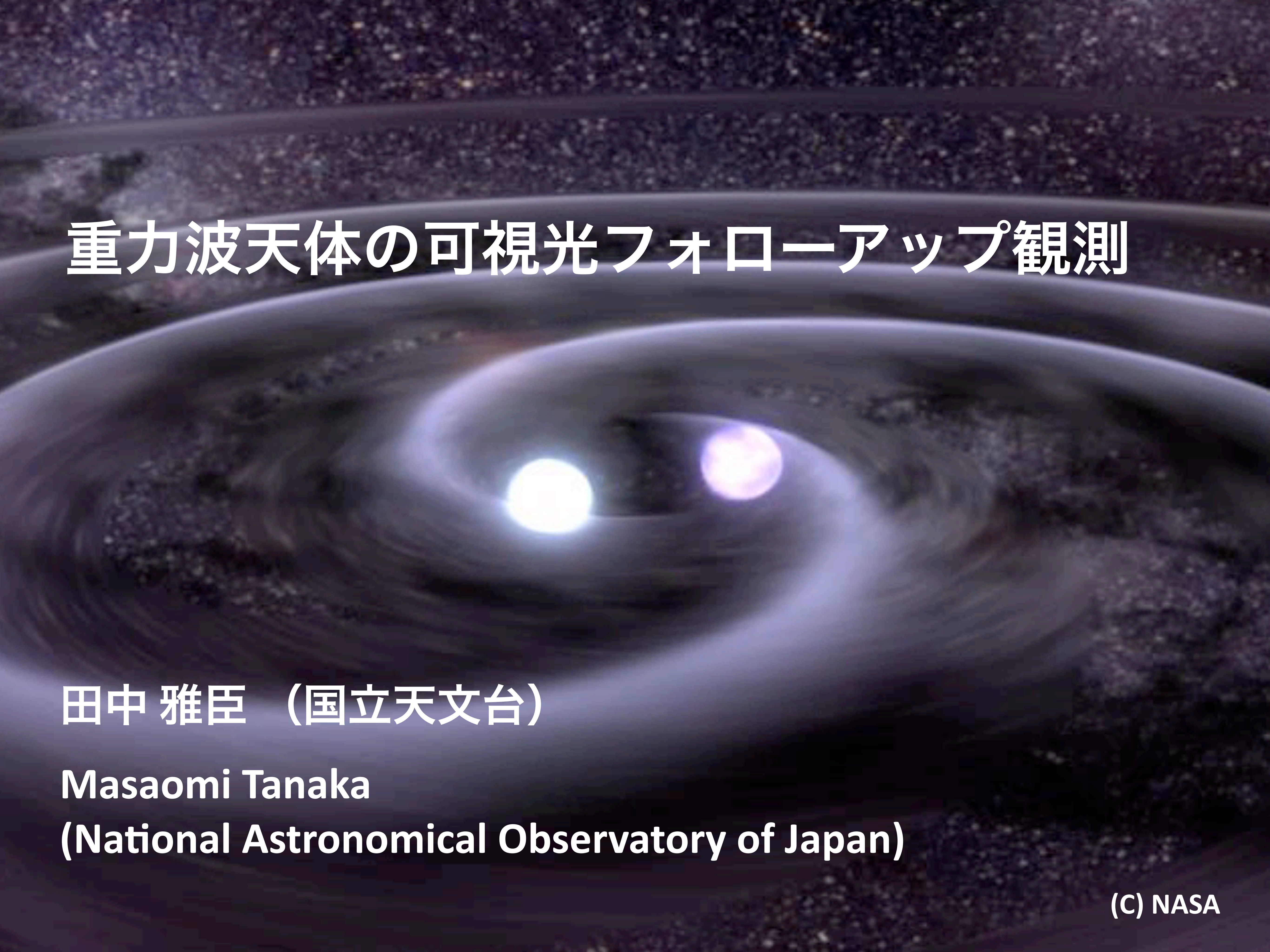
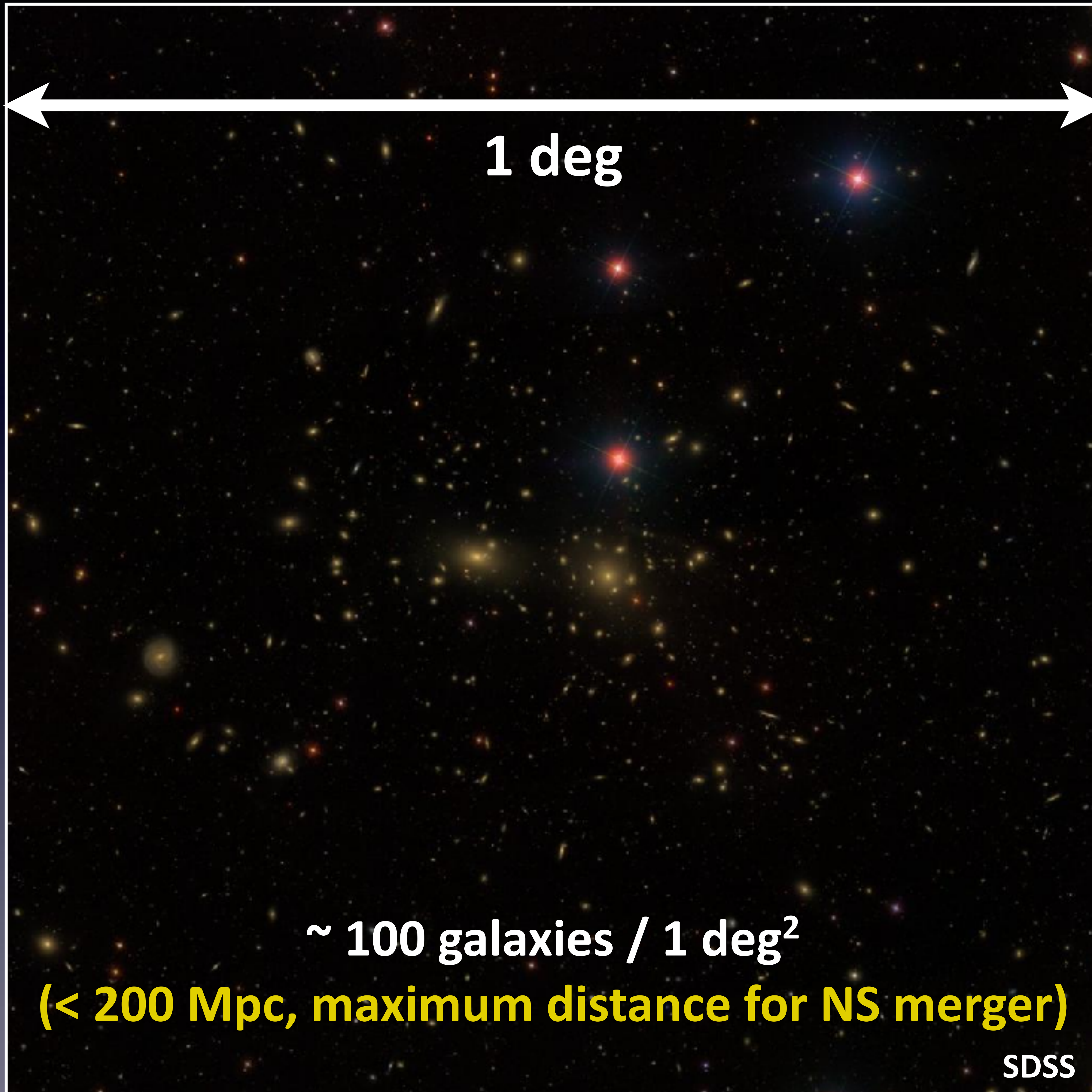
重力波天体の可視光フォローアップ観測

