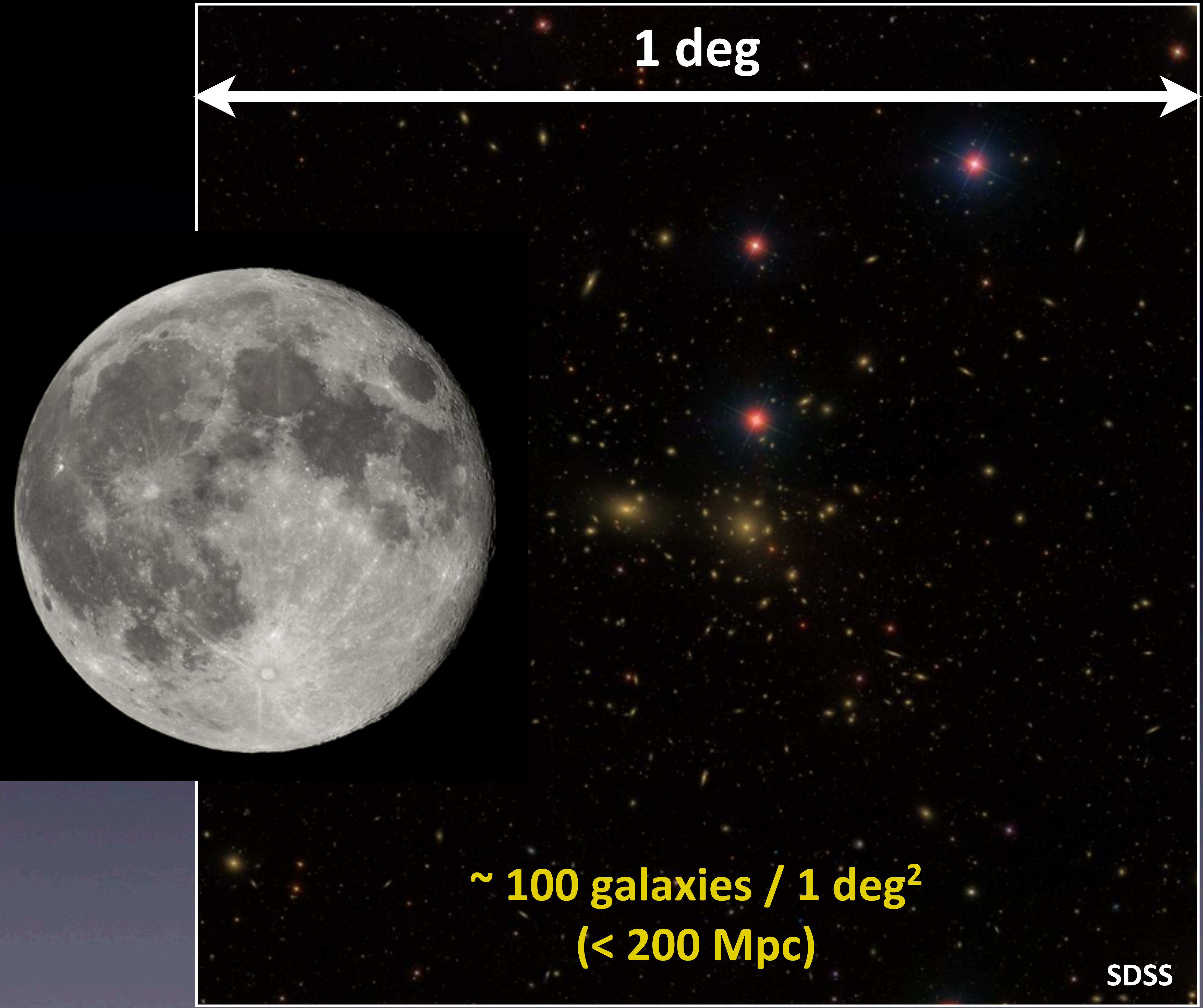
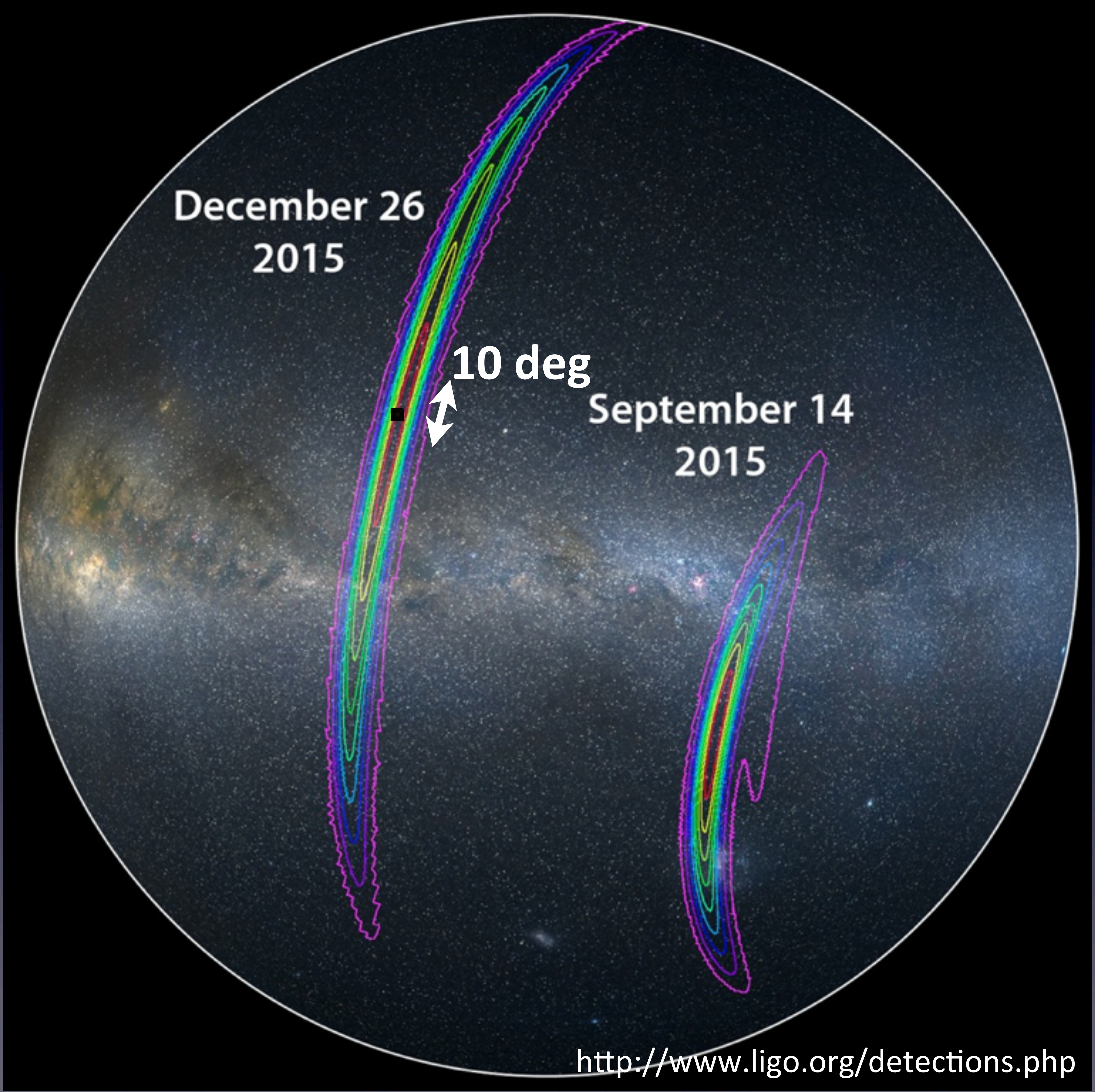
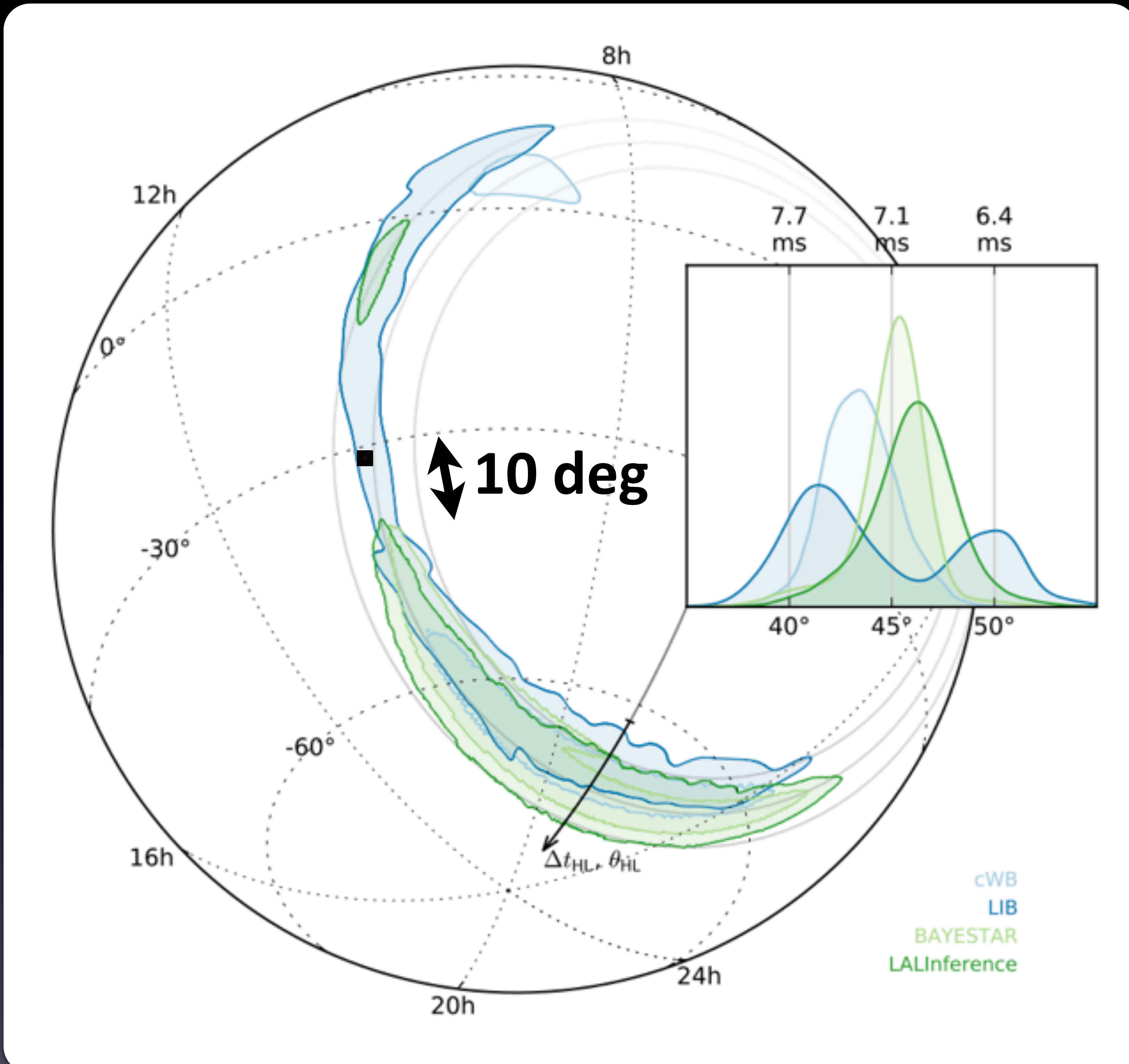
Kilonova/Macronova Emission from Compact Binary Mergers

Masaomi Tanaka
(National Astronomical Observatory of Japan)


1 deg
~ 100 galaxies / 1 deg^2
(< 200 Mpc)
SDSS


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



Abbott et al. 2016, ApJ, 826, L13

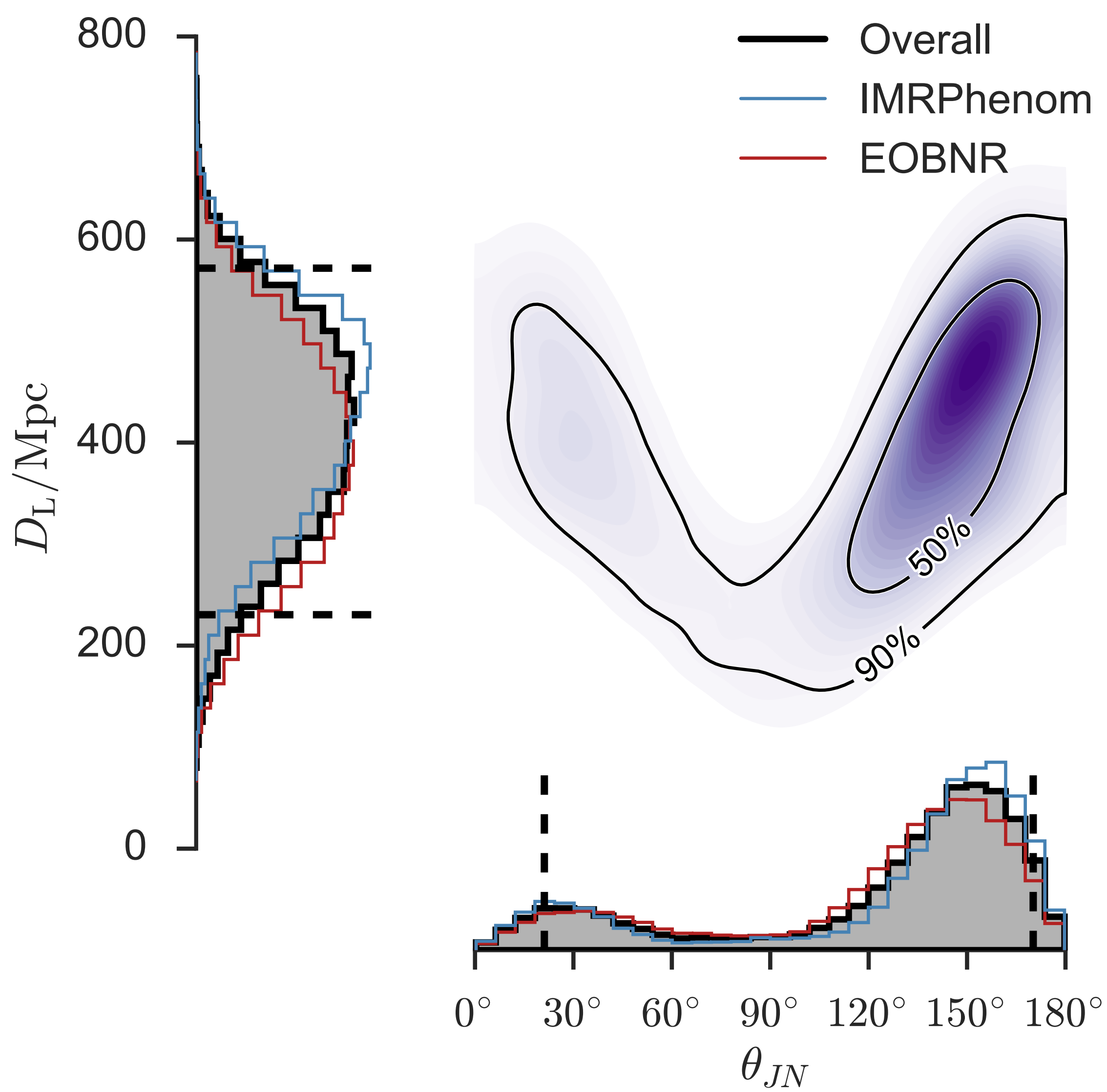
Localization ~ 600 deg^2
(~< 10 deg^2 with Advanced Virgo and KAGRA)

Detection of electromagnetic (EM) counterparts is essential

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

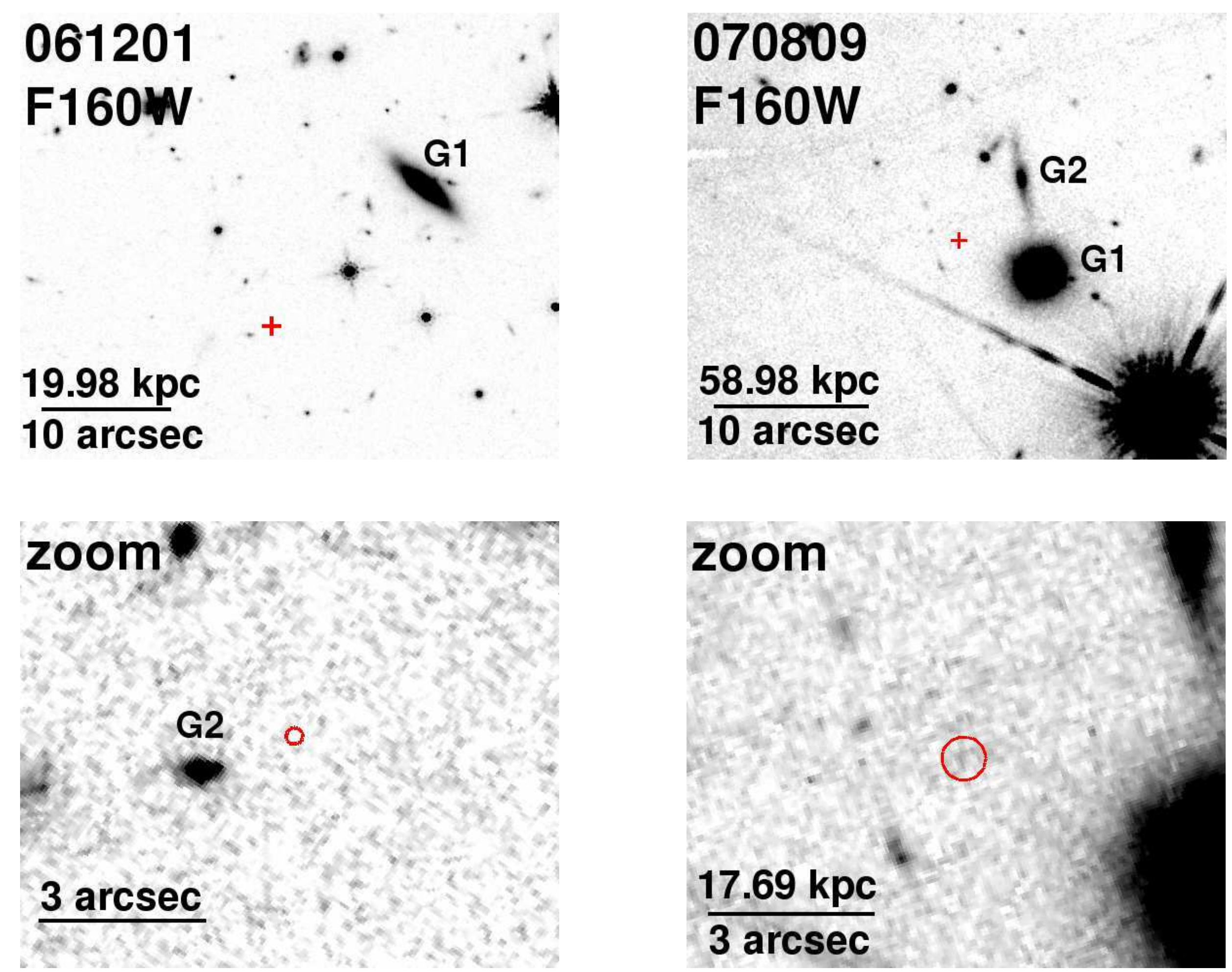
see Samaya Nissanke's talk

Degeneracy between inclination and distance



Abbott et al. 2016, PRL, 116, 241102

Local environments



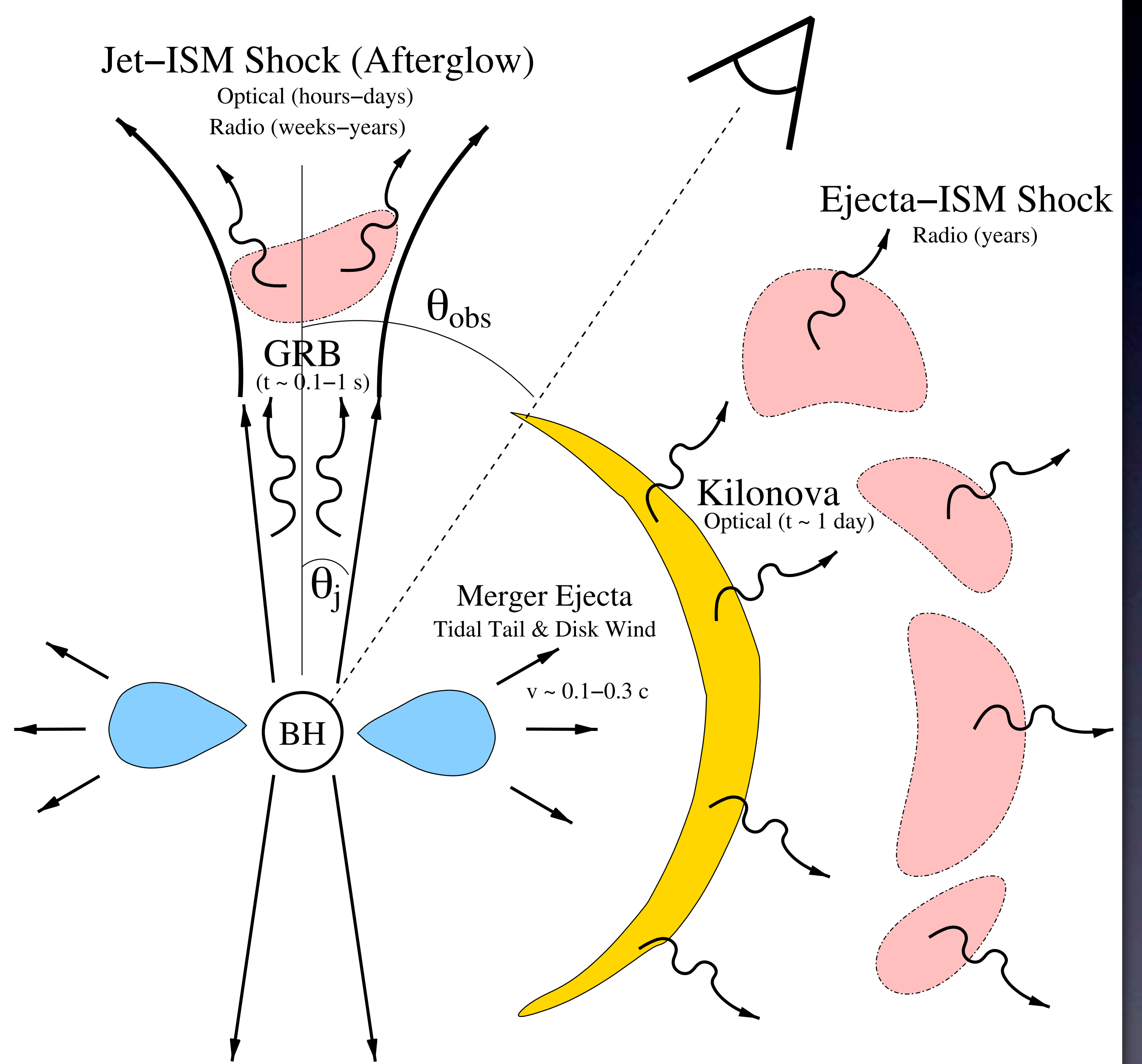
Berger 2014 (for short GRBs)

