

A visualization of gravitational waves, showing two bright, glowing spheres (representing black holes or neutron stars) in the center, surrounded by concentric, rippling waves that spread outwards. The background is a dark, starry space.

Tomo-eによる重力波天体の探査観測

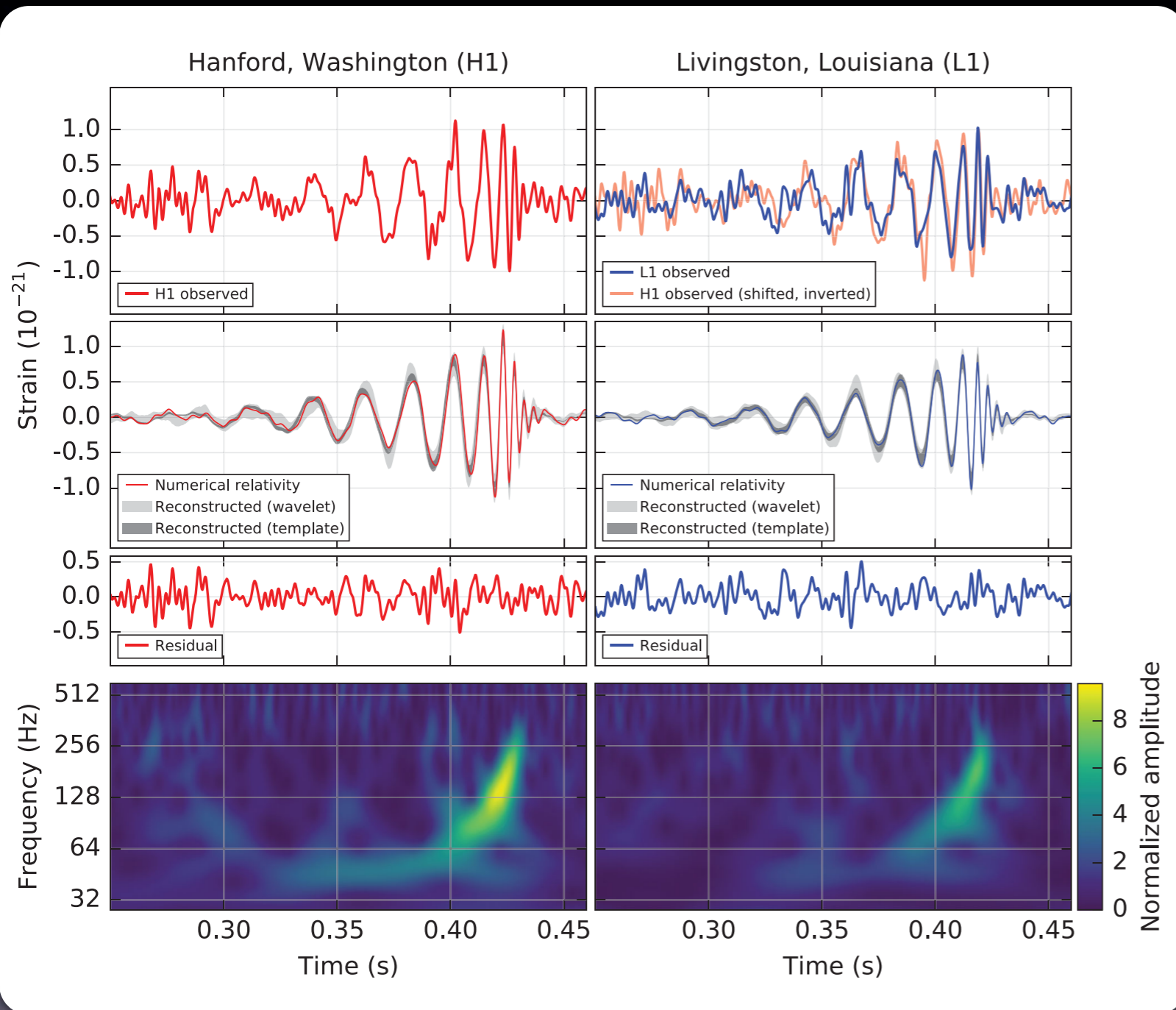
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Masaomi Tanaka

(National Astronomical Observatory of Japan)

- **Importance of EM observations**
- EM emission from GW sources
- Prospects for Tomo-e Gozen

Dawn of GW astronomy

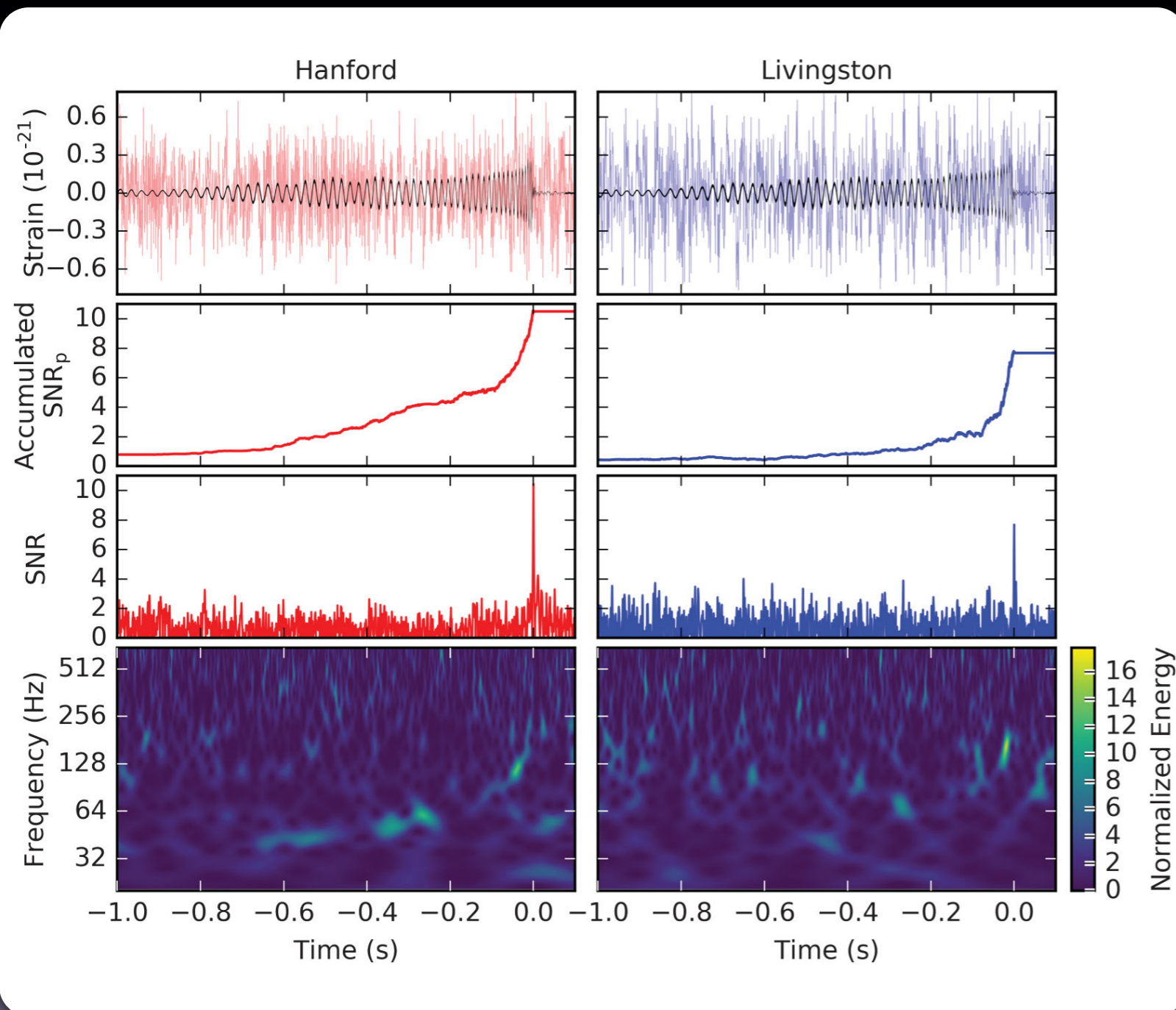


GW150914
BH-BH merger
(~30 Msun) @ 400 Mpc

NEXT!
NS-NS merger (~< 200 Mpc)
or BH-NS merger (~< 800 Mpc)

