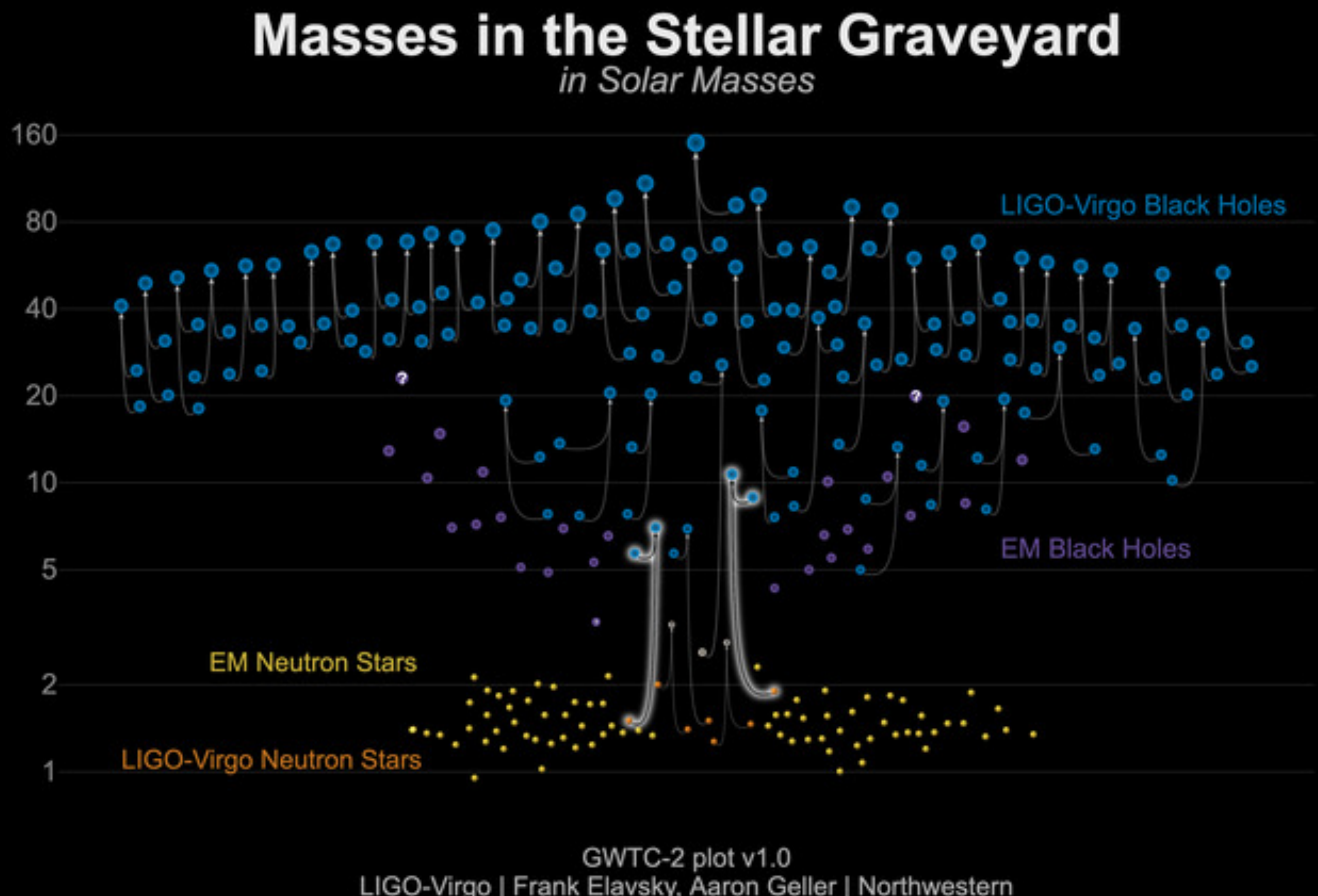
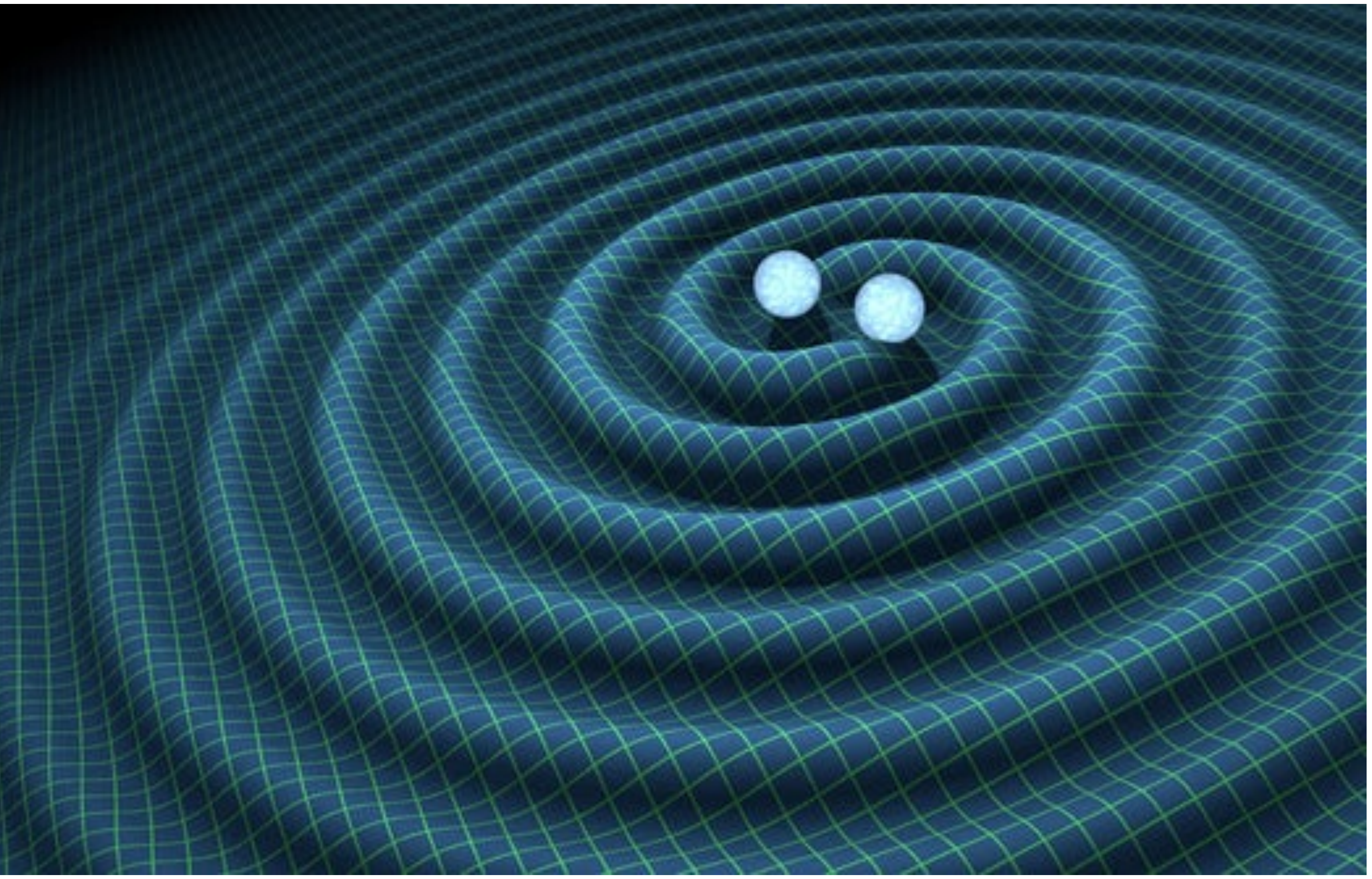
(ASTRO)PHYSICAL IMPLICATIONS OF THE O3 GRAVITATIONAL WAVE DETECTIONS



Astrid Lamberts
Observatoire de la Côte d'Azur
On behalf of the LVK

WHAT IS A GRAVITATIONAL WAVE?



"Ripples in spacetime"

Changes relative distances

Changes are tiny ($dl/l = h \sim 10^{-20}$)

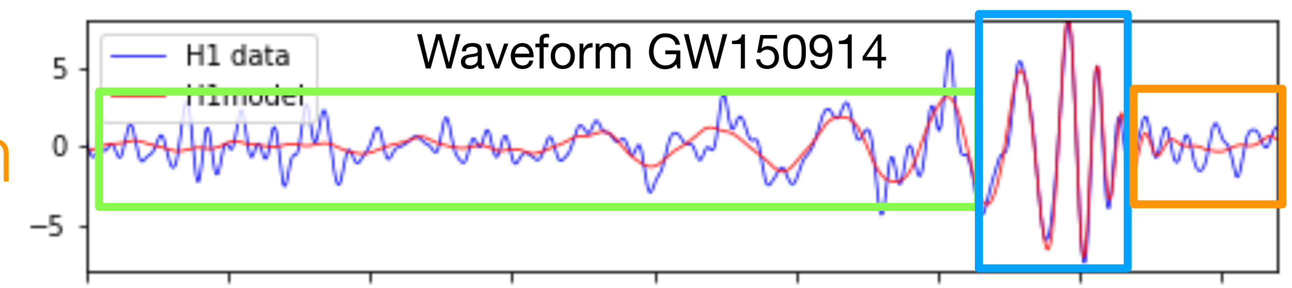
Hard to detect: 100 yrs between prediction and direct observation -> needs extreme phenomena

Requires quadrupole moment -> binaries…

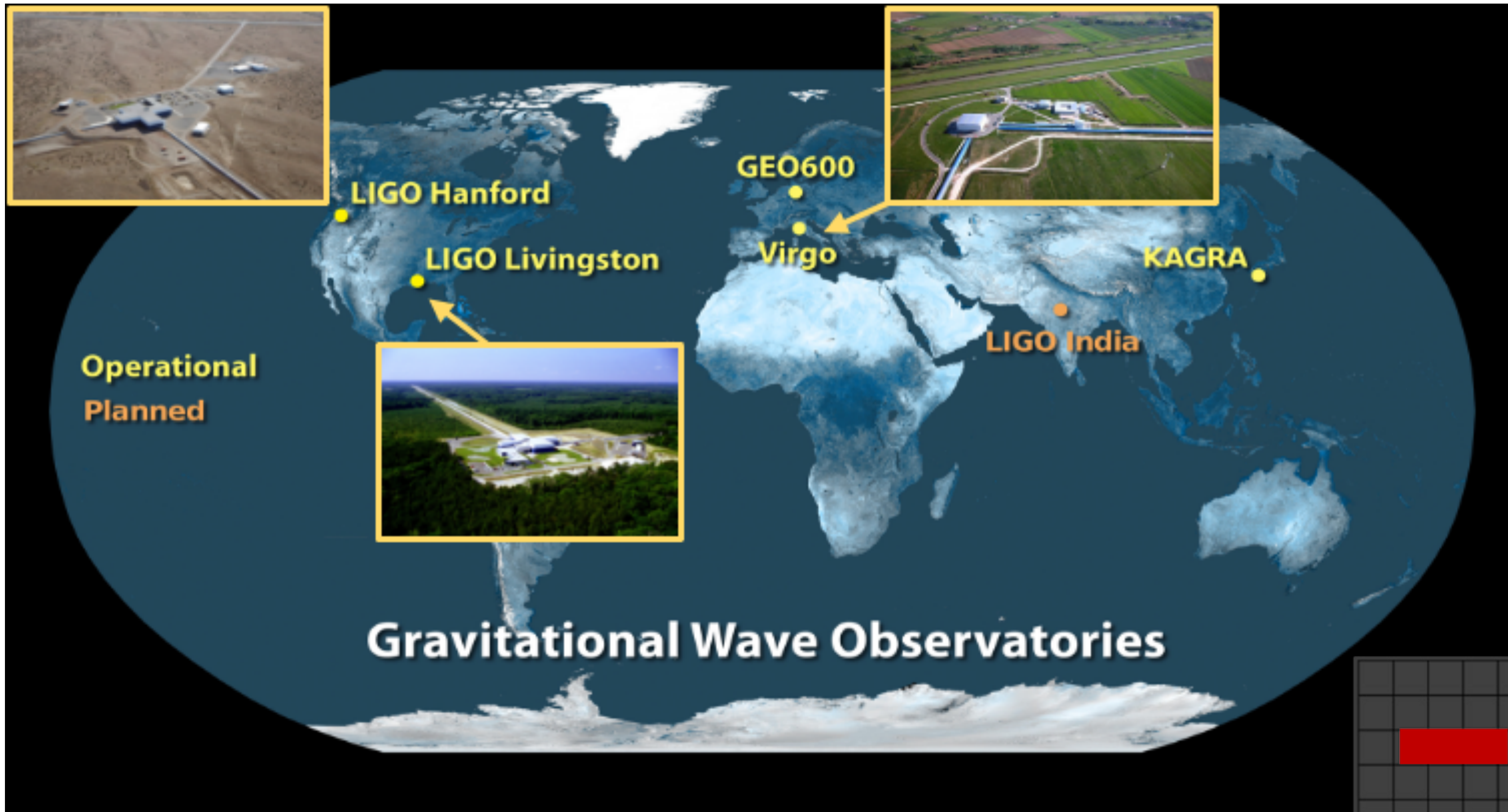
->Compact binaries: black holes, neutron stars, white dwarfs