Kilonova/Macronova Emission from Compact Binary Mergers

- EM emission from compact binary mergers
- Kilonova/macronova emission
- Lessons from past observations and prospects for EM follow-up observations

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

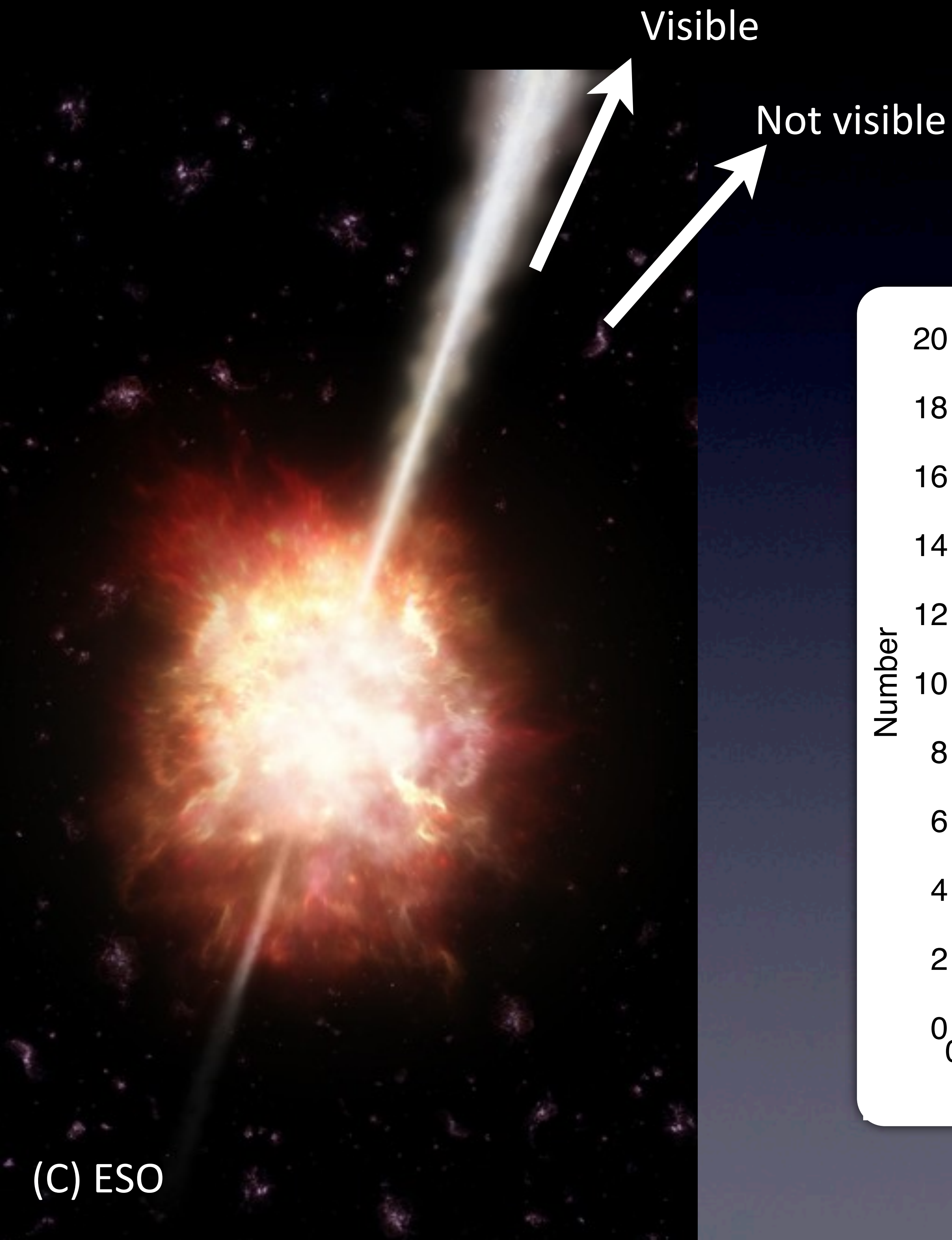
- On-axis short GRB
- Radio afterglow
- Optical/NIR emission “kilonova” or “macronova”



Metzger & Berger 2012, ApJ 746, 48

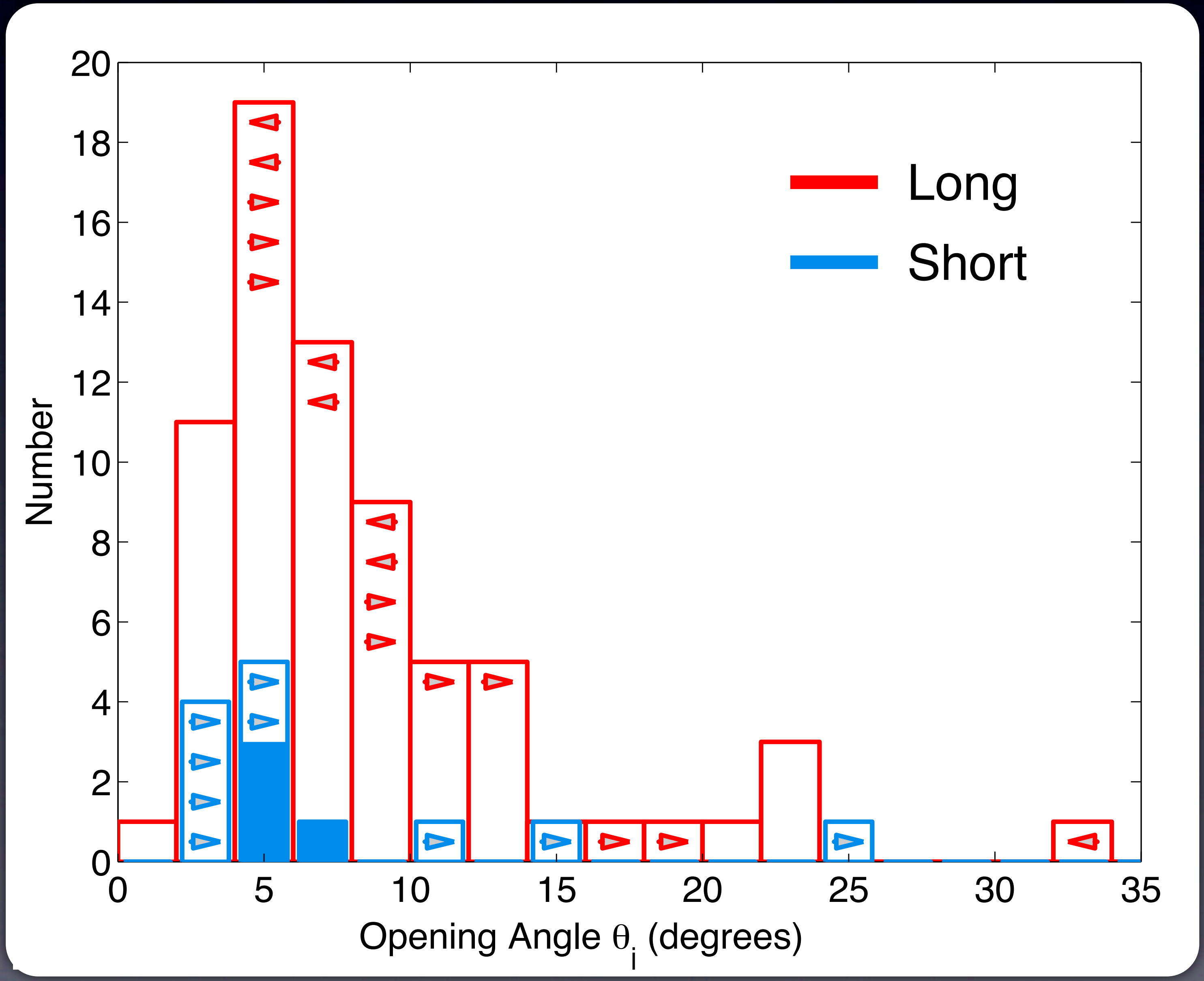
see talks by Nissanke, Piran, Zhang, ...

Short gamma-ray burst (GRBs)

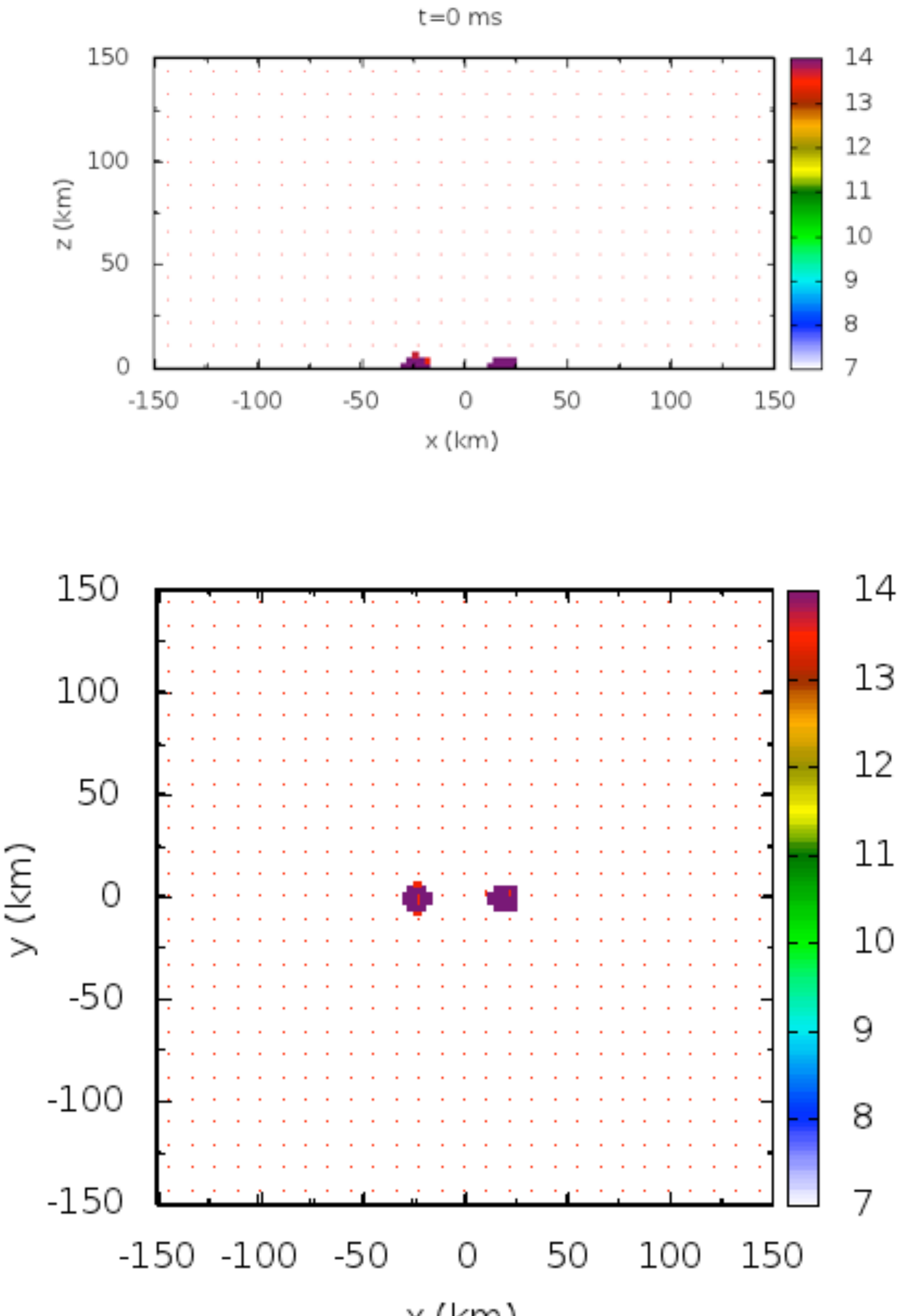


(C) ESO

Opening angle ~ 10 deg
=> probability ~ a few %



Fong et al. 2014, ApJ, 780, 118



Hotokezaka+13

Mass ejection from NS mergers

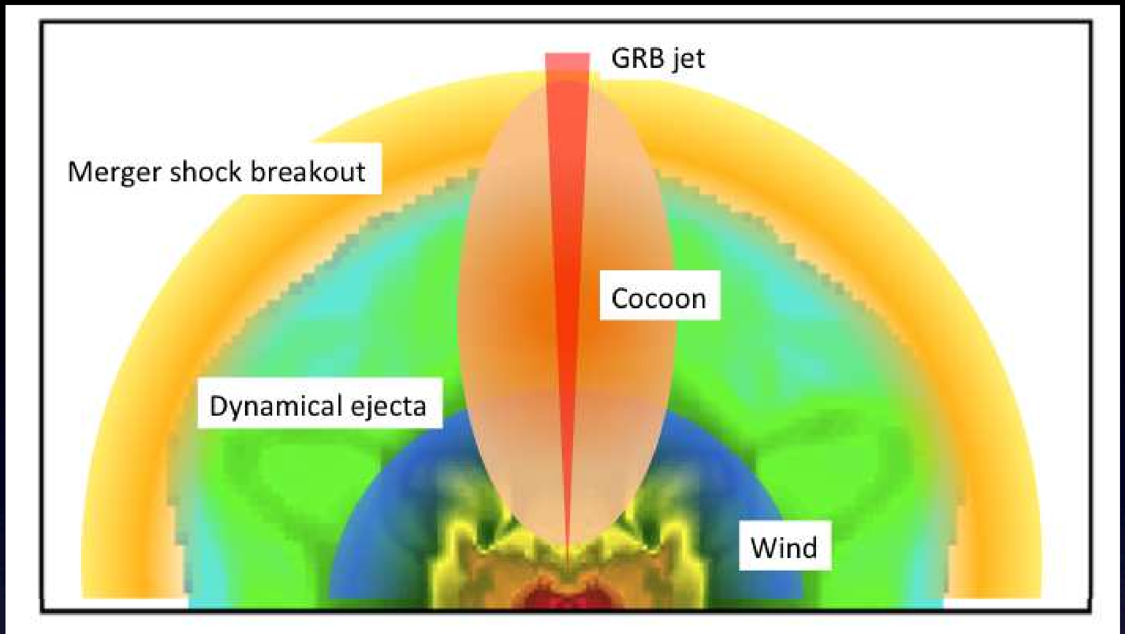
- tidal disruption
- shock heating

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

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

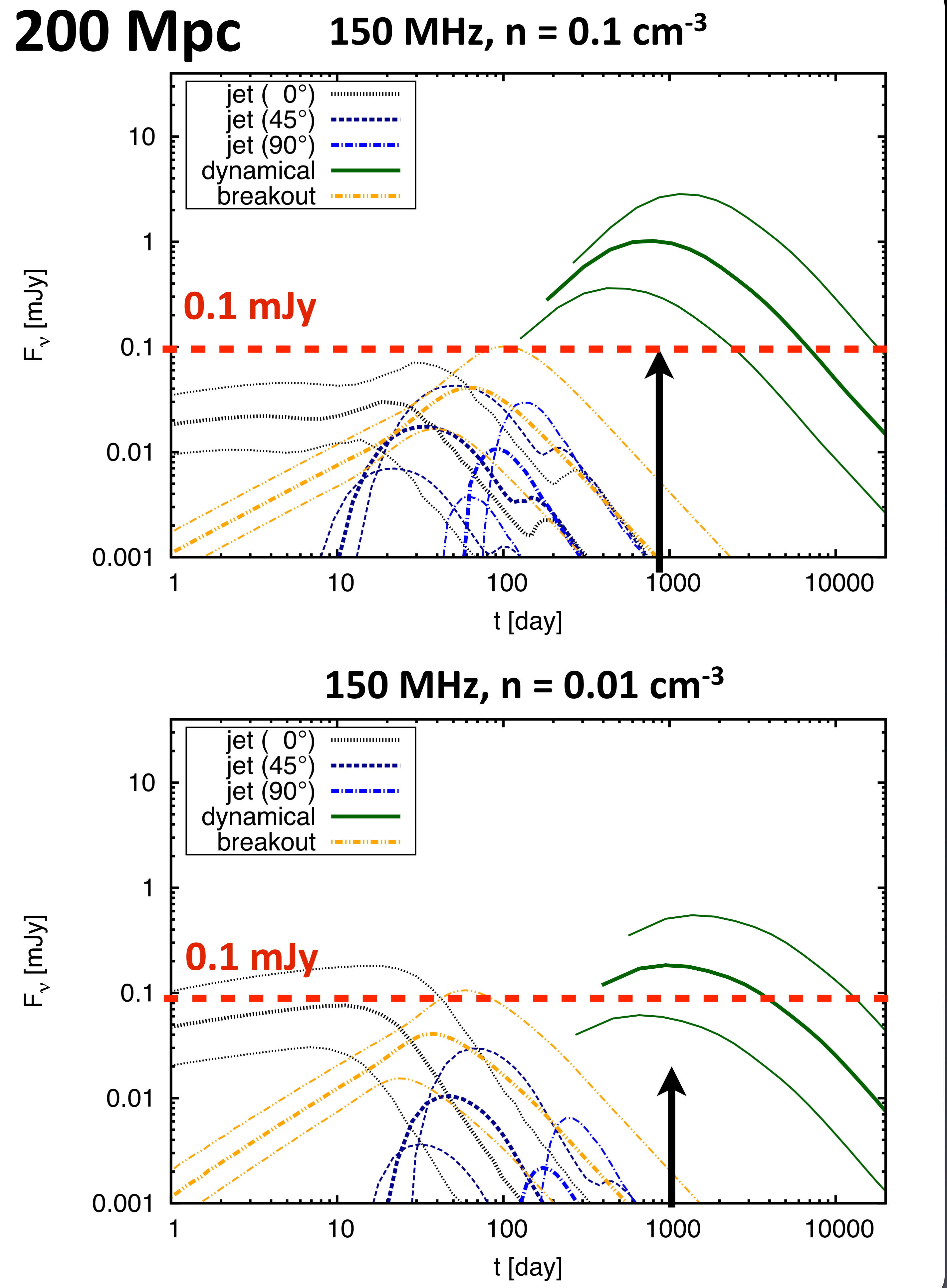
see talks by Rezzolla, Janka, Sekiguchi, ...

Radio emission (afterglow)



- Delayed by ~> years
- Too faint?
  (low environment density)

Nakar & Piran 11
Hotokezaka & Piran 15



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

- **On-axis short GRB**

  strongly beamed ✗

  (isotropic soft X-ray?)

