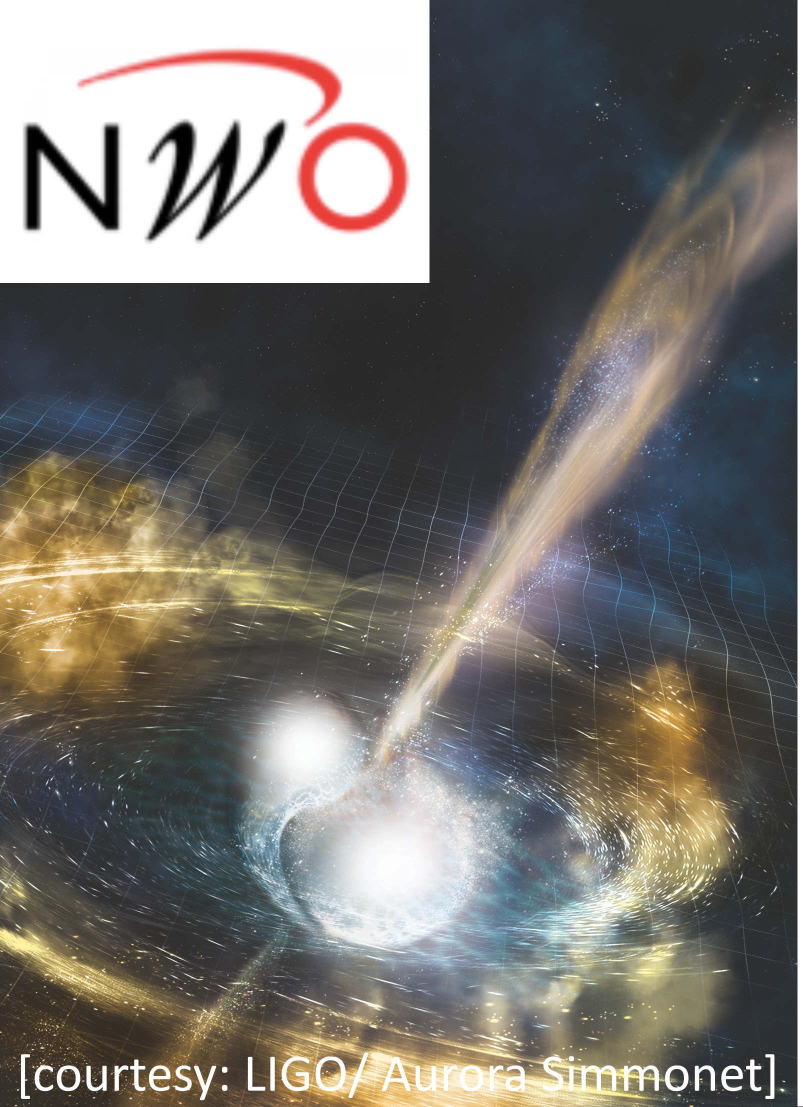


[courtesy: LIGO/ Aurora Simmonet]

New perspectives onto the Universe in the era of multi-messenger astronomy

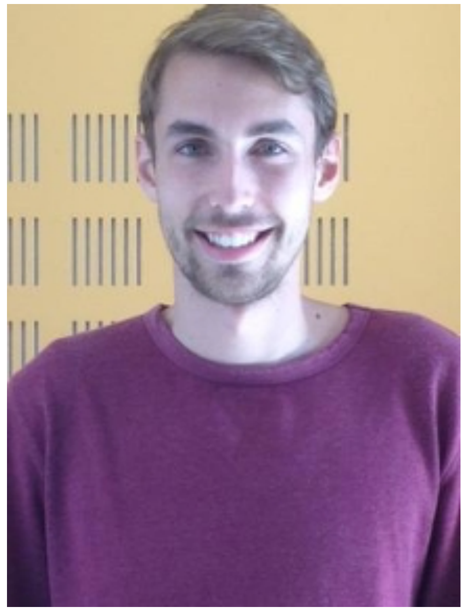
[courtesy: JIVE/ Beabudai Design]

Samaya Nissanke,
GRAPPA - Center of Excellence in Gravitation and Astroparticle Physics,
University of Amsterdam, NL

KICC10, University of Cambridge,
20th September 2019

Group and collaborations

Dr Tanja Hinderer,
Delta ITP Fellow



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PhD

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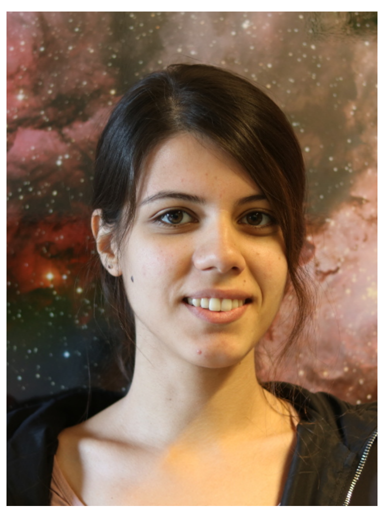
outgoing postdoc —>
faculty at U. Virginia

Dr Andrew Williamson,
outgoing postdoc —>
Portsmouth



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incoming PhD

Andreas
Guerra-Chavas,
BSci

Archisman Ghosh
DITP postdoc
(joint Leiden-Amsterdam)

