BLACK HOLES IN THE GRAVITATIONAL WAVE COSMIC LANDSCAPE

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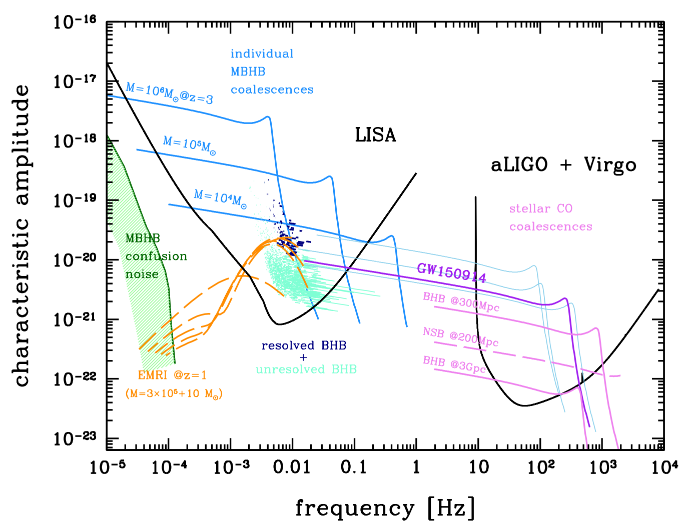
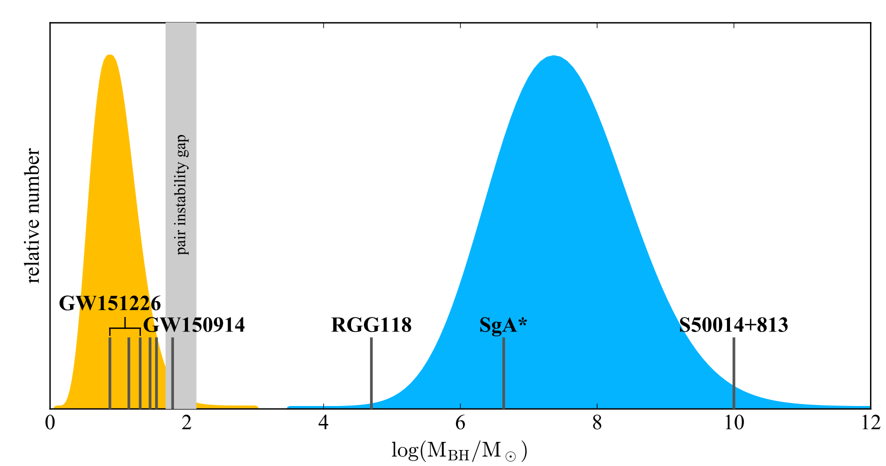
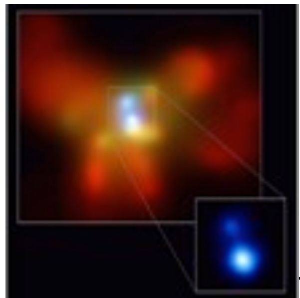
LISA Consortium Board

PROGRESS ON OLD AND NEW THEMES IN COSMOLOGY

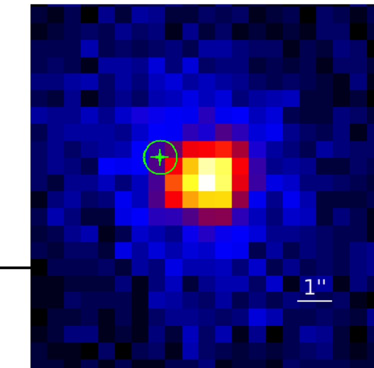
PALAIS DES PAPES AVIGNON, 24 APRIL 2017



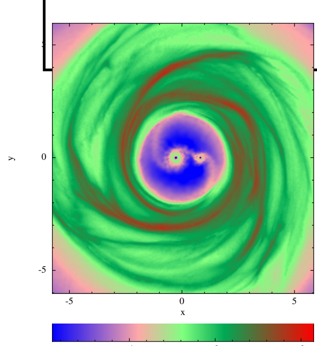


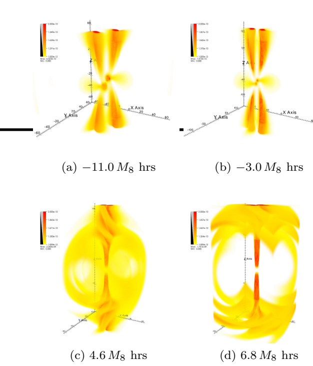


OUTLINE

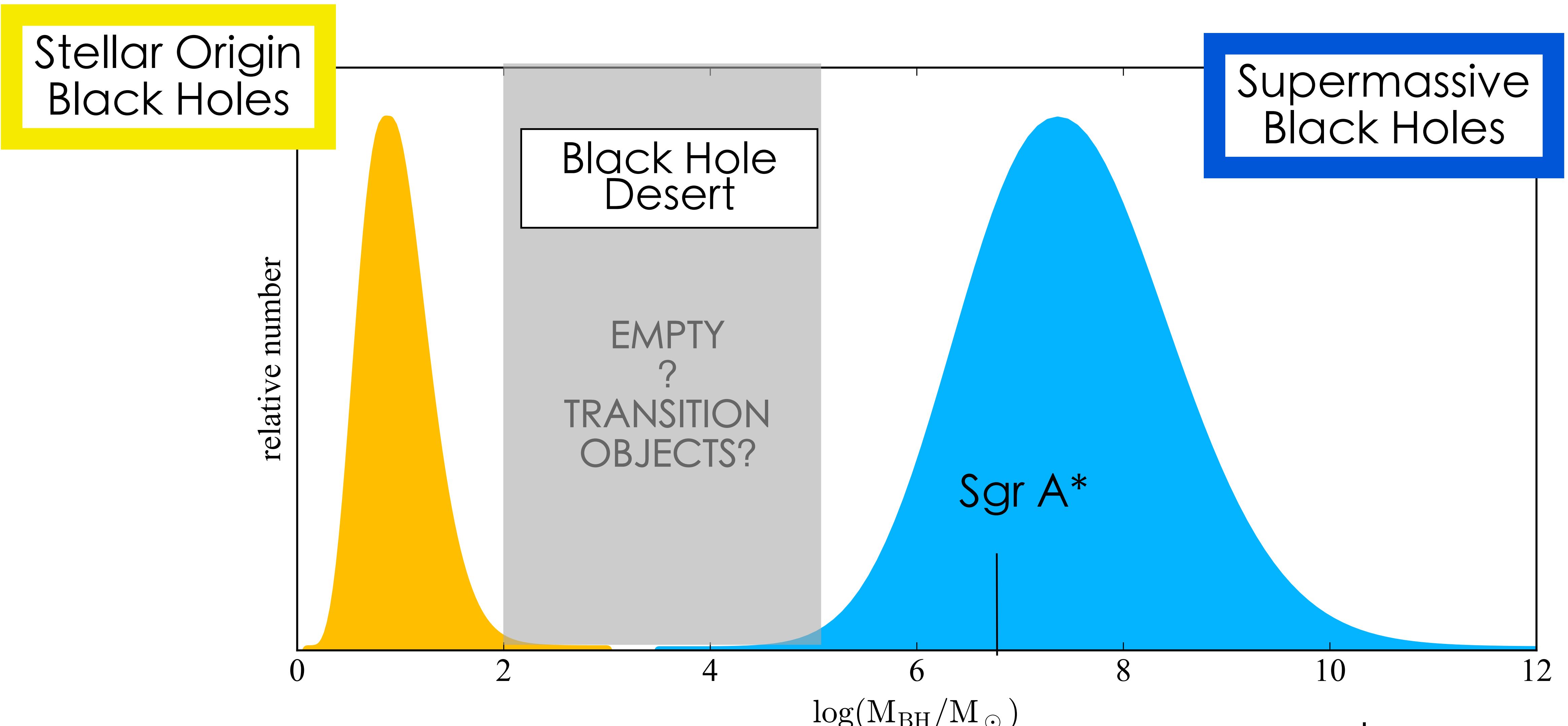


- black holes of the EM universe in a nut shell
- black hole "binaries" of the GW universe
- digression of stellar-origin black holes
- the "fil rouge" between "stellar-origin" and "seed" black holes in the high redshift universe
- LISA golden binaries - EM counterparts - cosmography?
- 3C168: sign of a recoiling massive black hole that merged few Myrs ago?





THE BLACK HOLES
OF
THE ELECTROMAGNETIC UNIVERSE



cartoon

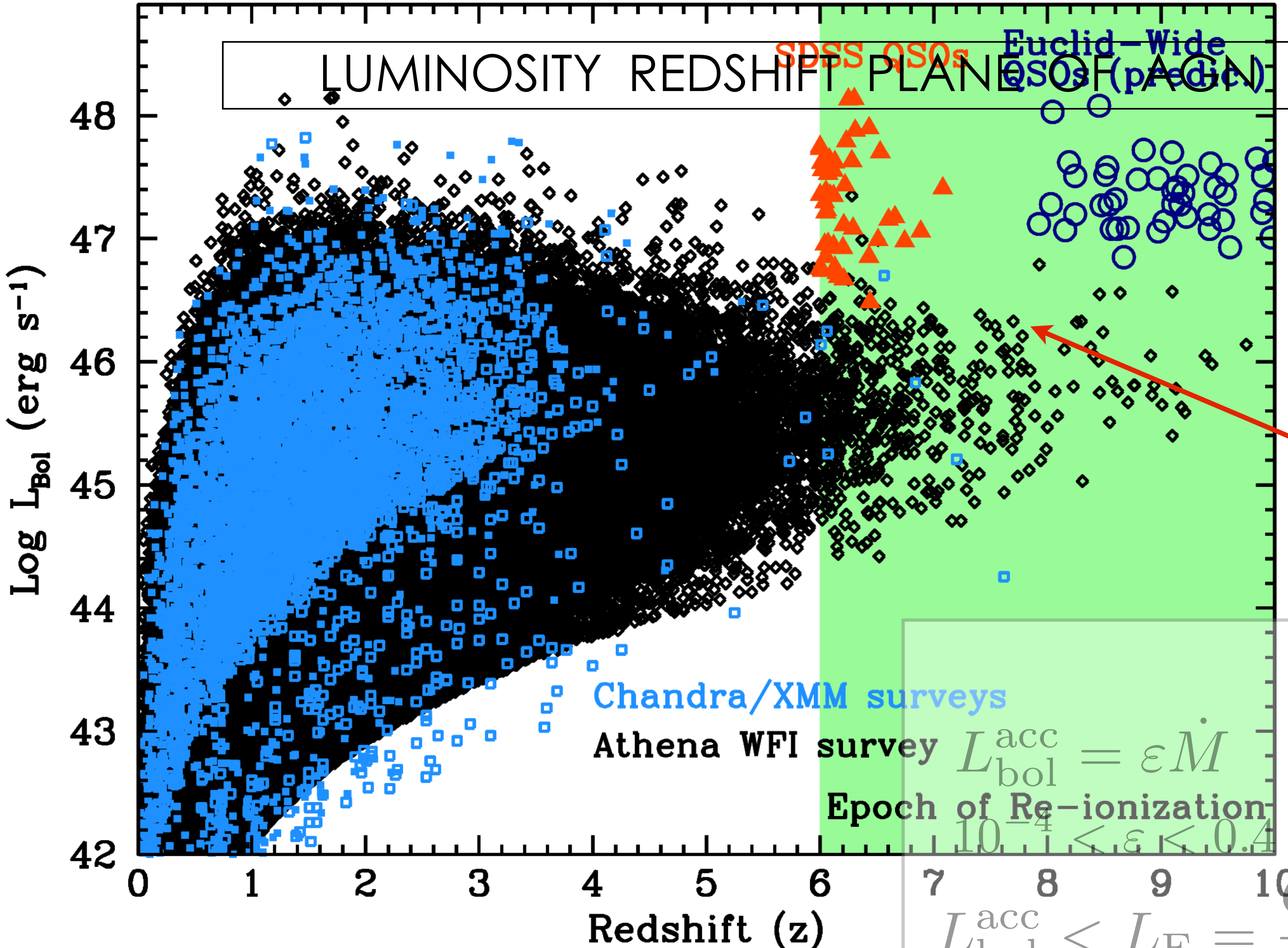
Accretion Paradigm

$$L_{\mathrm{bol}}^{\mathrm{acc}} = \varepsilon \dot{M}$$

$$10^{-4} < \varepsilon < 0.4$$

$$L_{\mathrm{bol}}^{\mathrm{acc}} < L_{\mathrm{E}} = \frac{G M_{\mathrm{BH}} m_{\mathrm{p}} c}{4\pi\sigma_{\mathrm{T}}}$$

LUMINOSITY REDSHIFT PLANE OF AGN



ULAS J1120+0641
@z=7.08
770 Myrs
A RARE OBJECT
10^9 $M_\odot$
SMBH

$$L_{\rm bol}^{\rm acc} = \varepsilon \dot{M}$$

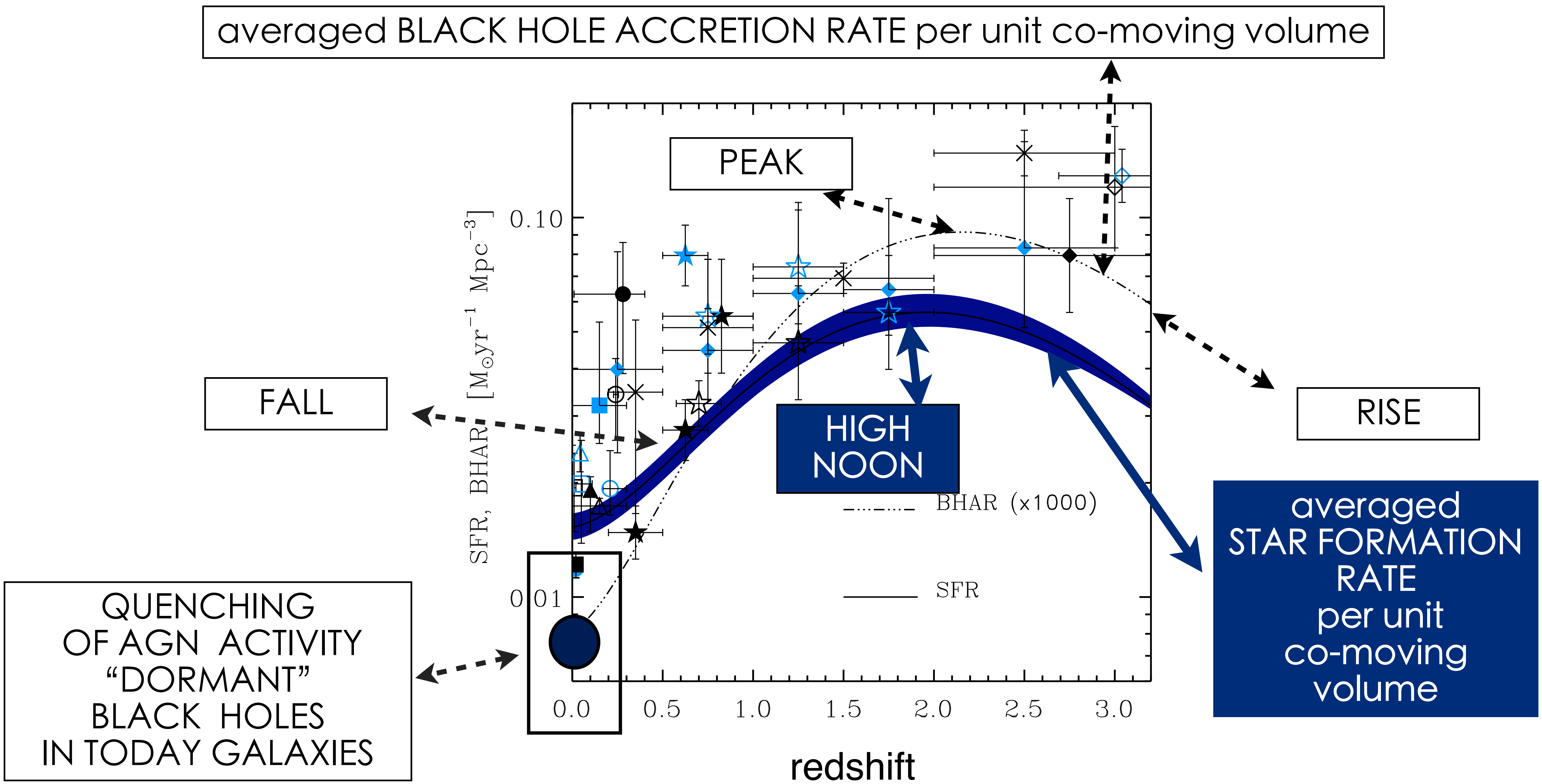
$$10^{-4} < \varepsilon < 0.4$$

$$L_{\rm bol}^{\rm acc} < L_{\rm E} = \frac{G M_{\rm BH} m_{\rm p} c}{4\pi\sigma_{\rm T}}$$

Athena white paper

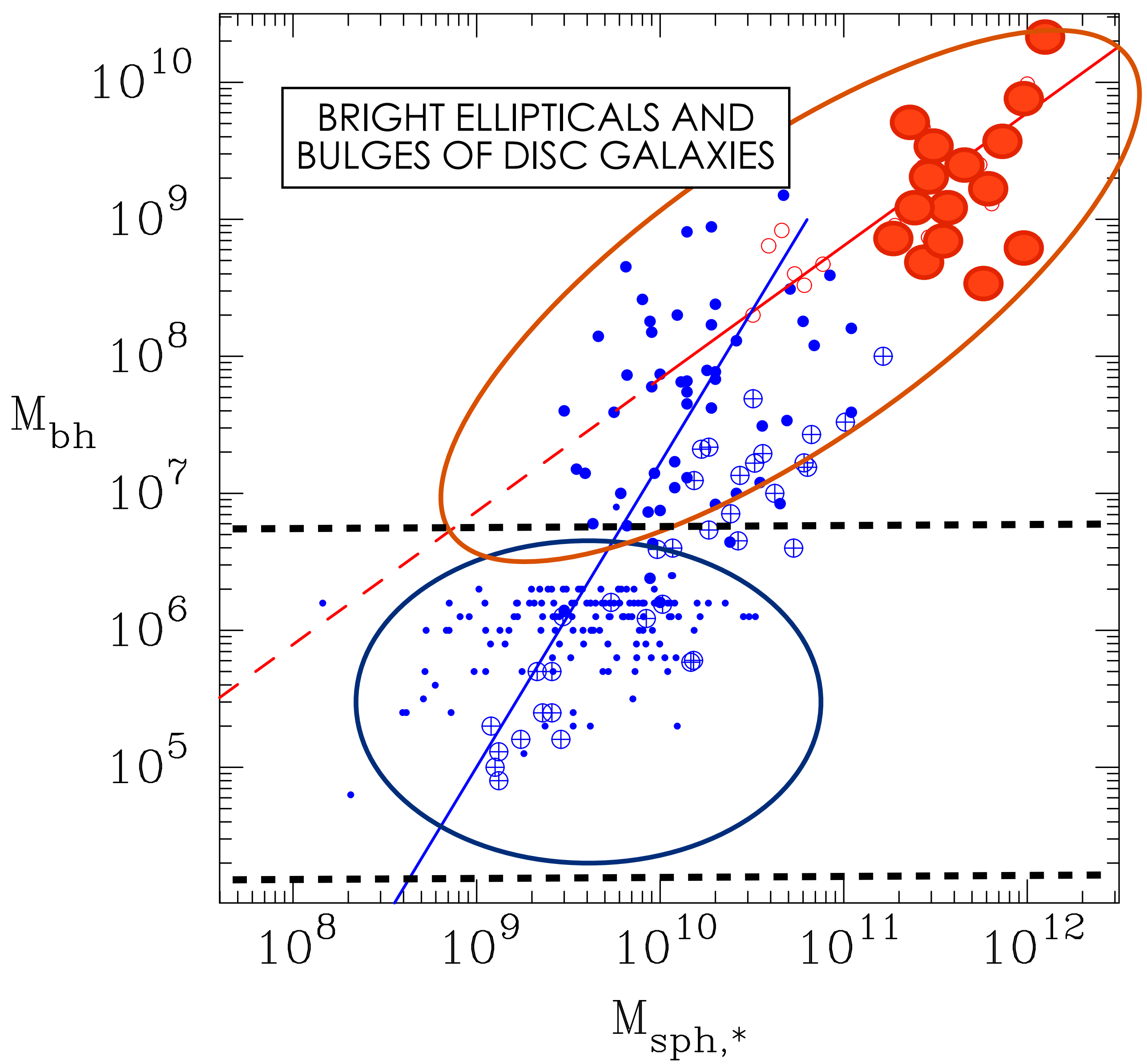
STARS & AGN
COSMIC EVOLUTION

“ THE COSMIC HIGH NOON”



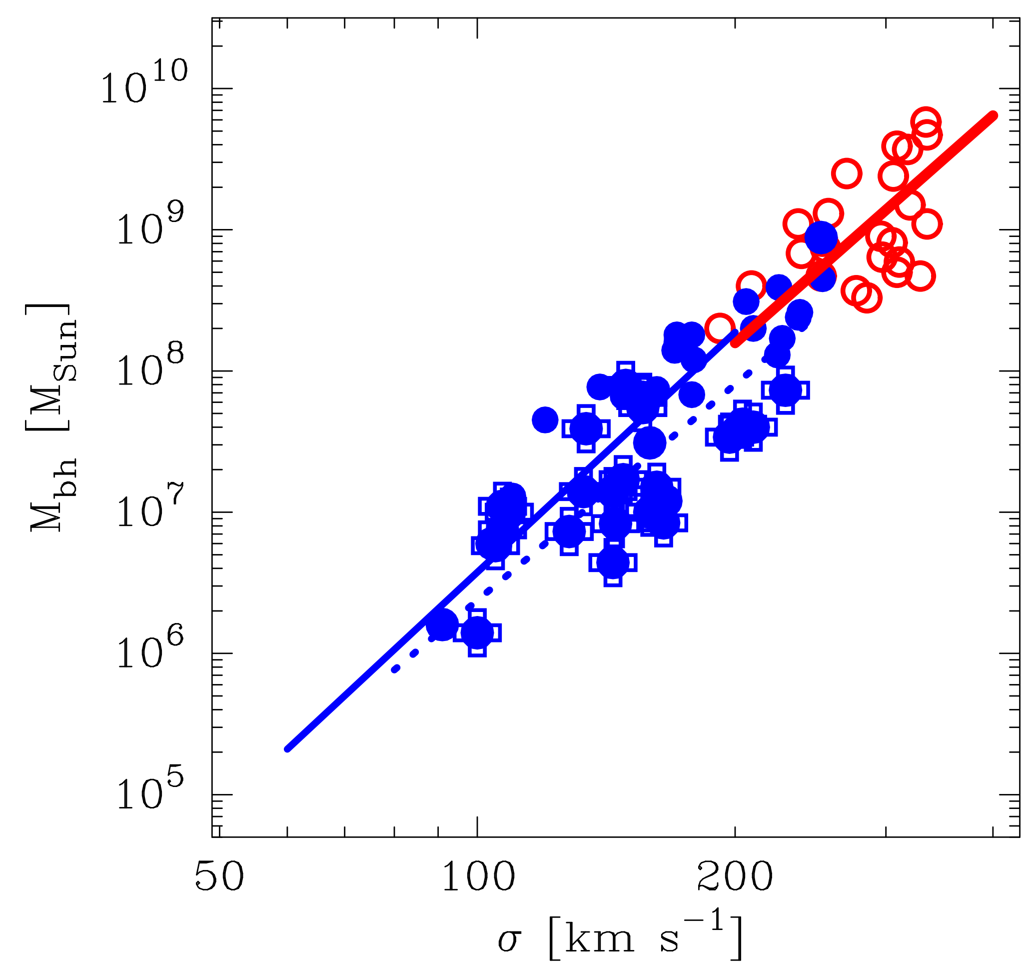
the build up of stars in the Universe is nearly synchronous to the build up of light from accretion
<u>the rate of “gas consumption” to feed star formation and black hole growth go hand in hand</u>

