

重力波天体からの電磁波放射

Electromagnetic Emission from Gravitational Wave Source

田中 雅臣

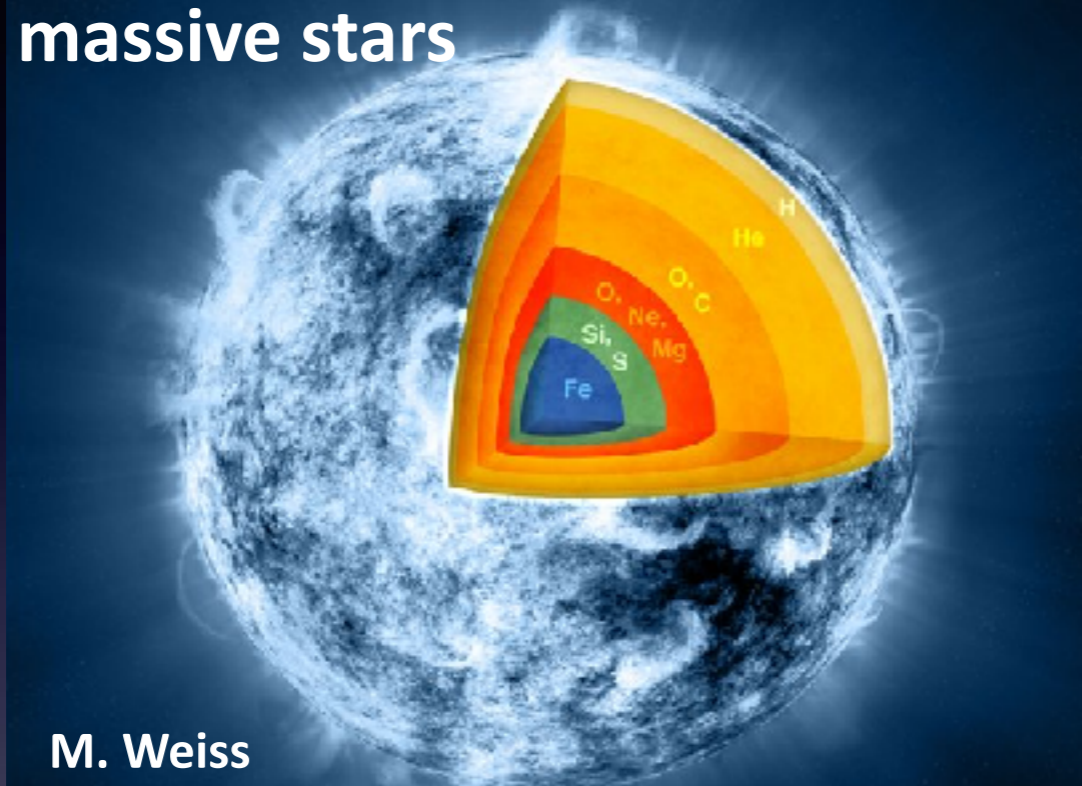
Masaomi Tanaka

(National Astronomical Observatory of Japan)

GW sources

Supernova

massive stars



Rate

$\sim 0.01-0.02 \text{ yr}^{-1} \text{ Gal}^{-1}$

Distance

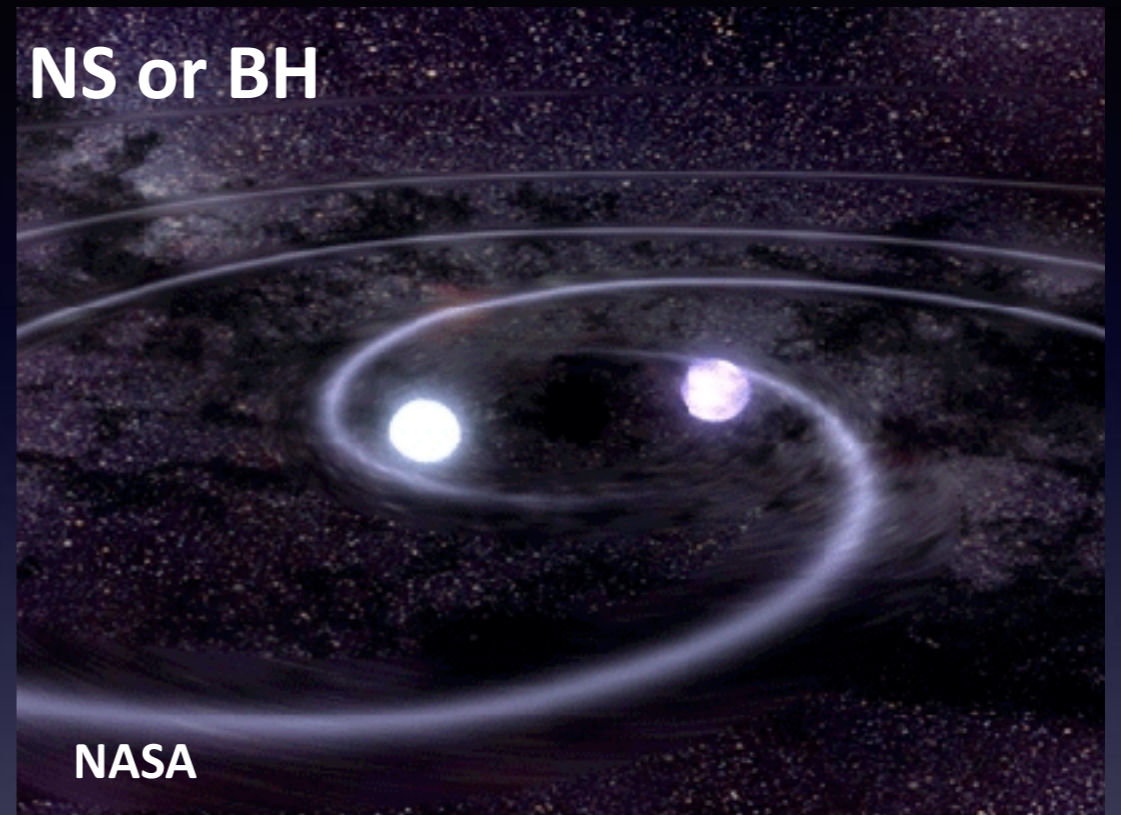
Galactic

Expected
number

$\sim 0.01-0.02 \text{ events yr}^{-1}$

Compact binary merger

NS or BH



NS-NS: $\sim 10^{-4} \text{ yr}^{-1} \text{ Gal}^{-1}$
BH-NS/BH-BH: $\sim 10^{-6} \text{ yr}^{-1} \text{ Gal}^{-1}$

Extragalactic
d $\sim 100 \text{ Mpc} - 1 \text{ Gpc}$
z $\sim 0.02-0.2$

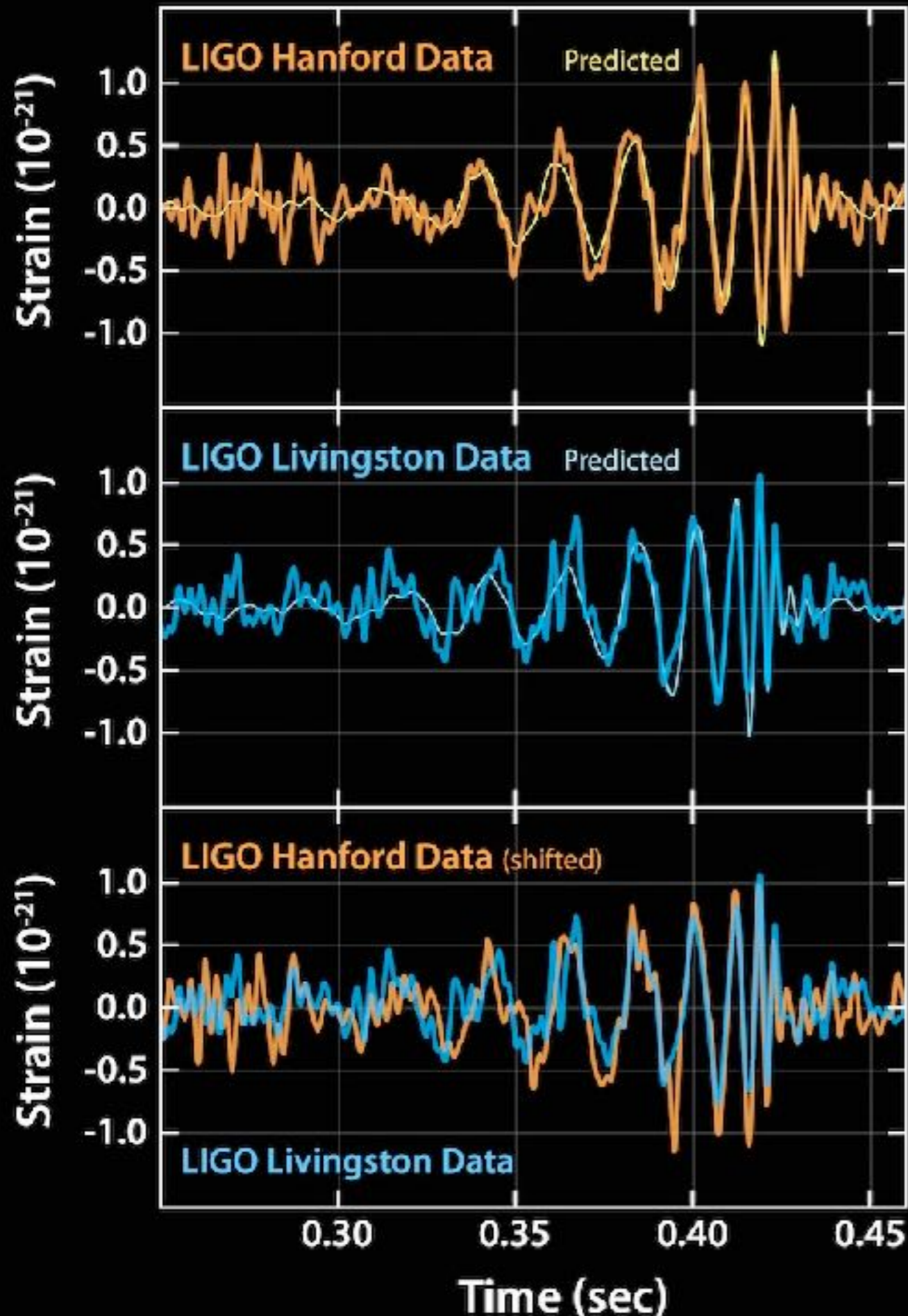
$\sim 0.1-100 \text{ events yr}^{-1}$

The first detection!!

- Direct proof of GWs
- Existence of ~ 30 Msun BH
- Existence of 30 Msun BH binary

=> Kanda-san's talk

LIGO Scientific Collaboration
and Virgo Collaboration, 2016, PRL, 061102





GW150914

Localization $\sim 600 \text{ deg}^2$

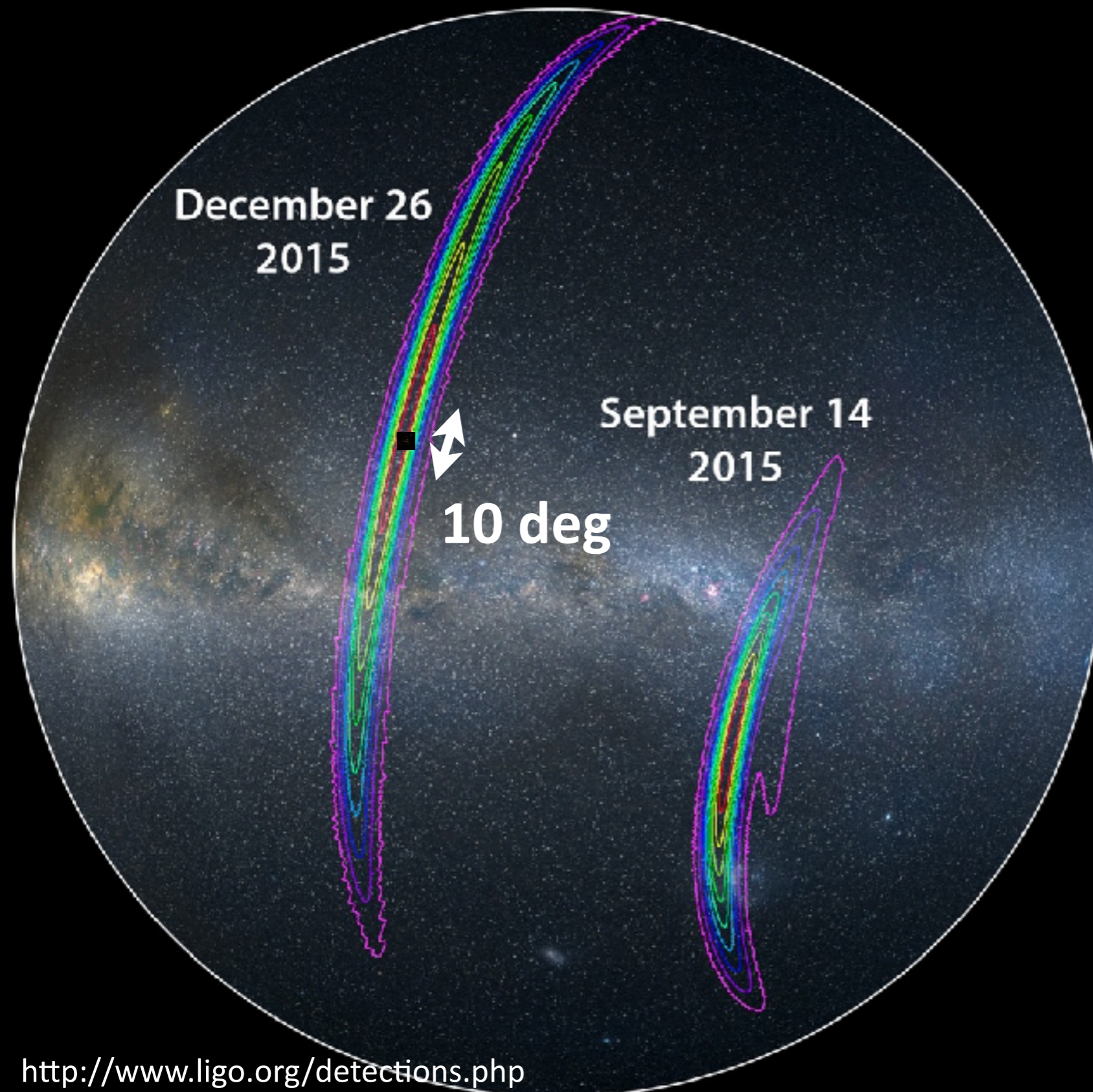
**($\sim < 10 \text{ deg}^2$ with
Advanced Virgo and KAGRA)**



**Electromagnetic (EM)
counterparts**

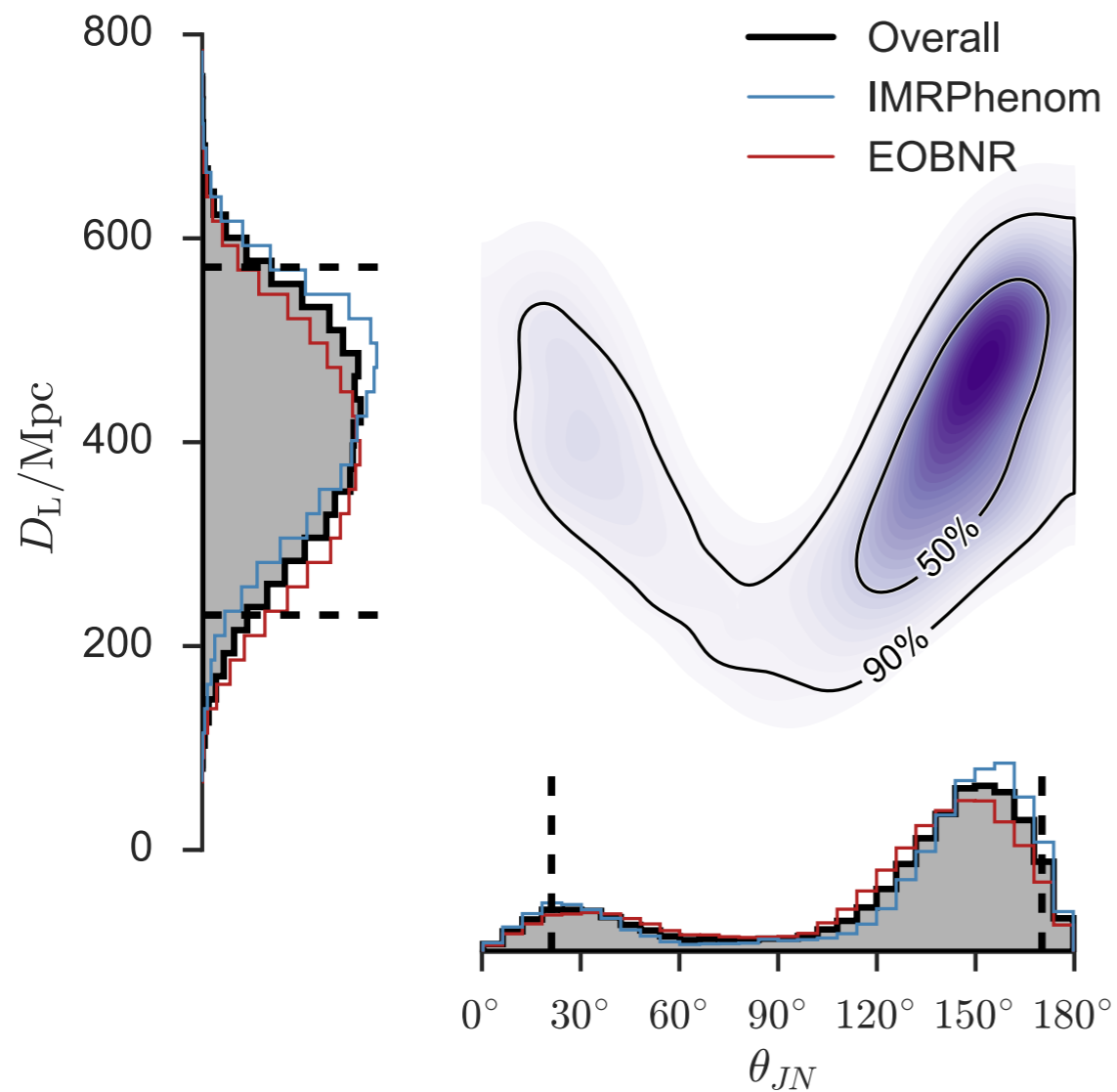
- Redshift (distance)
- Host galaxy
- Local environment