N ~30 (0.3-300) events/ 1 yr

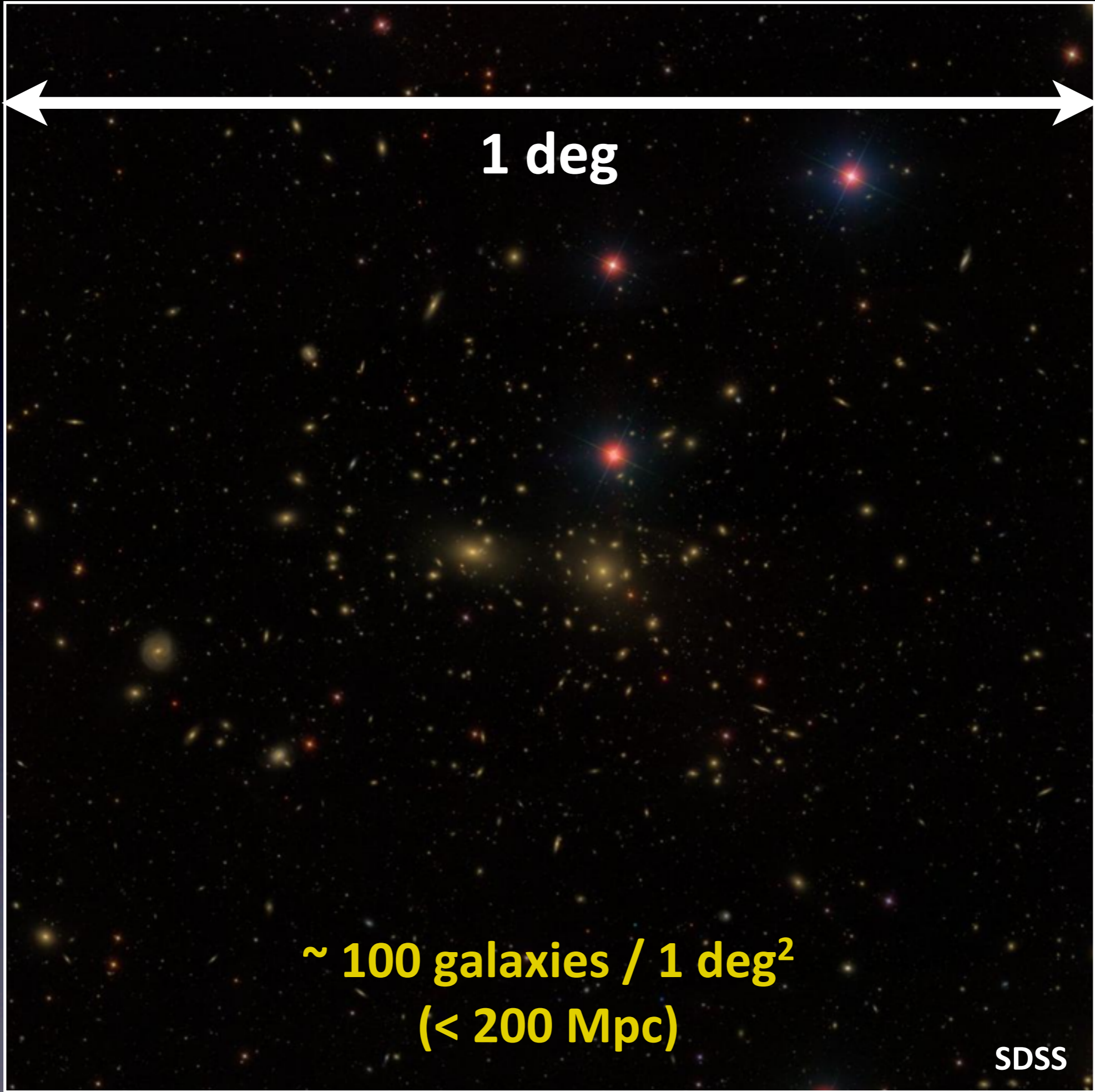
The 2nd is also a BH-BH merger



GW151226

BH-BH merger

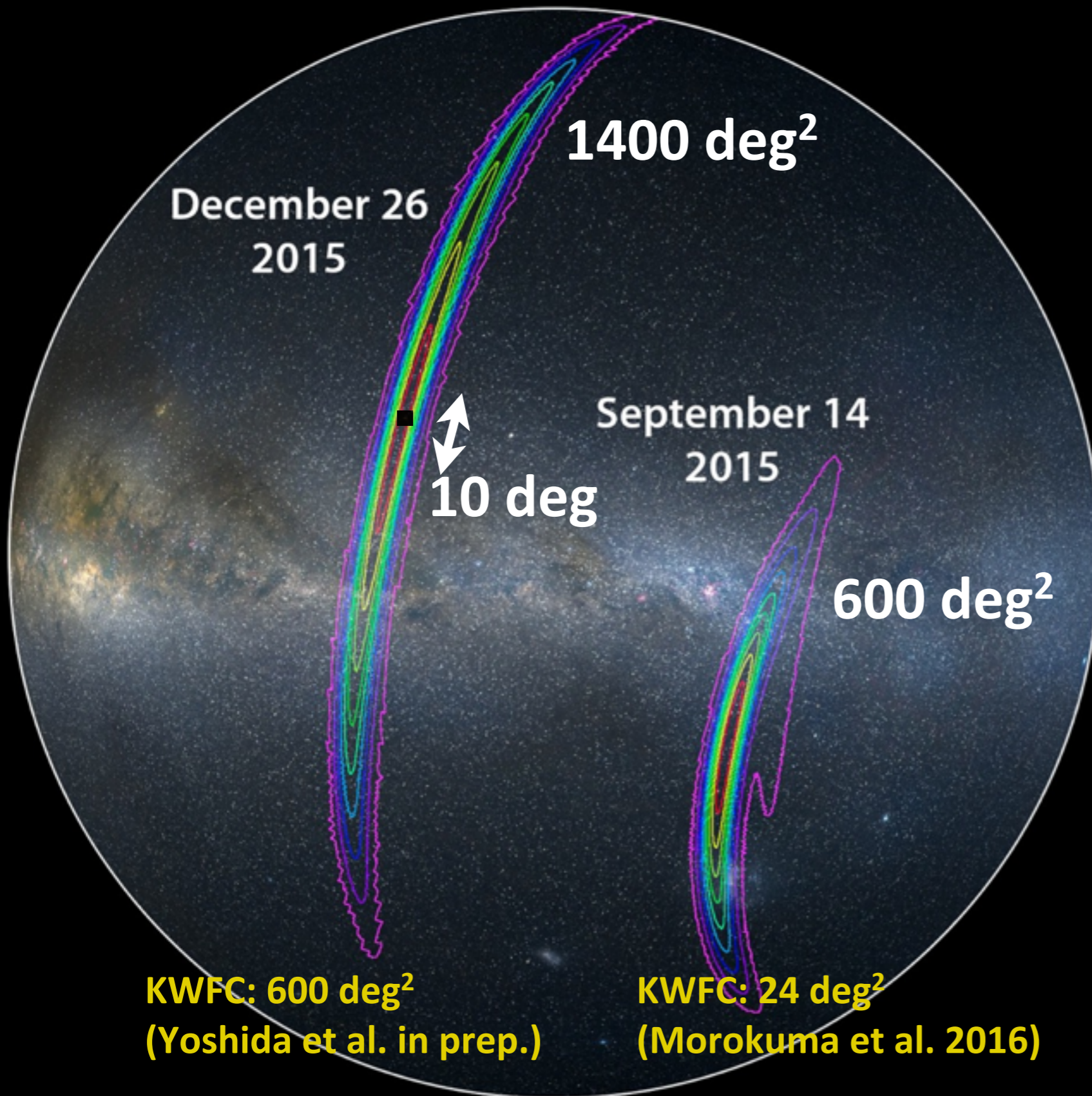
(~14+8 Msun) @ 440 Mpc



1 deg

**~ 100 galaxies / 1 deg²
(< 200 Mpc)**

SDSS



Localization $\sim 600 \text{ deg}^2$!!
($\sim 10 \text{ deg}^2$ with
Advanced Virgo and KAGRA)

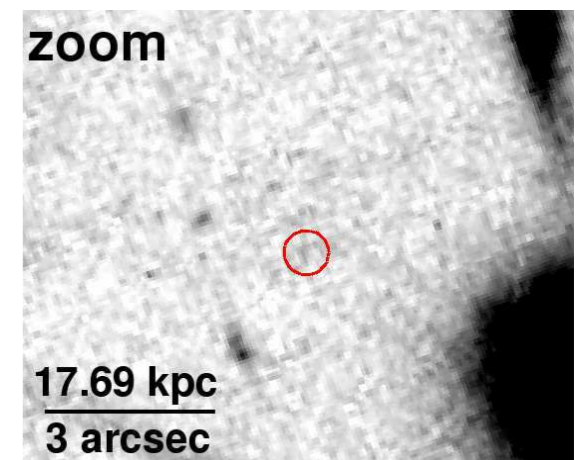
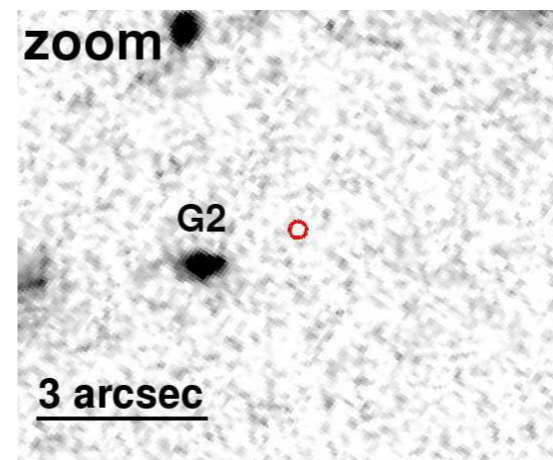
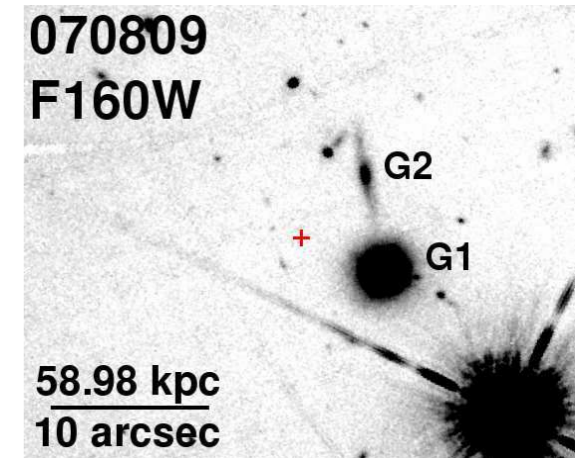
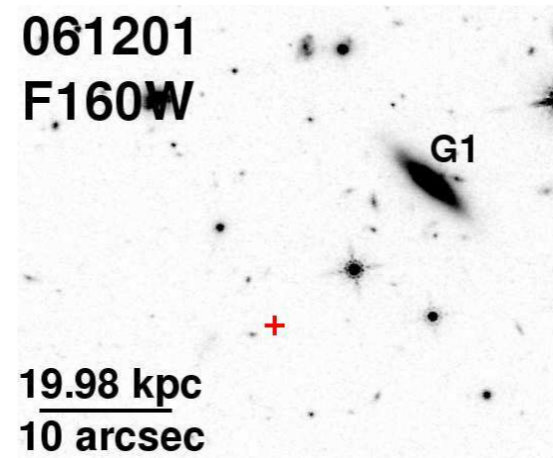
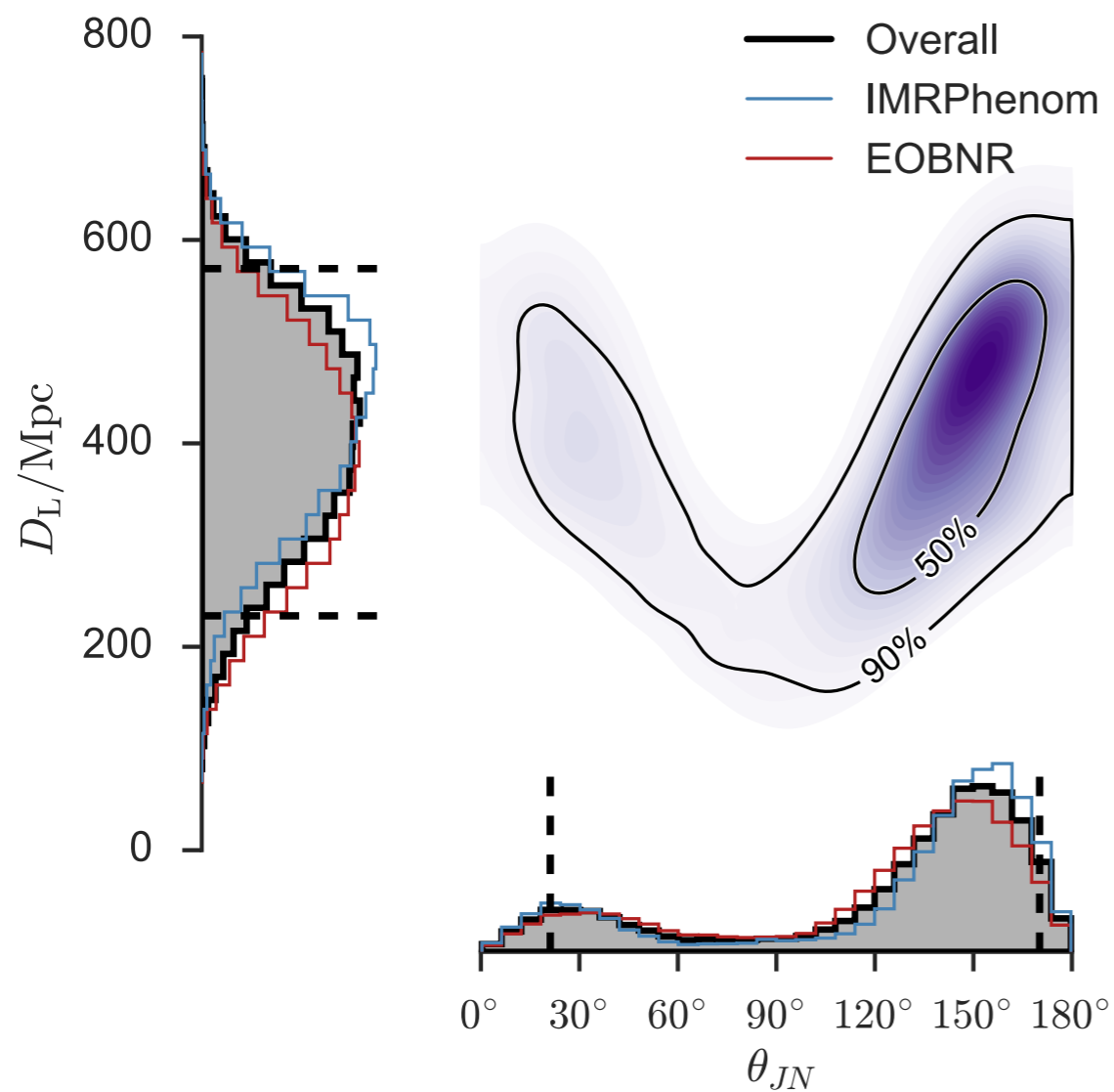