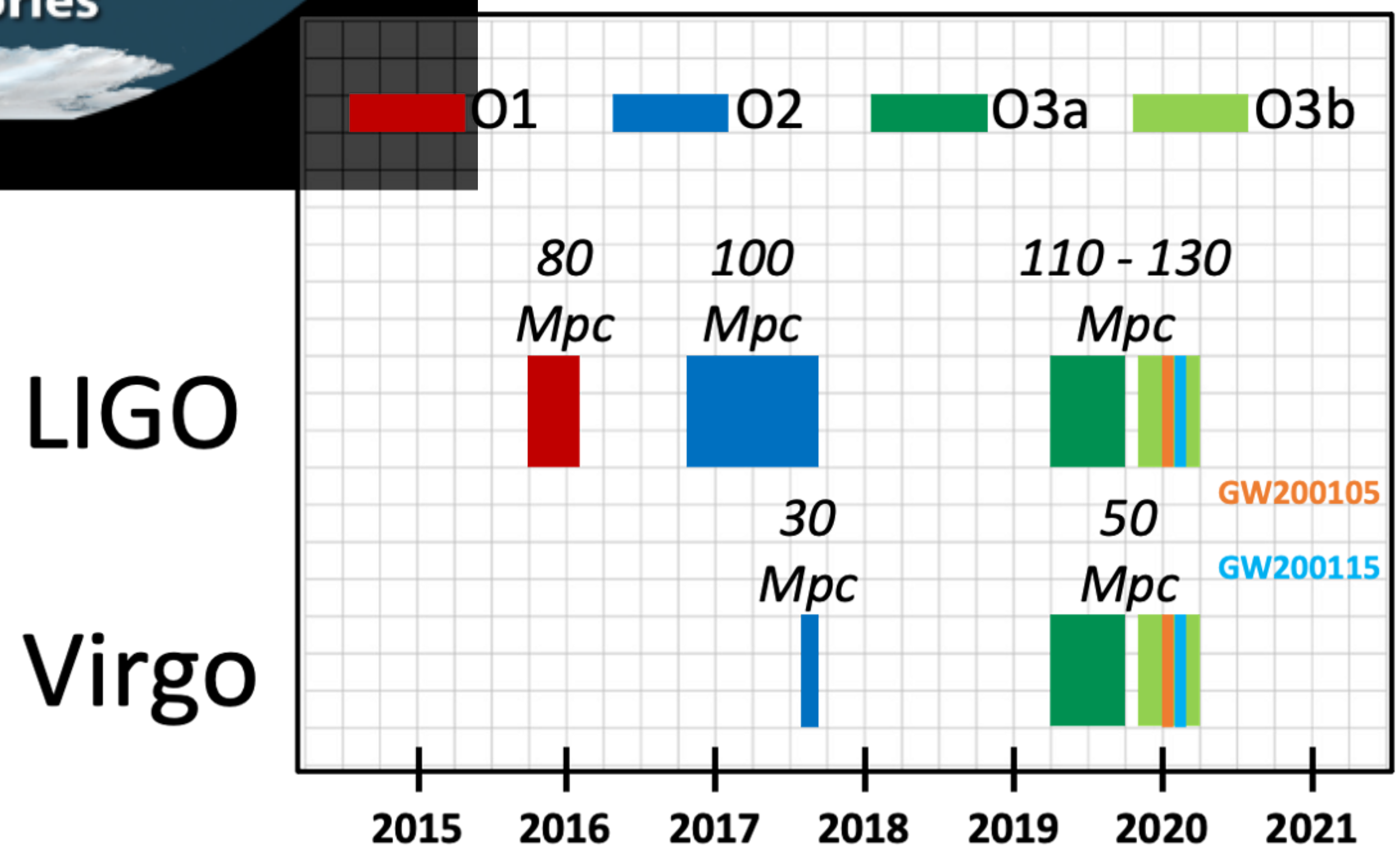
$f_{GW} = 2 \times f_{orb}$ -> lower mass = higher frequency

3 phases: inspiral, merger, ringdown



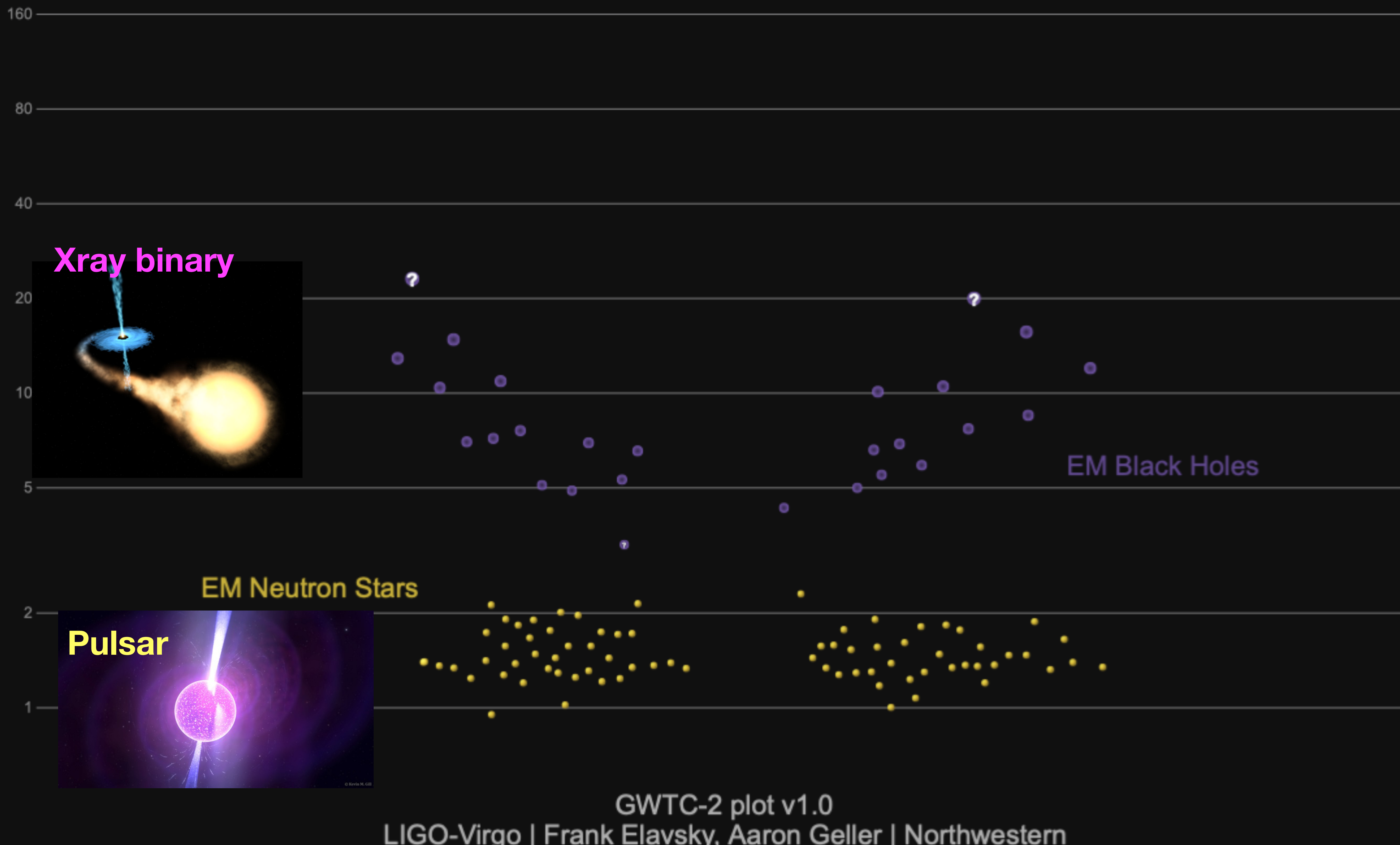
NETWORK OF DETECTORS





O3 : April 2019 - March 2020
LIGO Hanford, LIGO Livingston, Virgo

BEFORE GRAVITATIONAL WAVES



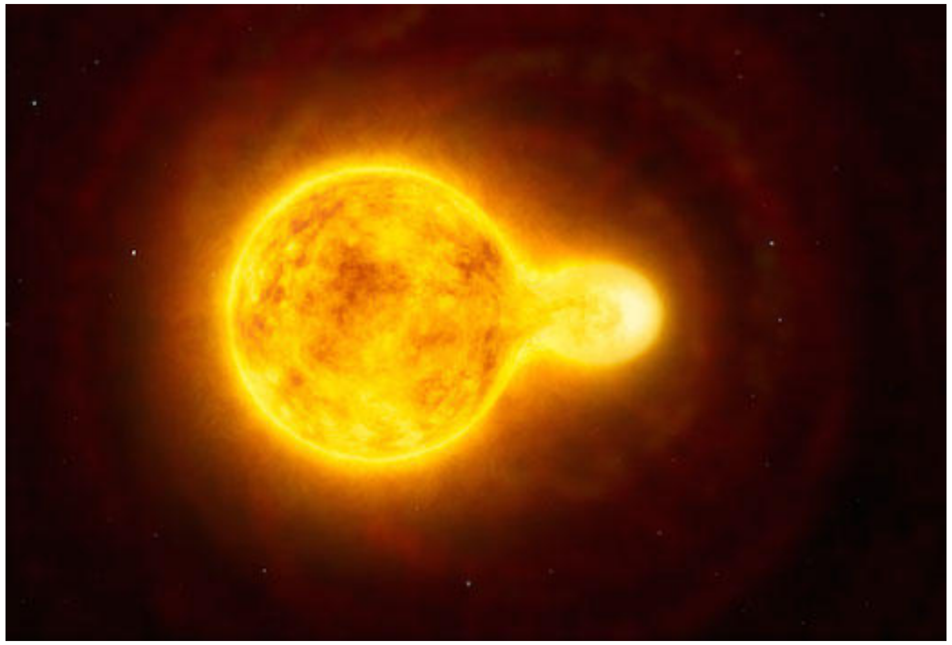
BLACK HOLES AND NEUTRON STARS: COMPACT OBJECTS

Compact objects: unique way to study massive stars (1 out of 10 000 stars)

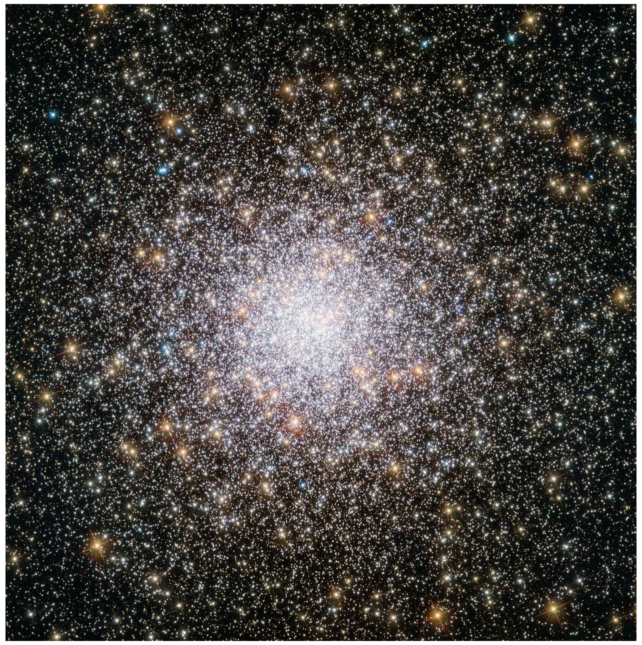
Stars with ~8 to ~20 $M_\odot$ → neutron stars

