Multi-messenger from compact binary mergers

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Initial request

“Could you speak on “The impact on Astroparticle Physics from LIGO-Virgo’s detection of gravitational waves?””

Astroparticle…

- cosmic rays?
- neutrinos?
- (very) high-energy gamma rays?

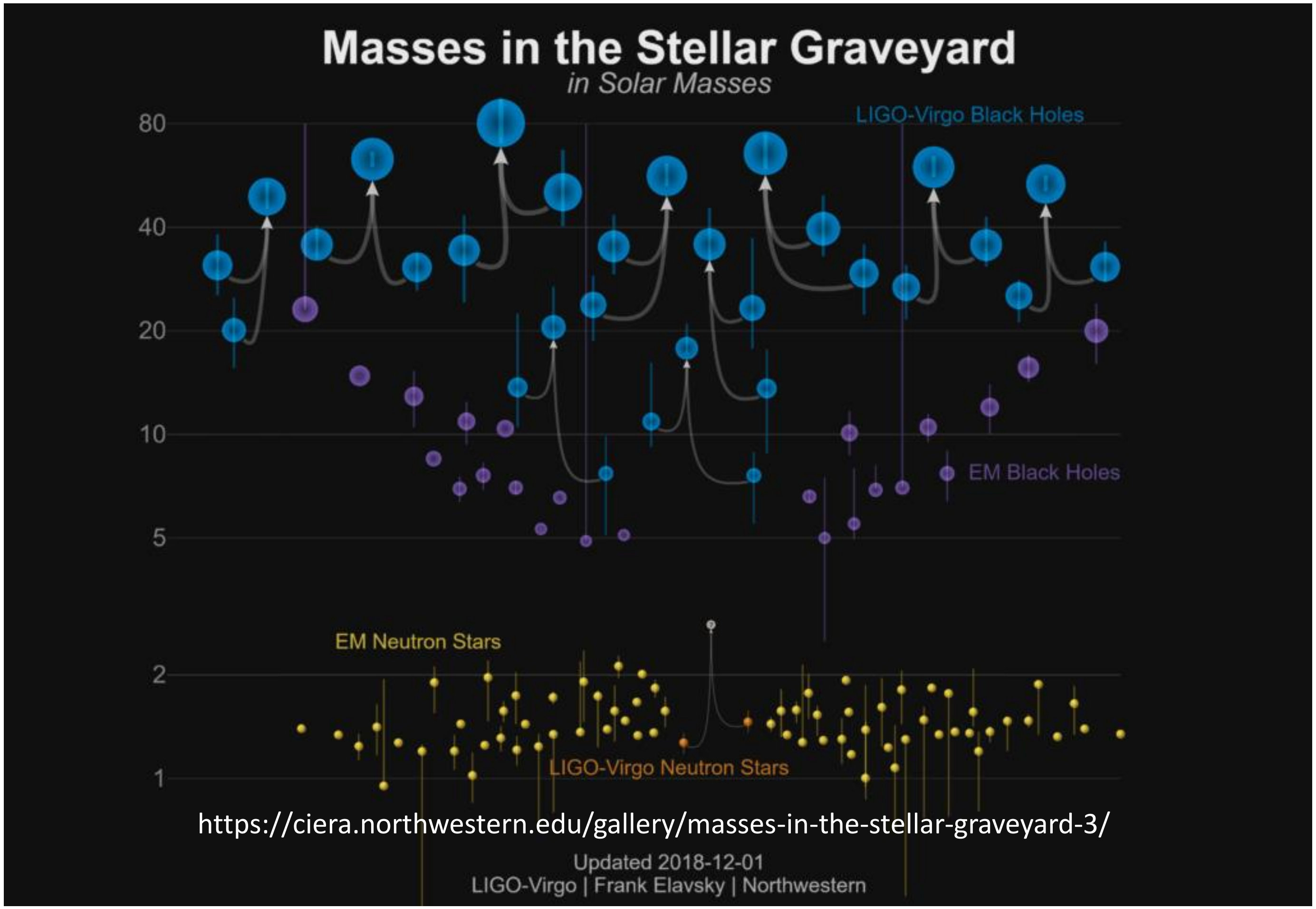
Contents

1. Introduction: current LIGO-Virgo results
2. Kilonova AT 2017gfo and r-process cosmic rays
3. Gamma-ray burst GRB 170817A and magnetars
4. Future prospect and summary

1. Introduction: current LIGO-Virgo results

Era of gravitational-wave astronomy

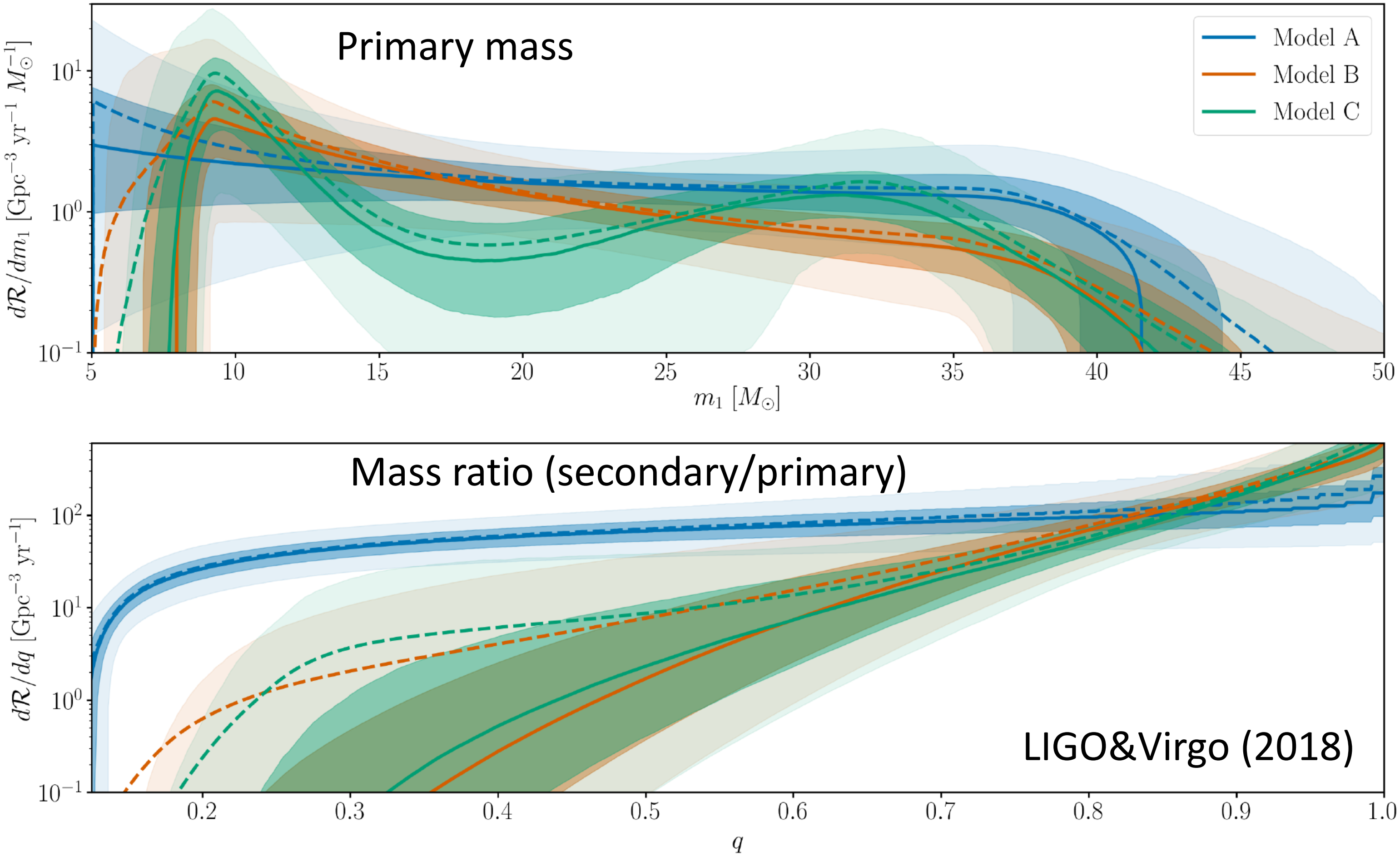
10 binary black holes and 1 binary neutron stars



https://ciera.northwestern.edu/gallery/masses-in-the-stellar-graveyard-3/

Mass distribution of black holes

Beginning to be understood to some accuracy

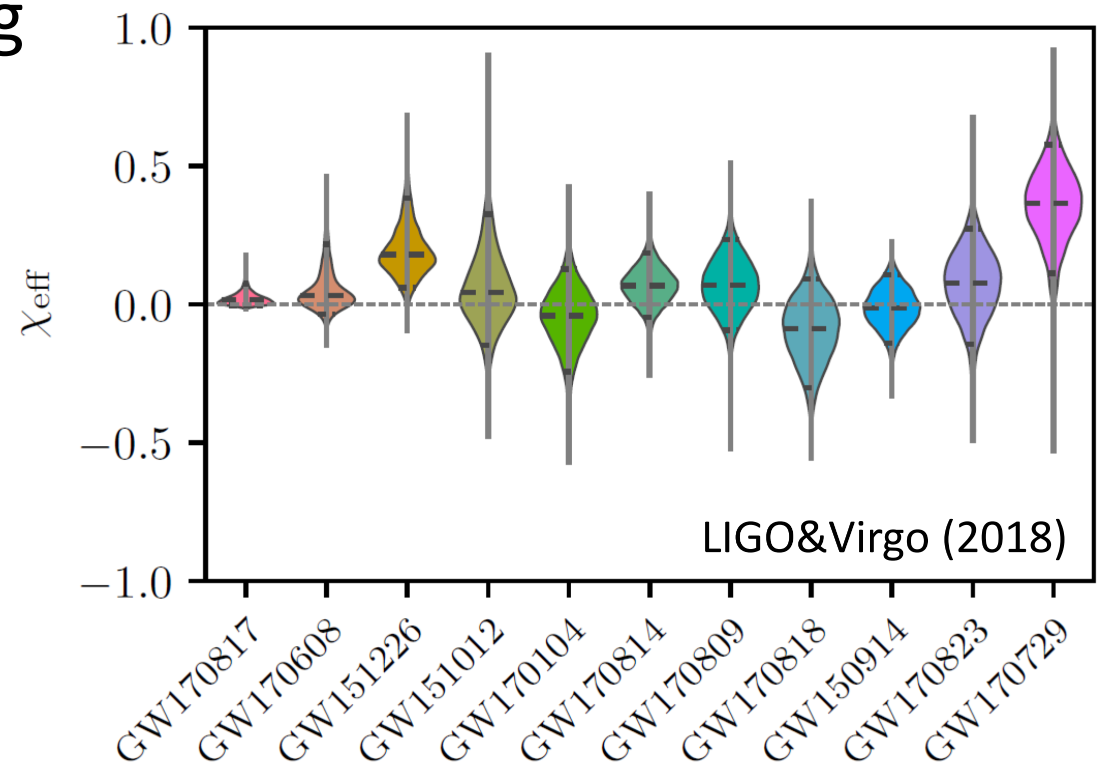


Spin distribution of black holes

$$\chi_{\text{eff}} = (m_1\chi_{1,\parallel} + m_2\chi_{2,\parallel})/(m_1 + m_2)$$

Not likely to be extremely rapidly spinning, but not necessarily preferring non-spinning or random orientation

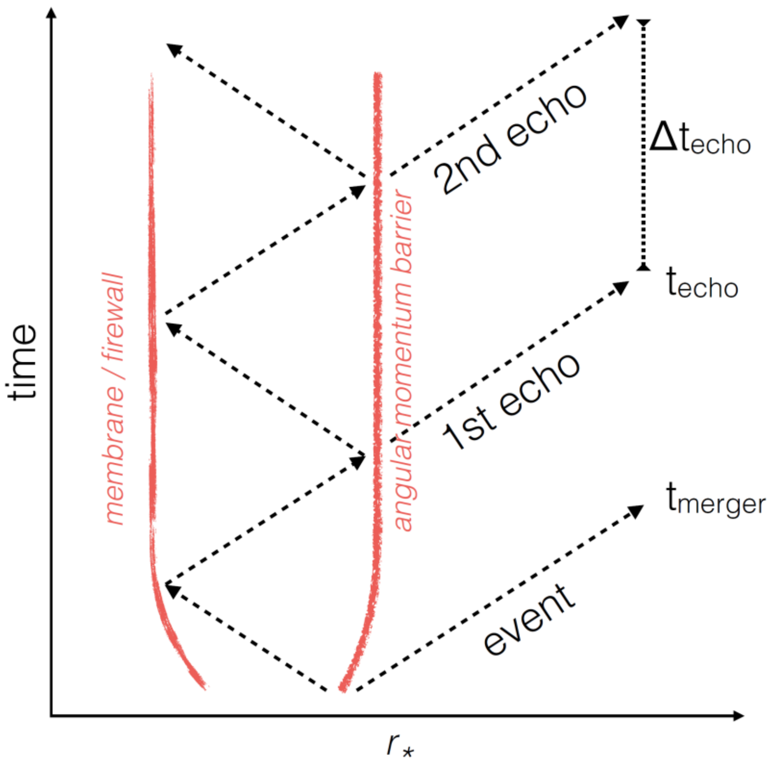
Seems premature

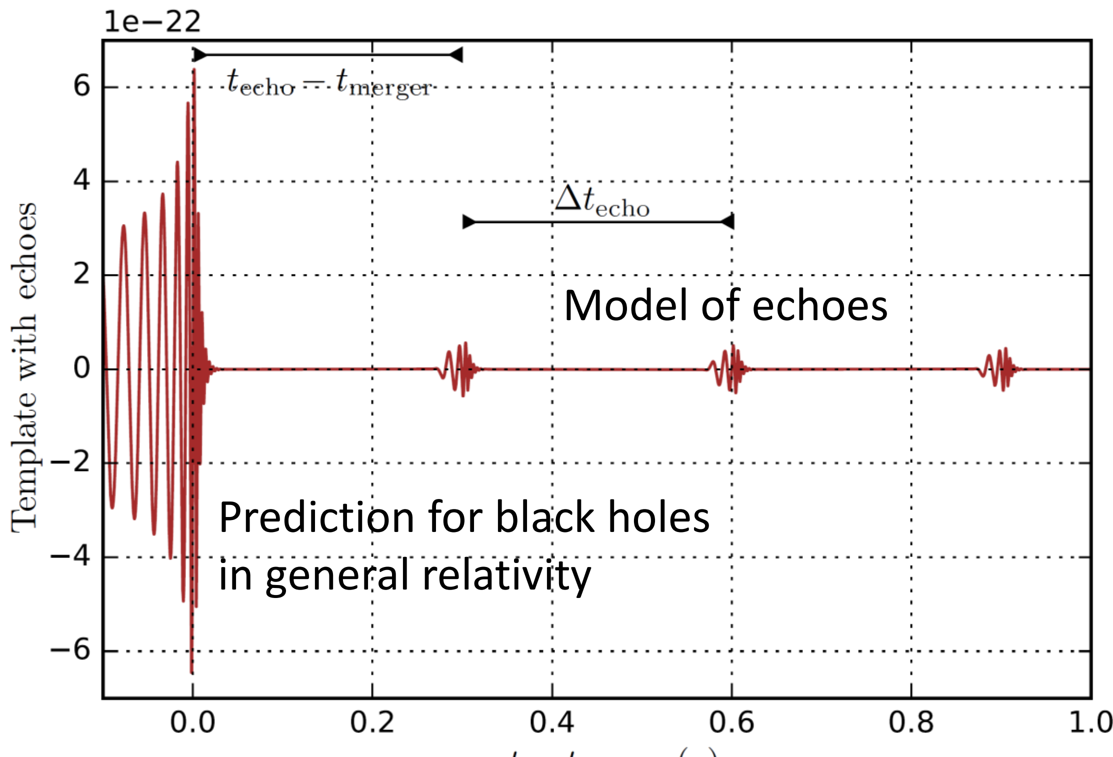


On black-hole echoes

It is possible if it was NOT a genuine black hole

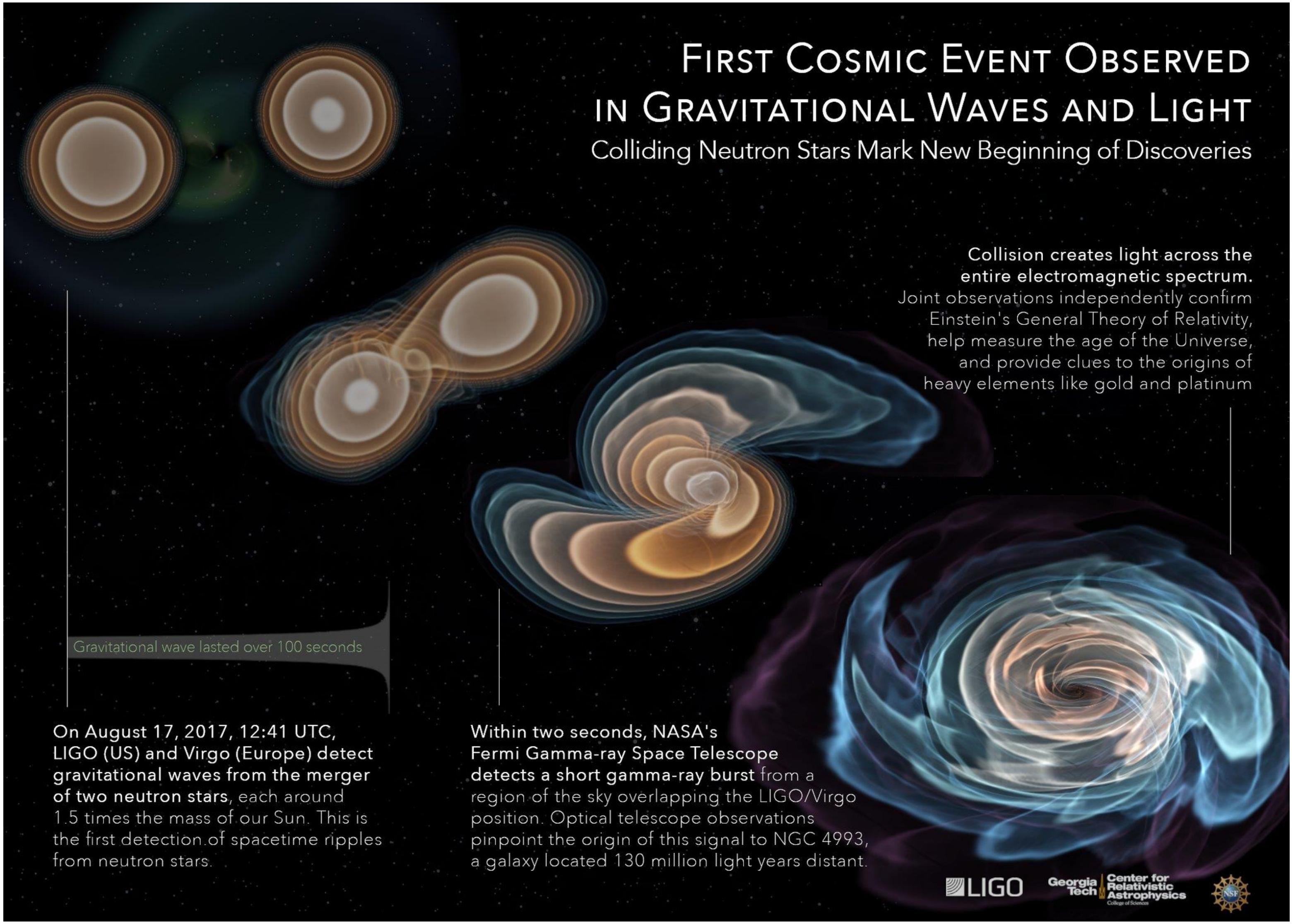
e.g., boson stars, gravastars, or firewalls …





Abedi+ (2017)

GW170817



FIRST COSMIC EVENT OBSERVED
IN GRAVITATIONAL WAVES AND LIGHT
Colliding Neutron Stars Mark New Beginning of Discoveries
Collision creates light across the entire electromagnetic spectrum.
Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum
Gravitational wave lasted over 100 seconds
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.
Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.
LIGO
Georgia Tech
Center for Relativistic Astrophysics

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

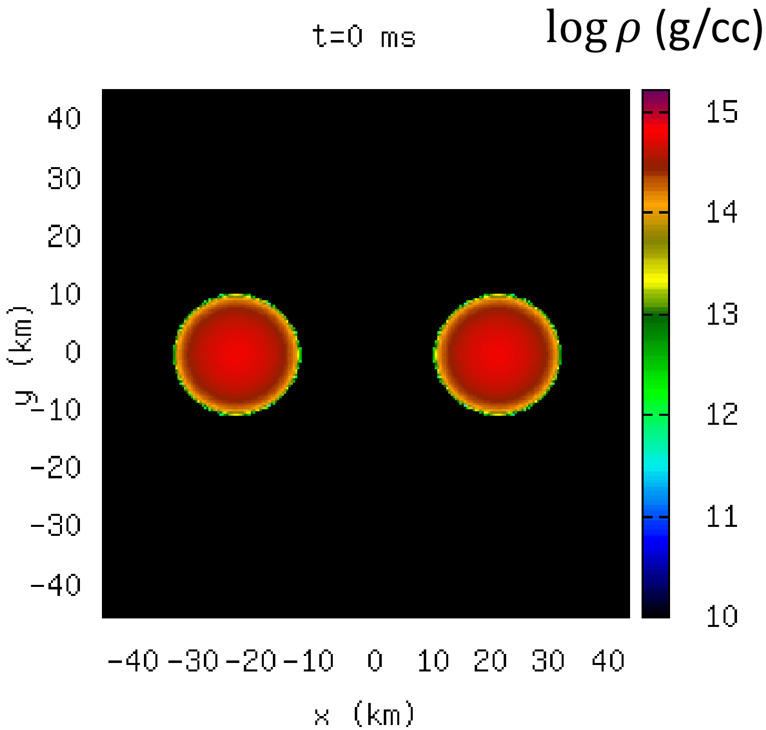
- Mass ejection of neutron-rich material

 - r-process nucleosynthesis

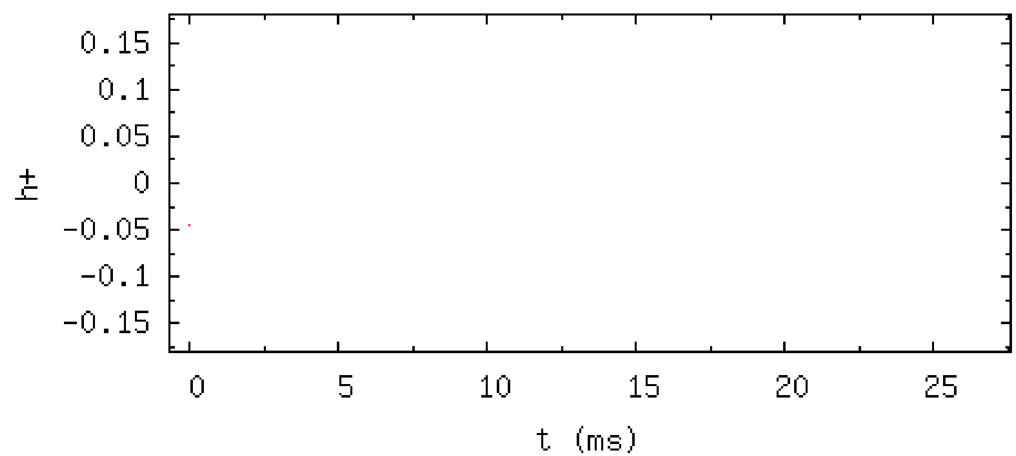
 - radioactively-driven “kilonova/macronova”

Example of the binary merger

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

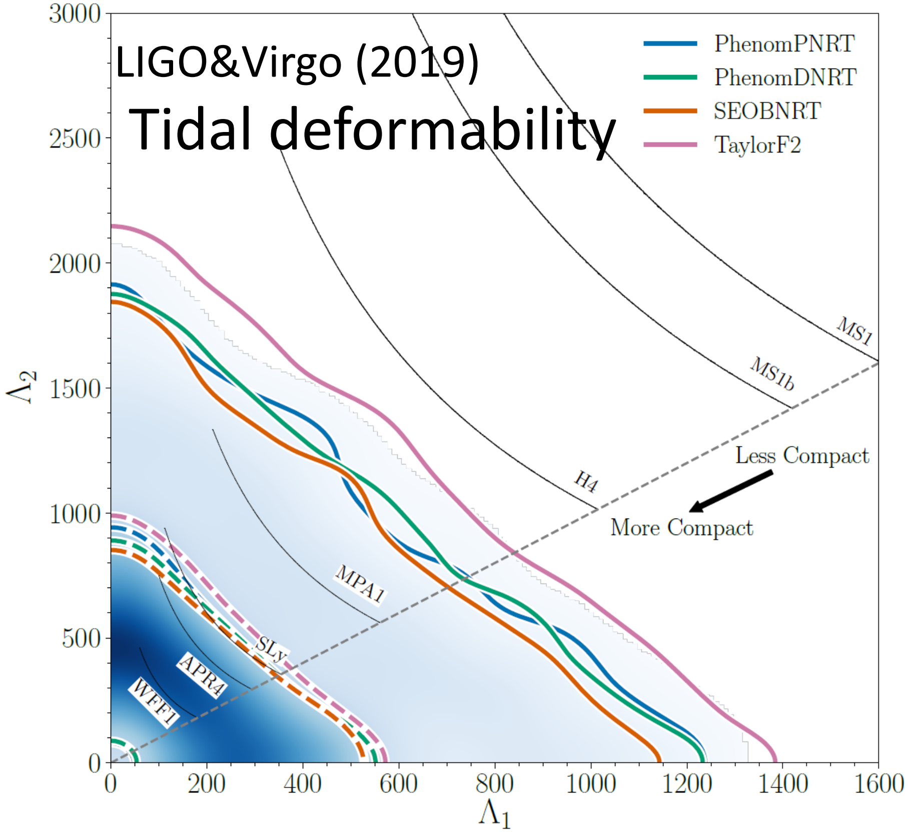


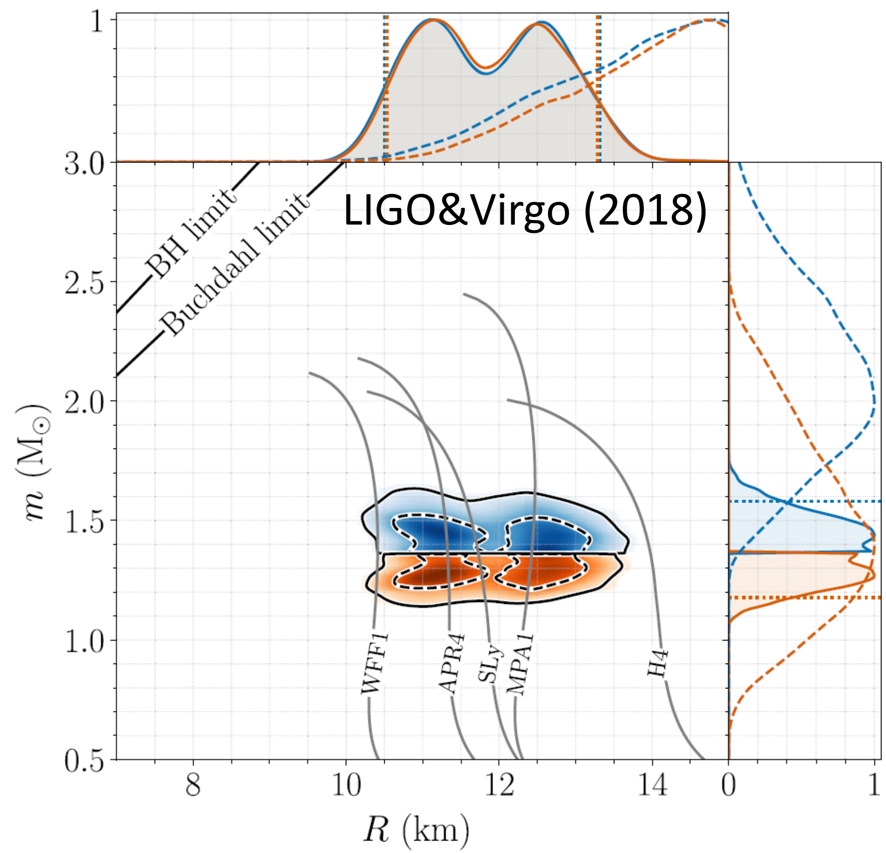
(old) Movies by Kenta Hotokezaka
Based on Hotokezaka, KK+ (2011)



Constraint on neutron-star properties

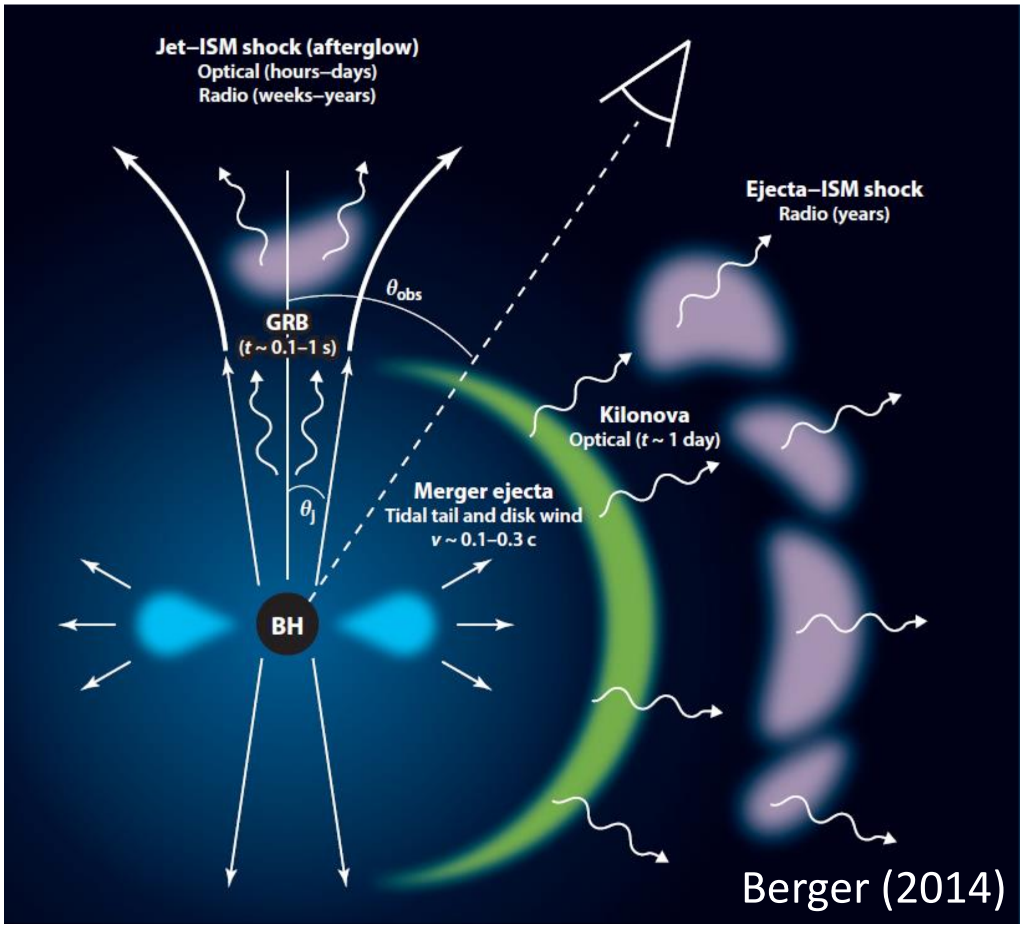
Model-insensitive constraints are obtained, and aggressive assumptions derive strong constraints





Electromagnetic counterpart

EM radiation accompanies neutron star mergers



localization

- host identification
- cosmological redshift

ejecta properties

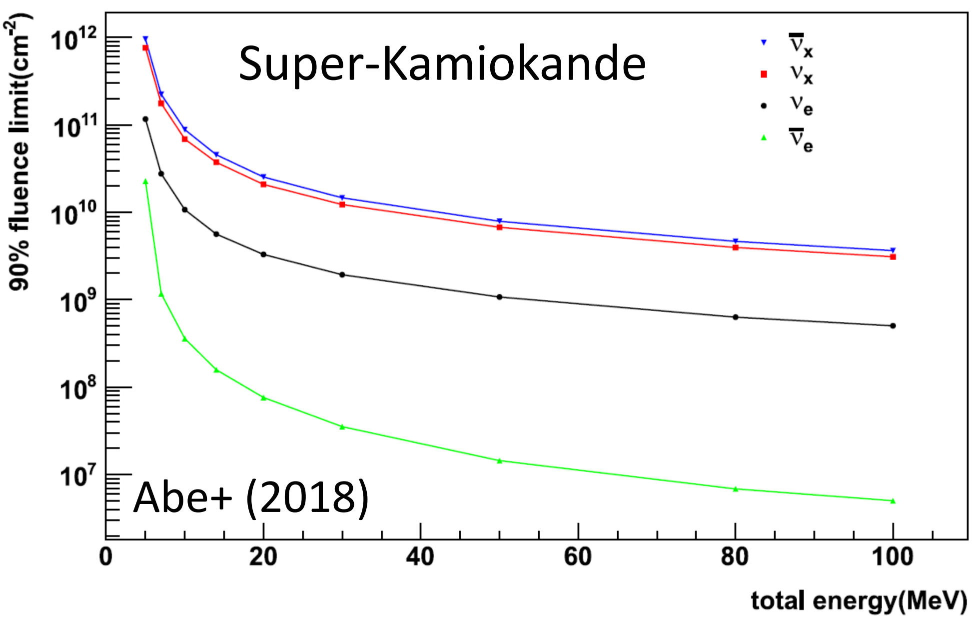
- ejection mechanism
- r-process element

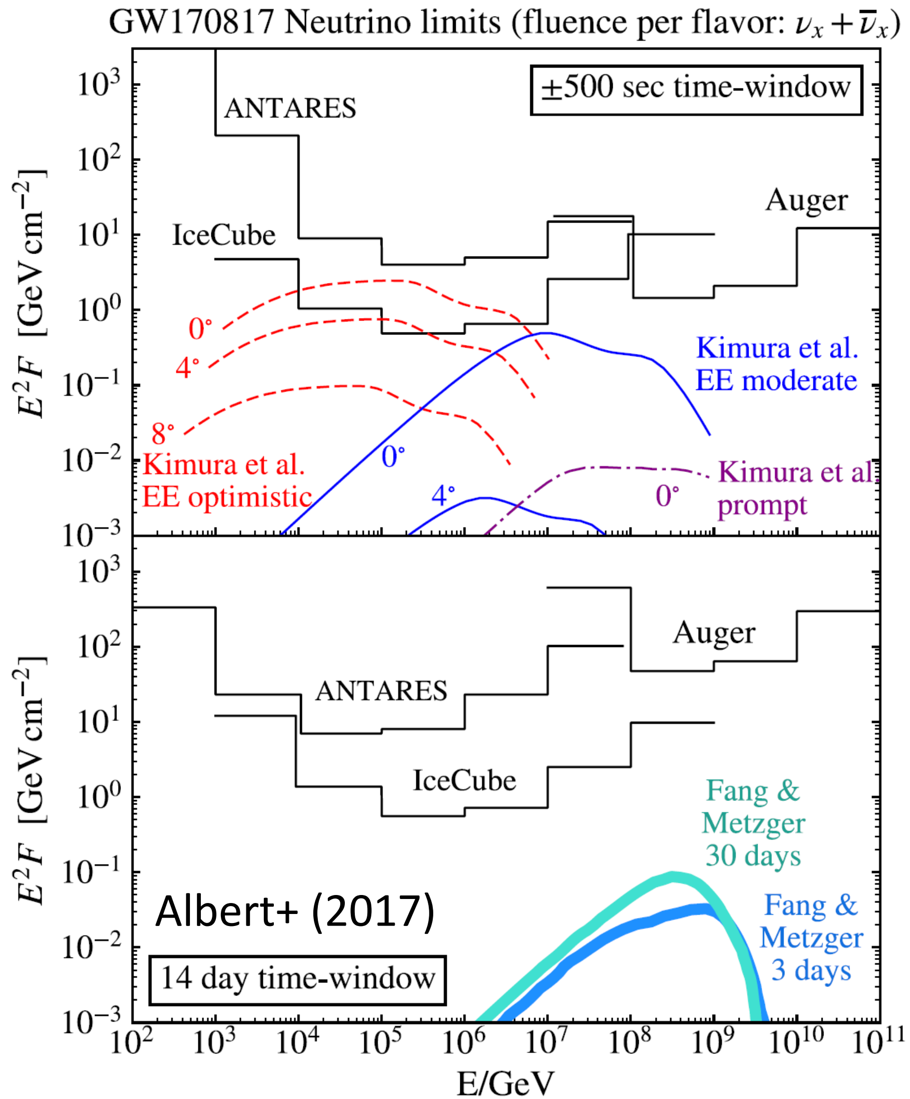
Neutrino upper limit

No coincident event

No model is rejected

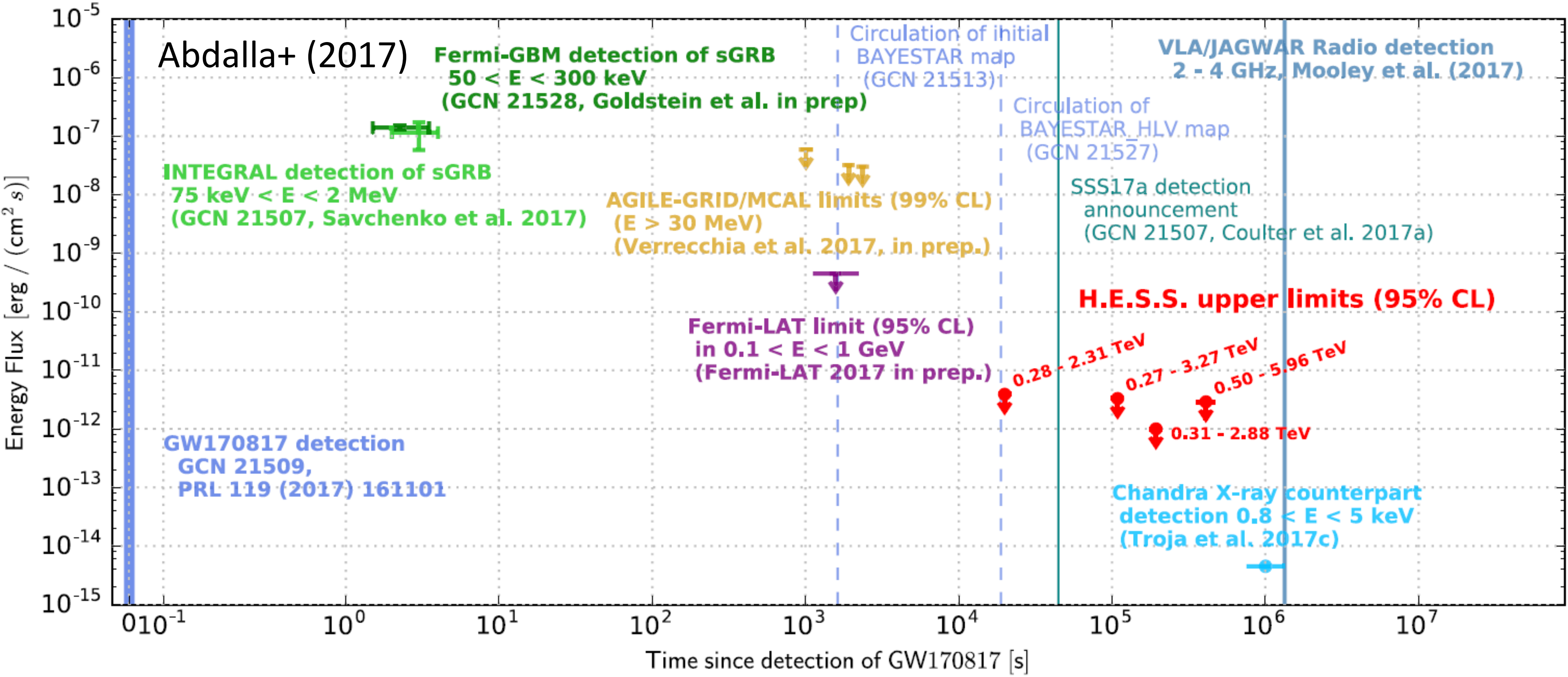
(except for on-axis GRBs)





