Remaining issues about compact binary coalescences

Koutarou Kyutoku/久徳浩太郎

High Energy Accelerator Research Organization (KEK)

Institute of Particle and Nuclear Studies

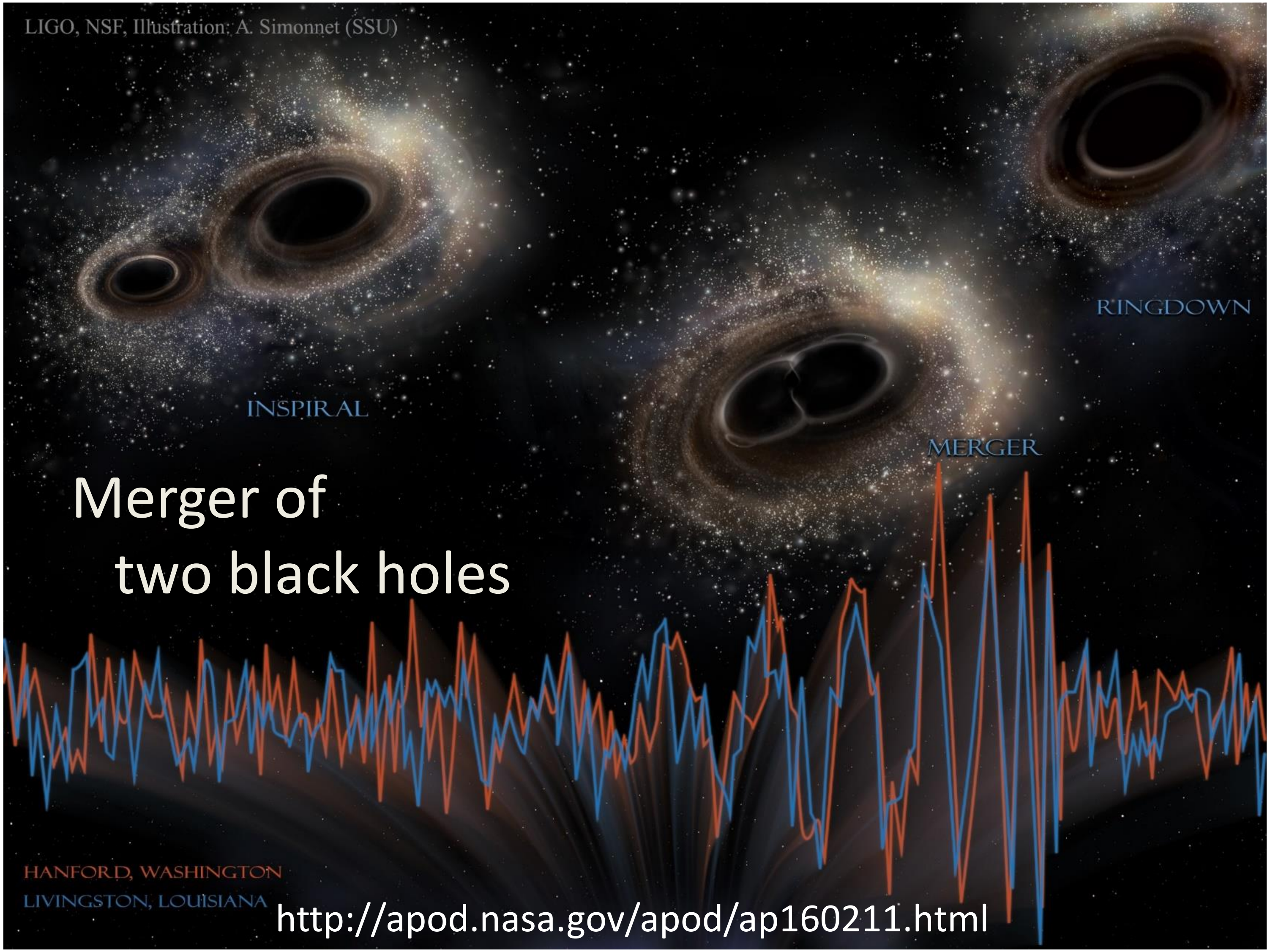
Contents

1. Previous observation
2. Future with ground-based detector
3. Future with space-borne detector
4. Summary

1. Previous observation

Gravitational-wave detector network

The first event: GW150914



Observed events

- Binary black holes

LIGO O1: GW150914, GW151226 (+LVT151012)

LIGO O2: GW170104, GW170608 (+another?)

LIGO O2 with Virgo: GW170814

- Binary neutron stars

LIGO O2 with Virgo: GW170817

 - electromagnetic: GRB 170817A/AT 2017gfo

Example: parameters of GW150914

- Masses of individual stars are measured

 - even at 400Mpc (Milky way is only ~10kpc)

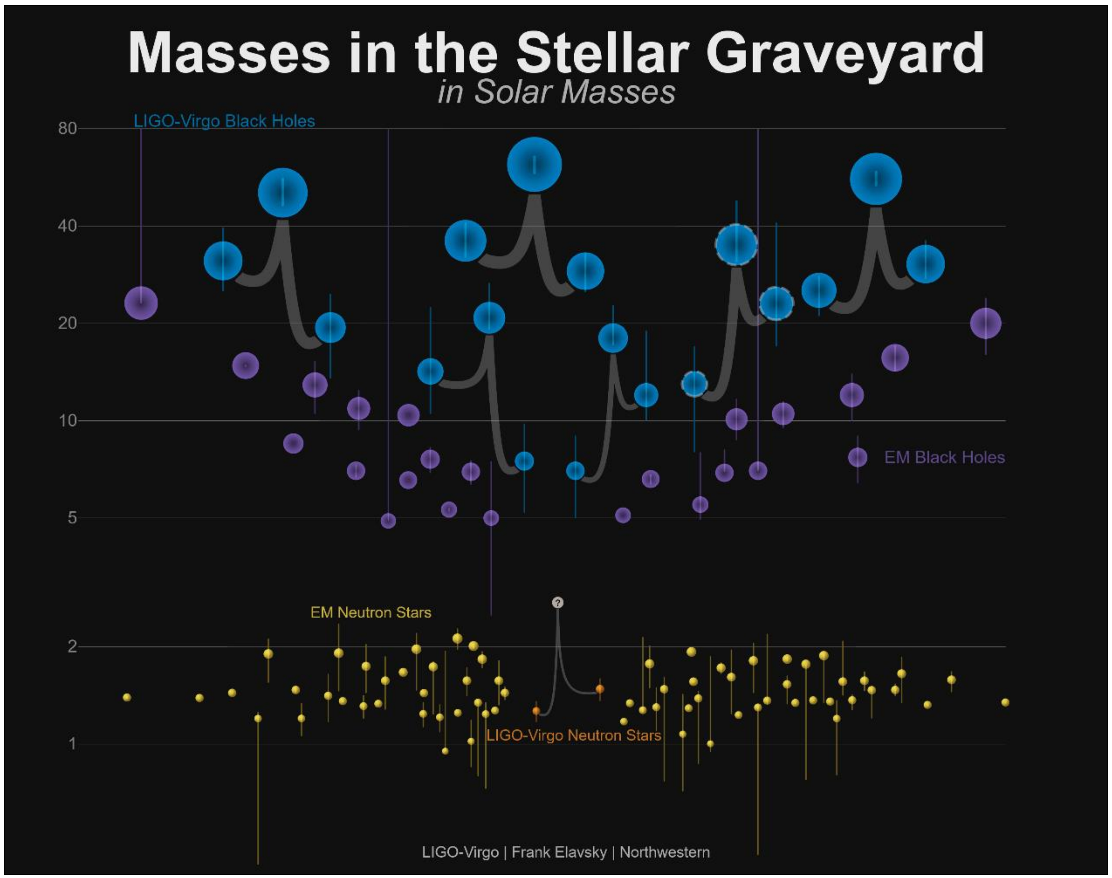
- The luminosity distance is measured directly

Primary black hole mass		$36^{+5}_{-4} M_\odot$
Secondary black hole mass		$29^{+4}_{-4} M_\odot$
Final black hole mass		$62^{+4}_{-4} M_\odot$
Final black hole spin		$0.67^{+0.05}_{-0.07}$
Luminosity distance	1Mpc ~ 3 million light years ~ 3 x 10^24 cm	410^{+160}_{-180} Mpc
Source redshift z	Obtained from the luminosity distance using Planck cosmology … not important	$0.09^{+0.03}_{-0.04}$

LIGO&Virgo (2016)

Summary of binary black holes

We saw many heavier-than-expected black holes



- low metal pop I/II?
  isolated binary?
  dynamical capture?
- pop III (first stars)?
- primordial BHs?

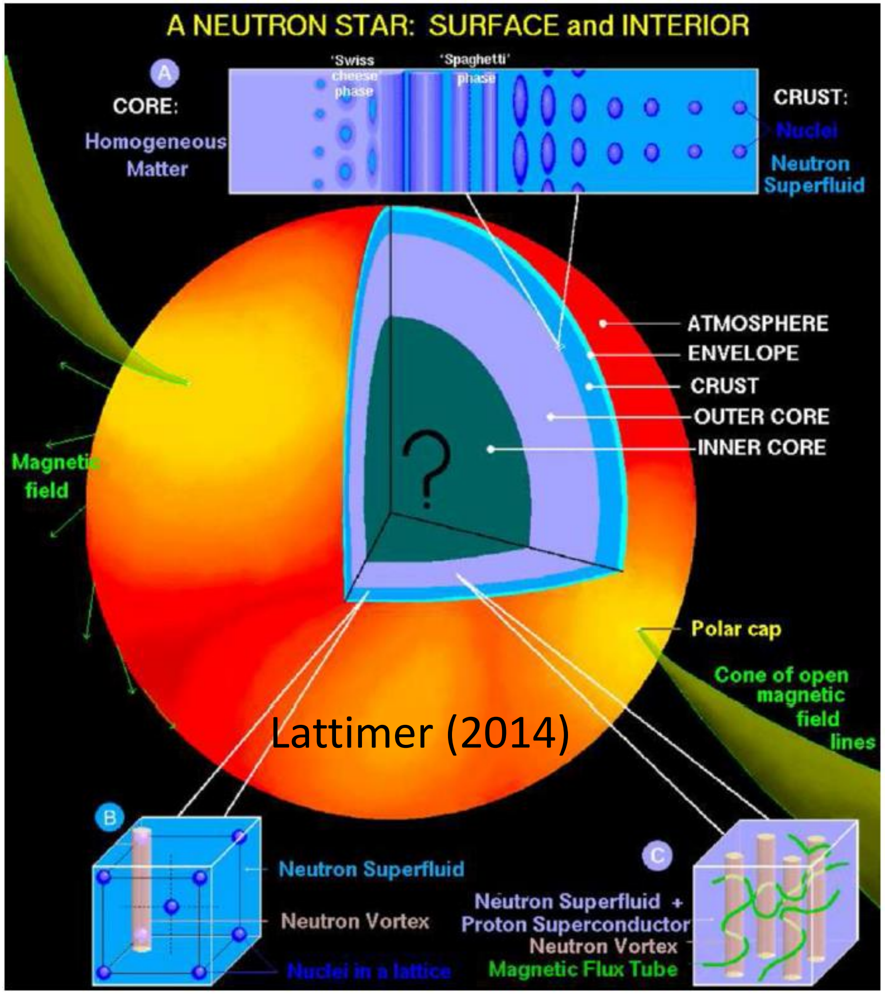
statistics necessary

https://www.ligo.org/detections/GW170608/images-GW170608/BH_NSmassplot_error_bars.png

Neutron star

Remnant of massive stars
(mass range is uncertain)

Mostly consists of neutrons
1.4 solar mass, ~10km
The density is higher than nuclear saturation values
“a huge nucleus”
Arena for nuclear physics



GW170817

LIGO twins observed

clear “chirp” signals, i.e.,

gravitational waves with

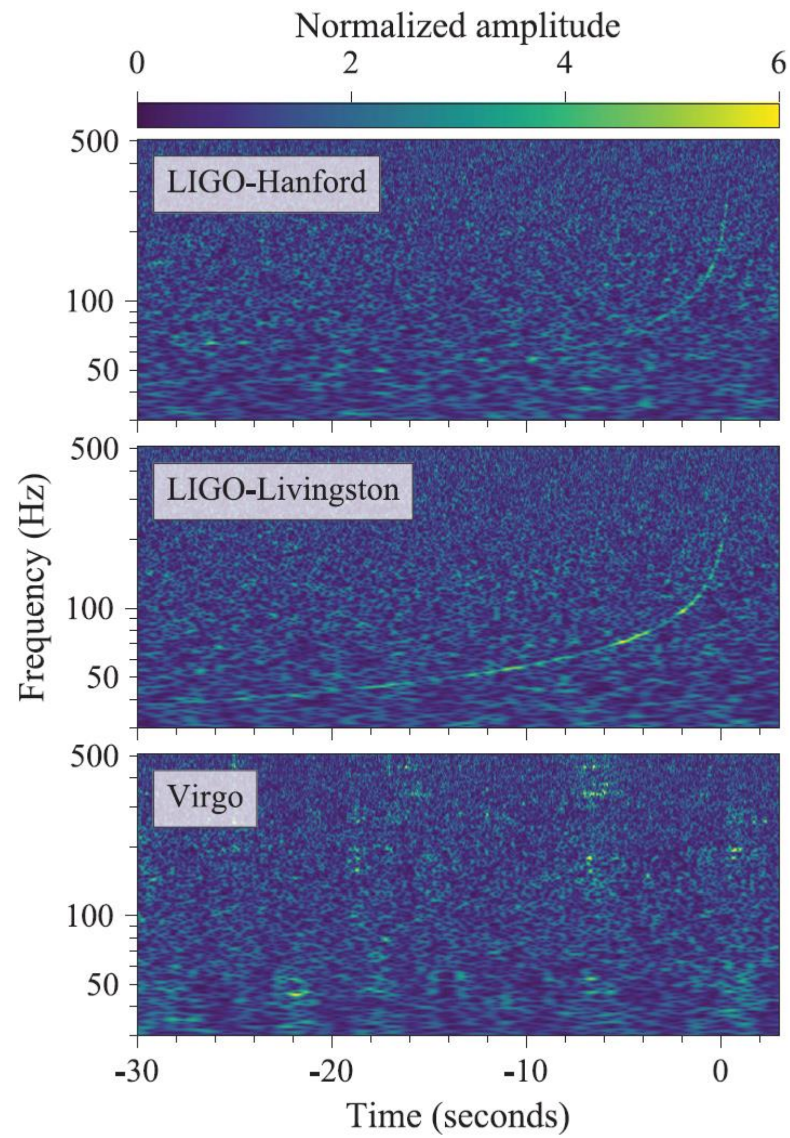
increasing frequency

and amplitude in time

But Virgo did not see…

-> the source should be

at Virgo’s blind spot!

