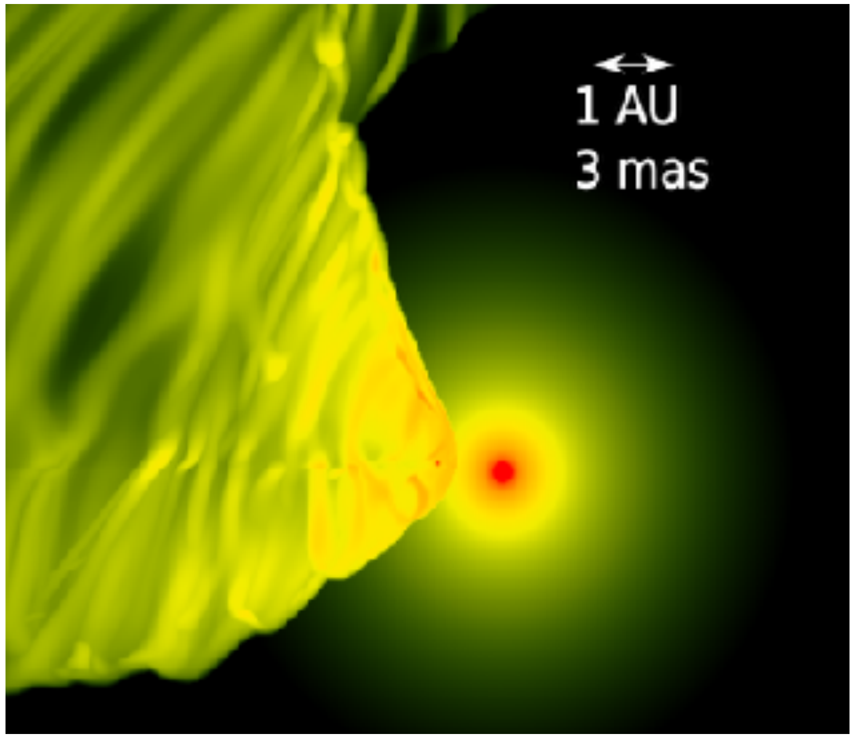
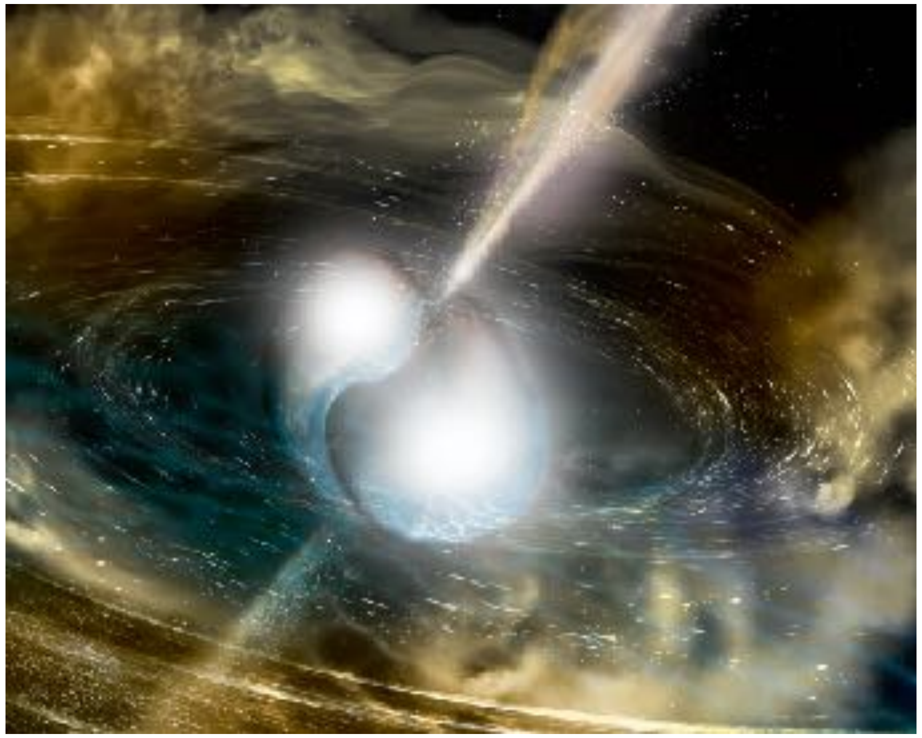
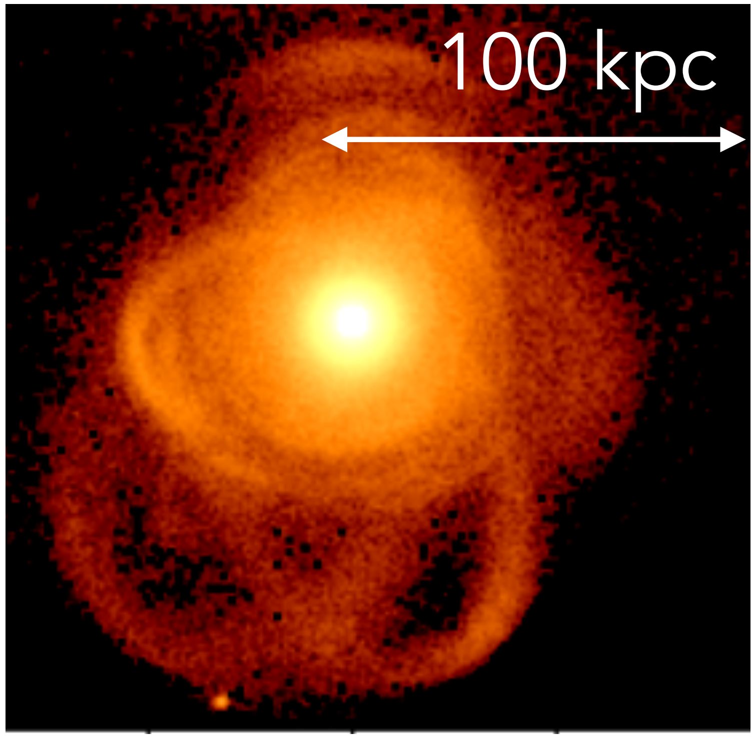
SIGNATURES OF MASSIVE BINARIES

FROM COLLIDING WINDS
TO ZOMBIE BLACK HOLES







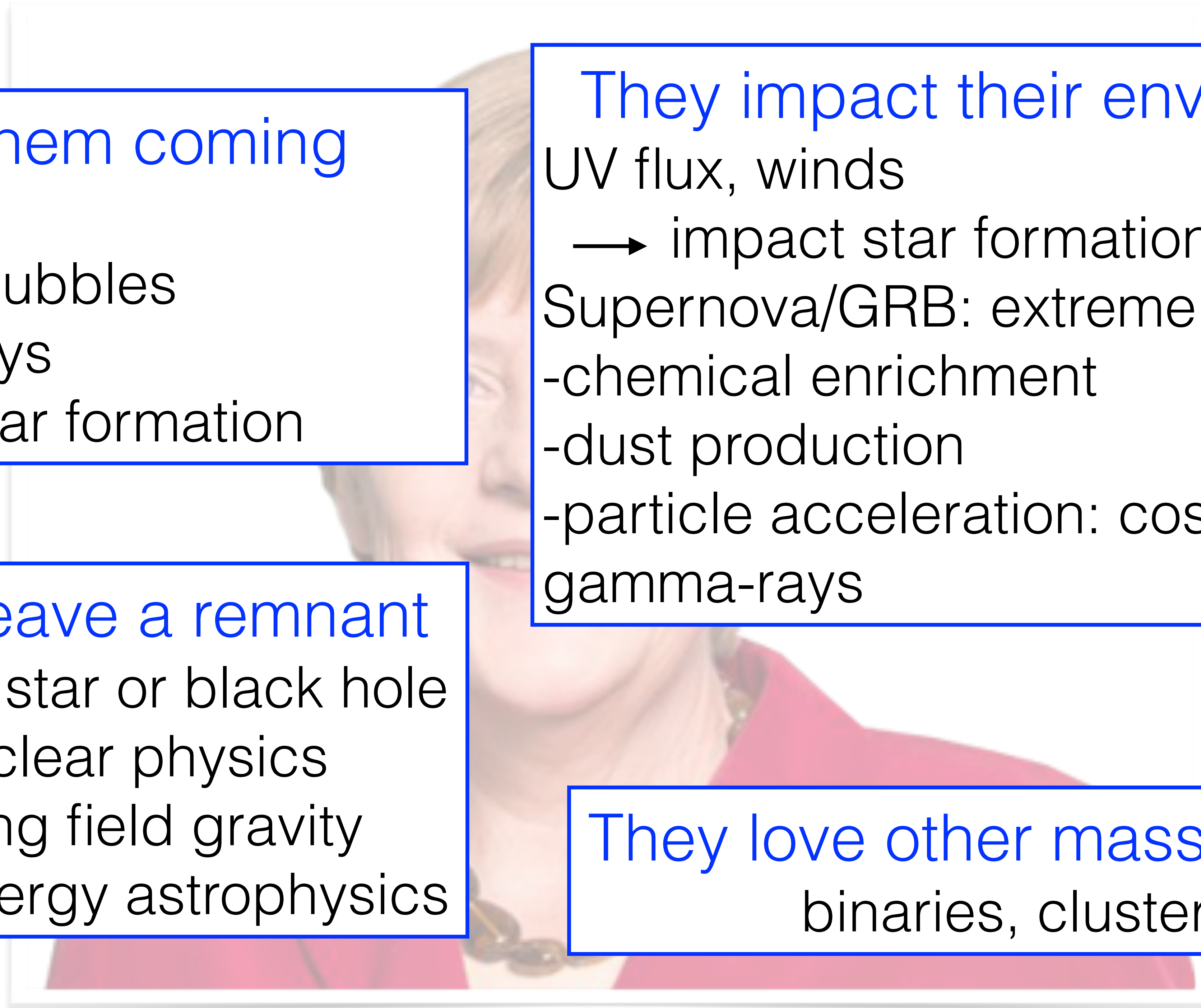
Astrid Lamberts

Observatoire de la CÔTE d'AZUR

LUTh, January 24, 2019

MASSIVE STARS: RARE BUT MIGHTY

MASSIVE STARS: RARE BUT MIGHTY



We see them coming

- $L = 10^4 L_{sun}$
- UV flux : HII bubbles
- radio to X-rays

trace recent star formation

They impact their environment

UV flux, winds

→ impact star formation

Supernova/GRB: extreme explosions

- chemical enrichment
- dust production
- particle acceleration: cosmic rays, gamma-rays

They leave a remnant

Neutron star or black hole

- nuclear physics
- strong field gravity
- high energy astrophysics

They love other massive stars

binaries, clusters

3/4 MASSIVE STARS IN CLOSE BINARIES

Massive binary evolution is complicated

And there's a lot we don't know

(ALMOST) ALL MASSIVE STARS INTERACT

- ☹️Poorly understood

mass loss, mass transfer, impact of supernovae

- ☹️Often ignored

stellar evolution, galaxy formation/evolution

- 😊More signatures than single stars

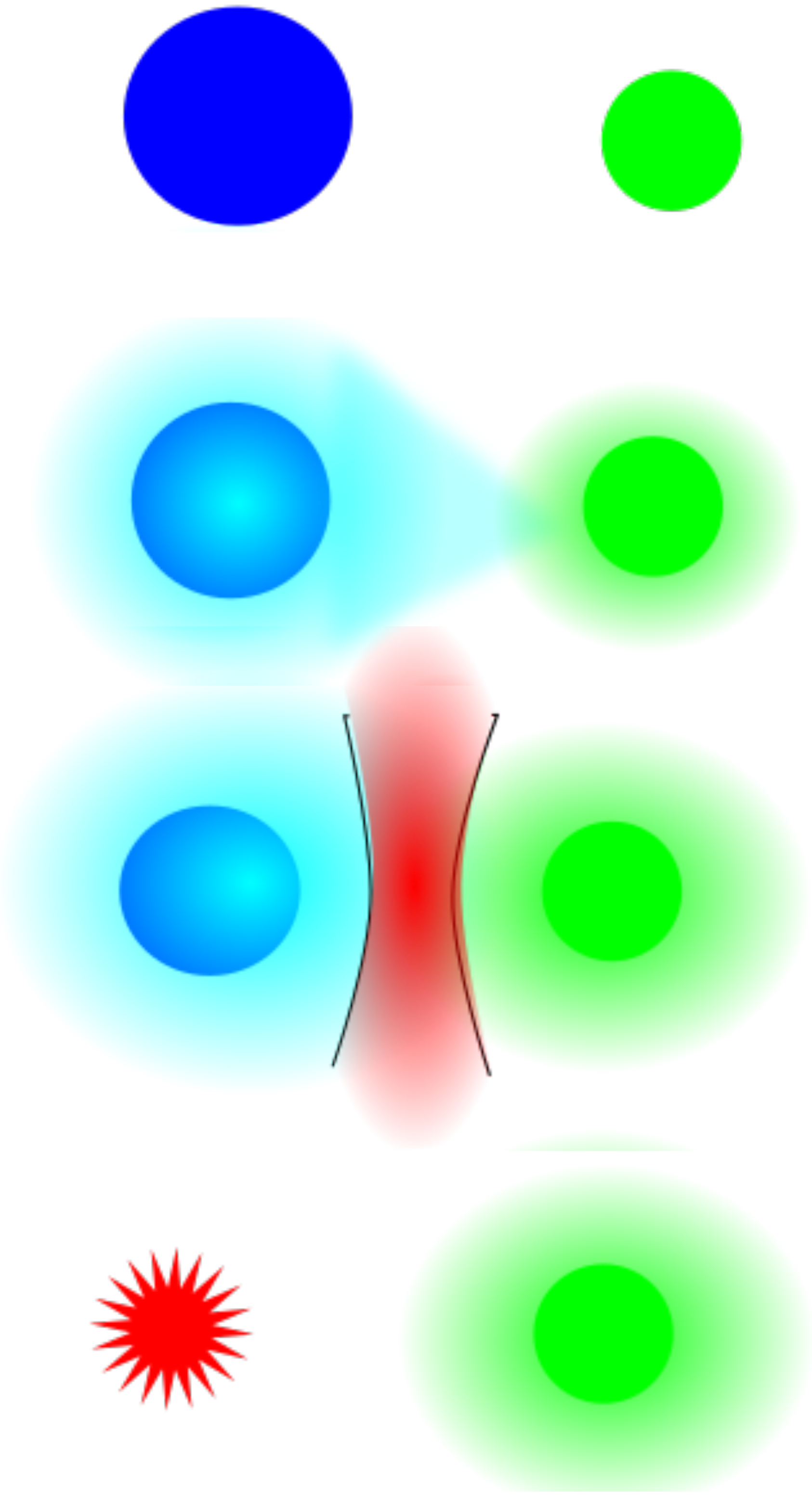
Masses, radii, mass loss, compact object

- 😊Extreme physics labs

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

My goal:
Understand dynamics, emission mechanisms of massive binaries
Individually and globally

NO COMPACT OBJECT : STELLAR ASTROPHYSICS



Formation : 30 M_{sun} O stars

UV, Hα,[OIII], reprocessed

main sequence mass transfer

Circumbinary material?

wind collisions

X-rays, line variability, radio, dust

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

collapse 1: supernova/gamma-ray burst

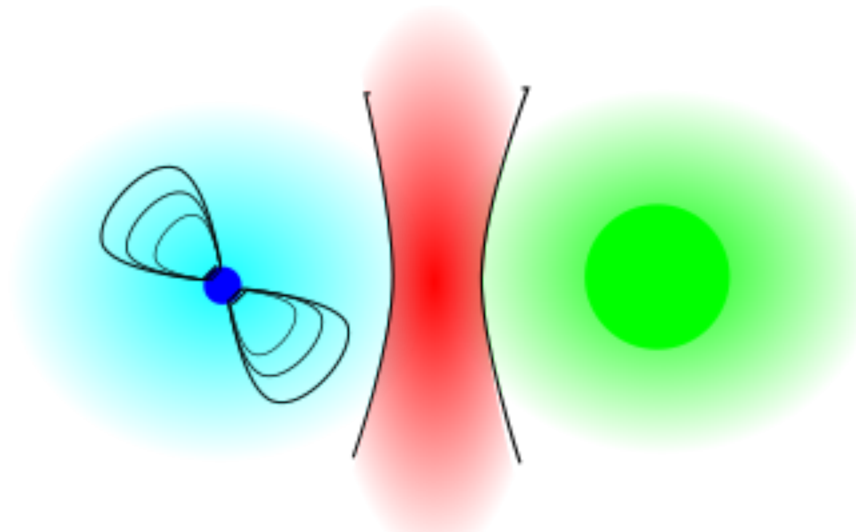
Time domain astronomy: gamma-rays to radio

Gravitational waves/neutrinos?

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

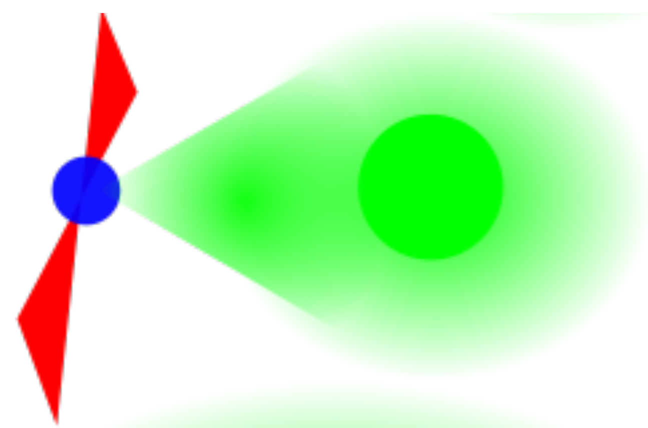
1 COMPACT OBJECT : HIGH ENERGY ASTROPHYSICS

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



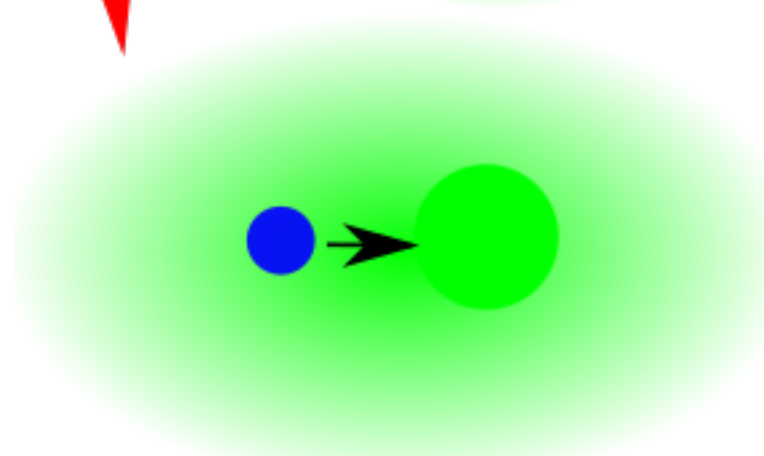
from radio to
TeV gamma rays

High-mass X-ray binary



X-rays, radio

Common envelope



faint transient

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

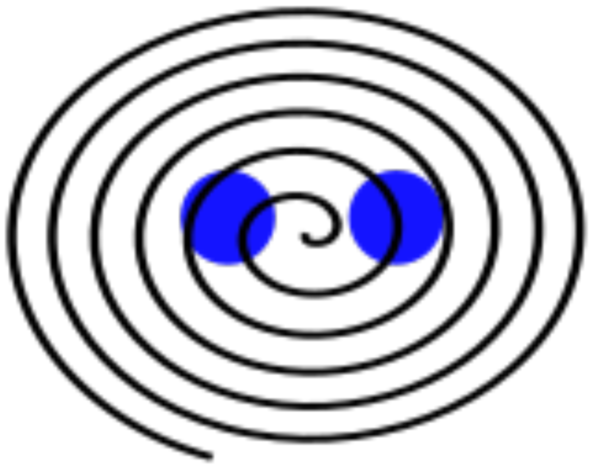
Time domain
multi-messenger astronomy

2 COMPACT OBJECTS : GRAVITATIONAL WAVE ASTRONOMY

Billion years of inspiral

(***Lamberts***+2018b)

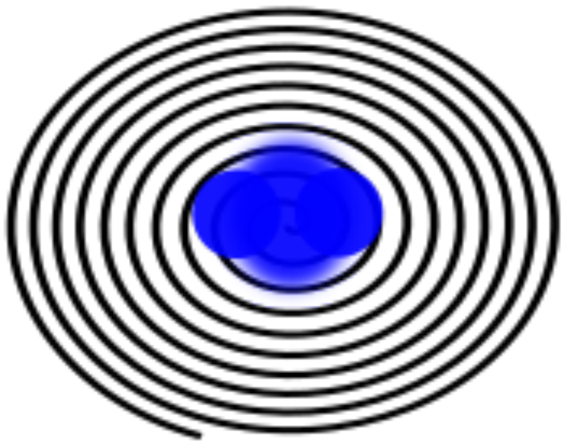
Low frequency gravitational waves,
double pulsars (Nobel Prize '93)



