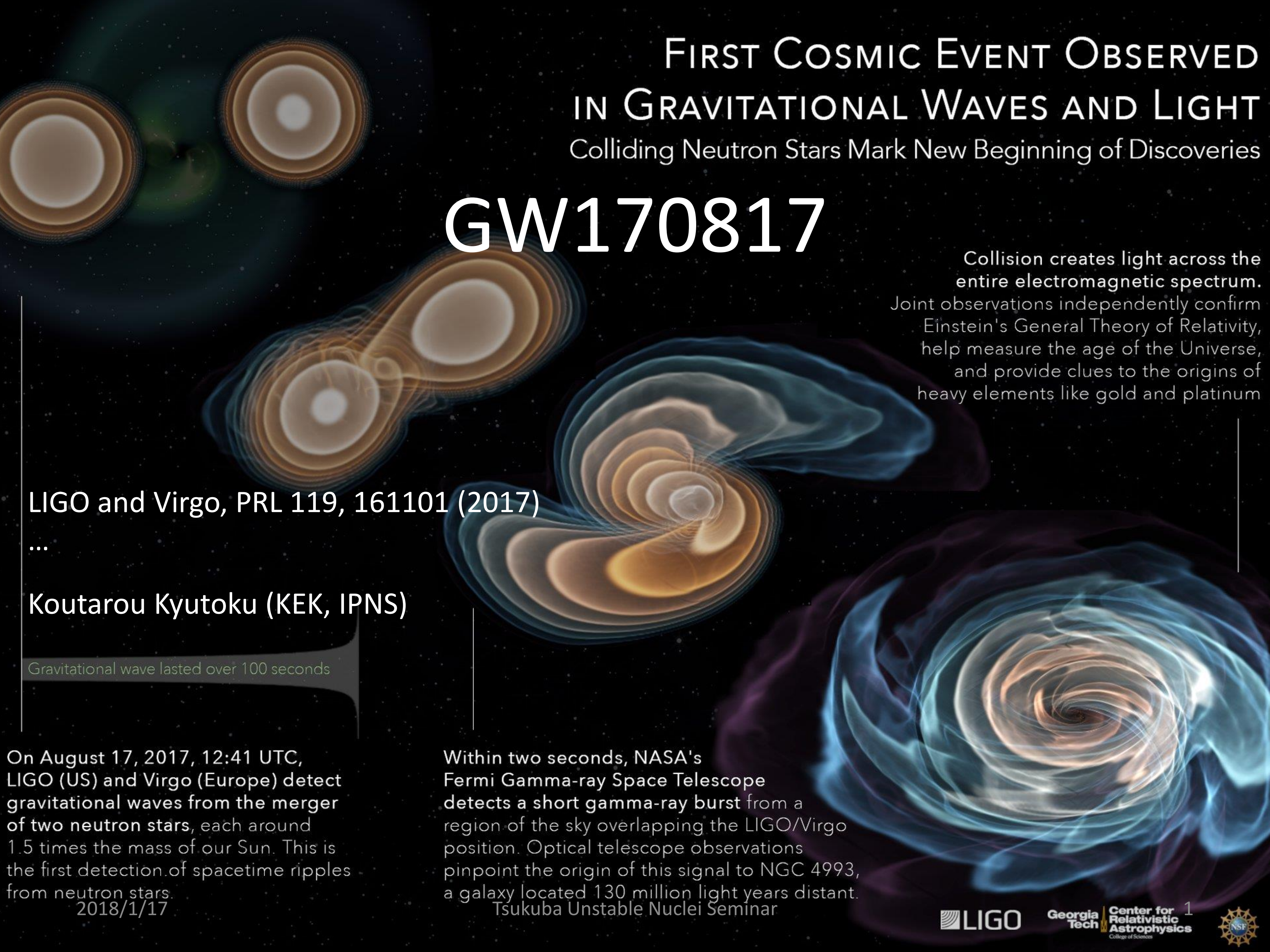
GW170817

LIGO and Virgo, PRL 119, 161101 (2017)

…

Koutarou Kyutoku (KEK, IPNS)



Contents

1. Gravitational waves from binary black holes
2. Gravitational waves from binary neutron stars
3. r-process and kilonova/macronova (AT 2017gfo)
4. Future prospect and summary

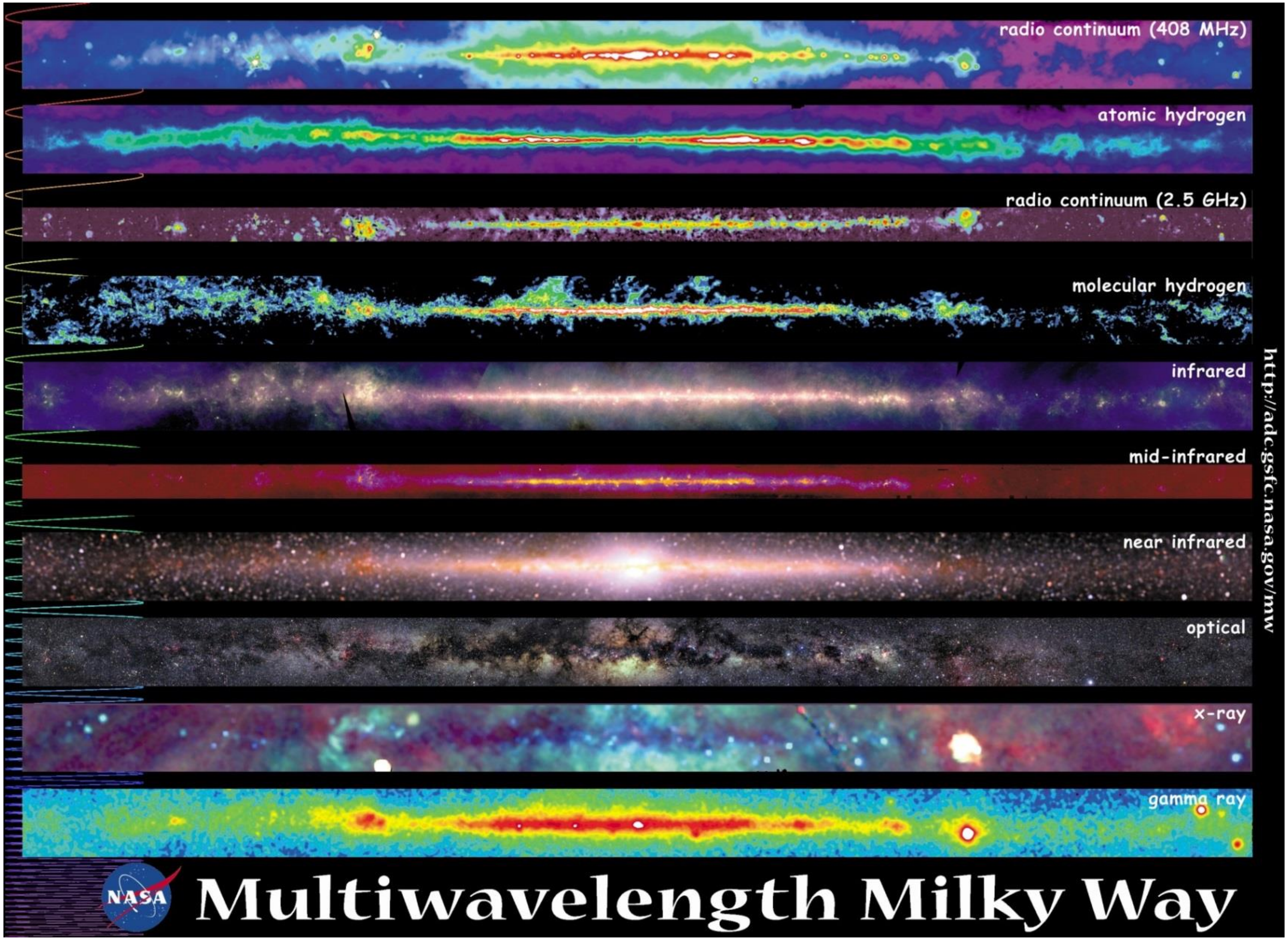
Skipped:

- Test of general relativity
- Short gamma-ray burst or not? (GRB170817A)

1. Gravitational waves from binary black holes

Nightly sky as our eyes see

Multi-wavelength sky



Toward multi-messenger astronomy

strong / opaque

Strong interaction: (strong but short-range)

Electromagnetic interaction: electromagnetic waves

Signals are strong but also hidden very easily

Weak interaction: neutrino

Another interesting messenger, particle physics

Gravitational interaction: gravitational waves

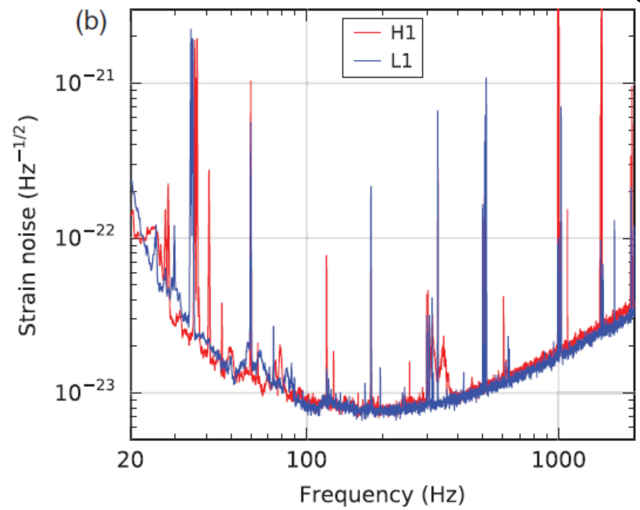
Signals are weak but extremely penetrating

weak / transparent

LIGO detector

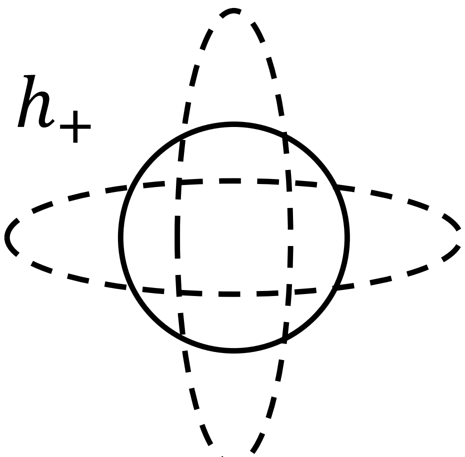
Measures the propagating strain of spacetime, i.e., gravitational waves, with the precision of $< 10^{-21}$

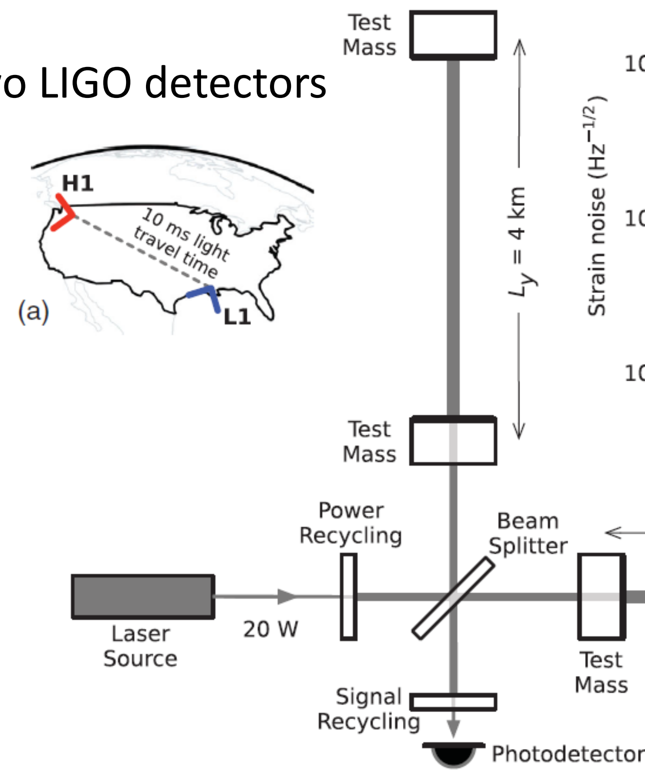
Noise level at the first observing run



Location of two LIGO detectors
Hanford, WA
Livingston, LA

h_+

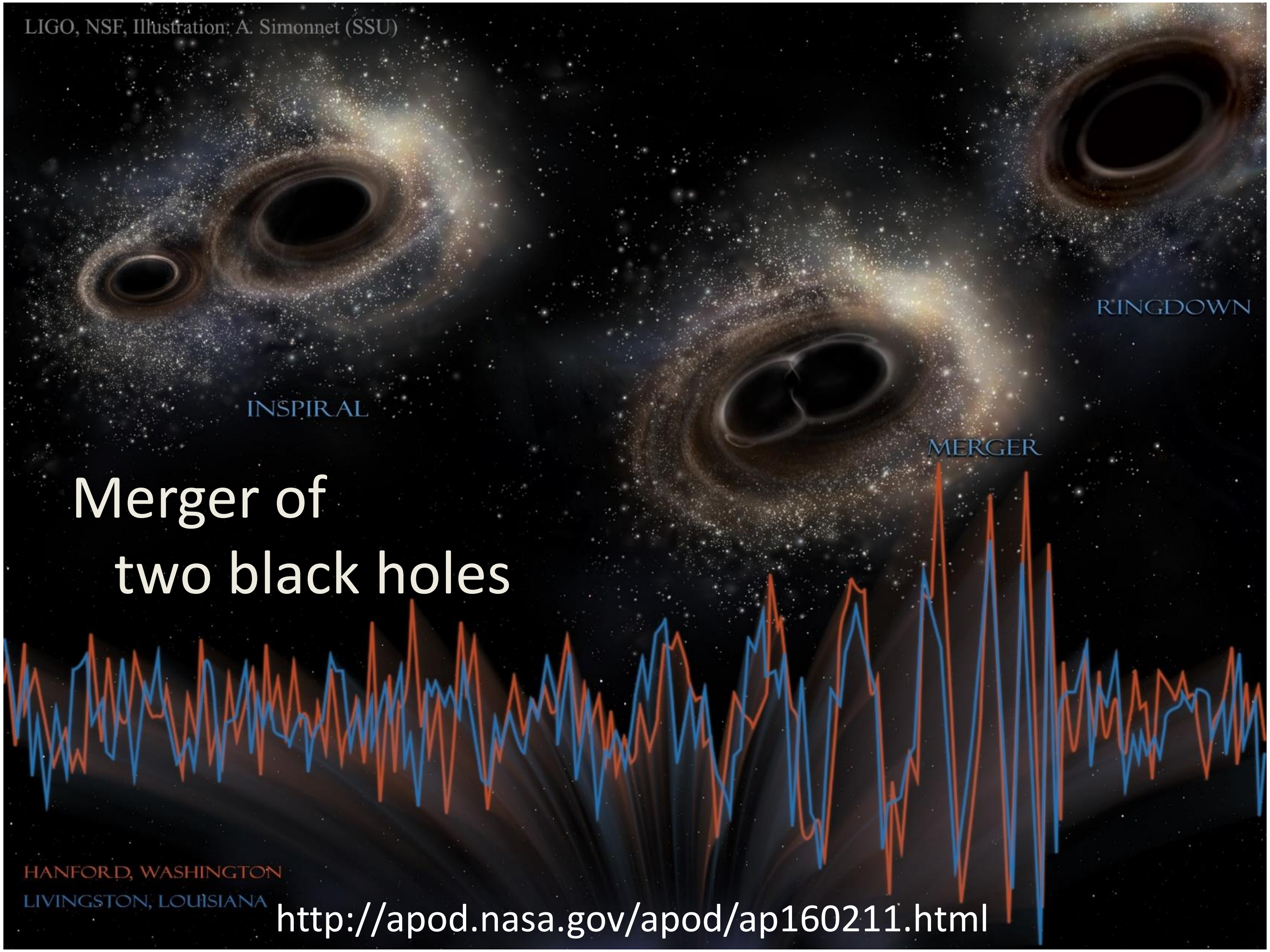




LIGO&Virgo (2016)

Schematic picture of Michelson-Morley interferometer

The first event: GW150914



Parameters of GW150914

- Masses of individual stars are measured

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

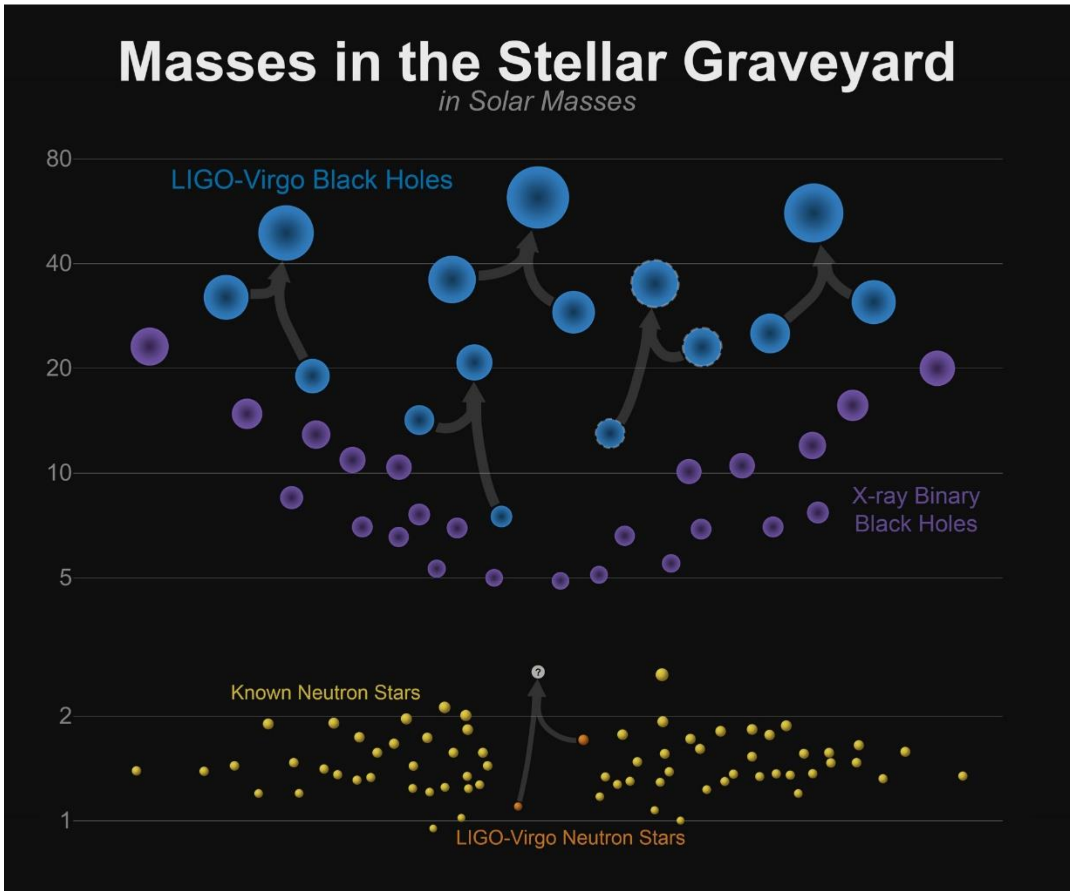
- The luminosity distance is measured directly

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 origin?

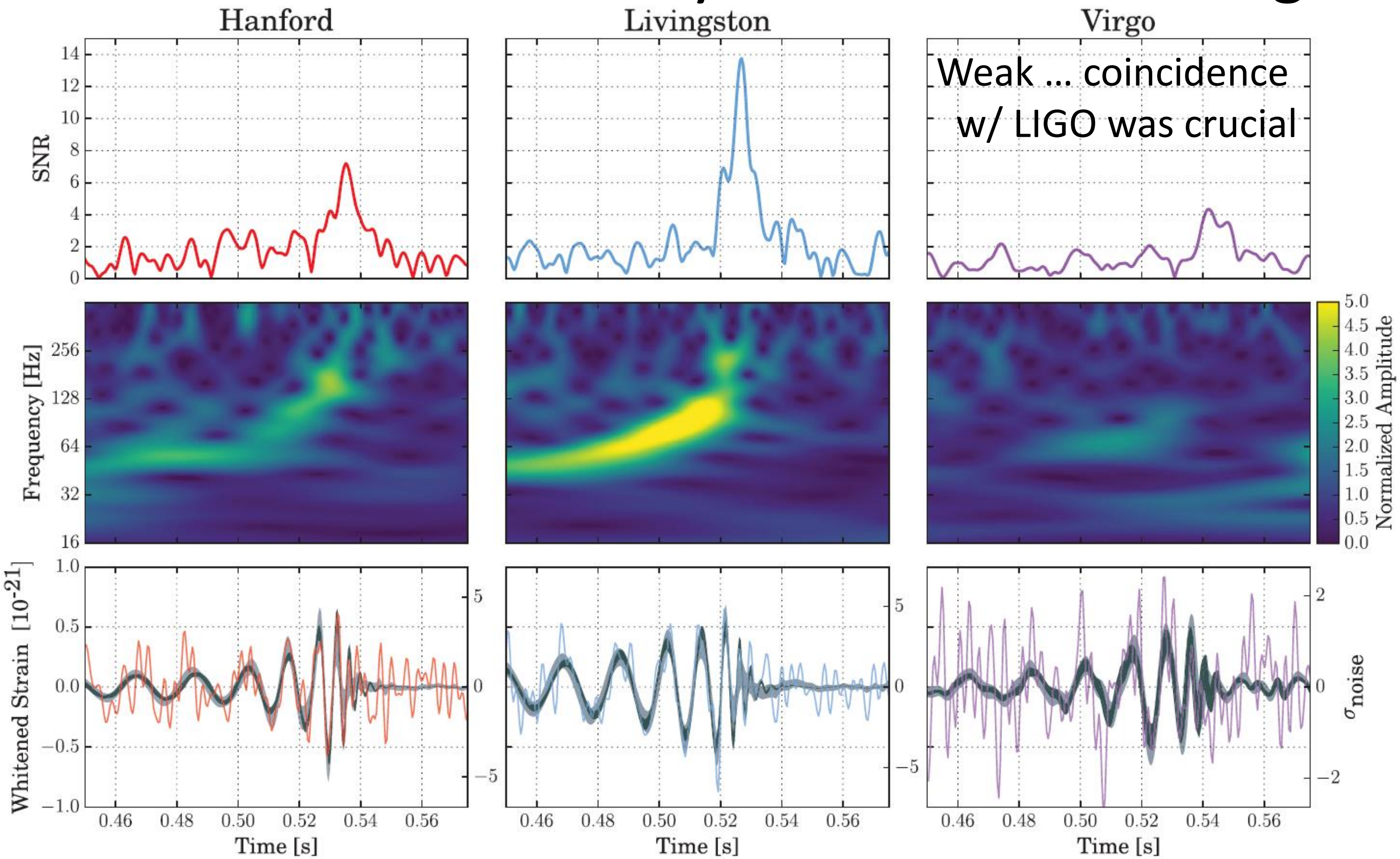
statistics necessary

https://www.ligo.caltech.edu/system/avm_image_sqls/binaries/91/original/Mass_plot_black_no_gap.jpg?1508029040

Gravitational-wave detector network

GW170814 (not 170817)

Simultaneous detection by LIGO twins and Virgo



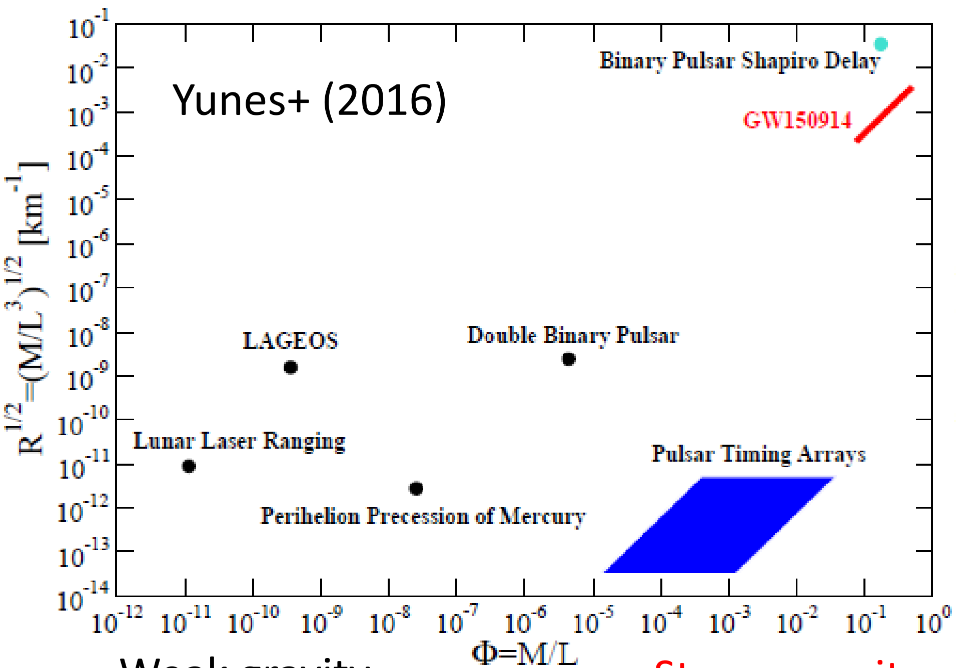
LIGO&Virgo (2017)

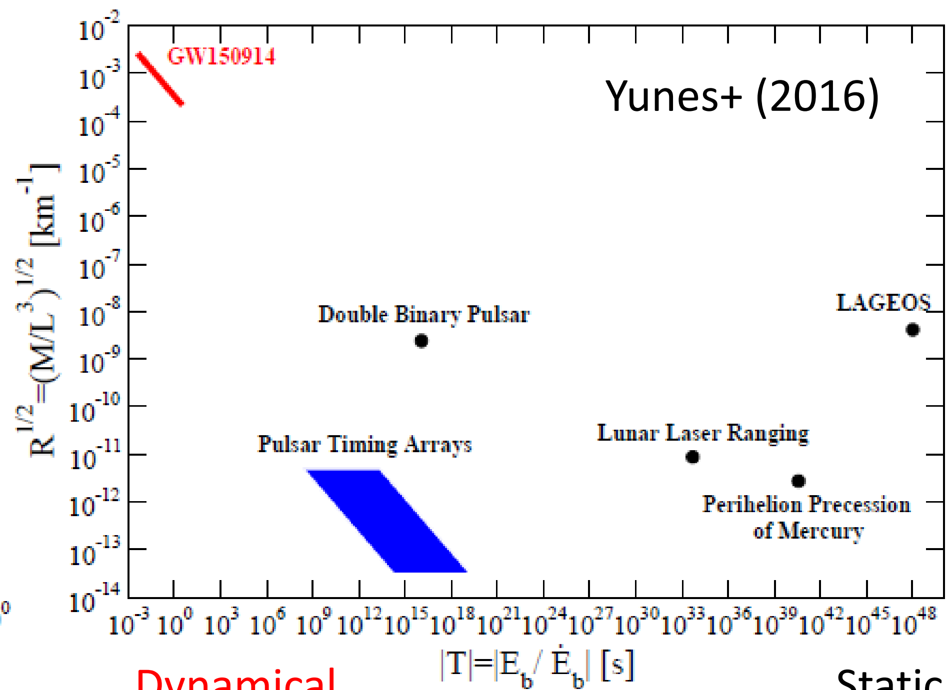
Test of general relativity (skipped)

This event probes the strong and dynamical gravity

Small curvature scale (quantum somewhere)

$G = c = 1$ assumed





Weak gravity — Strong gravity

Dynamical — Static

Large curvature scale (classical)

2. Gravitational waves from binary neutron stars (GW170817)

Neutron star binary coalescence

- Gravitational waves

 - test of the theory of gravitation in a non-vacuum

 - high-density matter signature: equation of state

- Formation of a hot massive remnant (star/disk)

 - central engine of short gamma-ray bursts

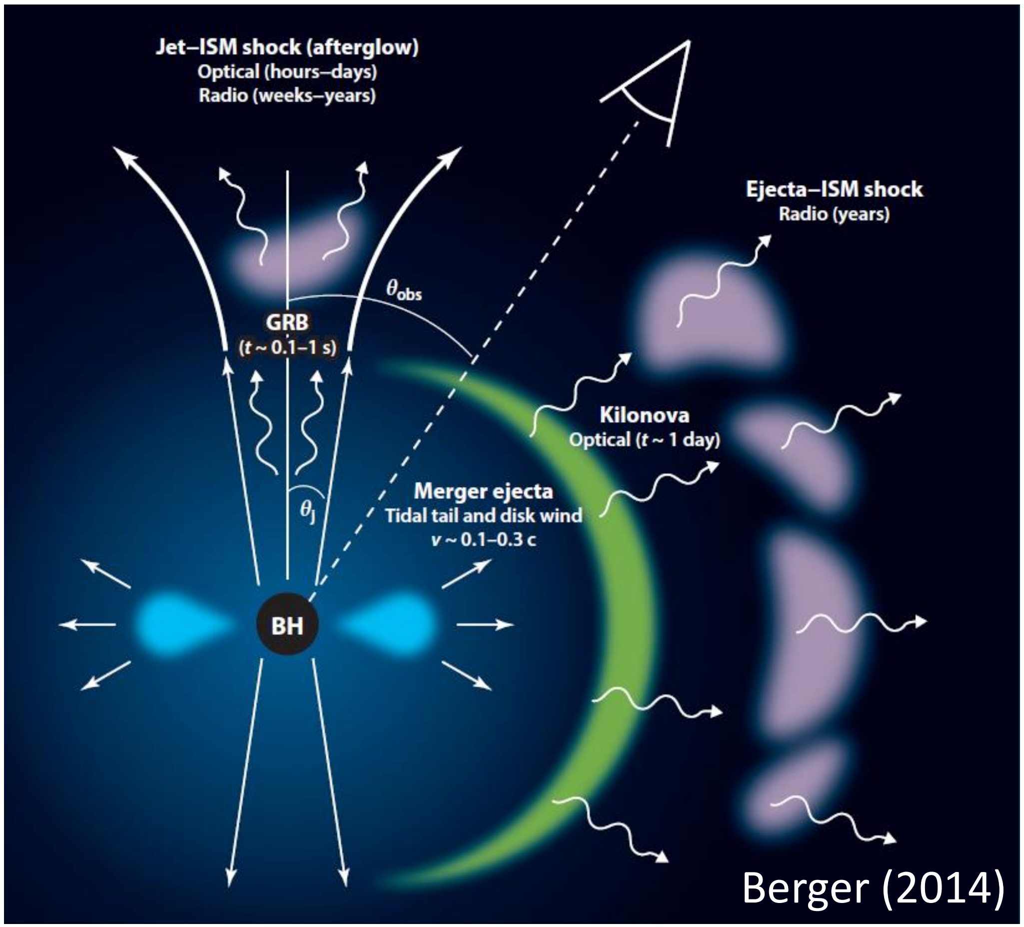
- Mass ejection of neutron-rich material

 - r-process nucleosynthesis

 - radioactively-driven “kilonova/macronova”

Electromagnetic counterpart

EM radiation will accompany neutron star mergers



localization

- host identification
- cosmological redshift

ejecta properties

- ejection mechanism
- r-process element

Short gamma-ray burst (skipped)

About 10^{51}erg/s explosions

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

Long-soft GRB: ≥ 2s

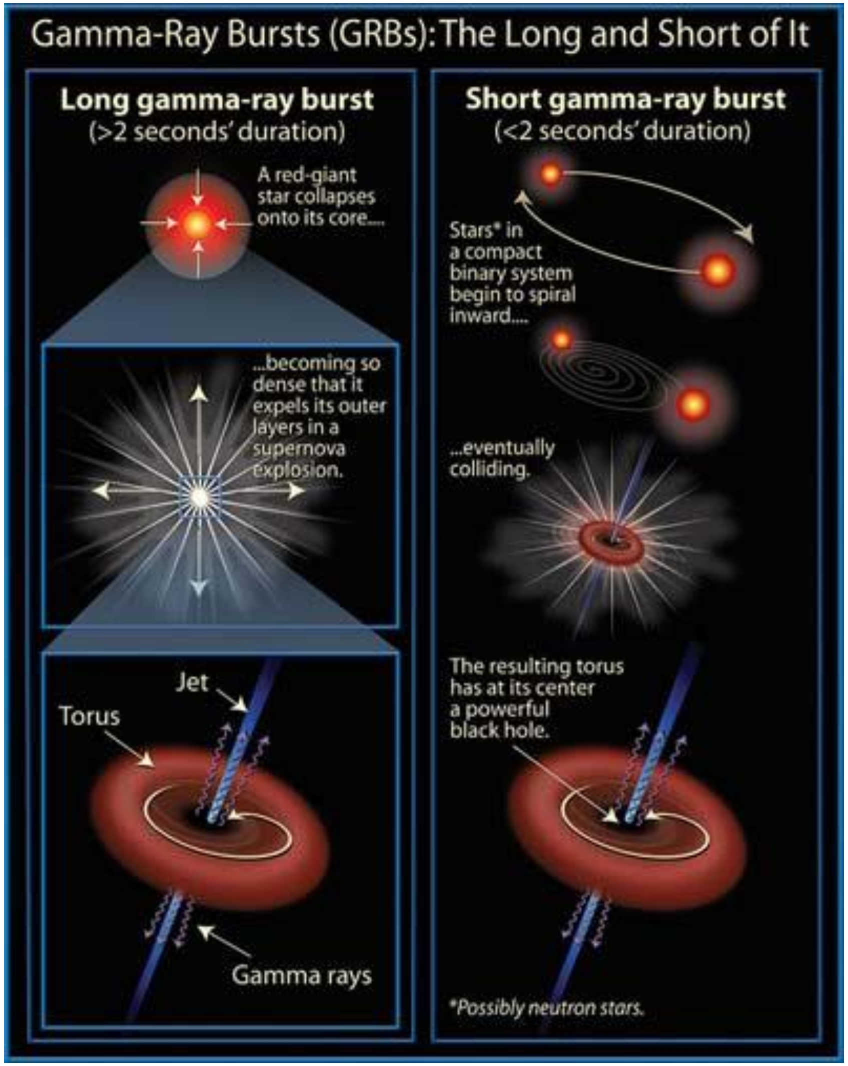
deaths of massive stars

Short-hard: ≤ 2s

neutron star binary merger?

rigorous confirmation needs

gravitational waves

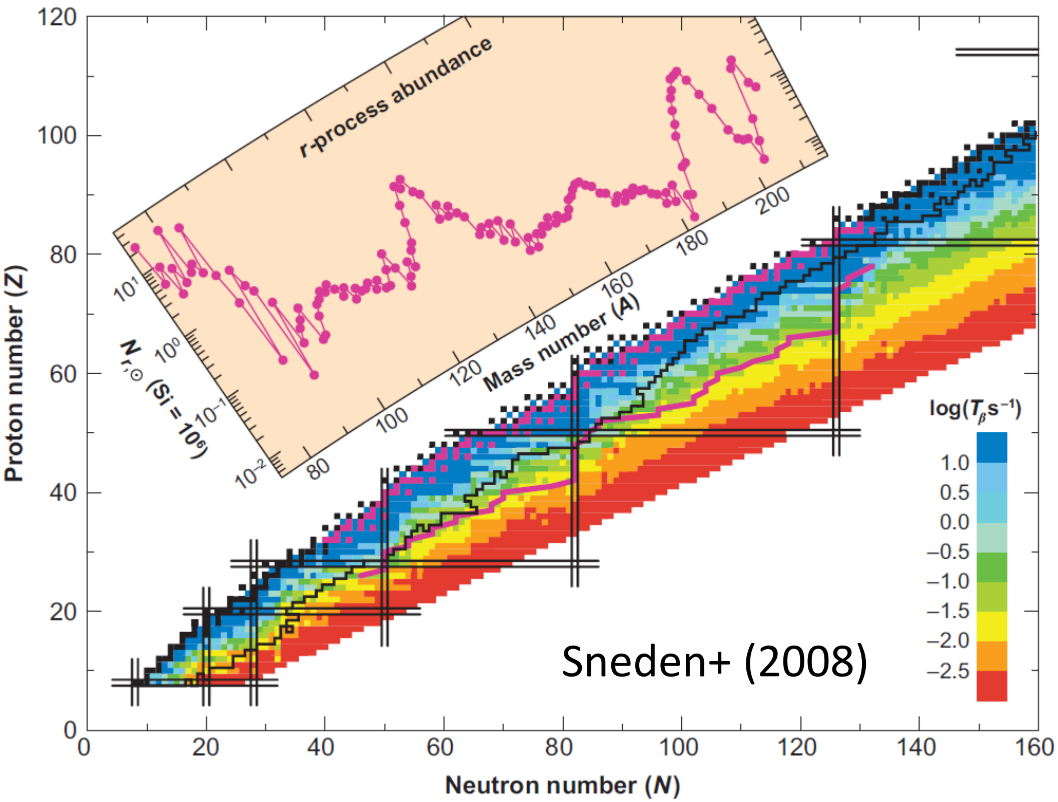


http://www.daviddarling.info/images/gamma-ray_bursts.jpg

r-process nucleosynthesis

Synthesize heavy, neutron-rich elements (Au, Pt…)

r = rapid: neutron capture faster than beta decay



need very dense and neutron-rich matter

supernova explosions now seem to fail to achieve r-process

Neutron star

Remnant of massive stars

(mass range is uncertain)

