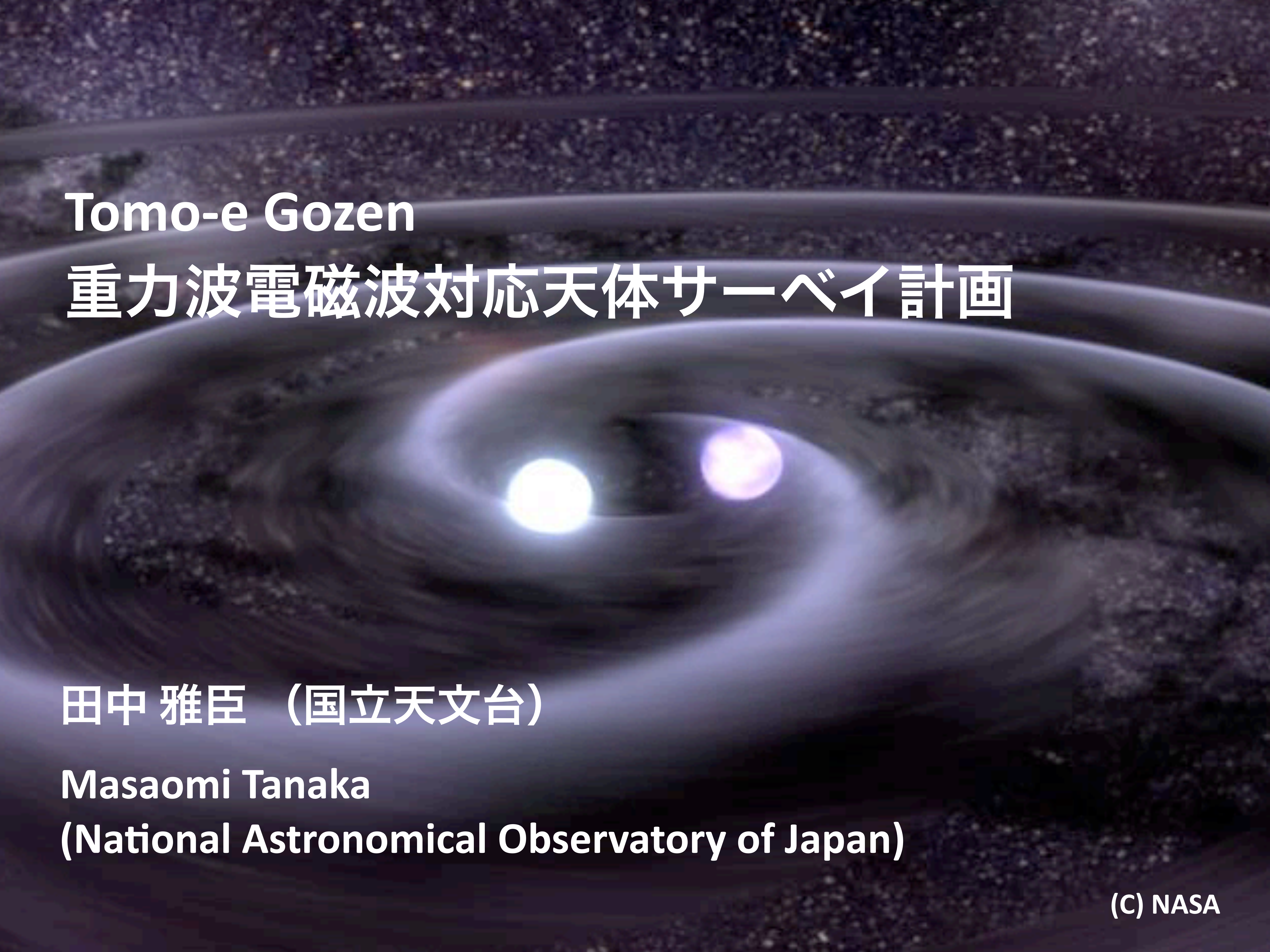


Tomo-e Gozen
重力波電磁波対応天体サーベイ計画

田中 雅臣 （国立天文台）

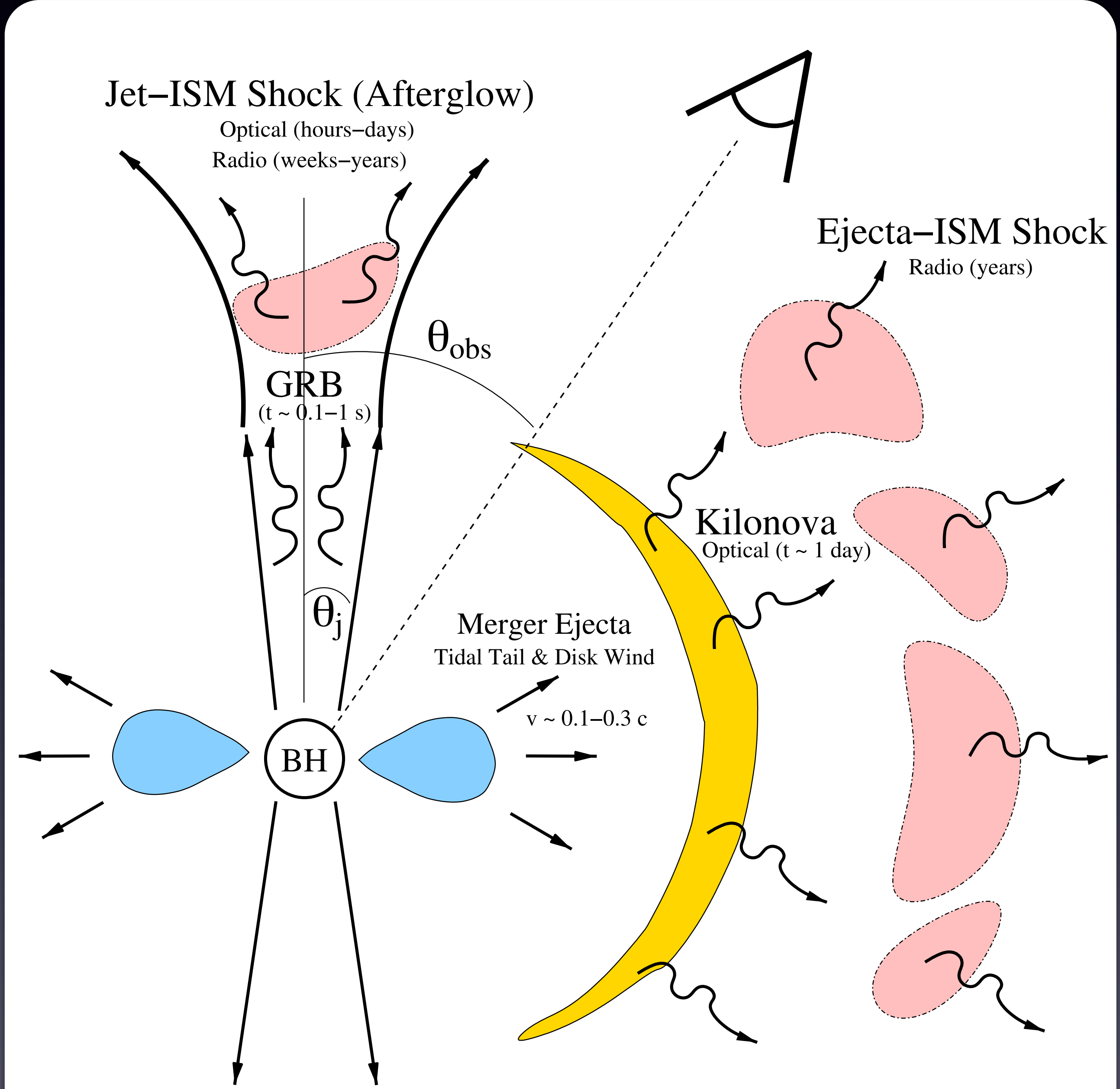
Masaomi Tanaka
(National Astronomical Observatory of Japan)

(C) NASA

- Optical emission from GW sources
- Follow-up survey with Tomo-e

Electromagnetic signature from NS mergers

- On-axis short GRB
  - strongly beamed ✗
  - (isotropic soft X-ray?)
- Off-axis radio afterglow
  - isotropic ✓
  - delayed by ~> 1 yr ✗
- Radioactive emission "kilonova" or "macronova"
  - isotropic ✓
  - short delay ✓



