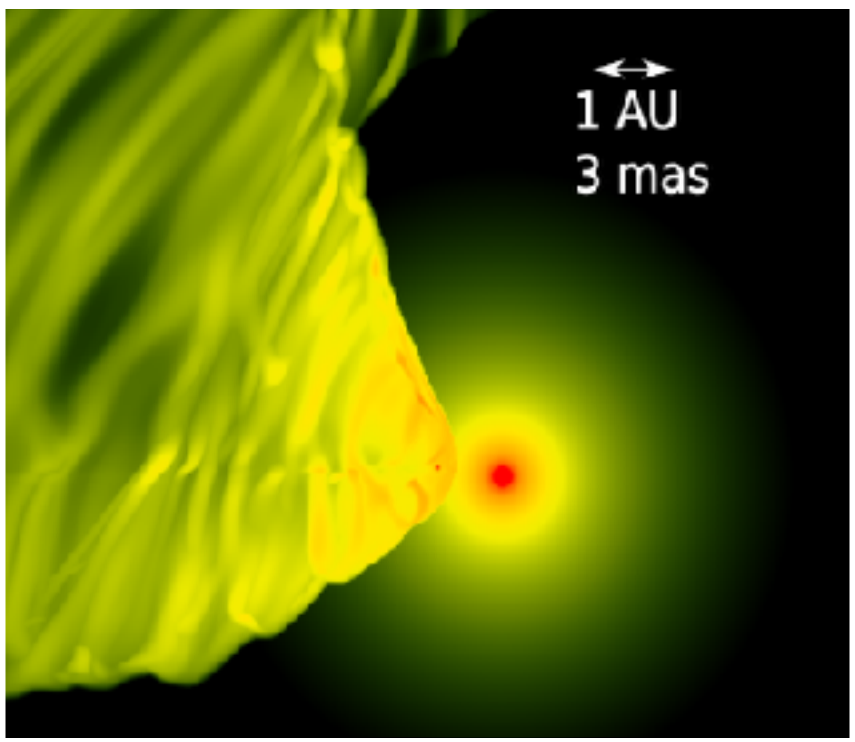
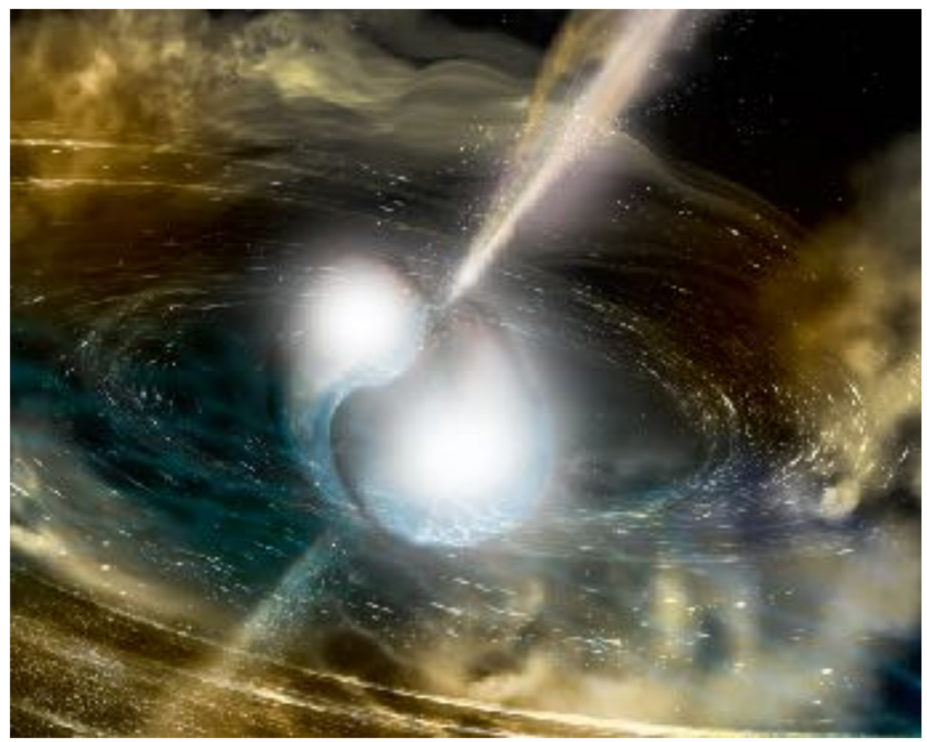
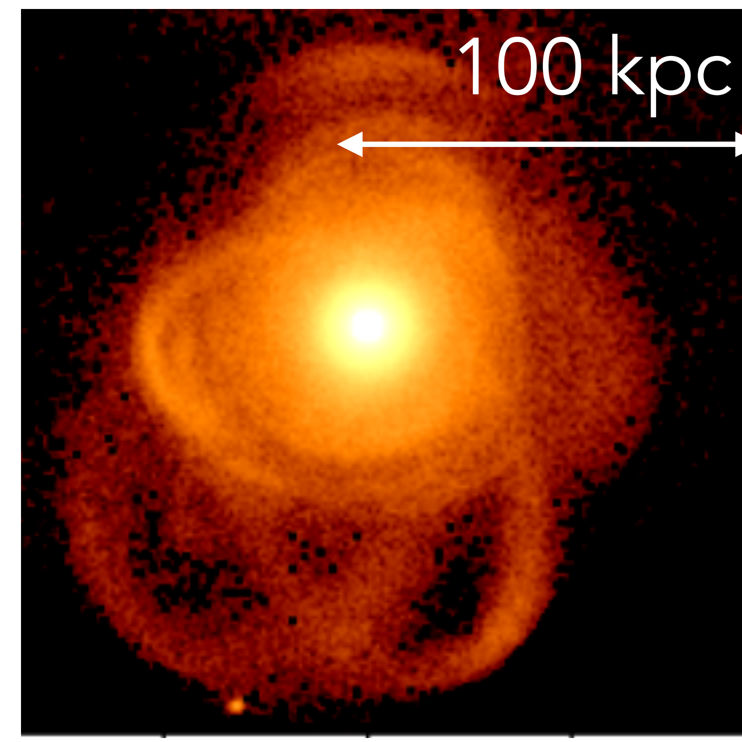
THE LIVES OF BINARY STARS WITH ELECTROMAGNETIC OBSERVATIONS AND GRAVITATIONAL WAVES







Astrid Lamberts

Observatoire de la CÔTE d'AZUR

Lagrange, 03/09/2019

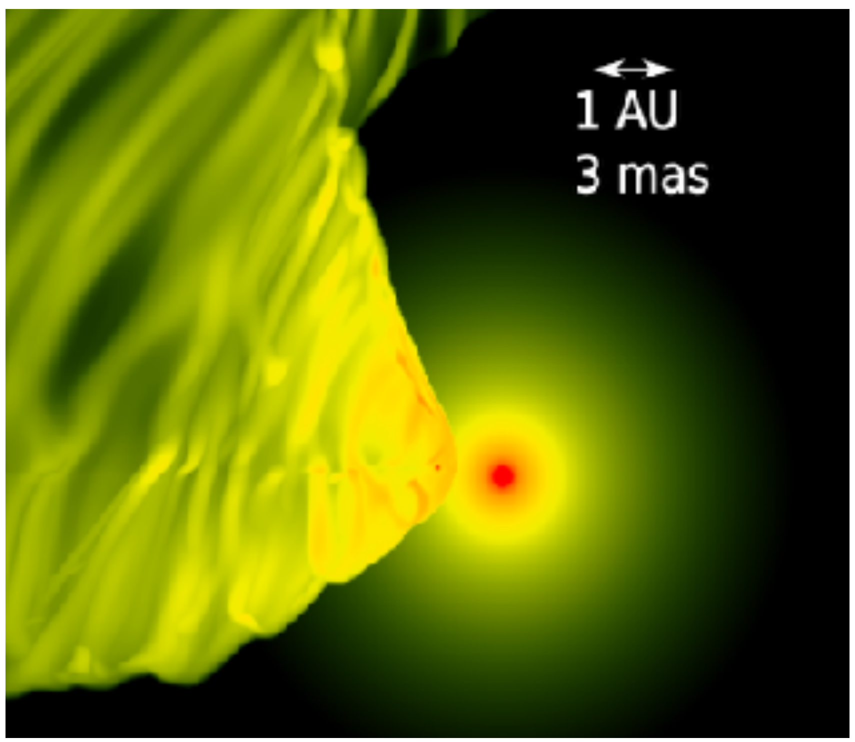
WHERE IS ASTRID?

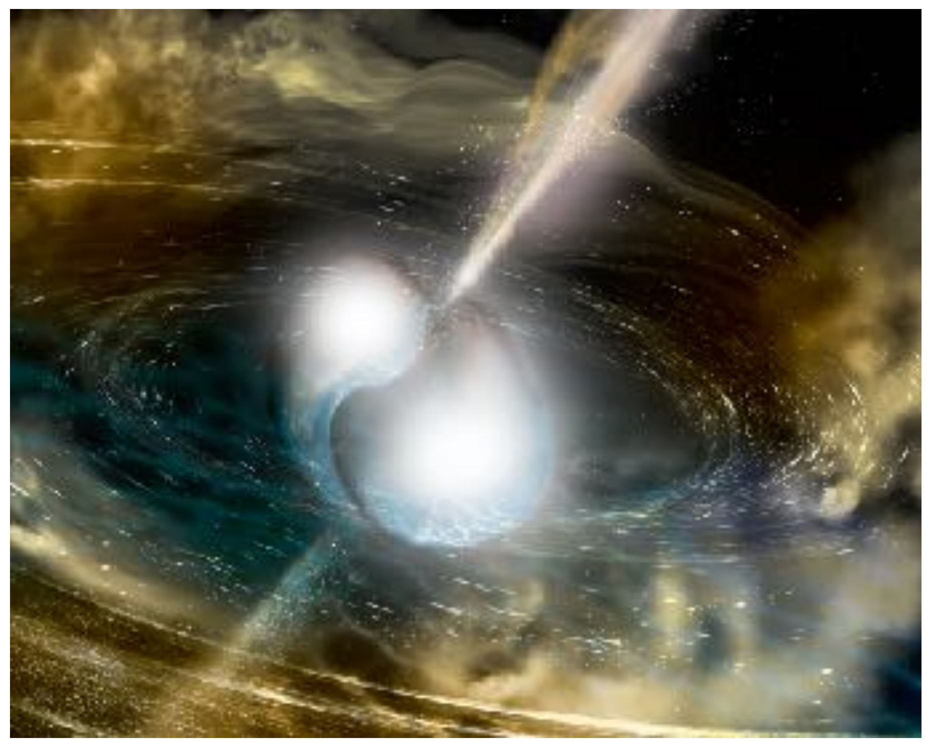
Default: Valrose, Physique Stellaire et Solaire
office 1-008 (after the printer on 1st floor)

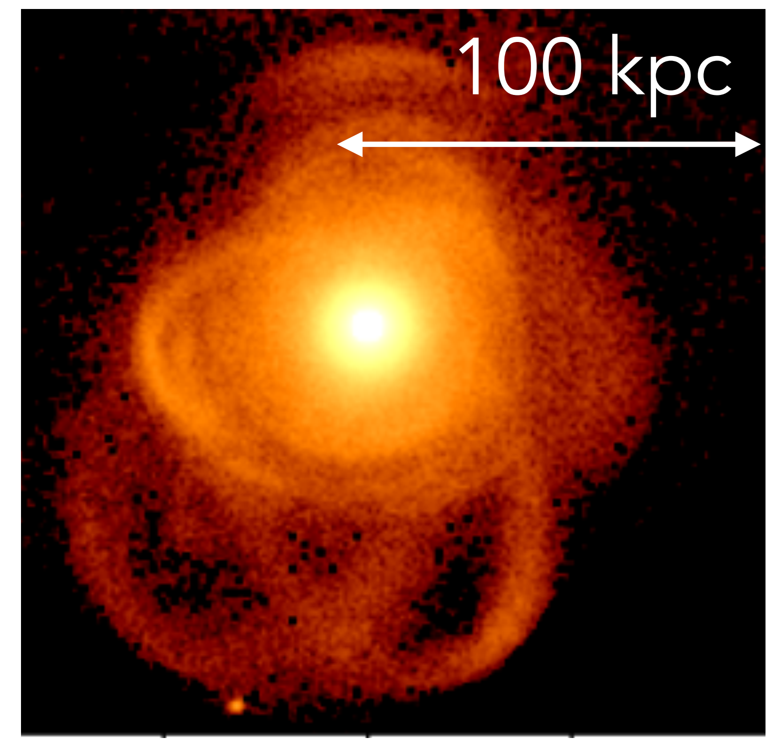
2 days a week: Mont-Gros:
Maison Jumelle, office 2-00 (2nd floor, in the corner.)

Usually Tuesday/Wednesday but depends on meetings, menu of the restaurant, vegetable garden….

THE LIVES OF BINARY STARS WITH ELECTROMAGNETIC OBSERVATIONS AND GRAVITATIONAL WAVES





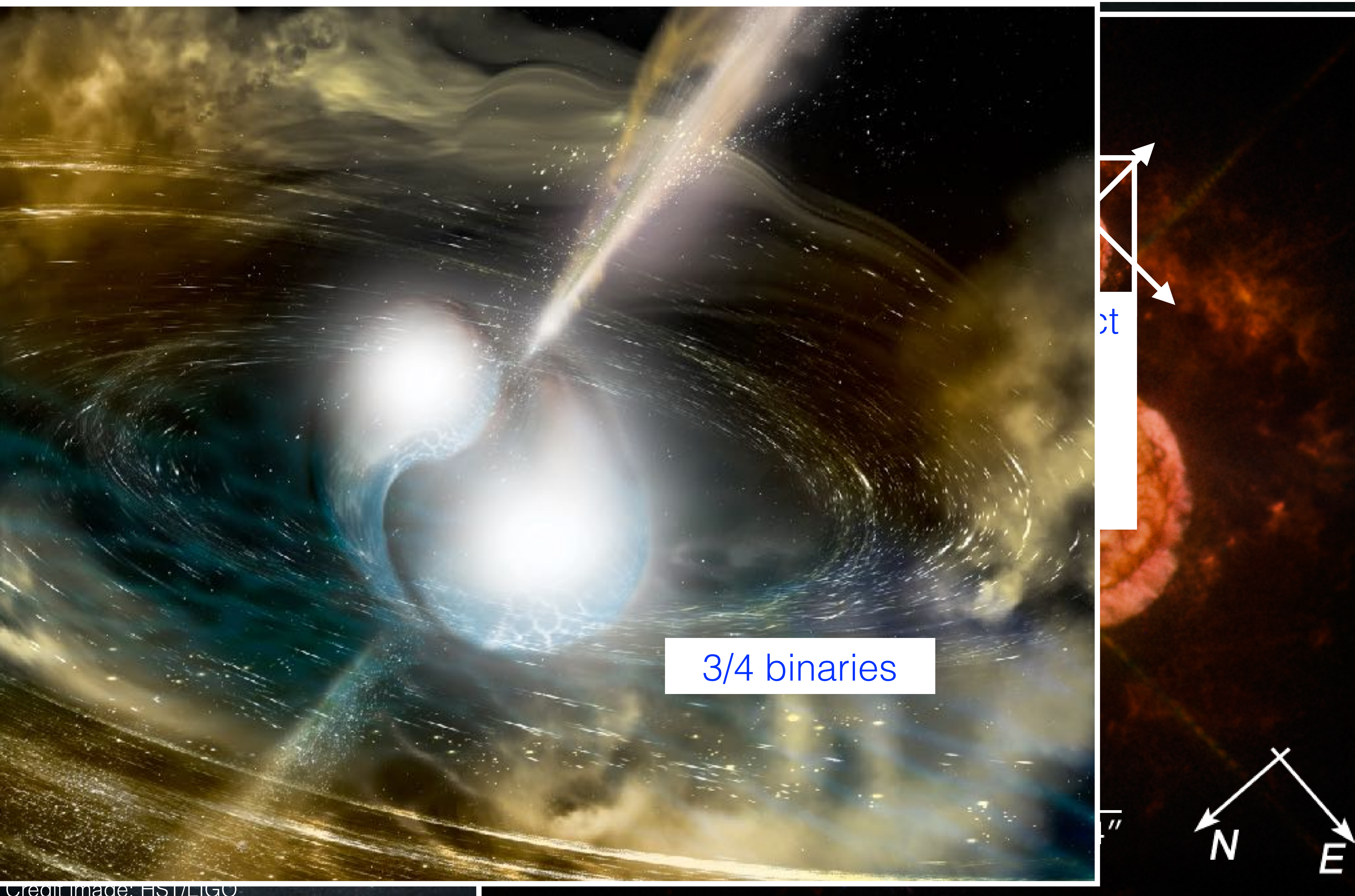


Astrid Lamberts

Observatoire de la CÔTE d'AZUR

Lagrange, 02/09/2019

MASSIVE STARS: COSMIC ENGINES AND FUNDAMENTAL PHYSICS



Credit image: HST/LIGO

(ALMOST) ALL MASSIVE STARS INTERACT

- ☹️Poorly understood

mass loss, mass transfer, impact/progenitors of supernovae

- ☹️Often ignored

Stellar evolution, galaxy evolution, contamination for population studies

- 😊More signatures than single stars

Masses, radii, mass loss, compact object

- 😊Extreme physics labs

particle acceleration, shocks, relativistic outflows, gravitational waves….

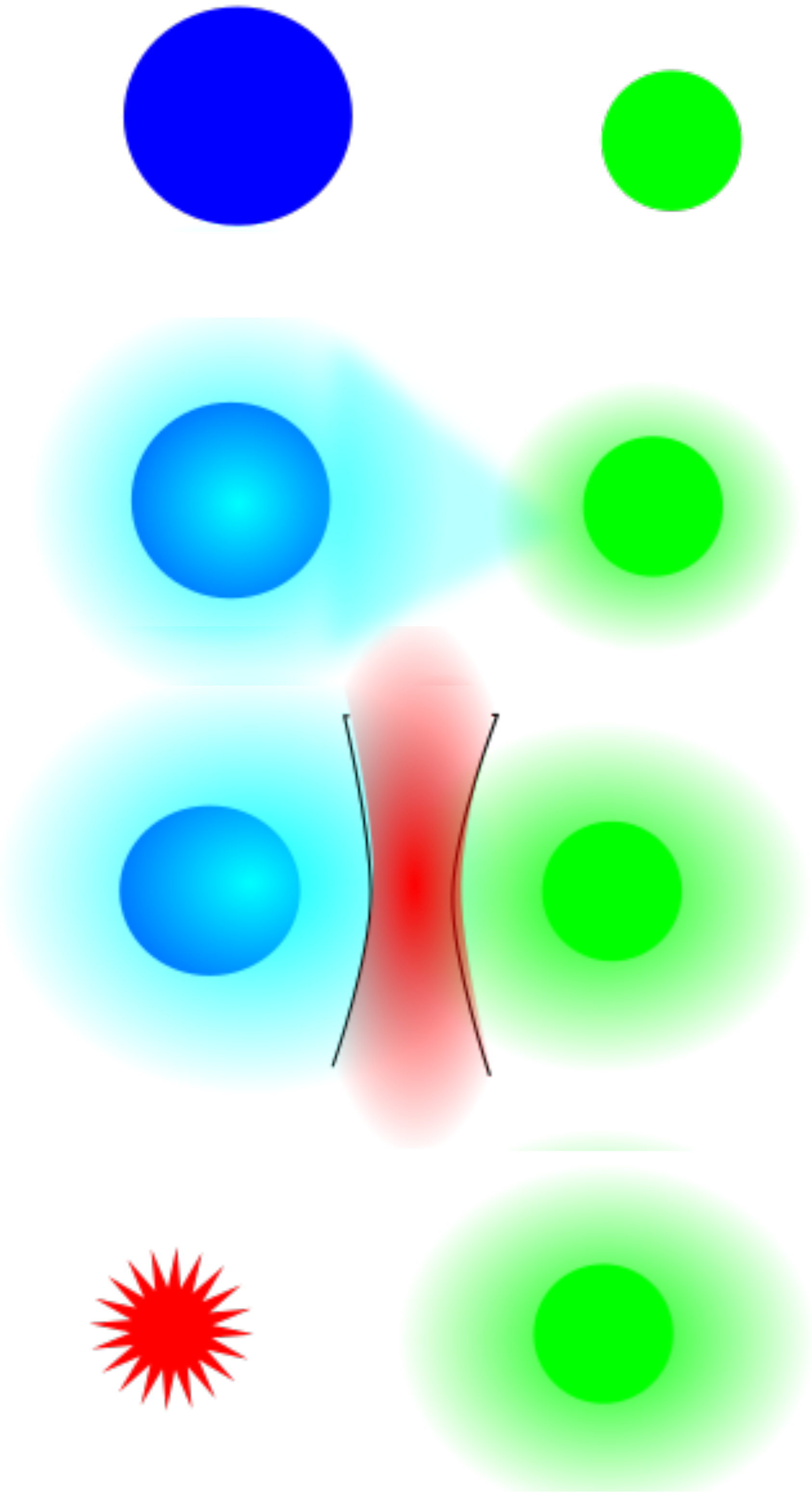
Understand dynamics, emission mechanisms of massive binaries

Individually and globally

Detailed observations of a few systems

Stellar populations:
Gravitational waves
Surveys

NO COMPACT OBJECT: STELLAR ASTROPHYSICS



Formation: 30 M_{sun} O stars

UV, Hα,[OIII], reprocessed

mass transfer

Circumbinary material?

wind collisions

X-rays, line variability, radio, dust

*(**Lamberts**+11,12,17)*

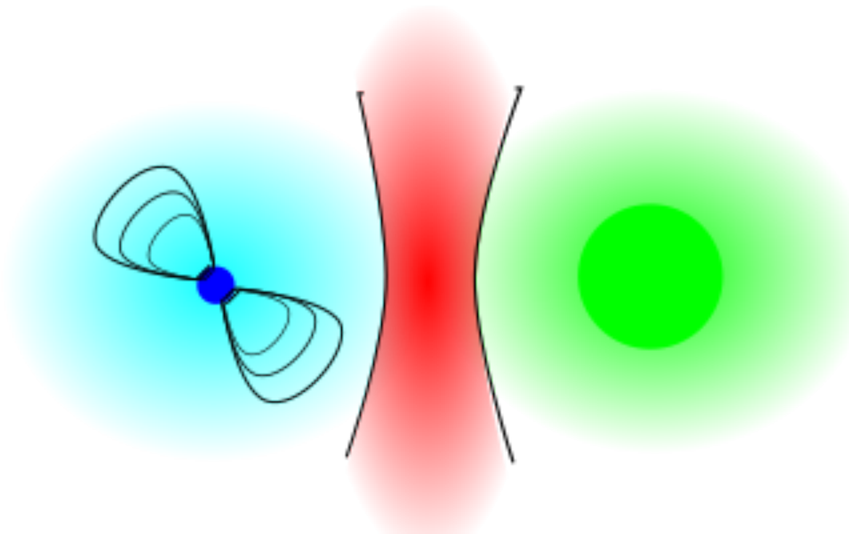
collapse 1: supernova/gamma-ray burst

Time domain multi-messenger astronomy

*(**Lamberts**, Daigne, 2018)*

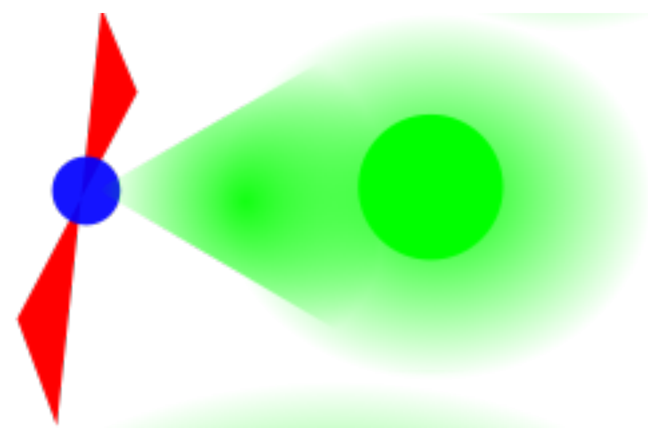
1 COMPACT OBJECT: HIGH ENERGY ASTROPHYSICS

if neutron star:
gamma-ray binary
(***Lamberts***+13;
Dubus, ***Lamberts***+15)