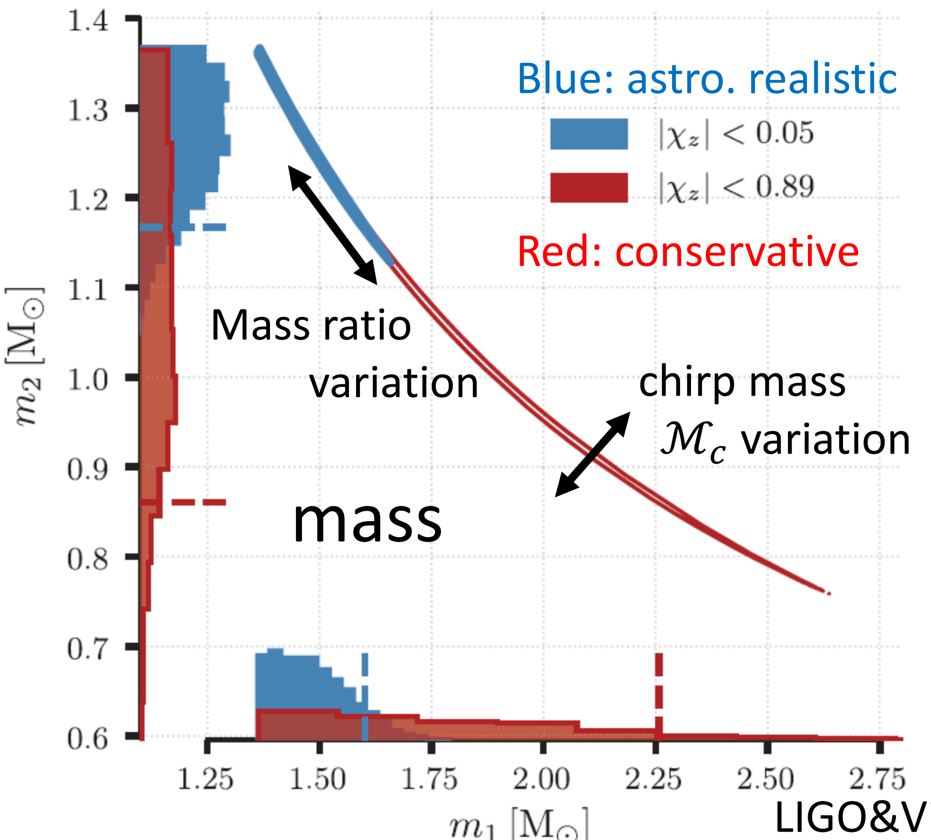


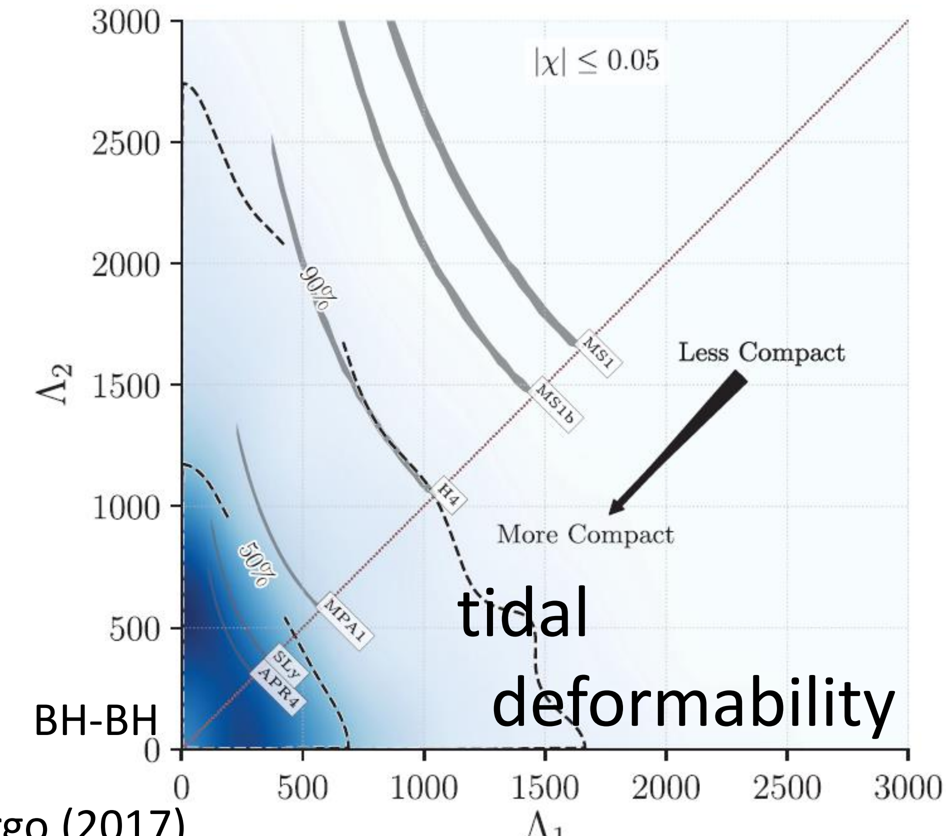
LIGO&Virgo (2017)

Constraints on parameters

The NS radius may be smaller than ~13-14km

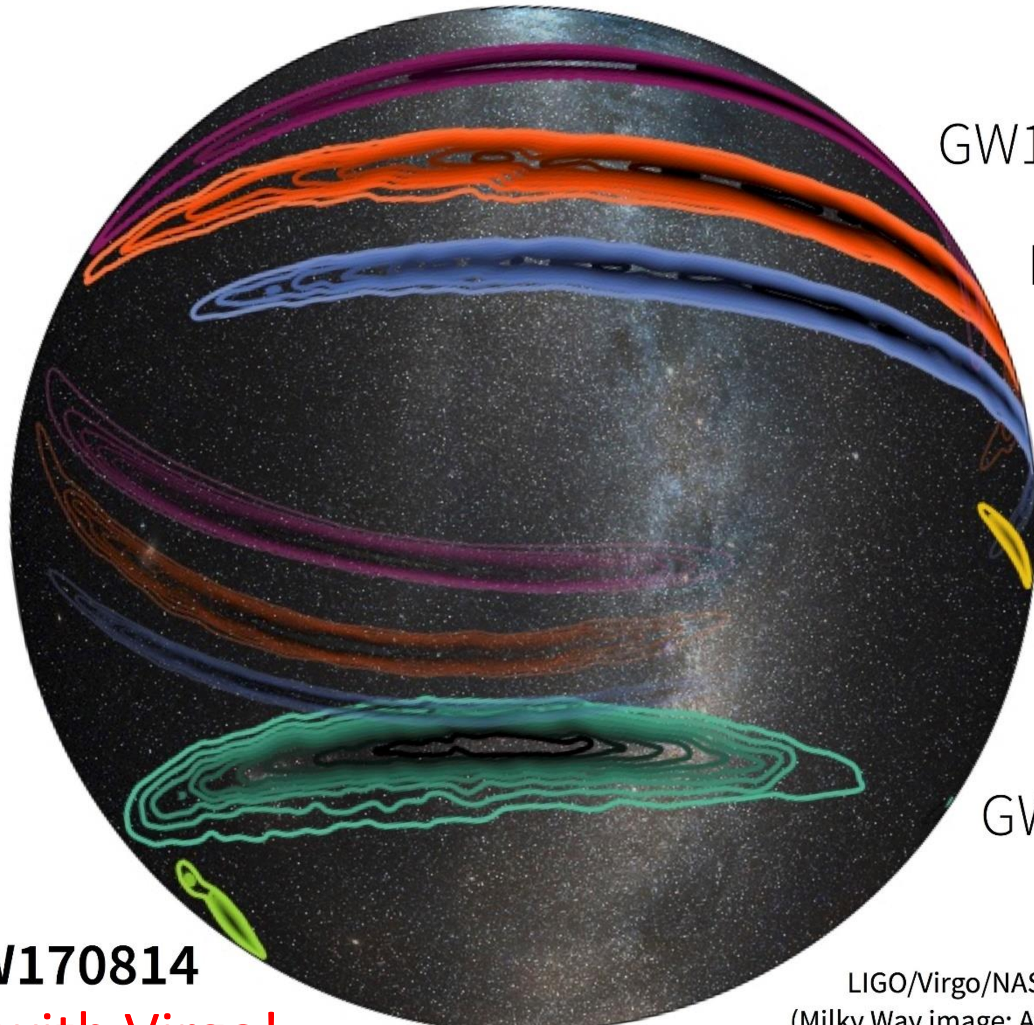
- this can be made tighter with better waveforms





LIGO&Virgo (2017)

Sky map and localization accuracy



GW170104

LVT151012

GW151226

GW170817

Improved with Virgo!

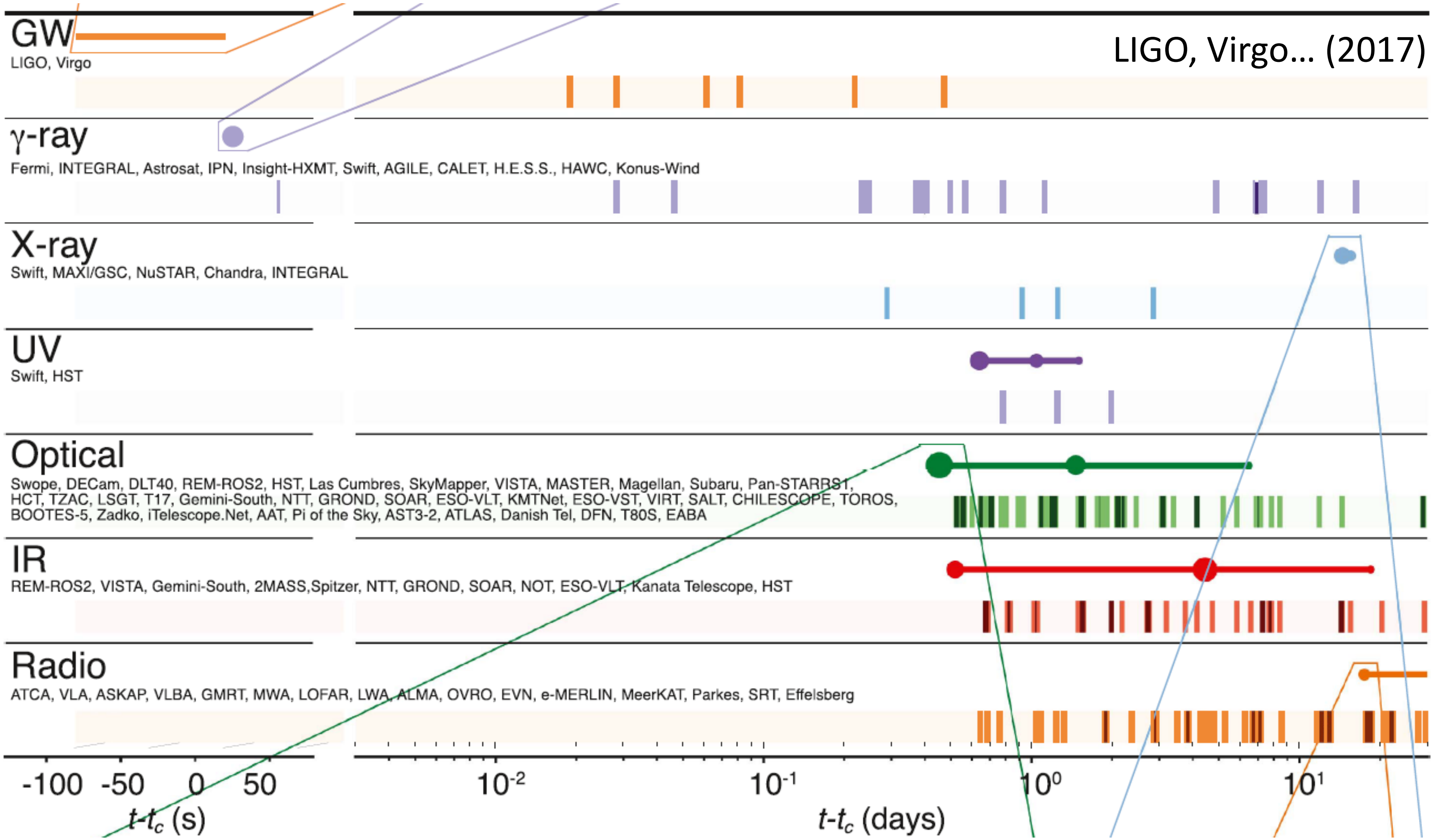
GW150914

GW170814

Improved with Virgo!

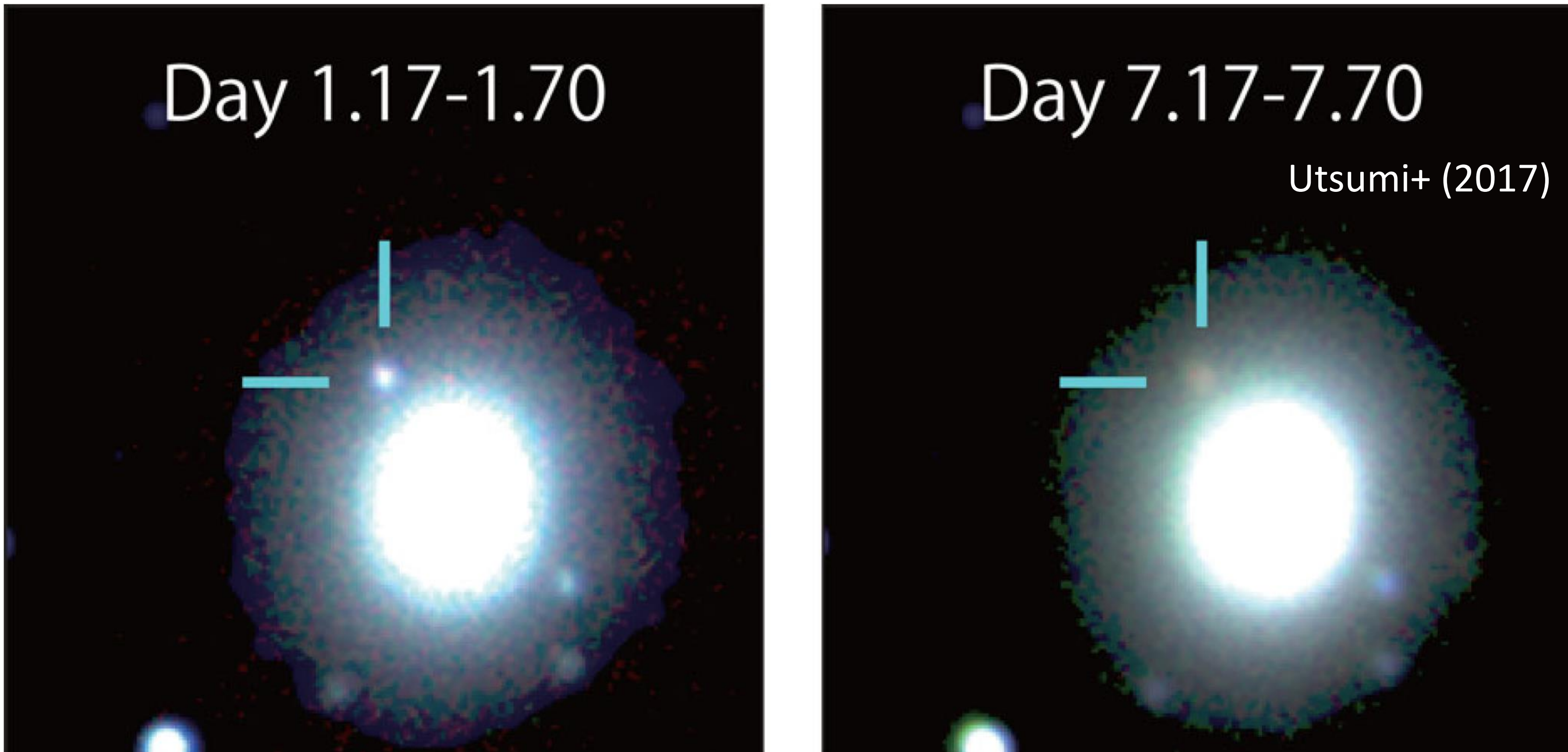
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)
http://www.ligo.org/detections/GW170817/images-GW170817/O1-O2-skymaps-white.jpg