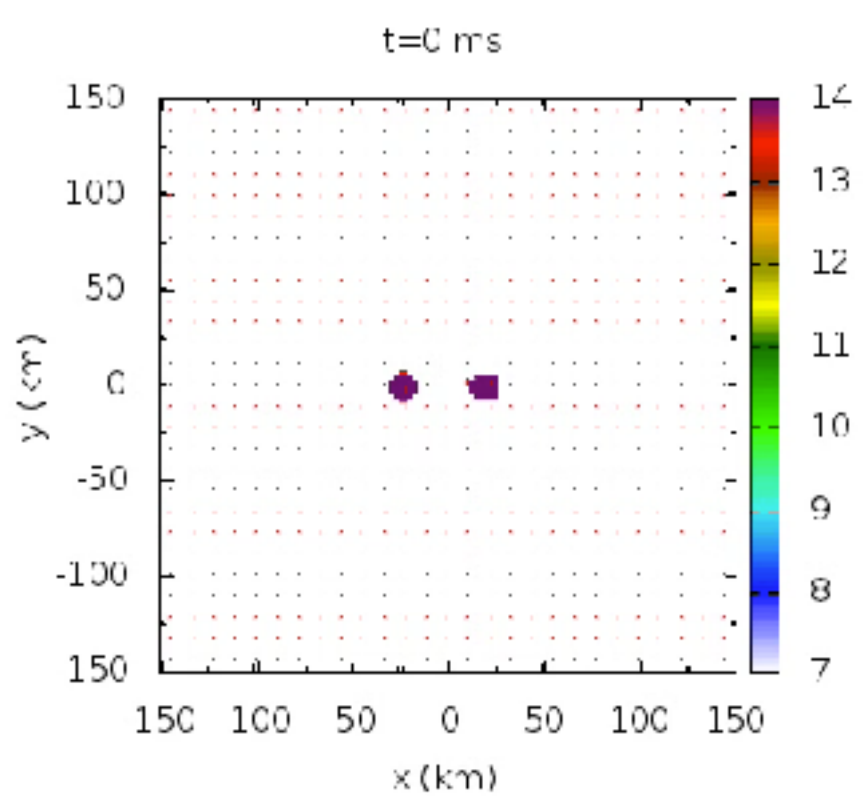
Metzger & Berger 2012

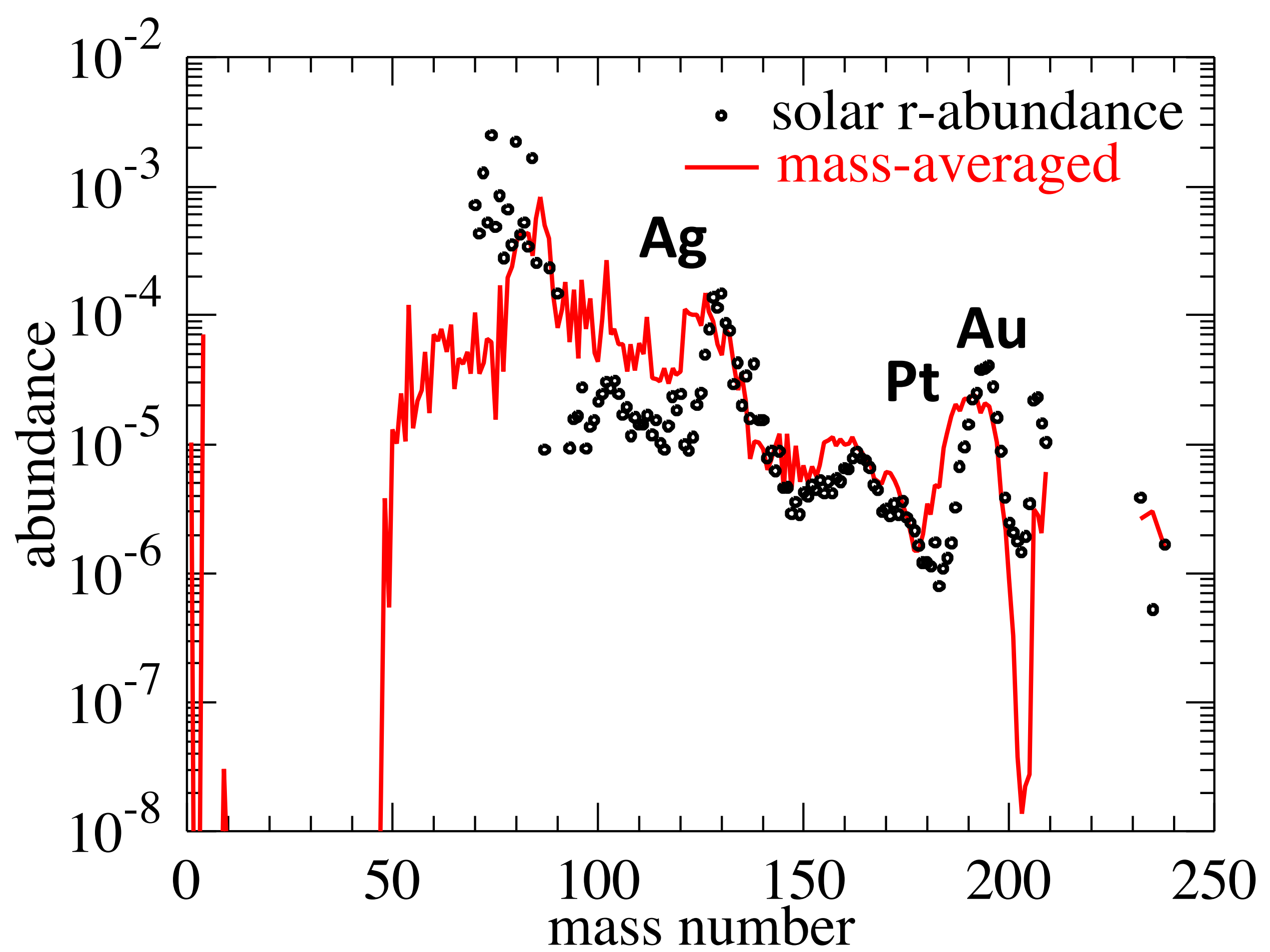
Mass ejection

r-process nucleosynthesis

M ~ 10^{-3} - 10^{-2} Msun
v ~ 0.1 - 0.2 c

=> solar abundance





Hotokezaka+13, Rosswog+13, …

Wanajo+14, Just+15, …

NS merger as a possible origin of r-process elements

Event rate

$R_{NSM} \sim 10^3$ Gpc^{-3} yr^{-1}
$\sim$ 30 GW events yr^{-1}
(w/ Adv. detectors, < 200 Mpc)

↑ **GW**

LIGO O1
$R_{NSM} < 10^4$ Gpc^{-3} yr^{-1}

Ejection per event

M_{ej}(r-process) $\sim 10^{-2}$ Msun

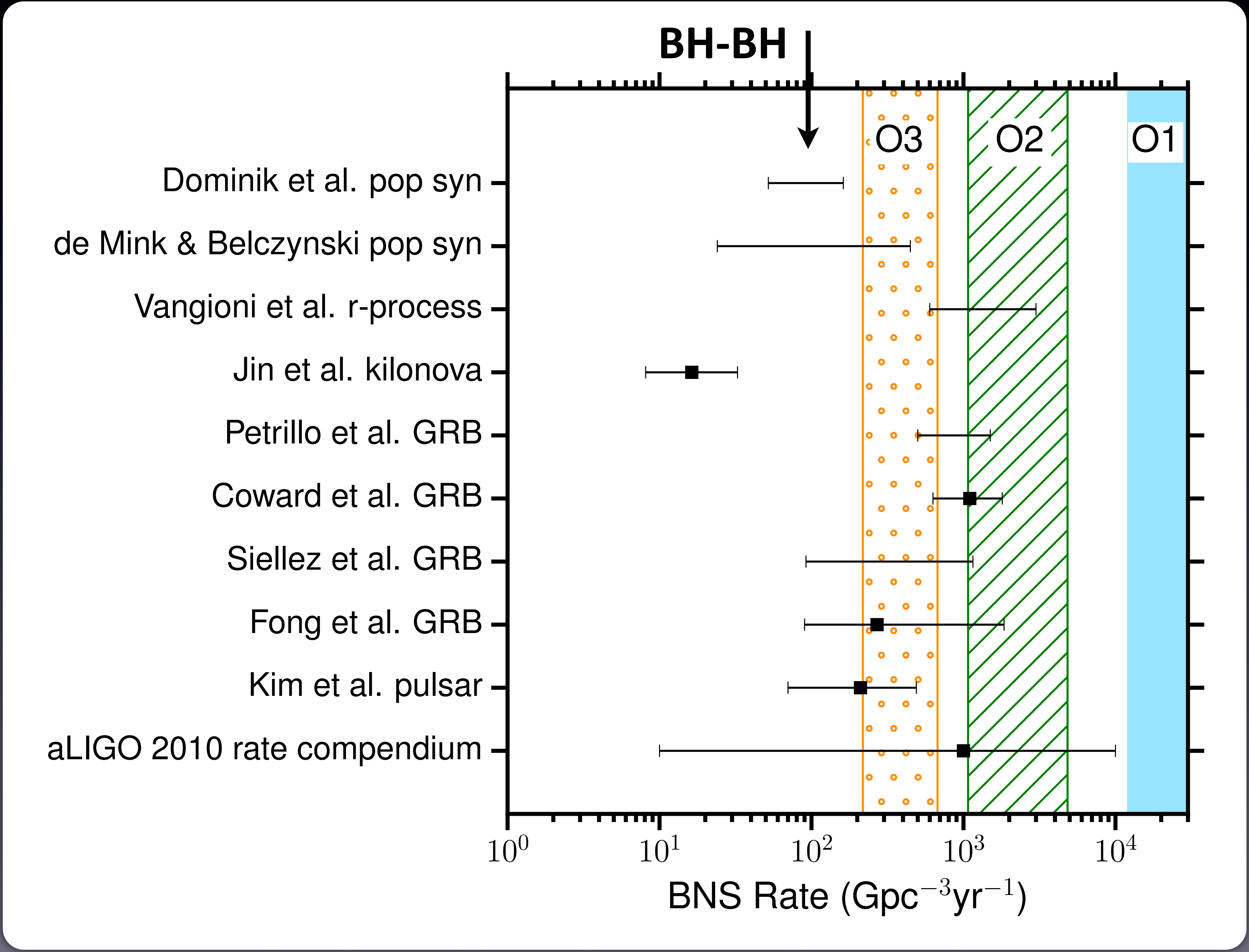
↑ **EM**

Enough to explain the r-process abundance in our Galaxy

M(Galaxy, r-process) $\sim M_{ej}(r) \times (R_{NSM} \times t_G)$
$\sim 10^{-2} \times 10^{-4} \times 10^{10} \sim 10^4$ Msun

