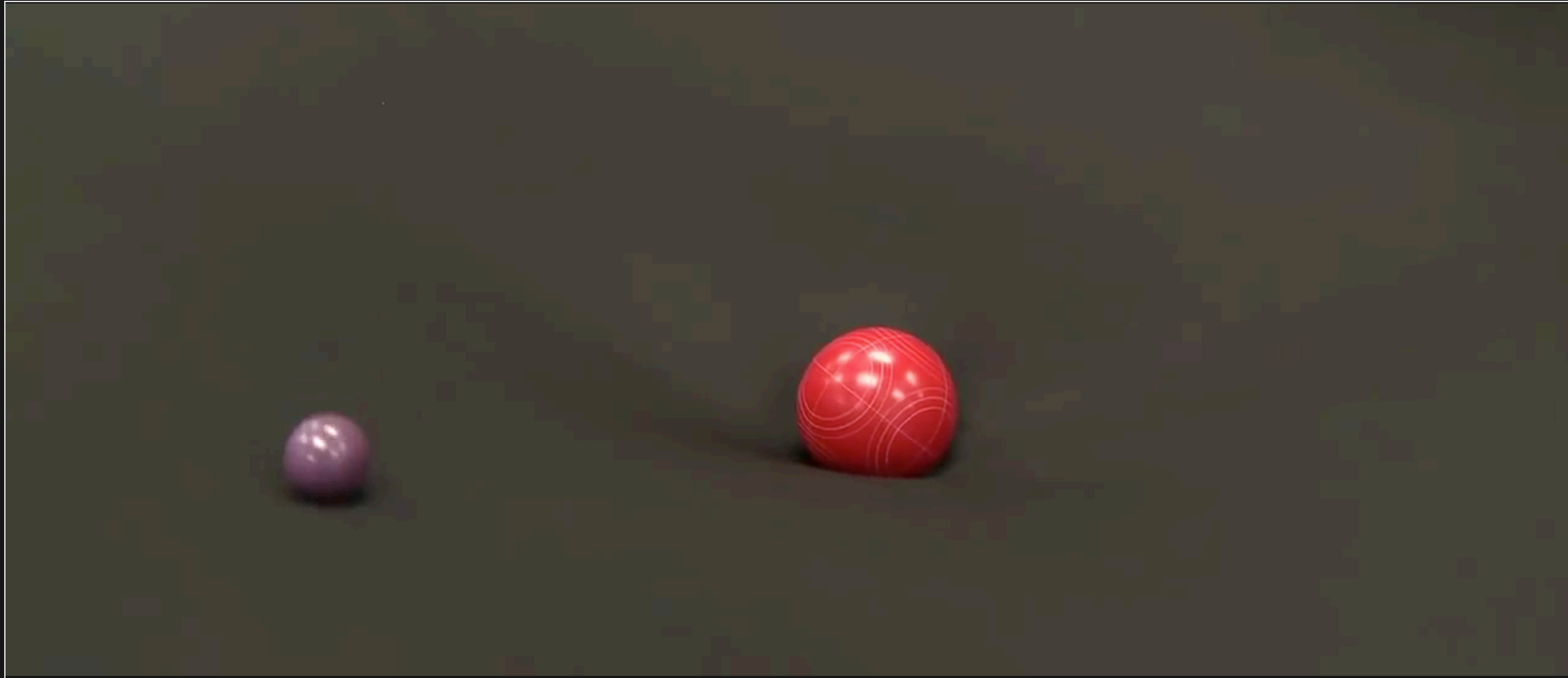


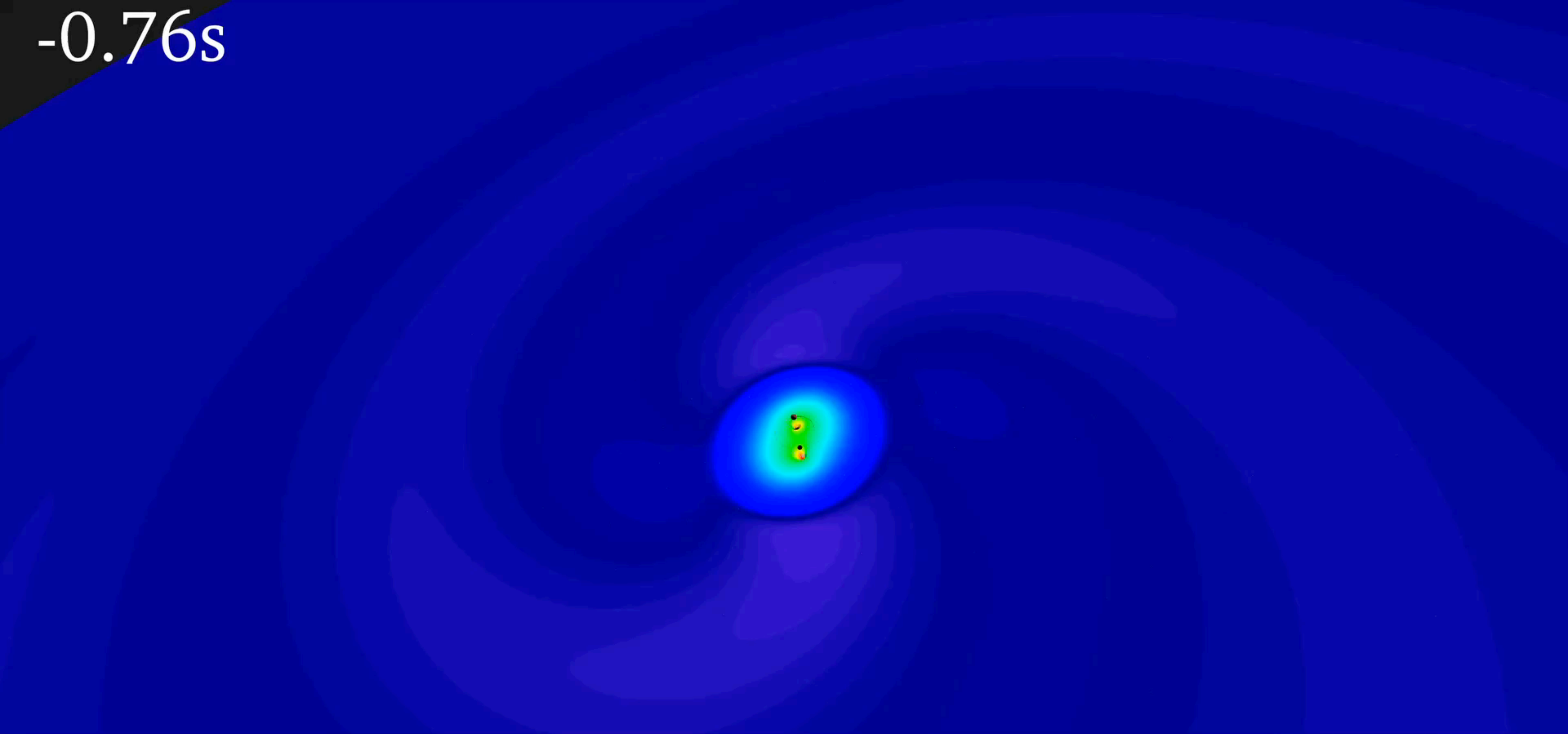
General Relativity



“Spacetime tells matter how to move;
matter tells spacetime how to curve.”

— John Wheeler

-0.76s



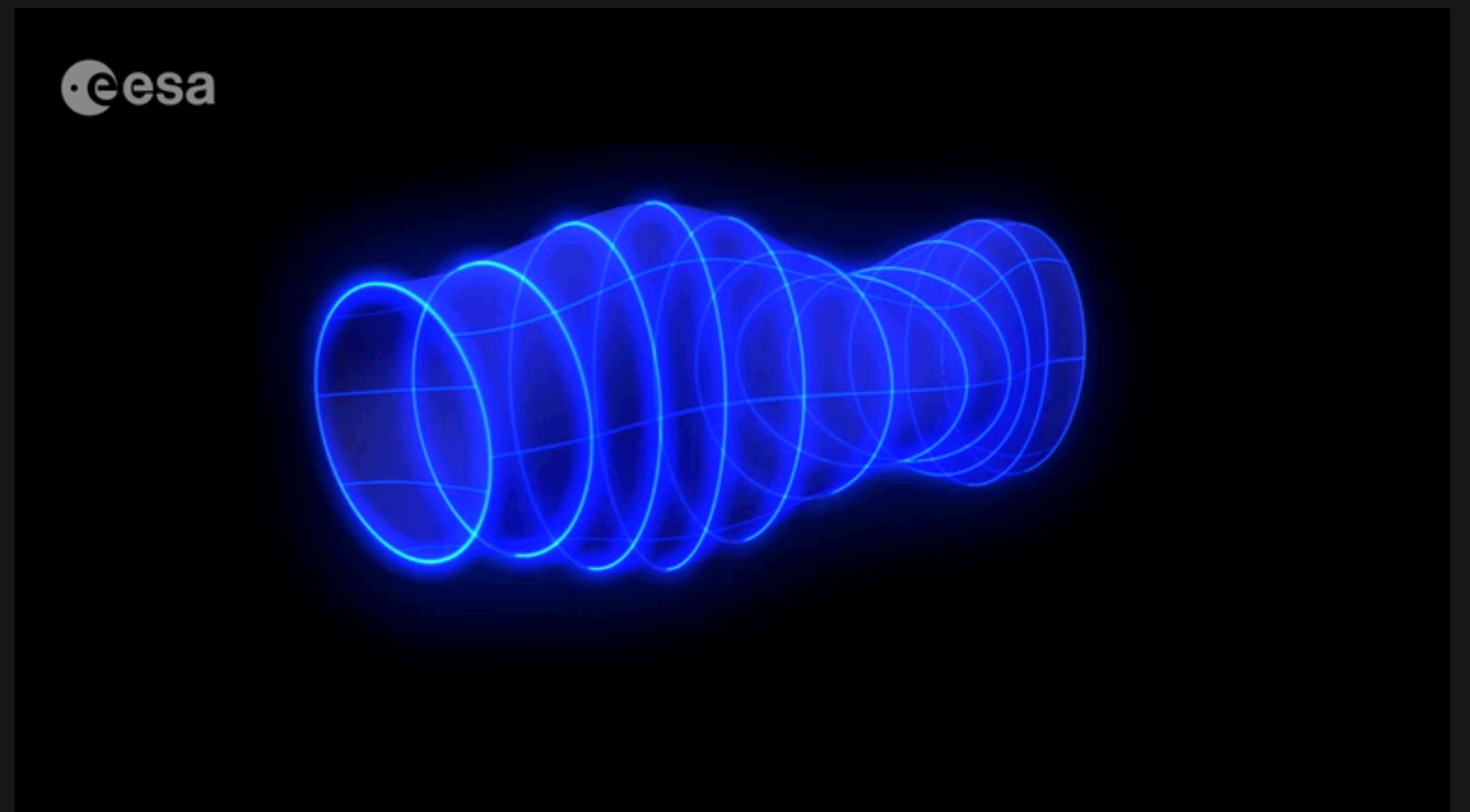
Gravitational Waves

Strain on spacetime.

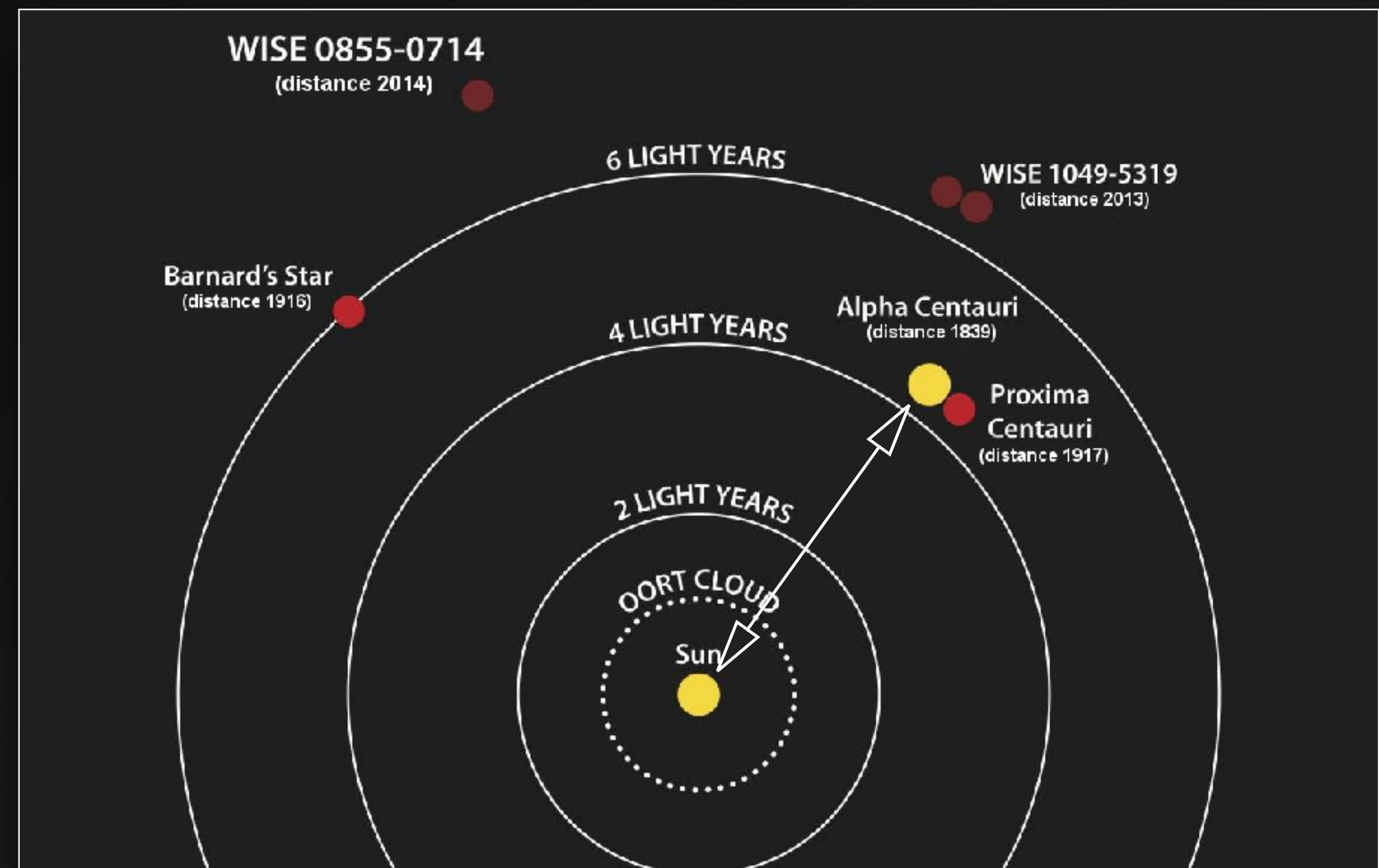
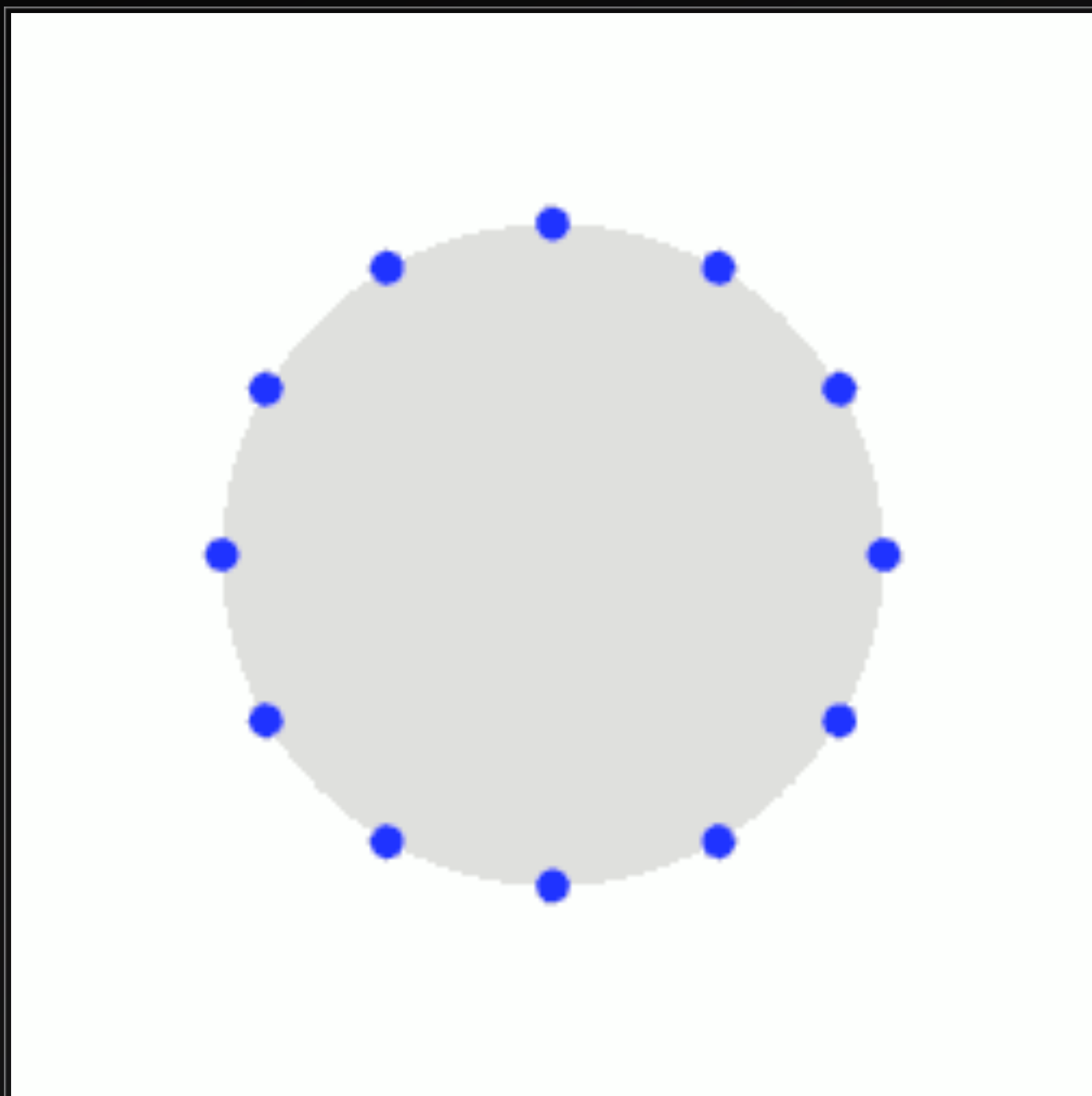
Generated by time-varying quadrupole moment.

Propagate at speed of light.

Unimpeded by matter.



