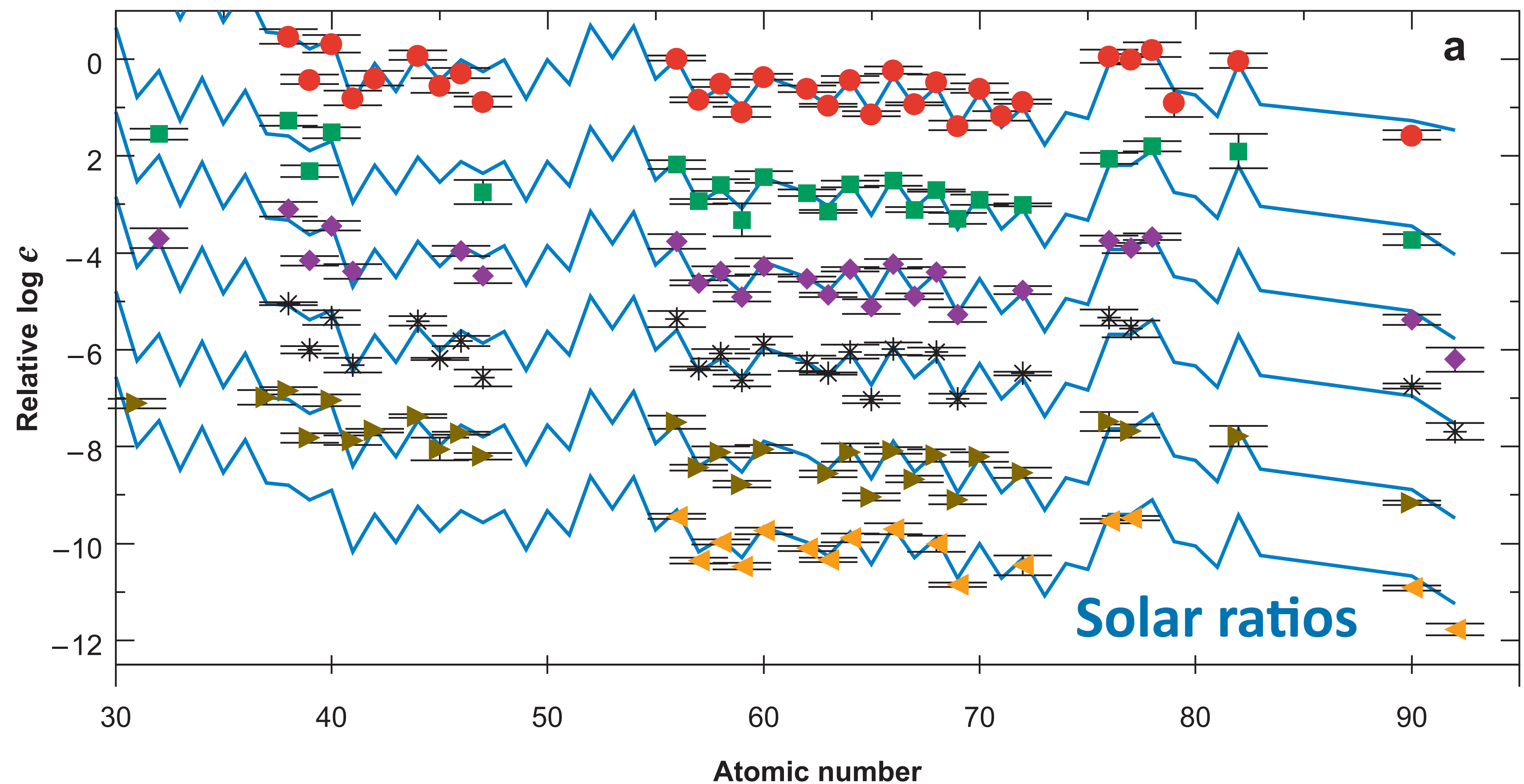
-16
-15
-14
-13
-12
-11
-10
0
5
10
15
Observed magnitude
Absolute magnitude
Days after GW170817
g
r
i
z
J
H
K
1m
optical
2m
(PS1 3pi, z-band)
8m
(1 min, z-band)

