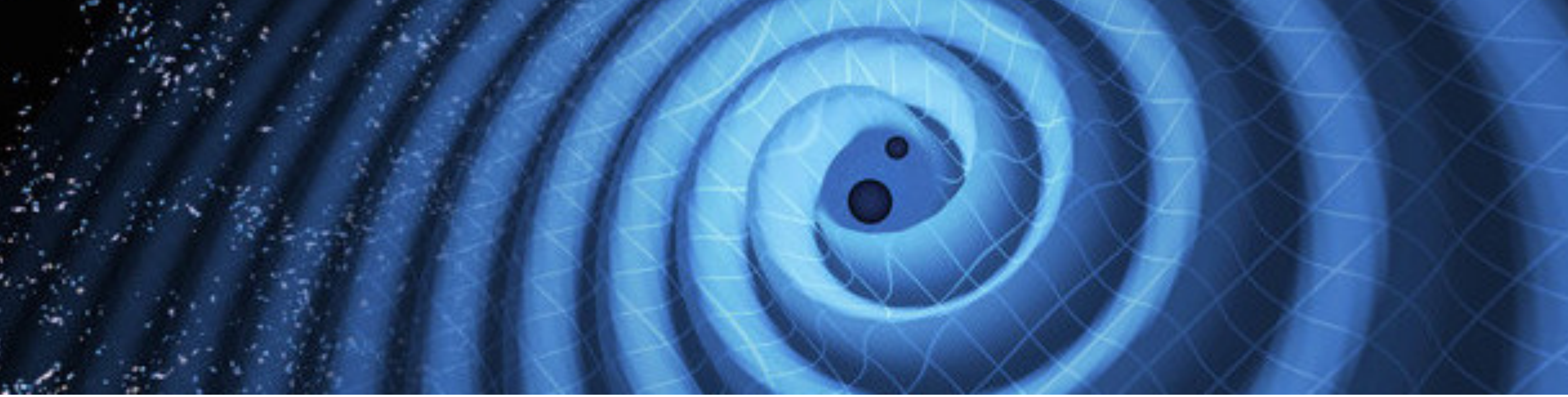


ASTROPHYSICAL IMPLICATIONS OF GRAVITATIONAL WAVE DETECTIONS

FUTURE OF GRAVITATIONAL WAVE ASTRONOMY

ICTS, BANGALORE, AUGUST 19-22, 2019

B.S. Sathyaprakash

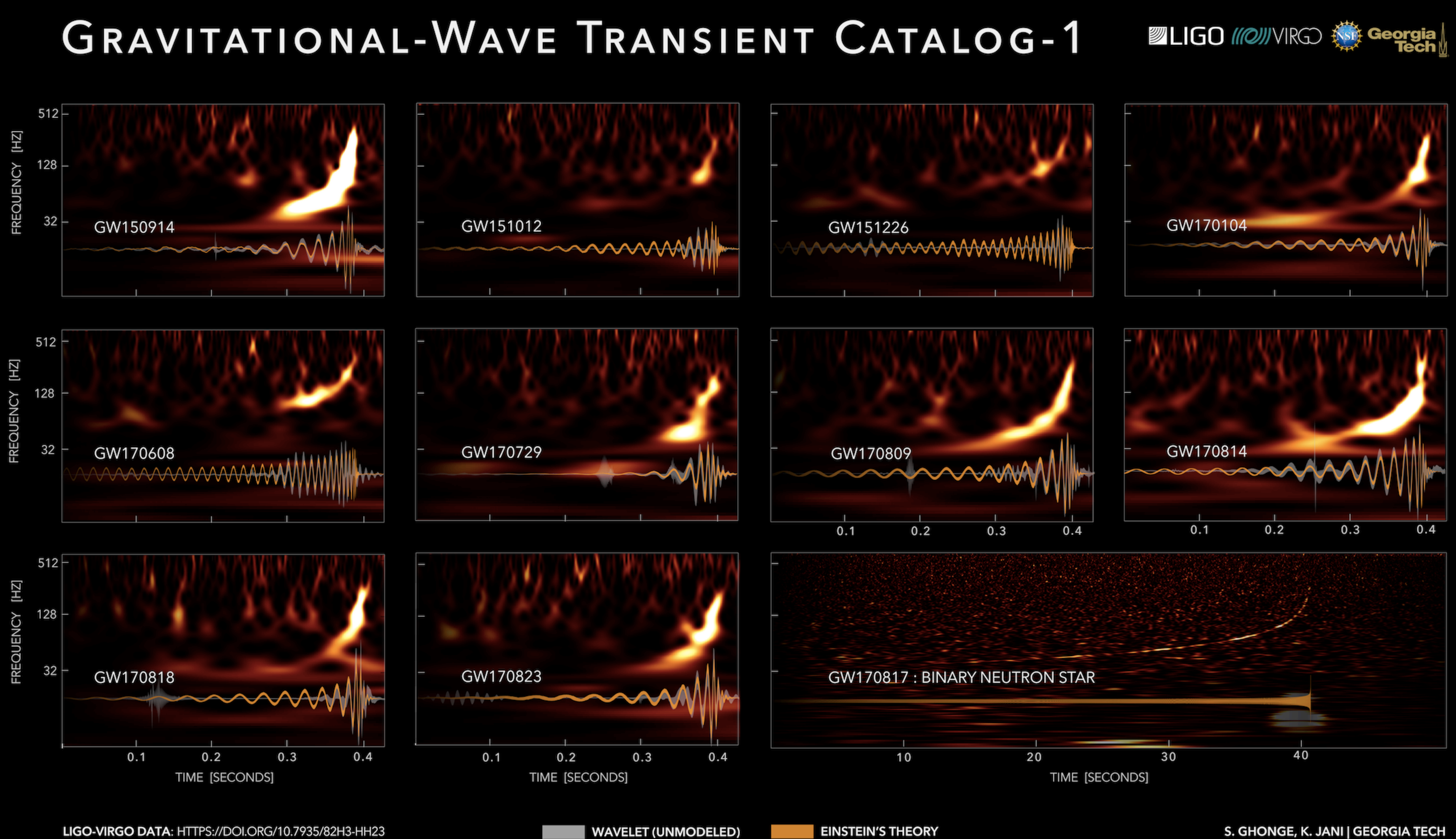
The Pennsylvania State University and Cardiff University

OVERVIEW

- expected detection rate of binary coalescences
  - current and, future (3G) network
- properties of observed events
  - masses and spins, remnant properties
- electromagnetic alerts
  - low-latency alerts
- other sources
- challenges and questions

LIGO-VIRGO DISCOVERIES:

A NEW ERA IN FUNDAMENTAL PHYSICS, ASTROPHYSICS AND COSMOLOGY



LV PUBLIC ALERTS DURING O3

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | LATEST | DOCUMENTATION | LOGIN

Superevent Info

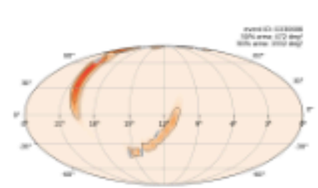
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S190426c	Production	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.947e-08	1 per 1.6276 years	1240327332.331668	1240327333.348145	1240327334.353516	2019-04-26 15:22:15 UTC	Data

Preferred Event Info

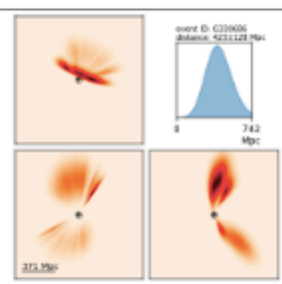
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	H1,L1,V1	1240327333.3365	2019-04-26 15:22:17 UTC

Superevent Log Messages

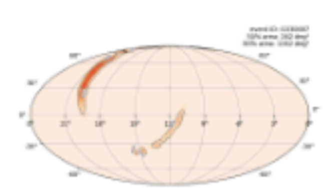
Sky Localization



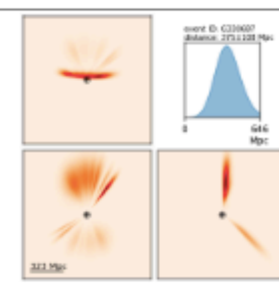
Mollweide projection of bayestar.fits bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019



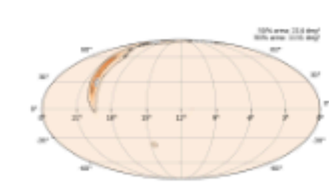
Volume rendering of bayestar.fits bayestar.volume.png. Submitted by LIGO/Virgo EM



Mollweide projection of bayestar1.fits bayestar1.png. Submitted by LIGO/Virgo EM Follow-Up on Apr 26, 2019



Volume rendering of bayestar1.fits bayestar1.volume.png. Submitted by LIGO/Virgo EM

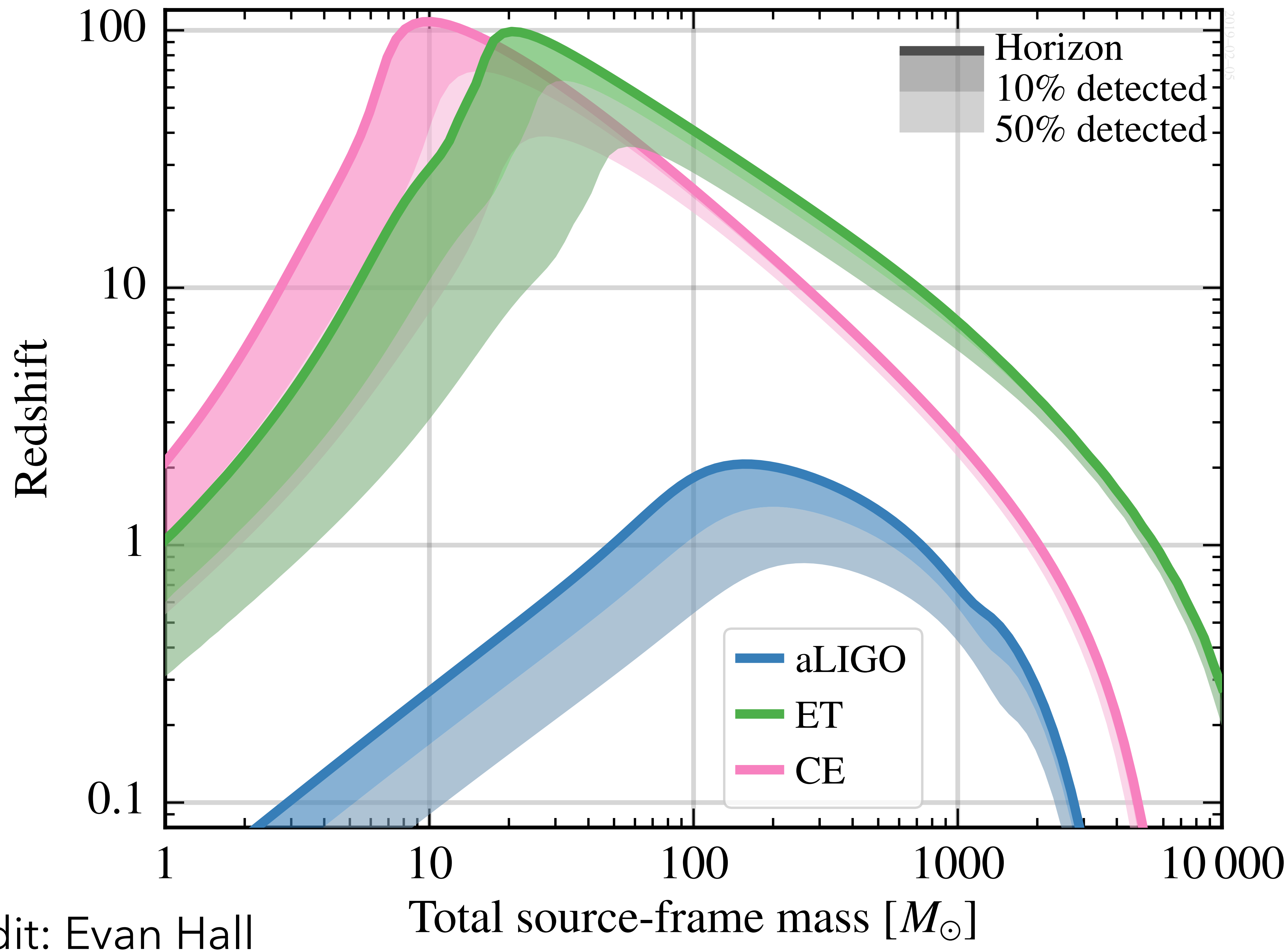


manually uploading LALInference.png LALInference.png. Submitted by Shaon Ghosh on Apr 27

- gracedb.ligo.org total of 19 astrophysical alerts so far
- ~two events with "matter", but no EM observations

