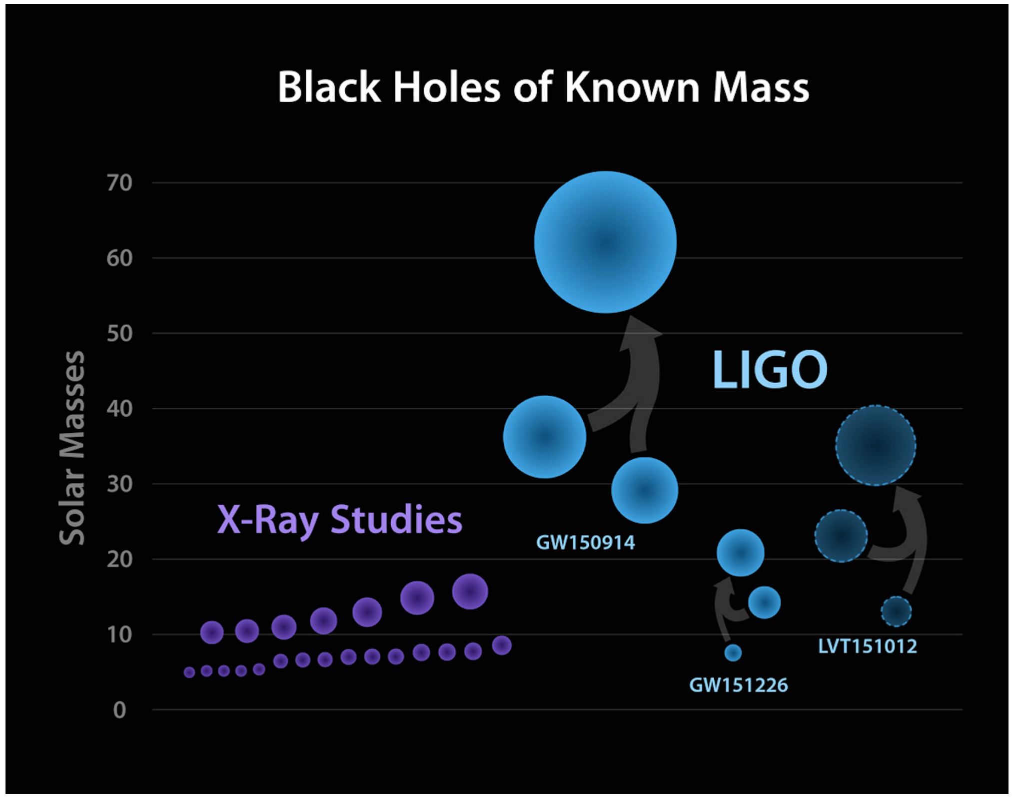
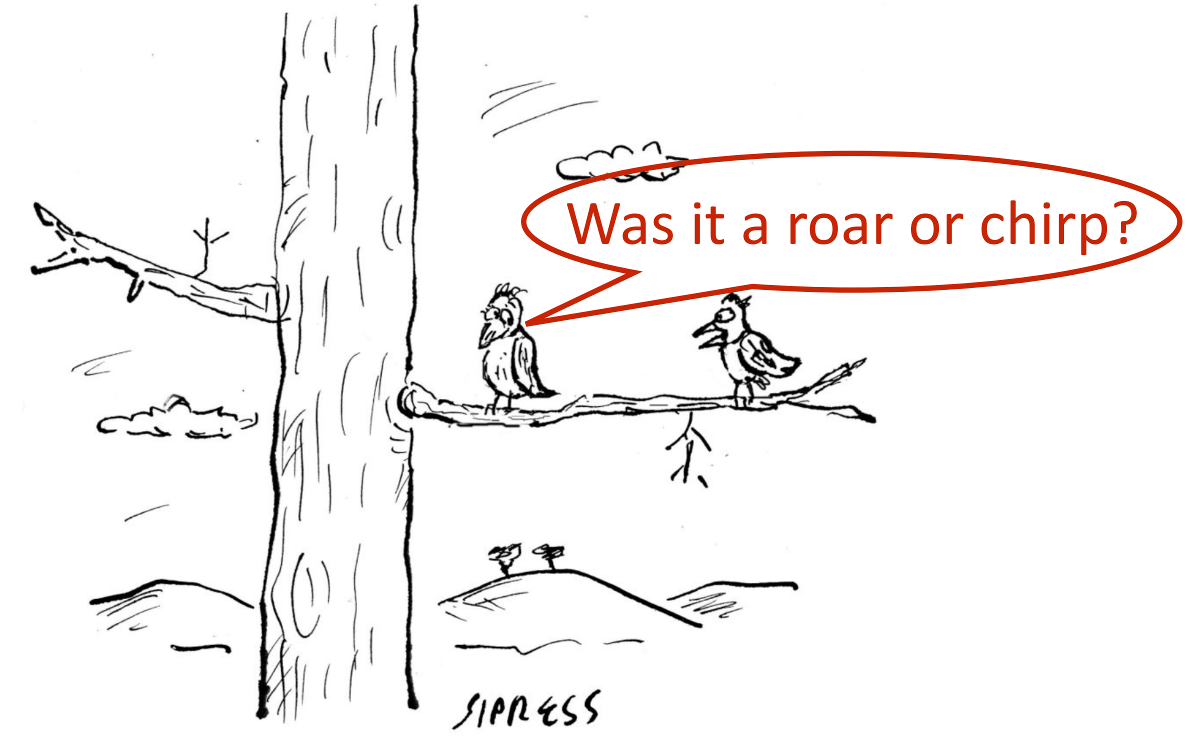
LSC LIGO Scientific Collaboration

VIRGO

Electromagnetic follow-up and new astrophysics of binary black holes (BBHs) from LIGO's observations





"Was that you I heard just now, or was it two black holes colliding?"

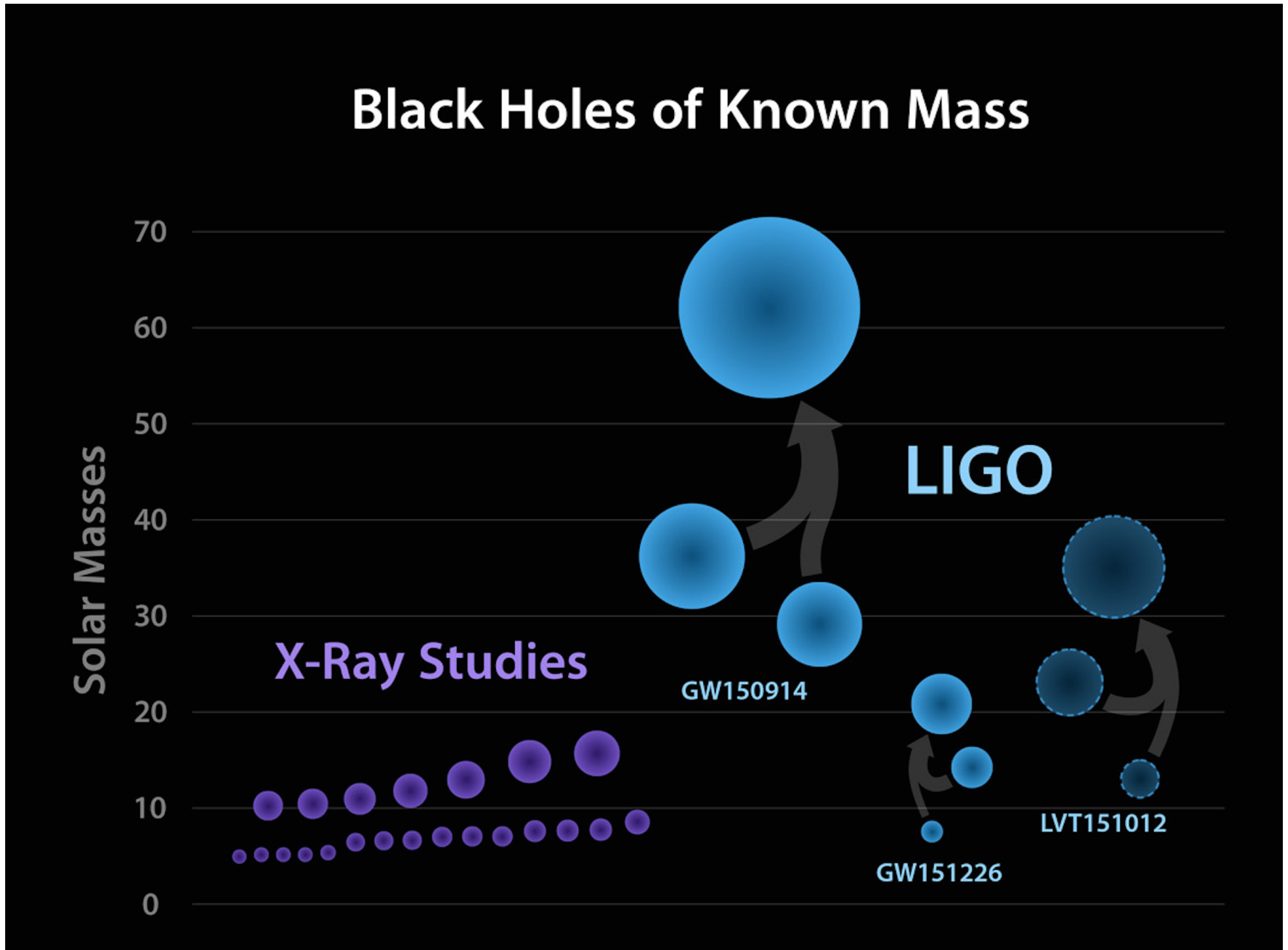
Samaya Michiko Nissanke

Radboud University, Nijmegen, the Netherlands
for the LIGO Scientific Collaboration & Virgo Collaboration

Nuclear Physics, Compact Stars, and Compact Star Mergers Conference
YITP, Kyoto, 31st October 2016

Radboud University

This year: diversity of Black Hole masses



[courtesy LIGO labs, Caltech]

22 (19 Galactic) X-ray binaries with dynamical mass measurements $< 20\ M_\odot$

[see review Cesares & Jonker 2014 & references therein]

GW150914:
Heavy ($> 25\ M_\odot$) BHs

Astrophysical Implications

i) are there Electromagnetic (EM) counterparts of binary black holes (BBH) mergers ?

ii) how to form heavy Black Holes (BHs)?

iii) how & where do BBHs form?

iv) astrophysical rates ?

Astrophysical Implications

i) are there Electromagnetic (EM) counterparts of binary black holes (BBH) mergers ?

ii) how to form heavy Black Holes (BHs)?

iii) how & where do BBHs form?

[see Ken'ichi Nomoto's talk]

iv) astrophysical rates ?

[see Laura Nuttall's talk]

Main papers referenced in this talk

Discovery Paper: "Observation of Gravitational Waves from a Binary Black Hole Merger," arXiv:1602.03837, Physics Review Letters 116, 061102 (2016).

Astrophysical paper: "Astrophysical Implications of the Binary Black-Hole Merger GW150914," Astrophys. J. Lett. 818, L22 (2016).

Parameter Estimation: "Properties of the binary black hole merger GW150914," arXiv: 1602.03840, Physics Review Letters 116, 241102 (2016).

EM follow-up paper: "Localization and Broadband Follow-up of the Gravitational-wave Transient GW150914", ApJLetters, 826, Issue 1, article id. L13, (2016).

GW151226 discovery: "GW151226: Observation of Gravitational Waves from a 22 Solar-mass Binary Black Hole Coalescence," arXiv:1606.04755, Physics Review Letters 116, 241103 (2016)

O1 BBH paper: "Binary Black Hole Mergers in the first Advanced LIGO Observing Run," arXiv:1606.04856, PRX 6, 041015.


LIGO Hanford

Main characters


LIGO Livingston

September 14, 2015 *October 12, 2015* **December 26, 2015**

GW150914

September event
SNR ~ 23.7, > 5.3σ

LVT151012

October candidate
SNR ~ 9.7, 1.7σ

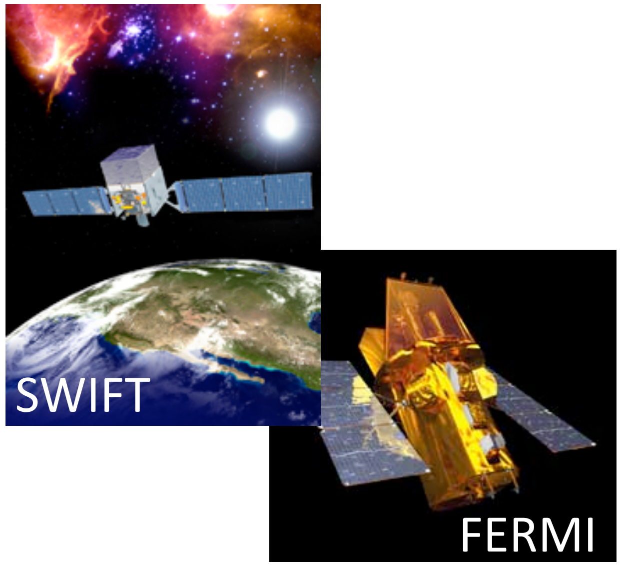
GW122615

Boxing day event
SNR ~13.0, > 5.3σ

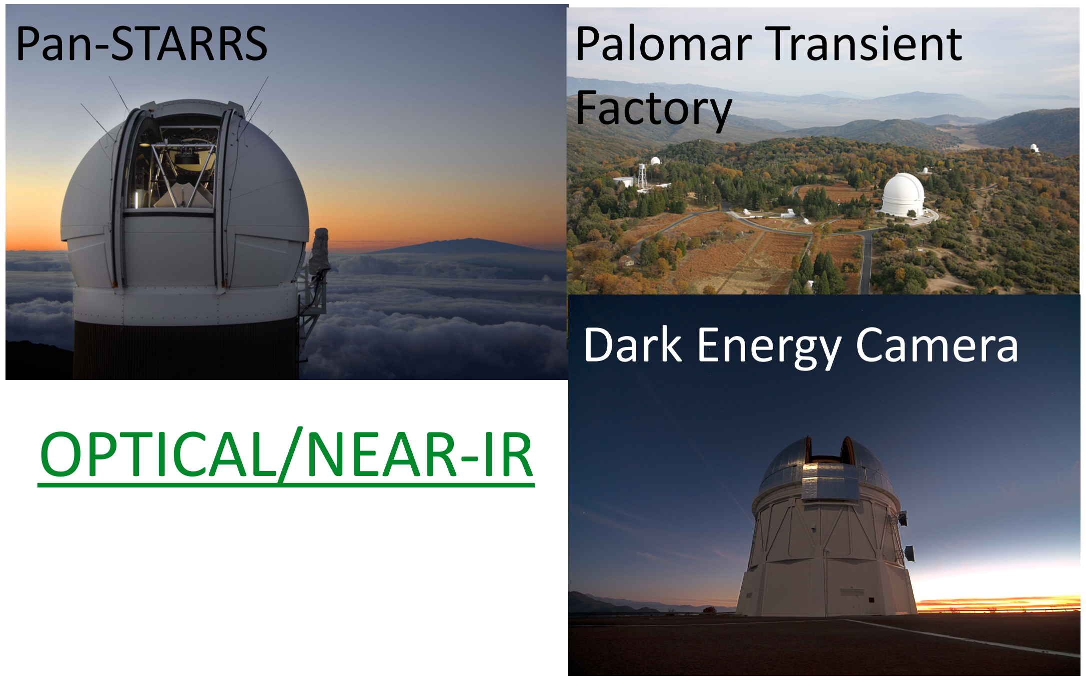
Electromagnetic (EM) Partners

Photometric and spectroscopic facilities over a wide-range of EM wavelengths

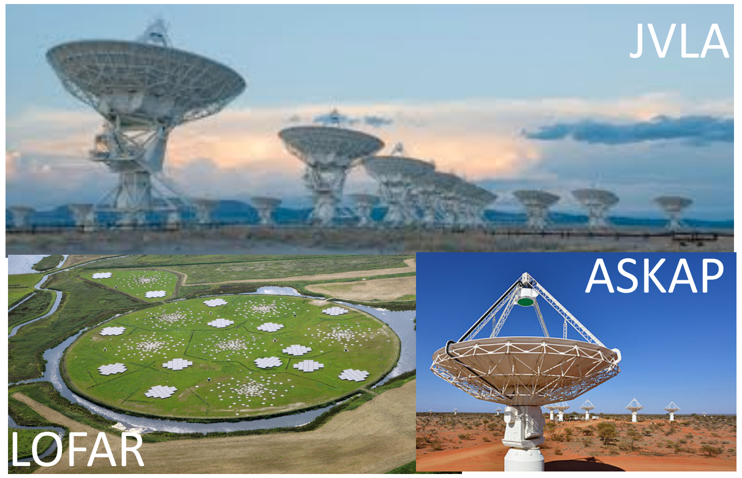
74 groups comprising 170 EM instruments,
at least 40 groups followed up at least one event



HIGH ENERGY



OPTICAL/NEAR-IR



RADIO

e.g., GW150914: ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, INTEGRAL, IPN, Swift, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, INAF/GRAWITA, iPTF, J-GEM/ KWFC, La Silla–QUEST, Liverpool Telescope, PESSTO, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VISTA

Plan of Talk

Part 1: EM follow-up of GW mergers

Part 2: Astrophysical Implications [if time]

Part 3: Perspective & what's next? [my views]

Part Ia: EM follow-up

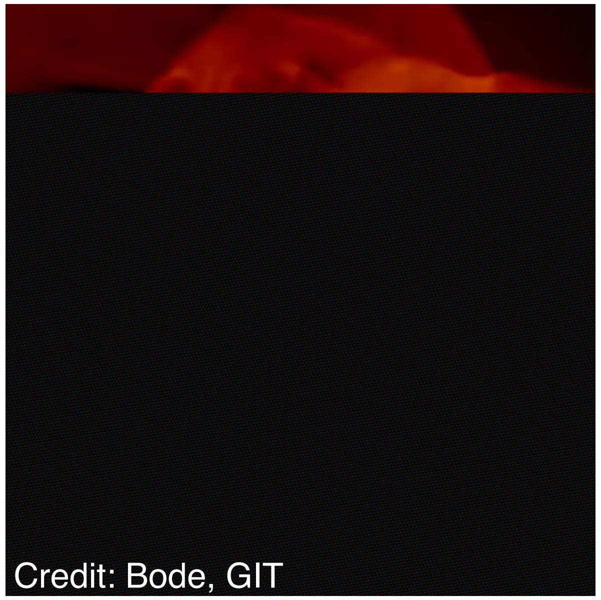
some motivation
& background

Why we should care about EM counterparts? (some motivation)

1. Strong field gravity astrophysics
   Physical processes in strongly curved space-times
2. Stellar Evolution
   Understanding the fate of compact binary stellar systems?
3. Cosmic Enrichment
   Sites of r-process nucleosynthesis
4. Cosmological Probes
   Measuring the expansion history of the Universe

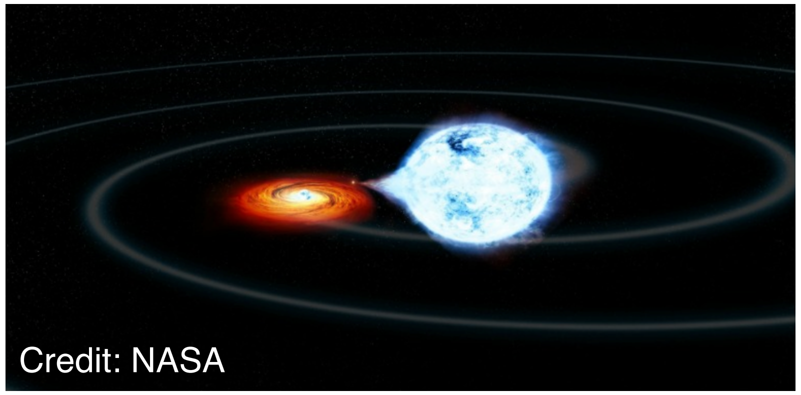
EM counterparts of GW sources

Low Frequency GWs


Credit: Bode, GIT

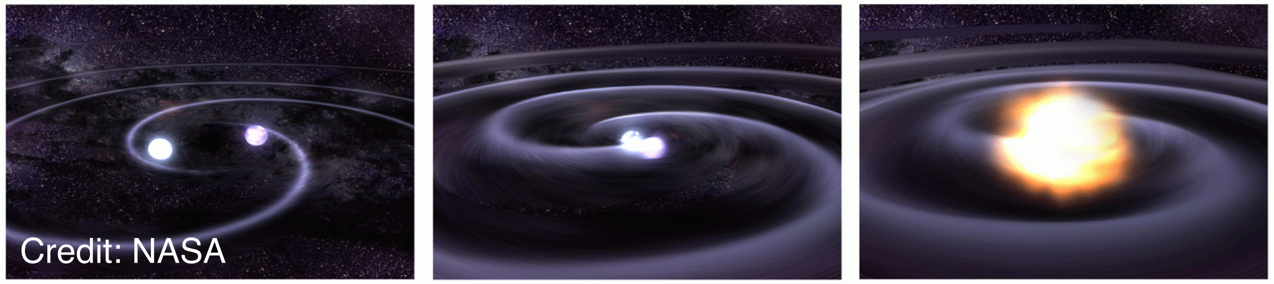
Supermassive Black Hole Binary Mergers with gas

AM CVn (mass-transferring White Dwarfs)

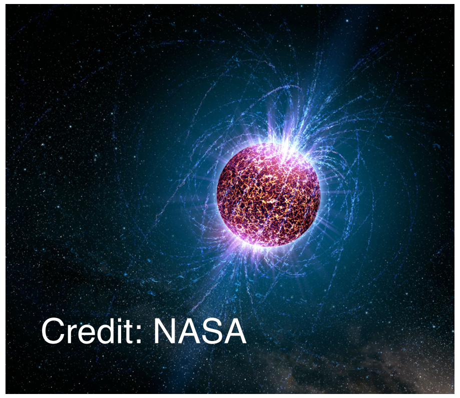

Credit: NASA

High Frequency GWs

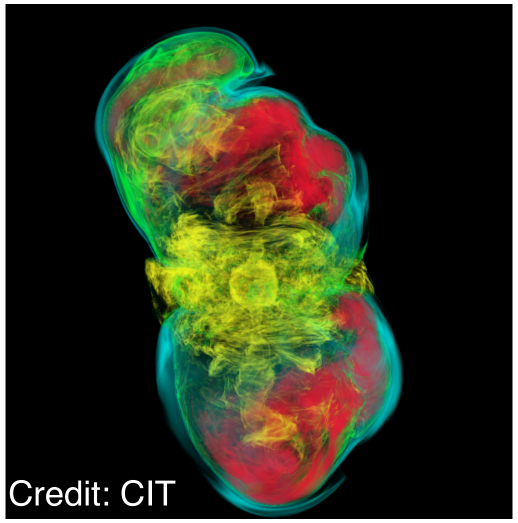
Neutron Star Binary Mergers


Credit: NASA

Pulsar


Credit: NASA

Supernova

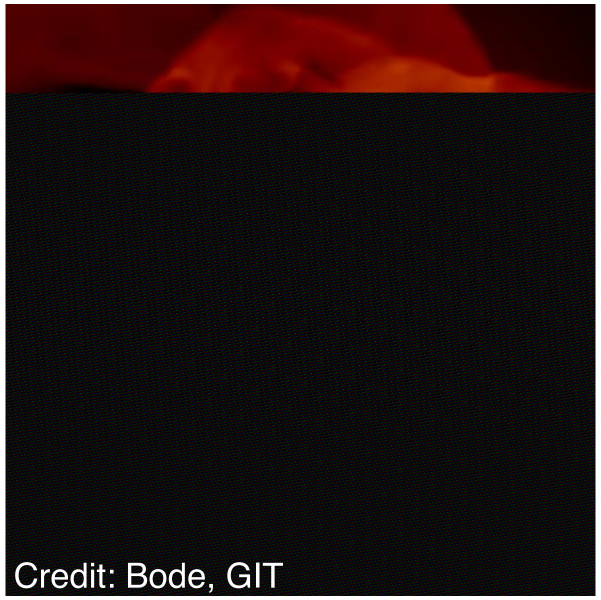

Credit: CIT

Heavy BINARY BLACK HOLES (BBH) ??

Delayed matter outflows are responsible for EM signatures

EM counterparts of GW sources

Low Frequency GWs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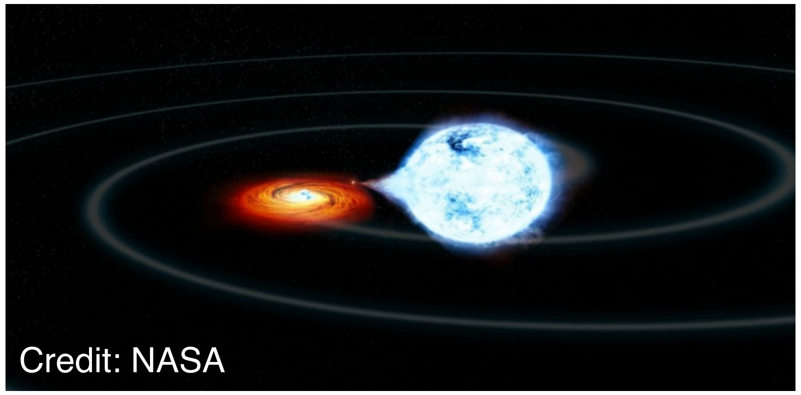
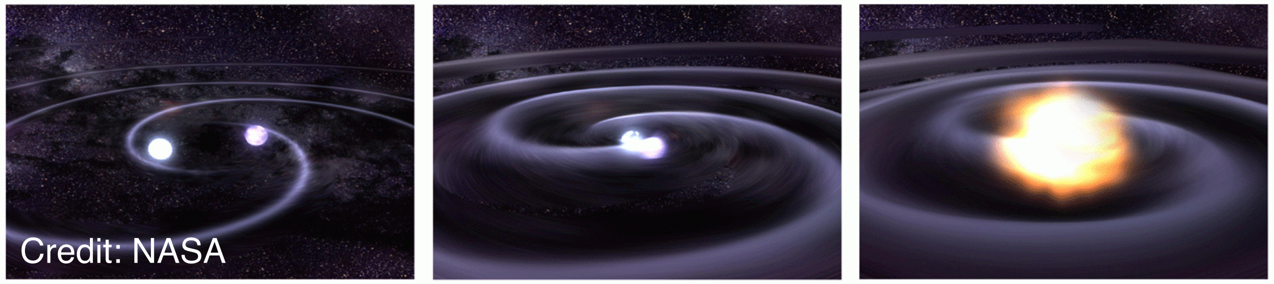
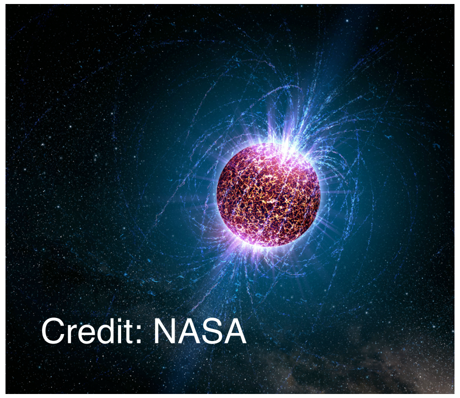

Credit: NASA

High Frequency GWs

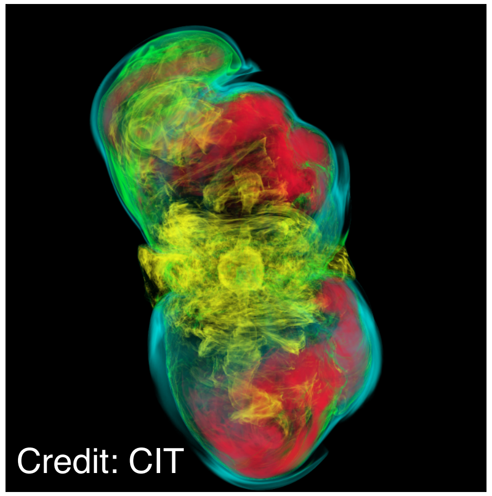
Neutron Star (NS) Binary Mergers


Credit: NASA

Pulsar


Credit: NASA

Supernova

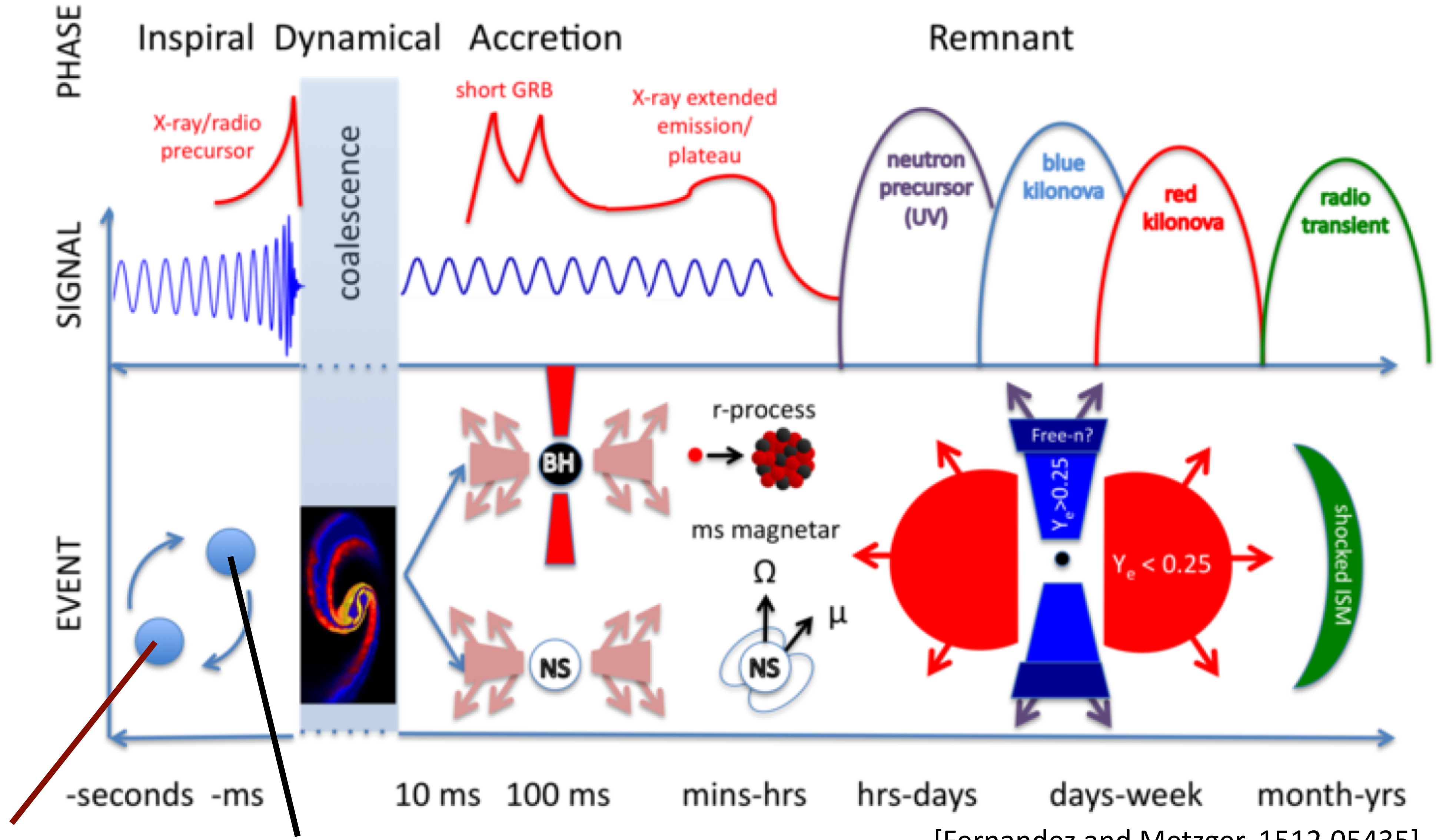

Credit: CIT

Heavy BINARY BLACK HOLES (BBH) ??