Suvodip Mukherjee
incoming GRAPPA
fellow from IAP/CCA

Bob Jacobs,
MSci

COLLABORATIONS

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- GROWTH team
- JAGAWR team
- BlackGEM team, NL
- LOFAR, MeerKAT, APERTIF, NL
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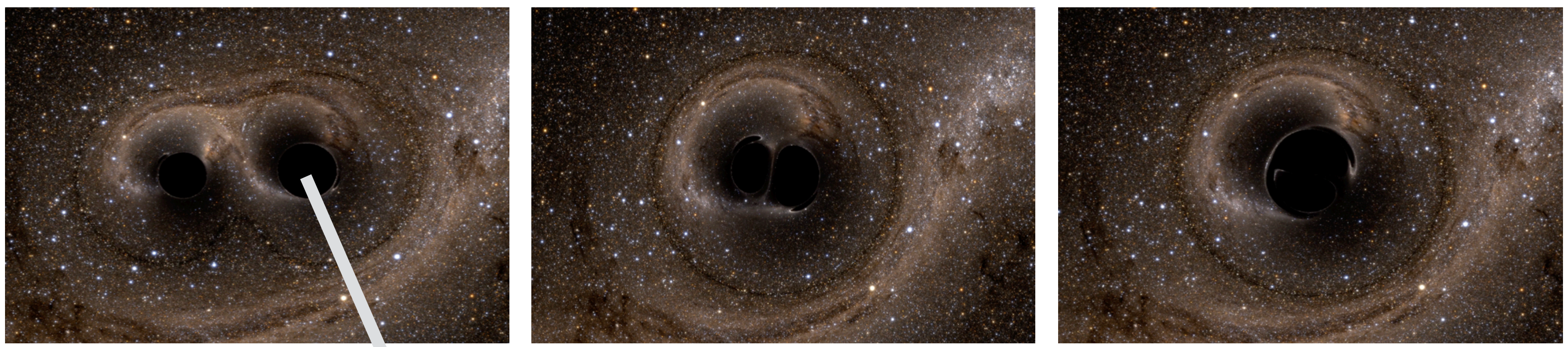
- Kenta Hotokezaka (Princeton)
- Gregg Hallinan (Caltech)
- Mansi Kasliwal (Caltech)
- Kunal Mooley (Caltech)
- Alessandra Corsi (Texas Tech)
- Shri Kulkarni (Caltech)
- Dale Frail (NRAO)
- David Tsang (Southampton)
- Jennifer Barnes (Columbia)
- Hiranya Peiris (UCL, Stockholm)
- Daniel Mortlock (Imperial)
- Stephen Feeney (Flatiron, Simons)
- Neal Dalal (PI)
- Chris Hirata (OSU)
- Matthew Liska (Harvard)

Philipp Moesta
(new faculty
at GRAPPA)

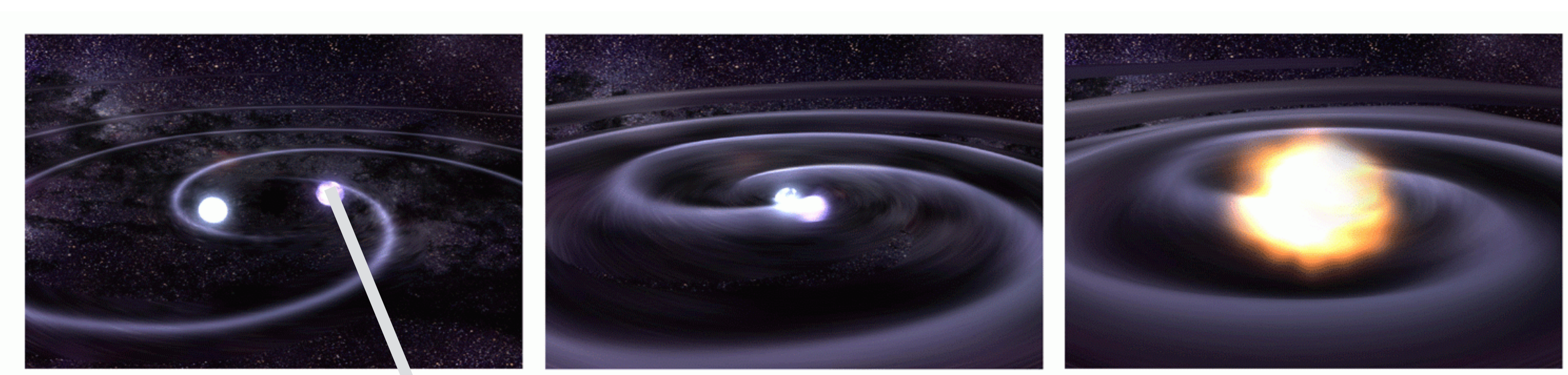
A new revolution in the past four years: gravitational waves (GW), black holes and neutron stars

time



Black Holes (BHs)

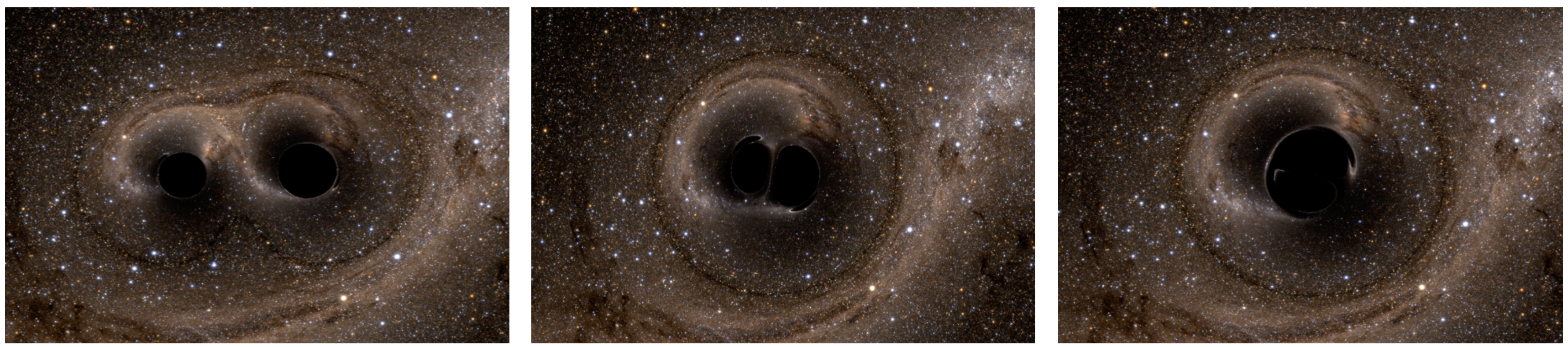
2015-2017:
Ten+
Black Hole-Black Hole Mergers
[~ 7.5 - 50 $M_\odot$]



Neutron Stars (NSs)

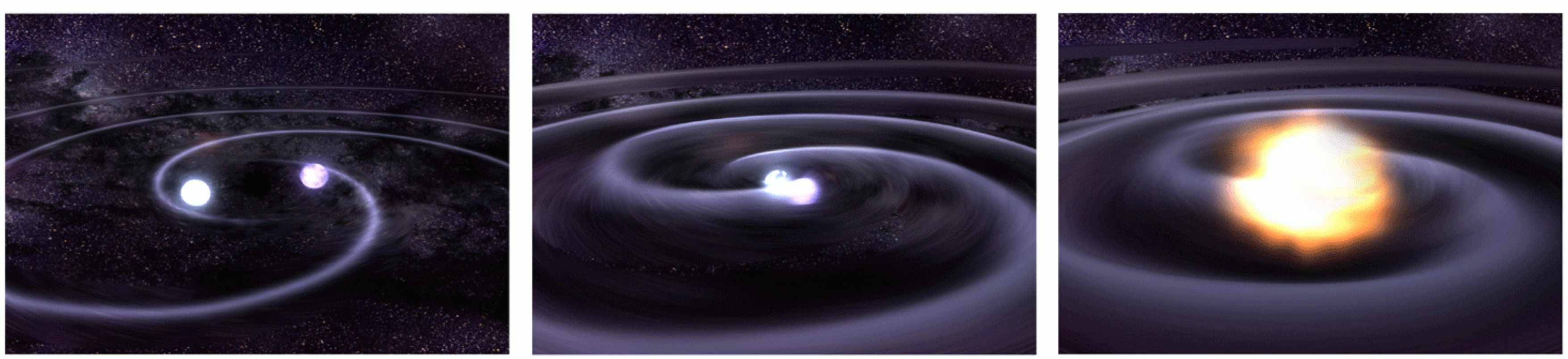
2017:
One Neutron Star - Neutron Star Merger
"GW170817"
[~ 1.1 - 1.6 $M_\odot$]