Merger

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

(***Lamberts***+2016)



60 M_{sun} black hole
Game over

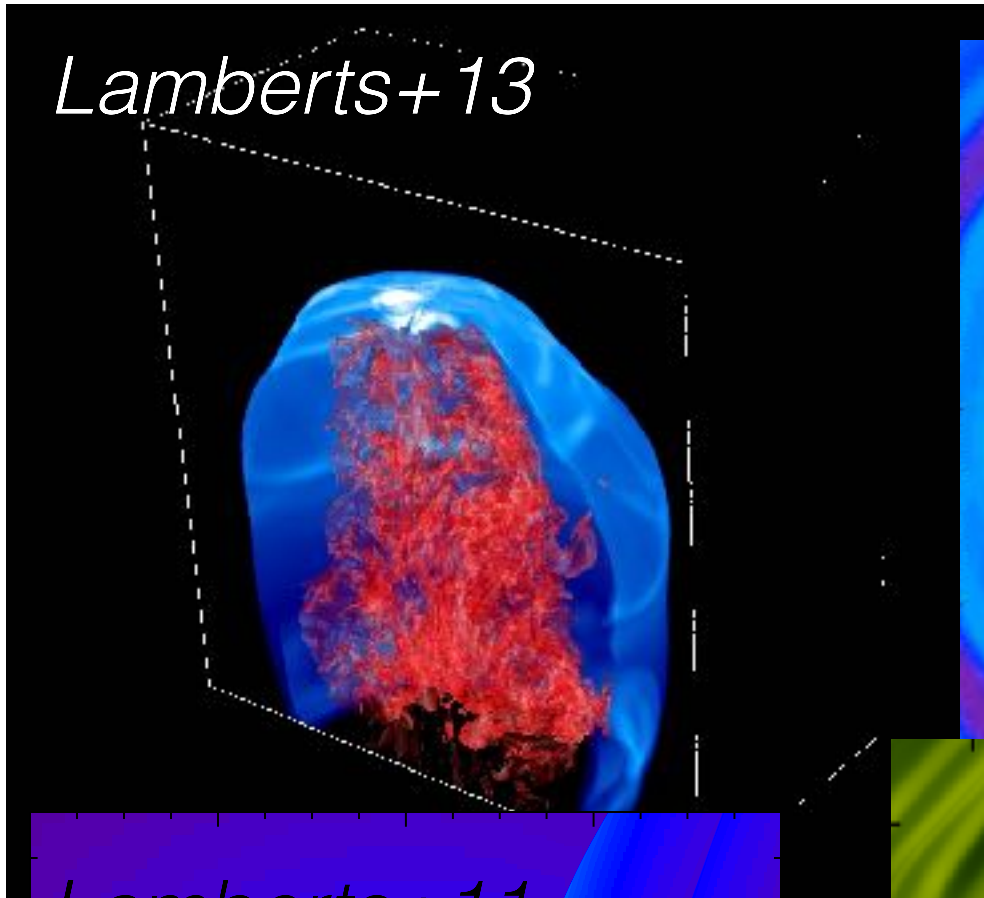
CONNECTING THE DOTS

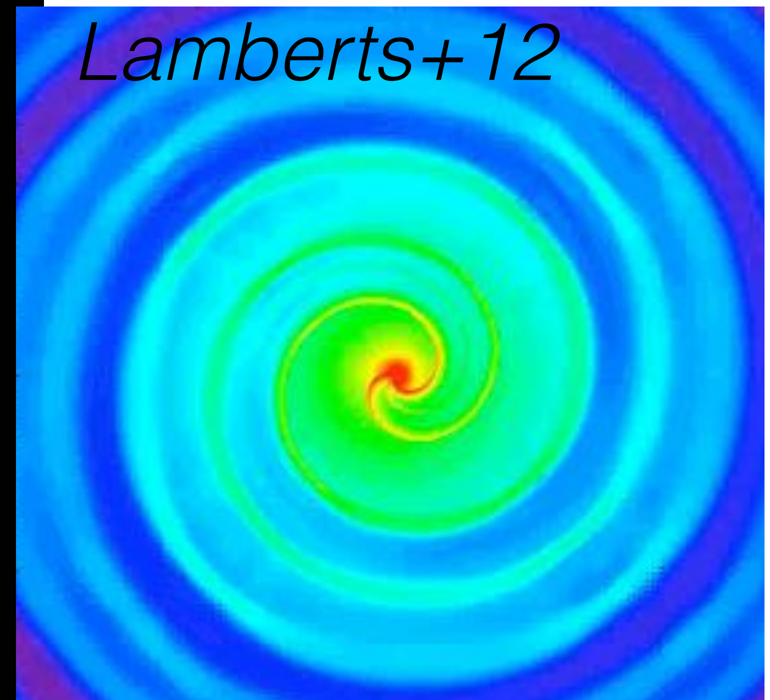
Understand dynamics, emission mechanisms of massive binaries
Individually and globally

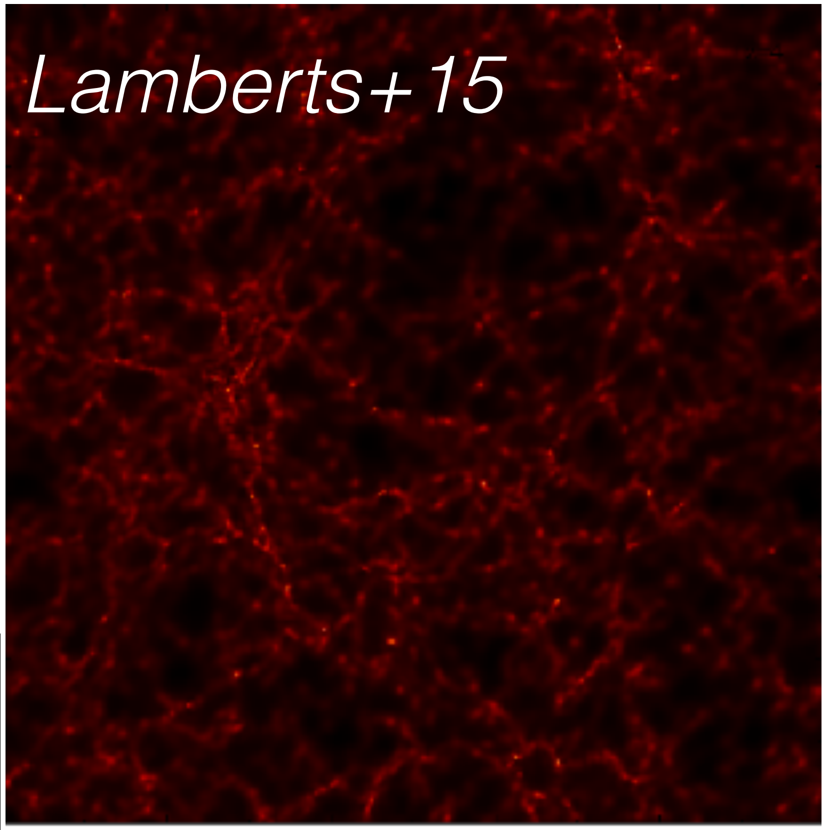
Study stellar astrophysics, high-energy astrophysics and gravitational wave astronomy

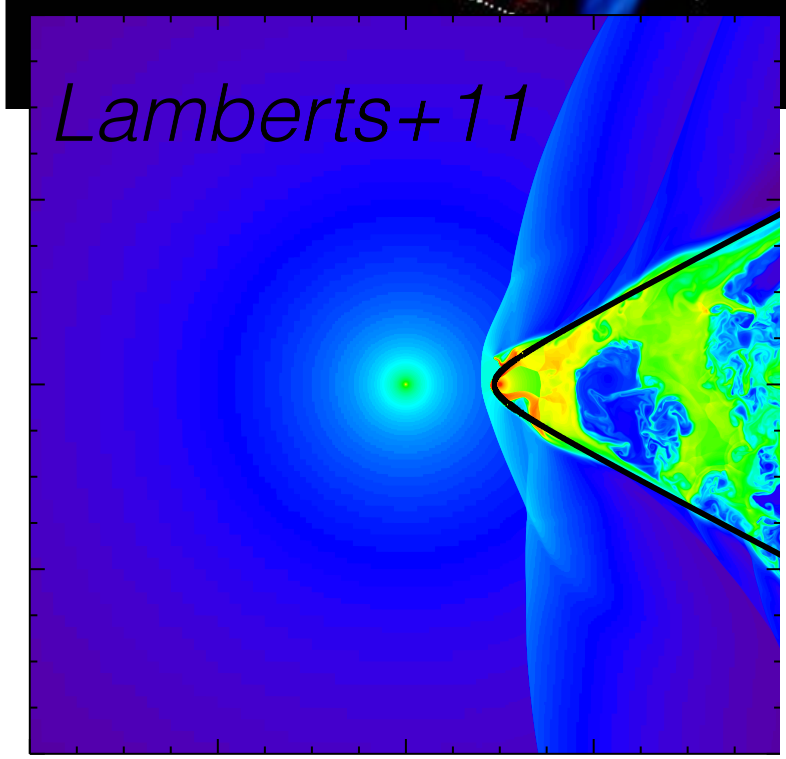
Combine high resolution hydrodynamic simulations, emission models, analytic estimates with observations

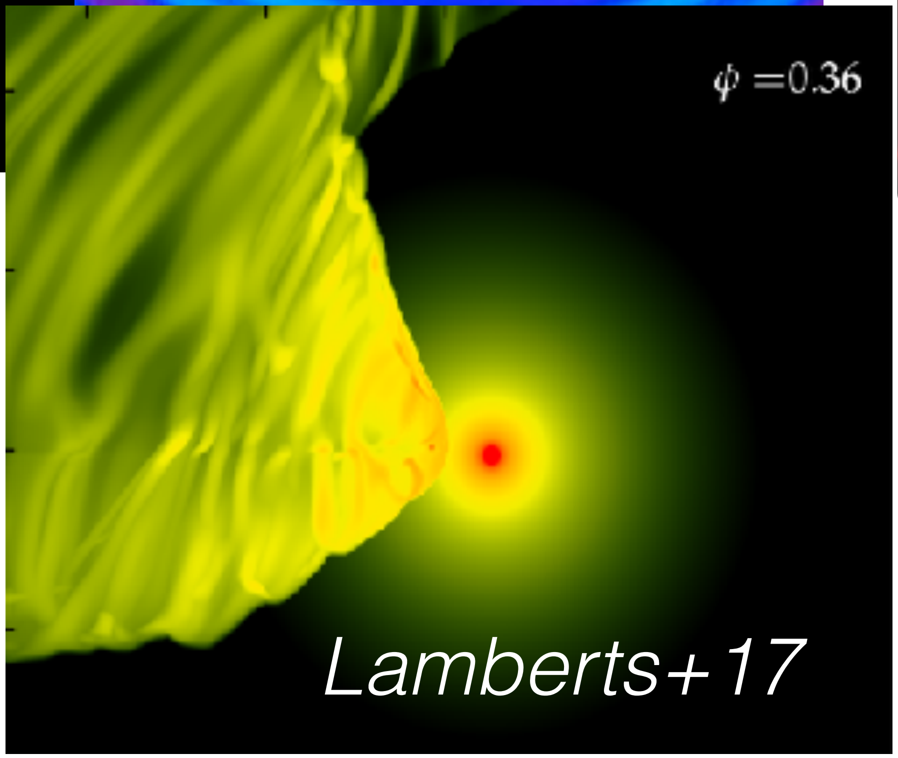
NUMERICAL DEVELOPMENTS











~5 million hours
~500 years
RAMSES, GADGET
Special relativity

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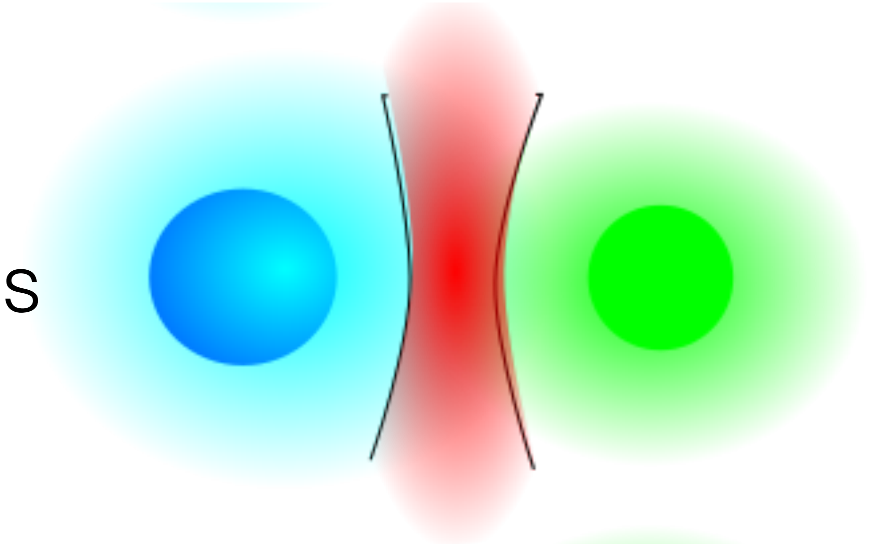
Revealing the wind collision in Wolf Rayet binaries
*(**Lamberts**, Millour +, 2017)*



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Where do GW progenitors form ?
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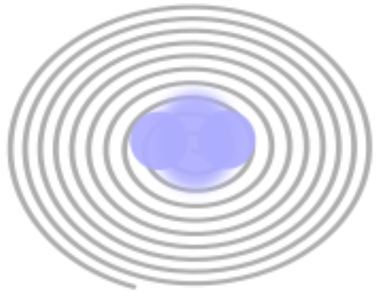
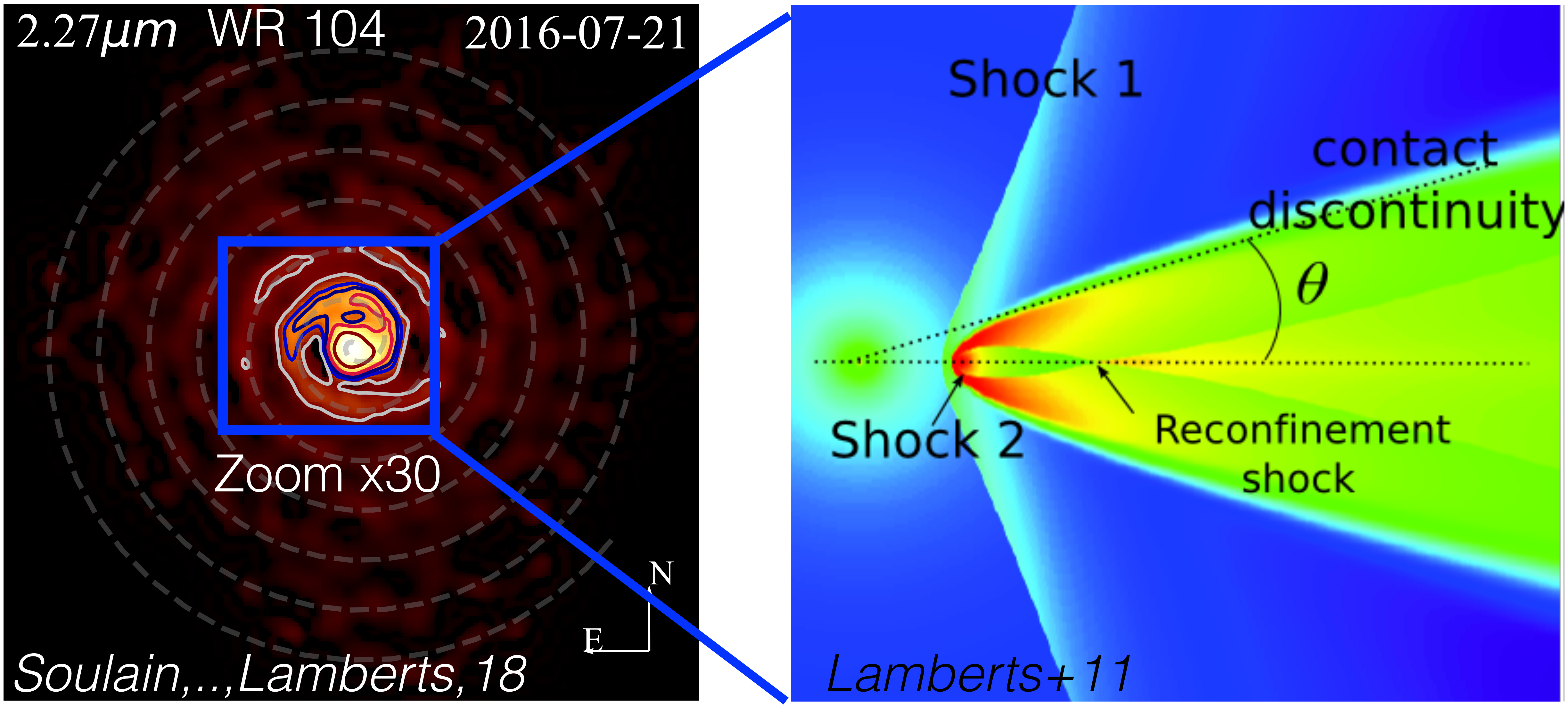


EXTREME MASS LOSS IN WOLF RAYET STARS

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

Dust production in some binary/triple systems

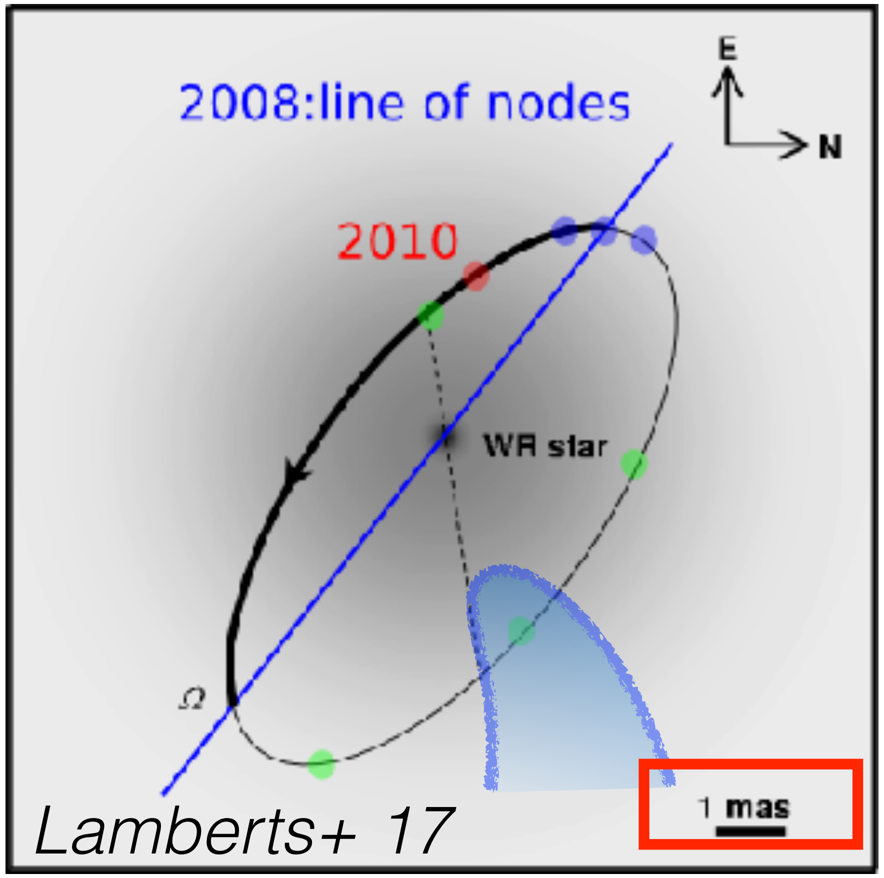


Questions: structure of the winds?

How to make the dust? Impact of dust?