Constraints on the NS-NS merger rate

Expected event rates



O1: 2015-2016

O2: 2016-2017

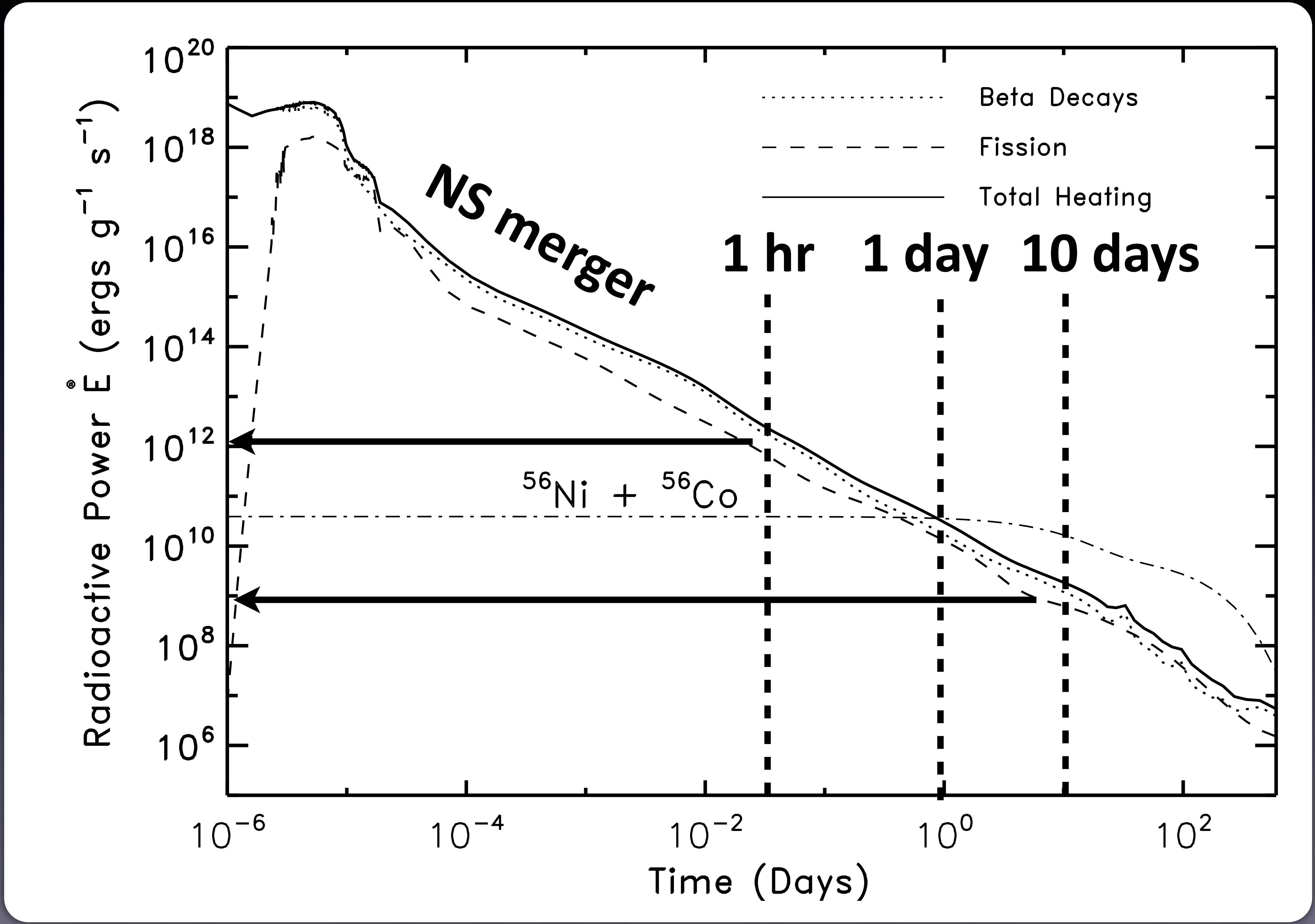
O3: 2018

arXiv:1607.07456

Heating by radioactive decay of r-process nuclei

10^{43} erg s^{-1}

10^{40} erg s^{-1}

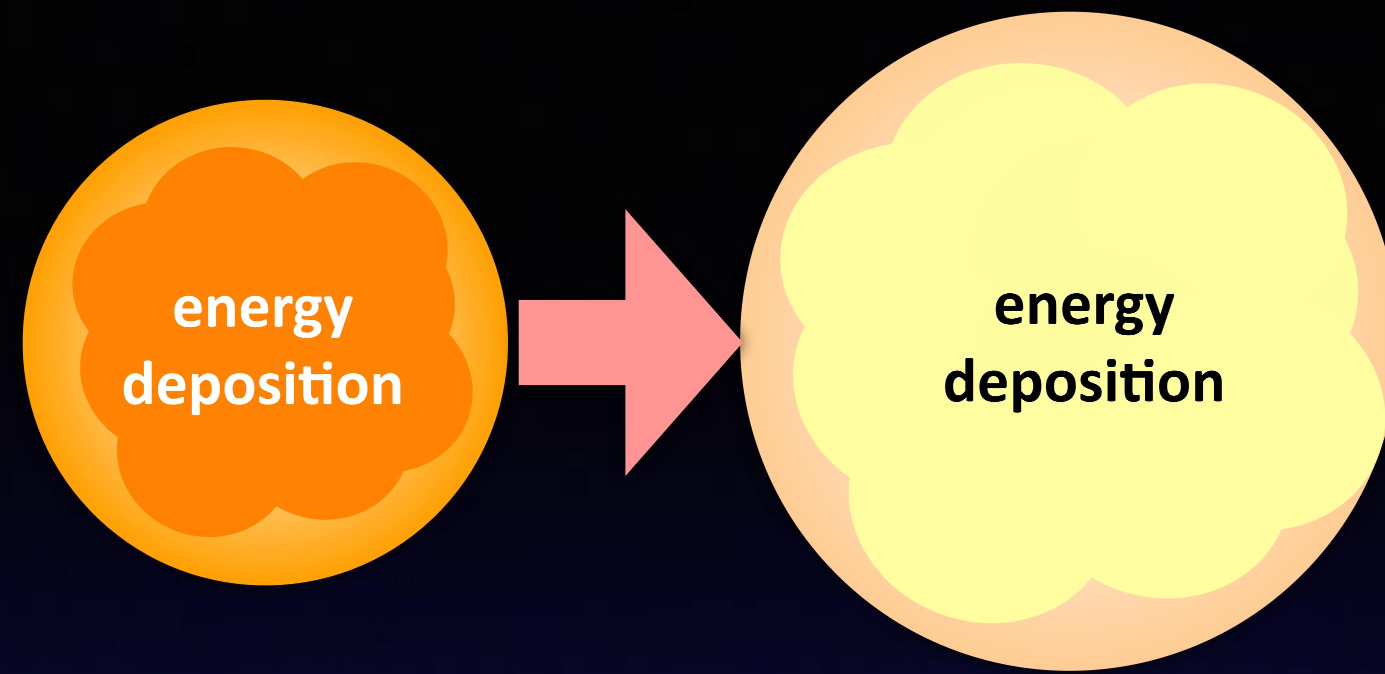


(for M = 0.01 Msun)

Metzger+10

"kilonova/macronova"

Li & Paczynski 98, Metzger+10,
Kasen+13, Barnes & Kasen 13,
MT & Hotokezaka 13, MT+14,



Timescale

$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$
$$\simeq 8.4\ {\rm days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10\ {\rm cm^2\ g^{-1}}}\right)^{1/2}$$

Luminosity

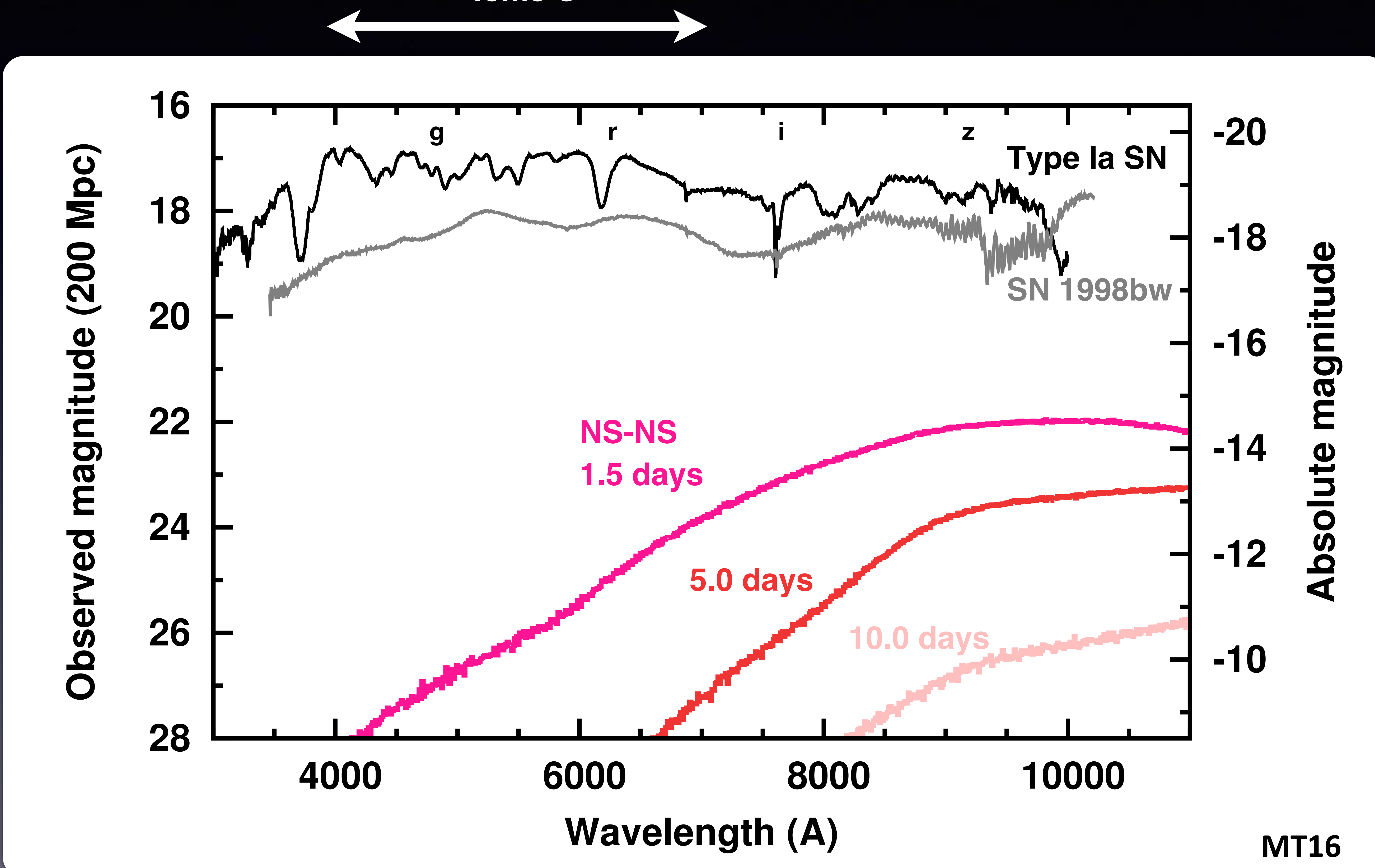
$$L_{\rm peak} = L_{\rm dep}(t_{\rm peak})$$
$$\simeq 1.3 \times 10^{40}\ {\rm erg\ s^{-1}} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{10\ {\rm cm^2\ g^{-1}}}\right)^{-0.65}$$

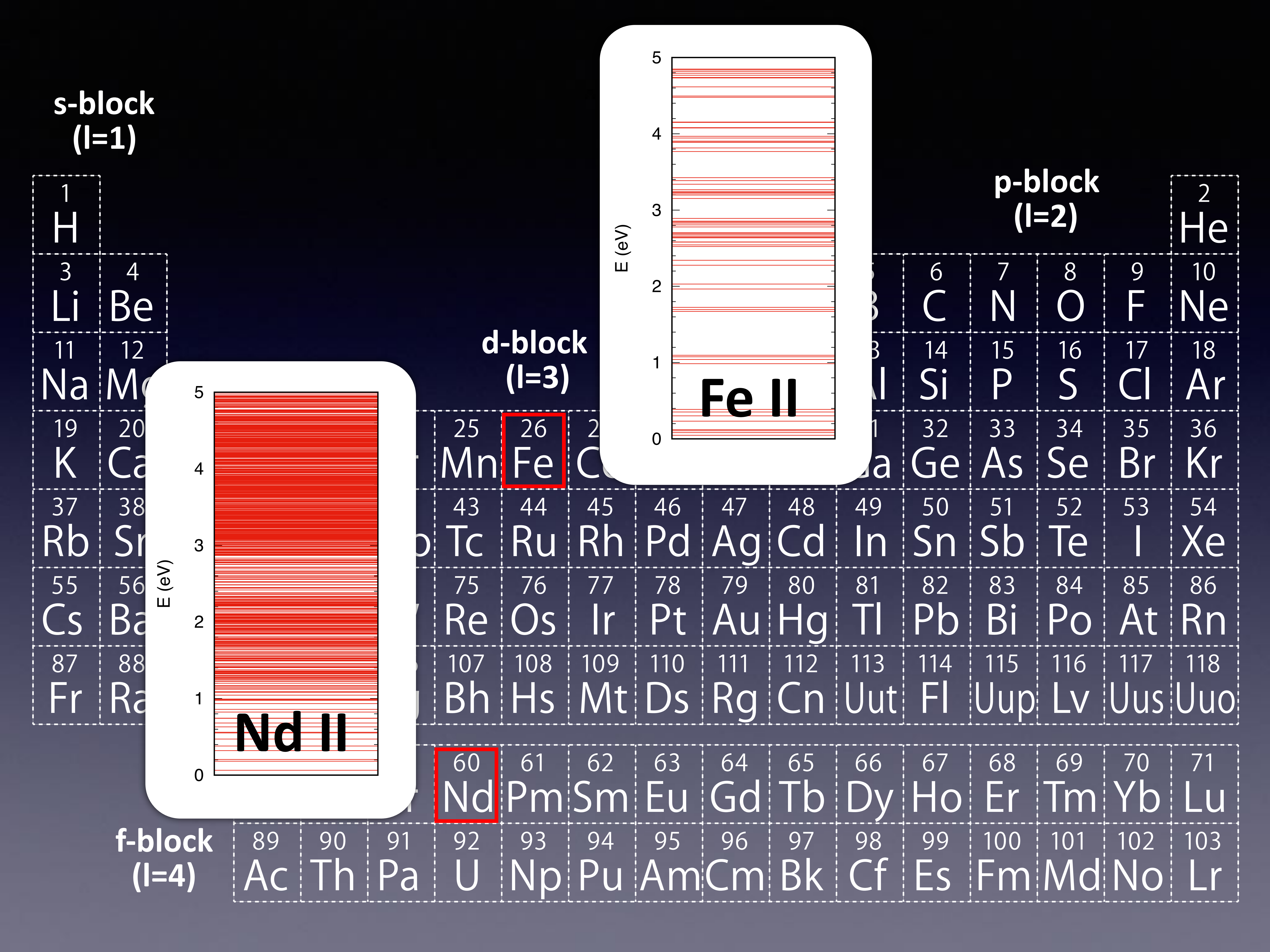
see Tanaka 2016, Advances in Astronomy

Faint (~ -14 mag), fast (~ week), and red (~ NIR)

