

ASTROPHYSICS WITH GRAVITATIONAL WAVES

Astrid Lamberts

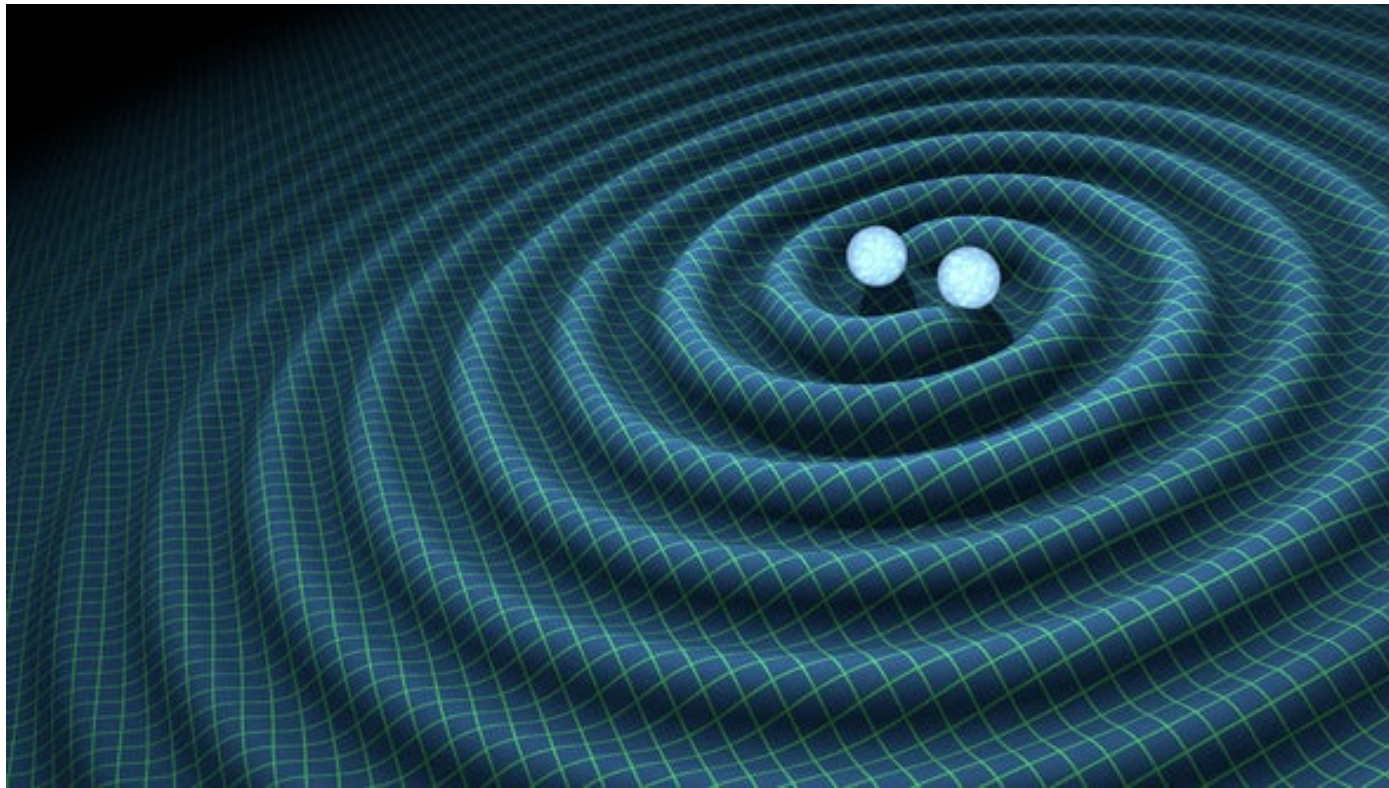


OBSERVATOIRE
DE LA CÔTE D'AZUR

UNIVERSITÉ CÔTE D'AZUR

MaNiTou 2026

HOW TO CREATE GRAVITATIONAL WAVES?



Propagation of disturbance
of spacetime

Needs: very massive objects

Speeds $\sim$ speed of light

-> Extreme objects/phenomena: compact objects, explosions

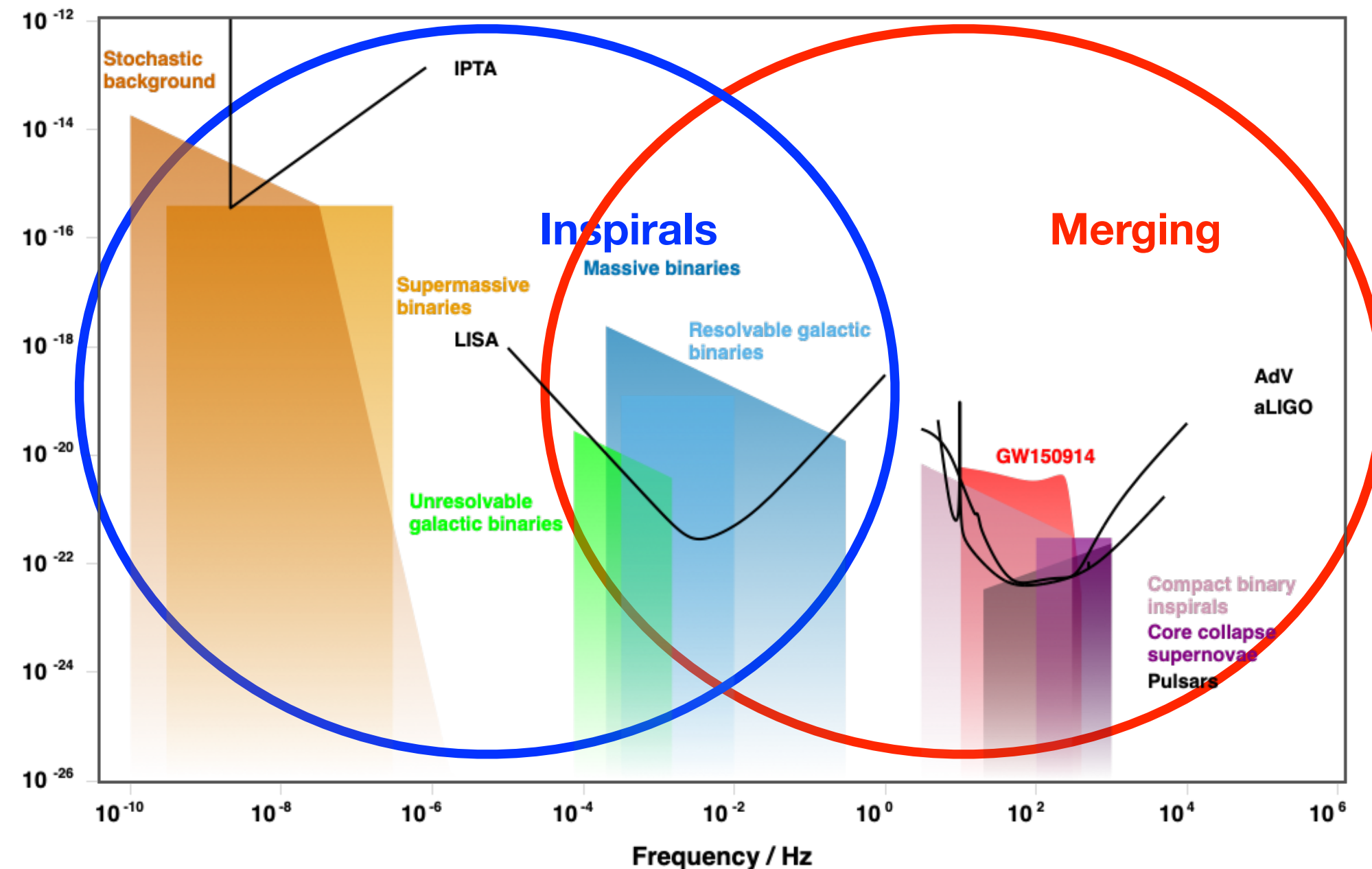
Anything with a quadrupole moment (not spherically symmetric):
binaries...

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



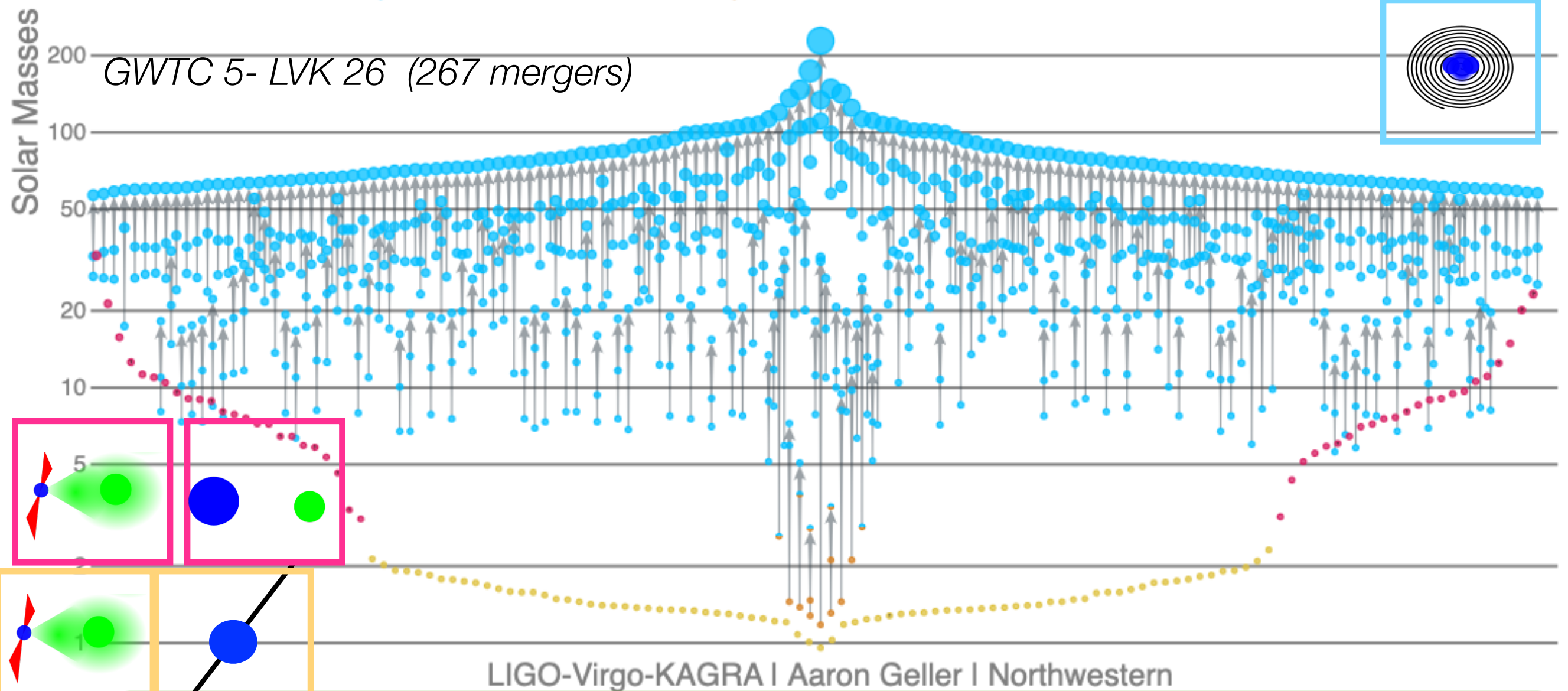
$$h \propto \frac{M^{2/3} \mu f^{2/3}}{d}$$

GW frequency $\sim$ 2 orbital frequency

GWplotter.com

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



White dwarfs (EM only, until LISA)

Where do these distributions come from?

FROM STARS TO COMPACT OBJECTS

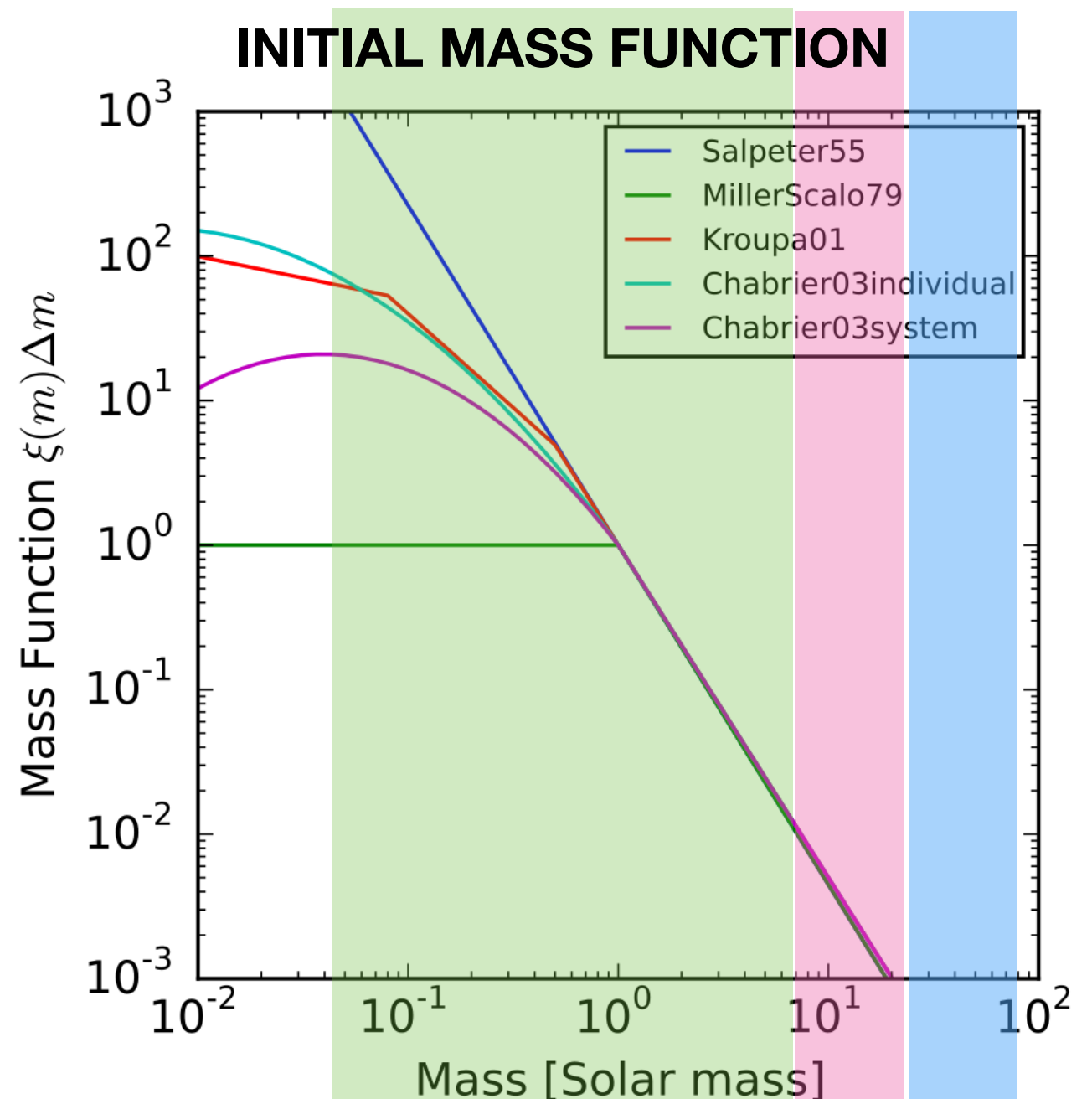
Single stars :

$M < 8-10 M_{\text{sun}}$: White dwarf

$8-10 < M < \sim 20 M_{\text{sun}}$: Neutron Star

$M > \sim 20 M_{\text{sun}}$: Black holes

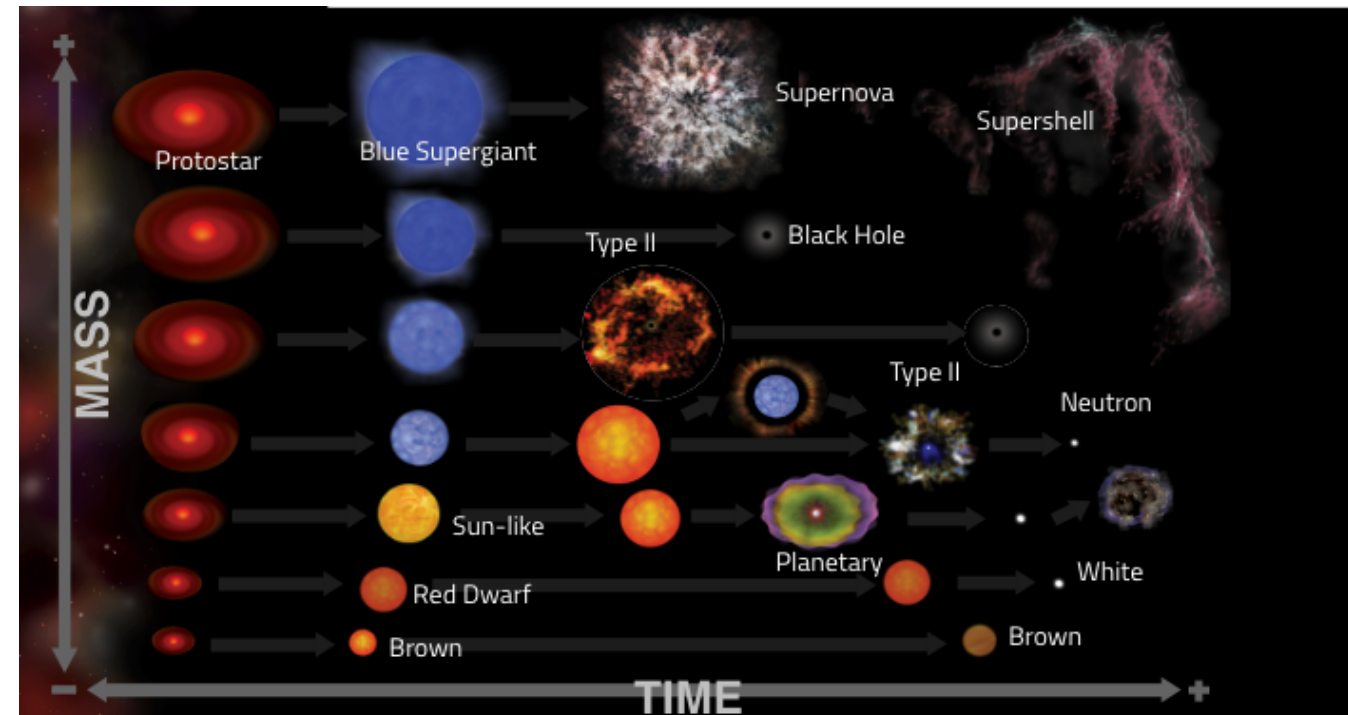
Many more white dwarfs
than NS and BH



SINGLE STELLAR EVOLUTION

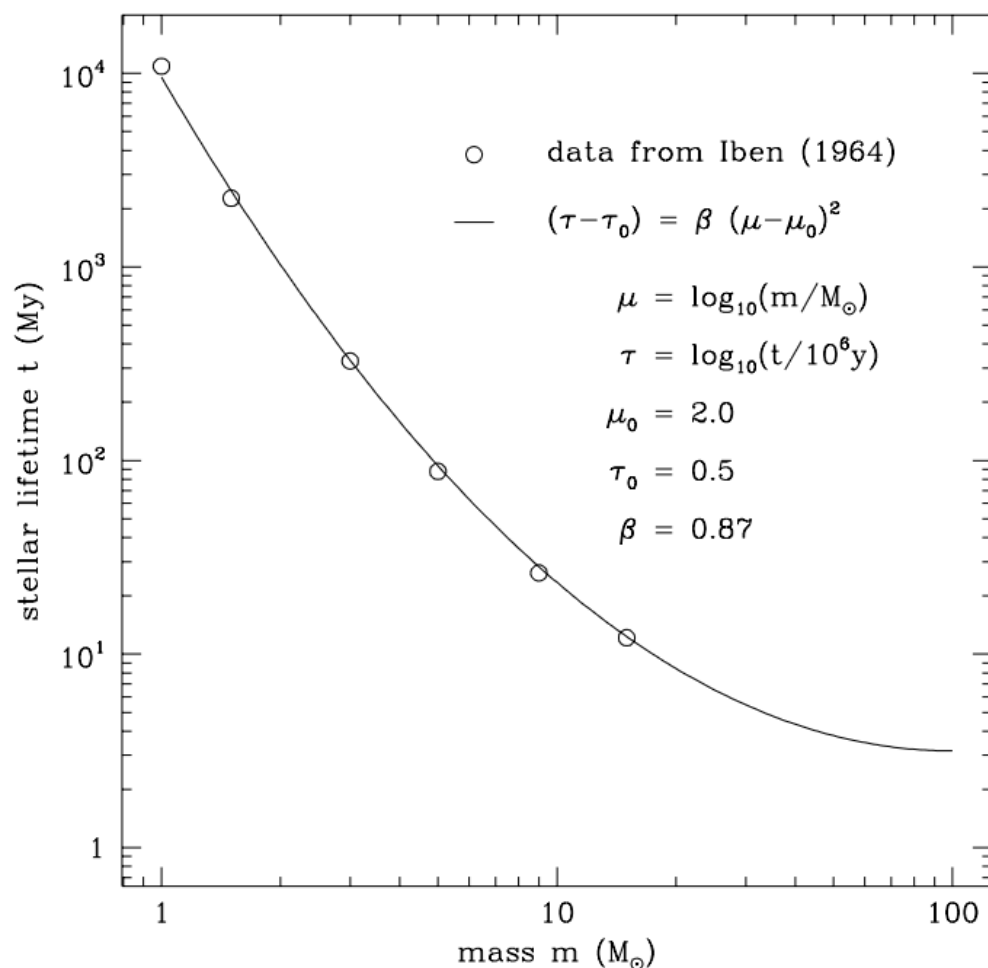
Mass: most important factor

Chemical composition (metallicity)
important for BH



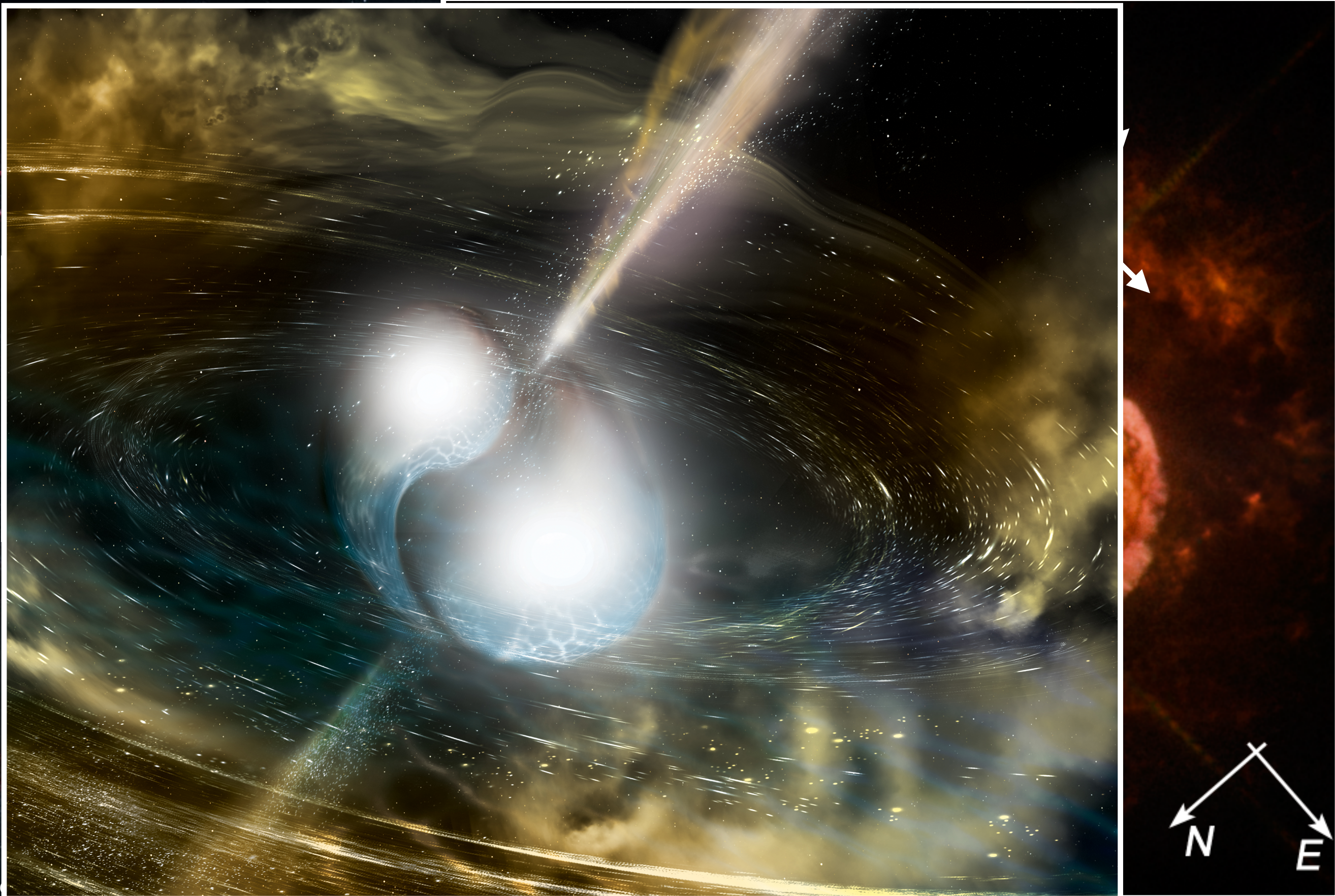
Chandra X-ray observatory

Massive stars are very short-lived
And there are not many of them at birth
=> not many at a given time
=> **Compact objects are unique way to study them**



Arabadijs et al, 98

MASSIVE STARS : COSMIC ENGINES AND FUNDAMENTAL PHYSICS

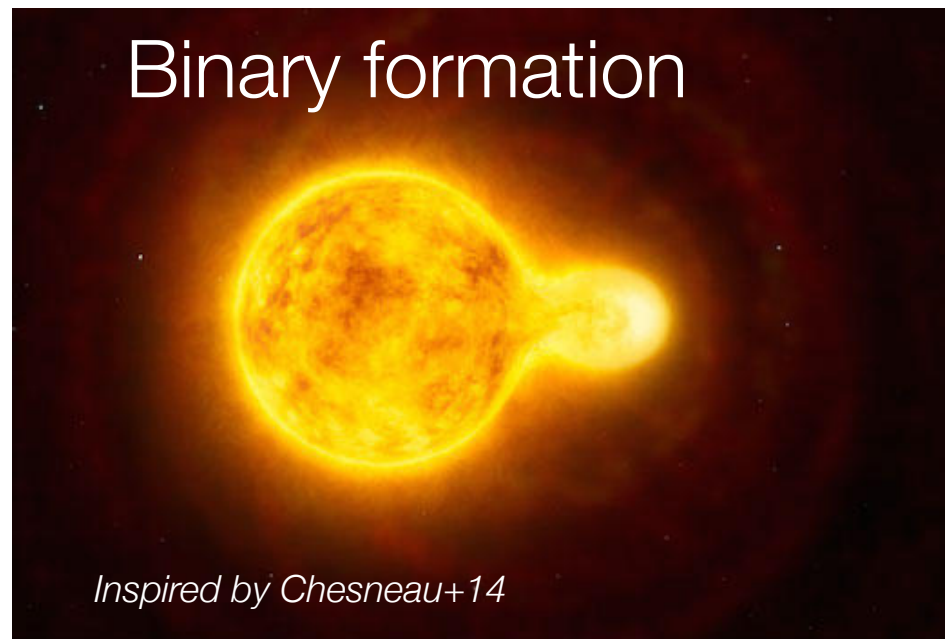


HOW TO GET COMPACT OBJECTS TO MERGE?

