SIGNATURES OF MASSIVE BINARIES

FROM COLLIDING WINDS TO ZOMBIE BLACK HOLES

Astrid Lamberts

Caltech

OCA, Nice, March 14, 2017

MASSIVE STARS: RARE BUT MIGHTY

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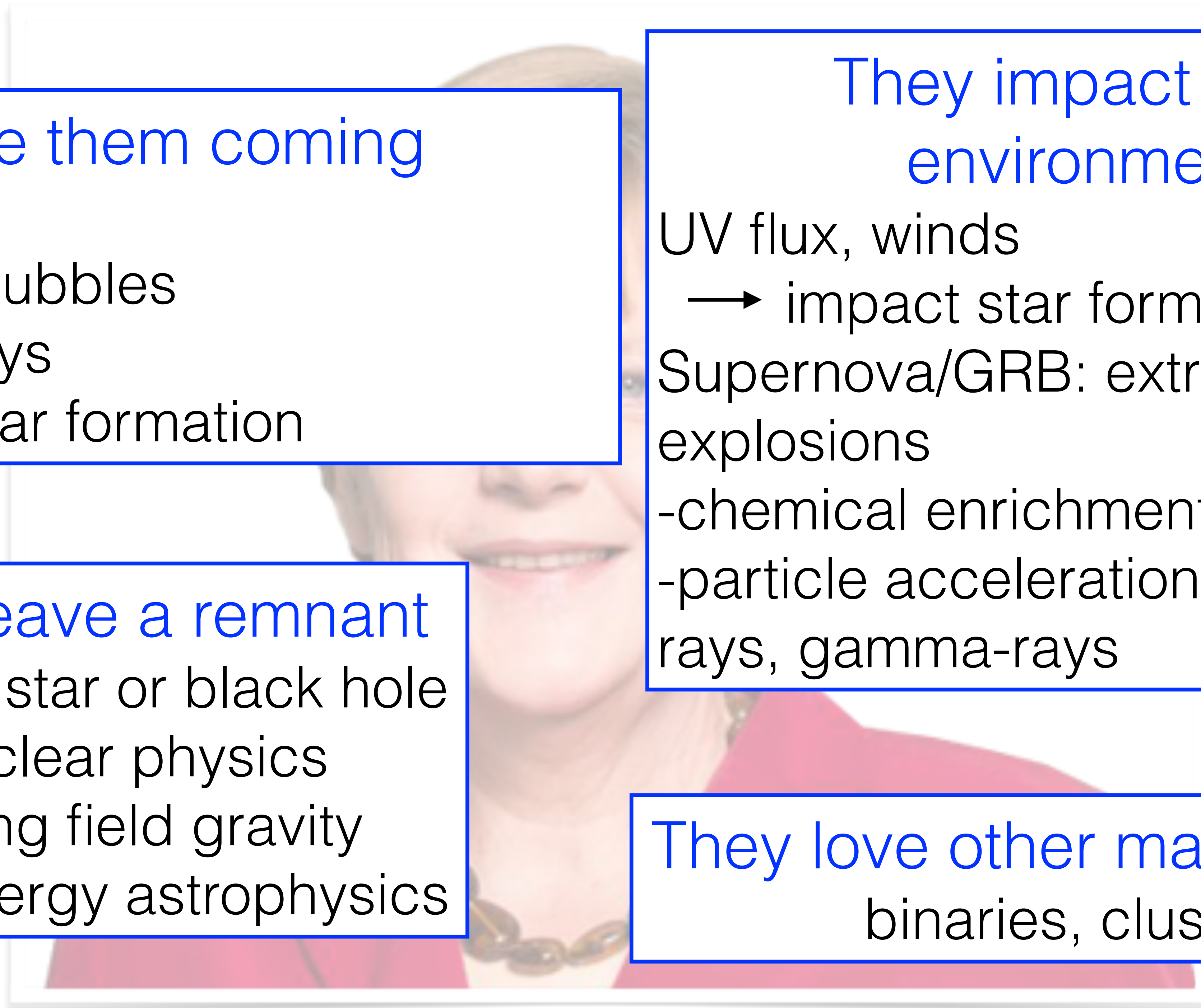


We see them coming

-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
-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 isn't smooth

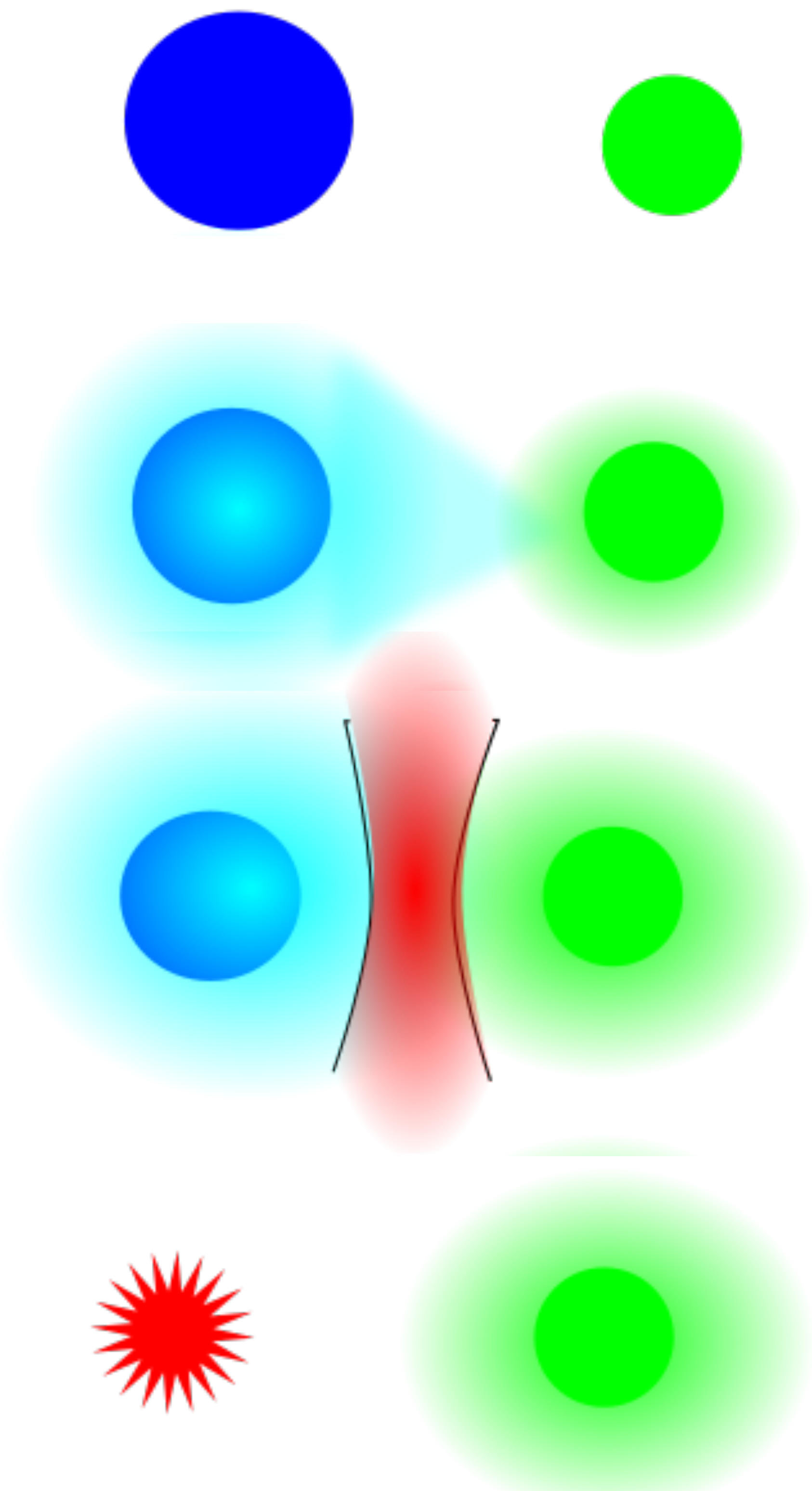
And there's a lot we don't know

(ALMOST) ALL MASSIVE STARS INTERACT

- Often ignored, poorly understood
  stellar evolution, galaxy formation/evolution
- More signatures than single stars
  Masses, radii, mass loss, compact object
- Extreme physics labs
  particle acceleration, shocks, relativistic outflows, strong gravity….

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***+*11,12,17a*)

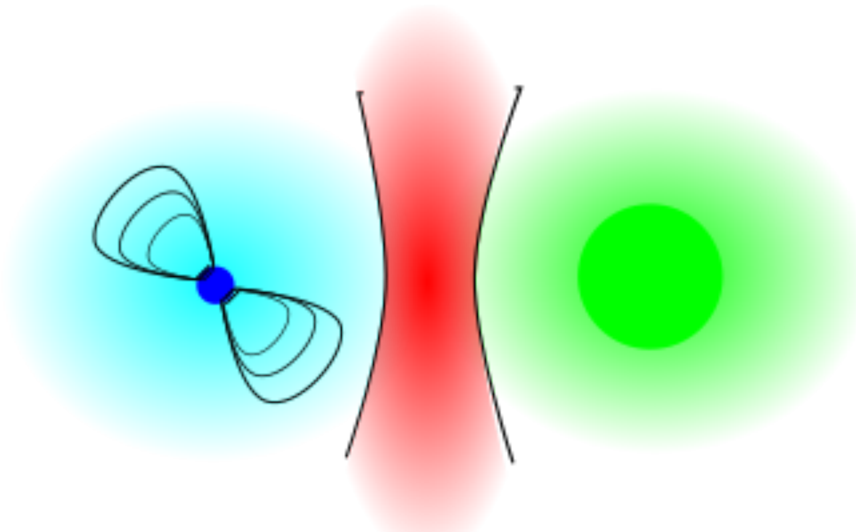
collapse 1: supernova/gamma-ray burst

Time domain astronomy: gamma-rays to radio

Gravitational waves/neutrinos

(***Lamberts***, *Daigne, 2017b*)

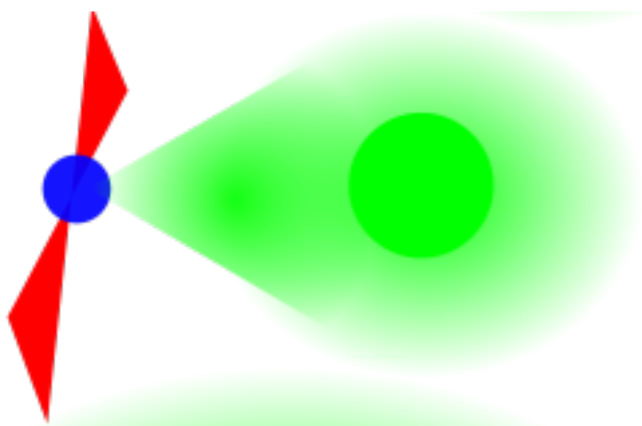
1 COMPACT OBJECT : HIGH ENERGY ASTROPHYSICS



if neutron star : gamma-ray binary

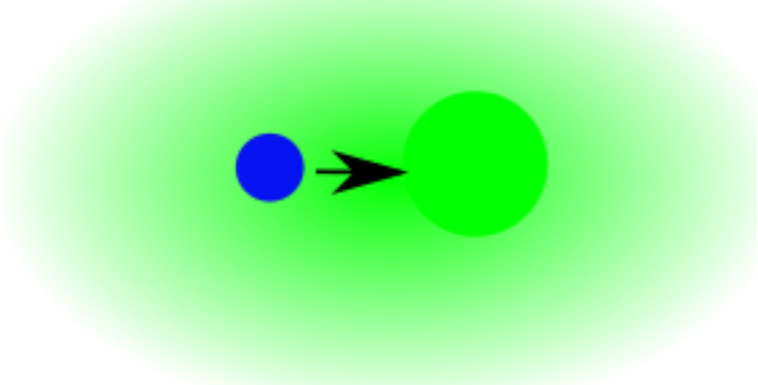
from radio to TeV gamma rays

*(**Lamberts**+13, Dubus, **Lamberts**+15)*



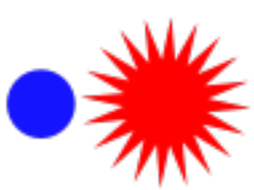
High-mass X-ray binary

X-rays, radio



Common envelope phase

faint transient

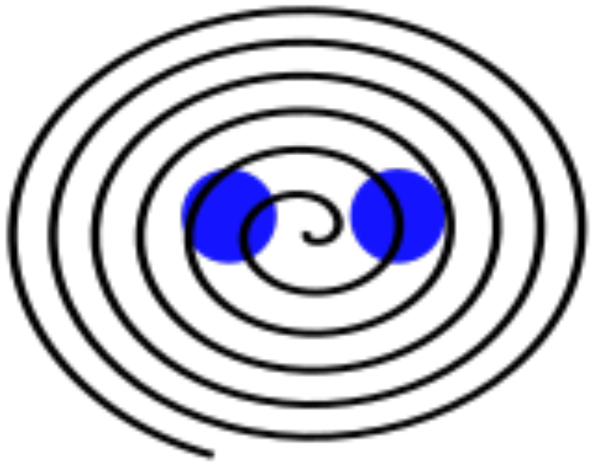


Collapse 2: supernova/gamma-ray burst

*(**Lamberts**, Daigne, 2017b)*

Time domain, multi-messenger astronomy

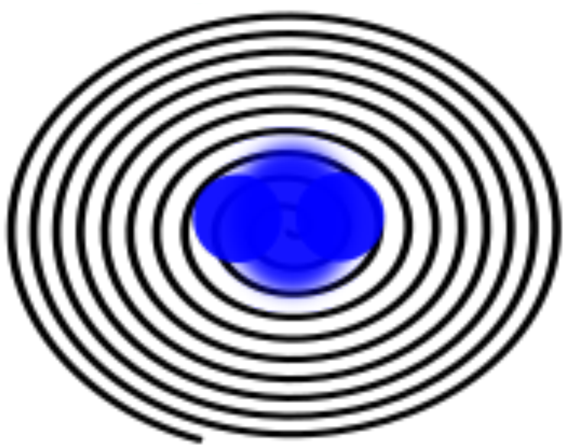
2 COMPACT OBJECTS :
GRAVITATIONAL WAVE ASTRONOMY



Billion years of inspiral

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

(***Lamberts***+*2016*)



Merger

Higher frequency GW
possible GRB, kilonova, neutrinos, other?

60 M_{sun} black hole

Game over

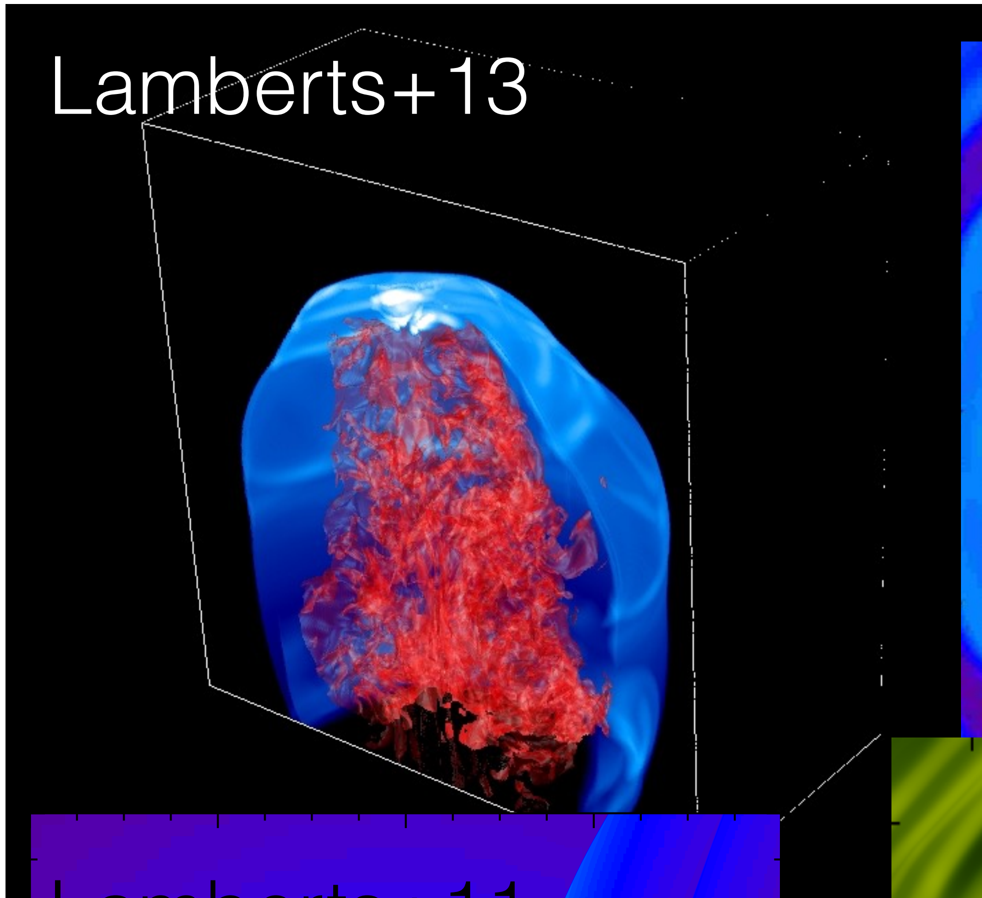
CONNECTING THE DOTS

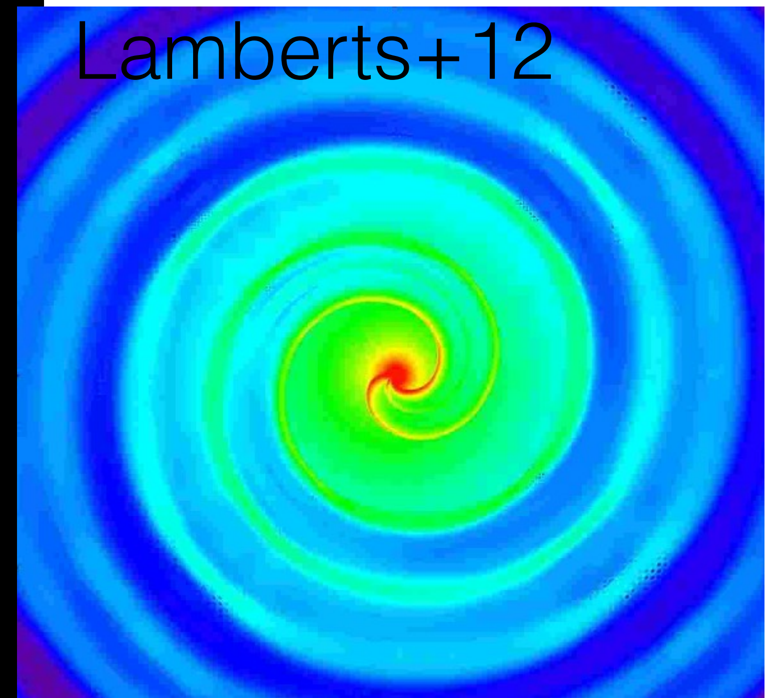
Understand dynamics, emission mechanisms of massive binaries
Individually and globally

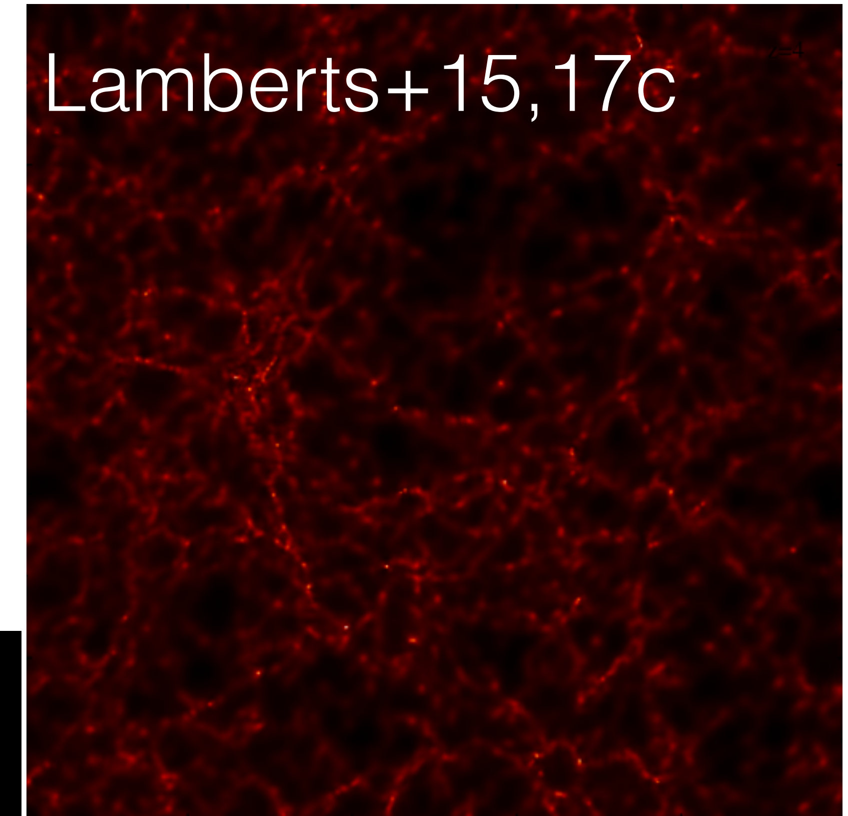
Study stellar astrophysics, high-energy astrophysics and gravitational wave astronomy