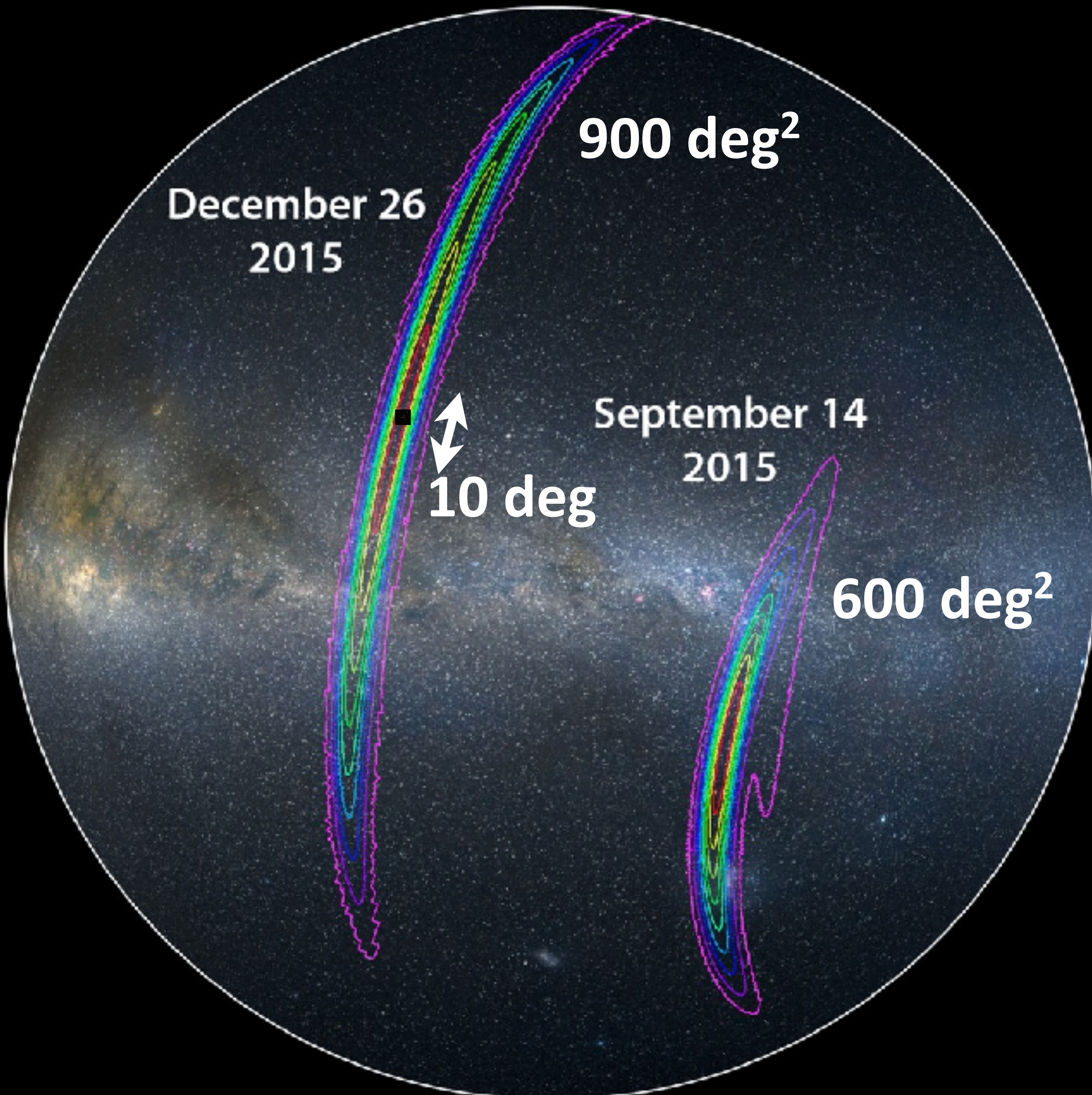
田中 雅臣 （国立天文台）

Masaomi Tanaka
(National Astronomical Observatory of Japan)



(C) NASA


1 deg
~ 100 galaxies / 1 deg^2
(< 200 Mpc, maximum distance for NS merger)
SDSS



Localization ~ 600 deg^2
(~ 10 deg^2 with
Advanced Virgo and KAGRA)

Detection of
electromagnetic (EM)
counterparts is essential

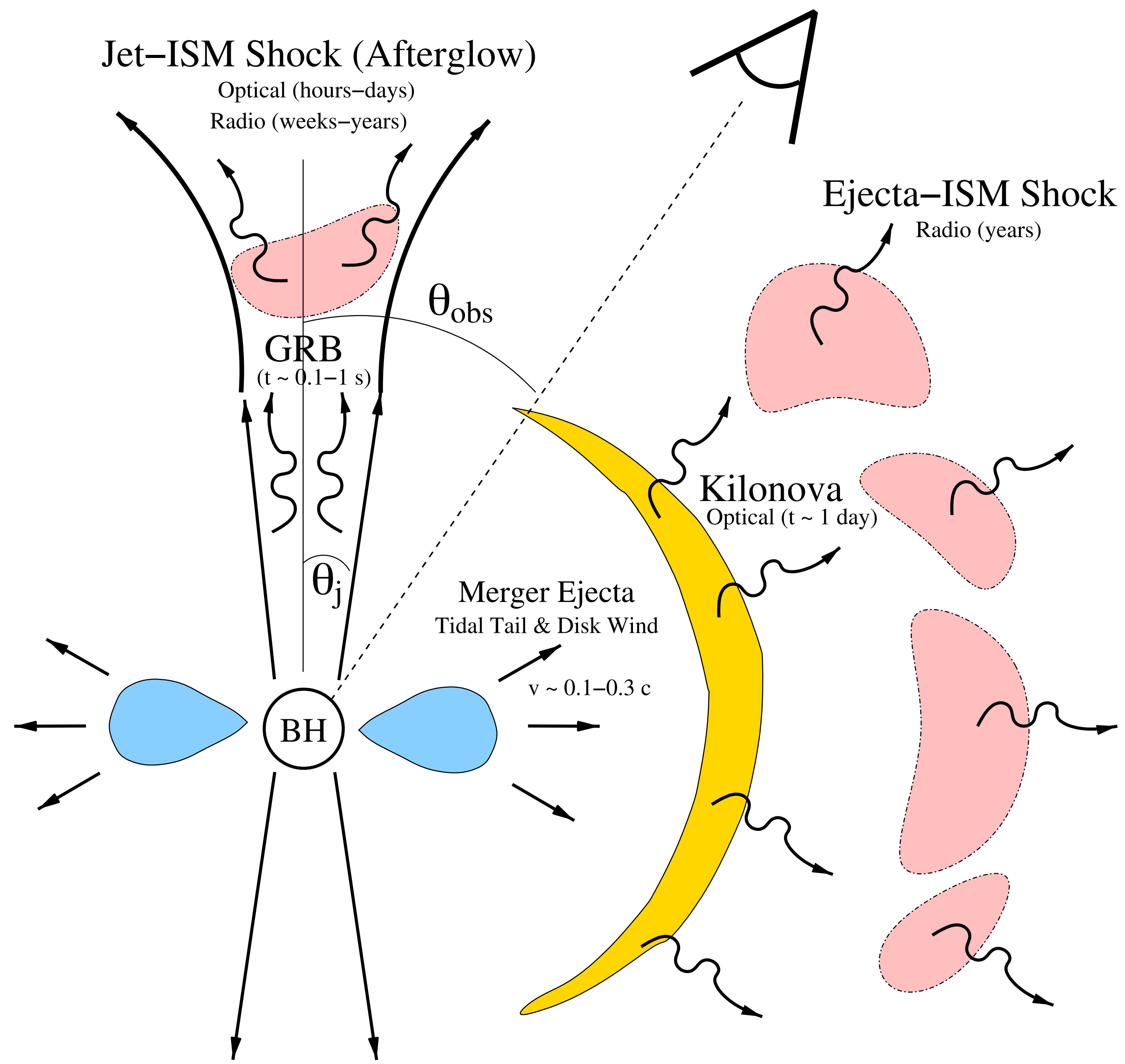
- Redshift (~distance)
- Host galaxy
- Local environment

http://www.ligo.org/detections.php

- **Optical emission from GW sources**
- **Prospects for Tomo-e and KOOLS-IFU**

Electromagnetic signature from NS mergers

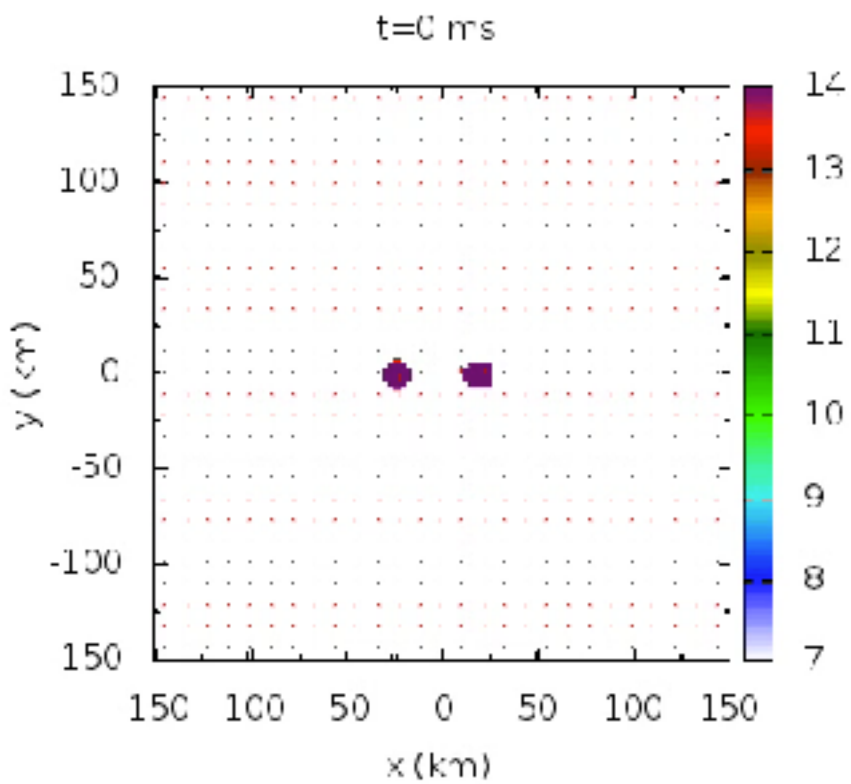
- On-axis short GRB
  - strongly beamed ✗
  - (isotropic soft X-ray?)
- Off-axis radio afterglow
  - isotropic ✓
  - delayed by ~> 1 yr ✗
- Radioactive emission “kilonova” or “macronova”
  - isotropic ✓
  - short delay ✓



