Neutron star mergers and kilonovae

連星中性子星合体とキロノバ

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(National Astronomical Observatory of Japan)

キロノバ？
マクロノバ？

コラム　まだ名前もない天体

この章では、中性子星の合体により飛び出した物質の中でｒプロセスが起き、放射性エネルギーを使って光る、超新星のような現象を紹介しました。実はこの現象、あまりに最近登場したため、まだ名前がありません。実際の研究現場でも人によって呼び名が違うのです。あるグループは、"kilonova" と呼んでいます。この "kilo" は「1000倍」の意味で、新星（nova，3章で登場した超新星と区別された天体）より1000倍ぐらい明るいことが予想されることから名づけられたようです。一方、違うグループは "macronova" と呼んでいます。nova よりもスケールが大きい（マクロ）という意味合いですね。

ではこれを日本語にすると……それぞれ「千新星」と「巨新星」でしょうか？　なんだかイマイチですね。ｒプロセスが起きて初めて光るので「ｒプロセス新星」というのが自然かもしれません。ただ、ｒプロセスを知らない人にはやや難しい言葉ですね。いっそ、金をつくるので「金新星」なんていうのはどうでしょうか？　おそらく金はつくられているでしょうが、もし中性子星の合体が宇宙のほんの一部の金しかつくっていなかったら紛らわしい言葉になってしまいますね。

というわけで、この本ではこの天体を「超速新星」と名づけました。中性子星の表面から飛び出してくる物質なので、その速度が普通の超新星よりも速いことは絶対に正しそうです。しかも、ｒプロセスは「速い」中性子捕獲反応でしたね。激しい合体により飛び出してきて輝き、あっという間に消えてしまう現象にピッタリだと思いませんか？　この名前も10年後にどうなっているか、楽しみにしようと思います。

田中 (2015)

Neutron star mergers and kilonovae

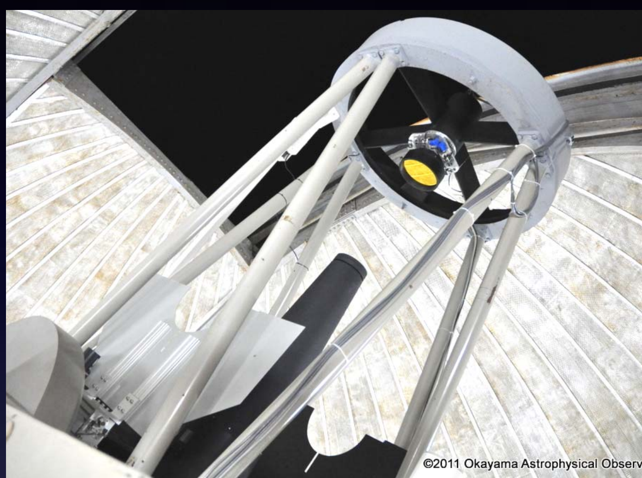
- Optical and NIR observations of GW170817
- Lessons from GW170817
- Related works

J-GEM

Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up

(MOU w/ LIGO/Virgo Collaboration in 2014)

Okayama 0.91m



Okayama 1.88m

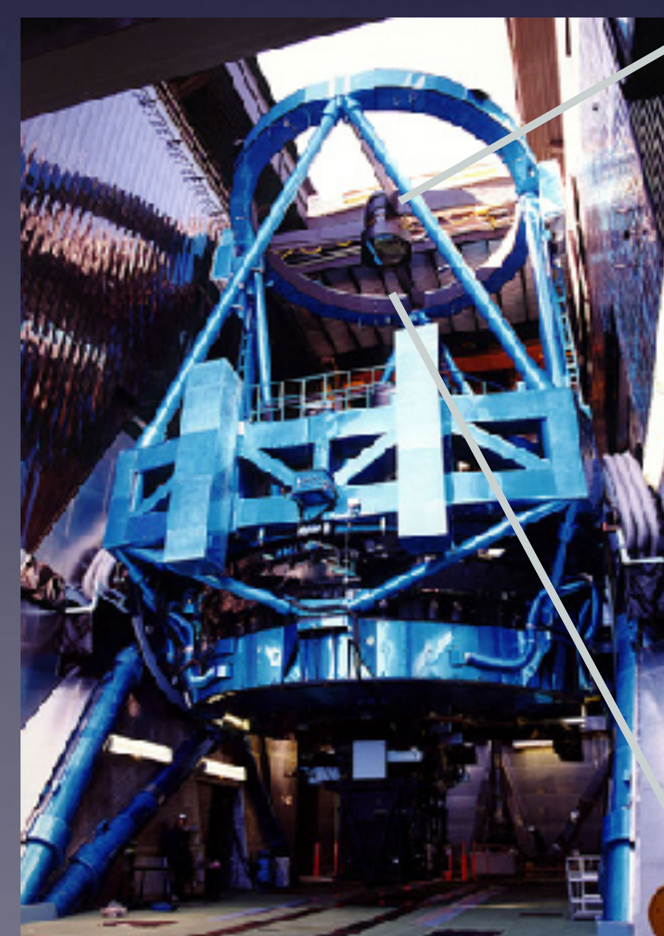
Hiroshima 1.5m

Kiso 1m (wide field)

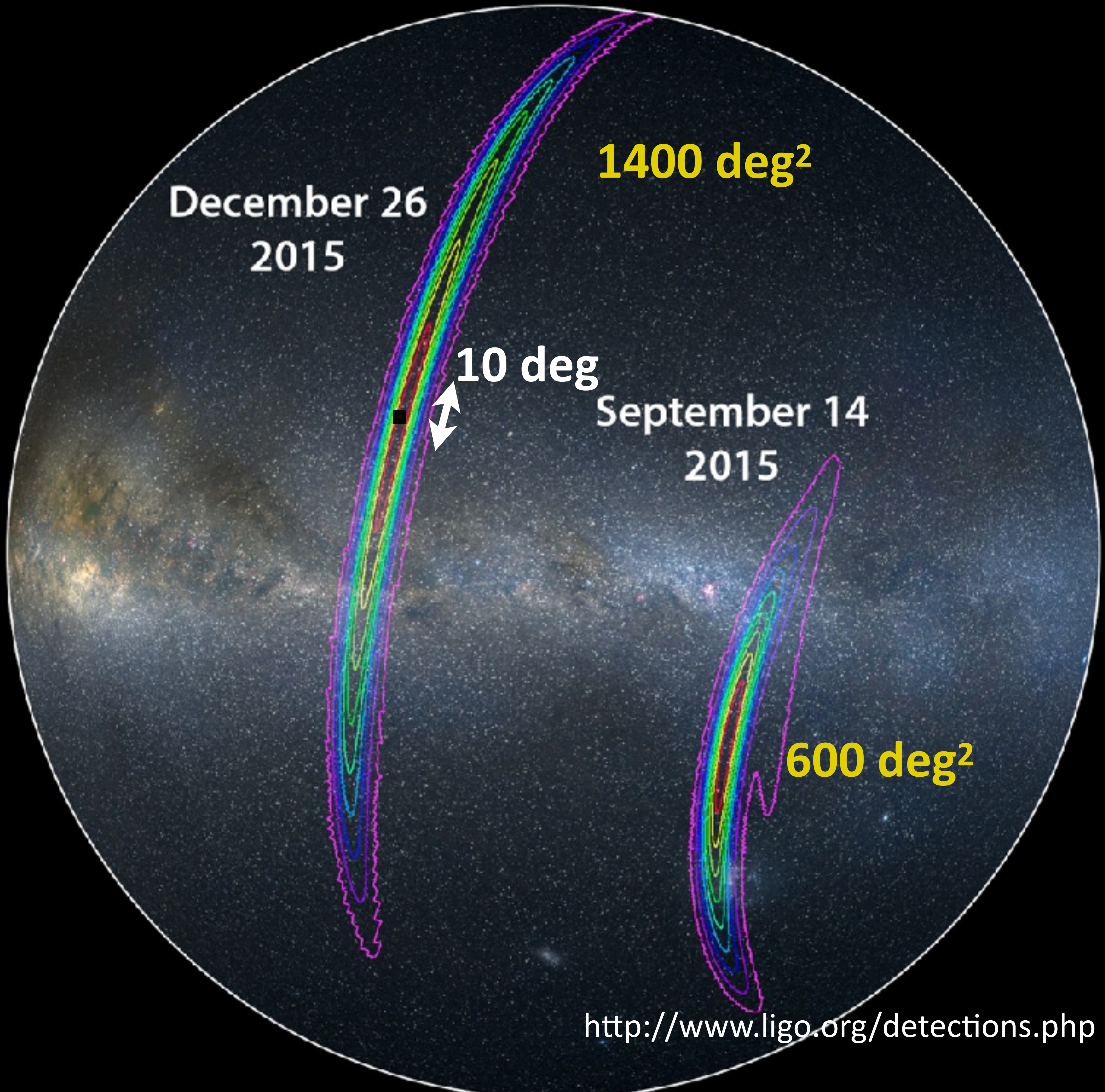
MOA-II 1.8m (wide field, south)

IRSF 1.4m (south)

Subaru 8.2m



HSC (wide field)



1400 deg²
December 26
2015
10 deg
September 14
2015
600 deg²
http://www.ligo.org/detections.php

The first alert

☆ **LIGO/Virgo Circulars** box 2017年8月17日 22:22 詳細 LC

Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification o...

宛先: Masaomi Tanaka

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 22:21 (JST)
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.

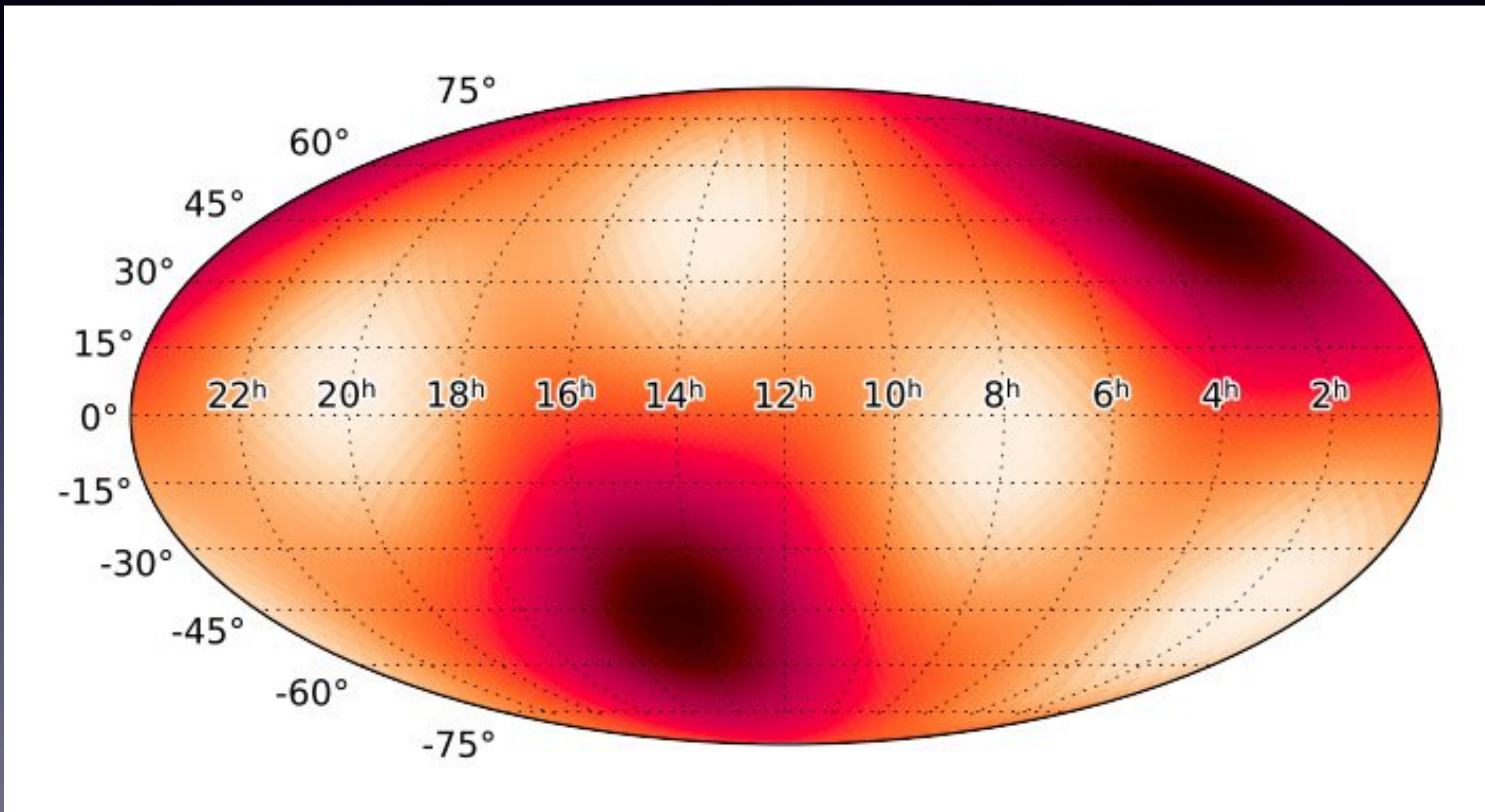
21:41 (JST)

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

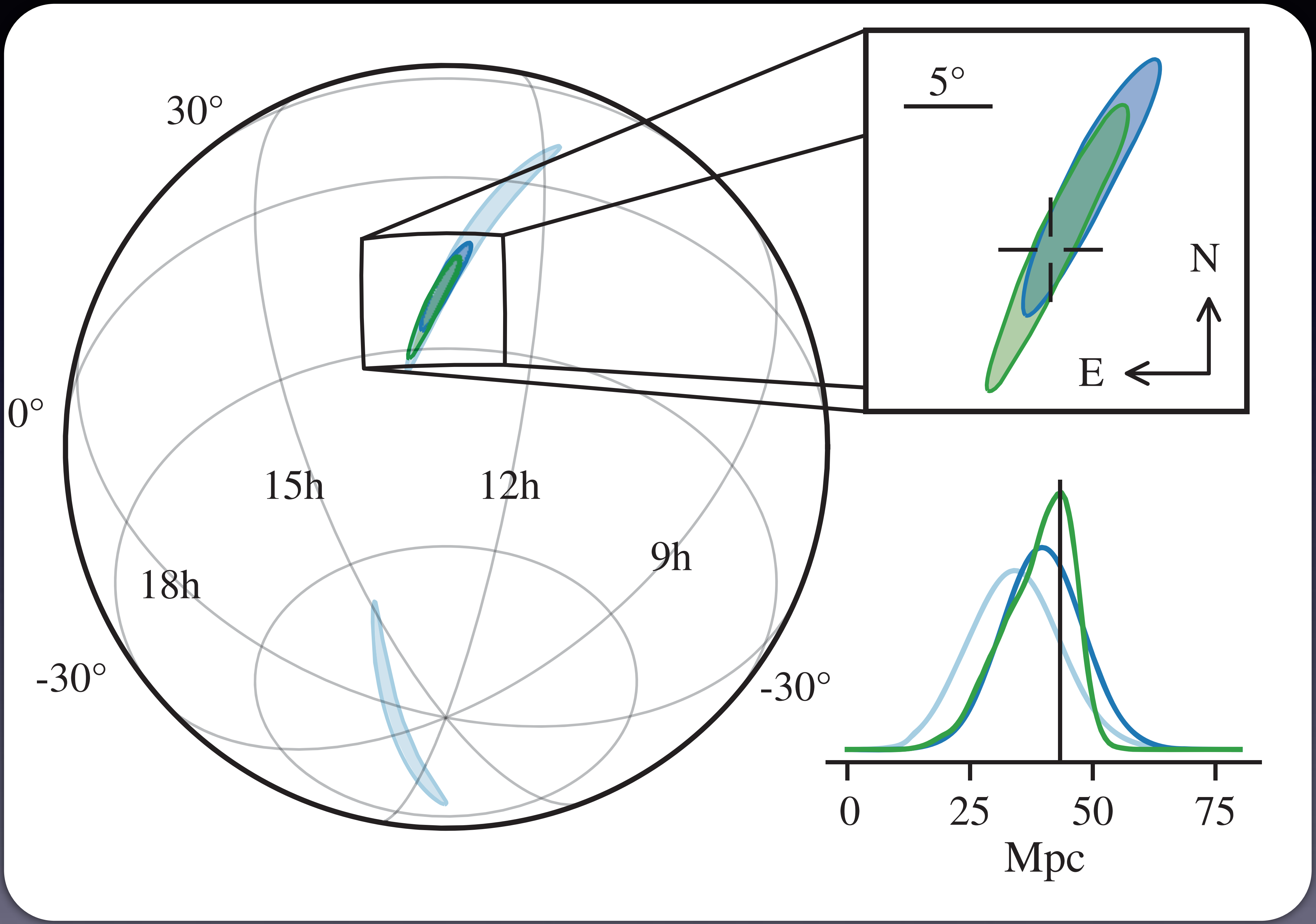
An offline analysis is ongoing. Any significant updates will be provided by a new Circular.