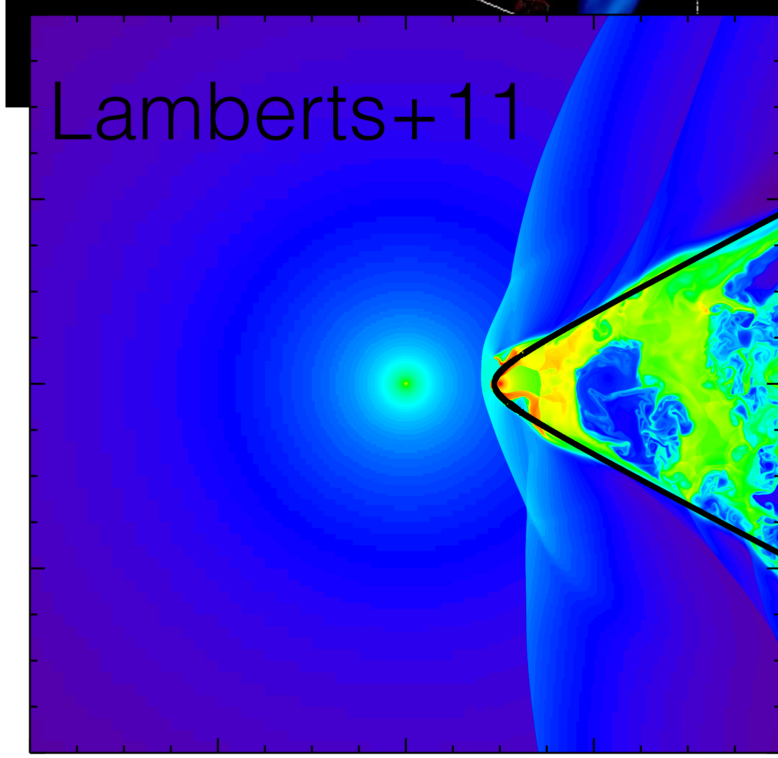
Combine high resolution hydrodynamic simulations, emission models, analytic estimates with observations

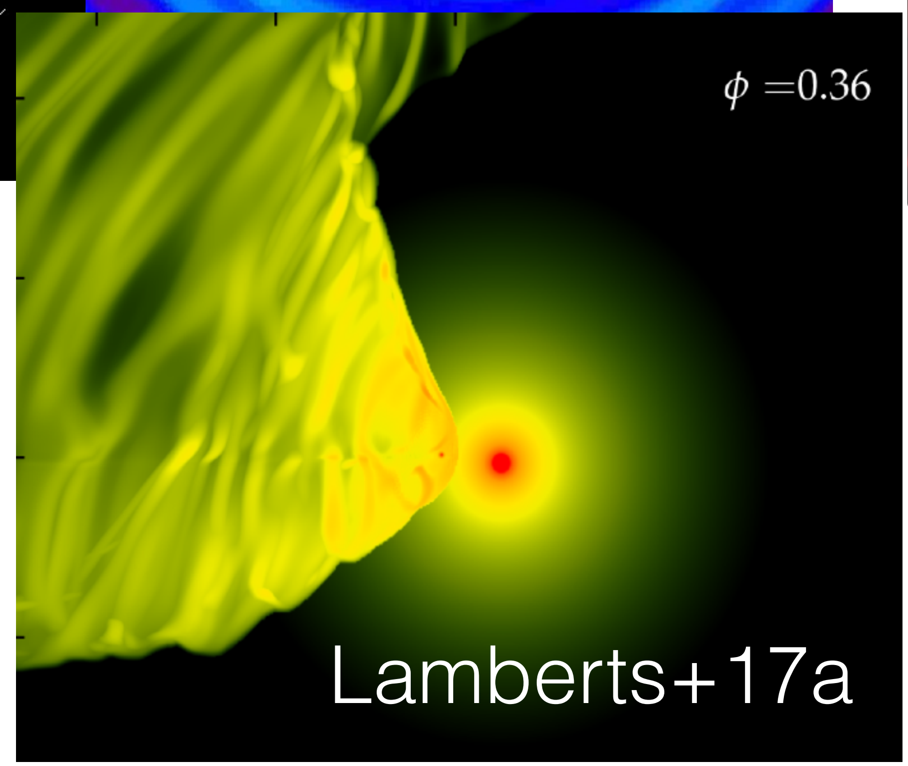
NUMERICAL DEVELOPMENTS







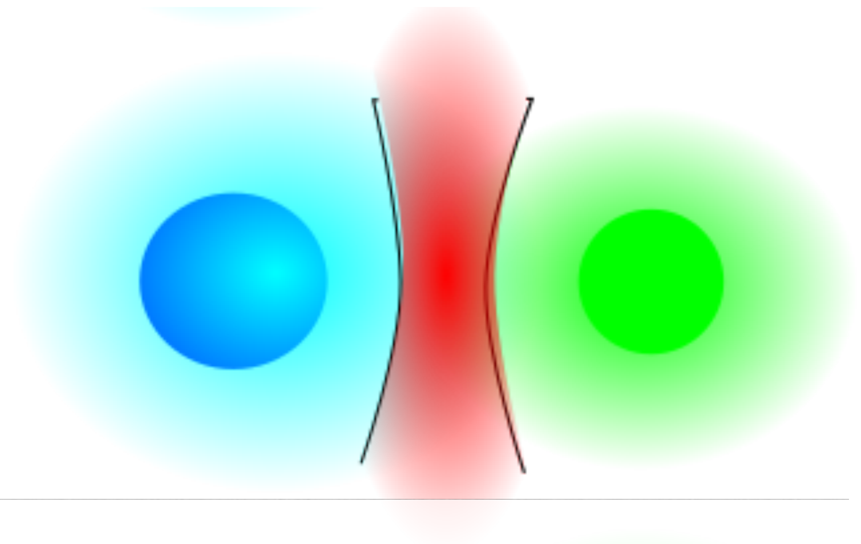




~3.5 million hours
~400 years
RAMSES, GADGET
Special relativity

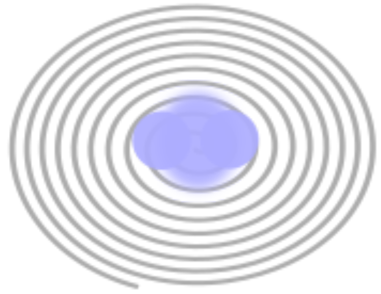
CONNECTING THE DOTS

1. Colliding stellar winds
Revealing the wind collision in γ^2 Velorum
(***Lamberts***, *Millour +, accepted)*



2. Gamma-ray bursts
X-ray flares in GRB afterglows from relativistic shock interactions
(***Lamberts***, *Daigne, submitted)*

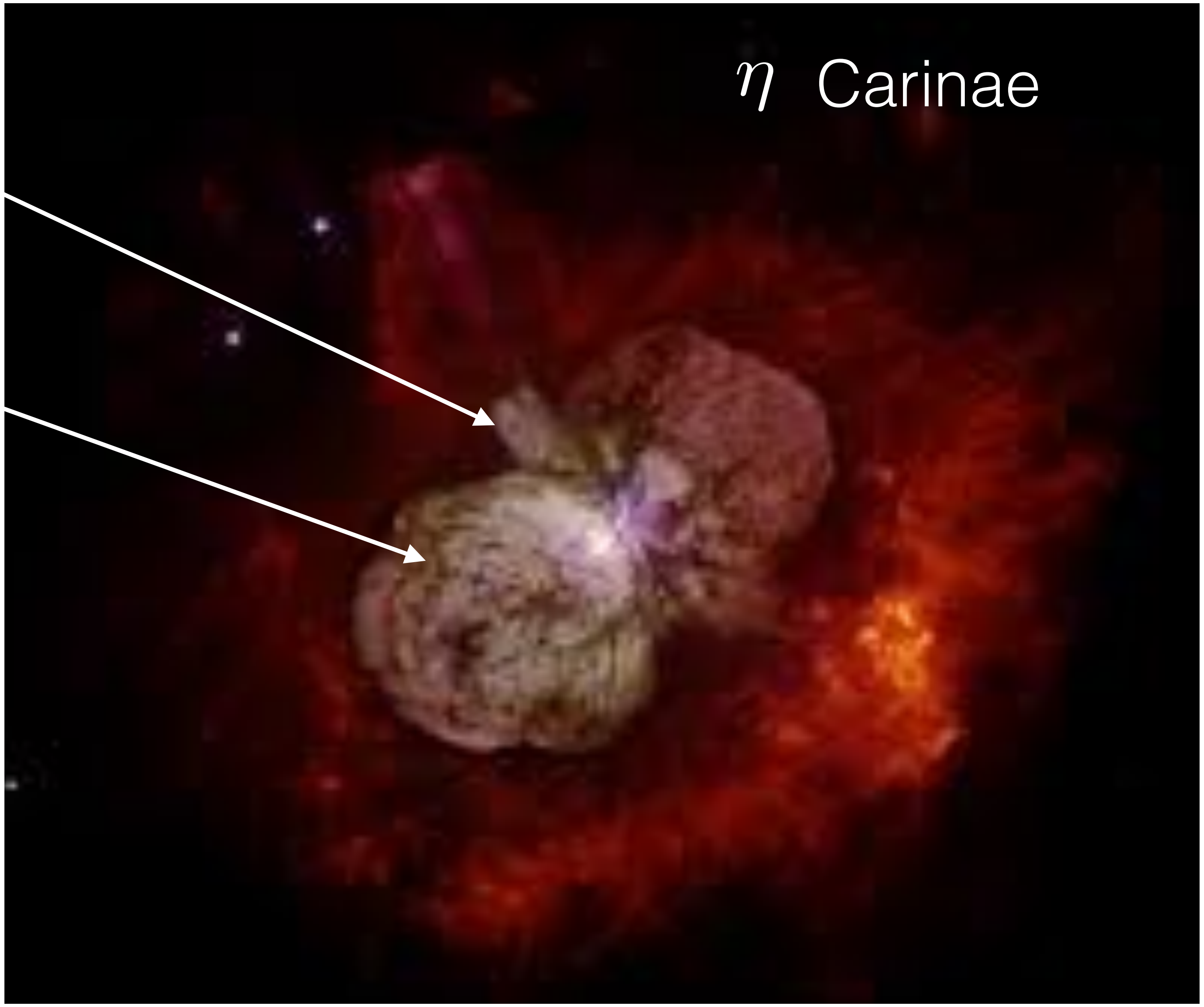
3. Gravitational wave progenitors
The formation conditions of GW 150914
(***Lamberts***, *Garrison-Kimmel, Clausen, Hopkins, 2016)*



COLLIDING STELLAR WINDS

shocks

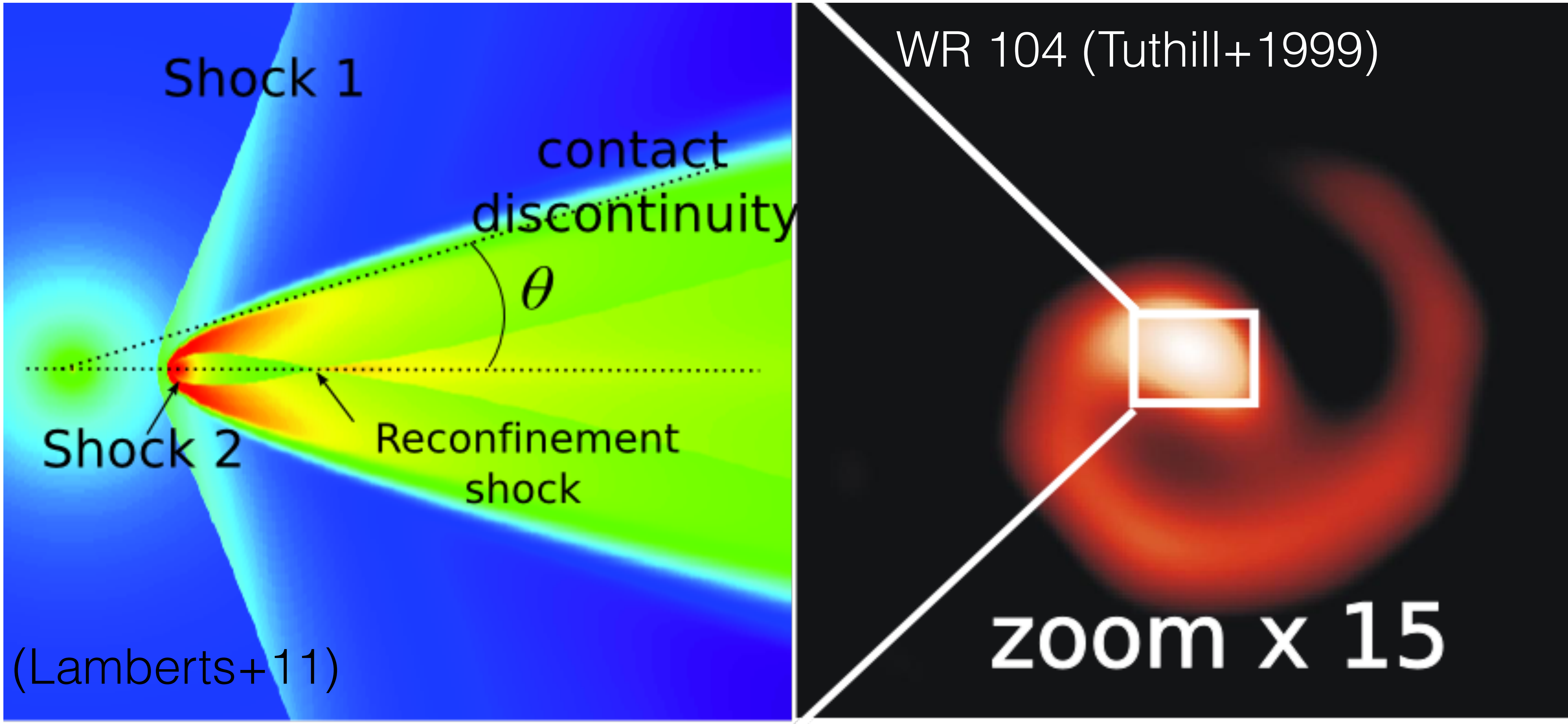
mass loss



Crucial : stellar evolution, interstellar medium but uncertain

Binarity helps

COLLIDING WIND STRUCTURE



thermal X-rays
line variability
non-thermal radio
infrared emission if dust

} Wind structure at given distance

γ^2 VELORUM: CLOSEST WR +O BINARY

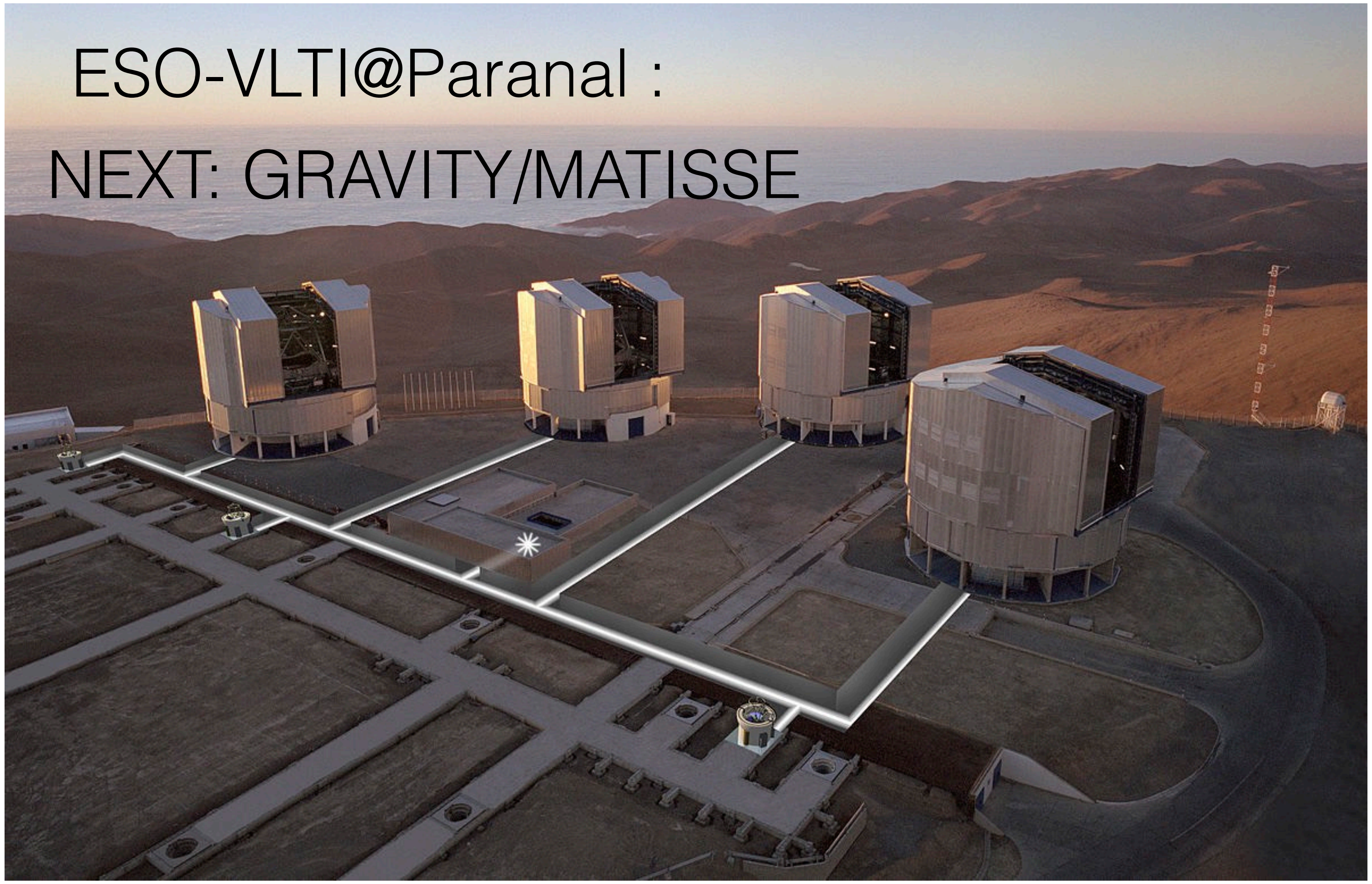
- Wolf-Rayet: more mass loss
- P=78 d
- optical/UV: detection of wind c
  region. (StLouis+1993; DeMarco+

Separation ~ few milli-arcse

SUB-MAS RESOLUTION WITH VLTI/AMBER

Near IR interferometry
→ spatial information
- orbital solution
- brightness ratio
- angular sizes

→ separate spectra



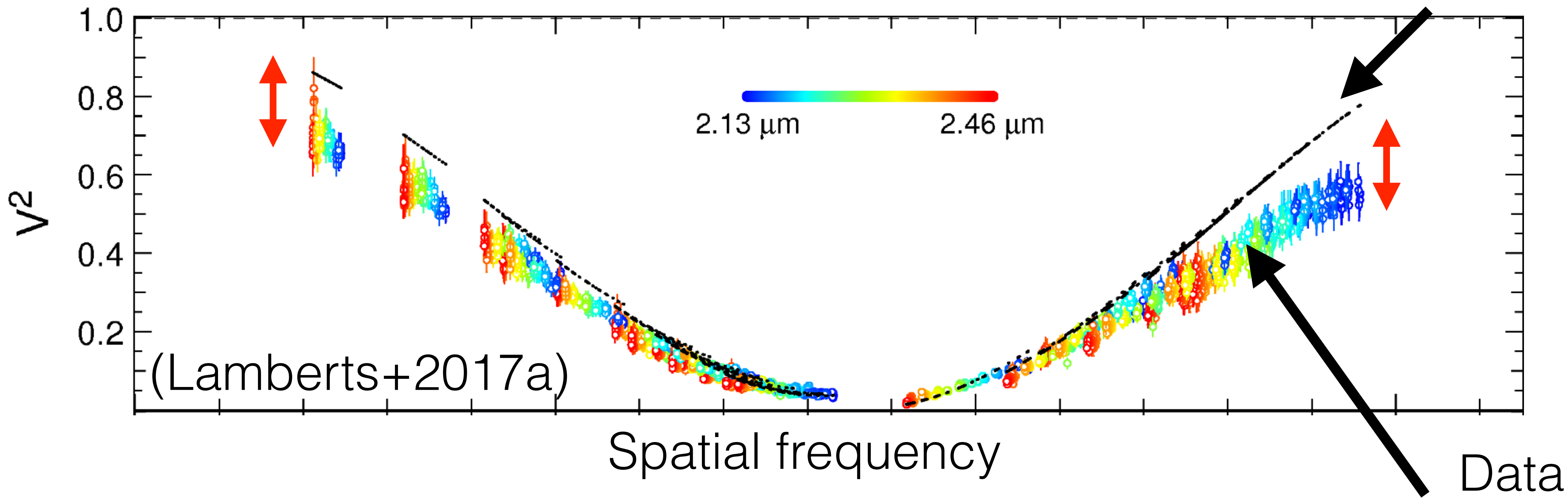
possibility for 1st direct detection of close wind collision
(see Weigelt+16 for η Car)


GOLD
MINE

CONTINUUM ANALYSIS

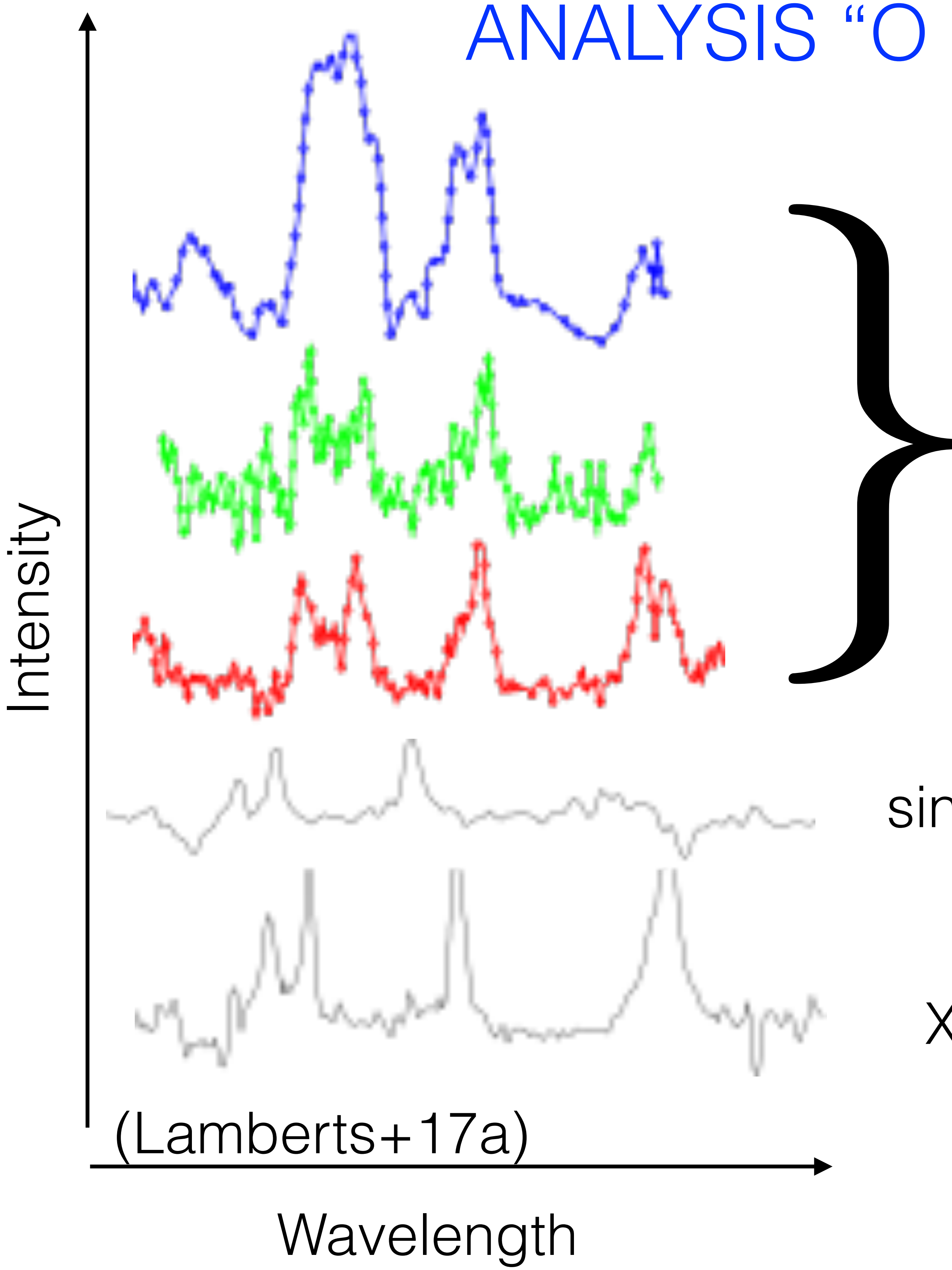
Visibility curve : spatial extension+flux ratios

Model :
2 point-sources



extended component needed (confirms Millour+07)
wind collision ?