0.00



credit: wikipedia

LIGO-Virgo Network



Hanford, WA

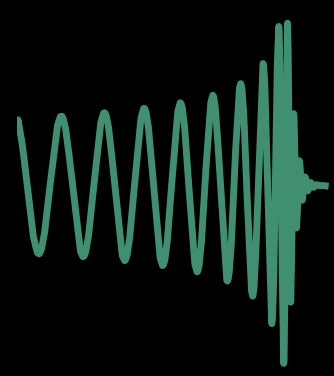


Pisa, Italy

Livingston, LA



GW150914



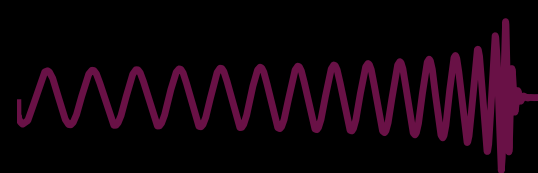
LVT151012



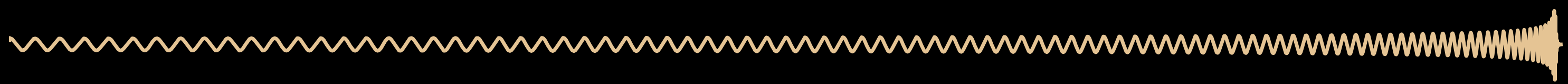
GW151226



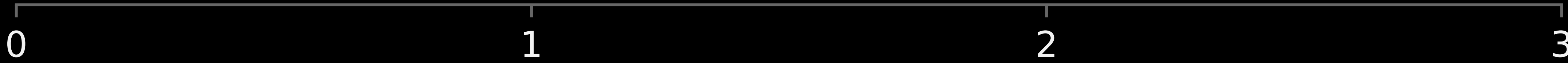
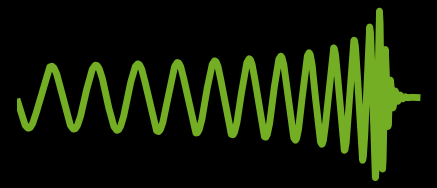
GW170104



GW170608



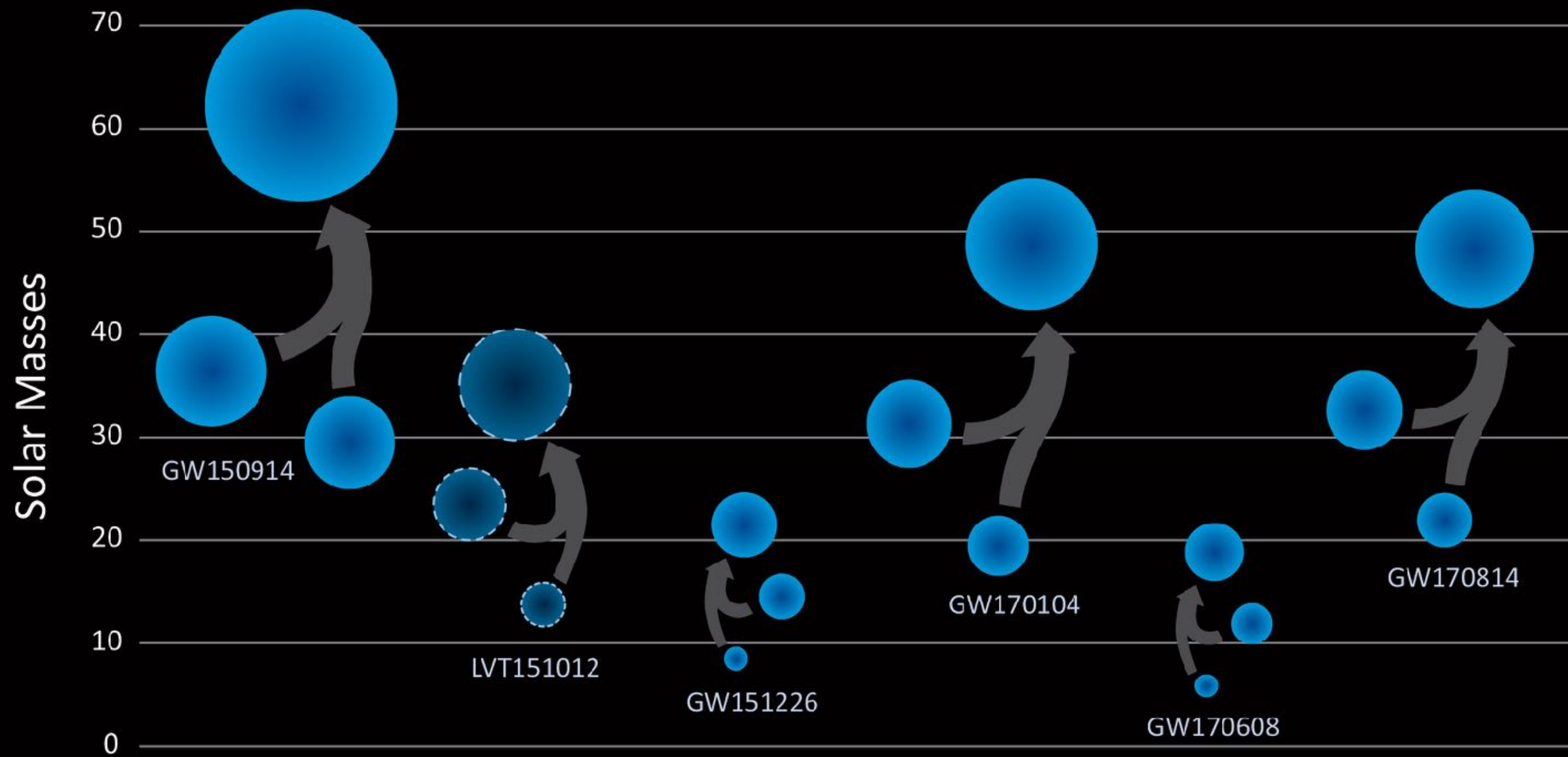
GW170814



time observable (seconds)

LIGO/University of Oregon/Ben Farr

Black Holes of Known Mass

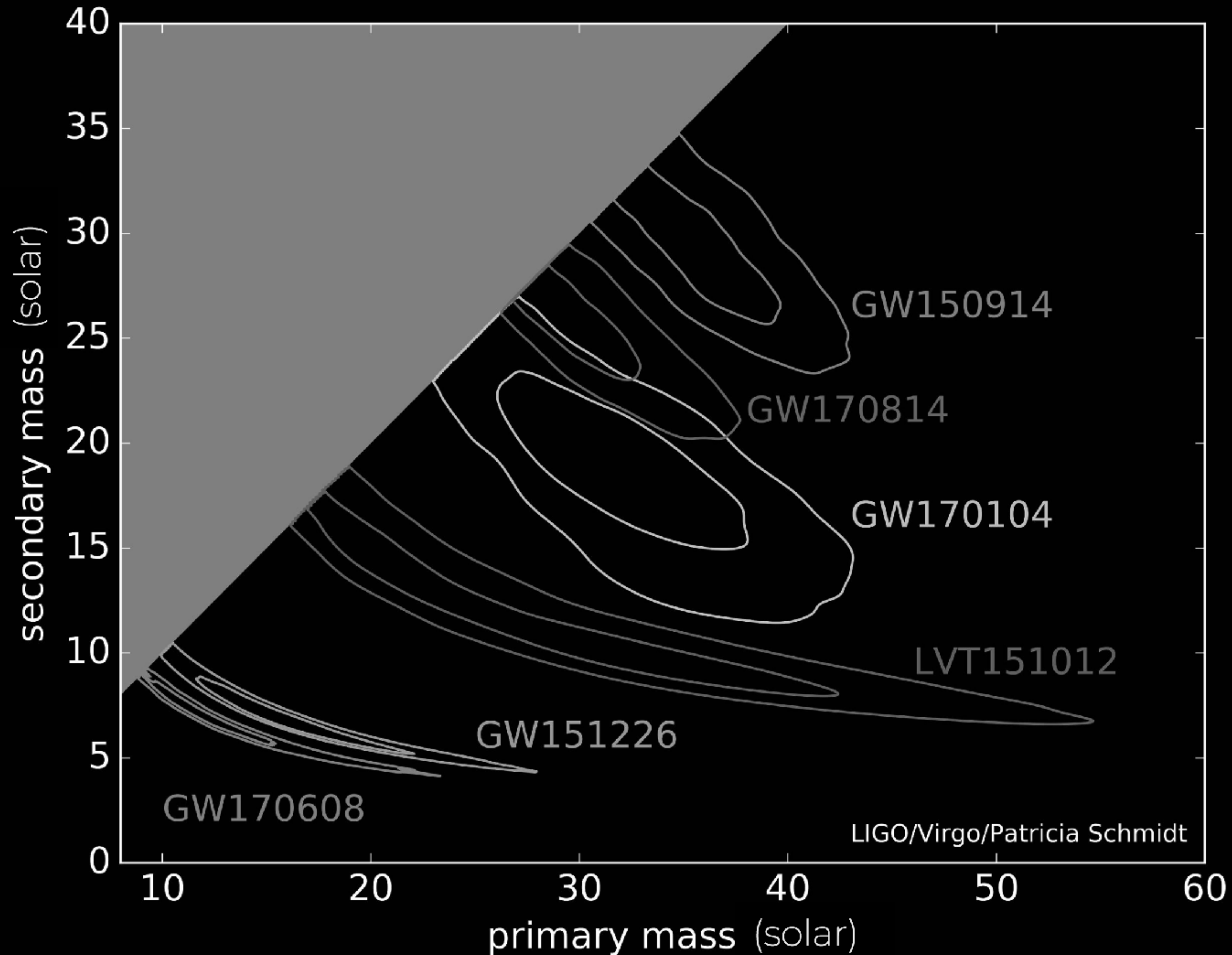


OI BBH:
Abbott et al. (2016)
PRX 6, 041015

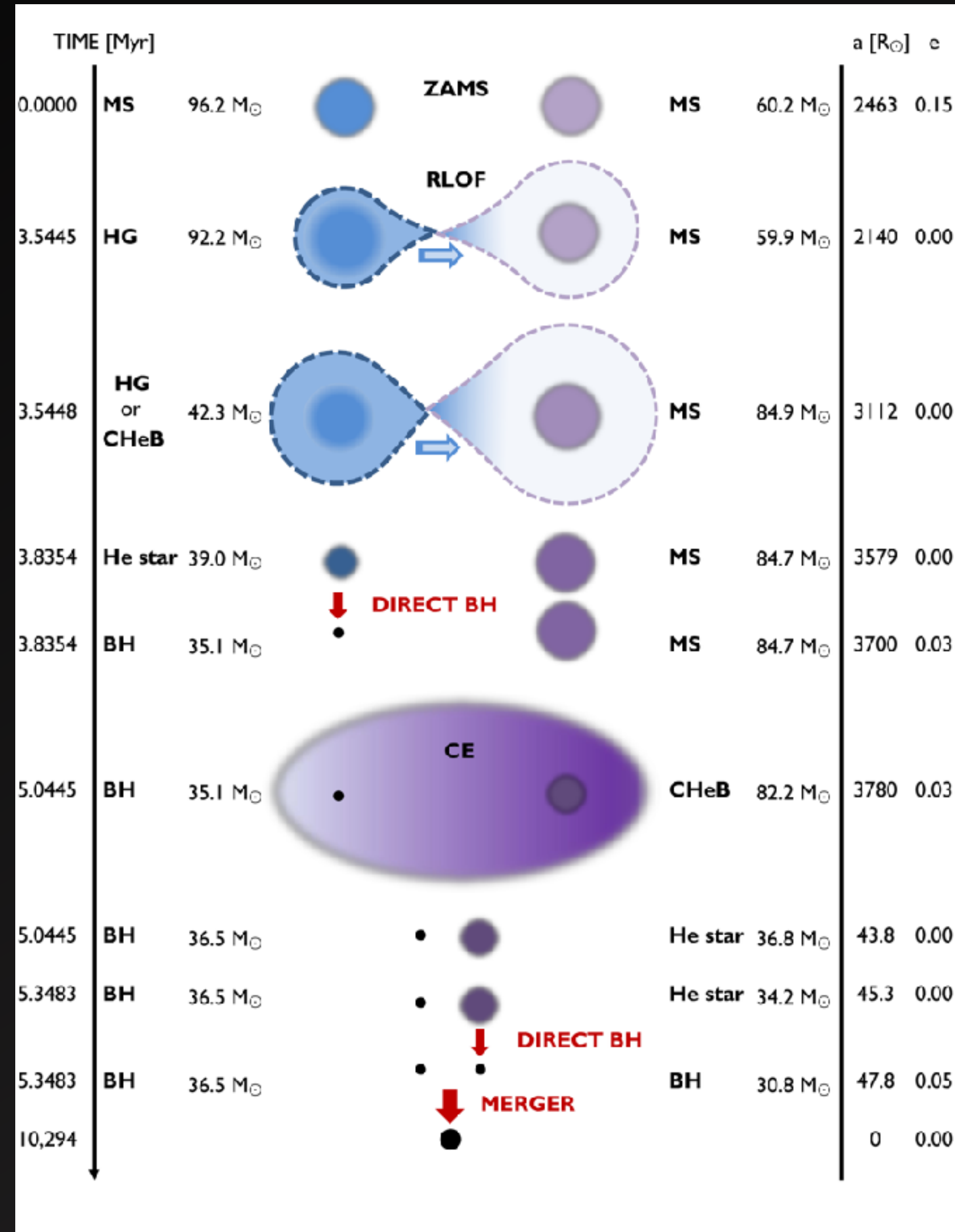
GW170104:
Abbott et al. (2017)
PRL 118, 221101

GW170608:
Abbott et al. (2017)
ApJL 851 L35

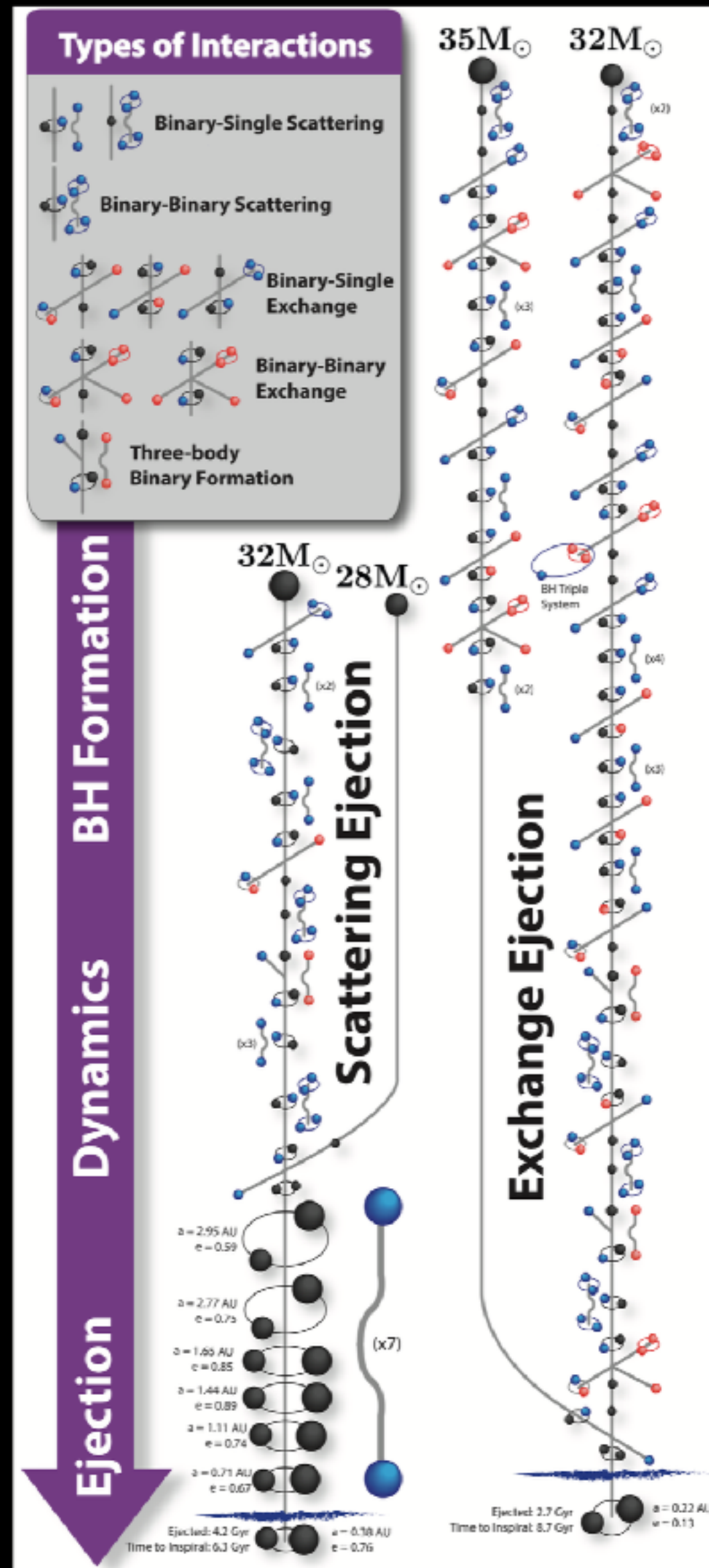
GW170814:
Abbot et al. (2017)
PRL 119, 141101



Isolated (“Field”) Formation



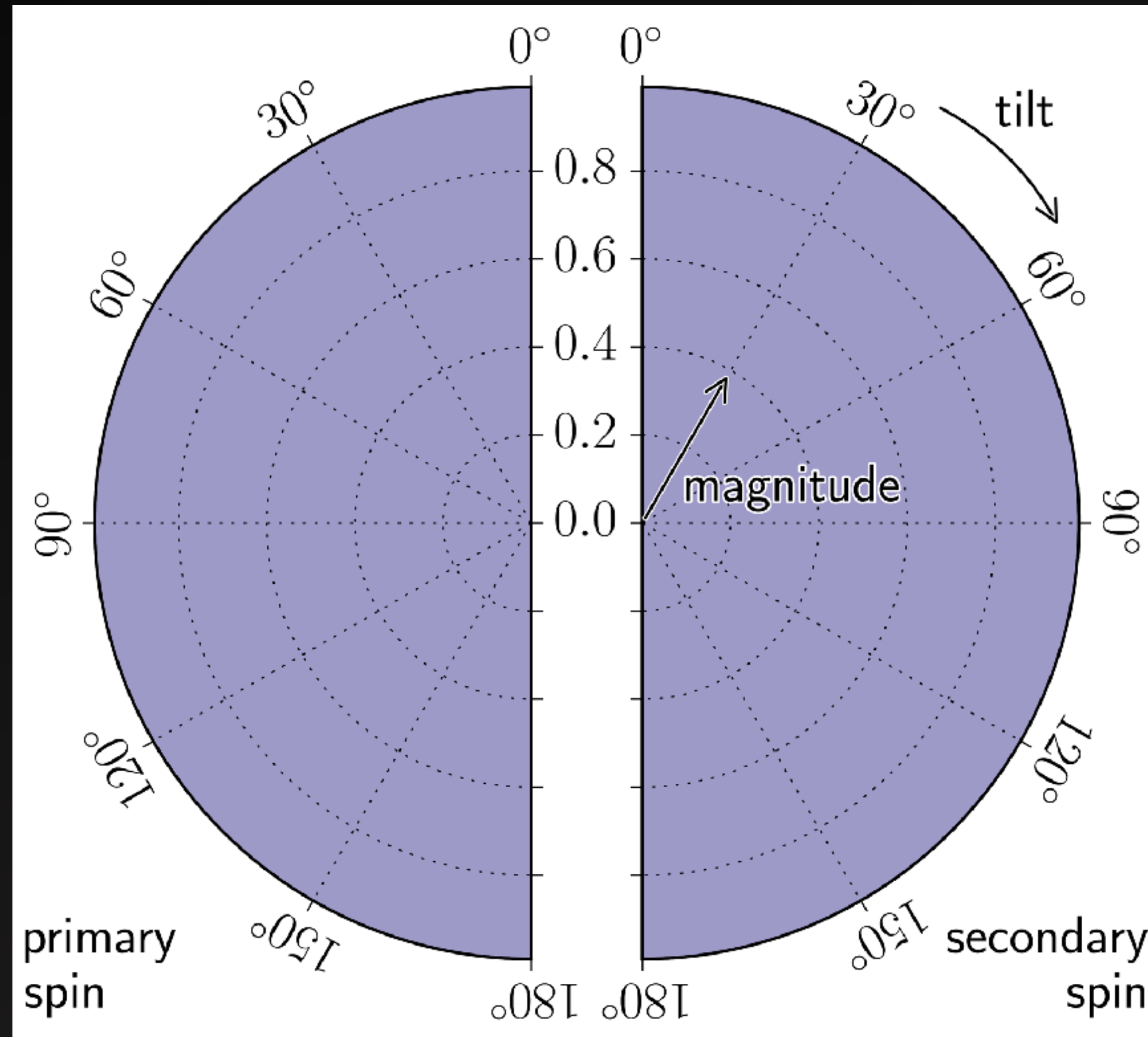
Dynamical Formation



Rodriguez et al. (2016)

