Electromagnetic Counterparts of Gravitational Wave Sources

Masaomi Tanaka
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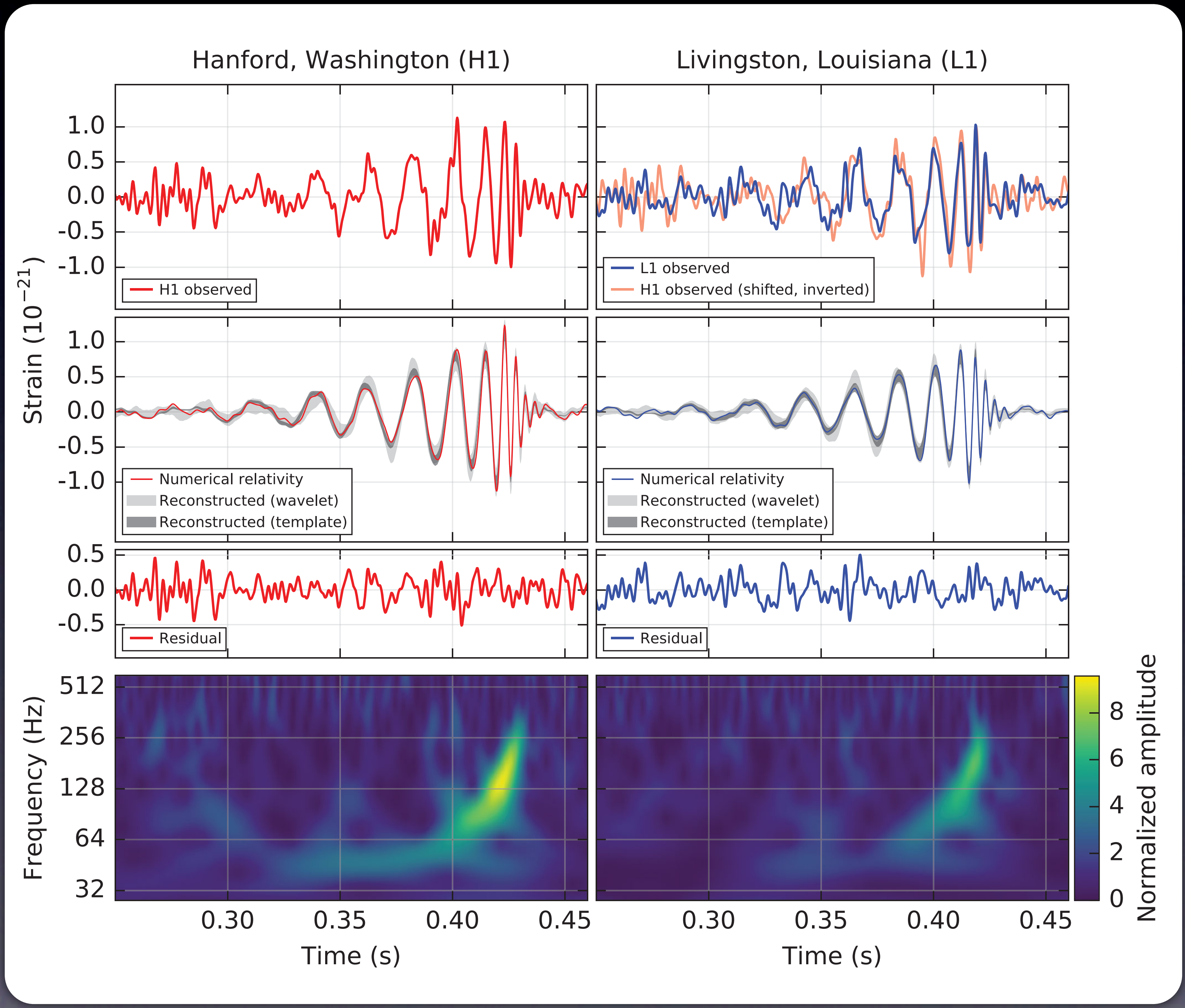
- Why electromagnetic emission
- Optical and IR emission - kilonova -
- Follow-up observations: GW150914 and future

Dawn of GW astronomy

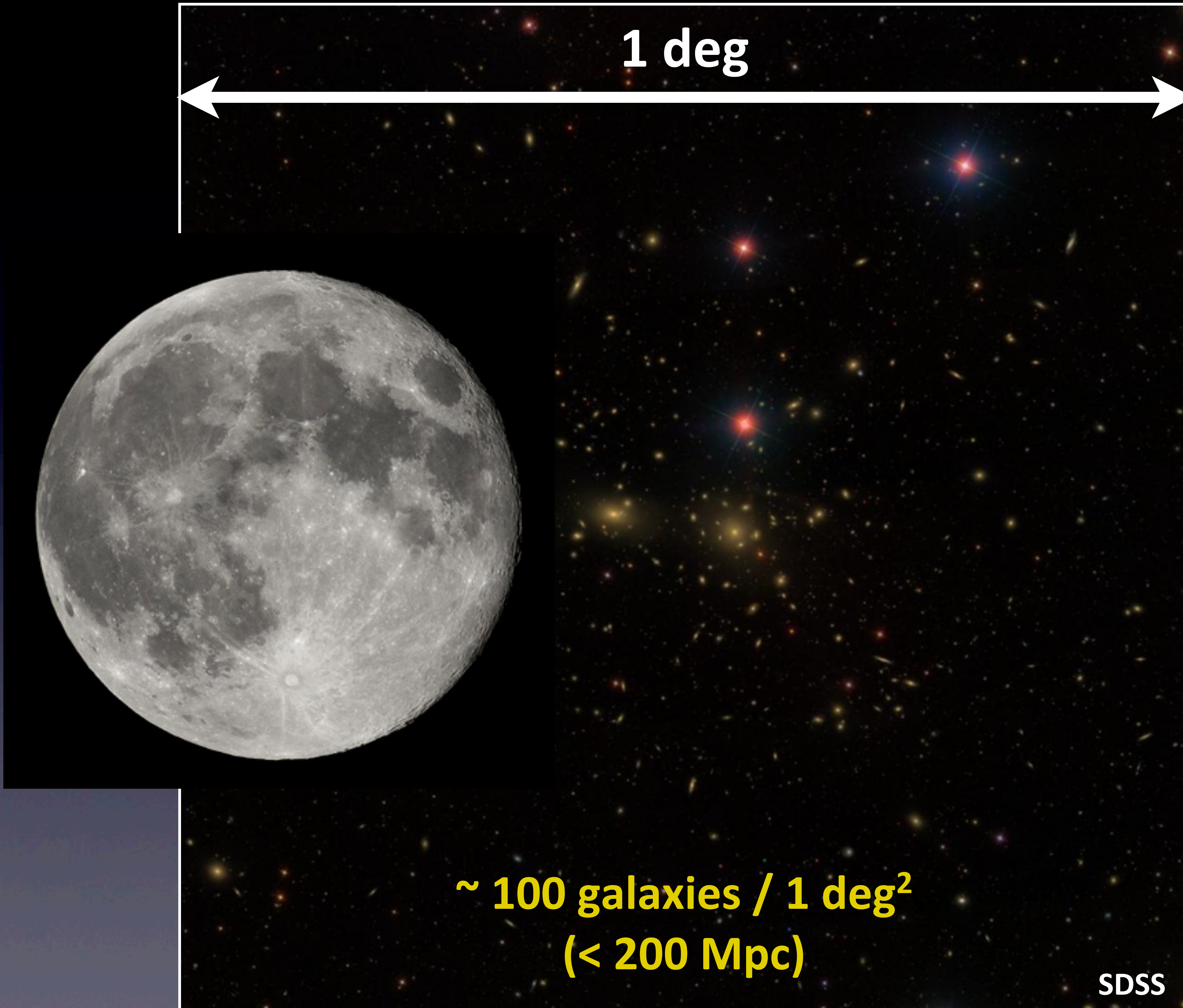


GW 150914
BH-BH merger
(~30 Msun) @ 400 Mpc

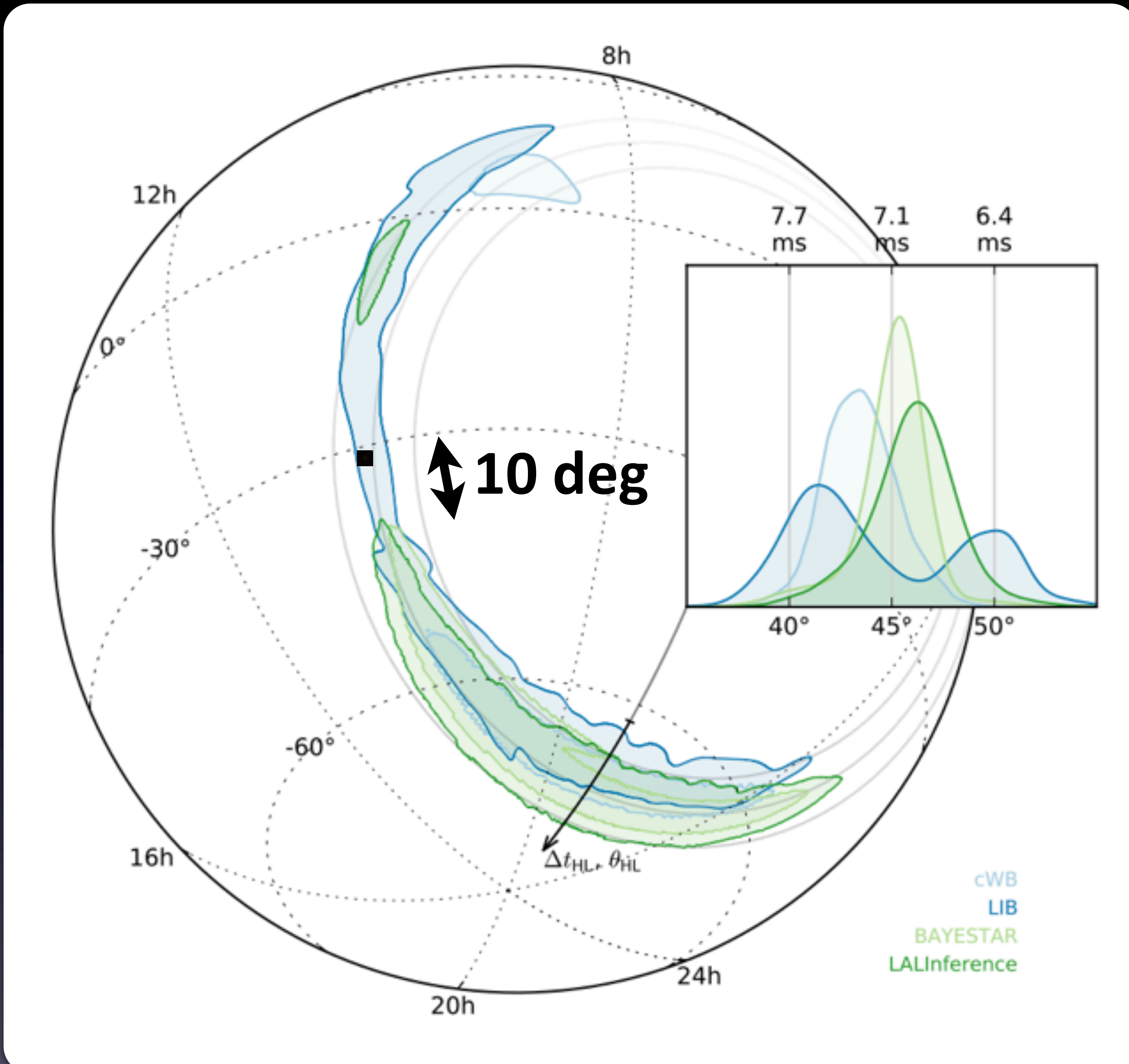
NS-NS merger (~< 200 Mpc)
or BH-NS merger (~< 800 Mpc)

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

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



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



Abbott et al. (including MT) 2016, submitted, arXiv:1602.08492

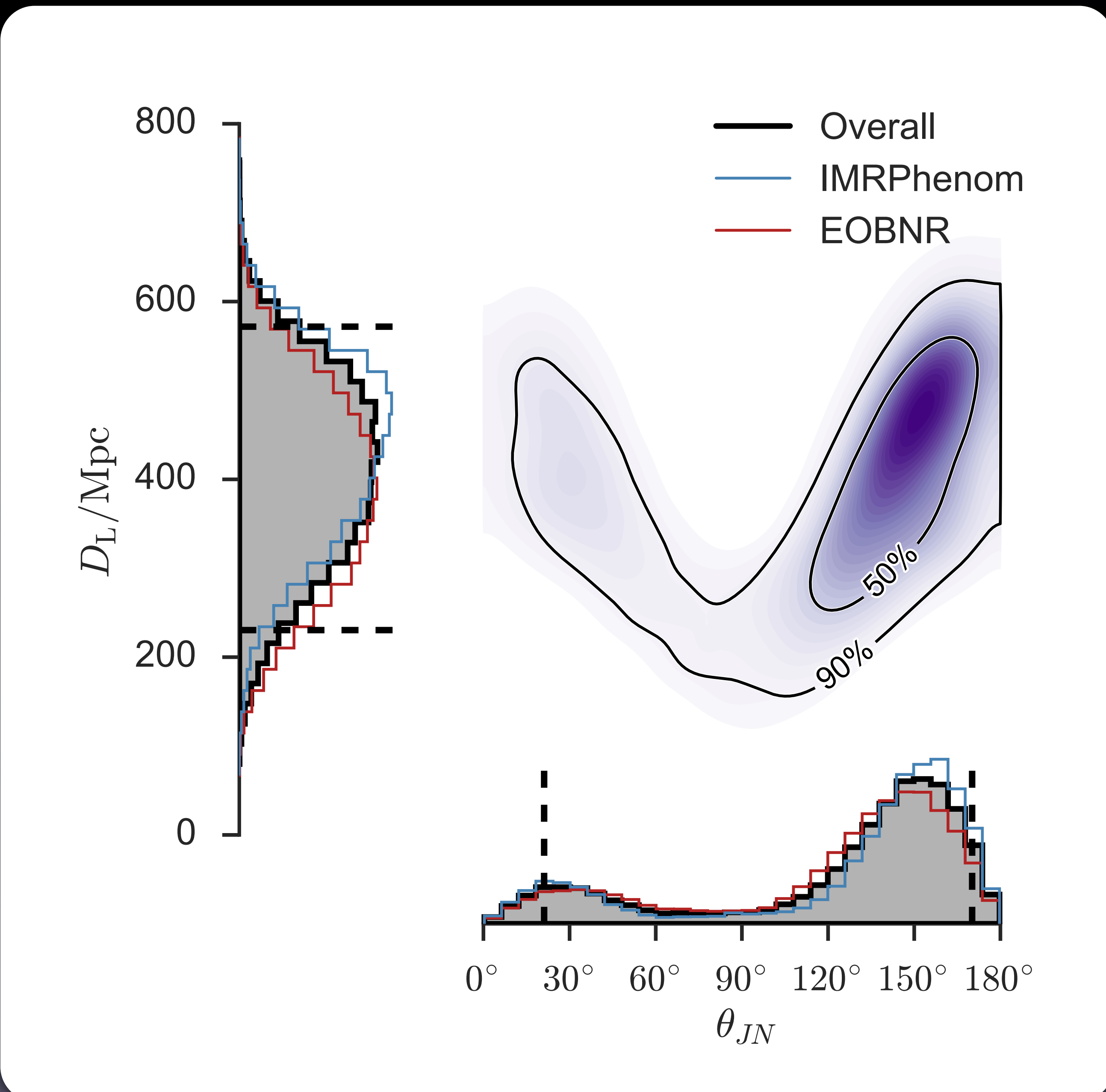
Localization ~ 600 deg^2!!
(~< 50 deg^2 with Advanced Virgo and KAGRA)