- **Off-axis radio afterglow**

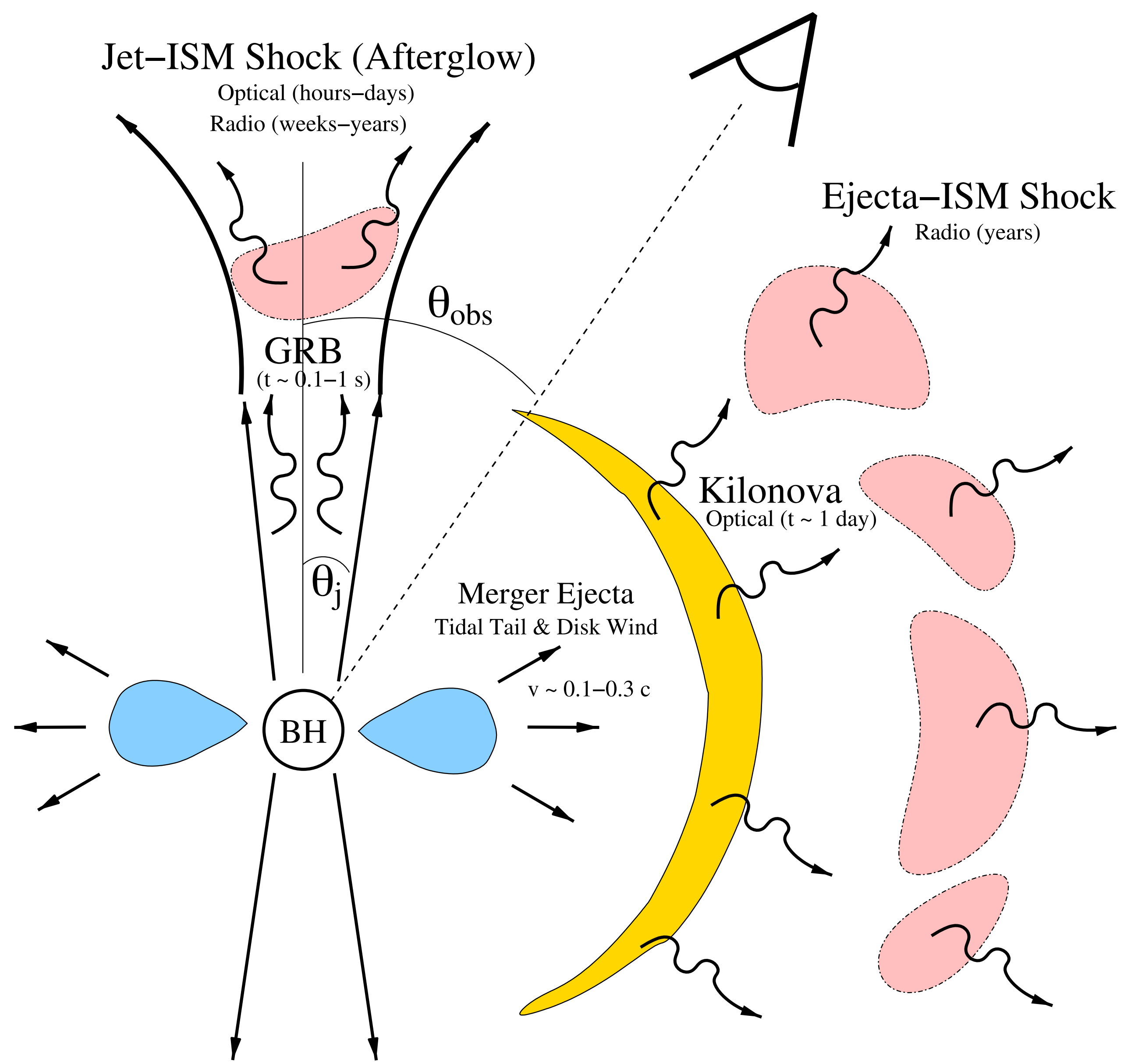
  isotropic ✓

  delayed by ~> 1 yr ✗

- **Optical/NIR emission "kilonova" or "macronova"**

  isotropic ✓

  short delay ✓



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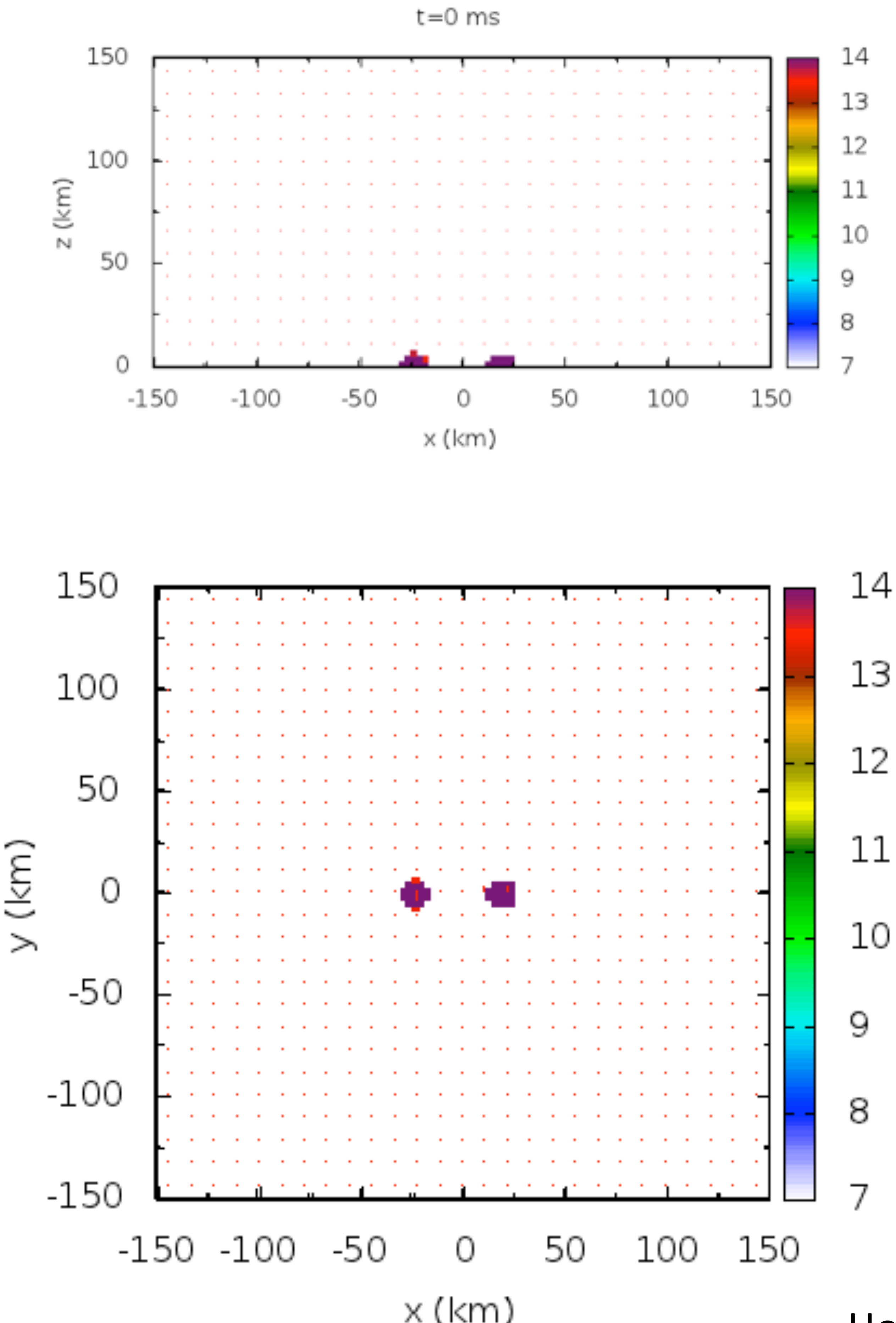

Hotokezaka+13

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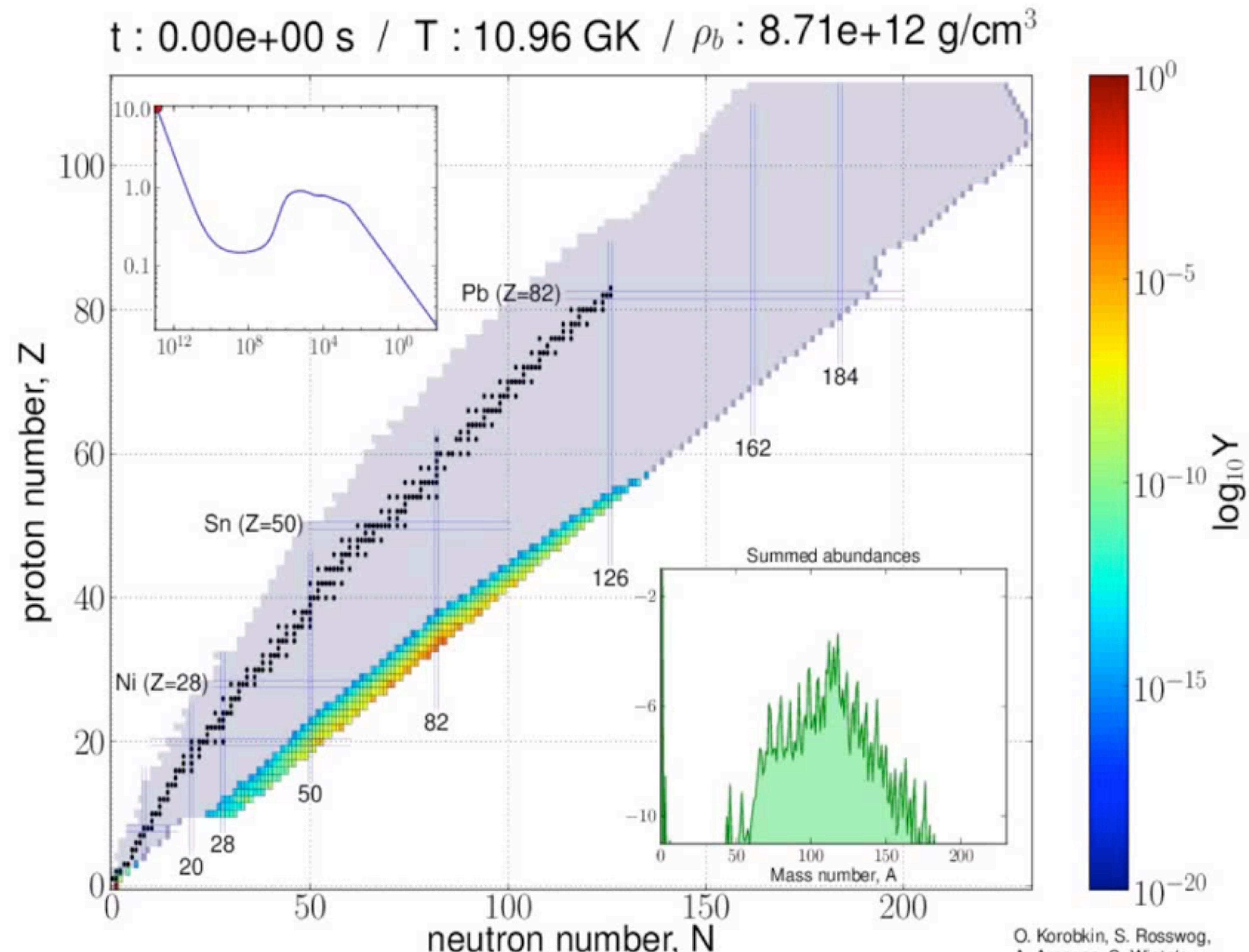
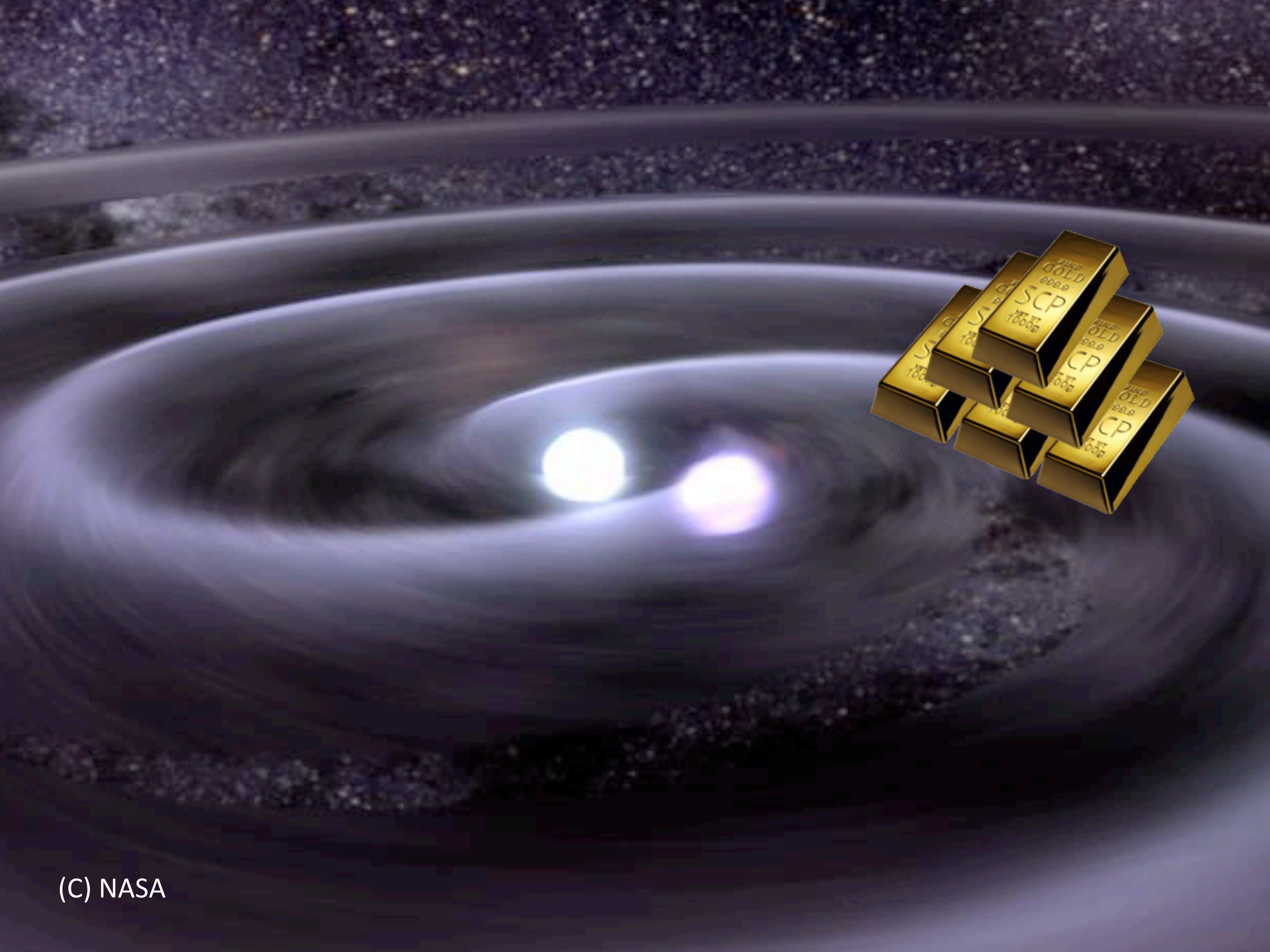
Nucleosynthesis in NS merger



O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379



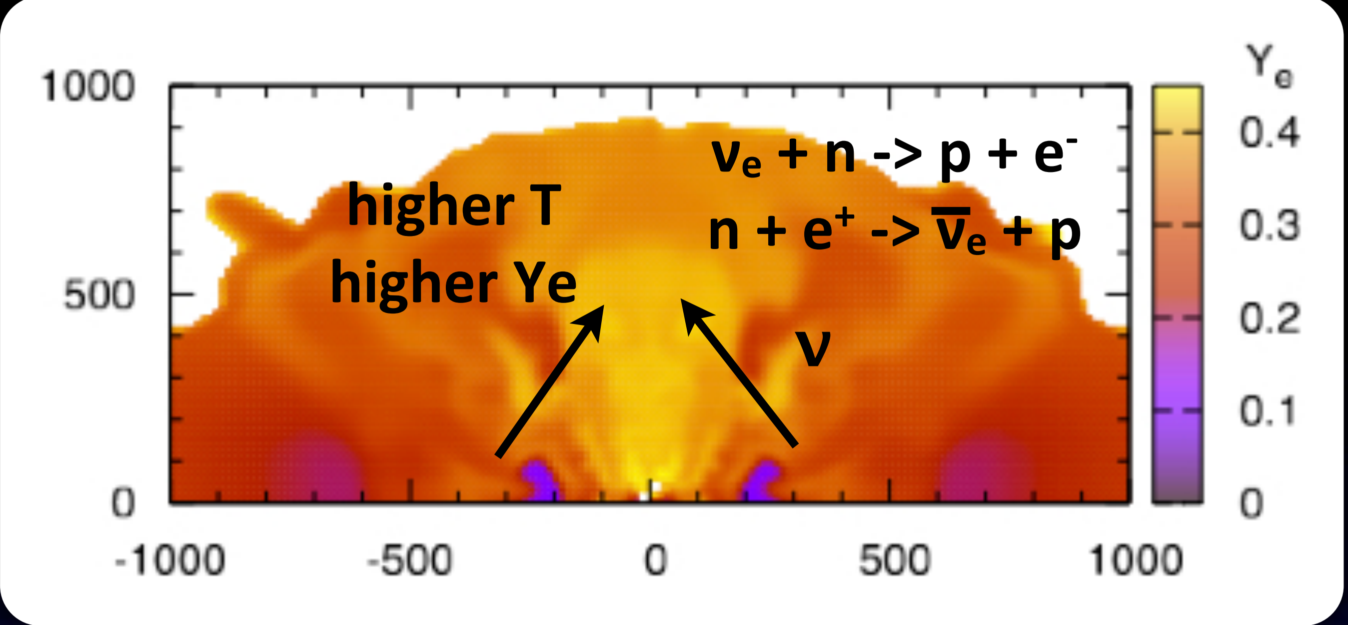
(C) NASA

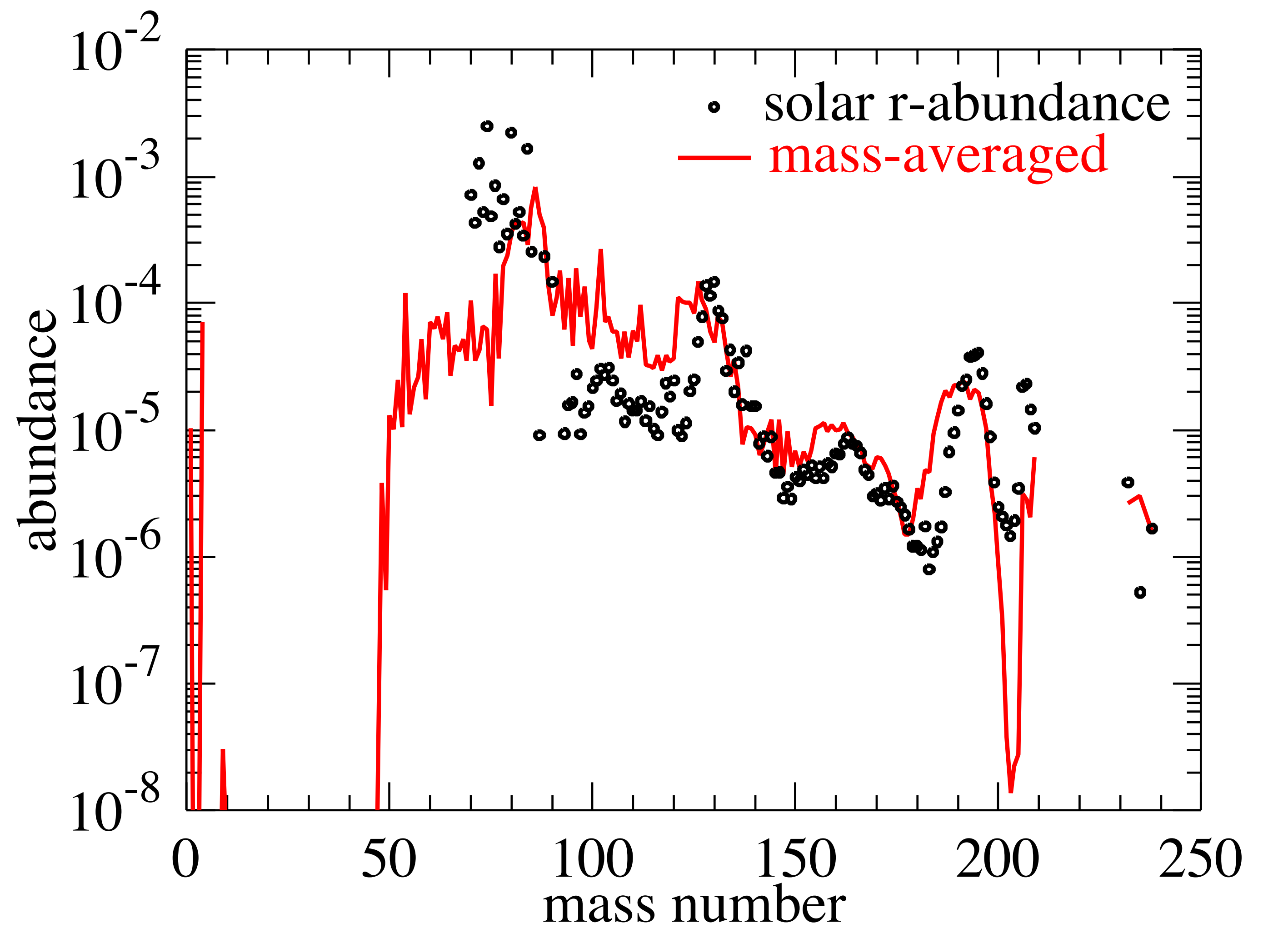
Nucleosynthesis in NS merger

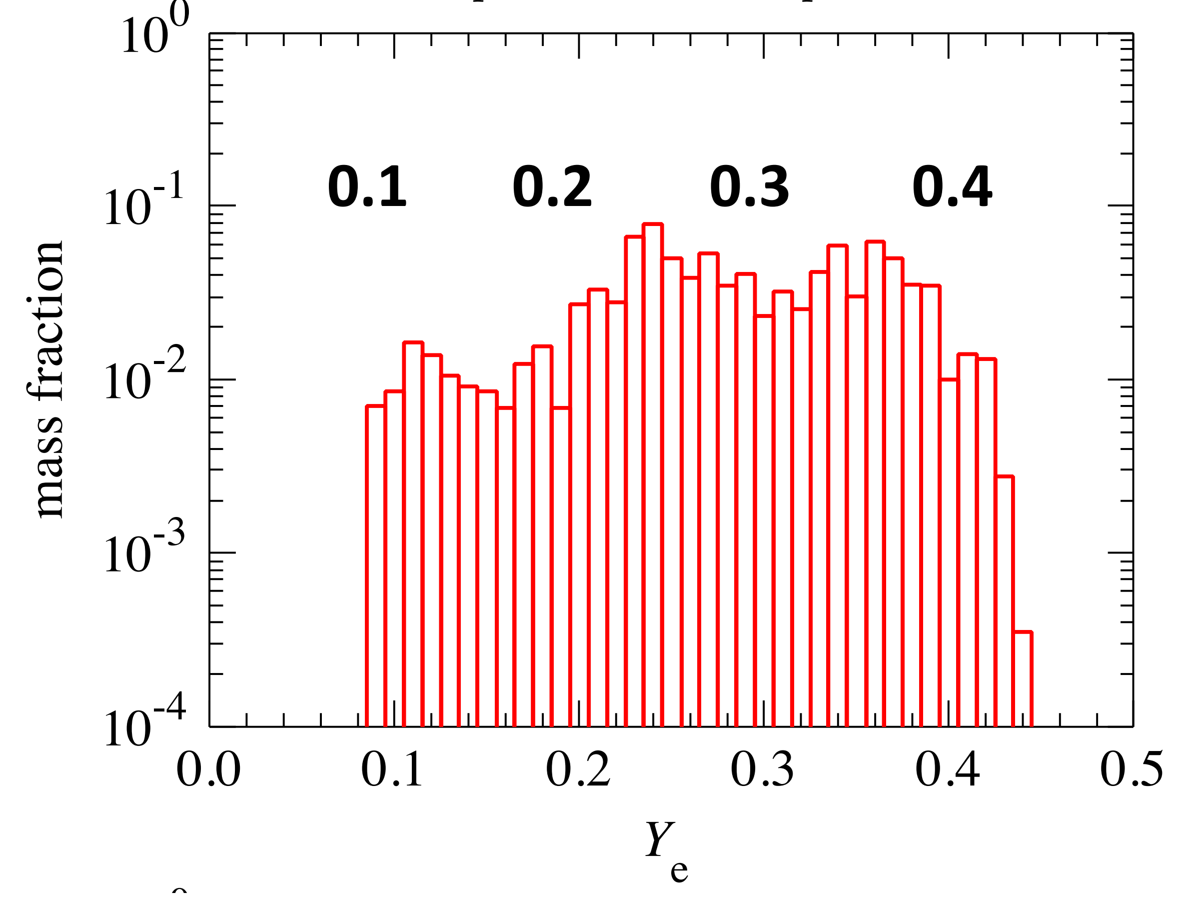
=> solar abundances

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

see talks by Janka, Sekiguchi, ...