Talks by Kanda-san
and Yoshida-san

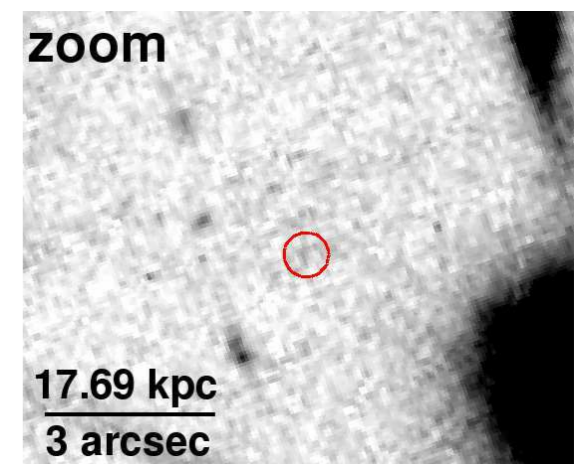
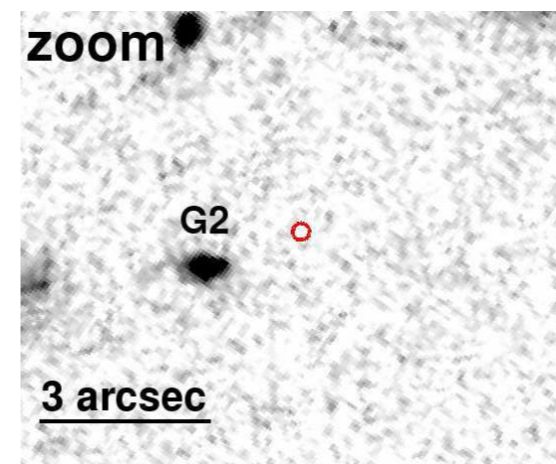
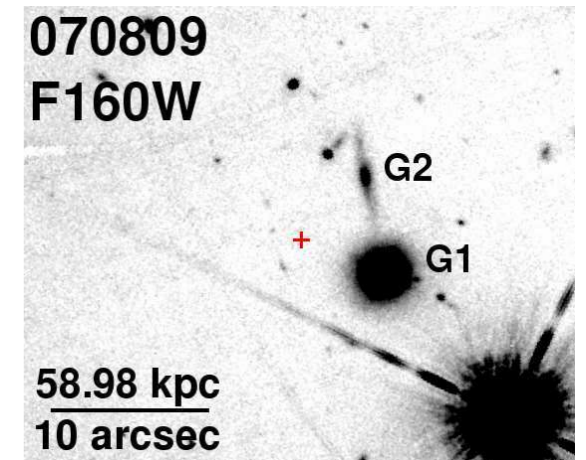
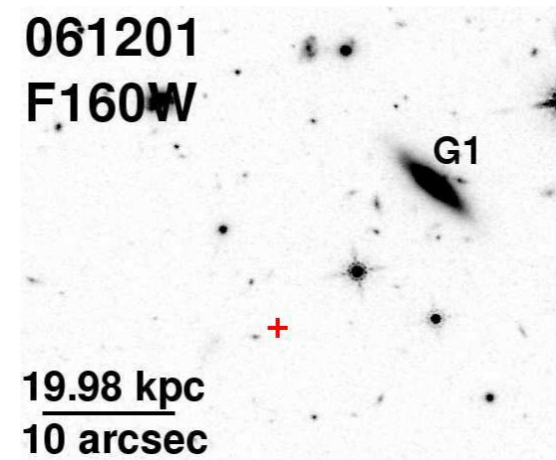


Degeneracy between inclination and distance

Local environments



Abbott et al. 2016



Berger 2014 (for short GRBs)

Electromagnetic Emission from Gravitational Wave Source

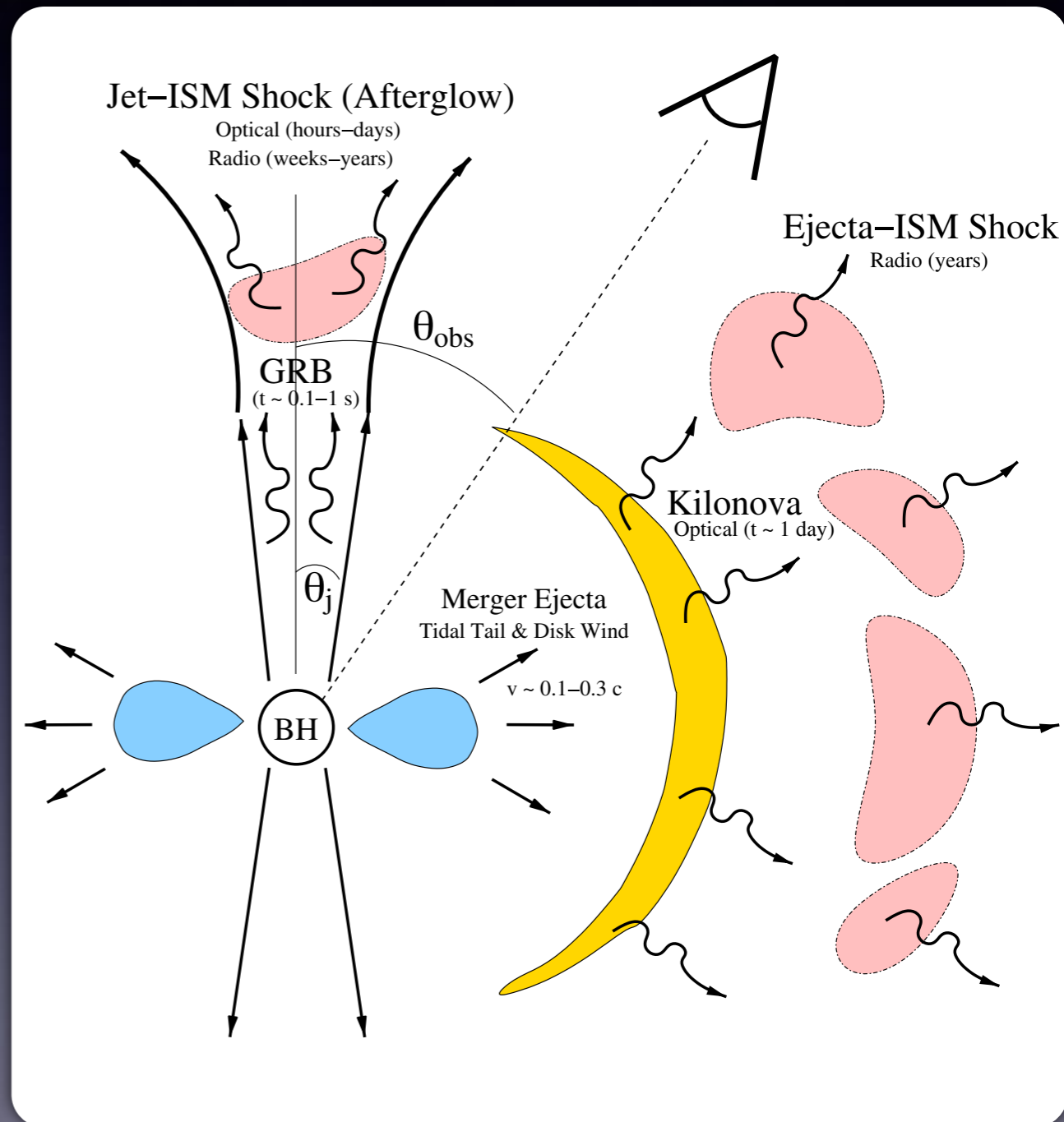
- **EM emission from compact binary mergers**
- Kilonova/macronova emission and the origin of r-process elements