Mostly consists of neutrons

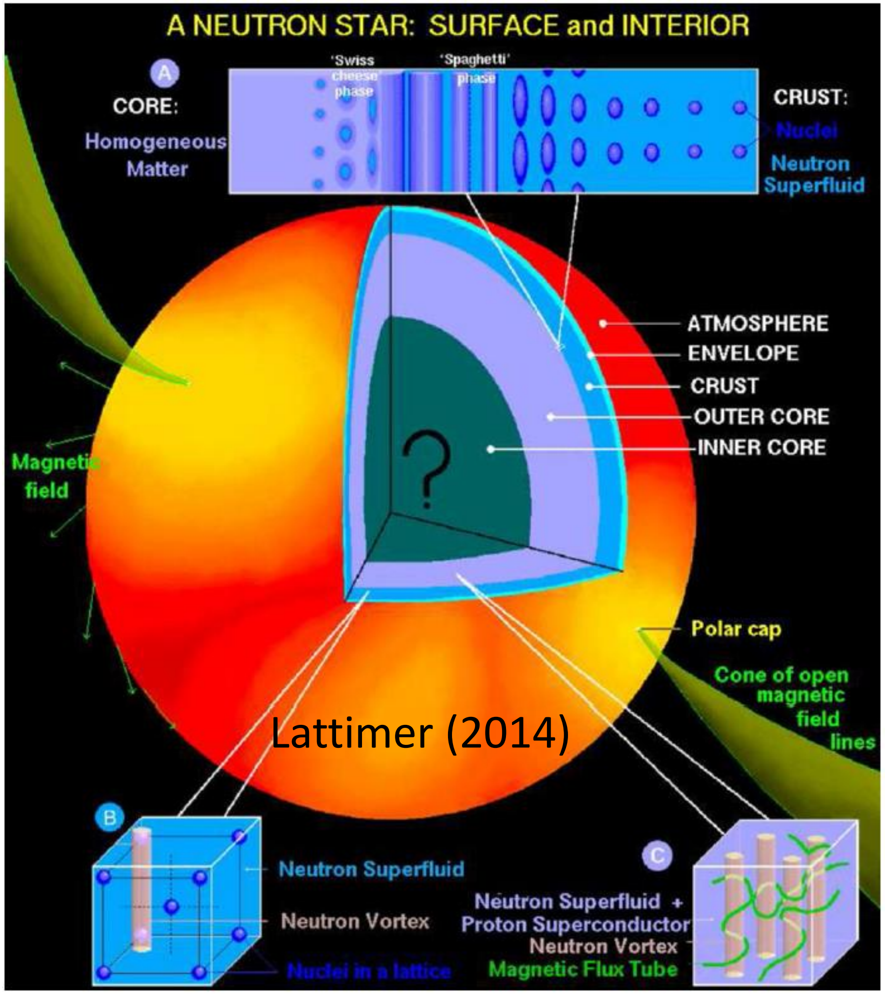
1.4 solar mass, ~10km

The density is higher than

nuclear saturation values

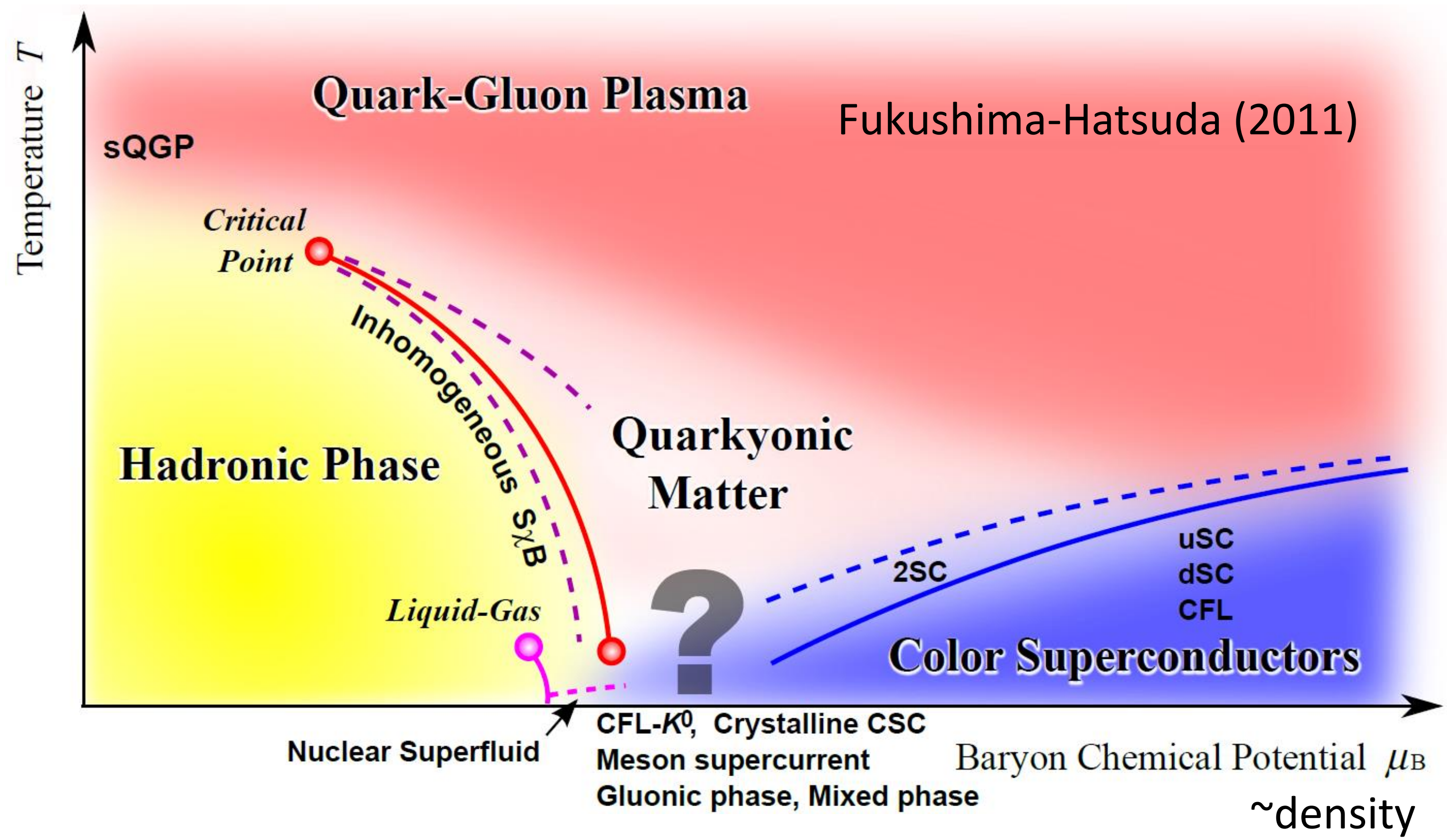
"a huge nucleus"

Arena for nuclear physics



Neutron-star matter

Cold, high-density, highly neutron-rich matter
also could be magnetized up to ~10^{17}G (10^{13}T)

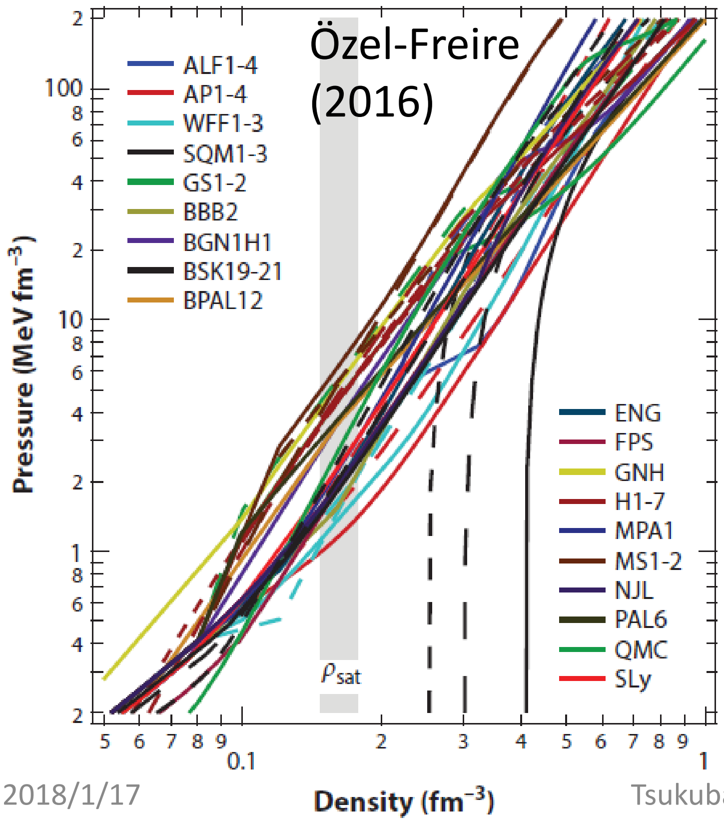


Neutron star equation of state

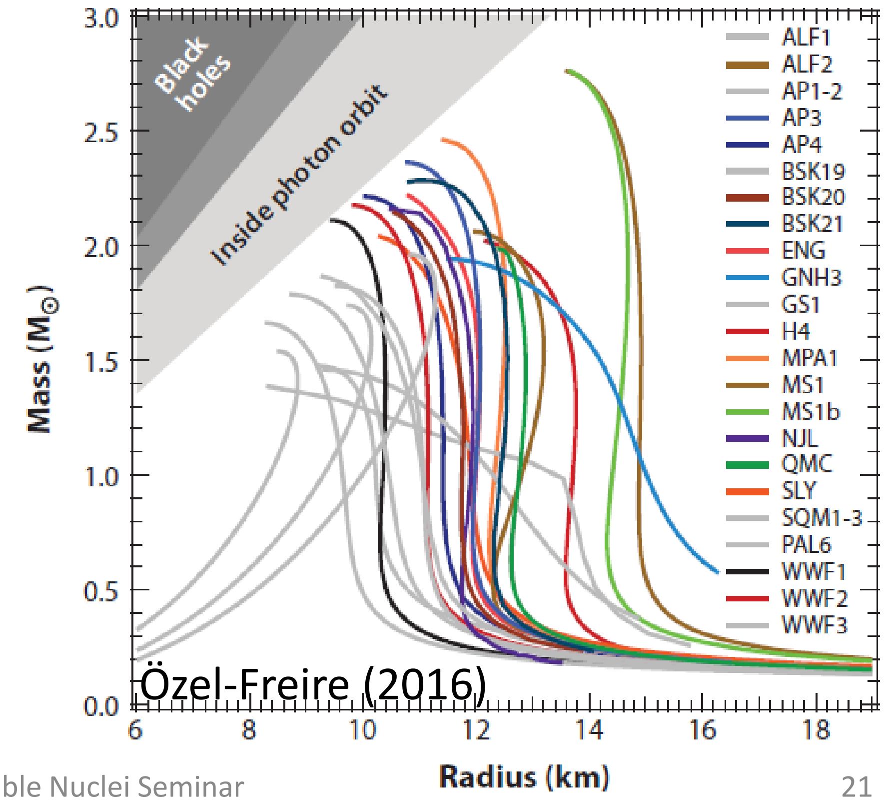
Note: not need to observe the radius, and other quantities may be fine

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

Equation of state: Nuclear physics

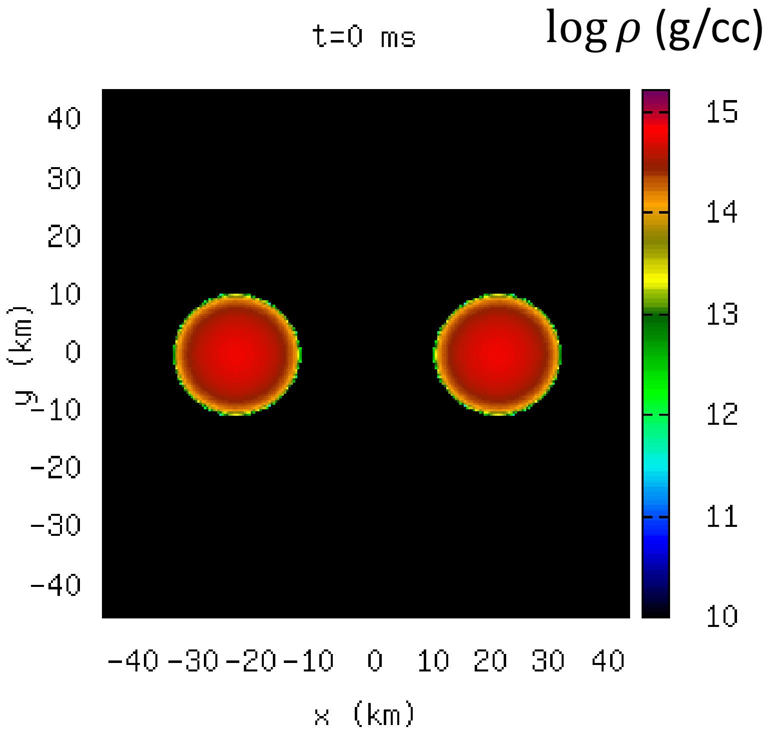


Mass-Radius relation: Astrophysics

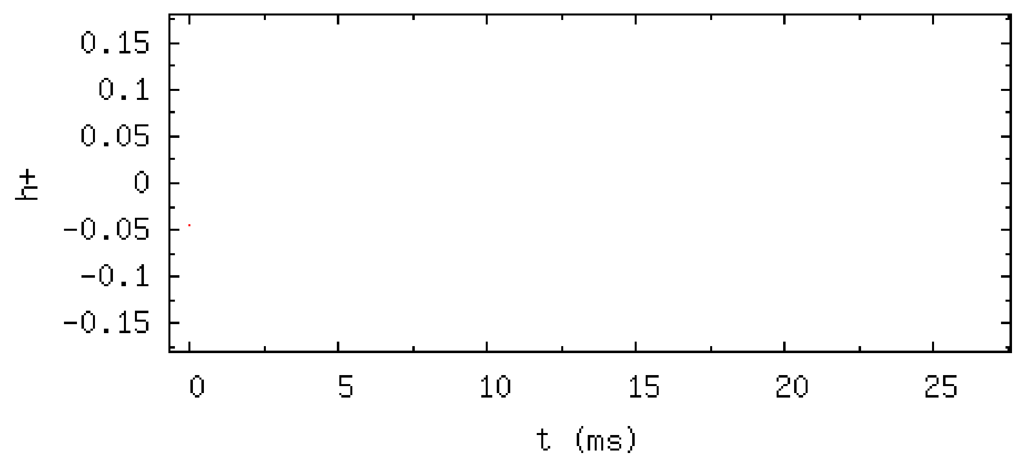


Example of the binary merger

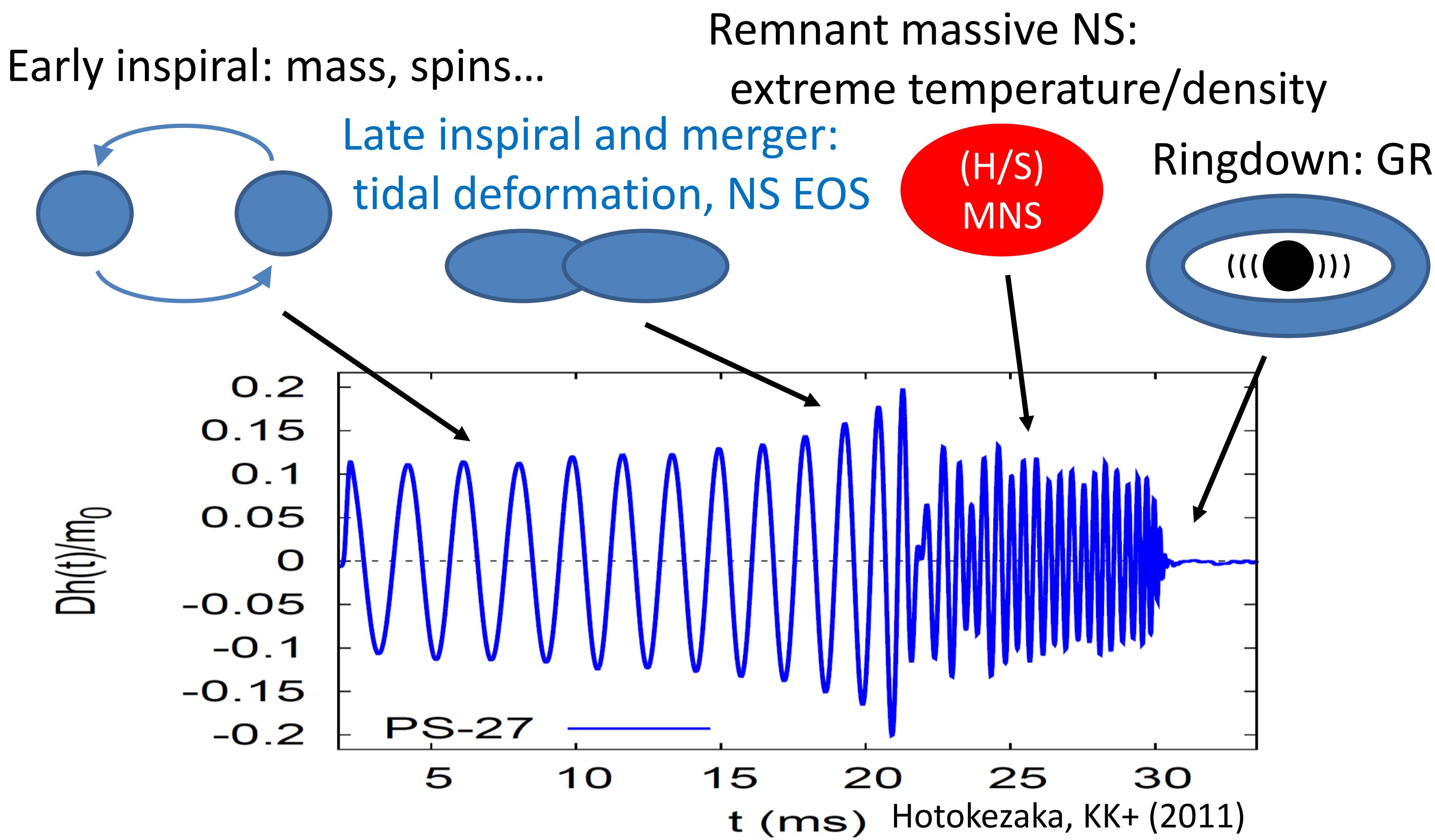
A massive rotating star can be left after merger, and emit gravitational waves to collapse to a black hole



(old) Movies by Kenta Hotokezaka
Based on Hotokezaka, KK+ (2011)

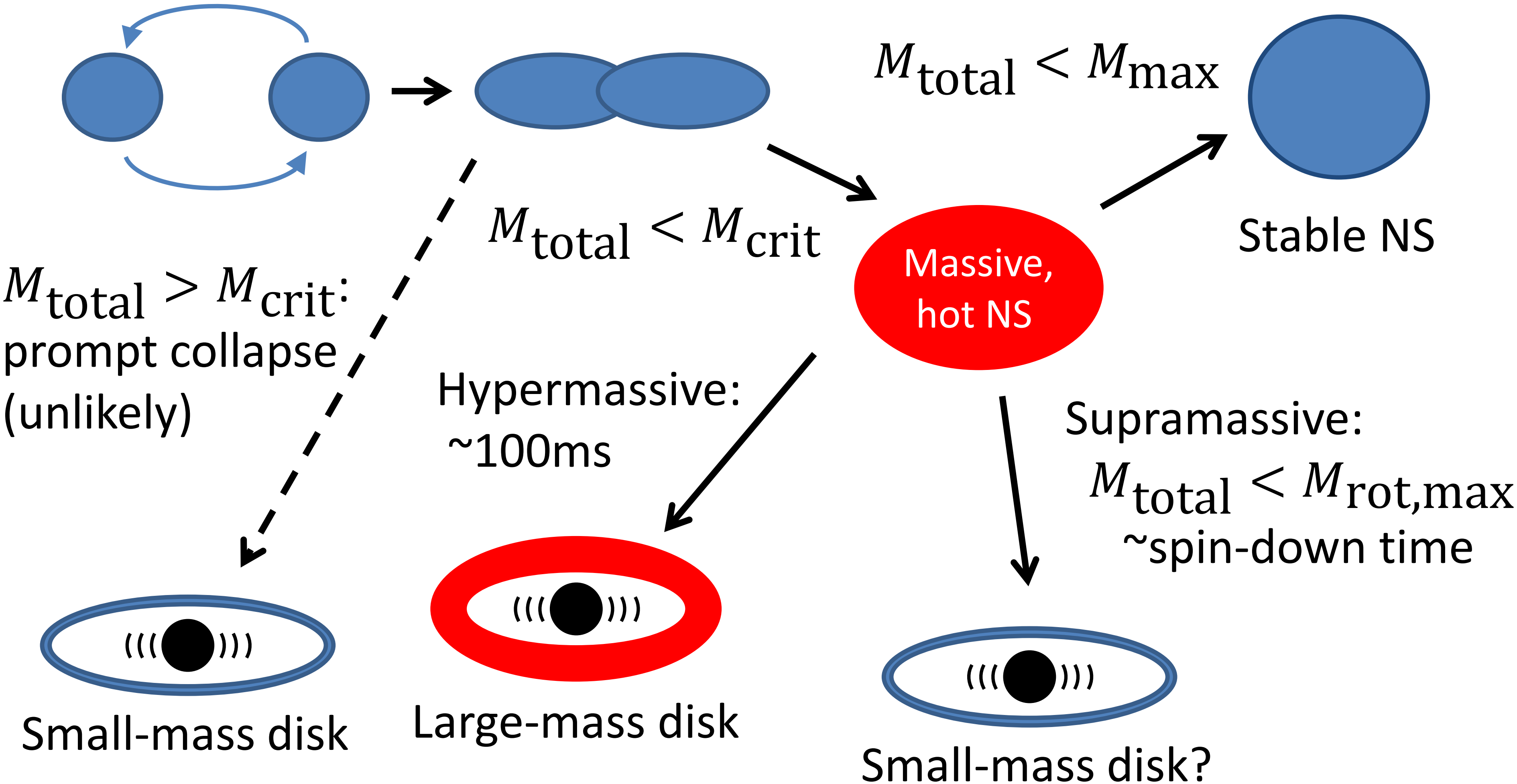


Encoded physics



Hotokezaka, KK+ (2011)

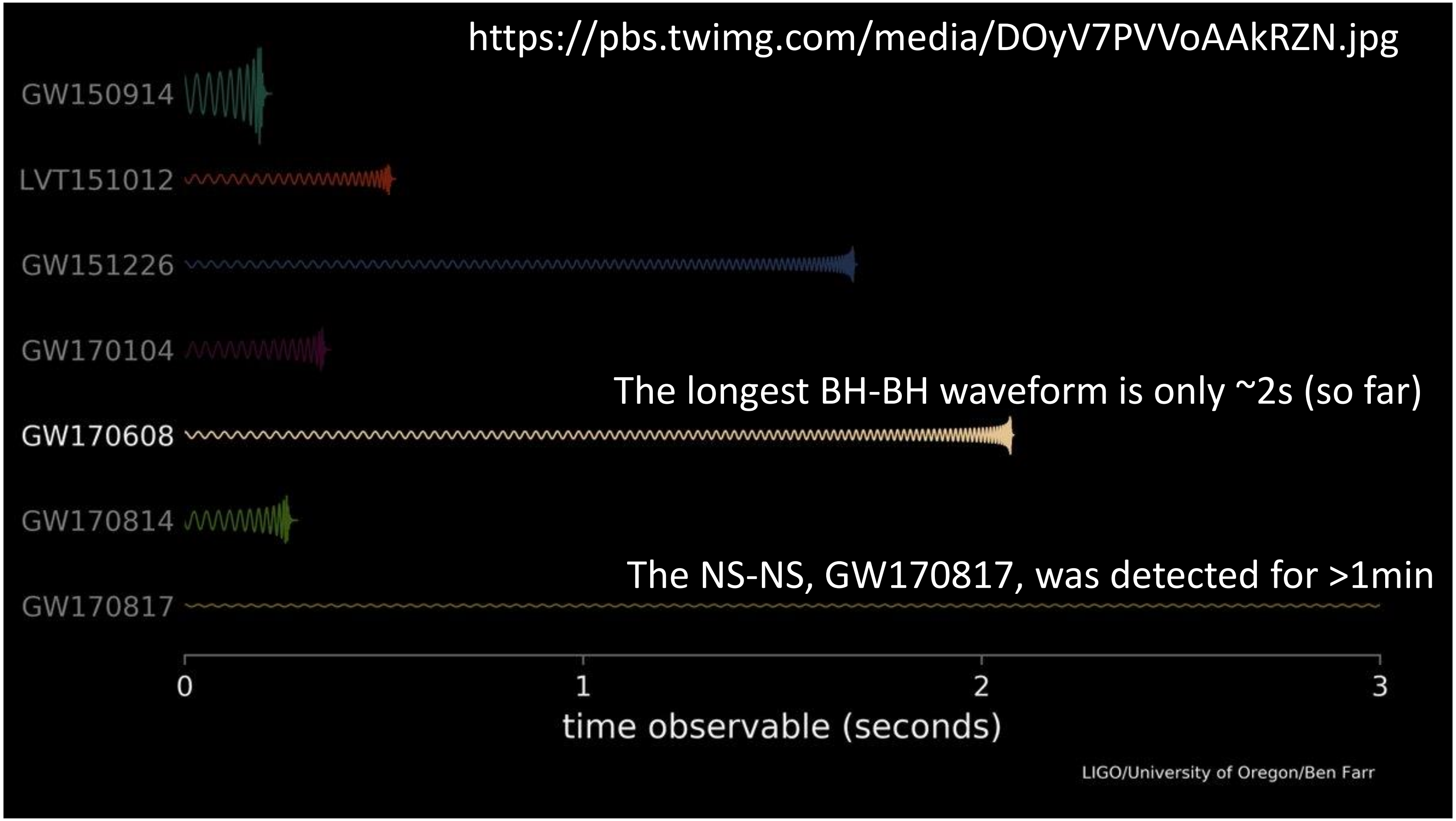
Merger dynamics of NS-NS



[See e.g., Hotokezaka+KK+ (2013)]

GW170817

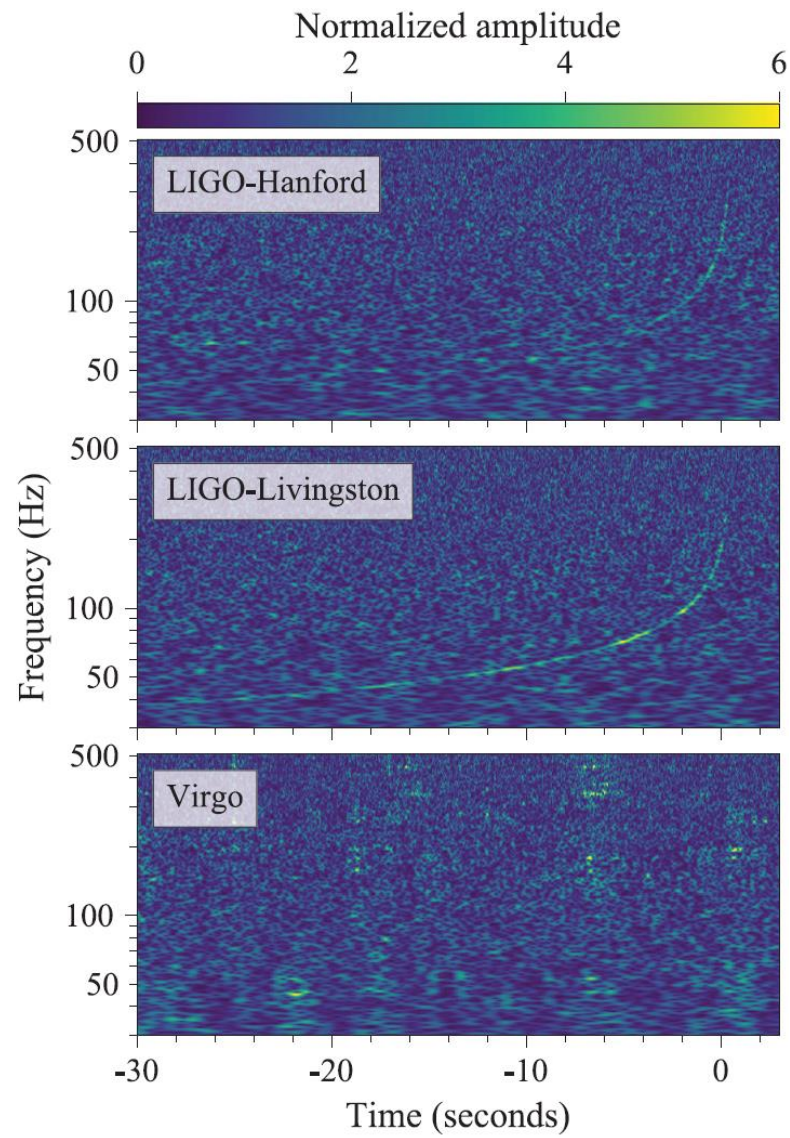
http://www.ligo.org/detections/GW170817.php



Spectrogram

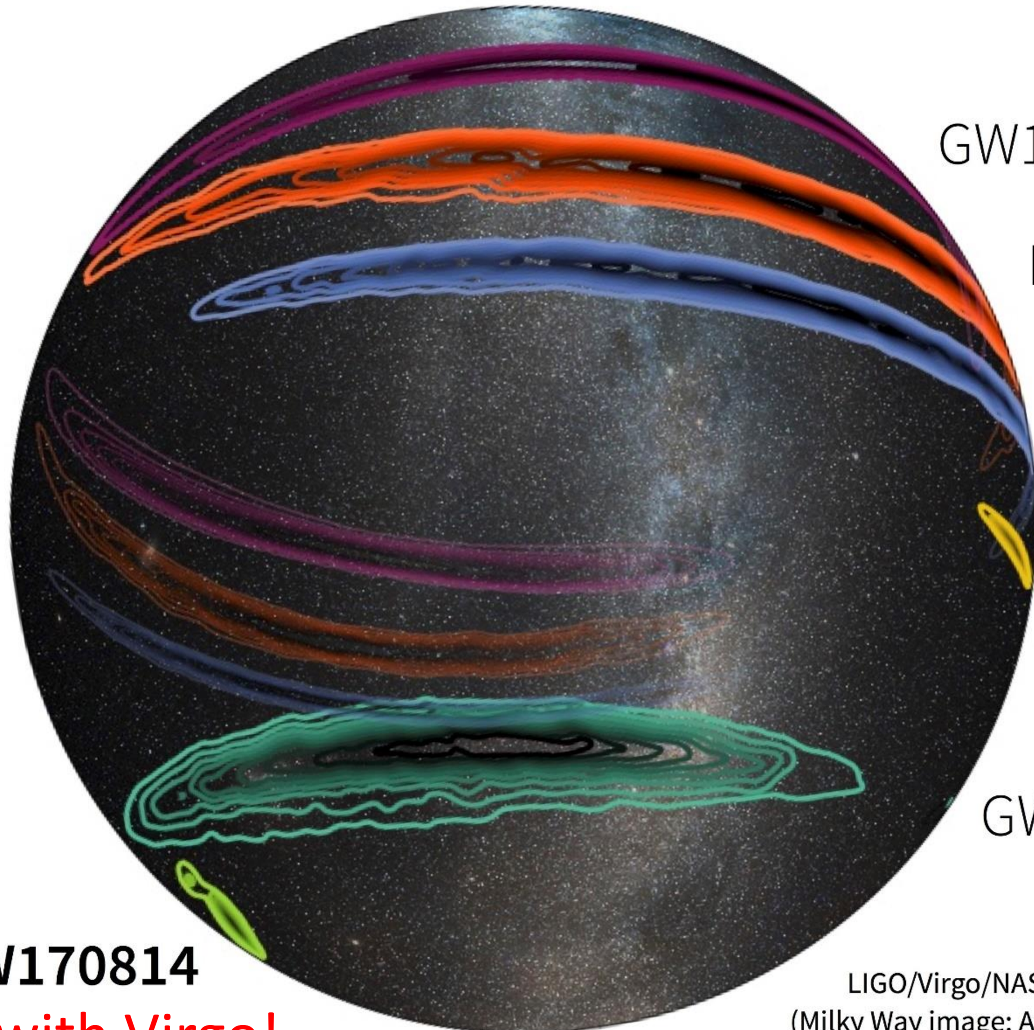
LIGO twins observed
clear "chirp" signals, i.e.,
gravitational waves with
increasing frequency
and amplitude in time

But Virgo did not see…
-> the source should be
at Virgo's blind spot!



LIGO&Virgo (2017)

Sky map and localization accuracy

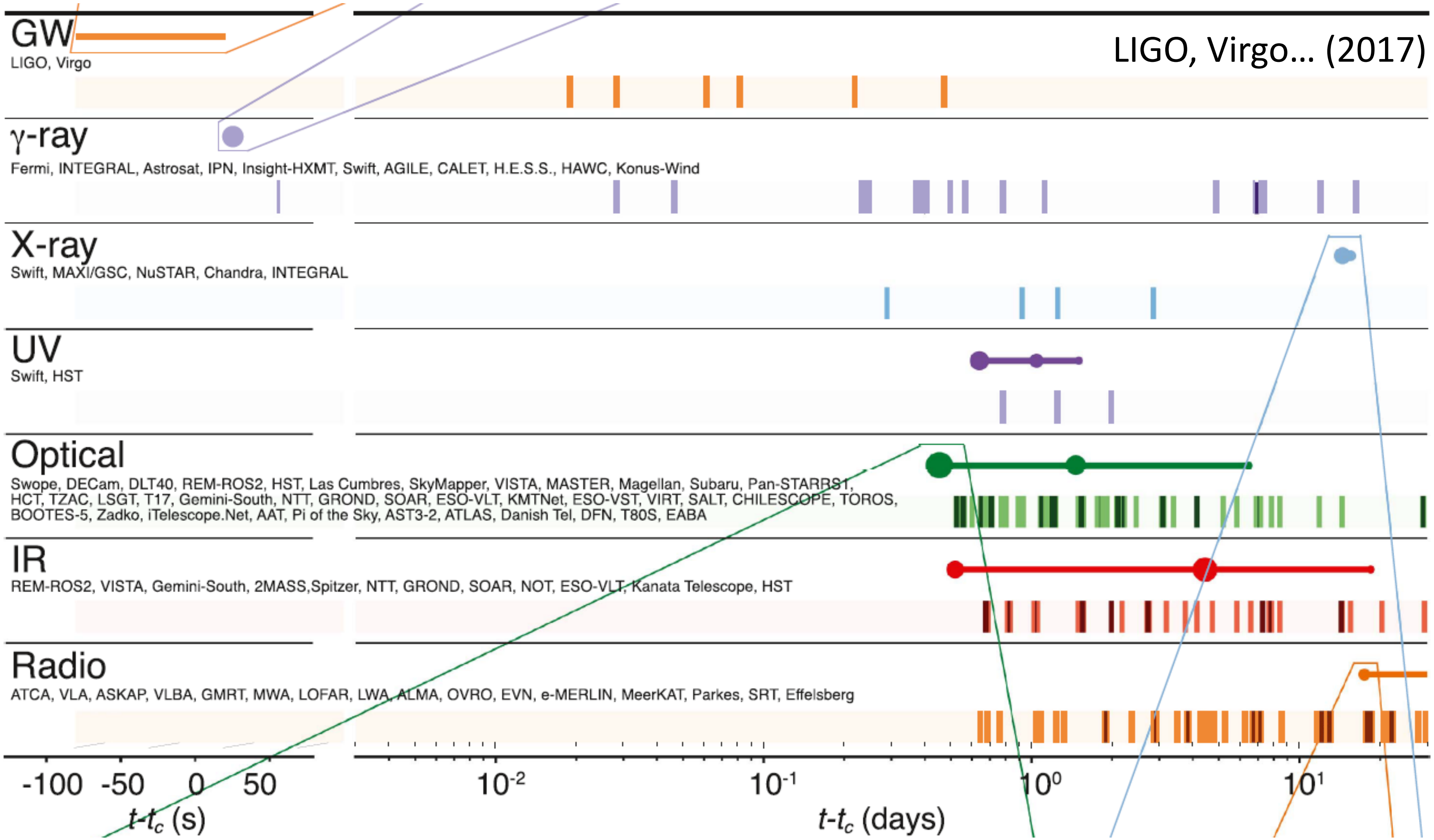


GW170817
Improved with Virgo!

GW170814
Improved with Virgo!