The initial skymap (only from LIGO/Hanford)

*LIGO/Livingstone data suffer from a glitch



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

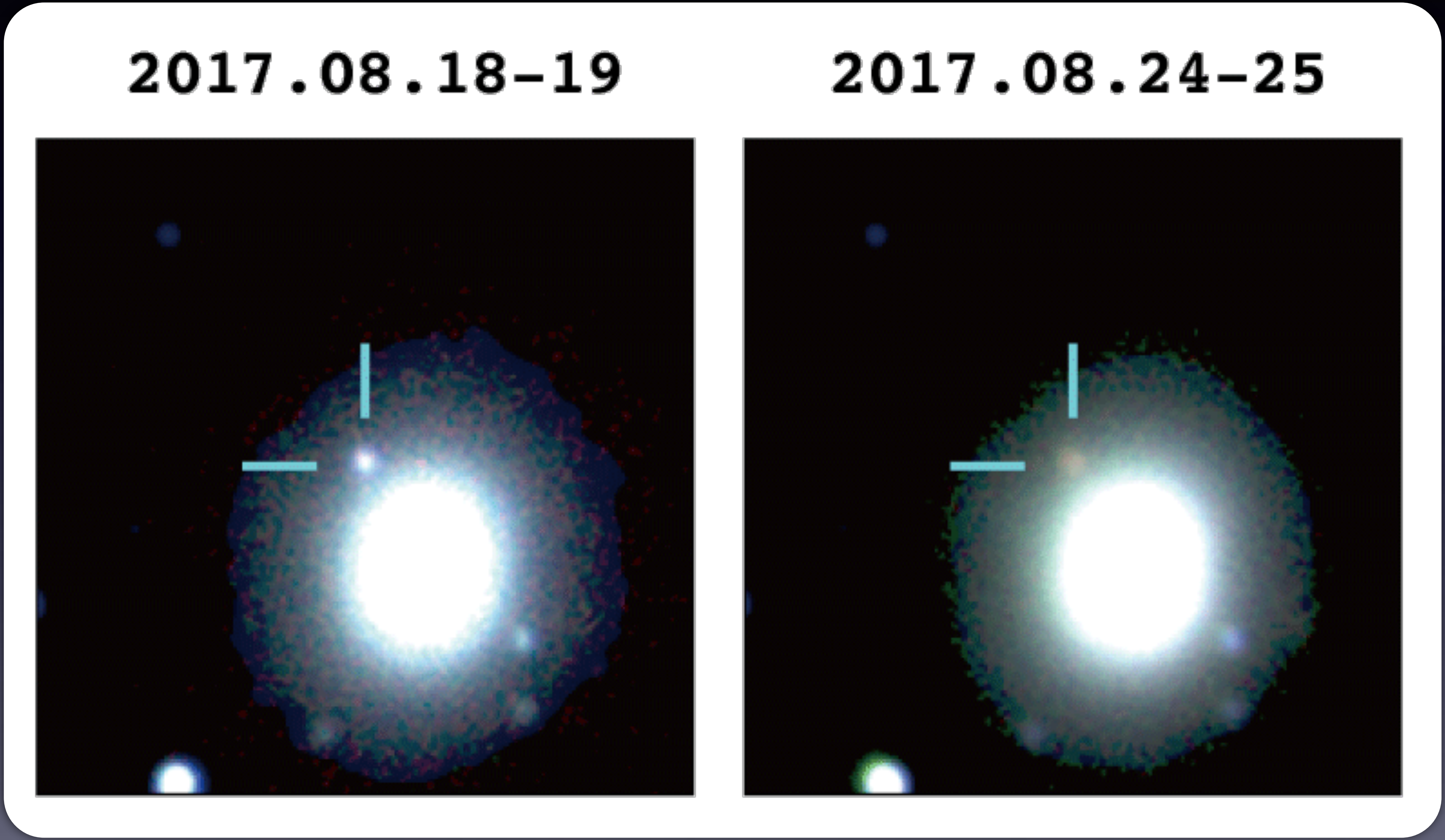


LIGO Scientific Collaboration and Virgo Collaboration, 2017


hscMap
背景の天の川：ESO/S.Brunier

Electromagnetic counterpart of GW170817 @ 40 Mpc

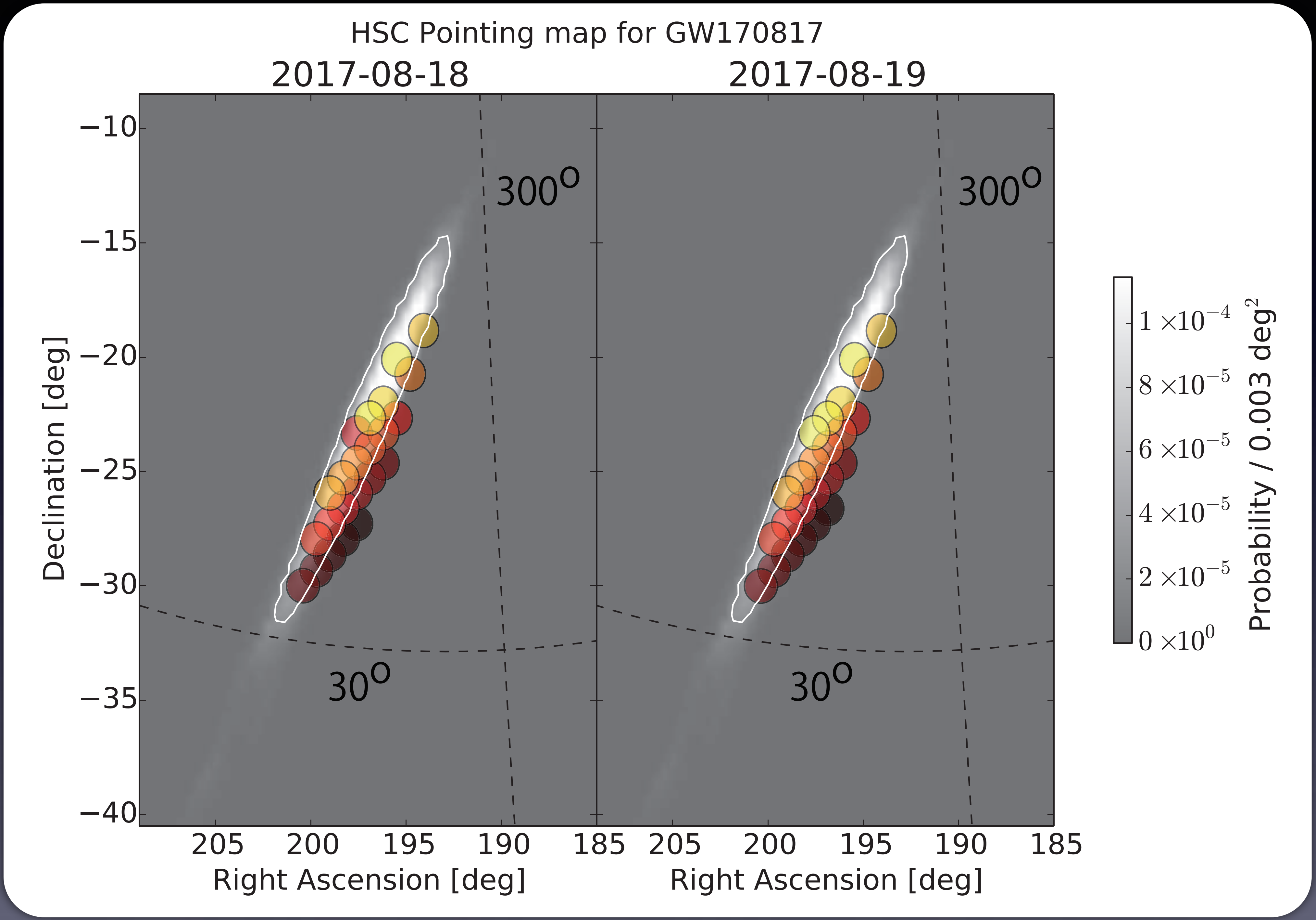
SSS17a (Coulter+17; Sibert+17; Arcavi+17, …)



Subaru/HSC z +IRSF/SIRIUS H, Ks

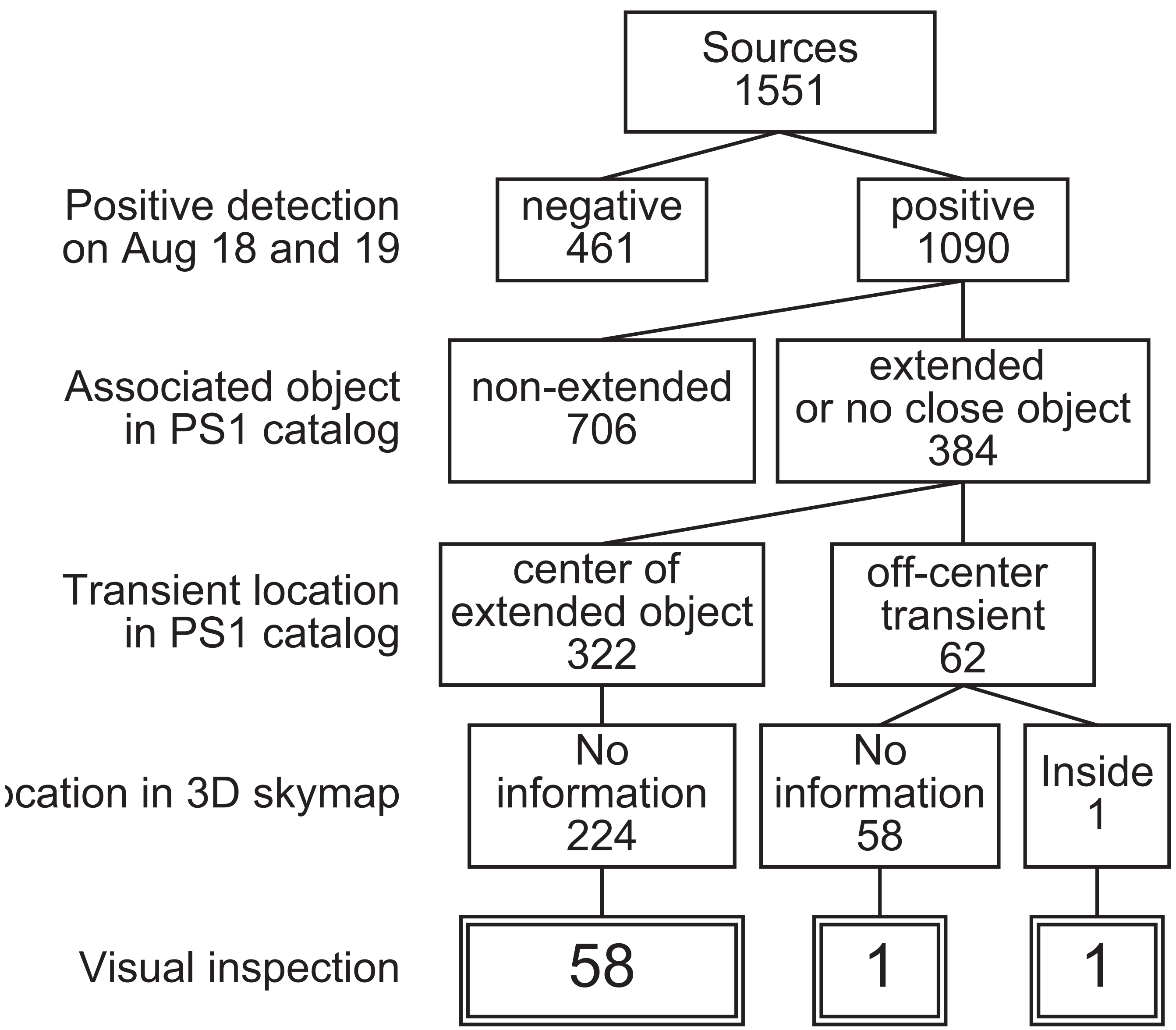
(Utsumi, MT et al. 2017, PASJ)

Survey with Subaru/HSC



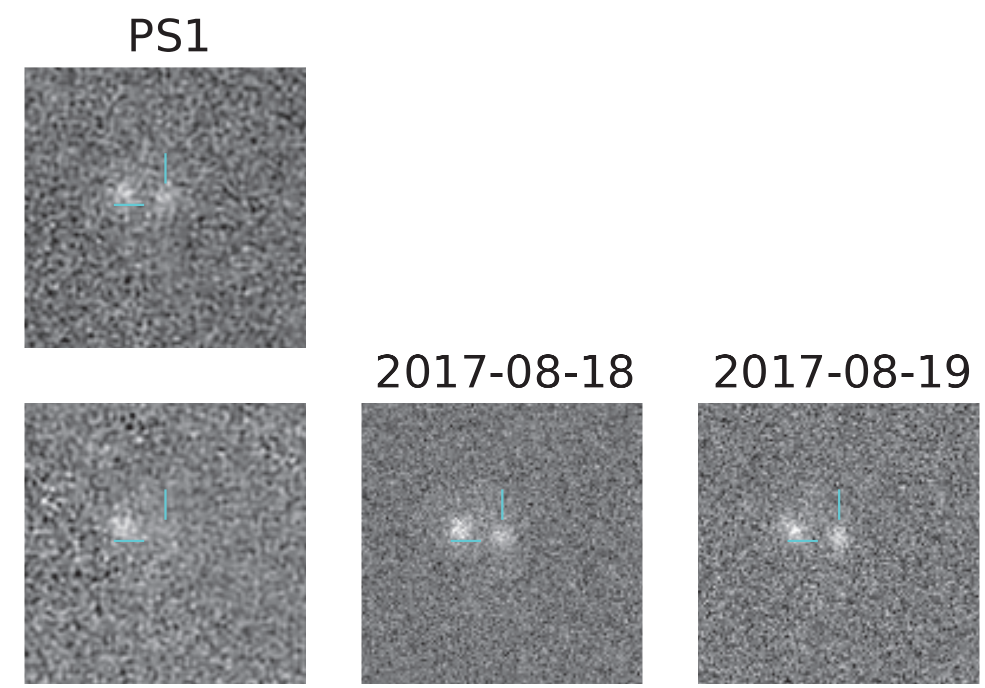
Tominaga, MT et al. 2017, PASJ, arXiv:1710.05865

DECam: Soares-Santos et al. 2017



Remaining 59 objects
(58 center, 1 offset)

Tominaga, MT et al. 2017,
PASJ, arXiv:1710.05865



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

(Faint end of luminosity function)