Electromagnetic followup



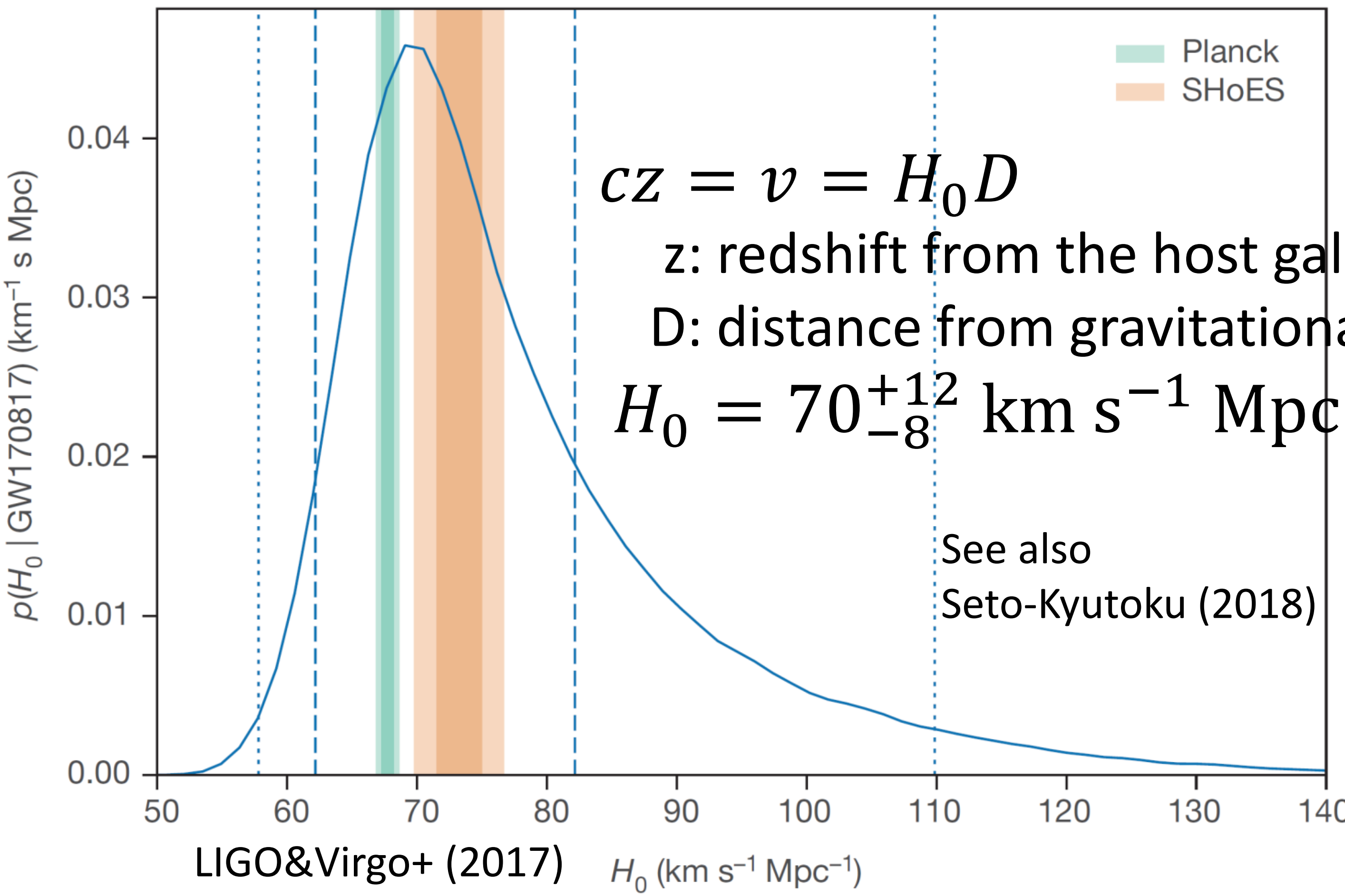
Transient and host galaxy

Lenticular galaxy that experienced minor merger



Gravitational-wave cosmology

Hubble's constant is determined in a novel manner



CMB
Supernova

$$cz = v = H_0 D$$

z: redshift from the host galaxy

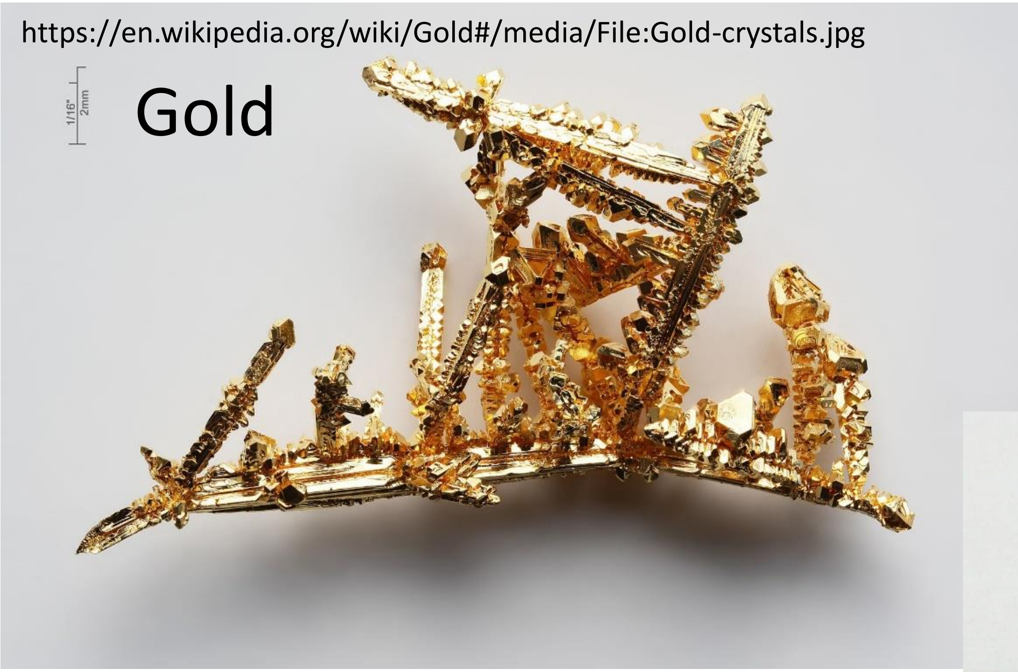
D: distance from gravitational waves

$$H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

See also
Seto-Kyutoku (2018)

LIGO&Virgo+ (2017)

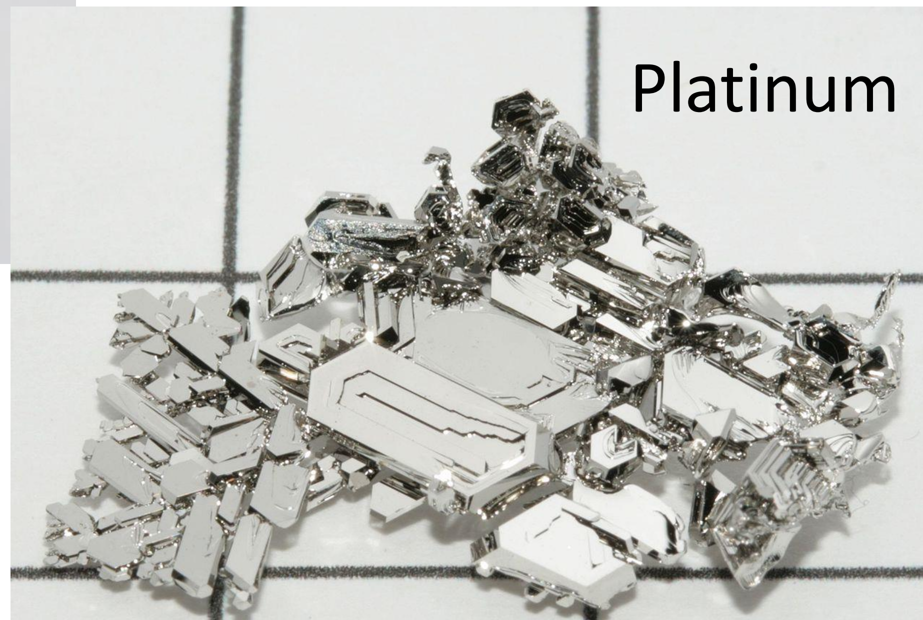
r-process element



a half of nuclides heavier than the iron

- the other half for “s”

Where in the Universe are they produced?



https://en.wikipedia.org/wiki/Platinum#/media/File:Platinum_crystals.jpg

Kilonova/macronova

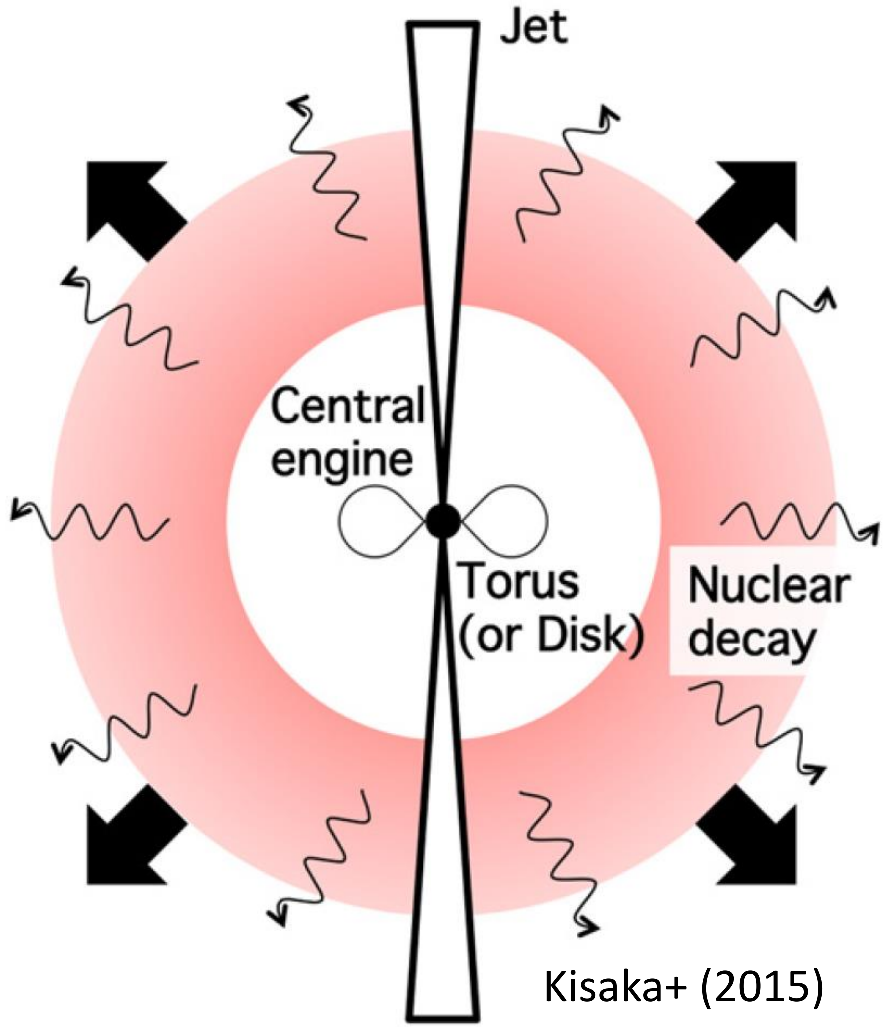
Ejected material contain radioactive r-elements

Their decay heat the ejecta

Thermal photons try to diffuse from the ejecta

But r-elements efficiently traps the photon inside

Characteristic “kilonova”!



Kisaka+ (2015)

AT 2017gfo

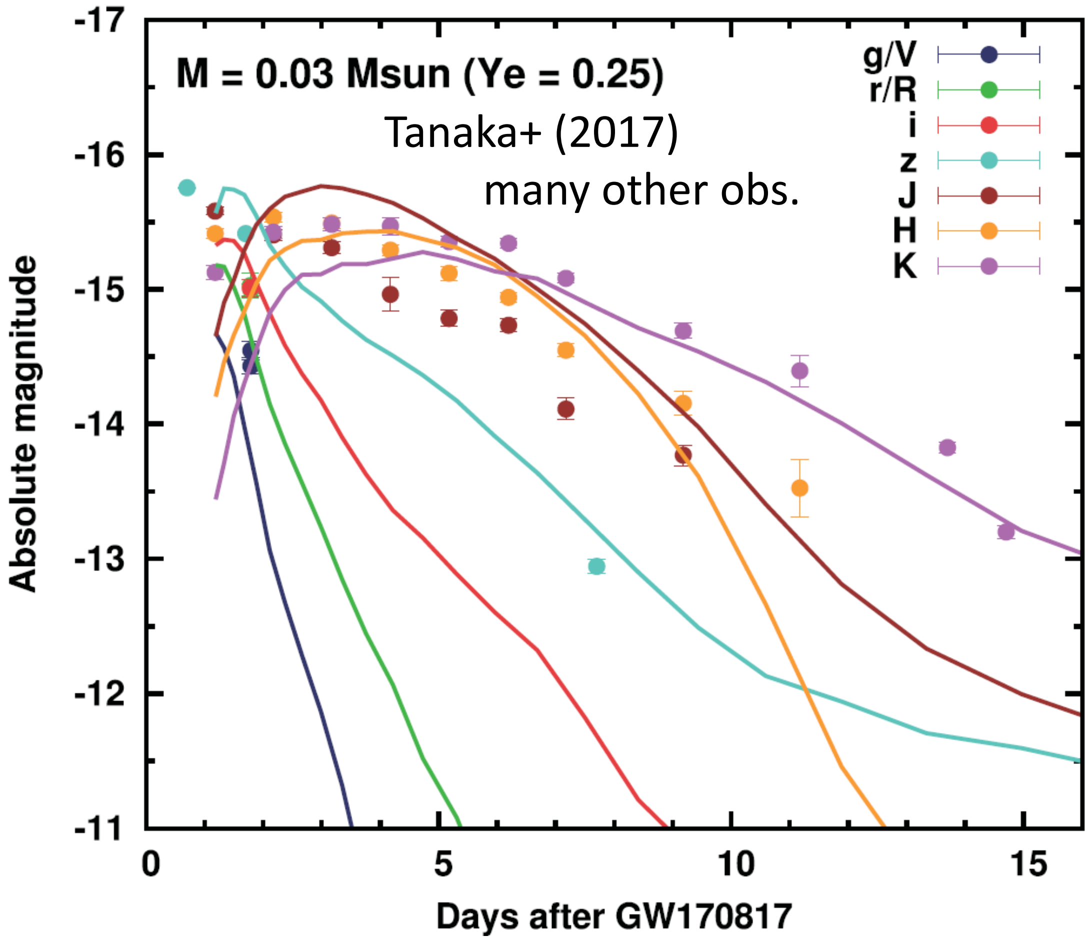
In general agreement with theoretical models

particularly in NIR

Compared to SNe

- small mass
- high velocity
- high opacity
- no time scale

  of the heating



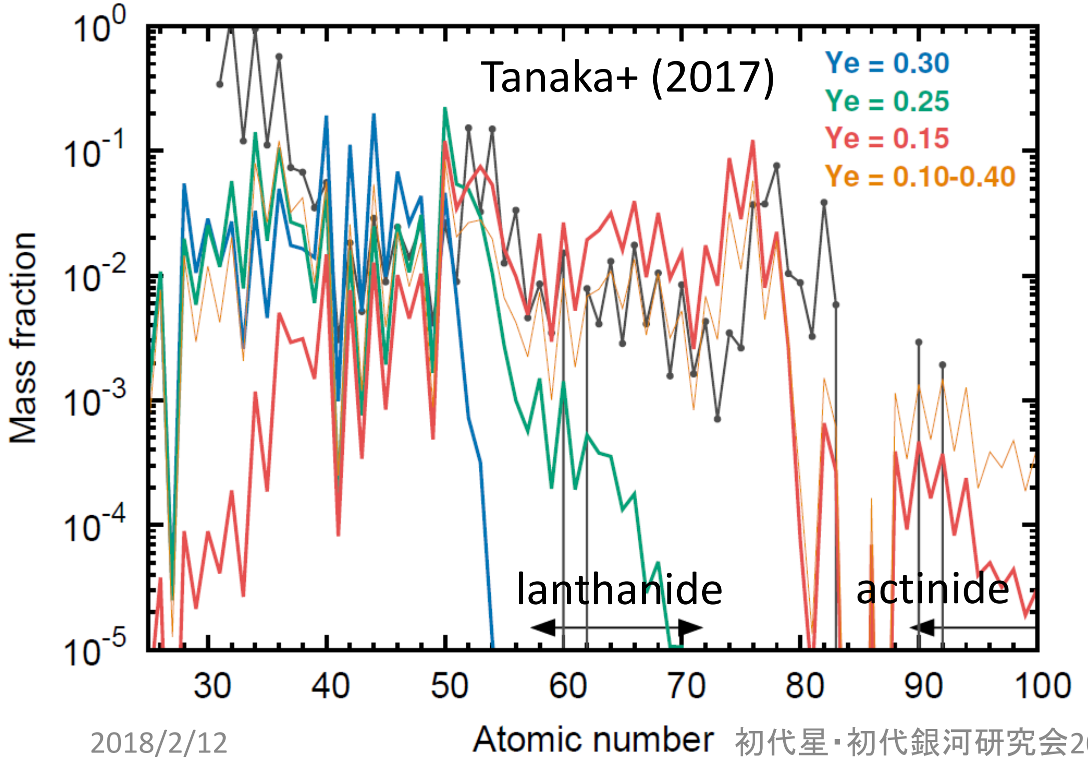
Two component?