<ins>Delayed matter outflows</ins> are responsible for EM signatures

Lifetime of a NS-NS and NS-BH merger

[see Piran, Rezzolla, Roberts, Tanaka, Zhang talks]



Neutron Stars (NS)   NS or Black Hole (BH)

[Fernandez and Metzger, 1512.05435]

[e.g., <u>prompt radio emission</u>: Hansen & Lyutikov (2001), Moortgat and Kuipjers (2002,5,6), Postnov and Pshirkov (2010), Lai (2012, Piro (2012)); <u>kilonova</u>: Lattimer and Schramm 1976, Li and Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Metzger & Berger 2012,…Barnes et al. 2013, Grossman et al. 2013, Tanaka et al. 2013, Tanvir et al. 2013, Berger et al. 2013, … ; <u>slow radio</u>: Nakar and Piran 2011, Hotokezaka et al., 2015]

Recent Change: we now have the potential to detect GW and EM radiation

Gravitational radiation

EM radiation

Learn about sources'
<u>dynamic</u> and
<u>fundamental properties</u>

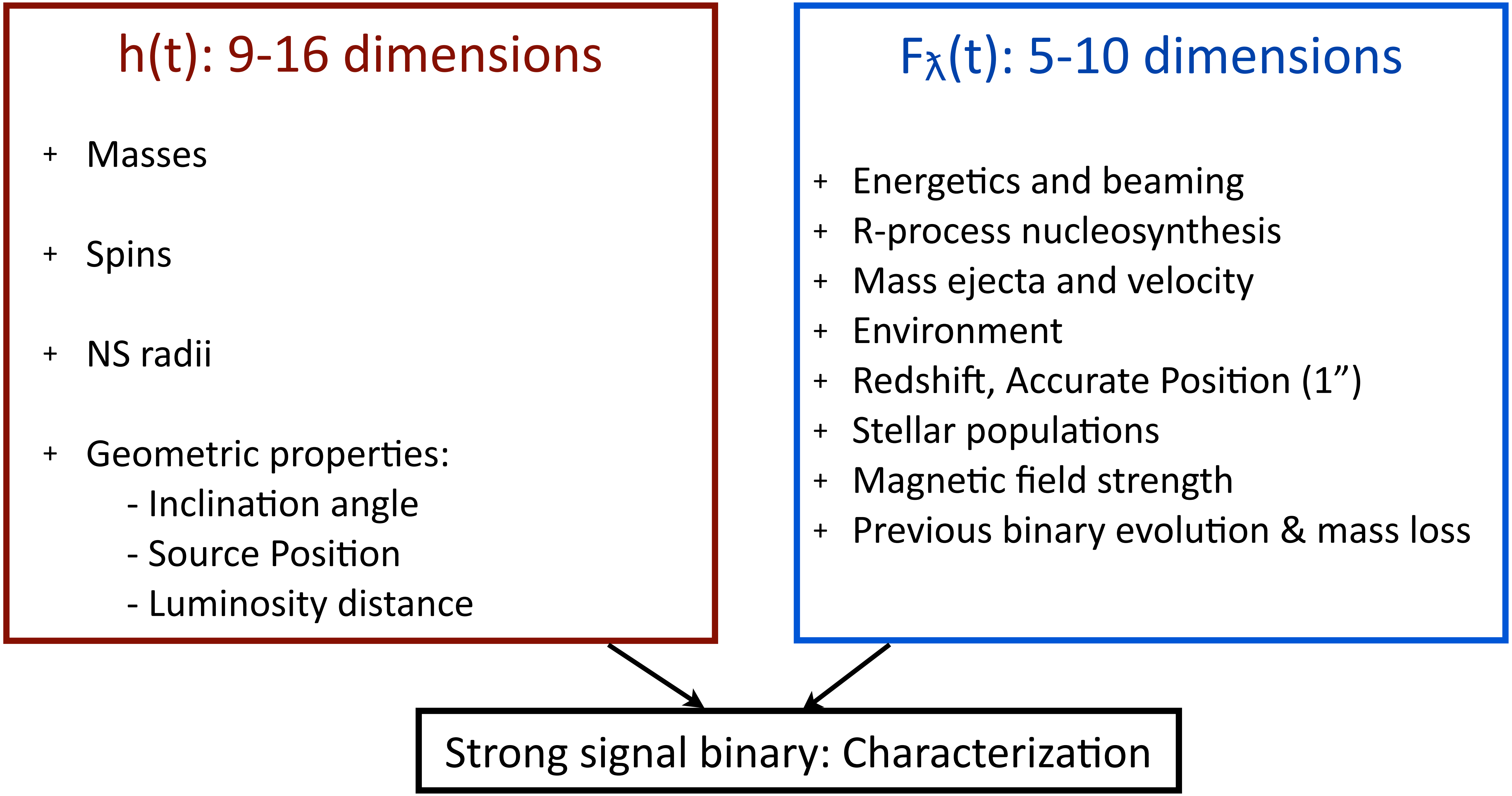
Learn about sources'
<u>environment</u> and
<u>energetics</u>

Next step: combine & interpret GW + EM

h(t): 9-16 dimensions

- Masses
- Spins
- NS radii
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Next step: combine & interpret GW + EM



$h(t)$: 9-16 dimensions

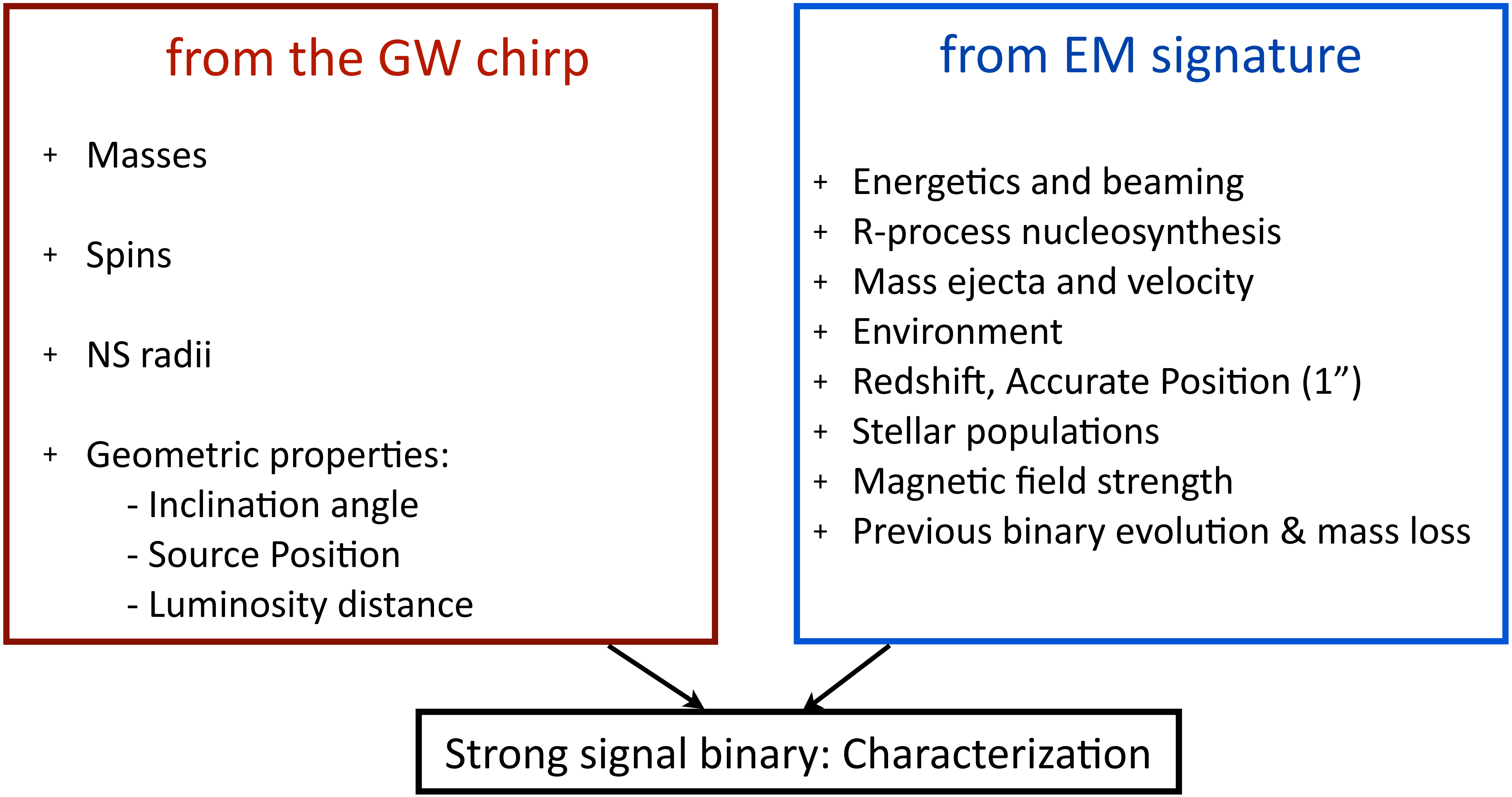
- Masses
- Spins
- NS radii
- Geometric properties:
  - - Inclination angle
  - - Source Position
  - - Luminosity distance

$F_\lambda(t)$: 5-10 dimensions

- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position (1”)
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss

Strong signal binary: Characterization

Next step: combine & interpret GW + EM



from the GW chirp

- Masses
- Spins
- NS radii
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

from EM signature

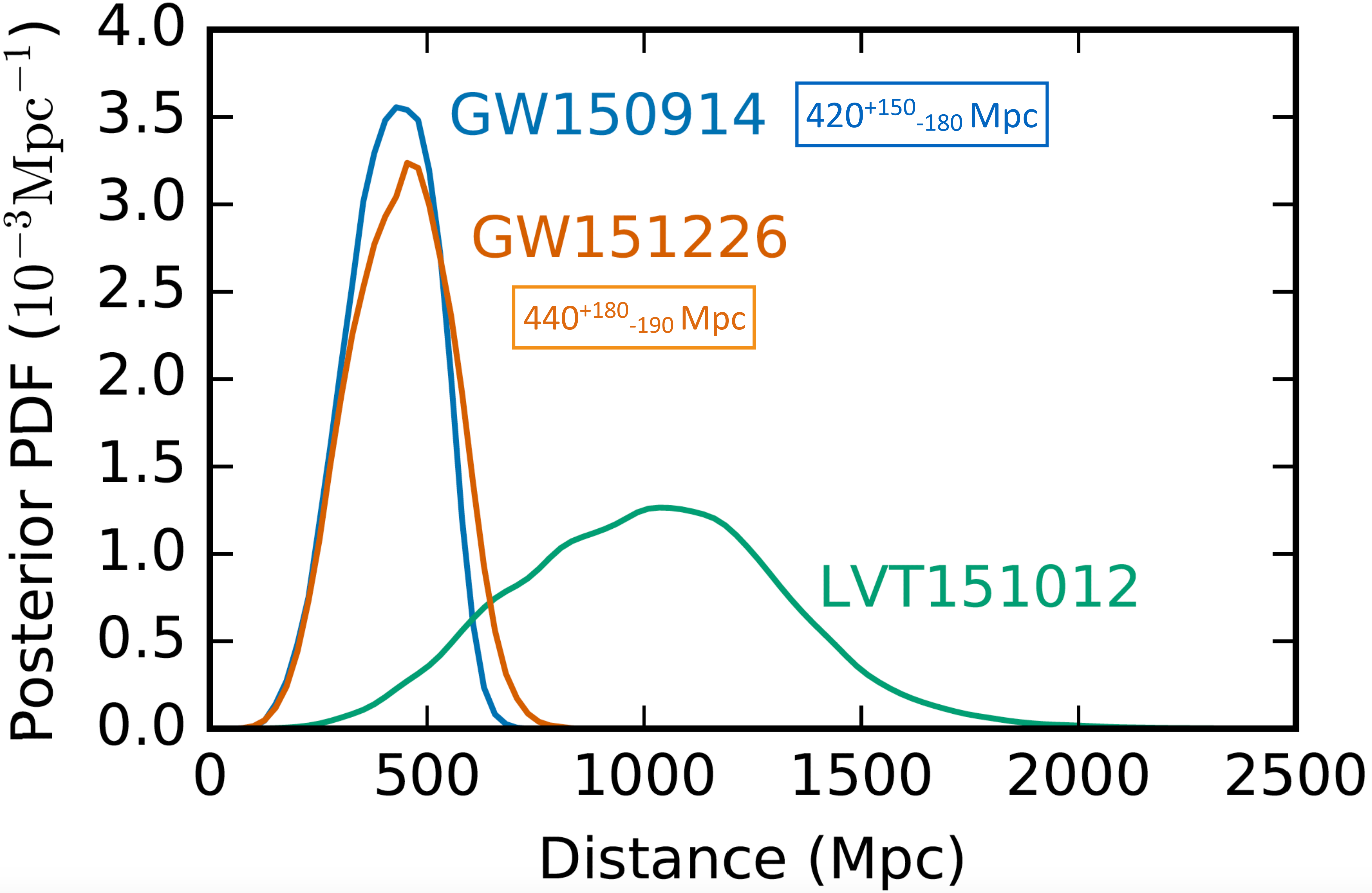
- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position (1”)
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss

Strong signal binary: Characterization

Population: Demographics, ecology and census

Part Ib: EM follow-up
in practice

Luminosity distance: beyond existing spectroscopic GW galaxy catalogs



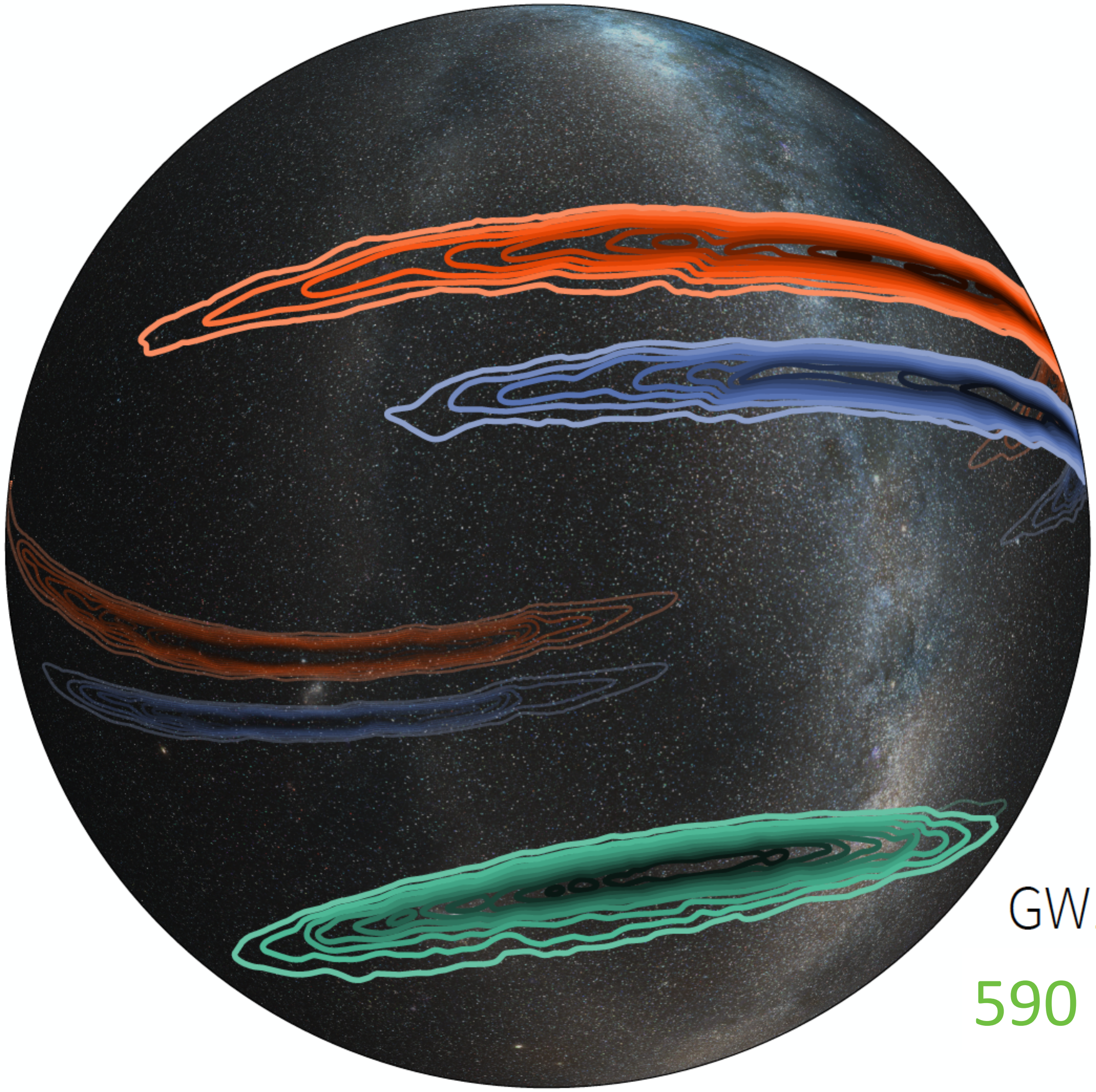
Xiv:1606.04856, PRX 6, 041015 , 2016]

GW challenge: how well?

$$\theta \sim \frac{\lambda}{D} \sim \frac{c}{fD} \sim 10\ \mathrm{deg}$$

[e.g., Fairhurst 2010, 2011, Wen and Chen 2011, Nissanke et al. 2011, 2013, Veitch et al. 2012, Aasi et al. 2013, Rodriguez et al. 2013, Grover et al. 2014, Sidery et al. 2014. Kasliwal and Nissanke 2014, Singer et al. 2014]

How well can we localise the source on the sky?



1600 sq. deg. (90% c.r.)

LVT151012

GW151226

1000 [850] sq. deg. (90% c.r.)

GW150914

590 [230] sq. deg. (90% c.r.)

[Image credit: LIGO/L. Singer/A. Messinger]

[LVC, arXiv:1606.04856, PRX 6, 041015, 2016]

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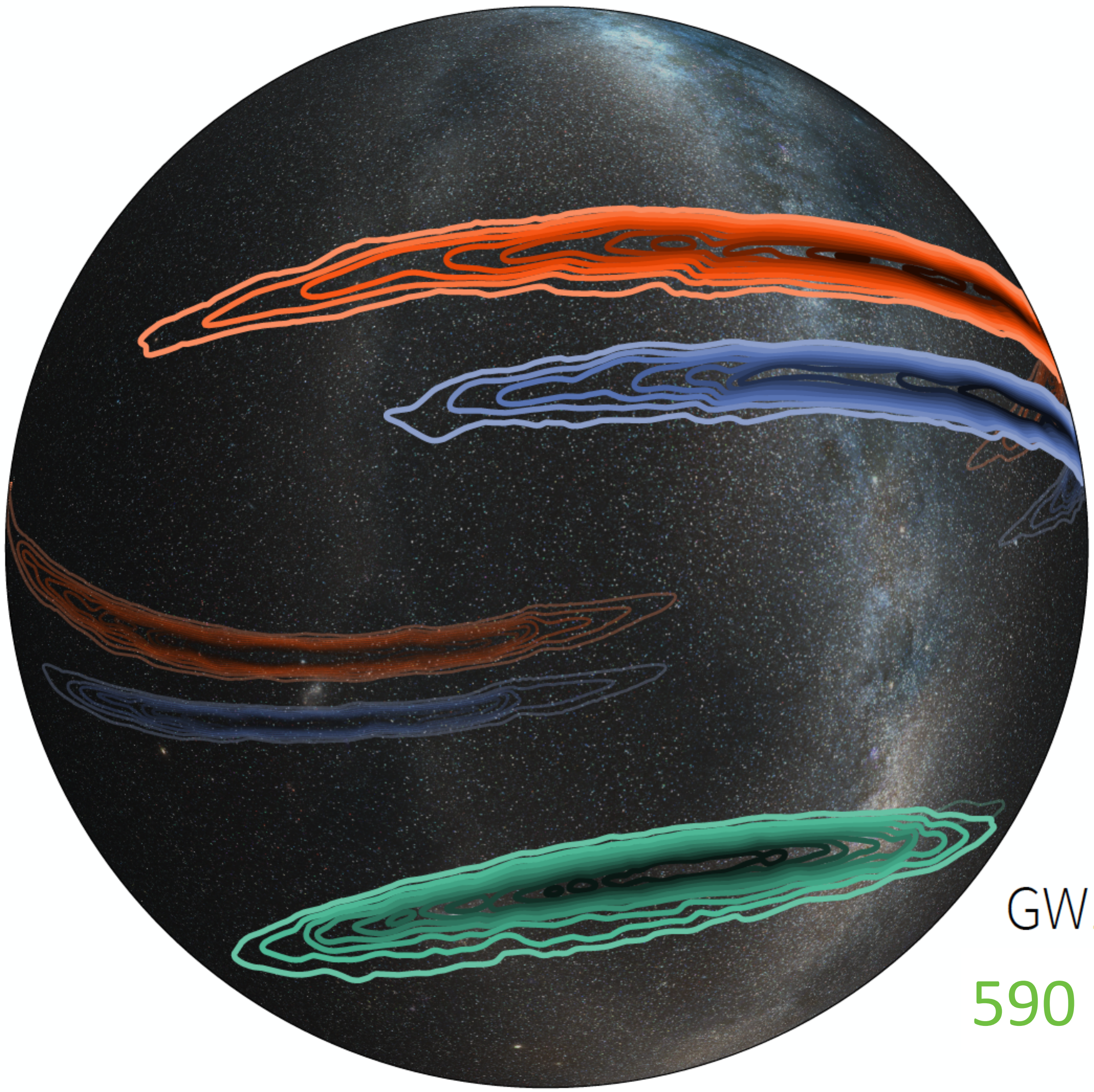


1600 sq. deg. (90% c.r.)

1000 [850] sq. deg.
(90% c.r.)

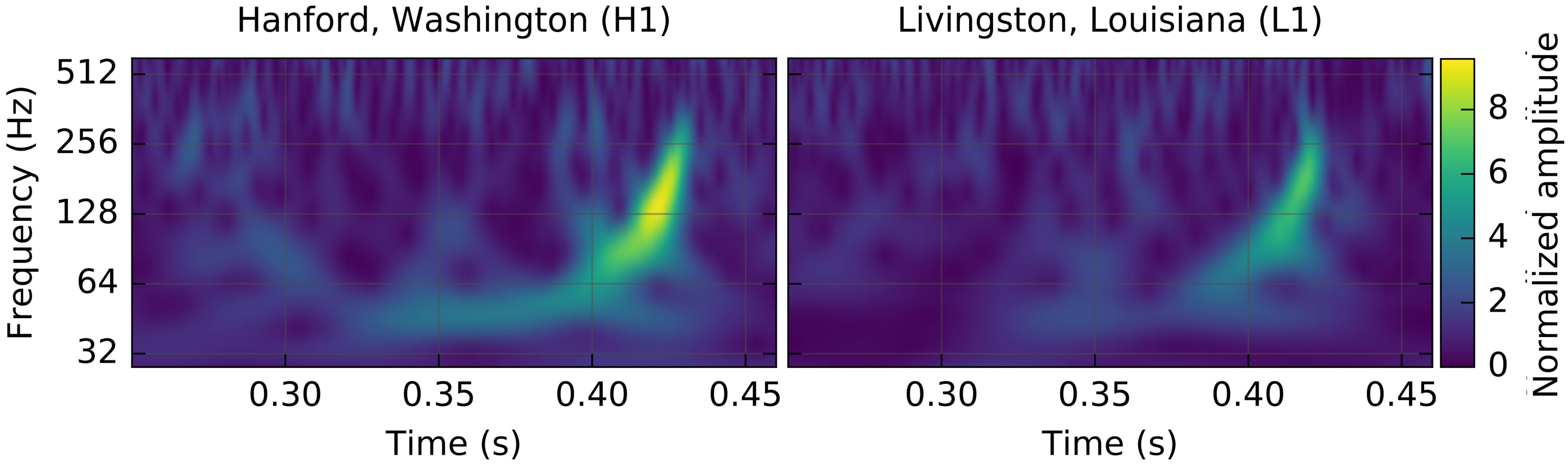
590 [230] sq. deg. (90% c.r.)

[Image credit: LIGO/L. Singer/A. Messinger]

Xiv:1606.04856, PRX 6, 041015 , 2016]

10^5-10^7 galaxies in these volumes

Binary Black Hole (BBH) merger !



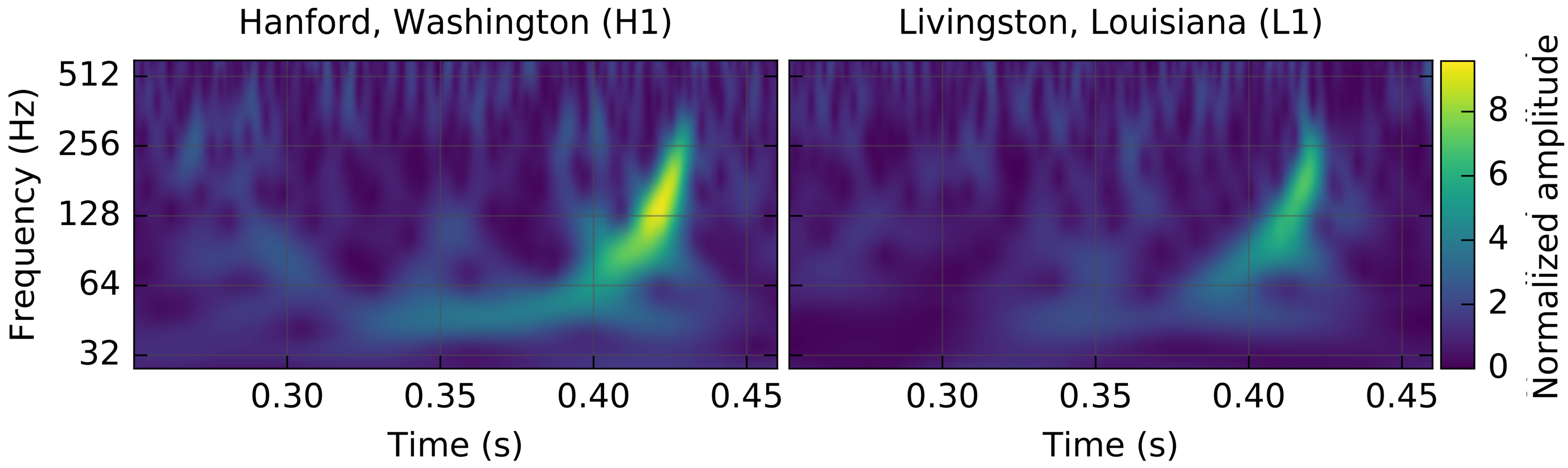
A surprise: 4 days before the first Science Run …

Burst: SNR of 23.45 and FAR < 0.371 yr^{-1} [1 $month^{-1}$]

Max Frequency → Orbital Frequency → Total mass > 70 $M_\odot$

[LVC,arXiv:1602.03837, PRL 116, 061102, 2016]

BBH merger ! …



A surprise: 4 days before the first Science Run …

Burst search (cWB): SNR of 23.45 and FAR < 0.371 yr^{-1} [1 $month^{-1}$]

Max Frequency → Orbital Frequency → Total mass > 70 $M_\odot$

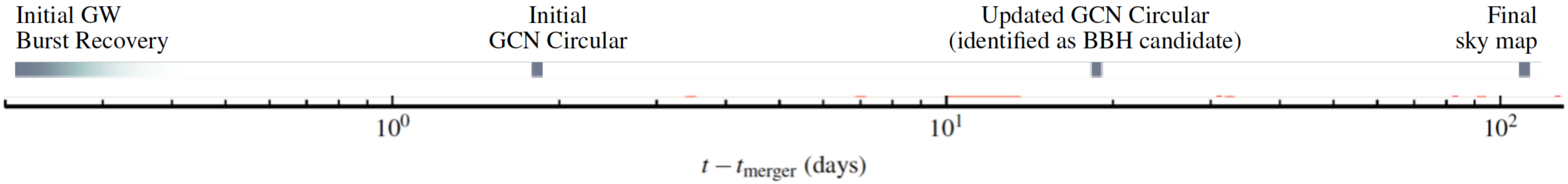
NO EM COUNTERPART IS GENERALLY EXPECTED

(unless in highly dense magnetized plasmas or in extremely gas rich environments)

[LVC,arXiv:1602.03837, PRL 116, 061102, 2016]

Timeline of release of GW parameters

Several announcements sent via GW-alert GCNs to MOU EM partners



[LVC, APJL, 826, 1, L13, 2016]

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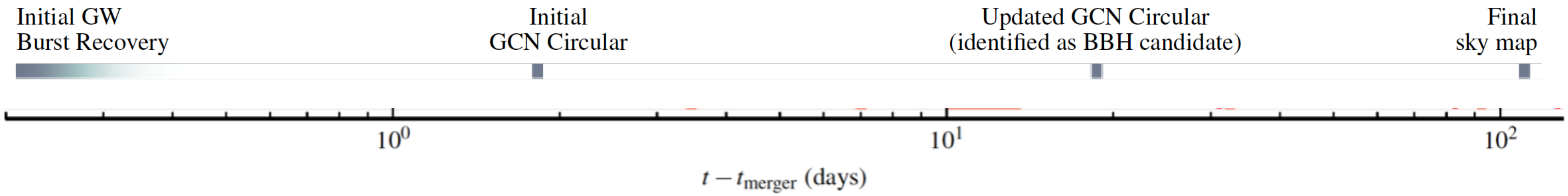
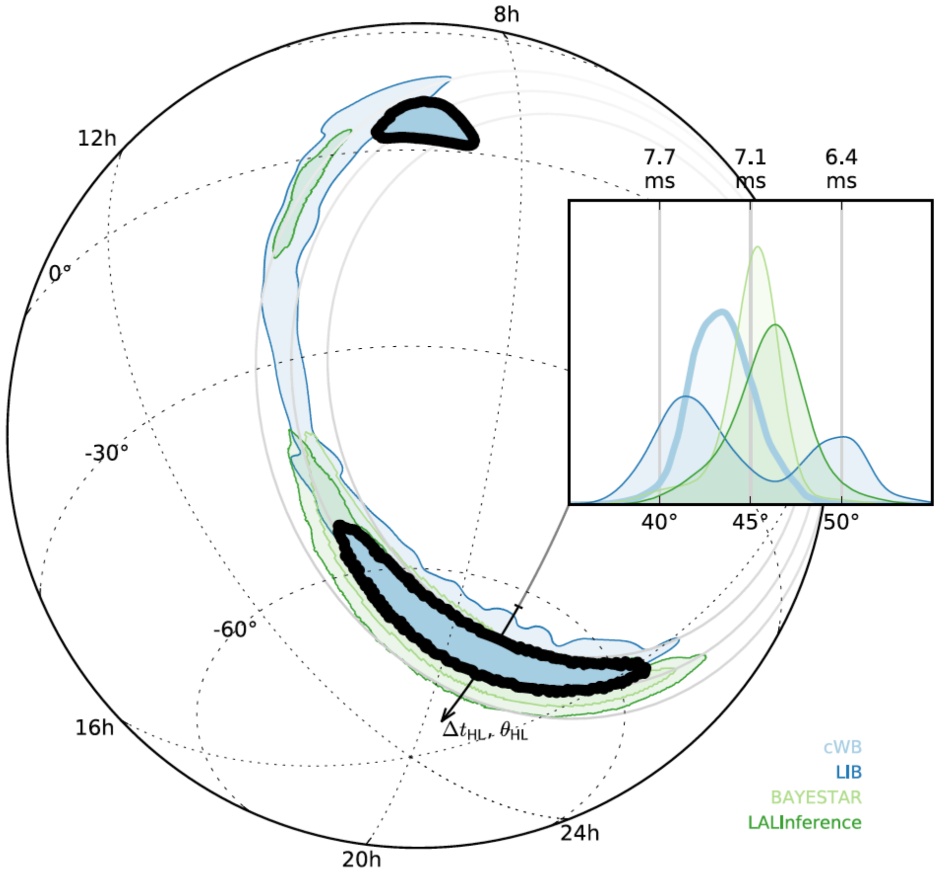


GW150914

+ 2 days after: first set of sky maps
+ 19 days after: BBH candidate
+ 4 months after: final sky map



annulus where polar angle is determined by the arrival time at two detectors

[LVC, APJL, 826, 1, L13, 2016]

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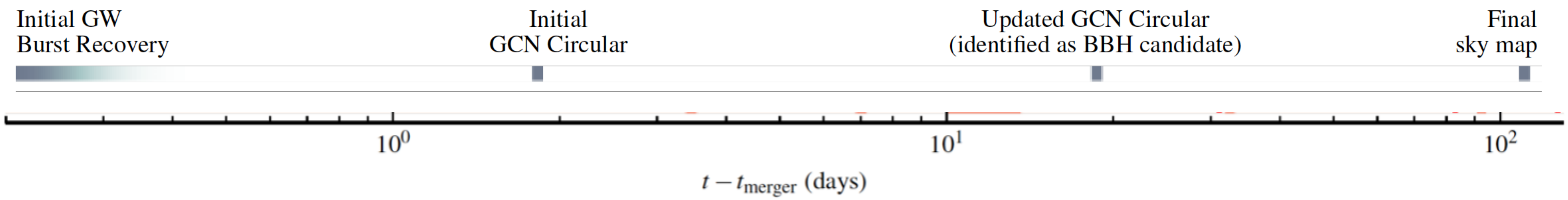