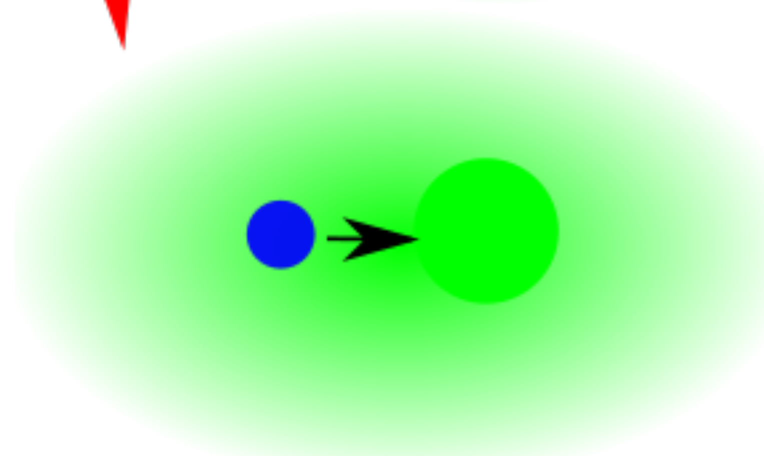
from radio to
TeV gamma rays

High-mass X-ray binary



X-rays, radio

Common envelope



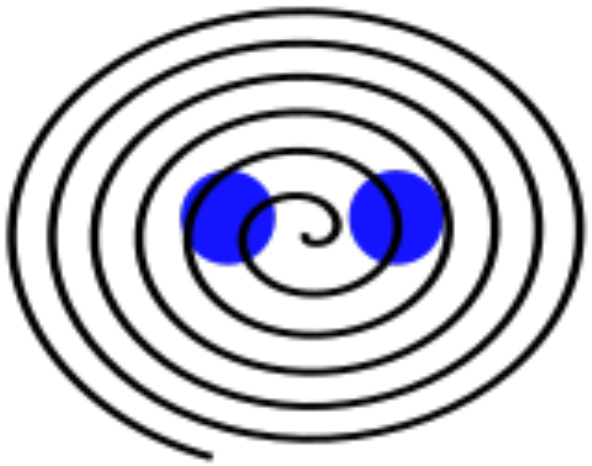
faint transient

Collapse 2
(***Lamberts***, *Daigne, 2018*)

Time domain
multi-messenger astronomy

2 COMPACT OBJECTS: GRAVITATIONAL WAVE ASTRONOMY

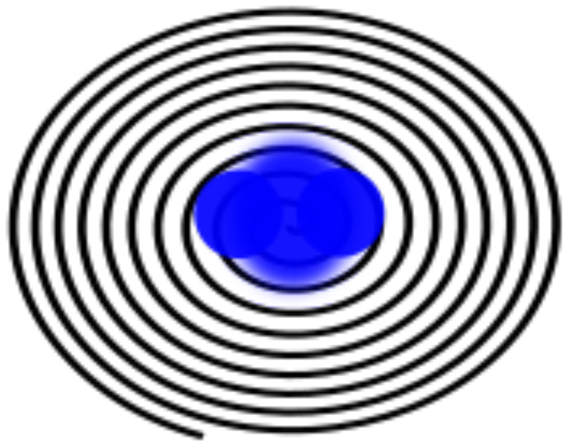
Billion years of inspiral



Low frequency gravitational waves,
double pulsars (Nobel Prize '93)

*(**Lamberts**+2018b, 2019)*

Merger



Higher frequency GW (Nobel Prize '17)
Possible GRB, kilonova, neutrinos, other?

*(**Lamberts**+2016)*

Final remnant

Game over

CONNECTING THE DOTS

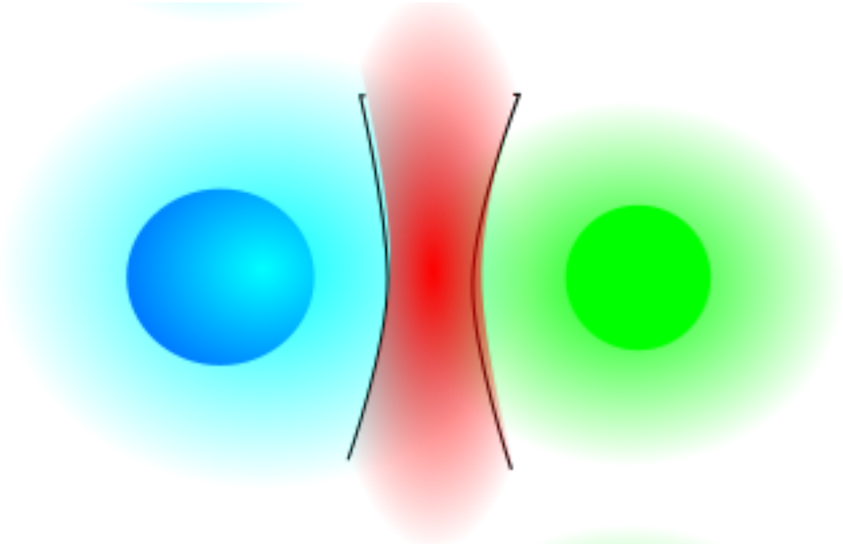
Study stellar astrophysics, high-energy astrophysics and gravitational wave astronomy

Understand dynamics, emission mechanisms of massive binaries
Individually and globally

Combine high resolution hydrodynamic simulations, emission models, analytic estimates with observations

CONNECTING THE DOTS

1. Colliding stellar winds
Origin and impact of dust-producing Wolf-Rayet binaries
(**Lamberts**, Millour +, 2017)



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X-ray flares in relativistic gamma-ray burst afterglows
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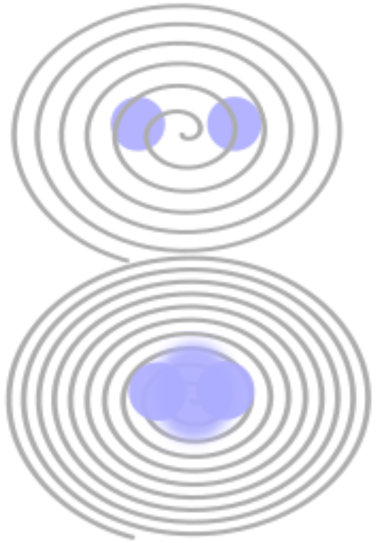
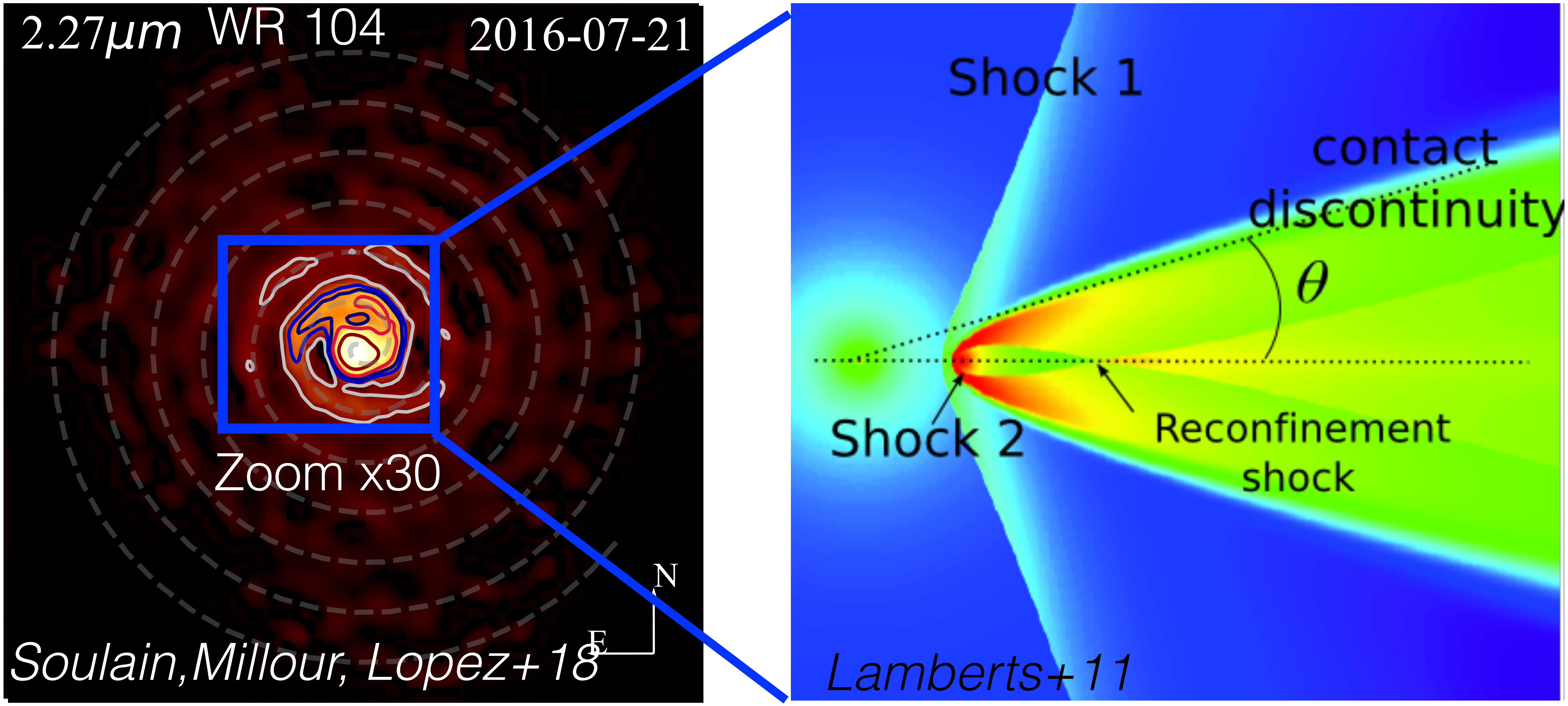
Where do GW progenitors form ?
*(**Lamberts**, Garrison-Kimmel+ 2016)*
*(**Lamberts**+ 2018b, 2019)*



EXTREME MASS LOSS IN WOLF RAYET STARS

Wolf Rayet: final stage massive stars, mass loss 10^{-5} M_{sun}/yr

Dust production in some binary/triple systems

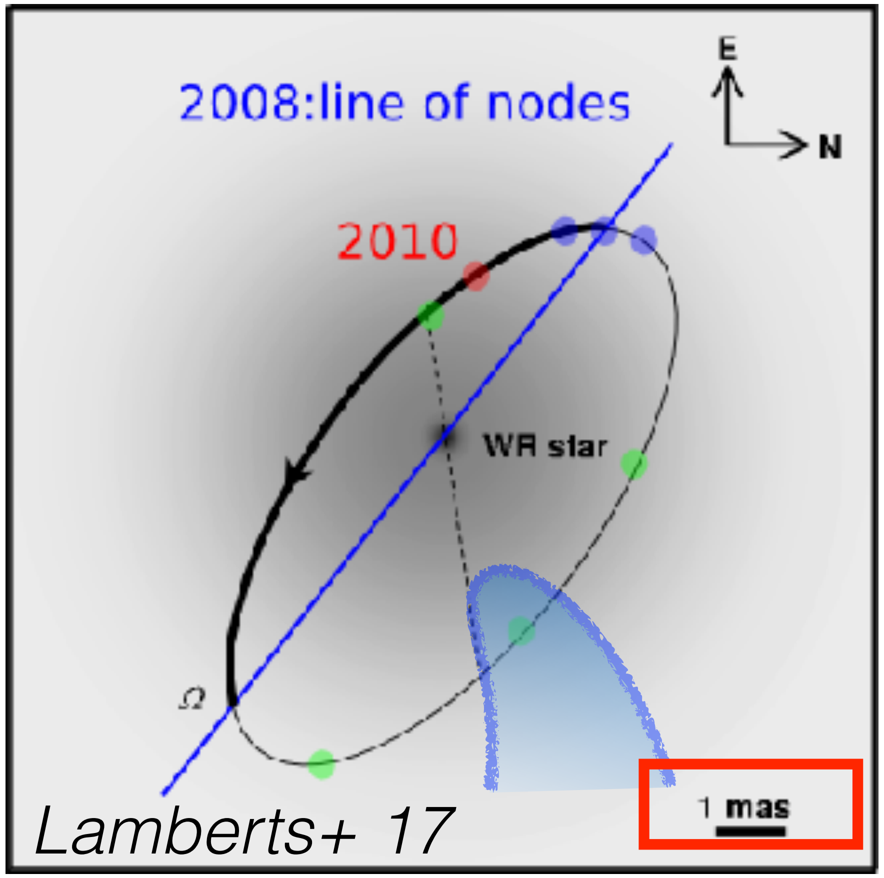


Questions: structure of the winds?

How to make the dust? Global impact?

γ^2 VELORUM: CLOSEST WR +O BINARY

- P=78 d
- optical/UV: detection of wind collision region.
  StLouis+1993; DeMarco+2002
- No dust detected



Mas separation: Near IR interferometry (AMBER)

→ spatial information

- orbital solution
- brightness ratio
- angular sizes

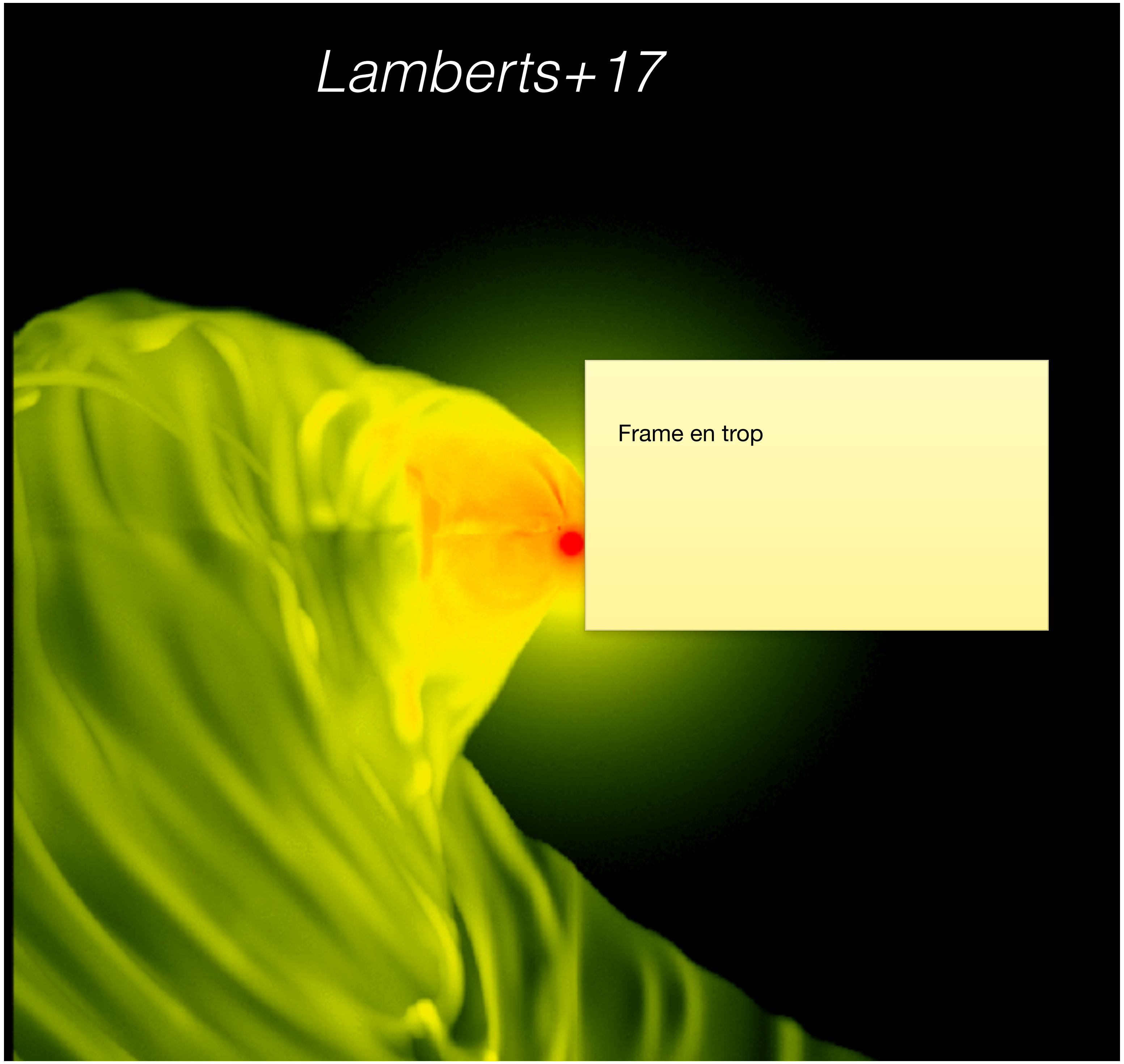
→ separate spectra

possibility for 1st direct detection of close wind collision

(see Weigelt+16 for ηCar)