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

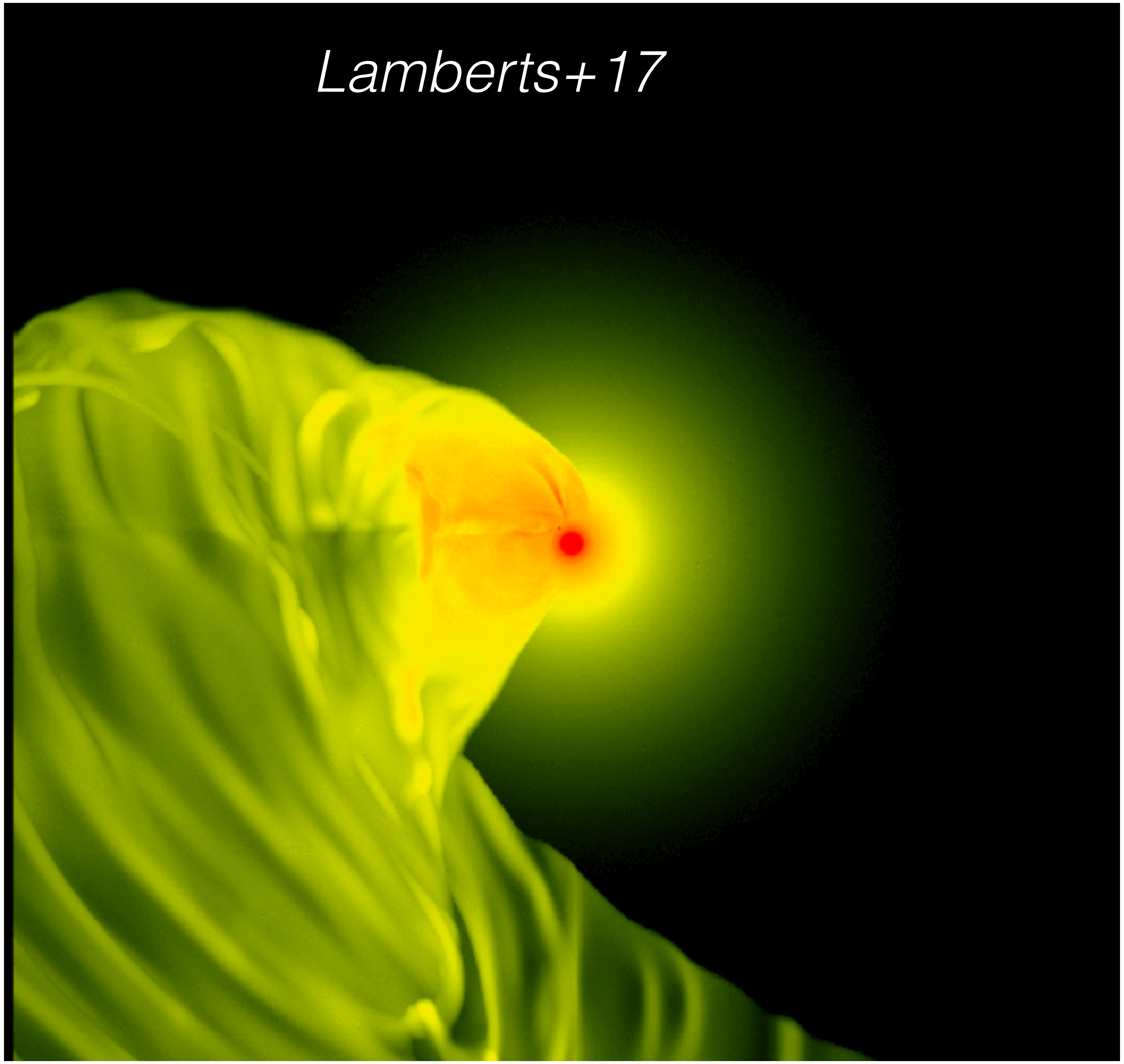
→ separate spectra

possibility for 1st direct detection of close wind collision

(see *Weigelt+16* for ηCar)

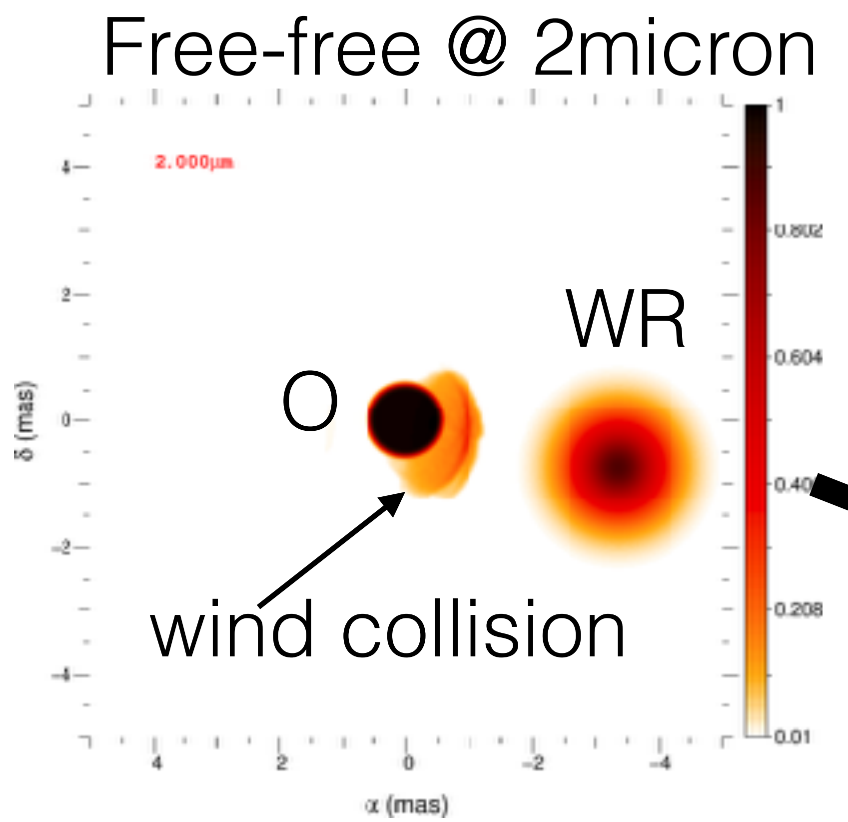
Geometrical models fail to reproduce observations : need simulations

GAMMA VEL: THE MOVIE

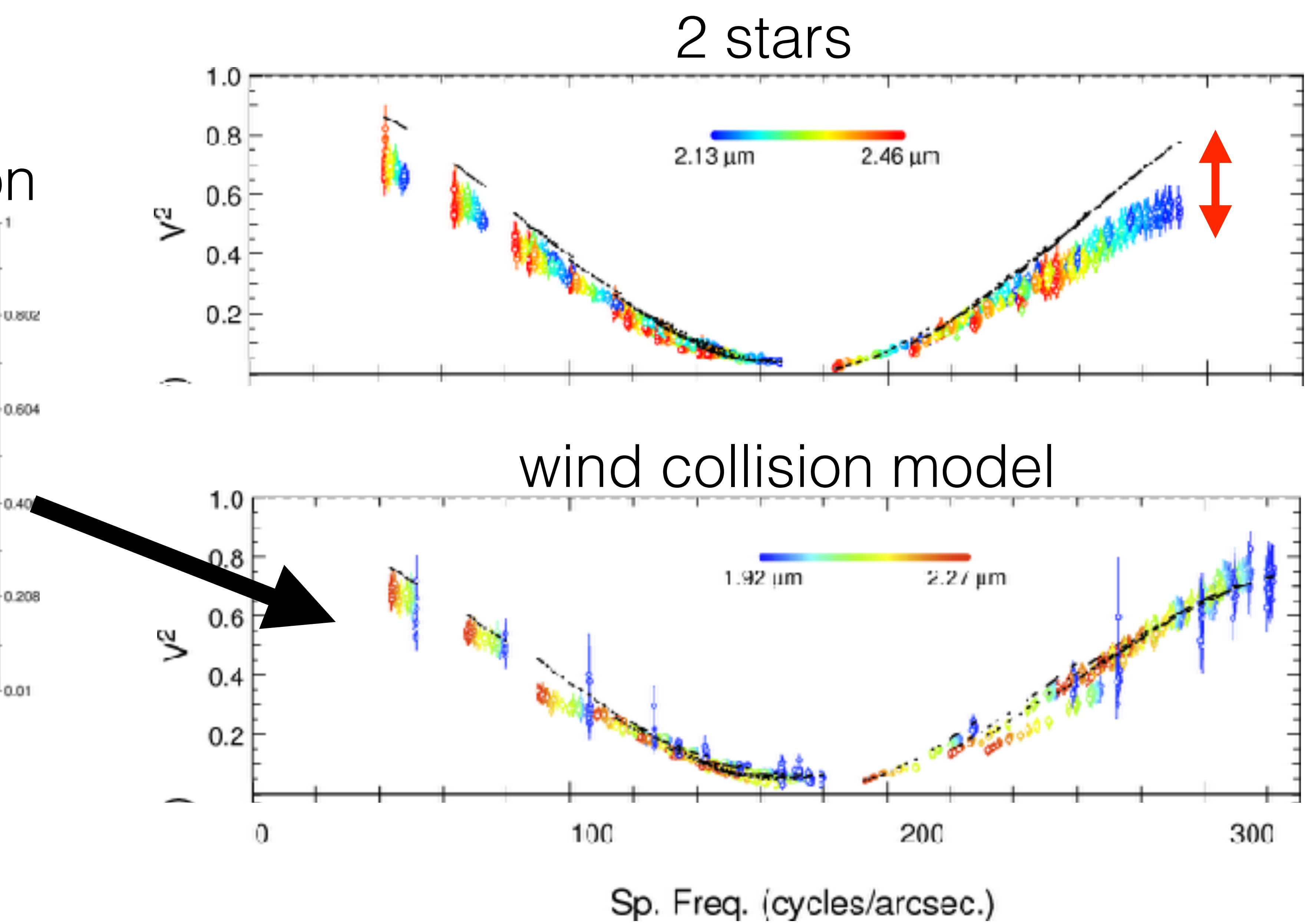


- L_{box}=16 x separation
- resolution ~ R_{sun}
- radiative cooling

MODEL OBSERVATIONS FROM SIMULATIONS



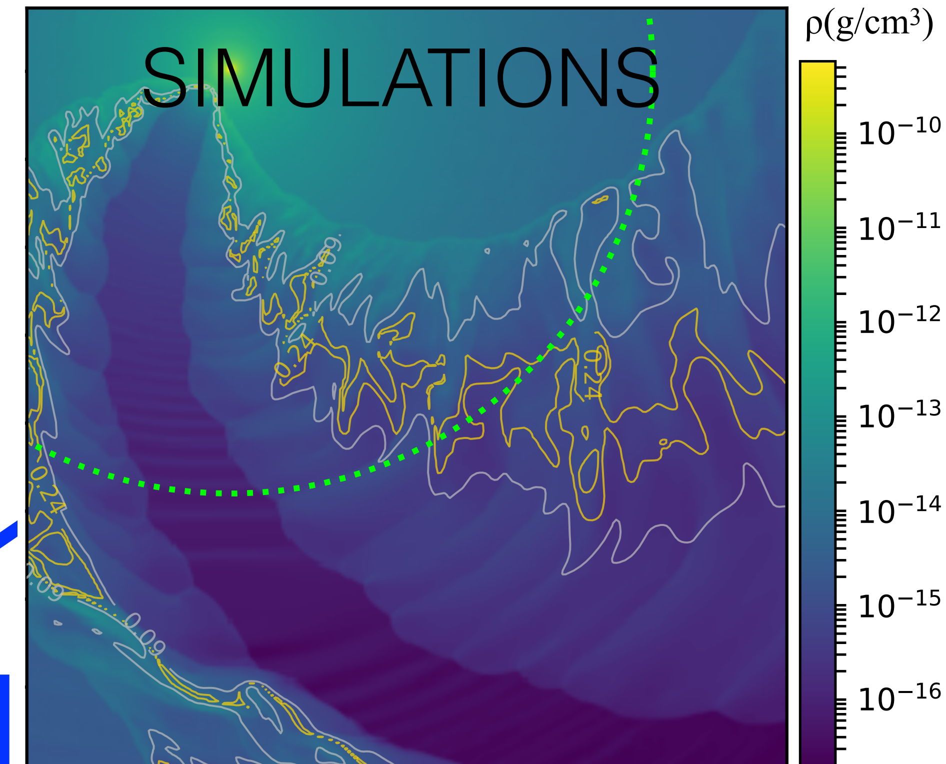
Lamberts+17



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

CIRCUMSTELLAR ENVIRONMENTS: PATH FORWARD

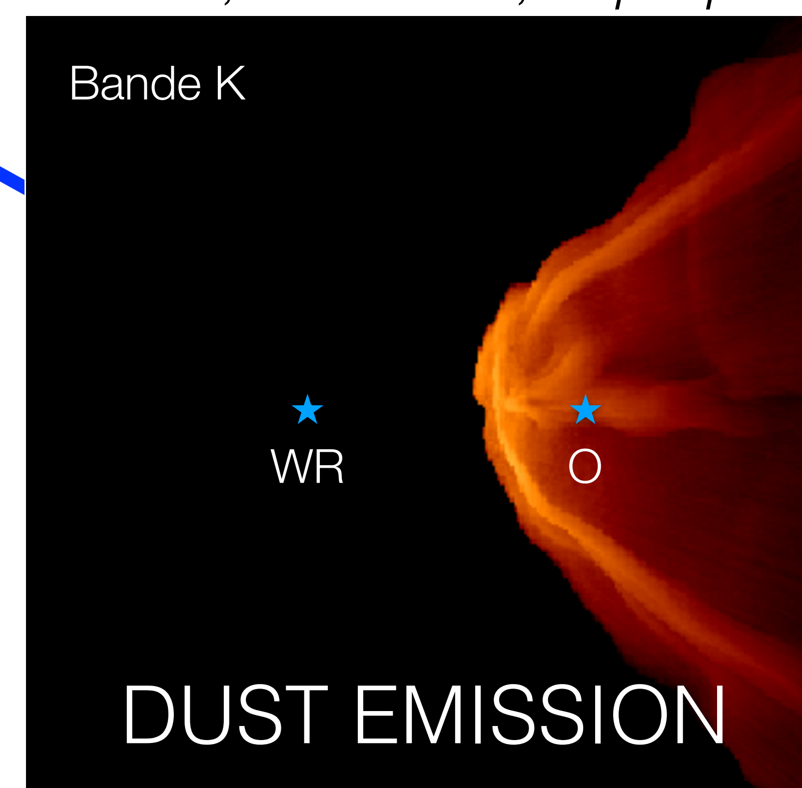
Member of MATISSE
2 accepted proposals
+ GTO time



Soulain, Lamberts, in prep.

Understand, quantify
Dust production

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



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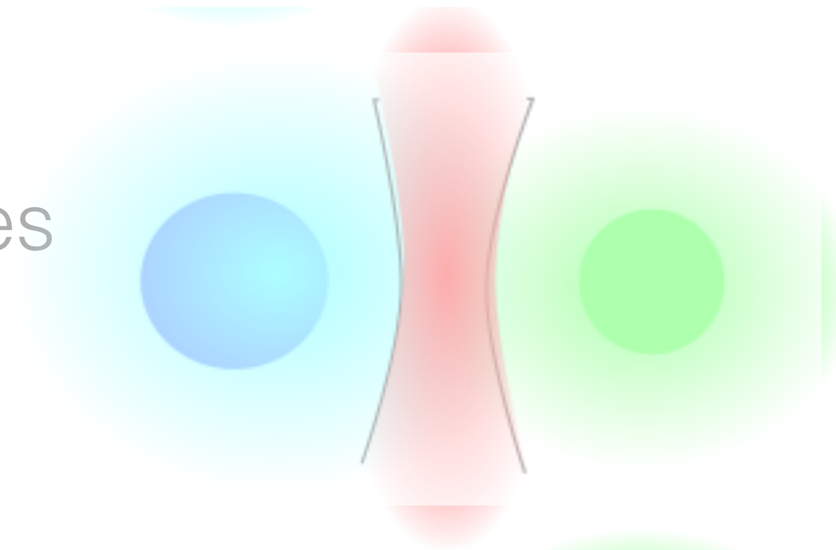

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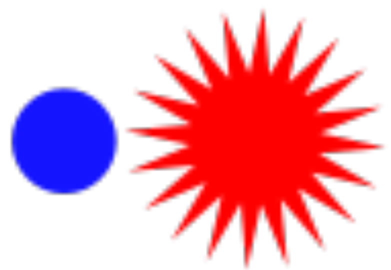

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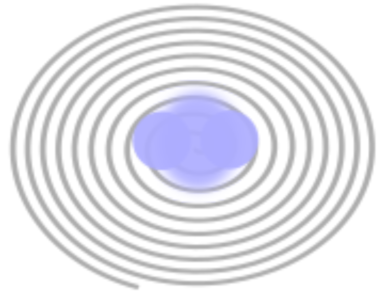


EXTREME HYDRODYNAMICS IN GAMMA-RAY BURSTS

Extragalactic gamma-ray flashes ~once/day

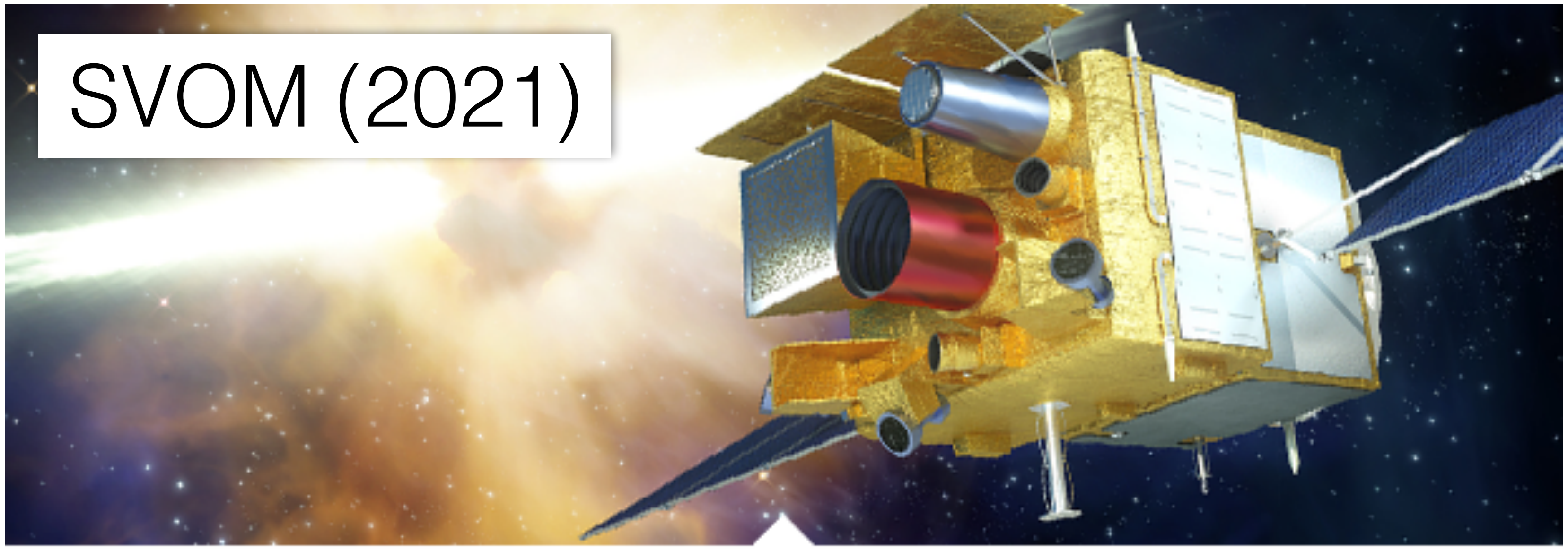
- up to z>9 : trace early universe
- extreme physics

Different populations: prompt emission

- massive stellar collapse (long)
- GW 170817 confirms neutron star merger (short)

Then afterglow

Provides host galaxy + global energetics



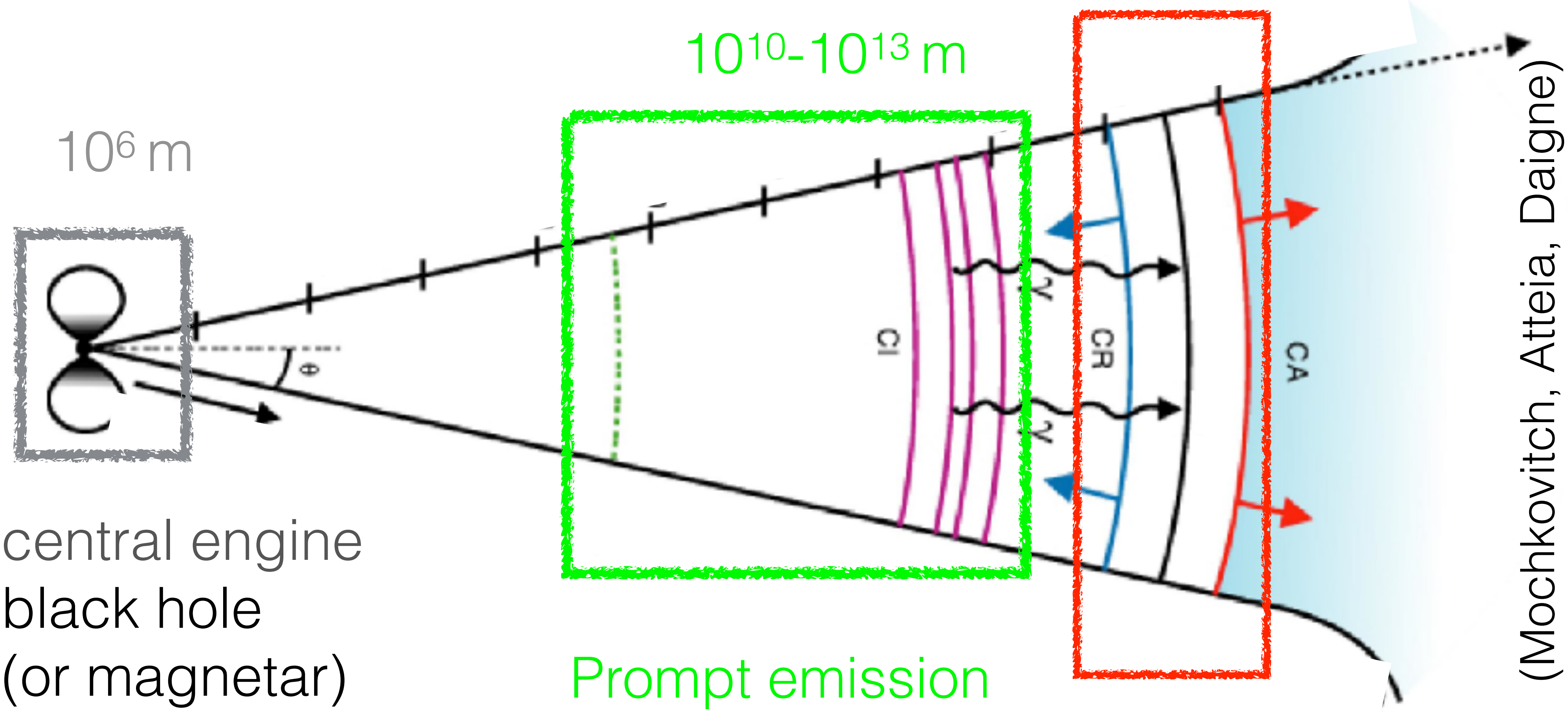
FIREBALL MODEL F0R GAMMA-RAY BURSTS

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

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

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

10^{6} m



central engine
black hole
(or magnetar)