Extremely red spectra

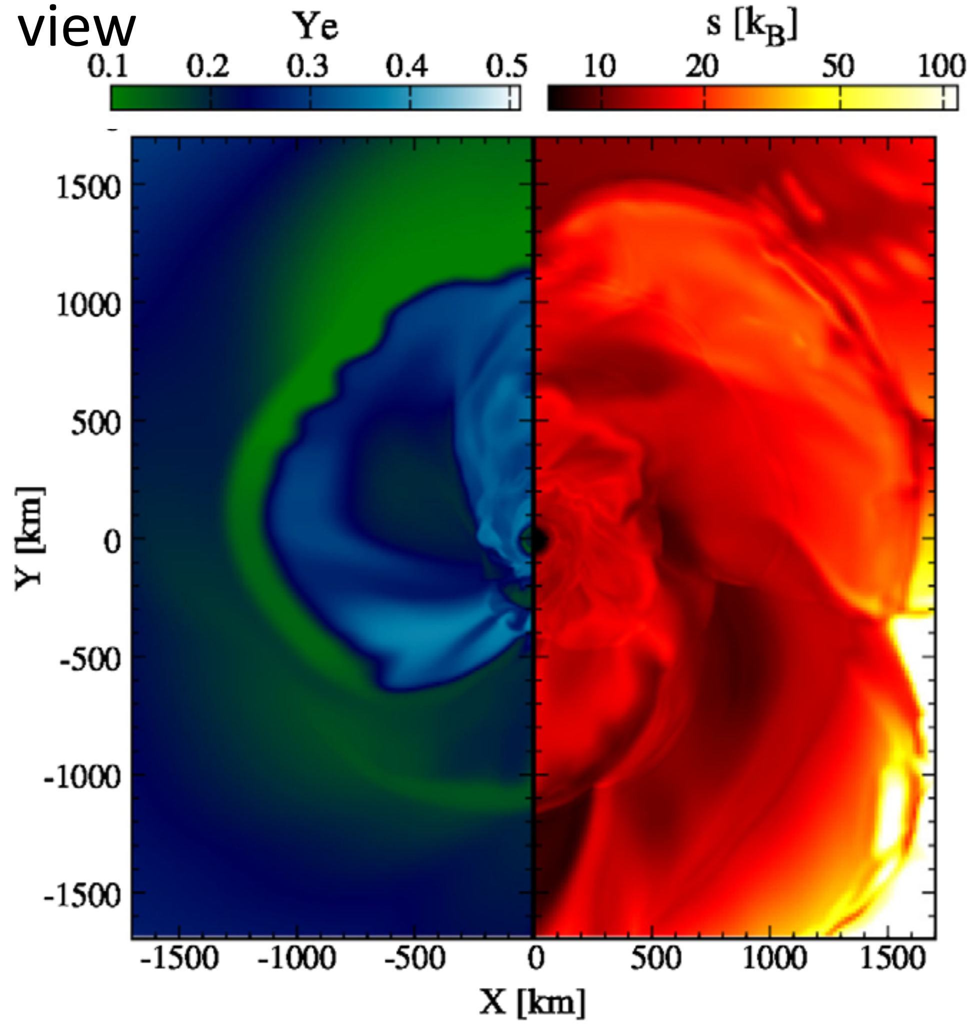
Tomo-e




s-block
(l=1)
p-block
(l=2)
d-block
(l=3)
f-block
(l=4)
Fe II
E (eV)
0 1 2 3 4 5
Nd II
E (eV)
0 1 2 3 4 5
1 H
2 He
3 Li
4 Be
6 C
7 N
8 O
9 F
10 Ne
11 Na
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
25 Mn
26 Fe
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
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
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
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

Dynamical ejecta

Top view



Sekiguchi+16

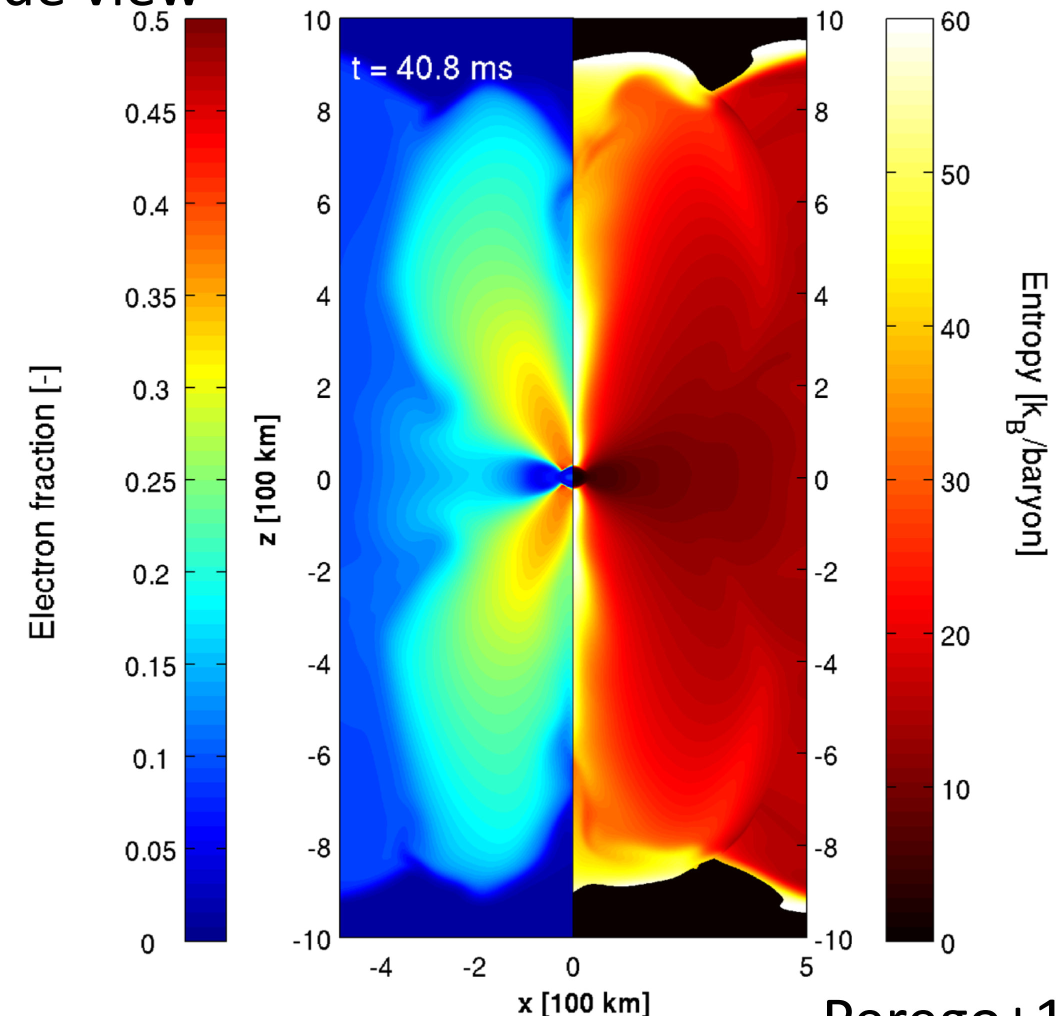
Rosswog+99, Lee+07, Goriely+11, Hotokezaka+13, Bauswein+13, Radice+16…

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

(wide Ye)

Post-dynamical ejecta

Side view



Perego+14

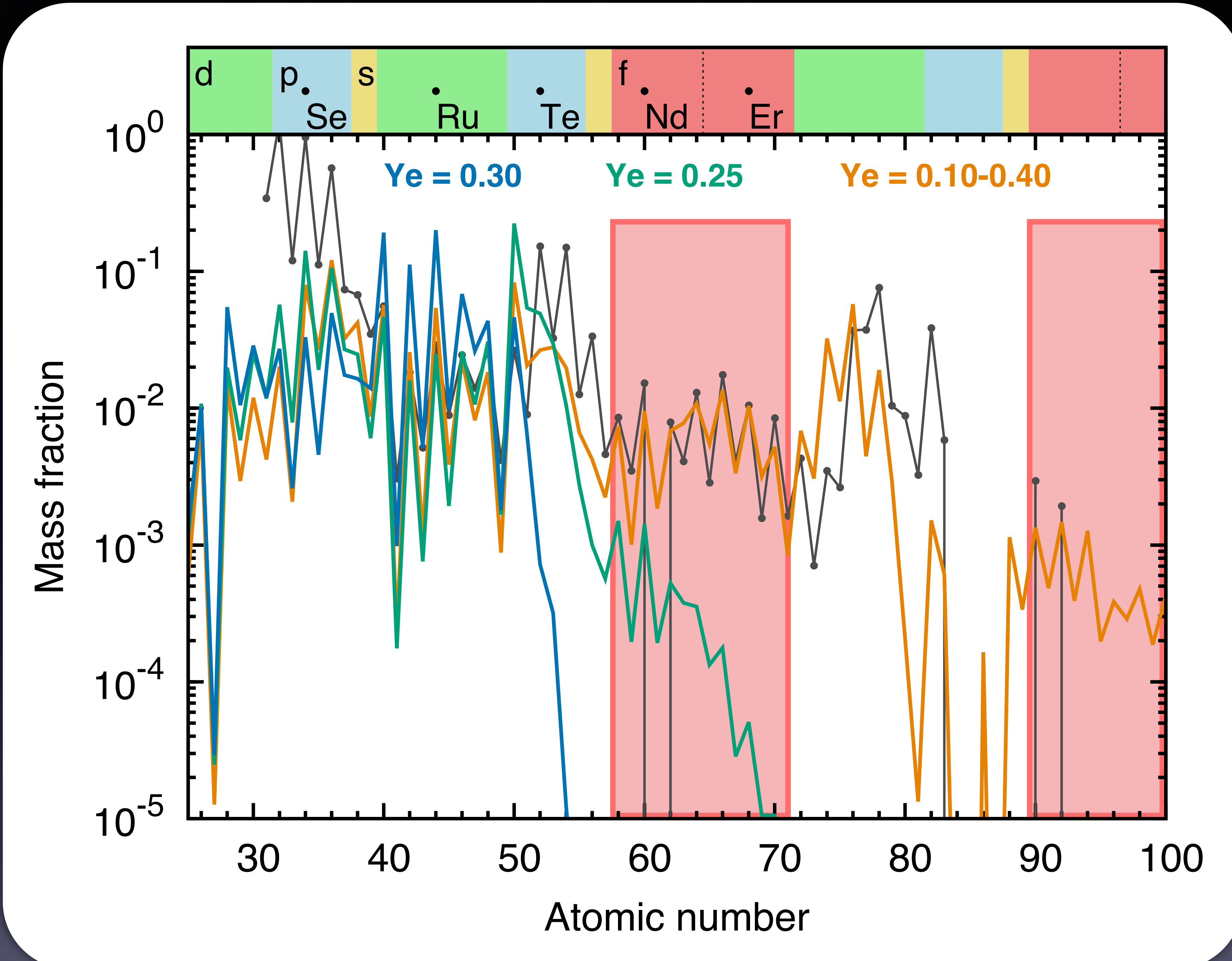
Fernandez+13,15, Perego+14, Kiuchi+14,15, Martin+15, Just+15, Wu+16, Siegel & Metzger 17…

Mej >~ 10^{-3} Msun

(high Ye)

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

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



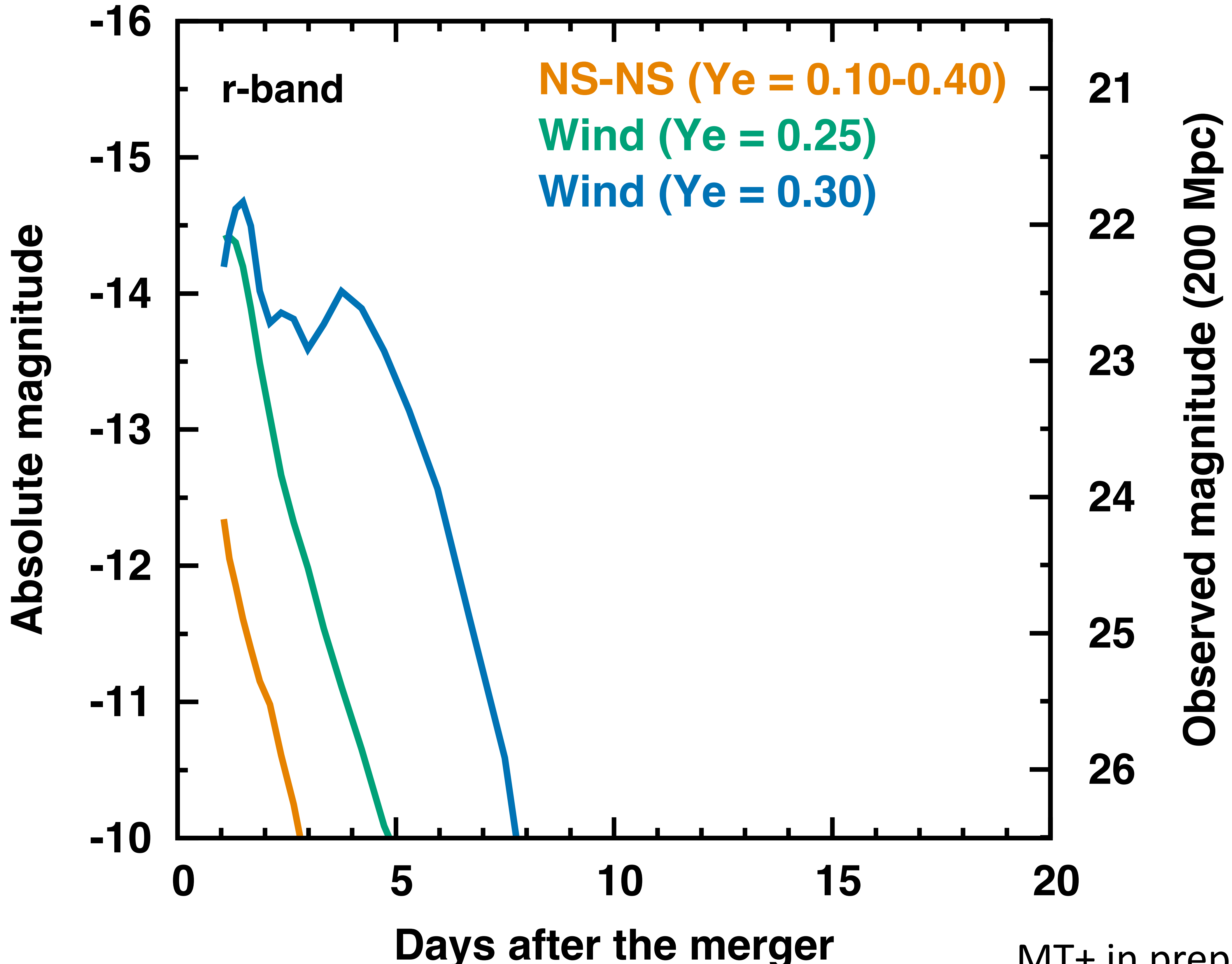
from Wanajo+14

"Blue" kilonova? Metzger+14, Kasen+15, Fernandez & Metzger 16, Metzger 16

New opacity calculations for
Se (Z=34), Ru (Z=44), Te (Z=52), Nd (Z=60), Er (Z=68)
==> κ ~ 0.5 cm^2 g^{-1} for Lanthanide-free ejecta (Ye ~ 0.3) MT+ in prep

