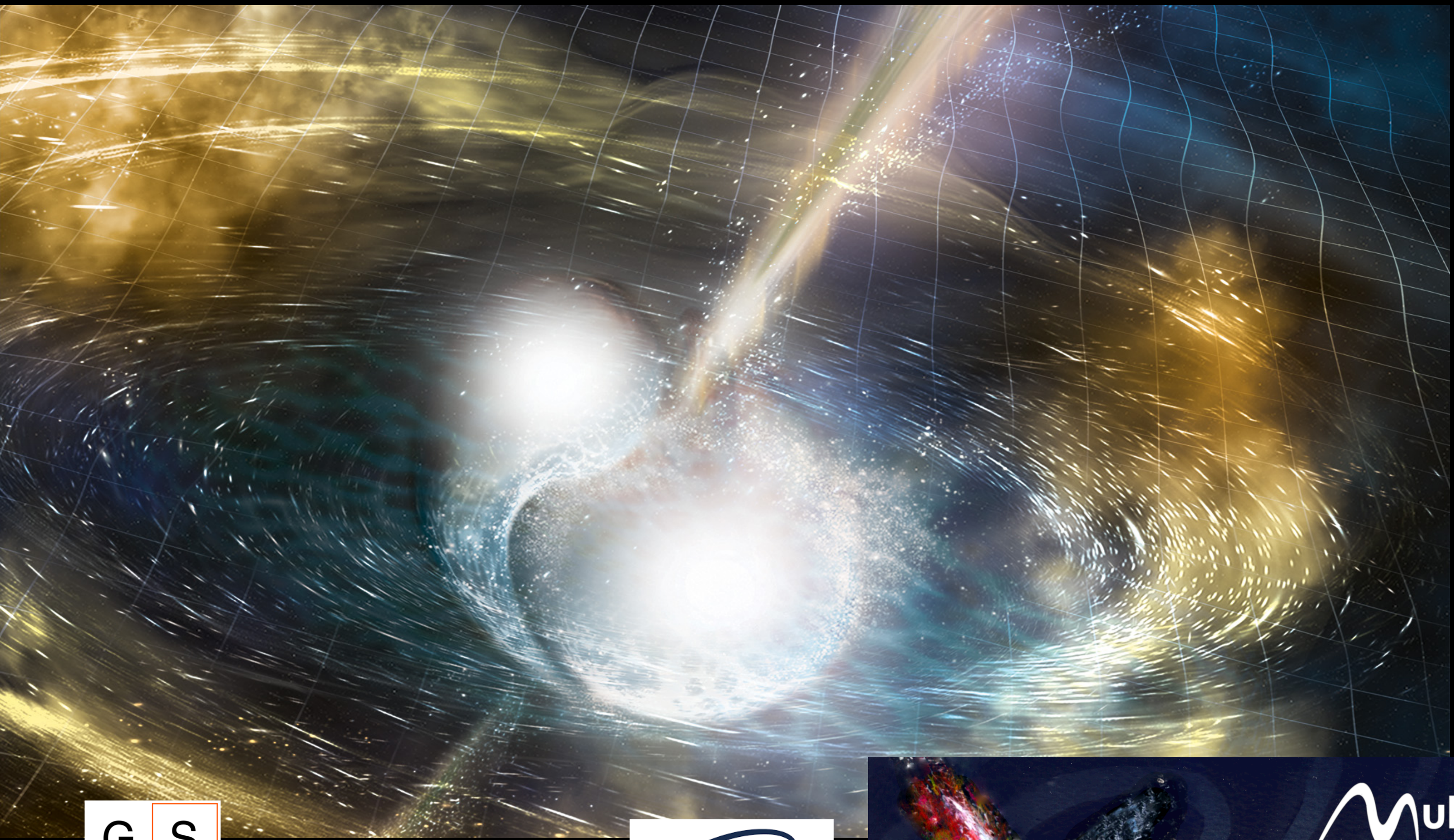
Multi-messenger Astrophysics and Gravitational Waves



GSSI

INFN Istituto Nazionale di Fisica Nucleare

INAF

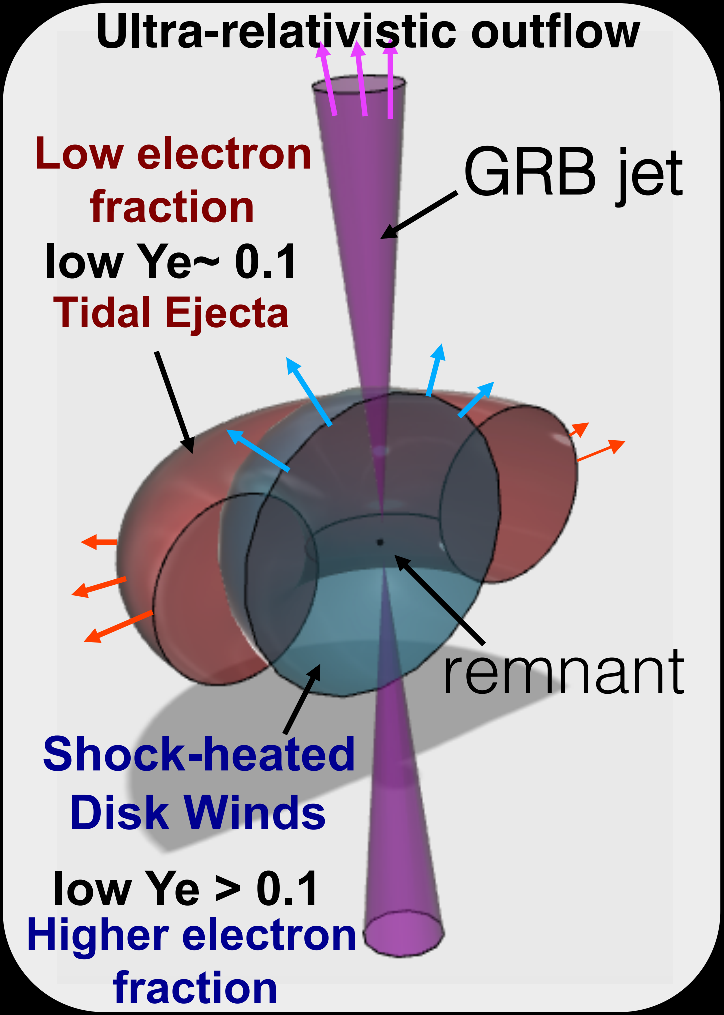
M. Branchesi

Gran Sasso Science Institute

INFN/LNGS and INAF

Thermal-emission

Geometry and color of the different ejecta components



Courtesy of S. Ascenzi

Tidal Ejecta → **Red Macronova "equatorial"**

unbound by hydrodynamic interaction and gravitational torques

Peaks at days - 1 week after the merger

Secular – isotropic

accretion disk matter unbound by viscous and nuclear heating

Shock-heated → **Blue Macronova "Polar"**

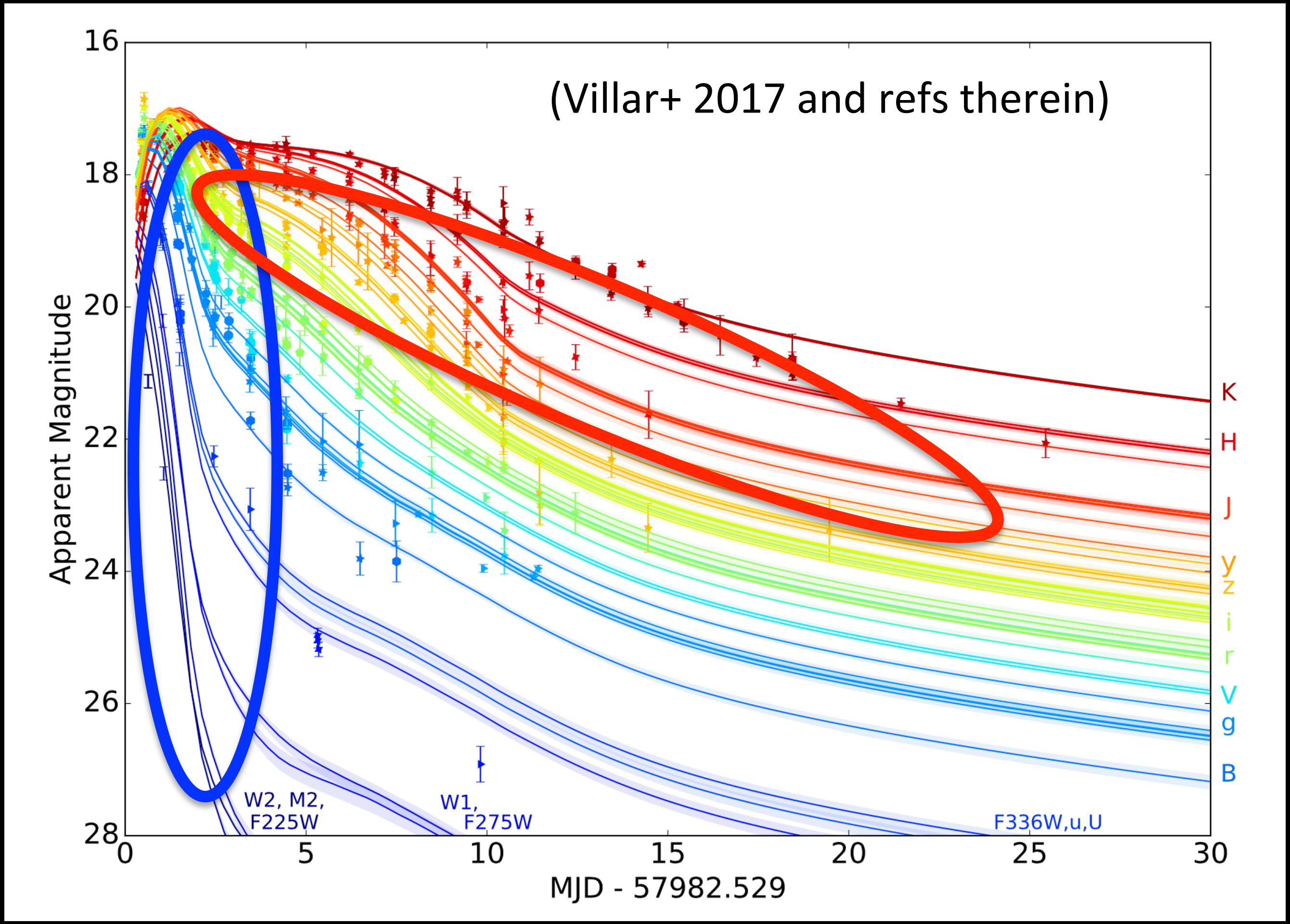
squeezed matss at NS contact interface ejected by remnant pulsations

Peaks at 1-2 day after the merger

Disk Winds

neutrino absorption or magnetically launched winds

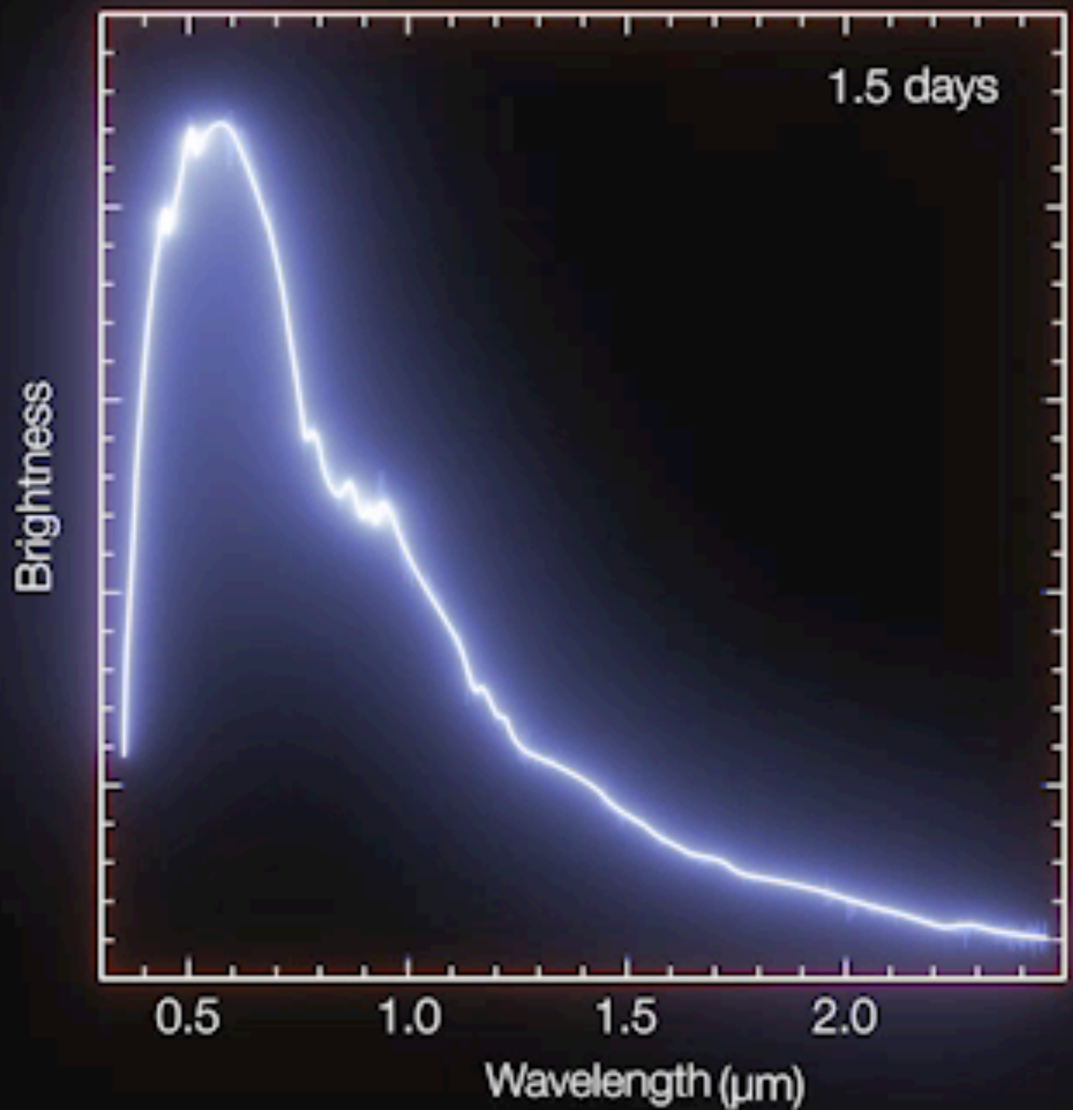
UV/Optical/NIR Light Curves



Extremely well characterized photometry of a Kilonova:

thermal emission by radiocative decay of heavy elements synthesized in multicomponent (2-3) ejecta!