Black Hole Spins

prior

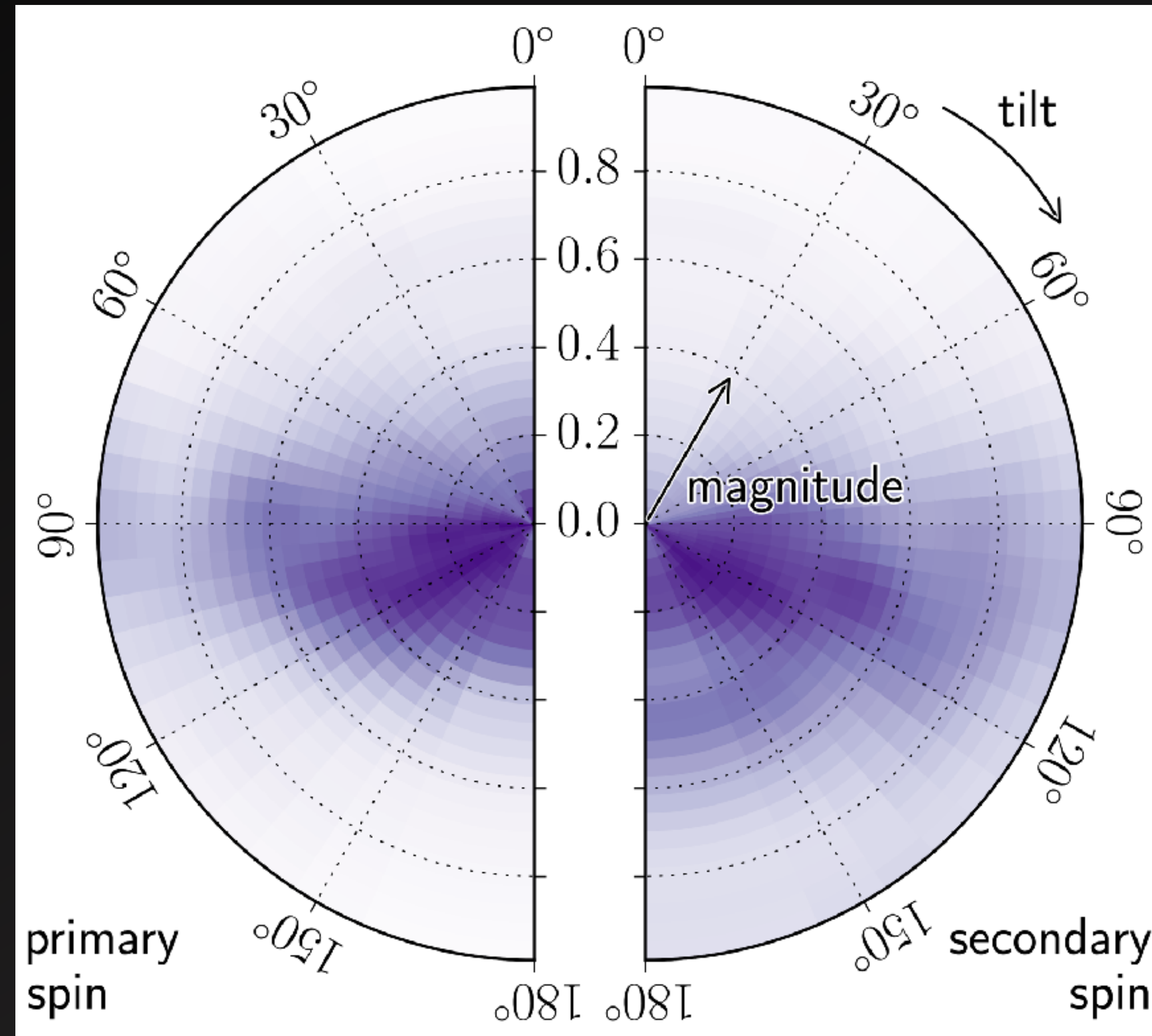


Black Hole Spins

Abbott et al. (2016):
PRX 6, 041015

GW150914

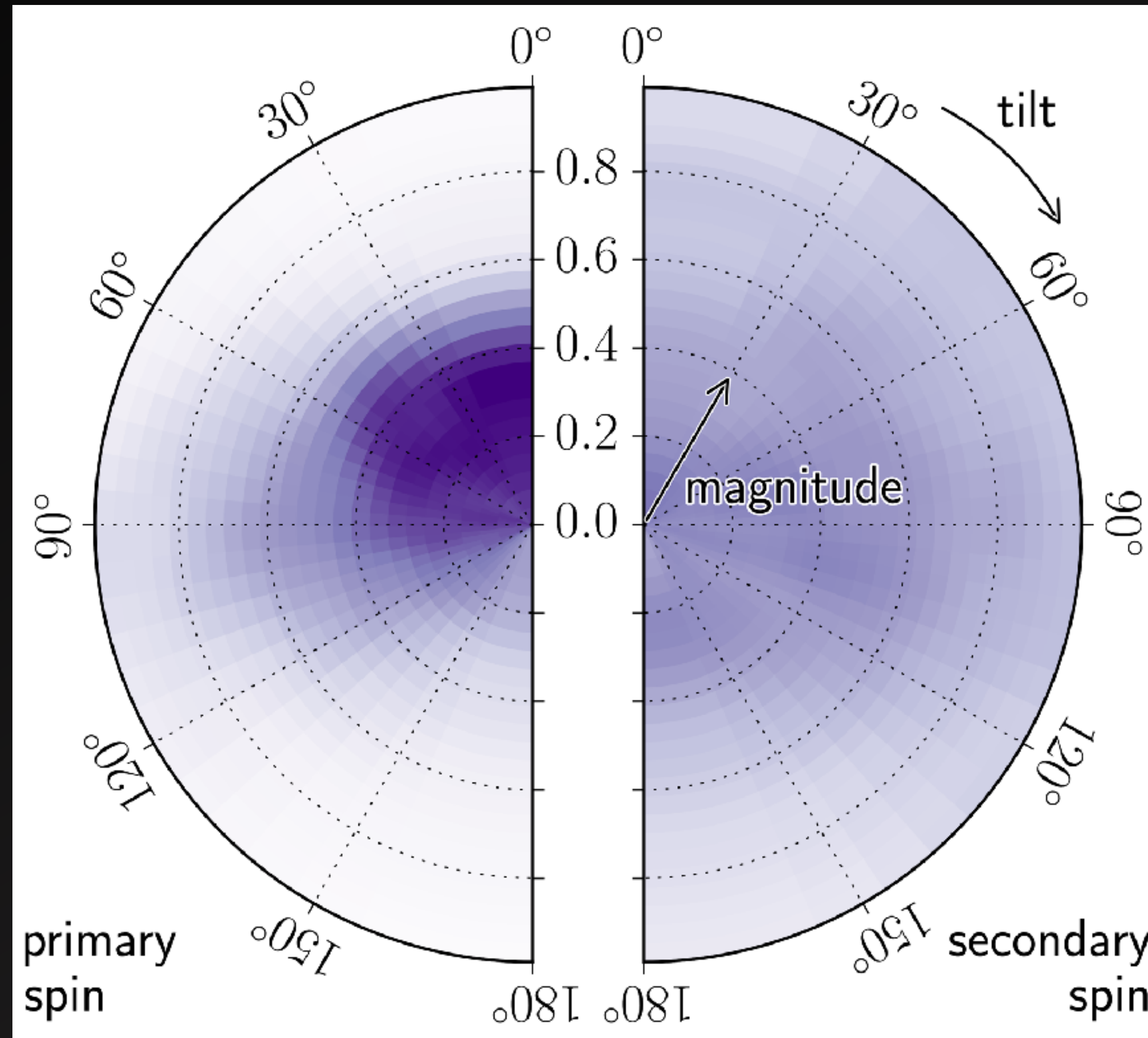
BH spin
not extremal



Black Hole Spins

Abbott et al. (2016):
PRX **6**, 041015

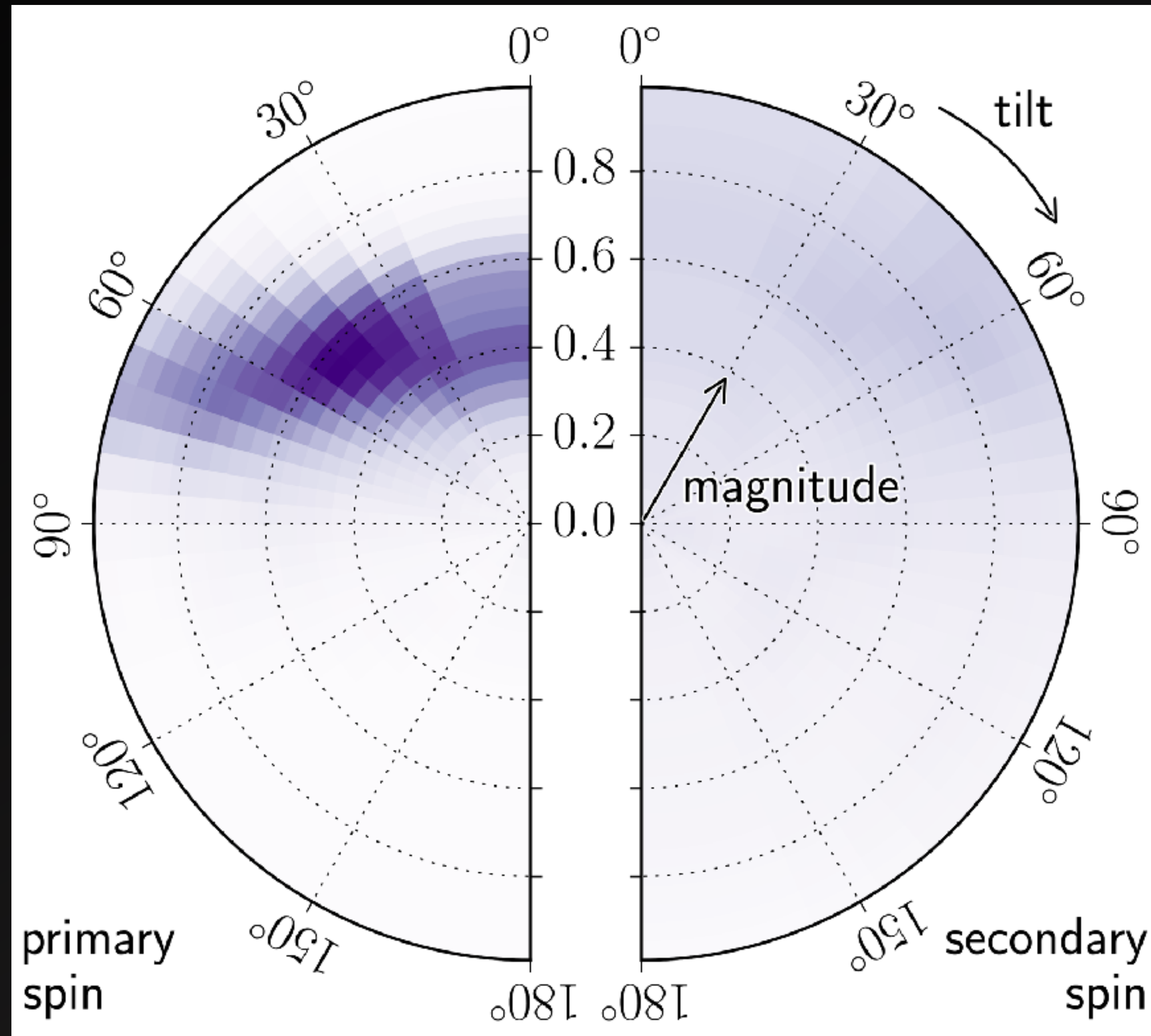
LVT151012



Black Hole Spins

Abbott et al. (2016):
PRX 6, 041015

GW151226

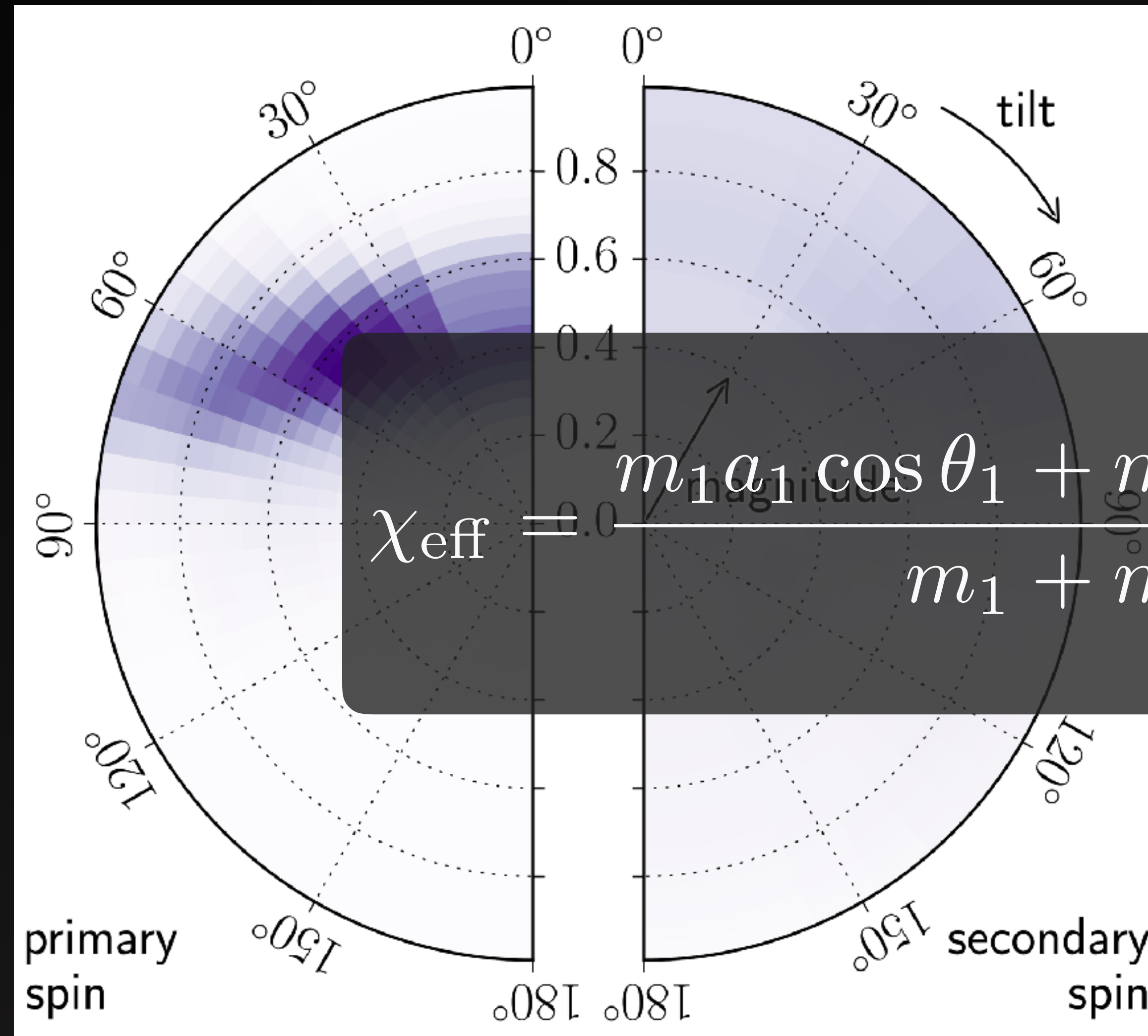


At least one
spinning BH

Black Hole Spins

Abbott et al. (2016):
PRX 6, 041015

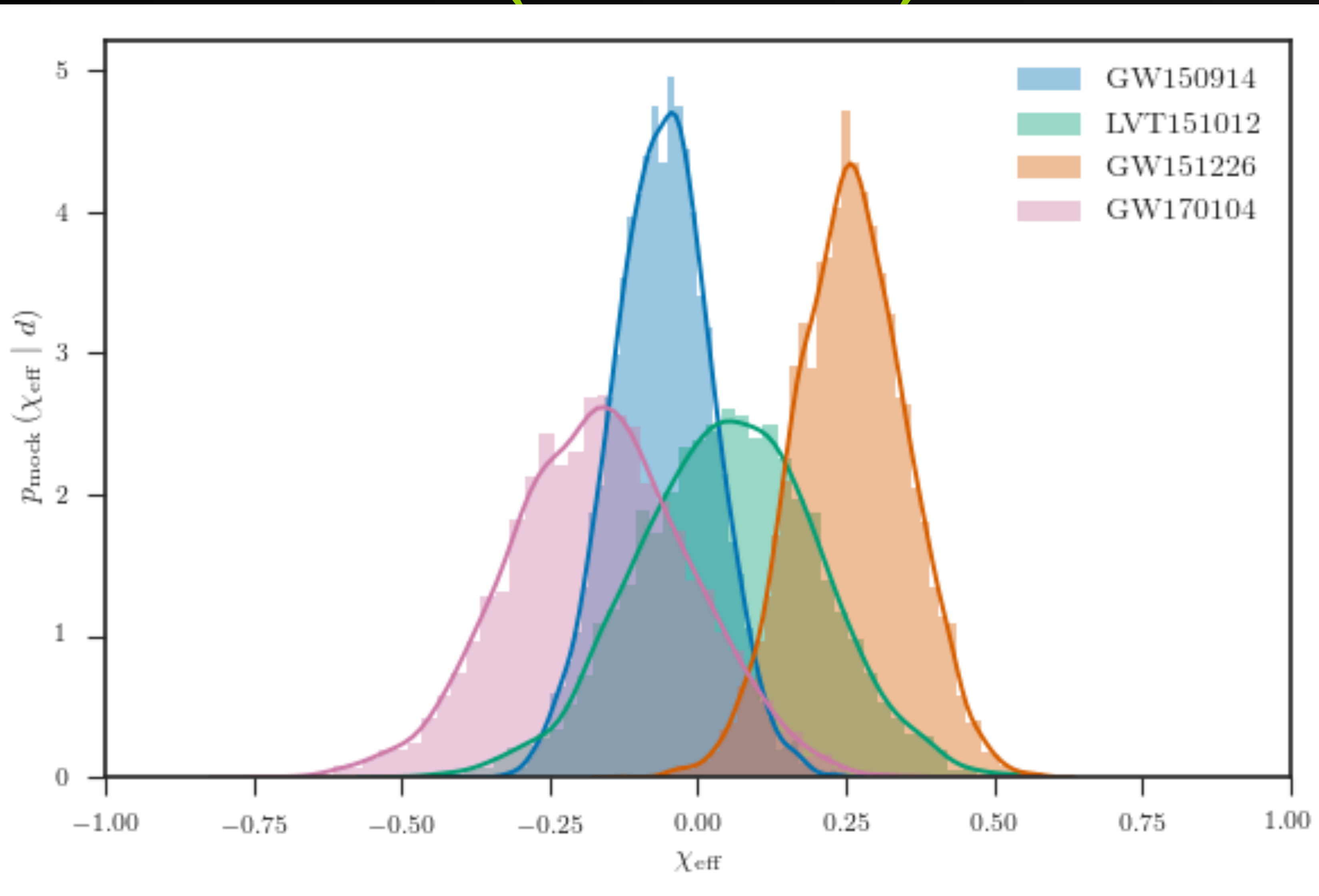
GW151226



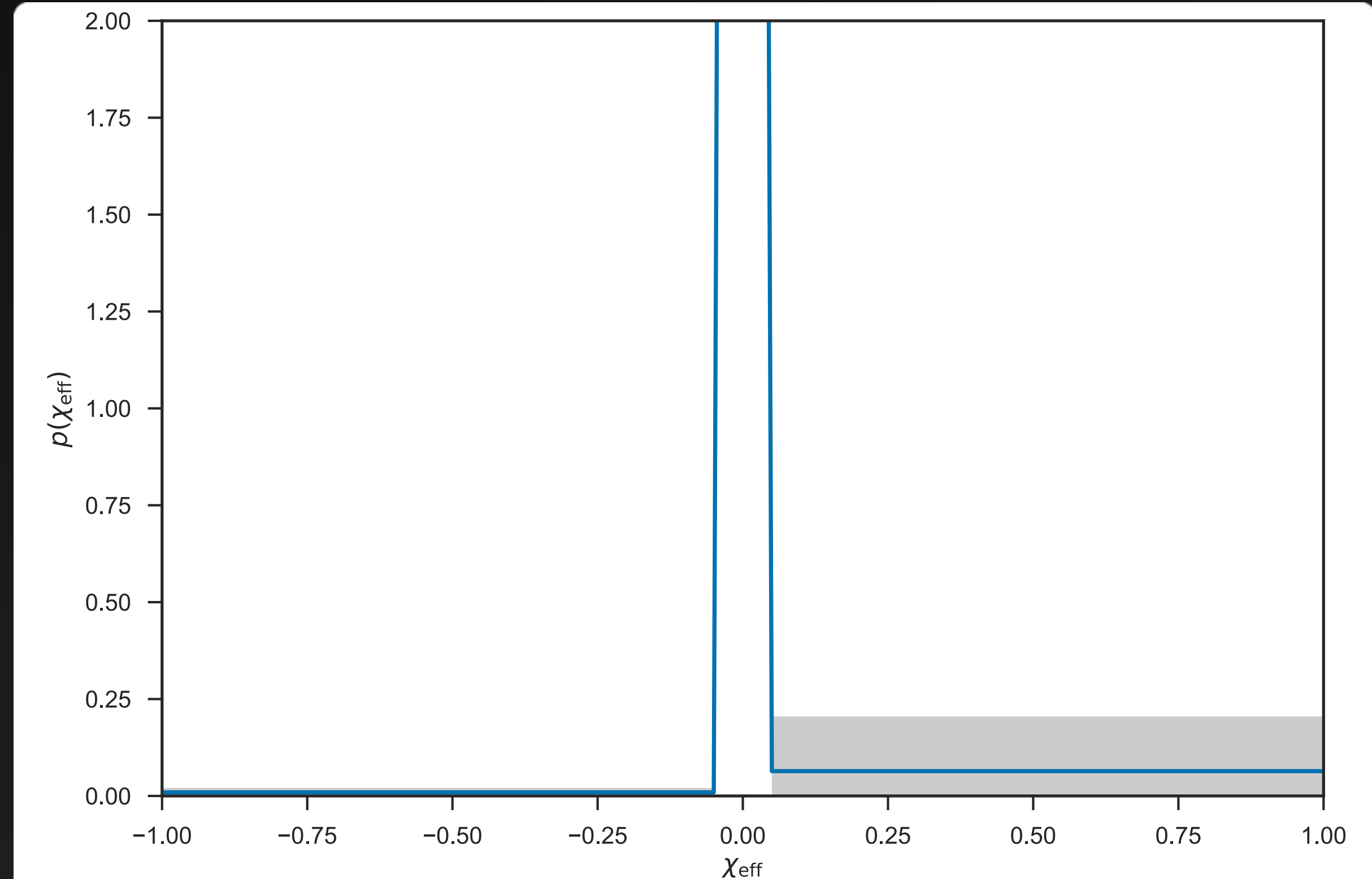
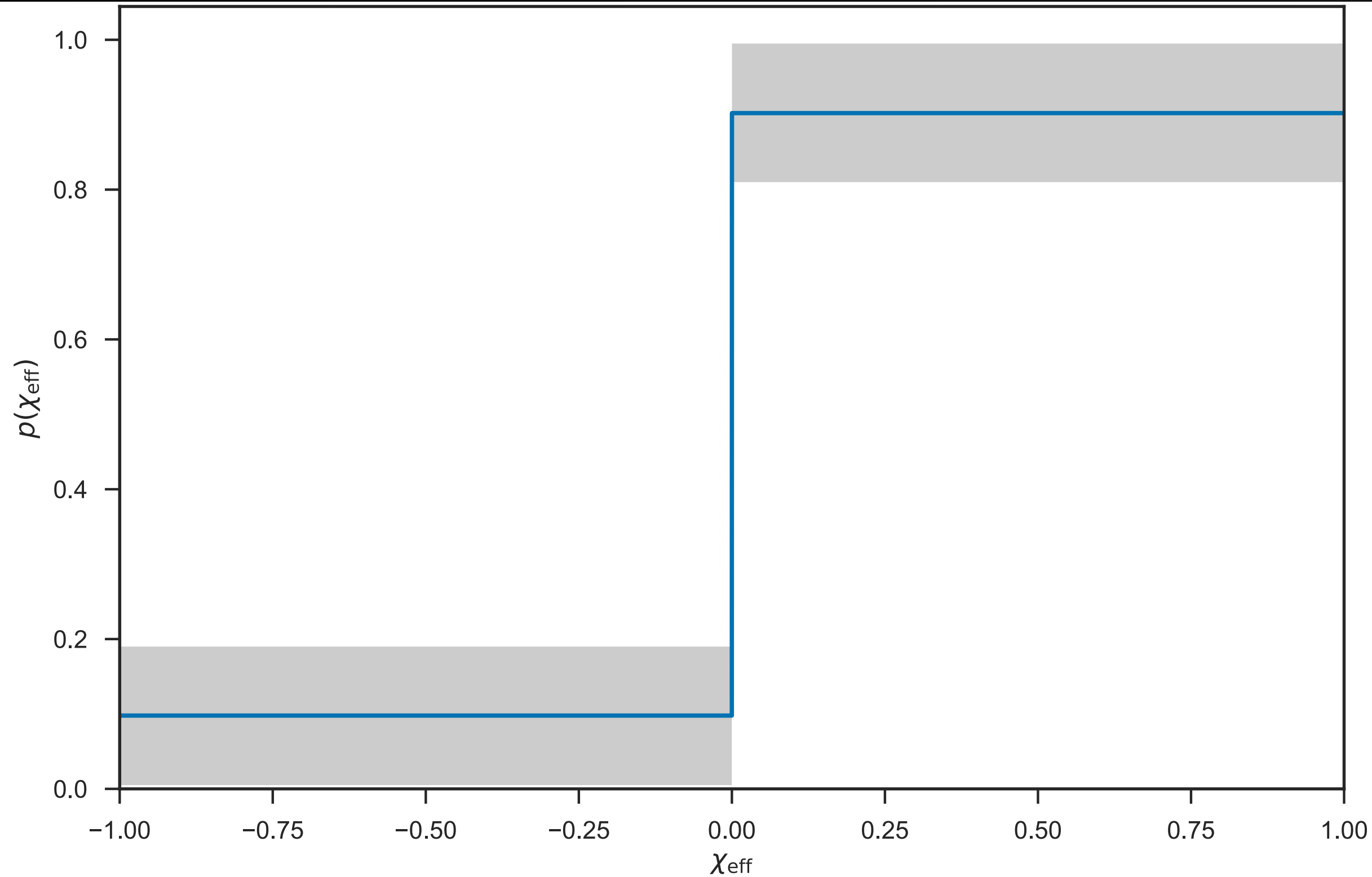
$$\chi_{\text{eff}} = \frac{m_1 a_1 \cos \theta_1 + m_2 a_2 \cos \theta_2}{m_1 + m_2}$$

