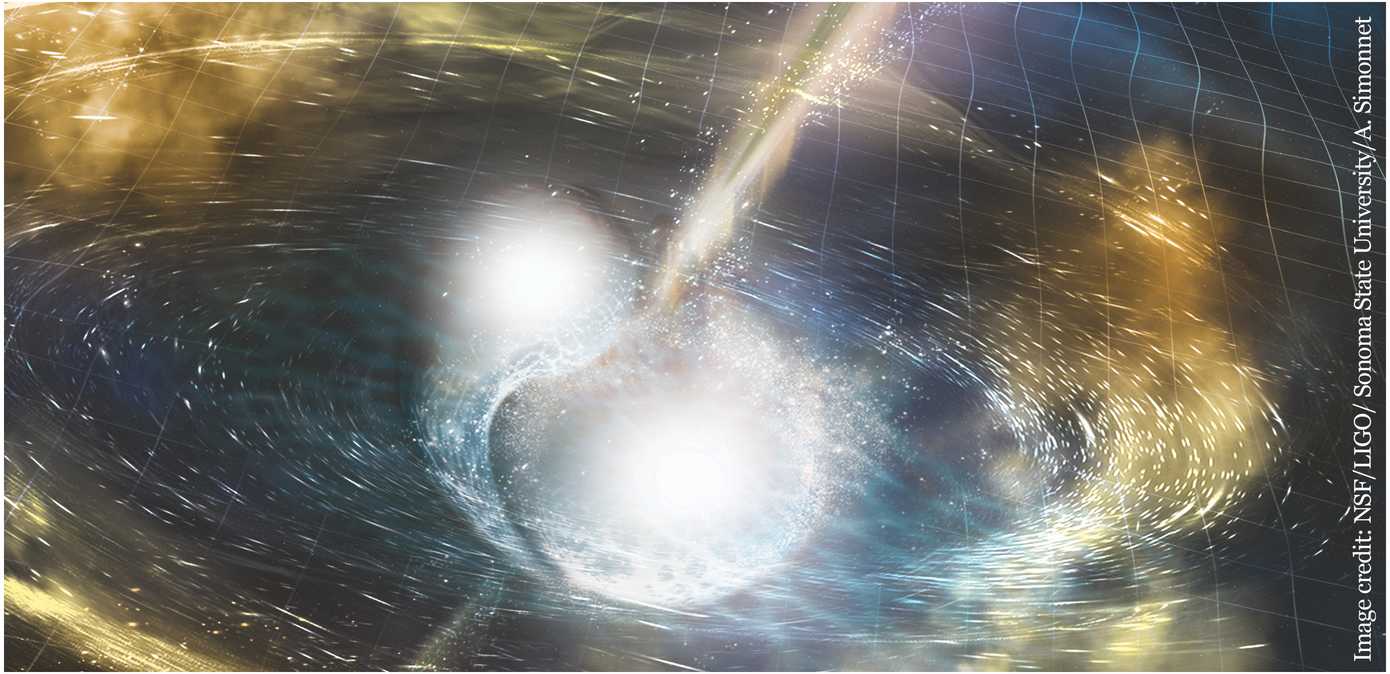
MEASURING the HUBBLE CONSTANT with KILONOVAE

Mattia Bulla

with L. Issa, S. Dhawan, M. W. Coughlin and many more

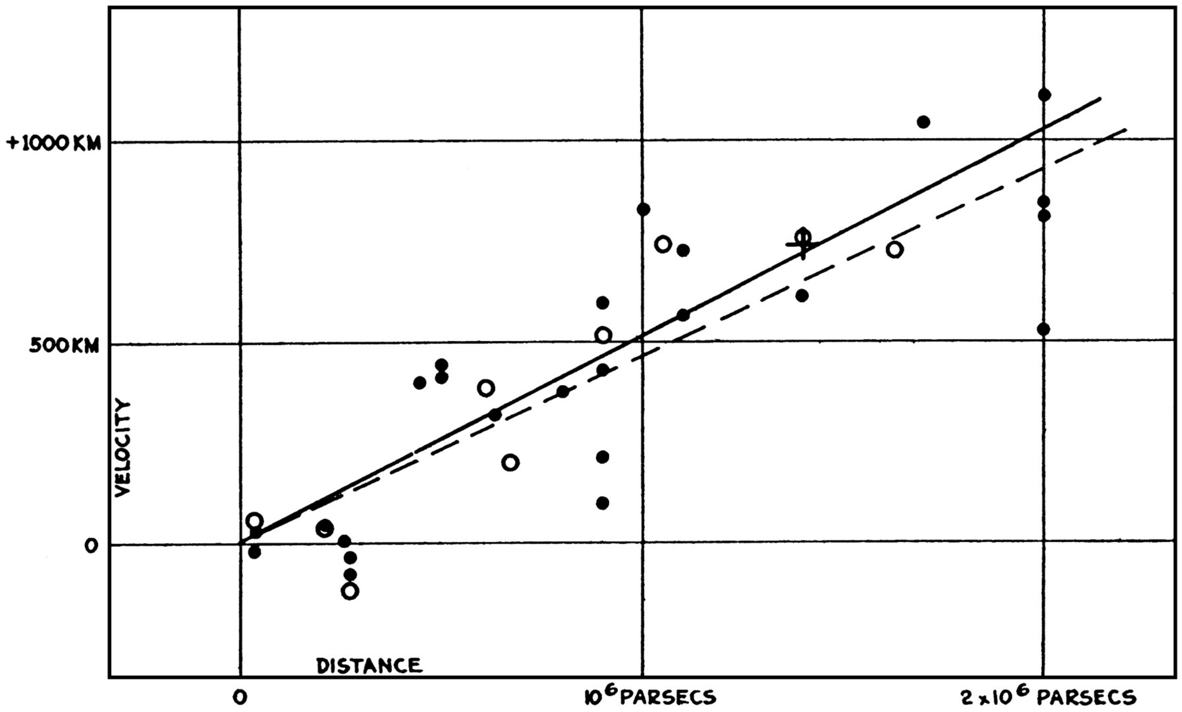
NORDITA



The Hubble constant H_o

The expansion rate of our Universe

Hubble 1929



$$H_o = \frac{\text{Velocity}}{\text{Distance}}$$

$H_o \sim 500$ km s^{-1} / Mpc

The Hubble constant H_o

The expansion rate of our Universe

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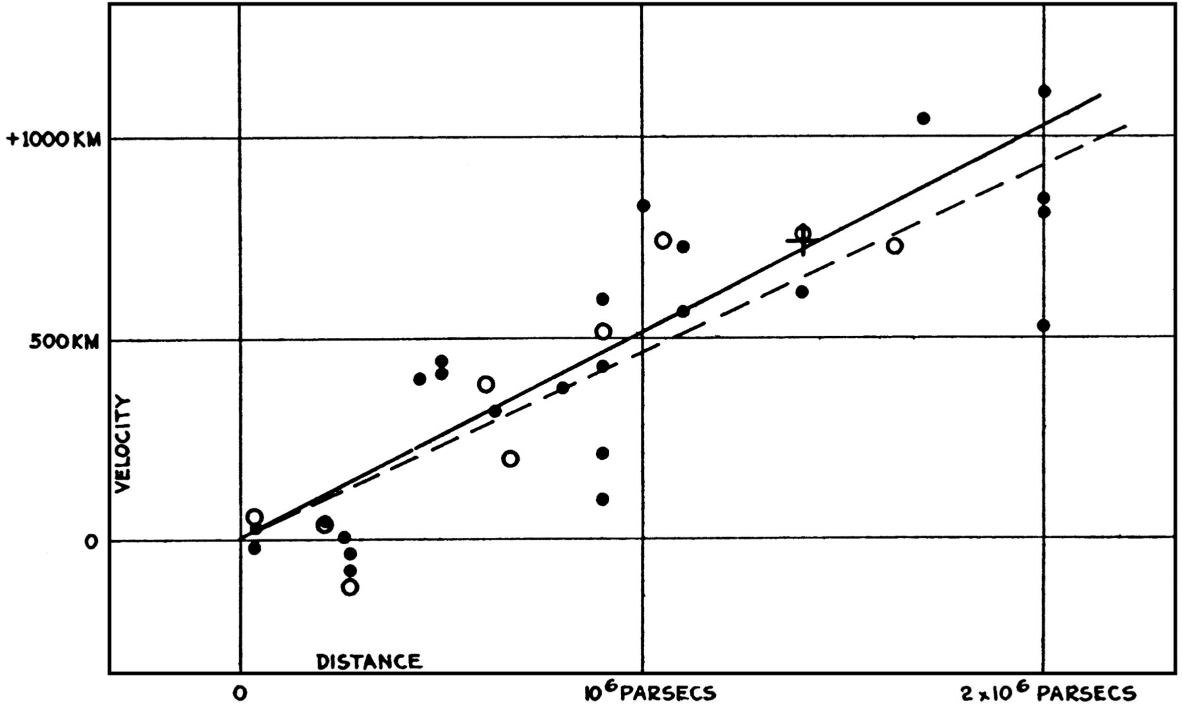


$$H_o = \frac{\text{Velocity}}{\text{Distance}}$$

H_o ~ 500 km s^{-1} / Mpc

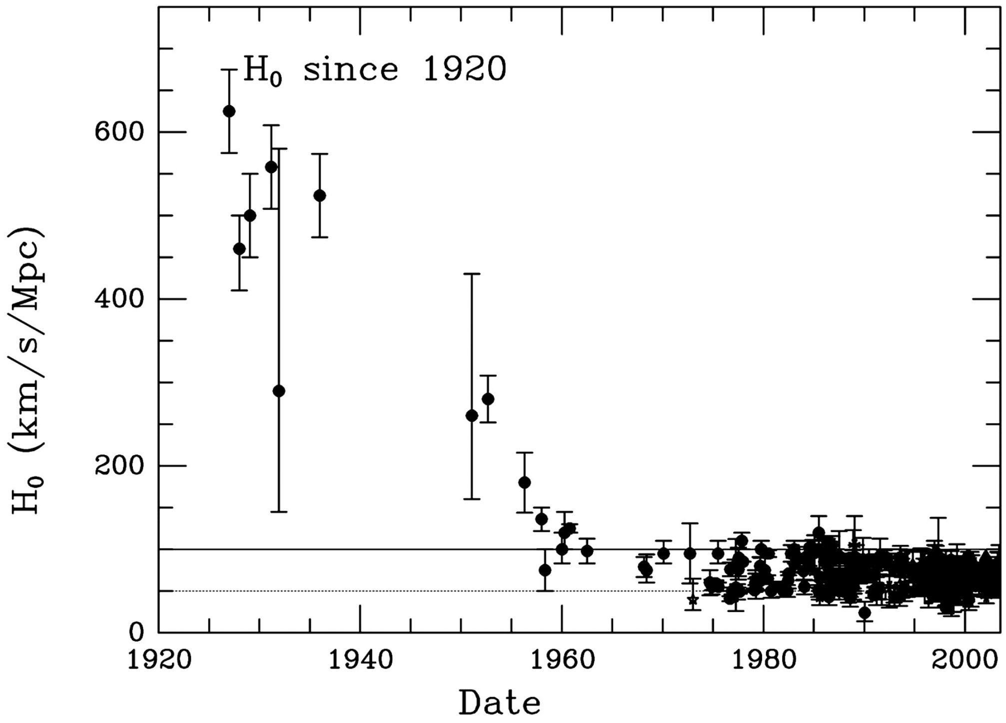
$$\text{Age of the Universe} = \frac{1}{H_o}$$

~ 2 billion years ??

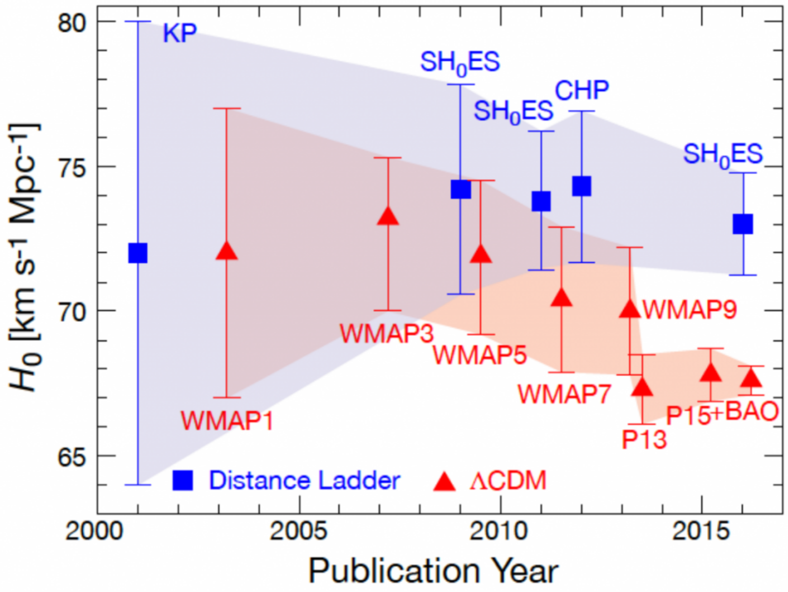
The Hubble constant H_o

The expansion rate of our Universe

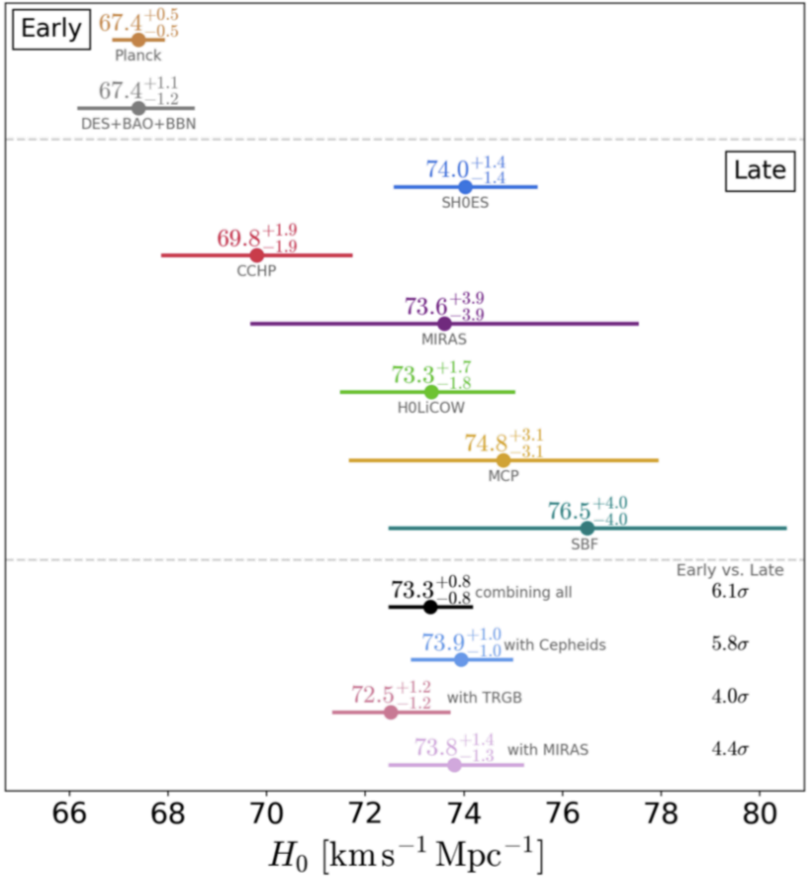
Kirshner 2004



Freedman 2017



The Hubble tension



Verde, Treu & Riess 2019

Gravitational Waves as "Standard Sirens"

Schutz 1986; Holz & Hughes 2005

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

Department of Applied Mathematics and Astronomy, University College Cardiff, PO Box 78, Cardiff CF1 1XL, UK

I report here how gravitational wave observations can be used to determine the Hubble constant, H_0. The nearly monochromatic gravitational waves emitted by the decaying orbit of an ultra-compact, two-neutron-star binary system just before the stars coalesce are very likely to be detected by the kilometre-sized interferometric gravitational wave antennas now being designed[1–4]. The signal is easily identified and contains enough information to determine the absolute distance to the binary, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy.