ESO-VLT/X-Shooter



First spectral identification of the kilonova emission

- the data revealed signatures of the radioactive decay of **r-process nucleosynthesis**

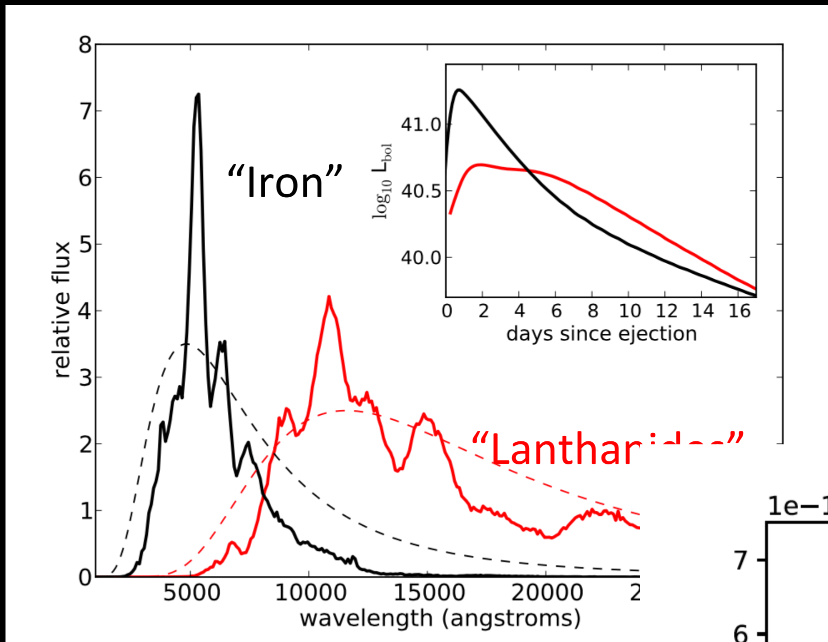
(Pian et al. 2017, Smartt et al. 2017)

- BNS merger **site for heavy element production in the Universe!**

(Cote et al. 2018, Rosswog et al. 2017)

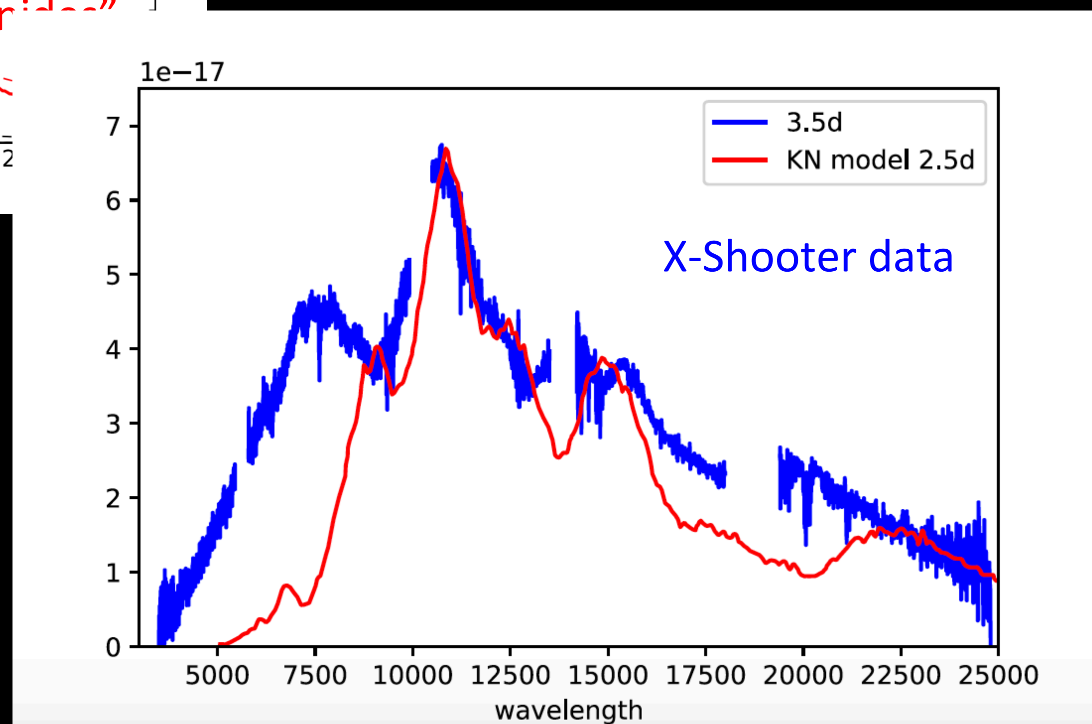
Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

NUCLEOSYNTHESIS

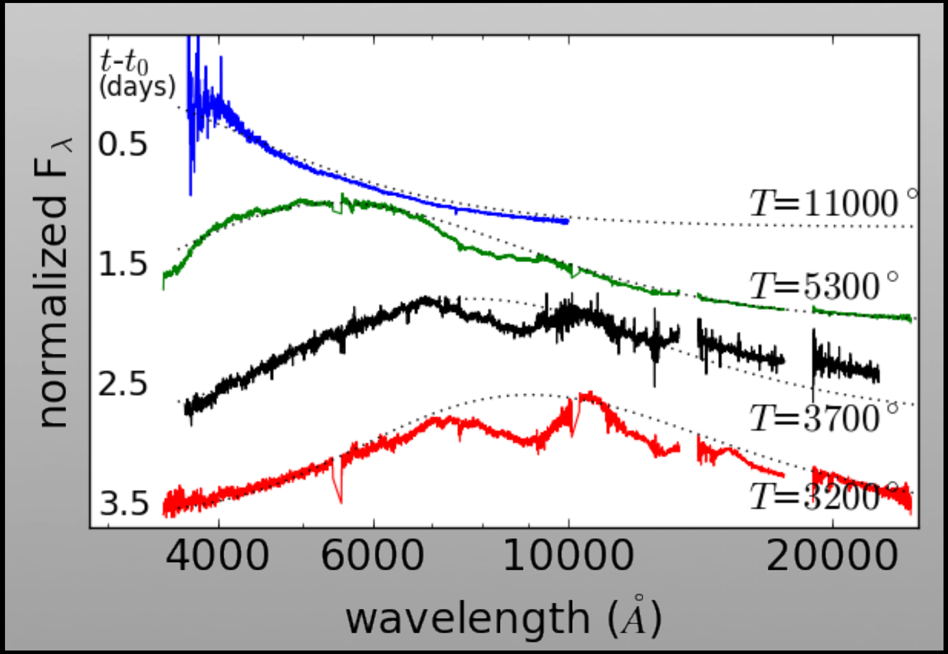


Kasen et al. 2013

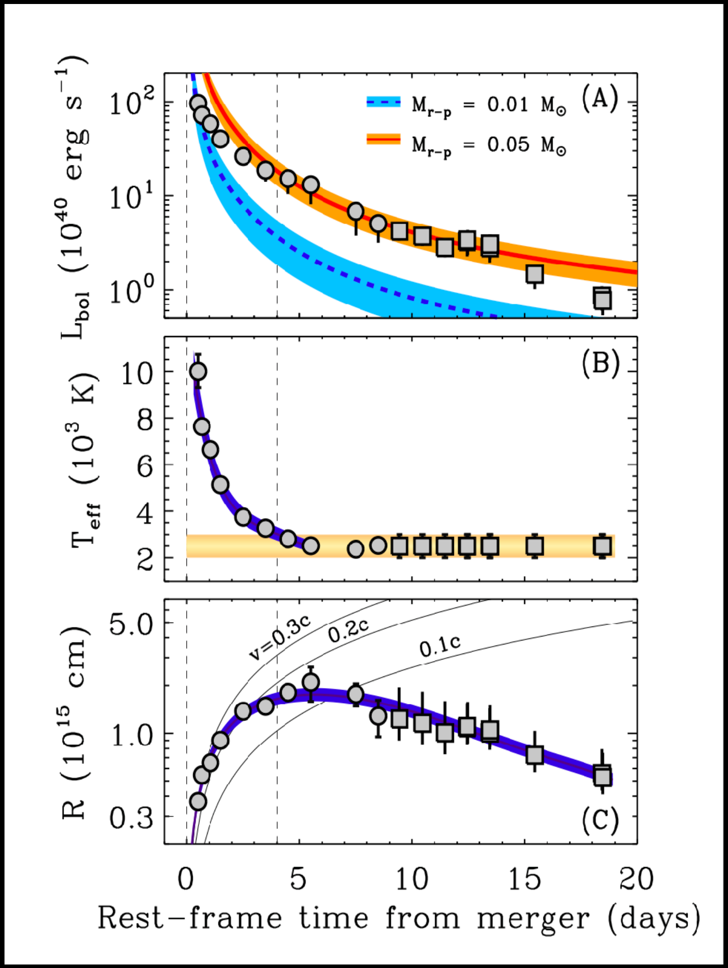
Kilonova models predict the emergence of broad features of r-process elements



Basic parameters



Drout et al. 2017



Bolometric luminosity decline

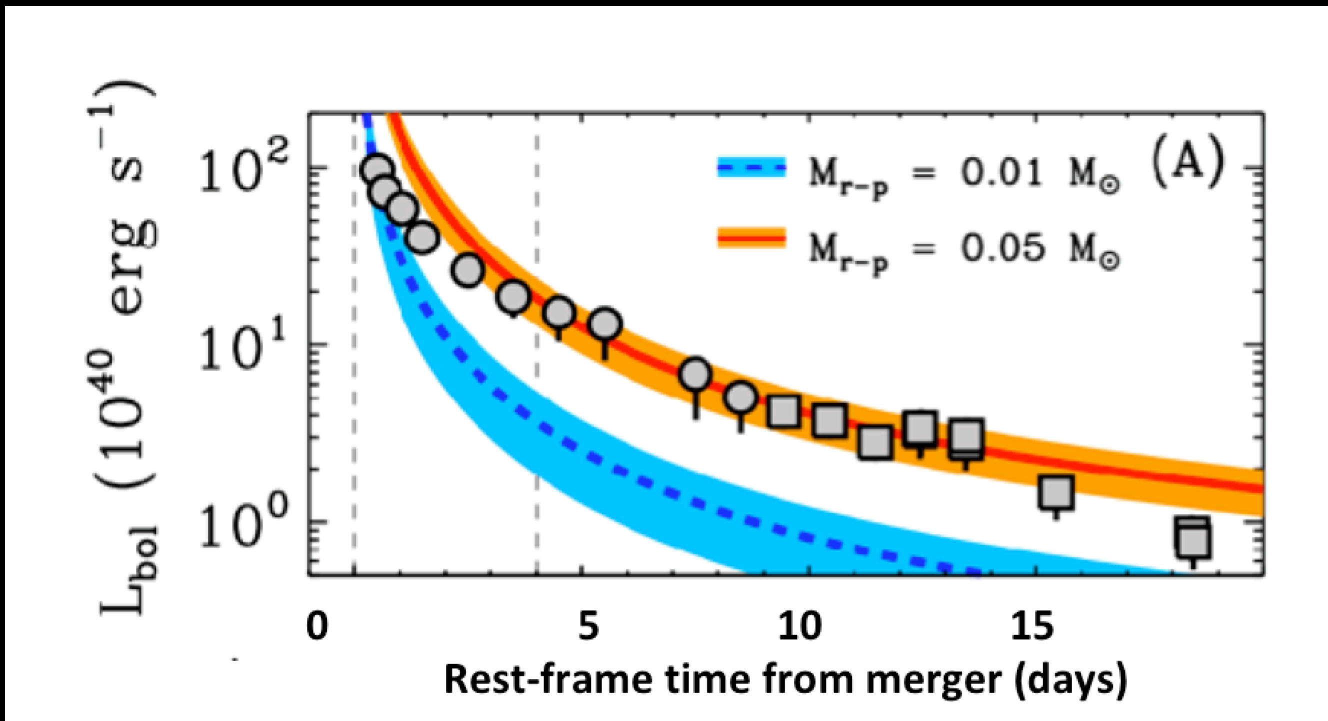
Very rapid expansion and cooling in 4 days

Then remains temperature almost constant.