NS merger as a possible origin of r-process elements

Event rate

R_{NSM} ~ 10^{-4} event/yr/Galaxy

~ 10^{3} Gpc^{-3} yr^{-1}

~ 40 GW events yr^{-1}

(w/ Adv. detectors, < 200 Mpc)

↑

GW

Ejection per event

M_{ej}(r-process) ~ 10^{-2} Msun

↑

EM

Enough to explain the r-process abundance in our Galaxy

M(Galaxy, r-process) ~ $M_{ej}(r)$ x (R_{NSM} x t_G)

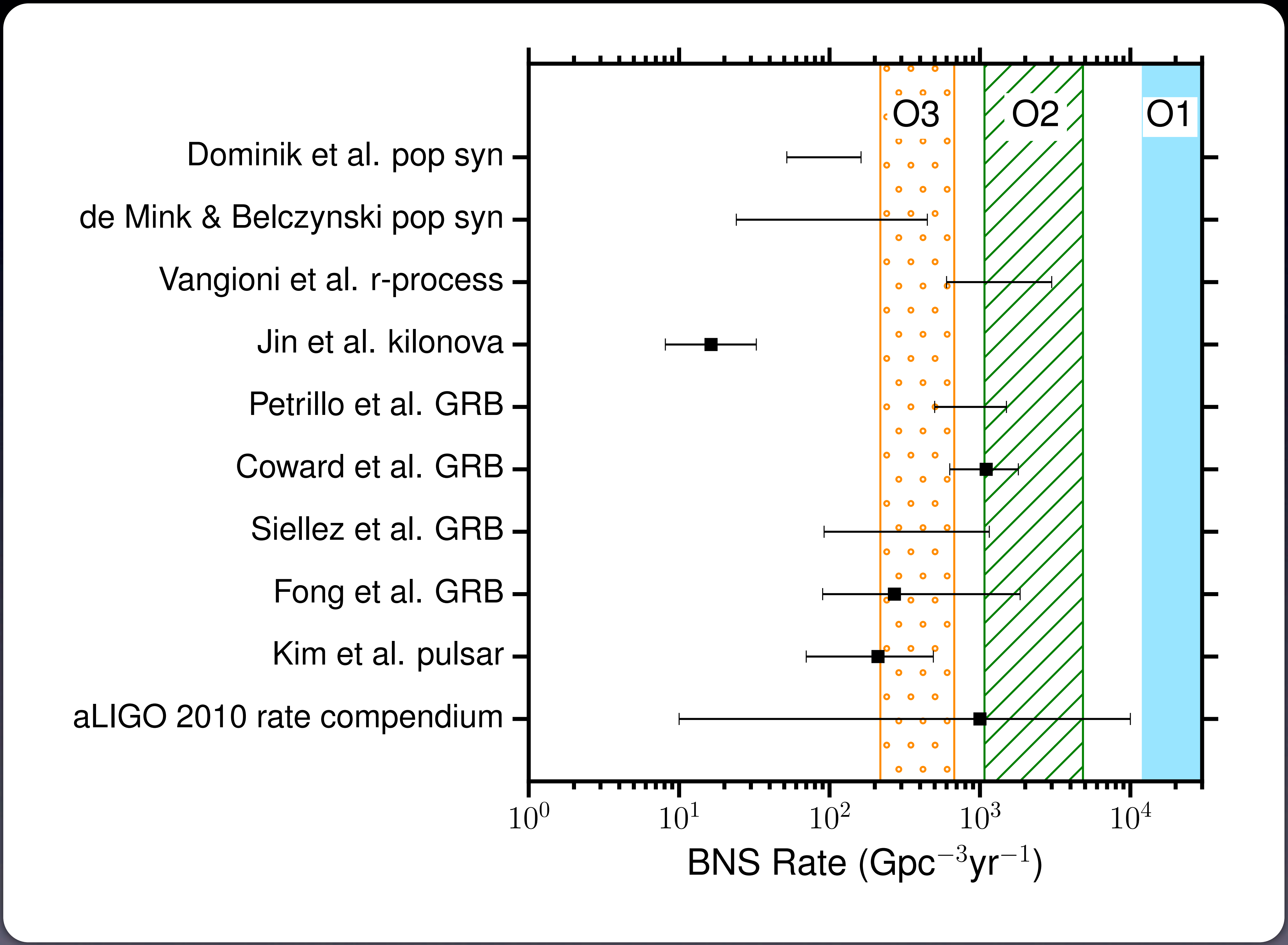
~ 10^{-2} x 10^{-4} x 10^{10} ~ 10^{4} Msun

(e.g., Piran+14, Matteucci+14, Tsujimoto+14, Cescutti+15)

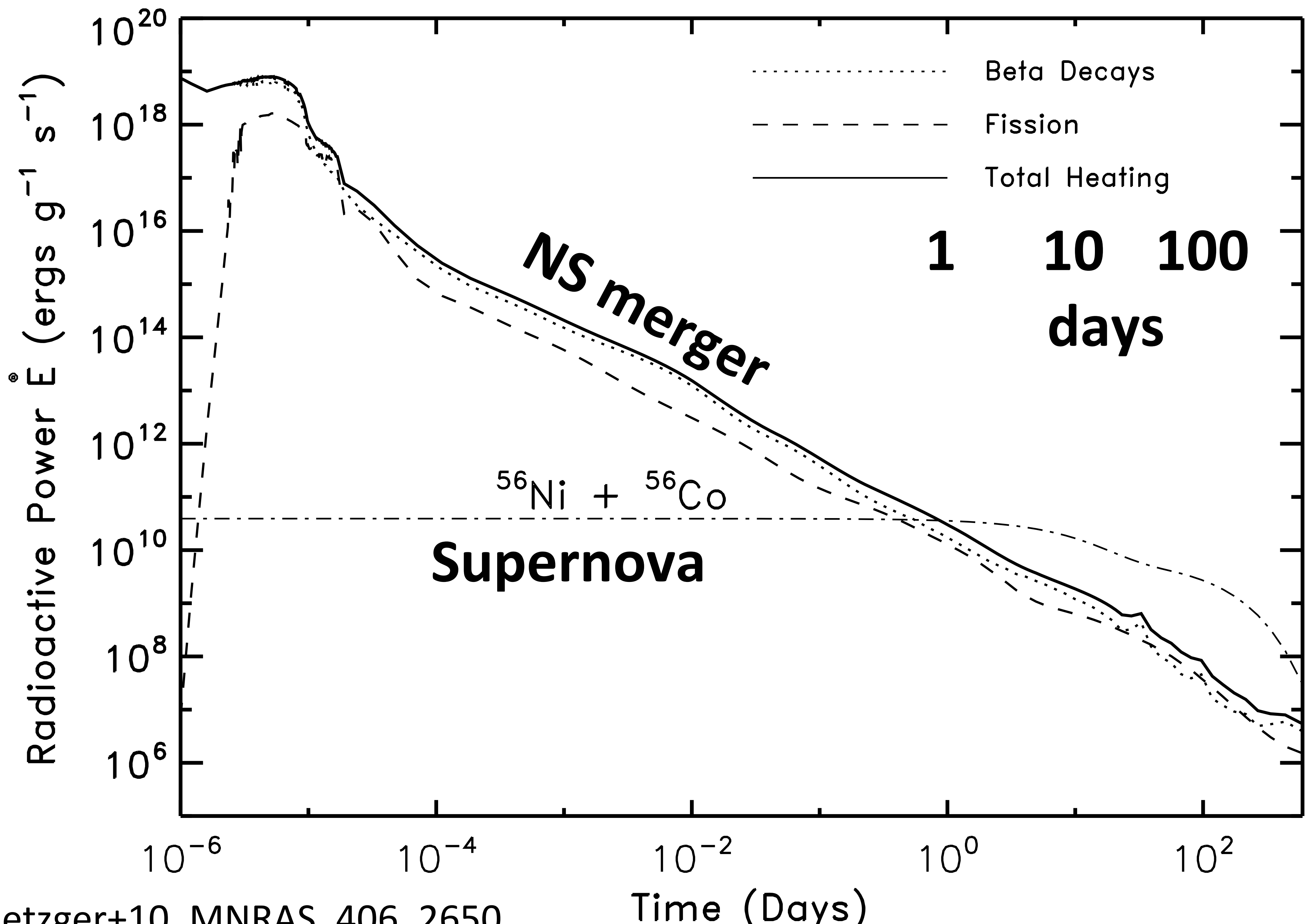
LIGO O1: Limit to the NS merger rate

R_{NSM} ~< 10^4 Gpc^{-3} yr^{-1} Abbott et al. (arXiv:1607.07456)

see Laura Nuttall's talk



Radioactive energy => optical emission



Metzger+10, MNRAS, 406, 2650

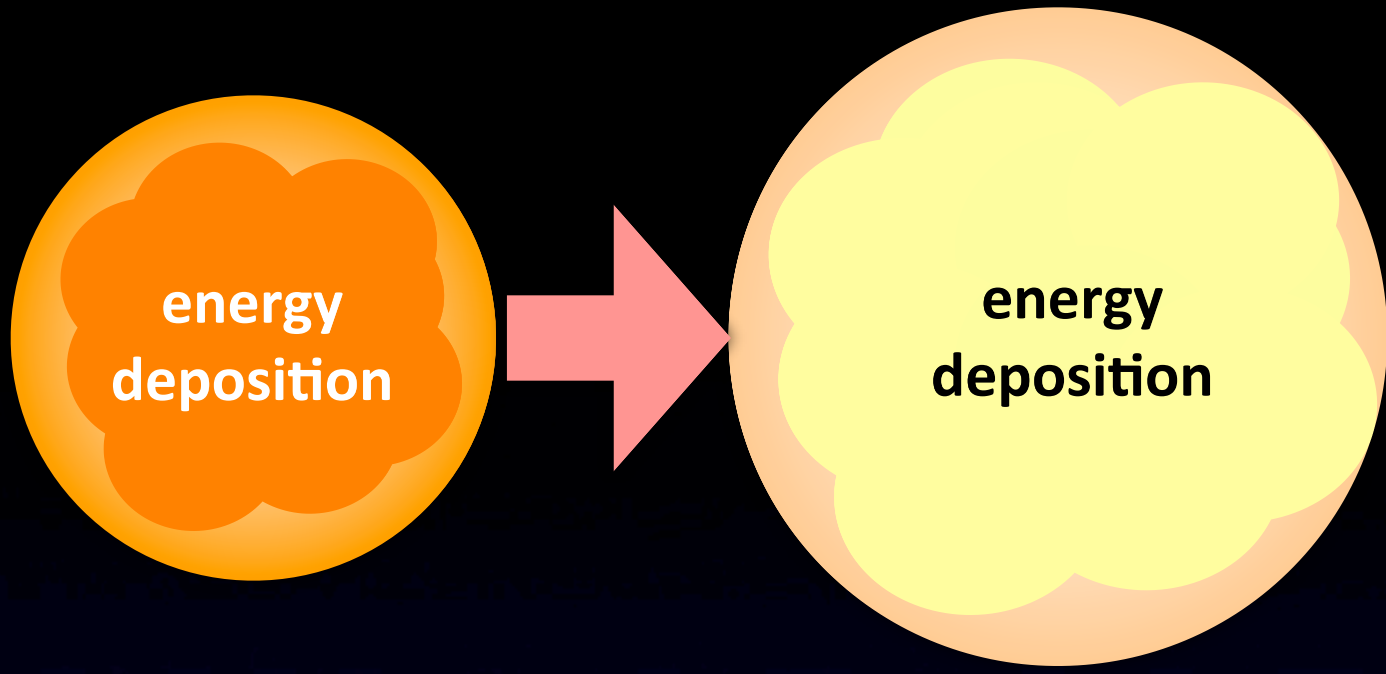
see also Wanajo+14, Lippuner+15, Barnes+16

Supernova vs NS merger

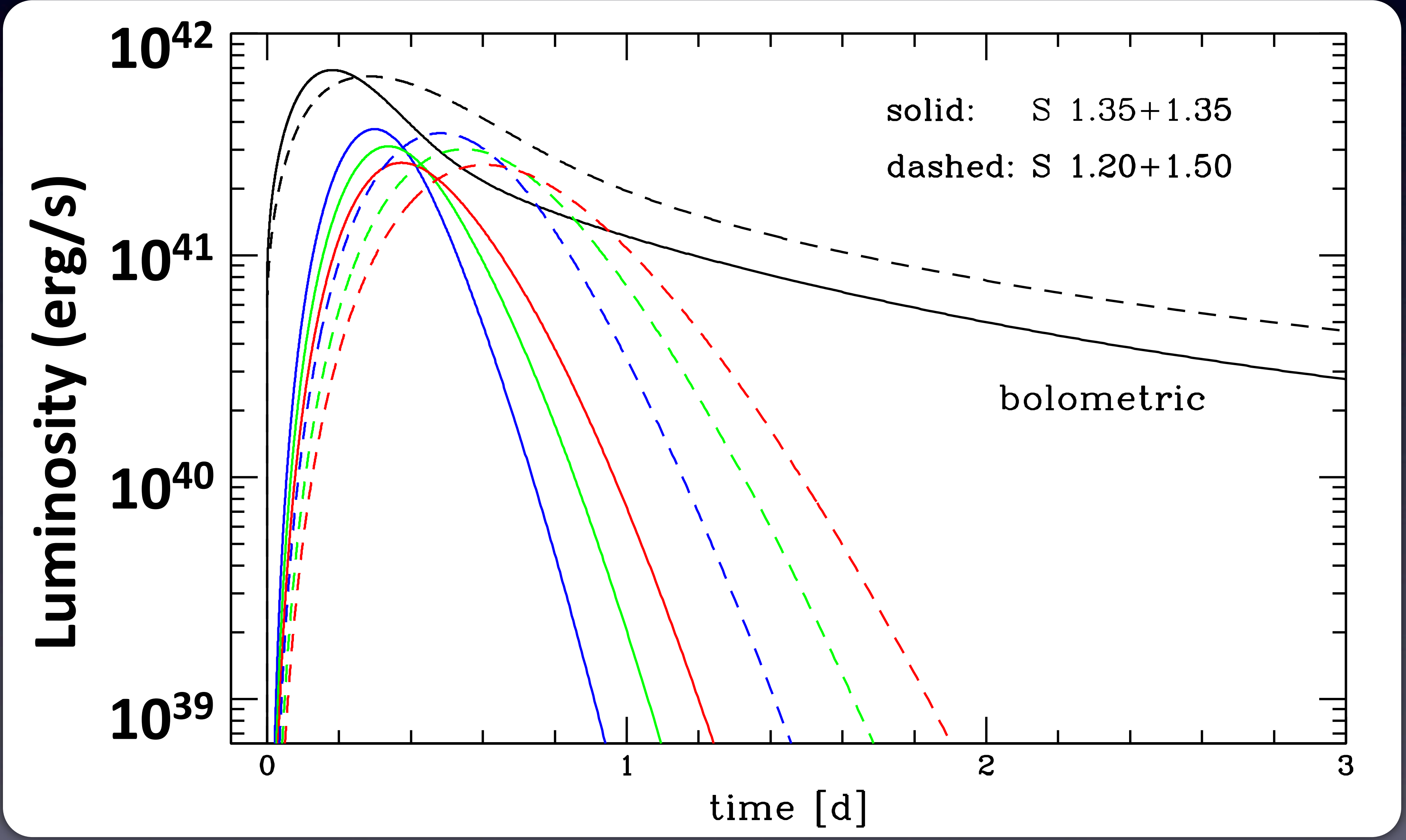
	Supernova (Type Ia)		NS merger
Mass	1.4 Msun	$>$	0.01 Msun
Velocity	10,000 km/s	$<$	30,000-60,000 km/s
Kinetic energy	10^{51} erg	$\gtrsim$	(1-5) x 10^{50} erg
Composition	Fe-group, Si, S, C, O		r-process elements
Power source	^{56}Ni		r-process elements

"kilonova/macronova"

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



~ 19-20 mag
@200 Mpc
(=> 1m telescope)

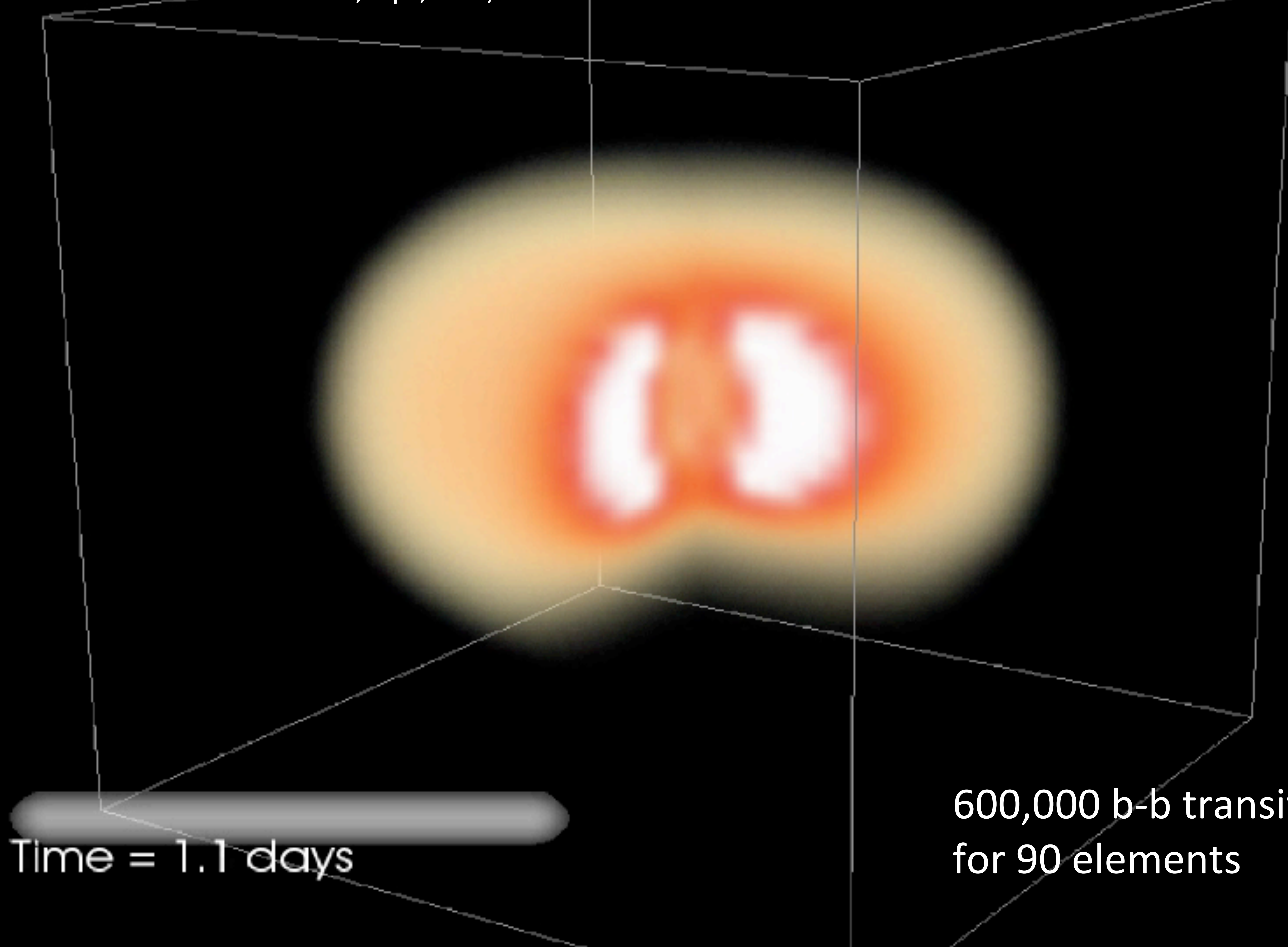


Goriely+11

***Opacity of Fe is assumed**
(b-b transitions)

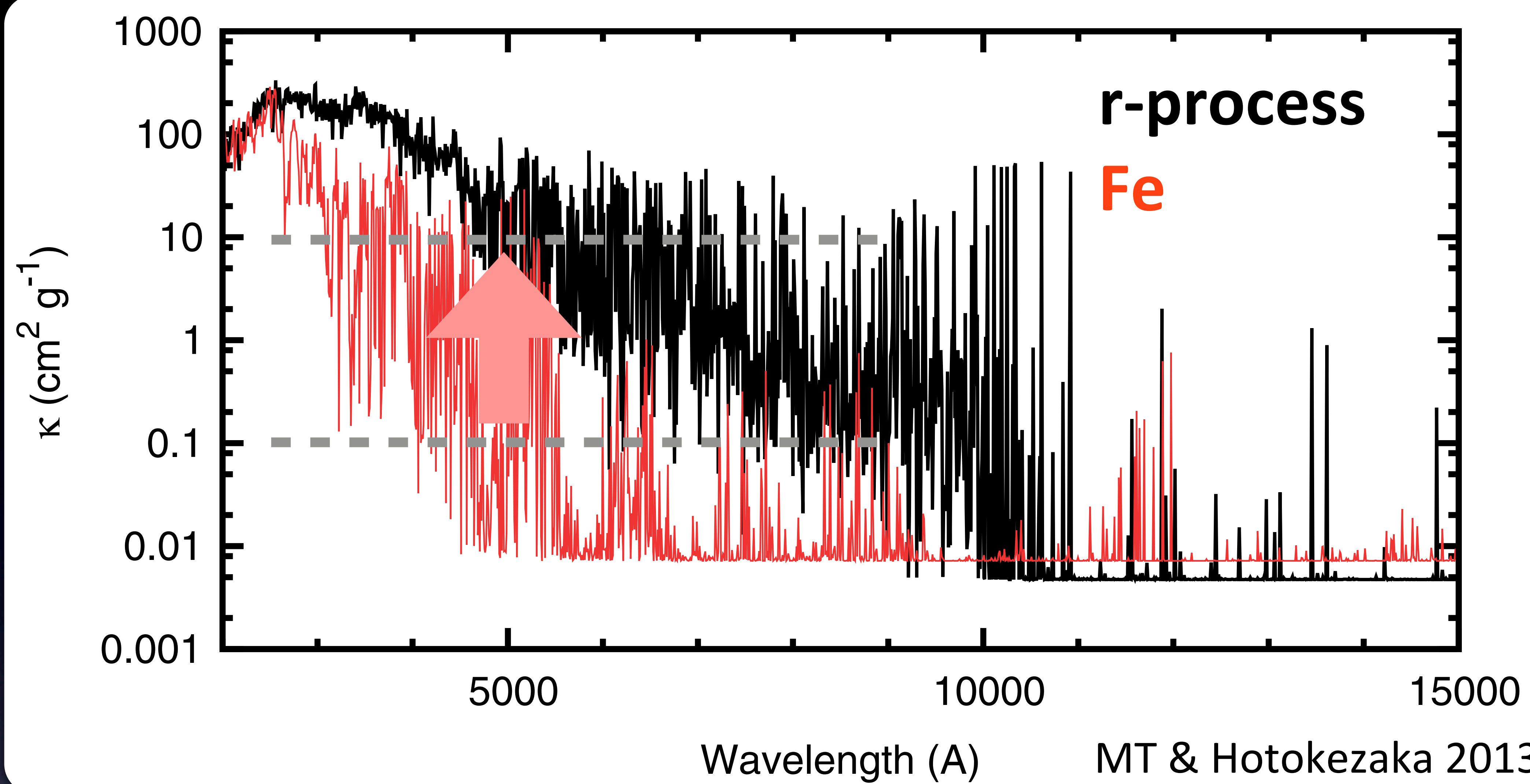
3D frequency-dependent radiative transfer for NS merger

MT & Hotokezaka 2013, ApJ, 775, 113



600,000 b-b transitions
for 90 elements

Opacity



$$t_{\rm peak} \simeq 0.8 \ {\rm days} \ \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{0.1 \ {\rm cm^2 \ g^{-1}}}\right)^{1/2}$$

8 (replacing 0.8) **10** (replacing 0.1 cm^2 g^{-1})