Prompt emission
internal

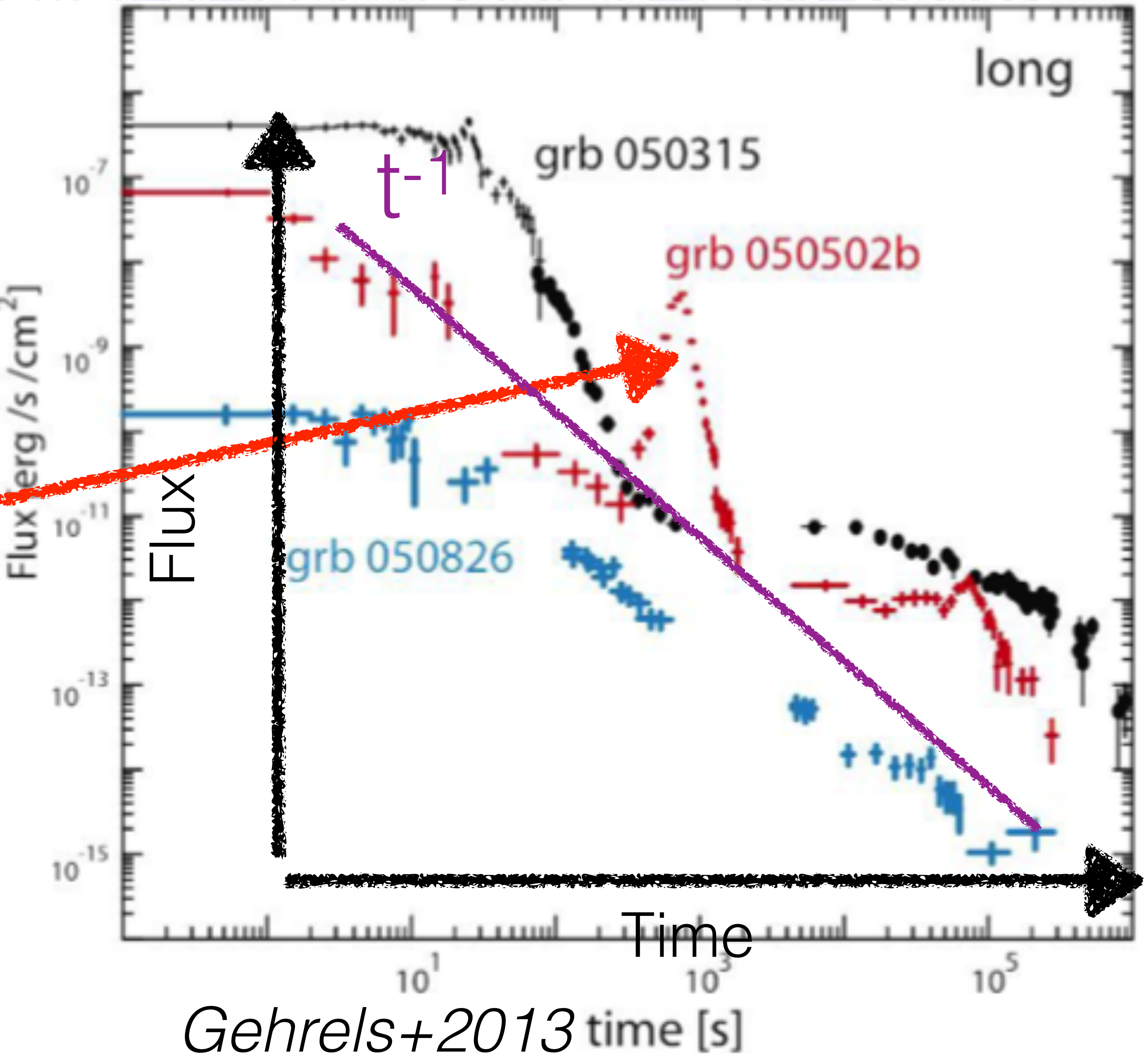
Afterglow
External
Expected t^{-1}

A LOT OF X-RAY VARIABILITY IN AFTERGLOWS

Swift: sensitivity+timing

Diverse/variable

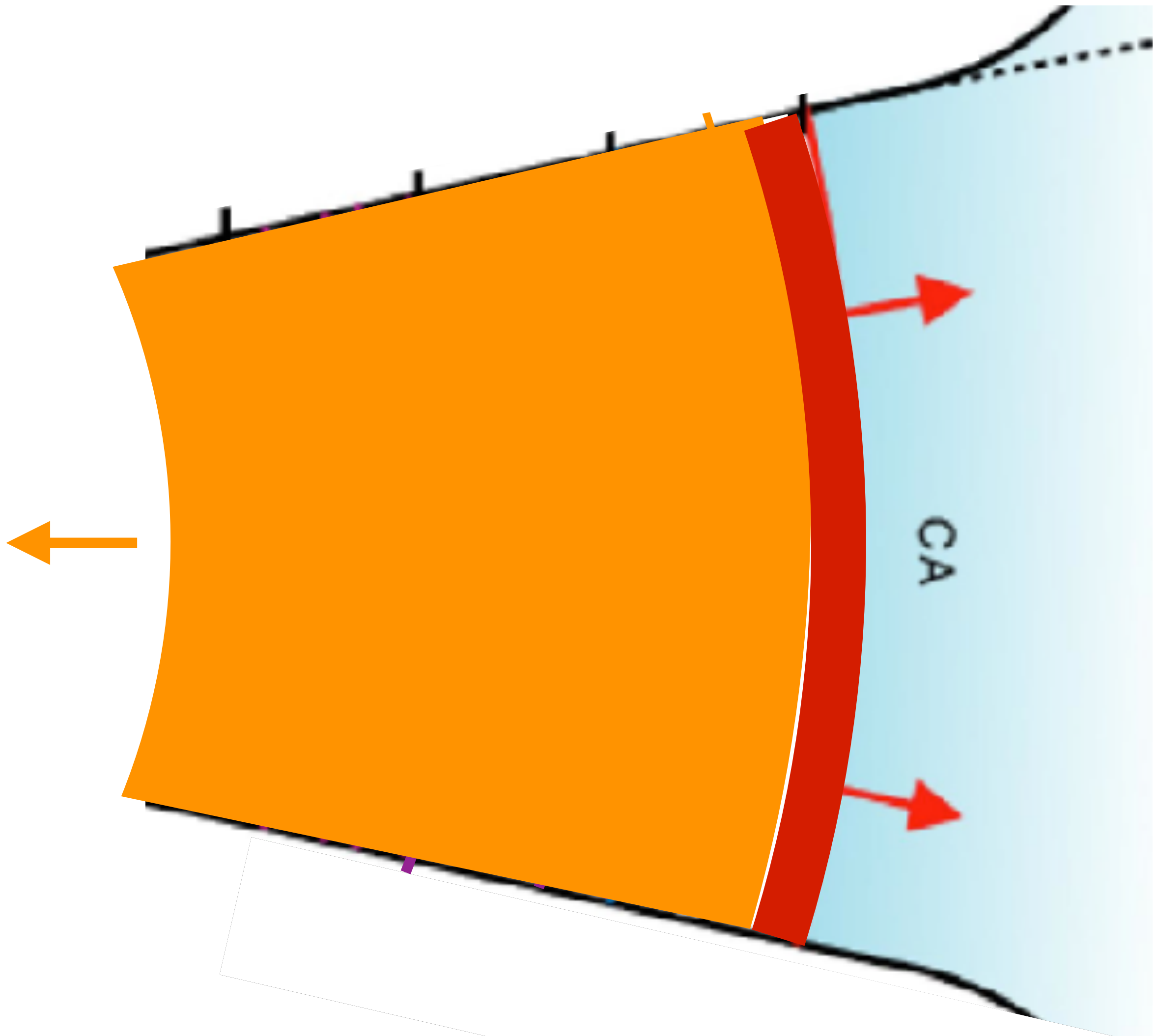
- steep declines
- flares
- plateaus



Gehrels+2013

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

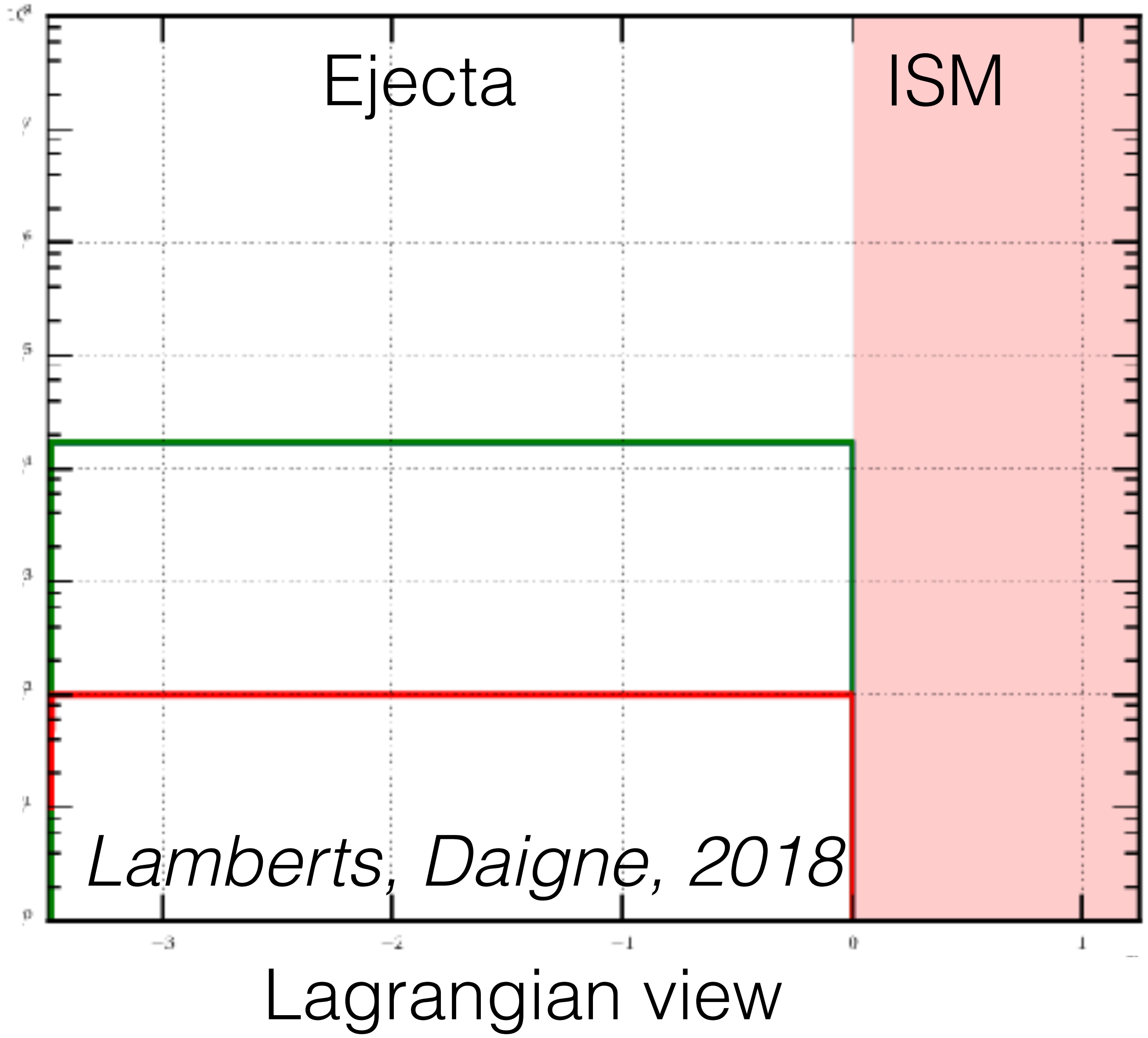
->1D spherical grid + moving boundaries

Uniform setup

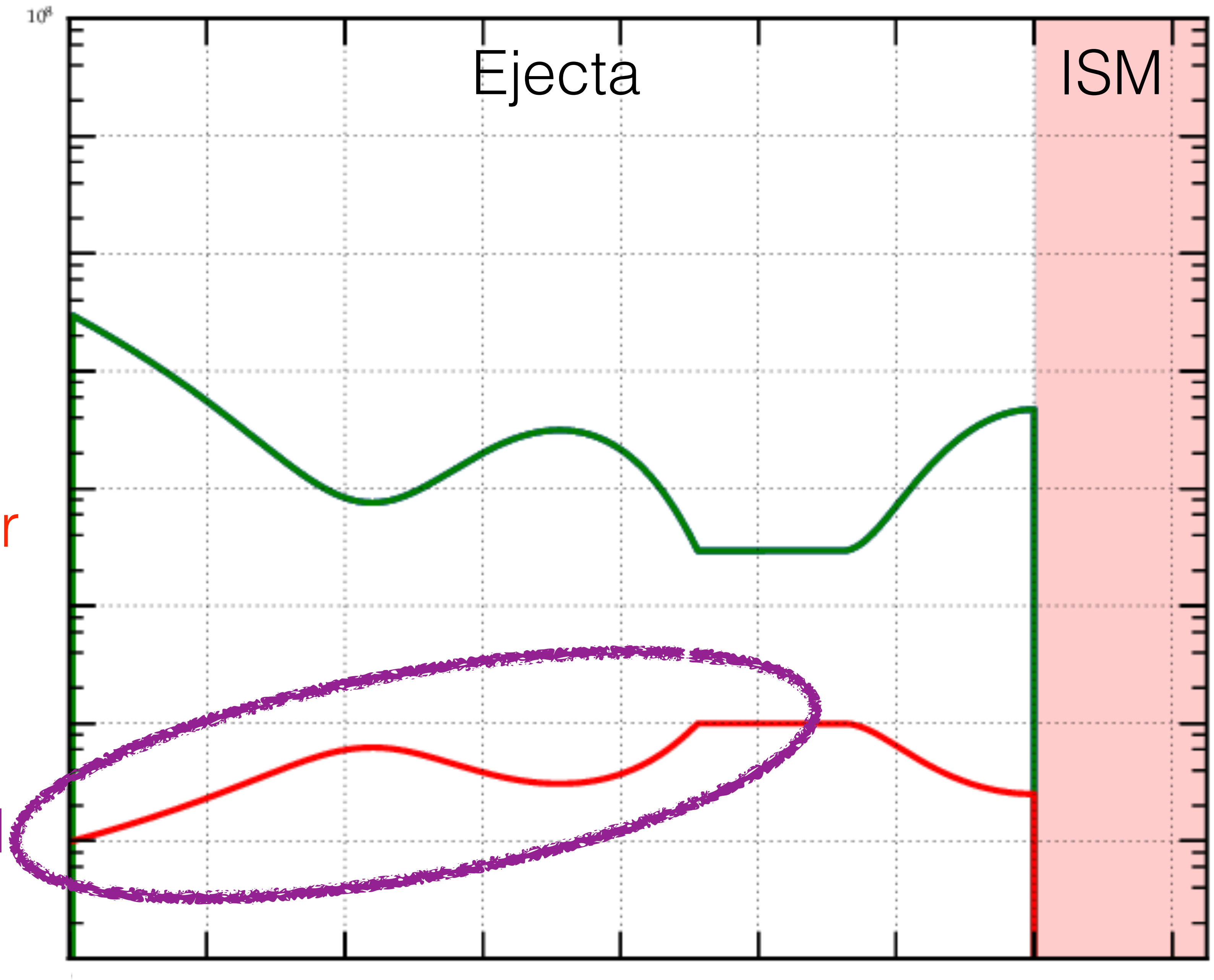
pressure

density

Lorentz factor



STRATIFIED EJECTA CREATE SHOCKS



pressure
density
Lorentz factor

Fast material
behind slow
flares expected

Lagrangian view

Lorentz factor profile-> complex dynamics with multiple shocks

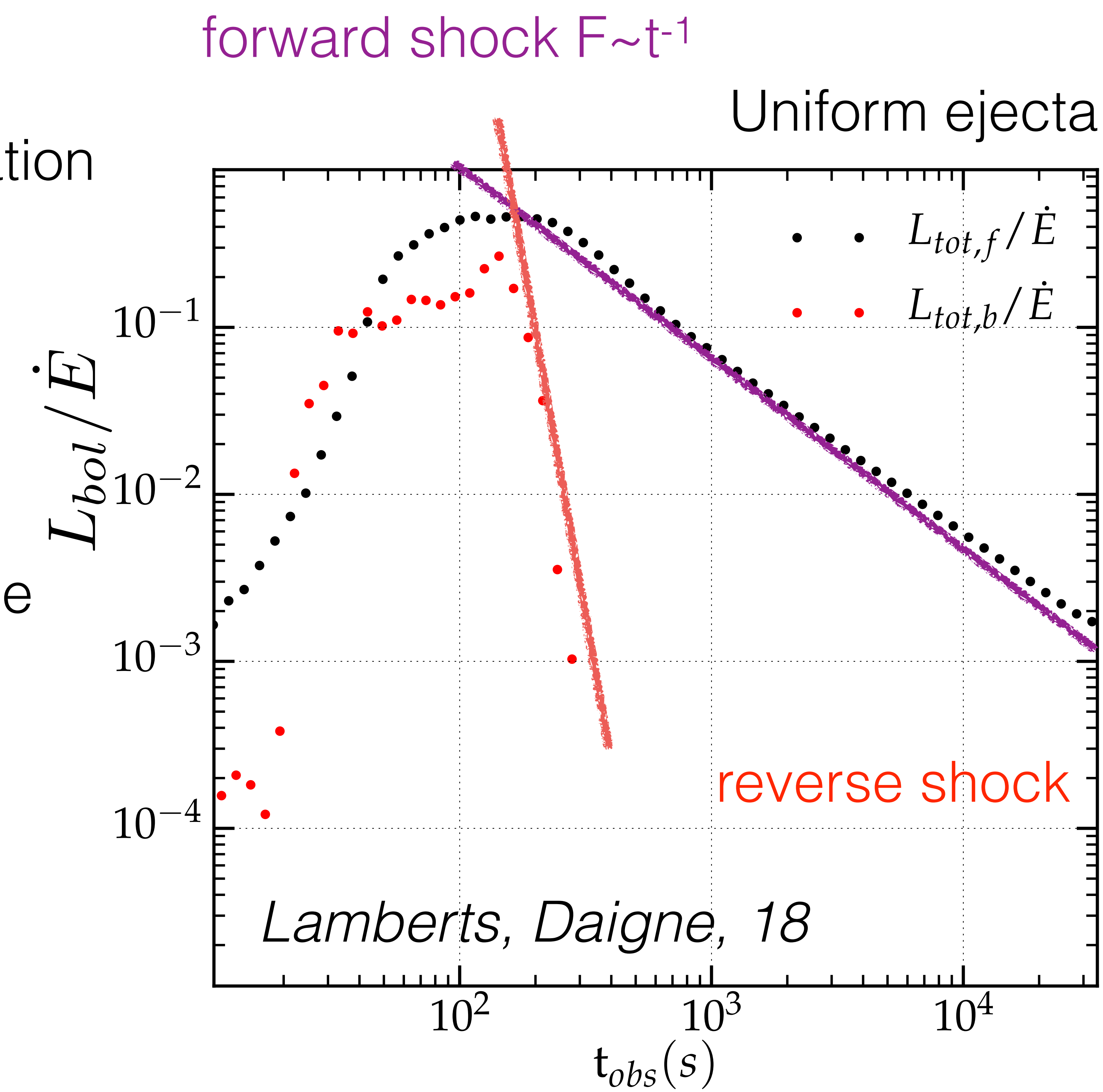
BOLOMETRIC EMISSION FROM SIMULATIONS

shocks -> particle acceleration
synchrotron fast cooling

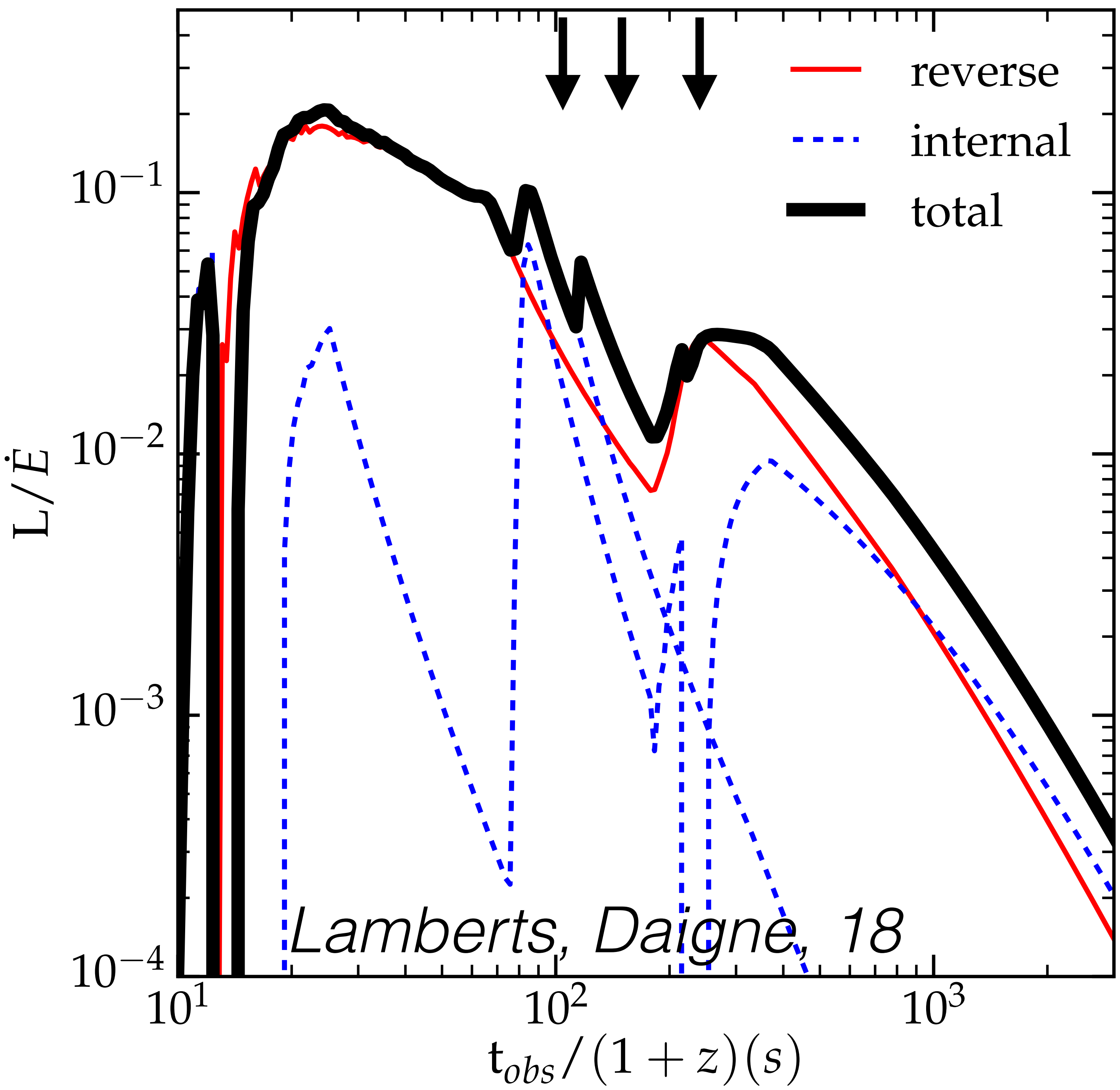
- Find shocks
- compute energy release