ANALYSIS "O STAR" SPECTRUM



data

Variability

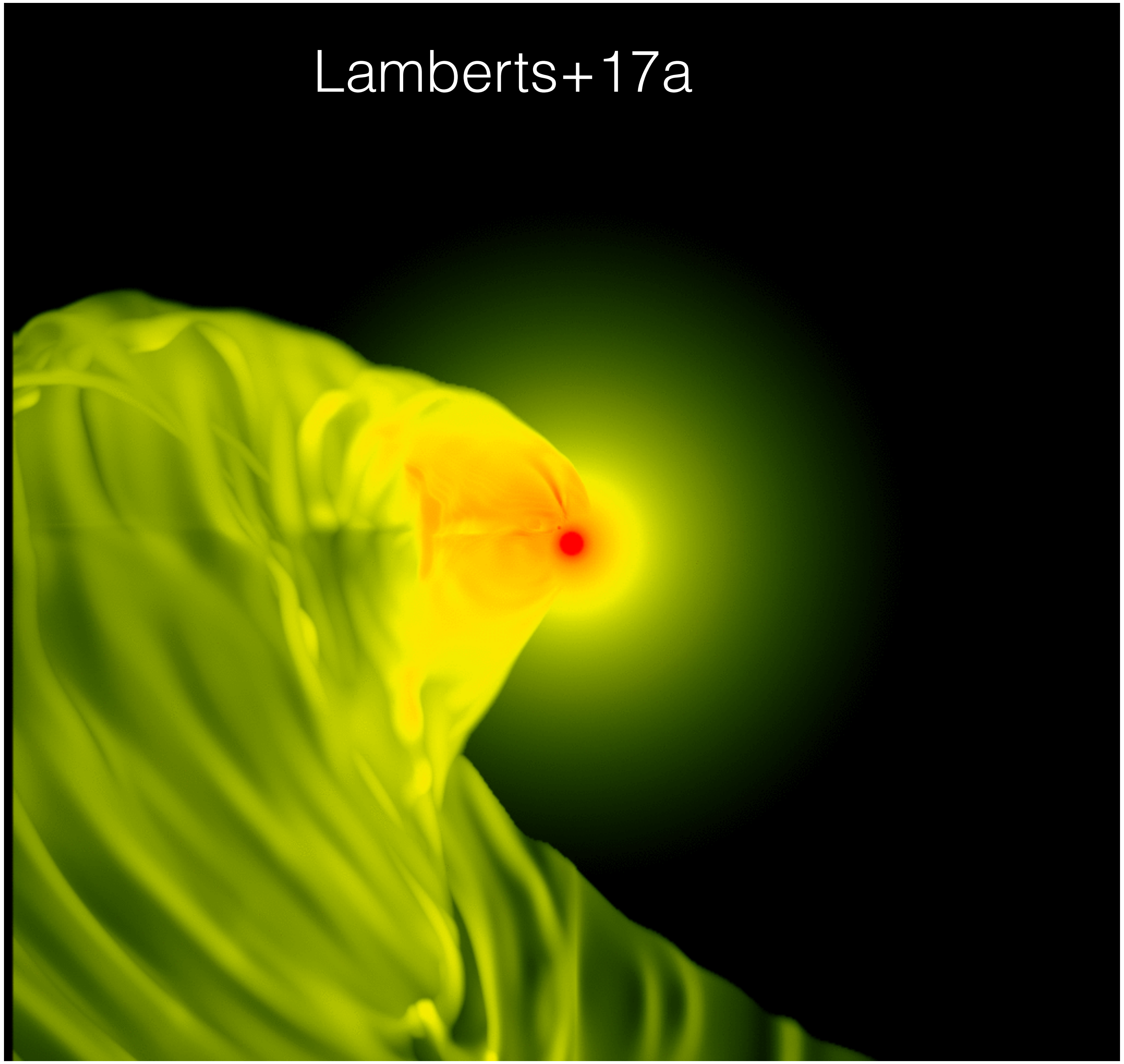
Residuals from wind collision zone?

need for simulations

single O star spectrum

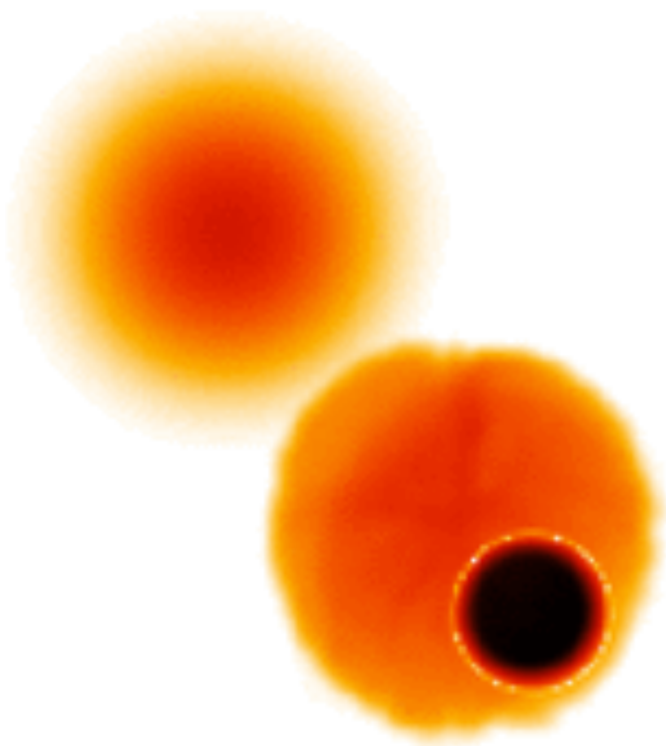
X-ray binary

GAMMA VEL: THE MOVIE



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

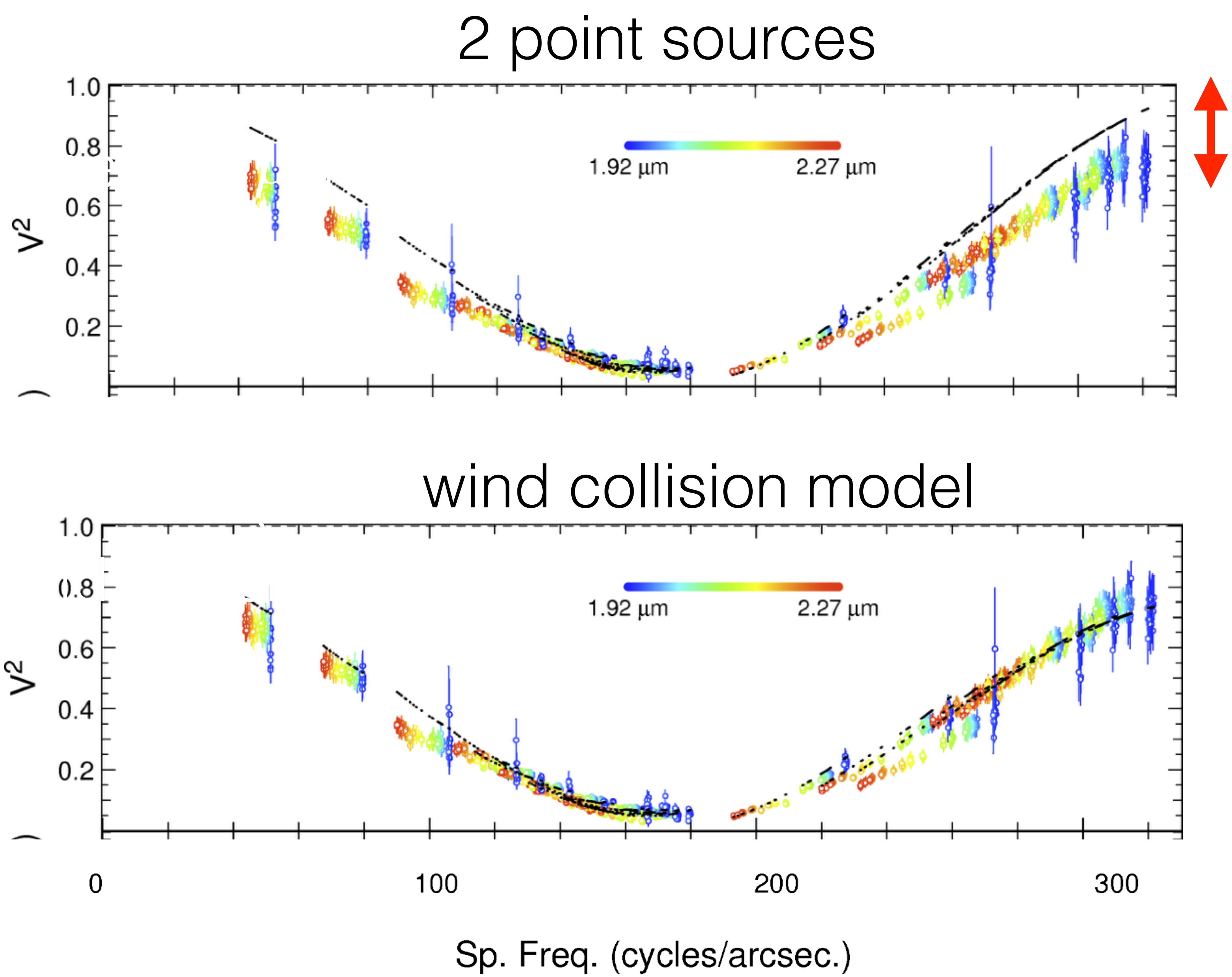
MODEL OBSERVATIONS



Free-free - 2 μm

(Lamberts+17a)

COMPARISON TO OBSERVATIONS



(Lamberts+17a)

detection wind collision region : 3-10% of continuum flux

CIRCUMSTELLAR ENVIRONMENTS: PATH FORWARD

interferometry + hydrodynamic simulations + emission = wind collision detection

Next: line analysis, full radiative transfer

2nd generation VLTI instruments : MATISSES/GRAVITY then E-ELT

CONNECTING THE DOTS

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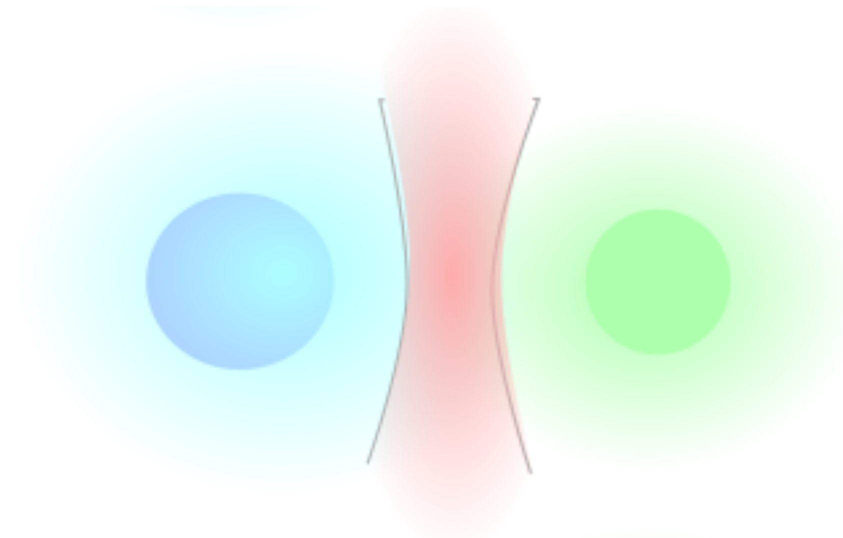
*(**Lamberts**, Millour et al, accepted)*



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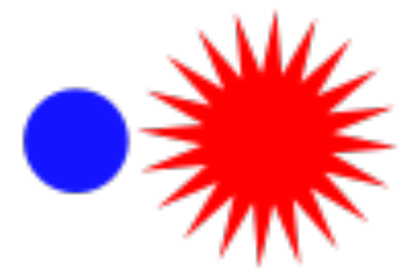

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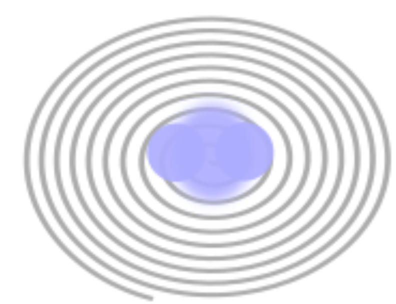


GAMMA-RAY BURSTS

Extragalactic gamma-ray flashes ~once/day

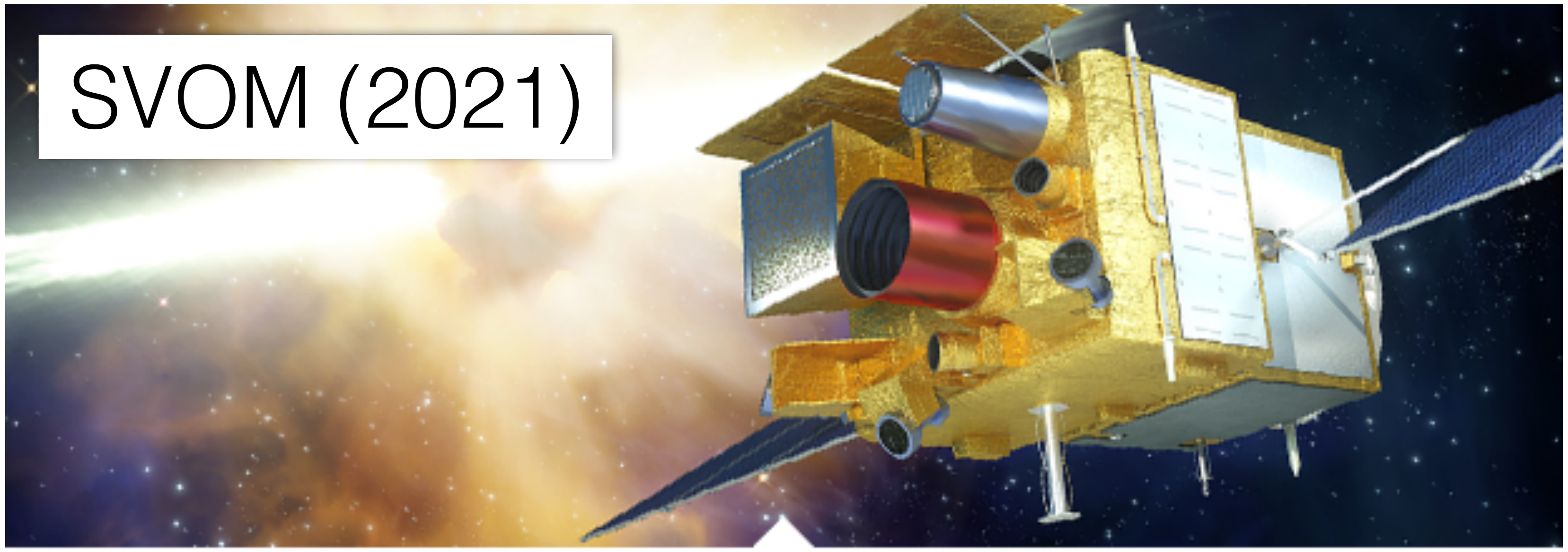
- up to z>9 : trace early universe
- extreme physics

Prompt emission

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

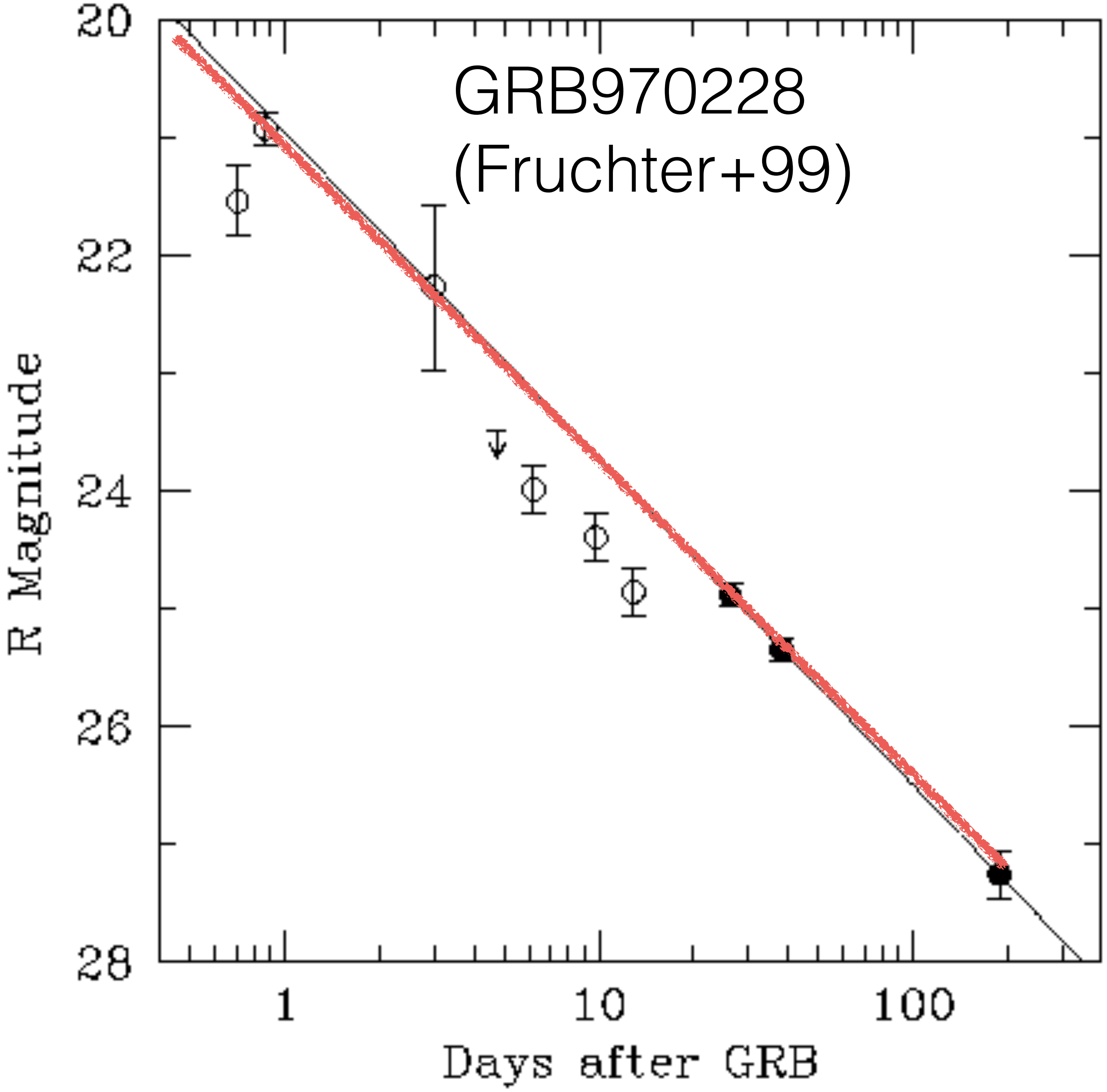
Then afterglow

Provides host galaxy



AFTERGLOWS BEFORE SWIFT

t^{-1}



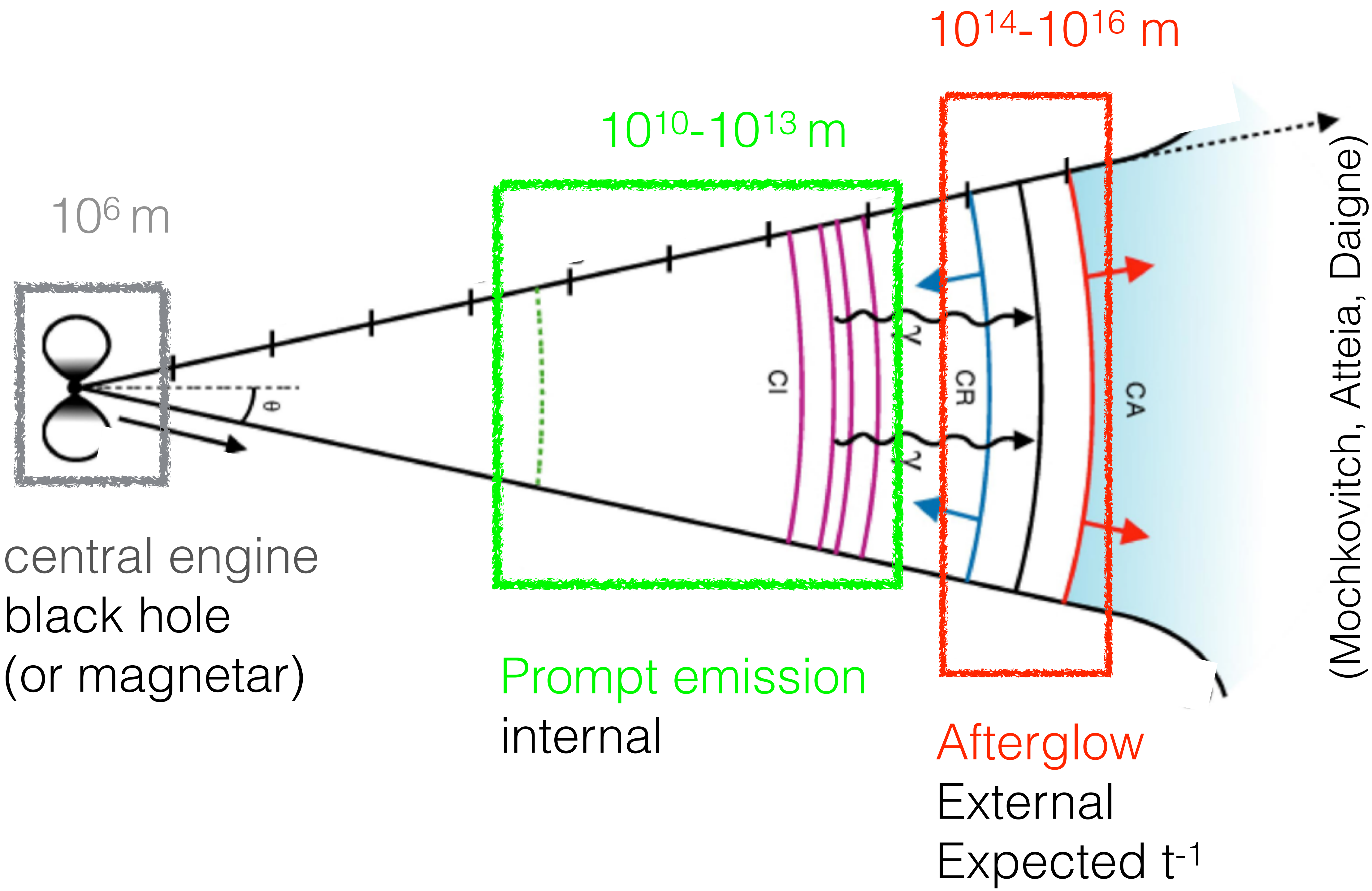
X-rays -> optical -> radio

Expected flux $F \sim t^{-1}$

Non-thermal spectrum

HOW TO MAKE A GRB?