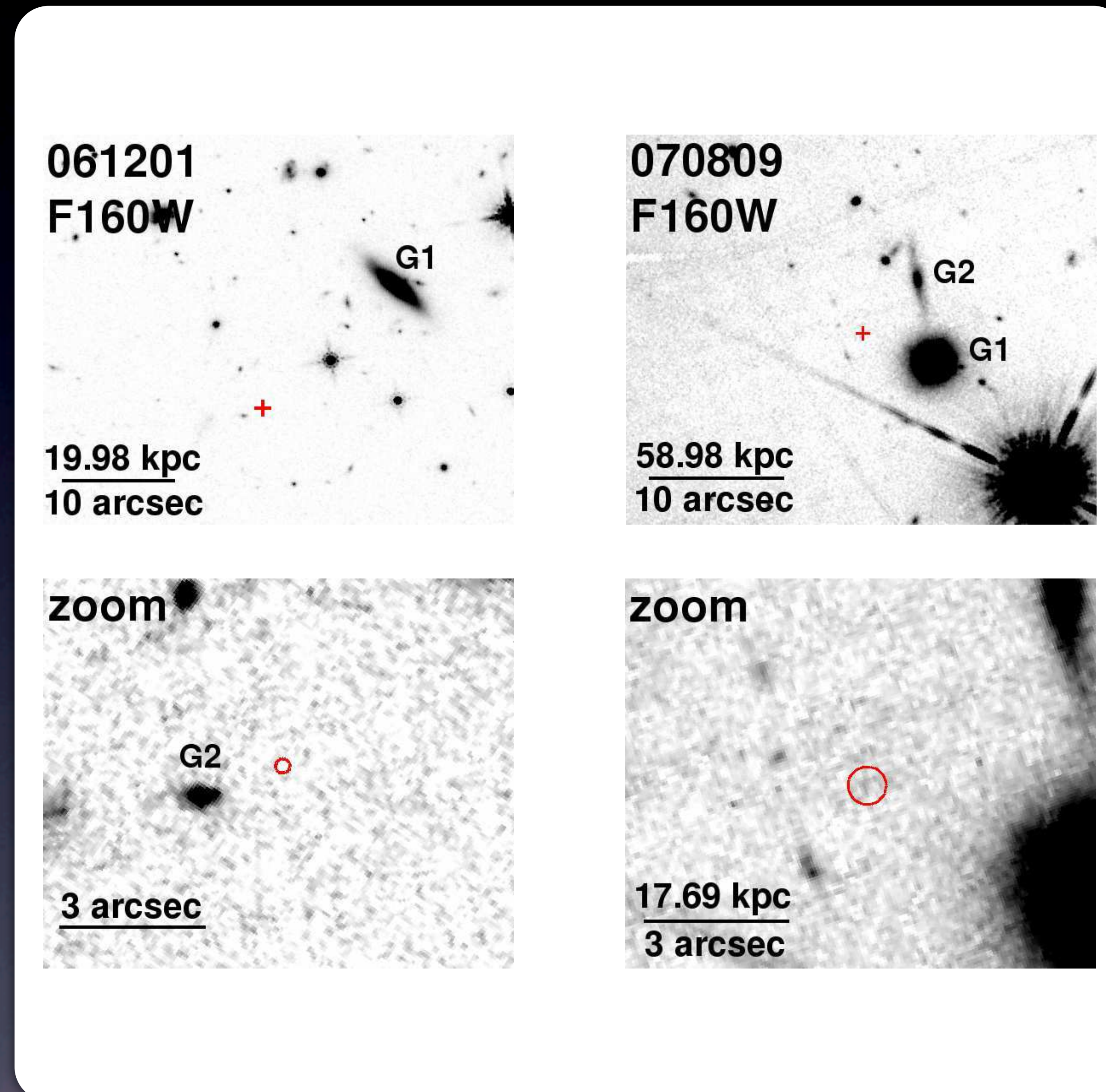
Detection of electromagnetic (EM) counterparts is essential

- **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)

Electromagnetic signature from NS merger

- On-axis short GRB

  strongly beamed ✗

  (isotropic soft X-ray?)

- Off-axis radio afterglow

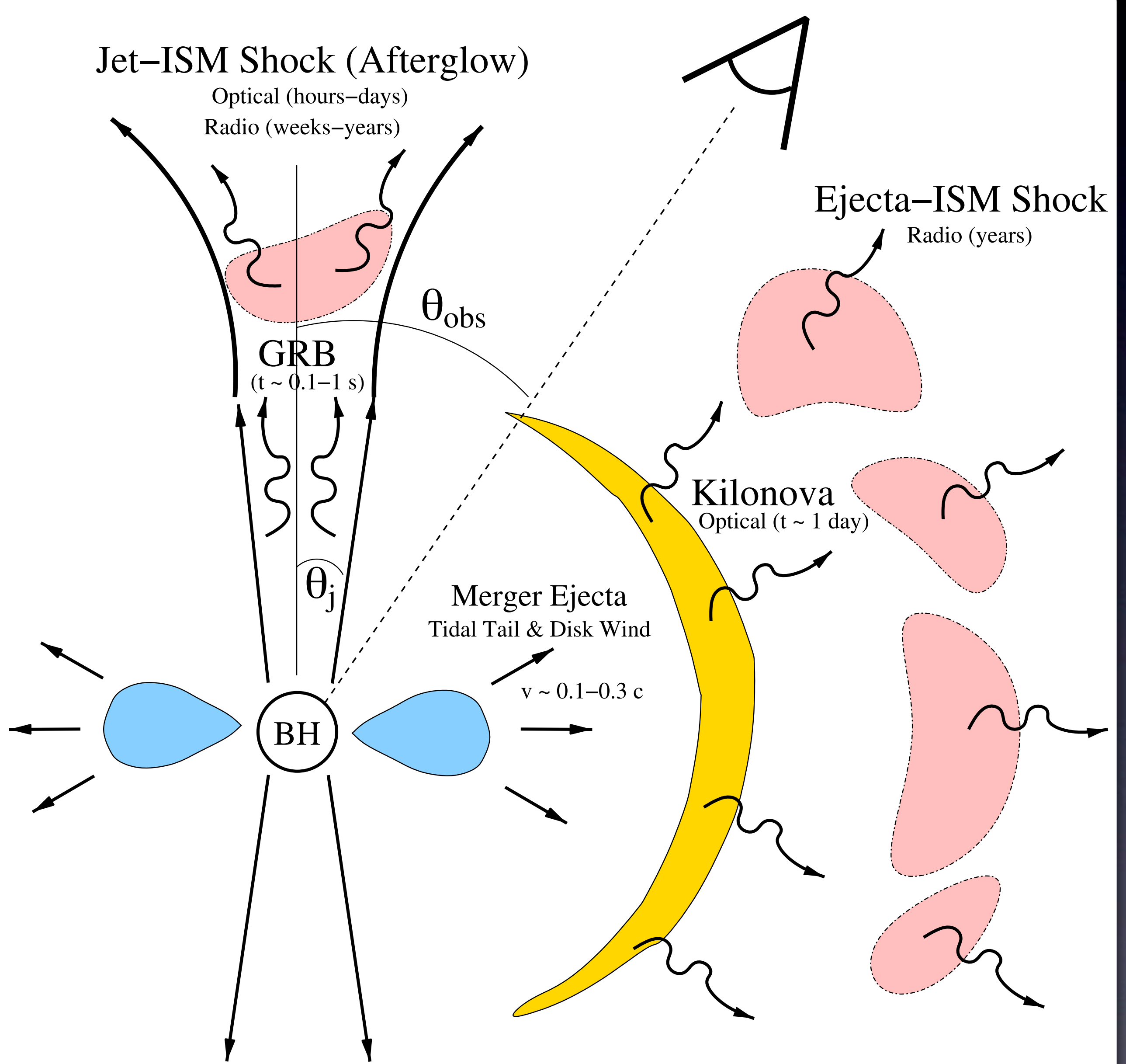
  isotropic ✓

  delayed by ~> 1 yr ✗

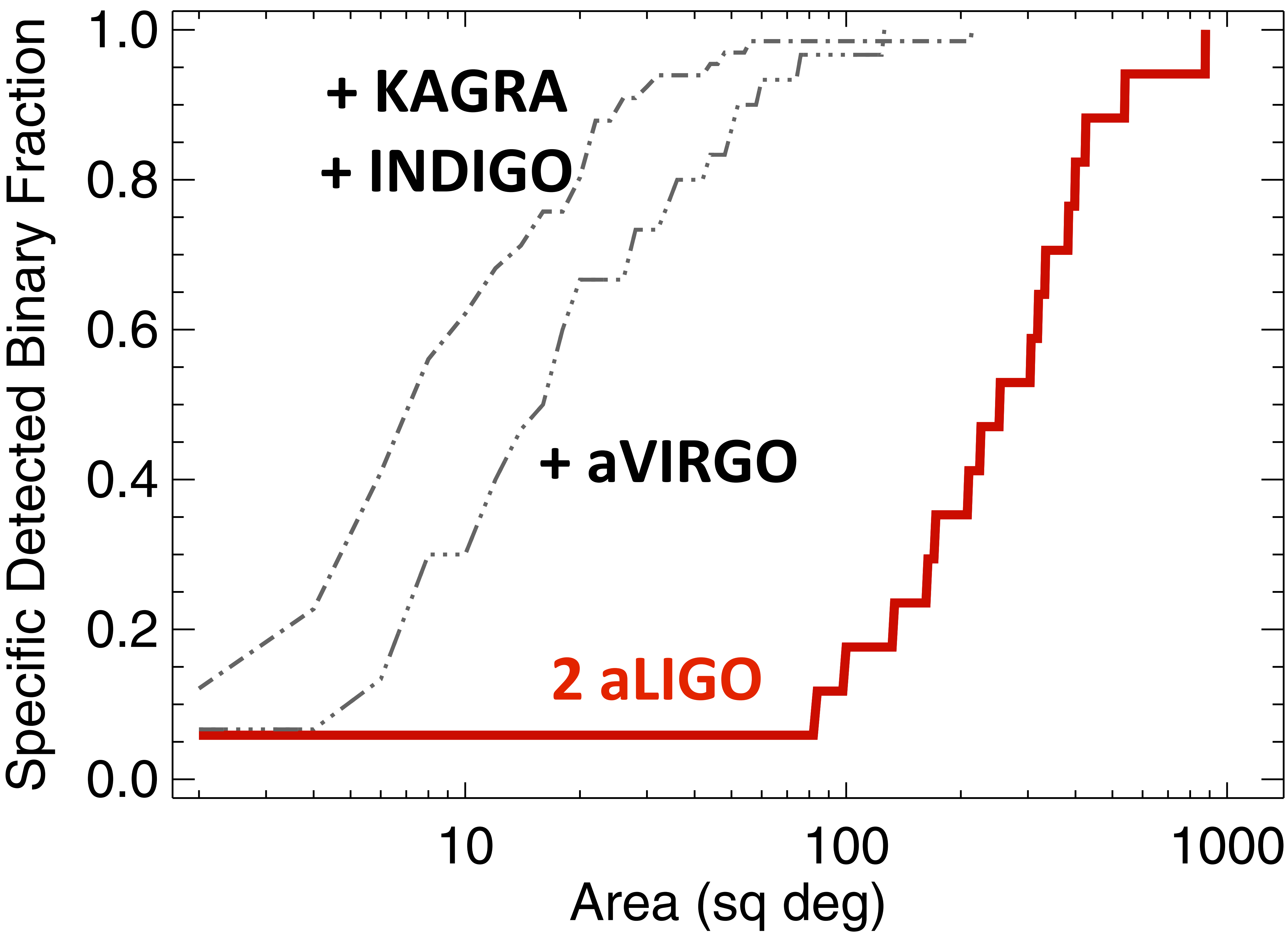
- Radioactive emission "kilonova" or "macronova"

  isotropic ✓

  short delay ✓



Metzger & Berger 2012, ApJ 746, 48



Kasliwal & Nissanke 2014

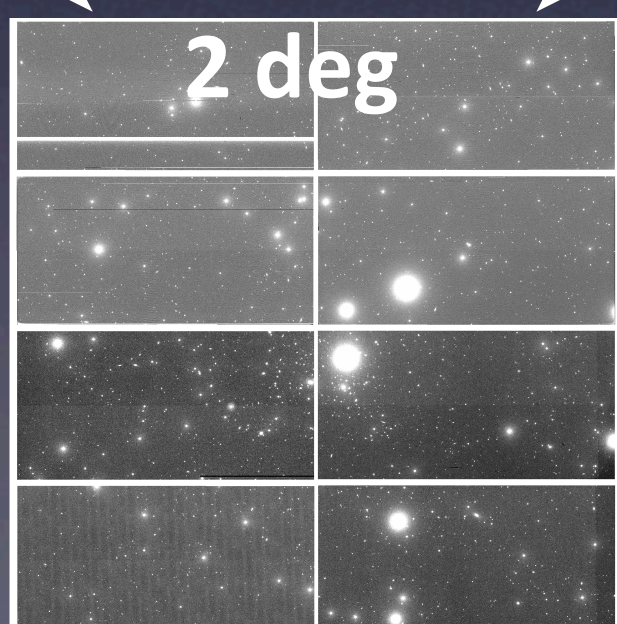
GW alert error box
e.g. 6 deg x 6 deg
(not box shape in reality)