FUTURE OF GW ASTRONOMY

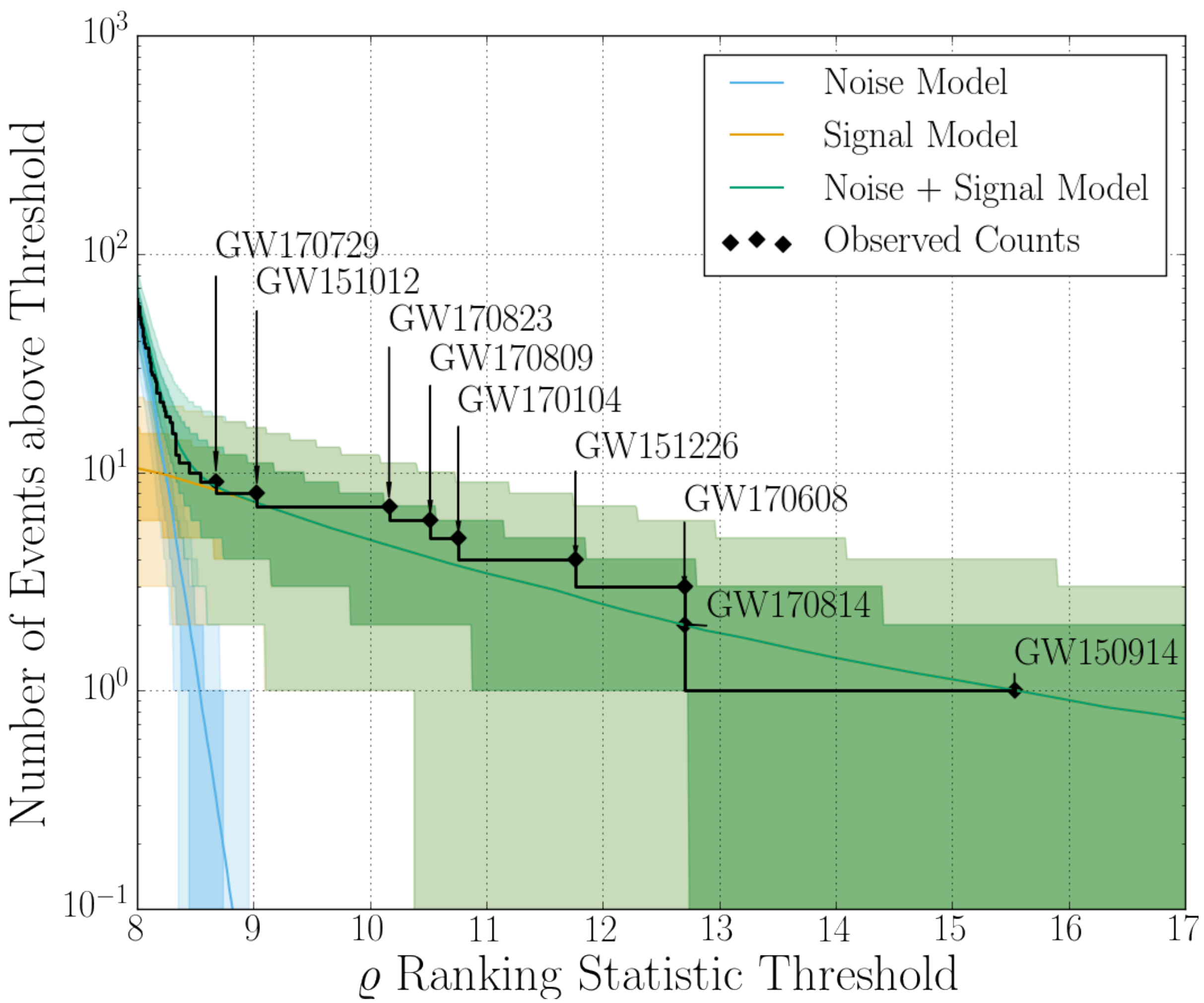
EINSTEIN TELESCOPE AND COSMIC EXPLORER



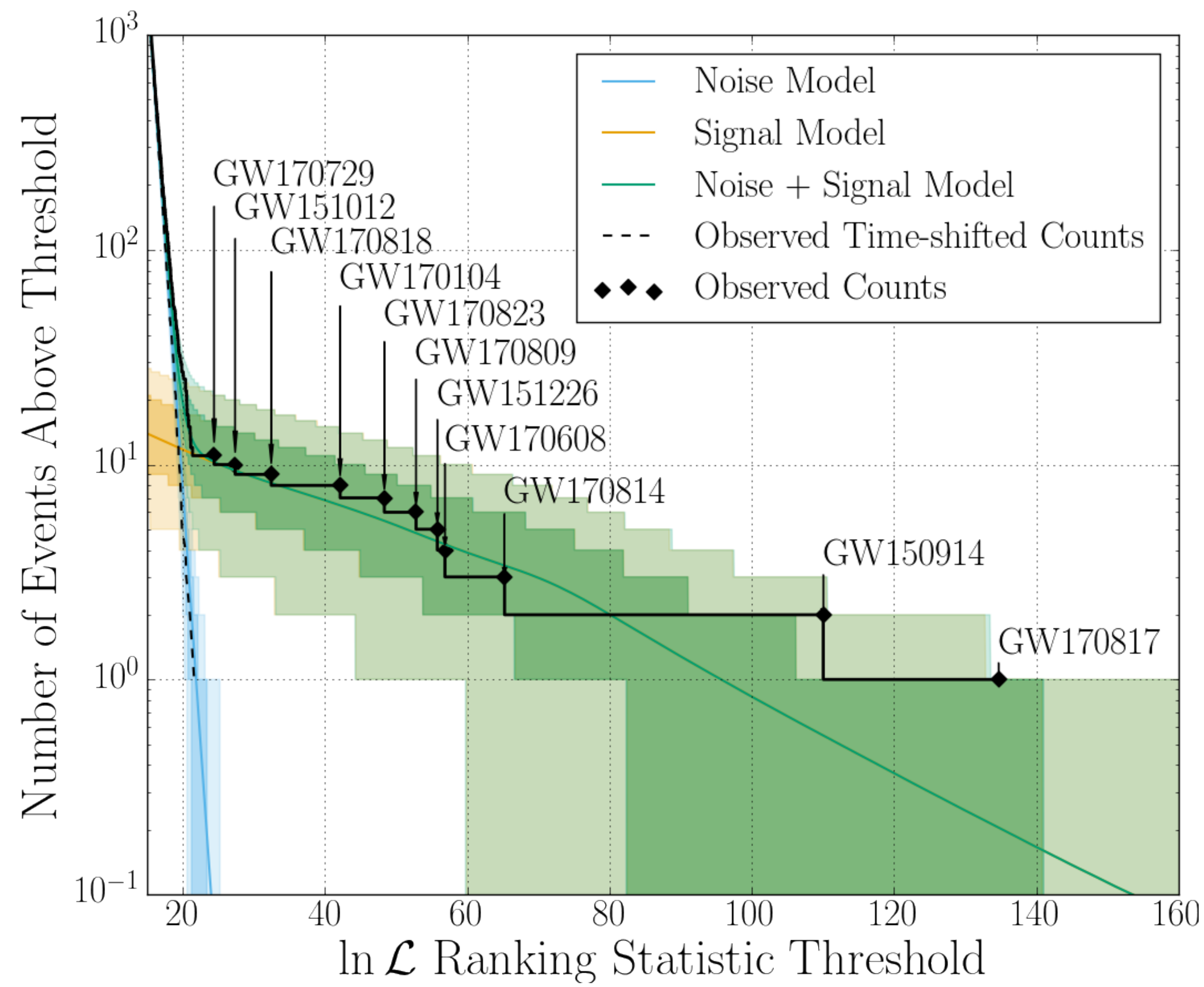
Credit: Evan Hall

EVENTS AND THEIR ASTROPHYSICAL SIGNIFICANCE

PyCBC



GSTLAL



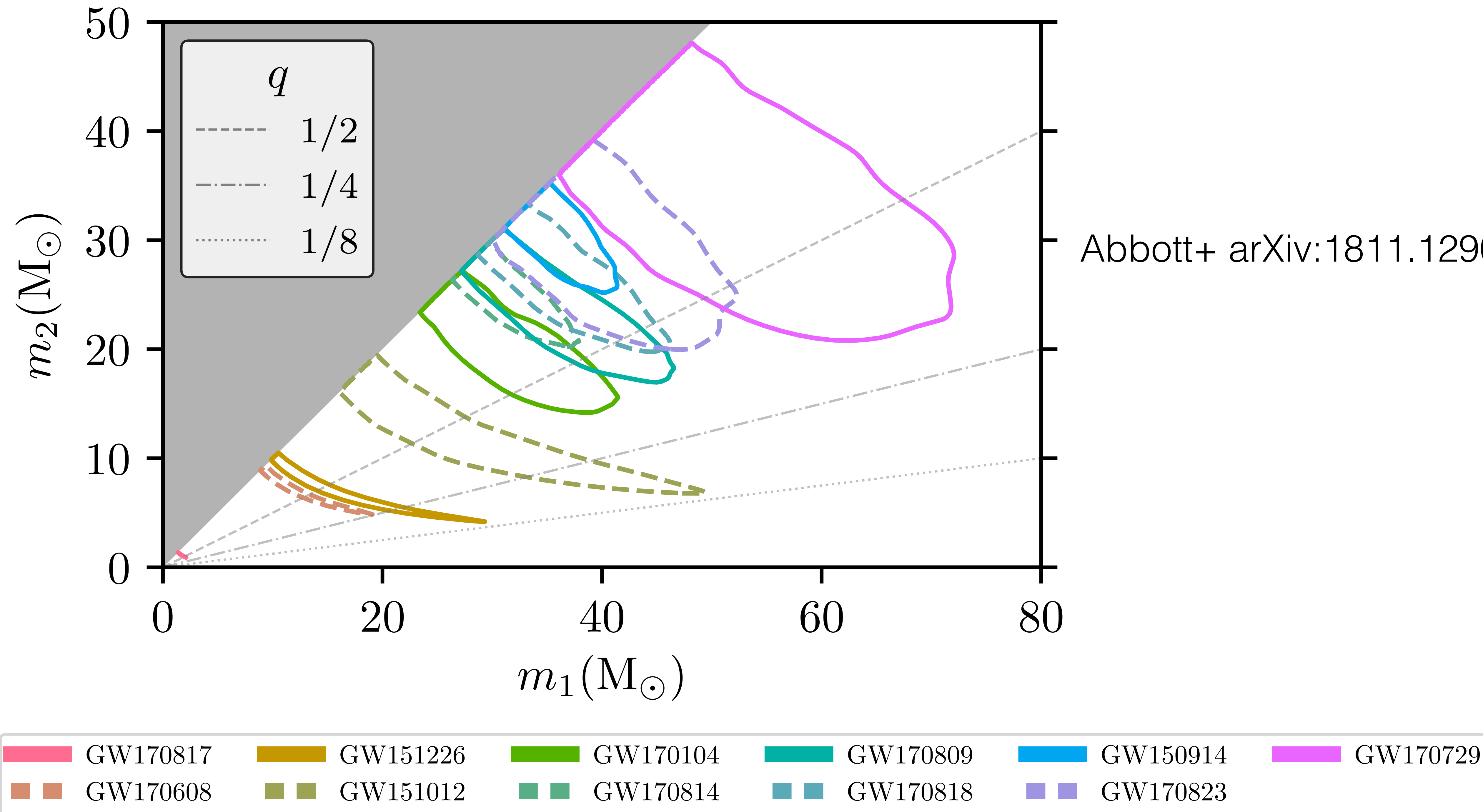
Abbott+ arXiv:1811.12907

GROUNDBREAKING SCIENCE FROM GW DISCOVERIES

- opened a new window to observe the dark sector, inaccessible to others
  - confirmed existence of merging binary black holes, **~10-100 yr^{-1} Gpc^{-3}**
  - binary neutron star mergers: **~100-4000 yr^{-1} Gpc^{-3}**
    - equation of state of matter in neutron stars, NS radius 9-13 km
    - gravitational waves travel at the speed of light: $|1-c_{GW}/c| < 10^{-15}$
- confirmed gravitational wave generation beyond the quadrupole formula
  - tails of gravitational waves, absorption of radiation by black holes, …
- discovered a completely new class of black holes
  - unexpected properties:
    - $> 30\ M_\odot$ black holes, spins ~ 0, a challenge to theoretical astrophysics
- origin of short GRBs resolved by GW170817 and GW170817A
  - helped identify sites of heavy element production

arXiv:1811.12907 arXiv:1811.12940

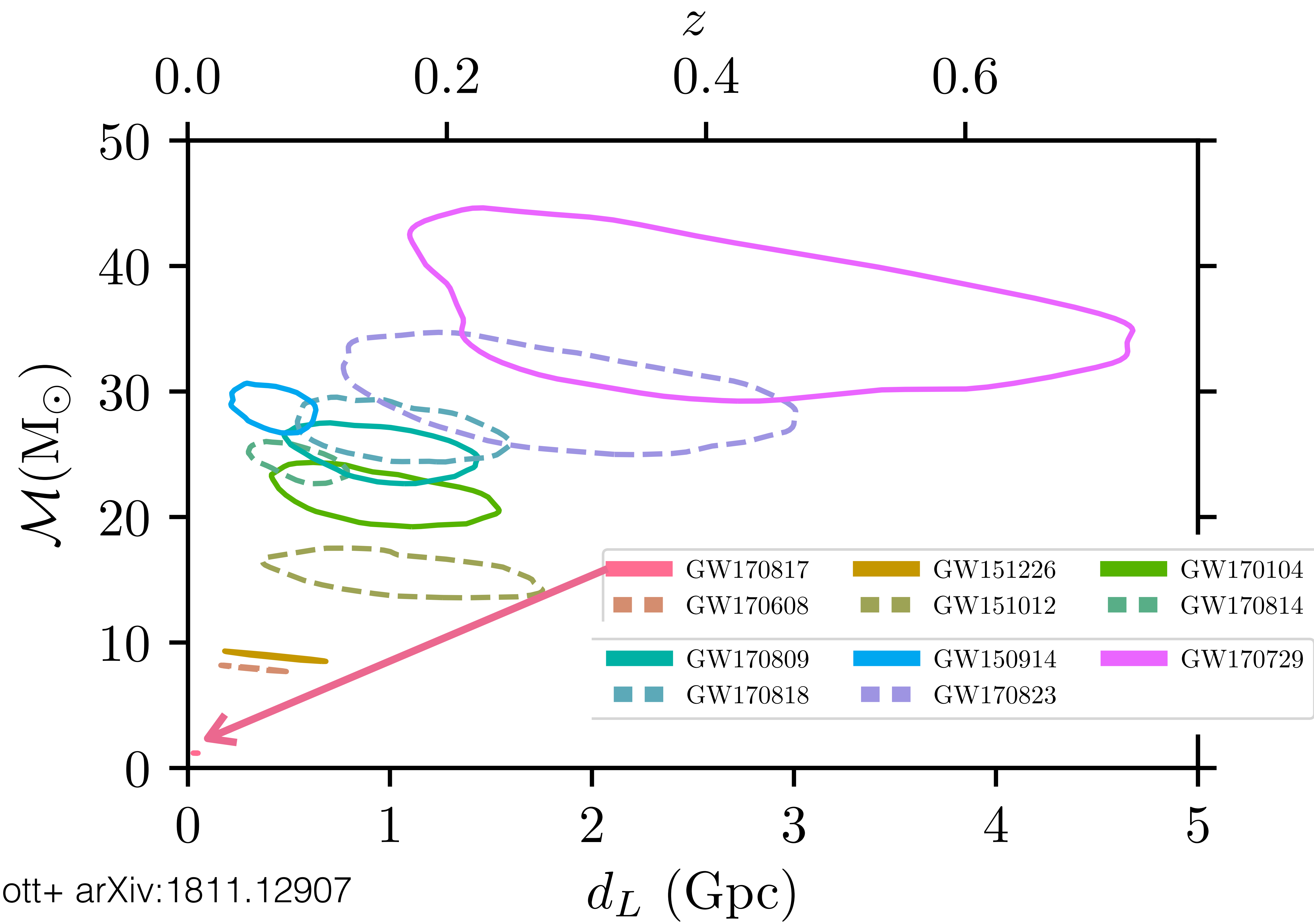
MASS AND SPIN DISTRIBUTIONS



Abbott+ arXiv:1811.12907

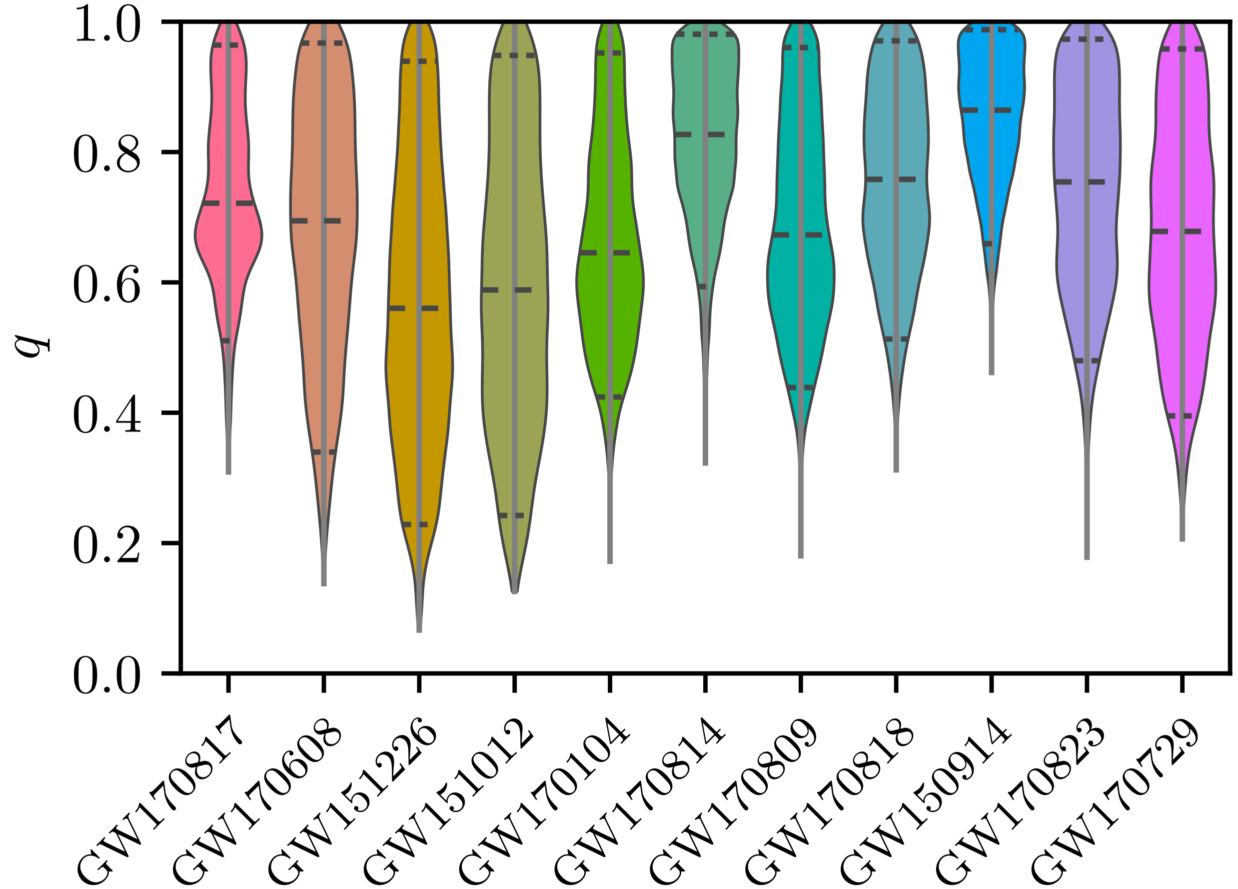
- observed systems are consistent with comparable masses
    - the only exception is GW170729, which finds q ~ 0.3-0.8 after reanalysis
      Chatziioannou+ 2019
- spin of the remnant is less than extremal for all systems

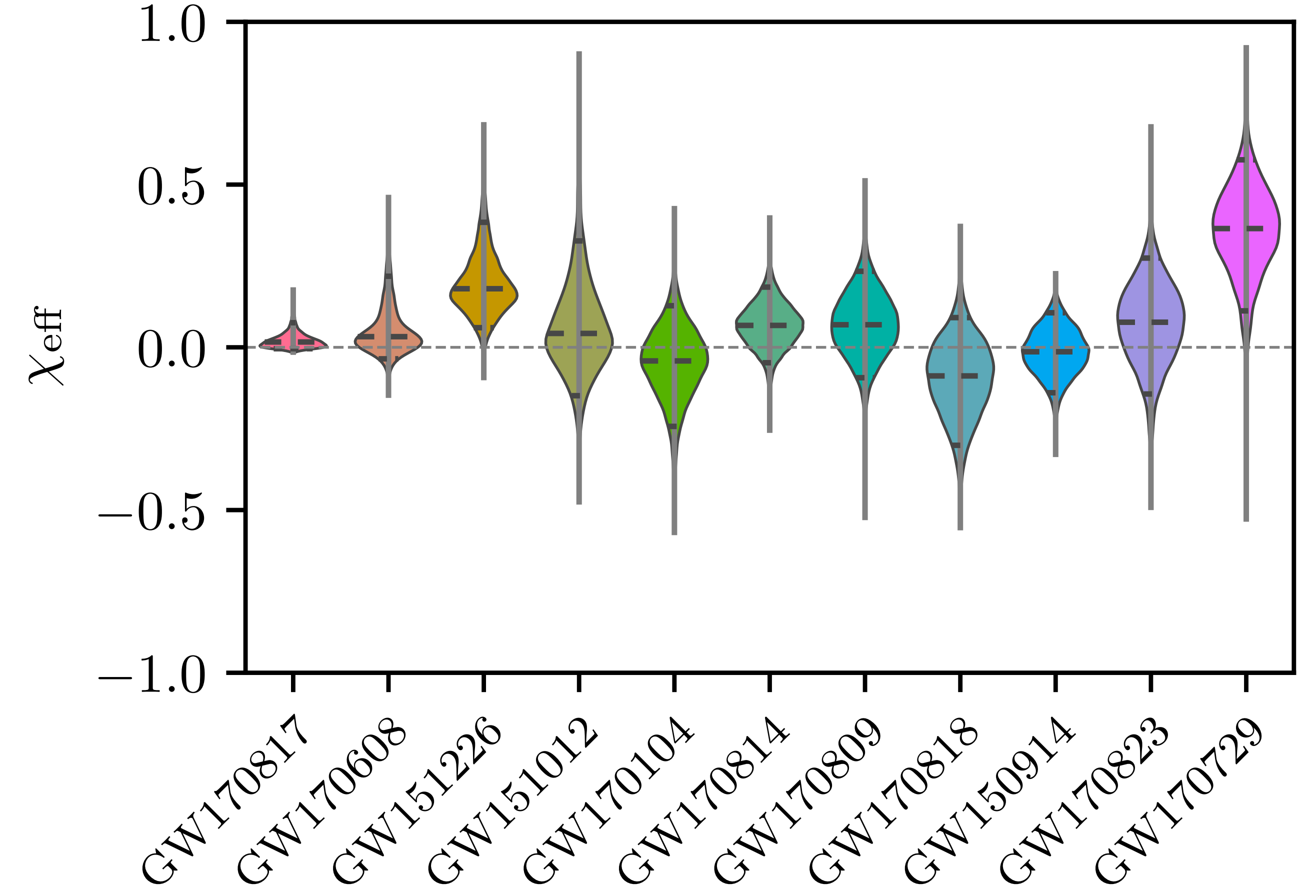
CHIRPMASS AND DISTANCE



Abbott+ arXiv:1811.12907

MASS RATIO AND EFFECTIVE SPIN

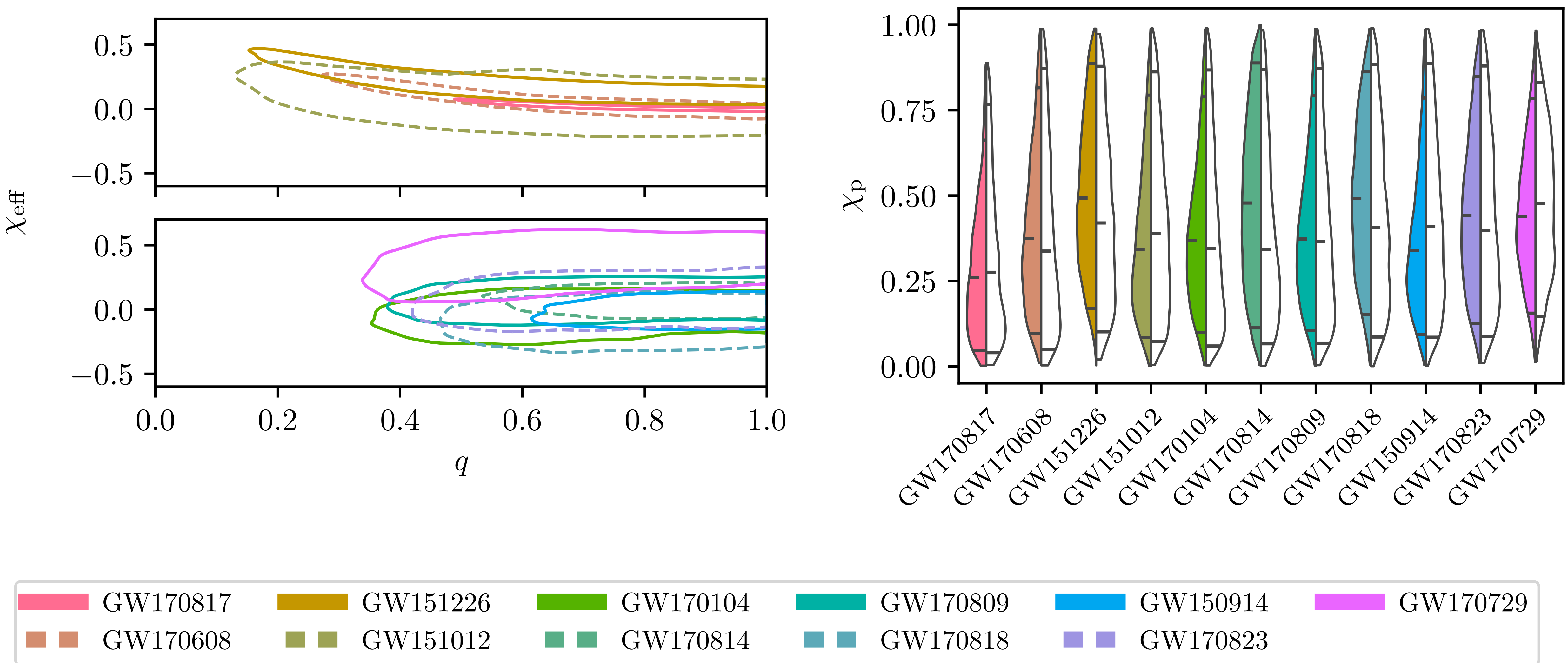




- have mostly observed equal mass systems (except GW170729)
- effective spin consistent with zero
  - spins such that the merger is similar to that of two Schwarzschild black holes

Abbott+ arXiv:1811.12907

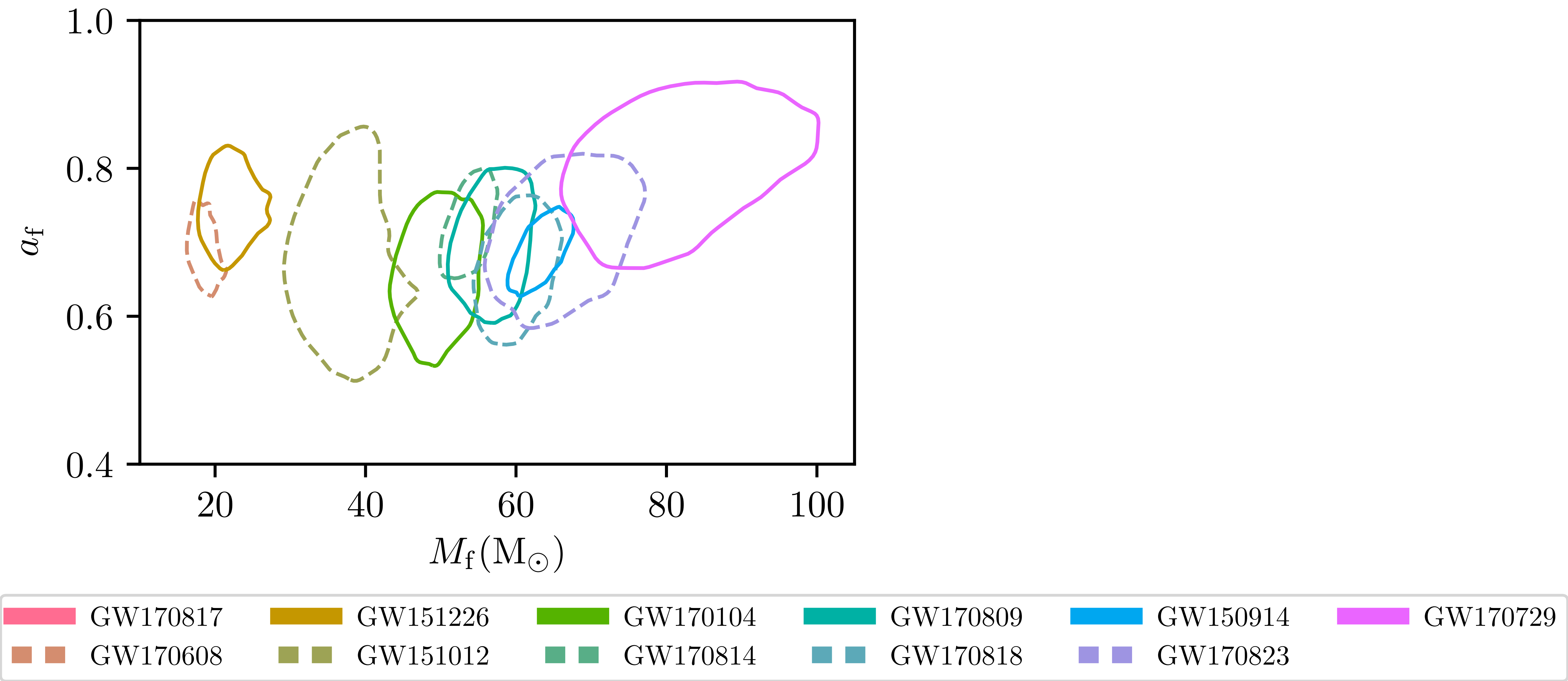
CORRELATIONS BETWEEN PARAMETERS



- find no correlation between effective spin and mass ratio (may be because these are mostly equal mass systems)
- there is no evidence for spin precession/data is insensitive to spin precession
    - posterior distributions are similar to priors