- discovery of fundamental scaling relations: the relations indicate that the processes fostering the growth of stars and black holes are physically linked to the environment and the way structure formation proceeds, but that energy/momentum deposition by the active black hole + stellar feedbacks affect the BH growth inside the galaxy



$$M_{\rm BH} \sim 10^{-3} M_{{\rm psh},*}$$

- symbiotic evolution implies the necessity of understanding black hole and galaxy formation within a "cosmological framework"



Graham+, 2016
Kormendy & Ho, 2014 for a review

- X-ray light from accretion <-> mass increment
- mass density increment that black holes in the mass range (log M_{BH}~8-9) experienced from redshift 3 to the present

$$\Delta\rho_{\bullet}^{\mathrm{AGN}} \sim 3.5 \times 10^5\,(\varepsilon/0.1)^{-1}\,M_{\odot}\ \mathrm{Mpc}^{-3}$$

- mass density of the dormant black holes at z=0

$$\rho_{\bullet} \sim [2-5] \times 10^5\,M_{\odot}\ \mathrm{Mpc}^{-3}$$

- supermassive black holes have grown in mass due to radiative efficient accretion and mergers

- when and where and how black hole seeds form is UNKNOWN
- seeds are rare & EM dim

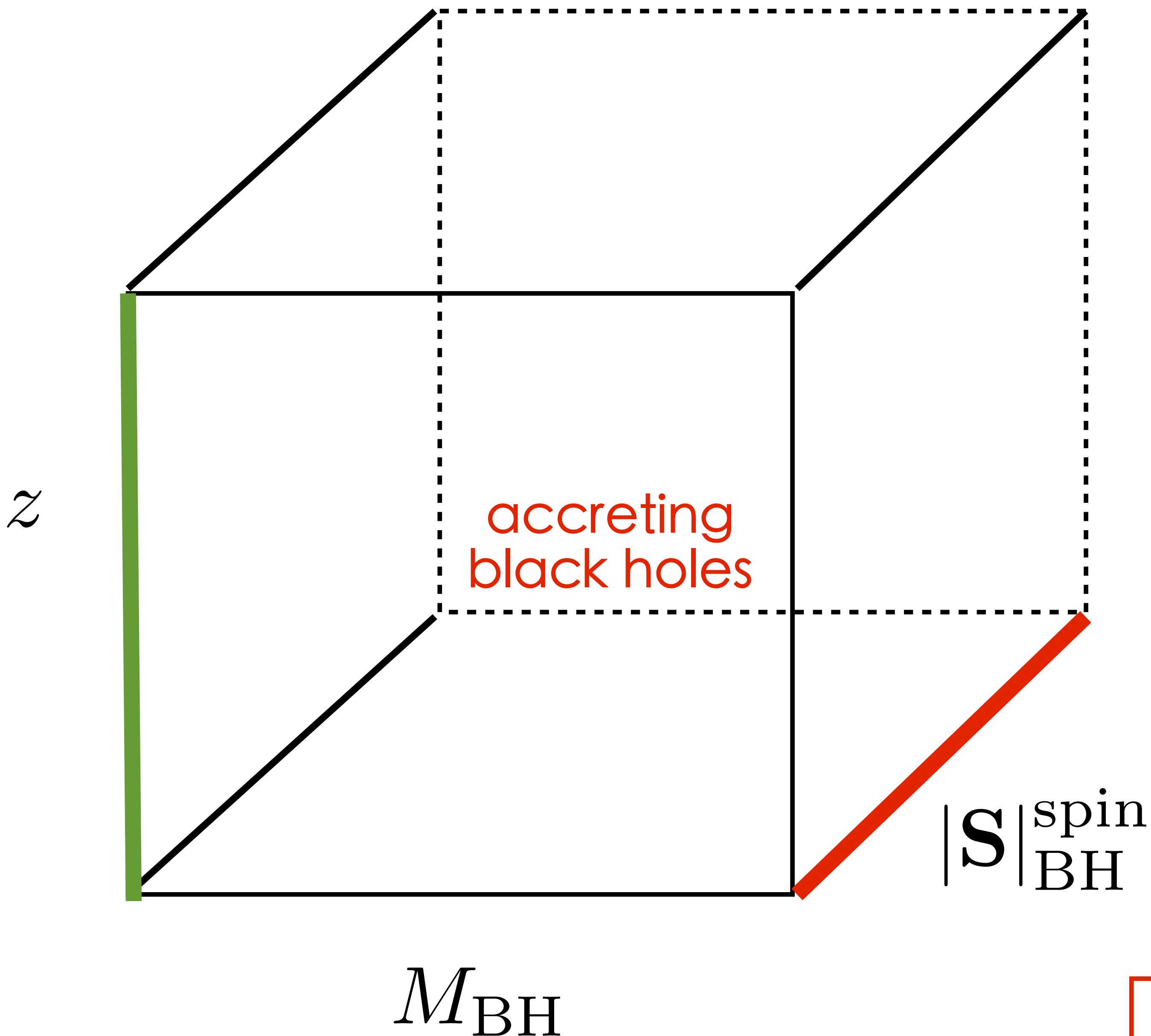
  - black holes in AGN do not provide any information on the seeding mechanism
  - <u>loss of memory of the mass and spin at birth</u>
  - <u>spin is modeled by accretion and mergers</u>

    - spin increases from 0 to 1 after accreting (for prograde accretion) $\sqrt{6}M_{\rm BH,initial}$
    - spin decrease from 1 to 0 after accreting (for retro-grade accretion) $\sqrt{3}/2M_{\rm BH,initial}$
    - accretion torques re-orientation of BH (disc-spin alignment)
    - e-folding times for accretion of ~ 100 million years
    - chaotic versus coherent accretion shape the spins in relation to the environment and feeding process

COLPI & SESANA 2016 for a review

Parameter space of accreting black holes in active galactic nuclei

- EM observations probe the “environment” close to the horizon
- masses and spin moduli “indirectly measured” fitting the EM spectra

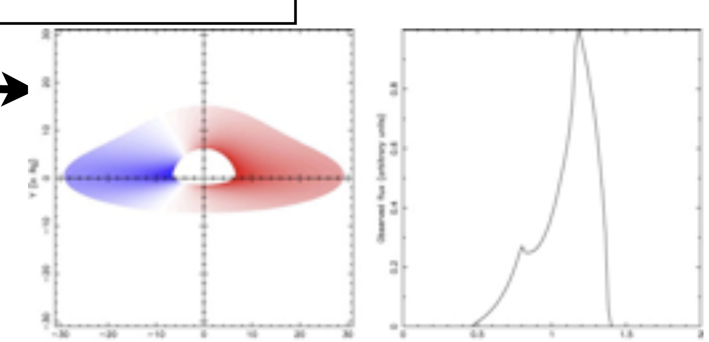


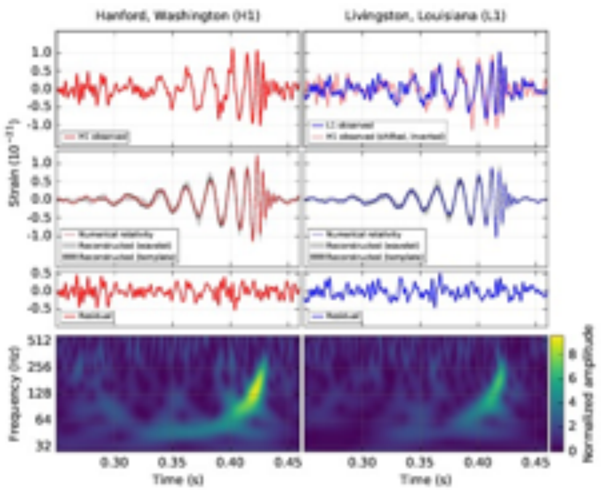
$$L^{\rm acc}_{\rm bol} = \varepsilon \dot{M}$$

$M_{\rm BH}$ → spectral lines

$M_{\rm BH}$ → fitting of the continuum

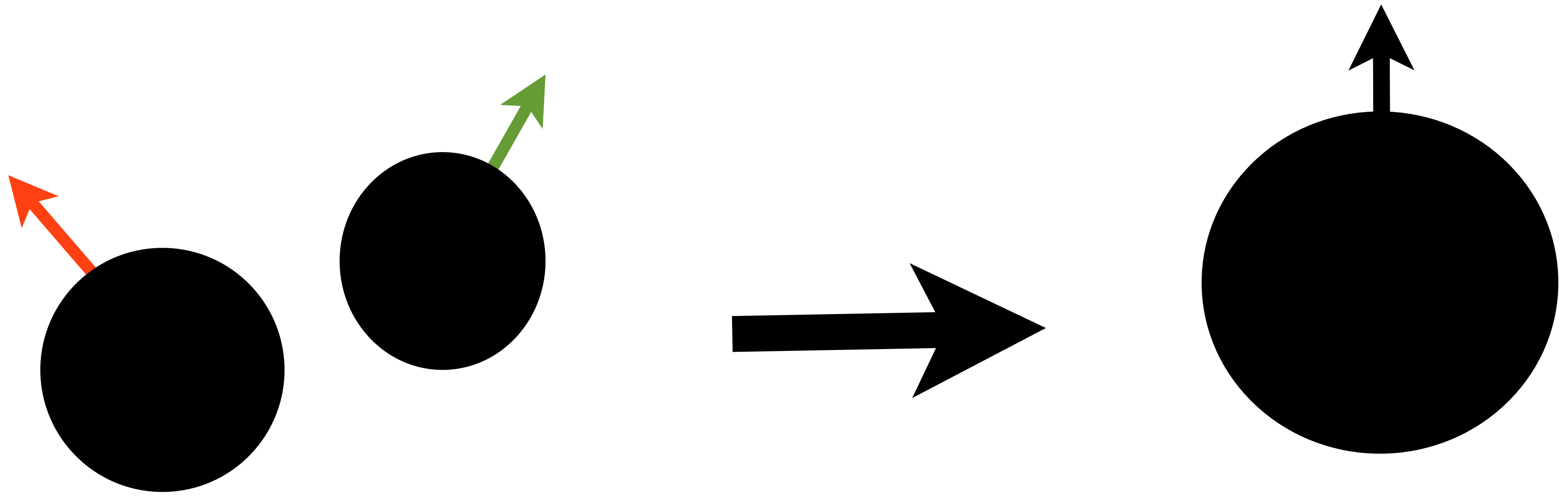
$\mathbf{S}^{\rm spin}_{\rm BH}$ → iron lines



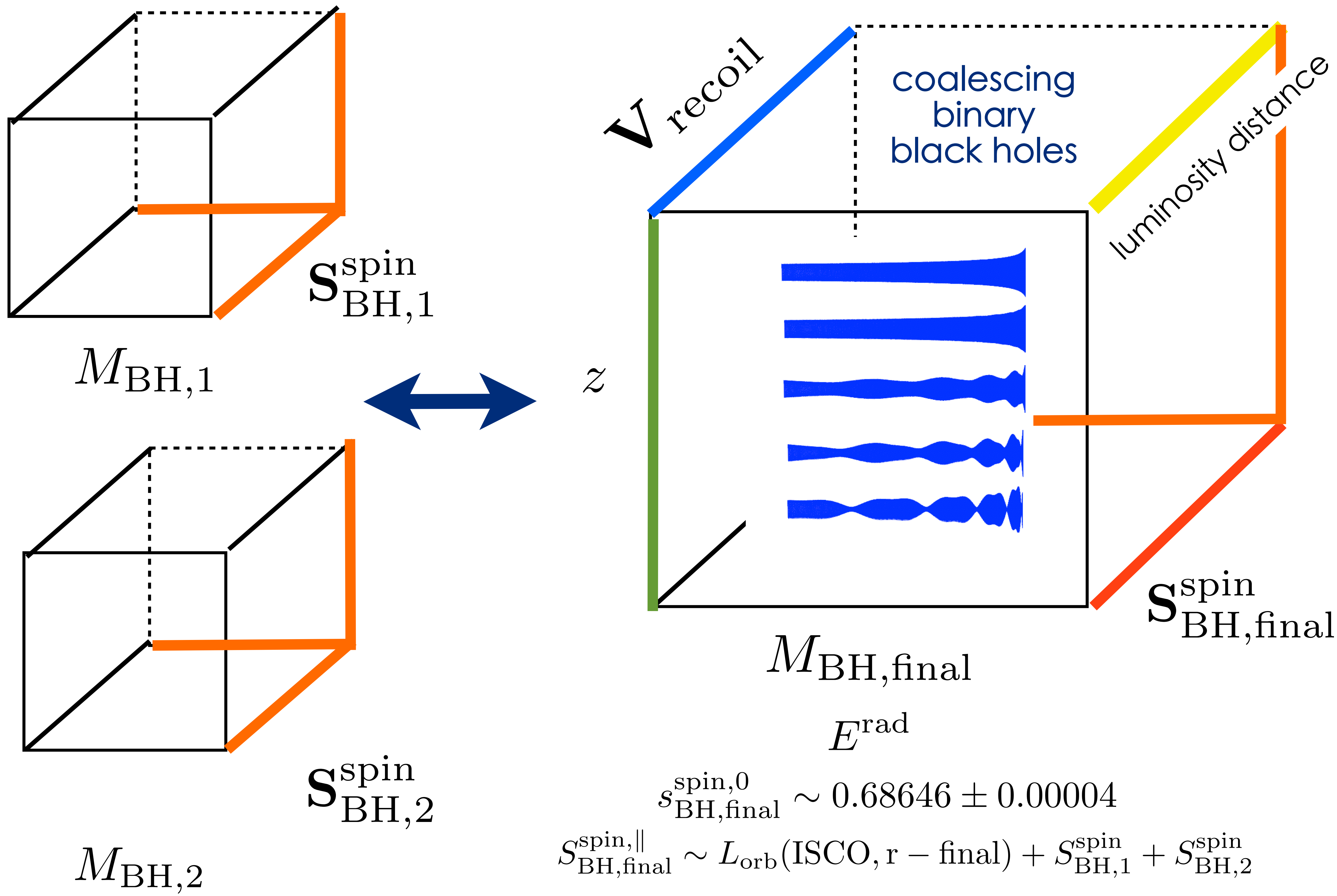


GRAVITATIONAL UNIVERSE
COALESCING BINARY BLACK HOLES

- the elementary "gravito-dynamic" process to probe gravity under extreme conditions is occurring in Nature



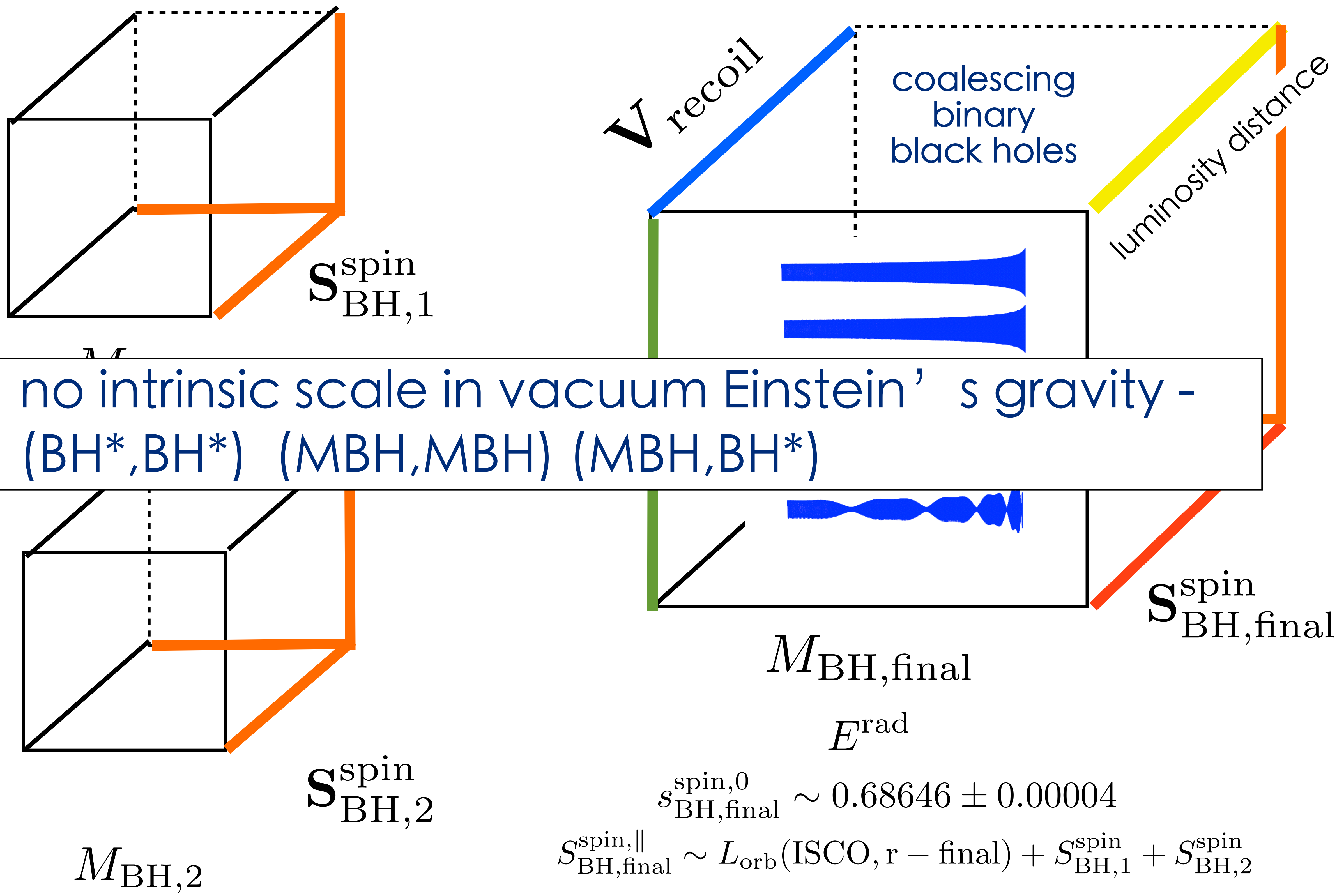
- exquisite and direct measurement of the "charges" of the "Kerr Black Hole"



$$s^{\mathrm{spin},0}_{\mathrm{BH,final}} \sim 0.68646 \pm 0.00004$$

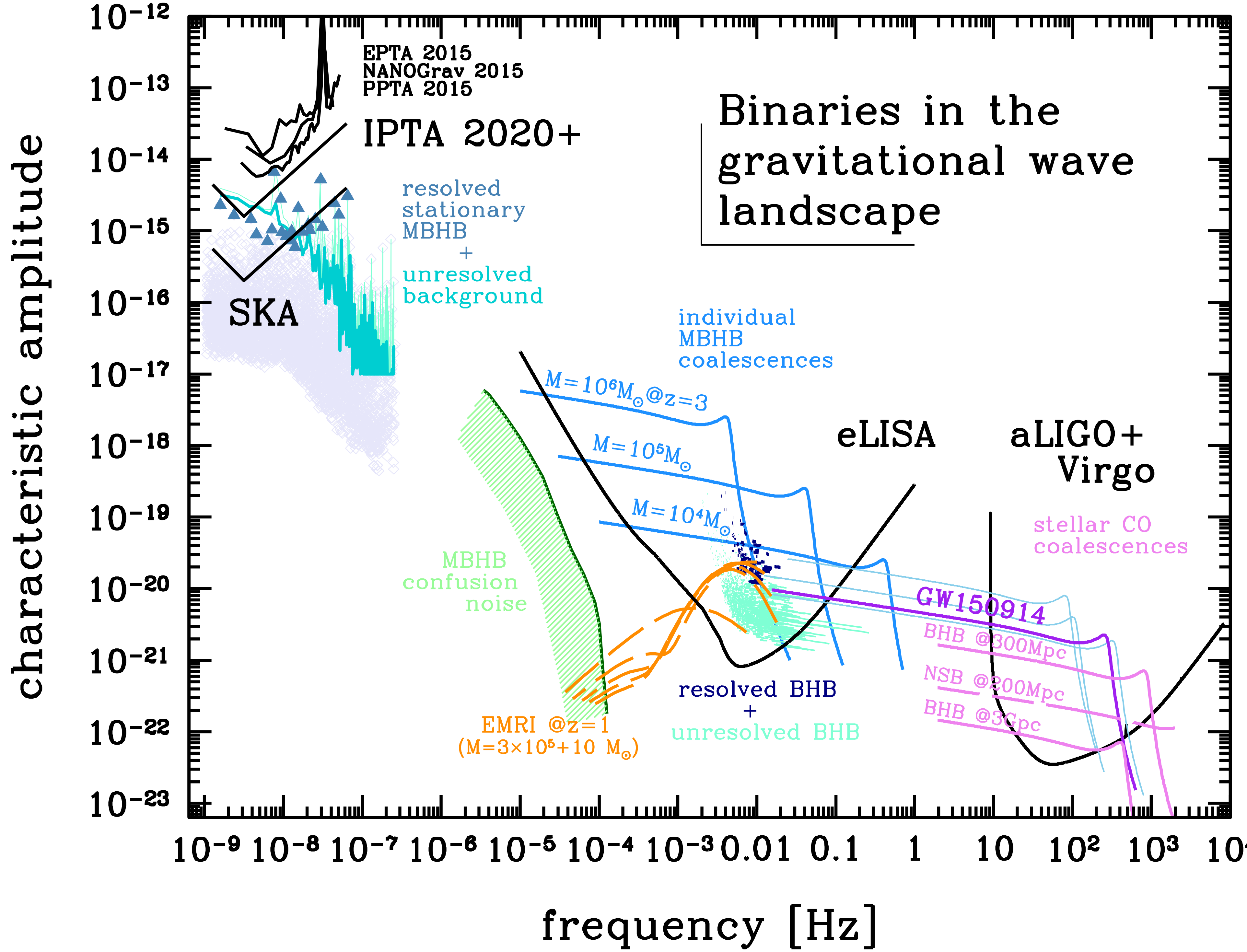
$$S^{\mathrm{spin},\|}_{\mathrm{BH,final}} \sim L_{\mathrm{orb}}(\mathrm{ISCO}, \mathrm{r}-\mathrm{final}) + S^{\mathrm{spin}}_{\mathrm{BH,1}} + S^{\mathrm{spin}}_{\mathrm{BH,2}}$$