That of NGC4993
= 0.64

Neutron star mergers and kilonovae

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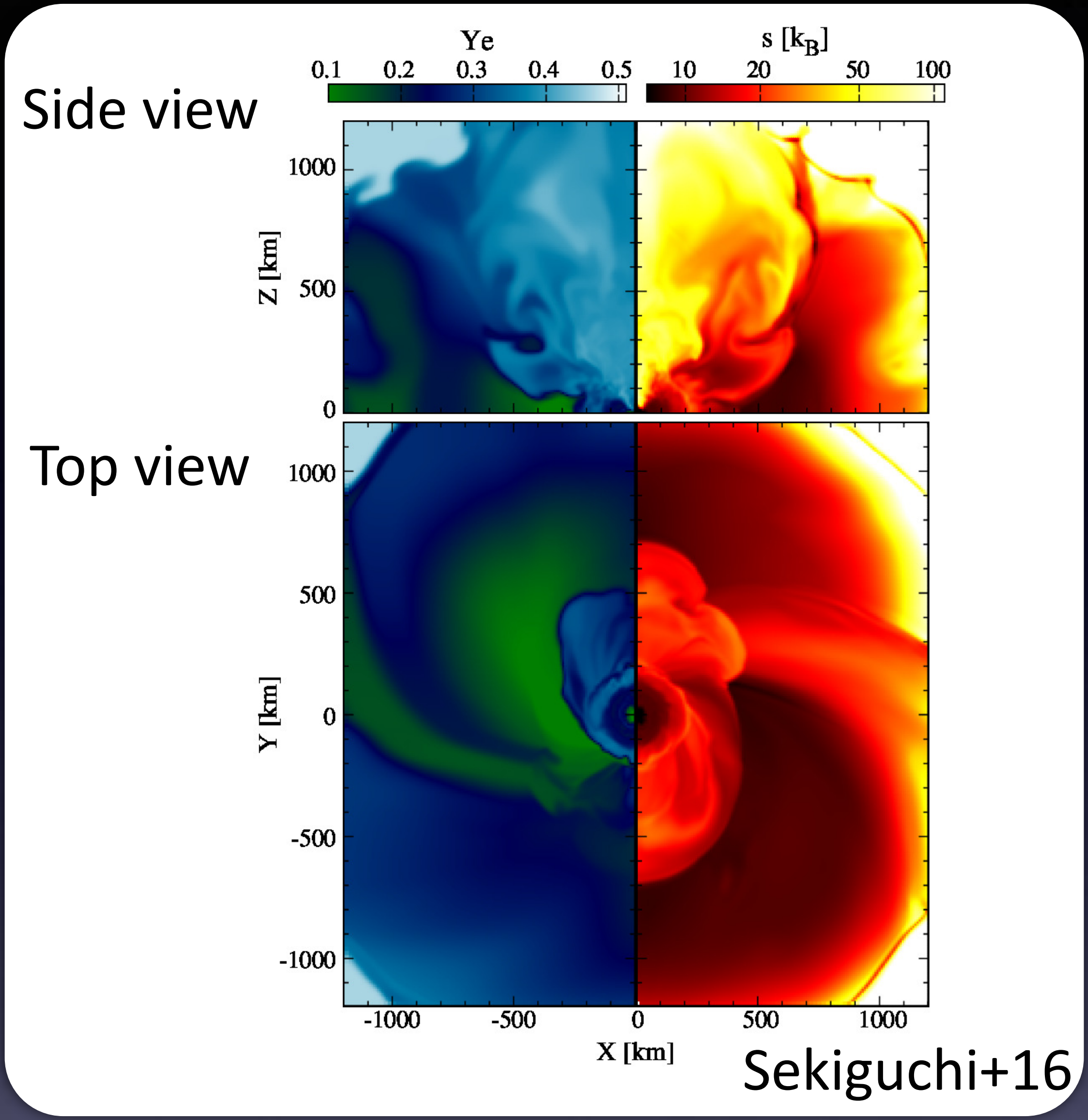
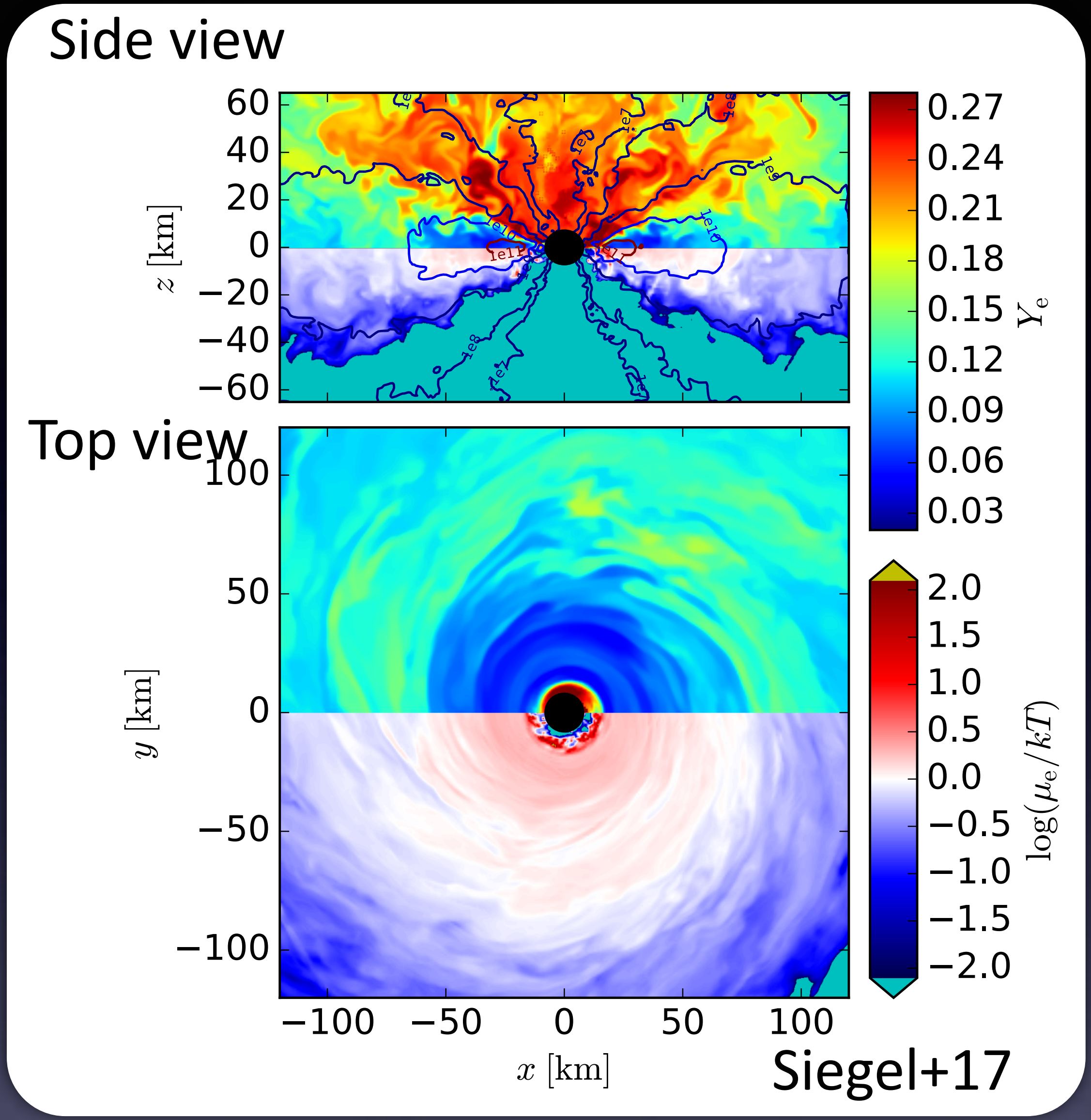
Dynamical ejecta (~< 10 ms)



Rosswog+99, Lee+07, Goriely+11, Hotokezaka+13, Bauswein+13, Radice+16…

- Mej ~ 10^{-3} - 10^{-2} Msun
- v ~ 0.1-0.2 c
- wide Ye

Post-merger ejecta (~< 100 ms)



Fernandez+13,15, Perego+14, Kiuchi+14,15, Martin+15, Just+15, Wu+16, Siegel & Metzger 17…