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

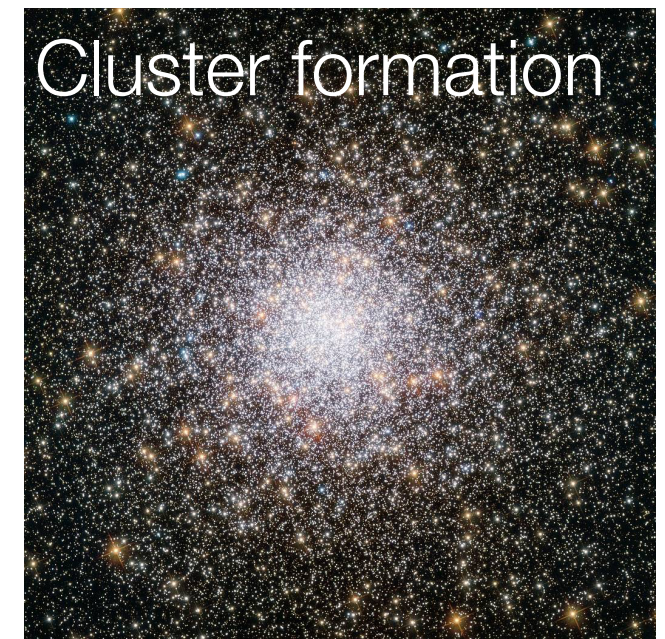
Initial stellar radii: already too far apart to ever merge

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 (actually triples)

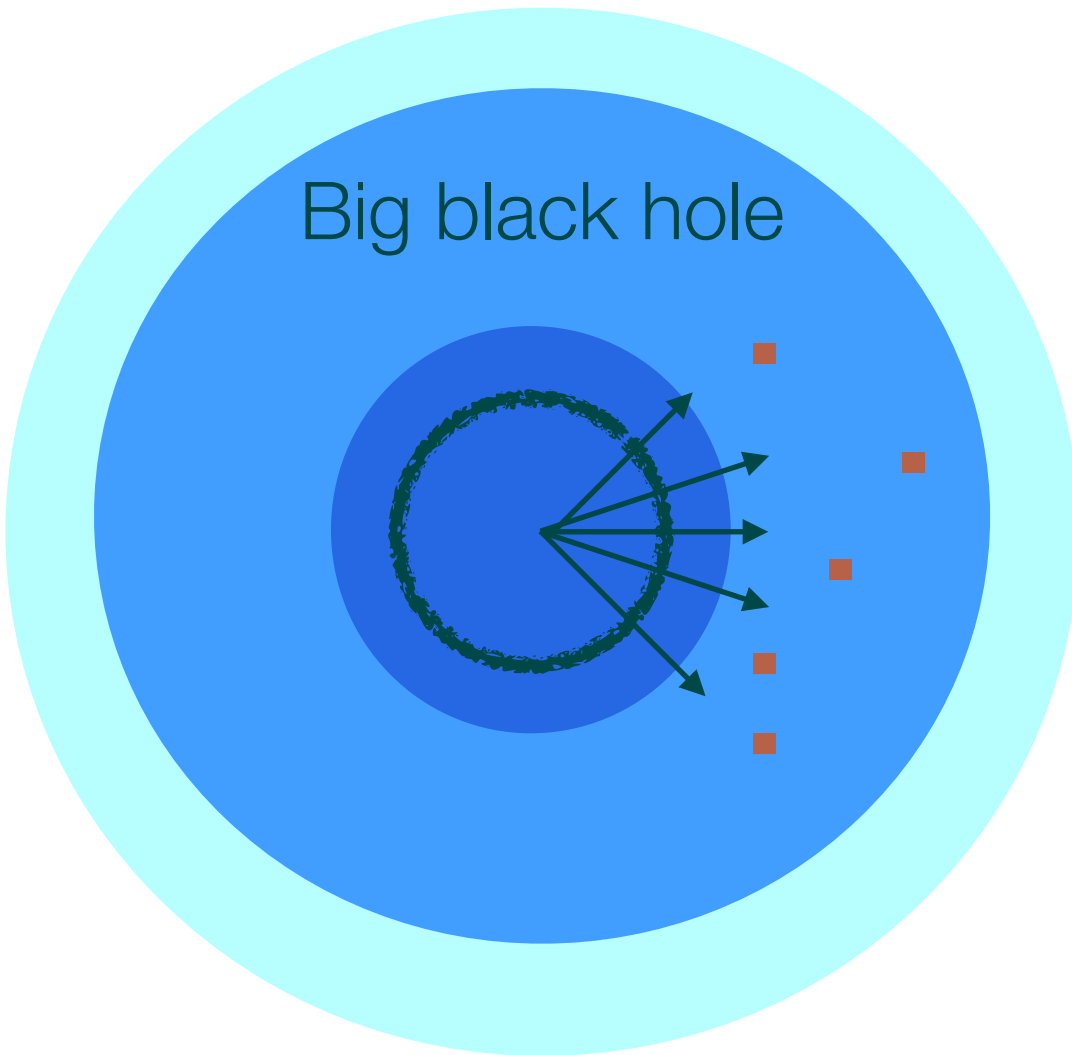
PROBLEM 1 : WINDS



IMPORTANCE OF METALS (C, O, Ne, Fe...)

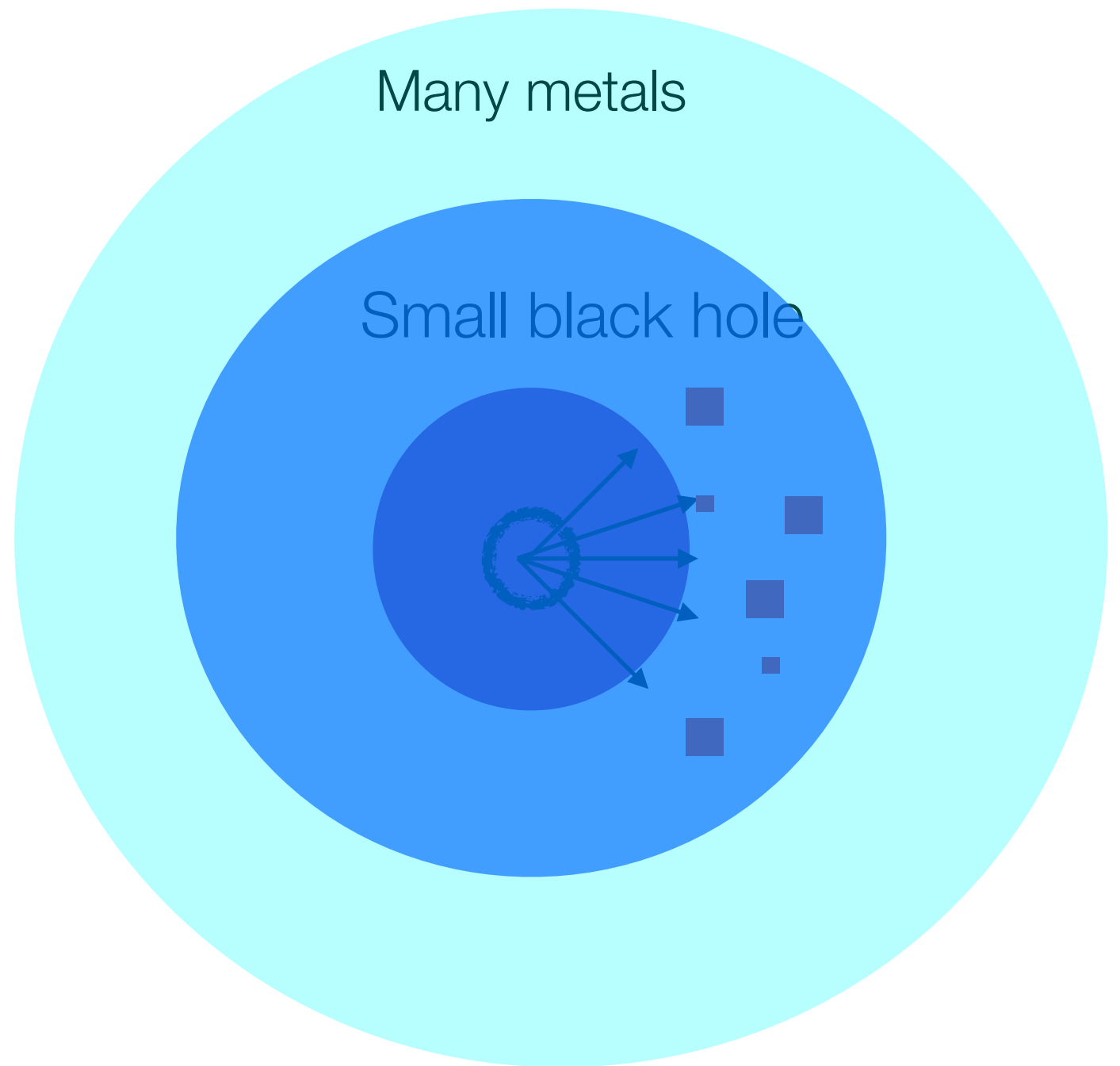
Few metals

Big black hole

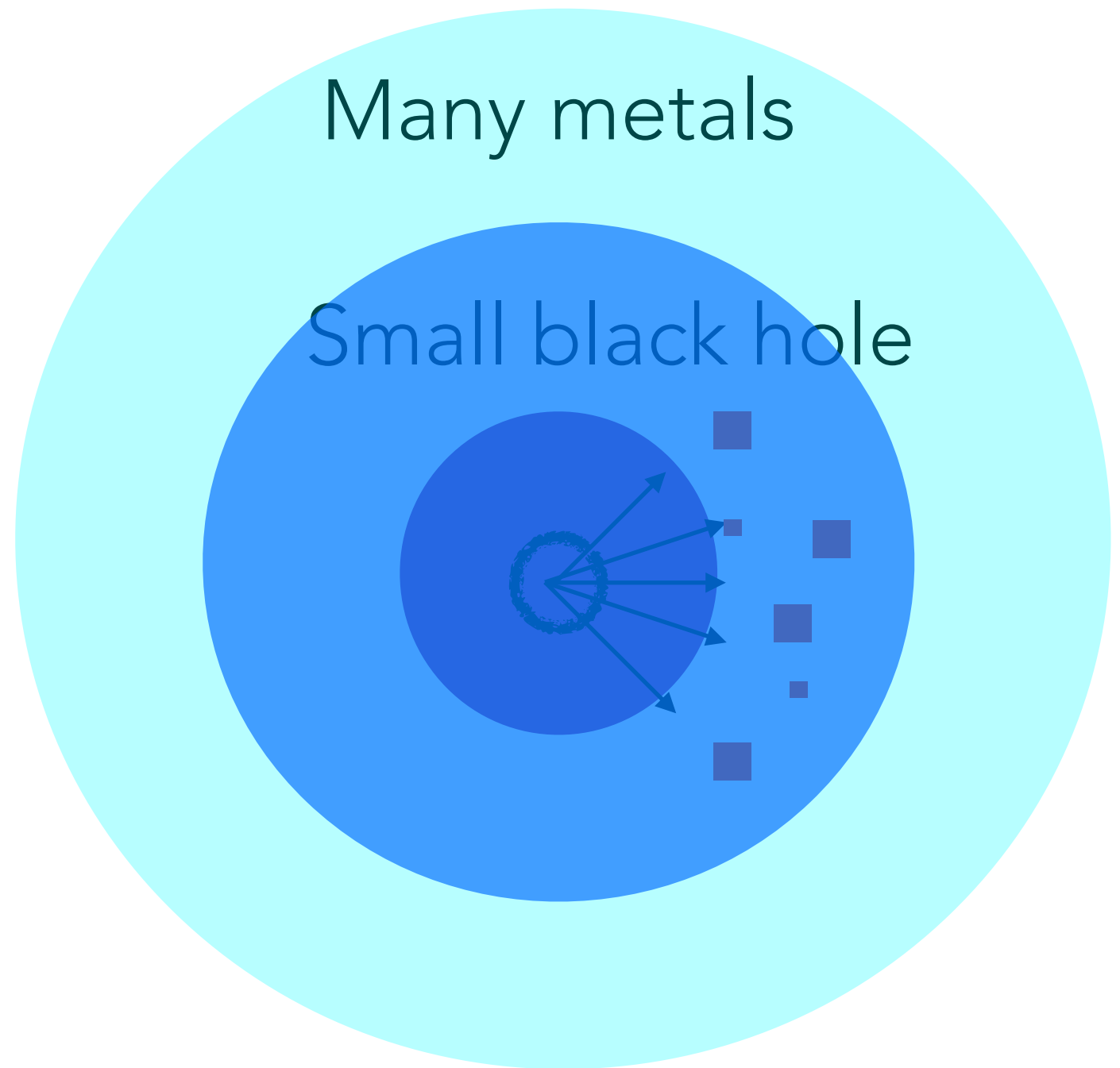
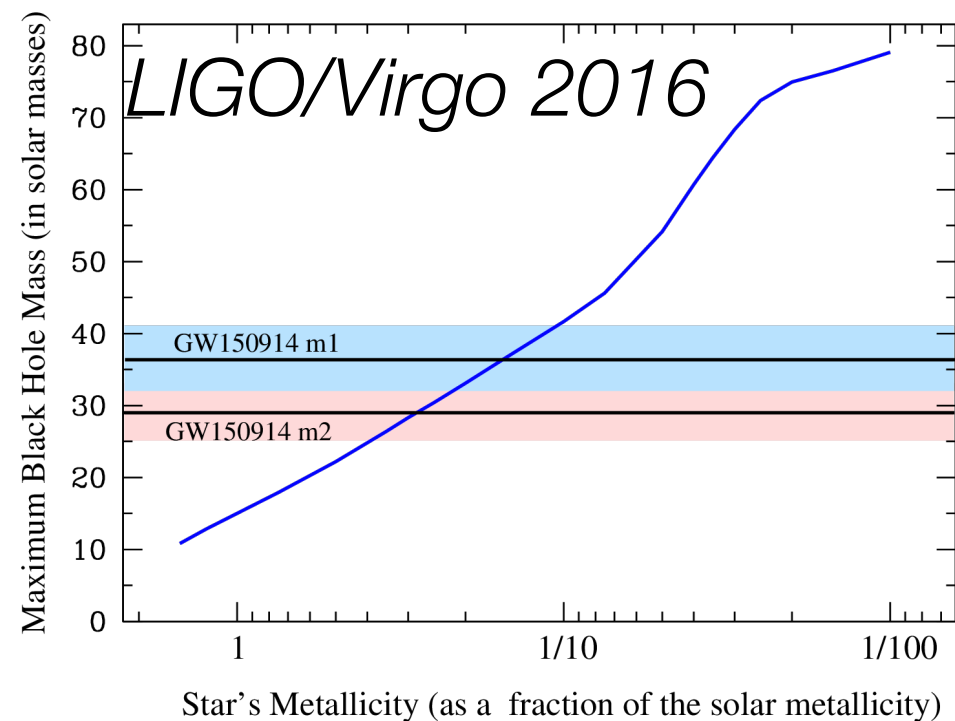


Many metals

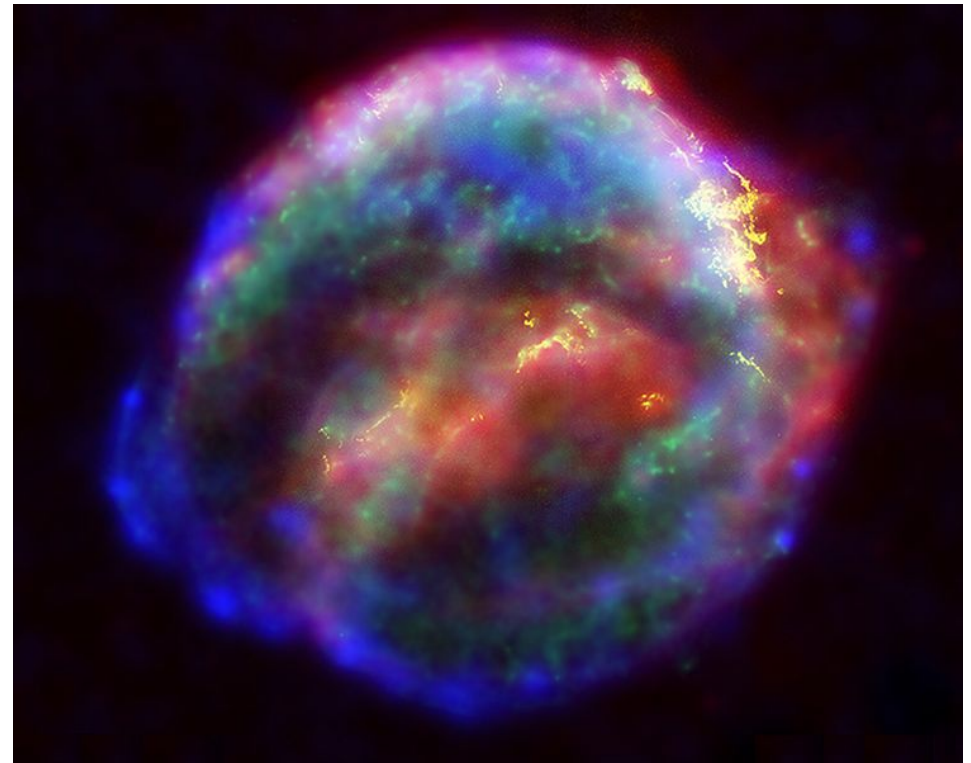
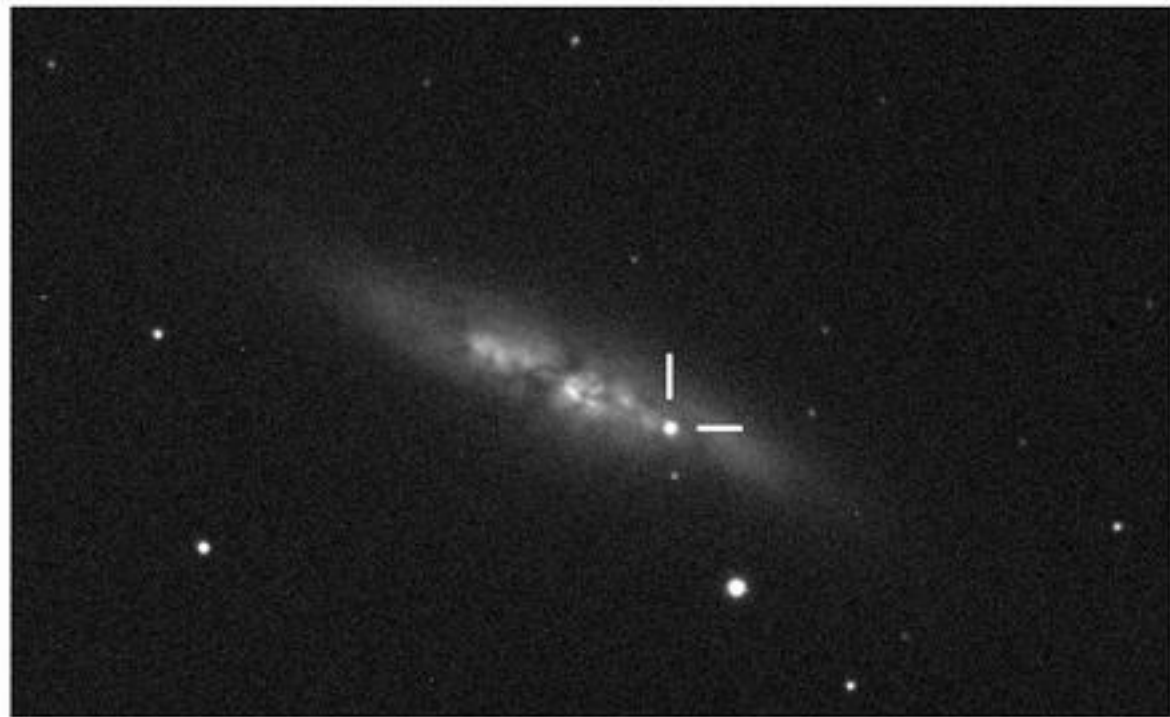
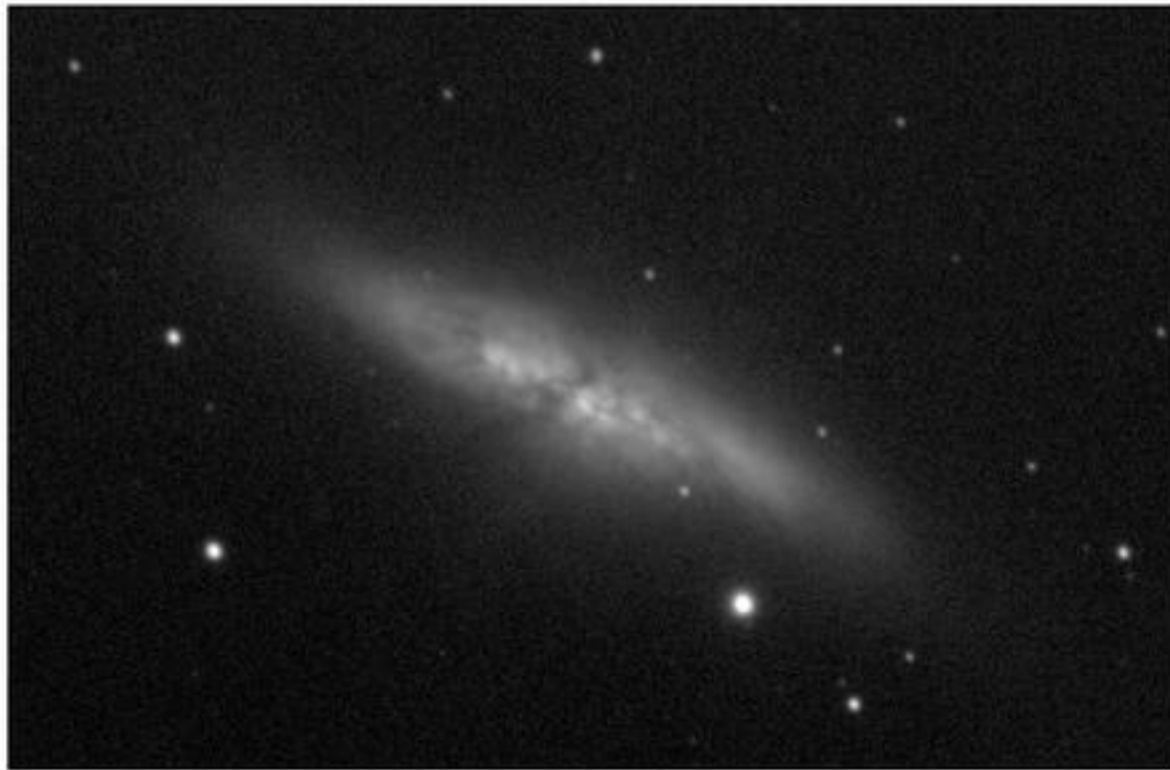
Small black hole



IMPORTANCE OF METALS (C, O, Ne, Fe...)