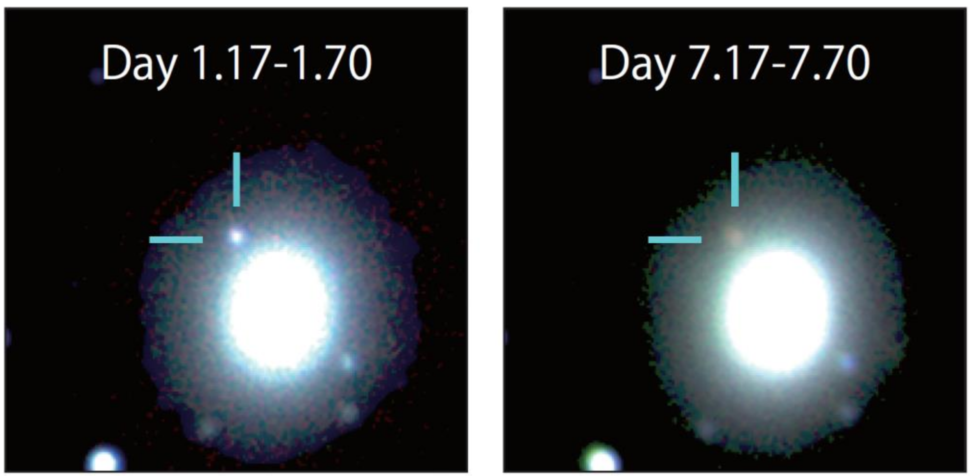
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)
http://www.ligo.org/detections/GW170817/images-GW170817/O1-O2-skymaps-white.jpg

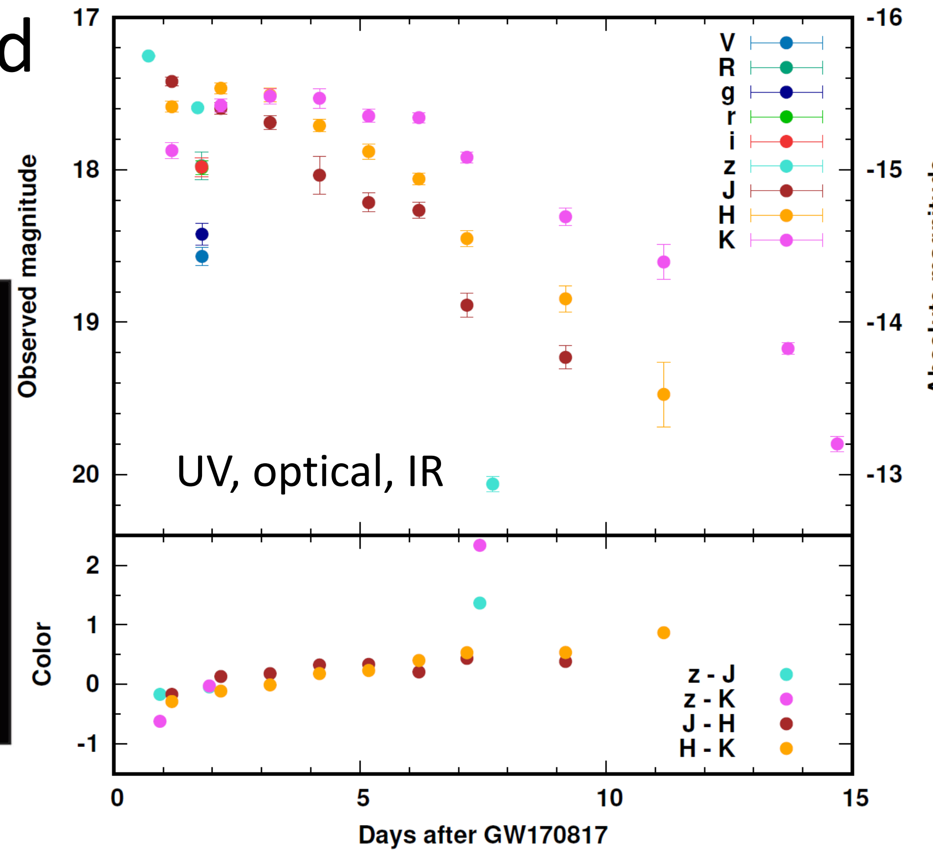
Electromagnetic followup



Transient and host galaxy

The kilonova/macronova and associated host galaxy are successfully discovered by various telescopes

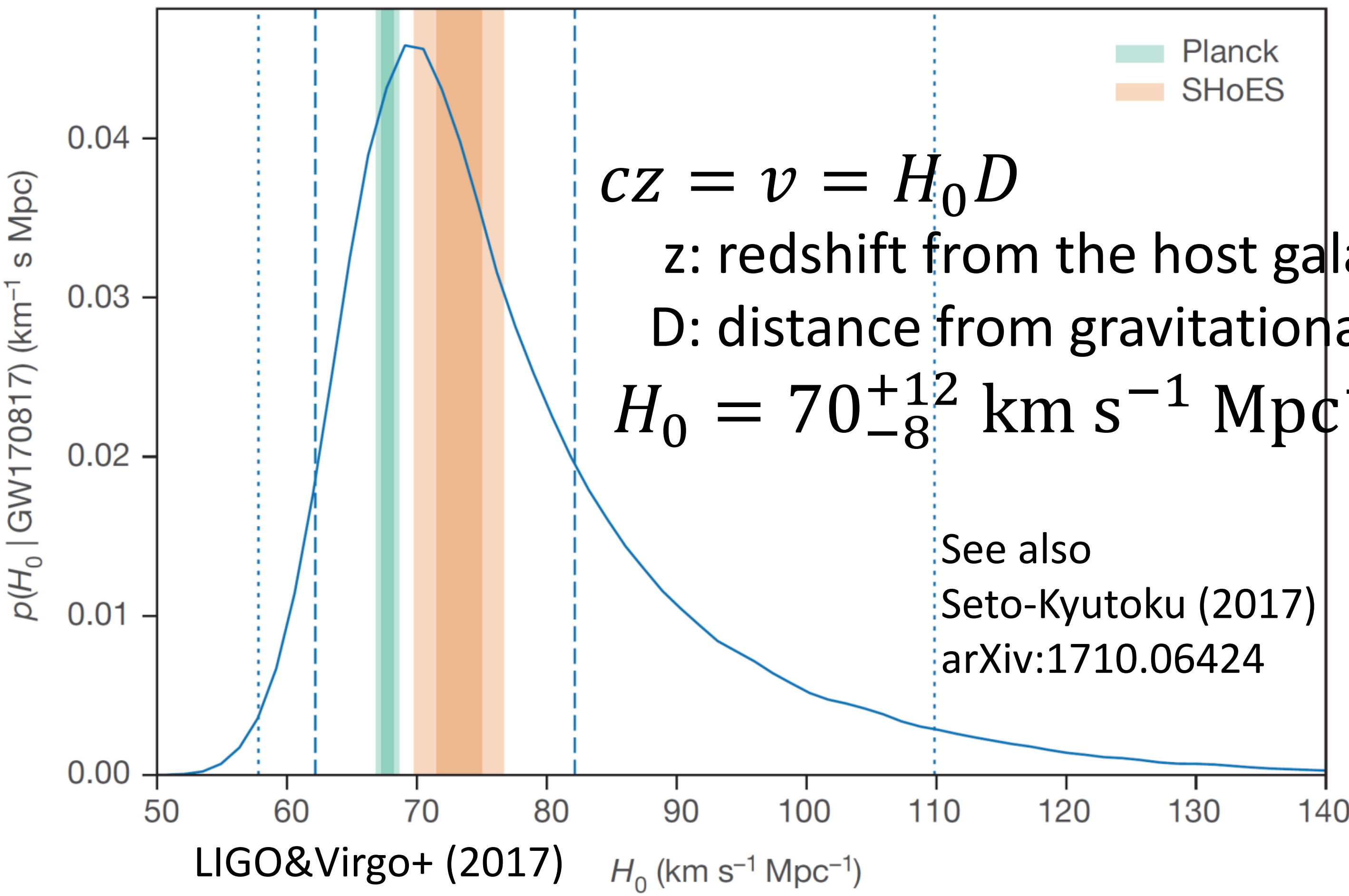




Utsumi+ (2017)

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

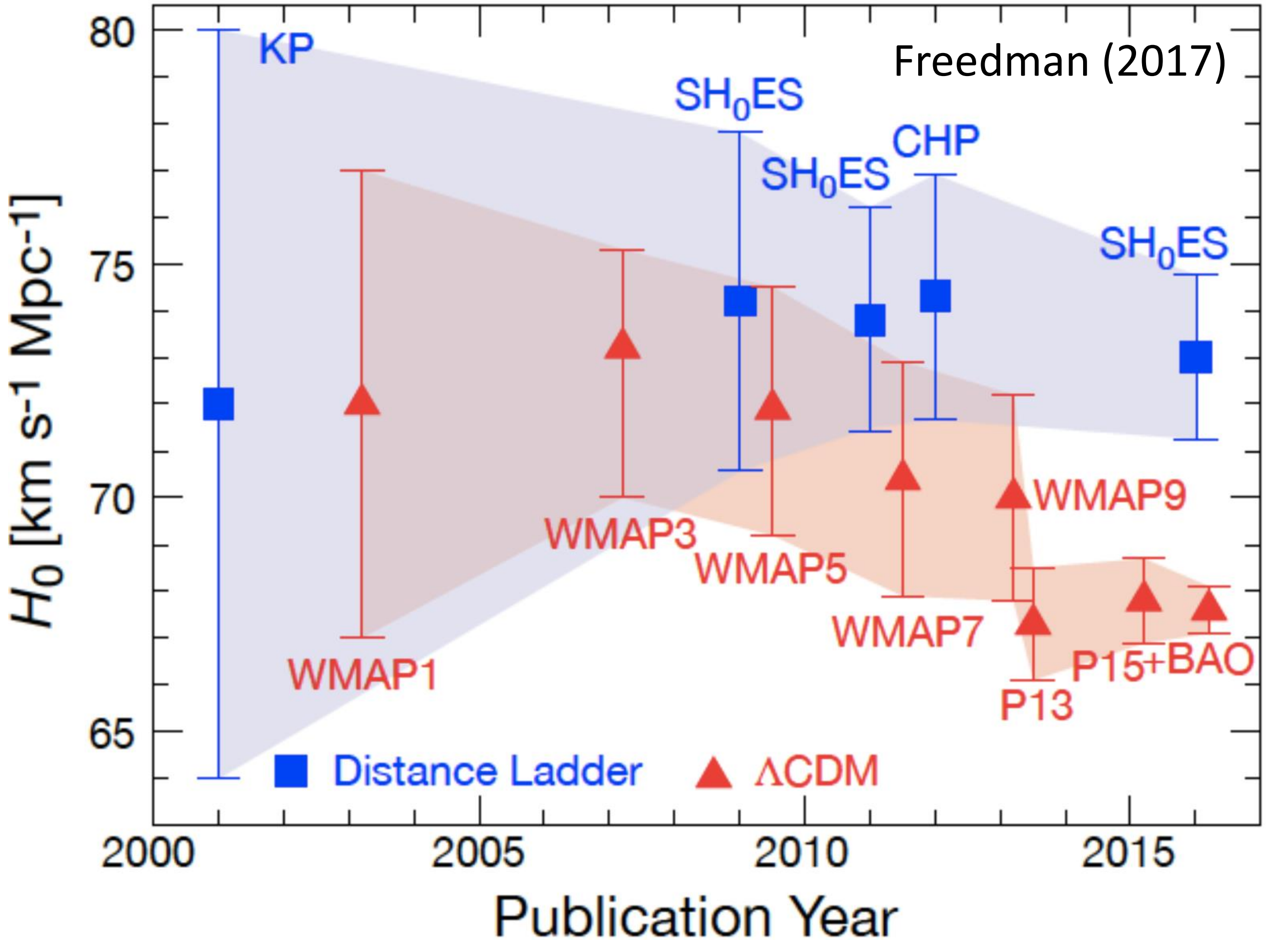
$$H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

See also
Seto-Kyutoku (2017)
arXiv:1710.06424

LIGO&Virgo+ (2017)

Hubble tension?

GW-EM can examine this 3.4sigma~9% discrepancy

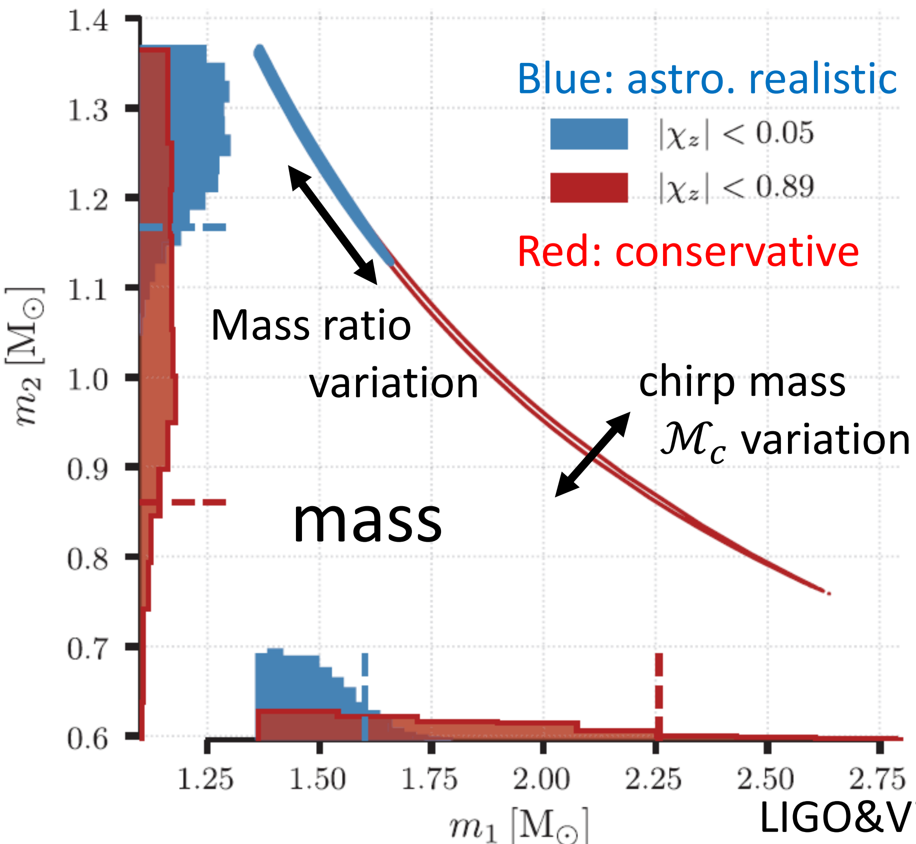


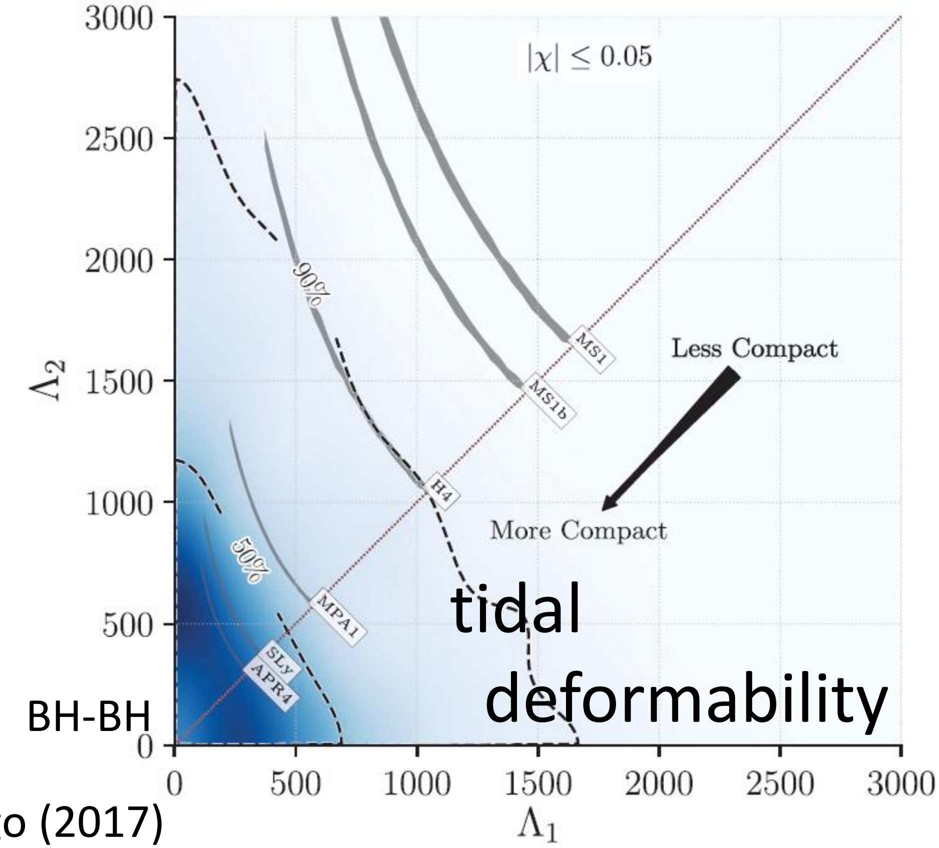
Freedman (2017) adapted from Beaton+ (2016)

Constraints on parameters

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

- this can be made tighter with better waveforms





LIGO&Virgo (2017)

Definition of parameters

Total mass $M = m_1 + m_2$

Reduced mass $\mu = m_1 m_2 / M$

Chirp mass $\mathcal{M} = \mu^{3/5} M^{2/5}$: accurately measured!

Symmetric mass ratio $\eta = \mu / M$: not very accurate...

Binary tidal deformability ($m_1 \leq m_2$)

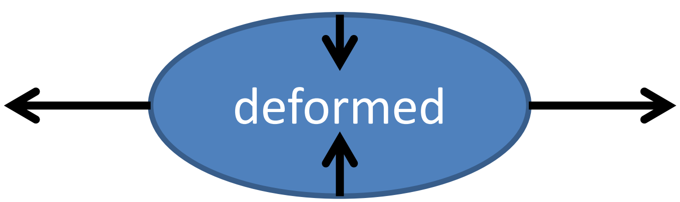
$$\tilde{\Lambda} = \frac{8}{13}[(1 + 7\eta - 31\eta^2)(\Lambda_1 + \Lambda_2) - \sqrt{1 - 4\eta}(1 + 9\eta - 11\eta^2)(\Lambda_1 - \Lambda_2)]$$

Quadrupolar tidal deformability

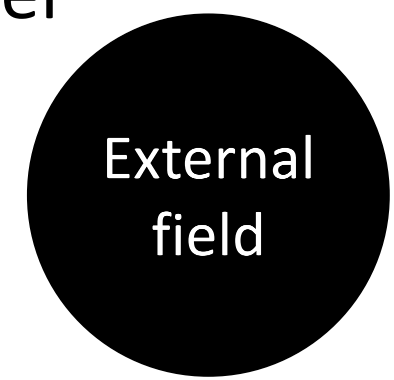
Leading-order finite-size effect on orbital evolution (strongly correlated with the neutron-star radius)

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

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



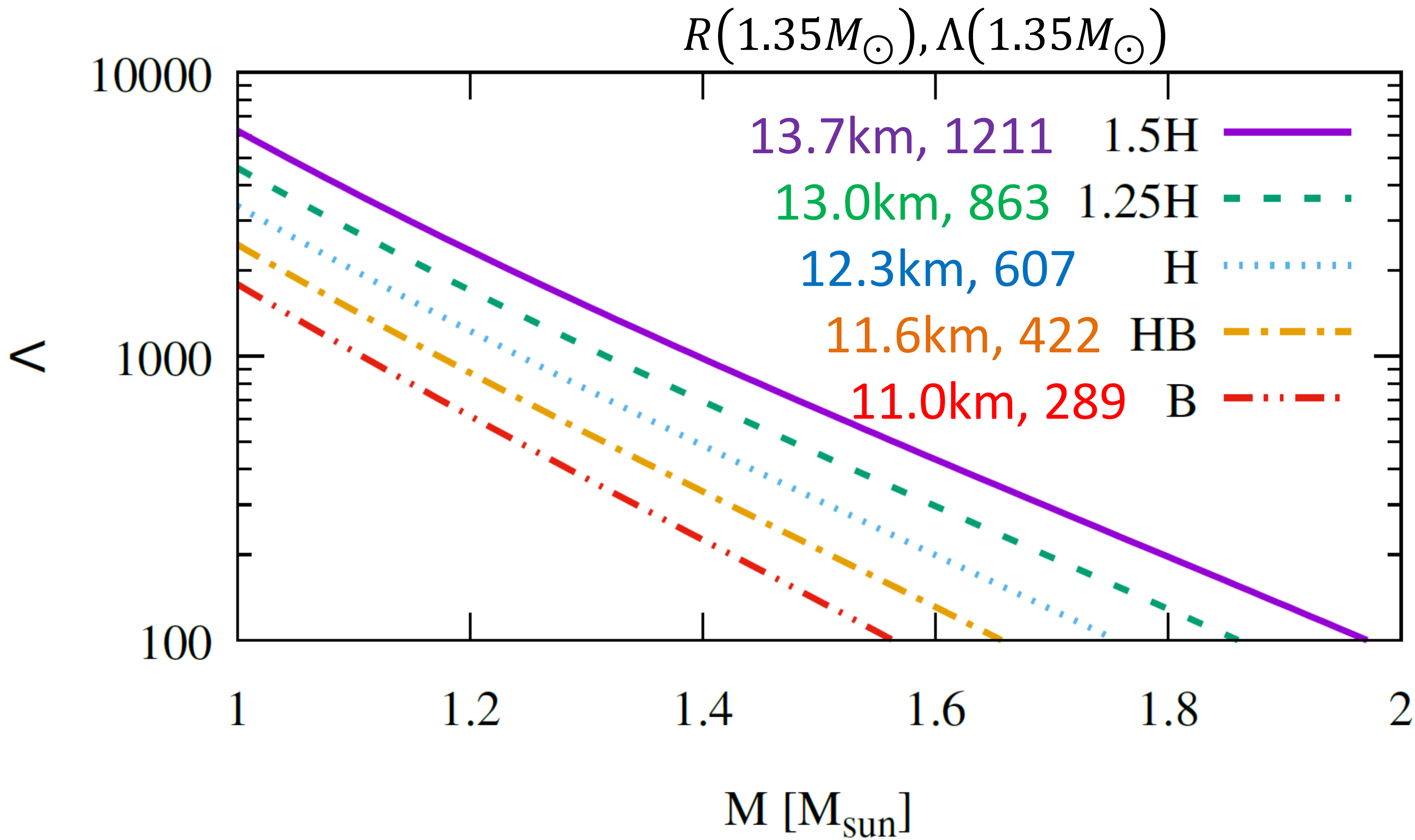
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



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

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

Representative example of EOSs

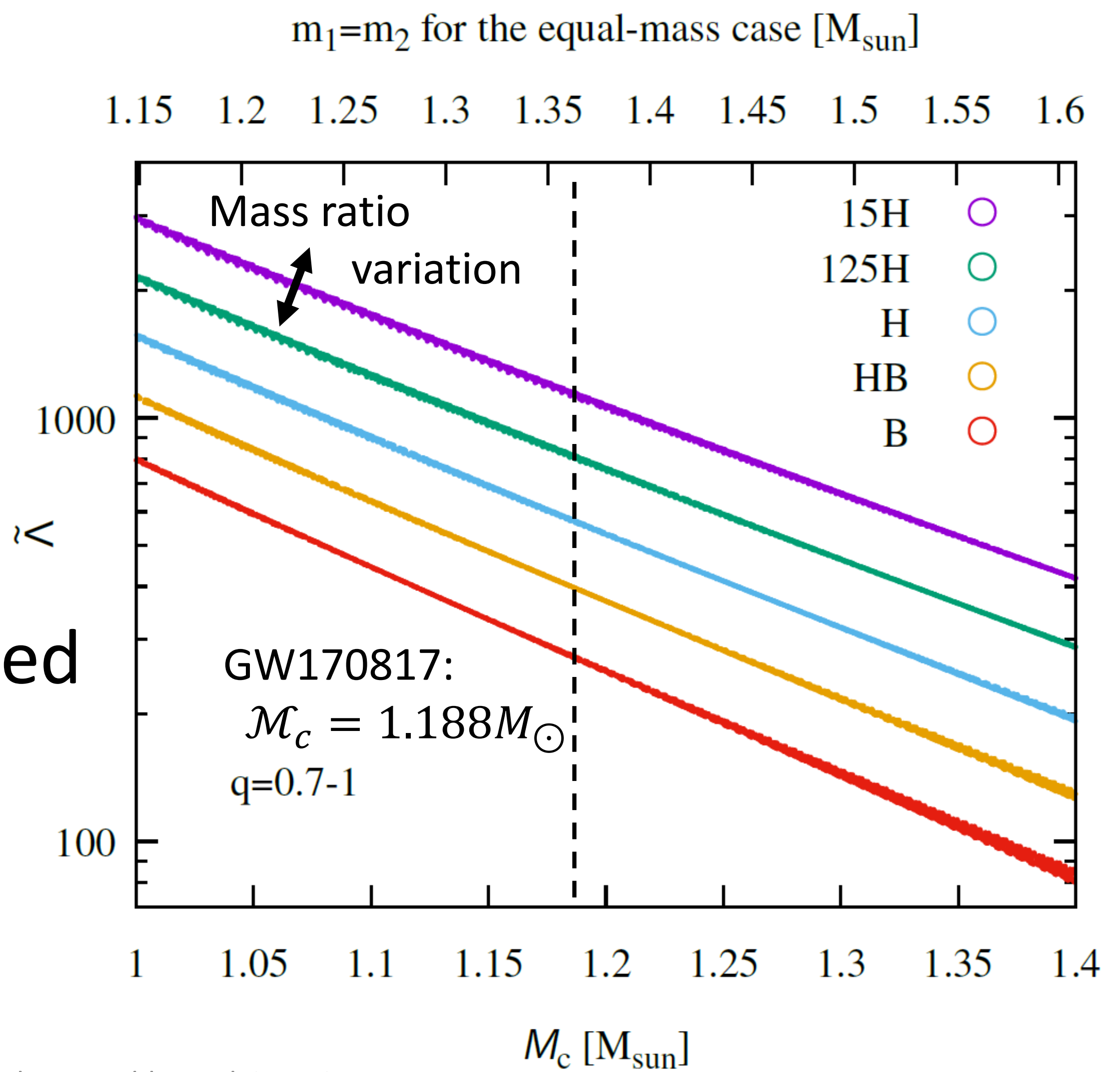


Tight correlation of $\tilde{\Lambda} - \mathcal{M}_c$

GW-measured $\tilde{\Lambda}$ is tightly correlated w/ the chirp mass

$\Lambda\left(M = 2^{1/5}\mathcal{M}_c\right)$ is effectively constrained

>13km is not favored

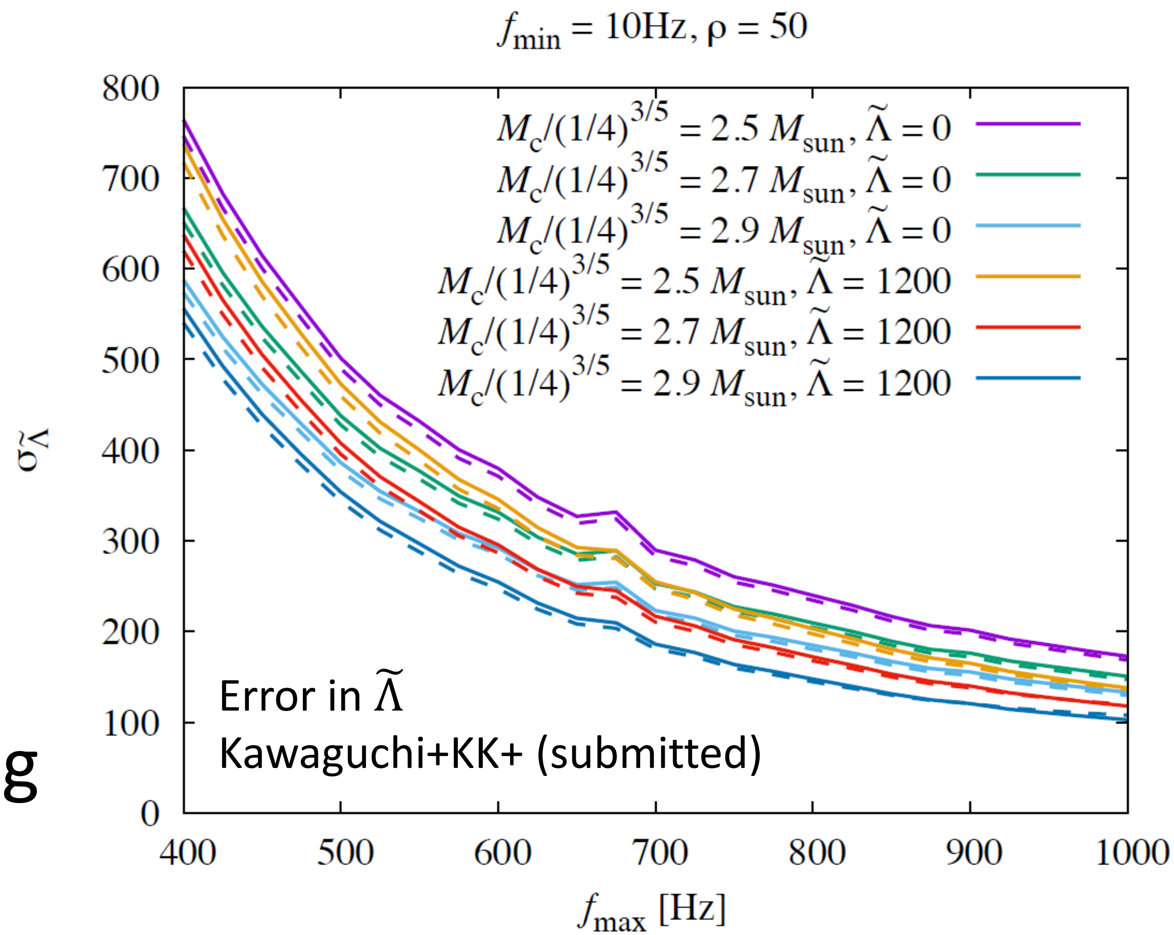


Only upper limits?

Information at high frequency is crucially important

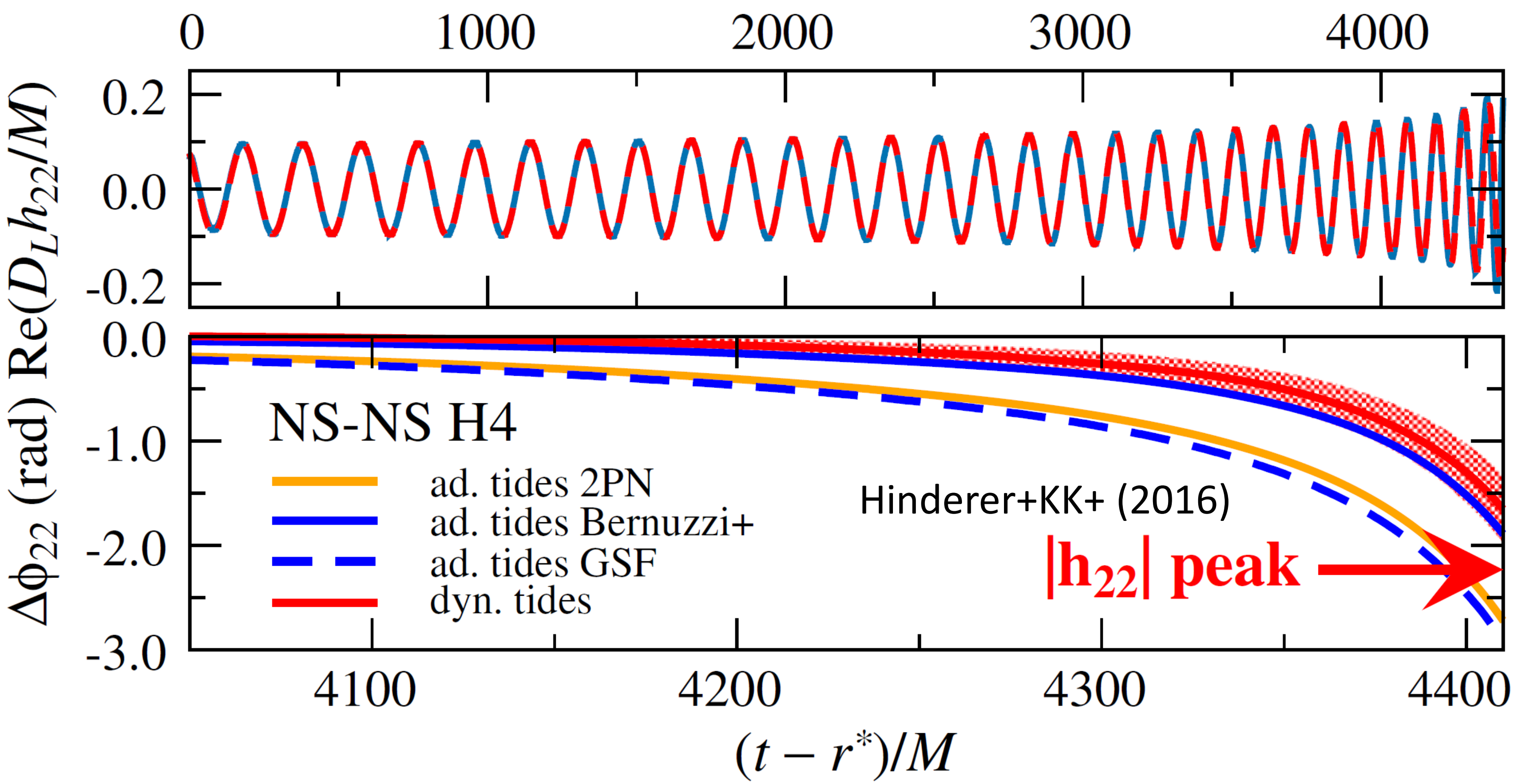
- low sensitivity of detectors
- unreliable theoretical waveforms

-> our work ongoing



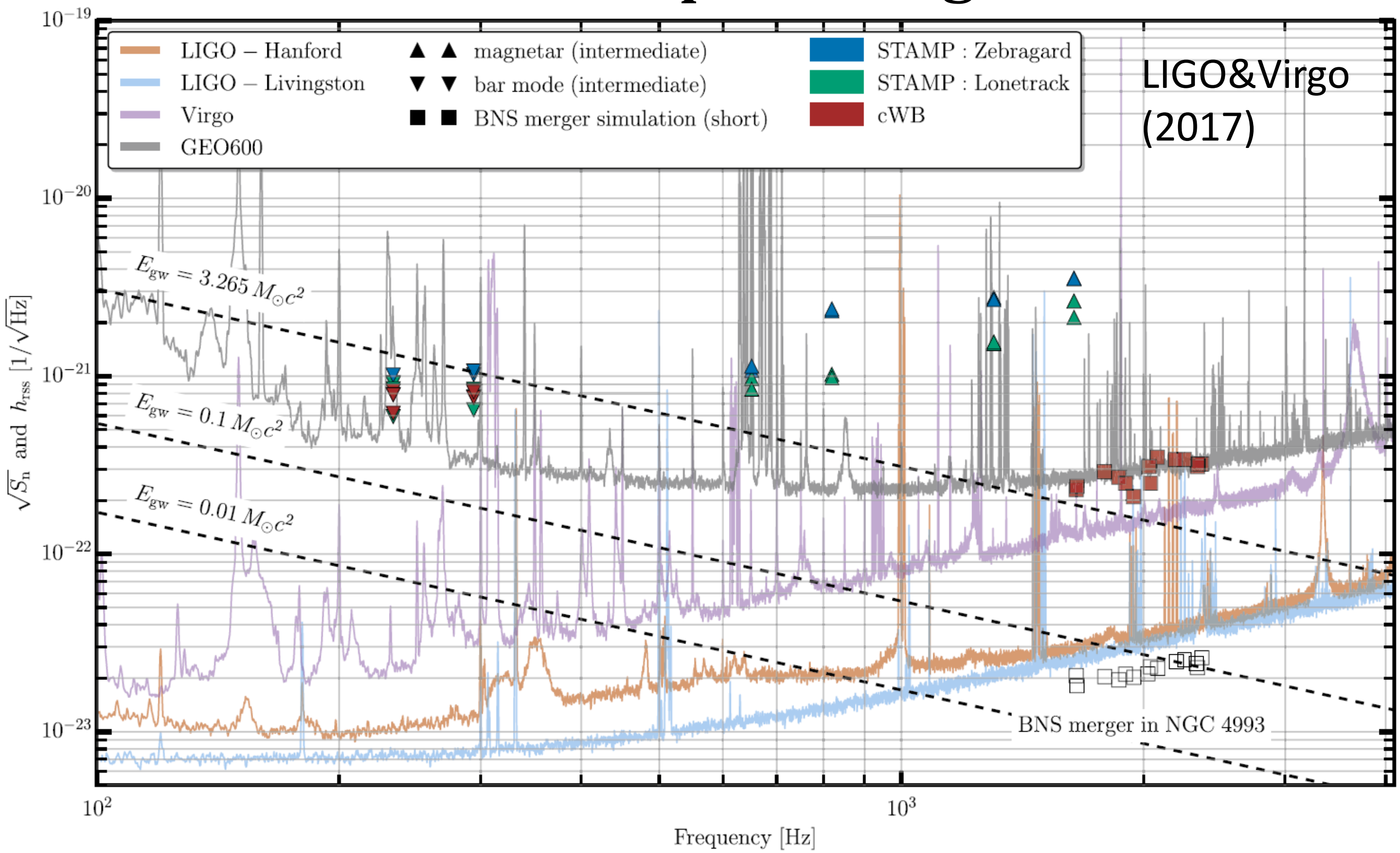
Theoretical waveform issue

The best analytic model so far is not yet accurately reproduce numerical-relativity waveforms