Relativistic outflow

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



X-RAY FLARES FROM SHOCK INTERACTIONS



Result: Shock interactions produce X-ray flares in afterglow

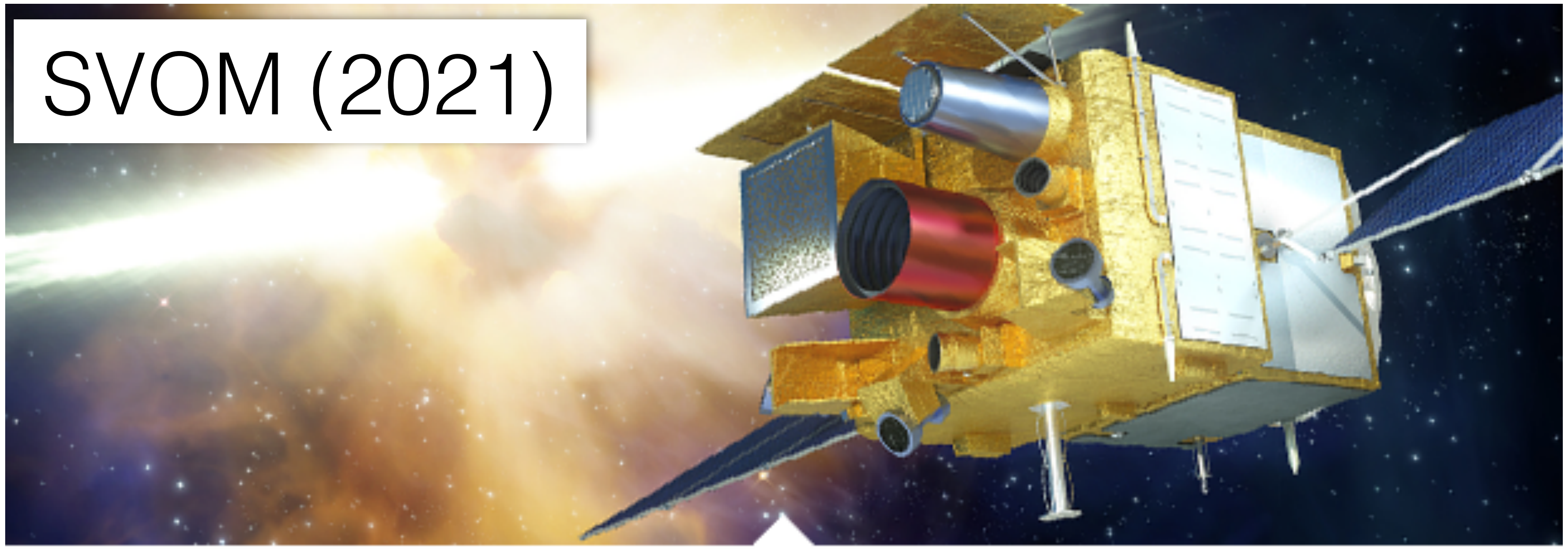
- > constraints on microphysics

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 ?
- 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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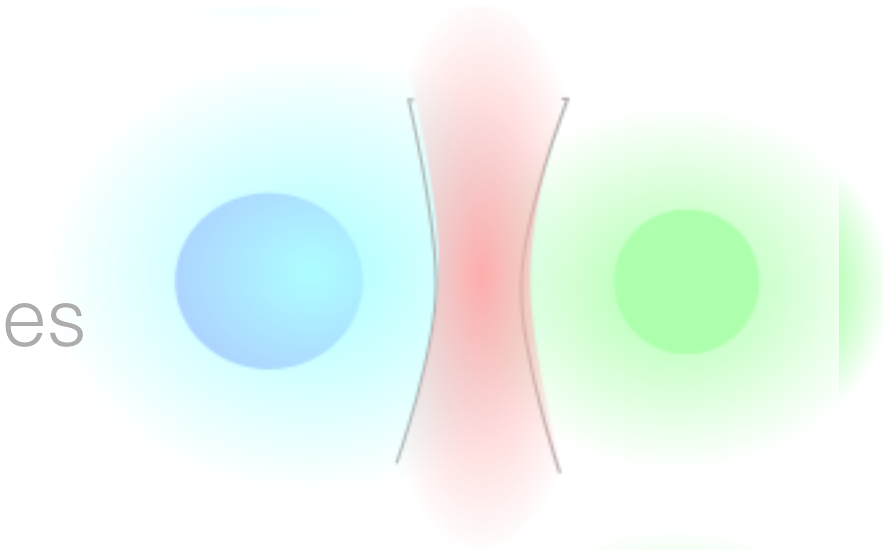

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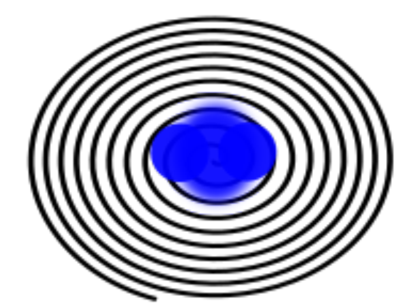
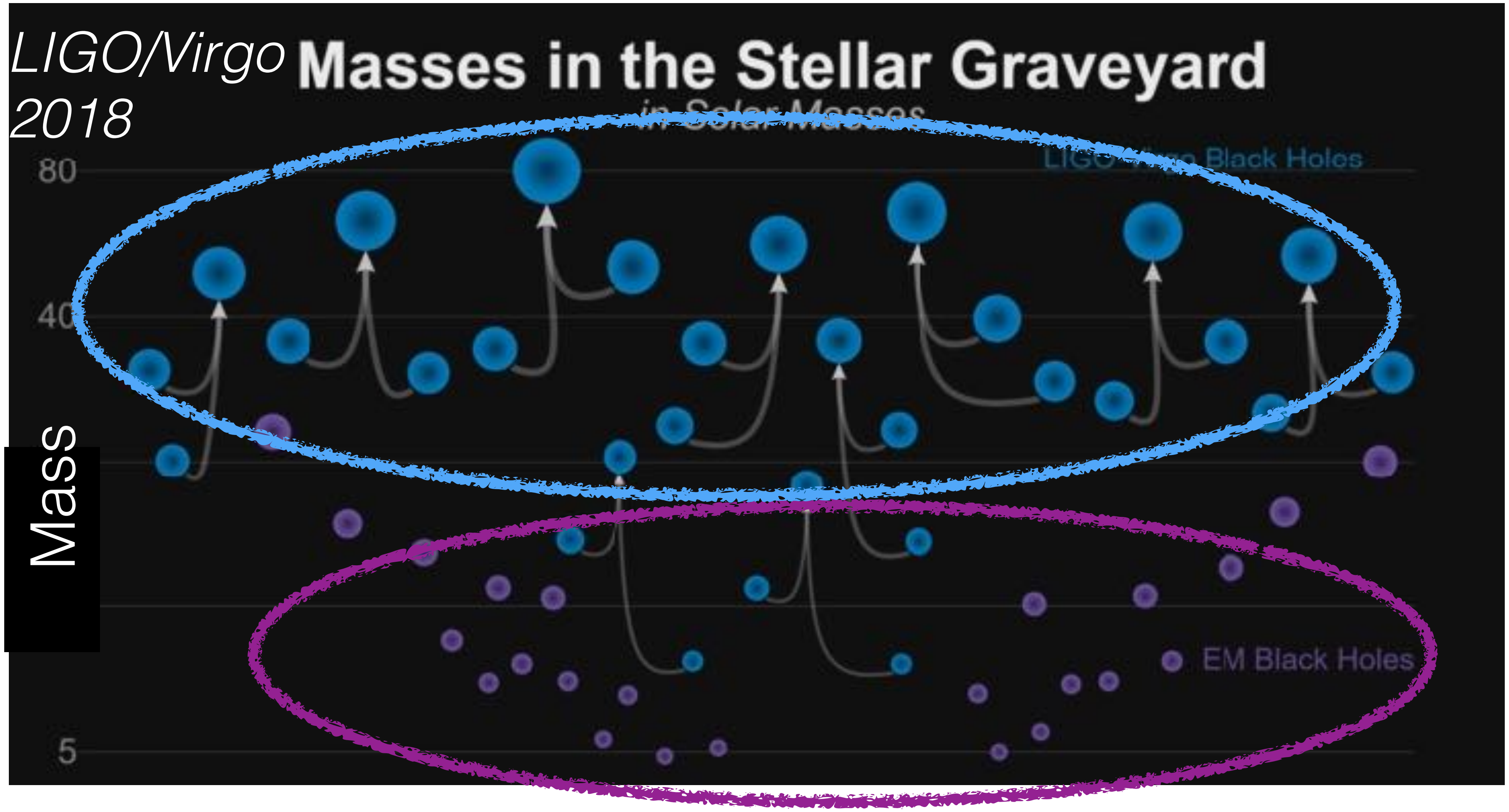


LIGO/VIRGO REVEAL MASSIVE BLACK HOLES



Different masses

↓

How to make them?

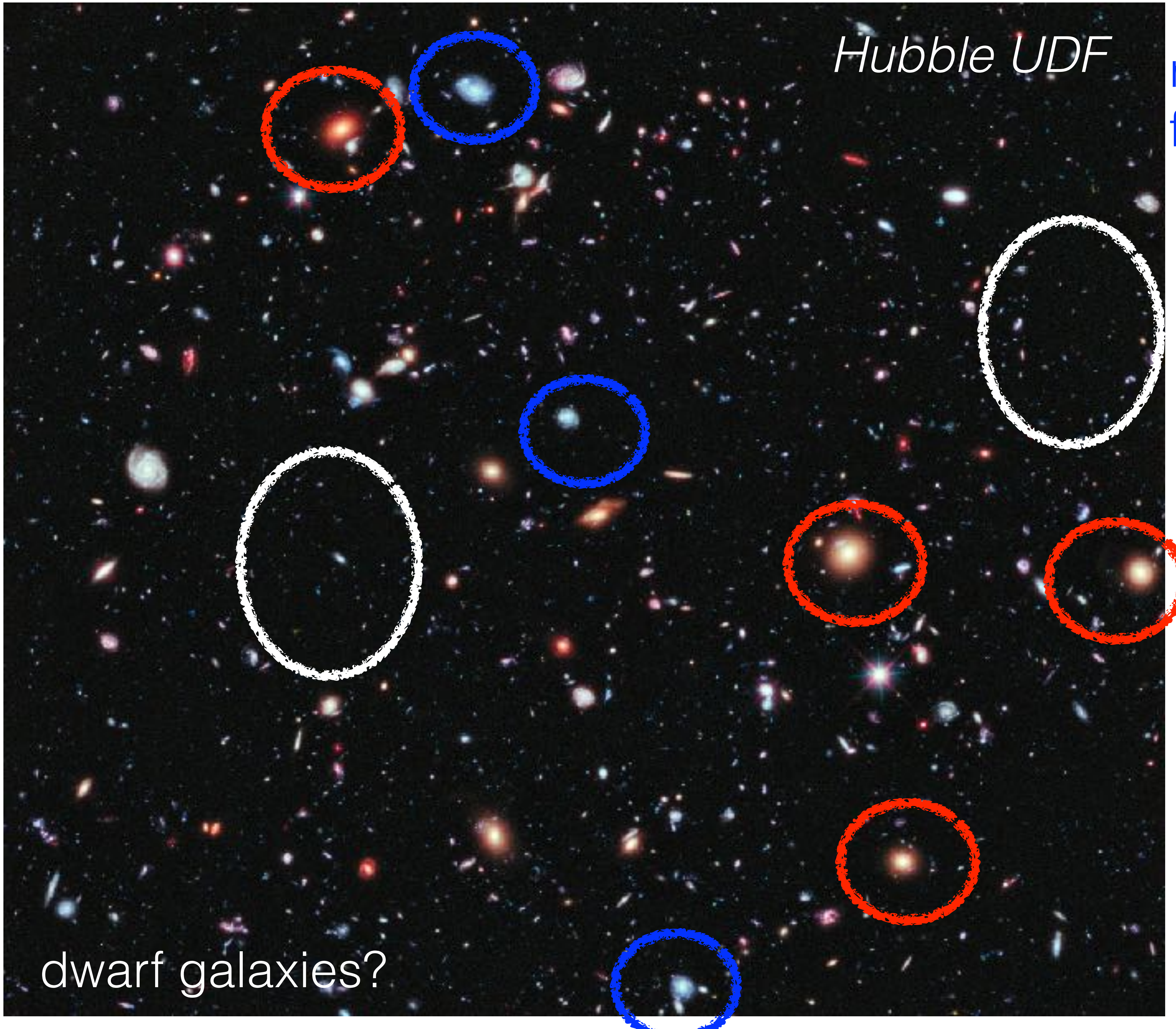
↓

low metallicity stars

Low-metallicity star formation: specific conditions

Questions Where ? galaxy type
When ? Epoch of star formation

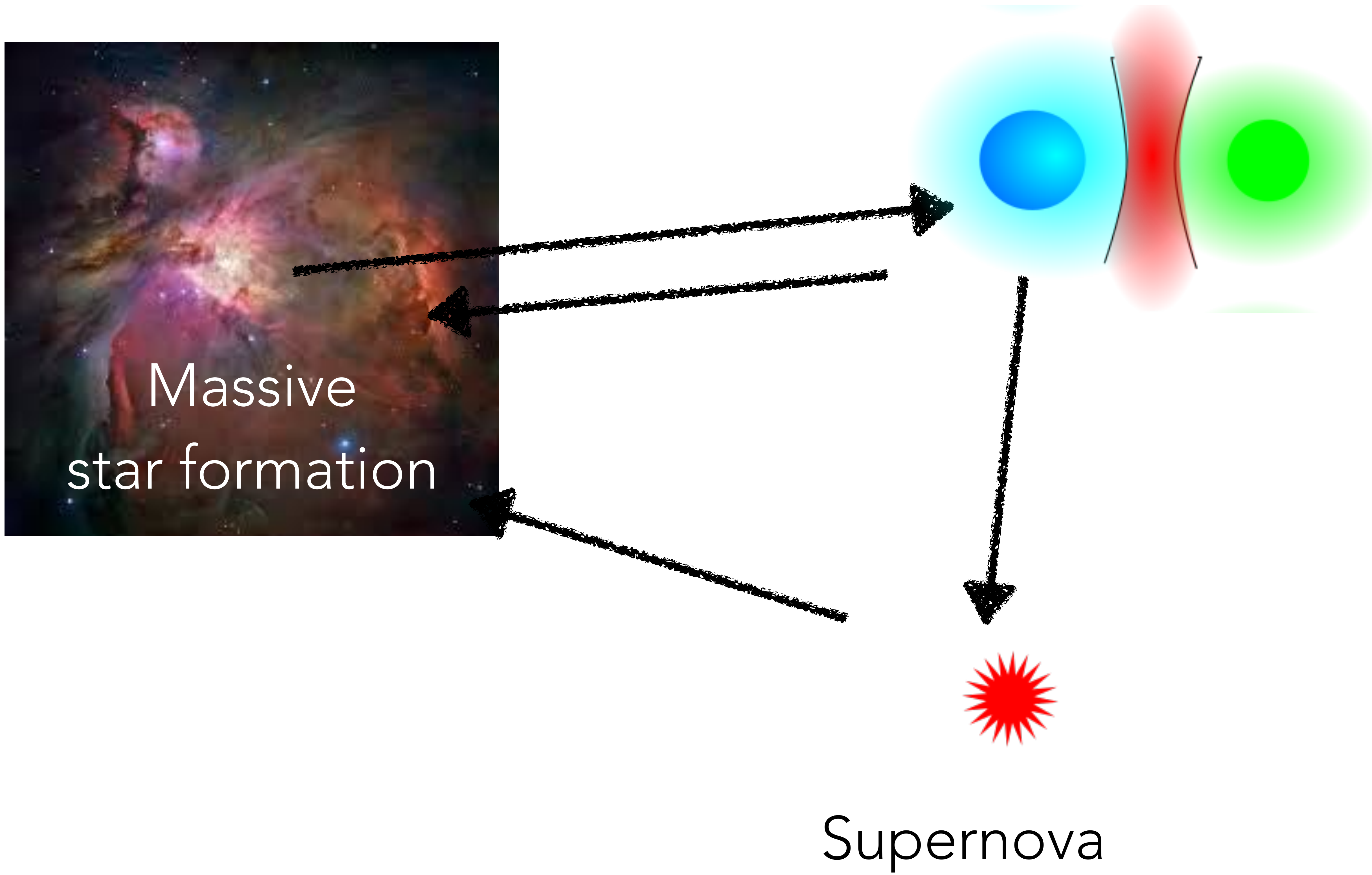
WHERE ARE THE LOW-METALLICITY STARS?