Typical optical telescope
~0.3 deg

We need good prediction

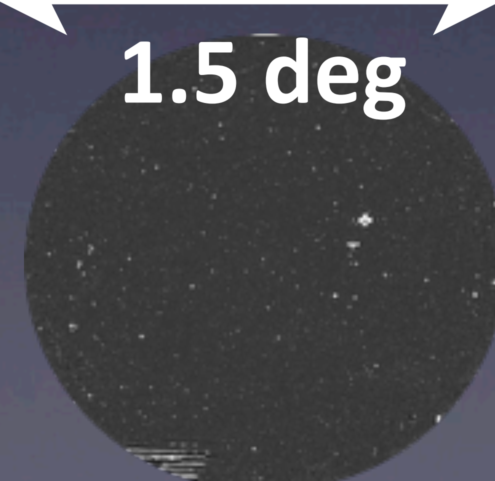
1m wide-field

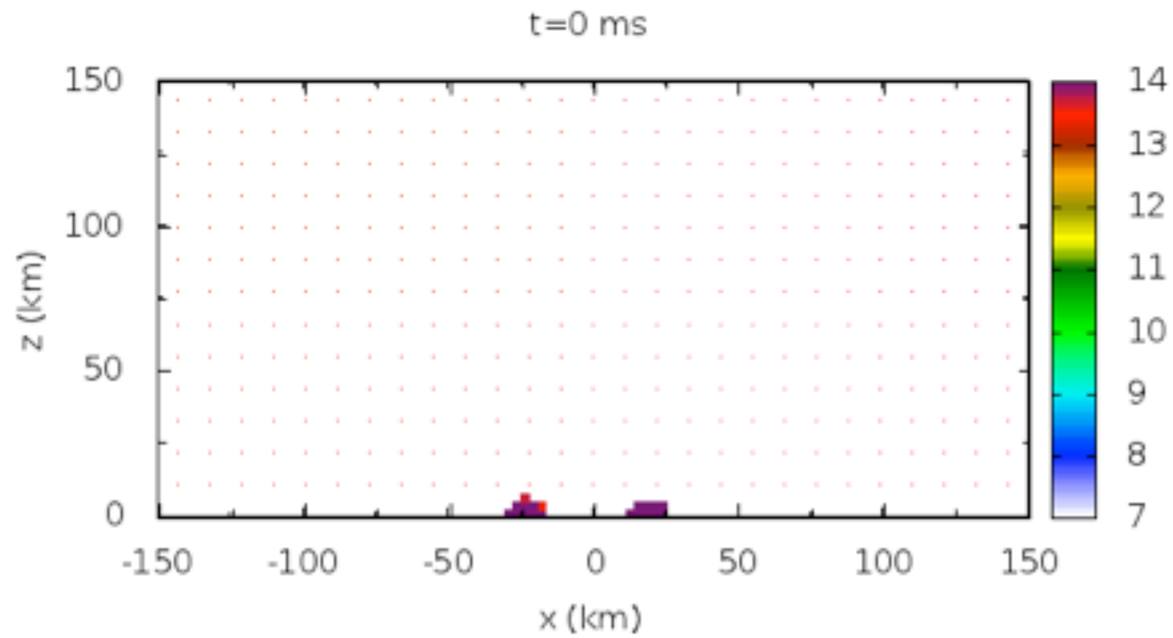
2 deg

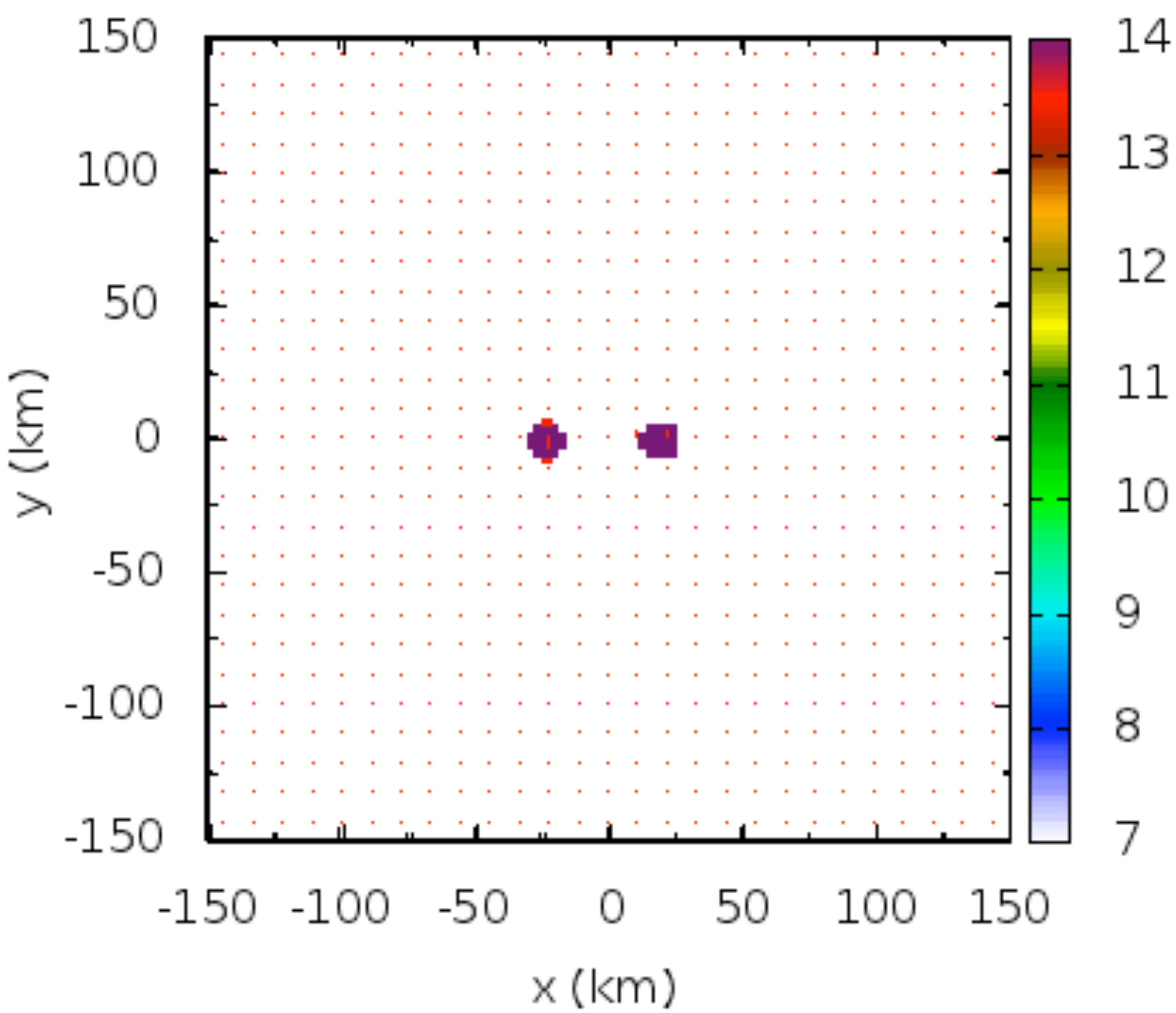


Subaru 8.2m

1.5 deg







Mass ejection from NS mergers

see Sekiguchi-san's talk

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

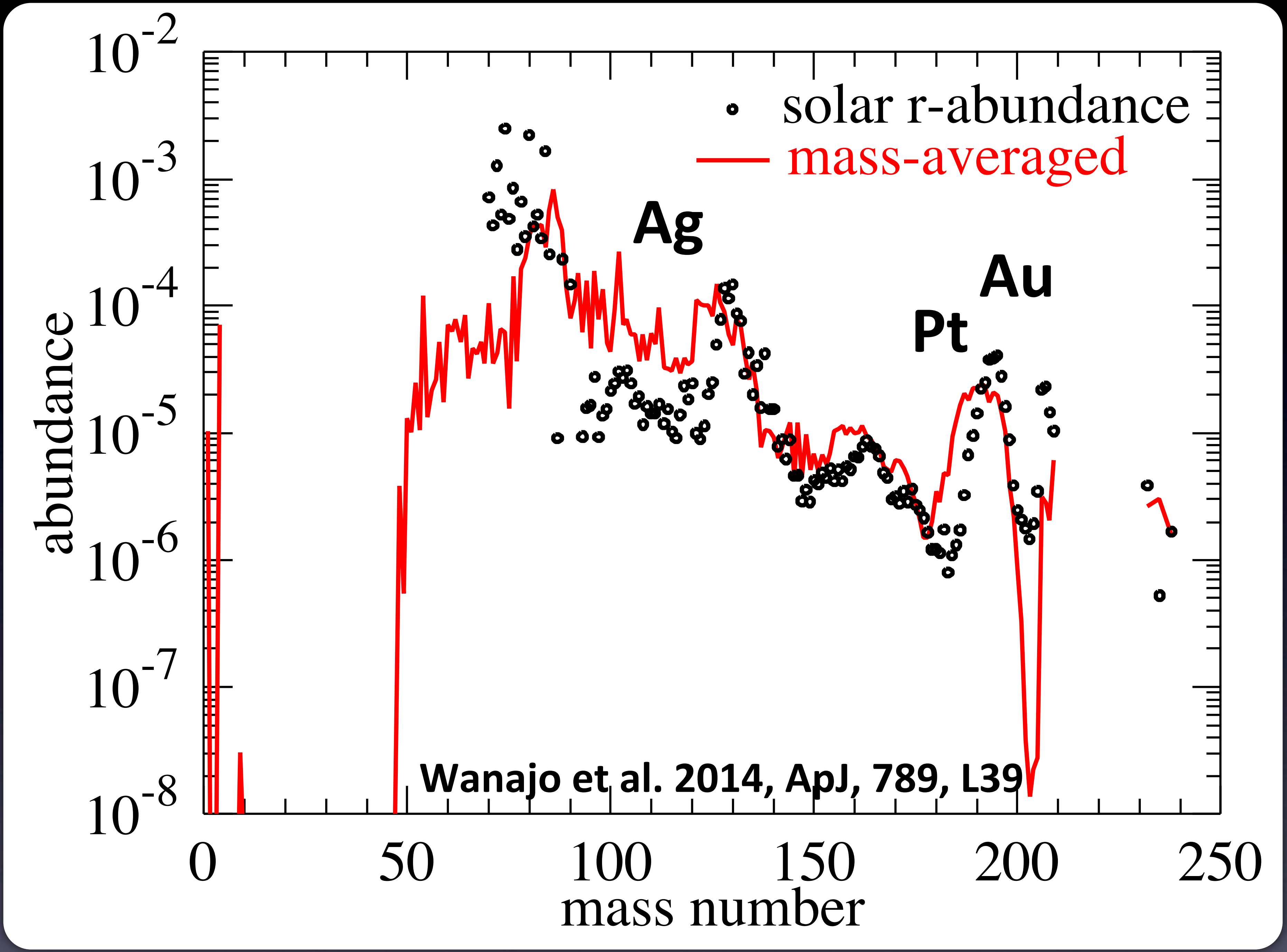
v ~ 0.1 - 0.2 c

Hotokezaka+13, PRD, 87, 4001

Rosswog+13, MNRAS, 430, 2580

r-process nucleosynthesis

see Sekiguchi-san's talk

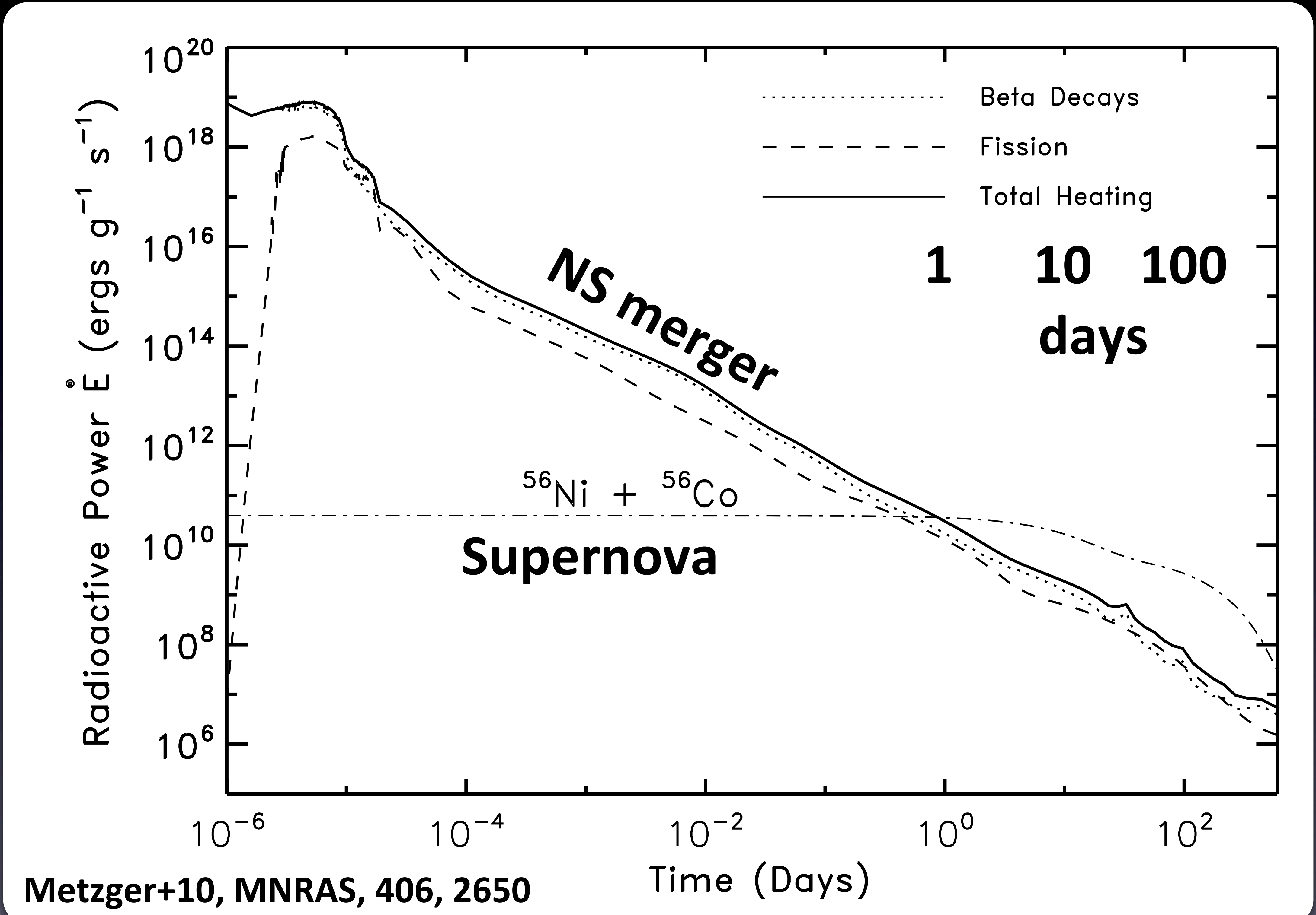


M(Au)
~ 30 M_{Earth}
(~10^{33} JPY)

NS merger can be the origin of r-process elements

- Rate ~ 10^{-4} events/yr/Galaxy (<= GW)
- Mej ~ 10^{-2} Msun/event (<= Opt/IR)