Metzger & Berger 2012, ApJ 746, 48

Mass ejection

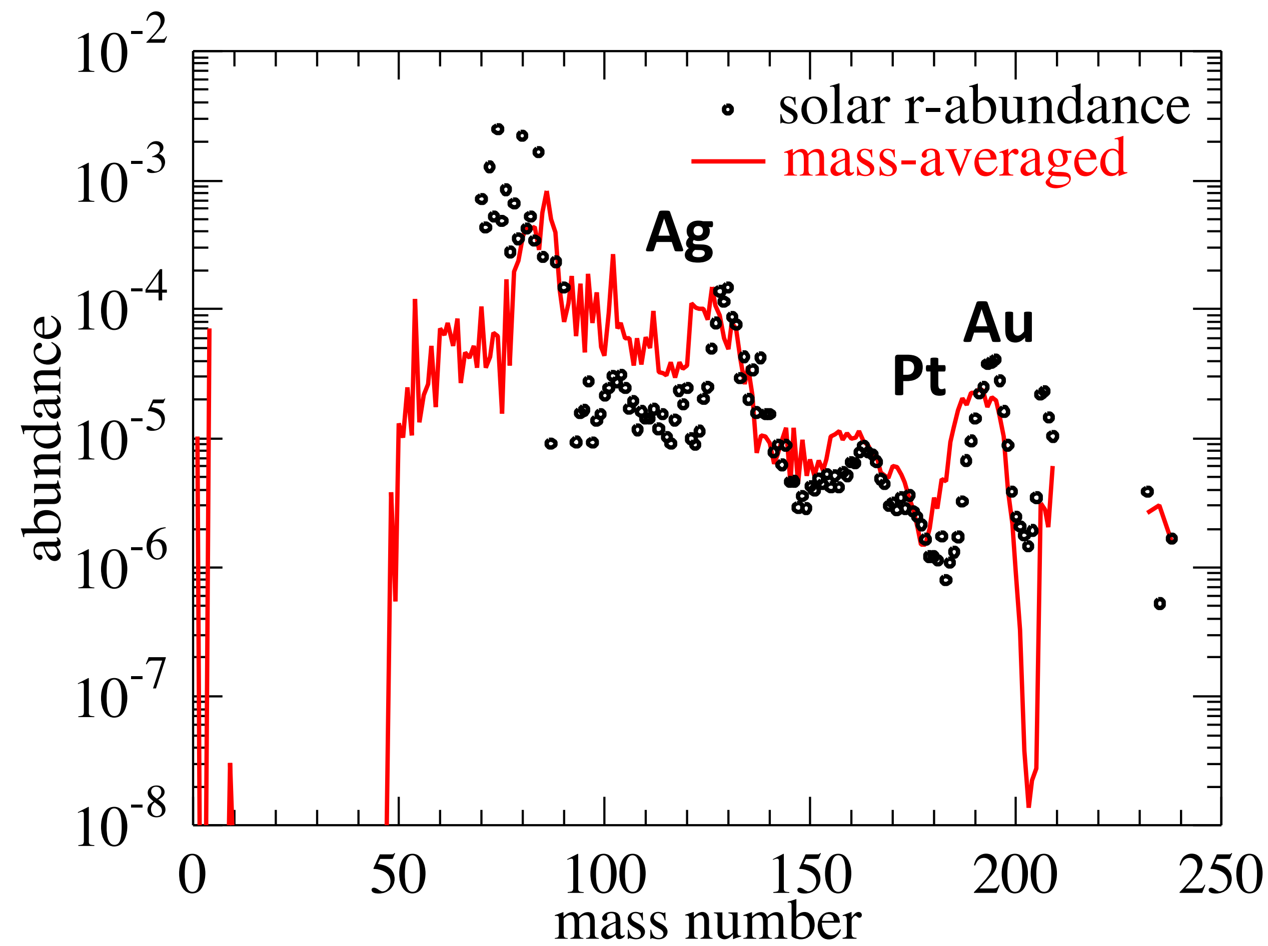
$M \sim 10^{-3} - 10^{-2}$ Msun
$v \sim 0.1 - 0.2$ c



Hotokezaka+13, PRD, 87, 4001
Rosswog+13, MNRAS, 430, 2580

r-process nucleosynthesis

=> solar abundance



Wanajo et al. 2014, ApJ, 789, L39
Just et al. 2015, MNRAS, 448, 541

NS merger as a possible origin of r-process elements

Event rate

$R_{NSM} \sim 10^3\ \mathrm{Gpc^{-3}\ yr^{-1}}$

~ 30 GW events $\mathrm{yr^{-1}}$

(w/ Adv. detectors, < 200 Mpc)

GW

LIGO O1

$R_{NSM} < 10^4\ \mathrm{Gpc^{-3}\ yr^{-1}}$

Ejection per event

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

EM

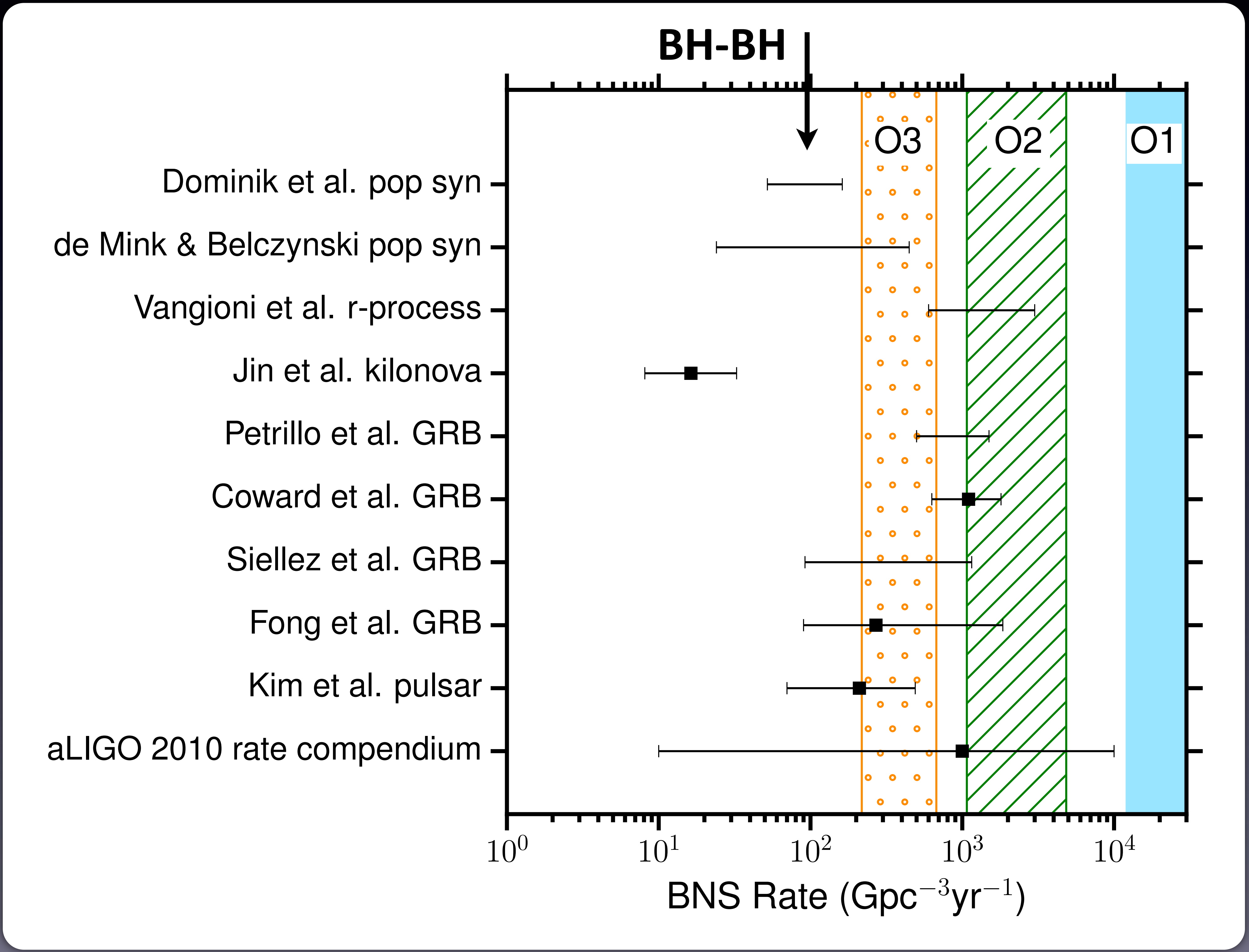
Enough to explain the r-process abundance in our Galaxy