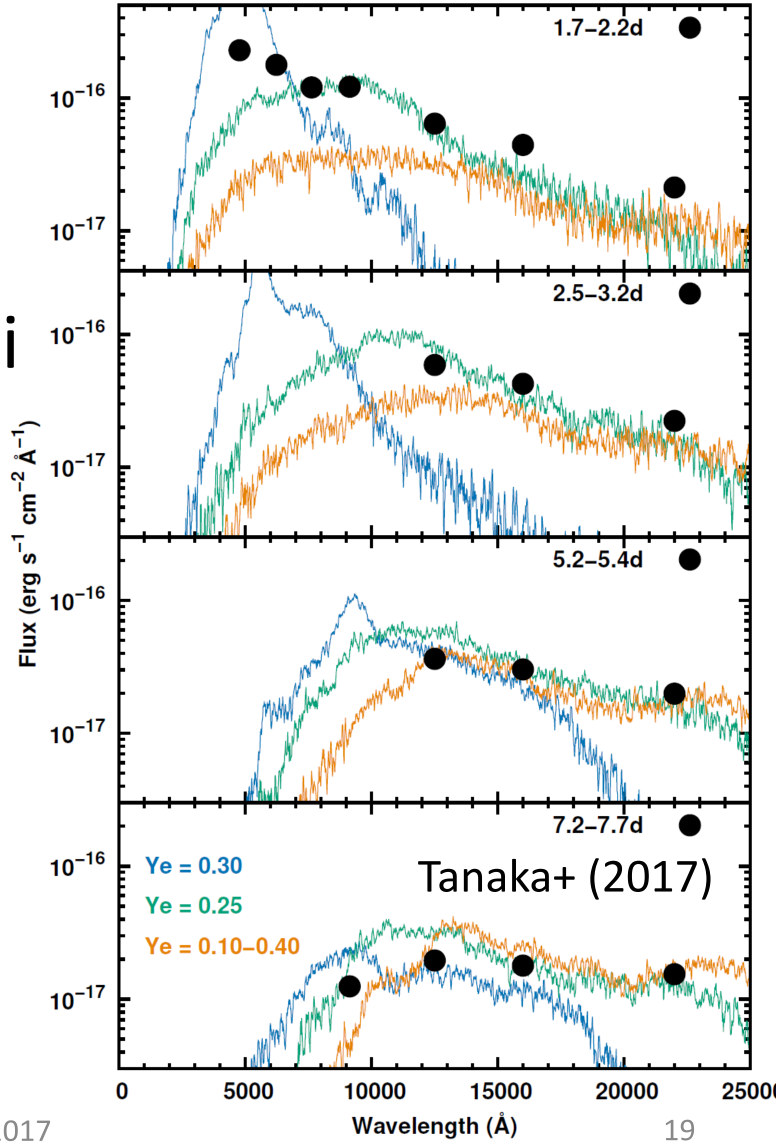
lanthanide-free
intermediate
lanthanide-rich

Early lanthanide-free +

late lanthanide is very likely

No evidence for heaviest nuclei

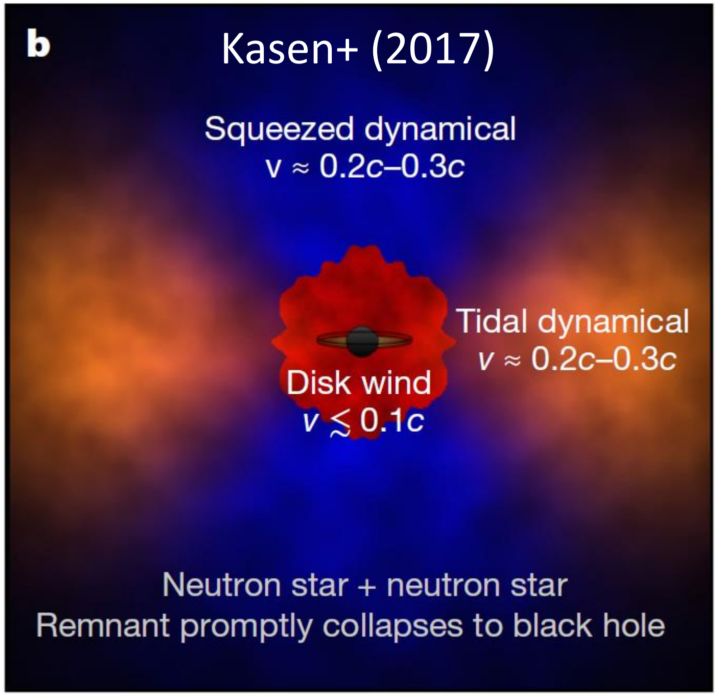




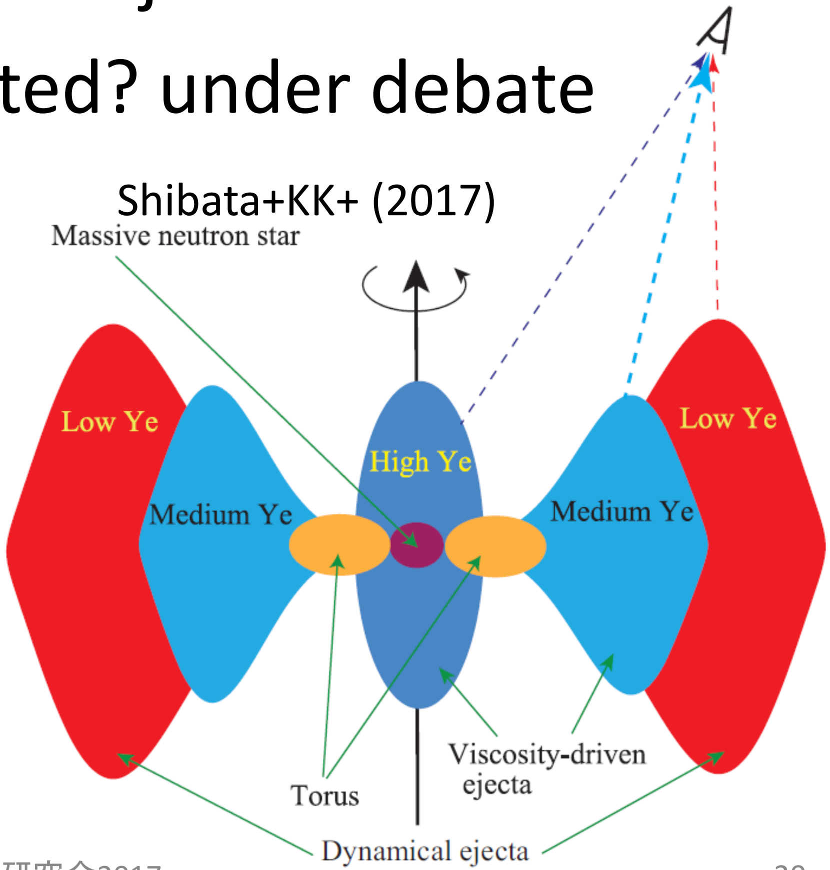
Theoretical modeling

Likely fast light r-elements + slow heavy r-elements

- the latter may be dynamical ejecta or disk wind
- how the former is generated? under debate



Shibata+KK+ (2017)



Short gamma-ray burst

About 10^{51}erg/s explosions

- the sun is $\sim 4 \times 10^{33}$erg/s

Long-soft GRB: ≥ 2s

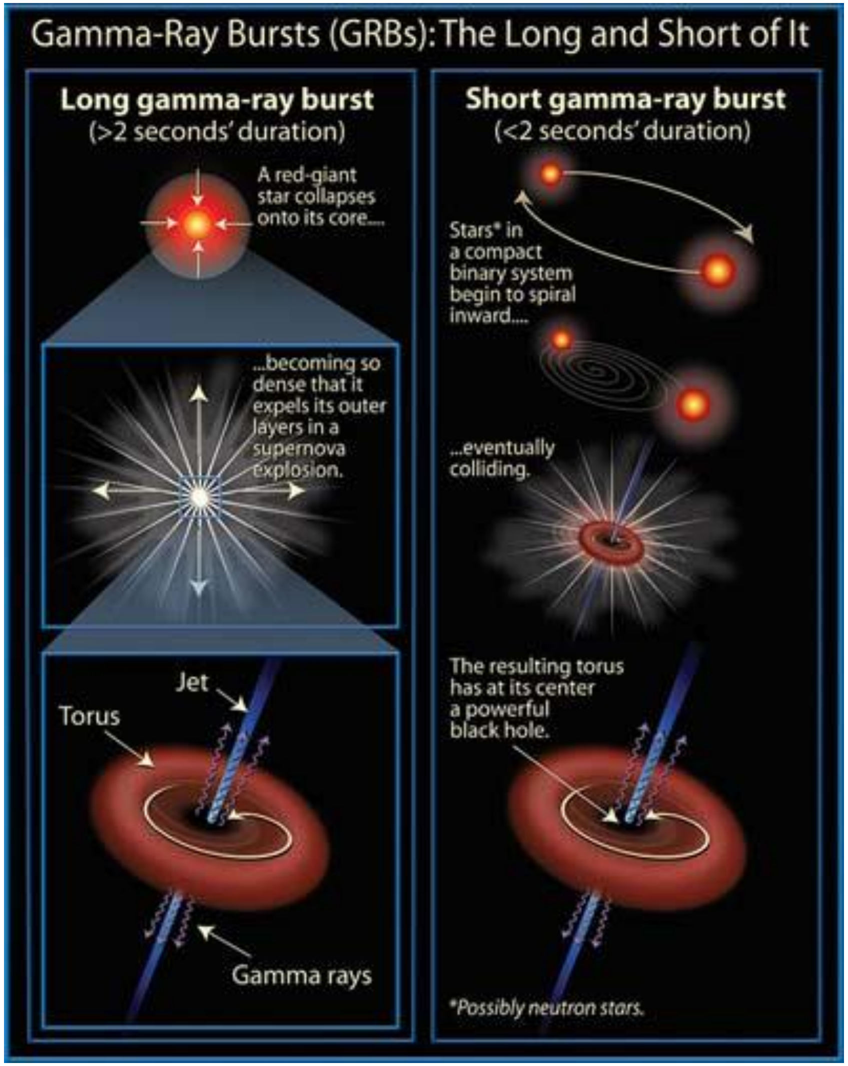
deaths of massive stars

Short-hard: $\leq$ 2s

neutron star binary merger?