- Mej >~ 10^{-3} Msun
- v ~ 0.05 c
- can be higher Ye

Expected light curves of kilonova

$L \sim 10^{40}$-10^{41} erg s^{-1}

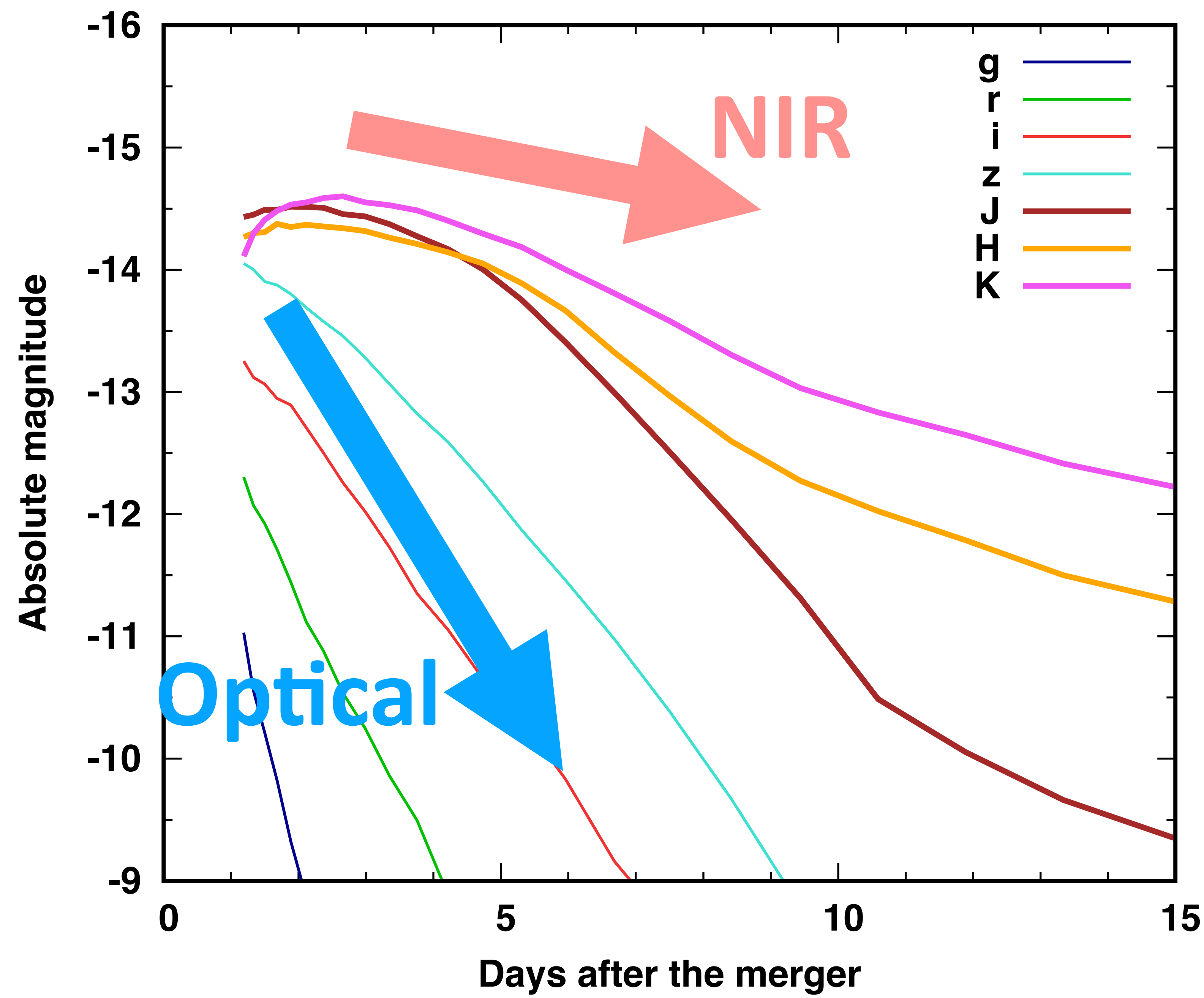
t ~ weeks

NIR > Optical

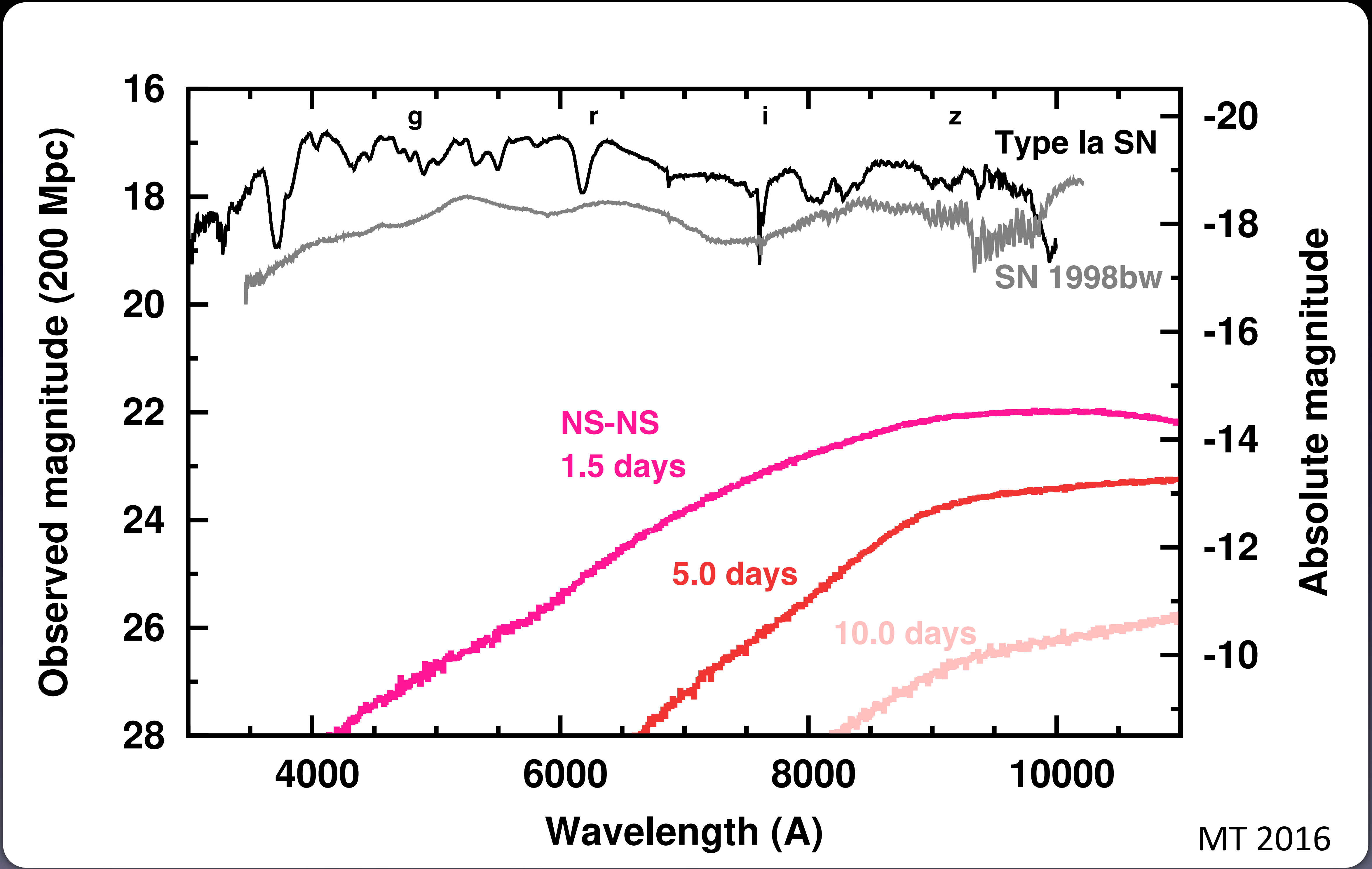
Smooth spectra

Kasen+13, Barnes & Kasen 13

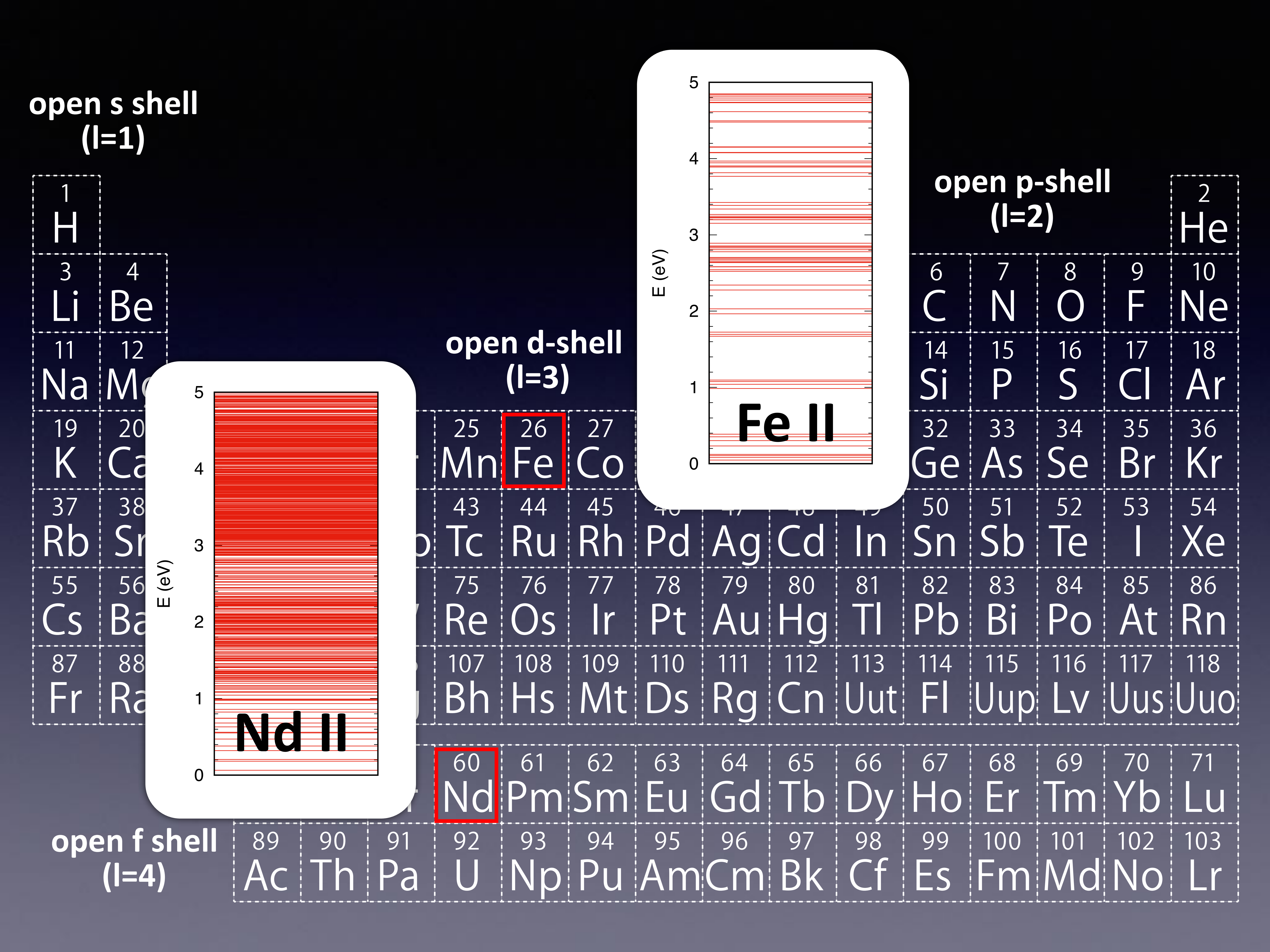
MT & Hotokezaka 13, MT+14,



Expected spectrum

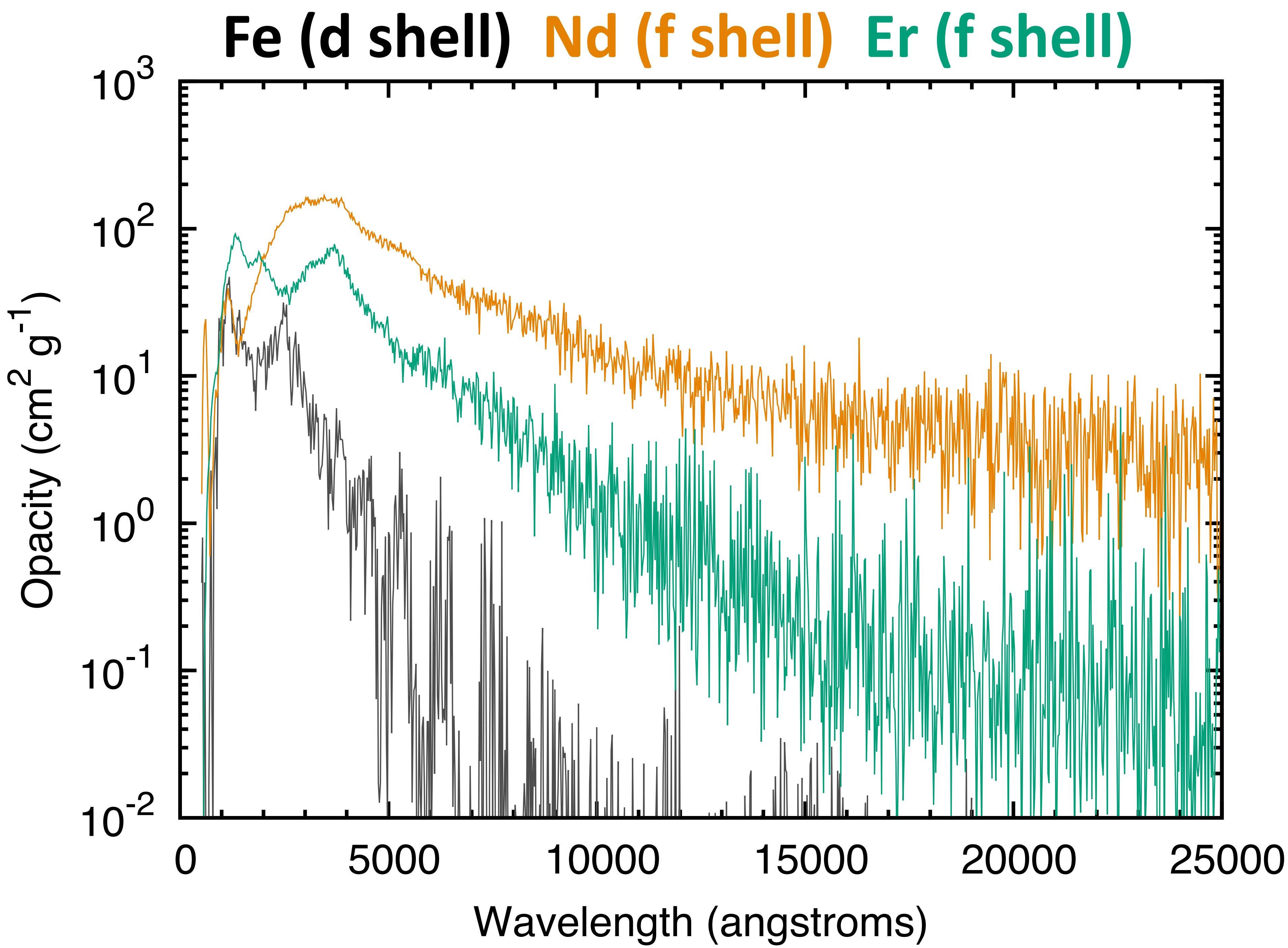


Extremely broad-line (feature-less) spectra



open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
Fe II
E (eV)
0
1
2
3
4
5
Nd II
E (eV)
0
1
2
3
4
5
26
Fe
60
Nd

Bound-bound opacities of lanthanide elements

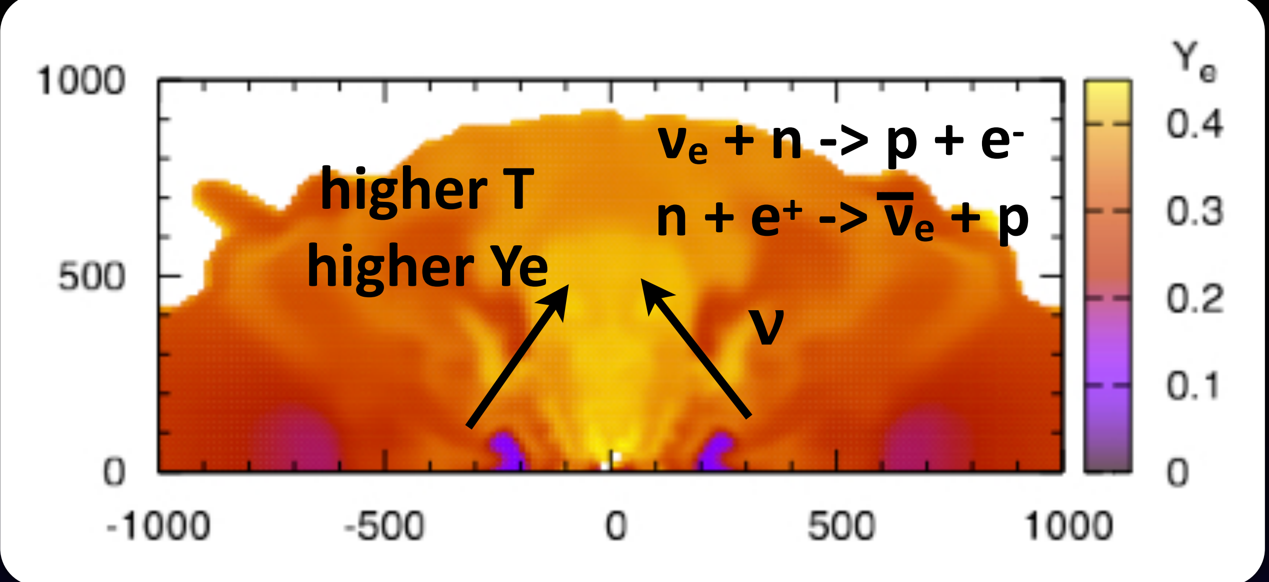


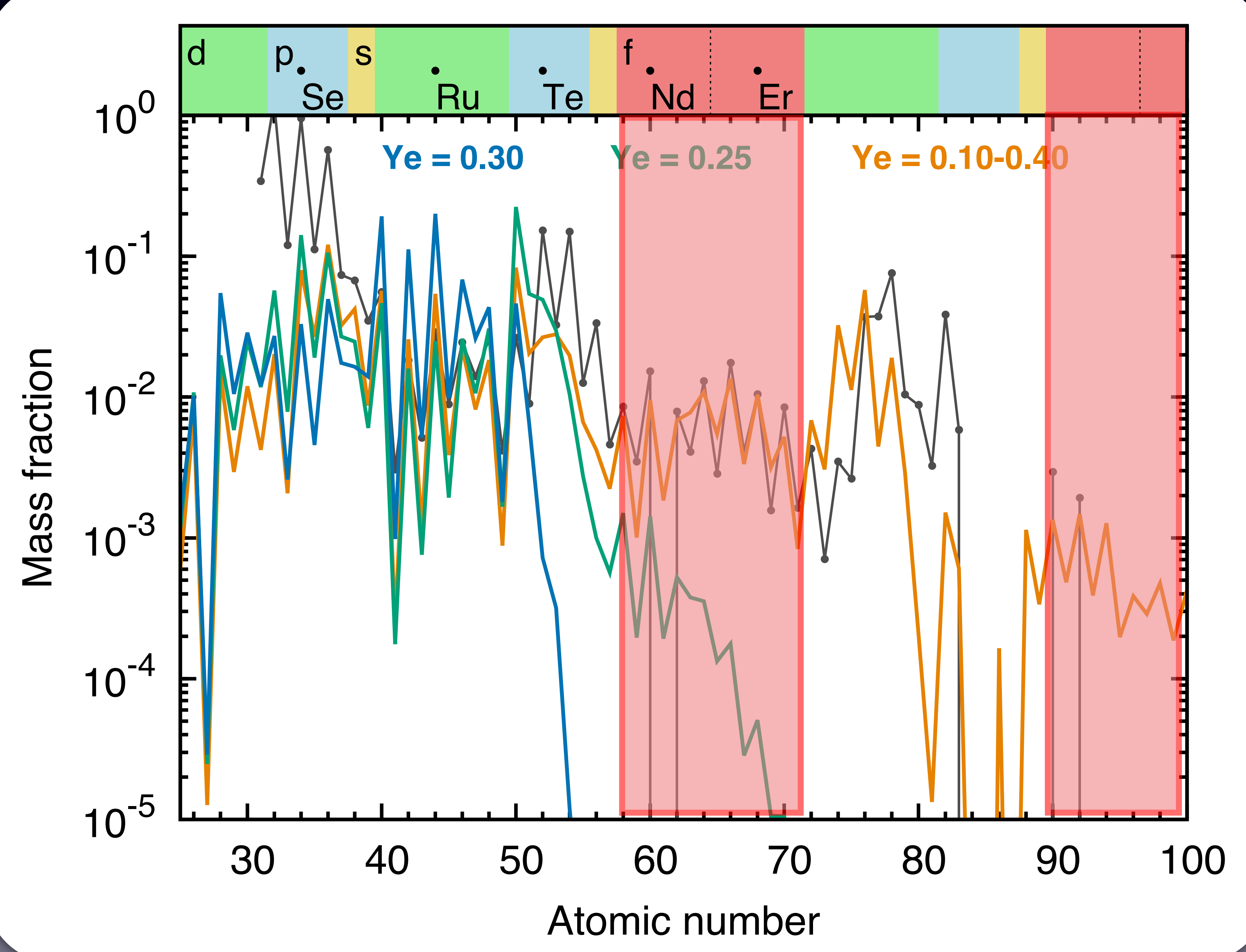
MT+17

κ (p shell) << κ (d shell) << κ (f shell)

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

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





Nucleosynthesis are imprinted in the spectra

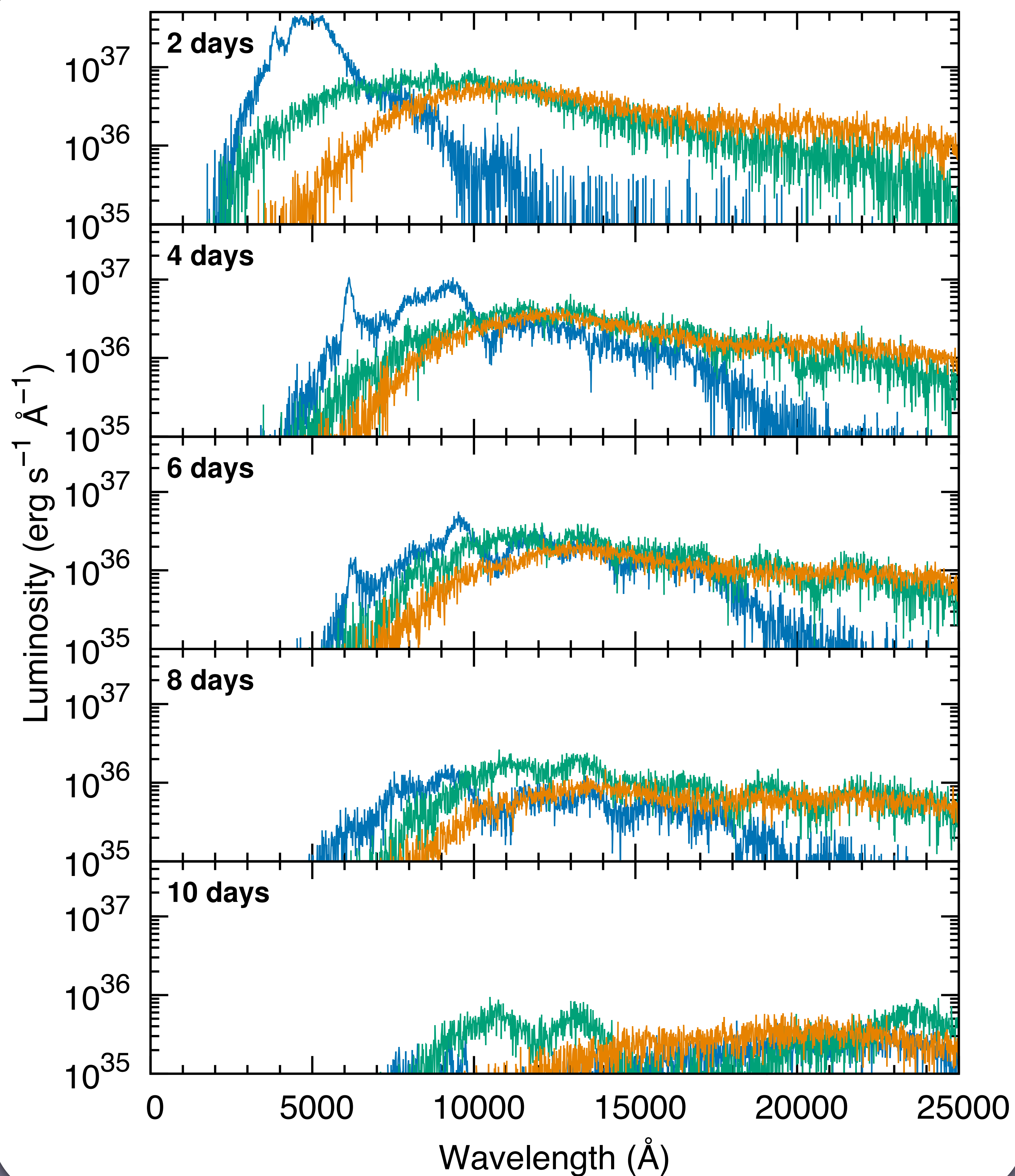
"Blue kilonova"

High Ye (0.30)
(Lanthanide-free)

Medium Ye (0.25)

"Red kilonova"

Low Ye
(Lanthanide-rich)



