ASTROPHYSICS WITH GRAVITATIONAL WAVES

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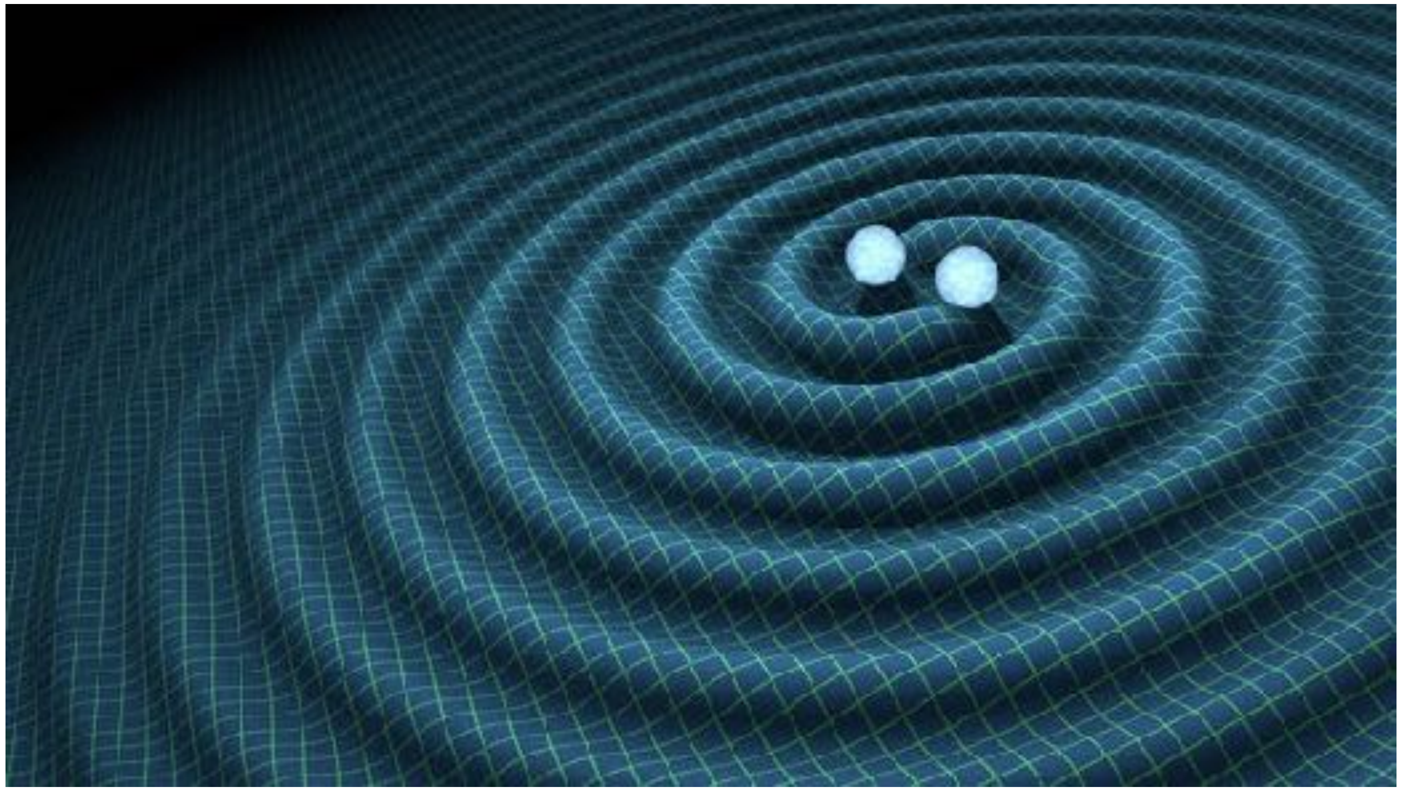
HOW TO CREATE GRAVITATIONAL WAVES?



Propagation of disturbance of spacetime

Needs: very massive objects

Speeds ~ speed of light

-> Extreme objects/phenomena: compact objects, explosions

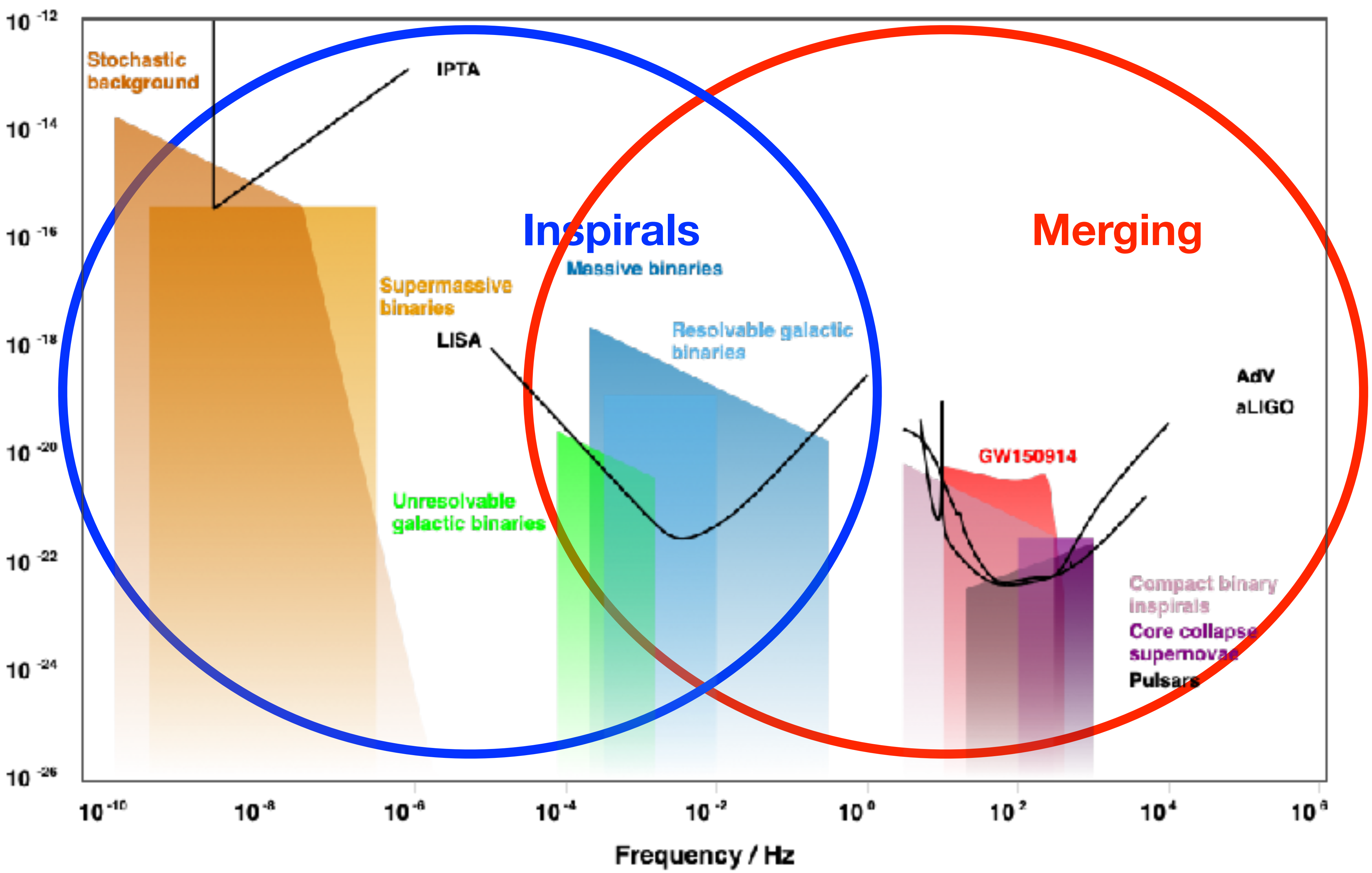
Anything with a quadrupole moment (not spherically symmetric): binaries…

Compact binaries: black holes, neutron stars, white dwarfs and others

DIFFERENT SOURCES OF GW

Stellar objects with LVK detectors

GWs at lower frequencies: white dwarfs and supermassive black holes

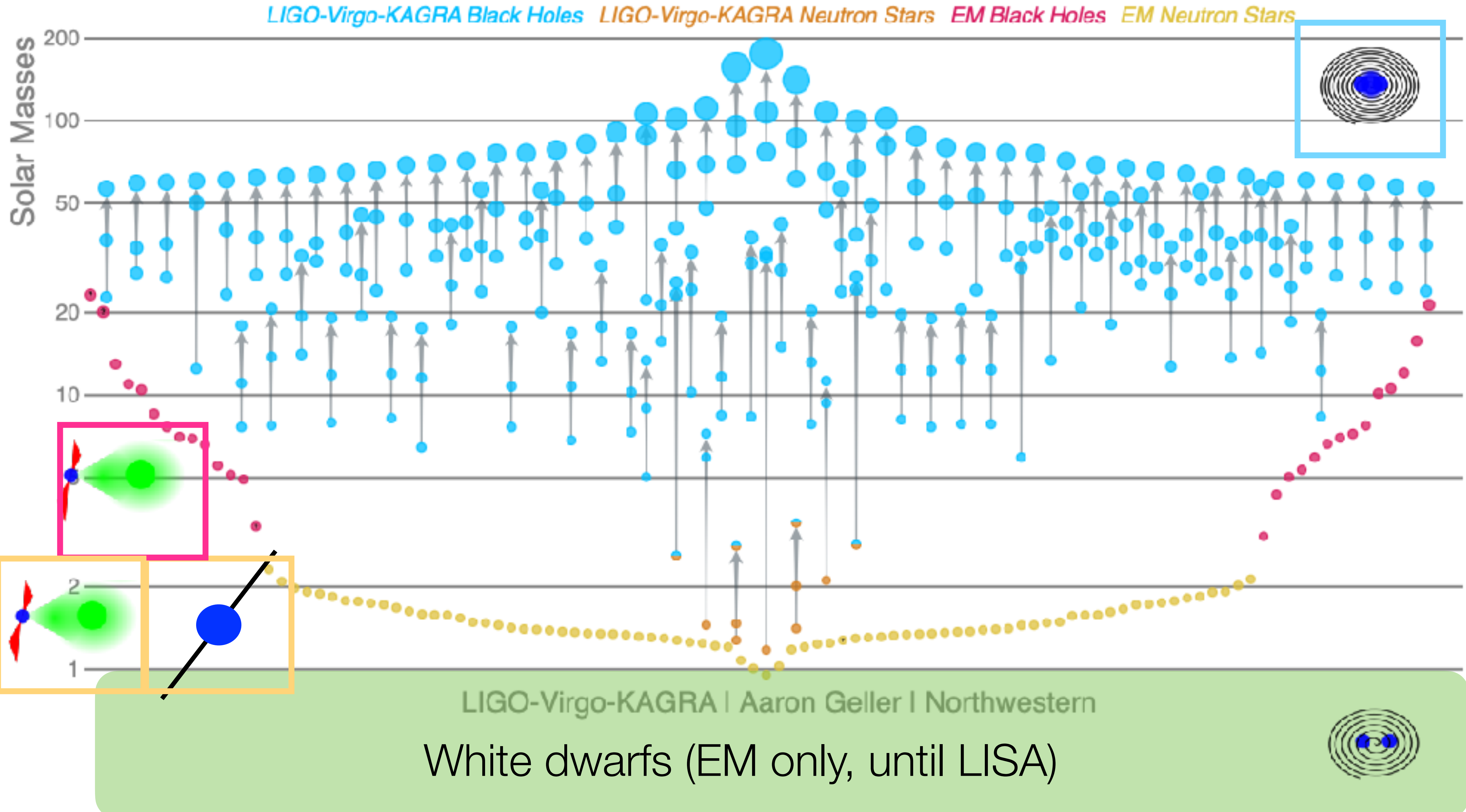


$$h \propto \frac{M^{2/3} \mu f^{2/3}}{d}$$

GW frequency~ 2 orbital frequency

GWplotter.com

Masses in the Stellar Graveyard



Where do these distributions come from?

FROM STARS TO COMPACT OBJECTS

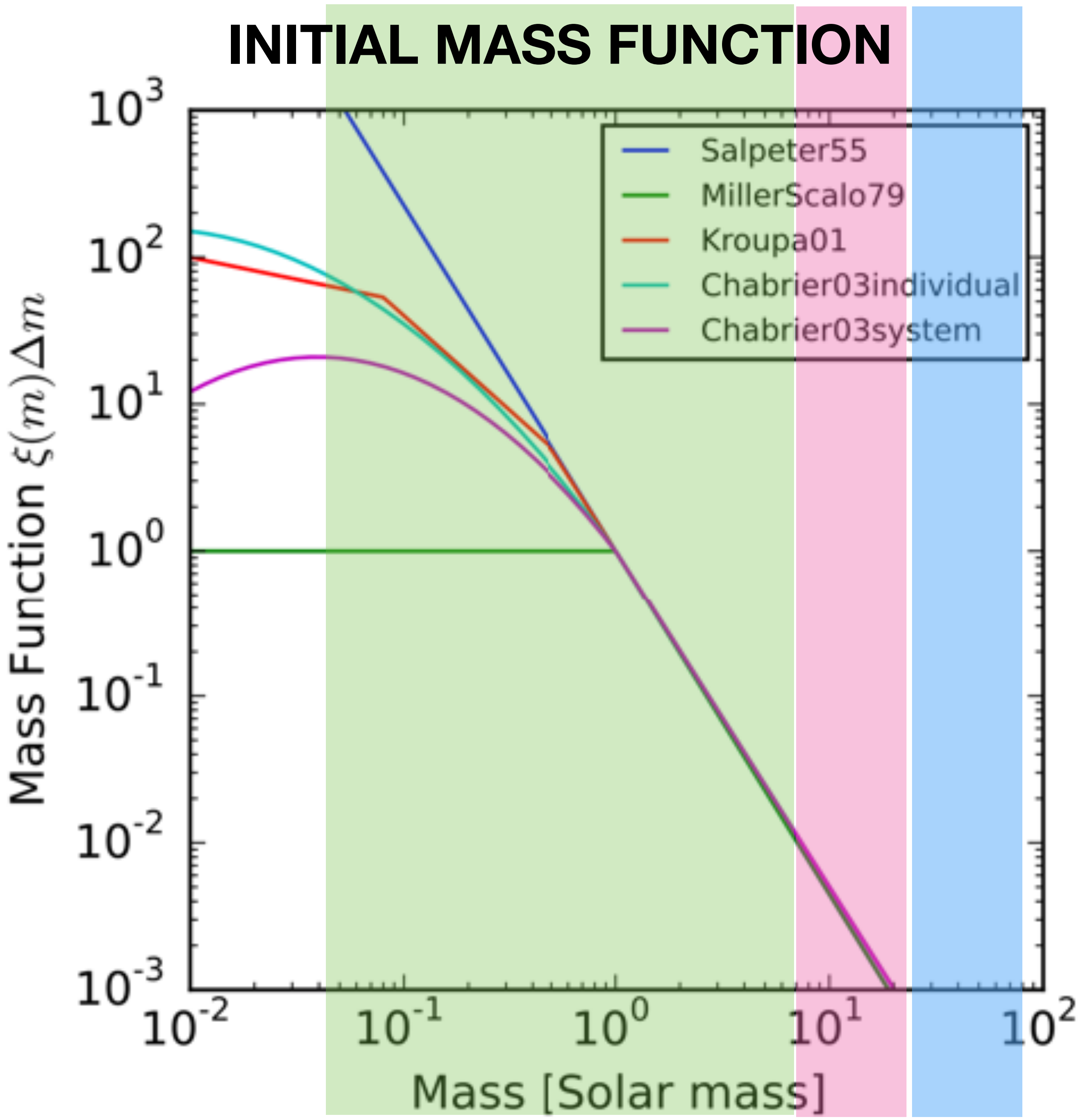
Single stars :