Geometrical models fail to reproduce observations: need simulations

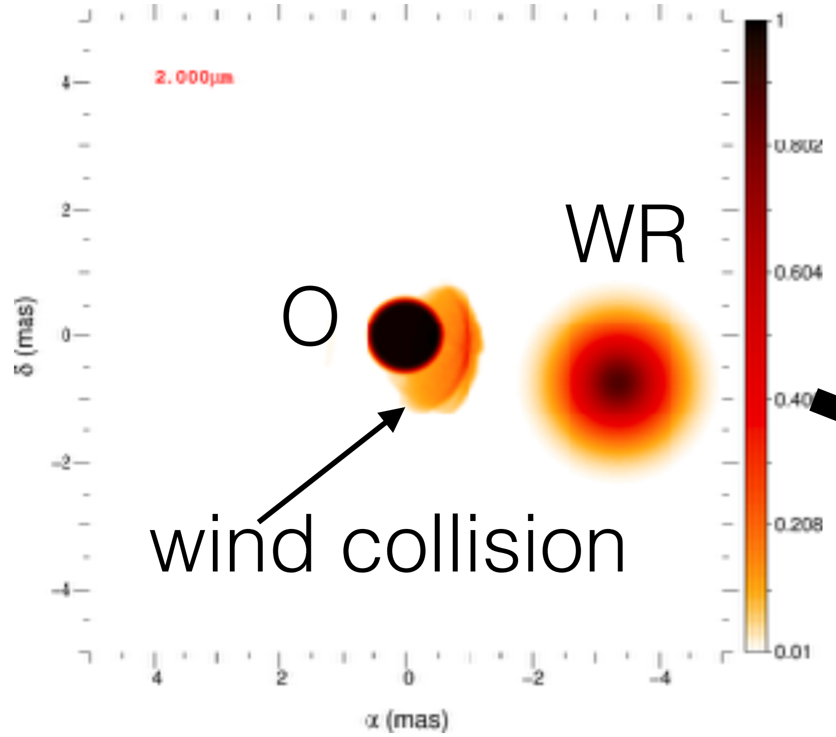
GAMMA VEL: THE MOVIE



- L_{box}=16 x separation
- resolution ~ R_{sun}
- radiative cooling

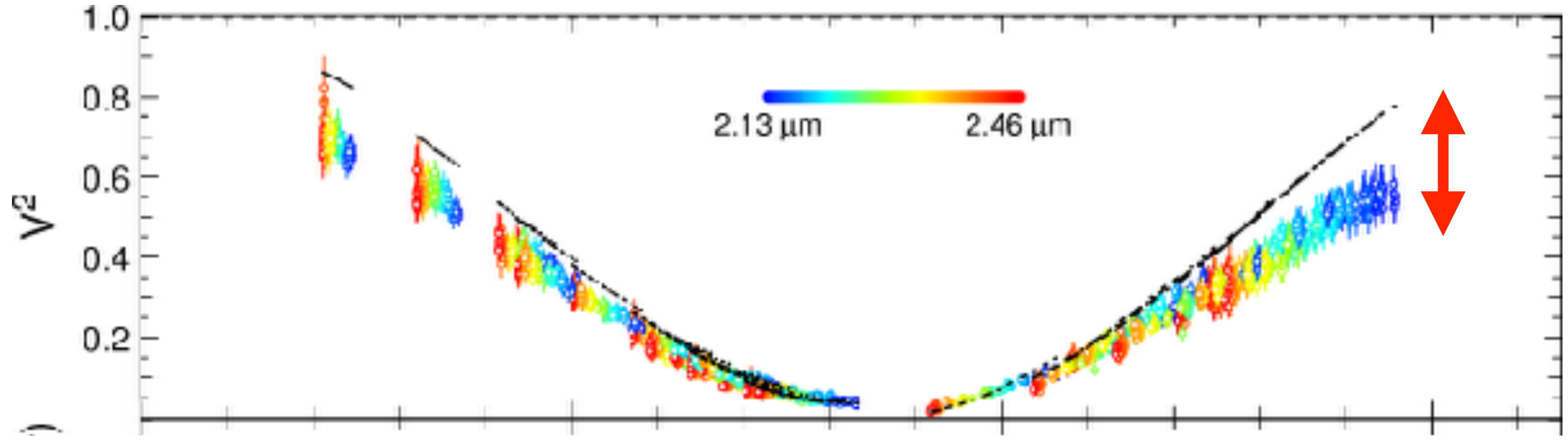
MODEL OBSERVATIONS FROM SIMULATIONS

Free-free @ 2micron

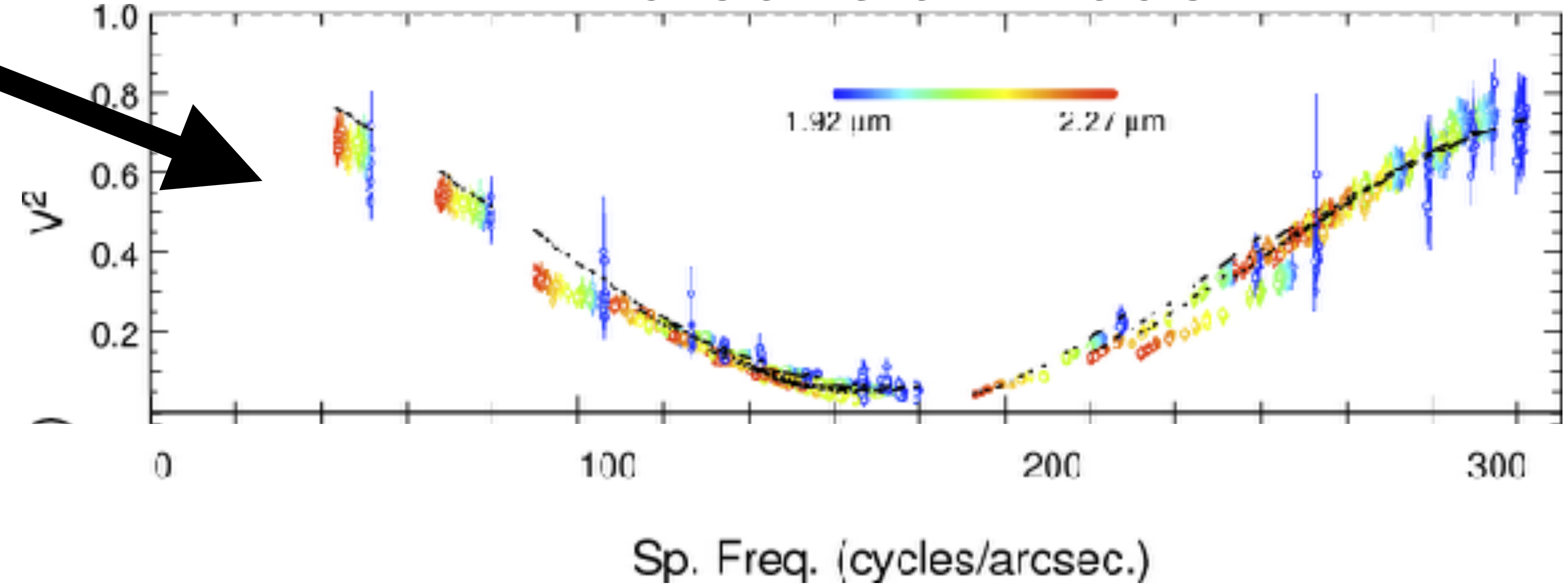


Lamberts+17

2 stars

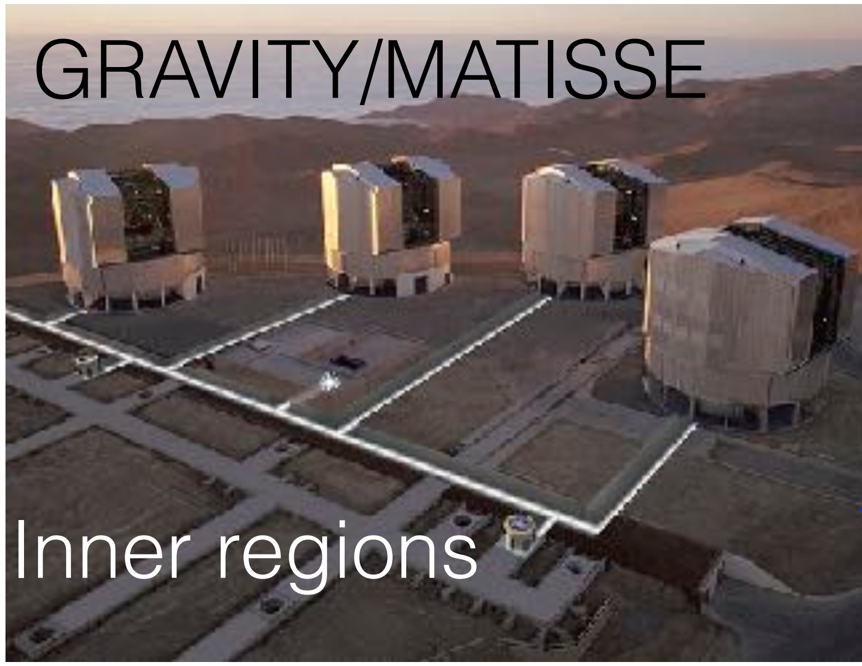


wind collision model

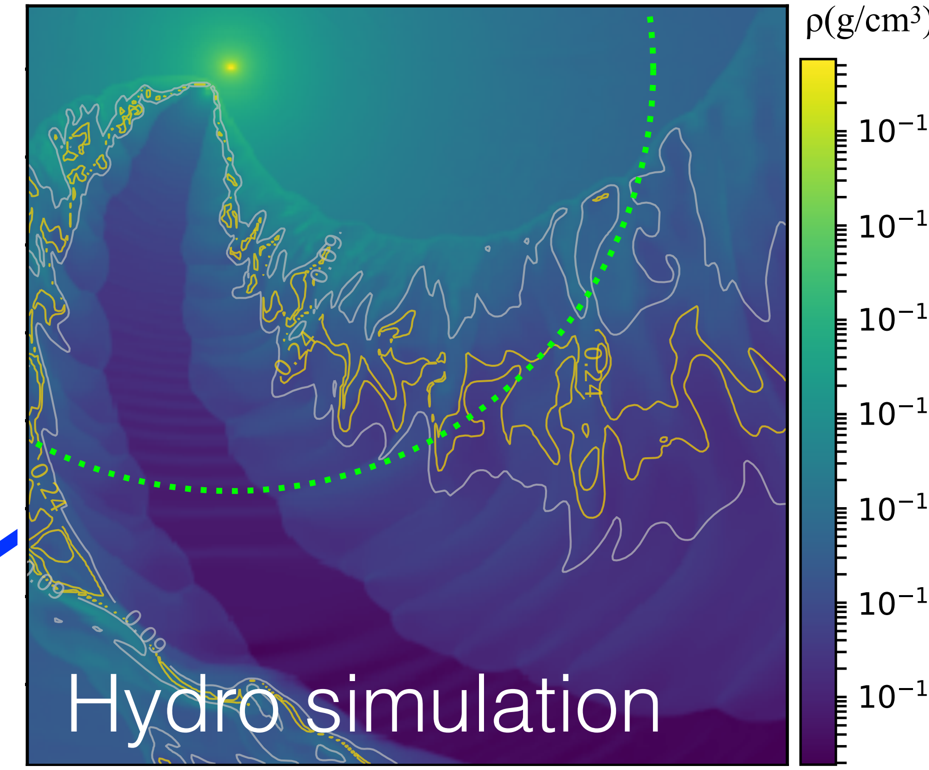


Result: Detection of wind collision region: 3-10% of continuum flux

CIRCUMSTELLAR ENVIRONMENTS: PATHS FORWARD



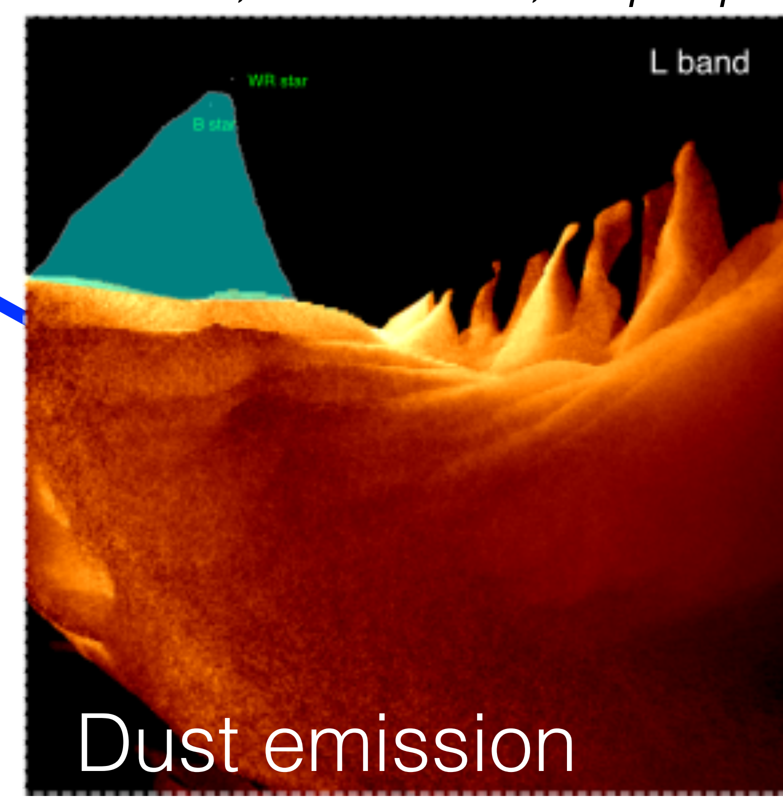
MATISSE
2 open time programs
(PI: Soulain, Millour)
+ GTO time



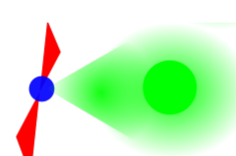
Soulain, Lamberts, in prep.

Understand, quantify
dust production
Global impact

Theory group leader
accepted DustERS
proposal (PI: R. Lau)



Other systems with MATISSE



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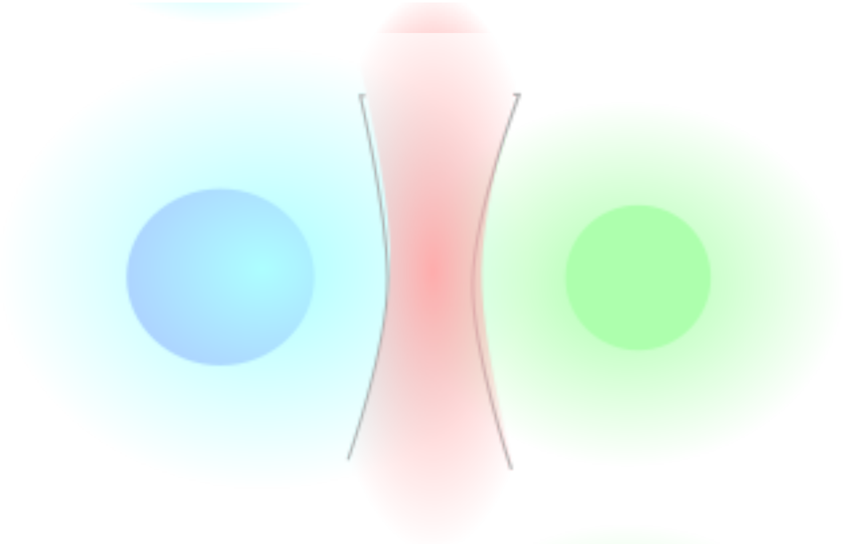

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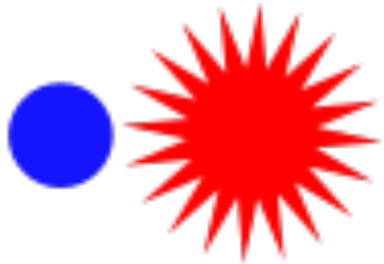

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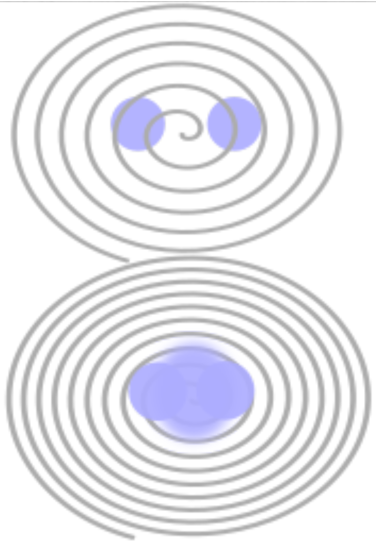
Where do GW progenitors form ?
*(**Lamberts**, Garrison-Kimmel+ 2016)*
*(**Lamberts**+ 2018b, 2019)*



EXTREME HYDRODYNAMICS IN GAMMA-RAY BURSTS

Extragalactic gamma-ray flashes ~once/day

- up to z>9: trace early universe
- extreme physics

Prompt gamma-ray emission: 2 types

- massive stellar collapse (long)
- GW170817 confirms neutron star merger (short)

Then afterglow

Provides host galaxy + global energetics

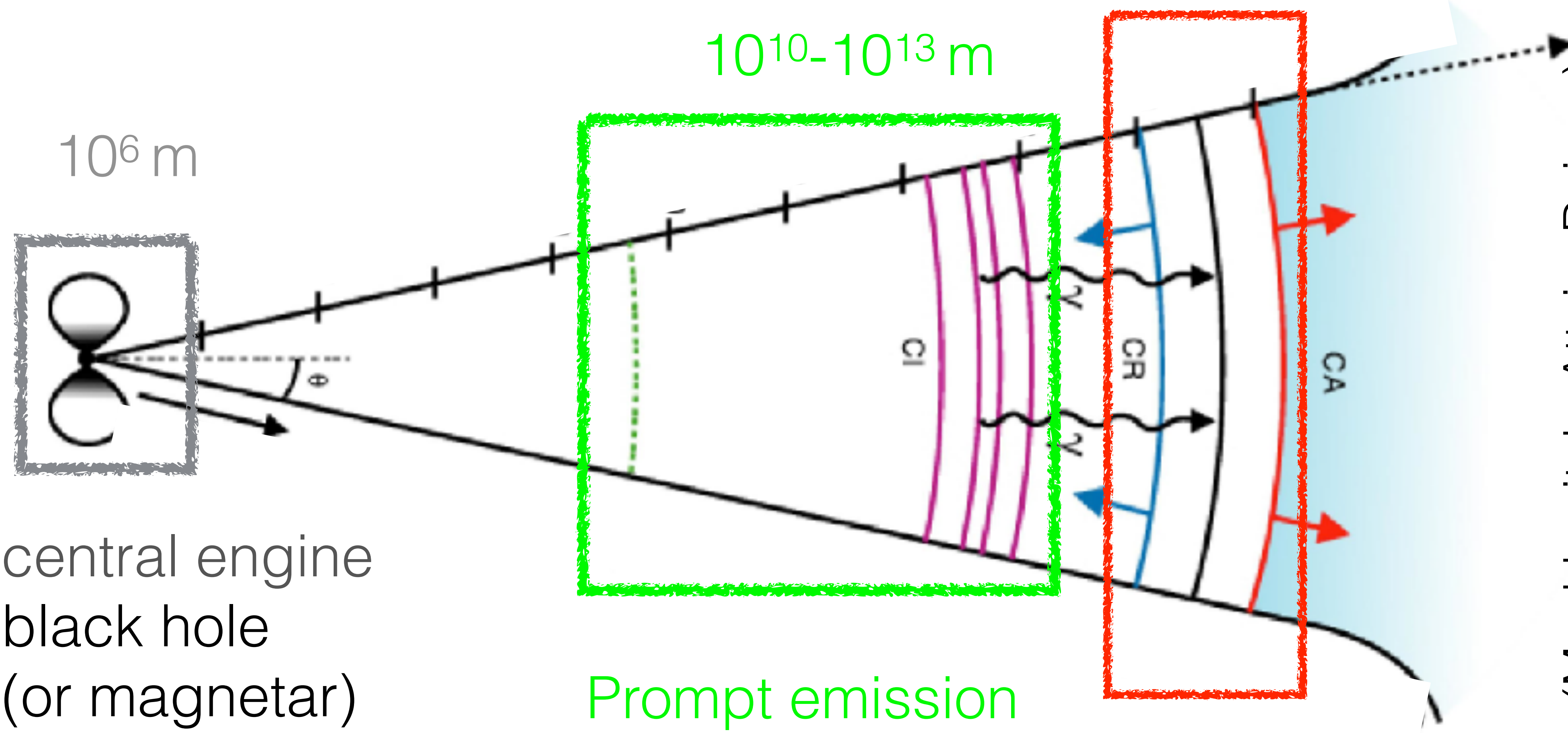
FIREBALL MODEL F0R GAMMA-RAY BURSTS

huge energy : $E_{iso} \sim 10^{50-55}$ erg, gamma rays → relativistic flow

10^{14}-10^{16} m

10^{10}-10^{13} m

10^{6} m



(Mochkovitch, Atteia, Daigne)

central engine
black hole
(or magnetar)

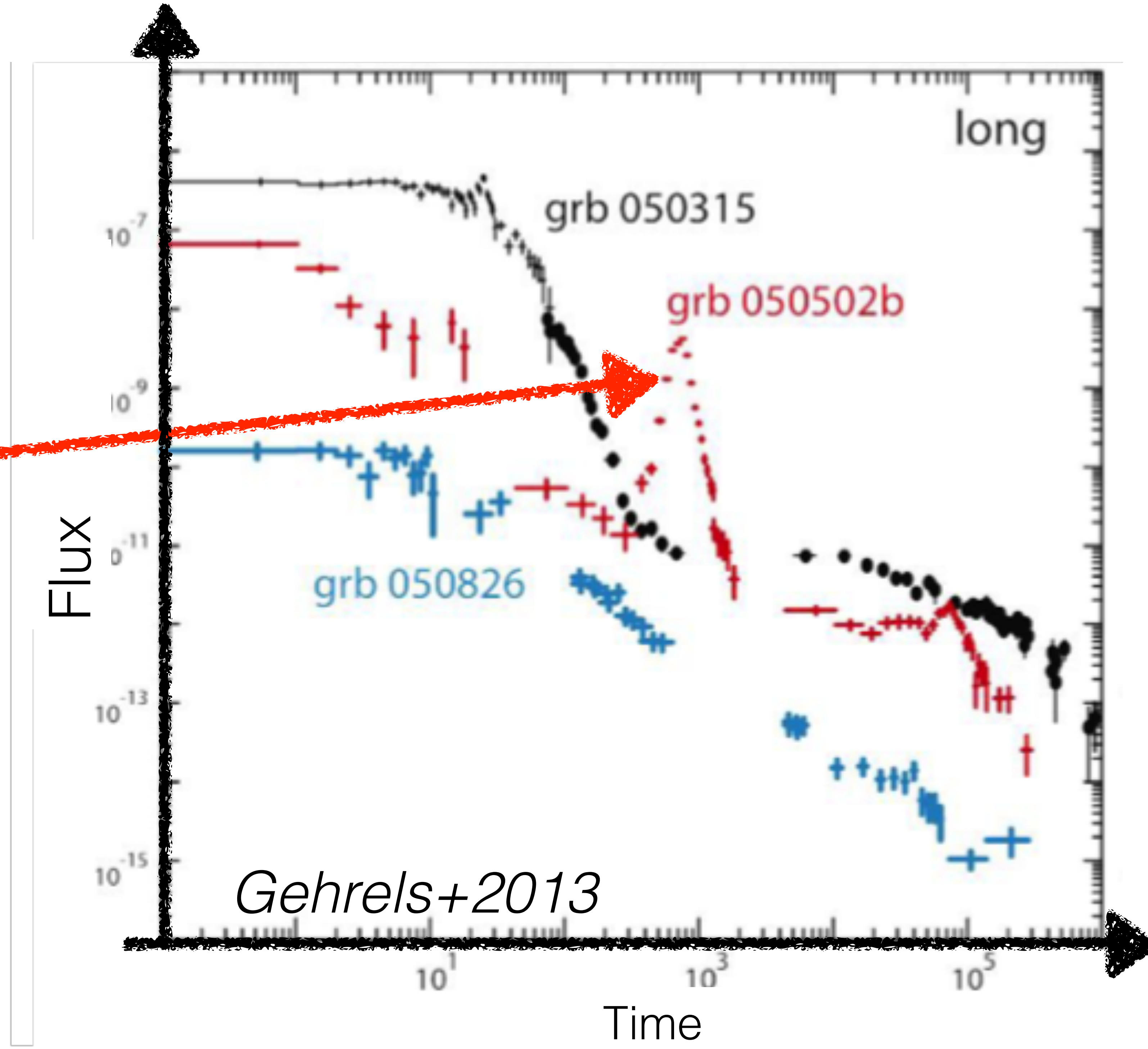
Prompt emission
internal

Afterglow
External
Expected t^{-1}

A LOT OF X-RAY VARIABILITY IN AFTERGLOWS

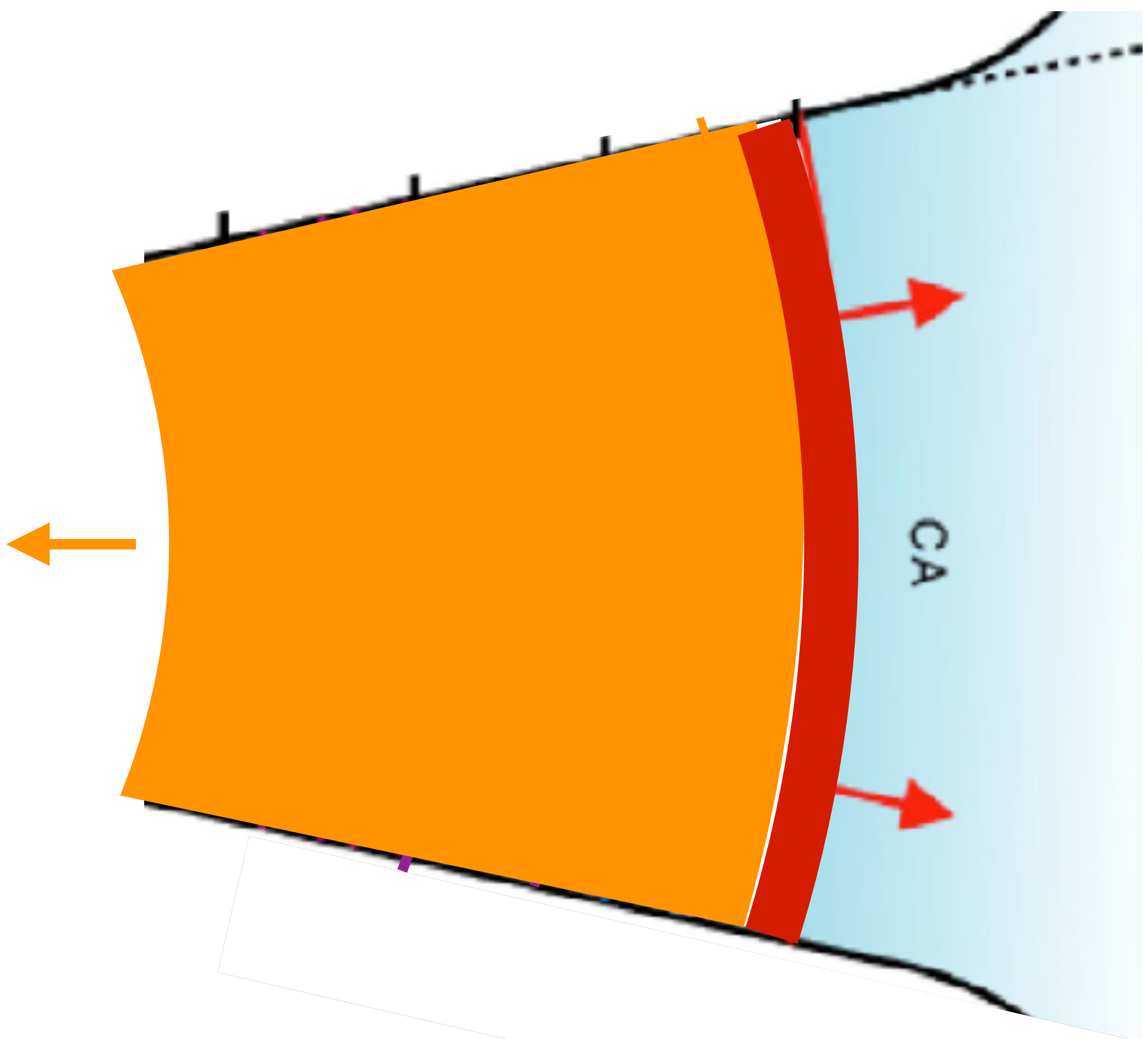
Swift: sensitivity+timing

Diverse/variable
flares



Question: Where do the flares come from?