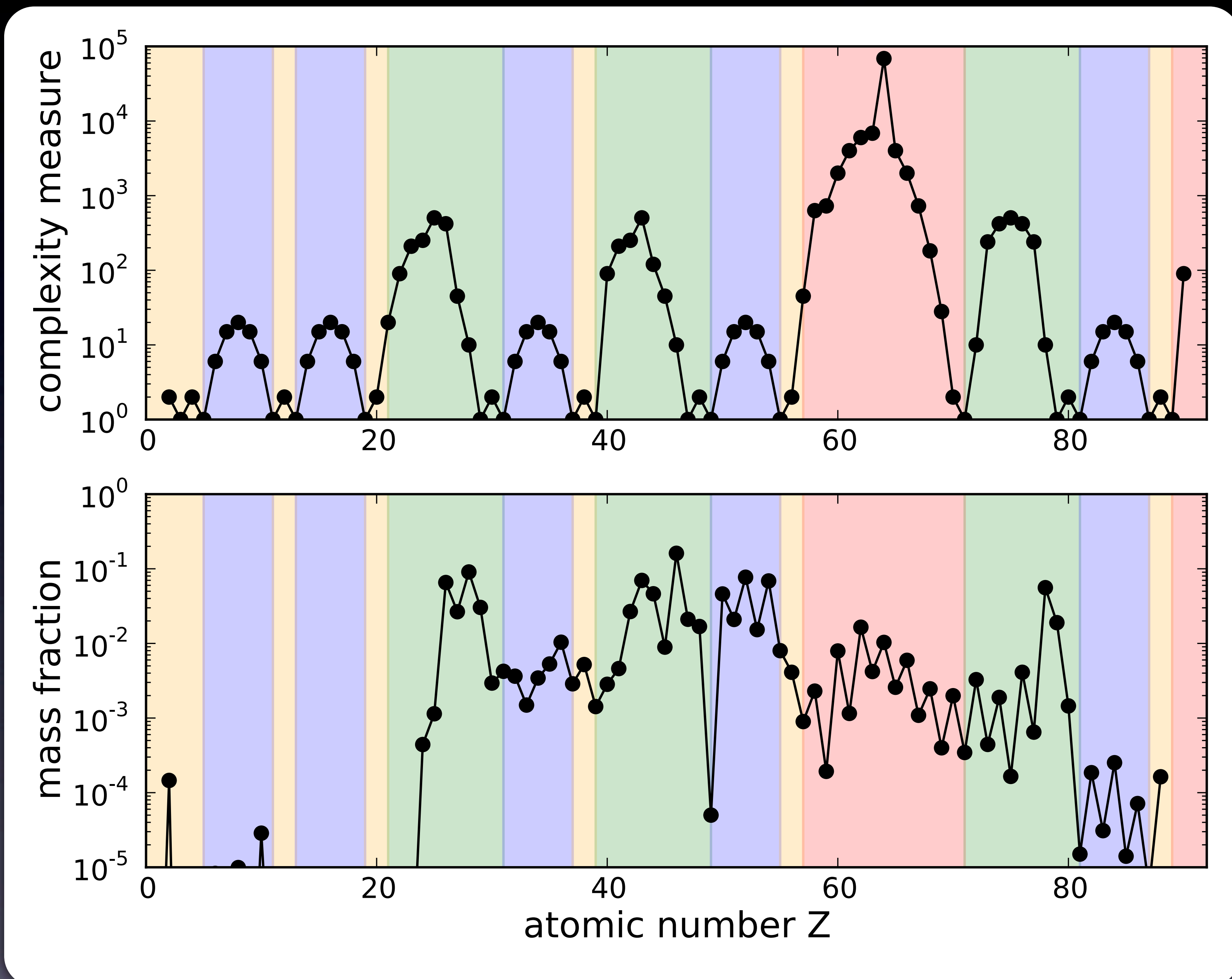
$$L_{\rm peak} \simeq \ 2 \times 10^{41} \ {\rm erg \ s^{-1}} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{0.35} \left(\frac{v}{0.1c}\right)^{0.65} \left(\frac{\kappa}{0.1 \ {\rm cm^2 \ g^{-1}}}\right)^{-0.65}$$

1×10^{40} (replacing 2×10^{41}) **10** (replacing 0.1 cm^2 g^{-1})

Similar conclusions by Kasen+13 and Barnes & Kasen 13
with different opacity database (more complete table for a few elements)

Lanthanide => high opacity

Lanthanide



Kasen+13

"Complexity"

$$C = \Pi_i \frac{g_i!}{n_i!(g_i - n_i)!}$$

g: number of sublevels

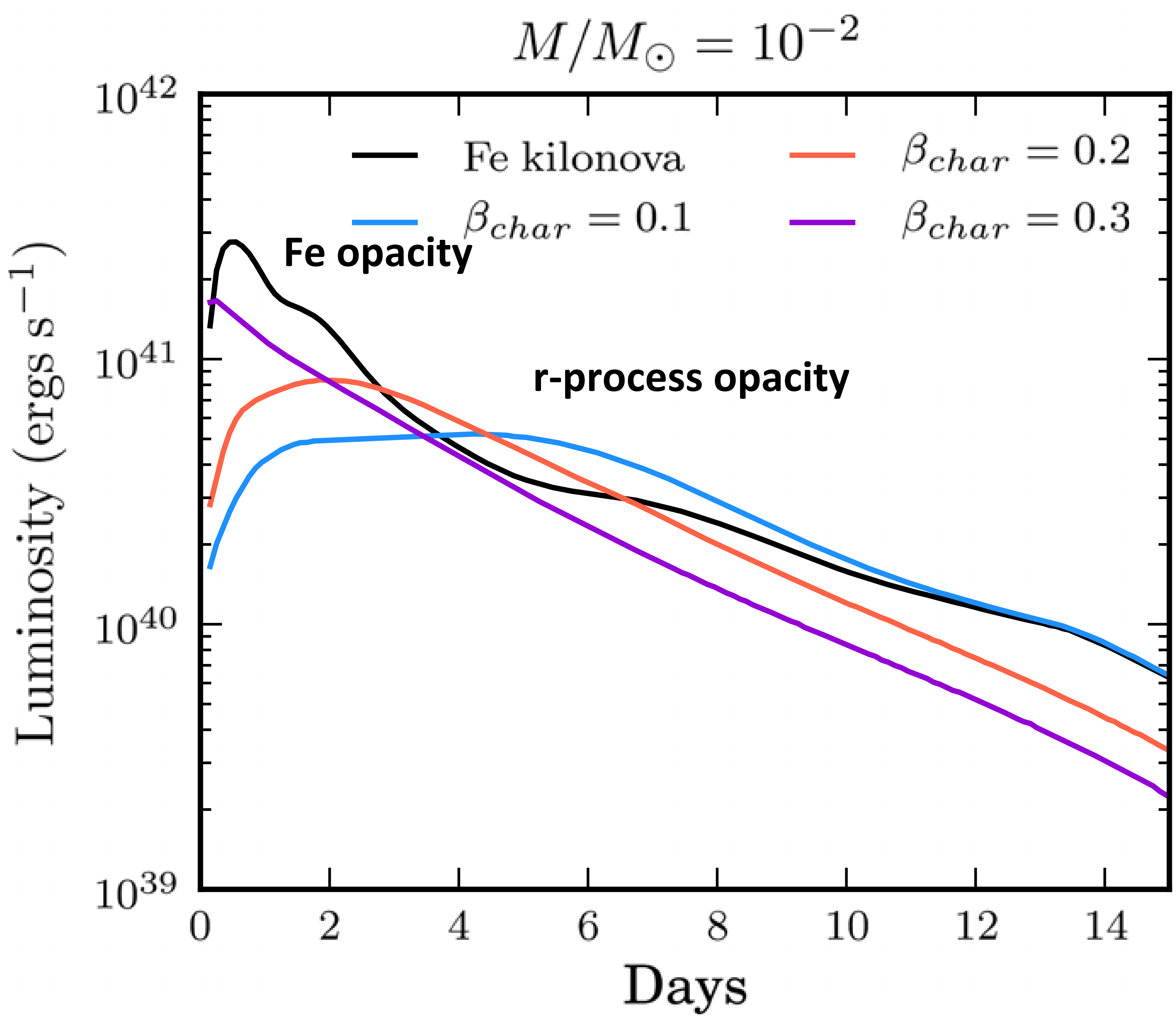
$$g = 2(2l + 1)$$

n: number of electrons

Number of lines ~ C^2

Luminosity

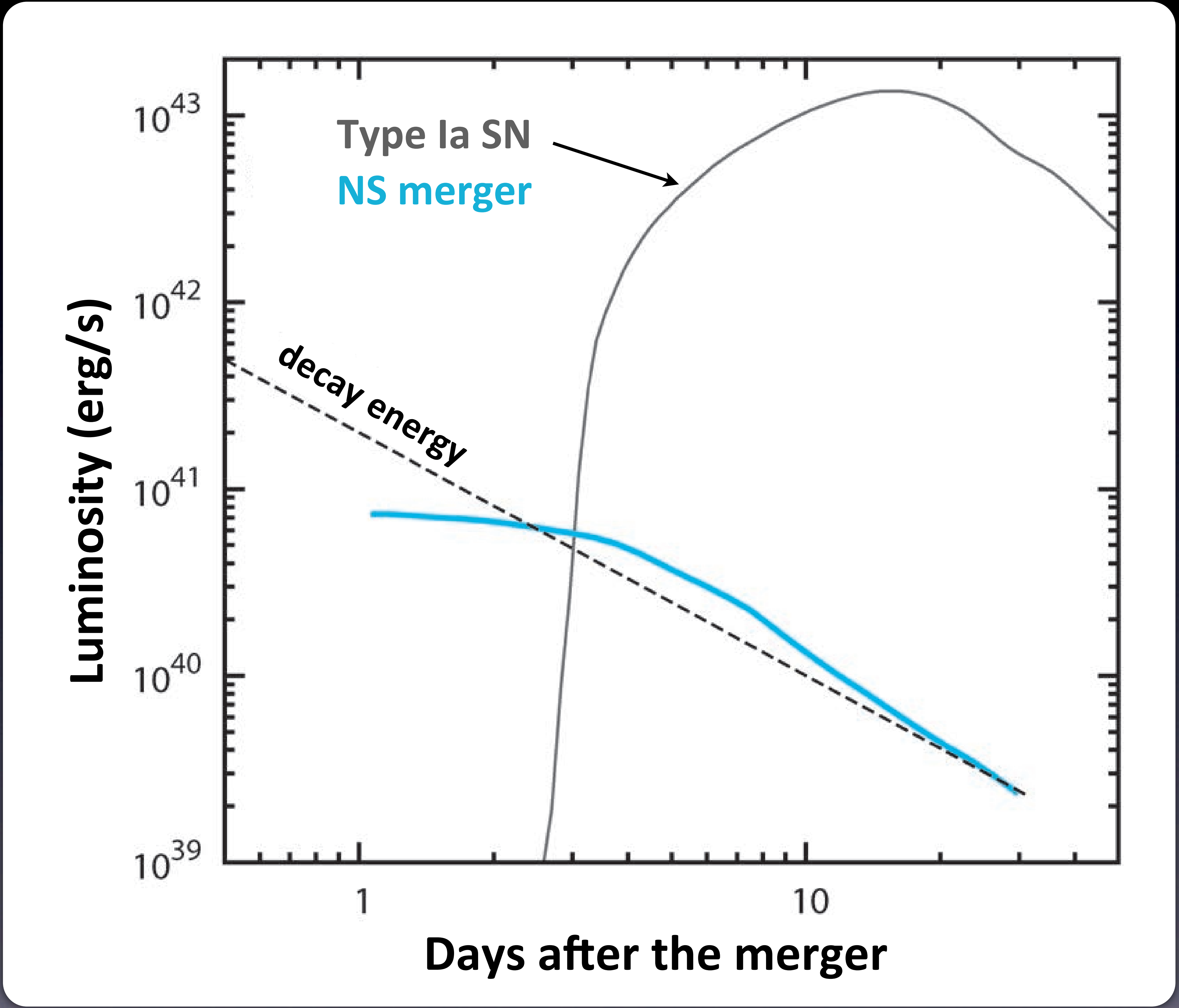
previous expectation (Fe opacity)



Barnes & Kasen 13

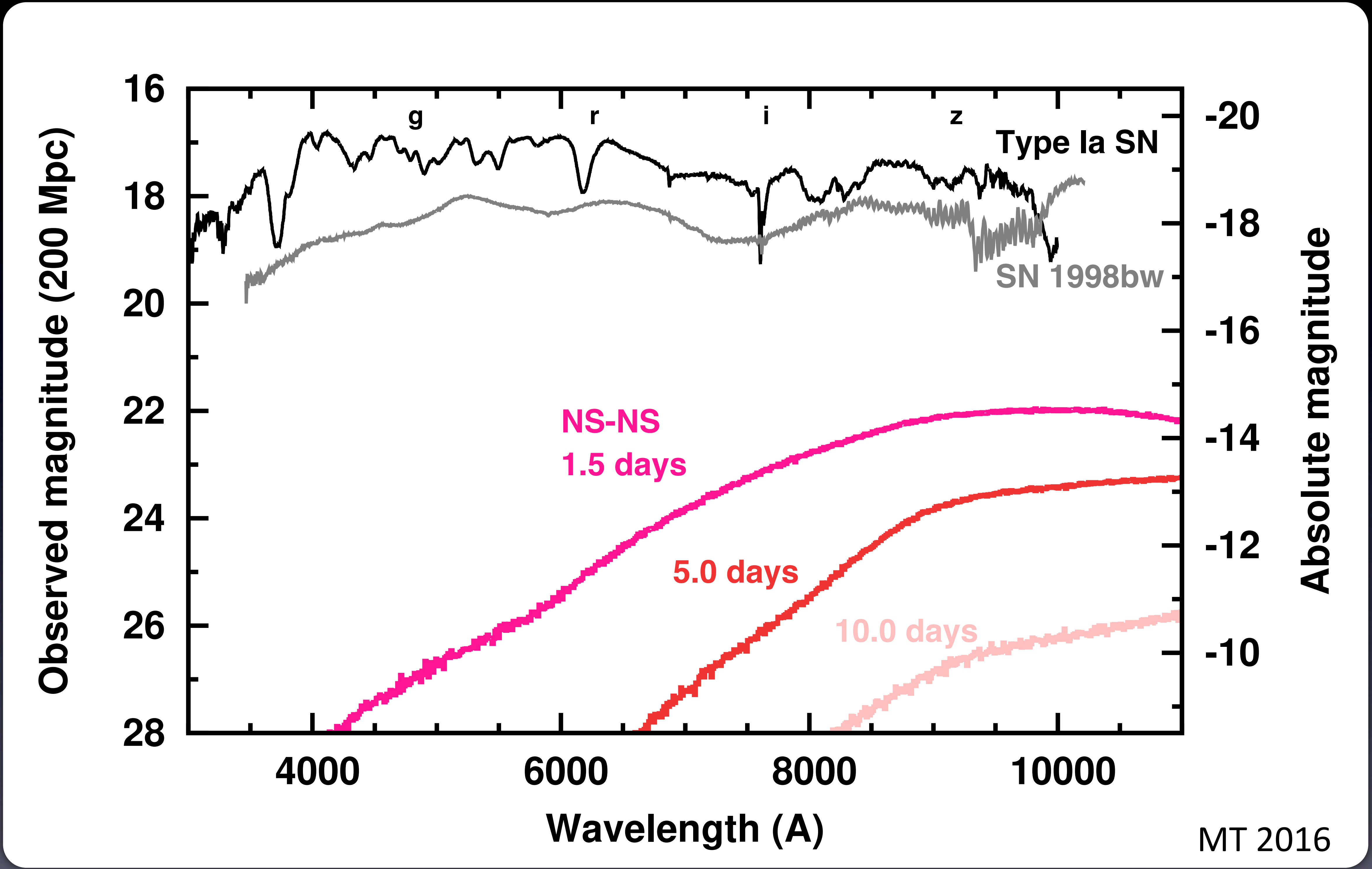
Luminosity

previous expectation (Fe opacity)



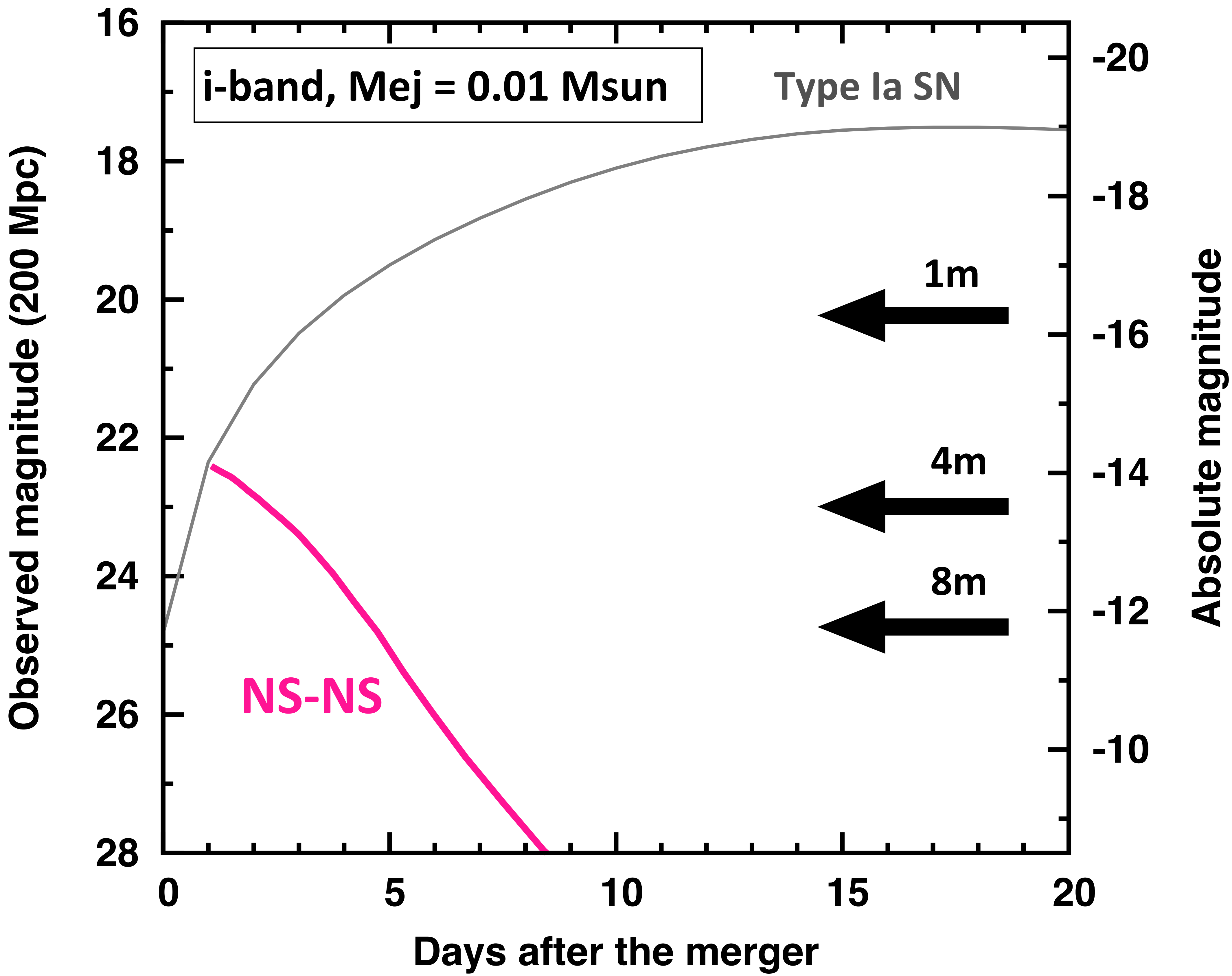
MT & Hotokezaka 13
MT 16

Spectrum



Red spectrum (peak at near-infrared)

Extremely broad-line (feature-less) spectra


i-band, Mej = 0.01 Msun
Type Ia SN
NS-NS
1m
4m
8m
Observed magnitude (200 Mpc)
Absolute magnitude
Days after the merger
16
18
20
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28
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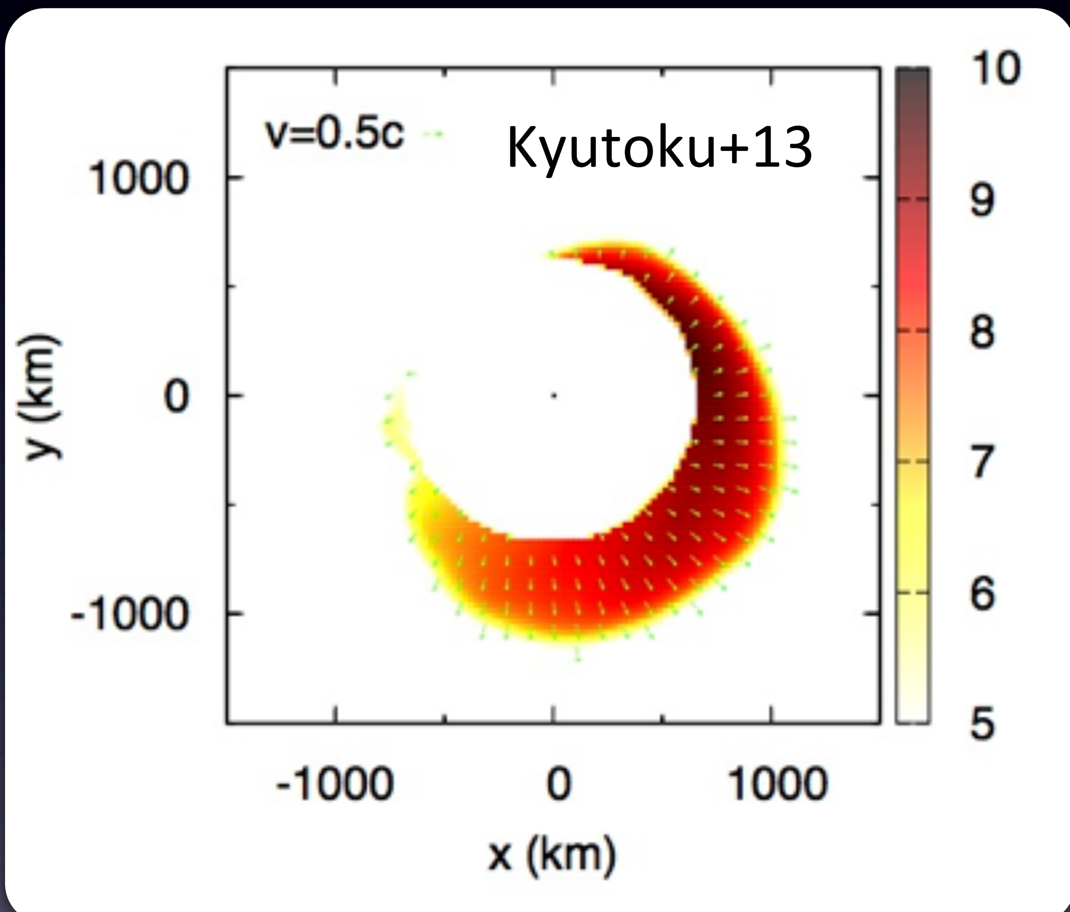
15
20