Stars above ~20 $M_\odot$ → black holes

Most massive stars form in pairs, triples or dense groups => many interactions

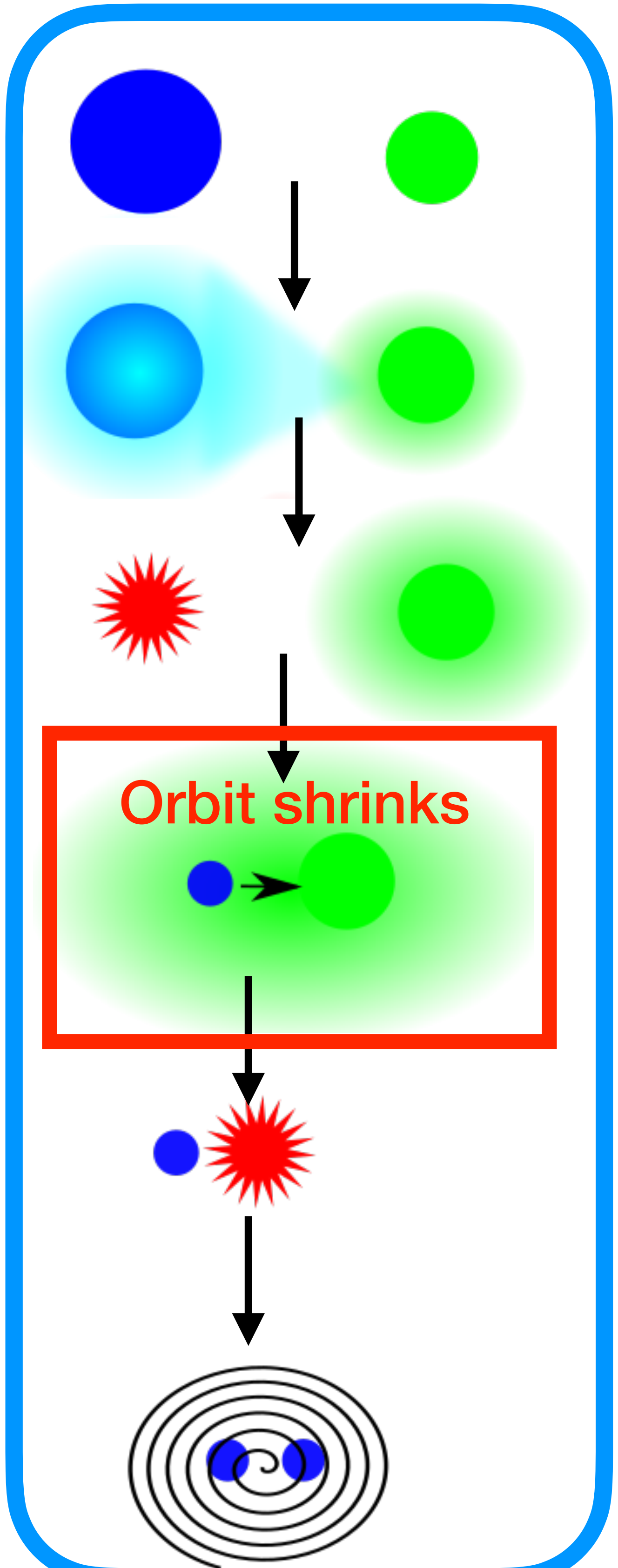


Interacting binary HR5171 Credit ESO



Cluster NGC 362 Credit: ESA/Hubble& NASA

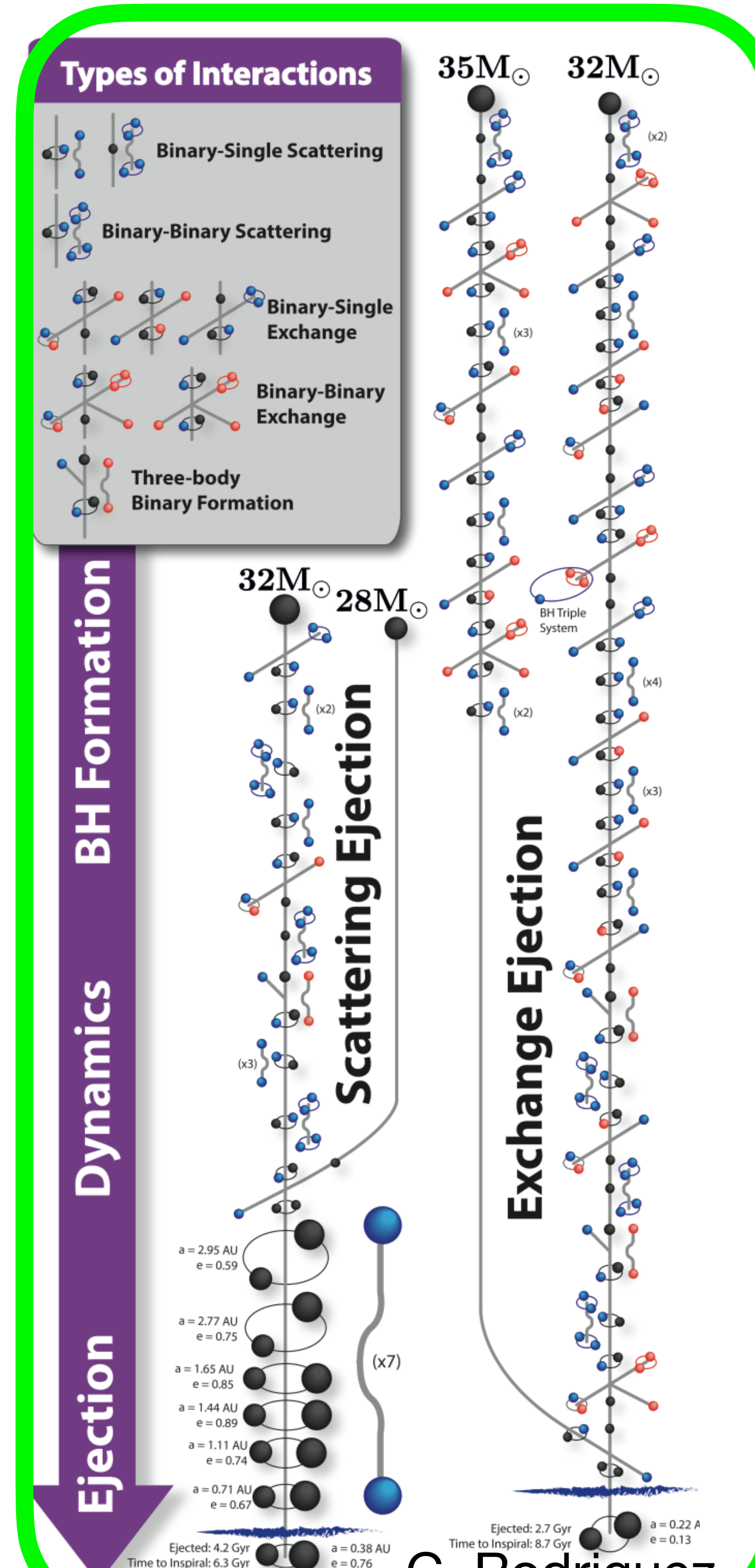
HOW DO COMPACT BINARIES FORM?



Isolated binary formation:
Open questions: mass transfer, supernova explosions, mass loss

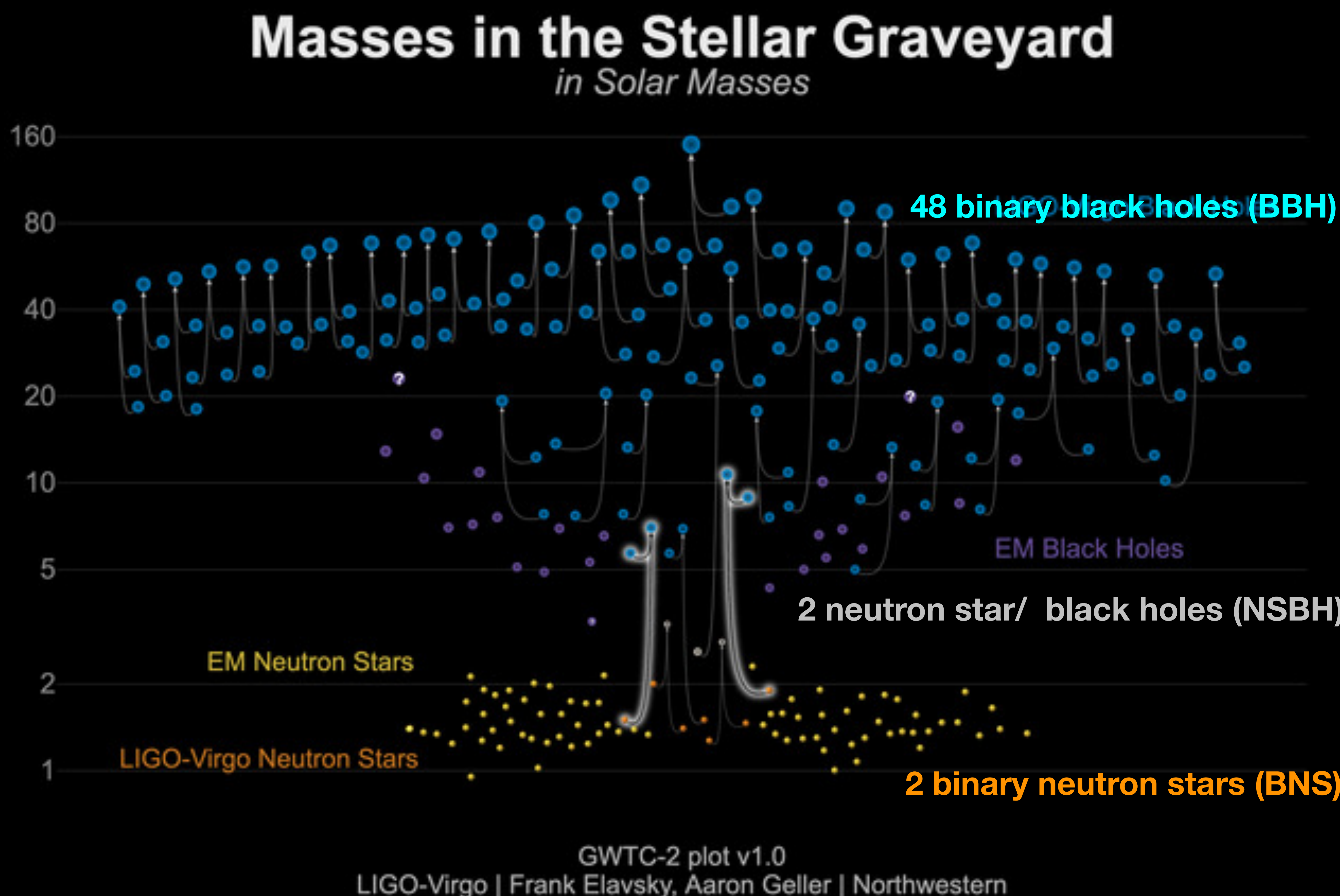
Dynamical formation (clusters):
Open questions: initial conditions, Supernovae, mass loss, dynamics

Others: AGN disks, triples, nuclear star clusters

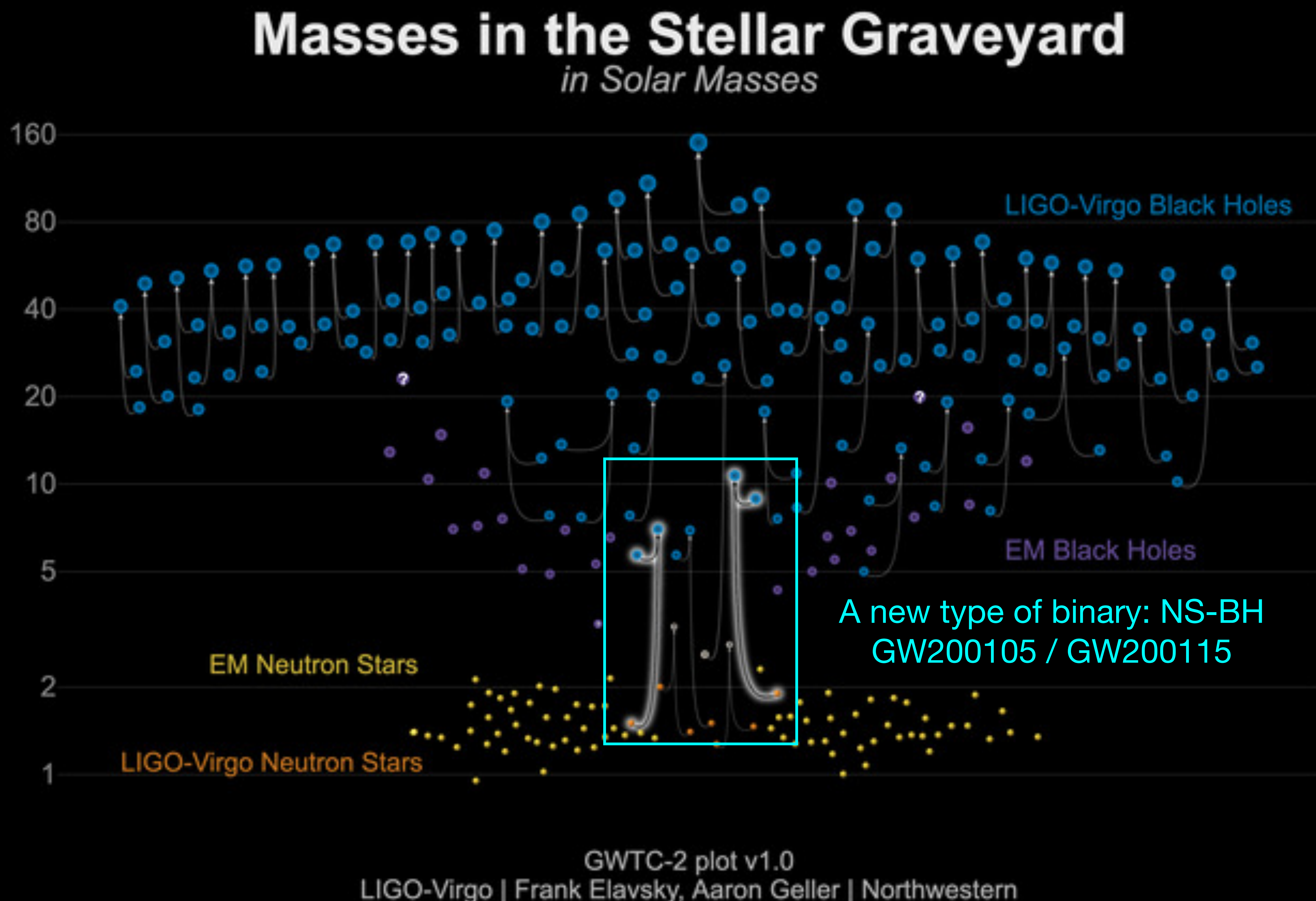


C. Rodriguez

ABOUT 50 NEW PAIRS (GWTC-2)