HYPOTHESIS: HIGHLY STRUCTURED EJECTA



Genet+07, Uhm+07, Hascoet+15

Forward shock into ISM/wind

↓

Shocked material piles up

↓

reverse shock forms
and propagates

+

internal shocks develop

↓

reverse shock interacts with internal shocks

↓

emission ?

Needs confirmation from simulations

RELATIVISTIC SIMULATIONS

Relativistic RAMSES (*Lamberts+13*)

- Γ_{max} =100: ultra relativistic
- GRB scales: 6 orders of magnitude in space

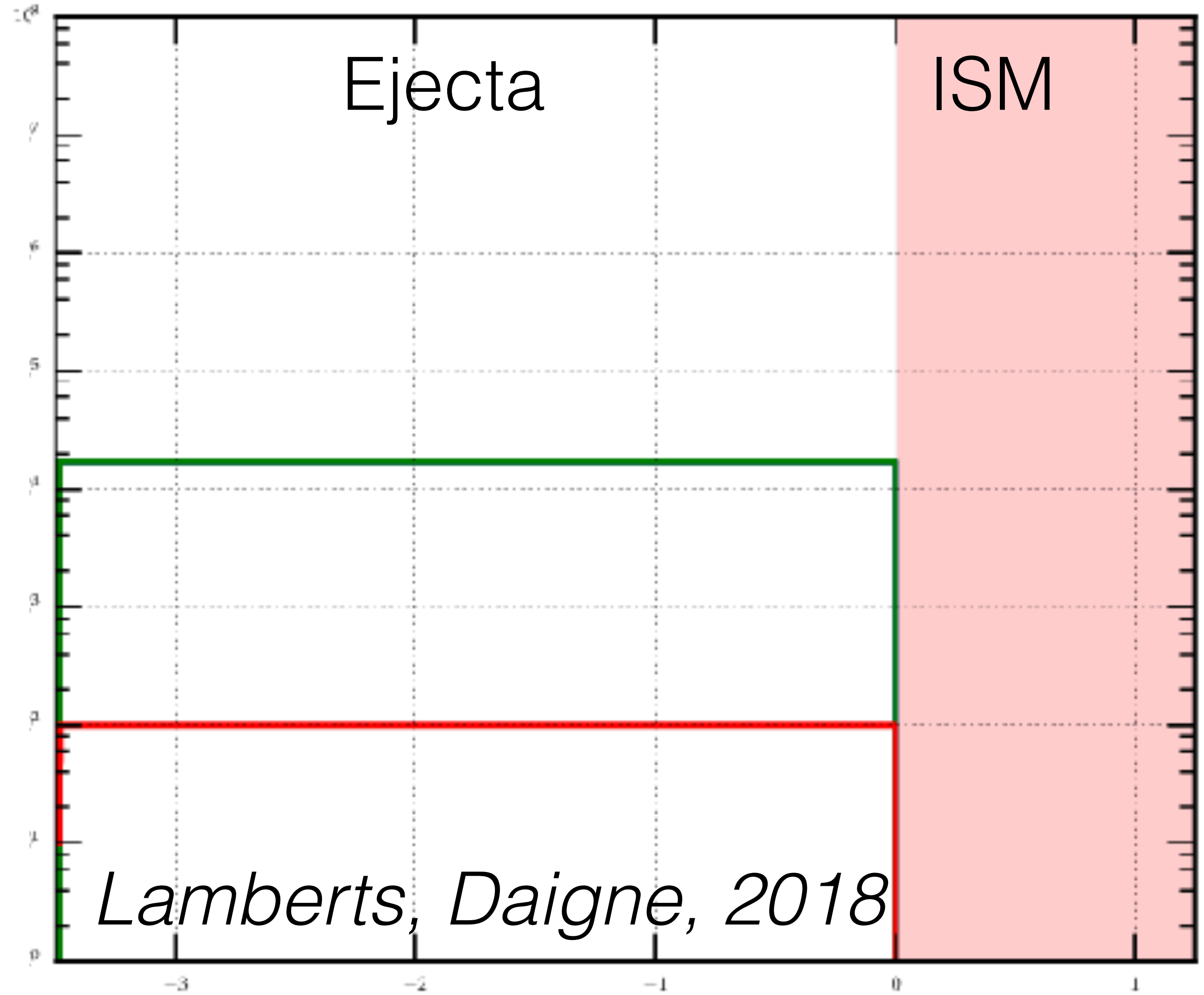
->1D spherical grid + moving boundaries

Uniform setup

pressure

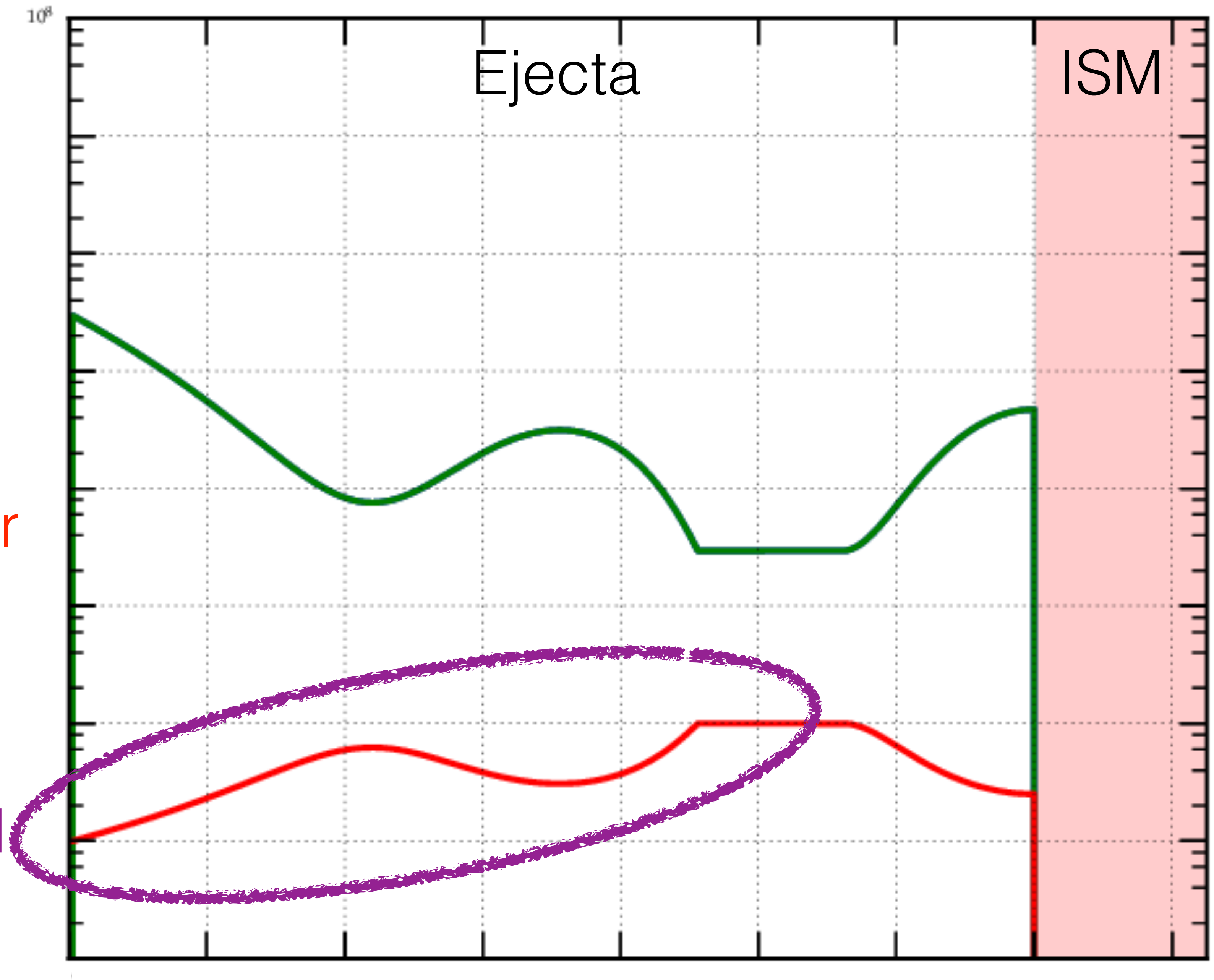
density

Lorentz factor



Lagrangian view

STRATIFIED EJECTA CREATE SHOCKS



pressure
density
Lorentz factor

Fast material
behind slow
flares expected

Lagrangian view

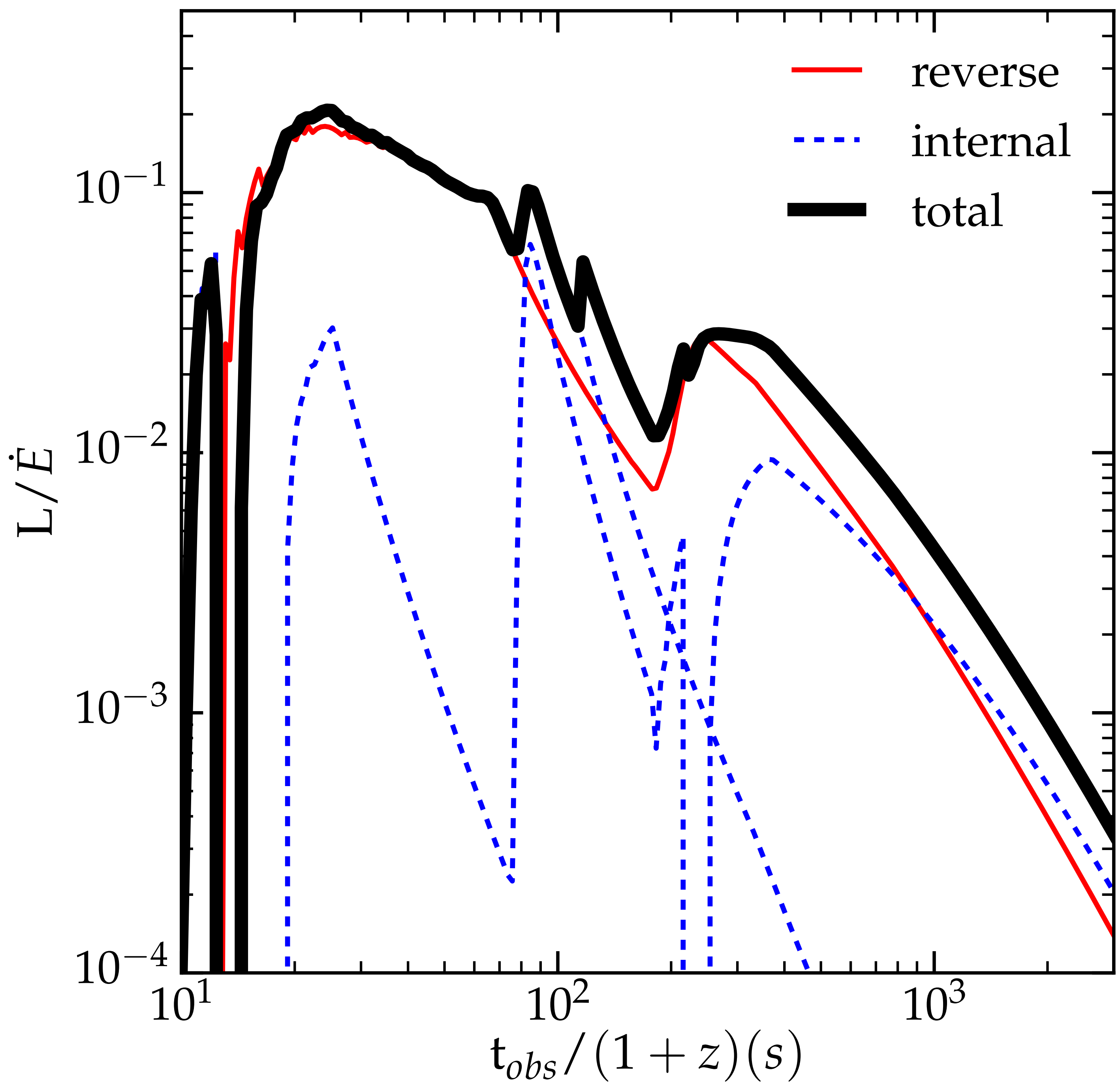
Lorentz factor profile-> complex dynamics with multiple shocks

X-RAY FLARES FROM SHOCK INTERACTIONS

shocks -> particle acceleration
synchrotron fast cooling
- Find shocks
- compute energy release

Relativistic outflow
- delays to observer's frame
- account for curvature of emitting shells

Lamberts, Daigne, 18



Relire methode

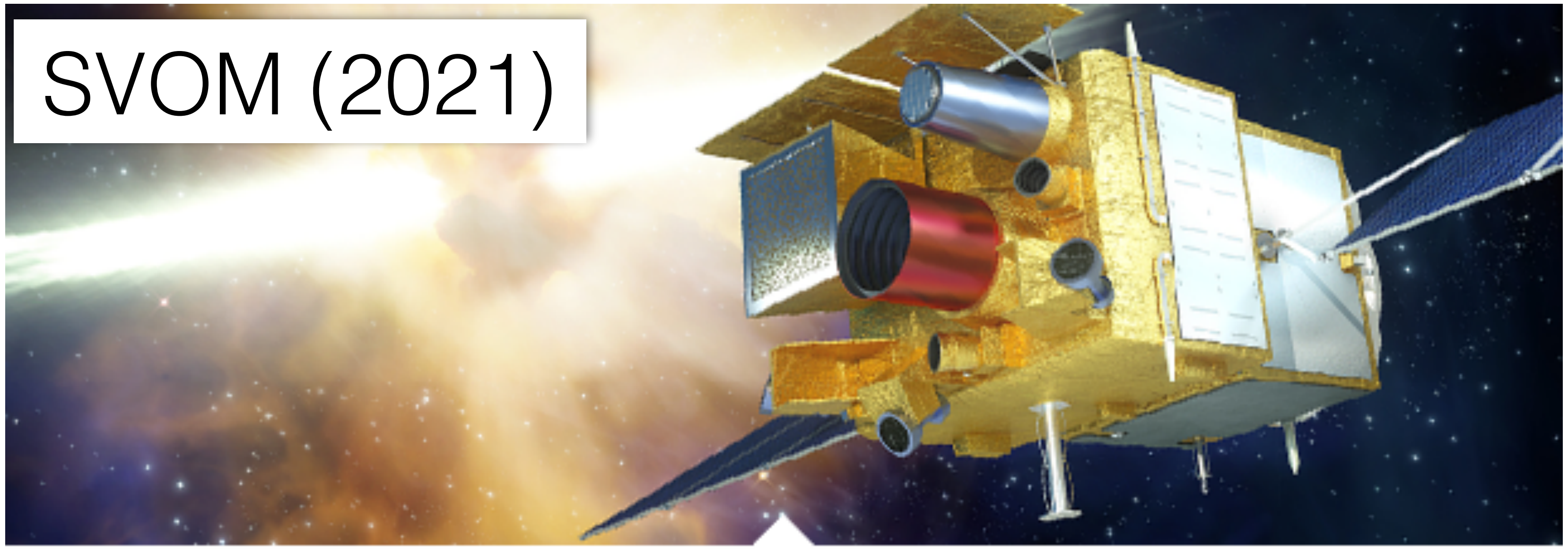
Result: Shock interactions produce X-ray flares in afterglow
- > constraints on microphysics

GAMMA-RAY BURSTS: PATHS FORWARD

A different view of gamma-ray bursts to be expected soon

- gravitational waves: GW170817: fainter gamma rays, later afterglow
central engine ? Structure ?
  -> 2D simulations with Z. Meliani (LUTh), F. Daigne (IAP)
- SVOM: French-Chinese GRB monitor for multi messenger detections
Energetics, host galaxies -> populations
- time-domain astronomy: supernova connection, kilonova, other transients (ASAS, PANSTARRS, ZTF, LSST, SKA, CTA…)

Identify populations, understand energetics and structure



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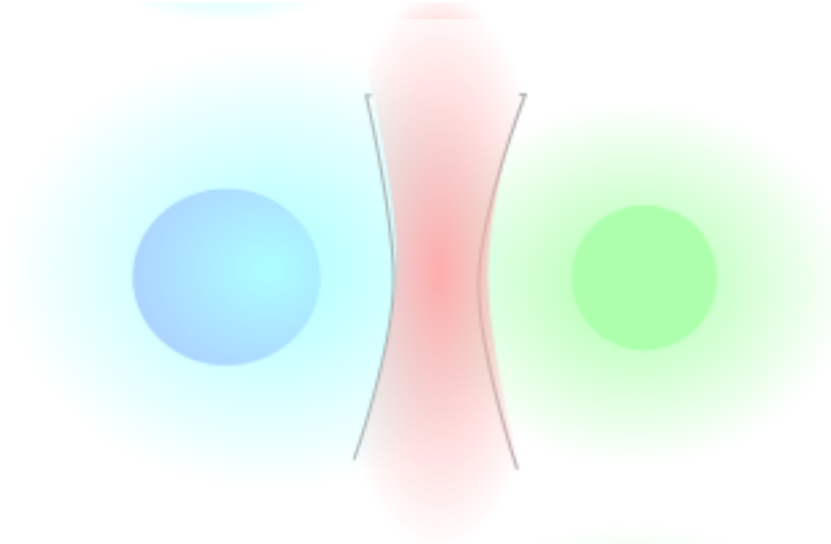

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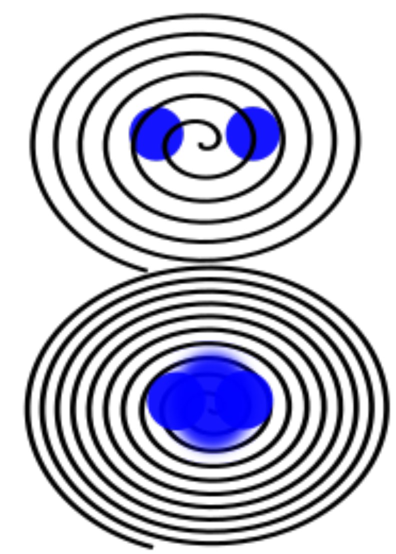
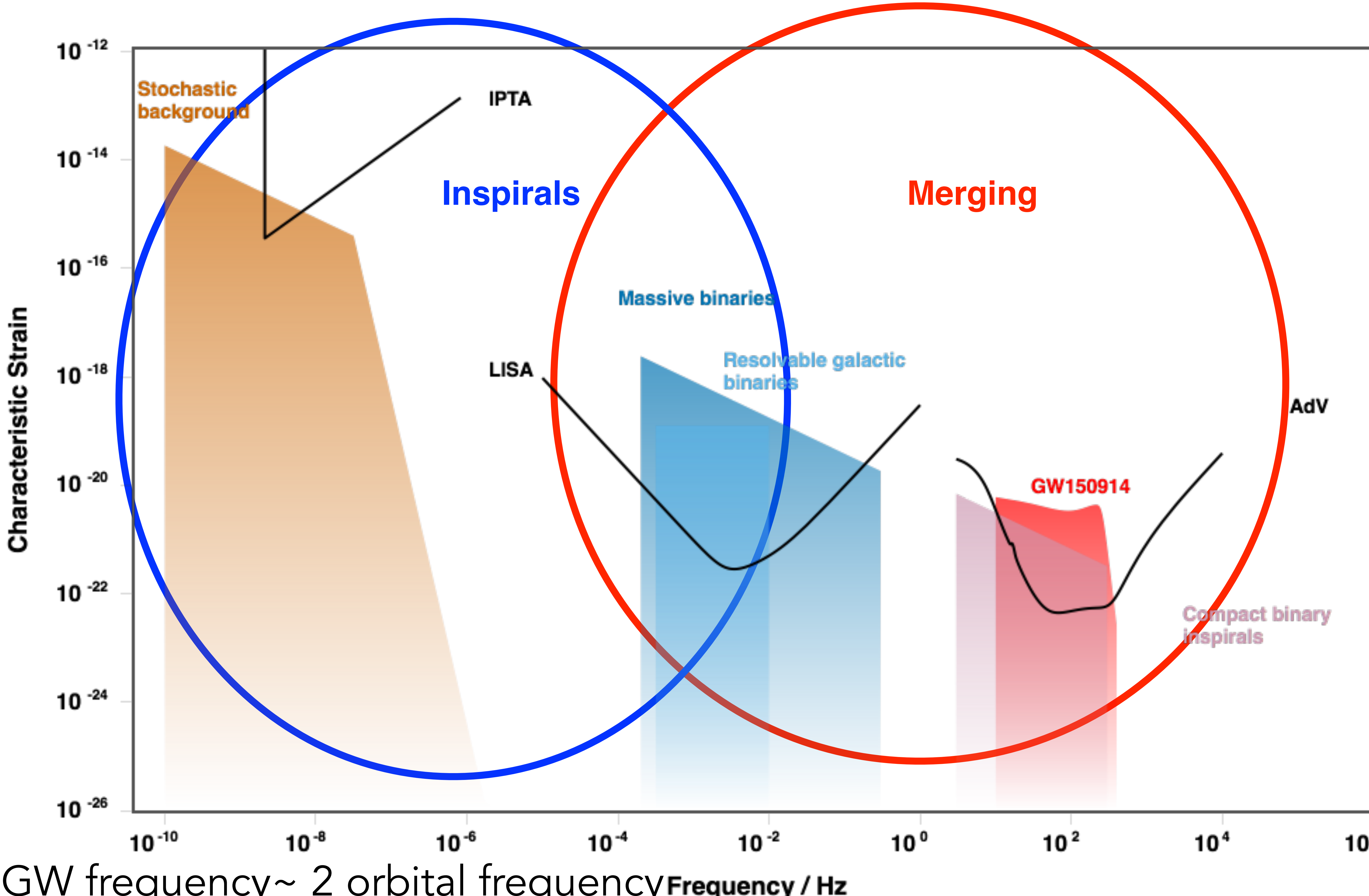
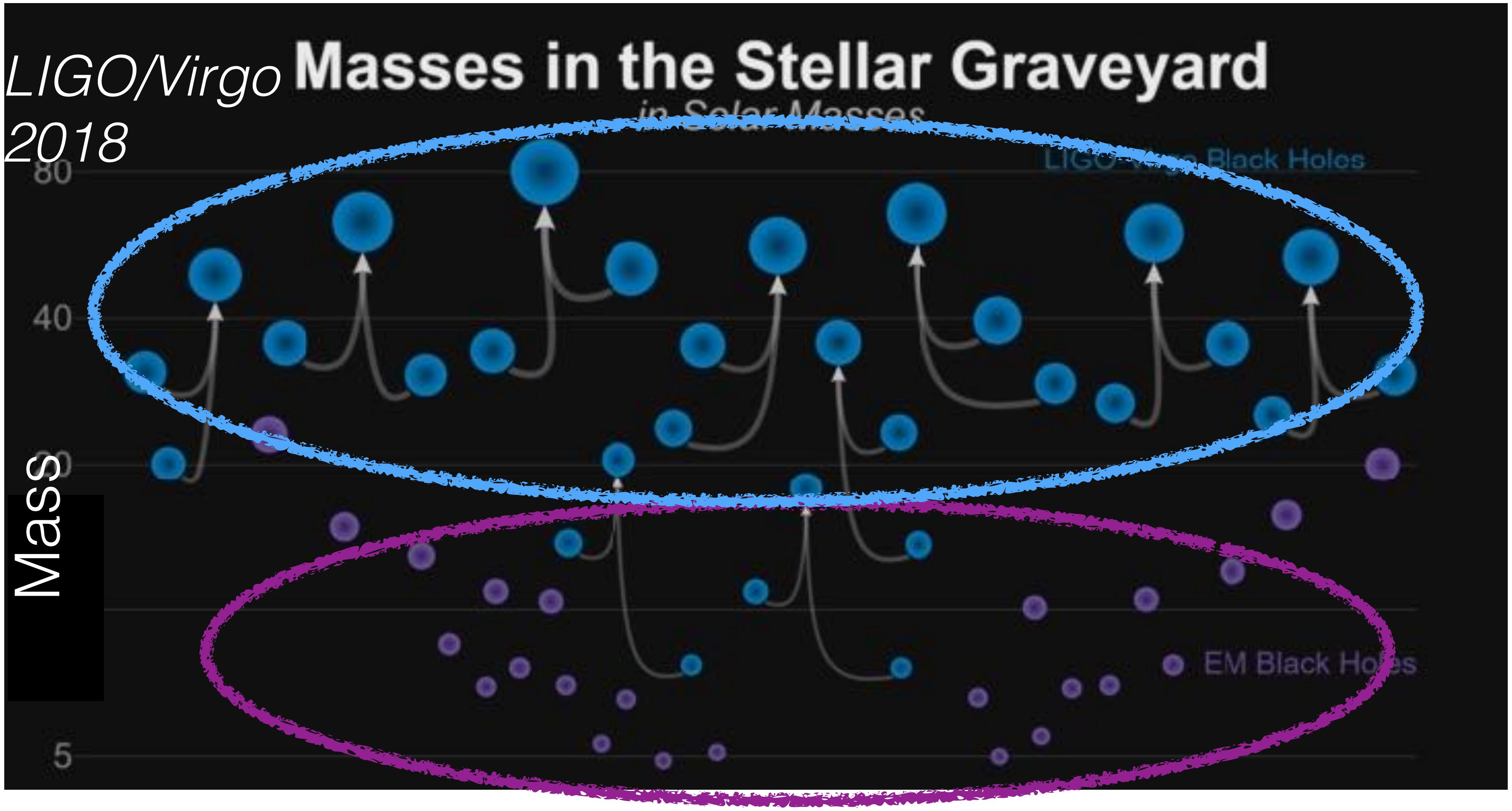