MT 2016

BH-NS Mergers

see e.g., Shibata & Taniguchi 06, Duez+08, Kyutoku+10,11
Deaton+13, Foucart+14

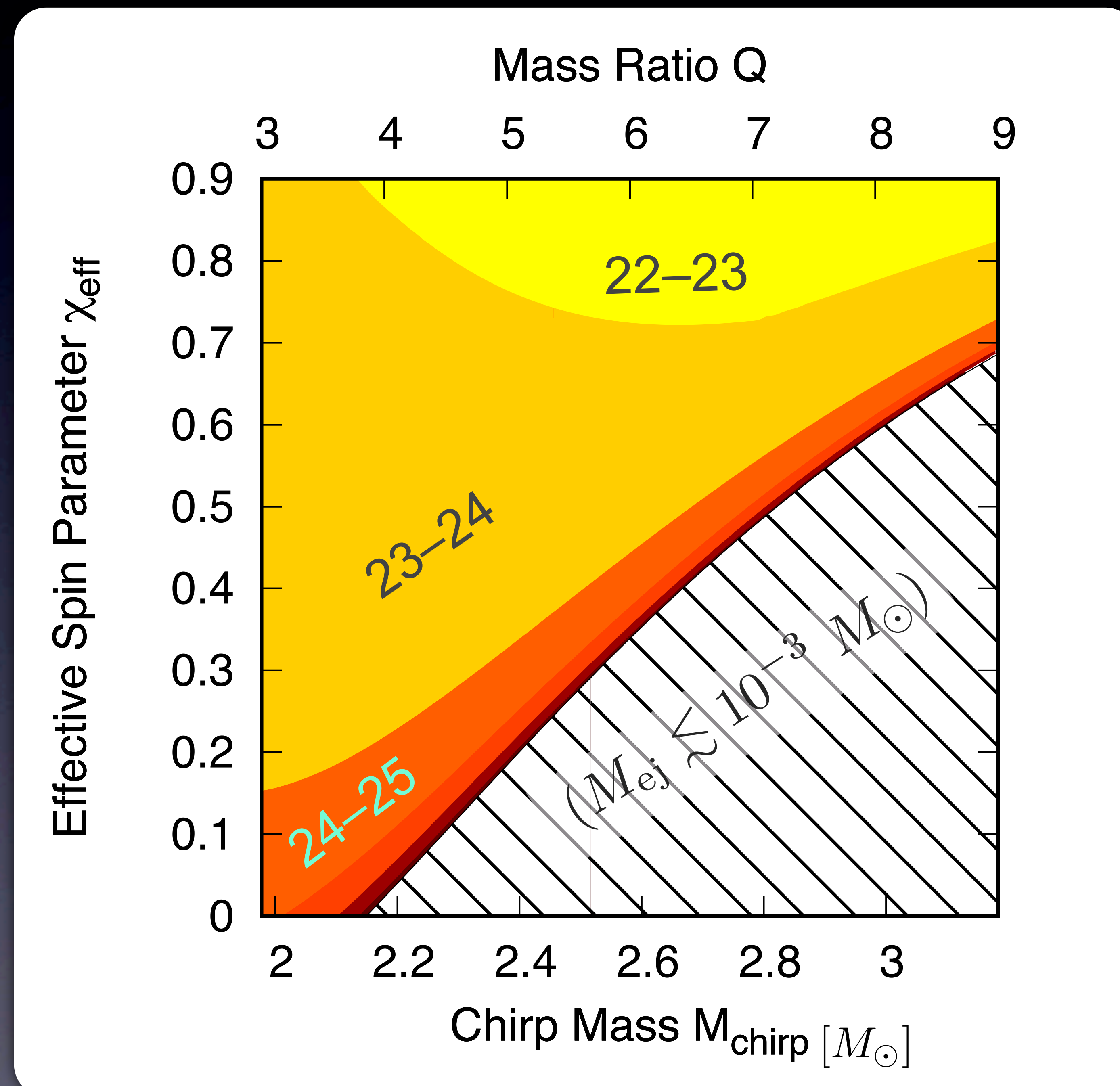
N(<800 Mpc)
~ 10 (0.2-300) / yr



Emission can be bluer (higher T) MT+14

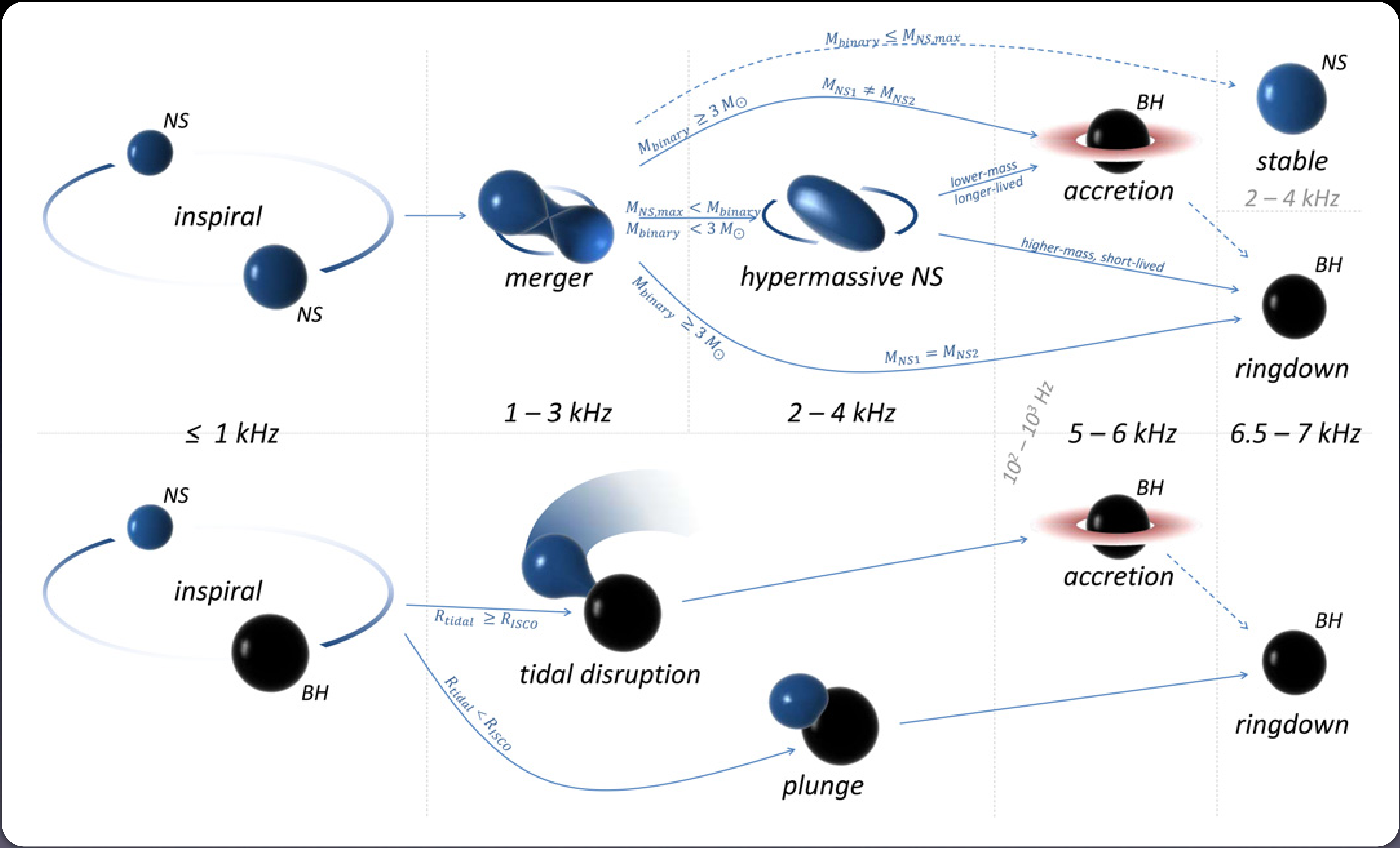
higher spin

more massive BH



Kawaguchi+16 Poster I-10

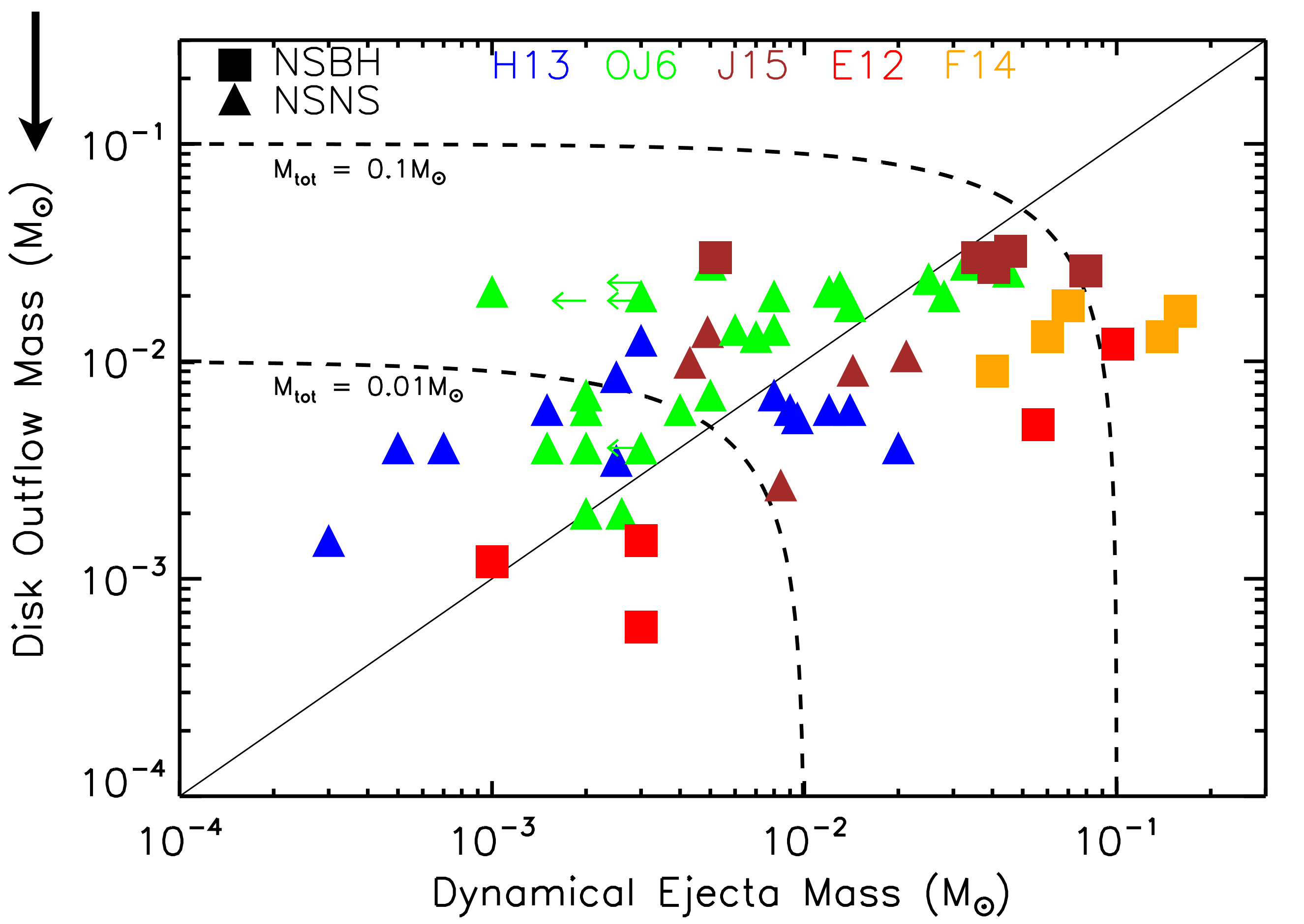
Formation of the disk around hypermassive NS/BH



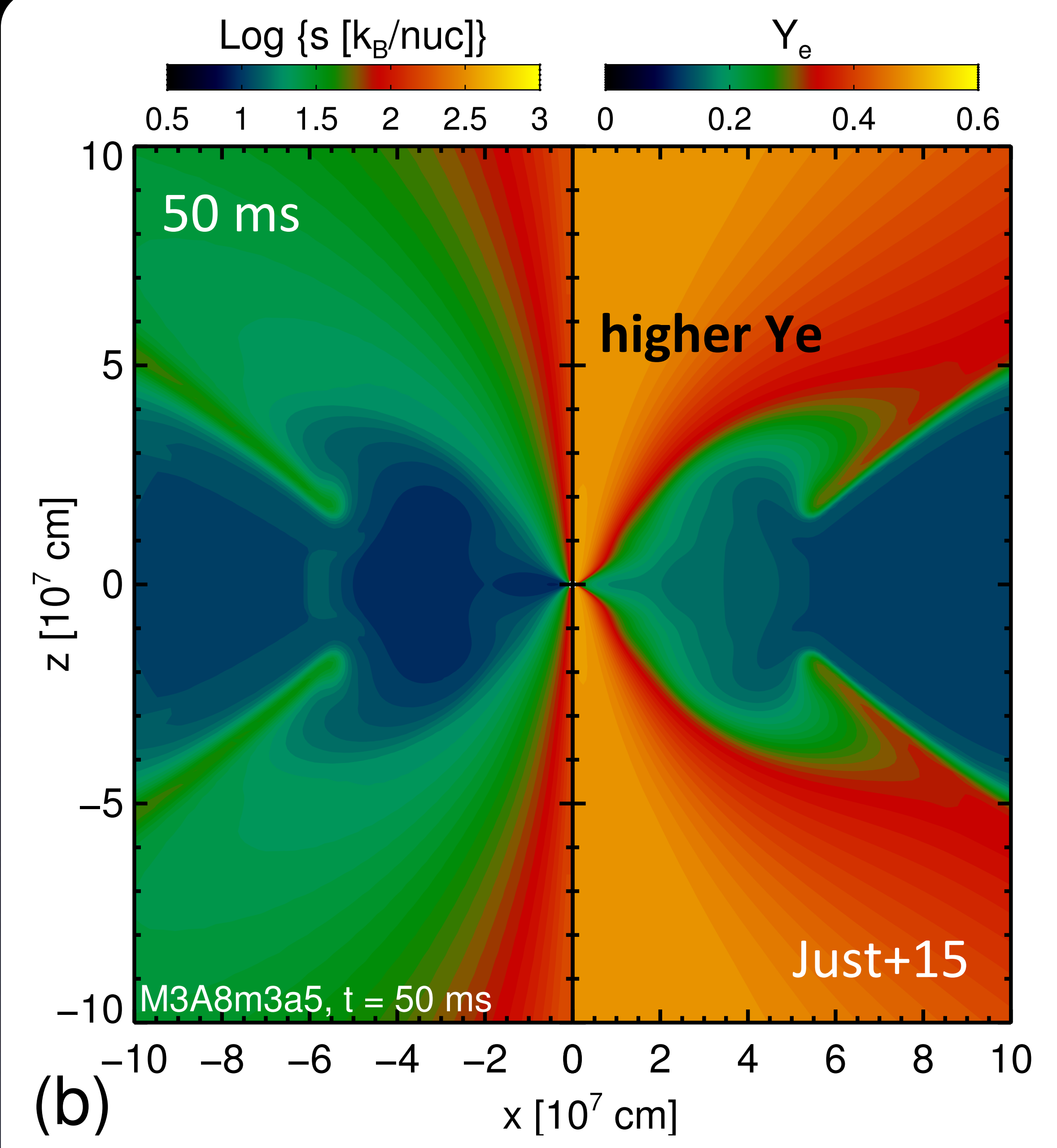
Bartos et al. 2012

Mass ejection from the disk

10% of disk mass



Wu+16



Disk wind ~ Dynamical ejecta

(Fernandez+13, Just+15, Kiuchi+14,15)

Poster I-7 by Sho Fujibayashi

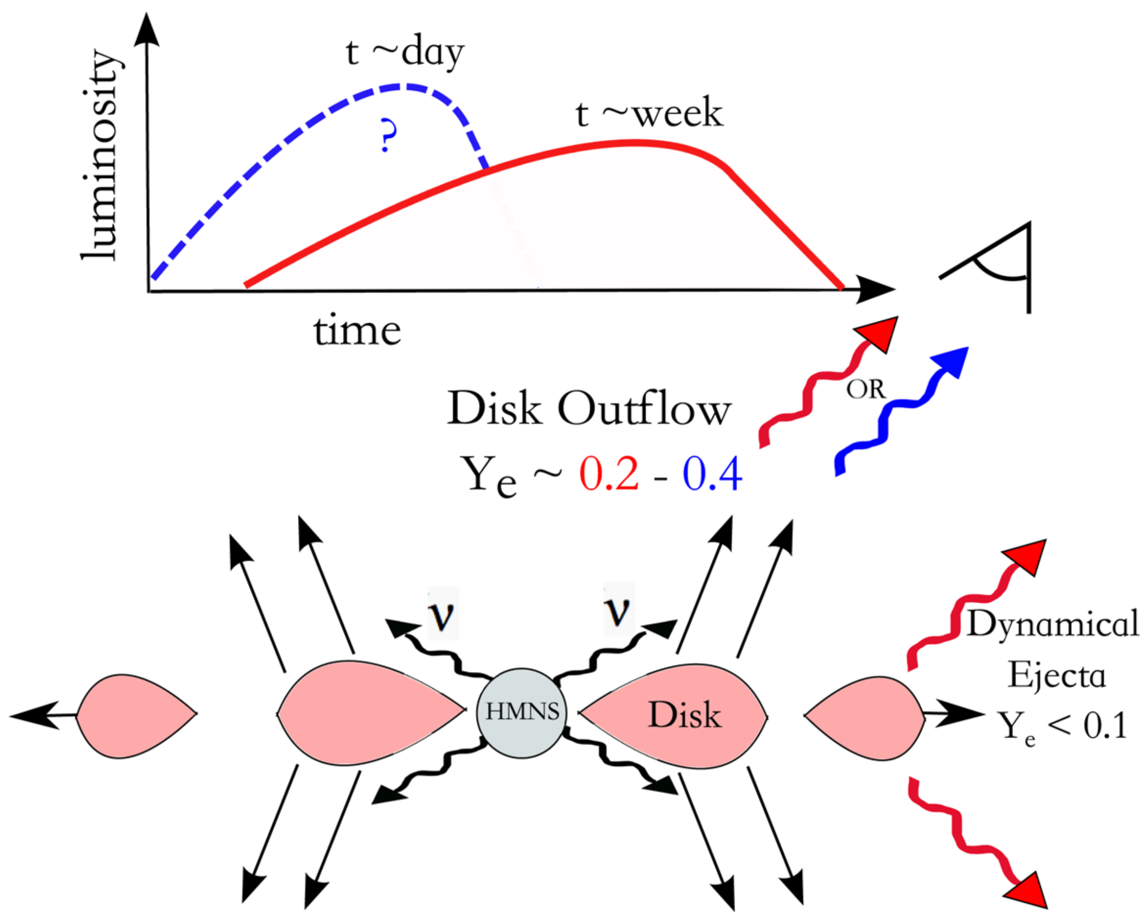
Higher Ye

=> Synthesis of lighter elements

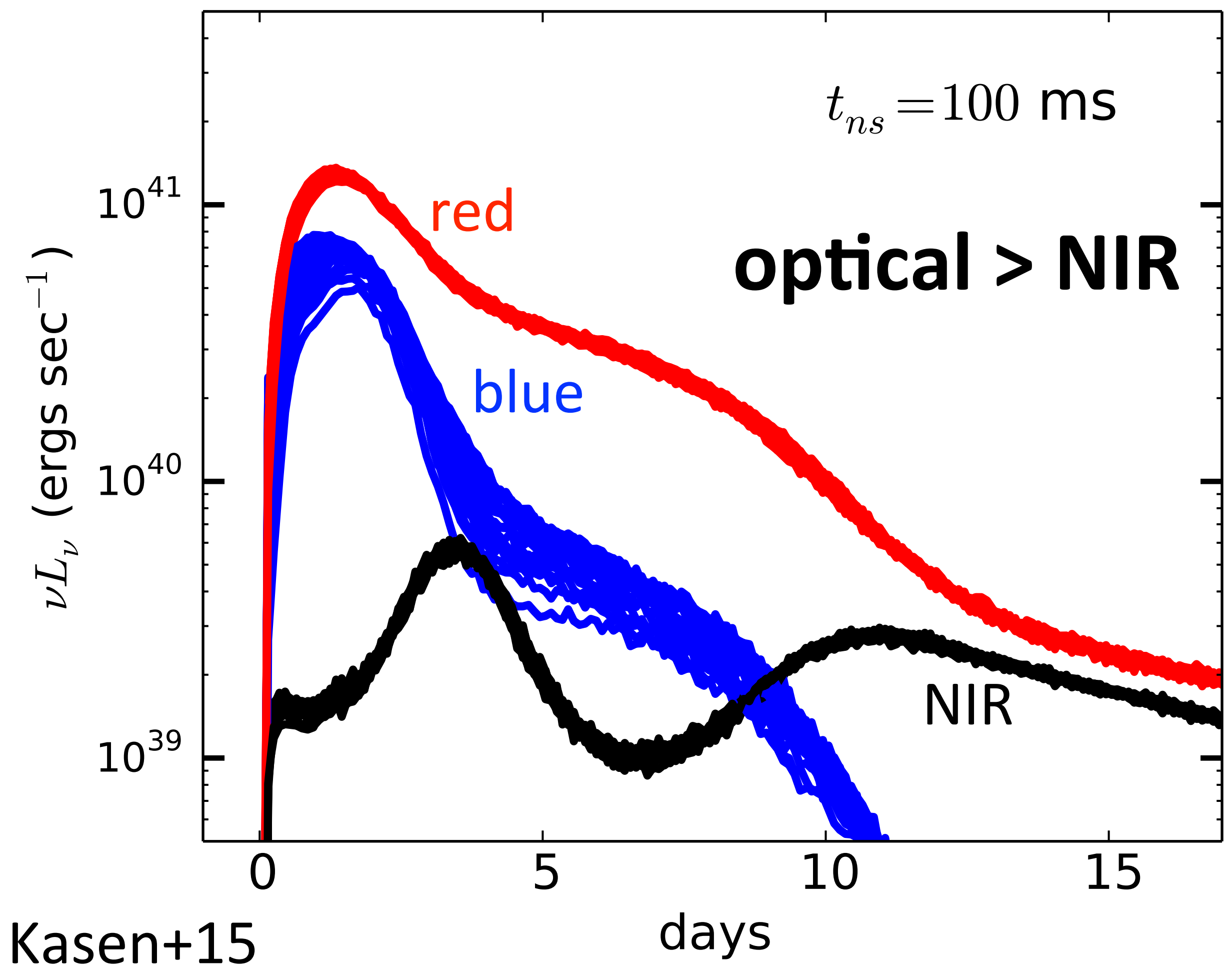
(Fernandez+13, Metzger+ 2014, Just+15, Fernandez & Metzger 16, Wu+16)

“Blue kilonova”

Higher Ye => Lower opacity (if Lanthanide free)
=> Brighter emission at earlier epochs