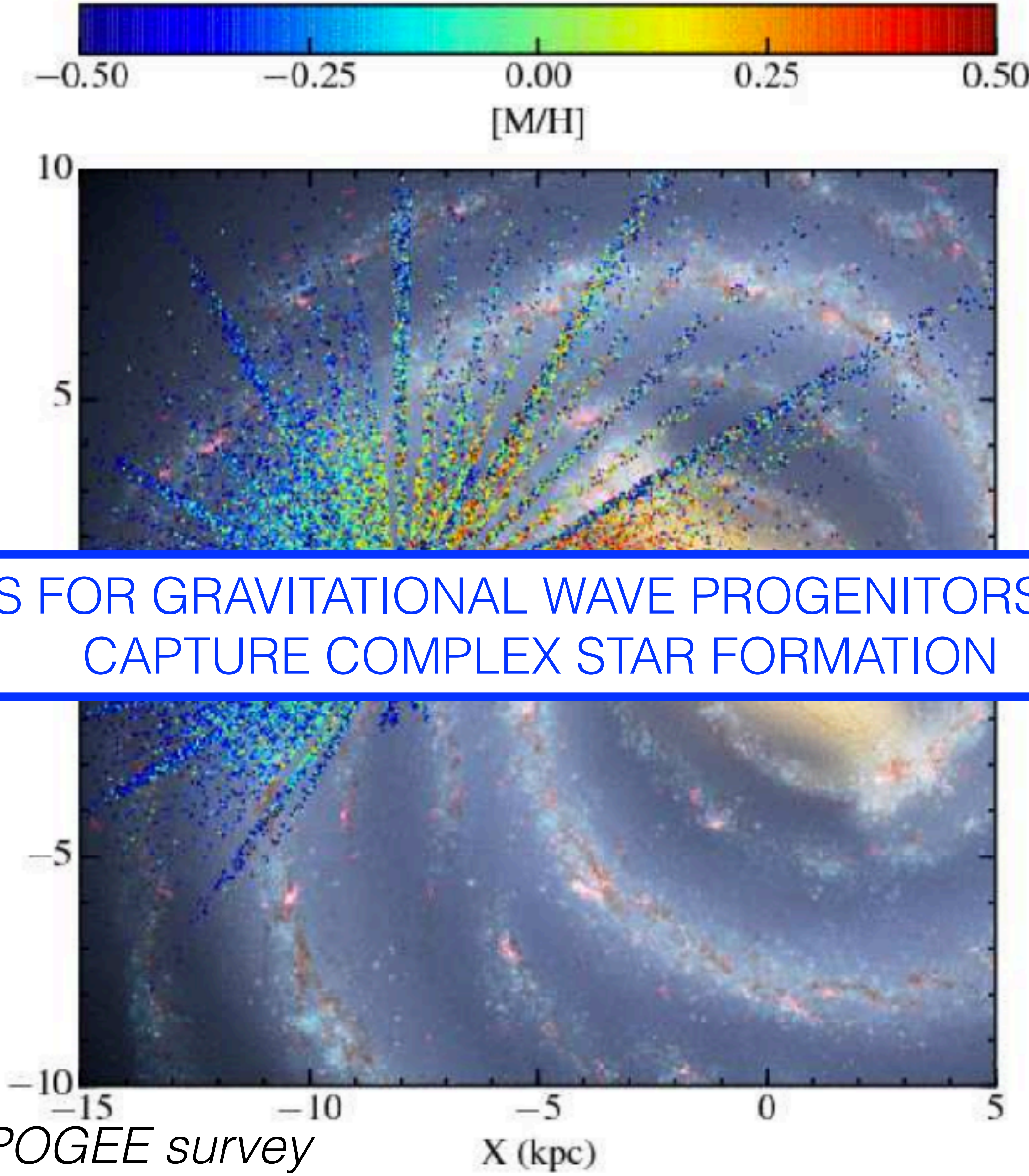
recent star formation?

older star formation?

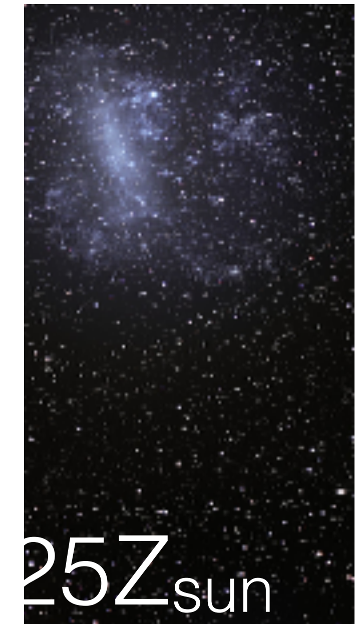
THE CYCLE OF GAS AND METALS



DIFF ... ALLICITY



APOGEE survey



ulum II :

00 stars

.01 Z_{sun}

MODELS FOR GRAVITATIONAL WAVE PROGENITORS SHOULD CAPTURE COMPLEX STAR FORMATION

NEW COMBINATION:
BINARY MODEL + GALAXY MODEL

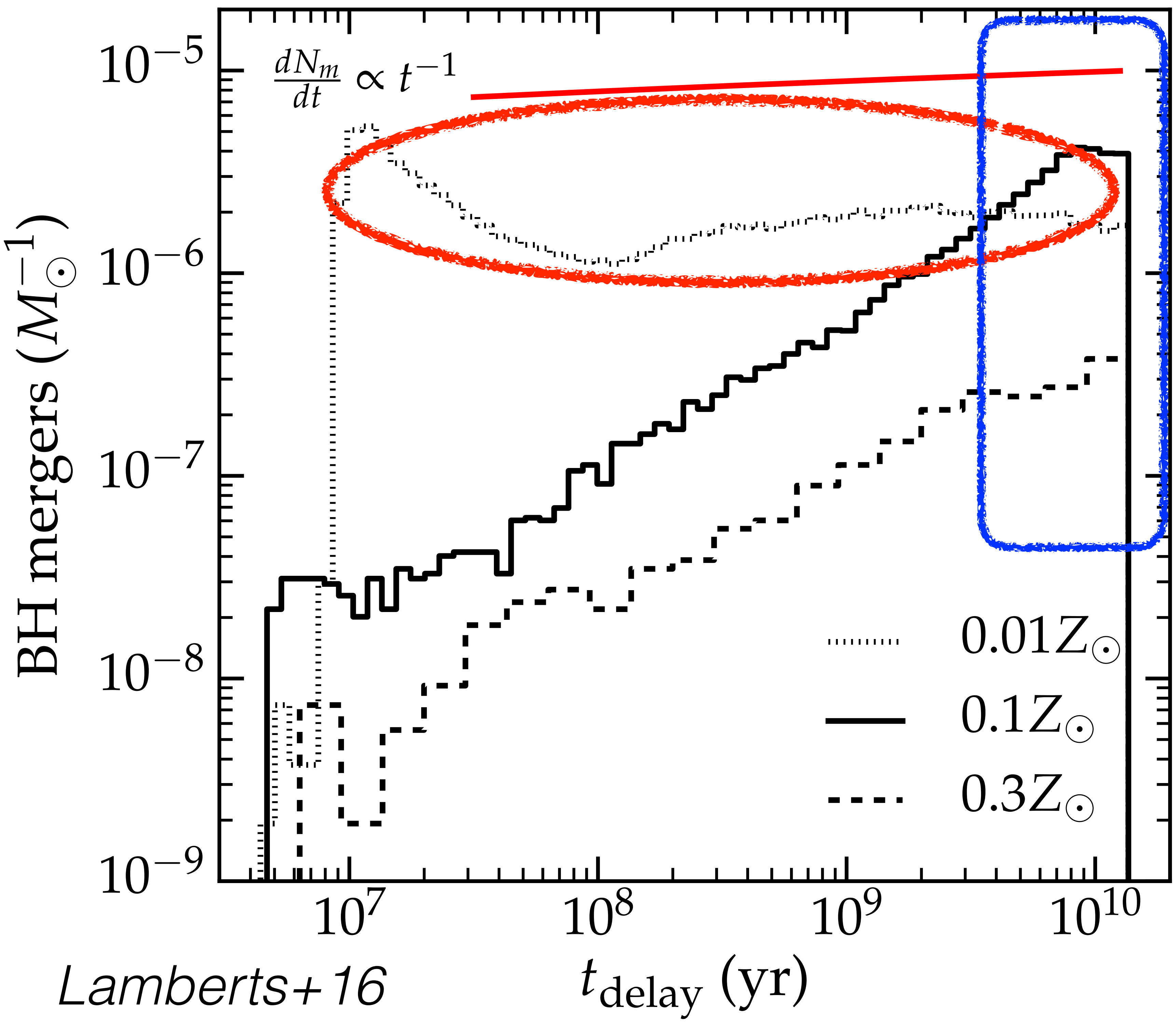
Ingredient: Semi-analytic model

star formation (metallicity, time, galaxy mass)

Ingredient: Binary population synthesis code (BSE, Hurley+2002)

- Complete distribution of periods and eccentricity
- current model of binary evolution
- Explore metallicity from 1% of Solar to Solar
- Make database of final binary black holes

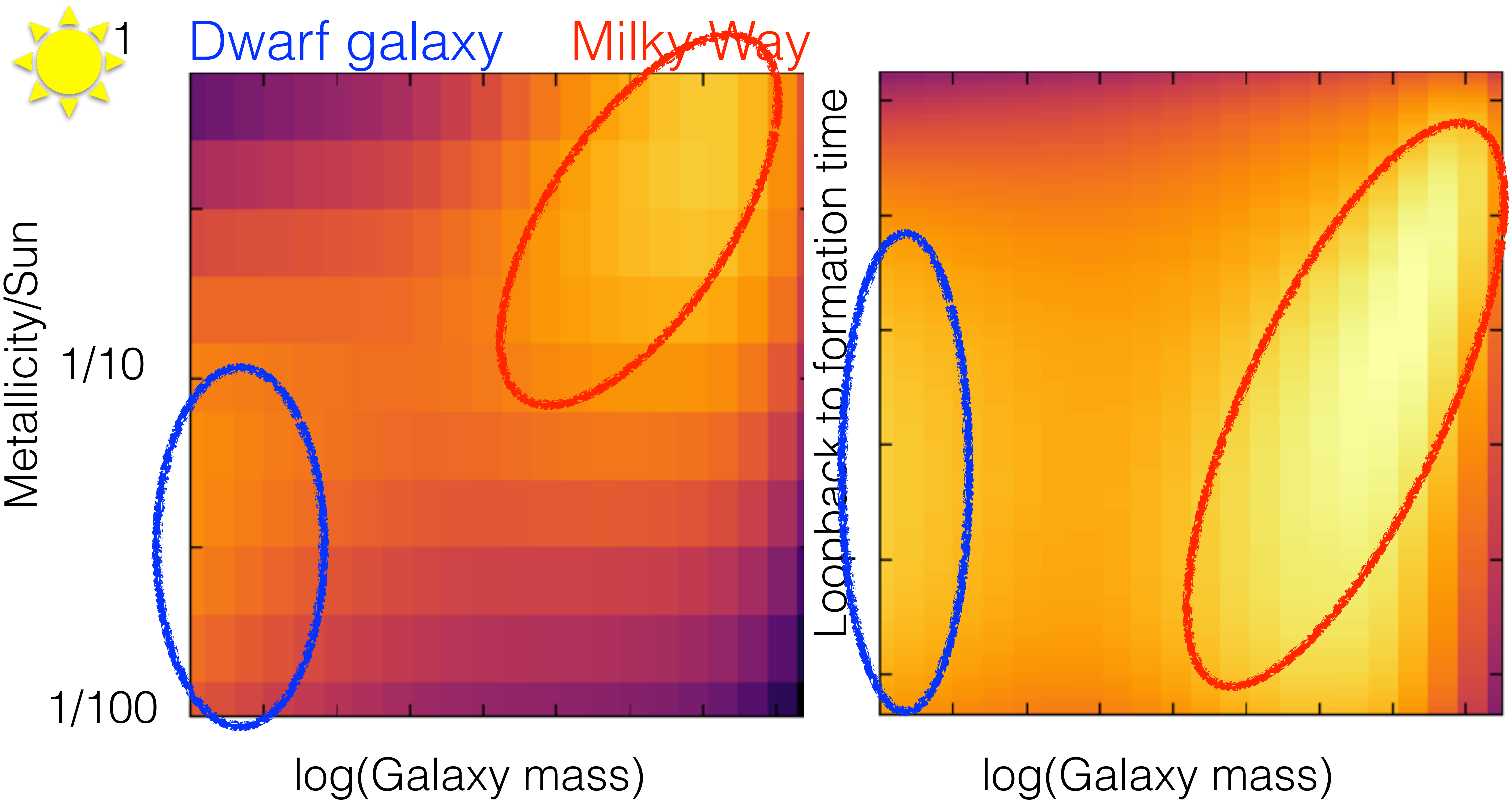
INGREDIENT : LONG DELAYS TO MERGERS



Lamberts+16

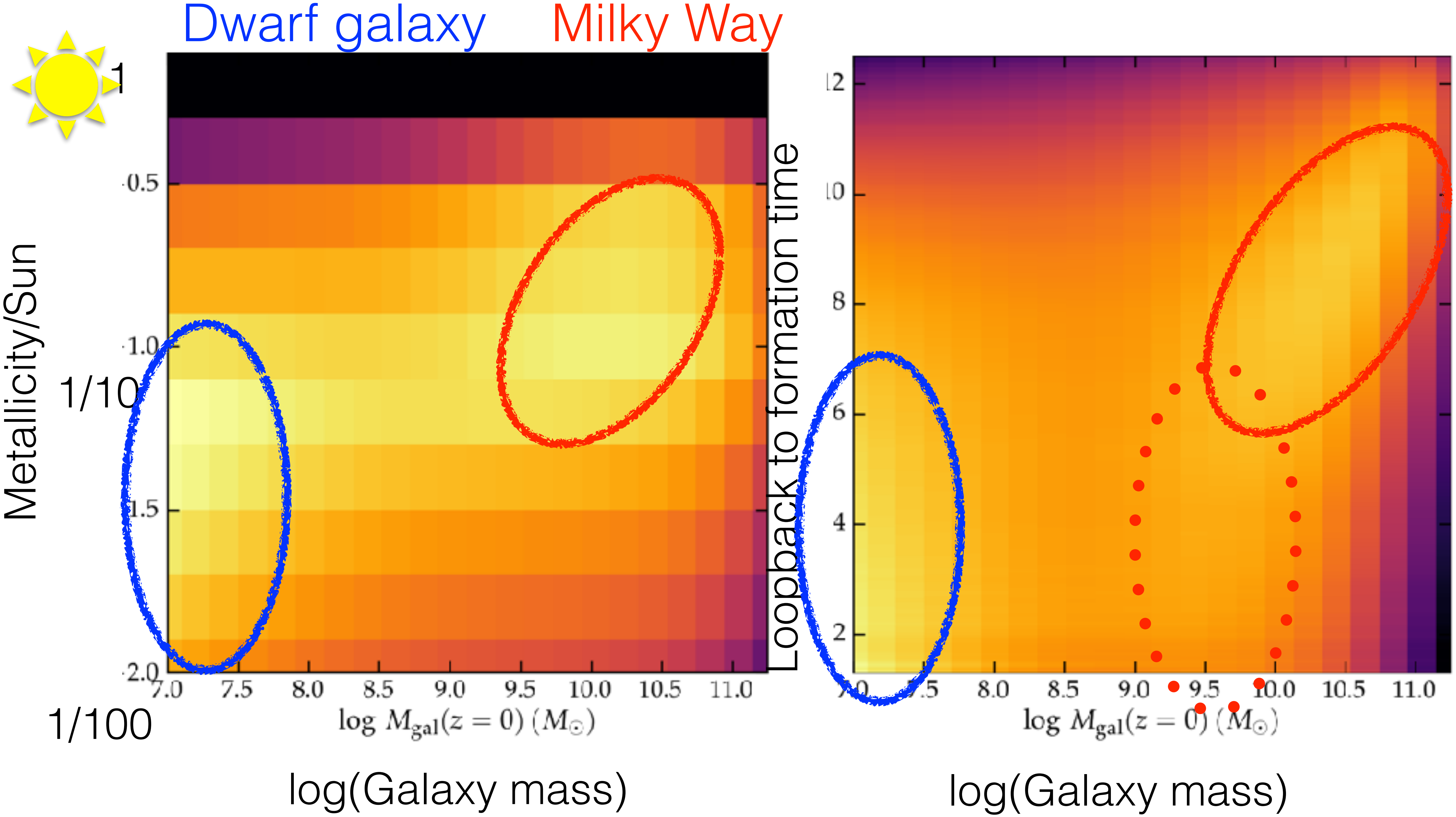
- Low metallicity: most massive remnants
- higher metallicity : long delay