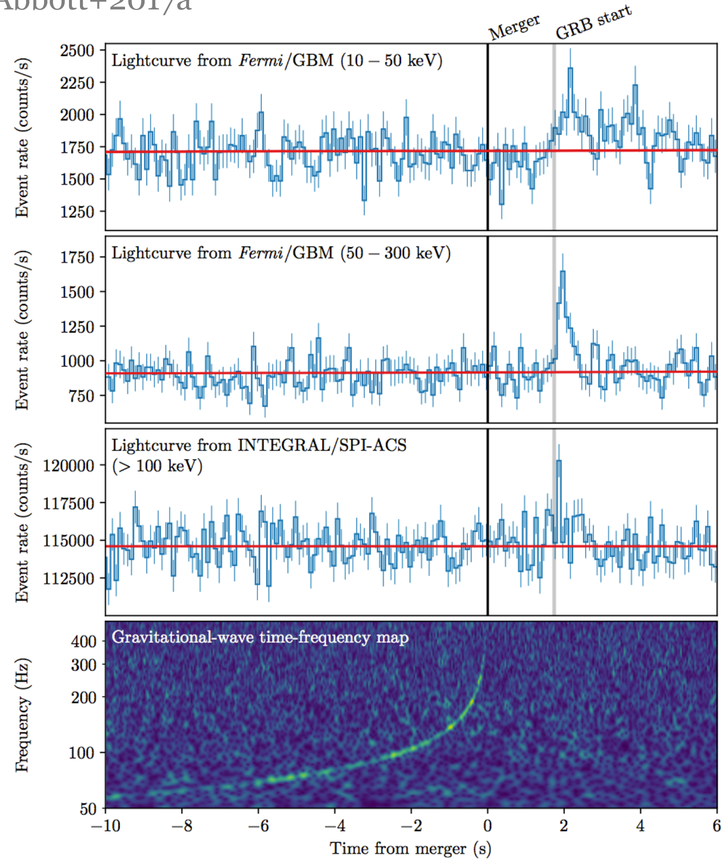
Identification of the source / host galaxy

$$H_0 = \frac{\text{Velocity}}{\text{Distance}} = \frac{\text{[speed of light] x Redshift}}{\text{Distance}}$$

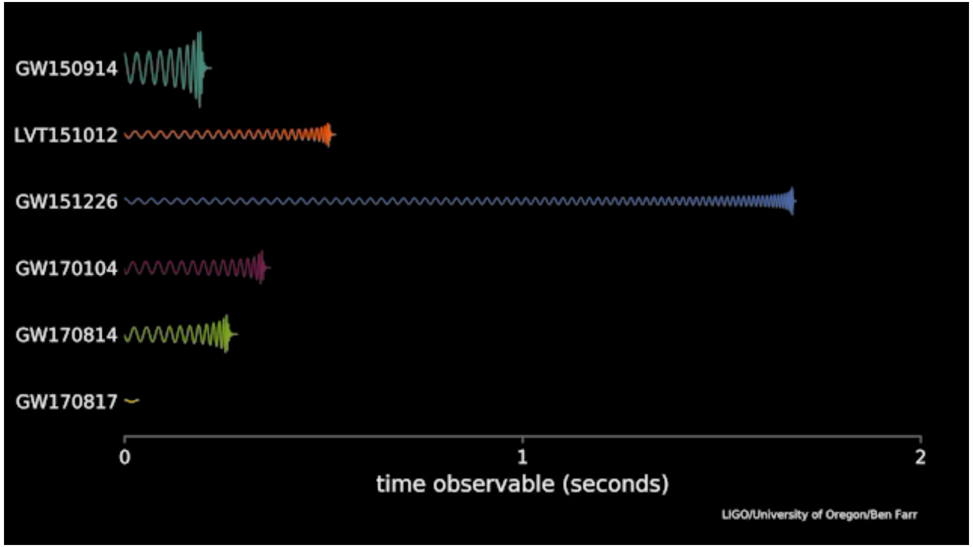
GW 170817 / AT 2017gfo

The first Electromagnetic Counterpart of a Gravitational Wave event

Abbott+2017a



Gravitational-wave signal consistent with the merger of two neutron stars



Video credits: ESO

GW 170817 / AT 2017gfo

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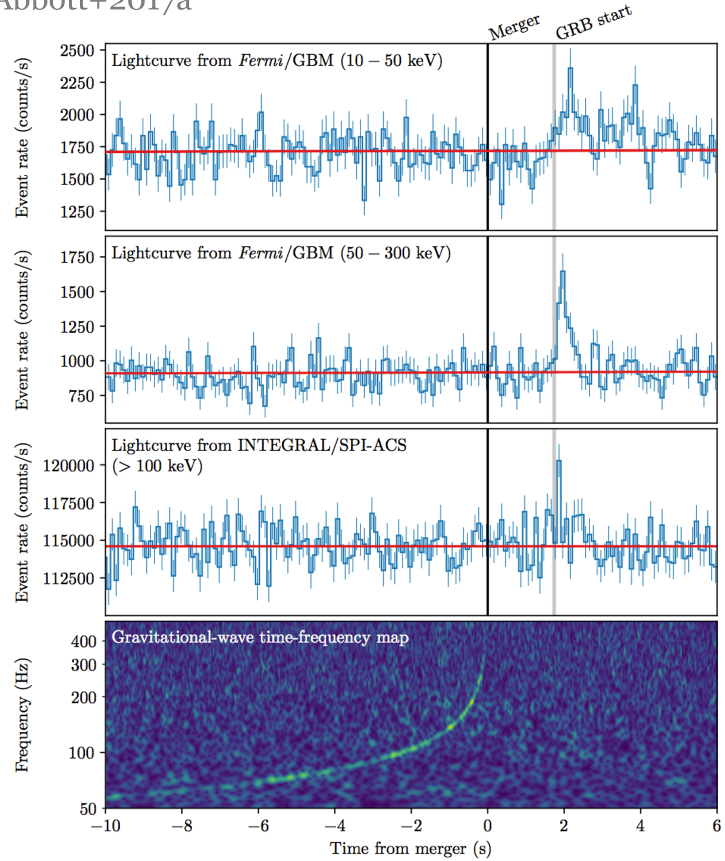

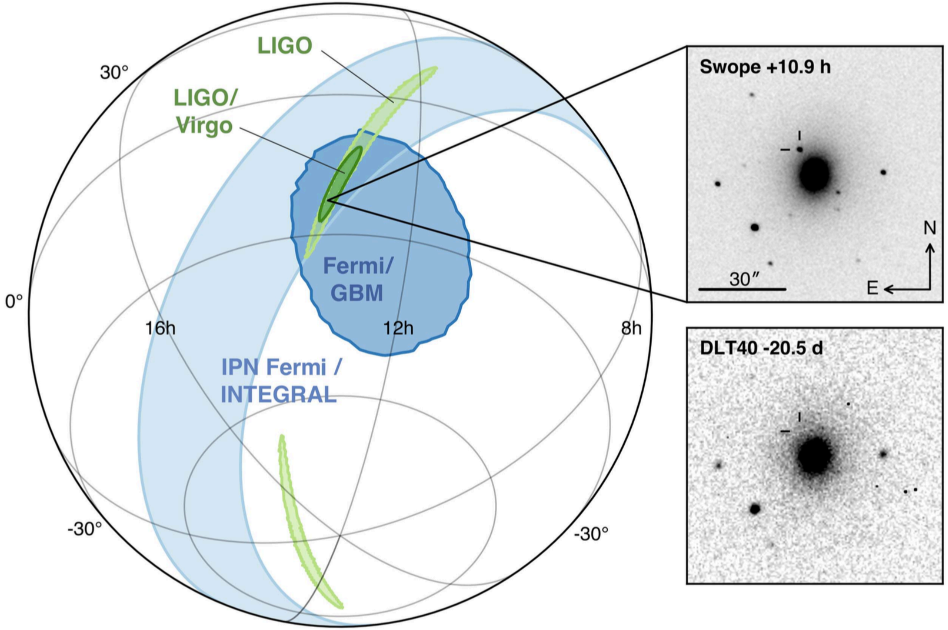

Abbott+2017b

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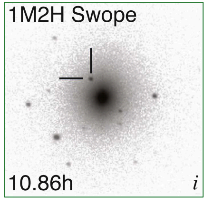

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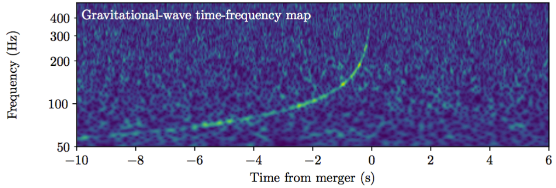


Gravitational Waves as "Standard Sirens"

GW170817 / AT2017gfo

Abbott+2017c

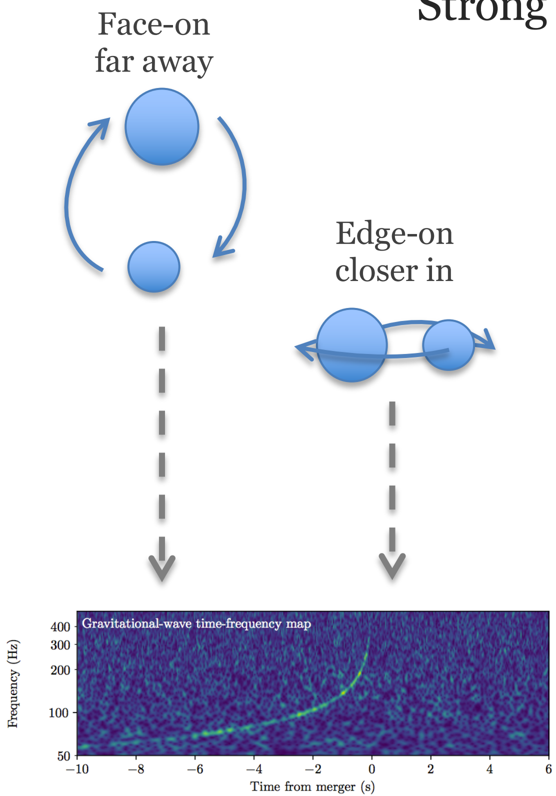
Extended Data Table 1. Summary of constraints on the Hubble constant, binary inclination, and distance

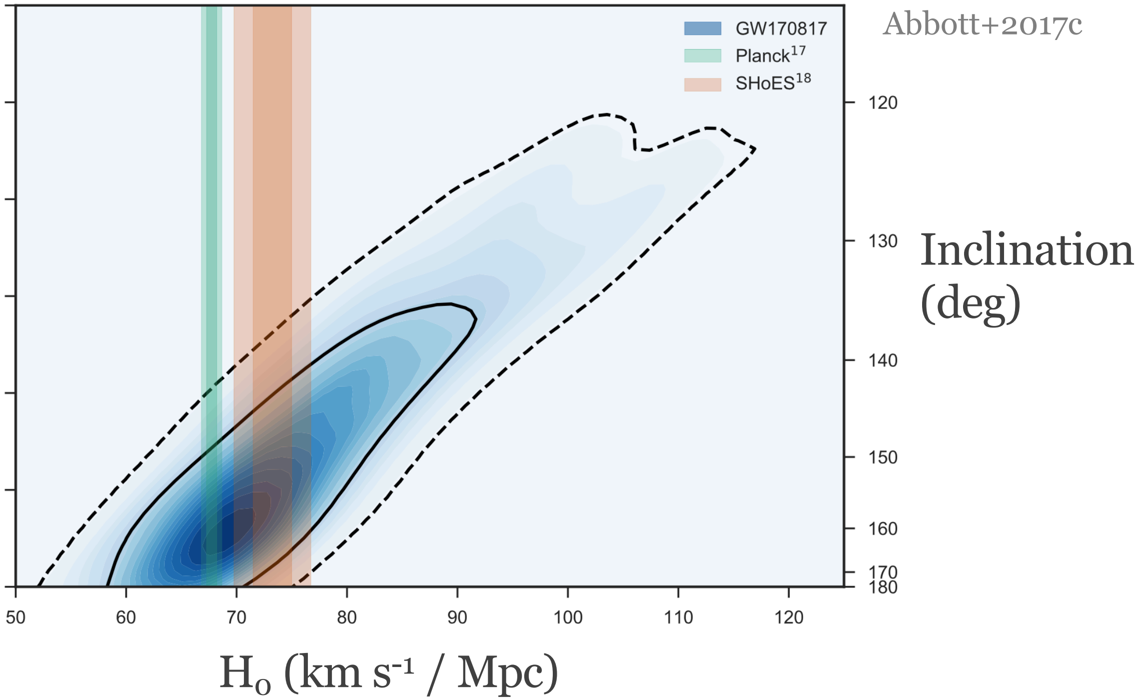
Parameter	68.3% Symm.	68.3% MAP	90% Symm.	90% MAP
$H_0/\left(\mathrm{km\,s^{-1}\,Mpc^{-1}}\right)$	$74.0^{+16.0}_{-8.0}$	$70.0^{+12.0}_{-8.0}$	74.0^{+33}_{-12}	70.0^{+28}_{-11}
$H_0/\left(\mathrm{km\,s^{-1}\,Mpc^{-1}}\right)$ (flat in z prior)	81^{+27}_{-13}	$71.0^{+23.0}_{-9.0}$	81^{+50}_{-17}	71.0^{+48}_{-11}
$H_0/\left(\mathrm{km\,s^{-1}\,Mpc^{-1}}\right)$ ($250\,\mathrm{km\,s^{-1}}\ \sigma_{v_r}$)	$74.0^{+16.0}_{-9.0}$	$70.0^{+14.0}_{-9.0}$	74.0^{+33}_{-14}	70.0^{+29}_{-14}
$\cos\iota$ (GW only)	$-0.88^{+0.18}_{-0.09}$	$-0.974^{+0.164}_{-0.026}$	$-0.88^{+0.32}_{-0.11}$	$-0.974^{+0.332}_{-0.026}$
$\cos\iota$ (SHoES)	$-0.901^{+0.065}_{-0.057}$	$-0.912^{+0.061}_{-0.059}$	$-0.901^{+0.106}_{-0.083}$	$-0.912^{+0.095}_{-0.086}$
$\cos\iota$ (Planck)	$-0.948^{+0.052}_{-0.036}$	$-0.982^{+0.060}_{-0.016}$	$-0.948^{+0.091}_{-0.046}$	$-0.982^{+0.104}_{-0.018}$
ι/deg (GW only)	152^{+14}_{-17}	167^{+13}_{-23}	152^{+20}_{-27}	167^{+13}_{-37}
ι/deg (SHoES)	$154.0^{+9.0}_{-8.0}$	$156.0^{+10.0}_{-7.0}$	154.0^{+15}_{-12}	156.0^{+21}_{-11}
ι/deg (Planck)	$161.0^{+8.0}_{-8.0}$	$169.0^{+8.0}_{-12.0}$	161.0^{+12}_{-12}	169.0^{+11}_{-18}
$d/\left(\mathrm{Mpc}\right)$	$41.1^{+4.0}_{-7.3}$	$43.8^{+2.9}_{-6.9}$	$41.1^{+5.6}_{-12.6}$	$43.8^{+5.6}_{-13.1}$

Gravitational Waves as "Standard Sirens"

GW170817 / AT2017gfo

Strong degeneracy between distance and inclination



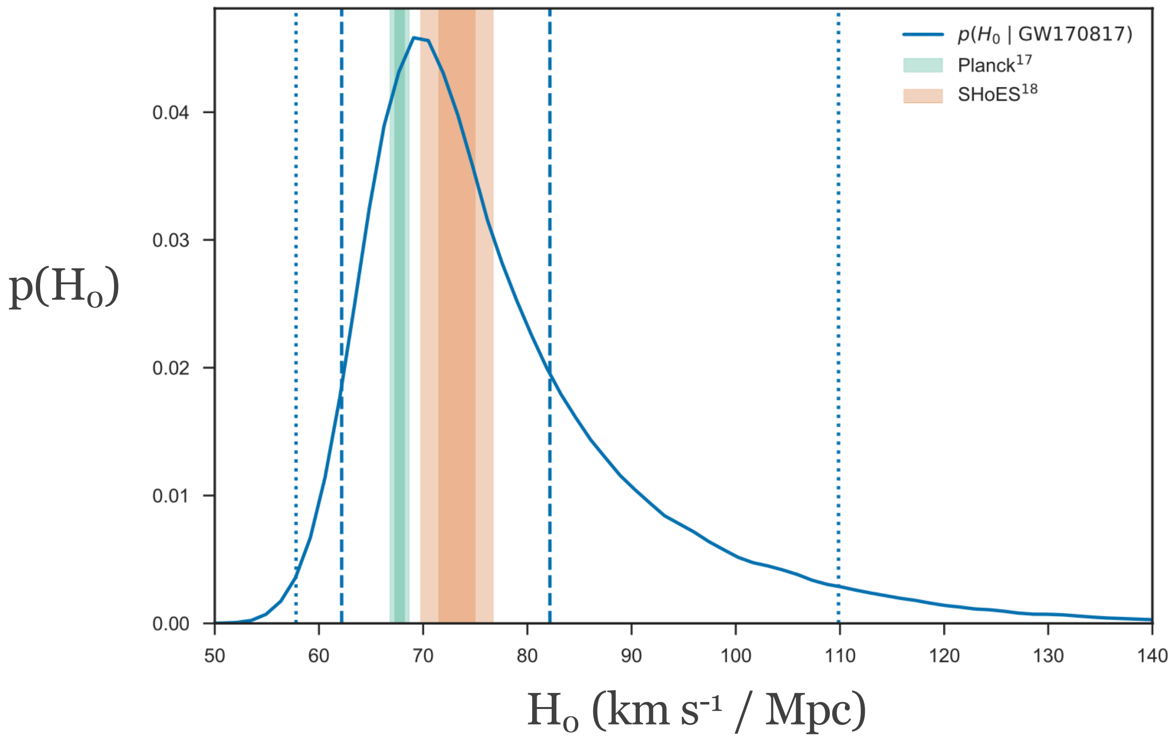


Abbott+2017c

Gravitational Waves as “Standard Sirens”