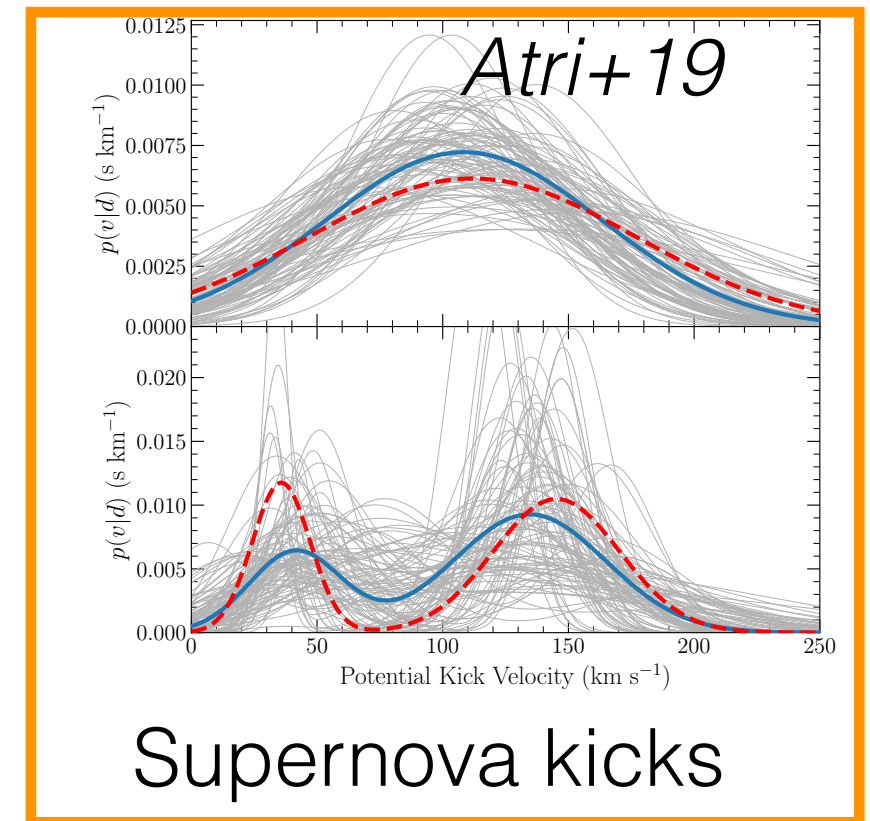
PROBLEM 2 : SUPERNOVA



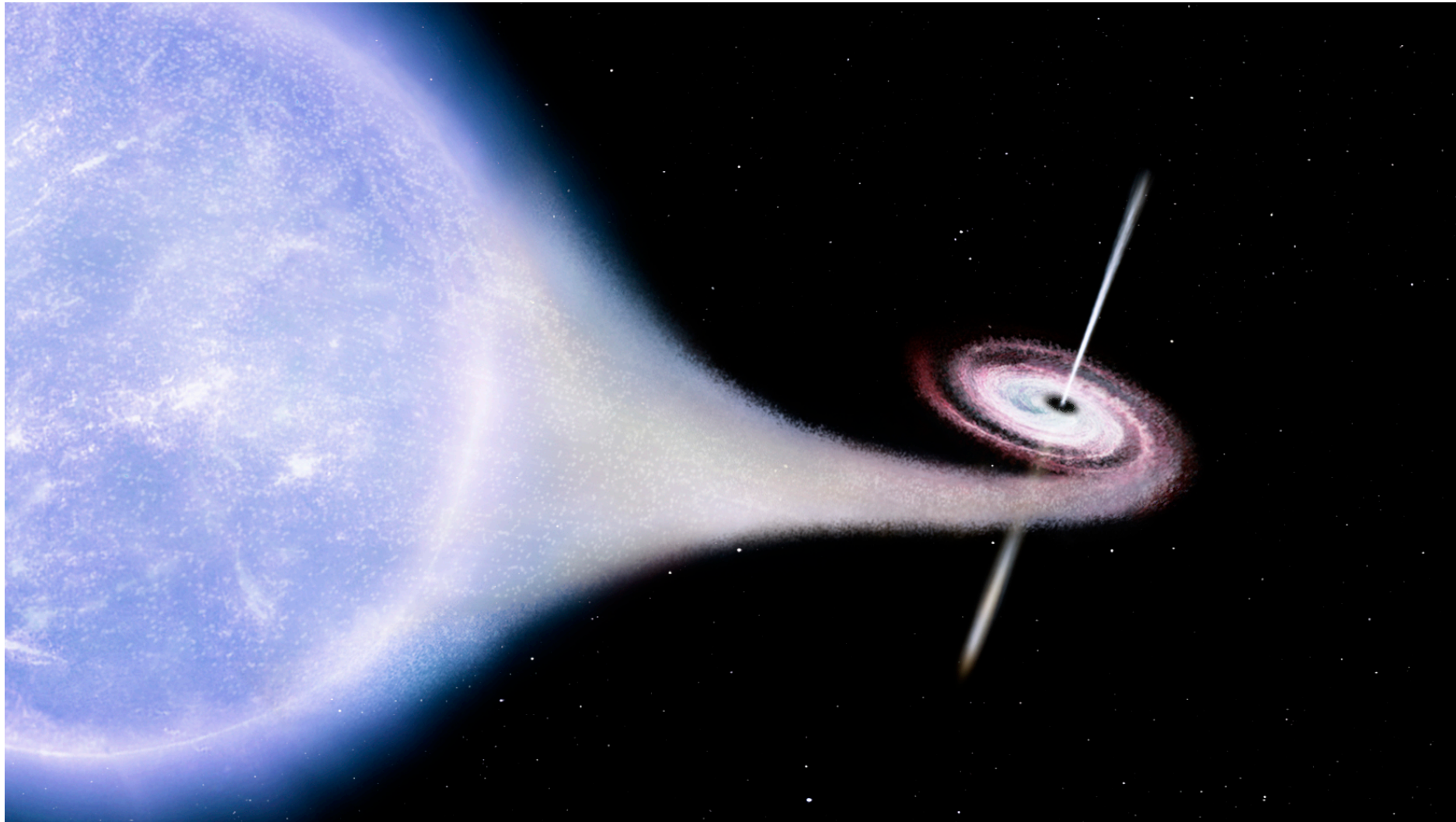
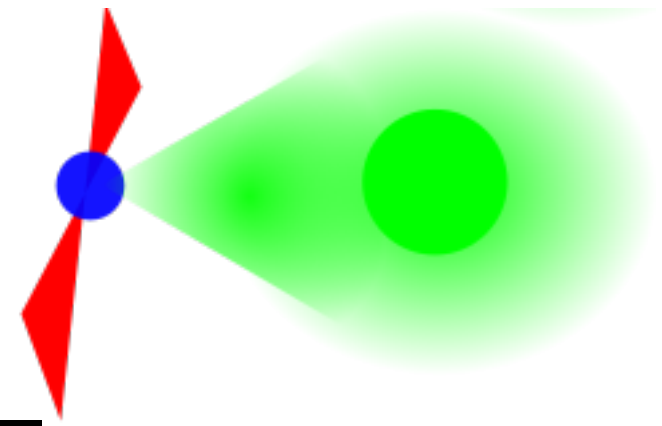
PROBLEM 2 : SUPERNOVA

Most NS binaries don't get formed because of kicks

For BHs it's quite uncertain (no observations)



X-RAY BINARIES



Mass transfer through winds (or Roche Lobe overflow)

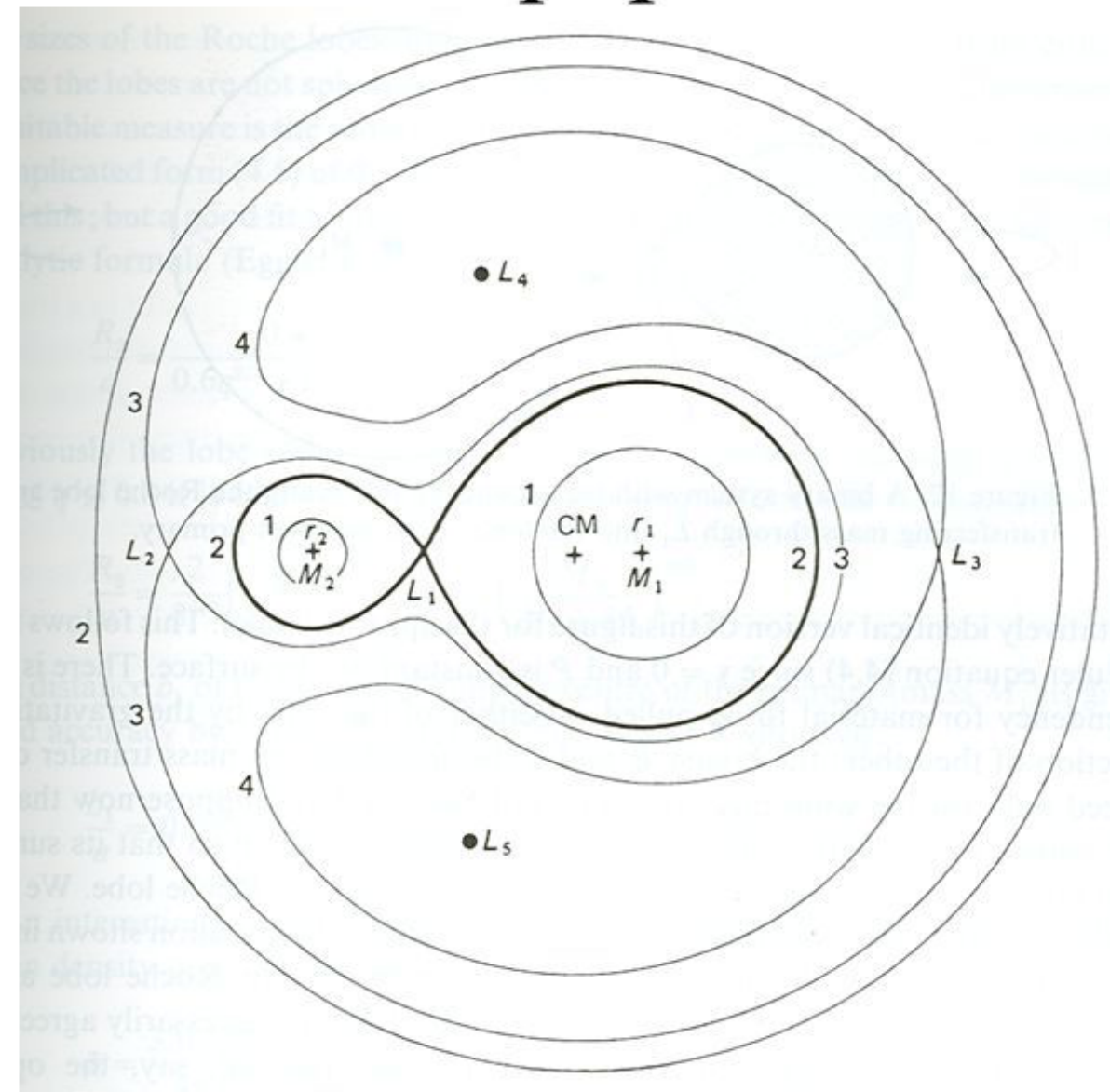
ROCHE LOBE OVERFLOW

Roche Lobe: boundary
between gravitational influence
of both stars

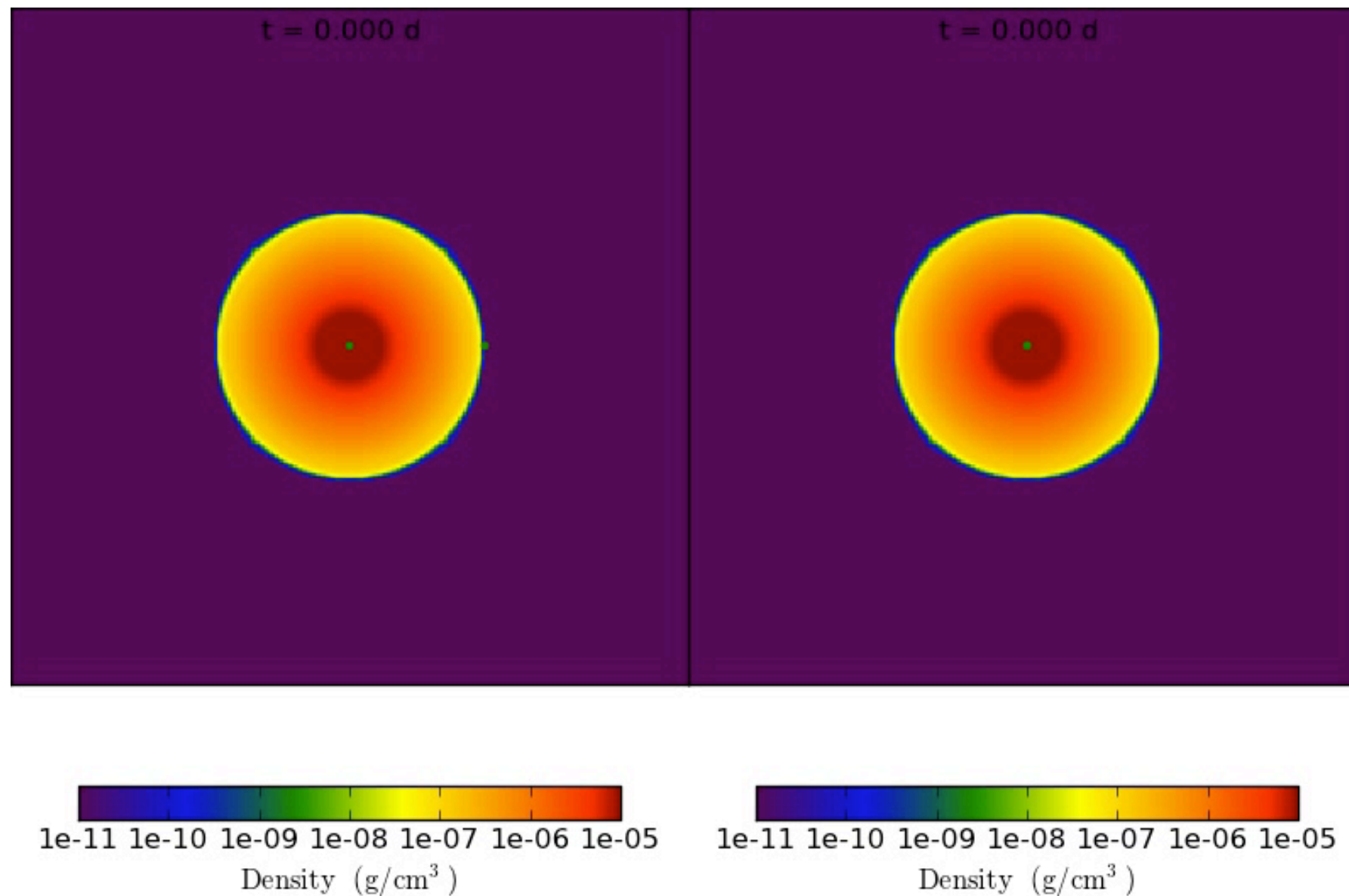
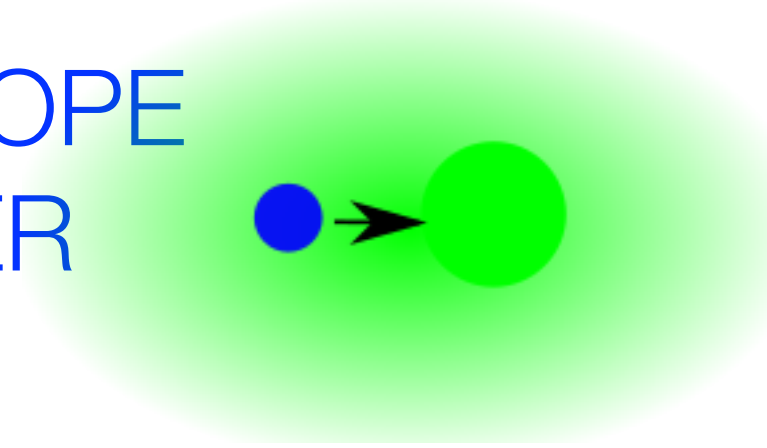
Matter beyond RL goes to other
star

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

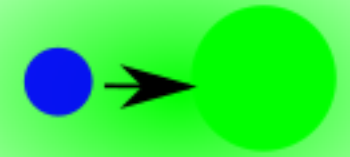
Roche equipotentials



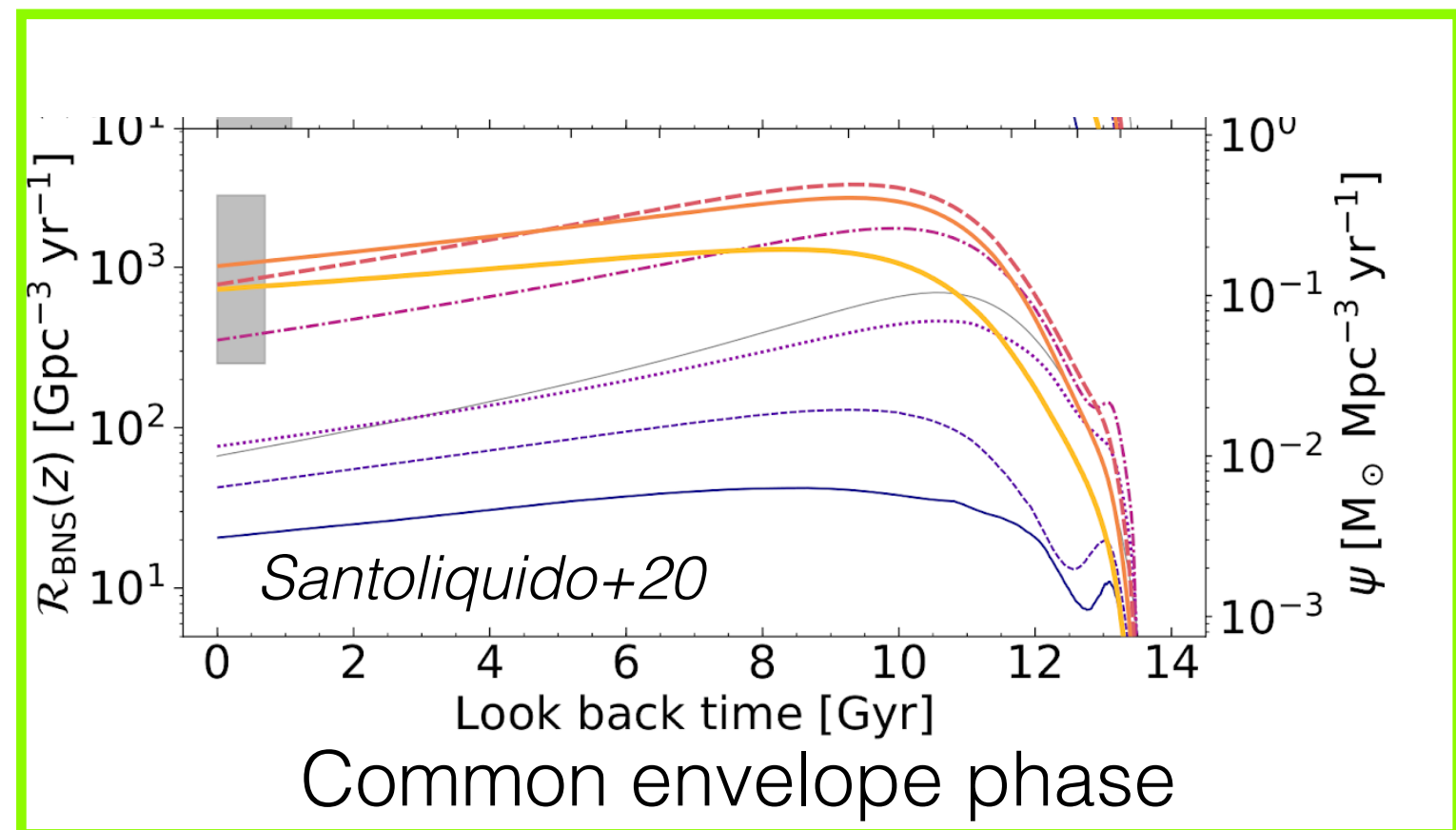
CRUCIAL: COMMON ENVELOPE BRINGS BINARIES CLOSER



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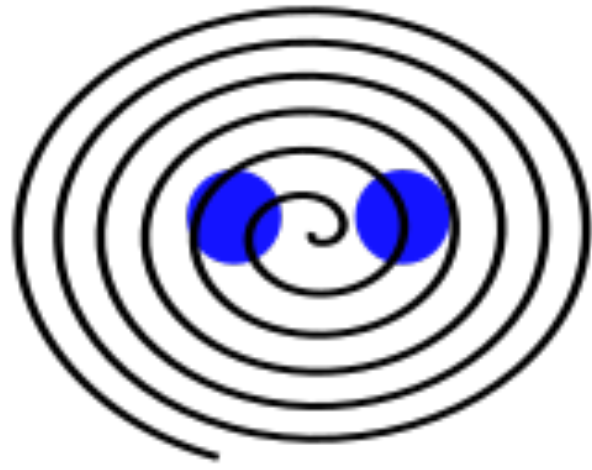
Highly unconstrained, major
hope from GW detections



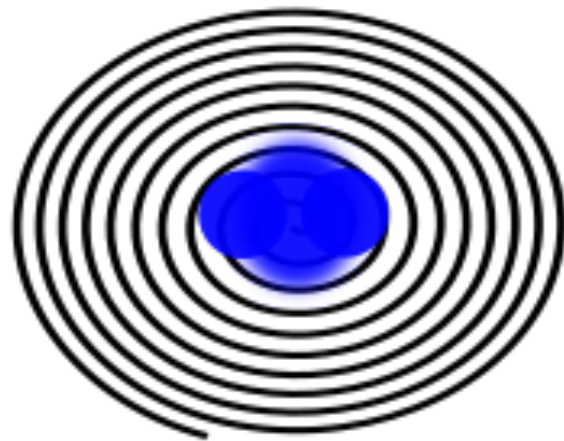
PROBLEM 3 : 2ND SUPERNOVA



IF BLACK HOLES: ONLY GWS



Billion years of inspiral



Merger (few seconds)

Tidal effects for BNS and white dwarfs



Final remnant

HOW DID THE BINARY SHRINK?