rigorous confirmation needs

gravitational waves

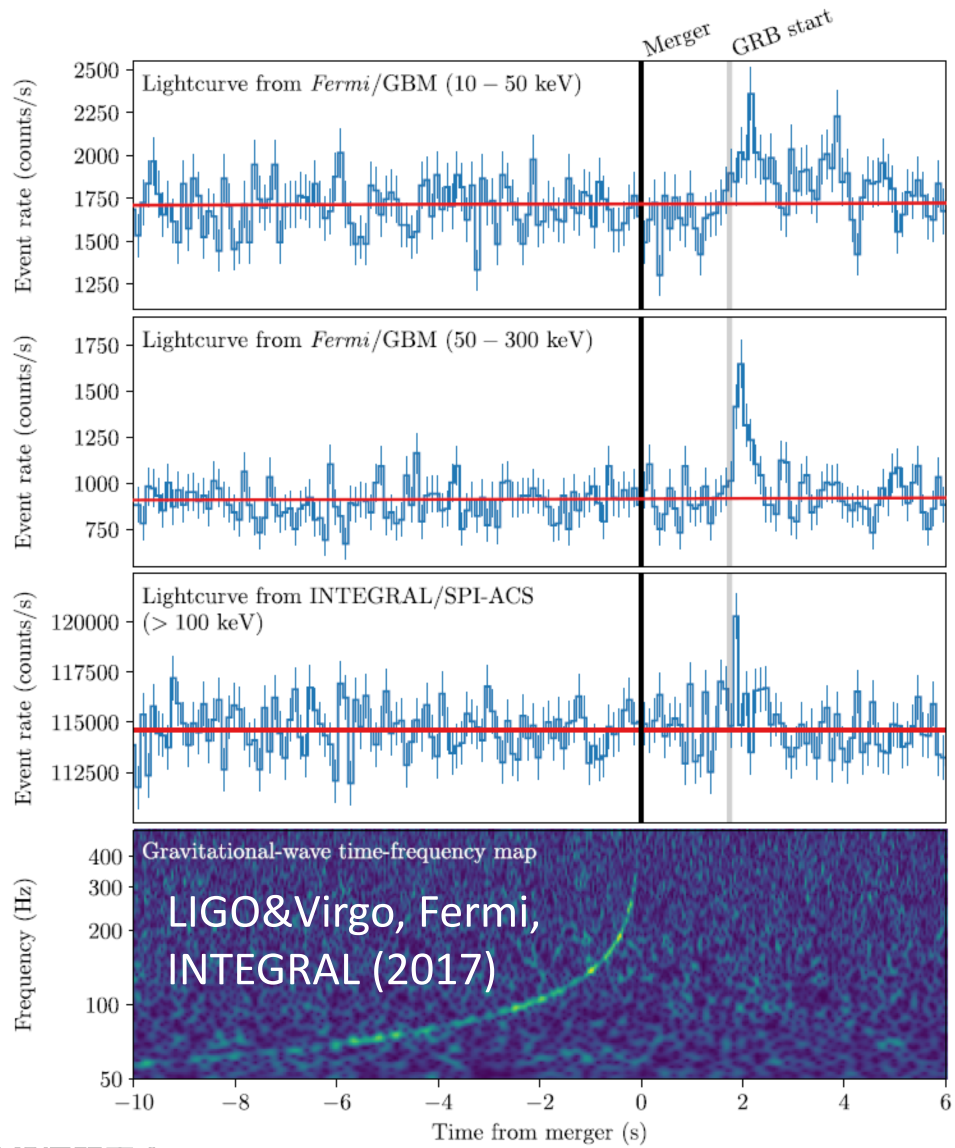


http://www.daviddarling.info/images/gamma-ray_bursts.jpg

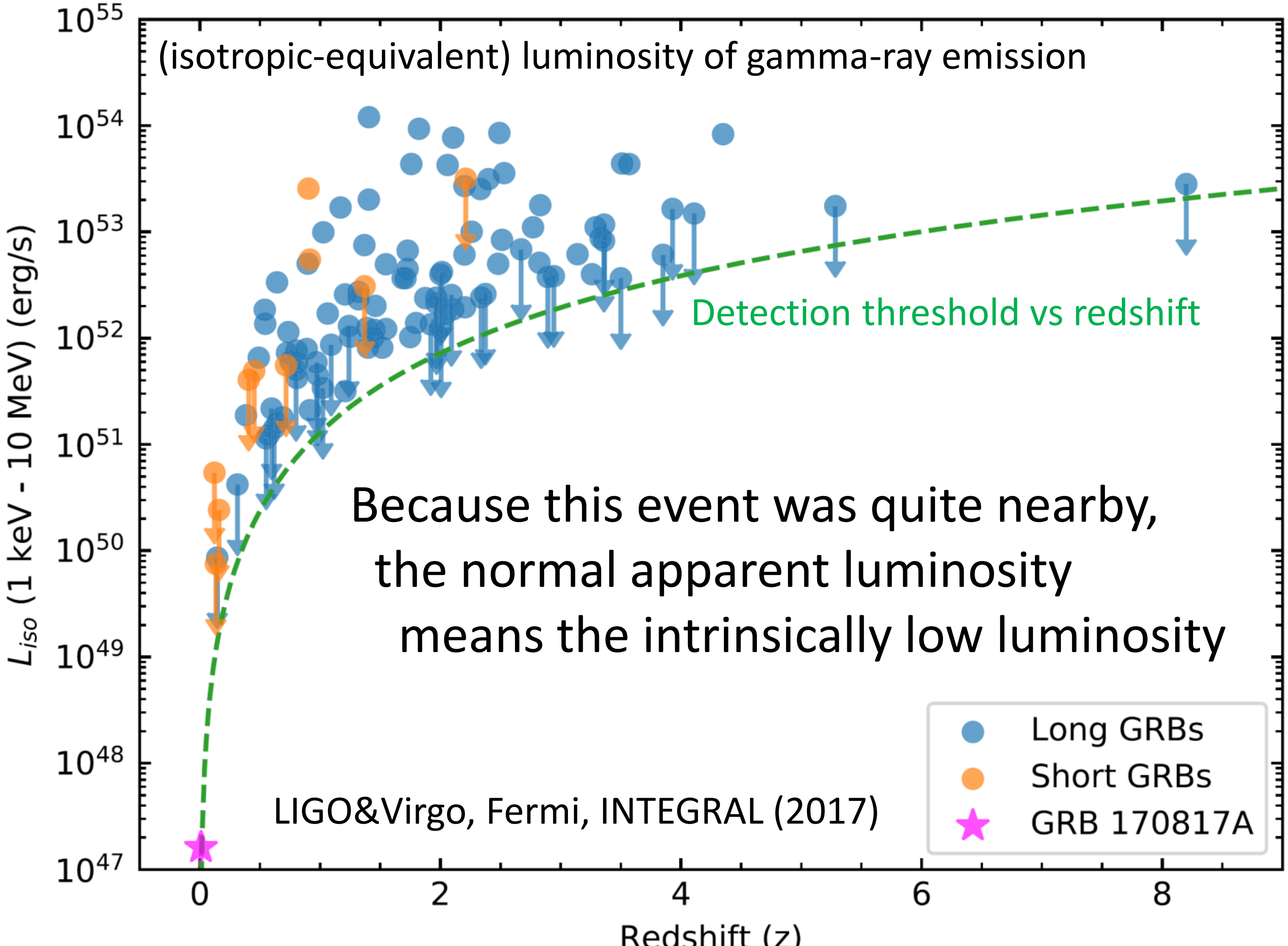
GRB 170817A

Fermi and INTEGRAL
agree each other
though relatively weak

This also implies that
gravitational waves
propagate with
the speed of light

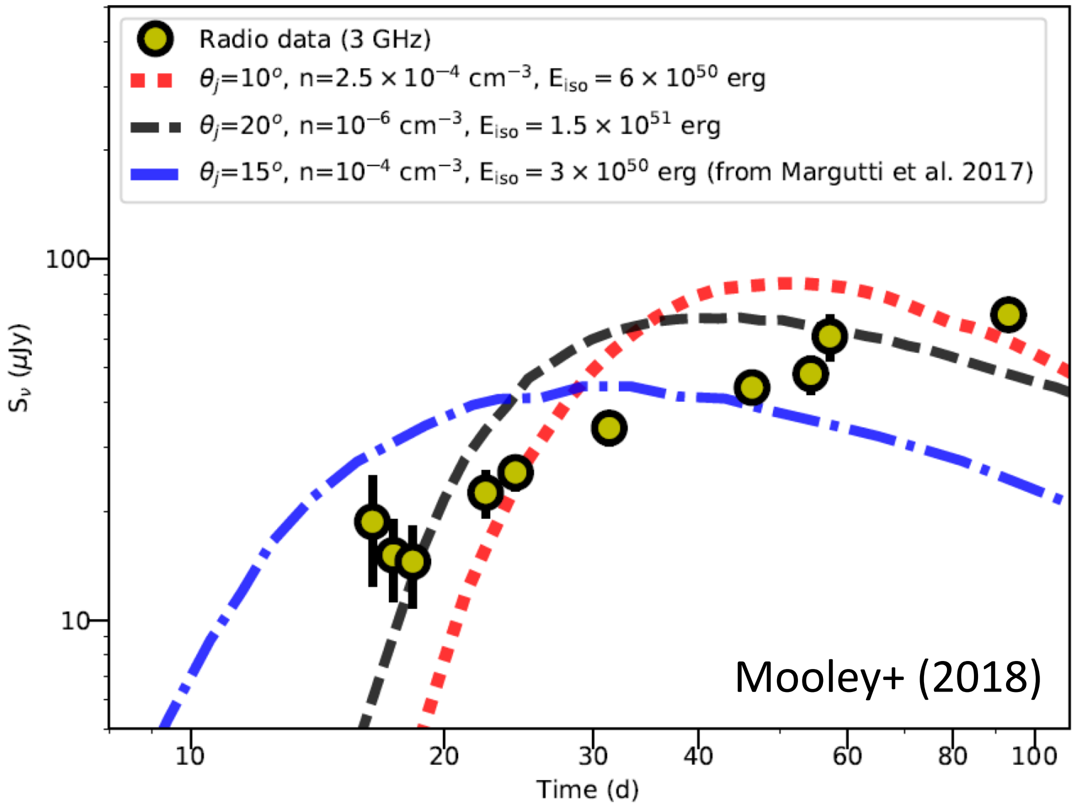


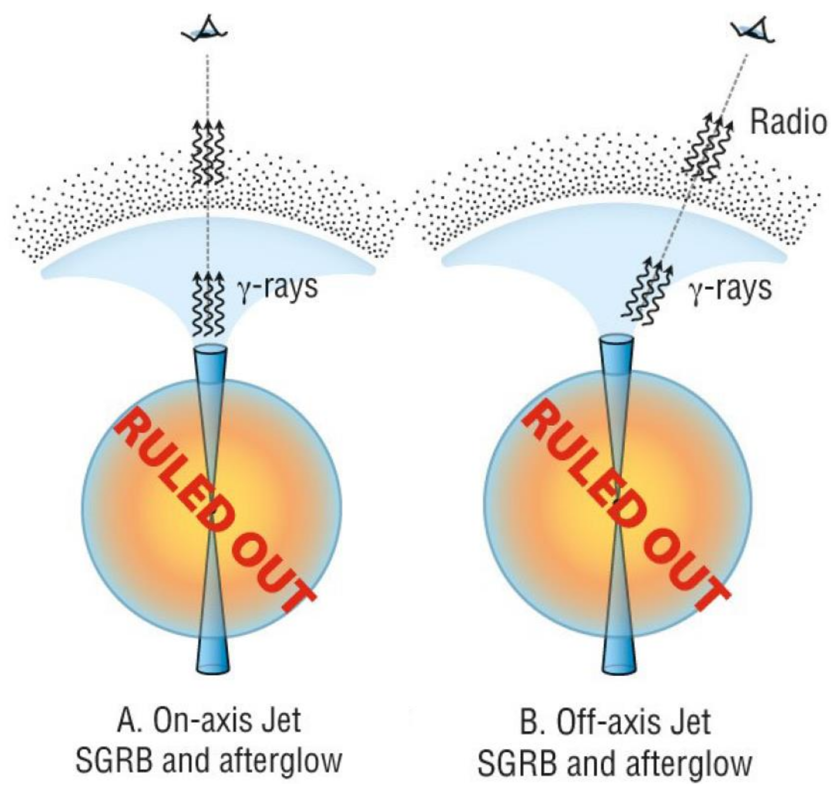
Underluminous…



Continuously brightening afterglow

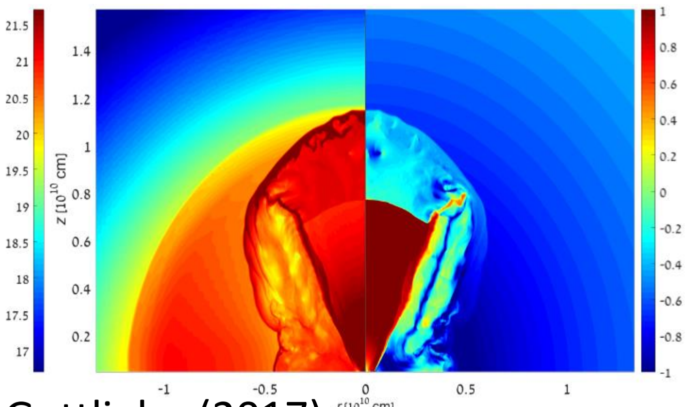
An ultra-relativistic top-hat jet is not consistent with continuously brightening afterglow (X/opt/radio)



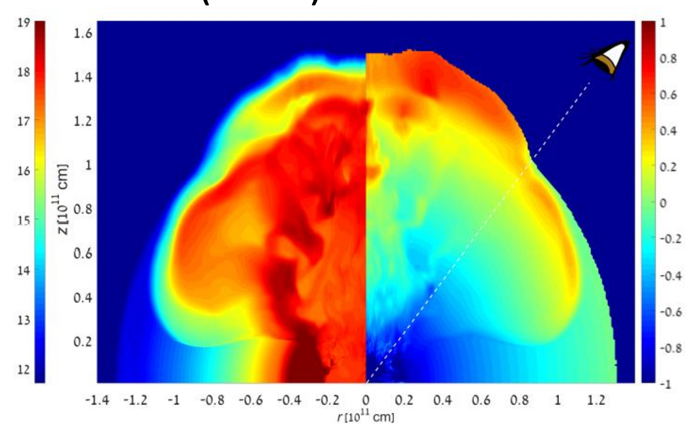


Cocoon or structured jet?

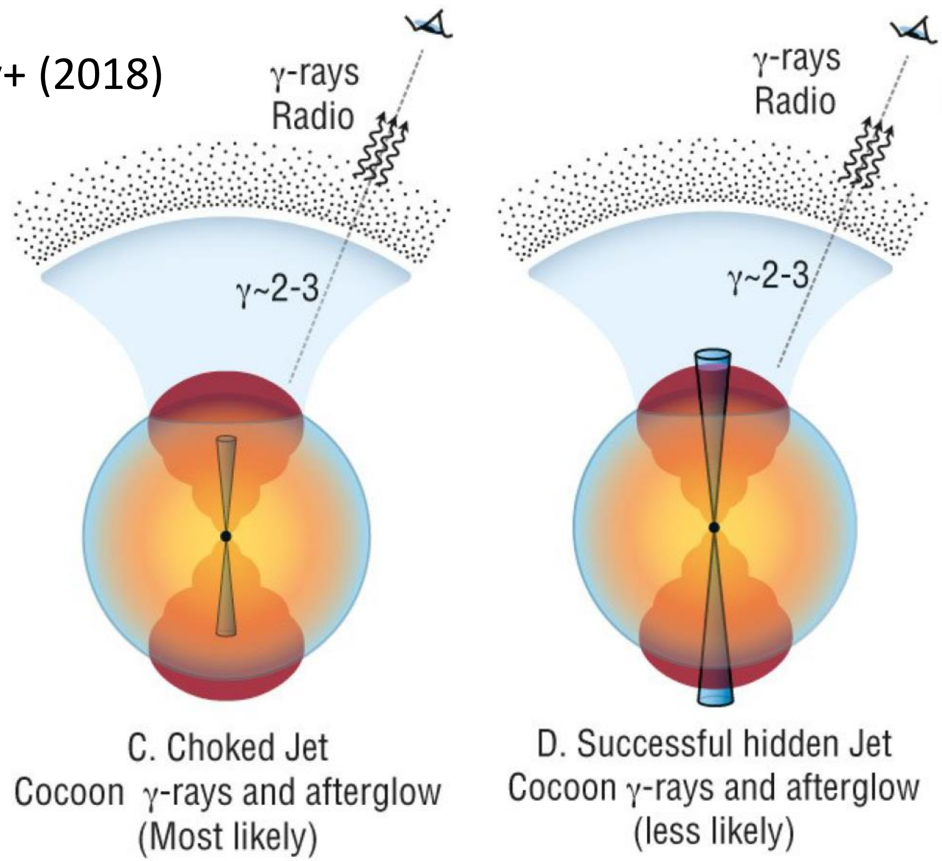
Jet-ejecta interaction should be the key ingredient but whether the jet has break out or not is unclear



Gottlieb+ (2017)



Mooley+ (2018)



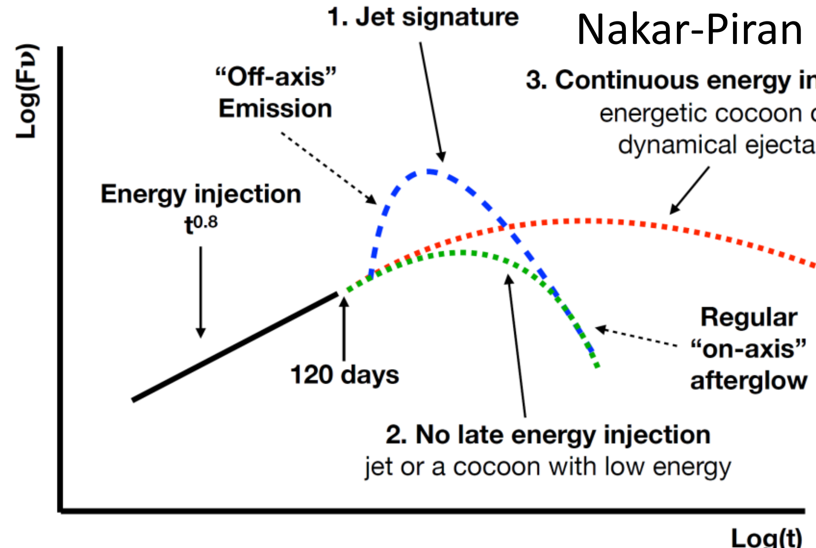
Distinguishable?