Abbott+ arXiv:1811.12907

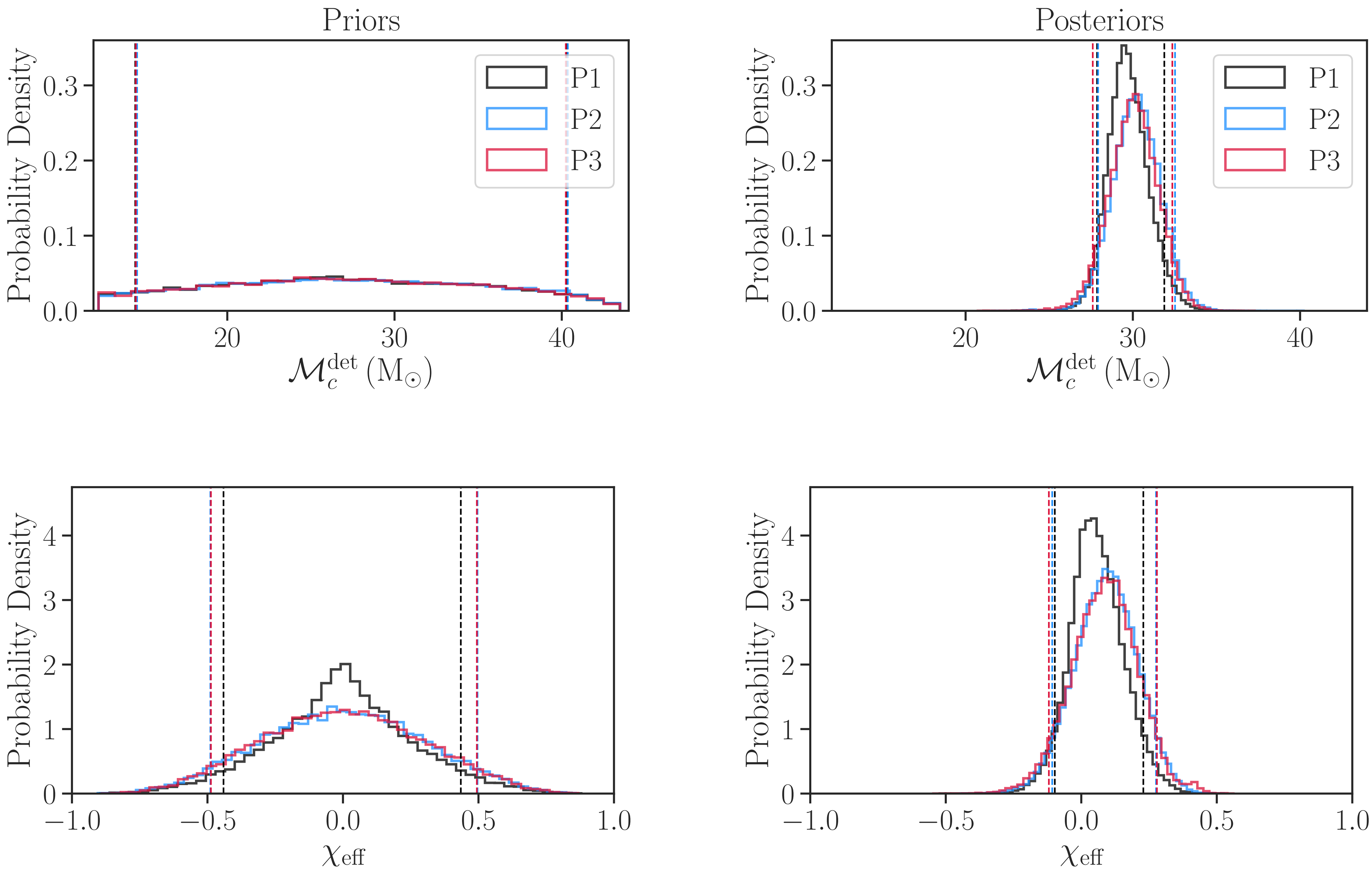
REMNANT MASS AND SPIN



- final spin consistent with zero spins for progenitor black holes
  - alternatively, progenitor spins oriented so as to mimic merger of zero spin black holes

Abbott+ arXiv:1811.12907

SENSITIVITY TO PRIOR



Abbott+ arXiv:1811.12907

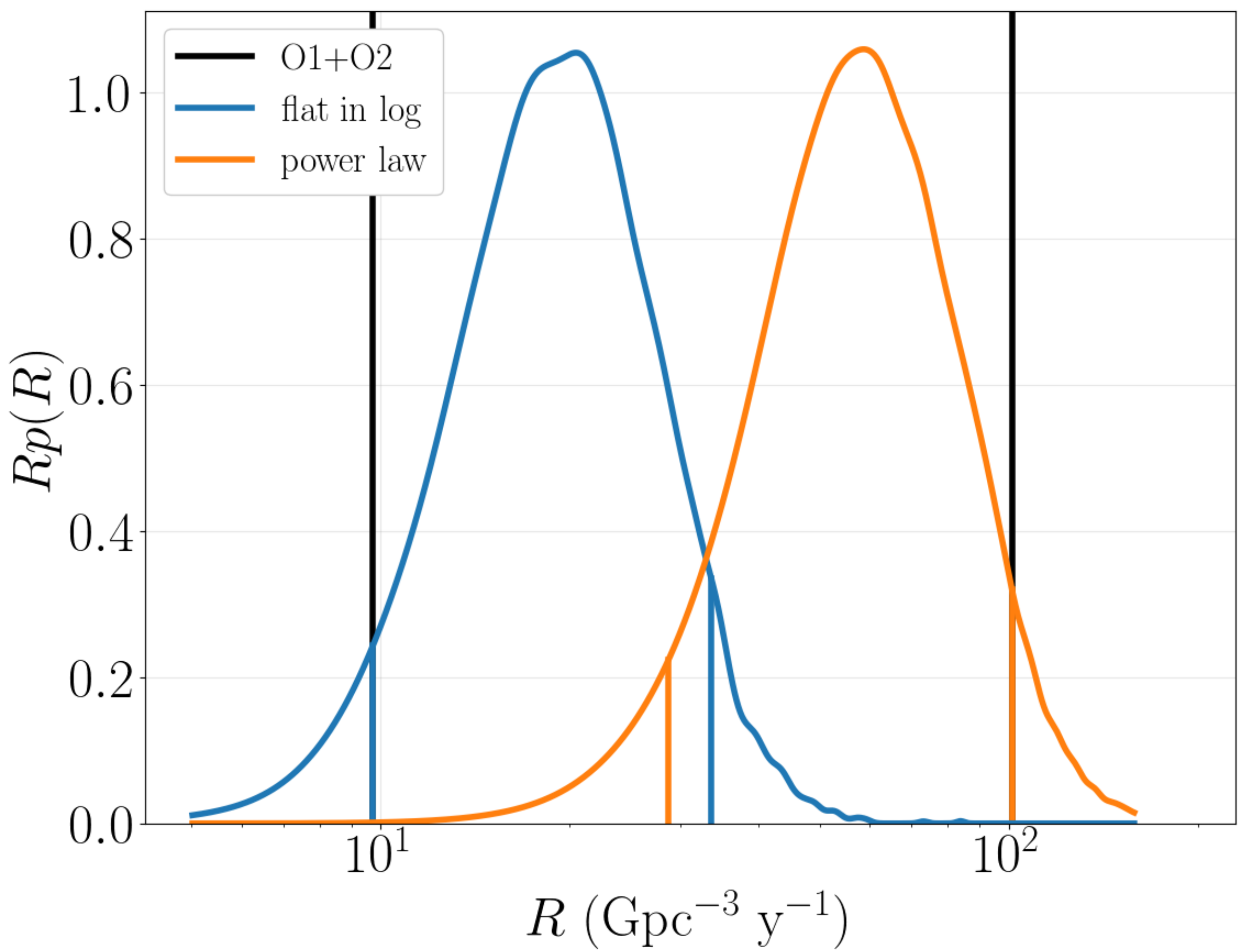
RATES

BINARY BLACK HOLE PROPERTIES

arXiv:1903.04467

Event	Properties			
	D_L [Mpc]	M_{tot} [$M_\odot$]	M_f [$M_\odot$]	a_f
GW150914[b]	430^{+150}_{-170}	$66.2^{+3.7}_{-3.3}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$
GW151012[b]	1060^{+550}_{-480}	$37.3^{+10.6}_{-3.9}$	$35.7^{+10.7}_{-3.8}$	$0.67^{+0.13}_{-0.11}$
GW151226[b,c]	440^{+180}_{-190}	$21.5^{+6.2}_{-1.5}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$
GW170104	960^{+440}_{-420}	$51.3^{+5.3}_{-4.2}$	$49.1^{+5.2}_{-4.0}$	$0.66^{+0.08}_{-0.11}$
GW170608	320^{+120}_{-110}	$18.6^{+3.1}_{-0.7}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$
GW170729[d]	2760^{+1380}_{-1340}	$85.2^{+15.6}_{-11.1}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$
GW170809	990^{+320}_{-380}	$59.2^{+5.4}_{-3.9}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$
GW170814	580^{+160}_{-210}	$56.1^{+3.4}_{-2.7}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$
GW170818	1020^{+430}_{-360}	$62.5^{+5.1}_{-4.0}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$
GW170823	1850^{+840}_{-840}	$68.9^{+9.9}_{-7.1}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$

COALESCENCE RATE



- In aLIGO/AdV expect 1 BBH event per day, 1 BNS event every couple of days

arXiv:1903.04467

$9.7 - 101\ \mathrm{Gpc}^{-3}\ \mathrm{y}^{-1}$

BNS Rate: $110 - 3840\ \mathrm{Gpc}^{-3}\ \mathrm{y}^{-1}$

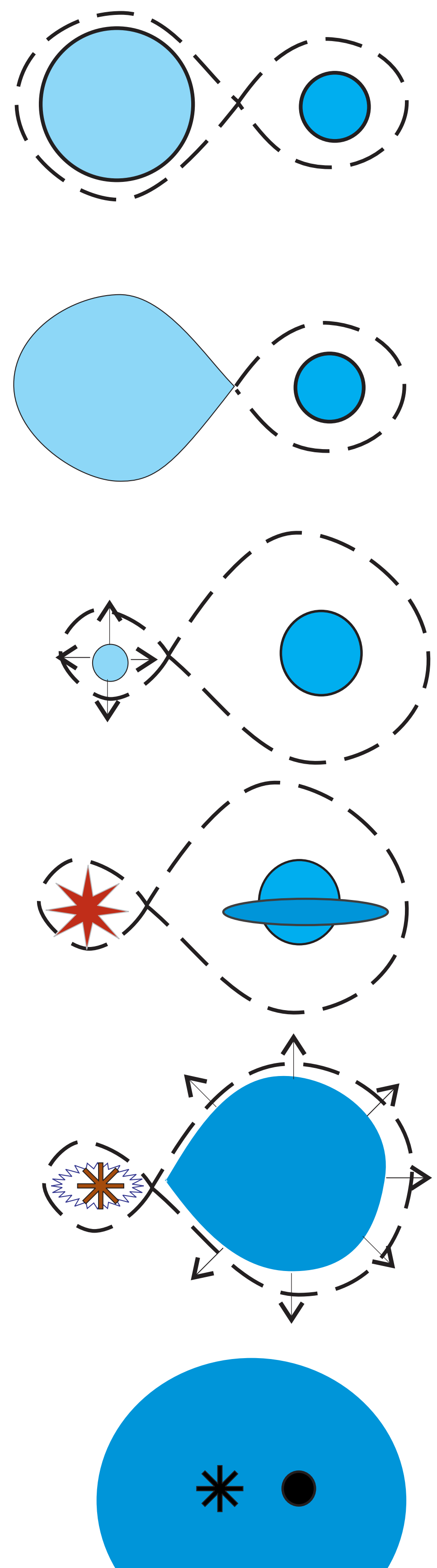
FORMATION SCENARIOS

FORMATION AND EVOLUTION COMPACT BINARIES

- in isolated binaries
- in dense stellar clusters
- primordial black holes

(Lipunov+ 1997, Belczynski+ 2010, Dominik+ 2015, Belczynski+ 2015, Nelemans+ 2001, Rodriguez+ 2016, Rodriguez+ 2019, de Mink+ 2009, Marchant+ 2016, de Mink & Mandel 2016, Belczynski+ 2016; Bird+ 2016, Carr 2019)

FORMATION OF BINARY BLACK HOLES- ISOLATED BINARY



$T \sim 3$ Myr, $N \sim 10^4$ — **Two OB main-sequence stars**

$T \sim 10^4$ yr, $N \sim 30$ — **More massive star (primary) overfills Roche lobe. Stable or unstable nonconservative mass exchange**

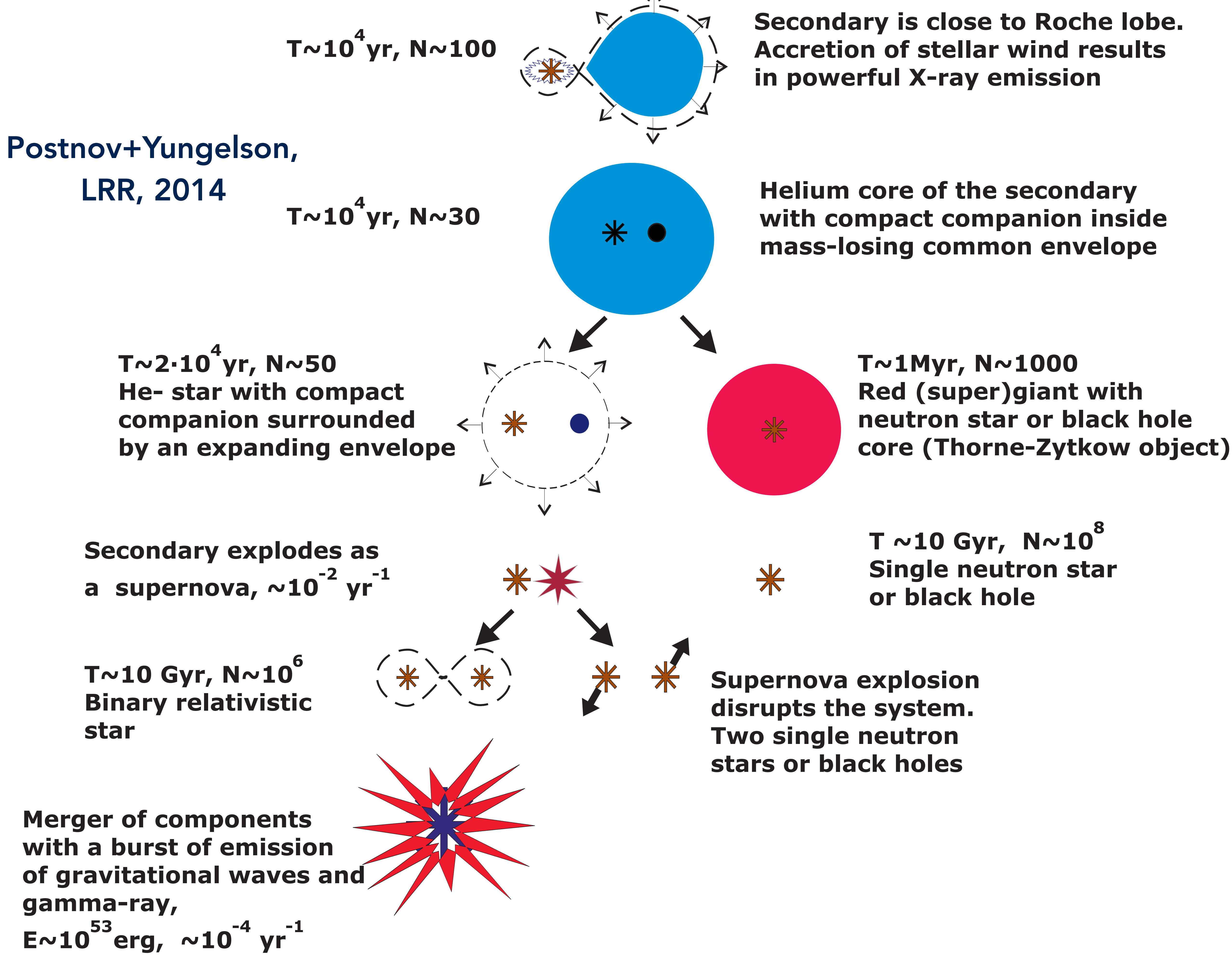
$T \sim 2 \cdot 10^5$ yr, $N \sim 500$ — **Helium-rich star with OB-companion**

$\sim 10^{-2}$ yr^{-1} — **Primary explodes as core-collapse SN or ECSN and becomes a neutron star or black hole**

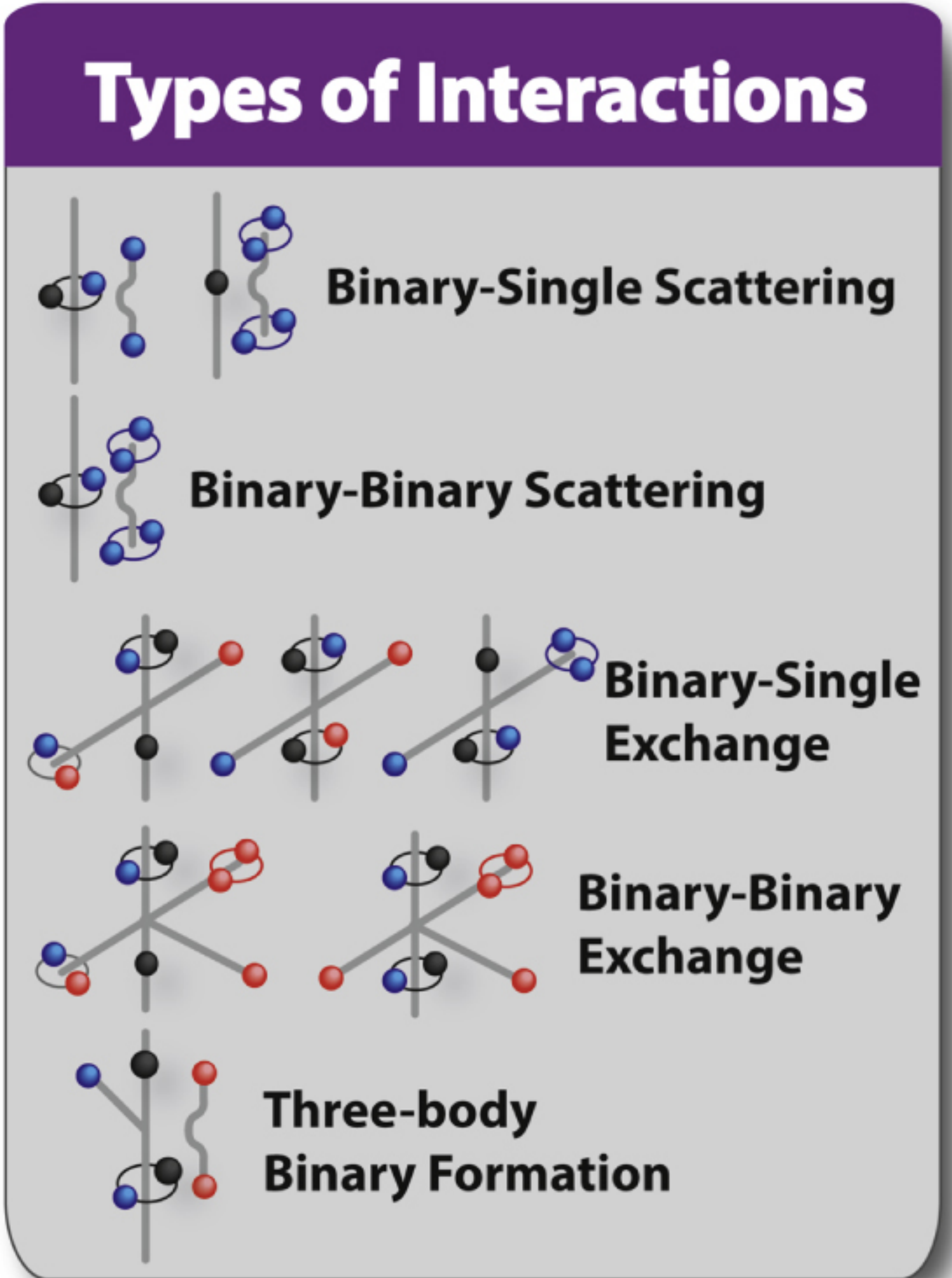
$T \sim 10^4$ yr, $N \sim 100$ — **Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission**