→ **EJECTED MASS ~ 0.03 – 0.05 $M_{\odot}$**

→ **EXPANSION VELOCITY IS OF 0.3 -0.1 C**

BASIC PHYSICAL PARAMETERS DERIVED FROM THE ULTRAVIOLET TO NEAR-INFRARED KILONOVA EMISSION



$$L_r = \epsilon_{\rm th}\dot{q}_r M_r$$

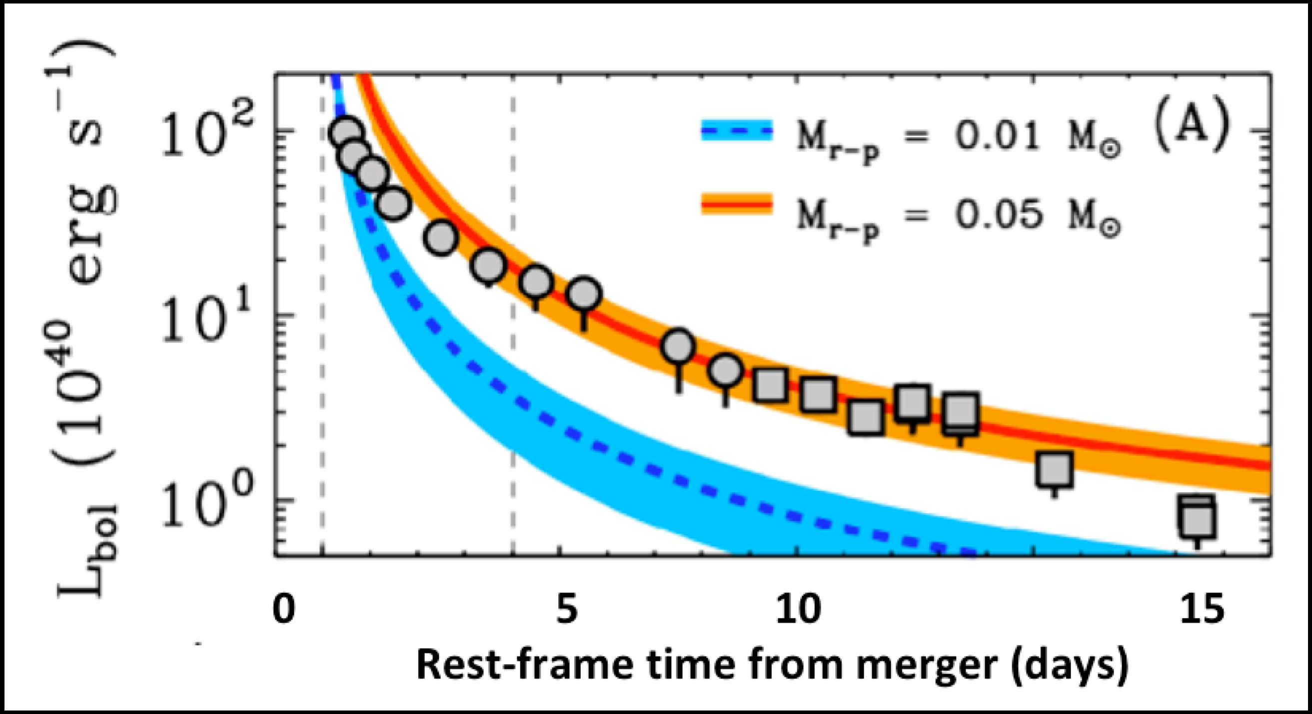
HEATING RATE

$$\dot{q}_r = 3 \times 10^{10} t_{\rm day}^{-1.3}\, {\rm erg\, s^{-1}\, g^{-1}}$$

THERMALIZATION EFFICIENCY

$$\epsilon_{\rm th} = 0.36 \left[\exp(-a t_{\rm day}) + \frac{(1 + 2bt^d)}{2bt_{\rm day}^d} \right]$$

BASIC PHYSICAL PARAMETERS DERIVED FROM THE ULTRAVIOLET TO NEAR-INFRARED KILONOVA EMISSION



- REPRESENTATIVE R-PROCESS RADIOACTIVE HEATING CURVES:

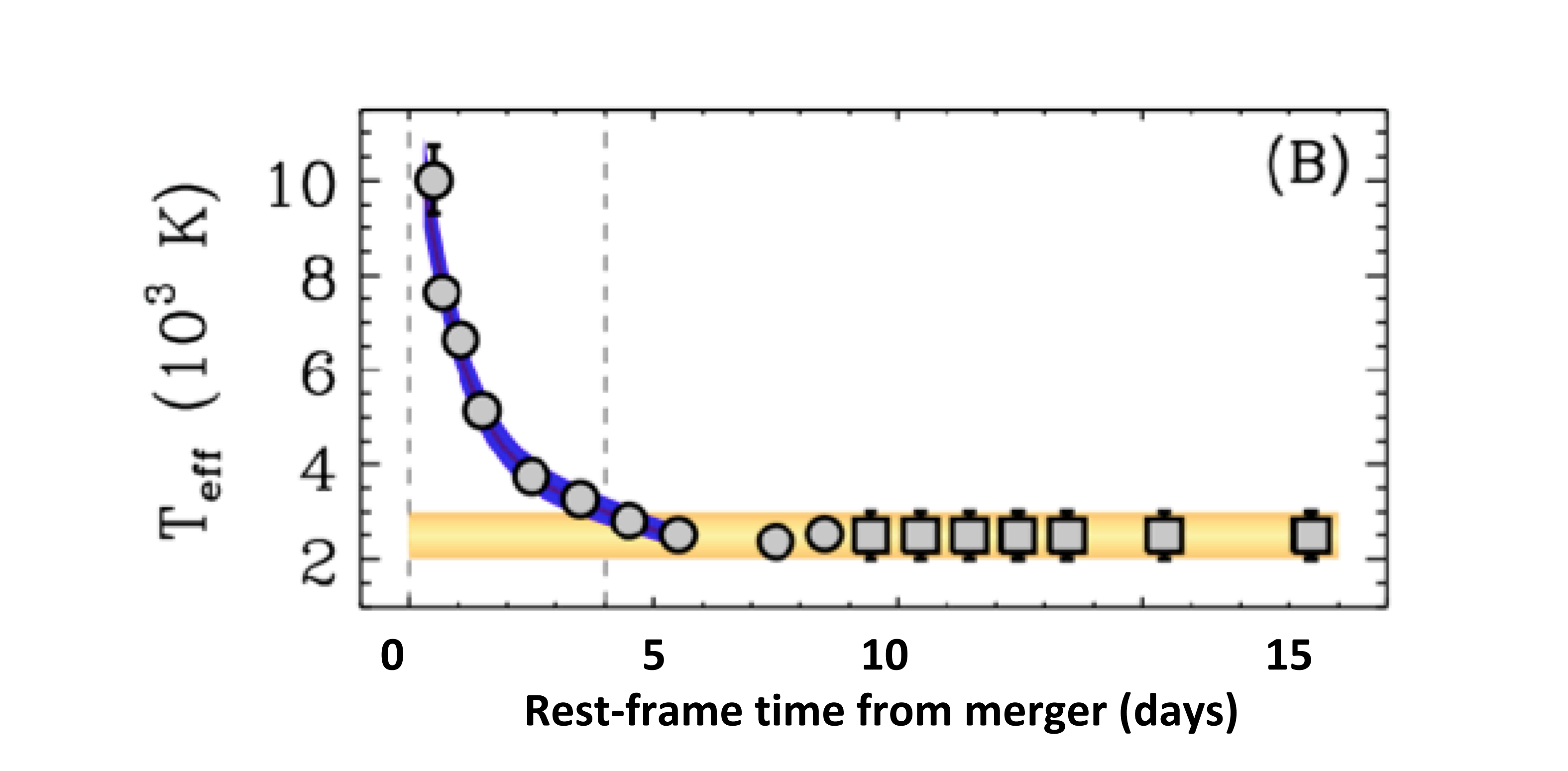
~0.01 $M_\odot$ of r-process material (blue curve) −EARLY TIME

~0.05 $M_\odot$ of r-process material (red curves) – LATE TIME

Stefan-Boltzman law relates bolometric luminosity, surface area, and temperature

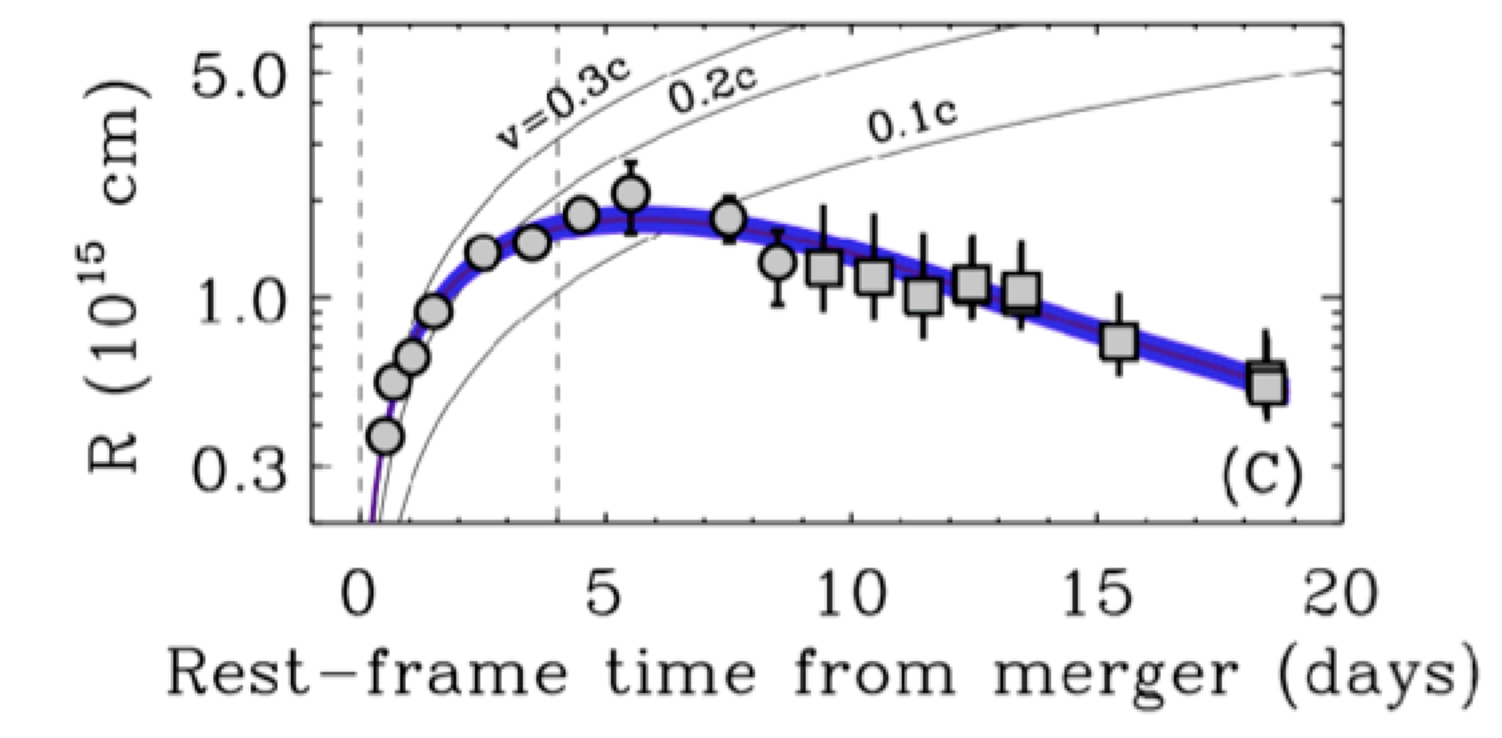
$$L = 4\pi R^2 \sigma T_e{}^4$$

BEST-FITTING BLACK-BODY MODEL TEMPERATURES



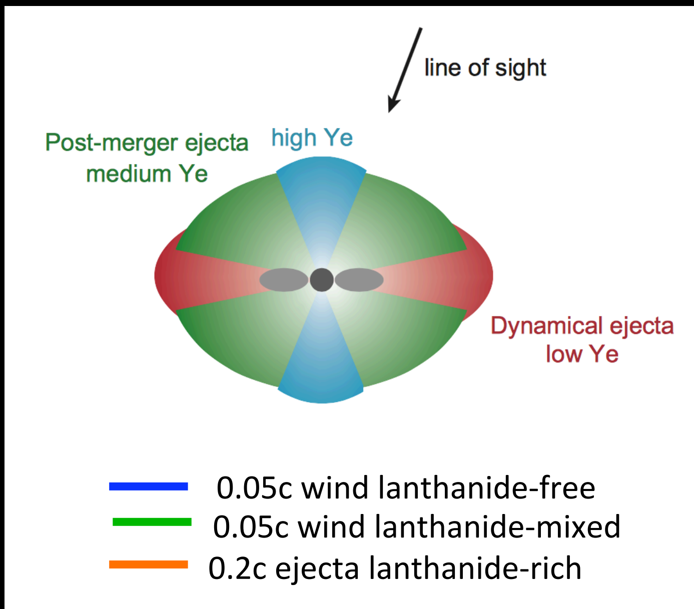
- Between 4.5 and 8.5 days, the temperature asymptotically approaches ~2500K
- At 2500K→ recombination of open f-shell lanthanide elements, rapidly reduced opacity and photsphere move inward (square in the plot)