M <8-10 Msun : White dwarf

8-10<M <~20 Msun : Neutron Star

M>~20 Msun : Black holes

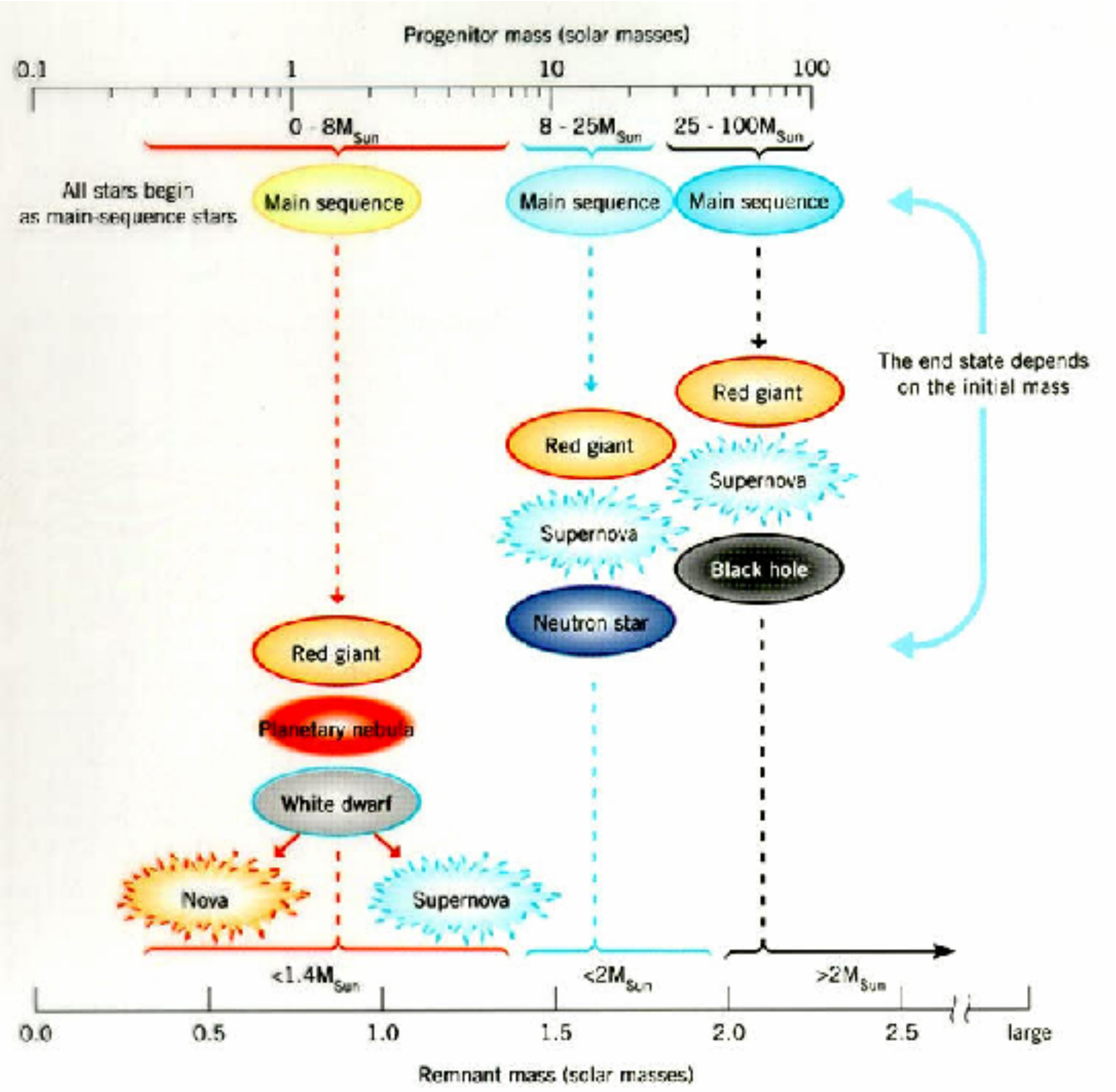
Many more white dwarfs than NS and BH



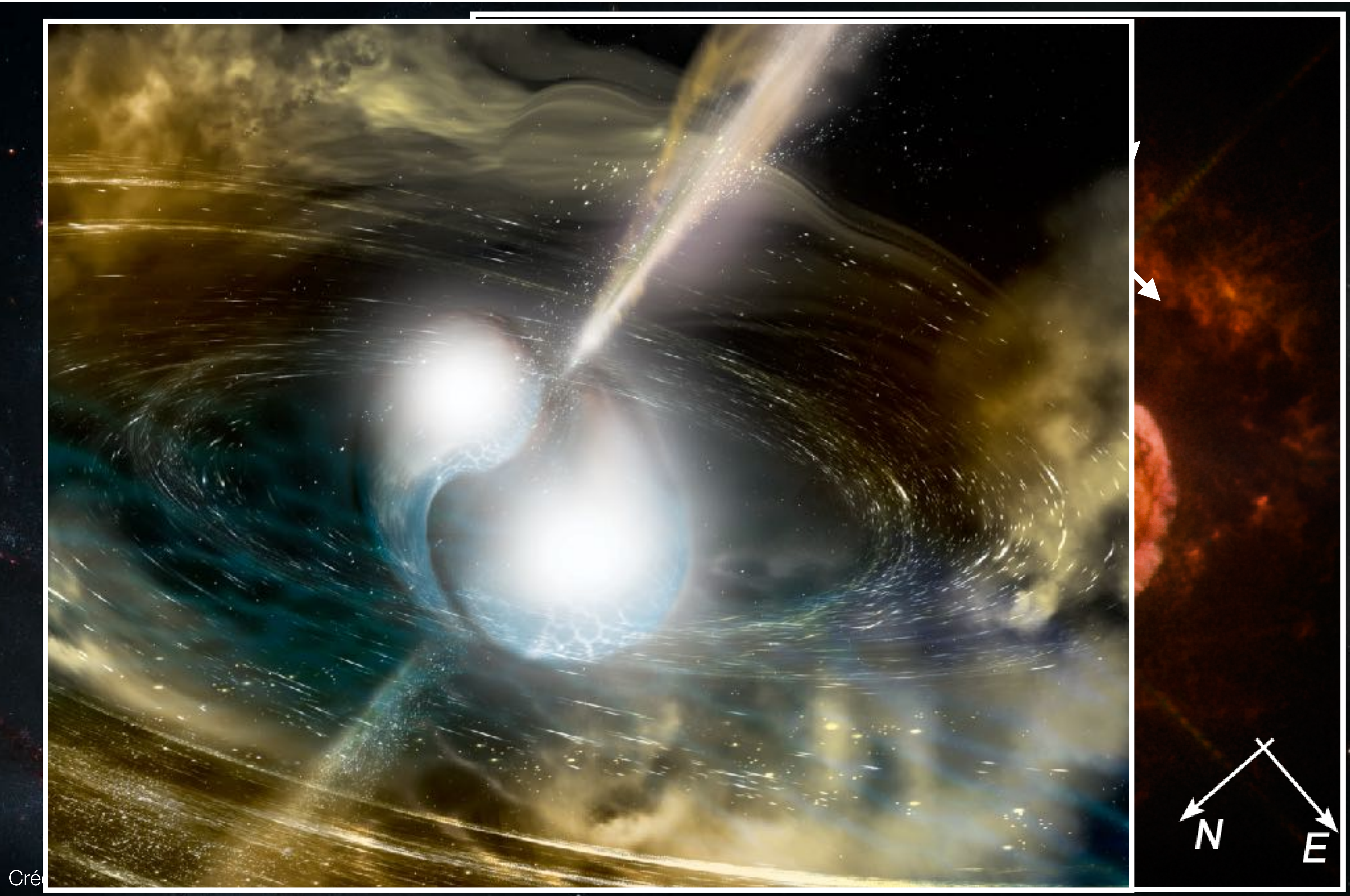
SINGLE STELLAR EVOLUTION

Mass: most important factor

Chemical composition (metallicity) important for BH



MASSIVE STARS : COSMIC ENGINES AND FUNDAMENTAL PHYSICS

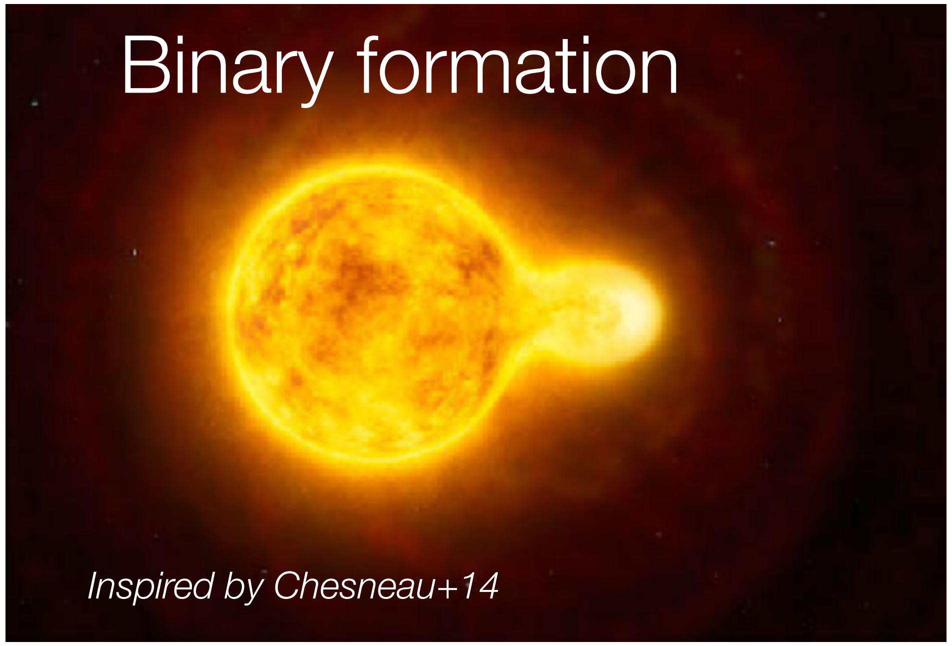


HOW TO GET COMPACT OBJECTS TO MERGE?

Problem: $t_{merger} \propto a^4$

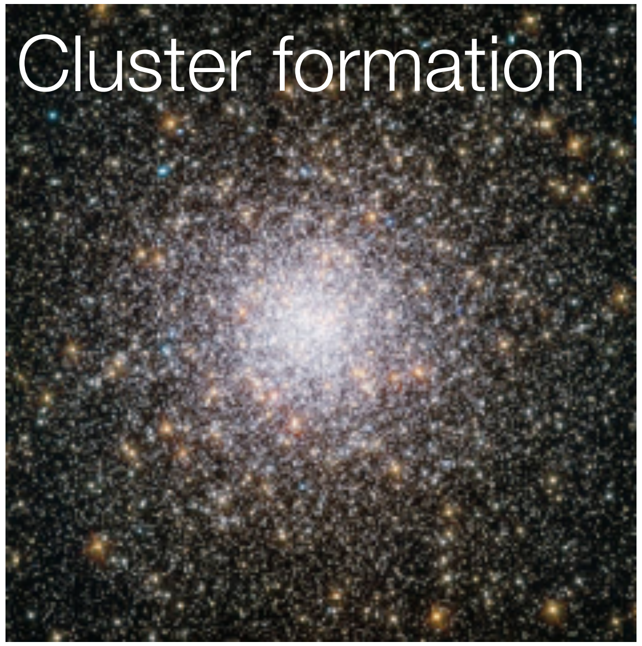
Initial stellar radii: already too far apart to ever merge

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



Mapelli, 22 for a review

Formation channel?



GW

Stellar physics

HOW TO MAKE BLACK HOLE BINARIES?

Step 1 :

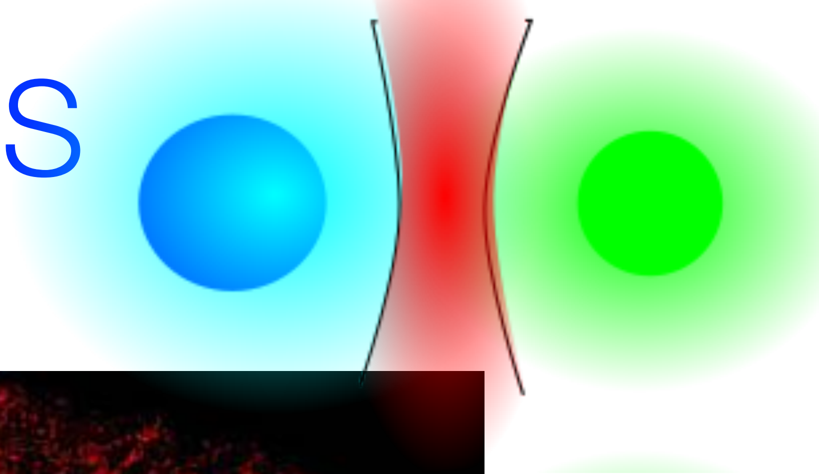
Create 2 massive stars

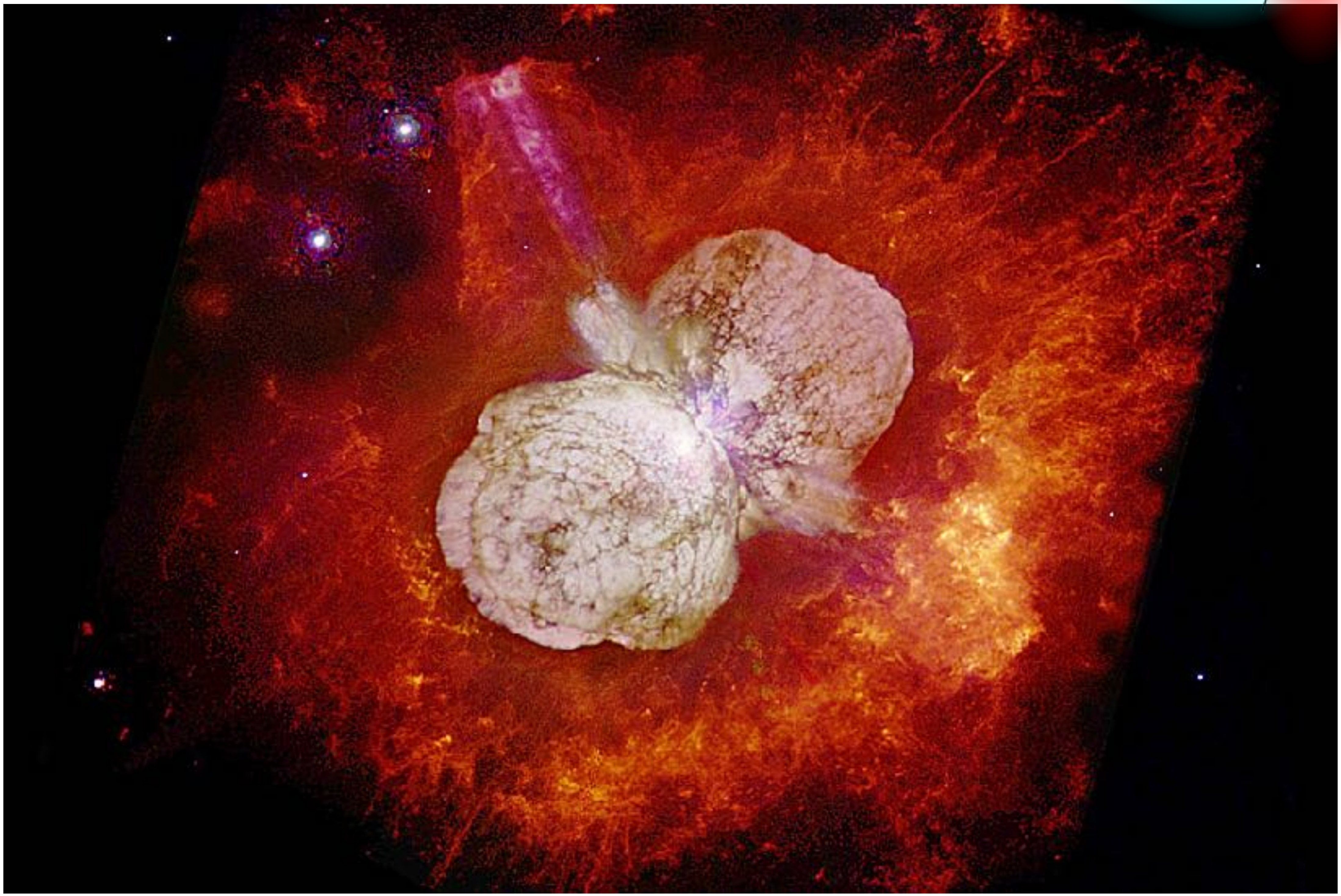
At least 20 x Sun

Disadvantage : Massive stars are rare

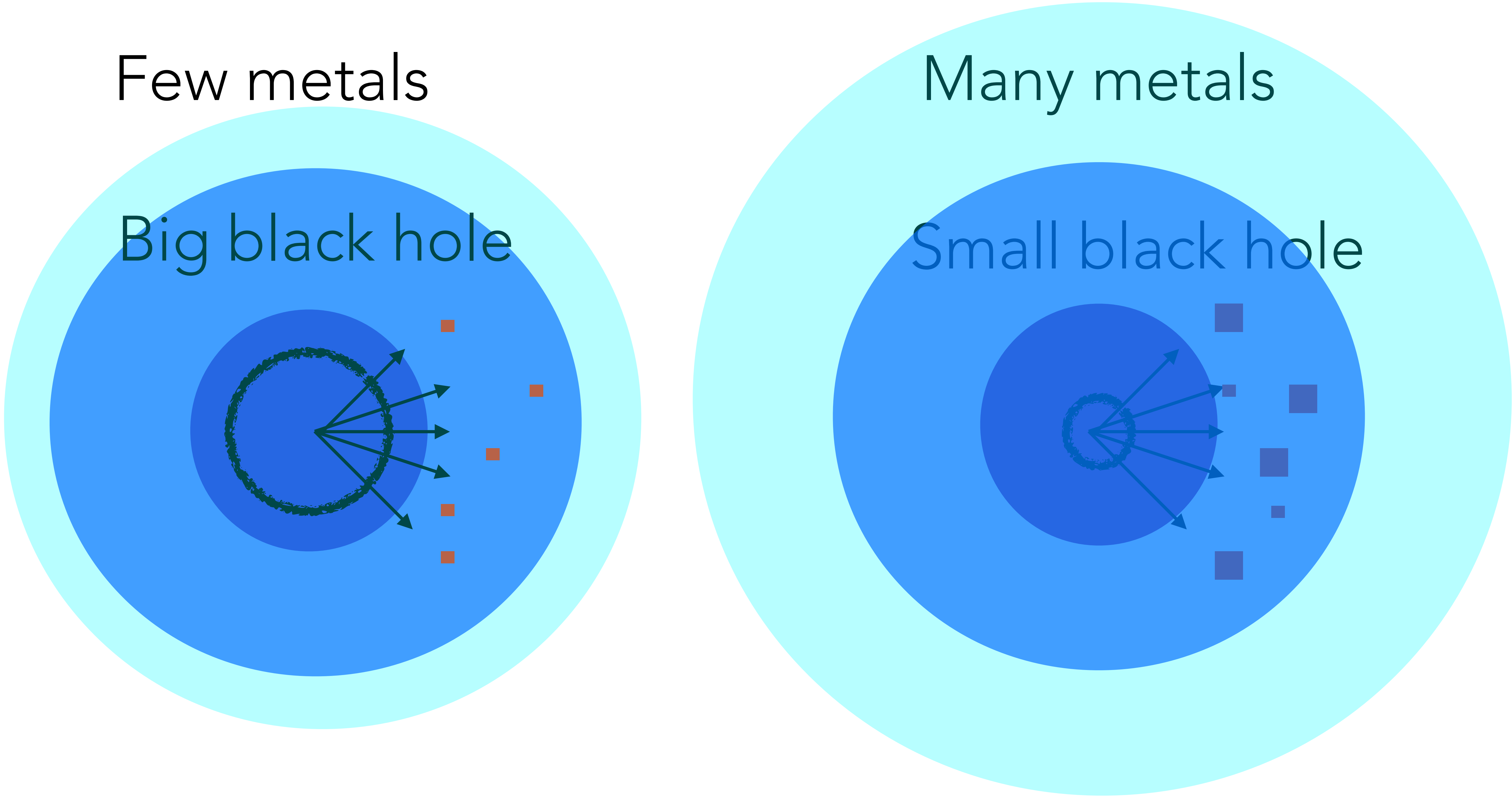
Advantage : Most massive stars form in close binaries

PROBLEM 1 : WINDS

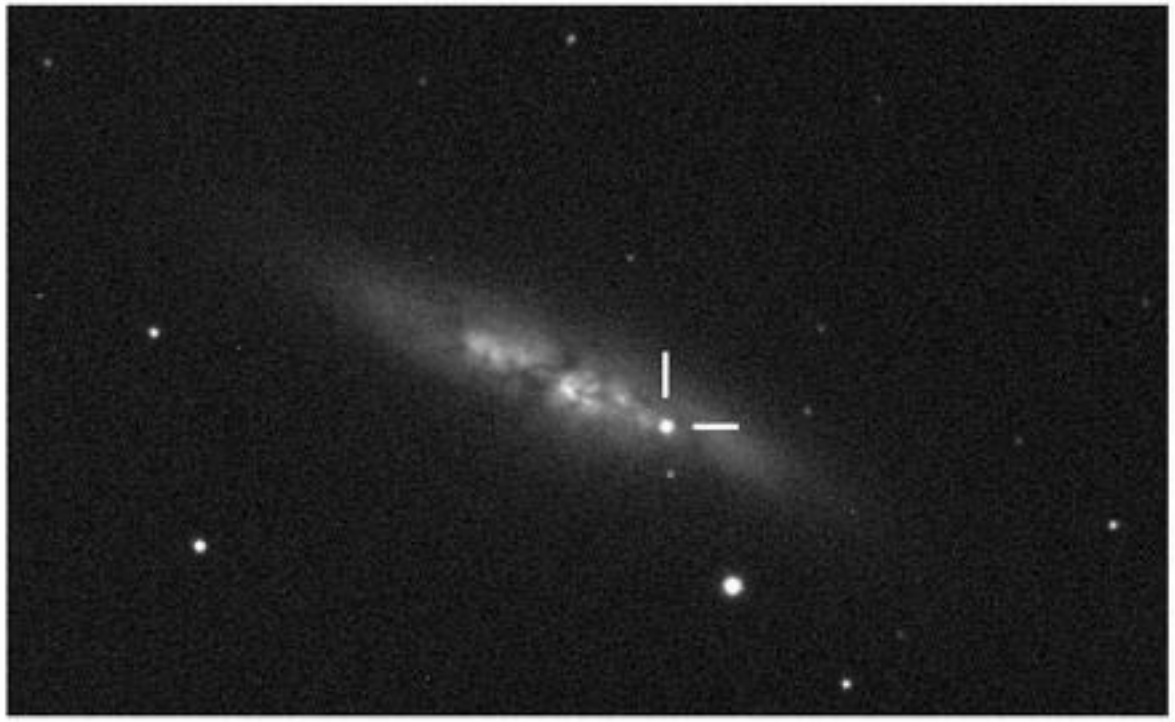


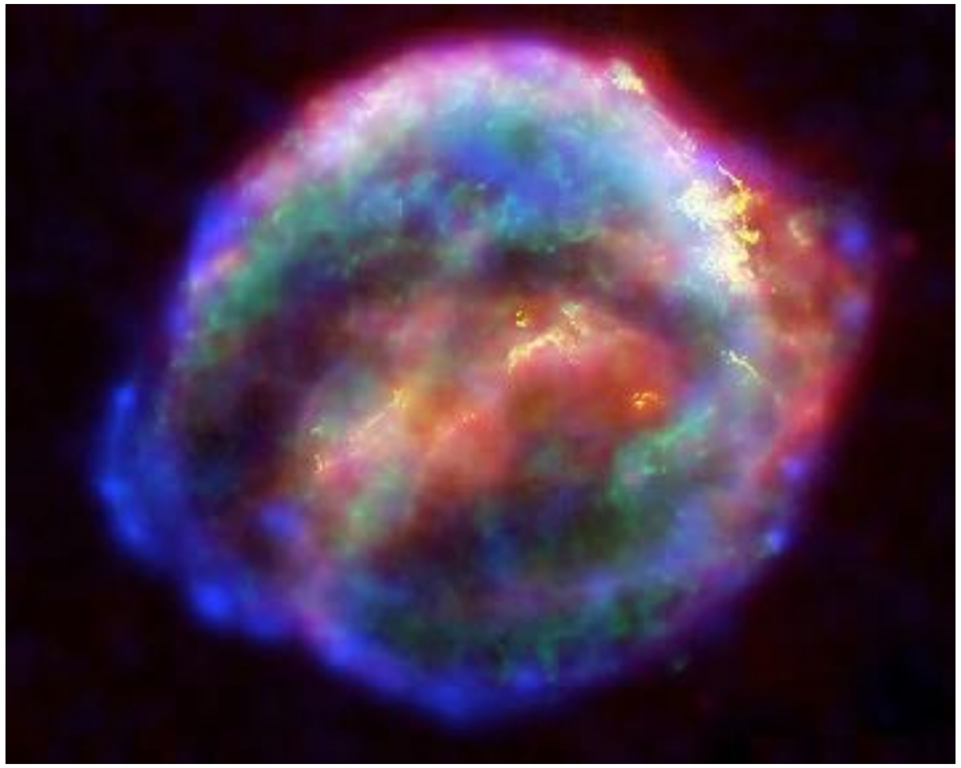


IMPORTANCE OF METALS (C, O, Ne, Fe…)