- exquisite and direct measurement of the "charges" of the "Kerr Black Hole"

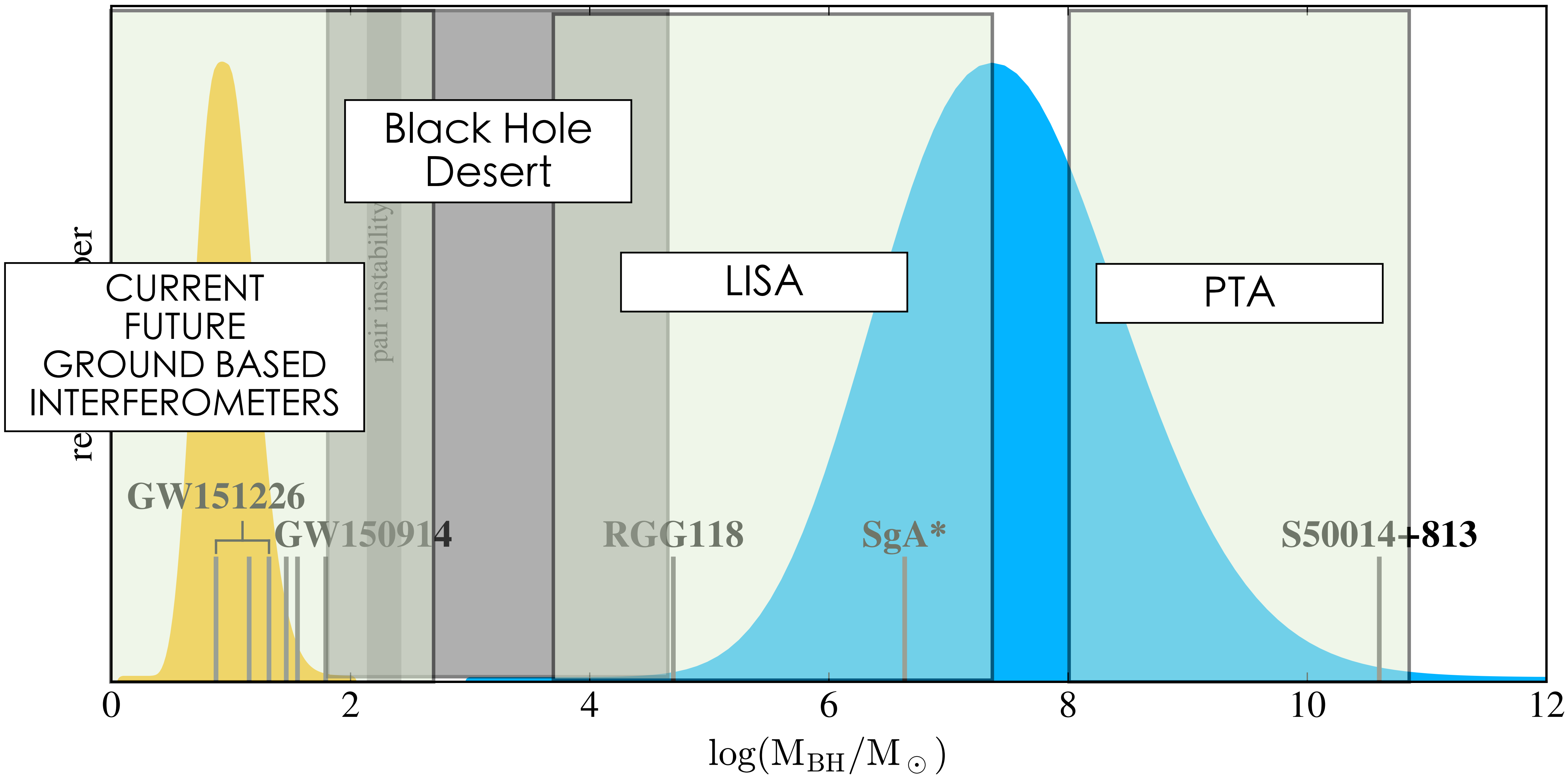


- no intrinsic scale in vacuum Einstein's gravity - (BH*,BH*) (MBH,MBH) (MBH,BH*)

THE MULTI-FREQUENCY GRAVITATIONAL UNIVERSE



frequency is mass @ coalescence



- stellar- origin black holes
- a little digression!

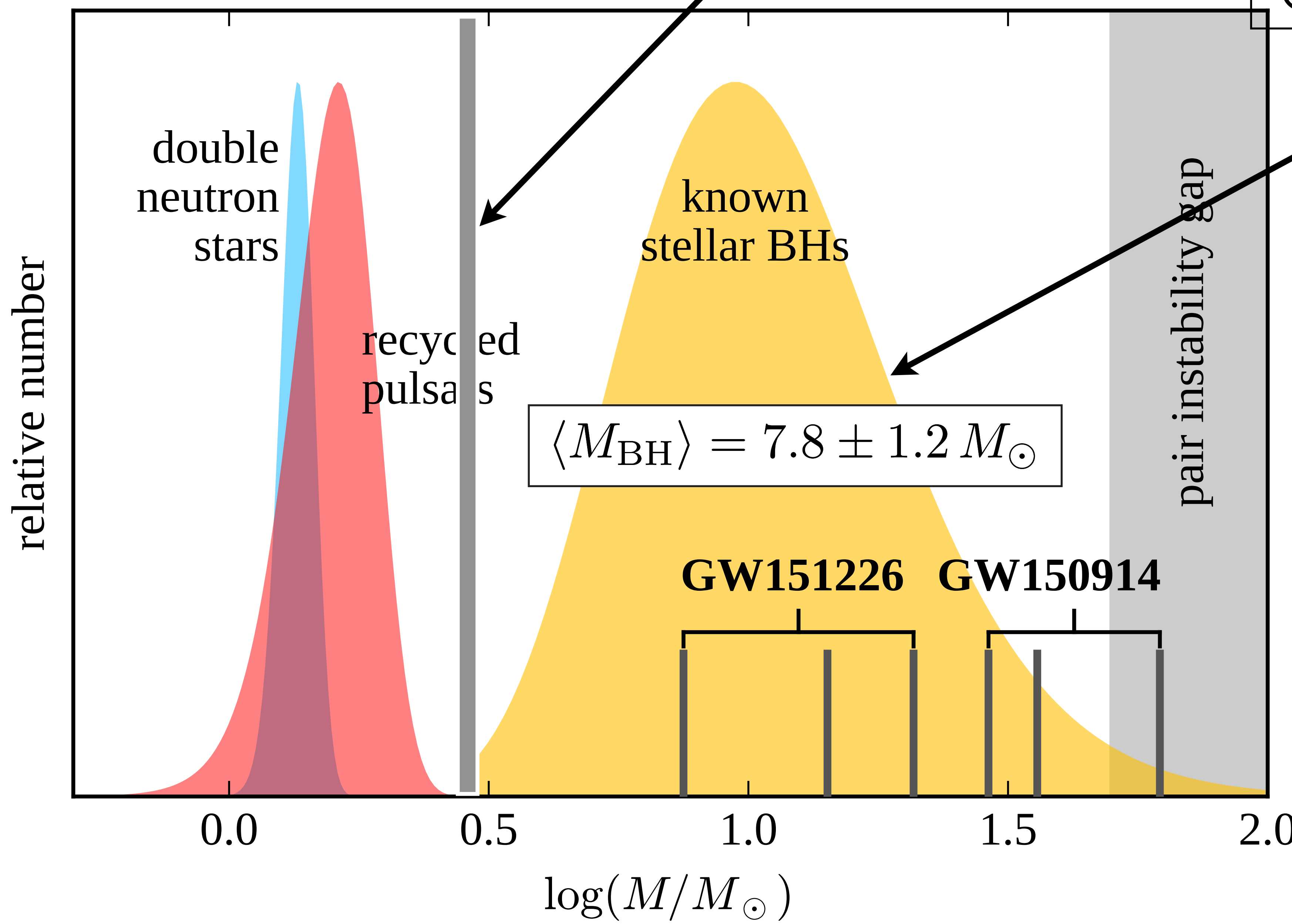
Neutron Stars
&
Stellar-Origin Black Holes

$\langle M_{\rm NS}^{\rm DNS} \rangle = 1.33 \pm 0.09\, M_\odot$

$\langle M_{\rm NS}^{\rm recycled} \rangle = 1.49 \pm 0.19\, M_\odot$

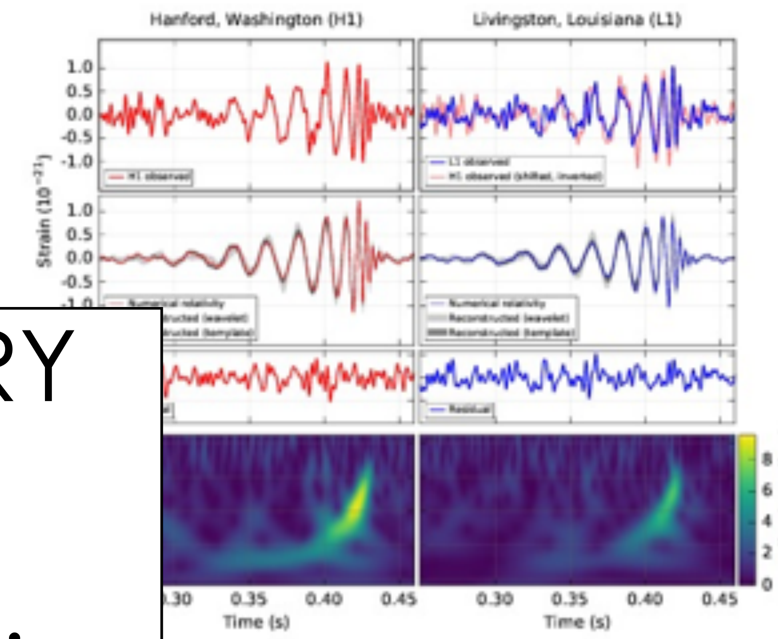
MAXIUM NEUTRON STAR MASS
~3 $M_\odot$

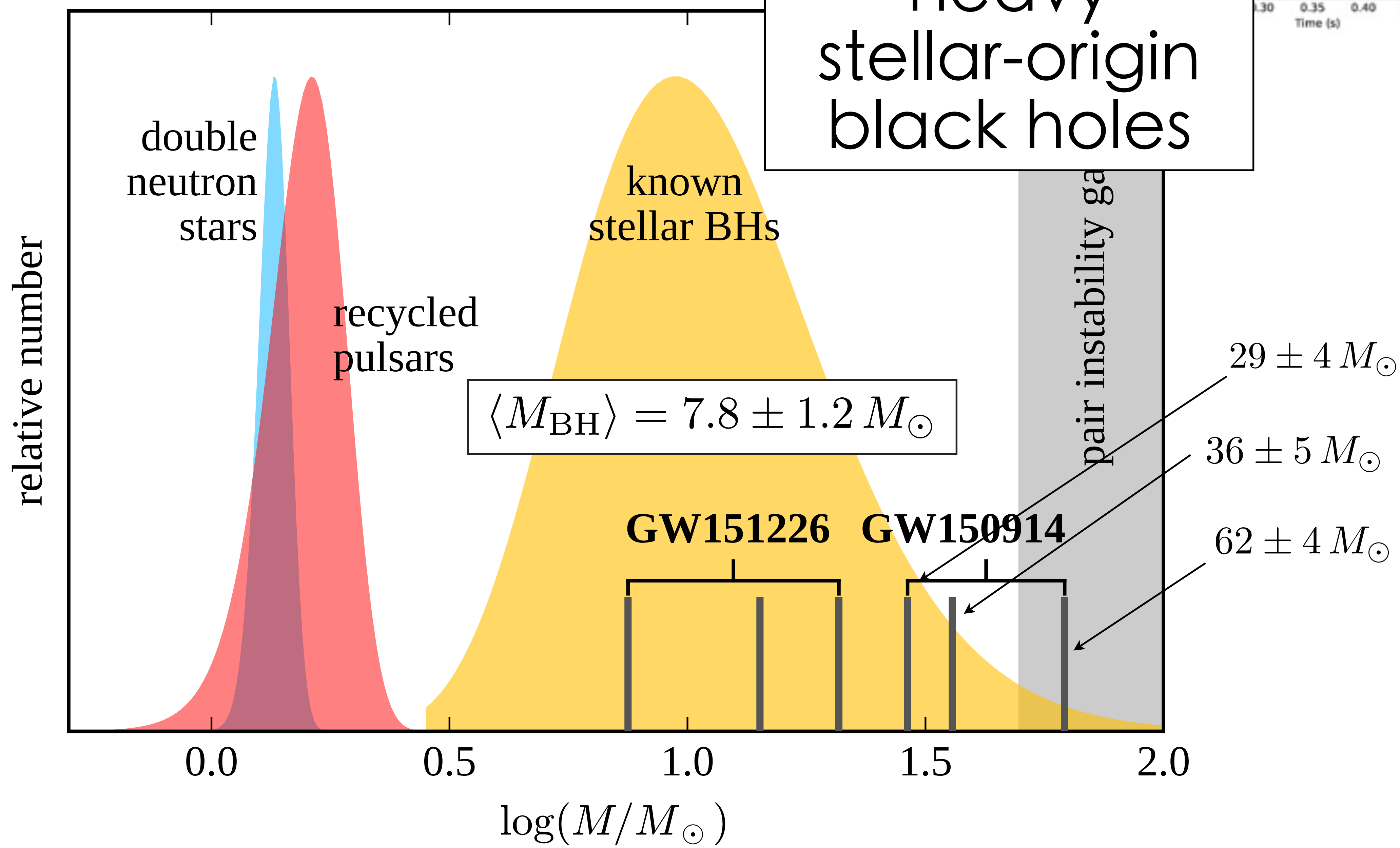
BLACK HOLE MASSES FROM GALACTIC BINARIES



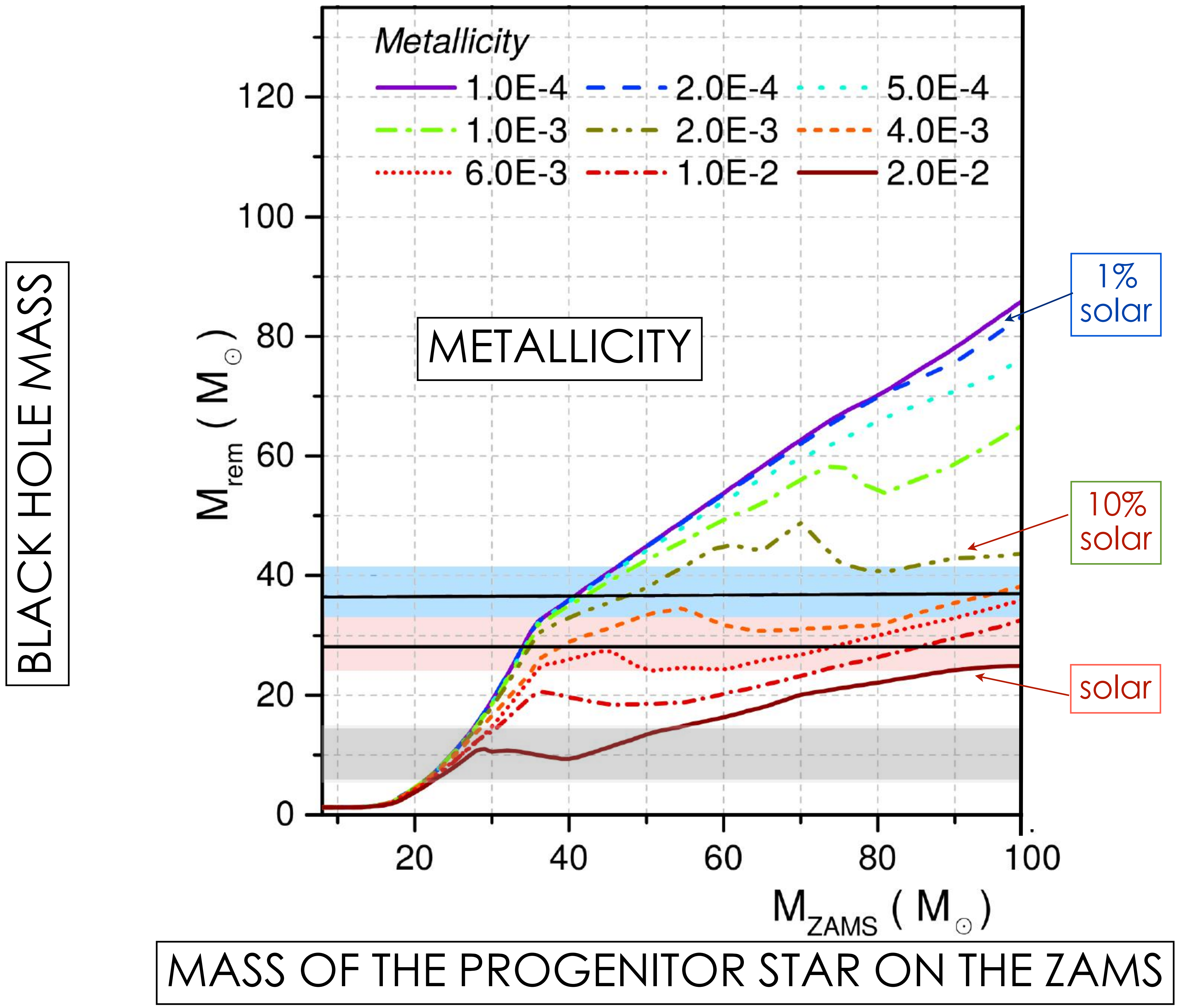
GENERAL RELATIVITY
+
STANDARD MODEL
collapsed stars heavier than ~3 $M_\odot$ are Kerr black holes

DISCOVERY of heavy stellar-origin black holes



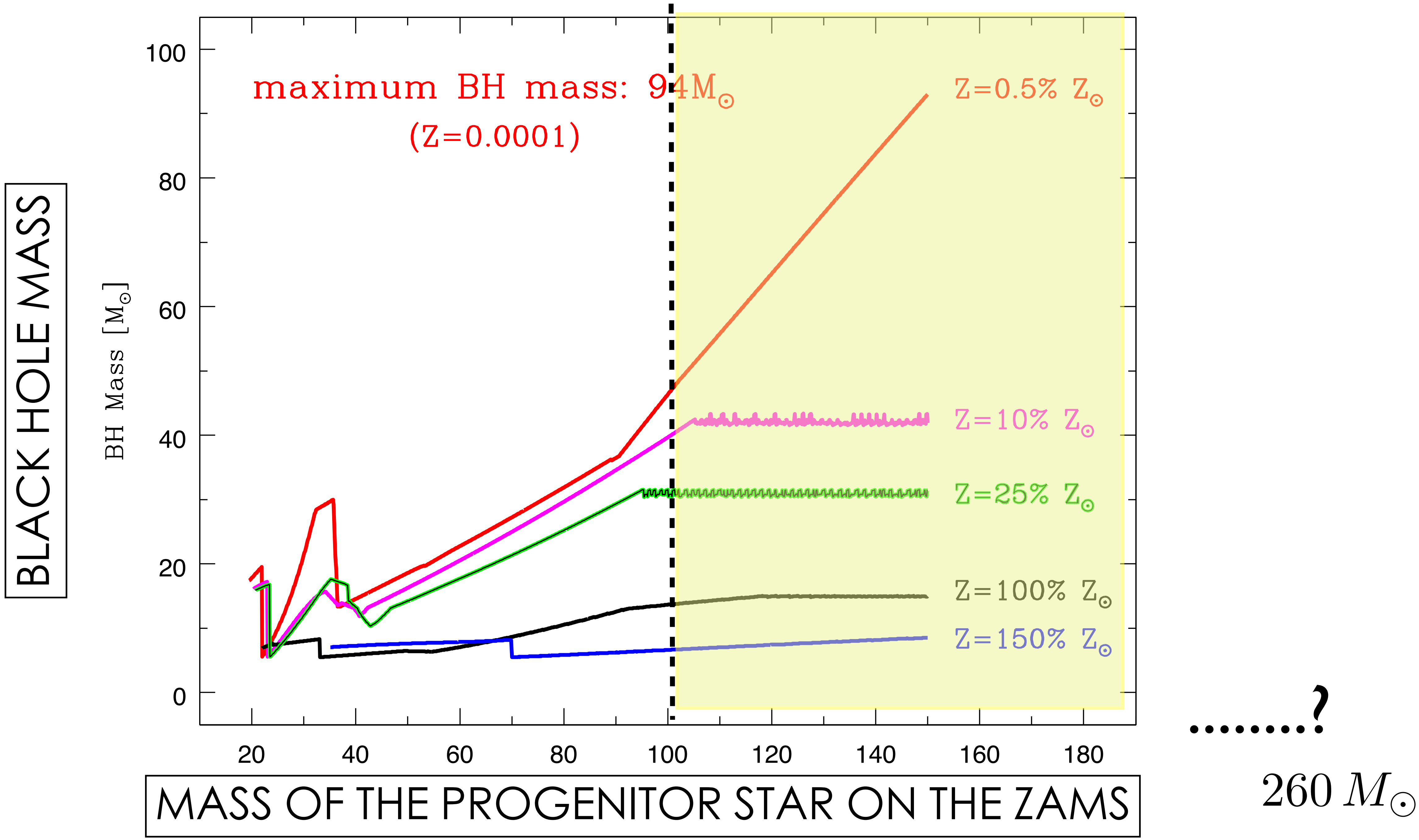


a wide black hole mass spectrum at birth



Heger+ 2002, Vink+05, Mapelli+2009, Fryer+ 2012, Spera+ 2015,Dominik+ 2012, Belczynsky+2016a