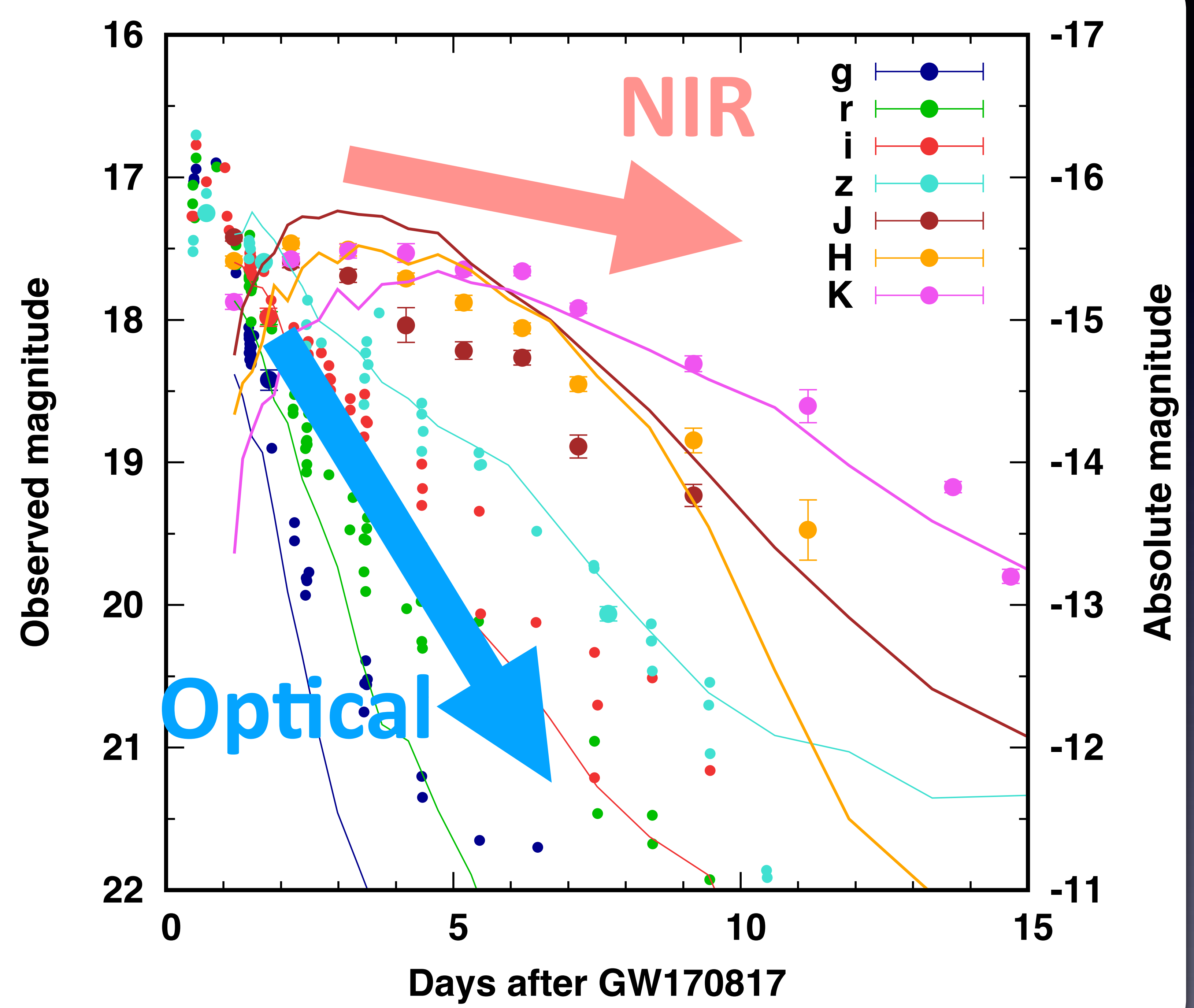
MT+17

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



Ejecta mass (La-rich) ~0.03 Msun => post-merger ejecta?

Constraints to the opacities

Timescale

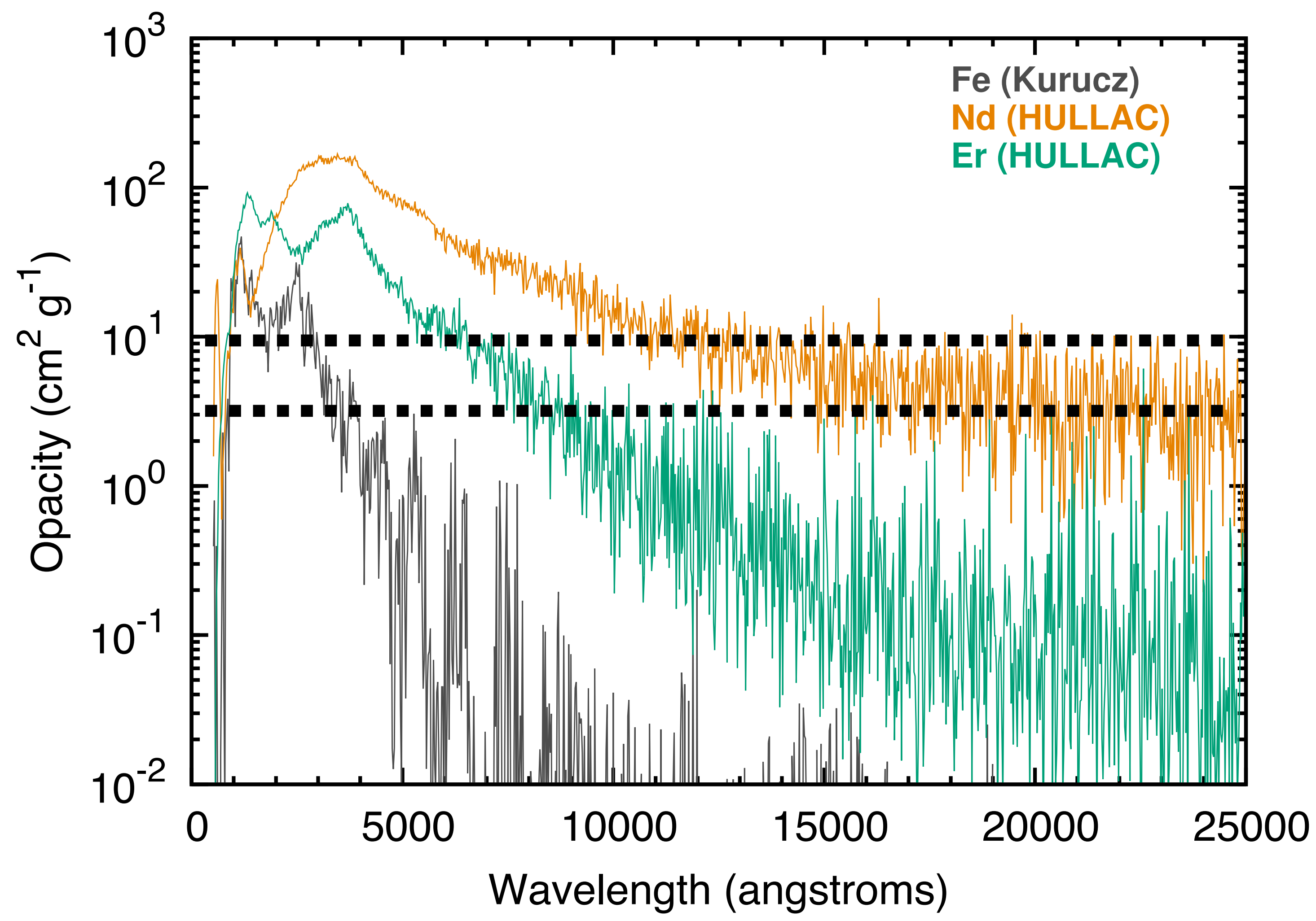
$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$

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

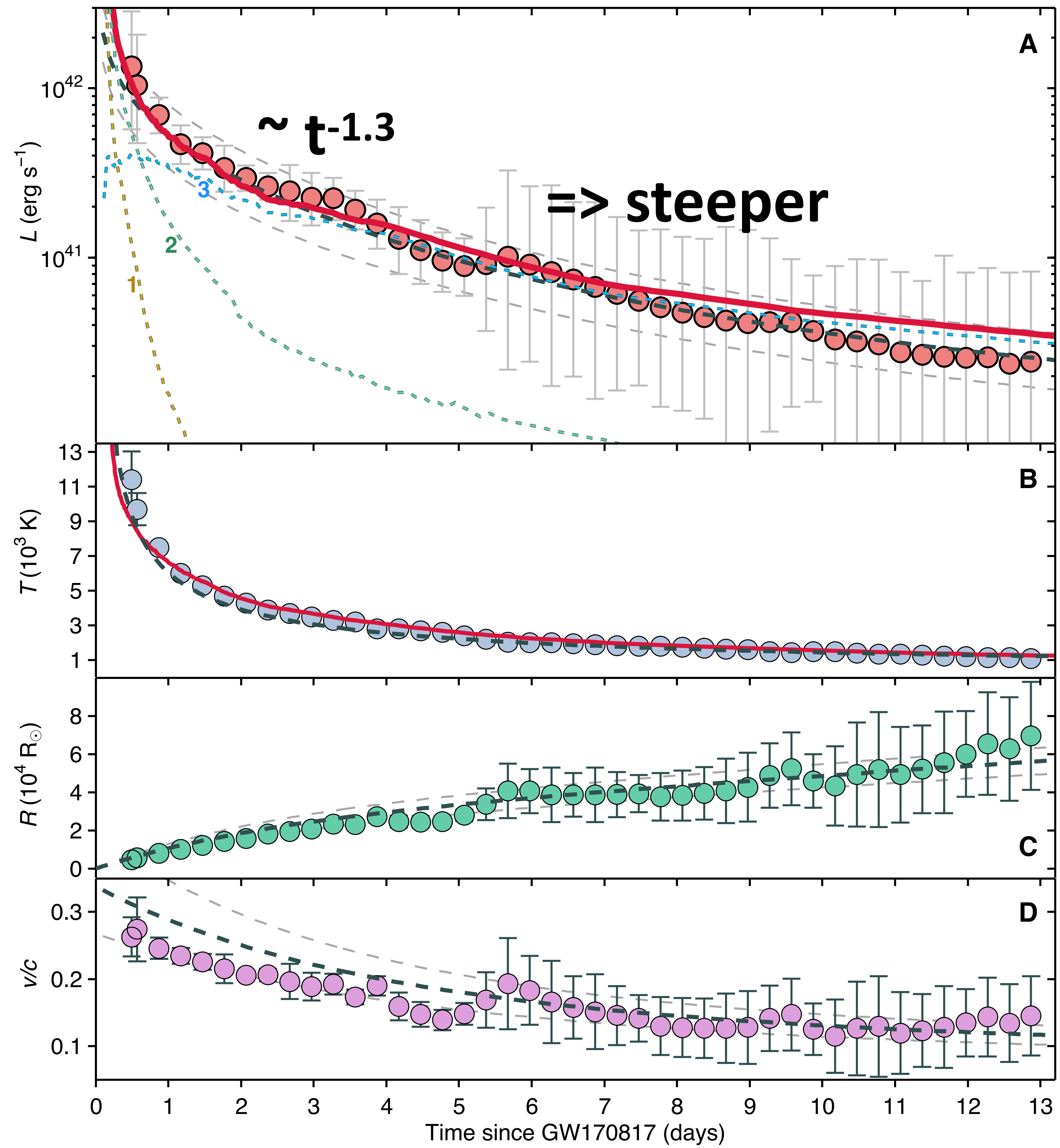
bound-bound transitions of heavy elements