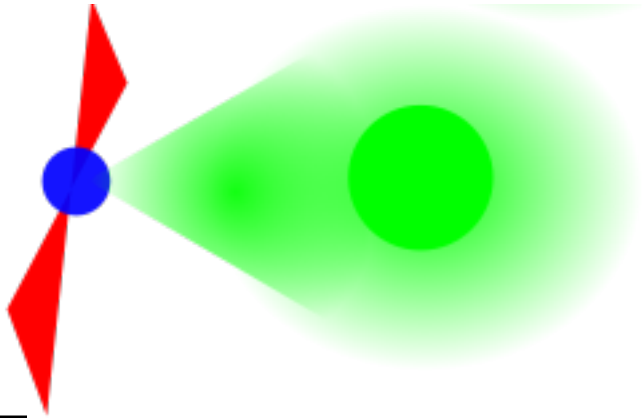


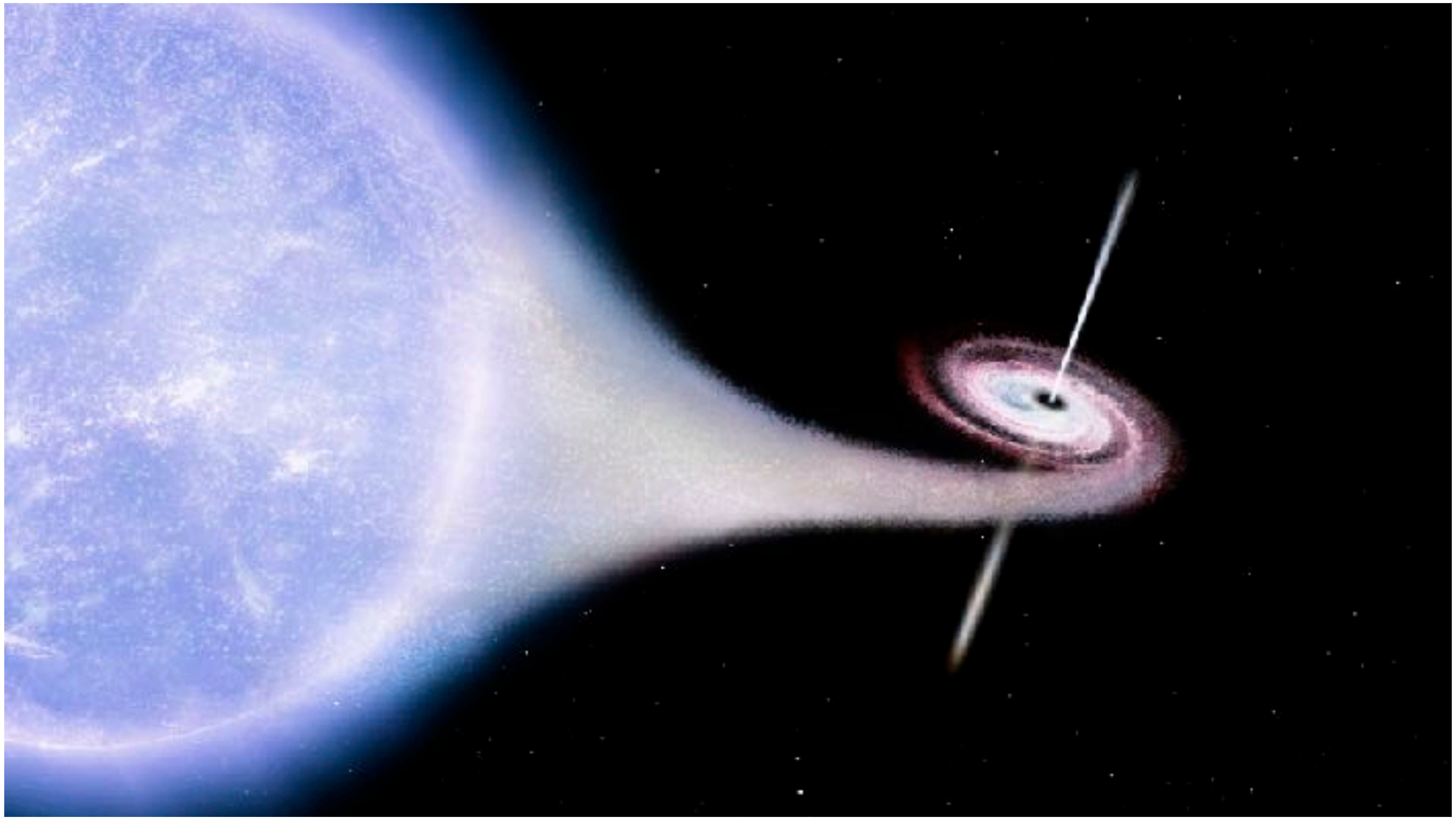
PROBLEM 2 : SUPERNOVA





X-RAY BINARIES





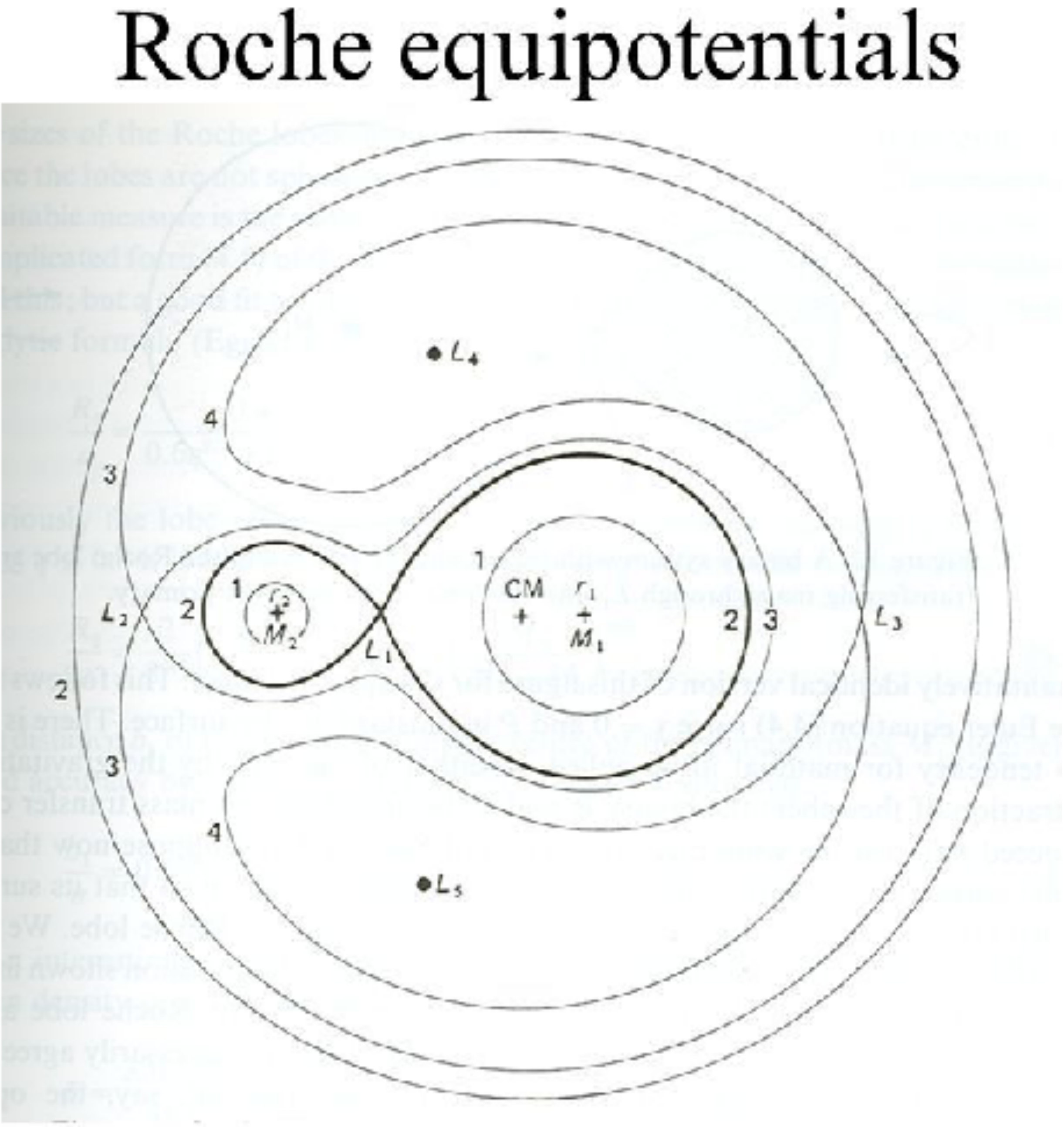
Mass transfer through winds (or Roche Lobe overflow)

ROCHE LOBE OVERFLOW

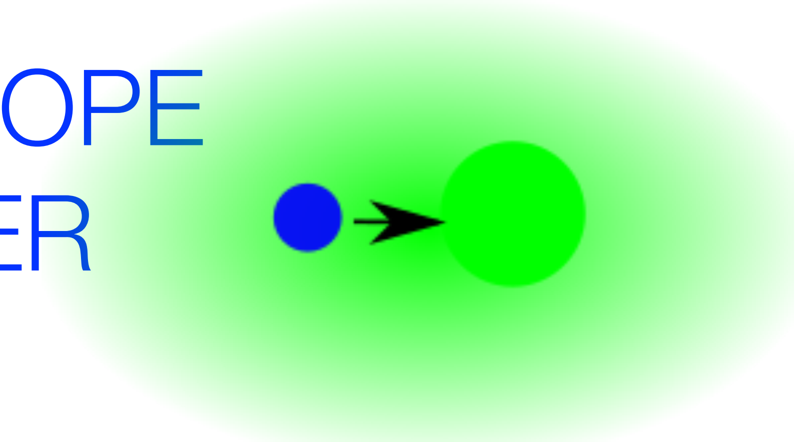
Roche Lobe: boundary between gravitational influence of both stars

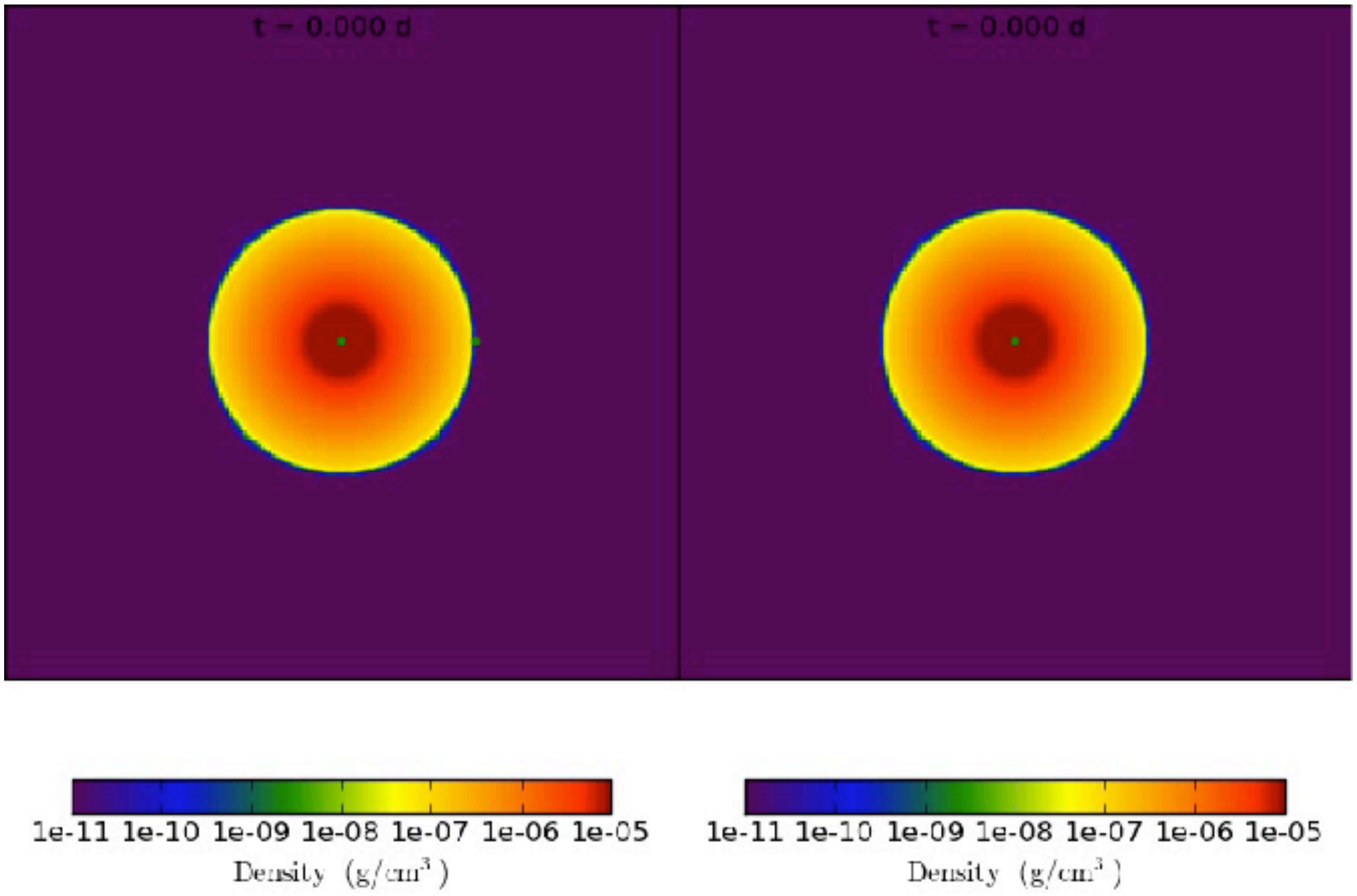
Matter beyond RL goes to other star

Stops when stars are contained in their RL, or unstable transfer starts



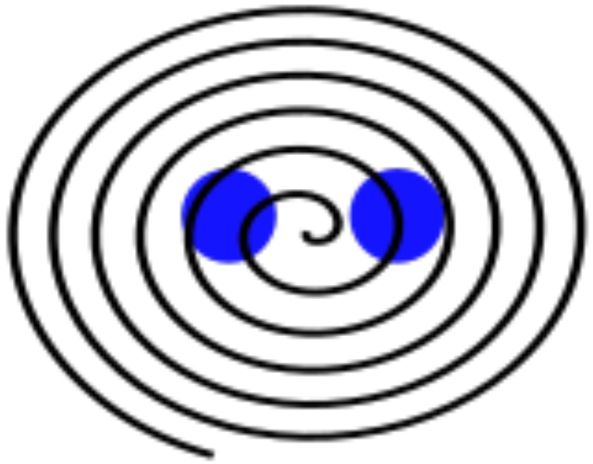
CRUCIAL: COMMON ENVELOPE BRINGS BINARIES CLOSER



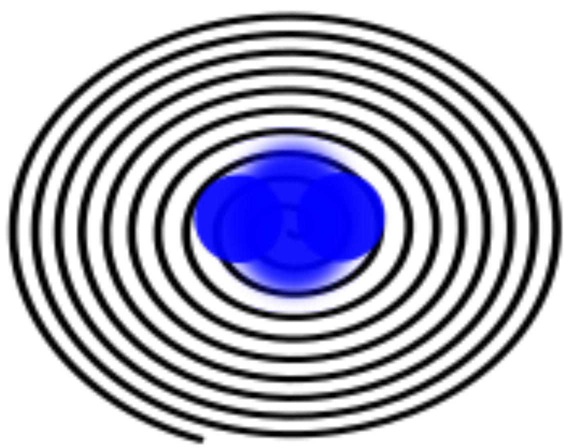


PROBLEM 3 : 2ND SUPERNOVA

IF BLACK HOLES: ONLY GWS



Billion years of inspiral



Merger (few seconds)

Tidal effects for BNS

Final remnant

HOW DID THE BINARY SHRINK?

Angular (AM) momentum needs to be lost

$$J_{orb} = \Omega_{orb}(M_1 a_+ M_2 a_2) \qquad \Omega_{orb} = \left(\frac{G(M_1 + M_2)}{a^3}\right)^{1/2}$$

Options: mass loss through winds

Conservative mass transfer (Mtot=constant)

Binary shrinks if mass transfer from primary to secondary

Binary expands if mass transfer from primary to secondary

Non-conservative mass transfer: common envelope leads to very Important shrinking

DIFFERENT TIMESCALES

Billions of years
Universe is ~14 billion years old

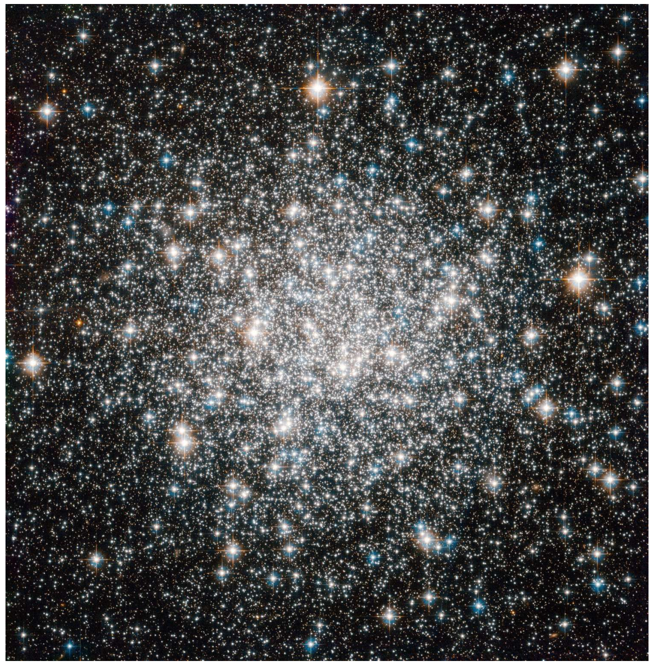
Tracer of past massive star formation
Properties set by binary evolution

< 5 million years

FORMATION CHANNEL: CLUSTER EVOLUTION

Star clusters : 10^3-10^7 stars radius < 100 pc

Evolution dominated by N-body interactions

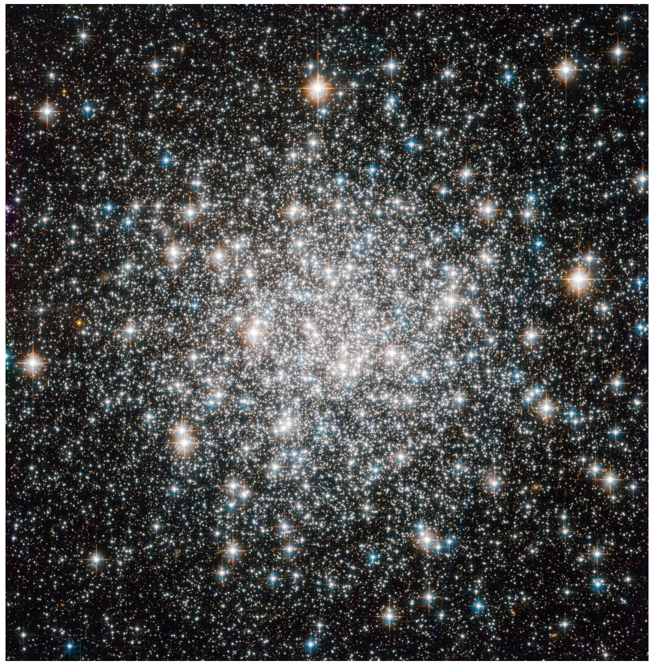


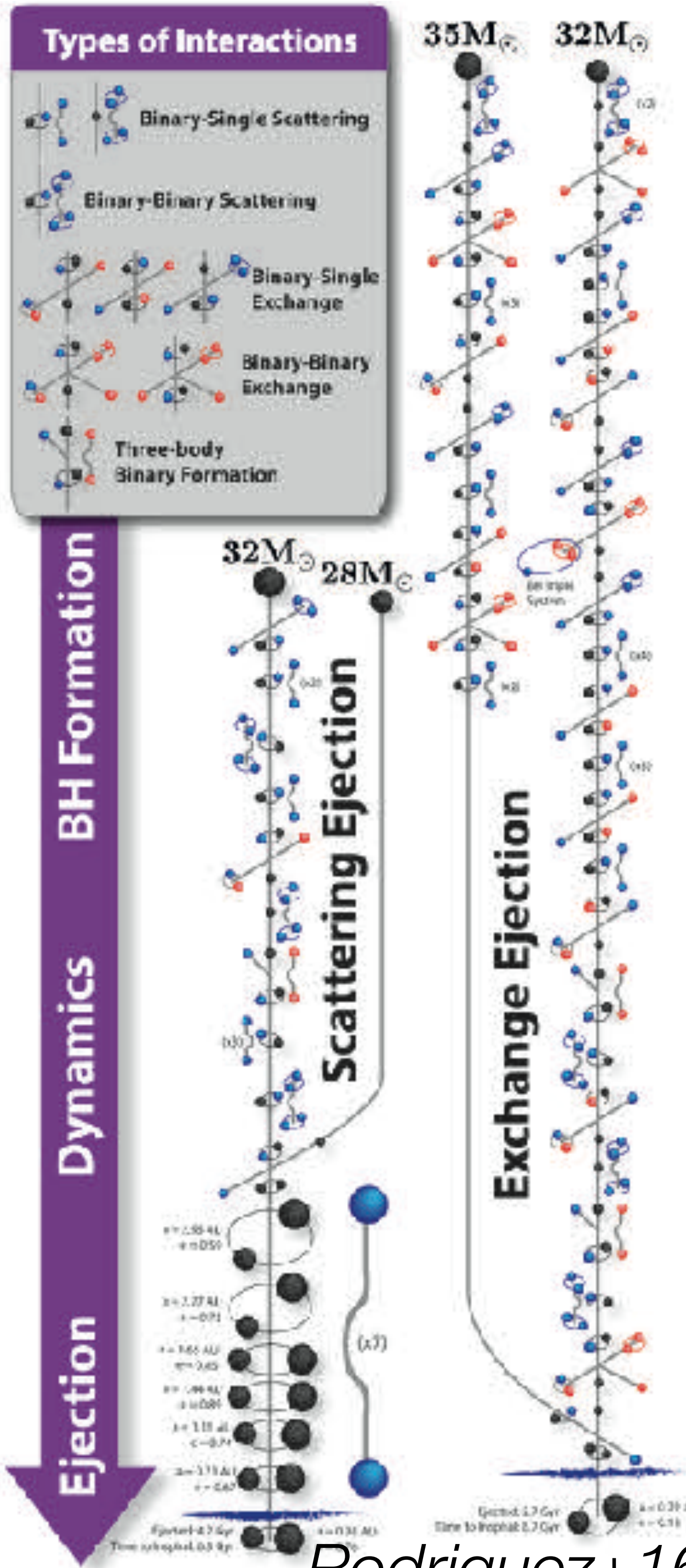
Globular clusters: old stars, very dense and massive
Young star clusters: less dense and less massive -> will dissolve quickly
Nuclear star clusters: Very dense, at center of galaxies