High-energy gamma ray upper limit

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

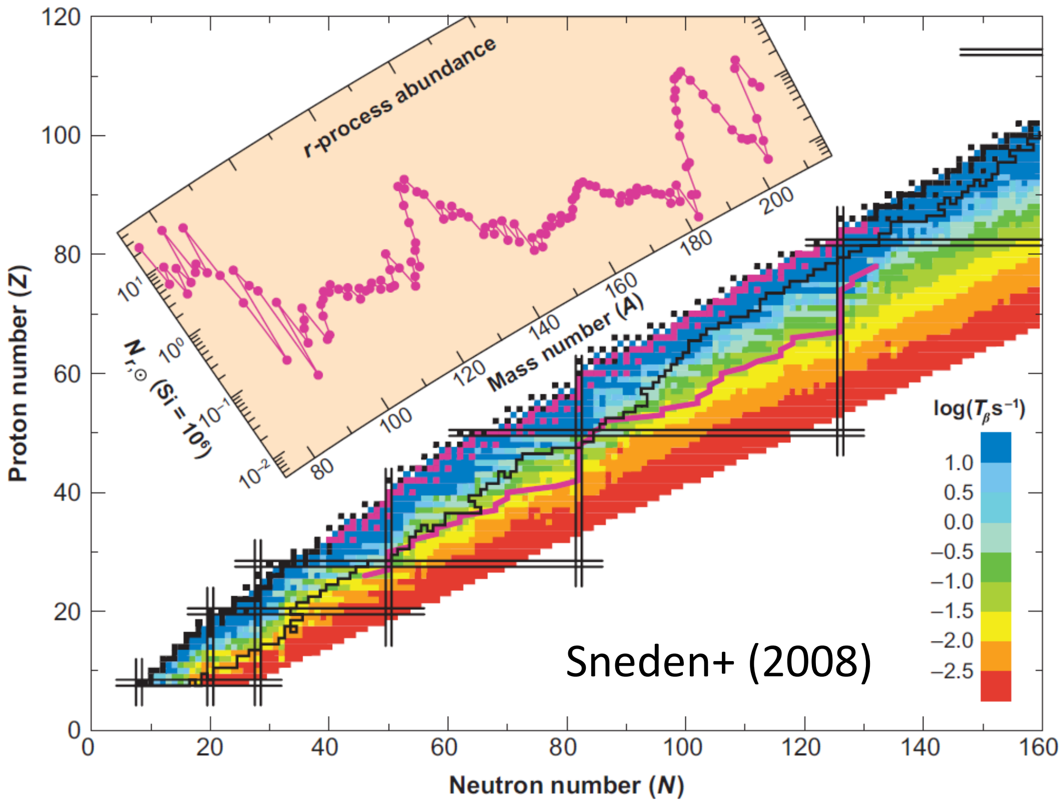


2. Kilonova AT 2017gfo and r-process cosmic rays

r-process nucleosynthesis

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

r = rapid: neutron capture faster than beta decay

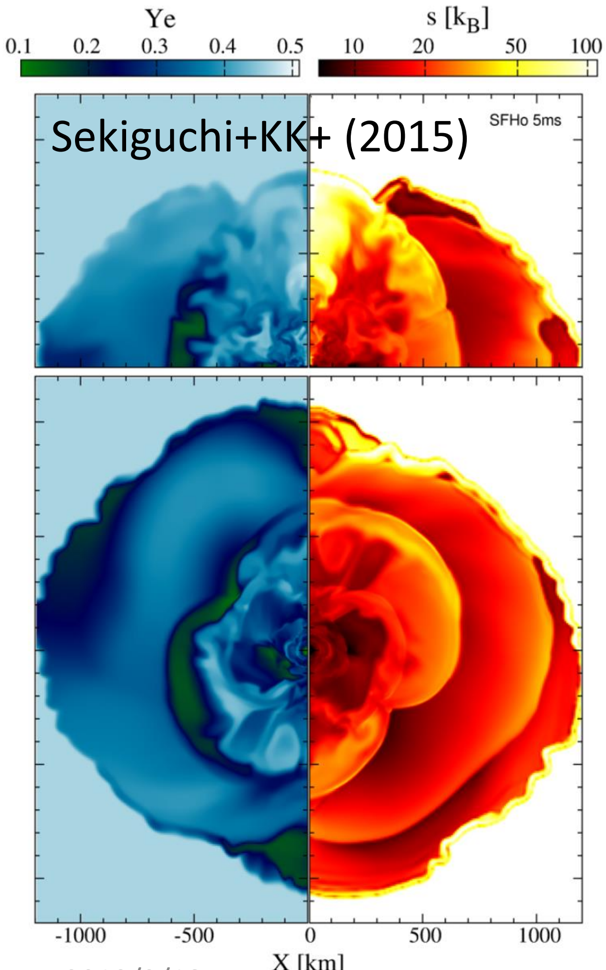


need very dense and neutron-rich matter

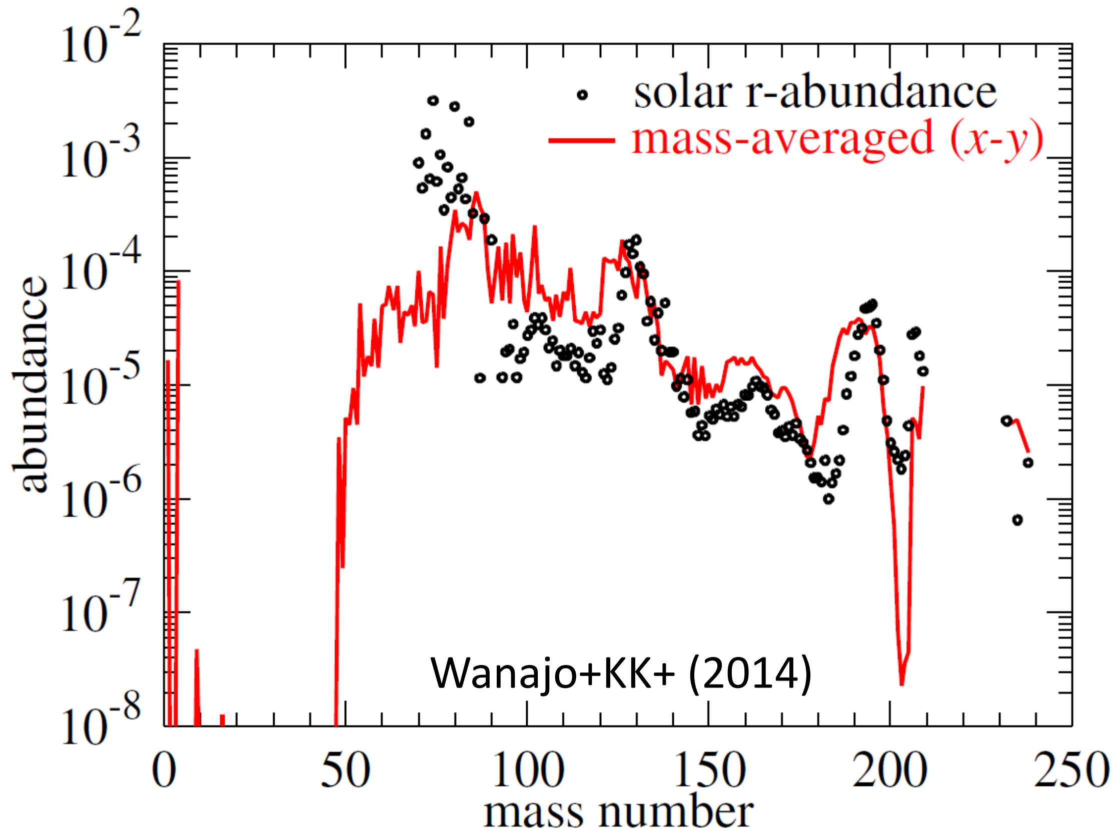
supernova explosions now seem to fail to achieve r-process

Mass ejection from binary mergers

Successful at least for some binary models



how can we confirm this idea?



Kilonova/macronova

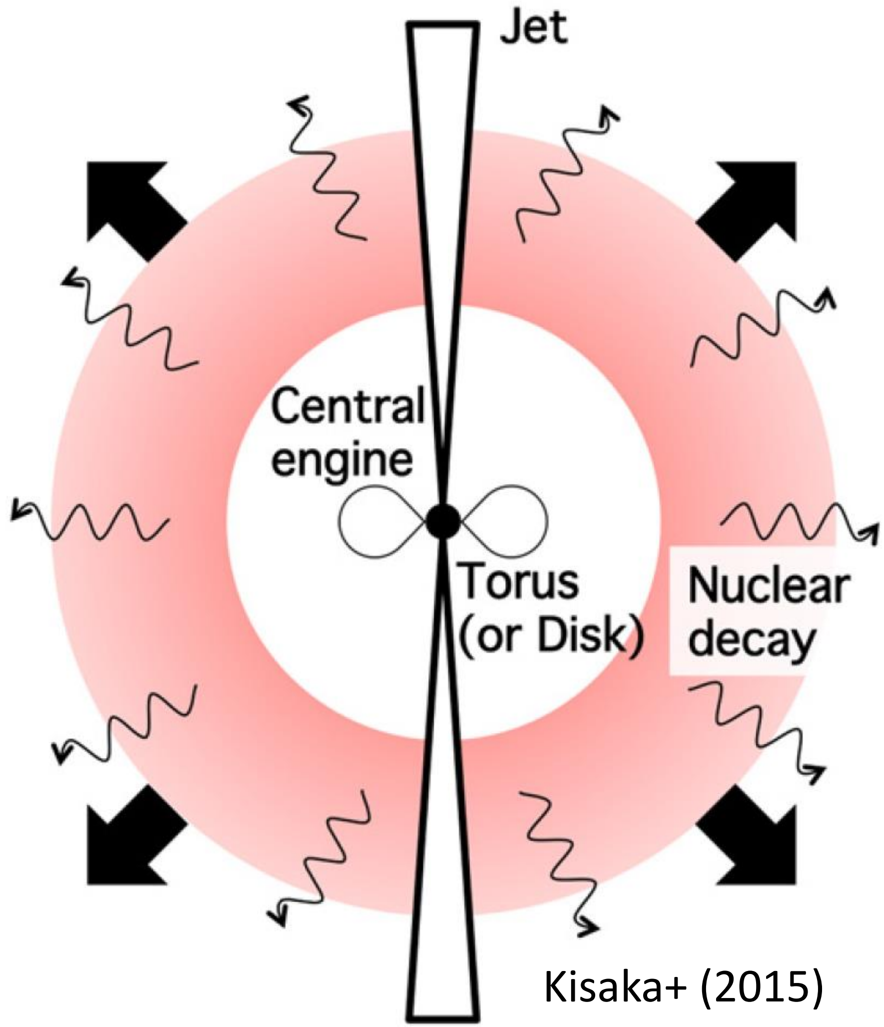
Ejected material contain radioactive r-elements

Their decay heat the ejecta

Thermal photons try to diffuse from the ejecta

But r-elements efficiently traps the photon inside

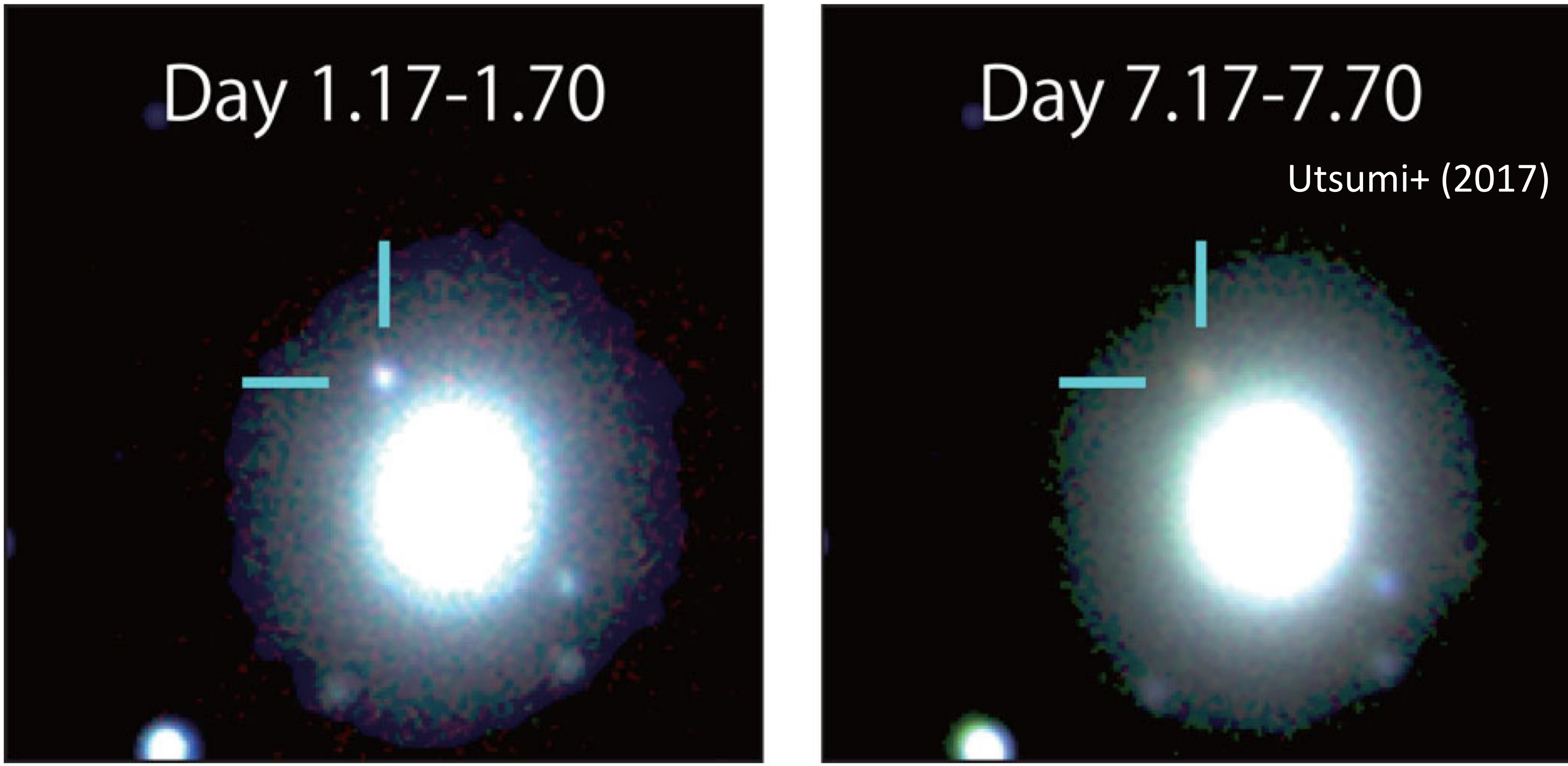
Characteristic “kilonova”!



Kisaka+ (2015)

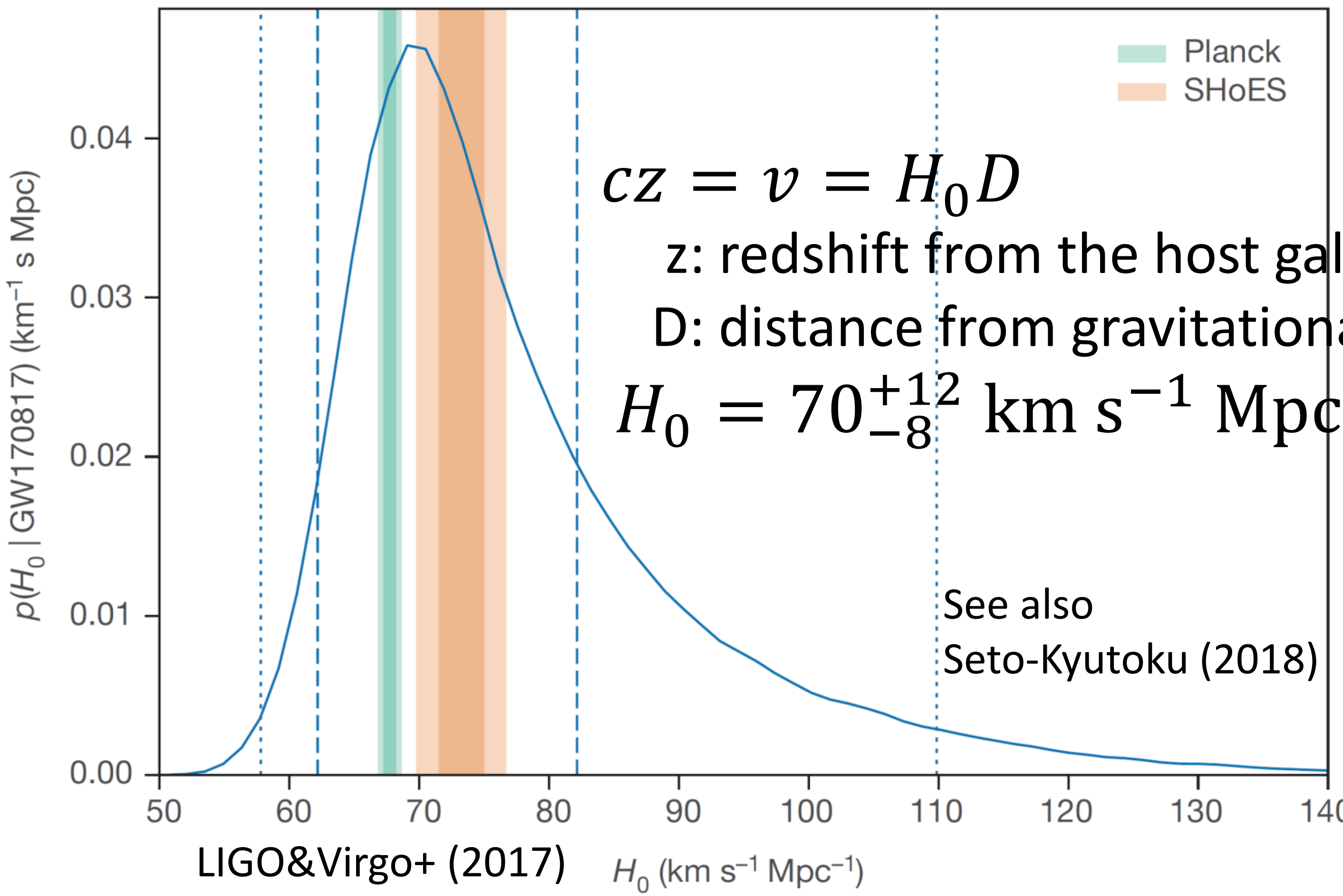
UV/optical/IR transient AT 2017gfo

The host galaxy and redshift are determined



Gravitational-wave cosmology

Hubble's constant is determined in a novel manner



LIGO&Virgo+ (2017)

CMB
Supernova

$$cz = v = H_0 D$$

z: redshift from the host galaxy

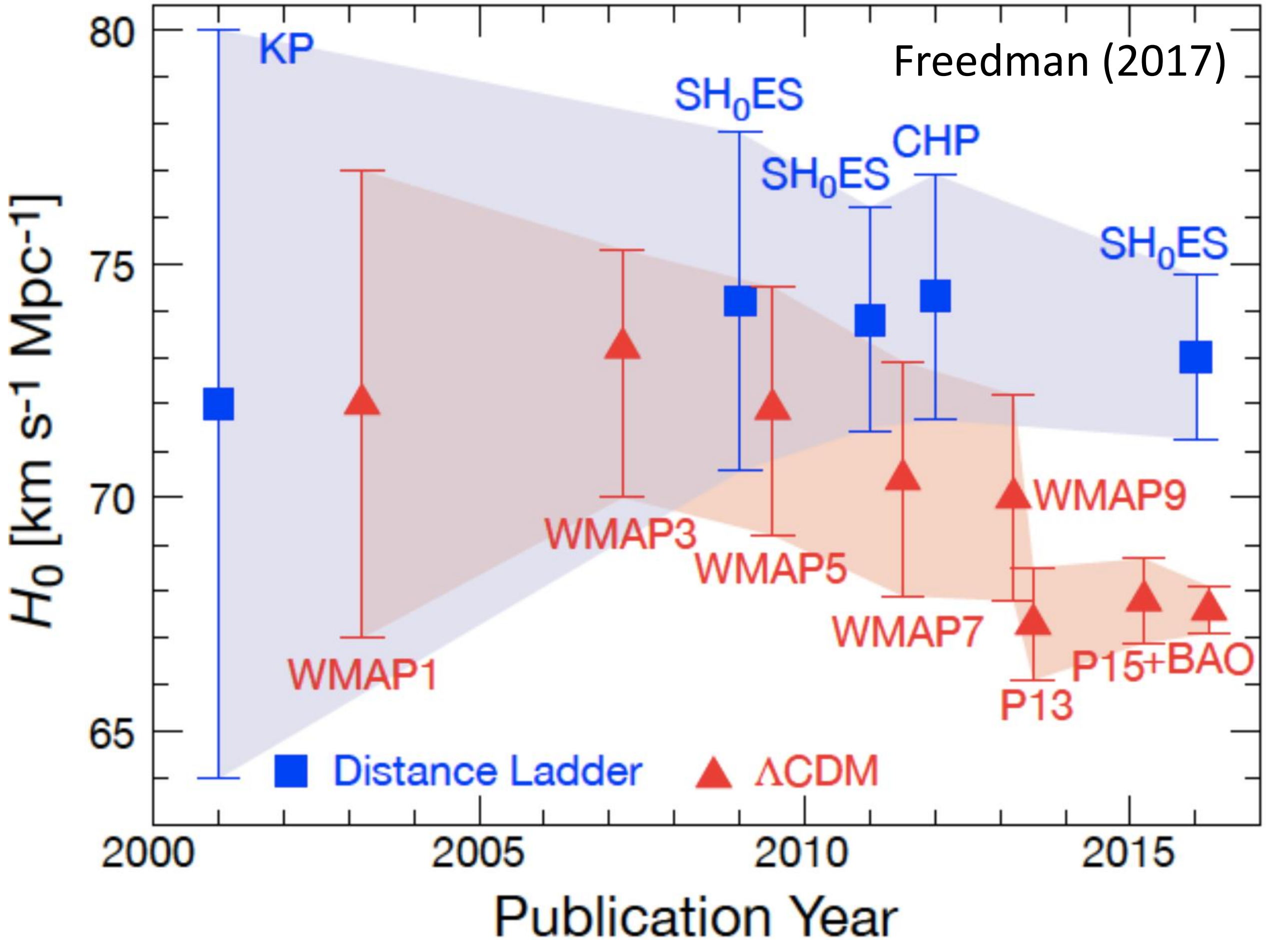
D: distance from gravitational waves

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

See also
Seto-Kyutoku (2018)

Hubble tension?

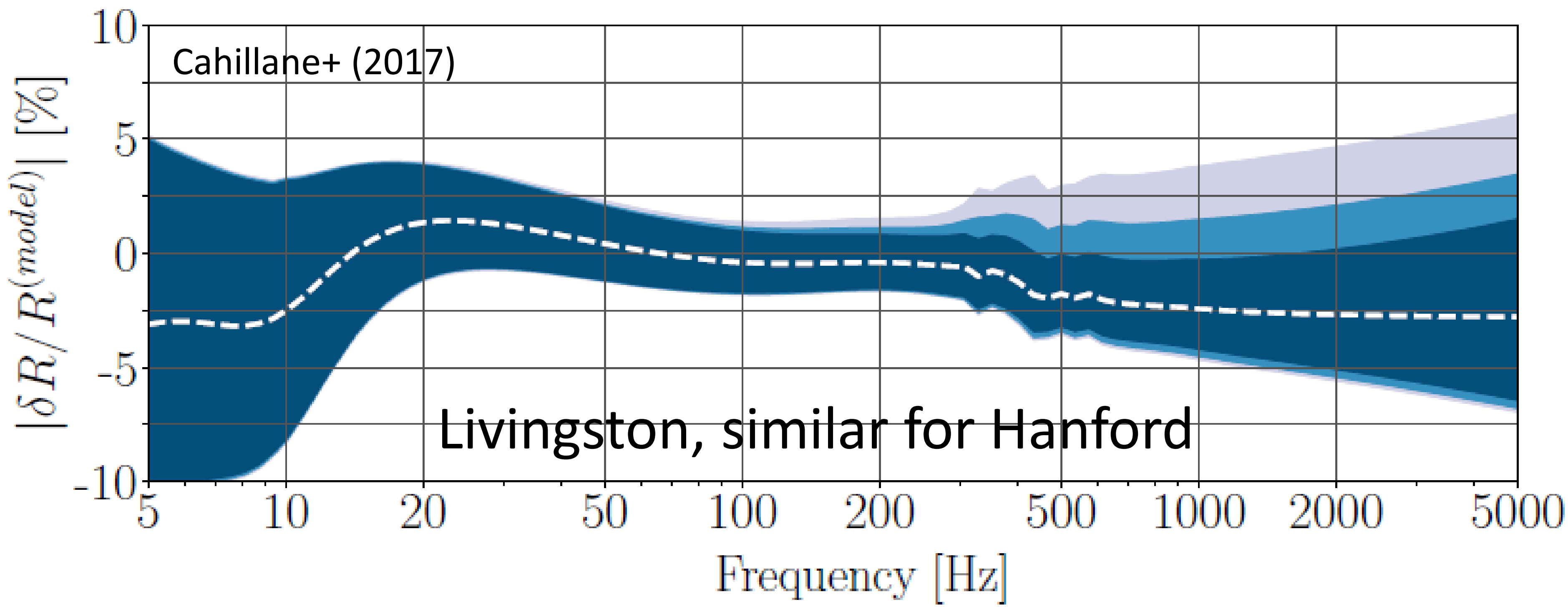
GW-EM can examine this 3.4sigma~9% discrepancy



Freedman (2017) adapted from Beaton+ (2016)

But caution! Calibration accuracy

Amplitude measurements by LIGO/Virgo have ~5% systematic errors … as are the distance errors



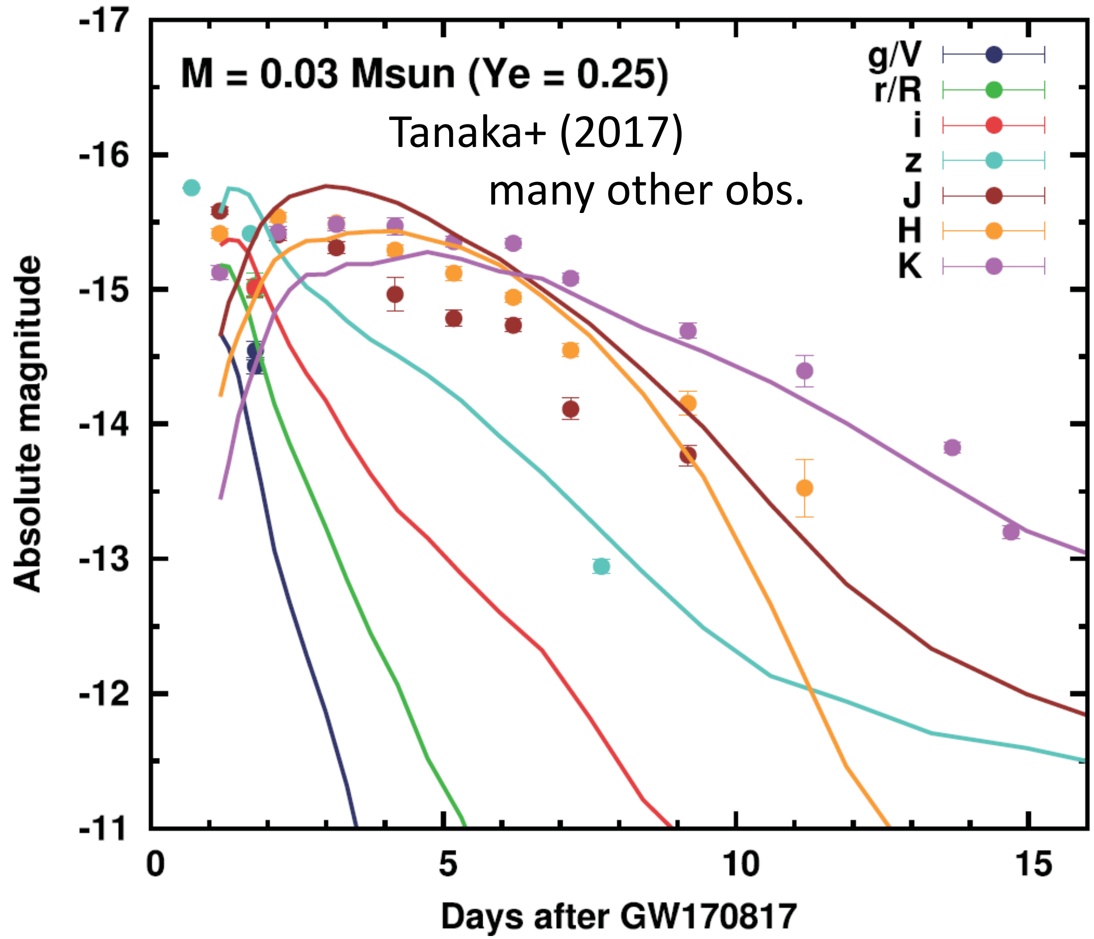
AT 2017gfo

In general agreement with theoretical models

particularly in NIR

Compared to SNe

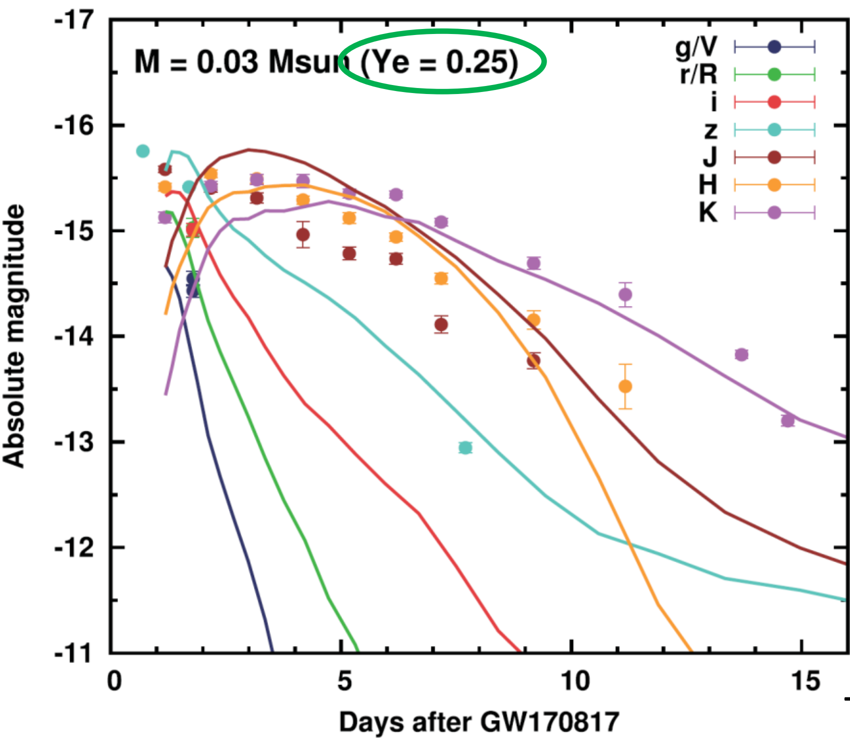
- small mass
- high velocity
- high opacity
- no time scale of the heating

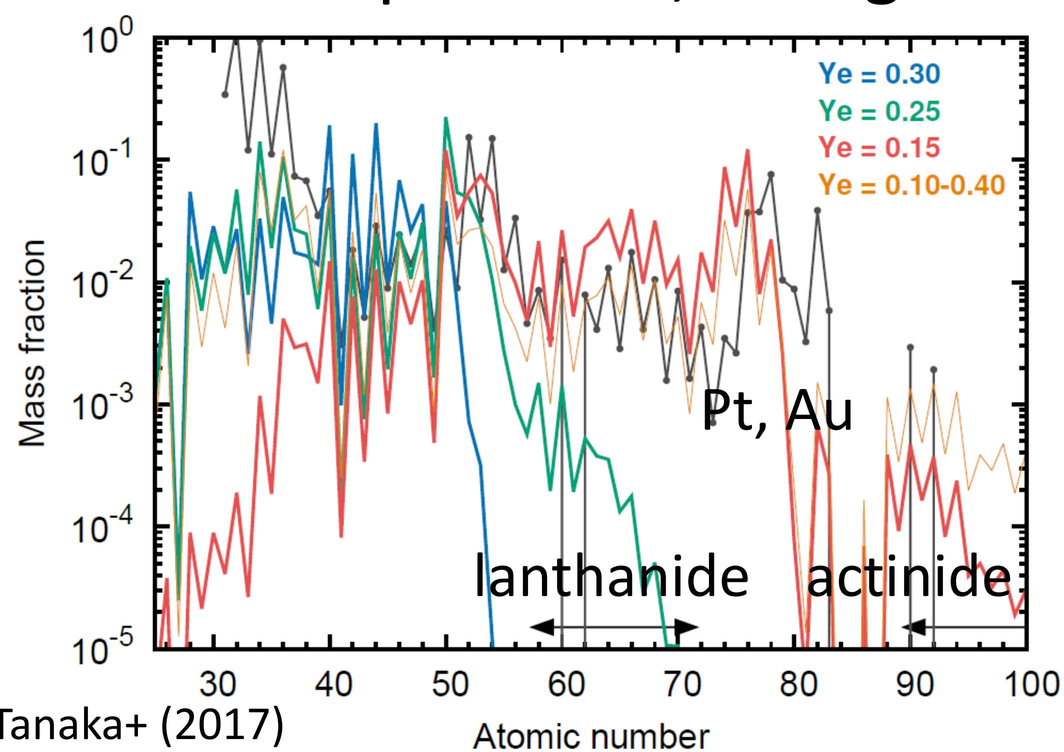


No indication of ultraheavy elements

A moderate amount of lanthanide is required but gold, platinum, etc. are not concretely detected

- it is simply hard to confirm their presence, though

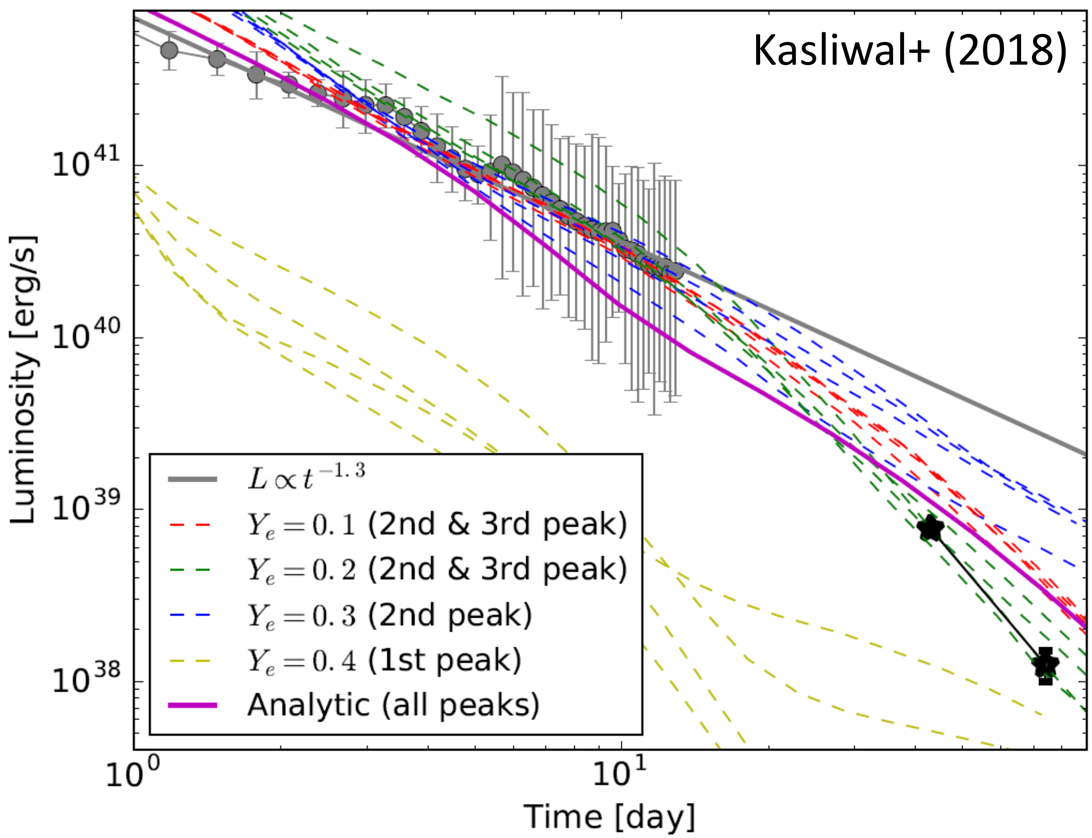




Tanaka+ (2017)

Heating source

Some people claim that heavy elements such as gold and platinum better explain late-time emission