PPI-PIS



PPIS=Pair Pulsational Instability

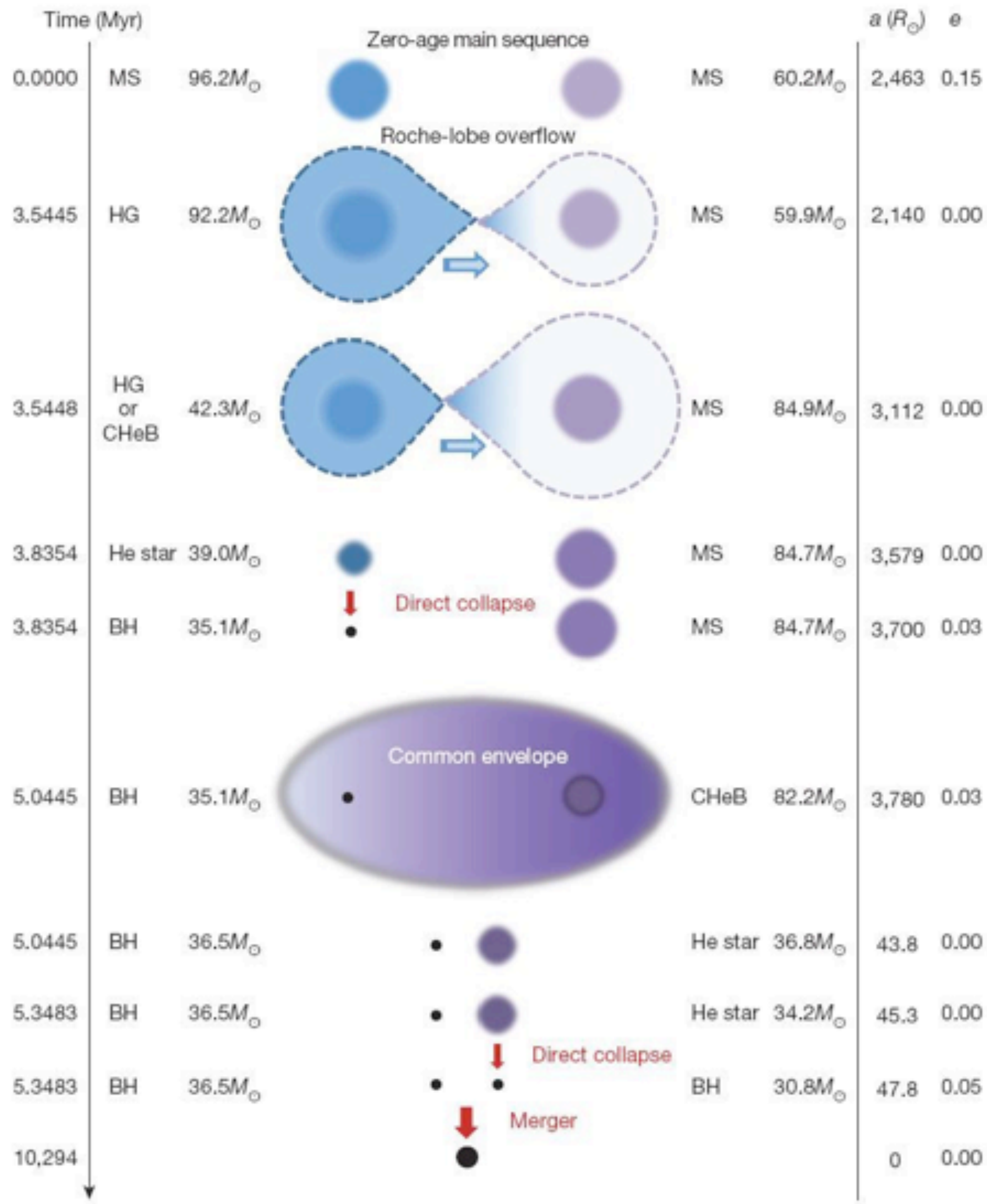
PIS=Pair Instability Supernovae

Belczynsky+2016b,Woosley 2016

PPIS-PIS
limit the BH mass @ Z=0.1- 0.5% Solar
to

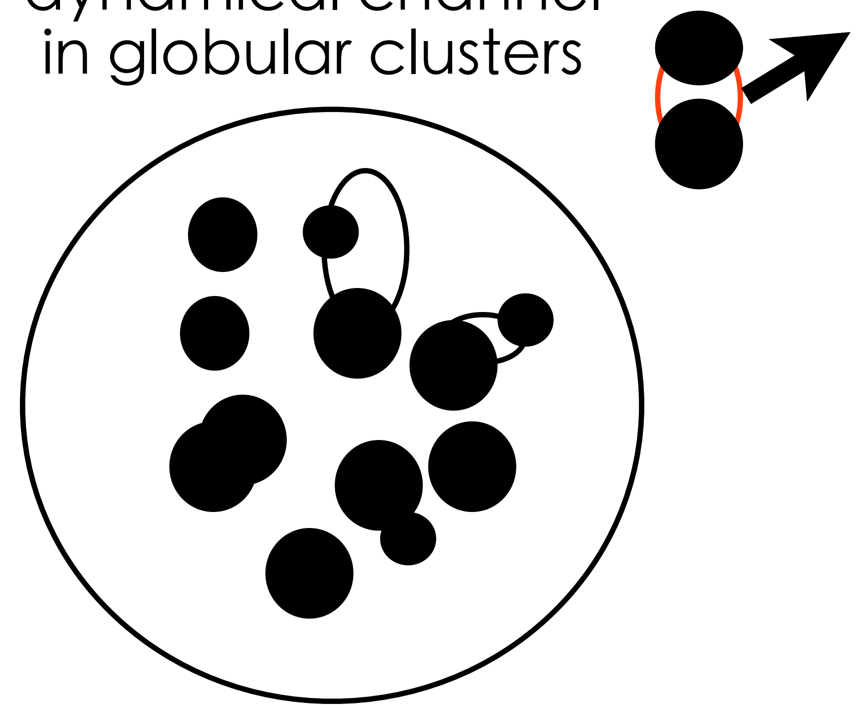
$$M_{\rm BH} \approx 40\ M_\odot$$

primordial binaries in
low metallicity fields



Kowalska+2011,Dominik+ 2012,2013,1015,
Belczynsky+2008,2016a,b
Postnov & Yungelson 2014 for a review

dynamical channel
in globular clusters

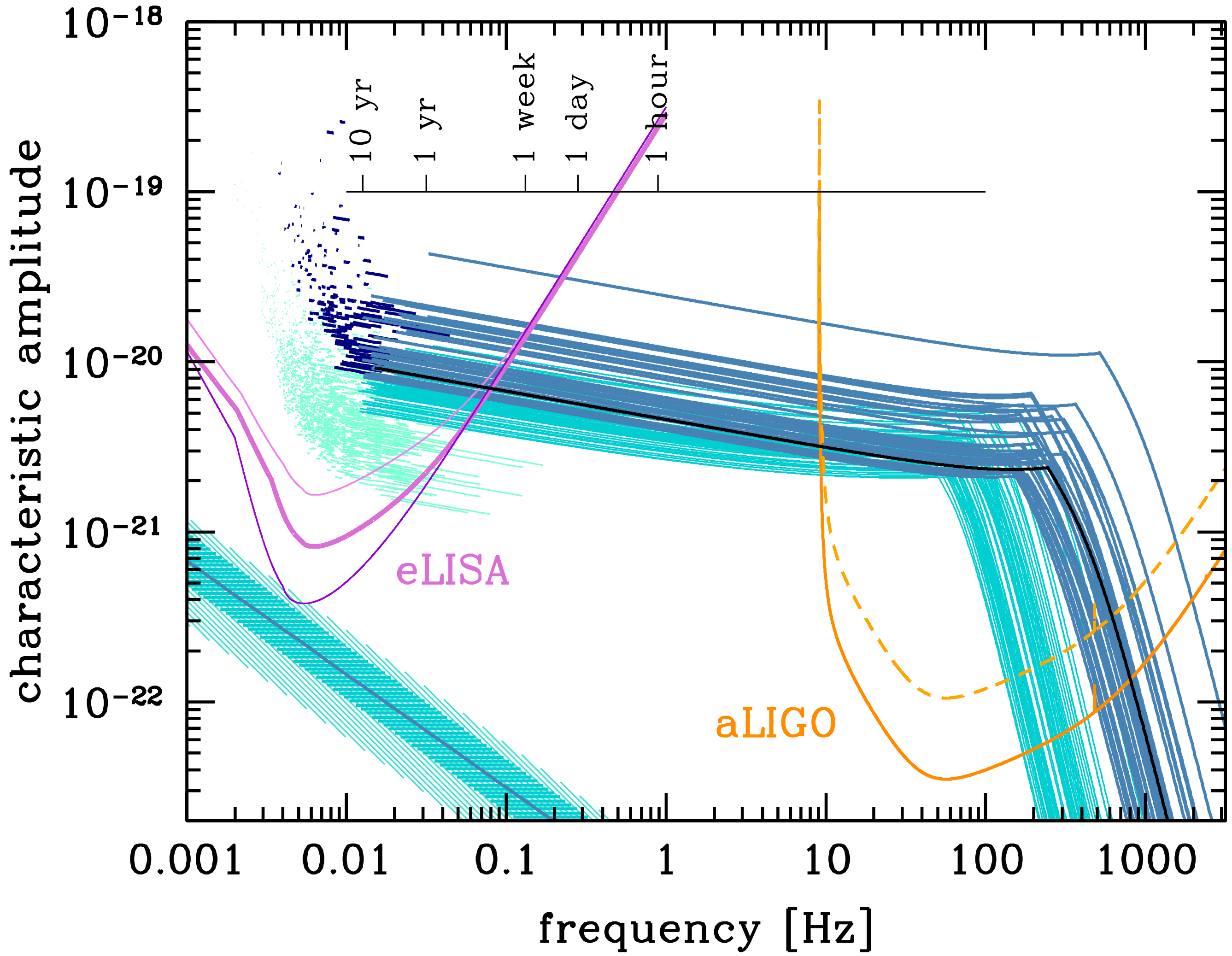


formation & hardening by
3 -body collisions in a mass segregated
core of a dense star cluster

Portegies Zart & McMillan 2008
Rodriguez+2015, 2016
Benacquista & Downing 2013 for a review

Antonini & Peretz, 2016
Mandel & Demink 2016
Hartwig+2016
for alternative models

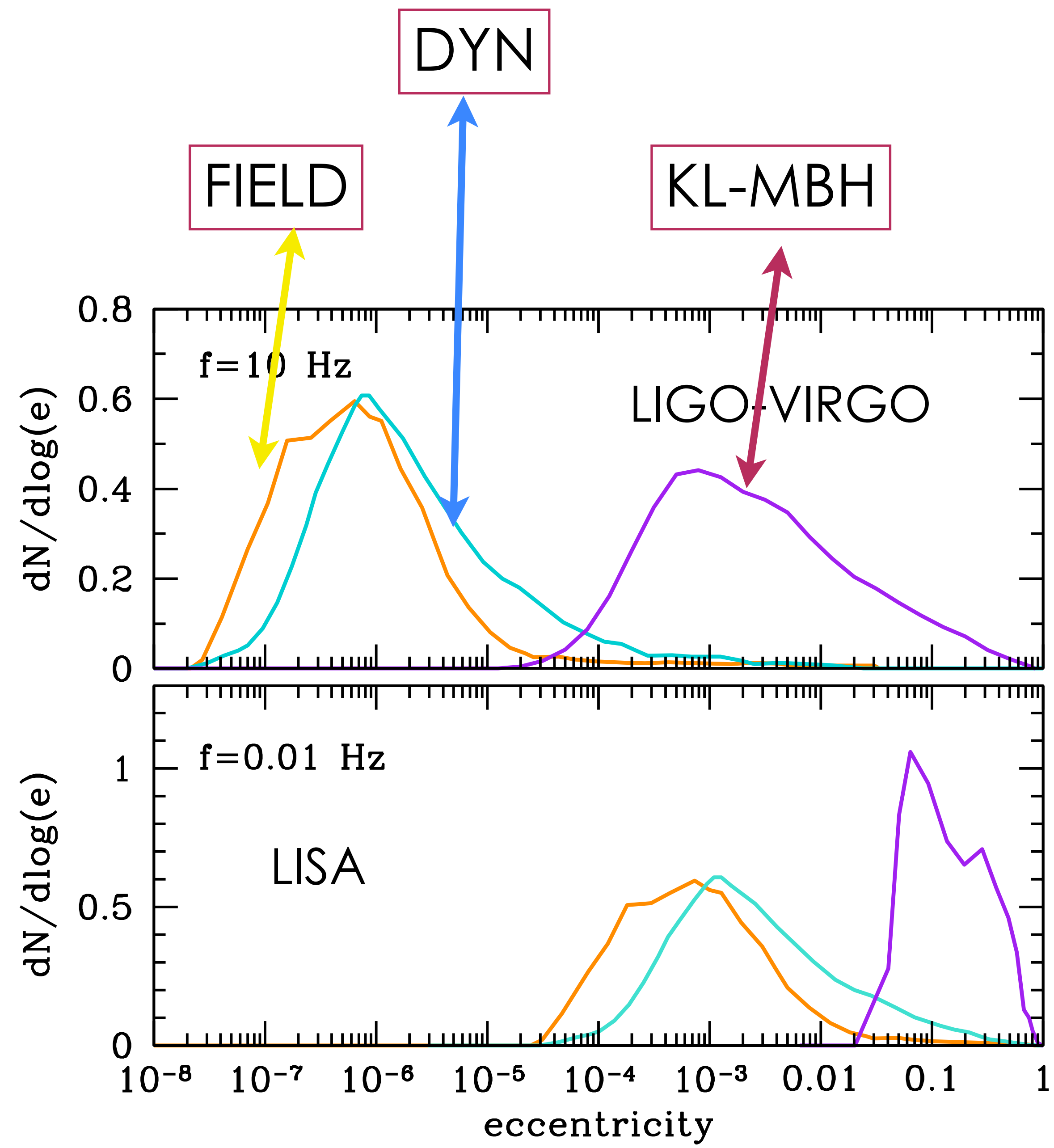
“eccentricity”



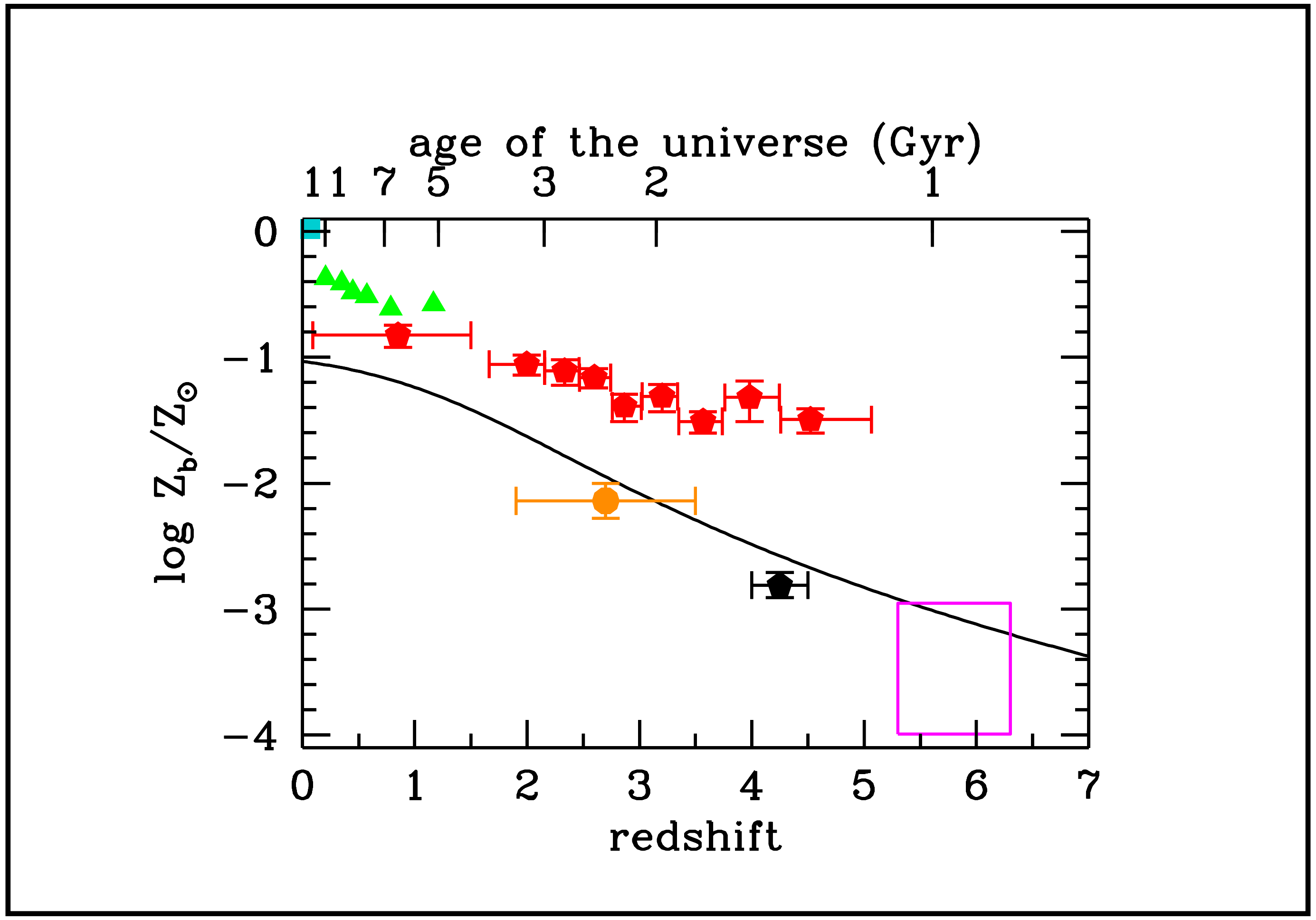
- several tens of observations are necessary to disentangle between “field” and “dynamical” channel in globular clusters

Sesana 2016, Nishizawa+ 2016

mock LISA observations
(Bayesian model selection)
to probe
formation channels

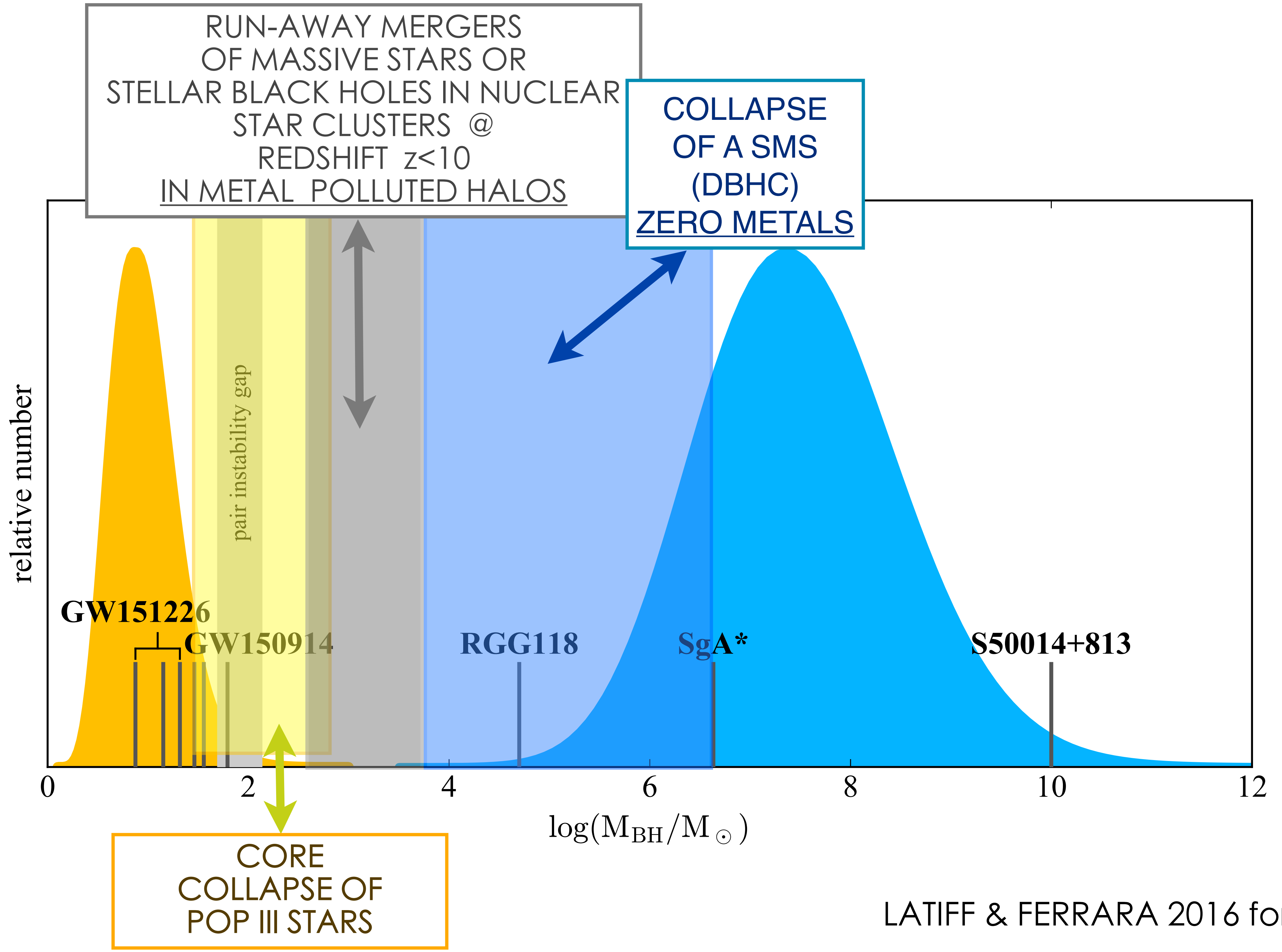


- heavy stellar- origin black holes might be the only seeds for massive black holes !