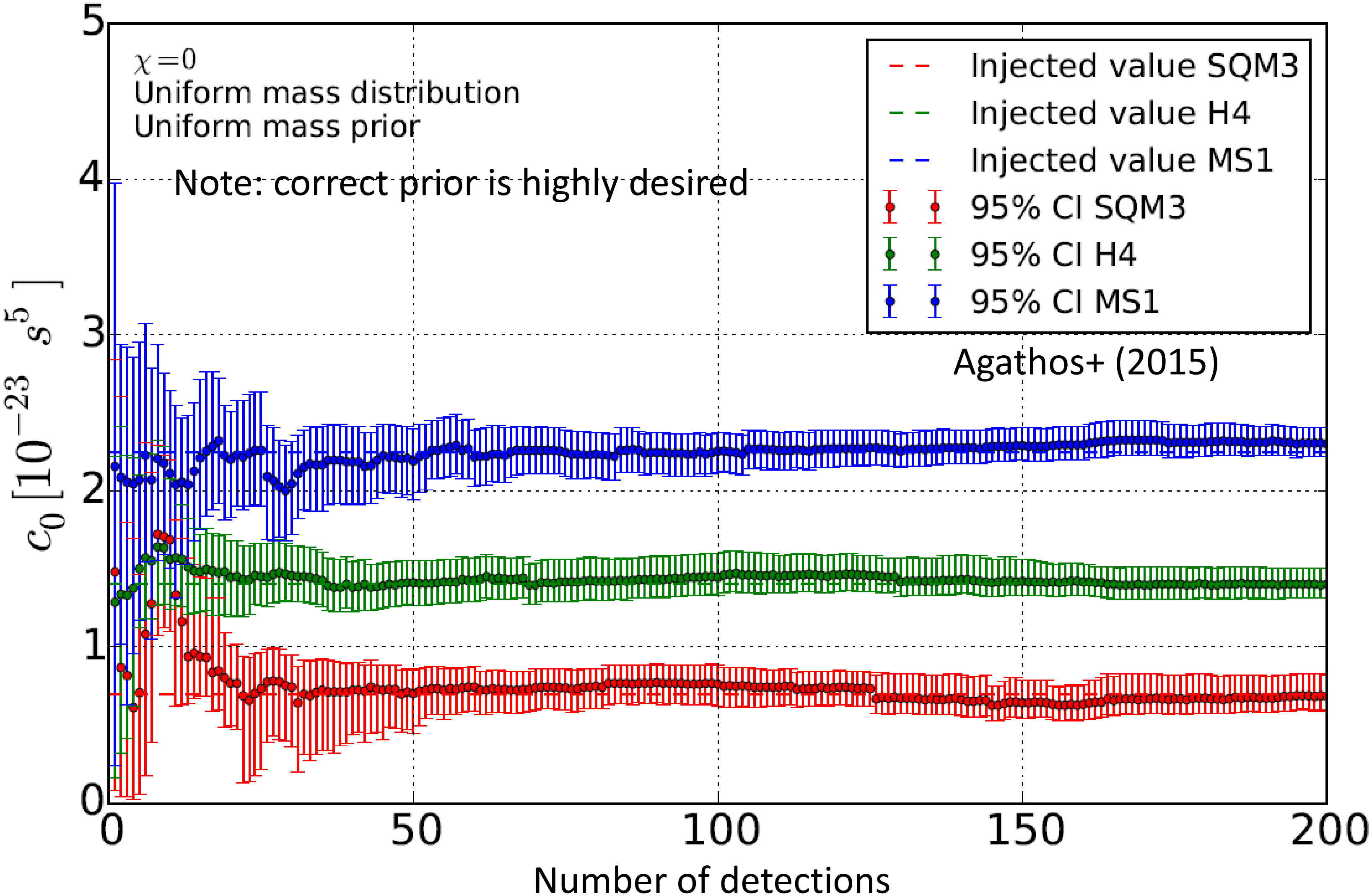
Postmerger information

The current limit ~ $E_{\mathrm{GW,postmerger}} < M_{\mathrm{total}}c^2$



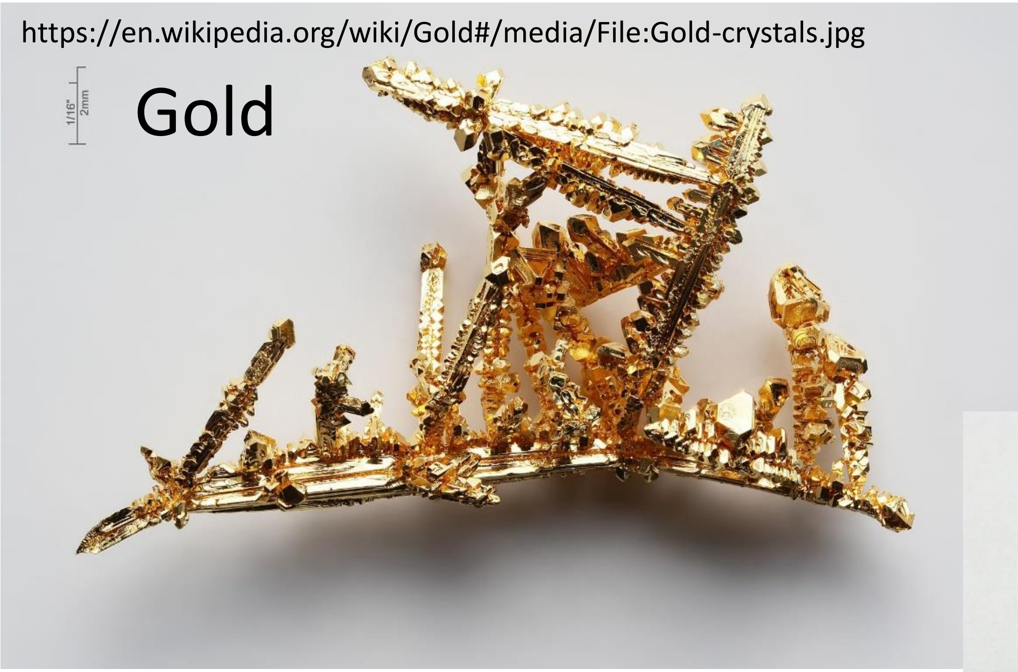
Stacking estimation

~tidal deformability



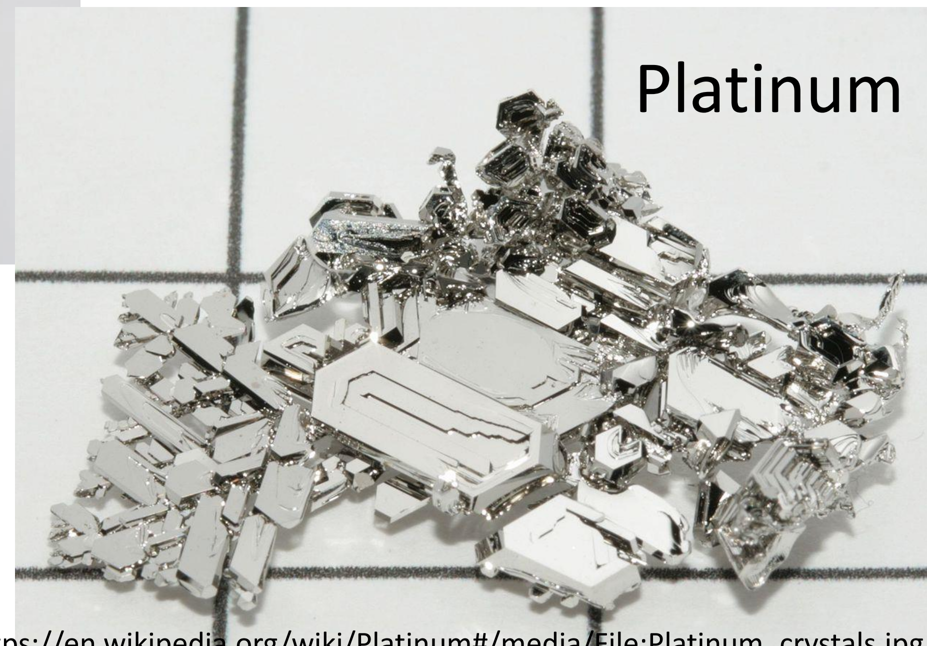
3. r-process and kilonova/macronova (AT 2017gfo)

r-process element



a half of nuclides
heavier than the iron
- the other half for “s”

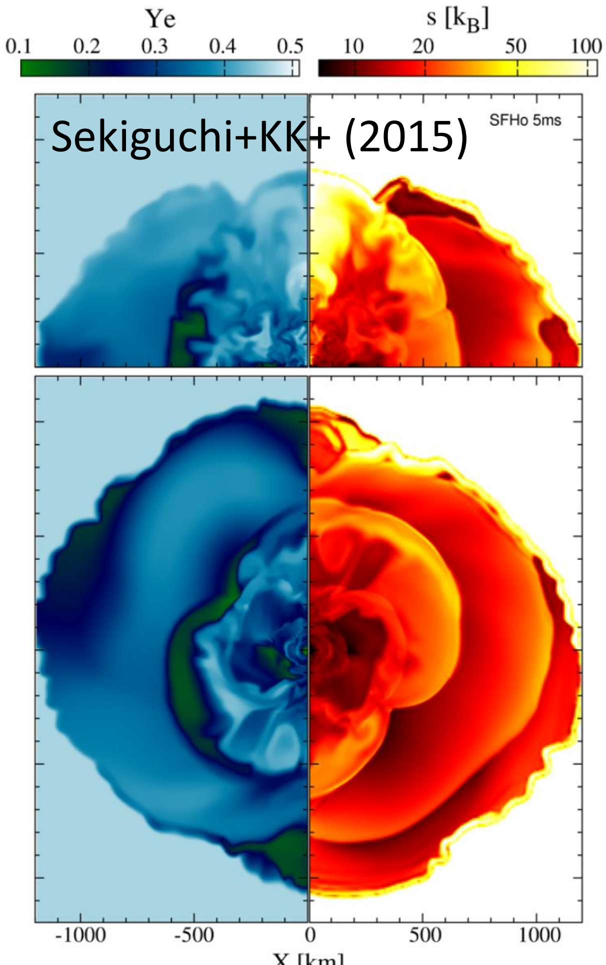
Where in the Universe
are they produced?



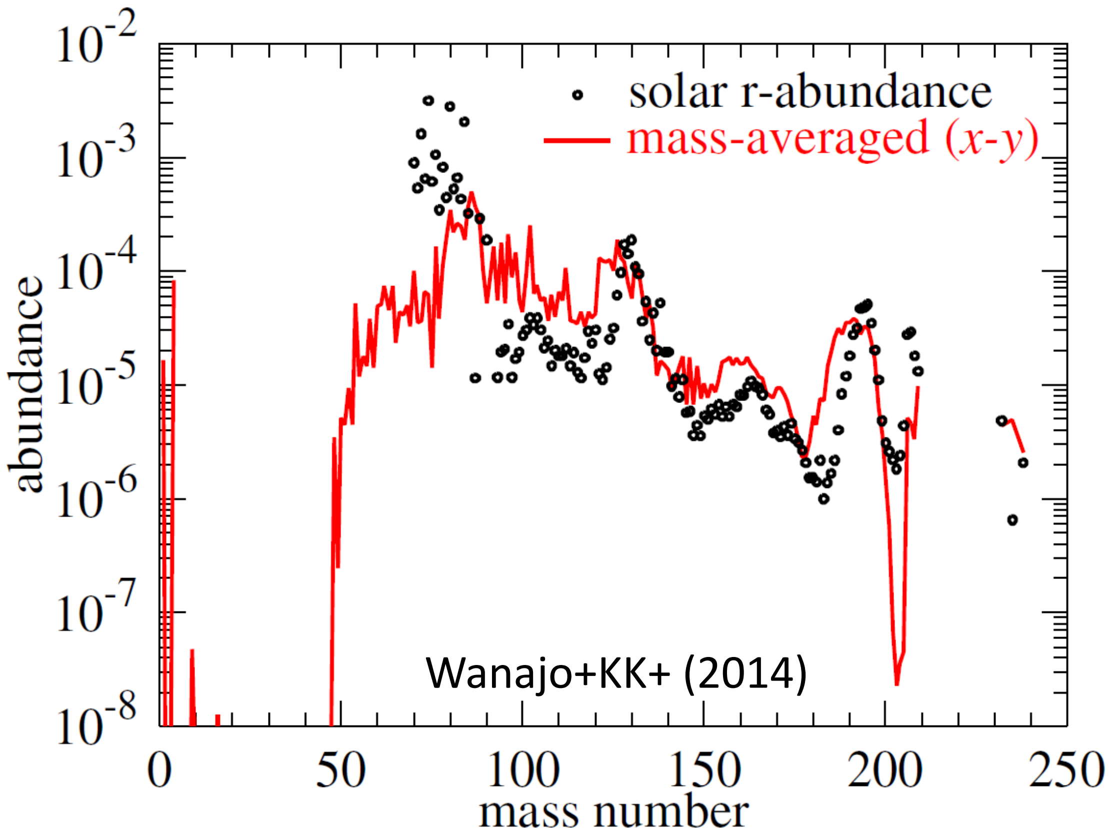
https://en.wikipedia.org/wiki/Platinum#/media/File:Platinum_crystals.jpg

Mass ejection from binary mergers

Successful at least for some binary models



how can we confirm this idea?



Kilonova/macronova

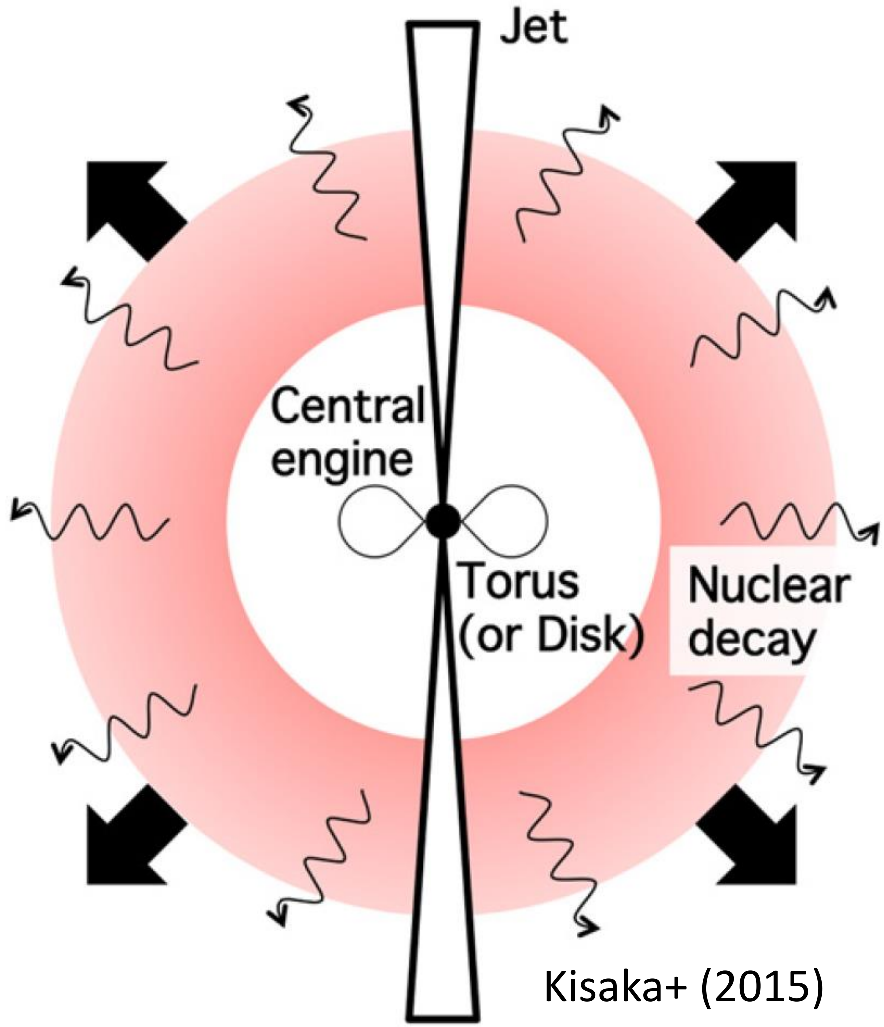
Ejected material contain radioactive r-elements

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)

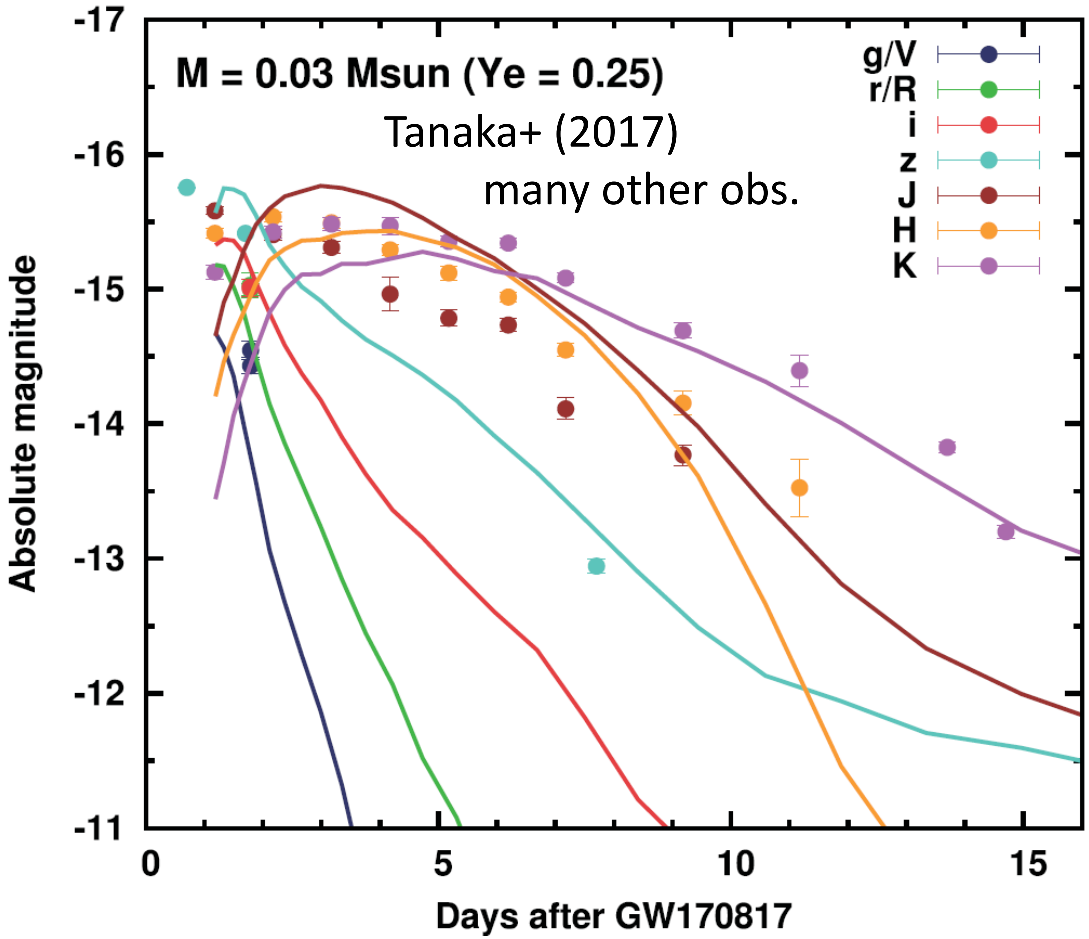
AT 2017gfo

In general agreement with theoretical models

particularly in NIR

Compared to SNe

- small mass
- high velocity
- high opacity
- no time scale of the heating



Uniqueness as an optical transient

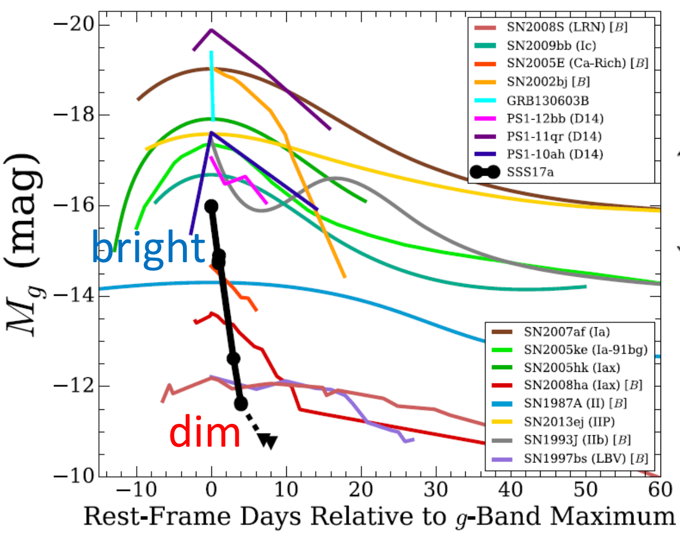
Consistent w/ kilonova/macronova

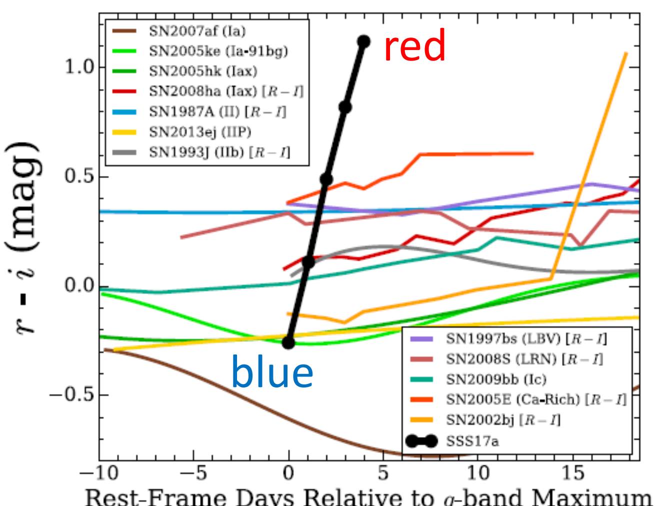
Black (SSS17a=AT 2017gfo): this event

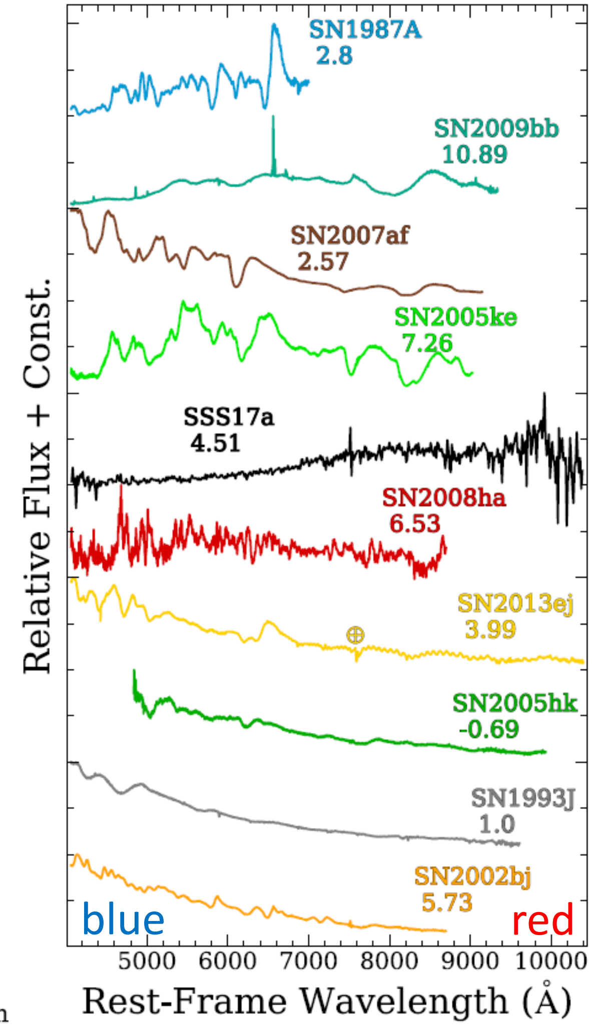
Colored: other known transients

featureless red spectrum

rapid dimming and reddening







Siebert+ (2017)

Kilonova/macronova characteristics

For spherical ejecta (Li-Paczynski 1998, also Arnett 1982)

The peak luminosity: $L_{\mathrm{peak}} \propto f\kappa^{-1/2} M^{1/2} v^{1/2}$

The peak time : $t_{\mathrm{peak}} \propto \kappa^{1/2} M^{1/2} v^{-1/2}$

Heating efficiency f and opacity κ – microphysics

particularly, r-process elements have high opacity

Ejecta mass M and ejecta velocity v – macrophysics

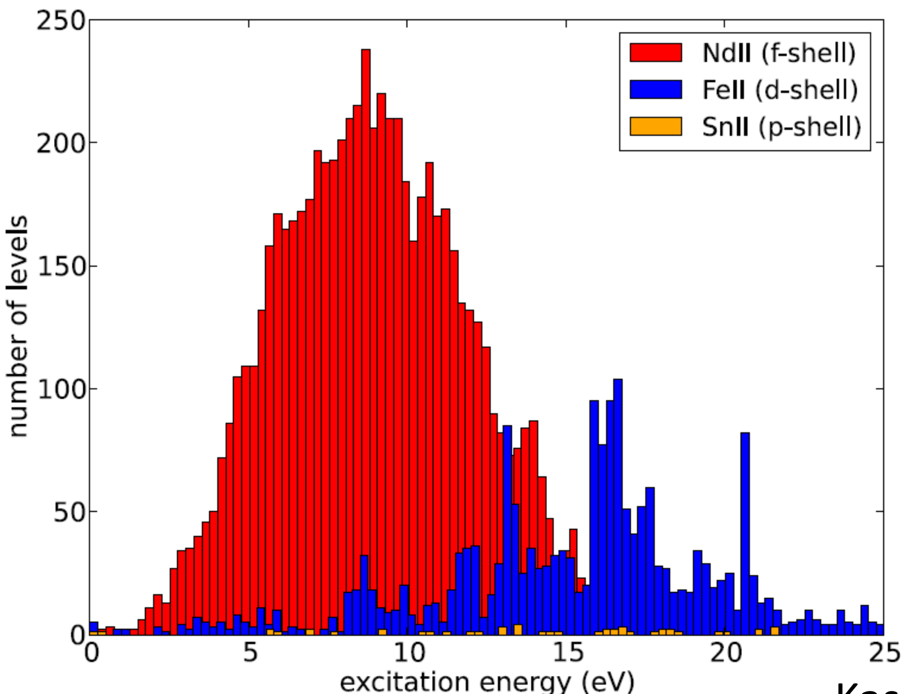
small mass and high velocity (vs supernovae)

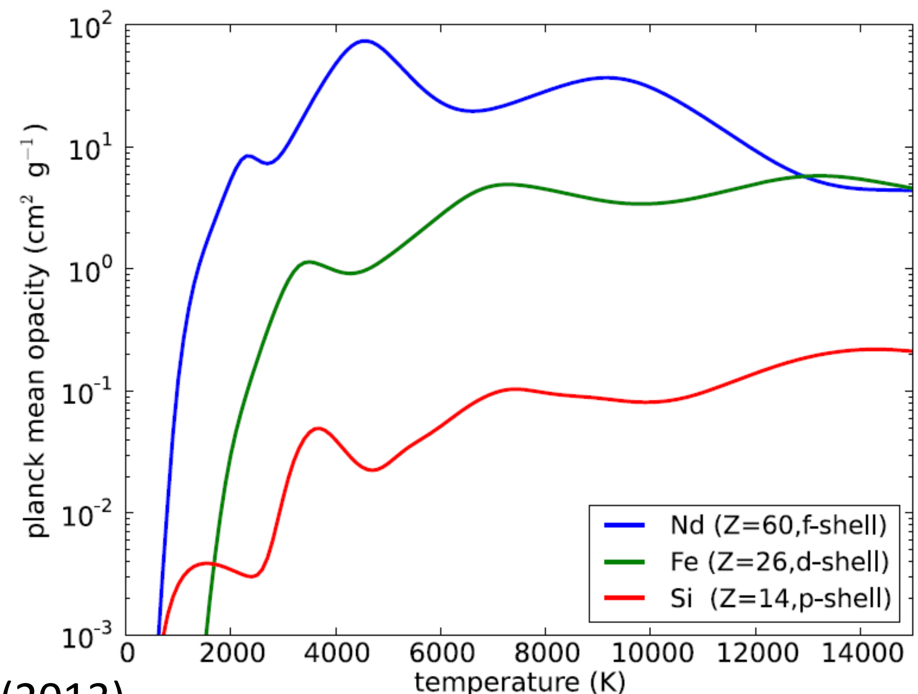
Too many lines of lanthanides

A bunch of energy levels -> complex line structures

-> very frequent interaction -> very high opacity

But modeling is incomplete (quantum many-body)





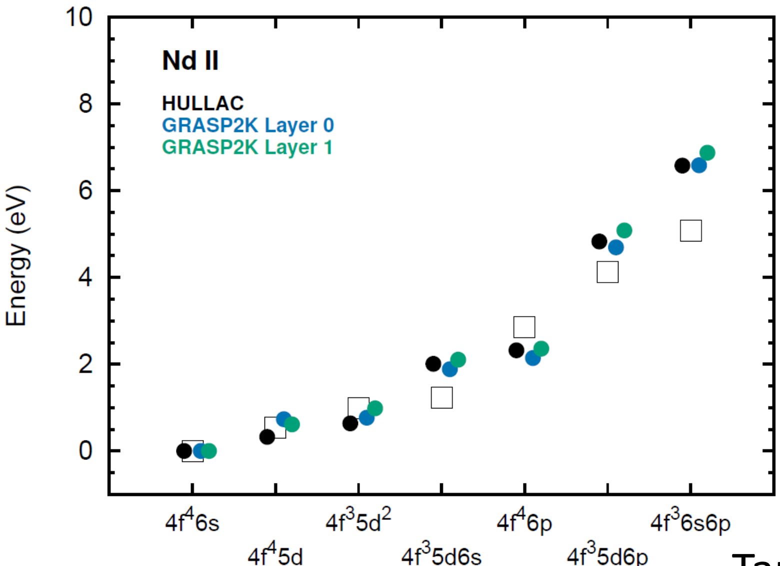
Kasen+ (2013)

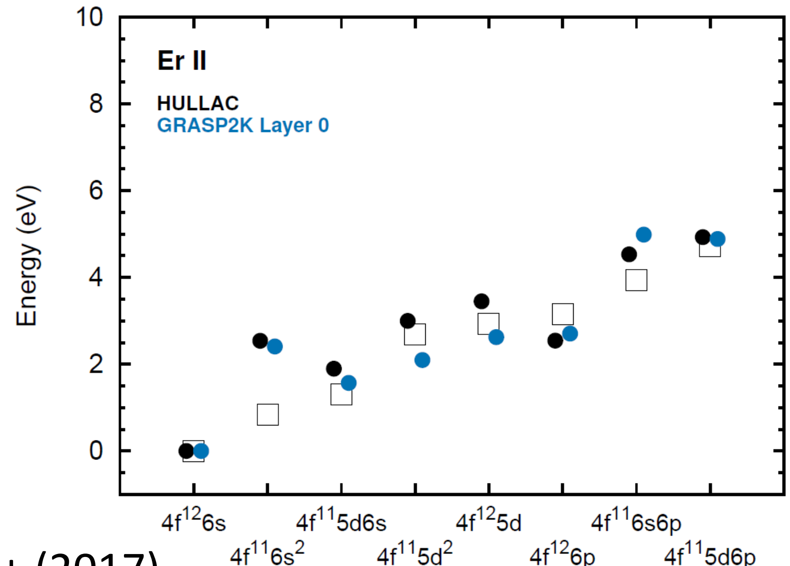
Number of lines

Ion	Configurations	Number of levels	Number of lines	Subset 1[a]	Subset 2[b]
Se I	$\mathbf{4s^24p^4}$, $4s^24p^3(4d,4f,5-8l)^c$, $4s4p^5$, $4s4p^4(4d,4f)$, $4s^24p^2(4d^2,4d4f,4f^2)$, $4s4p^3(4d^2,4d4f,4f^2)$	3076	973,168	2,395	654
Se II	$\mathbf{4s^24p^3}$, $4s^24p^2(4d,4f,5-8l)^c$, $4s4p^4$, $4s4p^3(4d,4f)$, $4s^24p(4d^2,4d4f,4f^2)$, $4s4p^2(4d^2,4d4f,4f^2)$	2181	511,911	1,978	584
Se III	$\mathbf{4s^24p^2}$, $4s^24p(4d,4f,5-8l)^c$, $4s4p^3$, $4s4p^2(4d,4f)$, $4s^2(4d^2,4d4f,4f^2)$, $4s4p(4d^2,4d4f,4f^2)$	922	92,132	2,286	882
Ru I	$\mathbf{4d^75s}$, $\mathbf{4d^65s^6}$, $\mathbf{4d^8}$, $4d^7(5p,5d,6s,6p)$, $4d^65s(5p,5d,6s)$	1,545	250,476	49,181	20,350
Ru II	$\mathbf{4d^7}$, $4d^6(5s-5d,6s,6p)$	818	76,592	27,976	14,073
Ru III	$\mathbf{4d^6}$, $4d^5(5s-5d,6s)$	728	49,066	30,628	17,451
Te I	$\mathbf{5s^25p^4}$, $\mathbf{5s^25p^3(4f,5d,5f,6s-6f,7s-7d,8s)}$, $5s5p^5$	329	14,482	410	348
Te II	$\mathbf{5s^25p^3}$, $\mathbf{5s^25p^2(4f,5d,5f,6s-6f,7s-7d,8s)}$, $5s5p^4$	253	9,167	705	569
Te III	$\mathbf{5s^25p^2}$, $\mathbf{5s^25p(5d,6s-6d,7s)}$, $5s5p^3$	57	419	249	227
Nd I	$\mathbf{4f^46s^2}$, $\mathbf{4f^46s(5d,6p,7s)}$, $\mathbf{4f^45d^2}$, $\mathbf{4f^45d6p}$, $4f^35d6s^2$, $4f^35d^2(6s,6p)$, $4f^35d6s6p$	31,358	70,366,259	12,365,070	2,804,079
Nd II	$\mathbf{4f^46s}$, $\mathbf{4f^45d}$, $4f^46p$, $4f^36s(5d,6p)$, $4f^35d^2$, $4f^35d6p$	6,888	3,951,882	3,682,300	1,287,145
Nd III	$\mathbf{4f^4}$, $4f^3(5d,6s,6p)$, $4f^25d^2$, $4f^25d(6s,6p)$, $4f^26s6p$	2252	458,161	303,021	136,248
Er I	$\mathbf{4f^{12}6s^2}$, $\mathbf{4f^{12}6s(5d,6p,6d,7s,8s)}$, $4f^{11}6s^2(5d,6p)$, $4f^{11}5d^26s$, $4f^{11}5d6s(6p,7s)$	10,535	9,247,777	443,566	129,713
Er II	$\mathbf{4f^{12}6s}$, $4f^{12}(5d,6p)$, $4f^{11}6s^2$, $4f^{11}6s(5d,6p)$, $4f^{11}5d^2$, $4f^{11}5d6p$	5,333	2,432,665	1,713,258	489,383
Er III	$\mathbf{4f^{12}}$, $4f^{11}(5d,6s,6p)$	723	42,671	41,843	16,787

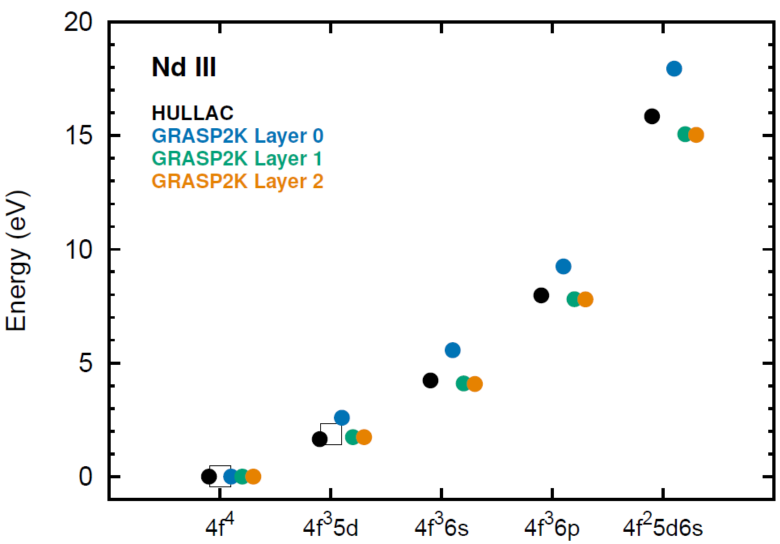
Tanaka+ (2017)

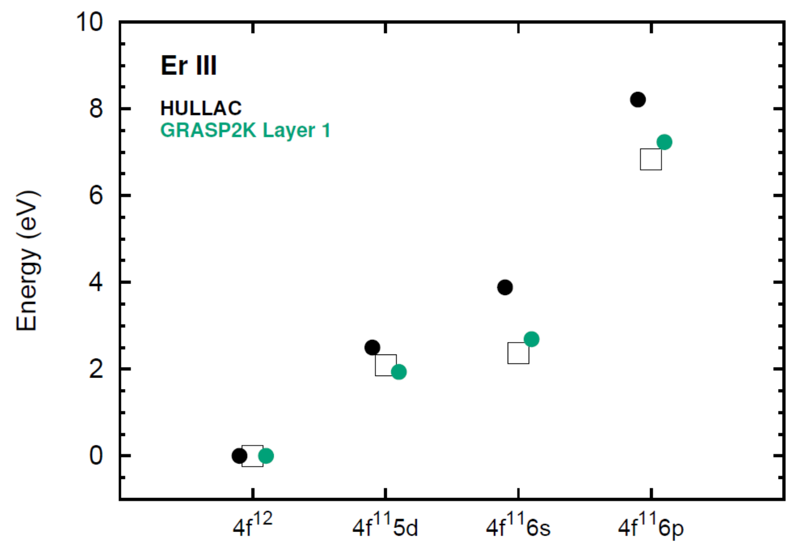
Theoretical uncertainties





Tanaka+ (2017)



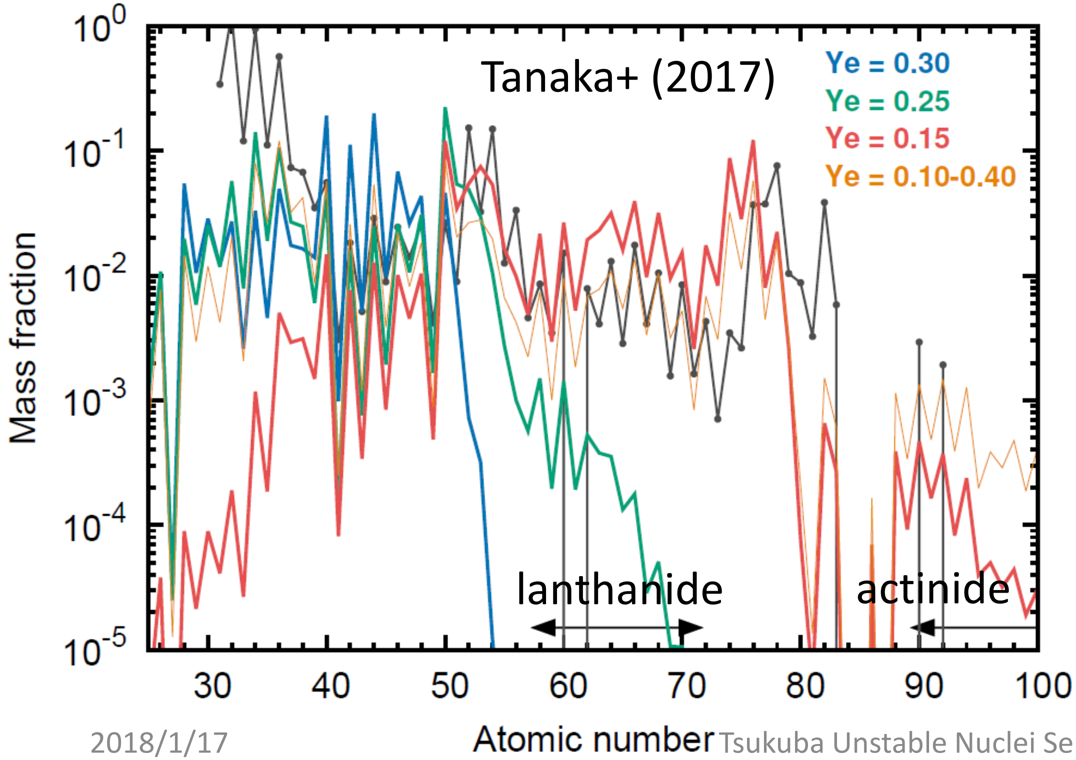


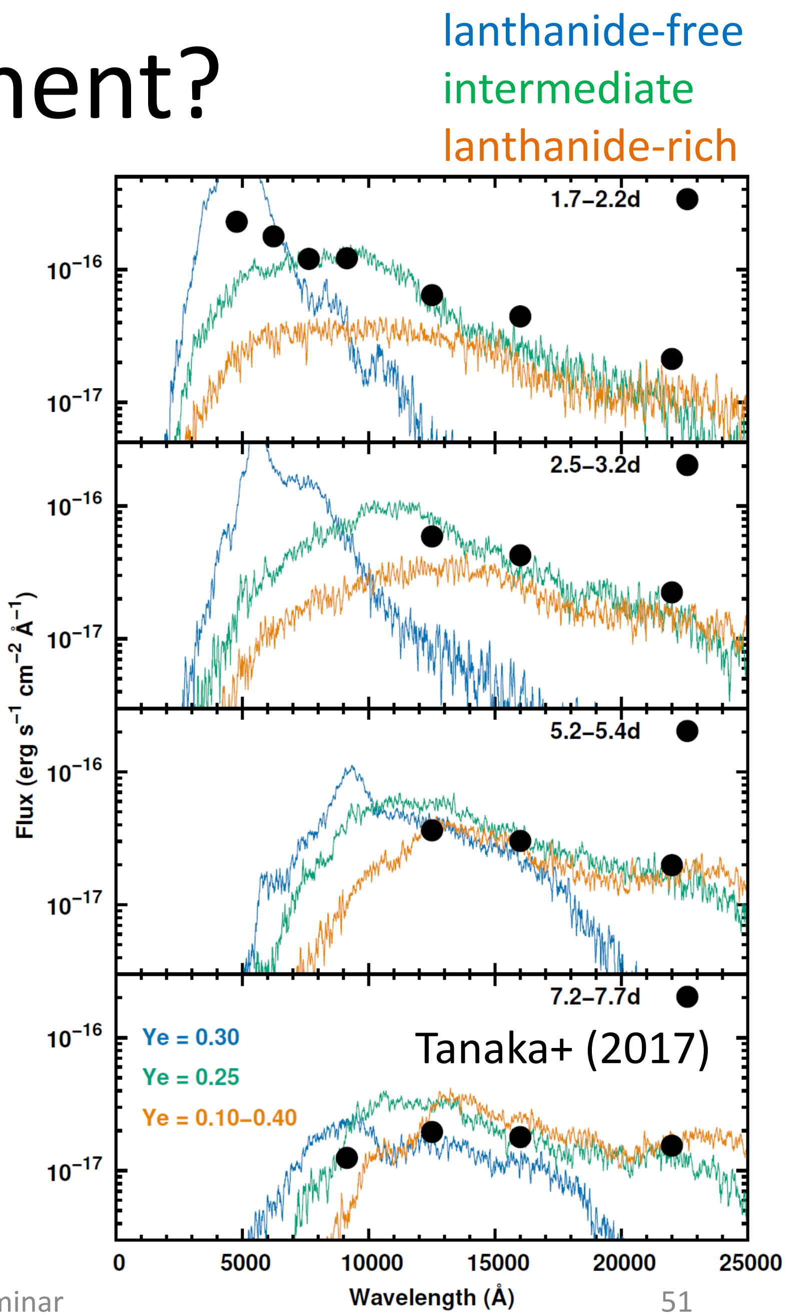
Two component?