Optical (r-band)

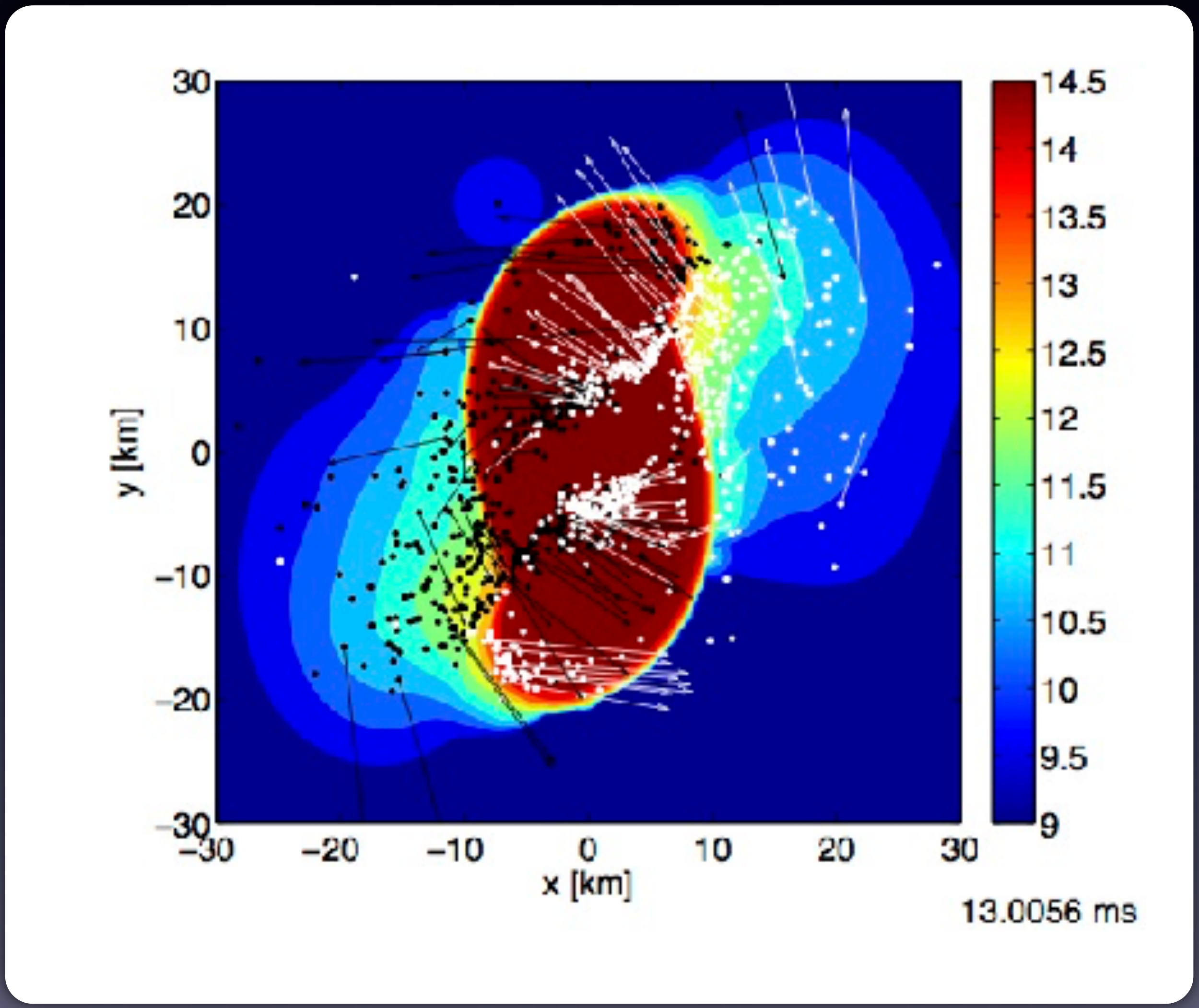
M = 0.01 Msun



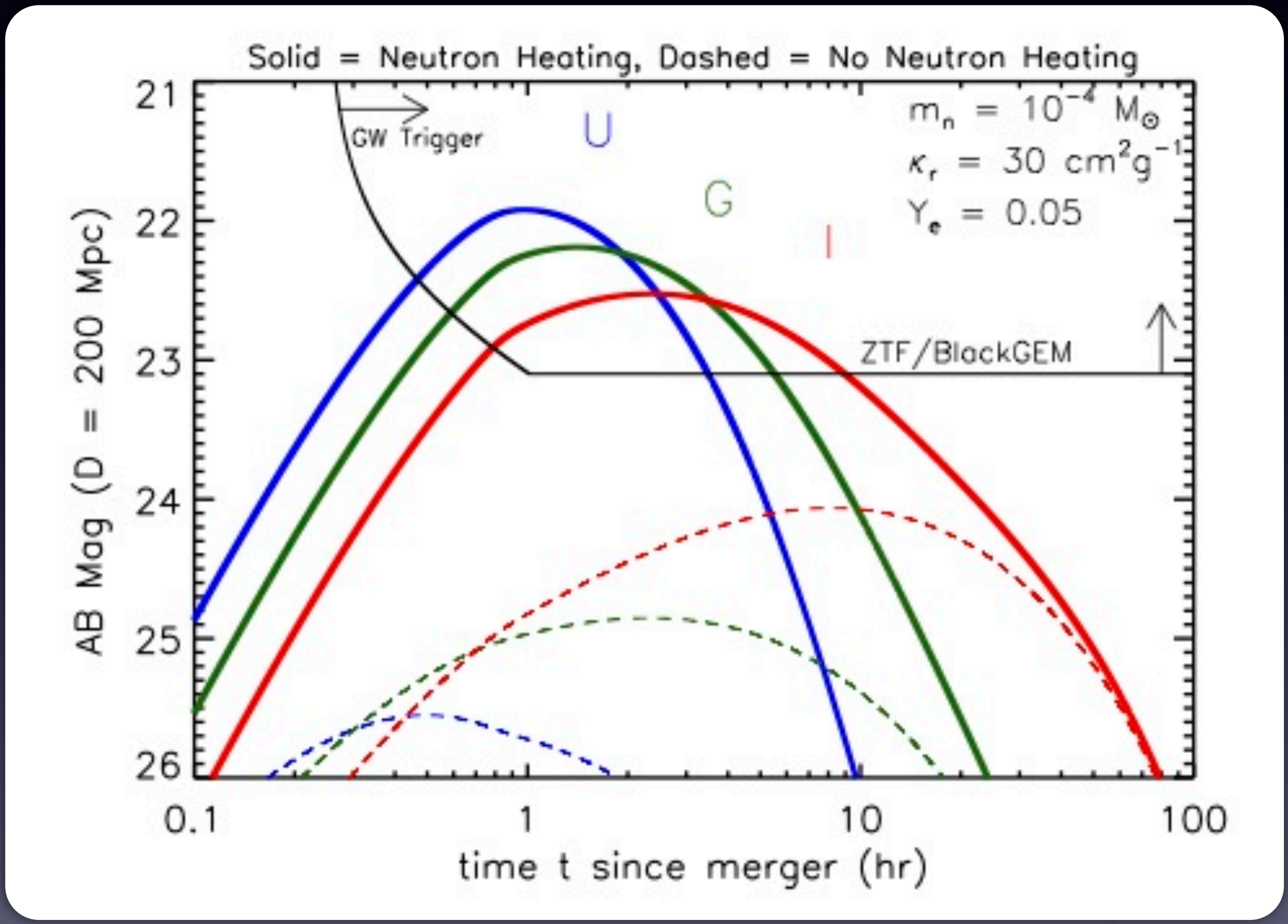
MT+ in prep.

Possible brighter/bluer/faster emission (1/2)

Precursor emission by free neutron decay?