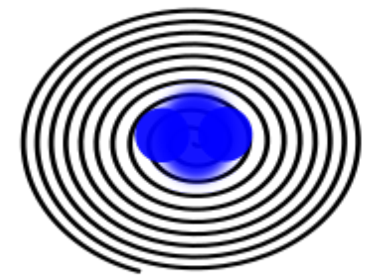
SOURCES OF GRAVITATIONAL WAVES

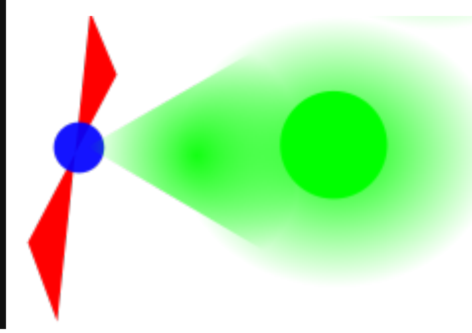


GW frequency~ 2 orbital frequency

LIGO/VIRGO REVEAL MASSIVE BLACK HOLES





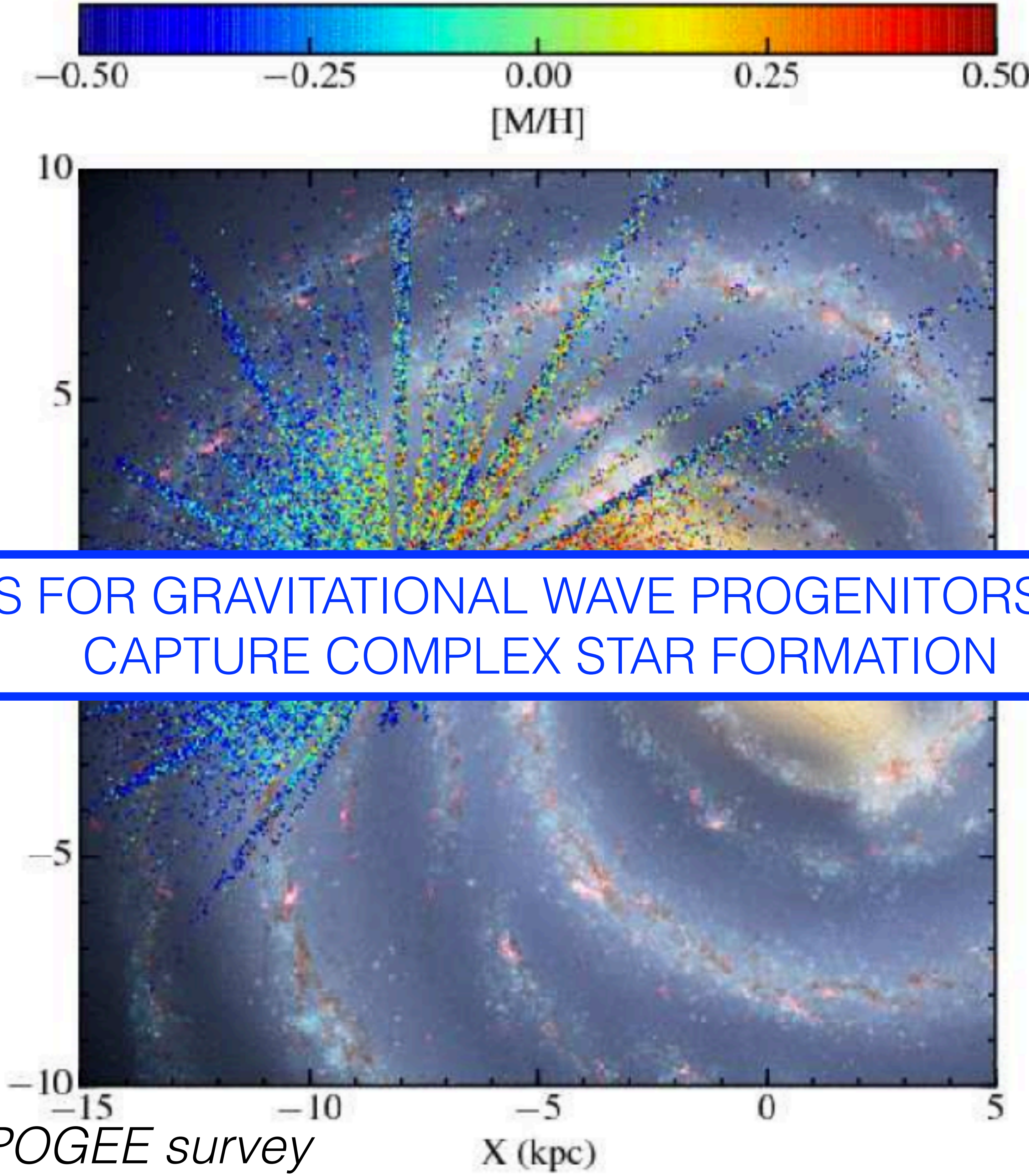


Question: where do black hole mergers come from?

low metallicity binaries: specific conditions for star formation

Multiple mergers in star clusters: specific conditions of star formation

DIFF … LLICITY



APOGEE survey

25Z sun

ulum II :
00 stars

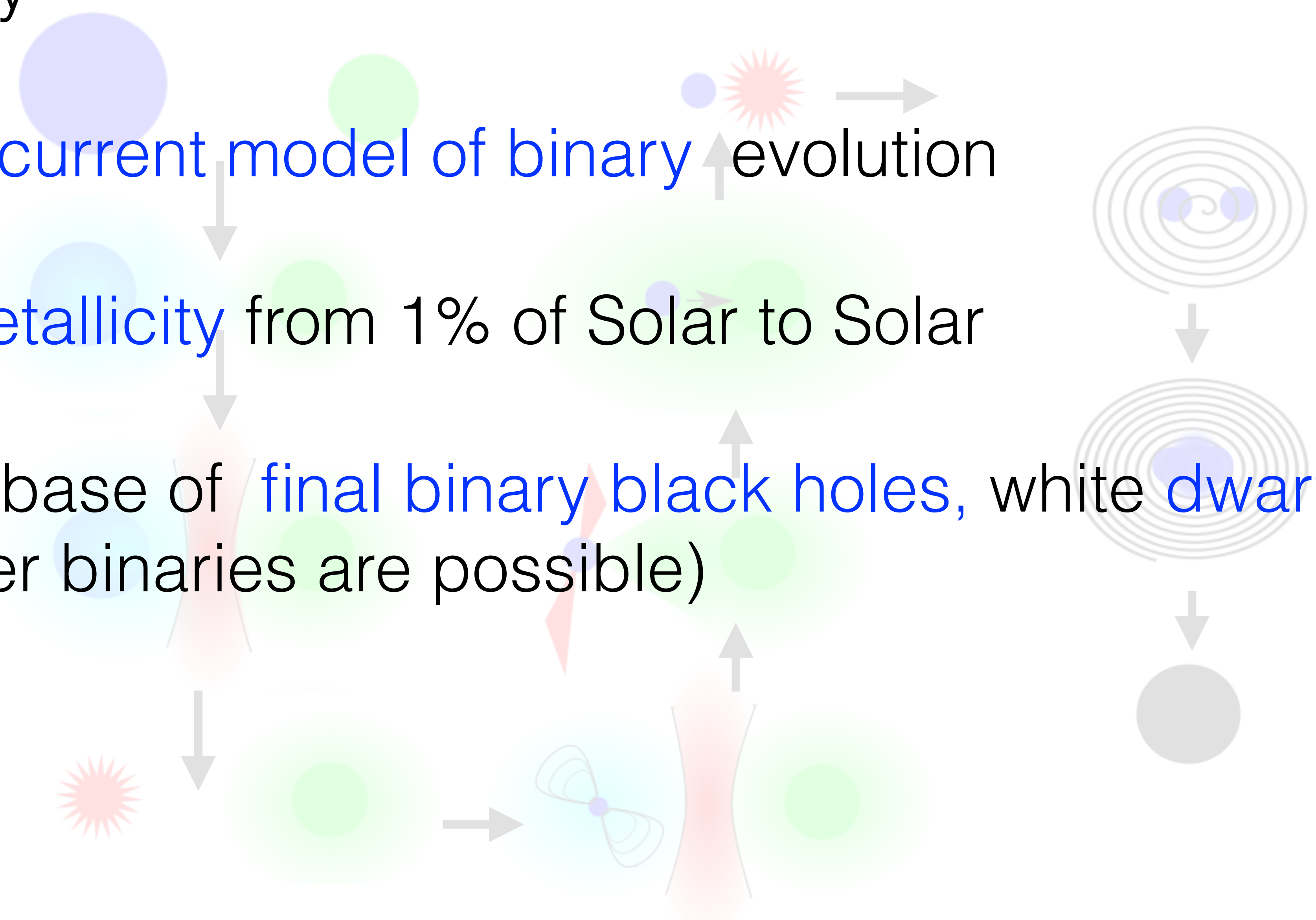
.01 Z sun

MODELS FOR GRAVITATIONAL WAVE PROGENITORS SHOULD CAPTURE COMPLEX STAR FORMATION

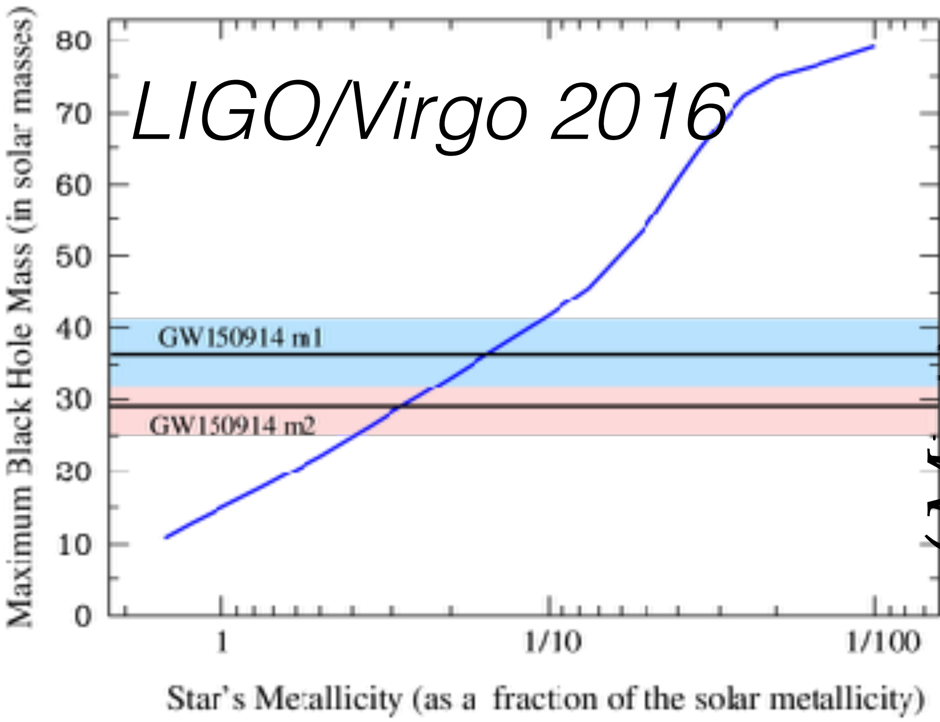
NEW COMBINATION:
BINARY MODEL + GALAXY MODEL

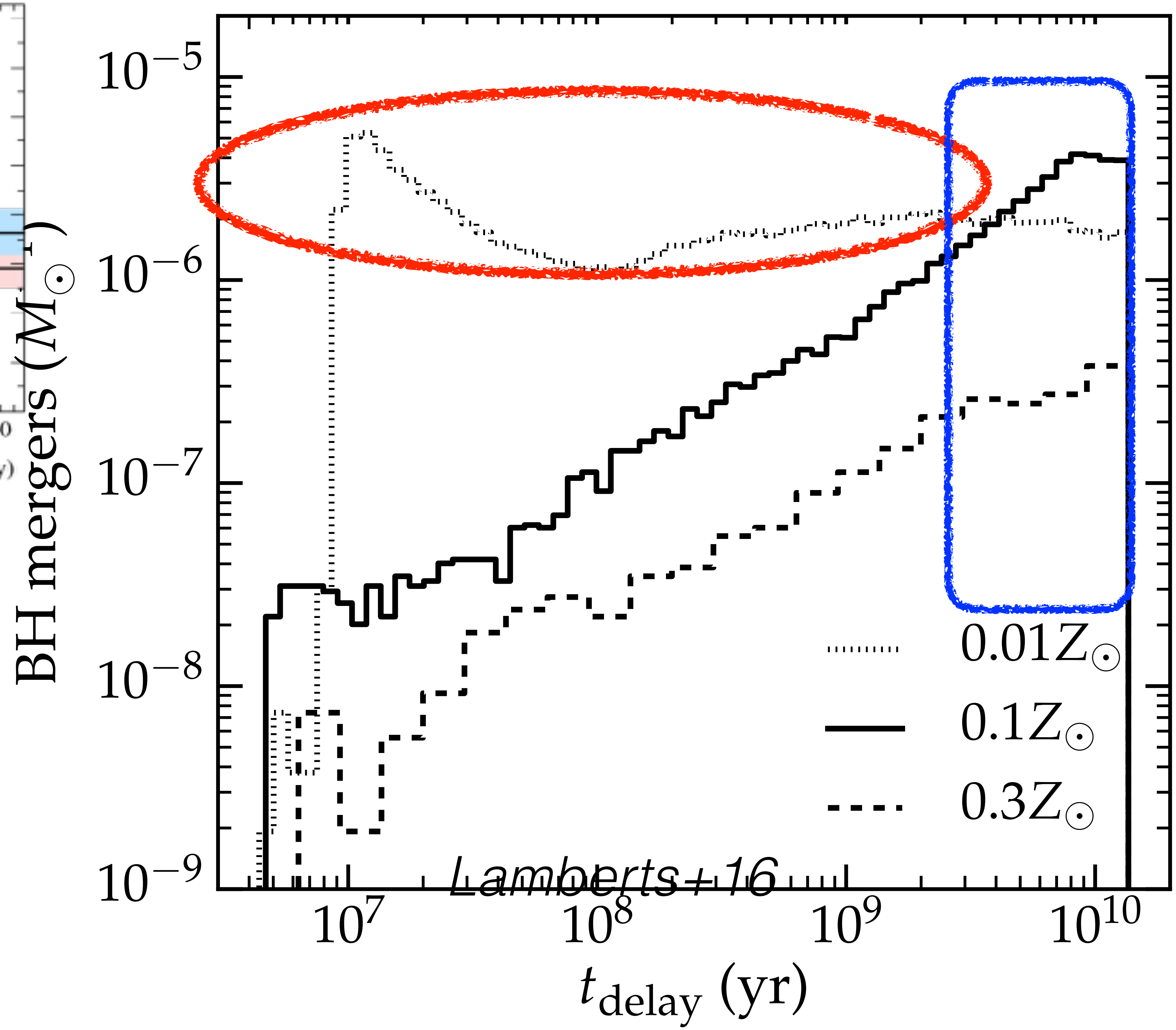
Binary population synthesis code (BSE, Hurley+2002)

- Input: Initial mass function, distribution of periods and eccentricity
- Simplified current model of binary evolution
- Explore metallicity from 1% of Solar to Solar
- Make database of final binary black holes, white dwarfs (many other binaries are possible)