Too bright at earlier epochs

Early lanthanide-free +

late lanthanide is very likely

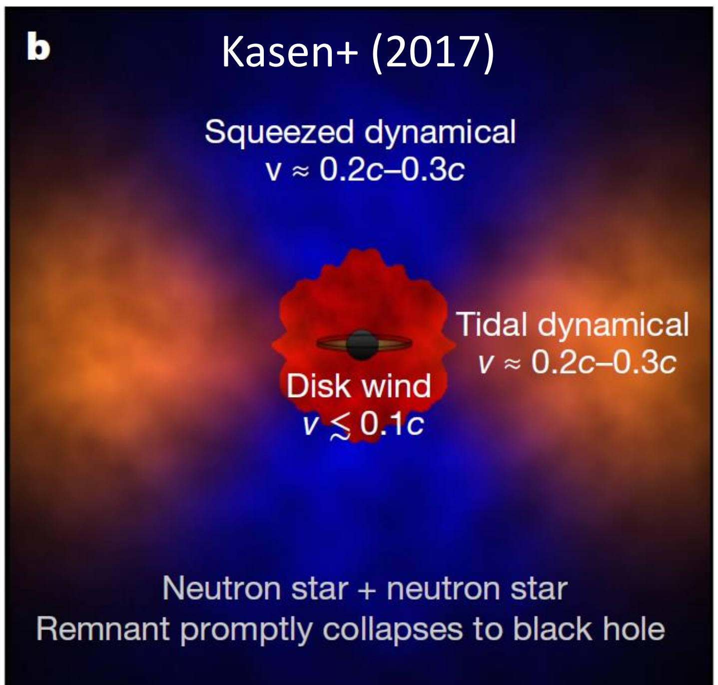


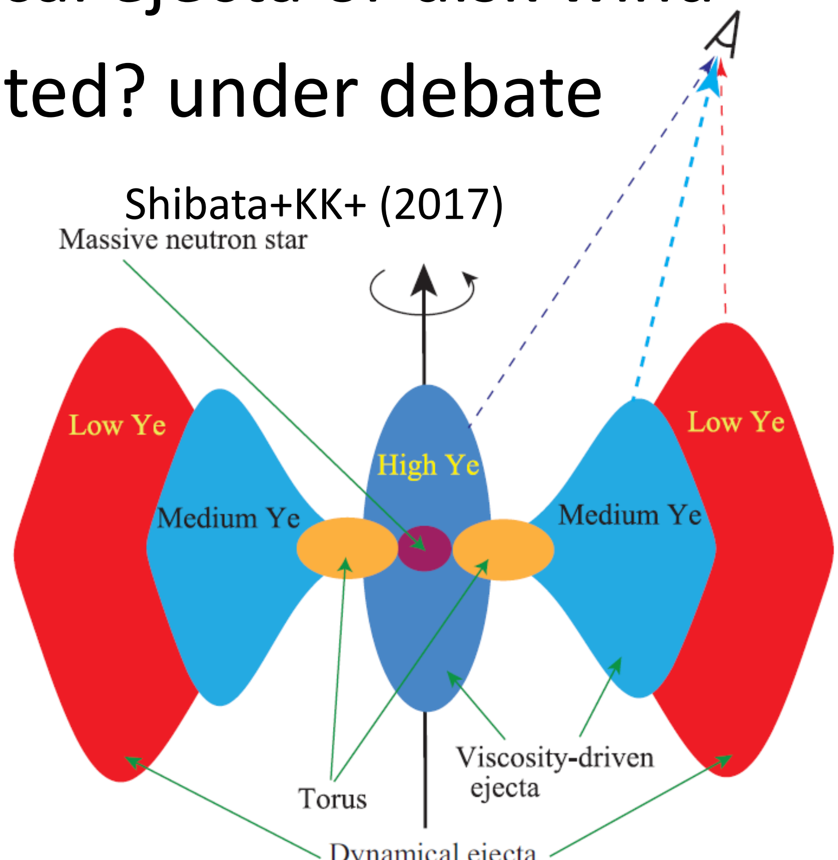


Theoretical understanding

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





Kyoto group's model

A moderately large maximum-mass of neutron stars

-> long-lived remnant massive neutron stars

-> strong neutrino irradiation

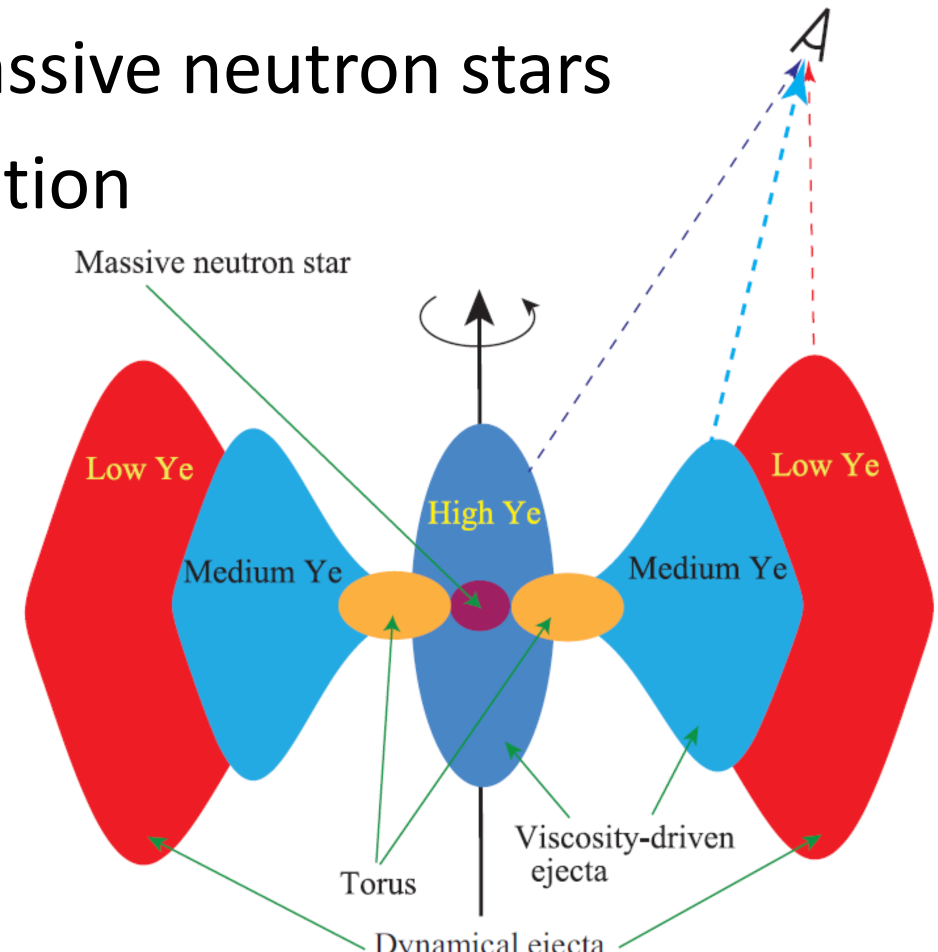
-> light r-elements

-> blue kilonova!

Remnant's lifetime

our model: >1s

Kasen's model: <10ms



Shibata+KK+ (2017)

Maximum mass from GW170817

Upper limits are proposed based on assumptions

- Optical emission rejects magnetar models

Margalit-Metzger: $\leq 2.17 M_{\odot}$

Shibata+KK+: $2.15 - 2.25 M_{\odot}$

- A GRB jet launch calls for gravitational collapse

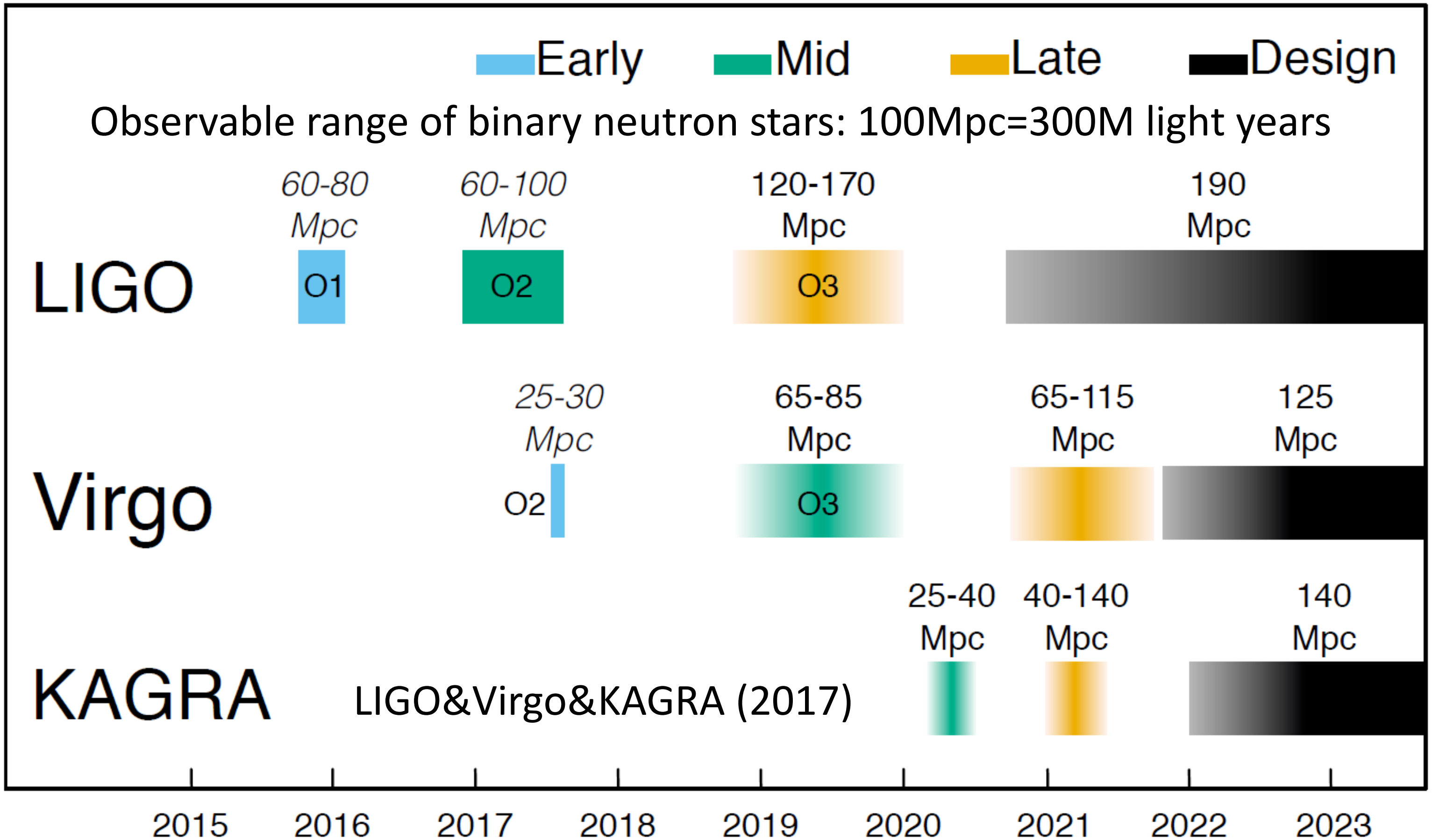
Rezzolla+, Ruiz+: $\leq 2.16 M_{\odot}$

I do not think any argument is strongly convincing, but similar values are inferred anyway

4. Future prospect and summary

Future observation

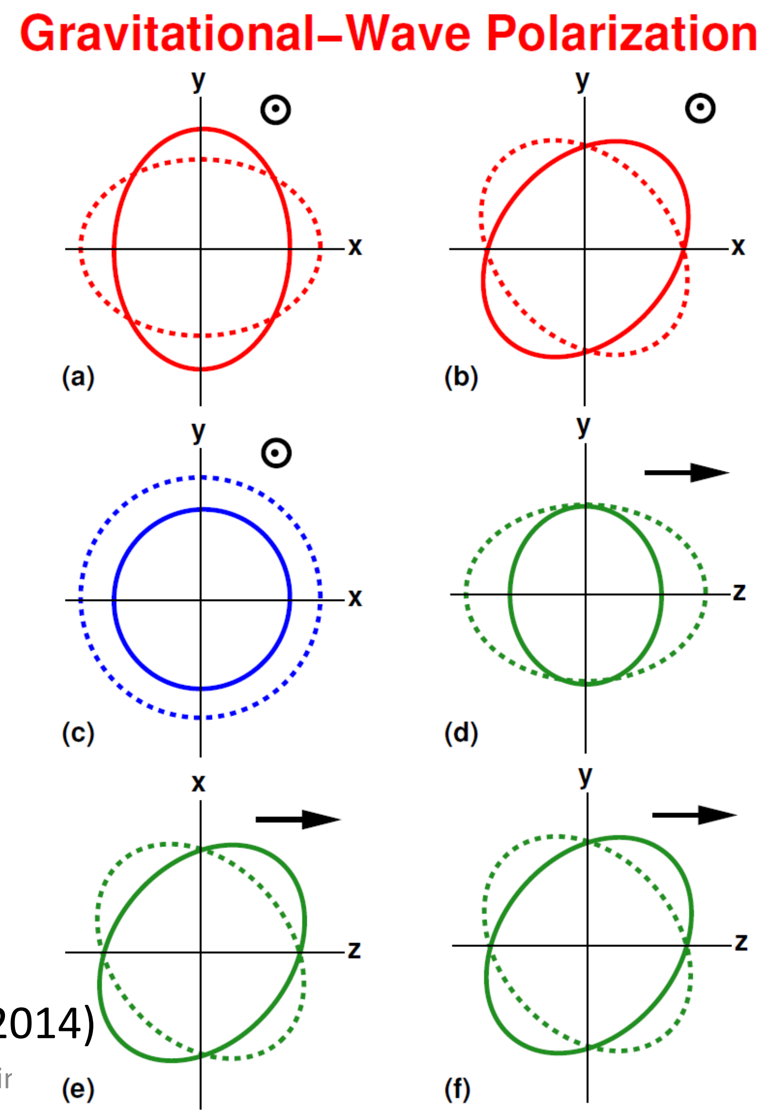
KAGRA will join in 2020s and see GW polarizations…



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)

Summary

- Gravitational waves from binary neutron stars are detected and confirmed to be a genuine event by followup electromagnetic observations.
- The neutron-star radius is now constrained to <13-14km via tidal deformability of <800.
- Hubble's constant is constrained independently.
- The short gamma-ray burst-ish transient may be associated with off-axis cocoon emission.
- The kilonova suggests r-process nucleosynthesis.

Appendix

x. Short gamma-ray burst (GRB 170817A)

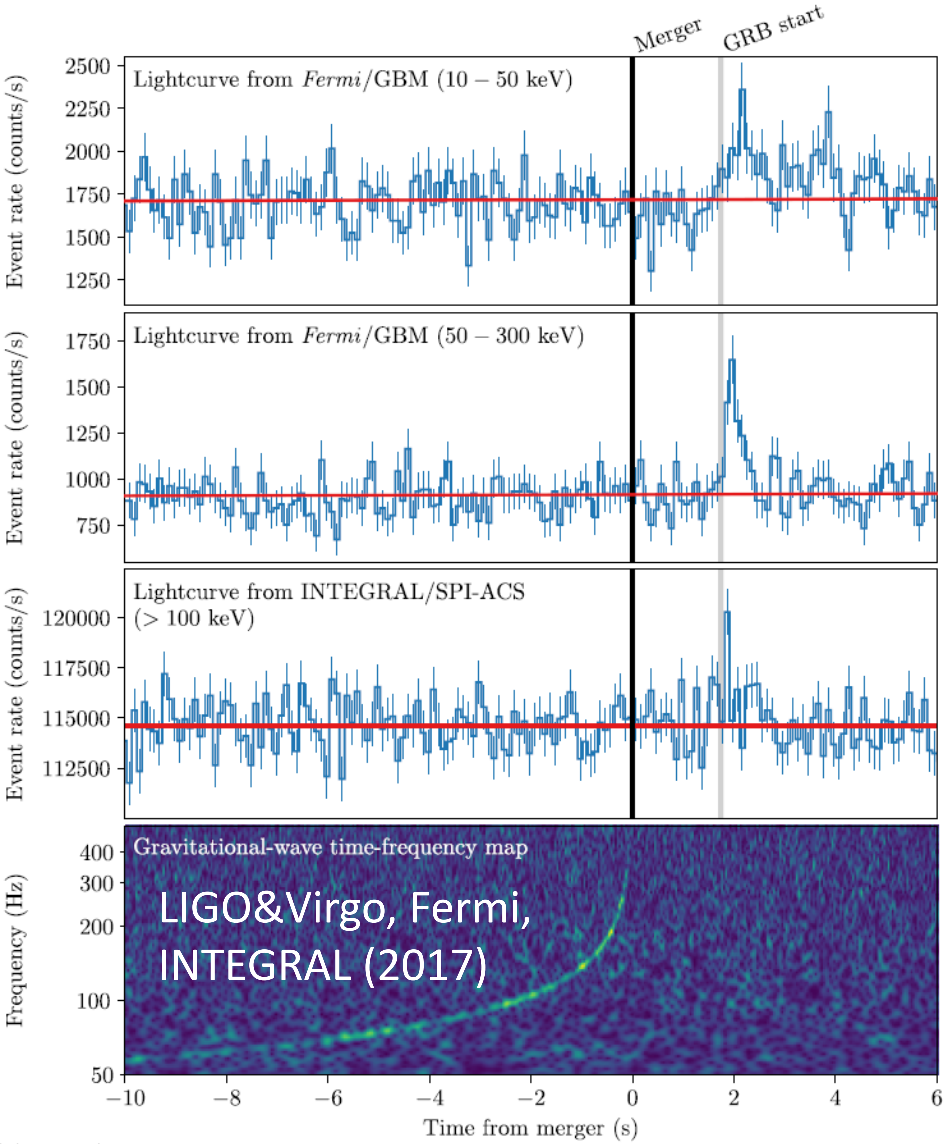
Short-hard gamma-ray burst

Is this really caused by neutron star mergers?

GRB 170817A

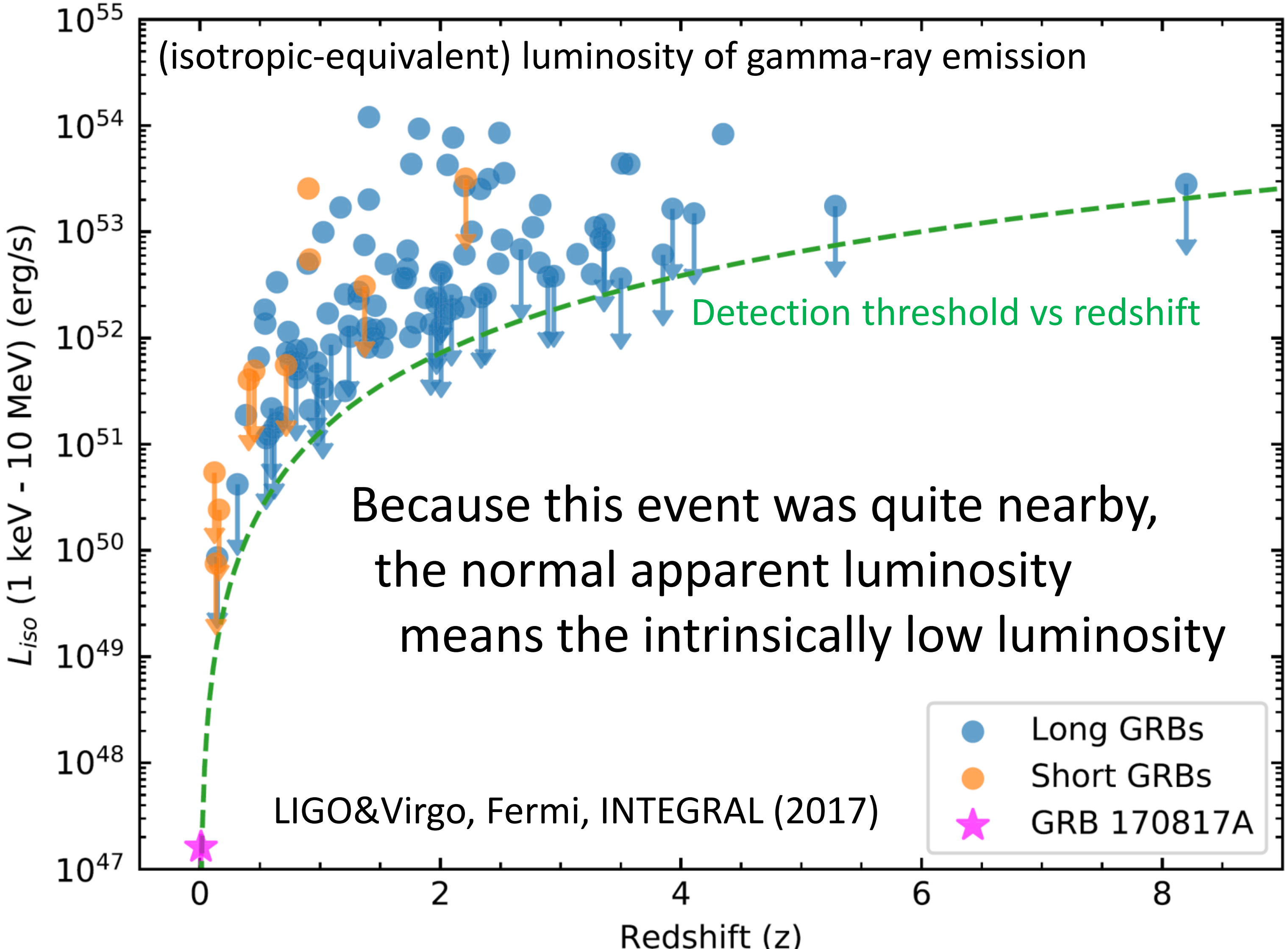
Fermi and INTEGRAL
agree each other
though relatively weak

The 1.7s delay from GWs
- jet launch
- jet propagation in
the ejected material
- onset of transparency



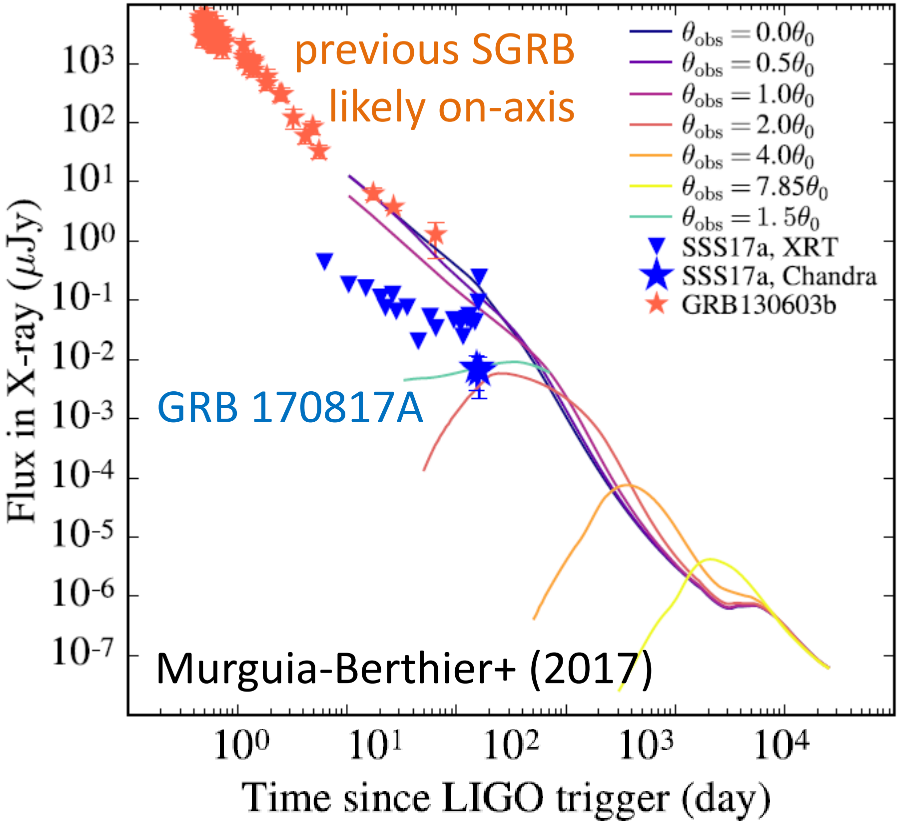
LIGO&Virgo, Fermi, INTEGRAL (2017)

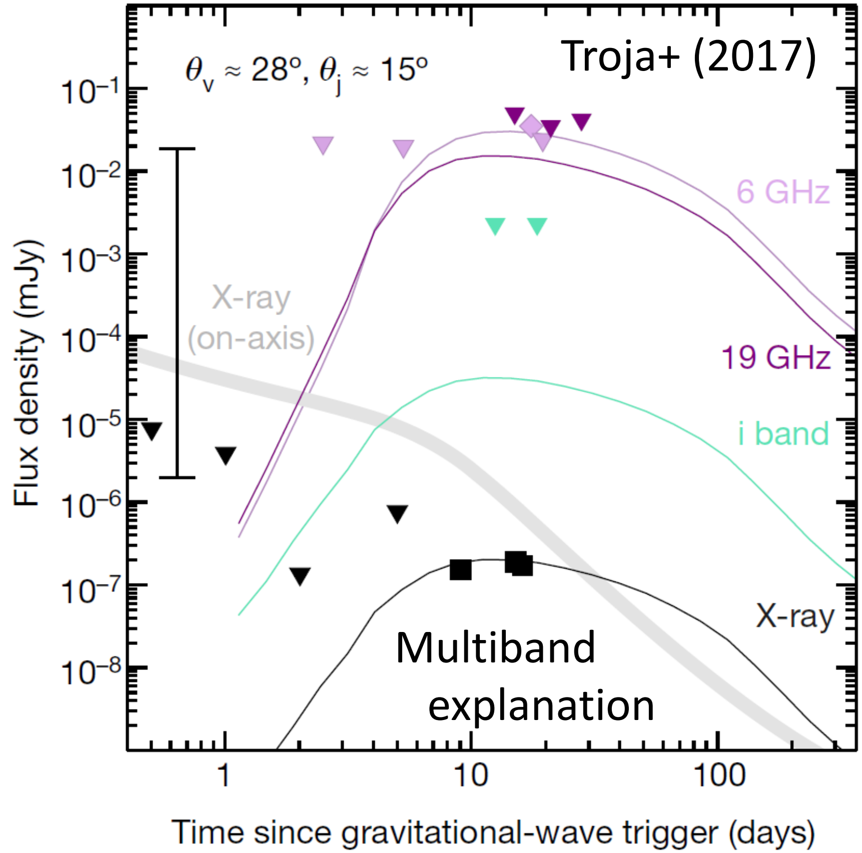
Underluminous...



Off-axis? early X/radio afterglow

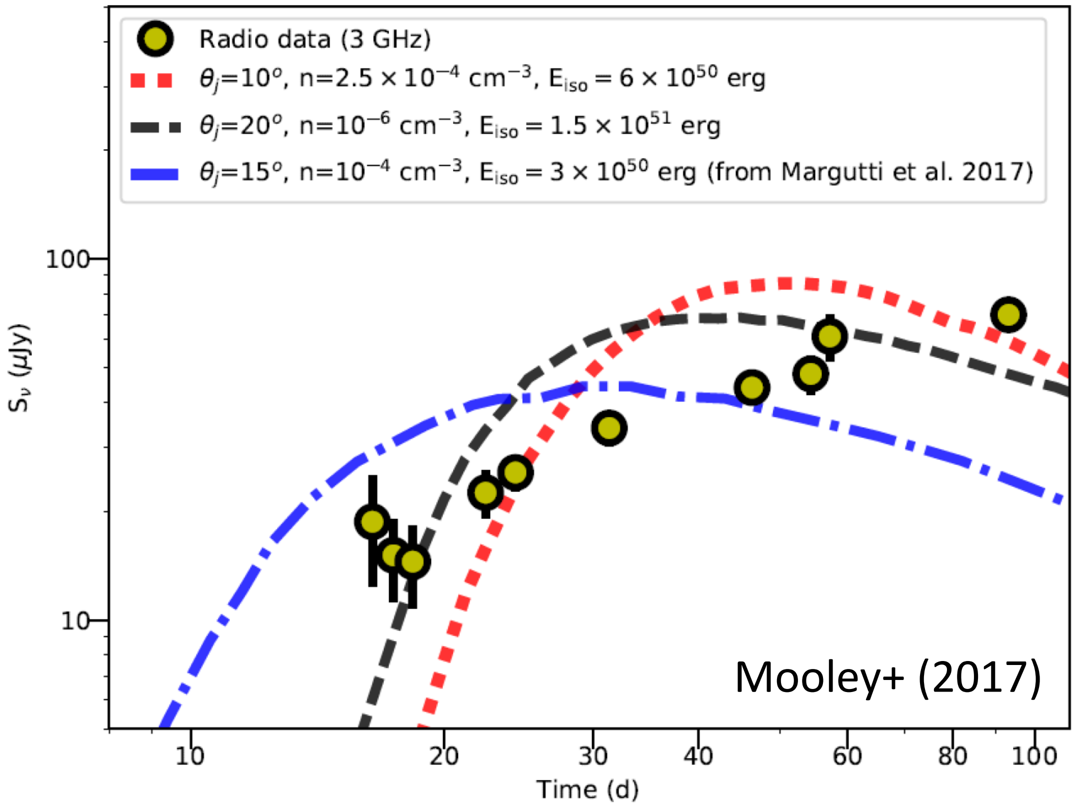
As of Oct 16, on-axis short GRBs were disfavored and an off-axis jet offered a natural interpretation

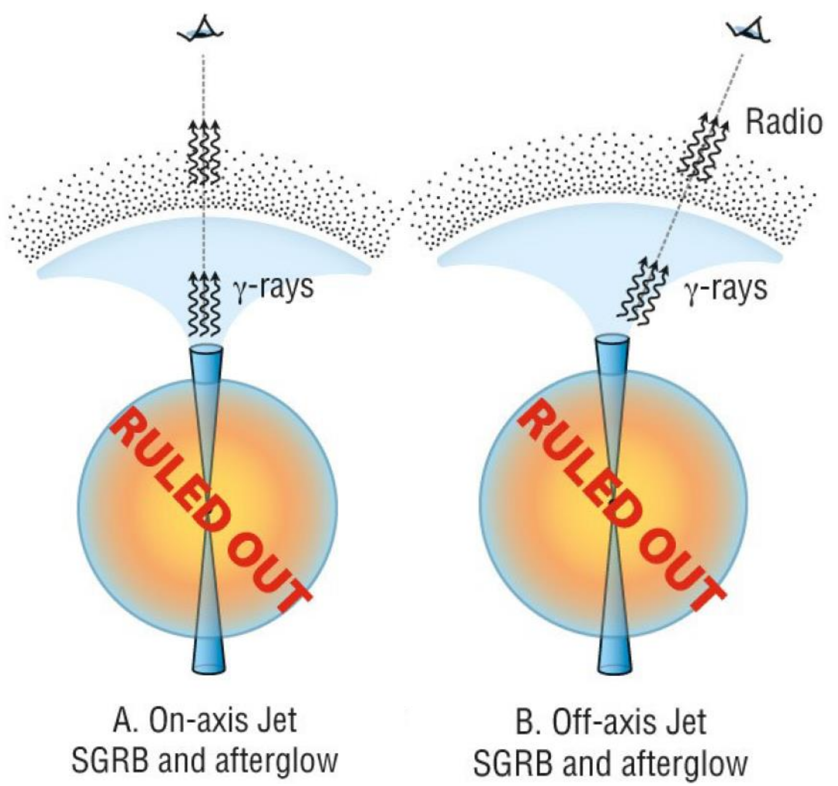




But … 100-day radio observation

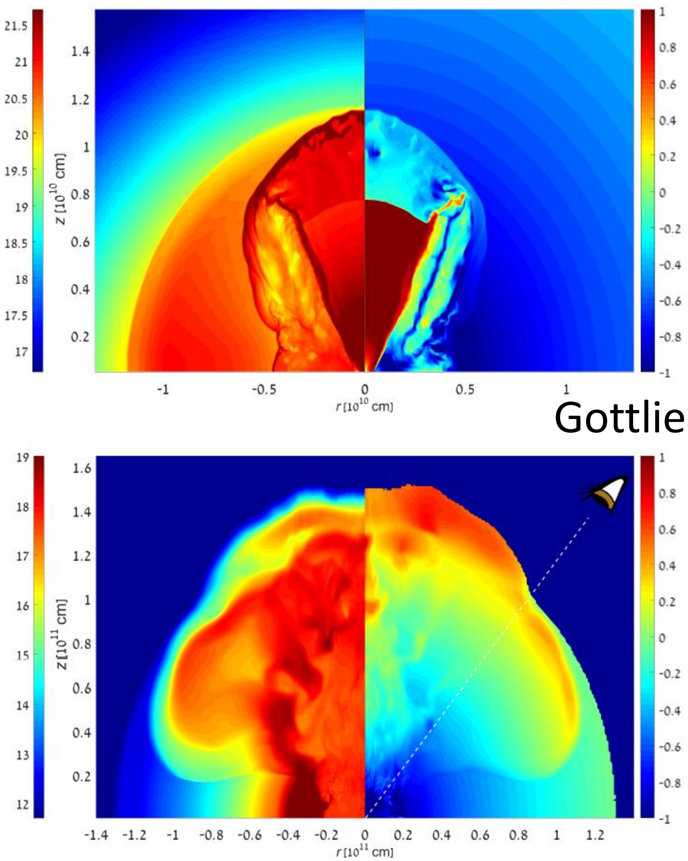
An ultra-relativistic top-hat jet seems to be rejected (though this “ruled out” may be a bit too strong)

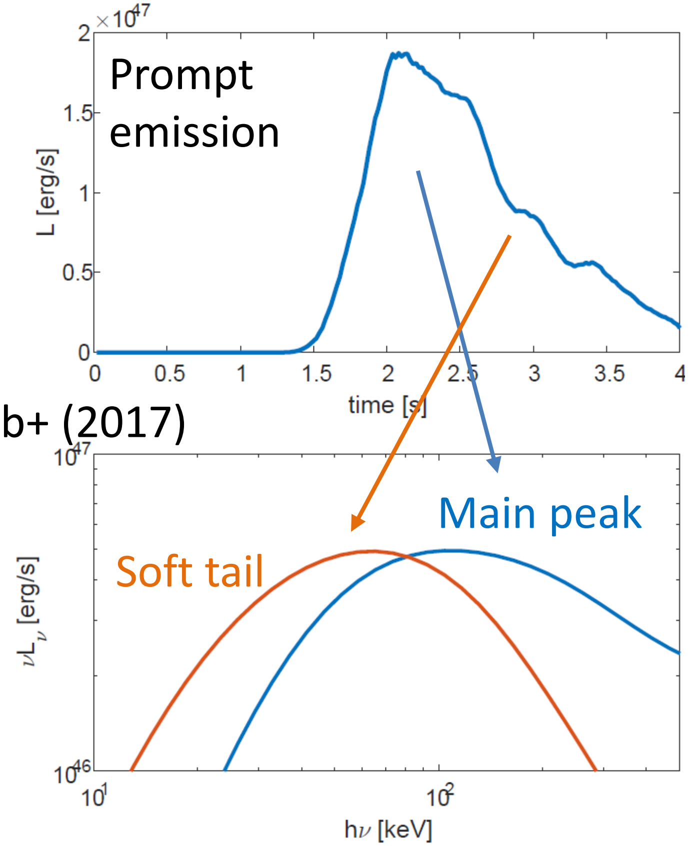




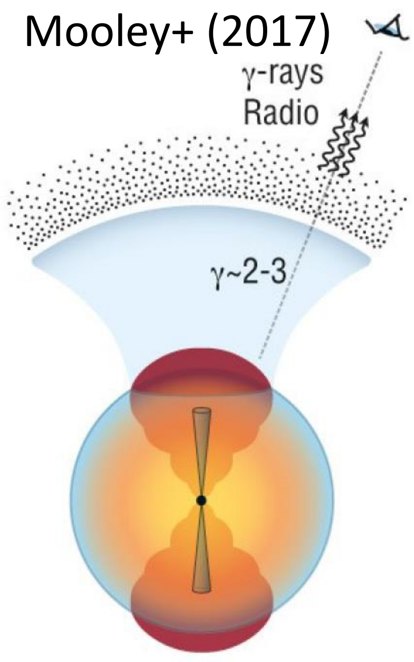
Cocoon with a chocked jet?