$T \sim 10^4$ yr, $N \sim 30$ — **Helium core of the secondary with compact companion inside mass-losing common envelope**

Postnov+Yungelson, LRR, 2014

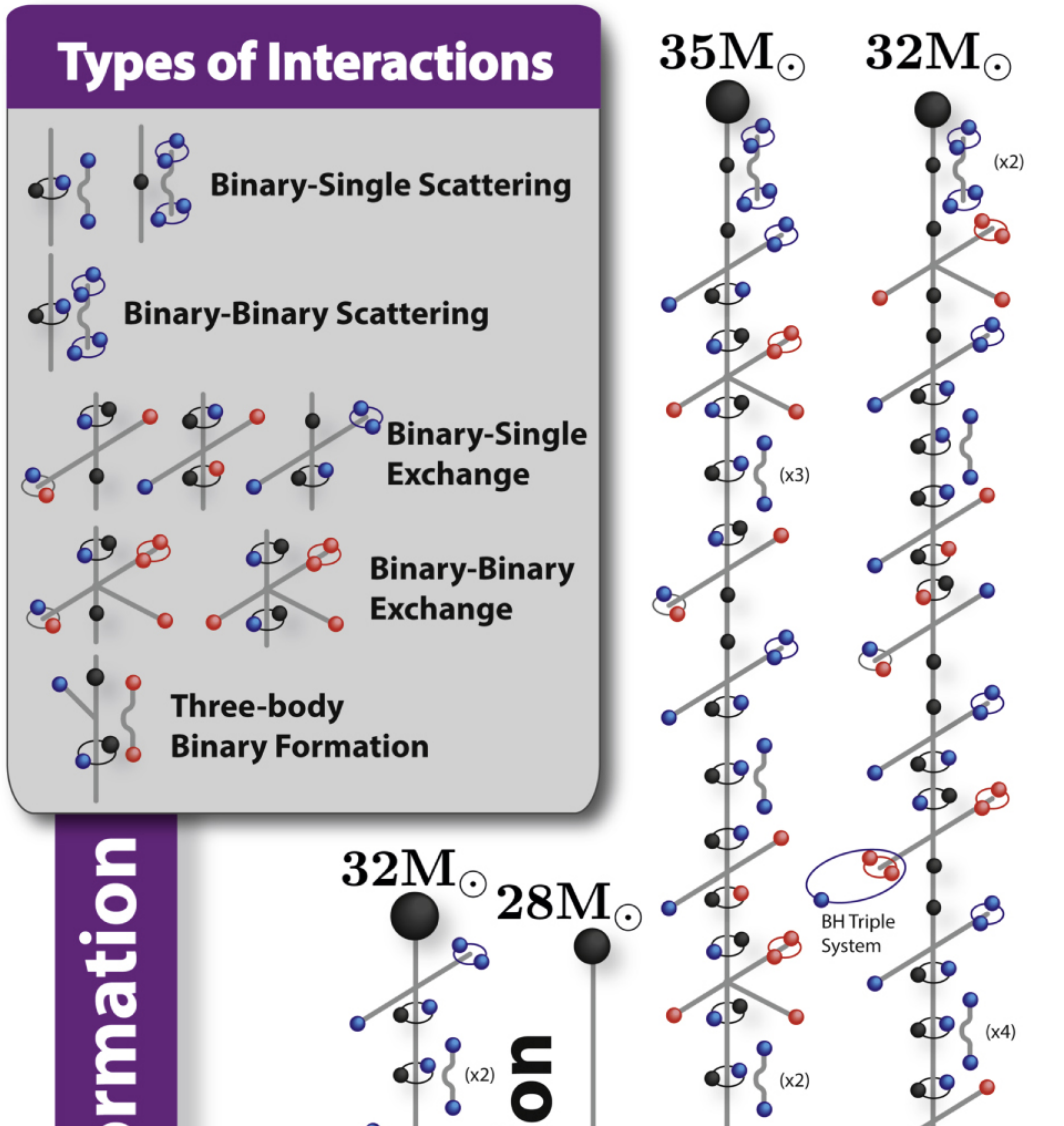

T~10^4 yr, N~100
Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission
Postnov+Yungelson, LRR, 2014
T~10^4 yr, N~30
Helium core of the secondary with compact companion inside mass-losing common envelope
T~2·10^4 yr, N~50
He- star with compact companion surrounded by an expanding envelope
T~1Myr, N~1000
Red (super)giant with neutron star or black hole core (Thorne-Zytkow object)
Secondary explodes as a supernova, ~10^-2 yr^-1
T ~10 Gyr, N~10^8
Single neutron star or black hole
T~10 Gyr, N~10^6
Binary relativistic star
Supernova explosion disrupts the system. Two single neutron stars or black holes
Merger of components with a burst of emission of gravitational waves and gamma-ray,
E~10^53 erg, ~10^-4 yr^-1

BINARY BLACK HOLE FORMATION VIA DYNAMICAL PROCESSES



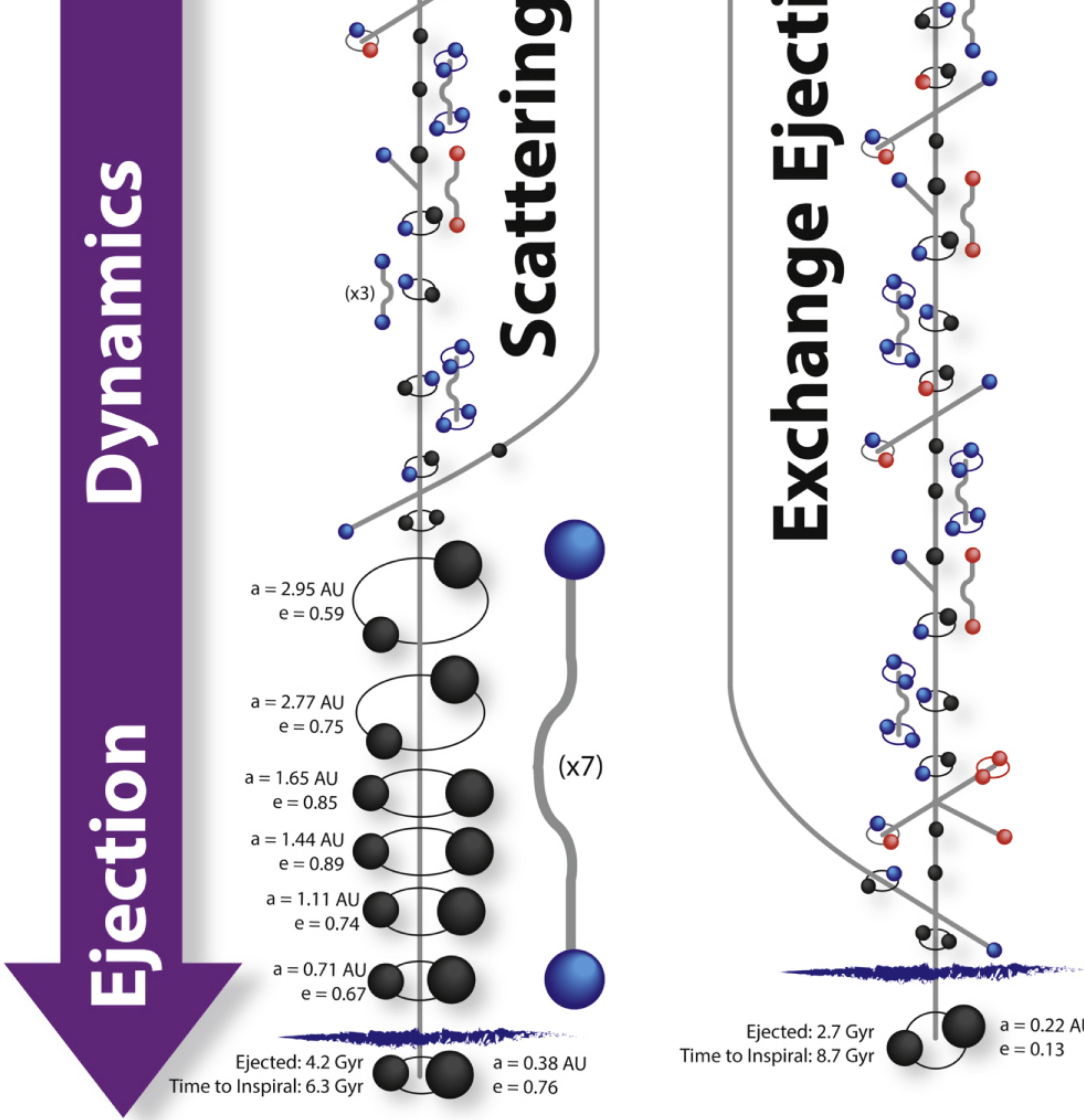
Rodriguez+, ApJL, 2016

BINARY BLACK HOLE FORMATION VIA DYNAMICAL PROCESSES

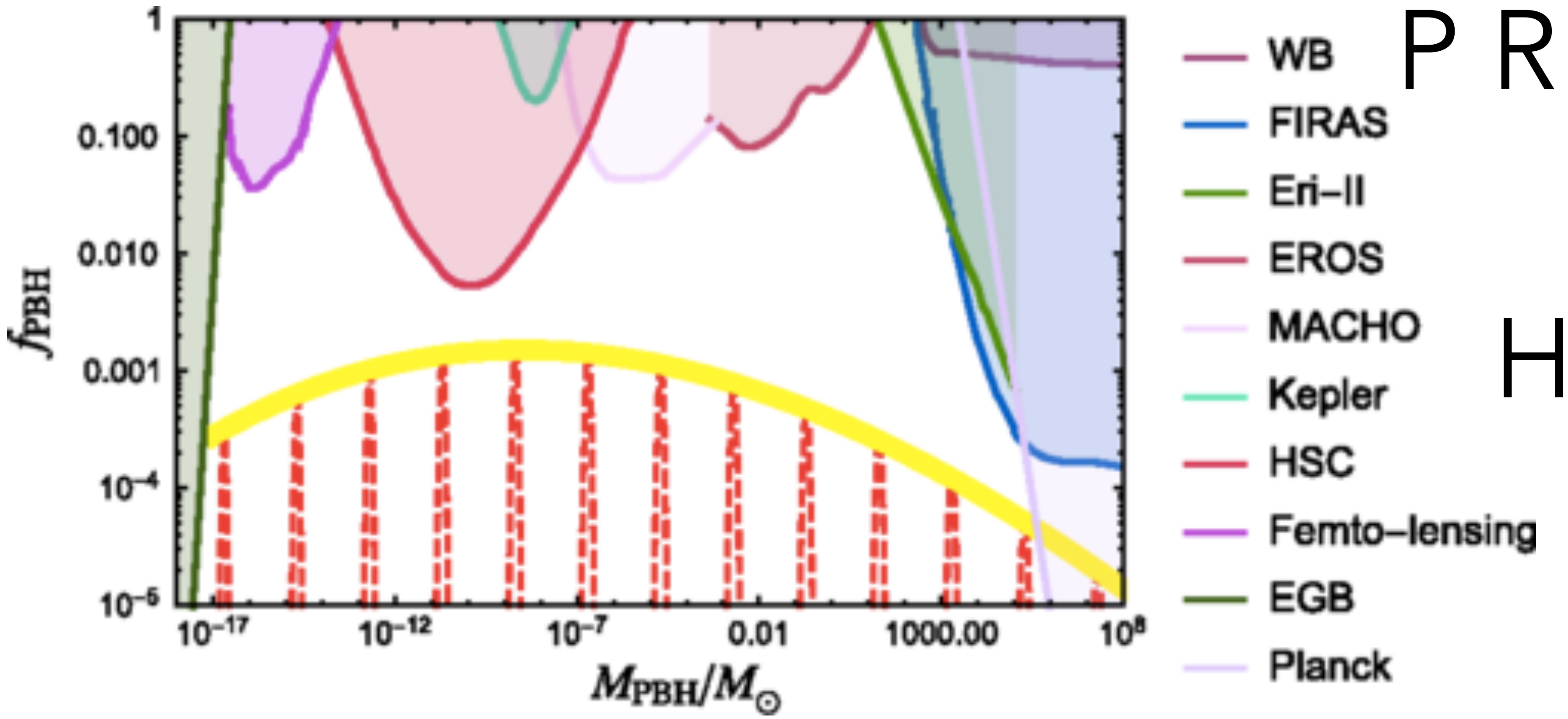


Rodriguez+, ApJL, 2016

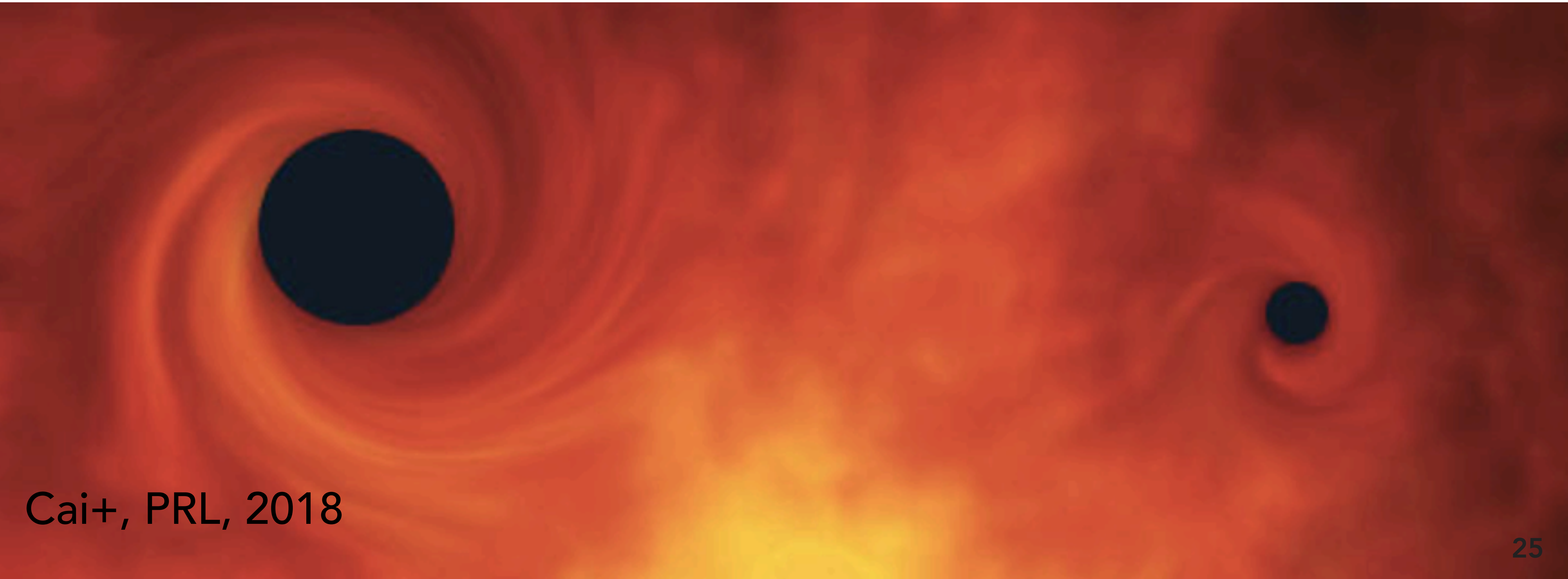
BINARY BLACK HOLE FORMATION VIA DYNAMICAL PROCESSES



Rodriguez+, ApJL, 2016



PRIMORDIAL BLACK HOLES AS DARK MATTER

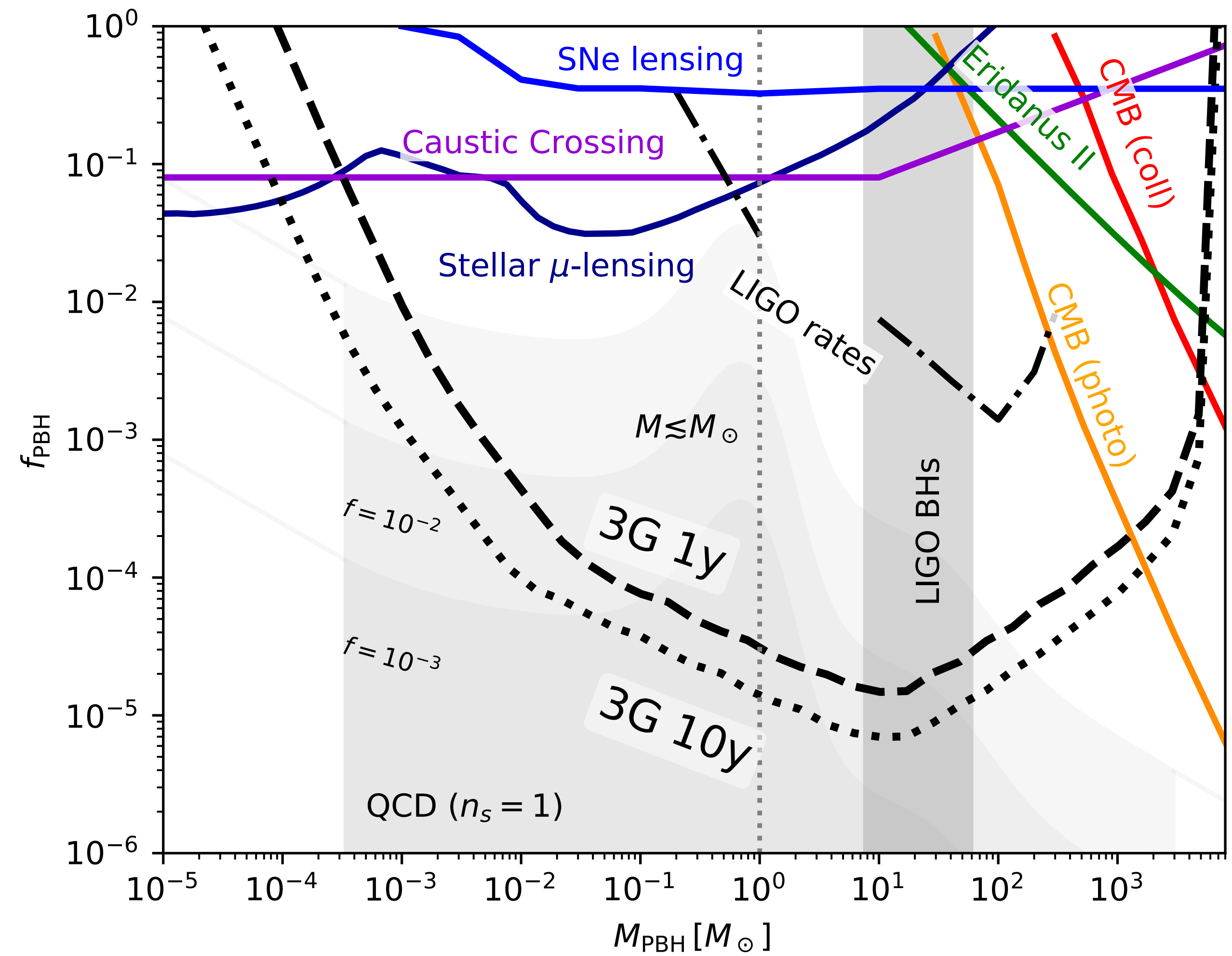


Cai+, PRL, 2018

PRIMORDIAL BLACK HOLES AS SOURCE OF LIGO-VIRGO BLACK HOLES

- sub-solar black holes cannot form by stellar evolution
- must be primordial in origin
- 3G detectors can probe existence of light black holes