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

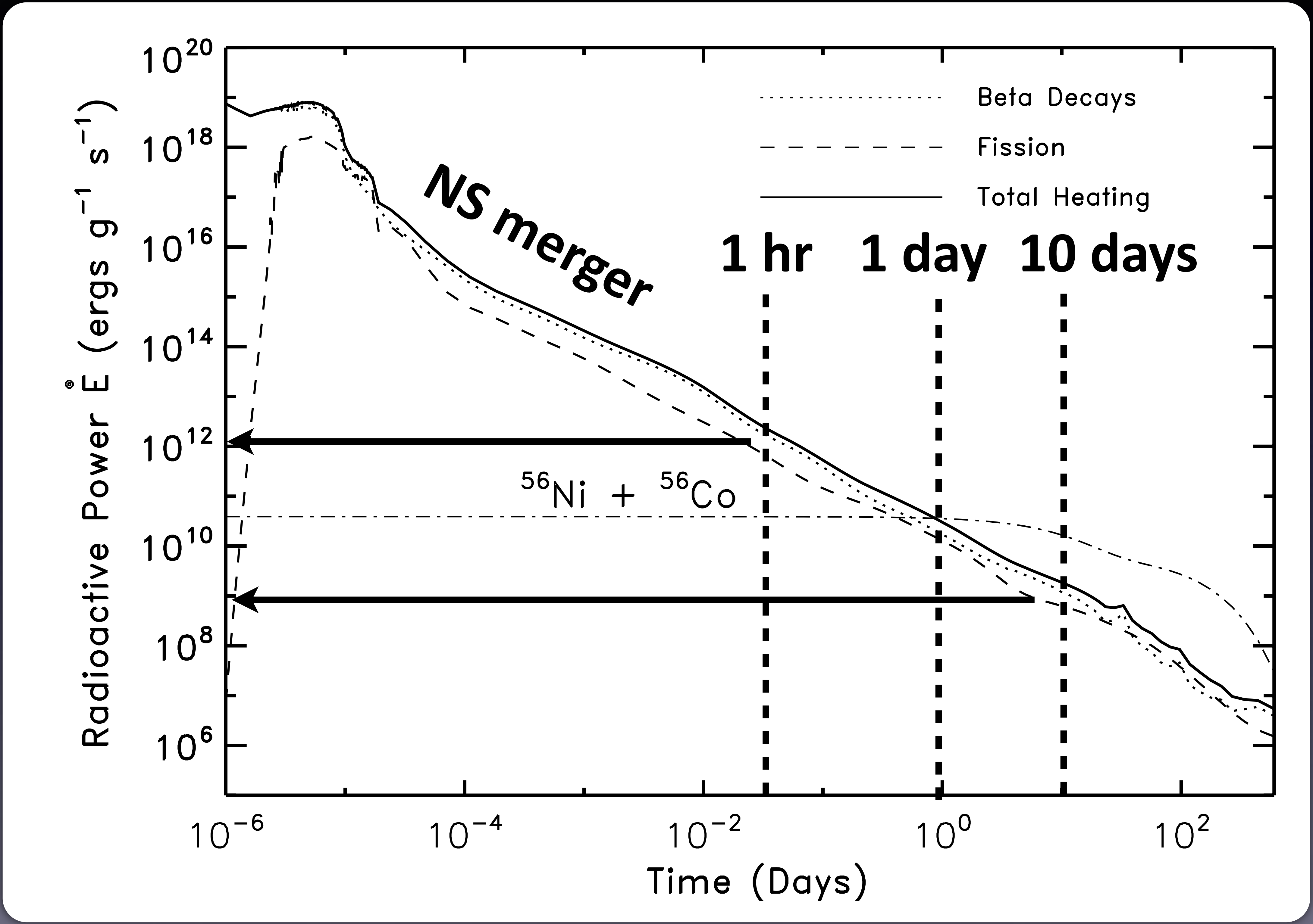
O3: 2018

arXiv:1607.07456

Heating by radioactive decay of r-process nuclei

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

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

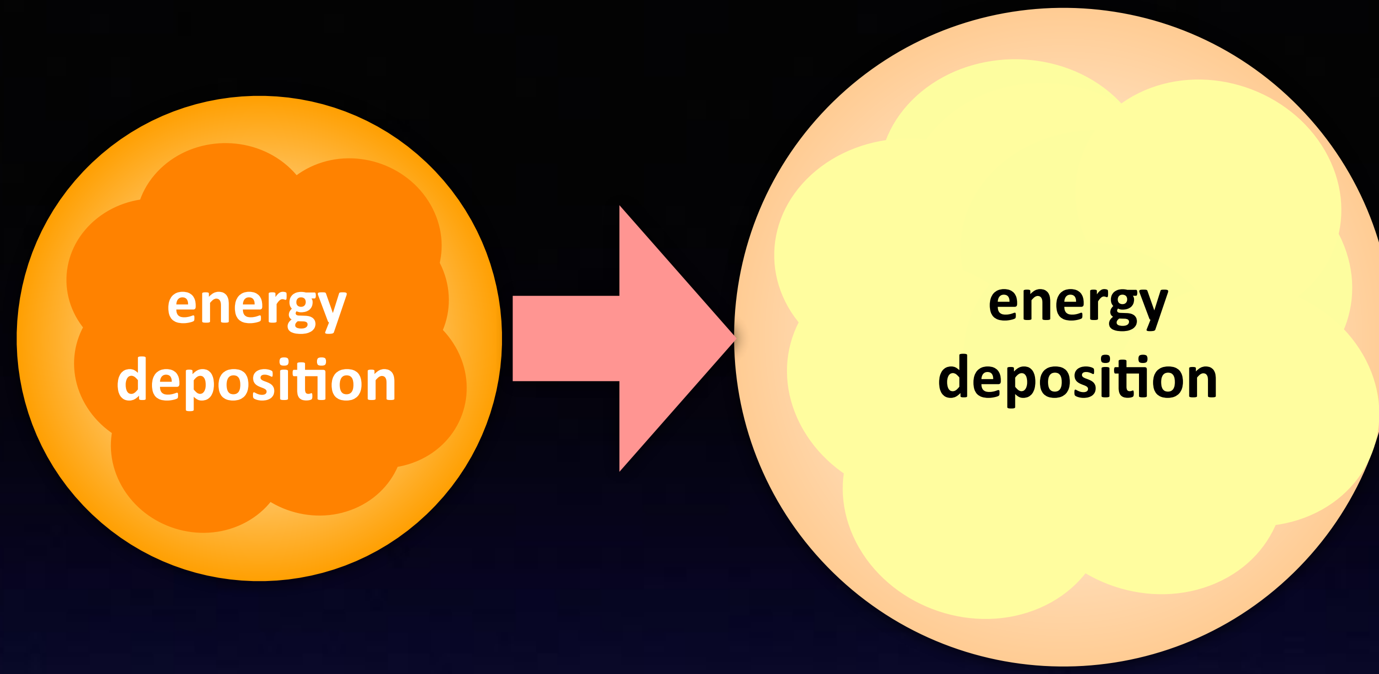


(for M = 0.01 Msun)

Metzger+10

“kilonova/macronova”

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



Timescale

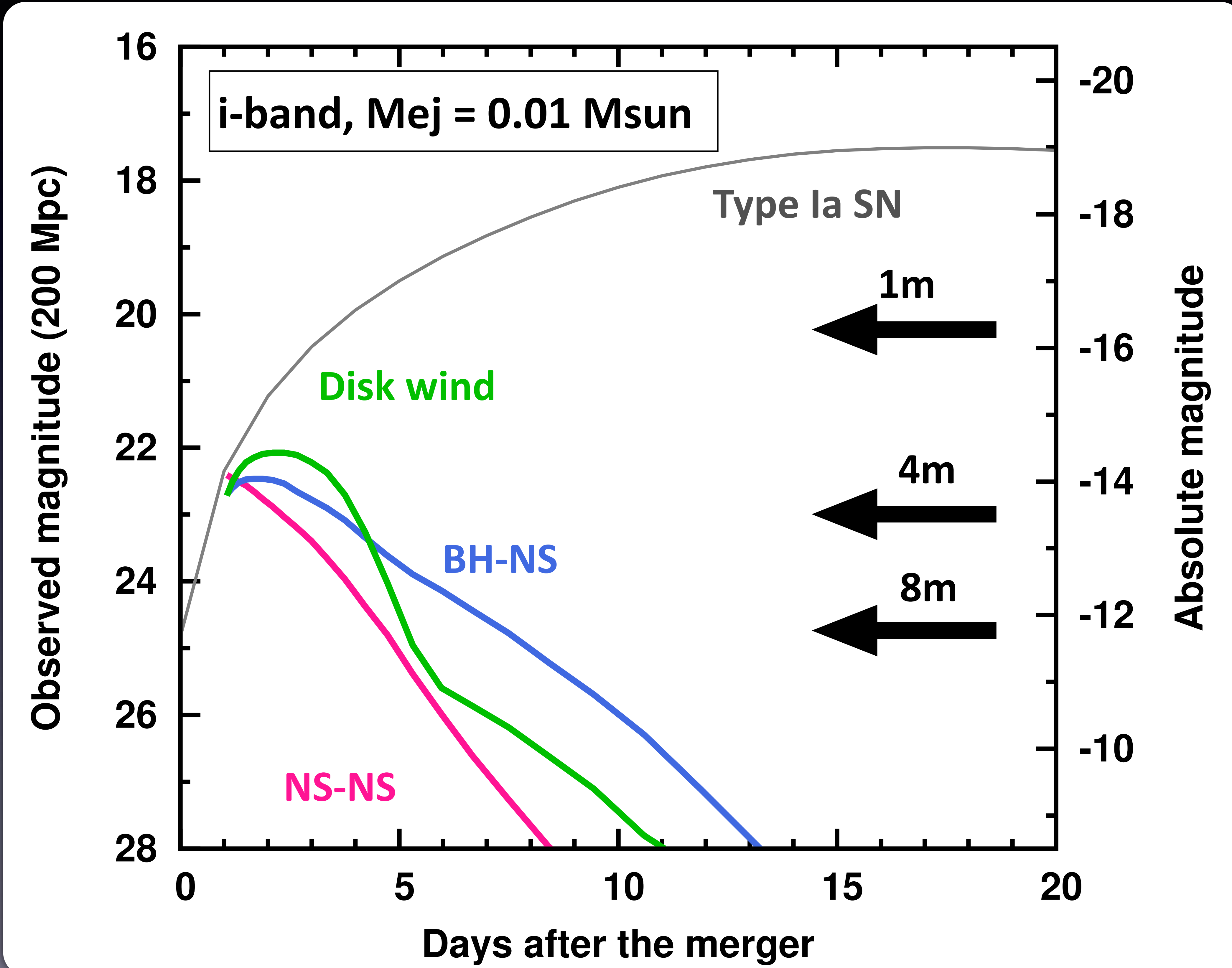
$$
\begin{aligned}
t_{\rm peak} &= \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2} \\
&\simeq 8.4 \text{ days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}
\end{aligned}
$$