When a jet interact w/ ejecta (macronova/kilonova), the energy is dissipated and hot material breaks out





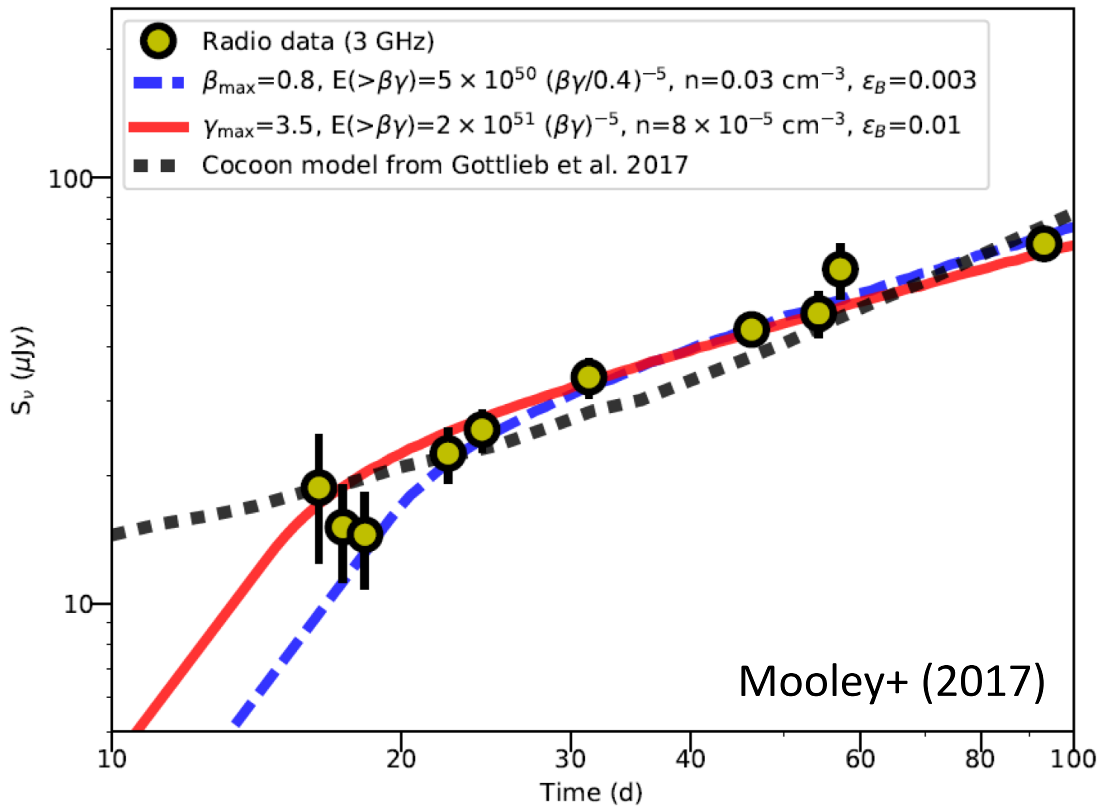
Gottlieb+ (2017)

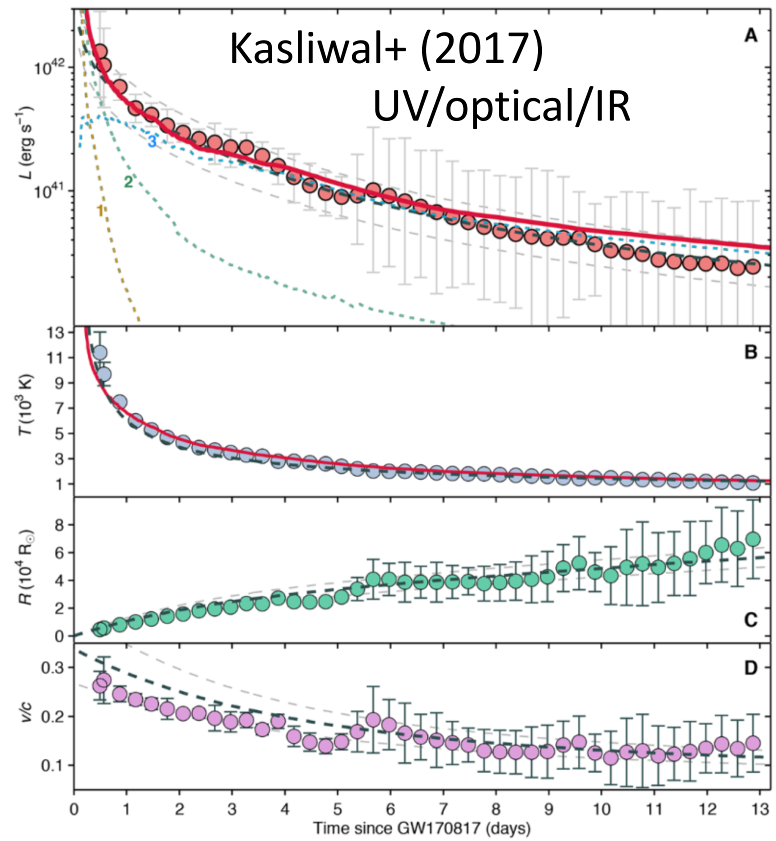


Seemingly satisfactory

Blue kilonova/macronova may also be explained

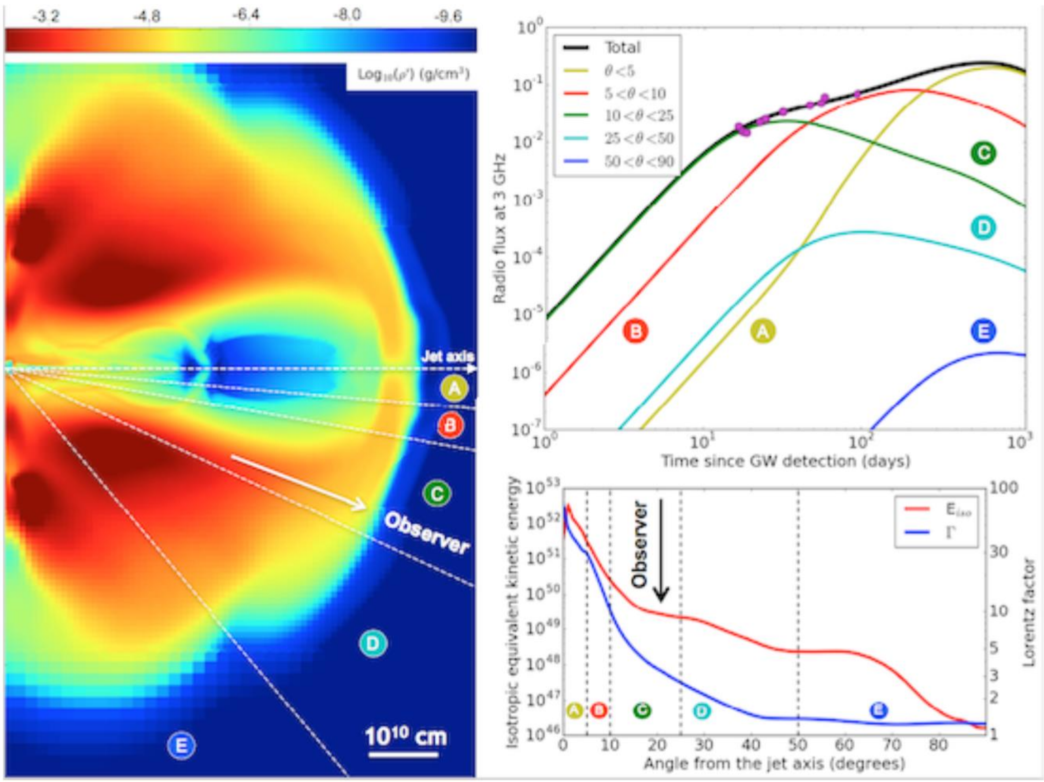
If so, GRB 170817A was not a typical short GRB

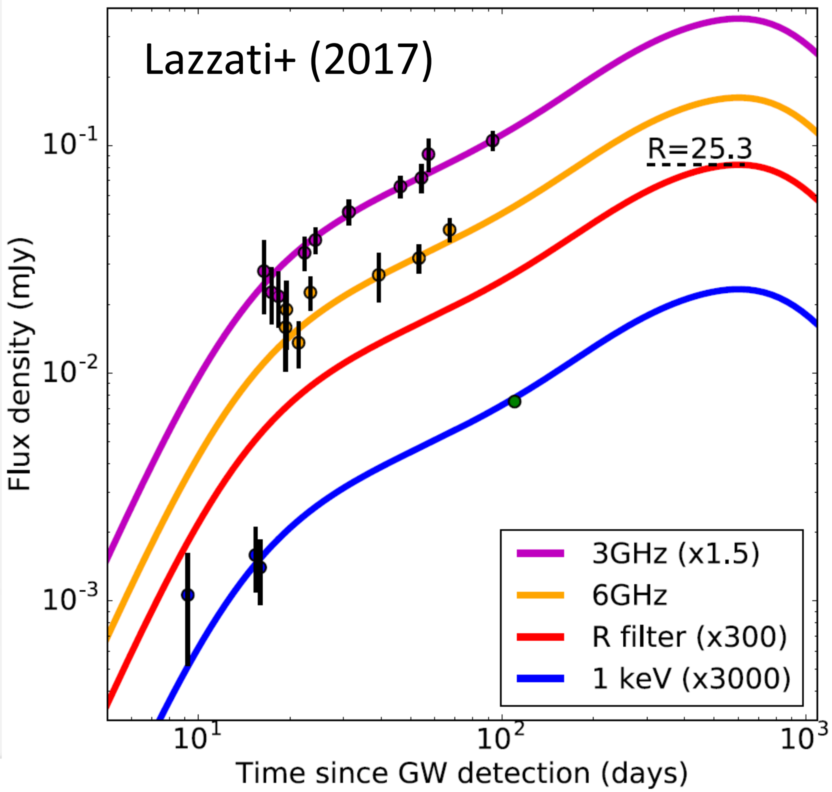




Structured jet?

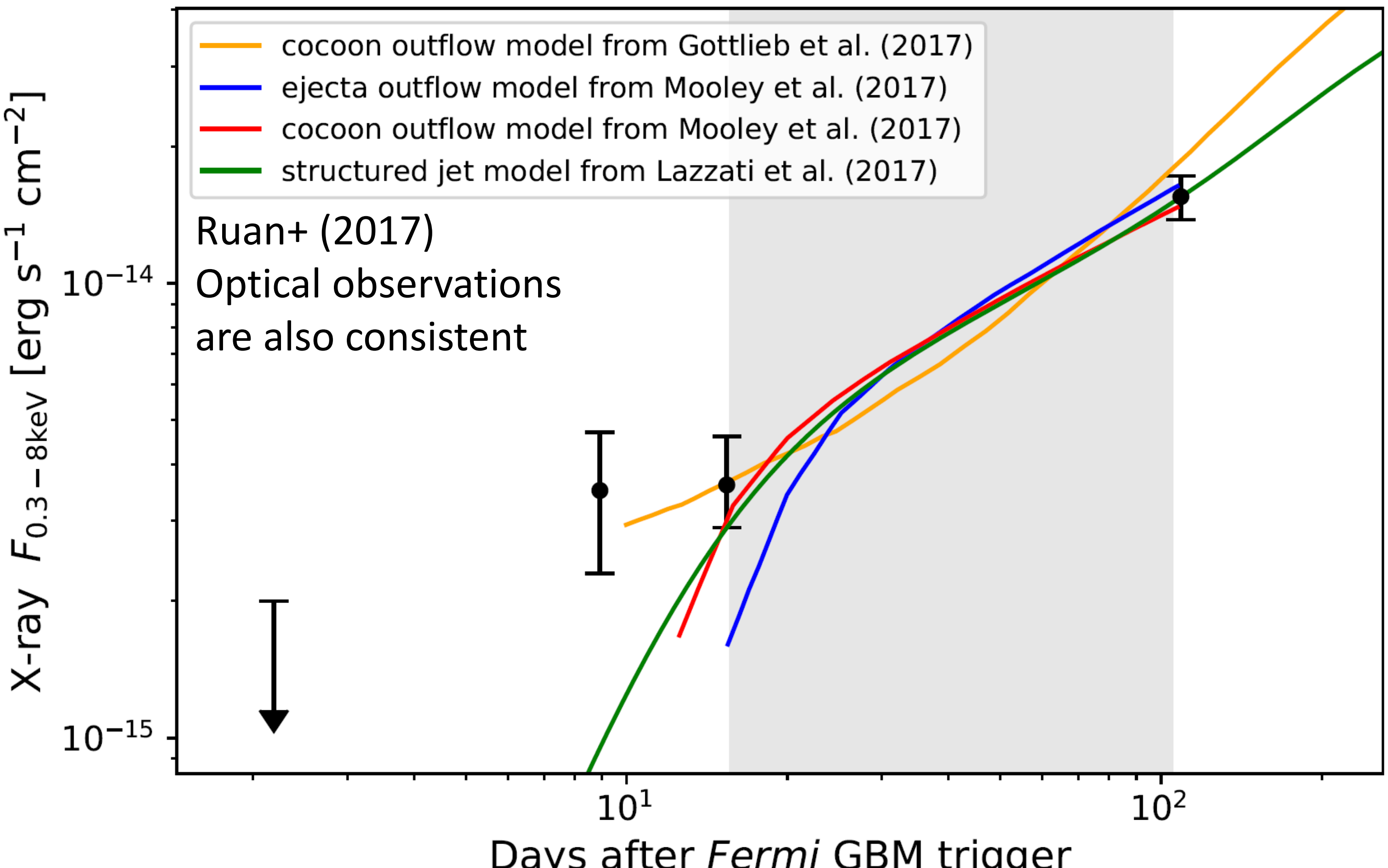
An ultra-relativistic jet is not necessarily ruled out (though a cocoon-like component is required)





X-ray at 100days

Fully consistent with radio, i.e., not requiring a jet



Where is the short gamma-ray burst?

The gamma-ray emission of GRB 170817A may not be a subclass of ultra-relativistic short-hard GRBs

- simply an ultra-relativistic and structured jet?
- missing the jet due to a large observing angle?
- dependence of success on binary characteristics?
- black hole-neutron star binaries are true origins?

The whole picture requires much more statistics …

- long-term observations of this event is also useful

Implication to fundamental physics

The timing difference of 1.7s for GW-GRB at 40Mpc~4e15s gives us novel constraints on gravity

- intrinsic time delay is assumed to be 0-10s

- Constraint on the velocity difference

$$-3 \times 10^{-15} \leq (v_{\mathrm{GW}} - v_{\mathrm{EM}})/v_{\mathrm{EM}} \leq 7 \times 10^{-16}$$

- disfavor modified gravity predicting $v_{\mathrm{GW}} \neq c$

- Test of weak equivalence principle for GW vs EM
- Constraint on Lorentz invariance violation

Black hole

Object with the strongest gravity in the world

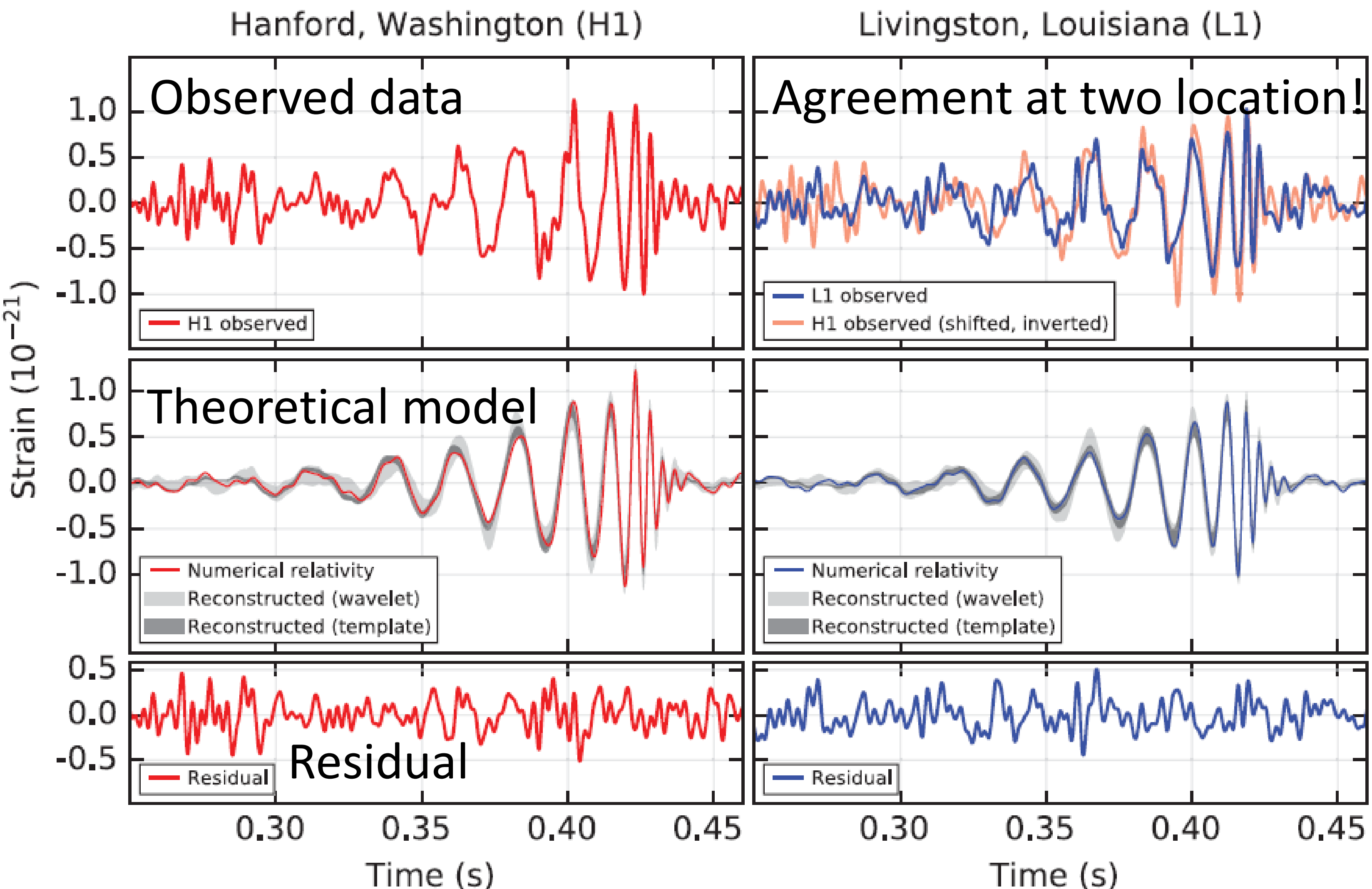
very bright in astronomy

- gamma-ray burst
- active galactic nuclei

quantum phenomena?

- Hawking radiation?
- information loss?

GW150914



LIGO&Virgo (2016), filtered to 35-350Hz

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)

Problem: degeneracy with the redshift

Signal frequency from z decreases to $f/(1+z)$

General relativity does not have a scale, and thus

$$t \to t(1+z), \mathcal{M} \to \mathcal{M}(1+z), D \to D(1+z)$$

makes both the amplitude and phase invariant

distant high-mass = near low-mass

- we can determine the luminosity distance
- but no cosmological redshift, in principle

[note: neutron stars could resolve this degeneracy]

Redshift from the host galaxy

The redshift has to be extracted from host galaxies by electromagnetic observations…

How can we determine the host galaxy? [Schutz 1986]

- Accurate localization by gravitational waves

This may be possible with space-borne detectors!

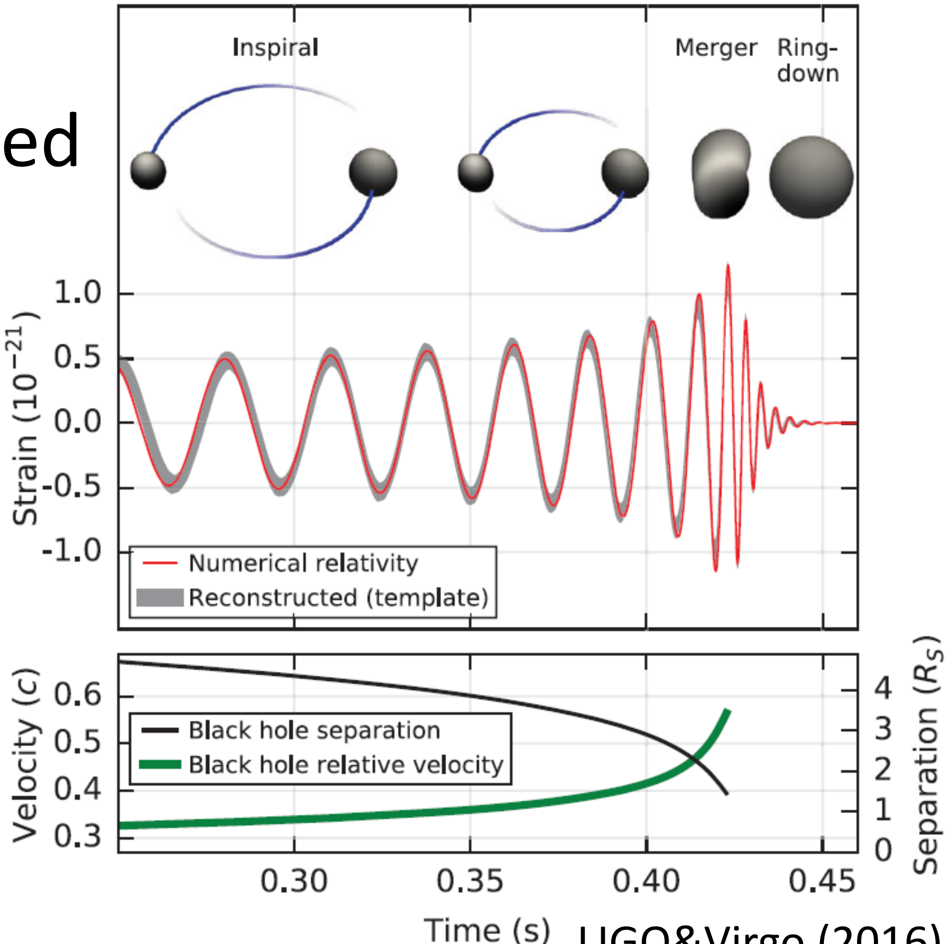
- Detect electromagnetic counterparts

short GRB, kilonova/macronova … for neutron stars

not applicable to stellar-mass binary black holes

What we learned

- Gravitational waves exist
  and propagate as expected
- Massive black holes exist
  (strongest evidence)
- Their binary merge
  within the Hubble time
- GR is reliable even for
  strong, dynamical fields



LIGO&Virgo (2016)

What is curious

The black holes seems to be too (or a bit) massive

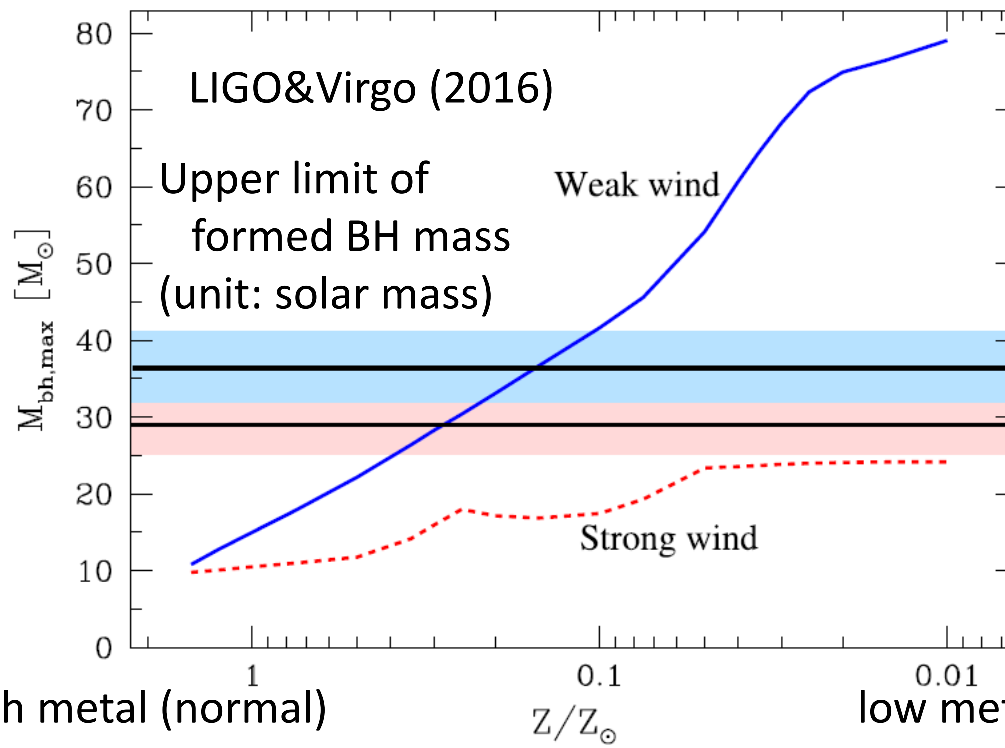
Stellar winds should have reduced the mass during the stellar lifetime…

This challenges

the stellar evolution

Low-metallicity

+ weak stellar wind



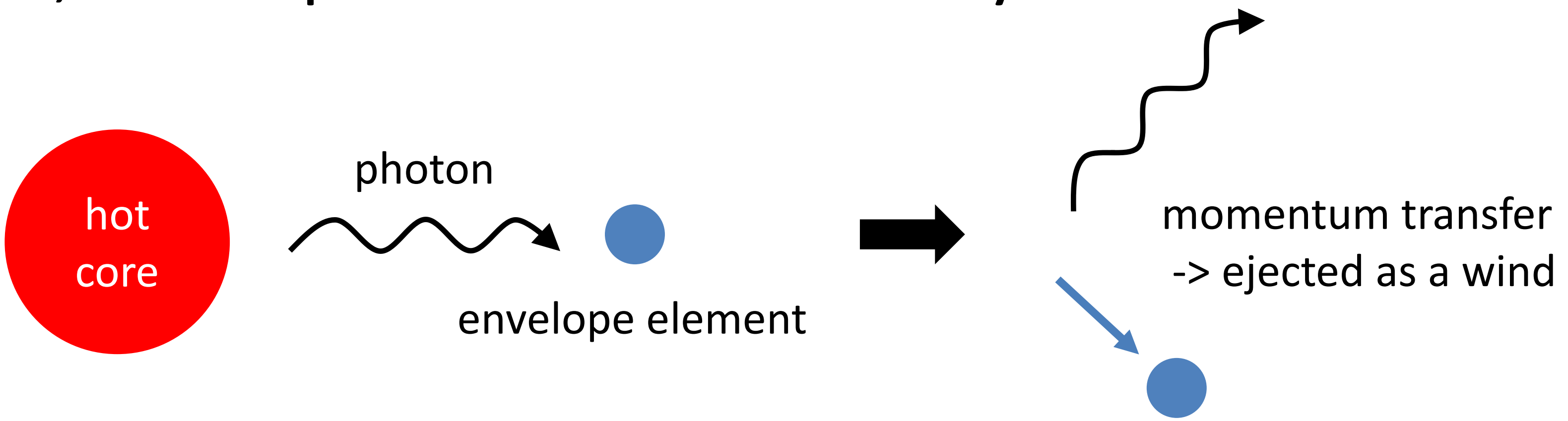
Abundances of metal = elements other than H/He, compared to solar values

Radiation-driven stellar wind

Photons emitted from the central region interact with the surrounding envelope via line structures

For heavier elements, the stellar wind is stronger because more lines give more frequent interaction

Thus, metal-poor stars tend to stay massive



Basic strategy

Compute post-Newtonian correction terms, say

$$\frac{df}{dt} = \left(\frac{df}{dt}\right)_{\text{quadrupole}} \left[1 + a_2 v^2 + a_3 v^3 + \cdots\right]$$

Usually, an expansion parameter is taken to be

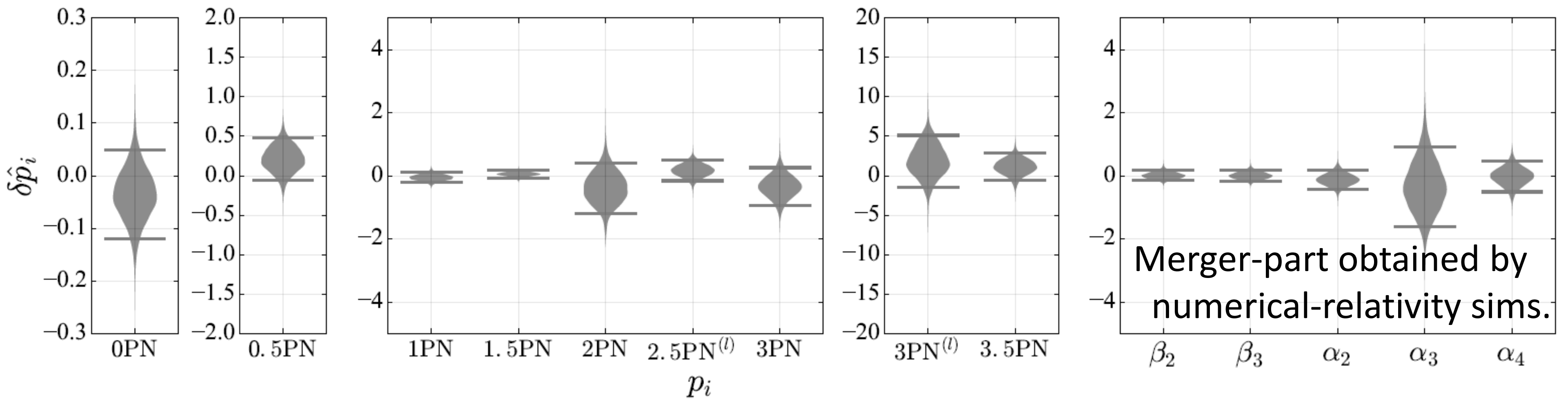
$$x = \left(\frac{v}{c}\right)^2 \equiv \left(\frac{G\pi f M}{c^3}\right)^{2/3}$$

A term at v^{2n} or $f^{2n/3}$ relative to the leading term is called the n-th post-Newtonian correction

Post-Newtonian coefficient

Combination of GW 150914, 151226, and 170104

- every terms are consistent with general relativity
- these constraints will keep becoming tighter



Note: The 0PN term = quadrupolar emission is much strongly constrained by binary pulsars

Graviton Compton wavelength/mass

Massive gravitons travel slower than the light

$$\frac{v_g^2}{c^2} \simeq 1 - \frac{m_g^2 c^4}{E^2} = 1 - \frac{h^2 c^2}{\lambda_g^2 E^2}$$

Gravitational waveforms are distorted

The Compton wavelength $\lambda_g > 1.6 \times 10^{13}$ km

Then the graviton mass $m_g < 7.7 \times 10^{-23}$ eV

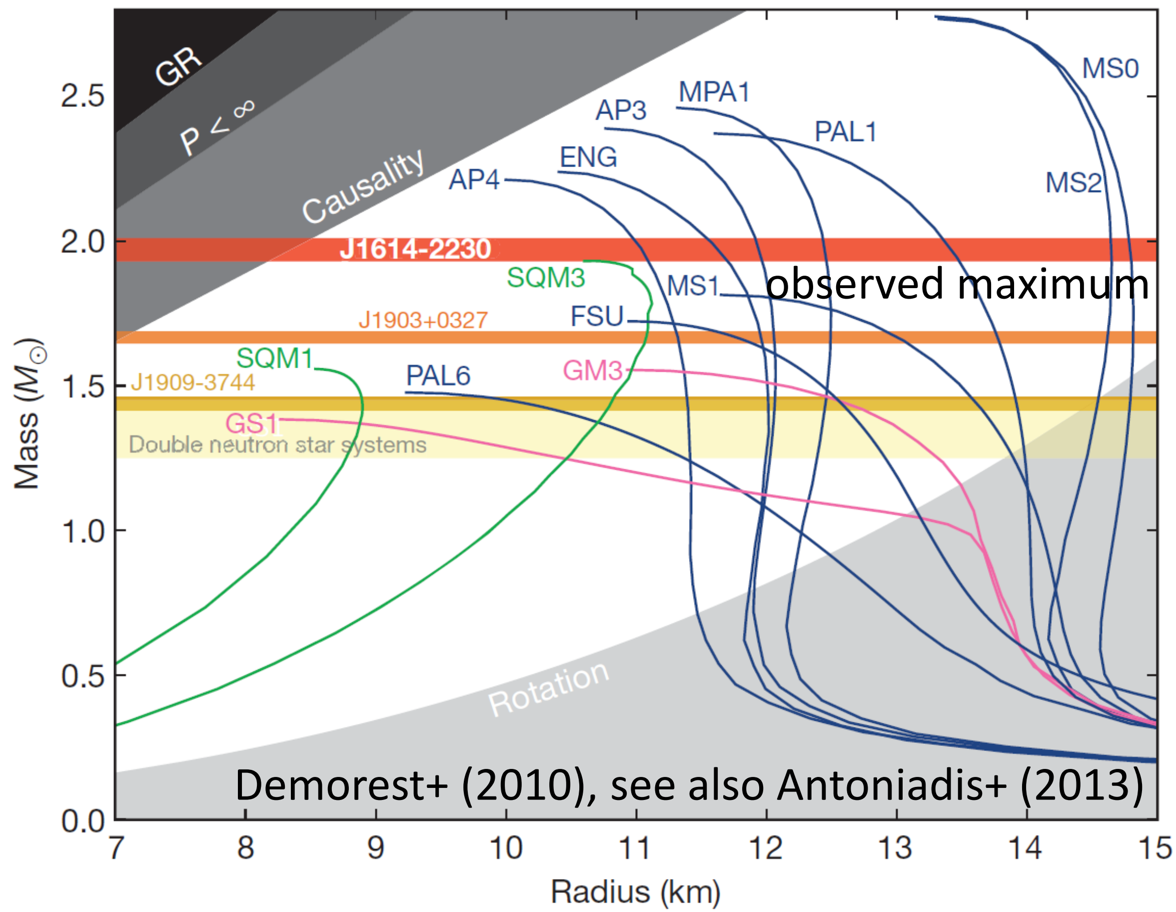
- nearly strongest model-independent bounds