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




HOME OF THE
BIG MESS

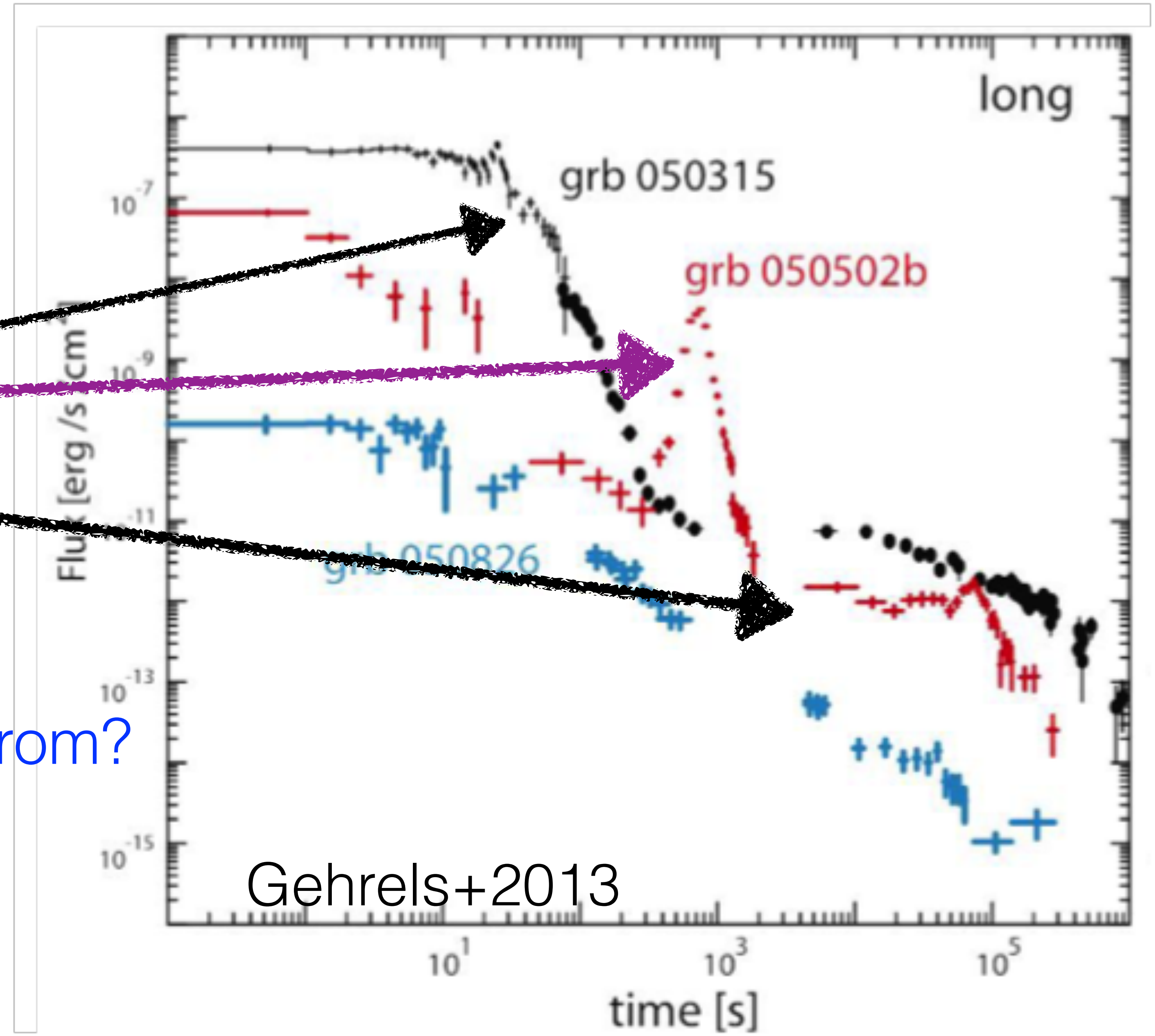
AFTERGLOWS IN THE SWIFT ERA

Swift: sensitivity+timing

Diverse/variable

- steep declines
- flares
- plateaus

Where do the flares come from?



Gehrels+2013

EXPLAINING VARIABILITY AND DIVERSITY IN X-RAY AFTERGLOWS

- Variable external medium ?
  😞gives too smooth variations

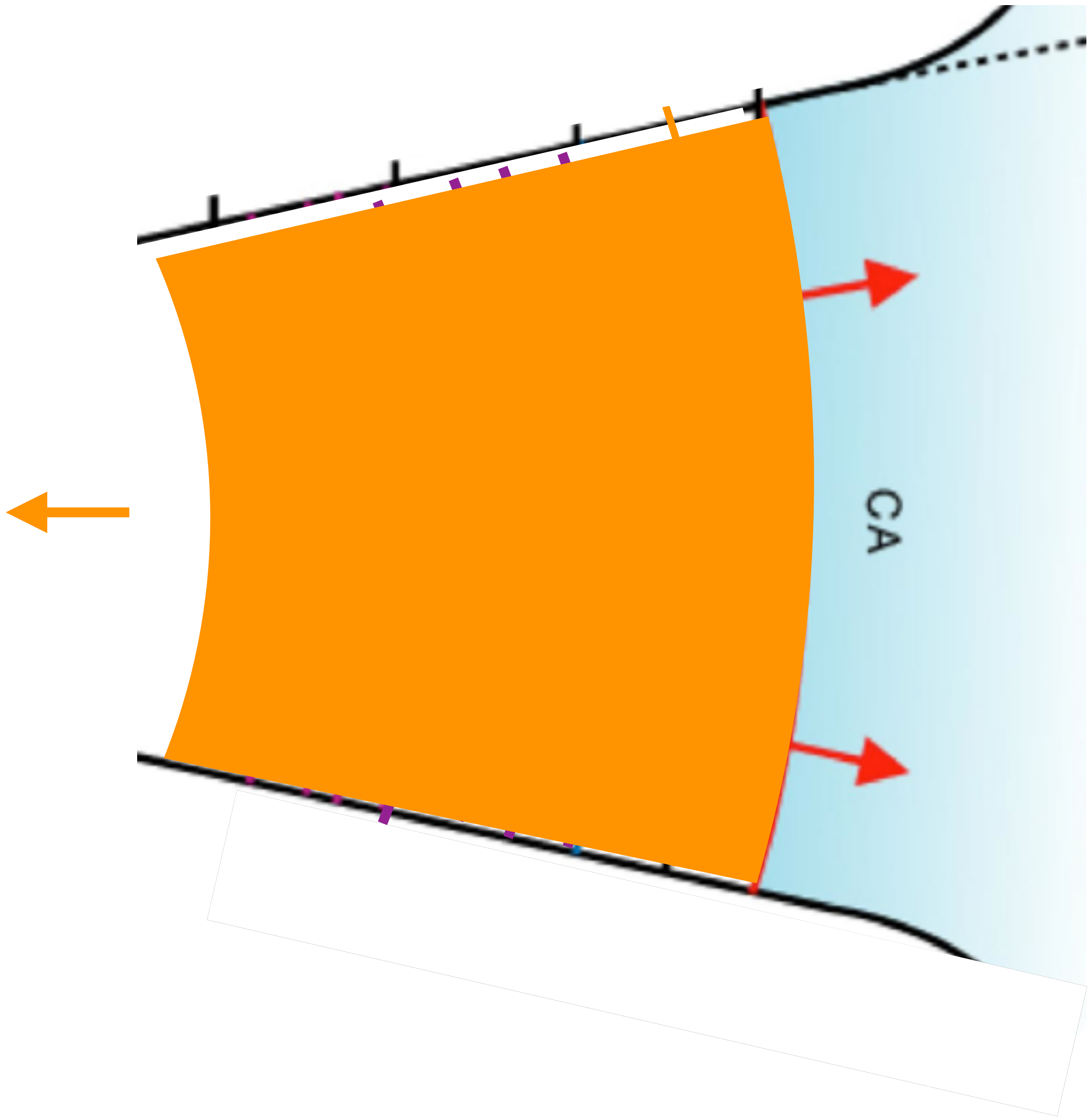
- Central engine (Burrows+2005, Zhang+2006)?
  - plateaus : late energy injection do delay forward shock
  - flares : late internal shocks

  😞strong constraints on central engine

  😞flares very different from prompt variability

- Shock interactions within the ejecta?

HIGHLY STRUCTURED EJECTA



Forward shock into ISM/wind

↓

Shocked material piles up

↓

reverse shock forms and propagates

+

internal shocks develop

↓

emission ? ← reverse shock interacts with internal shocks

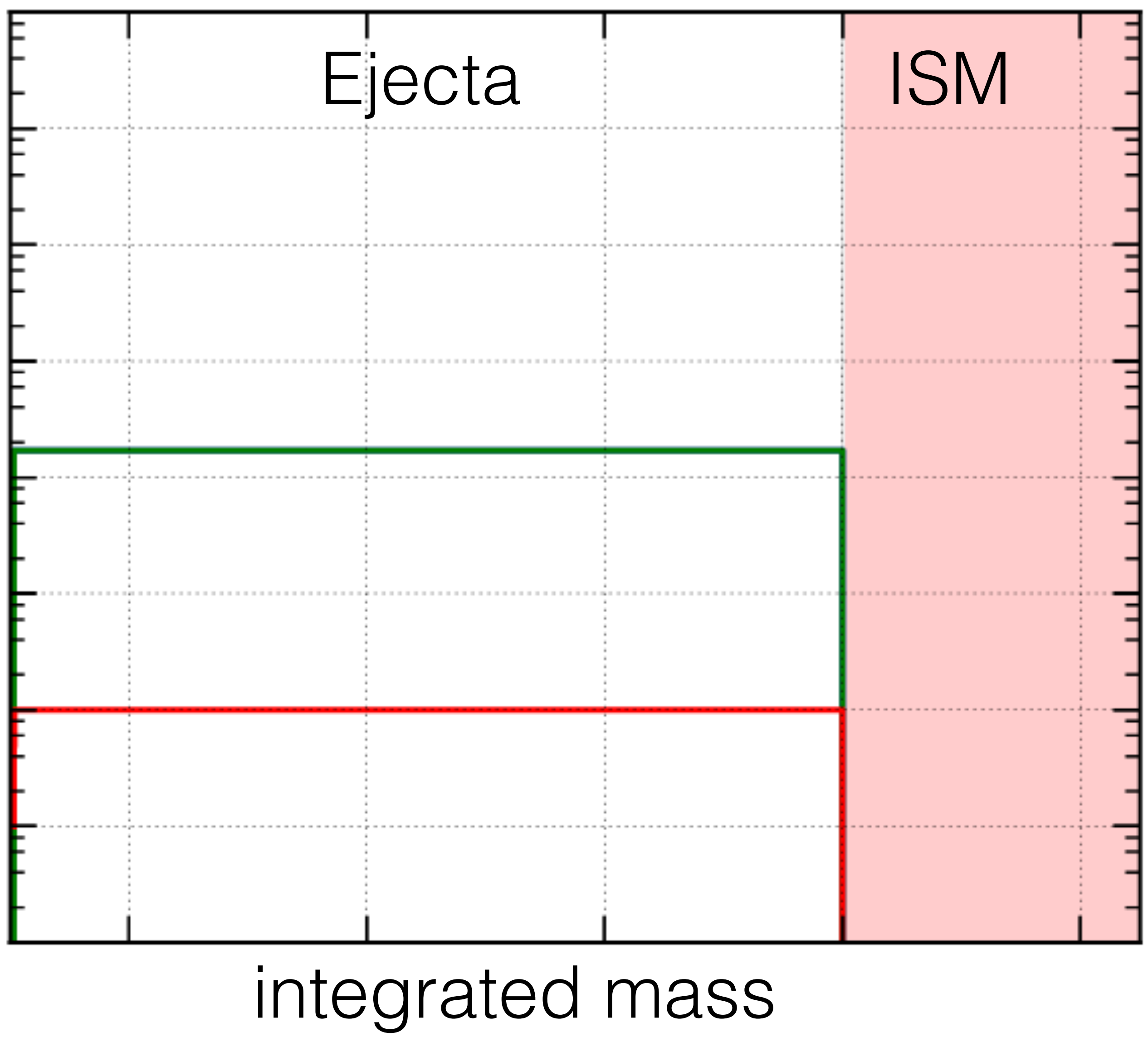
Genet+07, Uhm+07, Hascoet+15, needs confirmation from simulations

RELATIVISTIC SIMULATIONS

Relativistic RAMSES (Lamberts+13)
setup for GRB scales

- Γ_{max}=100 : ultra relativistic
- 1D spherical grid + moving boundaries

Uniform setup

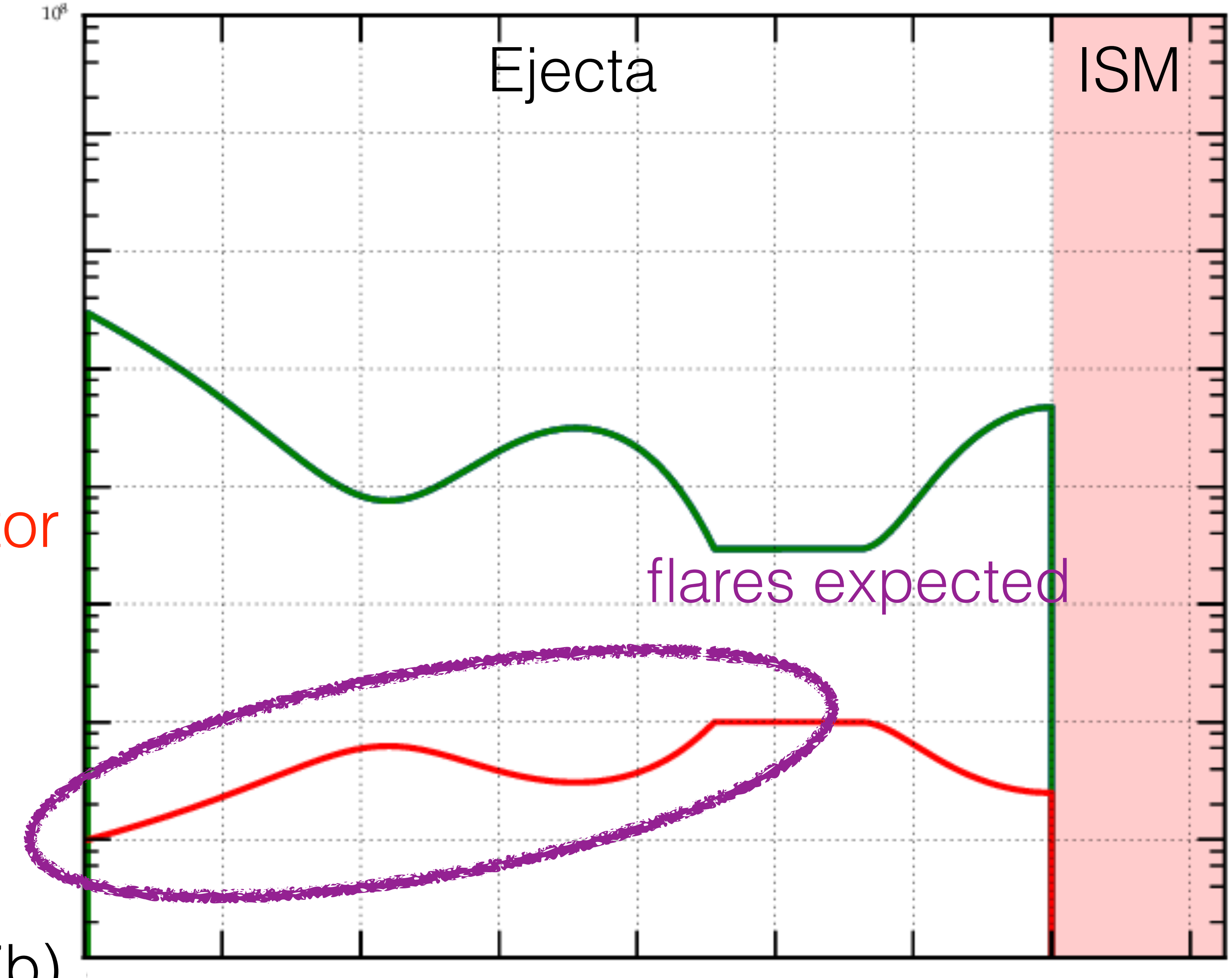


pressure
density
Lorentz factor

(Lamberts, Daigne, 2017b)

STRATIFIED EJECTA CREATE SHOCKS

pressure
density
Lorentz factor



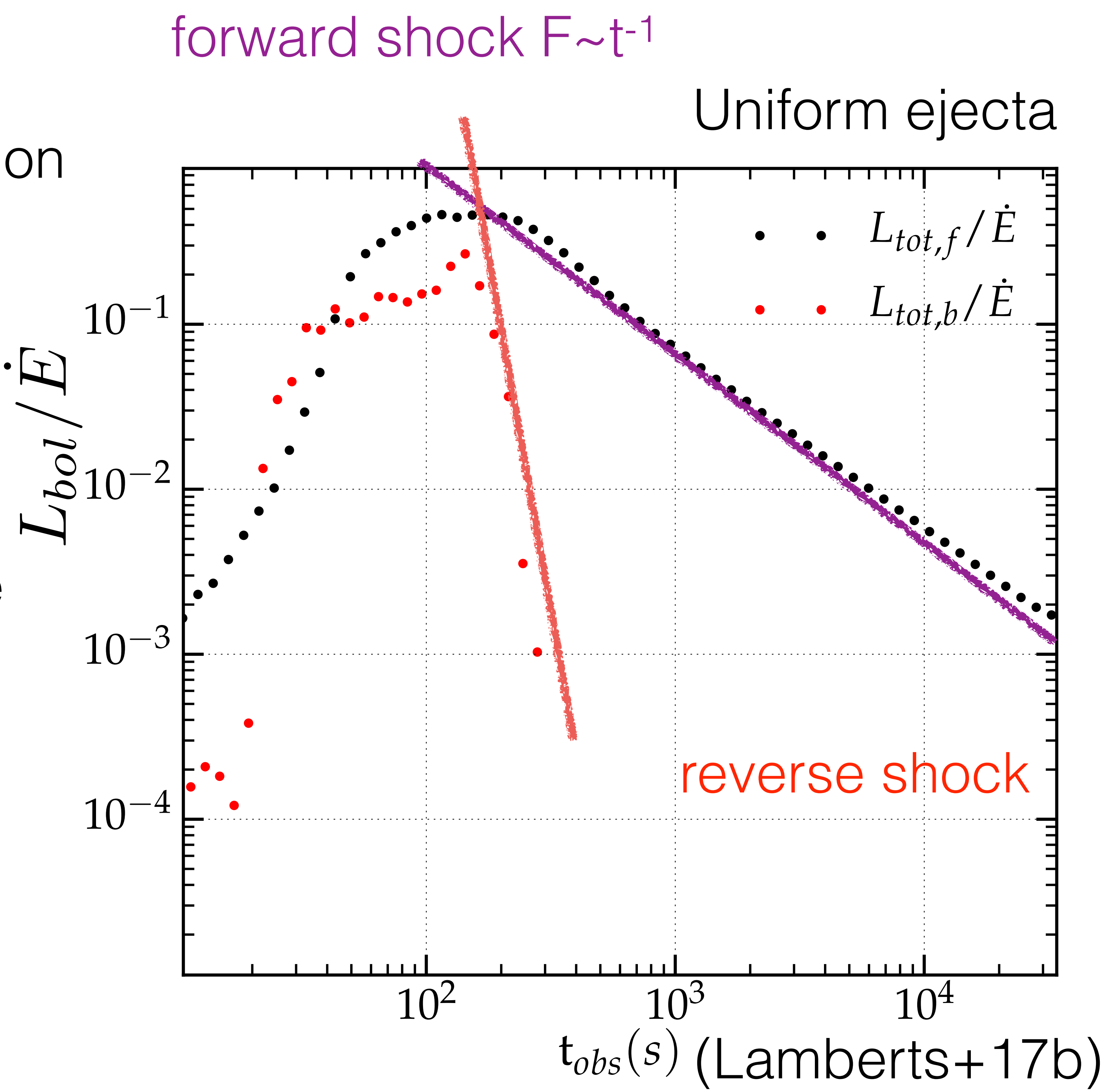
(Lamberts+17b)