Luminosity

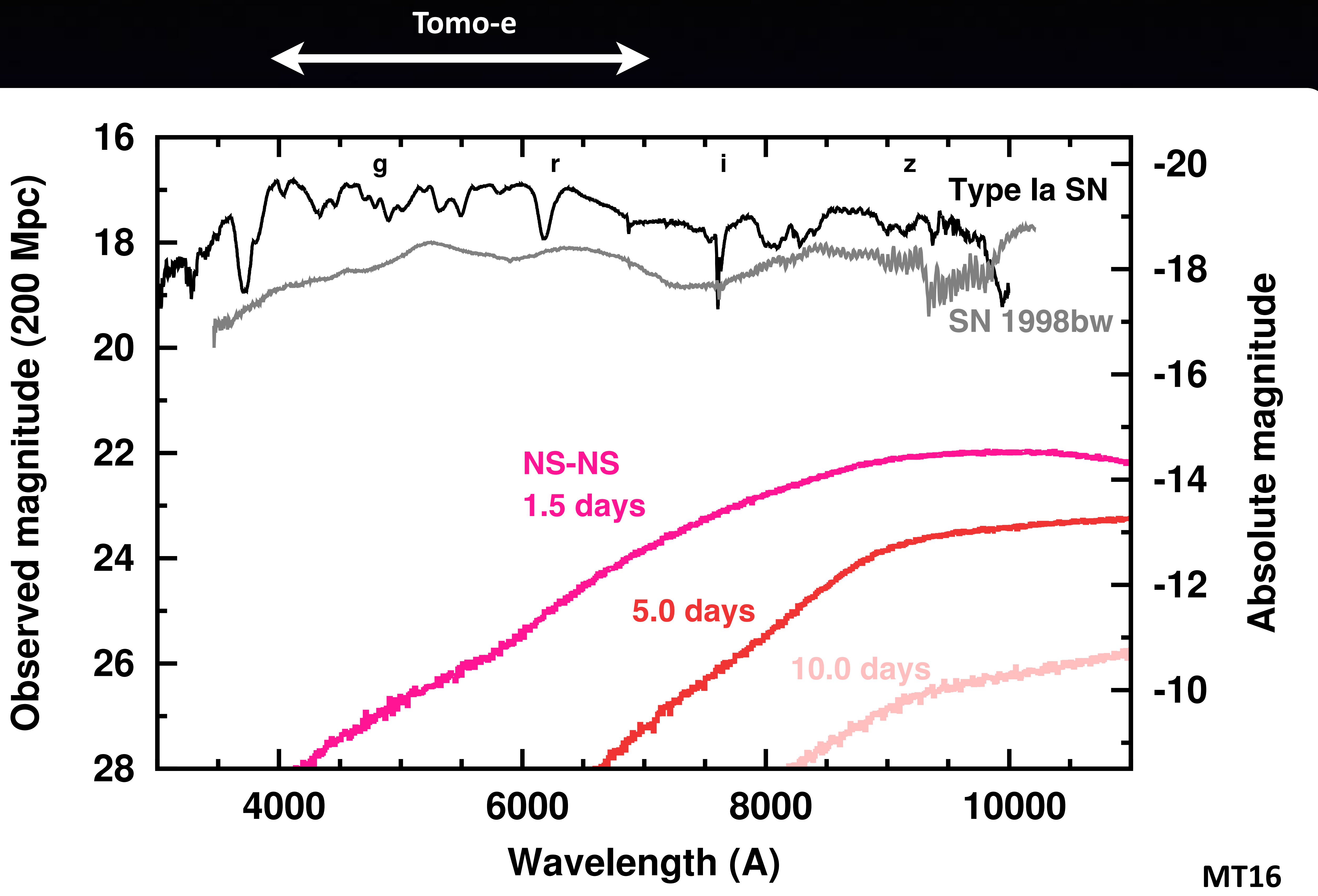
$$
\begin{aligned}
L_{\rm peak} &= L_{\rm dep}(t_{\rm peak}) \\
&\simeq 1.3 \times 10^{40} \text{ erg s}^{-1} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{-0.65}
\end{aligned}
$$

see Tanaka 2016, Advances in Astronomy

Light curves (~ 22-23 mag @ 200 Mpc)

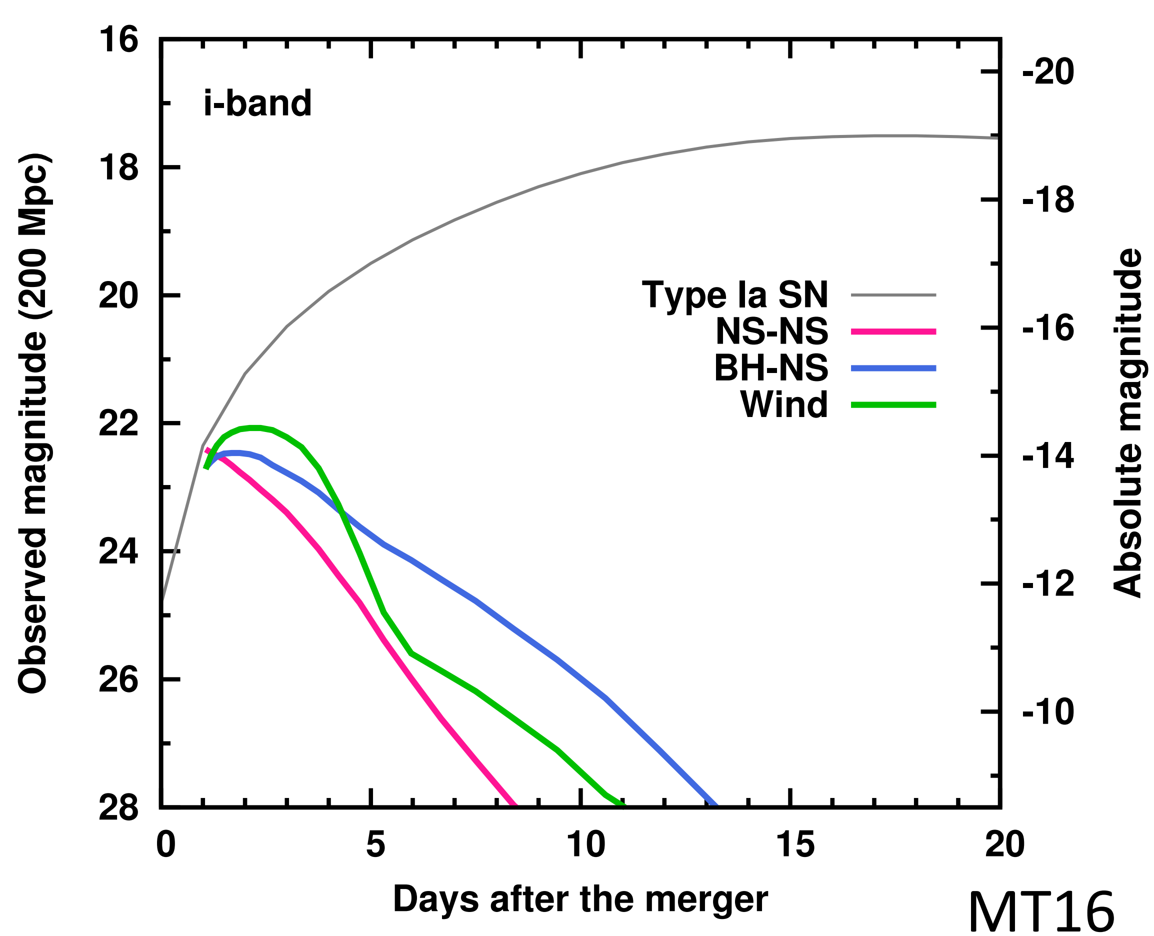


Extremely red spectra



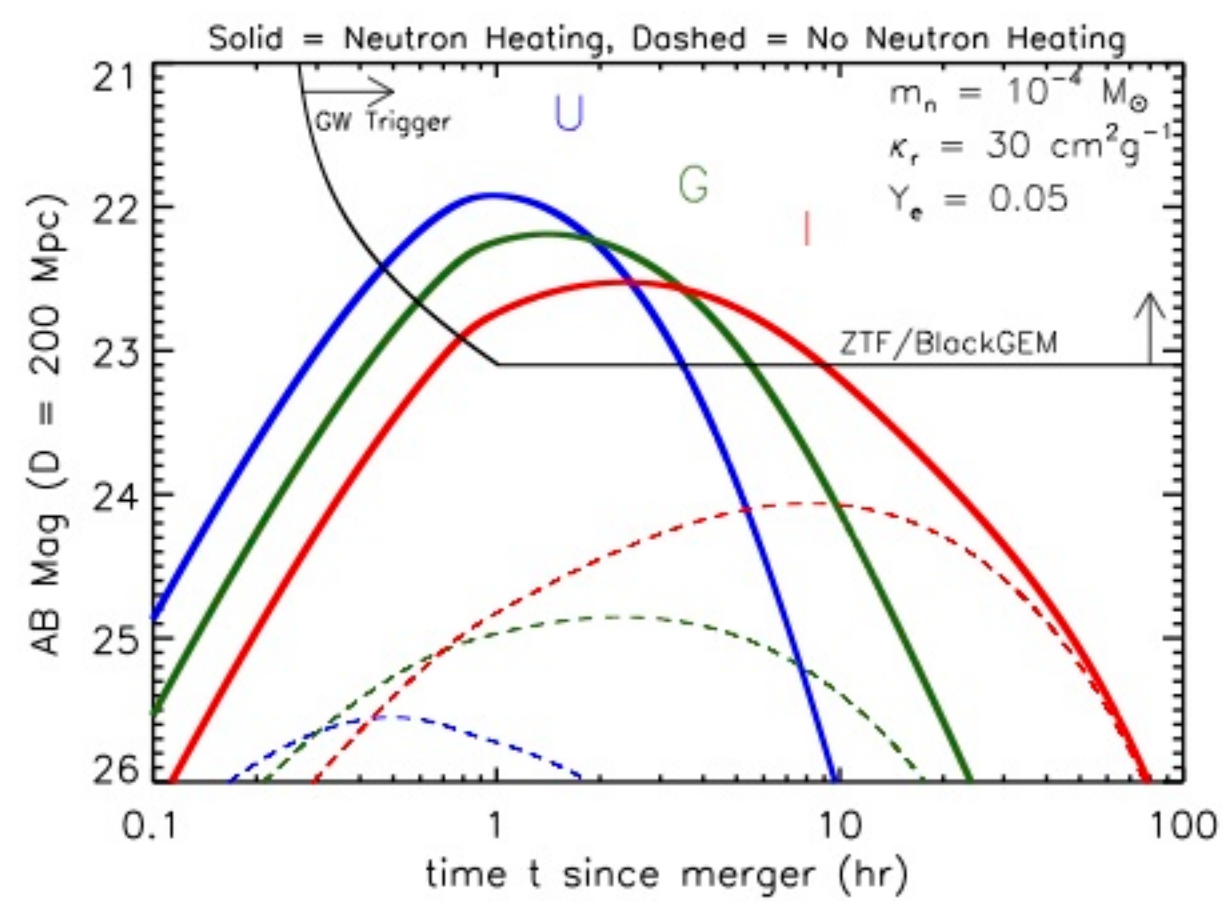
Possible brighter/bluer/faster emission

Disk wind (~10^{-2} Msun?)
t < 5d, blue,
~22 mag@200 Mpc (abs -15 mag)