FIRST NEUTRON STAR BLACK HOLE MERGERS

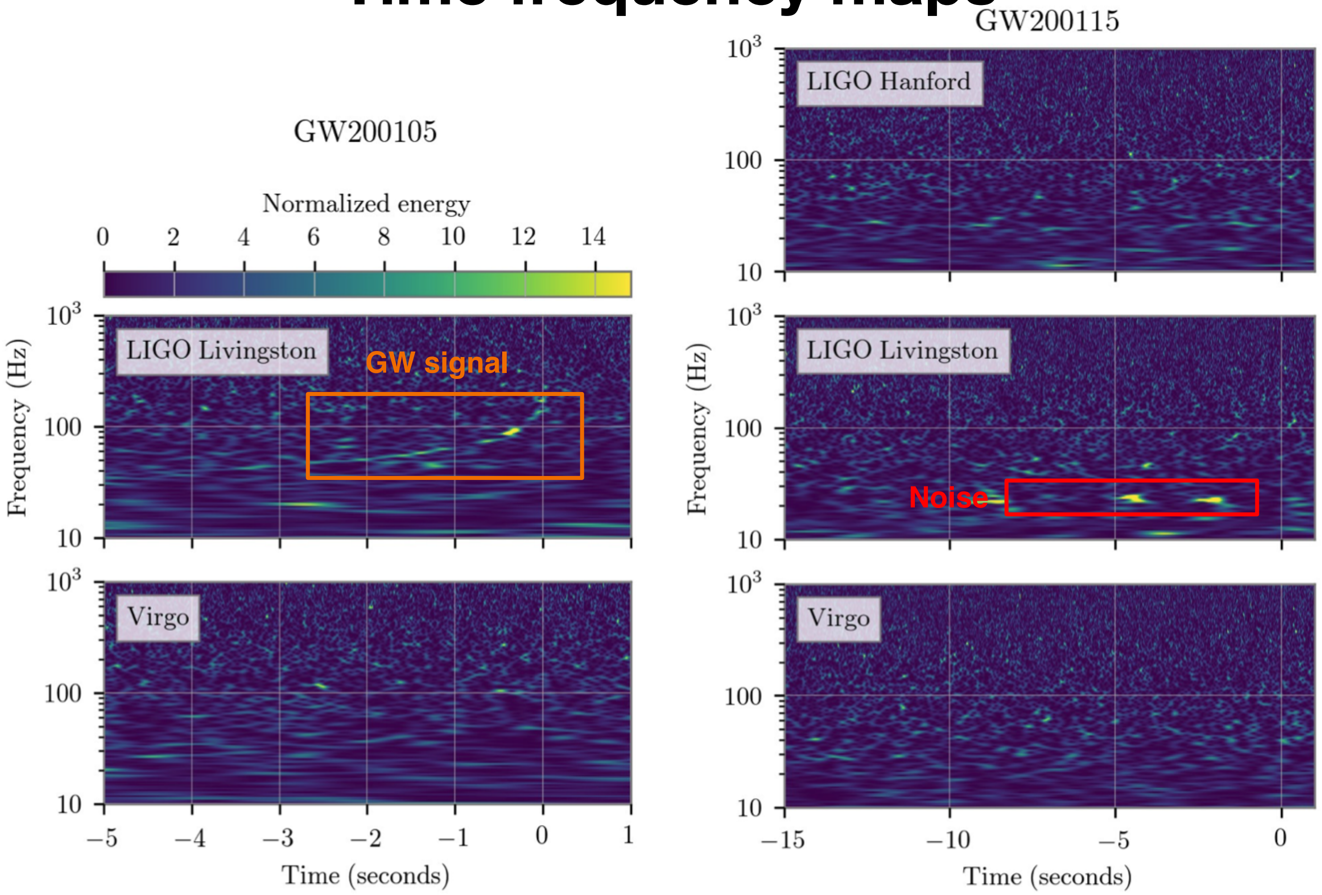


DETECTING THE FIRST NS-BH

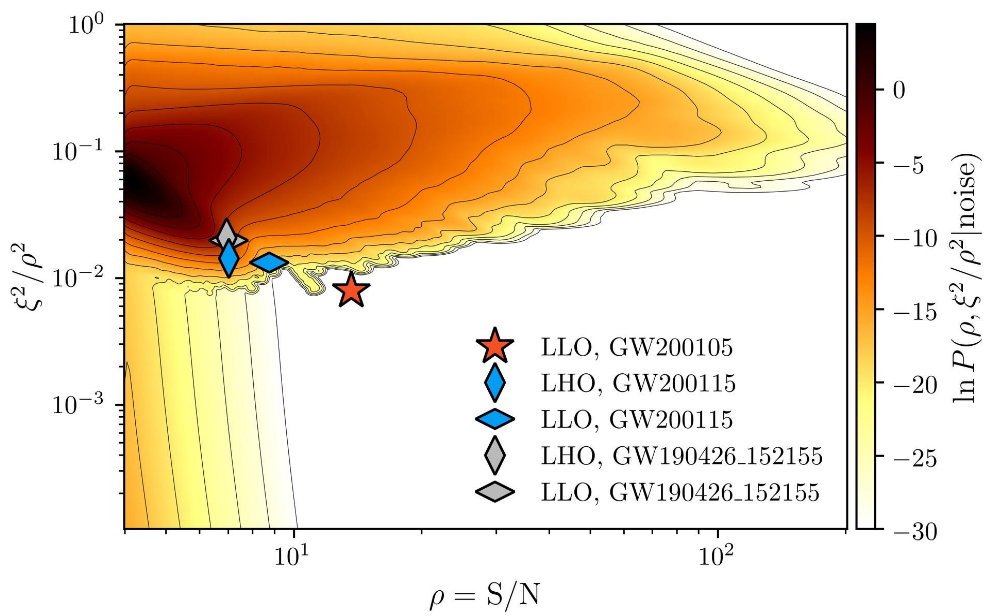
Searches based on matched filtering of template bank

Noise dominated detector: coincidence between detectors provides confidence

Time frequency maps



Trigger wrt background



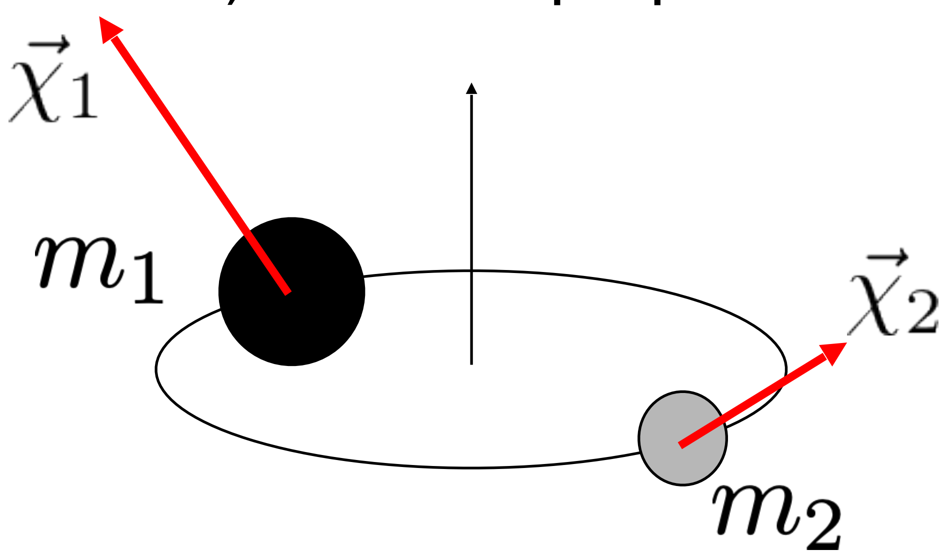
First NSBH: only one detector…

But event clearly stands out from background

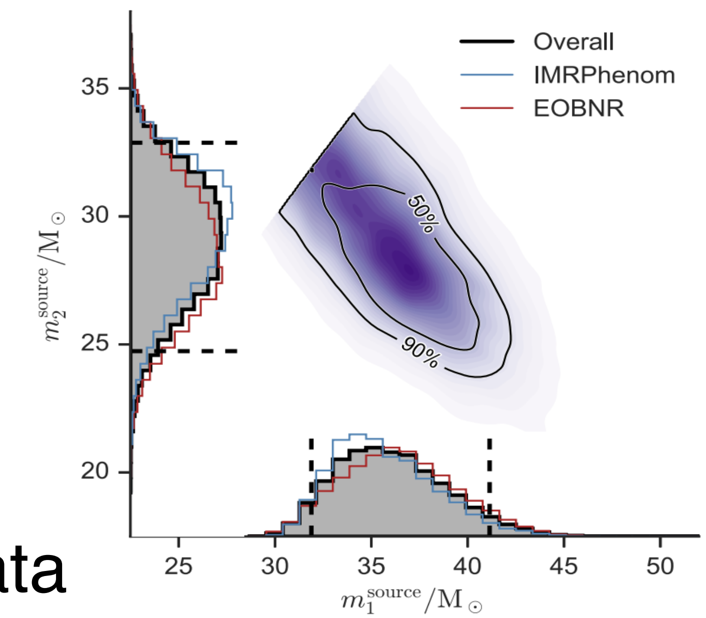
CHARACTERIZING GW DETECTIONS

Bayesian inference of properties (masses, spins, distance…)