Lorentz factor profile-> complex dynamics with multiple shocks

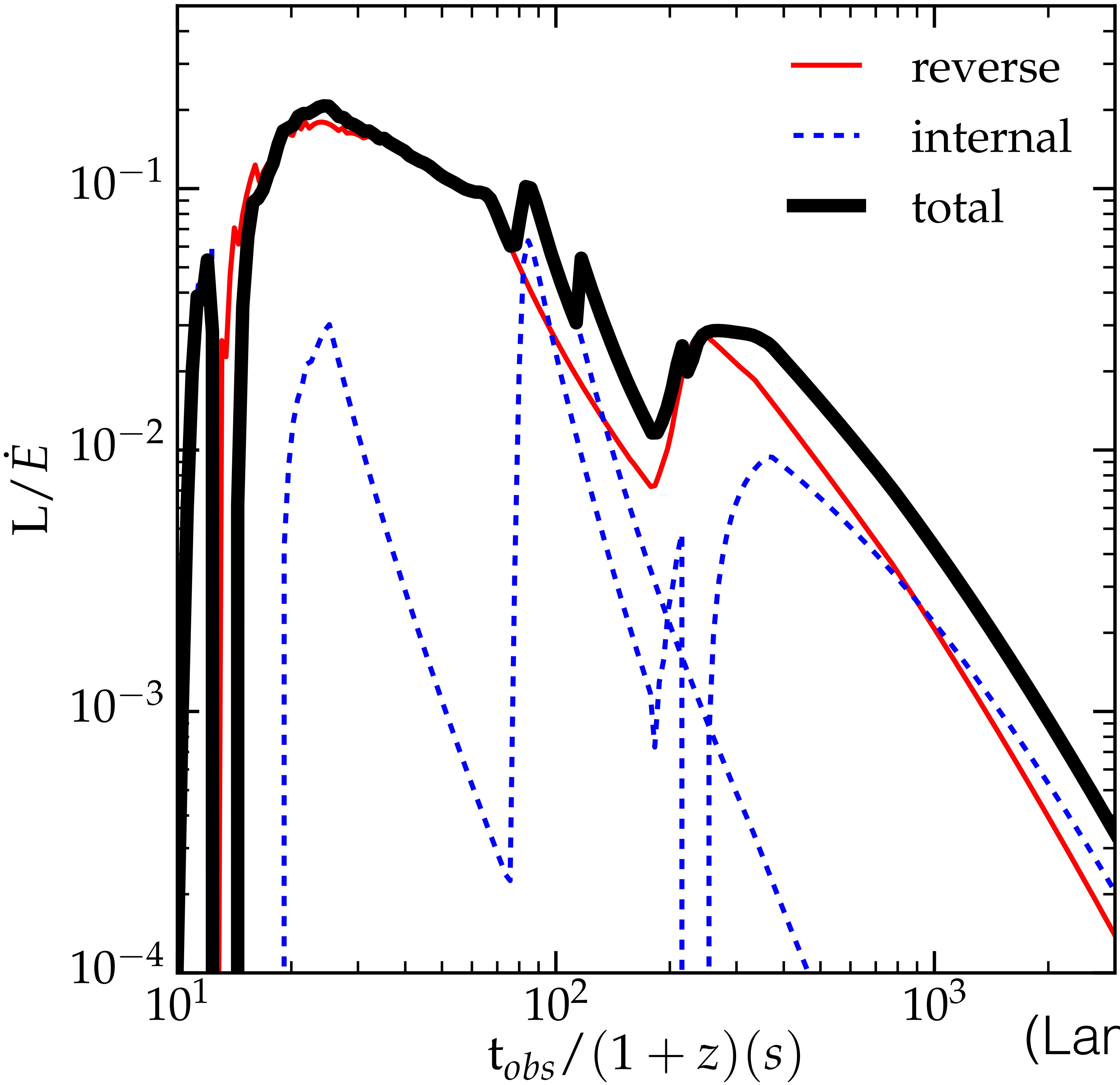
BOLOMETRIC EMISSION

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



(Lamberts+17b)

GAMMA-RAY BURSTS: PATHS FORWARDS

Shock interactions produce X-ray flares in afterglow

Next: multiwavelength model
-> microphysics of relativistic ejecta: magnetisation, particle acceleration
Similar mechanism expected in AGN jets, pulsar winds

Different GRB picture in 10 years?

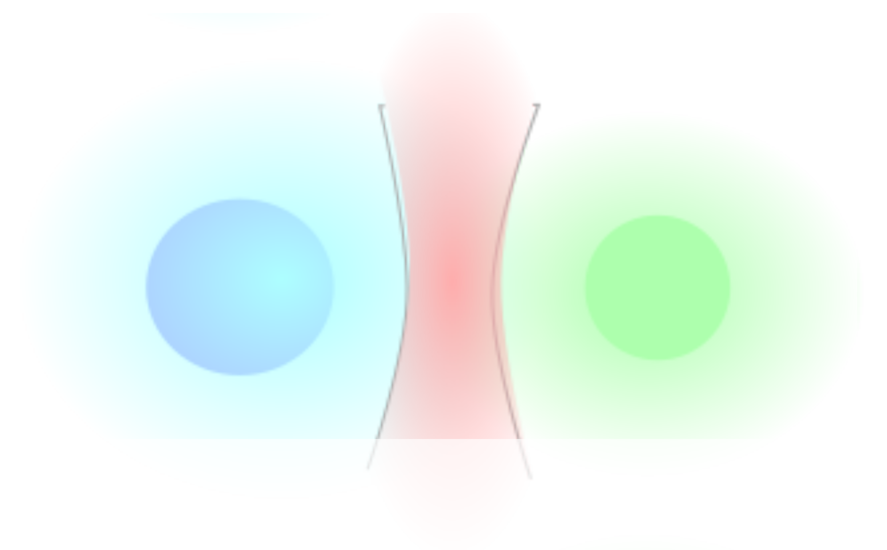
- SVOM: French-Chinese GRB monitor, joint detection with
- gravitational waves : central engine
- time-domain astronomy : supernova connection, kilonova, other transients

CONNECTING THE DOTS

1. **Colliding stellar winds**

Revealing the wind collision in γ^2 Velorum

*(**Lamberts**, Millour et al, accepted)*



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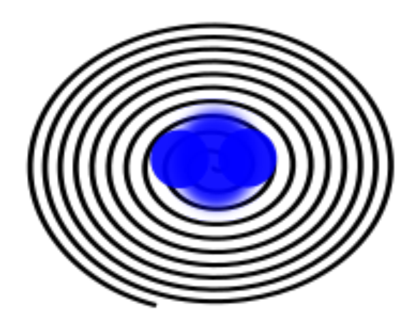
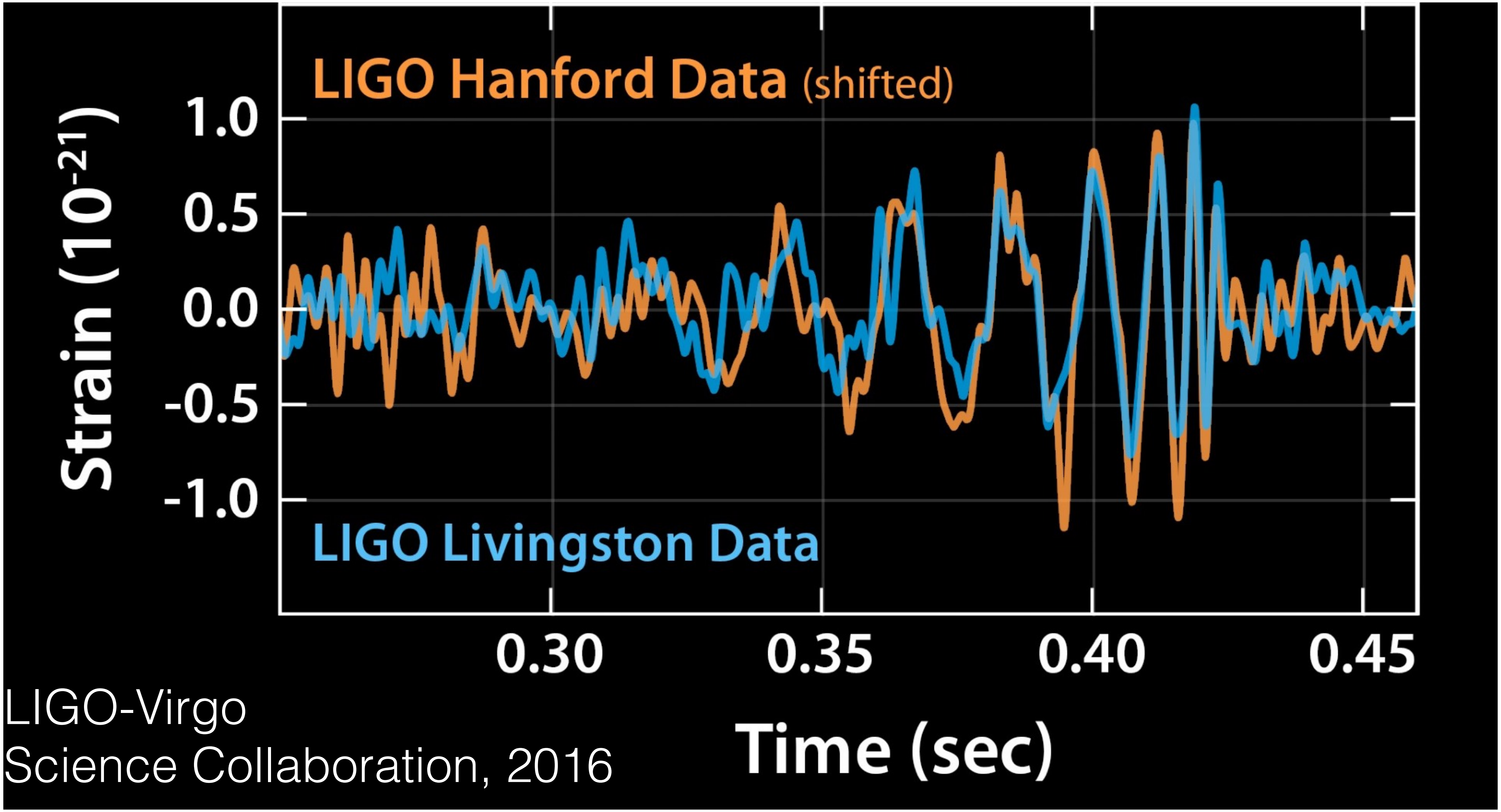


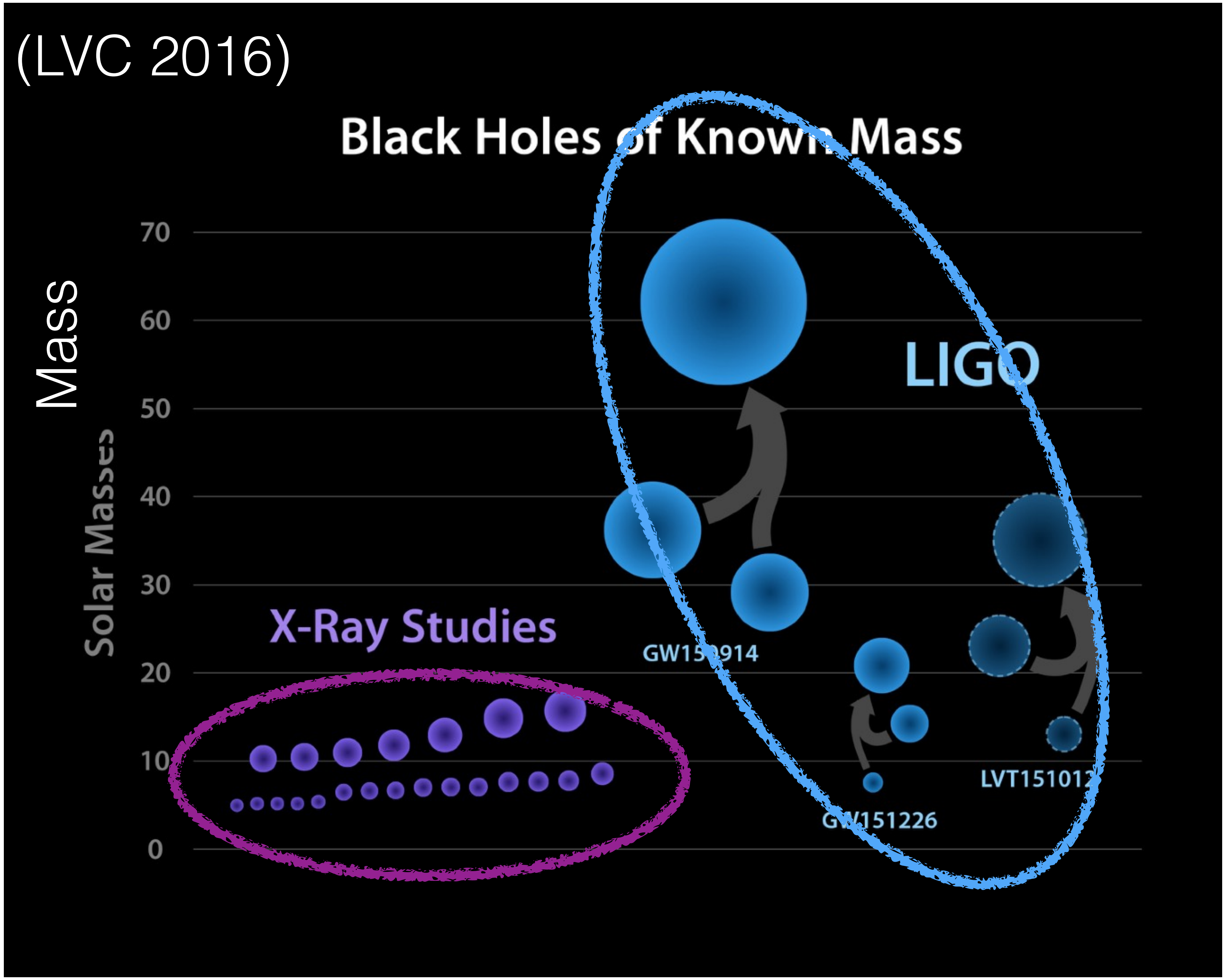
A NEW ERA IN ASTRONOMY



LIGO-Virgo
Science Collaboration, 2016

with important French involvement: Virgo, eLISA (~2030)

30 MSUN BLACK HOLES!

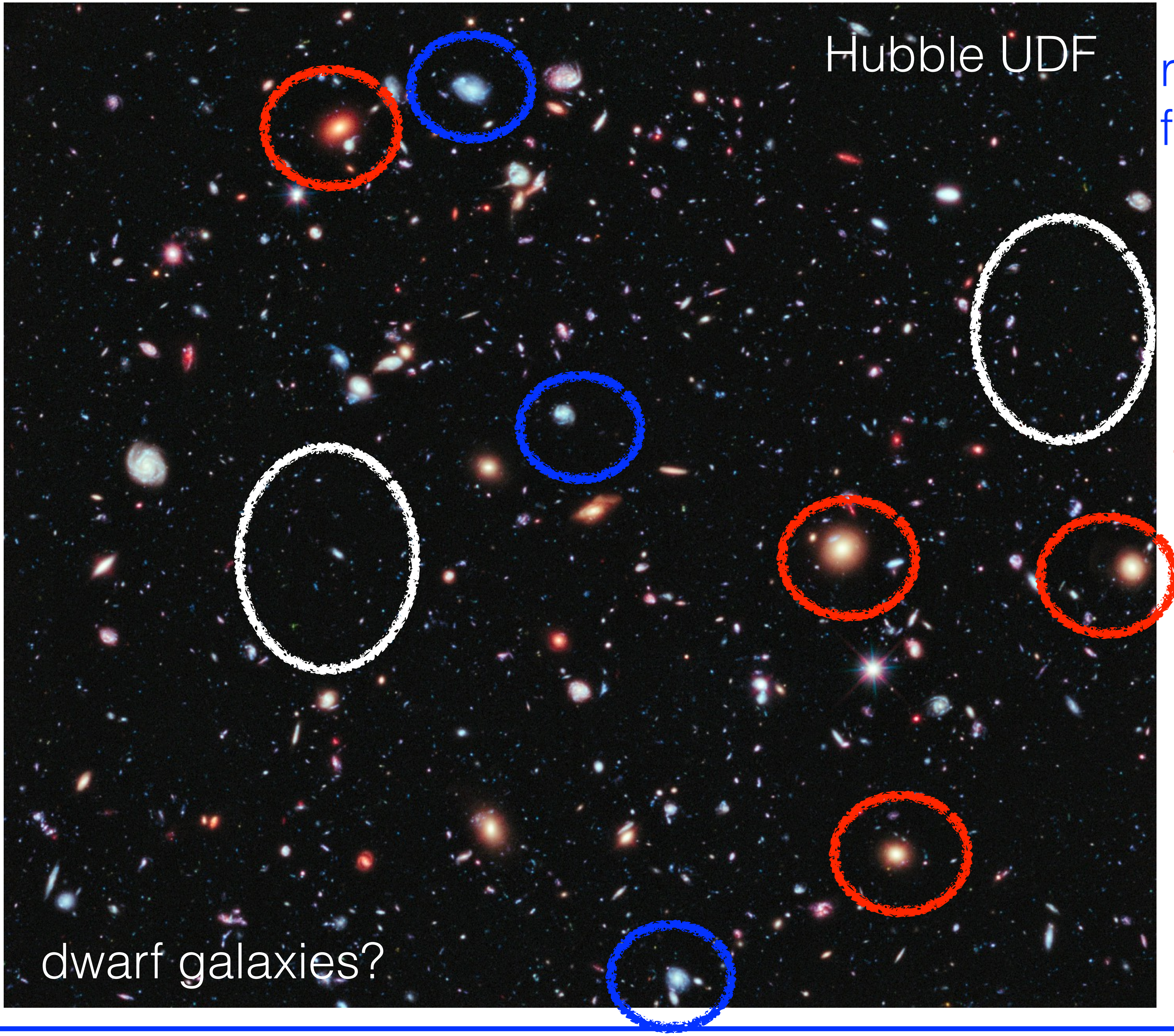


Unexpected masses

How to make them?

low metallicity stars

WHERE ARE THE LOW-METALLICITY STARS?



recent star formation?

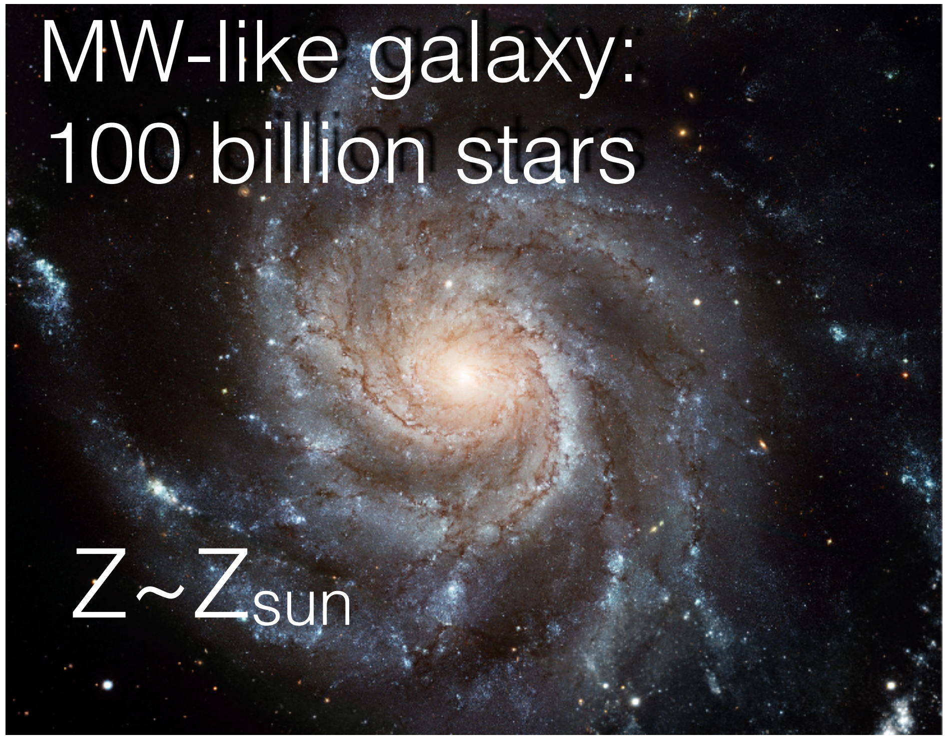
older star formation?