Metzger & Fernandez 14; Kasen+15

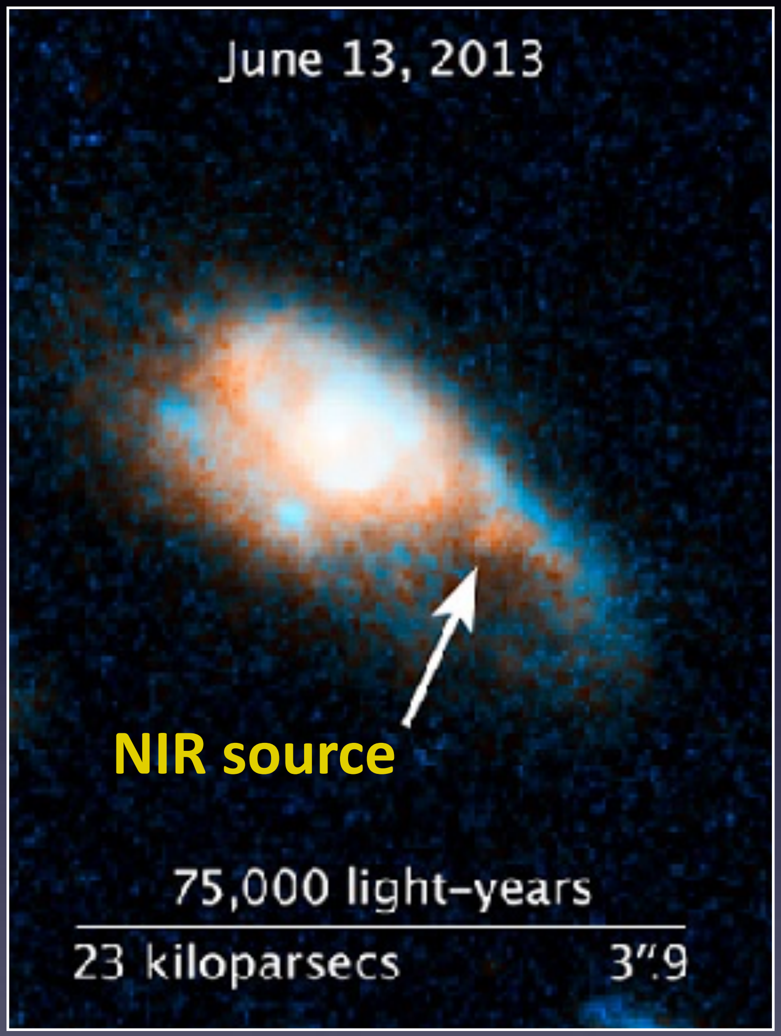
Free neutron (~10^{-4} Msun??)
t < 1d, blue,
~22 mag@200 Mpc (abs -15 mag)



Metzger+15

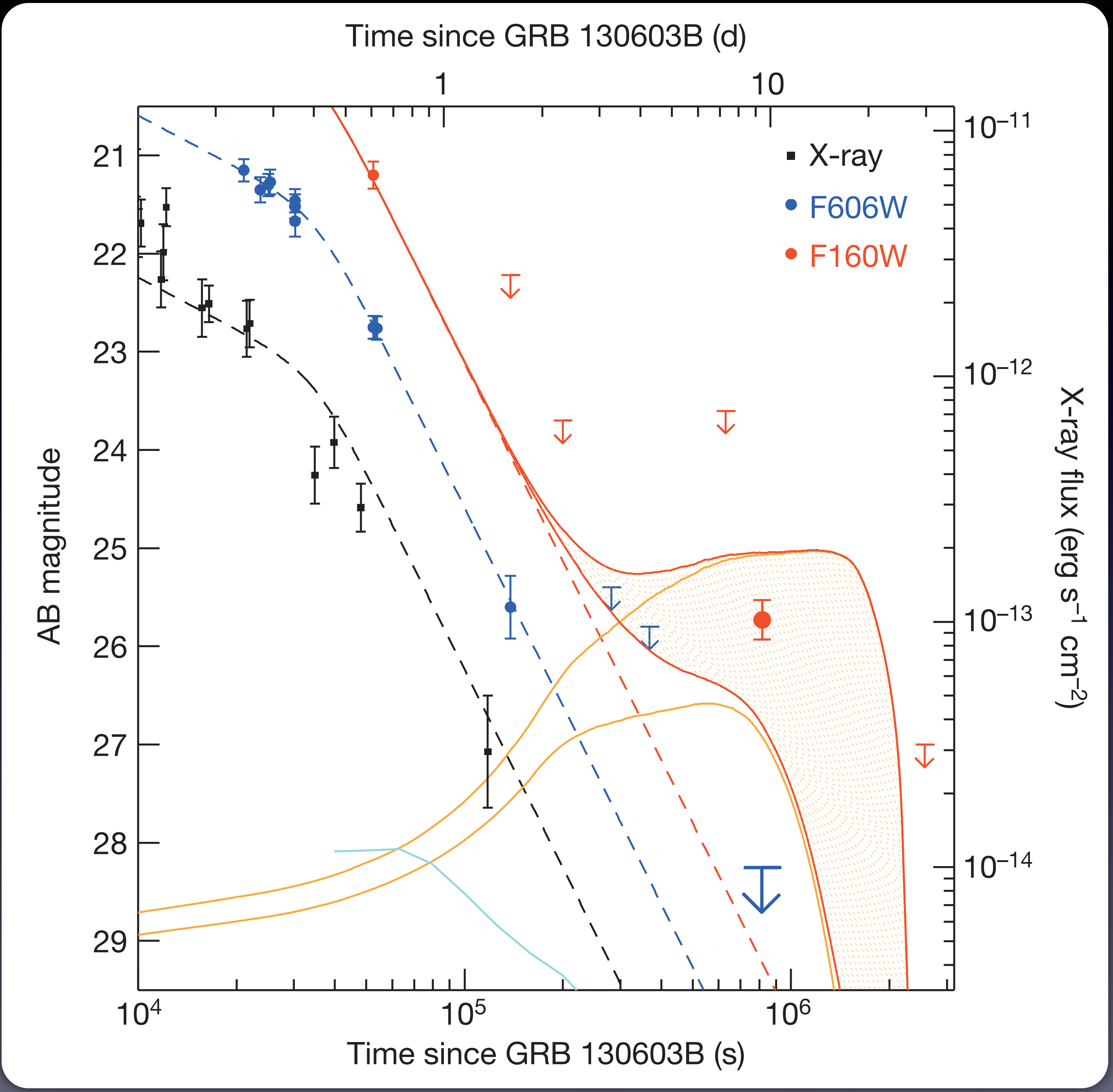
Constraints from short GRBs (1/3)

GRB 130603B



Tanvir+2013, Berger+2013

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



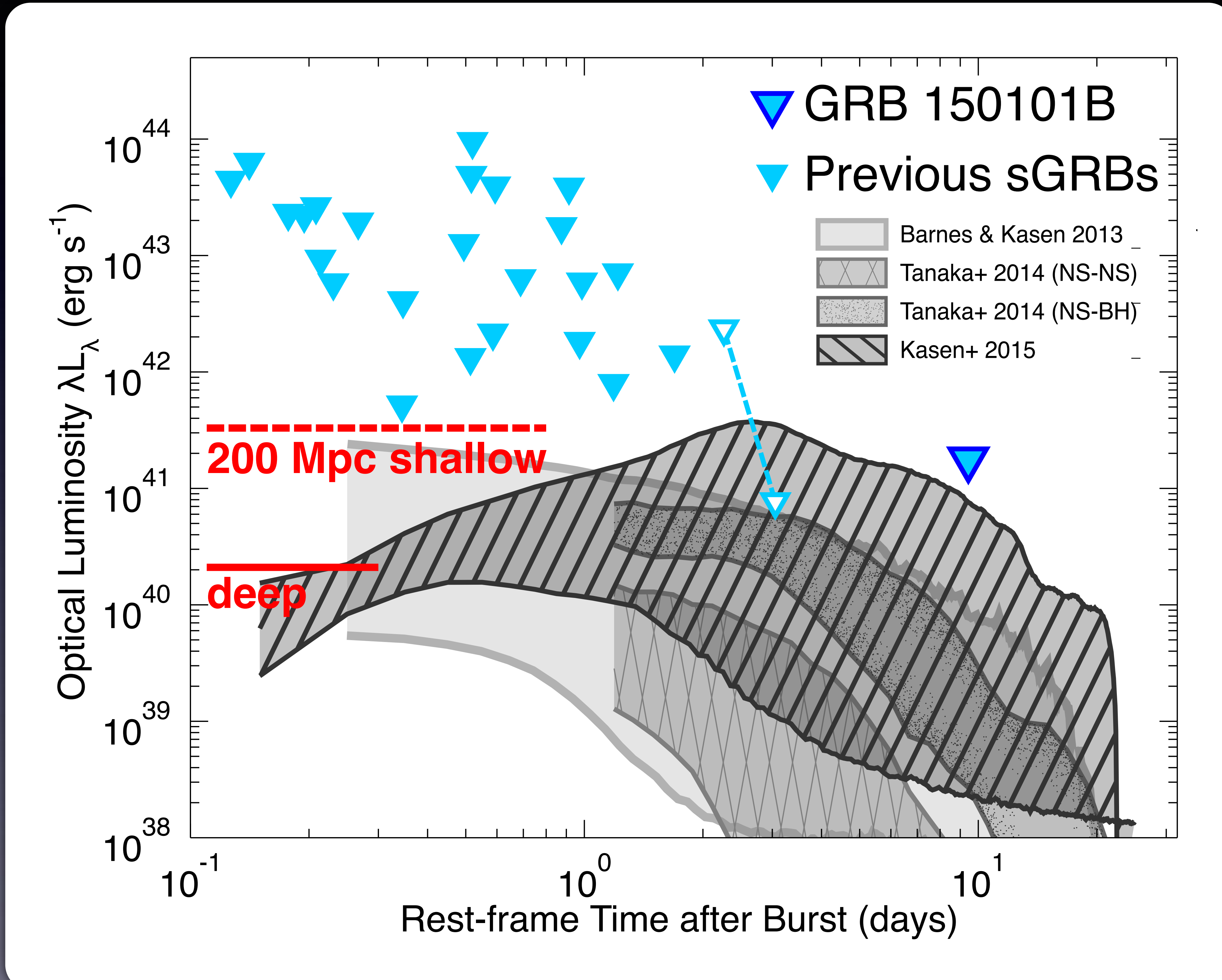
As expected by theoretical models
=> ejection of ~0.02 Msun