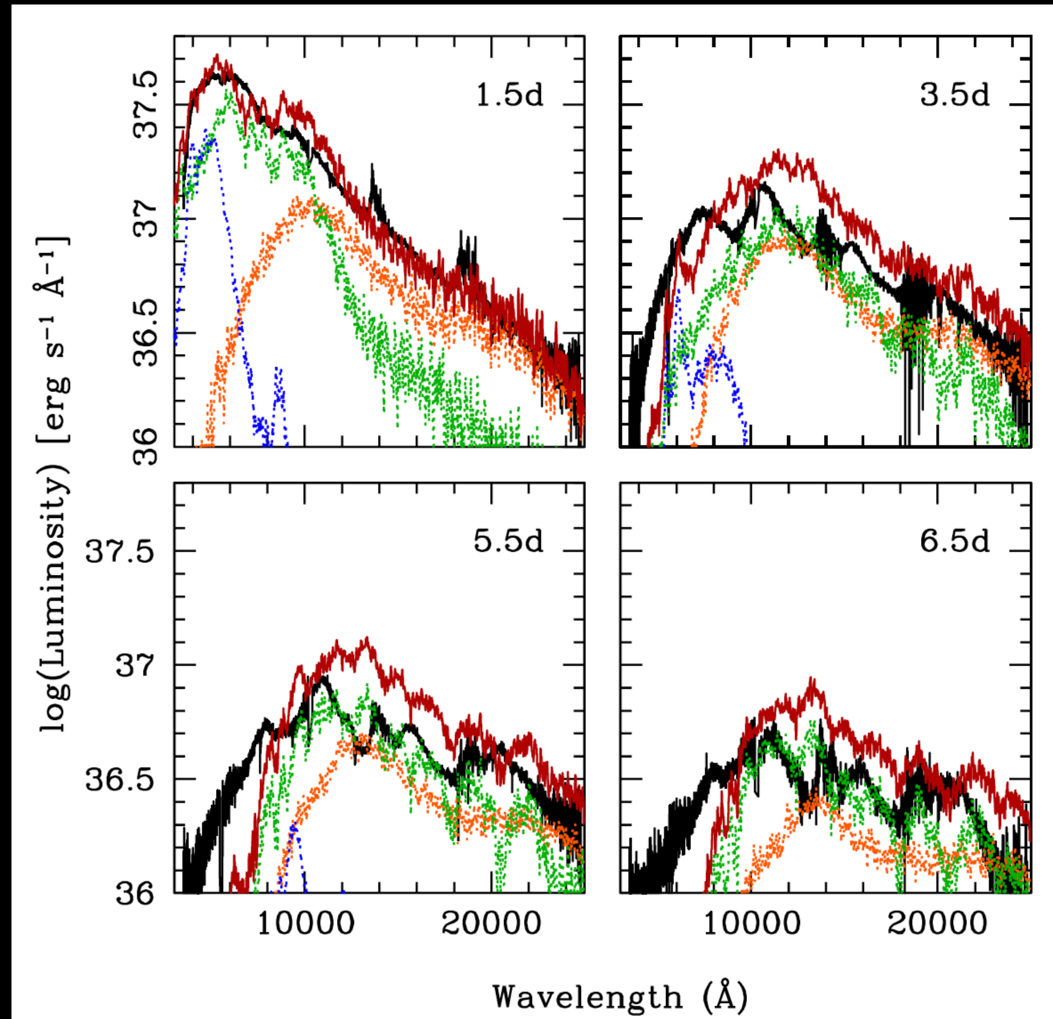
BEST-FITTING BLACK-BODY MODEL RADII



- Curved lines represent the radius of material moving at 10%, 20%, and 30% the speed of light.
- First days the radius increase with time implies that the ejecta (photosphere) expands at relativistic speeds
- after about 5 days, the measured radii decrease, likely due to recombination the photosphere begins moving inward.

Multi-component kilonova emission (Pian et al. 2017, Nature,551, 57)



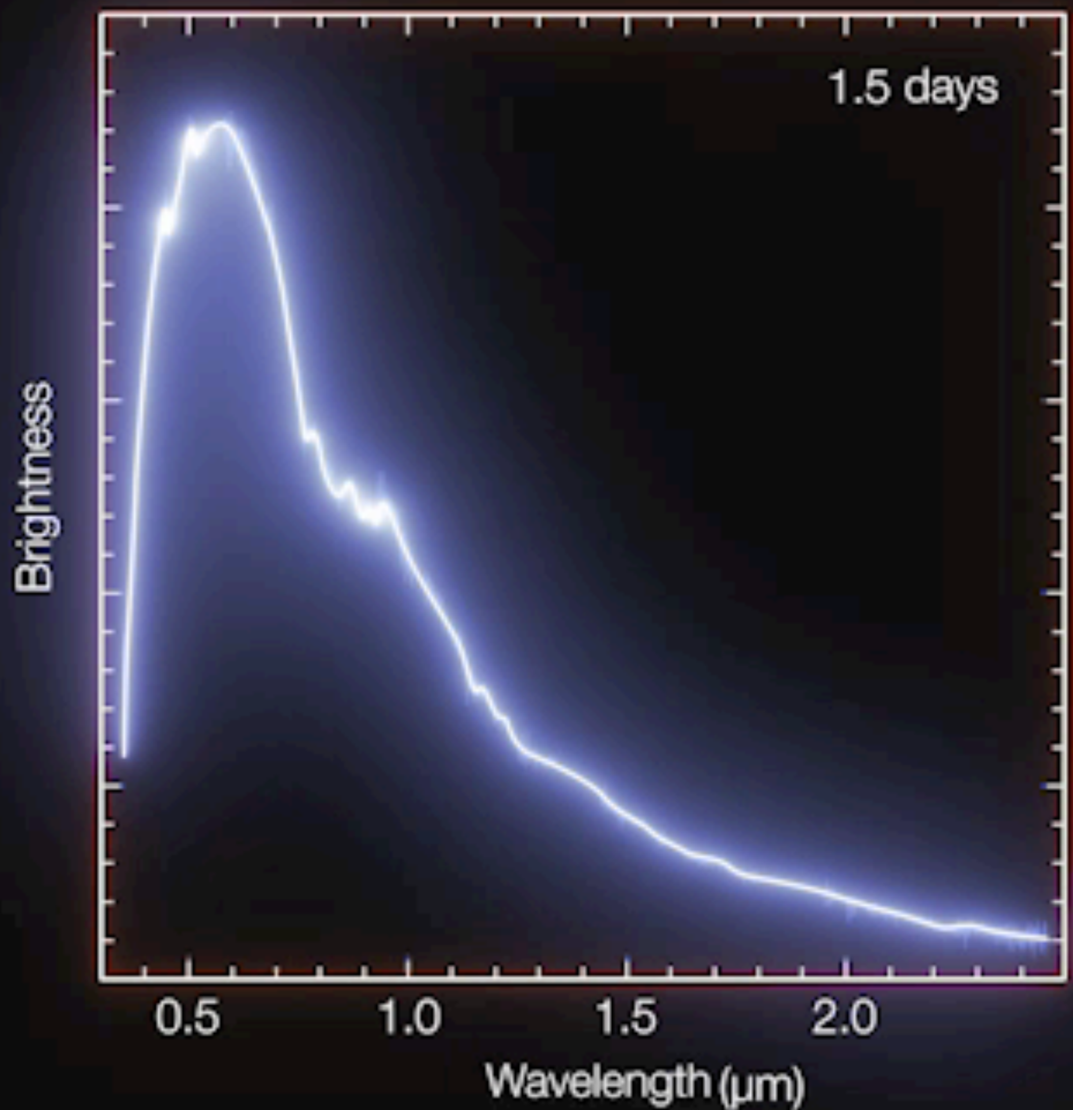


Best fit requires three components

ejected mass ~ 0.03 – 0.05 $M_\odot$

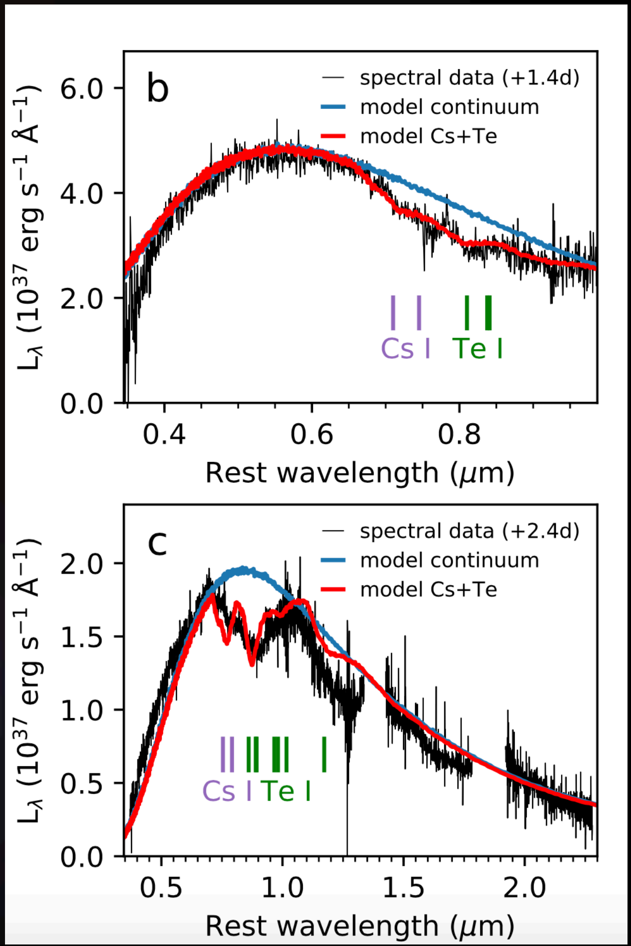
At present models are not able to reproduce consistently all the observed spectral features

ESO-VLT/X-Shooter



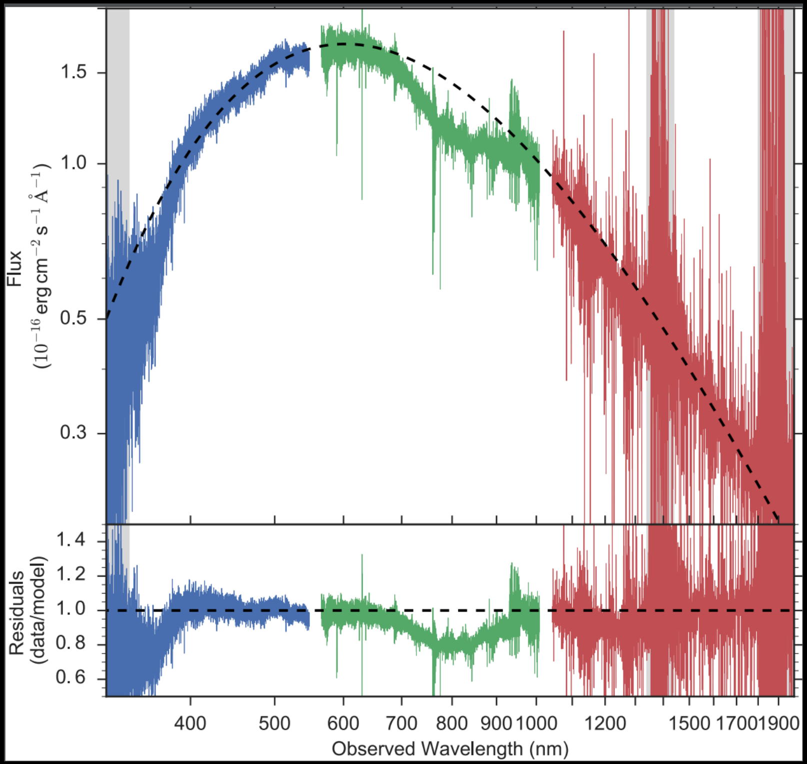
Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