A new revolution in the past four years: gravitational waves (GW), black holes and neutron stars



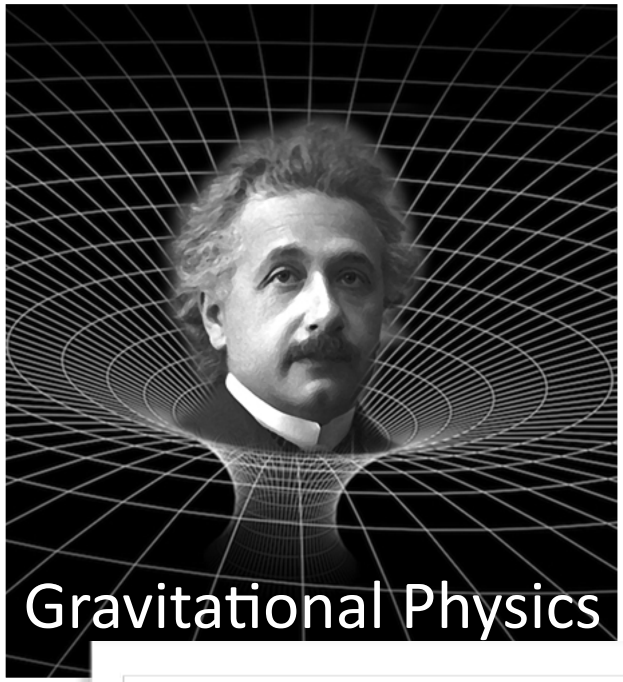
2015-2017:
Ten +
Black Hole-Black Hole
Mergers

[LVC arXiv:1811.12907; see also Venumadhav, Zackay, Dai, …2019]

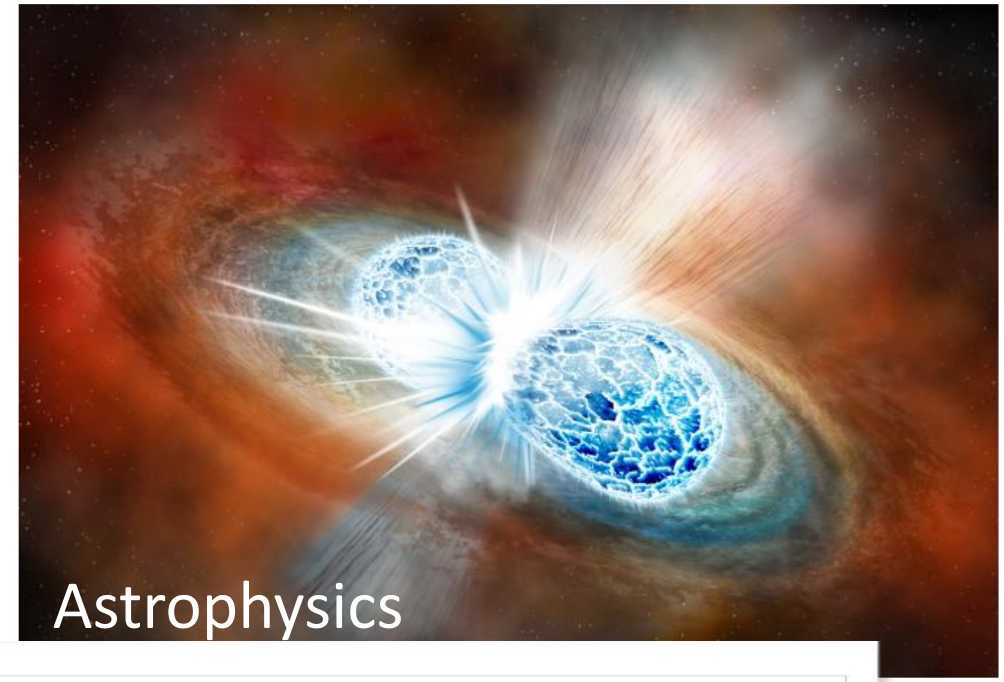


2017:
One Neutron Star -
Neutron Star Merger
“GW170817”

Third science run began 1st April 2019: 21 binary black hole and 6 neutron star binary merger candidates



Multiple Discoveries of GW170817 [the gift that keeps on giving]



First Binary Neutron Star detected in Gravitational Waves

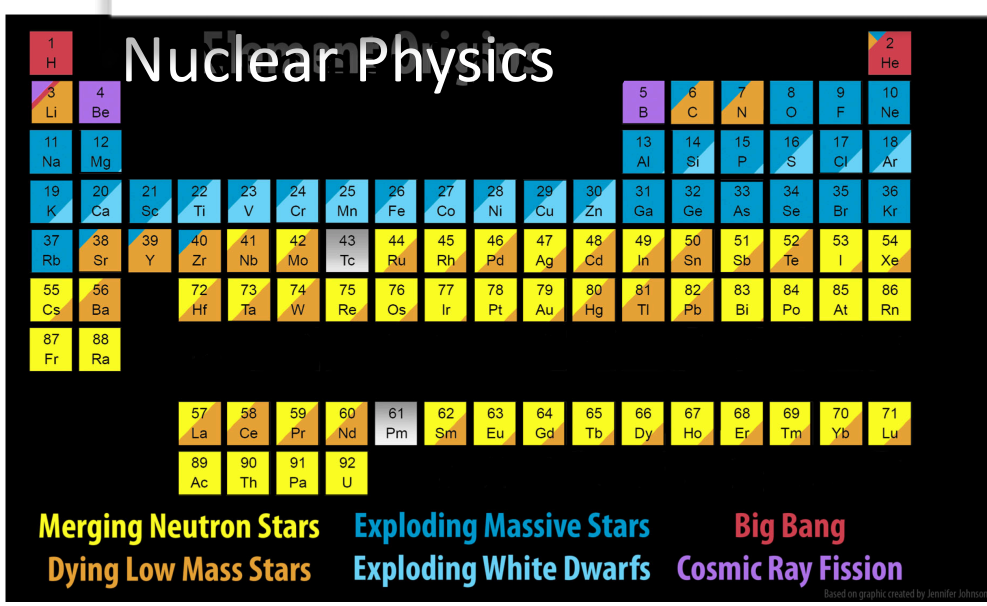
First Electromagnetic Counterpart of a GW merger in every waveband!