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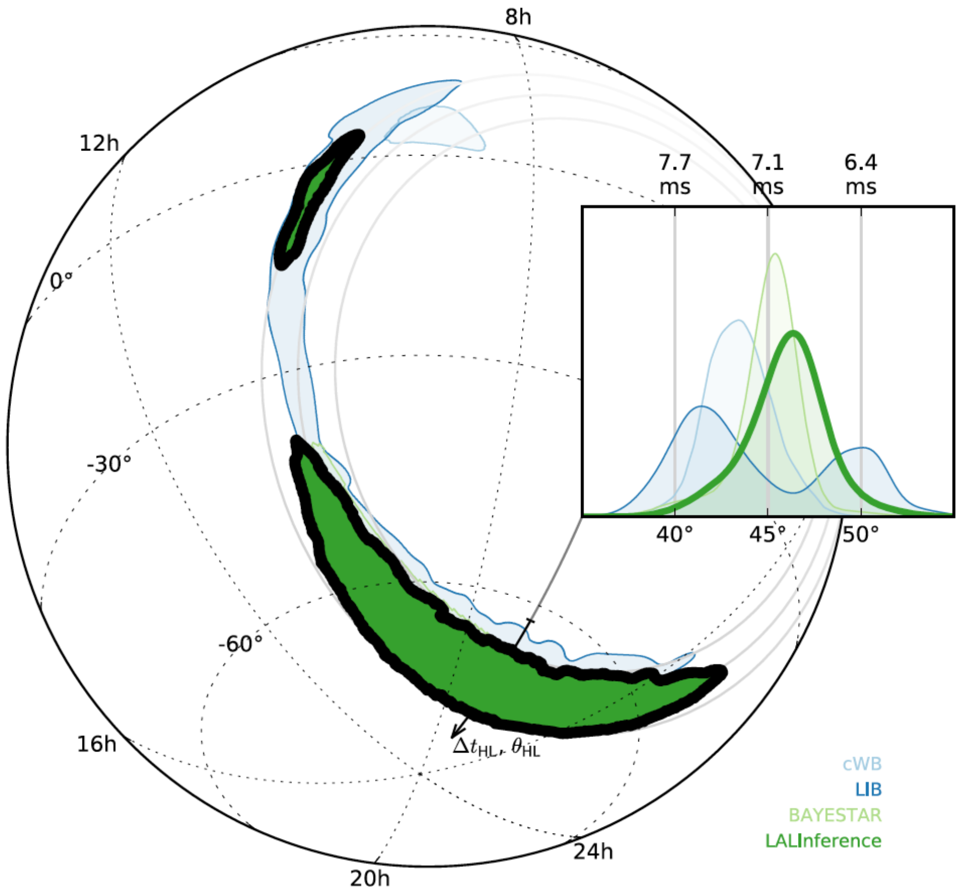

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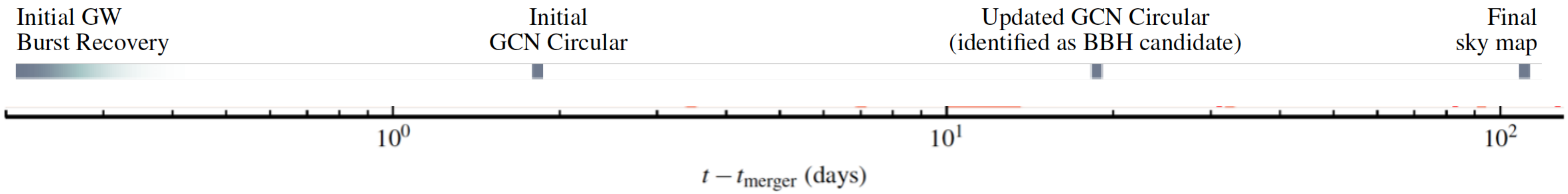


GW150914

+ 2 days after: first set of sky maps
+ 19 days after: BBH candidate
+ 4 months after: final sky map

GW151226

+ 1.6 days after: first set of sky maps
+ 15/17 days after: redshift
+ 23 days after: final sky map

Challenge for EM partners: BBH source information/redshift and different sky maps

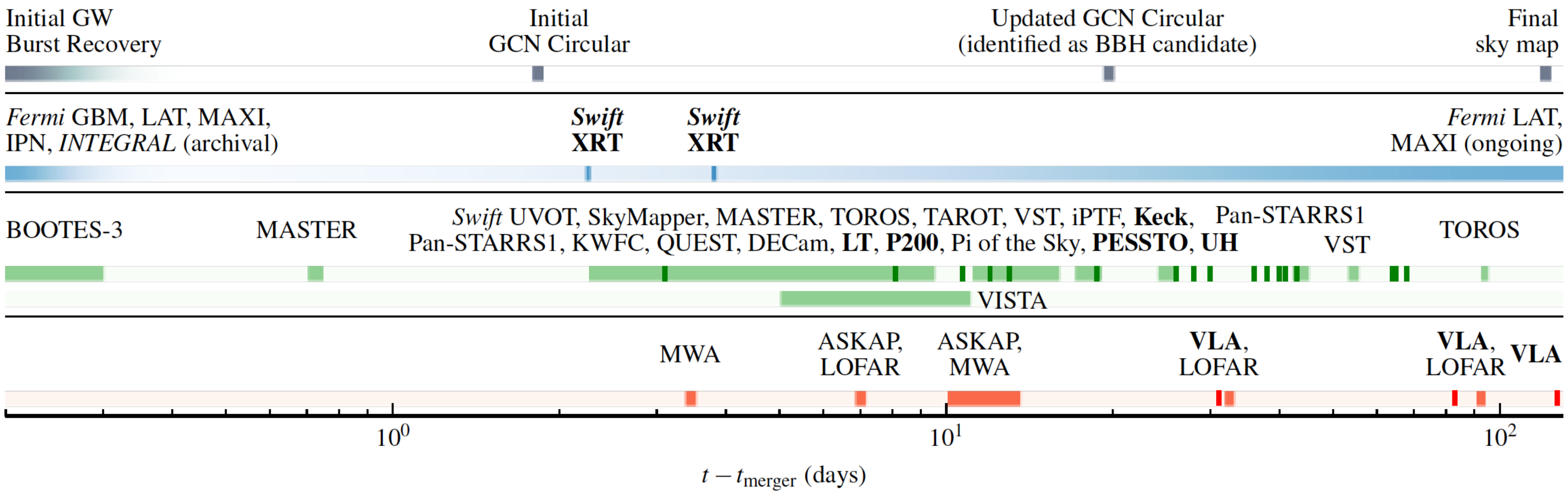
GW150914: Timeline of EM Follow-up

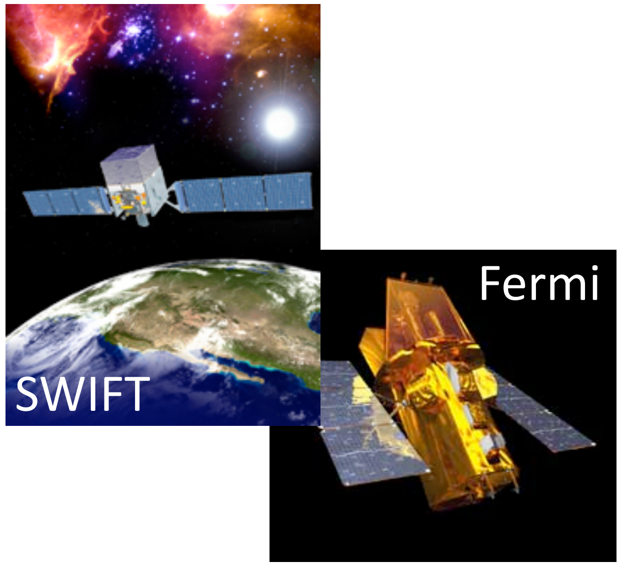
[LVC, APJL, 826, 1, L13, 2016]

HIGH ENERGY

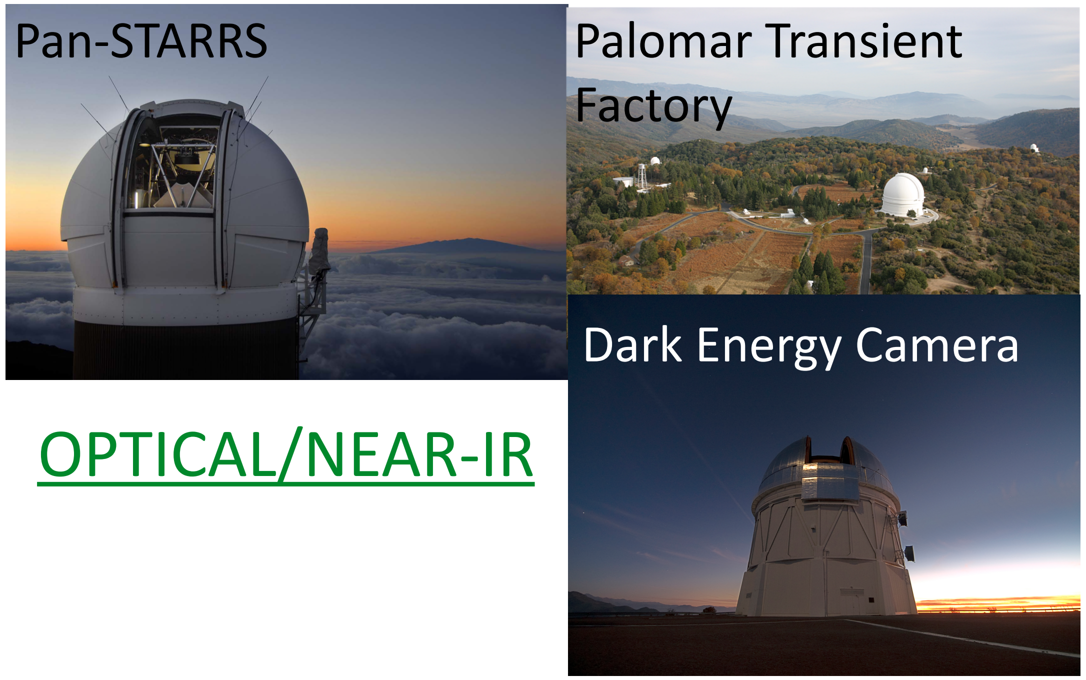
OPTICAL/NEAR-IR

RADIO

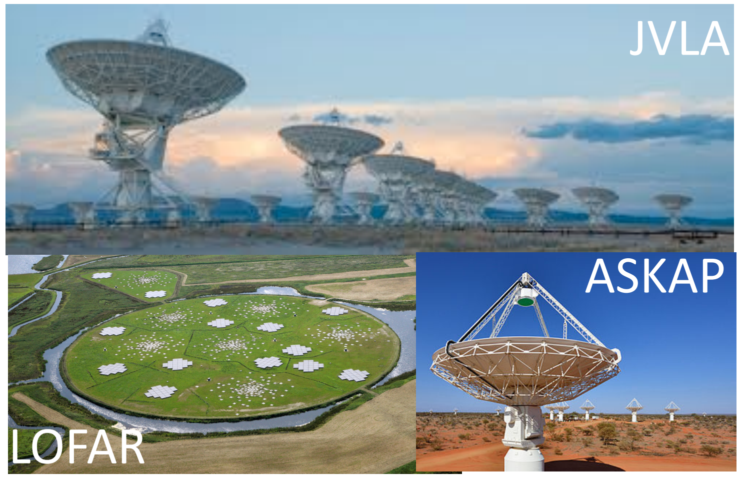




HIGH ENERGY



OPTICAL/NEAR-IR



RADIO

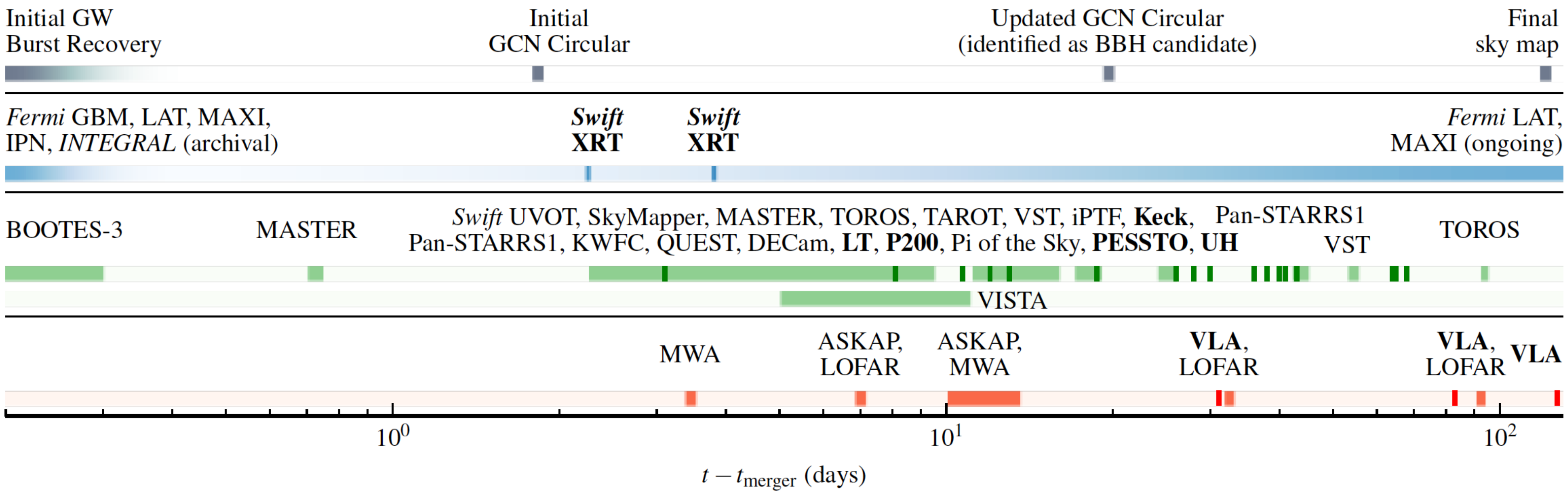
GW150914: Timeline of EM Follow-up

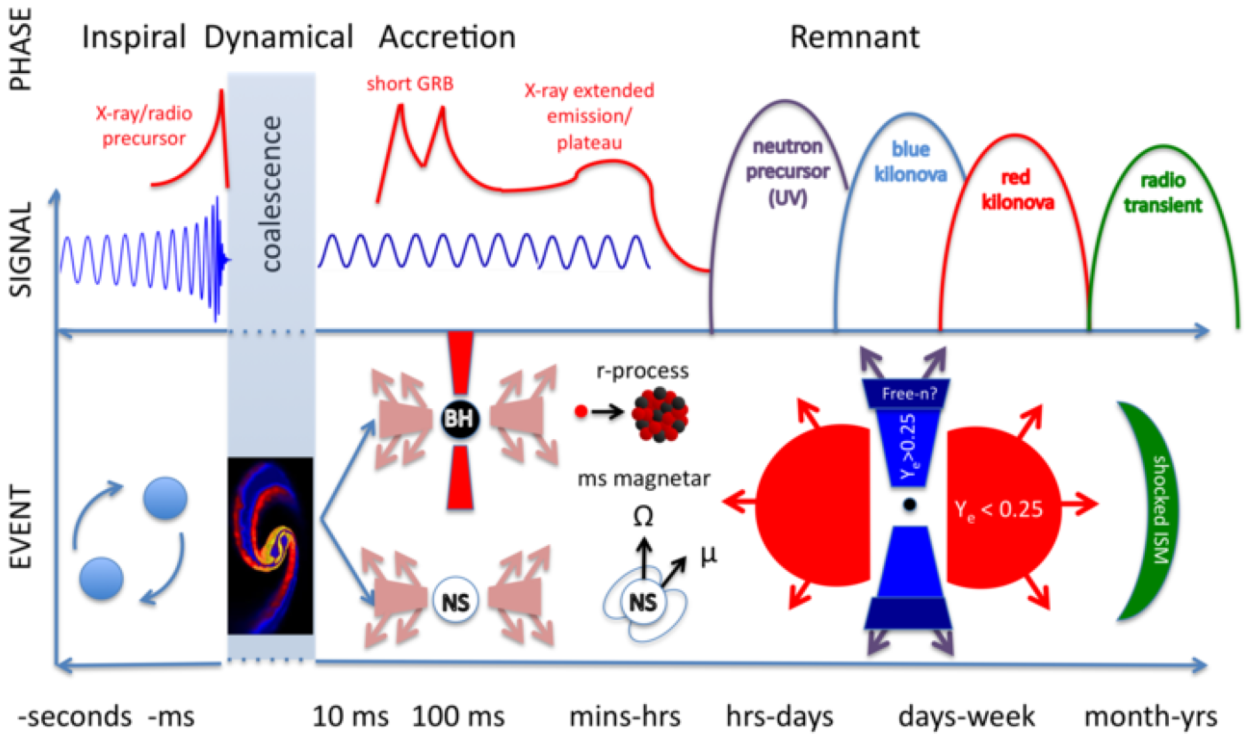
[LVC, APJL, 826, 1, L13, 2016]

HIGH ENERGY

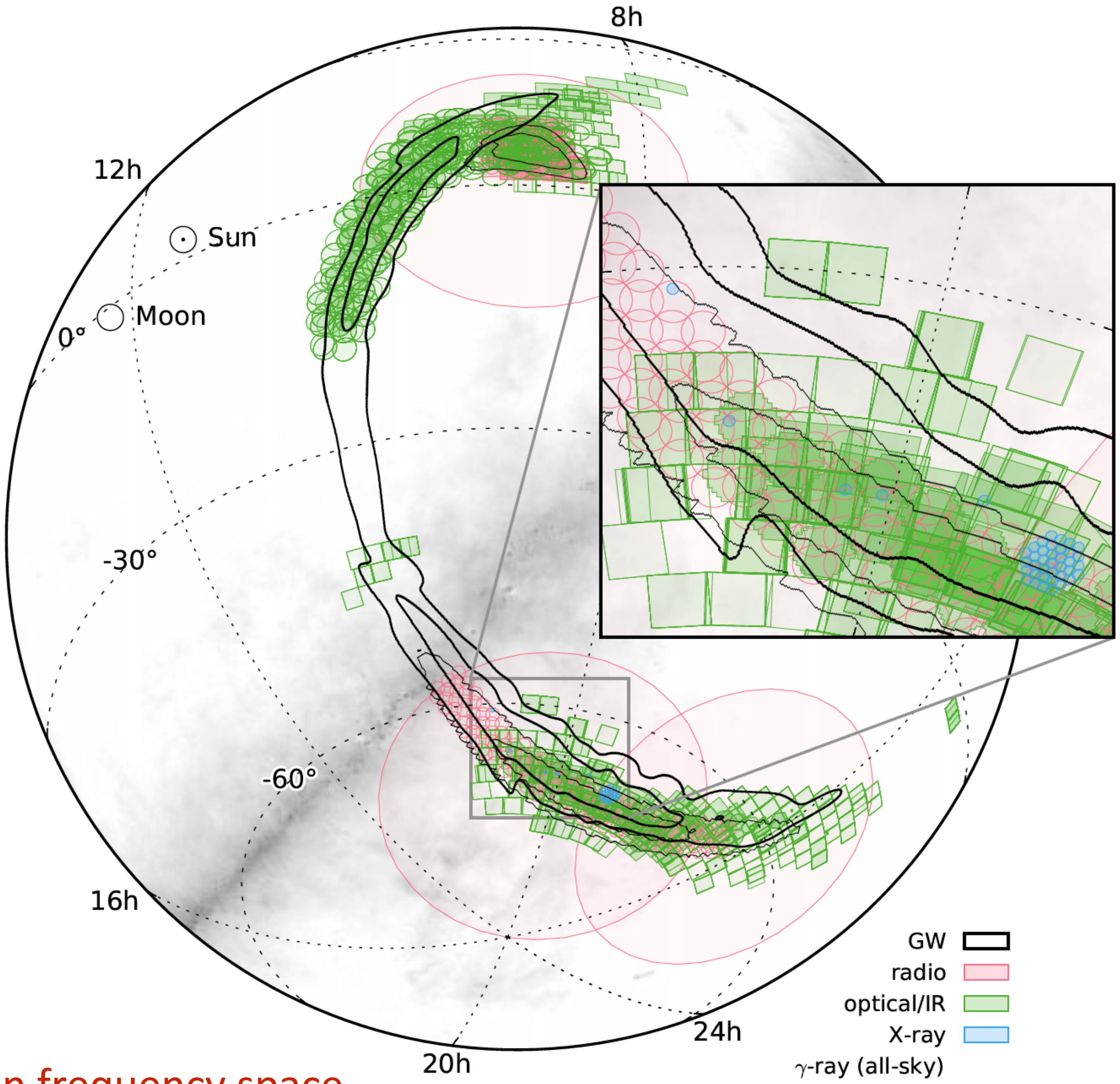
OPTICAL/NEAR-IR

RADIO





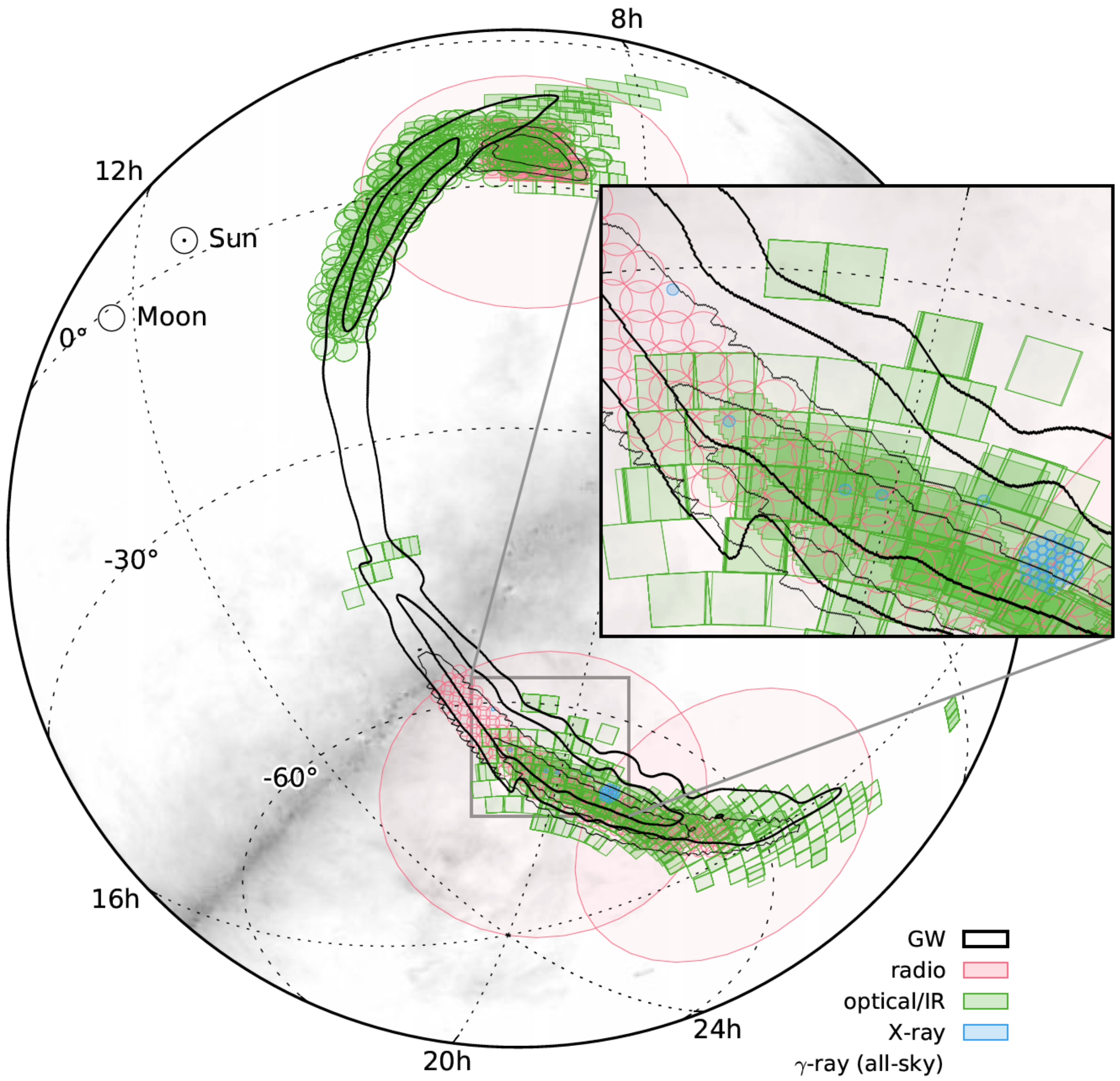
GW150914: Multi-wavelength EM Sky Coverage



19 orders of magnitude in frequency space

[LVC, APJL, 826, 1, L13, 2016]

GW150914: Sky Coverage versus depth



Gamma Ray:
100% coverage down to 10^{-7} ergs $cm^{-2}s^{-1}$

X-Ray:
large sky errors were far more challenging
— SWIFT targeted 5 nearby (< 80 Mpc) galaxies

Optical/NIR:
1-4m class telescopes;
1/3 of OIR facilities targeted nearby galaxies;
36% of final sky map though not at requisite depth

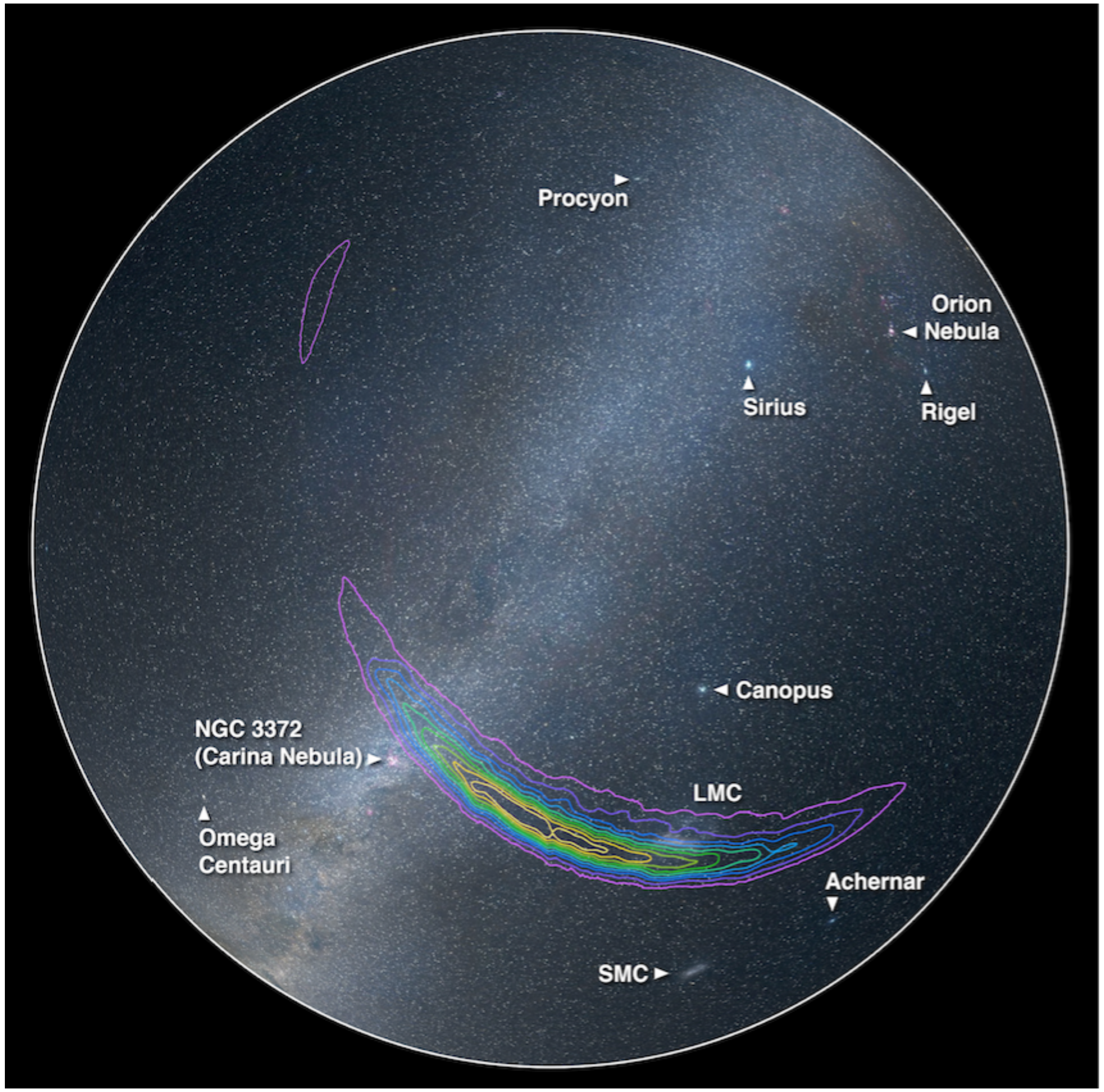
Only one NIR facility (VISTA)

Radio:
low frequency large field-of view but shallow at 5-200 mJy level—
86% of final sky map (MWA);
high frequency small field-of-view (JVLA) with microJy level.

19 orders of magnitude in frequency space

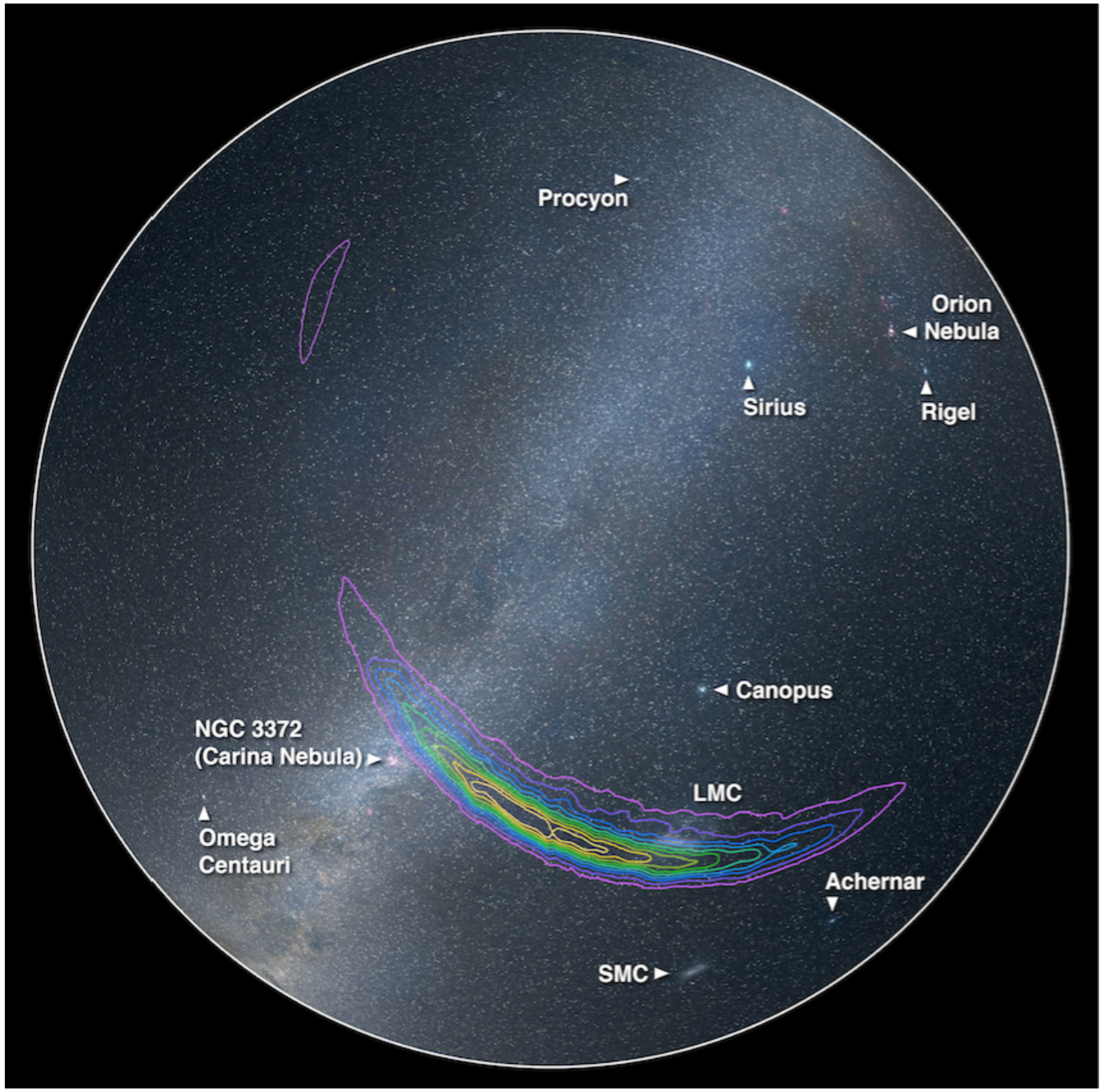
[LVC, APJL, 826, 1, L13, 2016]

GW150914: The rich transient sky — pulling the needle of out the haystack



590 [230] sq. deg. (90% c.r.)

GW150914: What about other transients and variables?