Note: “graviton mass” is a highly nontrivial quantity

Maximum mass of neutron stars

Put a robust constraint on equation-of-state models

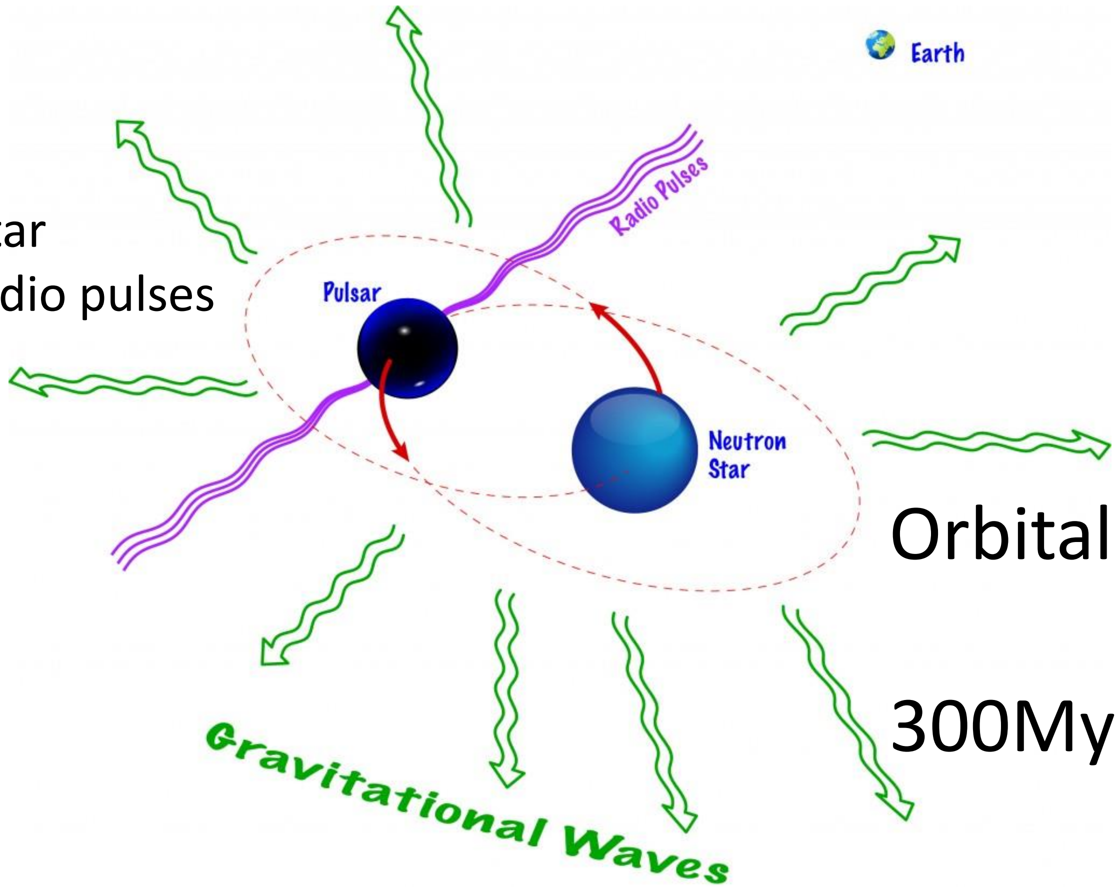
Generally,
emergence of
exotic particles
tend to reduce the
maximum mass
… not so preferred



Binary pulsar test with PSR B1913+16

Also known as Hulse-Taylor's binary (found in 1974)

Pulsar: neutron star emitting stable radio pulses



Orbital period ~7.75hr

300Myr to merger

http://asd.gsfc.nasa.gov/blueshift/wp-content/uploads/2016/02/htbinarypulsar-1024x835.jpg

Observational confirmation

Orbital decay of PSR B1913+16

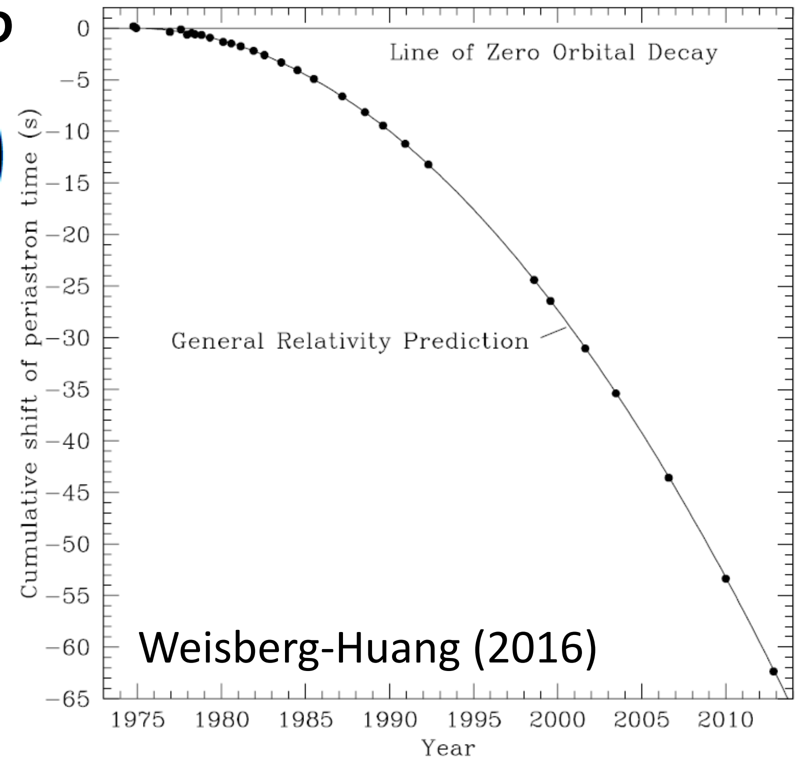
$$\dot{P}_b^{\mathrm{GR}} = -\frac{192\,\pi\,G^{5/3}}{5\,c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right) \times (1-e^2)^{-7/2}\,m_1\,m_2\,(m_1+m_2)^{-1/3}$$

derived originally in 1963(!)

Consistent with GR prediction

within ~1 sigma error

(roughly: number of orbital cycles)



But direct detection is important: propagation etc.

Neutron star binary coalescence

Now this is not a to-do list, but a done or ongoing list

- Gravitational waves

 - test of the theory of gravitation in a non-vacuum

 - high-density matter signature: equation of state

- Formation of a hot massive remnant (star/disk)

 - central engine of short gamma-ray bursts

- Mass ejection of neutron-rich material

 - r-process nucleosynthesis

 - radioactively-driven “kilonova/macronova”

Difference from binary black holes

Presence of matter: “RHS” of the Einstein equation

- the Einstein equation for BH-BH was only $R_{\mu\nu} = 0$

Hydrodynamic interaction becomes important

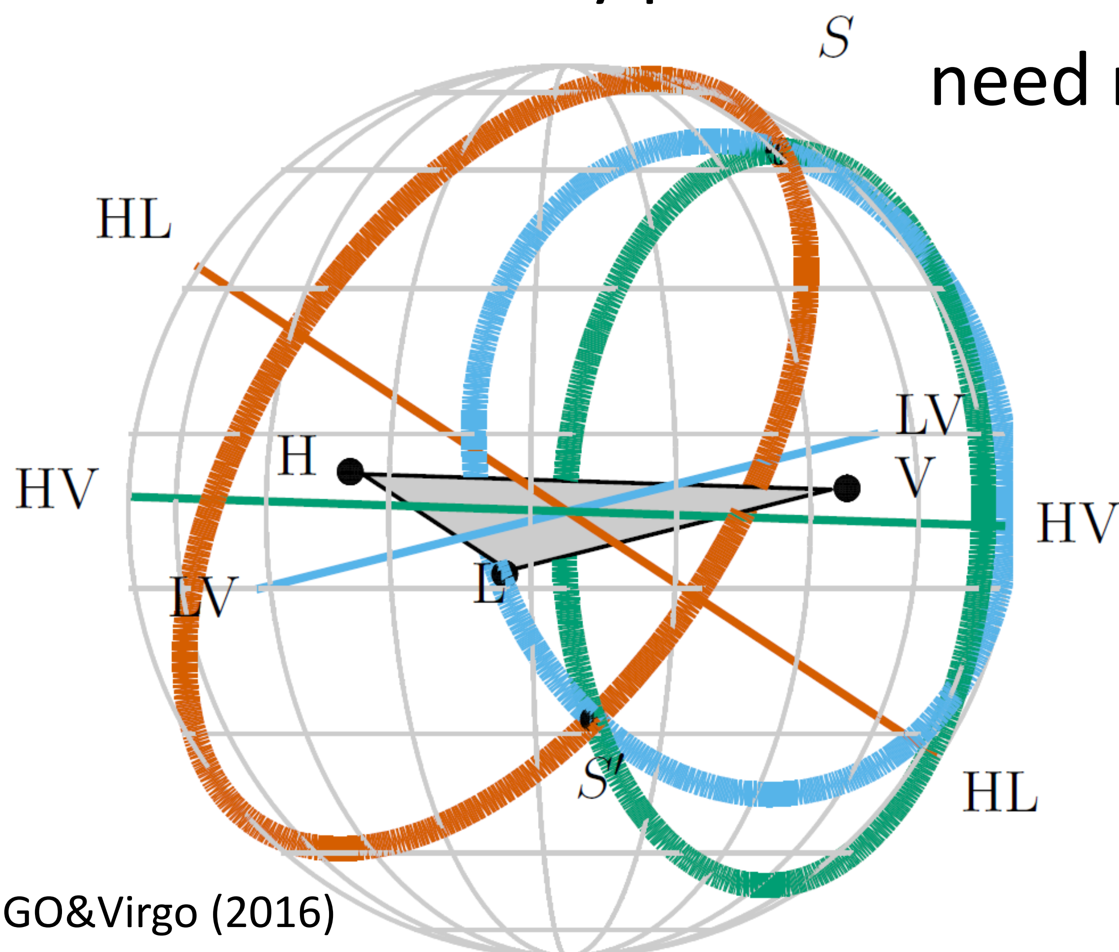
- stellar deformation modifies the orbital dynamics

All the four interactions become important

- nuclear force determines the equation of state
- magnetic fields affect the dynamics and radiation
- neutrinos are emitted from heated material

Triangulation by a detector network

Determine the sky position from timing difference

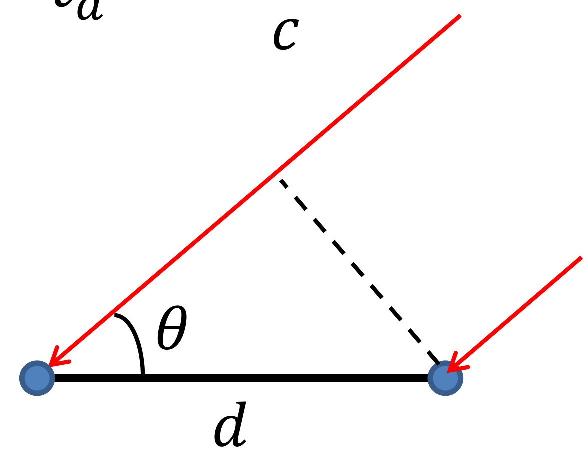


LIGO&Virgo (2016)

need multiple detectors

d~O(1000km)

$$t_d = \frac{d\cos\theta}{c}$$



Parameters of GW170817

Low-spin: limiting to spin values observed for Galactic binary neutron stars that merge within the Hubble time (with some safe margins)

High-spin: as far as GW models may be applicable

LIGO&Virgo (2017)	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–$1.60\ M_\odot$	1.36–$2.26\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$	0.86–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Shape of mass constraints

Gravitational waves tightly constrain the chirp mass

$$\mathcal{M} = \frac{m_1^{3/5} m_2^{3/5}}{(m_1 + m_2)^{1/5}} = \mu^{3/5} M^{2/5}$$

But the mass ratio (e.g., $q = m_2/m_1 < 1$) tends to be degenerated with the spin of components,

$$\chi_i = \frac{cS_i}{Gm_i^2} \quad (i = 1,2)$$

The error in q appears large particularly for nearly equal-mass systems like binary neutron stars

Action for orbital and hydrodynamics

Orbital motion

$$S_{\mathrm{orb}} = \int \left[\frac{1}{2}\mu(\dot{r}^2 + r^2\varphi^2) + \frac{M\mu}{r}\right] dt$$

Stellar oscillation (for each mode)

$$S_{\mathrm{osc}} = \int \frac{1}{4\lambda\omega^2}\left(\dot{Q}^{ij}\dot{Q}_{ij} - \omega^2 Q^{ij}Q_{ij}\right) dt$$

Interaction

$$S_{\mathrm{int}} = -\frac{1}{2}\int Q^{ij}\mathcal{E}_{ij} dt$$

Definition of parameters

Total mass $M = m_1 + m_2$

Reduced mass $\mu = m_1 m_2 / M$

Chirp mass $\mathcal{M}_c = \mu^{3/5} M^{2/5}$

Symmetric mass ratio $\eta = \mu / M$

Binary tidal deformability ($m_1 \leq m_2$)

$$\tilde{\Lambda} = \frac{8}{13} [(1 + 7\eta - 31\eta^2)(\Lambda_1 + \Lambda_2) - \sqrt{1 - 4\eta}(1 + 9\eta - 11\eta^2)(\Lambda_1 - \Lambda_2)]$$

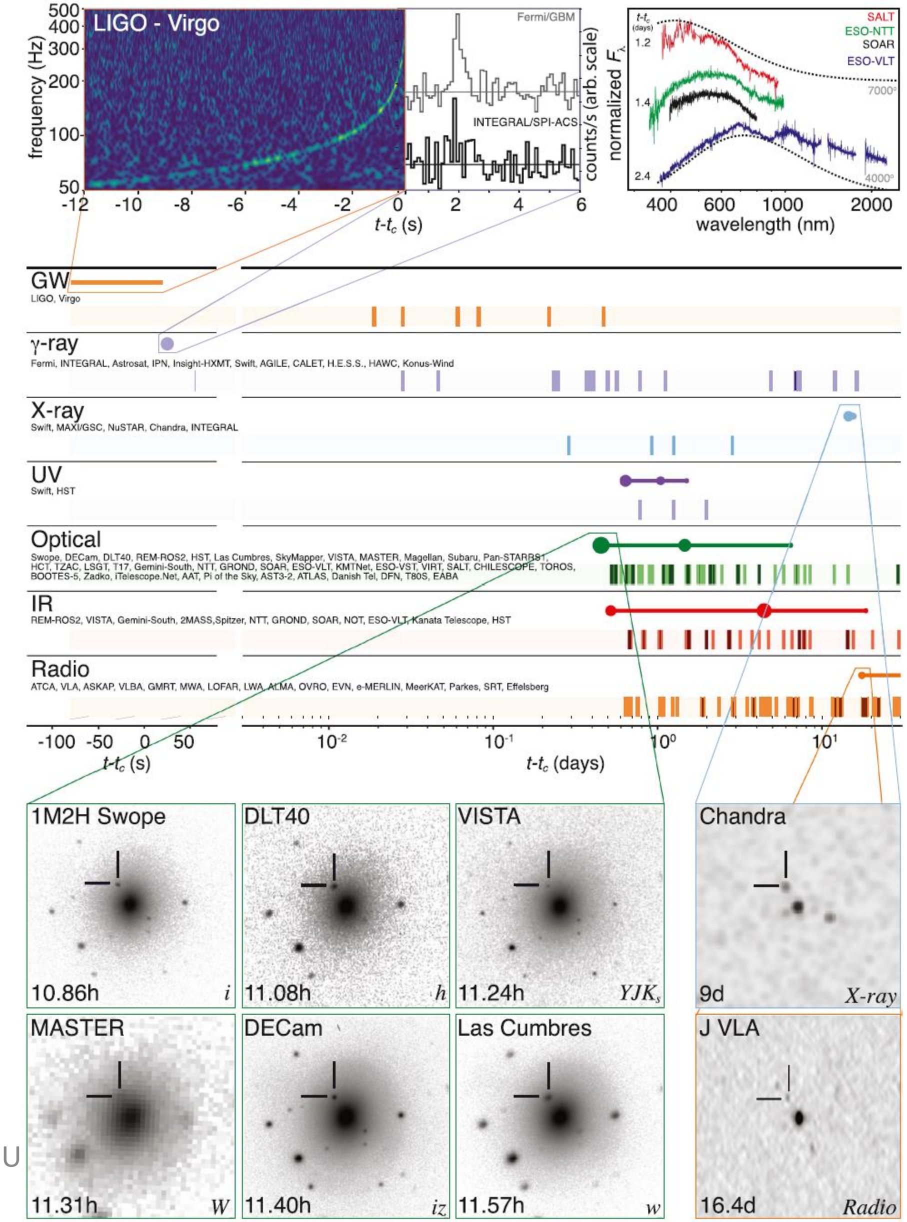
Electromagnetic followup

LIGO, Virgo…
(2017)

For the first time

I come to think that

humans may be great



Author list

>3,000 ppl was involved (well deserved I believe)

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

CrossMark

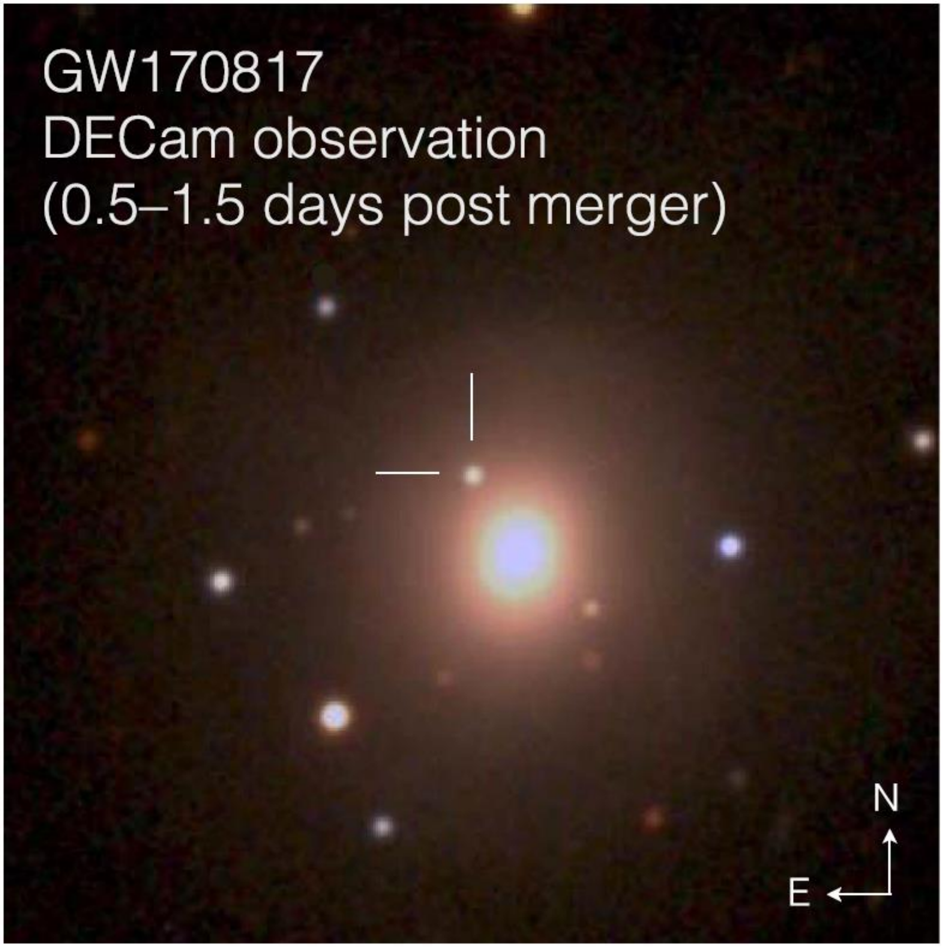
Multi-messenger Observations of a Binary Neutron Star Merger

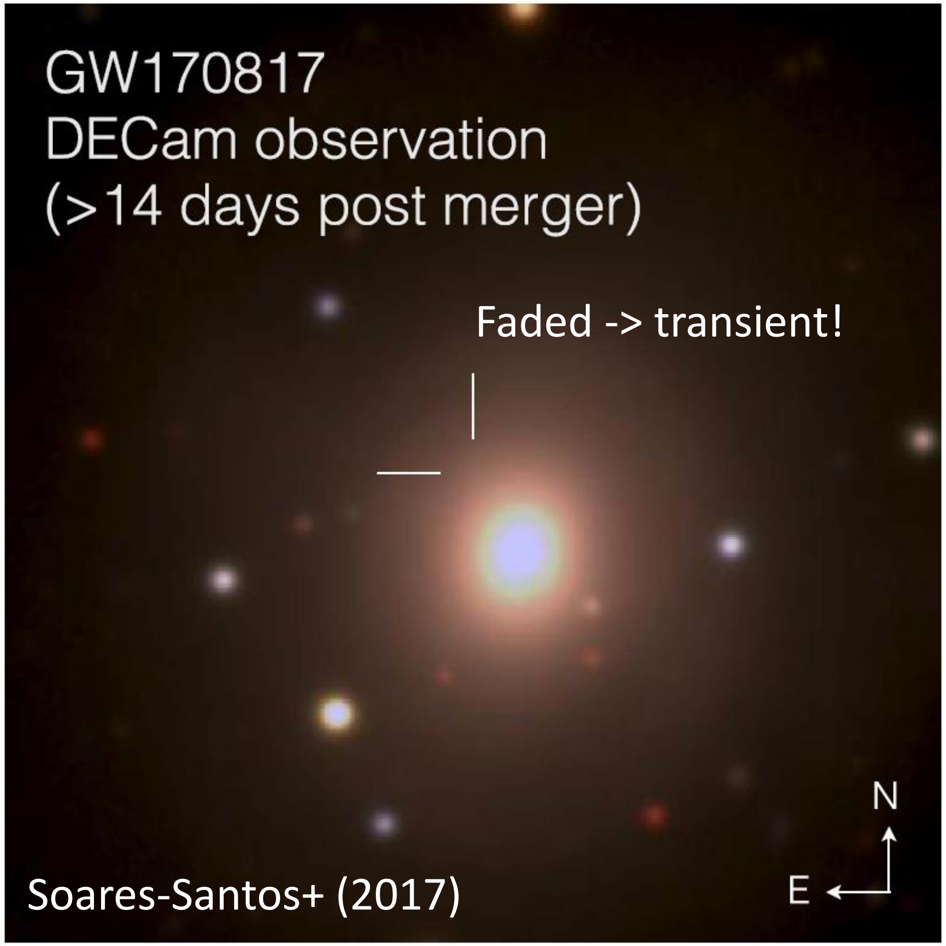
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Transient and host galaxy

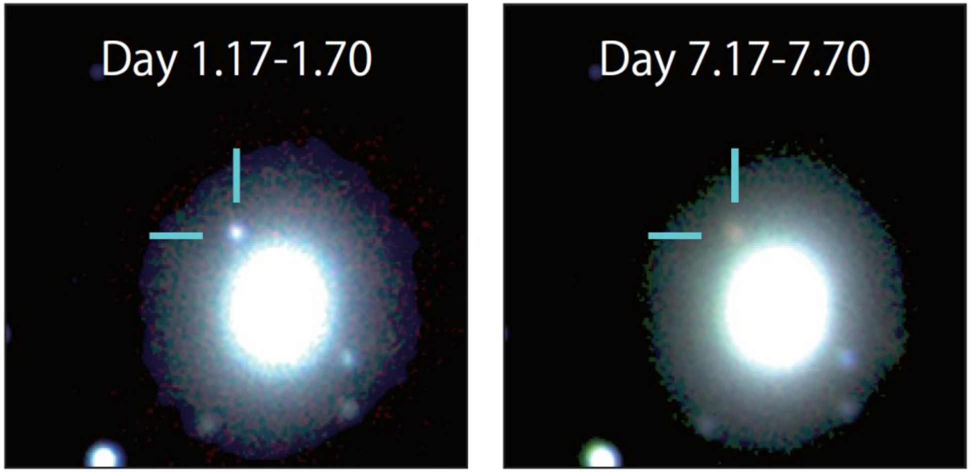
First found by Swope Supernova Survey (not this)



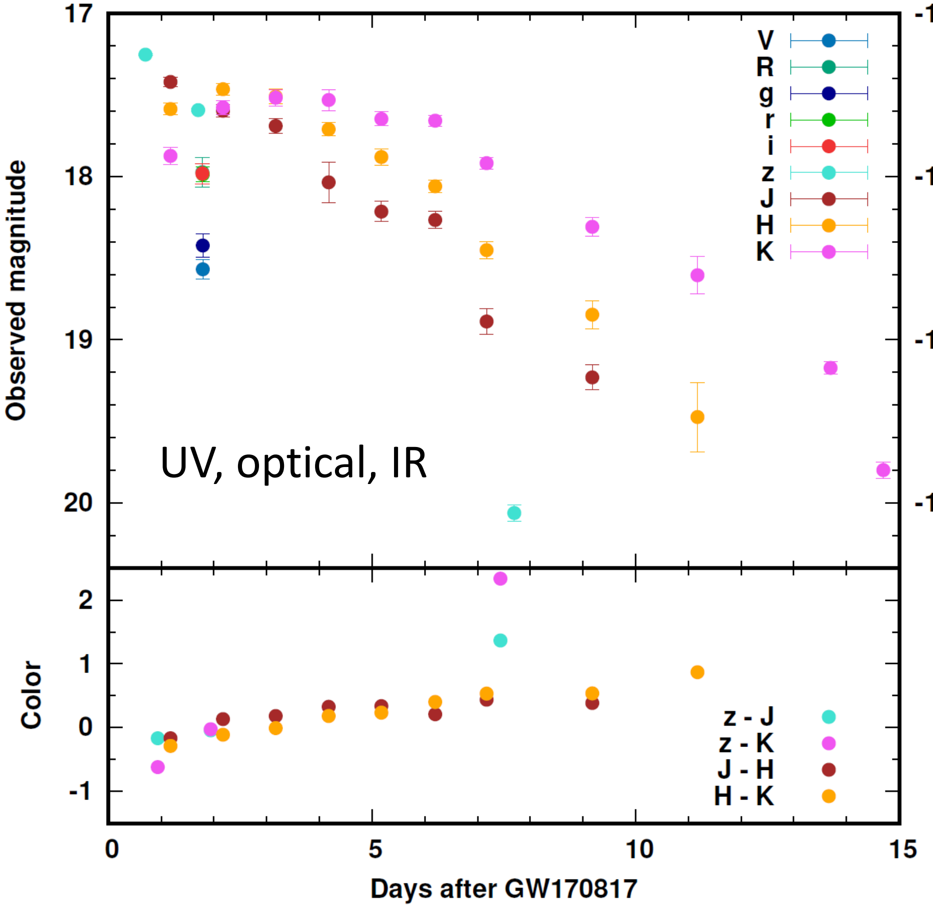


J-GEM observation

Japanese observatories, for example Subaru/HSC, took well-sampled images



Utsumi+ (2017)

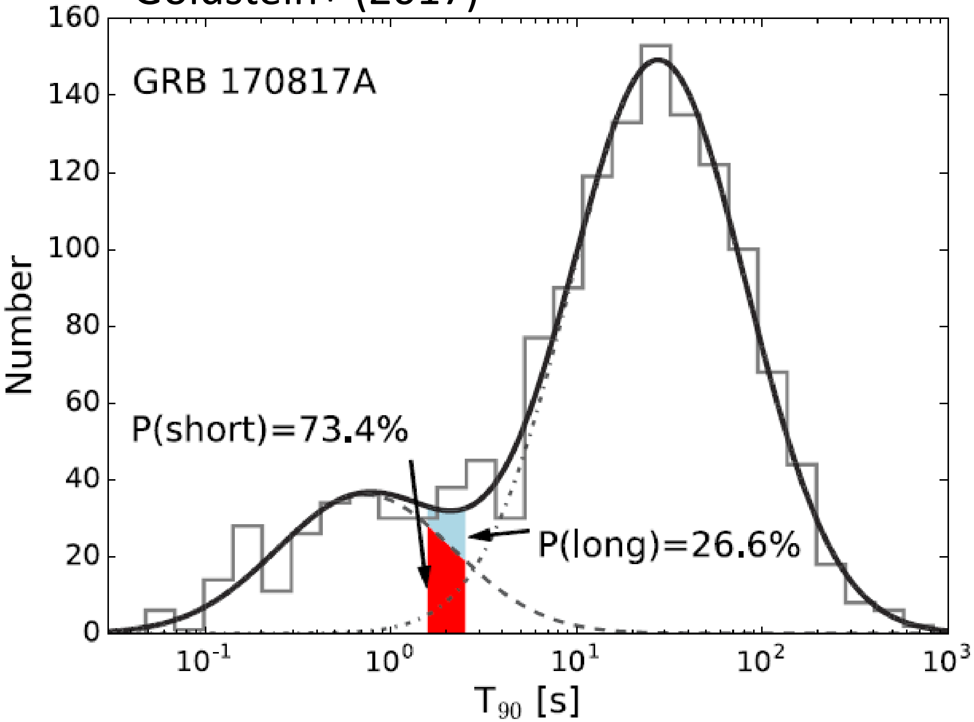


Scenario confirmation

Apparently, short gamma-ray burst (but not hard)

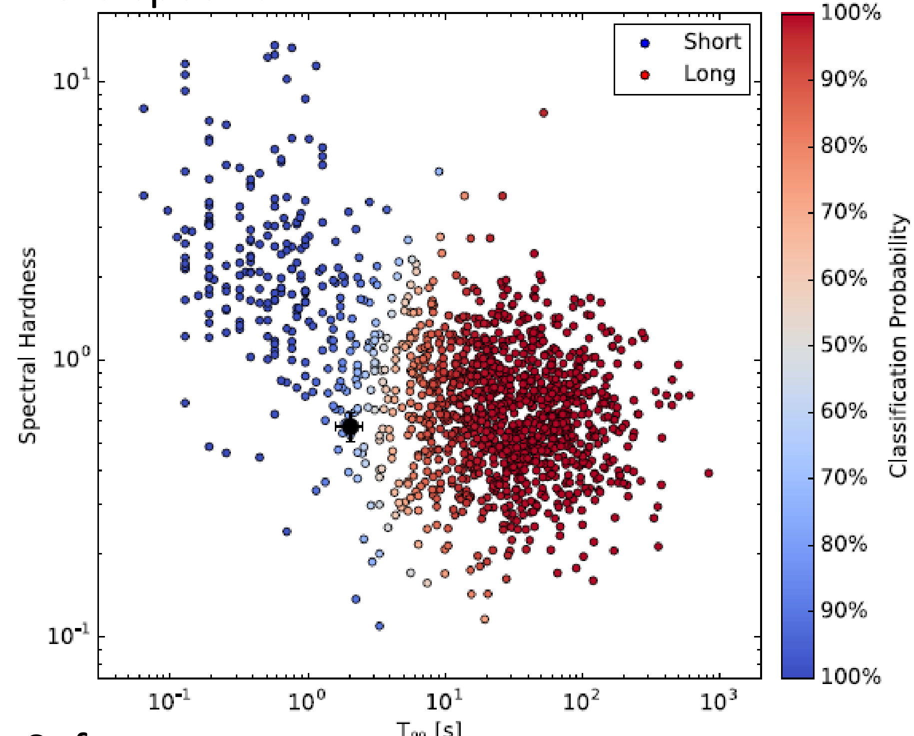
-> Binary neutron stars really drive short GRBs!

Goldstein+ (2017)



Duration of emission

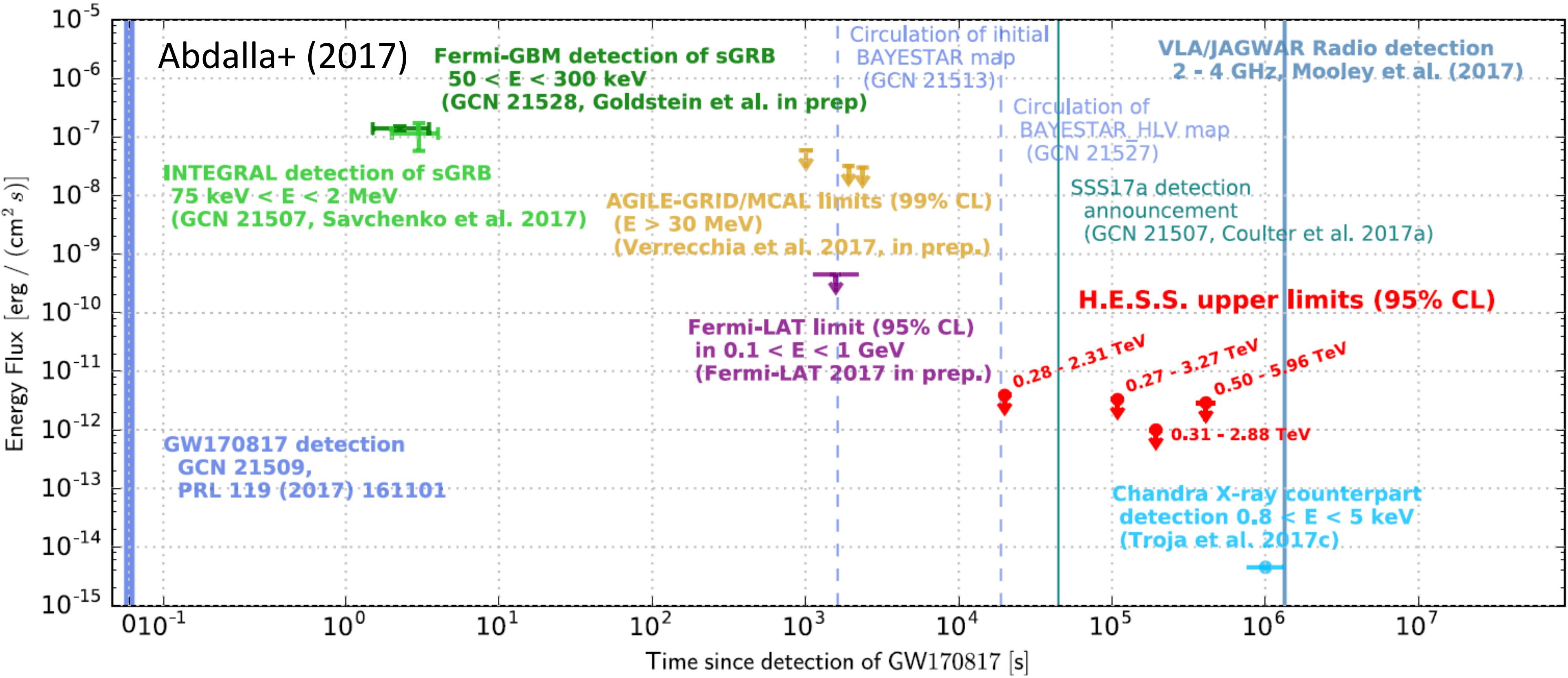
Hard spectrum



Soft spectrum

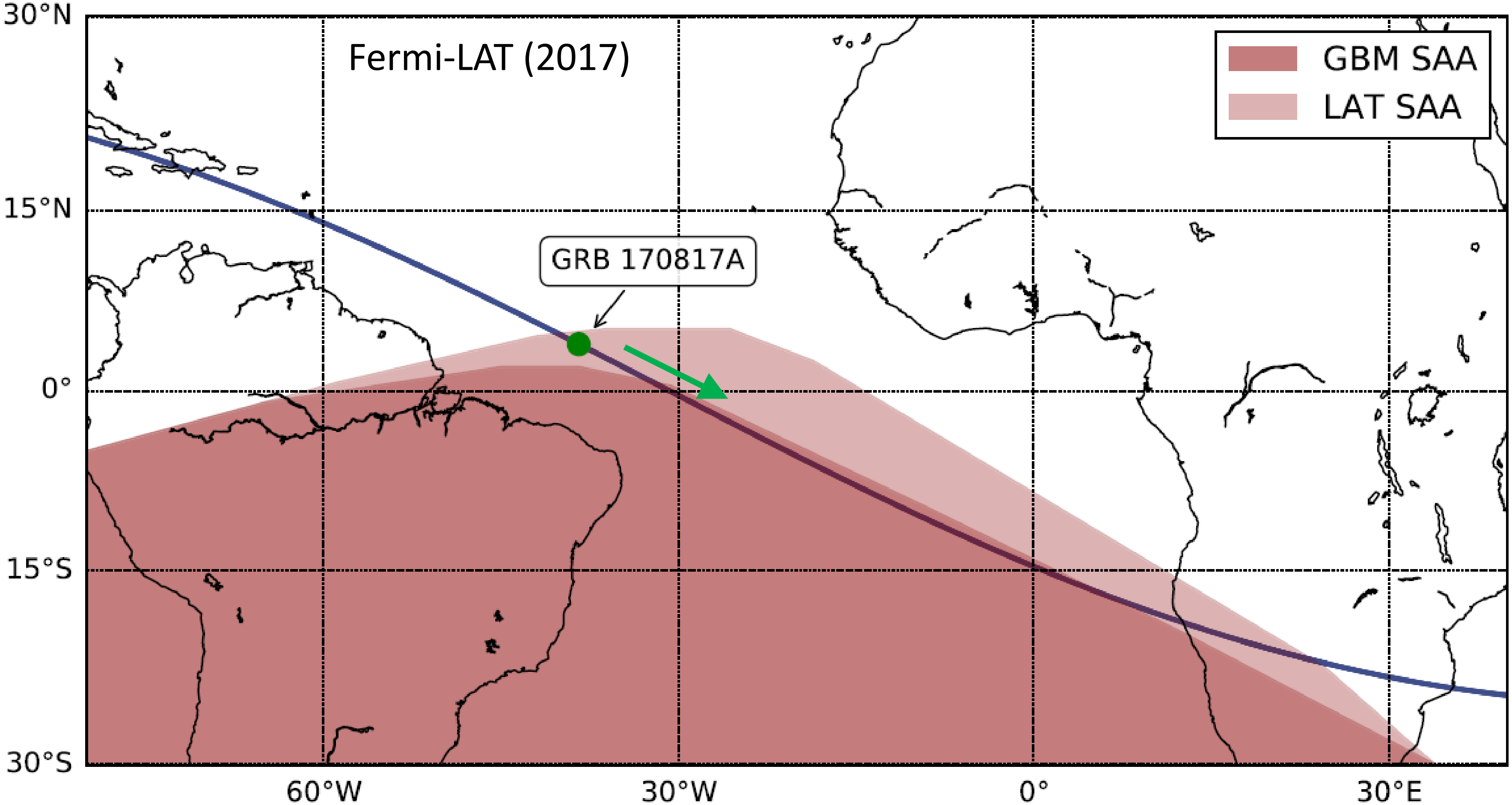
Other high-energy emission

Mostly upper limit for >MeV gamma and neutrinos, and Fermi/LAT put an upper limit only at late times