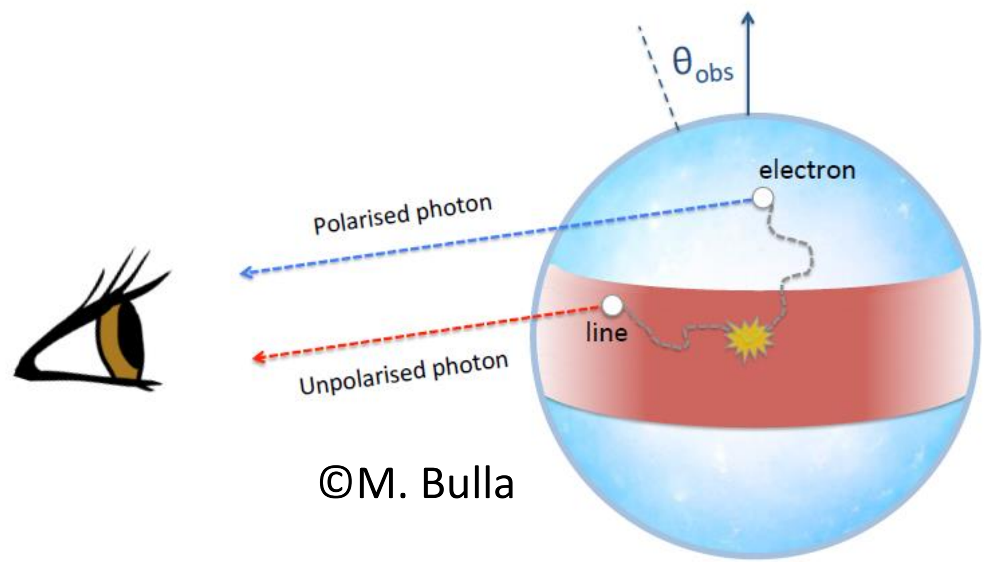
but

- the prediction is not very robust
- late bolometric luminosity is not very accurate

Polarization

Ejecta geometry and atomic distribution could be inferred from polarization due to electron scattering

This is possible only if both light and heavy r-process elements exist in the ejecta

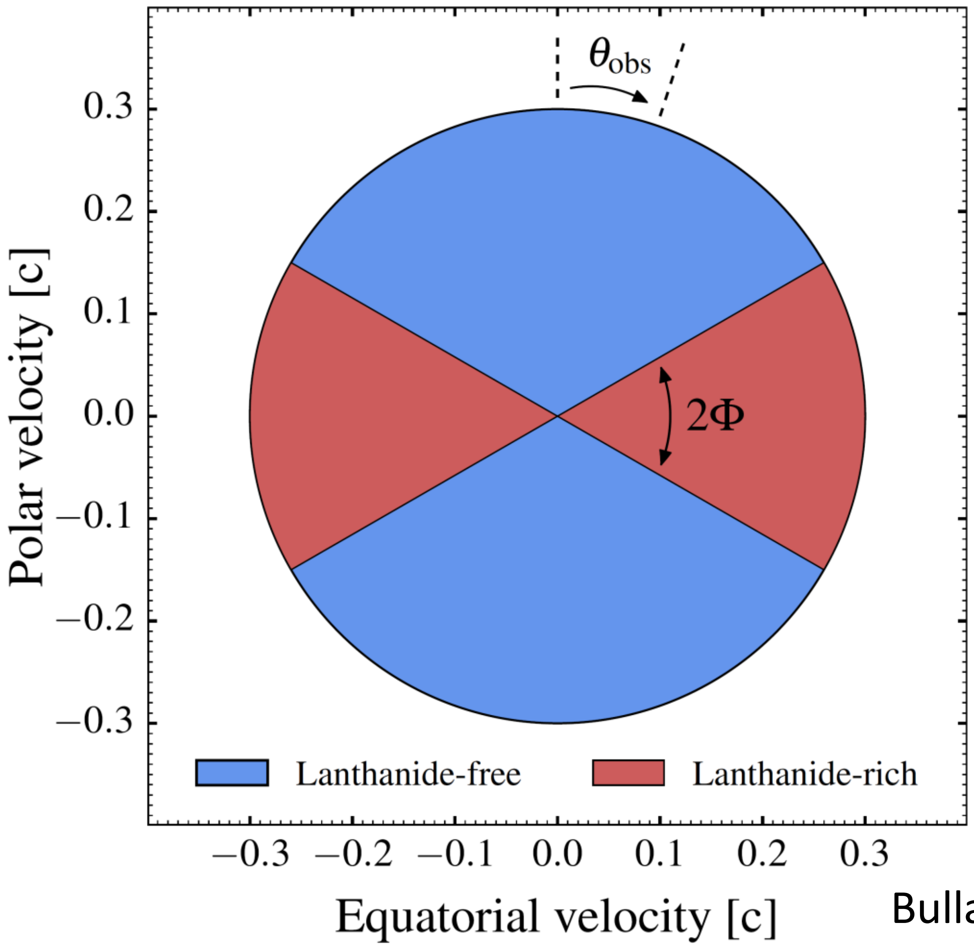


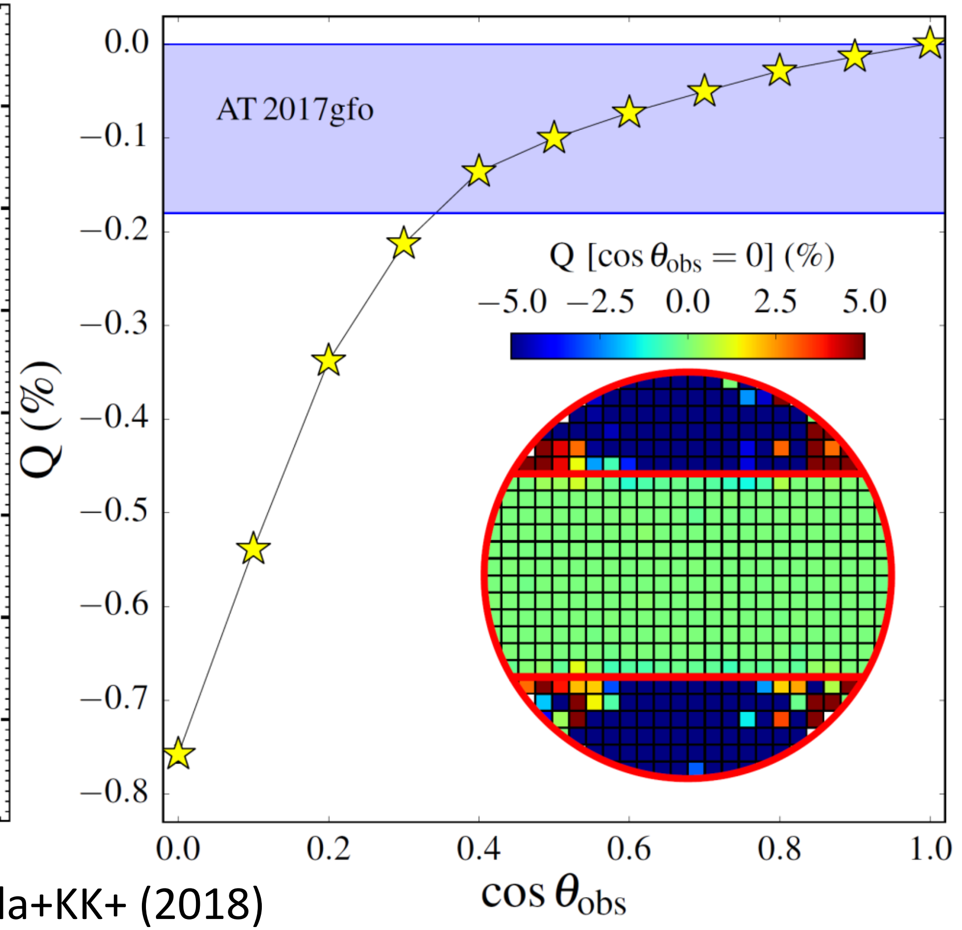
©M. Bulla

No polarization for AT 2017gfo [Covino et al. 2017]

Possible probe into atomic distribution

~1% polarization is possible for binary neutron stars





Bulla+KK+ (2018)

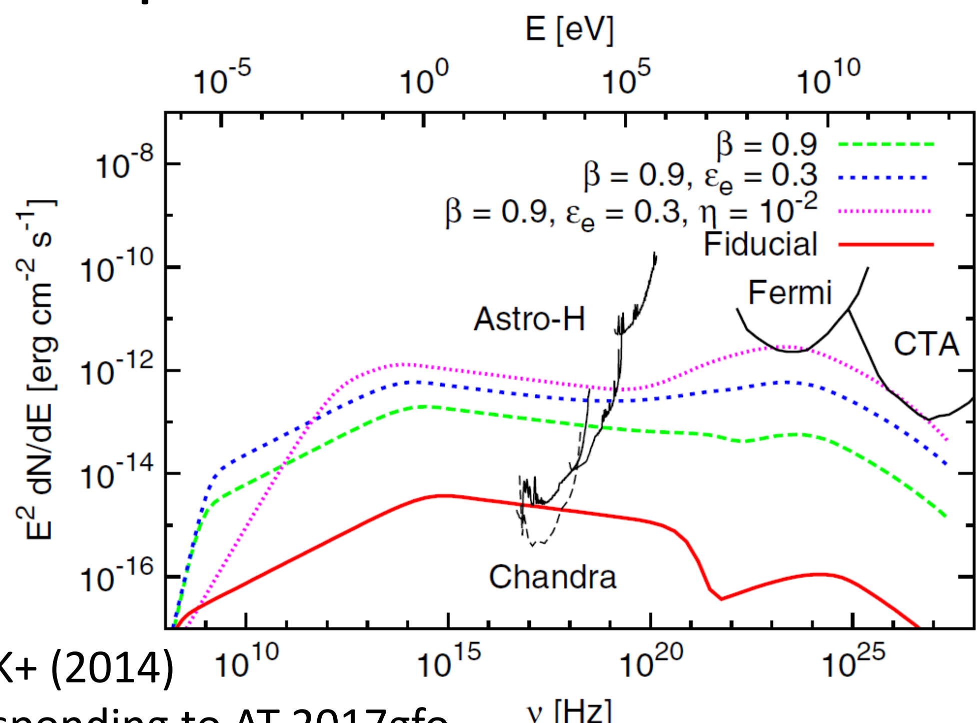
Future of the kilonova ejecta

The ejecta with $0.03 - 0.05M_\odot$ and $0.1 - 0.2c$ will eventually collide with the interstellar medium

-> a system very similar to supernova remnants

Broadband emission is expected (mainly radio)

Gamma-rays are possible for (very) extreme cases e.g., with magnetars



Takami, KK+ (2014)

Not corresponding to AT 2017gfo

Cosmic-ray acceleration?

The velocity of the r-process-enriched ejecta is larger by an order of magnitude than supernova's

If all the r-process elements are produced in mergers, they must be born with two order-of-magnitude larger kinetic energy (per mass) than elements from the supernova explosion e.g., Fe

Then - r-process cosmic rays could be very intense as far as the reverse-shock acceleration is efficient

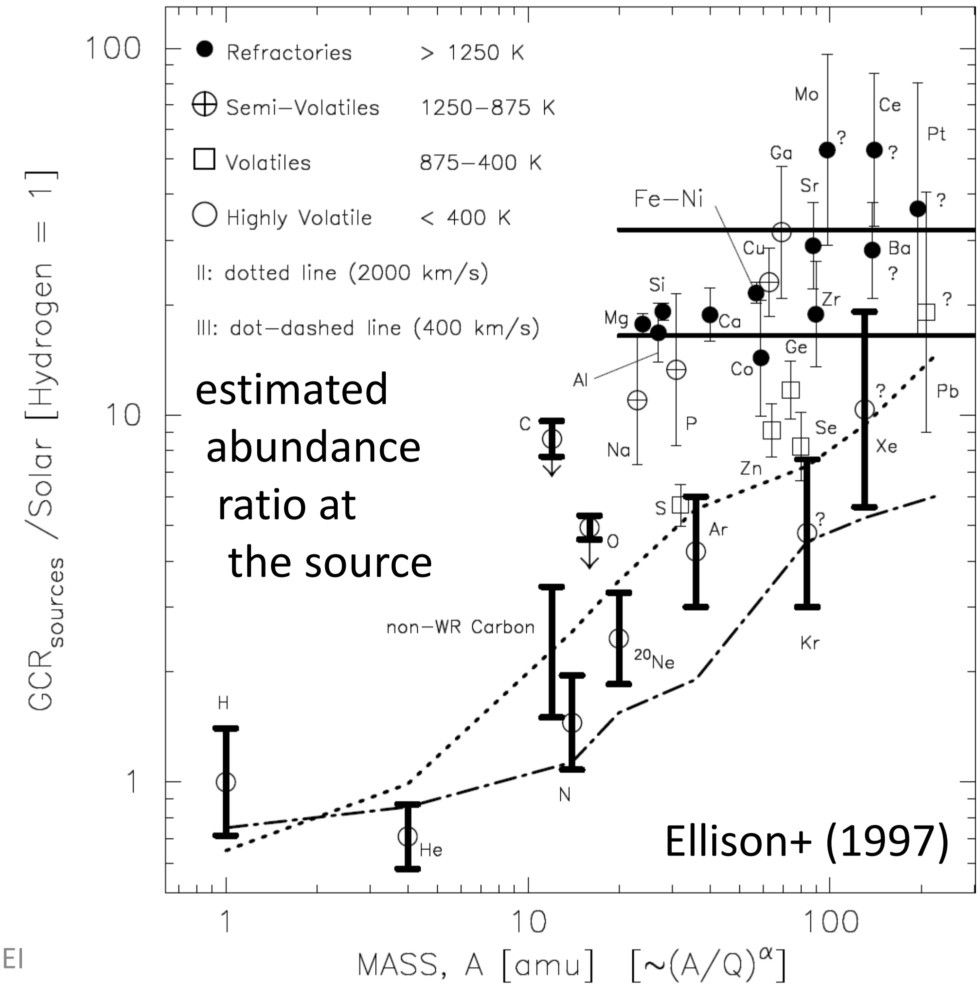
Observed cosmic-ray composition

No selective r-process enhancement is observed

"solar composition"

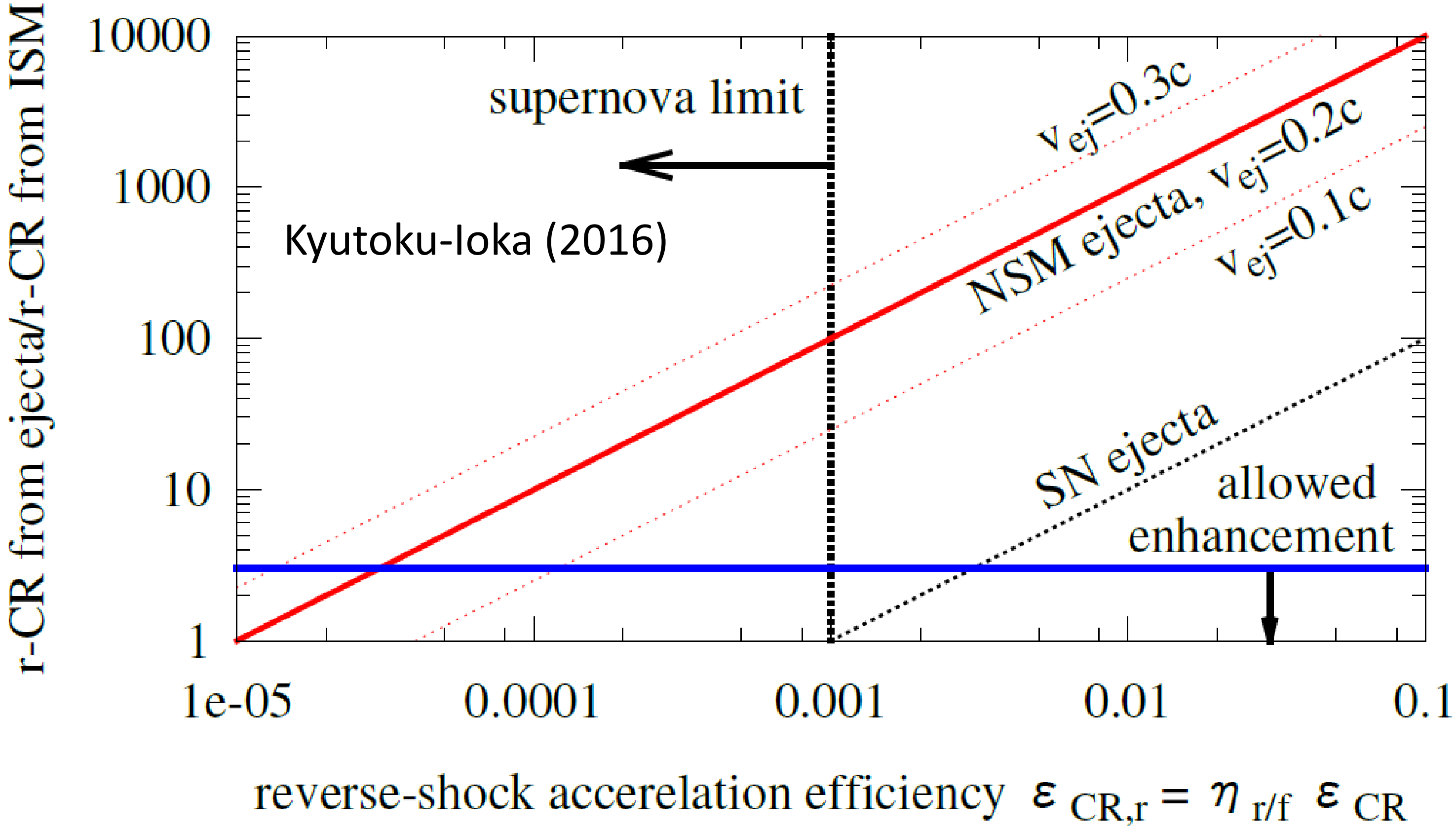
Enhancement for

- refractory elements that tend to form dusts
- all the heavy elements (or for large A/Q ?)



Limit on acceleration efficiency

Particle acceleration and emission will be inefficient in the reverse shock of the kilonova ejecta



3. Gamma-ray burst GRB 170817A and magnetars

Short gamma-ray burst

About 10^{51}erg/s explosions

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

Long-soft GRB: ≥ 2s

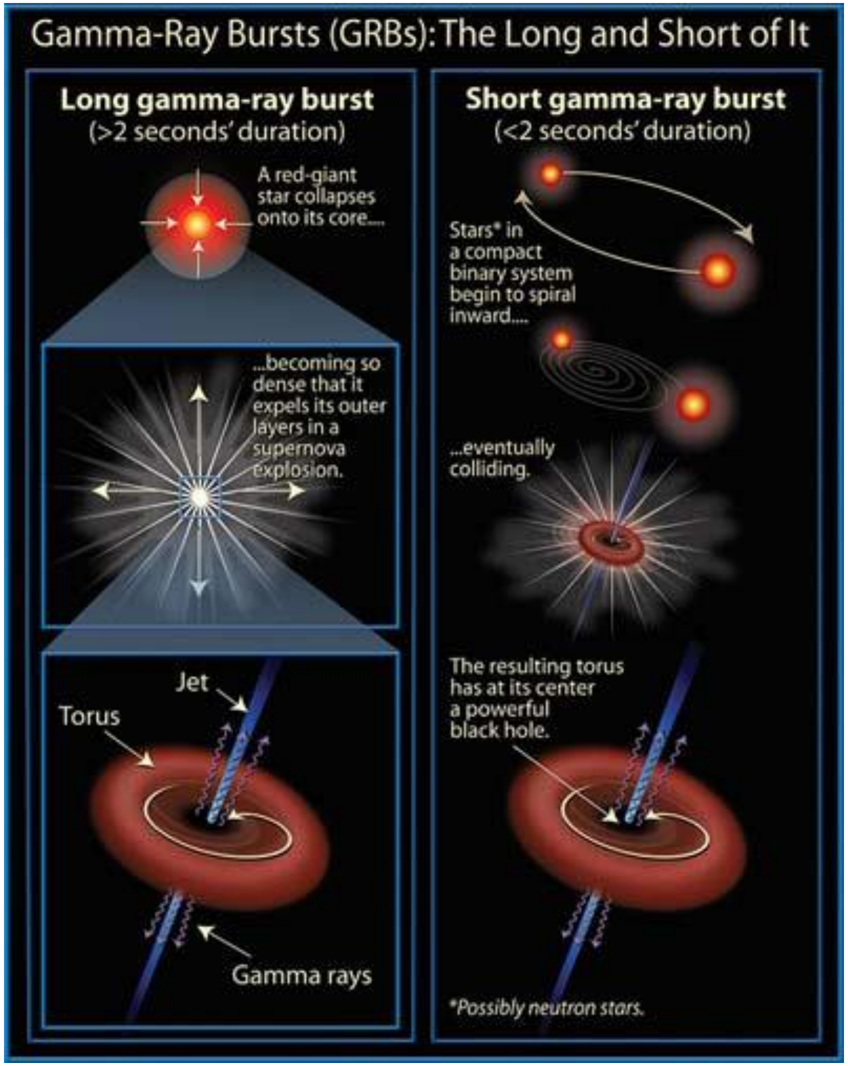
deaths of massive stars

Short-hard: ≤ 2s

neutron star binary merger?

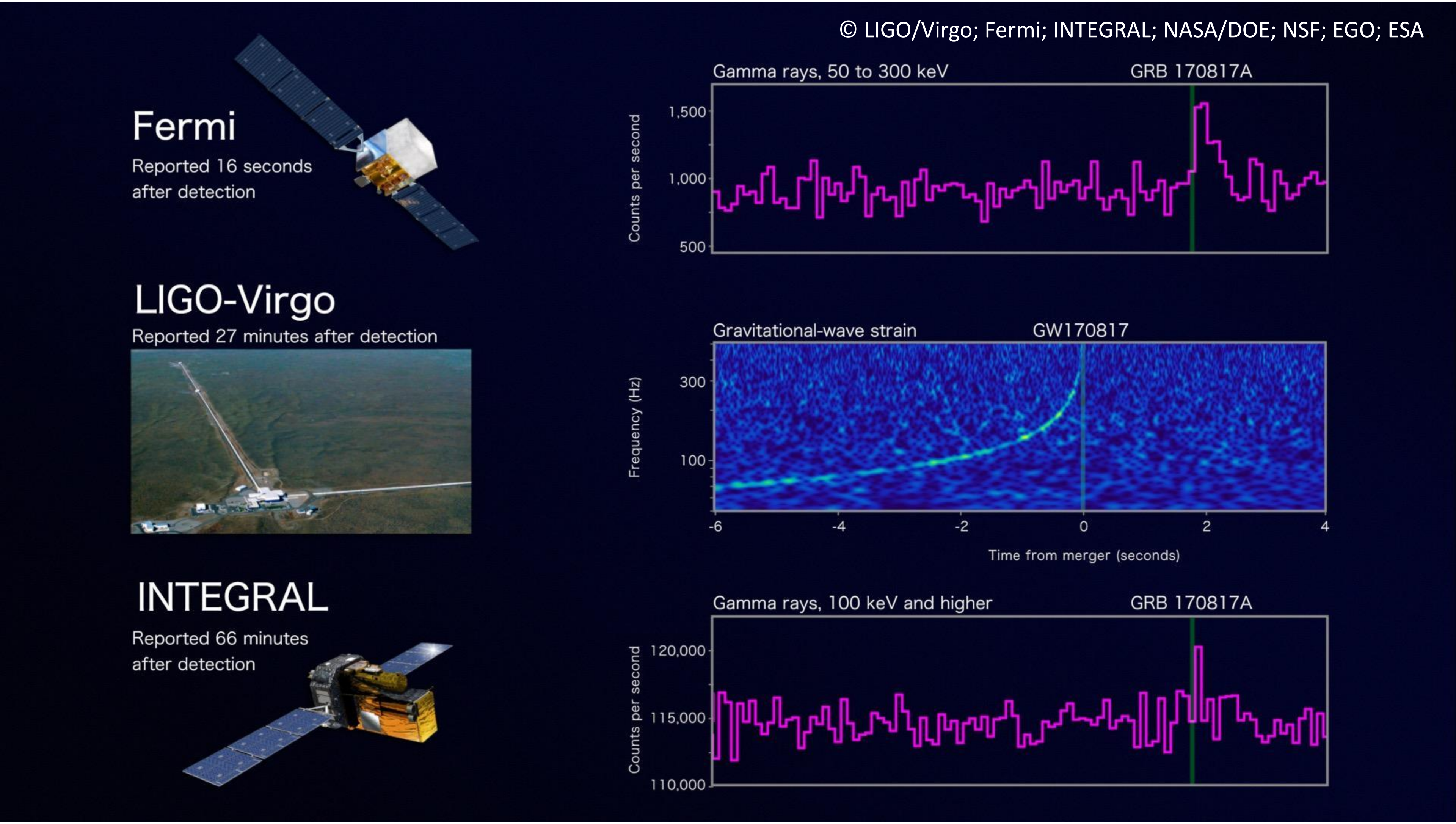
rigorous confirmation needs

gravitational waves



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

GRB 170817A



© LIGO/Virgo; Fermi; INTEGRAL; NASA/DOE; NSF; EGO; ESA
Fermi
Reported 16 seconds after detection
LIGO-Virgo
Reported 27 minutes after detection
INTEGRAL
Reported 66 minutes after detection
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)
Gamma rays, 100 keV and higher
GRB 170817A
Counts per second
120,000
115,000
110,000

The difference of speeds in GW/EM

Gravitational waves and gamma rays arrive
separated only by ~1.7s from ~40Mpc=4x10^15s

Timing difference $\Delta t = (D/v_{\mathrm{GW}}) - (D/v_{\mathrm{EM}})$
renders the velocity difference $\Delta v \coloneqq v_{\mathrm{GW}} - v_{\mathrm{EM}}$

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq 7 \times 10^{-16}$$

if the difference at the source is [0:10]s (model!)

 - multiple events will alleviate model dependence

Dispersion relation

Propagation of electromagnetic waves (in a suitable gauge) is governed by the spacetime metric as

$$\eta^{\mu\nu}\partial_\mu\partial_\nu A_\alpha = 0$$

Gravitational waves $h_{\alpha\beta}$ must obey the same causal structure, so that

$$\hat{g}^{\mu\nu}\partial_\mu\partial_\nu h_{\alpha\beta} = 0$$

with $\hat{g}^{\mu\nu} = \Omega^2\eta^{\mu\nu}$, no correction such as $\nabla^\mu\phi\nabla^\nu\phi$

This is not usually assuring for modified theory of gravity with higher derivatives of scalar fields

Constraint on modified gravity

Various theories are now regarded as rejected

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

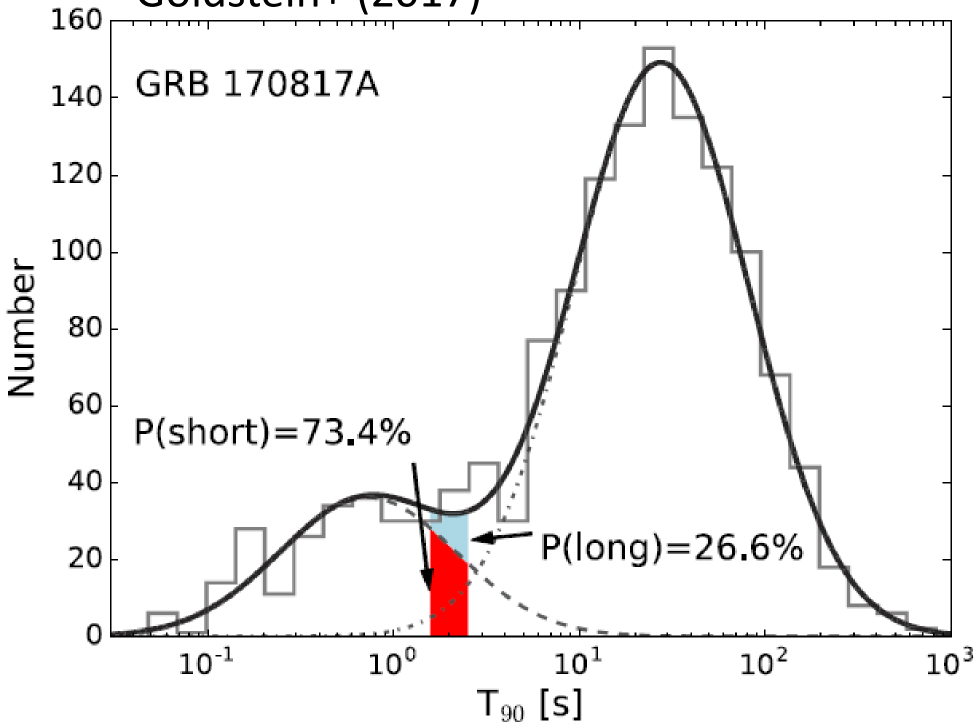
Ezquiaga-Zumalacarregui (2017)

Scenario confirmation

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

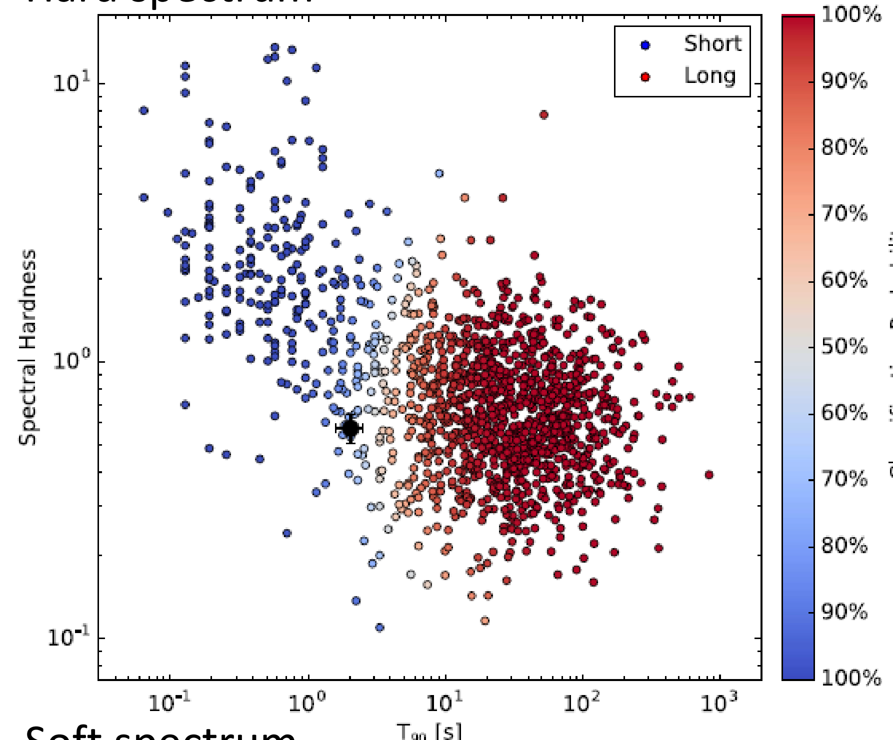
-> Binary neutron stars drive some short GRBs!

Goldstein+ (2017)



Duration of emission

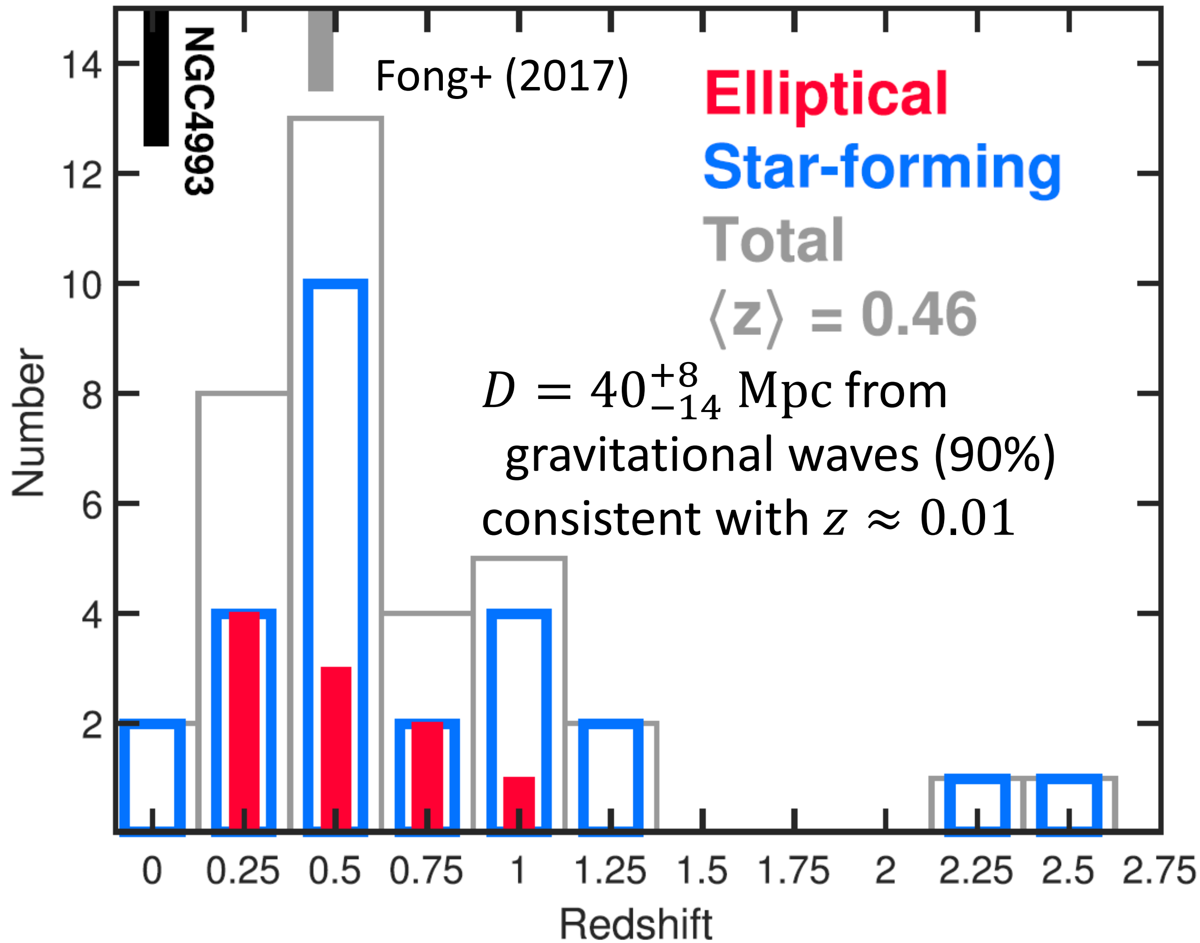
Hard spectrum



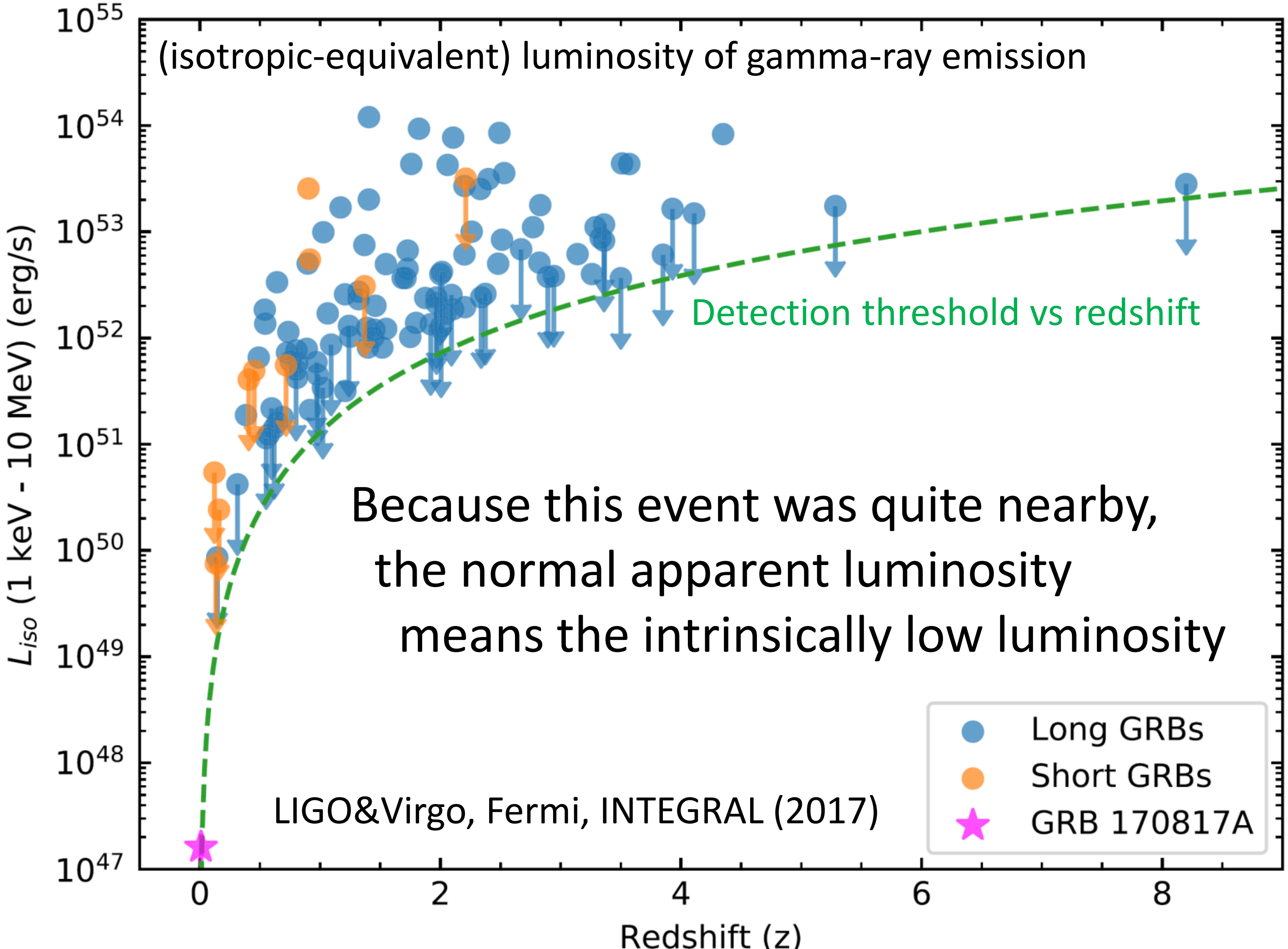
Soft spectrum

The closest short gamma-ray burst

Among the short GRBs with measured redshifts

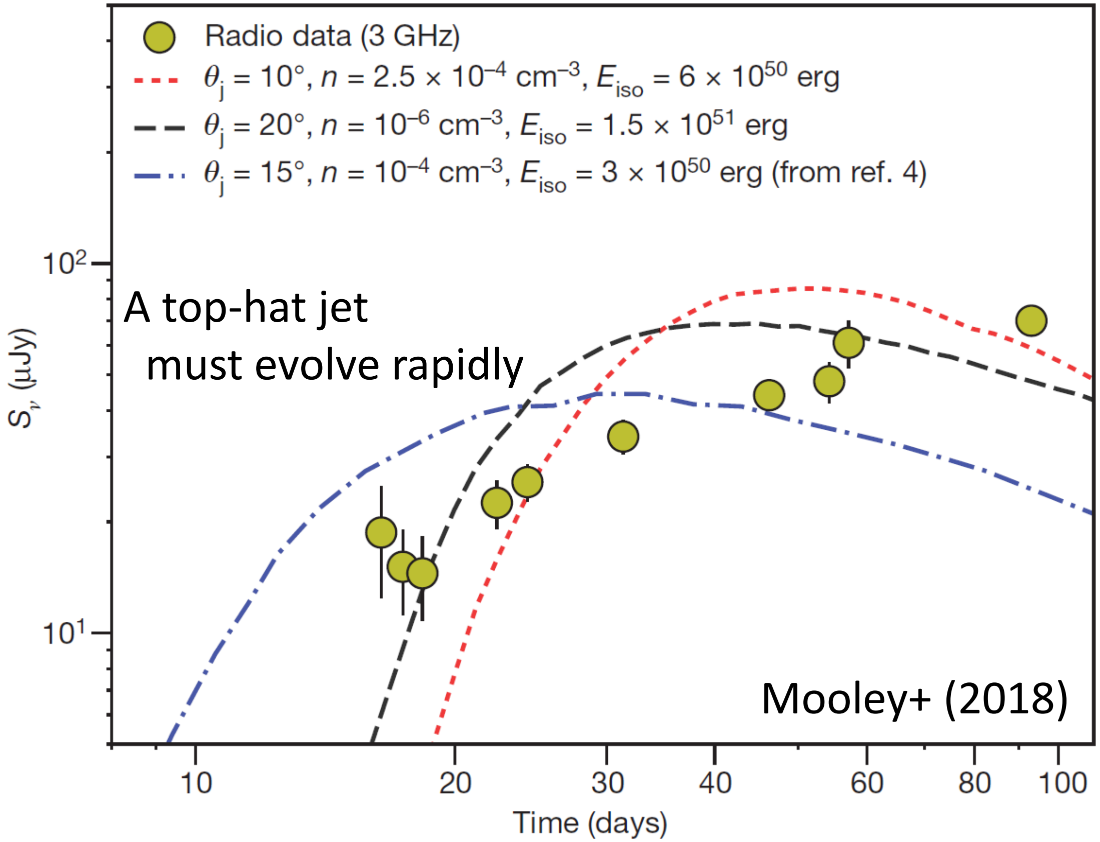


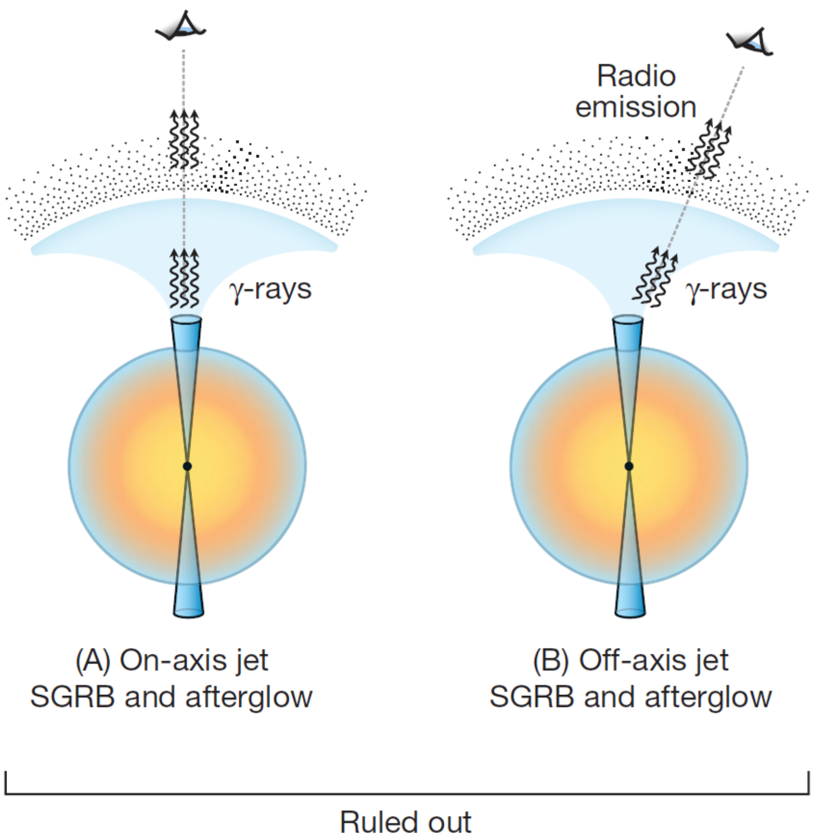
Underluminous...