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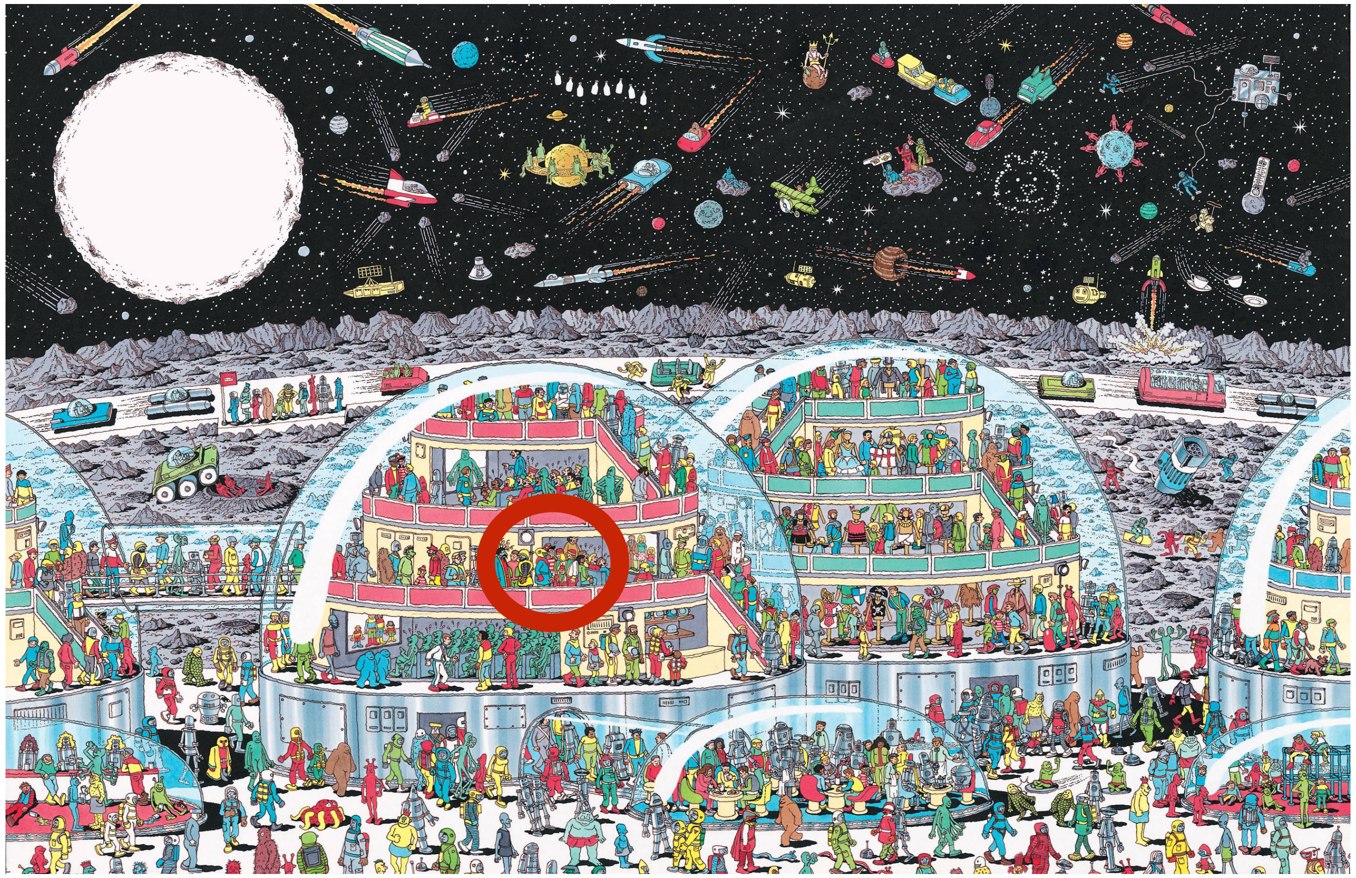
GW150914: What about other transients and variables?



Tens of other transients and variables

- Supernova type Ia and II
- Active Galactic Nucleii
- a few dwarf nova

comparison between GW distance and redshift is critical

[e..g., Connaughton et al. arXiv:1602.03920; Savchenko et al. 2016 ApJL 820, 36; Morokuma et al.arXiv:1605.03216; Fermi--LAT collaboration APJL, 823,2; Lipunov et al. arXiv:1605.01607; Soares-.-Santos et al., arXiv:1602.04198; Smartt et al. arXiv:160204156S; Evans et al. MNRAS 460, L40; Annis et al. arXiv:1602.04199; Kasliwal et al. arXiv:1602.08764 ,…]

BBH EM counterpart - Fermi GBM ?

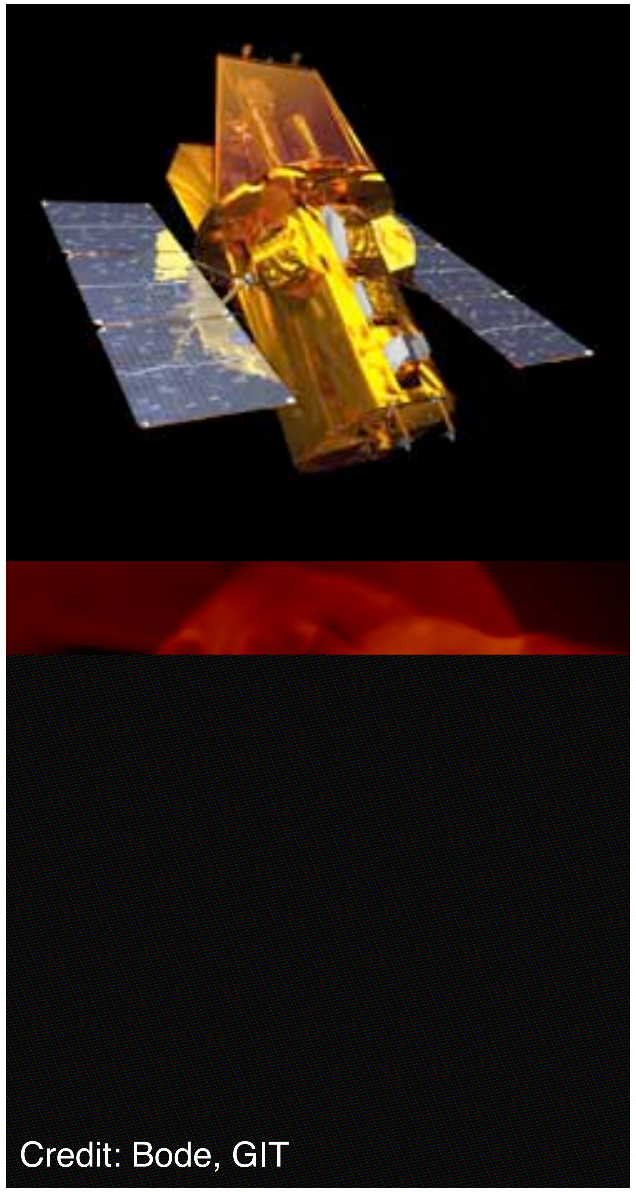
No reported real-time observed EM counterpart to GW 150914 …
..bar de facto, FERMI GBM: sub-threshold event above 50 keV, 0.4 s after the GW event, FAP of 0.0022, lasting 1s.

Ill-constrained location (if it were a counterpart, would reduce 600 -> 200 deg.^{2}).
Hard X-ray emission between 1 keV and 10 MeV of 1.8 × 10^{49} ergs/s.

[Connaughton et al. 2016]

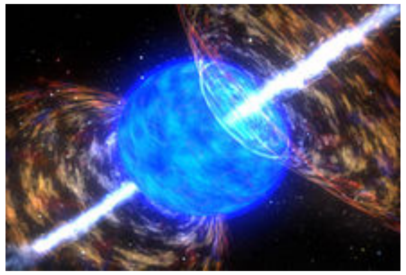
No candidates reported by Integral & independent second analysis of FERMI results are in tension.

[Savchenko et al. 2016, Grenier et al. 2016]



Credit: Bode, GIT

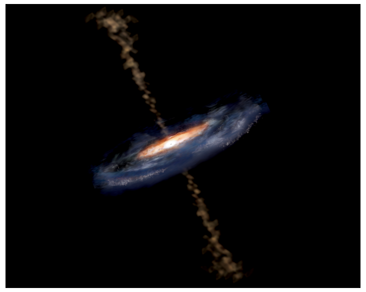
Speculative EM counterparts to BBH

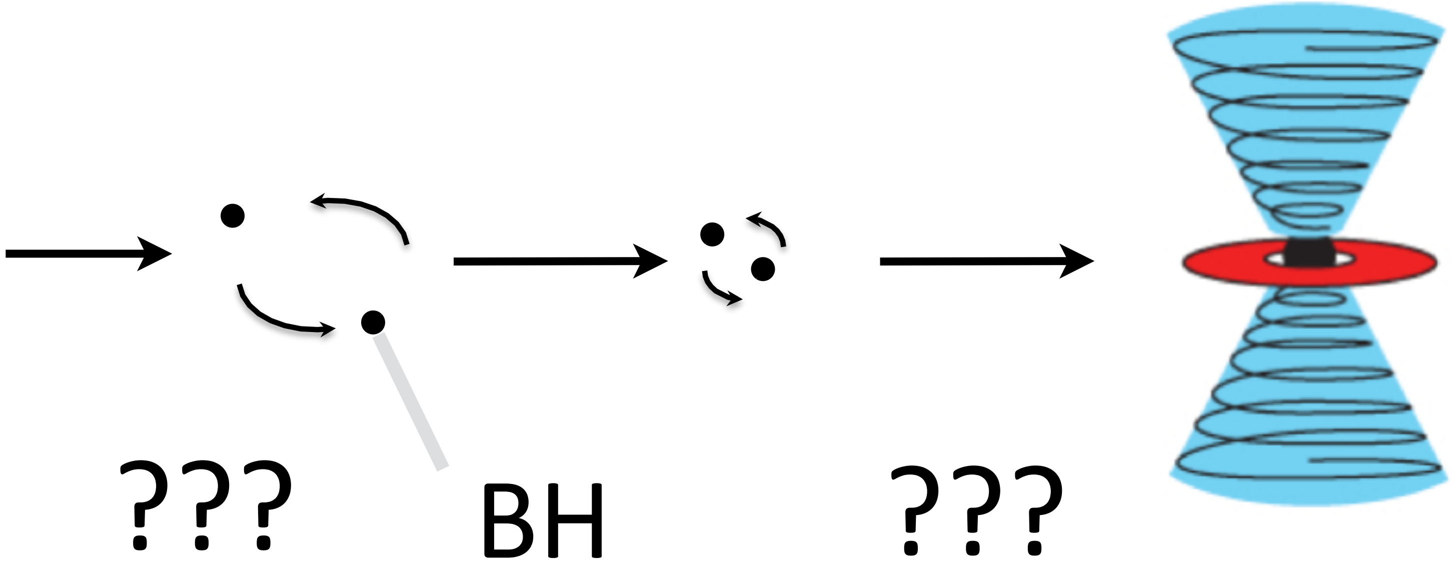


'collapsar-like'

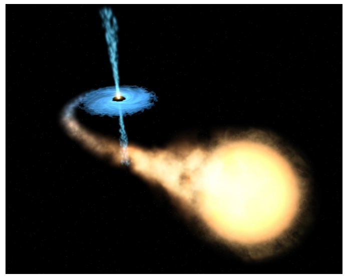
BBH embedded

in AGN disk ?





??? BH ???



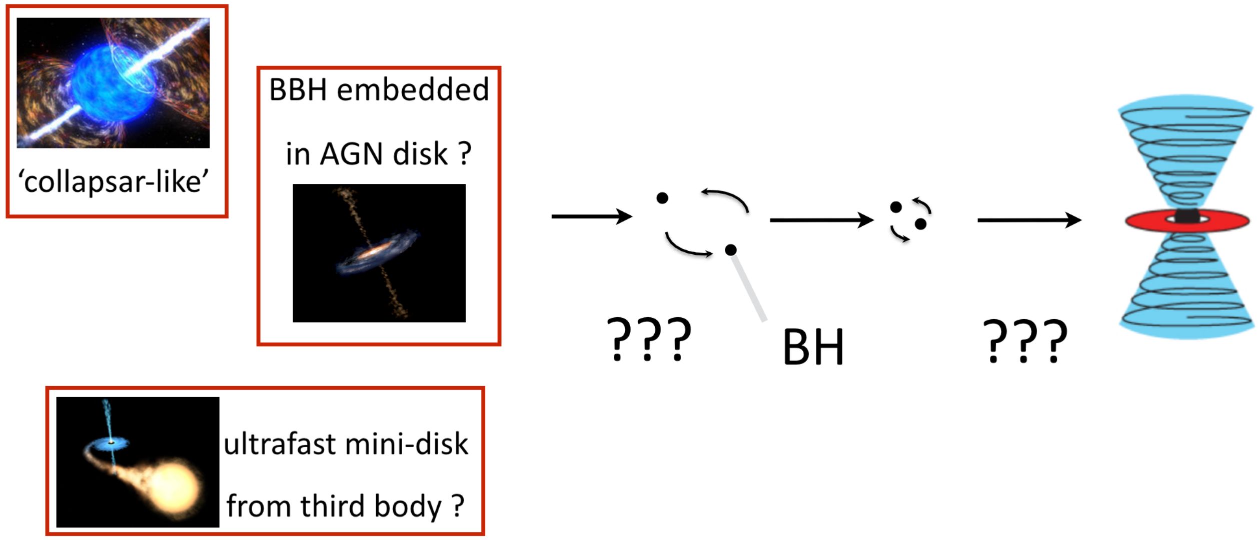
ultrafast mini-disk

from third body ?

e.g., arXiv in the week following the announcement:

Short Gamma-Ray Bursts from the Merger of Two Black Hole
Perna et al. 2016
Electromagnetic Counterparts to Black Hole Mergers Detected by LIGO
Loeb 2016
Electromagnetic Afterglows Associated with Gamma-Ray Emission Coincident with Binary Black Hole Merger Event GW150914
Yamazaki et al. 2016
Mergers of Charged Black Holes: Gravitational Wave Events, Short Gamma-Ray Bursts, and Fast Radio Bursts
Zhang 2016
Implication of the association between GBM transient 150914 and LIGO Gravitational Wave event GW150914
Li et al. 2016
Ultrafast Outflows from Black Hole Mergers with a Mini-Disk
Murase et al. 2016
Rapid and Bright Stellar-mass Binary Black Hole Mergers in Active Galactic Nuclei
Bartos et al. 2015
Ultrahigh Energy Cosmic Rays and Black Hole Mergers
Kotera and Silk, 2016

… and Exotic Formation Scenarios



'collapsar-like'

BBH embedded in AGN disk ?

??? BH ???

ultrafast mini-disk from third body ?

Single Star/Collapsar: collapse of a very massive, rapidly rotating stellar cores, which fissions into a pair of BHs that then merge [Loeb ApJL819 2016; see also Fryer+ 2001, Reisswig+2013, Woosley 16]

Instant BBH: massive star-BH binary triggers stellar collapse of star to BH, then immediately inspirals and merges. The final BH can be kicked into circumbinary disk and accretes from it. [Janiuk+ 2013, A&A 560]

BBH with fossil disk: activates and accretes long-lived cool disk [Perna+ 2016, ApJL 821]

BBH embedded in AGN disk: Binary merger assisted by gas drag +/or 3 -body interactions in AGN disk, which provides material to accrete [Bartos et al. 2016, Stone et al. 2016]

Third body: today disruption of a star in a hierarchical triple with the BBH at time of merger [Seto & Muto 2011, Murase + 2016]

Charged BHs: merging BHs with electric (or magnetic monopole!) charge could produce a detectable EM transient [Zhang 2016, Liebling+Palenzuela 2016]

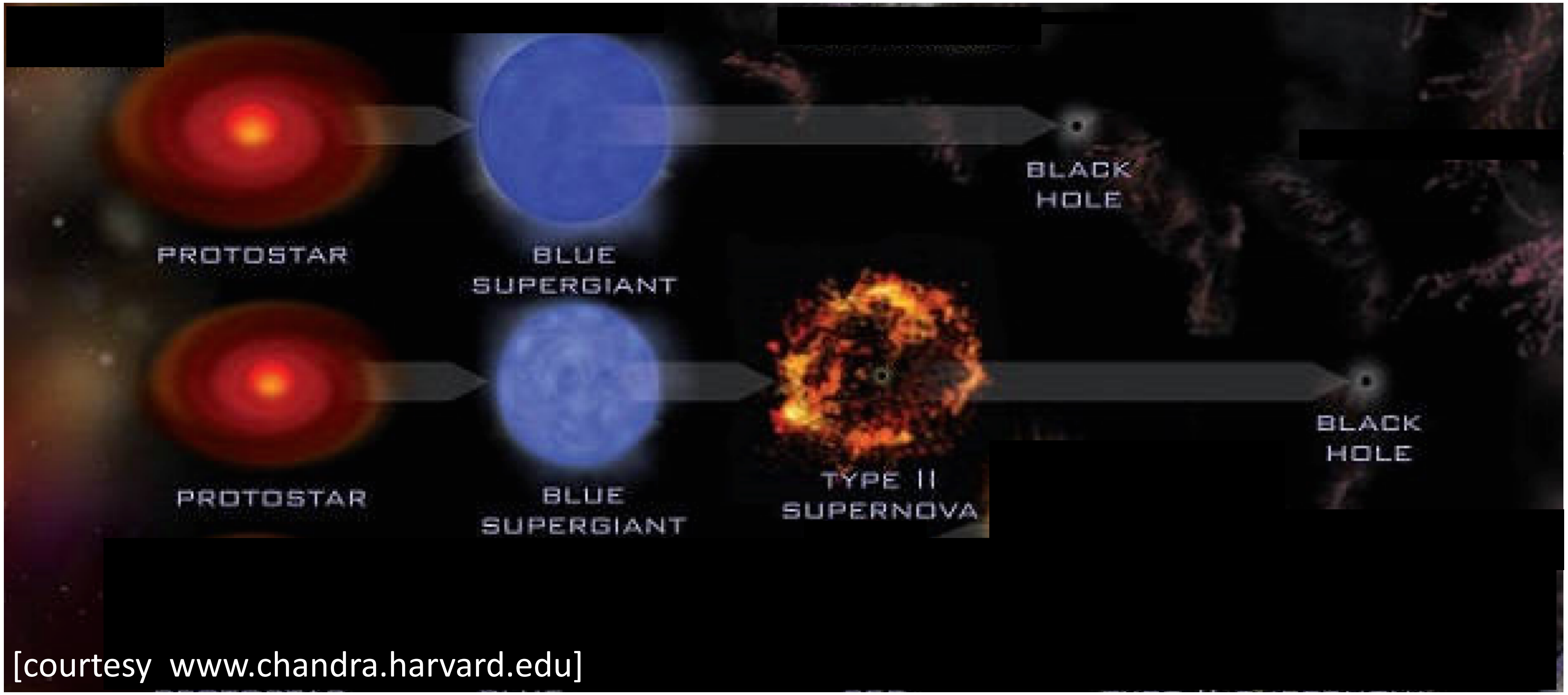
Magnetic reconnection [Fraschetti 2016]

Part II: Implications for Astrophysics

i) how to form heavy BHs?
ii) how & where do binary black holes (BBH) form?

How to make a stellar-mass BH?

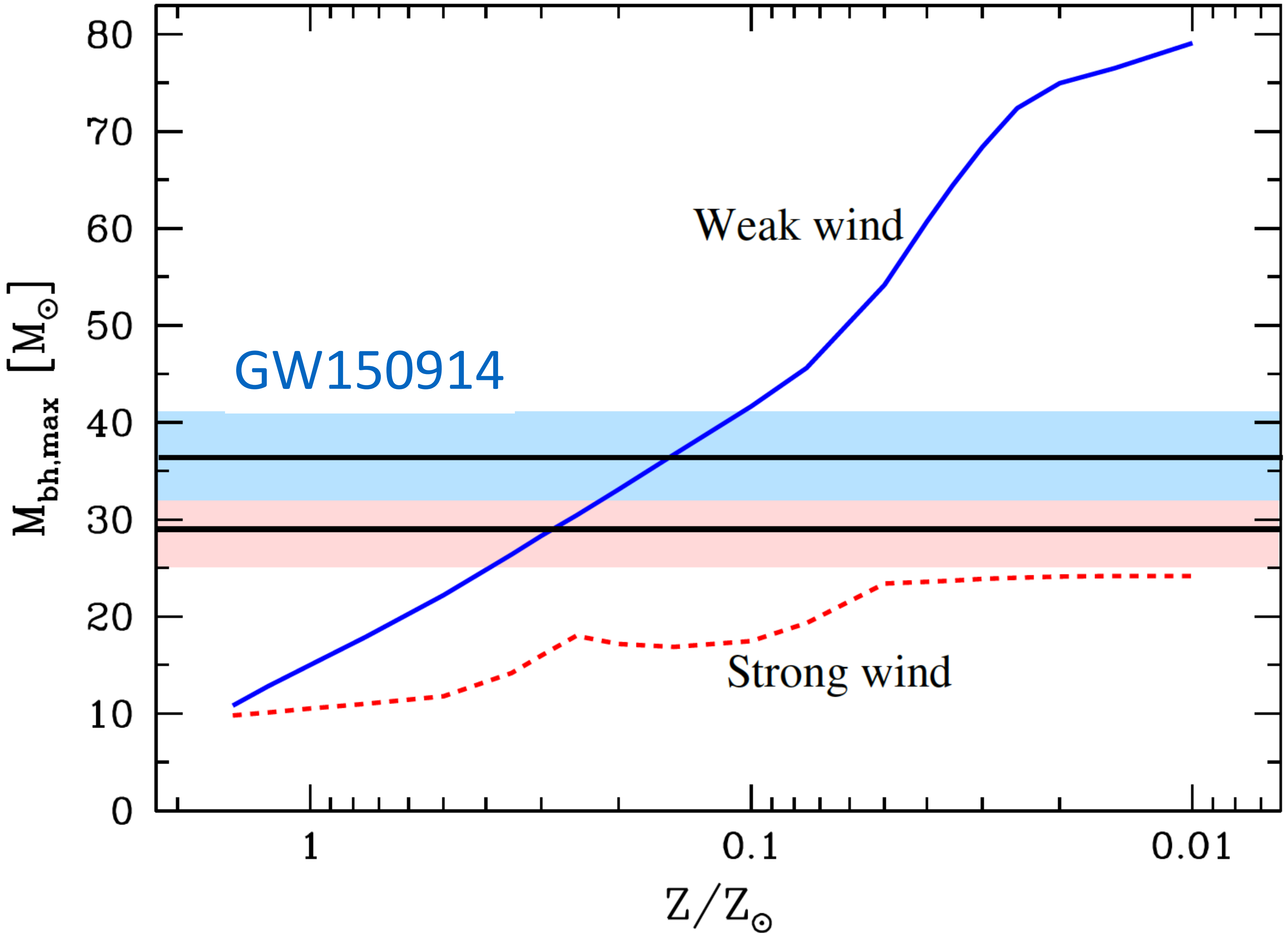
Stellar core collapse at end of lives of massive stars:
direct formation or fallback? first stars?



[courtesy www.chandra.harvard.edu]

Recipe for making heavy BHs

[LVC, ApJL 818, L22, 2016; adapted from Belczynski et al. 2010]



Low metallicity with $Z < 0.5\ Z_\odot$ (solar) and weak massive stellar winds

Tale of two binaries

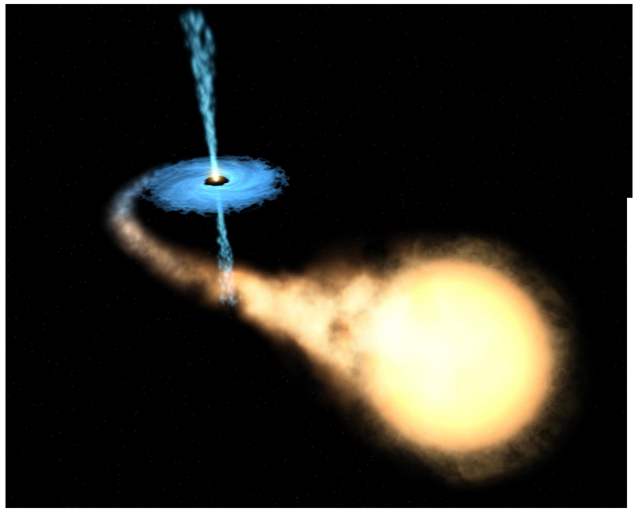
[see Nomoto's talk and review by Miller 2016;
LVC, ApJL 818, L22, 2016]

Isolated Binary in Field (0.15 pc^{-3})

range of binary interactions

low redshift to Pop III

rapidly rotating massive stars



[e.g., Tutukov & Yungelson 1993, Lipunov+97, … Belczynski+10, Mandel +deMink 16, Marchant+16, Belczynski+04, Kinugawa+14]

Dense Environments (e.g., Clusters): 10^5-10^9 pc^{-3})

BHs sink towards cluster core

Dynamical interaction -> pairs

Binaries ejected with inspiral < Hubble time

[e.g., Portegies Zwart+00, O'Leary +06, Downing+10, Morscher+13, Ziosi+14.; NB Galactic Center: Miller+Lauburg+09, O'Leary+09, Koscis+12, Bartos+16, Stone+16]

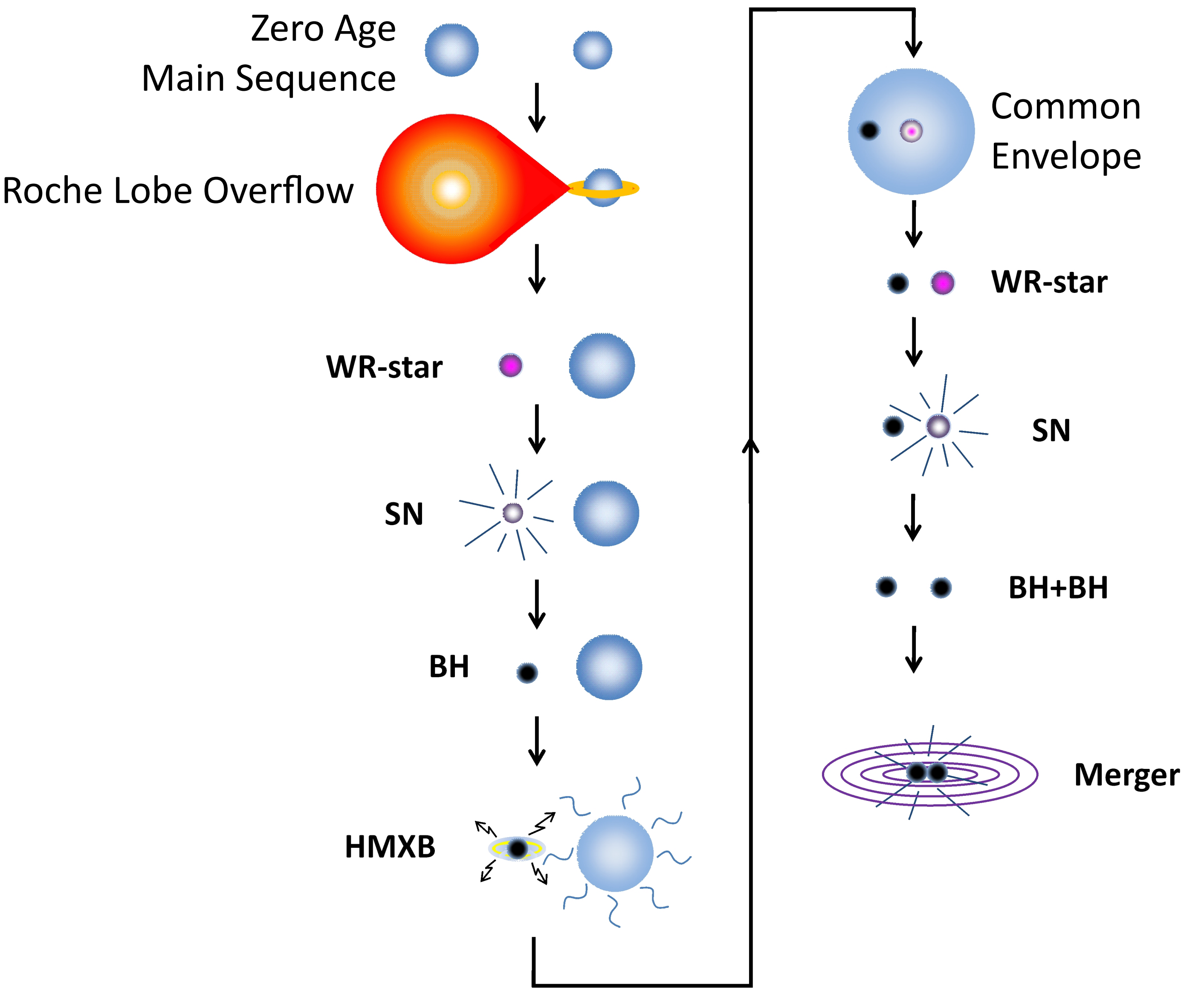
Lifecycle of Isolated Binary Massive Stars

Rare but important (feedback, chemical enrichment)

Complex physics in multi-staged evolutionary process

Supernova, Common Envelope, Mass Transfer, BH natal kicks

~ 6 to 9 steps: survival is 0.01-10%



[figure from Marchant et al. 2016]

GW150915 & GW151226: both field and cluster formation are possible

Isolated Binaries:

GW150914; weaker winds & weak metallicity. GW151226; tension with the chemically homogenous model & dark matter models.