South Atlantic Anomaly

Sensitivity is not good, LAT was not available



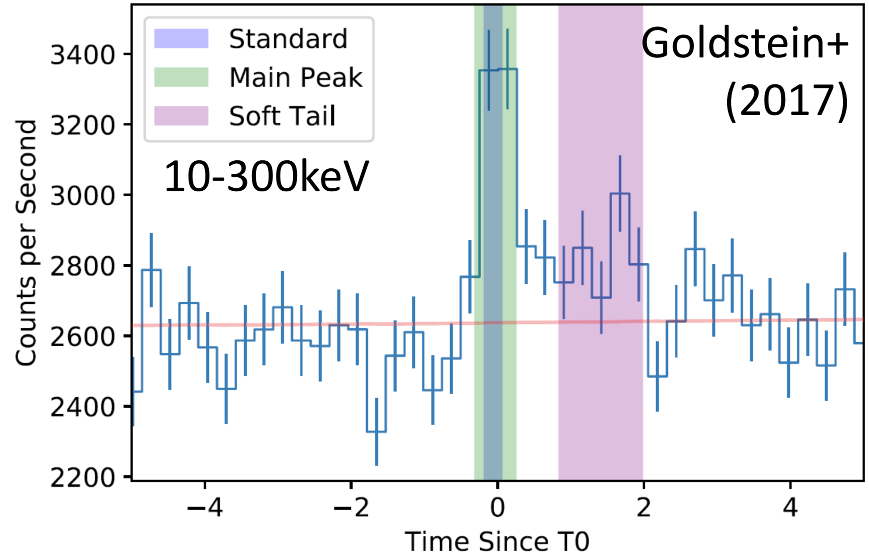
Two component prompt emission

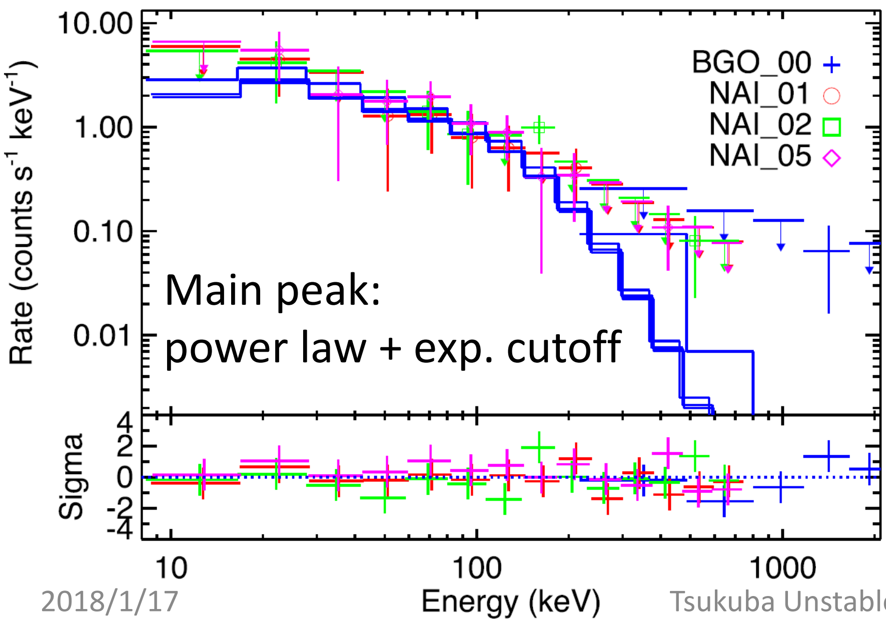
Main peak: $E_p \approx 185$ keV

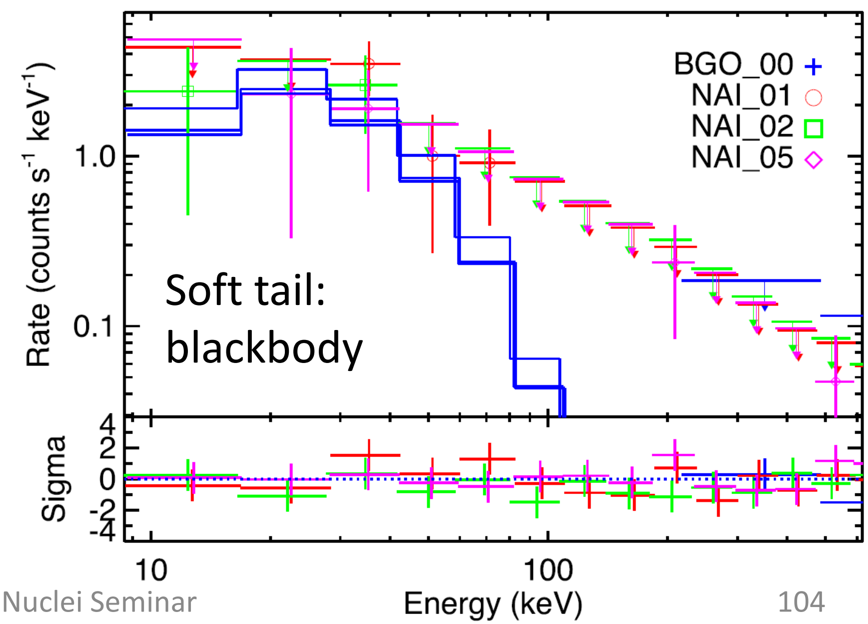
Soft tail: $k_B T \approx 10$ keV

not necessarily "compact"

$\Gamma > 2 - 3$ is sufficient

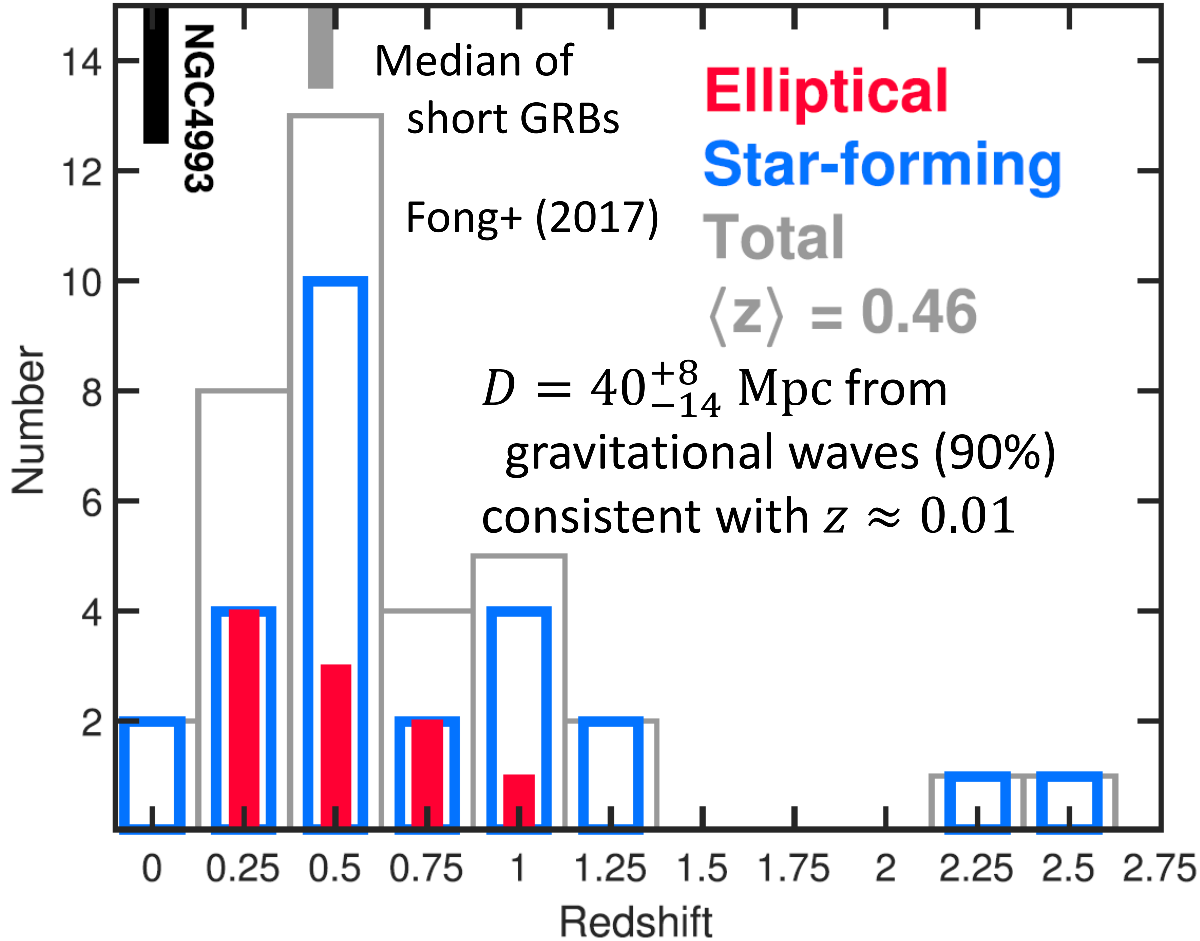






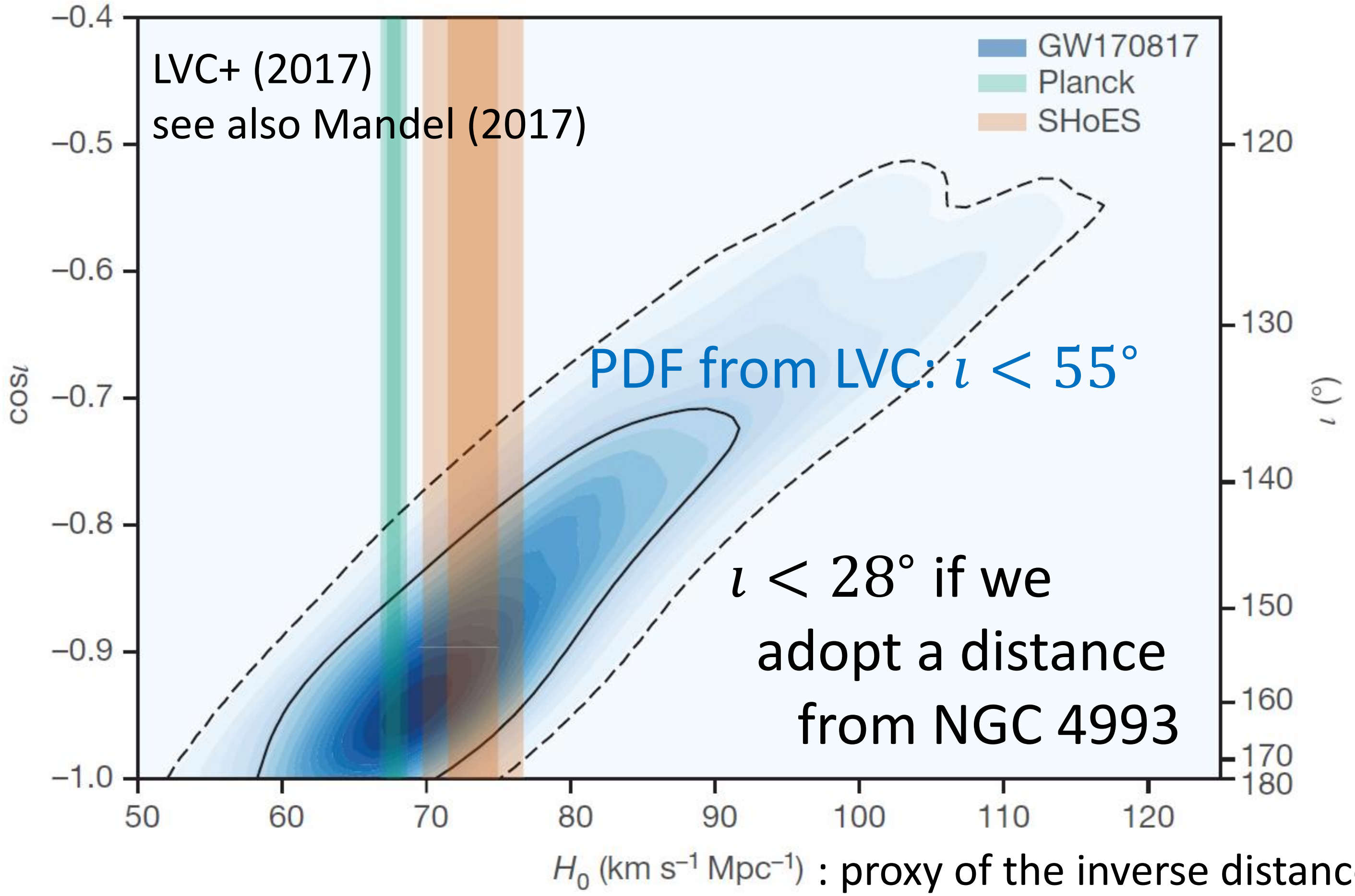
The closest short gamma-ray burst

Among the short GRBs with measured redshifts



Distance-inclination degeneracy

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



: proxy of the inverse distance here

Future prospect for the inclination

A distance measurement (3D localized) improves the localization accuracy by a factor of 2-3

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)

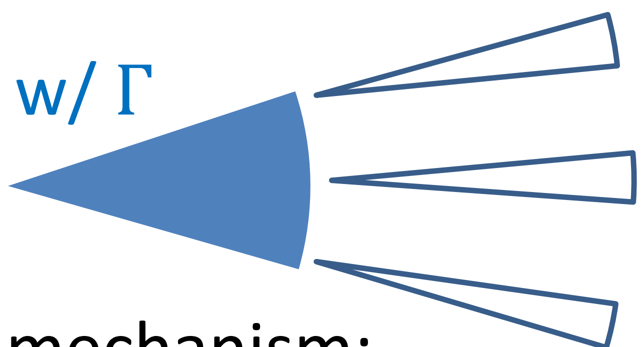
L: LIGO Livingston, H: LIGO Hanford, V: Virgo

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

Late rise due to relativistic beaming

Emission from relativistically moving material is concentrated (beamed) within an angle of $\theta \sim 1/\Gamma$

Jet w/ Γ



Usual GRB observer

Observable throughout

$\theta \sim 1/\Gamma$

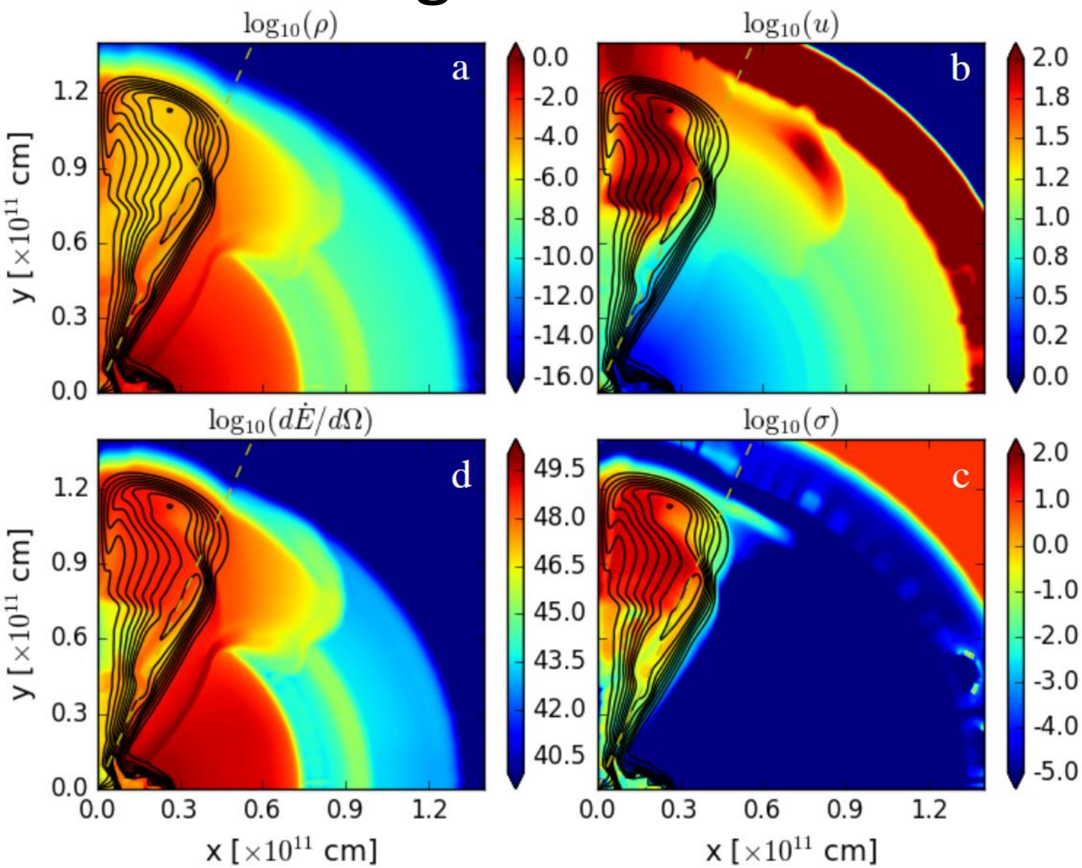
Emission mechanism:
nonthermal synchrotron

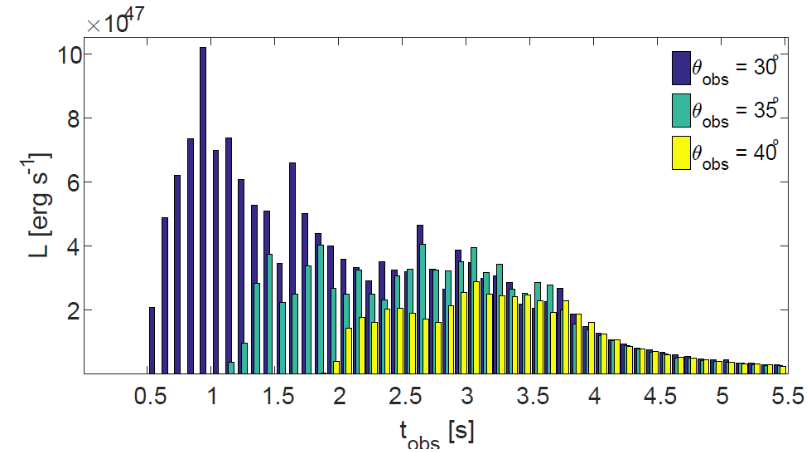
Off-axis observer

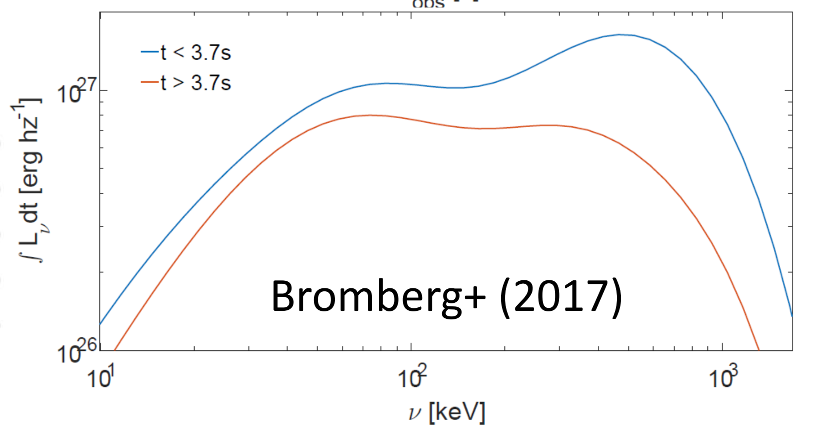
Observable only after the jet is decelerated to $\Gamma < 1/\theta_{\rm obs}$

Case of a magnetized jet

Similar emission may be expected even if the central engine was a massive remnant neutron star







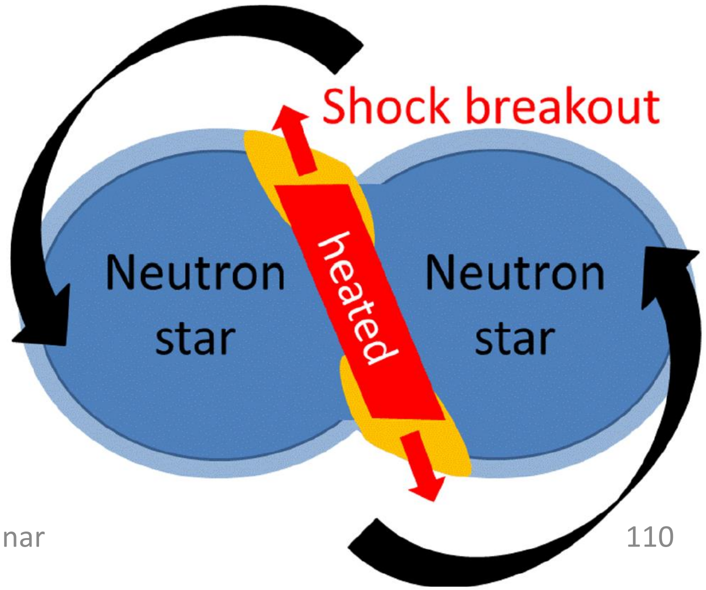
Prerequisite: very fast ejecta

This cocoon model requires $\sim 10^{-7} - 10^{-6} M_{\odot}$ with $> 0.5 - 0.6c$ for successful prompt emission

- dynamical mass ejection? (e.g., Hotokezaka+KK+ 2013)

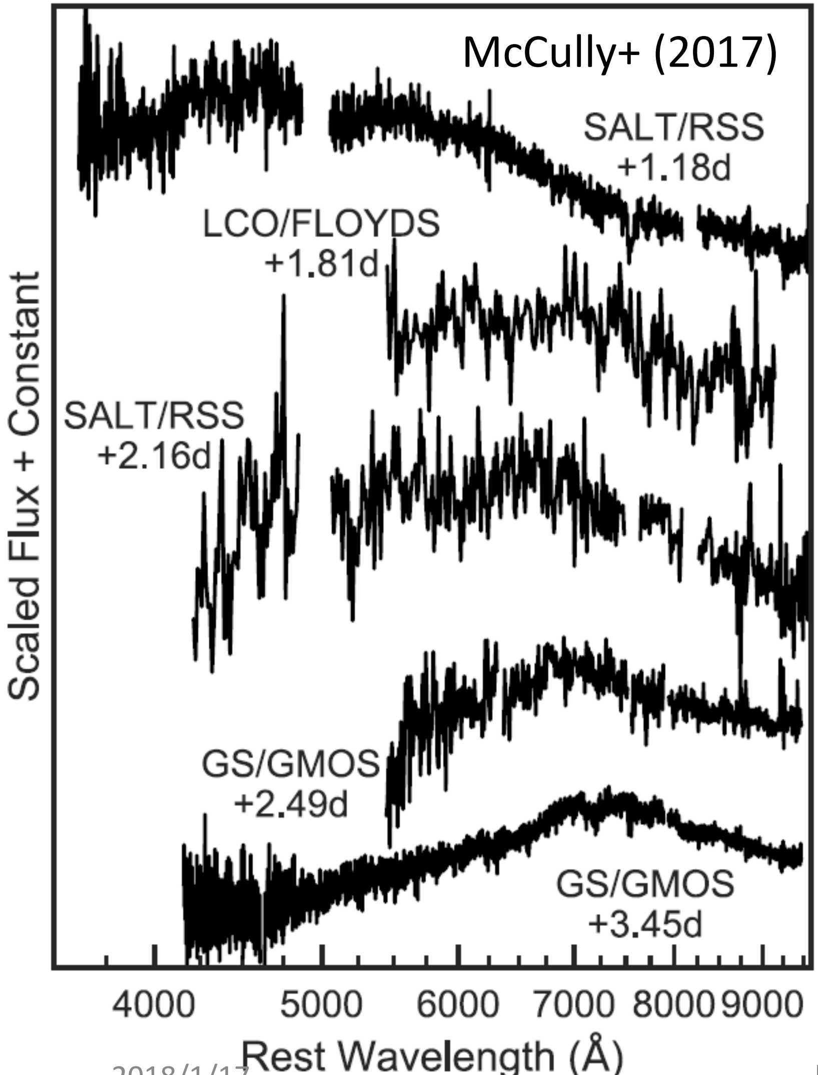
It is unclear whether such a fast component can be ejected particularly toward the polar direction

- merger shock breakout from neutron stars? (Kyutoku+ 2014)

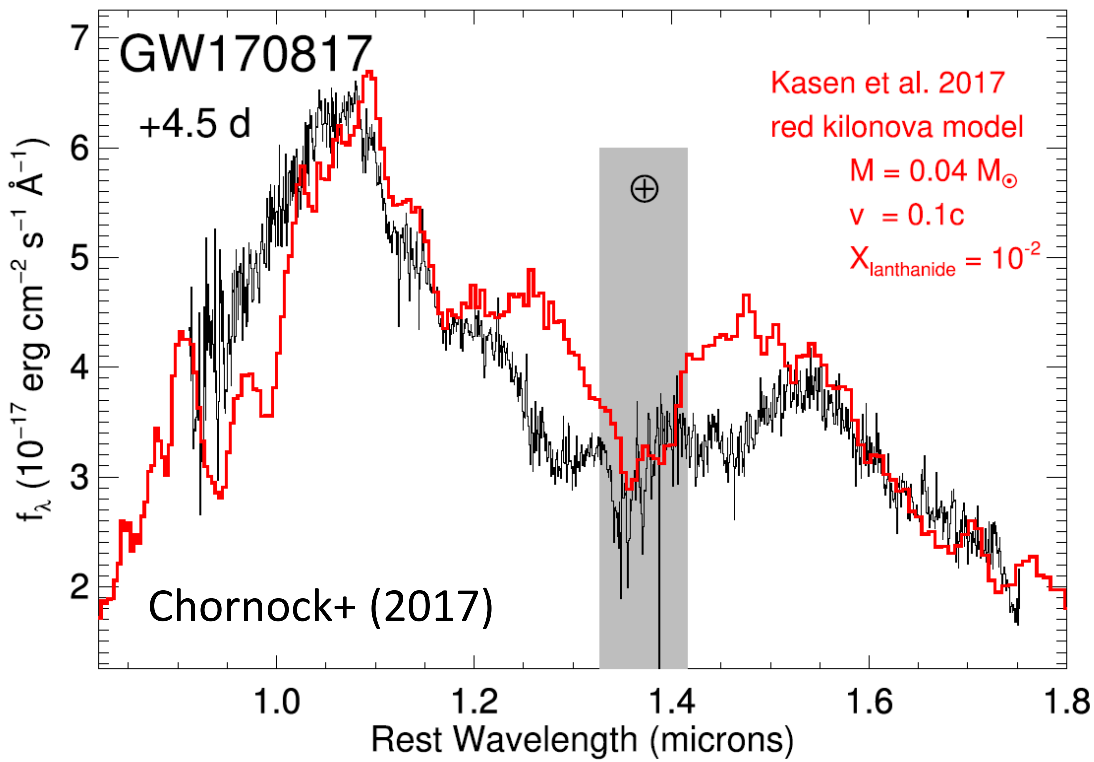


Seriously? This model itself might also explain the X/radio emission

Rapid reddening of the spectrum



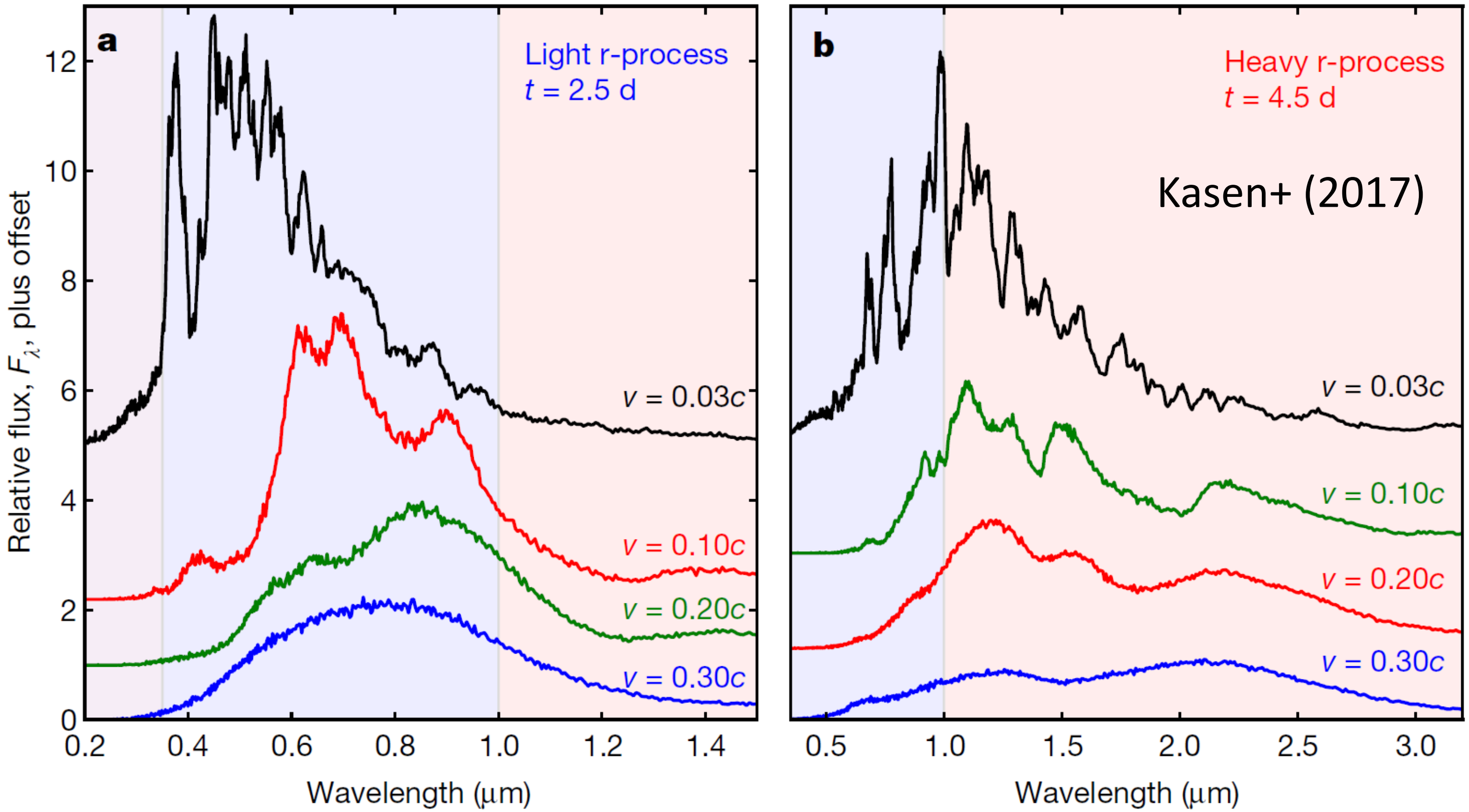
features are consistent w/ r-process element models



Why two components?

The early spectrum is blue and featureless

The late spectrum is red and has a broad peak

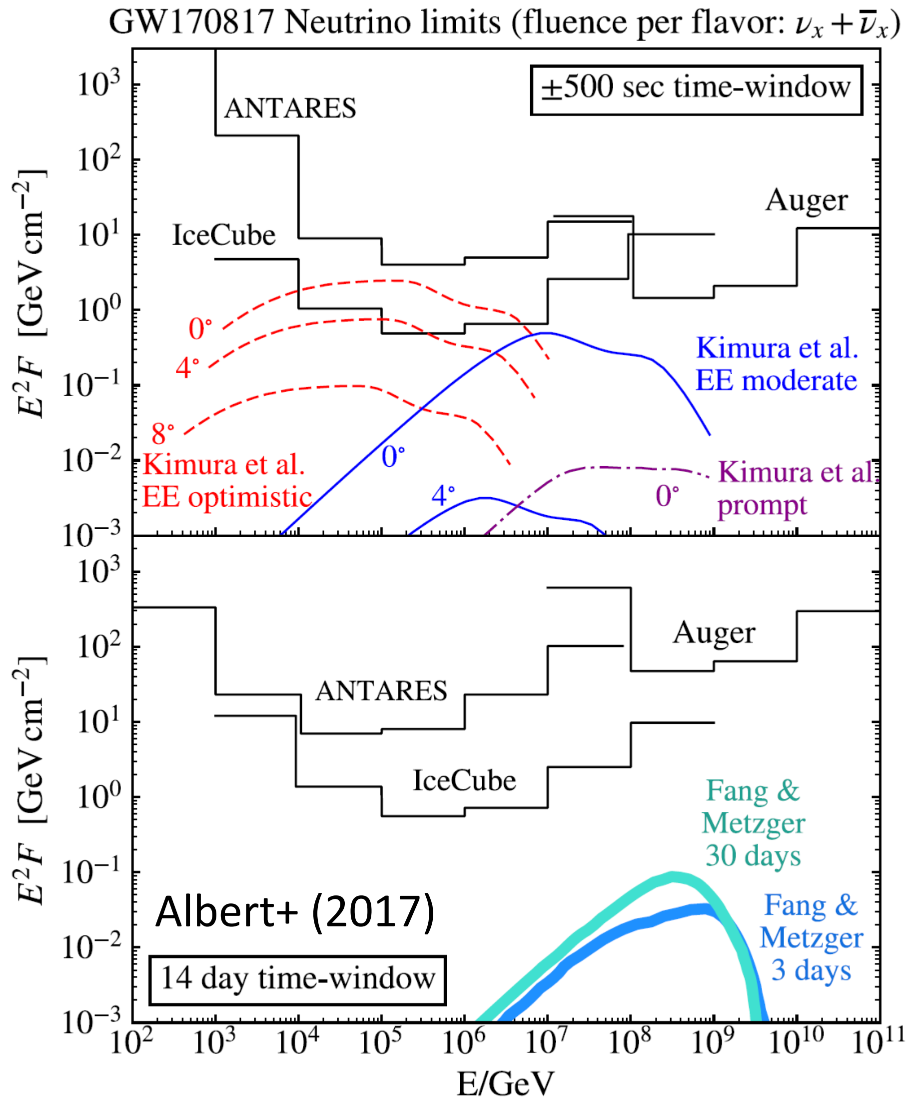


High-energy neutrino upper limit

No neutrino event with time/space coincidence

No model is rejected (except for on-axis ones)

Analyses by SK/KamLAND are both ongoing



Why don't you observe neutrinos?

I know it is a reckless attempt, but arXiv:1710.05922

Detectability of thermal neutrinos from binary-neutron-star mergers and implication to neutrino physics

Koutarou Kyutoku[1,2,3,4] and Kazumi Kashiyama[5]

We propose a long-term strategy for detecting thermal neutrinos from the remnant of binary-neutron-star mergers with a future M-ton water-Cherenkov detector such as Hyper-Kamiokande. Monitoring $\gtrsim 2500$ mergers within $\lesssim 200\,\mathrm{Mpc}$, we may be able to detect a single neutrino with a human-time-scale operation of $\approx 80\,\mathrm{Mt}$ years for the merger rate of $1\,\mathrm{Mpc}^{-3}\,\mathrm{Myr}^{-1}$, which is slightly lower than the median value derived by the LIGO-Virgo collaboration with GW 170817. Although the number of neutrino events is minimal, contamination from other sources of neutrinos can be reduced efficiently to ≈ 0.03 by analyzing only $\approx 1\,\mathrm{s}$ after each merger identified with gravitational-wave detectors if Gadolinium is dissolved in the water. The contamination may be reduced further to ≈ 0.01 if we allow the increase of waiting time by a factor of ≈ 1.7. The detection of even a single neutrino can pin down the energy scale of thermal neutrino emission from binary-neutron-star mergers and could strongly support formation of remnant massive neutron stars. Because the mass of gravitons are now securely constrained to $\lesssim 10^{-22}\,\mathrm{eV}/c^2$ by binary-black-hole mergers, the time delay of a neutrino from gravitational waves can be used to put an upper limit of $\lesssim O(10)\,\mathrm{meV}/c^2$ on the absolute neutrino mass in the *lightest* eigenstate. Large neutrino detectors will enhance the detectability, and in particular, 5 Mt Deep-TITAND and 10 Mt MICA planned in the future will allow us to detect thermal neutrinos every ≈ 16 and 8 years, respectively, increasing the significance.

Dark age of binary neutron star merger

What is ongoing in
the 1.7s delay between
gravitational waves
and gamma rays?
- black hole formation?
- magnetar?

Only neutrinos could be
possible messengers