FORMATION CHANNEL: CLUSTER EVOLUTION

N-body interactions:

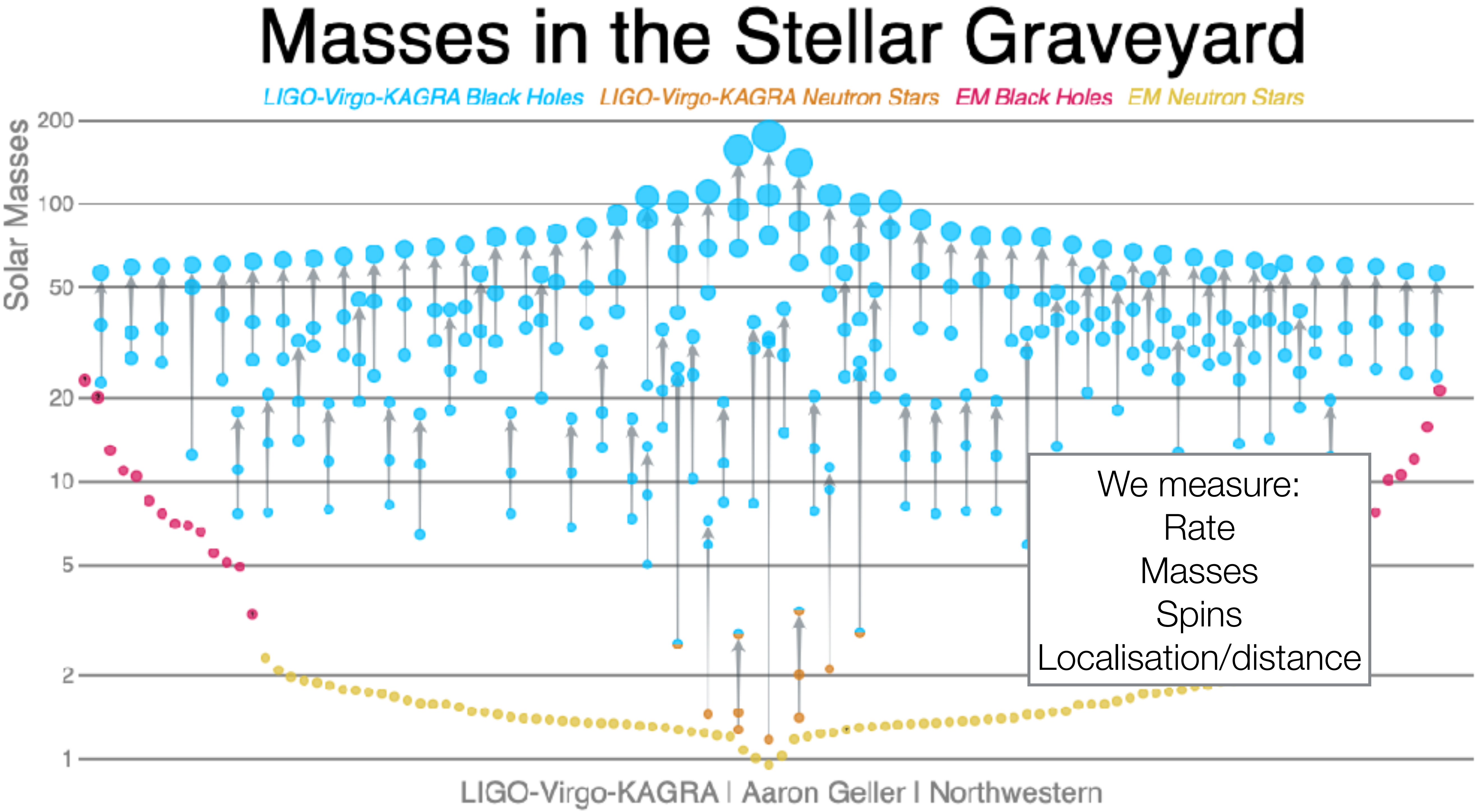
- BHs sink to center
- Mass exchanges make BH binaries
- 2nd generation mergers -> massive BHs
- Binaries can be kicked and merge outside





Rodriguez+16

SO WHAT DO WE LEARN HERE?

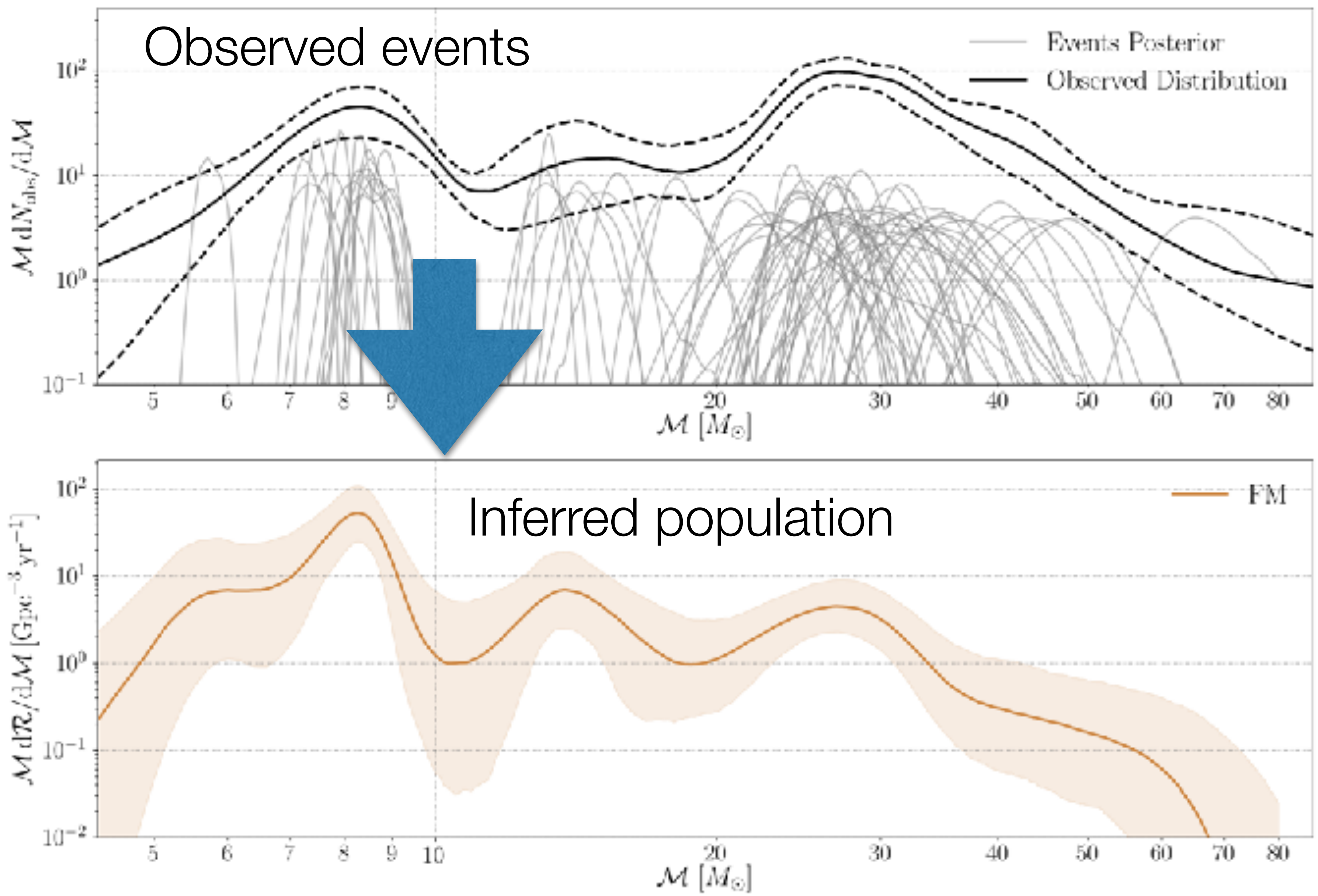


We measure:
Rate
Masses
Spins
Localisation/distance

~80 BINARY BLACK HOLES: A POPULATION

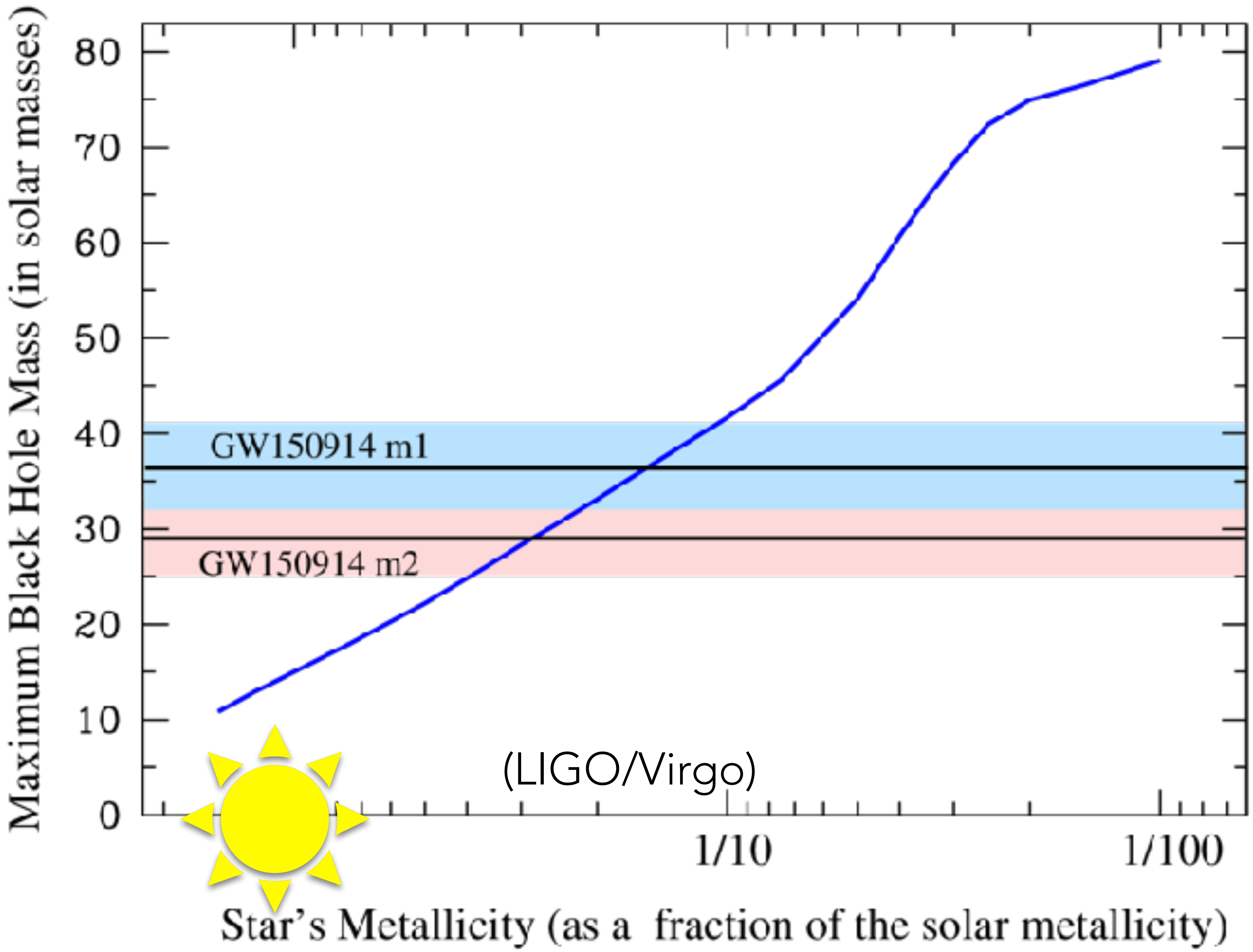
Phenomenological models for population
-> Rate: 17-45 $Gpc^{-3}\,yr^{-1}$

Mass spectrum
- Lots of « massive » black holes
- Uncertain gap between NS and BHs
- Features in spectrum



LVC: GWTC-3 populations paper based on O3a

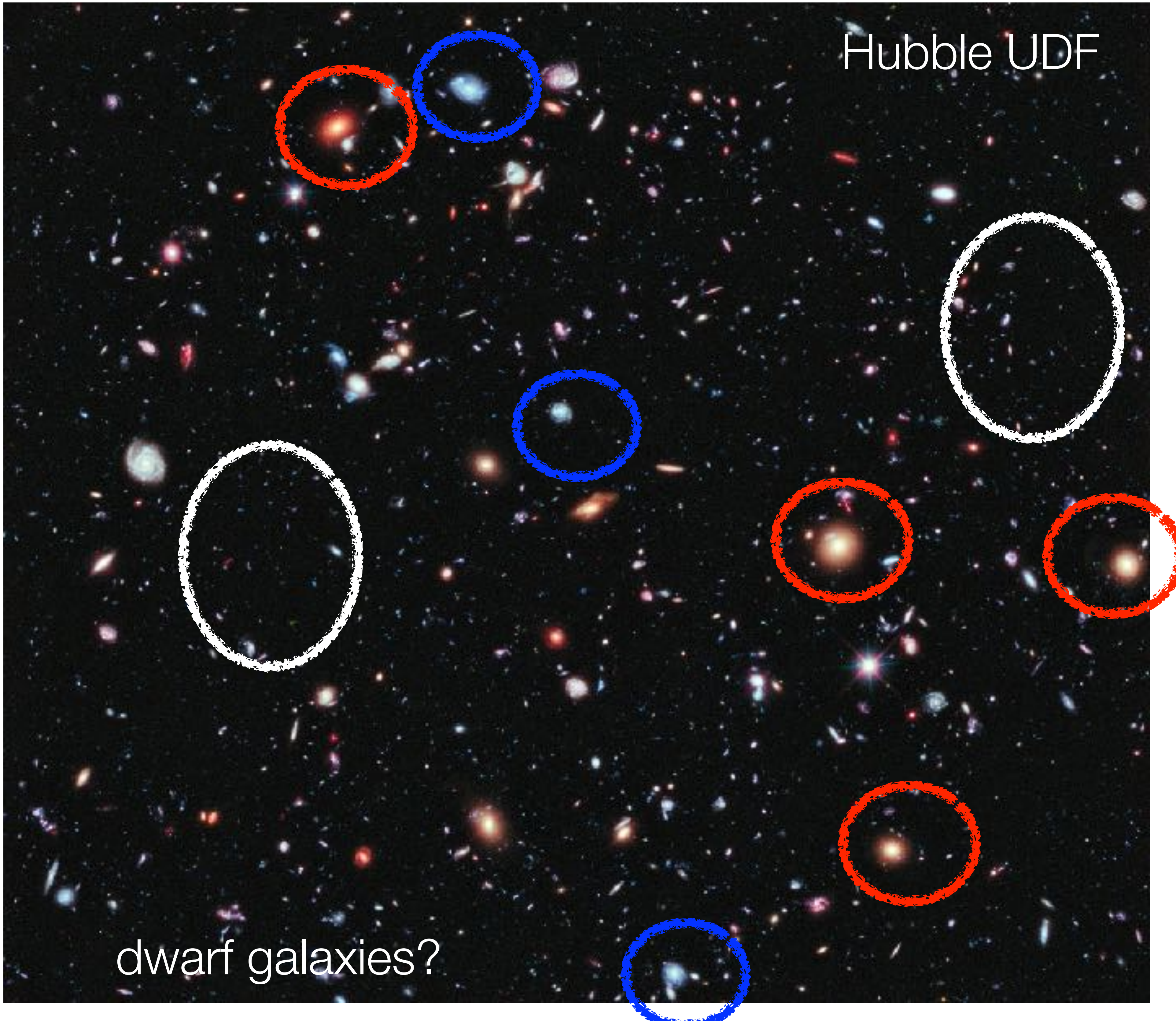
MAKING MASSIVE BHS IS HARD



Binary evolution -> low metallicity progenitor stars

Not well-known stellar population

WHERE ARE THE LOW-METALLICITY STARS?