Mej should be ~ 1 Msun if $\kappa \sim 0.1$ cm² g⁻¹

=> b-b opacities of lanthanide elements



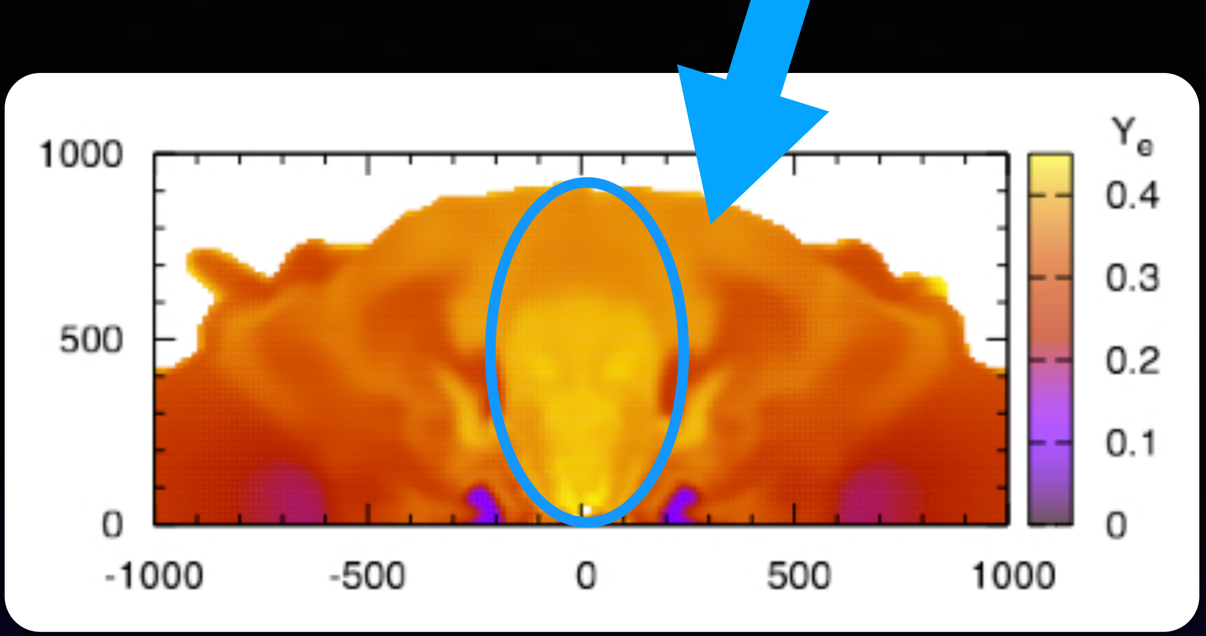
Bolometric light curves

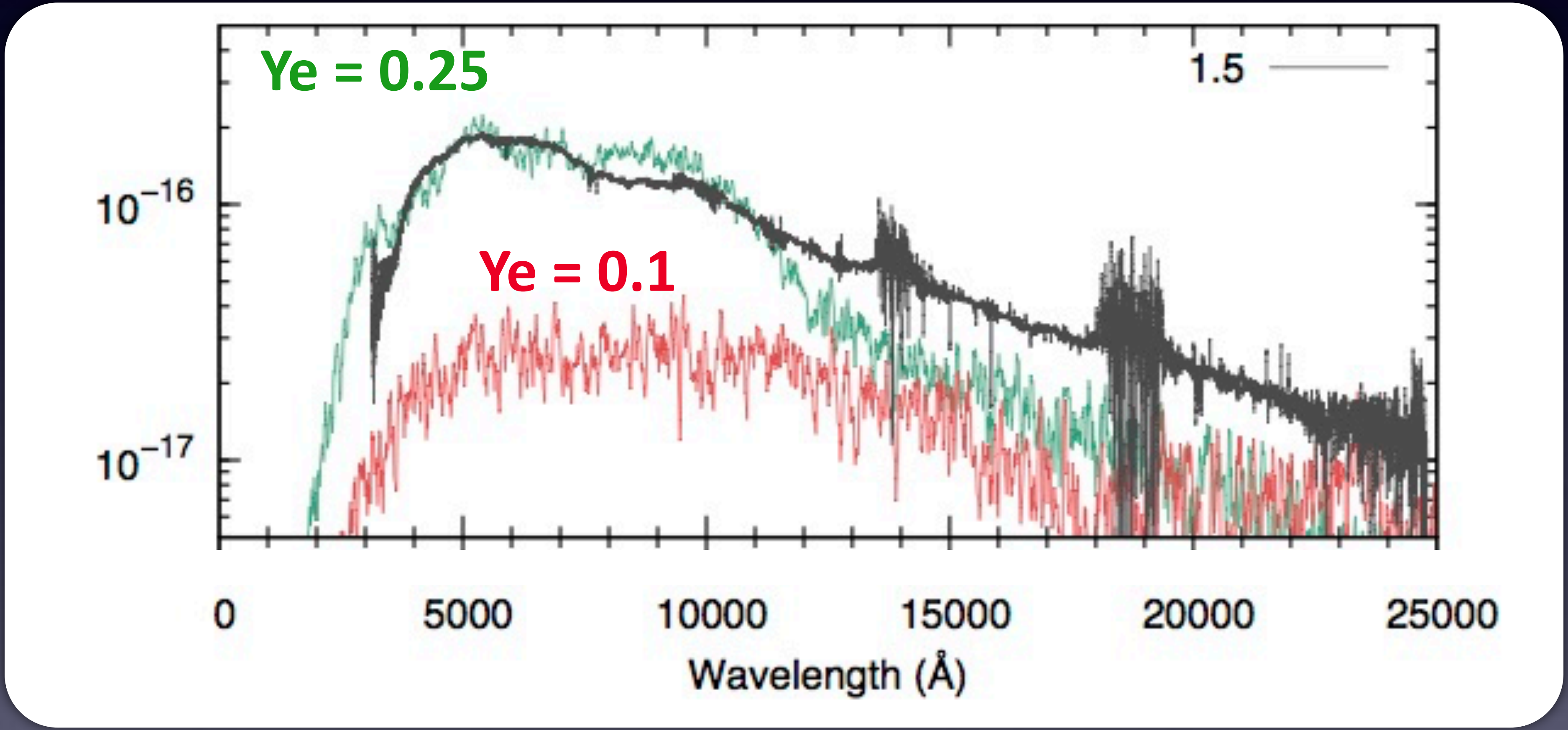


Kasliwal+17

Presence of “blue” kilonova

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





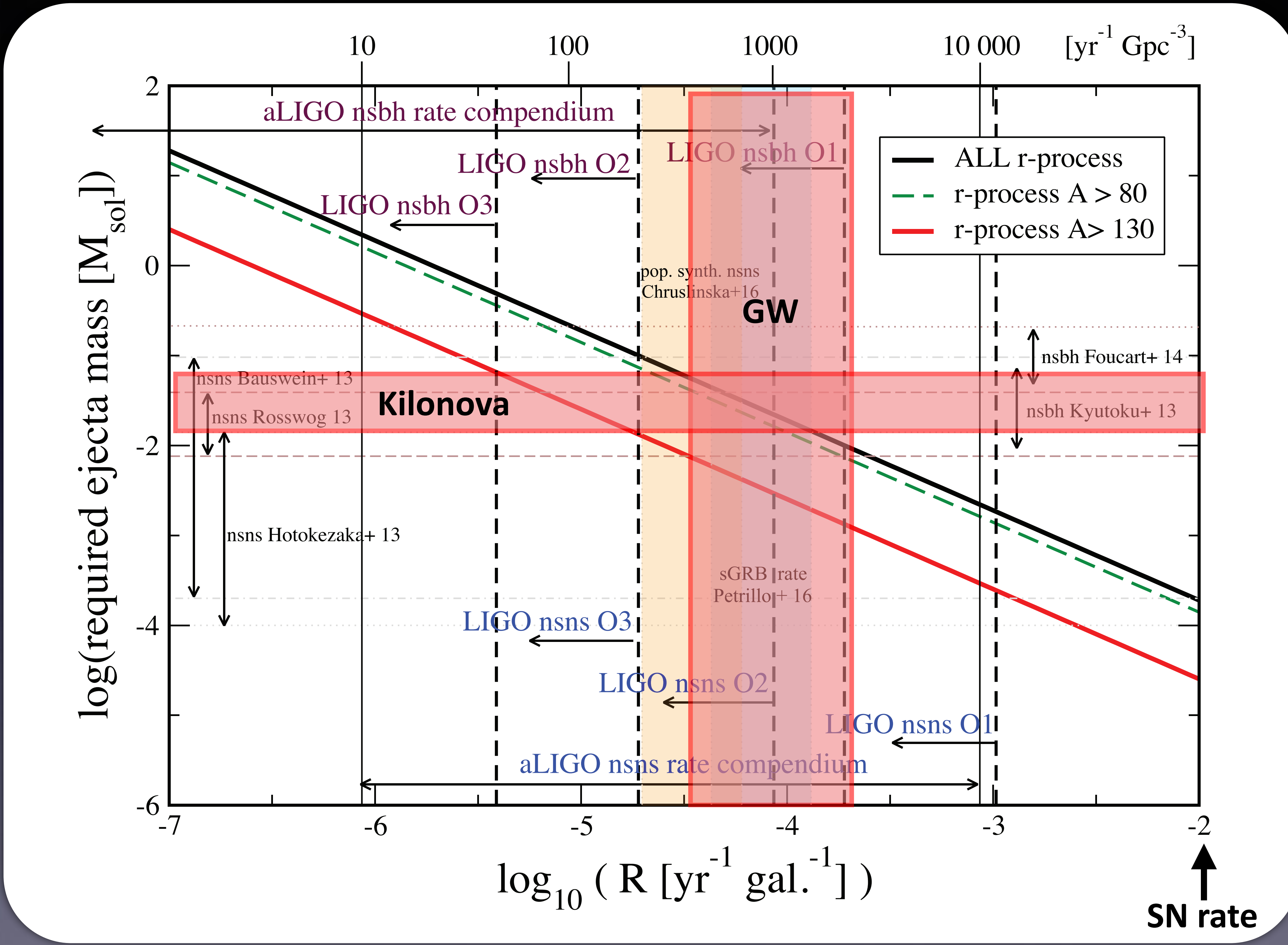
MT+2017

Mej ~ 0.02 Msun? => Additional energy deposition by jets?

Ioka-san’s talk, Ioka & Nakamura 2017

v ~ 0.3c ??

(estimate with BB radii is uncertain, spectra depends on density distribution)



Rosswog+17

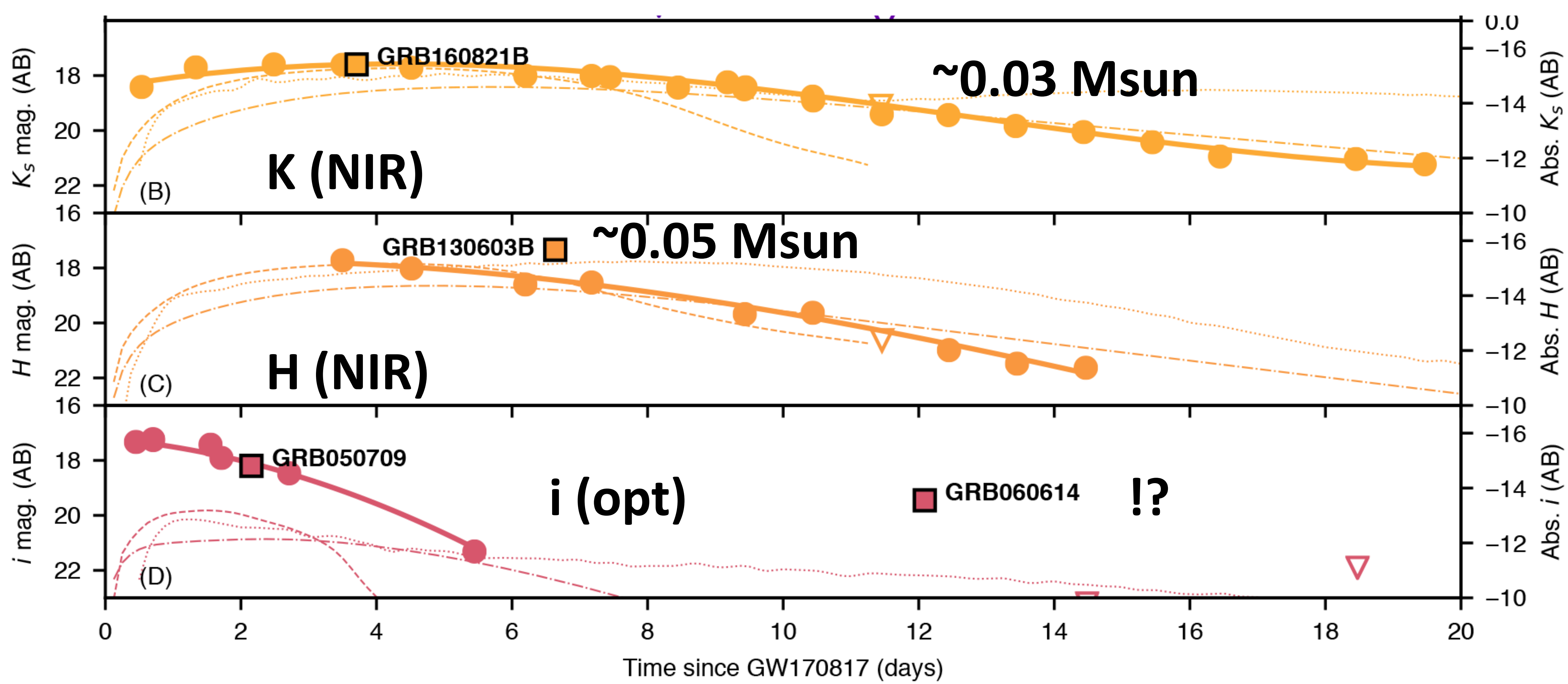
see also Hotokezaka+15

Many open questions

- **What is the origin of high ejecta mass?**
  - Viscous ejection?
- **What is the origin of "blue" component?**
  - Additional energy injection? (Cocoon?)
- **What is the abundance patterns?**
  - Consistent with solar abundances?
- **What is the final remnant (BH or NS)?**
  - Effects to Ye
- **What happens for different total masses, mass ratios, and BH-NS merger?**

Need more observations with different masses and viewing angles

Variety of red component?



Kasliwal+17

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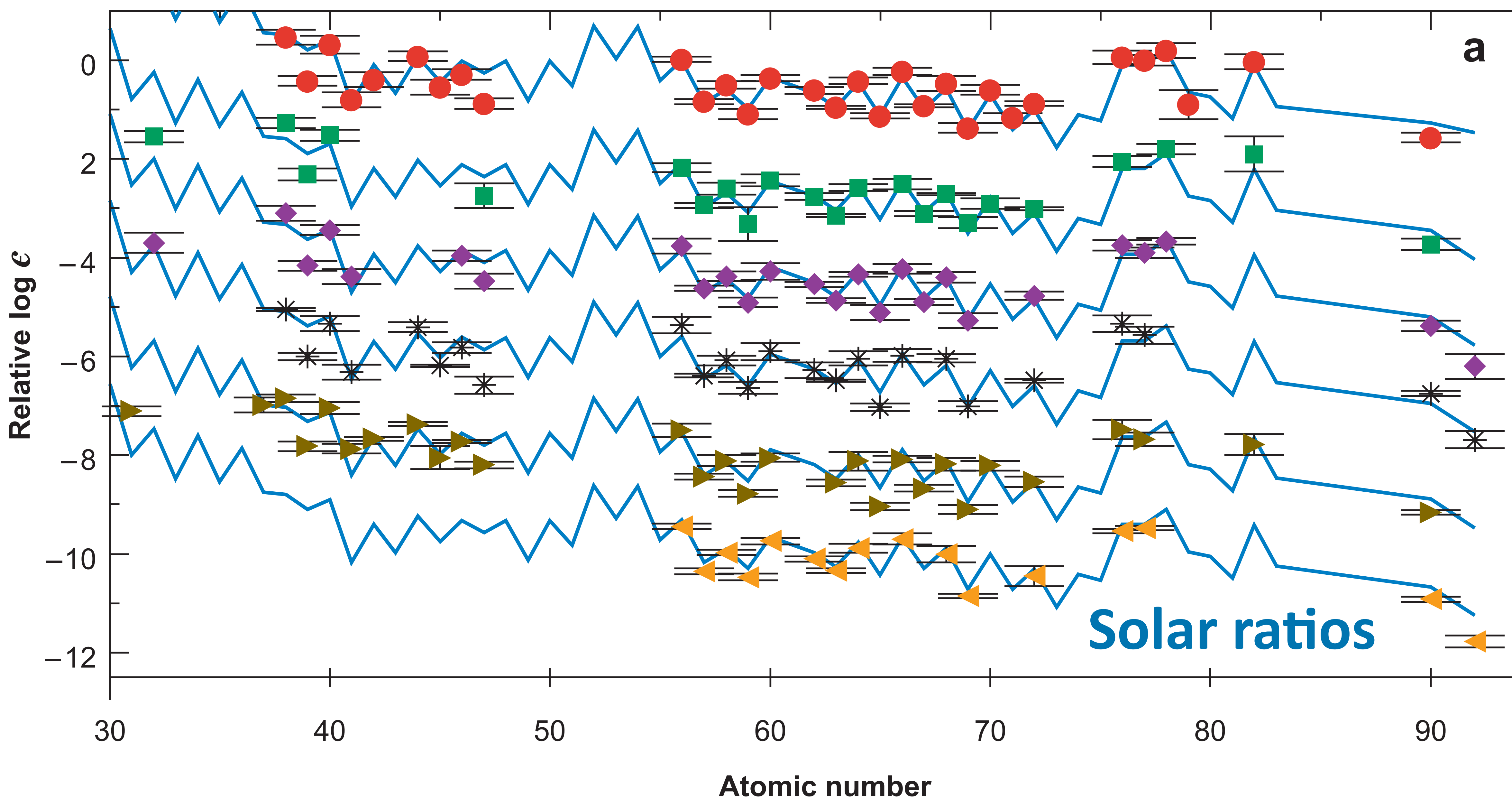
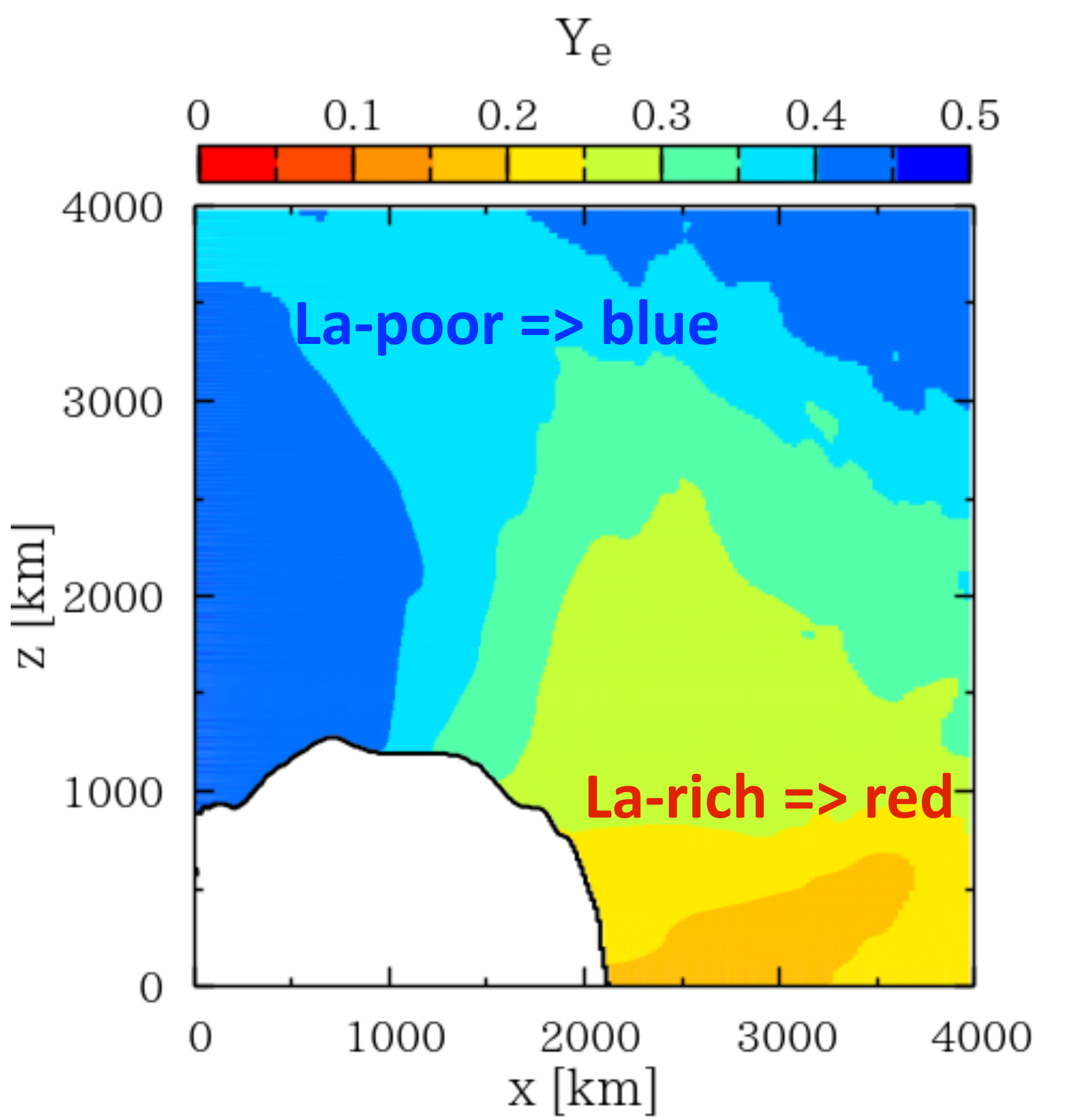
“Universality” of r-process abundances



Sneden+2008

NS mergers produce solar abundances??