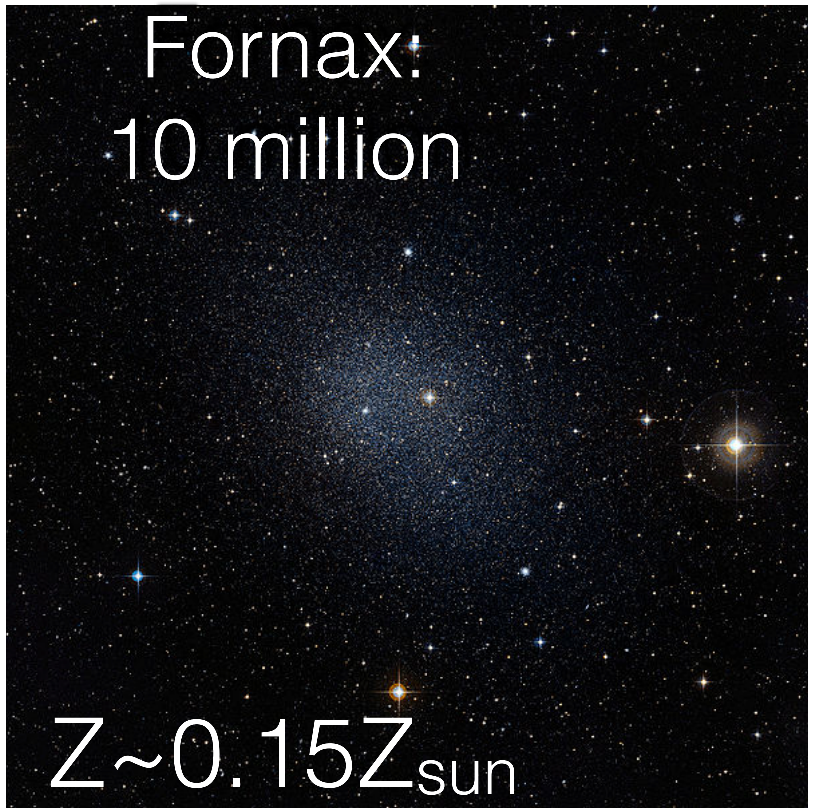
FORMING PROGENITOR OF GW150914

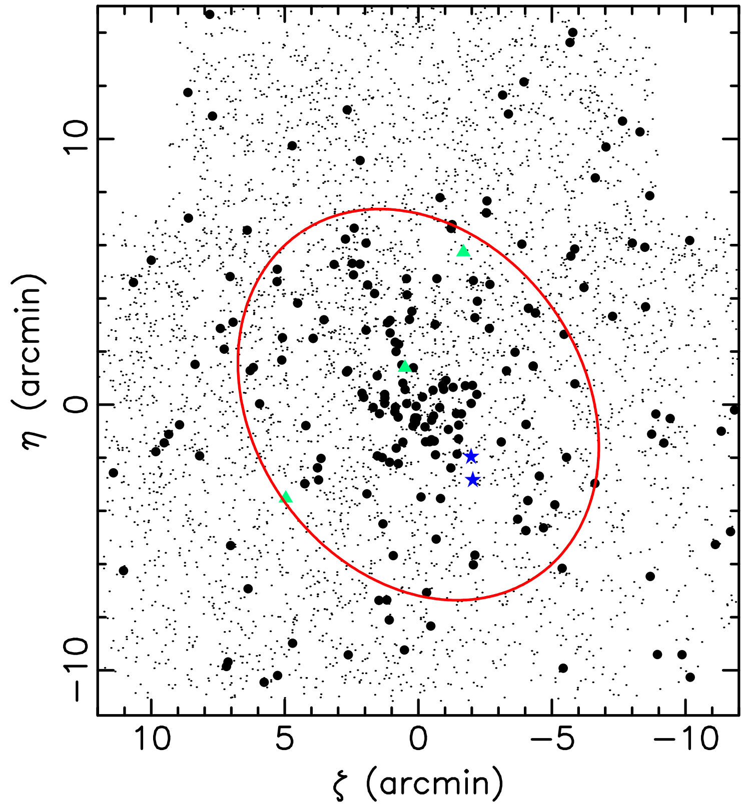
Low-metallicity star formation: specific conditions.
Where ? galaxy type
When ? Redshift

2 ingredients:
low metallicity stars : star formation
make them merge : binary evolution

LOW METALLICITY STARS



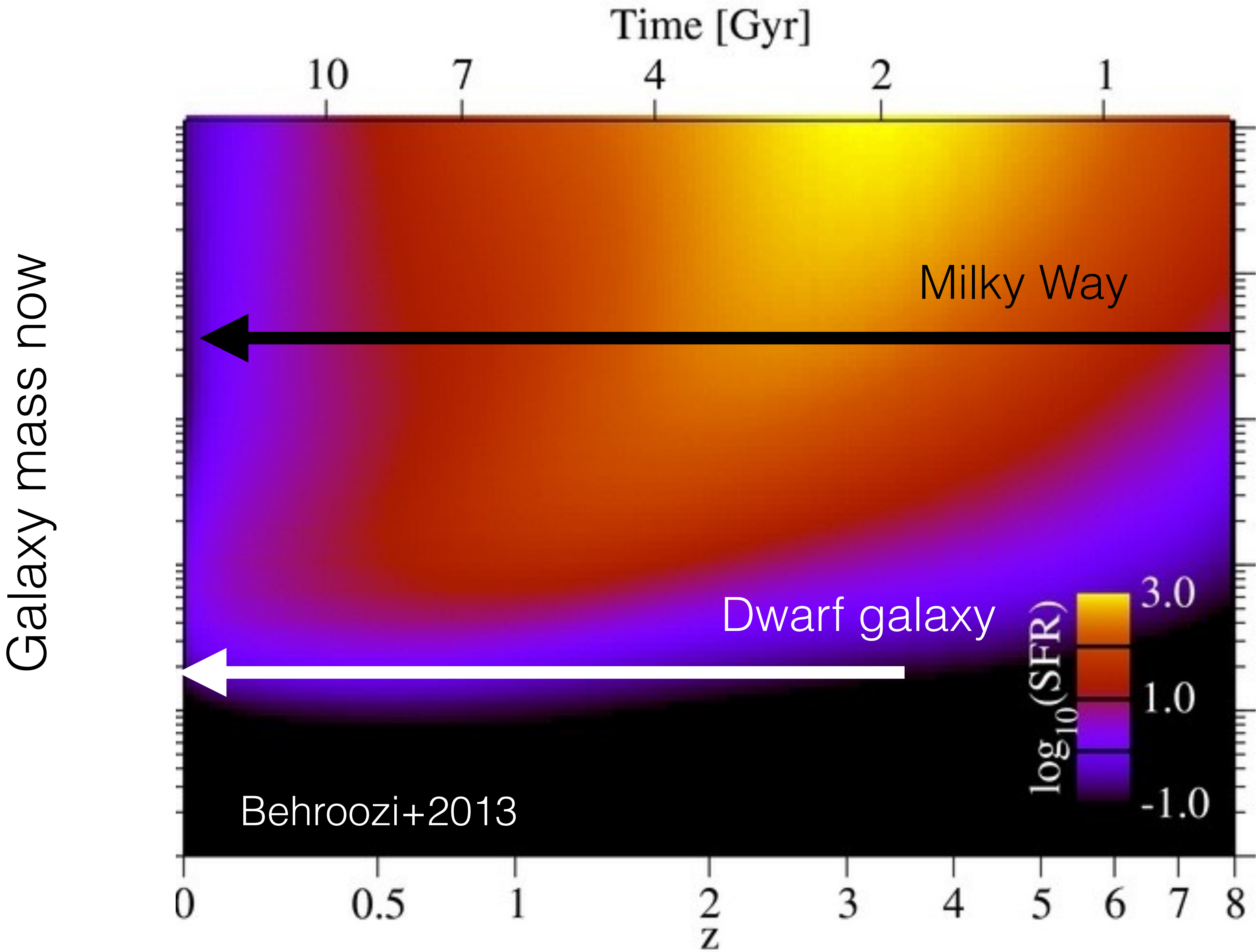




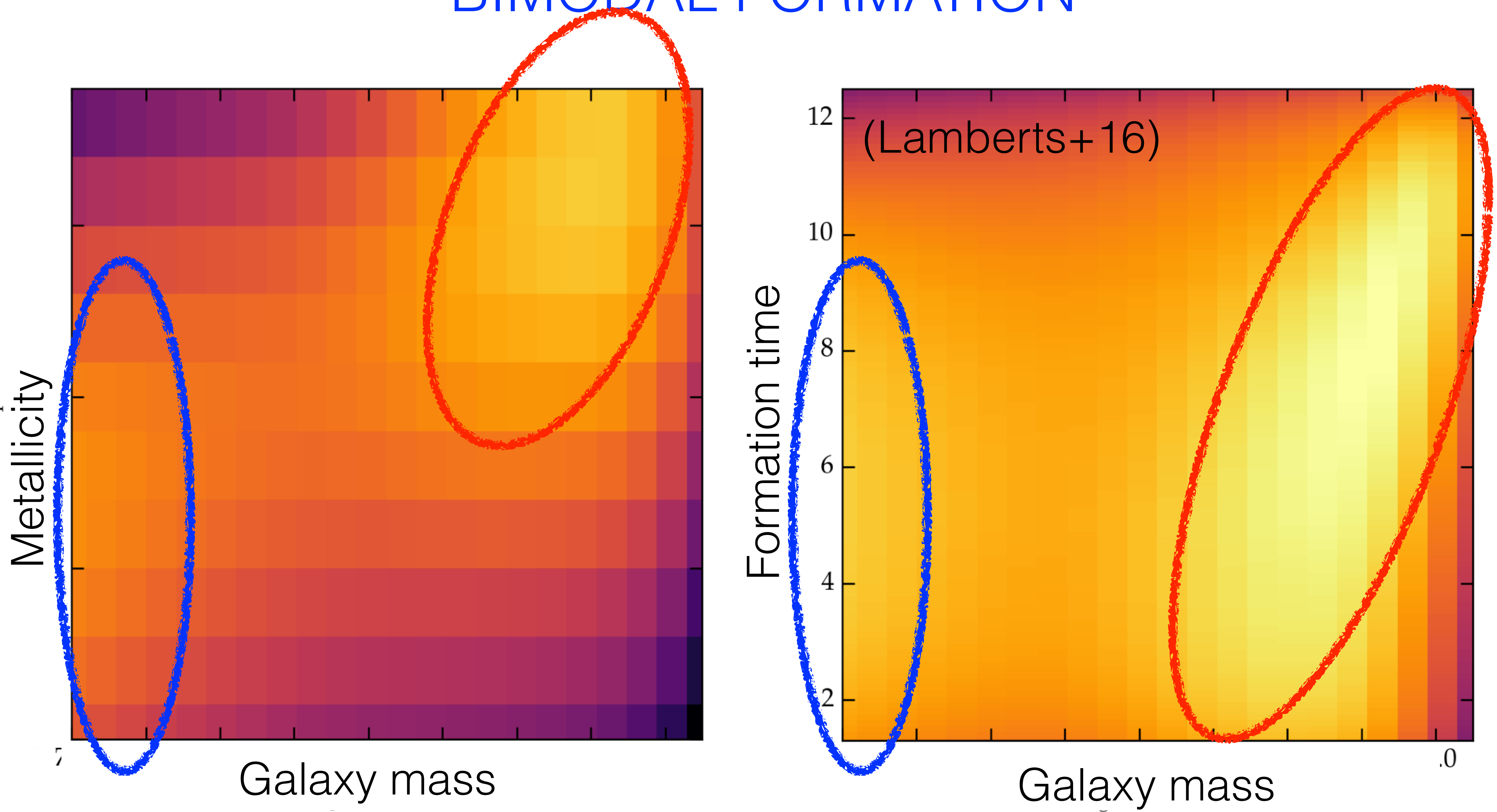
Reticulum II :
<1000 stars

$Z<0.01\ Z_{sun}$

STAR FORMATION RATE



LOW METALLICITY STARS: BIMODAL FORMATION



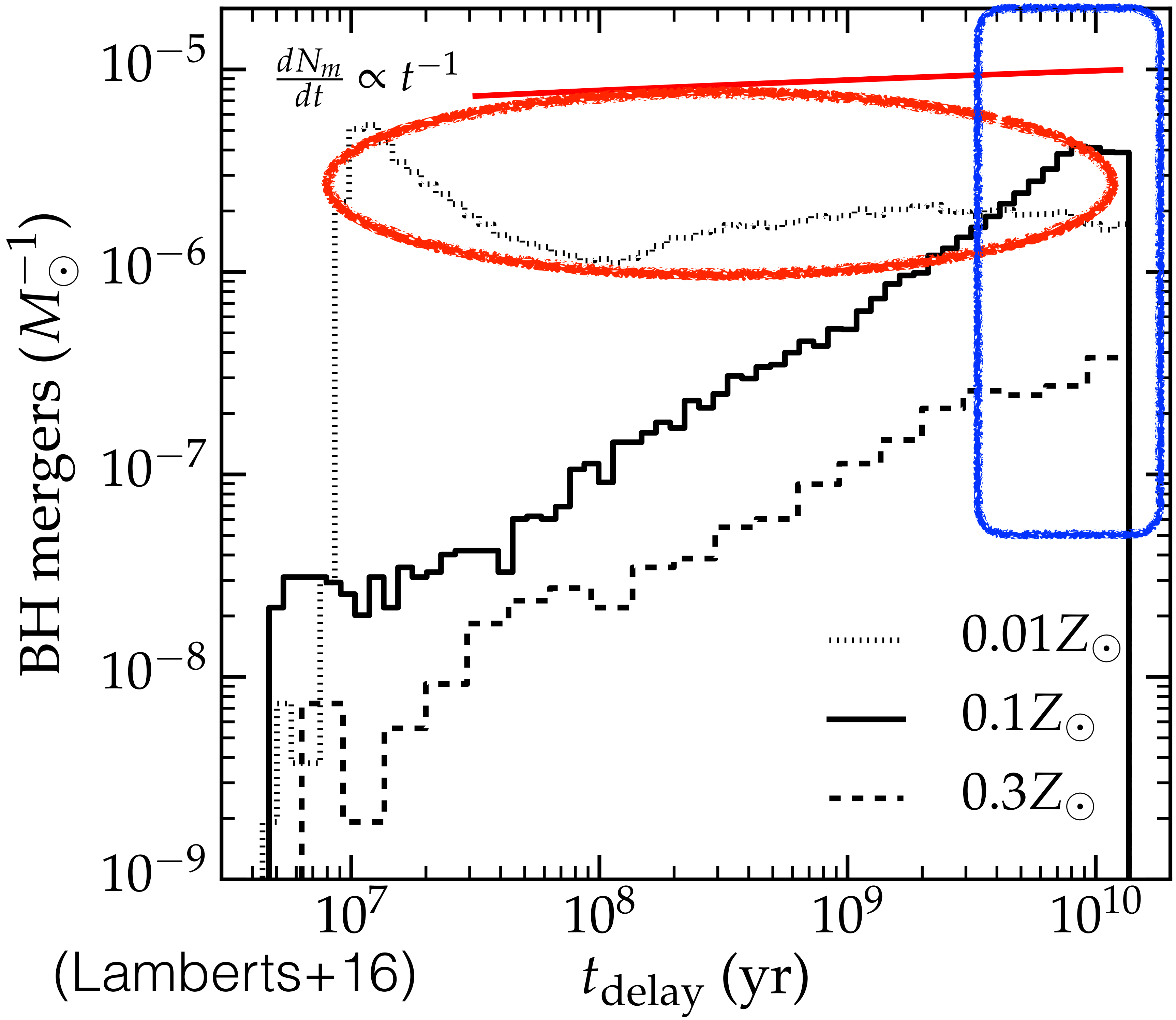
Dwarf galaxy Milky Way

data available at https://astridlambertts.wordpress.com/datacodes/

PATH TO BLACK HOLE MERGERS

- field binaries, standard evolution
- Kroupa IMF, 10^6 binaries with $25<M_1<150$
- BSE code (Hurley+2002)
- keep track of final remnants with $M_{BH1}>25$ $M_{BH2}>15$

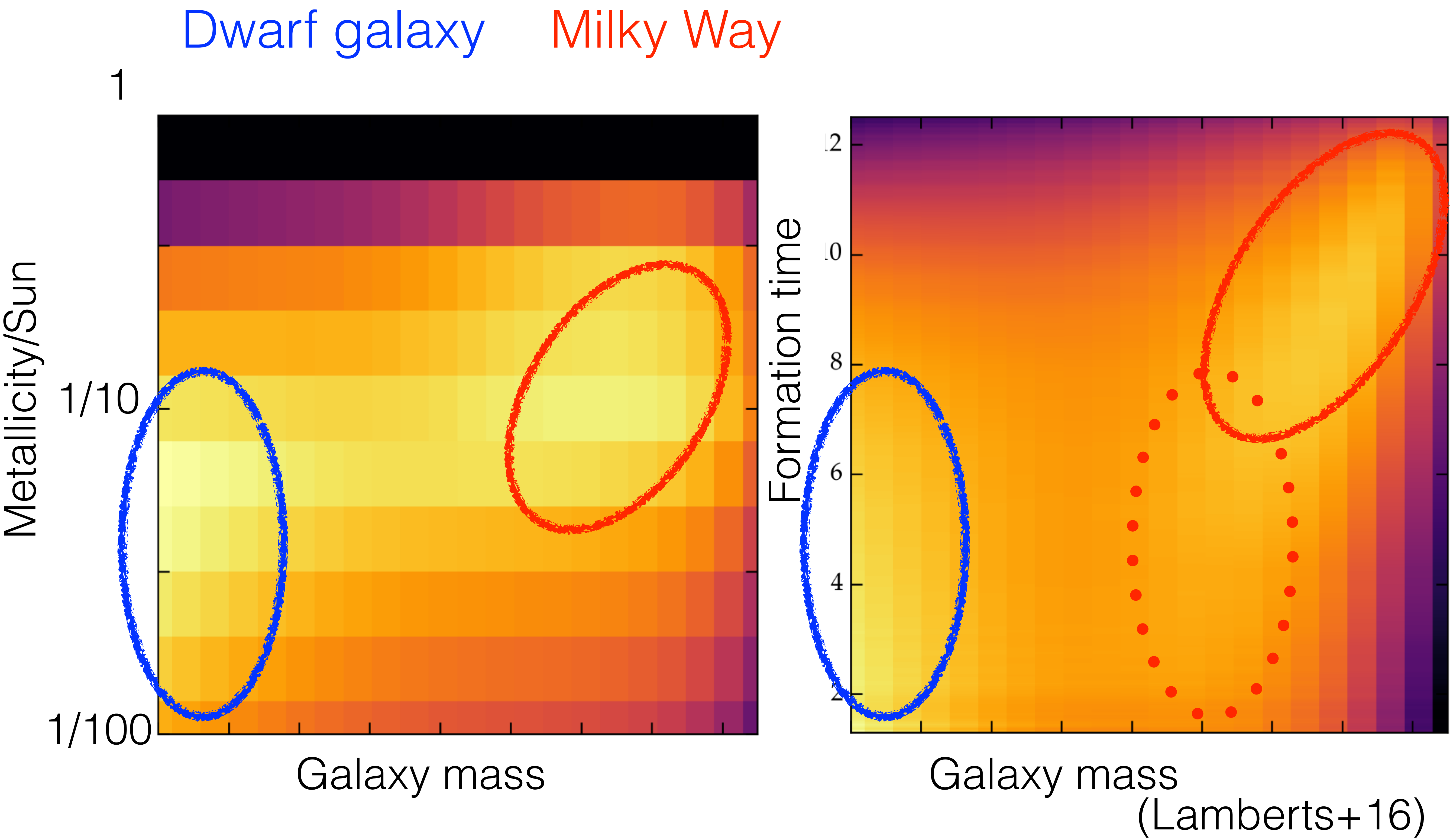
DELAY TIME DISTRIBUTION



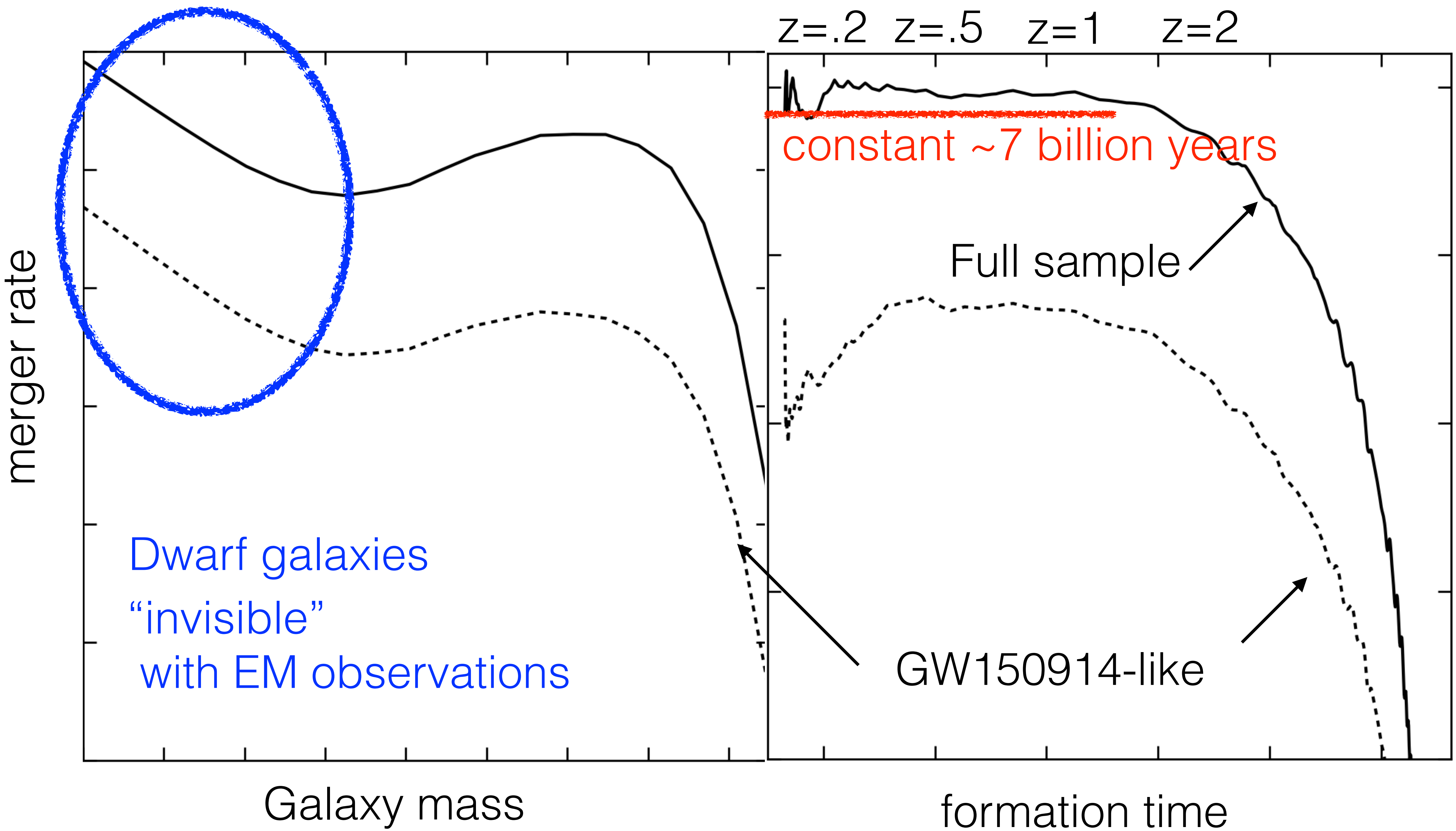
(Lamberts+16)

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

BIMODAL FORMATION OF GW150914 PROGENITORS



STAR FORMATION IN DWARF GALAXIES



(Lamberts+16)