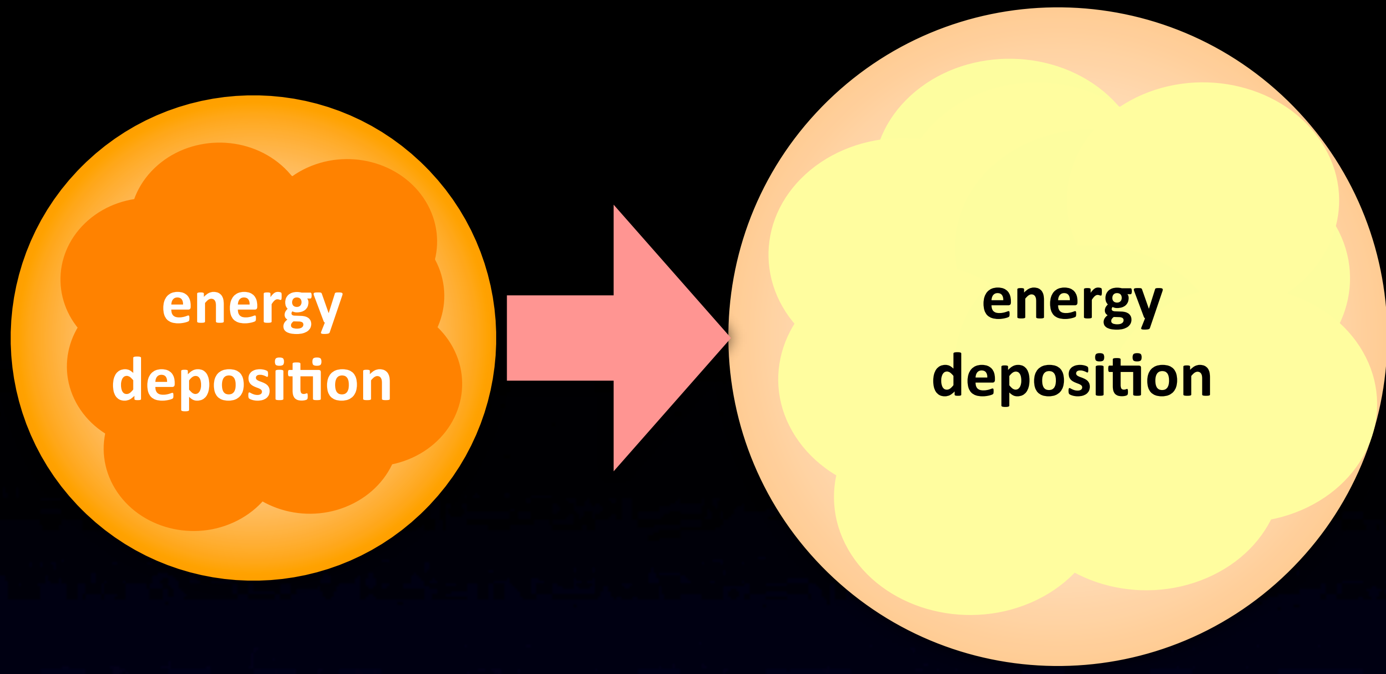
- Why electromagnetic emission
- Optical and IR emission - kilonova -
- Follow-up observations: GW150914 and future



Thick against gamma-rays => optical emission

“kilonova/macronova”

Li & Paczynski 98, Metzger+10,
MT & Hotokezaka 13, MT+14, MT 16
Kasen+13, Barnes & Kasen 13



Timescale

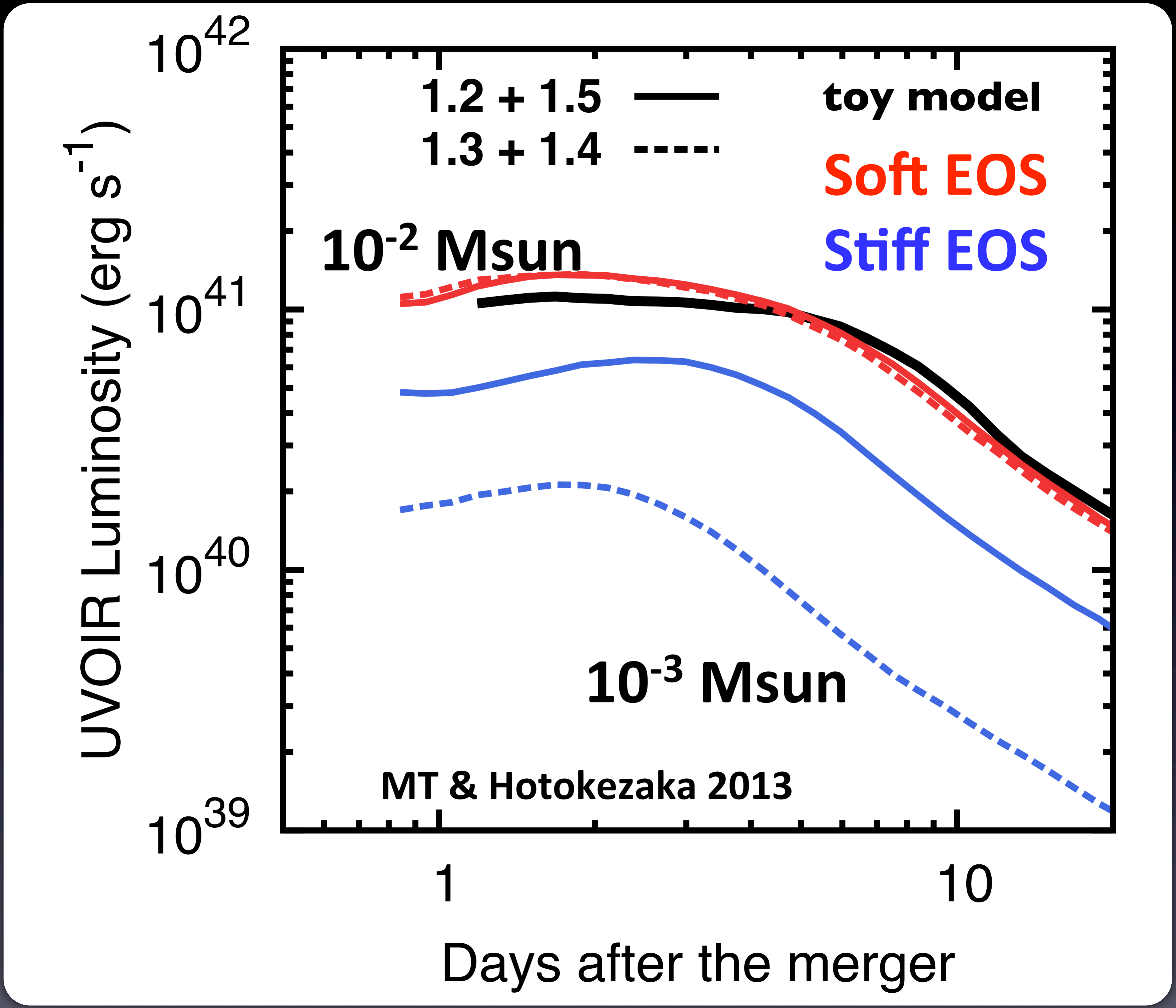
$$t_{\rm peak} = \left(\frac{3\kappa M_{\rm ej}}{4\pi c v}\right)^{1/2}$$
$$\simeq 8.4 \text{ days} \left(\frac{M_{\rm ej}}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}$$

Luminosity

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

Spectral peak at near IR (T ~ 3000 K)

Dependence on EOS



Radius of 1.35 Msun NS

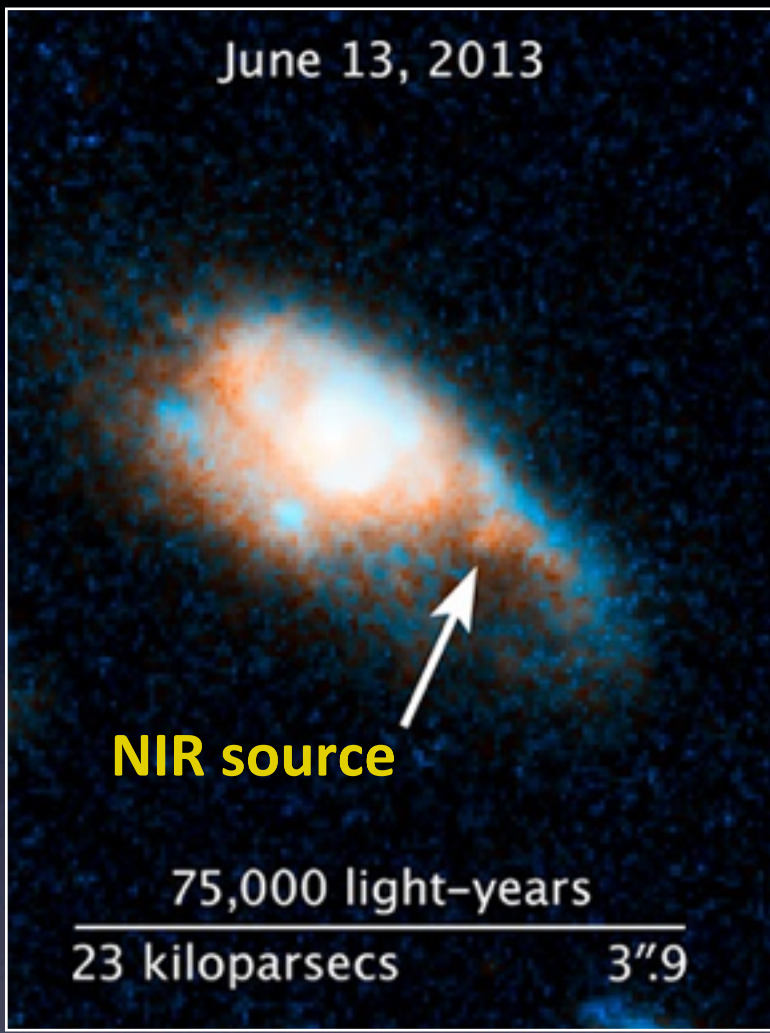
R = 11.1 km

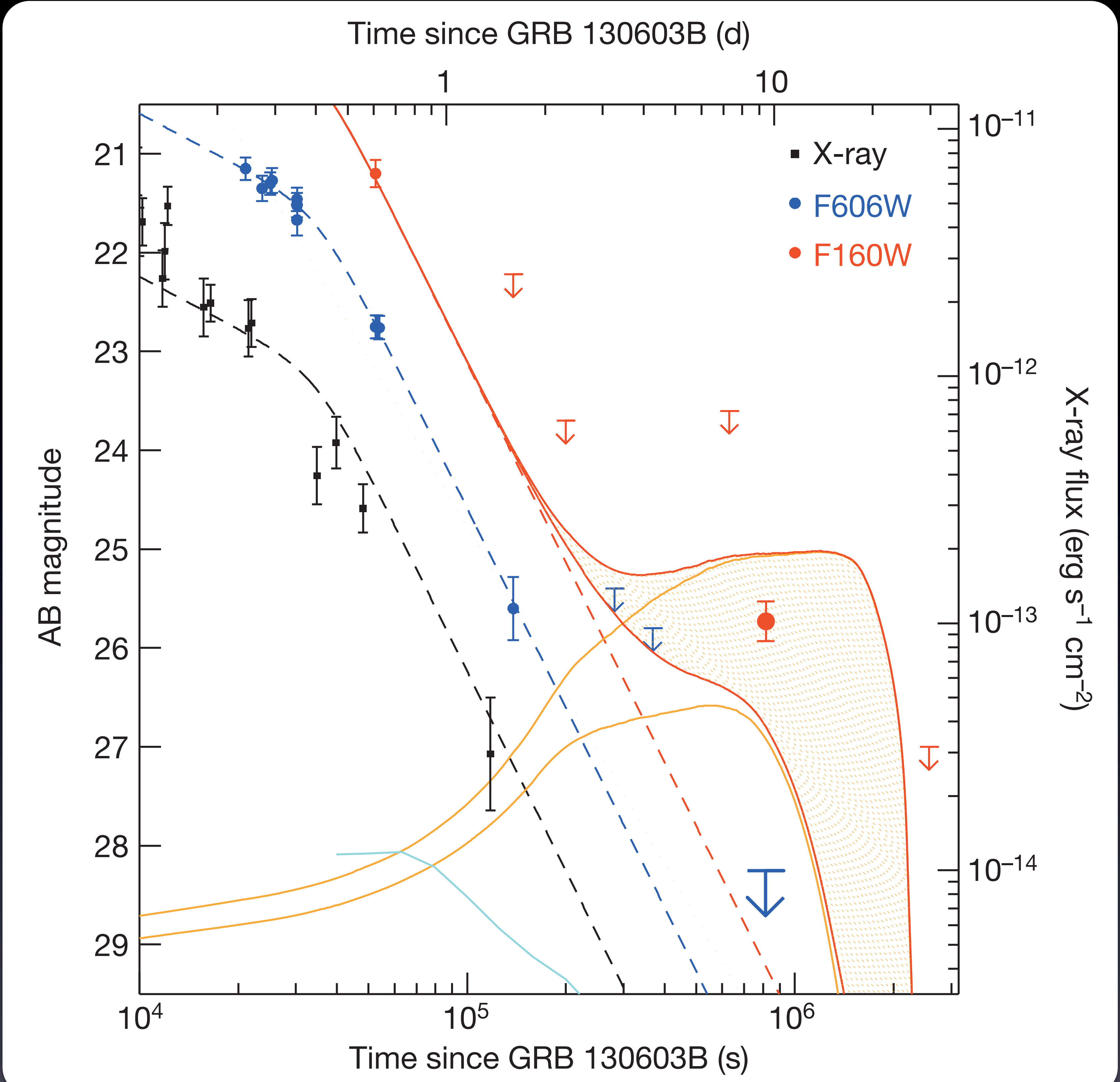
R = 13.6 km

Softer EOS/Higher NS mass ratio => stronger shock heating => more mass ejection => brighter emission

(see Hotokezaka+13; Bauswein+13)