Brightening of the afterglow

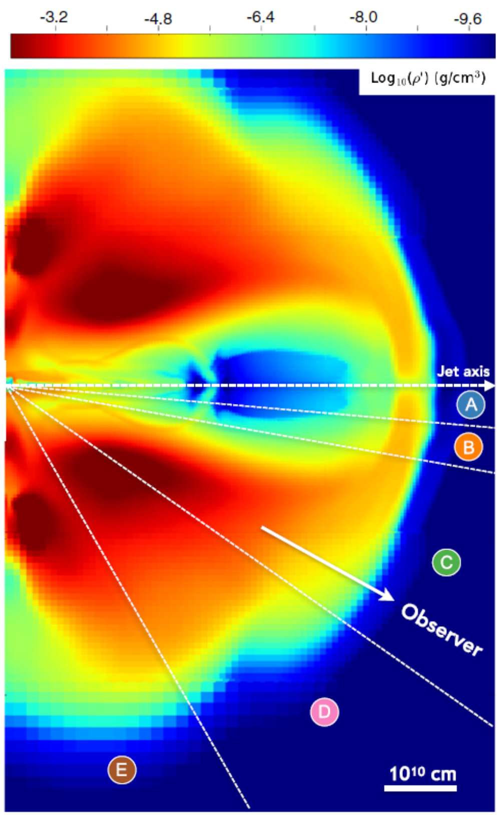
An off-axis jet is a good candidate, but an ultra-relativistic top-hat jet is rejected (for any angle)

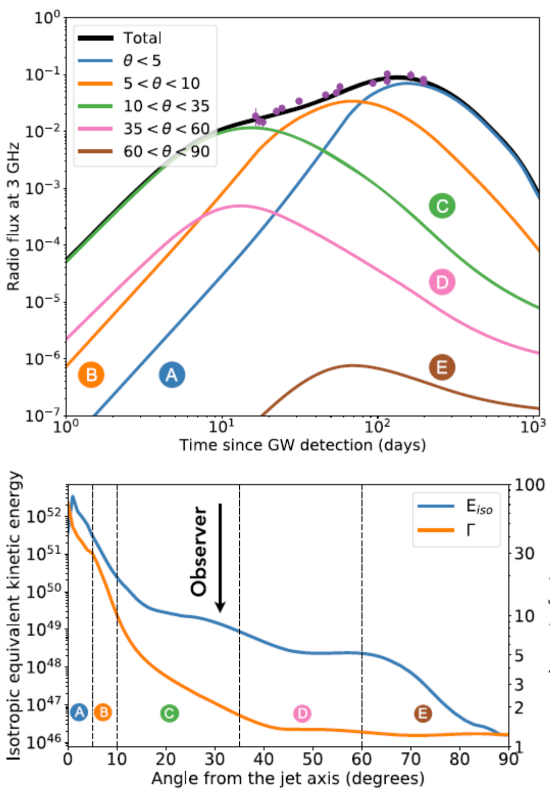


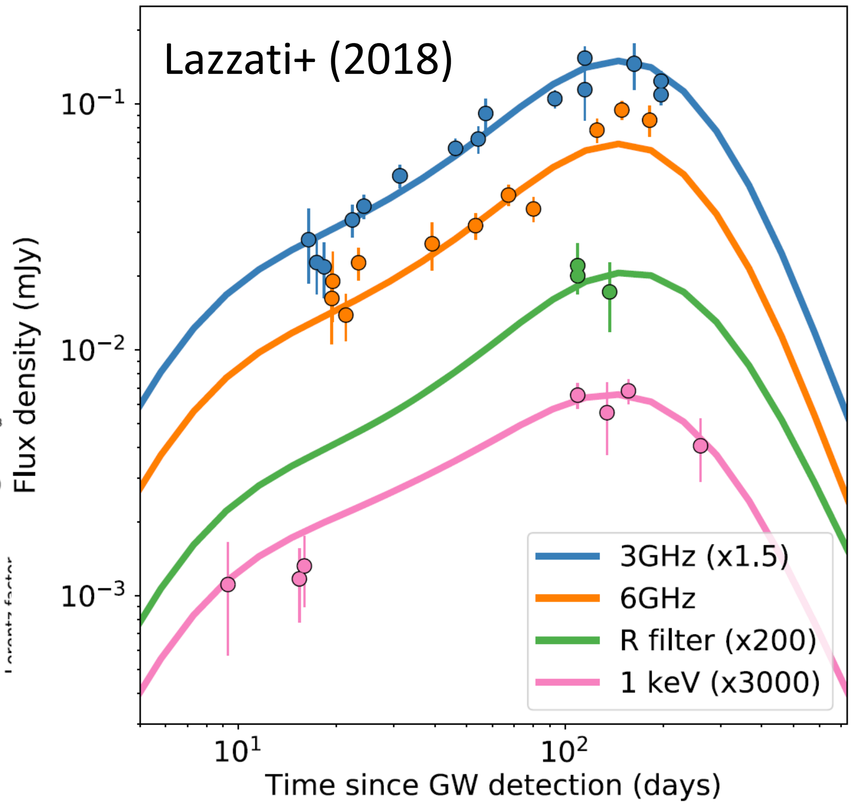


Structured jet

The jet of gamma-ray bursts is not very simple but is associated with a non-trivial angular structure



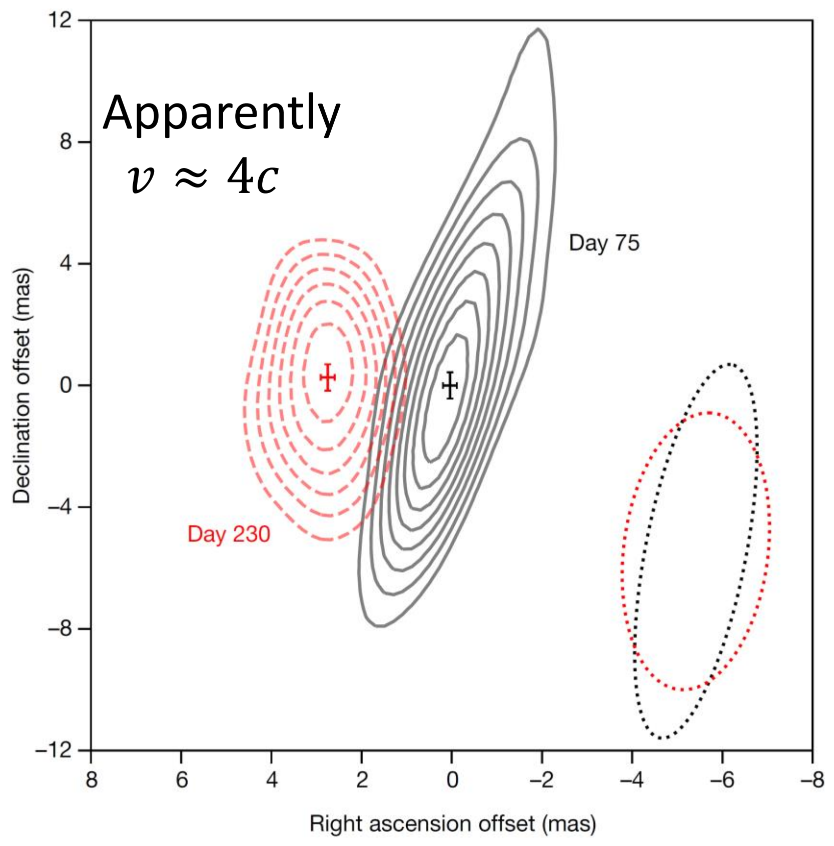




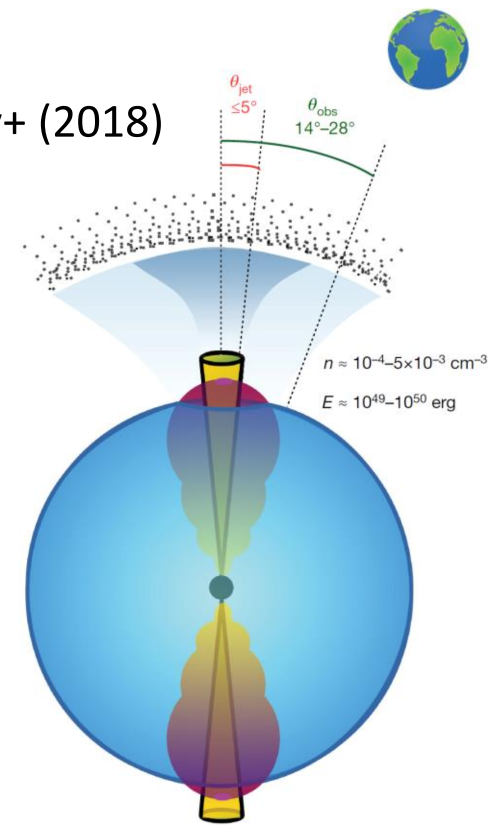
Superluminal motion

Radio VLBI resolved material moving with $\Gamma \approx 4$

Evidence of a jet! But $\Gamma > 30$ is not yet confirmed



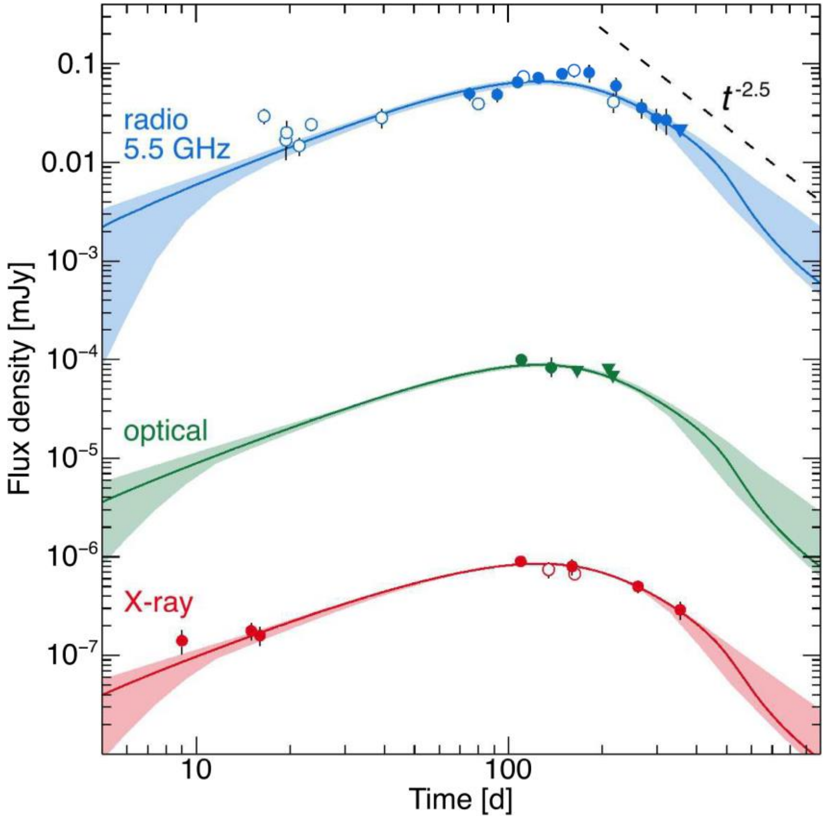
Mooley+ (2018)

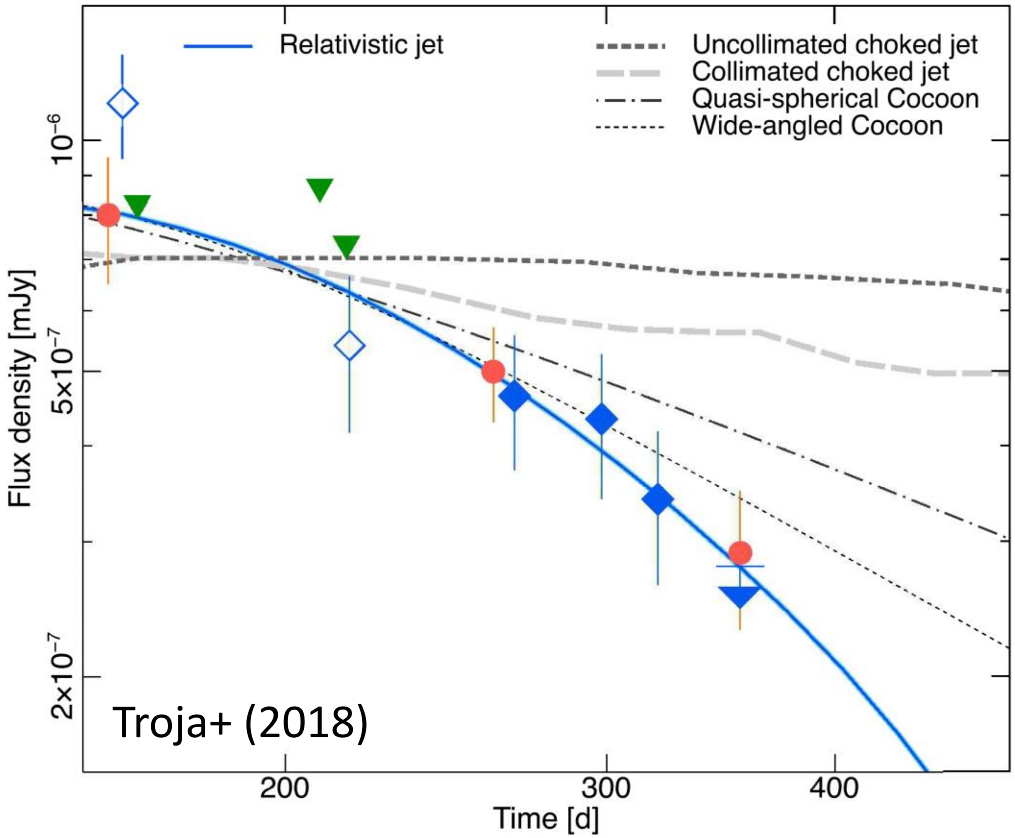


Peak and decline of the luminosity

Decline after the peak is not very slow: jet-like

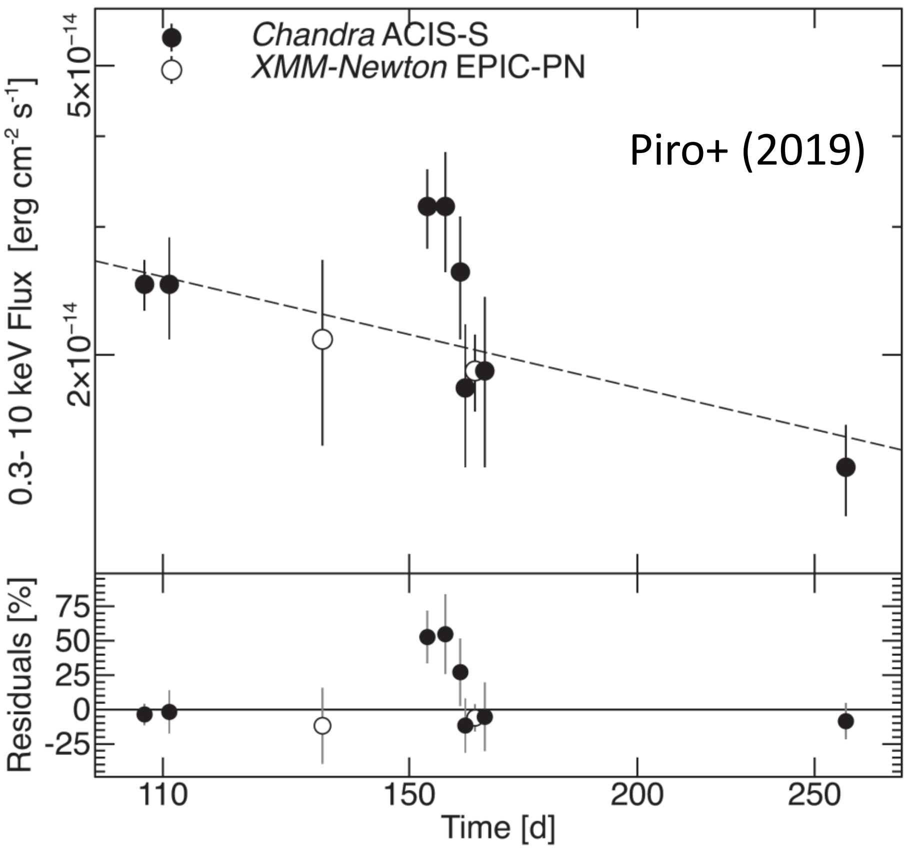
This does not fit with quasispherical cocoon models

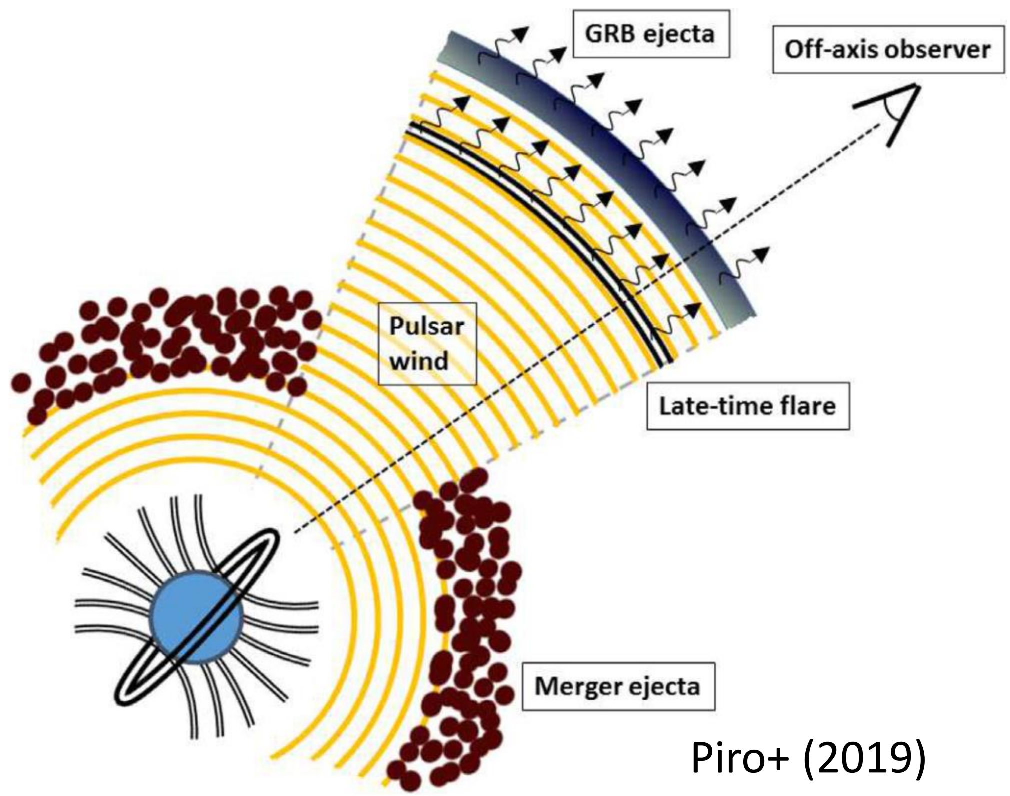




Late-time X-ray flare?

Was the remnant a magnetar w/ ~160day lifetime?
Very important to understand the central engine



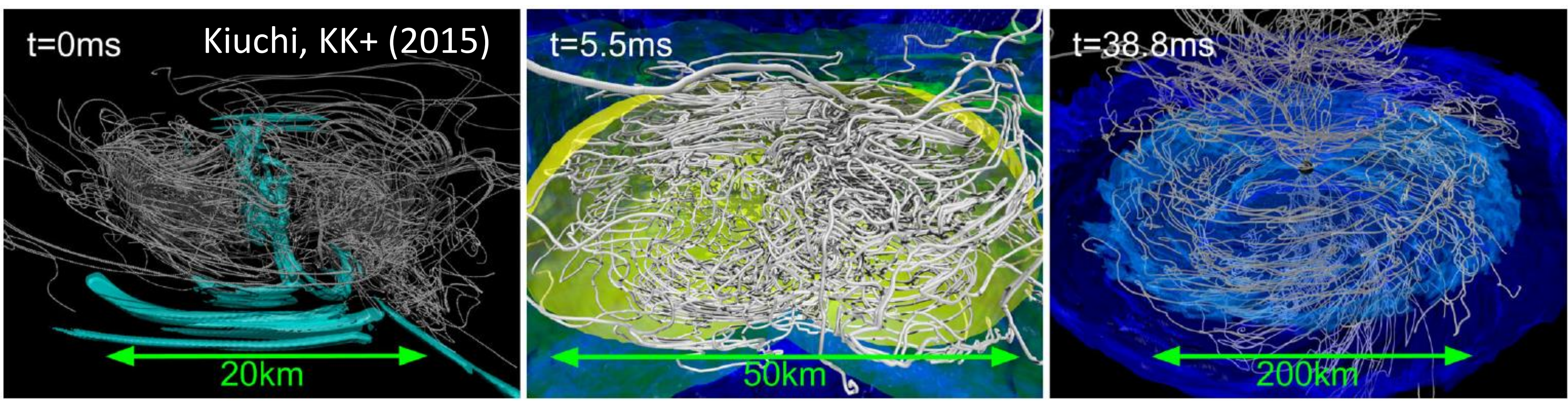


Piro+ (2019)

Magnetic-field amplification

Hydrodynamic and magneto-hydrodynamic instabilities amplify the magnetic field to 10^17G

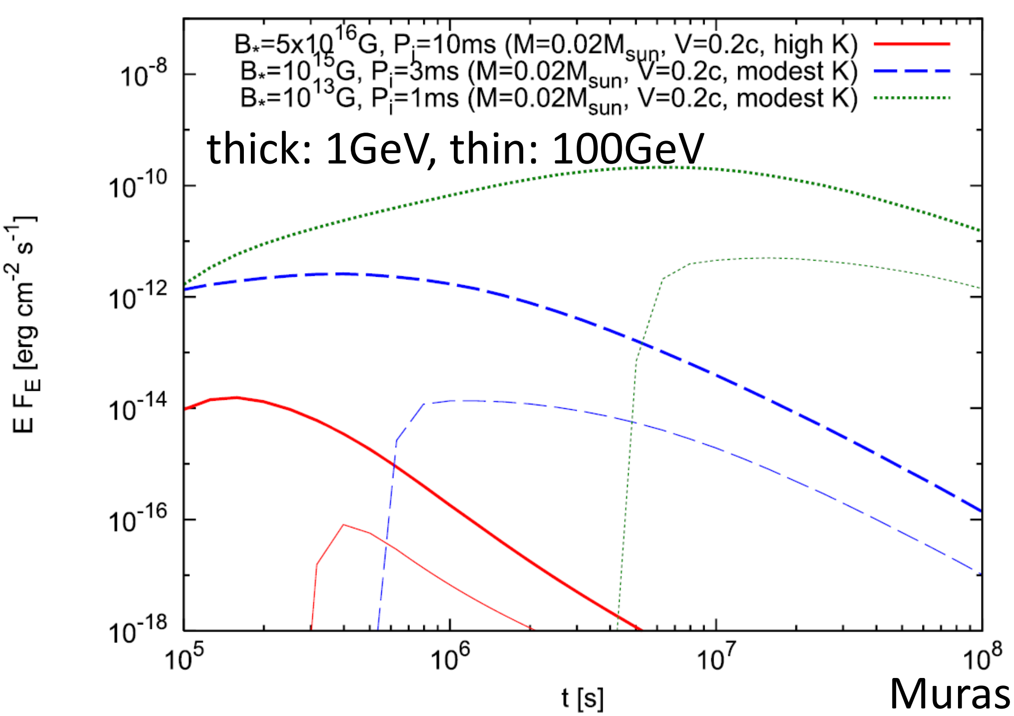
- Kelvin-Helmholtz instability at the contact surface
- winding and magneto-rotational instability



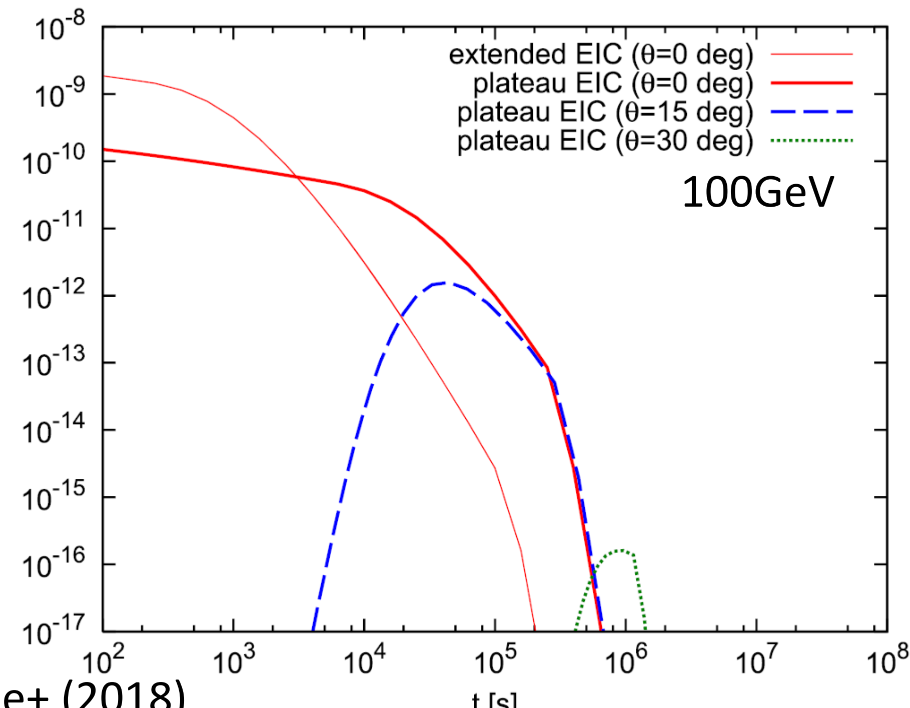
GeV-TeV gamma-ray emission

A central engine or late-time GRB activity may give us a chance of detecting ~100GeV gamma rays

magnetar case



on-axis GRB case



Murase+ (2018)

Dark age of binary neutron star merger

What is ongoing in

the 1.7s delay between

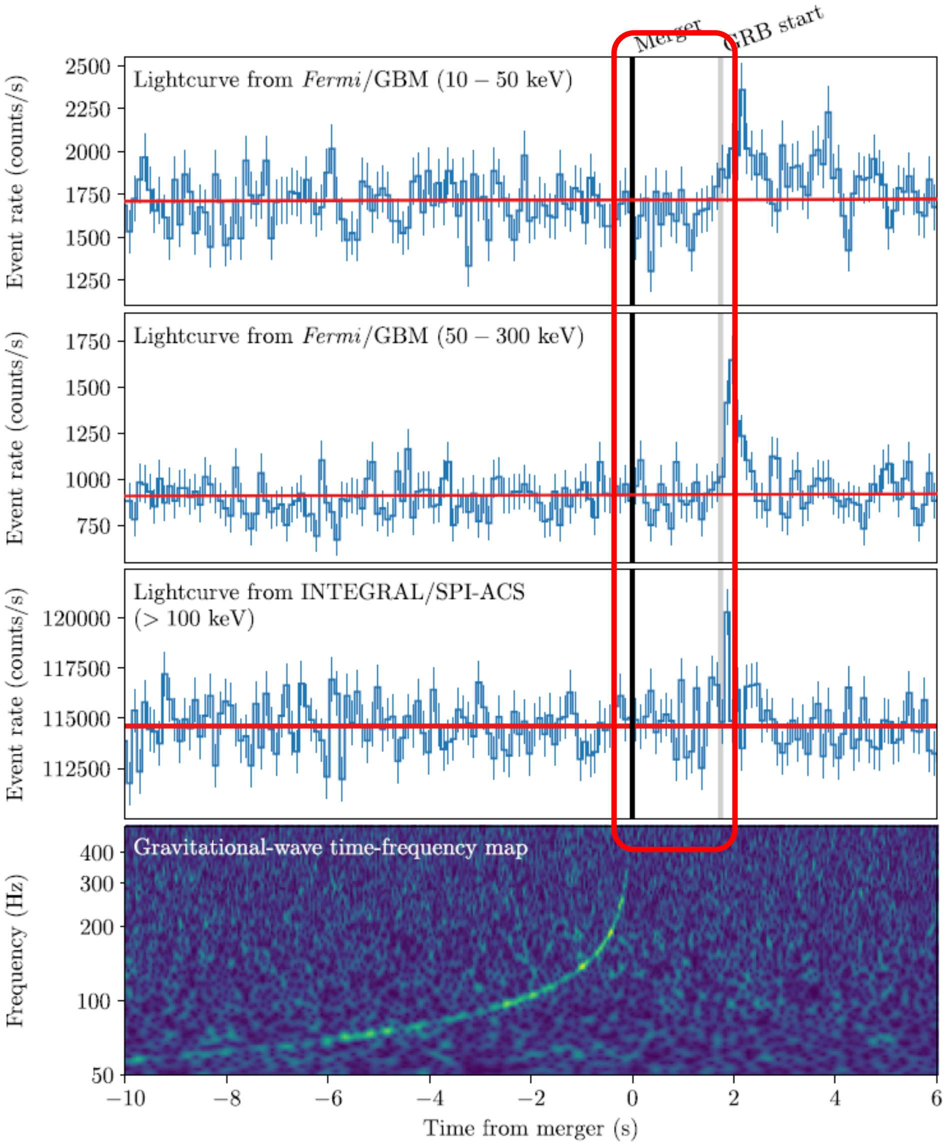
gravitational waves

and gamma rays?

- black hole formation?
- magnetar?