INGREDIENT: LOW METALLICITY STAR FORMATION



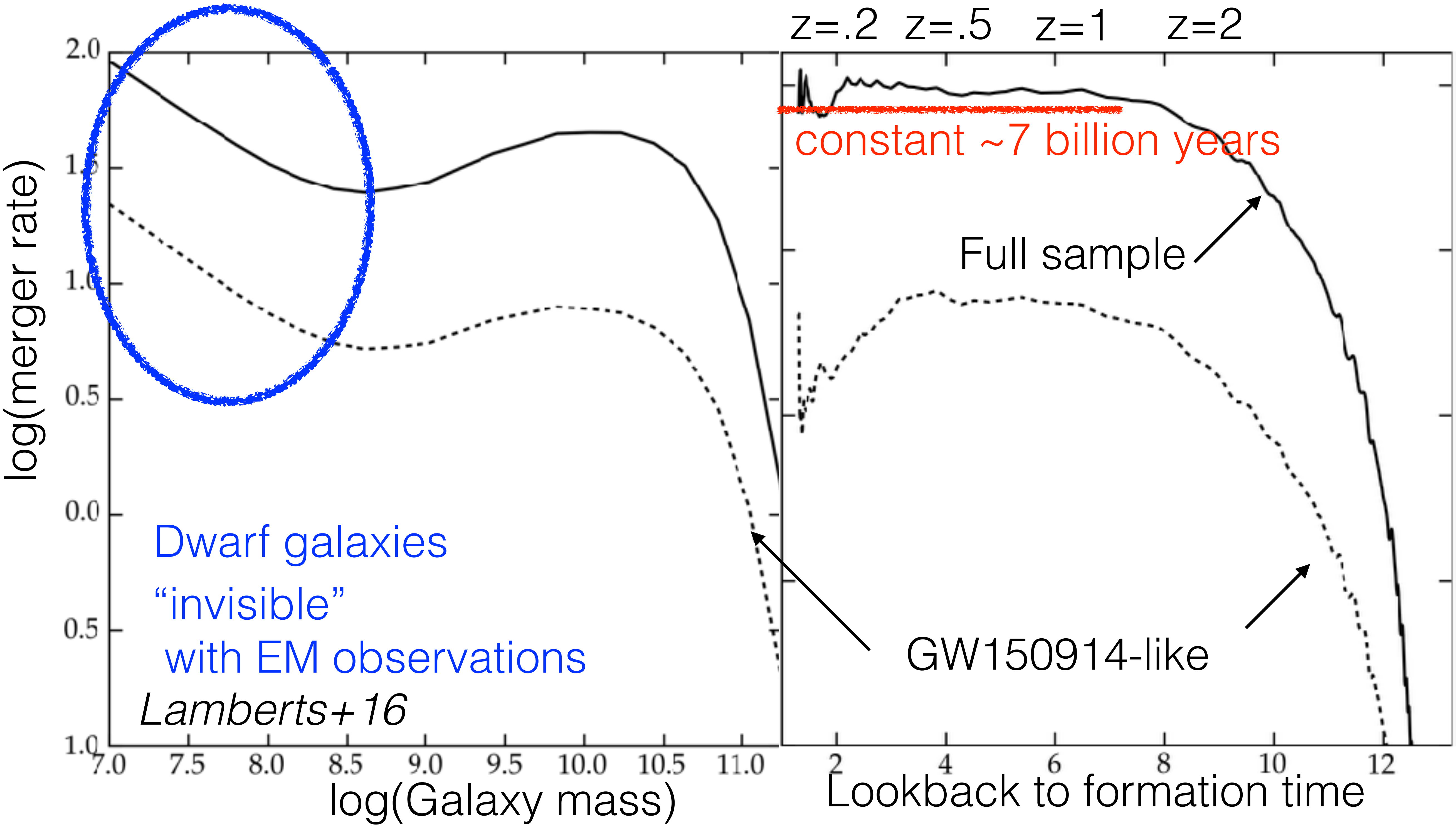
Lamberts+16

BIMODAL FORMATION OF MASSIVE BLACK HOLE PROGENITORS



Lamberts+16, data public, confirmed in Elbert+17, Mapelli+17

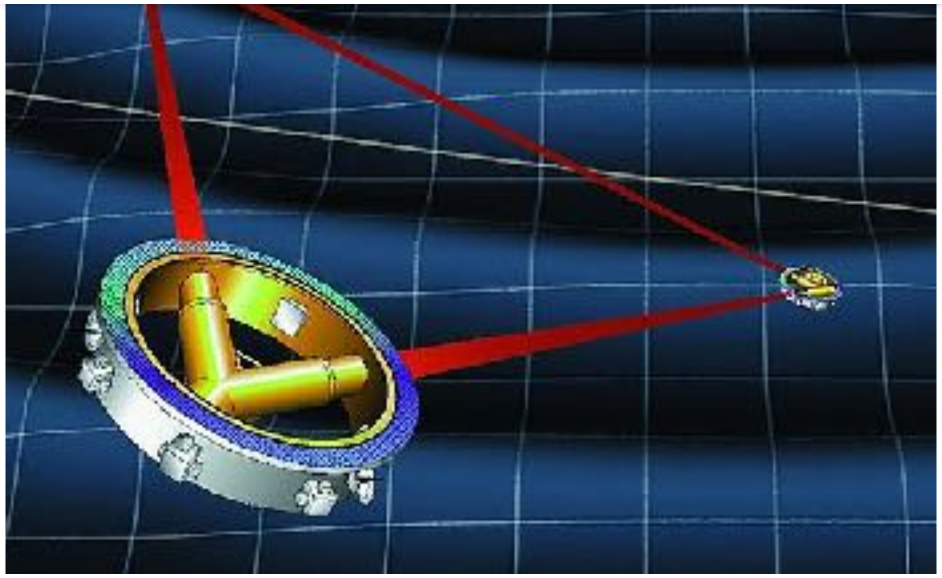
STAR FORMATION IN DWARF GALAXIES



Result: Complex star formation impact prediction/interpretation of GW

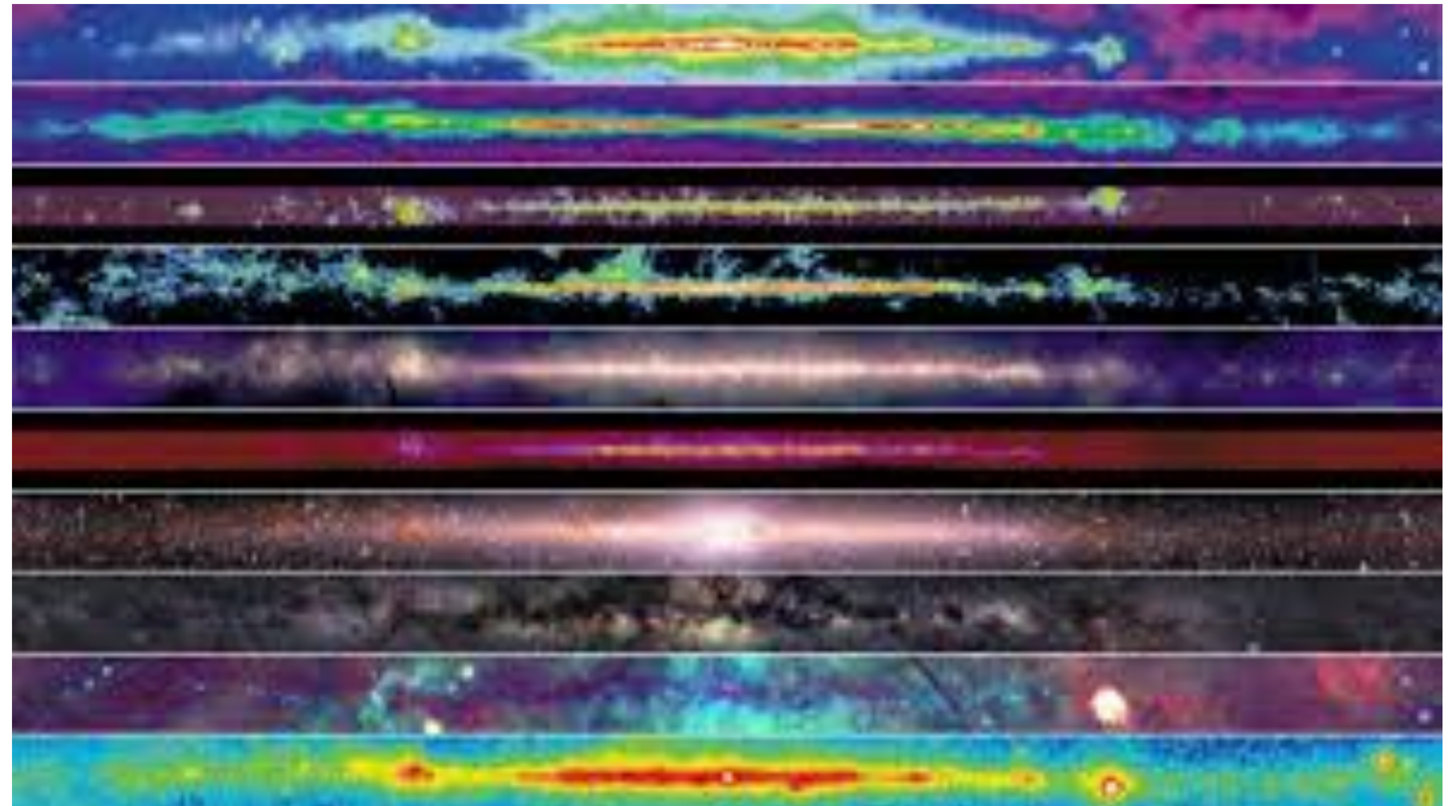
BINARIES IN THE MILKY WAY WITH LISA

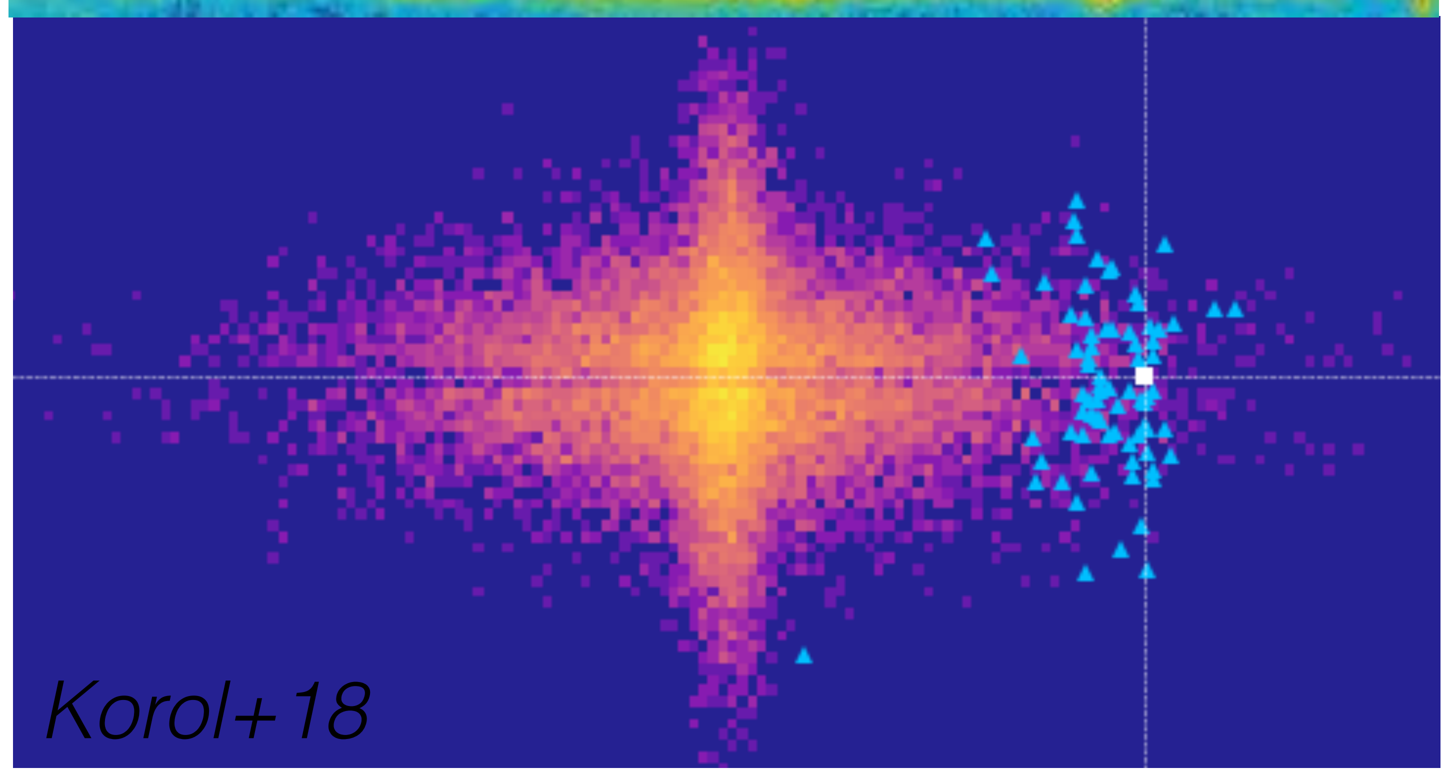
~2030 : LISA



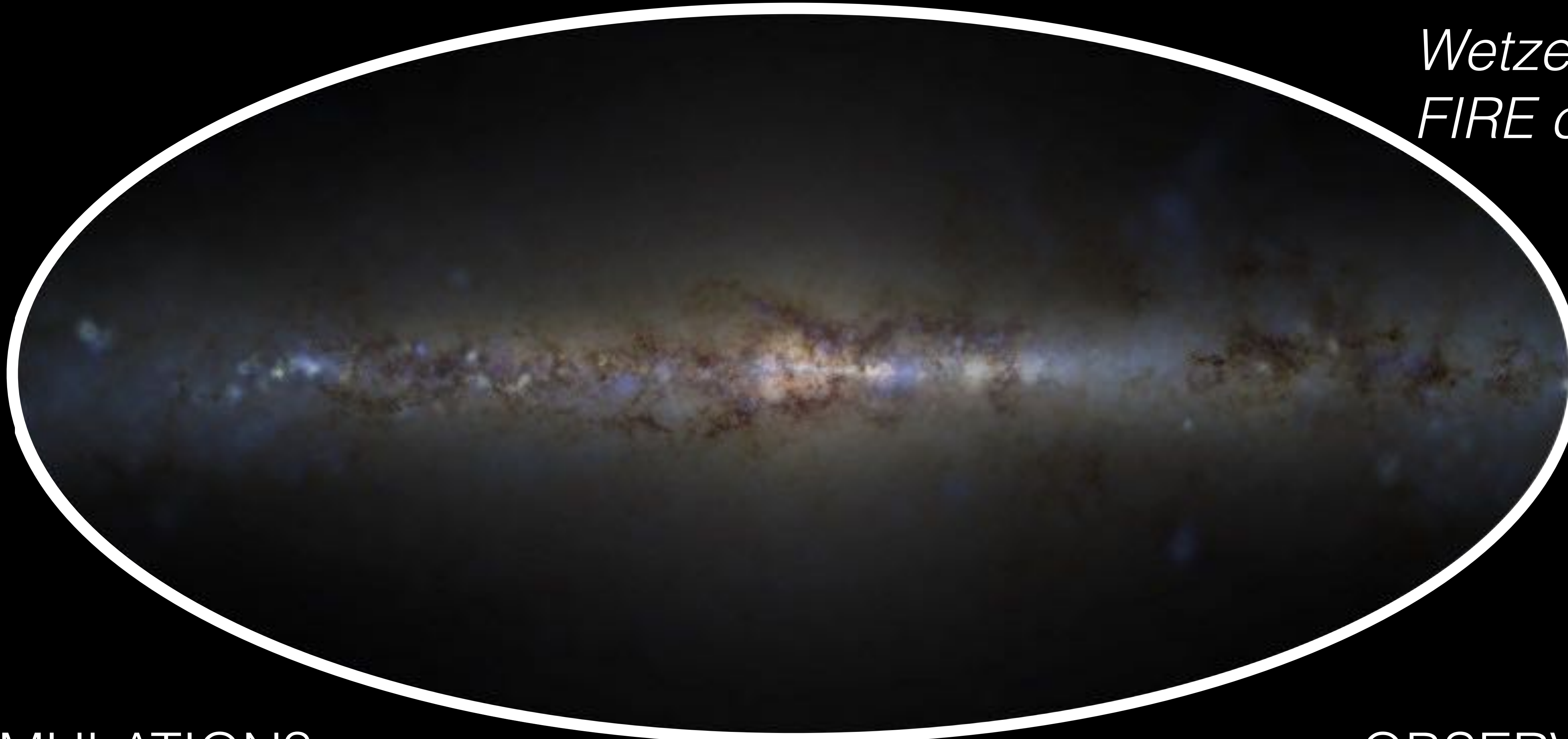
Detection of mHz waves

Need for realistic models of the Milky Way





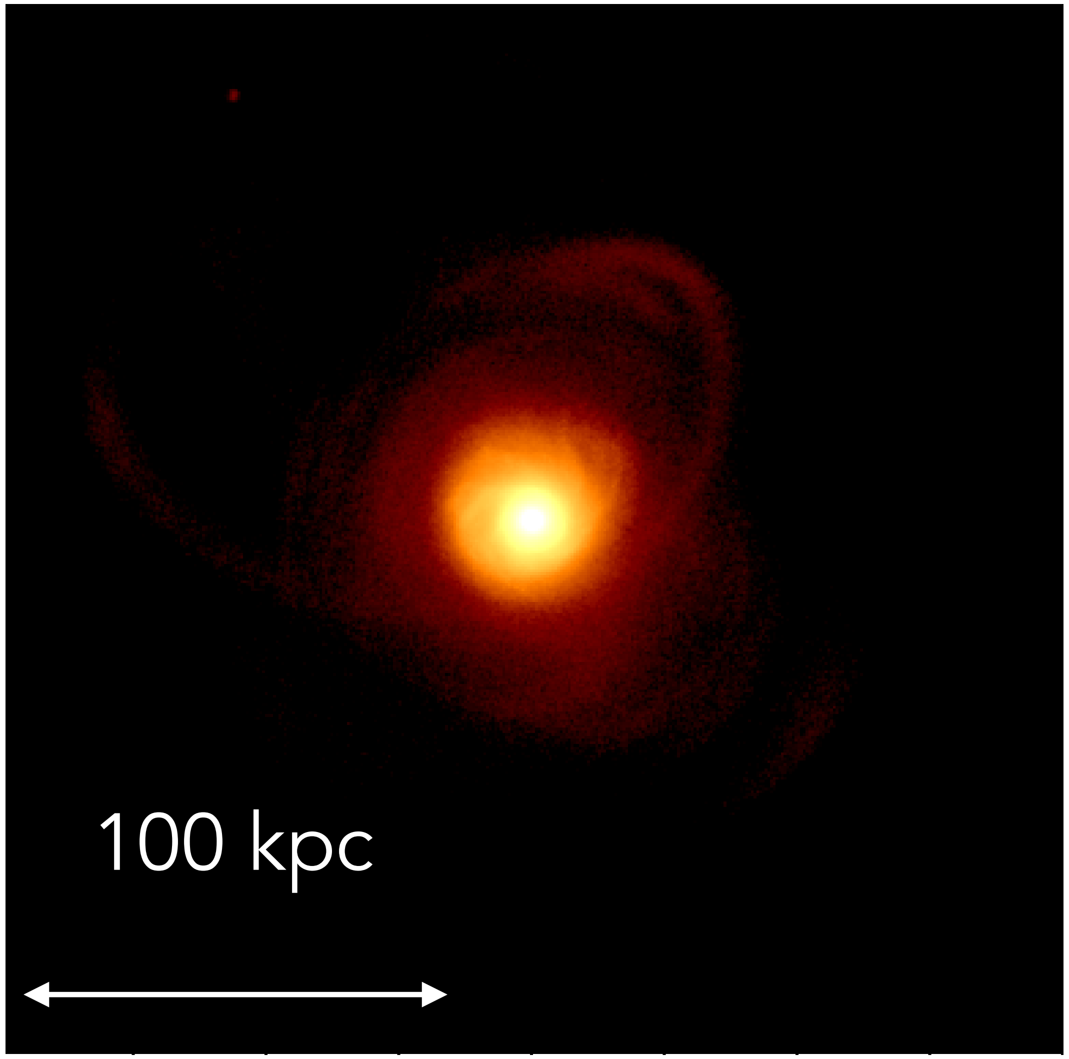
Wetzel+16
FIRE collab.



SIMULATION? OBSERVATION?