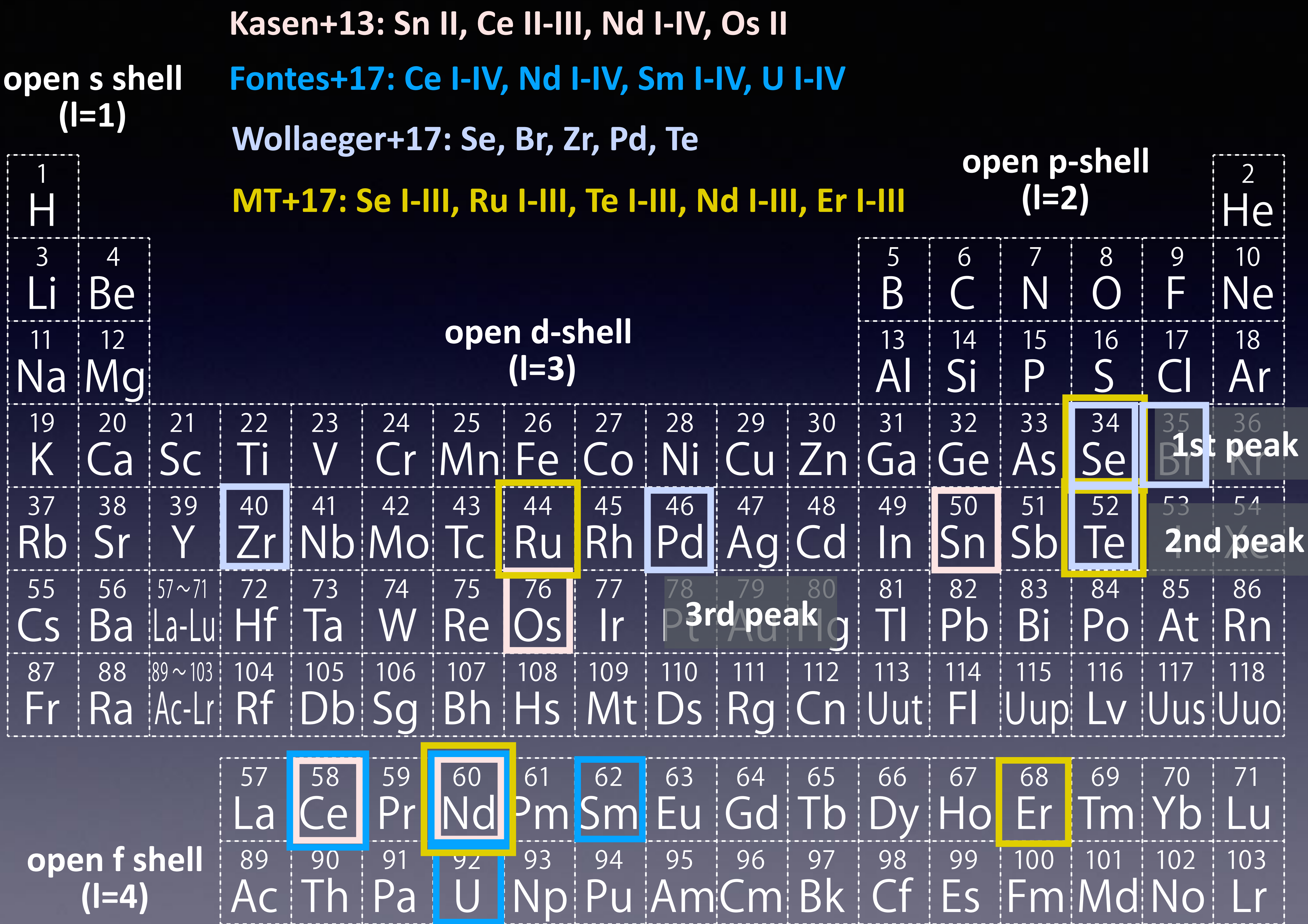


$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

Colors of kilonova should depend on a viewing angle

=> More events with different viewing angles!

Shibata+17
Fujibayashi+17


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
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
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 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

Atomic structure calculations

HULLAC code (Bar-Shalom+99)

GRASP2K code (Jonsson+13)

$$H_{DC} = \sum_{i=1}^{N} \left(c\boldsymbol{\alpha}_i \cdot \boldsymbol{p}_i + (\beta_i - 1)c^2 + V_i^N \right) + \sum_{i>j}^{N} \frac{1}{r_{ij}}$$

Se I-III
(Z=34, p)

Ru I-III
(Z=44, d)

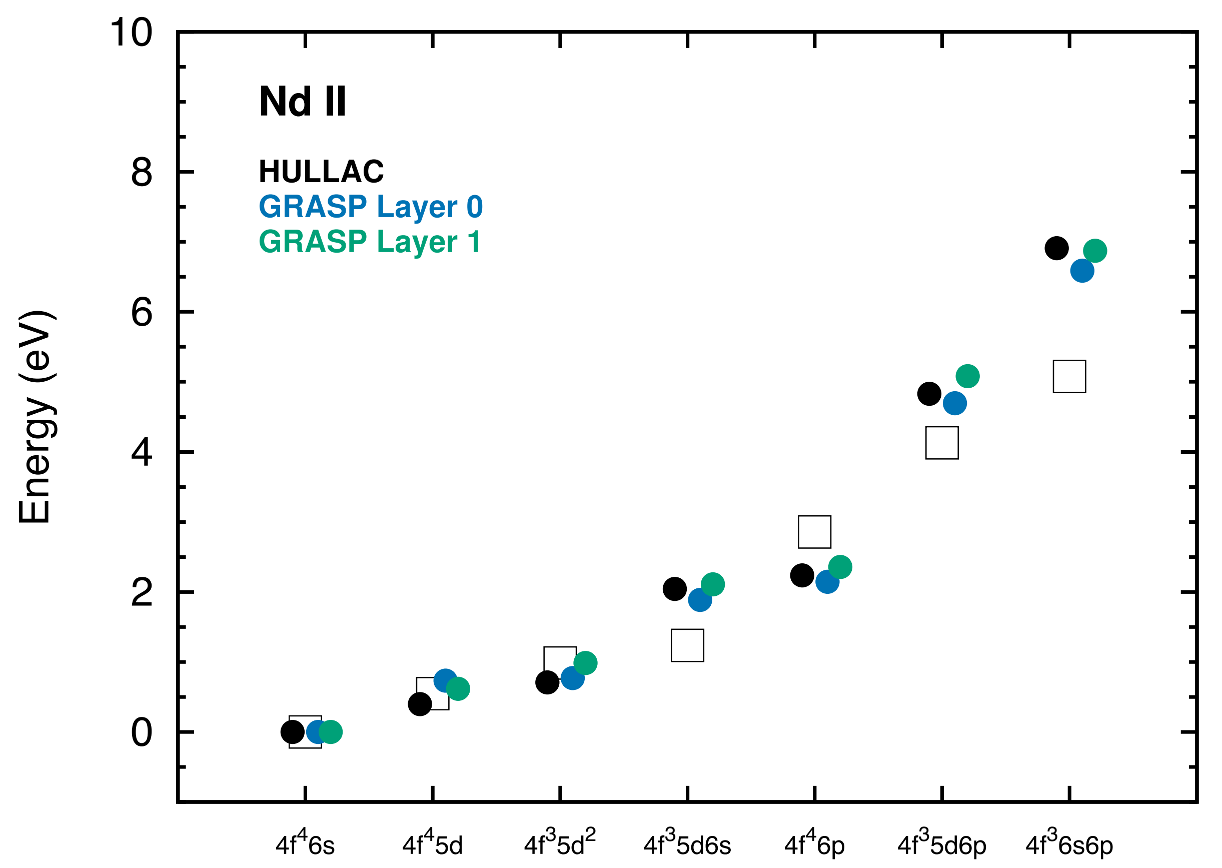
Te I-III
(Z=52, p)

Nd I-III
(Z=60, f)

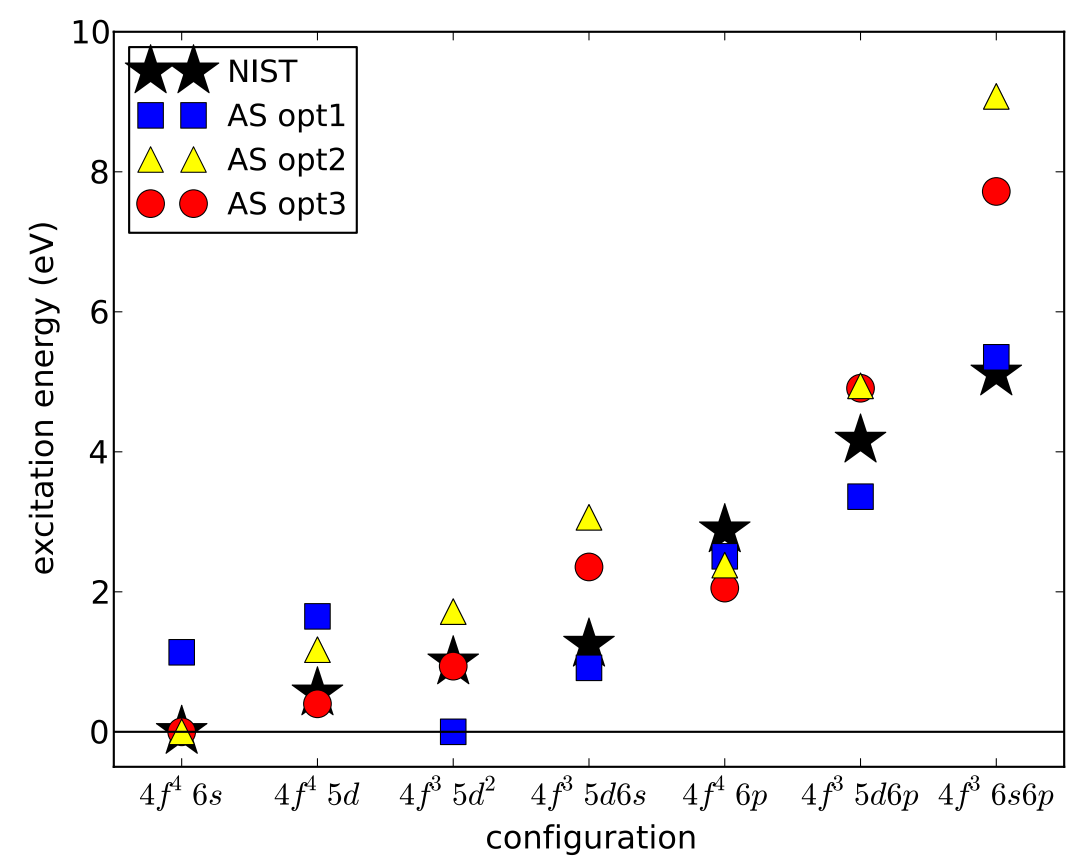
Er I-III
(Z=68, f)

Ion	Configurations	Number of levels	Number of lines
HULLAC			
Se I	$\mathbf{4s^2 4p^4}$, $4s^2 4p^3 (4d, 4f, 5-8l)$, $4s4p^5$, $4s4p^4(4d, 4f)$, $4s^2 4p^2 (4d^2, 4d4f, 4f^2)$, $4s4p^3(4d^2, 4d4f, 4f^2)$	3076	973,168
Se II	$\mathbf{4s^2 4p^3}$, $4s^2 4p^2 (4d, 4f, 5-8l)$, $4s4p^4$, $4s4p^3(4d, 4f)$, $4s^2 4p(4d^2, 4d4f, 4f^2)$, $4s4p^2(4d^2, 4d4f, 4f^2)$	2181	511,911
Se III	$\mathbf{4s^2 4p^2}$, $4s^2 4p(4d, 4f, 5-8l)$, $4s4p^3$, $4s4p^2(4d, 4f)$, $4s^2(4d^2, 4d4f, 4f^2)$, $4s4p(4d^2, 4d4f, 4f^2)$	922	92,132
Ru I	$\mathbf{4d^7 5s}$, $\mathbf{4d^6 5s^6}$, $\mathbf{4d^8}$, $4d^7(5p, 5d, 6s, 6p)$, $4d^6 5s(5p, 5d, 6s)$	1,545	250,476
Ru II	$\mathbf{4d^7}$, $4d^6(5s-5d, 6s, 6p)$	818	76,592
Ru III	$\mathbf{4d^6}$, $4d^5(5s-5d, 6s)$	728	49,066
Te I	$\mathbf{5s^2 5p^4}$, $\mathbf{5s^2 5p^3 (4f, 5d, 5f, 6s-6f, 7s-7d, 8s)}$, $5s5p^5$	329	14,482
Te II	$\mathbf{5s^2 5p^3}$, $\mathbf{5s^2 5p^2 (4f, 5d, 5f, 6s-6f, 7s-7d, 8s)}$, $5s5p^4$	253	9,167
Te III	$\mathbf{5s^2 5p^2}$, $\mathbf{5s^2 5p(5d, 6s-6d, 7s)}$, $5s5p^3$	57	419
Nd I	$\mathbf{4f^4 6s^2}$, $\mathbf{4f^4 6s(5d, 6p, 7s)}$, $\mathbf{4f^4 5d^2}$, $\mathbf{4f^4 5d6p}$, $4f^3 5d6s^2$, $4f^3 5d^2(6s, 6p)$, $4f^3 5d6s6p$	31,358	70,366,259
Nd II	$\mathbf{4f^4 6s}$, $\mathbf{4f^4 5d}$, $4f^4 6p$, $4f^3 6s(5d, 6p)$, $4f^3 5d^2$, $4f^3 5d6p$	6,888	3,951,882
Nd III	$\mathbf{4f^4}$, $4f^3(5d, 6s, 6p)$, $4f^2 5d^2$, $4f^2 5d(6s, 6p)$, $4f^2 6s6p$	2252	458,161
Er I	$\mathbf{4f^{12} 6s^2}$, $\mathbf{4f^{12} 6s(5d, 6p, 6d, 7s, 8s)}$, $4f^{11} 6s^2(5d, 6p)$, $4f^{11} 5d^2 6s$, $4f^{11} 5d6s(6p, 7s)$	10,535	9,247,777
Er II	$\mathbf{4f^{12} 6s}$, $4f^{12}(5d, 6p)$, $4f^{11} 6s^2$, $4f^{11} 6s(5d, 6p)$, $4f^{11} 5d^2$, $4f^{11} 5d6p$	5,333	2,432,665
Er III	$\mathbf{4f^{12}}$, $4f^{11}(5d, 6s, 6p)$	723	42,671