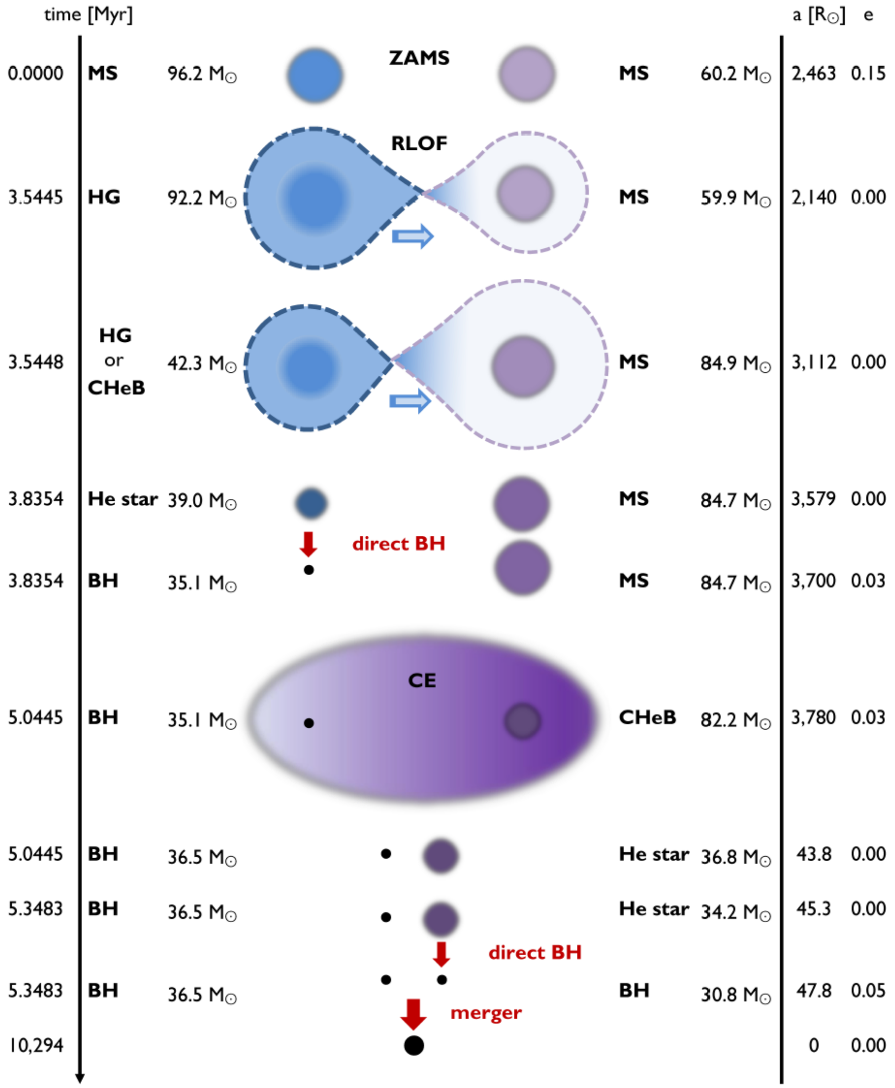
[e.g., Bird et al. 2016]

local Universe; recent formation, short merger delay time -or- early Universe formation with a long merger delay time

Cluster:

metallicity lower than solar

~1 Gyr to form binaries, wide range of delay times



[Belczynski et al. 2016; see also Kinagawa et al. 2016, Eldridge et al. 2016, …]

How to discriminate between formation channels

Isolated Binaries:

Spins - preferentially aligned

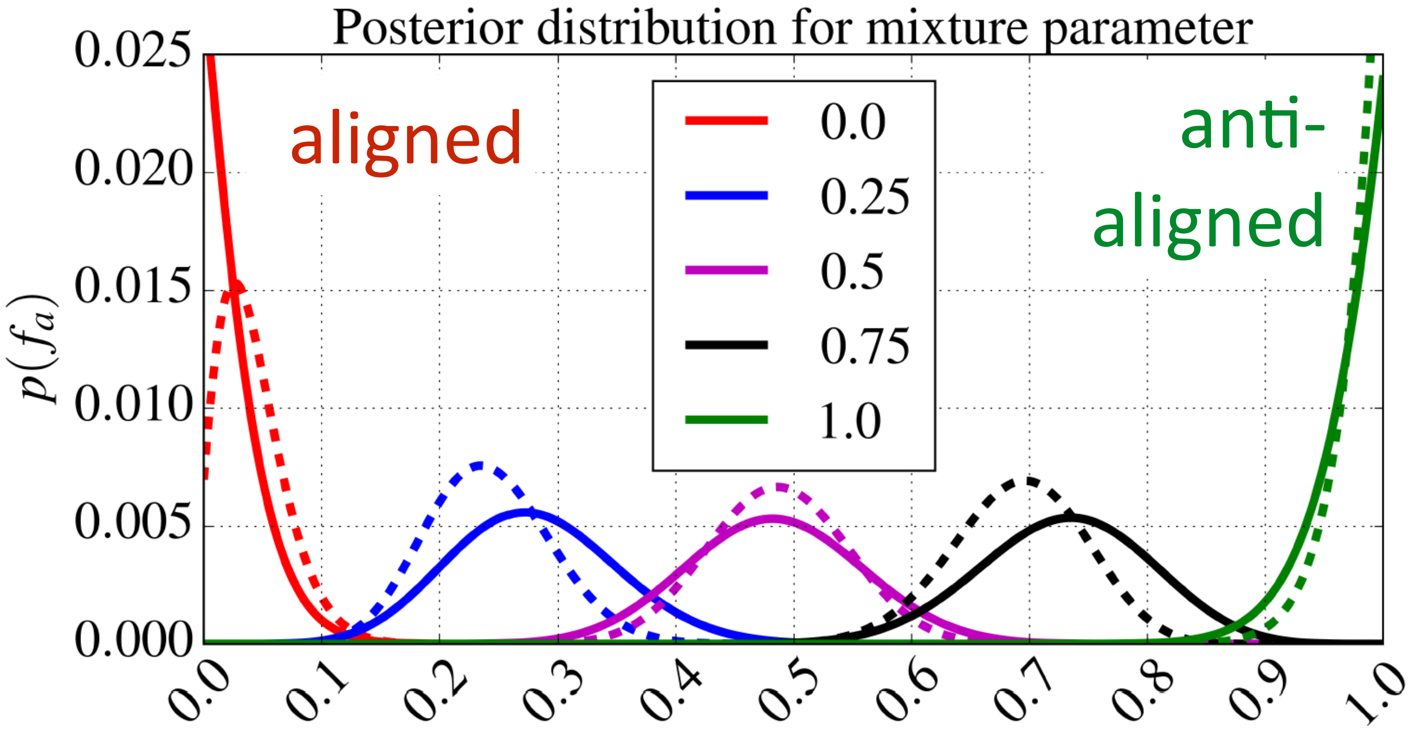
mass ratios < 0.5 are difficult to form

Dense Environment:

Spins - all configurations

mass ratios - all allowed

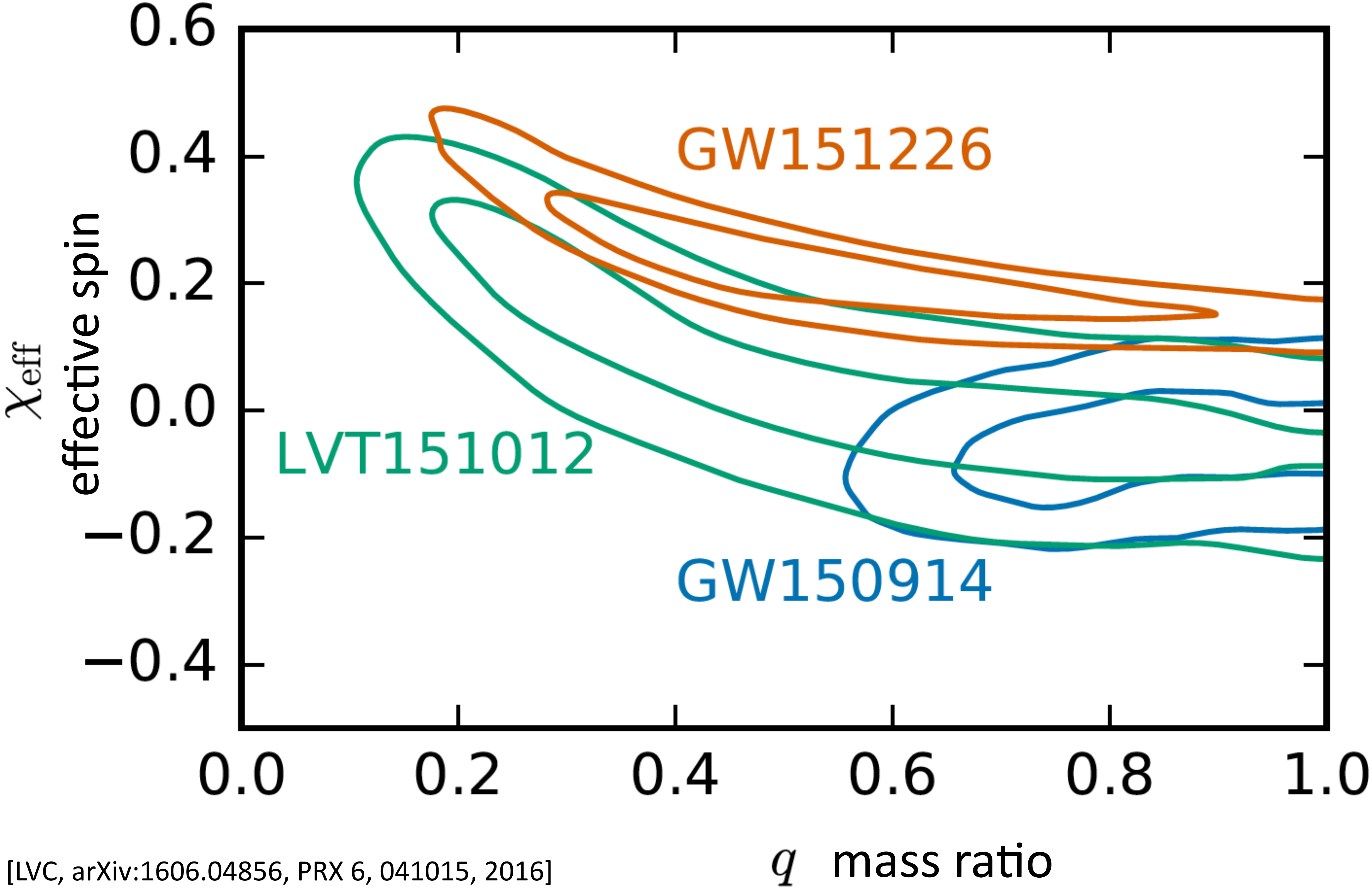
[Vitale et al. 2015]



f_a: mixing parameter between formation channels

⇒ 10% for 200 events

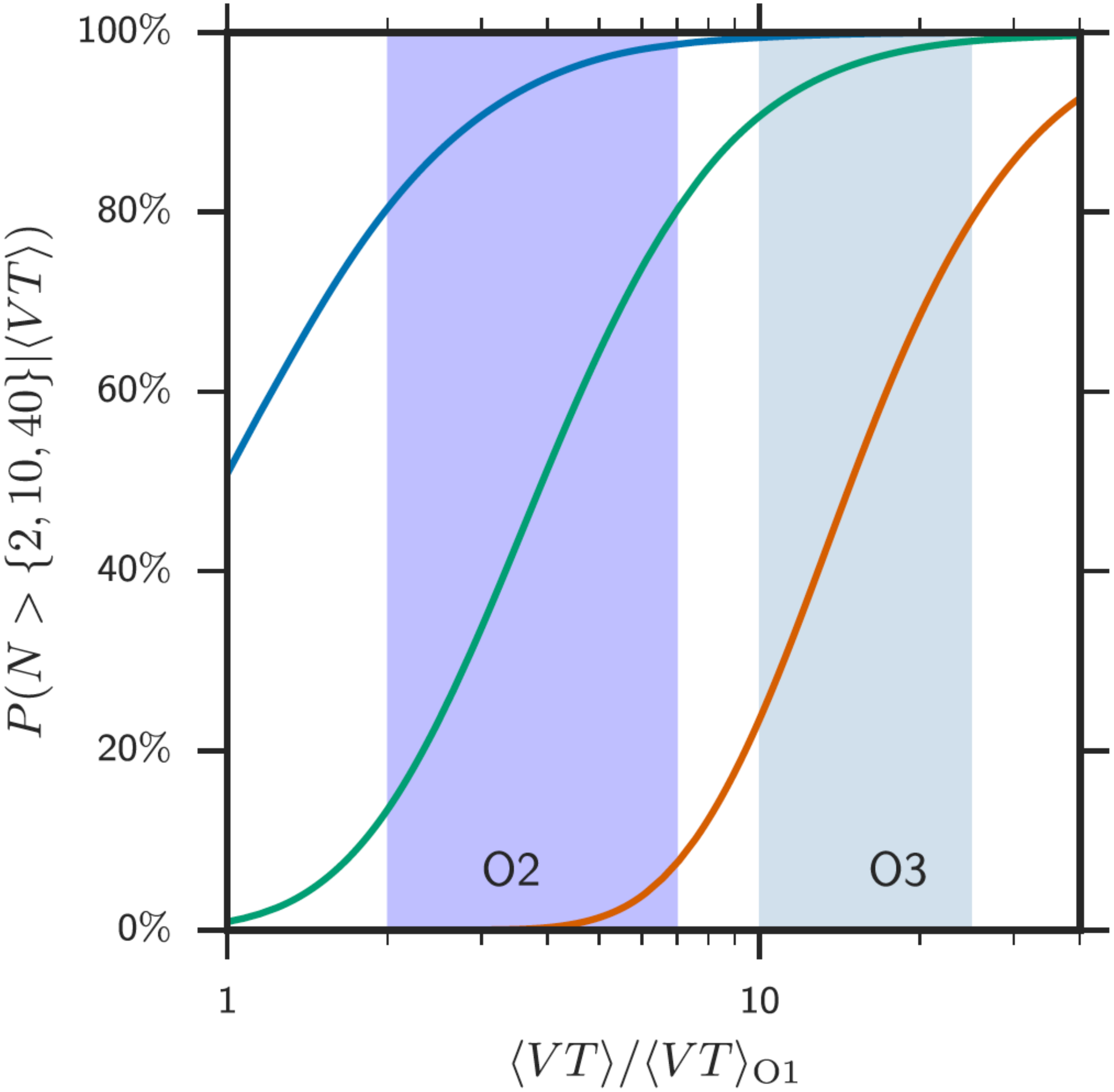
Challenge: large degeneracies between mass ratio and effective spin



[LVC, arXiv:1606.04856, PRX 6, 041015, 2016]

Part III: Future perspectives

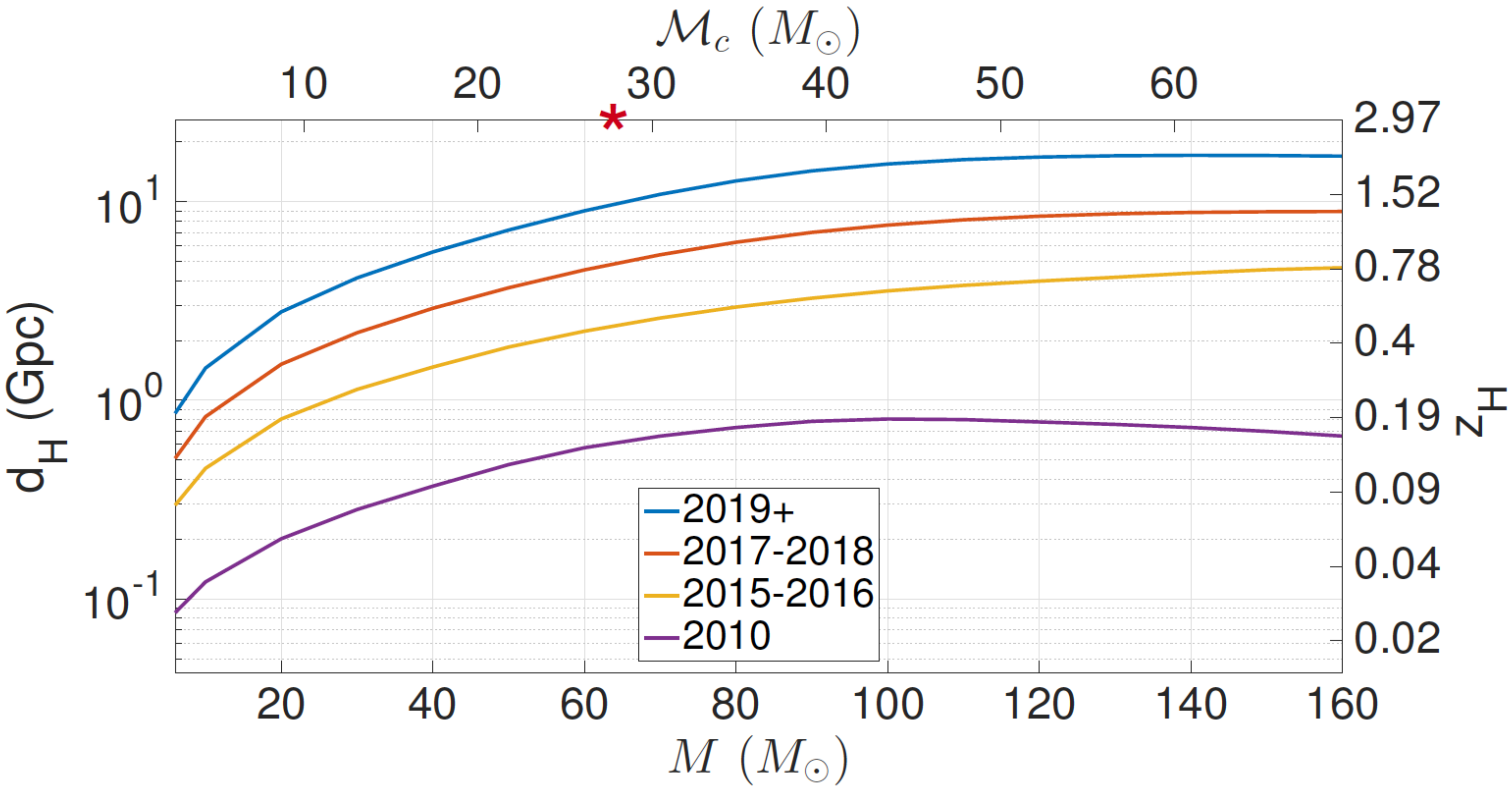
Tens of BH detections in the next few years



surveyed time volume

[LVC, arXiv:1606.04856, PRX 6, 041015, 2016]

BBH detections out to redshifts of a couple

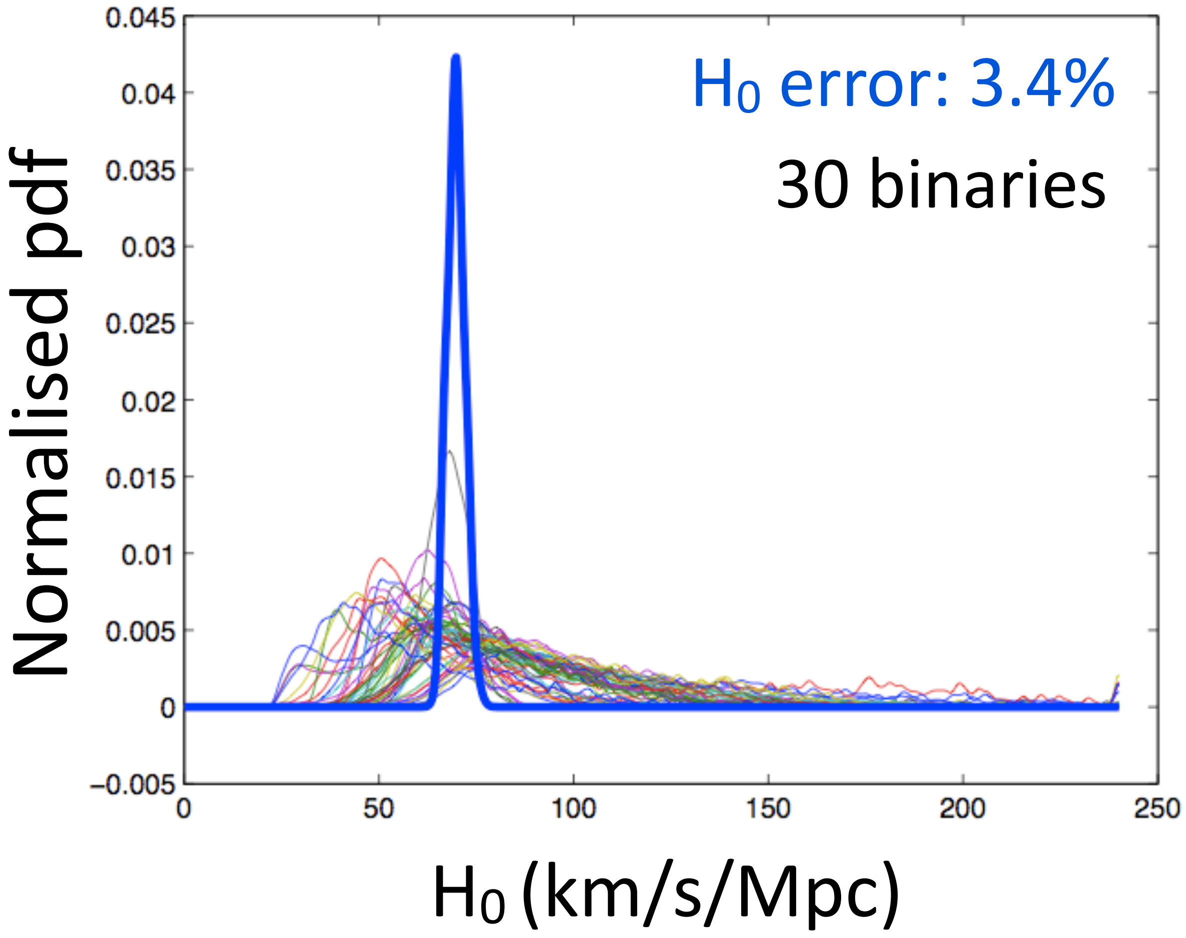


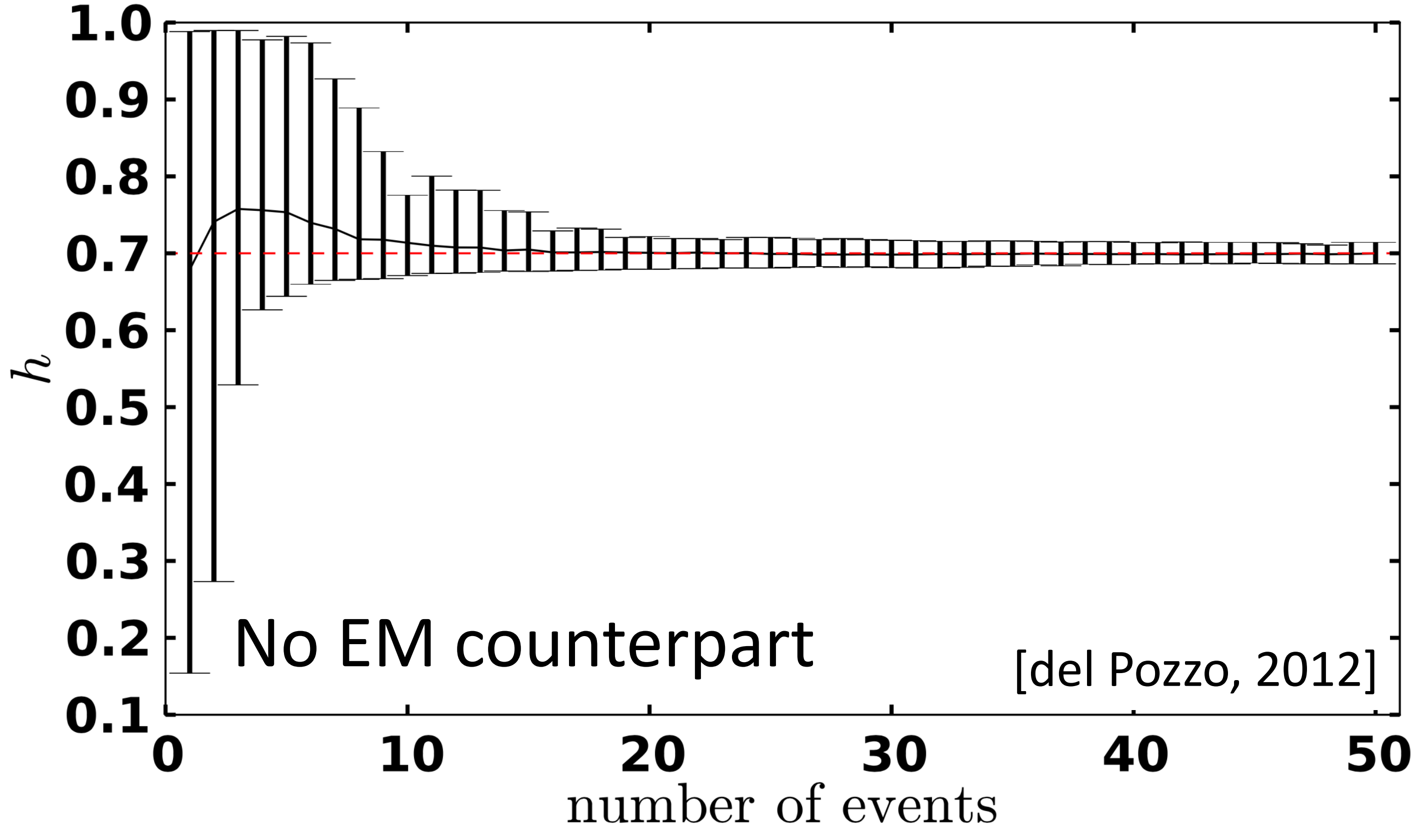
[LVC, ApJL 818, L22, 2016]

GW enable a few % error in Hubble constant … importance of populations !!!

[see also Schutz 1986, Dalal et al. 2006,
Sathyaprakash et al. 2010,
Messenger et al. 2012, Taylor et al. 2012, …]

[Nissanke et al., 2010,13]



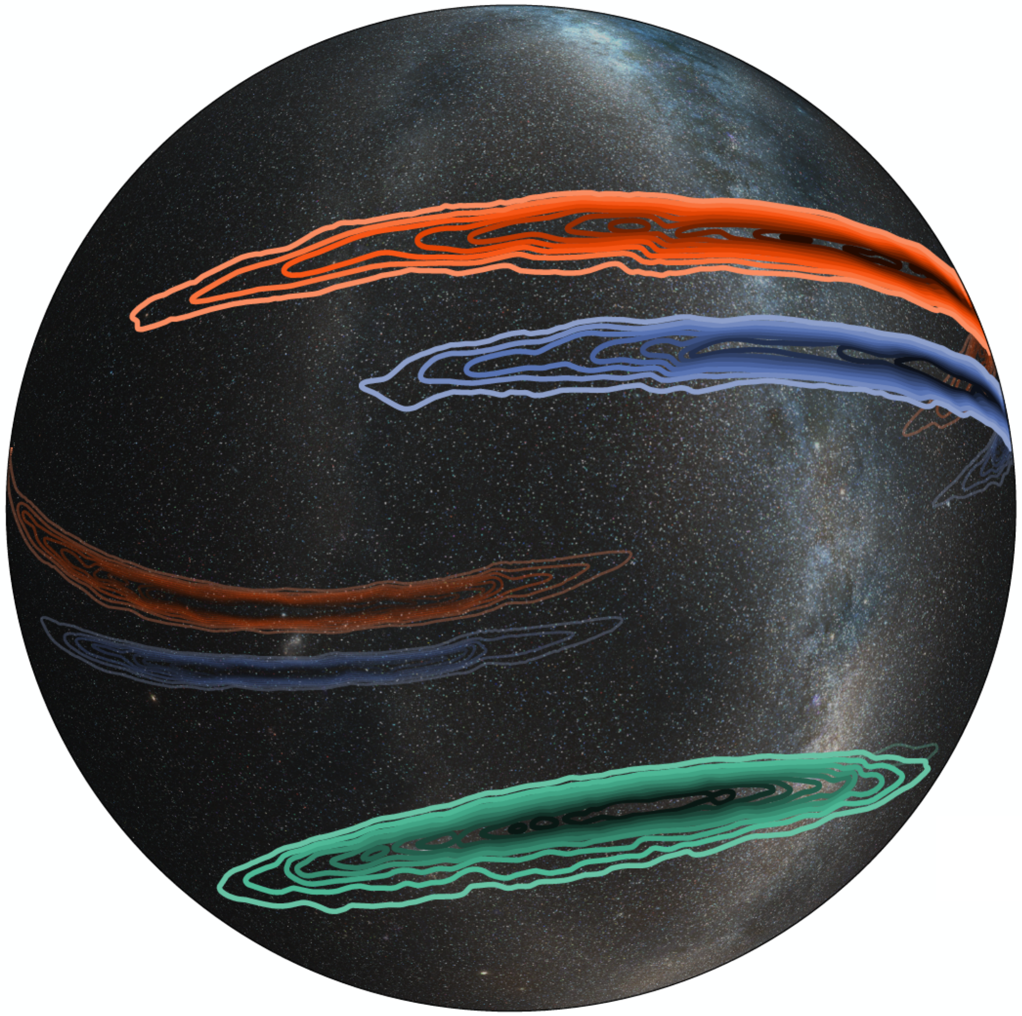


[del Pozzo, 2012]

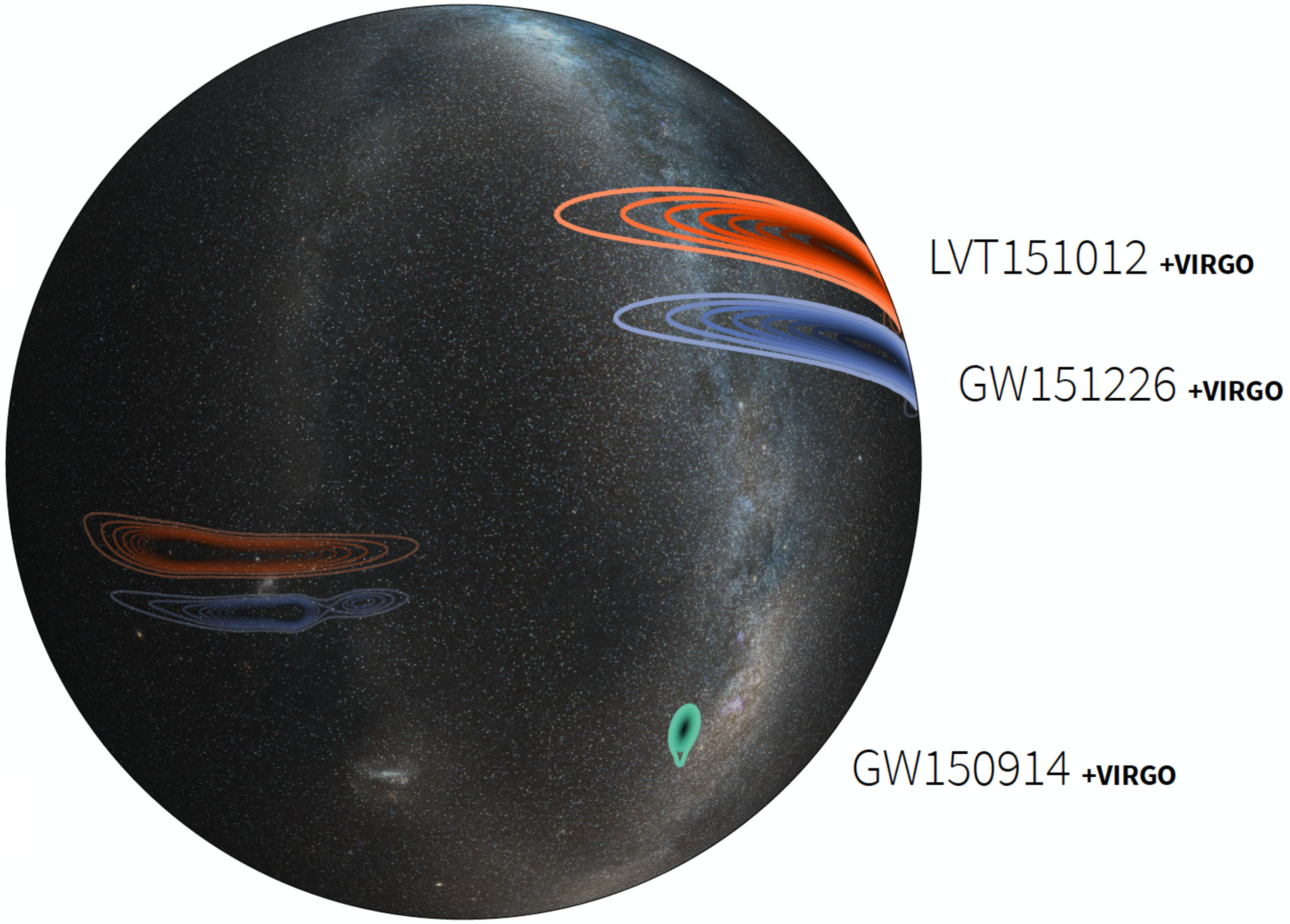
Similar reasoning applies detecting GW memory, testing GR and neutron star equation of states …

[e.g., Lasky et al. 2016, Yunes et al. 2013, Meidam et al. 2014, Lackay & Wade 2014, Agathos et al. 2014,15]

Expanding the GW network



[Image credit: LIGO/L. Singer/A. Messinger]

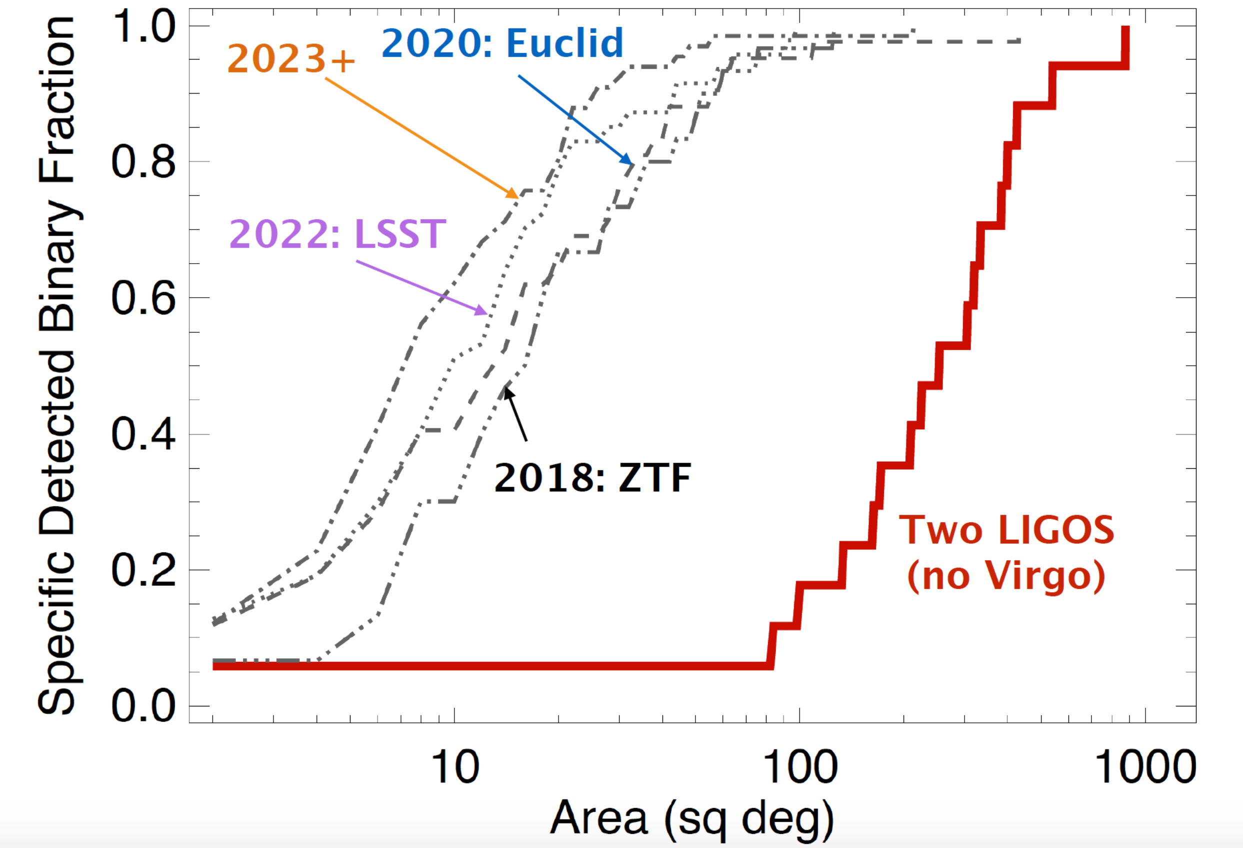


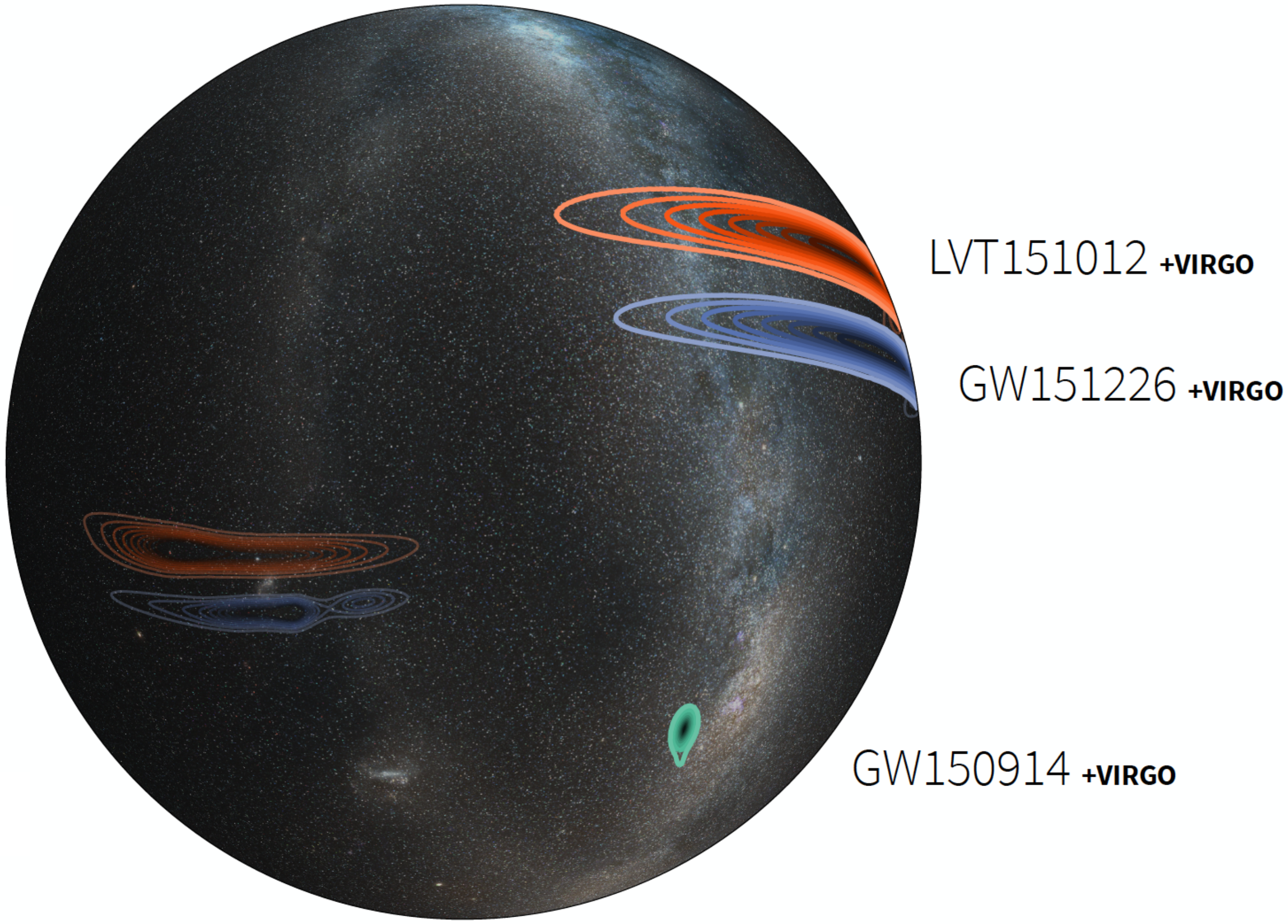
600 -> 10-20 sq. deg. (90% c.r.)