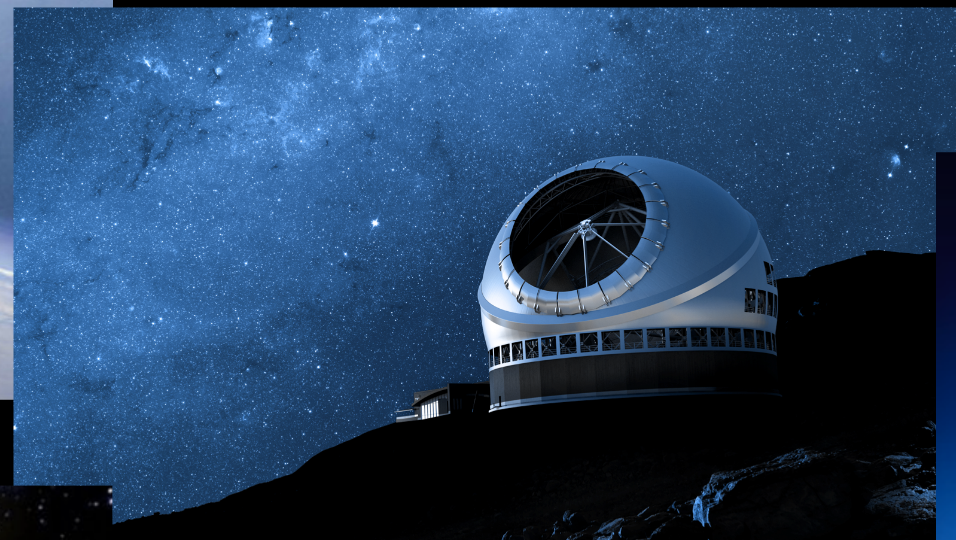
Credit:Miguel Zumalacarregui

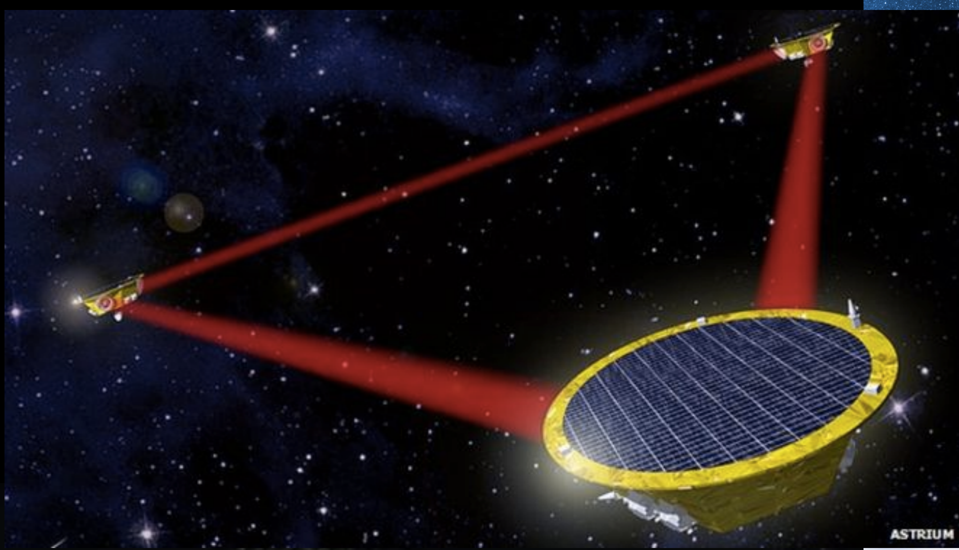


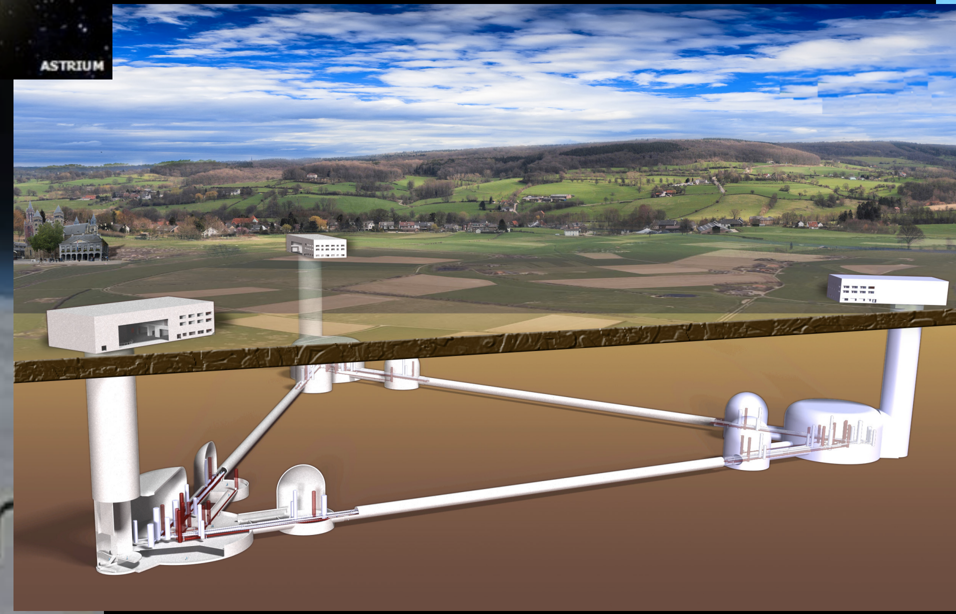
3G network would settle the question if LIGO-Virgo black holes constitute dark matter and are primordial in origin

LOW LATENCY ANALYSIS AND EM ALERTS

MULTIMESSENGER SCIENCE

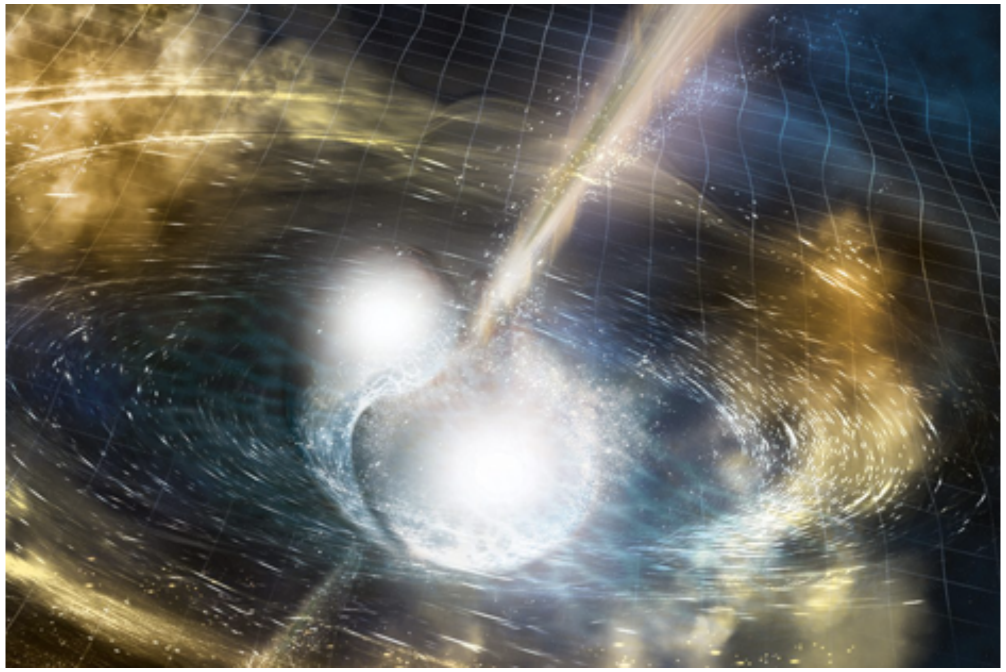


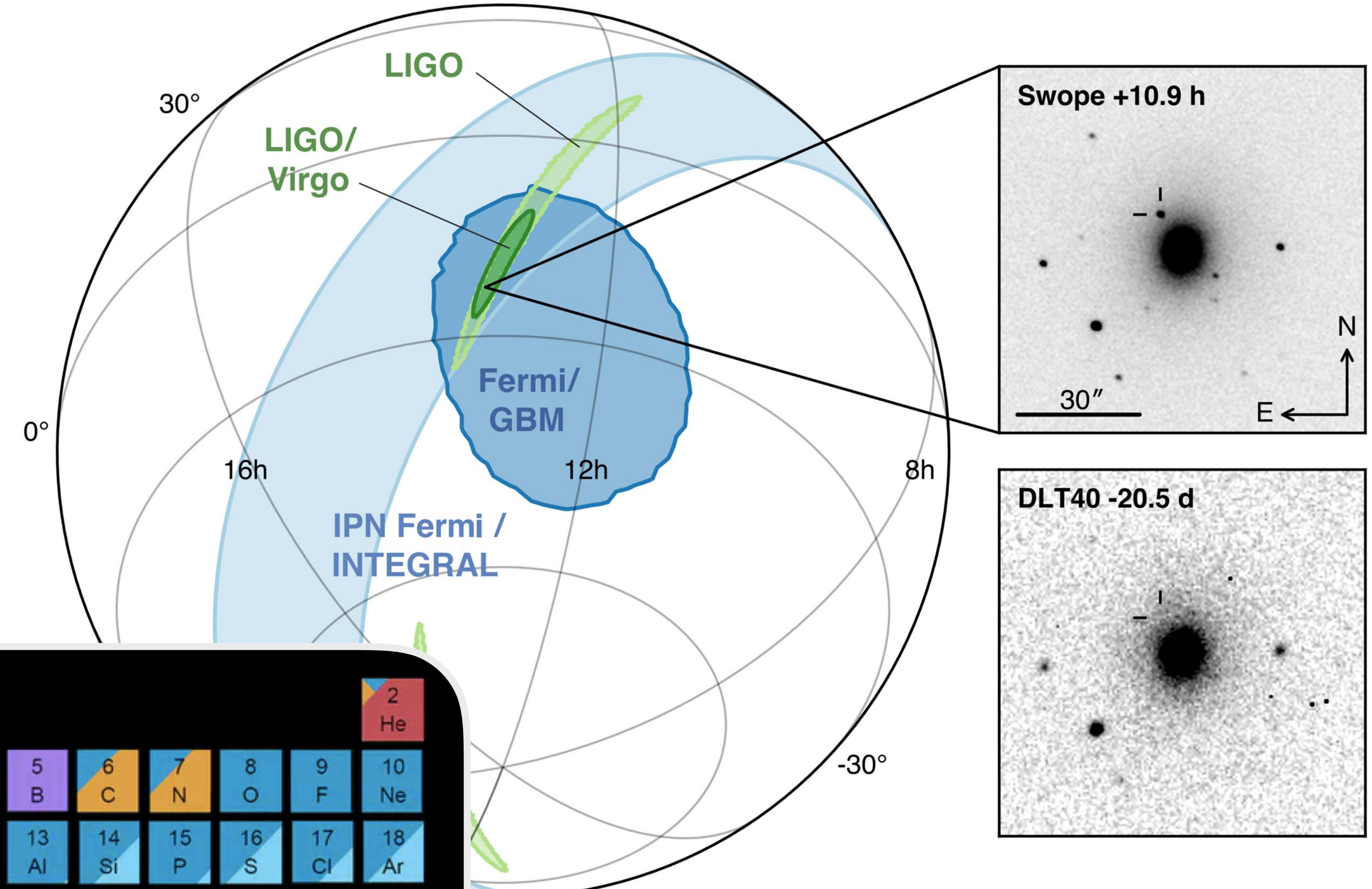


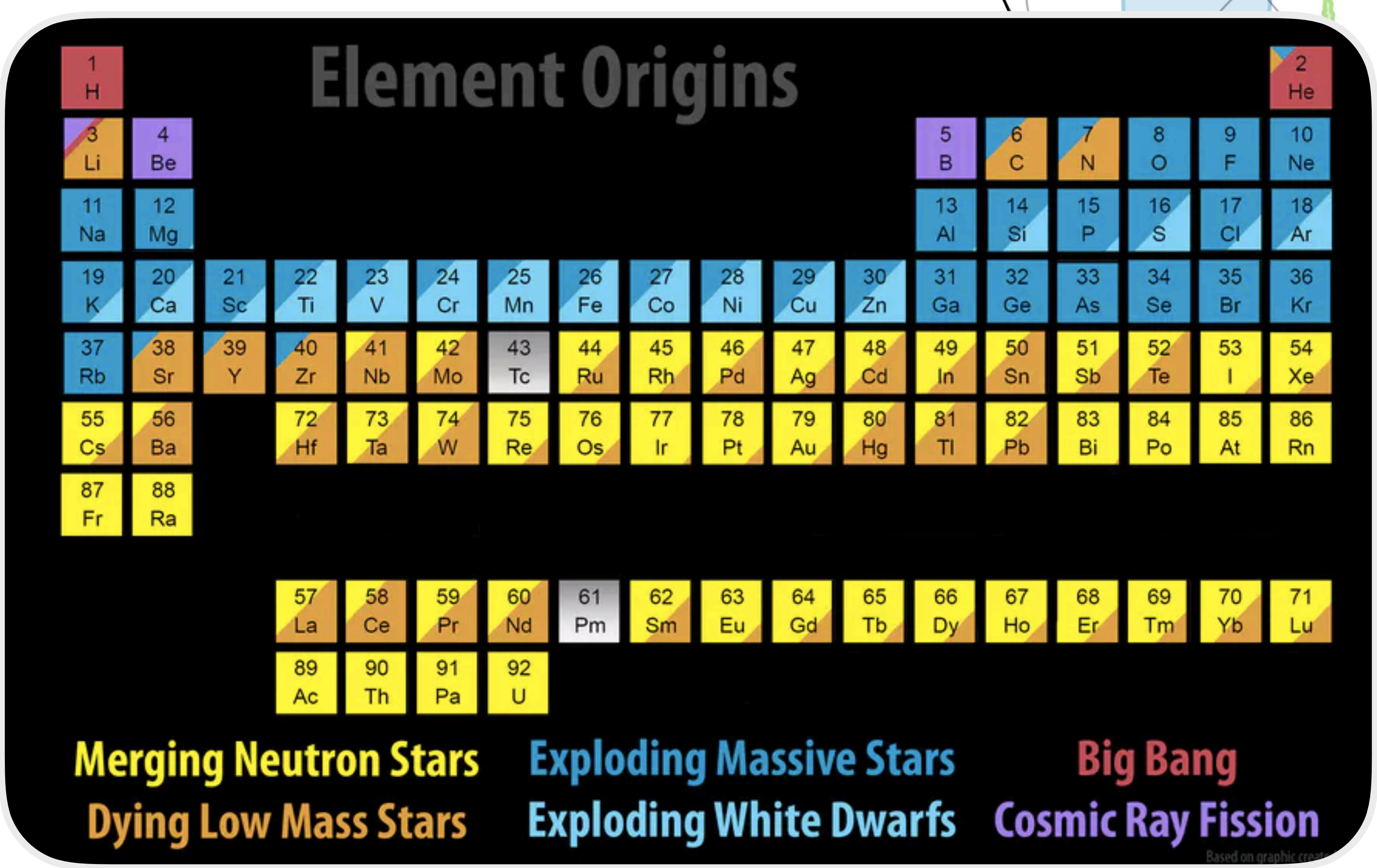


ORIGIN OF HEAVY ELEMENTS

Abbott+ ApJ Letters, 848, L12 (2017)







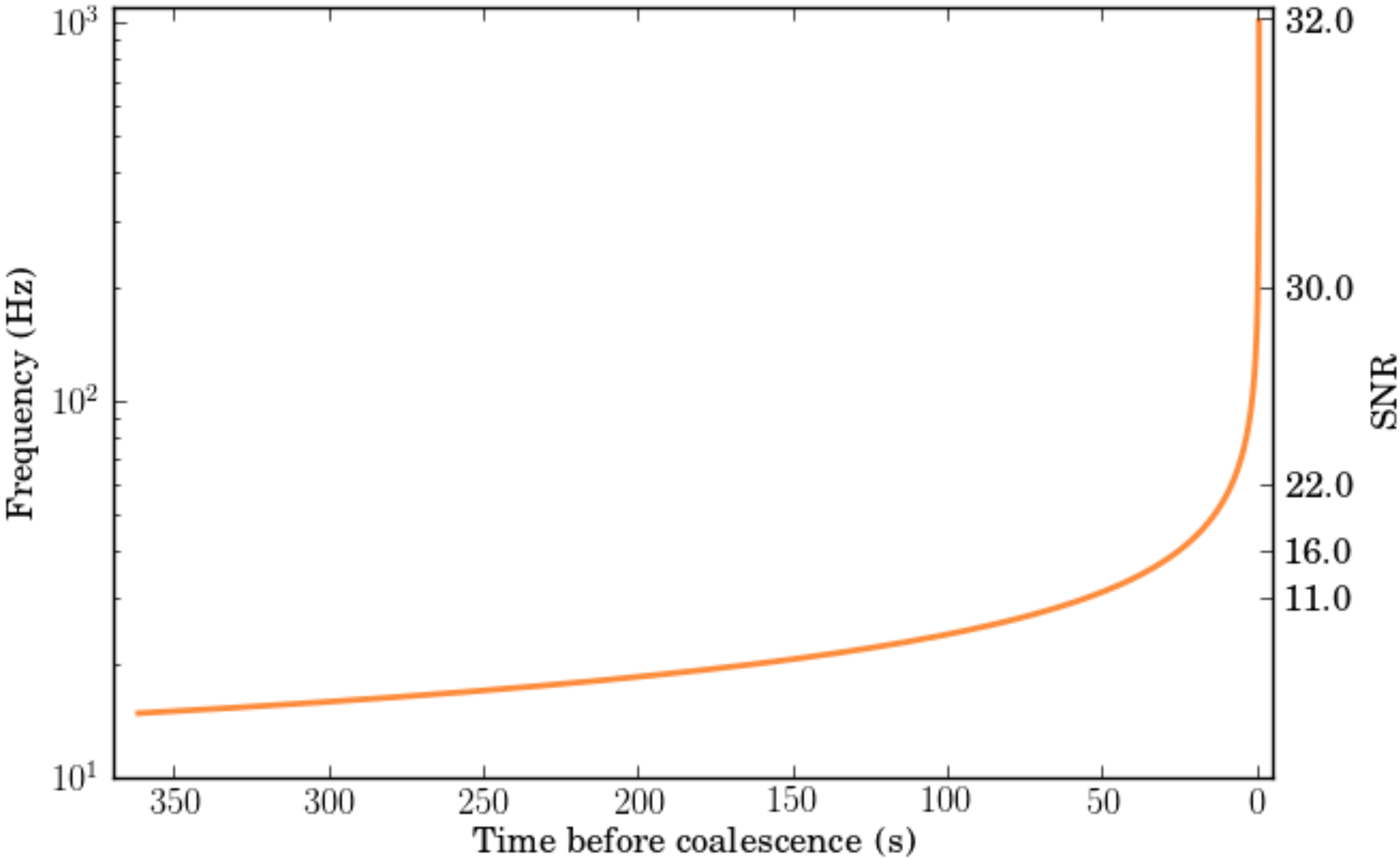
3G network will help identify thousands of kilonova and trace the origin of heavy elements

MOTIVATION FOR PRE-MERGER ALERTS

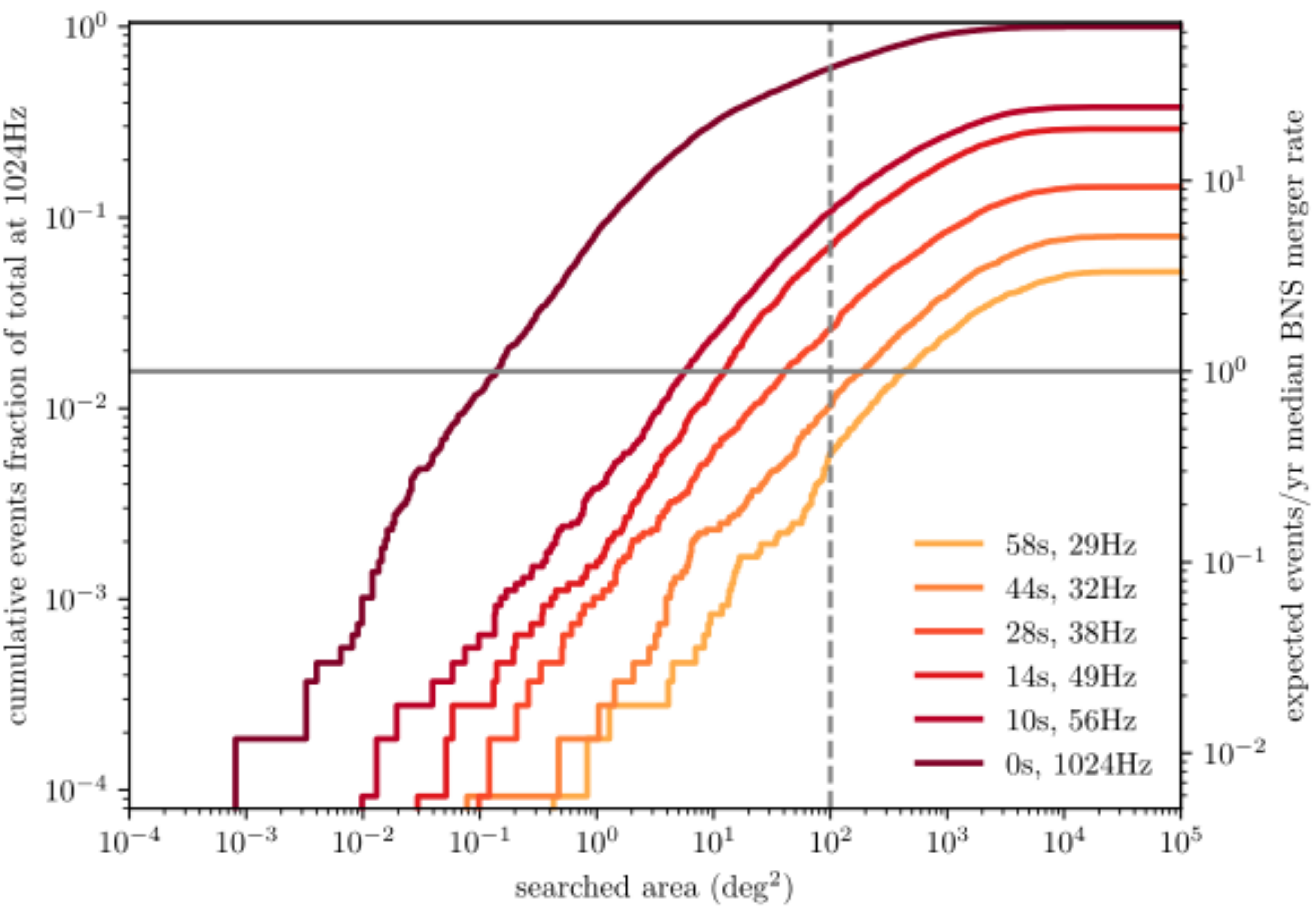
- Prompt radio emission
  - short coherent radio pulse near the instant of merger
    Usov & Katz 2000; Hansen & Lyutikov 2001; Pshirkov & Postnov 2010; Lai 2012; Lyutikov 2013; Totani 2013; Ravi & Lasky 2014; Metzger & Zivancev 2016; Wang et al. 2016; Lyutikov 2018; Wang et al. 2018
- Early UV/optical observations
  - properties of shock-heated ejecta, jet formation,…
    Metzger et al 2017 (arXiv:1710.05931)
- X-ray signatures
  - prior to merger from NS-NS magnetosphere interaction, crust breaking
  - immediately after merger, extended emission or X-ray plateaus
  - in case of a long-lived post-merger NS, there may be X-ray/UV emissions)
    Ciolfi & Siegel 2015; Metzger & Piro 2014; Siegel & Ciolfi 2015
- GRBs
  - for high total mass systems - delay O(ms) - O(10 ms)