At least one spinning BH

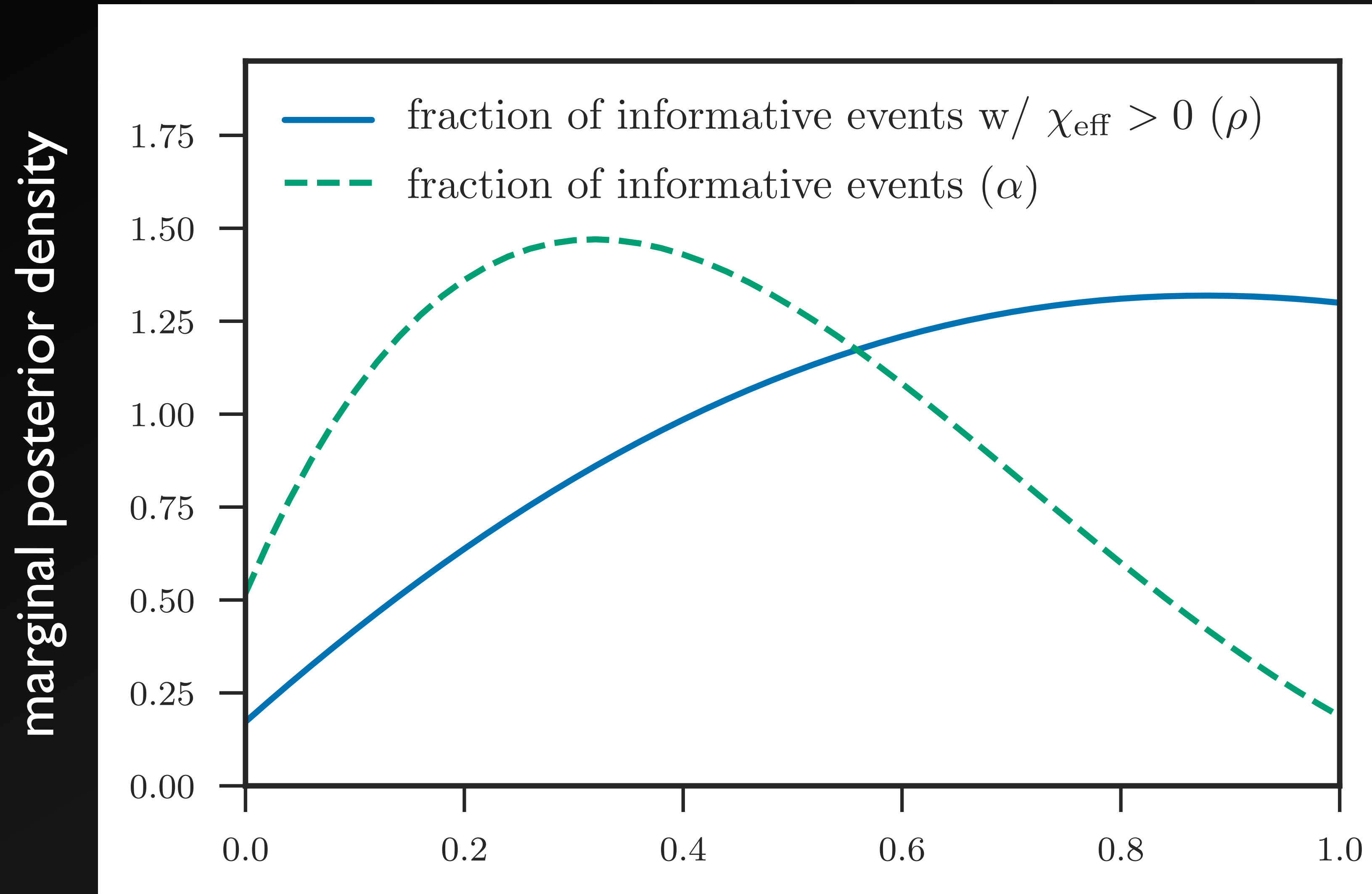
O1 + (some of) O2



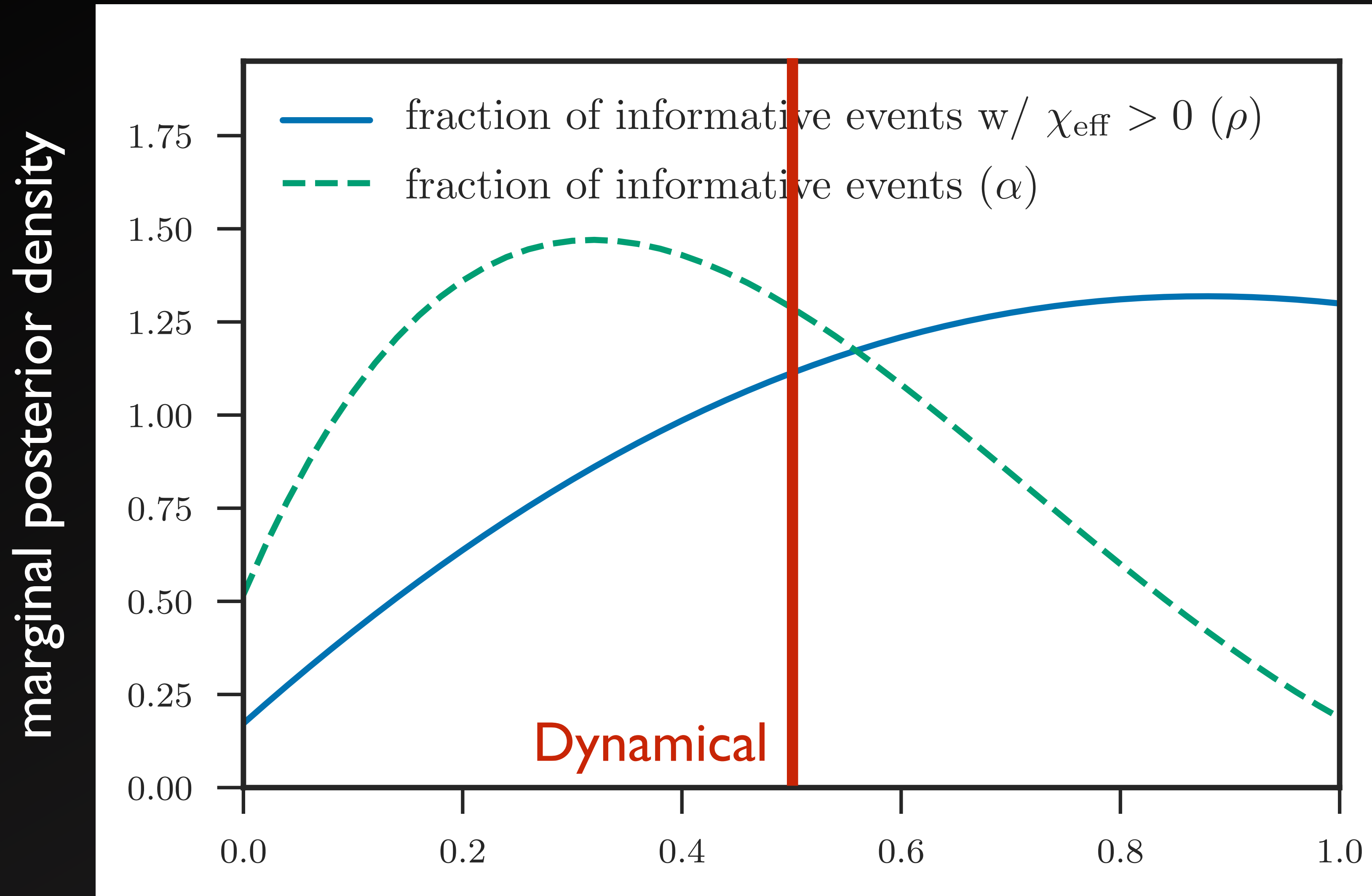
Simple Population Model



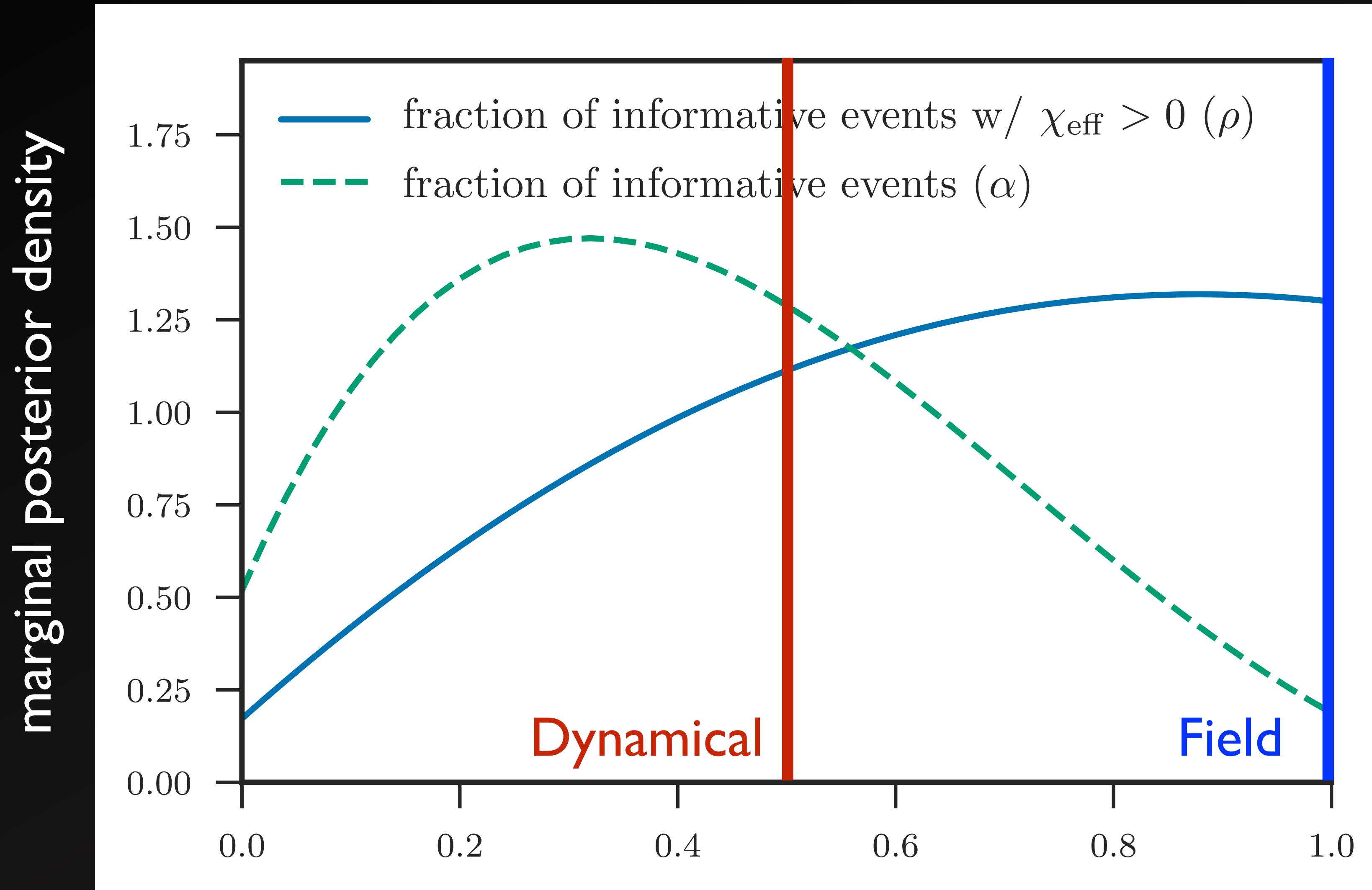
Current Results



Current Results