First Gravitational Wave Standard Siren Hubble Constant Constraint

First Short Gamma Ray Burst - Binary Neutron Star Merger Association

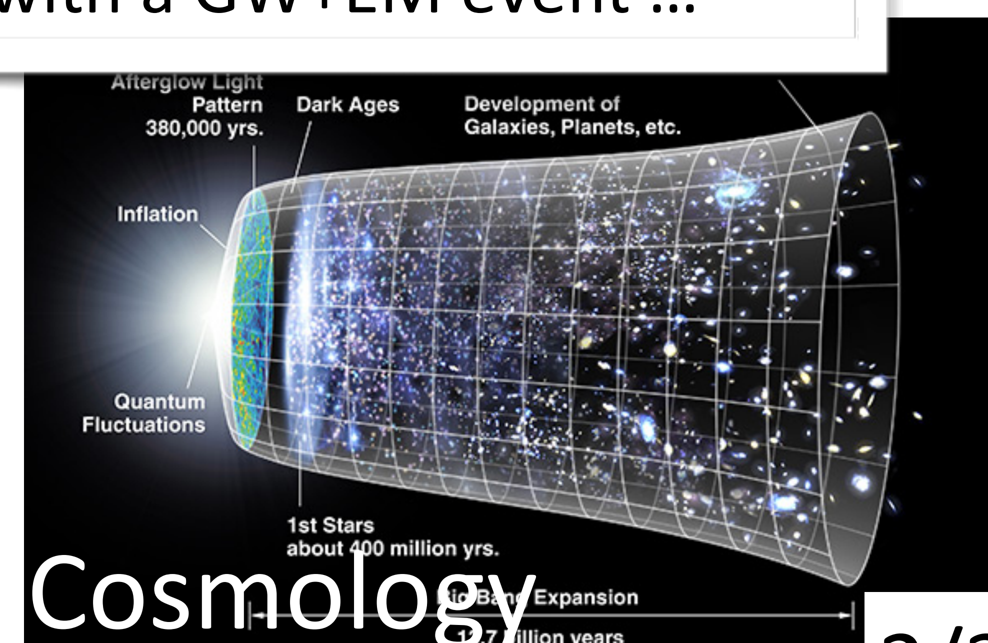
First kilonova discovery and astrophysical sites of r-process heavy elements

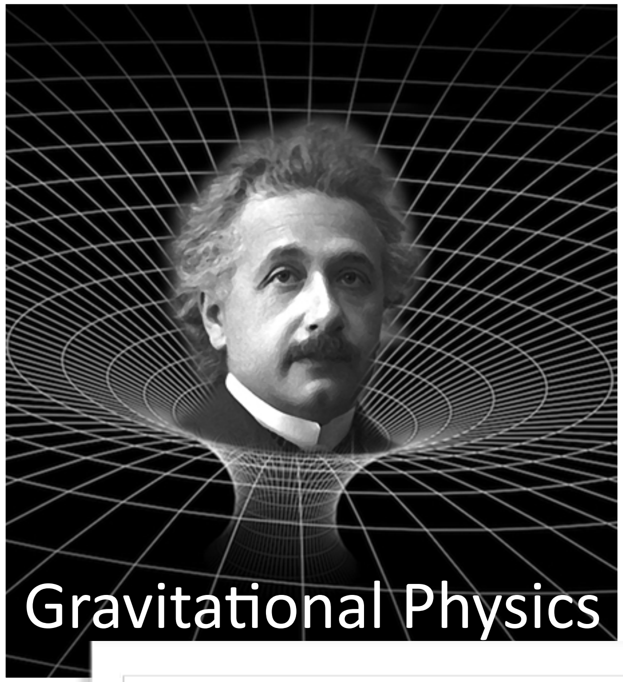
First tests of the speed of light and gravity with a GW+EM event …



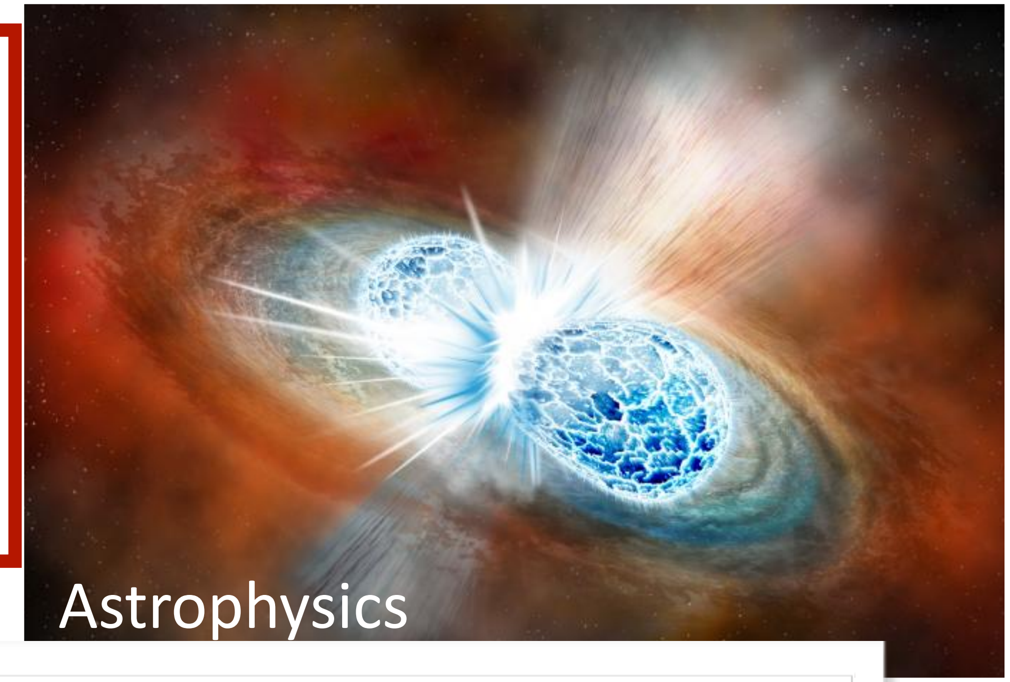
[see talks by Holz and Palmese]

[Note: ~ 2700 papers]