Only neutrinos could be

possible messengers

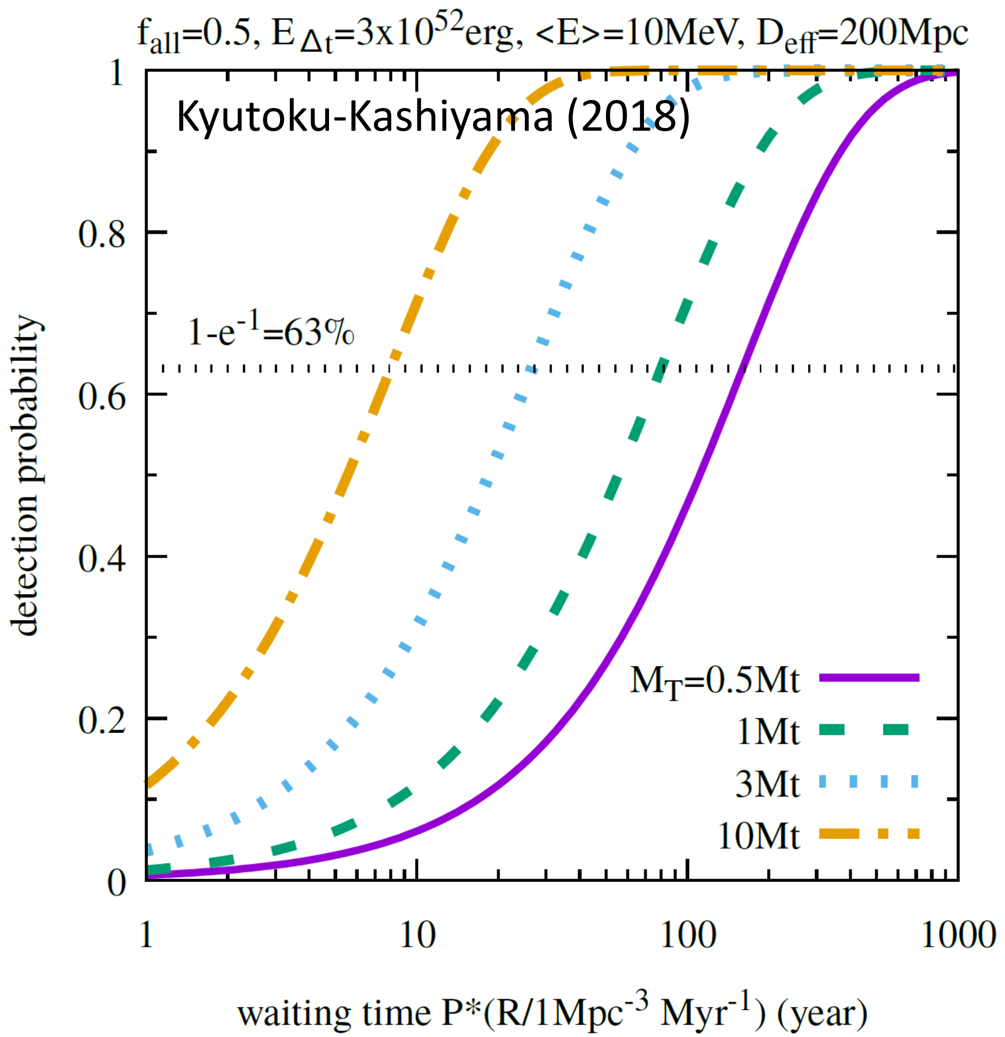


Waiting time for MeV neutrinos

Once (=one neutrino!) in 50-80 years with Mt-class detectors such as Hyper-K

If the remnant does not collapse to a black hole

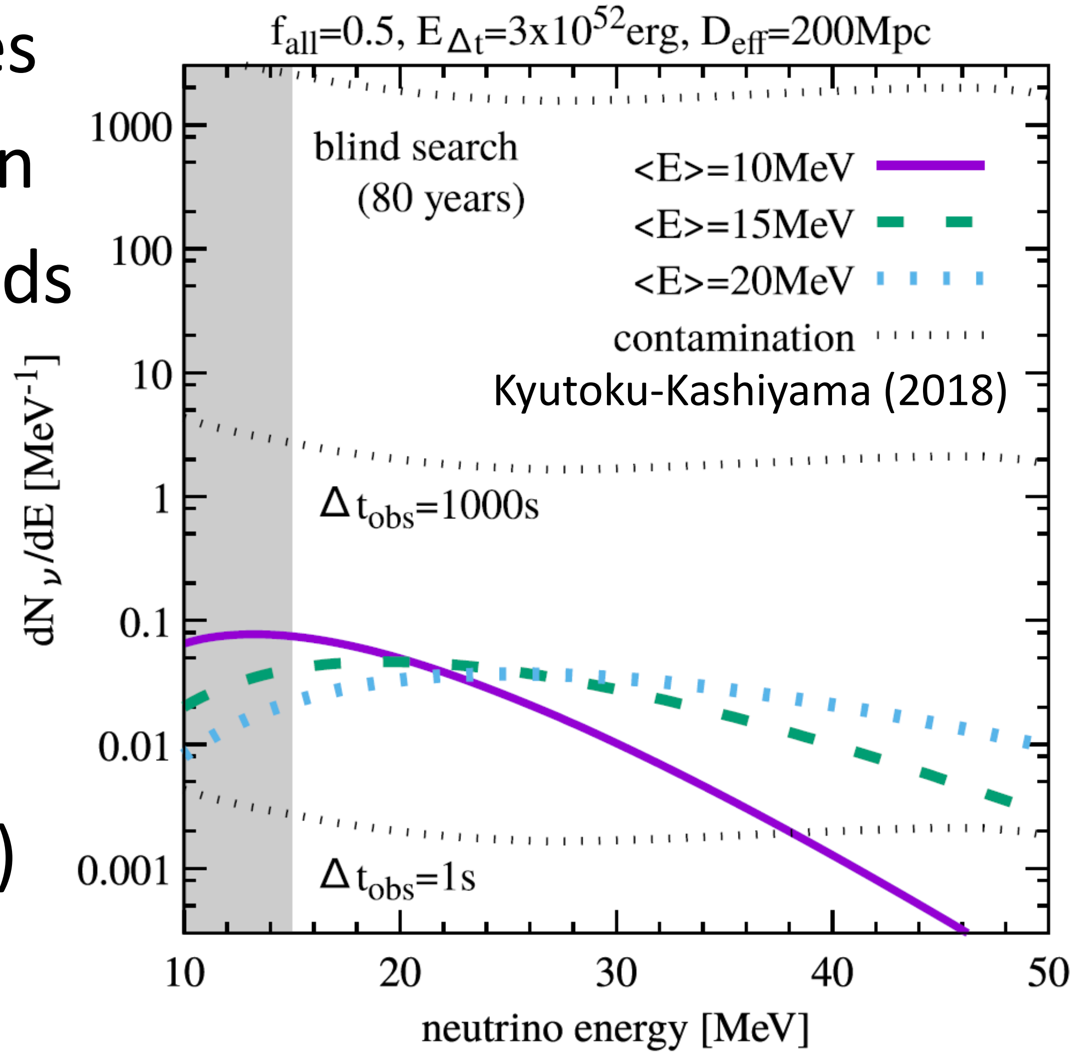
<-> 1 in 30-100 years of Galactic supernovae



Struggle with the background

Neutrinos from binaries are easily embedded in supernova backgrounds and other sources

Our message: analyze only ~1s from the merger time (GW)



Possible neutrino mass measurement

By using the time delay of neutrinos from GWs

$$m_\nu < 44\mathrm{meV}\left(\frac{\Delta t}{0.1\mathrm{s}}\right)^{1/2}\left(\frac{E}{10\mathrm{MeV}}\right)\left(\frac{D}{100\mathrm{Mpc}}\right)^{-1}$$

- $\Delta m_{21}^2 = 8 \times 10^{-5}\mathrm{eV}^2 \sim (9\mathrm{meV})^2$
- $\left|\Delta m_{31}^2\right| = 2.4 \times 10^{-3}\mathrm{eV}^2 \sim (50\mathrm{meV})^2$
- $\sum m < 0.1 - 0.2\mathrm{eV}$ from cosmology

KATRIN is aiming at directly measuring 200meV

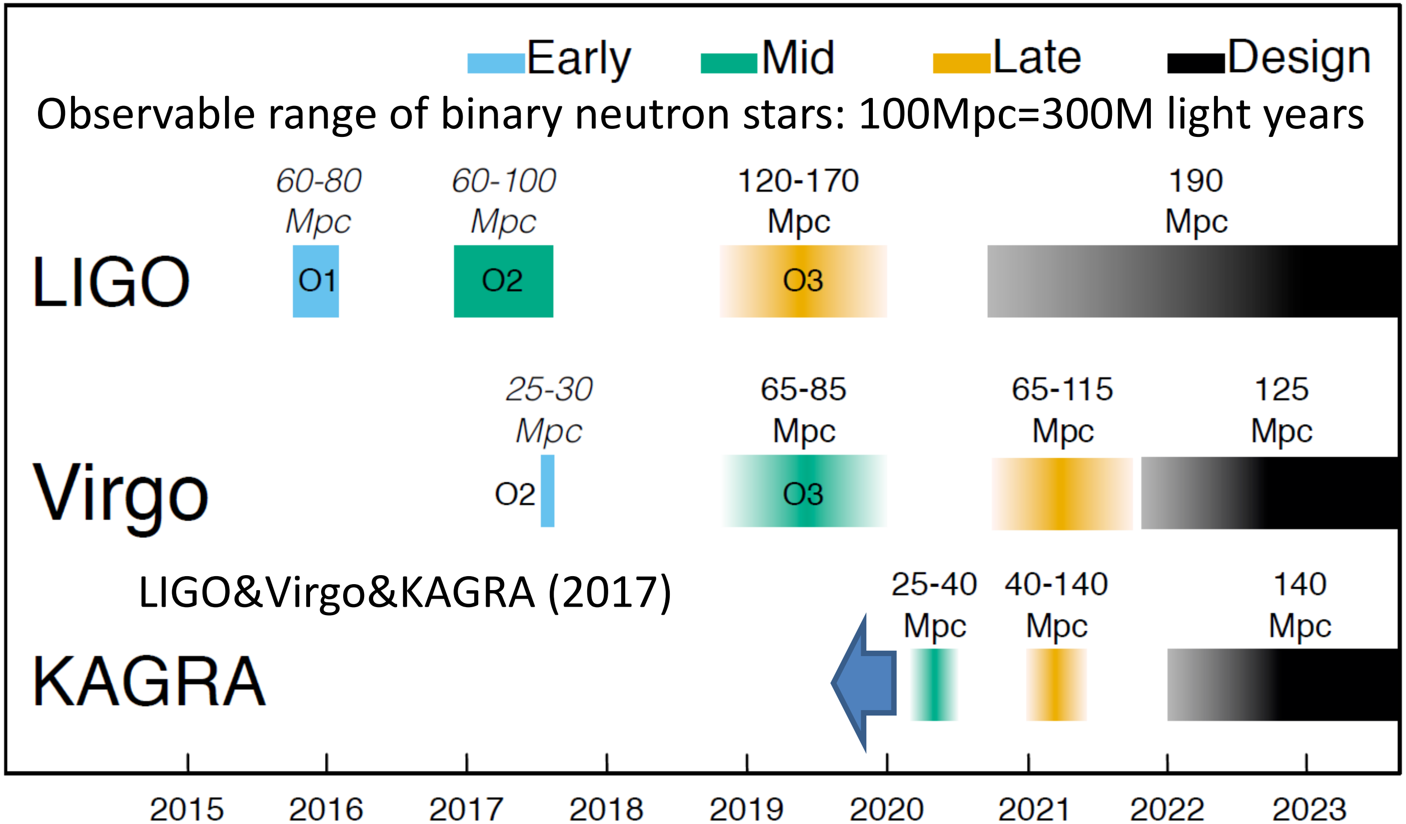
- but this comparison is not contemporaneous!

4. Future prospect and summary

Future observation

LIGO&Virgo resume observations from early 2019

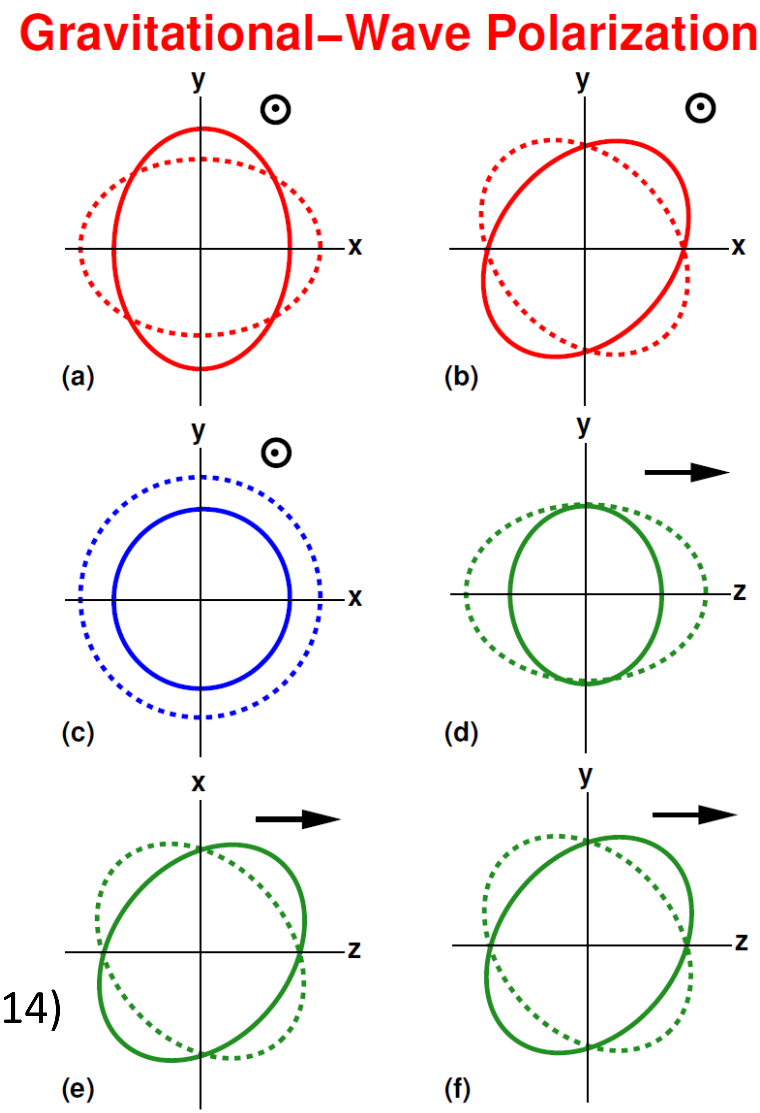
KAGRA would also join the observation in 2019



Polarization as a test of gravity

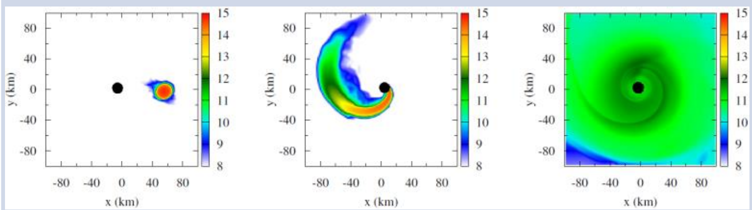
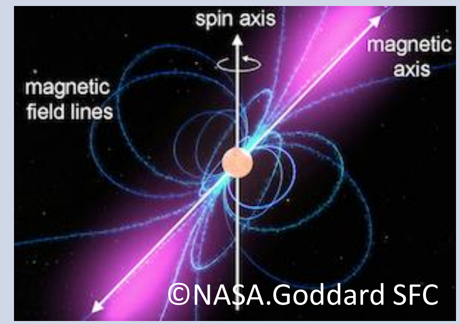
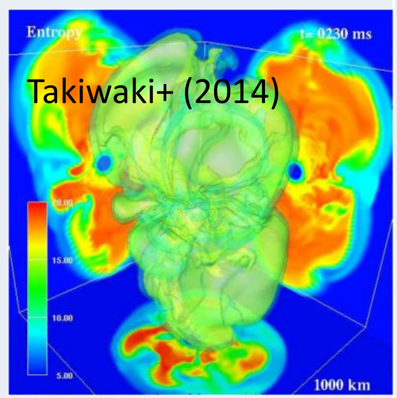
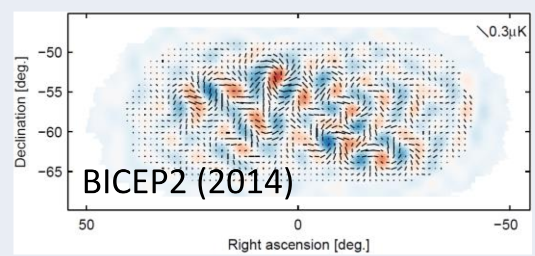
KAGRA will be important to investigate whether gravitational waves are really transverse as GR predicts

The number of available detectors determines the number of constraints



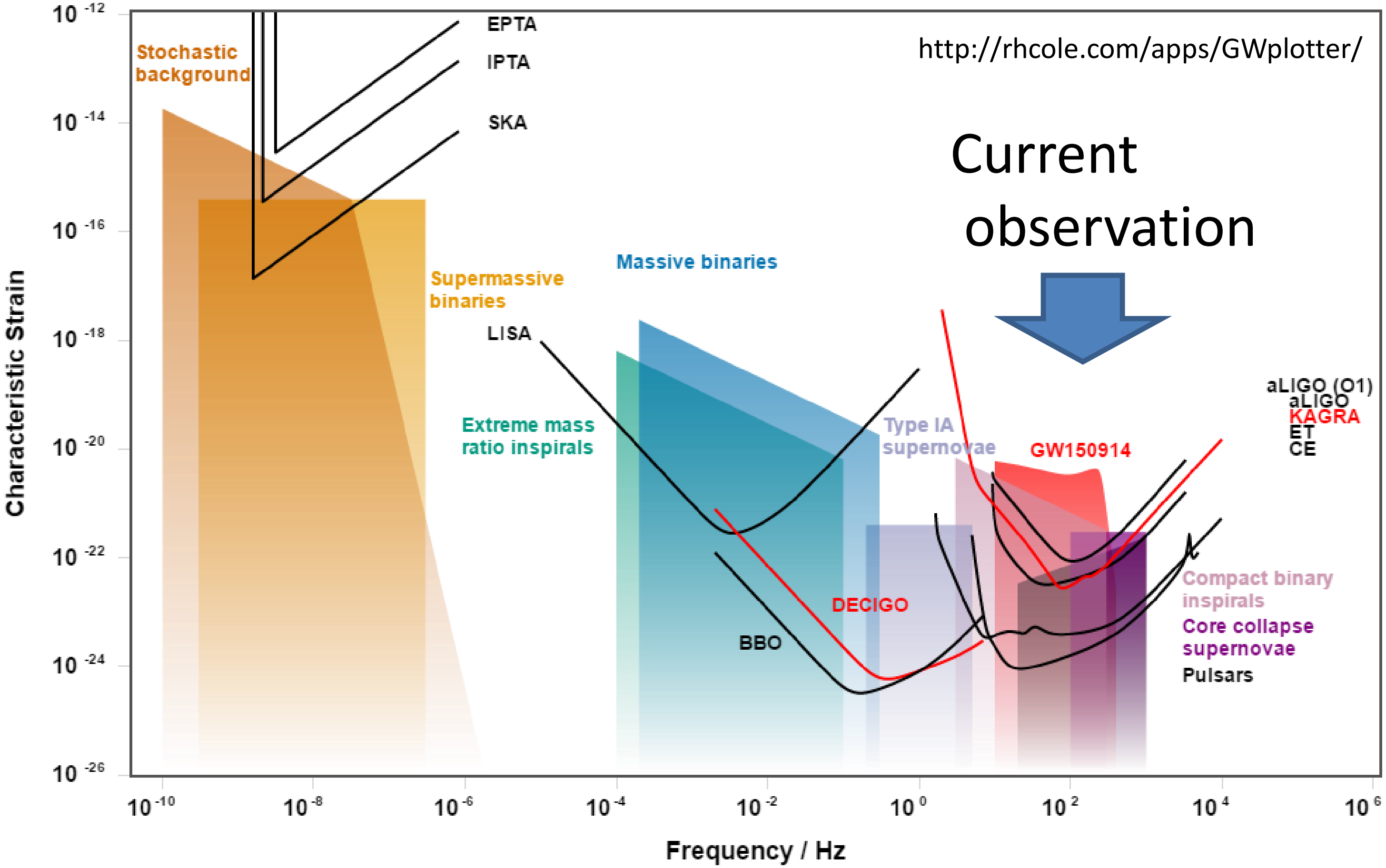
Will (2014)

Further gravitational-wave sources

	Transient	Persistent
Known waveform	inspiral: compact binaries BH-BH, BH-NS, NS-NS …  Kyutoku+ (2015)	continuous: deformed neutron stars  ©NASA.Goddard SFC
Unknown waveform	burst: supernova cosmic string …  Takiwaki+ (2014) unknown unknown?	stochastic: superposition of weak sources, inflation, phase transition…  BICEP2 (2014)

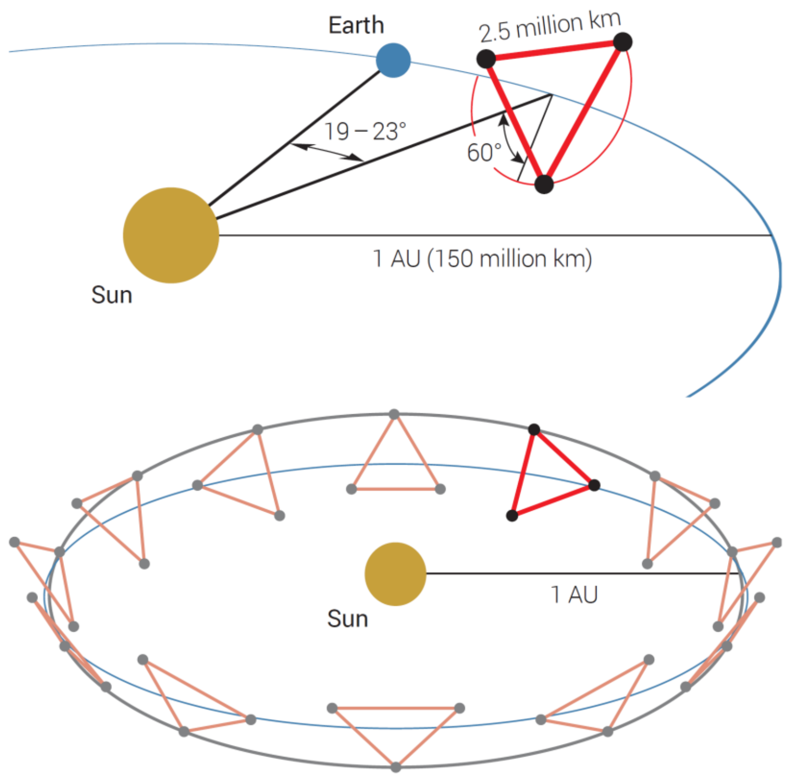
Multi-wavelength GW astronomy

May not be near, but the foreseeable future

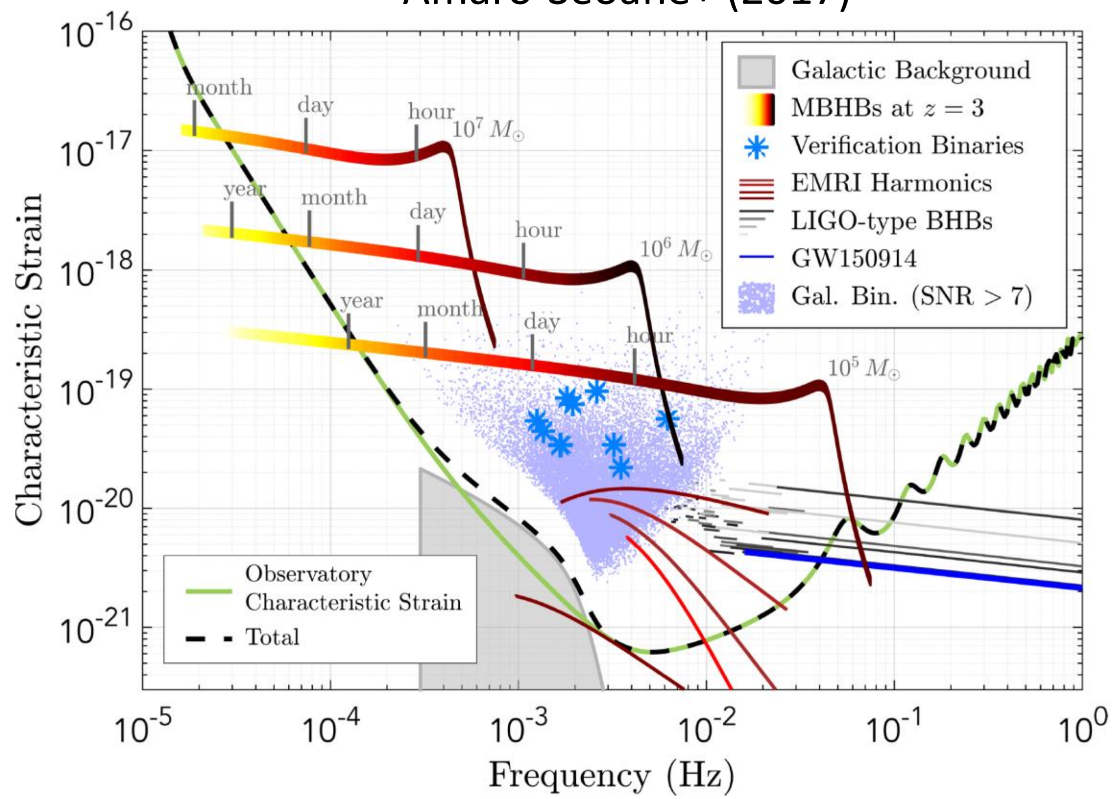


LISA

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



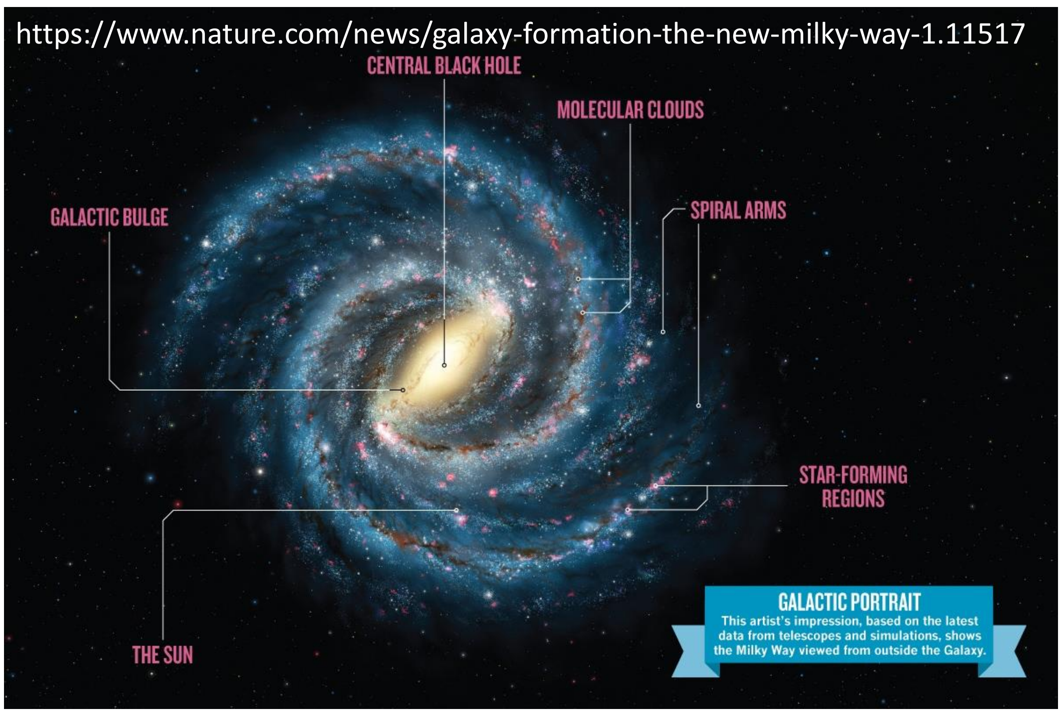
Amaro-Seoane+ (2017)

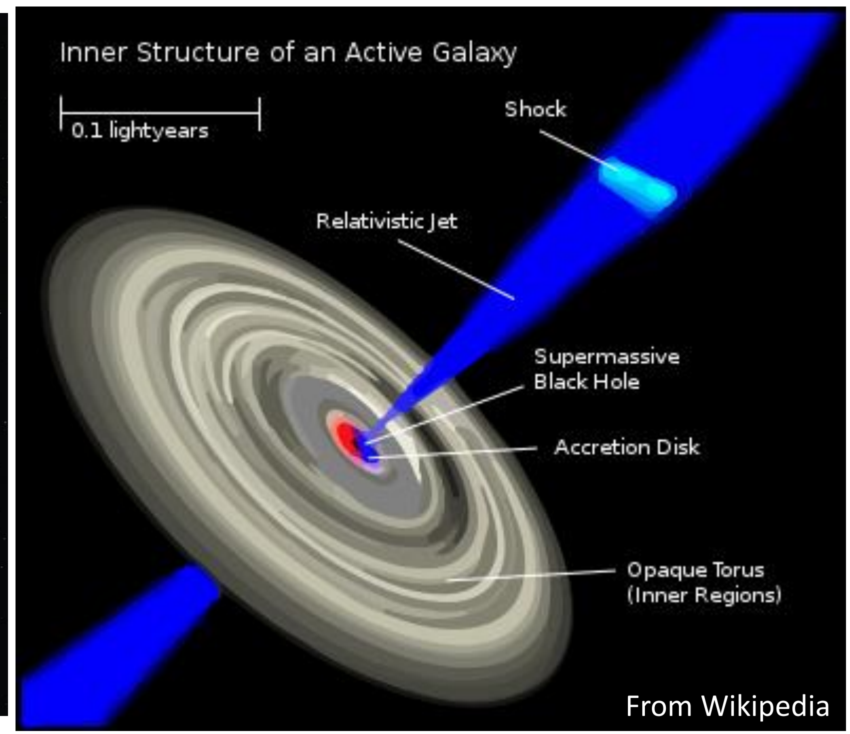


Supermassive black hole

Galaxies often host black holes with $10^6 - 10^9 M_\odot$ at their centers: How are they formed?

How did they affect evolution of galaxies/universe?

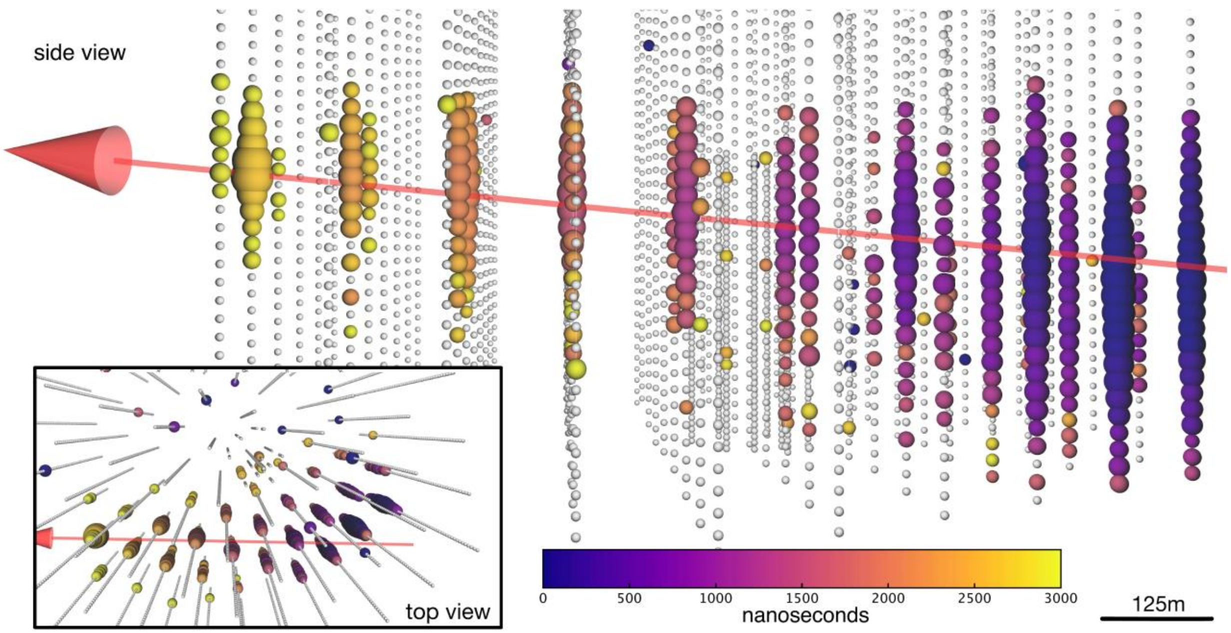


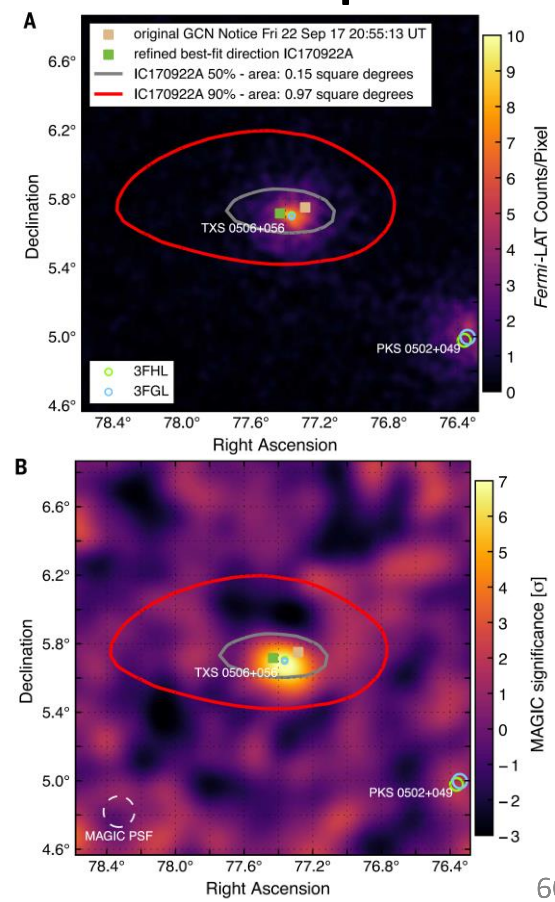


Toward all-messenger astronomy

Coincident neutrino and gamma-ray detections from a supermassive black hole have been reported

GW + neutrino + electromagnetc?





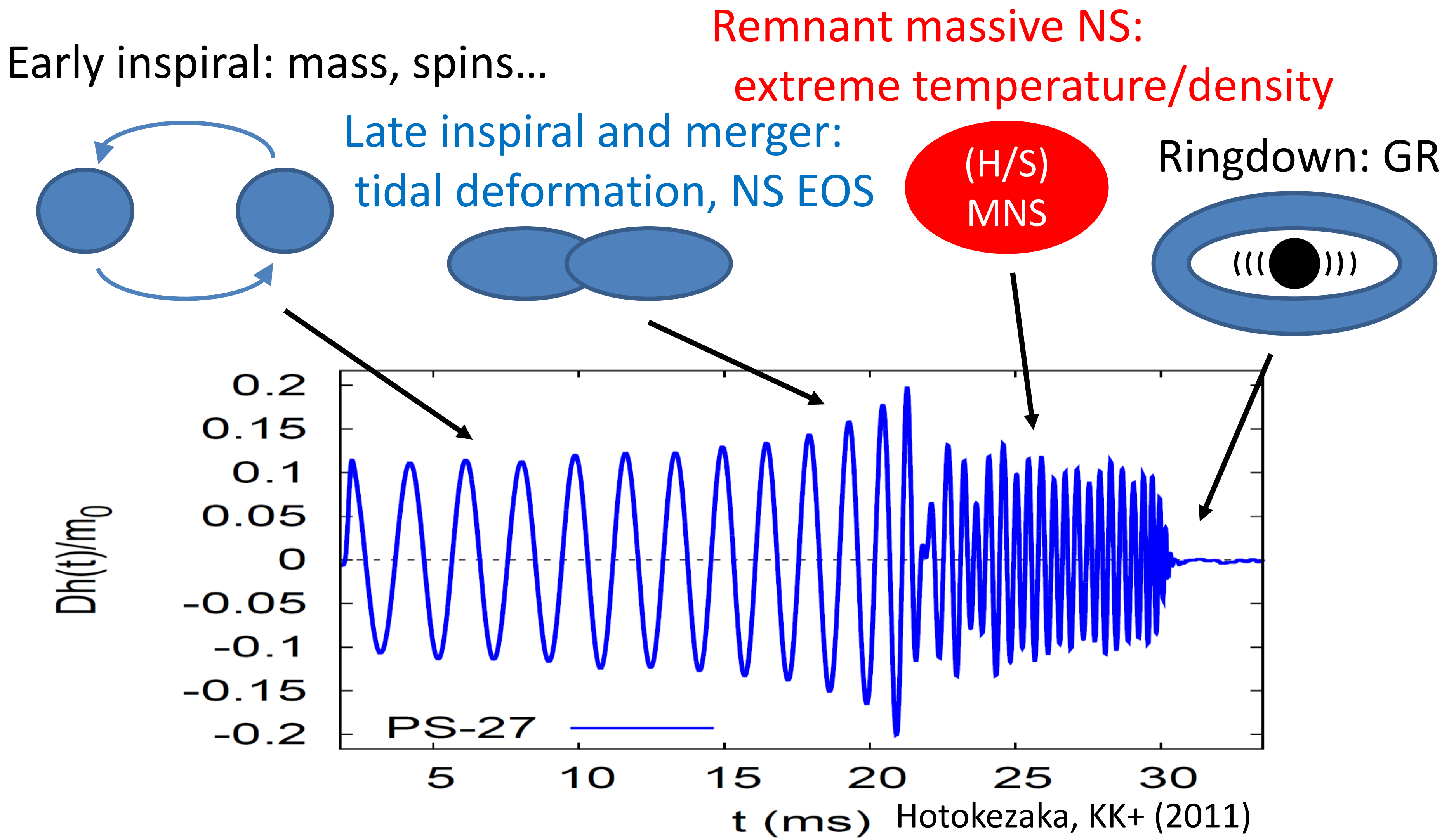
IceCube collaboration et al. (2018)

Summary

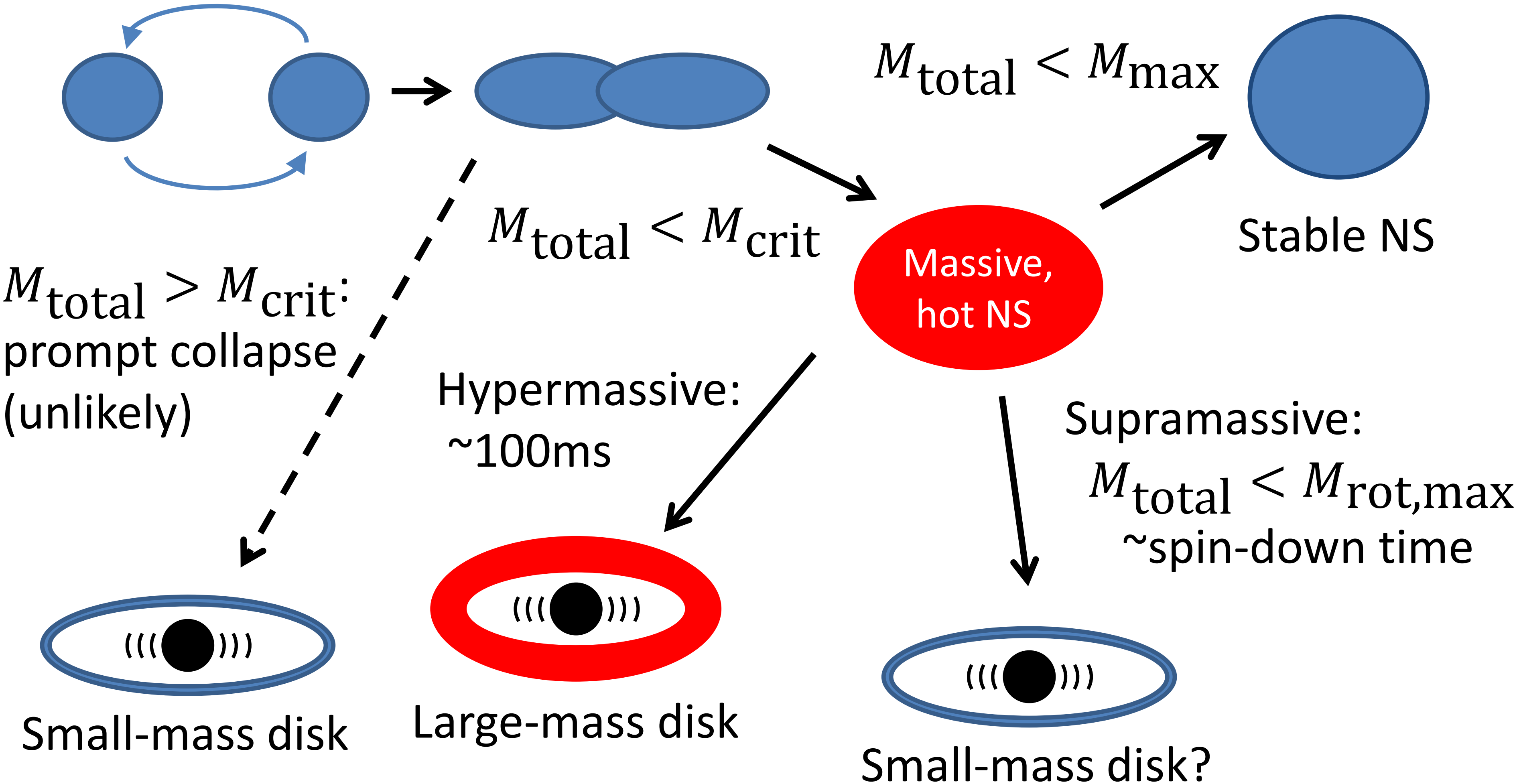
- Many gravitational-wave events are reported.
- A kilonova AT 2017gfo indicates the formation of lanthanides, but the presence of very heavy element such as Au and Pt is still debated.
- The reverse shock may be a poor accelerator.
- A short GRB 170817A indicates that the jet has a non-trivial angular structure.
- The central engine could be a magnetar, and it may be checked by gamma rays or neutrinos.