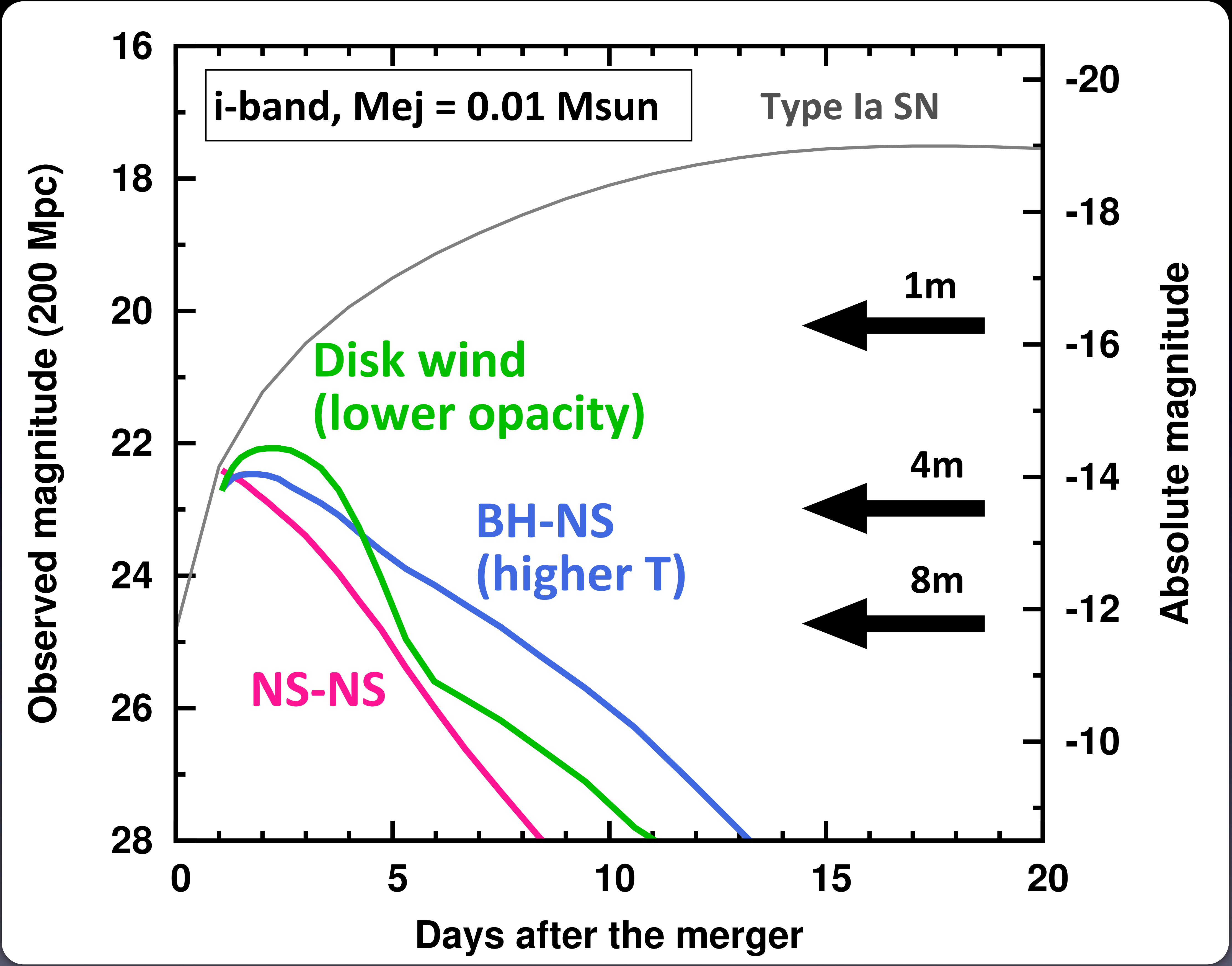
Metzger & Fernandez 14



Kasen+15

Emission properties depend on
- lifetime of hypermassive neutron star (<= EOS)
- presence of preceding ejecta (Lanthanide rich)

(Metzger & Fernandez 14, Kasen+15, Fernandez & Metzger 16)



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Type Ia SN
Disk wind
(lower opacity)
BH-NS
(higher T)
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1m
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MT 2016

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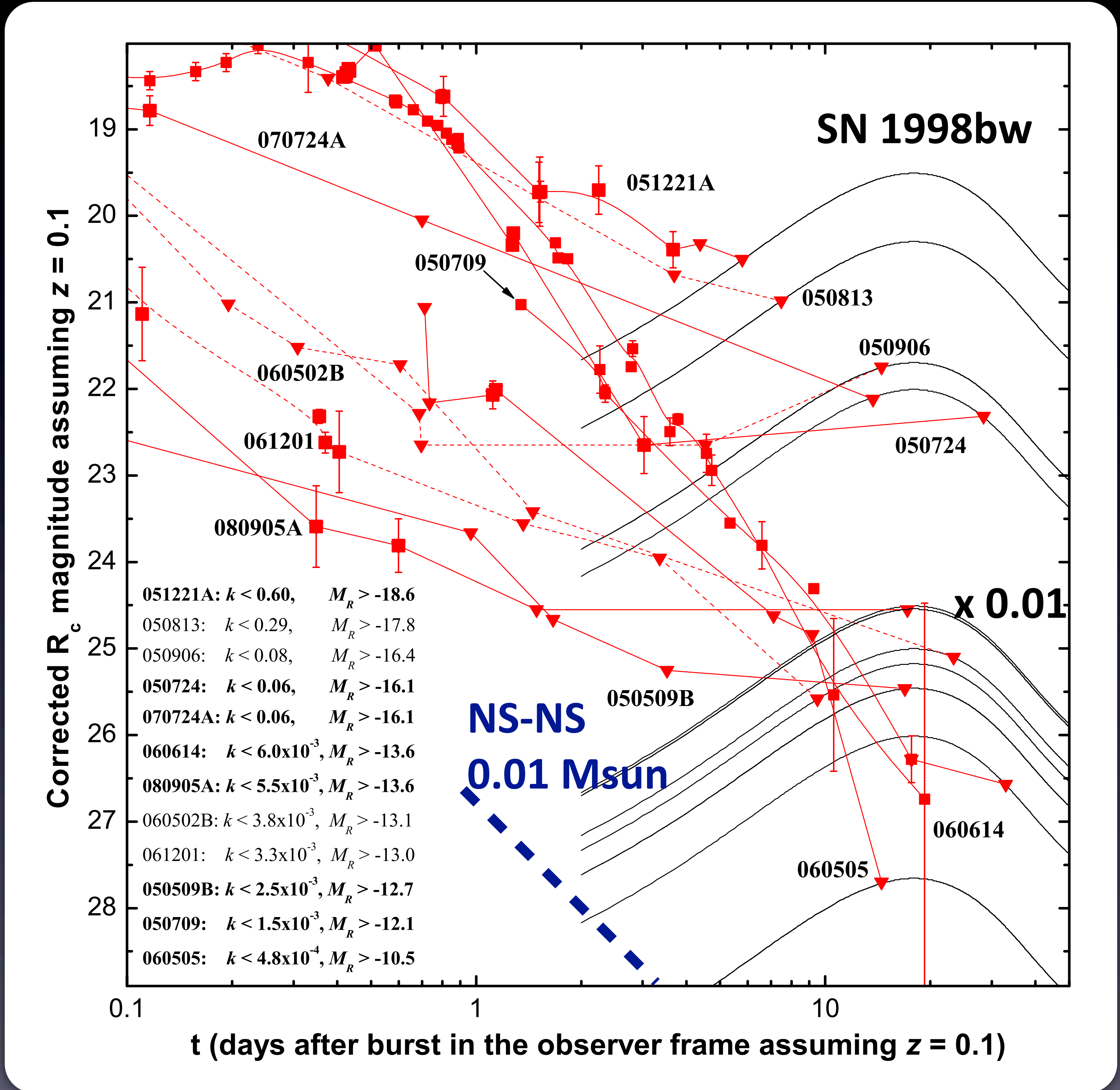
Test with short GRBs

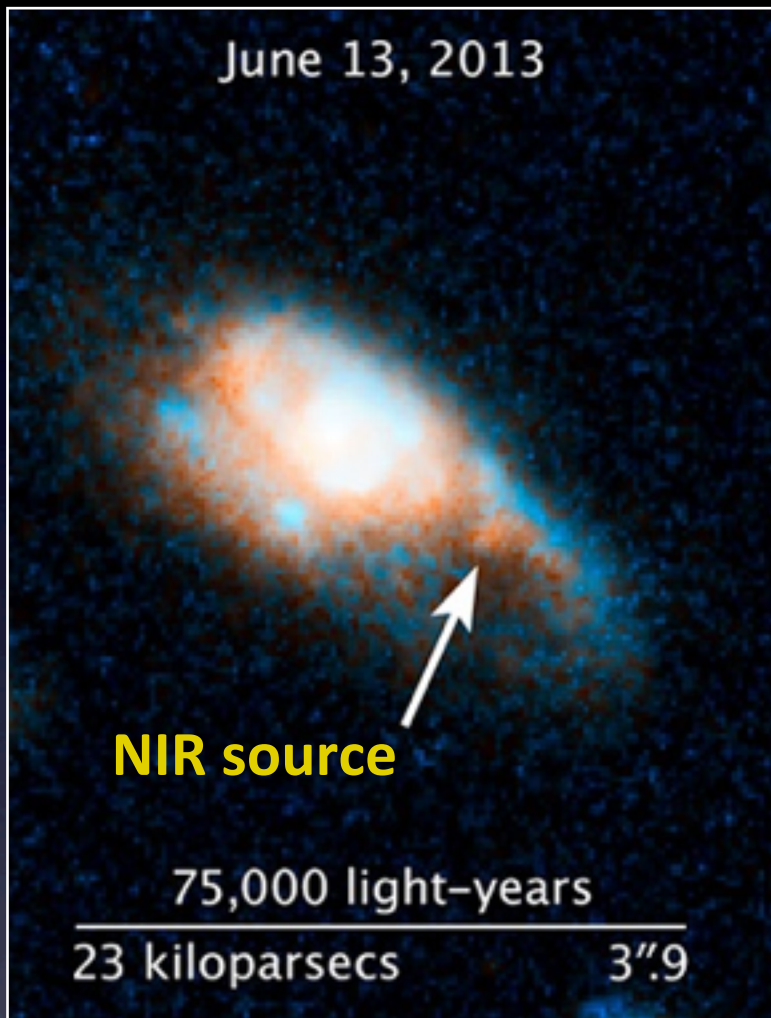
(C) ESO



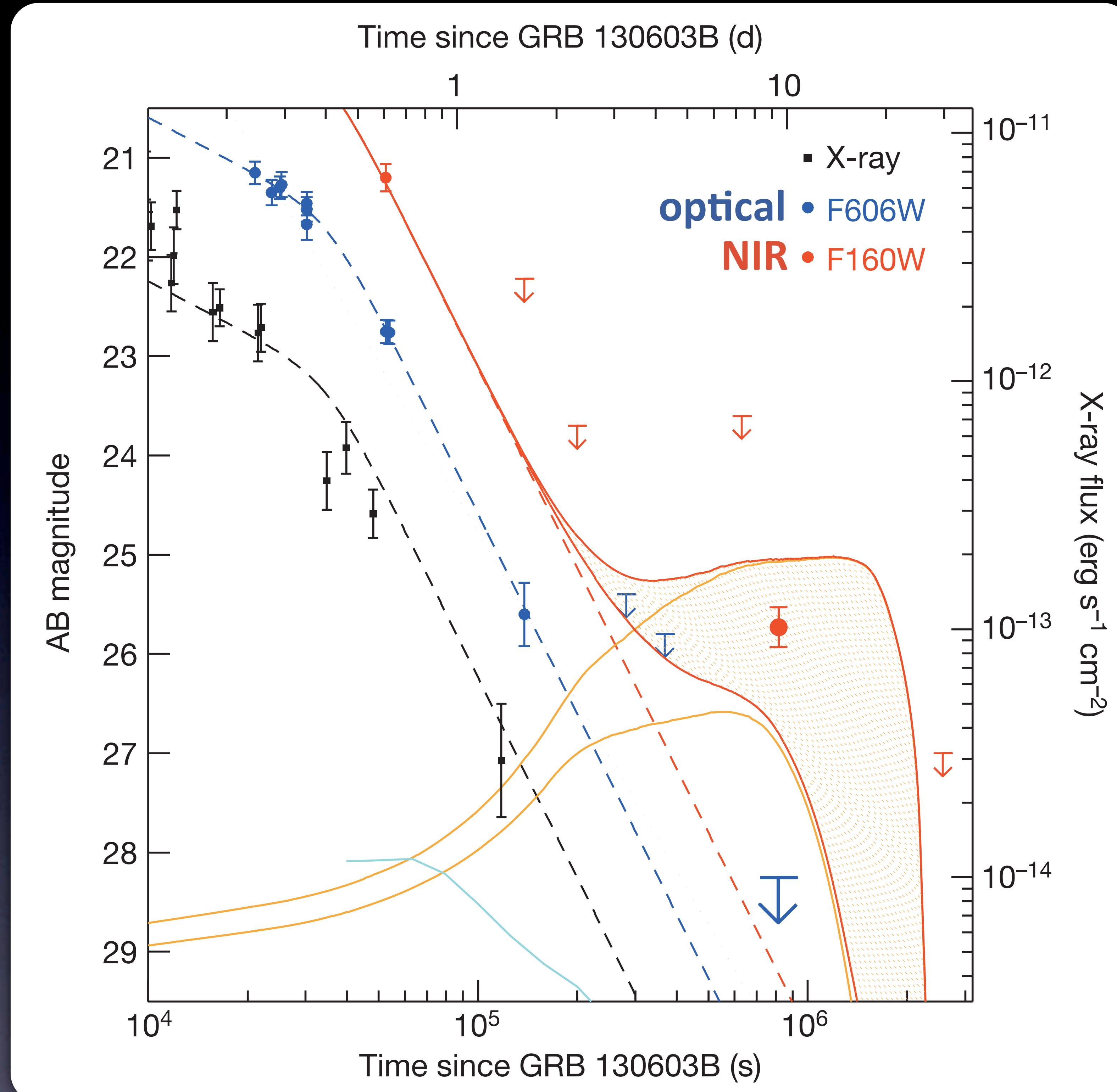
Kann+11

GRB 130603B

z=0.356



Tanvir+13, Berger+13

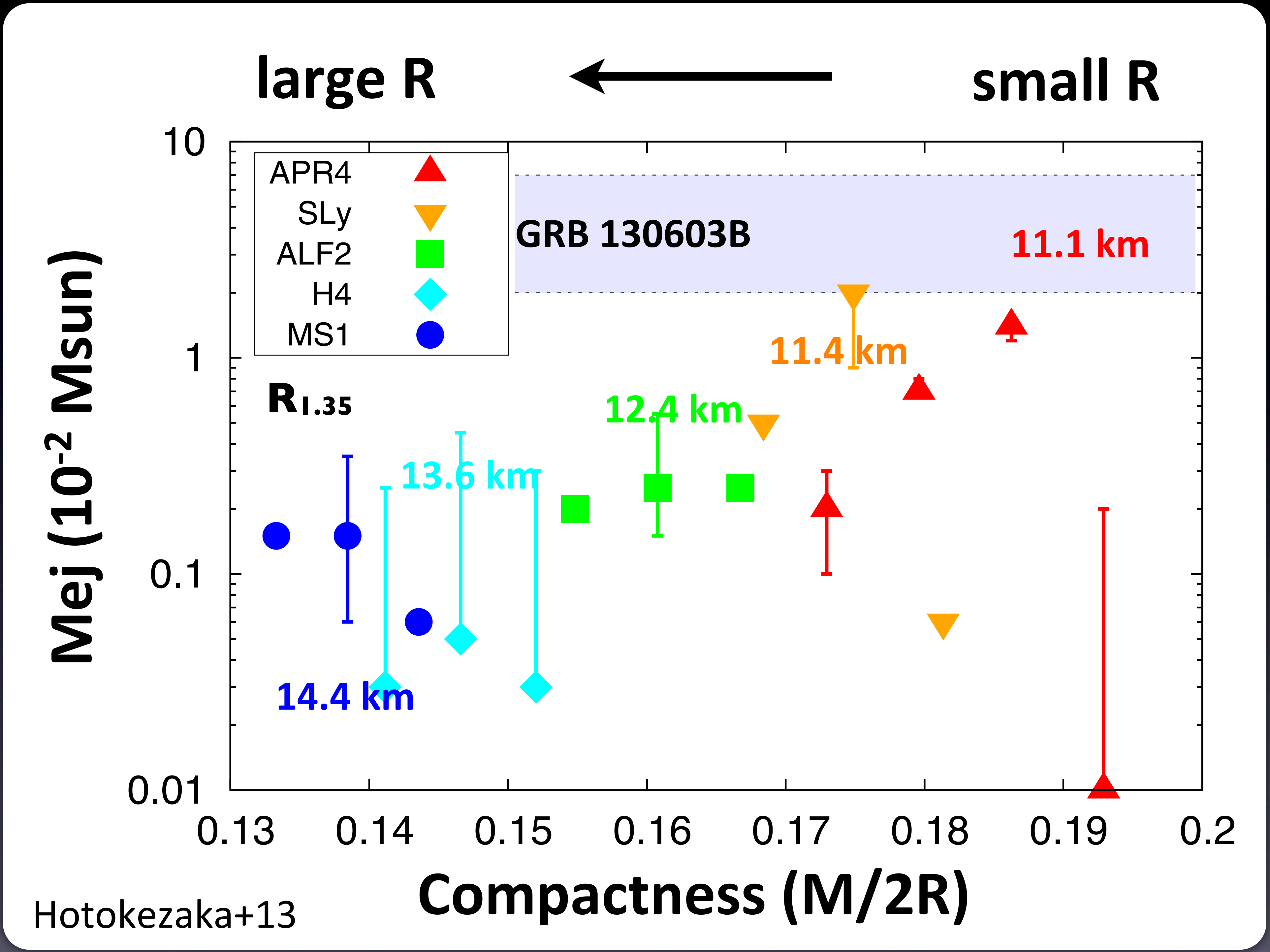


Very red source (R-H > 2.5 mag)

consistent with theoretical models

(mass ejection of ~0.02-0.06 Msun)

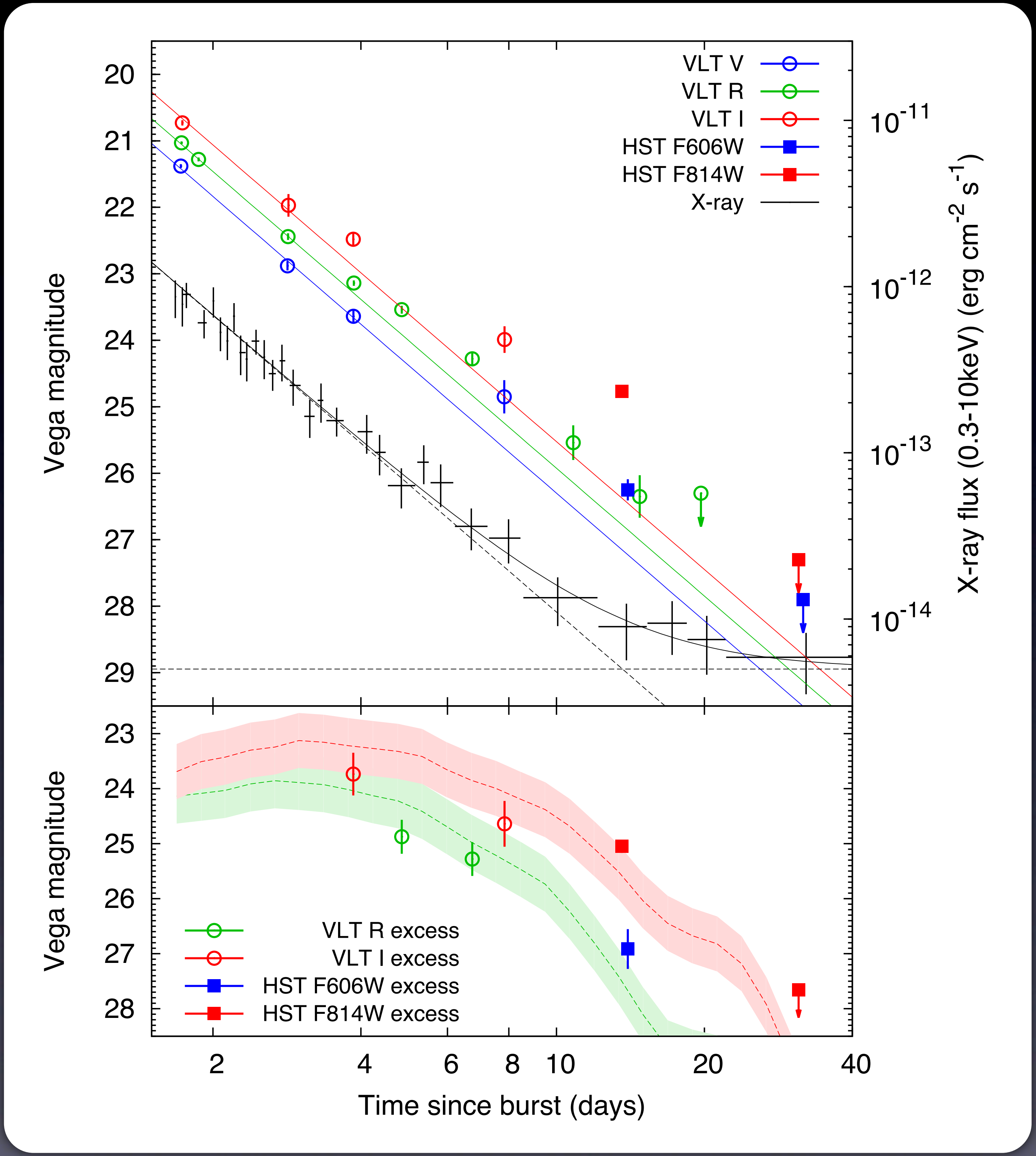
Possible probe of NS radius (EOS)



soft EOS
(smaller NS radius)
=> stronger shock
=> brighter emission

*NOTE: contribution from disk wind is NOT taken into account

GRB 060614 Yang+15, Jin+15 z=0.125



Mej ~0.1 Msun

- **Disk wind?**
- **BH-NS?**
- **Different mechanism associated X-ray emission??**

(Kisaka+15a,15b)

GRB160821b @ z = 0.16!!