Possible signatures of Cesium and Tellurium

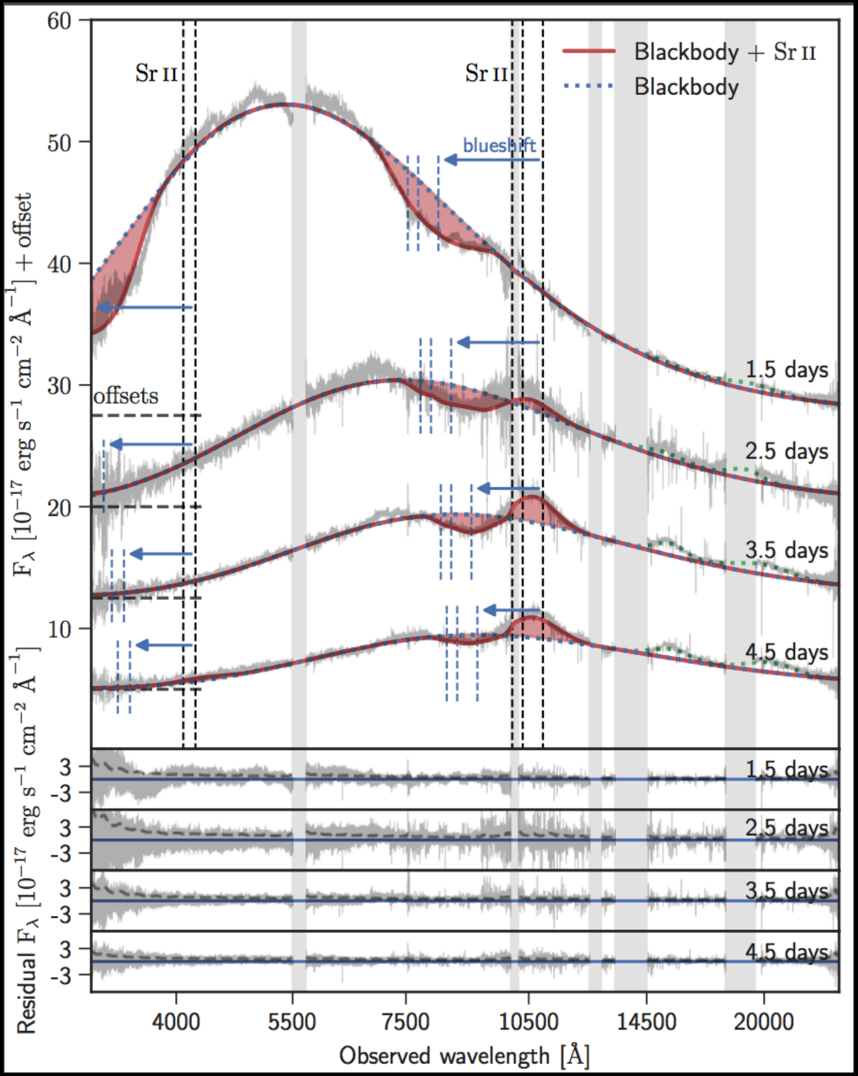


Smartt et al. 2017, Nature

A recent work…



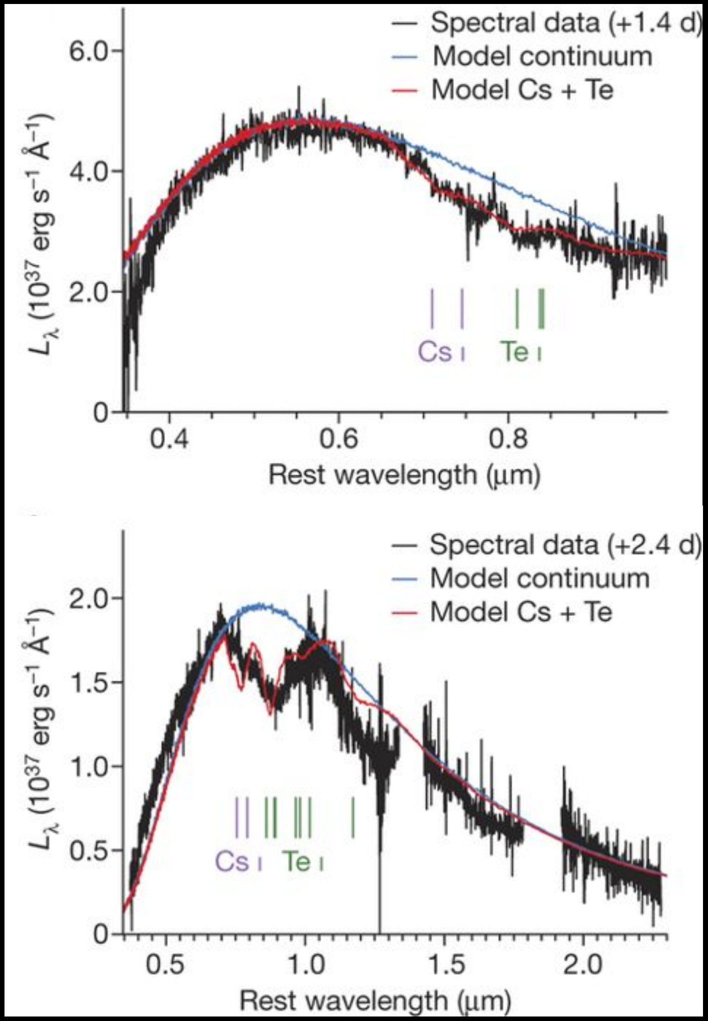
Watson, D. et al. accepted in Nature



identification of the neutron-capture element **strontium**

Nucleosynthesis

Smartt et al. 2017



Attempt to identify elements
Neutral caesium
Excited tellurium

(Gold has no optical lines ☹)

Spectral analysis hampered because of:

- heavy elements have forest of lines hence strong blending
- relativistic velocity makes for extremely broad lines (multi-components and different velocities)
- atomic data are incomplete and uncertain

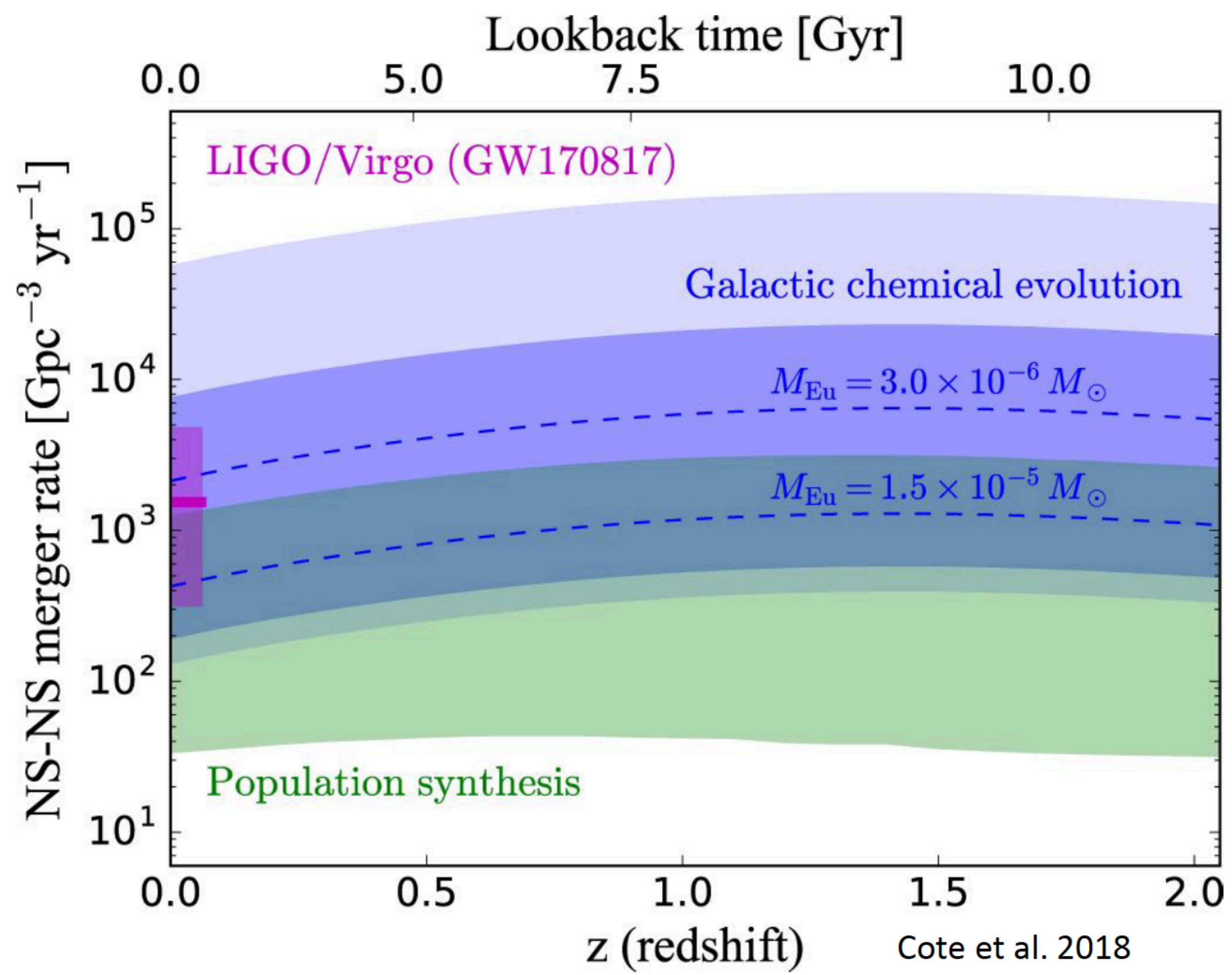
Media press..

THE BINARY NEUTRON STAR MERGERS IS A COSMIC MINE
FORGING ABOUT 100 EARTH-MASSES OF HEAVY GOLD

INFERRED RATE FROM GW170817 EXPLAIN R-PROCESS ELEMENTS ABOUNDANCE

R_{BNS}=320-4740 Gpc^{-3} yr^{-1}

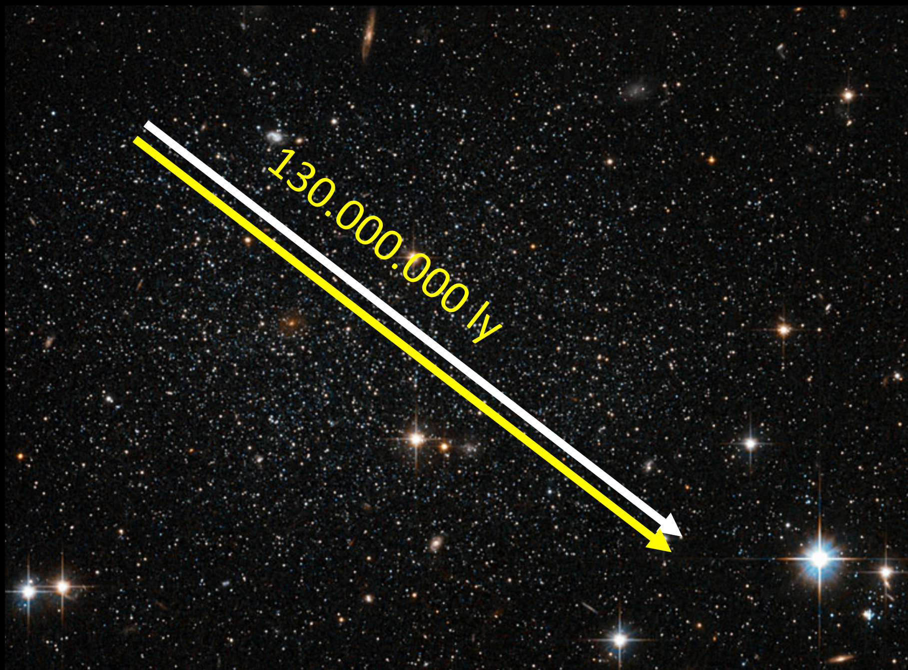
LVC 2017 PhRvL,119



Cote et al. 2018

Multi-messenger studies

GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY



GRB/GW delay

$$\Delta t = (1.74 \pm 0.05)\, s$$

and 40 Mpc distance
→ difference speed of gravity and speed of light between

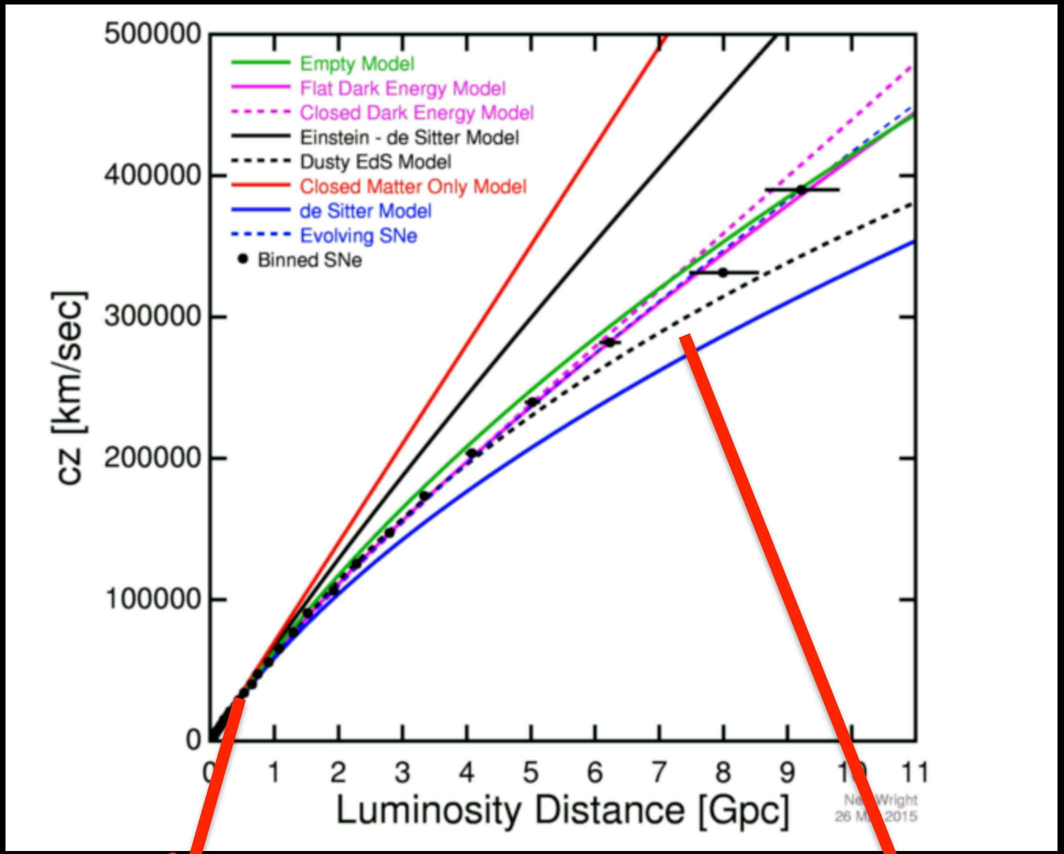
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

GWs propagate at the speed of light to within 1:10^{15}!