GRB 130603B



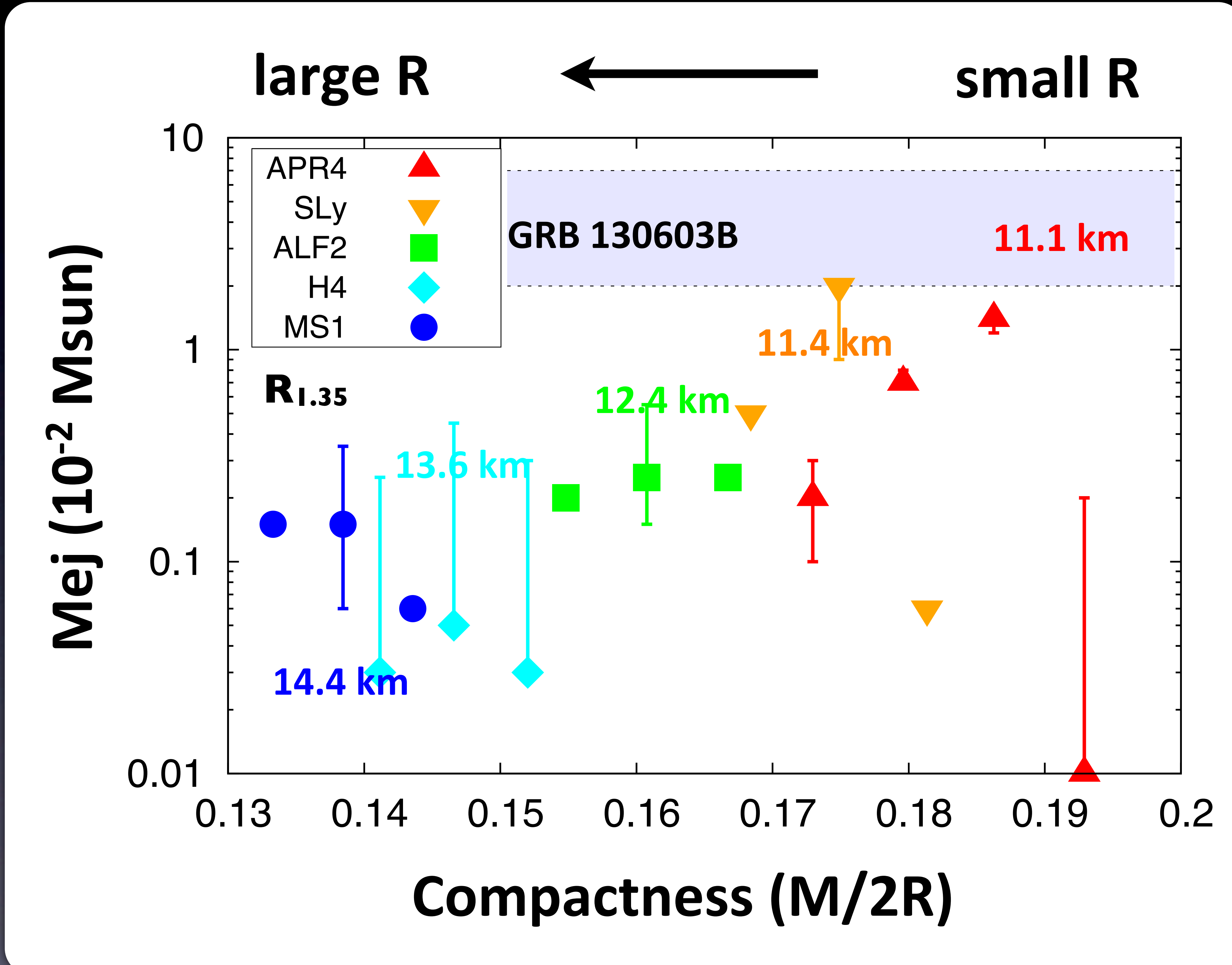


Tanvir+2013, Nature, 500, 547
Berger+2013, ApJ, 774, L23

As expected by theoretical models!!

==> ejection of ~0.02 Msun

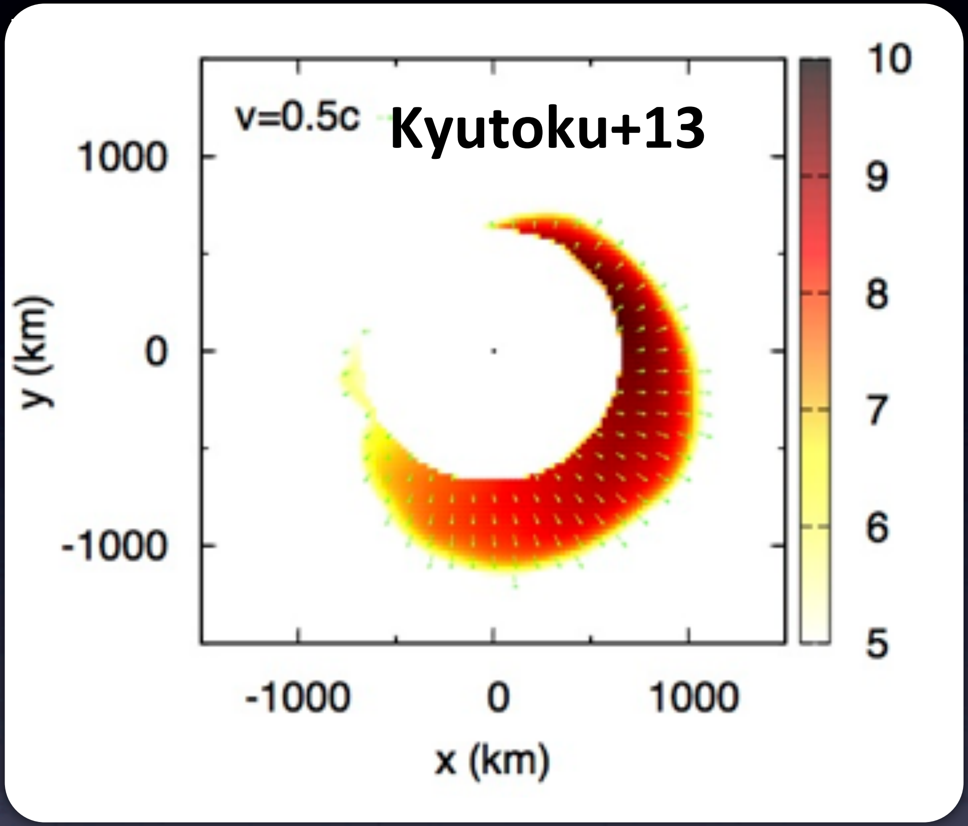
EM observations <=> EOS (NS radius)



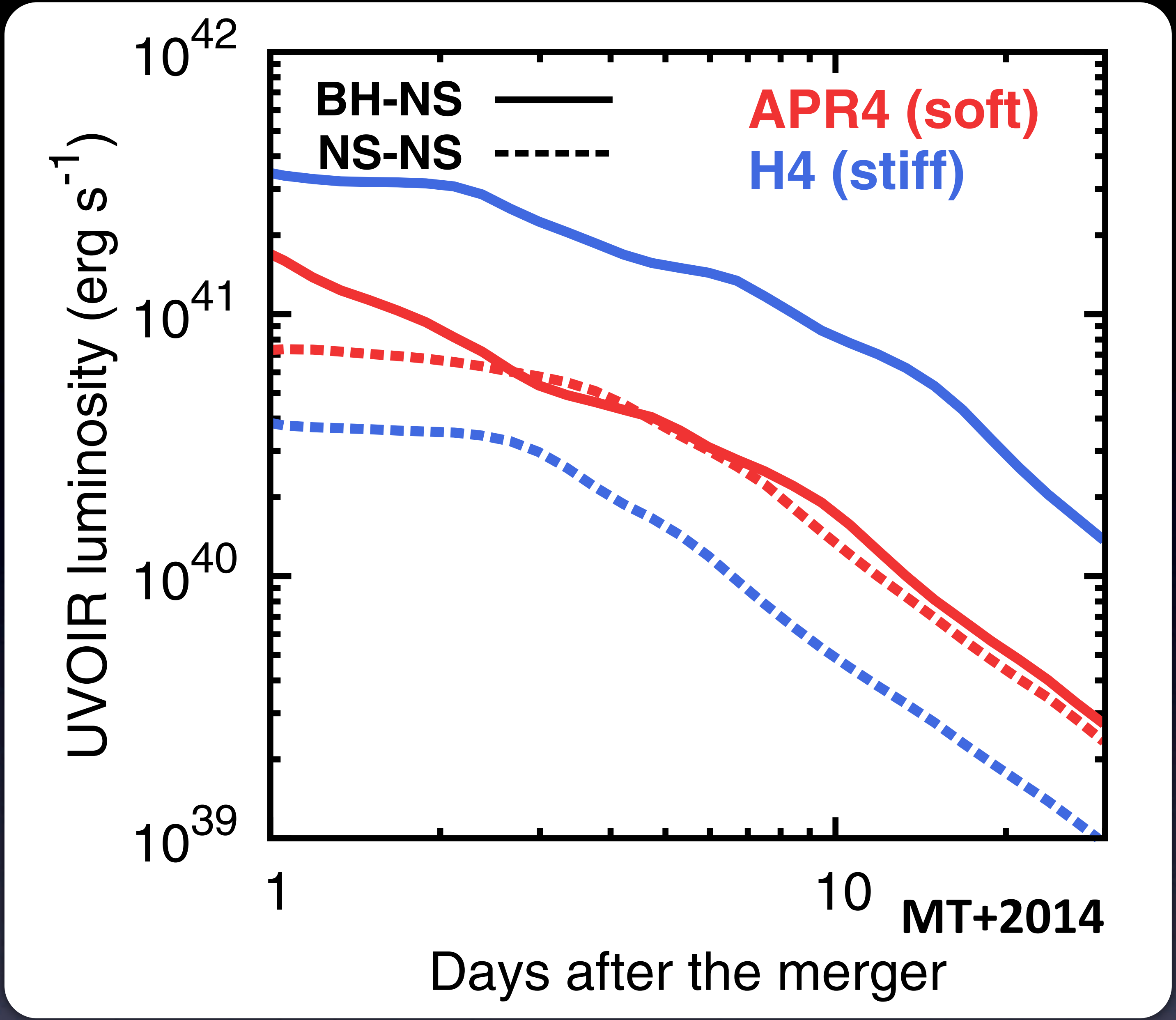
Hotokezaka, Kyutoku, MT+ 2013

BH-NS Mergers

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



Mej ~< 10^{-1} Msun

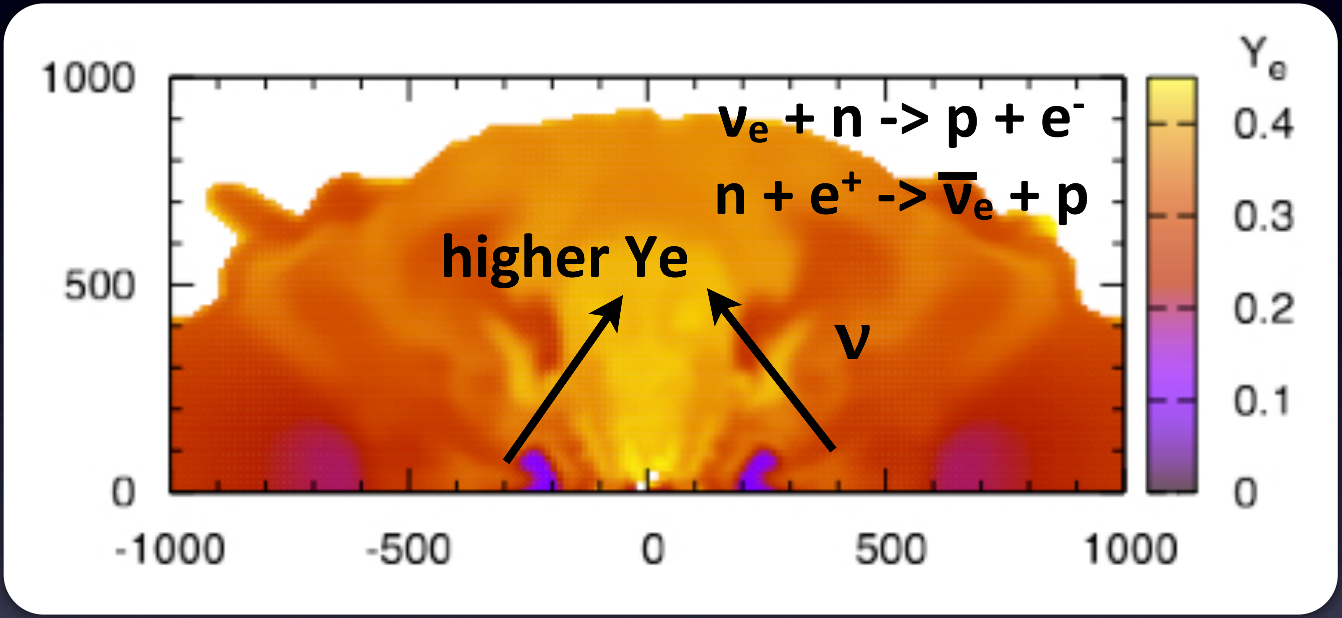


Stiff EOS (larger NS radius)
=> more tidal ejection
=> brighter emission

NOTE: depends strongly on BH mass, spin, and inclination (Kawaguchi+16, arXiv:1601.07711)