30

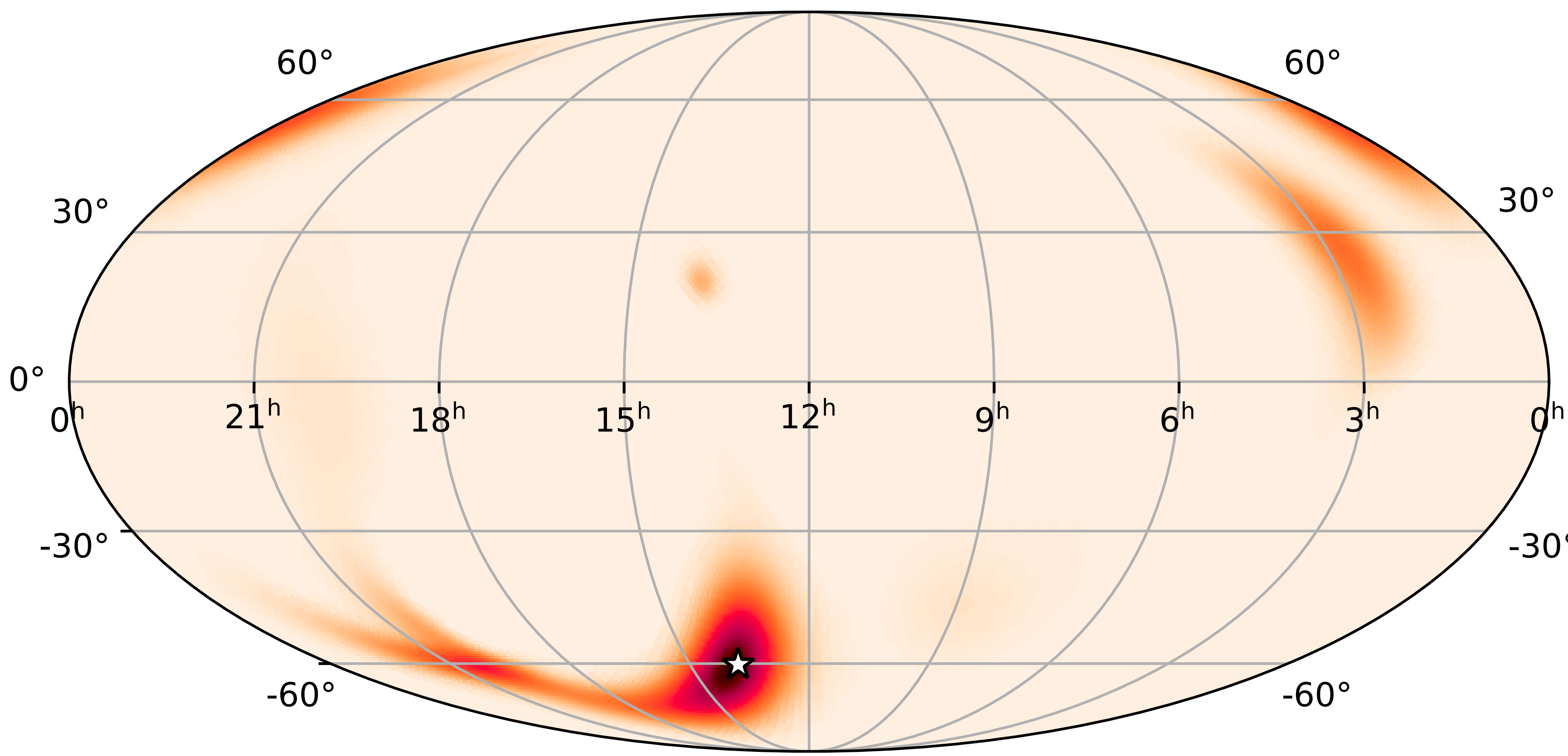
EARLY WARNING ALERTS



NUMBER OF EVENTS AND SKY LOCALIZATION

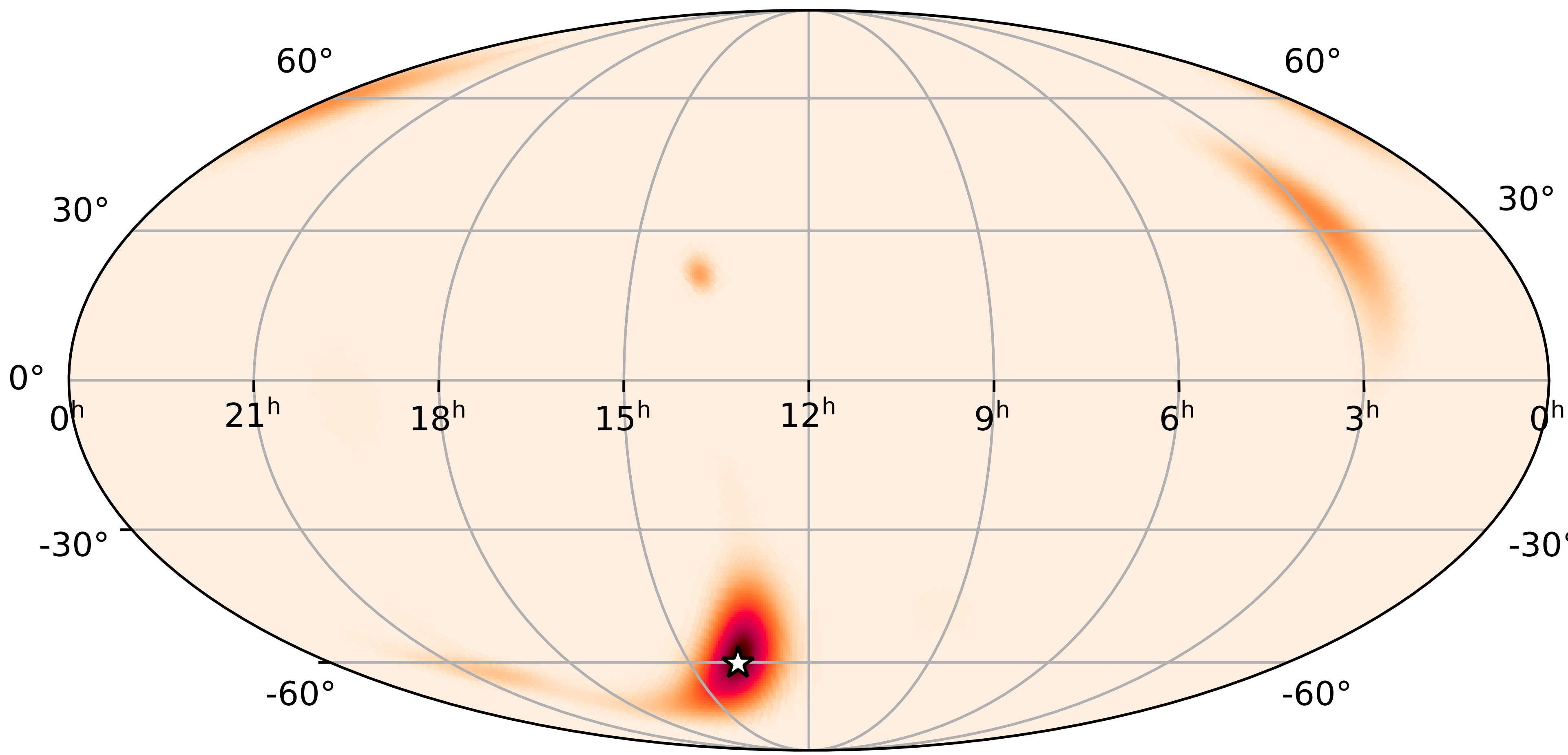


Example sky map 29 Hz



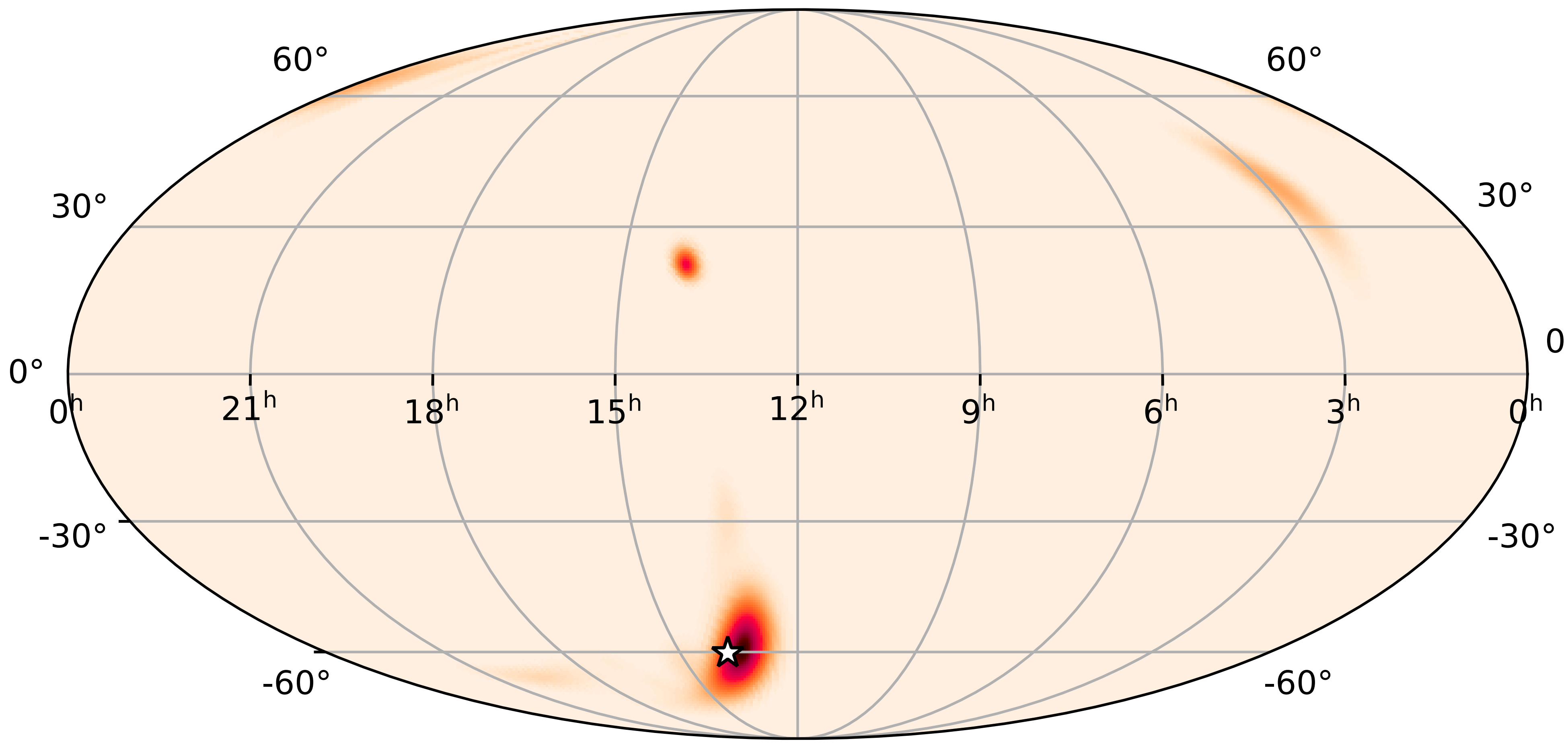
Sky maps created using BAYESTAR

Example sky map 32 Hz



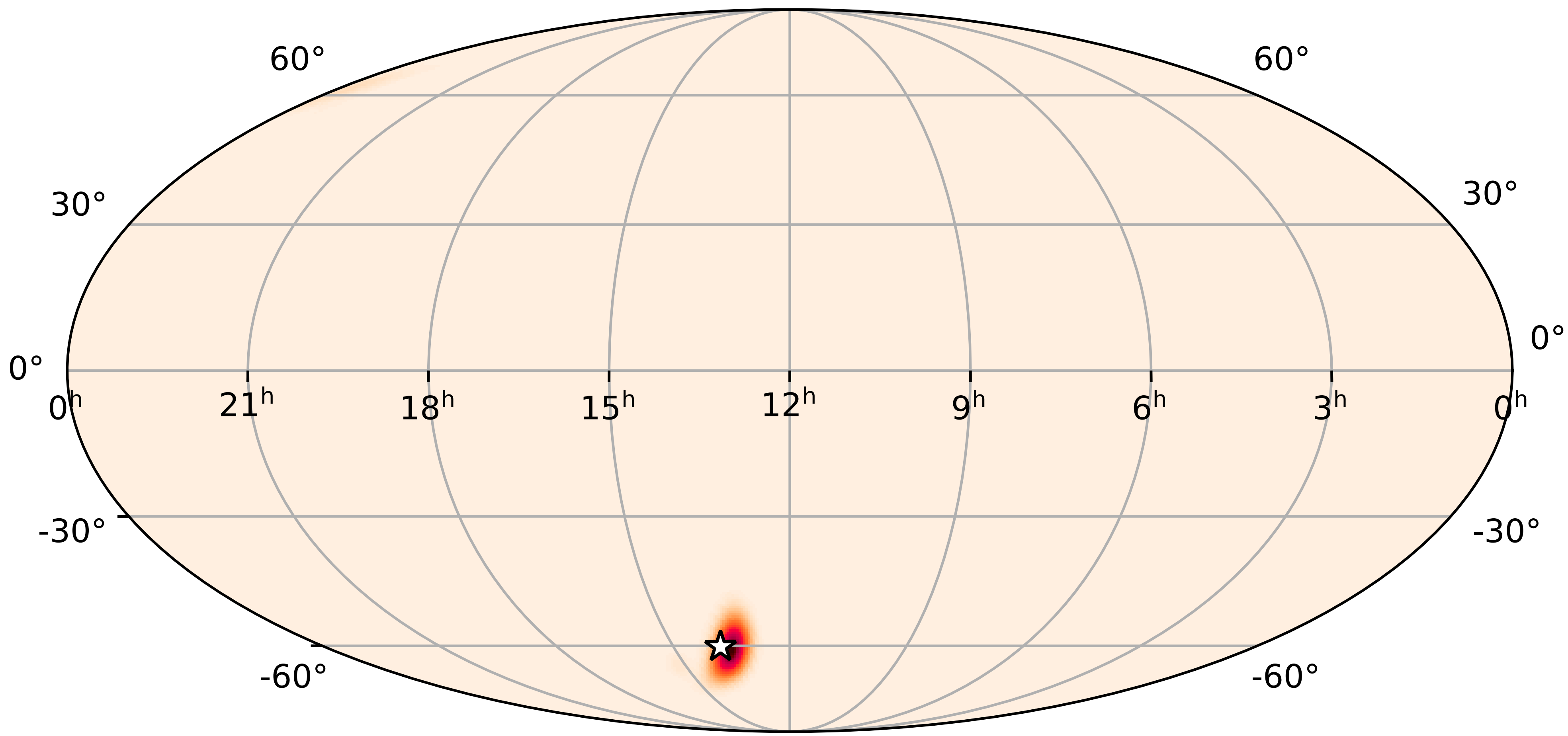
Sky maps created using BAYESTAR

Example sky map 38 Hz



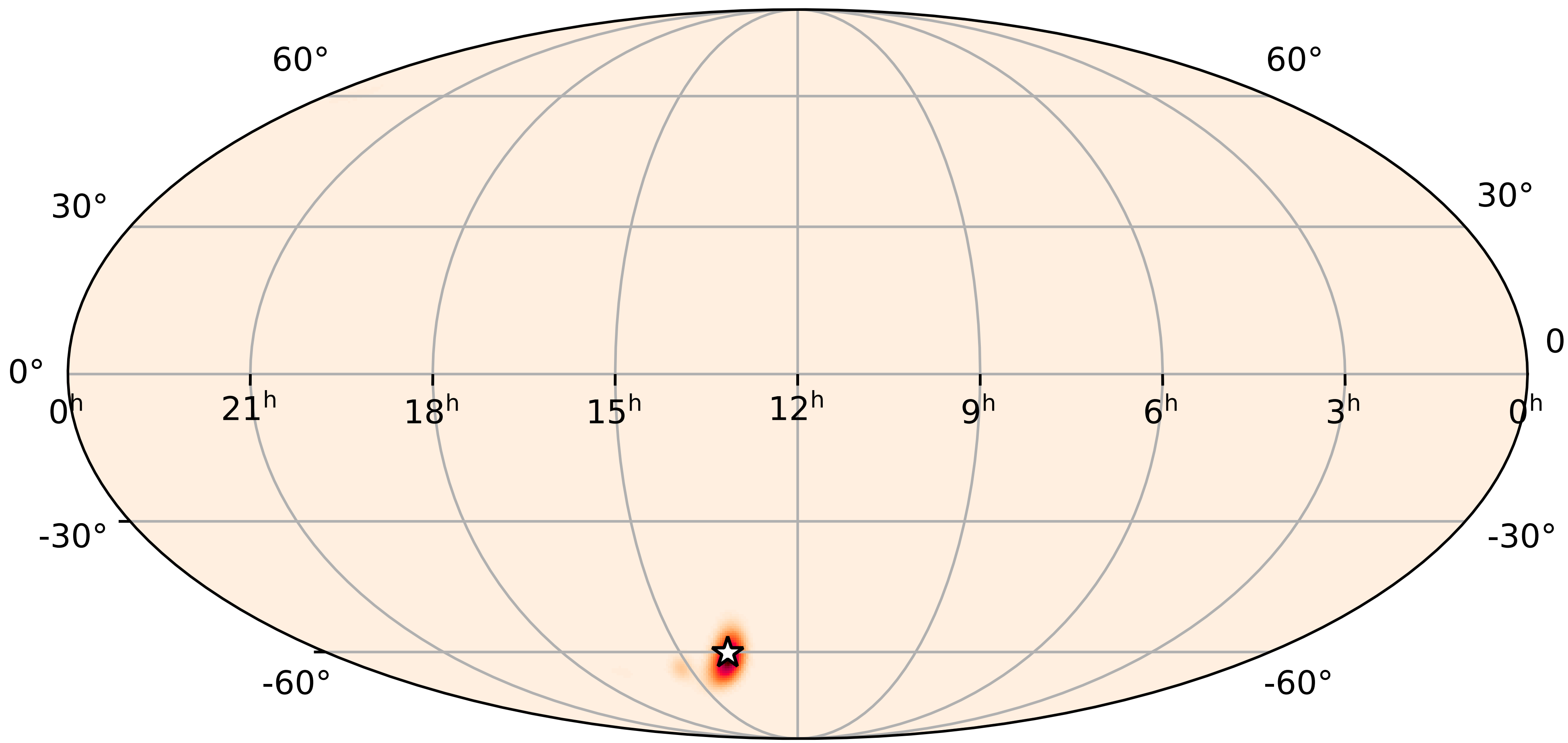
Sky maps created using BAYESTAR

Example sky map 49 Hz



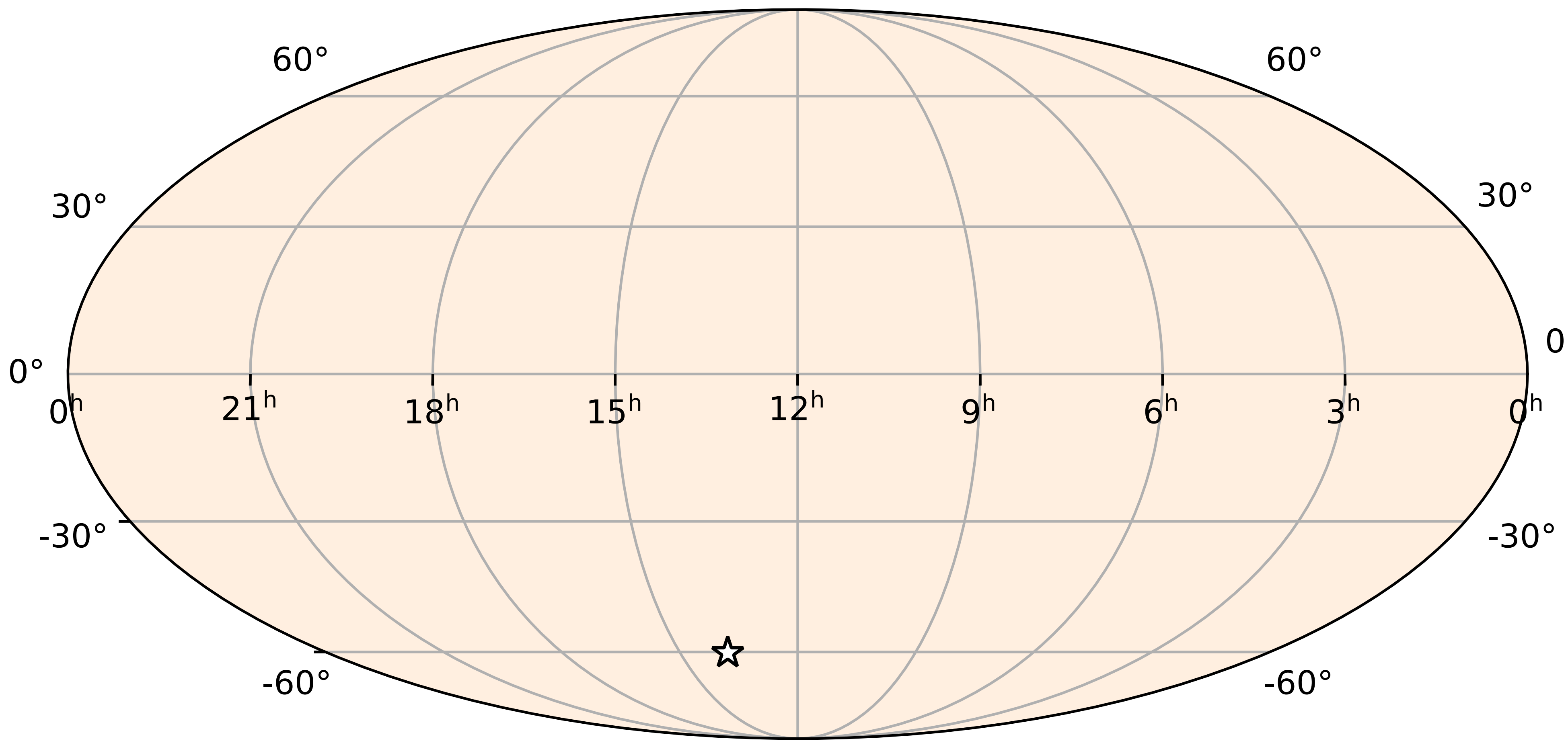
Sky maps created using BAYESTAR

Example sky map 56 Hz



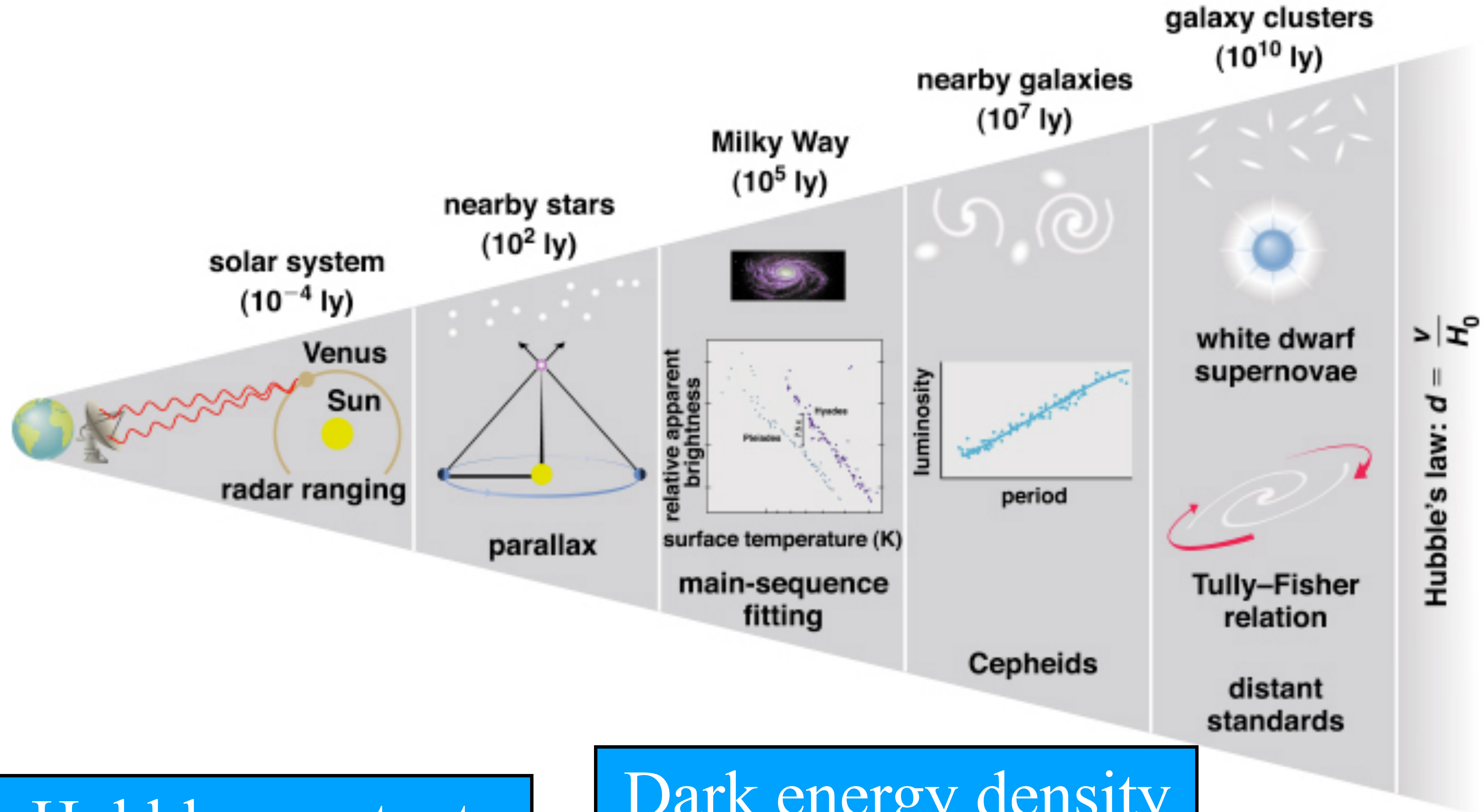
Sky maps created using BAYESTAR

Example sky map 1024 Hz



Sky maps created using BAYESTAR

Cosmic distance ladder



Hubble constant

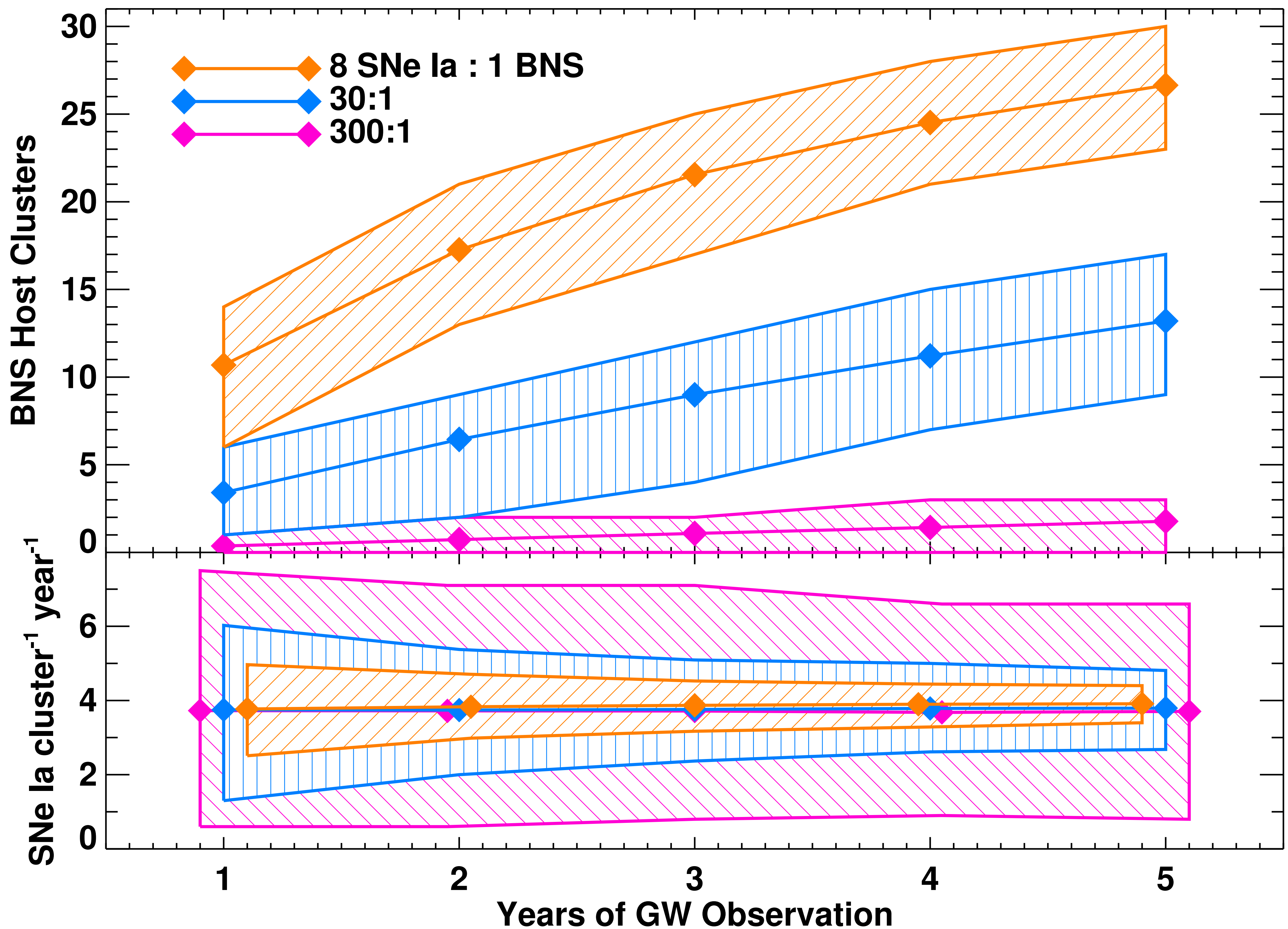
Dark matter density

Dark energy density

Dark energy equation of state

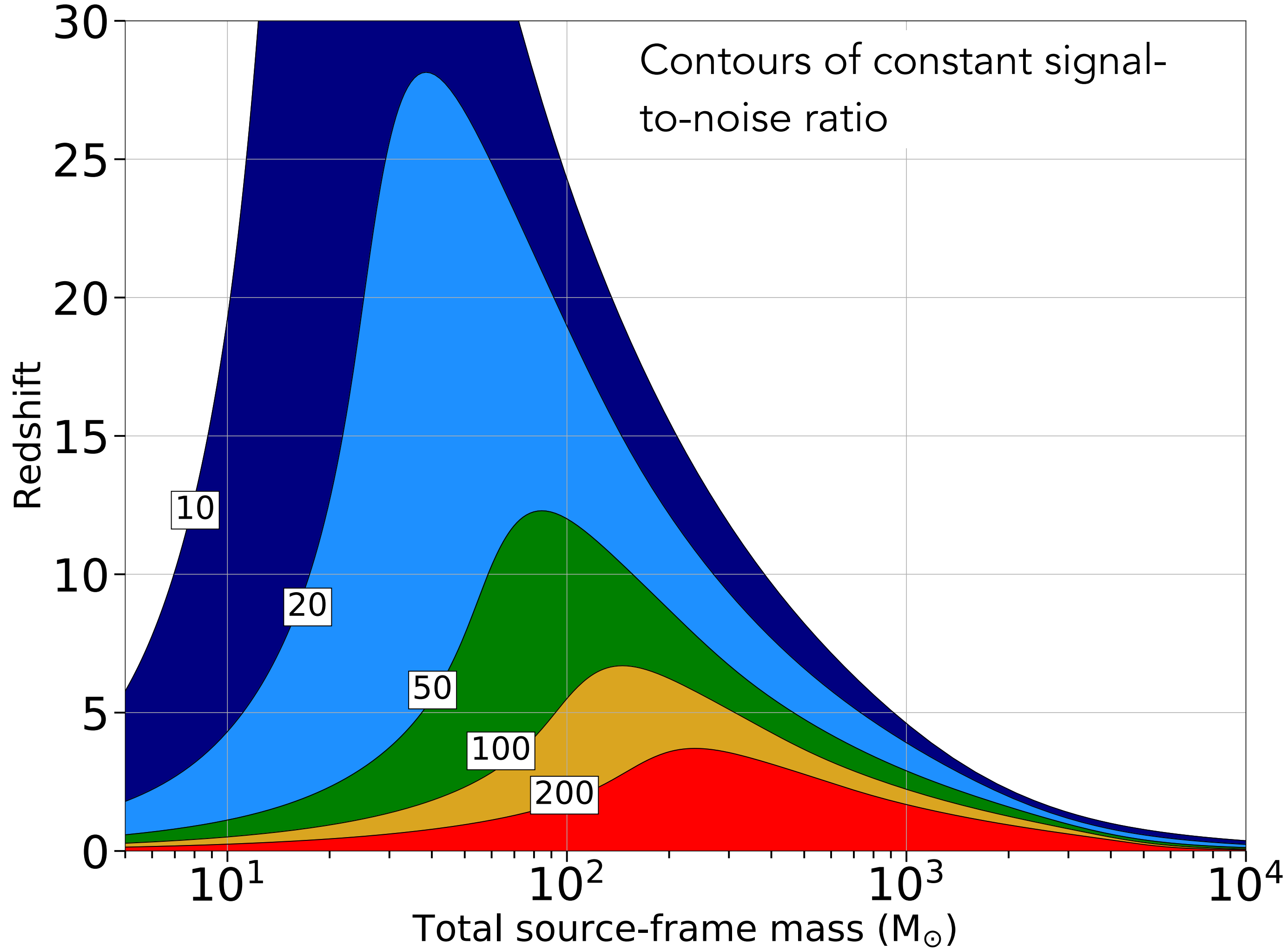
DIRECT CALIBRATION OF CORE COLLAPSE SUPERNOVA IN CLUSTERS

Gupta+, 2019

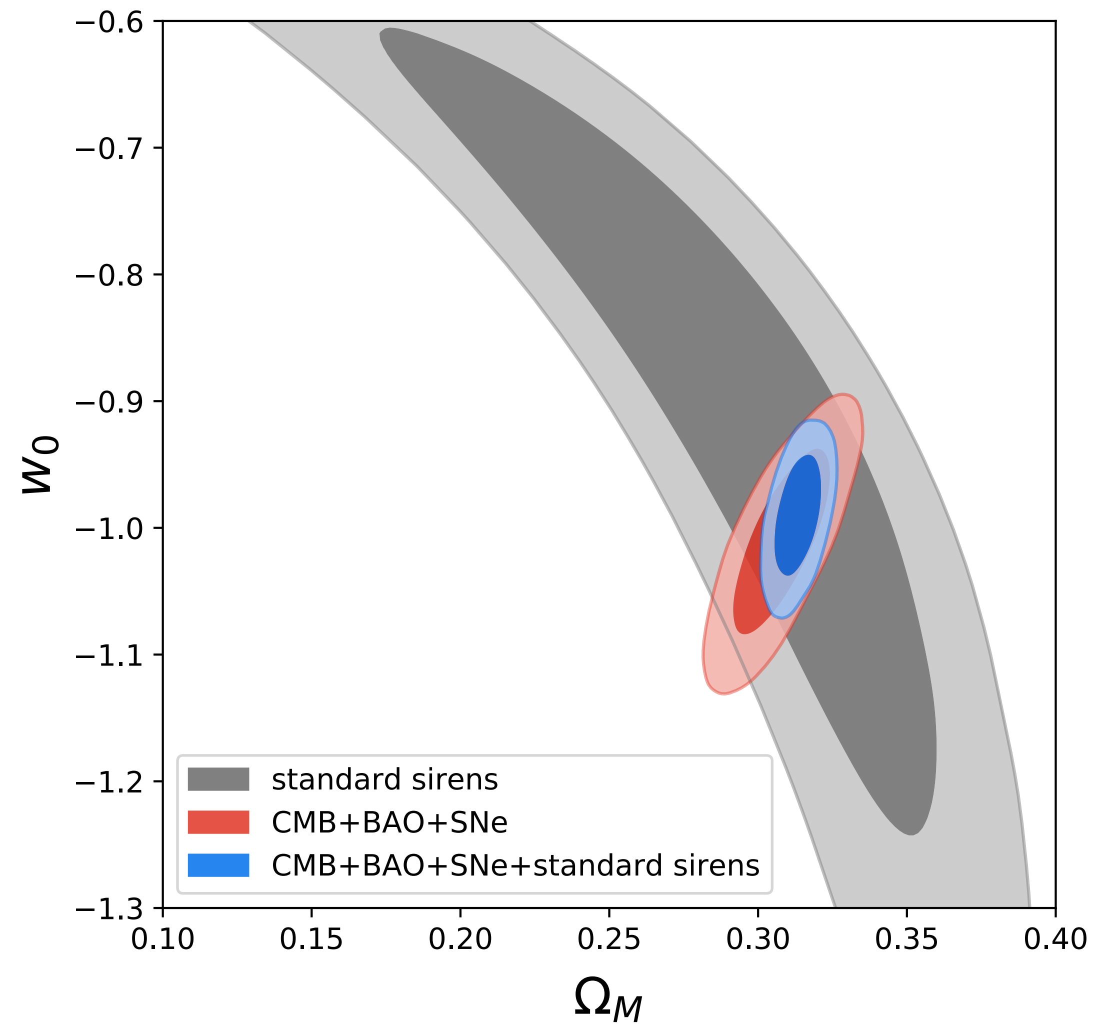


3G NETWORK WILL DETECT MILLIONS OF MERGERS

Credit: Alberto Mangiagli

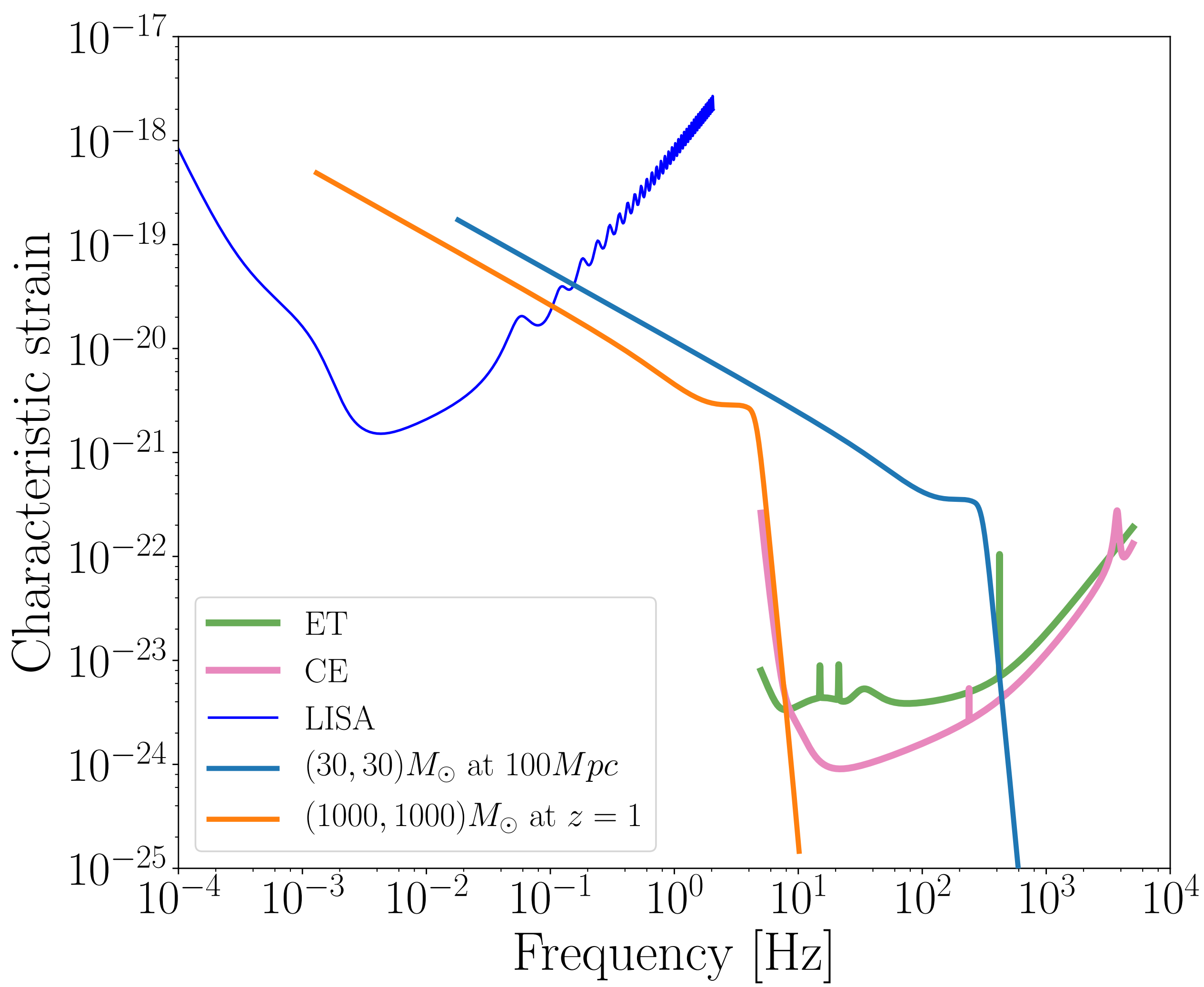


Credit: Michele Maggiore

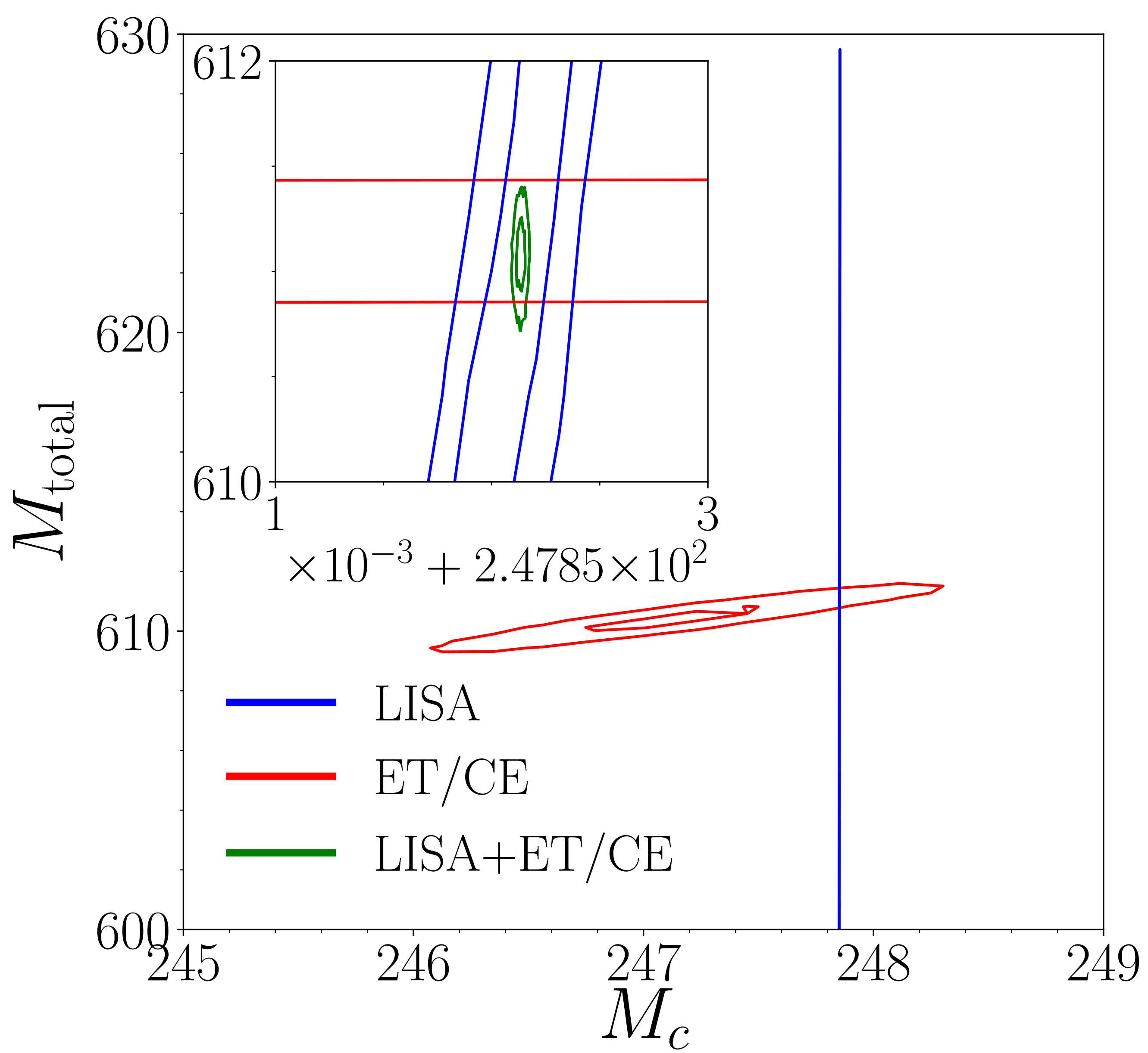


3G network will calibrate nearby supernovae, determine dark energy equation of state and its variation with redshift

MULTIBAND - LISA AND 3G

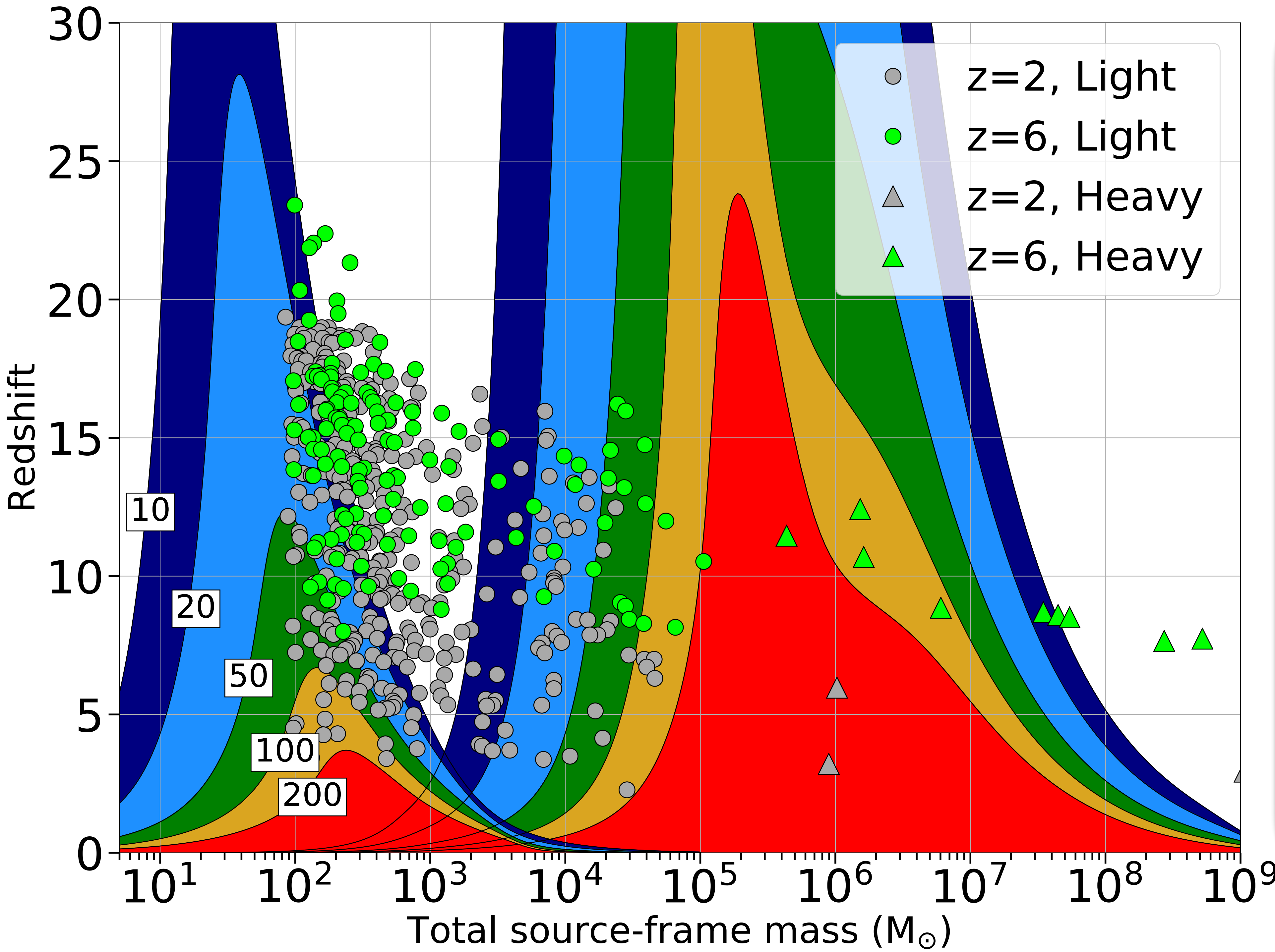


Cutler+ arXiv:1903.04069