see also Jin+16 for possible excess in GRB 050709 z=0.16

Constraints from short GRBs

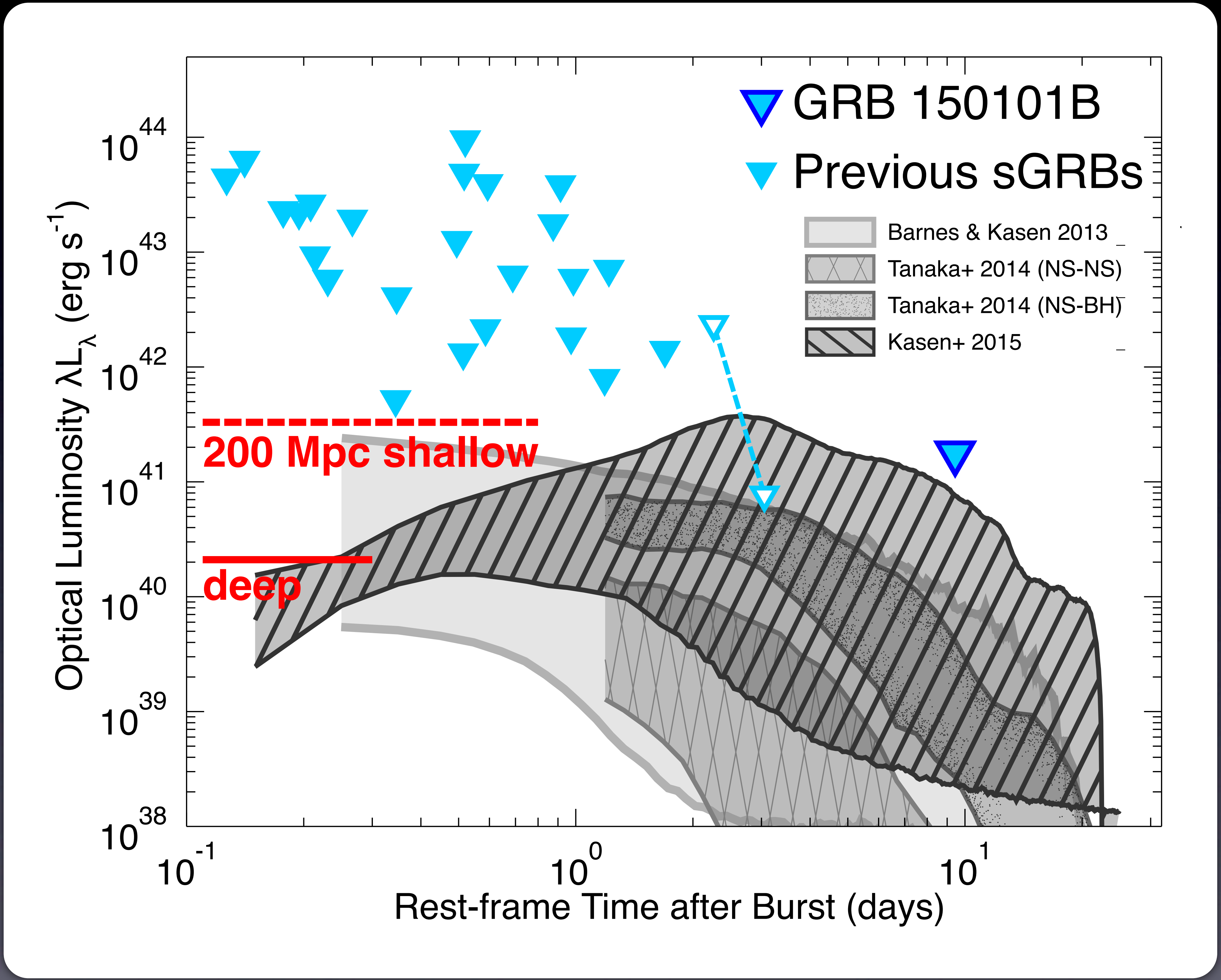
@ 200 Mpc

21 mag

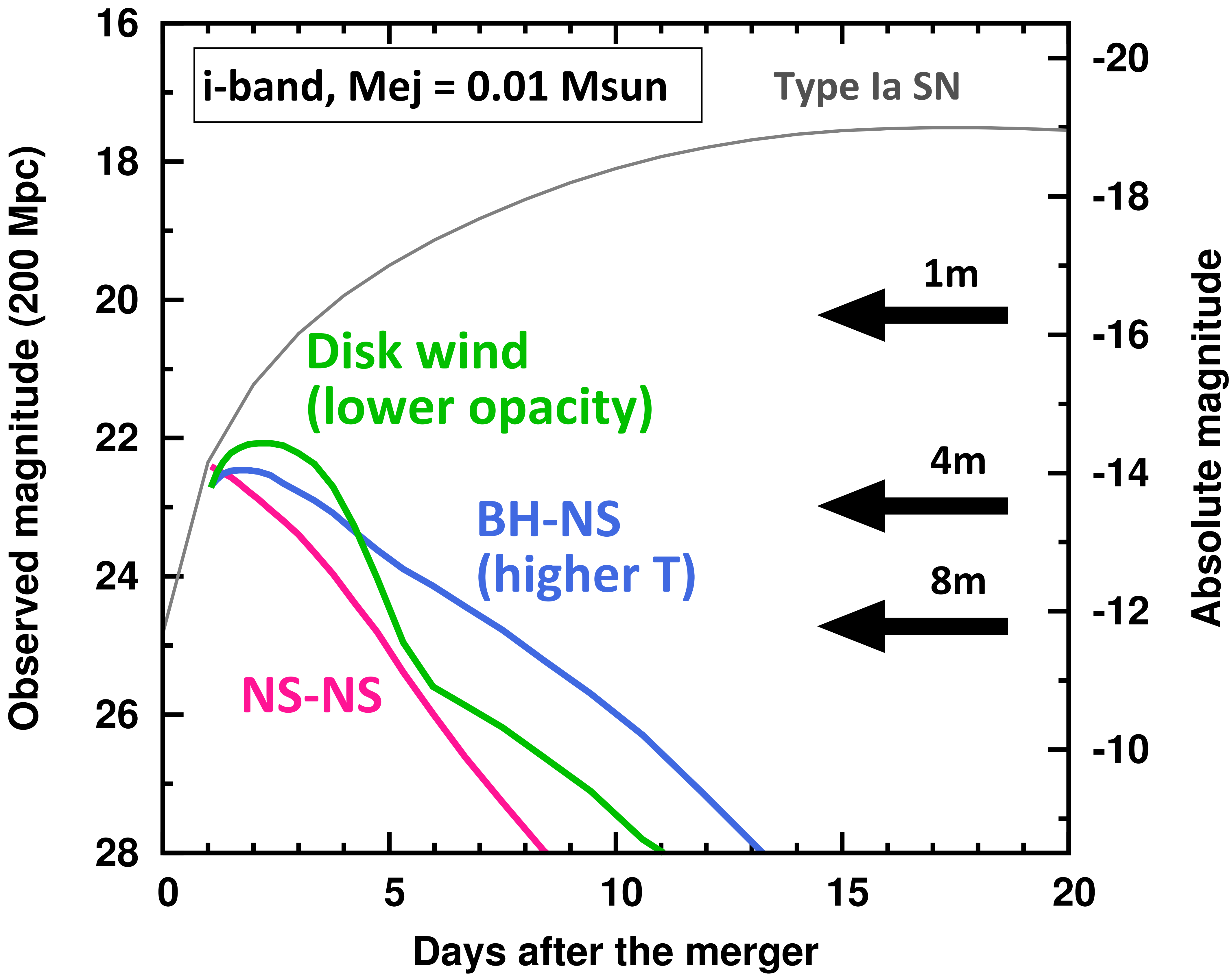
1m telescopes

24 mag

>4m telescopes



Fong+16



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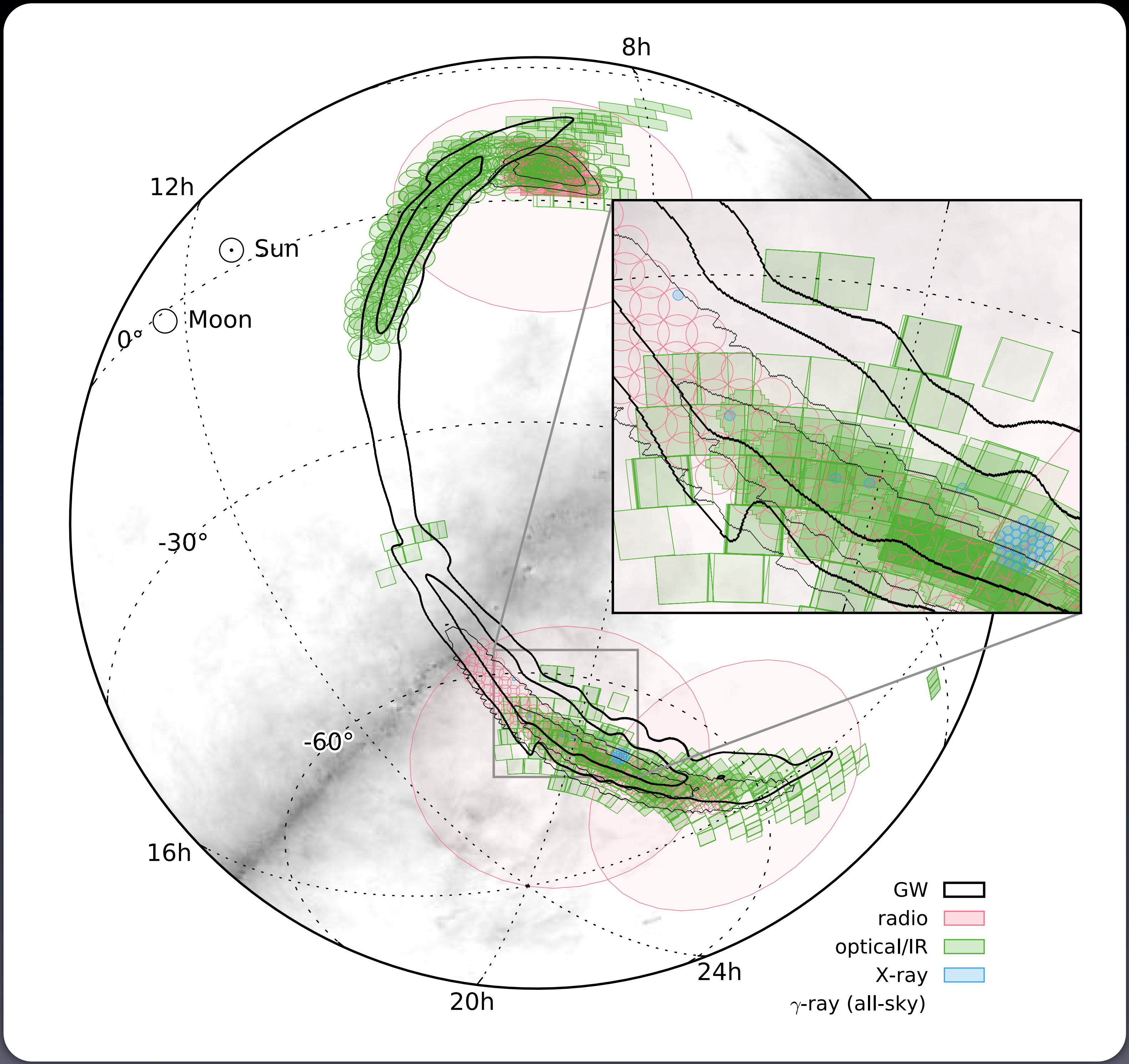
MT 2016

GW150914: EM follow-up

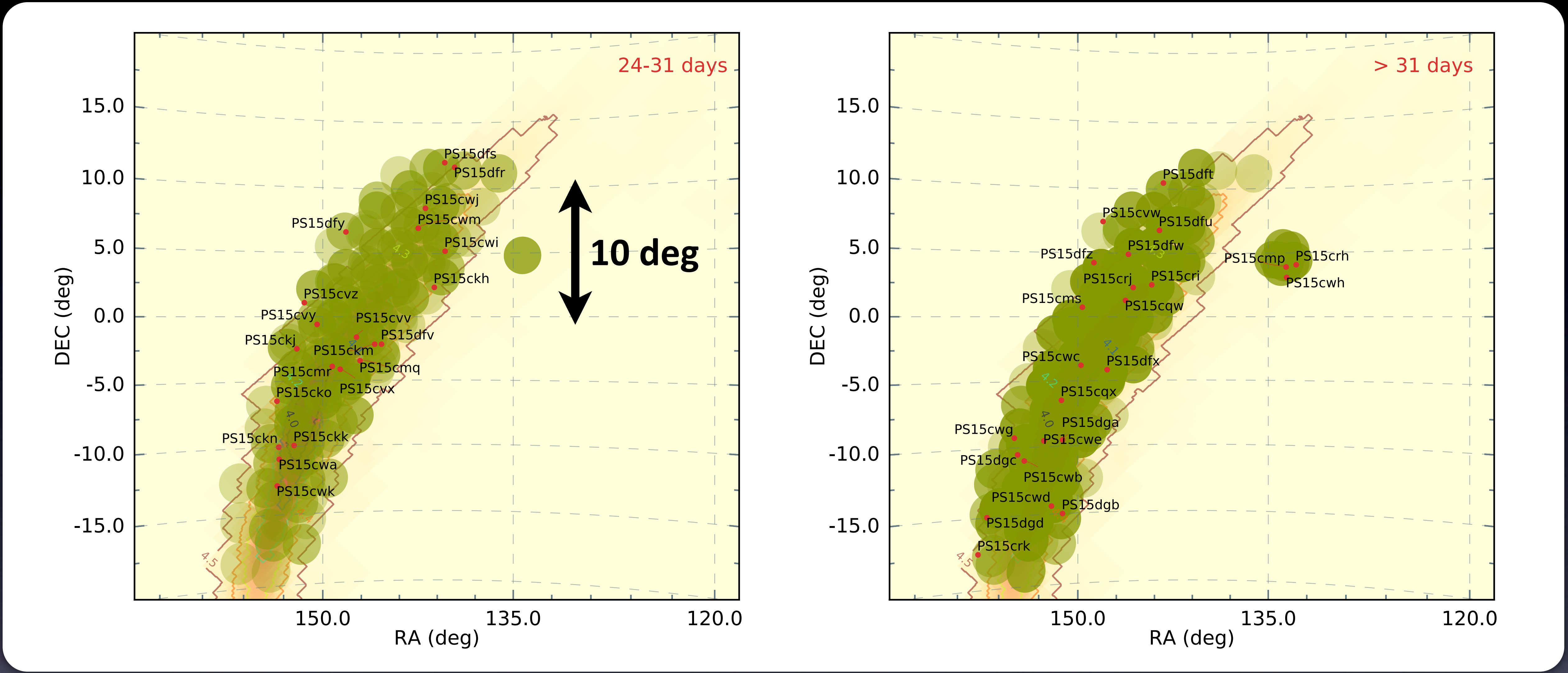
LVC and EM follow-up groups, 2016, ApJ, 826, L13



see talks by Nissanke and Tominaga for more details

Lessons from EM follow-up

Pan-STARRS and PESSTO (i ~20 mag)



Smartt et al. 2016 (see also Kasliwal et al. 2016; Soares-Santos et al. 2016; Morokuma et al. 2016)

50 deg^2 survey w/ 25 mag depth → >~ 1000 supernovae and 1 GW source!

Efficient selection is essential

Selection of GW sources (from larger number of SNe)

0. Association w/ nearby galaxies

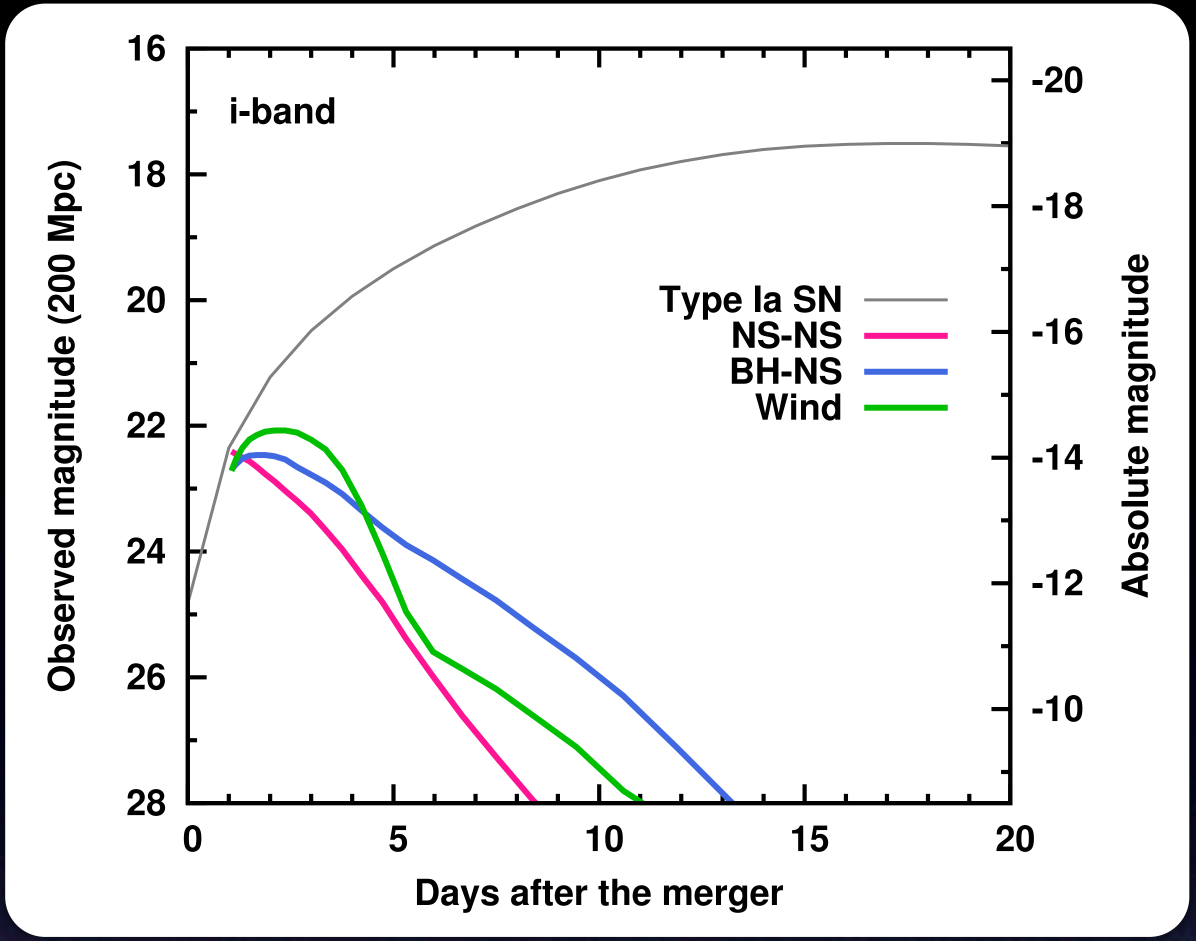
1. Short timescale <= lower mass

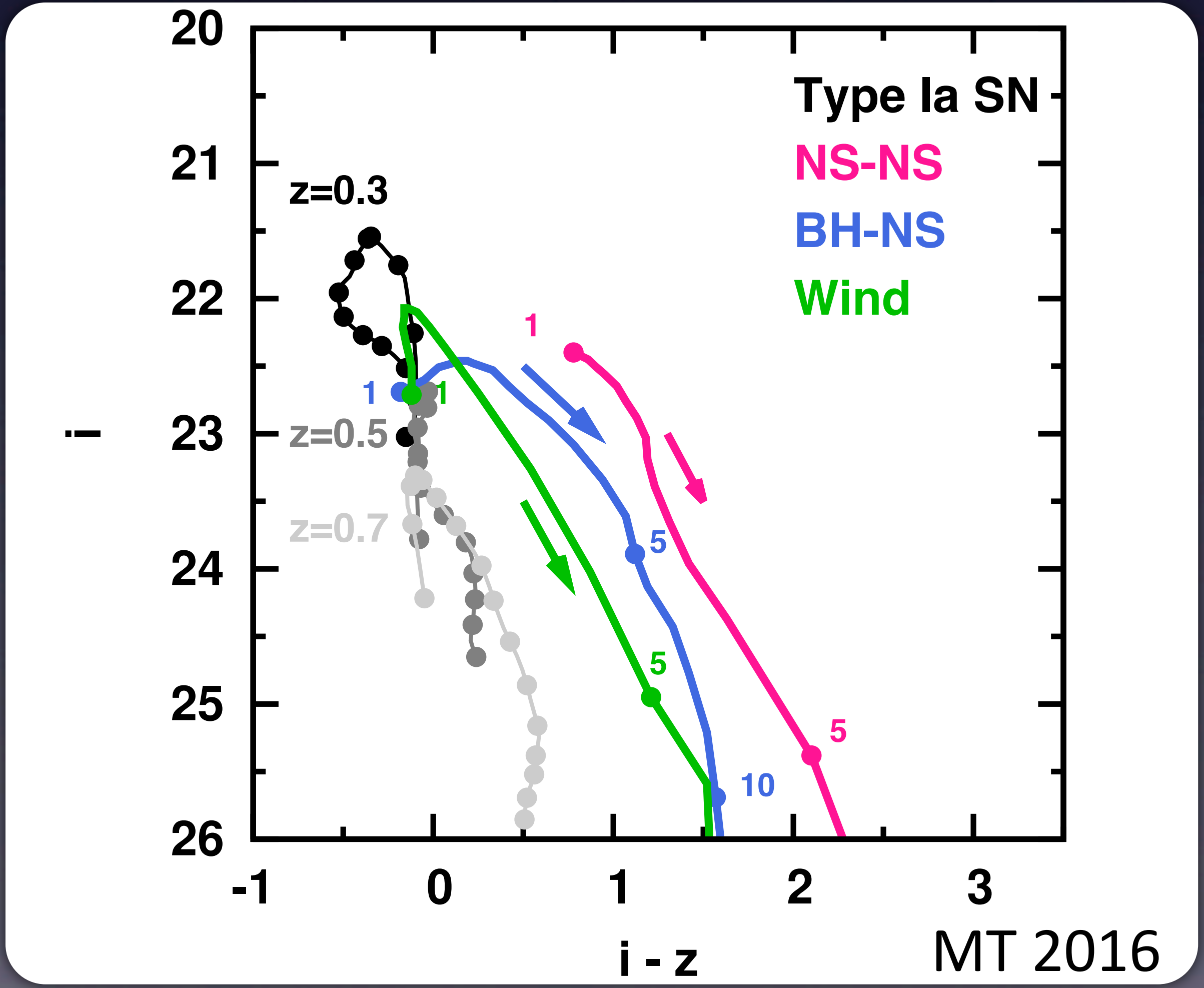
2. Faintness <= lower energy budget

3. Red colors <= higher opacity

Smoking gun

Extremely broad line spectrum <= higher velocity





Summary

- NS merger: possible origin of r-process elements
- Kilonova/macronova emission
  - Powered by radioactive decay of r-process nuclei
  - Short timescale, faint emission
  - Peaks at red optical or near infrared
  - Constrains from short GRBs: consistent with models
  - Uncertainty in disk wind (mass and composition)
- Prospects for GW-EM observations
  - Selection by timescale, faintness, and color
  - Smoking gun: the extremely broad-line spectra

GW+EM+Theory => Origin of r-process elements