Many open questions

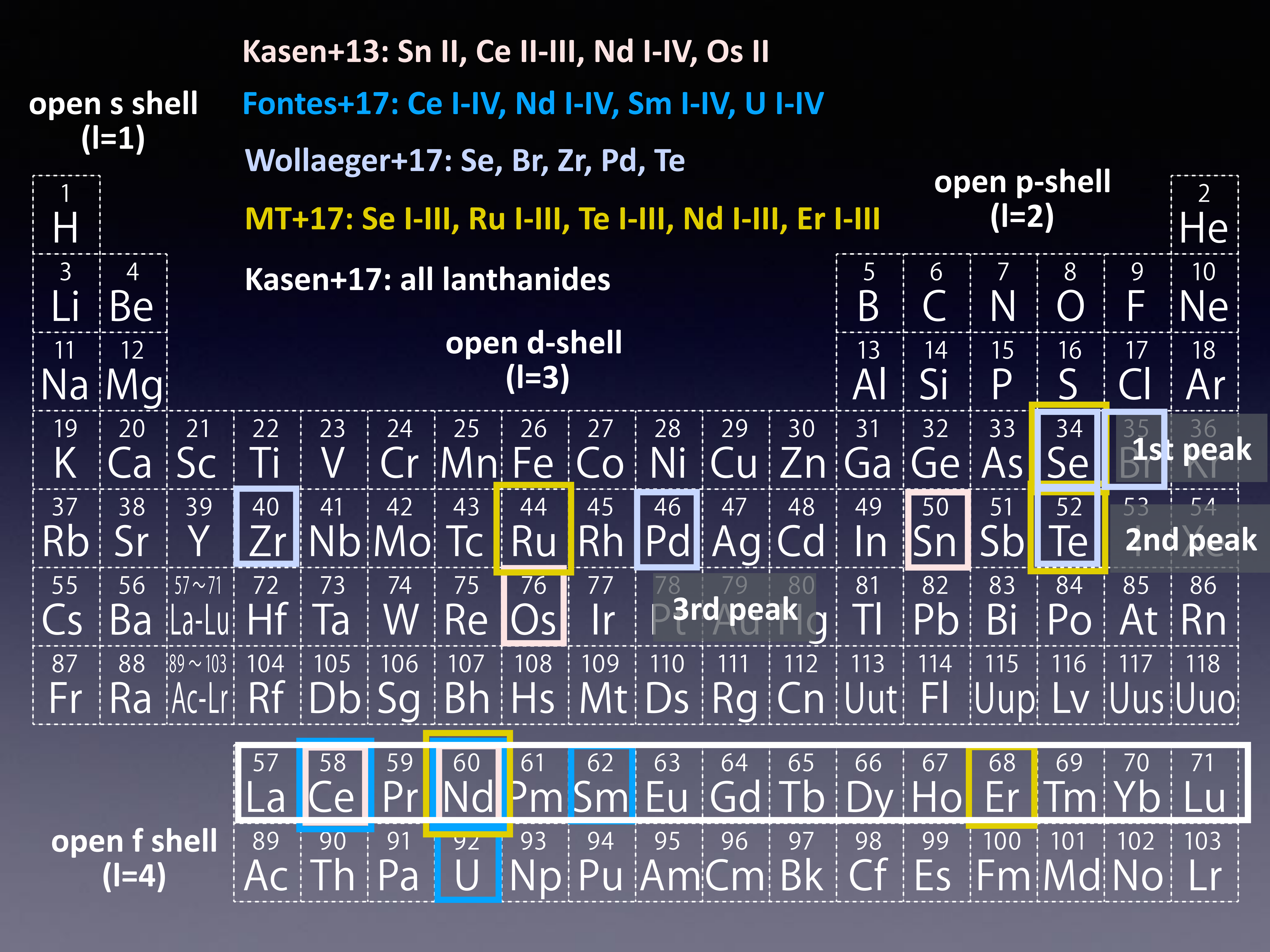
- **Origin of ejecta?**
  - Origin of “blue” and “red” component?
  - Blue component with high velocities?
- **Abundance pattern? Similar to solar abundances??**
  - 3rd peak?? (Au and Pt!)