- link is established by the "metallicity"

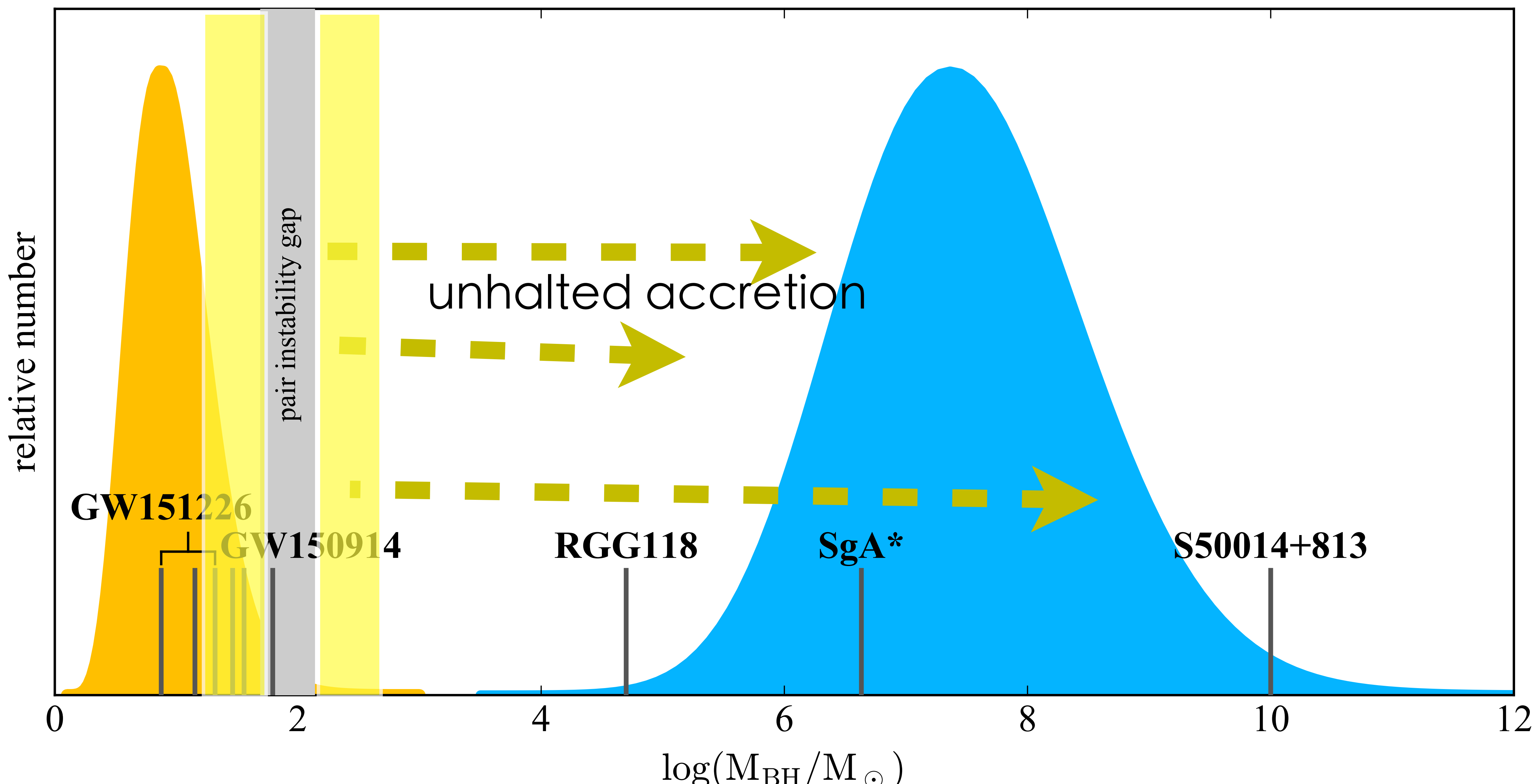
BLACK HOLE DESERT
SEEDS
which origin?



LATIFF & FERRARA 2016 for a review

LIGHT SEEDS: CORE COLLAPSE OF POP III STARS

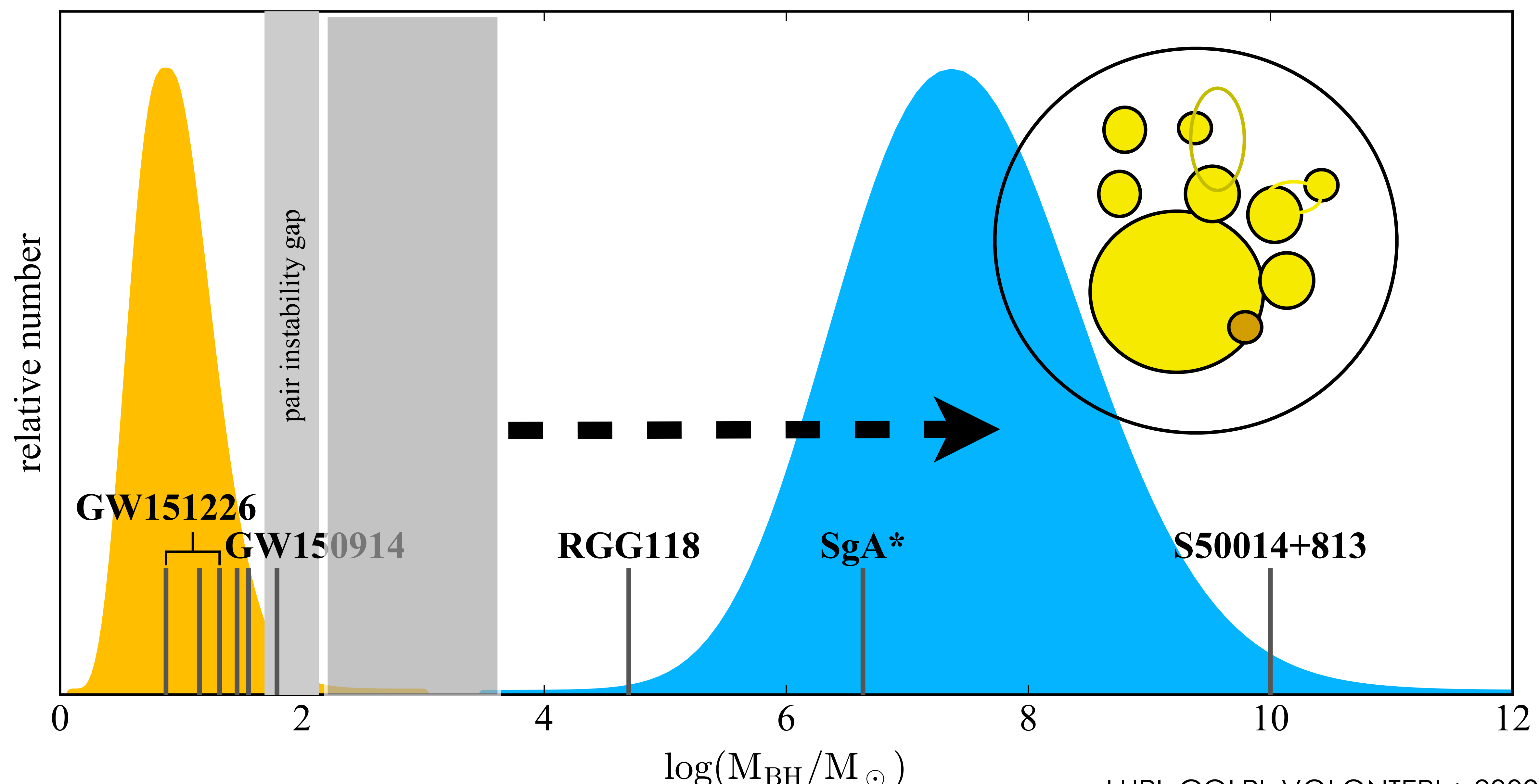
- POP III stars forming via molecular hydrogen cooling in metal free mini halos of million-10 million suns @ z~30=20
- the POP III relics are light seeds which accrete intensely at super Eddington rates to deliver heavier black holes



LATIFF & FERRARA 2016 for a review

RUN-AWAY MERGERS OF MASSIVE STARS OR STELLAR BLACK HOLES IN NUCLEAR STAR CLUSTERS @ REDSHIFT z<10

- transition objects, resulting from the dynamical clustering of stellar objects viewed as single building blocks, in "dense (nuclear) star clusters" : "RUNAWAY STAR"
  - this would lead to a more continuum mass spectrum
  - formation sites spread over DM halos of low but not null metallicity



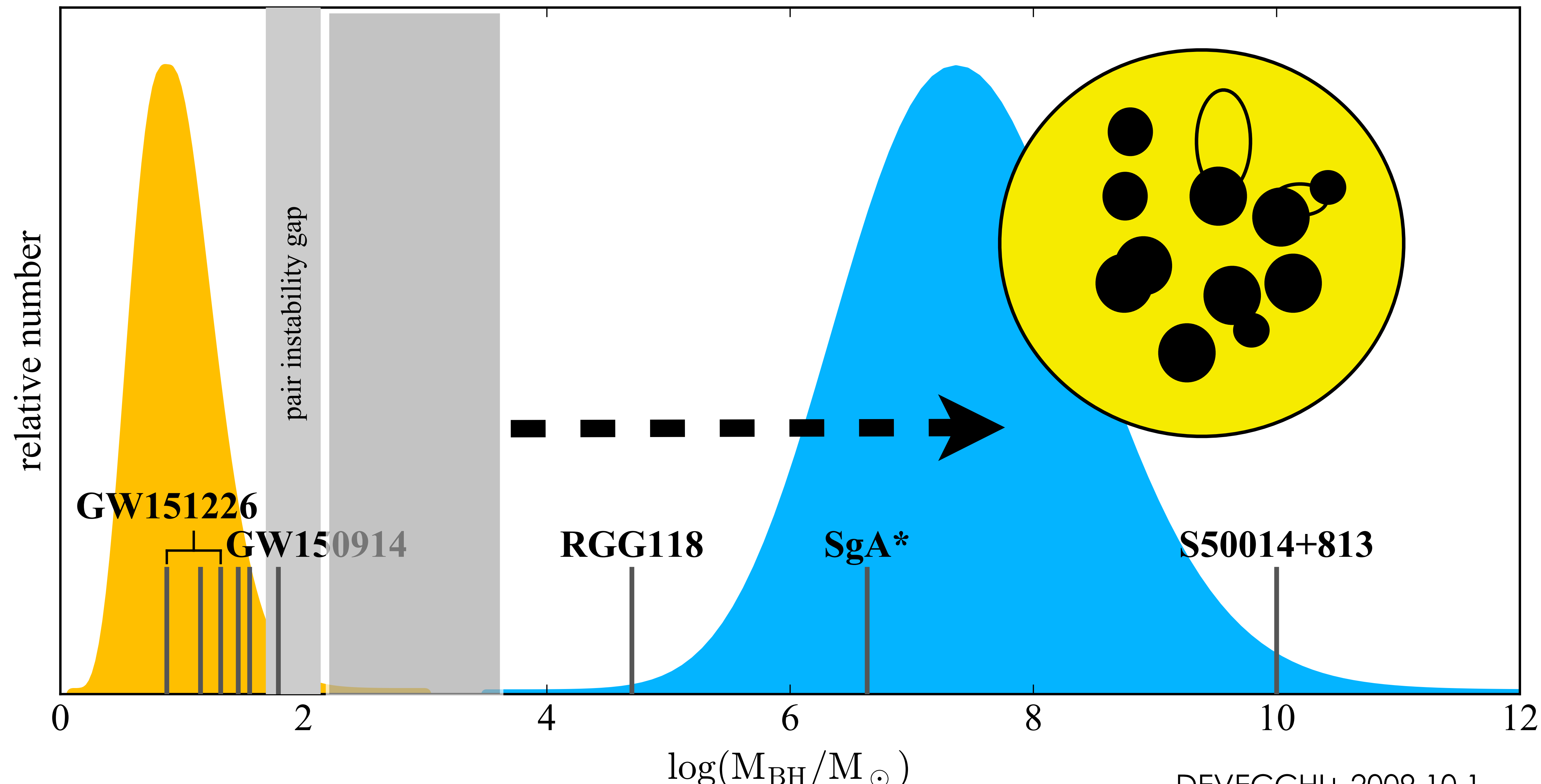
LUPI, COLPI, VOLONTERI + 2009,10,1

RUN-AWAY MERGERS OF MASSIVE STARS OR STELLAR BLACK HOLES IN NUCLEAR STAR CLUSTERS @ REDSHIFT z<10

- stellar origin black holes in dense gas rich star clusters

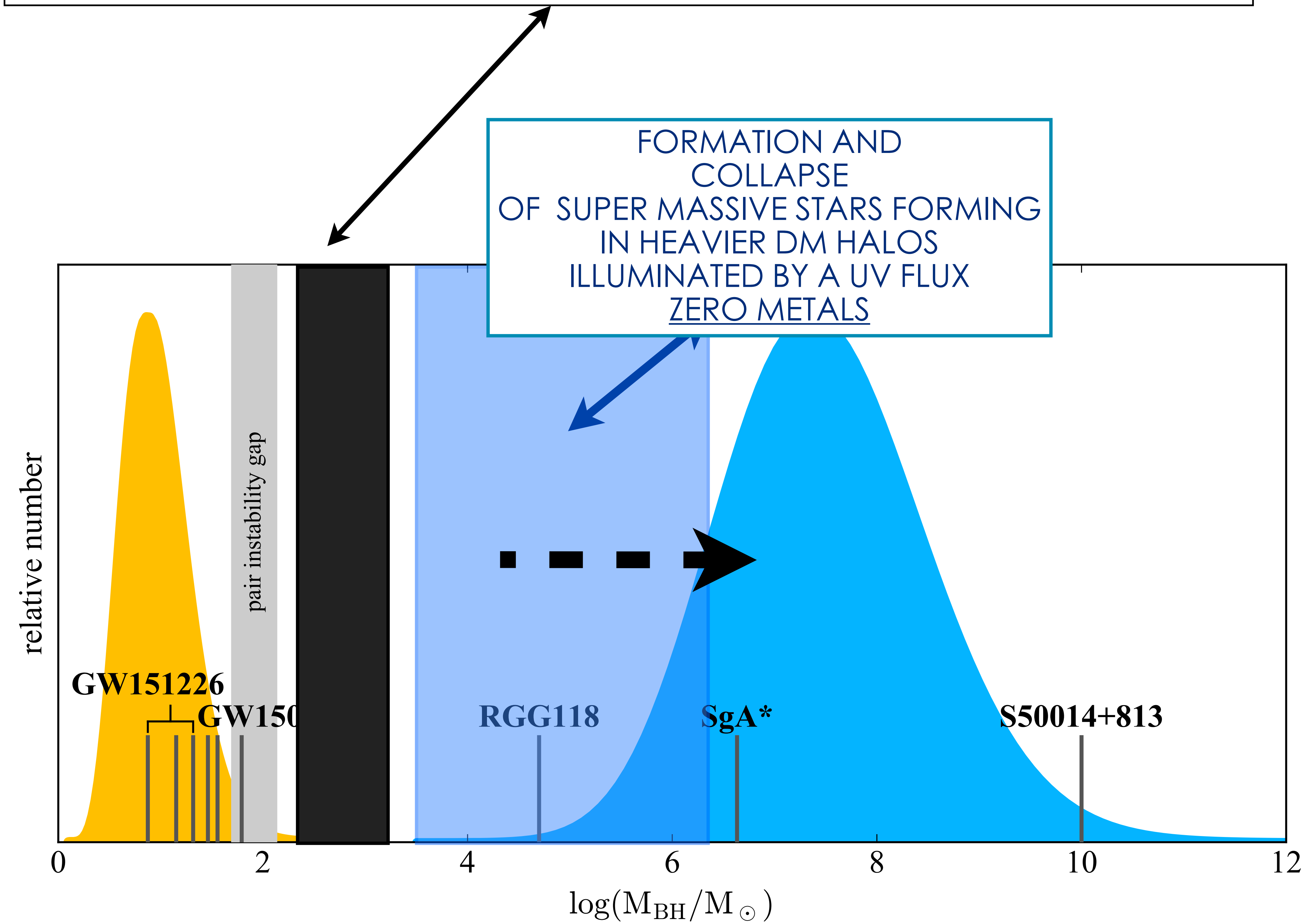
transition objects: RUNAWAY GAS-INDUCD COLLAPSE OF BH*

- this would lead to a more continuum mass spectrum
- formation sites spread over DM halos of low but not null metallicity



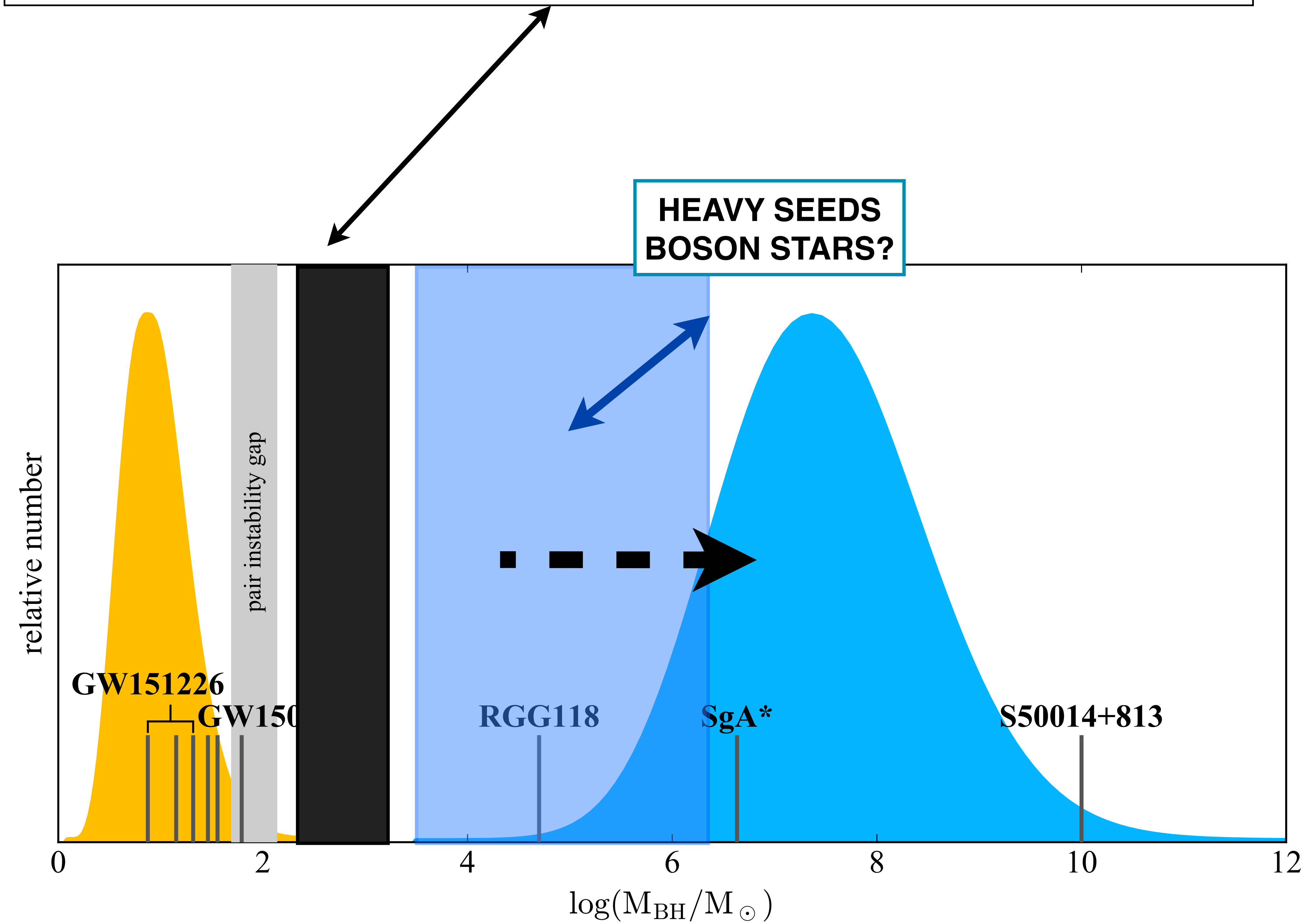
DEVECCHI+ 2009,10,1

a genetic divide - DIRECT BH SCENARIO



LATIFF & FERRARA 2016 for a review

a genetic divide



CARDOSO+2016

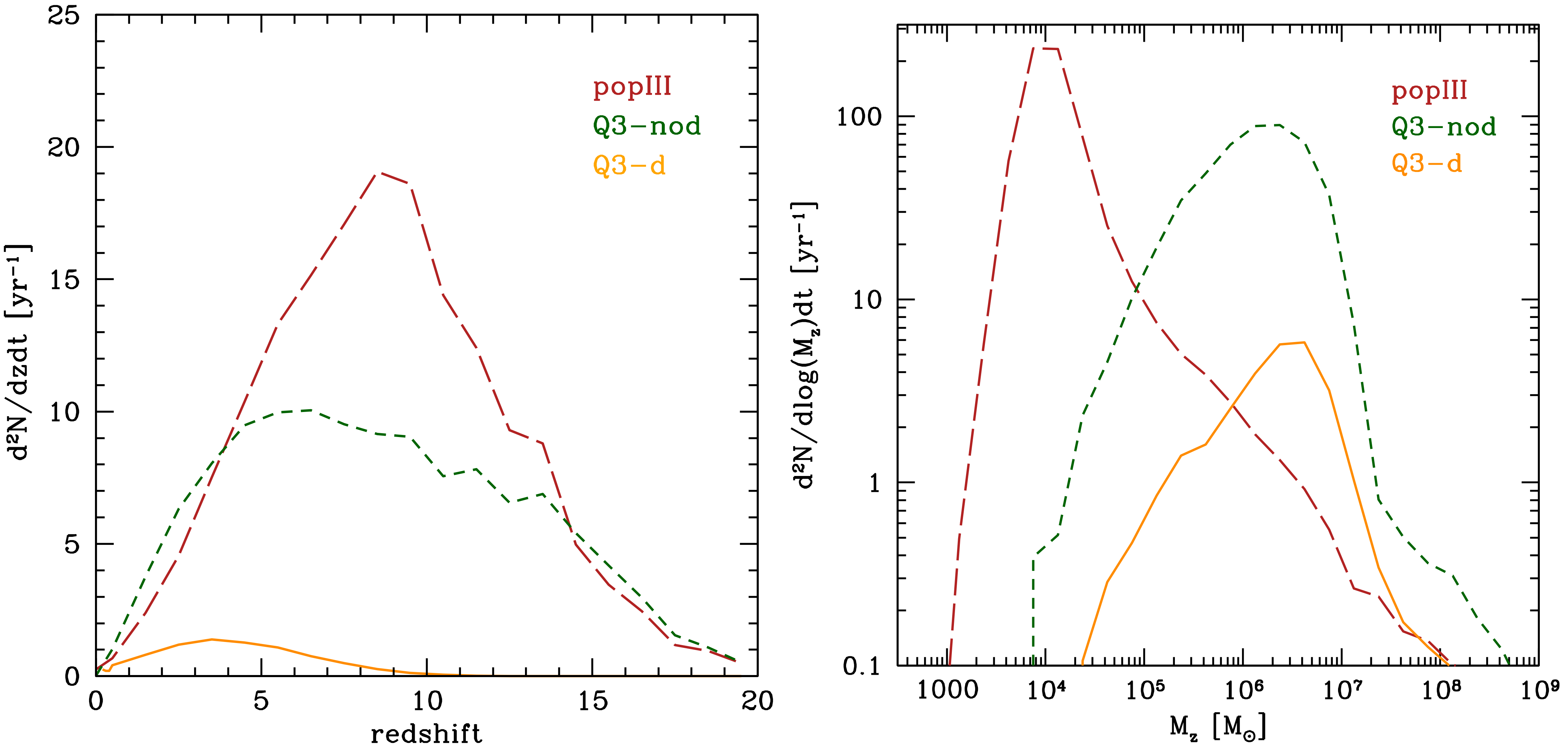
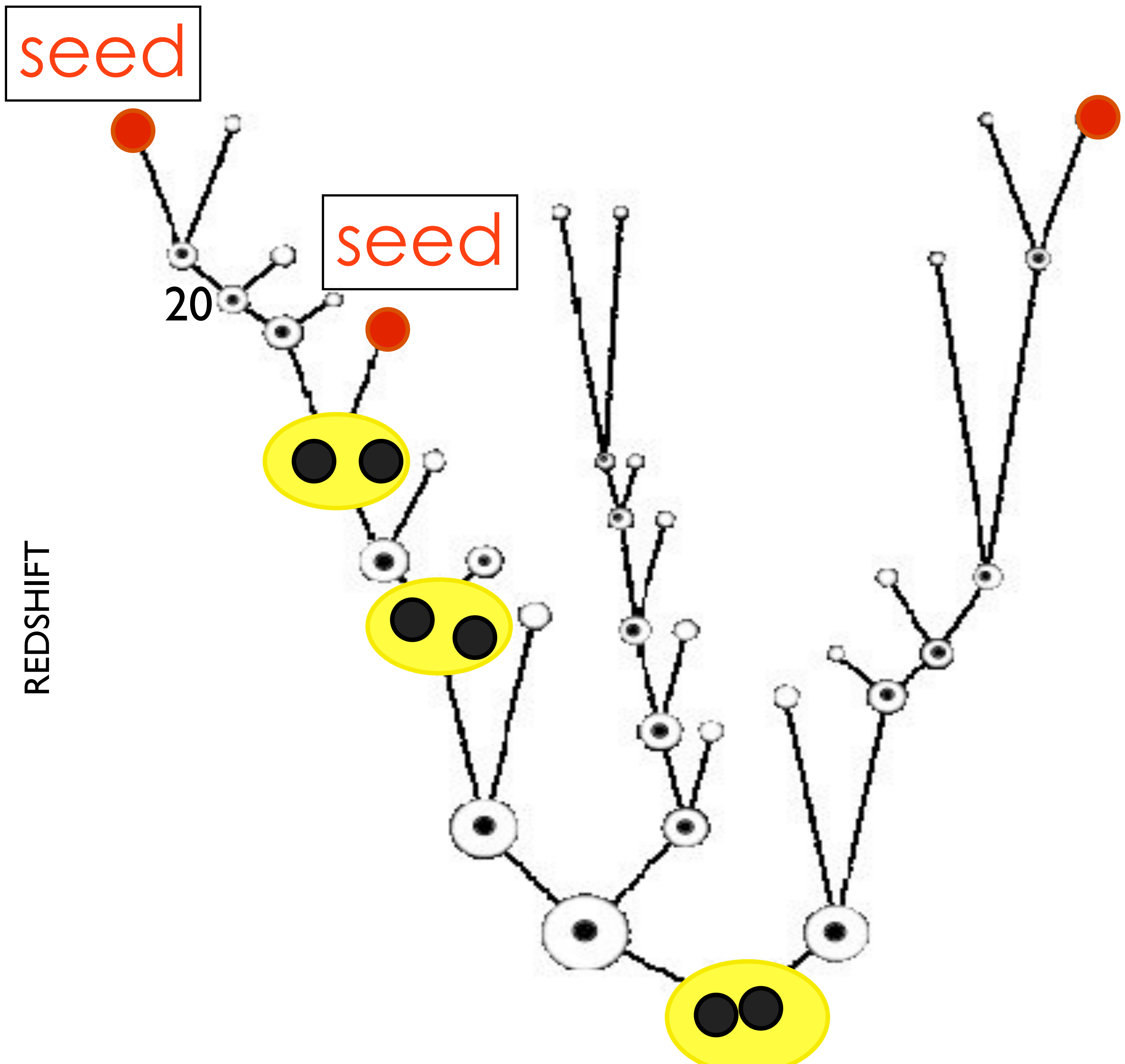