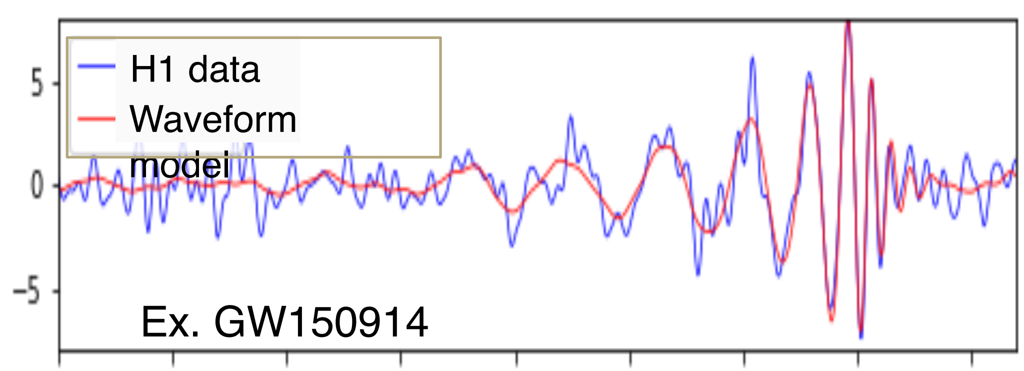
1) Binaries' properties



3) Find regions of good agreement



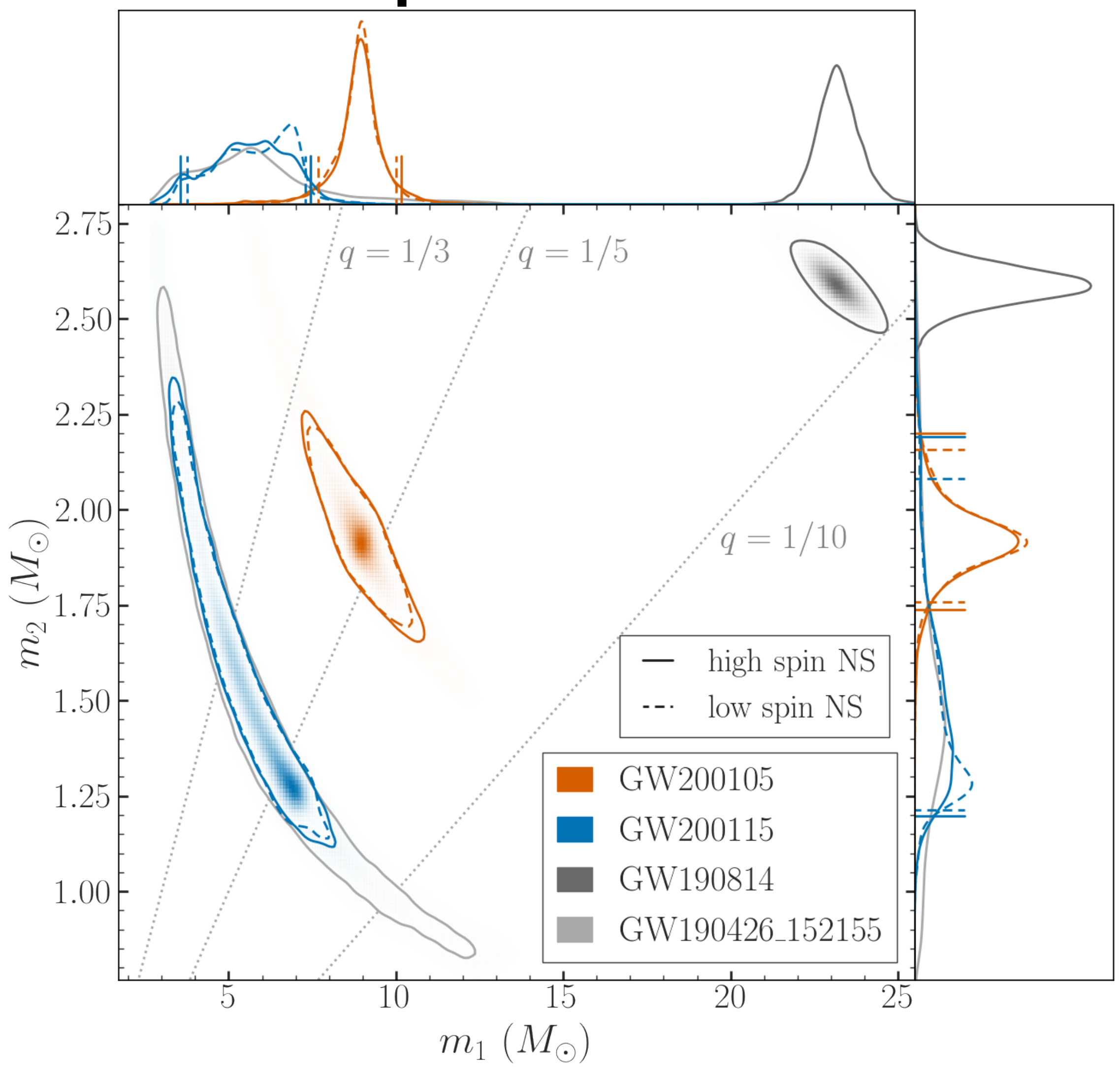
2) Compare mock waveforms with data



Complex and computationally expensive process

MASSES OF BINARY COMPONENTS

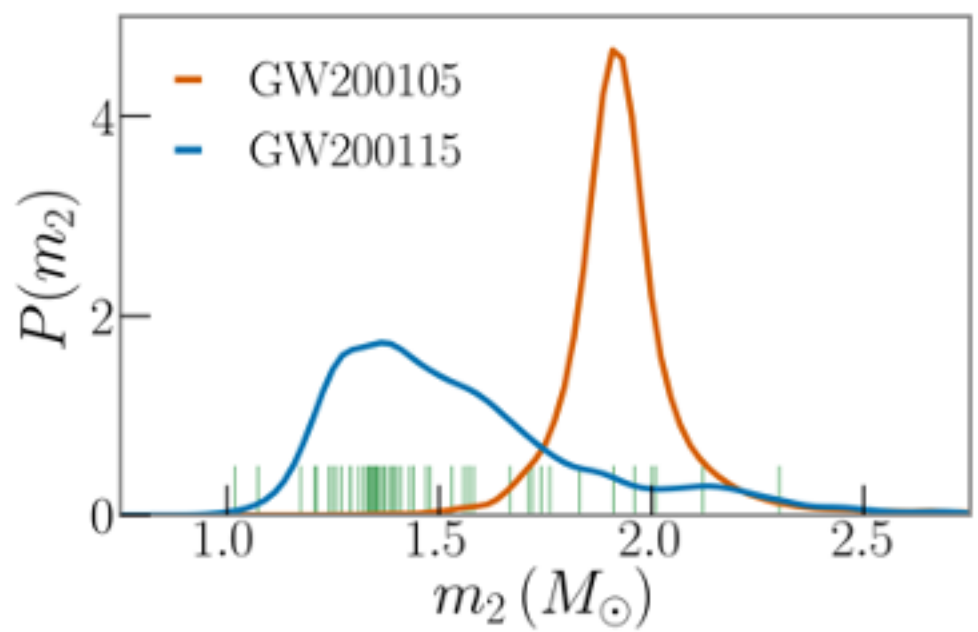
Component masses



	m_1	m_2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

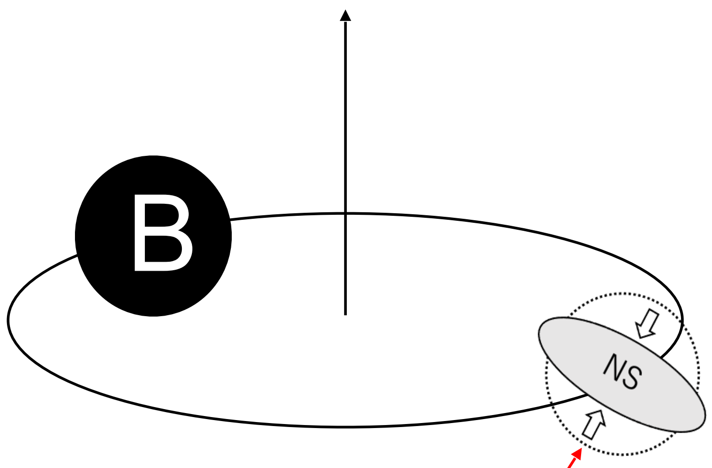
First proof of existence of NS-BH binaries

Comparison with known NS

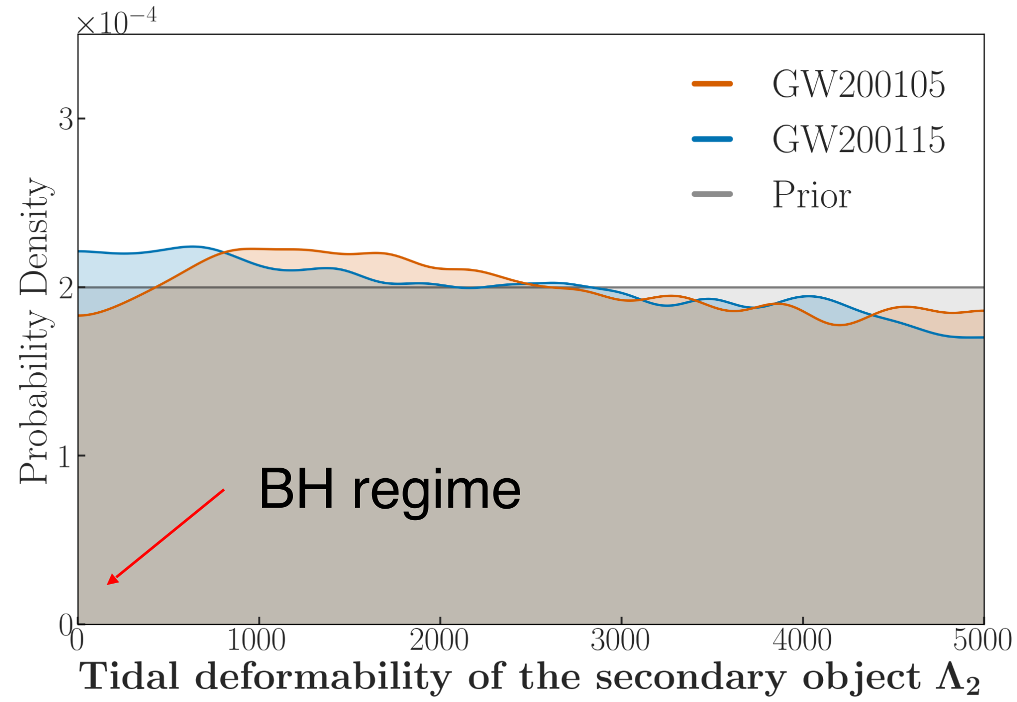


2 populations of NS?
Consistent with EM observations

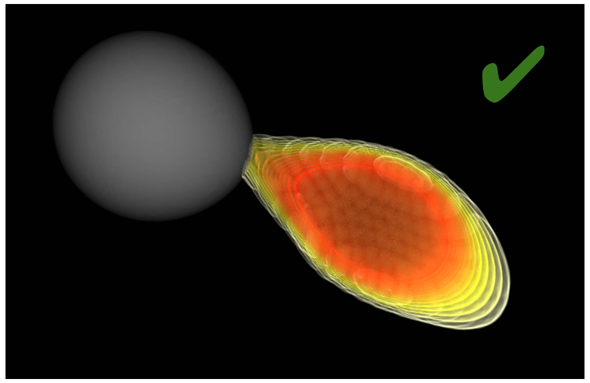
PROVING THE PRESENCE OF NS

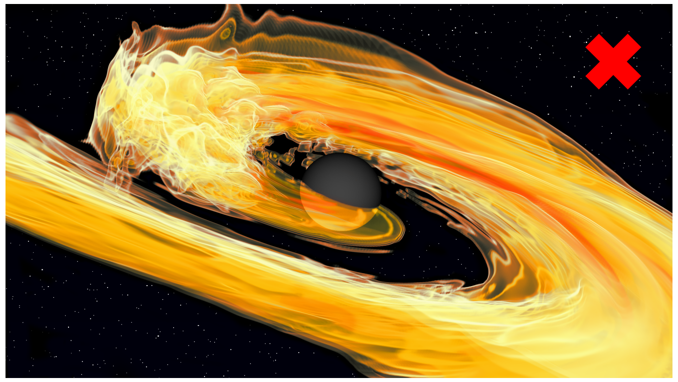


Tidal deformation:
dissipates energy,
changes inspiral rate



No information recovered from GWs (expected)





No EM counterpart (expected)

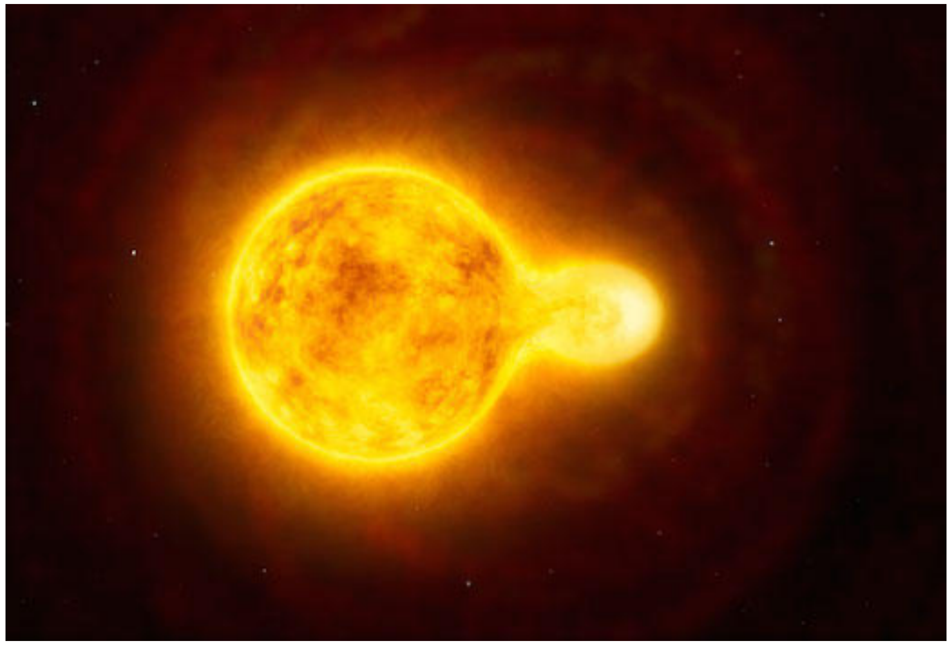
BUT ~95% probability of NS by comparison with known NS masses

ASTROPHYSICAL IMPLICATIONS

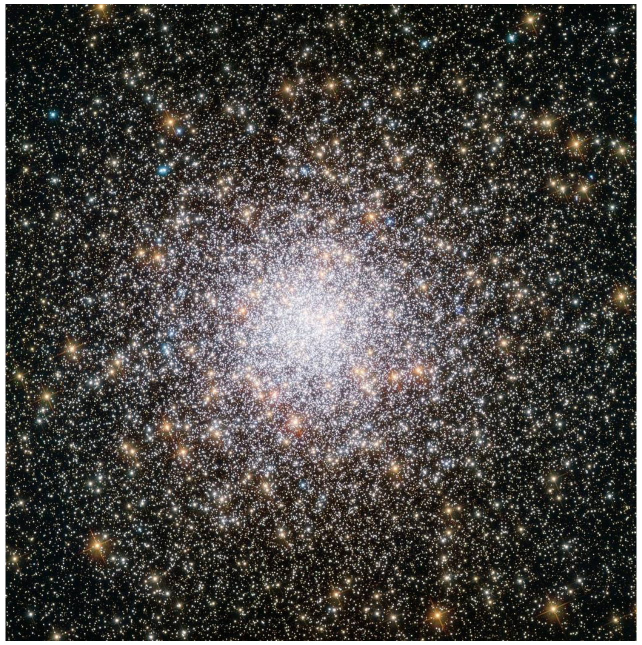
First *empirical inferrence* of merger rate: 12-242 Gpc^{-3} yr^{-1}

+mass + spin measurement

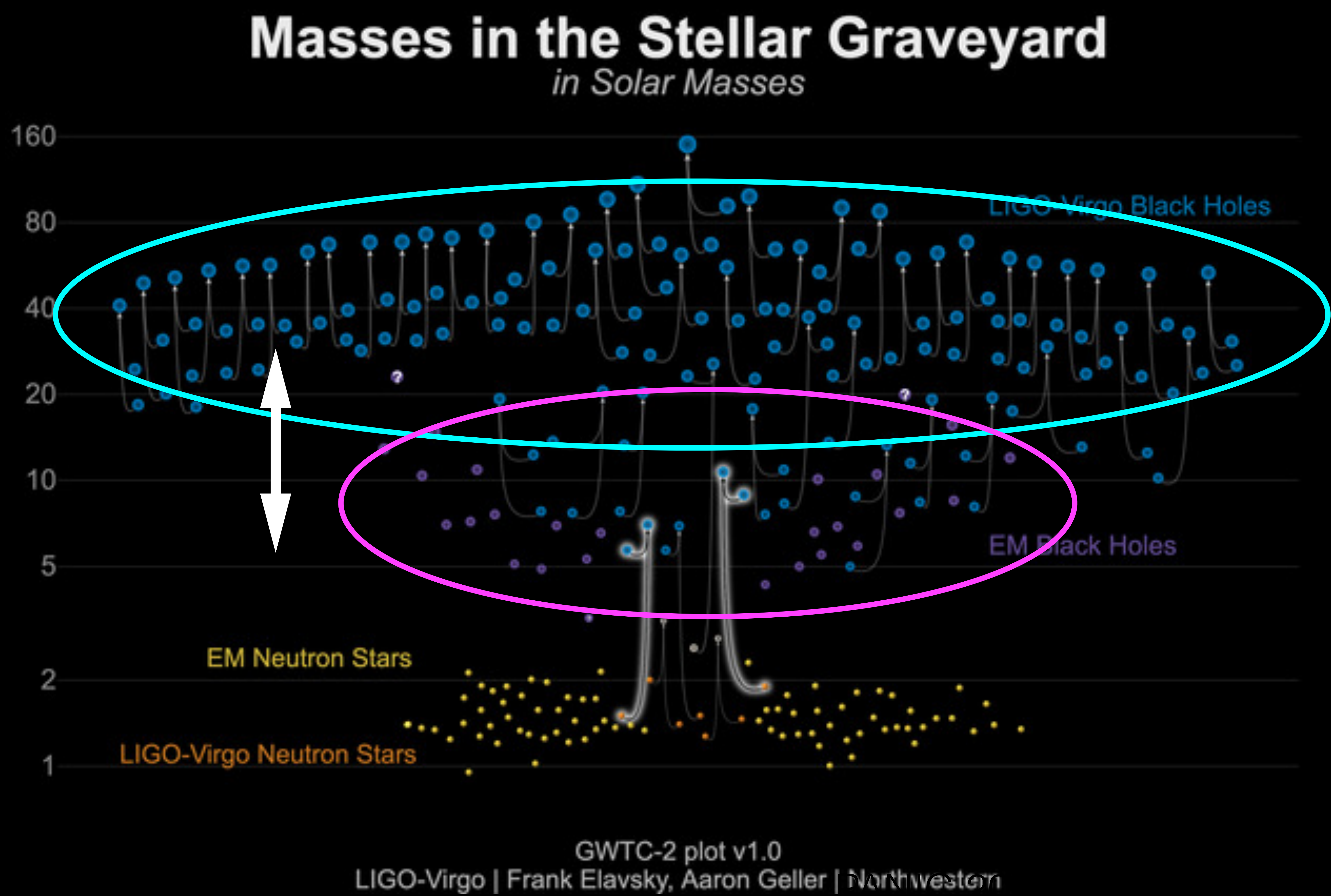
Formation channel?