INGREDIENT: LONG DELAYS TO MERGERS



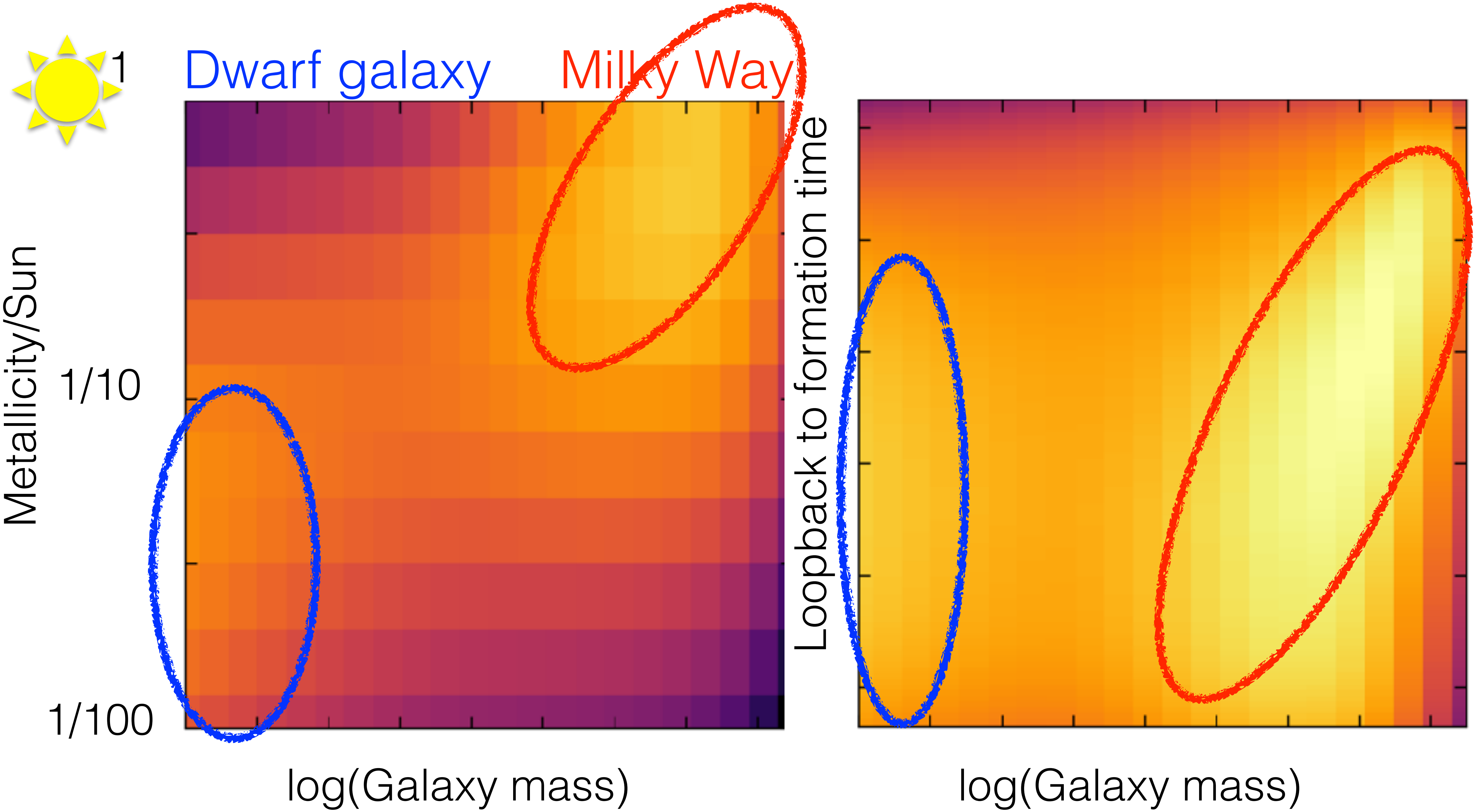


- Low metallicity: most massive remnants

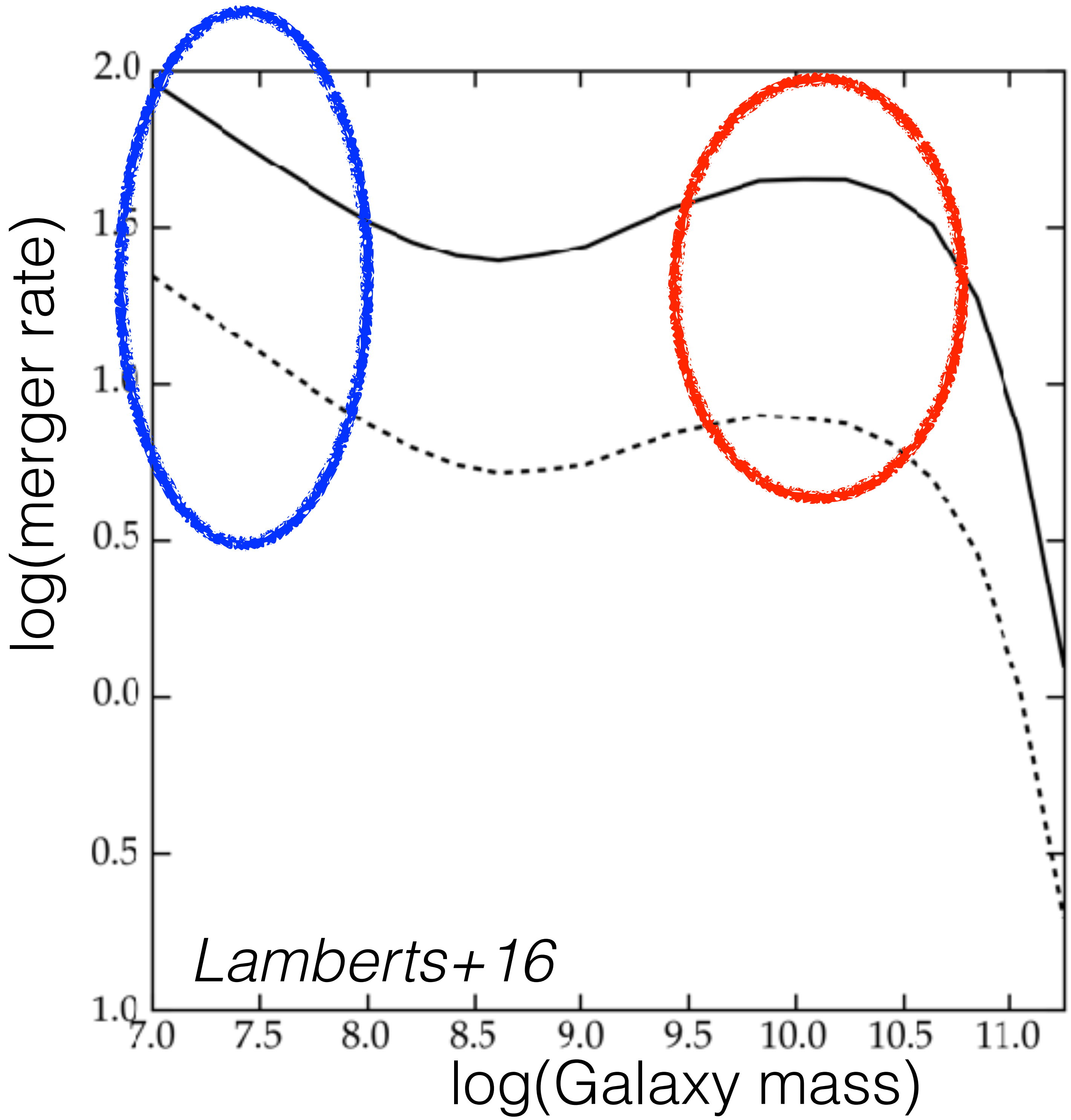
- higher metallicity : long delay

INGREDIENT: LOW METALLICITY STAR FORMATION

"homemade" semi-analytic model (*Lamberts+16)*



STRONG CONTRIBUTION FROM DWARF GALAXIES



Milky-Way-like galaxies

Dominant places of star Formation

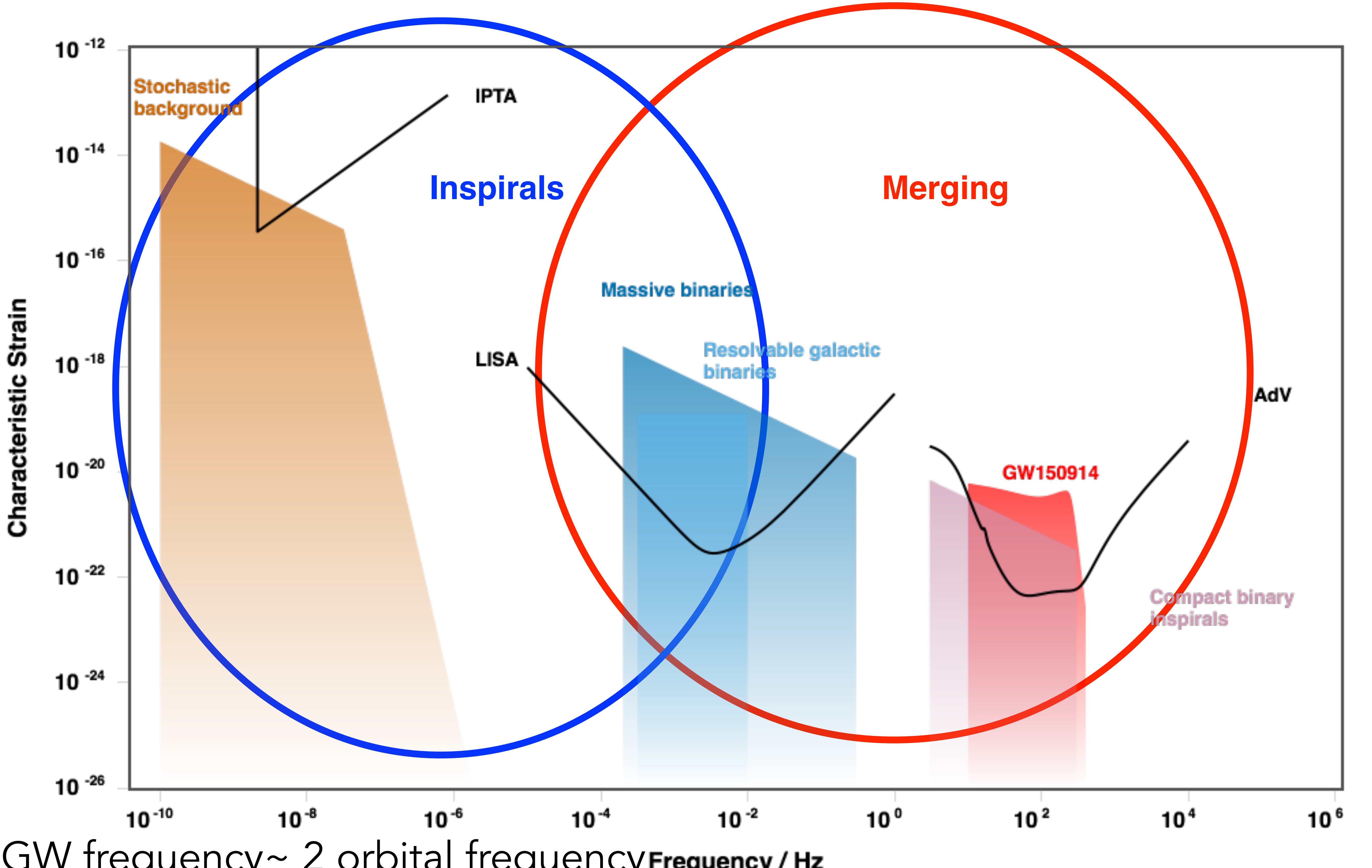
Dwarf galaxies

“invisible” with EM observations

(confirmed in Elbert+17, Mapelli+17)

Result: Complex star formation impacts prediction/interpretation of GW

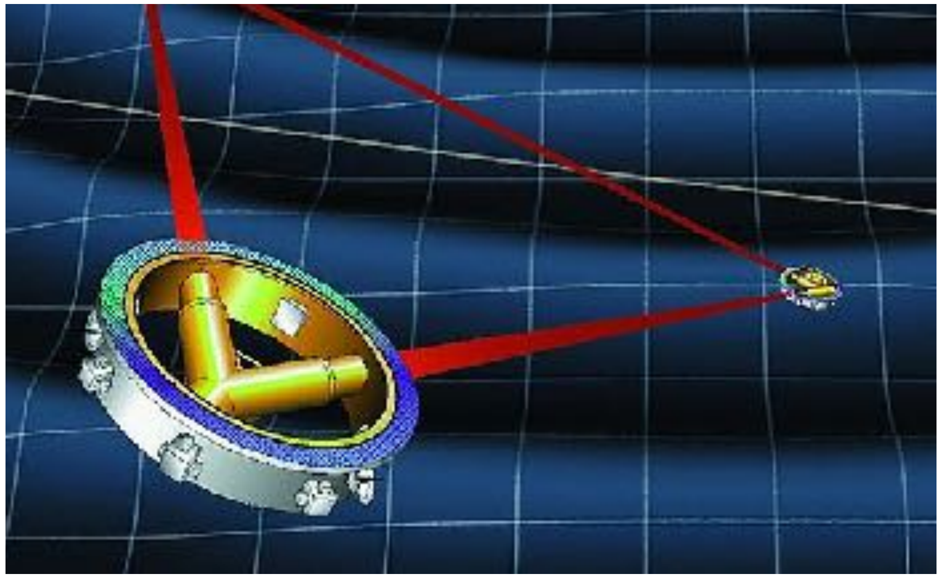
SOURCES OF GRAVITATIONAL WAVES



GW frequency~ 2 orbital frequency

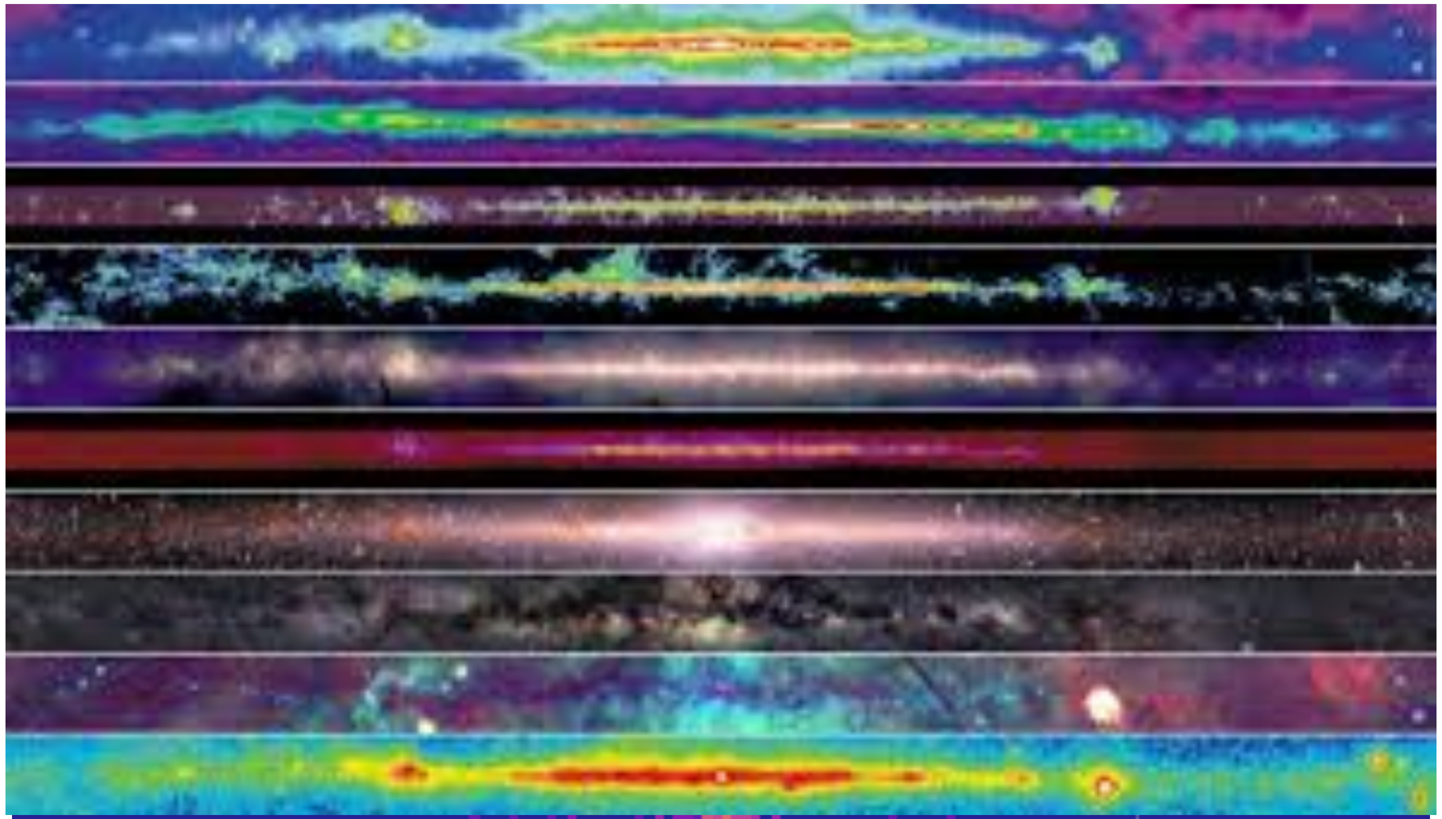
BINARIES IN THE MILKY WAY-LIKE GALAXIES

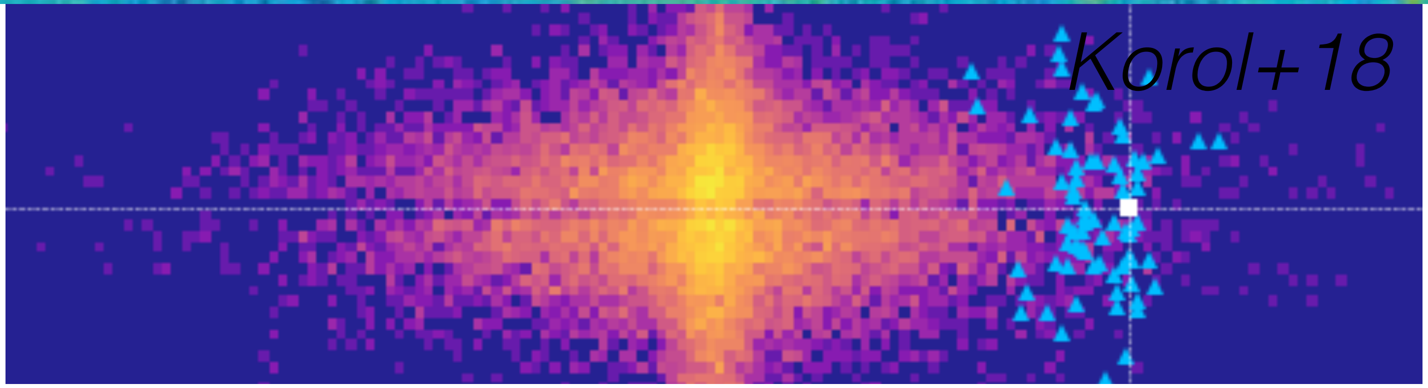
~2030 : LISA



Detection of mHz waves

Need for realistic models of the Milky Way





WHITE DWARFS, NEUTRON STARS AND BLACK HOLES

White dwarfs: 95% of stars!
Type Ia supernovae
Low mass evolution, common envelope
Tides and accretion

~6000 systems
(Nelemans+01)

Lamberts+19

Neutron Stars: Higher mass evolution
Common envelope, stellar wind, supernova kicks
Somewhat sensitive to metallicity

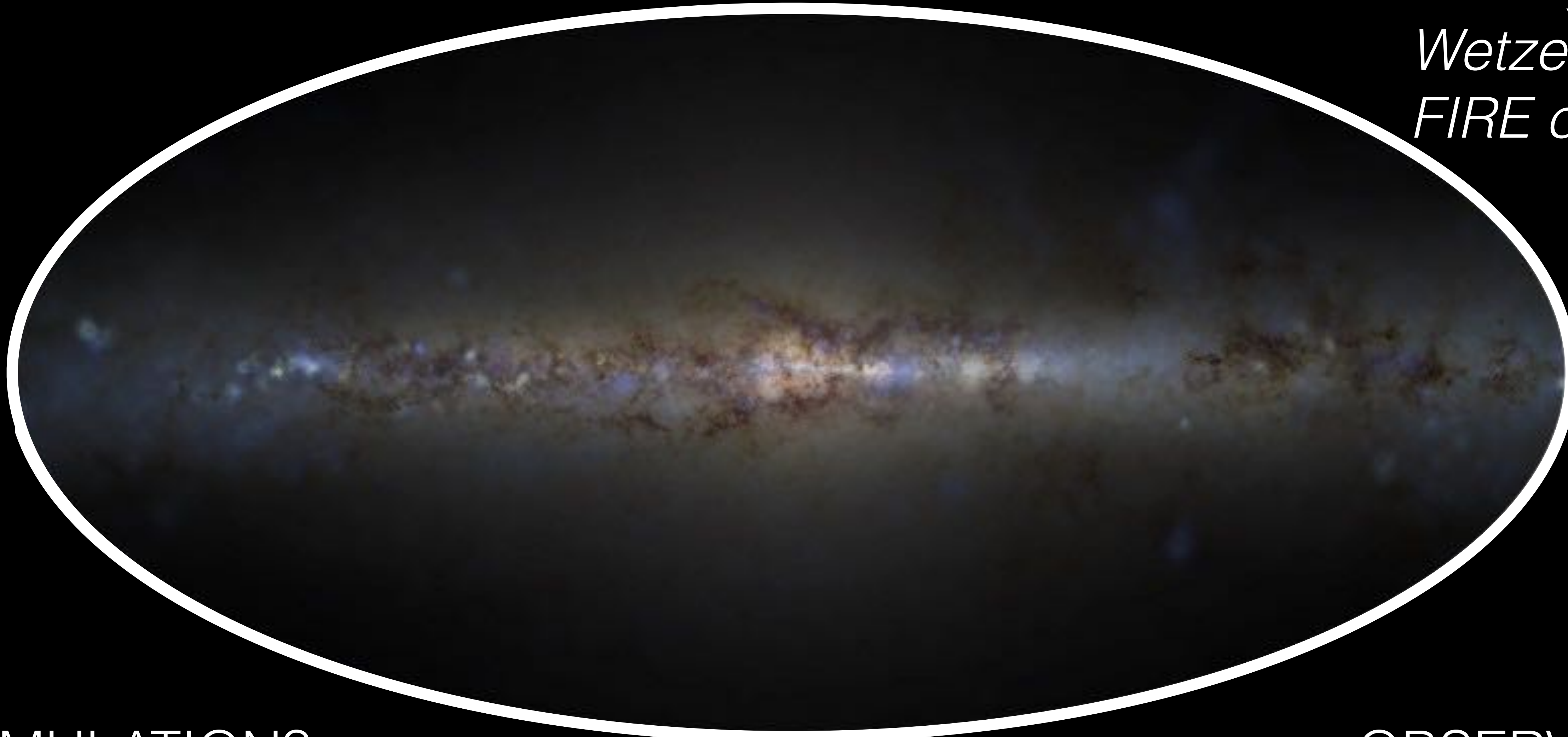
~5-30 systems
(Belczynski+10)

Black Holes: Highest mass evolution
common envelope, stellar wind, supernova kicks
High end of initial mass, very sensitive to metallicity

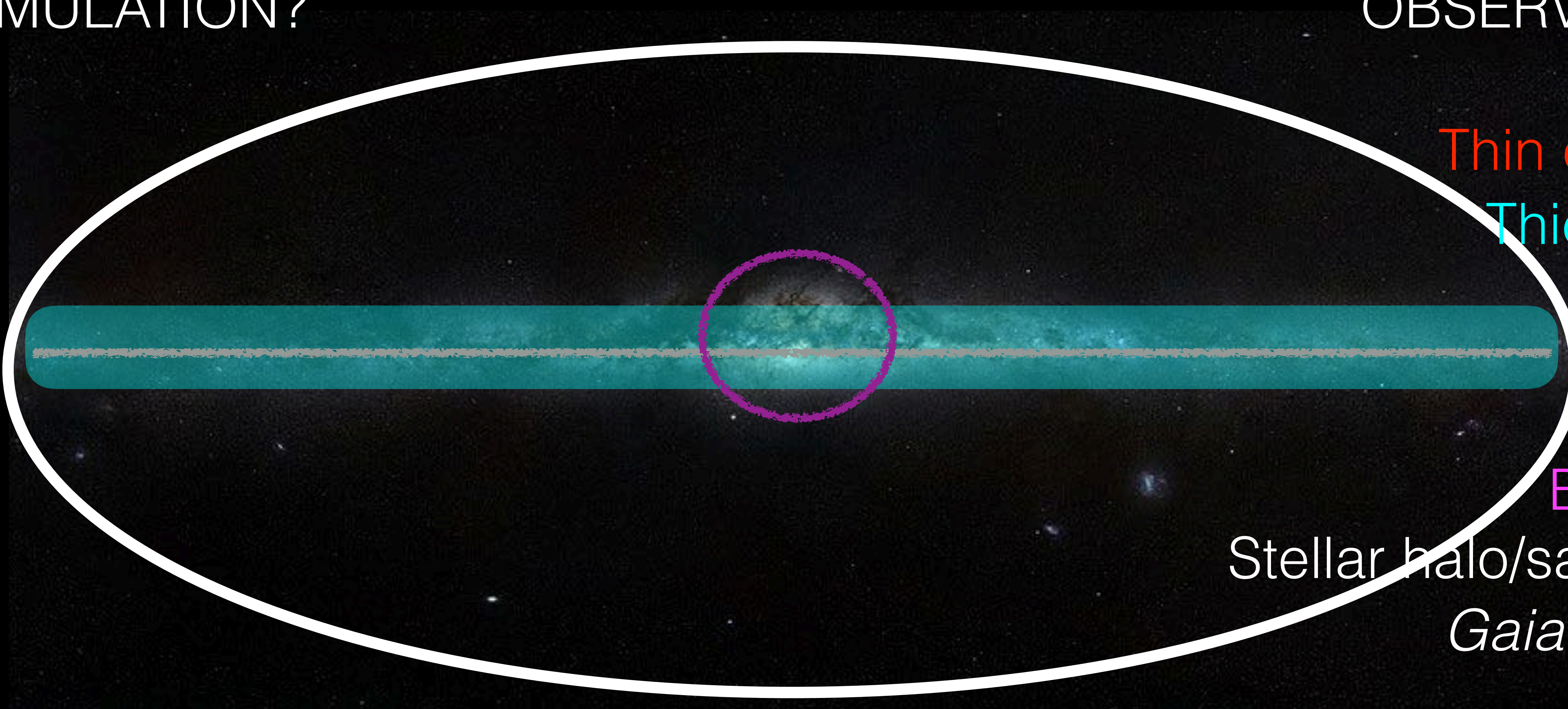
<10 systems
(Belczynski+10)

Lamberts+18b
Lamberts, Sesana, in prep.