LVC 2017, APJL, 848, L13

Consequences of multi-messenger detection of GW170817 for cosmology →
Constraint on the speed of GWs ruled out many classes of modified gravity models
(quartic/quintic Galileons, TeVeS, MOND-like theories, see, e.g., Baker et al. '17, Creminelli & Vernizzi '17)

COSMOLOGY →HUBBLE DIAGRAM



slope of the trend determines present normalized expansion rate, the LOCAL HUBBLE COSTANT H0

shape of the trend at large redshifts determines the global GEOMETRY OF THE UNIVERSE

Observations to determine z - dL(z), which depends on cosmology via H(z)

$$d_L(z) = c\,(1+z)\int_0^z \frac{1}{H(z')}dz'$$

GRAVITATIONAL-WAVE COSMOLOGY

Independent determination of the present-day expansion rate of the Universe, using binary system as STANDARD SIREN (Schutz Nature1986)

GWs from binary inspiral as measured in a single detector

$$h_+ = \frac{2(1+z)\mathcal{M}}{D_L}[\pi(1+z)\mathcal{M}f]^{2/3}(1+\cos^2\iota)\cos 2\Phi_N(t),$$
$$h_\times = -\frac{4(1+z)\mathcal{M}}{D_L}[\pi(1+z)\mathcal{M}f]^{2/3}\cos\iota\sin 2\Phi_N(t),$$

Lowest order contribution to the orbital phase

Frequency

Chirp mass

$$\Phi_N(t) = \Phi_c - \left[\frac{t_c - t}{5(1+z)\mathcal{M}}\right]^{5/8}$$

$$f \equiv \frac{1}{\pi}\frac{d\Phi_N}{dt}$$

$$\Phi_N(t) = \Phi_c - \left[\frac{t_c - t}{5(1+z)\mathcal{M}}\right]^{5/8}$$

→

$$(1+z)\mathcal{M}$$

↘

$$h_+ = \frac{2(1+z)\mathcal{M}}{D_L}[\pi(1+z)\mathcal{M}f]^{2/3}(1+\cos^2\iota)\cos 2\Phi_N(t),$$

$$h_\times = -\frac{4(1+z)\mathcal{M}}{D_L}[\pi(1+z)\mathcal{M}f]^{2/3}\cos\iota\sin 2\Phi_N(t),$$

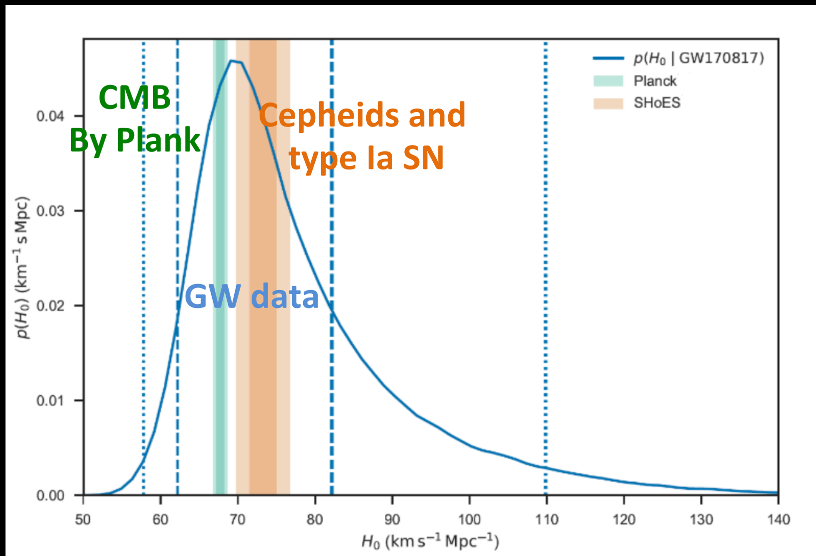
↙

D_L

Standard Siren → absolute calibration

But require independent z determination, e.g EM counterpart

GRAVITATIONAL-WAVE COSMOLOGY



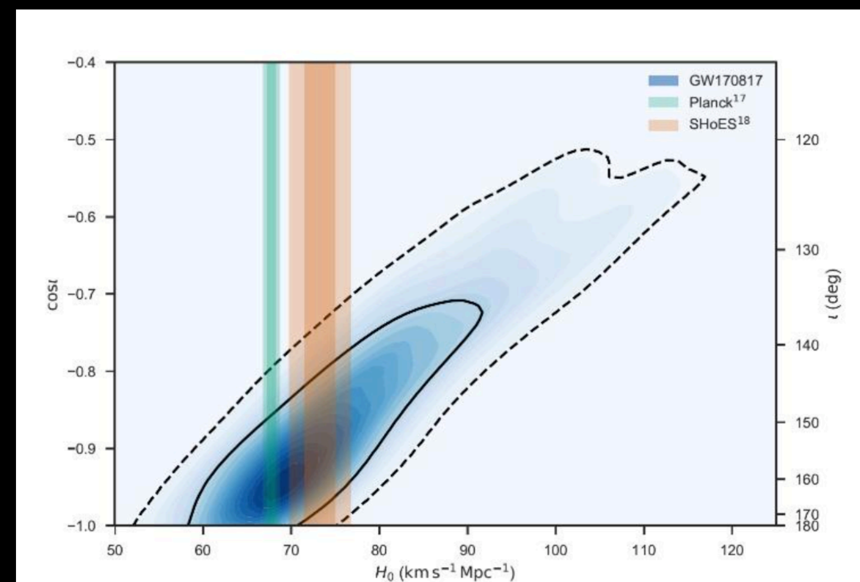
Recession velocity /redshift
GW distance

$v_H = H_0 d$ Combining the distance

measured from GWs $d = 43.8^{+2.9}_{-6.9}\,\mathrm{Mpc}$

and NGC4993 recession velocity

→ $H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

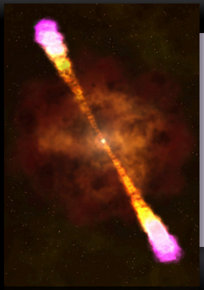


Abbott et al. 2017, Nature, 551, 85A

GRAVITATIONAL-WAVE COSMOLOGY

EM info improving GW H0 estimate:

- Break the degeneracy inclination/distance with **preicise measure of the host galaxy distance** (e.g. Surface brightness fluctuation → distance error less then 5%, Cantiello+ 2017)

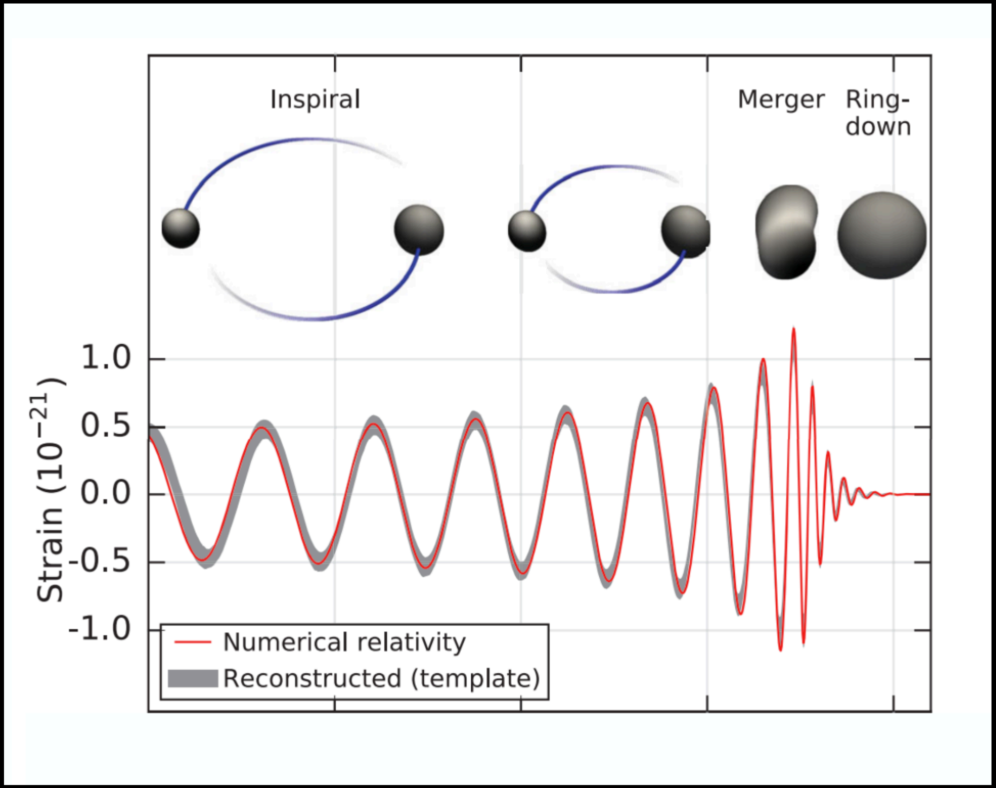


Using **inclination information from kilonova / afterglow models** (Hotokezaka+ 2018)

H0 statistical estimate, using **cross-correlation with potential host galaxies within the localization volumes**
(Chen+ 2017, arXiv:1712.06531, Fishbach+ arXiv:1807.05667)

NEUTRON STARS
NUCLEAR PHYSICS

General relativity makes detailed predictions for the inspiral and coalescence of two compact objects, which may be neutron stars or black holes.



$$q = m_2/m_1, \text{ where } m_1 \geq m_2$$

EARLY INSPIRAL **LATE INSPIRAL**

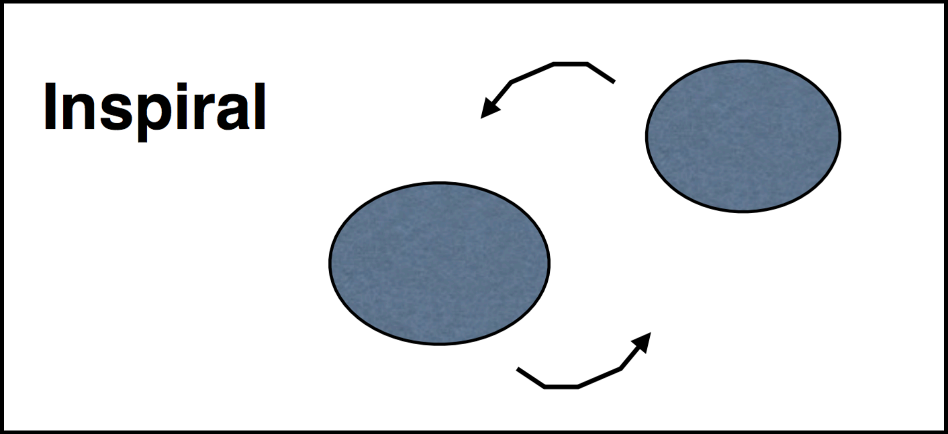
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

1- Time evolution of the frequency is determined primarily by chirp mass

2- As the orbit shrinks and GW frequency grows rapidly
→ GW phase is increasingly influenced by relativistic effects related to the mass ratio, spin-orbit and spin-spin couplings

NS EFFECT ON GW SIGNAL

The objects' internal structure become important as the orbital separation approaches the size of the bodies



Tidal deformation of each star's gravitational field on its companion induces a mass-quadrupole moment and accelerates the coalescence

TIDAL DEFORMABILITYTIDAL DEFORMABILITY → *how star gravitational potential changes when the star is squeezed by the gravity of the companion star*

Tidal effects imprinted in gravitational-wave signal through binary tidal deformability:

$$\tilde{\Lambda} = \frac{16}{13} \frac{(12q+1)\,\Lambda_1 + (12+q)\,q^4 \Lambda_2}{(1+q)^5} \qquad q = \frac{m_2}{m_1} \leq 1$$

where k2 = second Love number

R = stellar radius.

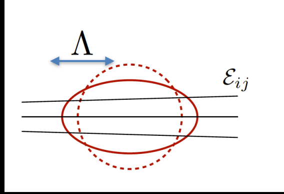
R and k2 are fixed for a given stellar mass by EOS

k2 ≃ 0.05–0.15 for realistic neutron stars

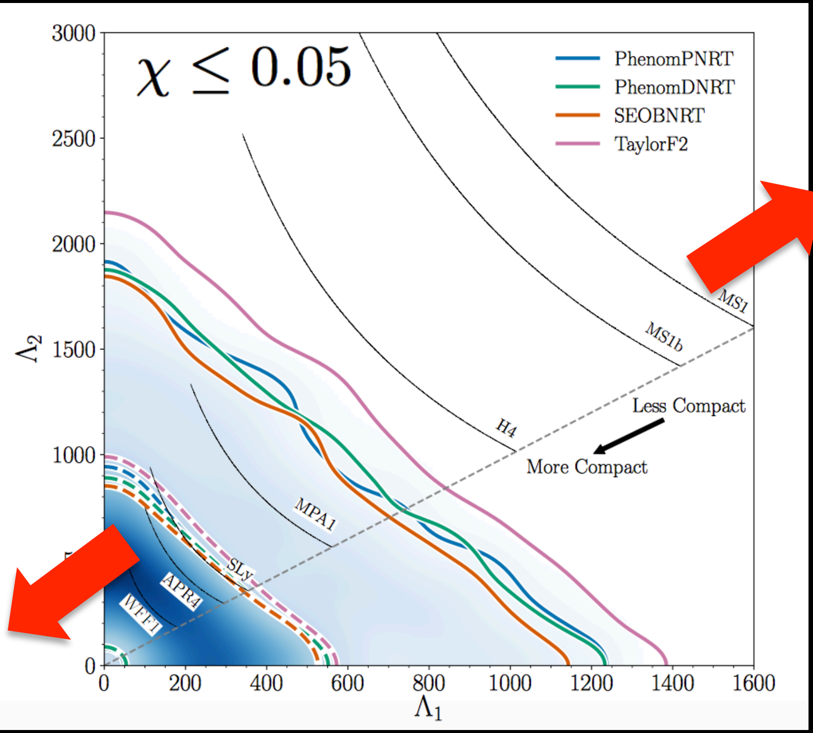
k2 = 0 for BH

Deformability of each star: $\Lambda_{1,2} = \frac{2}{3} k_2 \left(\frac{R_{1,2} c^2}{G m_{1,2}} \right)^5$

GW170817 PARAMETER ESTIMATION



- We know the location! Fix location in sky.
- Assume two NSs with properties that are described by the same EoS
- Small spin prior in agreement with galactic binary NS spin measurements