Appendix

Encoded physics



Merger dynamics of NS-NS



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

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

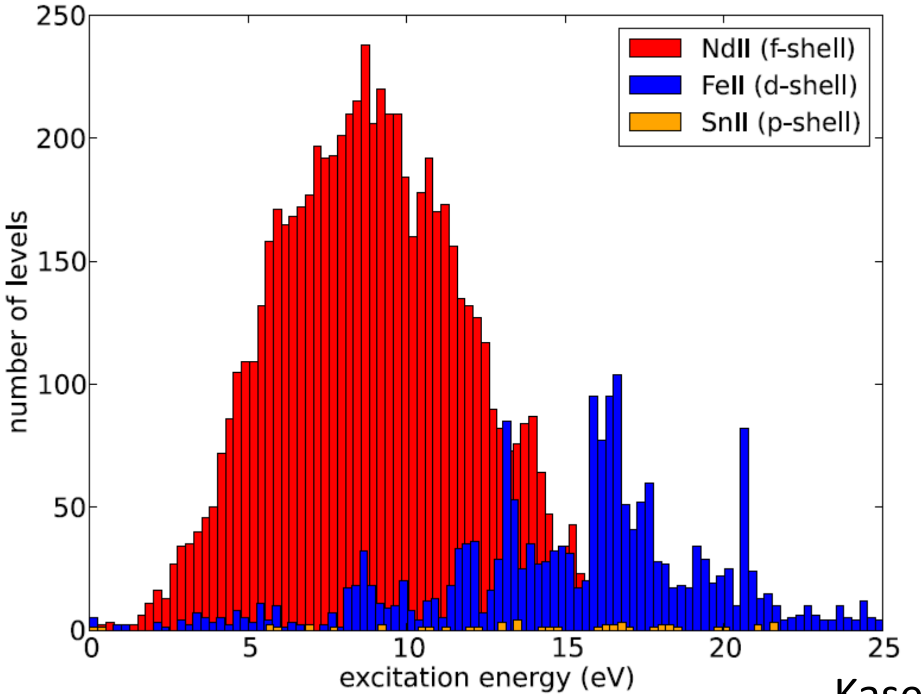
small mass and high velocity (vs supernovae)

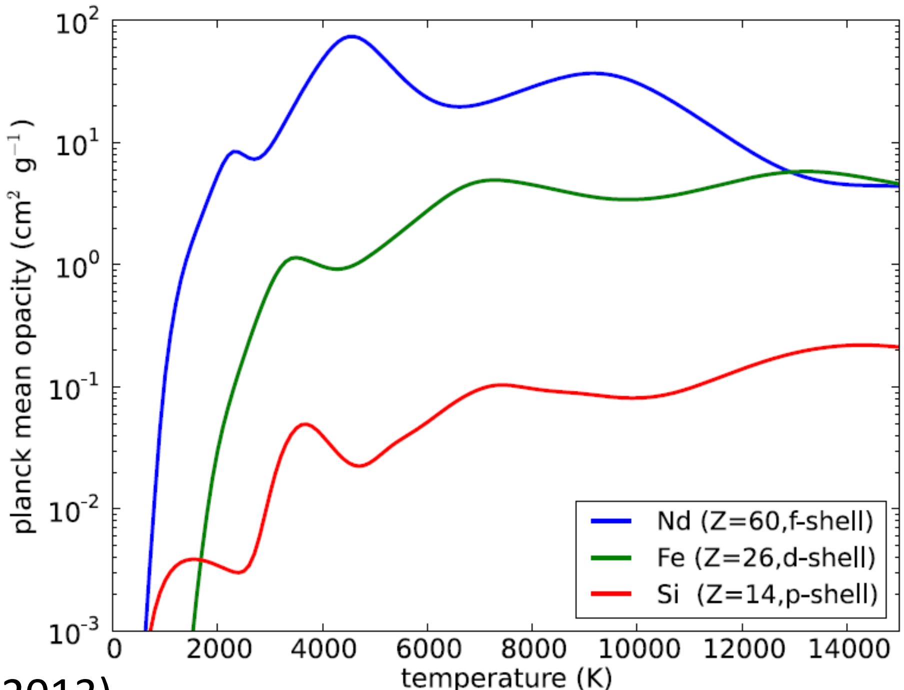
Too many lines of lanthanides

A bunch of energy levels -> complex line structures

-> very frequent interaction -> very high opacity

Especially, lanthanides are very opaque to photons





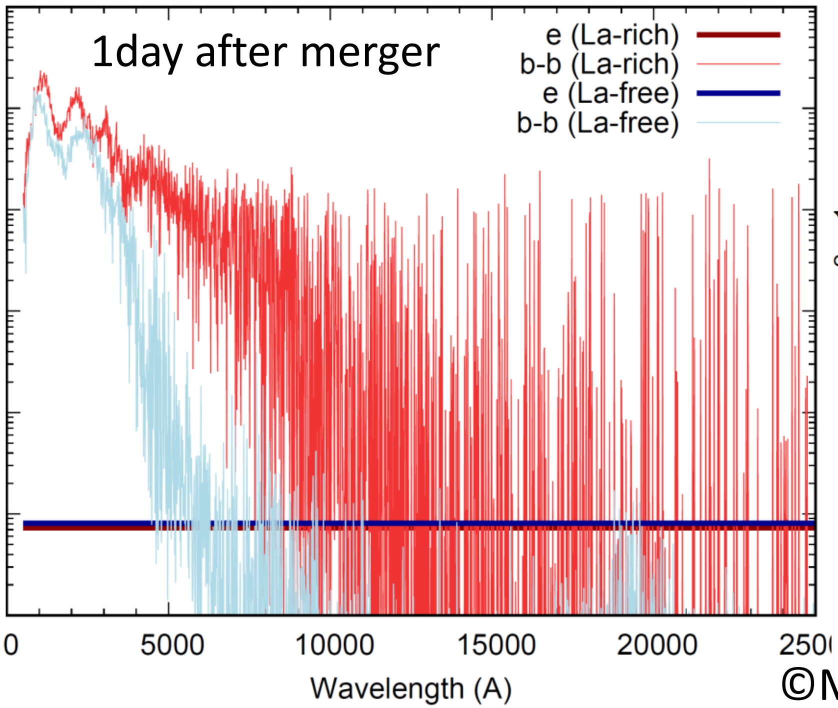
Kasen+ (2013)

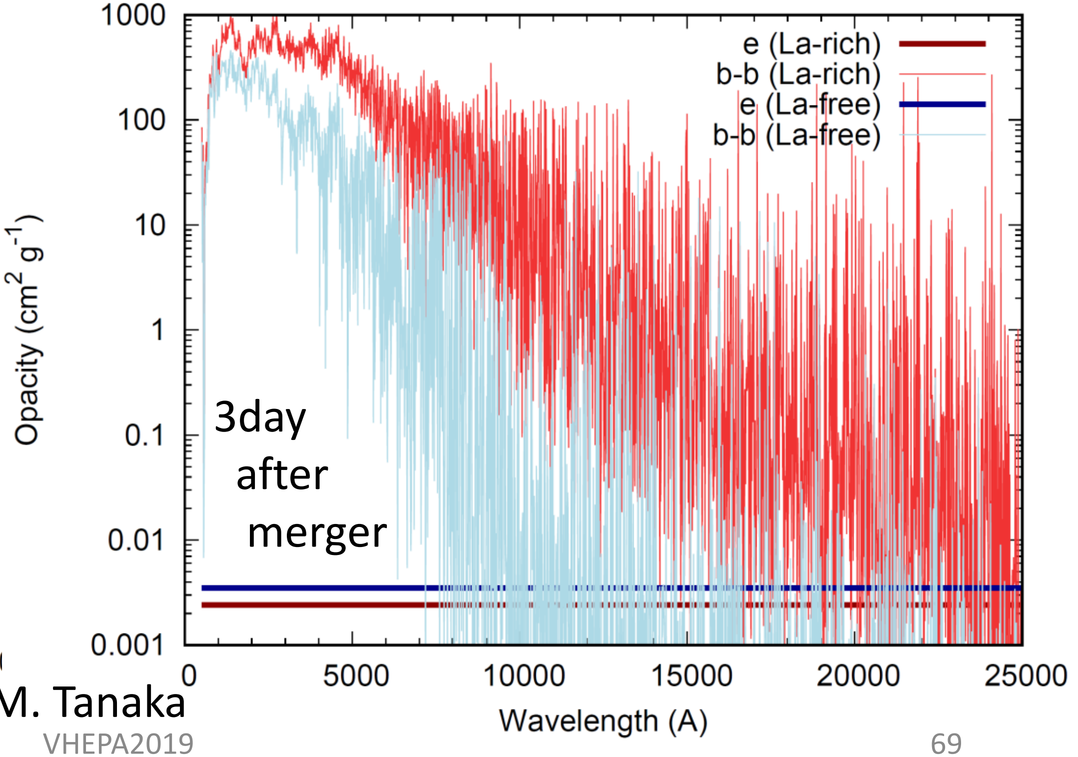
Opacity is not simple

Wavelength dependent: low at infrared

Epoch dependent: low at a hot and ionized state

Composition dependent: low at lanthanide-free





©M. Tanaka

Uniqueness as an optical transient

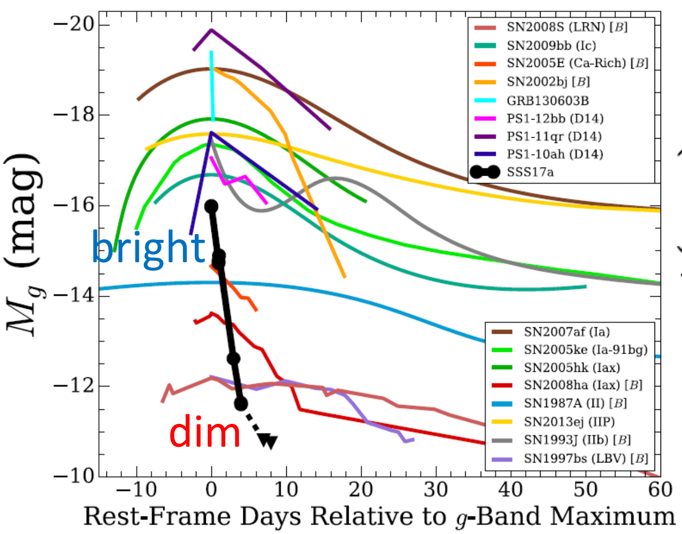
Consistent (only) with the kilonova

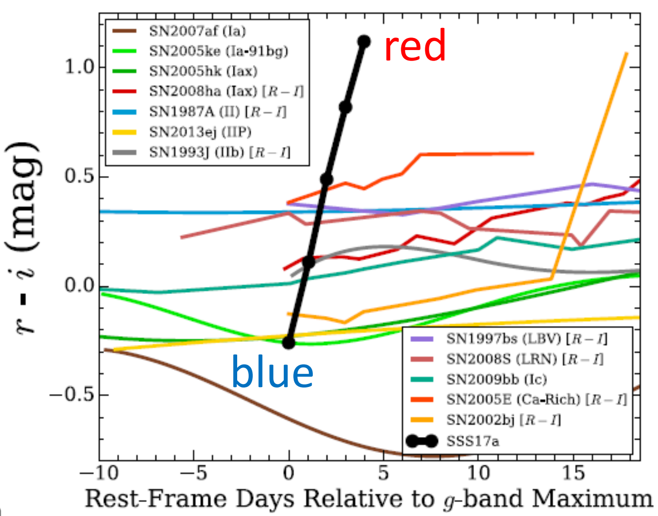
Black (SSS17a=AT 2017gfo): this event

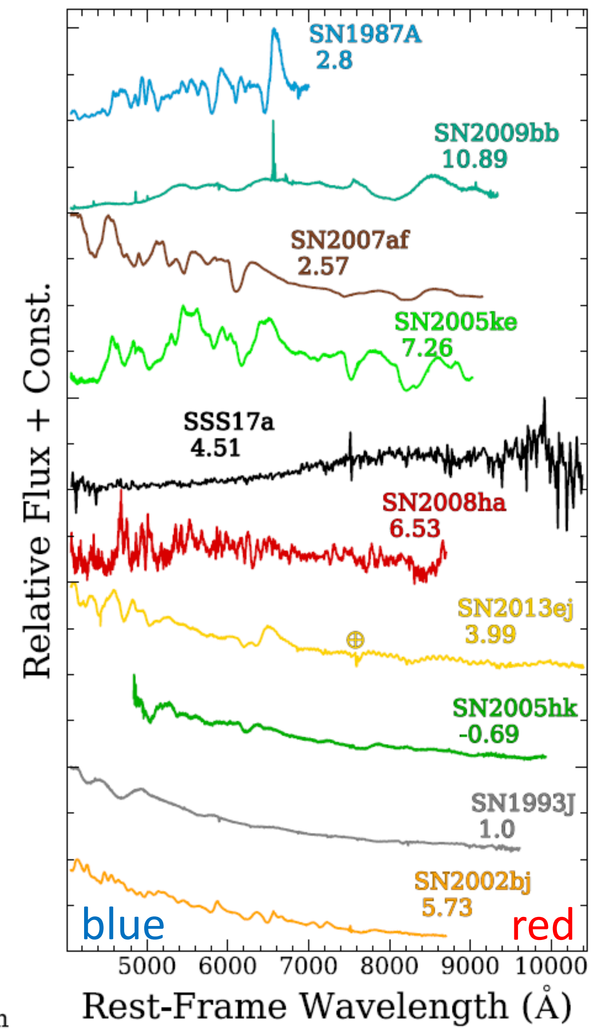
Colored: other known transients

featureless red spectrum

rapid dimming and reddening

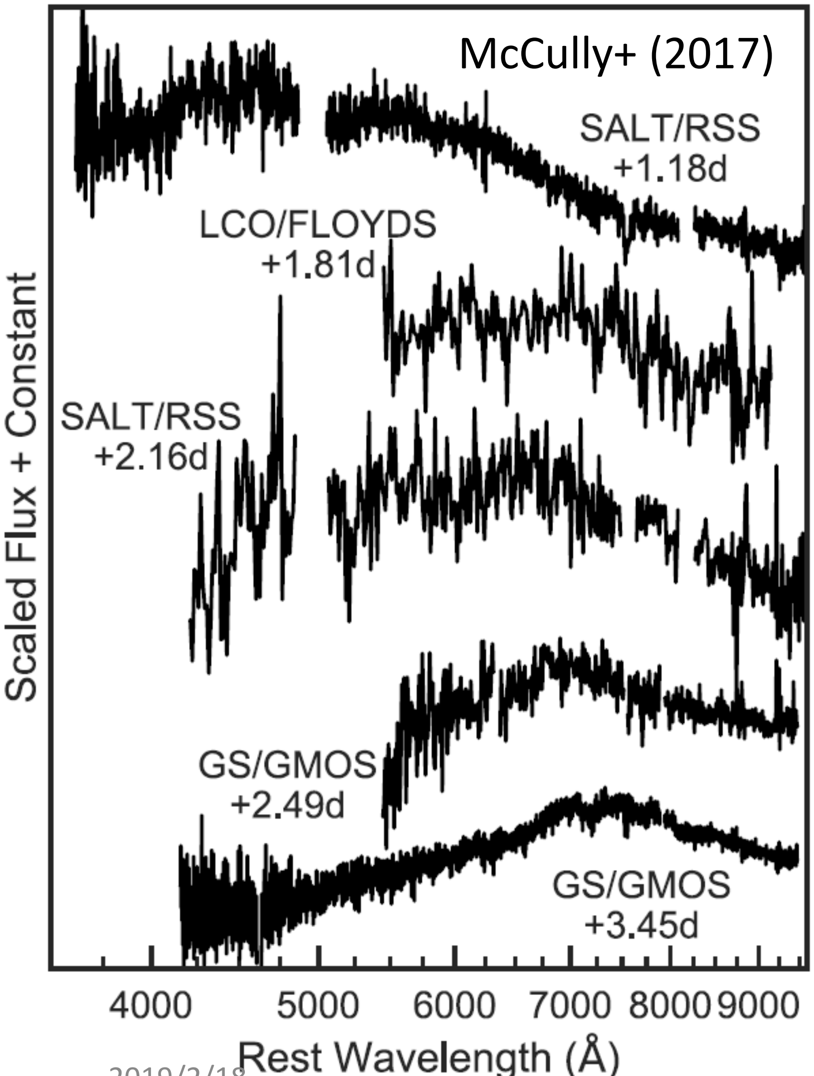




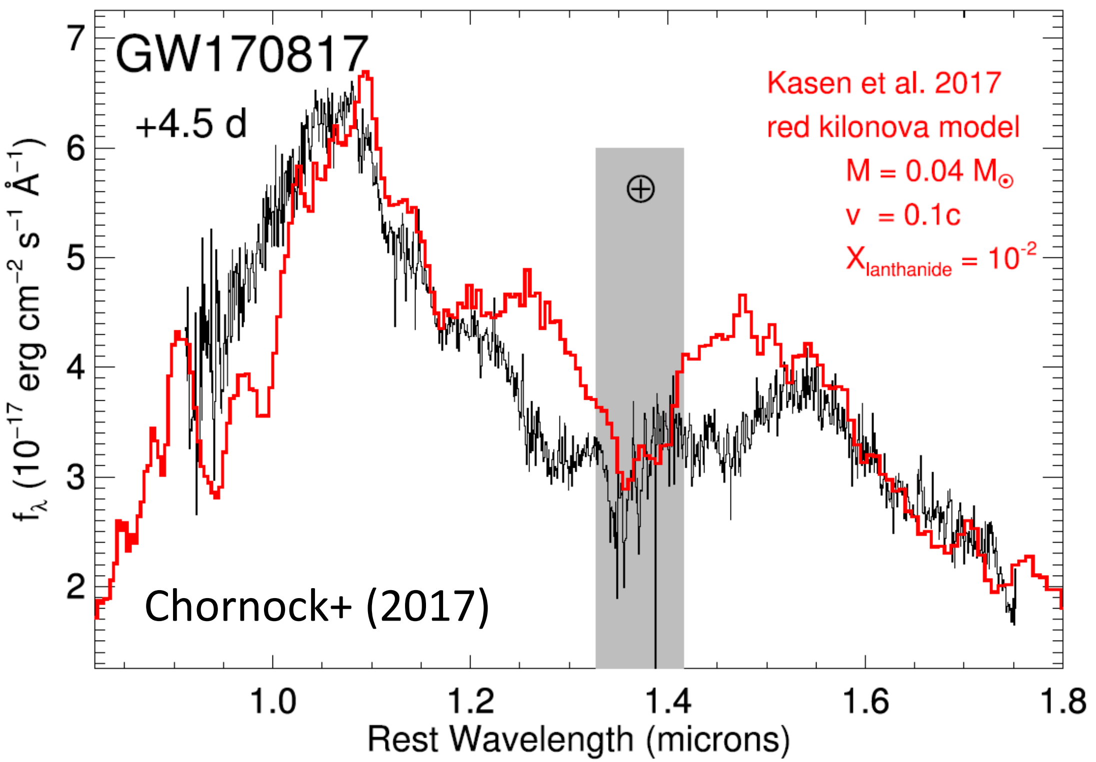


Siebert+ (2017)

Rapid reddening of the spectrum



features are consistent w/
r-process element models



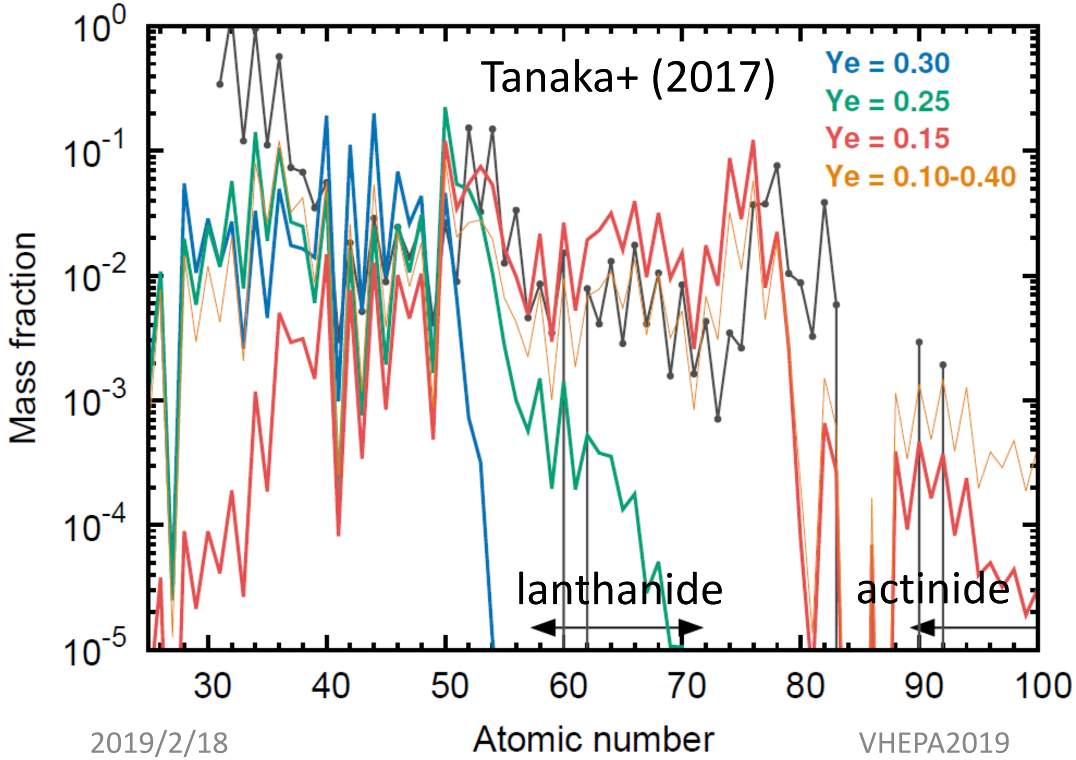
Two component?

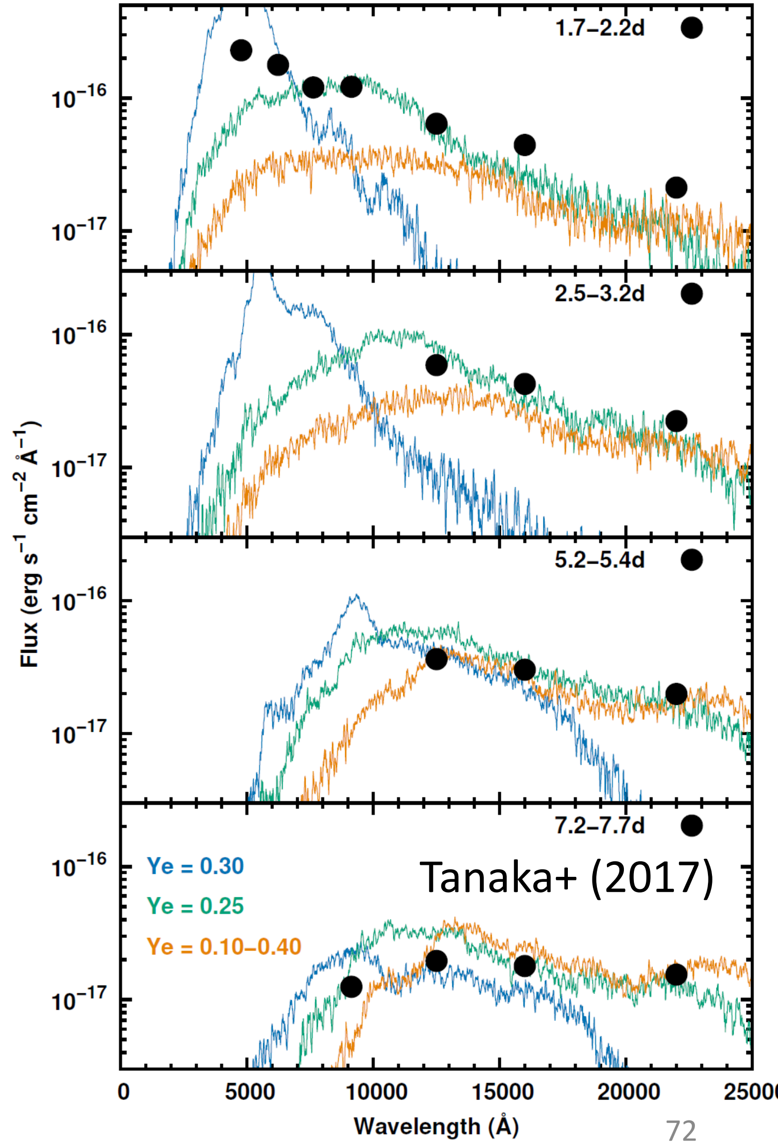
lanthanide-free
intermediate
lanthanide-rich

Too bright at earlier epochs

Early lanthanide-free +

late lanthanide is very likely

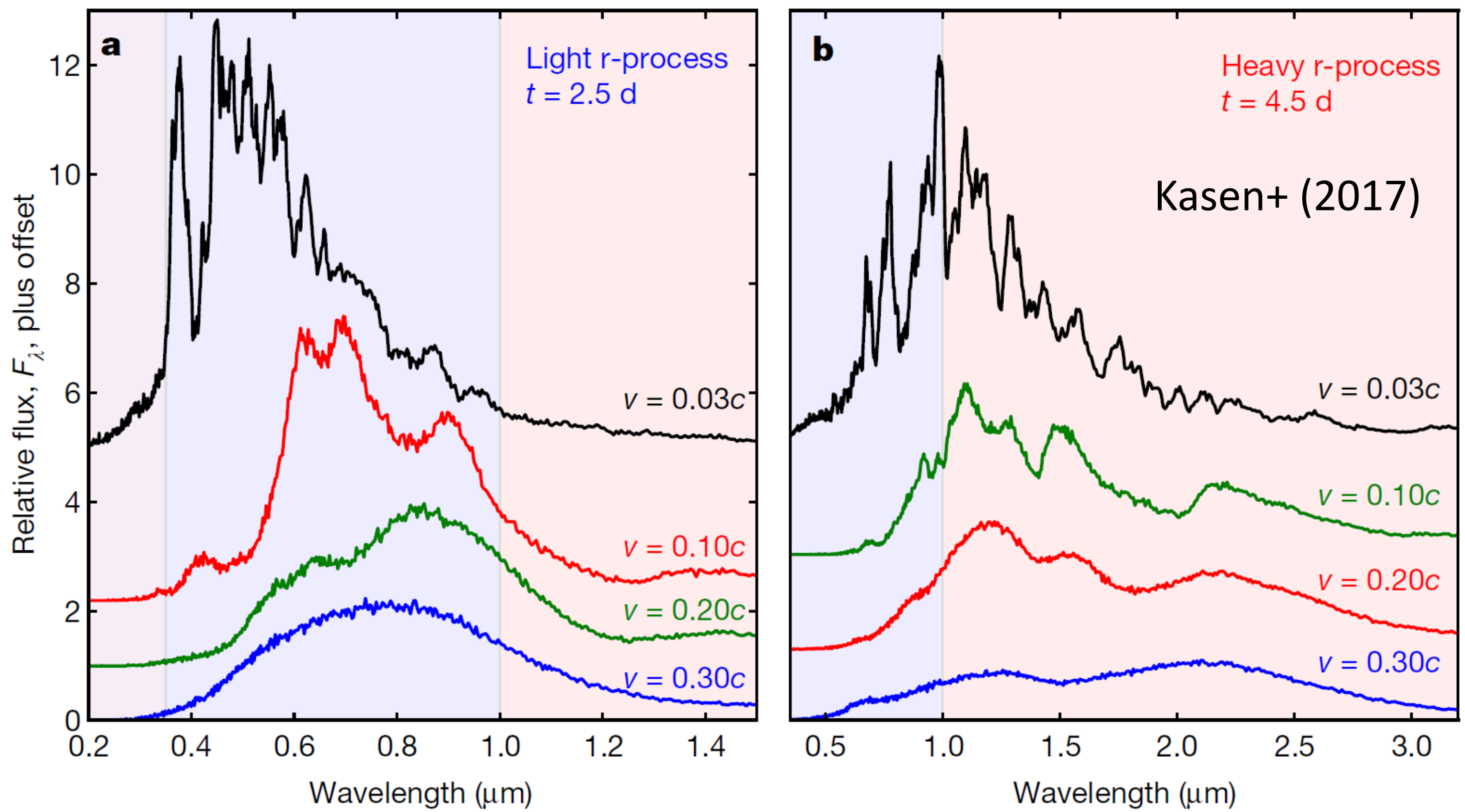




Why two components?

The early spectrum is blue and featureless

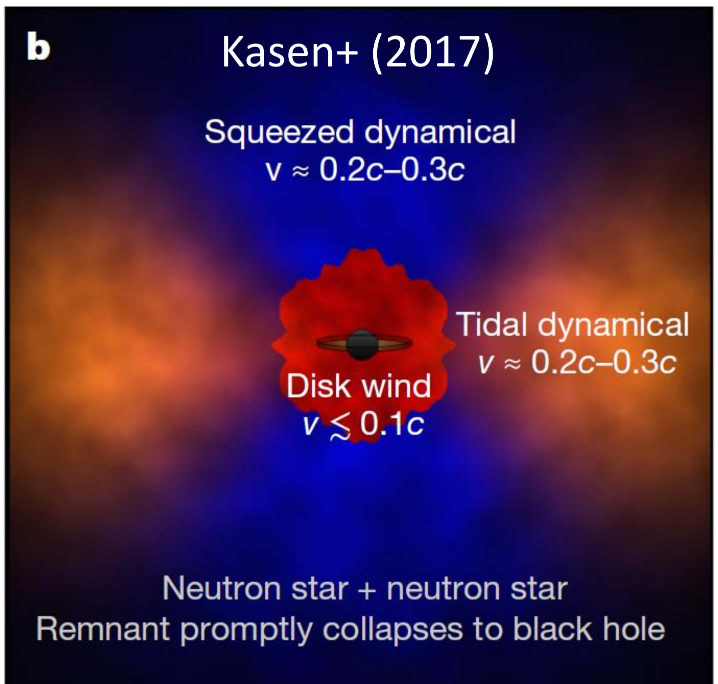
The late spectrum is red and has a broad peak

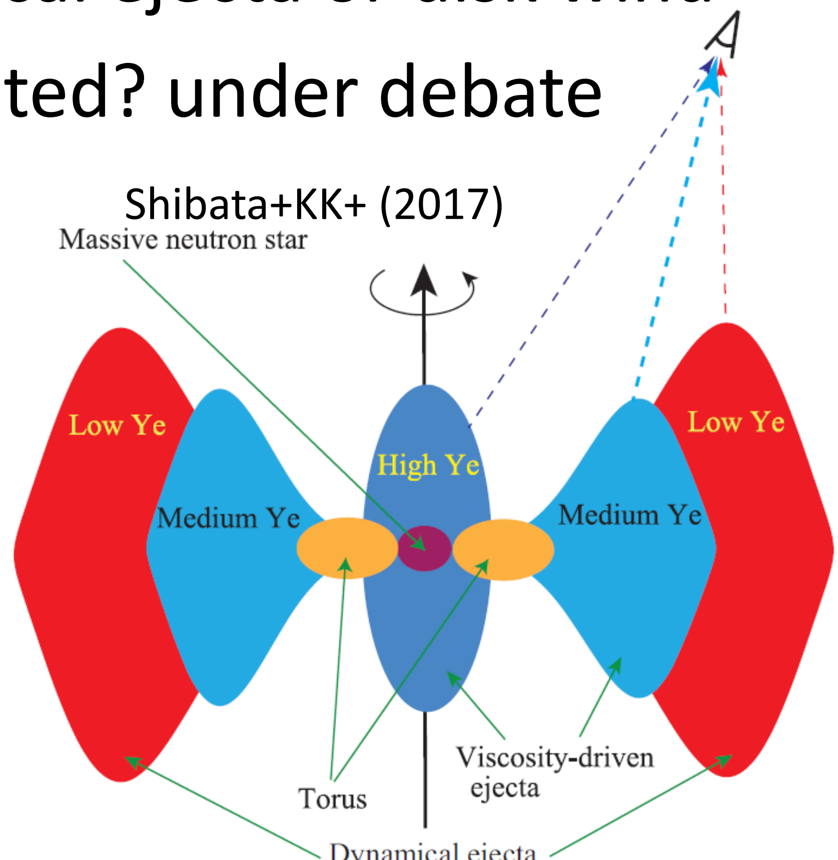


Theoretical interpretation

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

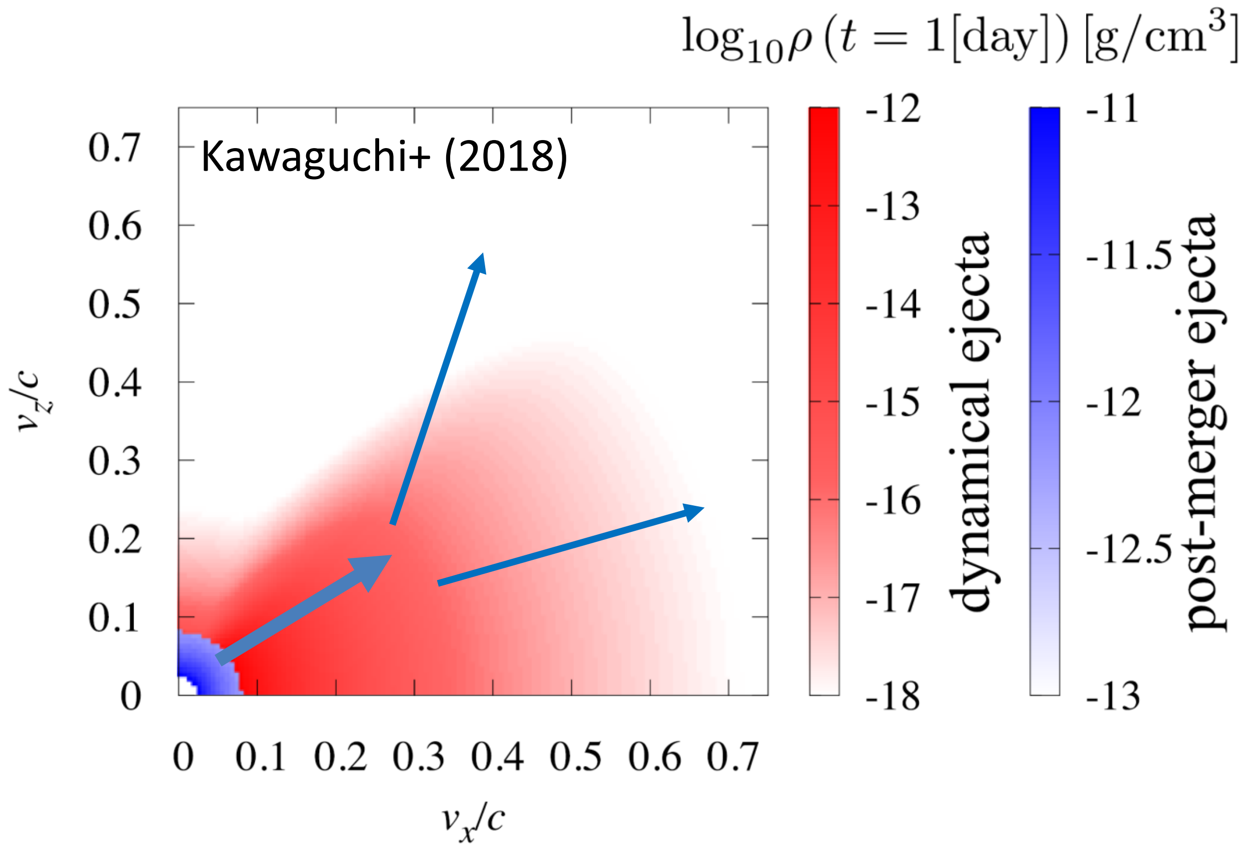
- the latter may be dynamical ejecta or disk wind
- how the former is generated? under debate





Mutual interaction may be essential

Another possibility is reprocessing of the light from a blue slow component by a red fast component



How to distinguish models?

Two-component? Dynamical or postmerger?

One (e.g., Waxman+ 2017)? Three (e.g., Villar et al. 2017)?