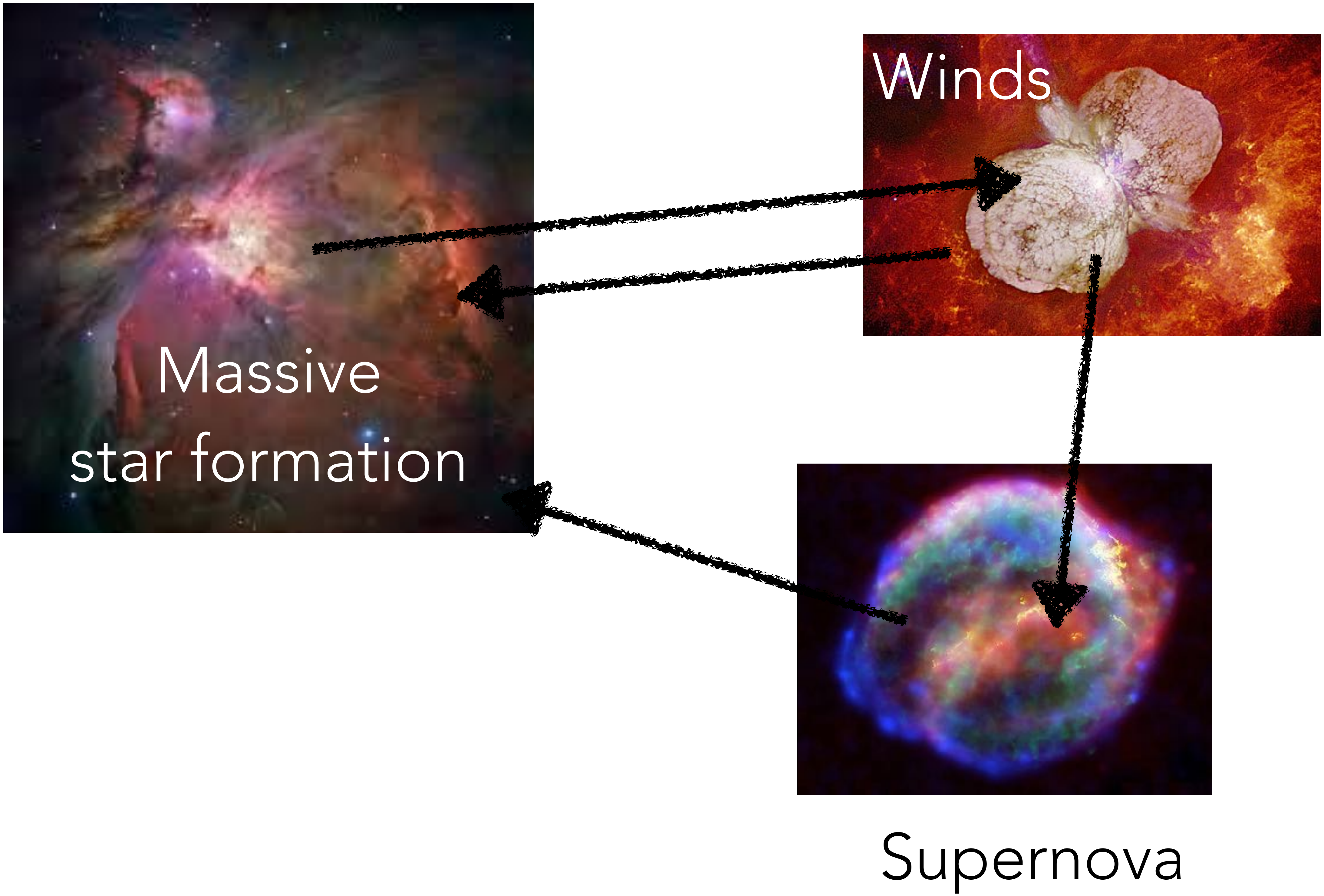


Less explored star formation

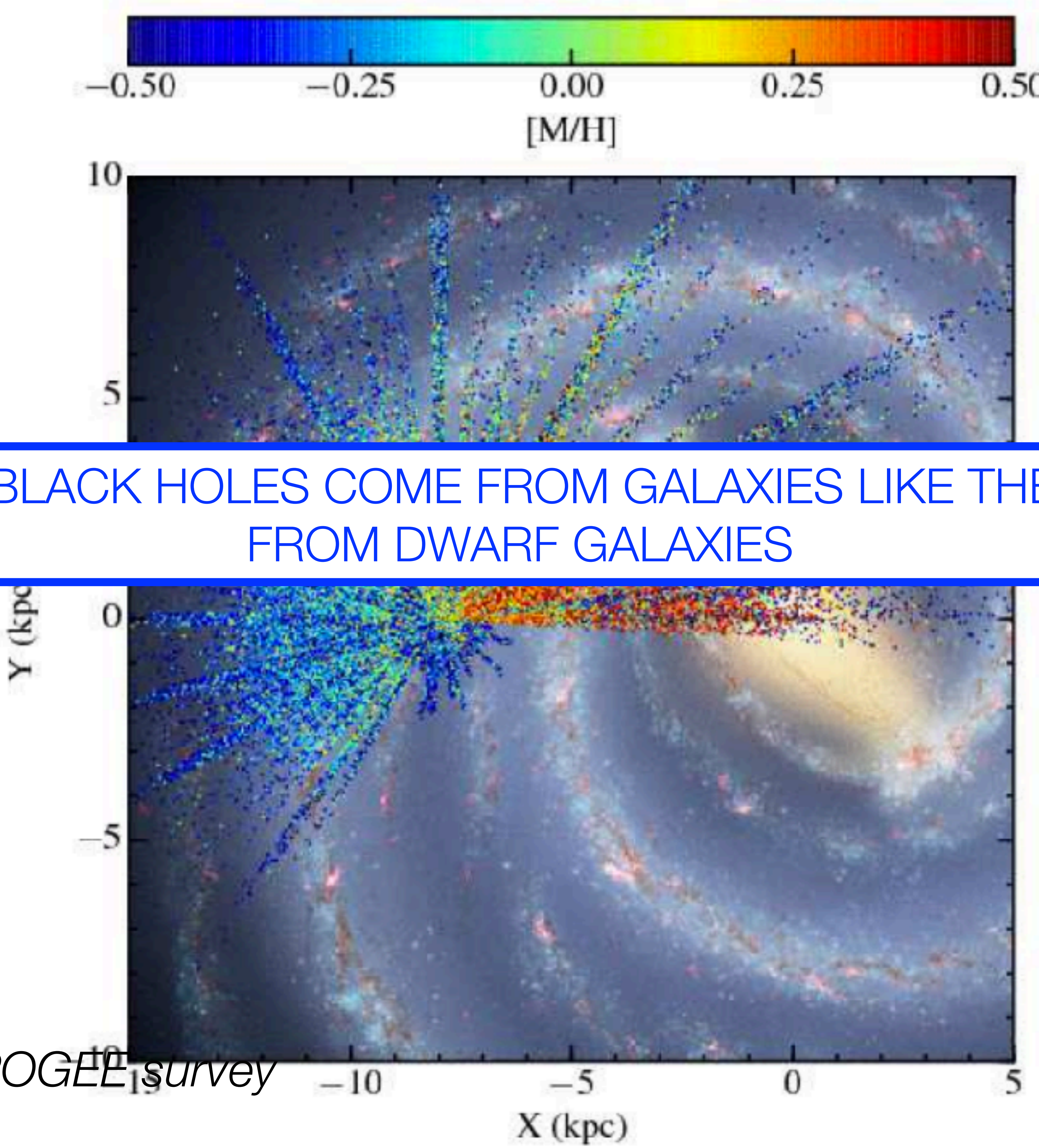
recent star formation?

older star formation?

THE CYCLE OF GAS AND METALS



WH… …RS?



APOGEE survey

…um II :
stars
…1 Z_{sun}

MASSIVE BLACK HOLES COME FROM GALAXIES LIKE THE MW AND FROM DWARF GALAXIES

IMPORTANCE OF BH SPINS

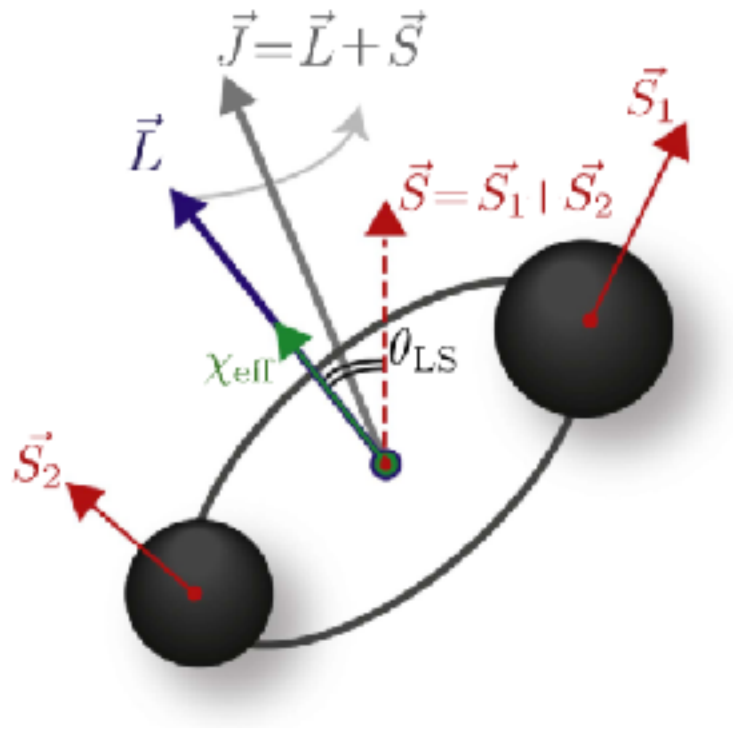
GWs carry information on (global) spin

Hard to measure

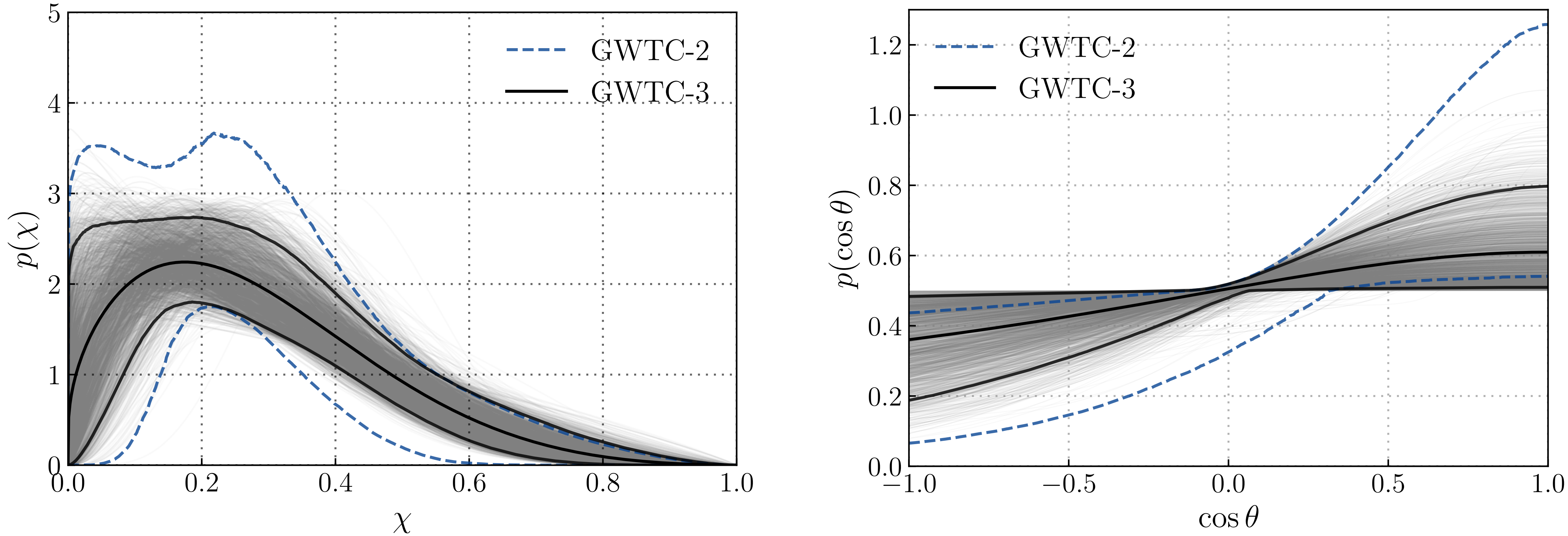
Binary evolution: spins align (tides, accretion, common envelope…), SN can disturb

Cluster dynamics : random motions

Amplitude is hard to predict from stellar evolution



SPINS TO DISCRIMINATE FORMATION?



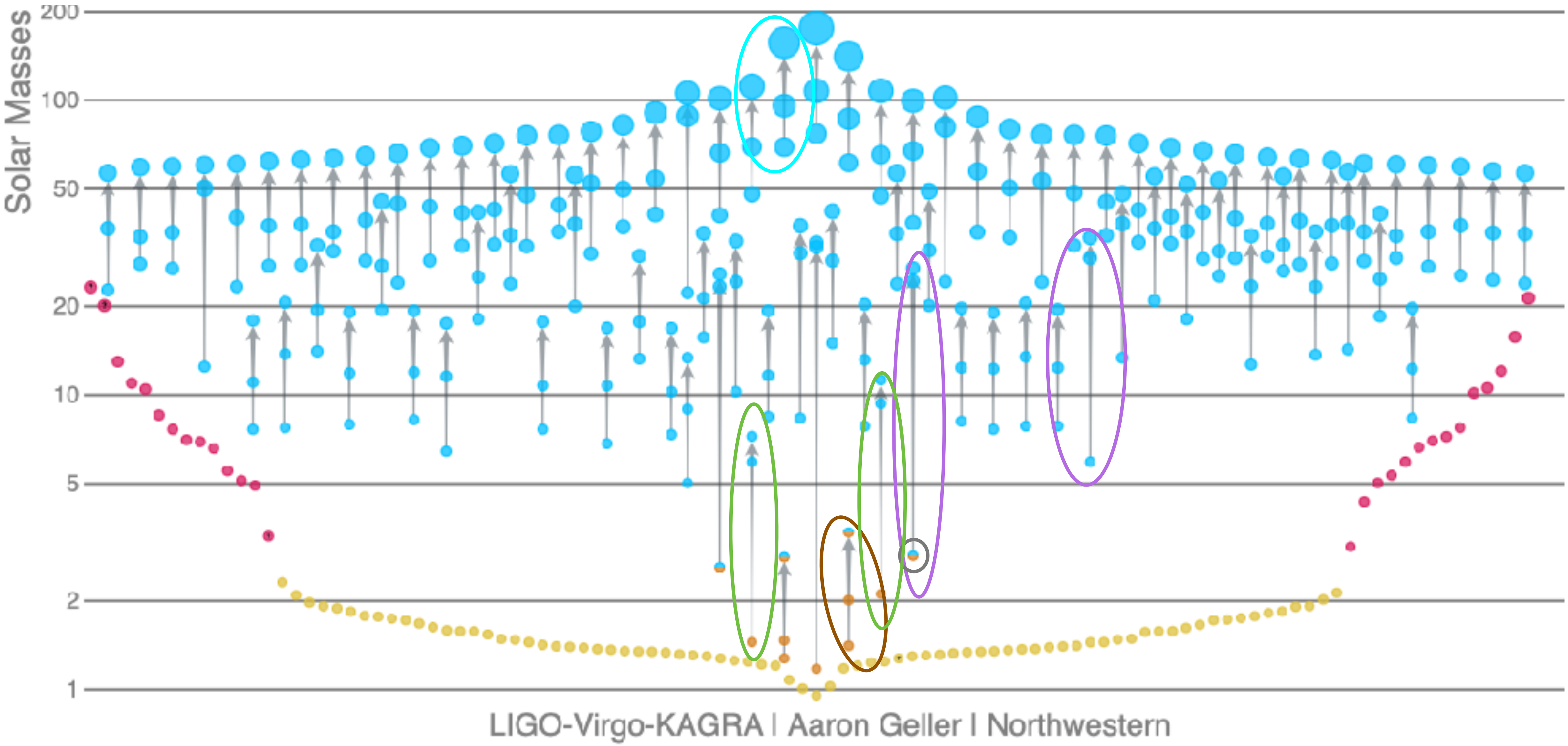
Spin magnitude and spin-orbit misalignment in GWTC-3

- Small but non-zero spins, long tail
- Isotropic spin distribution preferred -> cluster formation?
- overdensity for aligned spins -> binary formation?
- broader spin distribution above 30 Msun, correlated with unequal masses

=> (at least) two formation channels?

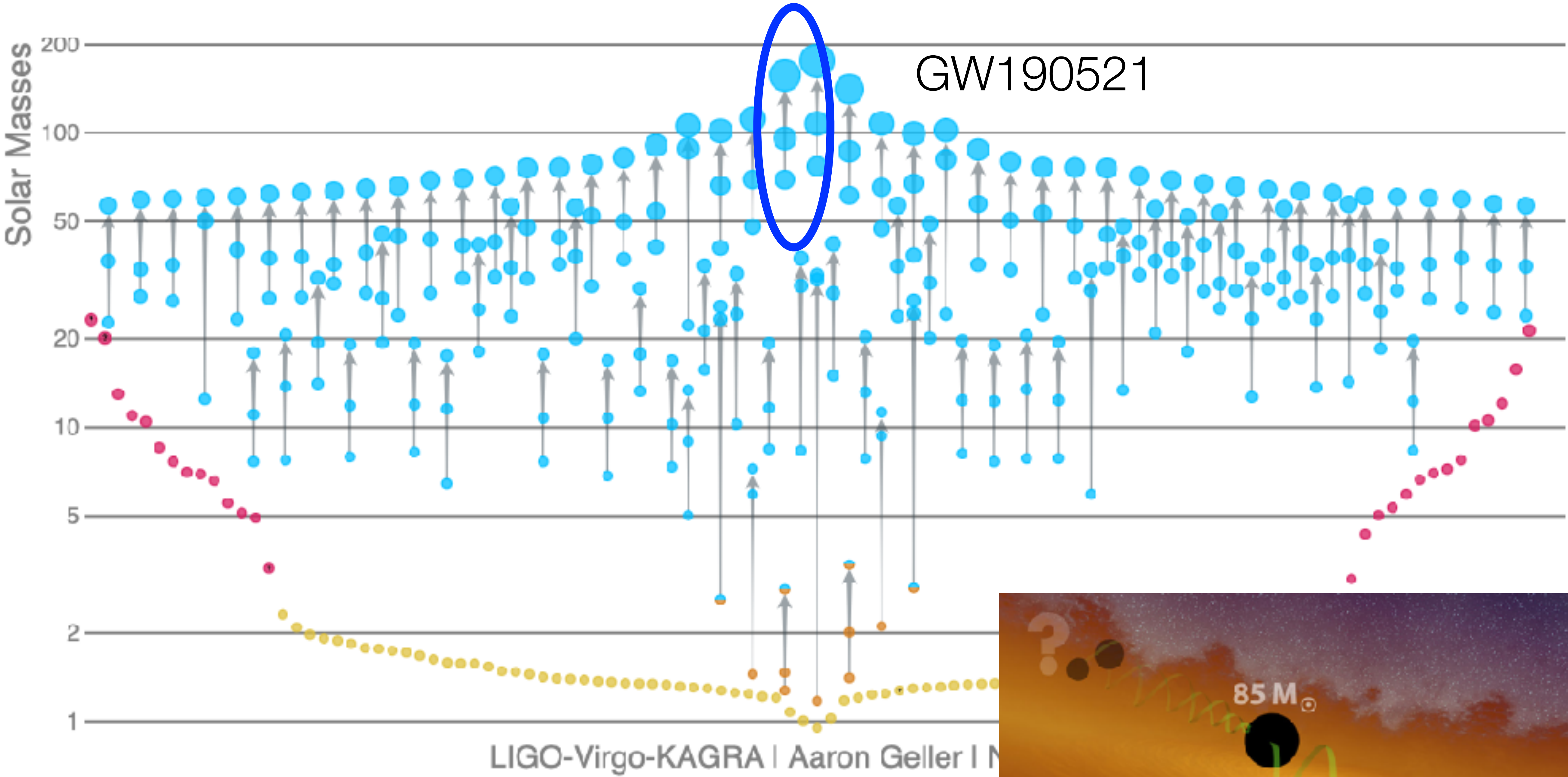
Confirmed in more detailed stiudies

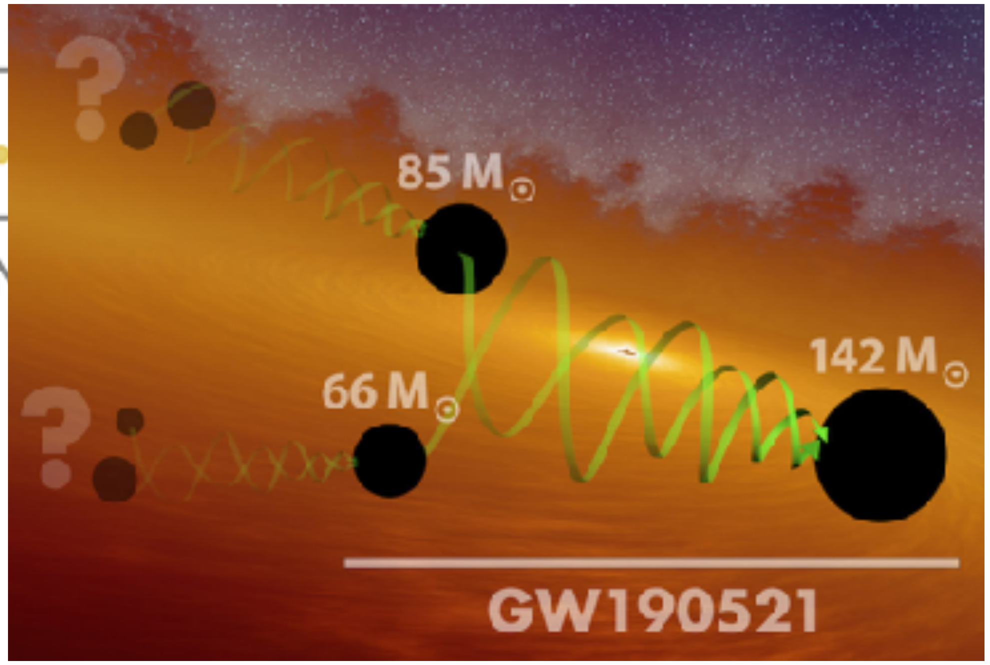
EXCEPTIONAL EVENTS (AFTER O3)