Binary evolution possible
Globular cluster unlikely
Other cluster environments possible

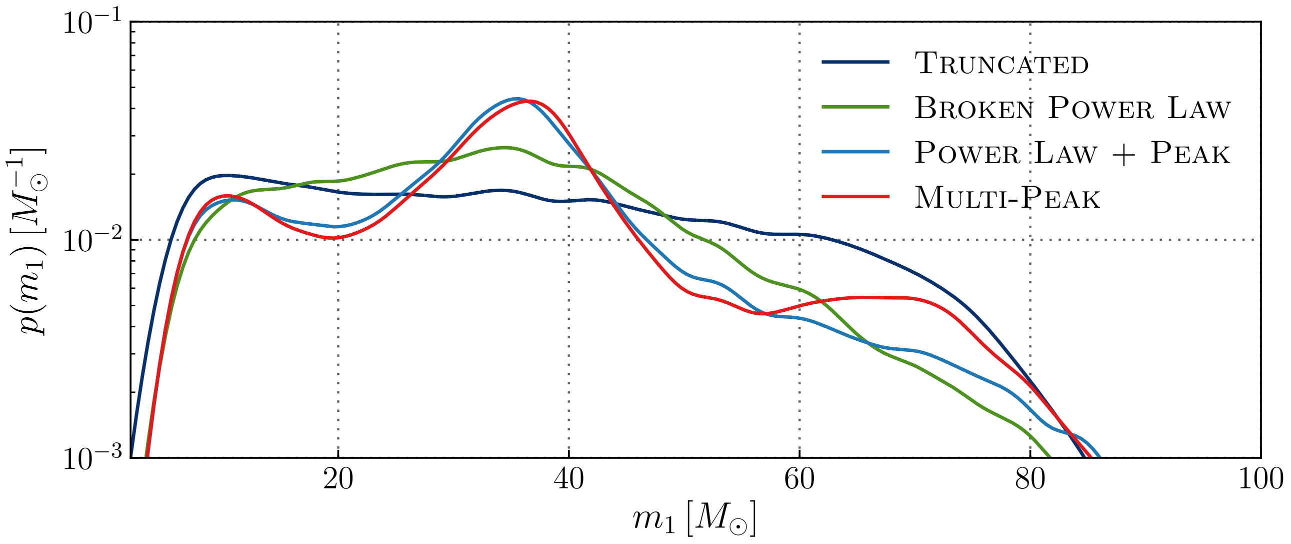


ABOUT 50 NEW PAIRS (GWTC-2)

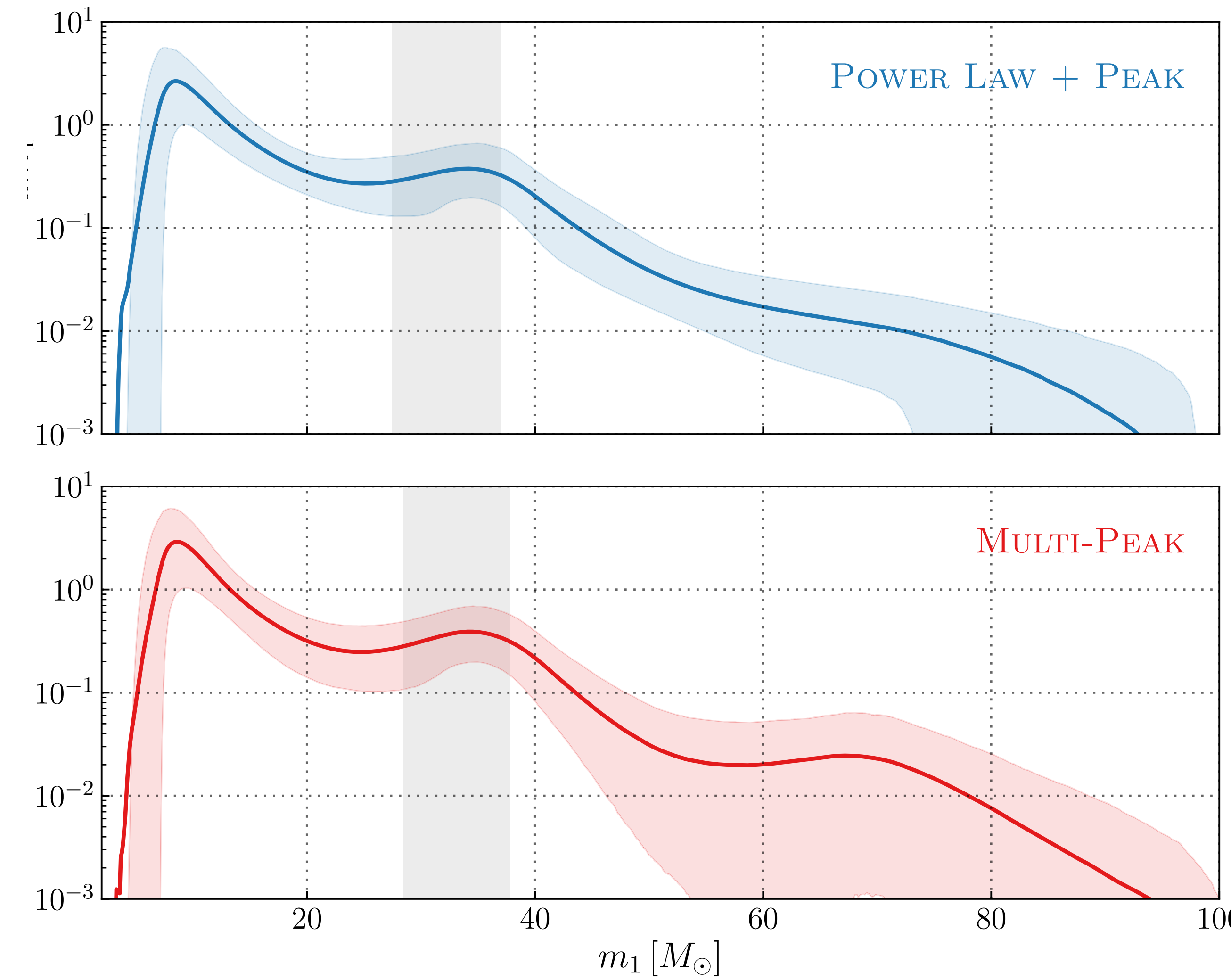


REFINED MASS SPECTRUM

GWTC-2: observed mass spectrum



GWTC-2: inferred mass spectrum



O3a

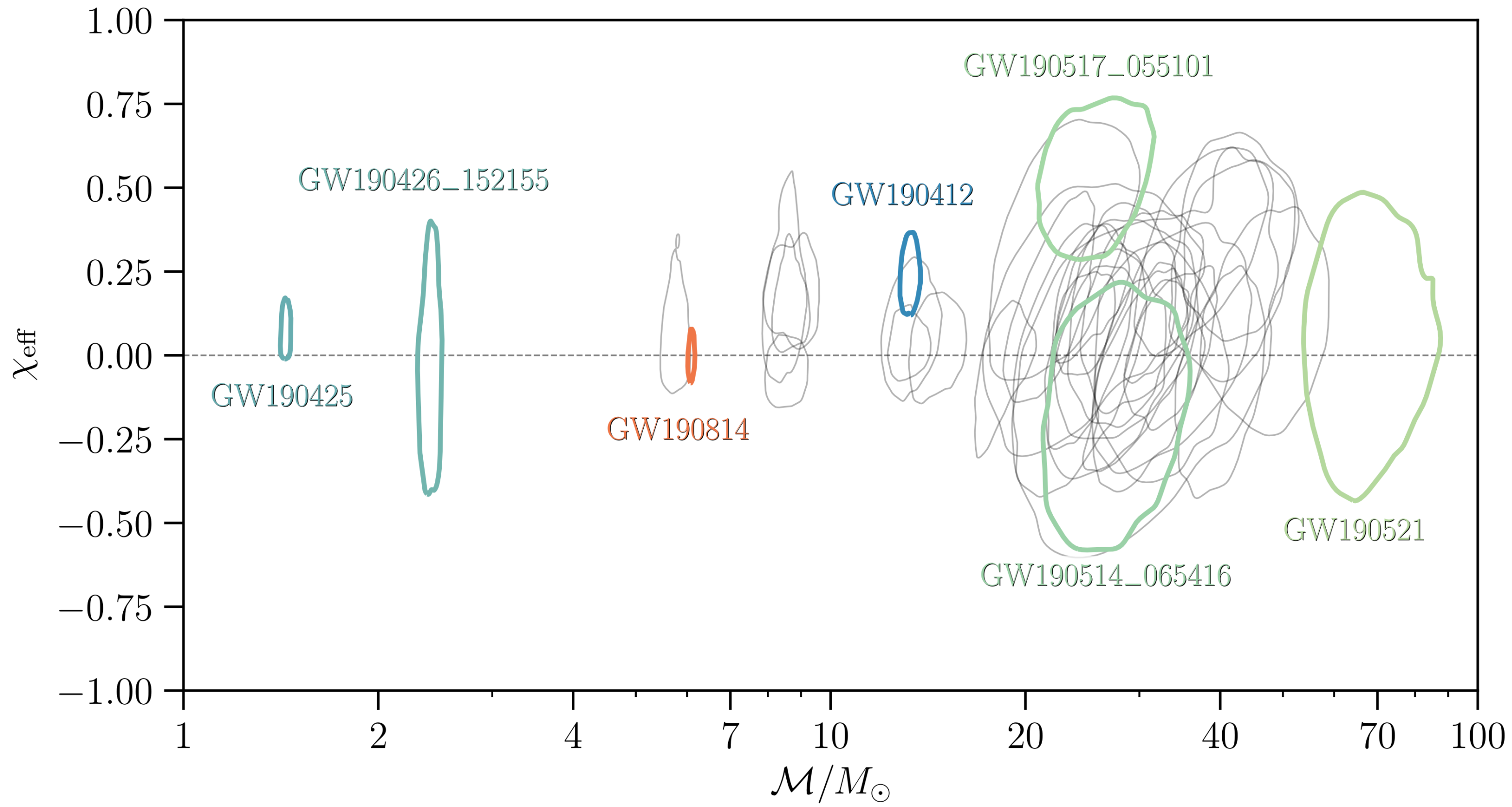
Observed mass spectrum

- Peak 35-40 Msun
- Decrease >60 Msun
- Cutoff <8 Msun
- > supernova physics? Environmental effects?

SPINS

Spin alignment wrt orbit: possibly strong indicator of formation channel
difficult measurement
many theoretical uncertainties

Spin aligned with orbit versus M_{chirp} in GWTC-2

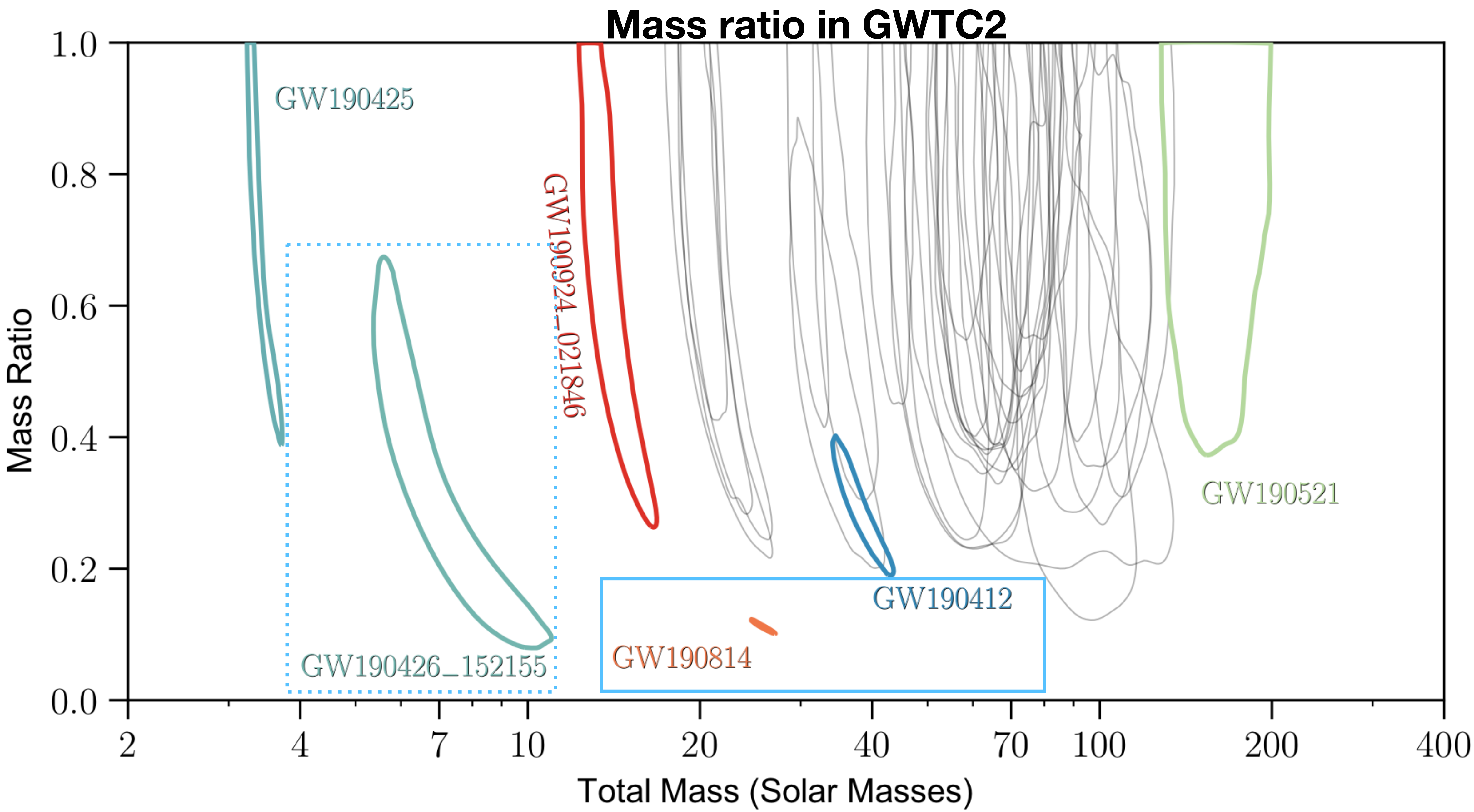


- Some systems are mis(anti)-aligned: challenge for binary channel

- Some systems have non-zero aligned spin

=> (at least) two formation channels?