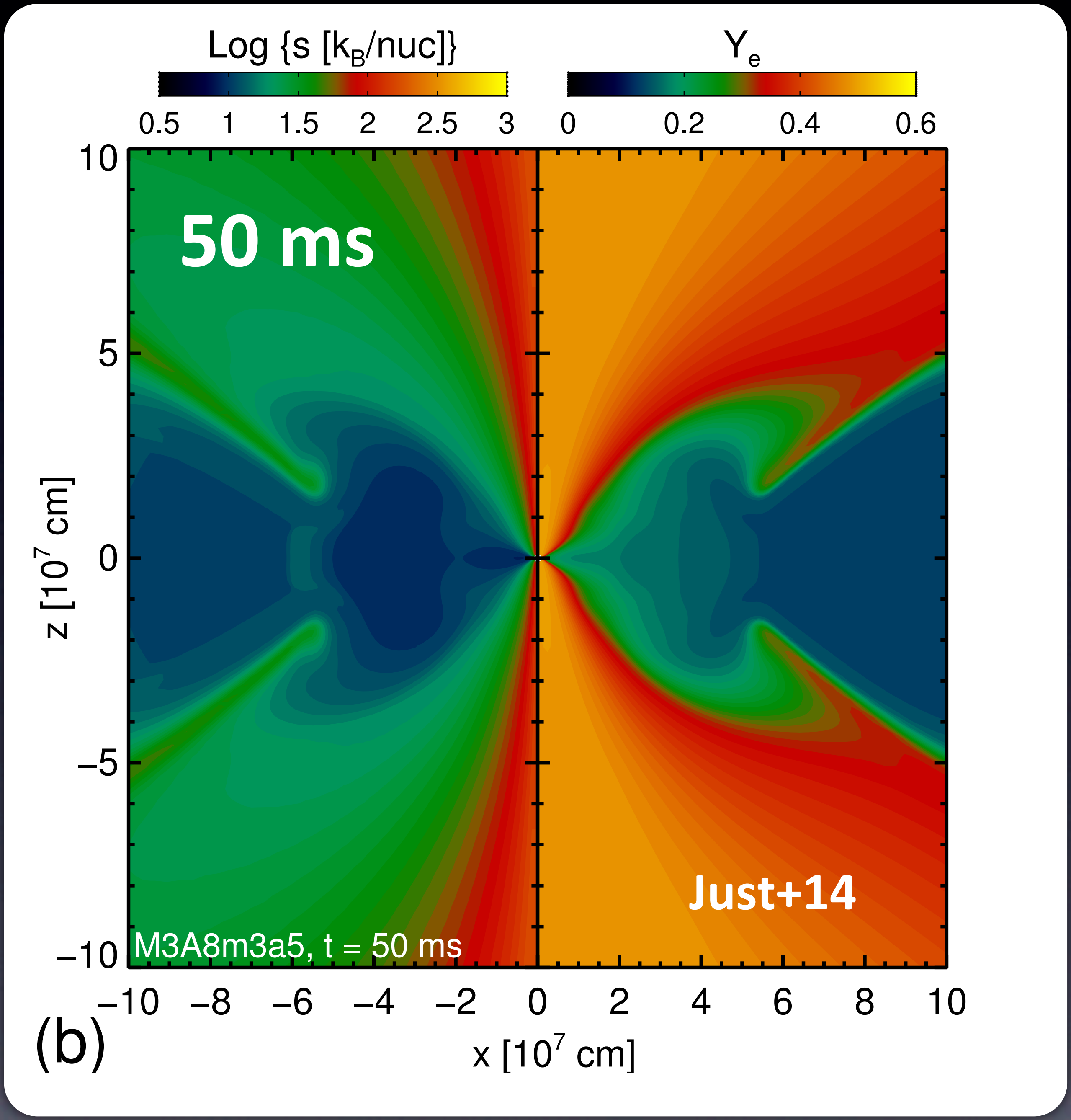
Caveats: additional components

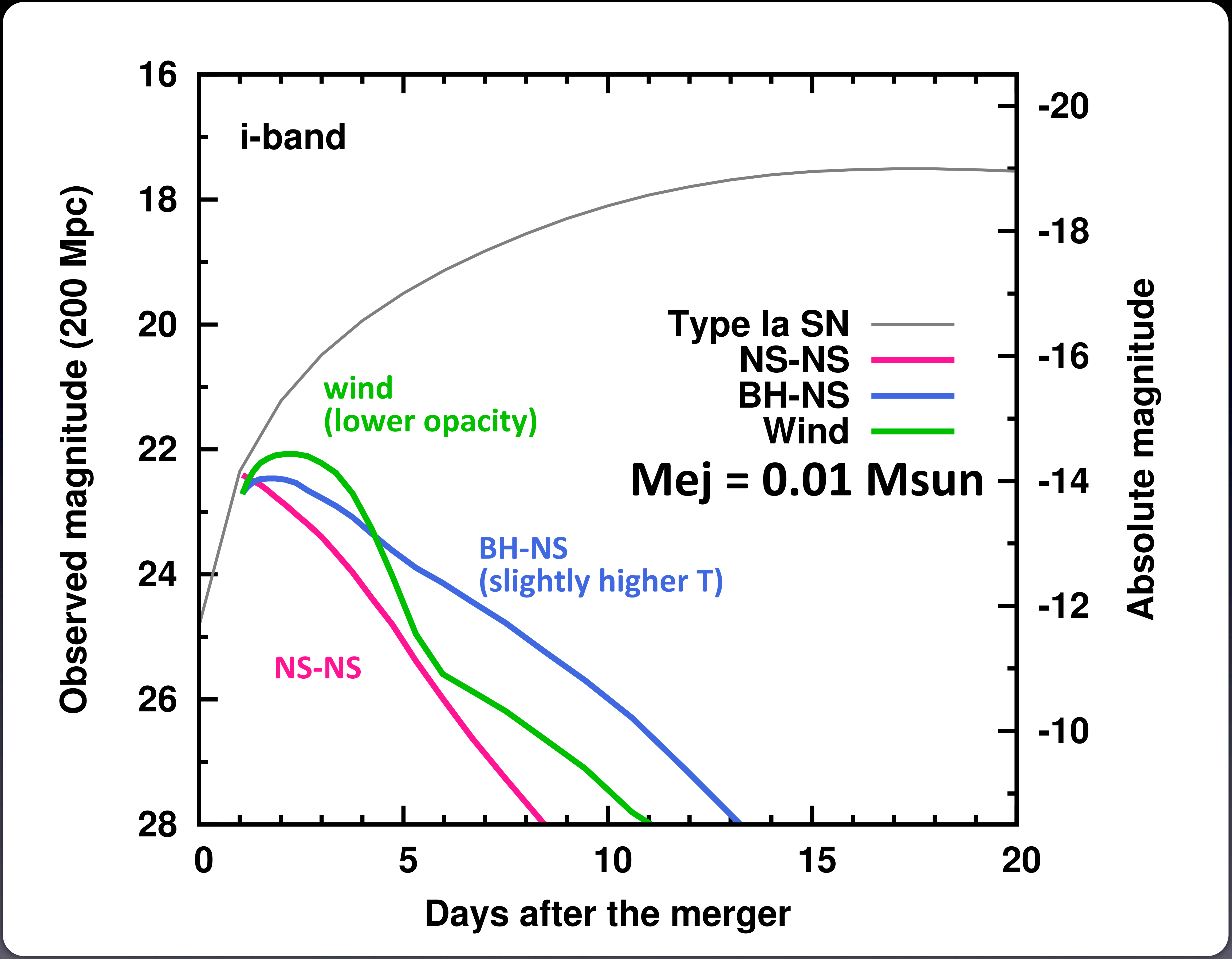
Effect of neutrino/shock
(Wanajo, Sekiguchi+2014)



Higher Ye
=> synthesis of lighter elements

Disk wind (at later phase)
(Fernandez 2013, Metzger+ 2014, Just+2014, Kasen+2015)




i-band
wind
(lower opacity)
Type Ia SN
NS-NS
BH-NS
Wind
Mej = 0.01 Msun
BH-NS
(slightly higher T)
NS-NS
Observed magnitude (200 Mpc)
Absolute magnitude
Days after the merger
16
18
20
22
24
26
28
-20
-18
-16
-14
-12
-10
0
5
10
15
20

- Why electromagnetic emission
- Optical and IR emission - kilonova -
- Follow-up observations: GW150914 and future

LIGO O1 started on Sep 18, 15:00 UT (24:00 JST)

Friday September 18, 2015 quietly marked the start of the first observing run (O1) of LIGO's advanced detectors, heralding a new, more sensitive than ever search for gravitational waves. (Photo: K. Burtnyk)

The Newest Search for Gravitational Waves has Begun

News Release • September 18, 2015

On, Friday, September 18th 2015, the first official 'observing run' (O1) of LIGO's advanced detectors in Hanford WA and Livingston LA quietly began when the clock struck 8 a.m. Pacific time. While this date marks the official start of data collection, both interferometers have been operating in engineering mode collecting data for some weeks already as technicians, scientists, and engineers worked to refine the instrument to prepare it for official data-collection duties. What *IS* different about today is the scope of the search for gravitational waves. Today, the broader astronomical community has been added to the team. From now on, LIGO will be able to notify any number of 75 astronomical observatories around the world who have agreed to, at a moment's notice, point their telescopes to the sky in search of light signals corresponding to possible gravitational wave detections.

For some, the start of O1 is just another day at the office. Nevertheless, it is still a day to celebrate as it comes after a grueling over 5-year complete redesign and rebuild of the interferometers at both Hanford and Livingston, work performed by hundreds of skilled staff and engineers at the two observatory sites, at Caltech, and at MIT. LIGO staff are excited about this new phase in LIGO's mission.

"It is incredibly exciting — and satisfying — to see the planning, designing, building, testing, installing, and commissioning of Advanced LIGO come together so successfully. Kudos to the whole team!", said Dr. David Shoemaker, Director of the MIT LIGO Laboratory.

https://ligo.caltech.edu/news/ligo20150918

d ~ 80 Mpc for NS mergers

Expected event rate ~ 0.1 events / 3 months (0.01-1)

(~10 events / 1 yr in 2017, d~200 Mpc)

J-GEM

Japanese collaboration for Gravitational-wave Electro-Magnetic follow-up

Okayama 0.91m

Okayama 1.88m

Hiroshima 1.5m

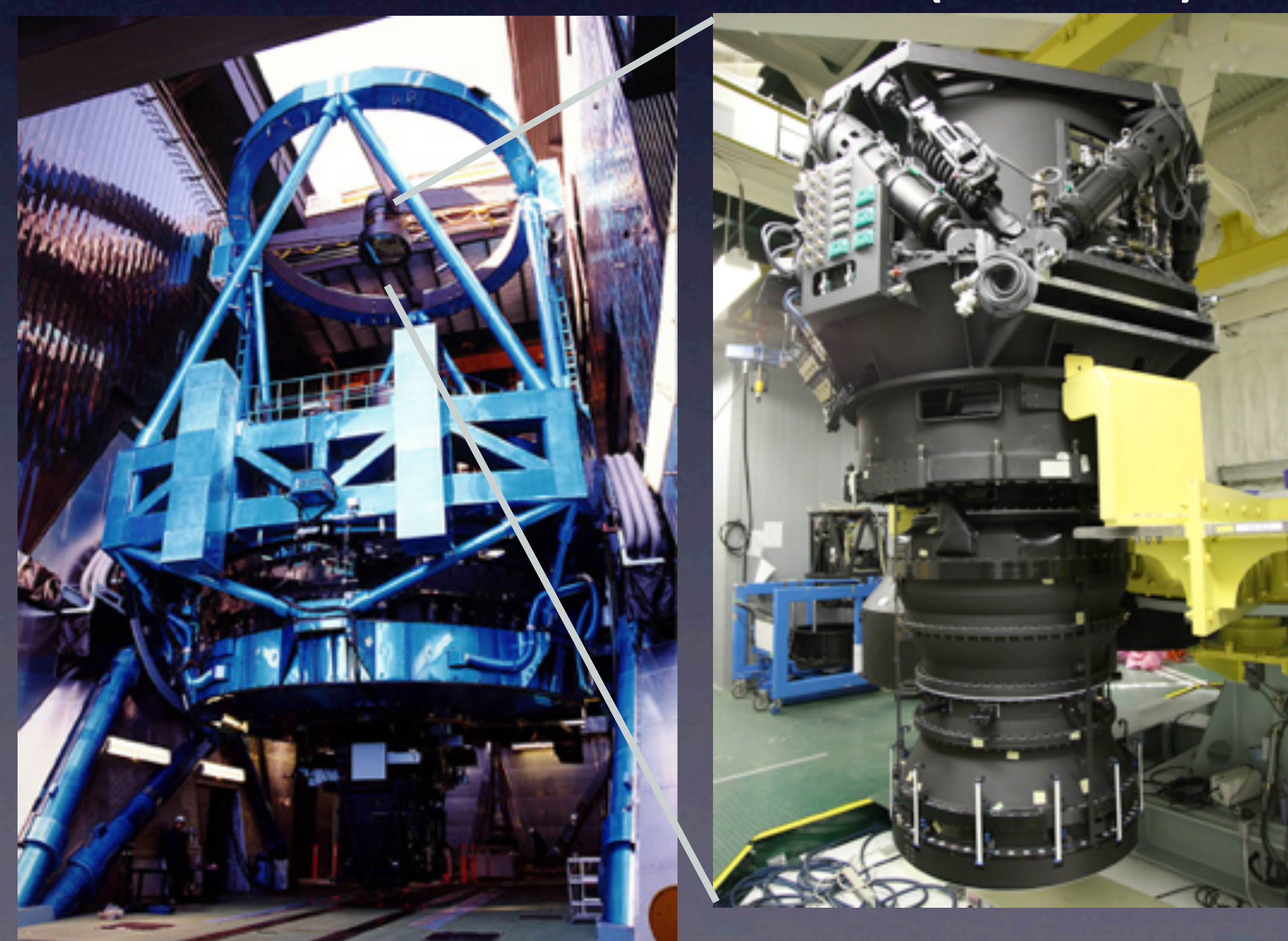
Kiso 1m (wide field)

MOA-II 1.8m (wide field, south)

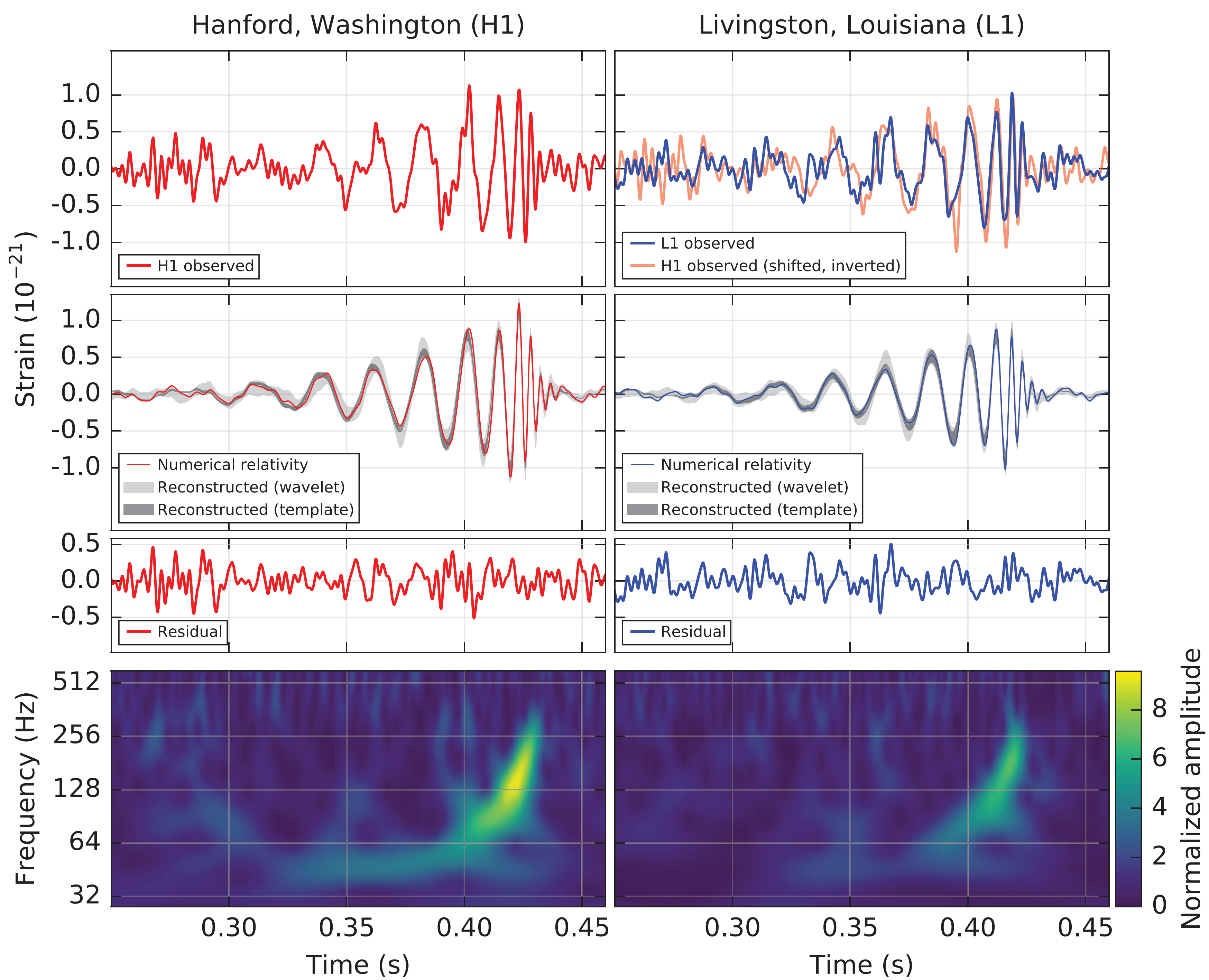
IRSF 1.4m (south)

Subaru 8.2m

HSC (wide field)