- Spatial resolution by radio observations
- Determine the postmerger remnant: BH vs NS

- GeV-TeV gamma rays could do (Murase+ 217)

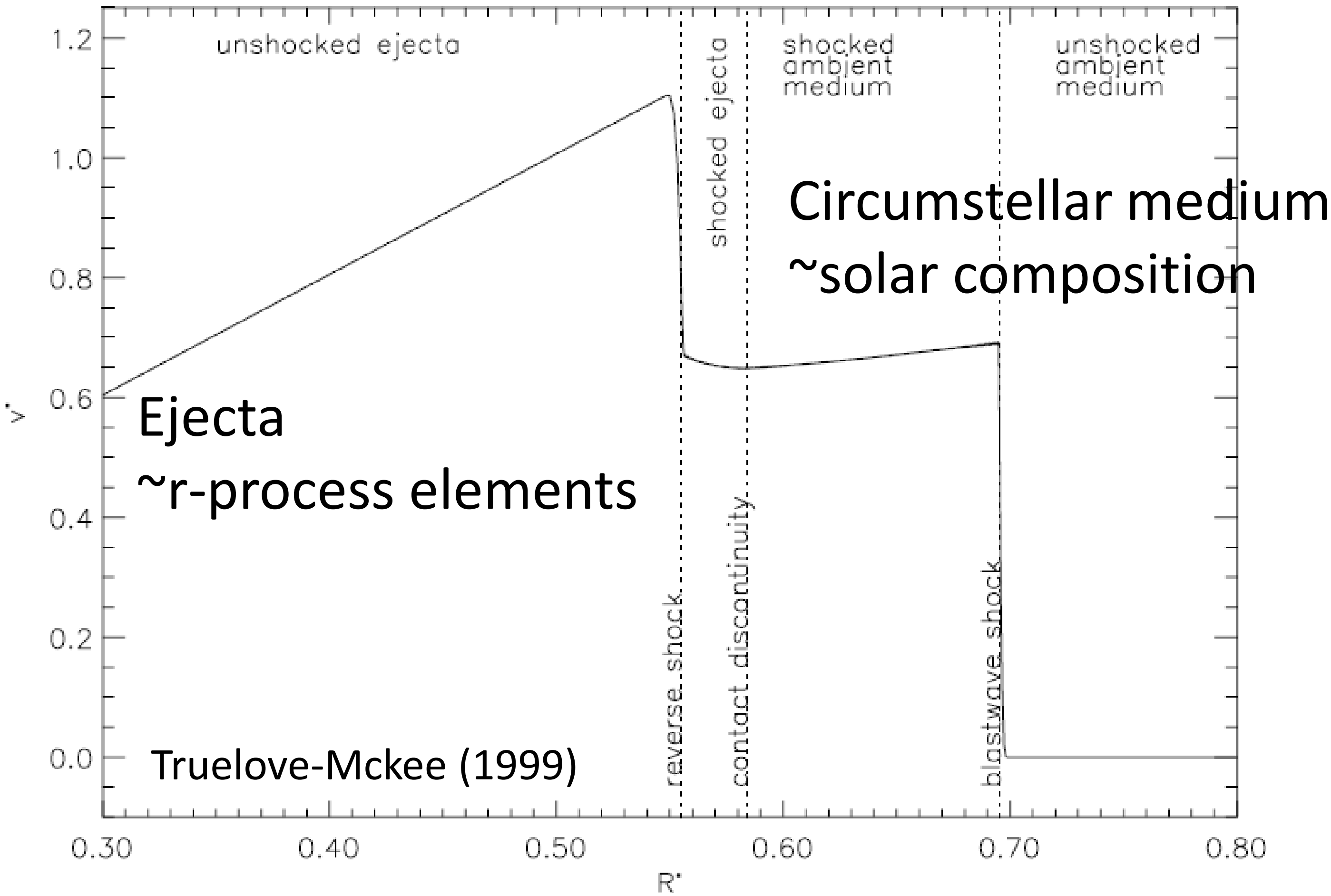
More detections seems necessary anyway

- Angular dependence of emission
- Polarization (ND for this event: Covino+ 2017)

Reverse shock

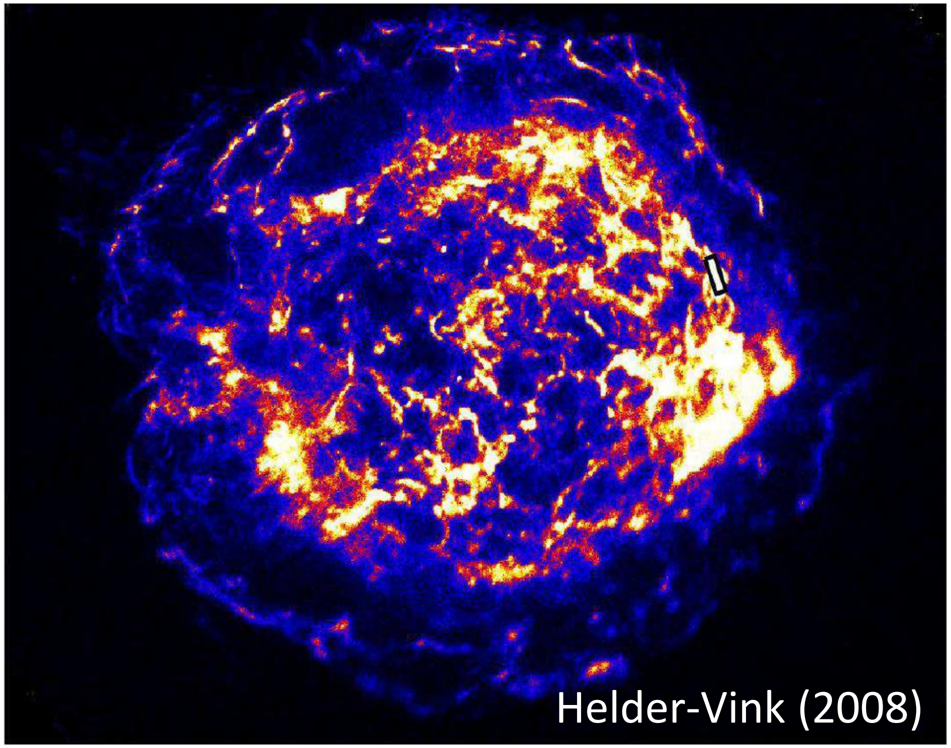
R-process elements reside in the ejecta region

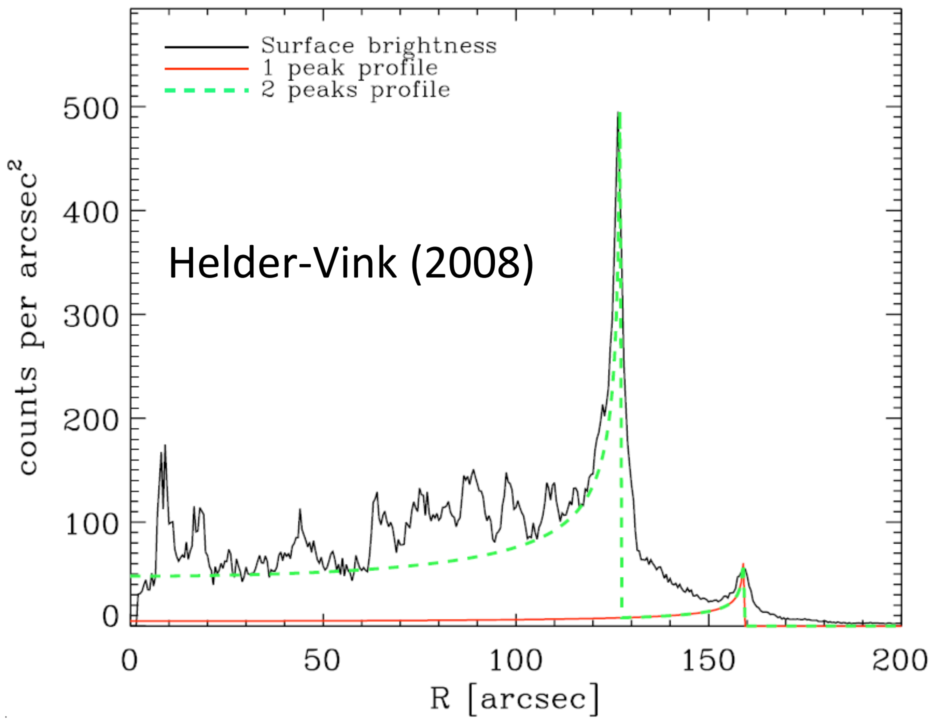
Fluid velocity



Observed reverse-shock acceleration

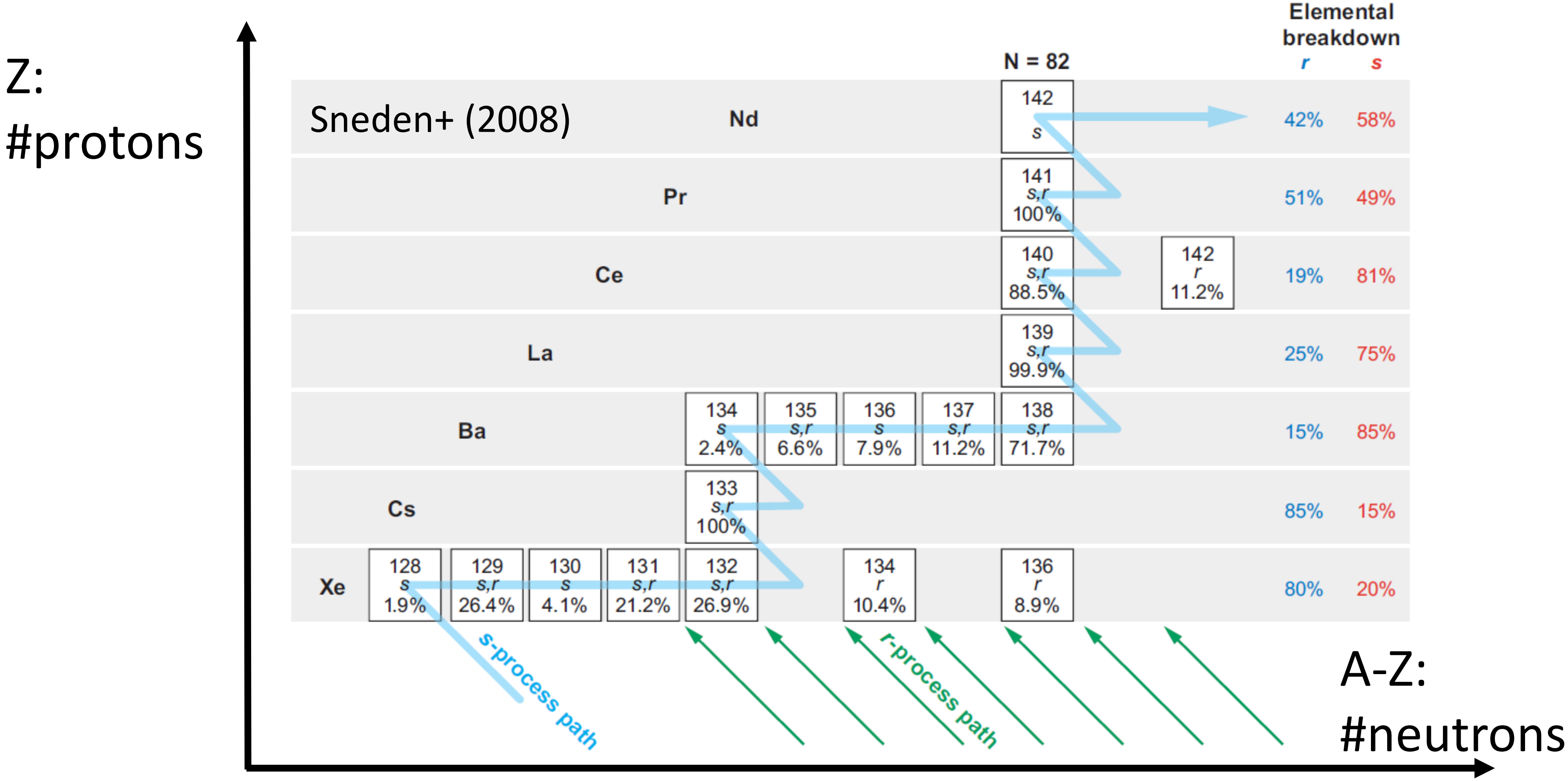
X-rays from Cas A reveal reverse-shock emission
magnetic-field amplification & electron acceleration





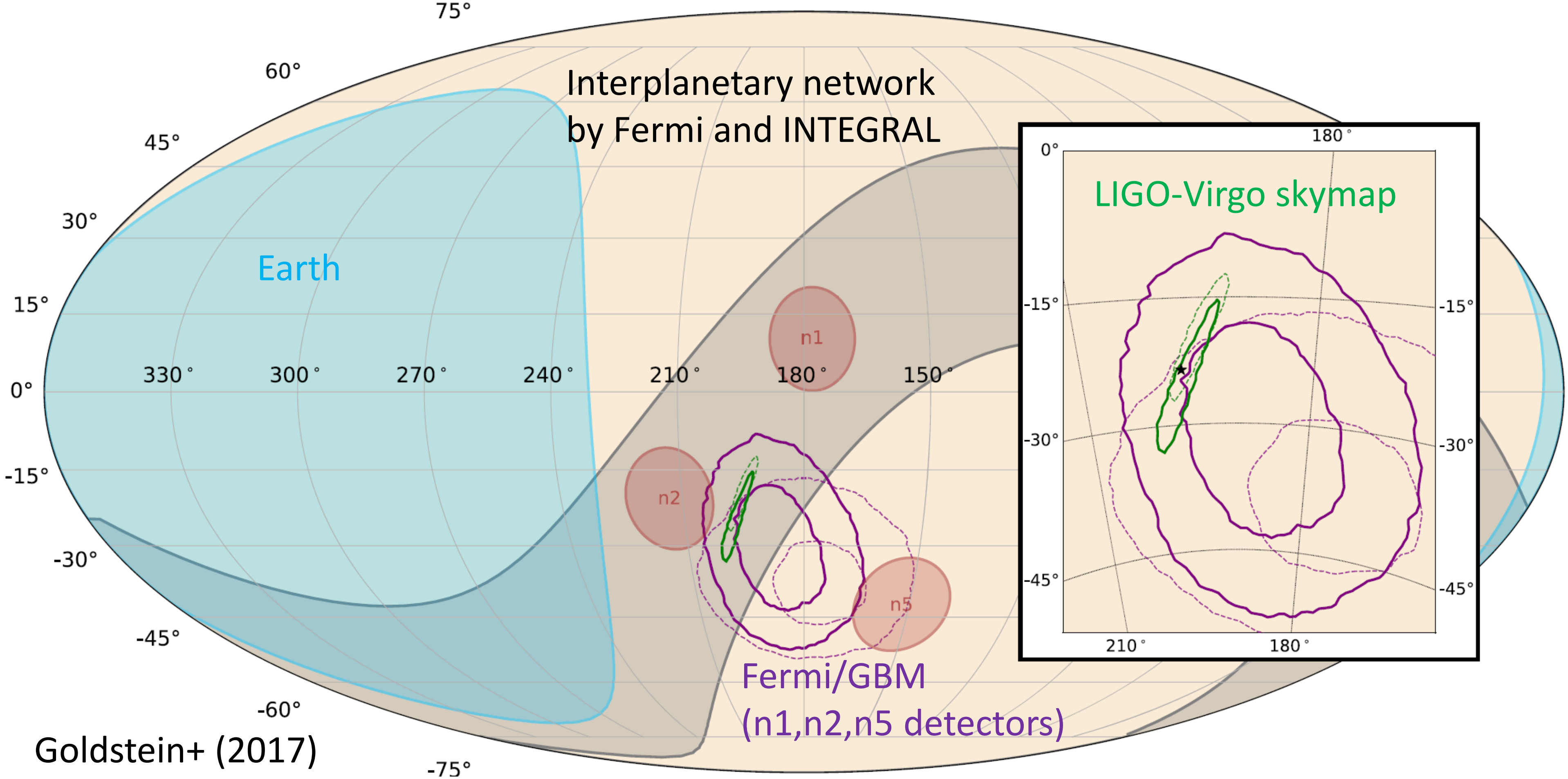
Caveat: isotopic contamination

We do not distinguish r-/s-process isotopes so far



Localization

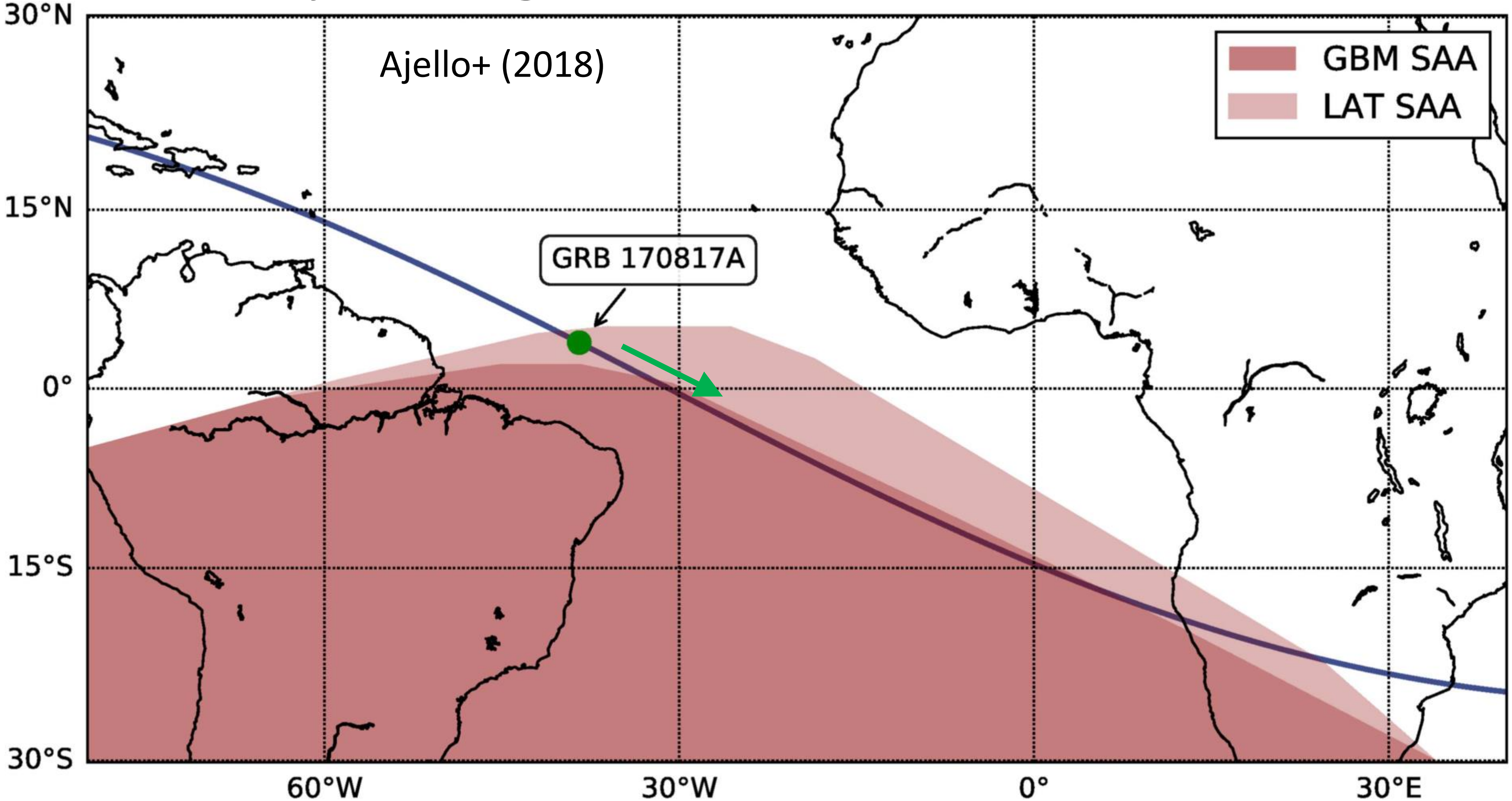
LIGO-Virgo three detectors did a good job this time



Goldstein+ (2017)

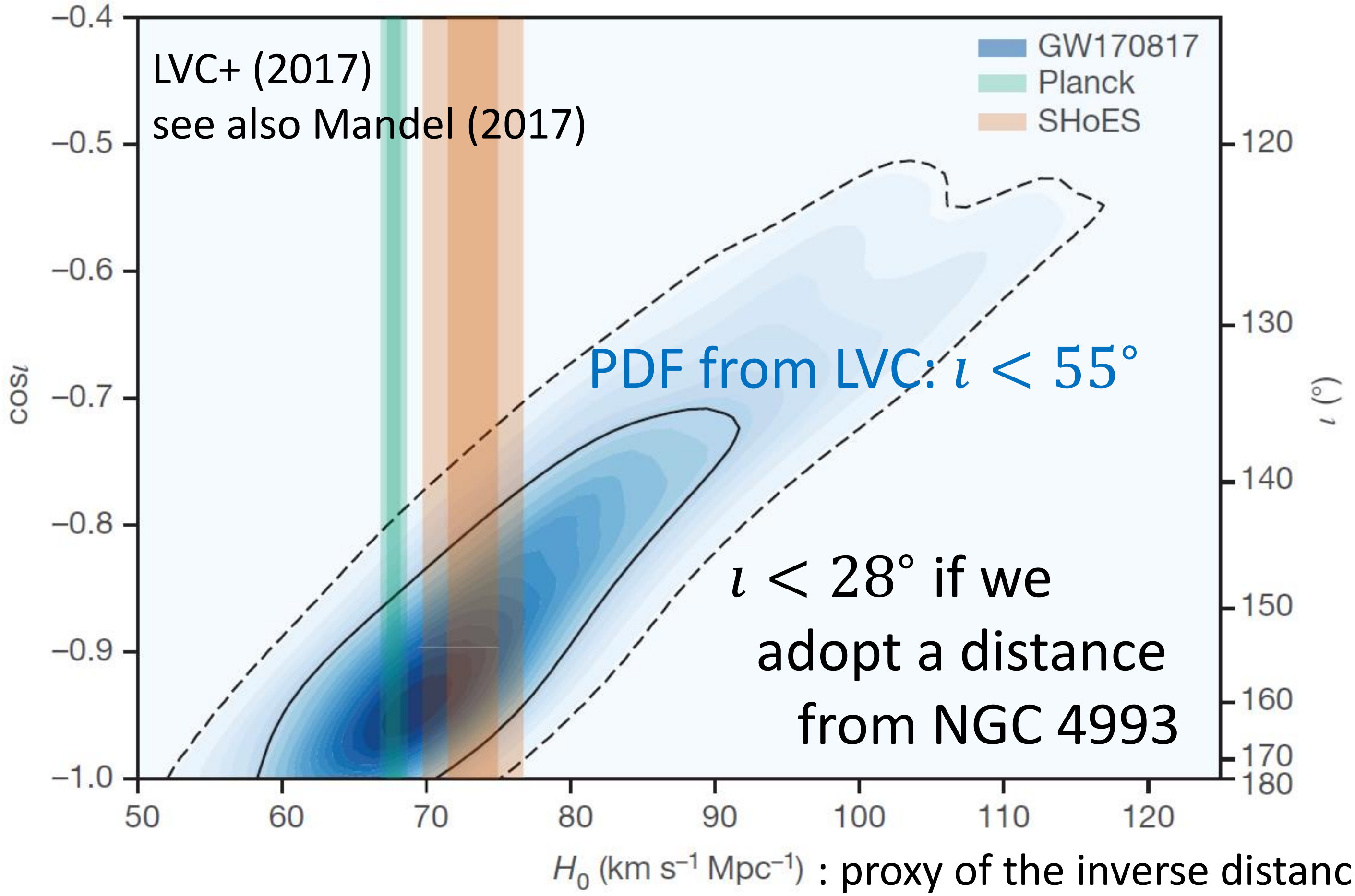
South Atlantic Anomaly

Sensitivity is not good, Fermi/LAT was not available



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

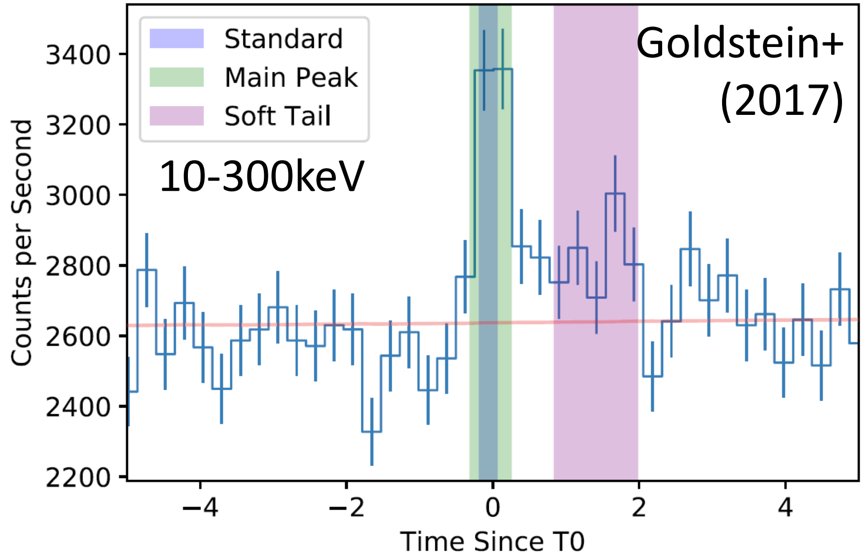
Two component prompt emission

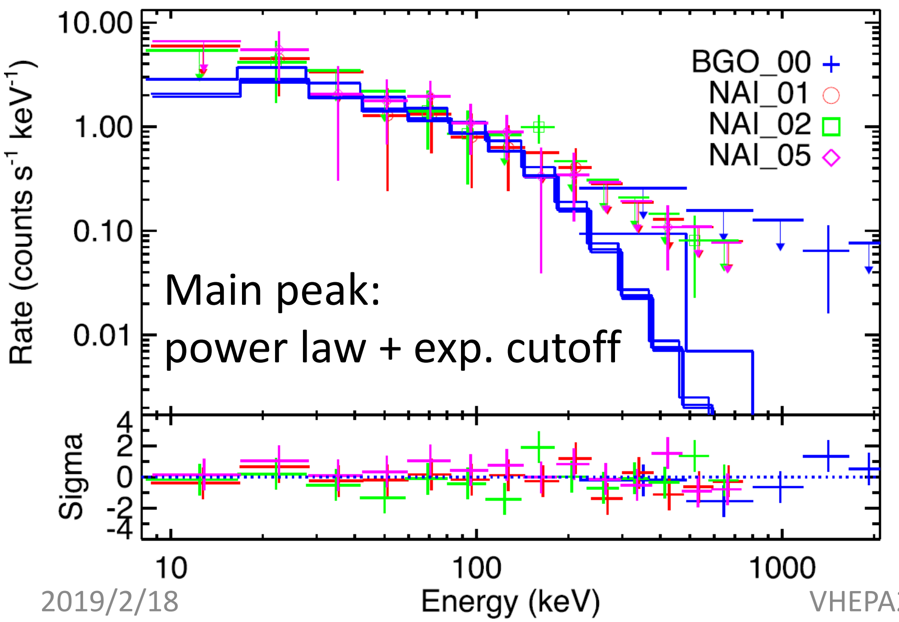
Main peak: $E_p \approx 185$ keV

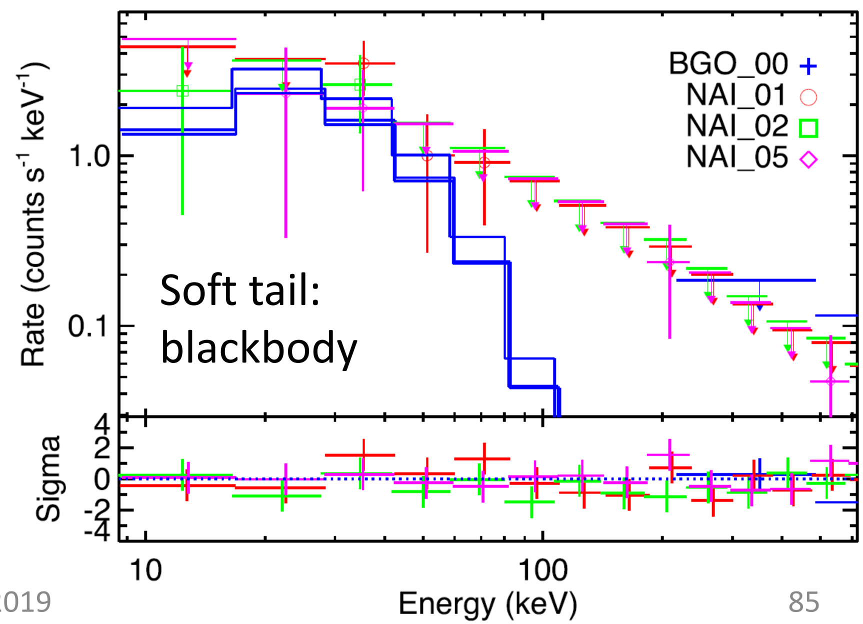
Soft tail: $k_B T \approx 10$ keV

not necessarily “compact”

$\Gamma > 2-3$ is sufficient

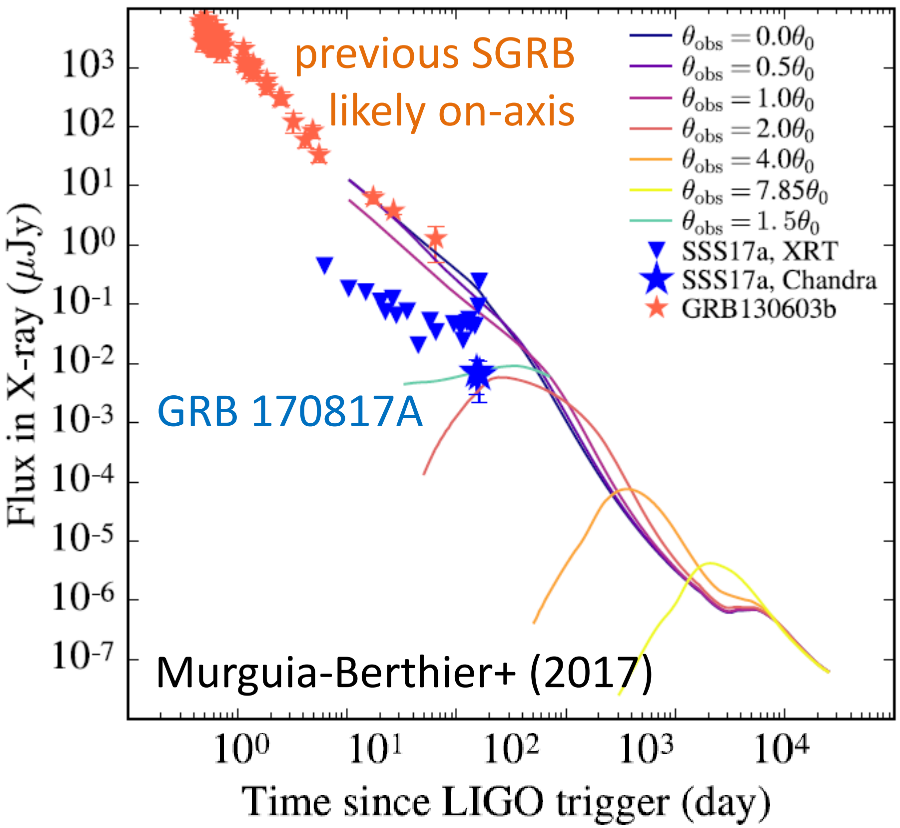


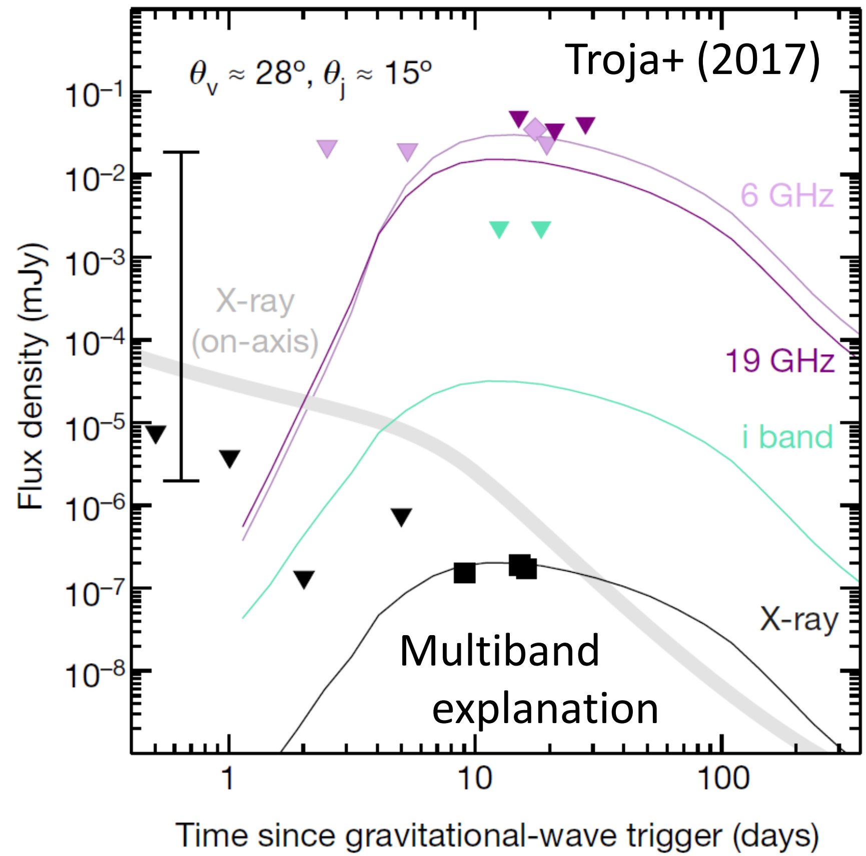




Off-axis? early X/radio afterglow

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

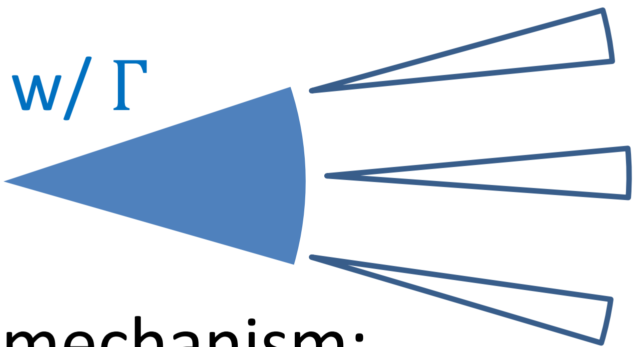




Late rise due to relativistic beaming

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

Jet w/ Γ



Usual GRB observer

Observable throughout

$\theta \sim 1/\Gamma$

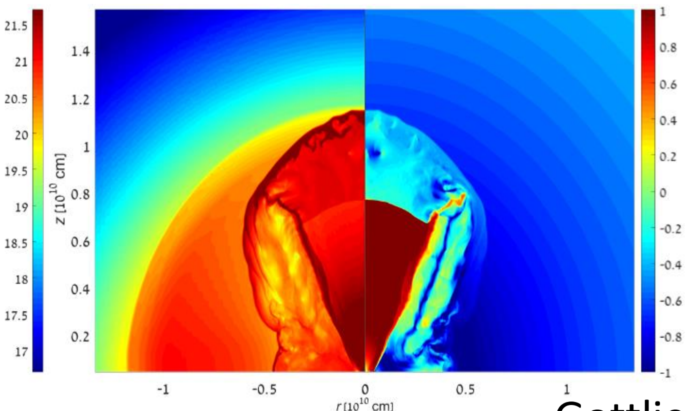
Emission mechanism:
nonthermal synchrotron

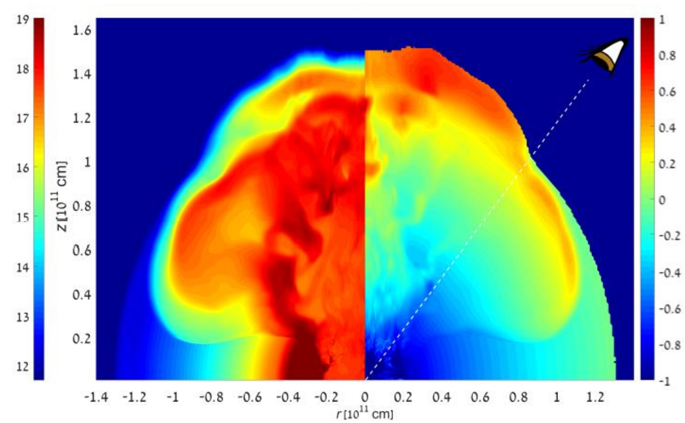
Off-axis observer

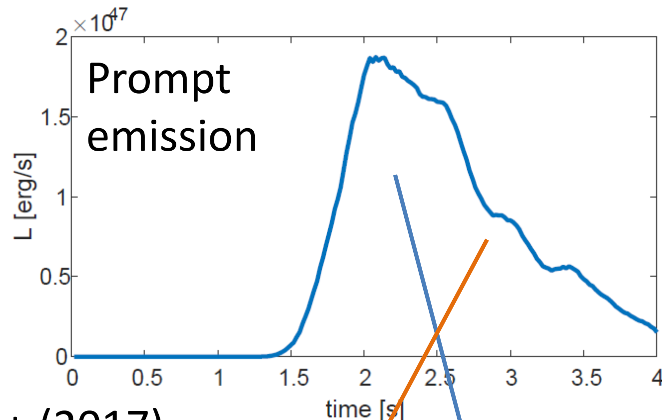
Observable only after the jet is decelerated to $\Gamma < 1/\theta_{\rm obs}$

Cocoon with a chocked jet?