Angular (AM) momentum needs to be lost

$$J_{orb} = \Omega_{orb}(M_1 a_1 + M_2 a_2) \quad \Omega_{orb} = \left(\frac{G(M_1 + M_2)}{a^3} \right)^{1/2}$$

Conservative mass transfer ($M_{tot} = \text{constant}$)

Binary shrinks if mass transfer from primary to secondary

Binary expands if mass transfer from secondary to primary

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

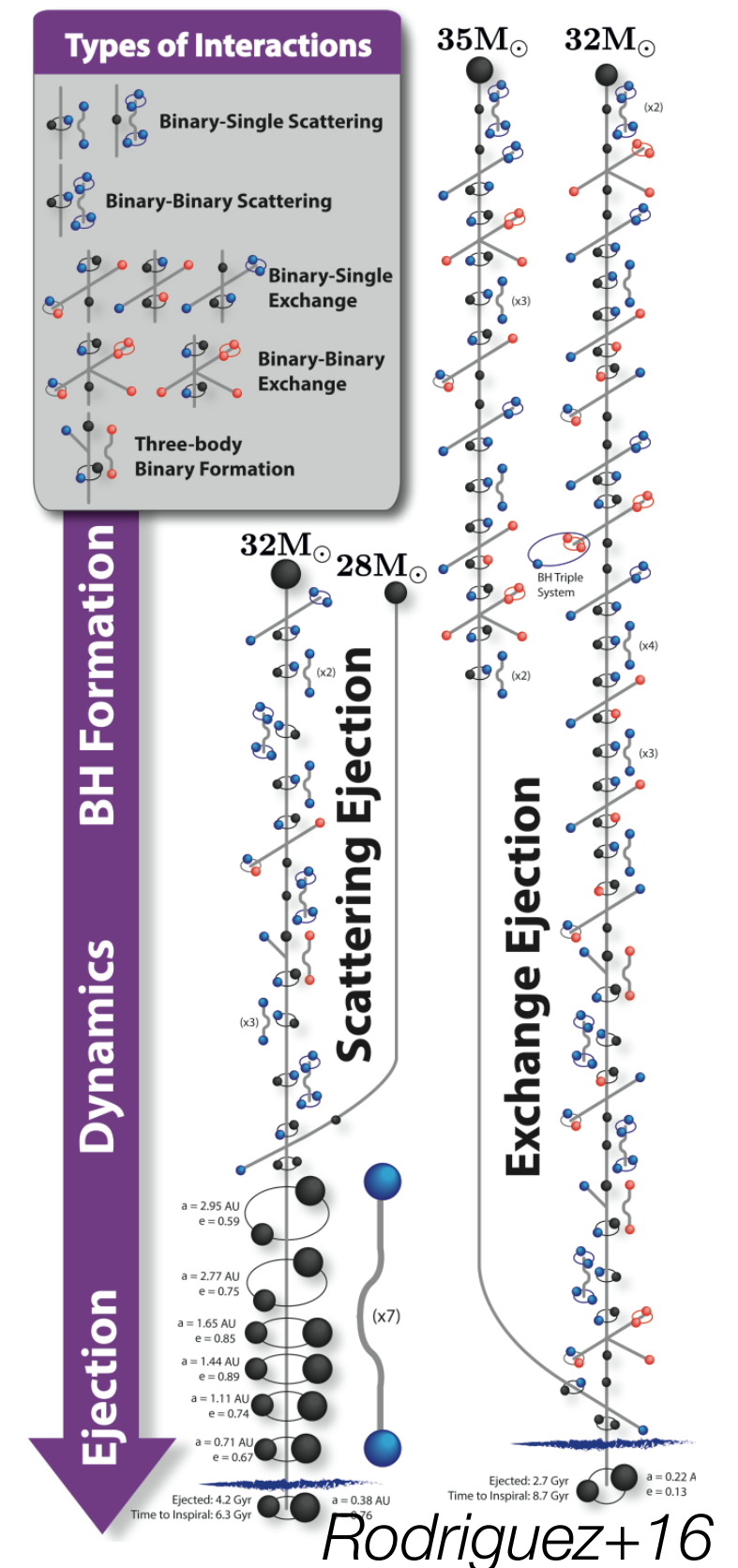
Young star clusters: less dense and less massive -> will dissolve quickly

Nuclear star clusters: Very dense, at center of galaxies

FORMATION CHANNEL: CLUSTER EVOLUTION

N-body interactions:

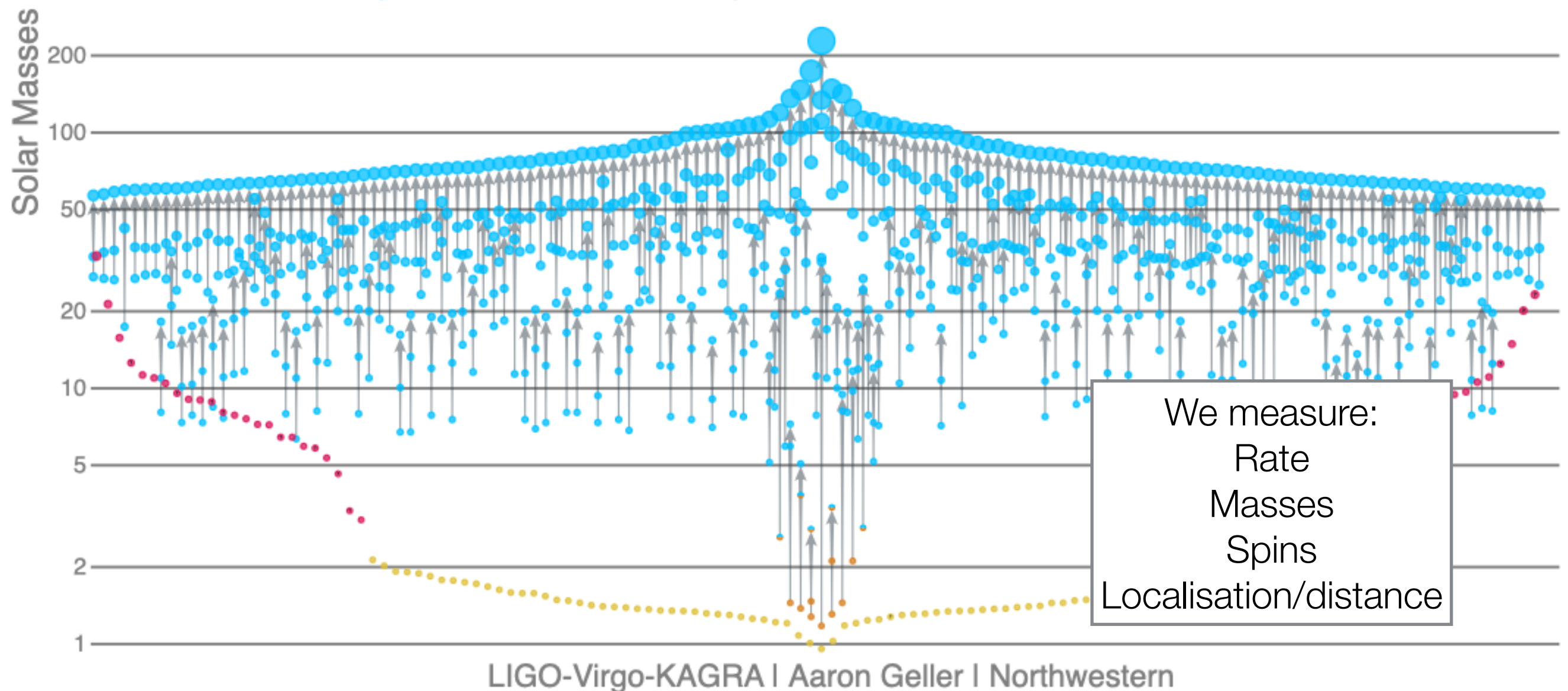
- BHs sink to center
- Mass exchanges make BH binaries
- 2nd generation mergers -> massive BHs
- Binaries can be kicked and merge outside



SO WHAT DO WE LEARN HERE?

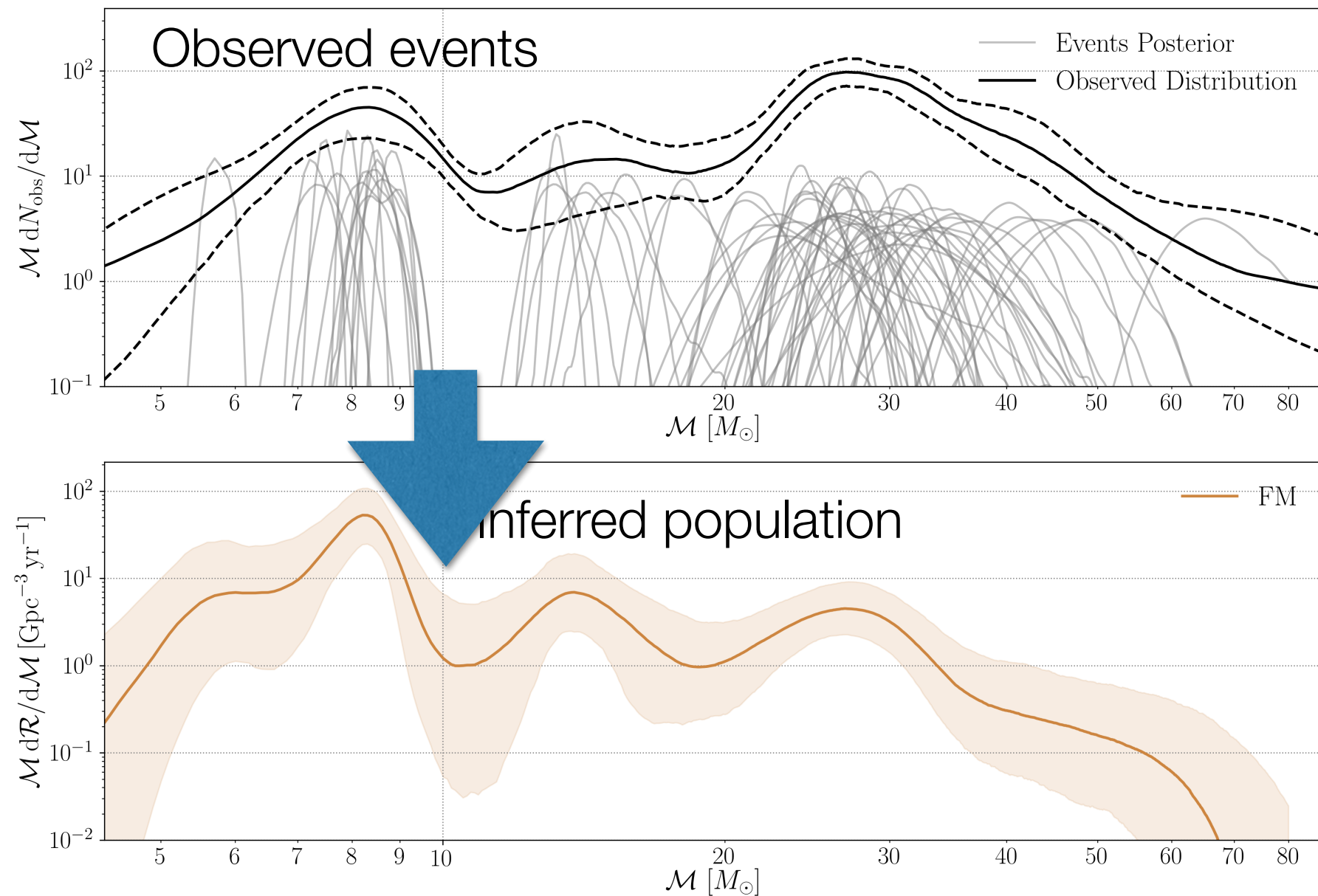
Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*



~250 BINARY BLACK HOLES: A POPULATION

Going from posteriors on observed events to an inferred mass spectrum



LVK: GWTC-3 populations paper

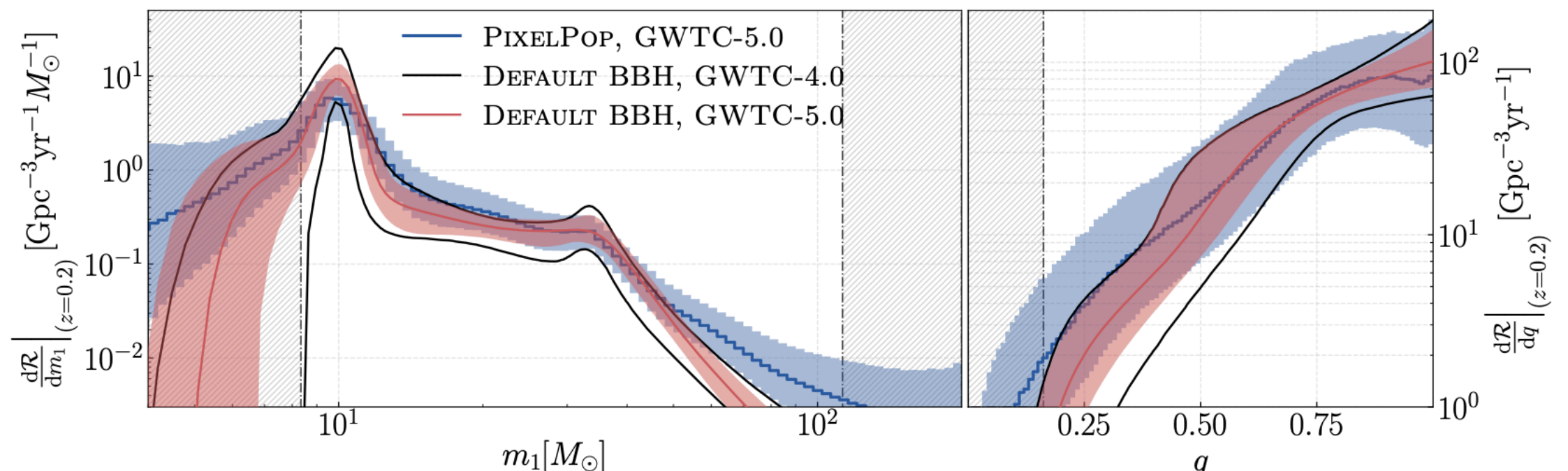
~250 BINARY BLACK HOLES: A POPULATION

Phenomenological models for population

-> Rate: 27-49 $\text{Gpc}^{-3} \text{yr}^{-1}$

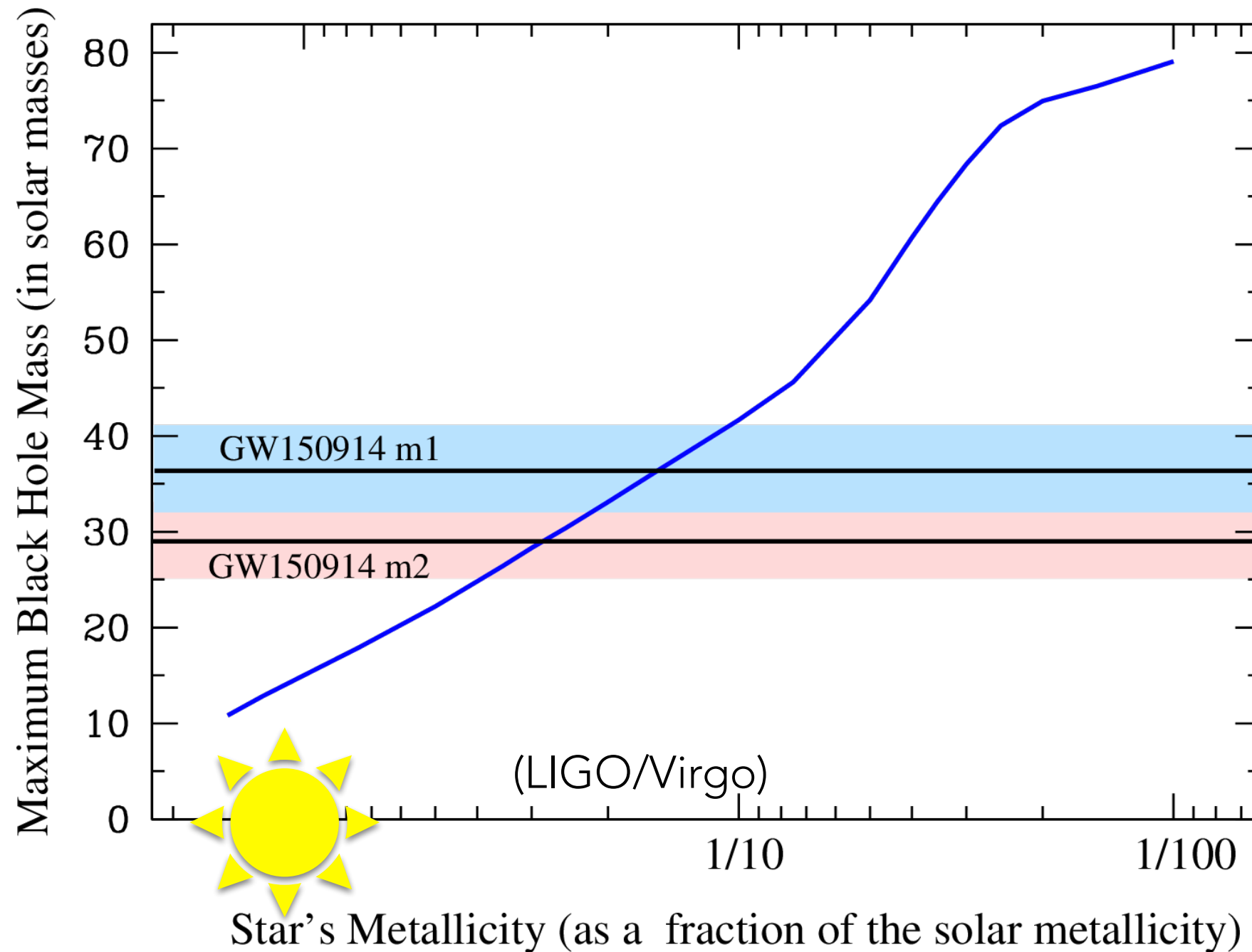
Mass spectrum

- Lots of « massive » black holes
- Probably no gap between NS and BHs (several events)
- Features in spectrum at 10 and 35 $M_{\odot}$
- Likely different mass ratio for $M_1 > 40 M_{\odot}$



LVK 26: GWTC-5 Populations paper

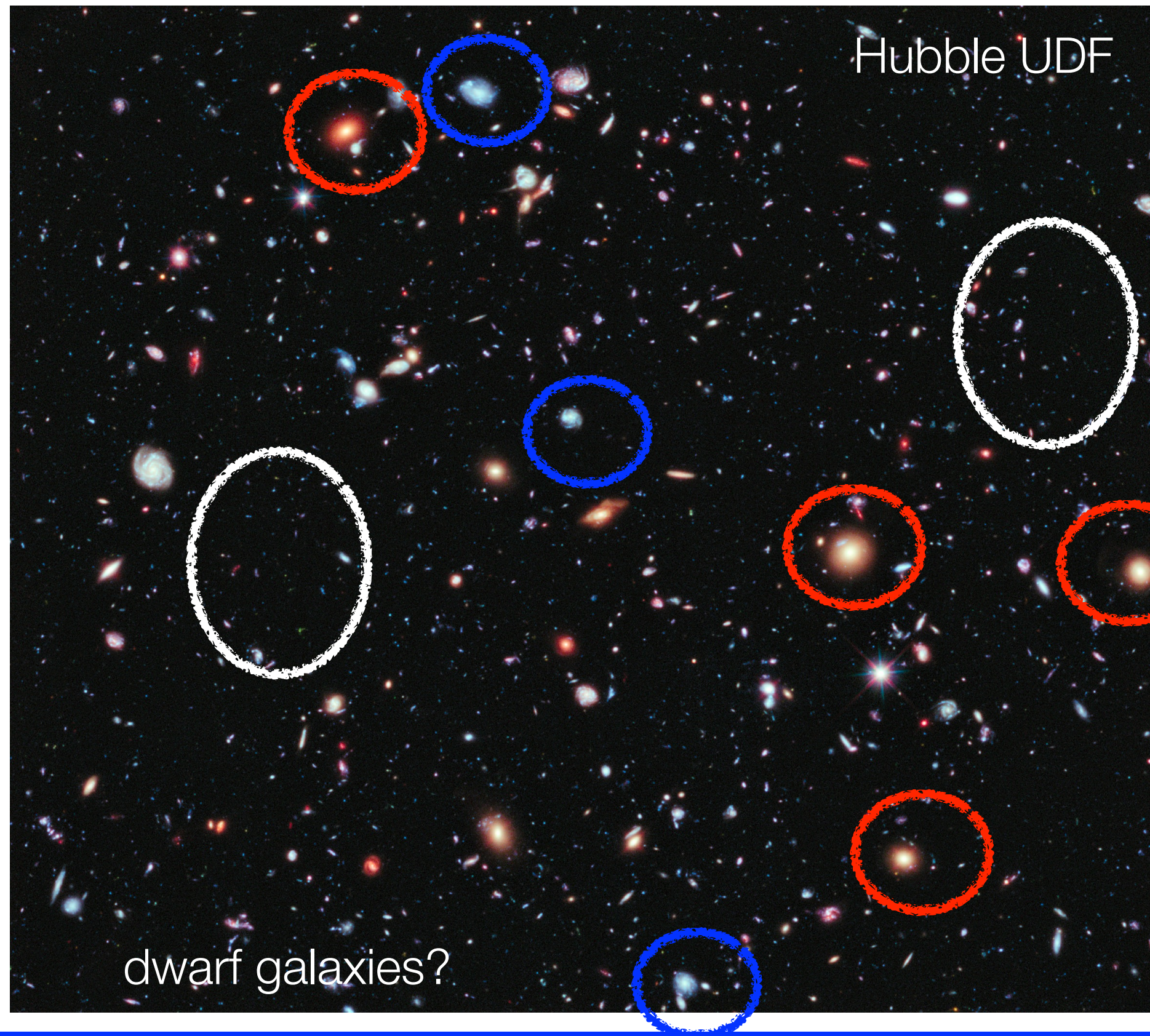
MAKING MASSIVE BHS IS HARD



Binary evolution -> low metallicity progenitor stars

Not well-known stellar population

WHERE ARE THE LOW-METALLICITY STARS?



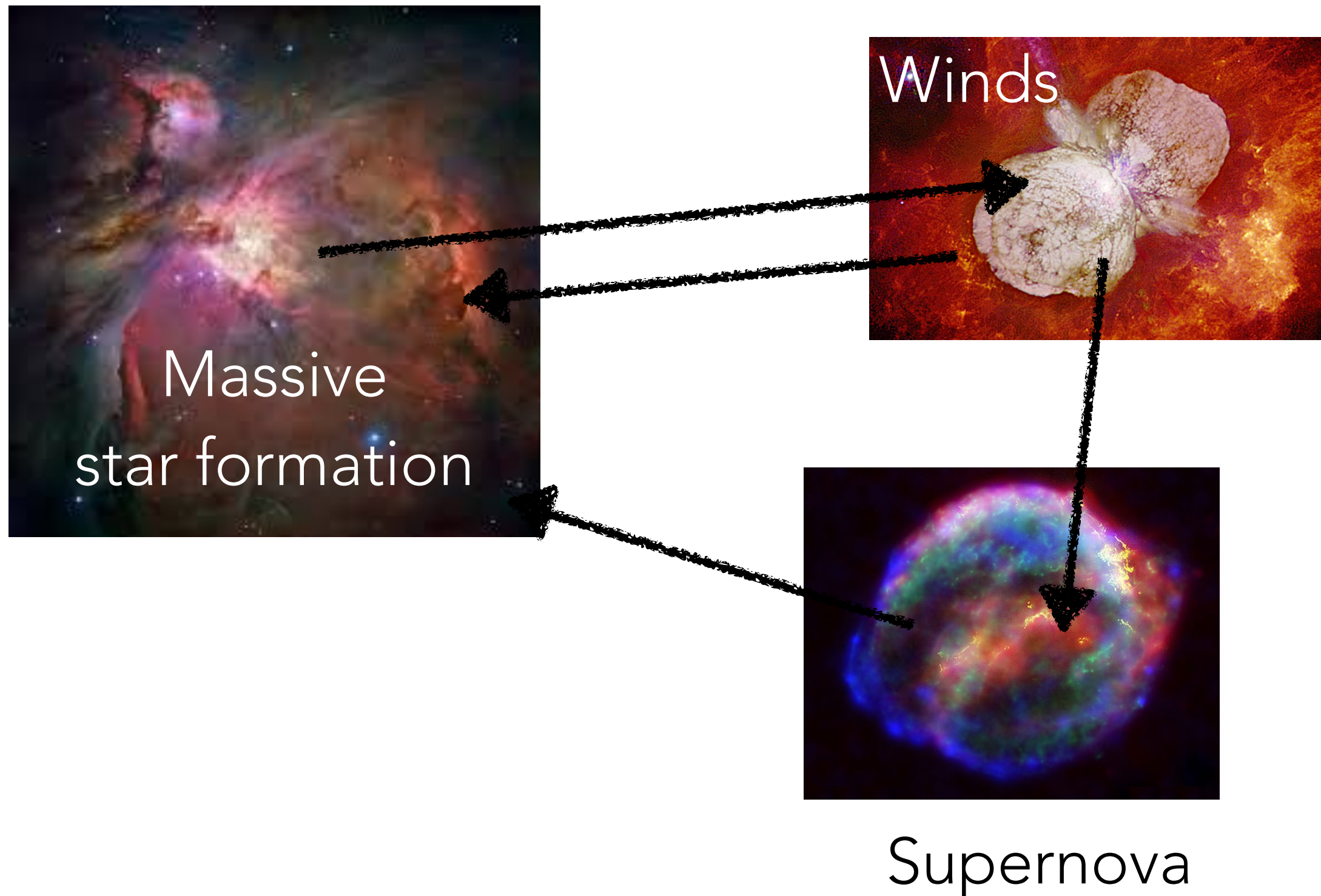
Less explored
star formation

recent star
formation?

older star
formation?