GW170817 / AT2017gfo

Strong degeneracy between distance and inclination



$H_0 = 74.0^{+16.0}_{-8.0}$ km s^{-1} / Mpc

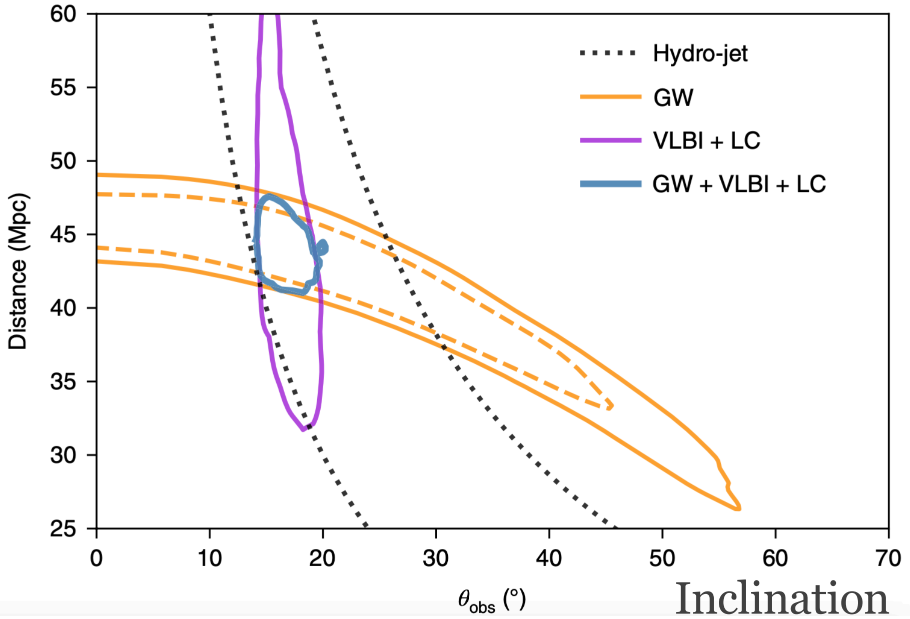
Abbott+2017c

Gravitational Waves as "Standard Sirens"

GW170817 / AT2017gfo

Strong degeneracy between distance and inclination

Hotokezaka+2020



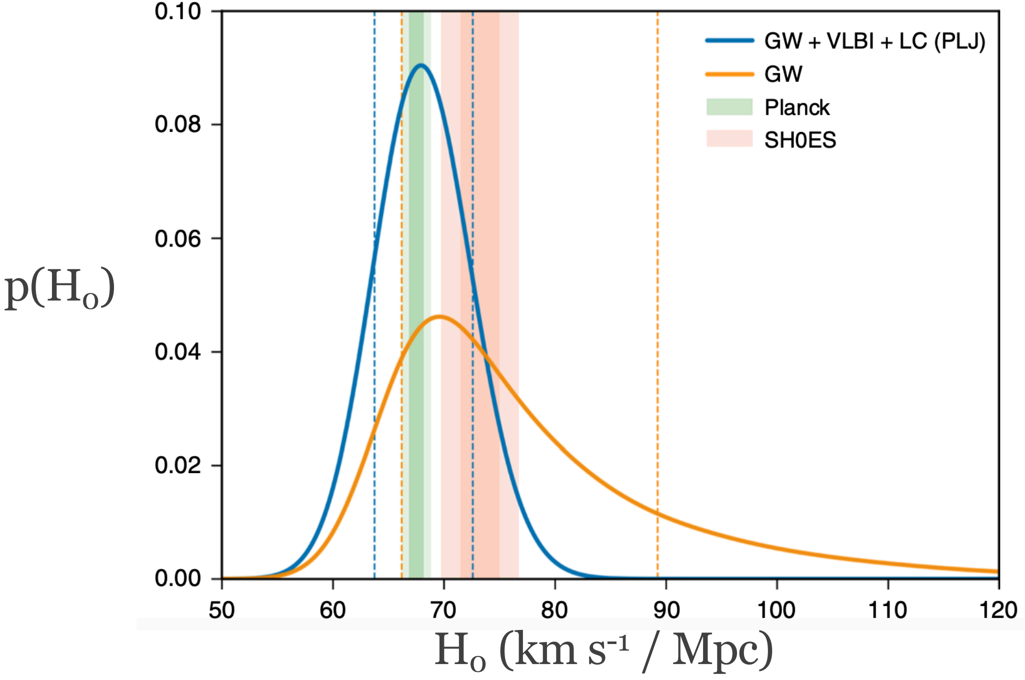
Inclination

Gravitational Waves as “Standard Sirens”

GW170817 / AT2017gfo

Strong degeneracy between distance and inclination

Hotokezaka+2020



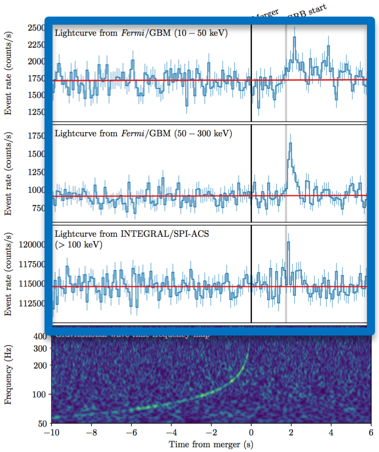
GW only

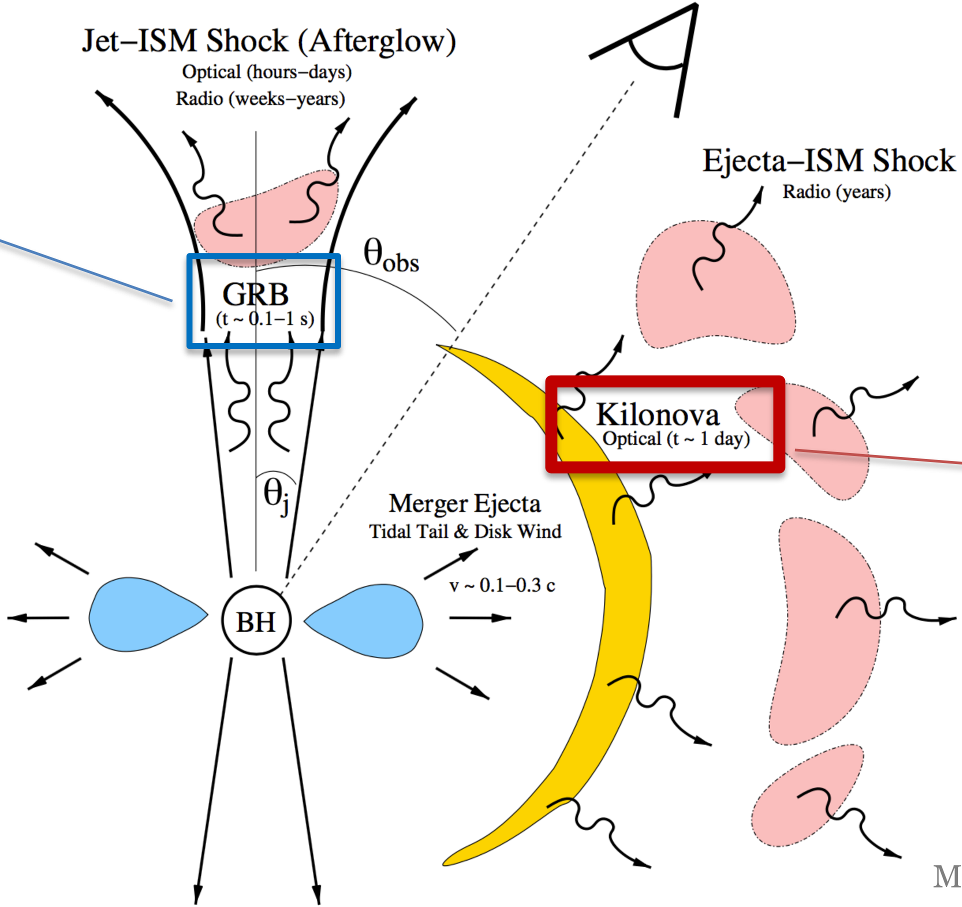
$H_0 = 74.0^{+16.0}_{-8.0}$ km s^{-1} / Mpc

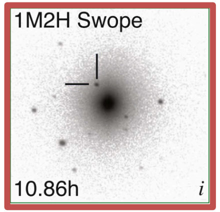
GW + radio

$H_0 = 70.3^{+5.3}_{-5.0}$ km s^{-1} / Mpc

Kilonova



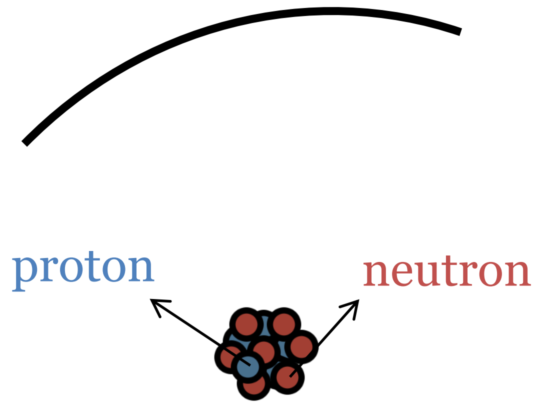




Metzger & Berger 2012

Kilonova

A radioactively-powered emission from NS-NS and NS-BH mergers



Seed nucleus

Kilonova

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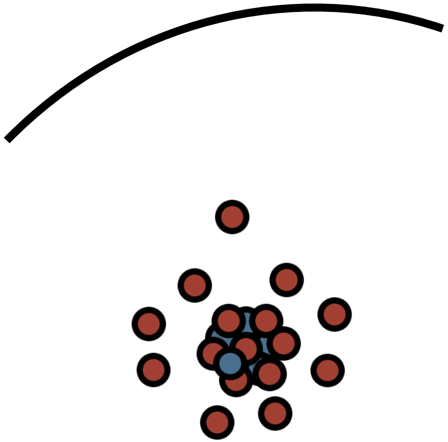

High density of free neutrons

Kilonova

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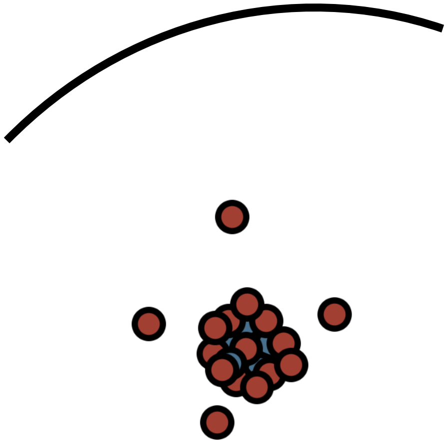
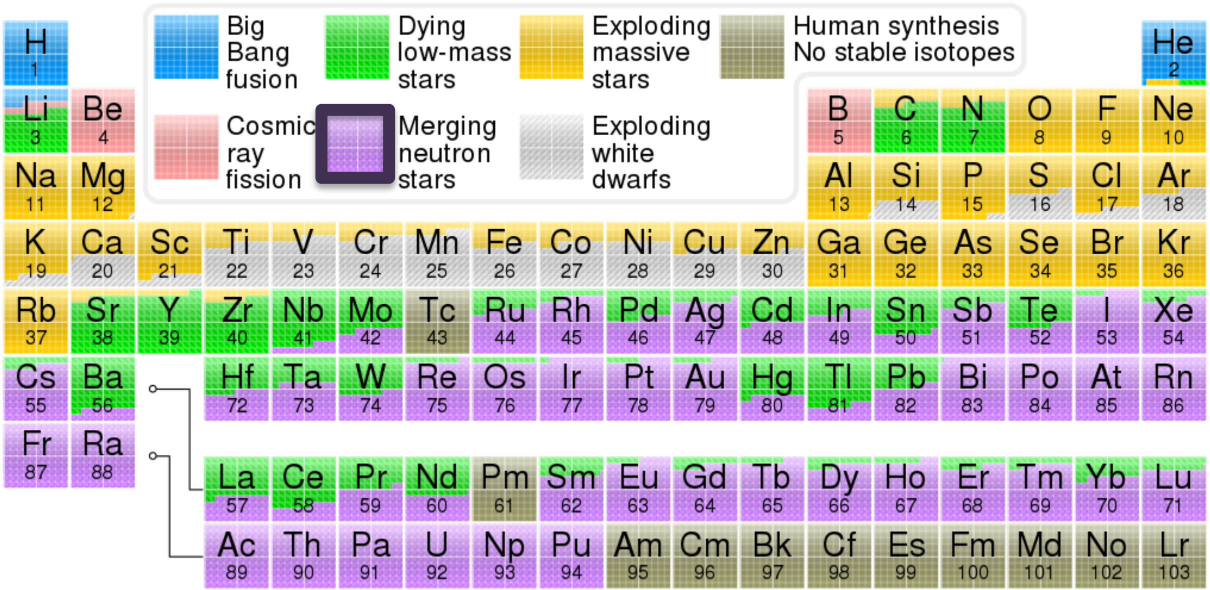


Neutron capture via “r-process” (“rapid process”)

Kilonova

A radioactively-powered emission from NS-NS and NS-BH mergers



Wikipedia 😉

r-process responsible for the creation of ~1/2 of the nuclei heavier than Fe

Kilonova

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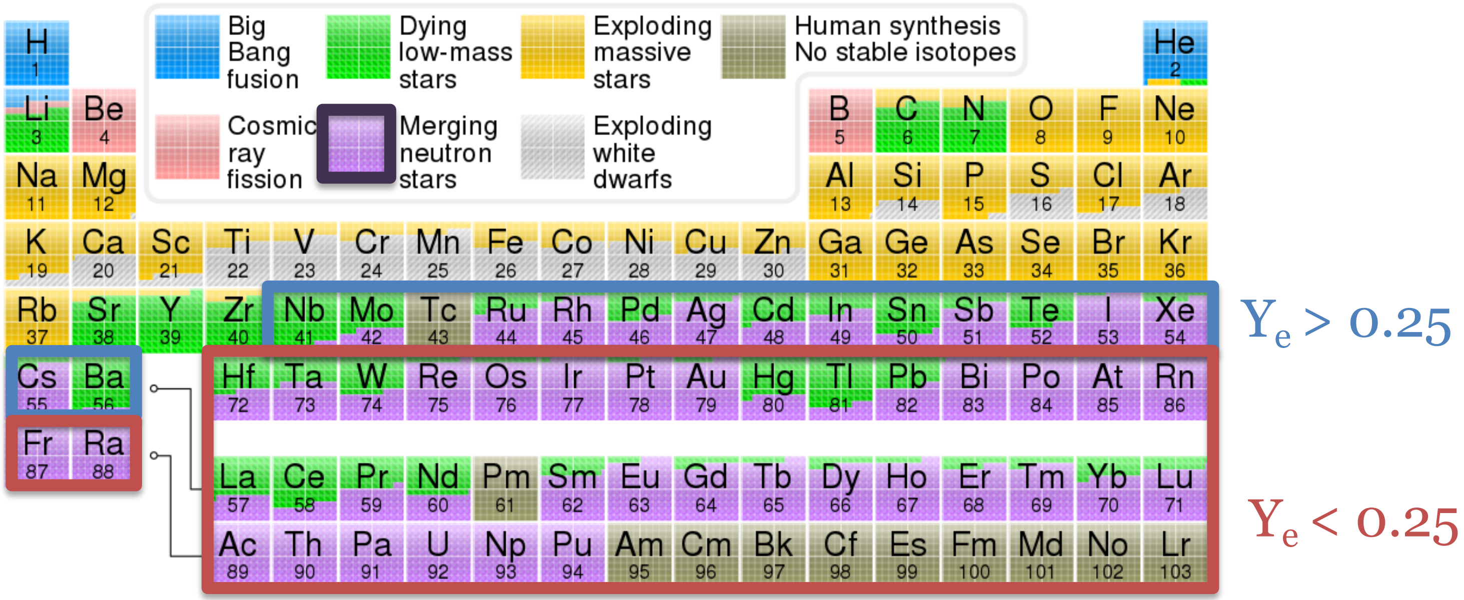

r-process nucleosynthesis controlled by the matter composition

Electron fraction $$Y_e = \frac{\text{number of protons [/electrons]}}{\text{number of protons+number of neutrons}}$$