From a discovery era to one of precision (astro)physics



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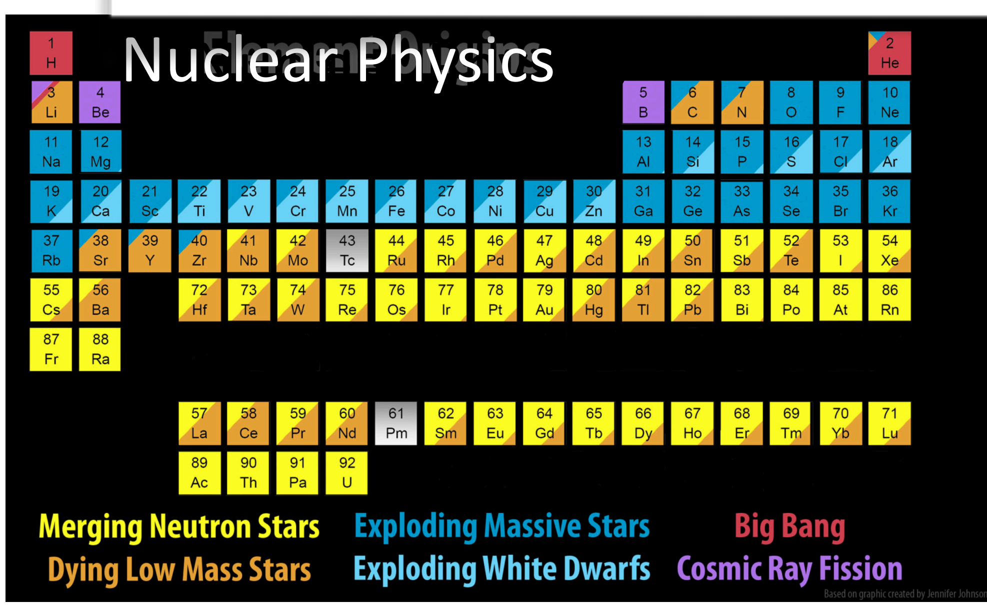
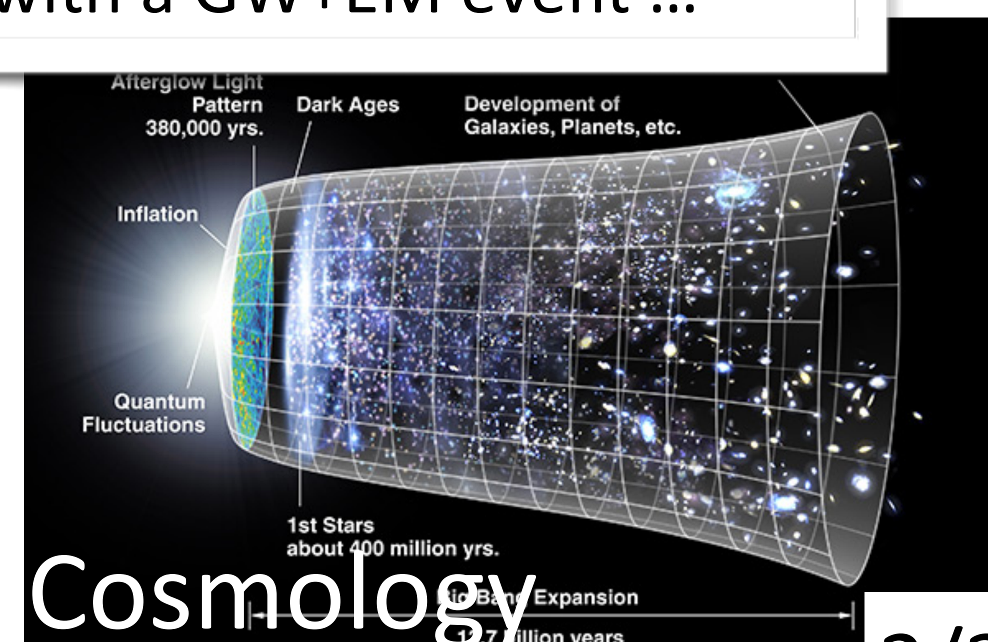




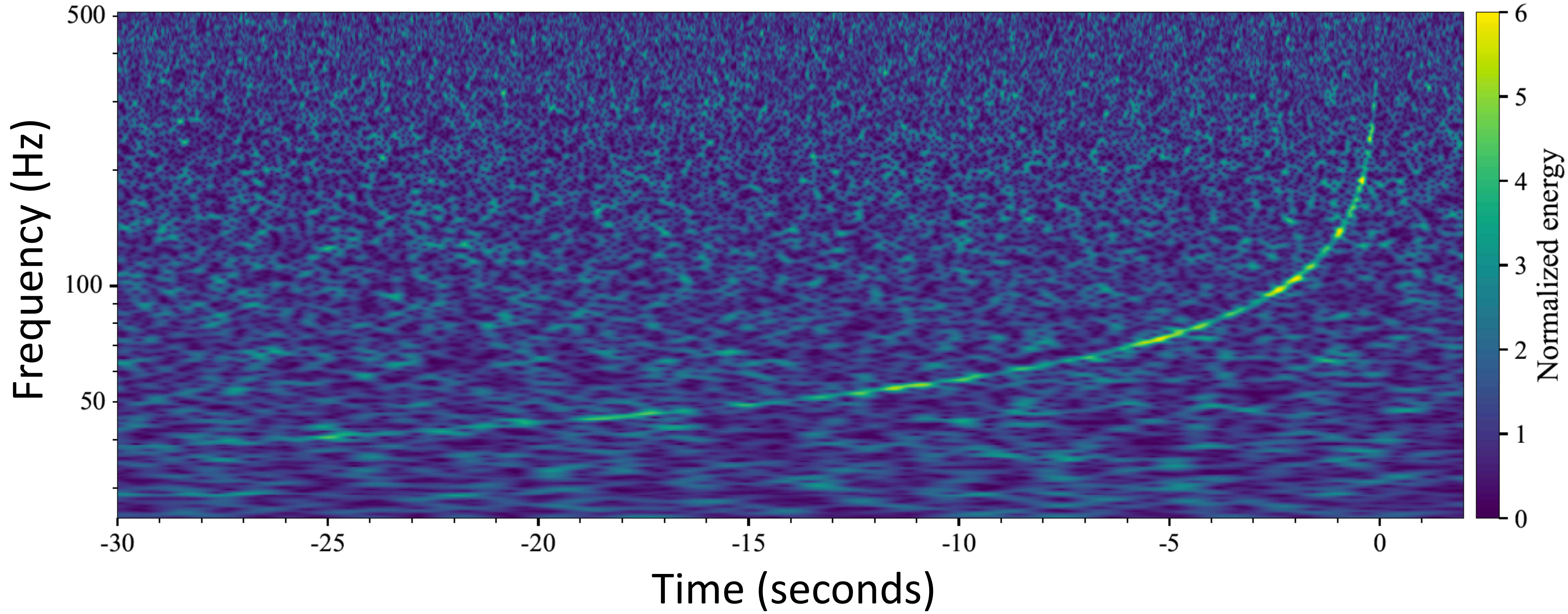
Part I:

The Physics of GW measurements

First Measurement of GWs from a Binary Neutron Star Merger

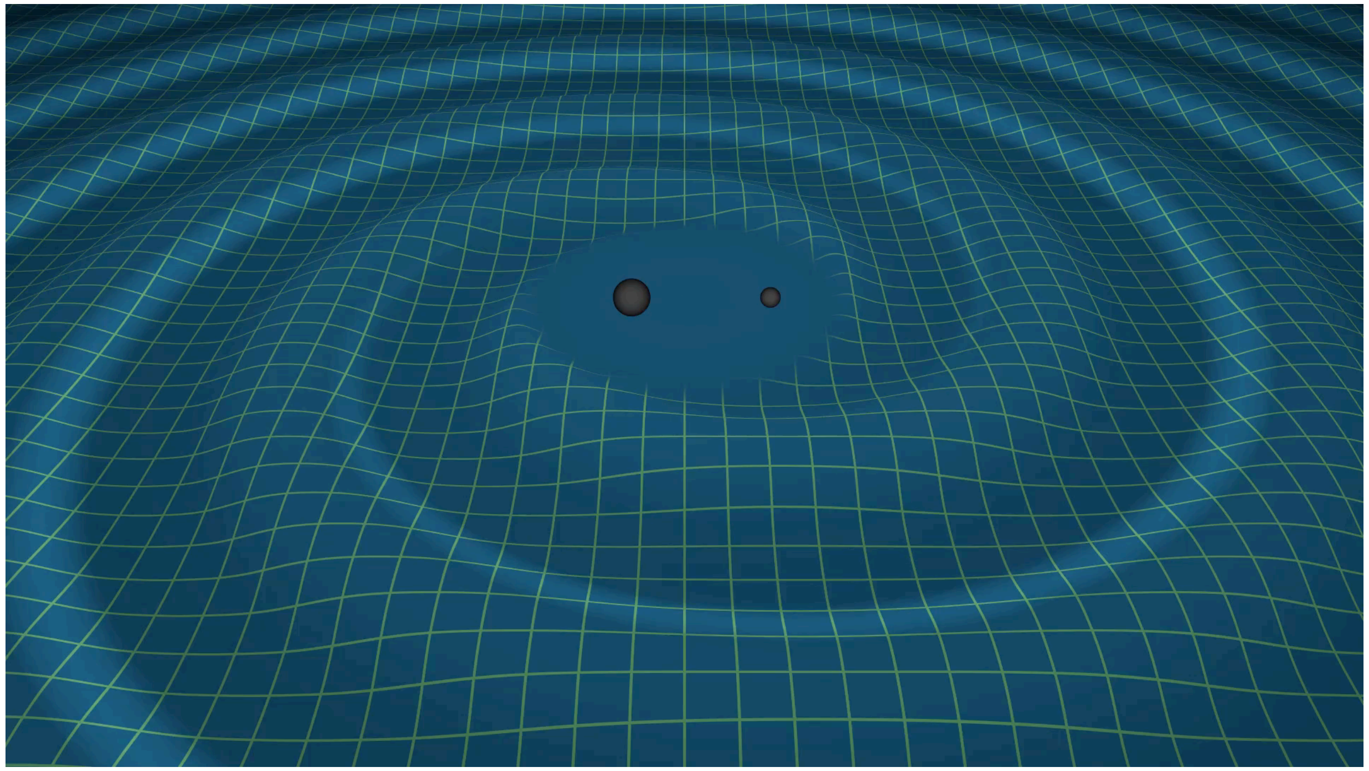
August 17th 2017 at 12:41:04 UTC (14:41, one hour after lunch!)

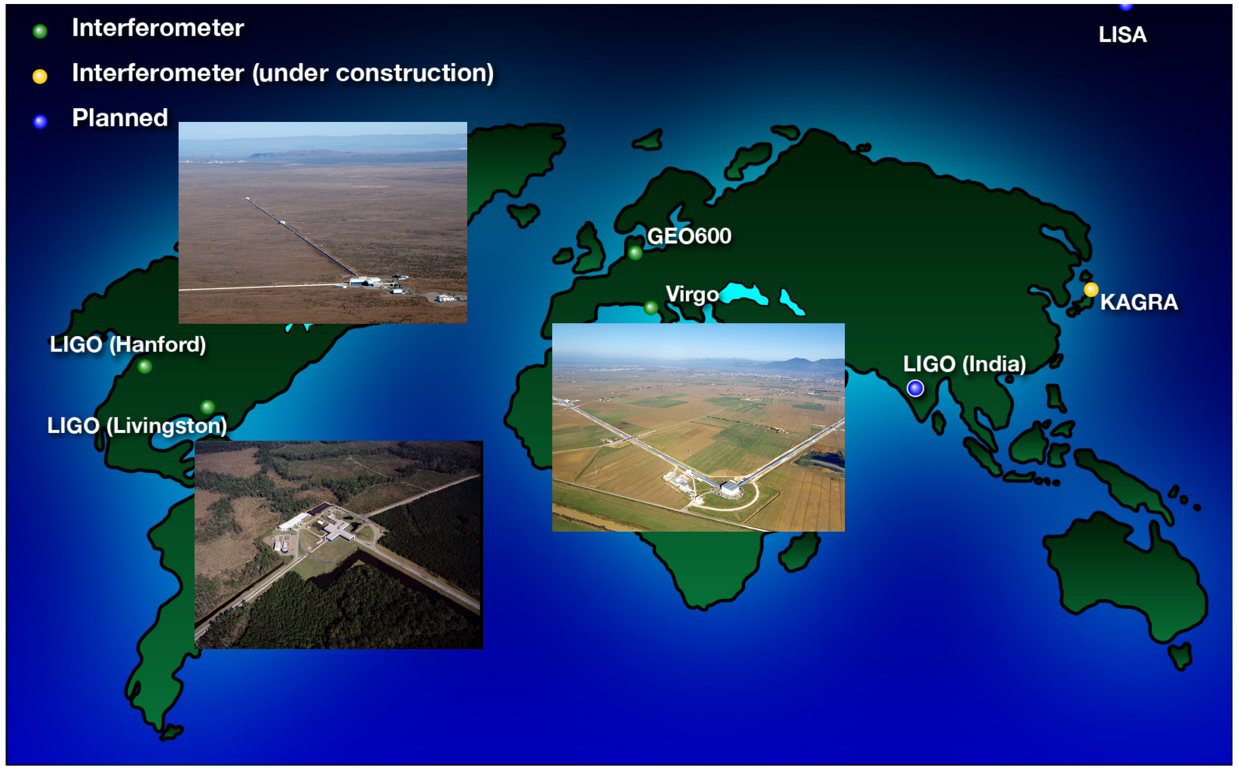
[LVC,PRL, 119, 161101 (2017)]