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

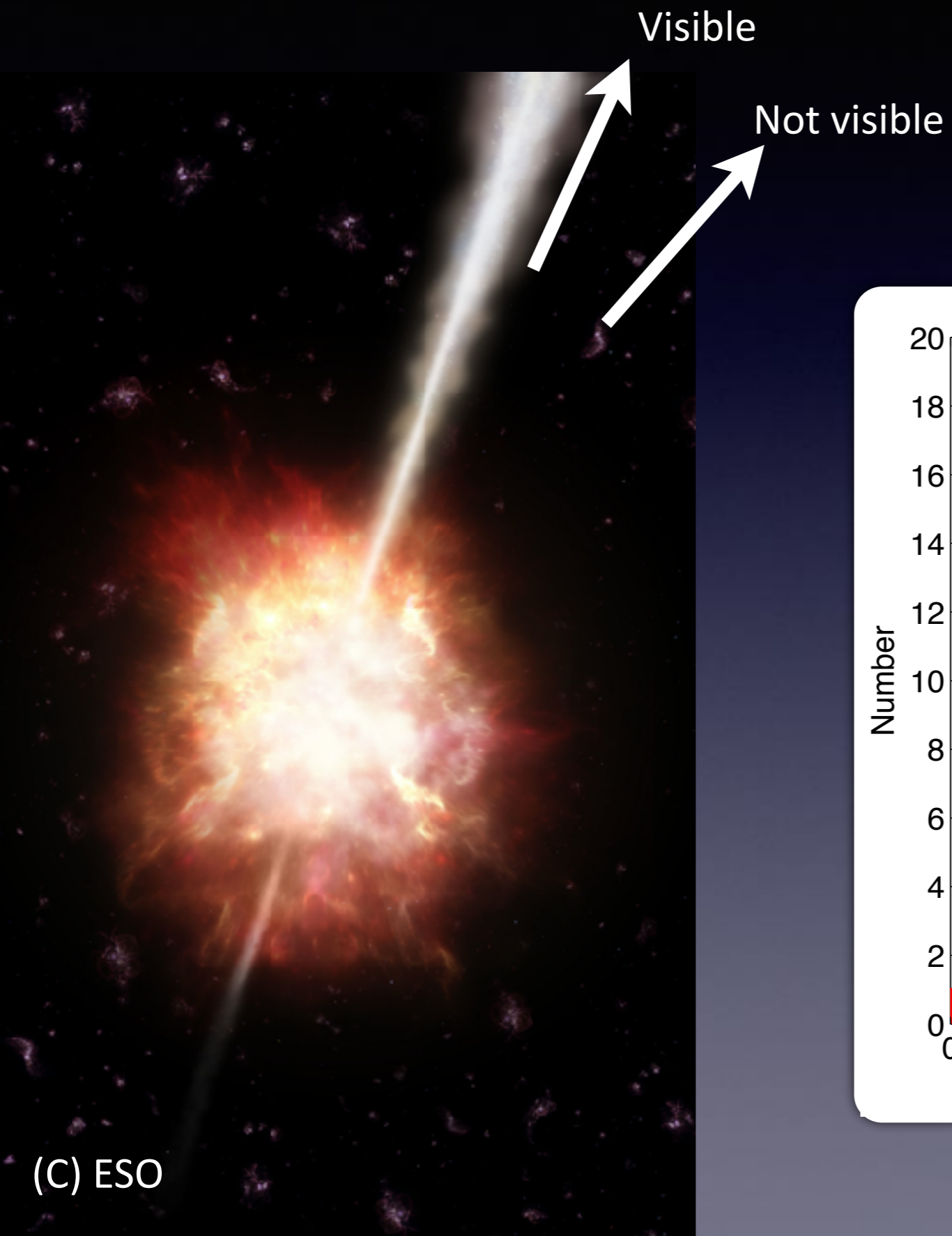
- X-ray/gamma-ray

- Radio

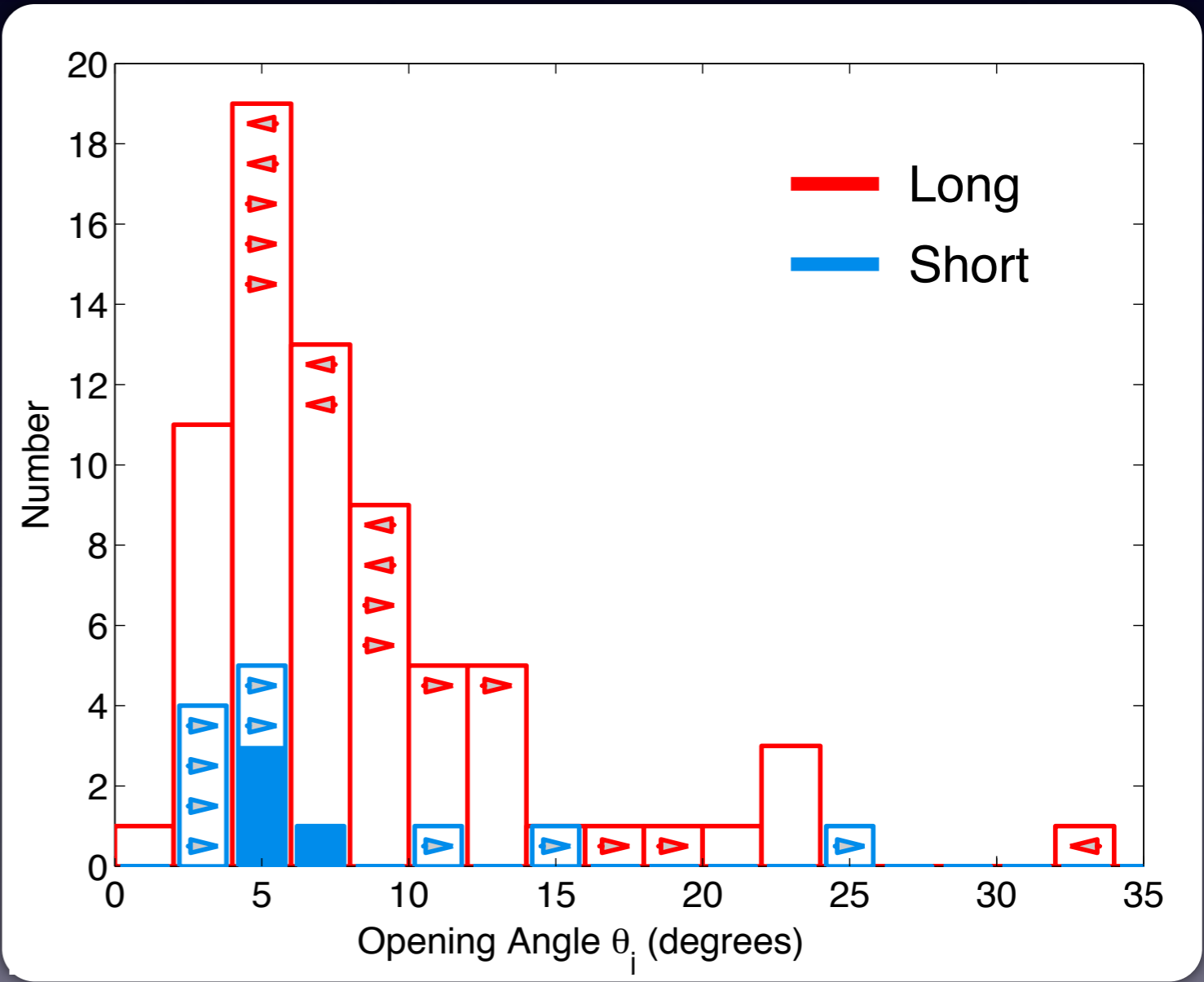
- Optical/NIR



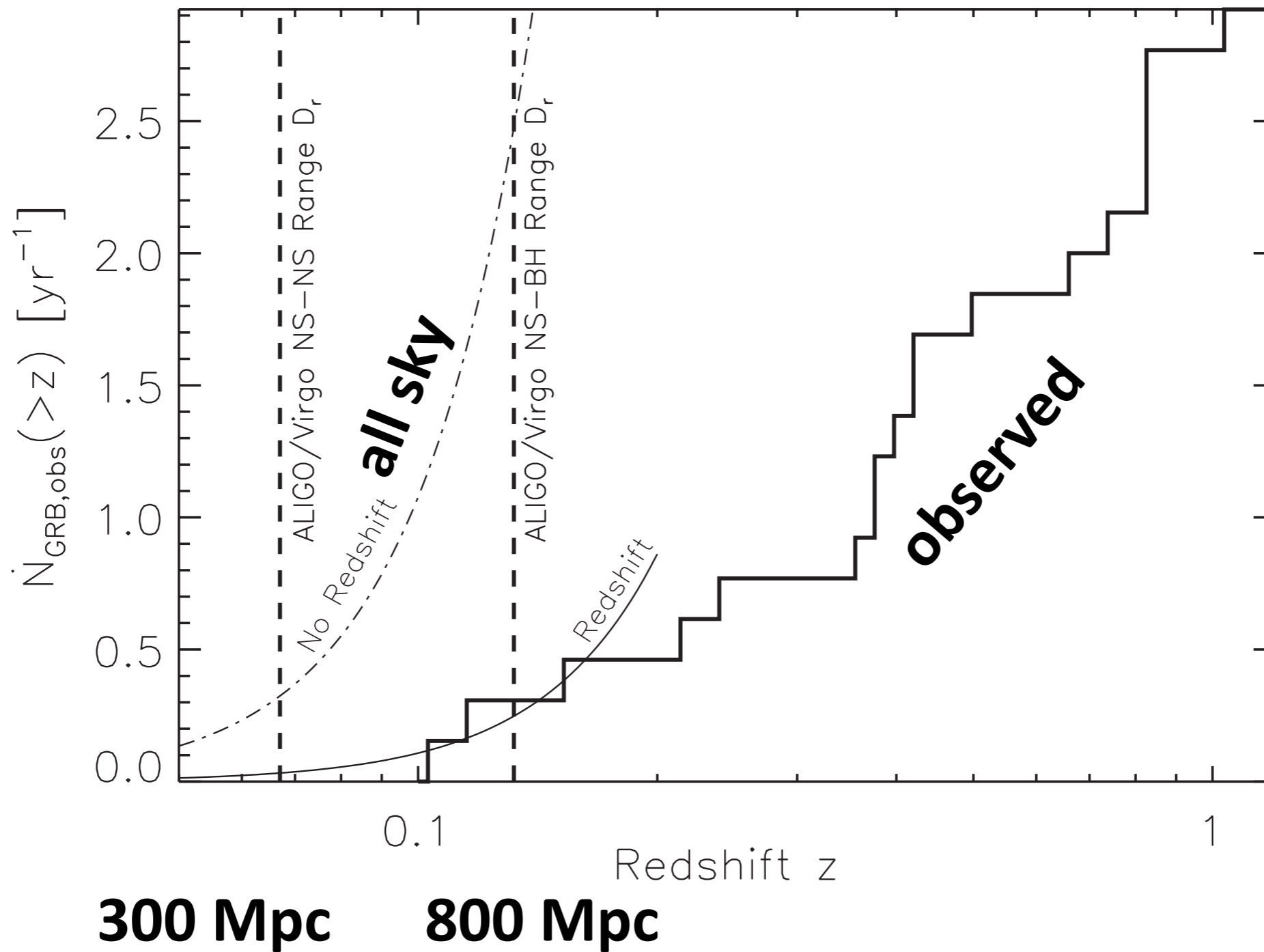
Short gamma-ray burst (GRBs)



Opening angle ~ 10 deg
 \Rightarrow probability \sim a few %

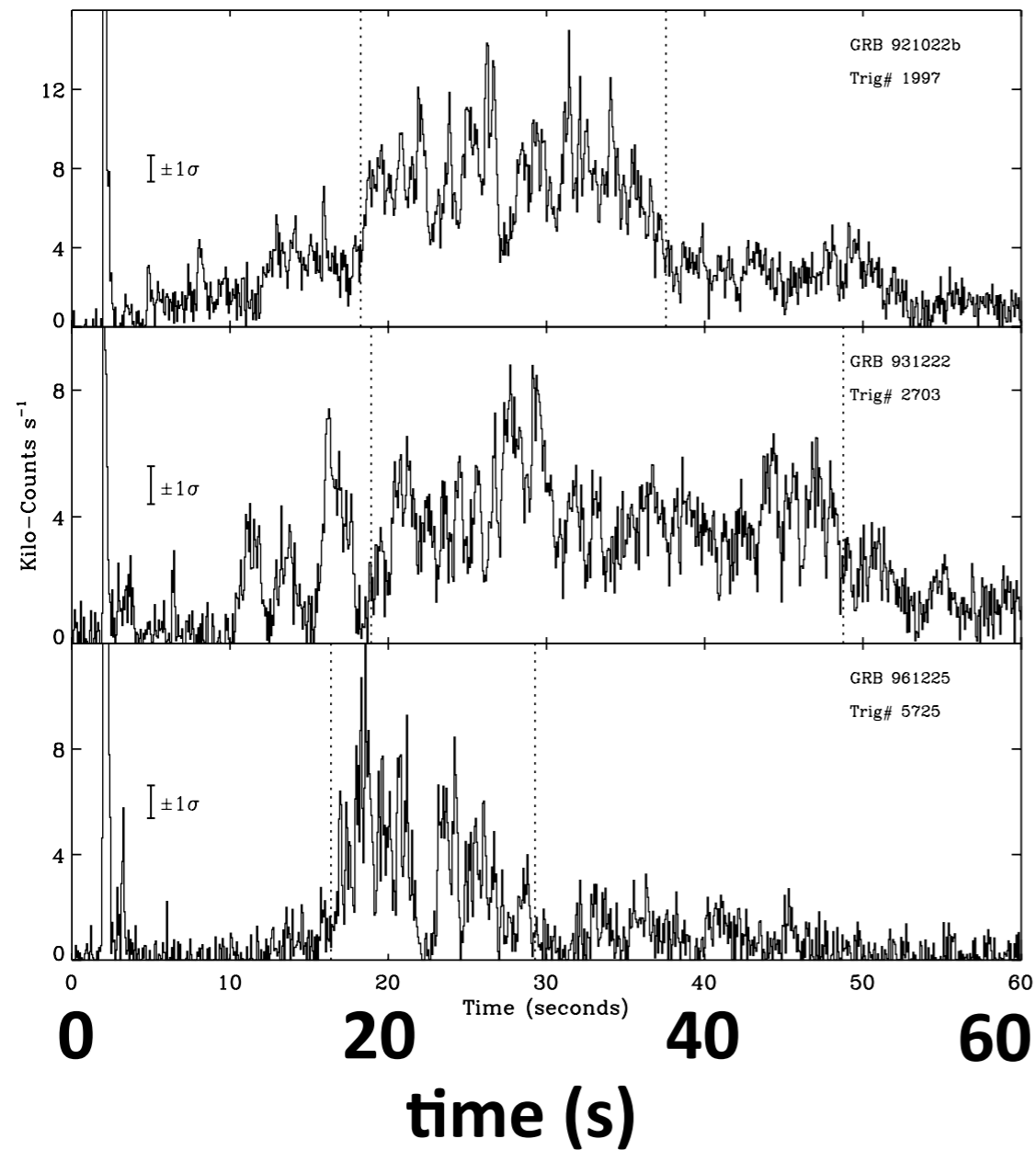


Cumulative redshift distribution of short GRBs



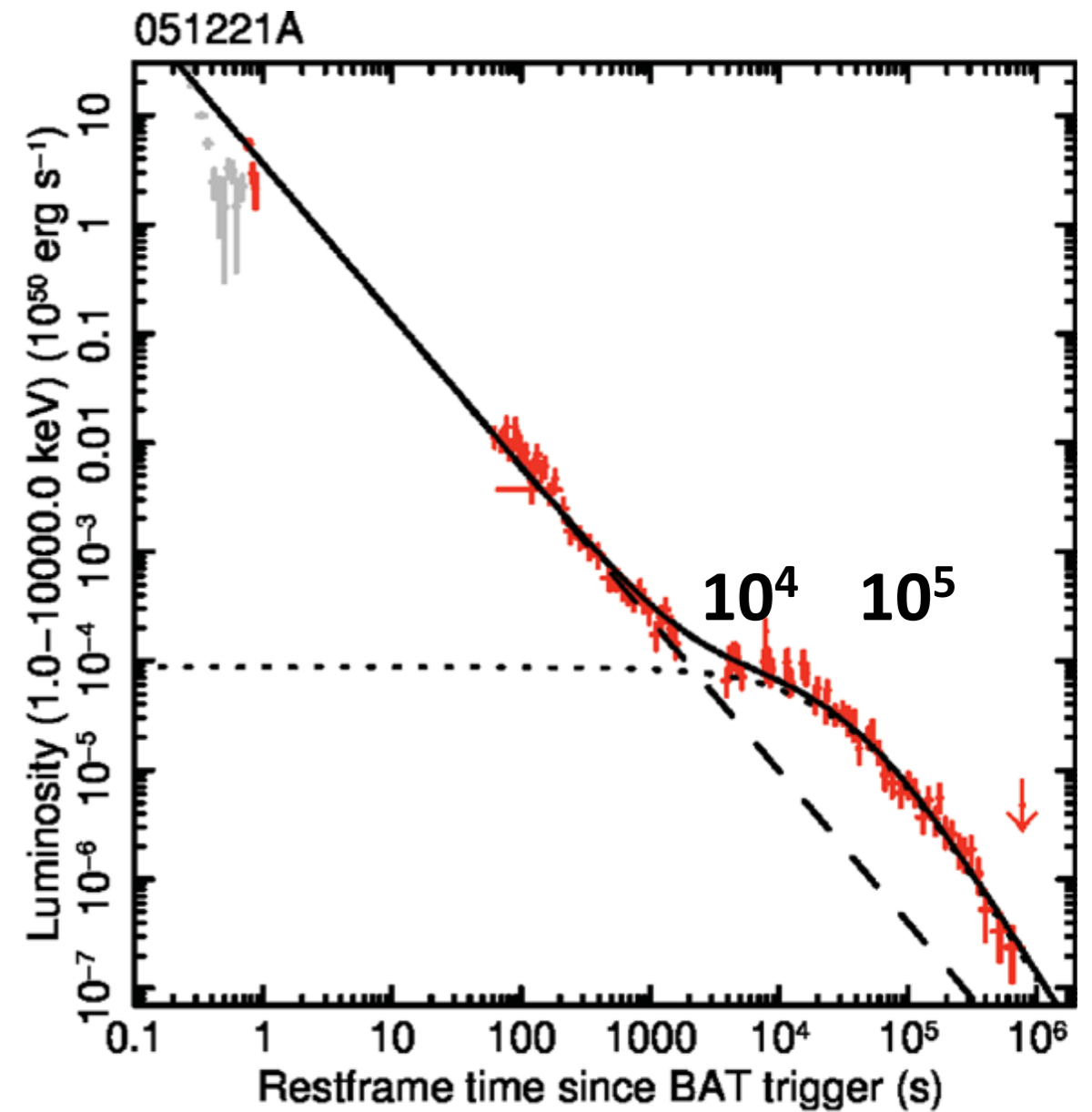
Late-phase activities?