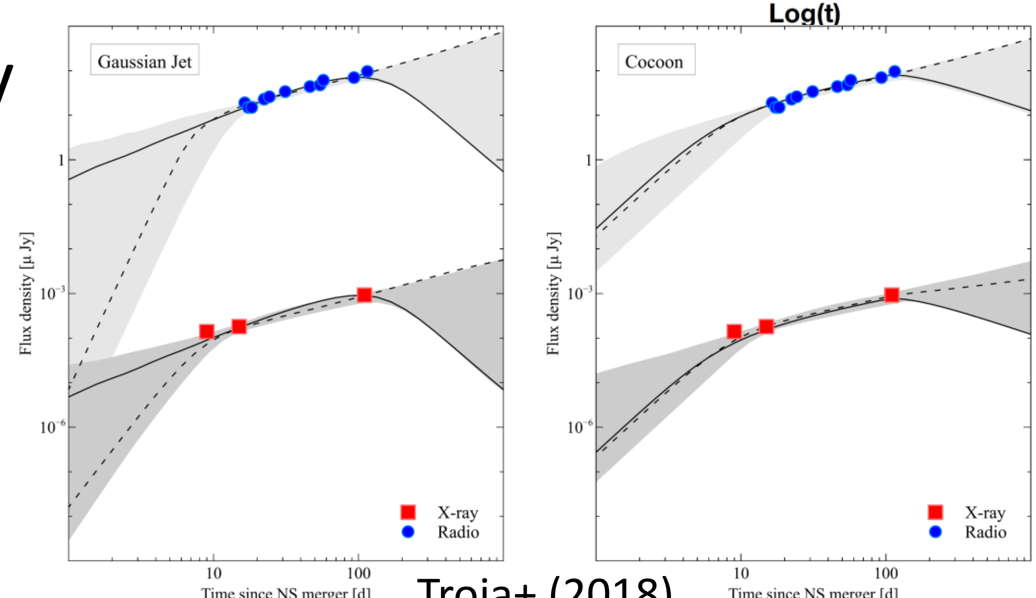
In principle possible
with late-time behavior

But it seems difficult
because of degeneracy

Eventually engulfed by
ejecta radio emission

Nakar-Piran (2018)





Troja+ (2018)

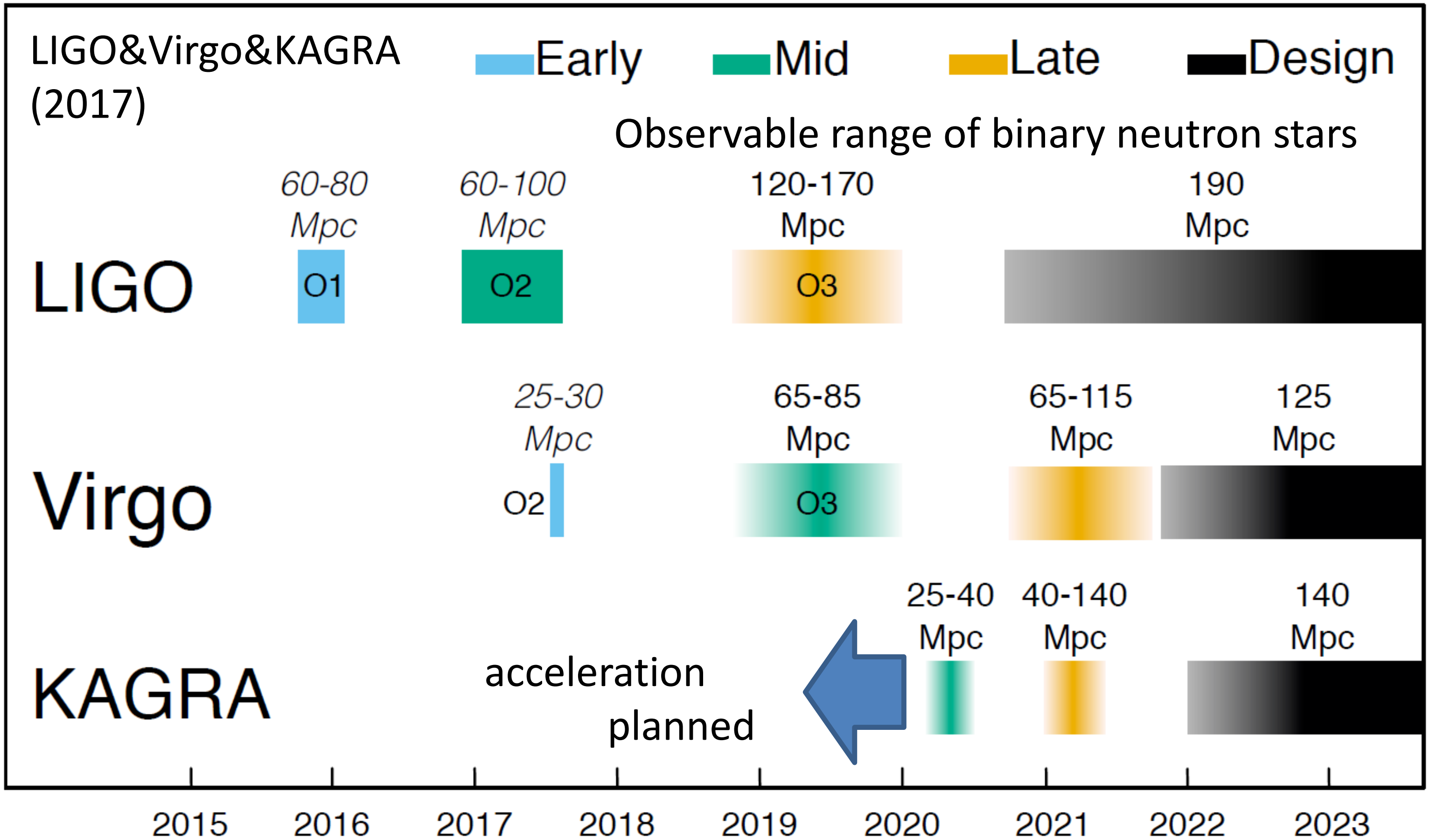
What we learned from GW170817

- Neutron stars are relatively compact (<13-14km), but GWs are consistent with binary black holes
- Short gamma-ray bursts can be driven, but this was not “the” short gamma-ray burst
- R-process elements seem to be produced, but no evidence for the heaviest (or abundance pattern)
- Hubble’s constant is measured independently and consistently with other studies
- Host galaxy, GW-EM simultaneity, etc..

2. Future with ground-based detector

Future observation

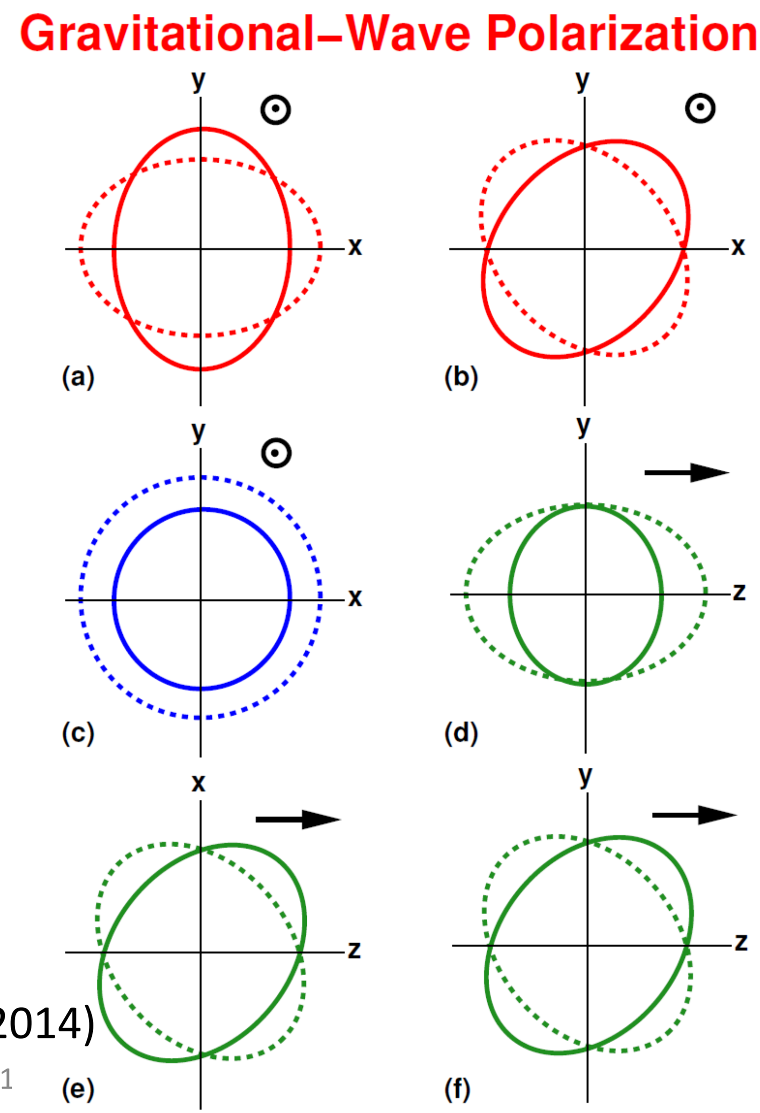
KAGRA will join in 2020s or earlier (LIGO O3?)



Polarization

KAGRA will be important to investigate whether gravitational waves are really transverse as GR predicts

The number of available detectors determines the number of constraints

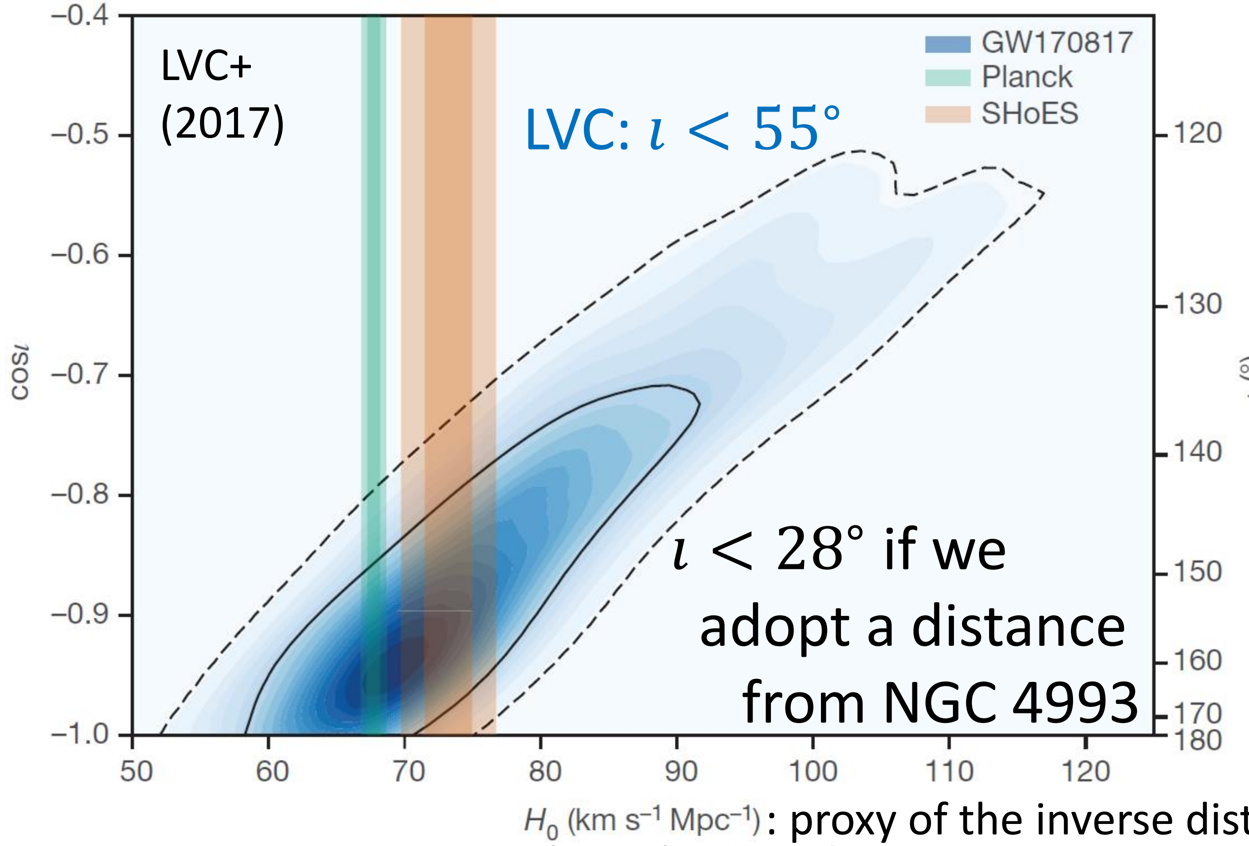


Will (2014)

Distance-inclination degeneracy

Key to understand short GRB/ejecta geometry

$\Delta\iota < 5^\circ$ is possible with Virgo or KAGRA (Arun+ 2014)



: proxy of the inverse distance here

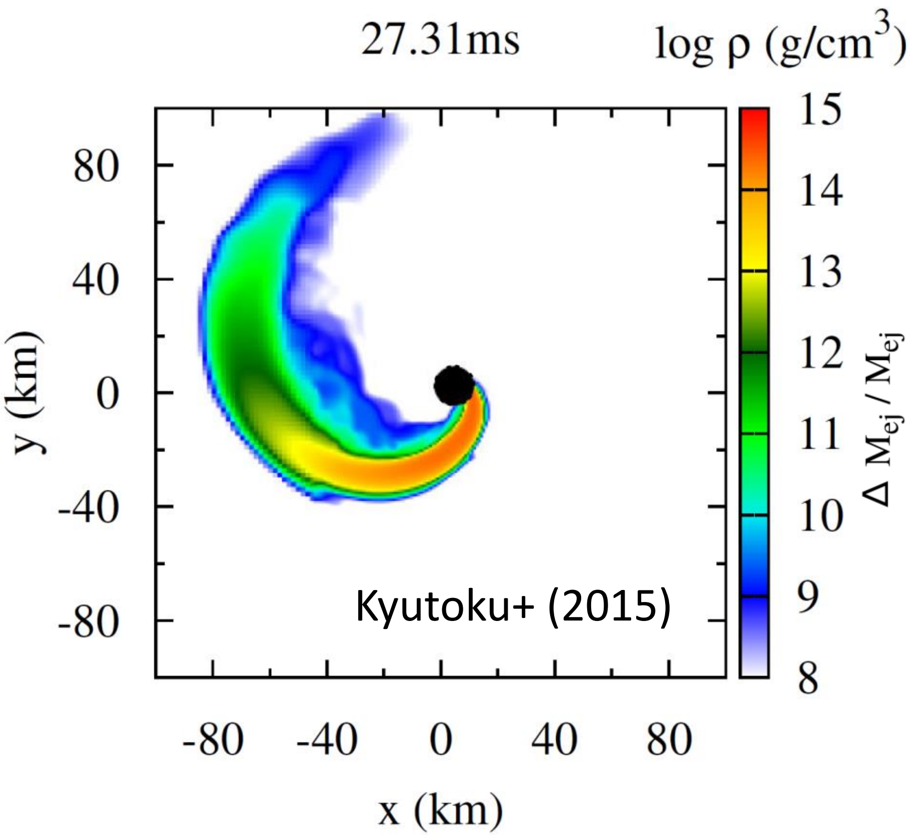
Note: Virgo did not detect GW170817

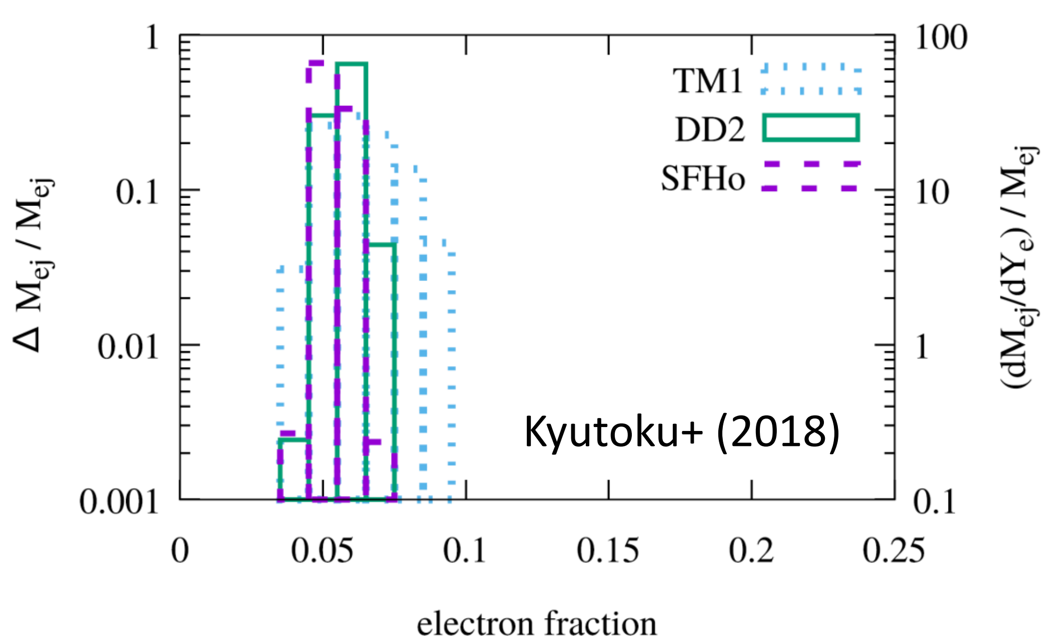
Black hole-neutron star binaries

Alternative central engines of short GRBs?