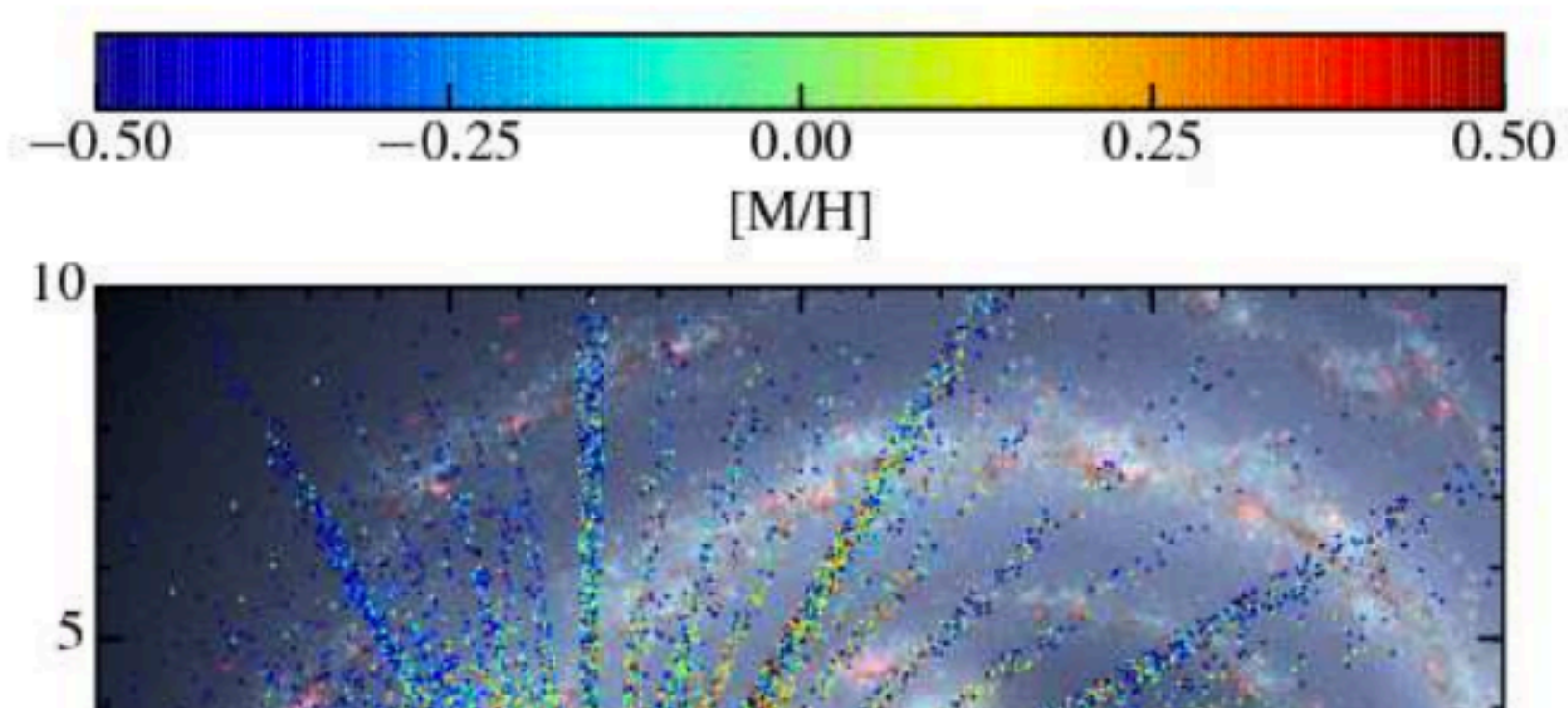
dwarf galaxies?

THE CYCLE OF GAS AND METALS

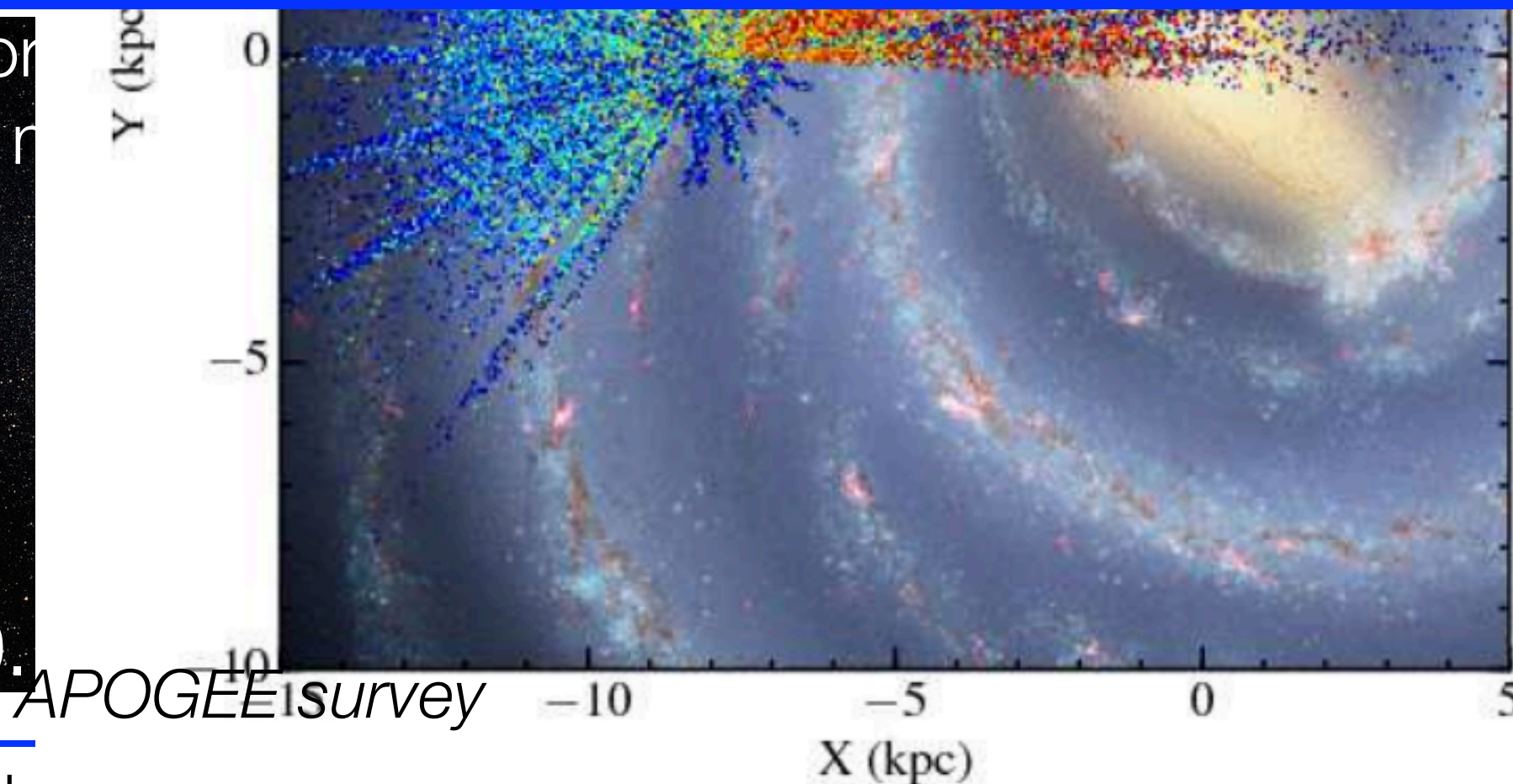


WH

RS?



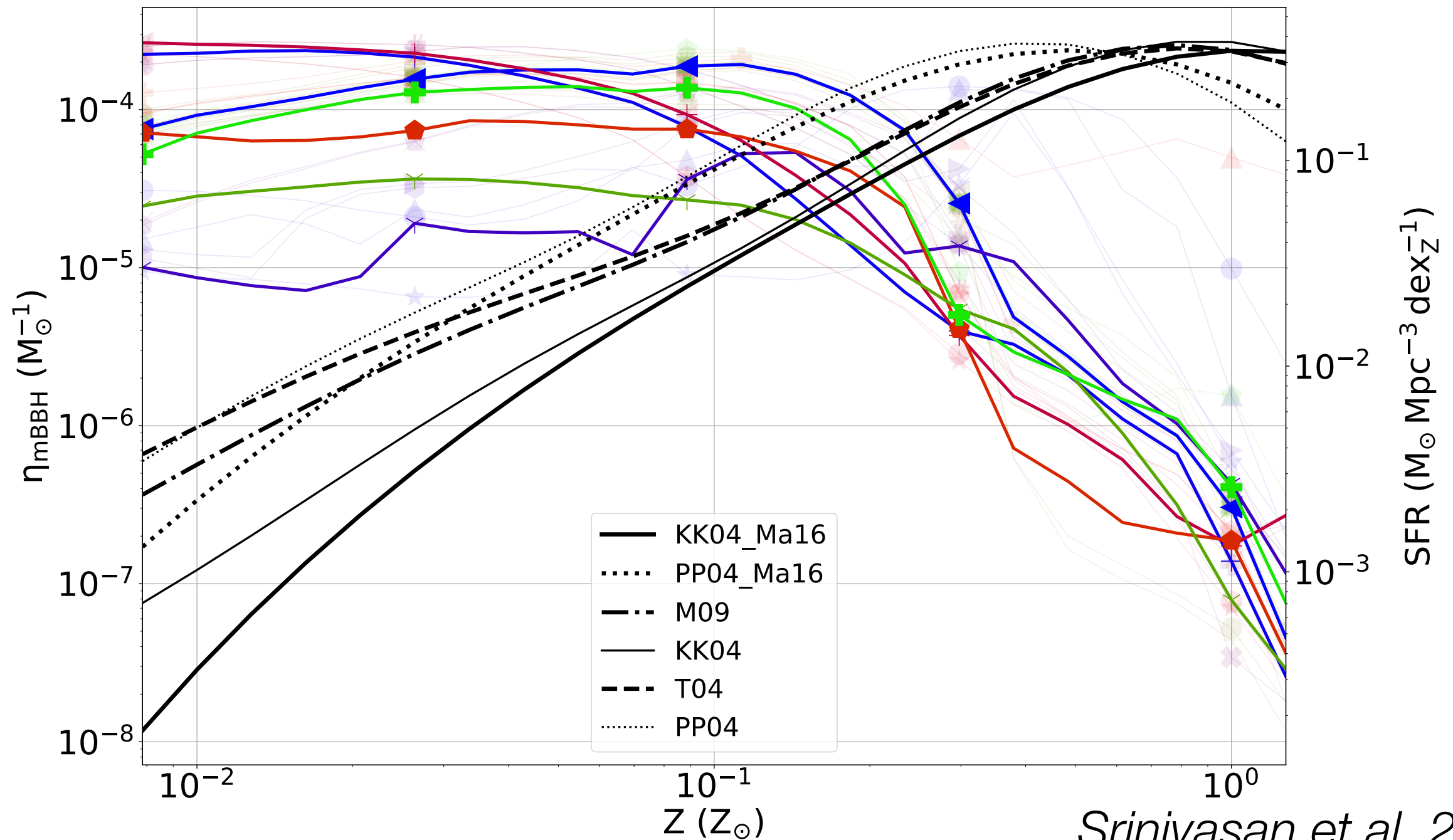
MASSIVE BLACK HOLES COME FROM GALAXIES LIKE THE MW AND
FROM DWARF GALAXIES



$\mu m II$:
stars

$1 Z_{\text{sun}}$

WHY IS ASTROPHYSICAL INTERPRETATION DIFFICULT?



Degeneracies between star formation and binary evolution models made GW interpretation difficult

IMPORTANCE OF BH SPINS

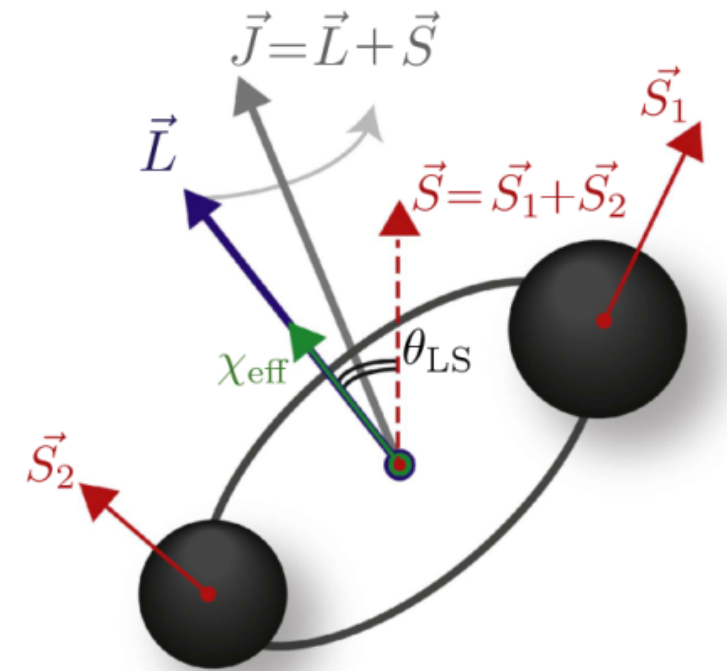
GWs carry information on (global) spin

Hard to measure, but it's coming

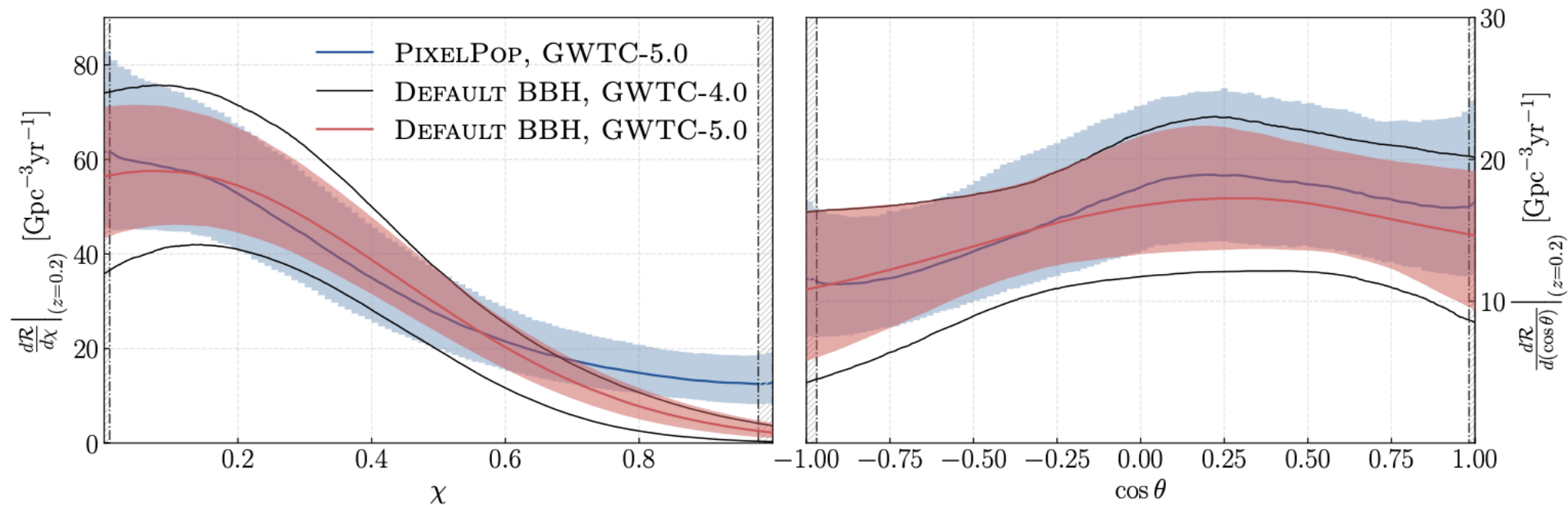
Binary evolution: spins align (tides, accretion, common envelope...), SN can disturb

Cluster dynamics : random motions

Amplitude is hard to predict from stellar evolution



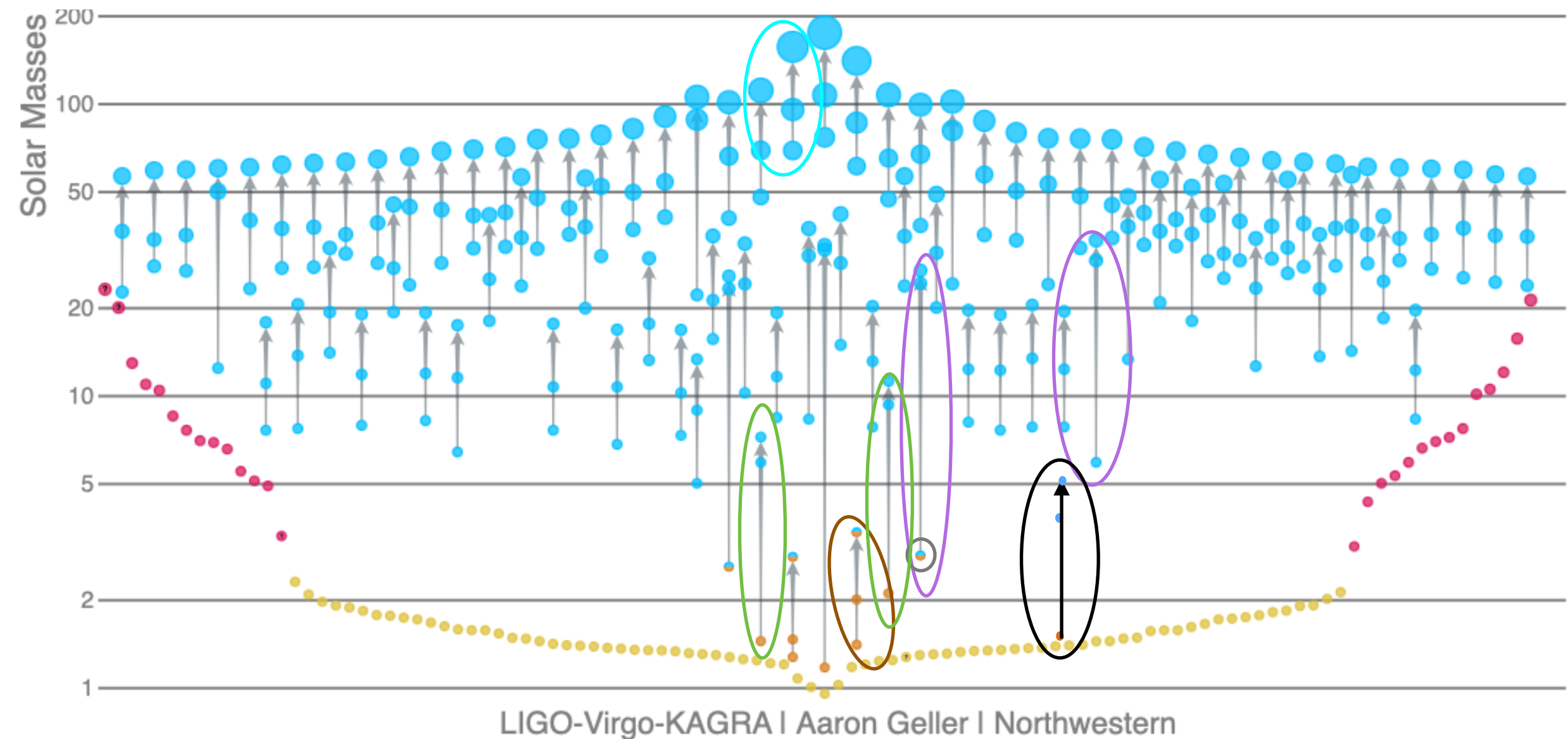
SPINS TO DISCRIMINATE FORMATION?



Spin magnitude and spin-orbit misalignment in GWTC-5

- Small but non-zero spins, long tail
 - Isotropic spin distribution preferred -> cluster formation?
 - 20-40% of population has strongly misaligned spins
 - overdensity for aligned spins -> binary formation?
 - broader spin distribution above 30 Msun, correlated with unequal masses
- => (at least) two formation channels?

ZOOM ON SOME EXCEPTIONAL EVENTS



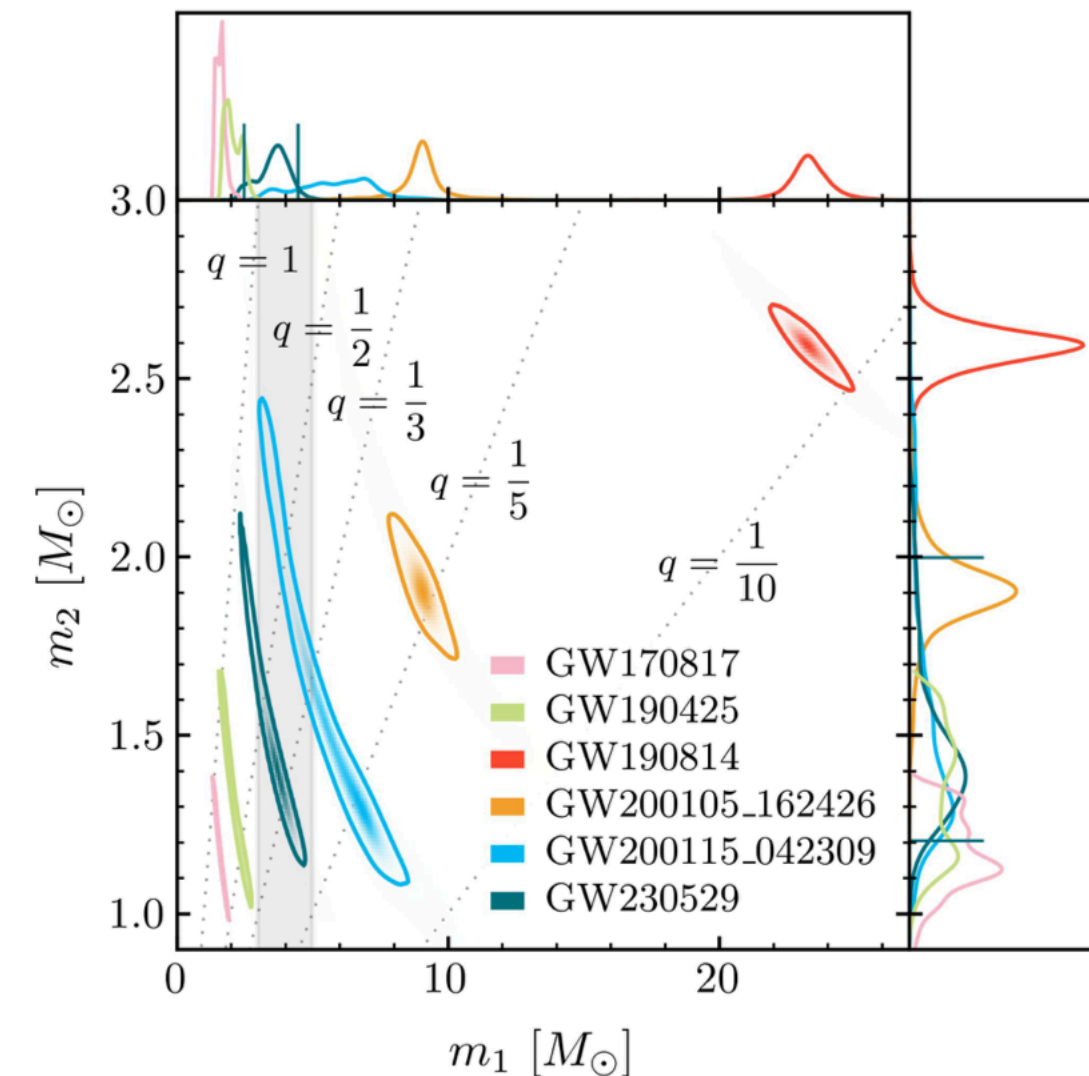
- First unequal masses (GW190412, GW190814)
- Massive BHs (GW190521, GW231123)
- Lower mass gap object (GW190814)
- BNS masses differ from MW (GW190425)
- NSBH (GW200105-GW200115)
- Primary in « mass gap » (GW230529)

NO LOWER MASS GAP?