Kilonova

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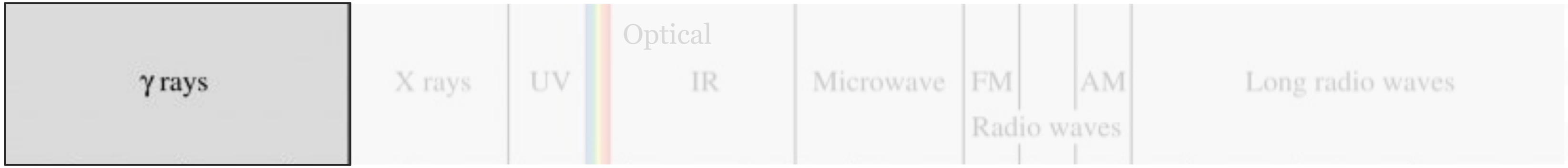
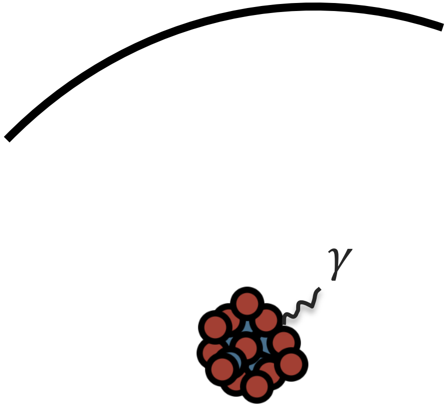


→ Increasing wavelength

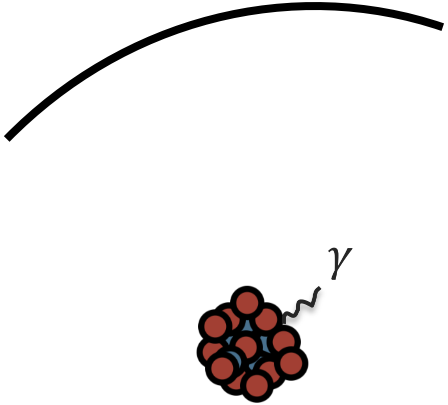


Radioactive elements -> decay -> γ photons

Kilonova

A radioactively-powered emission from NS-NS and NS-BH mergers

→ Increasing wavelength



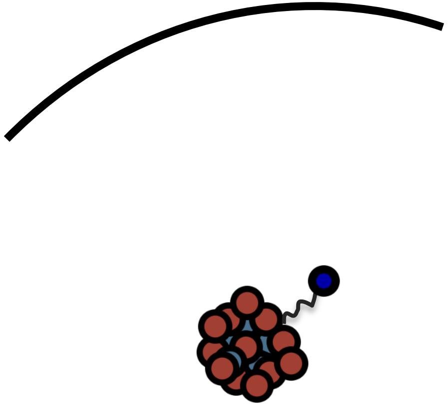
T ~ 5 000 – 10 000 K @ 1 day

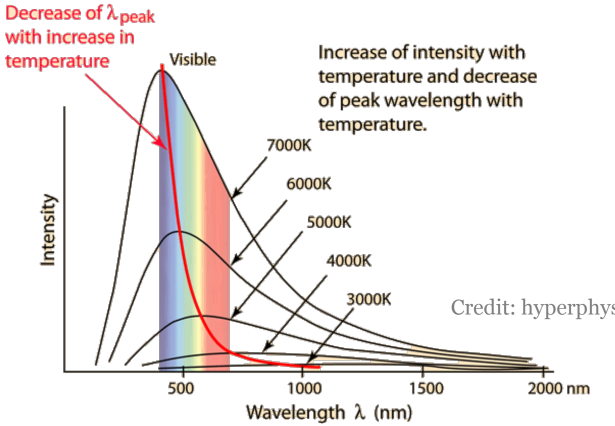
γ photons thermalize -> setting the temperature

Kilonova

A radioactively-powered emission from NS-NS and NS-BH mergers

→ Increasing wavelength



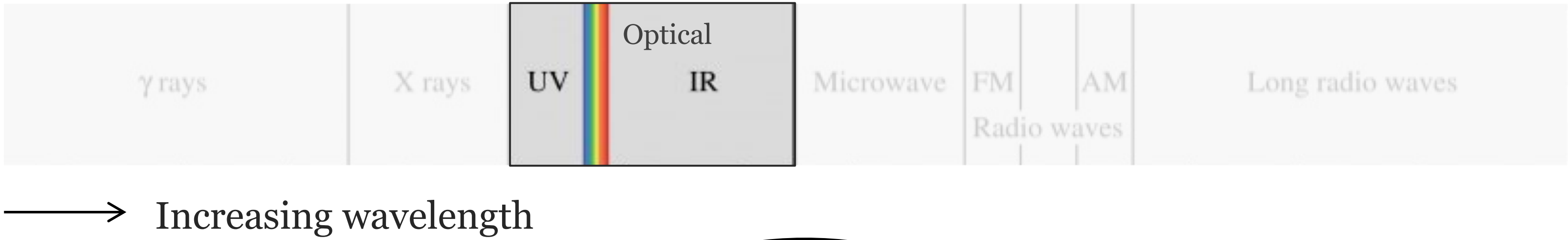


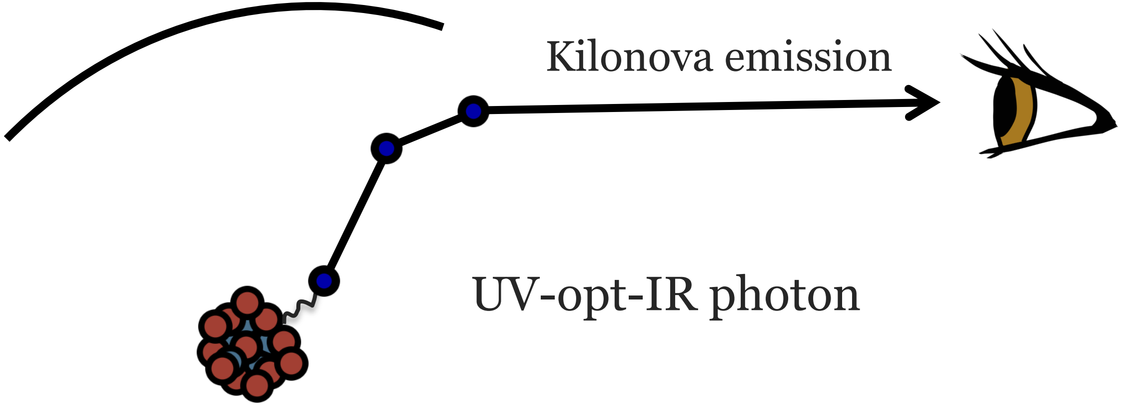
Credit: hyperphysics.phy

γ photons thermalize -> thermal emission at longer wavelengths (UV-opt-IR)

Kilonova

A radioactively-powered emission from NS-NS and NS-BH mergers





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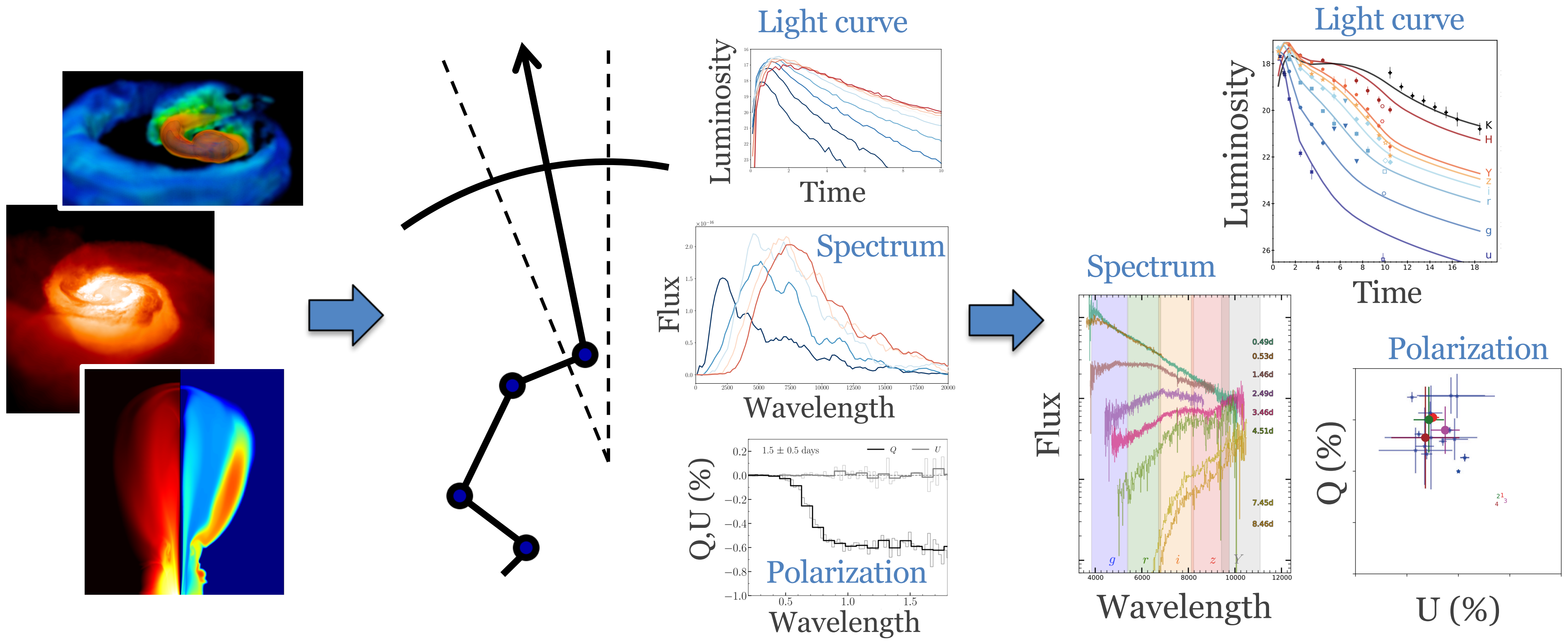
POSSIS

A Monte Carlo radiative transfer code to predict observables for kilonovae



Models

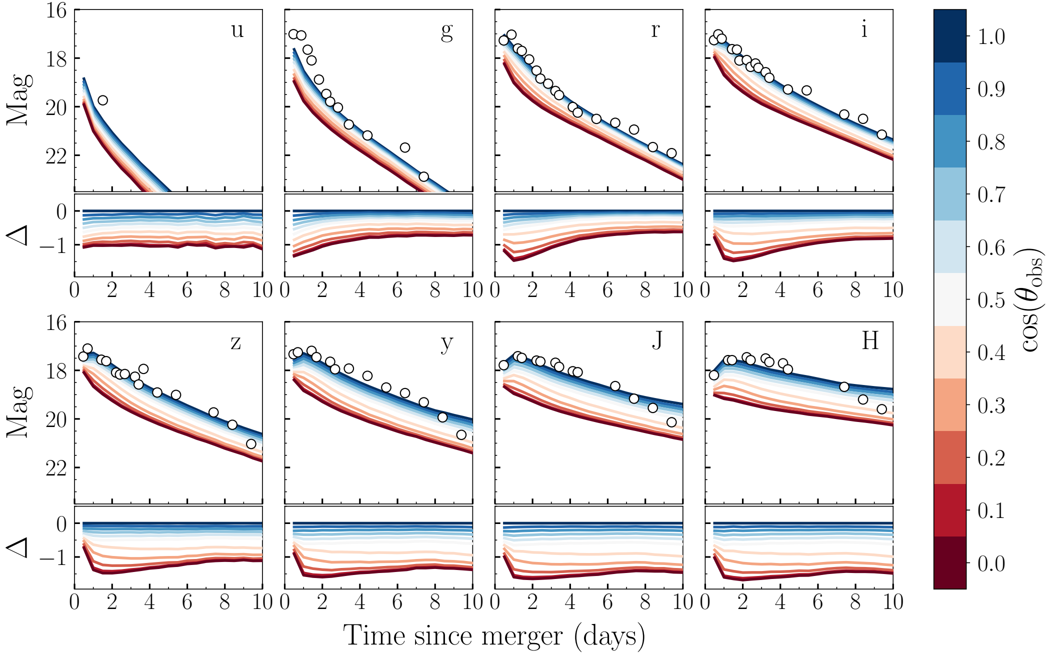
Radiative transfer

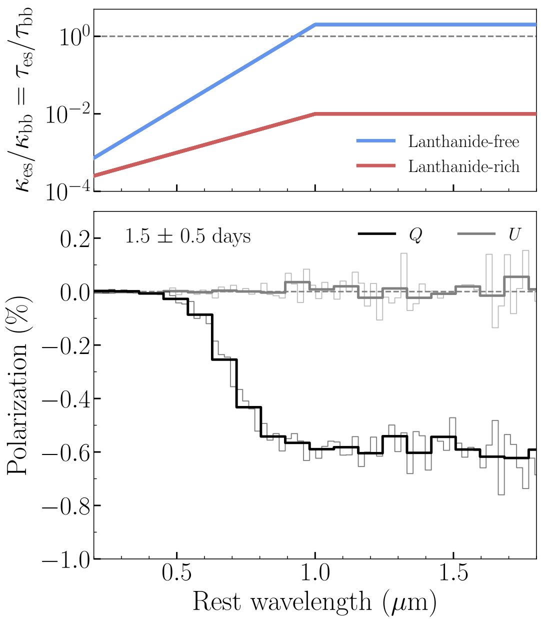
Observations

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **489**, 5037–5045 (2019) doi:10.1093/mnras/stz2495
Advance Access publication 2019 September 7

POSSIS: predicting spectra, light curves, and polarization for multidimensional models of supernovae and kilonovae

M. Bulla ★



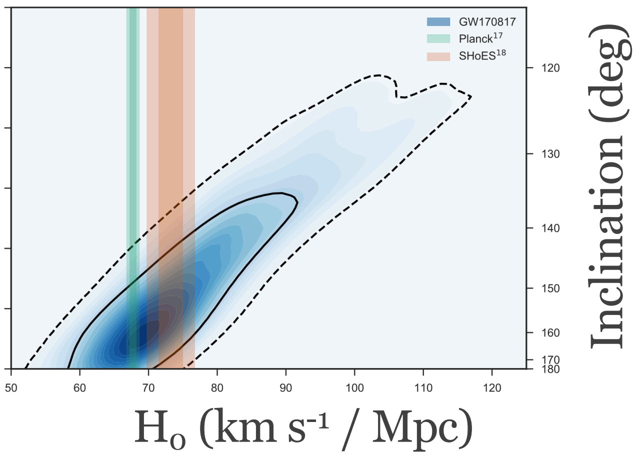


Latest version of POSSIS improved with better physics

H_0 and kilonovae

3 approaches to measure/improve on H_0

1. Constrain inclination with kilonova light curves -> GW + EM (improve standard sirens)
2. Constrain inclination with kilonova polarization -> GW + EM (improve standard sirens)
3. Constrain distance directly from kilonovae -> EM



$$H_0 = \frac{\text{[speed of light] x Redshift}}{\text{Distance}}$$

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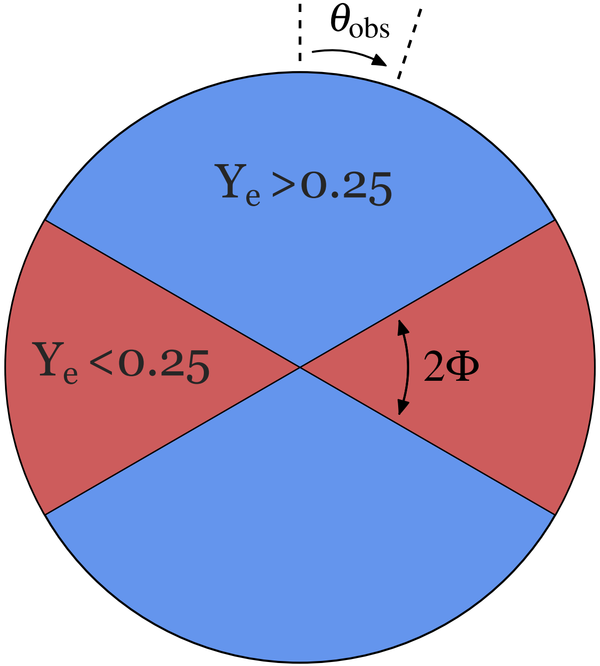