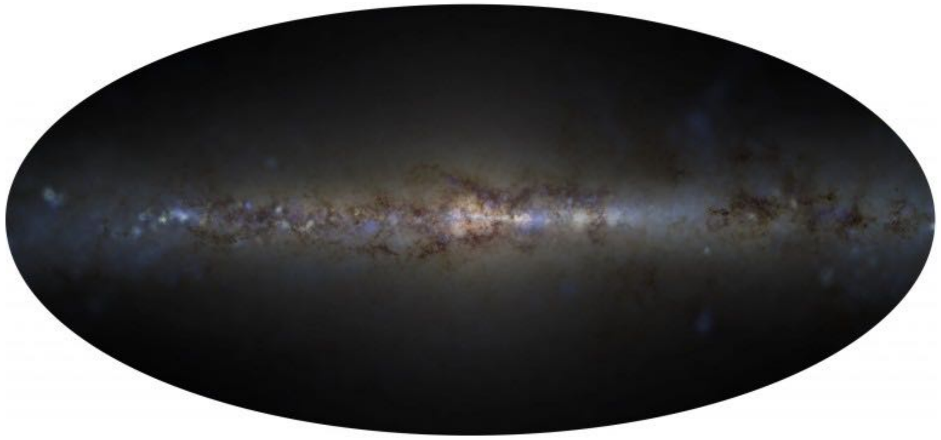
And even stellar binaries (*Gotberg, Lamberts, Korol, in prep.*)

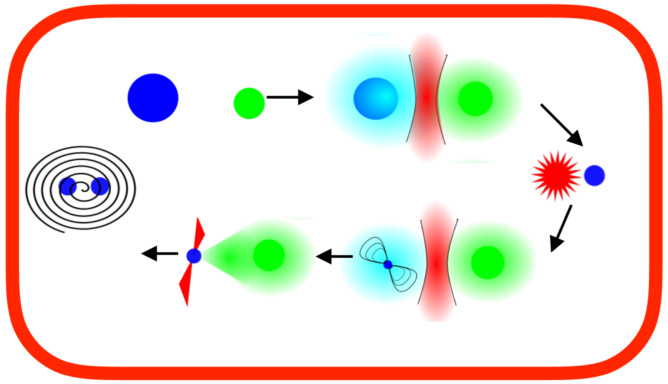


SIMULATION? OBSERVATION?



GROWING COMPACT BINARIES IN THE MILKY WAY

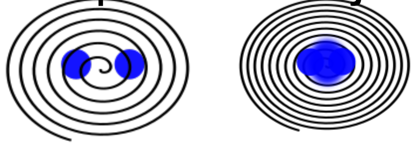




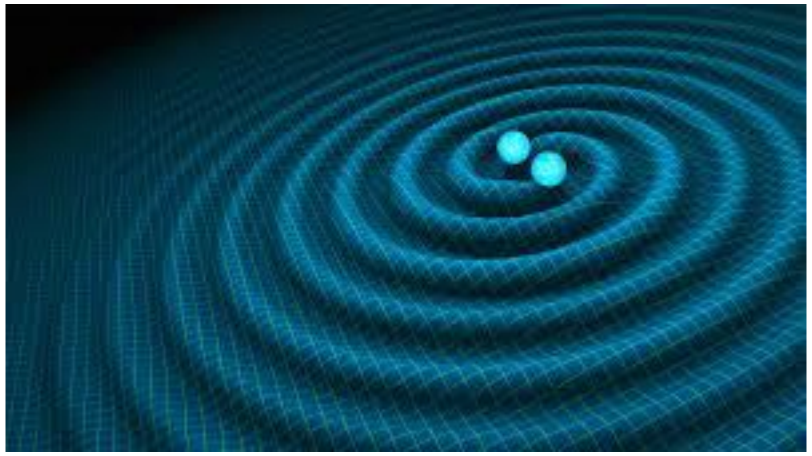
Star formation history
Metallicity
Positions/Trajectory

+

13 bins: Z=0.005 -1.3 Z_{sun}
M_1,M_2, t_{form}, orbit

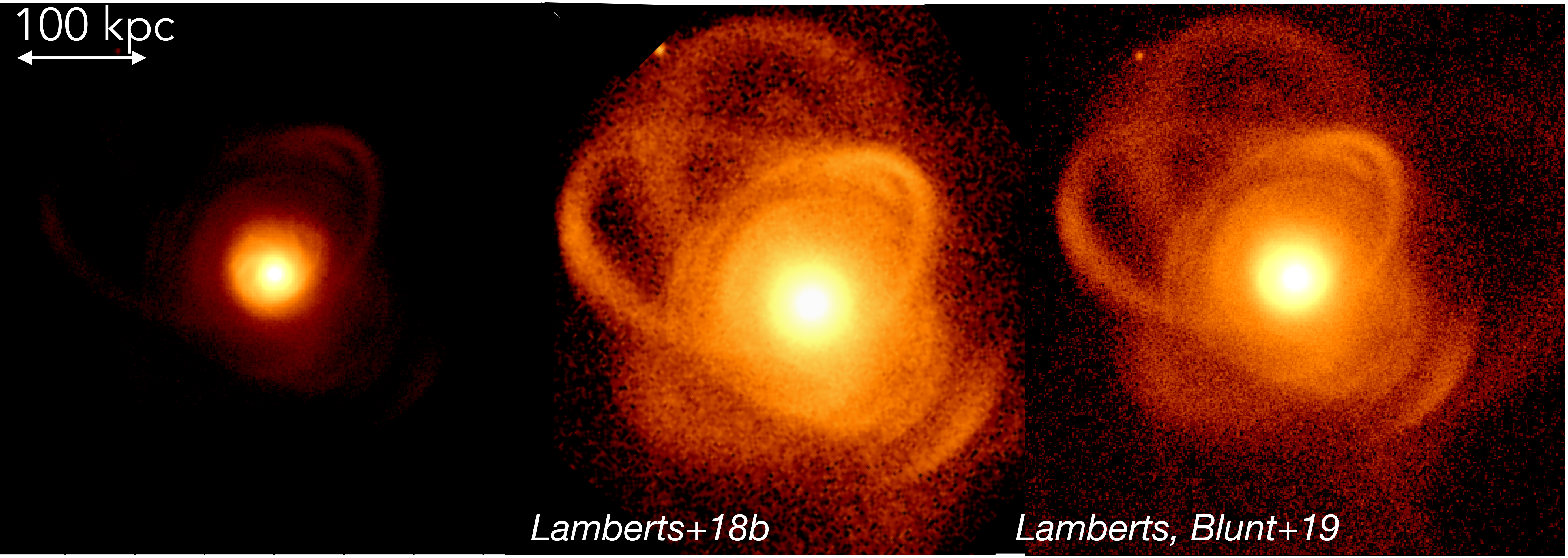


Keep track of binary compact objects



Final evolution through GW emission

IMPACT OF COMPLEX STAR FORMATION

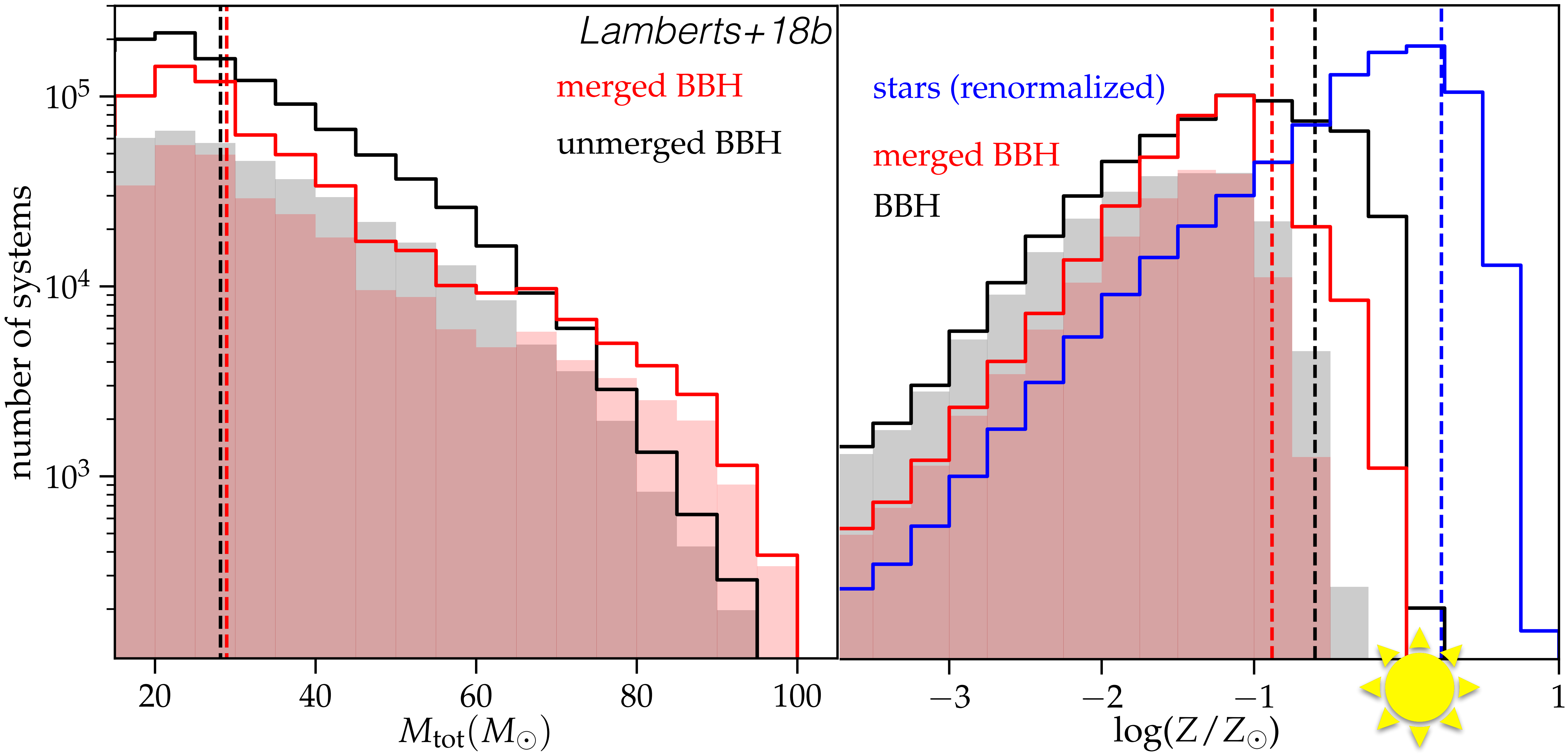


$>10^{10}$ stars

1 million
black holes

60 million binary white
dwarfs with periods <5h

A MILLION BINARY BLACK HOLES IN THE MILKY WAY

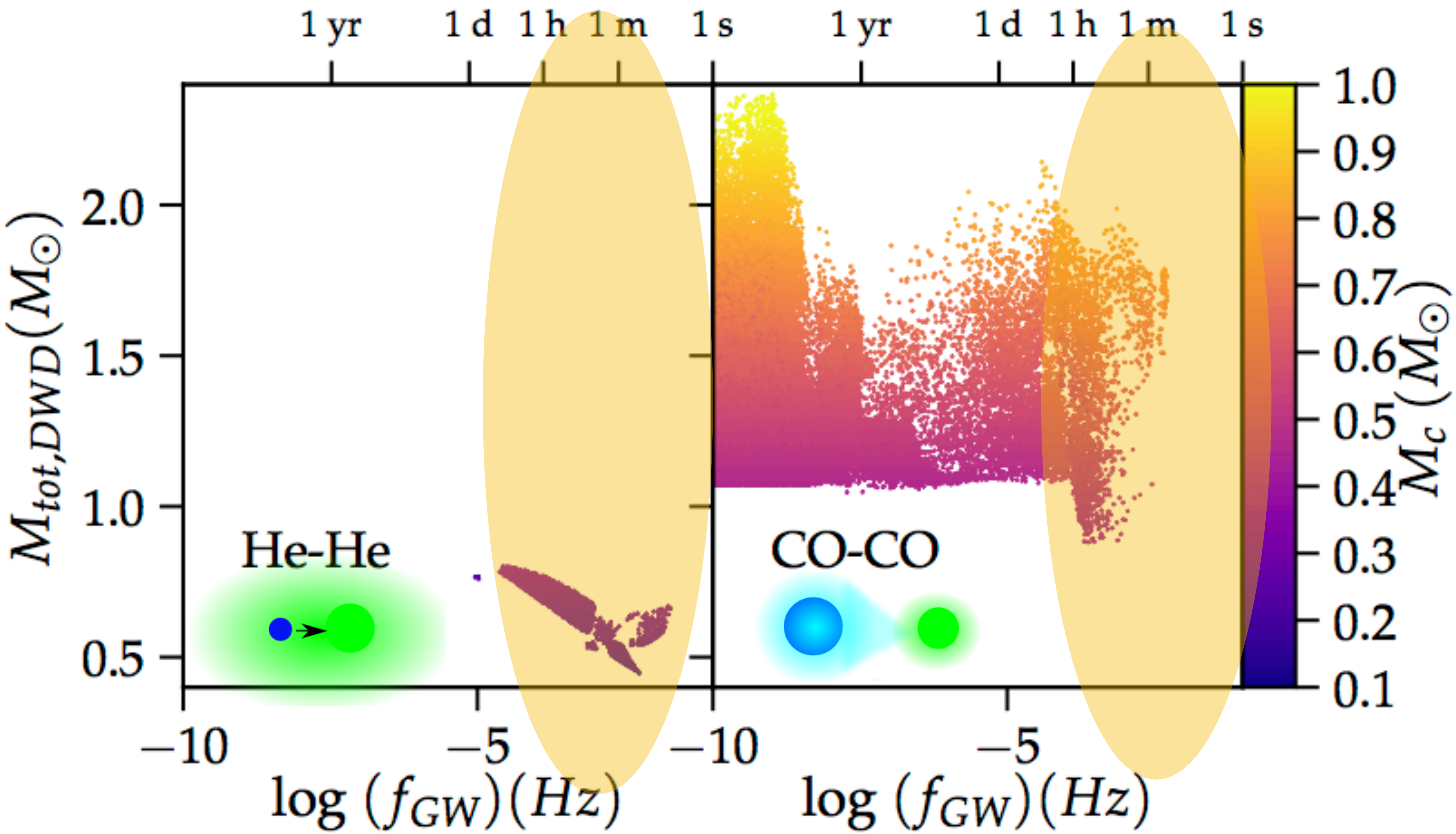


Masses compatible with LIGO/Virgo

Mean metallicity 15-30% of Sun

1/3 of black holes were
Formed outside Milky Way
-> dwarf galaxies matter
-> needs high resolution

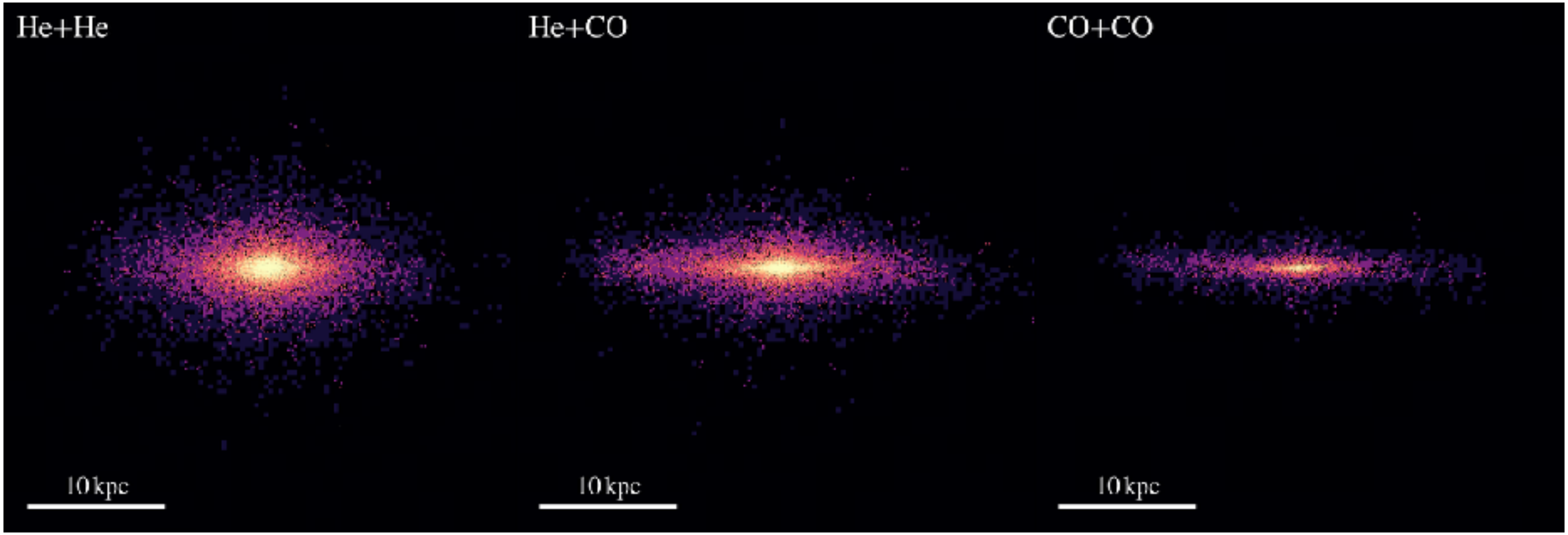
DIFFERENT TYPES OF BINARY WHITE DWARFS



Formation time: 2-13 Gyrs <3 Gyrs

All LISA binaries are recently formed DWD or would have merged

DIFFERENT BINARY BINARY POPULATIONS



He-He: old progenitor stars: bulge, thick disk and stellar halo

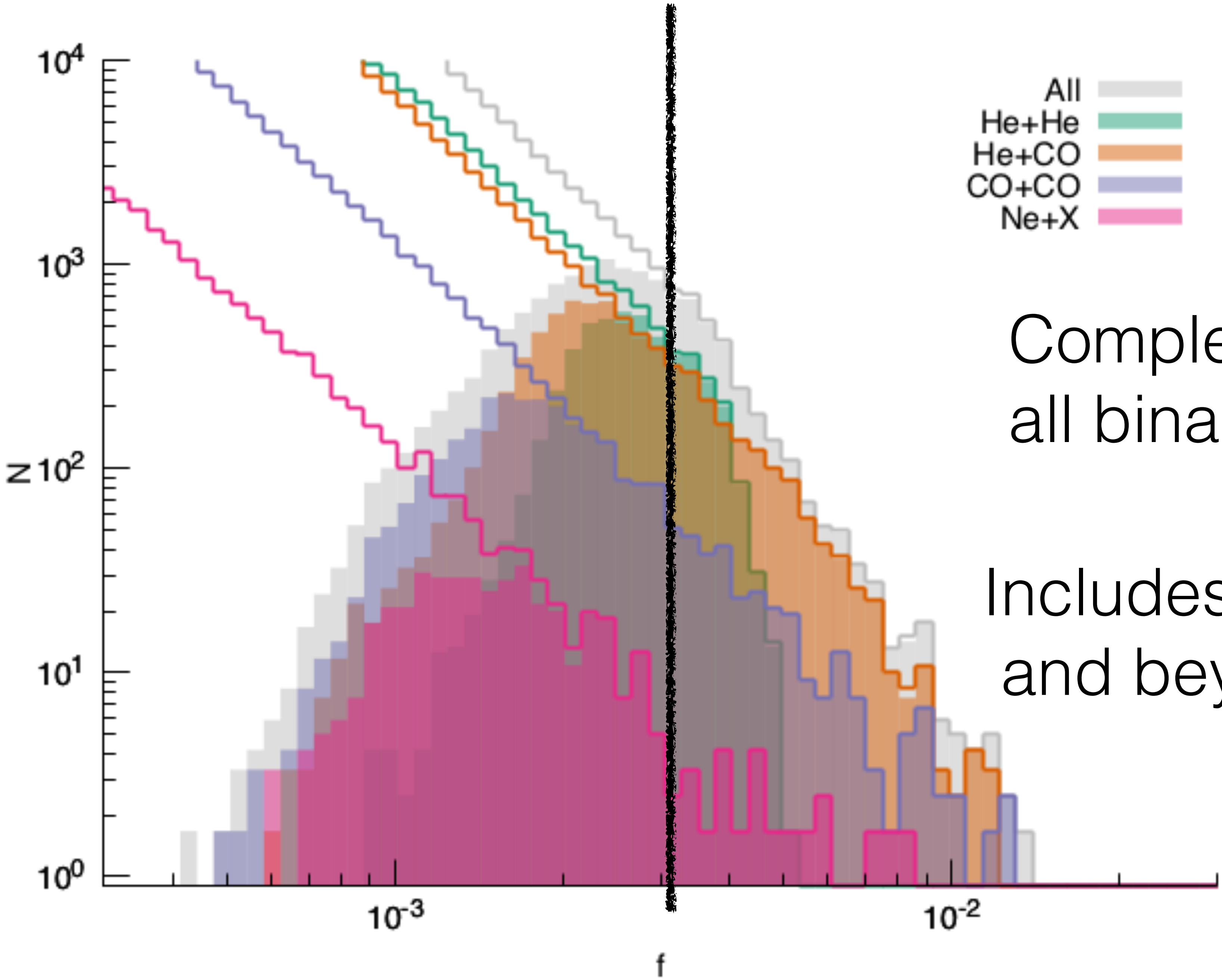
He-CO: intermediate case

CO-CO: young progenitor stars: think disk

Question: What will LISA detect?