EQUAL MASSES PREFERRED, SOME UNEQUAL MASSES

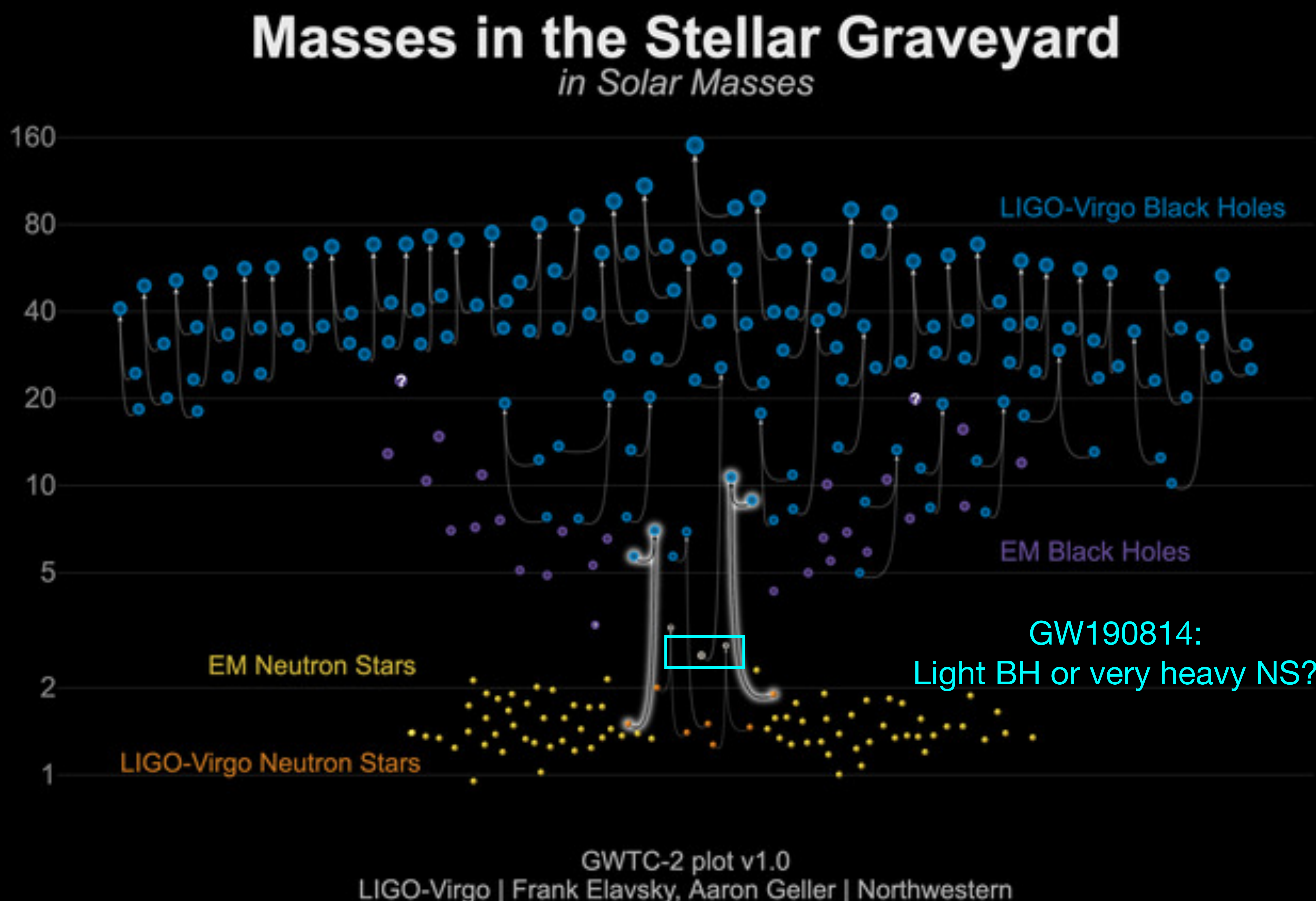


First systems with definitely unequal masses, consistent with theoretical models and other detections

Detection of higher order harmonics (breaks distance/inclination degeneracy)

no inconsistency with General Relavity

A MASS GAP OBJECT?



GW190814: 2.3 SOLAR MASS OBJECT

Mass gap: Observational lack of objects between 3 and 5 Msun- > what is it?

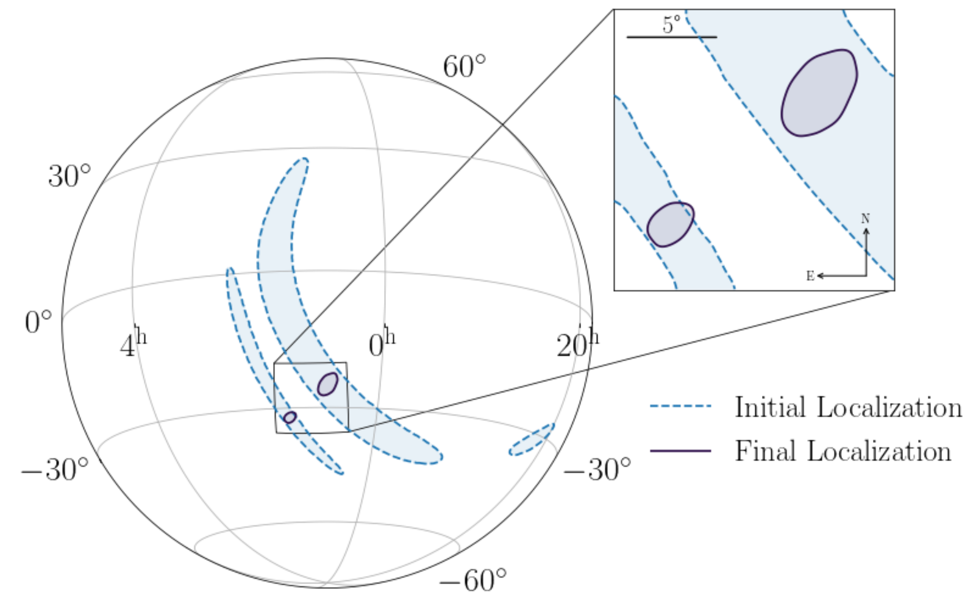
- Heaviest observed NS: 2.08 Msun
- Theoretical limit (Tolman Oppenheimer Volkoff, TOV): ~2.3 Msun, slightly higher if allowing for rotation

Comparable to merger remnant of BNS GW170817 (likely BH)

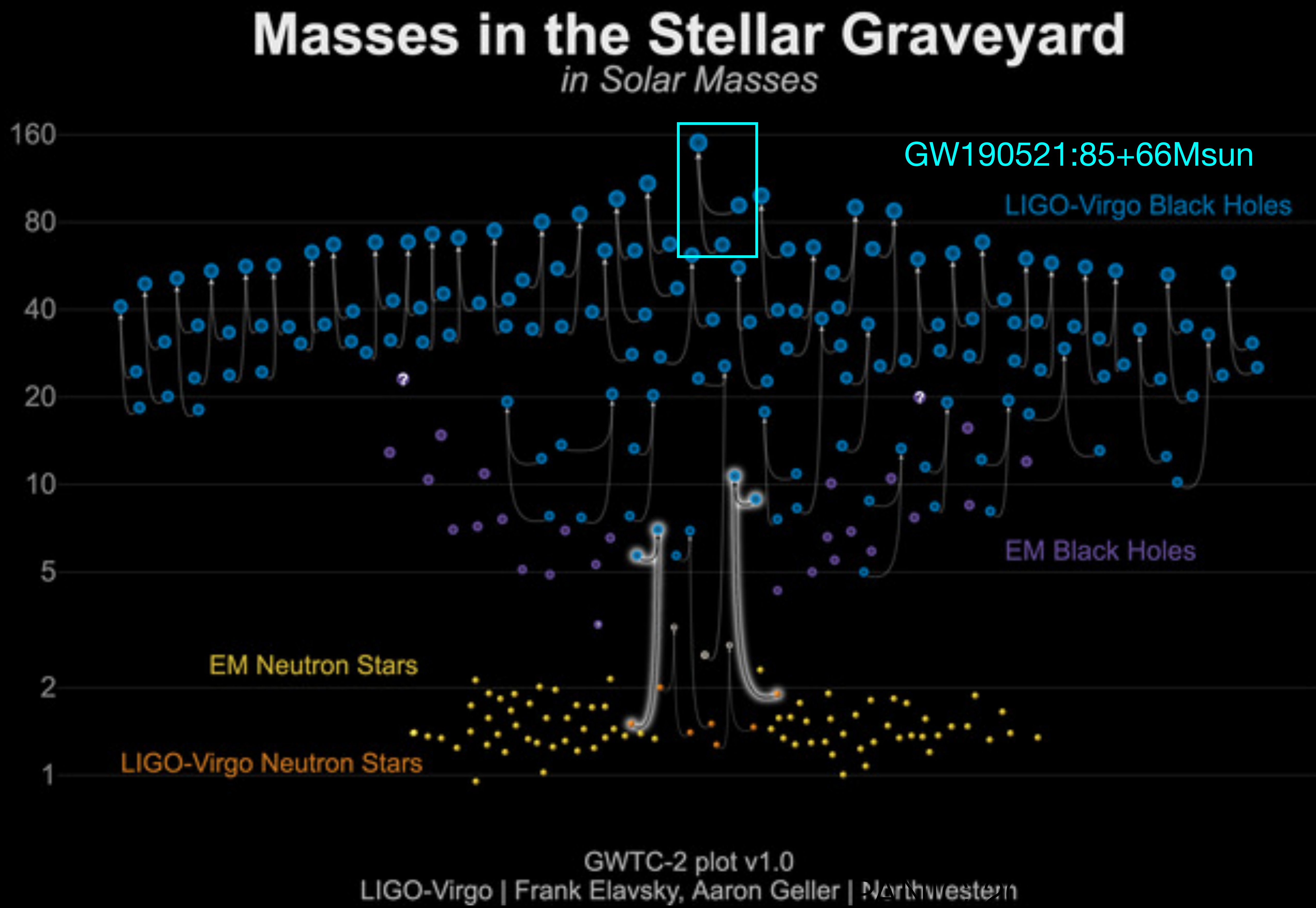
No information in GW signal (too unequal masses) and no EM counterpart