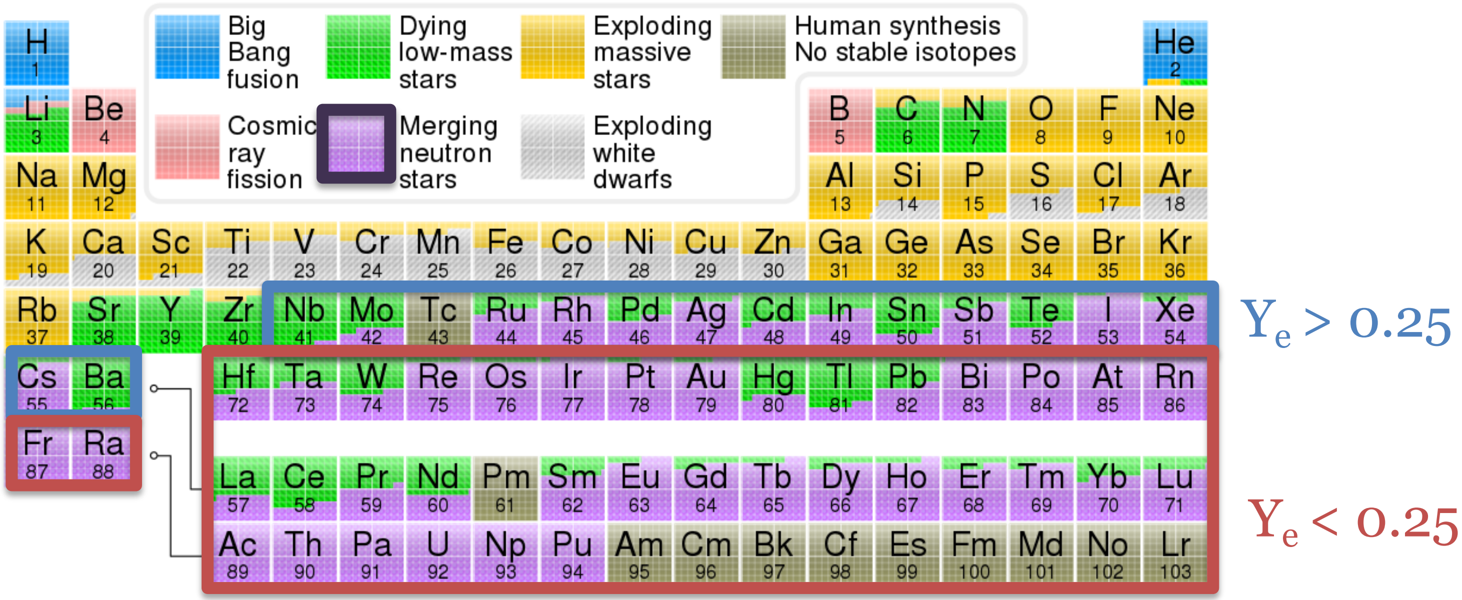
MB 2019

Material ejected anisotropically

Asymmetric distribution

(At least) Two components with different compositions and corresponding opacities

1. Constrain inclination with kilonova light curves



Nucleosynthesis controlled by the matter composition

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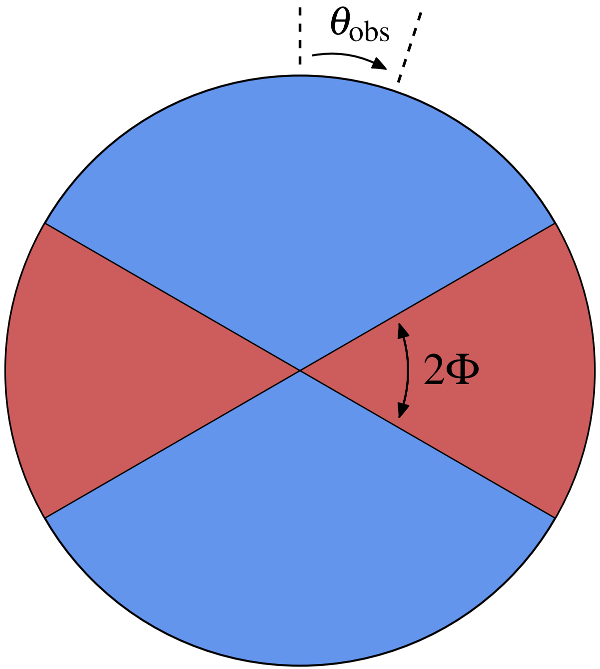


Opacity

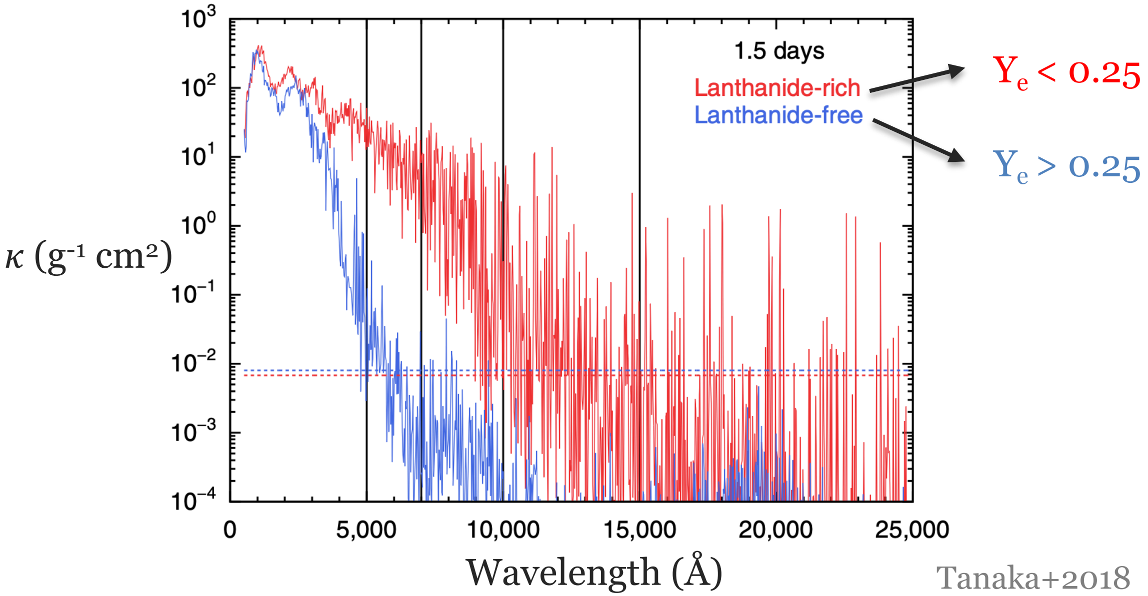
$$\tau = \int \kappa \rho \, dr$$

[g⁻¹ cm²]

Source of opacities in kilonovae

Electron scattering

Bound-bound (line) absorption



Tanaka+2018

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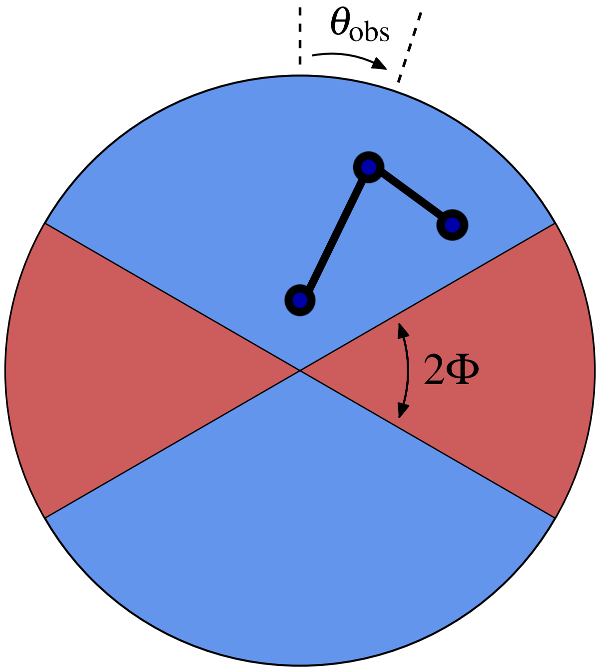

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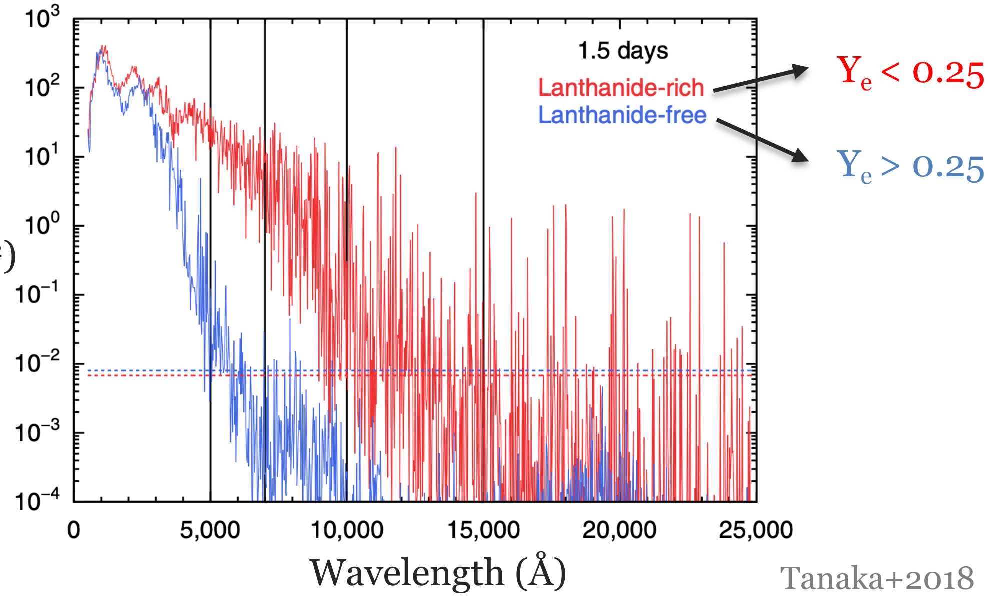

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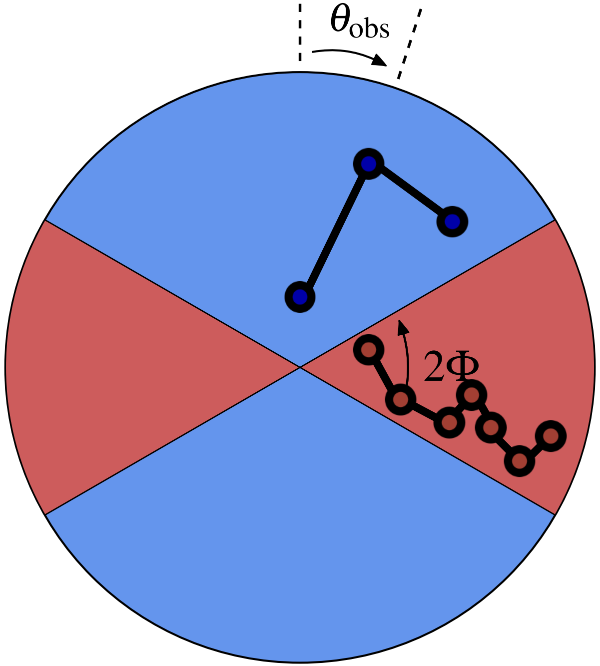

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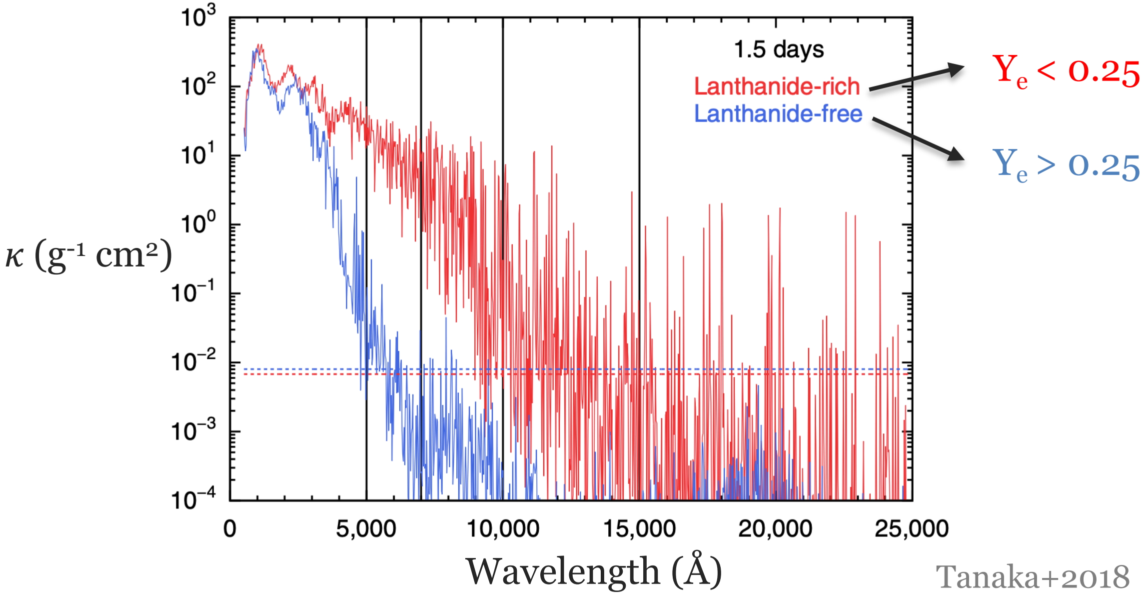

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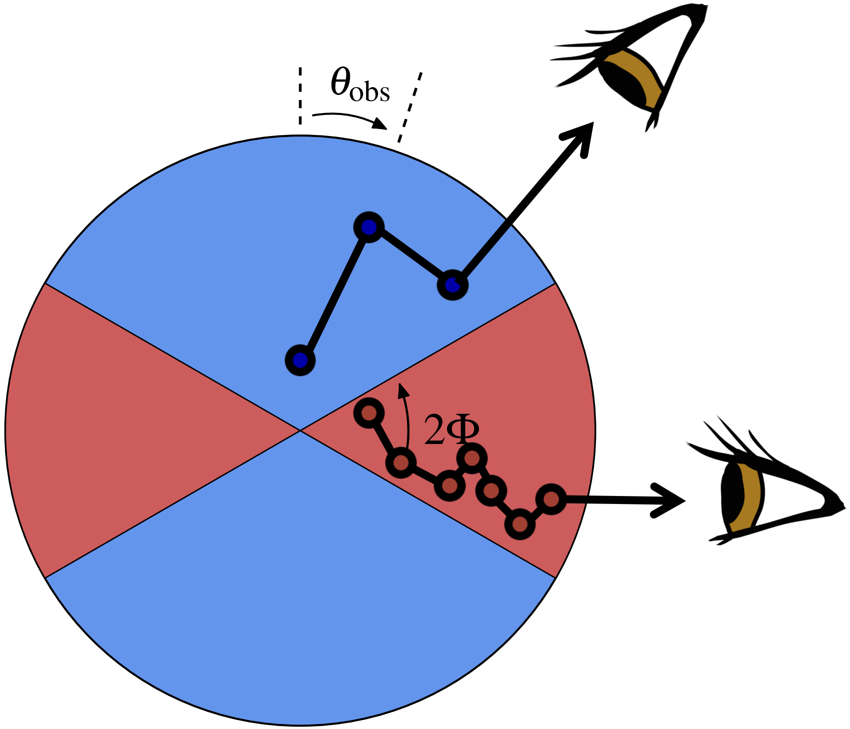
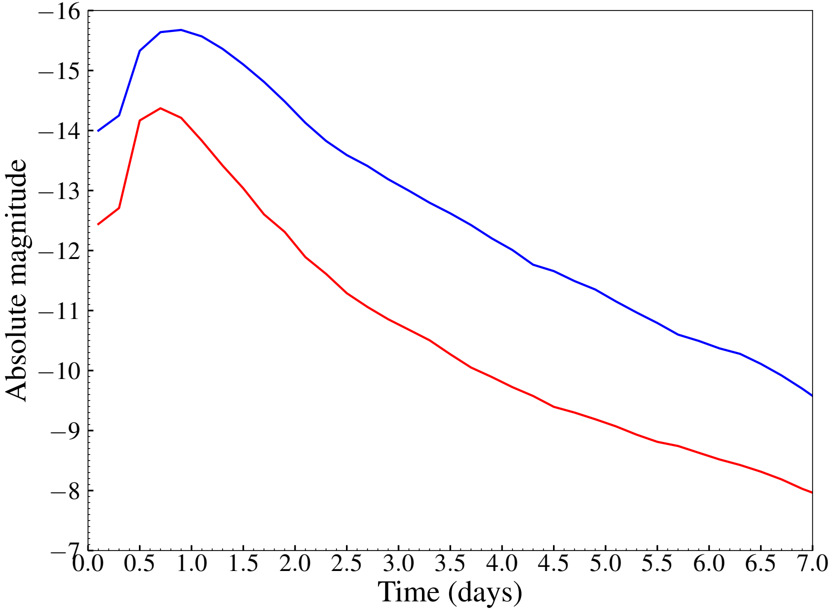