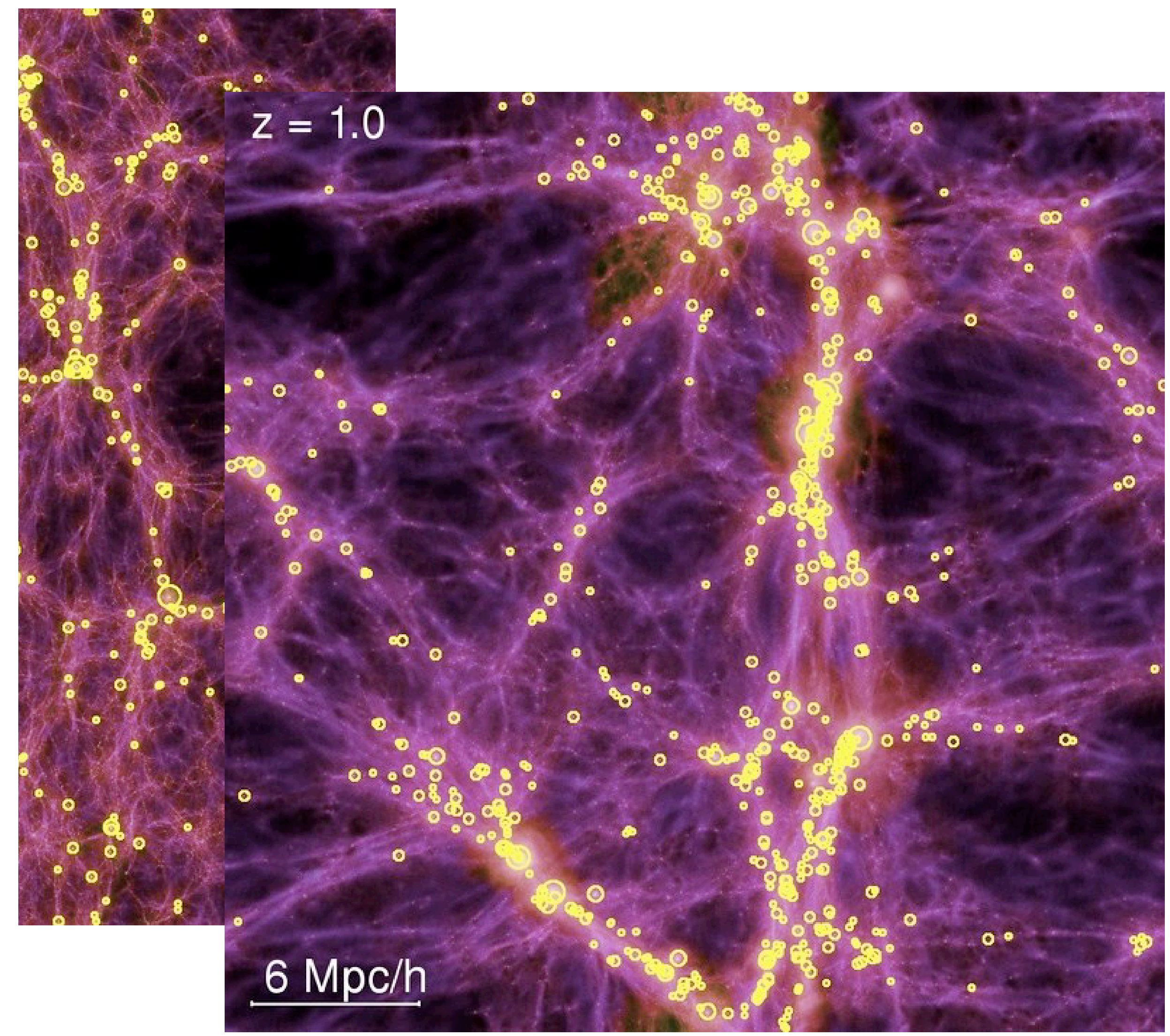
FIG. 3. Predicted merger rates per unit redshift (left panel) and per unit total redshifted mass $M_z = (m_1 + m_2)(1 + z)$ (right panel) for the three models described in the text.

KLEIN+ 2016

- how can we detected the seeds to unveil the origin and evolution of massive massive black holes ?

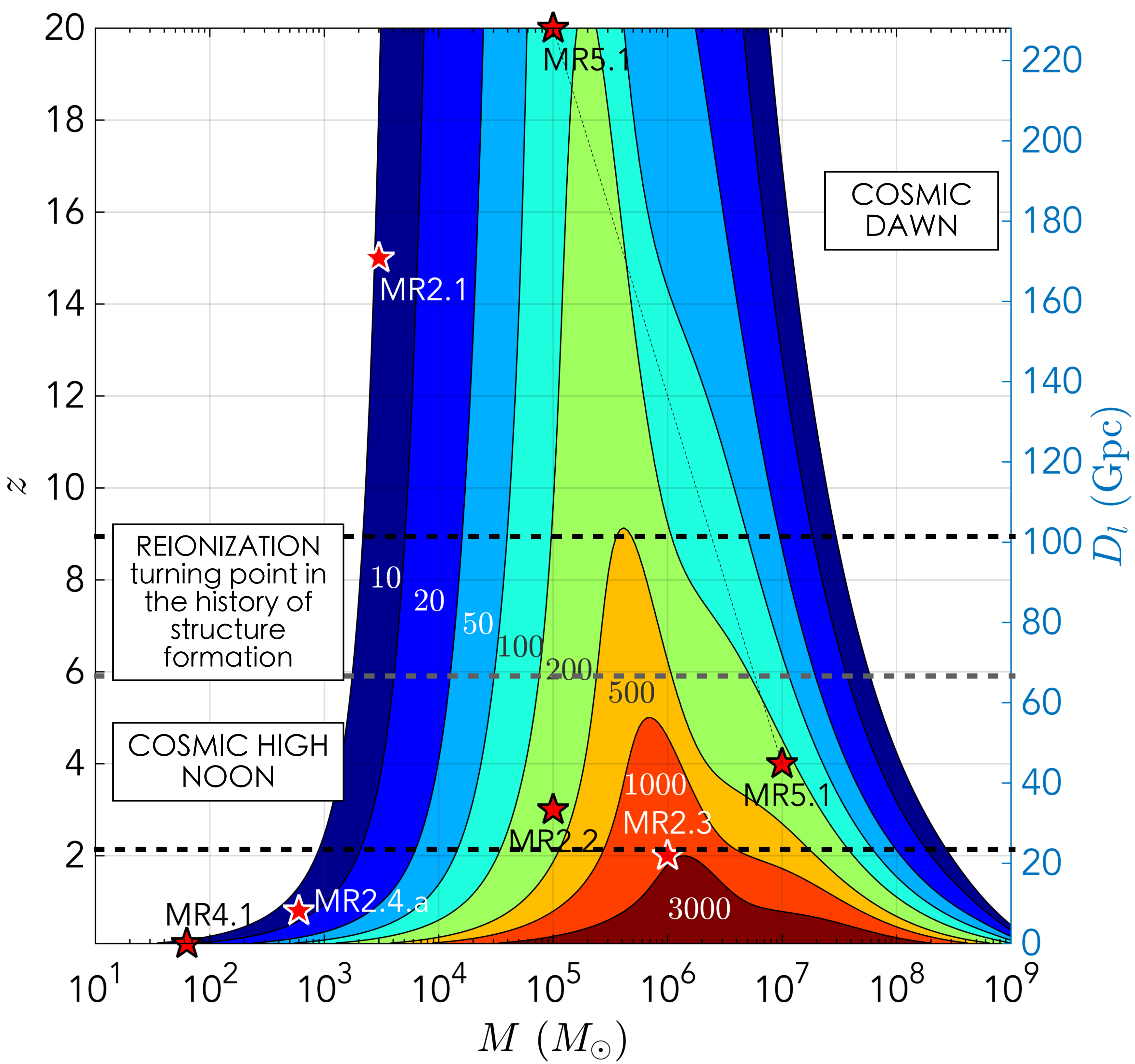
“COSMOLOGICAL APPROACH” THE BUILD UP OF A POPULATION OF BINARY BLACK HOLES DURING THE BULID UP OF GALAXY HALOS



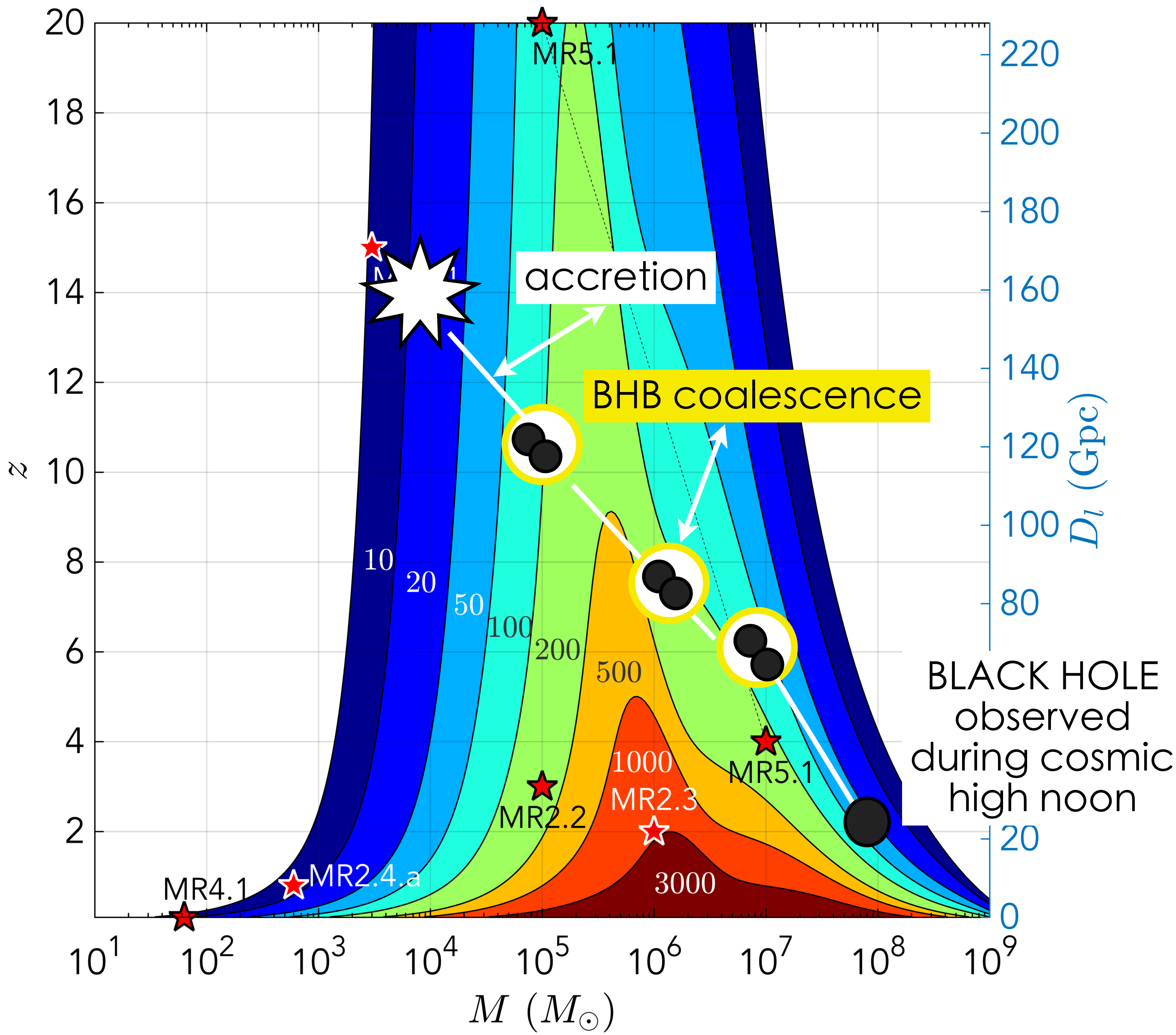


COLPI 2014 , for a review

the “redshift” dimension: LISA will peer deep into the early phases of halo assembly in a mass range that can not be probed by any other mean



spin evolution both due to accretion and merger



the black hole population is shaped by the details of the seeding process and accretion history - processes poorly understood and largely unconstrained observationally and theoretically

seed formation mechanism initial seed mass function	metallicity metal pollution in halos redshift interval of formation	accretion efficiency rate of growth
UV background fragmentation	occupation fraction of seed black holes natal or inherited black holes in halos	accretion geometry coherent chaotic
when and where the seeds form or are implanted	**mergers**	spin evolution

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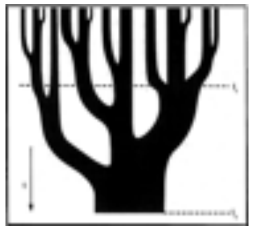
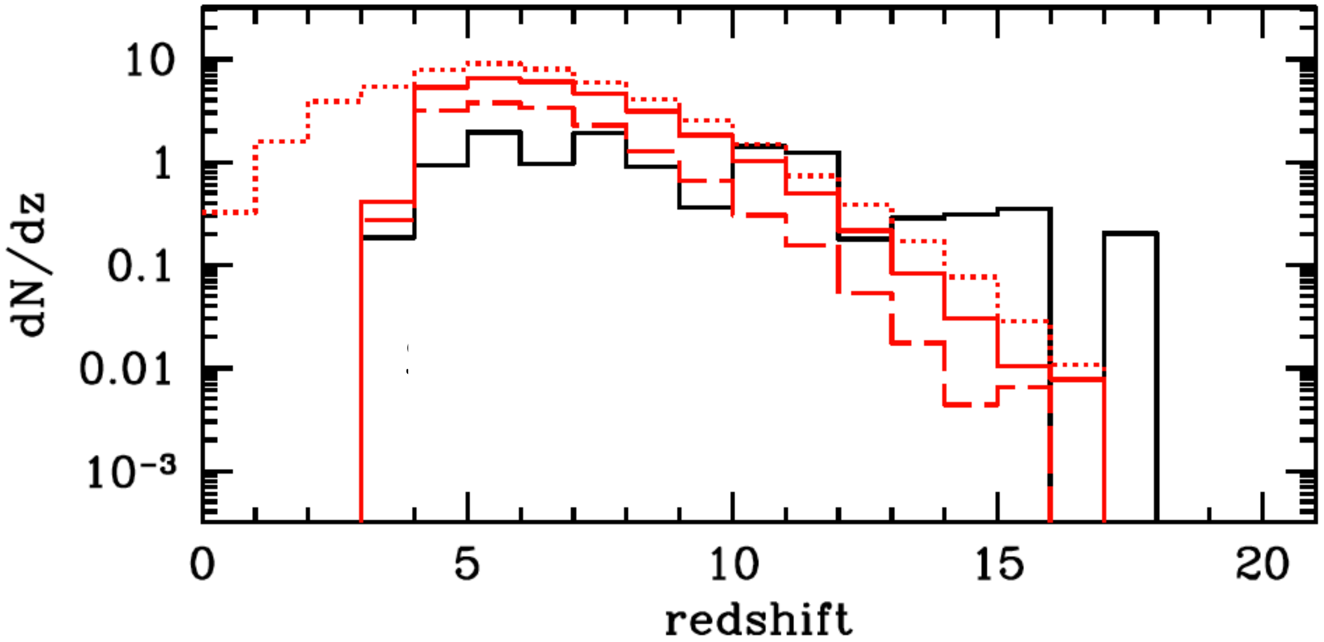
seed formation mechanism initial seed mass function	metallicity metal pollution in halos redshift interval of formation	accretion efficiency rate of growth
	occupation fraction black holes in halos	chaotic
when and where the seeds form or are implanted	**mergers**	spin evolution

LISA detections have the potential
to distinguish among theoretical models
thus among differences in the underlying physics

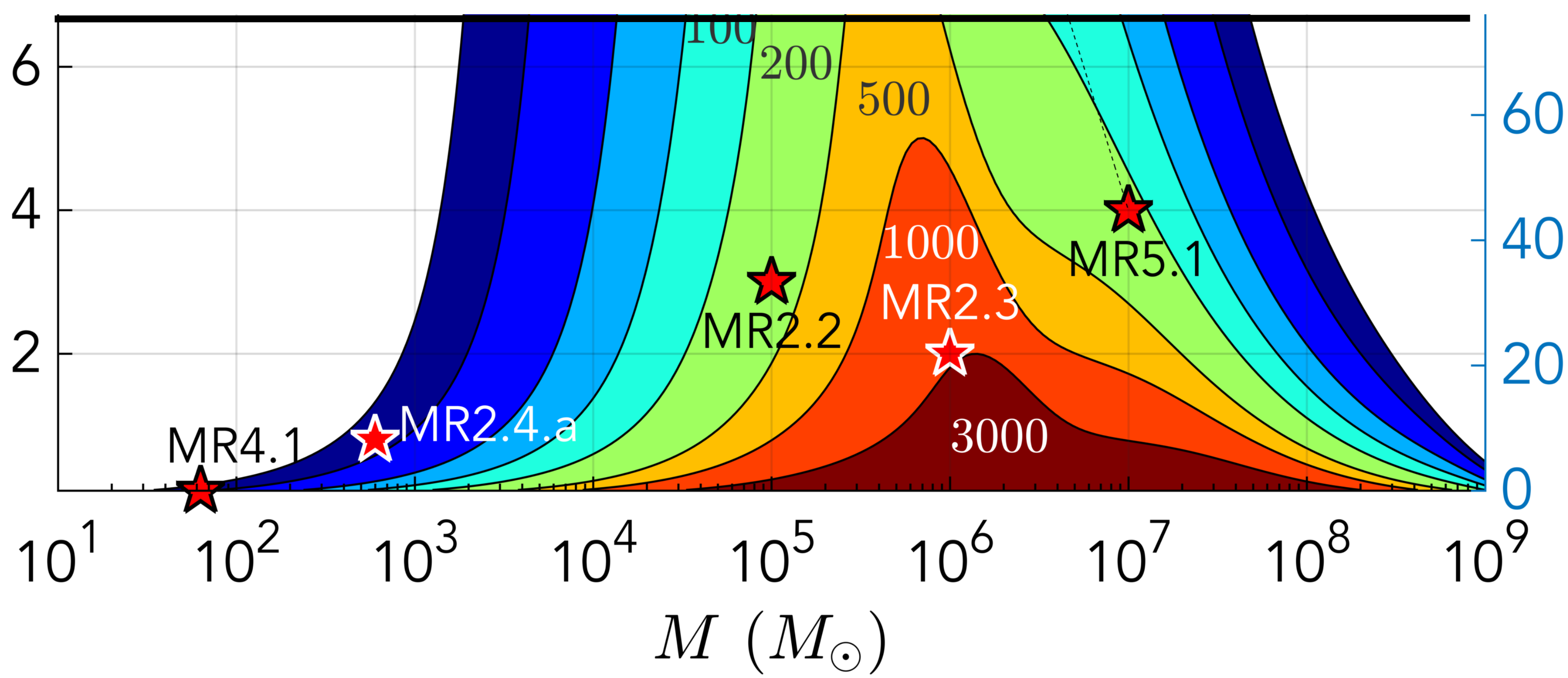


EVENT RATES OF BLACK HOLE MERGERS

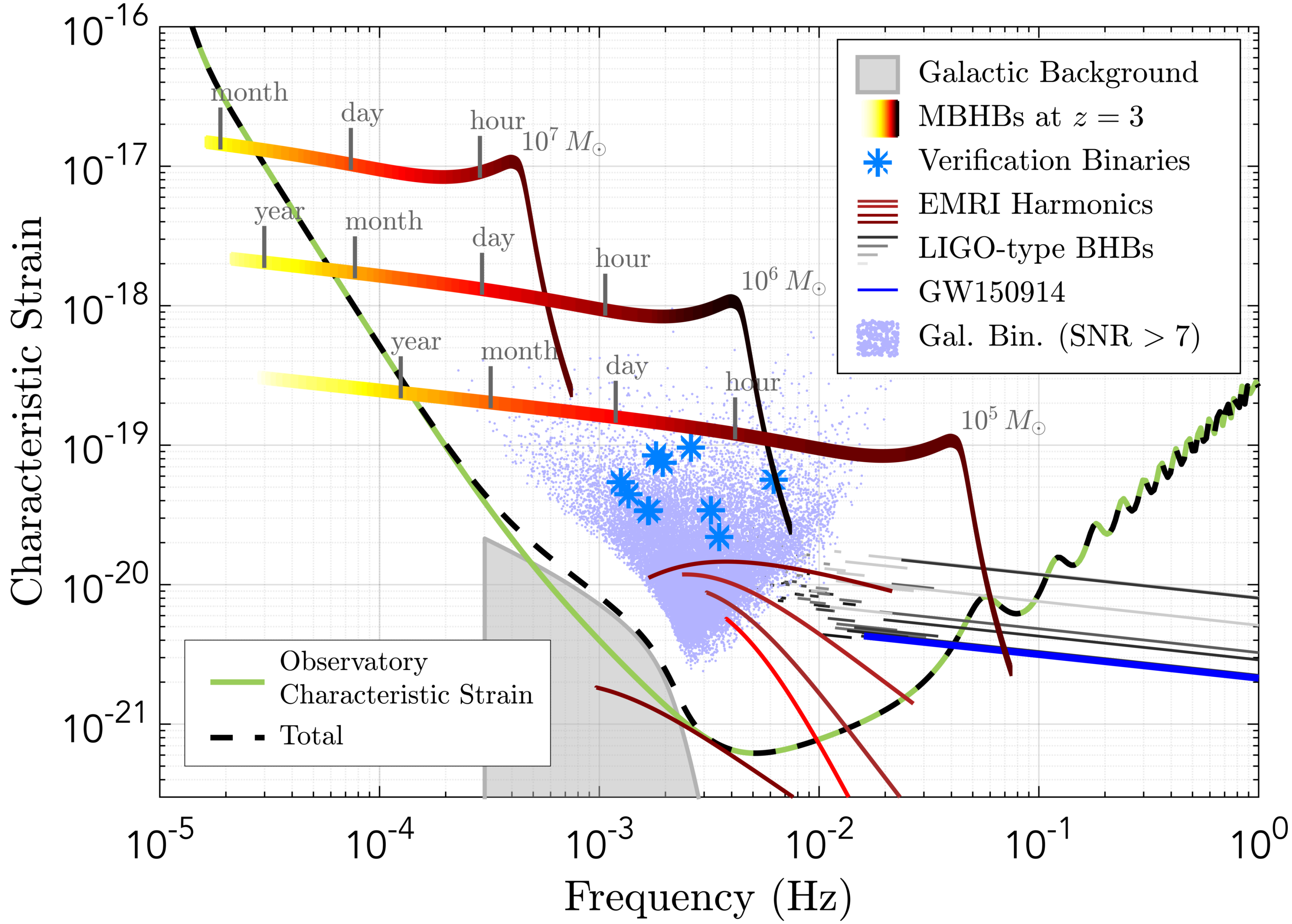
10-100 mergers/year
I. semi-analytical models
II. cosmological hydrodynamical simulations
(inclusive of cold flows)