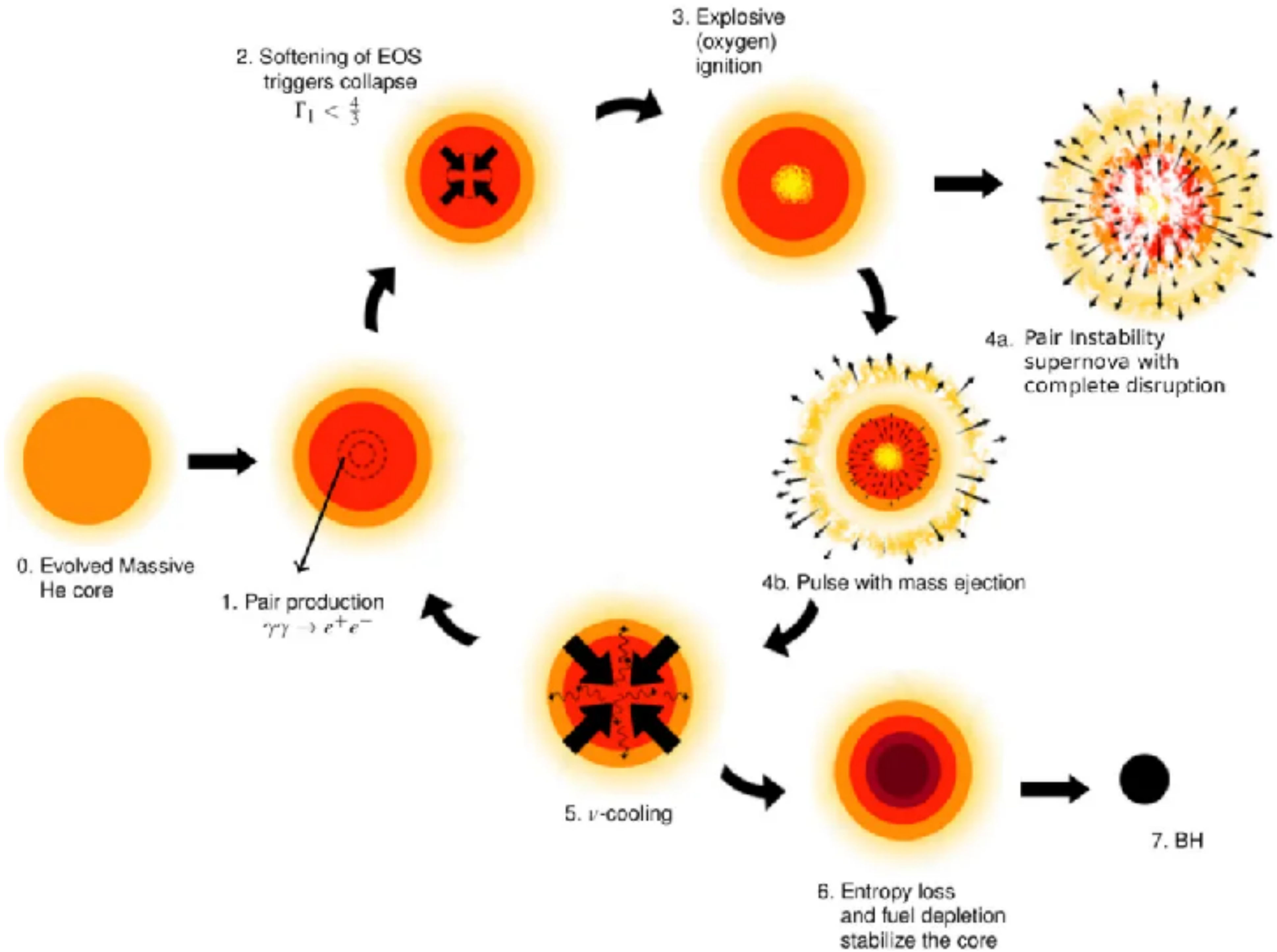
- First unequal masses (GW190412, GW190814)
- Massive BHs (GW190521)
- Lower mass gap object (GW190814)
- BNS masses differ from MW (GW190425)
- NSBH (GW200105-GW200115)

VERY MASSIVE BLACK HOLES





BHS OF 85 MSUN SHOULD NOT EXIST

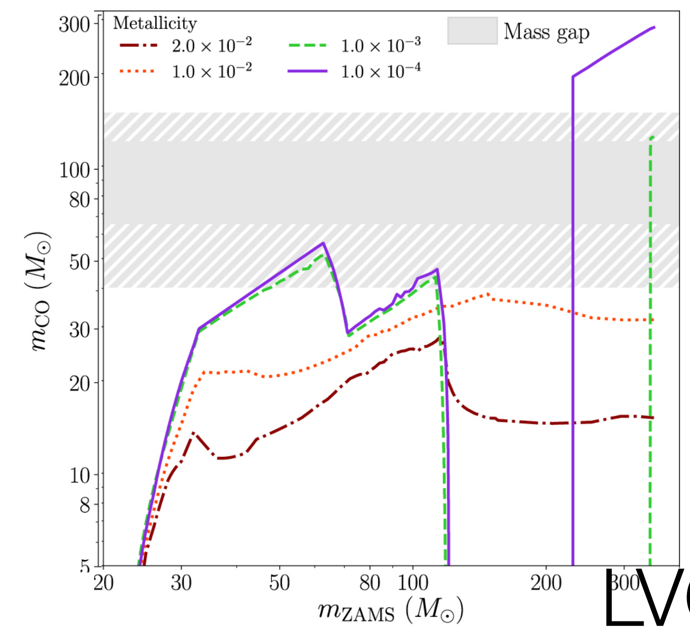


Pair instability supernova completely destroys star

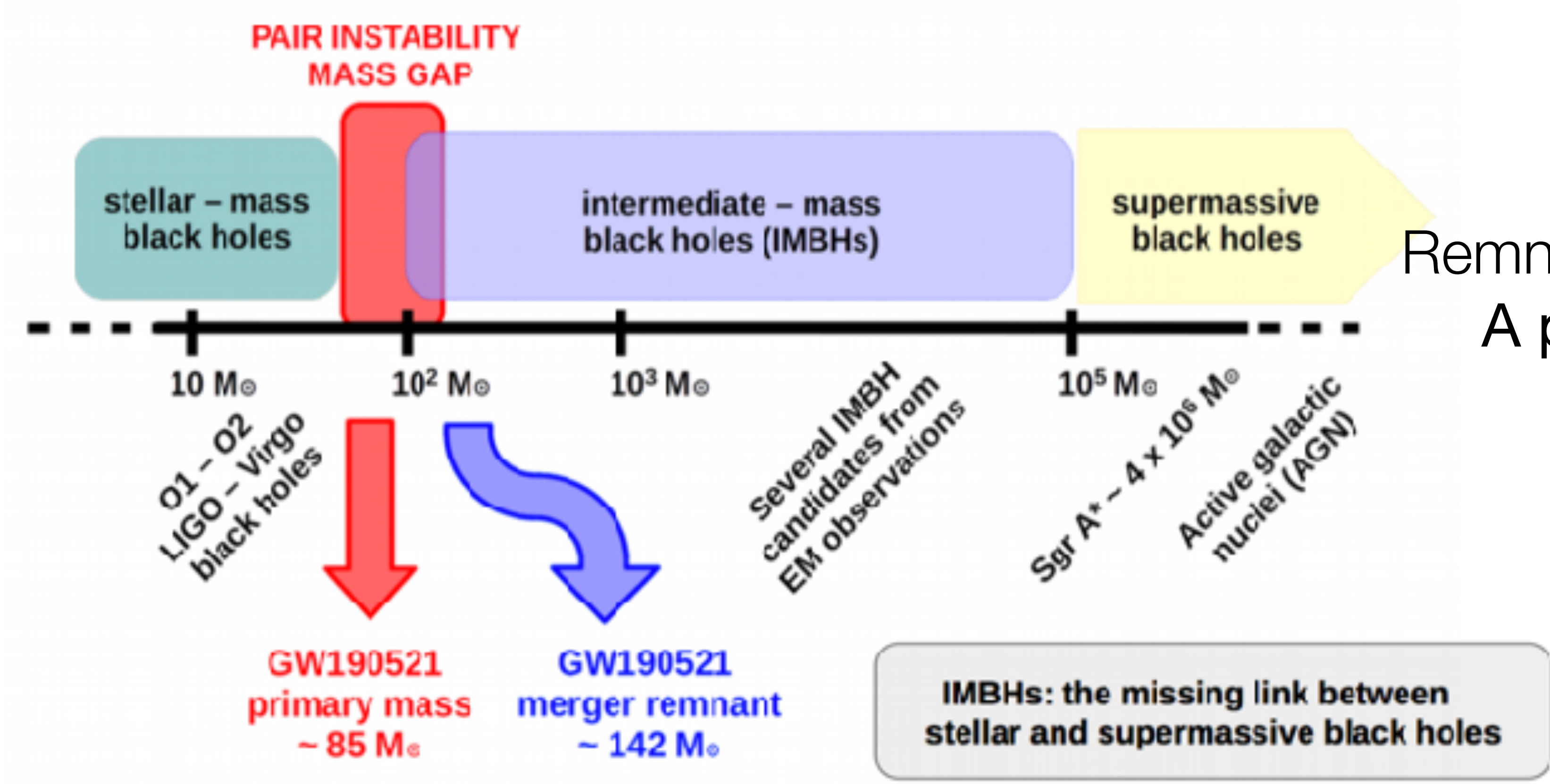
HIGH MASS STELLAR BLACK HOLES

BHs in pair instability supernova gap: challenge

- 2nd gen? But Expected high kick velocity
- Stellar merger?
- AGN disk



LVC+2020



Remnant mass: 142 Msun: IMBH

A pathway to intermediate mass black holes?

SUPERNOVAE AS GW SOURCES

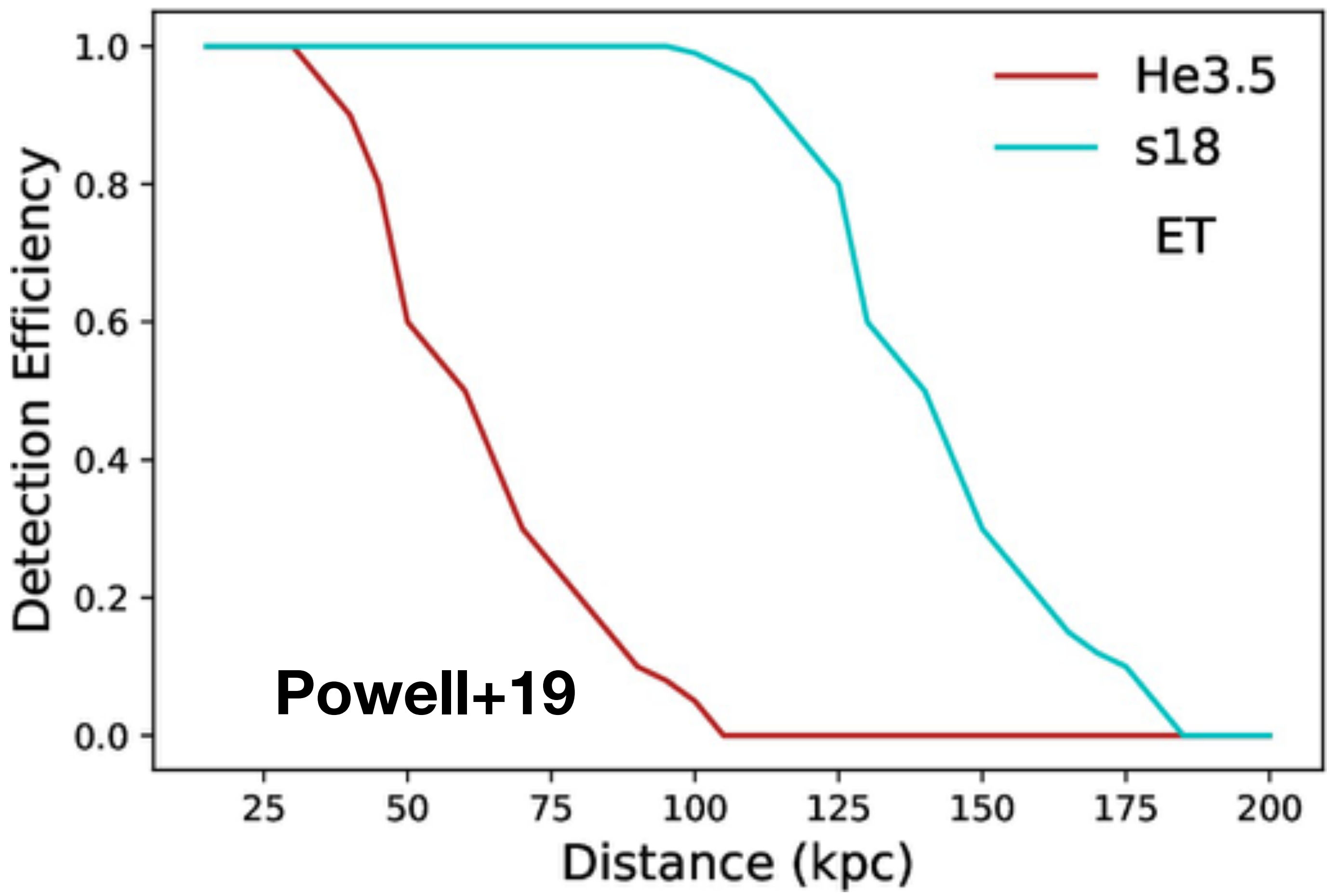
New class of sources

Major uncertainties on the GW emission

Lots of information on central engine, geometry of the explosion

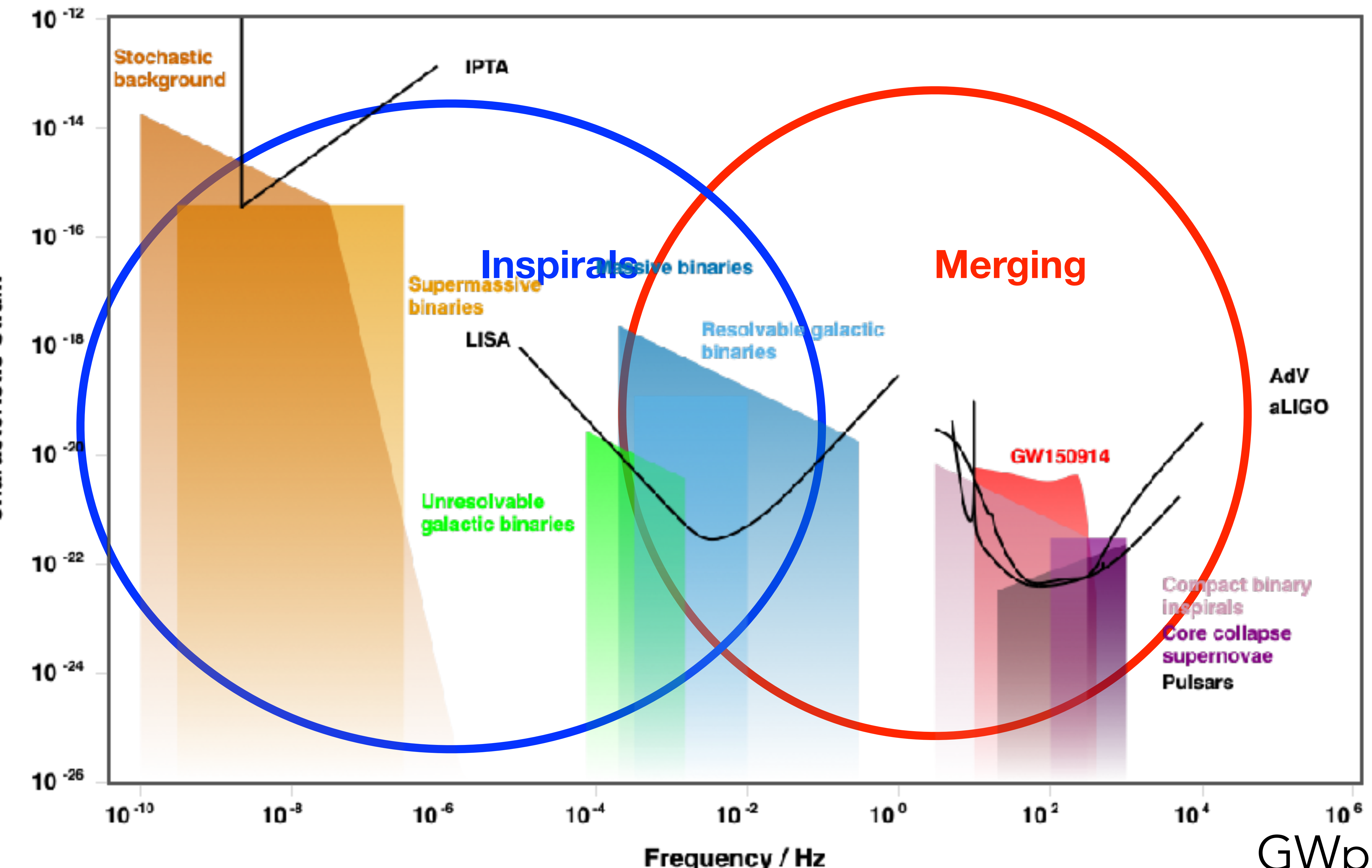
Multimessenger: Neutrino, GWs, EM

Most energetic model: <20 kpc by 2G, 200 kpc by Einstein Telescope



LOW FREQUENCY SOURCES

Supermassive black holes
Compact binaries in the Milky Way



GWplotter.com

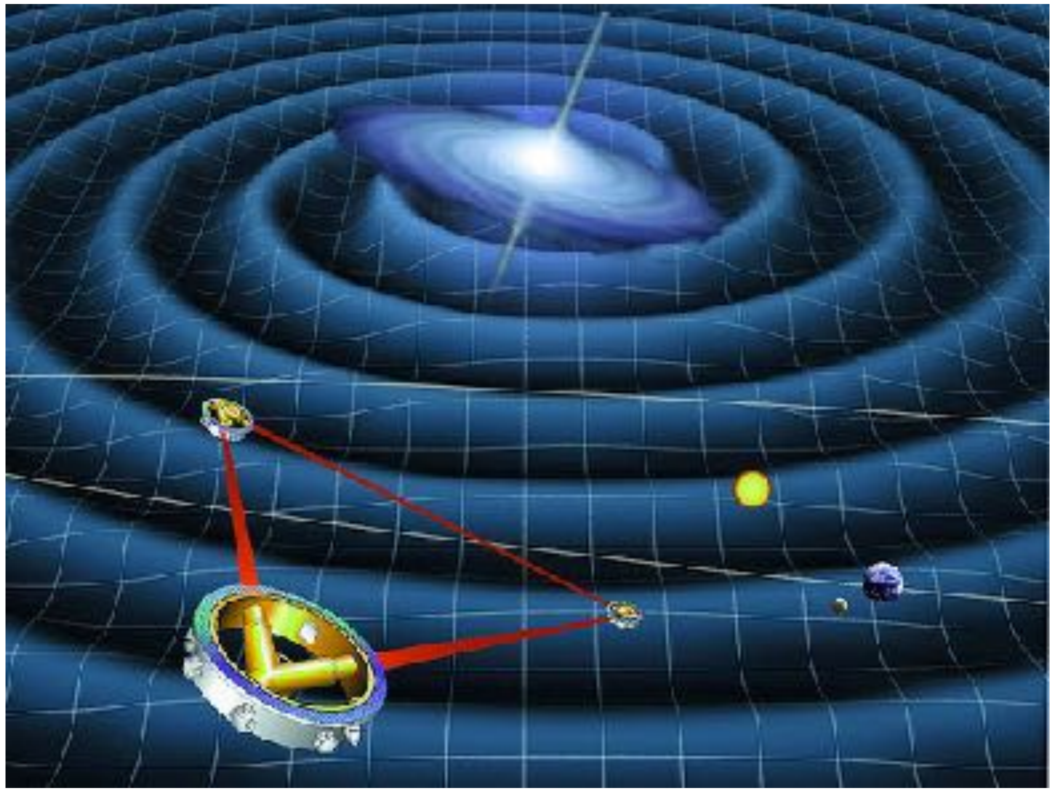
BLACK HOLE MERGERS IN THE MILKY WAY

Virgo/LIGO merger rate : 18-44 Gpc^{-3} yr^{-1}

Up to 4-50 mergers per million year in MW

No expected BBH merger
Detections in MW

How many are "close" to merger?