Viewing-angle dependence in kilonova light curves



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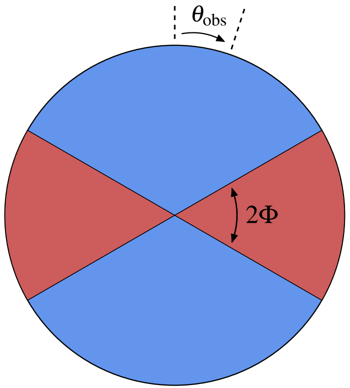


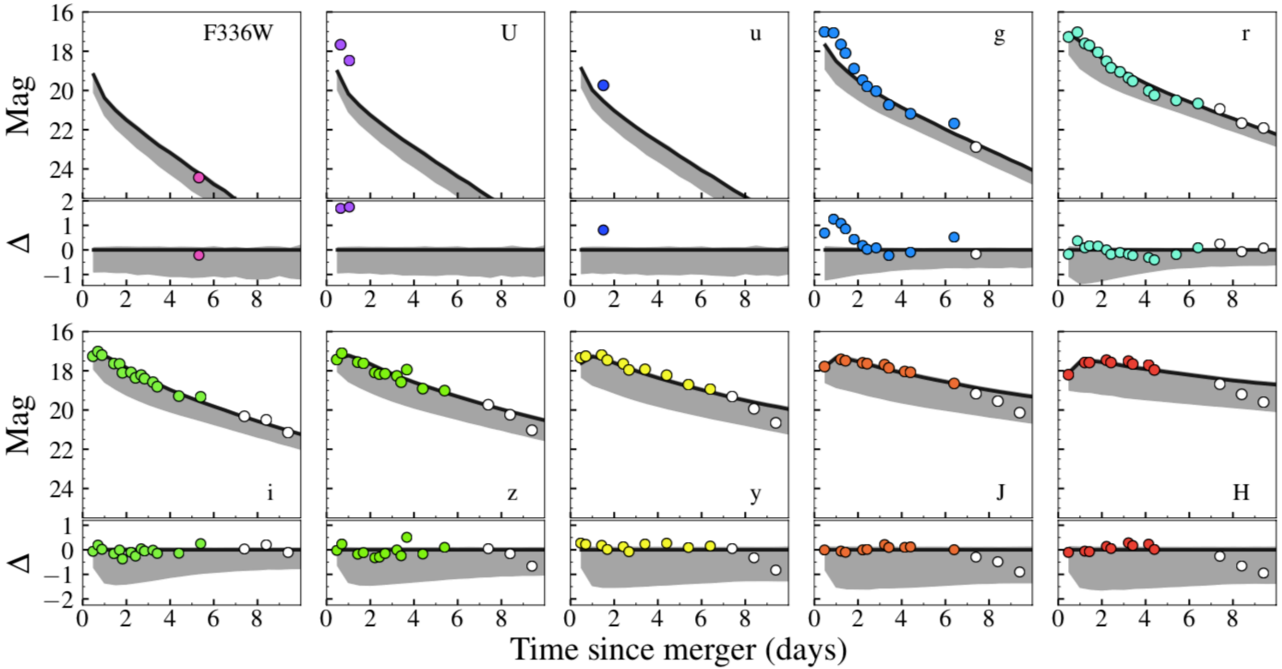
550 models varying Mej, Φ and ϑ_{obs}

Best-fit model:

M_{ej} = 0.05 $M_\odot$

Φ = 30 deg

$\cos(\vartheta_{obs})$ = 0.9



The Astrophysical Journal, 888:67 (5pp), 2020 January 10
https://doi.org/10.3847/1538-4357/ab5799

Constraining the Observer Angle of the Kilonova AT2017gfo Associated with GW170817: Implications for the Hubble Constant

S. Dhawan, M. Bulla, A. Goobar, A. Sagués Carracedo, and C. N. Setzer

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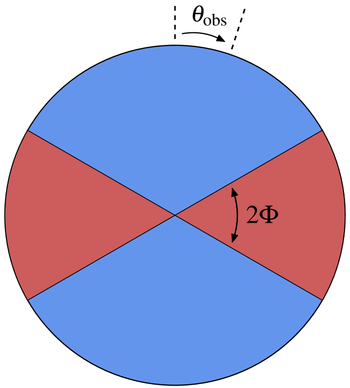


THE ASTROPHYSICAL JOURNAL, 888:67 (5pp), 2020 January 10
https://doi.org/10.3847/1538-4357/ab5799

CrossMark

Constraining the Observer Angle of the Kilonova AT2017gfo Associated with GW170817: Implications for the Hubble Constant

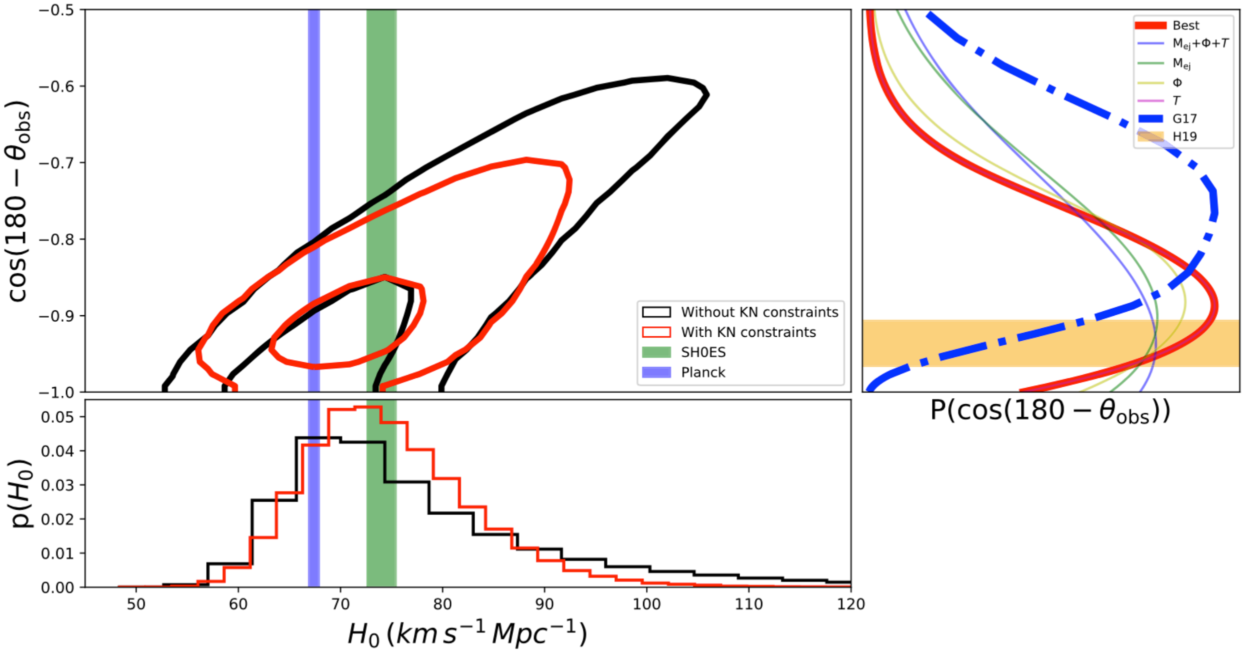
S. Dhawan, M. Bulla, A. Goobar, A. Sagués Carracedo, and C. N. Setzer

GW only

$H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} / Mpc

GW + kilonova

$H_0 = 72.4^{+7.9}_{-7.3}$ km s^{-1} / Mpc



24% improvement on H_0

2. Constrain inclination with kilonova polarization

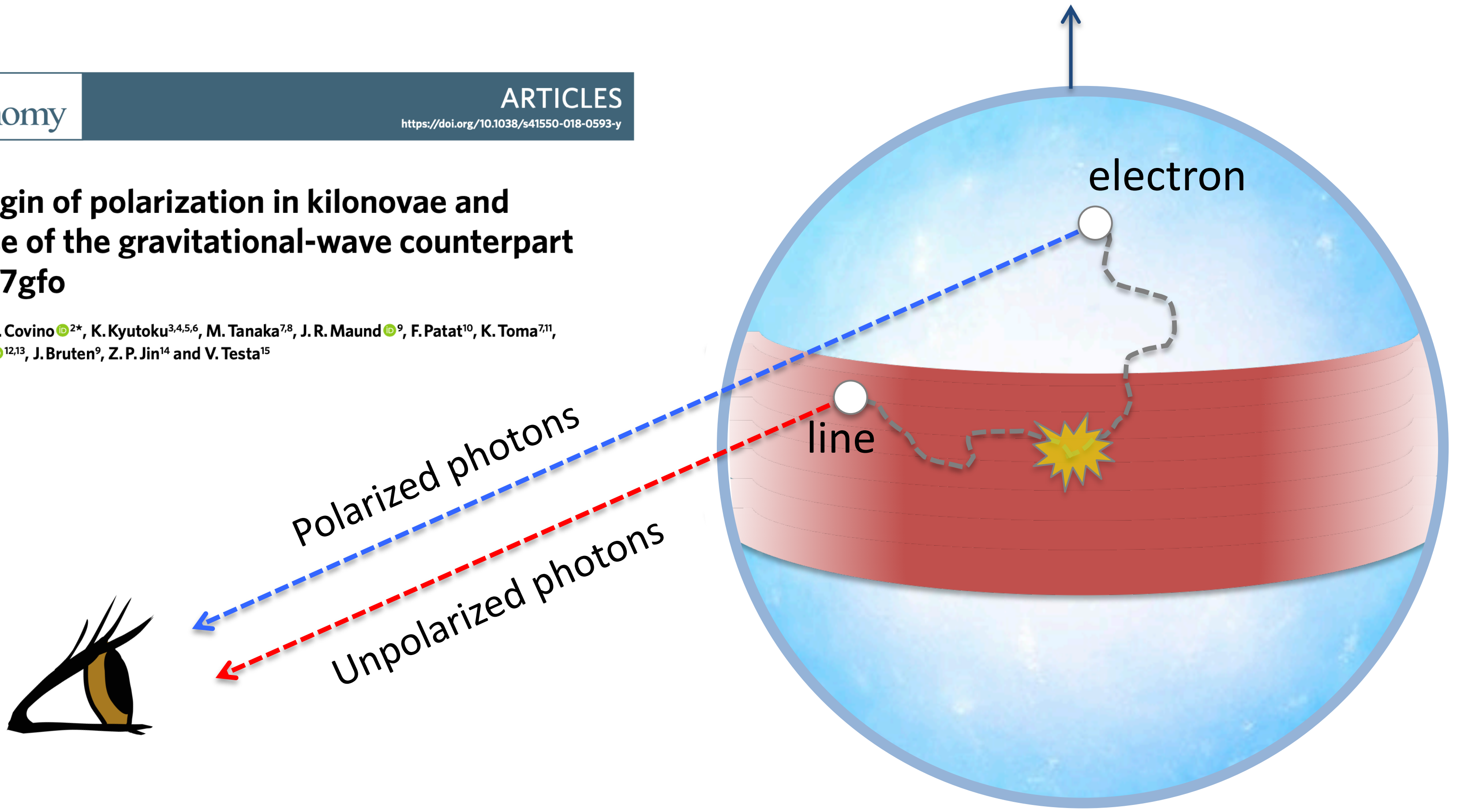
nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-018-0593-y

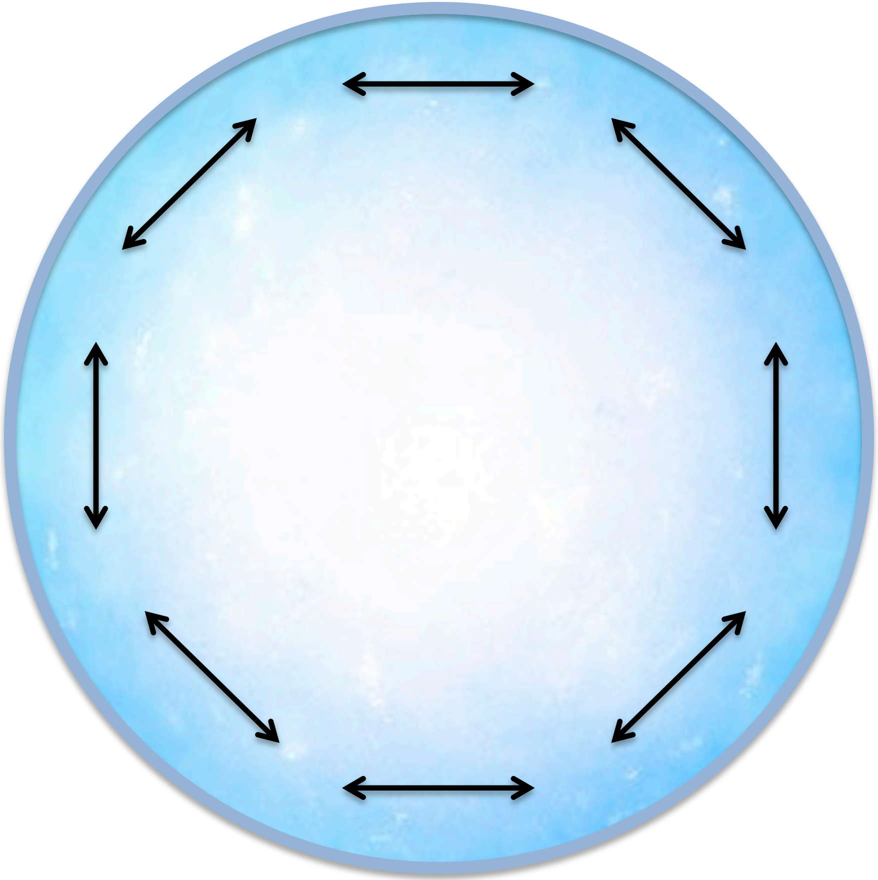
The origin of polarization in kilonovae and the case of the gravitational-wave counterpart AT 2017gfo

M. Bulla[1*], S. Covino[2*], K. Kyutoku[3,4,5,6], M. Tanaka[7,8], J. R. Maund[9], F. Patat[10], K. Toma[7,11], K. Wiersema[12,13], J. Bruten[9], Z. P. Jin[14] and V. Testa[15]



2. Constrain inclination with kilonova polarization

Polarizing
electron scattering:
each polarizing
contribution is cancelled by
one 90 degree away