Gaia DR2

IMPACT OF COMPLEX STAR FORMATION

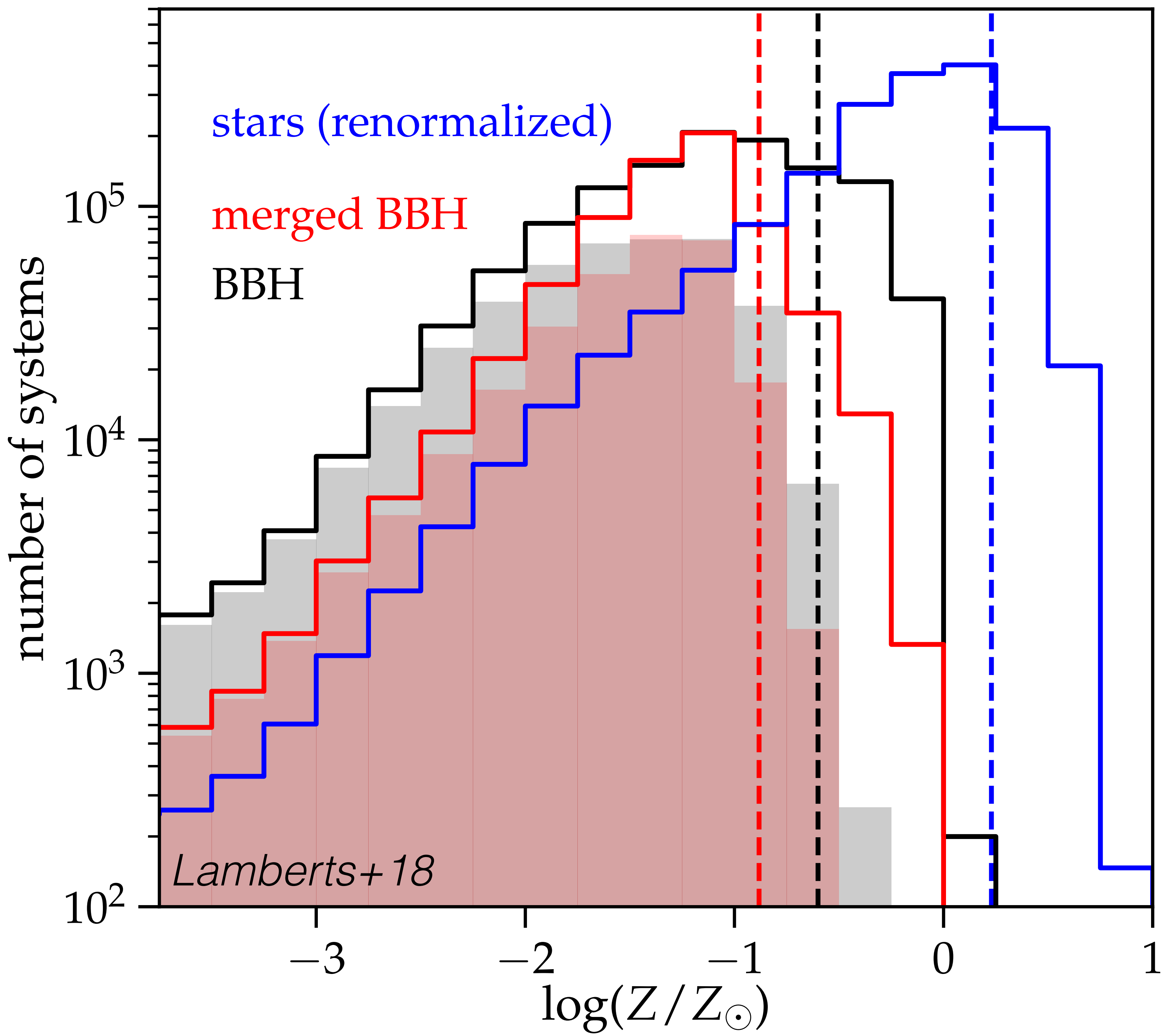


$>10^{10}$ stars

1 million binary black holes

Low metallicity : Binary black holes prefer outer galaxy and satellites

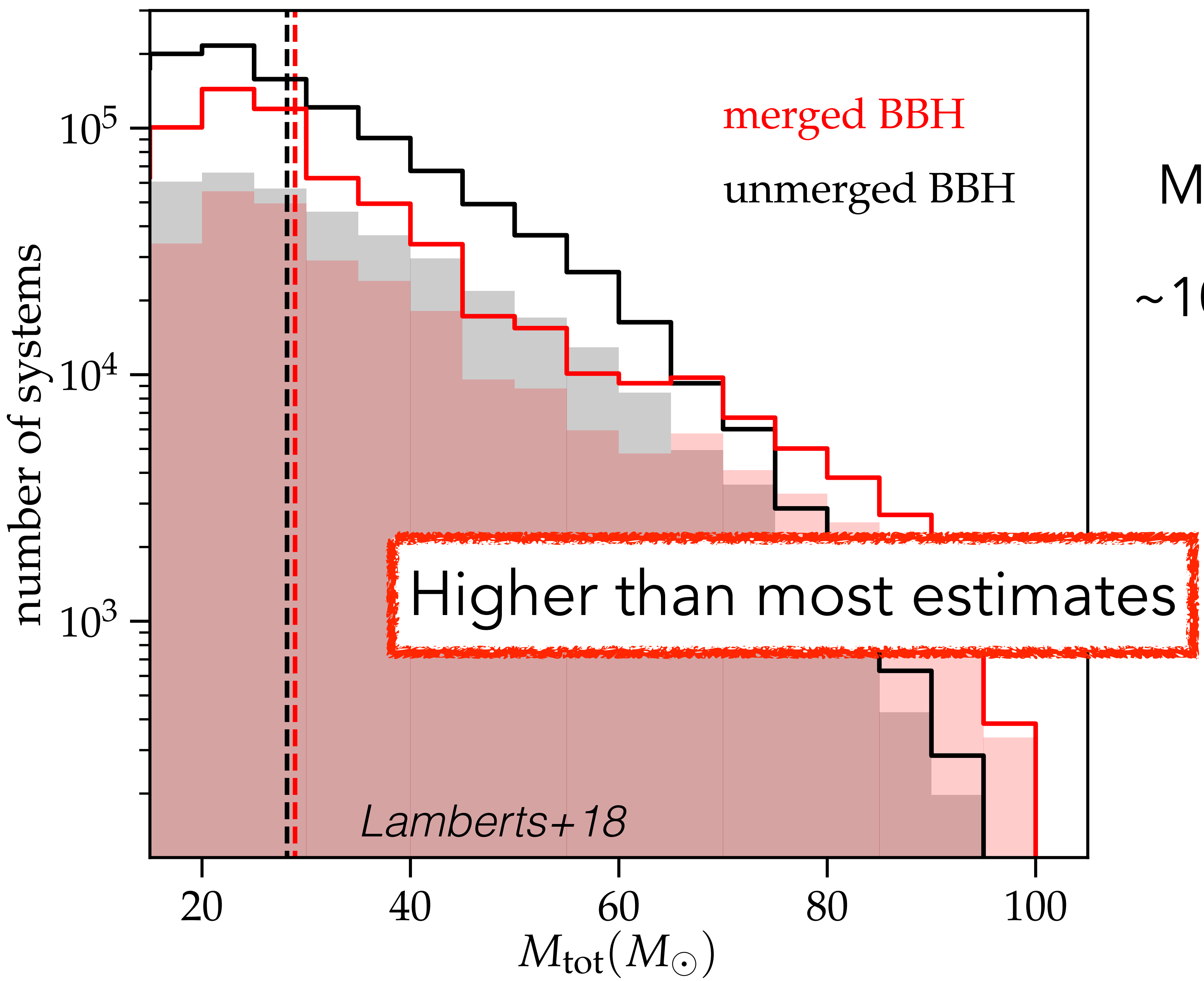
IMPACT OF SATELLITE GALAXIES



Mean metallicity
~ 20% of Sun

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

A MILLION BINARY BLACK HOLES IN THE MILKY WAY

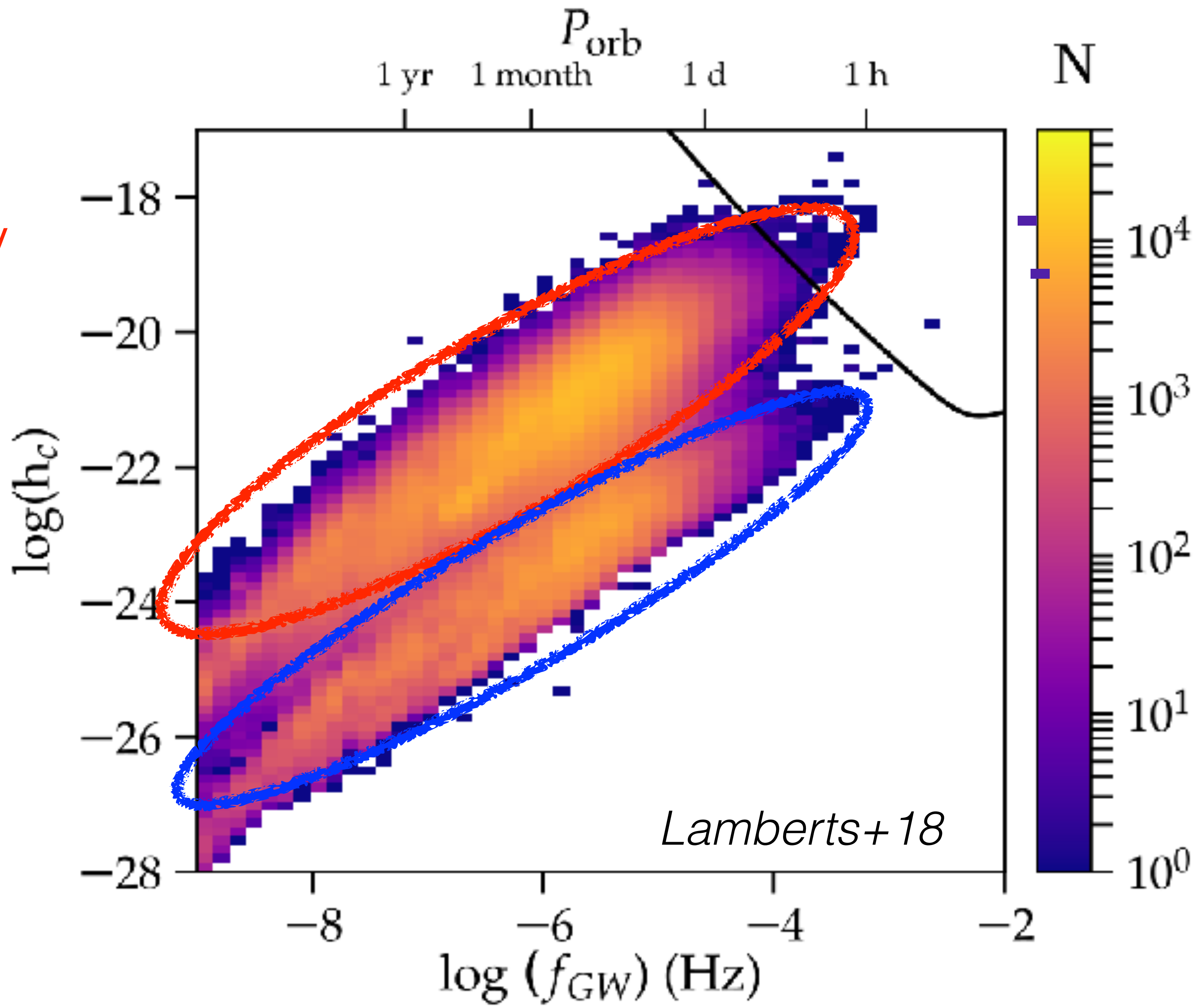


Mean total mass 28 M_{sun}

~10% of systems >50 M_{sun}

DETECTING BINARY BLACK HOLES IN THE MILKY WAY

Milky Way



Satellites

Result: Binary black holes are on the outside of the Galaxy, and hard to detect

STELLAR BINARIES WITH GRAVITATIONAL WAVES

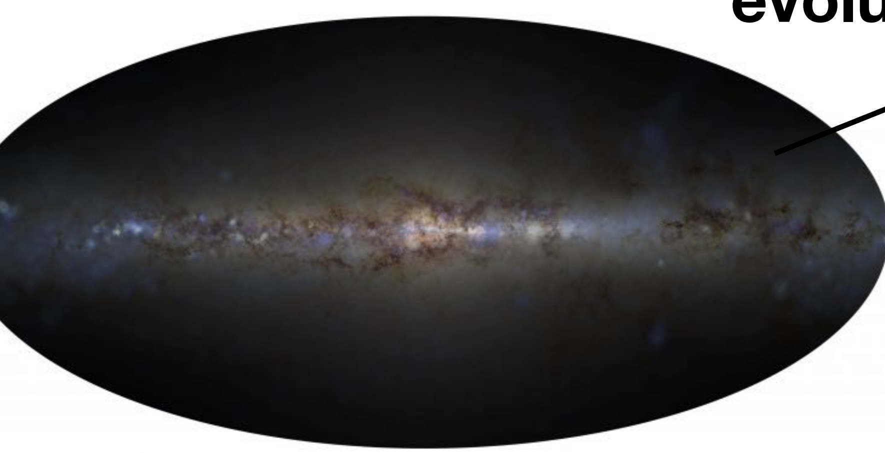
2019 : Virgo/LIGO O3

1 -10 multimessenger events

50-100 binary black holes: statistics

Detection of astrophysical background

Origin of mergers? Binaries or clusters?



binary/stellar evolution

Mergers In binaries

Molecular cloud properties (with C. Rodrigez, M. Grudic)

Cluster mass Profile

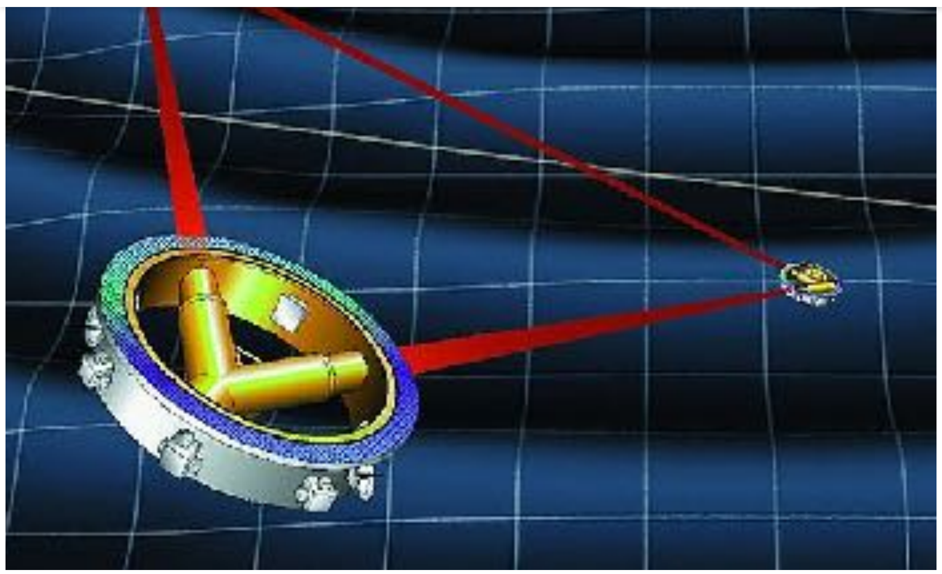
binary/stellar evolution

Mergers In clusters

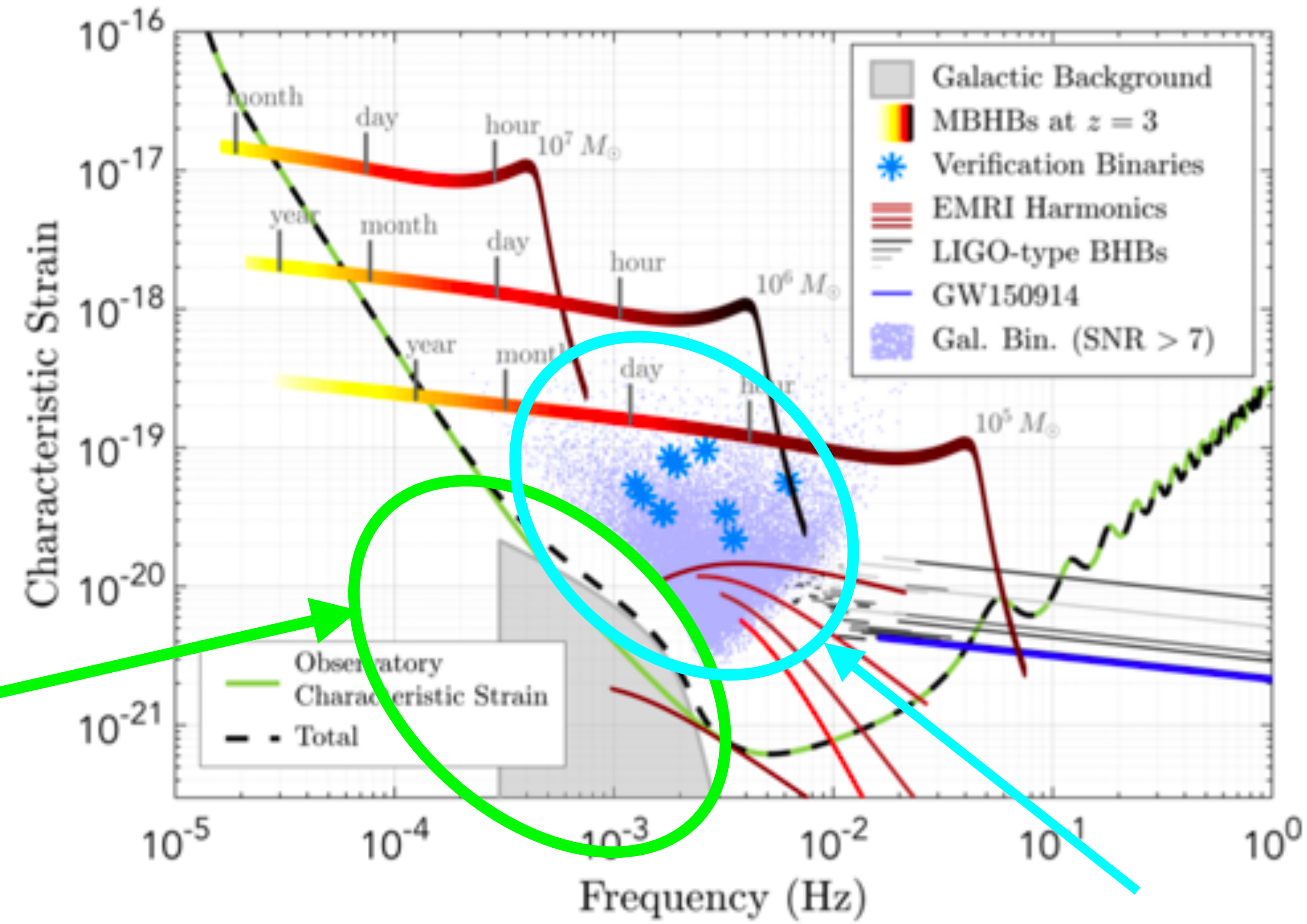
First consistent Joint prediction

STELLAR BINARIES WITH GRAVITATIONAL WAVES

~2030 : LISA



Detection of mHz waves



Unresolved sources:
Confusion noise

White Dwarf binaries

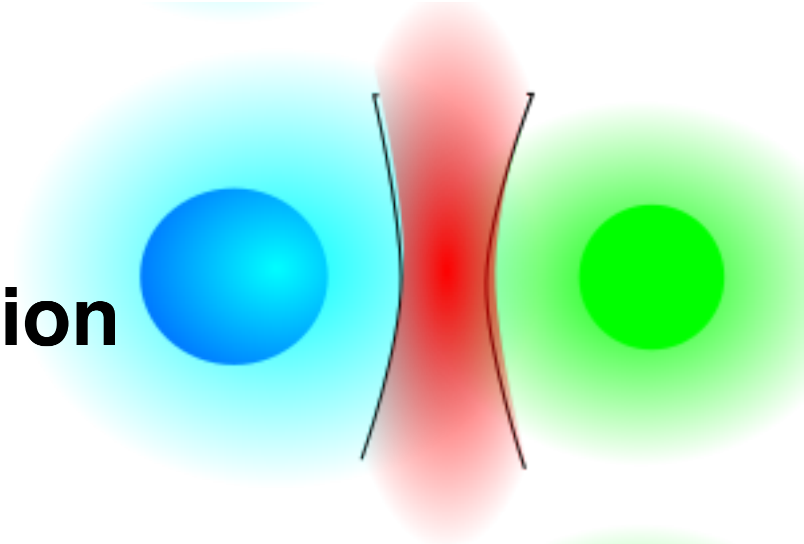
Blunt, ***Lamberts+*** *in prep:* 1st predictions based on cosmological model of Milky Way

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

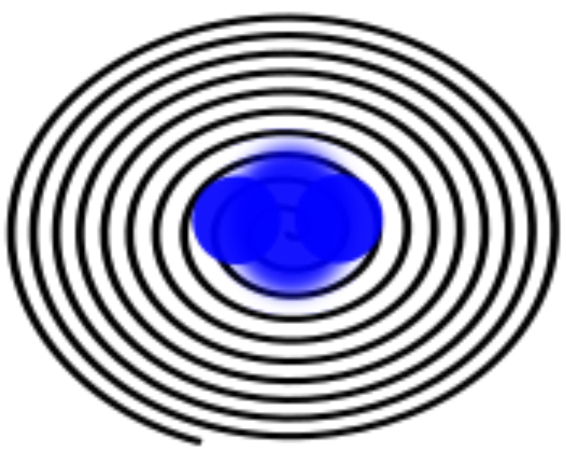


Shock interactions produce X-ray flares in GRB

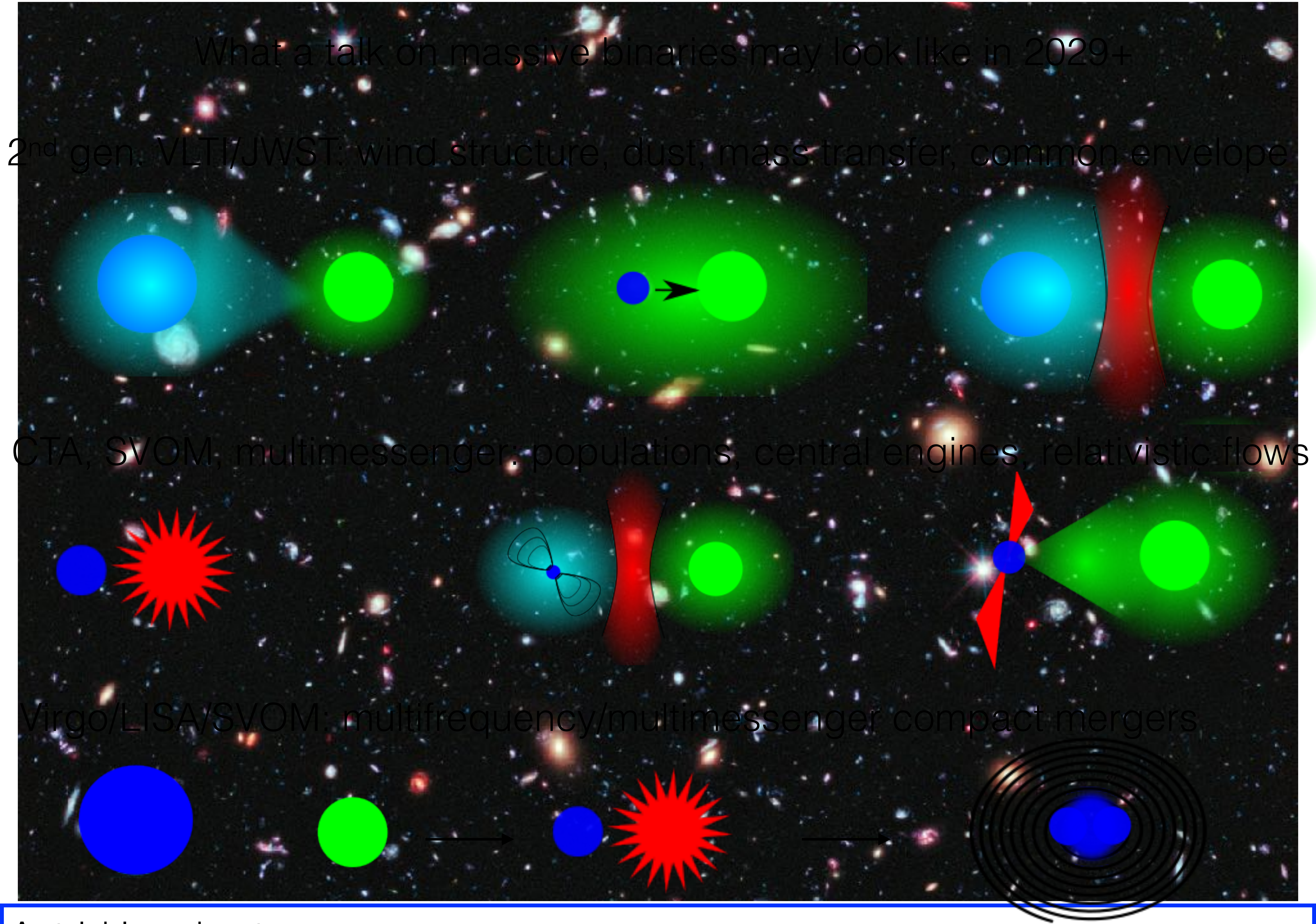
Understand structure of relativistic flows

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

GW : formation/evolution of massive binaries



Astrid Lamberts



Astrid Lamberts