- “golden binaries” @ z~ 2 during cosmic high noon

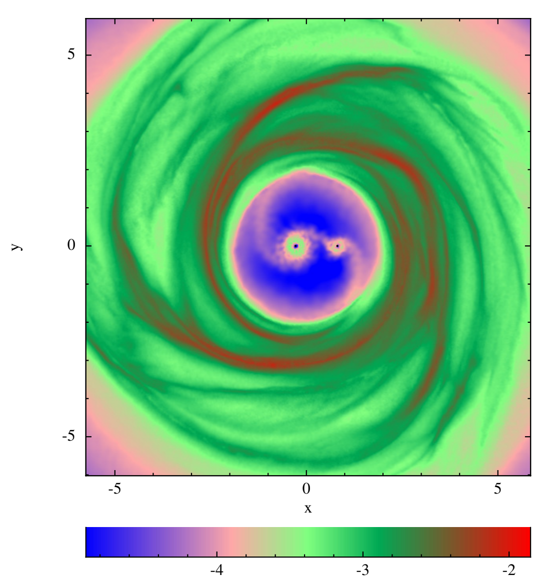


- accumulated SNR of 200 allows for estimate of the rest-frame mass with a precision limited by weak lensing (5%) , a spin with absolute error better than 0.1 and spin misalignment better than 10 degrees



A proposal in response to ESA call for the L3 mission

- LISA BHB coalescences may not occur in vacuum



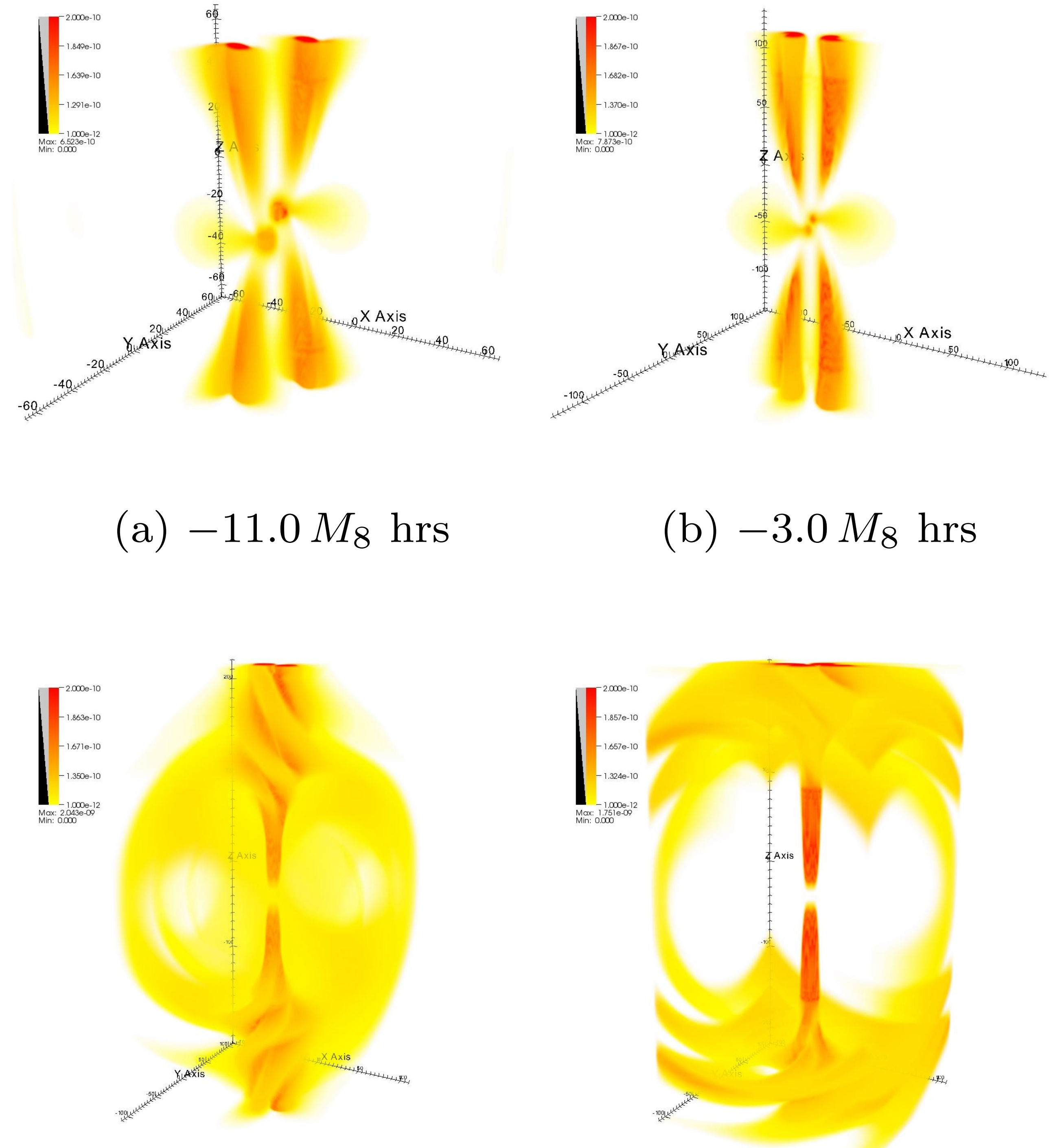
BARAUSSE+15

- "coincident detection" during final stage of the merger

- spacetime helps stir EM field lines, and akin the BZ mechanism, the plasma is able to tap translational and rotational energy from the system to produce dual jets, and a "braided" jet close to the merger

$$L \approx B^2 \sum_{i=1,2} [\Omega_{\rm horizon}(i)^2 + kV^2_{\rm translational}]$$

PALENZUELA + 2010



(a) $-11.0\, M_8$ hrs

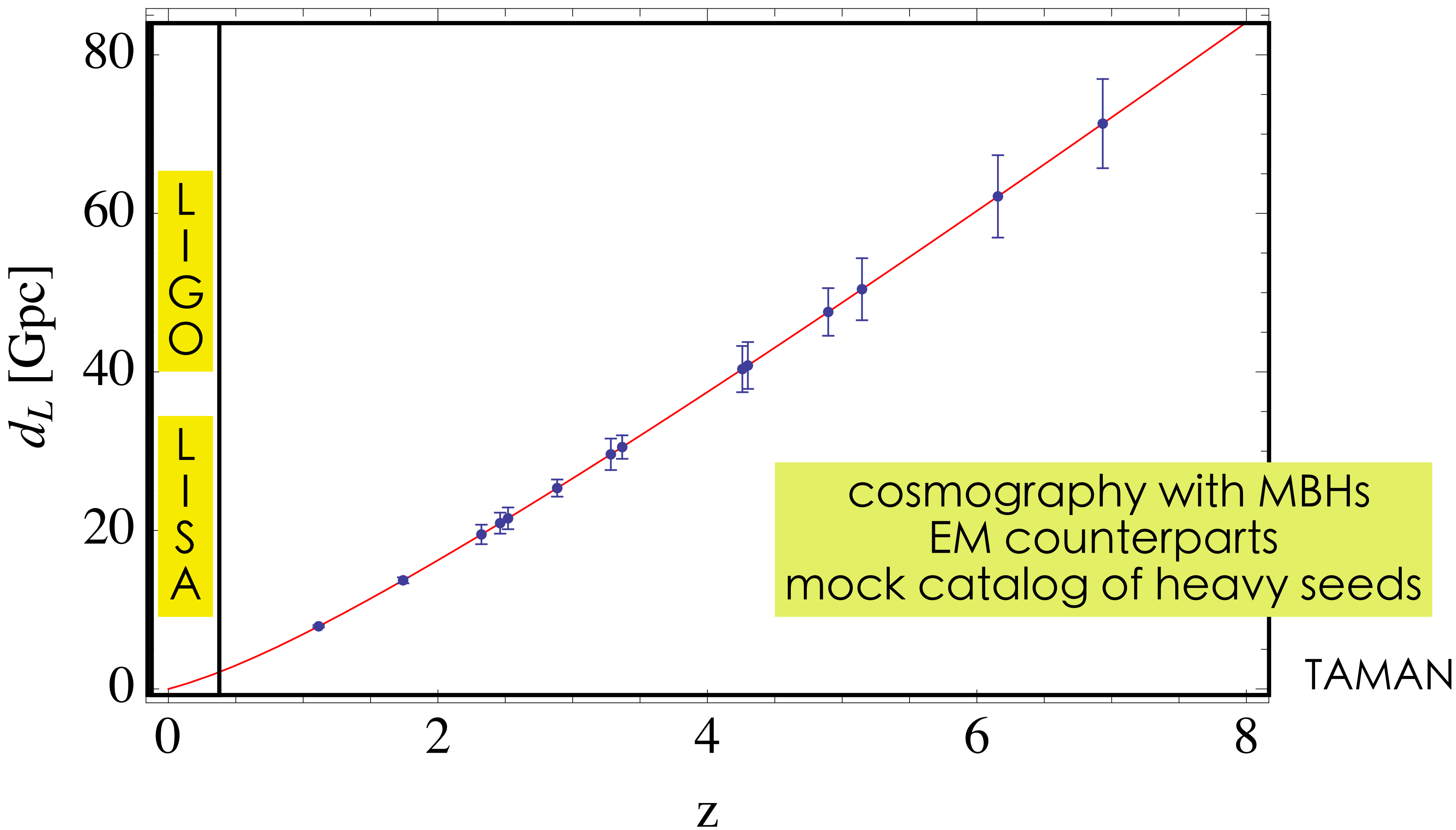
(b) $-3.0\, M_8$ hrs

(c) $4.6\, M_8$ hrs

(d) $6.8\, M_8$ hrs

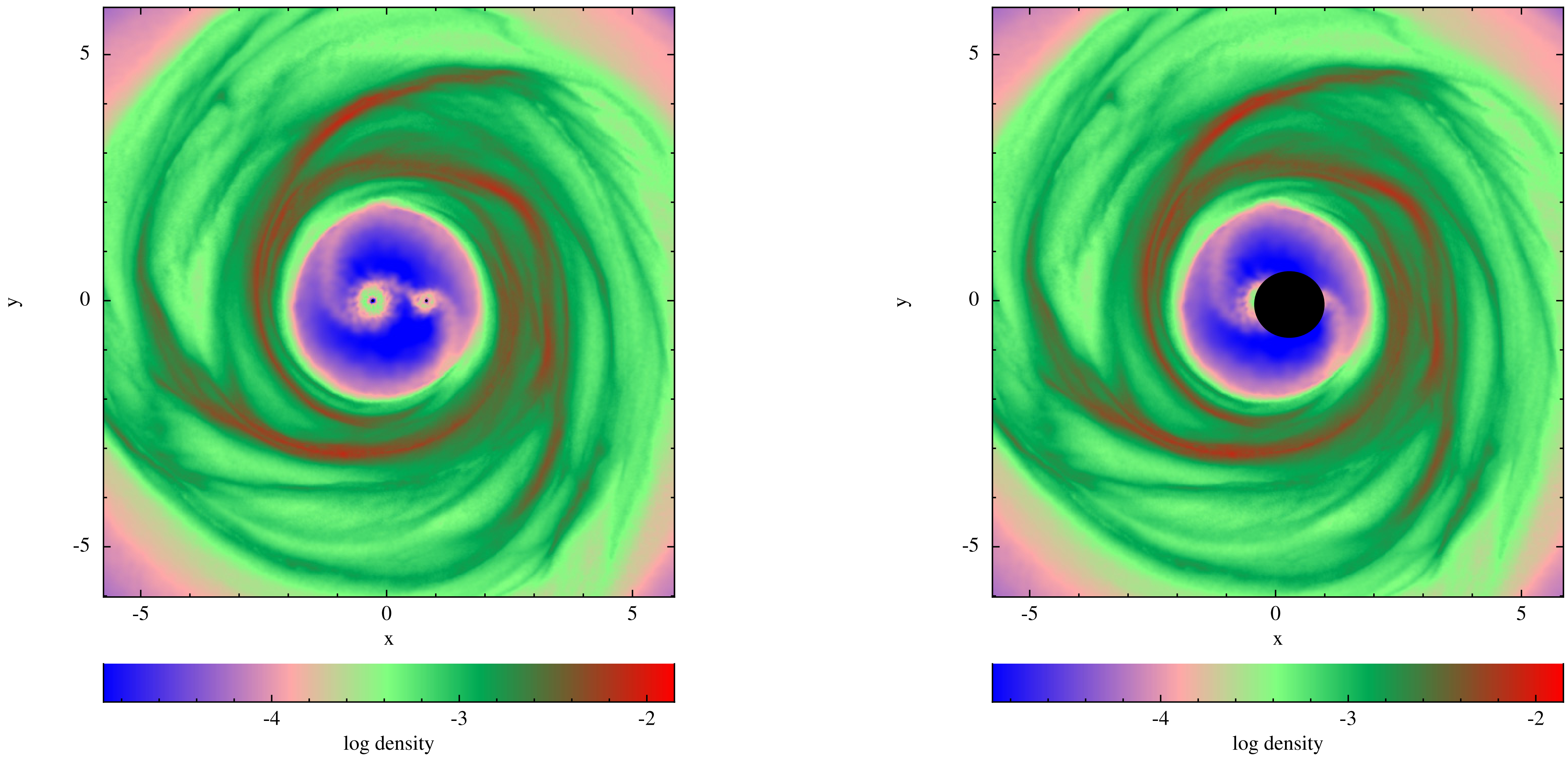
cosmography

- chirping binaries are standard sirens - their gravitational wave signal can determine the source <u>absolute luminosity distance</u>.
- used in concomitance of an independent measure of the <u>redshift of the host galaxy</u>
- standard siren observations provide information on the <u>luminosity distance -redshift relation: Hubble parameter at 1-2 % level of accuracy</u>

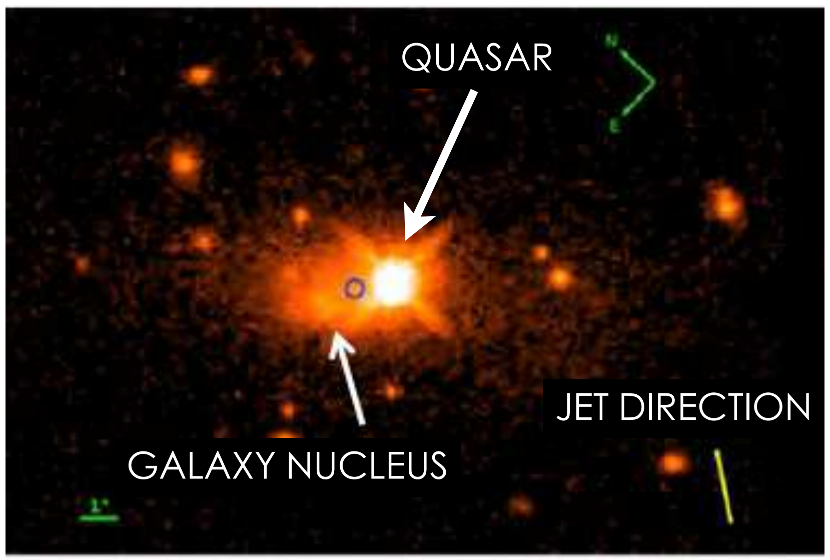


TAMANINI+2016

- <u>afterglow</u>: turn on of an AGN, weeks - months-years after the merger, when the "outer" disc which remains bound to the new black hole refills the empty cavity

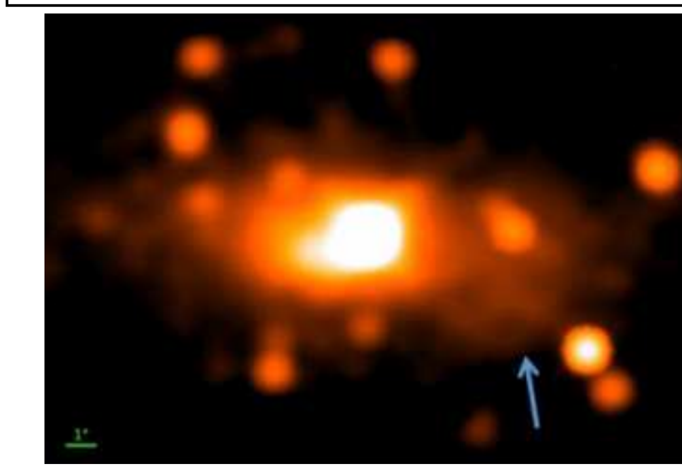


- "afterglow" & off nuclear emission
- the relic black hole can be surrounded by a disc partly bound and on the viscous time matter is accreted
- the near-impulsive perturbation of the gravitational potential leads to strong shock
- the case of RC186 - a powerful radio-loud QSO -- Chiaberge + 2017

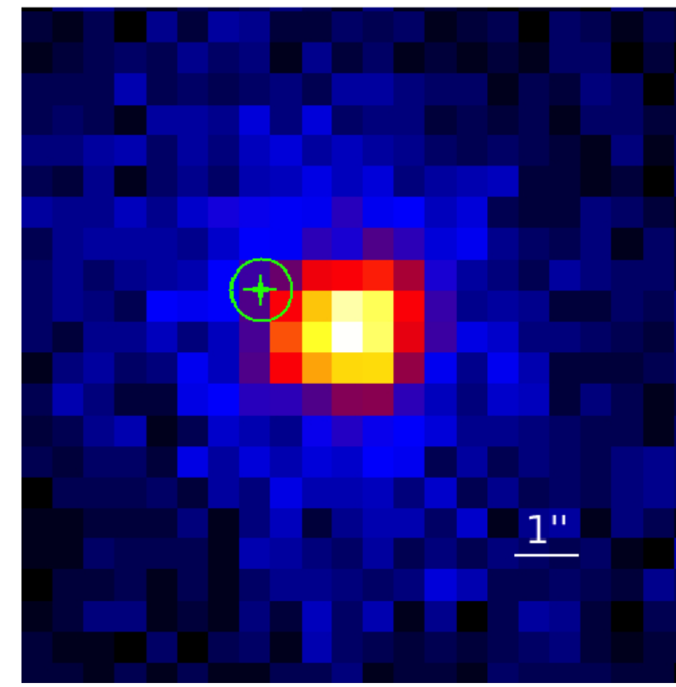


HST IMAGE

smoothed light profile
signs of a merger



HST IMAGE



CHANDRA IMAGE

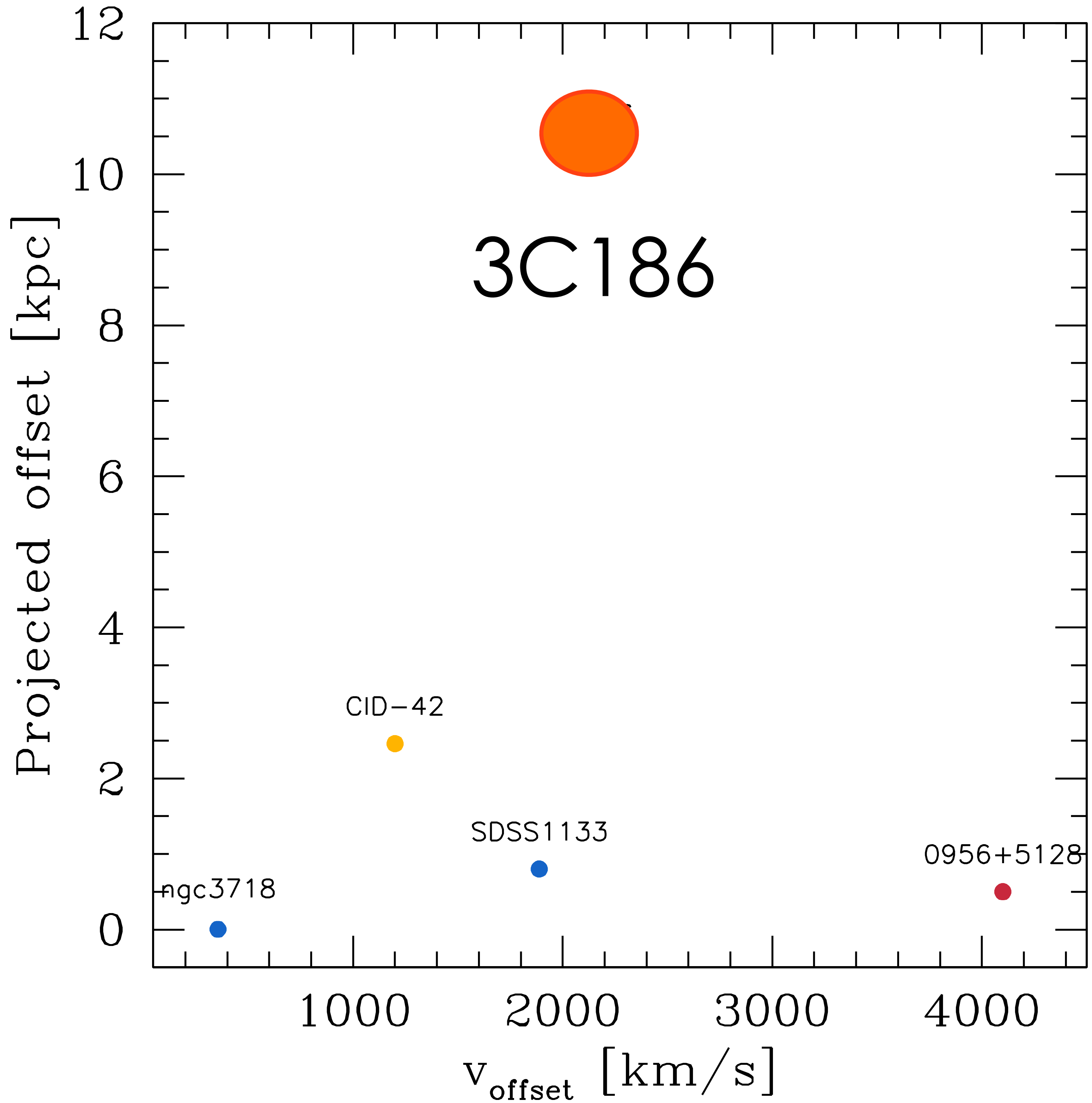
$$L \sim 10^{47}\,\mathrm{erg\,s^{-1}}$$