Detection of
electromagnetic (EM)
counterparts is essential

- Redshift (distance)
- Host galaxy
- Local environment

Degeneracy between inclination and distance

Local environments



(GW 150914, Abbott et al. arXiv:1602.03840)

(short GRBs, Berger 2014)

- Importance of EM observations
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Electromagnetic signature from **NS** mergers

- On-axis short GRB

strongly beamed ✖

(isotropic soft X-ray?)

- Off-axis radio afterglow

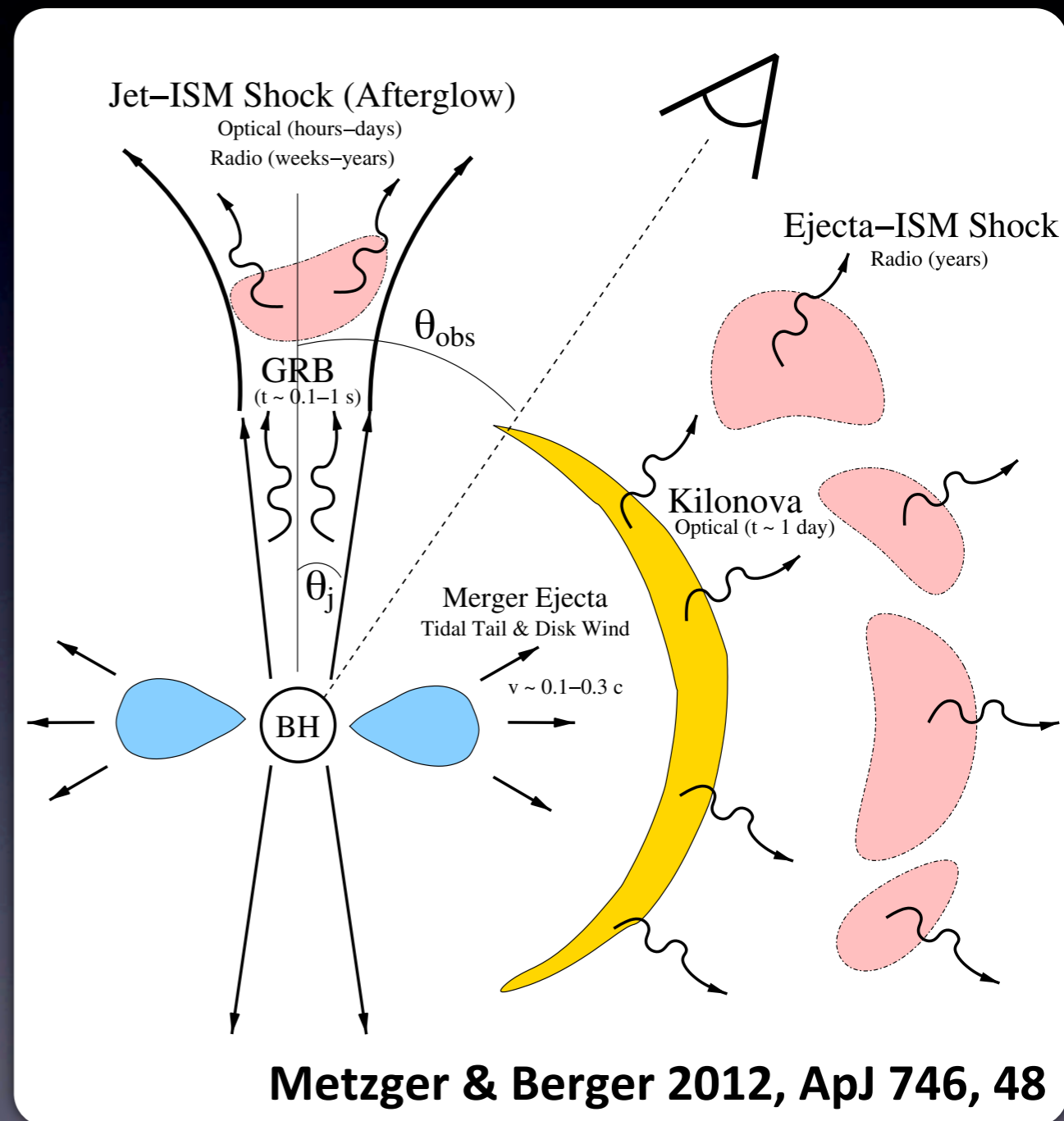
isotropic ✔

delayed by $\sim > 1$ yr ✖

- Radioactive emission
“kilonova” or “macronova”

isotropic ✔

short delay ✔



Mass ejection

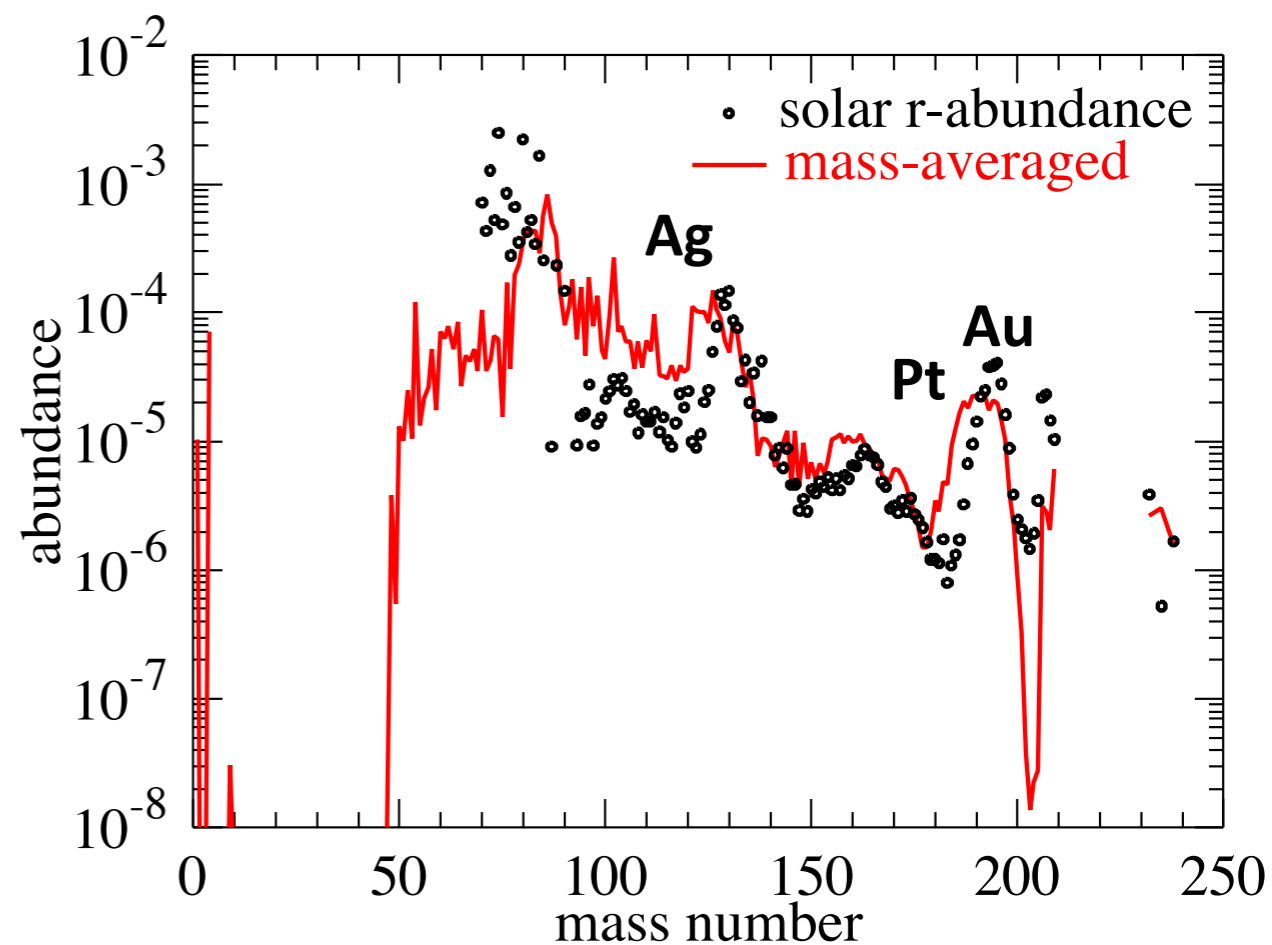
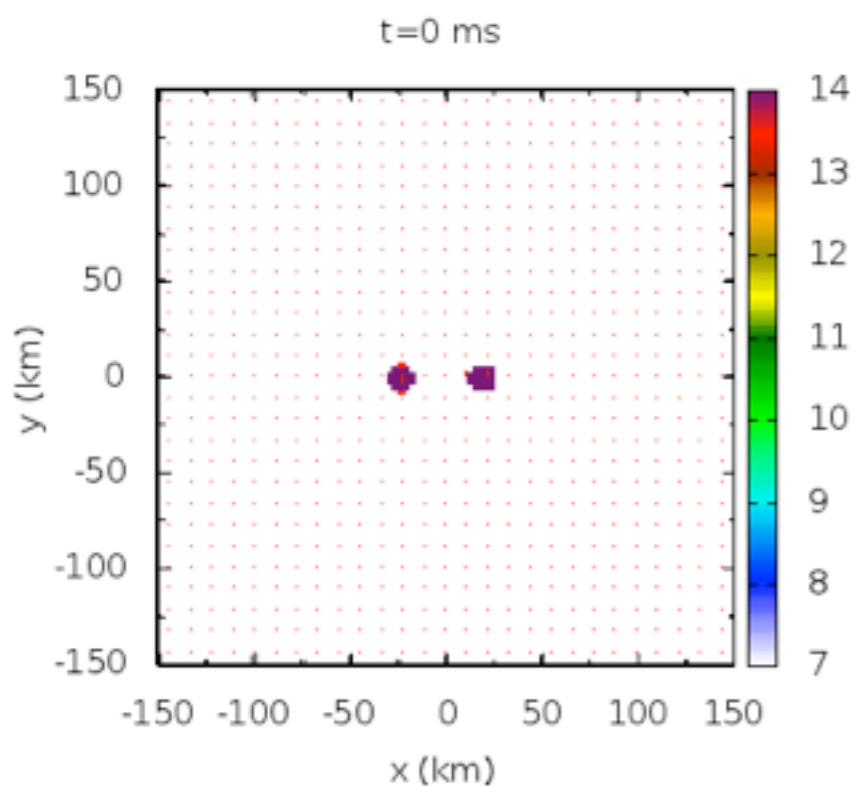
$M(\text{Au}) \sim 30 M_{\text{Earth}}$ **r-process nucleosynthesis**
($\sim 10^{33}$ JPY)