Bauswein+13



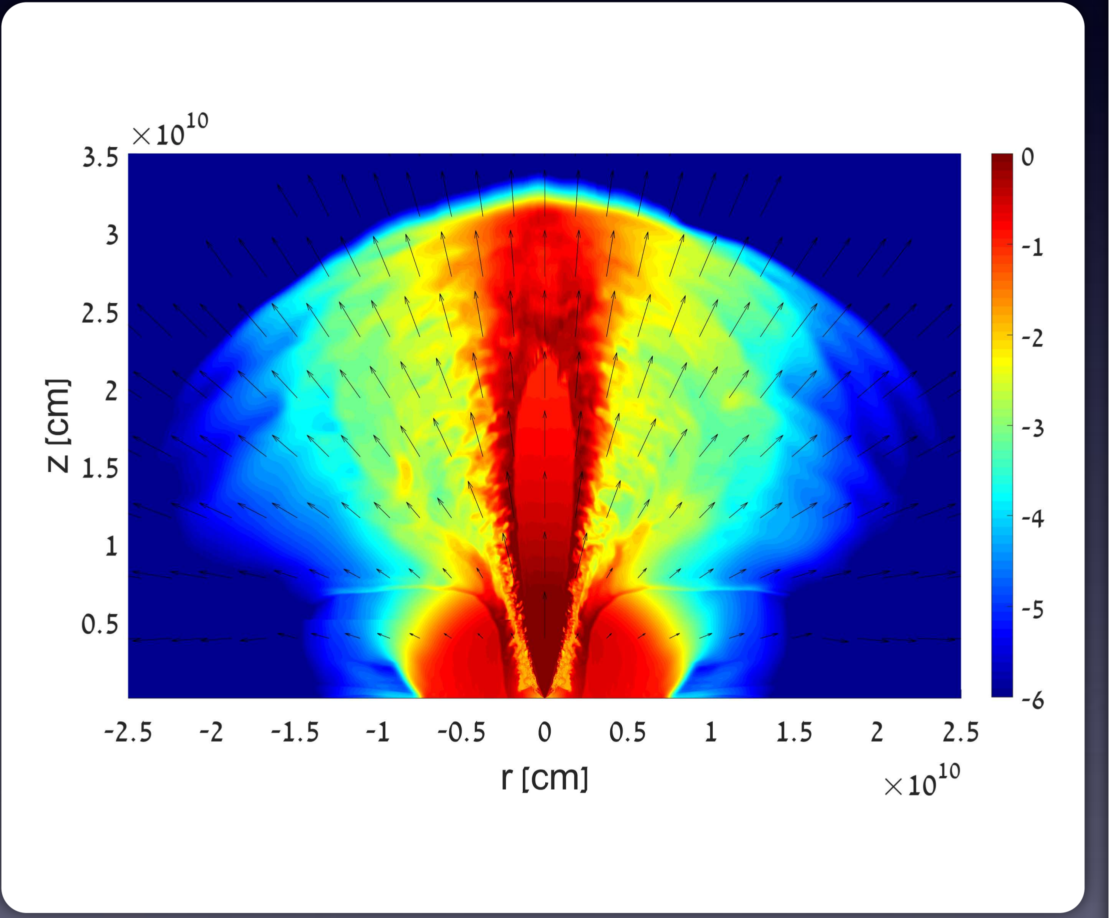
Metzger+15, Metzger 17

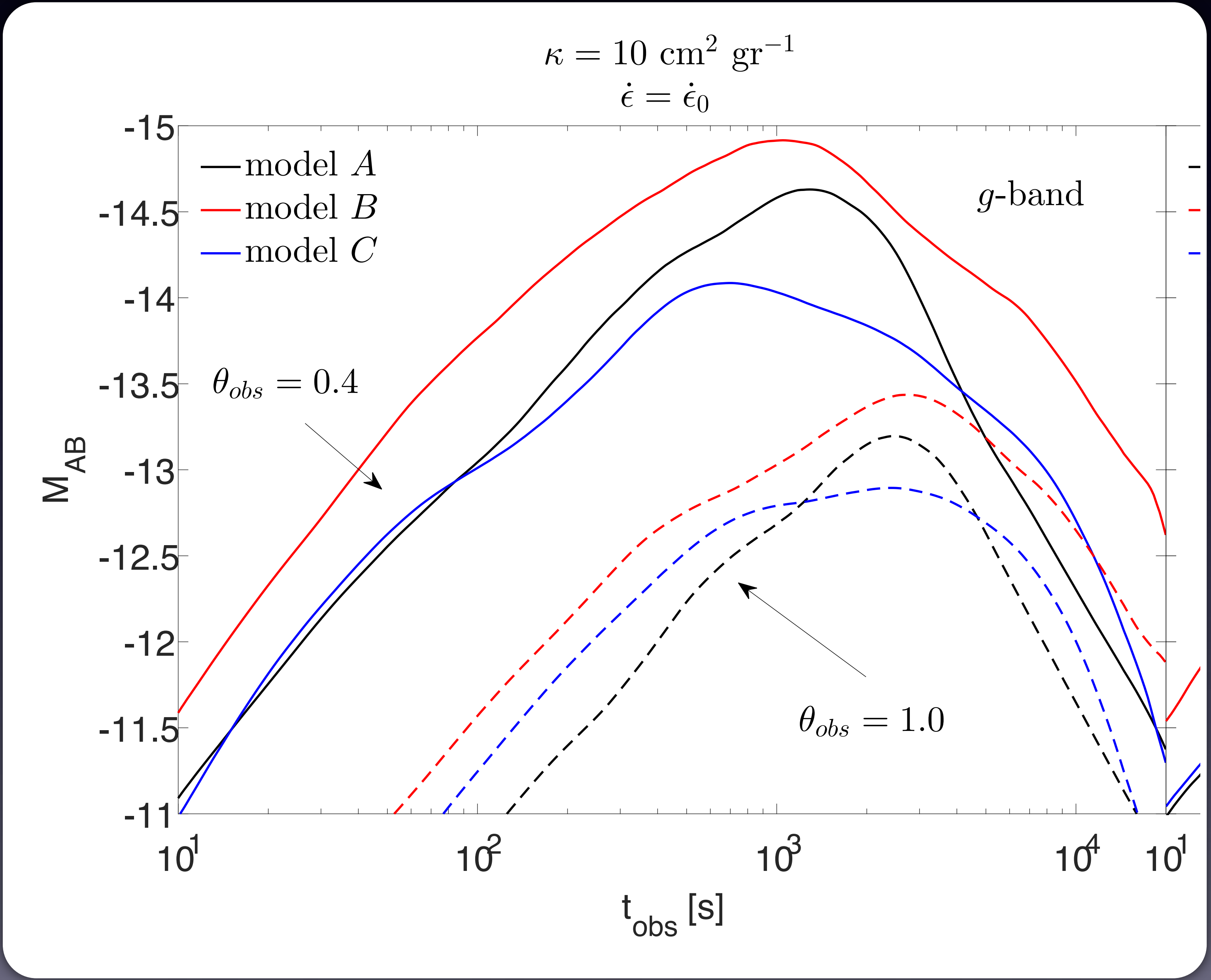
Fast material can exist also by shock (Kyutoku+14)

~3 hr, 22 mag @ 200 Mpc (absolute ~ -15 mag)

Possible brighter/bluer/faster emission (2/2)

Cocoon emission



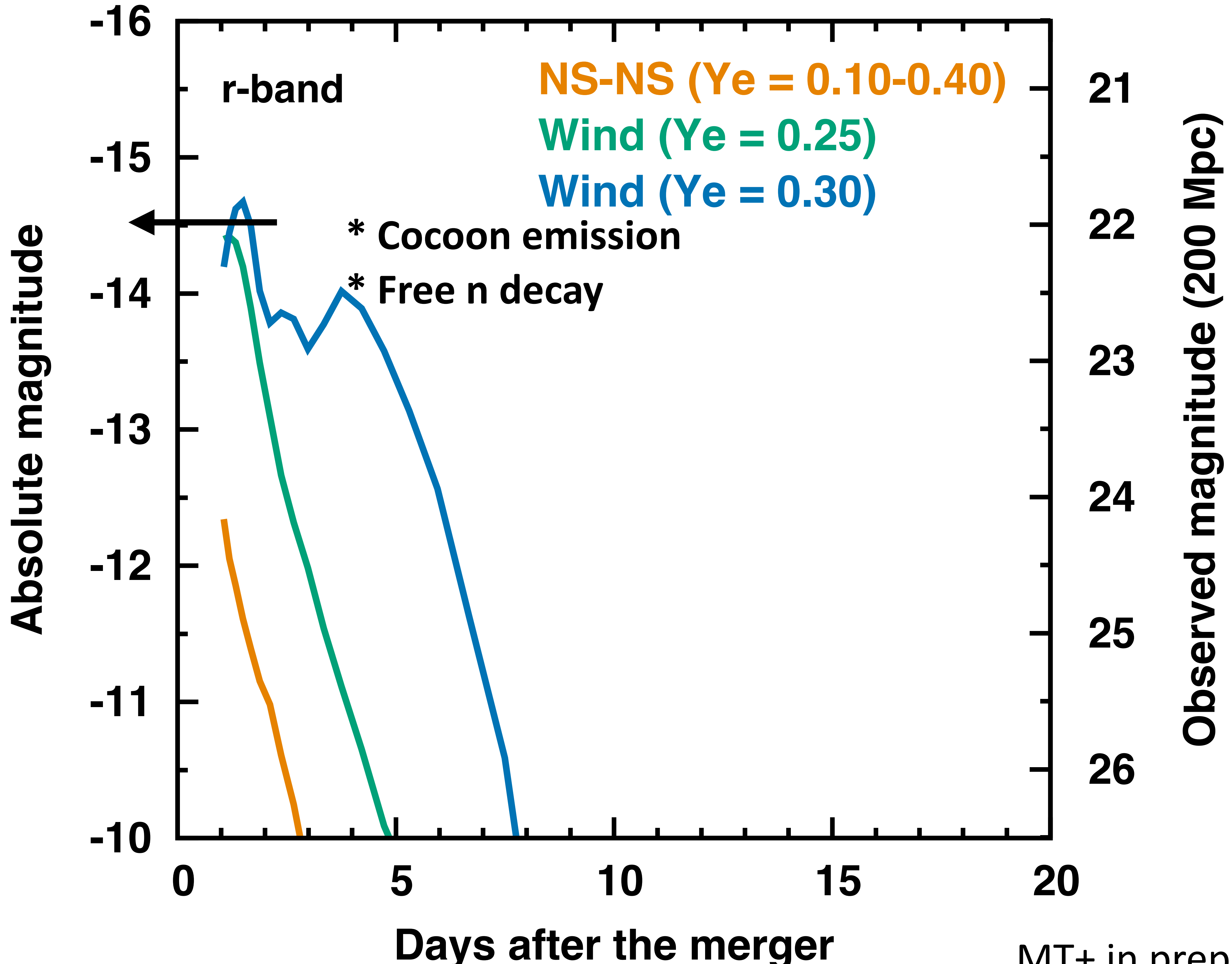


~3 hr, 22 mag @ 200 Mpc
(absolute ~ -15 mag)

Gottlieb+17

Optical (r-band)

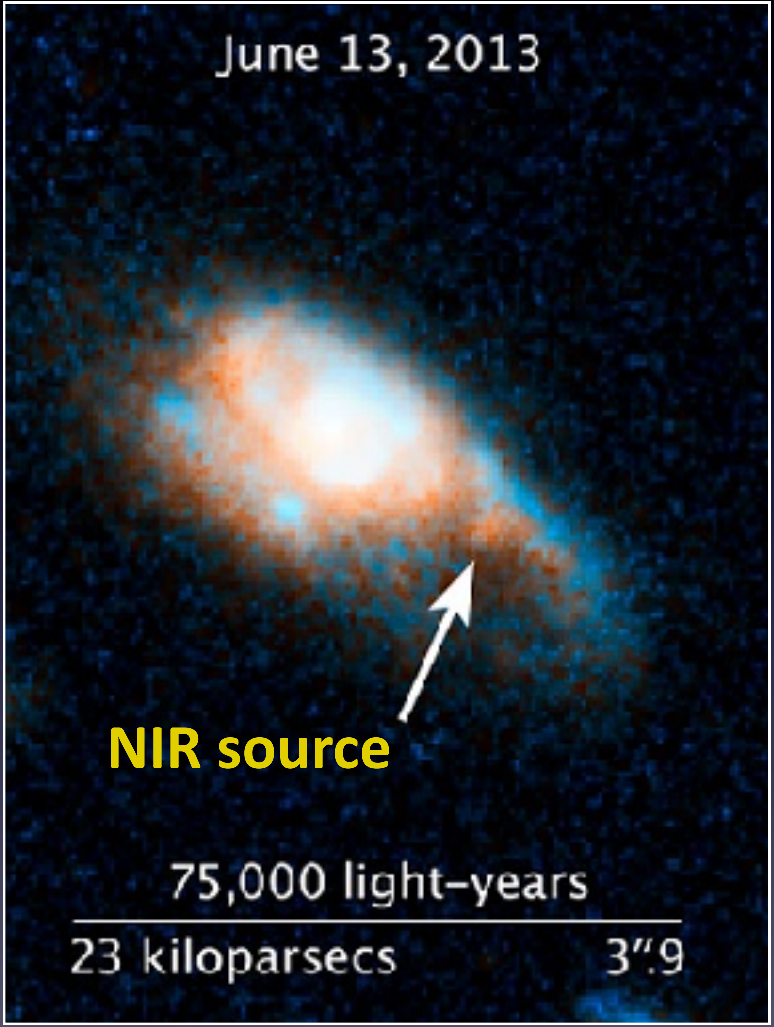
M = 0.01 Msun



MT+ in prep.