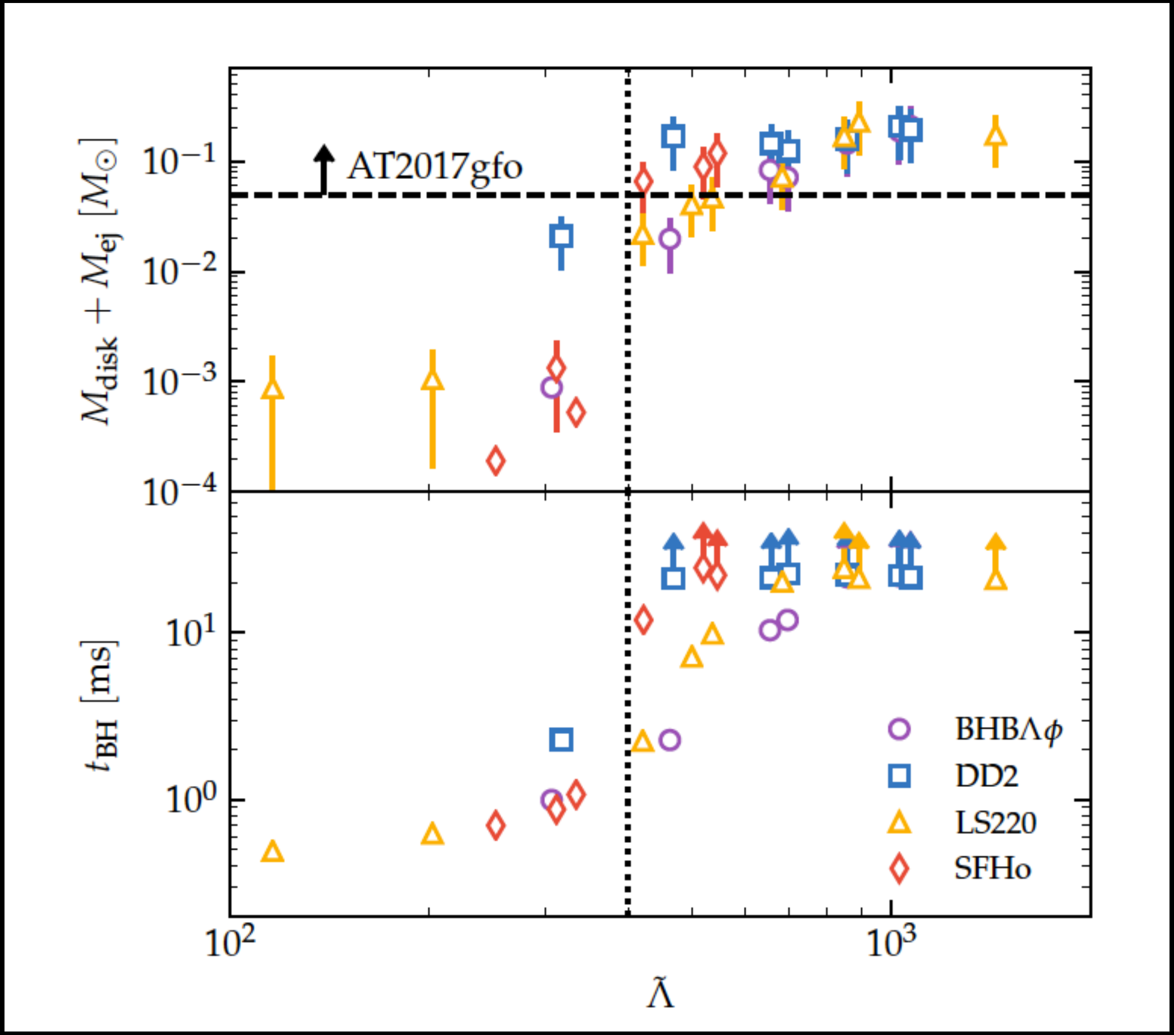


STIFF EOS: high maximum M and larger R for the same M (less compact)

SOFT EOS: low maximum M and smaller R for the same M (more compact)

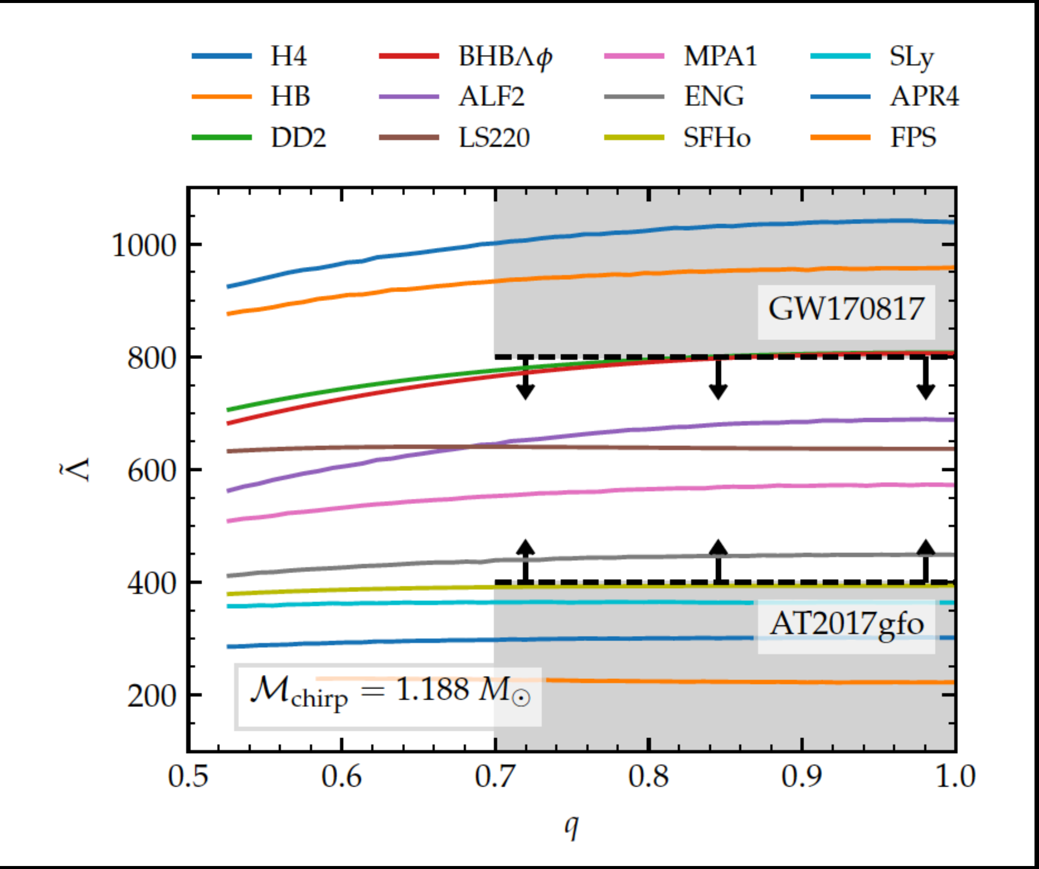
Multimessenger constraints on nuclear EOS

Simulations in NR



Multimessenger constraints on nuclear EOS

EM observations → Mej,tot > 0.05Mo suggests a lower limit Λ > 400

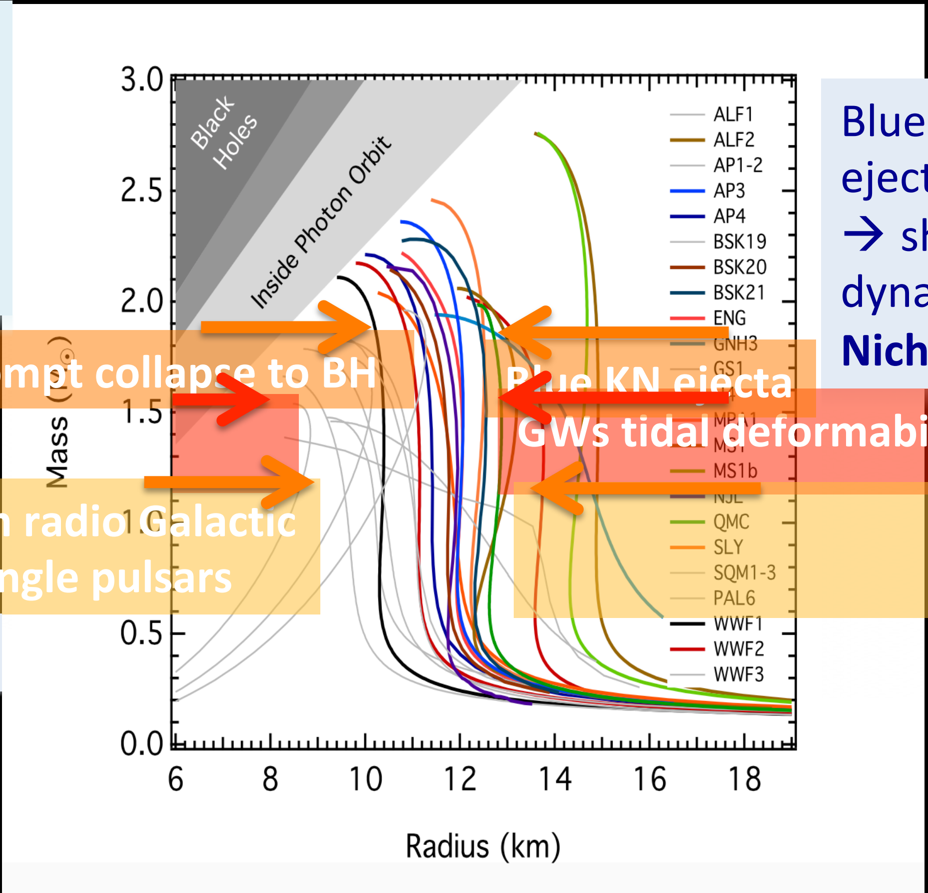


Radice, Perego, Zappa, Bernuzzi 2017

EM observations exclude very soft EOS!

EM constraints on the TYPE OF REMNANT and multi-messenger constraints on RADII and maximum MASS of (TOV) NSs

High ejecta mass
0.03 - 0.05 $M_{\odot}$
→ delayed/no collapse
GW Mtot < $M_{threshold}$
Bauswein+17



Blue component ejecta 0.2-0.3 c
→ shock-heated dynamical ejecta
Nicholl+ 17

No prompt collapse to BH

Blue KN ejecta

GWs tidal deformability (LVC 18)

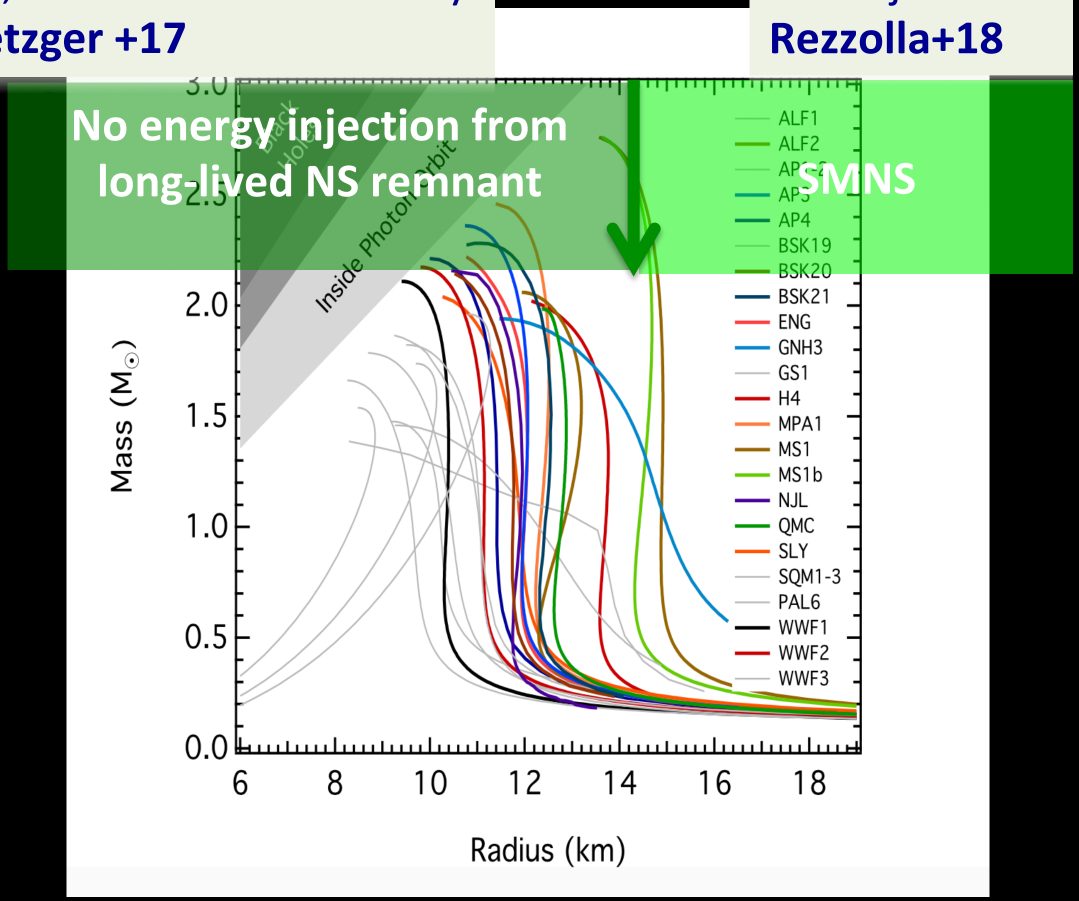
Mass priors from radio Galactic double NS, single pulsars