Challenge for formation models

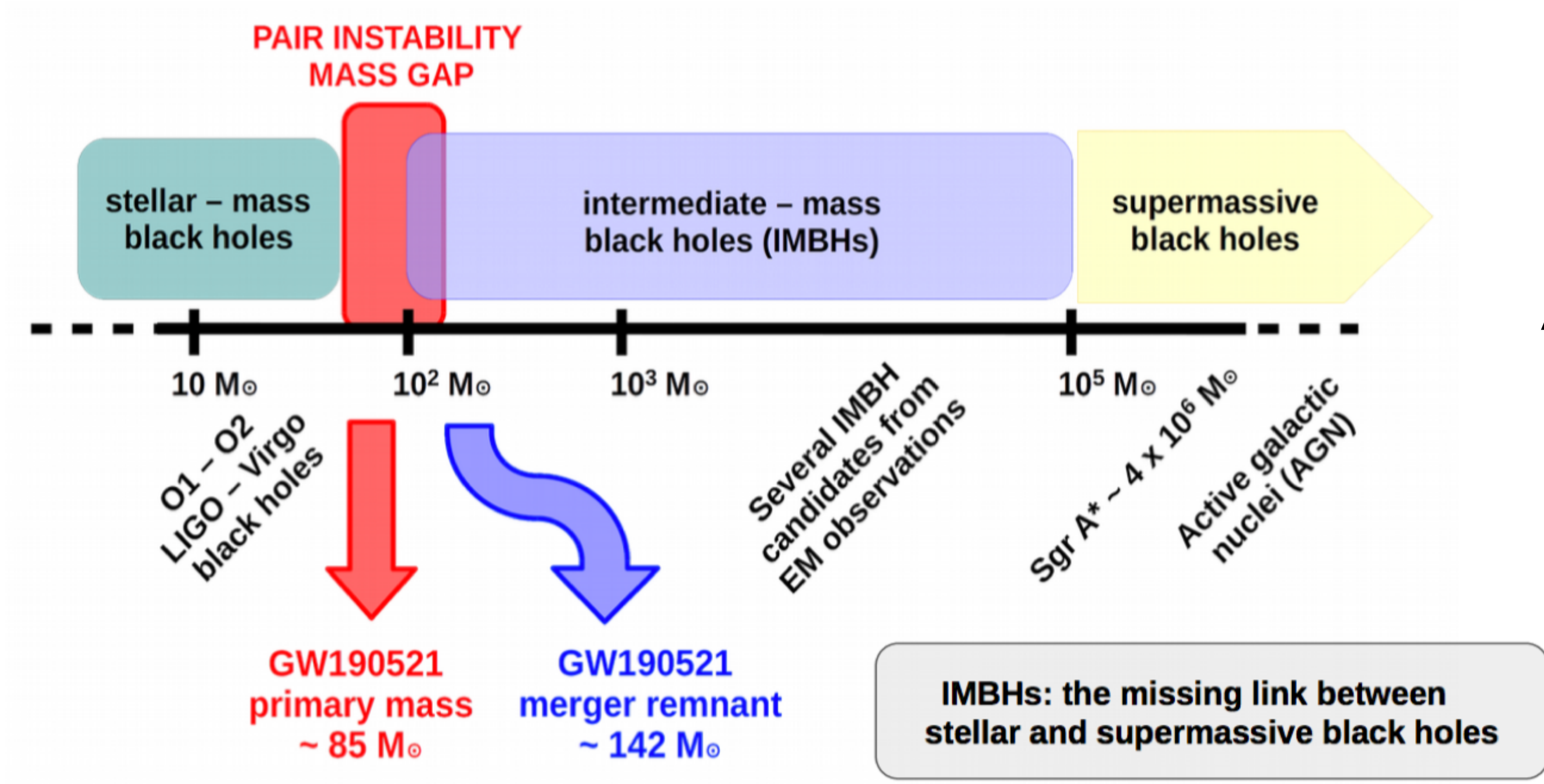
Best localized event with no EM counterpart: dark siren measurement of Hubble constant



FIRST INTERMEDIATE MASS BLACK HOLE



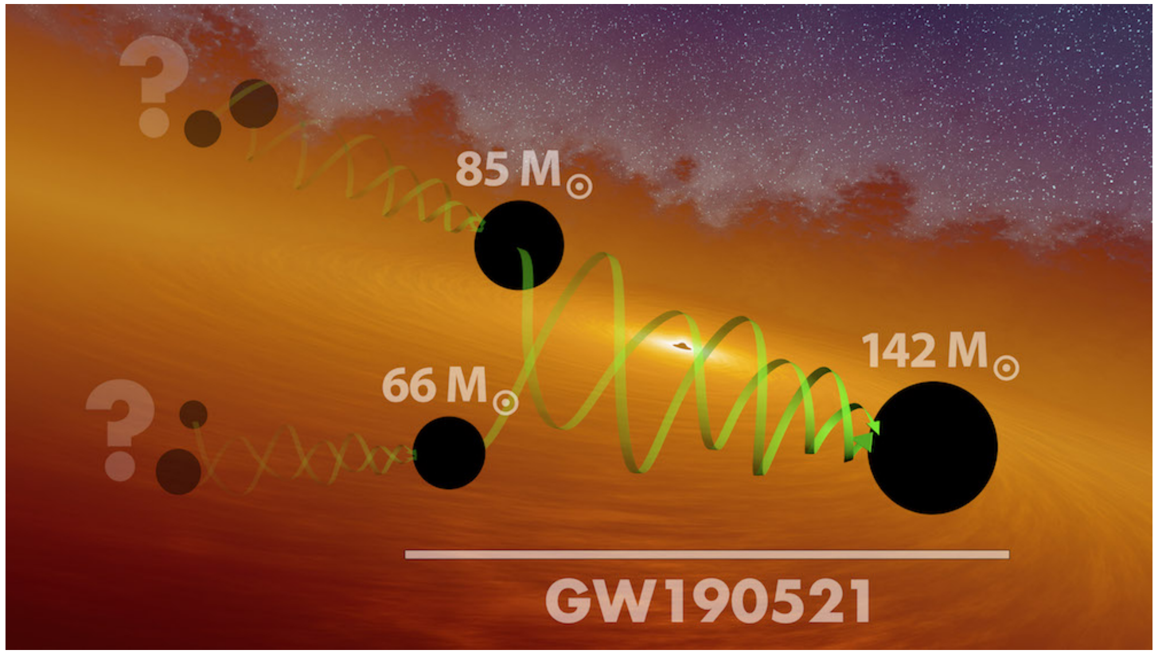
HIGH MASS STELLAR BLACK HOLES



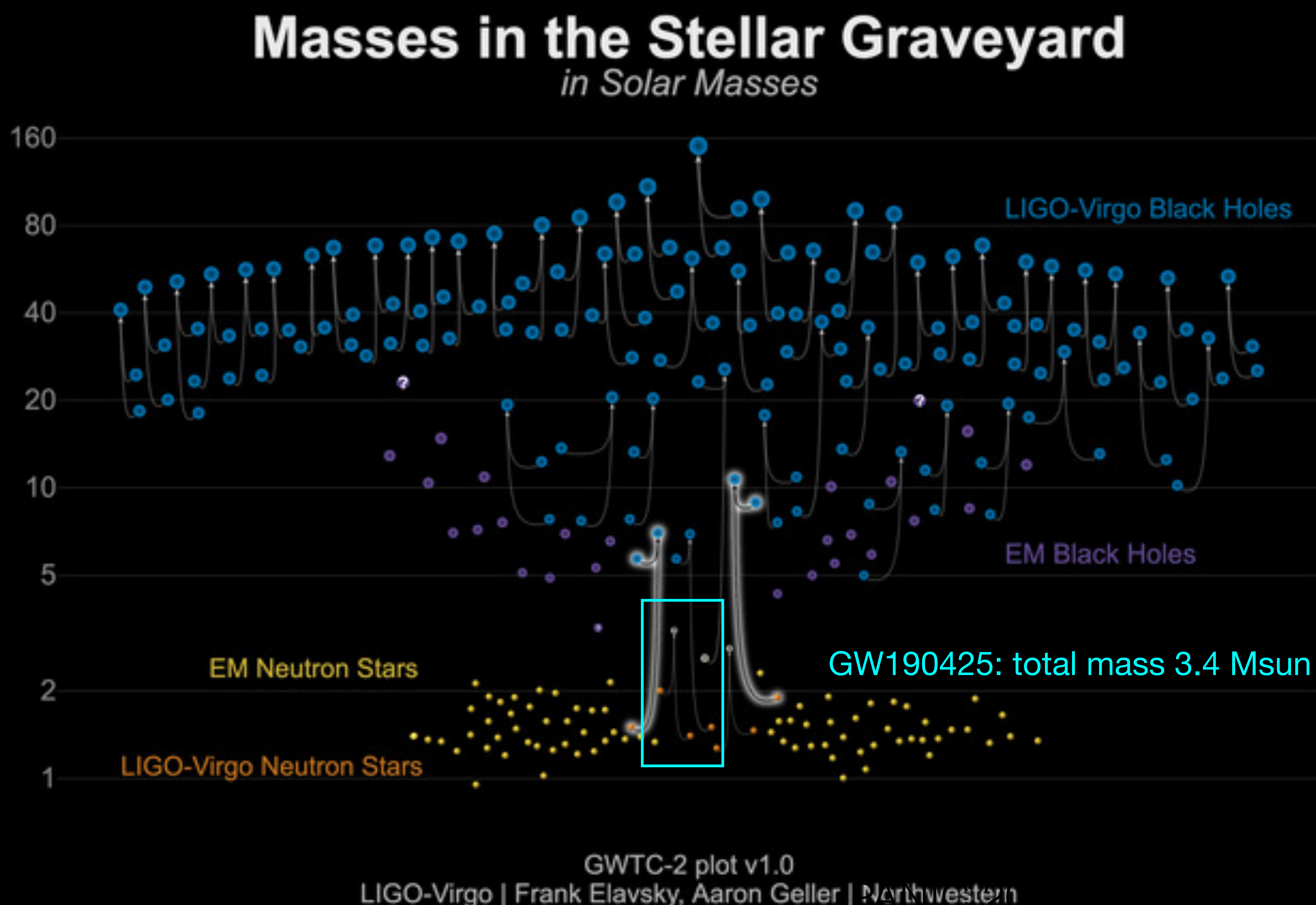
A pathway to intermediate mass black holes?

Formation challenges stellar evolution

High mass measured from ringdown,
No deviation of GR



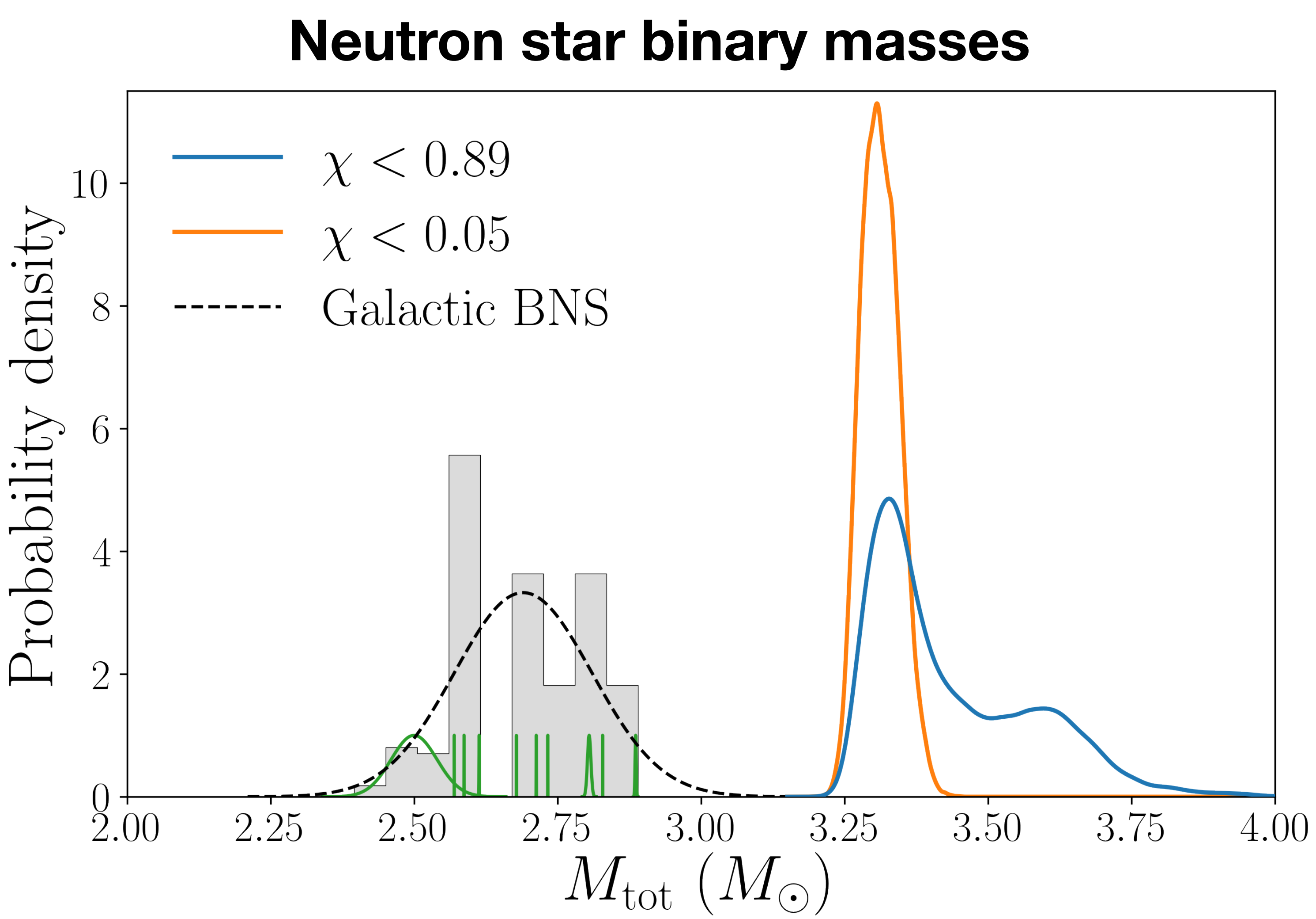
MOST MASSIVE NEUTRON STAR BINARY



A TOTAL MASS OF 3.4 SOLAR MASS

Heavier than any neutron star binary in the Milky Way
(5 sigma away from mean)

Accretion onto NS?
Low metallicity?
Globular cluster dynamics?
A missing (undetected) population in the Milky Way?



CONCLUSIONS AND OUTLOOK

A new messenger for (astro)physics of compact objects

~50 events: black holes, neutron stars

Measurements of rates for 3 types of binaries -> theoretical challenge

Growing statistical sample and several new discoveries bring new questions

Coming soon: publications about O3b

O4 observations: after June 2022

For more info (science summaries, webinars, open data…): ligo.org