ASTROPHYSICS WITH GRAVITATIONAL WAVES

massive black holes : low metallicity star formation, dwarf galaxies

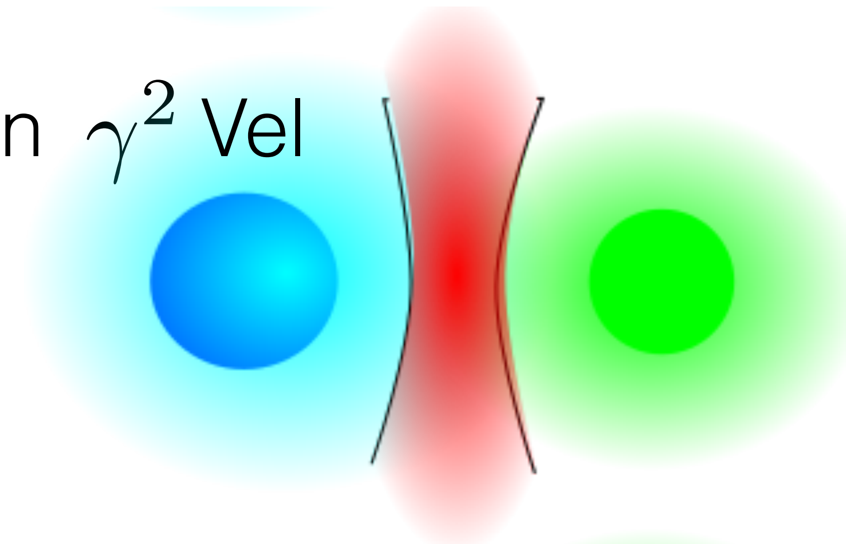
Compact object mergers : massive star formation / evolution

Coming:
- Virgo
-sensitivity : 50 events/yr
-follow-up : SVOM, PTF/BlackGEM, LSST, SKA
-multifrequency gravitational waves : eLISA

SUMMARY What a talk on massive binaries looks like in 2017

interferometry and simulations reveal wind collision in γ^2 Vel

probing circumstellar environments

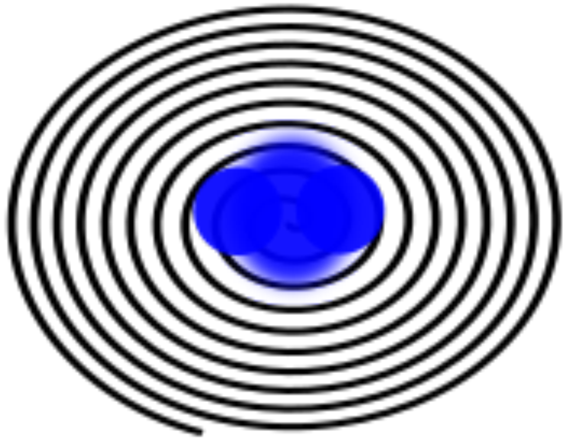


shock interactions produce X-ray flares in GRB

constraints on microphysics

Massive black hole mergers preferentially trace star formation in dwarfs

GW : formation/evolution of massive binaries



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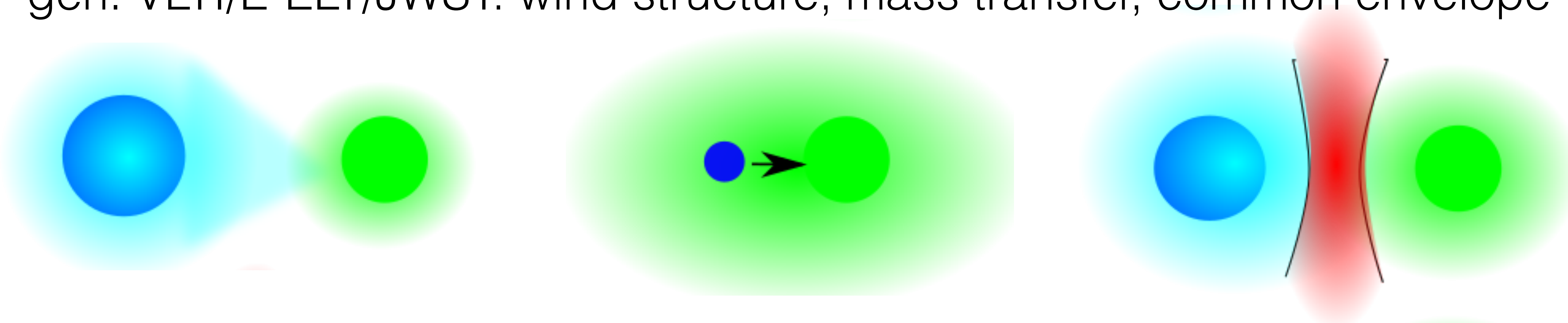
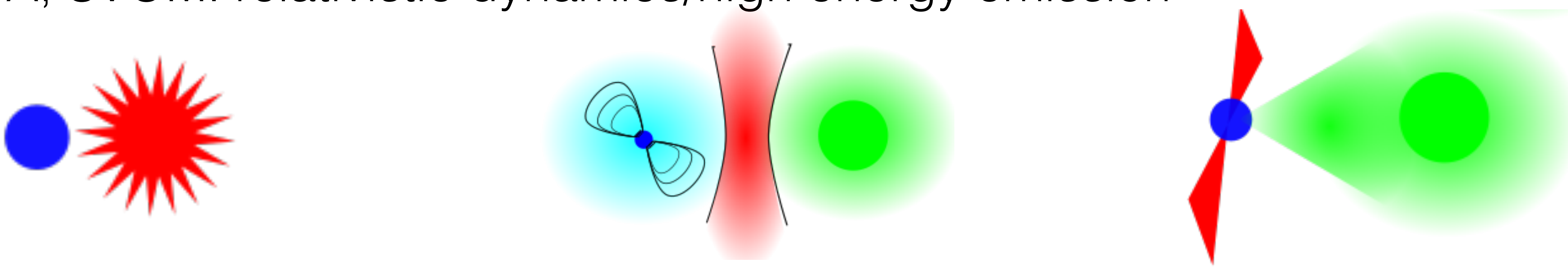
What a talk on massive binaries may look like in 2027+

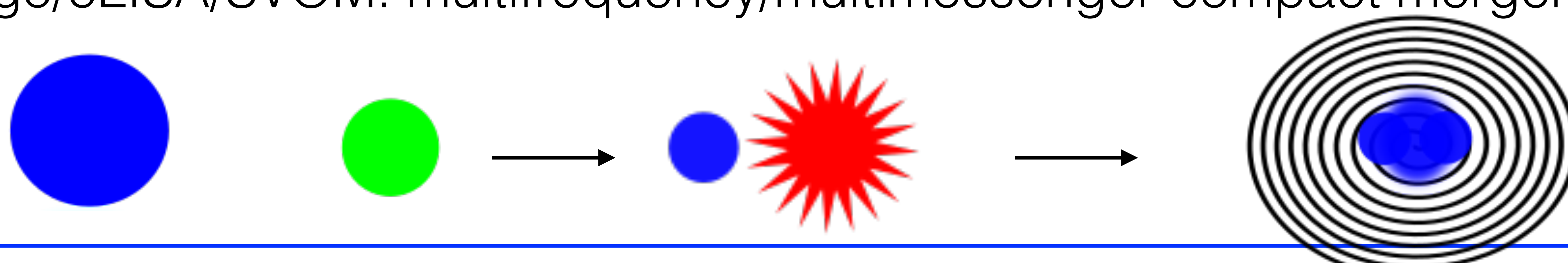
2nd gen. VLTI/E-ELT/JWST: wind structure, mass transfer, common envelope



CTA, SVOM: relativistic dynamics/high energy emission



Virgo/eLISA/SVOM: multifrequency/multimessenger compact mergers



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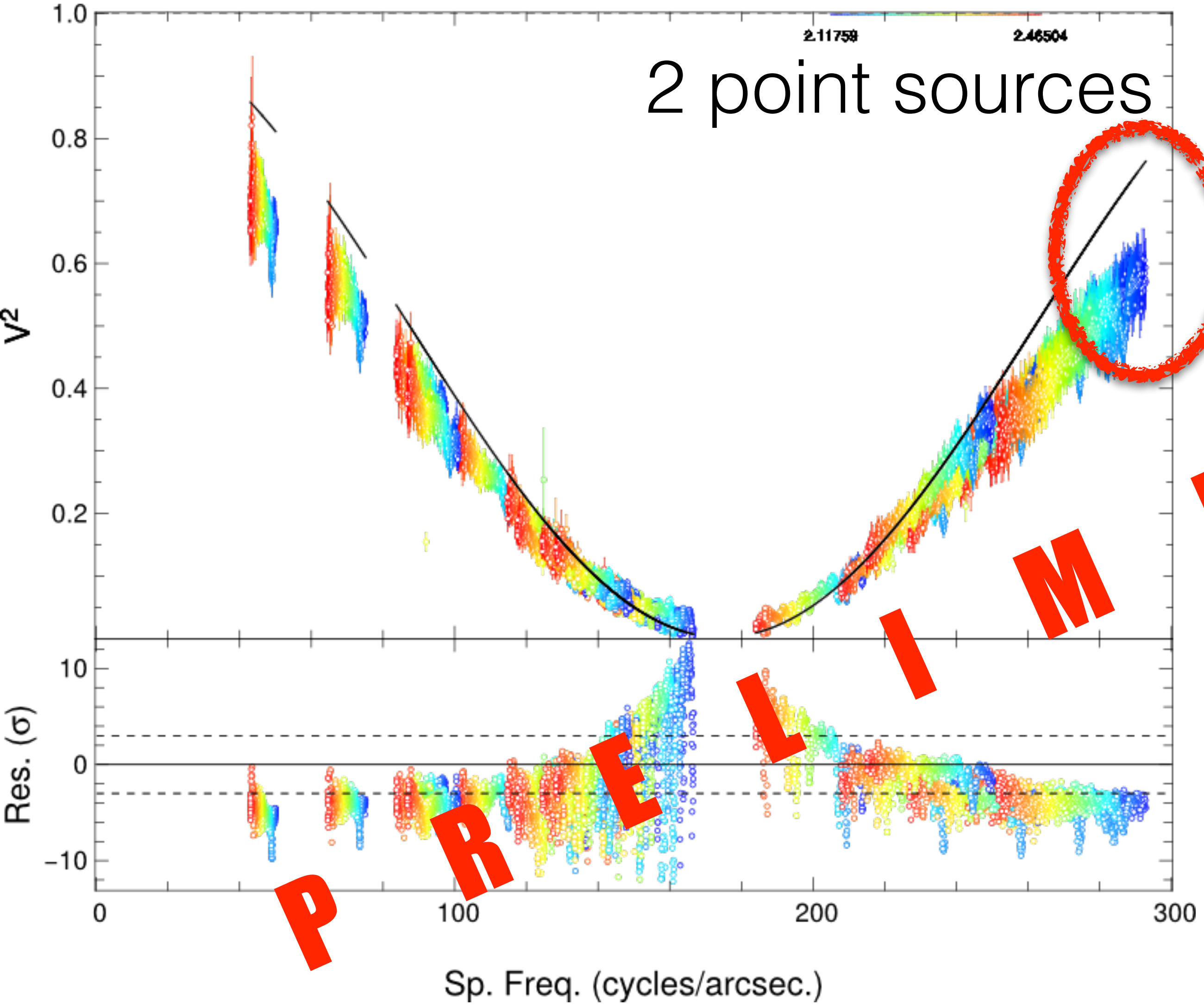
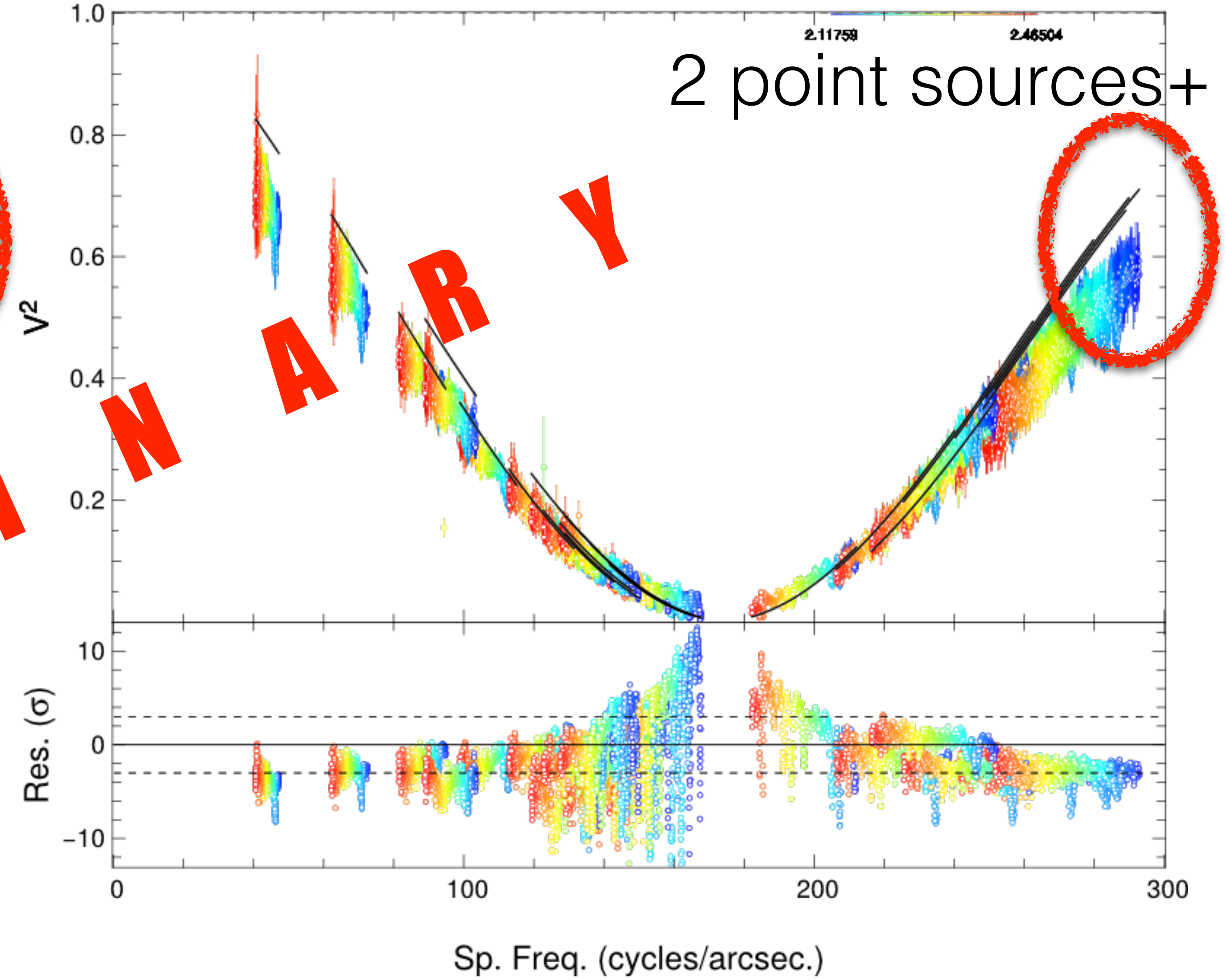
COMPARISON WITH OBSERVED VISIB

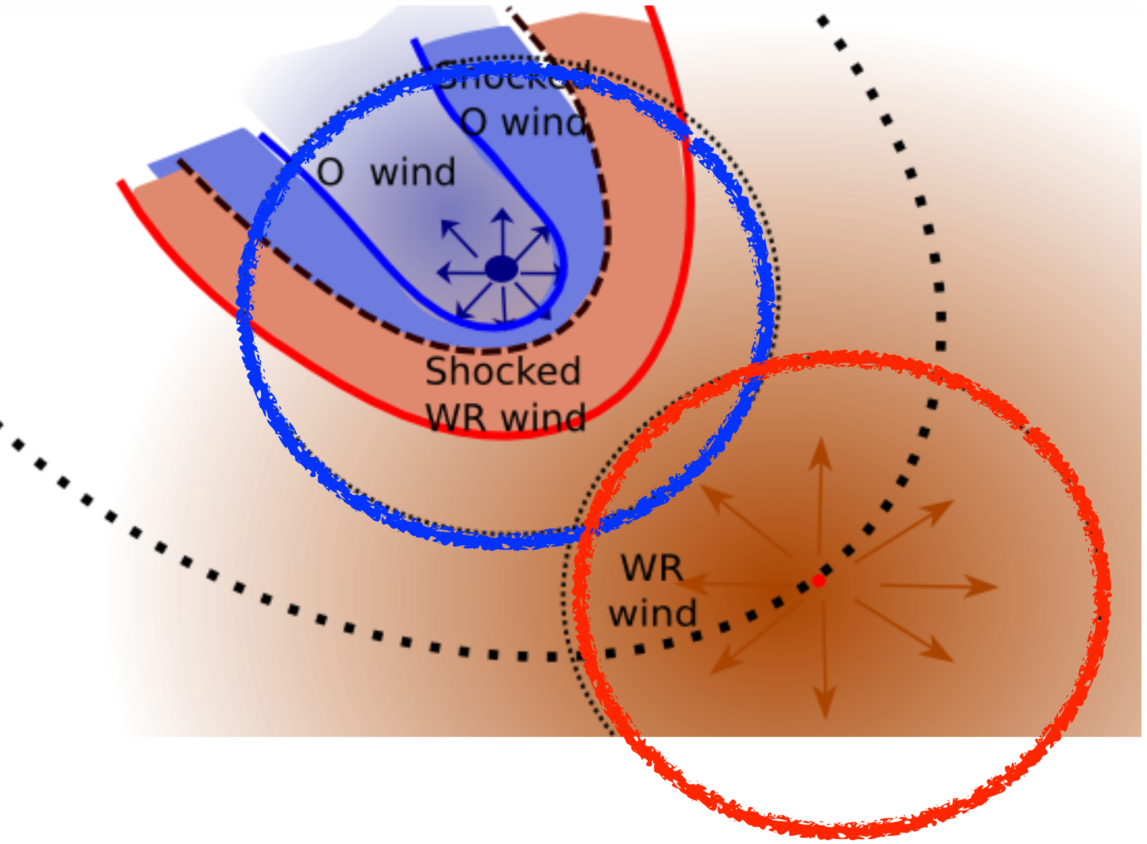
Visibility -> spatial extension of system +





Additional extended component necess

CONTINUUM ANALYSIS



2 components

CONNECTING THE DOTS

1. **Colliding stellar winds**

Combining hydrodynamic simulations with interferometric observations in Gamma 2 Velorum
(Lamberts, Millour et al, accepted)

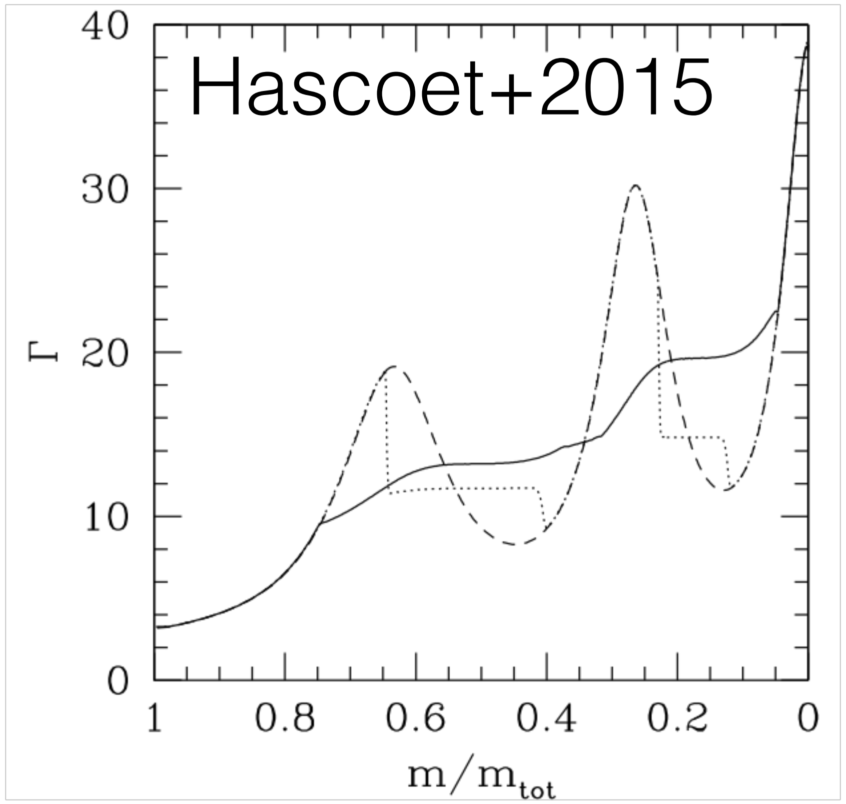
2. **Gamma-ray bursts**

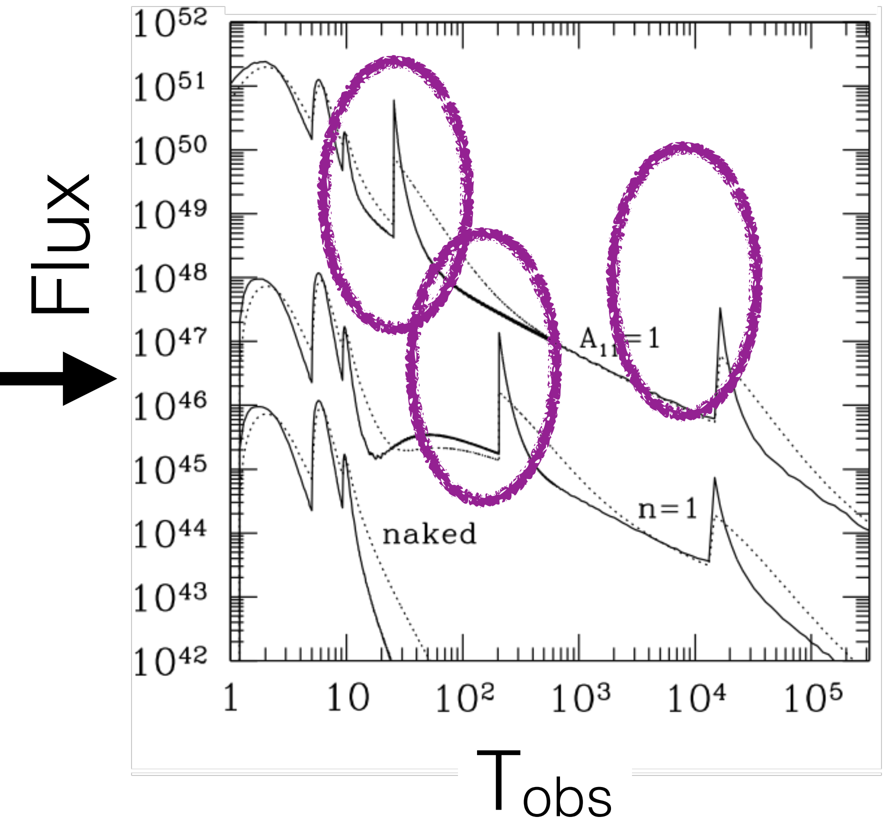
Explaining X-ray flares in GRB afterglows with relativistic shock interactions
(Lamberts, Daigne, submitted)

3. **Gravitational wave progenitors**

The formation conditions of GW 150914
(Lamberts, Garrison-Kimmel, Clausen, Hopkins, 2016)

FLARES FROM INTERNAL SHOCKS





Complex velocity: variable Lorentz factor -> internal shocks.