LISA DETECTIONS:
A COMPLETE CATALOG OF WHITE DWARF BINARIES

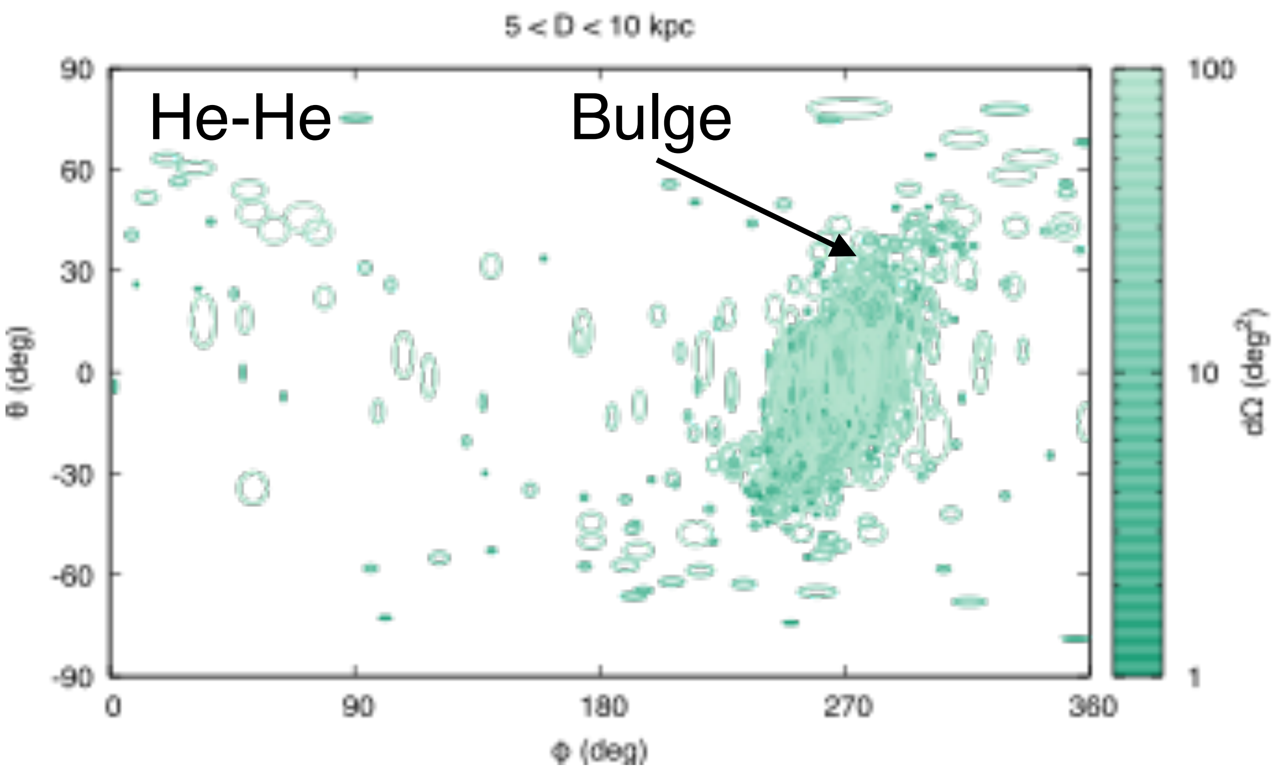
~12 000 systems: measurement of period and GW strain
☹️ No masses, no sky localisation unless high SNR
😊 GW Flux(r) ~ 1/r, no extinction, no spatial crowding

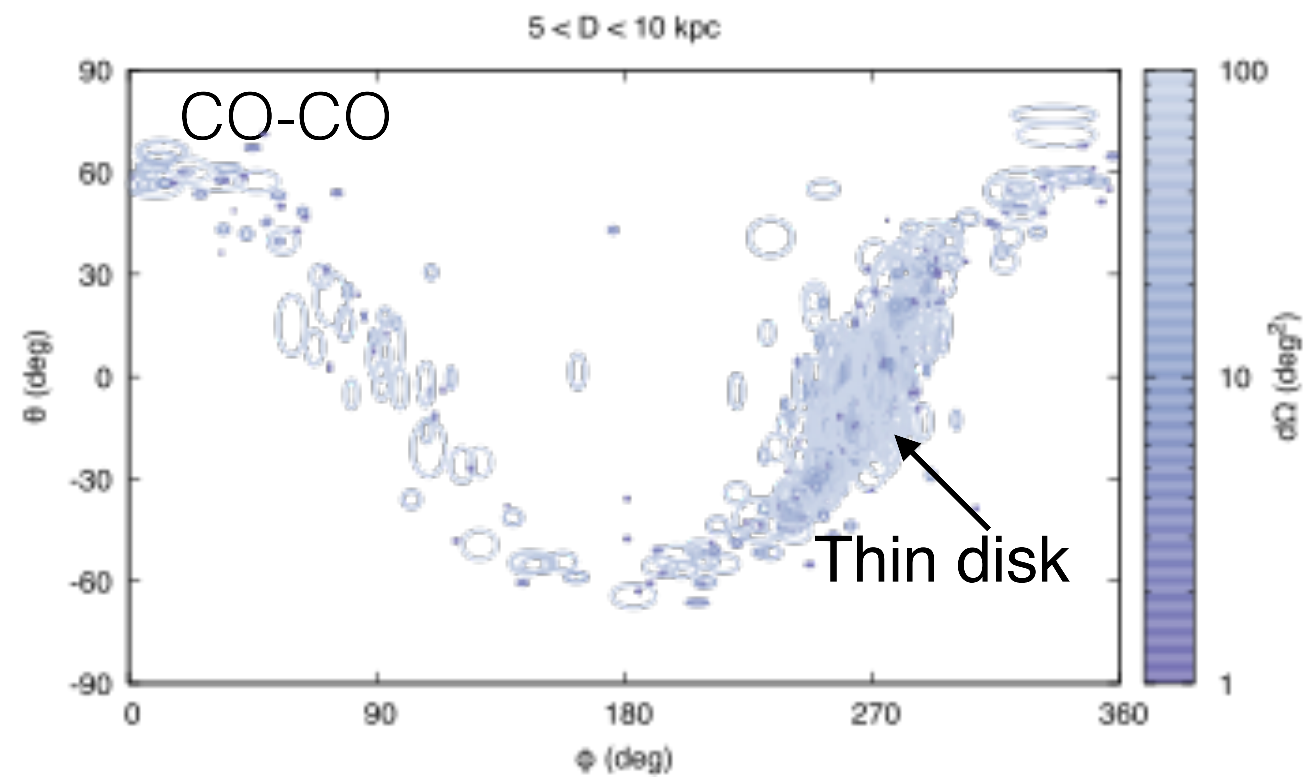


Complete down to f~3 mHz:
all binaries below 11 minutes

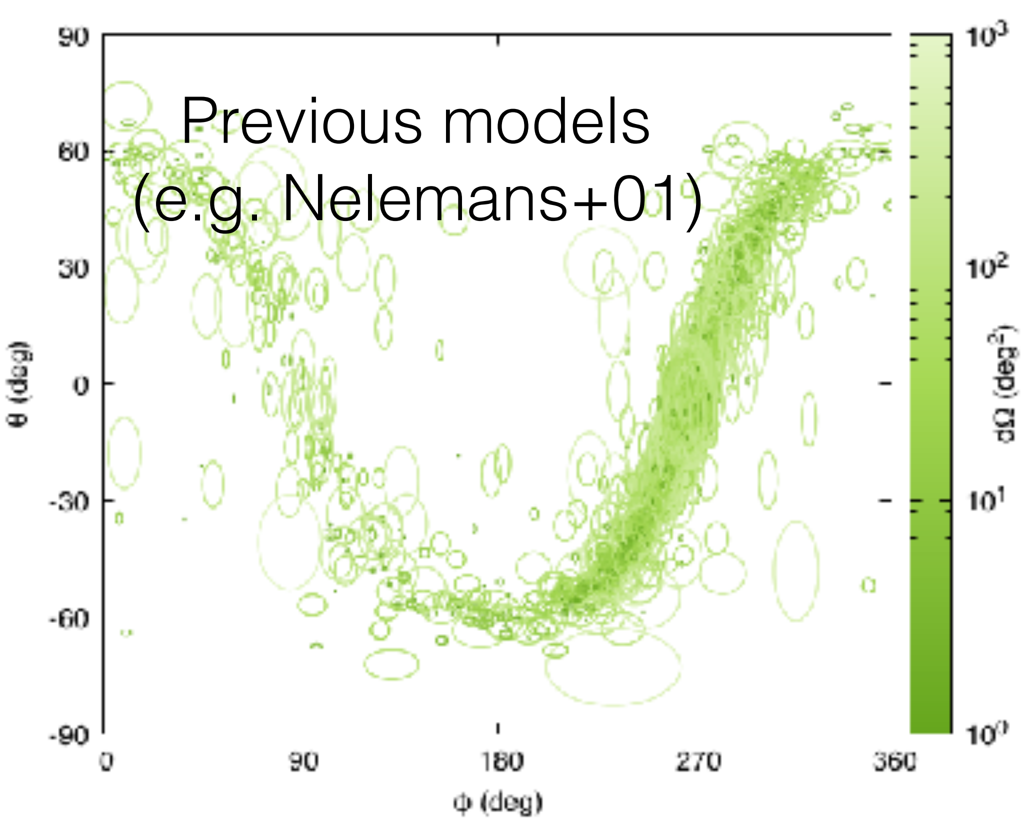
Includes binaries in whole galaxy, and beyond

MULTI MESSENGER DETECTIONS WITH LISA





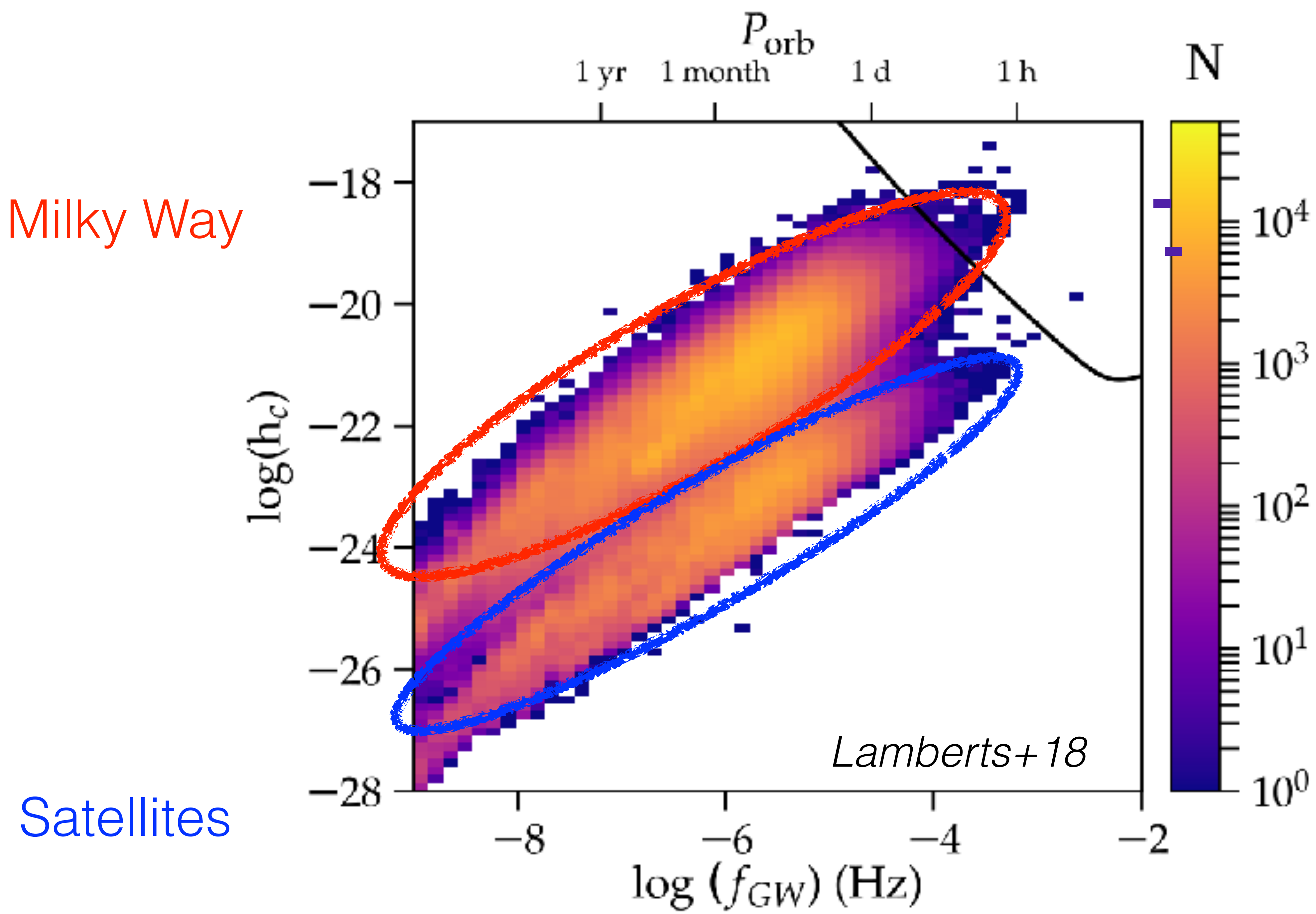
Systems within 10 kpc: potentially few thousand systems



Different spatial distributions:
Search strategies

Used for Lisa Mock Data Challenge

DETECTING BINARY BLACK HOLES IN THE MILKY WAY



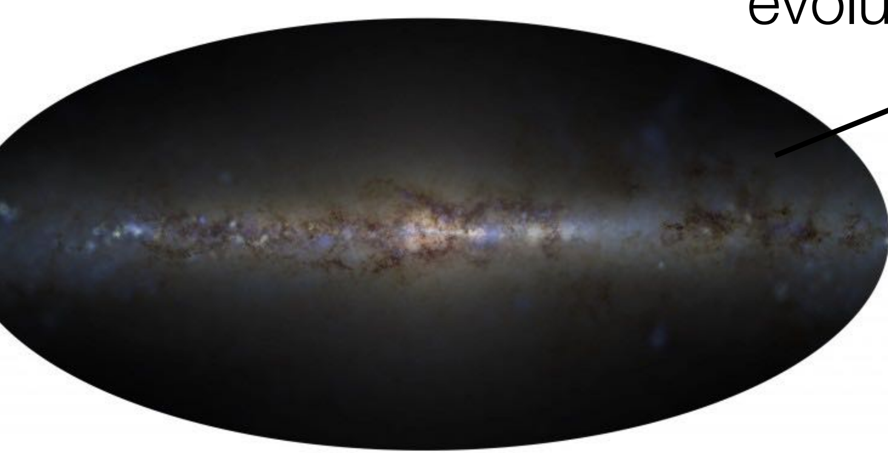
Lamberts, Sesana, in prep: Probably ~ 10 black hole binaries that we can IDENTIFY

STELLAR BINARIES WITH GRAVITATIONAL WAVES

Now: Virgo/LIGO O3

2 neutron star mergers so far
20 binary black holes: statistics soon!
https://gracedb.ligo.org/superevents/public/O3/

Origin of mergers? Binaries or clusters?

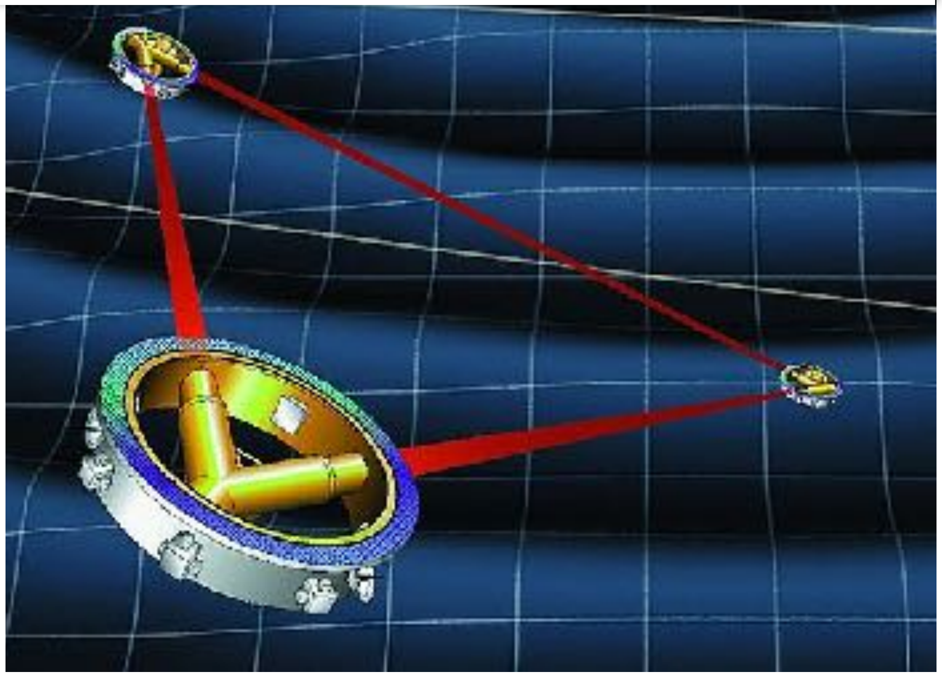


binary/stellar evolution → Mergers In binaries → First consistent Joint prediction In prep.

Molecular cloud properties (with C. Rodrigez, M. Grudic) → Cluster mass Profile → binary/stellar evolution → Mergers In clusters → First consistent Joint prediction In prep.

PREPARING LISA WITH ELECTROMAGNETIC SURVEYS

LISA: ~2034



Complete catalog down to ~ few mHz
Galactic structure, including halo
Probably a few binary black holes

Potential for multi messenger :
Gaia (+ spectro surveys), ZTF/BlackGem, LSST…

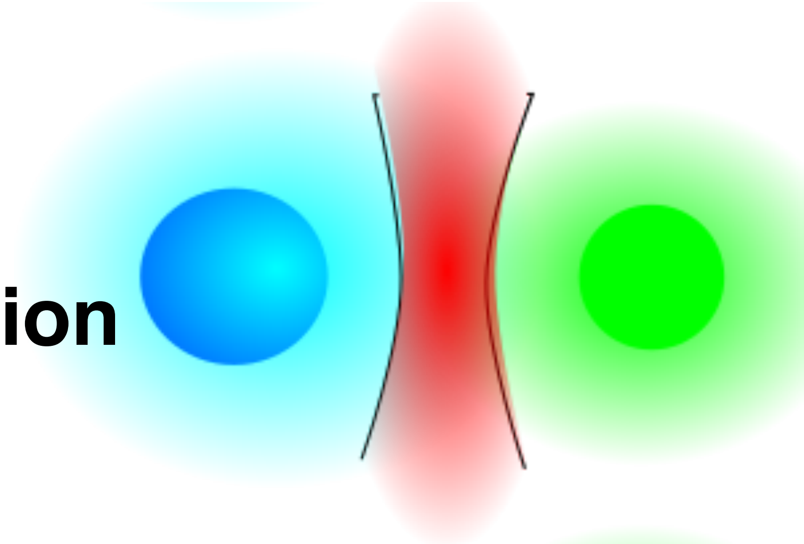
Preparing LISA:
Using current surveys to prepare : verification binaries, estimate of foreground from binary evolution
Other source types and impact on binary evolution?

SUMMARY

What a talk on massive binaries looks like in 2019

interferometry and simulations reveal wind collisions
In Wolf-Rayet binaries

probing circumstellar environments, dust production

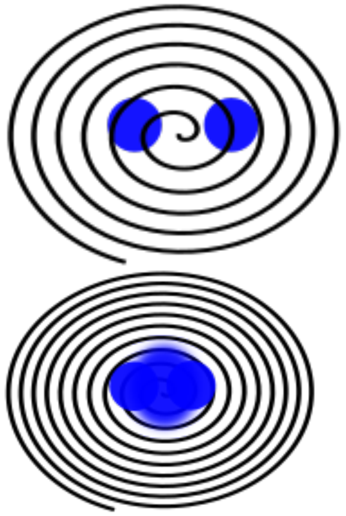


shock interactions produce X-ray flares in GRB

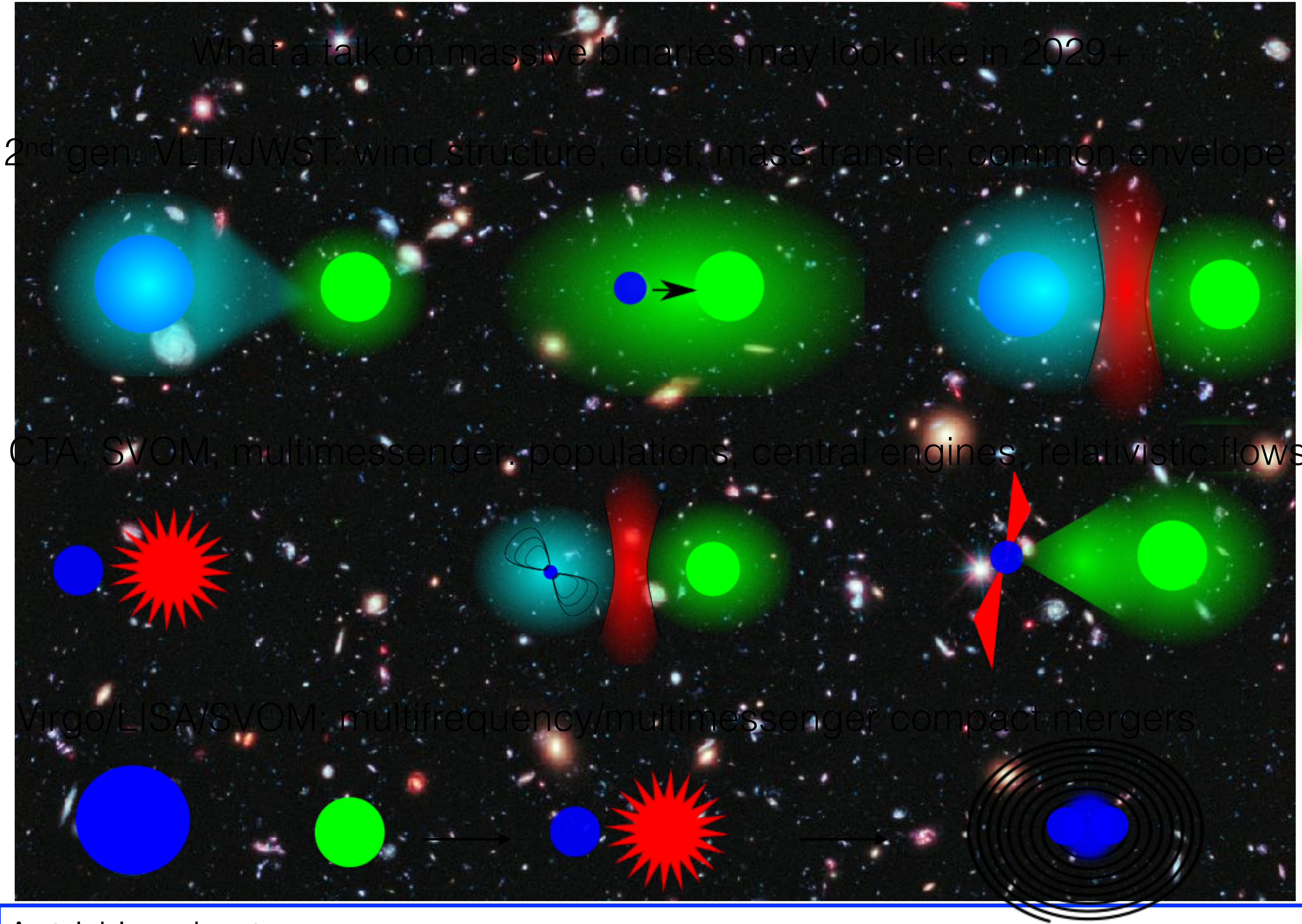
Understand structure of relativistic flows

Massive black hole mergers preferentially trace star formation in dwarfs and outskirts of galaxies

GW: formation/evolution of binaries



Astrid Lamberts



Astrid Lamberts