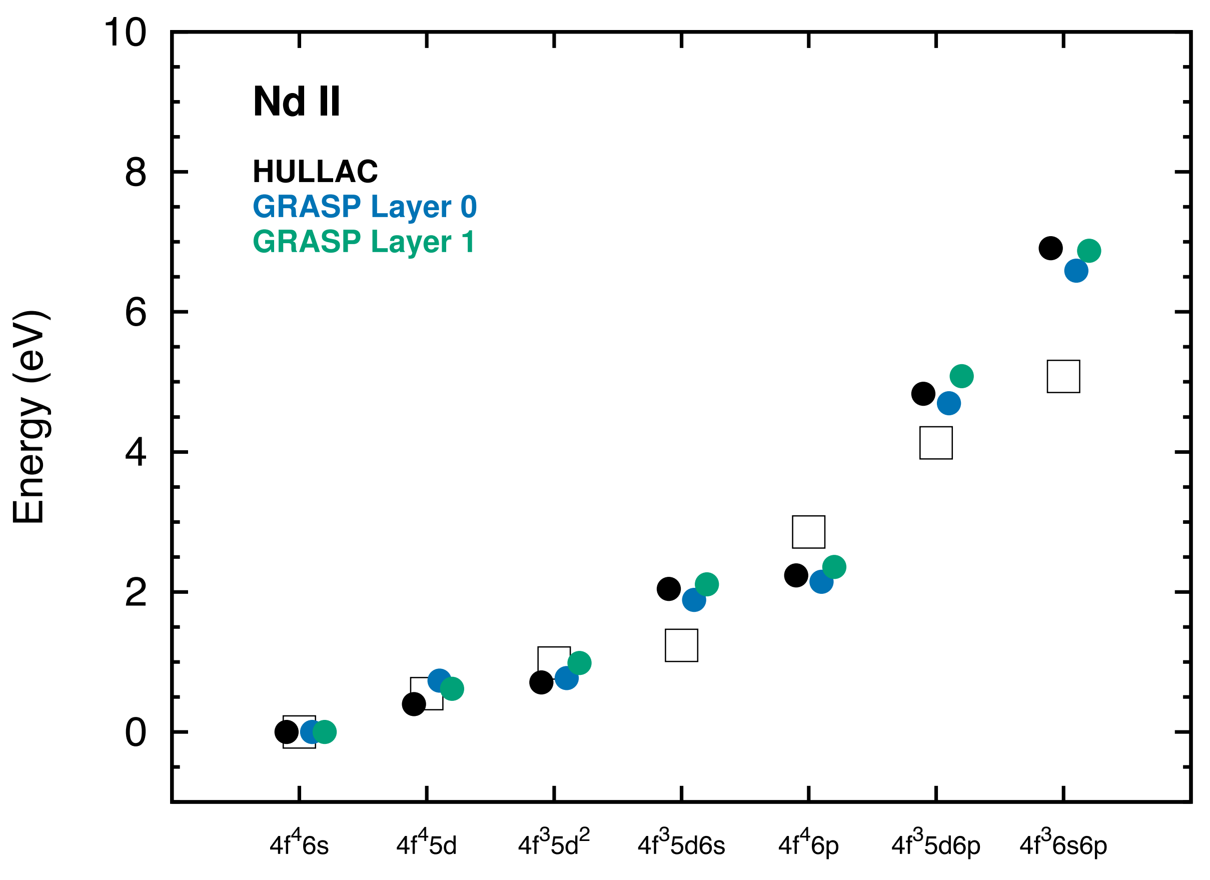
“Universality” of r-process abundances



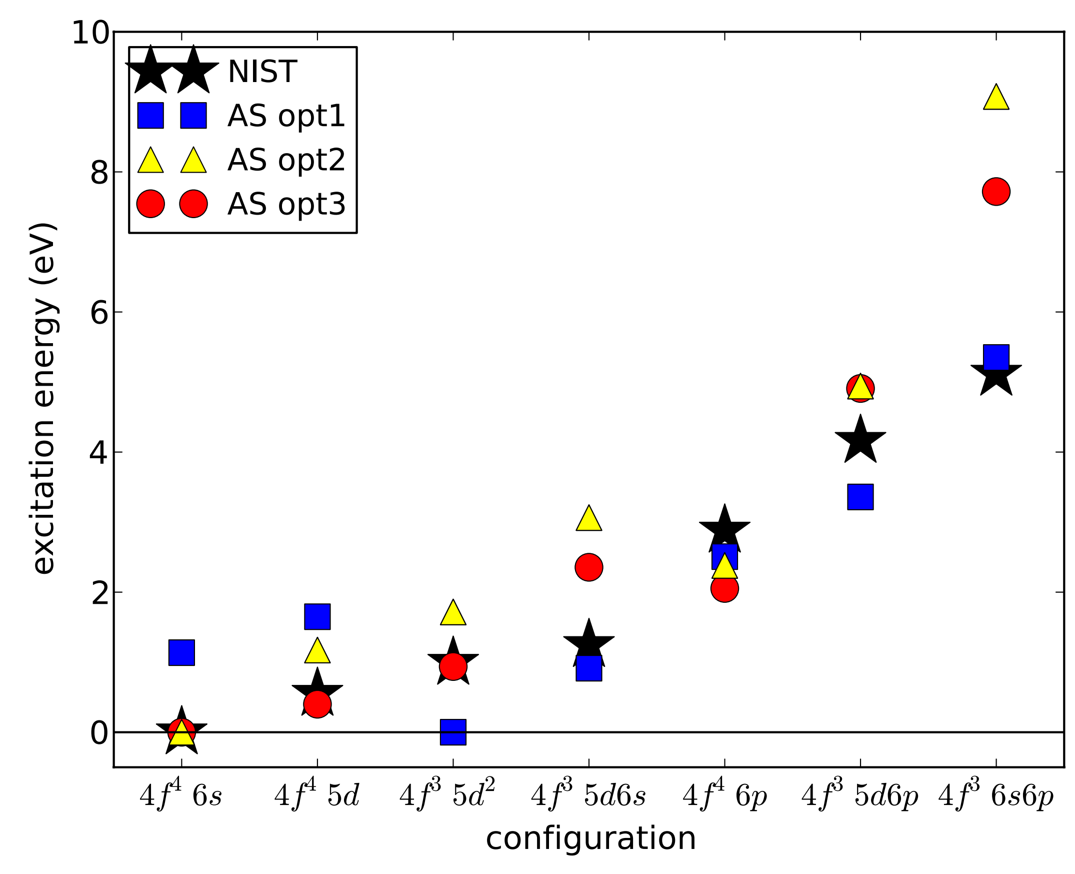
Sneden+2008


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+17: Se I-III, Ru I-III, Te I-III, Nd I-III, Er I-III
Kasen+17: all lanthanides
open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
1st peak
2nd peak
3rd peak

Energy levels of Nd II



MT+17



Kasen+13 (Autostructure code)

Not very accurate for transition wavelengths

Summary

- **GW170817 and kilonova**
  - Red and blue components
    => Ye ~ 0.25 or X(Lan) ~ 10^{-3}-10^{-2} if single component
  - ~0.03 Msun ejection with Lanthanide
    => Enough to explain the origin of r-process elements
- **Open questions**
  - Mechanism of high mass ejection
  - Abundance patterns (solar parttern?)
- **Future prospects**
  - More events with different masses, mass ratios, and viewing angles
  - Systematic construction of atomic data