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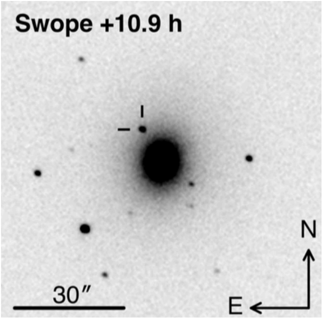
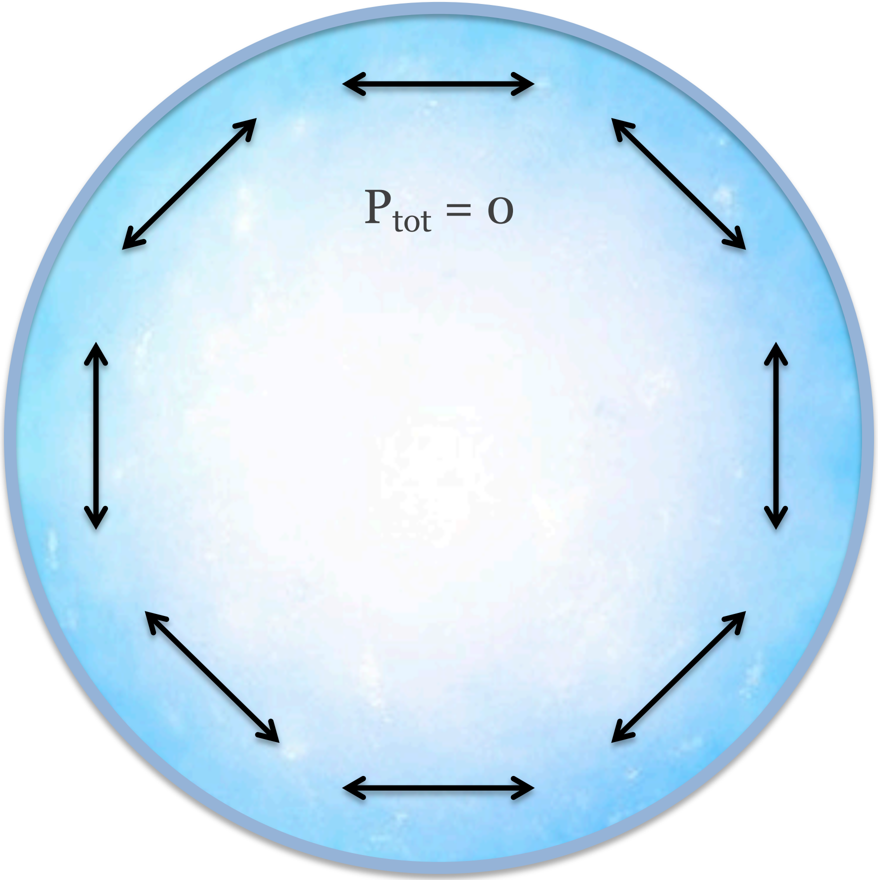
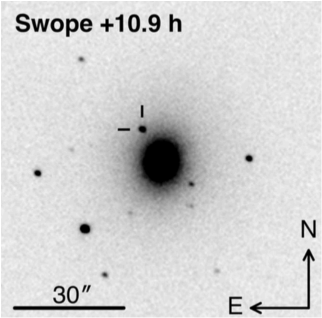
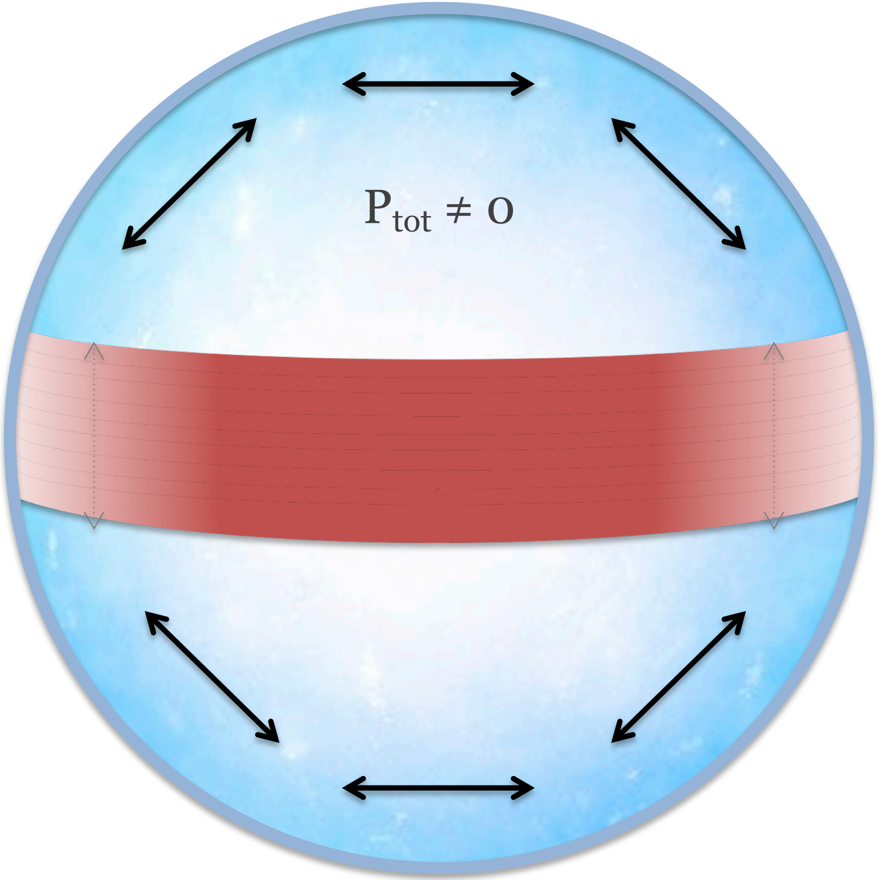




2. Constrain inclination with kilonova polarization

Polarizing
electron scattering
+ depolarizing line
Break of symmetry and
overall polarization signal





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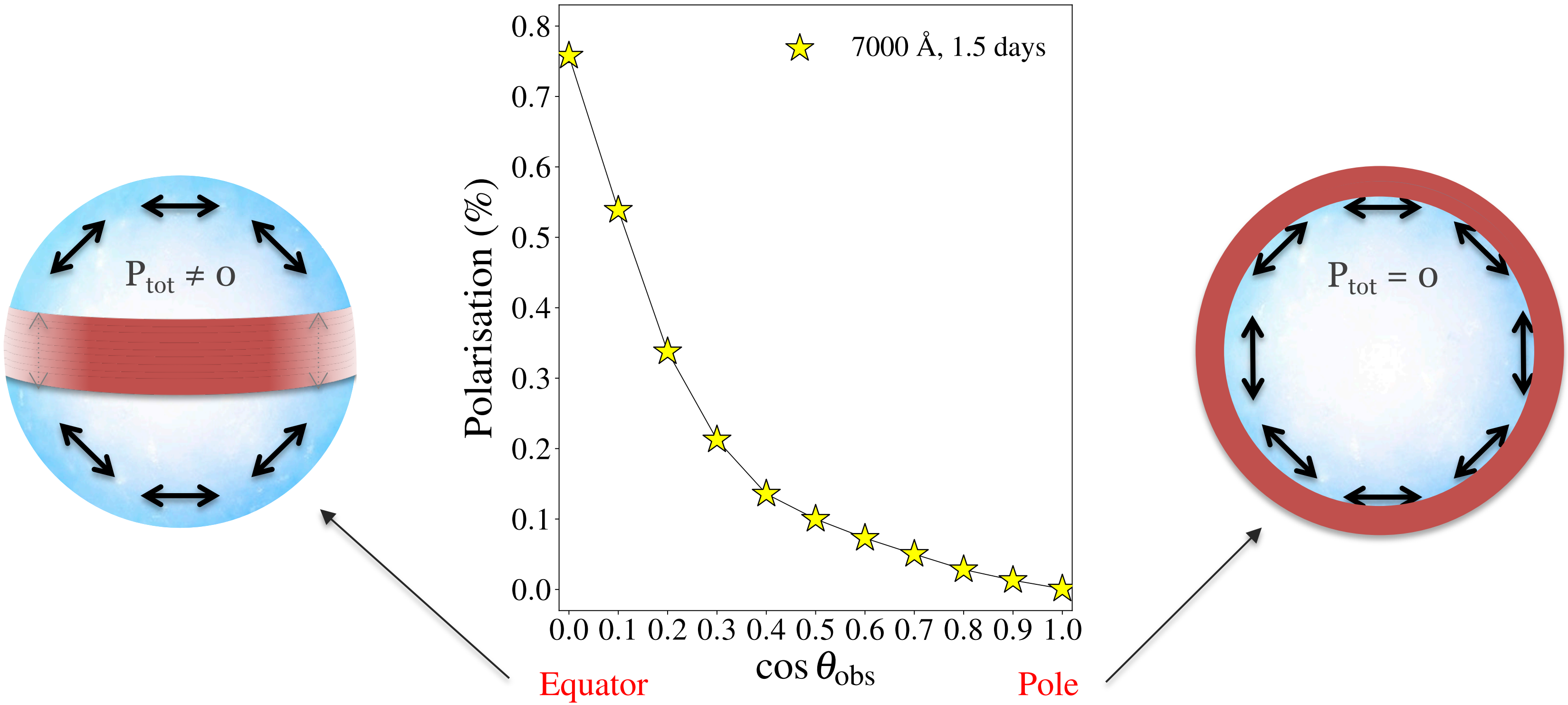
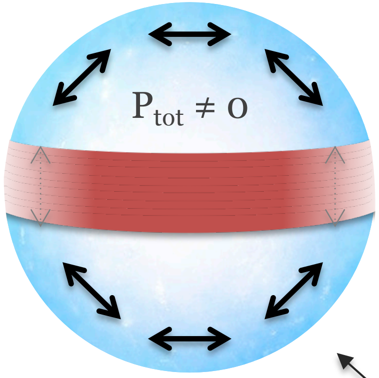
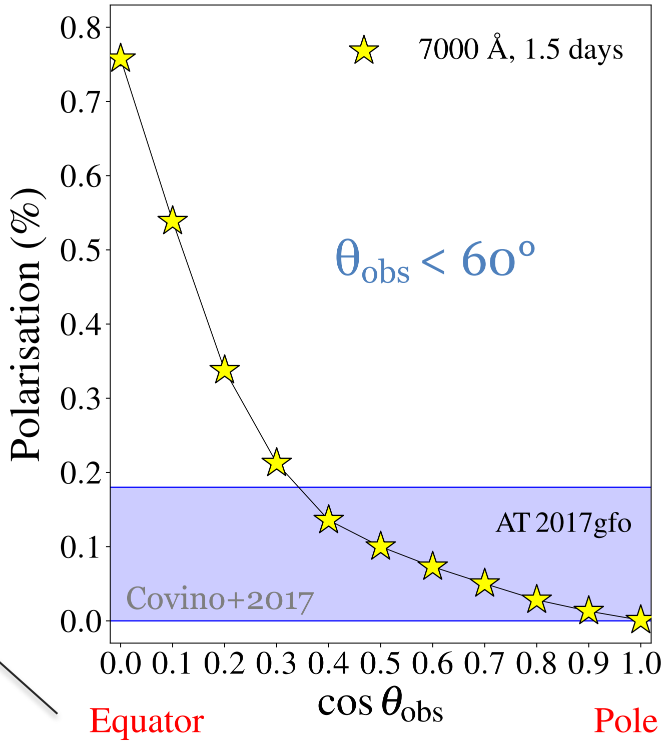
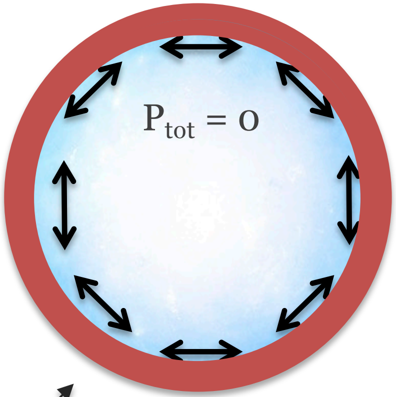


Polarization levels ≈ 1% could be detected in future kilonovae seen from favorable viewing angles

2. Constrain inclination with kilonova polarization







Polarization levels ≈ 1% could be detected in future kilonovae seen from favorable viewing angles

3. Constrain distance directly from kilonovae

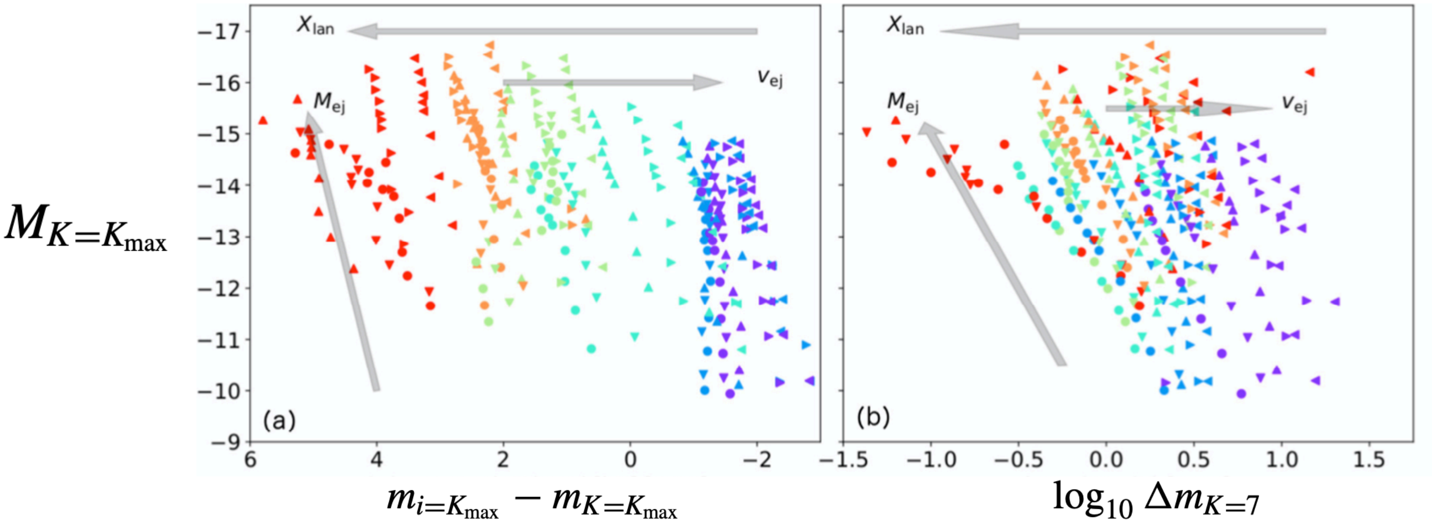
PHYSICAL REVIEW RESEARCH **2**, 022006(R) (2020)

Rapid Communications

Standardizing kilonovae and their use as standard candles to measure the Hubble constant

Michael W. Coughlin,[1,2] Tim Dietrich,[3,4] Jack Heinzel,[5,6] Nandita Khetan,[7] Sarah Antier,[8] Mattia Bulla,[9] Nelson Christensen,[5,6] David A. Coulter,[10] and Ryan J. Foley[10]

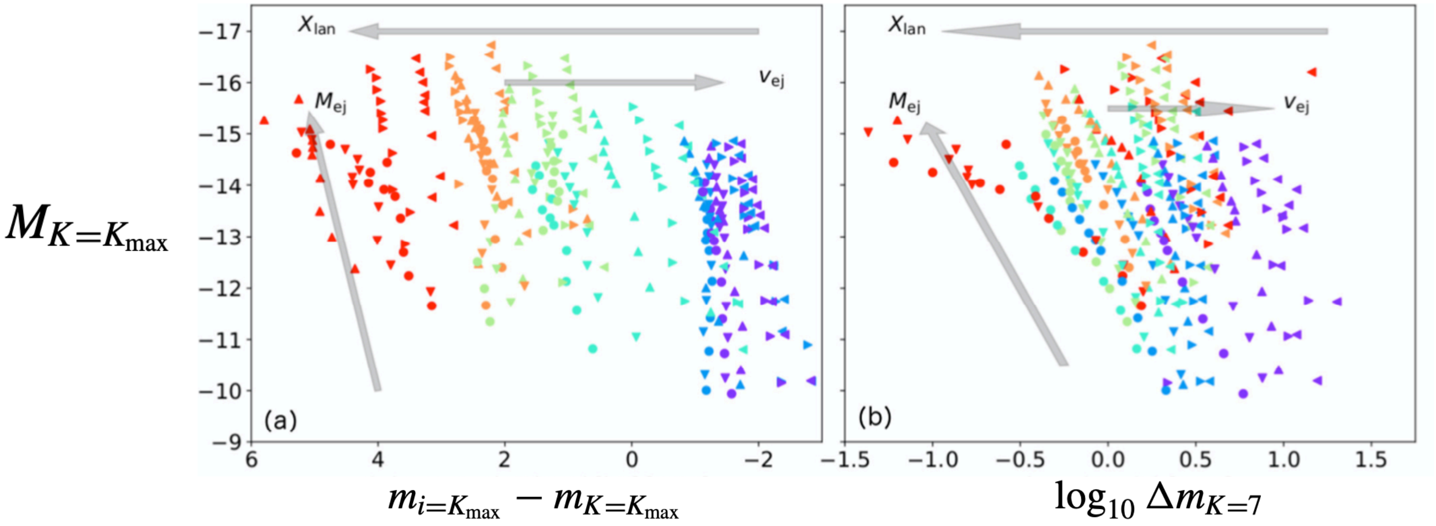
3. Constrain distance directly from kilonovae