“Extended” emission



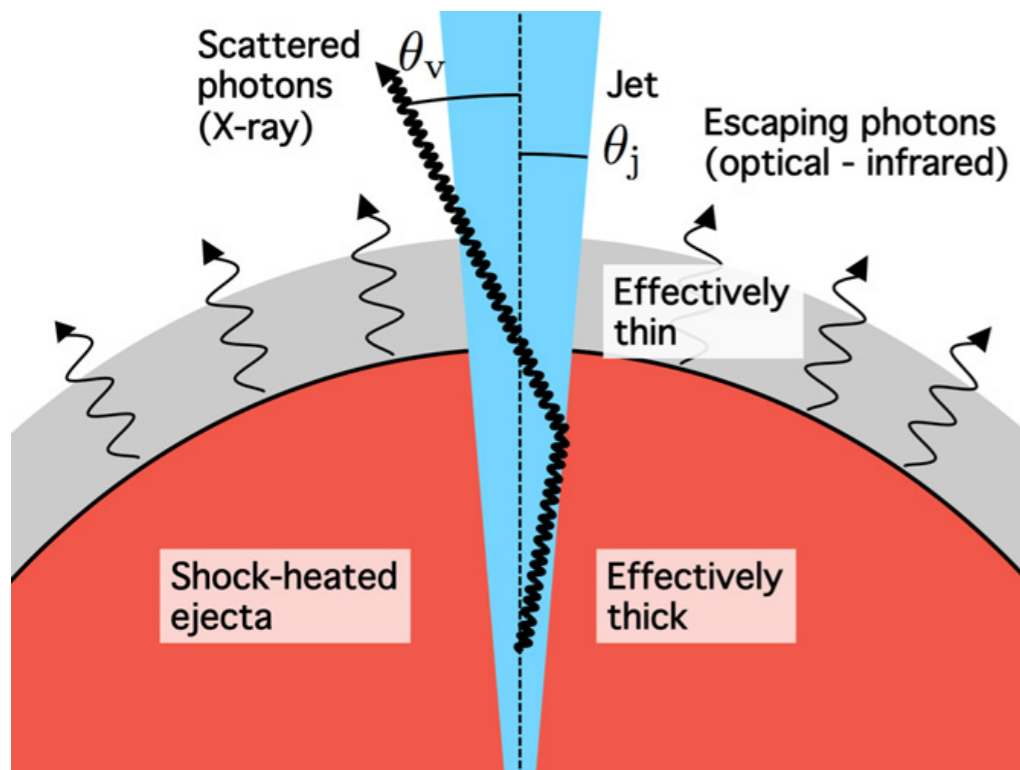
Norris & Bonnell 06

“Plateau” emission

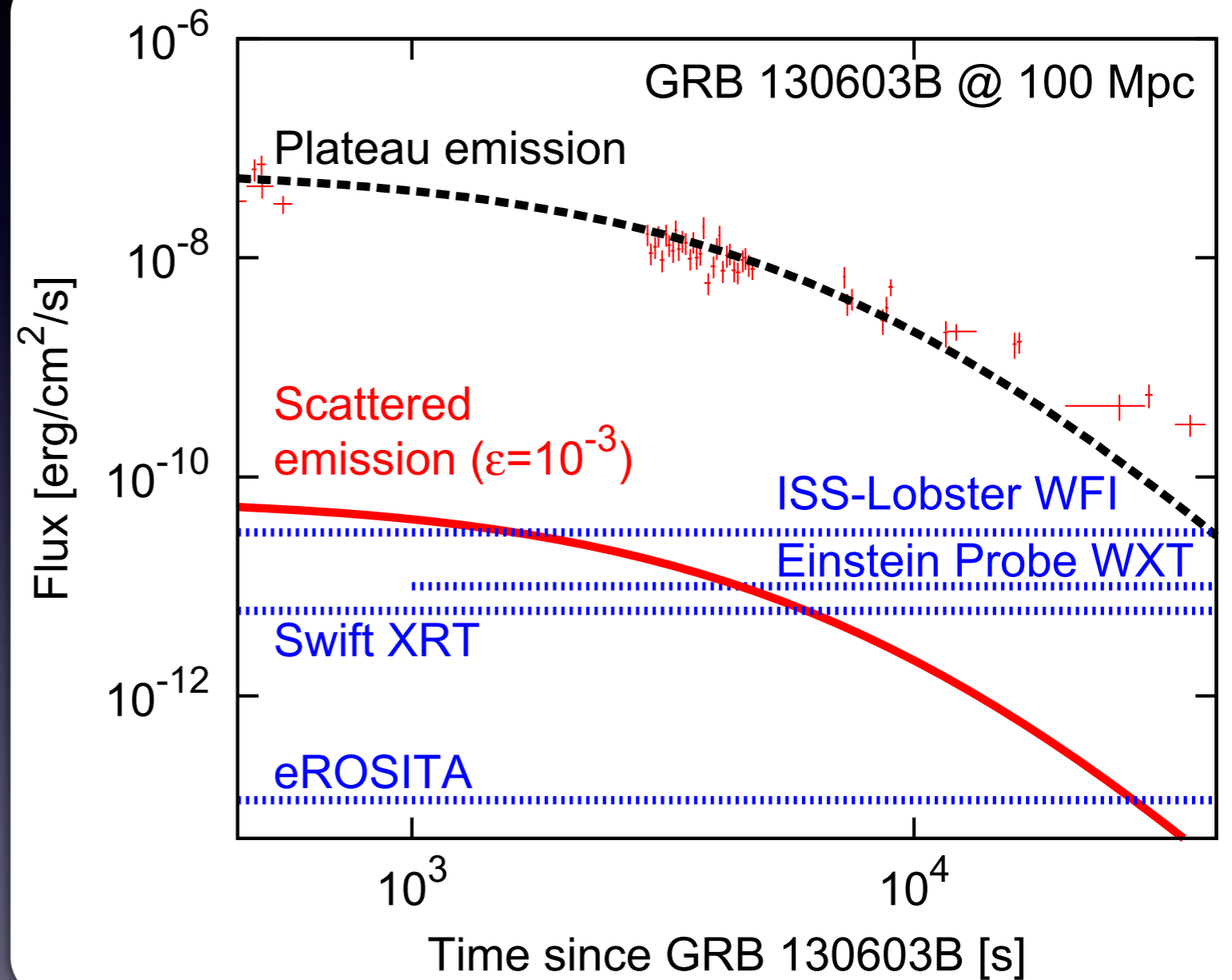


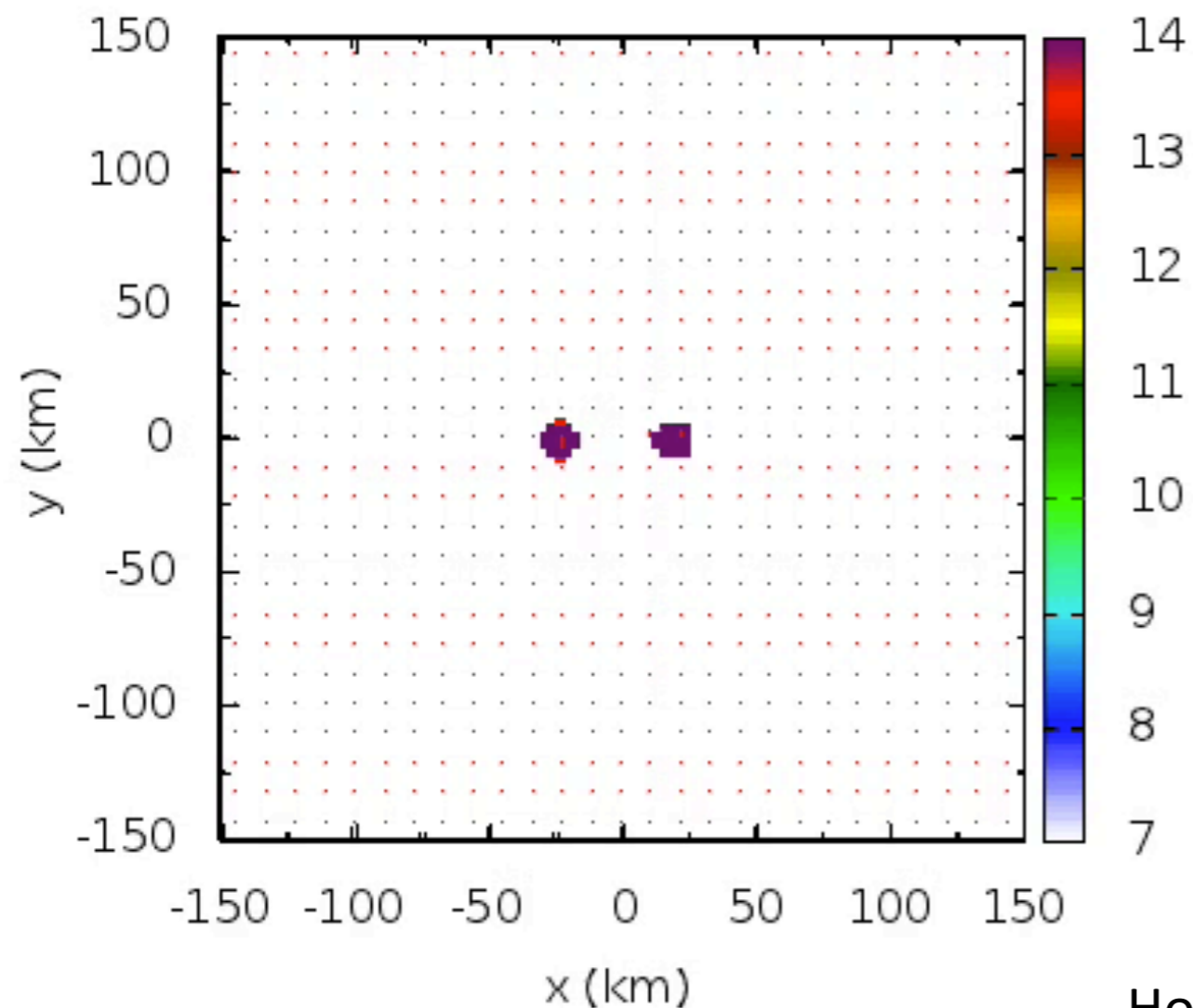
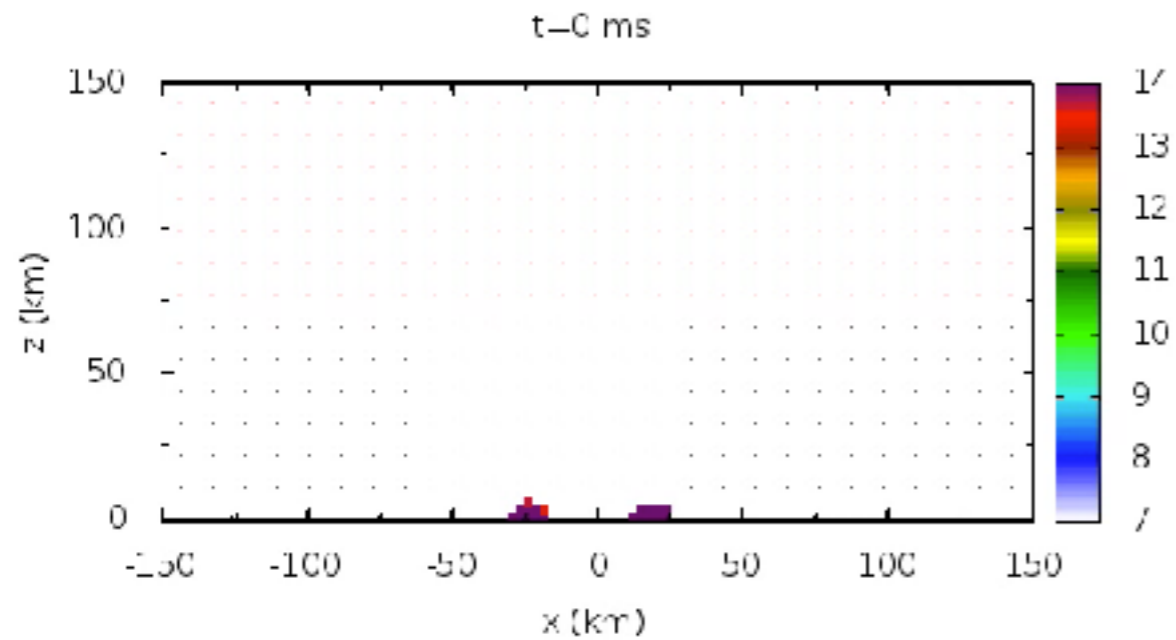
Rowlinson+13

X-ray emission to wider solid angle?



Kisaka+15





Mass ejection from NS mergers

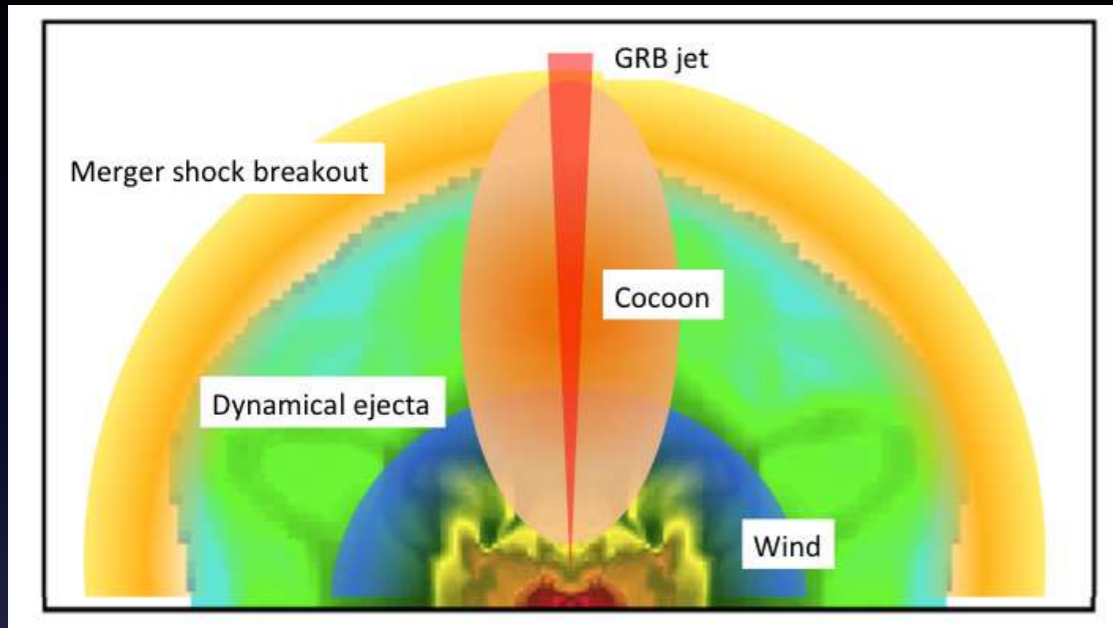
- tidal disruption
- shock heating

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

$$v \sim 0.1 - 0.2 c$$

Rosswog 99, 00, Ruffert & Janka 01
 Hotokezaka+13, Bauswein+13

Radio emission (afterglow)



Delayed by $\sim >$ years

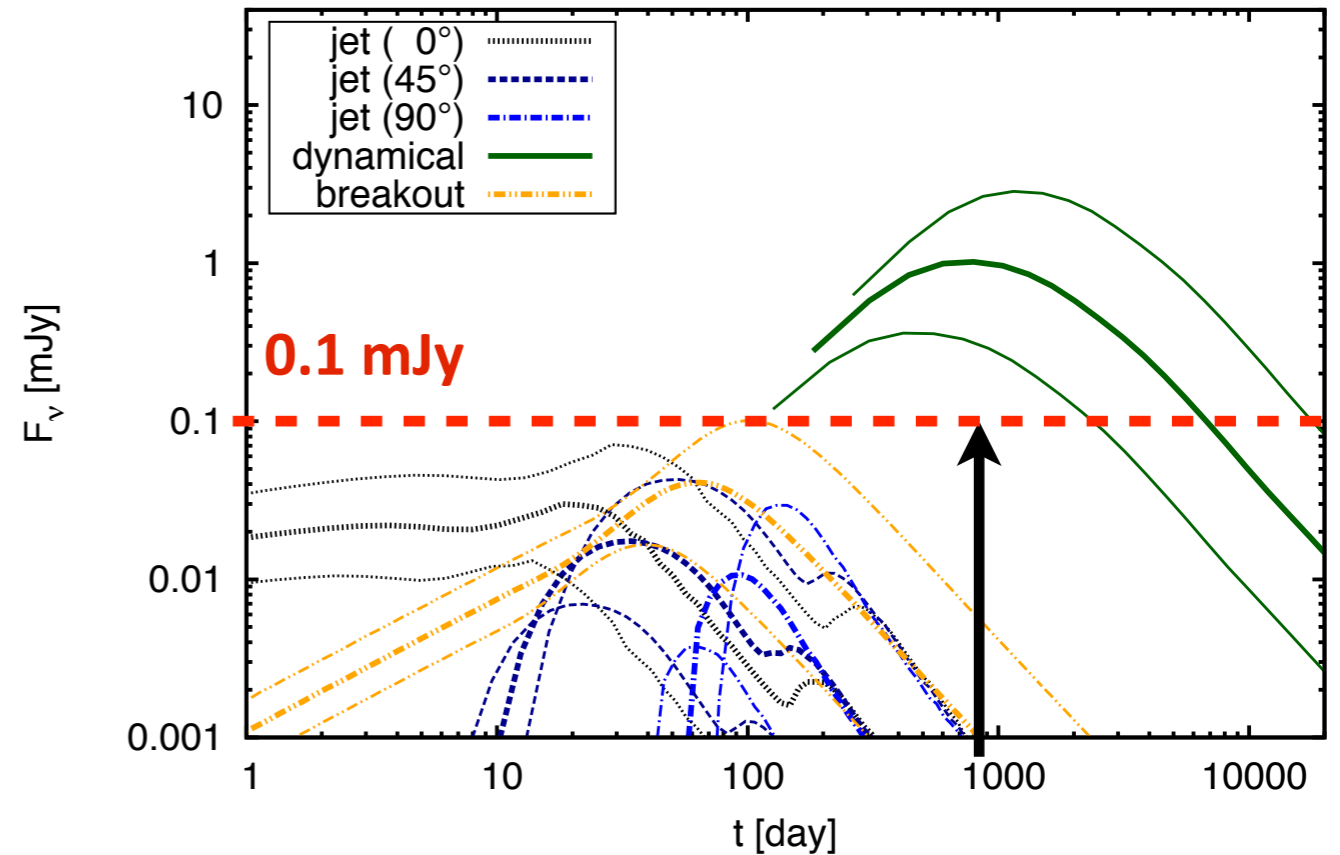
- Not immediate identification
- Good for confirmation
- Not affected by visibility