Constraints from short GRBs (2/3)

@ 200 Mpc

21 mag

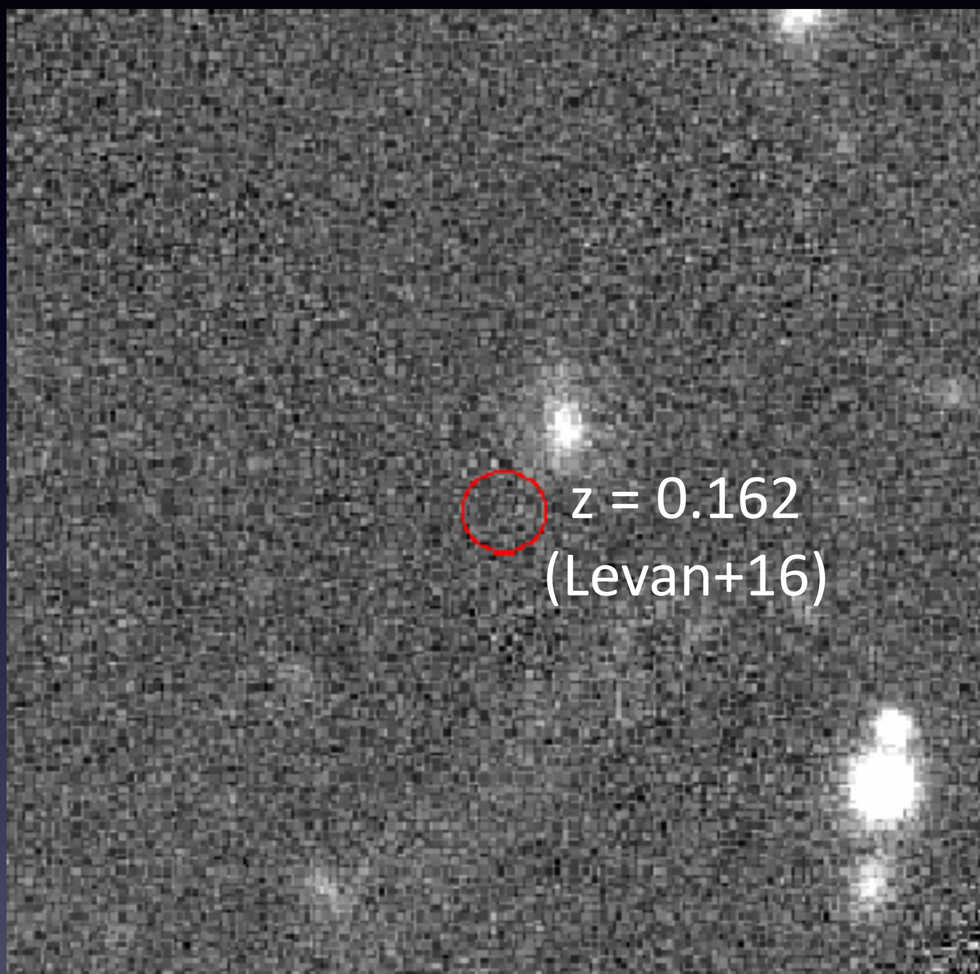
24 mag



Fong+16

Constraints from short GRBs (3/3)

GRB 160821B (z=0.16)



Pan-STARRS1 (r-band)

F606W ~ 25.8 mag @ z=0.16
=> Mabs -14 mag
=> **~22 mag @ 200 Mpc**

TITLE: GCN CIRCULAR
NUMBER: 20222
SUBJECT: GRB 160821B: HST detection of the optical and IR counterpart
DATE: 16/12/01 02:36:37 GMT
FROM: Eleonora Troja at GSFC <eleonora.troja@nasa.gov>

E. Troja (UMD/GSFC), N. Tanvir (U. Leicester), S. B. Cenko (NASA/GSFC), A. Levan (U. Warwick), J. Barnes (U. Berkeley), A. Castro-Tirado (IAA-CSIC), A. S. Fruchter (STScI), N. Gehrels (NASA/GSFC), J. Greiner (MPE), N. Kawai (Tokyo Tech), R. Hounsell (UCSC), J. Hjorth (DARK/NBI), A. Lien (NASA/GSFC), B. Metzger (Columbia), D. Perley (DARK/NBI), S. Rosswog (U. Stockholm), T. Sakamoto (AGU), C. Thoene (IAA-CSIC), A. de Ugarte Postigo (IAA-CSIC), and D. Watson (DARK/NBI) report:

We monitored the location of the short GRB 160821B (Siegel et al. GCN 19833; Xu et al. GCN 19834) with the Hubble Space Telescope under our approved guest observer programs (GO14237 PI: Tanvir; GO14087 PI: Troja). Observations were carried out with the Wide Field Camera (WFC3) in three filters, F606W, F110W and F160W, at epochs 3.6, 10.4 and 23.2 days post-burst. The GRB counterpart is clearly detected in all filters during the first two epochs, and fades from a magnitude of F606W~25.8 (AB) in the first epoch to become undetectable in the third epoch.

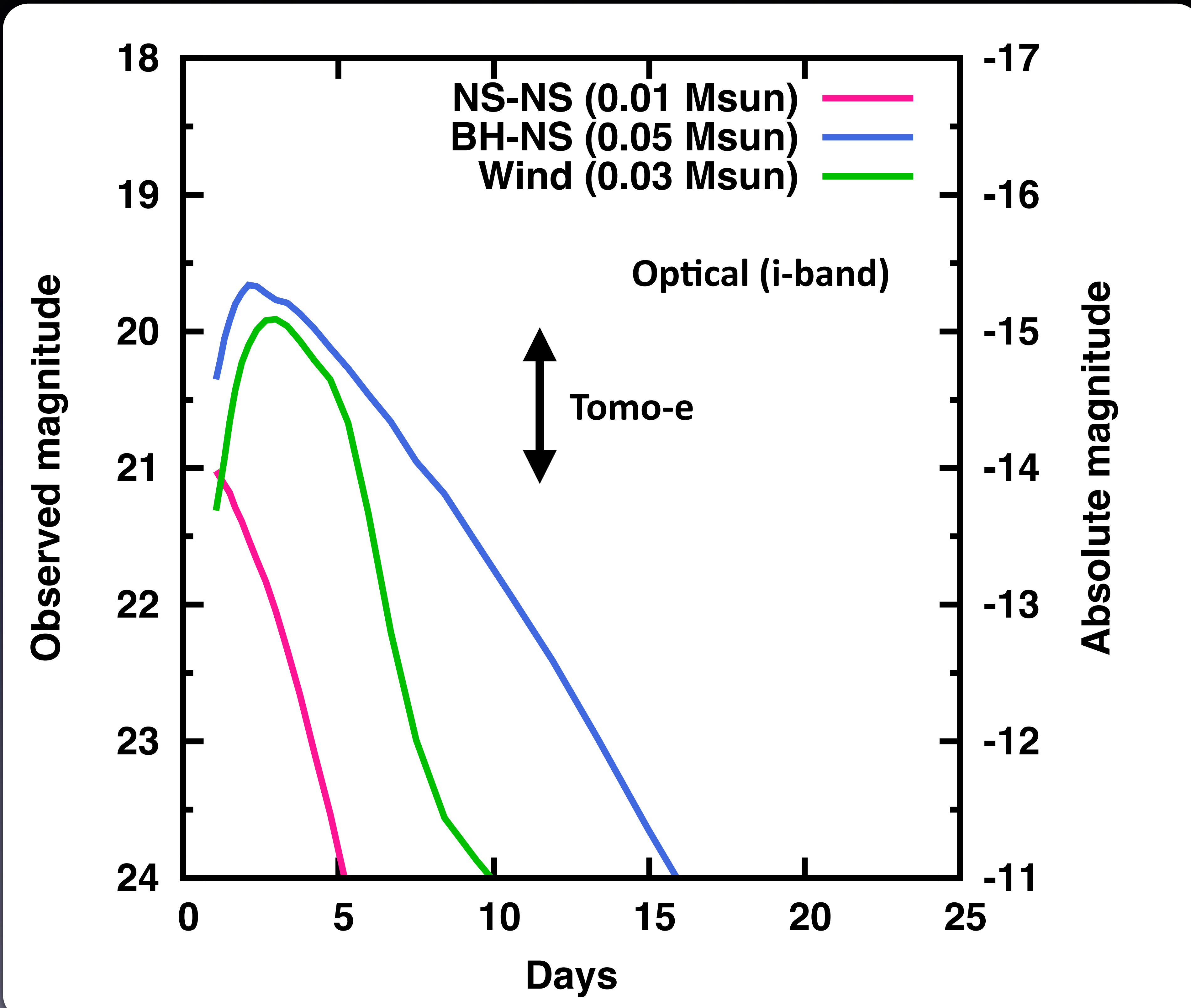
Assuming a redshift of z=0.162 from the nearby galaxy identified as the likely host (Levan et al. GCN 19846), our observations rule out the presence of an emerging supernova comparable to SN1998bw or to other SNe associated to long GRBs. The observed fluxes constrain the contribution of any r-process kilonova/macronova component to be at least a factor ~5 fainter in the IR than that seen in GRB 130603B. The lack of a bright supernova and the moderate-to-low ejecta mass implied by our observations are consistent with this event being produced by the merger of two neutron stars.