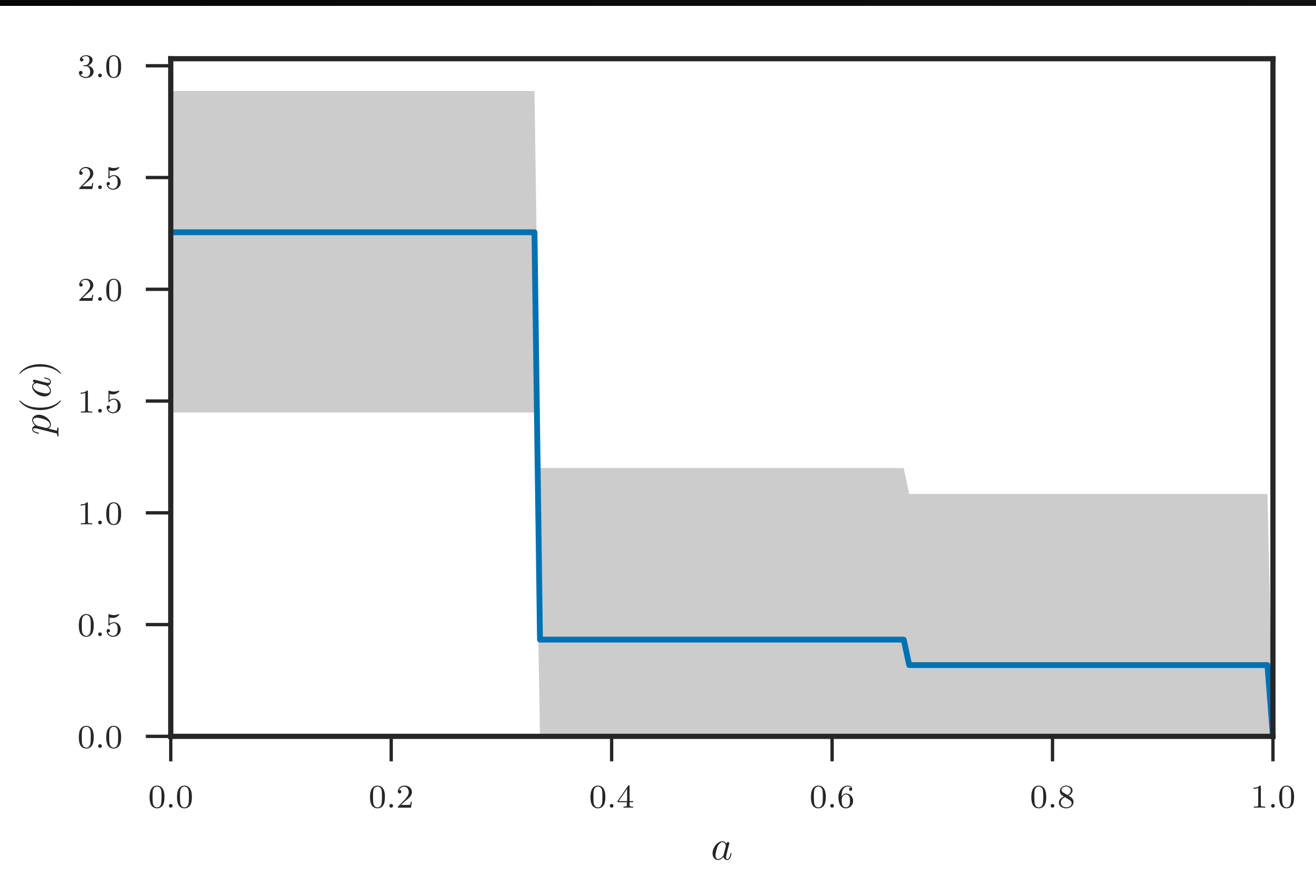


Current Results

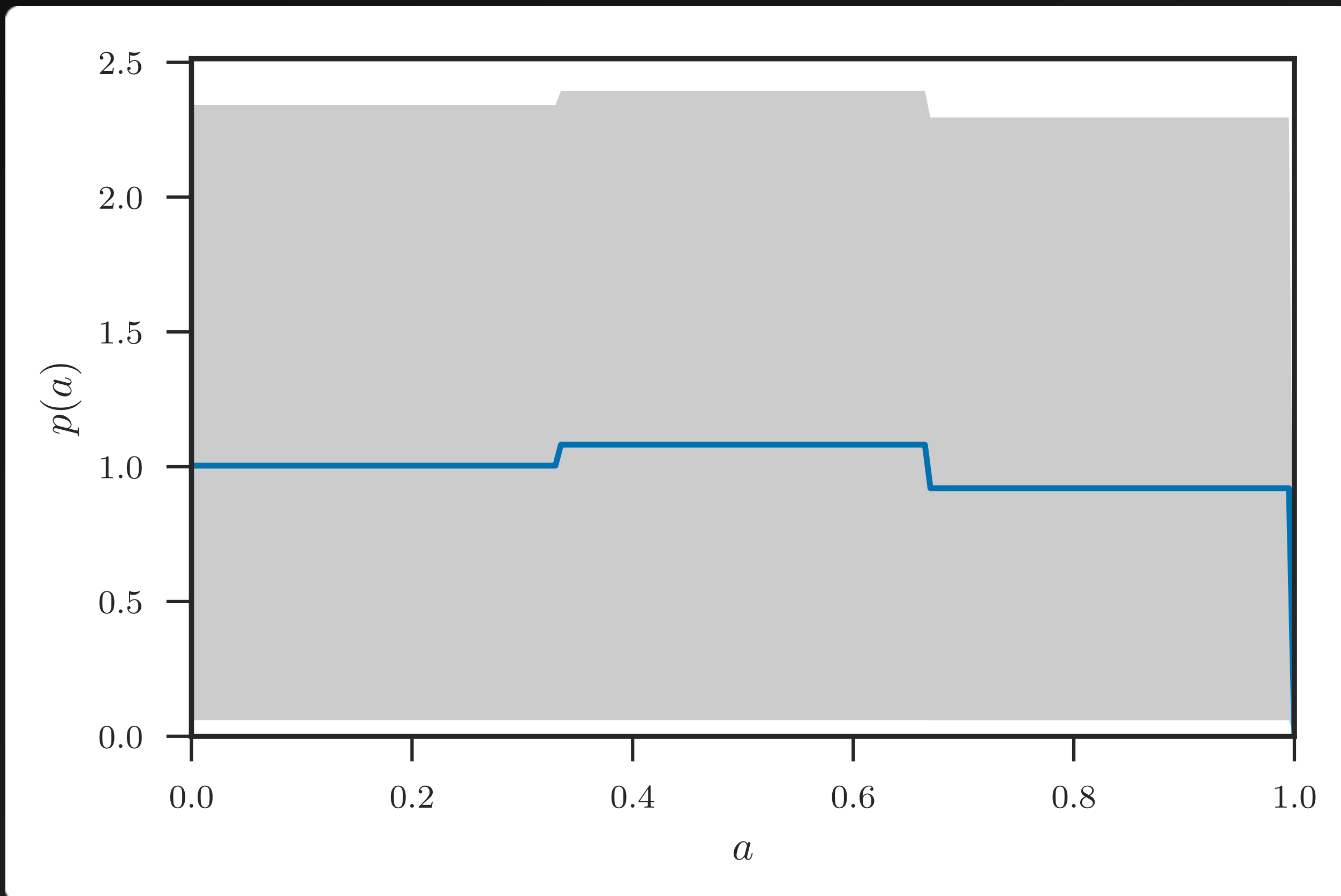


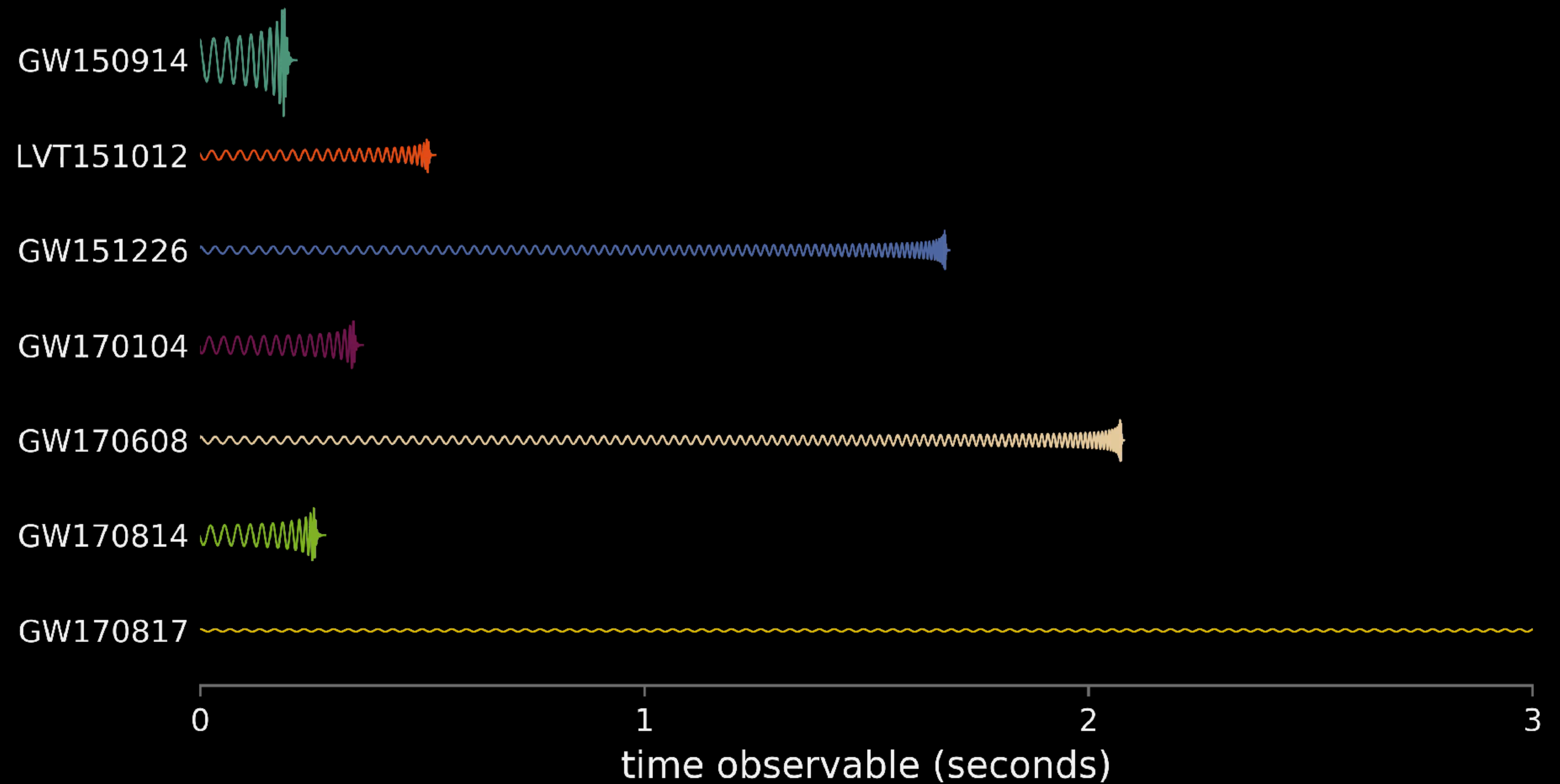
Spin Magnitudes

Aligned

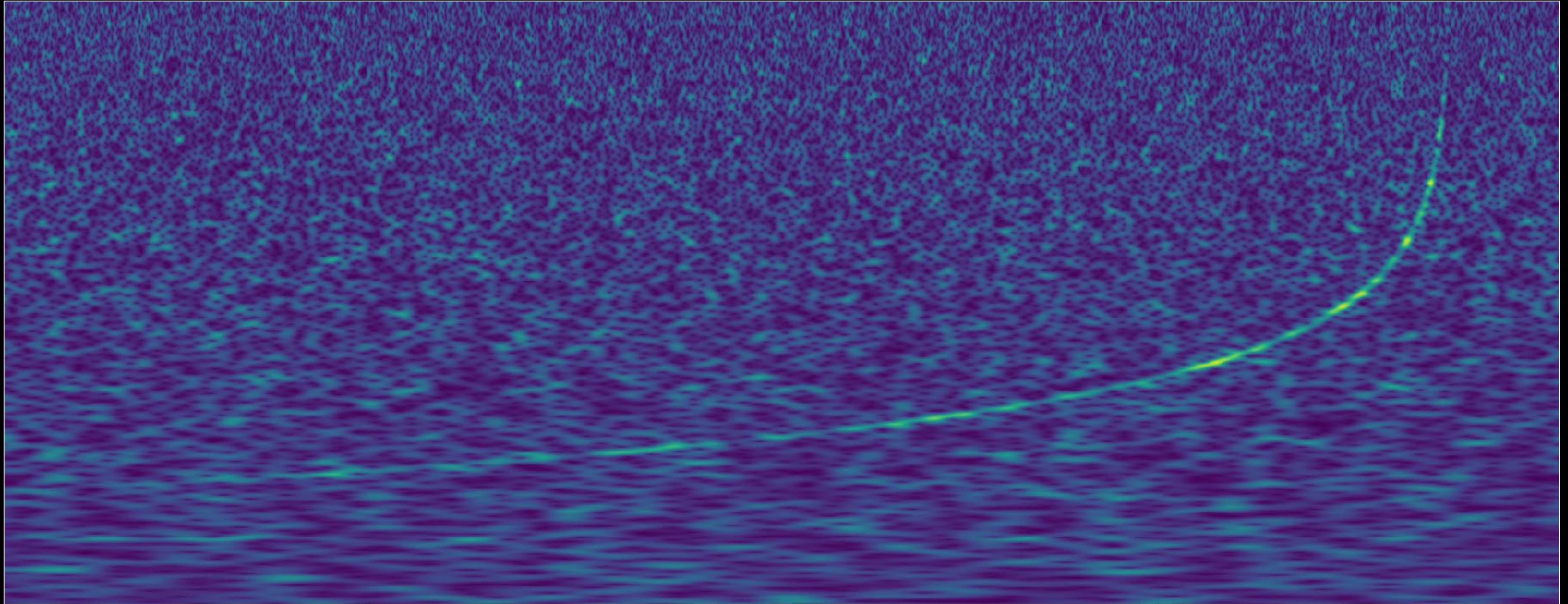


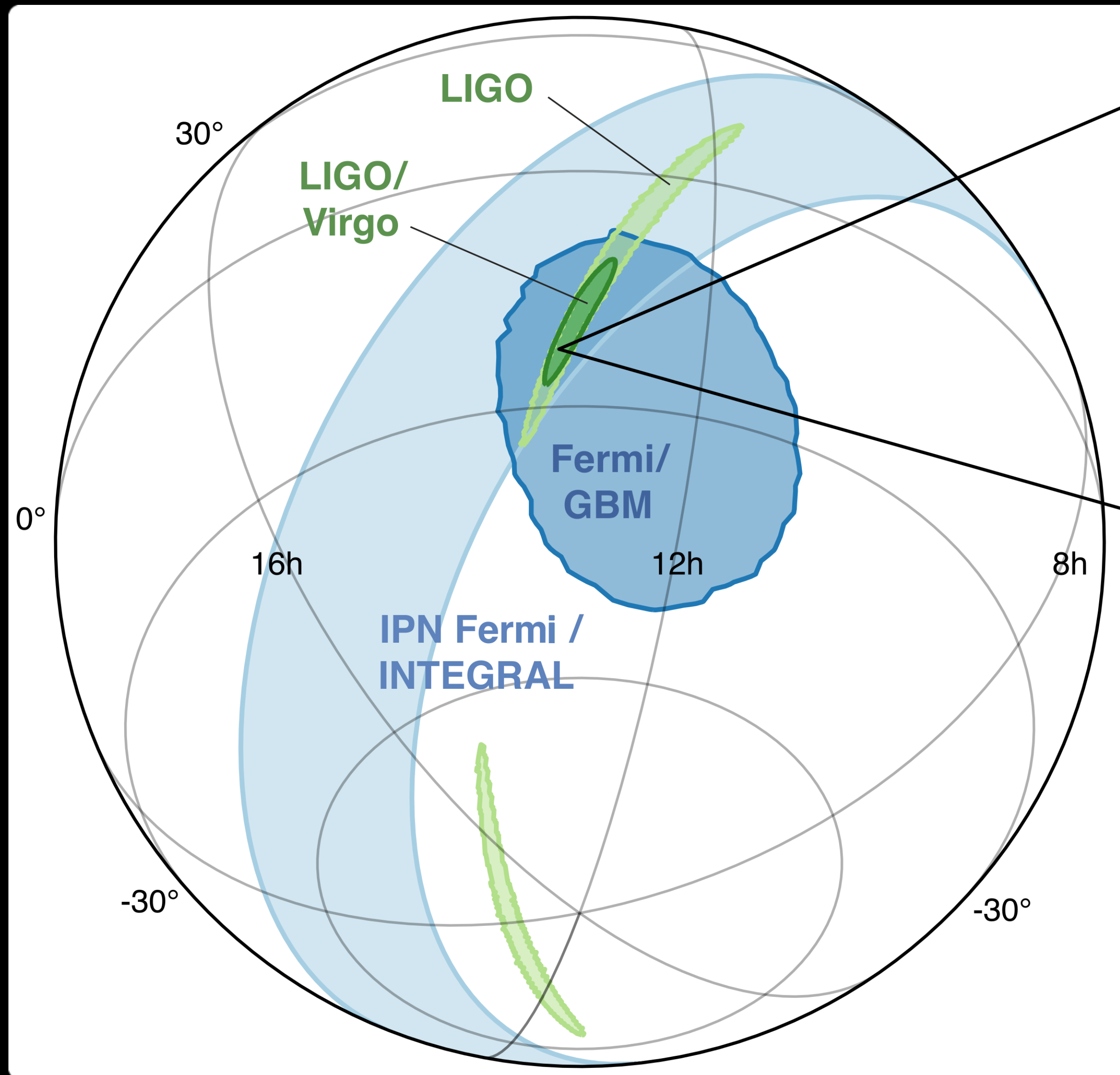
Isotropic