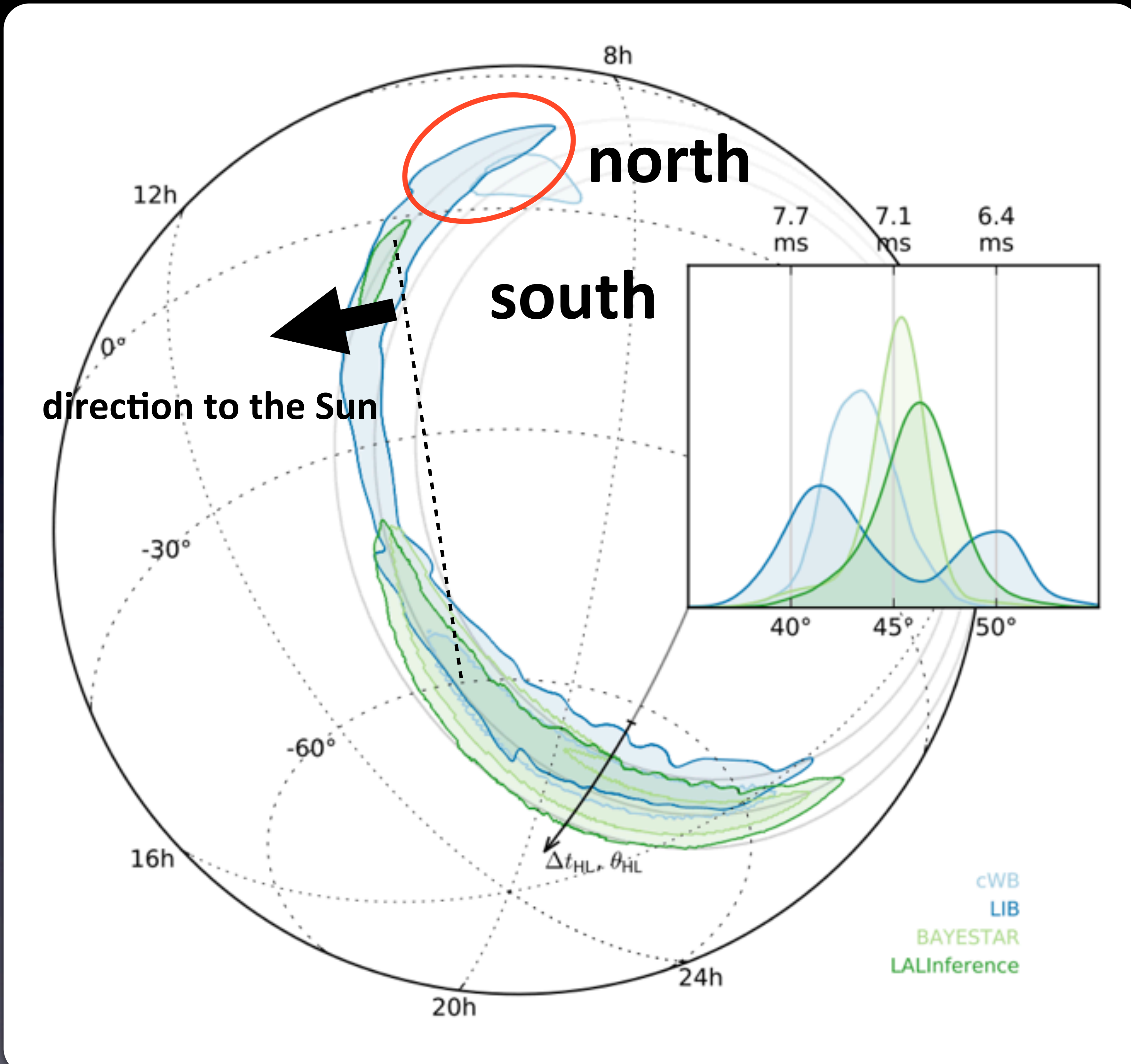


GW150914 (Alert to EM groups on 2015 Sep 16)



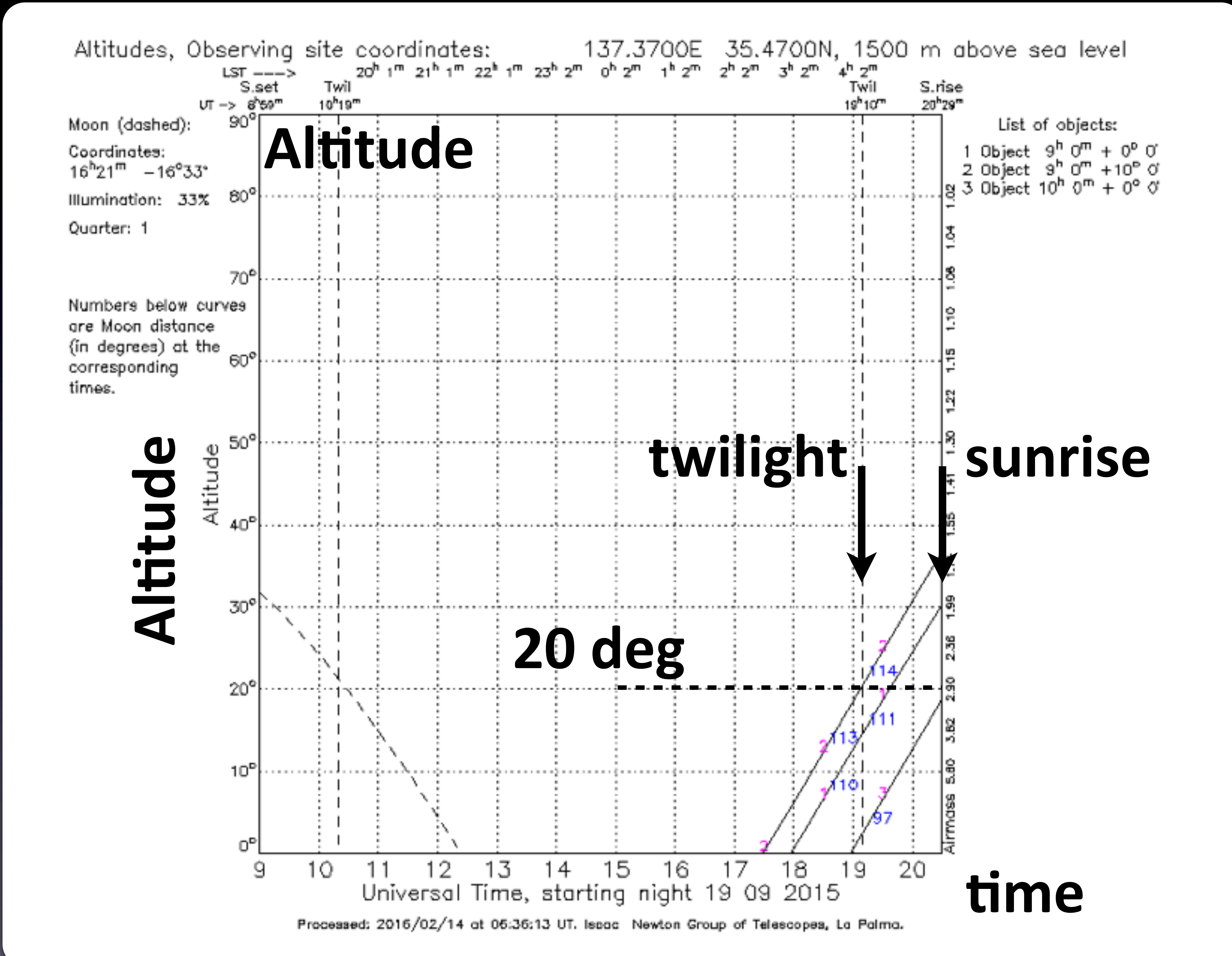
LIGO Scientific Collaboration and Virgo Collaboration, 2016, PRL, 061102

GW150914: Skymap



https://losc.ligo.org/events/GW150914/

GW150914: Visibility from Japan

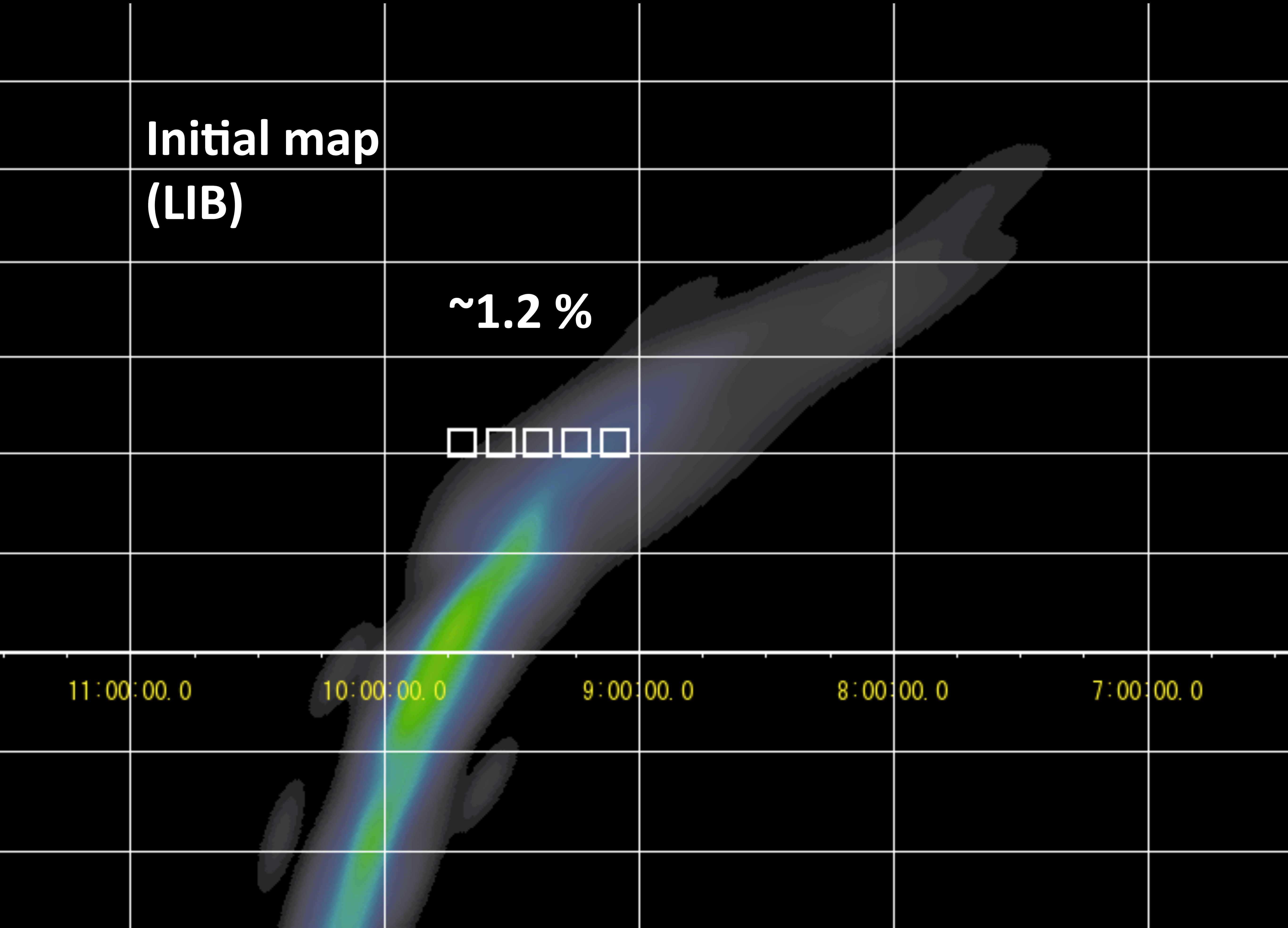


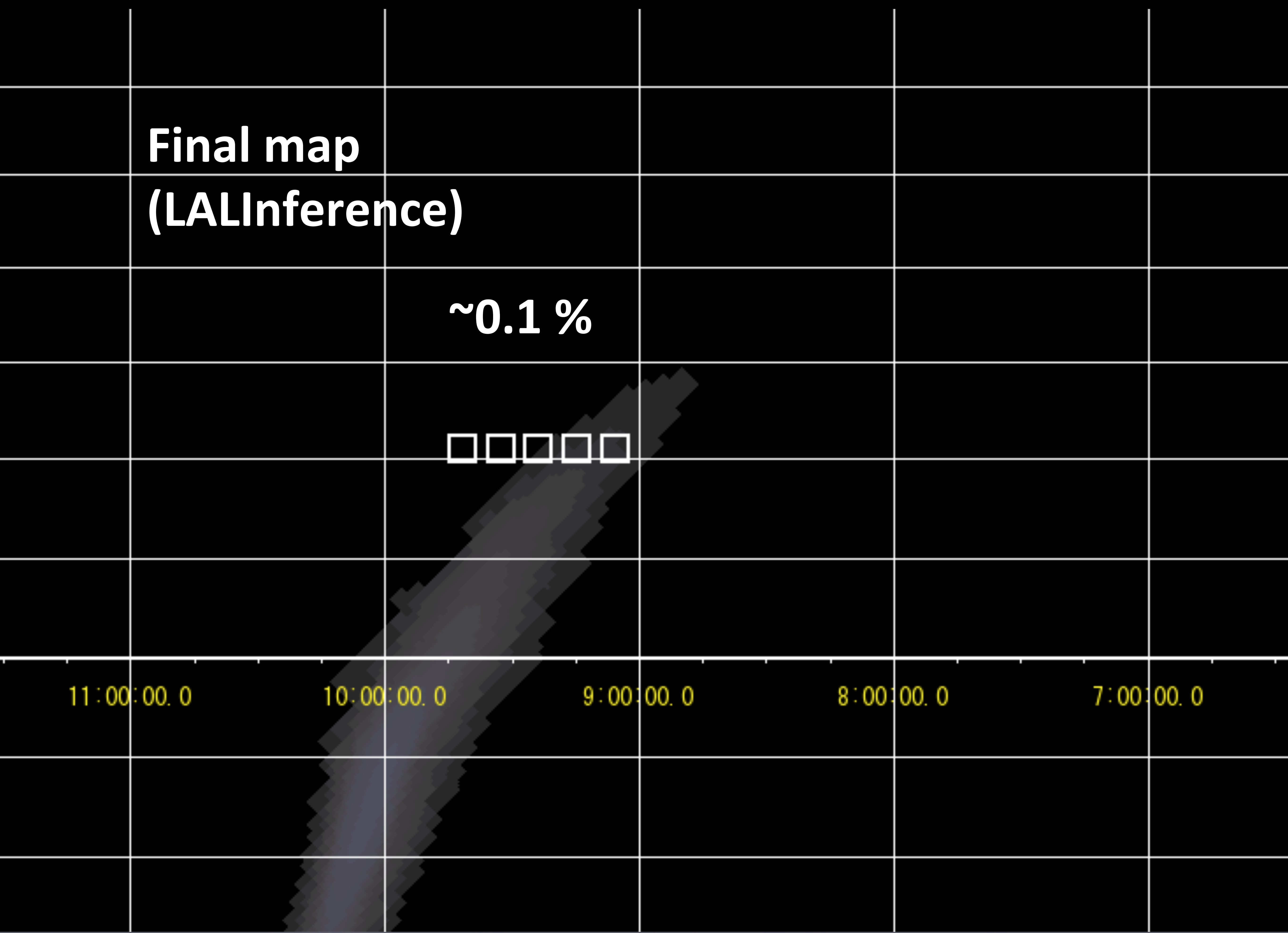
GW150914: Follow-up observations

Morokuma, MT, and J-GEM collaboration, 2016, submitted (arXiv:1605.03216)