Models from Kasen+2017

1. Use grid of kilonova models to infer absolute magnitude in the K-band

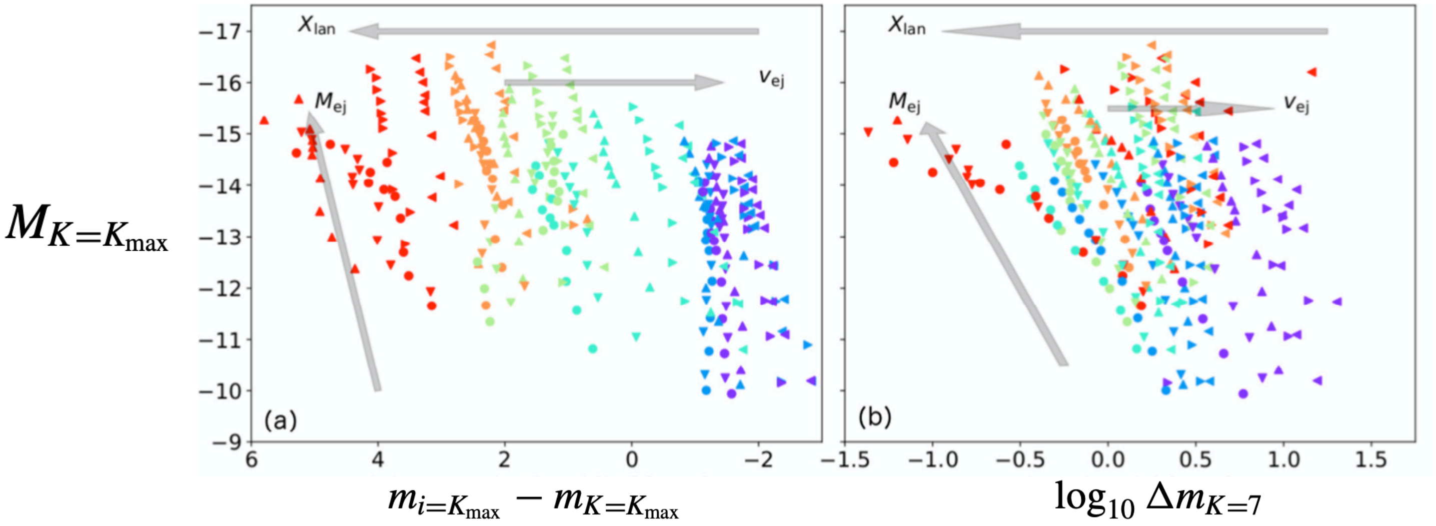
3. Constrain distance directly from kilonovae



Models from Kasen+2017

1. Use grid of kilonova models to infer absolute magnitude in the K-band as a function of:
   - Observed parameters ('measured') $M_{K=K_{\max}} = f(\log_{10} \Delta m_{K=7}, \log_{10} \Delta m_{i=7}, m_{i=K_{\max}} - m_{K=K_{\max}})$
   - Model parameters ('inferred') $M_{K=K_{\max}} = f(\log_{10} M_{\rm ej}, v_{\rm ej}, \log_{10} X_{\rm lan})$

3. Constrain distance directly from kilonovae



Models from Kasen+2017

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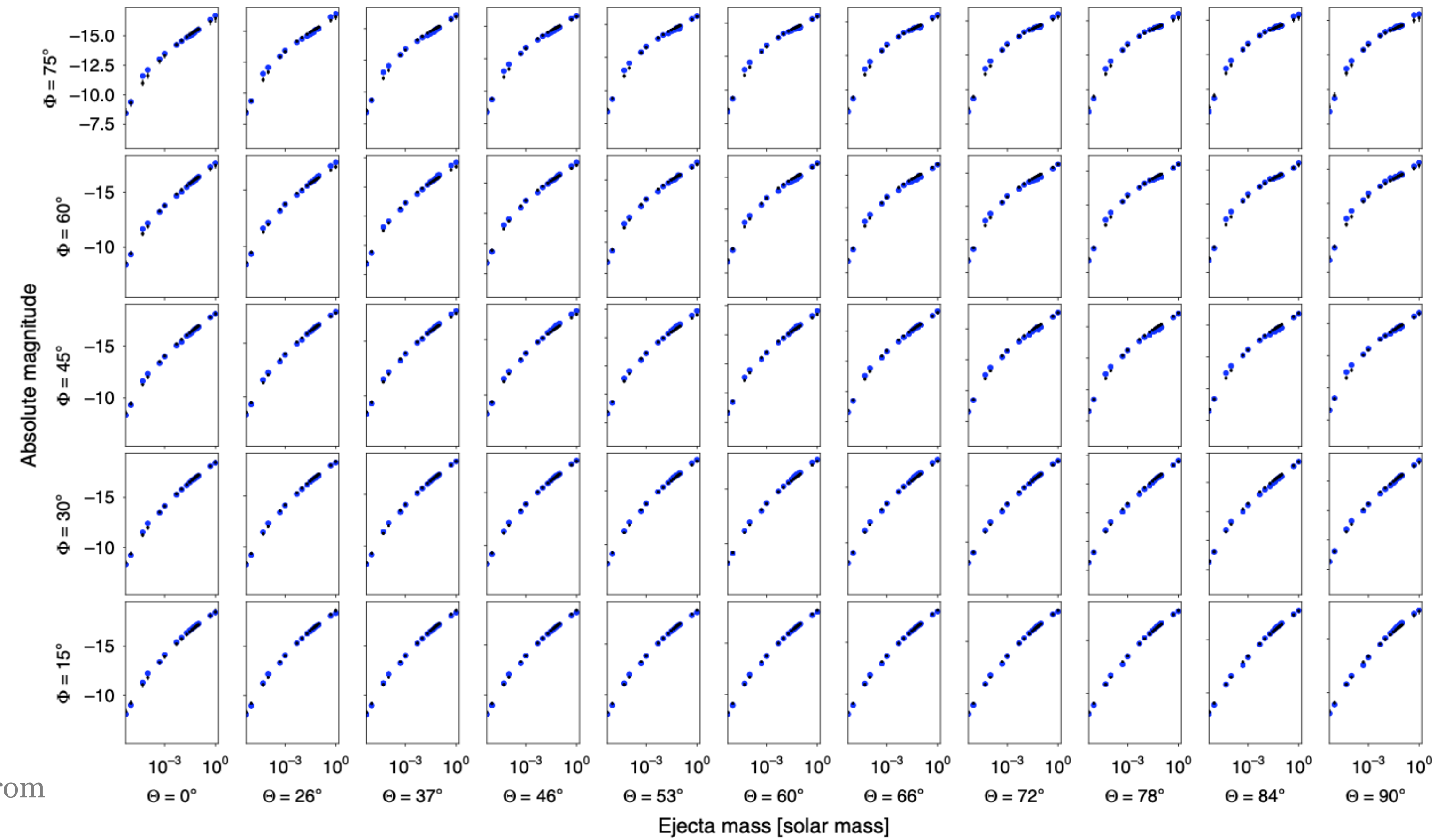
- Model parameters ('inferred') $M_{K=K_{max}} = f(\log_{10} M_{ej}, v_{ej}, \log_{10} X_{lan})$

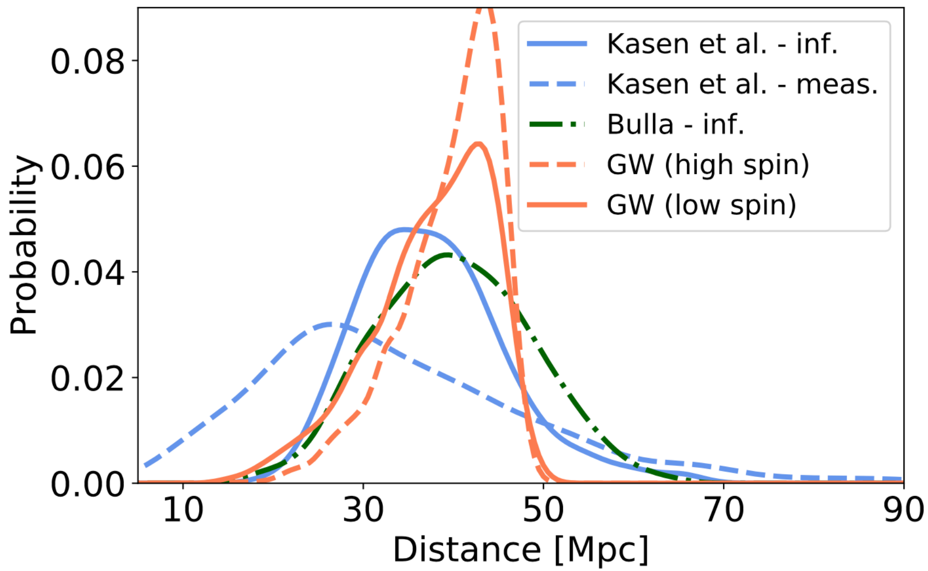
2. Infer distance modulus μ and thus distance D: $M_{abs} = m_{app} - \mu$ $\mu = 5 \log_{10}\left(\frac{D}{10\ \mathrm{pc}}\right)$

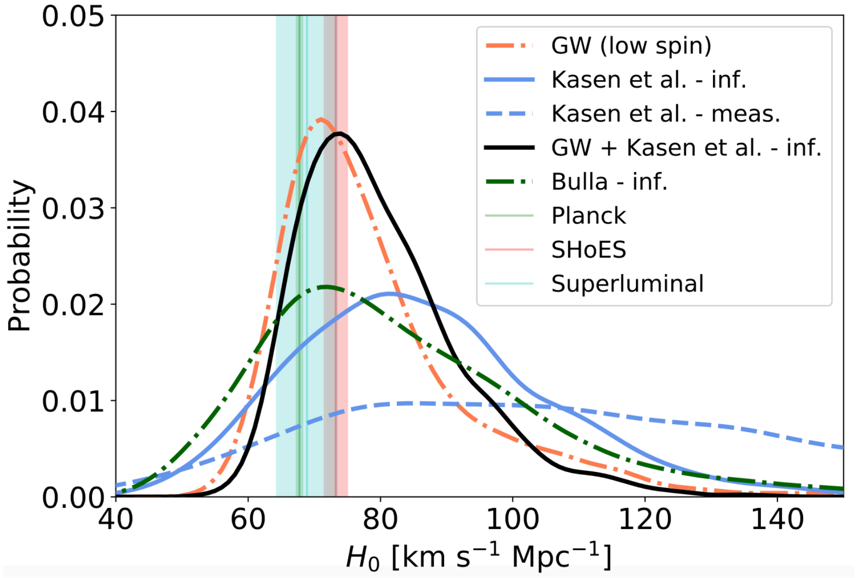
3. Constrain distance directly from kilonovae



Models from
MB 2019

3. Constrain distance directly from kilonovae





Kilonova only ('inferred')

GW only

$H_0 = 74.0^{+16.0}_{-8.0}$ km s^{-1} / Mpc

Kasen models

$H_0 = 85.0^{+22.0}_{-17.0}$ km s^{-1} / Mpc

Bulla models

$H_0 = 79.0^{+23.0}_{-15.0}$ km s^{-1} / Mpc

3. Constrain distance directly from kilonovae

nature COMMUNICATIONS

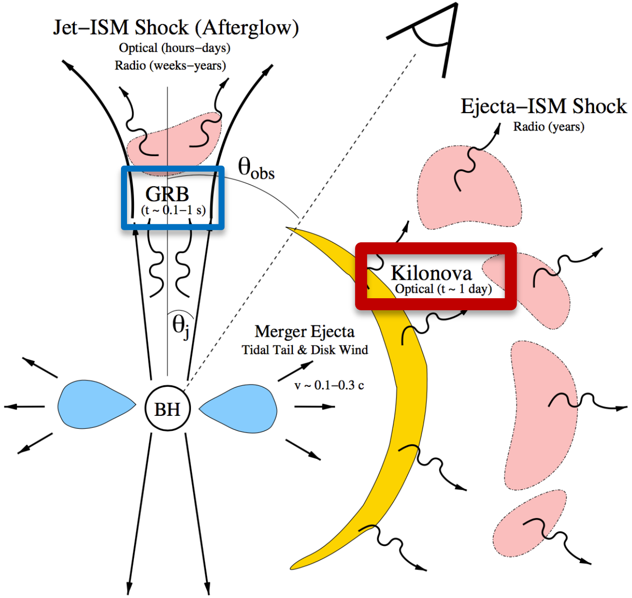
ARTICLE

Check for updates

https://doi.org/10.1038/s41467-020-17998-5 OPEN

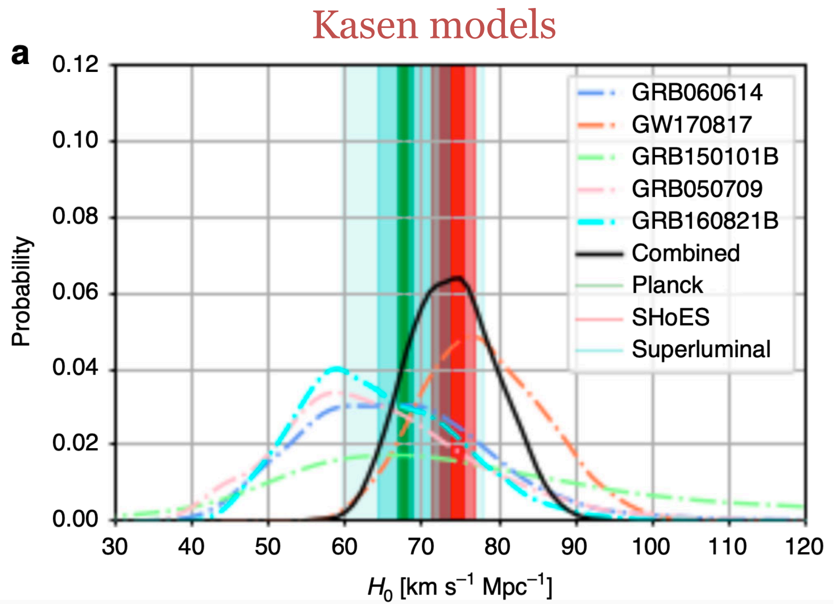
Measuring the Hubble constant with a sample of kilonovae

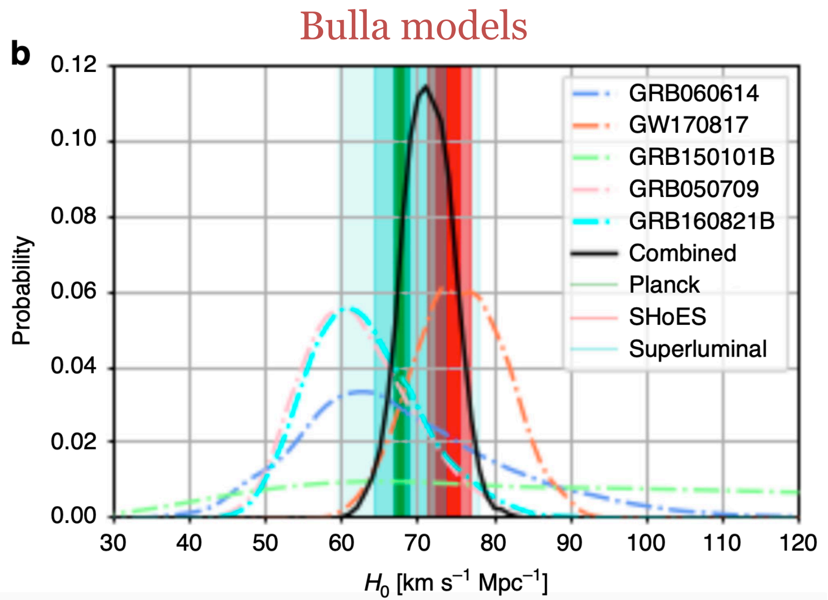
Michael W. Coughlin[1,2✉], Sarah Antier[3], Tim Dietrich[4,5], Ryan J. Foley[6], Jack Heinzel[7,8], Mattia Bulla[9], Nelson Christensen[7,8], David A. Coulter[6], Lina Issa[9,10] & Nandita Khetan[11]



Apply same technique to 4 GRBs from the literature + GW170817

3. Constrain distance directly from kilonovae





GW only

$H_0 = 74.0^{+16.0}_{-8.0}$ km s^{-1} / Mpc

Kilonova only ('inferred')

Kasen models

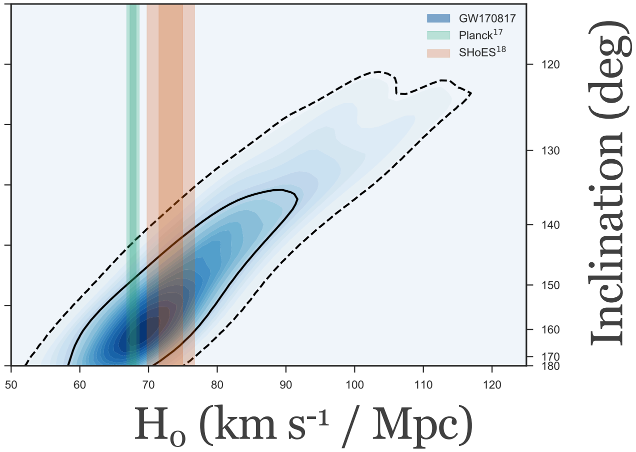
$H_0 = 73.8^{+6.3}_{-5.8}$ km s^{-1} / Mpc

Bulla models

$H_0 = 71.2^{+3.2}_{-3.1}$ km s^{-1} / Mpc

Conclusions

1. Constrain inclination with kilonova light curves -> GW + EM (improve standard sirens)
2. Constrain inclination with kilonova polarization -> GW + EM (improve standard sirens)
3. Constrain distance directly from kilonovae -> EM



$$H_0 = \frac{[\text{speed of light}] \times \text{Redshift}}{\text{Distance}}$$