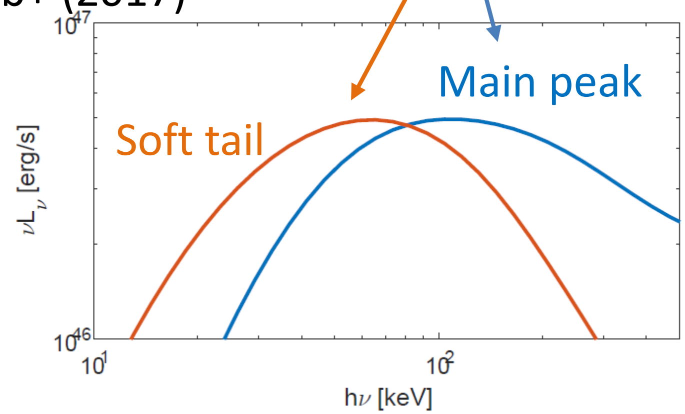
When a jet interact w/ ejecta (macronova/kilonova), the energy is dissipated and hot material breaks out



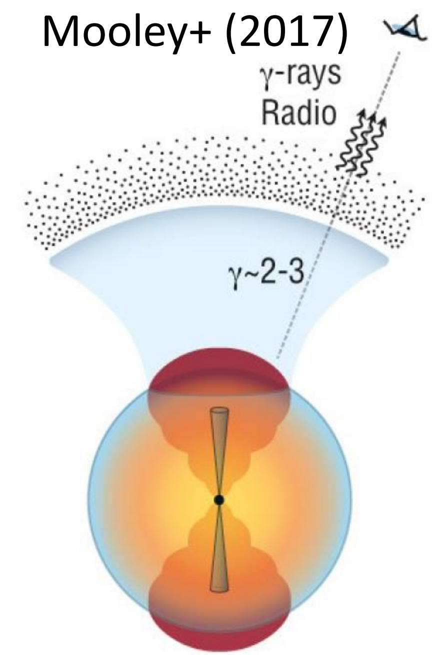




Gottlieb+ (2017)



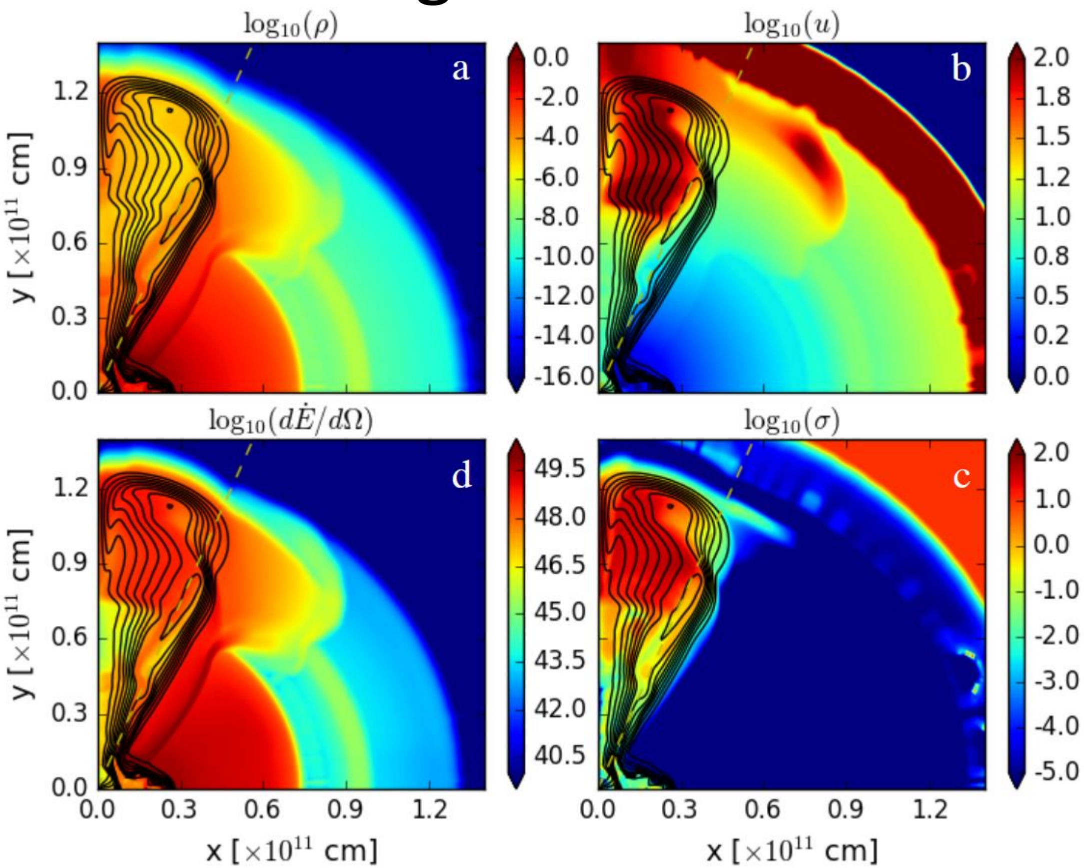
Mooley+ (2017)

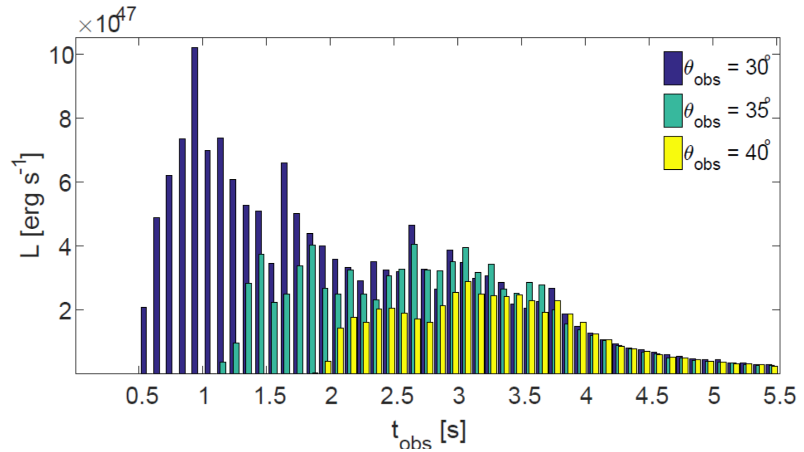


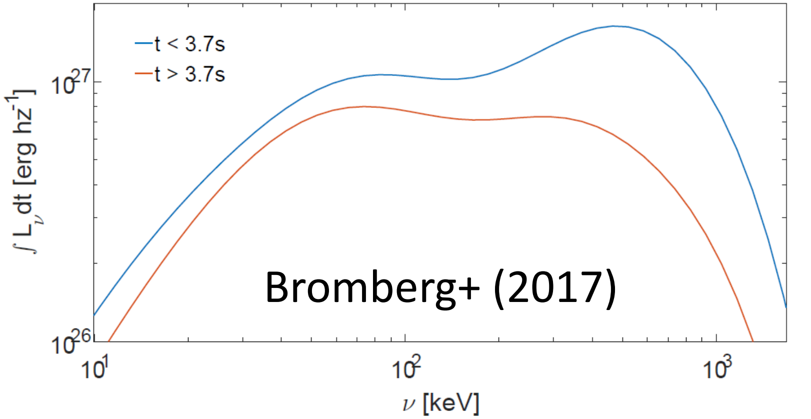
C. Choked Jet
Cocoon γ-rays and afterglow
(Most likely)

Case of a magnetized jet

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



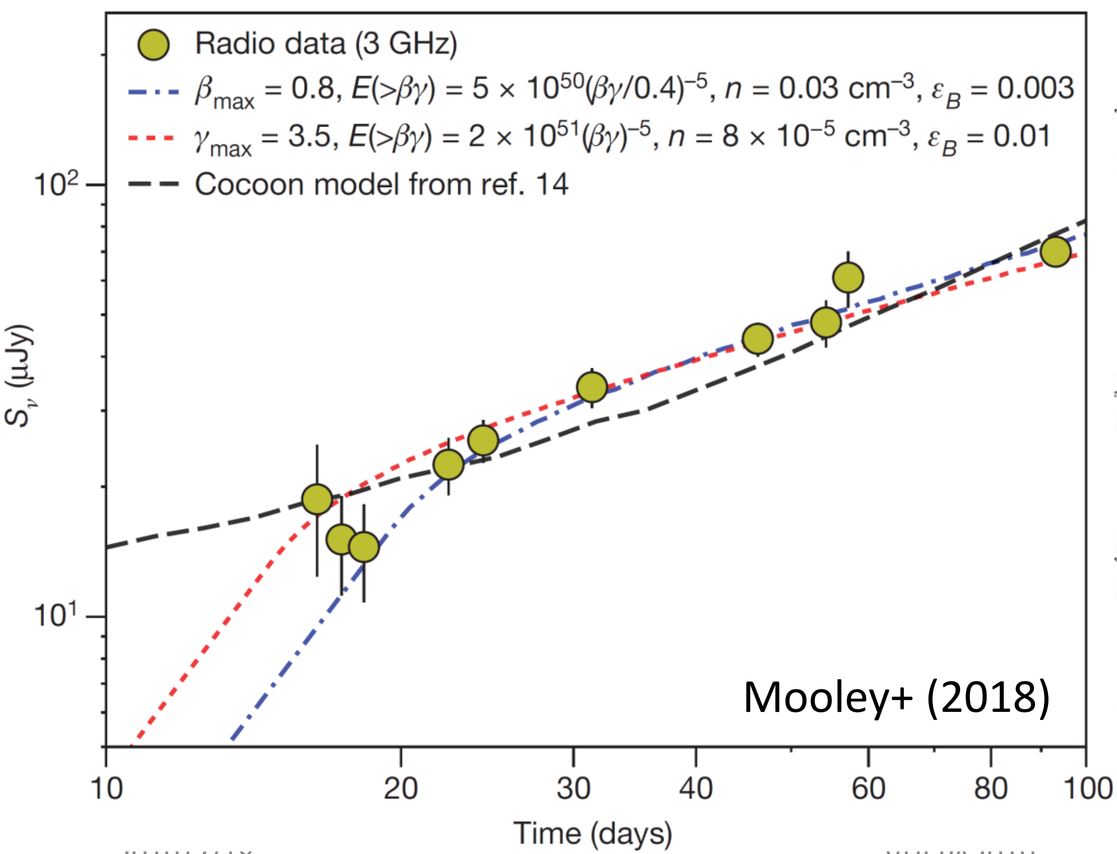


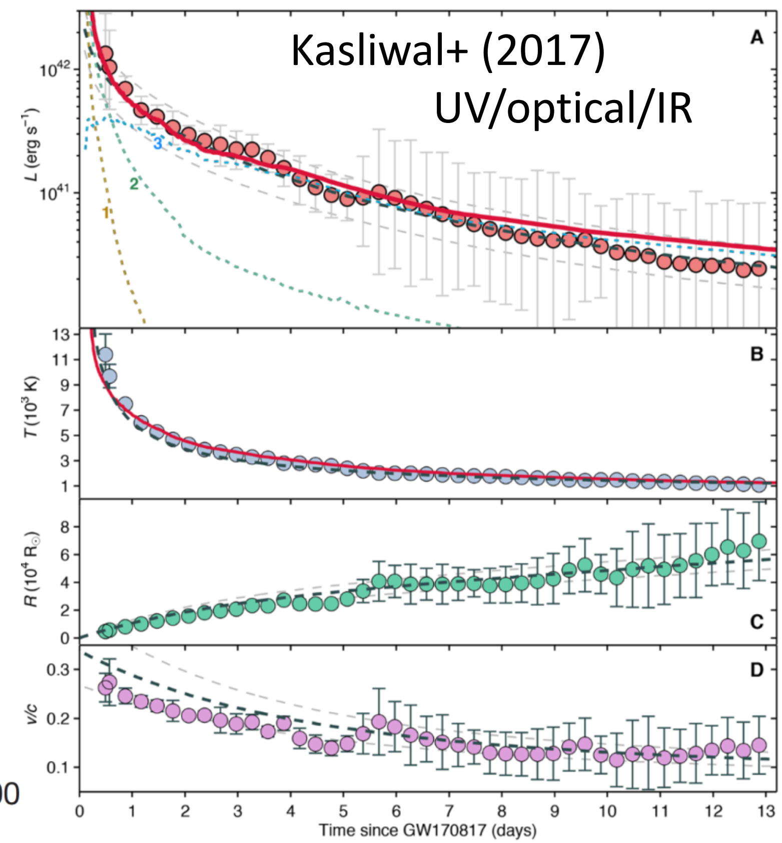


Seemingly satisfactory

Blue kilonova/macronova may also be explained

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





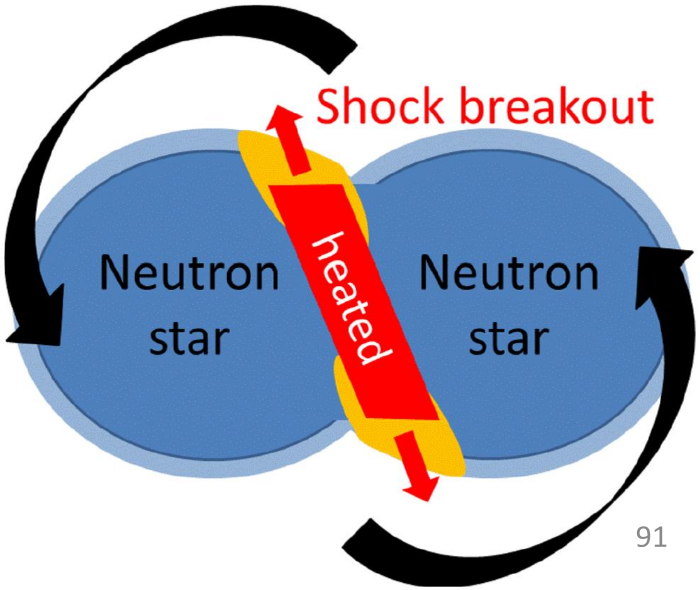
Prerequisite: very fast ejecta

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

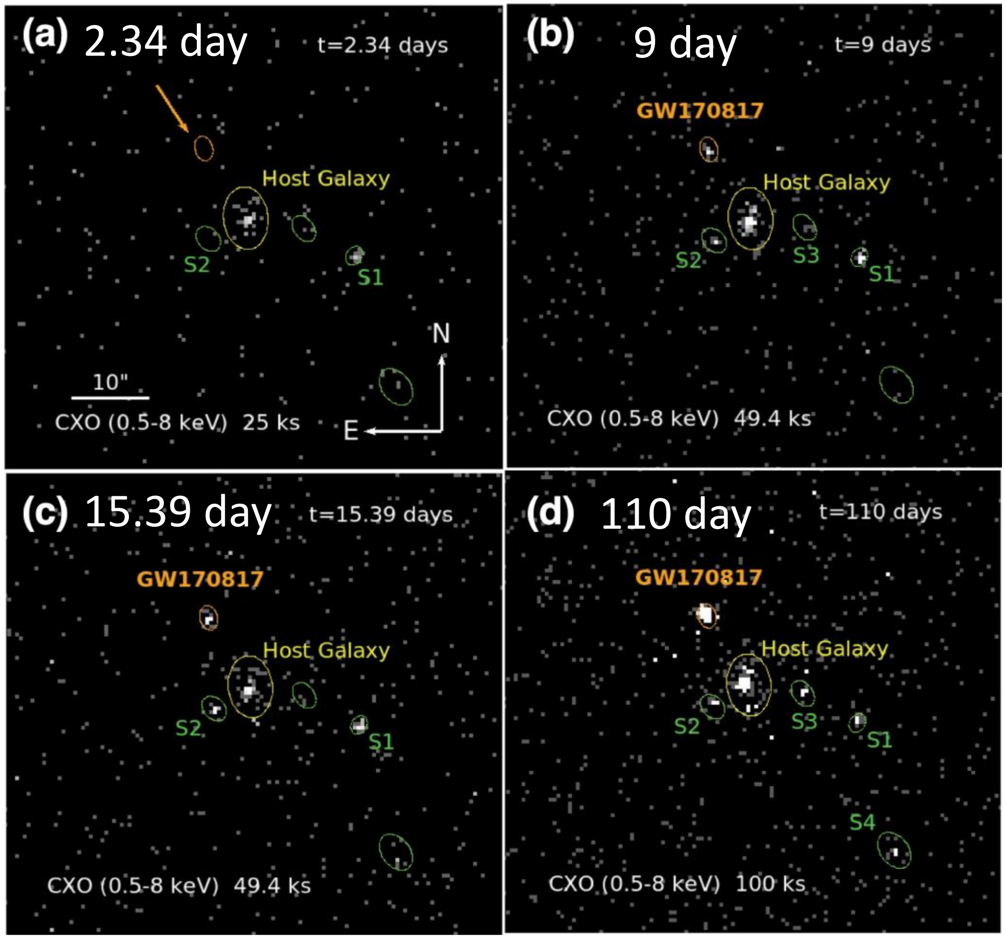
- merger shock breakout from neutron stars? (Kyutoku+ 2014)

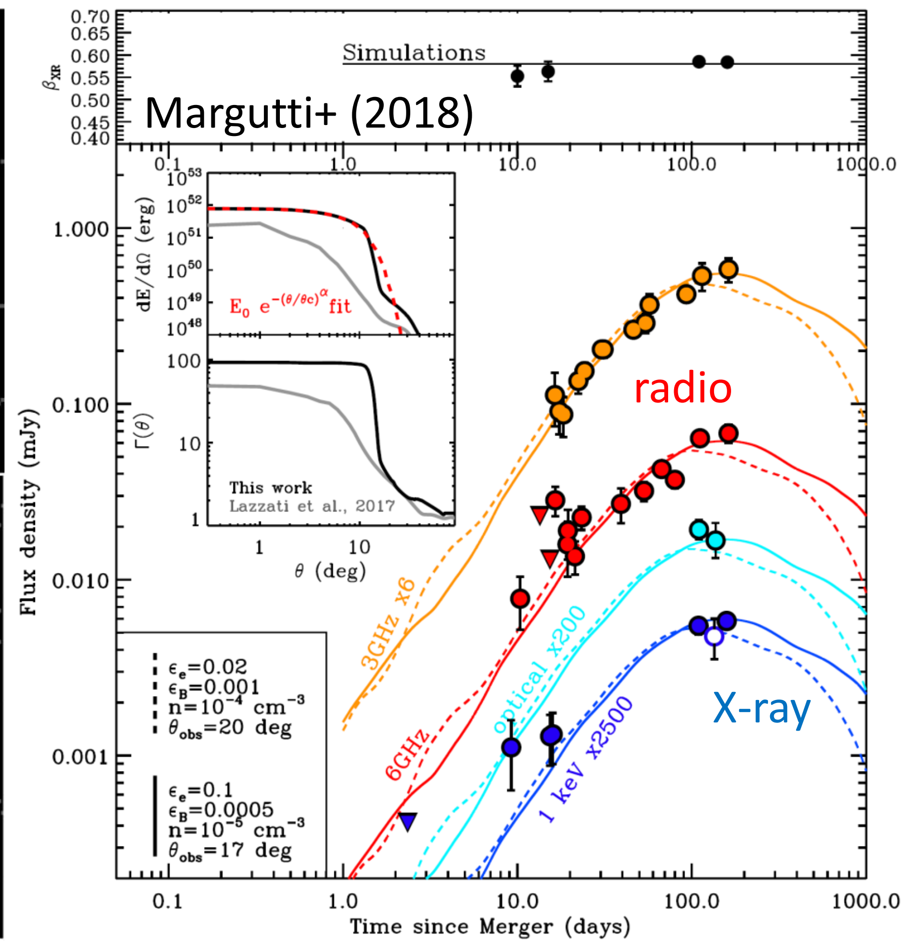


Seriously? This model itself might also explain the X/radio emission

Multi-wavelength observation

X-rays also brightened after Sun's 100day constraint



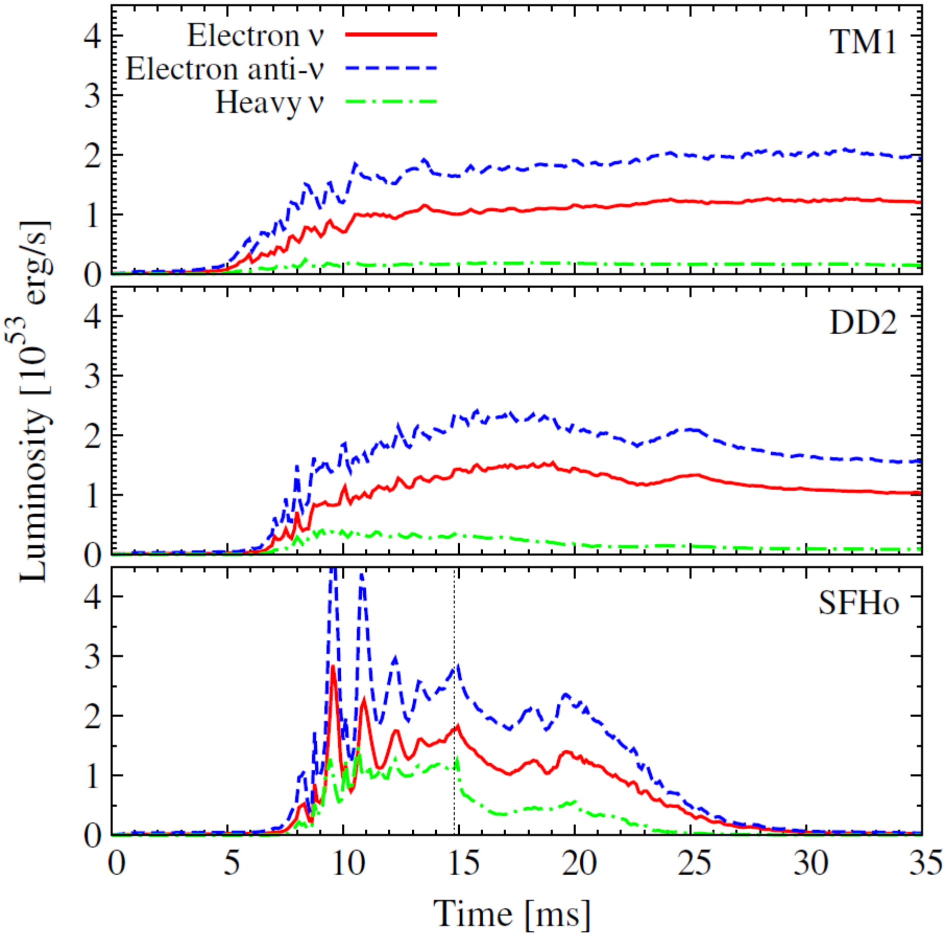


Neutrino emission

As bright as supernova explosions

Reflect equations of state

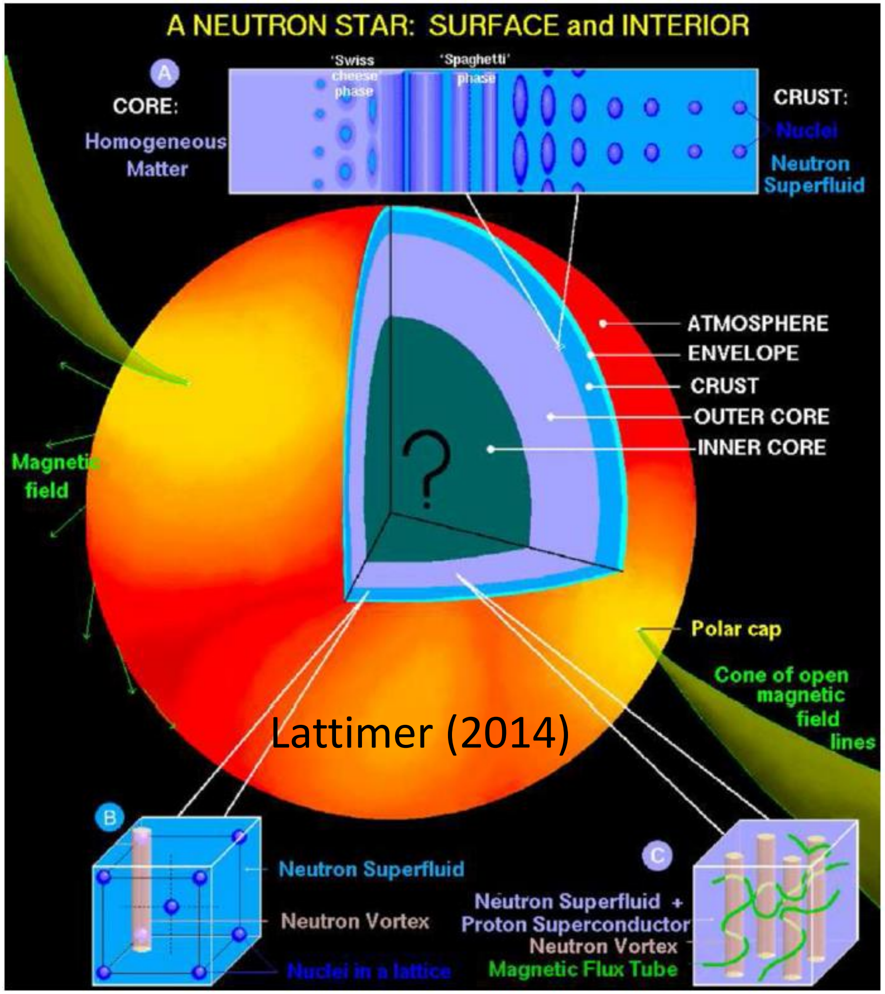
Directly detectable neutrinos are extremely rare, but they could affect various aspects



Neutron star

Remnant of massive stars
(mass range is uncertain)

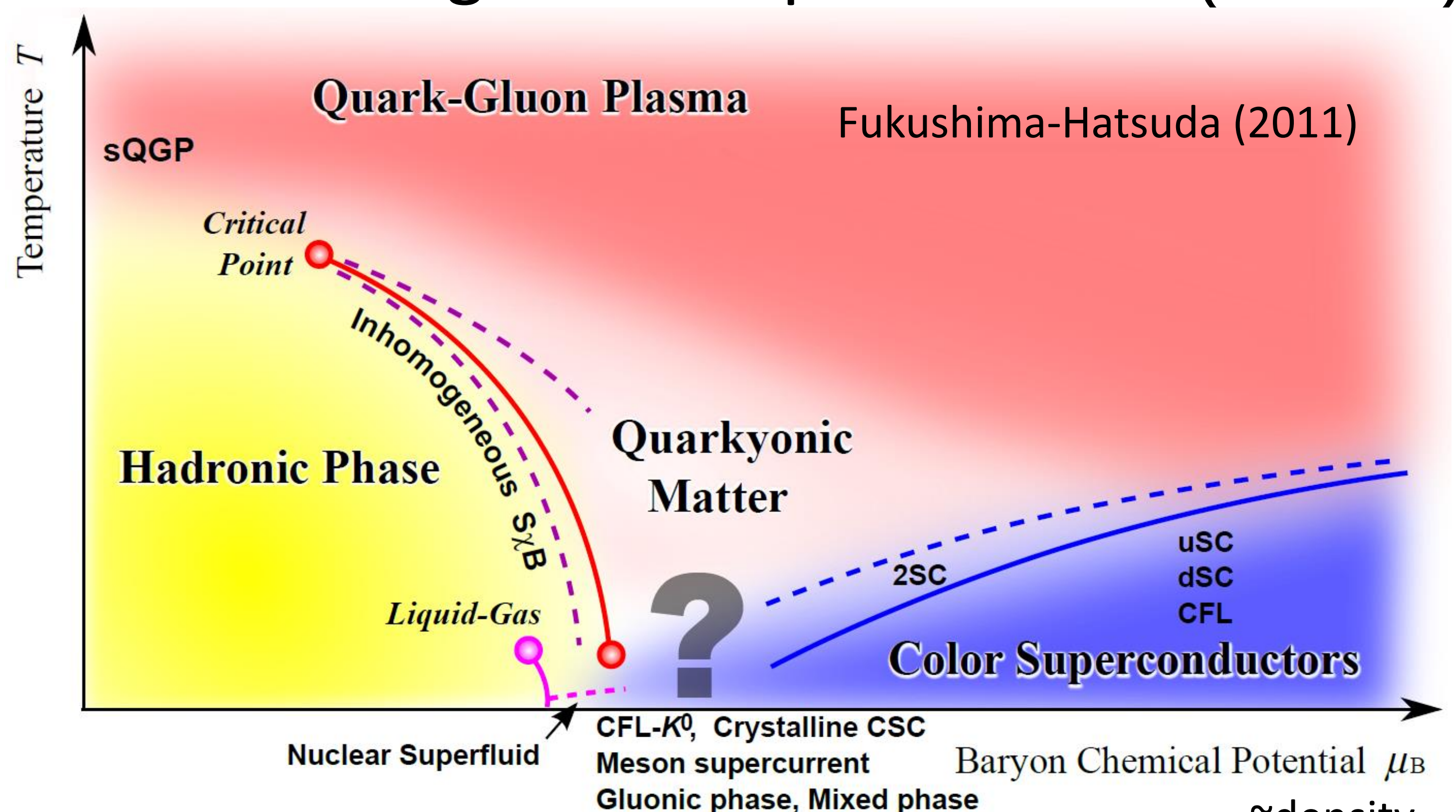
Mostly consists of neutrons
1.4 solar mass, ~10km
The density is higher than
nuclear saturation values
“a huge nucleus”
Arena for nuclear physics



Neutron-star matter

Cold, high-density, highly neutron-rich matter

also could be magnetized up to $\sim 10^{17}\mathrm{G}\ (10^{13}\mathrm{T})$

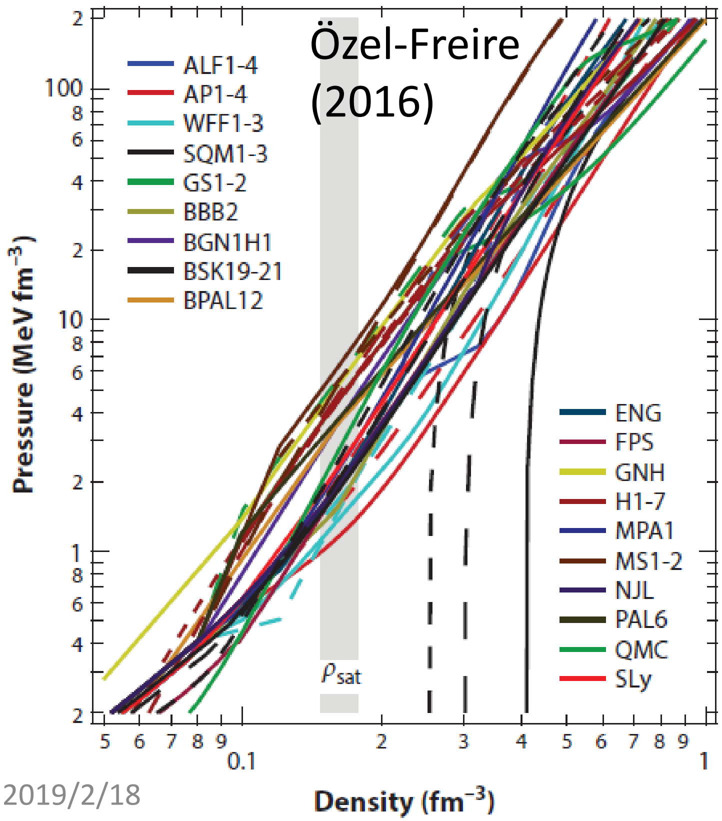


Neutron star equation of state

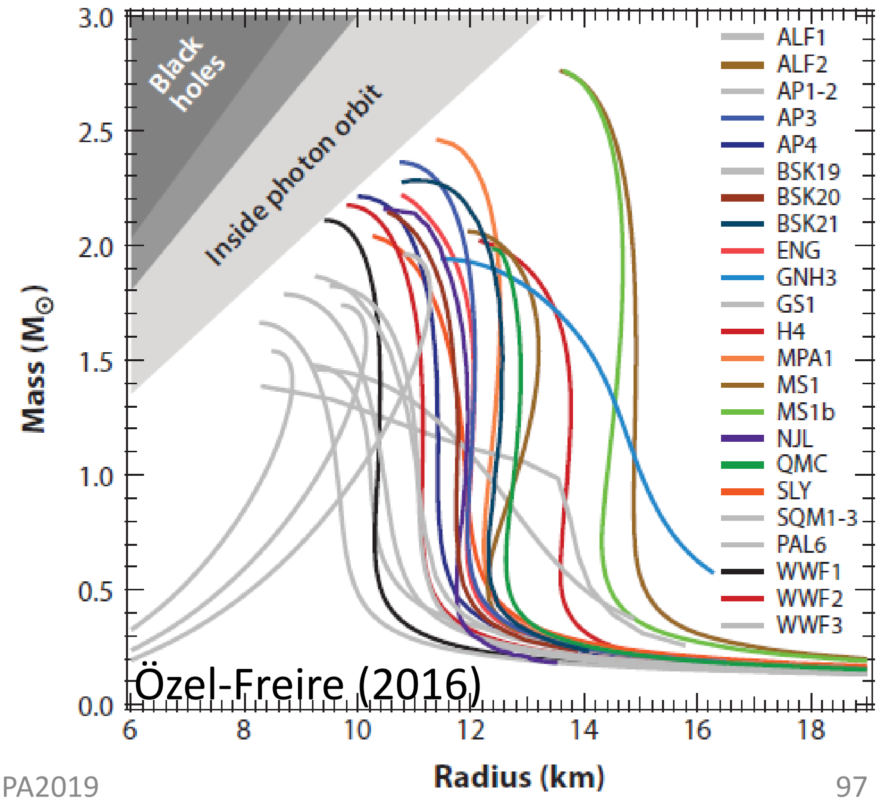
Note: not need to observe the radius, and other quantities may be fine

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

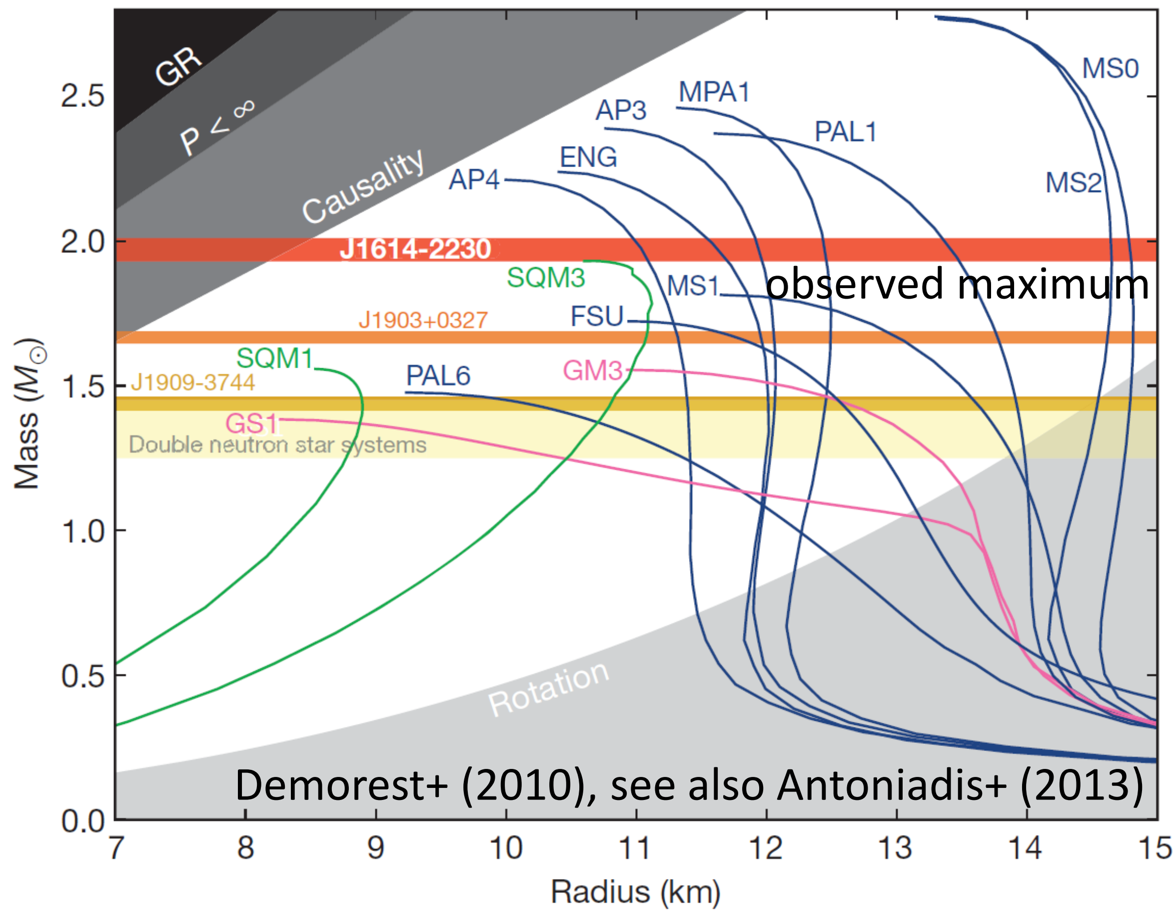


Maximum mass of neutron stars

Put a robust constraint on equation-of-state models

Generally, emergence of exotic particles tend to reduce the maximum mass

… not so preferred



Maximum mass from GW170817

Upper limits are proposed based on assumptions

- Optical emission rejects magnetar models

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

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

- A GRB jet launch calls for gravitational collapse

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

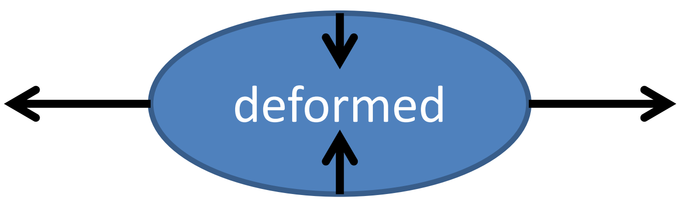
I do not think any argument is strongly convincing, but similar values are inferred anyway

Quadrupolar tidal deformability

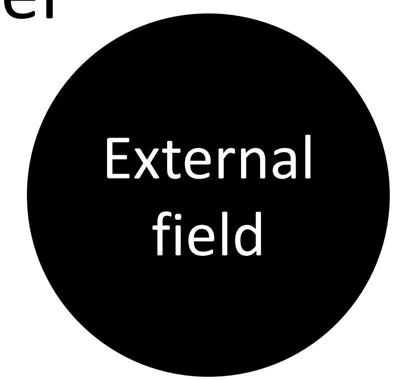
Leading-order finite-size effect on orbital evolution (strongly correlated with the neutron-star radius)

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

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



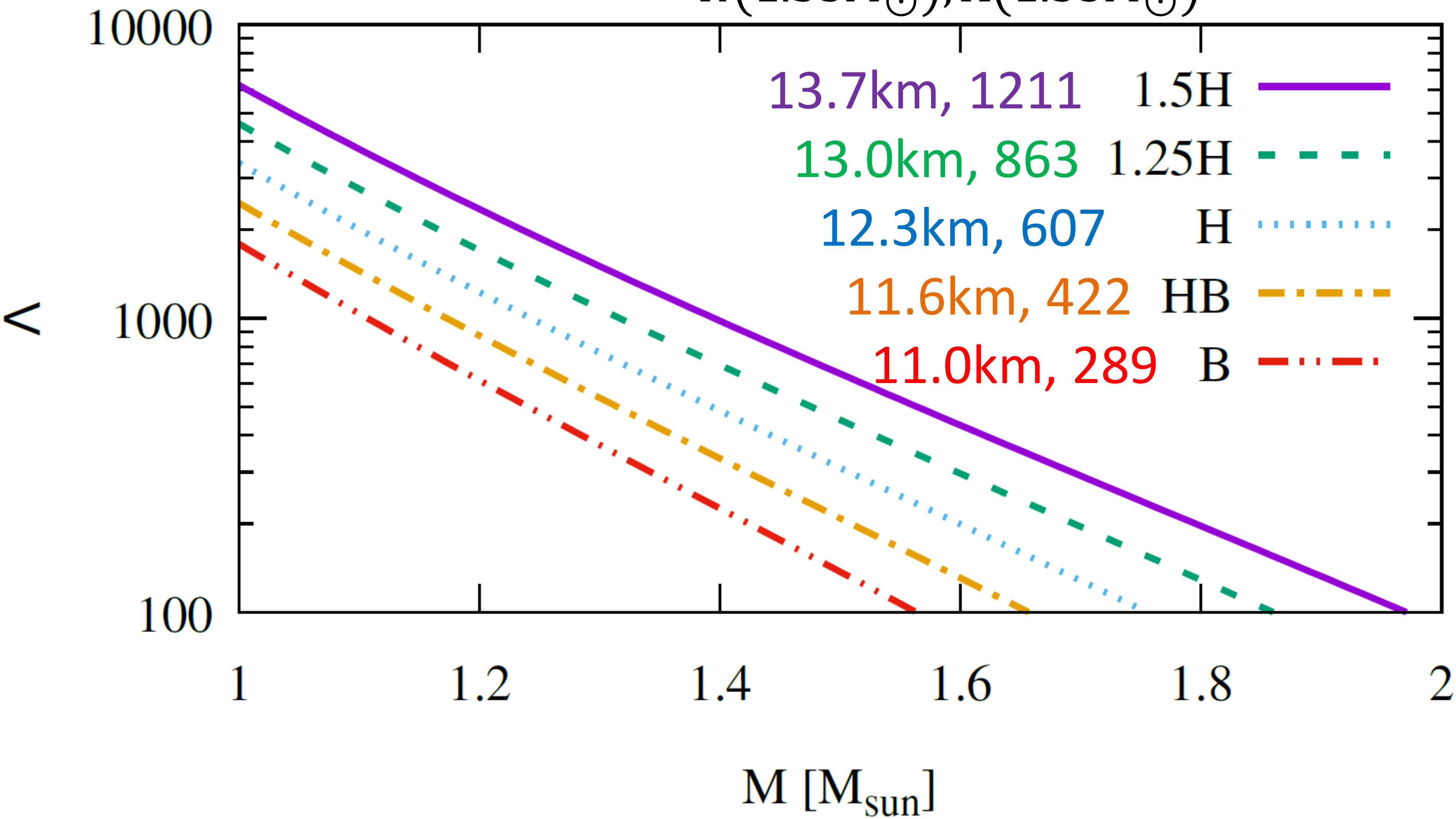
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



$$Q_{ij} \equiv \int \rho \left(x_i x_j - \frac{1}{3} x^2 \delta_{ij} \right) d^3 x \qquad \mathcal{E}_{ij} \equiv \frac{\partial^2 \Phi_{\text{ext}}}{\partial x^i \partial x^j}$$

$M - \Lambda$ relation

$R(1.35M_\odot), \Lambda(1.35M_\odot)$



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 ($m_1 \leq m_2$)

$$\tilde{\Lambda} = \frac{8}{13} [\left(1 + 7\eta - 31\eta^2\right)(\Lambda_1 + \Lambda_2)$$

$$- \sqrt{1 - 4\eta}\left(1 + 9\eta - 11\eta^2\right)(\Lambda_1 - \Lambda_2)]$$

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