[LVC, arXiv:1606.04856, PRX 6, 041015, 2016]

Expanding the GW network

[Nissanke, Kasliwal, Georgieva 2012]





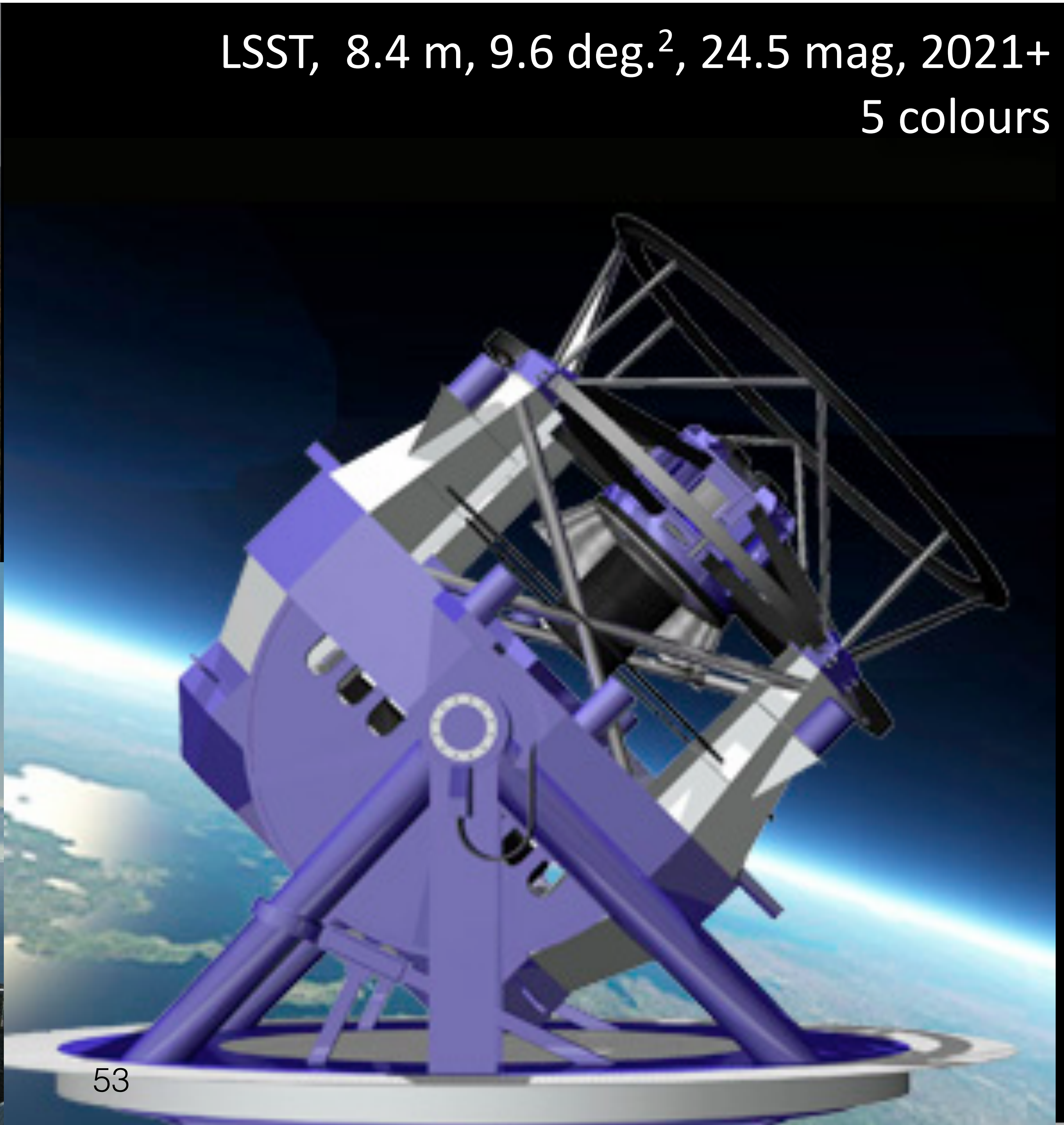
600 -> 10-20 sq. deg. (90% c.r.)

The future: Upcoming wide-field optical telescopes

Zwicky Transient Facility (ZTF),
1.2m, 45 deg.^{2}, 21 mag, 2017
2 colours

BlackGEM, 21 mag, 11/40 deg.^{2} , 2017
5 colours
www.blackgem.eu

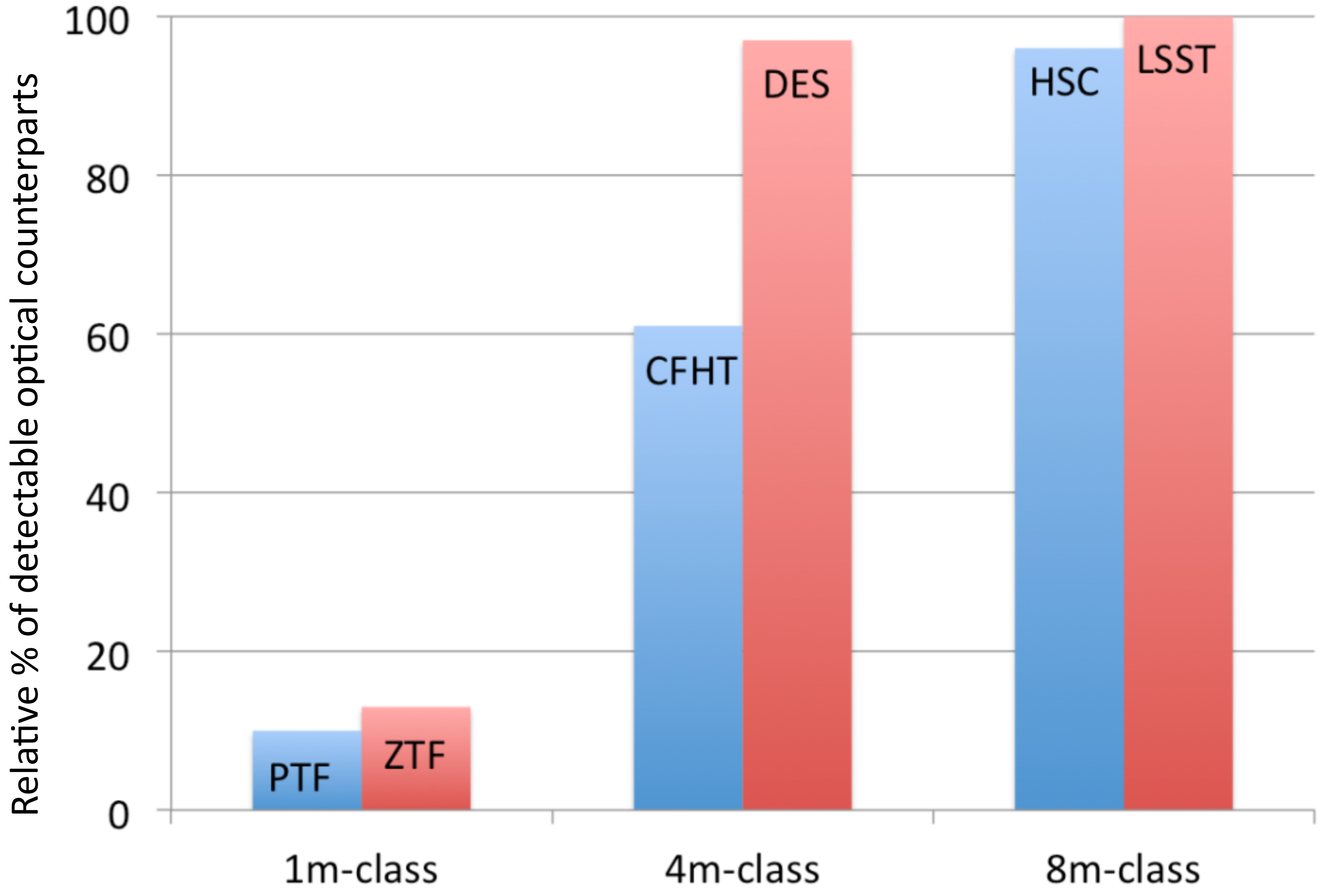
PanSTARRS II & GOTO



LSST, 8.4 m, 9.6 deg.^{2}, 24.5 mag, 2021+
5 colours

Optical detection in KAGRA era

5 GW detectors including KAGRA: 2019-21



[Nissanke, Kasliwal, Georgieva 2013]

The future: Current & Upcoming Radio facilities

[see Piran talk and Hotokezaka poster]

300 MHz


LOFAR, Netherlands, now


0.25 sq. deg.; 5 μ Jy hr^{-1}

JVLA, USA, now

1.4 - 3 GHz


ASKAP, Australia


MeerKAT, South Africa

0.86 sq. deg.;
4 μ Jy hr^{-1}

Strategy 1: overcoming the optical challenge: the BlackGEM telescope array in 2017

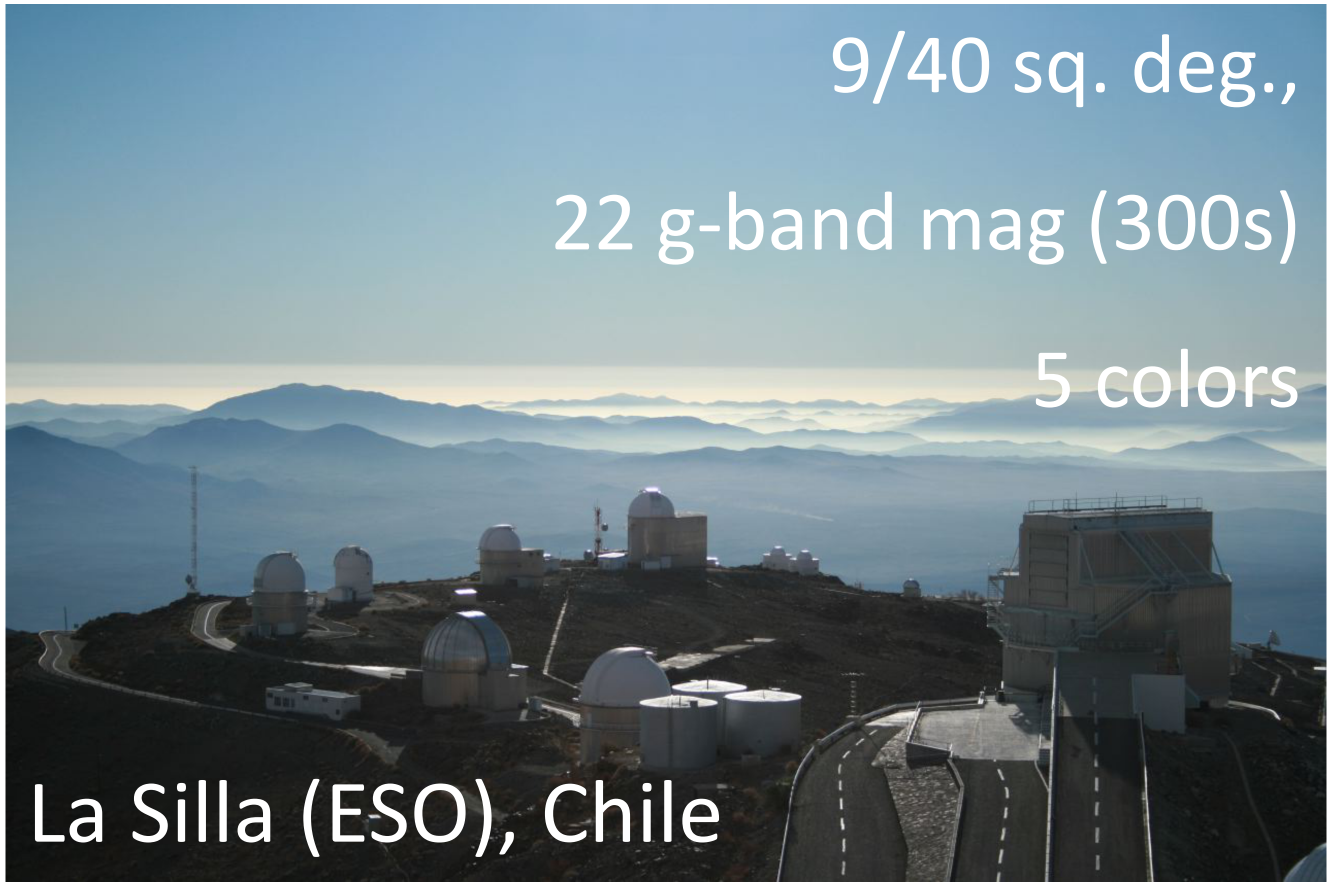
Phase-I: 3 telescopes, each with 65 cm diameter mirrors
Funded by Netherlands (NOVA, RU, FOM) and KU Leuven

Phase-II: 15 telescopes

Southern sky: La Silla

- Complementarity to iPTF/ZTF
- GW source positions often split
- Big Guns: Gemini/GMT/VLT/E-ELT, ALMA, SKA, etc.
- Good seeing allows for smaller mirror

Y1+2: All Sky and Fast Synoptic Surveys



9/40 sq. deg.,

22 g-band mag (300s)

5 colors

La Silla (ESO), Chile

Prototype: MeerLICHT slewed to MeerKAT (contemporaneous optical-radio)

Strategy 1: GW mergers & rates … & so much more

- Local Group Dwarf Galaxies
- Extragalactic globular clusters
- NS/BH binaries
- Eclipsing binaries
- Pulsating stars
- Tidal disruptions
- AGN variability
- Extragalactic science
- Supernovae
- GRBs
- CVs,Novae
- Asteroids/NEOs
- Hypervelocity stars
- White dwarfs
- Brown dwarfs
- Stellar populations and star clusters
- …

9/40 sq. deg.,

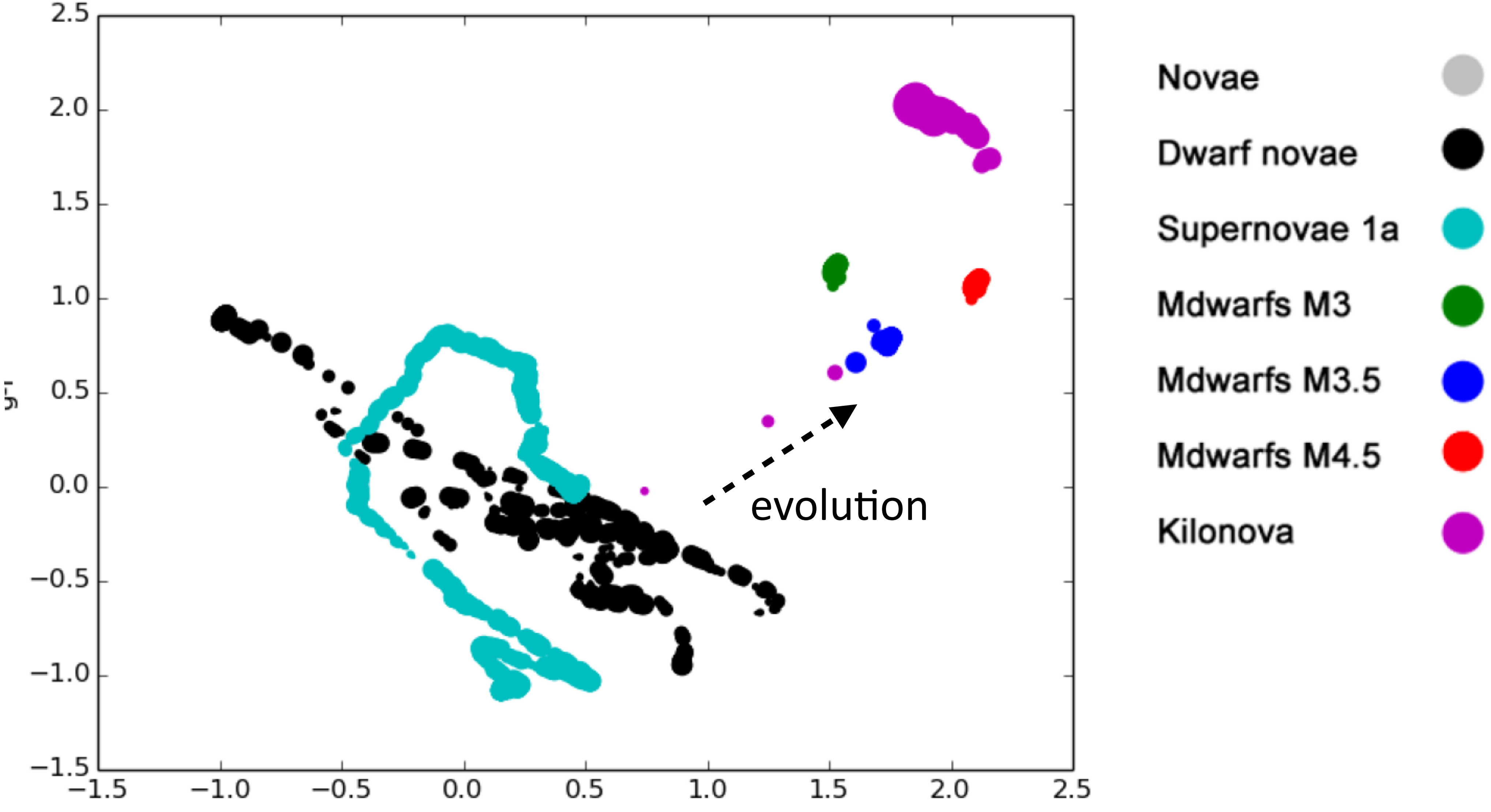
22 g-band mag (300s)

5 colors

www.blackgem.eu
@BlackGEM_Array

Strategy 2) Optical Identification through different colors over 7 days

[Jacobs, Barnes, Nissanke et al. in prep]



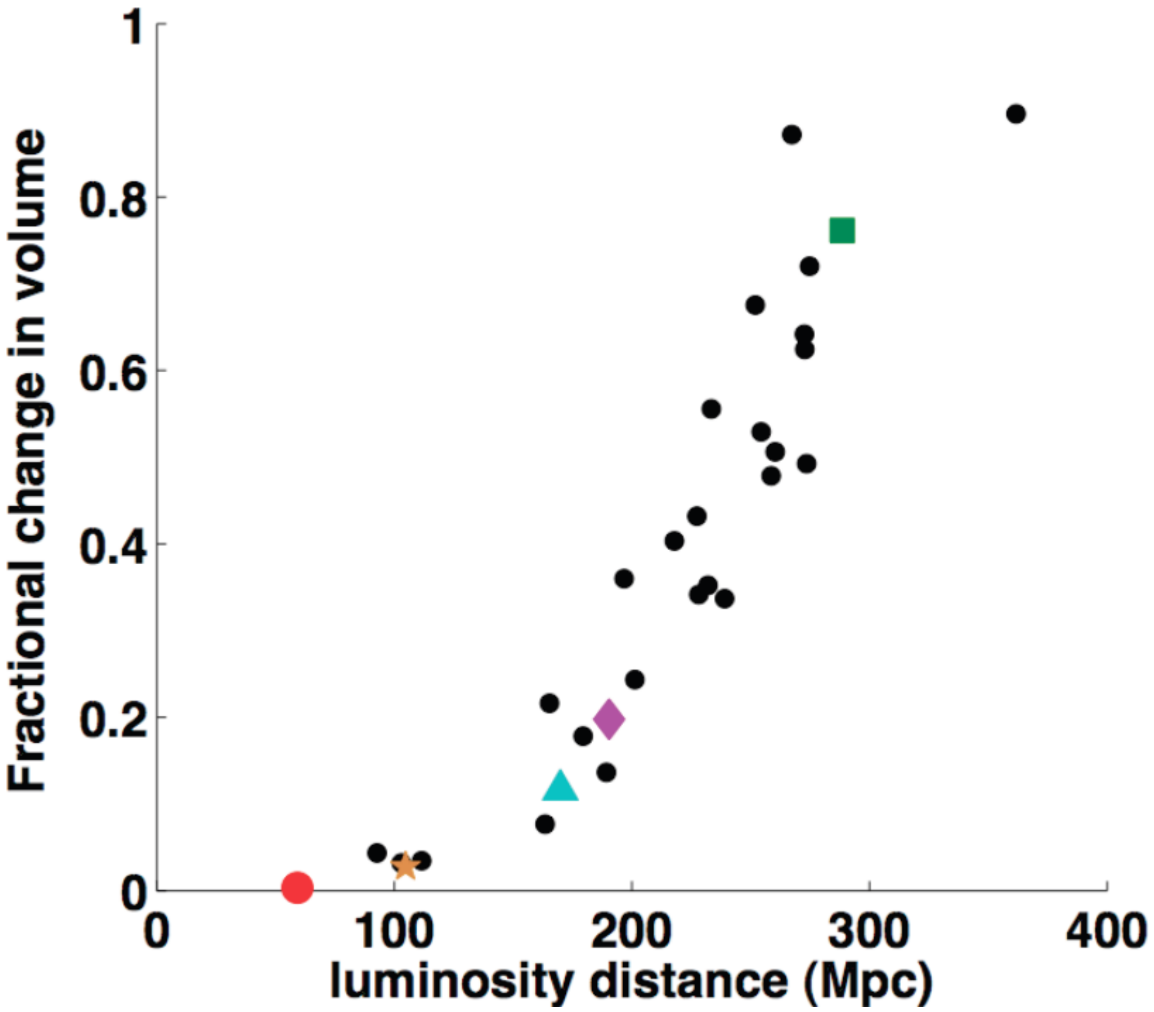
g band- r band

r band- i band

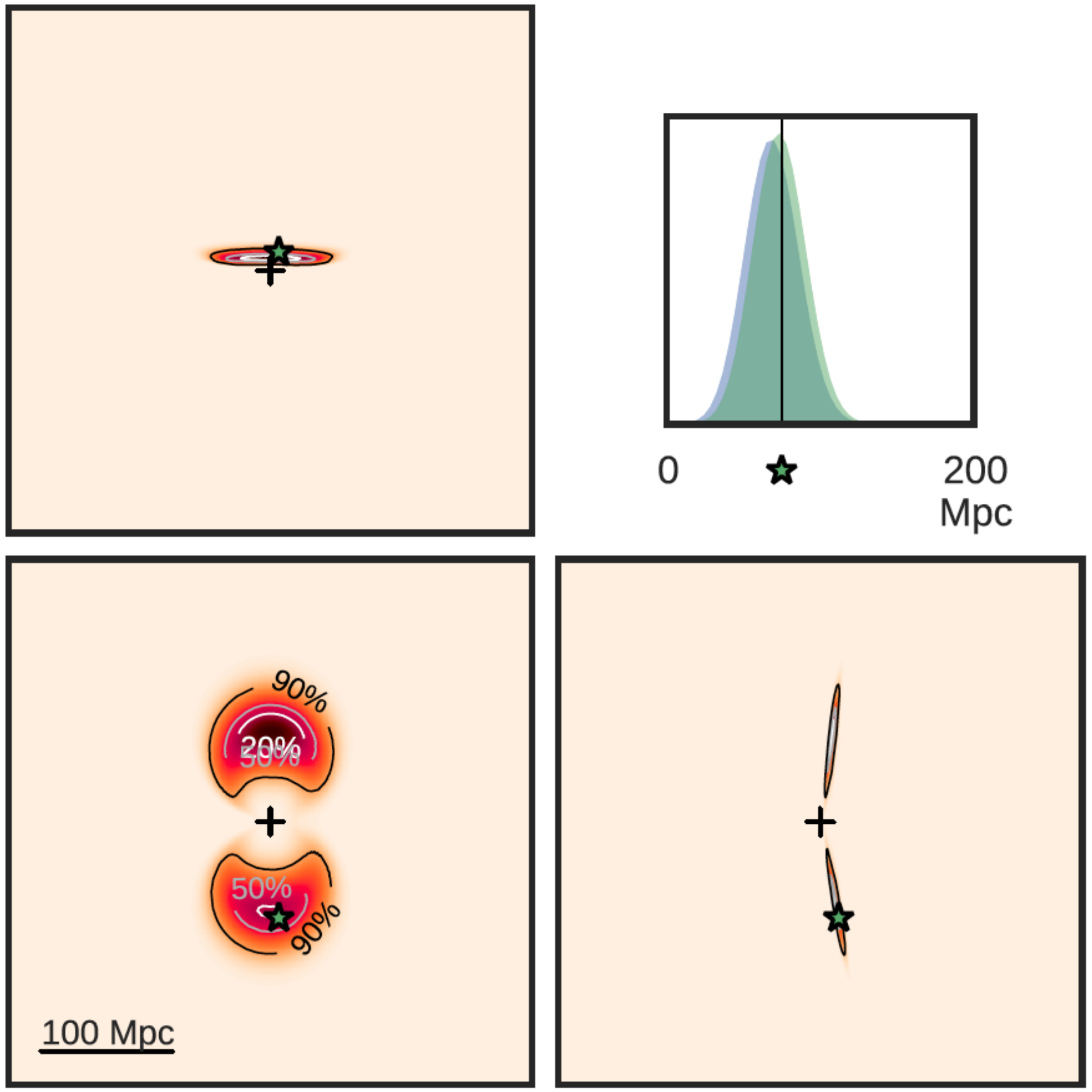
[Extragalactic only: see Tanaka & Hotokezaka 2014, Cowperthwaite and Berger 2015]

Strategy 3) Reduce false-positive rate with GW volumes

[LIGO, Virgo, advanced design sensitivity noise curves]

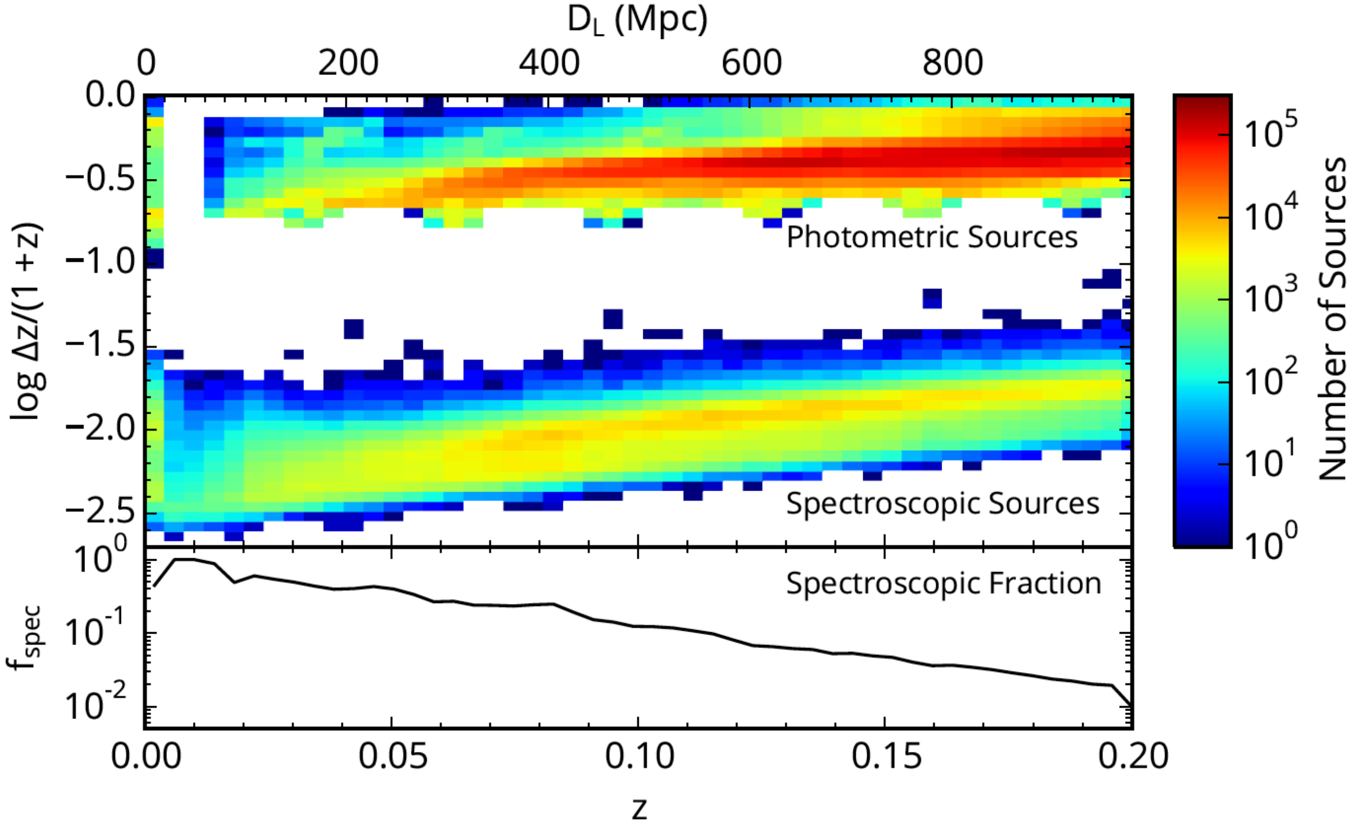


[Nissanke, Kasliwal, Georgieva 2013]



[Singer et al., arXiv:1603.07333, 2016]