Emission when crossed by reverse shock

Ballistic model -> hydrodynamic validation needed

1. **Colliding stellar winds**

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(Lamberts, Millour et al, accepted)

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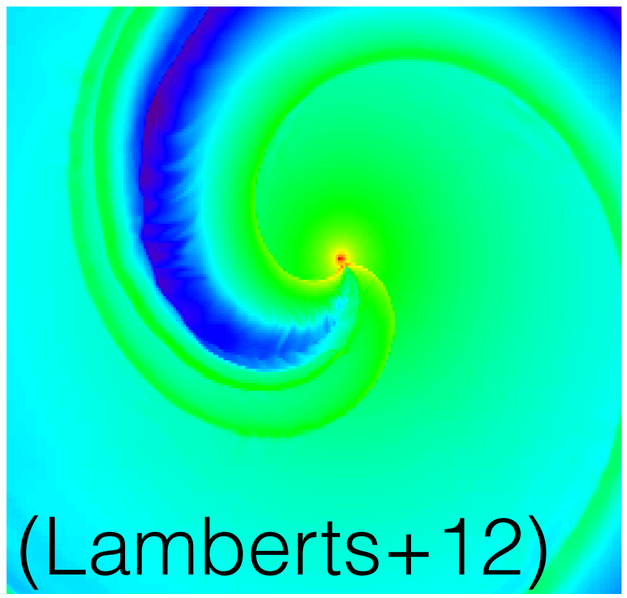
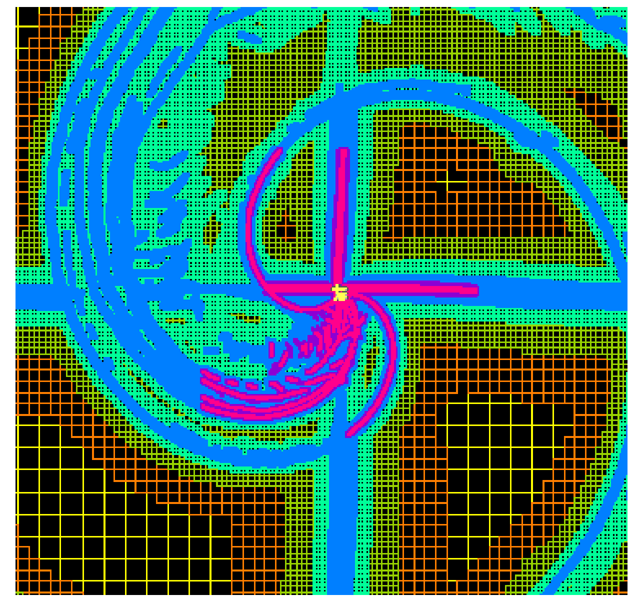
HYDRO SIMULATIONS WITH RAMSES

RAMSES (Teyssier+2002) solves hydro with adaptive mesh (AMR) -> great for discontinuities

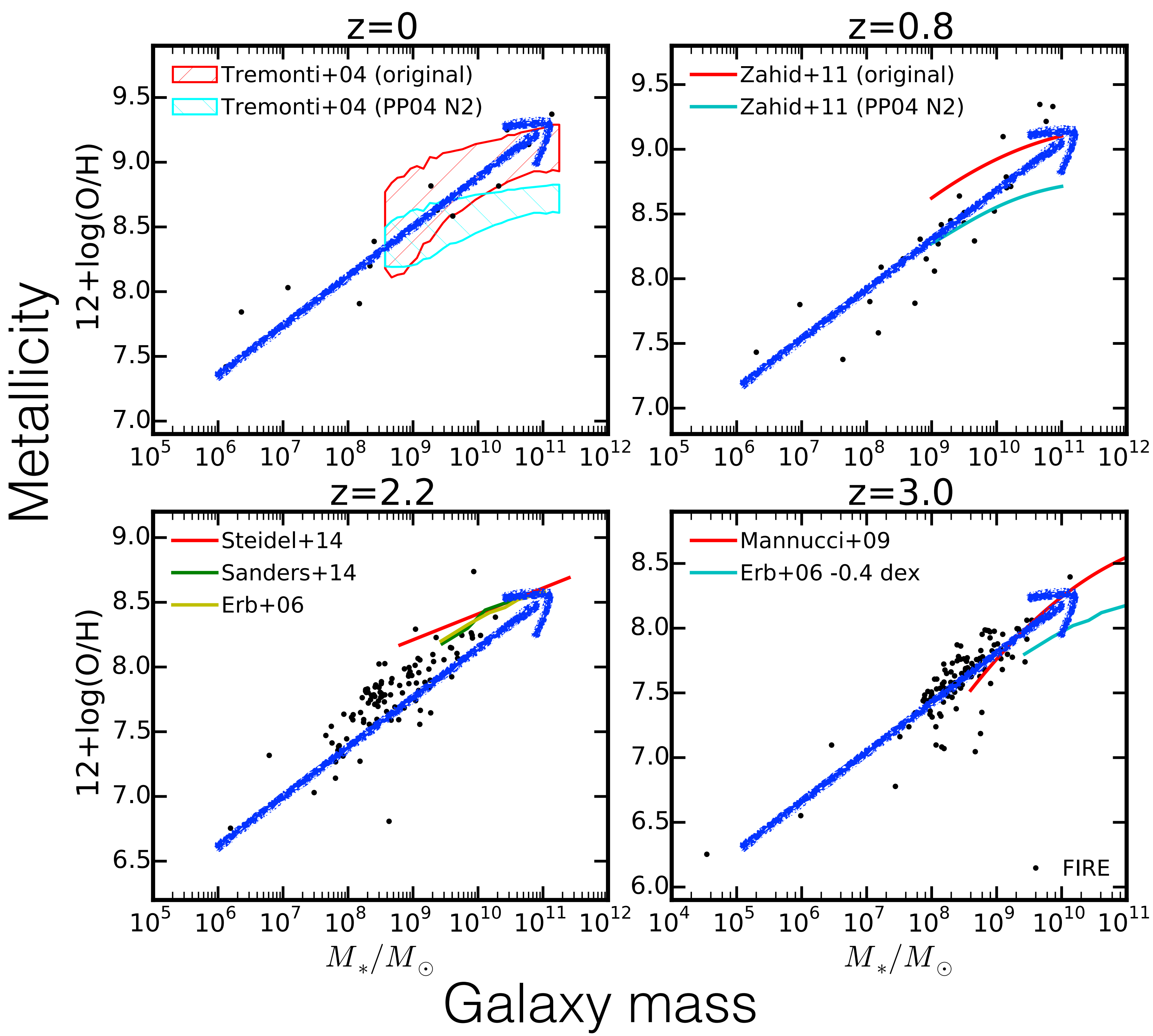

(Lamberts+12)



My setup:

- L_{box}=16 x separation, 3D
- resolution ~ R_{sun}
- radiative cooling
- orbital motion

MASS-METALLICITY RELATION



(Ma+2016 /FIRE simulations)

Z increases over time

mass dependence ~constant

limited scatter but systematic uncertainties

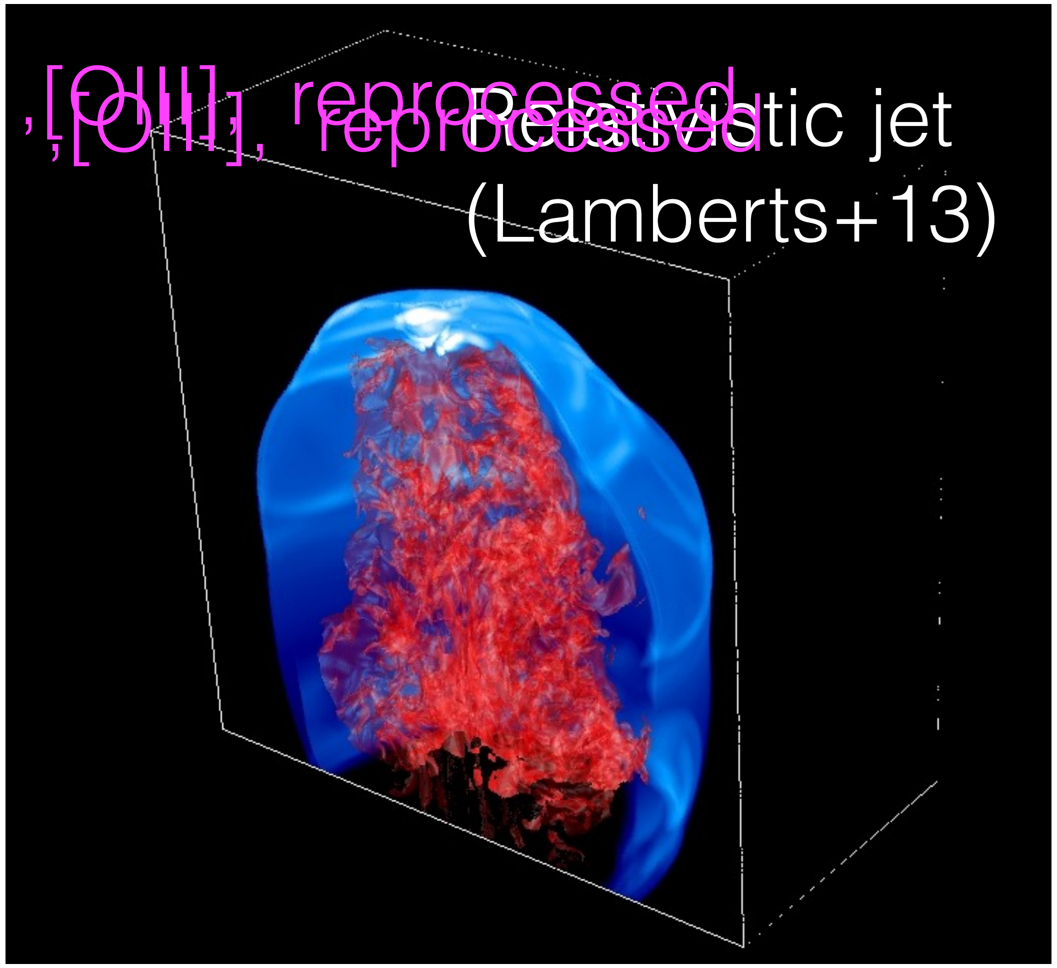
high z, low M hard to measure

NUMERICAL DEVELOPMENTS

RAMSES (Teyssier+2002) 3D hydro+ adaptive mesh refinement (AMR)

UV, H , [OIII], reprocessed
UV, H , [OIII], reprocessed

~500 cores : Lamberts+11,12,17a

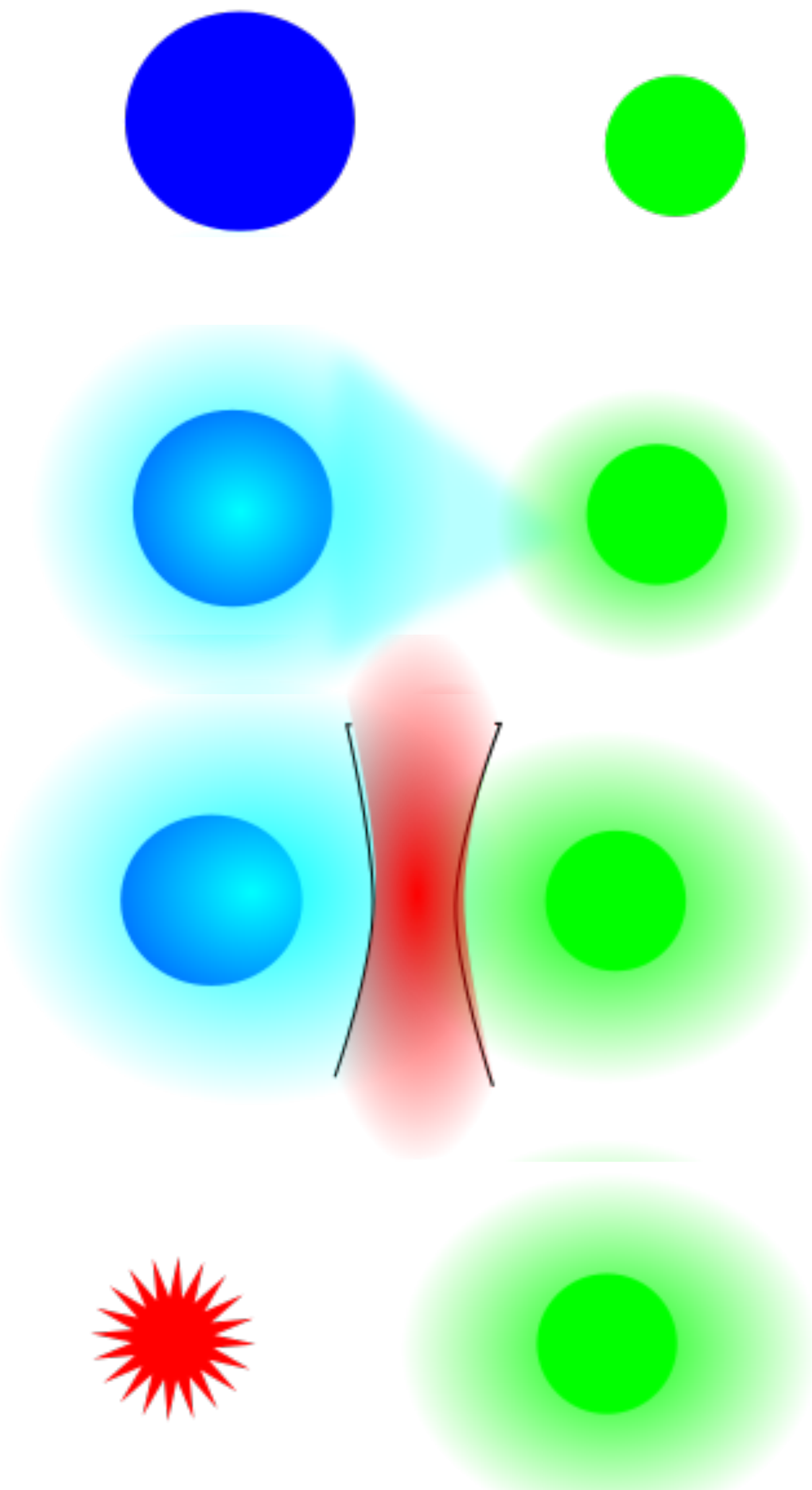


Extension to special relativity, public
Lamberts+13, Dubus, Lamberts+15,
Lamberts+17b

Cosmological simulations : GADGET2
Lamberts+15, Lamberts+17c

Post-processing : thermal, non-thermal emission, absorption spectra

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**+11,12,17a)*

collapse 1: supernova/gamma-ray burst

Time domain astronomy: gamma-rays to radio

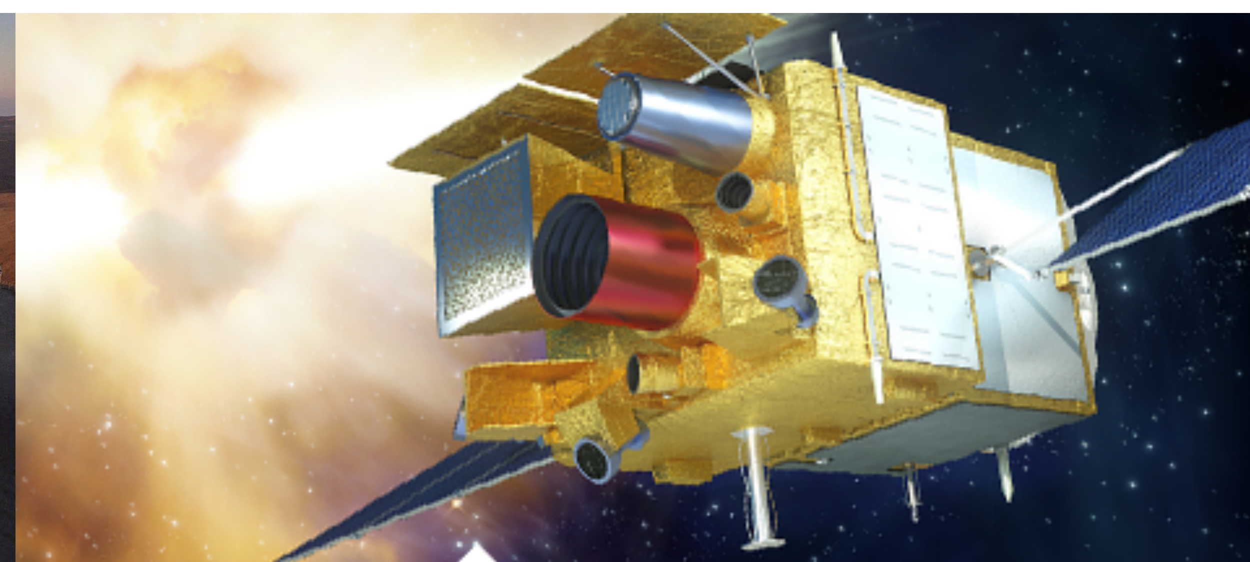
Gravitational waves/neutrinos

*(**Lamberts**, Daigne, 2017b)*

SIGNATURES OF MASSIVE BINARIES

FROM COLLIDING WINDS TO ZOMBIE BLACK HOLES

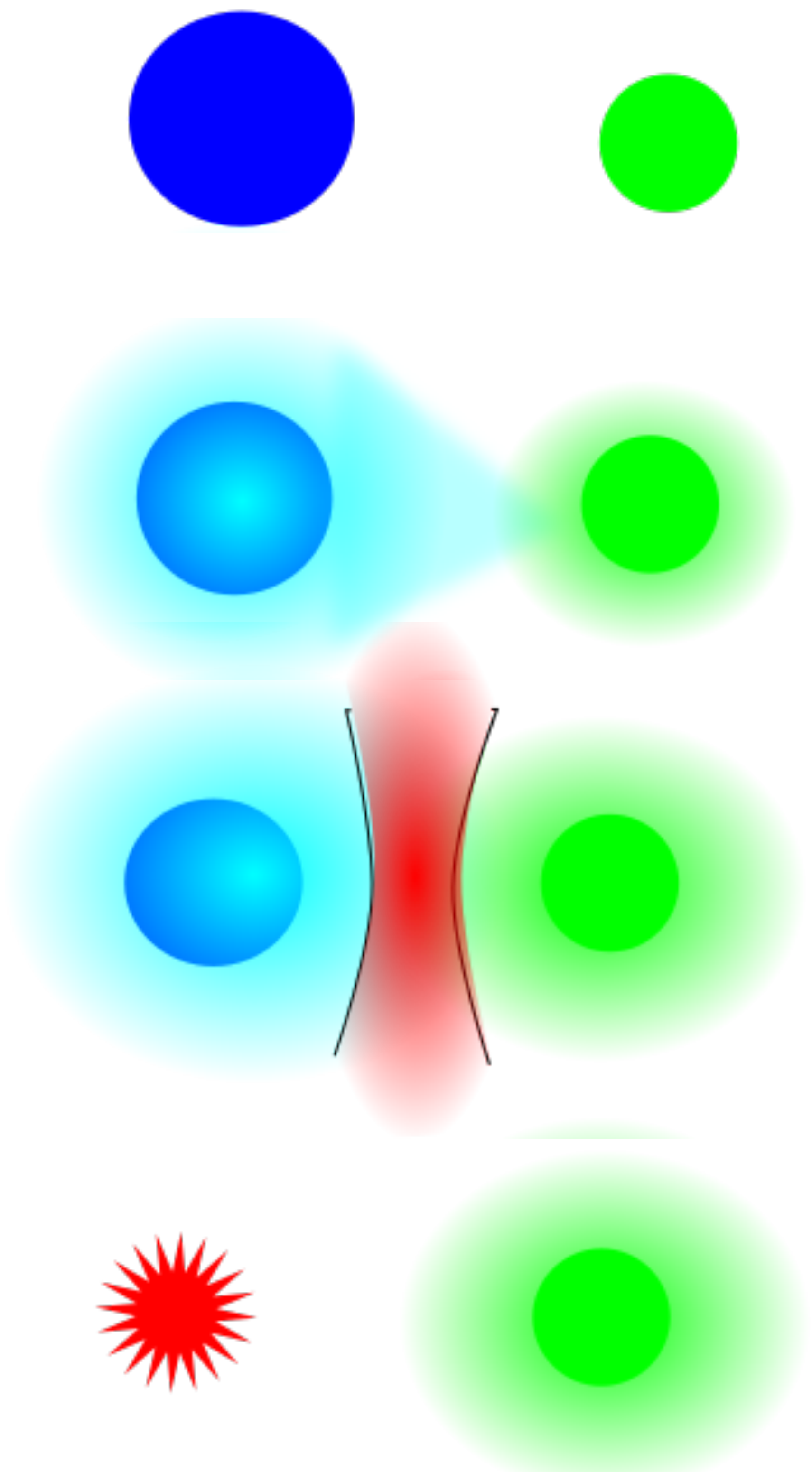
Astrid Lamberts


Caltech

OCA, Nice, March 14, 2017

NO COMPACT OBJECT : STELLAR ASTROPHYSICS



Formation : 30 M_{sun} O stars

VLT/E-ELT/JWST

main sequence mass transfer

VLTI

wind collisions

X-rays, line variability, radio, dust

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

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(***Lamberts***, *Daigne, 2017b*)