Depends on ISM density

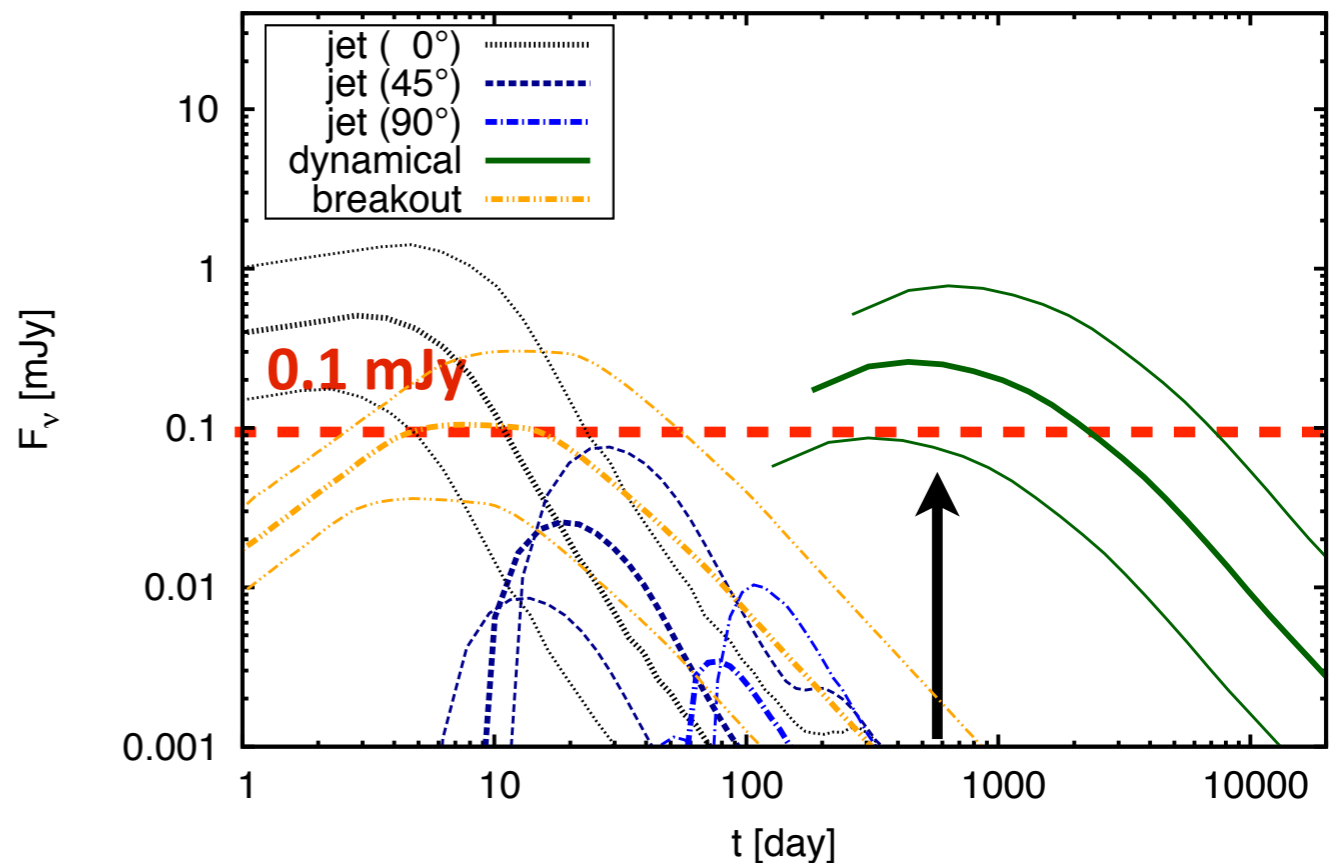
Nakar & Piran 11
Hotokezaka & Piran 15

200 Mpc

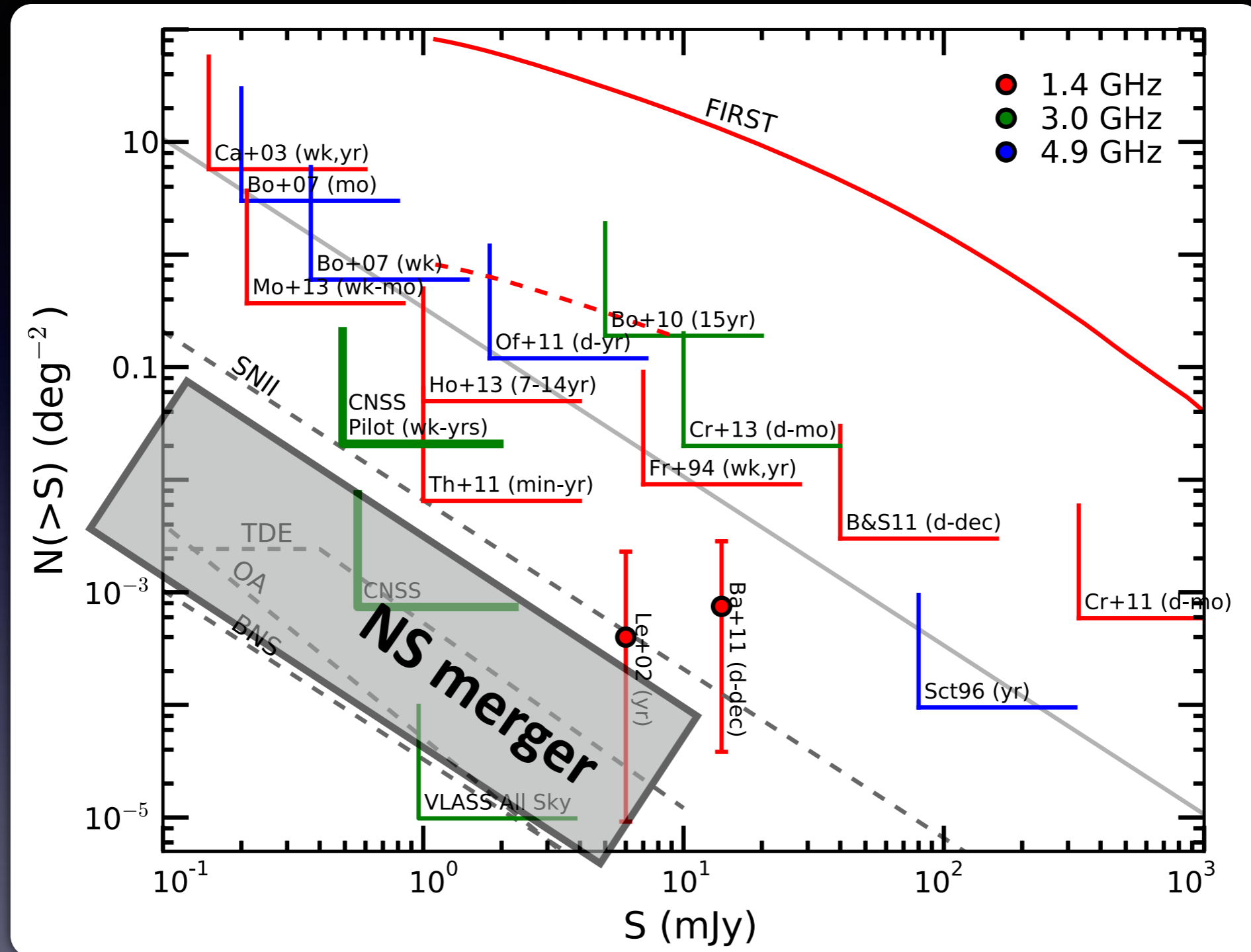
150 MHz, $n = 0.1 \text{ cm}^{-3}$



1.4 GHz, $n = 0.1 \text{ cm}^{-3}$



Radio transient sky is “quiet”



Mooley+2016

Low contamination rate

* Higher $L(\text{radio})/L(\text{optical})$ than supernova

$L(\text{radio}) \leq v$

$L(\text{optical}) \leq M$

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

- X-ray/gamma-ray

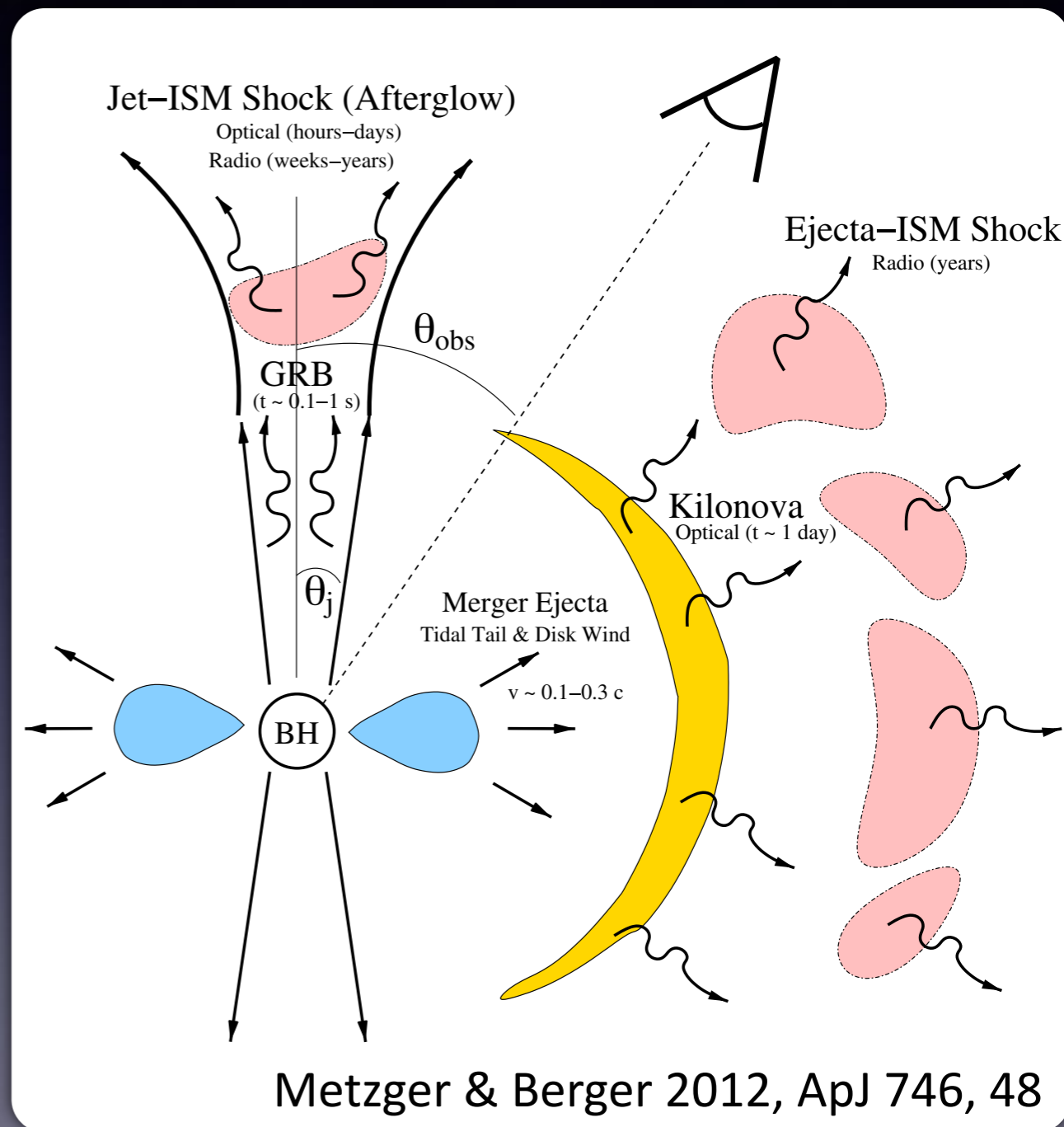
Short GRB: strongly beamed
Late activity: isotropic??

- Radio

Delayed by years
Low contamination rate

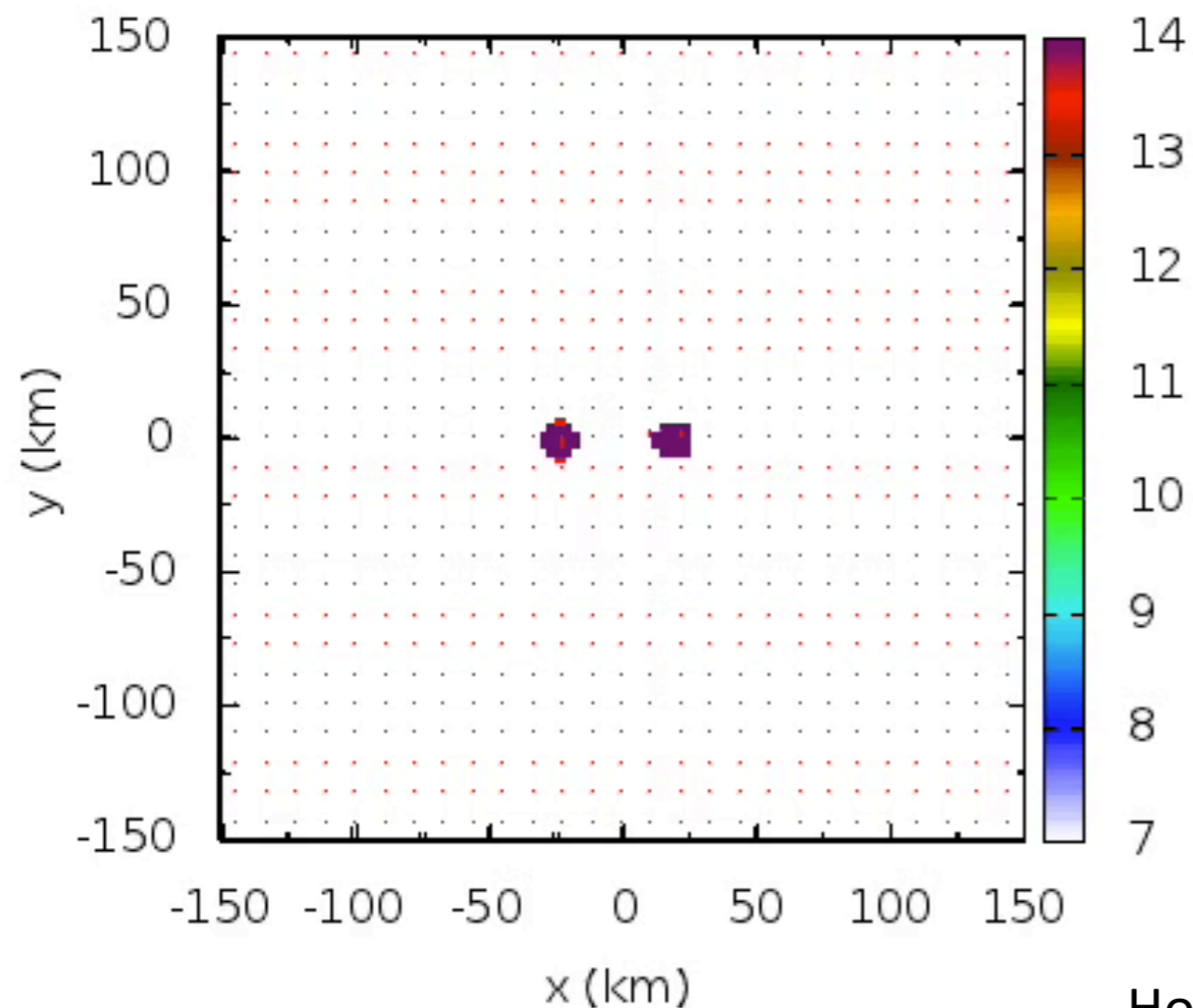
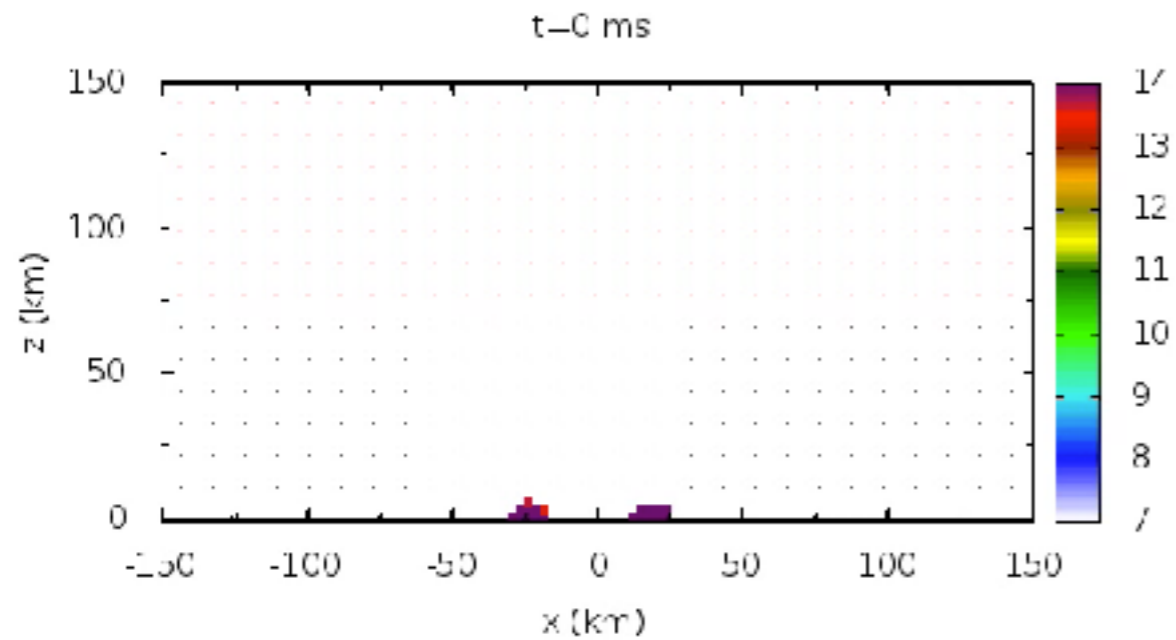
- Optical/NIR

Delayed by only ~ 1 week
Isotropic



Electromagnetic Emission from Gravitational Wave Source

- EM emission from compact binary mergers
- Kilonova/macronova emission and the origin of r-process elements