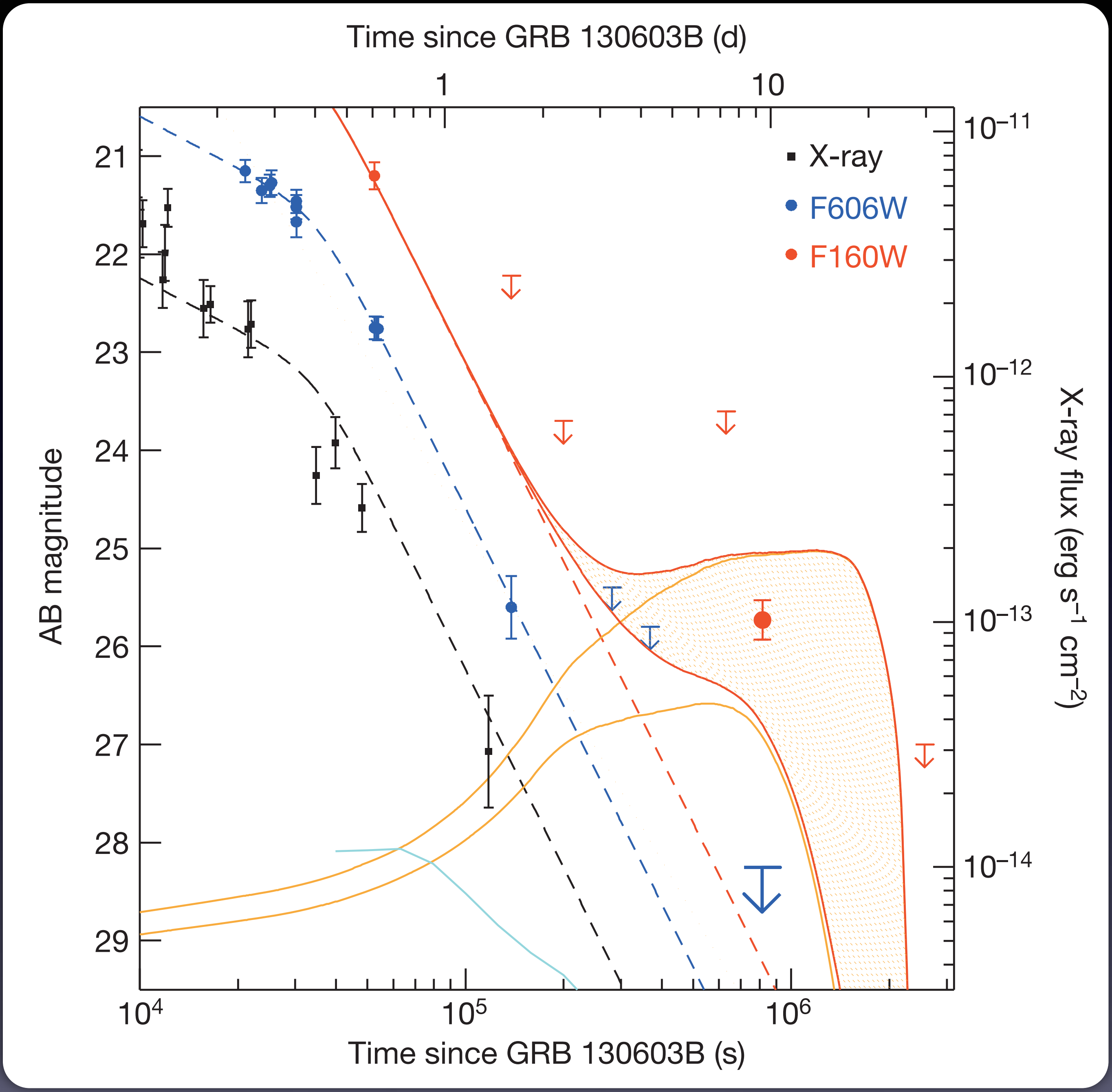
Constraints from short GRBs (1/2)

GRB 130603B



Tanvir+2013, Berger+2013

1 + 1(?) more cases
GRB 060614 & GRB 050709



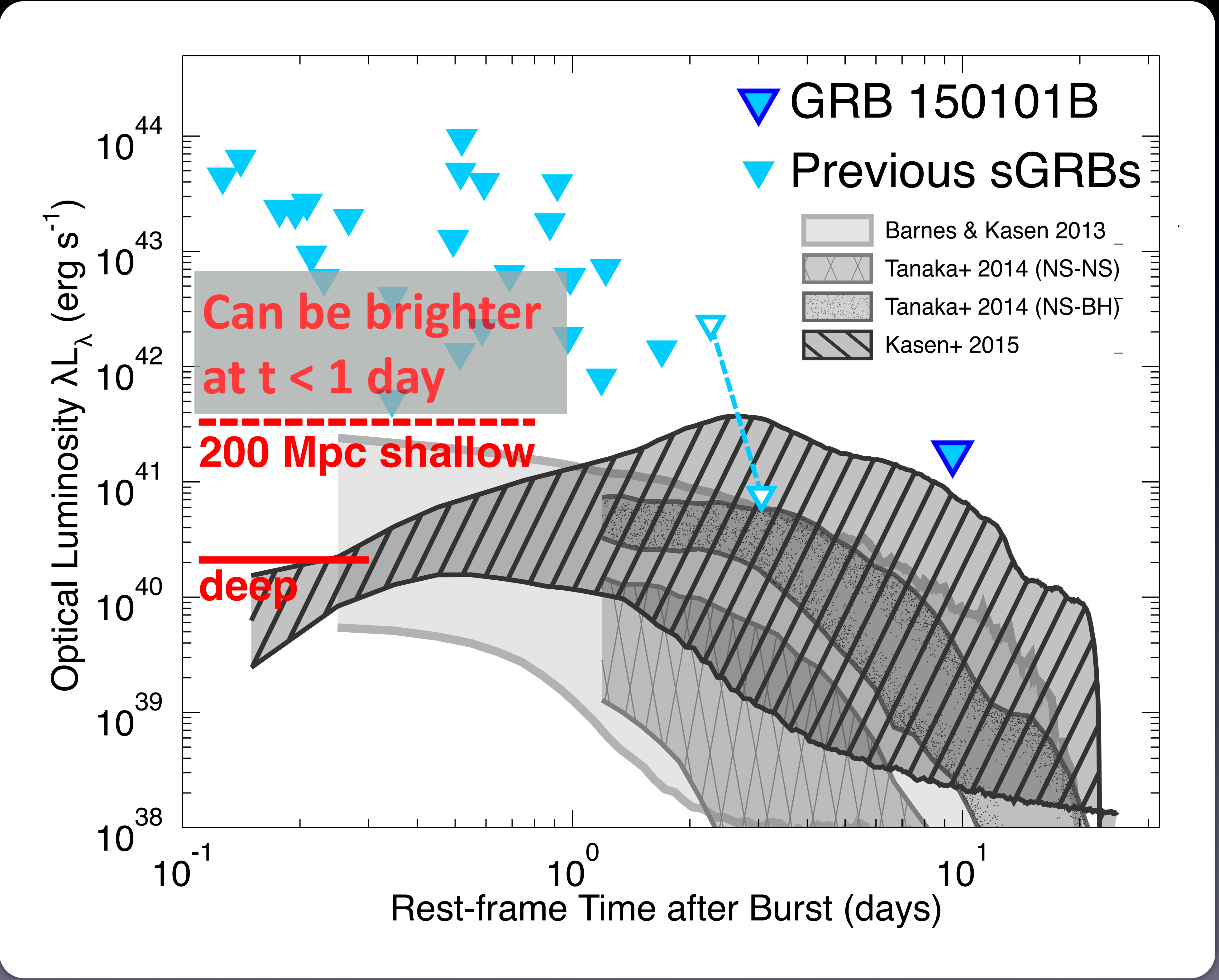
Ejection of ~0.06 Msun

Constraints from short GRBs (2/2)

@ 200 Mpc

21 mag

24 mag



Fong+16

- Optical emission from GW sources
- Follow-up survey with Tomo-e

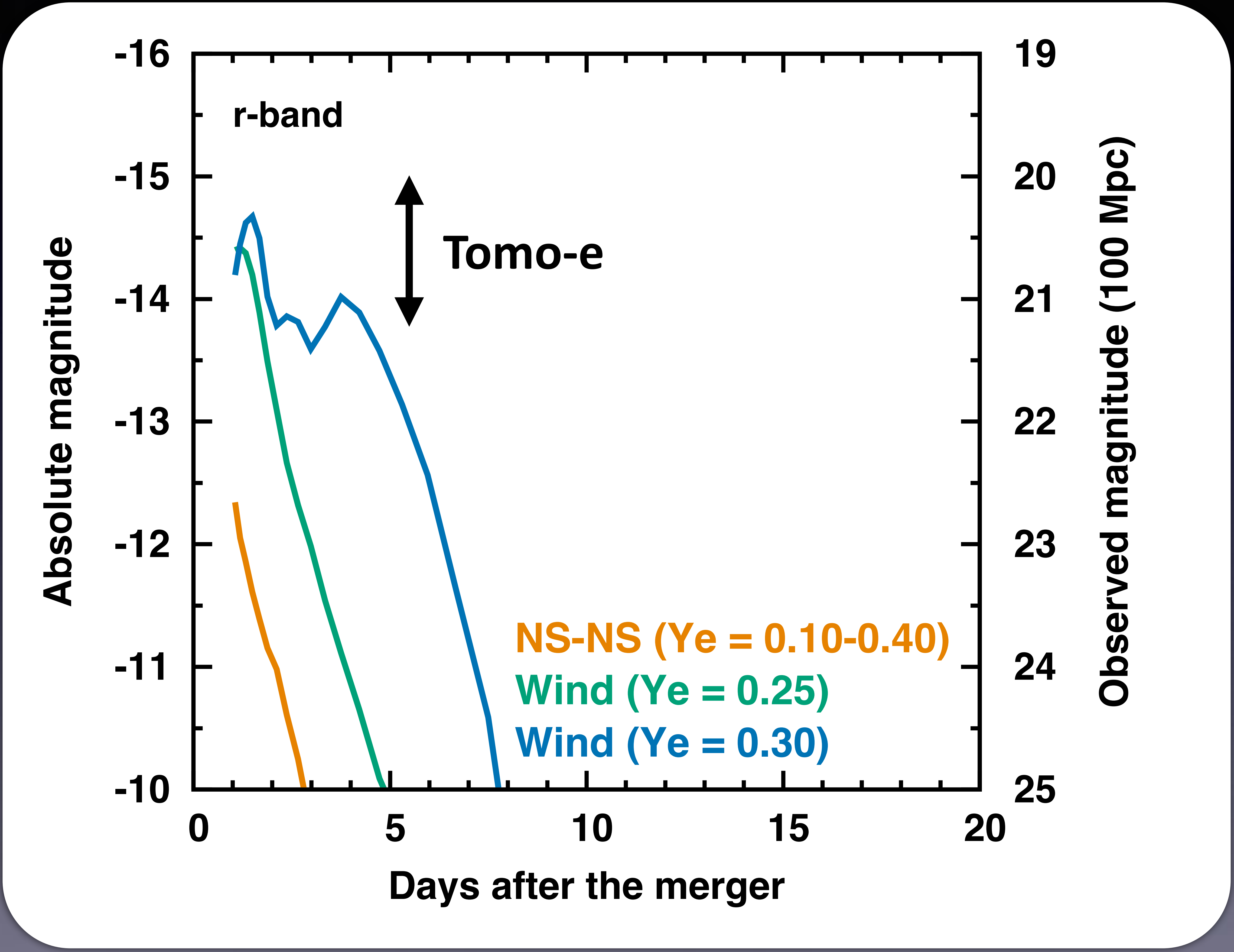
Timeline

2015 2016 **2017** 2018 2019 2020

	LIGO O1	LIGO O2 Virgo	LIGO O3 KAGRA
Localization	~1000 deg^2	~100-300 deg^2	~30 deg^2
Maximum distance	~80 Mpc	~100 Mpc	~200 Mpc
Kilonova brightness (-13 to -14 mag)	20.5-21.5 mag	~21-22 mag	~22.5-23.5 mag
# of NS-NS per yr	~0.1?	~1?	~10?