DETECTING COMPACT BINARIES IN THE MILKY WAY

Black Holes: highest mass evolution
Very sensitive to metallicity

<10 systems
For LISA

Neutron Stars: High mass evolution
Somewhat sensitive to metallicity

~5-30 systems
(Belczynski+10)
~300 (Andrews+19)

White dwarfs: 95% of stars!
Type Ia supernovae
Low mass evolution, common envelope, tides
EM counterparts
Map the Milky Way and its environment
Understand/quantify past star formation

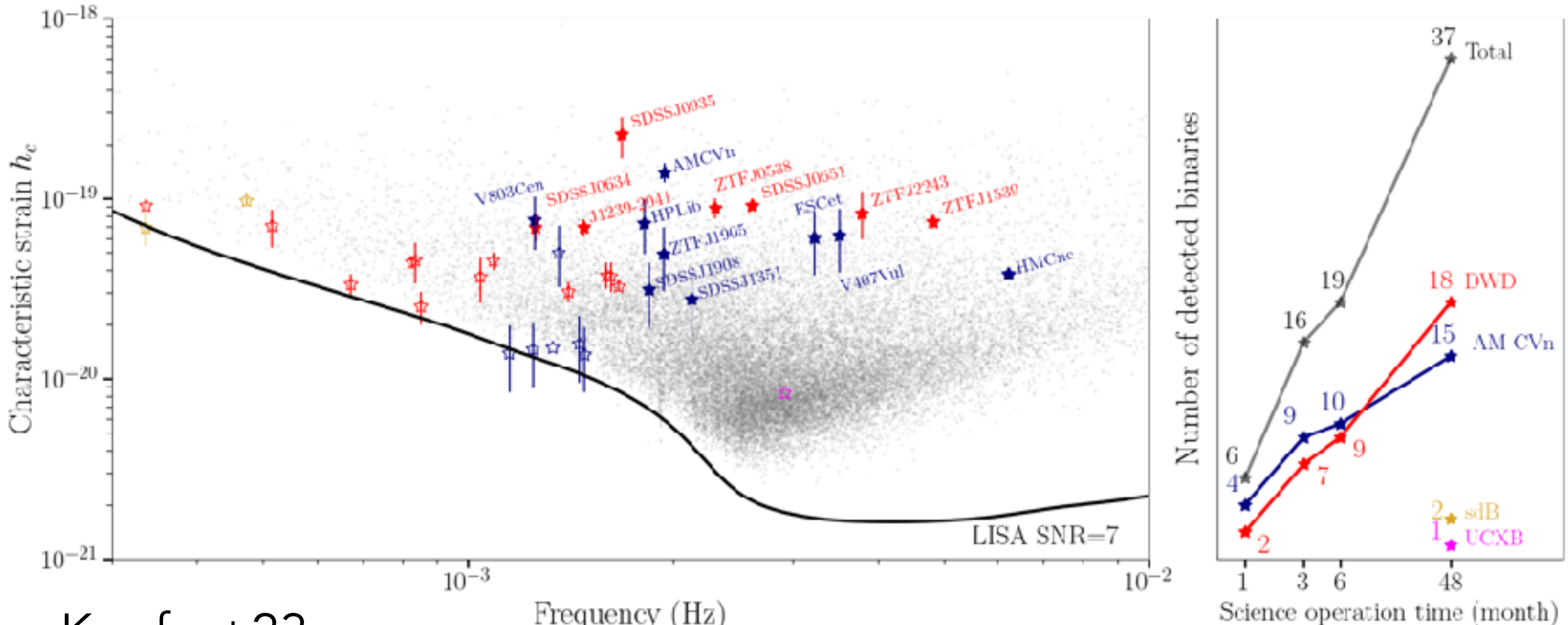
~6000 systems
(Nelemans+01)

Lamberts+19

And even stellar binaries and planets

THE PROMISE OF DETECTING COMPACT BINARIES IN THE MILKY WAY

Verification binaries: known LISA sources: great for calibration



Kupfer+23

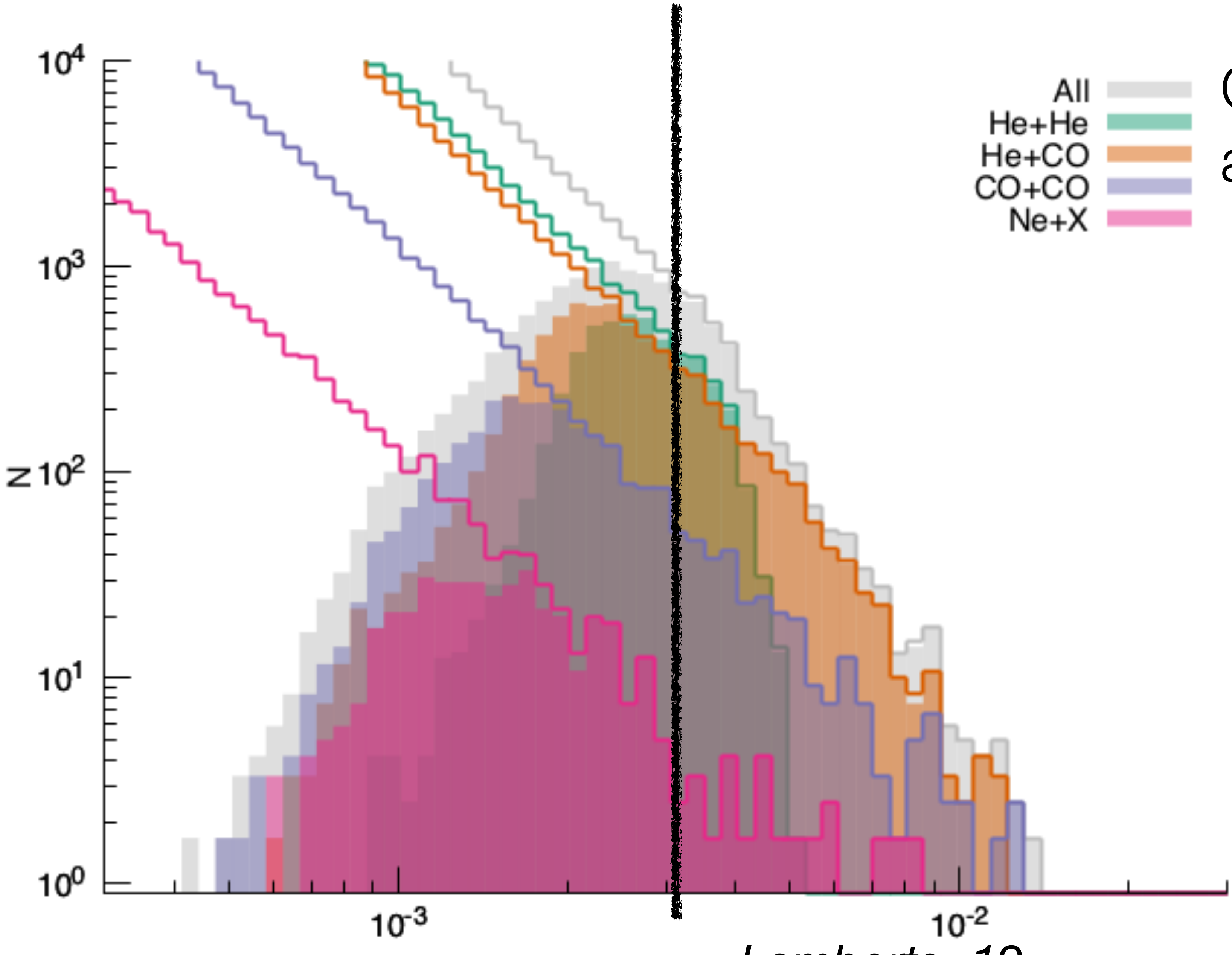
Much more information: sky localisation, distance, mass measurements, radii….

Understand binary evolution: common envelope, mass transfer, tides, supernovae *(Nelemans+01, Ruiter+10, Nissanke+12)*

Major effort: finding more EM binaries (ZTF, BlackGem, VRO/LSST)

LISA DETECTIONS: A COMPLETE CATALOG OF WHITE DWARF BINARIES

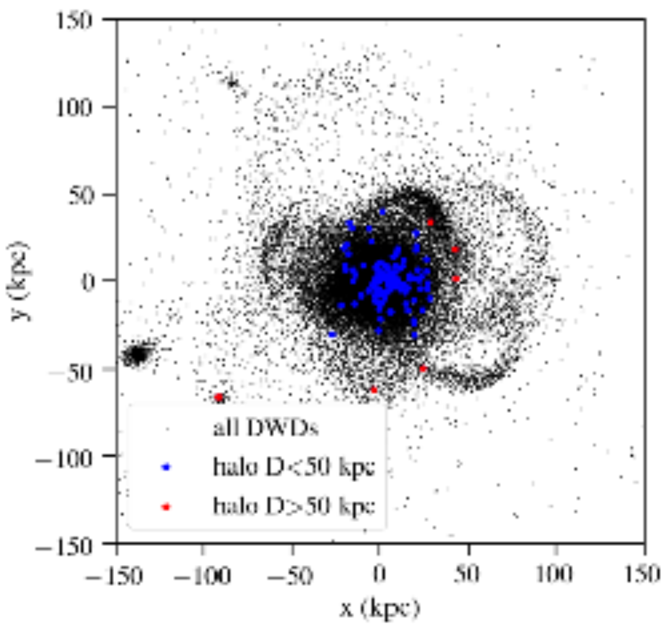
~12 000 systems: measurement of period and GW strain
☹️ No masses, no sky localisation unless high signal/noise
😊 GW amplitude(r) ~ 1/r, no extinction, no spatial crowding



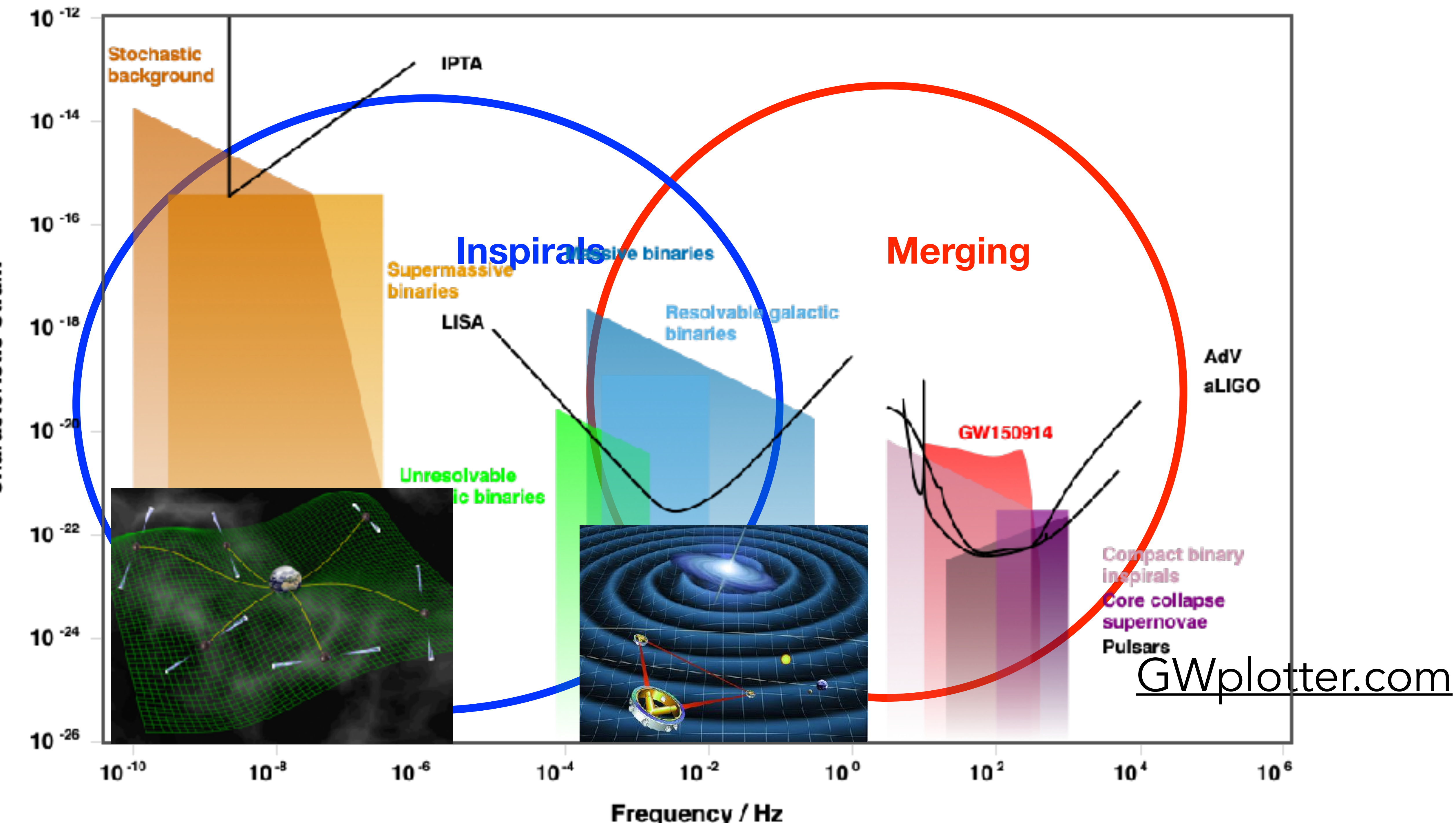
Lamberts+19

Complete down to f~3 mHz: all binaries below 11 minutes

Even in satellites!



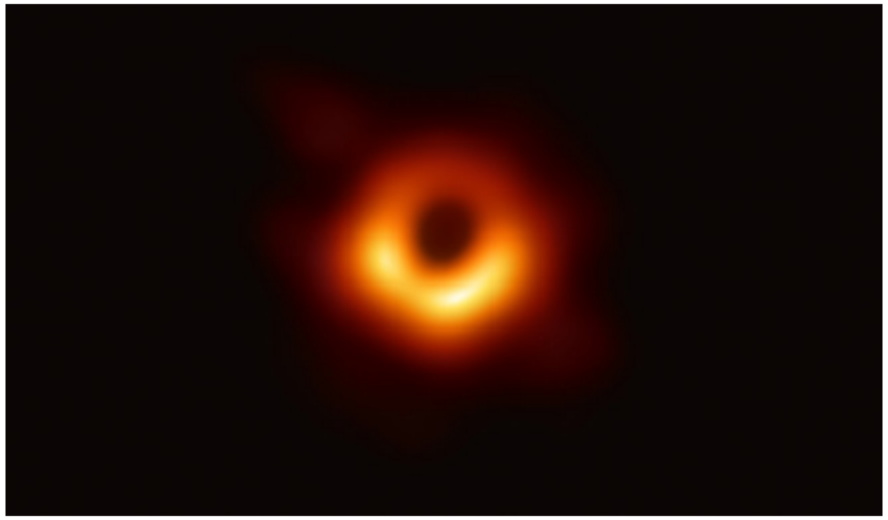
SUPERMASSIVE BHS: PULSAR TIMING & LISA



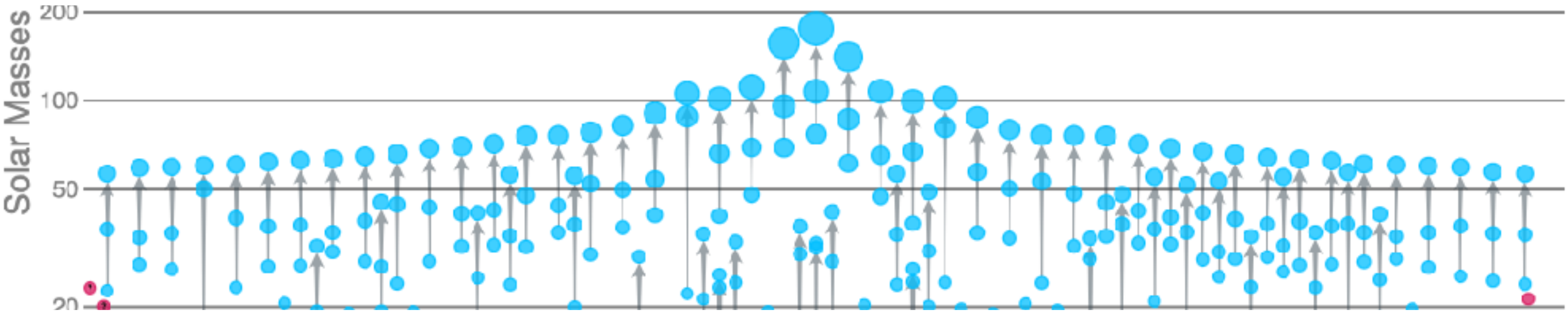
(PTA: Gilles' talk, and recent newspapers!)

MORE MASSIVE COMPACT OBJECTS

Supermassive black holes: millions- billions of Msun



Intermediate mass black holes?



SUPERMASSIVE BLACK HOLES

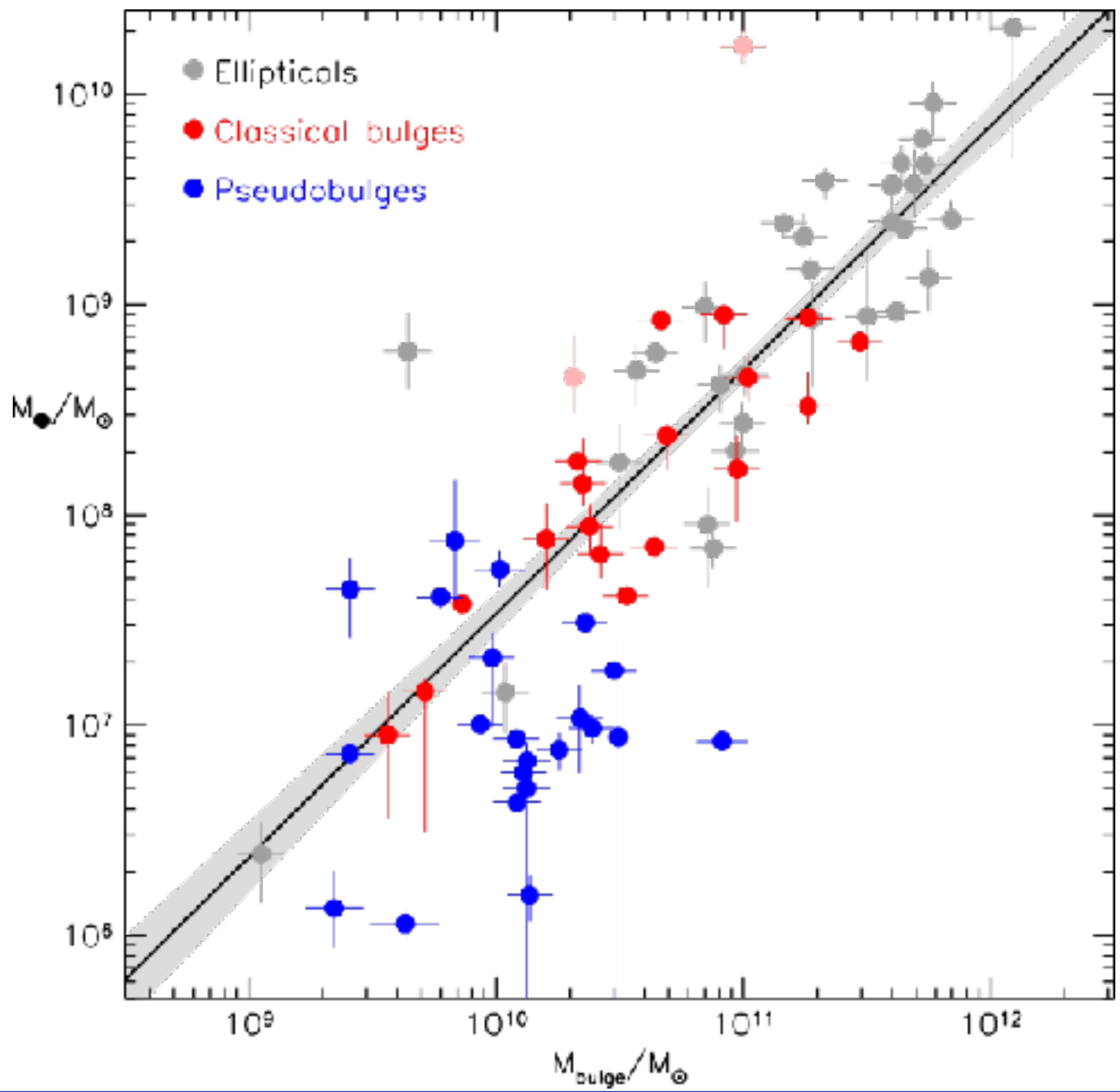
Found at the center of all (massive galaxies)

Kormendy, Ho 2013

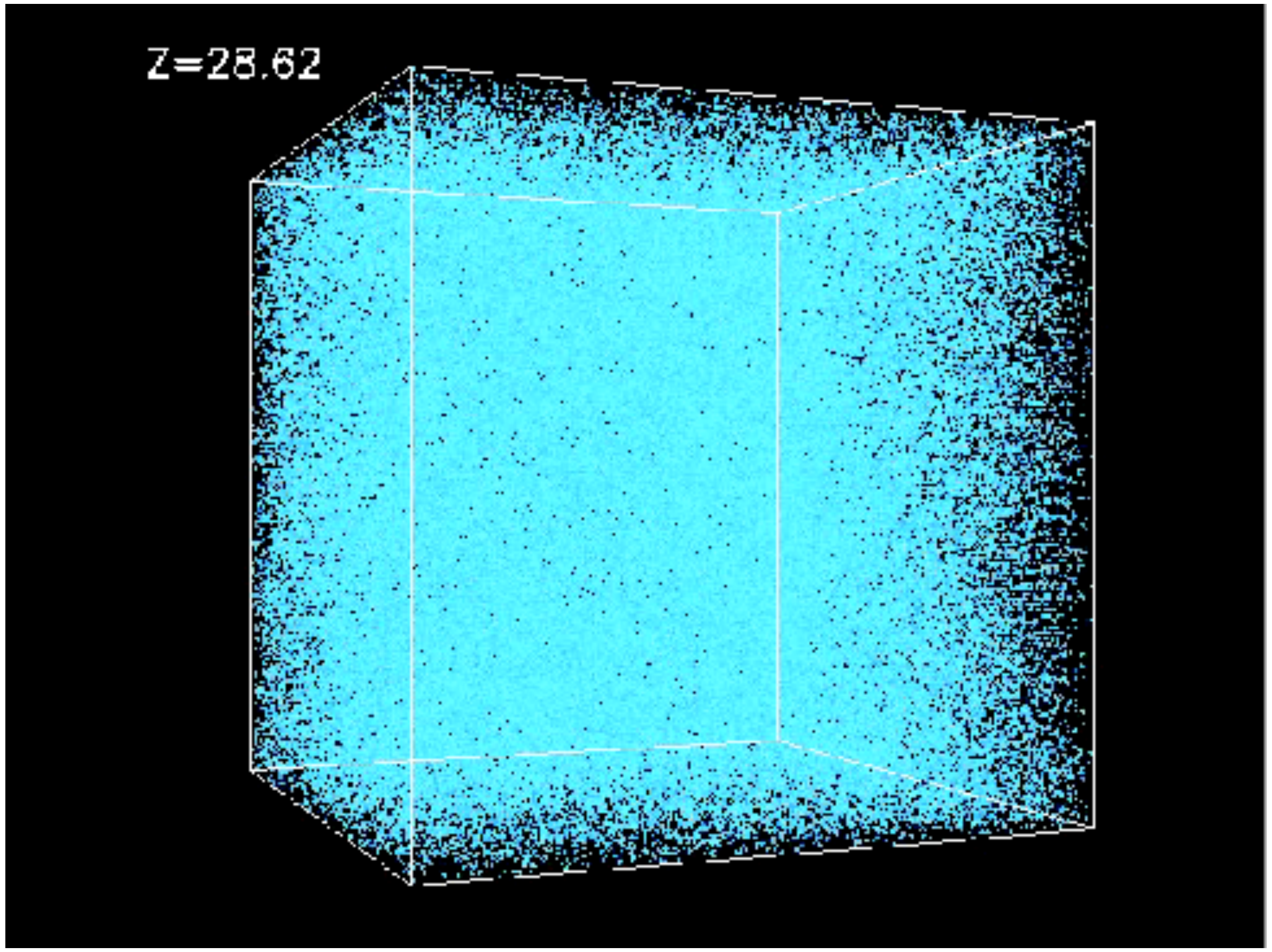
Masses correlate with Galactic properties
-> joint evolution -> how?