Likely to synthesize heaviest r-process elements

(extremely neutron rich)





But … headwind

Tidal disruption of neutron stars are necessary to form accretion disk and eject material, and requires

- Less massive black holes (say $< 10M_{\odot}$)
- Rapidly spinning black holes
- Less compact neutron stars

None of them are supported by GW observations

-> neutron stars may not be disrupted frequently

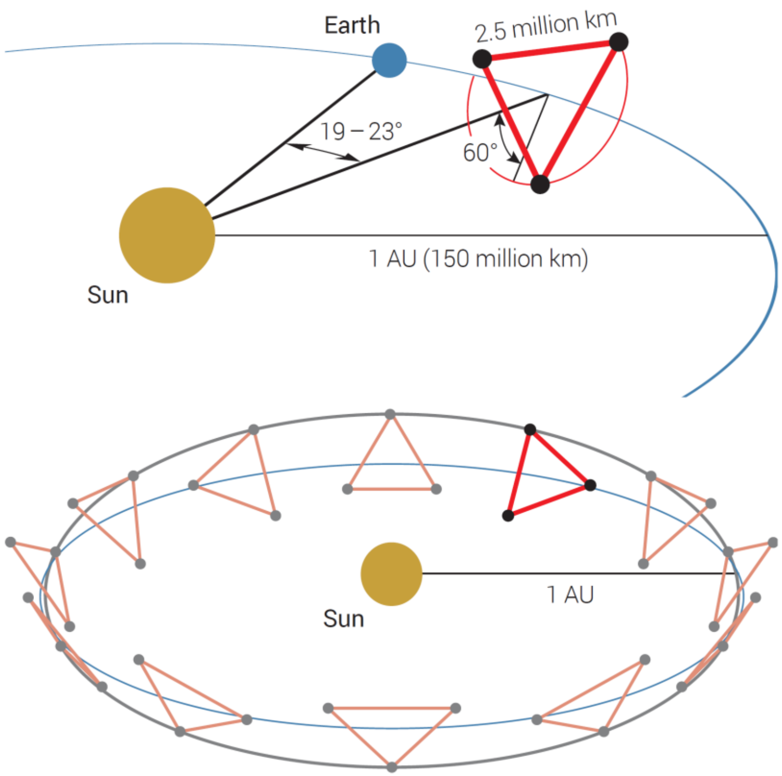
-> not distinguishable from binary black holes?

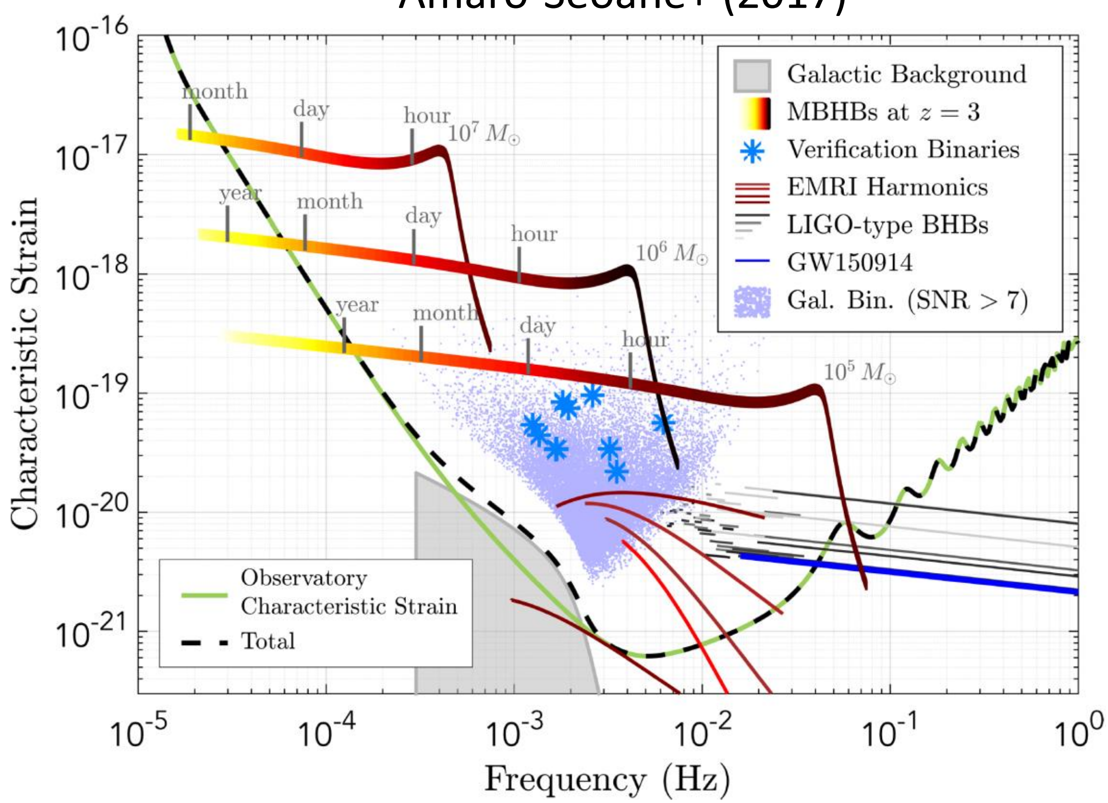
3. Future with space-borne detector

LISA

Space-borne gravitational-wave detector operated by ESA/NASA, sensitive at ~mHz bands

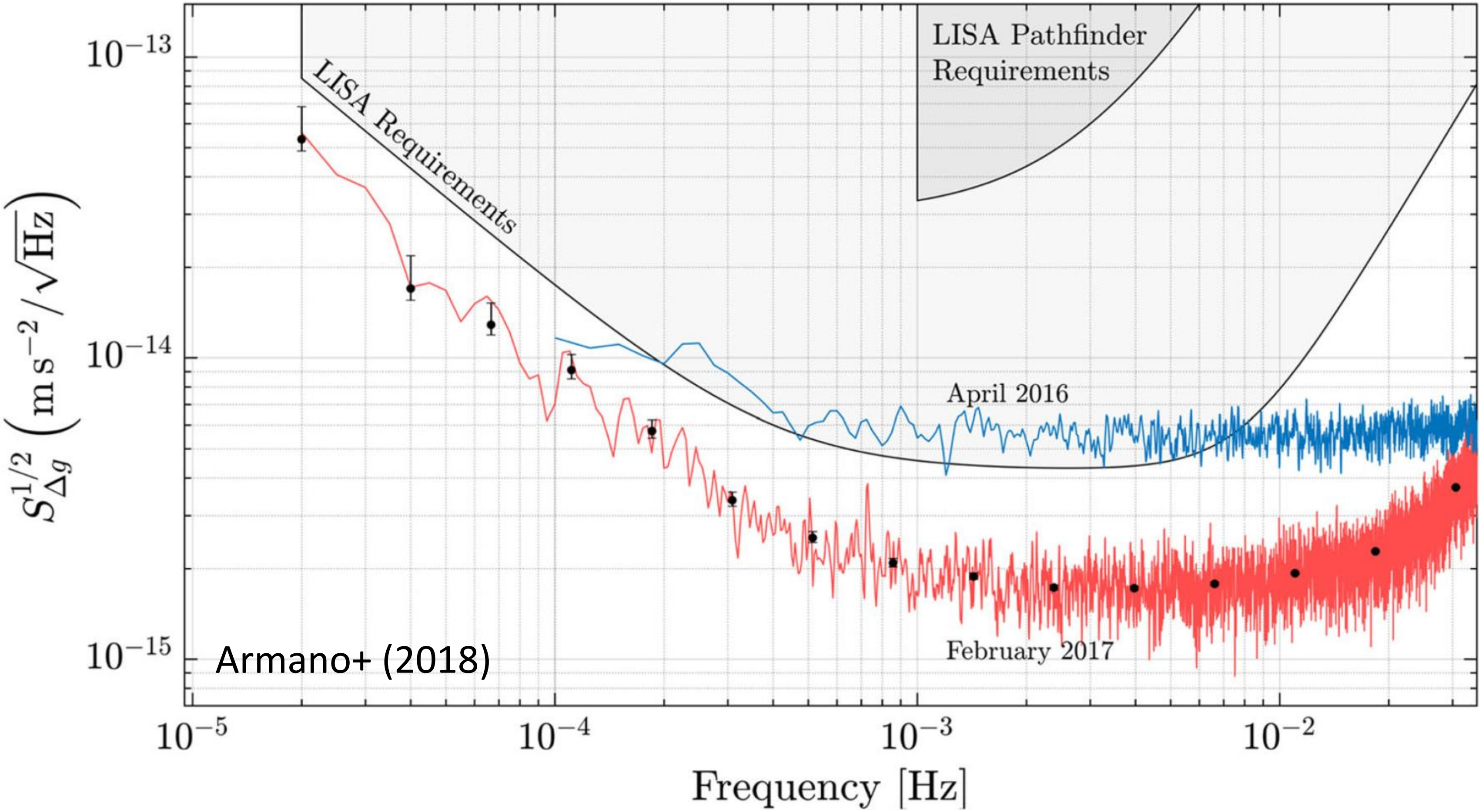
Amaro-Seoane+ (2017)





LISA Pathfinder

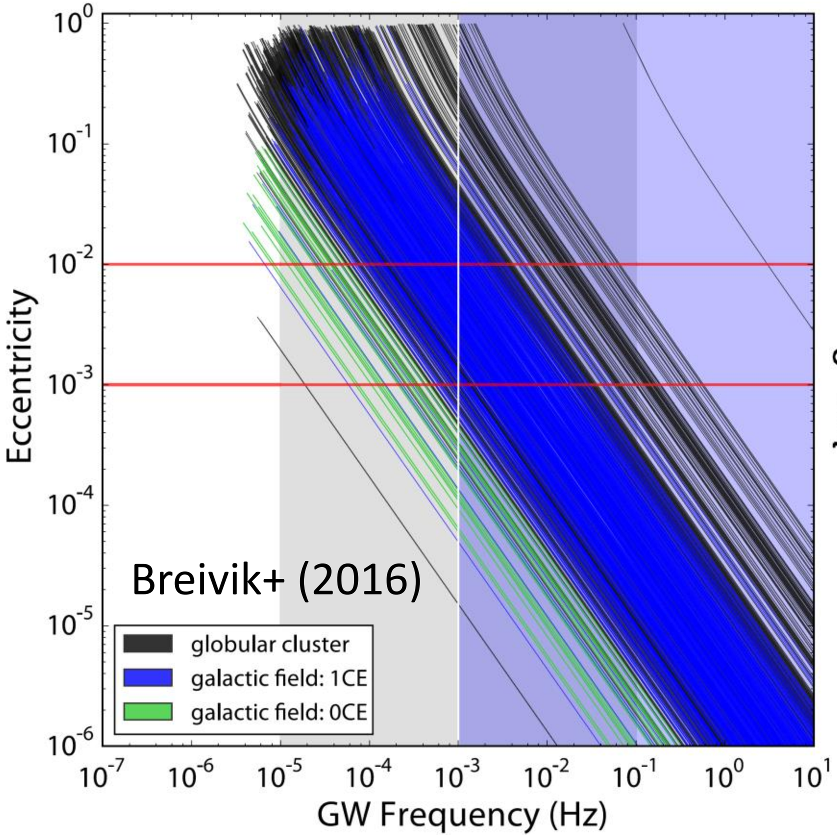
Noise requirement for LISA has already satisfied



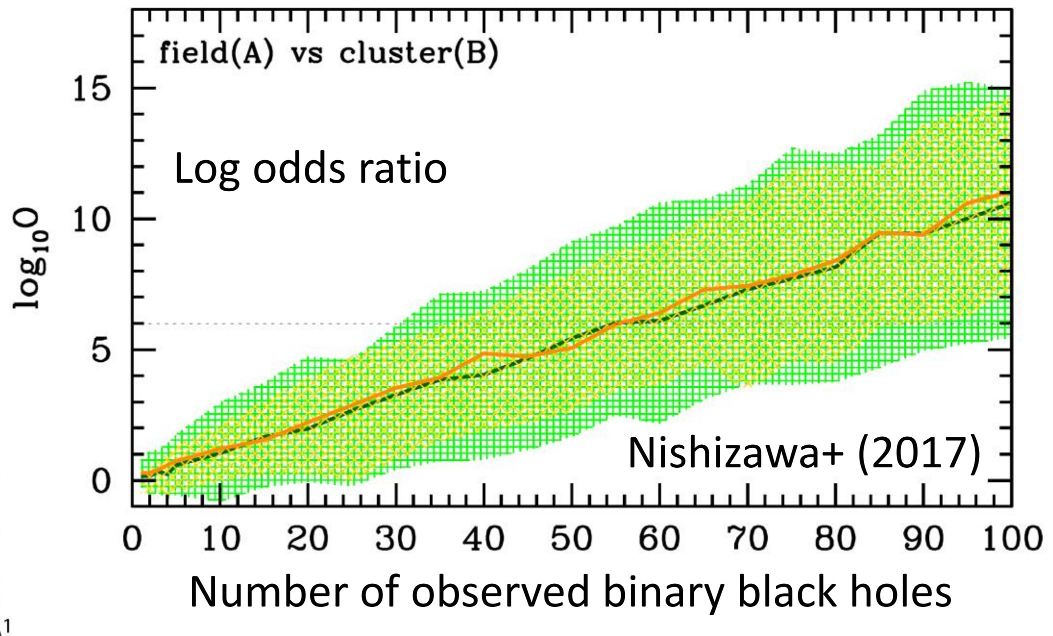
Formation scenario from eccentricities

Dynamical formation tends to give large eccentricity

100 obs. will allow us to distinguish scenarios



pop III? primordial BHs?



Other advantage of LISA

Q. Why observe binary black holes from space?

A. Good for positional astronomy (astrometry)

- The distance is determined more accurately

Detector calibration will be improved for LISA, and the amplitude will be determined accurately

- The sky location is determined more accurately

LISA uses the Doppler shift due to its own motion

On host galaxies of binary black holes

What is the host ost galaxy of massive black holes? suggested to be dwarf galaxies by some authors

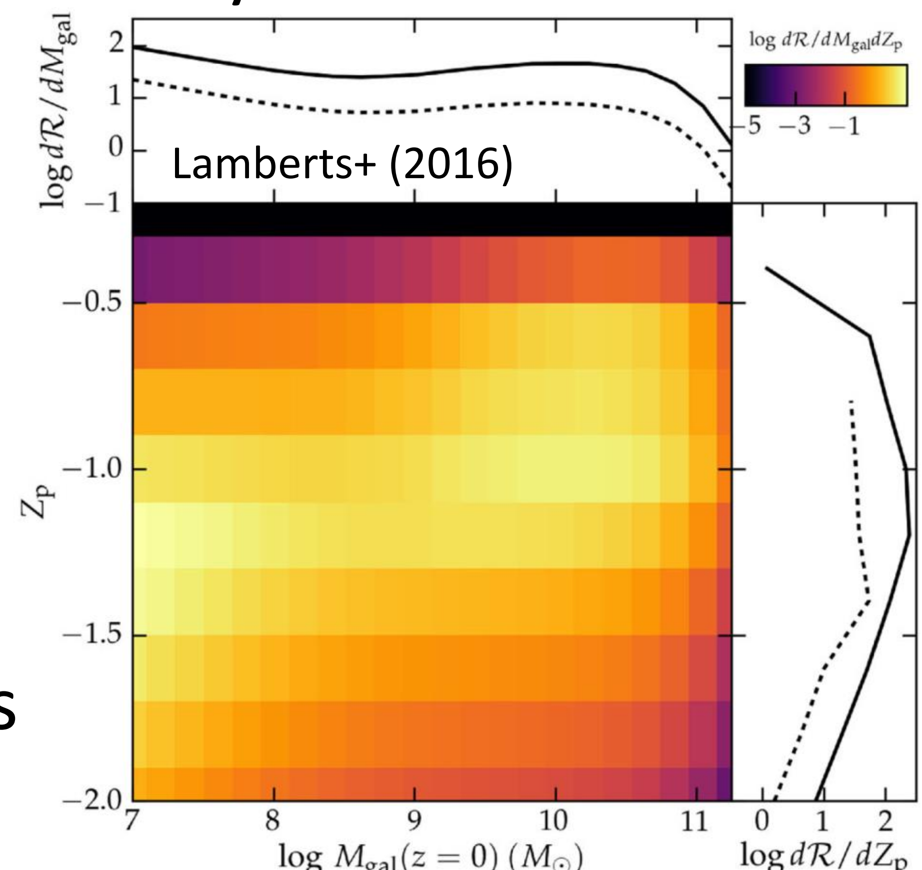
To determine the host,

- detect EM counterparts

  …hopeless (I believe)