$M \sim 10^{-3} - 10^{-2} M_{\text{sun}}$

$v \sim 0.1 - 0.2 c$



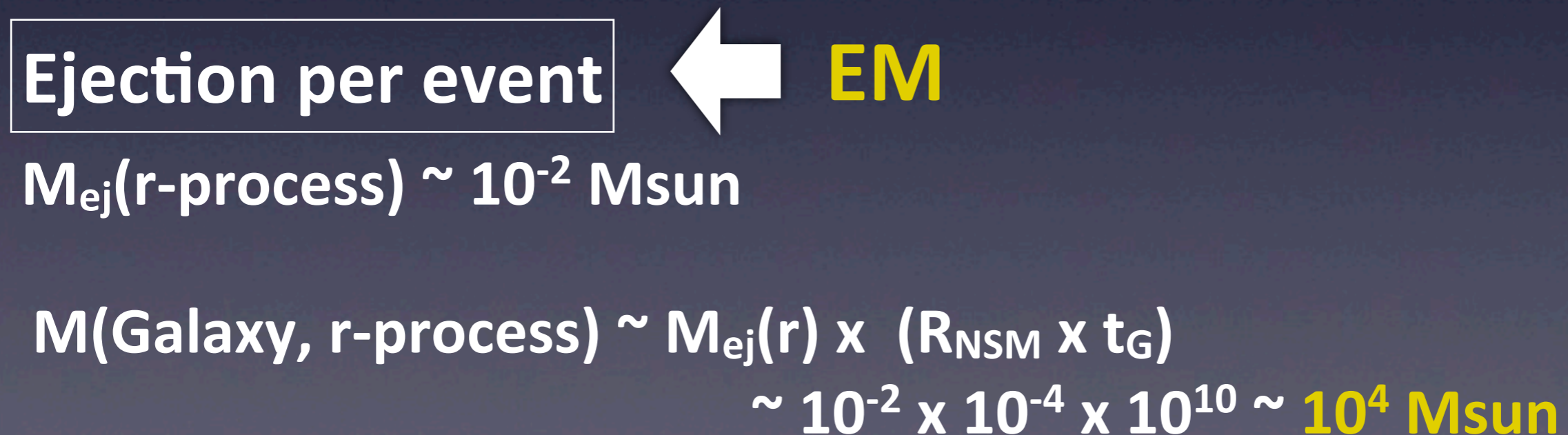
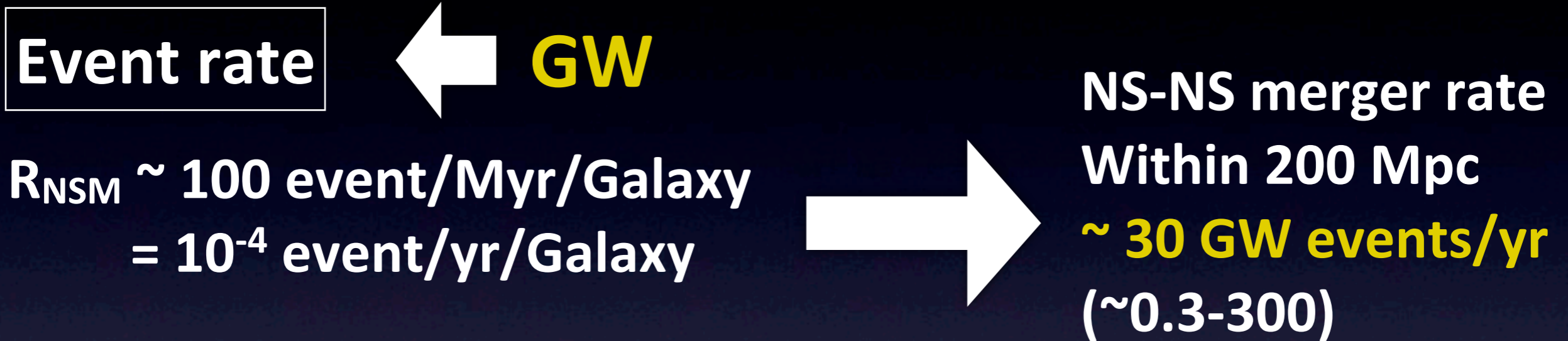
\sim solar abundance



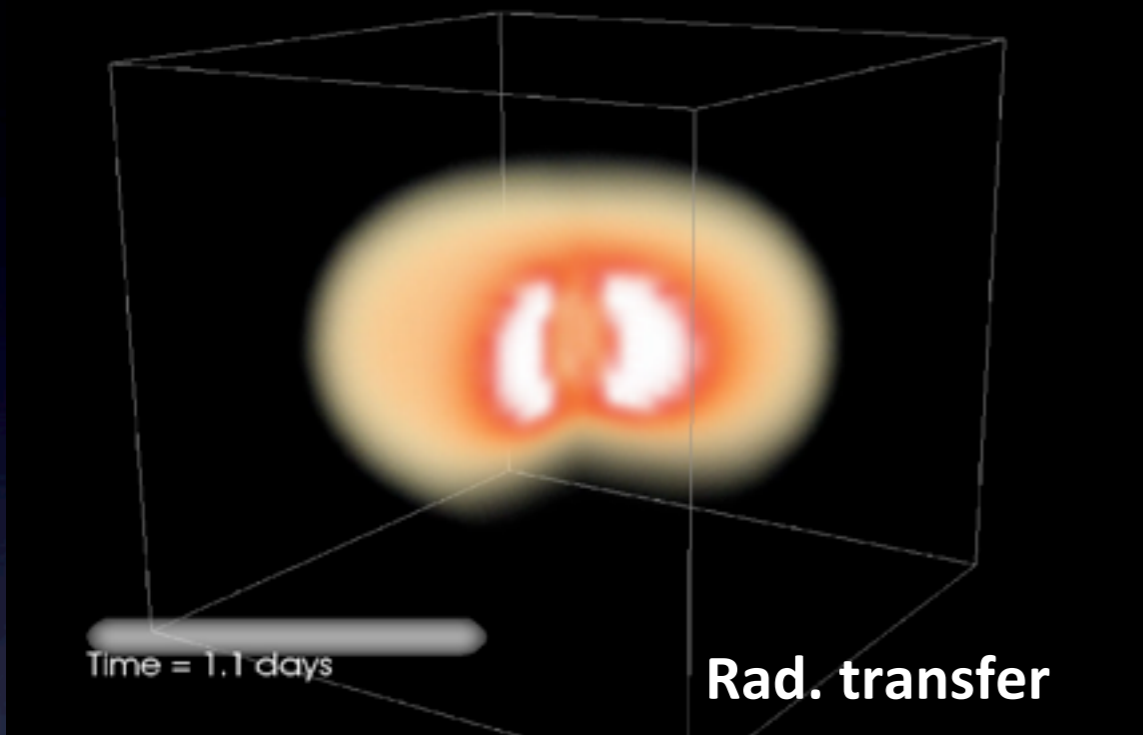
Hotokezaka+13, PRD, 87, 4001
Rosswog+13, MNRAS, 430, 2580