- 2015 Sep 18 (4 days after GW detection)
- ~24 deg^2 (5 pointing) using Kiso telescope

* BBH nature was informed in October


Initial map
(LIB)
~1.2 %
□□□□□
11:00:00.0
10:00:00.0
9:00:00.0
8:00:00.0
7:00:00.0


Final map
(LALInference)
~0.1 %
11:00:00.0
10:00:00.0
9:00:00.0
8:00:00.0
7:00:00.0

GW150914: Follow-up observations

Morokuma, MT, and J-GEM collaboration, 2016, submitted (arXiv:1605.03216)

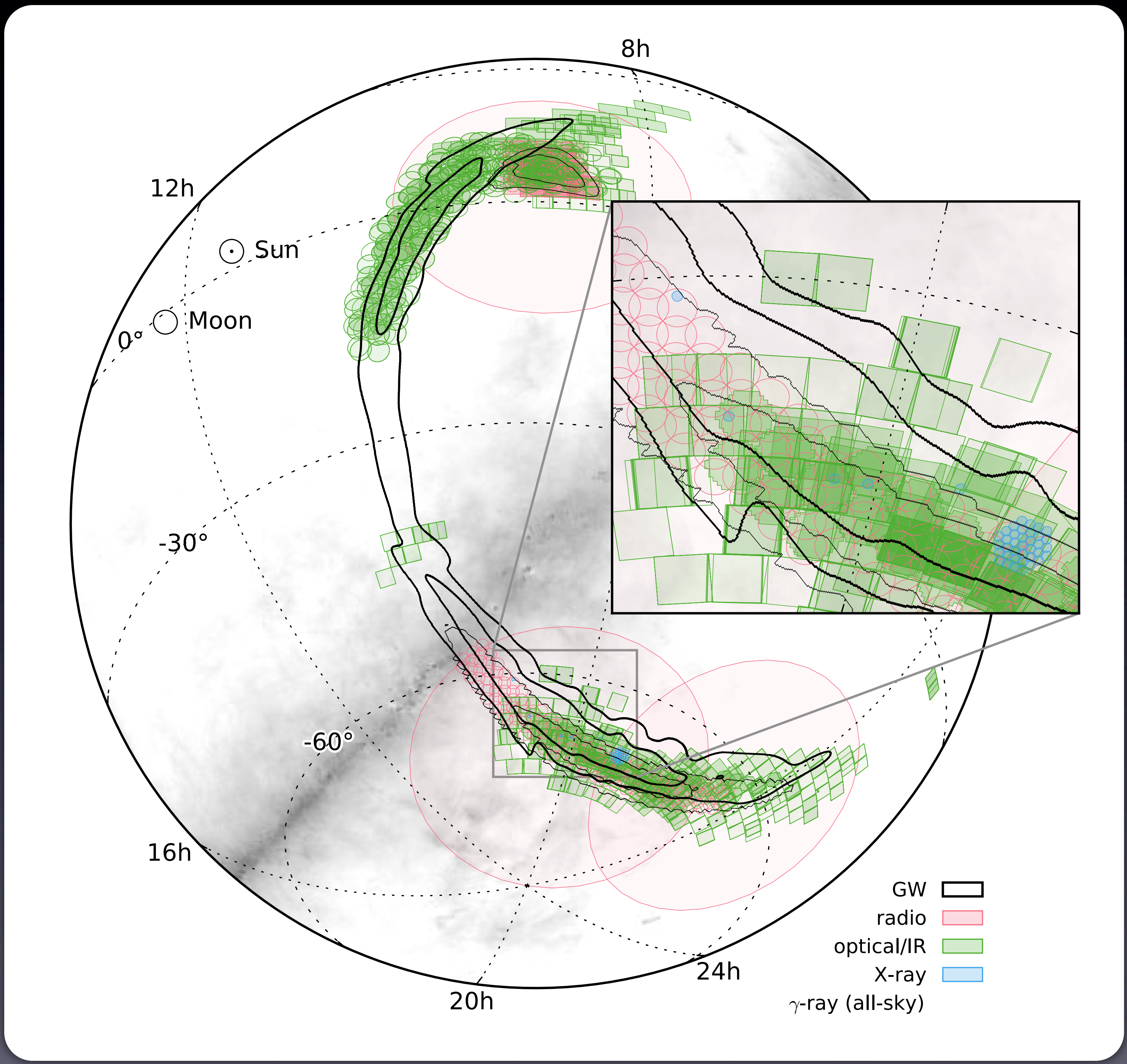
- 2015 Sep 18 (4 days after GW detection)
- ~24 deg^2 (5 pointing) using Kiso telescope
  - ~ 1.2% of the LIB skymap
  - ~ 0.1% of the LALInference skymap
- No extragalactic transients
  - Detection limit: ~ 18 mag
  - Absolute magnitude: ~ -20 mag @ 400 Mpc

    ~< 3 x 10^{43} erg s^{-1}

    (~ brightest Type Ia SN)

GW150914: Summary of follow-up

LVC collaboration and EM follow-up groups (incl. MT), 2016, in press, arXiv:1602.08492



- No plausible EM counterpart

Except for possible Fermi/GBM detection (arXiv:1602.03920)

but non detection w/ INTEGRAL (arXiv:1602.04180)

- EM emission from BH-BH merger??

LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], M. R. Abernathy[1], F. Acernese[3,4], K. Ackley[5], C. Adams[6], T. Adams[7],
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J. Hough[36], E. A. Houston[36], E. J. Howell[51], Y. M. Hu[36], S. Huang[73], E. A. Huerta[103,82], D. Huet[23], B. Hughey[97],
S. Husa[67], S. H. Huttner[36], T. Huynh-Dinh[6], A. Idrisy[72], N. Indik[8], D. R. Ingram[37], R. Inta[71], H. N. Isa[36], J.-M. Isac[60],
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F. Jiménez-Forteza[67], W. W. Johnson[2], D. I. Jones[26], R. Jones[36], R. J. G. Jonker[9], L. Ju[51], H. K[106], C. V. Kalaghatgi[24,91],
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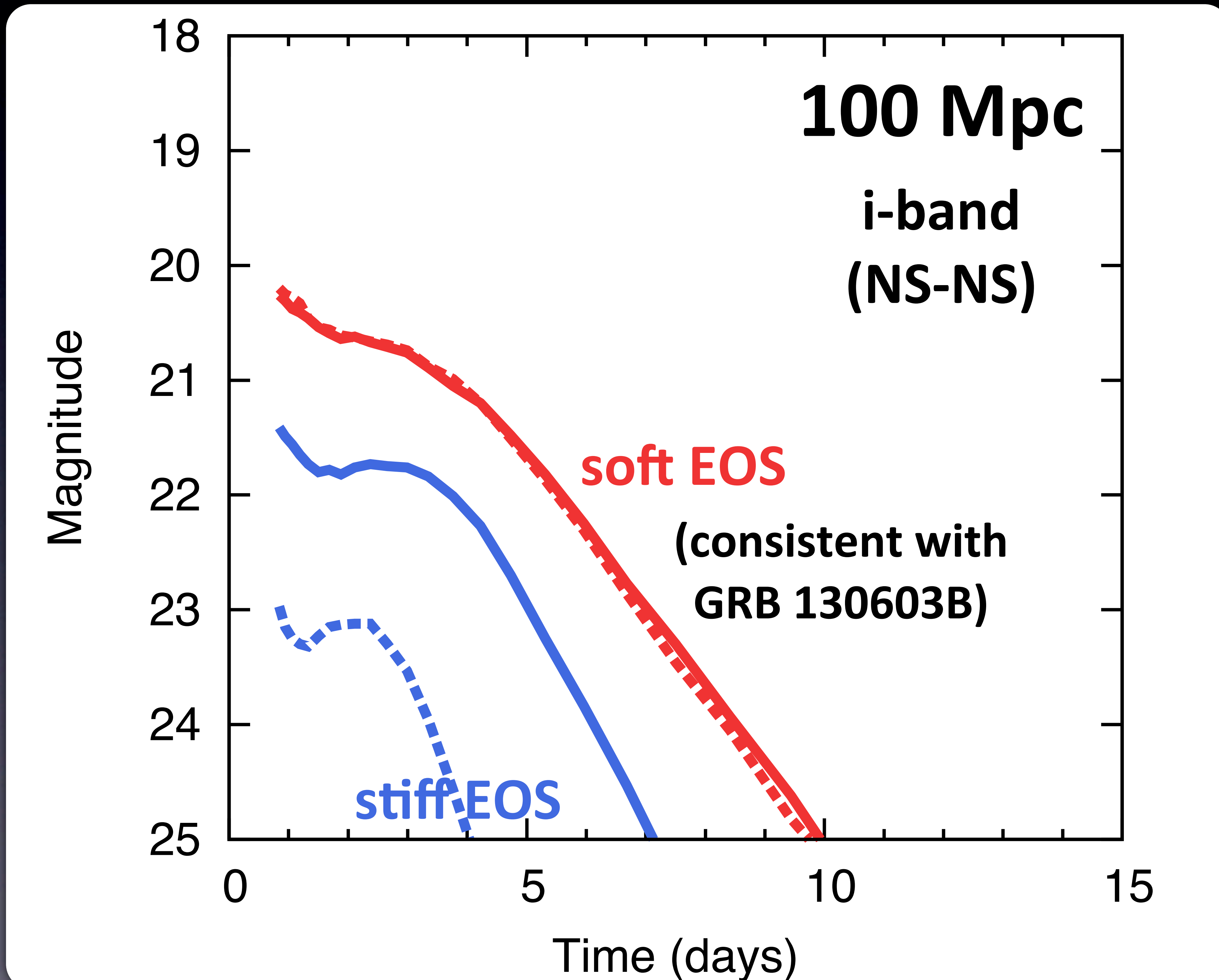
D. B. Kelley[35], W. Kells[1], R. Kennedy[86], J. S. Key[85], A. Khalaidovski[8], F. Y. Khalili[49], I. Khan[12], S. Khan[91], Z. Khan[95],

Let’s wait for NS-NS merger

EM follow-up groups became ready
aLIGO O2 plans to begin in this summer/autumn

LIGO O2 from 2016 summer

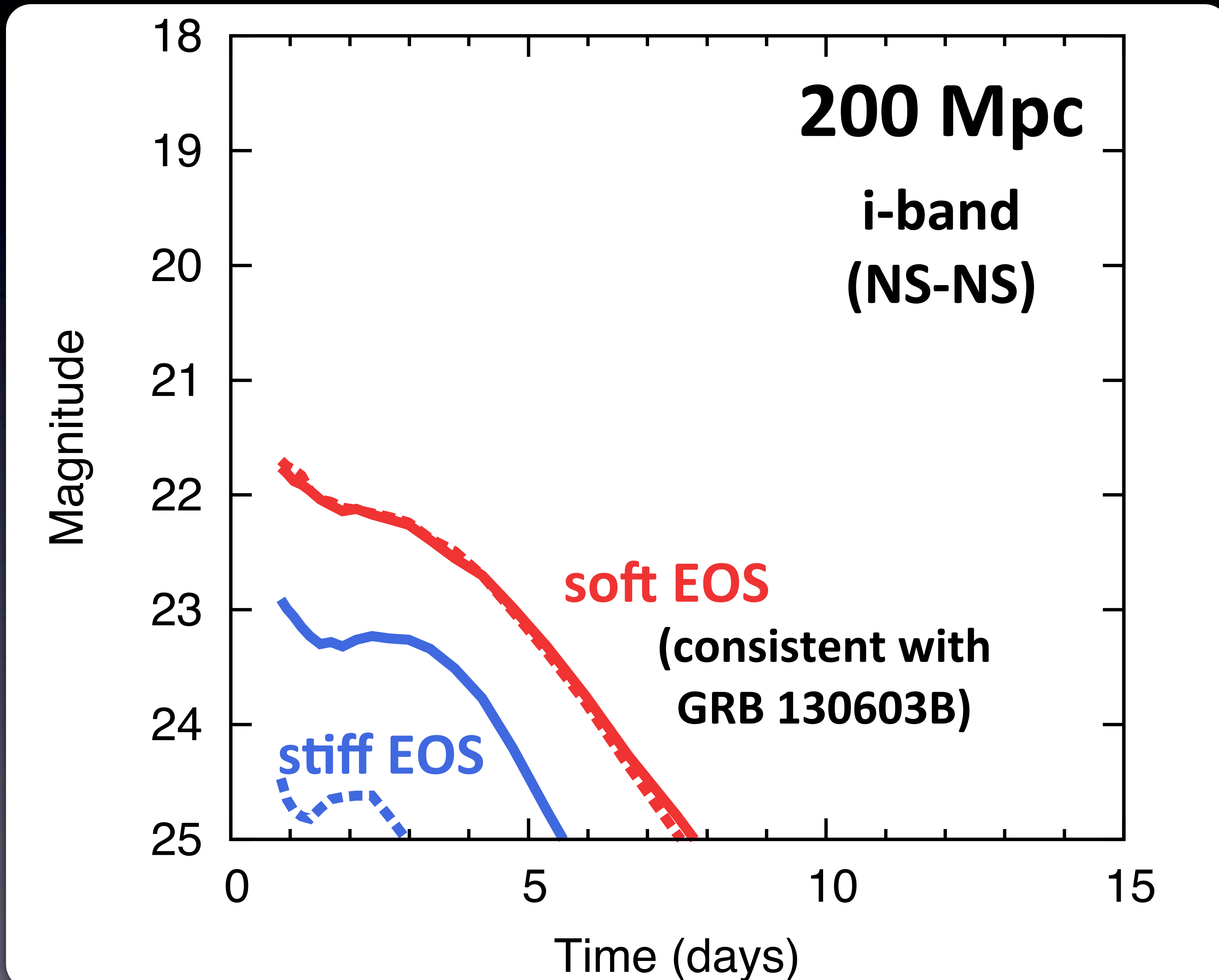


1m

4m

8m

Full sensitivity of Adv. LIGO/Virgo and KAGRA (2017-)



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Summary

- EM follow-up is essential for GW astronomy
- "kilonova" emission from compact binary merger
  - Peaks at red optical or near infrared
  - Brightness depends on EOS (NS radius)
  - GRB 130603B: mass ejection of ~0.02 Msun => EOS
  - Origin of r-process elements
  - More studies needed (disk wind, effects of neutrino)
- Follow-up observations
  - No plausible counterpart for GW150914 (BH-BH)
    (except for possible one by Fermi/GBM)
  - EM groups became ready thanks to the real "drill"