Soumi+ 18

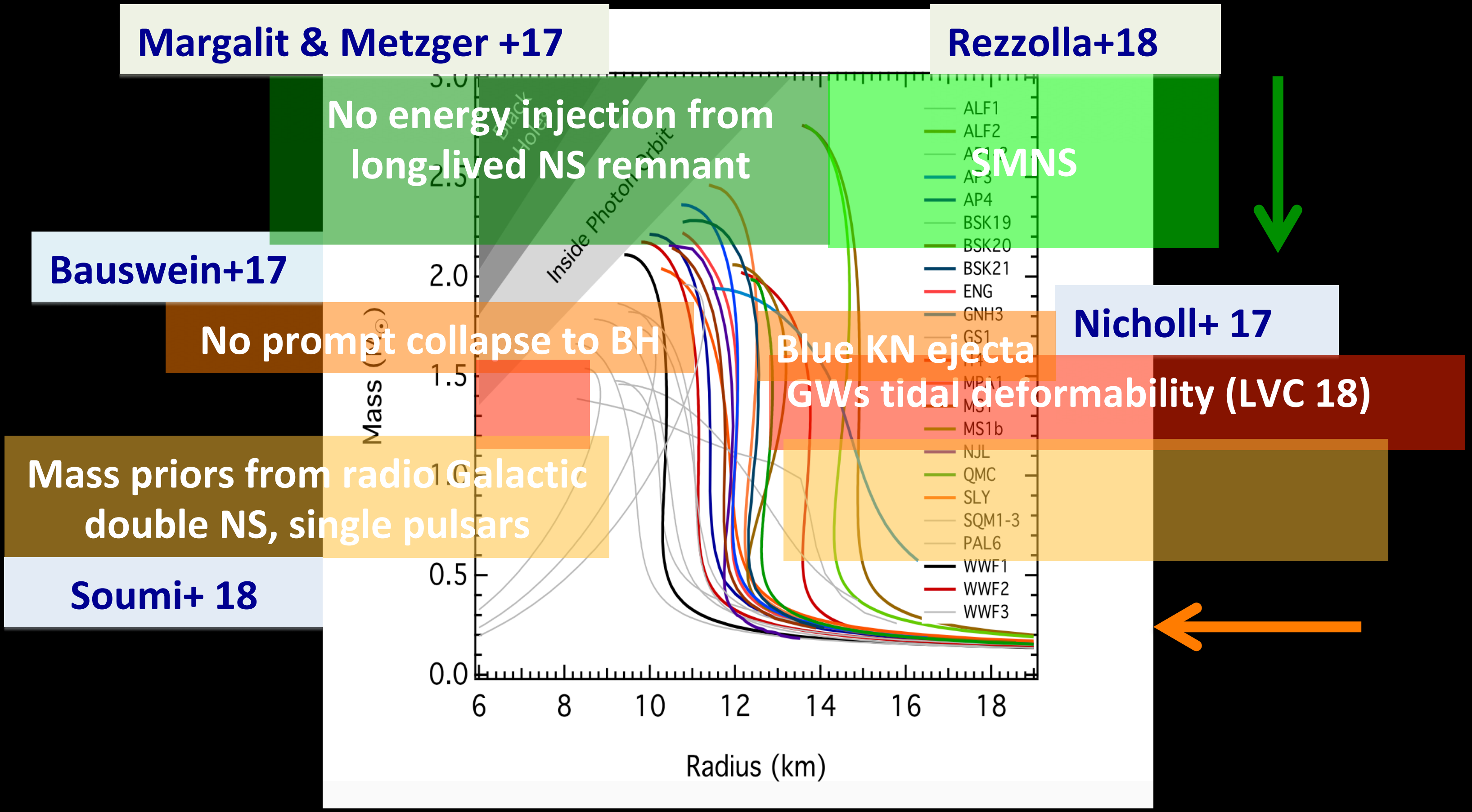
EM constraints on the TYPE OF REMNANT and multi-messenger constraints on RADII and maximum MASS of (TOV) NSs

No extended high-energy emission, moderate kinetic energy for kilonova and off-axis jet, GW mass of the binary
Margalit & Metzger +17

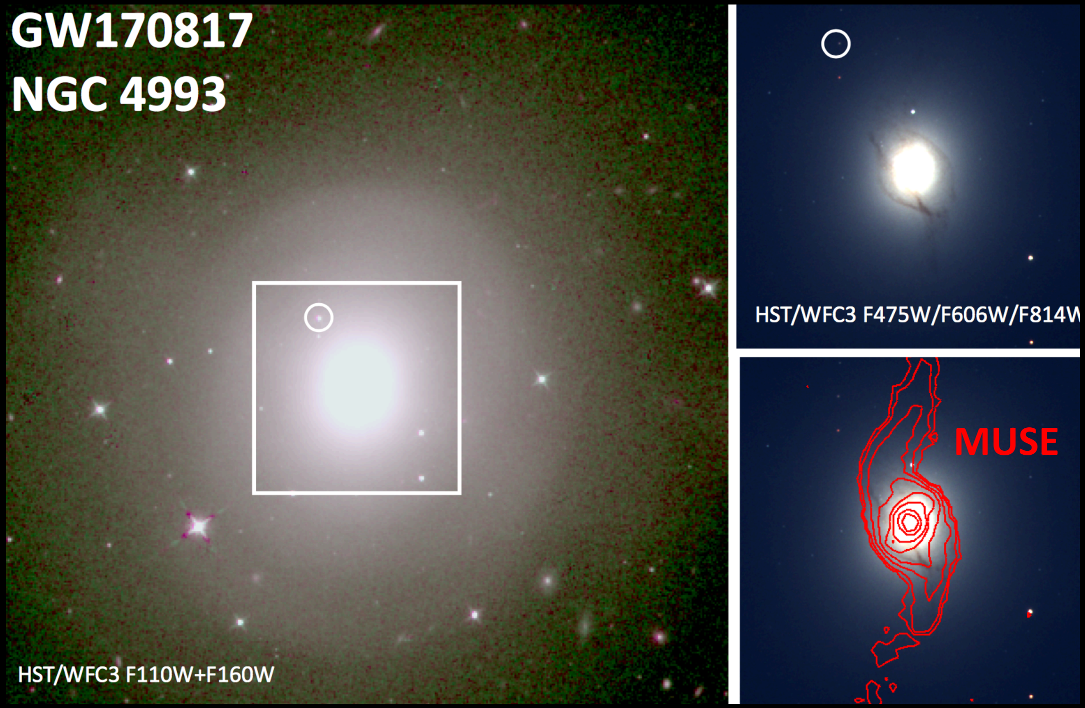
Blue ejecta
Rezzolla+18



EM constraints on the TYPE OF REMNANT and multi-messenger constraints on RADII and maximum MASS of (TOV) NSs



NGC4993 Host galaxy



Levan et al. 2017, ApJL, 848

log(M*/Msol) ~10.65
Median age ~ 11.2 Gyr
SFR ~ 0.01 Msol yr^{-1}

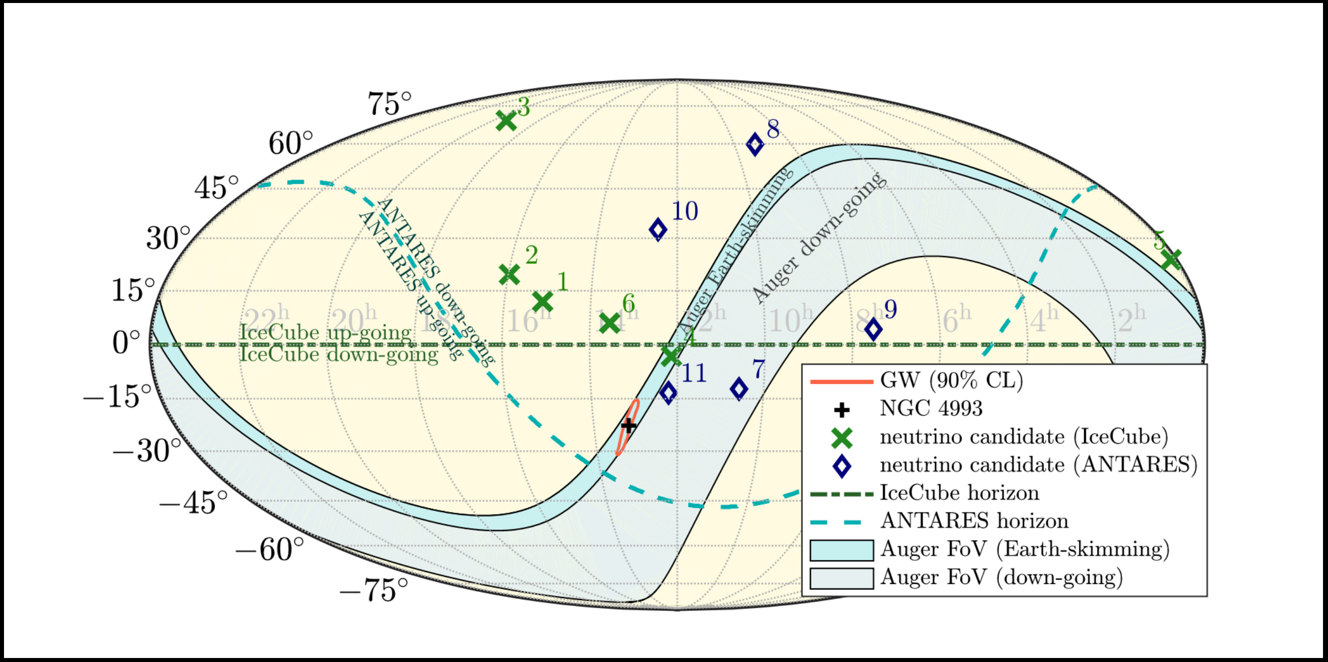
Blanchard et al. 2017

S0 galaxy at z = 0.009783

- Face-on spiral shells and edge-on spiral features → **recent (< 1 Gyr) galaxy merger**
- HST imaging → **no globular or young stellar clusters**
- **Old population** in the vicinity of GW source
- Age and offset from the galaxy center → **small natal kick velocity**

(Levan et al. 2017; Pan et al. 2017; Kasliwal et al. 2017; Im et al. 2017)

NEUTRINO SEARCHES WITH ANTARES, ICECUBE AND PIERRE AUGER OBSERVATORY

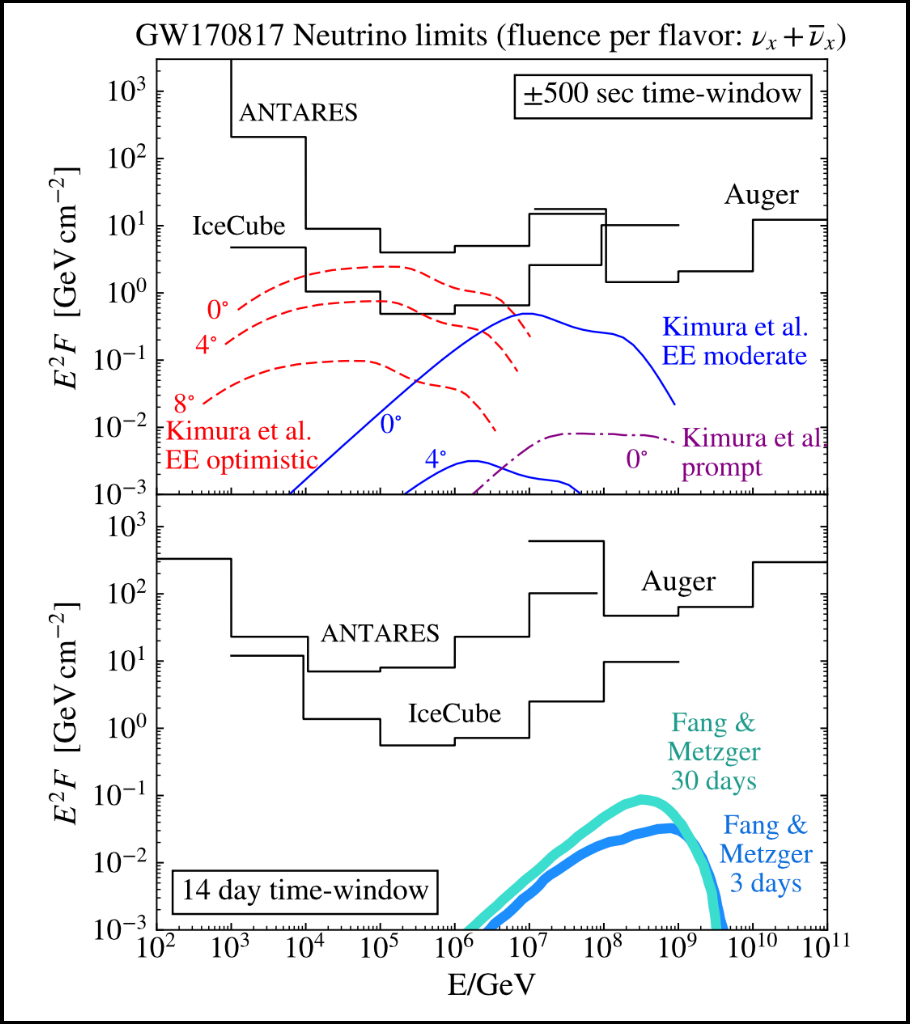


- No neutrinos directionally coincident with the source were detected within ±500 s around the merger time
- No HEN emission in the direction of the source within the 14-day period following the merger

ANTARES+IceCuce+Auger+LVC 2017, ApJ

NEUTRINO SEARCHES WITH ANTARES, ICECUBE AND PIERRE AUGER OBSERVATORY

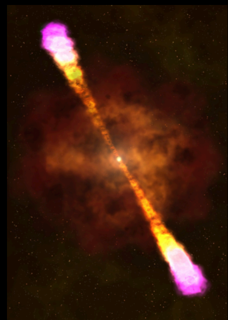
Non-detection consistent with model predictions of short GRBs observed at a large off-axis angle



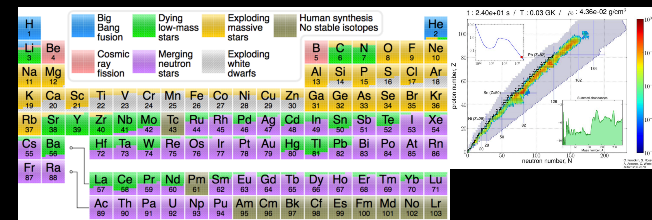
ANTARES+IceCuce+Auger+LVC 2017, ApJ

Radioactively powered transients

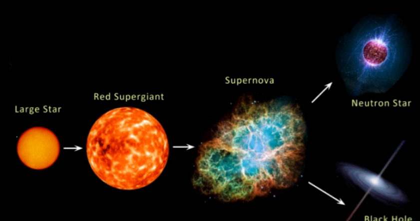
Relativistic astrophysics



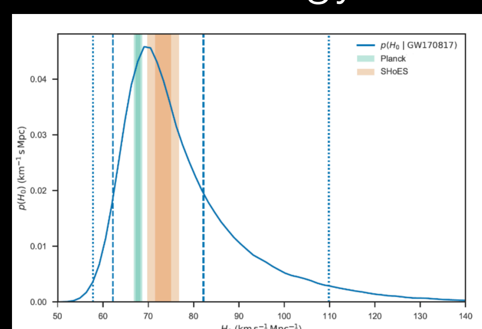
Nucleosynthesis and enrichment of the Universe



Compact object formation and evolution



Cosmology



Nuclear matter physics