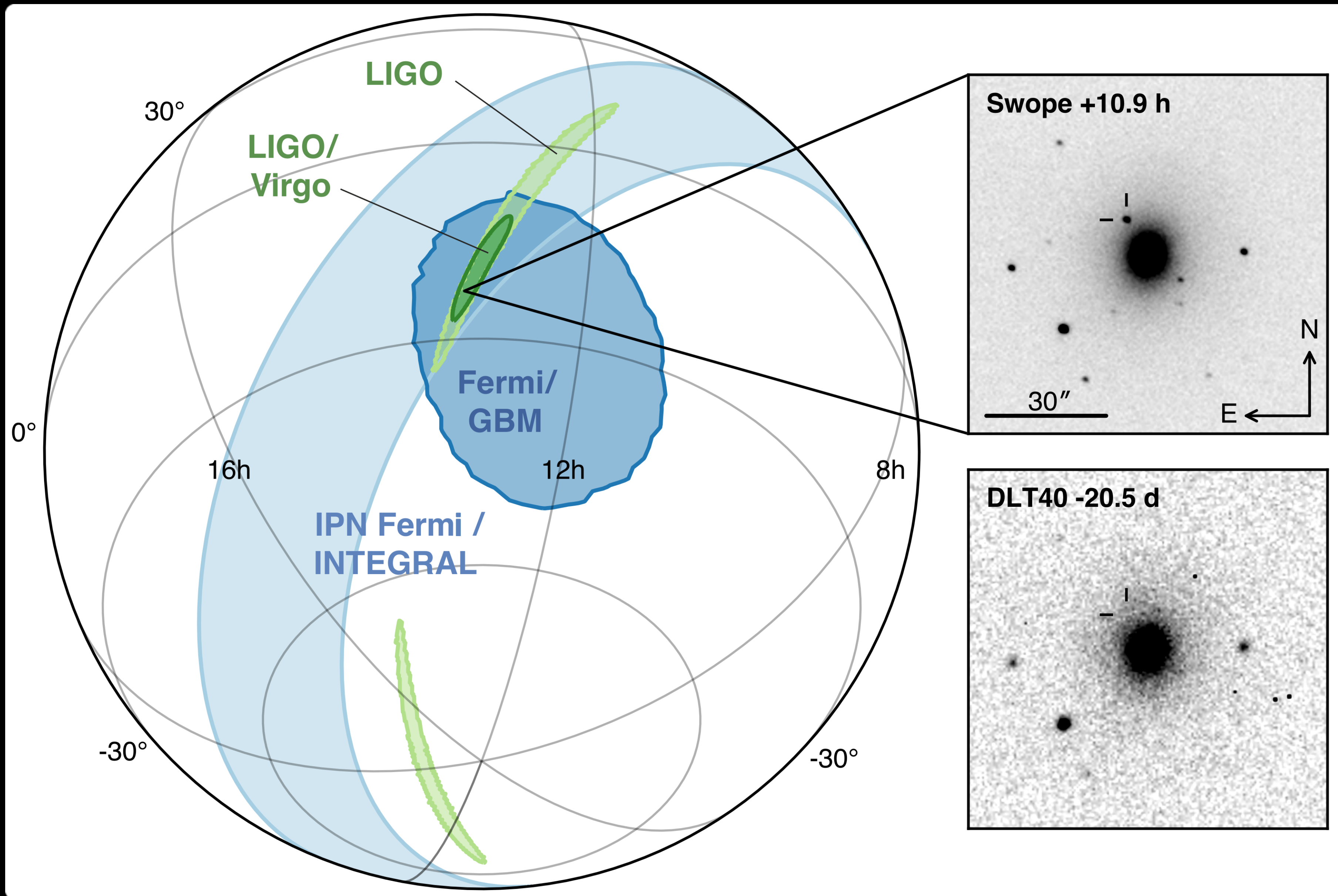




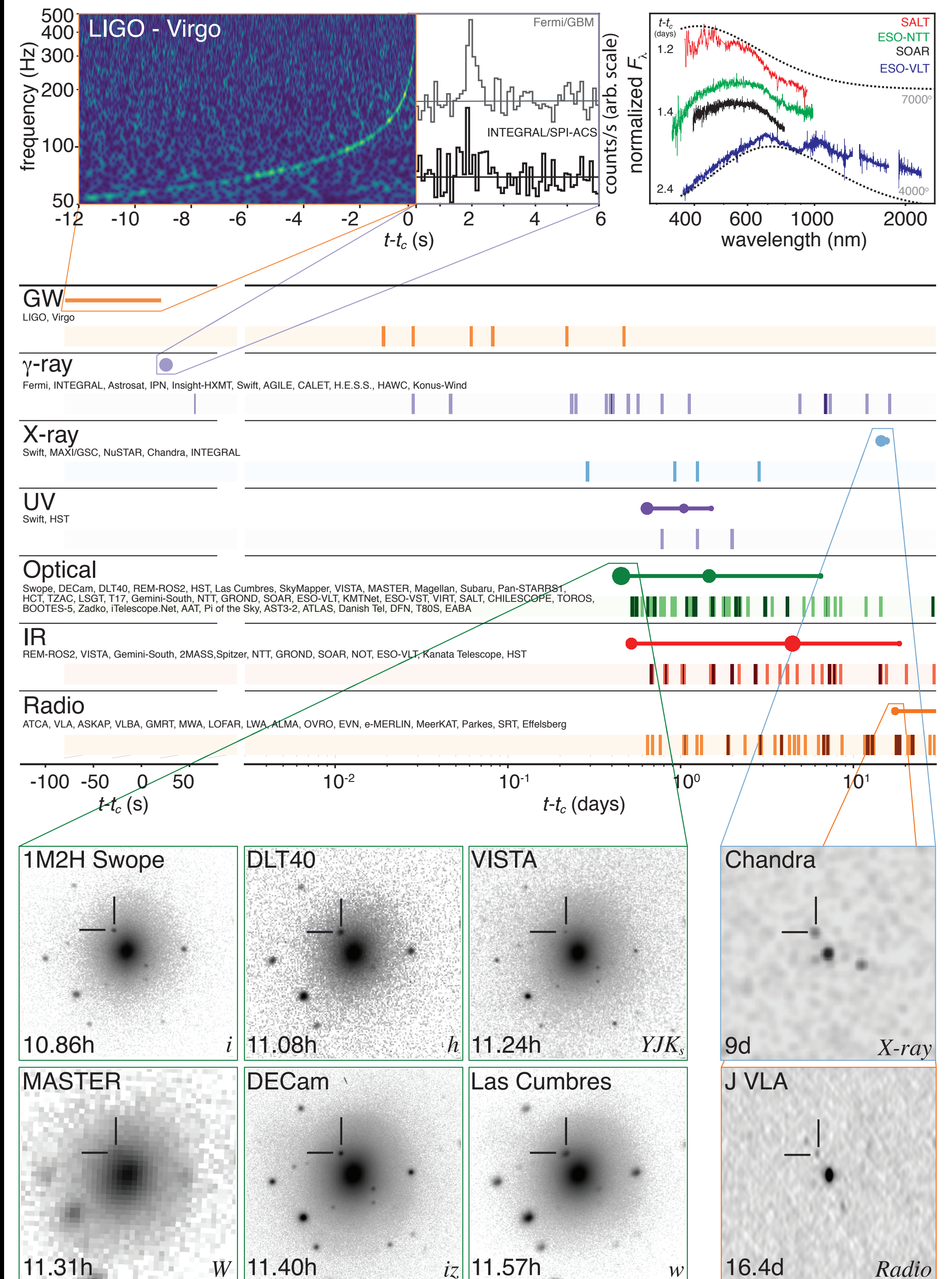
GW170817





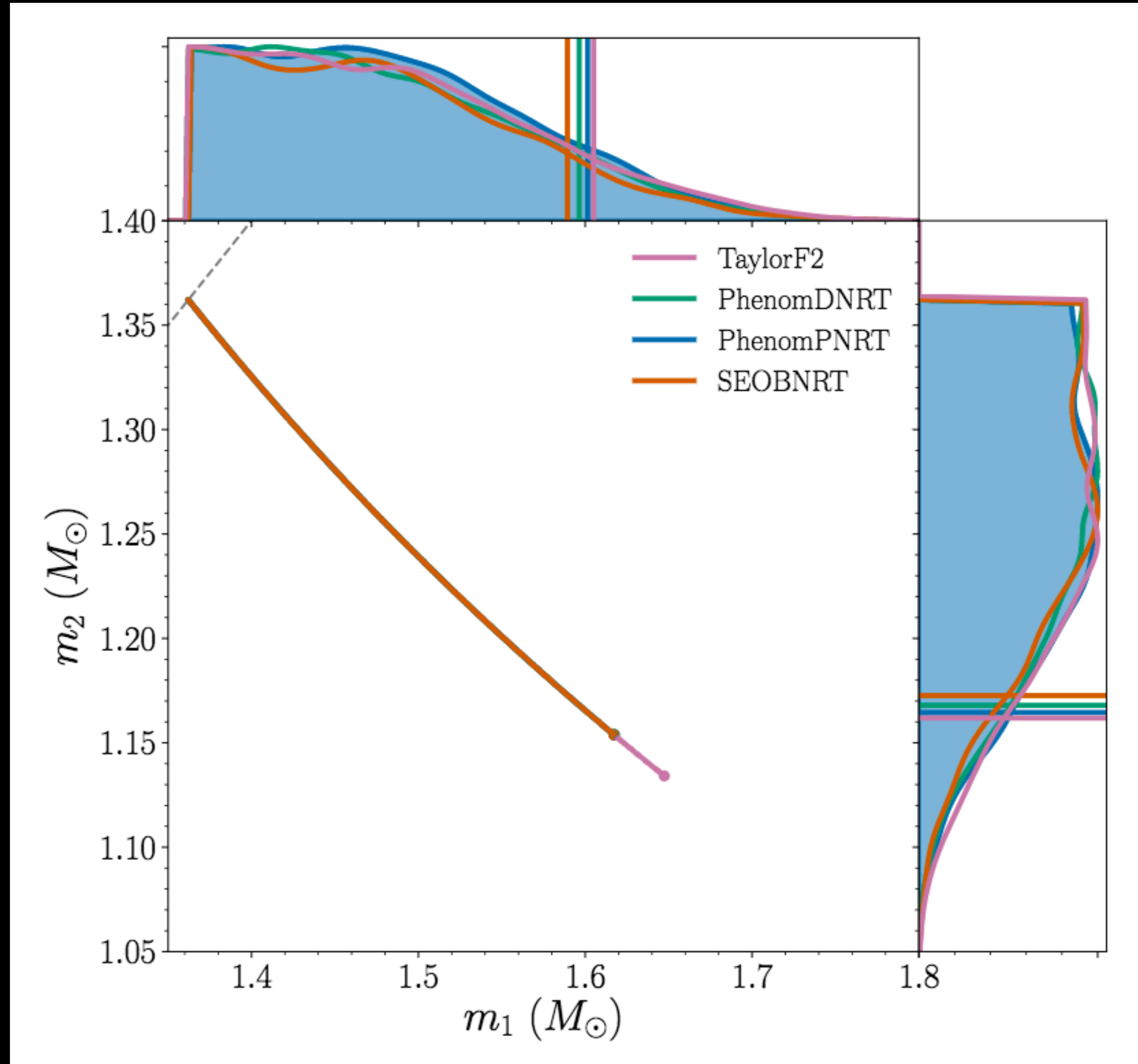


Talking Picture

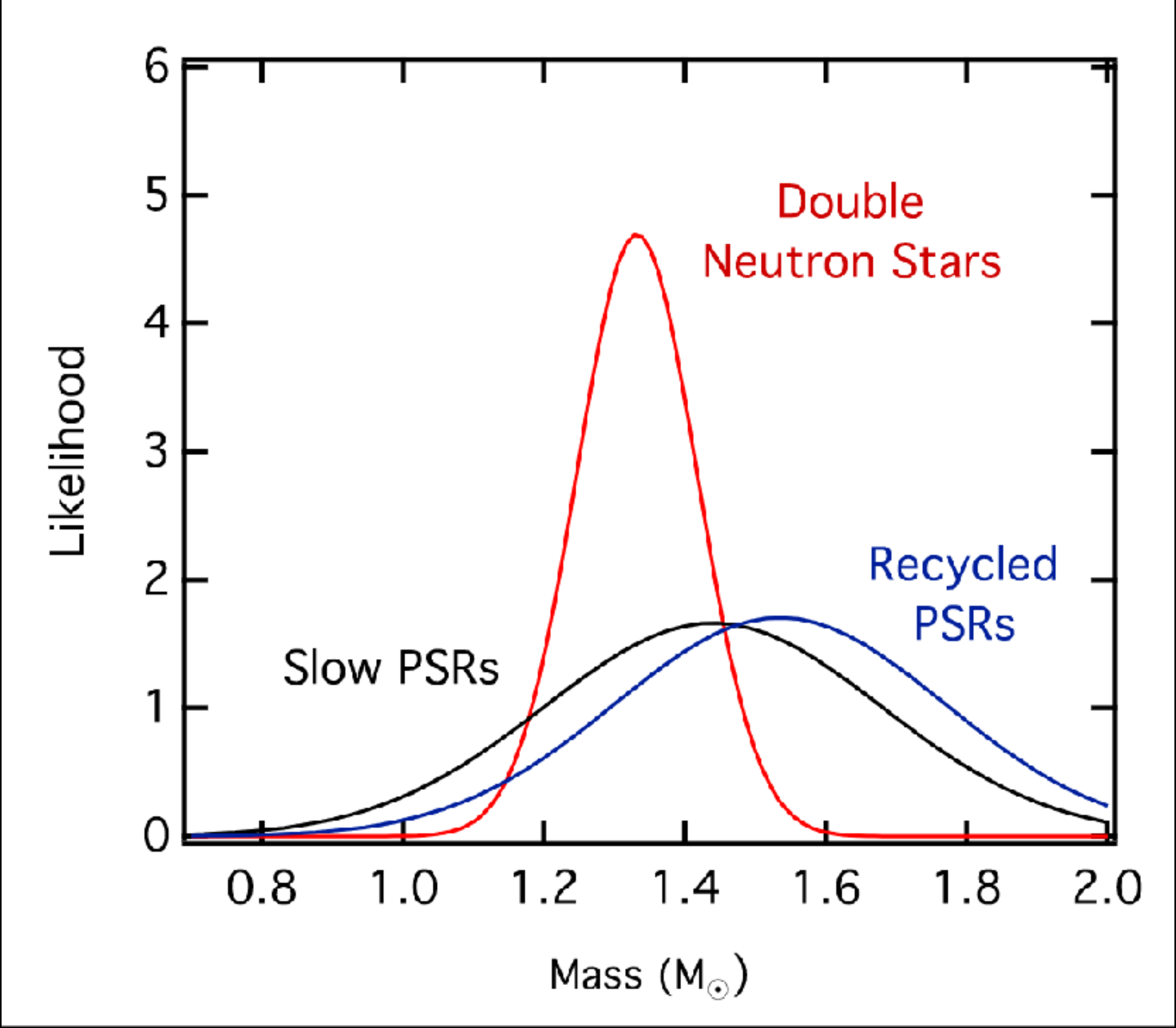
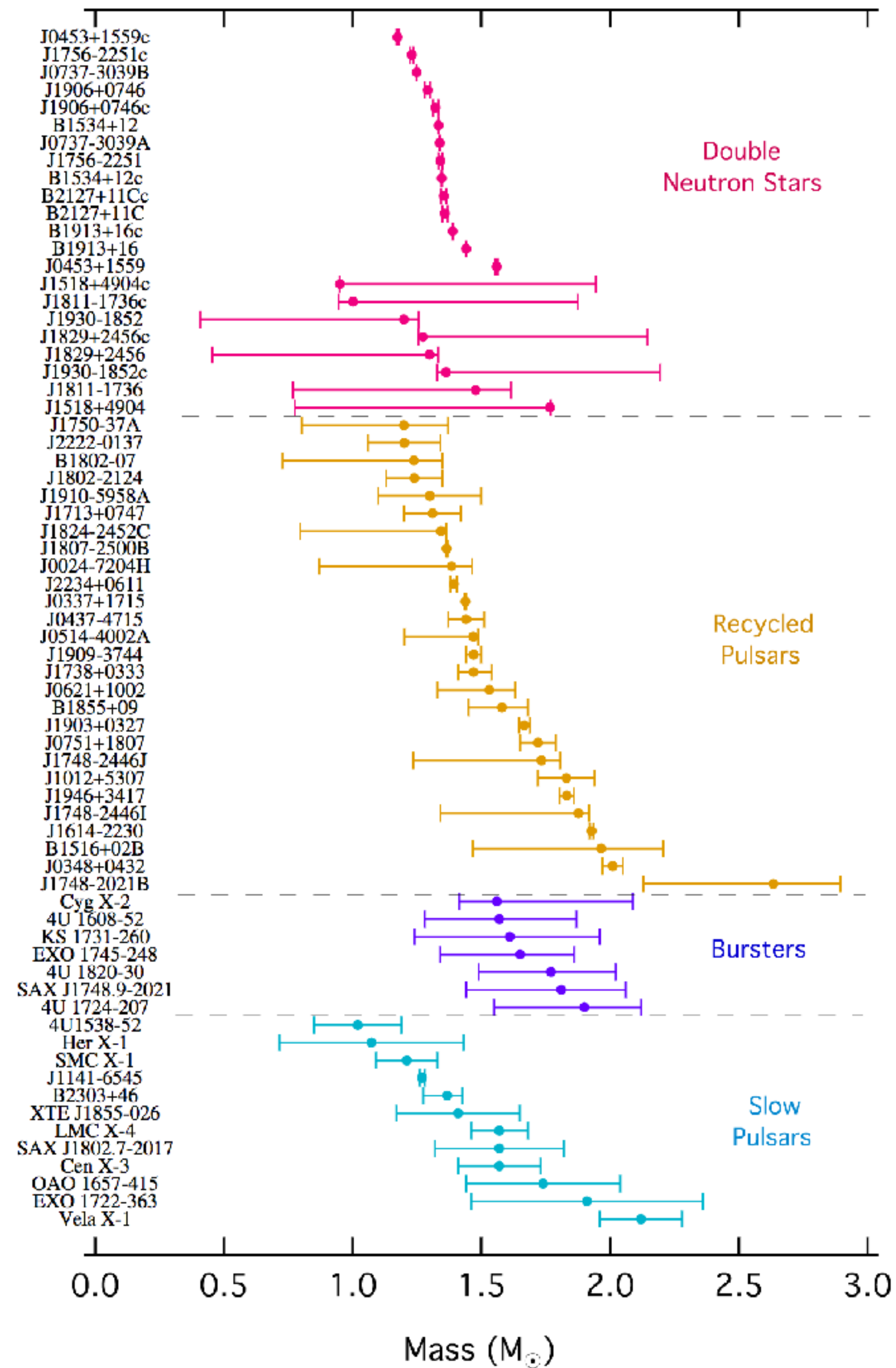