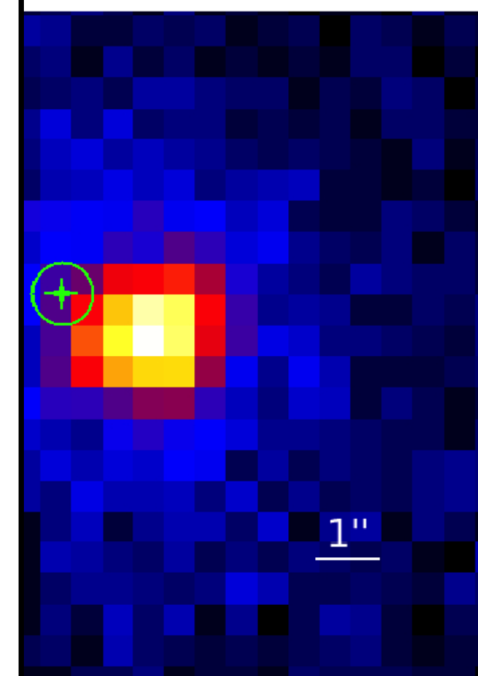
$$\tau_{\rm jet} \sim 10^5\ \mathrm{years}$$

$$\tau_{\rm merger} \sim 10^6\ \mathrm{years}$$

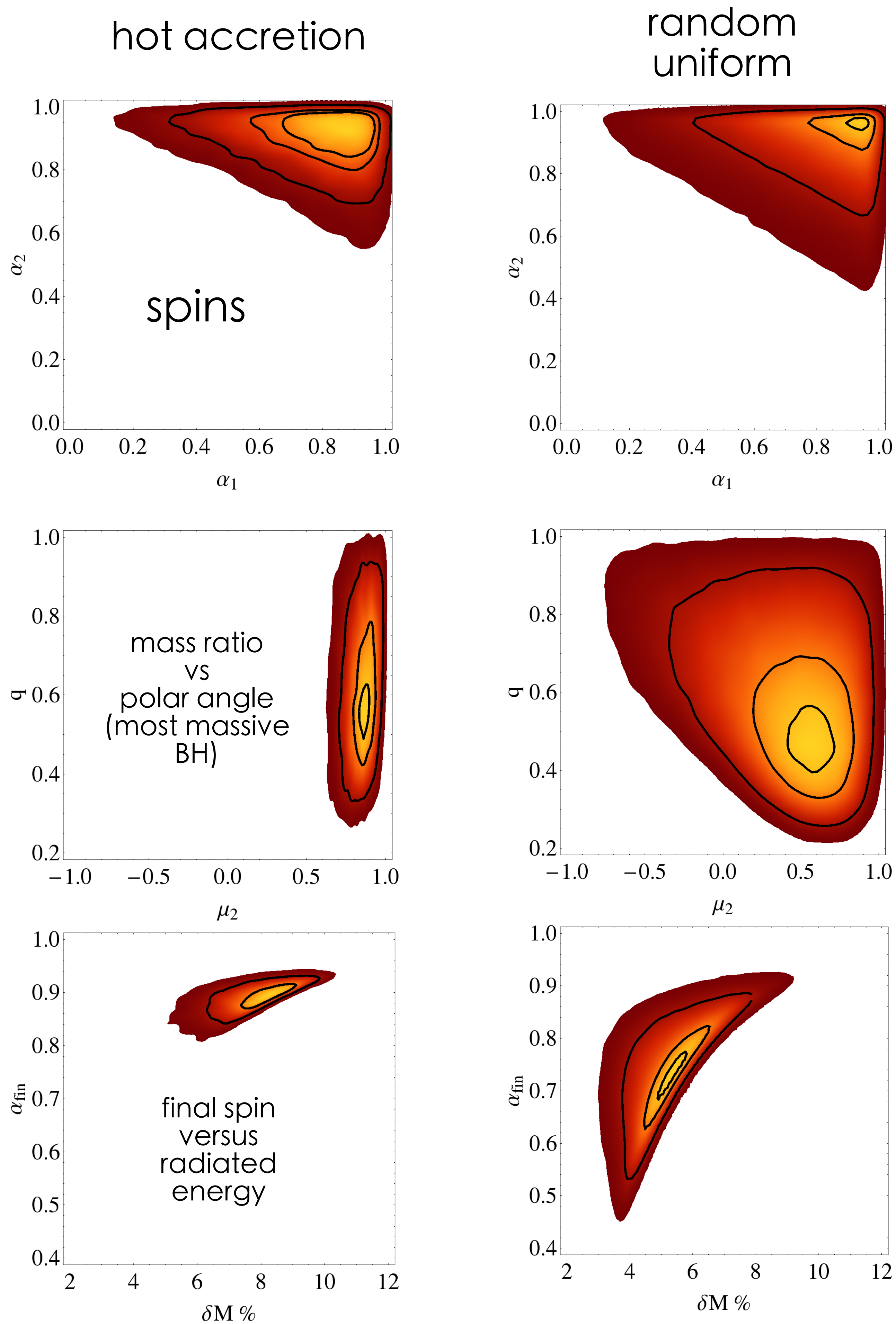
- “afterglo
- the relic b … d on the viscous tin
- the near-i … ds to strong sho
- the case c

HST





ANDRA IMAGE



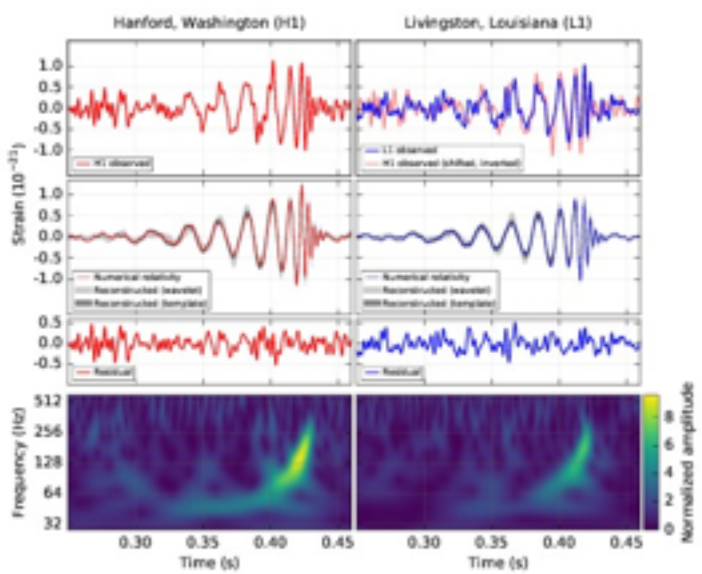
- high spins for both black holes (dimensionless spin>0.7)
- large mass ratio q>0.4 and in-plane component of the spin of the largest black holes
- large final spin and radiated energy about 9%
- the most energetic event ever observed

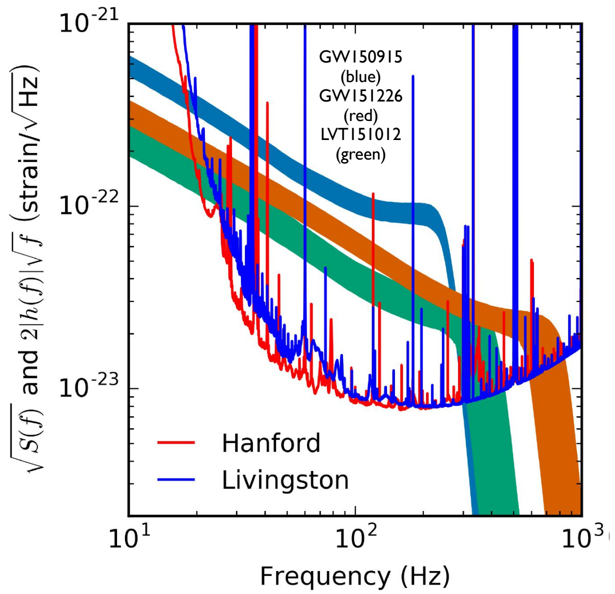
LOUSTO, ZLOCHOWER & CAMPANELLI, 2017

KEY QUESTIONS THAT LISA WILL ANSWER
"astrophysical black holes"

- *How do massive black hole form? Via accretion or/and aggregation of stellar origin black holes, or via the direct collapse of supermassive stars?*
- *How do seed black holes grow to become giant through accretion and mergers, and how fast do they grow over cosmic time?*
- *How often compact object binaries of the different flavours coalesce in galaxies and how does their coalescence rate evolve with redshift?*
- *When did the first black holes form in pre-galactic halos, and what is their initial mass and spin distribution?*
- *How do massive black holes pair in galaxy mergers and how fast to they coalesce?*
- *What is the role of black hole mergers in galaxy formation?*
- *Are massive black holes as light as* $10^{3-5}\,\mathrm{M}_\odot$ *inhabiting the cores of all dwarf galaxies?*

THE GRAVITATIONAL UNIVERSE
a quantum leap in knowledge of
THE ASTROPHYSICAL BLACK HOLES





S. Chandrasekhar

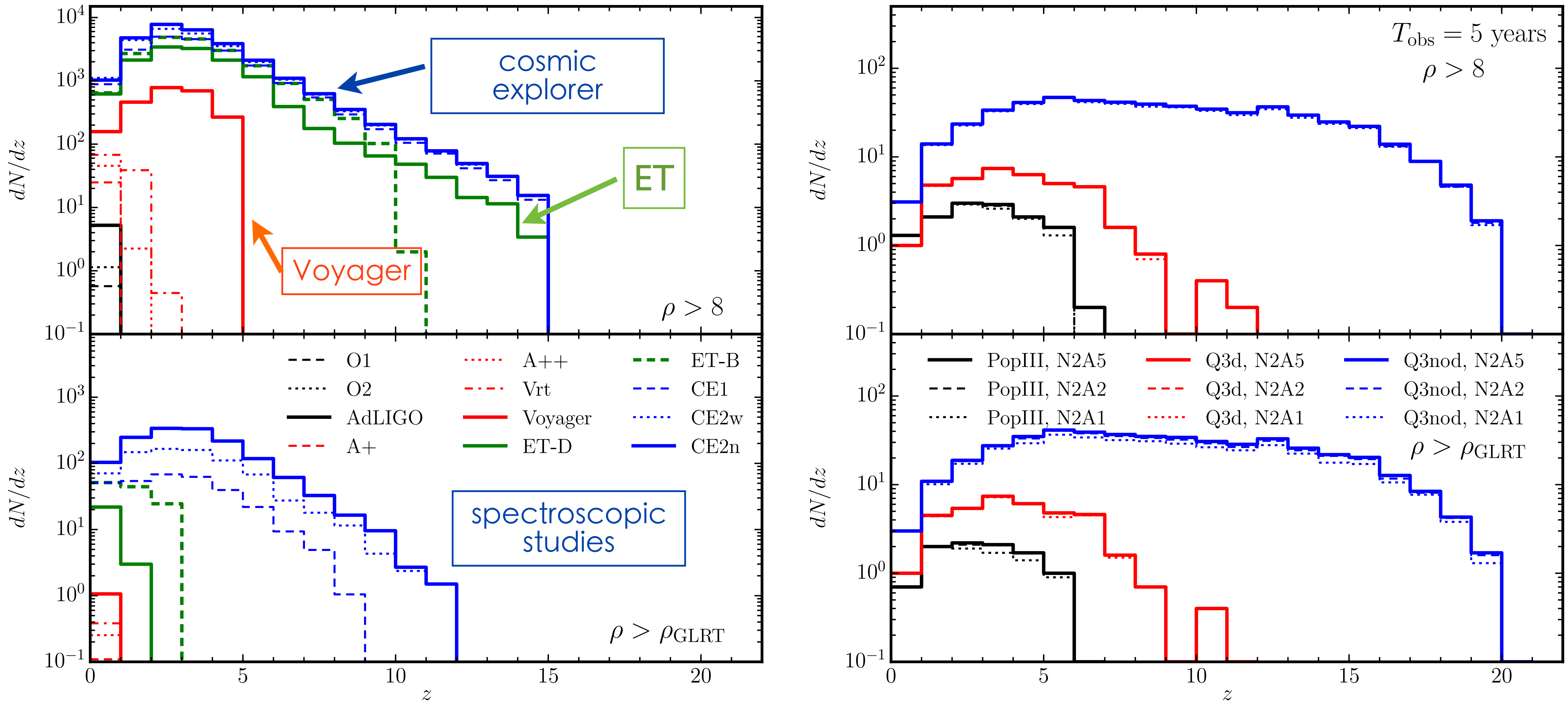
“In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein’s equations provides the absolutely exact representation of untold numbers of black holes that populate the Universe”

The Nora and Edward Ryerson lecture, Chicago April 22 1975

- end

Testing the "no hair" THEOREM

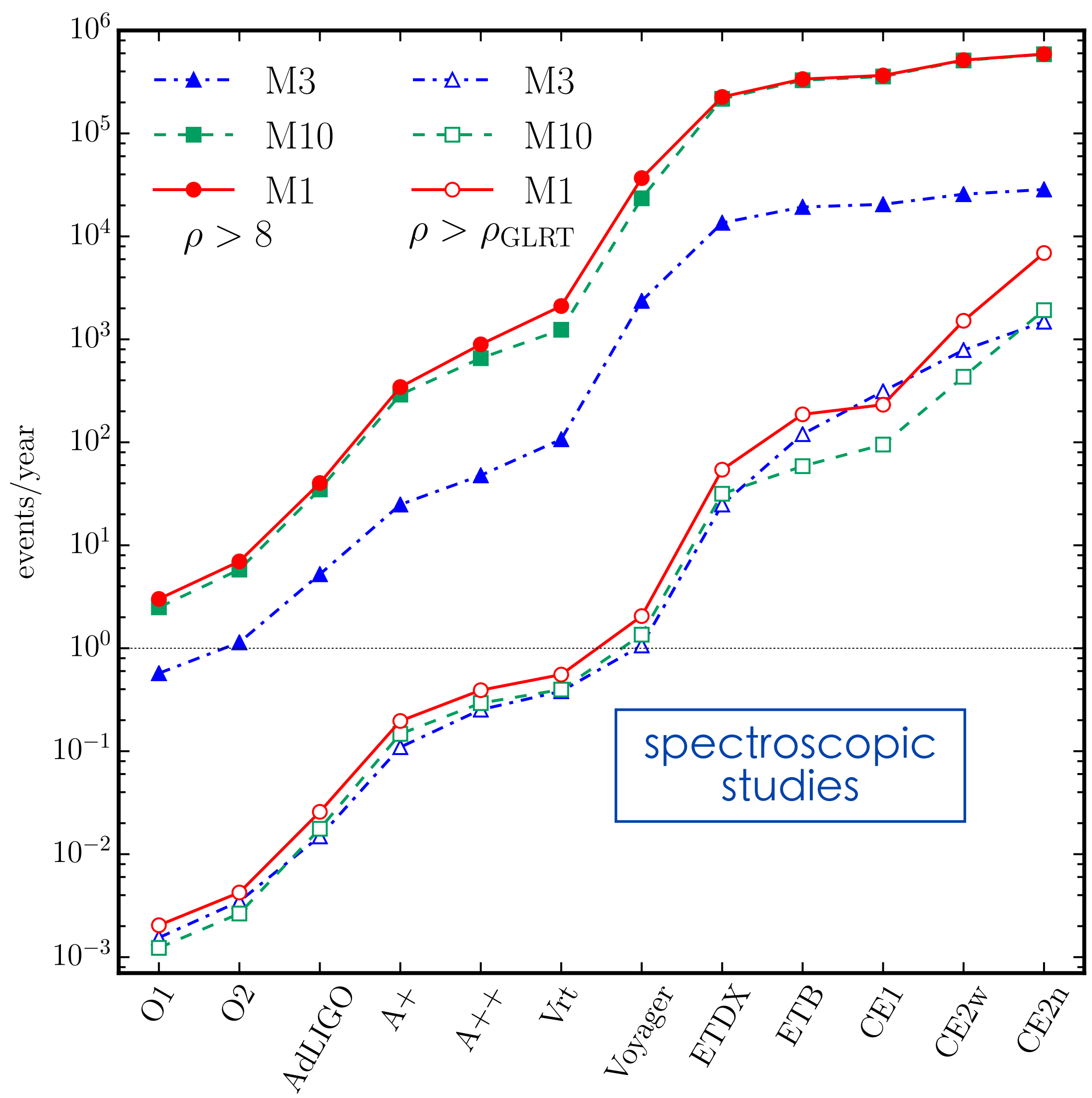
- routine spectroscopic tests requires third generation telescopes to reach binaries at z>1. LISA is dominated always by a SNR sources

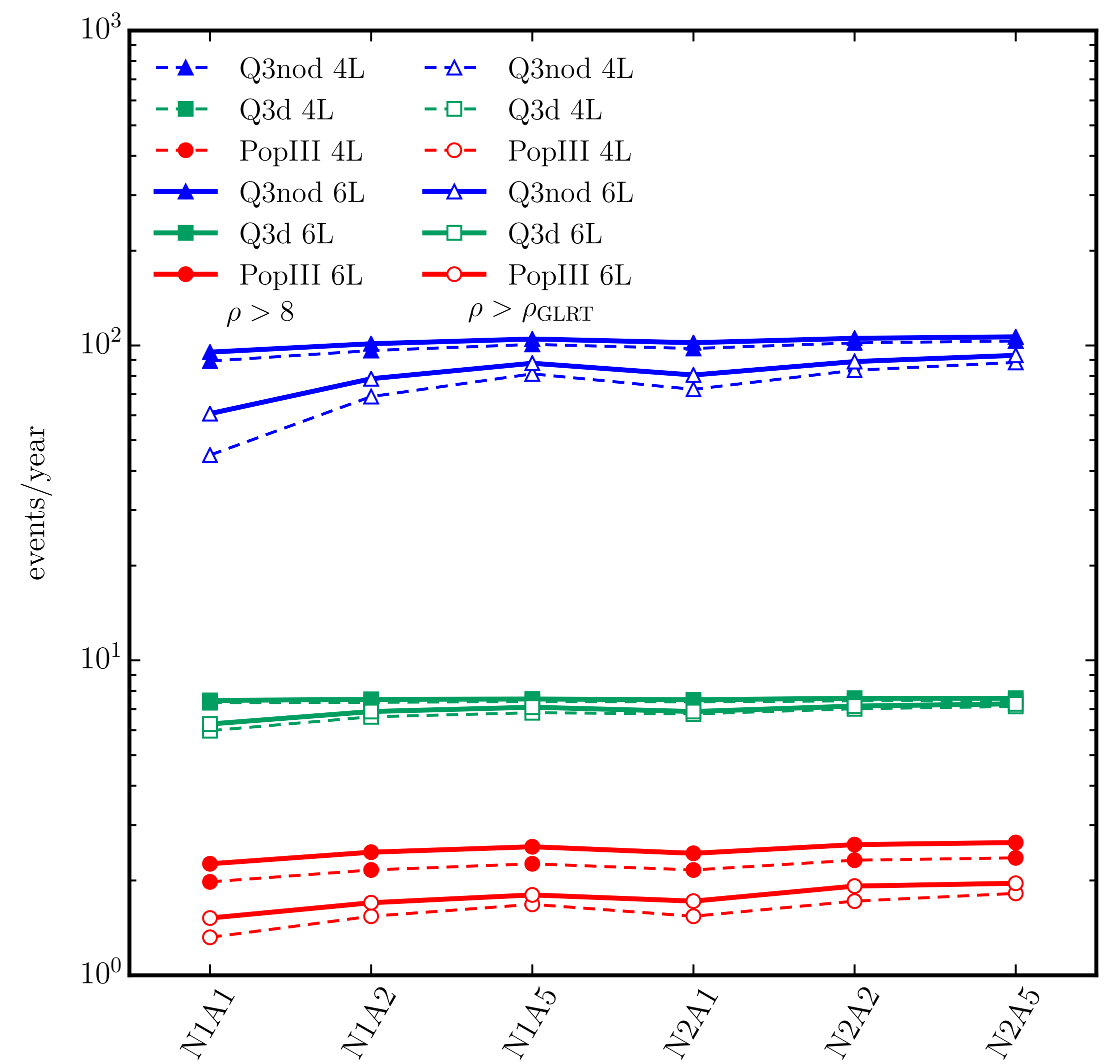


critical SNR (>50) for the second mode to be resolvable
either l=m=3 or l=m=4
for non spinning mergers

Berti + 2016

- routine spectroscopic tests requires third generation telescopes to reach binaries at z>1. LISA is dominated always by a SNR sources





solid 6 links
dashed 4 links