Energy levels of Nd II

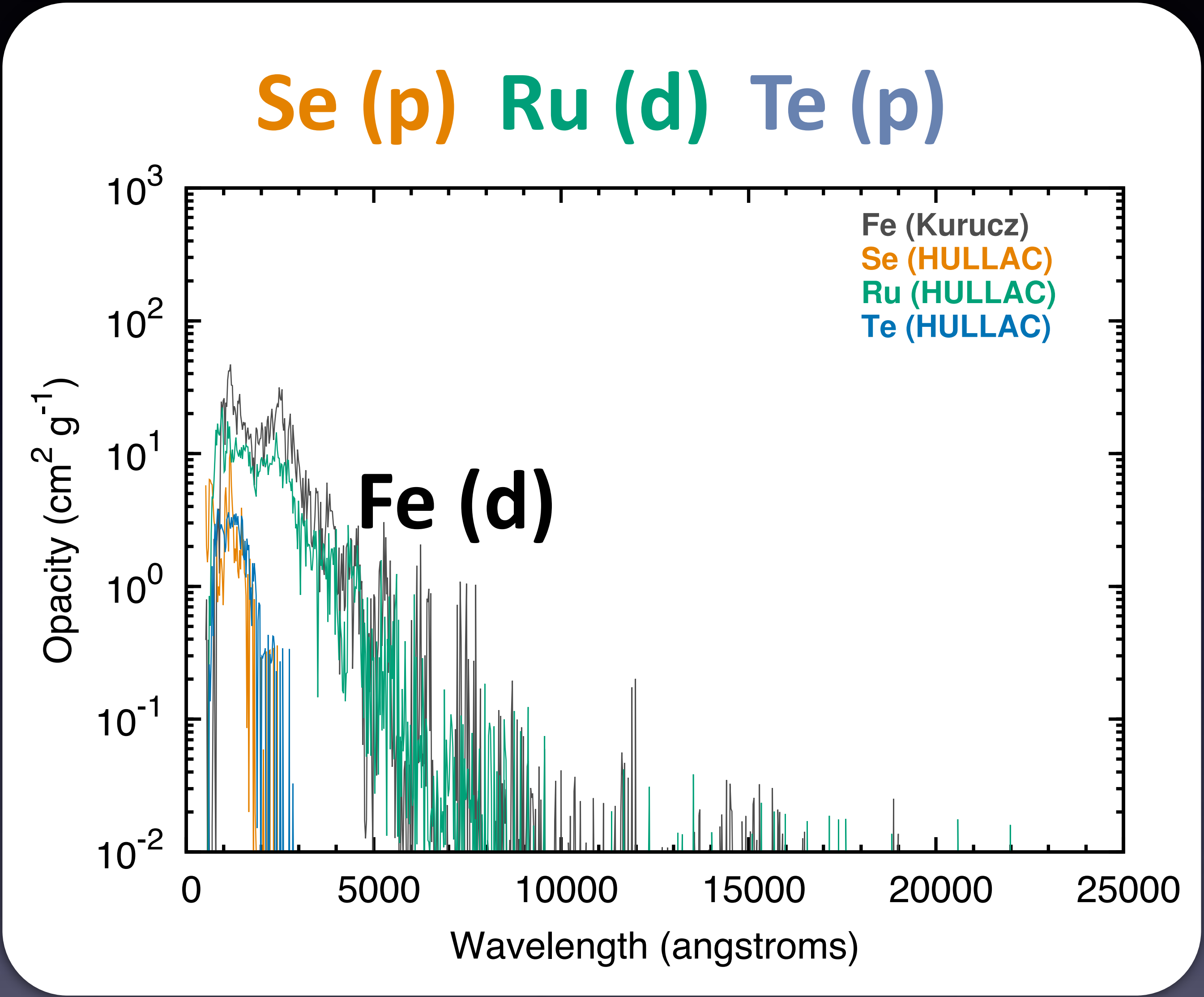


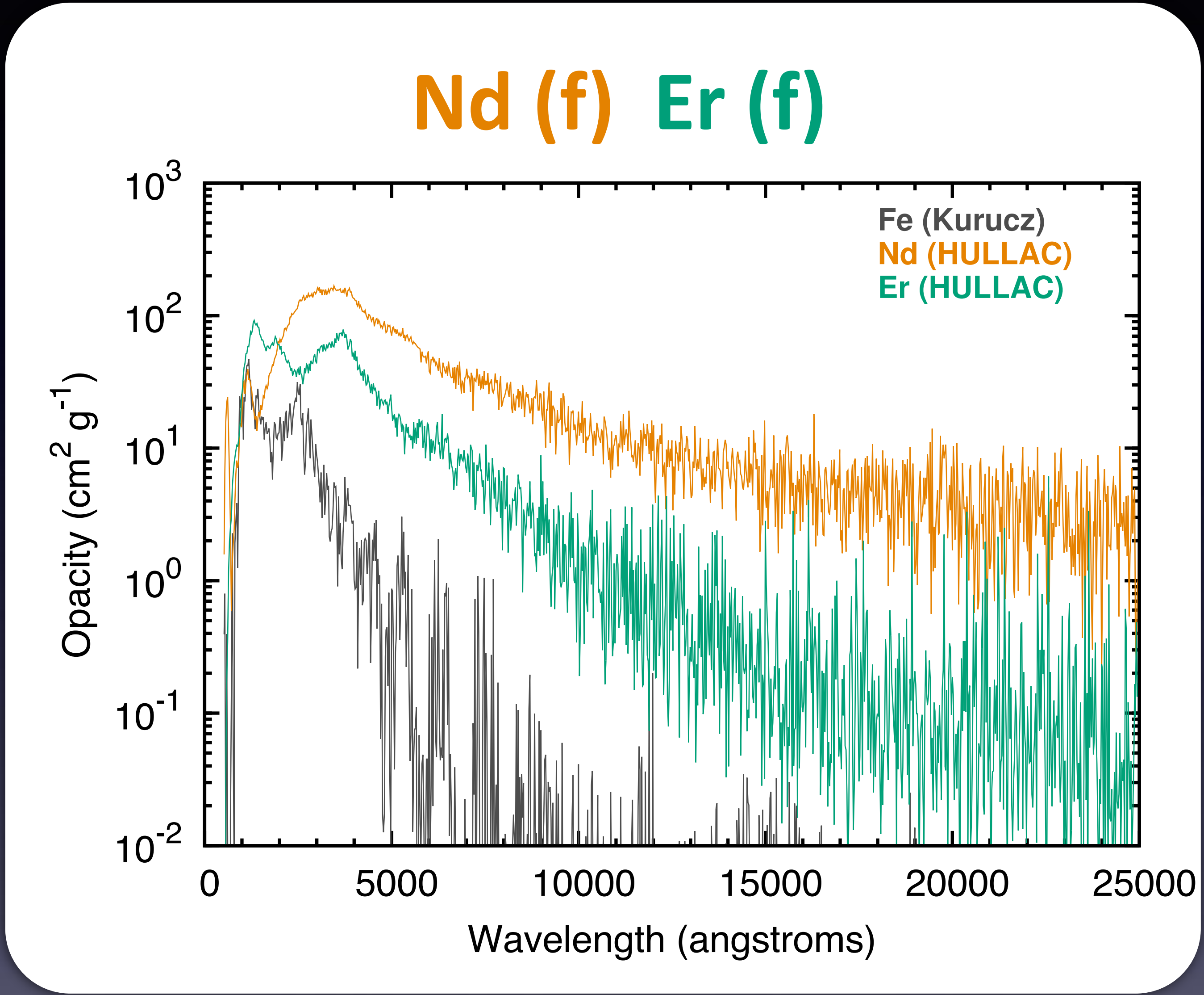
MT+17



Kasen+13 (Autostructure code)

Bound-bound opacity





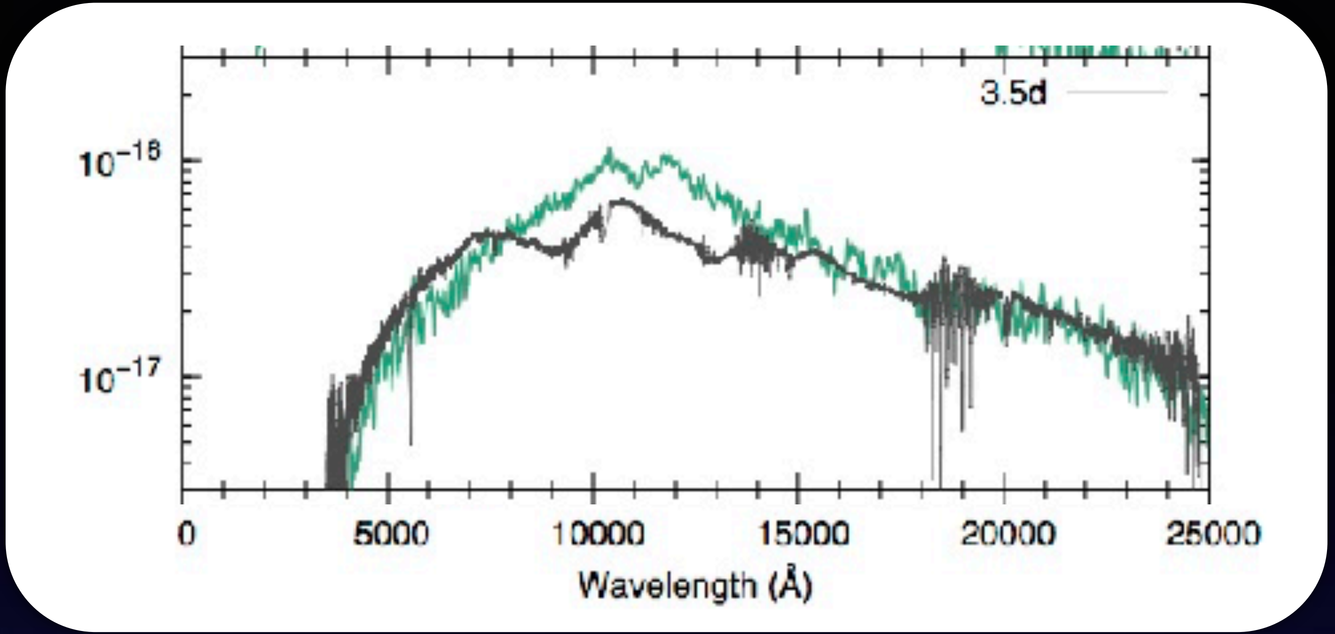
κ (p shell) << κ (d shell) << κ (f shell)

MT, Kato, Gaigalas, Rynkun, Radziute, Wanajo, Sekiguchi, Nakamura, Tanuma, Murakami, Sakaue 2017 (arXiv:1708.09101)

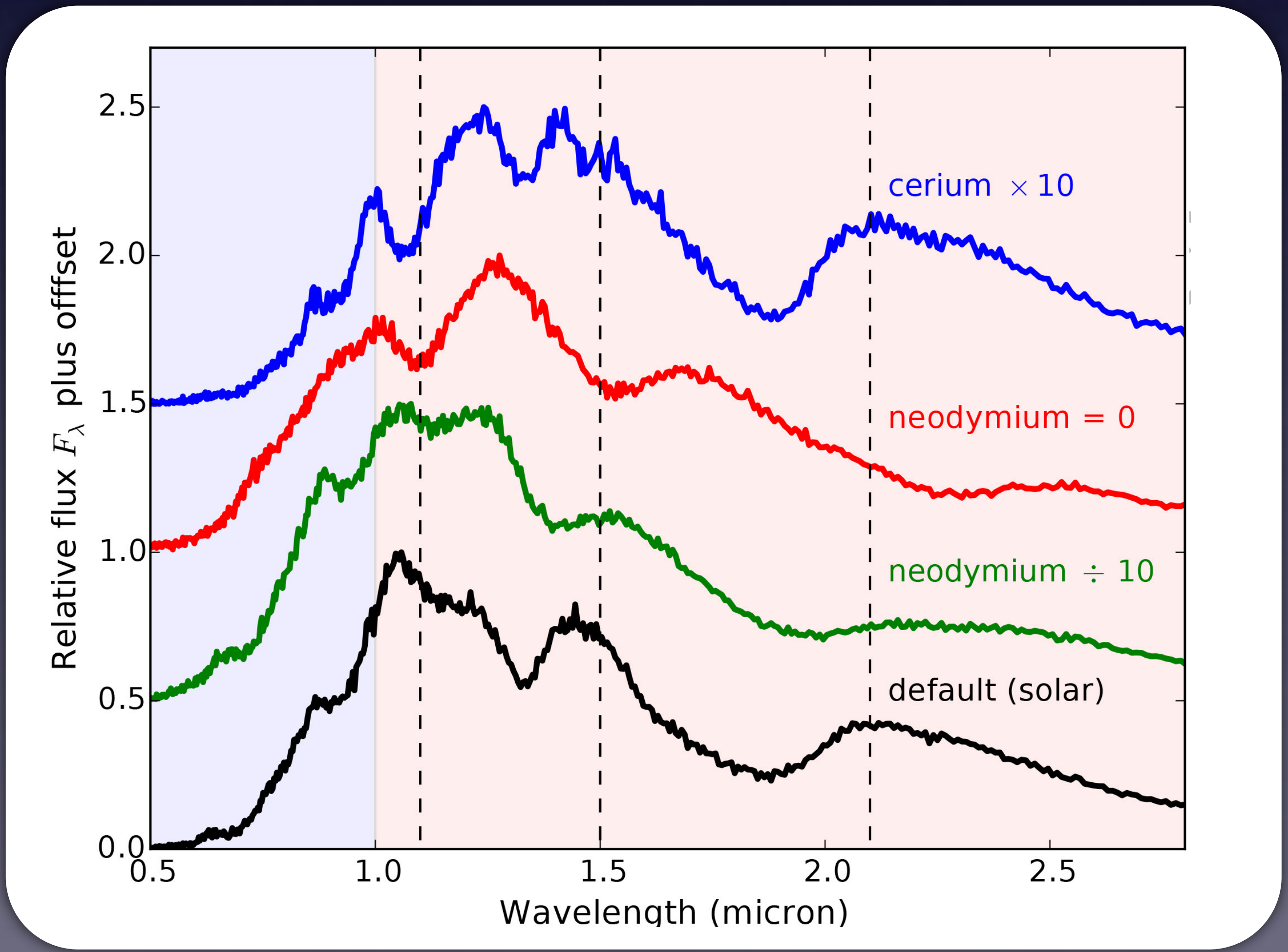
==> Application to GW170817 (MT+17b)

New atomic calculations (Kasen et al. 2017)

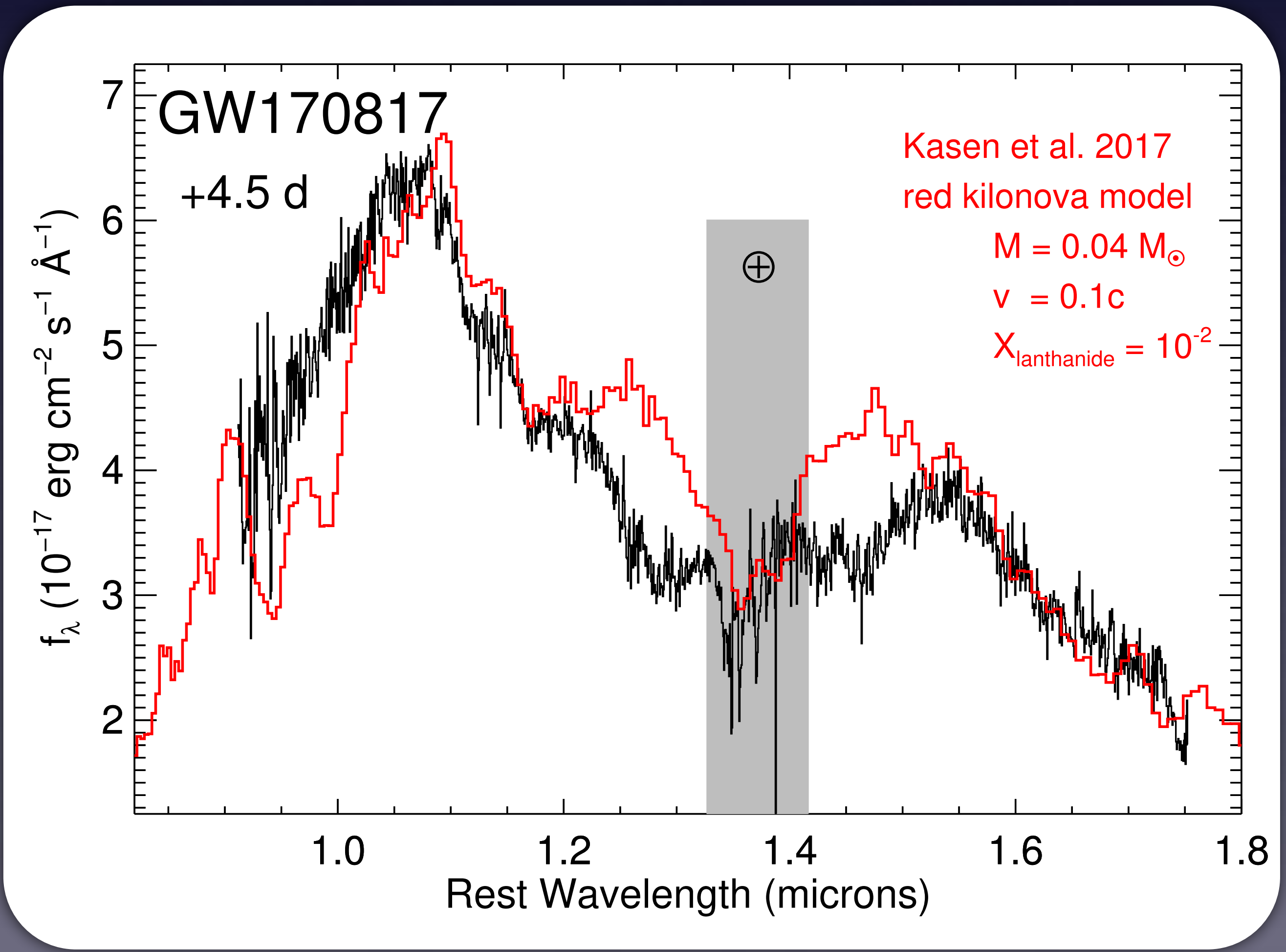
All lanthanide elements (neutral to +4 ion)



MT+17



Kasen+17



Chornock+17

Summary

- **Lessons learned from GW170817**
  - Red and blue component
  - Mej (La-rich) ~ 0.03 Msun ==> post-merger?
  - Mej (La-poor) ~ 0.02 Msun ==> origin? jet?
  - Wide range of r-process elements in NS mergers
- **Future**
  - More events with different masses, mass ratios, viewing angle as well as BH-NS mergers
  - Origin of r-process elements? => Test of solar pattern => atomic data are crucial (theory + experiments)