Mass ejection from NS mergers

- tidal disruption
- shock heating

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

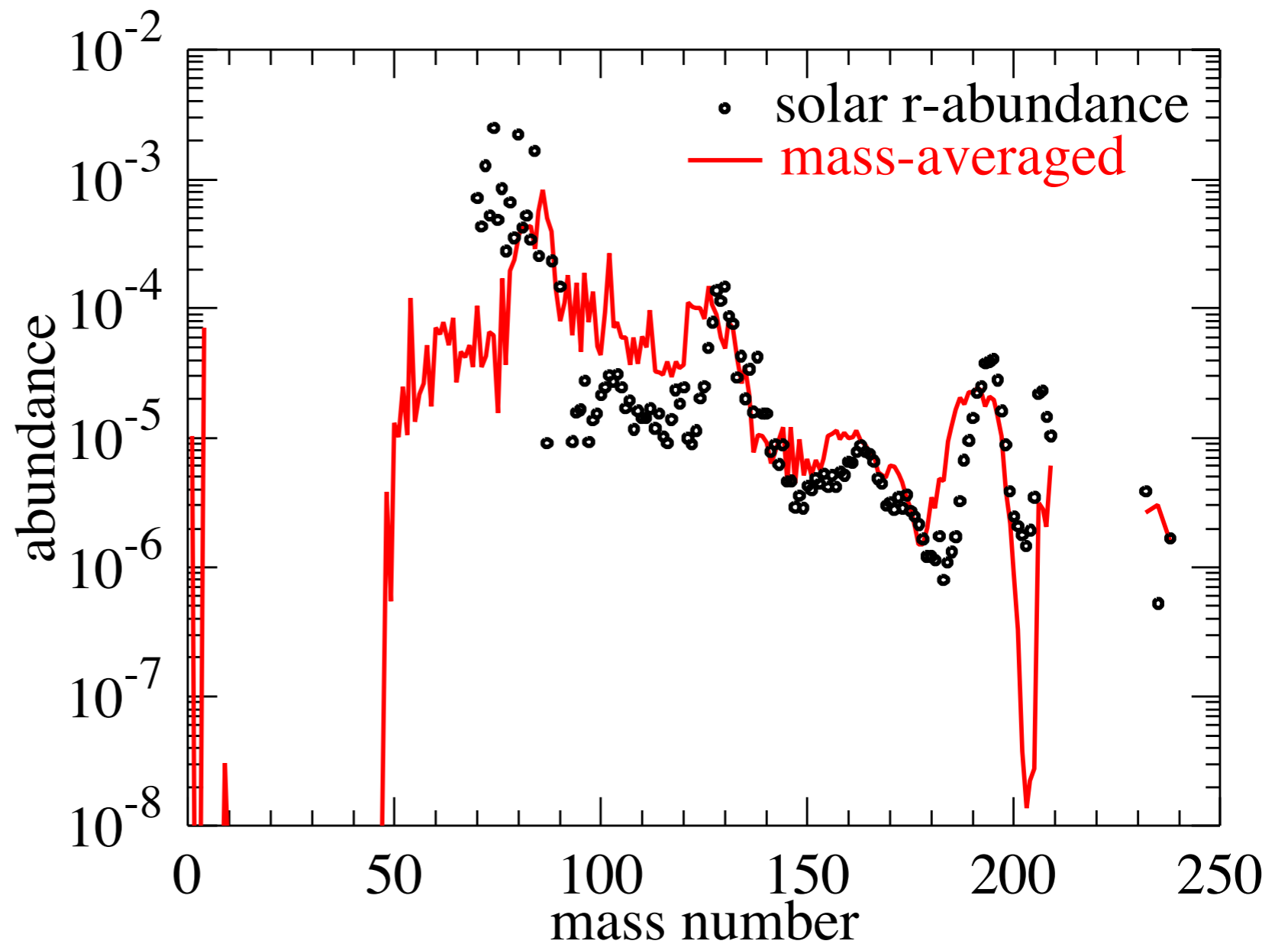
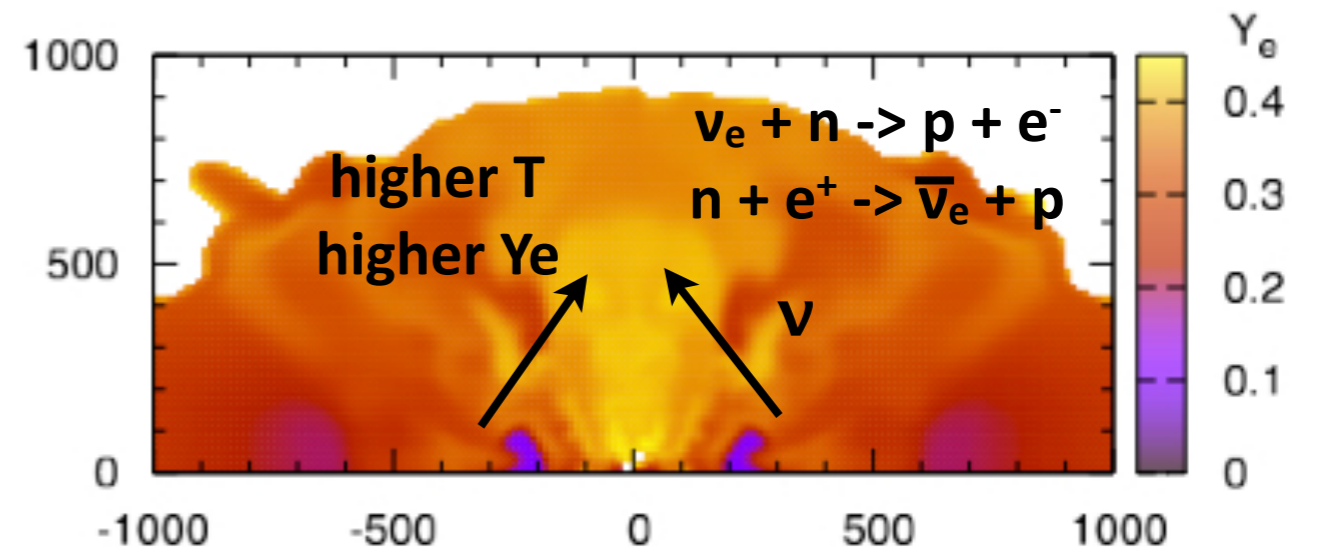
$$v \sim 0.1 - 0.2 c$$

Rosswog 99, 00, Ruffert & Janka 01
Hotokezaka+13, Bauswein+13

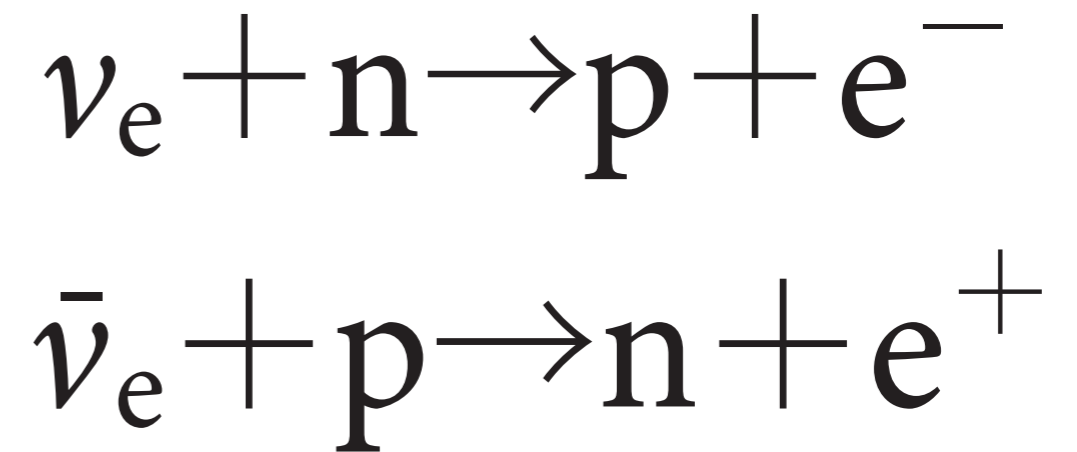
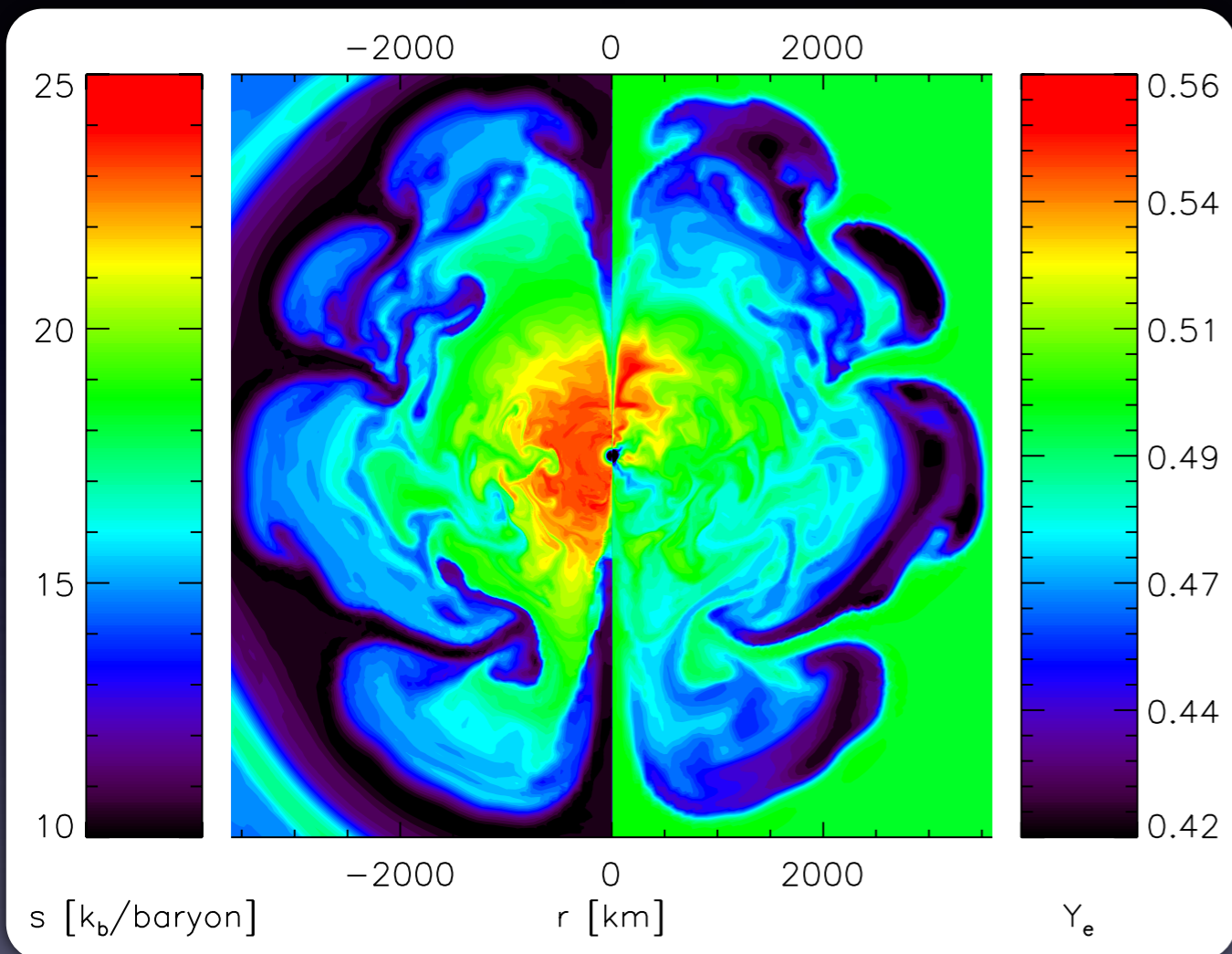
r-process nucleosynthesis in NS mergers

=> **solar abundances**

(e.g., Wanajo+14, Just+15, Wu+16)



r-process nucleosynthesis in core-collapse supernovae



Wanajo+11, Wanajo 14

Difficult to produce r-process elements
in (normal) core-collapse supernovae

NS merger as a possible origin of r-process elements

Event rate

$$R_{\text{NSM}} \sim 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$$
$$\sim 30 \text{ GW events yr}^{-1}$$

(w/ Adv. detectors, < 200 Mpc)



GW

LIGO O1

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

Ejection per event

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



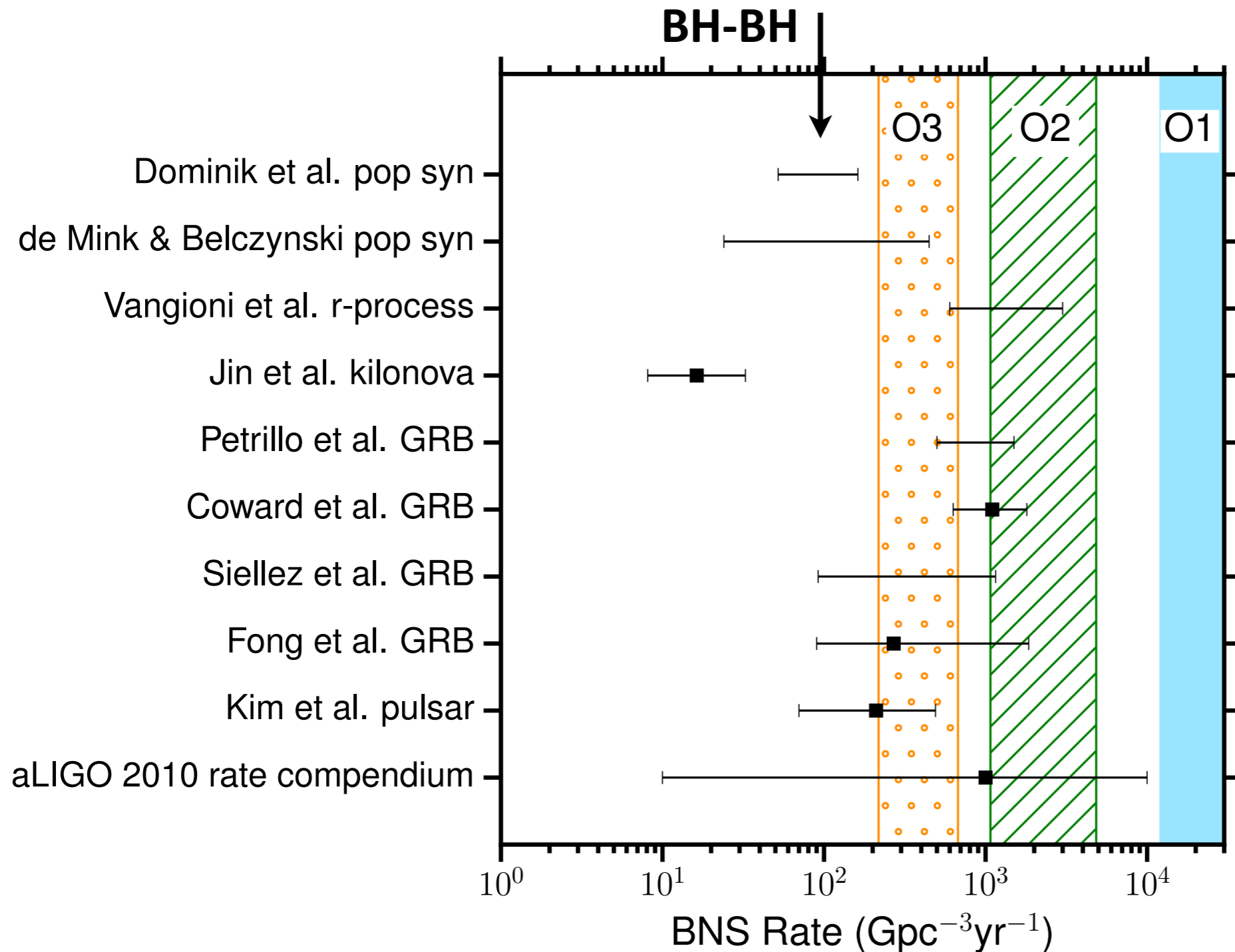
EM

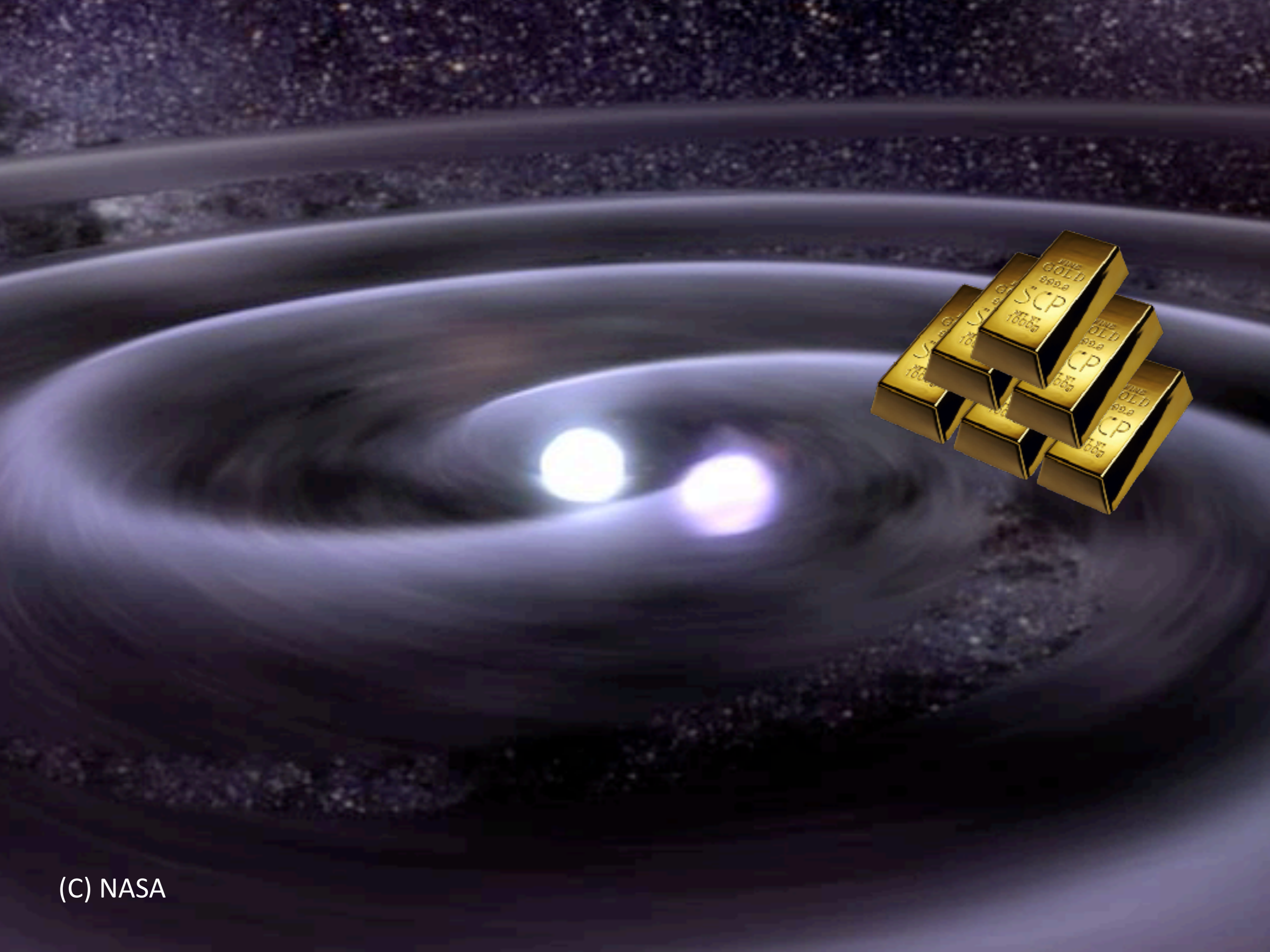
Enough to explain the r-process abundance in our Galaxy