Multi-band observations with LISA will help 3G detectors to improve characterization of sources and tests of GR by several orders of magnitude

ORIGIN AND EVOLUTION OF SEED BLACK HOLES



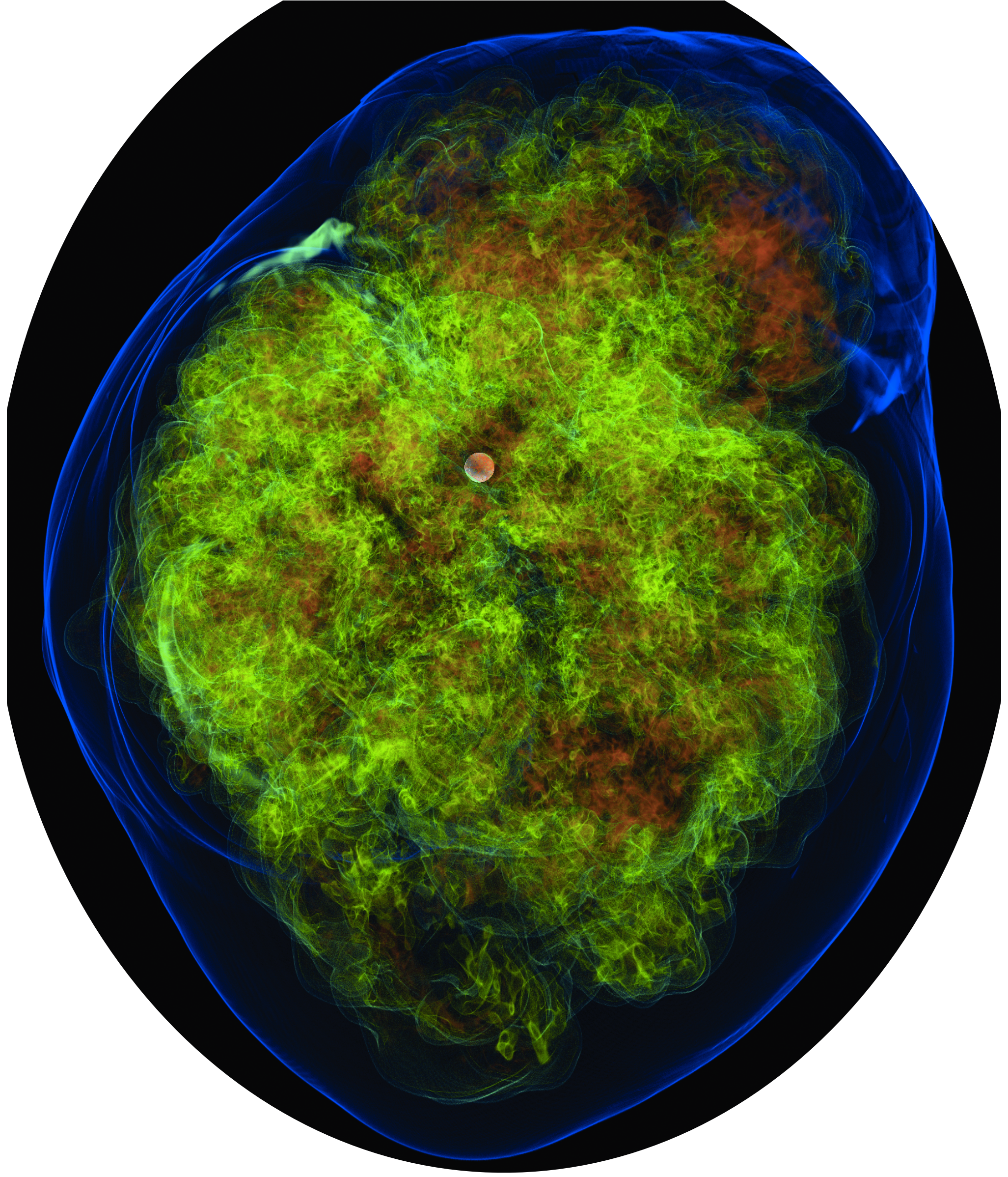
3G + LISA, will characterize every binary black hole merger in the universe, and explore demographics of seed black holes and their growth

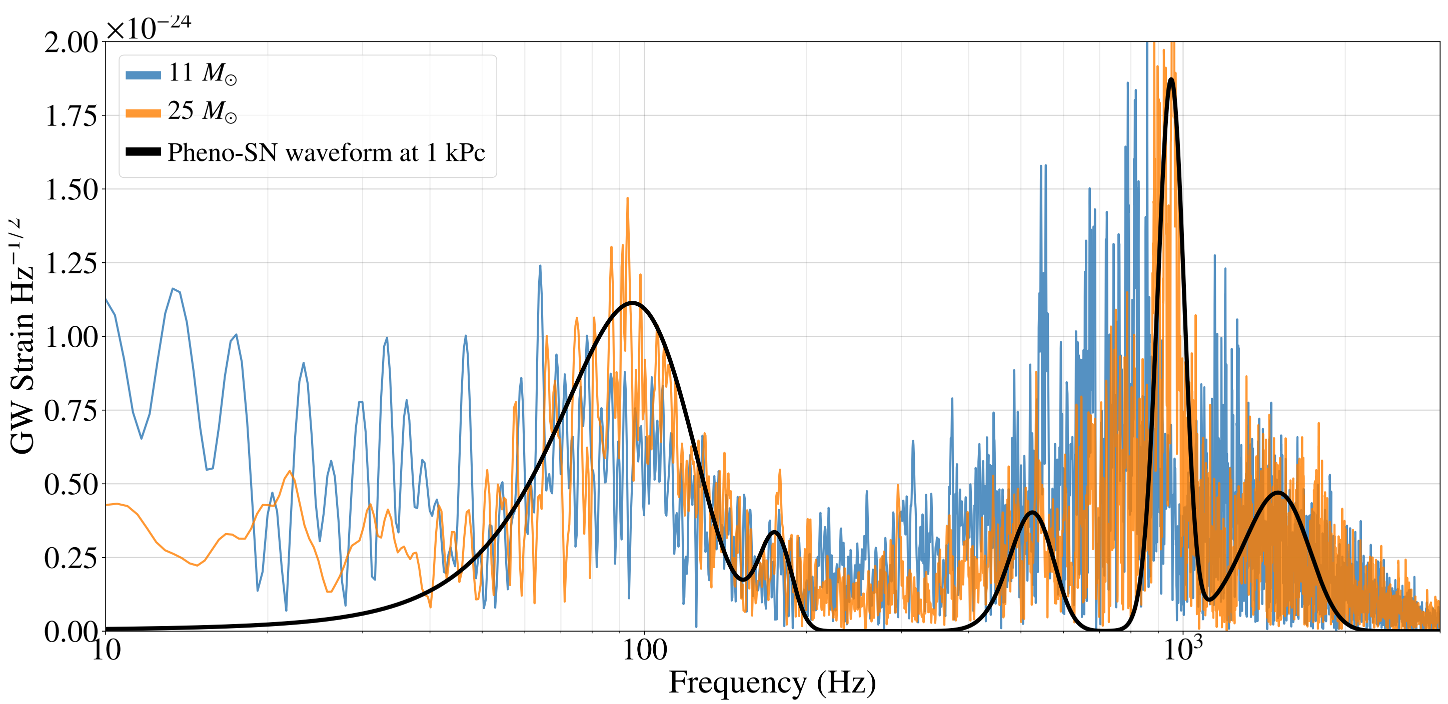
Credit: Alberto Mangiagli

R Valiante+ in preparation

SUPERNOVAE

- signature of physics of supernova
  - progenitor mass
  - proto-NS core oscillation modes
  - core rotation rate
  - mass accretion rate from shock
  - geometry of collapse
- NS equation of state
  - spectrum of GW signal
  - following the phase evolution
- fate of collapse
  - neutron star vs black hole formation
- **3G sensitive to CCSN in the Milky Way, rates 1-2 per century**

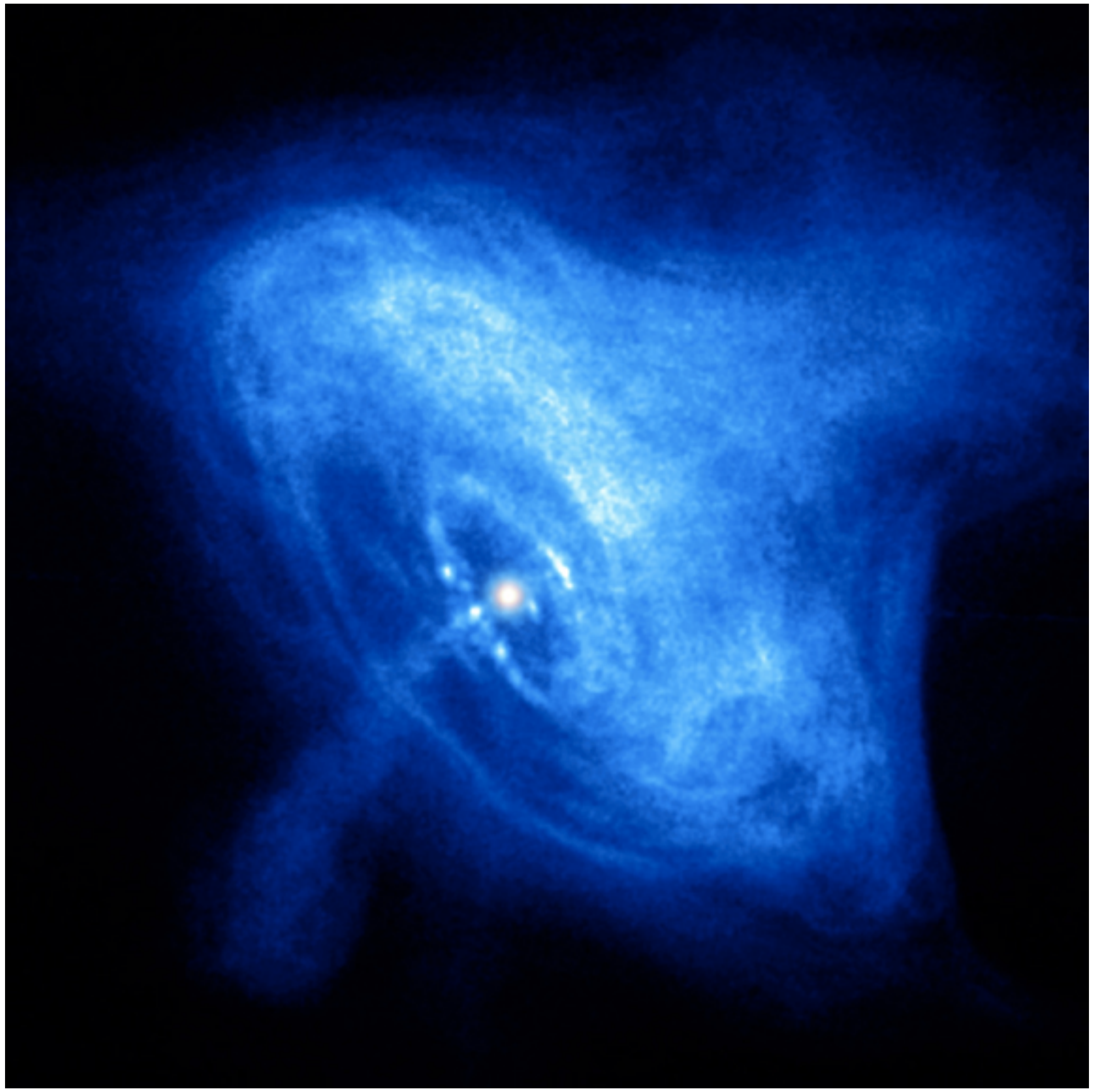




Srivastava+ arXiv:1906.00084

CONTINUOUS WAVES, PULSAR GLITCHES, MAGNETAR FLARES, ...

- continuous wave sources
  - EOS, elasticity (mountains) of phases; deformations and precession
  - microphysics input: transport in cold matter (shear, bulk viscosities), neutrino cooling
  - GR modeling of oscillations, stability and dependence on EoS
  - effect of magnetic fields, spin-evolution, magnetically induced deformations
  - binary systems: dynamics, X-rays, spin-evolution, QPOs



NEUTRON STAR QUAKES

- transients
  - EOS of cold matter, superfluidity for glitches and relaxations, hot-matter in core-collapse
  - microphysics of neutrino interactions in core-collapse, mutual friction in superfluids
  - modelling magnetar oscillations and bursts
  - modeling pulsar glitches, precession, elasticity
- beyond standard model physics GR
  - effects of dark matter particles
  - testing GR with observations of GW
  - modeling phenomena in theories beyond GR

OPPORTUNITY FOR NEW DISCOVERIES

- gravitational window is a completely different observational tool compared to em window
  - experience tells us that each observational window had led to discoveries never imagined before
    - x-ray, radio, infra-red, gamma-ray, cosmic rays, …
- gravitational wave detectors, especially at good sensitivities, should be expected to make new discoveries
  - could lead to new physics that help us understand missing links in fundamental physics and astrophysics

CHALLENGES AND QUESTIONS

- origin and evolution of compact binary mergers?
  - can primordial black holes account for LIGO-Virgo black holes?
- can stellar evolution produce black holes in the mass gap?
  - low- and high-mass gaps
- why are effective spins close to zero?
  - we have greater sensitivity to higher spins
- are any of our events lensed?
- what are the different components in kilonova?
- what is the origin and evolution of supermassive black holes?
- are there any systematics in the luminosities of type Ia SNe?
- how large are NS ellipticities?