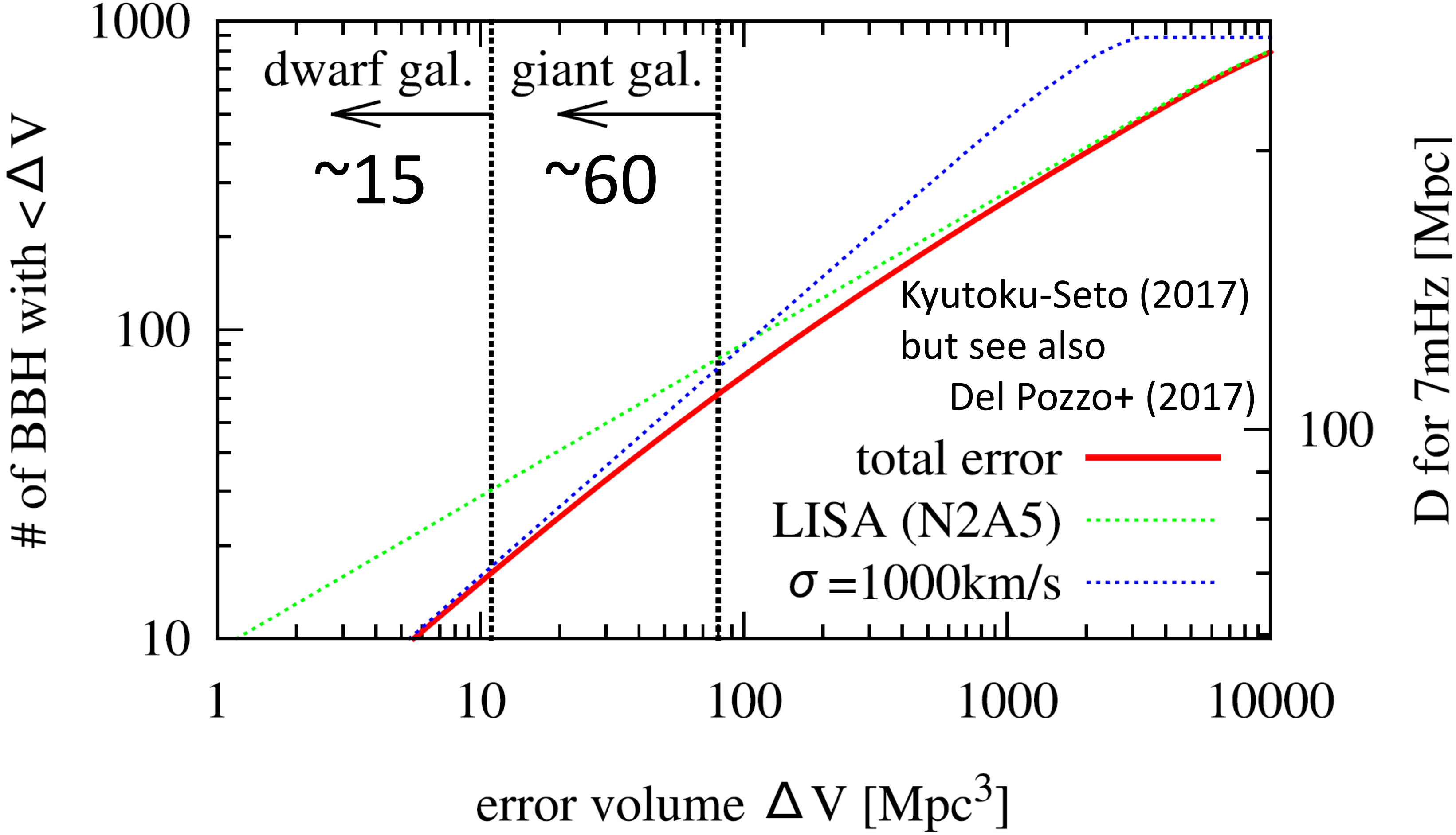
- GW localization

  …very difficult with ground-based detectors



Number of accurately localized sources

Assuming $\mathcal{M} = 28M_{\odot}, R = 100\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$



4. Summary

Summary

- Binary black holes are massive with diversity
- GW170817 confirmed various expectations but very little is understood in a conclusive manner
- Future ground-based observations will measure inclination and help to understand GRB and ejecta geometry (+ GW polarization with KAGRA)
- Future space-borne observatories will be useful to determine the origin and host of massive binary black holes

Appendix

GW distance determination

Observed gravitational-waves are (schematically)

$$h(t) = F(\theta, \varphi, \iota, \psi) \frac{\mathcal{M}^{5/3} f^{2/3}}{D} \cos[\Phi(t)]$$

$$\Phi(t) \simeq 2\pi\left(ft + \dot{f}t^2/2 + \cdots\right)$$

$$\dot{f} = (96/5)\pi^{8/3}\mathcal{M}^{5/3}f^{11/3}$$

The phase tells us binary parameters, e.g., the mass

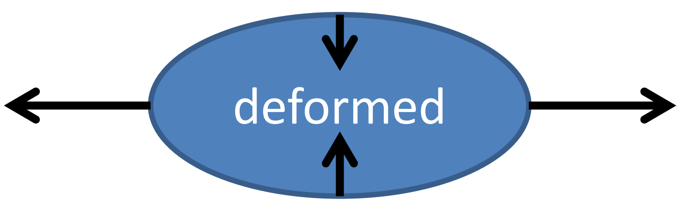
The amplitude can be predicted, and the distance D is found (degenerated w/ the direction, inclination)

Quadrupolar tidal deformability

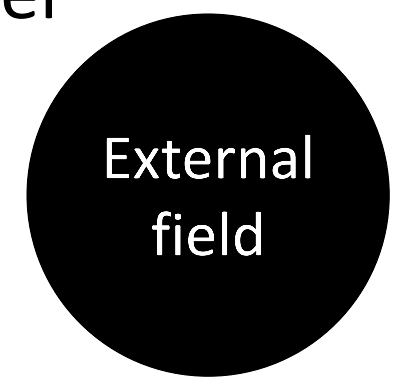
Leading-order finite-size effect on orbital evolution (strongly correlated with the neutron-star radius)

$$\Lambda = G\lambda\left(\frac{c^2}{GM}\right)^5 = \frac{2}{3}k\left(\frac{c^2R}{GM}\right)^5 \propto R^5$$

$k \sim 0.1$: (second/electric) tidal Love number



$$\mathcal{Q}_{ij} = -\lambda\mathcal{E}_{ij}$$



$$\mathcal{Q}_{ij} \equiv \int \rho\left(x_i x_j - \frac{1}{3}x^2\delta_{ij}\right)d^3x$$

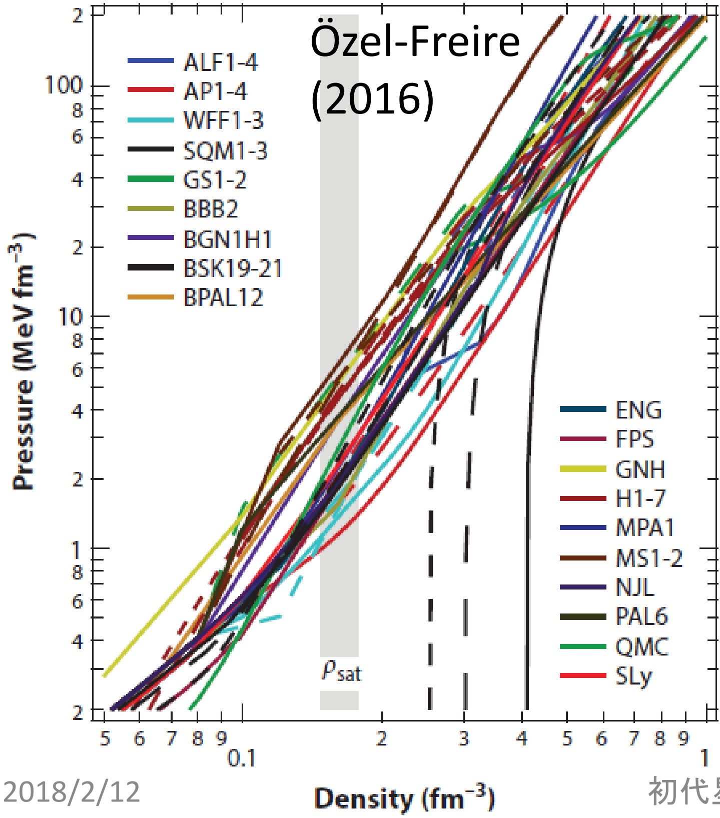
$$\mathcal{E}_{ij} \equiv \frac{\partial^2\Phi_{\rm ext}}{\partial x^i \partial x^j}$$

Neutron star equation of state

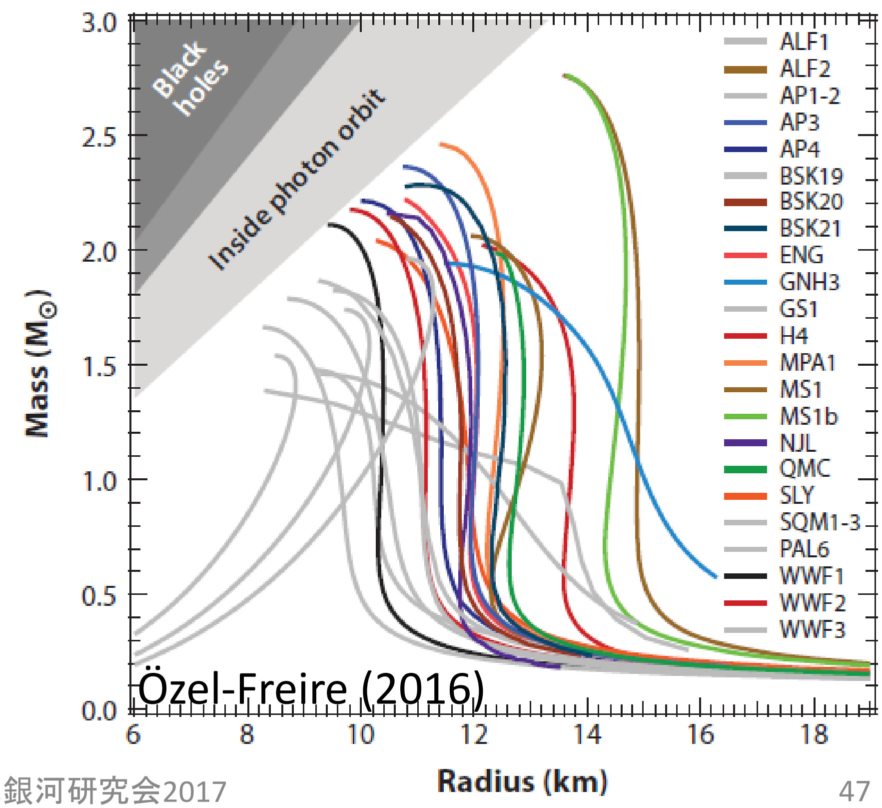
Note: not need to observe the radius, and other quantities may be fine

We want to know the realistic equation of state, that uniquely determines the mass-radius relation

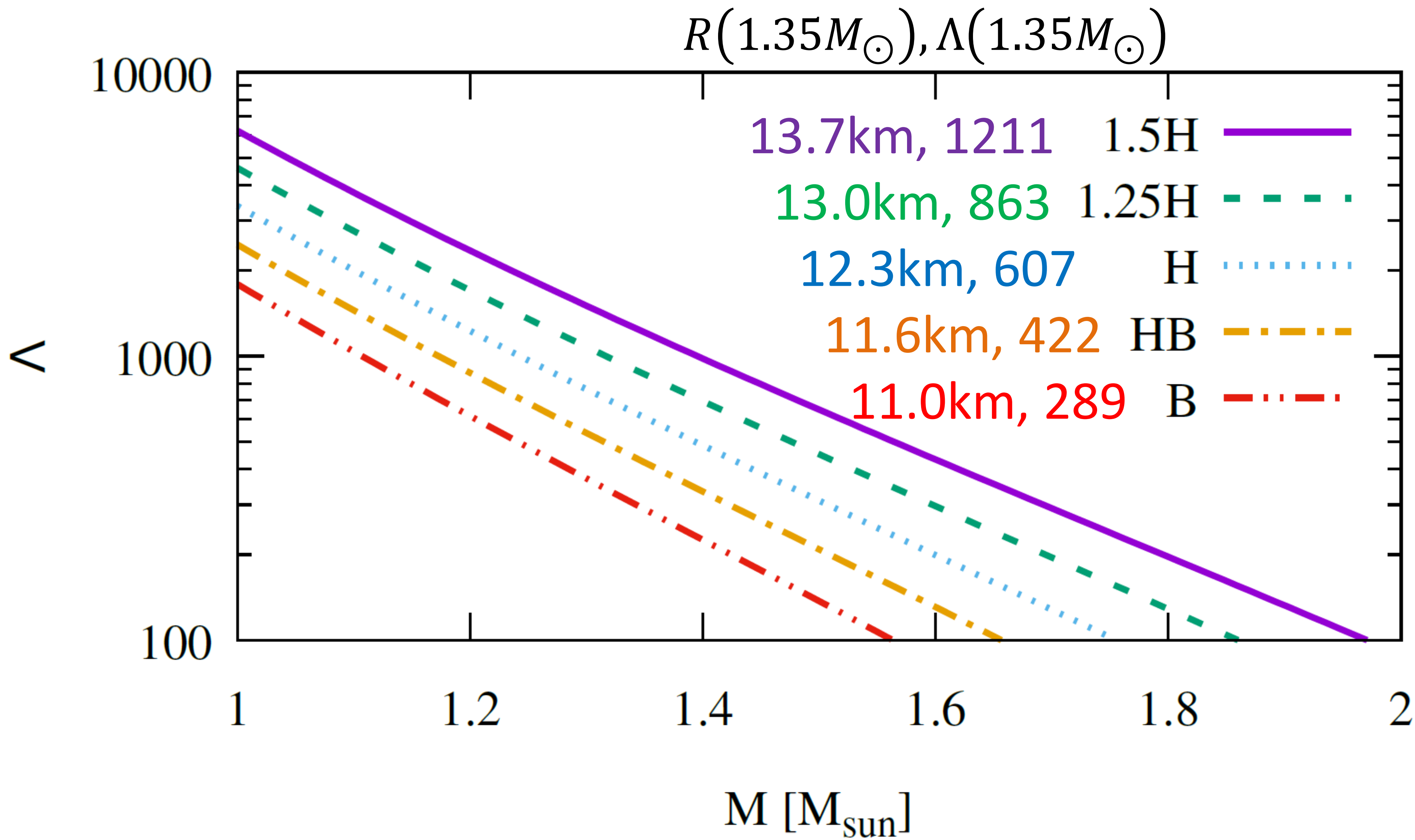
Equation of state: Nuclear physics



Mass-Radius relation: Astrophysics



Representative example of EOSs



Future prospect for the inclination

Key to understand short GRBs + ejecta geometry

Note: GW170817 was not detected by Virgo

Network	No EM information	Direction known	3D localized
LHV	9.3 (41.5)	8.3 (34.4)	3.3 (8.6)
LHVK	7.1 (24)	6.5 (21.0)	2.7 (6.4)
LHVKI	5.8 (15.5)	5.5 (14.3)	2.2 (5.1)

Arun+ (2014)

L: LIGO Livingston, H: LIGO Hanford, V: Virgo

K: KAGRA, I: LIGO India   BH-NS (NS-NS)@200Mpc

Errors associated with the Hubble

When the host galaxy is large … ($M_* > 10^9 M_\odot$)

host galaxies may be determined for ~60 binaries

statistical errors and shot noises will be OK

suffer from voids (cosmic variance) up to 2-3%?

- this may be what we want to observe

When the host galaxy is small … ($M_* > 10^7 M_\odot$)

only ~15 binaries are useful … not very happy

still we can investigate black holes’ host galaxies