Abbott et al. (2017)
arXiv:1710.05833

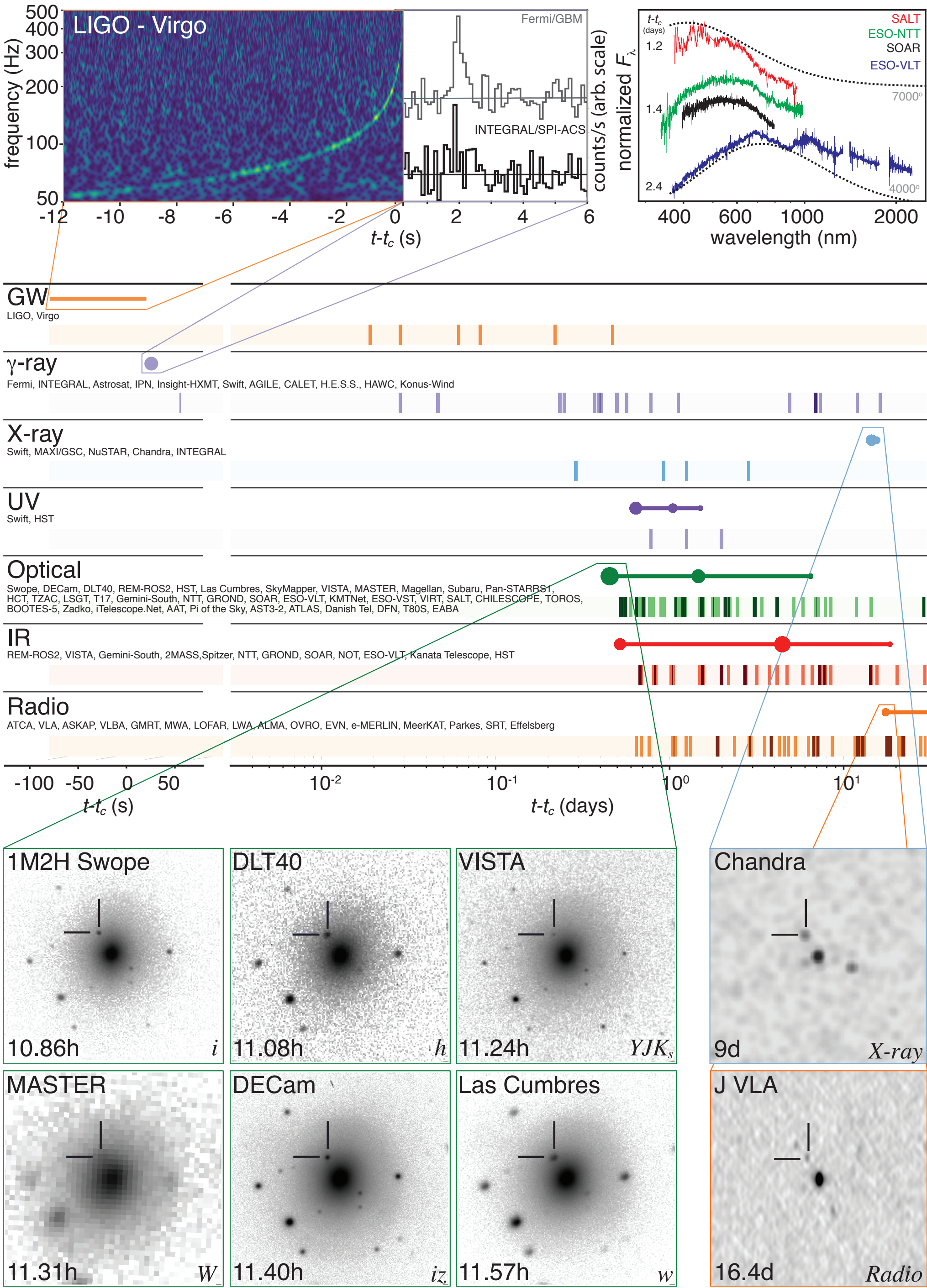
Masses



Known NSs

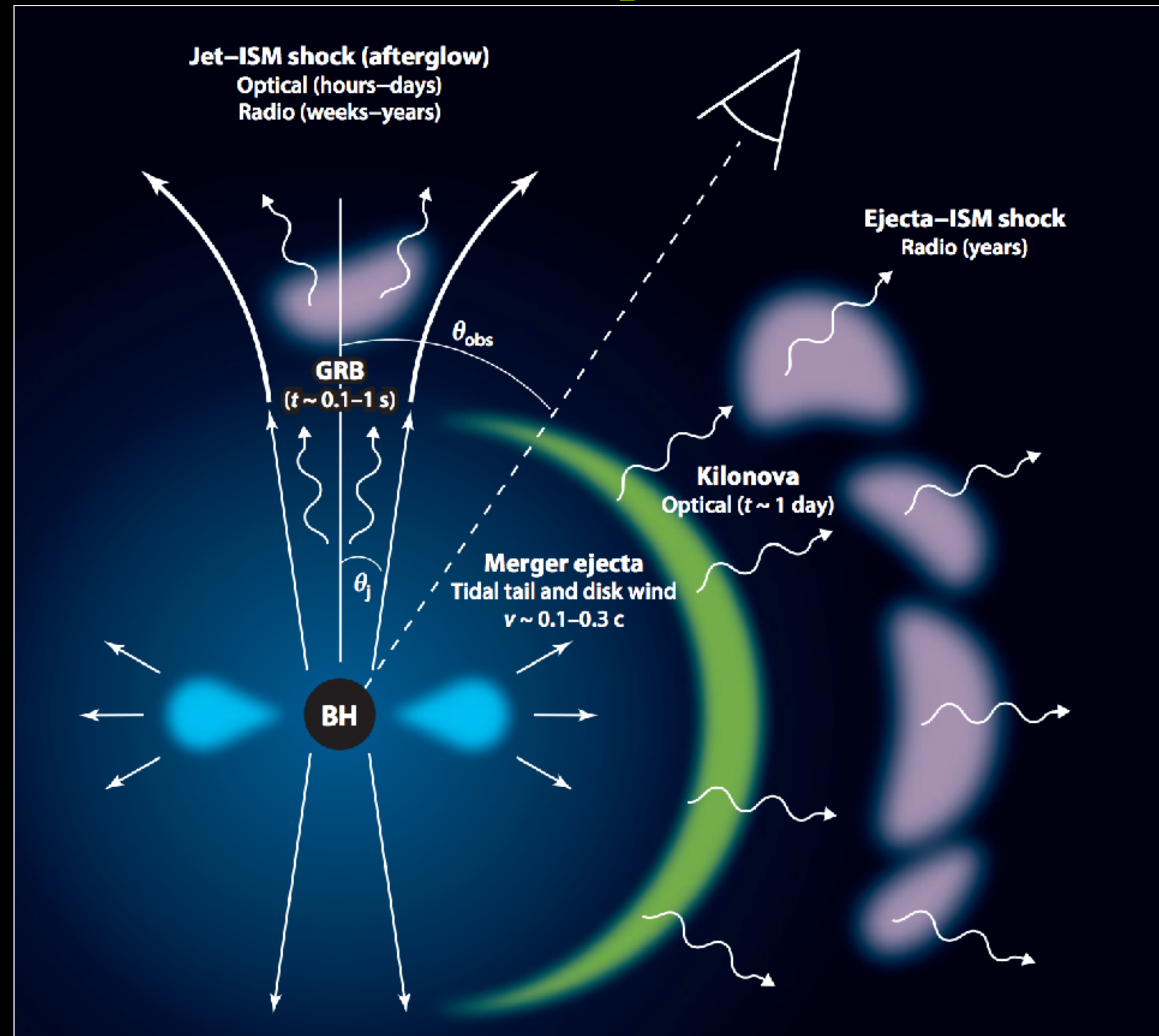


Talking Picture



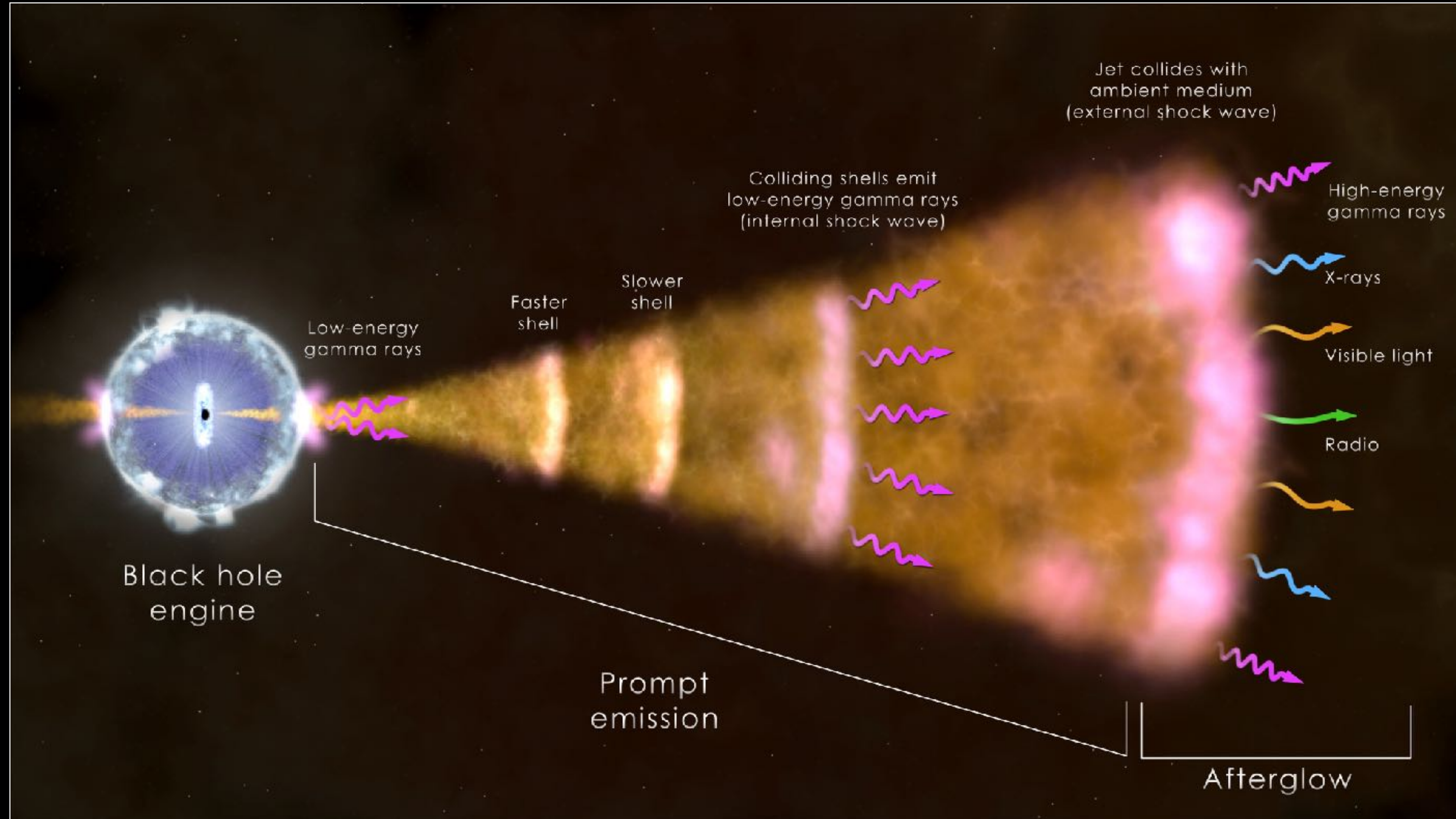
Abbott et al. (2017)
arXiv:1710.05833

EM Counterparts to BNS

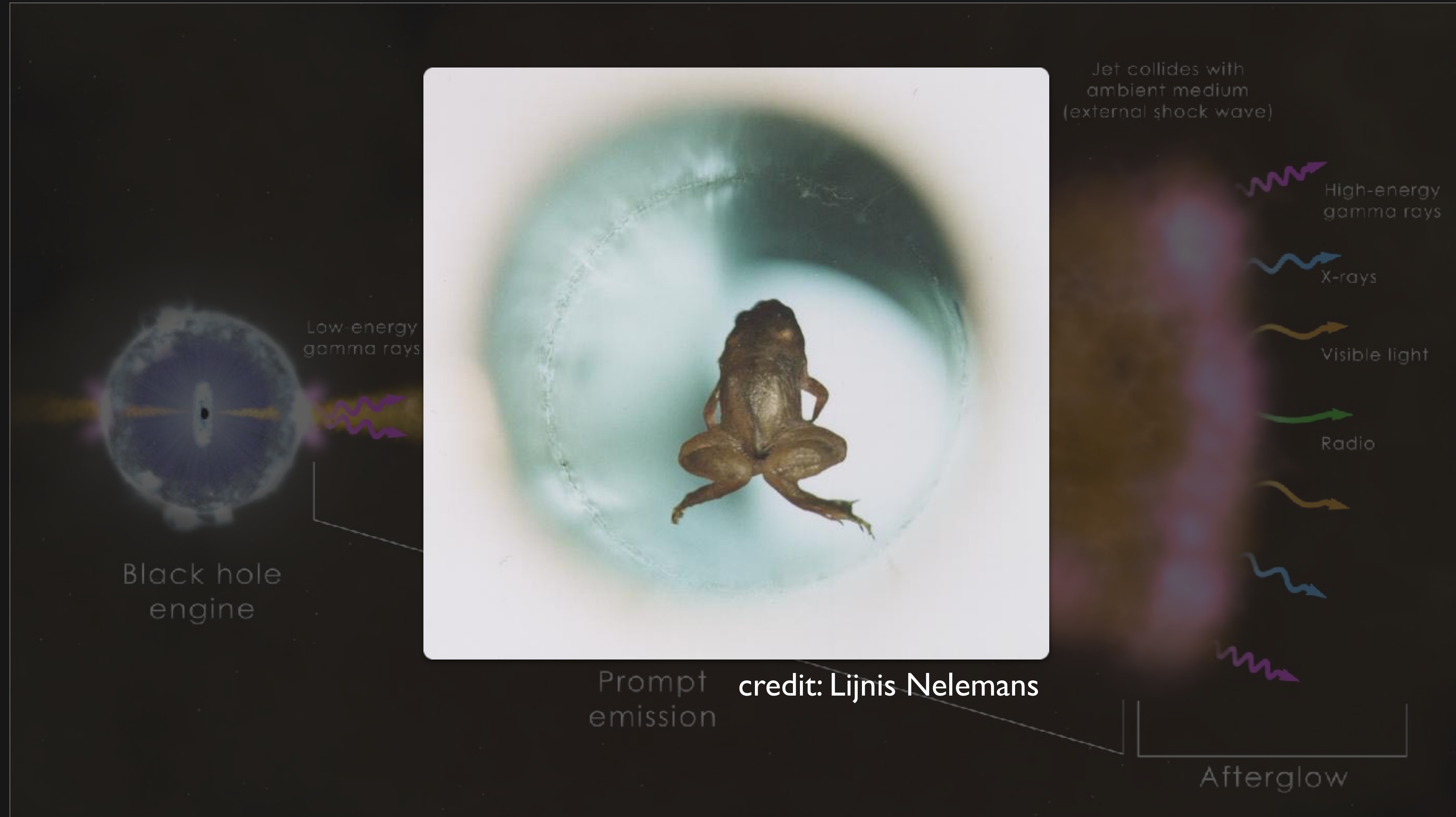


credit: Berger (2014)

GRB and afterglow



GRB and afterglow

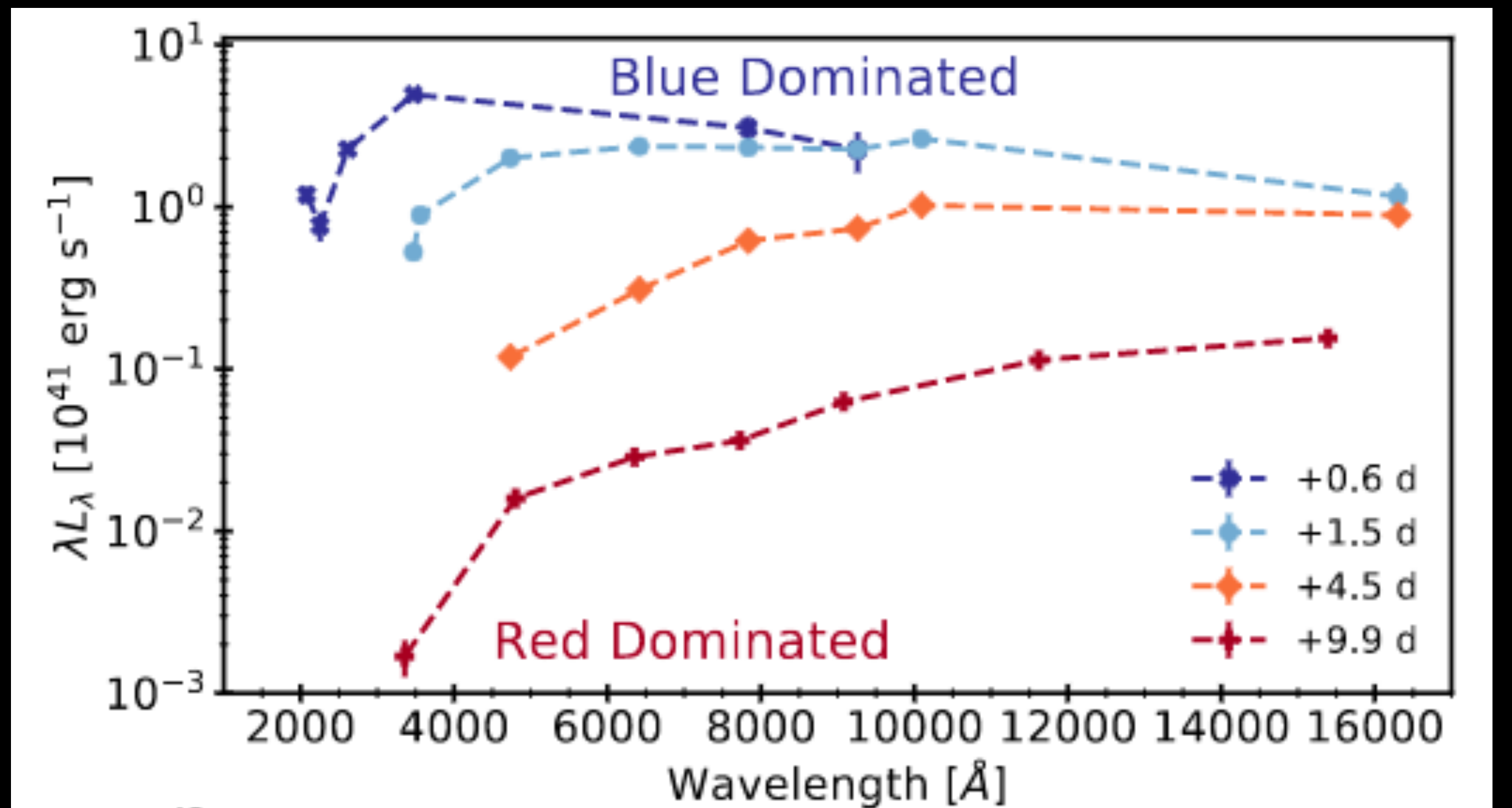
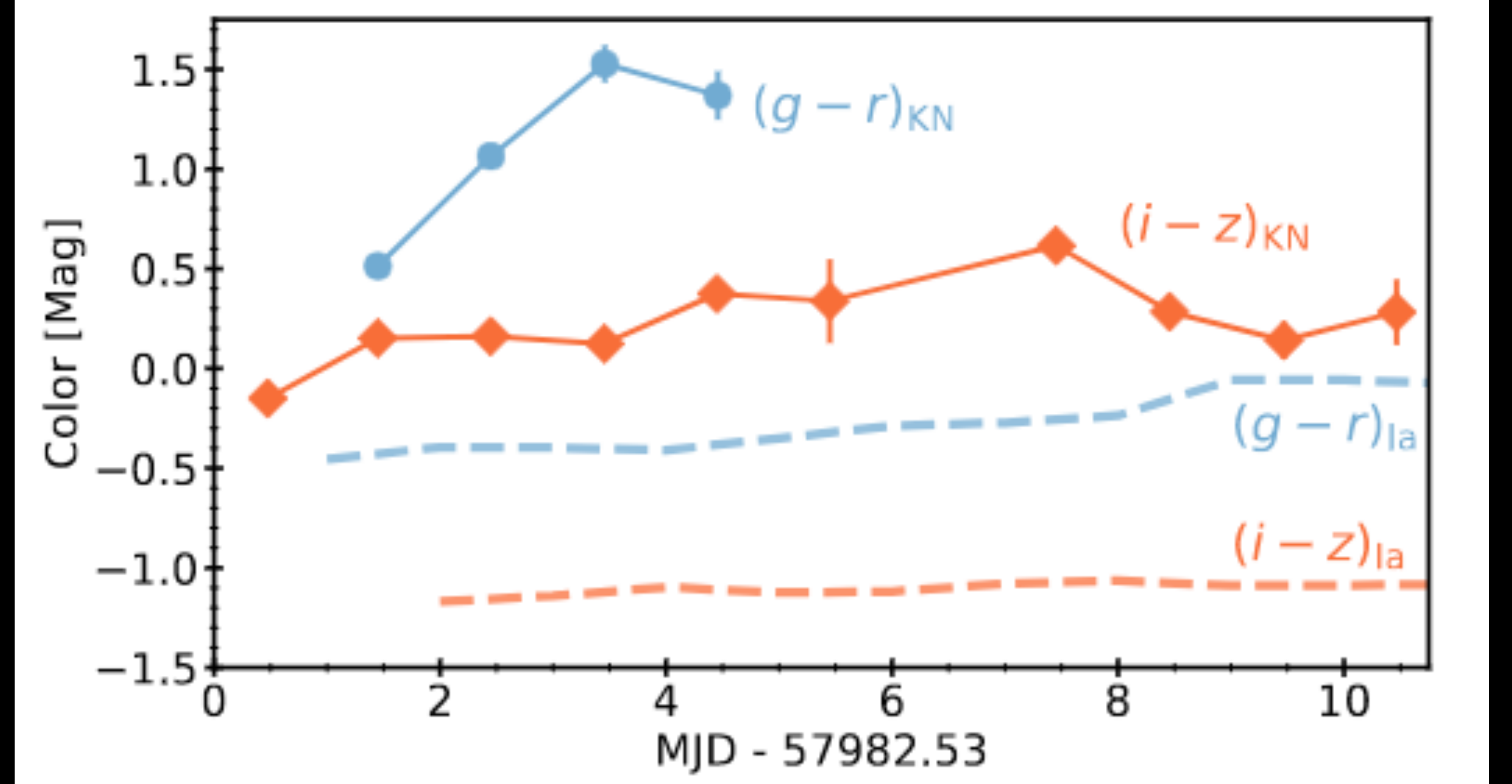
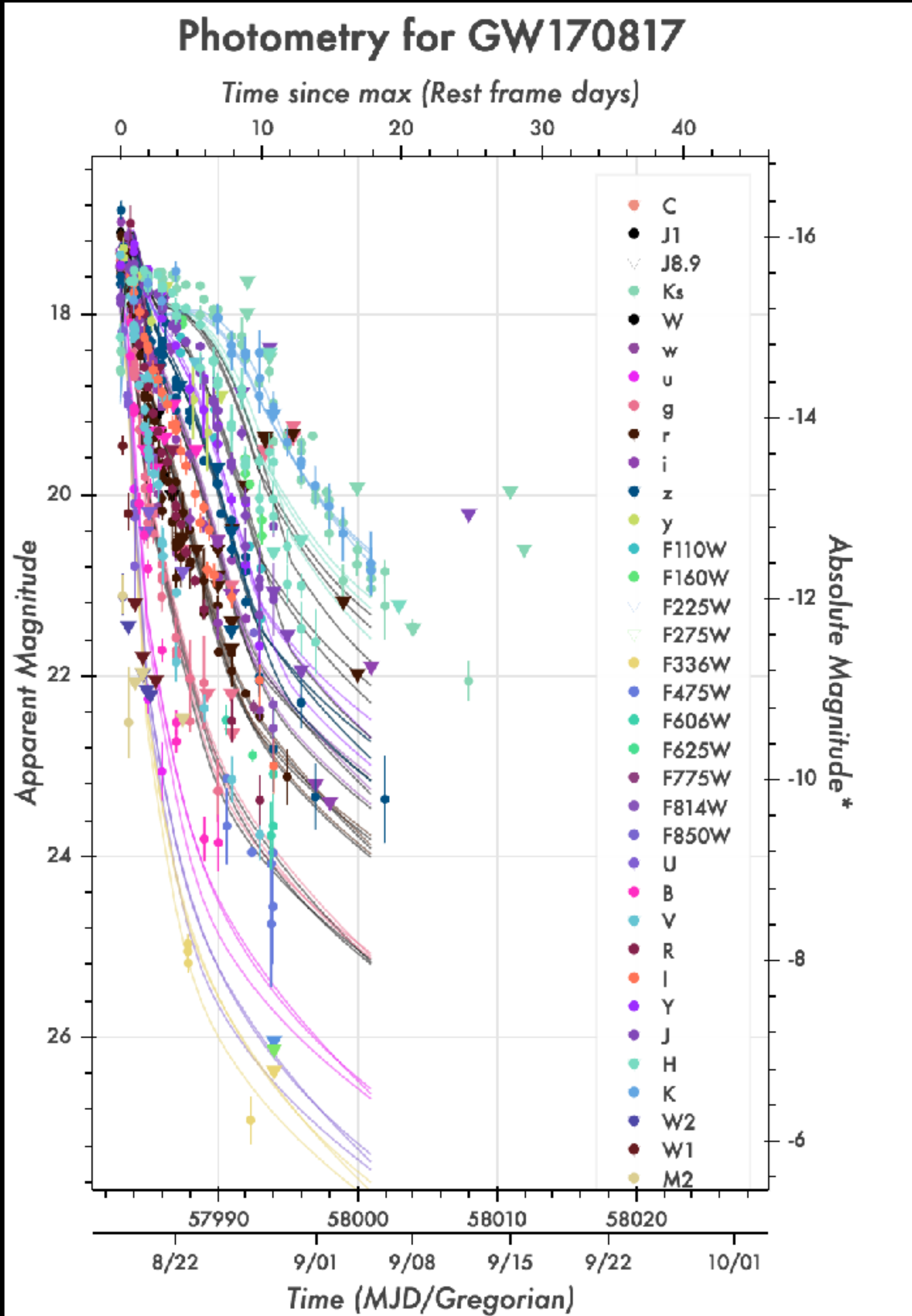