Evidence of very massive BHs very early (10^8 Msun in less than a Gyr)
-> how?

Hard to observe with EM

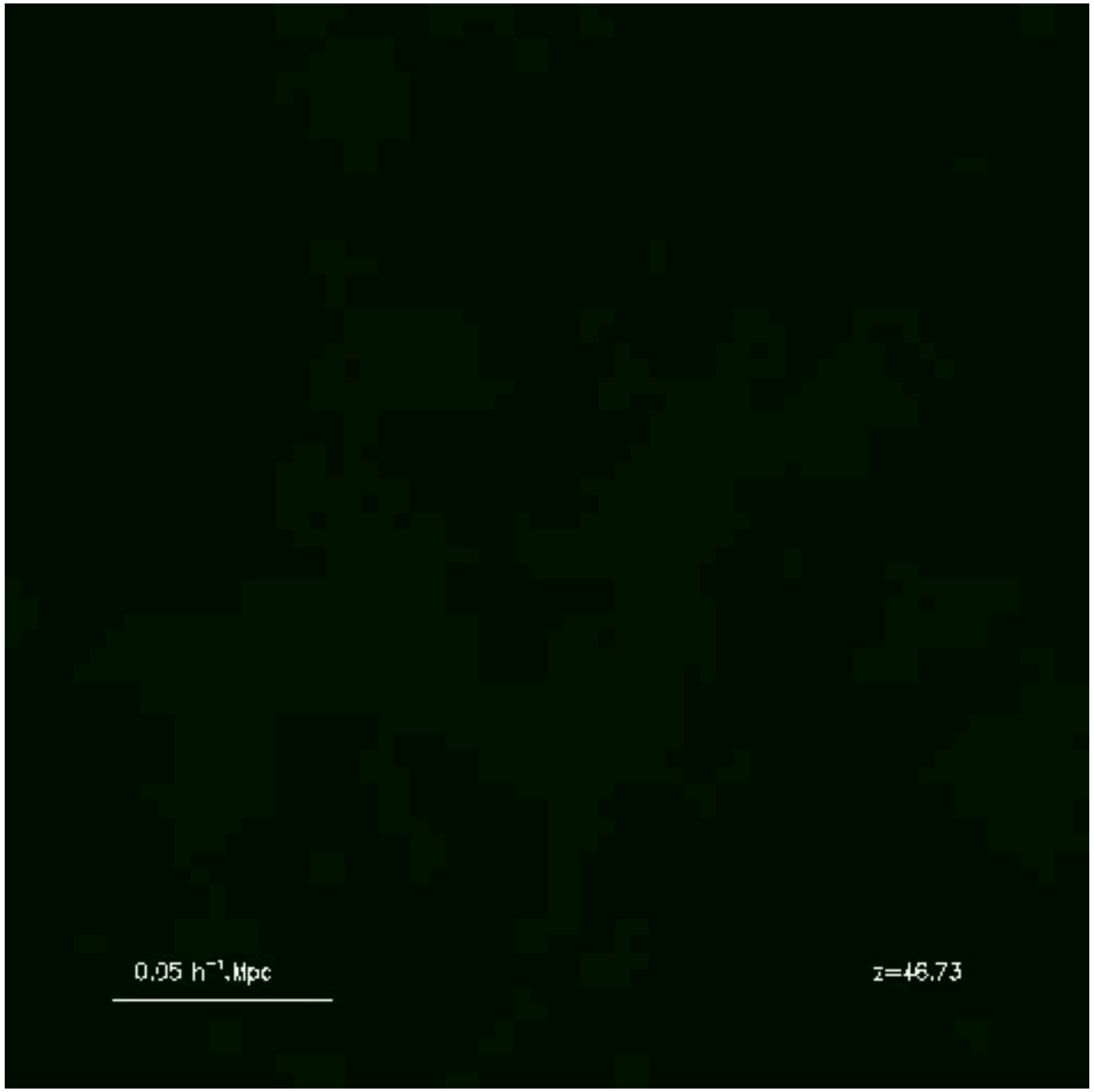


HOW DO GALAXIES GROW?

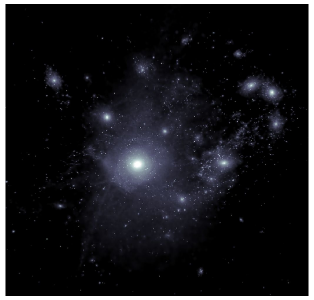


Cosmic web -> structure increases over time with accretion and mergers

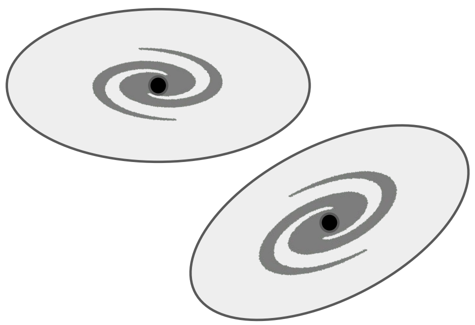
Active Galactic Nuclei strongly Affect galaxies



HOW DO SUPERMASSIVE BH MERGE? HOW DOES THE BINARY SHRINK?

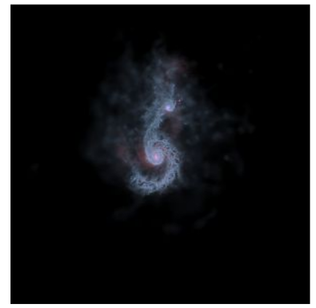


Credit: Lupi et al. (2019)

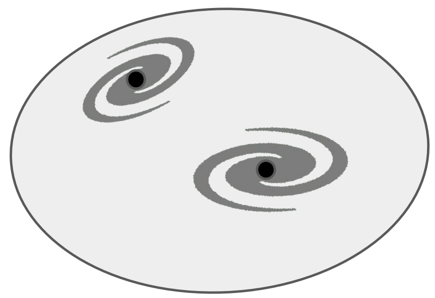


Mpcs:
The large scale structure

Influence of the large scale environment on: black hole seeding, frequency of mergers, galaxy transformation

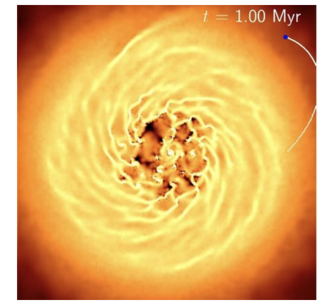


Credit: Capelo et al. (2015)

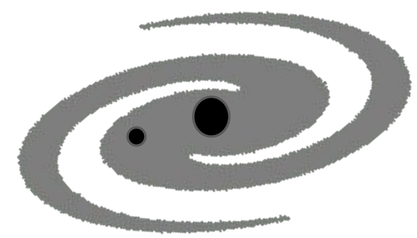


1-100s kpcs:
Galaxy interactions/merger

Details of the merger have influence on: black hole growth via gas accretion, formation of a black hole binary, galaxy transformation

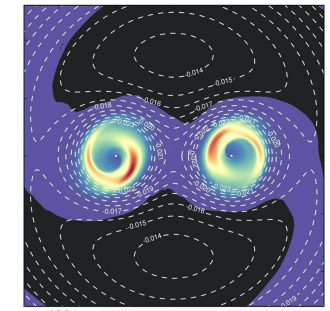


Credit: Souza Lima et al. (2017)

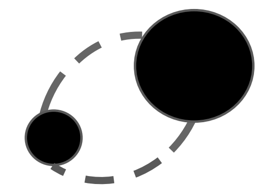


1-10s pc:
Formation of a bound binary

The host properties have influence on: hardening of the binary, accretion episodes



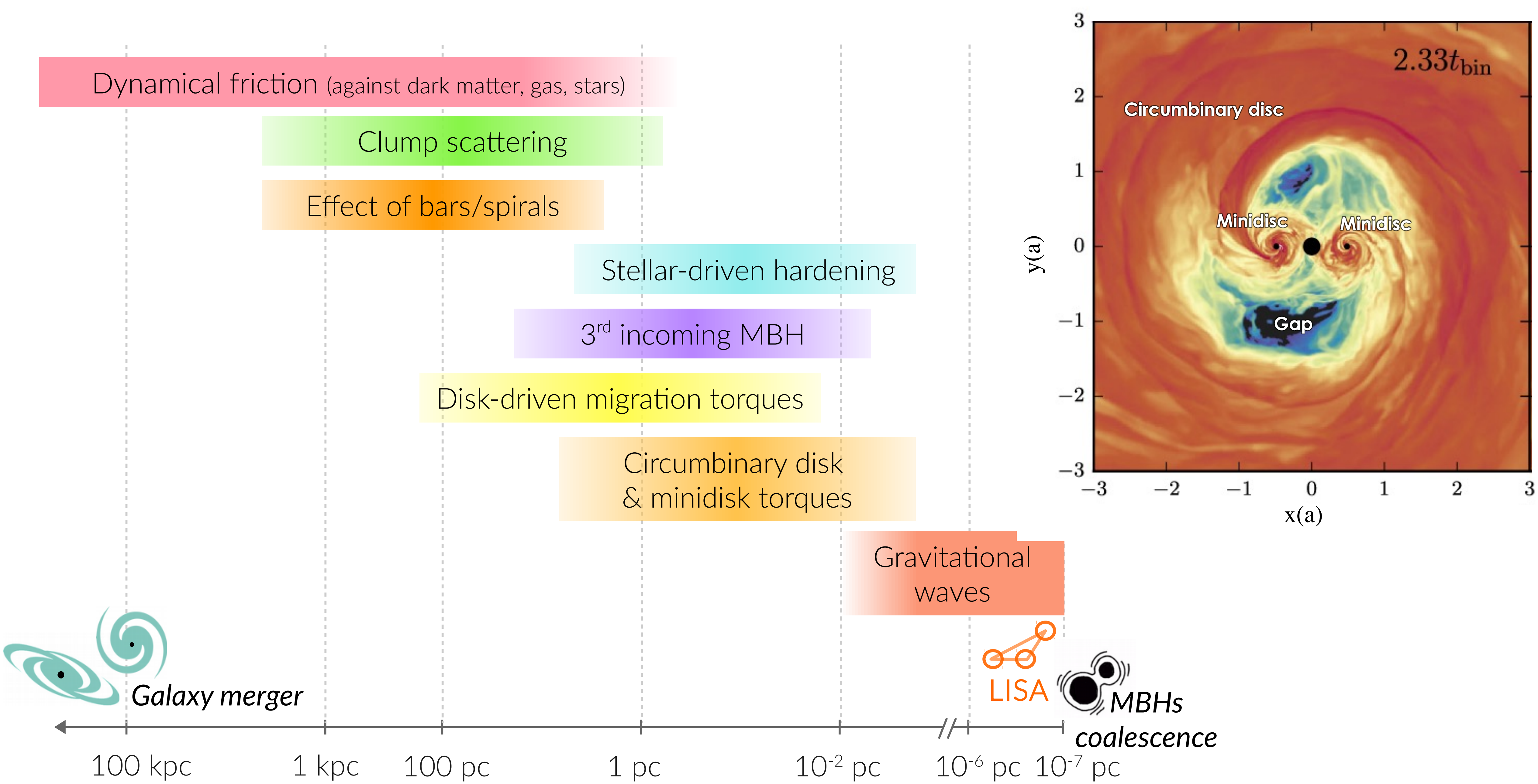
Credit: Bowen et al. 2017



<1 pc:
Hardening of the binary

The host properties have influence on: timescale of hardening
Effect of circumbinary disc
Three-body interactions (hyper-velocity stars)

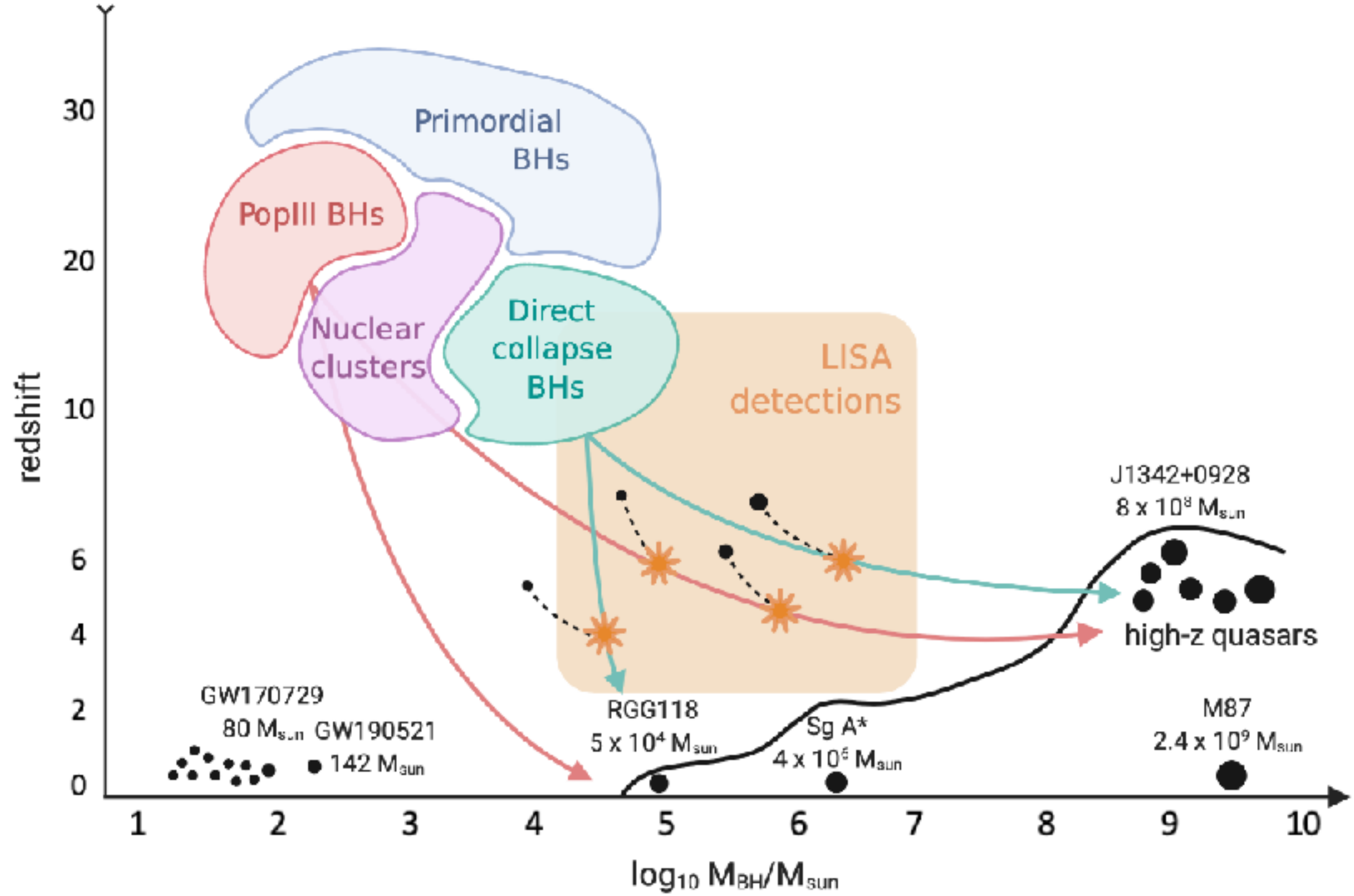
MULTISCALE-MULTIPHYSICS PROBLEM



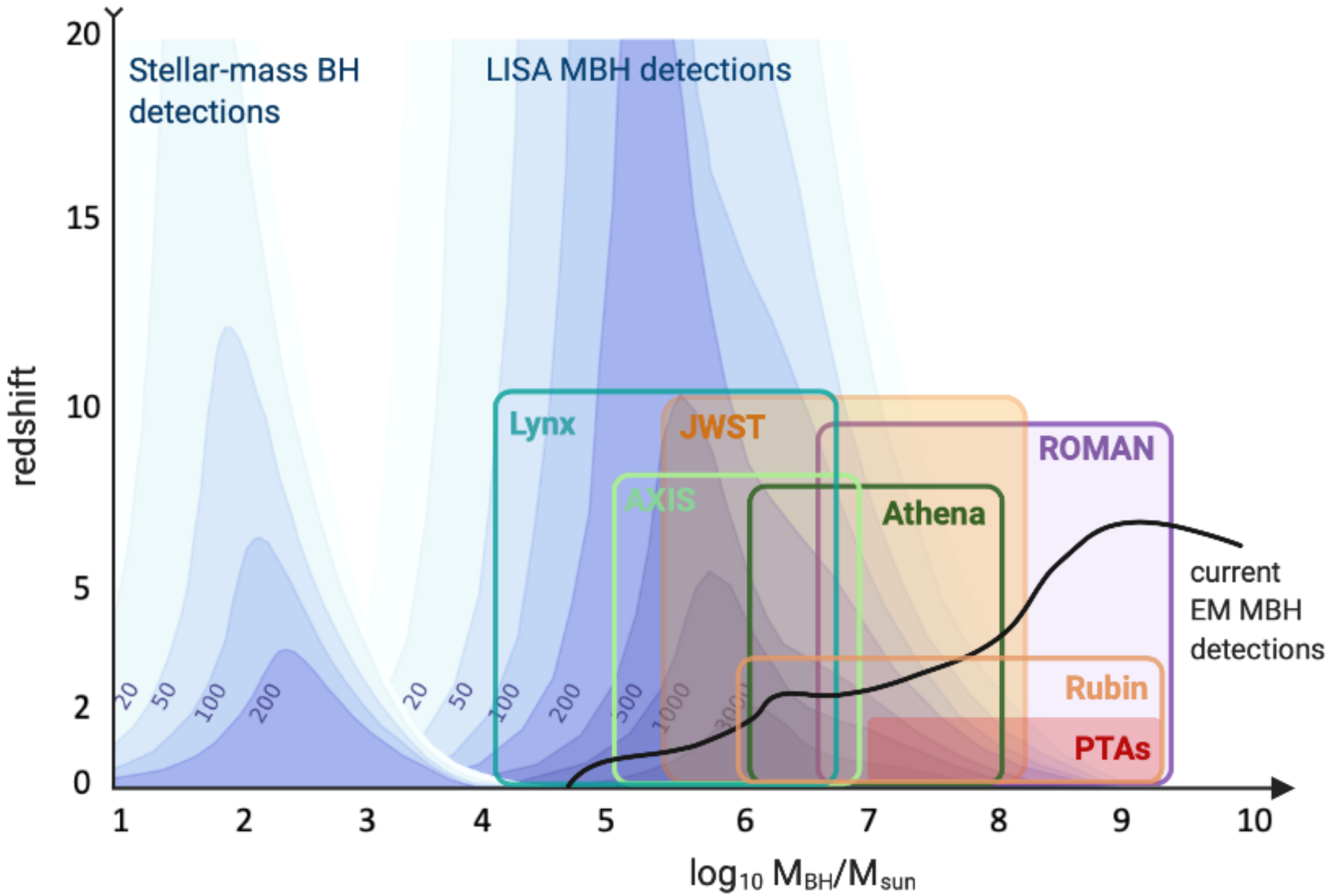
Observations, models, simulations are hard: rates uncertain
-> observations will have strong astrophysical implications

ORIGIN OF SUPERMASSIVE BLACK HOLES?

Very massive BHs are found in early Universe -> major challenge



OBSERVING BLACK HOLES OVER A WIDE MASS RANGE



GWs observe much further, with different biases

ASTROPHYSICS WITH GW

GW are a new way to understand fundamental components of the Universe: compact objects, stars, galaxies

Different frequencies <-> different objects, different timescales, different distances

Crucial information: merger rate, masses, spins

Core question: bringing the binaries to merger -> hard problem