Observed magnitude @ 100 Mpc

M = 0.01 Msun



GW-EM survey with Tomo-e

ToO: < 3 days after the merger

Cadence: ~2-4 hr <= 2-3 visits /night

No filter <= faint, colors are uncertain

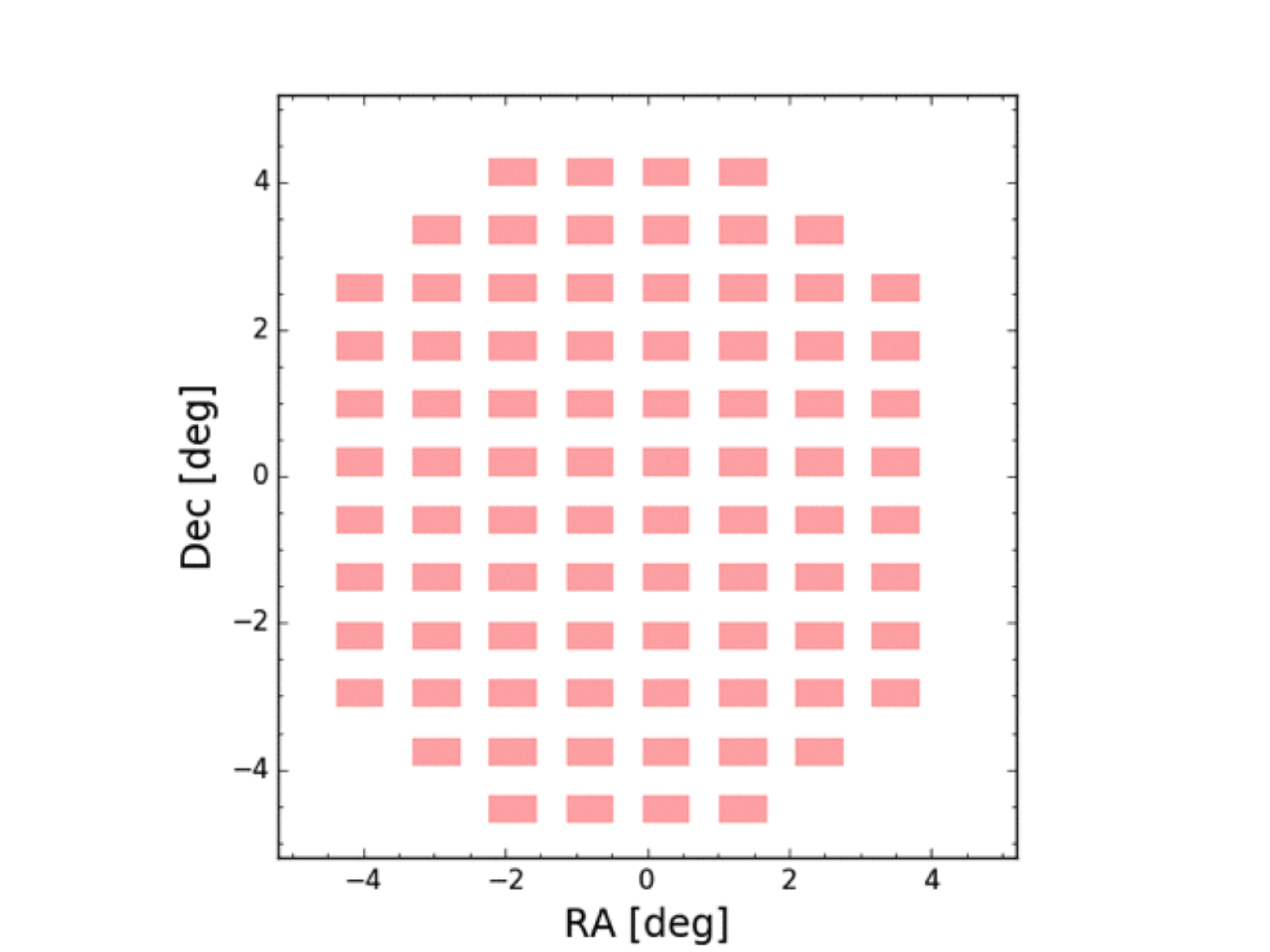
Depth: 20-21 mag

15 min (3 min x 5) on-source exposure

2x2 dithering => ~ 60 deg^2 in ~1 hr

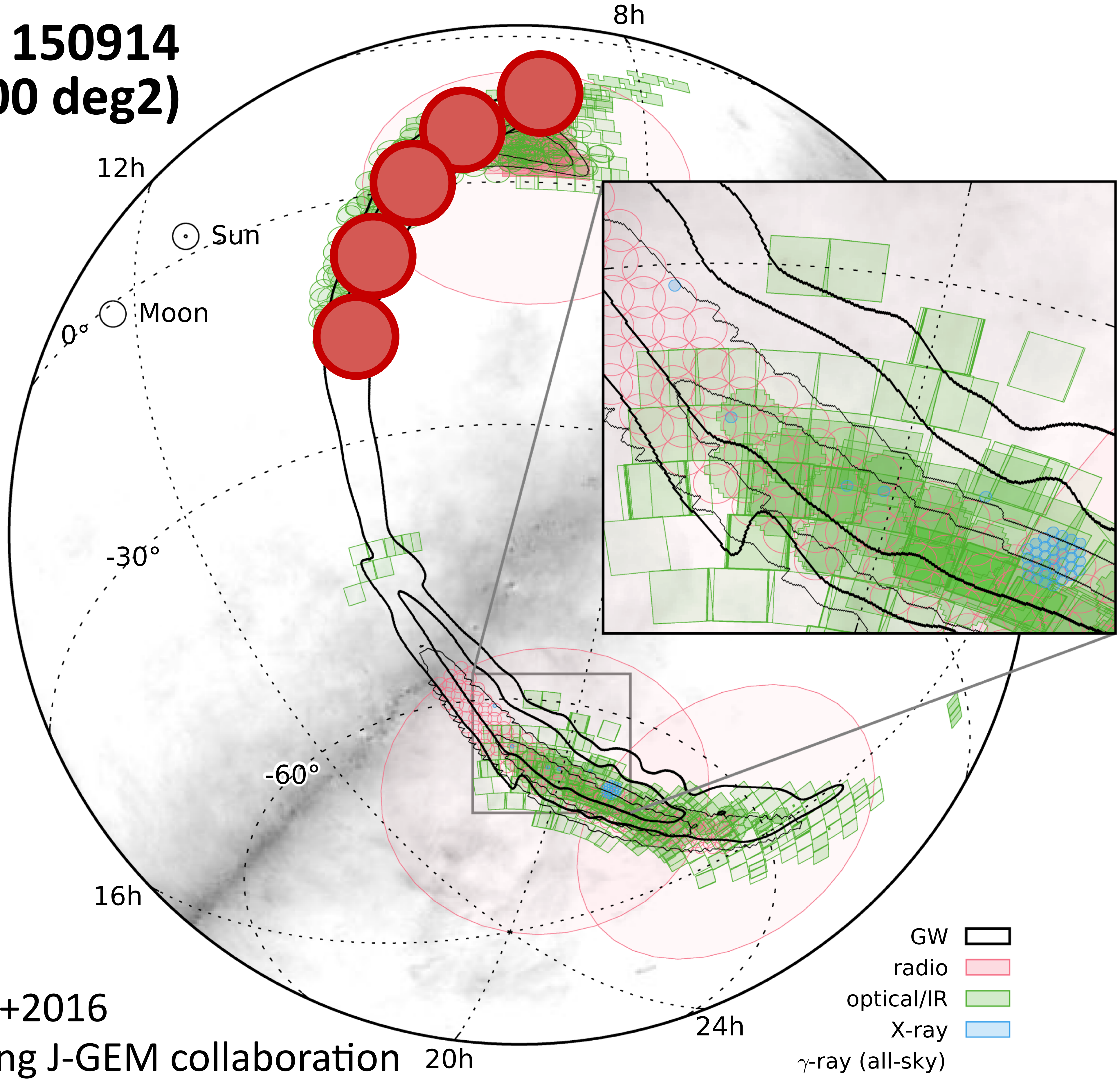
(~500 deg^2 in 1 night!)

2 x 2 dithering => ~60 deg^2 (15 min x 4 ~ 1hr)



Taken from Morokuma-san's slide

GW 150914
(~600 deg2)



Abbott+2016
including J-GEM collaboration

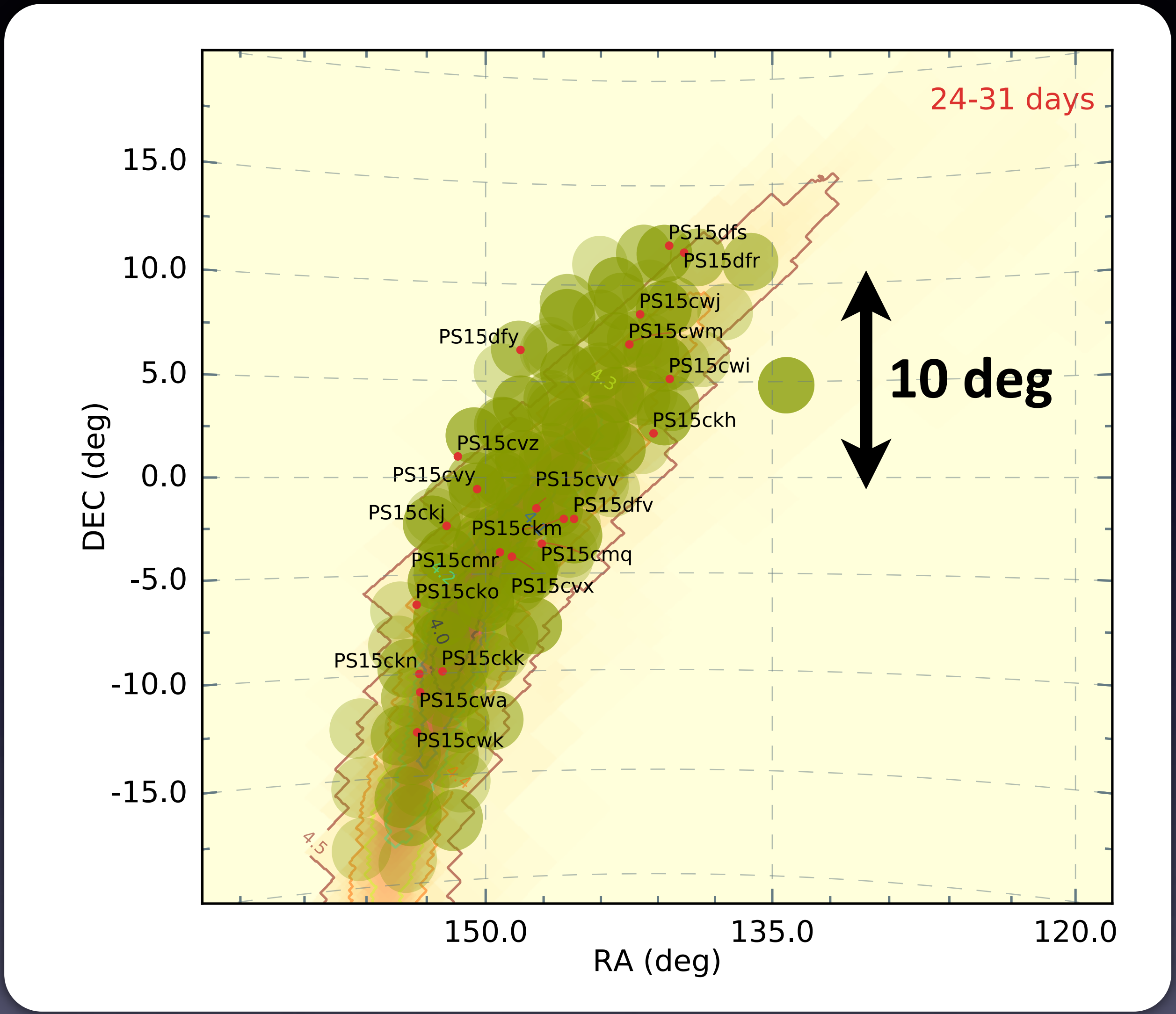
Lessons from follow-up observations

Selection by

(1) short timescale
<= lower mass

(2) faintness
<= lower energy source

(3) red colors
<= higher opacity



Follow-up for GW150914
Smartt+2016, Kasliwal+2016
Soares-Santos+2016, Morokuma+2016

Smoking gun: spectroscopy (smooth spectrum)
=> 3.8m + KOOLS-IFU

GW follow-up with Tomo-e

- **GW-EM synergy**
  - Localization of GW sources
  - Origin of r-process elements
- **Optical emission from GW sources**
  - ~22 mag @ 200 Mpc <= theory and observations
  - Possible bluer emission
- **Follow-up survey with Tomo-e**
  - Play important roles from "poor localization" period
  - ~100-300 deg^2 / 20-21 mag / 2hr cadence / no filter
  - Low-resolution spectroscopy with 3.8m/KOOLS-IFU