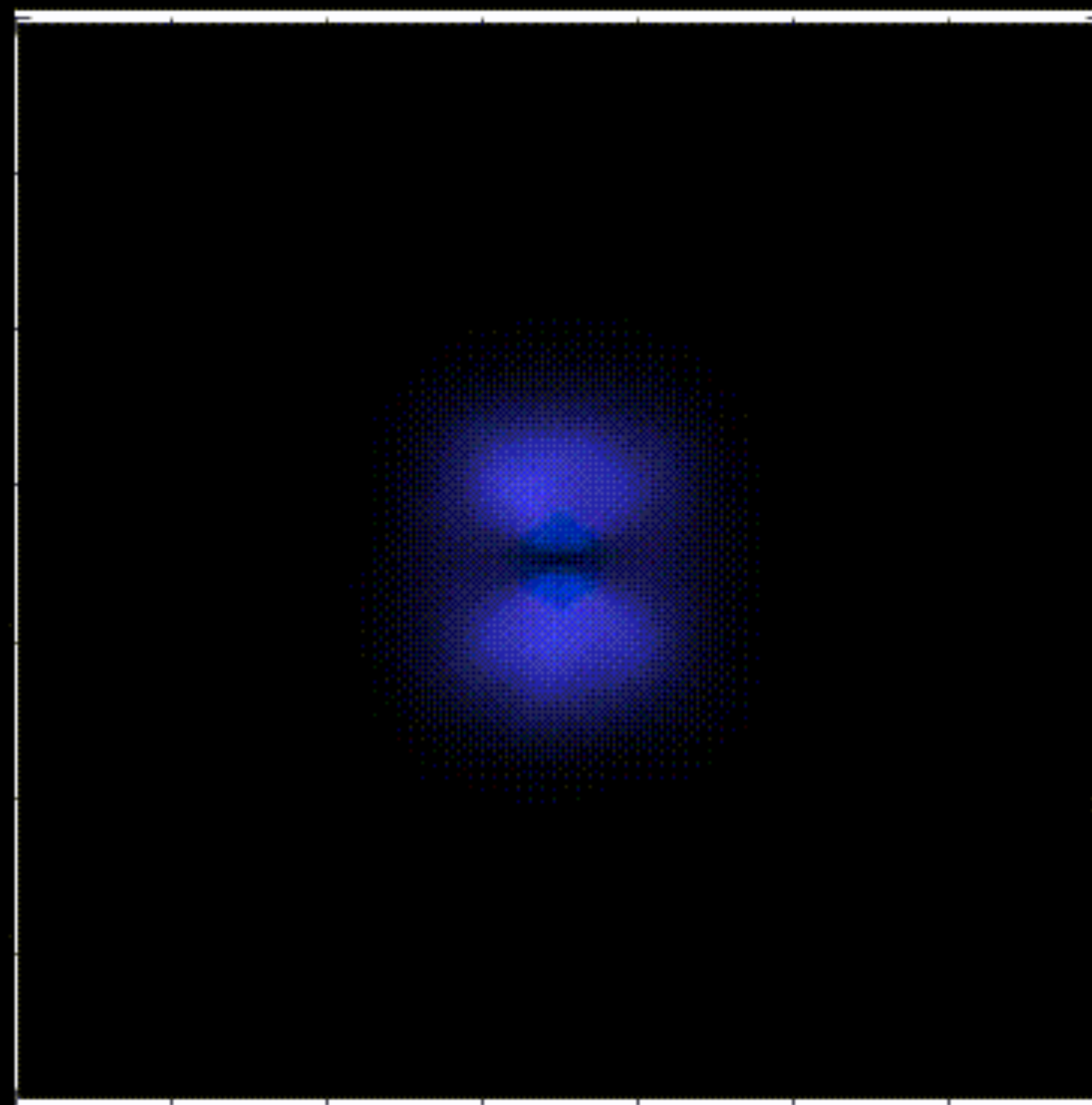
Kilonova

Dark Energy Camera / CTIO
i-band
Time Relative to 2017 August 17

+0.5 days

Credit: P. S. Cowperthwaite / E. Berger
Harvard-Smithsonian Center for Astrophysics





radioactive debris cloud

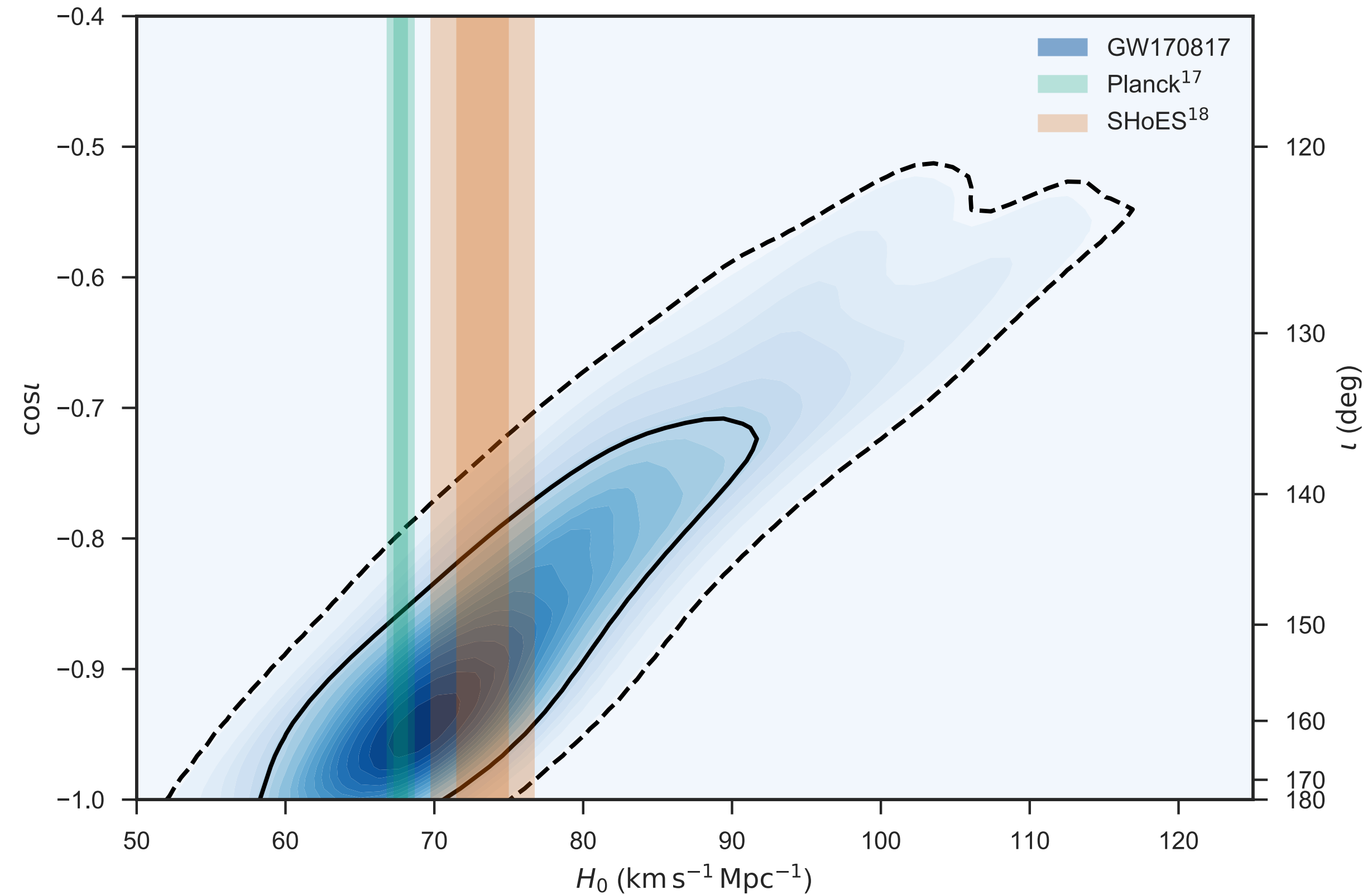
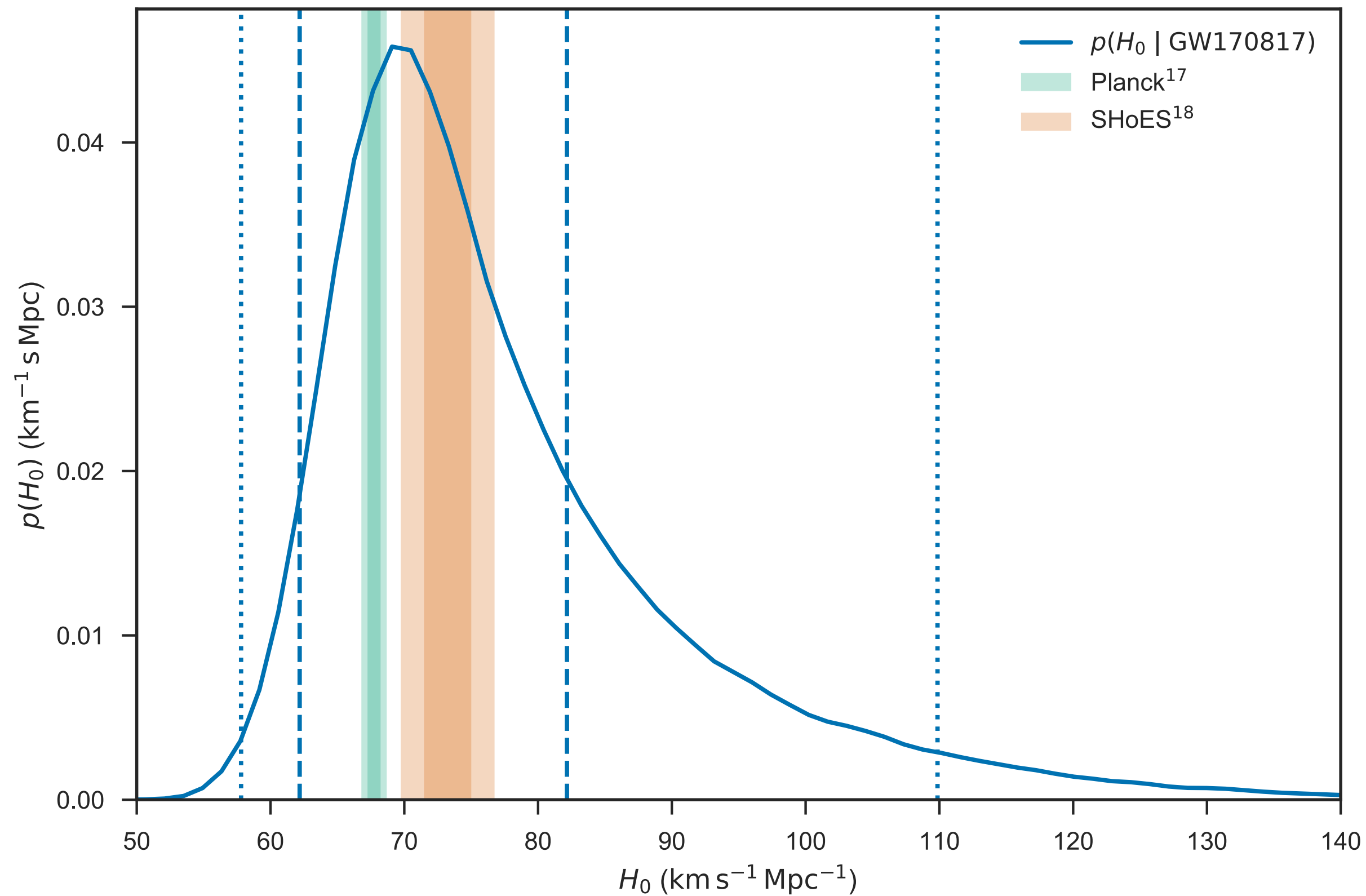
The Origin of the Solar System Elements

1 H	big bang fusion 										cosmic ray fission 						2 He								
3 Li	4 Be	merging neutron stars? 										exploding massive stars 						5 B	6 C	7 N	8 O	9 F	10 Ne		
11 Na	12 Mg	dying low mass stars 										exploding white dwarfs 						13 Al	14 Si	15 P	16 S	17 Cl	18 Ar		
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr								
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe								
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn								
87 Fr	88 Ra																								
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu								
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu																	

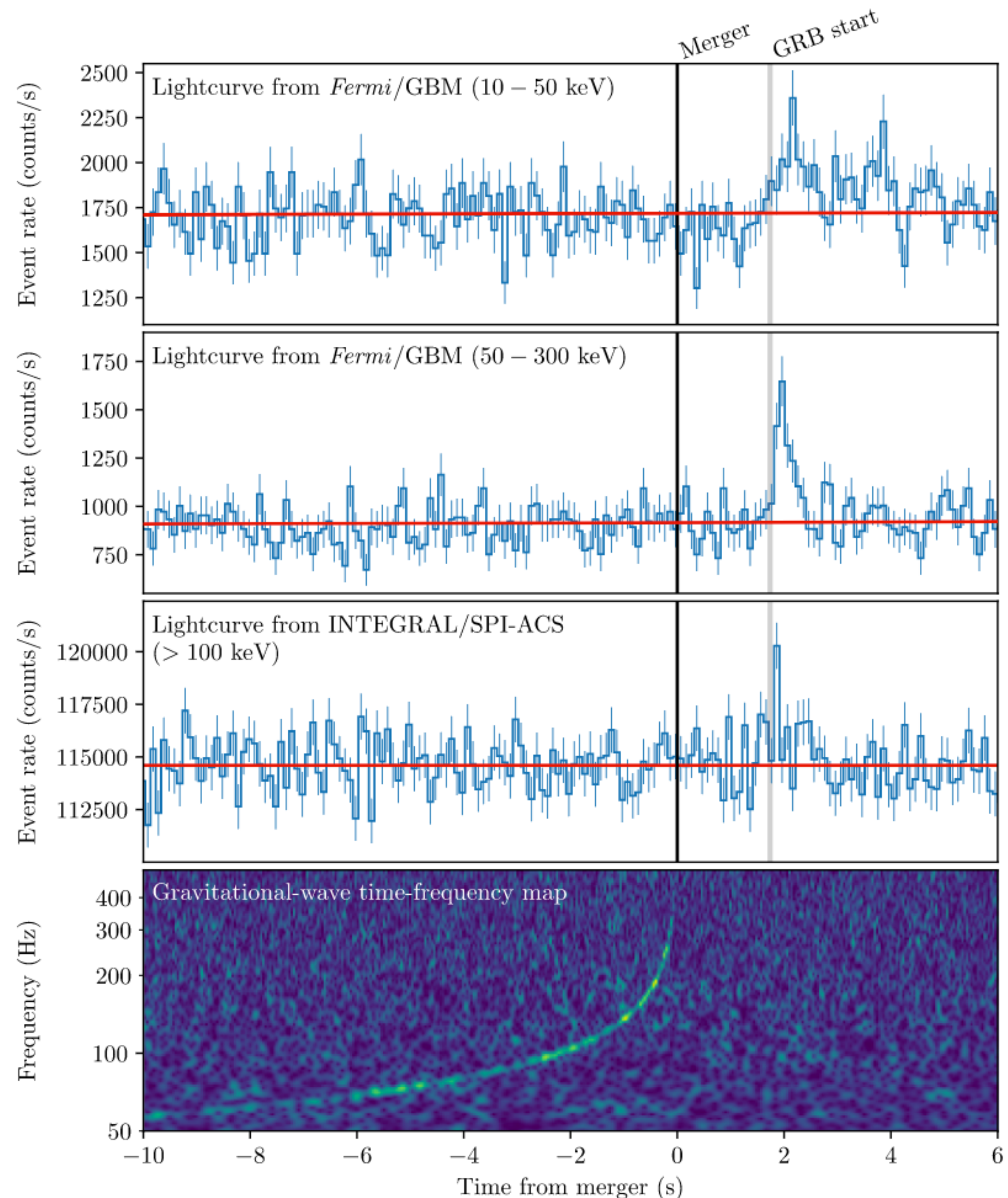
Graphic created by Jennifer Johnson
<http://www.astronomy.ohio-state.edu/~jaj/nucleo/>

Astronomical Image Credits:
 ESA/NASA/AASNova

Standard Siren



Speed of Gravity



temporal offset: 1.74 ± 0.05 s

$$-3 \times 10^{-15} \leq \frac{\Delta v}{\nu_{\text{EM}}} \leq +7 \times 10^{-16}$$

Abbott et al. (2017)
arXiv:1710.05834

Conclusions

GW170817 was most likely a BNS merger

Successful observations of kilonova and afterglow emission

Novel measurement of Hubble constant

Best measurements of the speed of gravity

More to come:

O3: 1 event per **week**

Design: 1 event per **day**