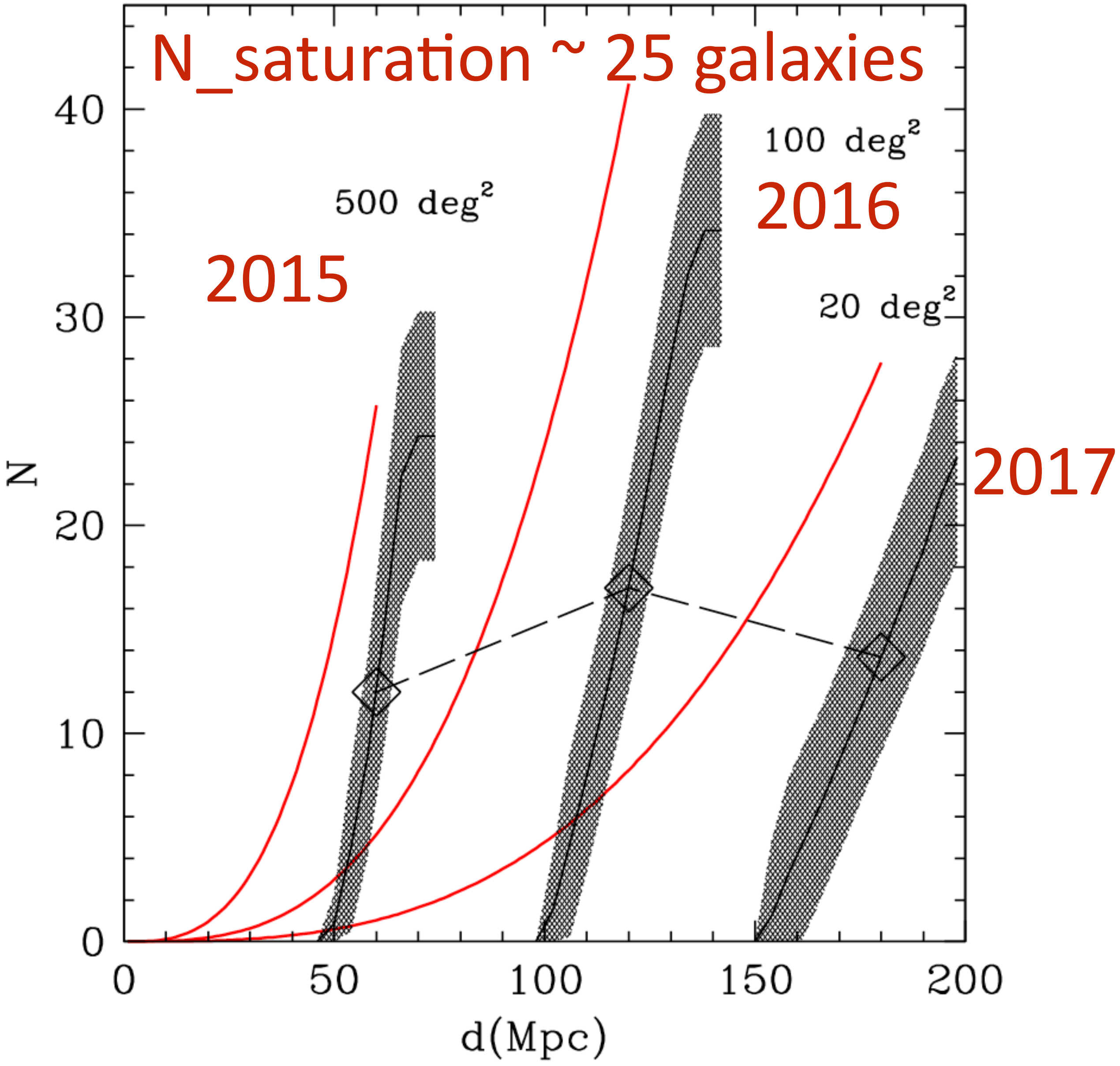
Strategy 4) Reduce false-positive rate with GW volumes & galaxy catalog



SDSS GW galaxy catalog
see https://astro.ru.nl/catalogs/sdss_gwgalcat/index.html

[Rahman, Nissanke + in prep]

brightest galaxies that produce 50% of the light

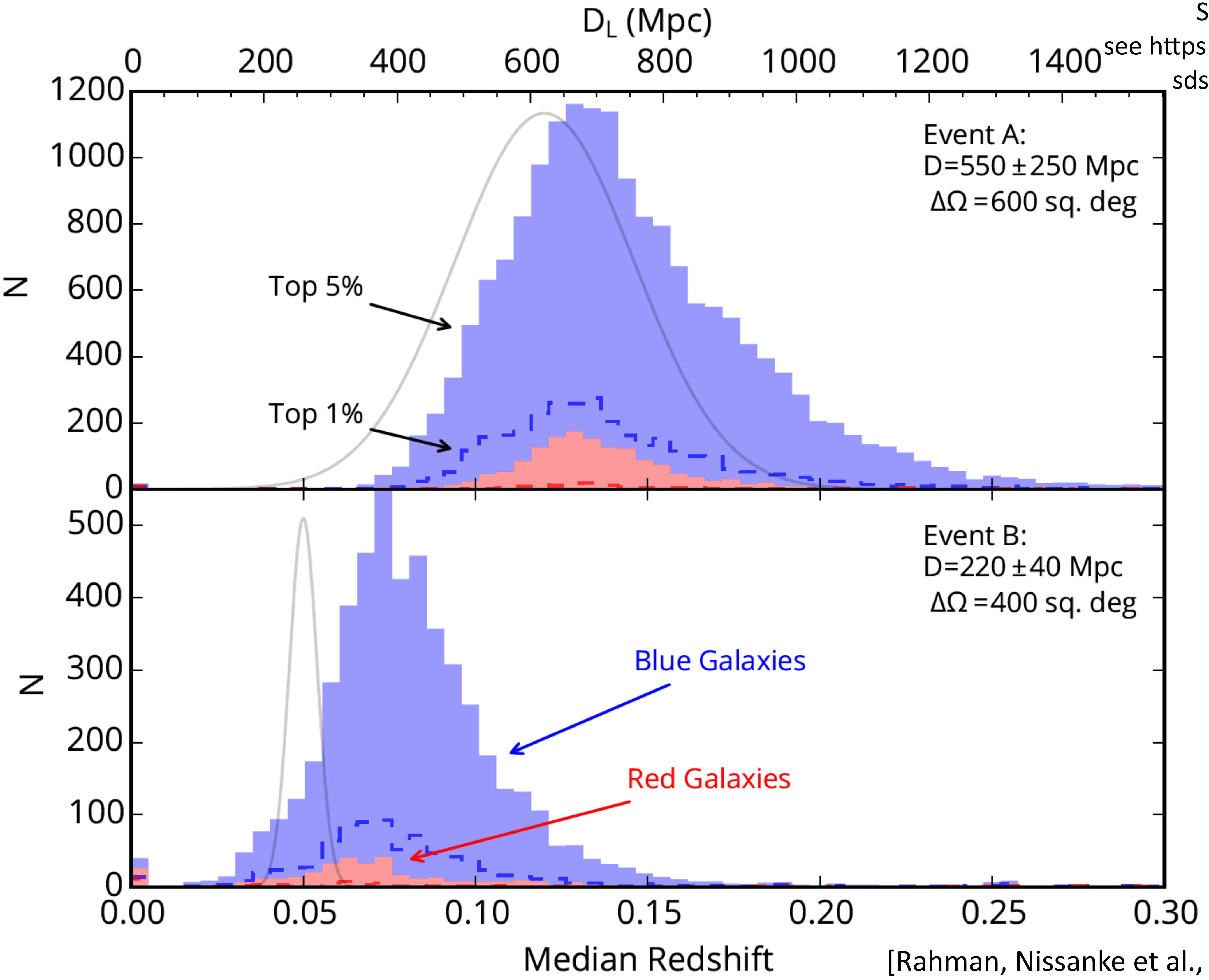


[Gehrels, Canizzaro, … Nissanke + 2015]

Reduce astrophysical false positive by factor of 10-100s

Strategy 5) Statistical host galaxy demographics with no counterpart

SDSS GW galaxy catalog
see https://astro.ru.nl/catalogs/sdss_gwgalcat/index.html



[Rahman, Nissanke et al., in prep]

The immediate future is loud and bright!

Immediately: GW detector sensitivity & network increases => Tens of BBH mergers yr^{-1} and first EM-GW detections

Astrophysical implications from EM-GW characterization:

1) Constraints from rates and spin/mass ratios: binary stellar evolution & BHs through cosmic history;
2) Nature and environments (circumstellar, etc…), neutron star equation of state, internal structure;
3) Cosmological constraints H_0: geometry and dynamics of large scale structure.
4) Nuclear Astrophysics: sites of r-process elements.

What needs to be done urgently:

EM-GW joint characterization & statistical tools required now (to make detection!)
Characterisation of transient skies in all wavelengths

Beyond LIGO, Virgo era: Witness the opening of the entire GW spectrum with CMB, PTAs, eLISA, new generation ground based detectors …

…together with next generation of wide-field synoptic surveys LSST, SKA … and E-ELTs …

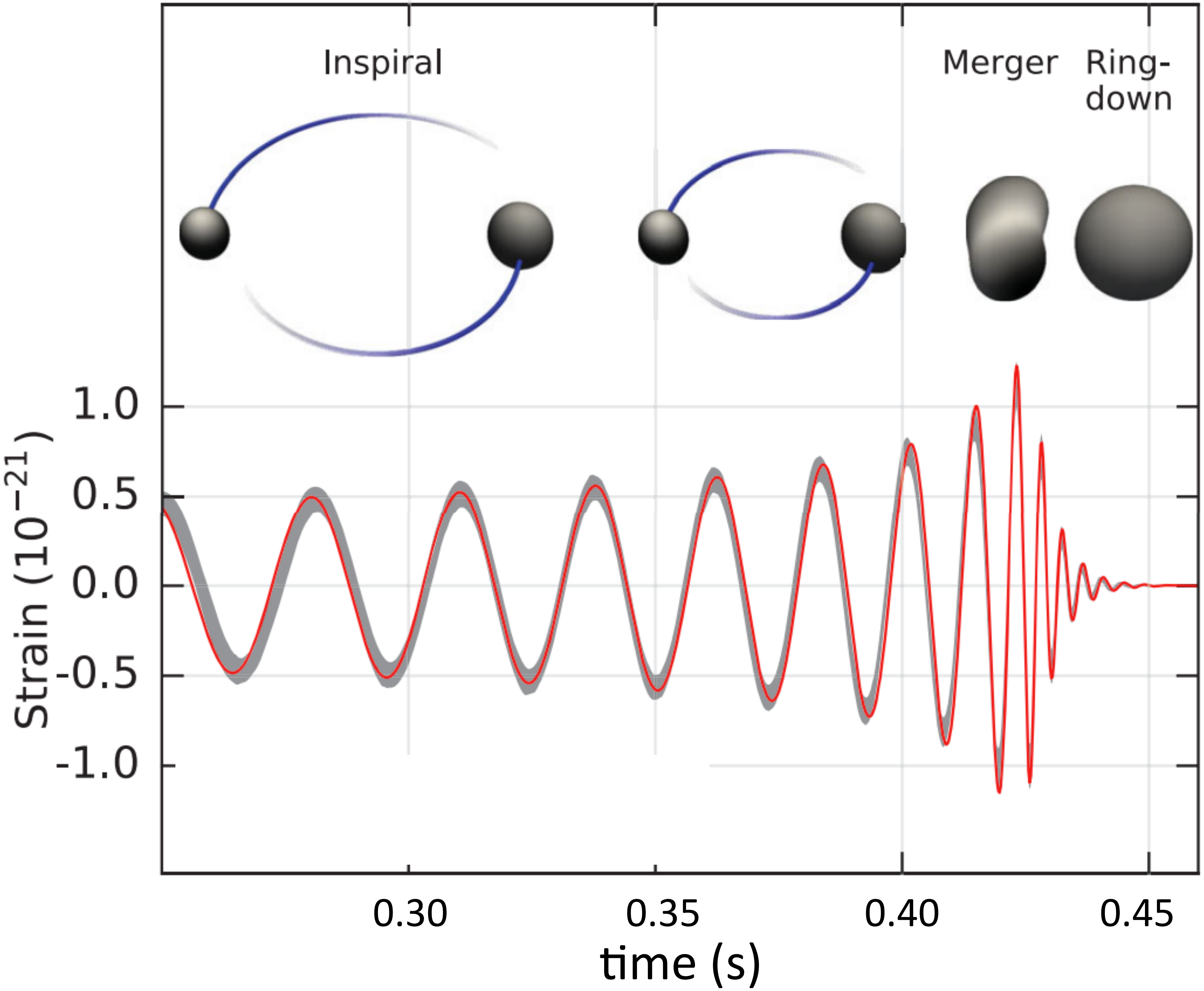
The physics of extreme gravity stars: using binaries to probe the violent universe

NORDITA, Stockholm, Sweden, 5-30th June 2017

Nissanke (contact lead, Radboud),
co-organisers: Davies (Lund), Fender (Oxford),
Fynbo(Dark Cos.), Kulkarni (Caltech), Ofek (Weizmann)

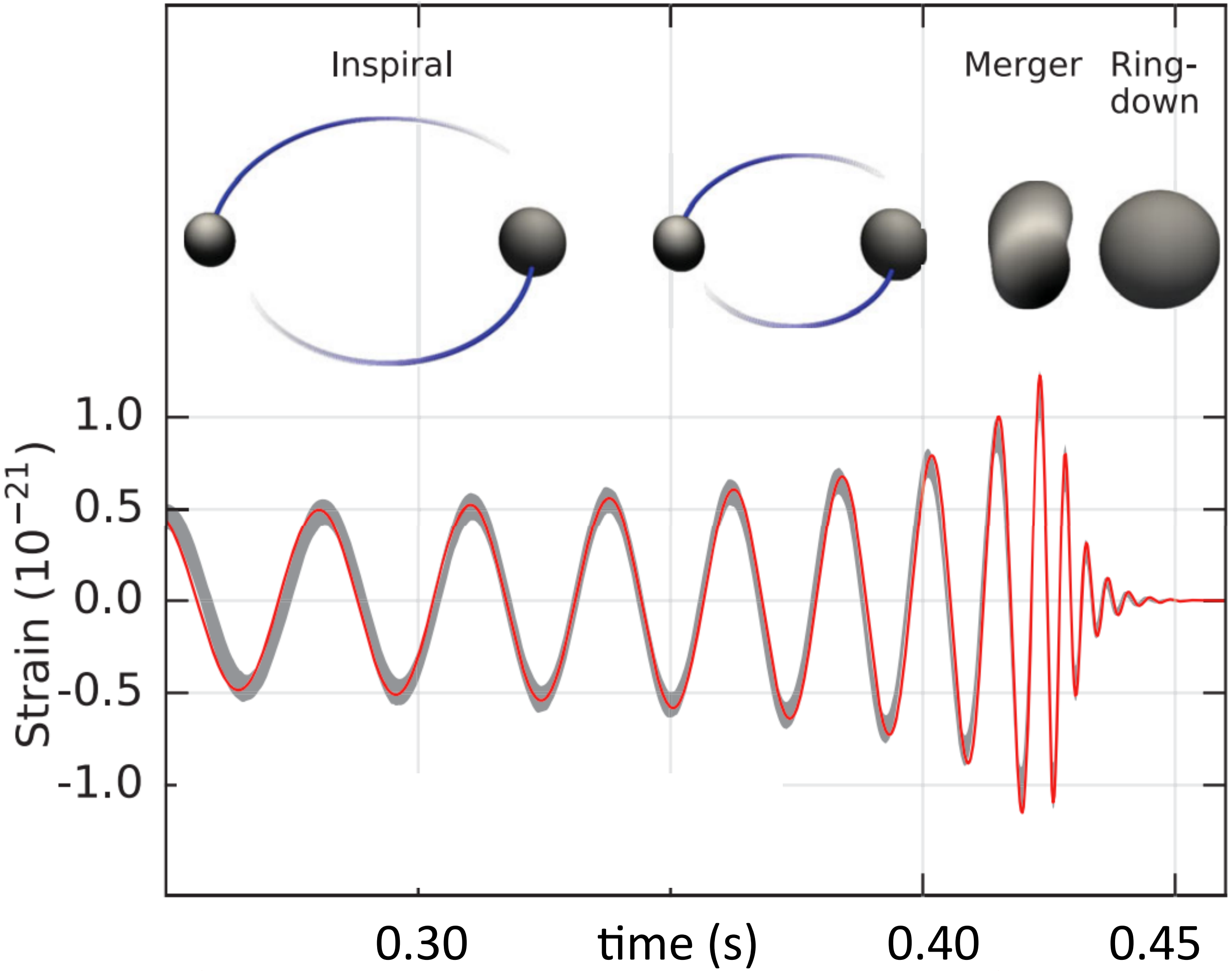
Part I:
Retrieving BH parameters
[if General Relativity is correct]

The GW waveform encapsulates Binary Black Hole Evolution



[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Decades of theoretical effort in source modelling



post-Newtonian

numerical relativity

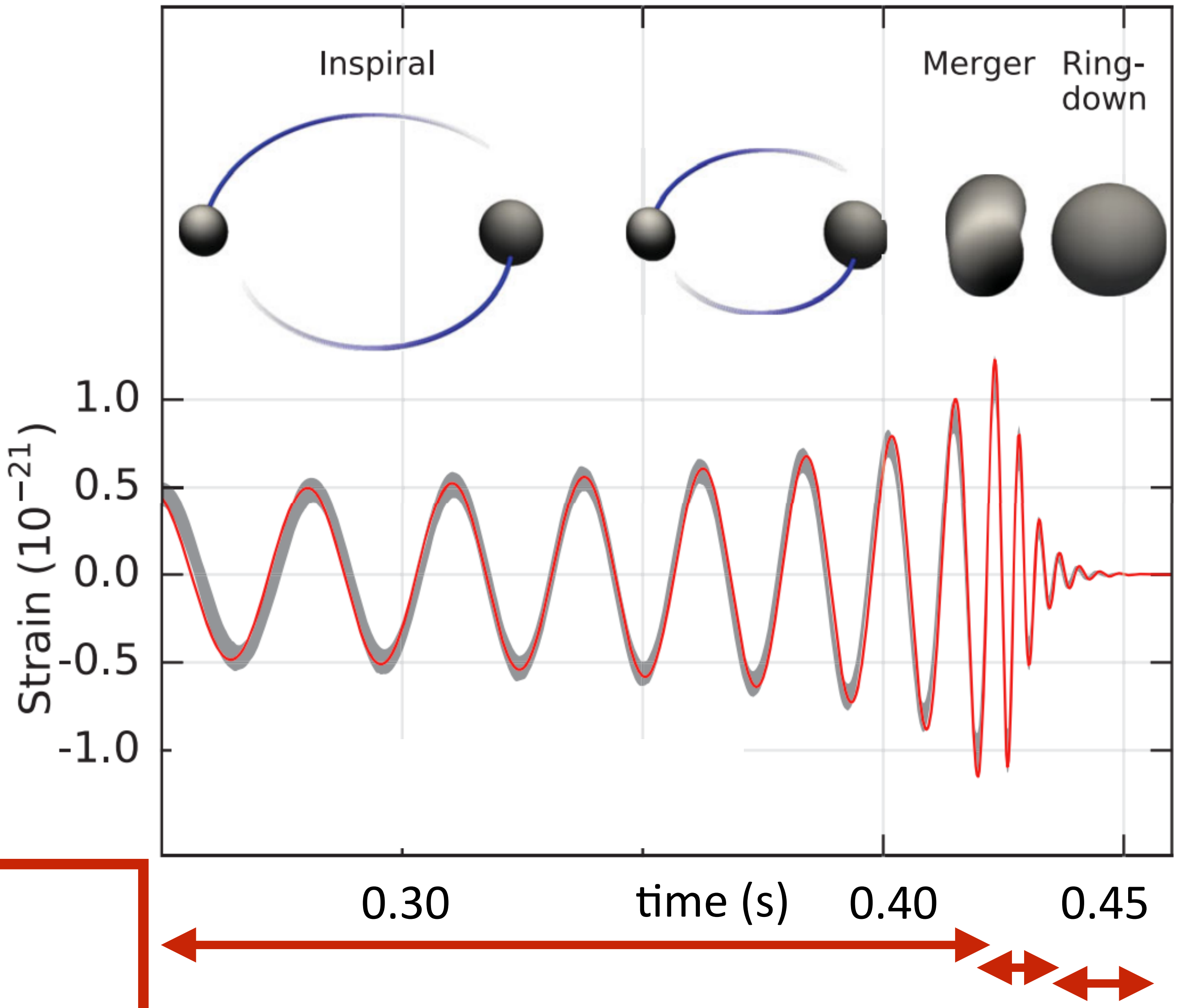
quasi-normal modes

$$\boxed{1\text{PN} \sim \frac{v^2}{c^2} \sim \frac{Gm}{rc^2} << 1}$$

[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Chirp mass drives inspiral waveform

[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]



chirp mass:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$
$$= \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

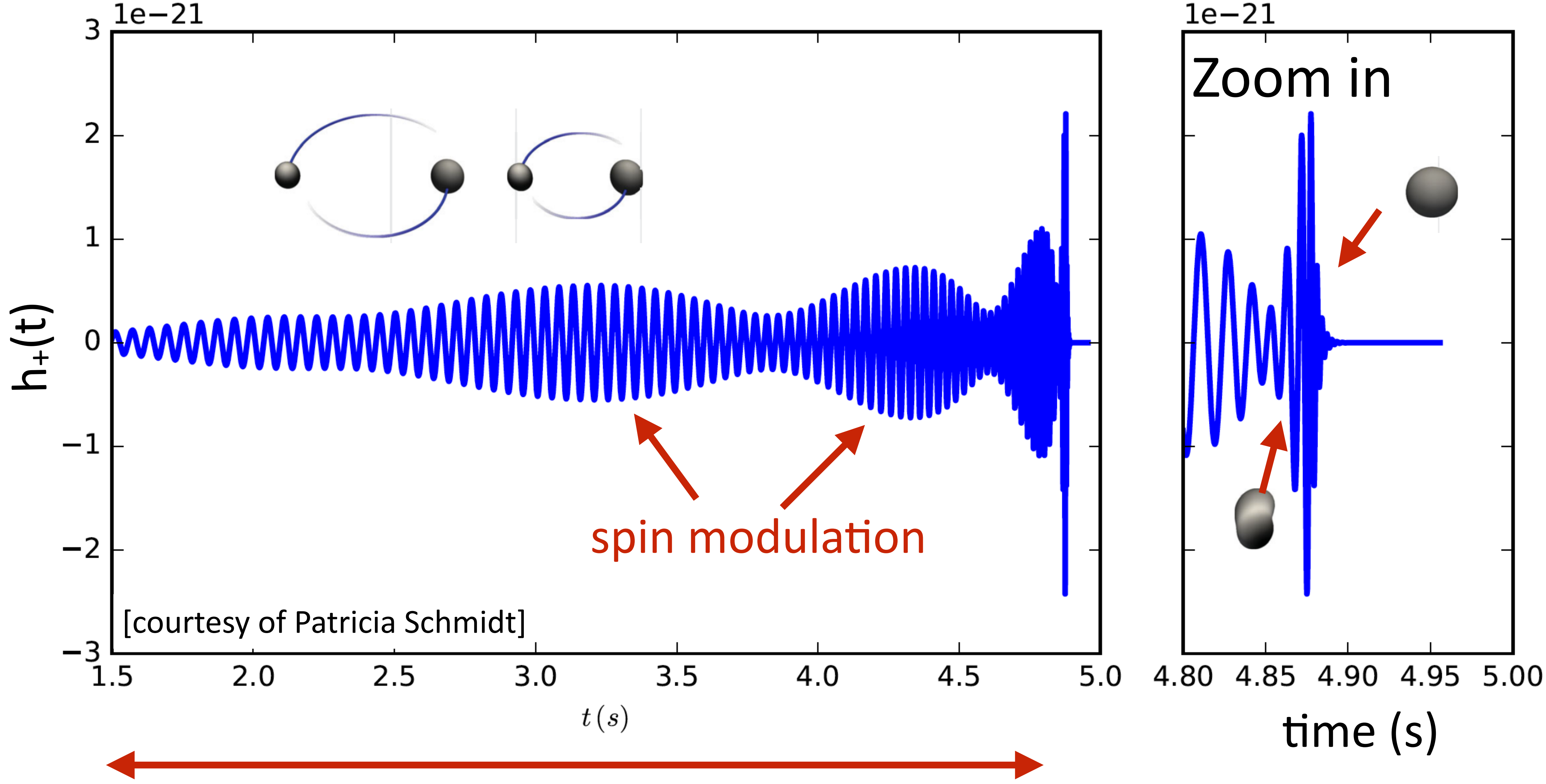
Inspiral ~ Chirp

Ringdown

<u>driven</u> by the chirp mass

… remnant mass & spin

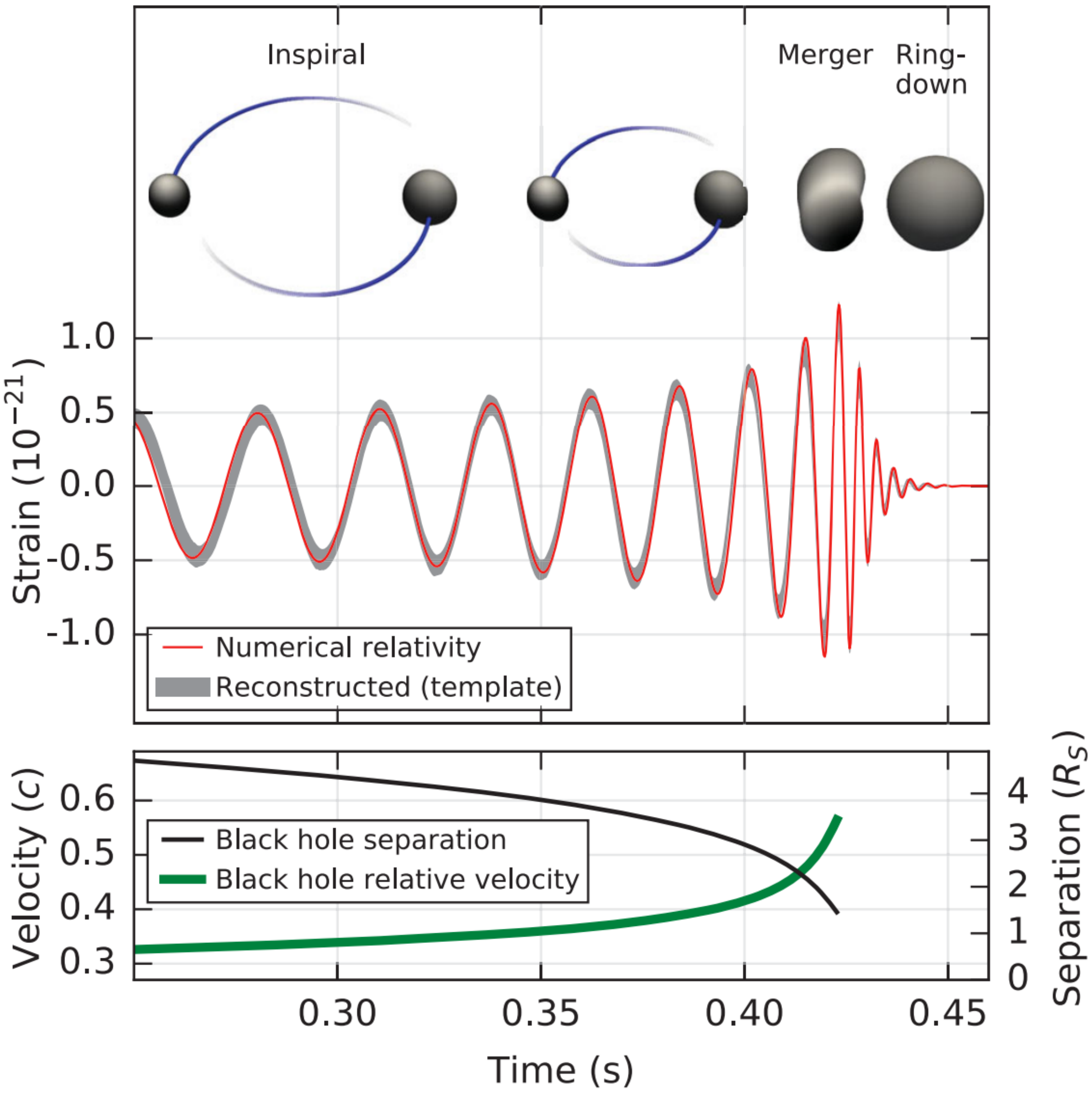
The GW waveform encodes source parameters



[courtesy of Patricia Schmidt]

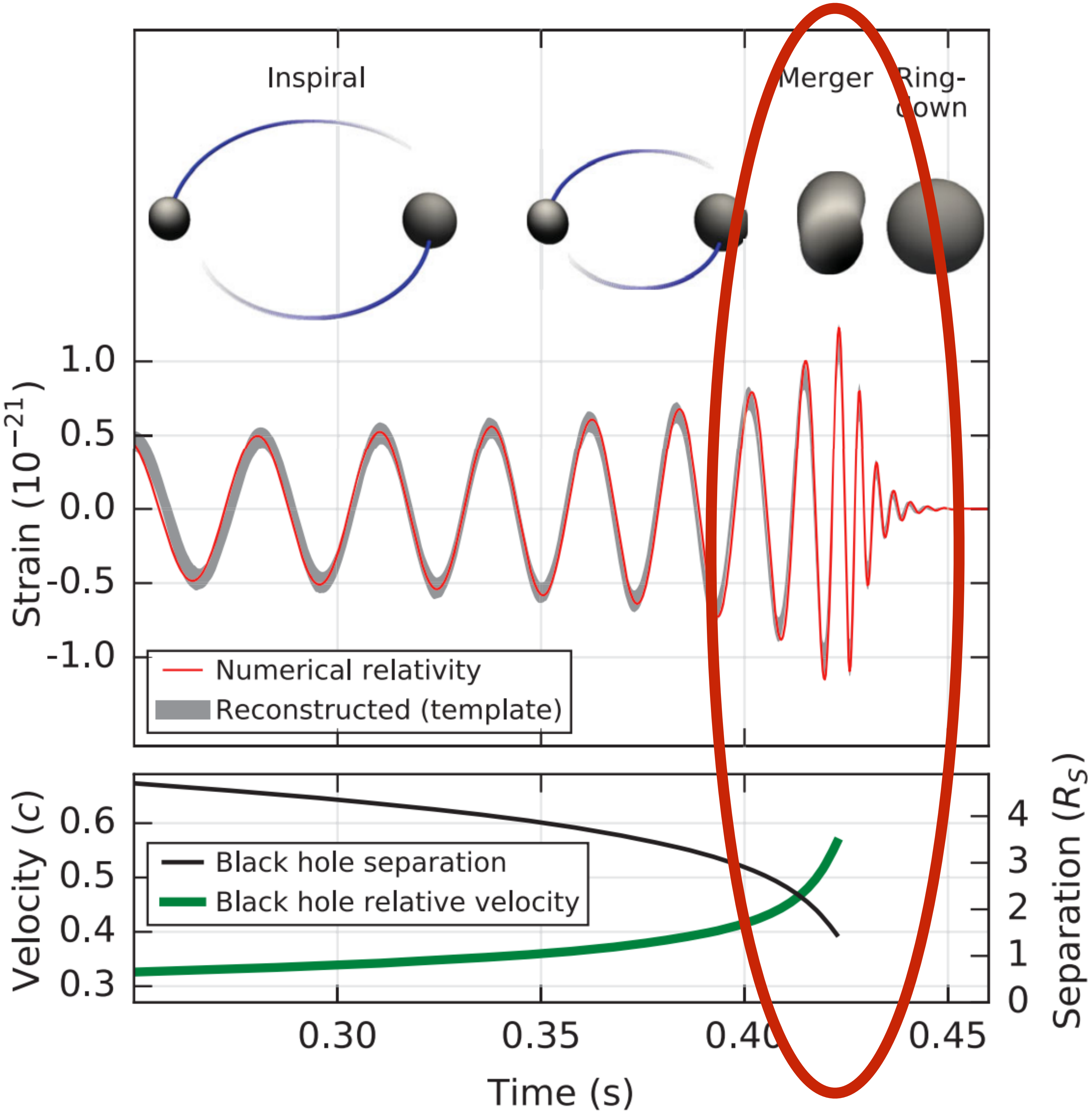
$\Phi_{\mathrm{GW}}(t)$ ⇒ chirp mass, reduced mass (1PN), spin-orbit (1.5PN), …

Necessity of Numerical Relativity



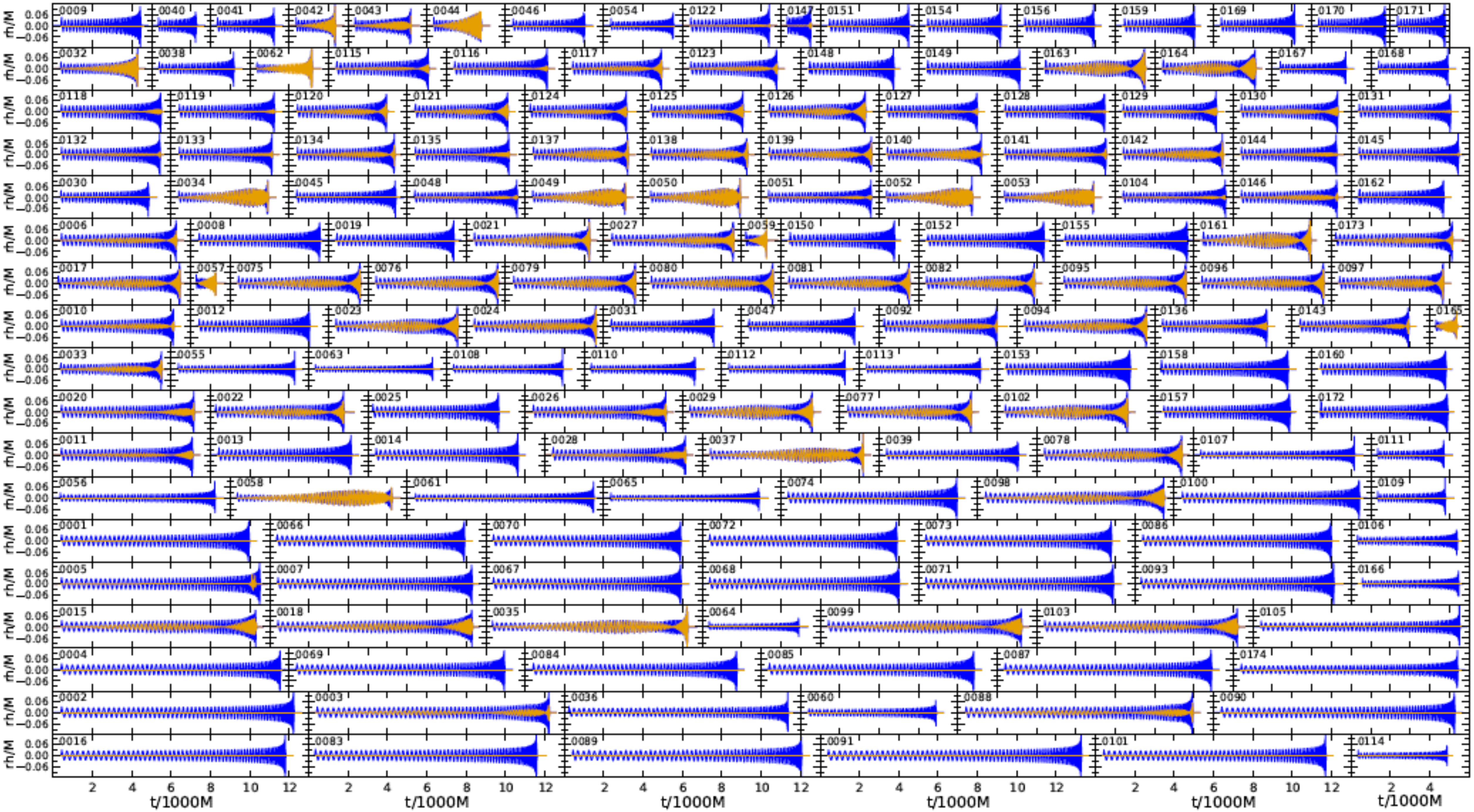
[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Unprecendented high velocity, dynamic regime of strong-field gravity