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

Constraints on the NS-NS merger rate

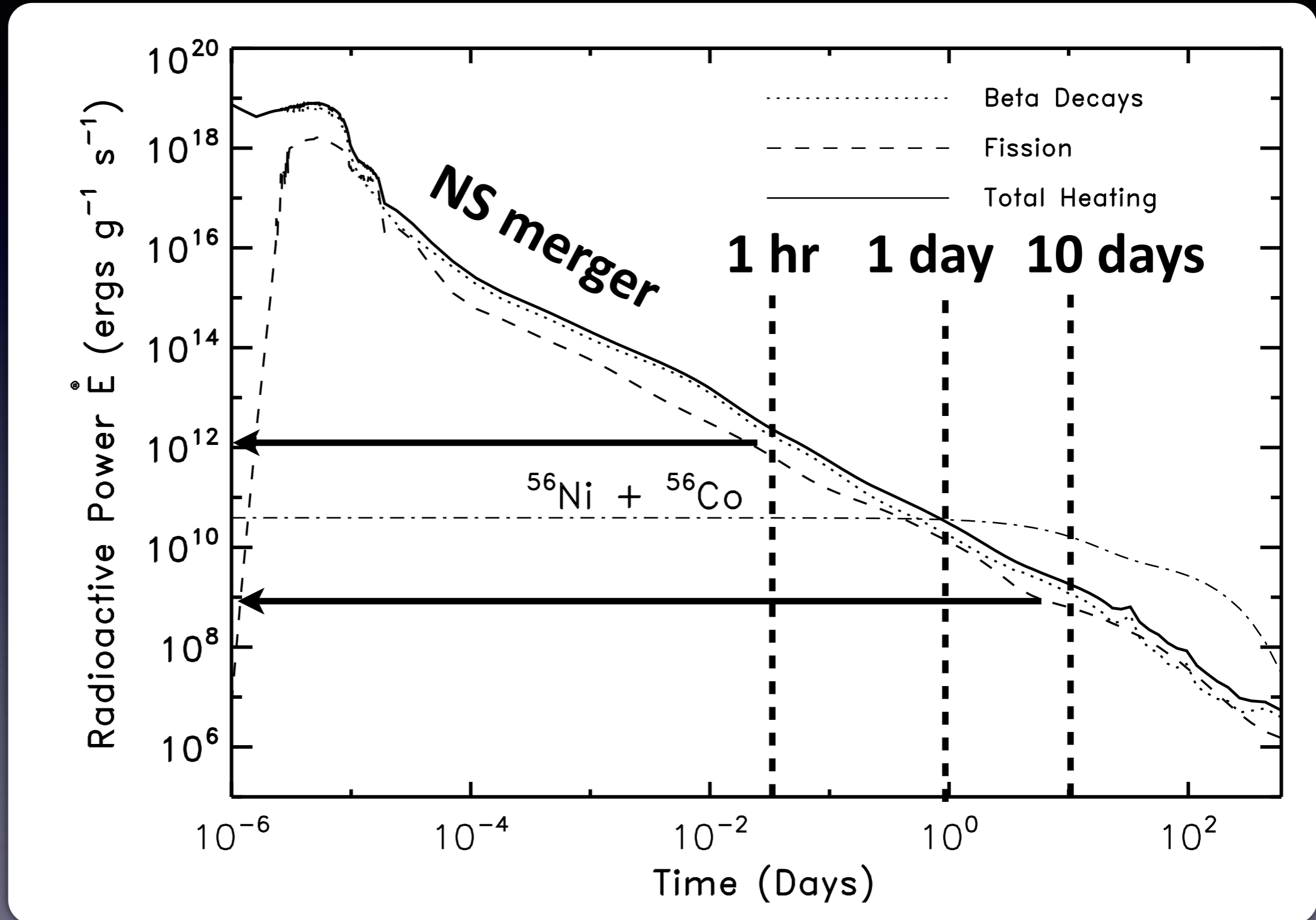
Expected event rates





(C) NASA

Heating by radioactive decay of r-process nuclei



$10^{43} \text{ erg s}^{-1}$

$10^{40} \text{ erg s}^{-1}$

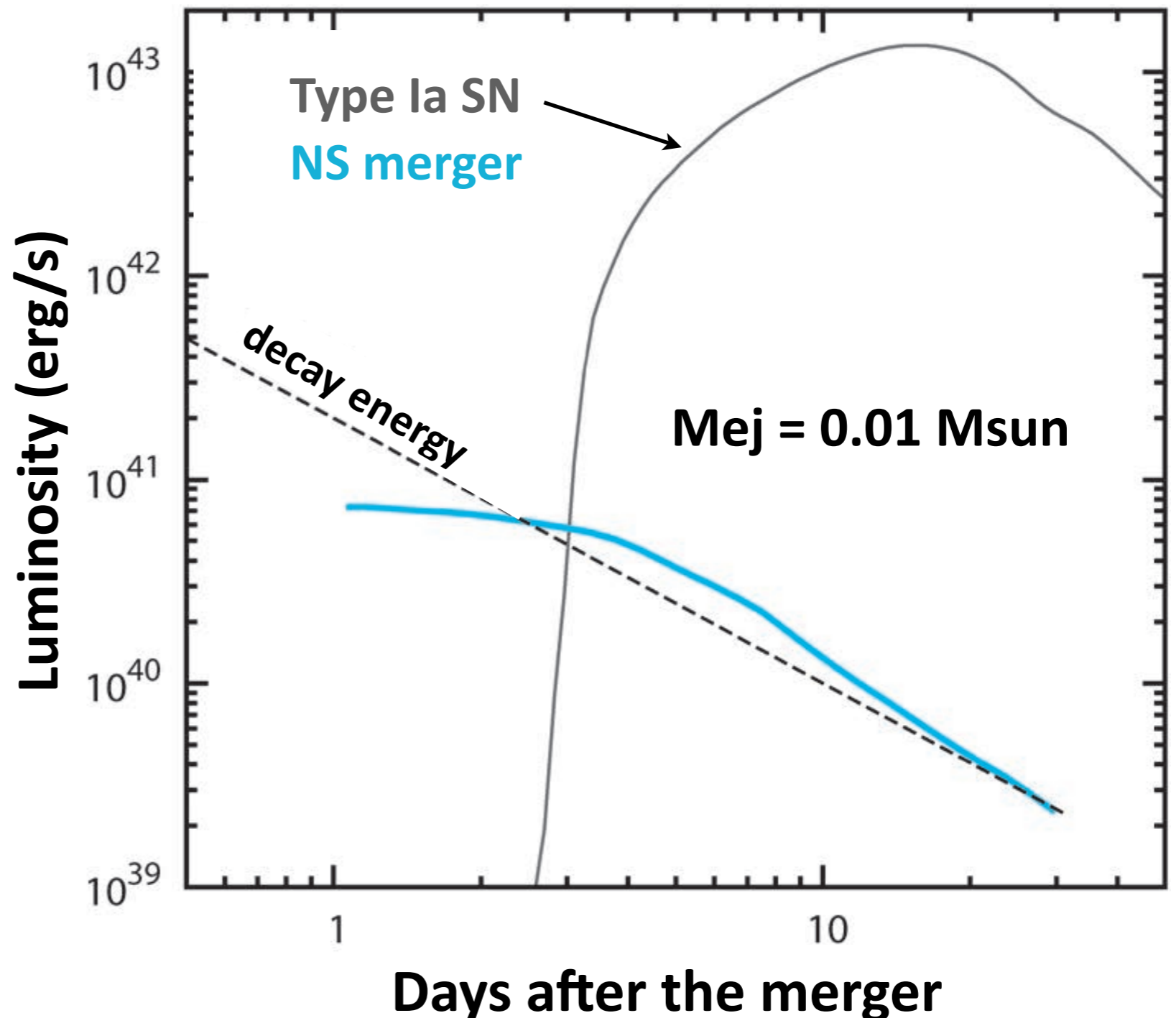
(for $M = 0.01 M_{\text{sun}}$)

Metzger+10

“kilonova/macronova”

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

$L \sim 10^{40-41}$ erg/s
@ ~1 week



Magnitude

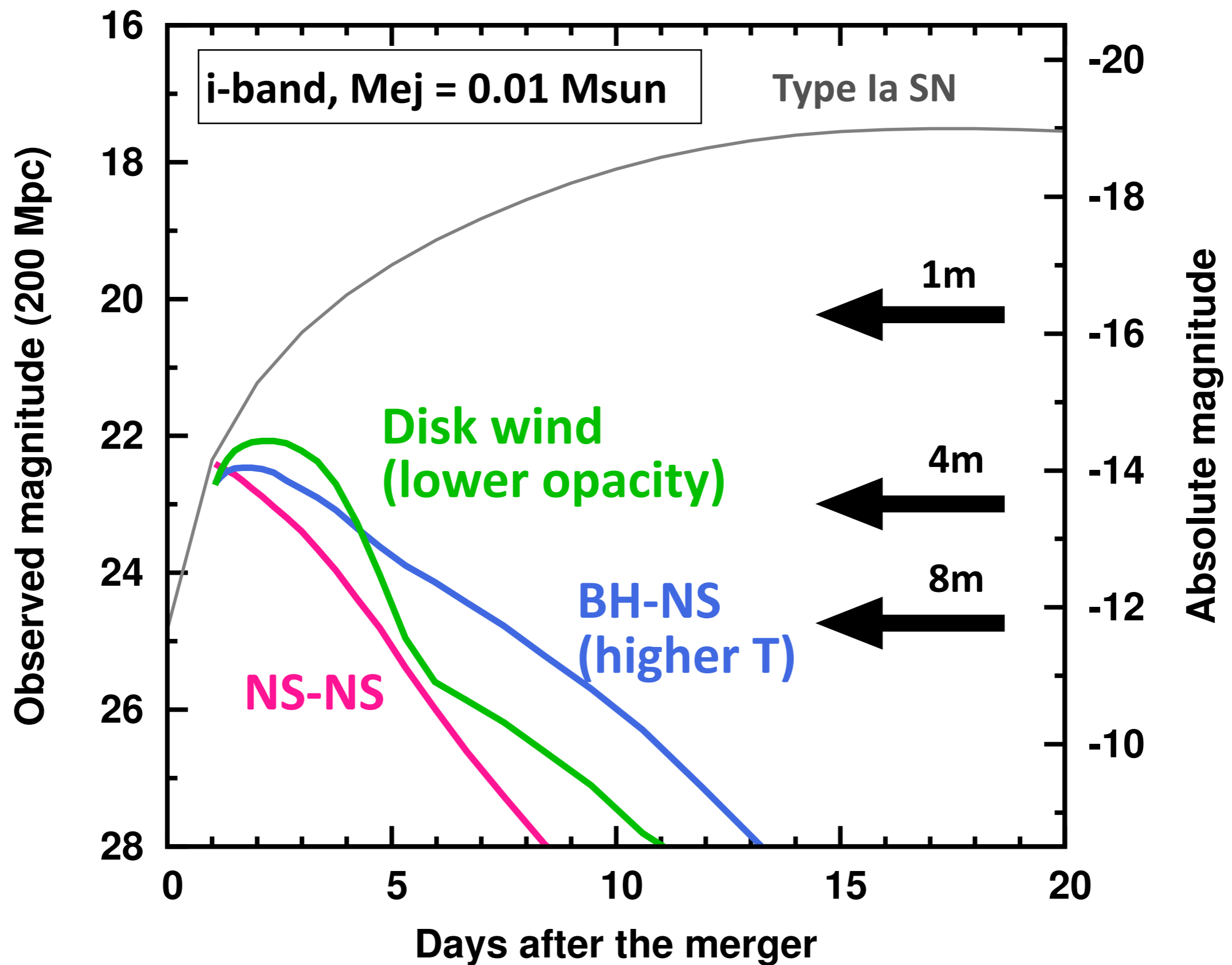
$$m = -2.5 \log(F/F_0) + m_0$$

Absolute magnitude

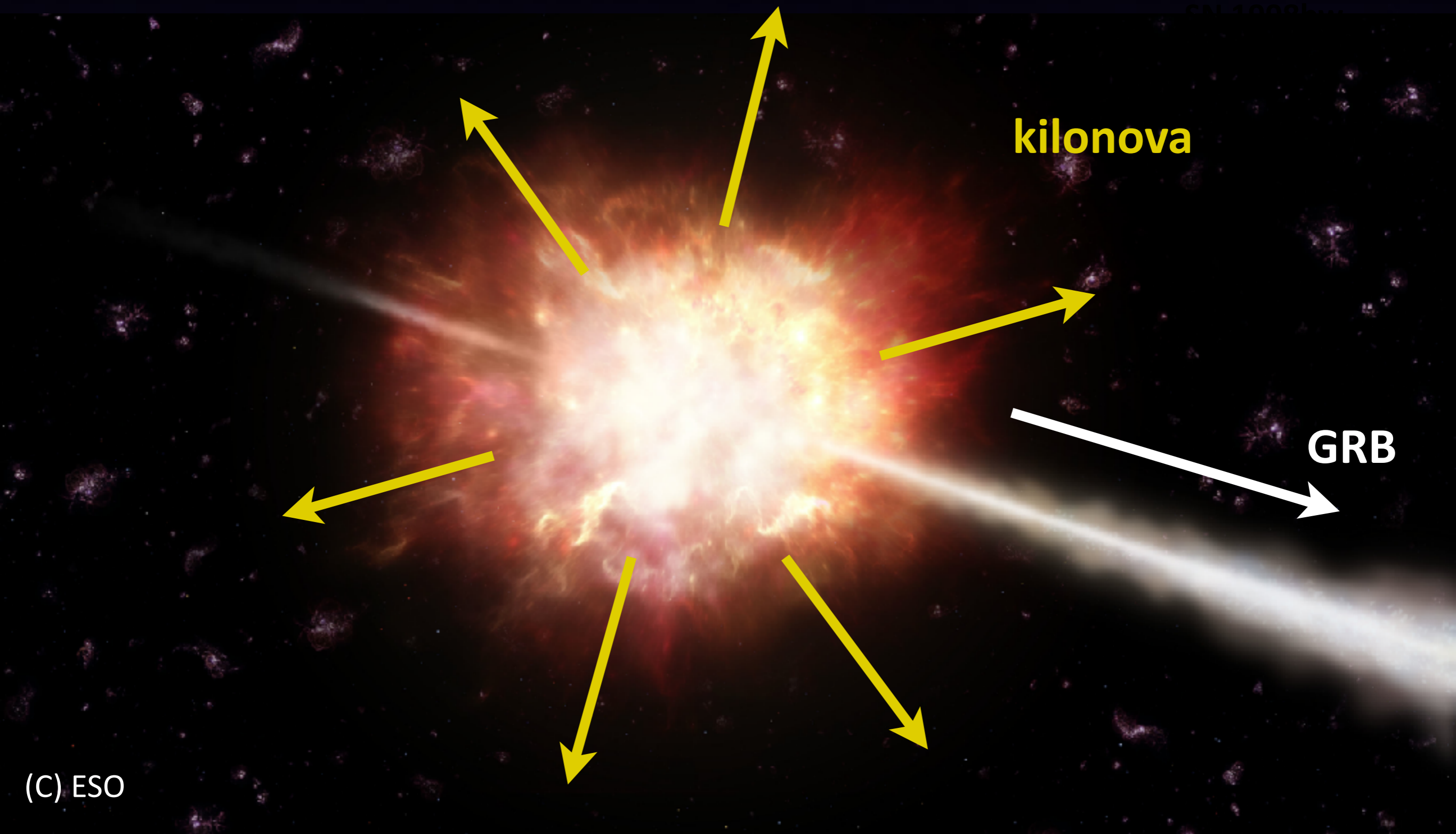
brightness if the object is located at 10 pc