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

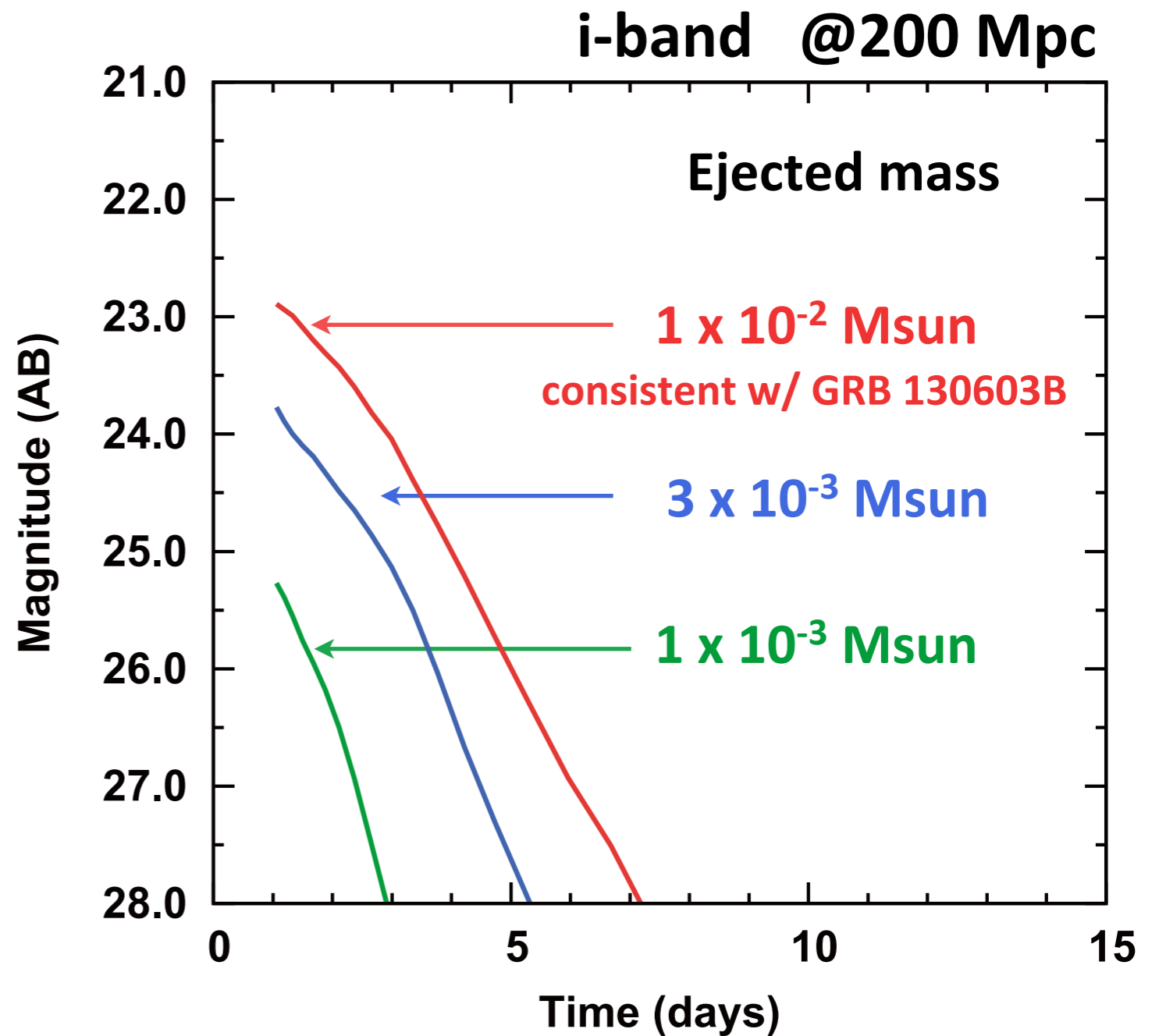
NS merger as a possible origin of r-process elements



“kilonova”: Radioactively-powered emission



- Fast time evolution
- Faint (absolute -14 mag)
- Red ($T \sim 3000\text{K}$)



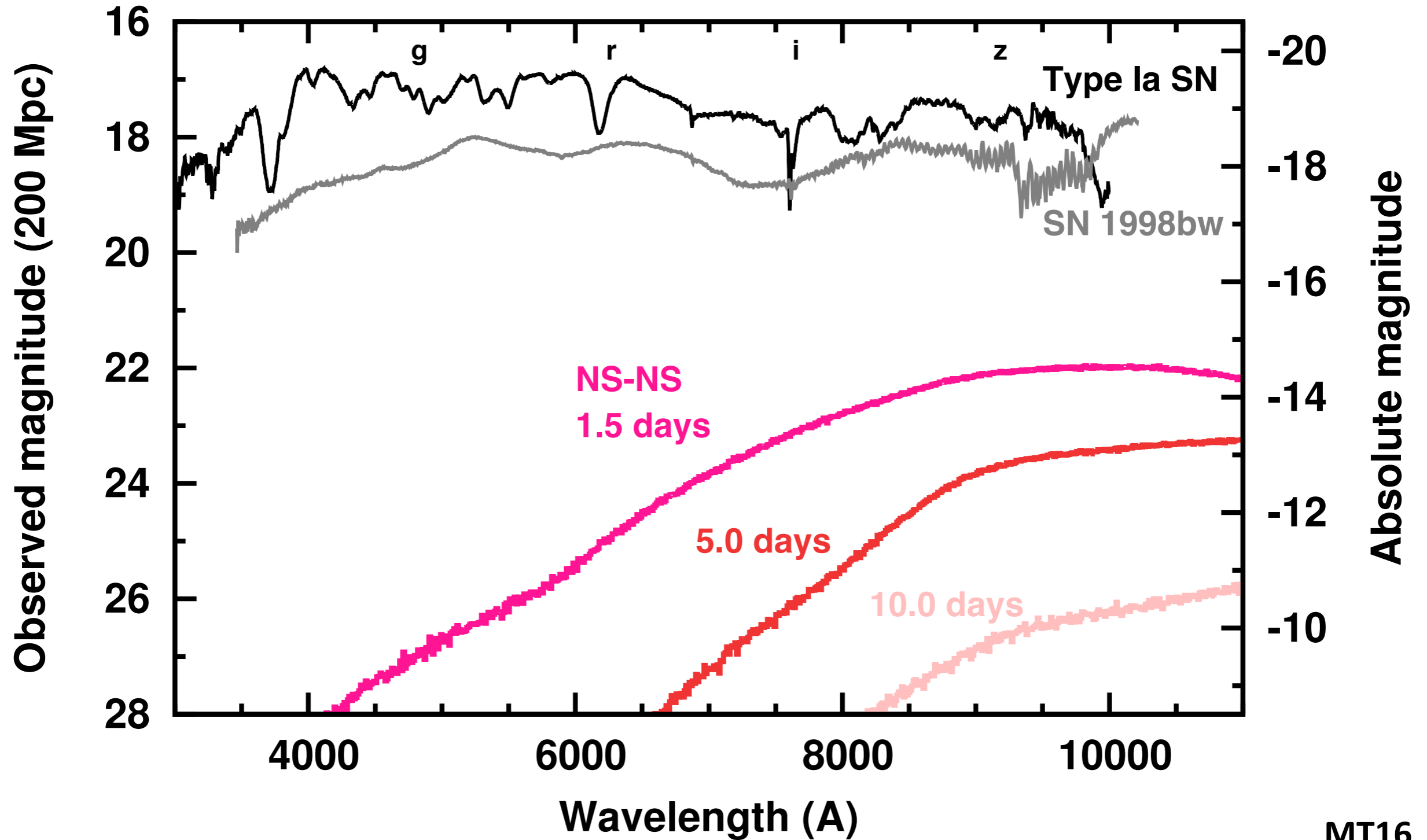
MT & Hotokezaka 2013, ApJ, 775, 113

MT+, 2014, ApJ, 780, 31

MT 2016 (review), Advances in Astronomy (arXiv:1605.07235)

Extremely red spectra

← Tomo-e →



Possible brighter/bluer/faster emission

* too bright models conflict with observations of short GRBs (Kann+10) ==> $M_{\text{opt}} > \sim -16$ mag

Disk wind ($\sim 10^{-2} M_{\text{sun}}$)

$t < 5$ d, blue,

22 mag@200 Mpc (abs -15 mag)

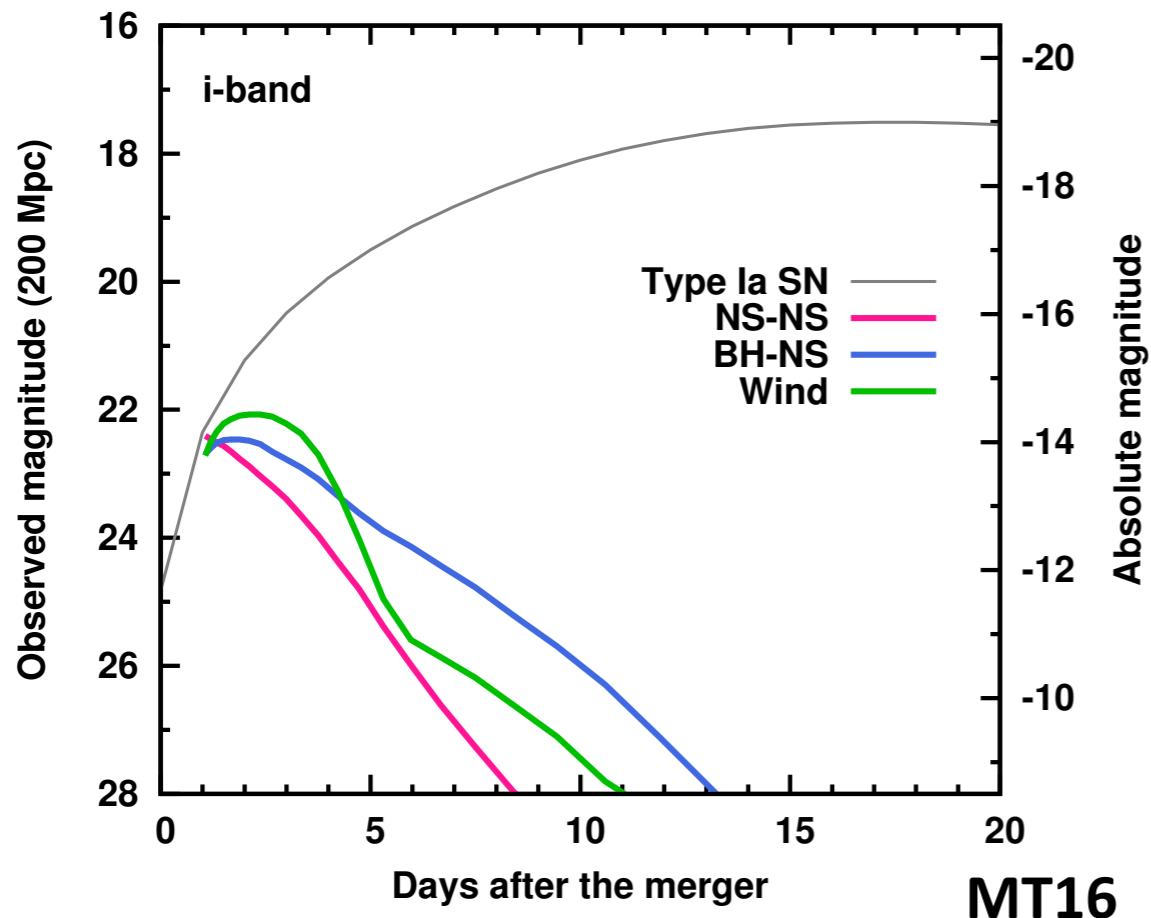
* may be absorbed by dynamical ejecta

Free neutron ($\sim 10^{-4} M_{\text{sun}}$??)