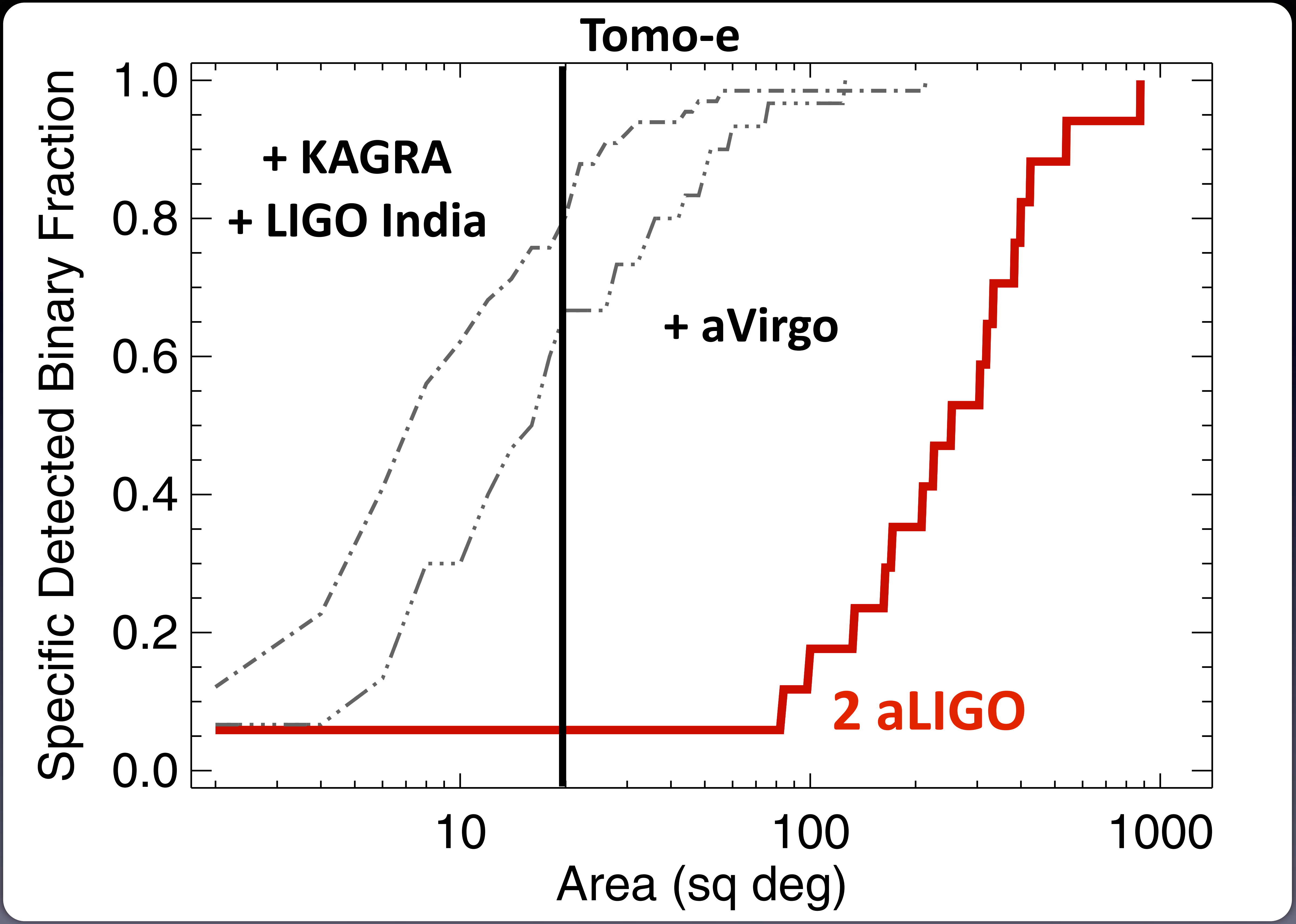
However, the current dataset cannot firmly exclude the presence of an underlying, higher redshift host galaxy. Deeper HST observations aimed at placing better constraints on the GRB redshift are on-going.

We thank the STScI staff, in particular Tricia Royle, for assistance with rapidly scheduling our observations.

- Optical emission from GW sources
- Prospects for Tomo-e and KOOLS-IFU

Observed magnitude @ 100 Mpc





Kasliwal & Nissanke 2014

Timeline (as of 2016)

2015 2016 2017 2018 2019

	LIGO O1	LIGO O2 Virgo	LIGO O3 KAGRA
Localization	~600 deg^2	~100 deg^2	~10 deg^2
Max dist.	~80 Mpc	~150 Mpc	~200 Mpc
Kilonova	19-20 mag	20-21 mag	~22 mag
Expected # of NS-NS	? (~0.1)	? x 10 (~1)	? x 100 (~10)

iPTF (7 deg^2), PS1 (7 deg^2)
DECam (3 deg^2), HSC (1.8 deg^2)

Tomo-e (20 deg^2)
ZTF (47 deg^2)

Timeline (as of 2017)

	2015	2016	2017	2018	2019
	LIGO O1		LIGO O2		LIGO O3
			Virgo		KAGRA
Localization	~600 deg^2				~100 deg^2
Max dist.	~80 Mpc				~150 Mpc
Kilonova	19-20 mag				20-21 mag
Expected # of NS-NS	? (~0.1)				? x 10 (~1)

iPTF (7 deg^2), PS1 (7 deg^2)
DECam (3 deg^2), HSC (1.8 deg^2)

Tomo-e (20 deg^2)
ZTF (47 deg^2)

GW-EM survey with Tomo-e

ToO type

Area: ~100 deg^2 per night <= 5 pointing!

Depth: 20-21 mag (1 visit = 3 min x 5 ~ 15 min exposure)

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

No filter <= faint, models are uncertain

Lessons from follow-up observations

Selection by

(1) short timescale

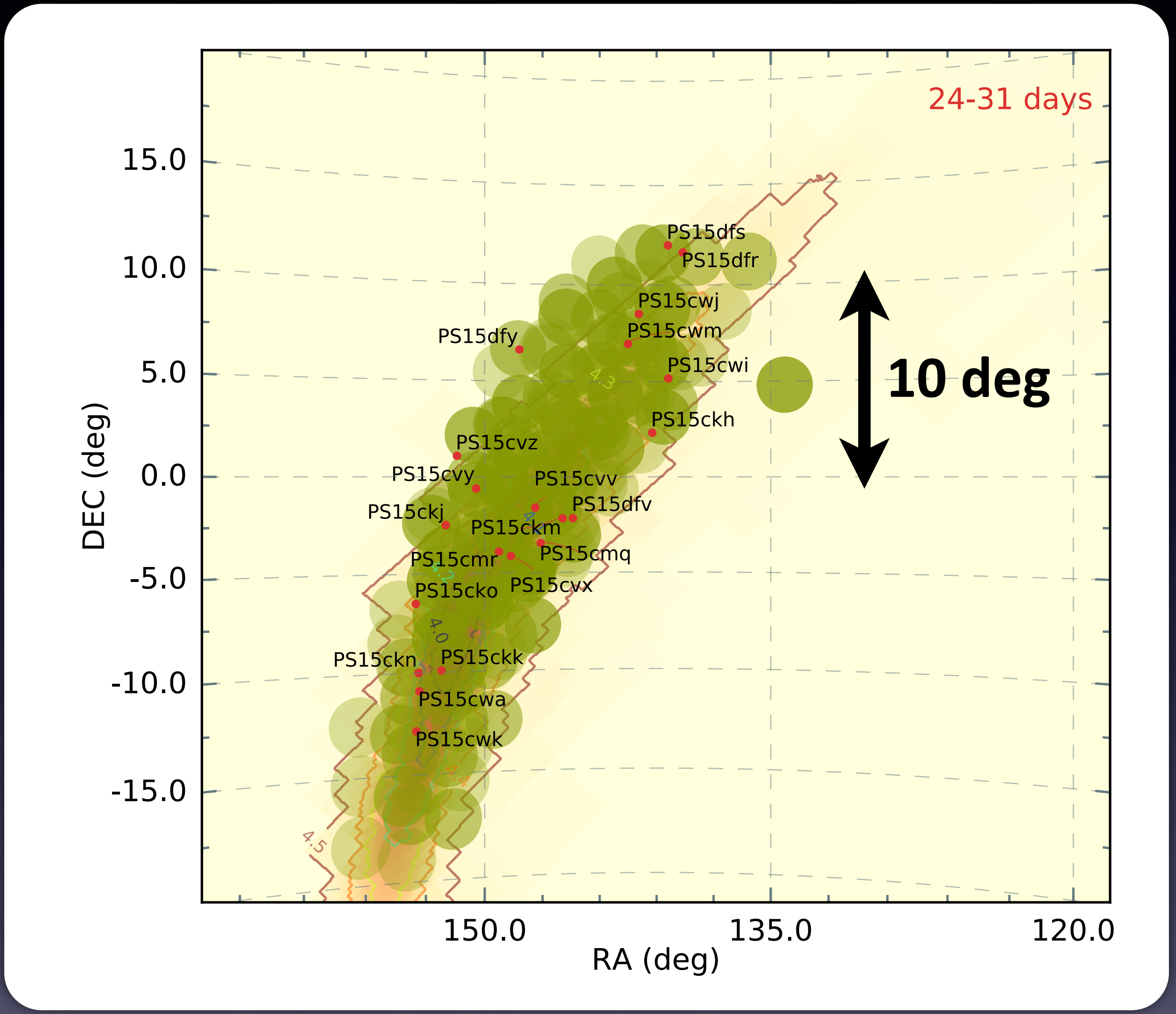
<= lower mass

(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 and 3.8m telescope

- **GW-EM synergy**
  - Localization of GW sources
  - Origin of r-process elements
- **Optical emission from GW sources**
  - ~22 mag @ 200 Mpc <= theory and observations
- **Tomo-e and 3.8m telescope**
  - Year 2018 is critical for Tomo-e (~100 deg^2 localization and ~150 Mpc distance)
  - 100 deg^2 / 20-21 mag / 2hr cadence / no filter
  - Low-resolution spectroscopy with KOOLS-IFU