The sun: Observed magnitude = -27 mag

Absolute magnitude = +4.8 mag

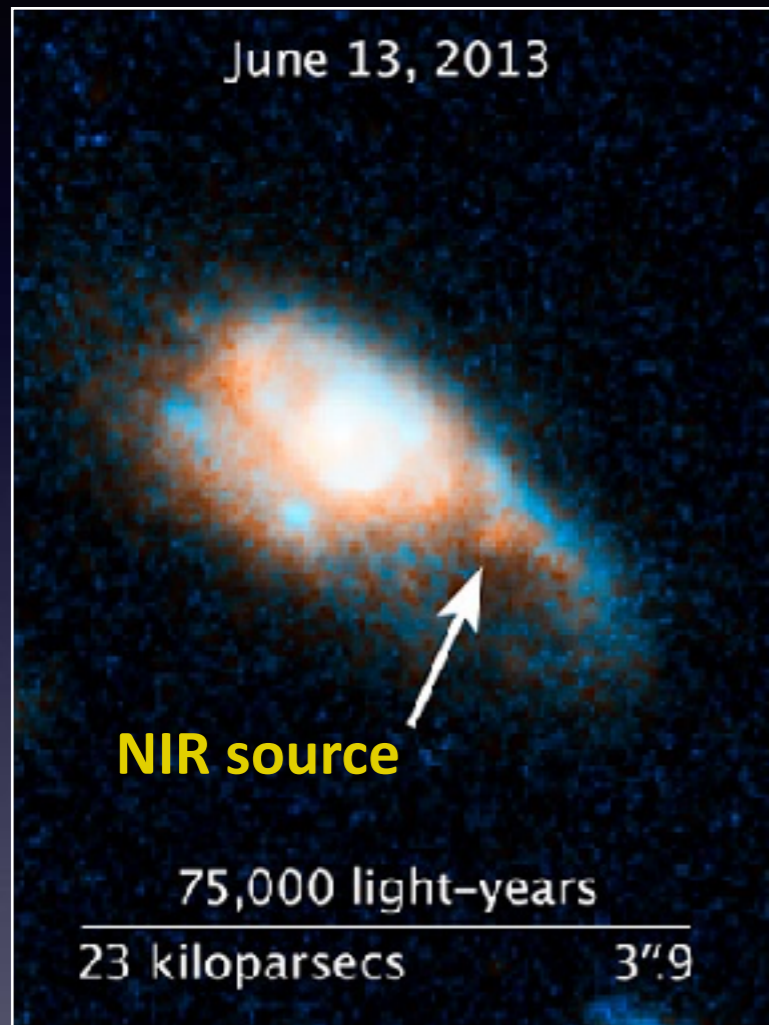


Constraints from short GRBs

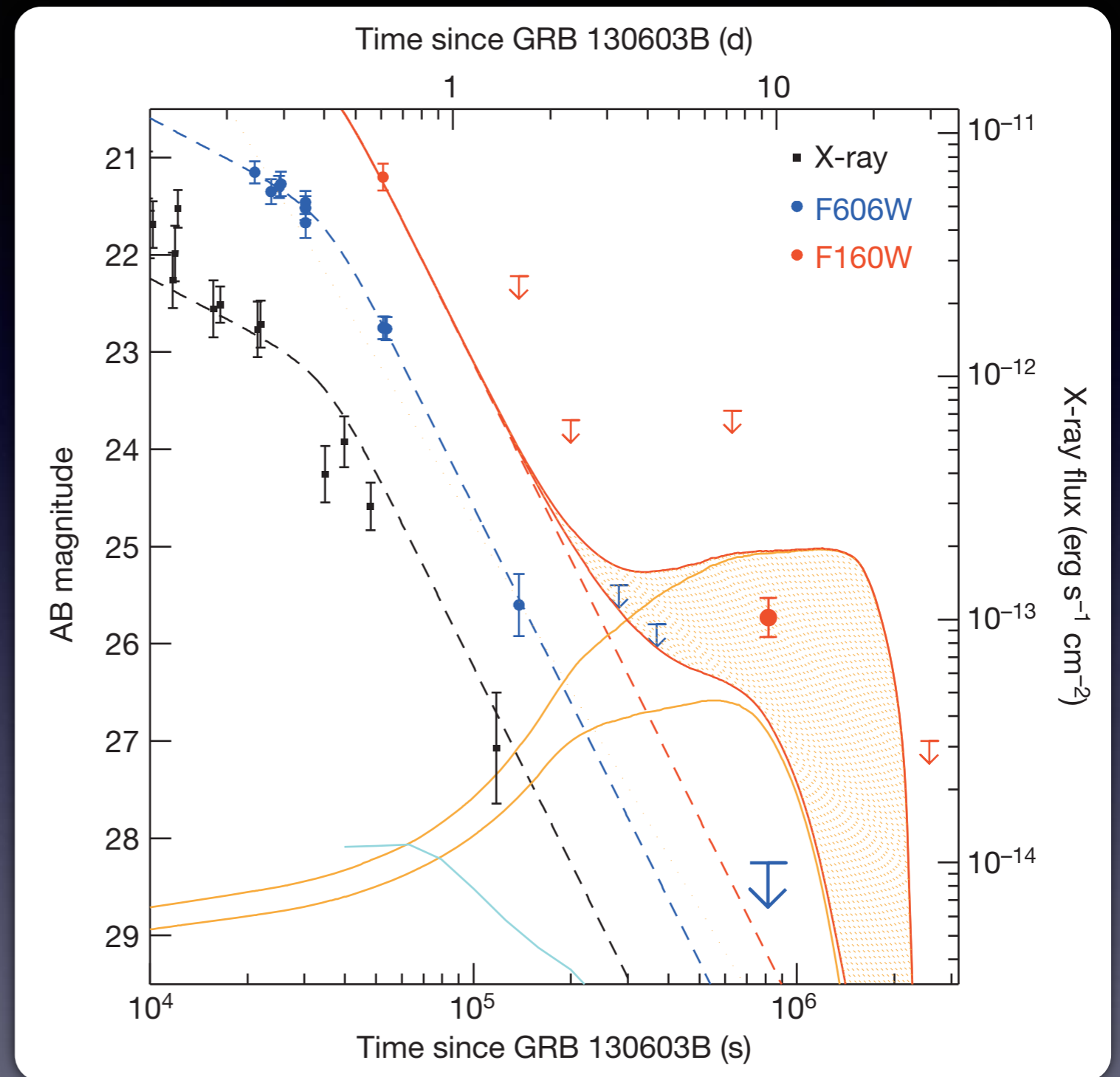


Constraints from short GRBs (1/3)

GRB 130603B



Tanvir+2013, Berger+2013



Possible detections also in
GRB 060614 ($z=0.125$) Yang+15, Jin+15
GRB 050709 ($z=0.16$) Jin+16

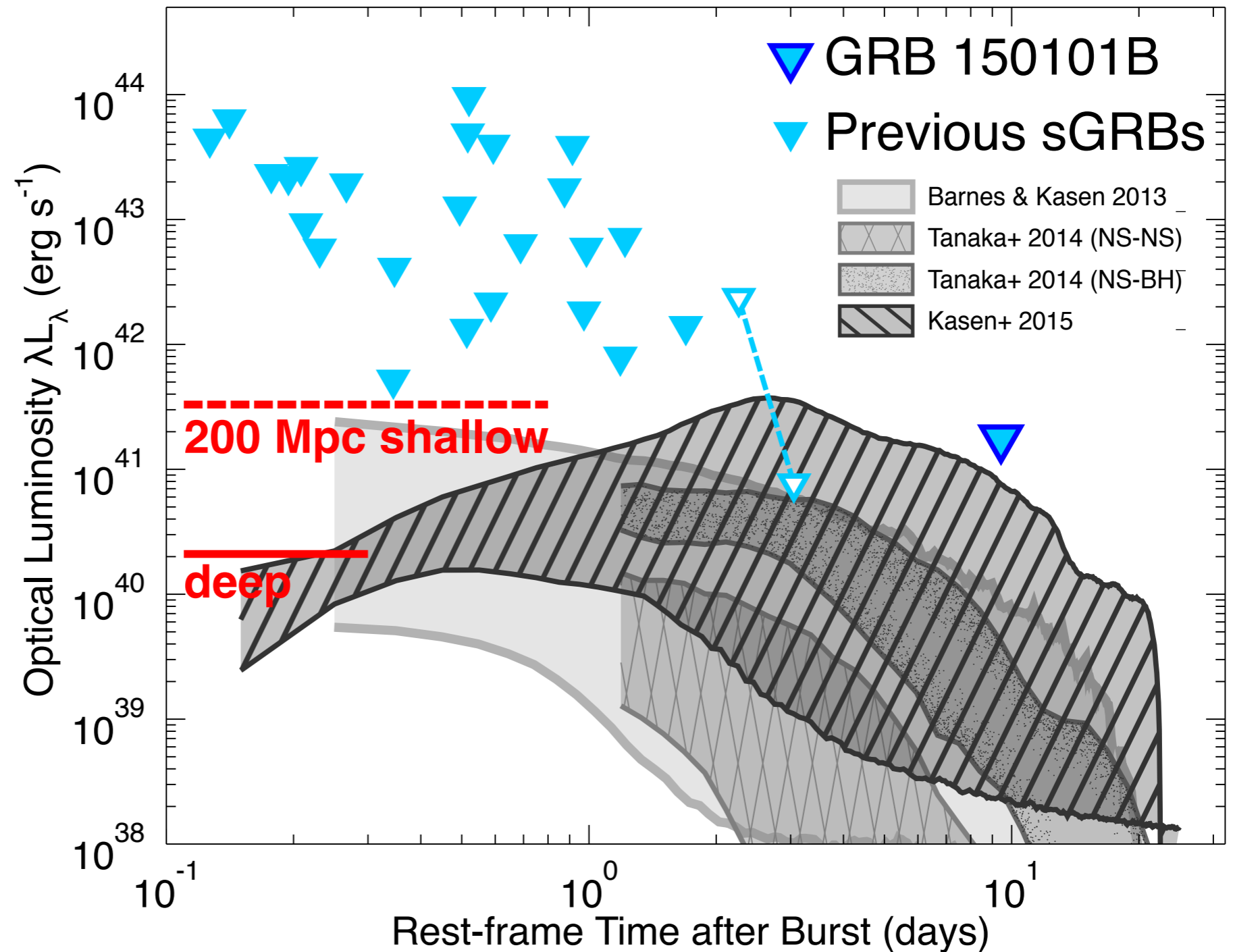
=> ejection of $M \sim 0.02 M_{\text{sun}}$

Constraints from short GRBs (2/3)

@ 200 Mpc

21 mag

24 mag

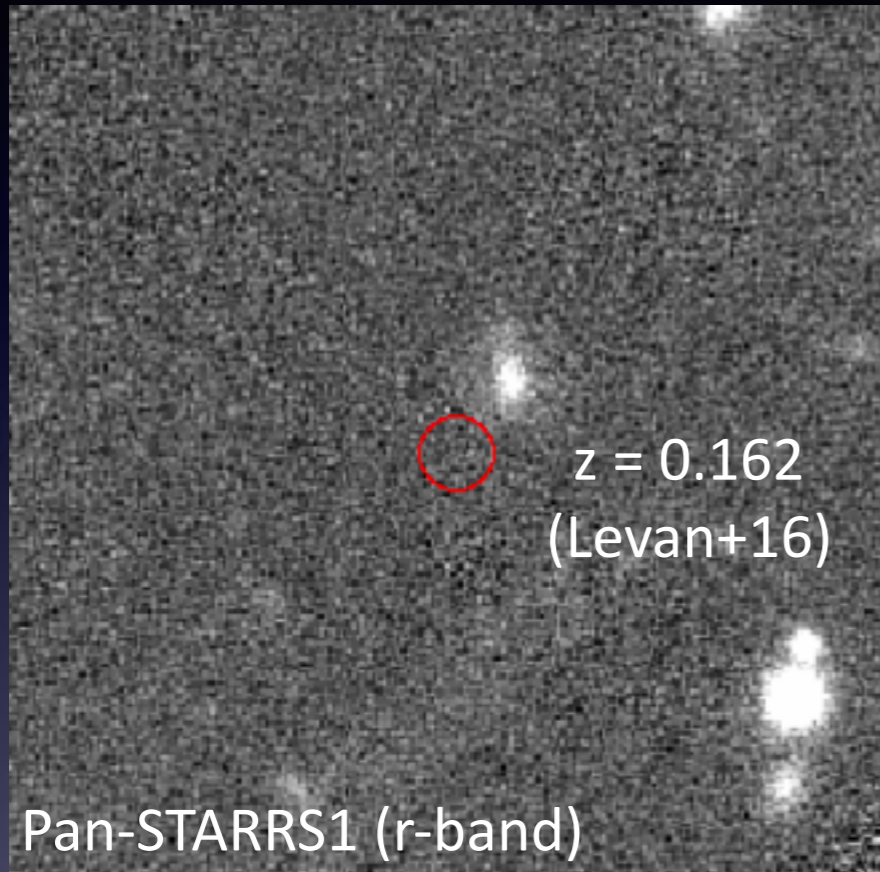


$M \sim < 0.3 M_{\text{sun}}$

Fong+16

Constraints from short GRBs (3/3)

GRB 160821B ($z=0.16$)



F606W ~ 25.8 mag @ $z=0.16$

\Rightarrow $M_{\text{abs}} -14$ mag

\Rightarrow **~ 22 mag @ 200 Mpc**

$M \sim 0.01 M_{\text{sun}}$

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:

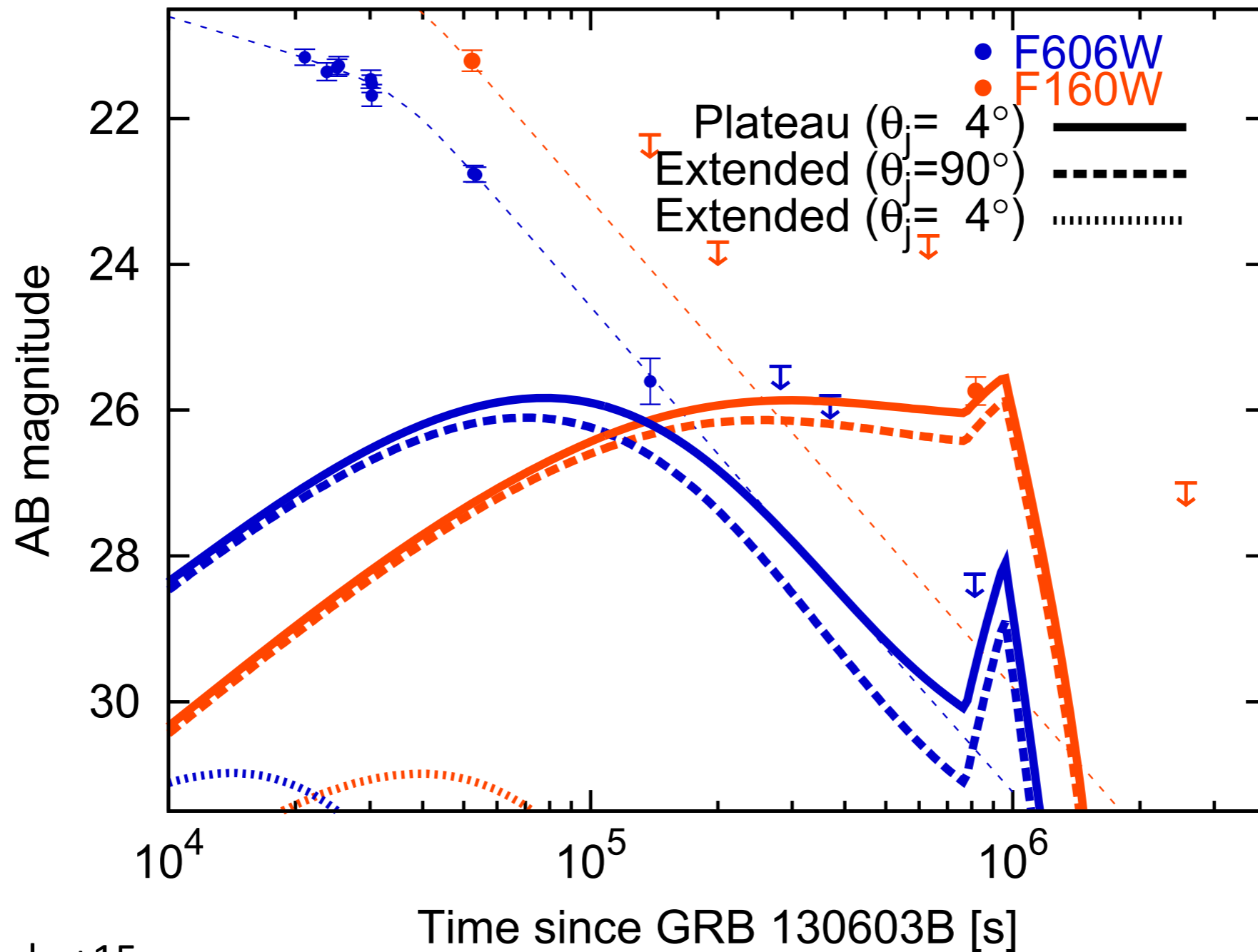
We monitored the location of the short GRB 160821B (Siegel et al. GCN 19833; Xu et al. GCN 19834) with the Hubble Space Telescope under our approved guest observer programs (GO14237 PI: Tanvir; GO14087 PI: Troja). Observations were carried out with the Wide Field Camera (WFC3) in three filters, F606W, 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.

Re-processed emission of extended/plateau emission



Kisaka+15

==> Need detailed follow-up of GW sources

EM emission from GW sources

- X-ray/gamma-ray
 - Short GRBs: promising, but strongly beamed
 - Central engine activity (isotropic??)
- Radio
 - Afterglow: delayed by \sim years
 - Good for confirmation and low contamination rate
- Optical/infrared
 - r-process nucleosynthesis \Rightarrow kilonova/macronova
 - Probably detected in short GRB observations
 - GW + EM \Rightarrow r-process production rate

Multi-messenger astronomy \Rightarrow Origin of r-process elements