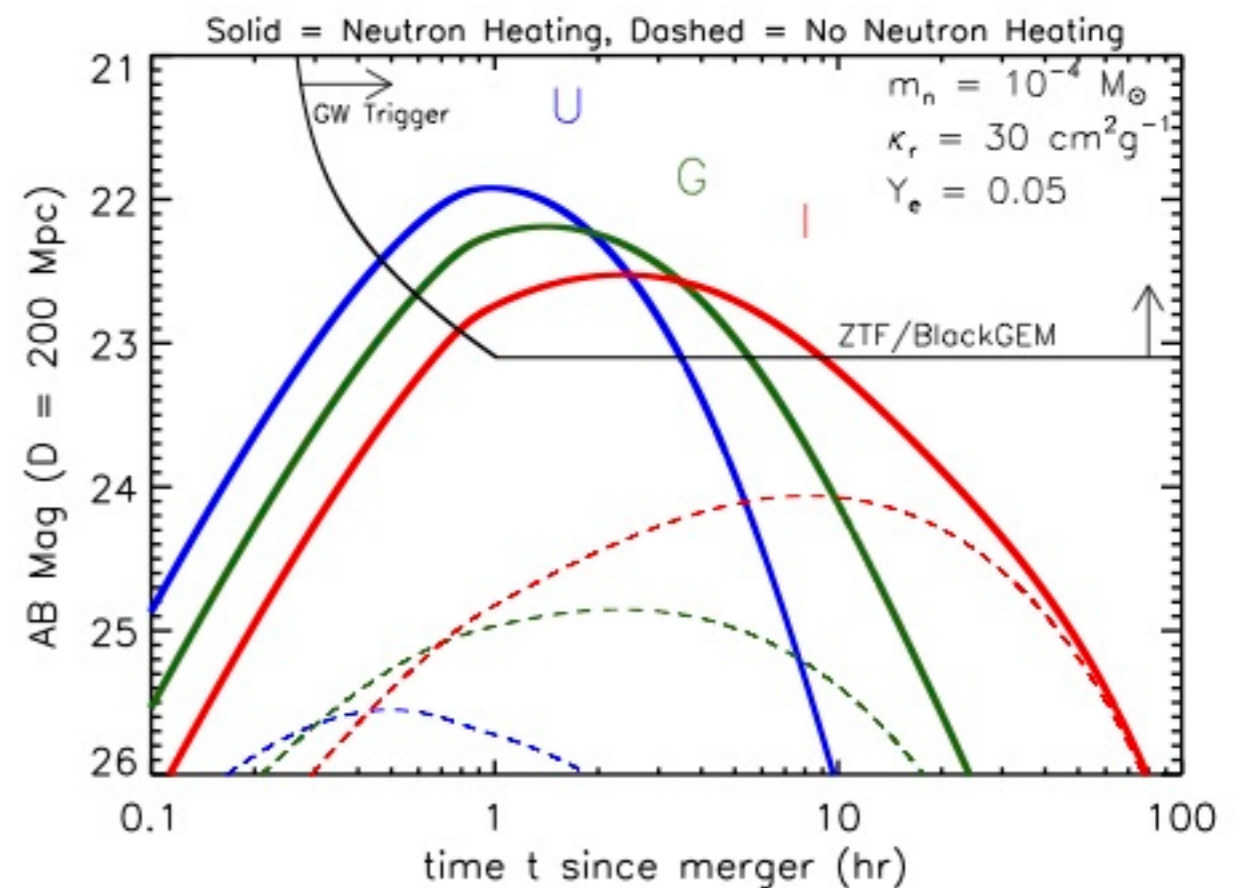
$t < 1$ d, blue,

22 mag@200 Mpc (abs -15 mag)

* large uncertainty in mass



Metzger & Fernandez 2014; Kasen+15



Metzger+2015

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Follow-up observations for GW150914 and GW151226

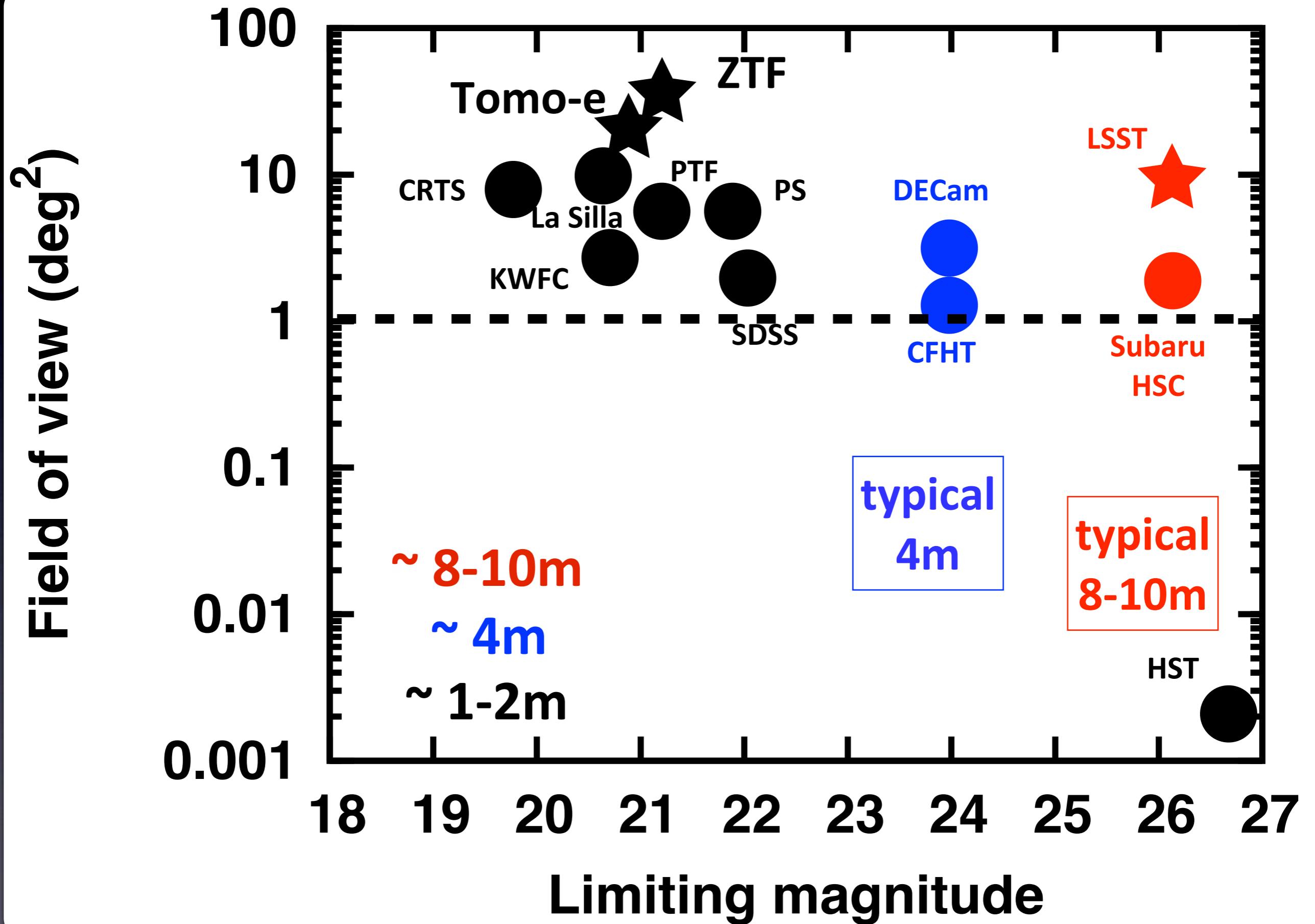
● GW150914

- Smartt et al. (PS1, arXiv:1602.04156) 20 mag, 442 deg², 56 SNe
- Kasliwal et al. (iPTF, arXiv:1602.08764) 21 mag, 135 deg², 8 SNe
- Soares-Santos et al. (DECam, arXiv:1602.04198) 22 mag, 40 deg²
- Morokuma et al. (J-GEM, arXiv:1605.03216) 18 mag, 24 deg²

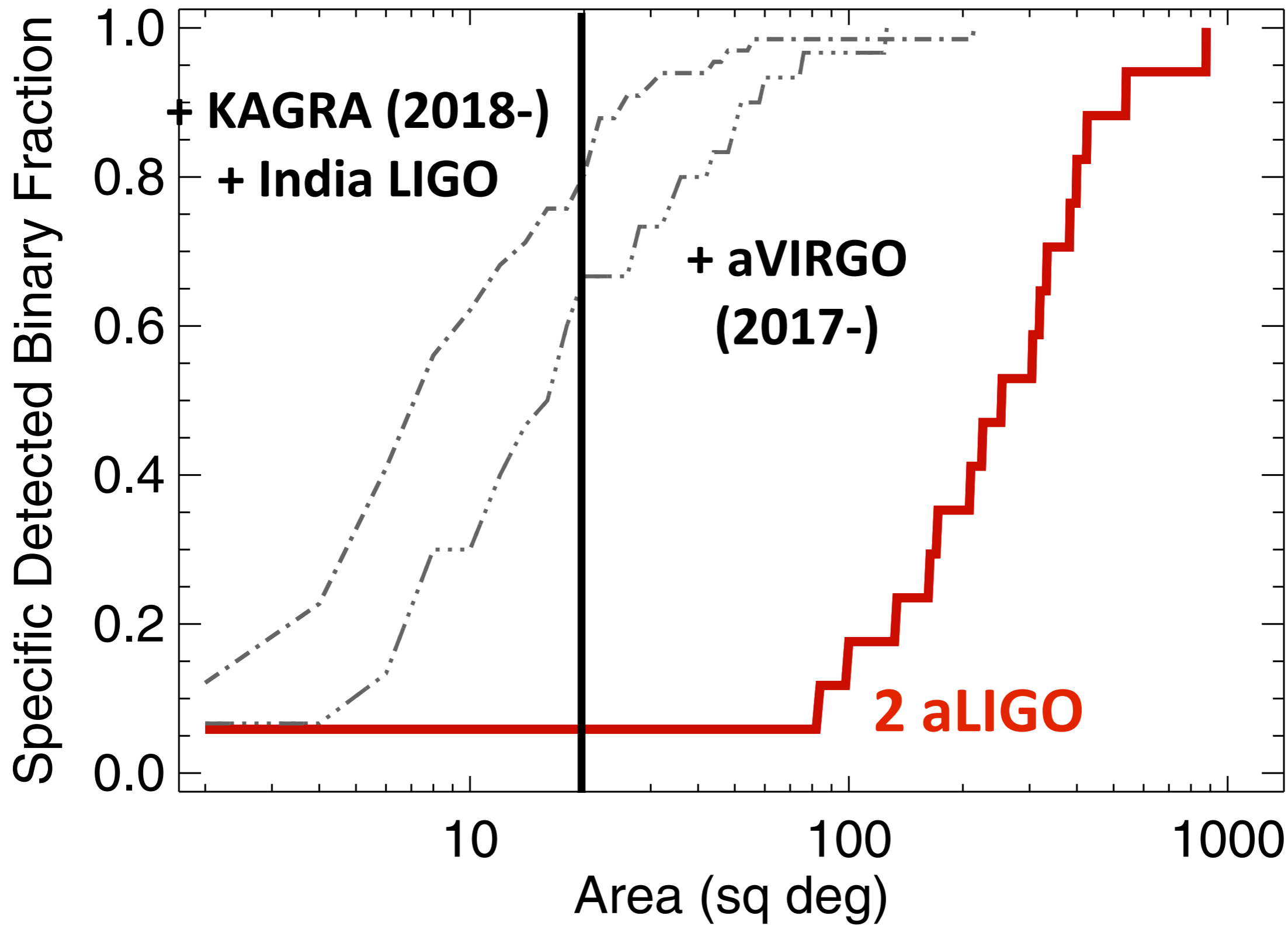
● GW151226

- Smartt et al. (PS1, arXiv:1606.04795) 21 mag, 290 deg², 20 SNe
- Cowperthwaite et al. (DECam, arXiv:1606.04538) 22 mag, 29 deg², 4 SNe
- Copperwheat et al. (LT, arXiv:1606.04574) spectroscopy