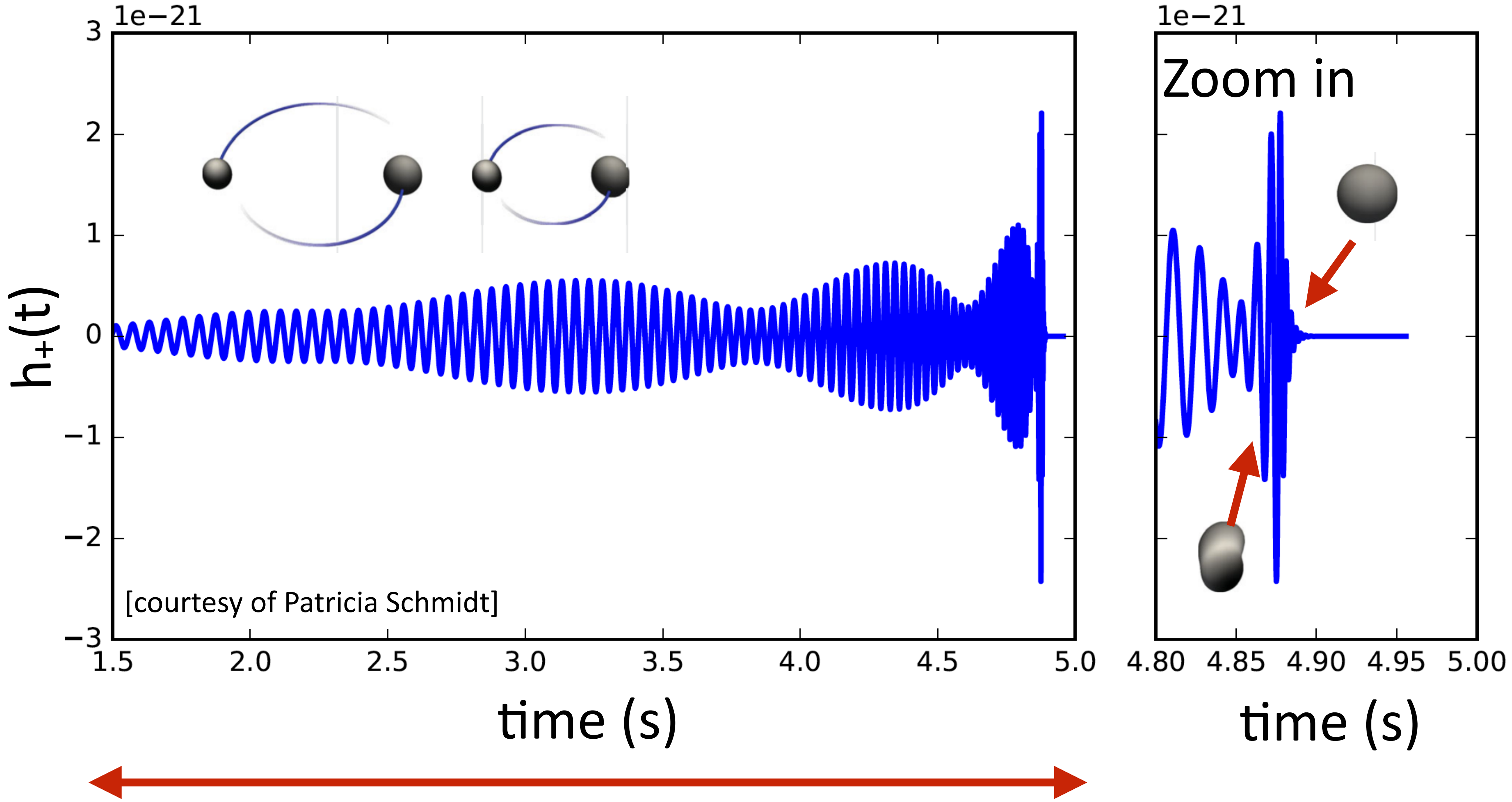
[LVC, arXiv:1602.03837, PRL 116, 061102, 2016]

Different flavors of numerical relativity waveforms



[e.g., SXS Collaboration 2014; see also simulations by Cardiff, UIB, RIT and GATech;
combined analysis with several hundred simulations from all groups for GW150914 detailed in arXiv: 1606.01262]

Two classes of model waveforms used in O1



[courtesy of Patricia Schmidt]

State-of-the-Art:

Inspiral-Merger-Ringdown Phenomenological Fit with Numerical Relativity

[Khan et al. 2016, Hannam et al. 2016]

&

Spinning Effective-One-Body Numerical Relativity [Taracchini et al., Purrer et al. 2016]

⇒ Allows for systematic error analysis and consistency check

Extract source information from GWs

h(t): 9-15 dimensions

- Masses
- Spins
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

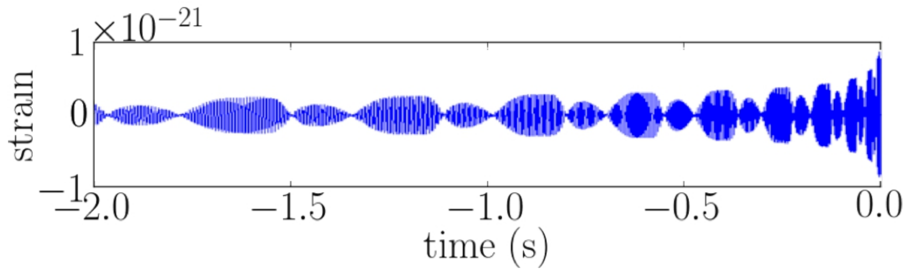
[see e.g. Cutler and Flanagan 1994, Poisson and Will 1996…]

Extract source information from GWs

h(t): 9-15 dimensions

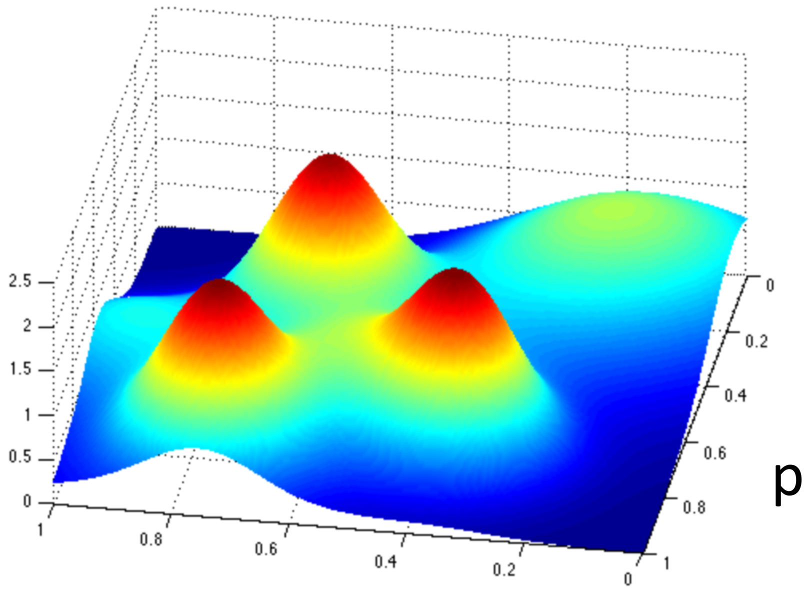
- Masses
- Spins
- Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Model h(t)



Detector output

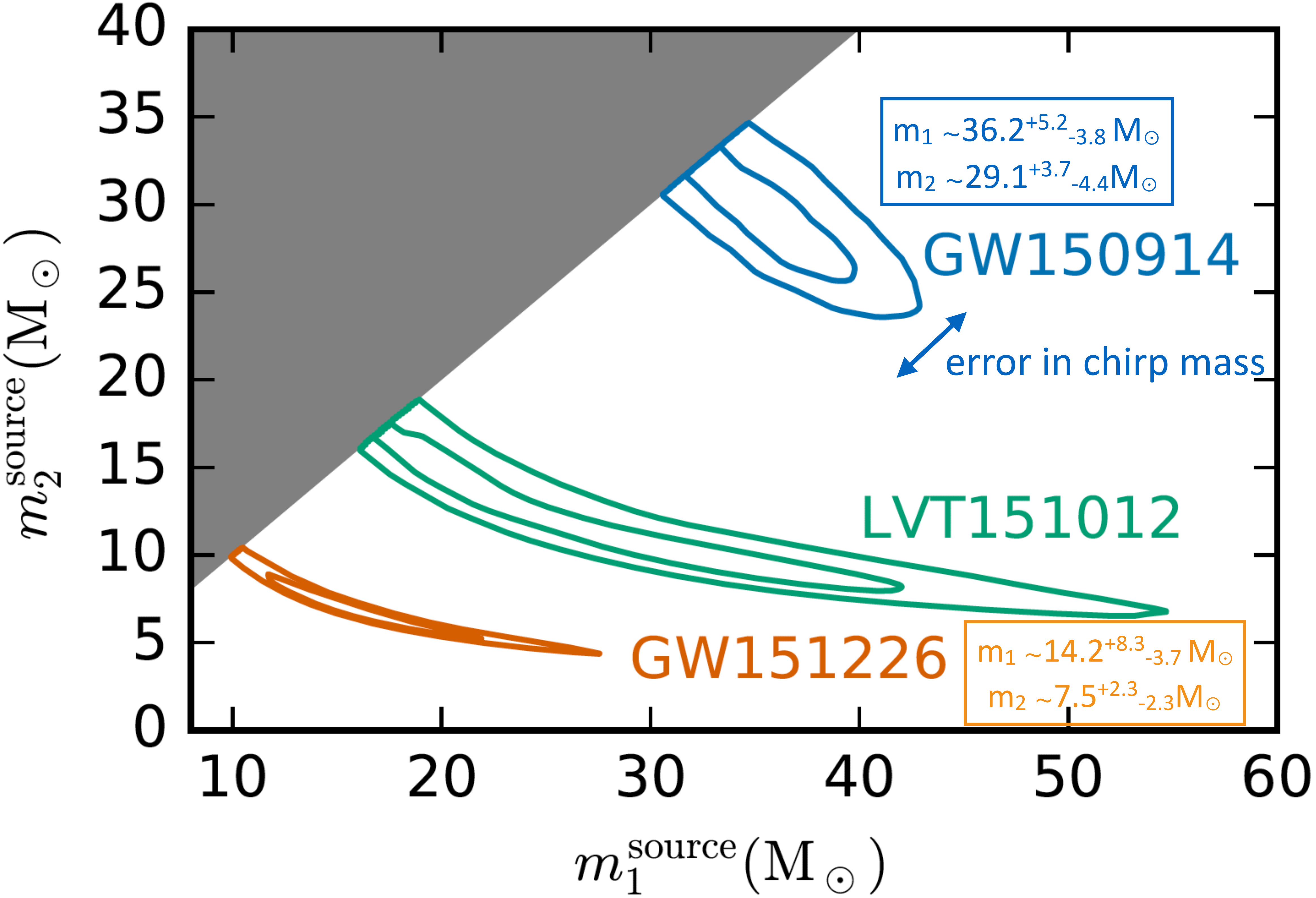
Explicitly map out: $p(\boldsymbol{\theta}|s) \propto p(\boldsymbol{\theta})\mathcal{L}_{\text{total}}(s|\boldsymbol{\theta})$



using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

[see e.g. Veitch et al. 2015;
LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]

Diversity of BH masses and errors …



$m_1 \sim 36.2^{+5.2}_{-3.8}\,M_\odot$

$m_2 \sim 29.1^{+3.7}_{-4.4}M_\odot$

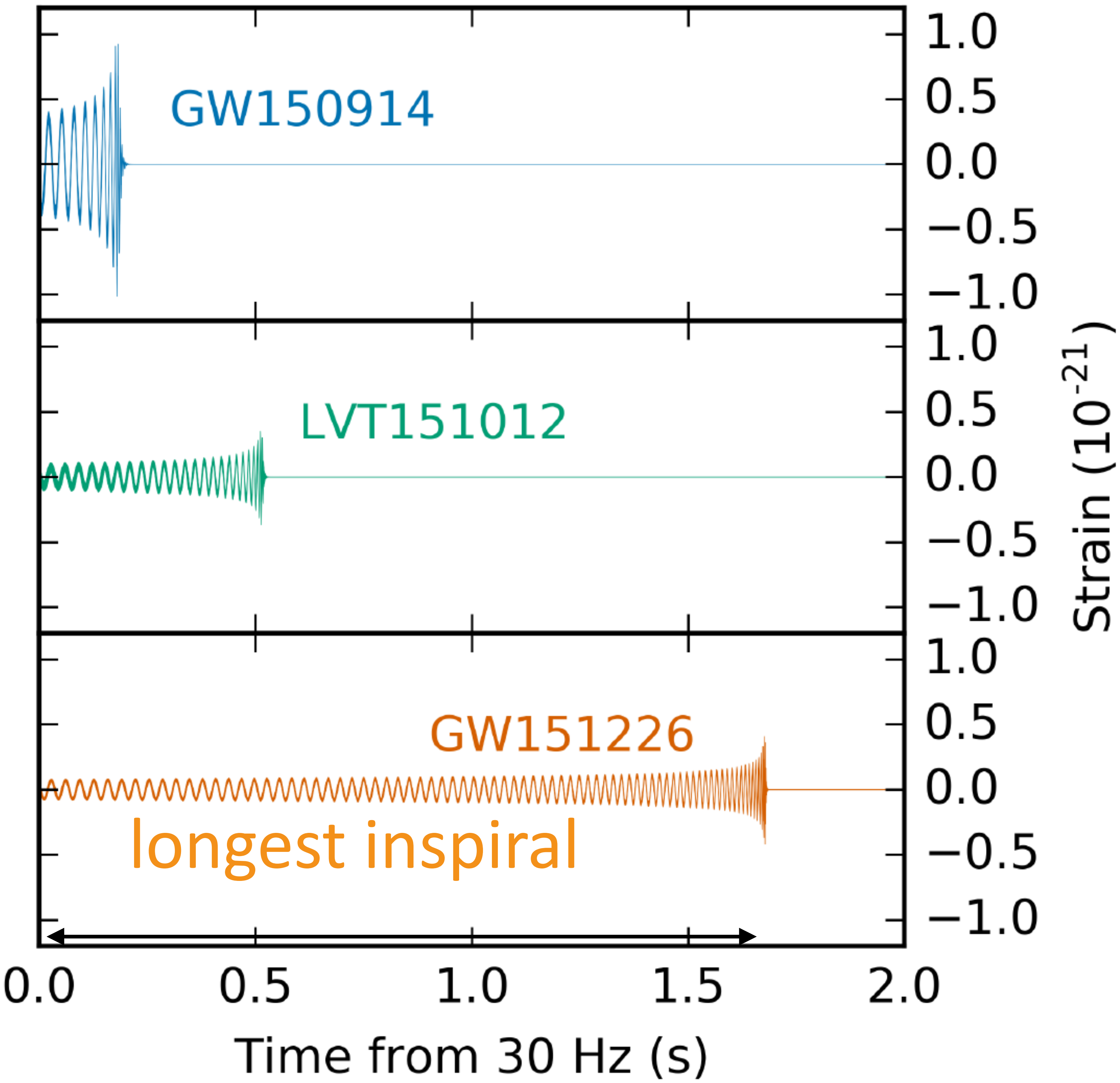
error in chirp mass

$m_1 \sim 14.2^{+8.3}_{-3.7}\,M_\odot$

$m_2 \sim 7.5^{+2.3}_{-2.3}M_\odot$

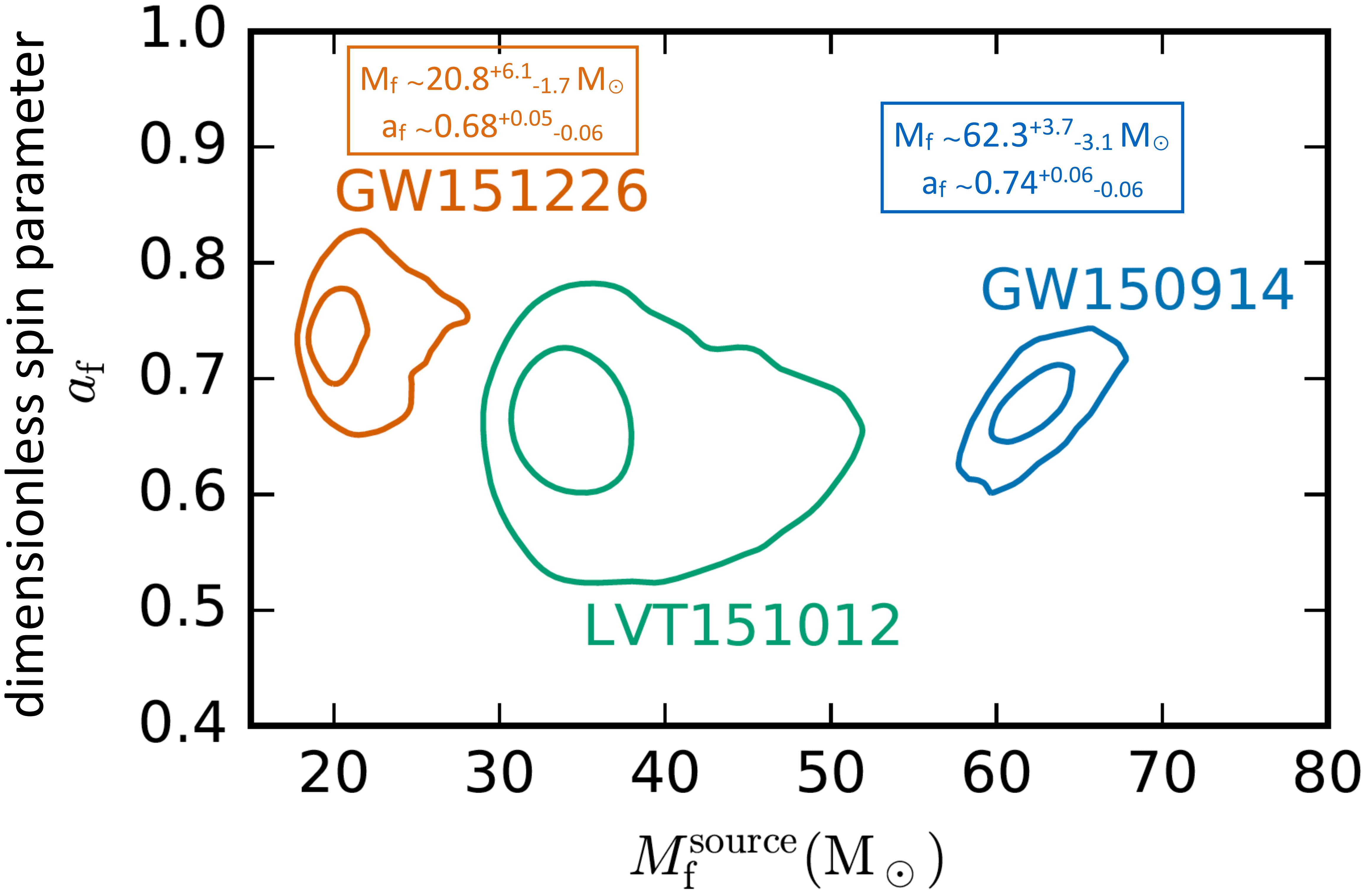
Xiv:1606.04856, PRX 6, 041015 , 2016]

… length of the chirp signal



Xiv:1606.04856, PRX 6, 041015 , 2016; see also http://www.soundsofspacetime.org to listen to the chirps]

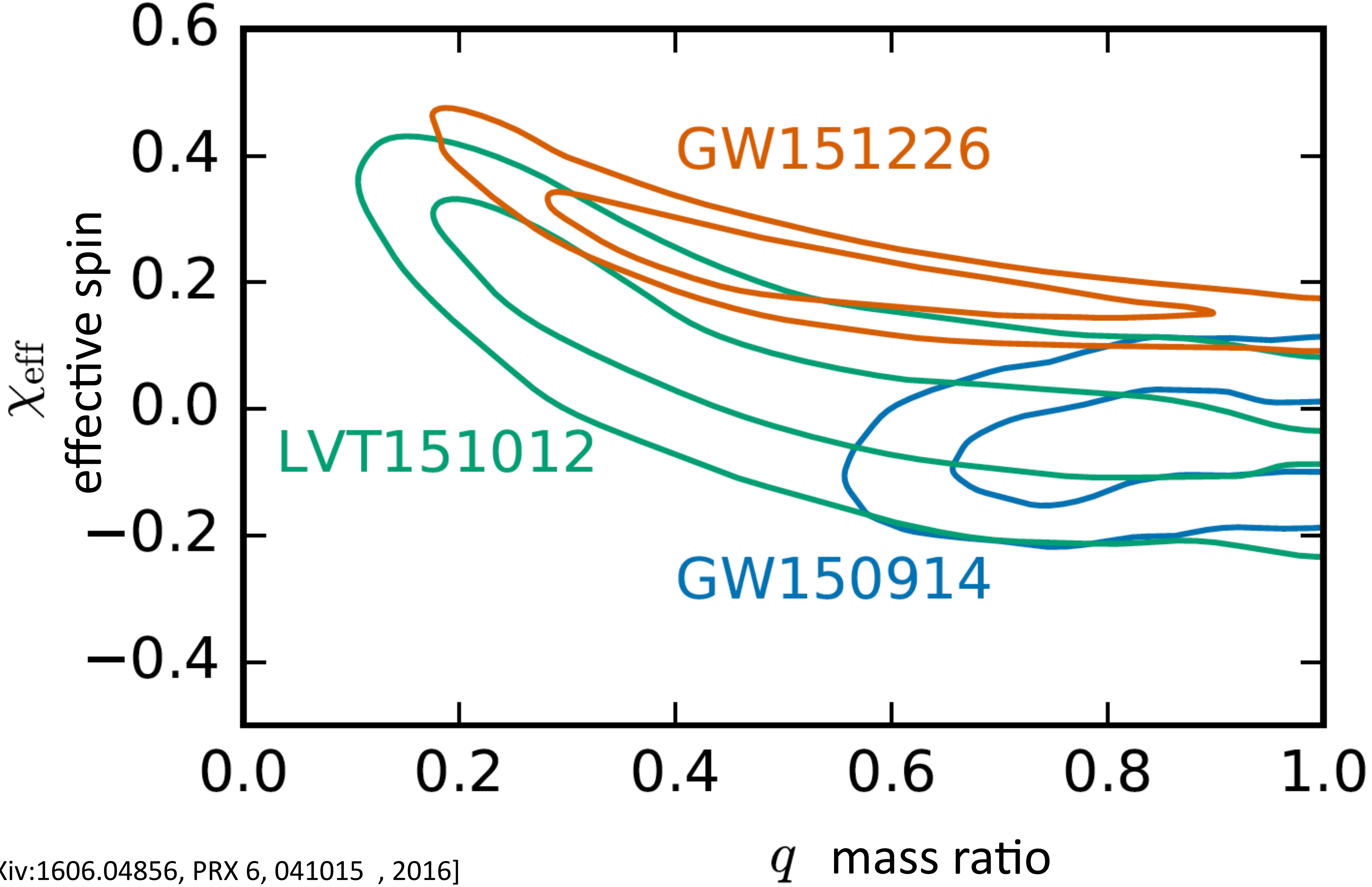
Remnant BH masses & spins



final remnant mass

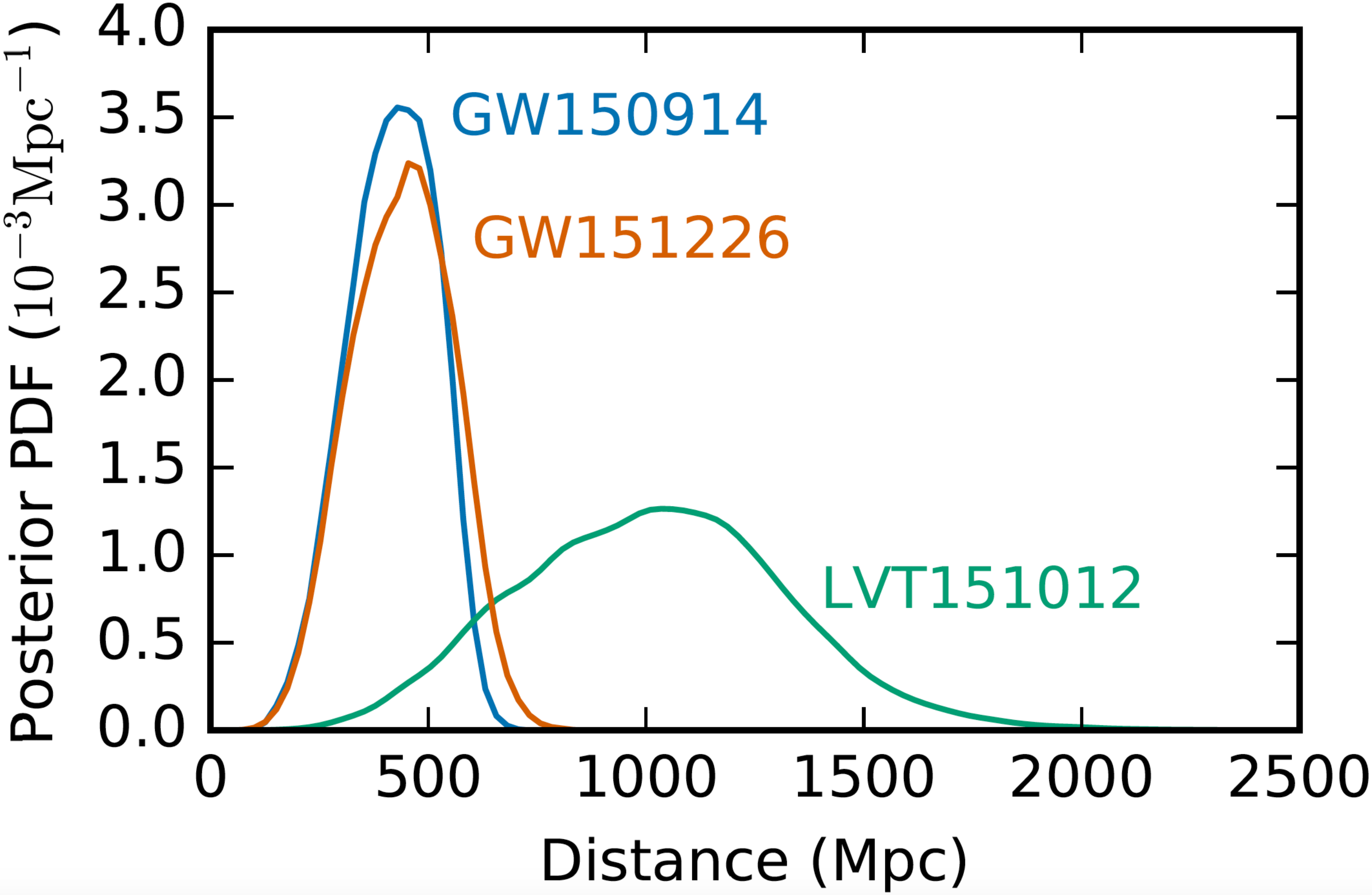
Xiv:1606.04856, PRX 6, 041015 , 2016]

Challenge: large degeneracies between mass ratio and effective spin



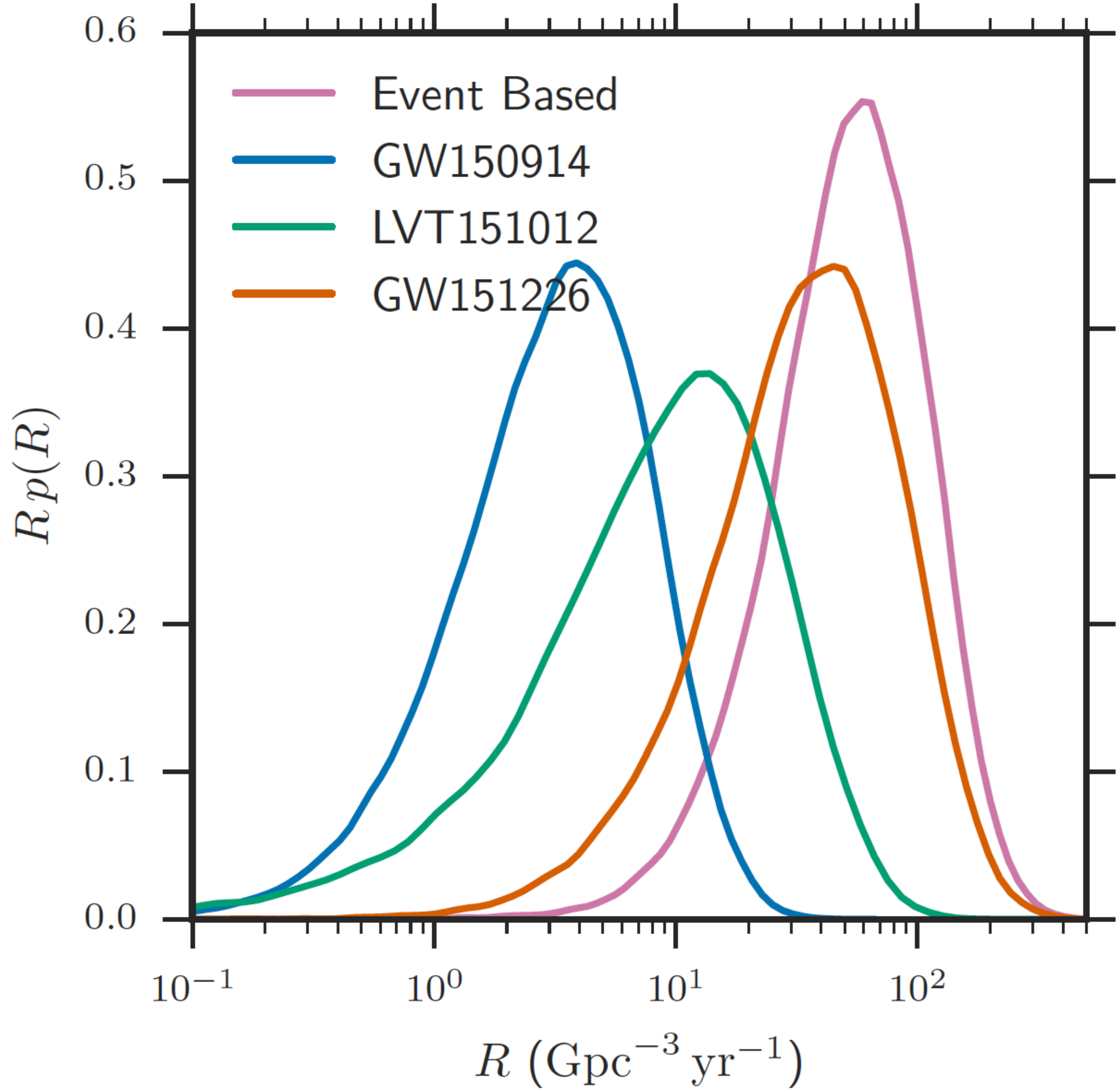
Xiv:1606.04856, PRX 6, 041015 , 2016]

Luminosity distance: beyond existing spectroscopic galaxy catalogs



Xiv:1606.04856, PRX 6, 041015 , 2016]

Astrophysical rates could soon probe formation scenarios



9 - 240 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Excludes < 10 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ ⇒

Isolated

Disfavours a v. low common envelope binding energy or v. high BH natal kicks (> several hundred km s^{-1})

Dynamical

Disfavours low-mass clusters

iv:1606.04856, PRX 6, 041015 , 2016; see Tom Dent's talk this afternoon]