Observations of neutron stars/black holes in the Milky Way have a gap between 2-5 M_{sun}

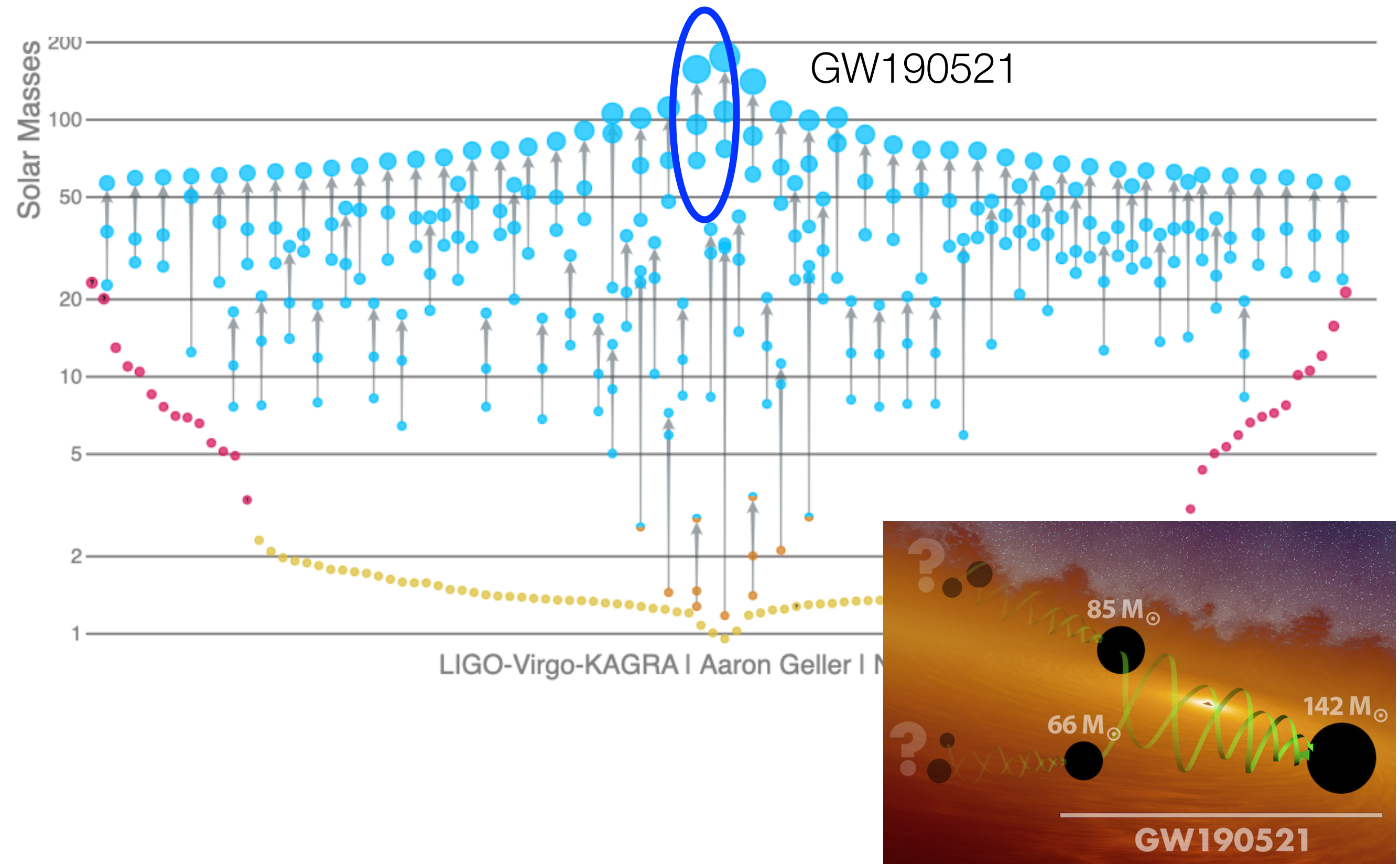
What is the highest mass of NS?

Can be explained in certain supernova models with fallback or those with slow-growing instabilities during core-collapse

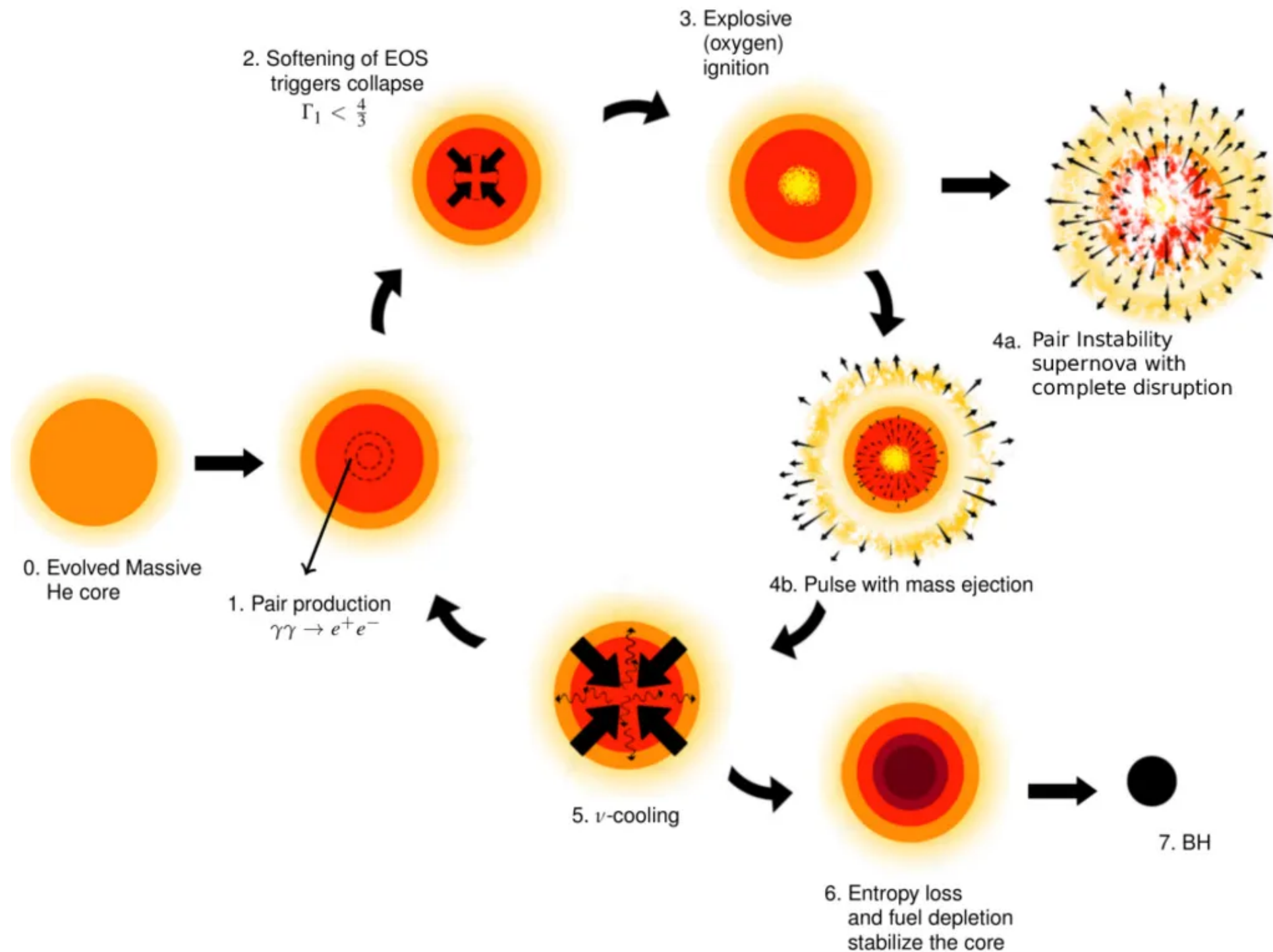


Info on nature of object is difficult from GW
EM counterpart -> signature of NS

VERY MASSIVE BLACK HOLES



THE UPPER MASS GAP

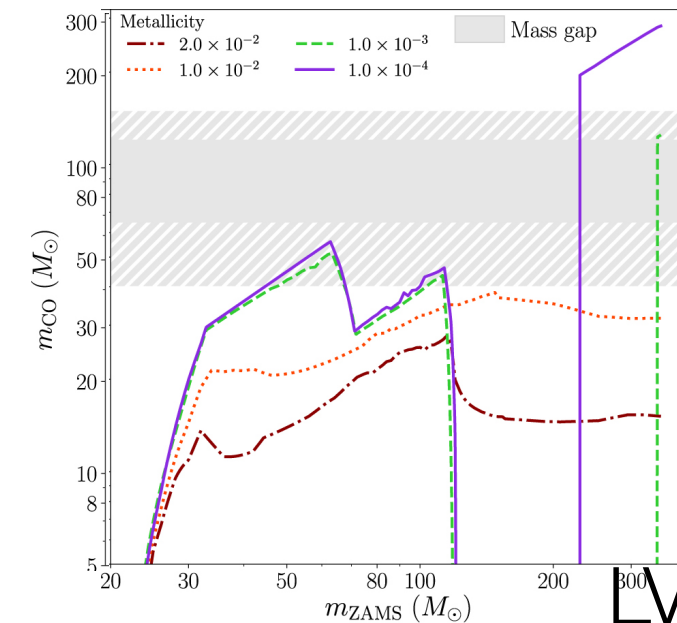


Pair instability supernova completely destroys star

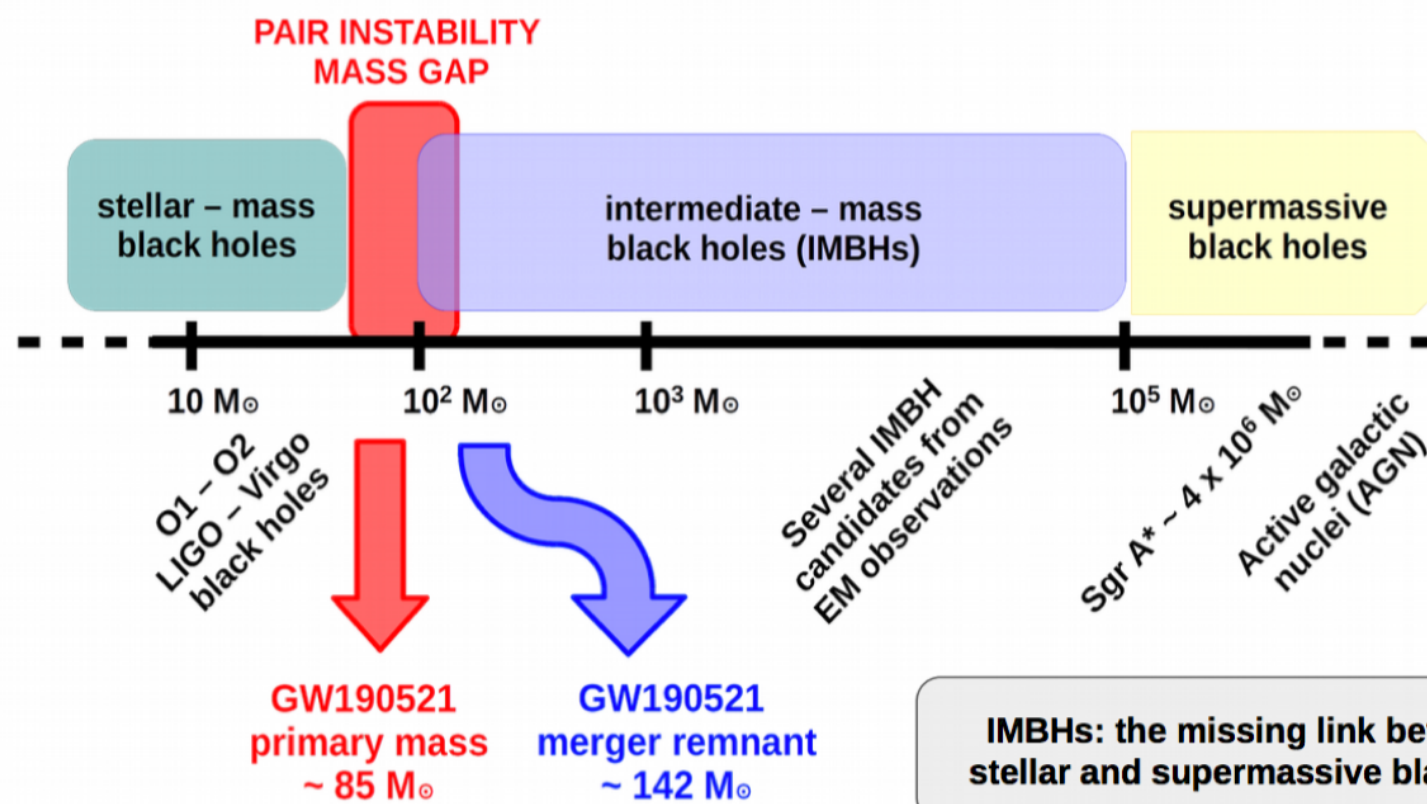
HIGH MASS STELLAR BLACK HOLES

BHs in pair instability supernova gap: challenge

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



LVK+2020



Remnant mass: 142 Msun: IMBH
A pathway to intermediate mass black holes?

LOOKING AHEAD

More data to come

At least two populations are found, stronger evidence at each data release

Population analysis become more powerful, features are confirmed, or not.

BUT: arising consensus in the field that astrophysical inference is reaching its current limitations:

- degeneracies between star formation/metallicity models
- Stellar evolution models

Multidimensional inference is necessary (mass, spins, redshift, mass ratios), much more data needed

Non-parametric models become more and more advanced

SUPERNOVAE AS GW SOURCES

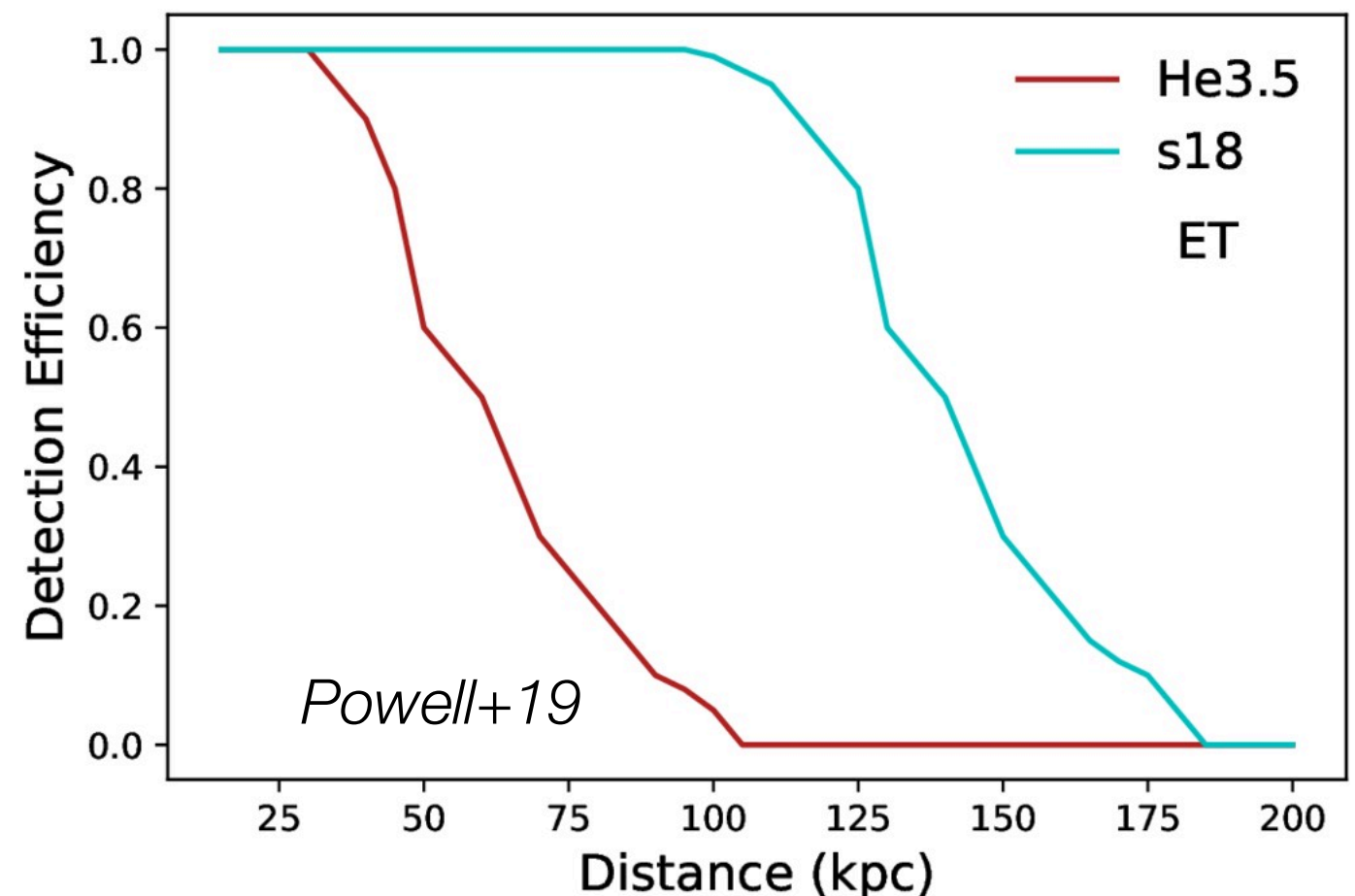
New class of sources

Major uncertainties on the GW emission

Lots of information on central engine, geometry of the explosion

Multimessenger: Neutrino, GWs, EM

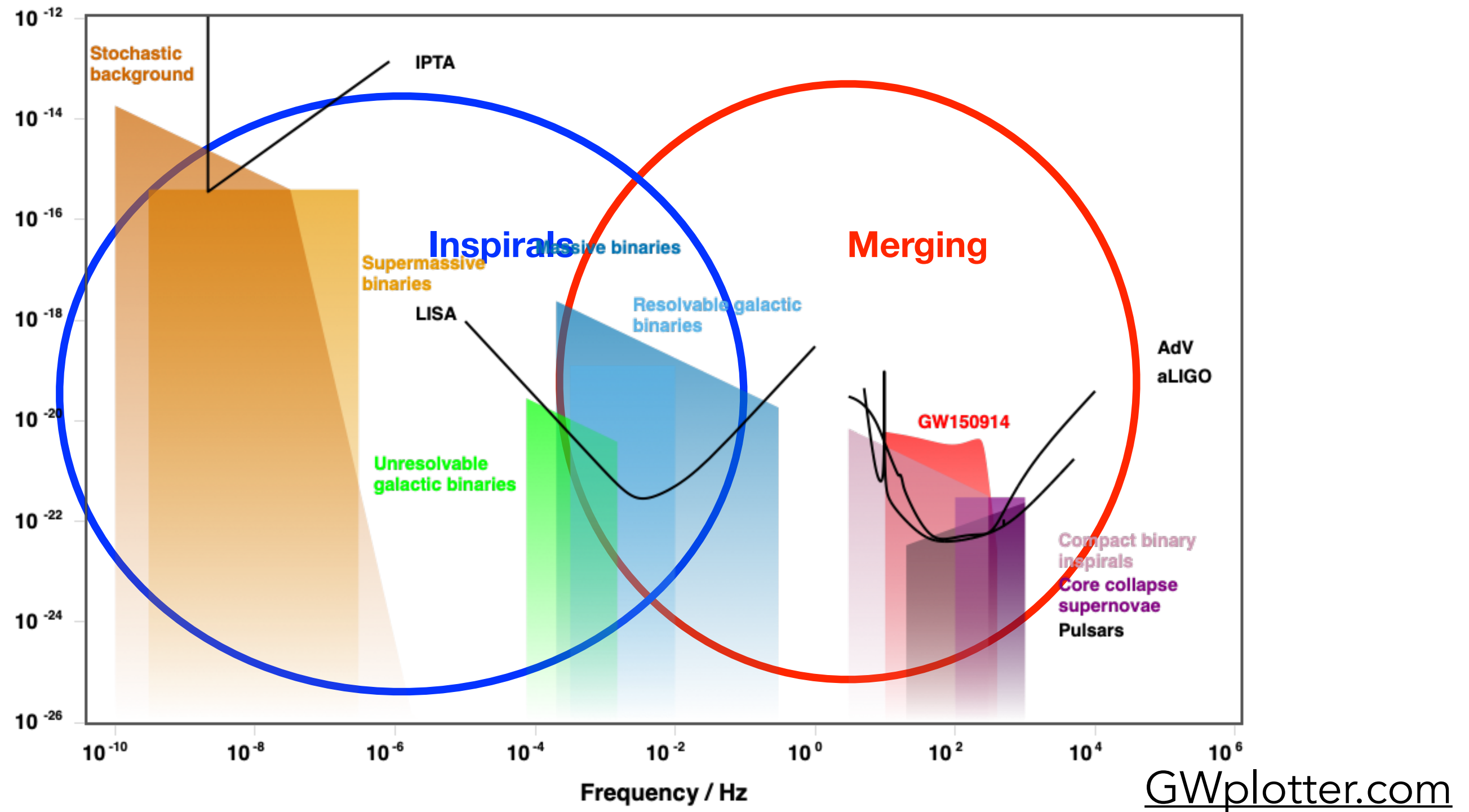
Most energetic model: <20 kpc by 2G, 200 kpc by Einstein Telescope



LOW FREQUENCY SOURCES

Supermassive black holes

Compact binaries in the Milky Way



BLACK HOLE MERGERS IN THE MILKY WAY

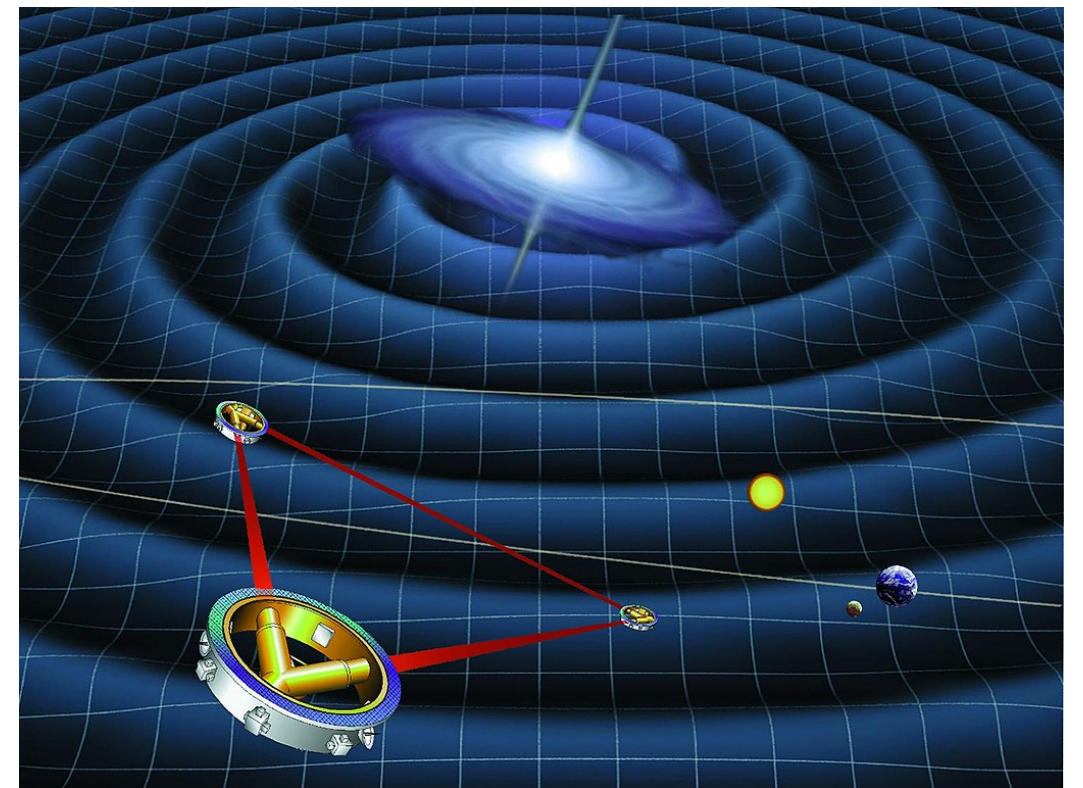
Virgo/LIGO merger rate : $27\text{-}49 \text{ Gpc}^{-3} \text{ yr}^{-1}$

Up to 4-50 mergers per million year in MW

No expected BBH merger
Detections in MW

What is the actual merger rate of
different types of sources?