see Morokuma-san's talk for Kiso/KWFC surveys



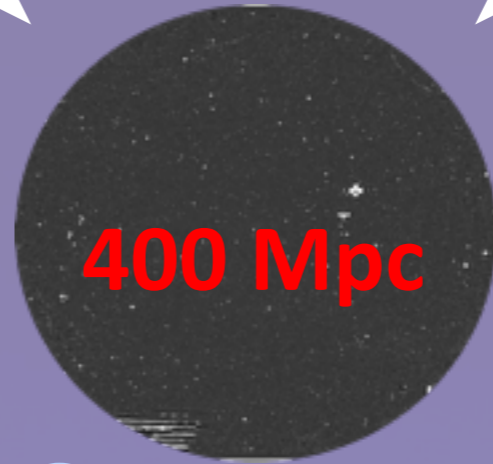
Tomo-e



GW alert error box
e.g. 6 deg x 6 deg

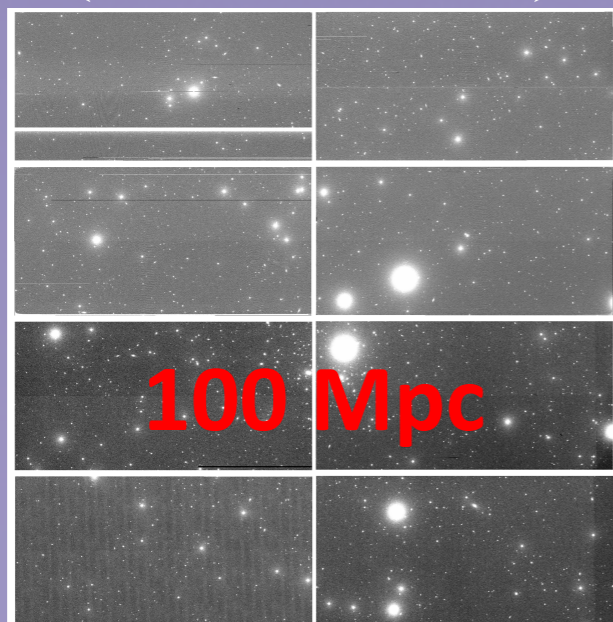
Subaru/HSC
1.5 deg

ZTF

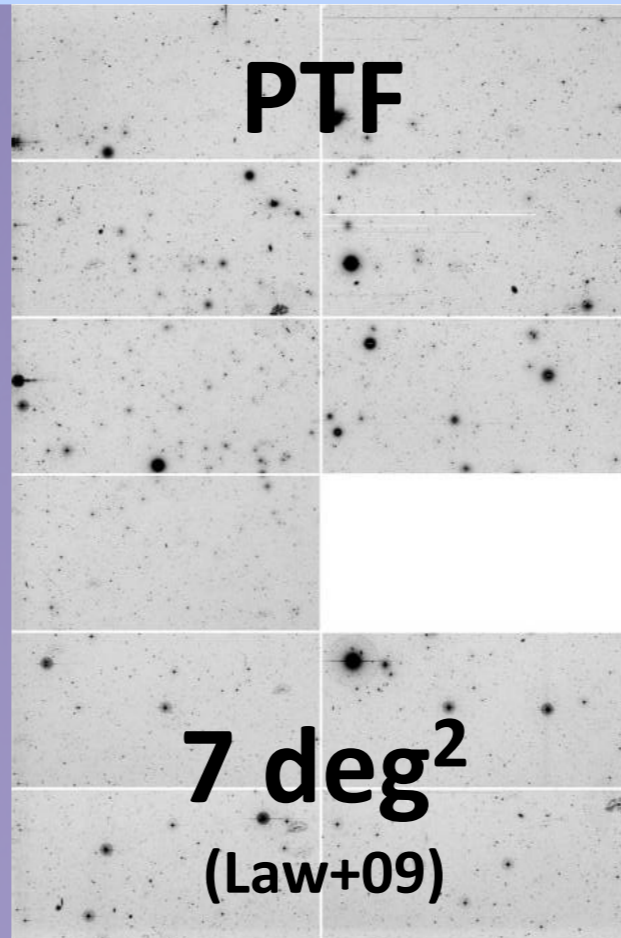


Tomo-e Gozen
9 deg

KWFC
2 deg



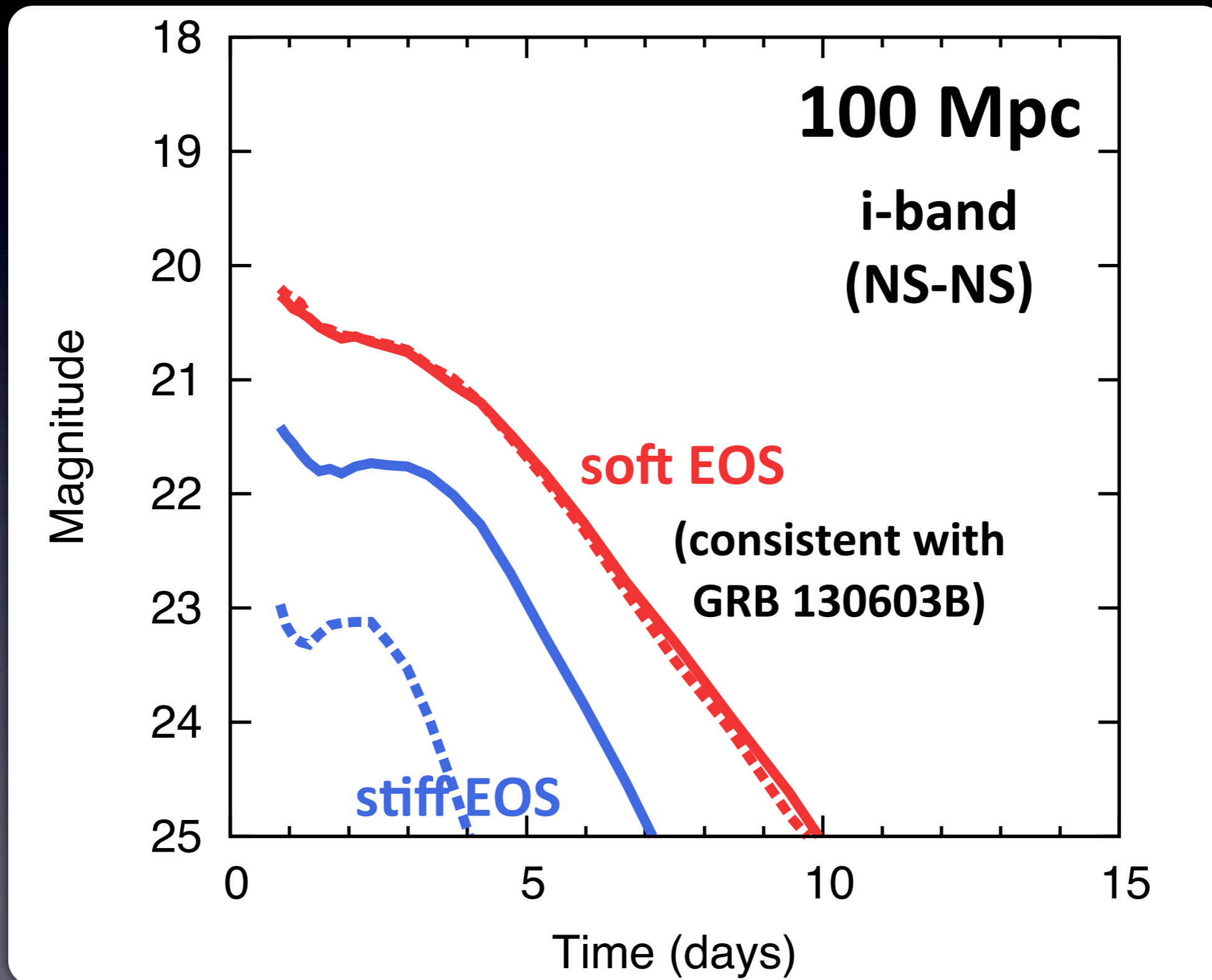
PTF



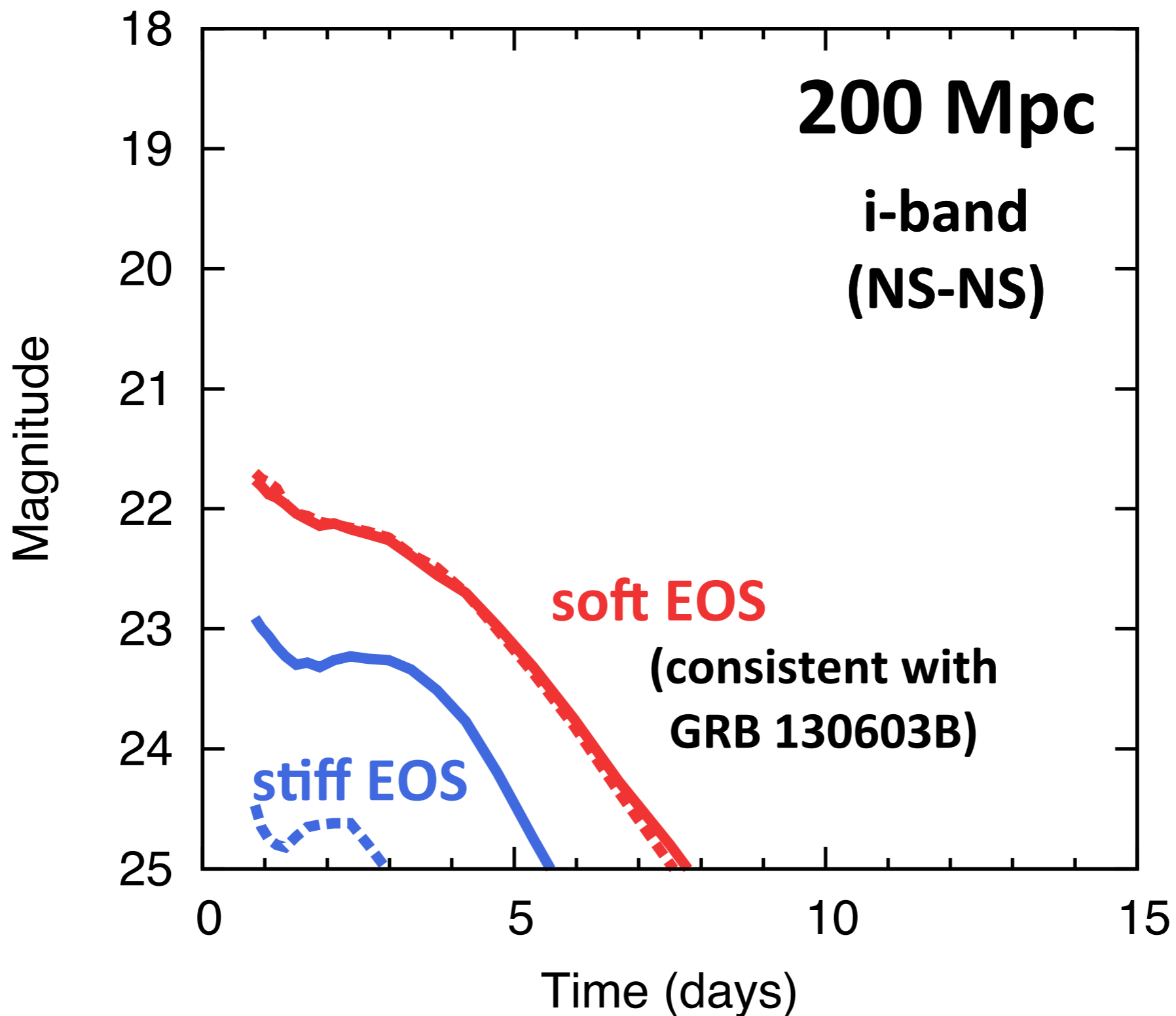
7 deg²
(Law+09)

2015: LIGO O1

2016-2017: LIGO O2 + Virgo



2018: LIGO, Virgo and KAGRA



Supernovae vs GW source

Selection by

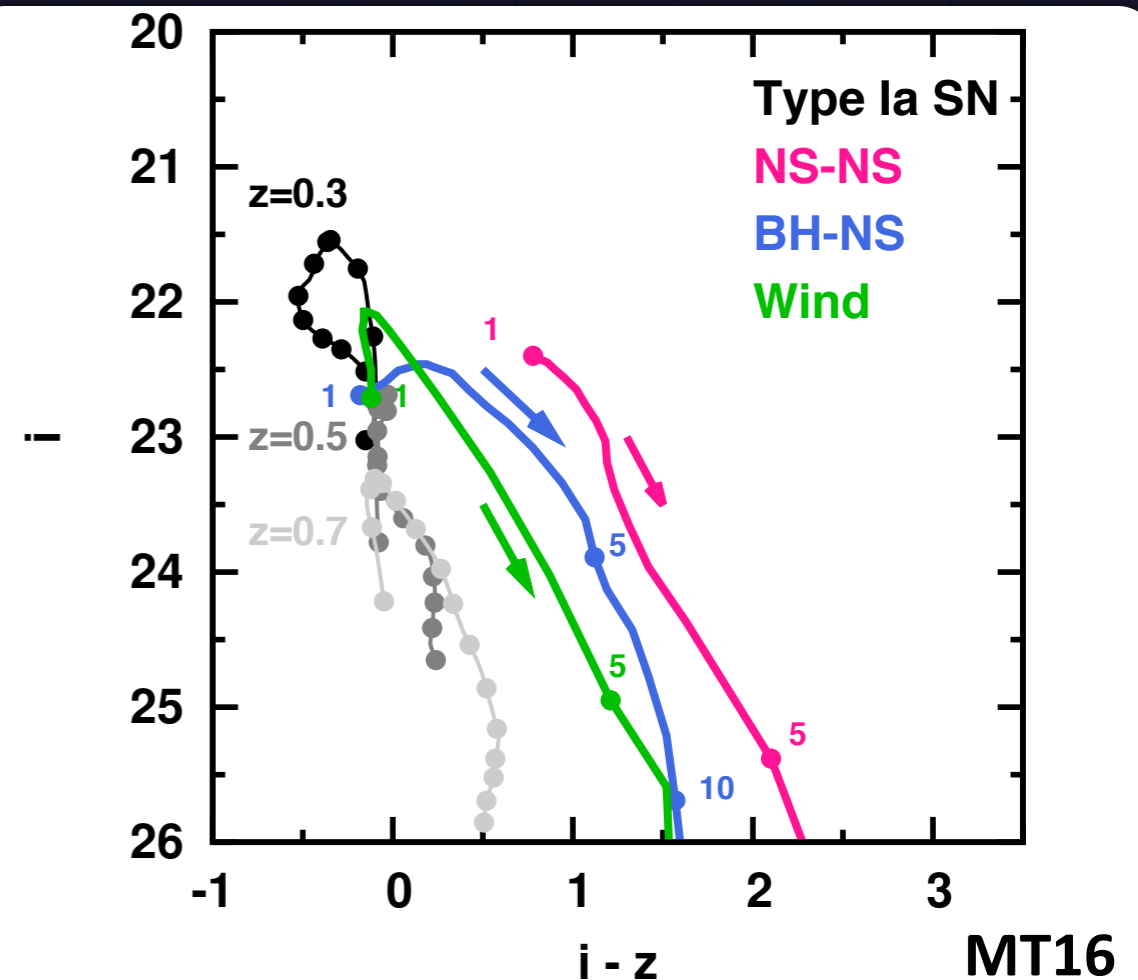
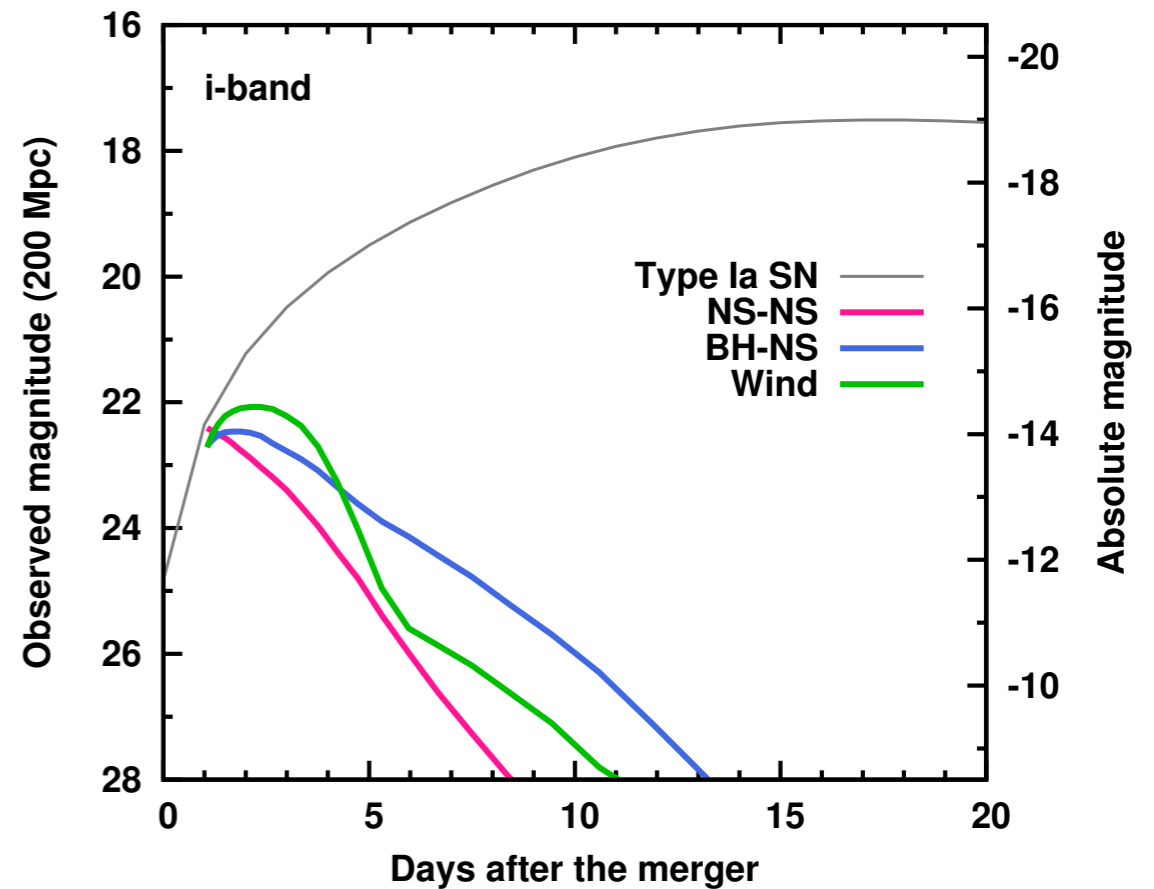
- (1) short timescale \Leftarrow lower mass
- (2) faintness \Leftarrow lower energy source
- (3) red colors \Leftarrow higher opacity



Strategy for Tomo-e survey

($\sim 100 \text{ deg}^2$)

- 1 visit = 3 min x 5 exposures (~ 20 min)
- 5 pointing (~ 2 hr)
- 2-3 visits /night
- **no filter** \Leftarrow faint, models are uncertain



Summary

	2015	2016	2017	2018
Localization	~600 deg ²	~100 deg ²		~10-50 deg ²
Max. dist	80 Mpc	~150 Mpc		200 Mpc
kilonova brightness	~ 19-20 mag	~ 20-21 mag		~22-23 mag
Expected number	? (~0.1)	? x 10 (~1)		? x 100 (~10)
		(+Virgo?)	+Virgo	+KAGRA?

iPTF (7 deg²)
PS1 (7 deg²)
DECam (3 deg²)

Tomo-e (20 deg²)
ZTF (47 deg²)