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)

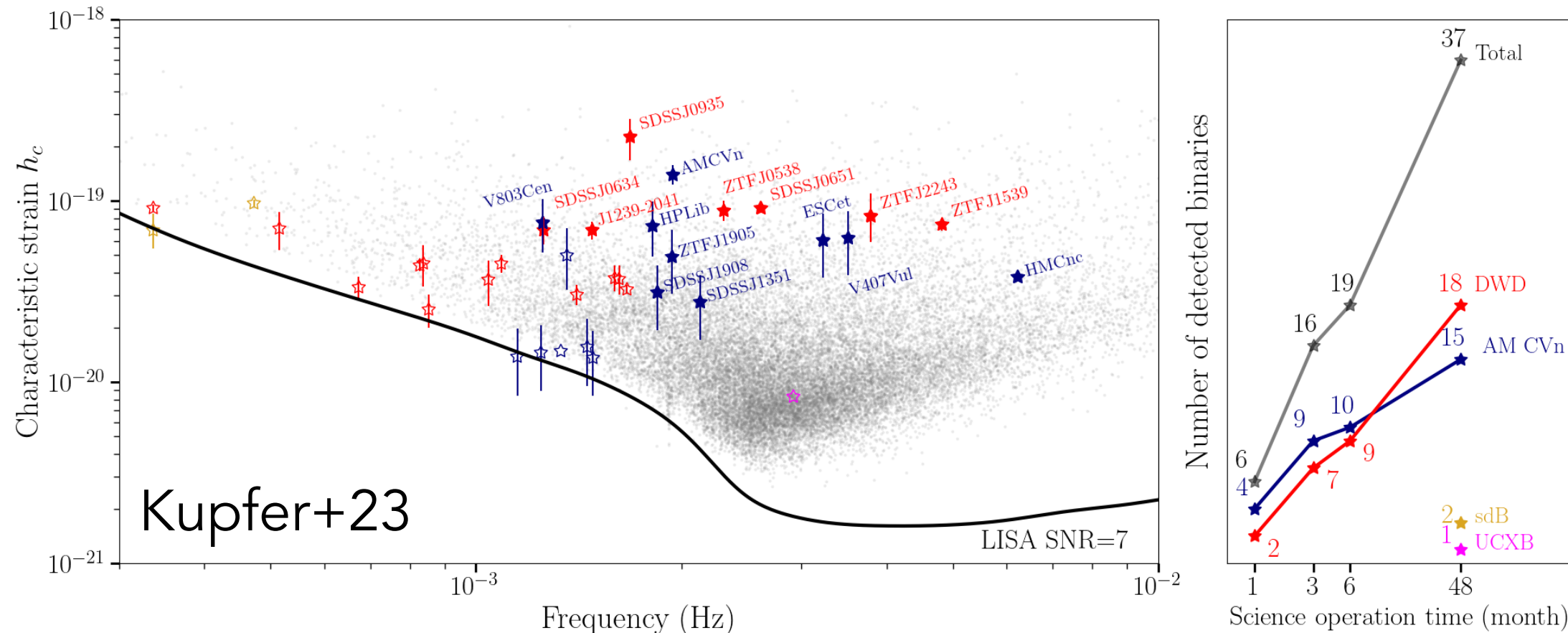
White dwarfs: 95% of stars!
Type Ia supernovae
Low mass evolution, common envelope, tides
EM counterparts
Map the Milky Way and its environment
Understand/quantify past star formation

~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 of instrument and data analysis



Much more information: sky localisation: stellar populations
distance, mass measurements, radii: more constraints on binary evolution
Measurement of orbital evolution: compare with GW evolution -> inference of tides (EM + GW needed)

Growing evidence of the need to decrease uncertainty on data analysis

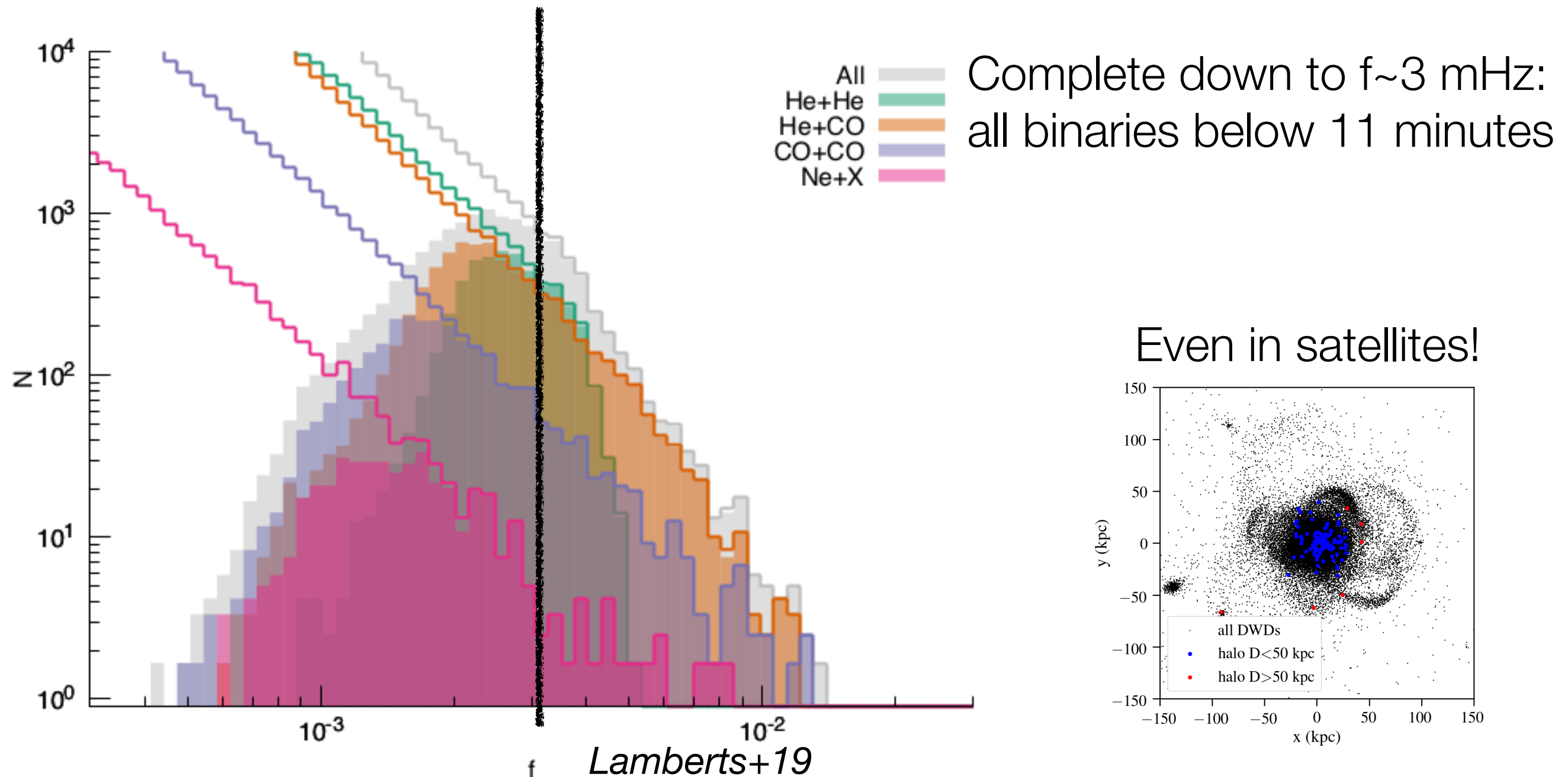
Major effort: finding more EM binaries (ZTF, BlackGem, VRO/LSST, CFHT)

LISA DETECTIONS: A COMPLETE CATALOG OF WHITE DWARF BINARIES

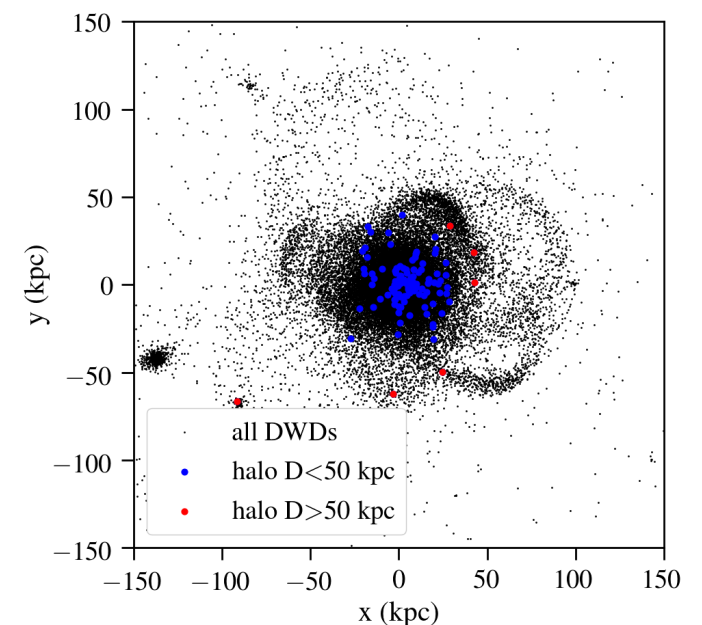
~12 000 systems: measurement of period and GW strain

☹️ No masses, no sky localisation unless high signal/noise

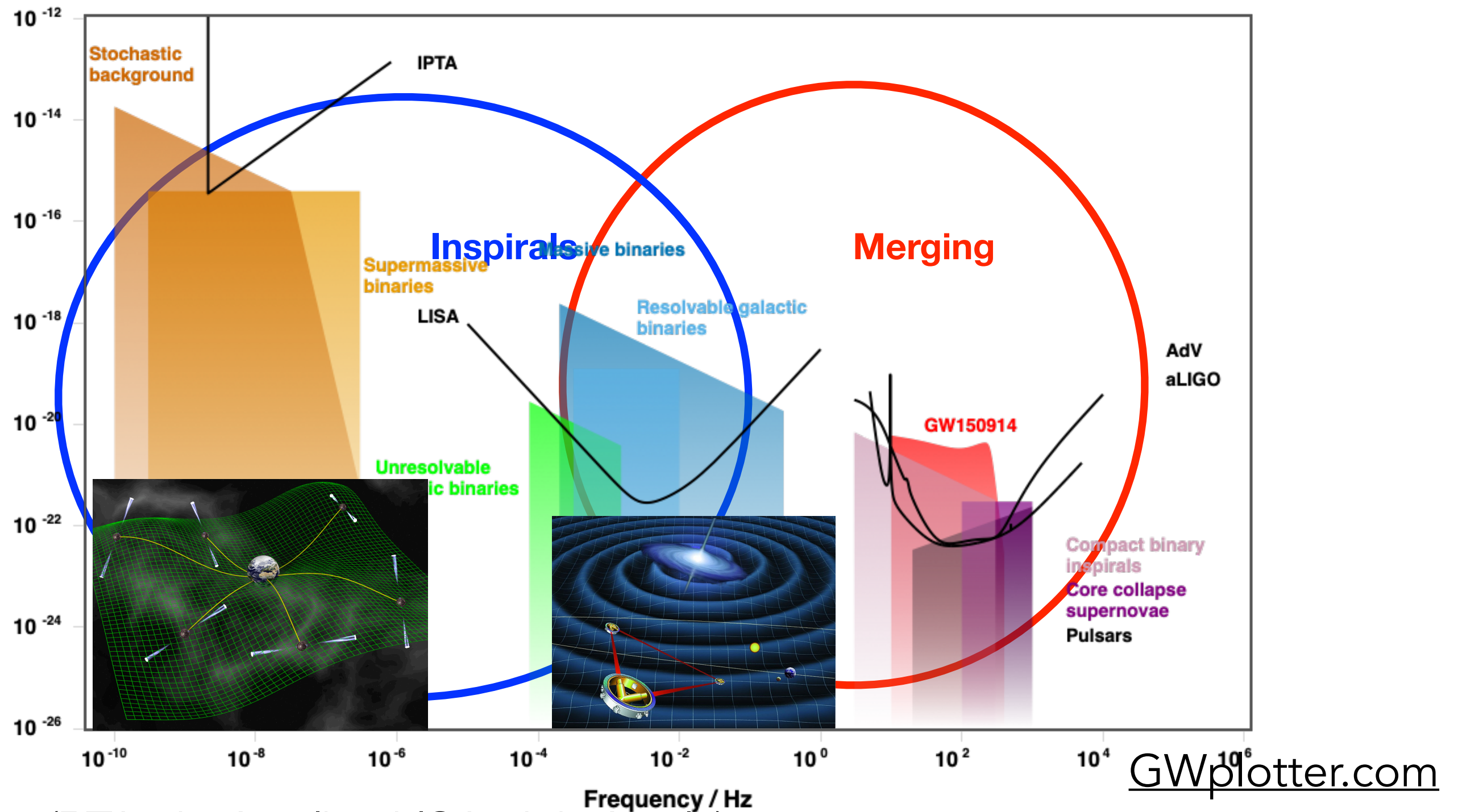
😊 GW amplitude(r) $\sim 1/r$, no extinction, no spatial crowding



Even in satellites!



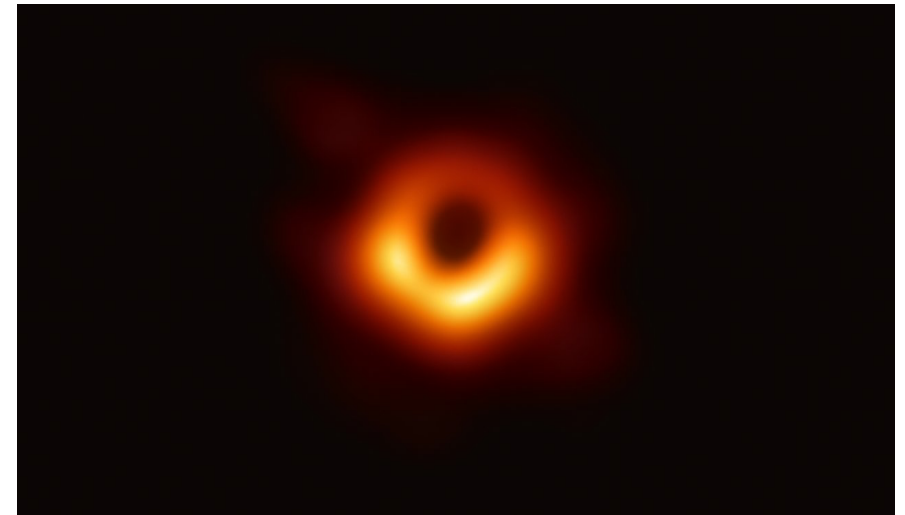
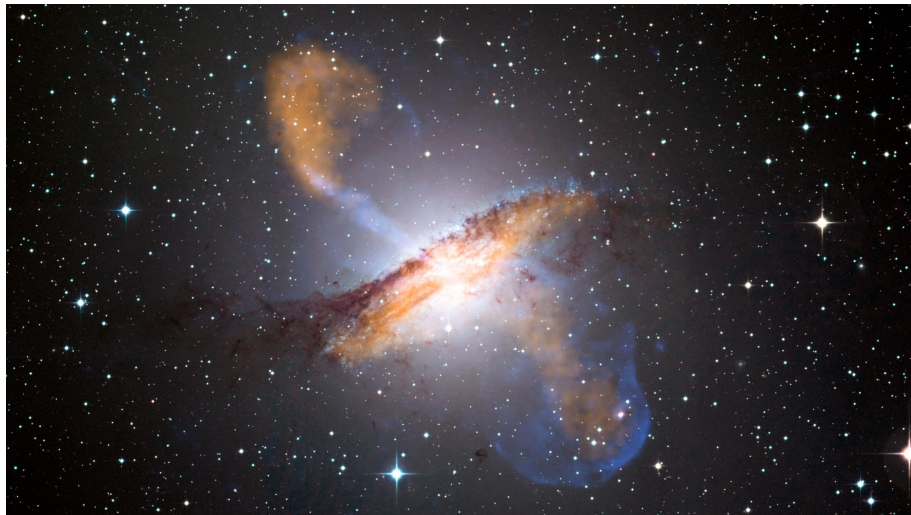
SUPERMASSIVE BHS: PULSAR TIMING & LISA



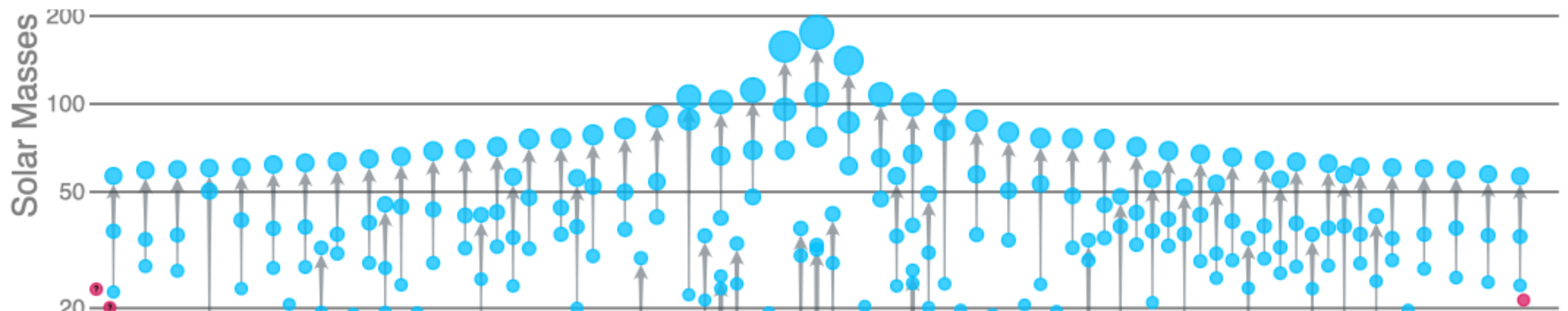
(PTA: Joe's talks; LISA: John's talk)

MORE MASSIVE COMPACT OBJECTS

Supermassive black holes: millions- billions of M_{sun}



Intermediate mass black holes?



SUPERMASSIVE BLACK HOLES

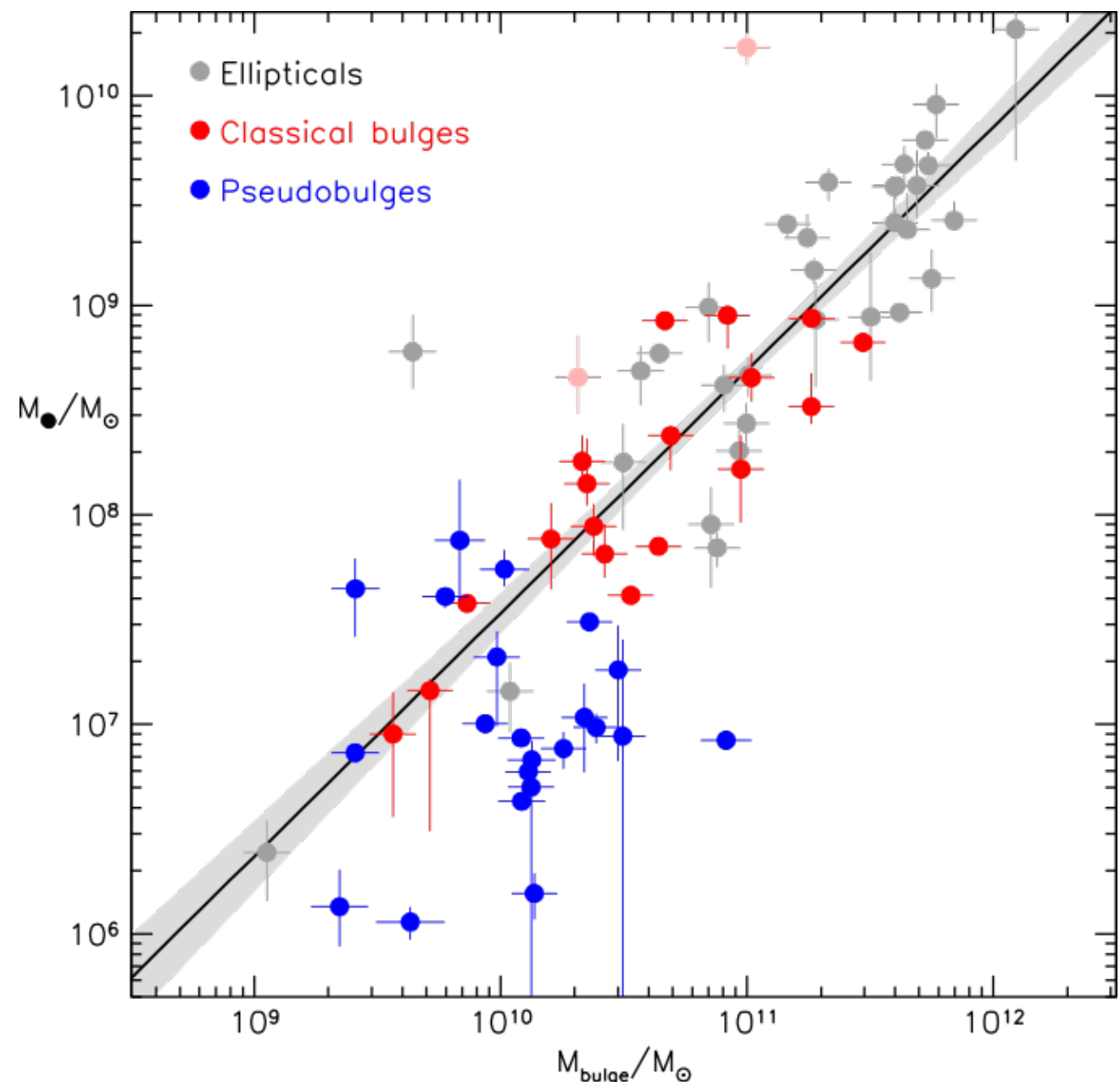
Found at the center of all (massive galaxies)

Kormendy, Ho 2013

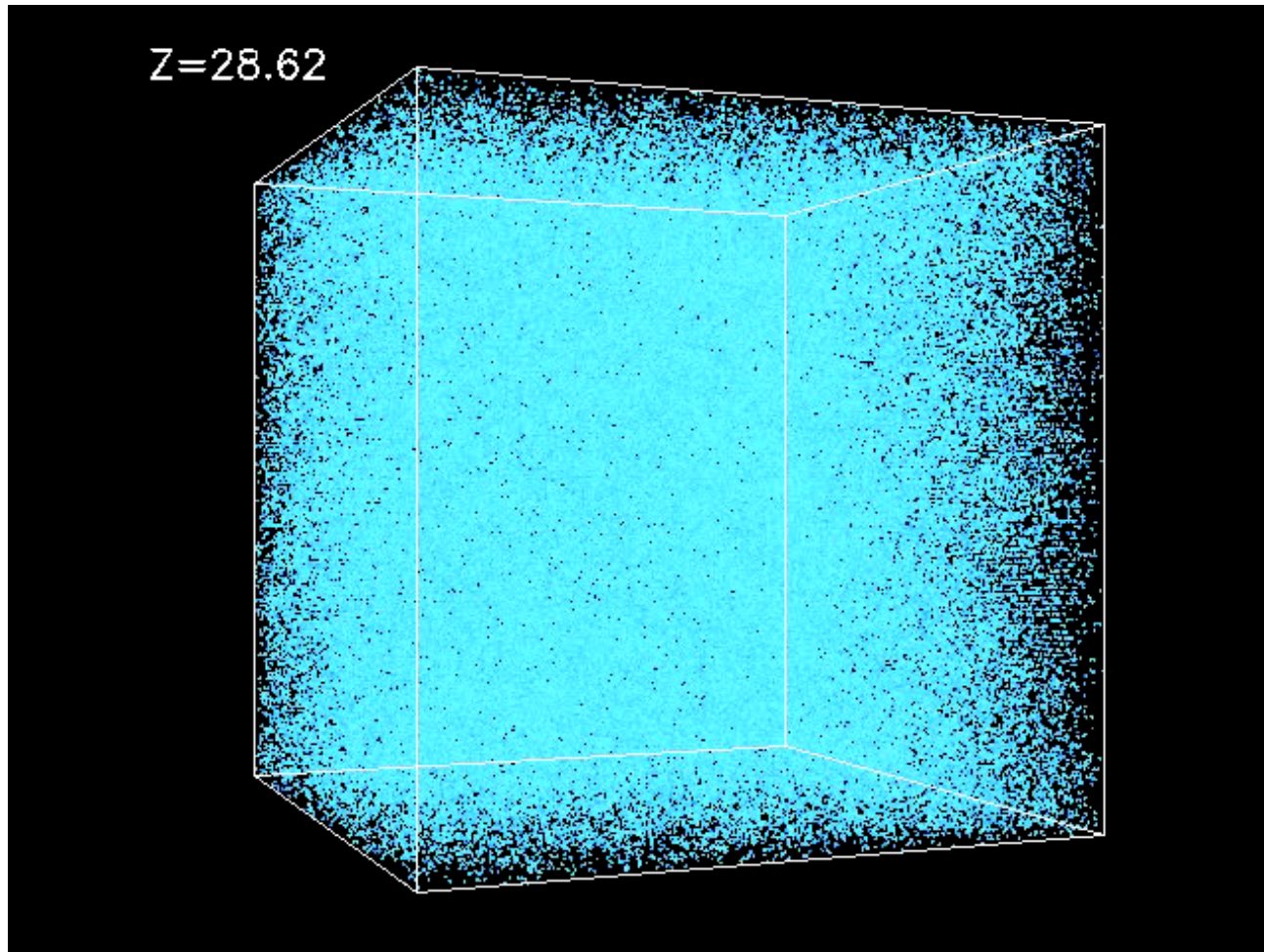
Masses correlate with
Galactic properties
-> joint evolution -> how?

Evidence of very massive
BHs very early ($10^8 M_{\odot}$ in
less than a Gyr)
-> how?

Hard to observe population
with EM (but JWST)

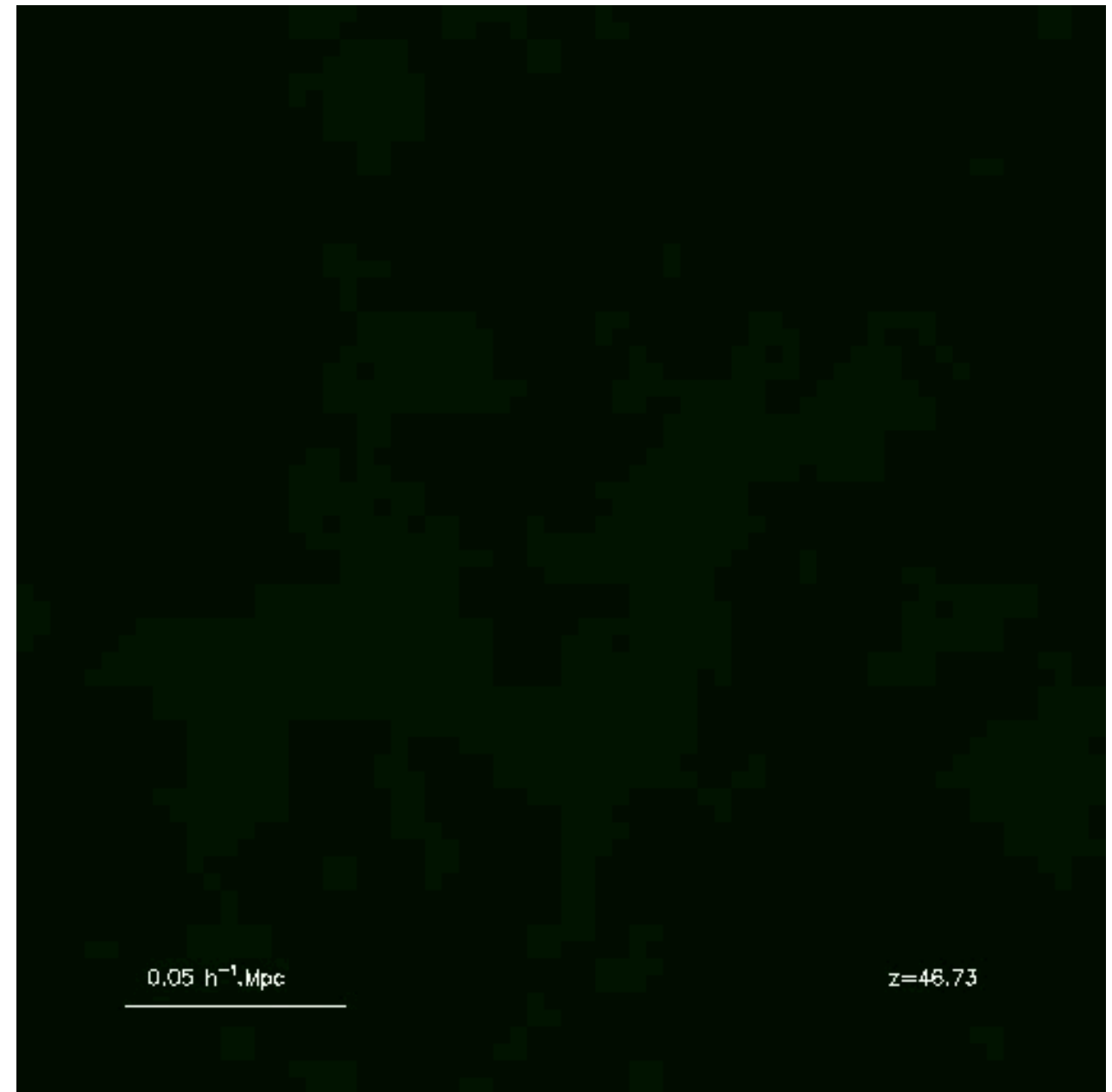


HOW DO GALAXIES GROW?



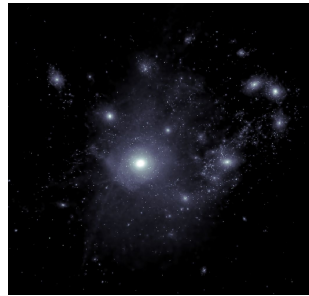
Cosmic web $\rightarrow$ structure increases over time with accretion and mergers

Active Galactic Nuclei strongly
Affect galaxies

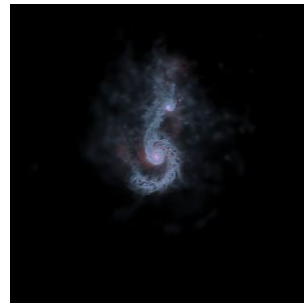


HOW DO SUPERMASSIVE BH MERGE?

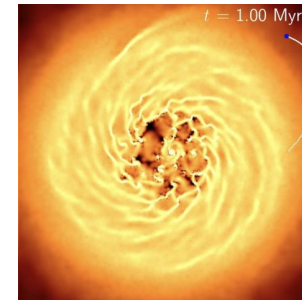
HOW DOES THE BINARY SHRINK?



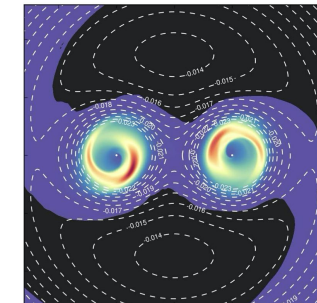
Credit: Lupi et al. (2019)



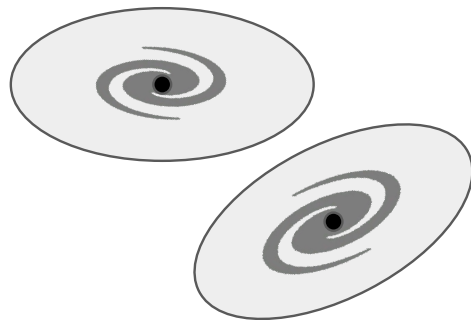
Credit: Capelo et al. (2015)



Credit: Souza Lima et al. (2017)

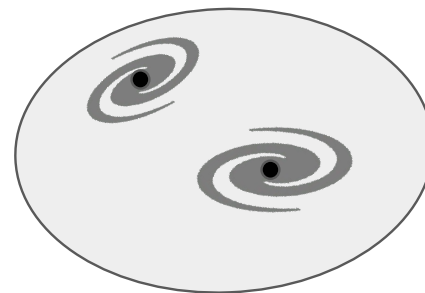


Credit: Bowen et al. 2017



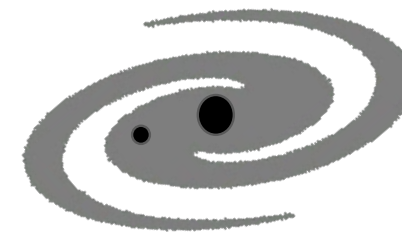
Mpcs:
The large scale structure

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



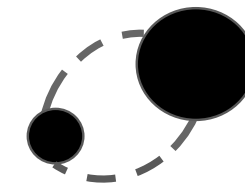
1-100s kpcs:
Galaxy interactions/merger

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



1-10s pc:
Formation of a bound binary

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



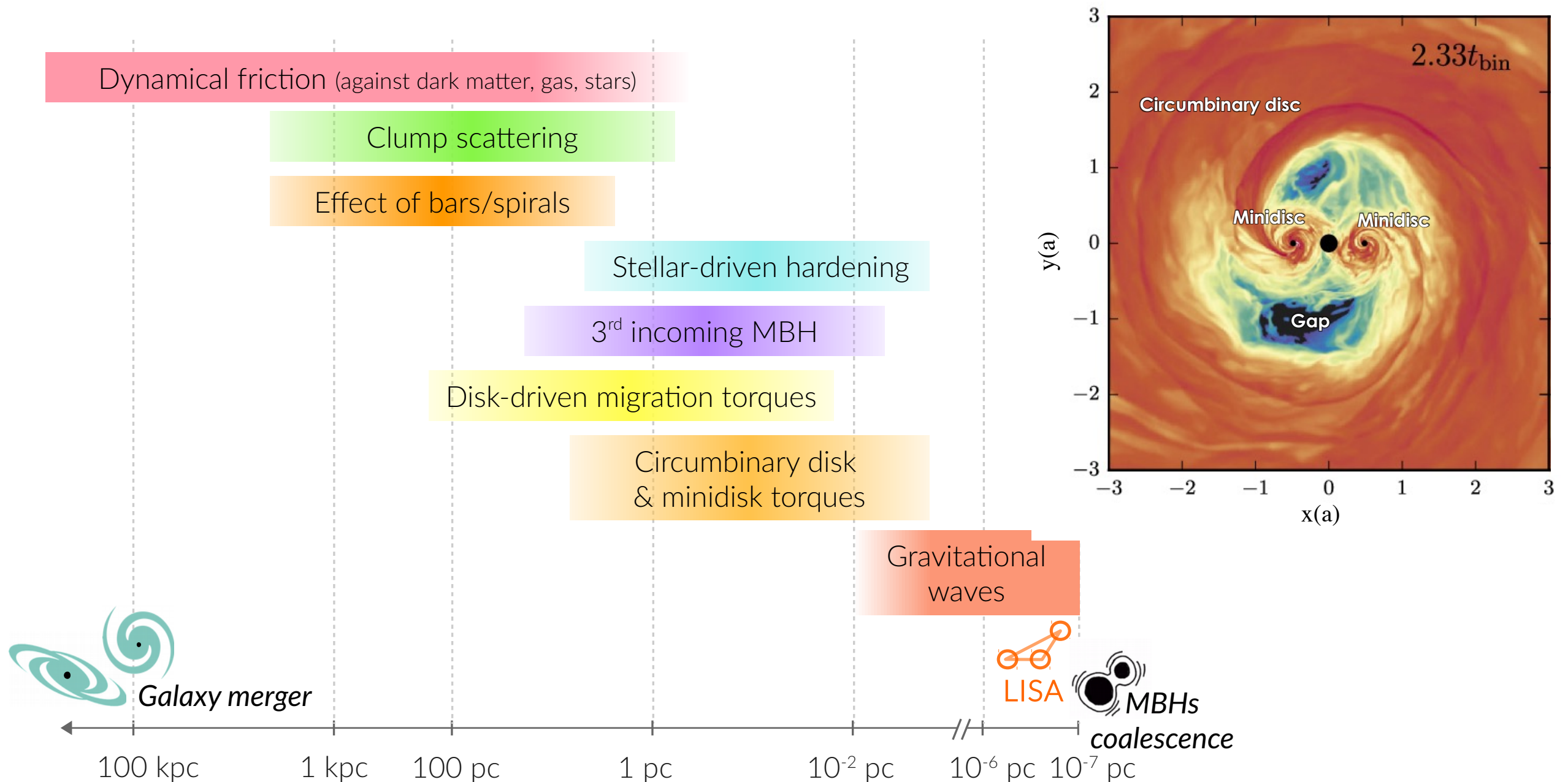
<1 pc:
Hardening of the binary

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

Spin measurements help disentangle accretion versus merger

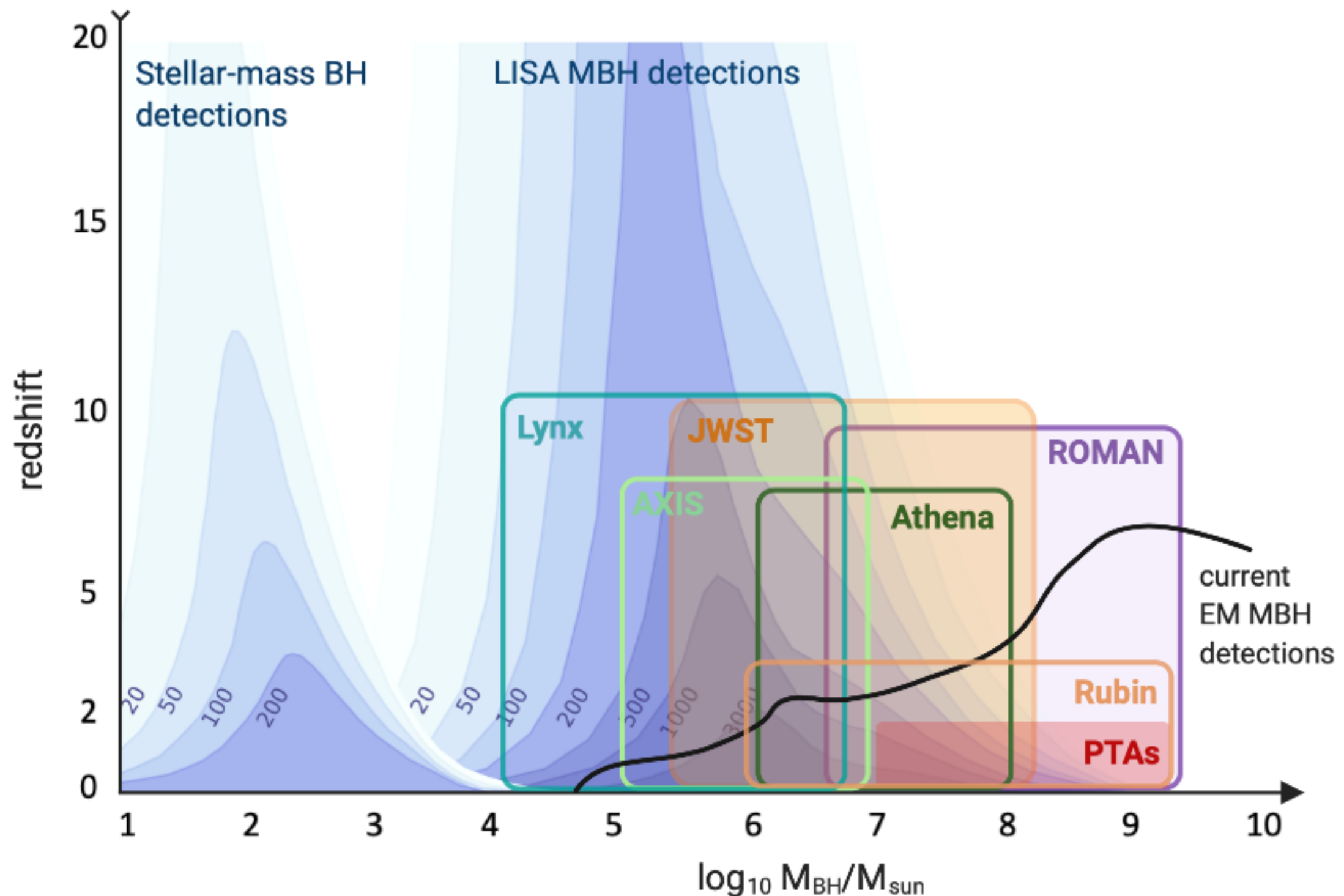
LISA Astrophysics White Paper

MULTISCALE-MULTIPHYSICS PROBLEM



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

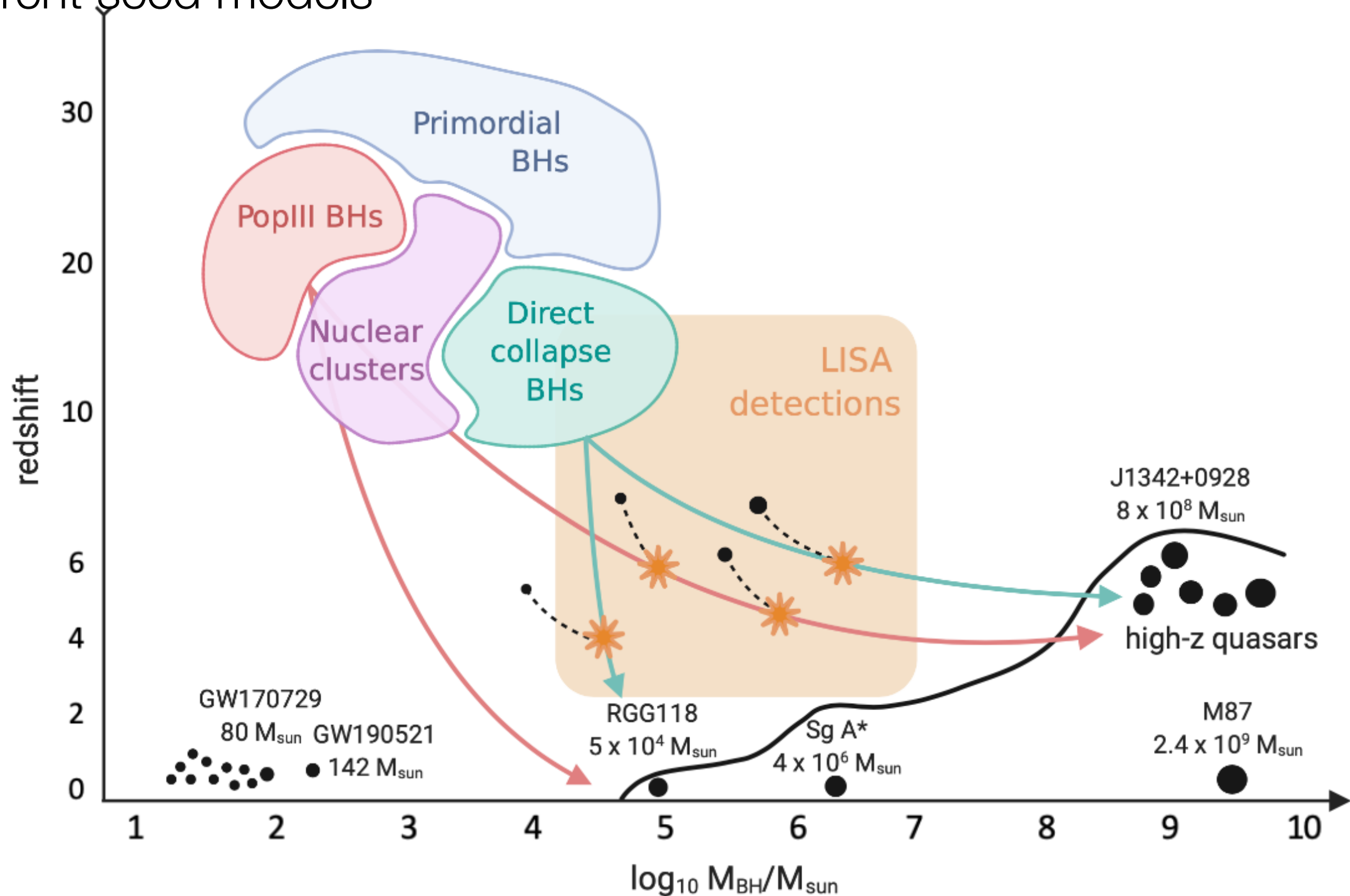
OBSERVING BLACK HOLES OVER A WIDE MASS RANGE



GWs observe much further, with different biases

ORIGIN OF SUPERMASSIVE BLACK HOLES?

Very massive BHs are found in early Universe, can distinguish between different seed models



COSMIC EVOLUTION OF SMBH

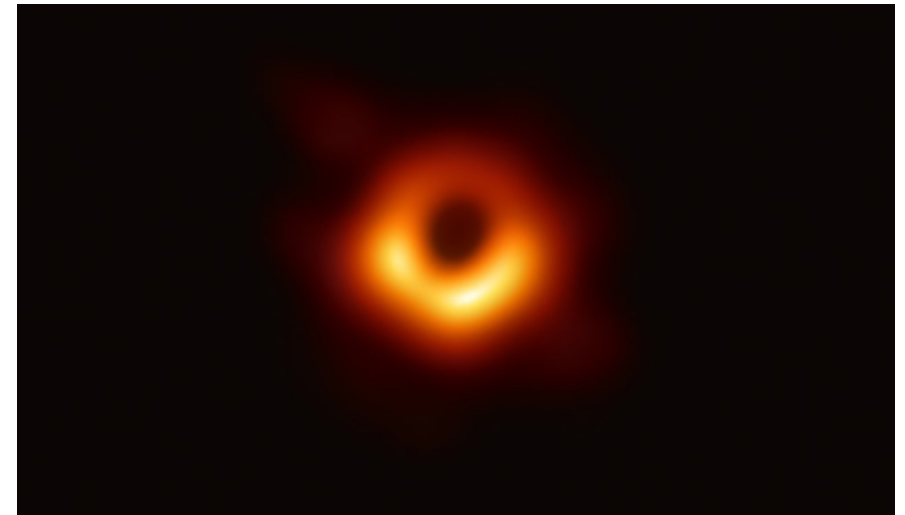
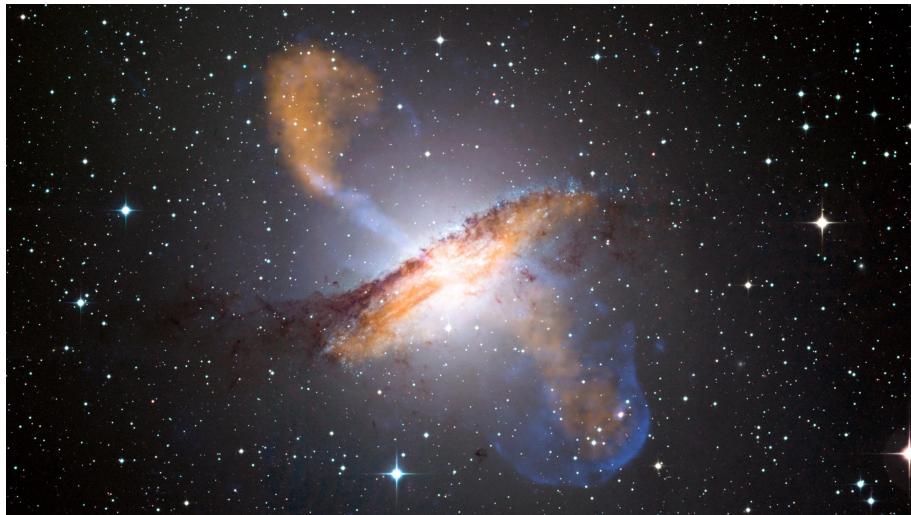
LISA: sensitive to $10^4 < M < 10^7 M_{\text{sun}}$: gap in EM observations
(demographics, host galaxies, dynamics...)
Masses, spins, redshift information will be crucial

Mergers in gas-rich environment -> possible precursors, EM counterparts,
post-merger emission from X-rays to radio, or neutrino

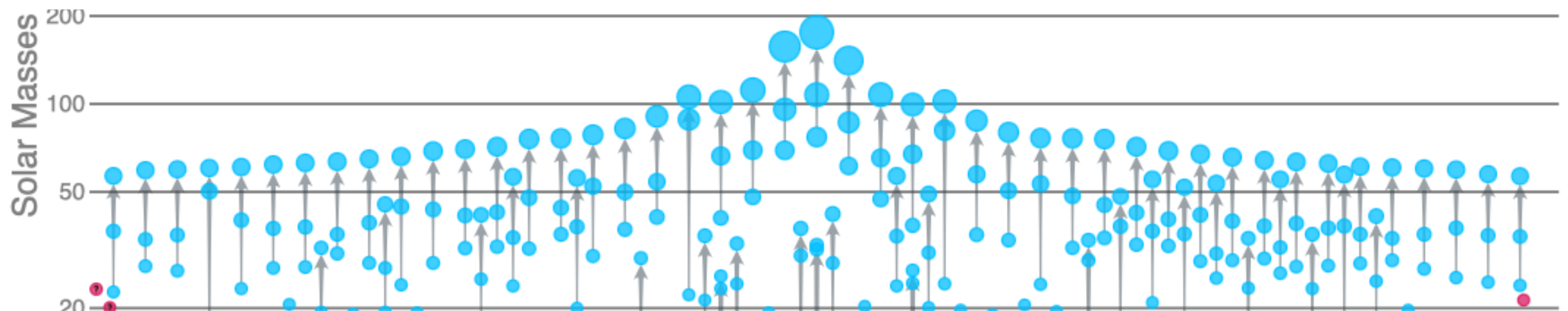
- detection of host galaxies
- Understanding accretion and ejection physics and associated emission

COMBINATIONS OF MASSES

Supermassive black holes: millions- billions of M_{sun}

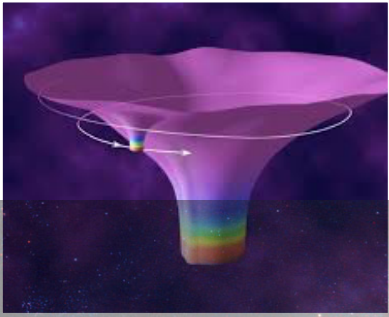


Extreme Mass Ratio Inspirals (EMRIs)



EXTREME MASS RATIO INSPIRALS

- LISA Science Objective: Probe the immediate environments of black holes in the local Universe using EMRIs and IMRIs



Stellar black hole around (super)massive black hole

mass and spin distribution of quiescent massive black holes nearby (IMBH)?
What dominates the stellar dynamics in these regions?

- Study the properties and immediate environment of Milky Way-like MBHs using EMRIs;
- Study the IMBH population using IMRI.
Very uncertain rates (few/yr $\rightarrow$ 100s /yr)

ASTROPHYSICS WITH GW

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

Different frequencies $\leftrightarrow$ different objects, different timescales, different distances

Crucial information: merger rate, masses, spins

Core question: bringing the binaries to merger $\rightarrow$ hard problem