Loudest (SNR ~ 32.2) and longest (~ 100 s) signal so far:
False alarm rate < 1 in 80 000 years

GWs are perturbations in spacetime curvature measurable by a network of detectors

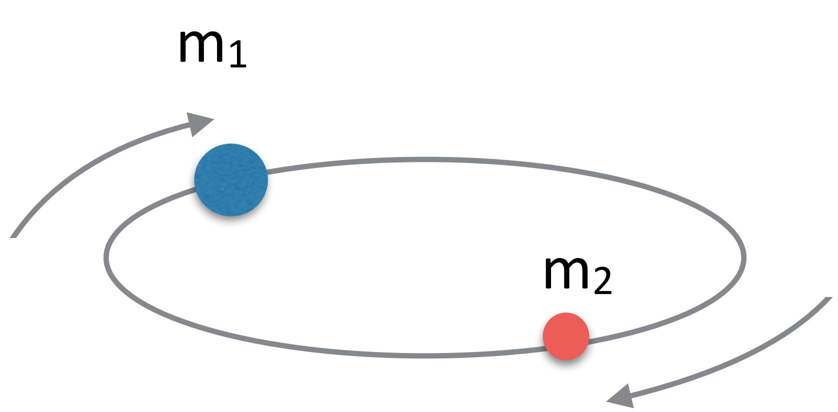




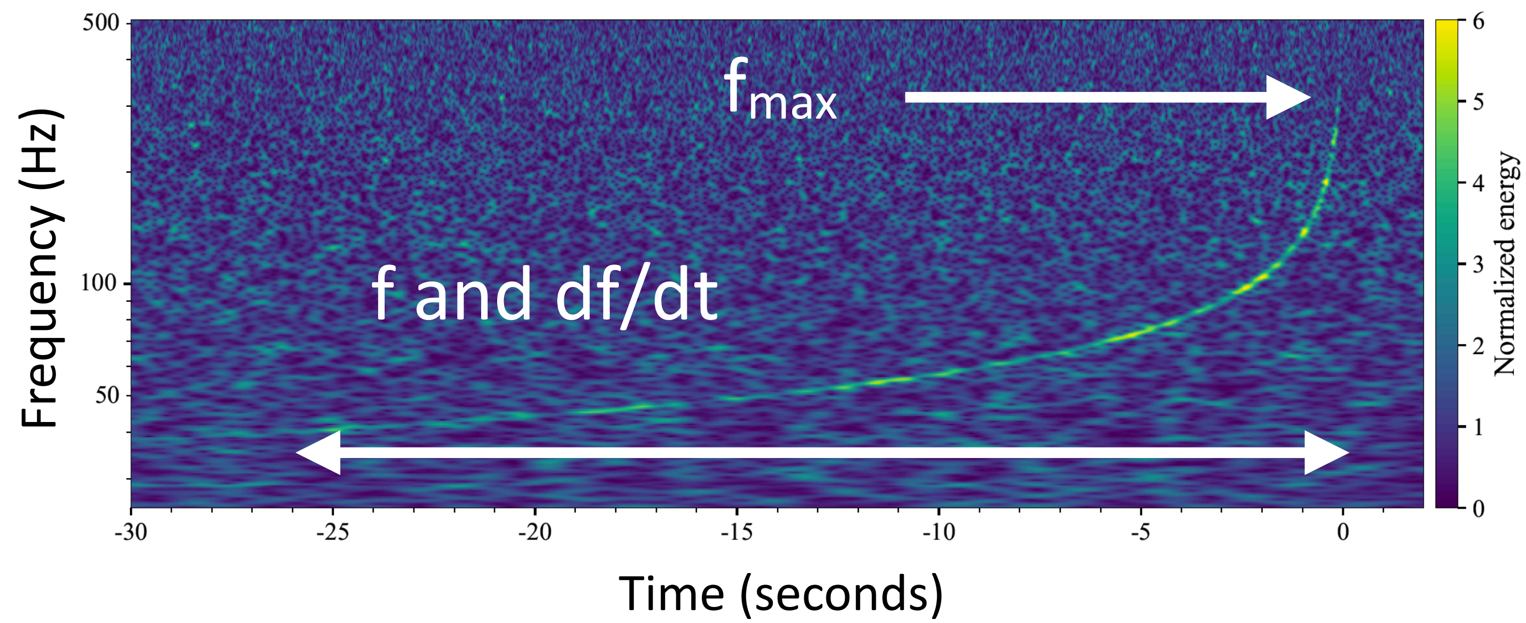
Measurable GW strain h (t) ~ 1/distance
two polarizations h_+ and $h_\times$

24 - 2048 Hz

Simplest "Newtonian" model explains frequency chirp



$$\left(\frac{dE}{dt}\right)_{\mathrm{rad}} + \left(\frac{dE}{dt}\right)_{\mathrm{orb}} = 0$$



[LVC, PRL 119, 161101 (2017)]

⇒ Frequency chirp:

$$\boxed{\frac{df}{dt} = \frac{96\,\pi}{5}\left(\frac{\pi\, G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}}$$

Chirp mass:

$$\boxed{\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}}$$

The GW waveform encodes source parameters

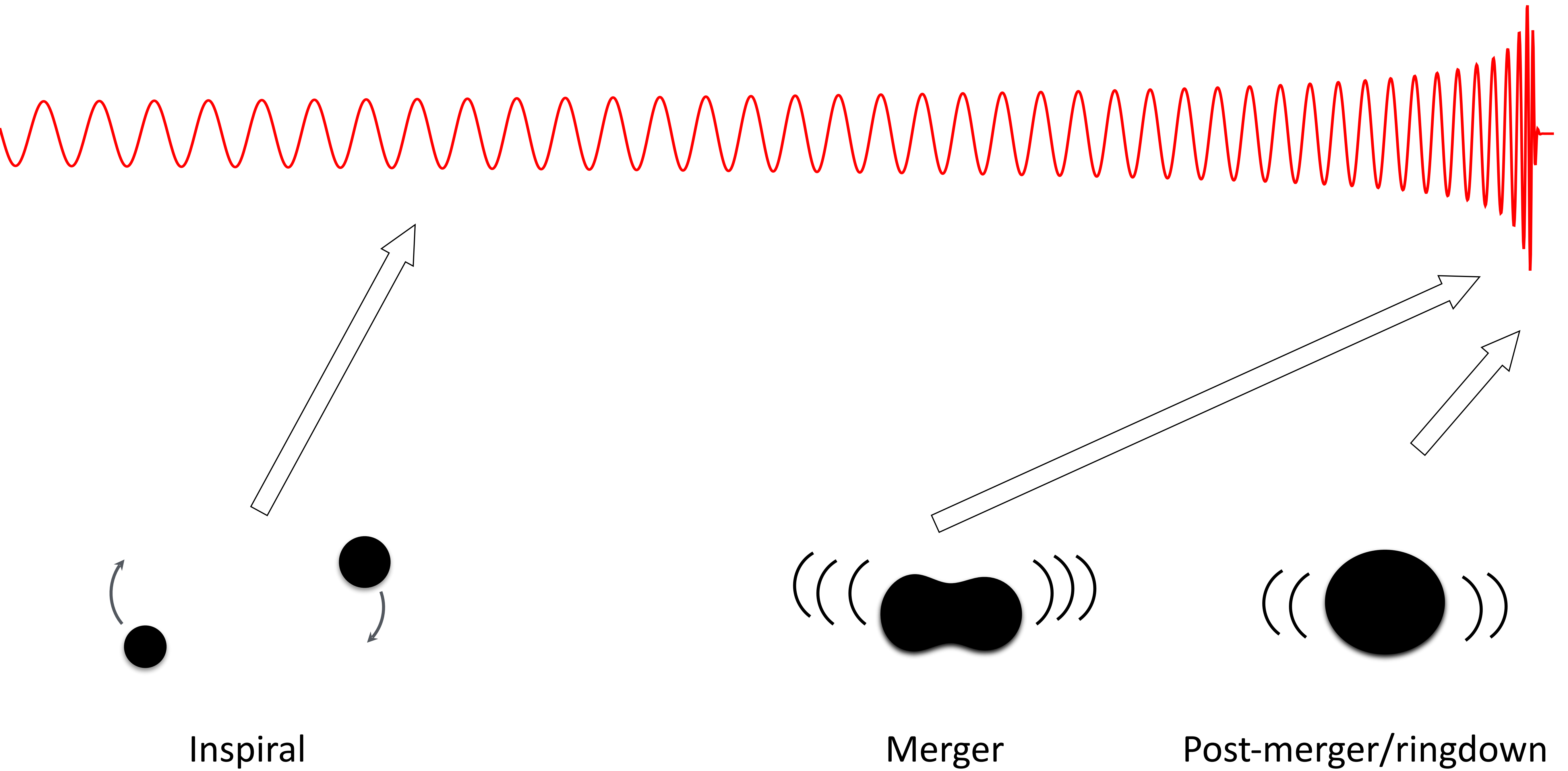
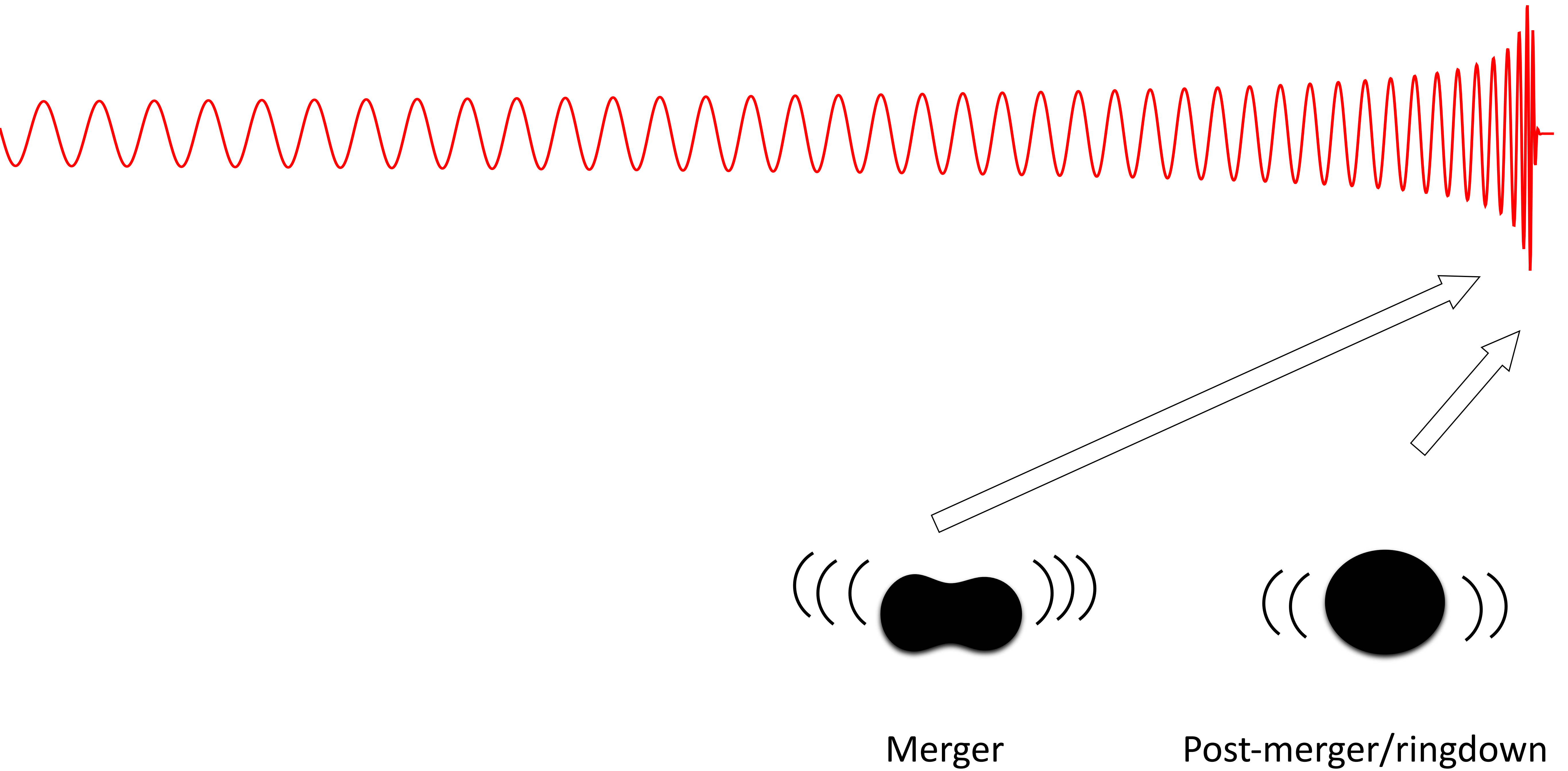


figure courtesy of Tanja Hinderer

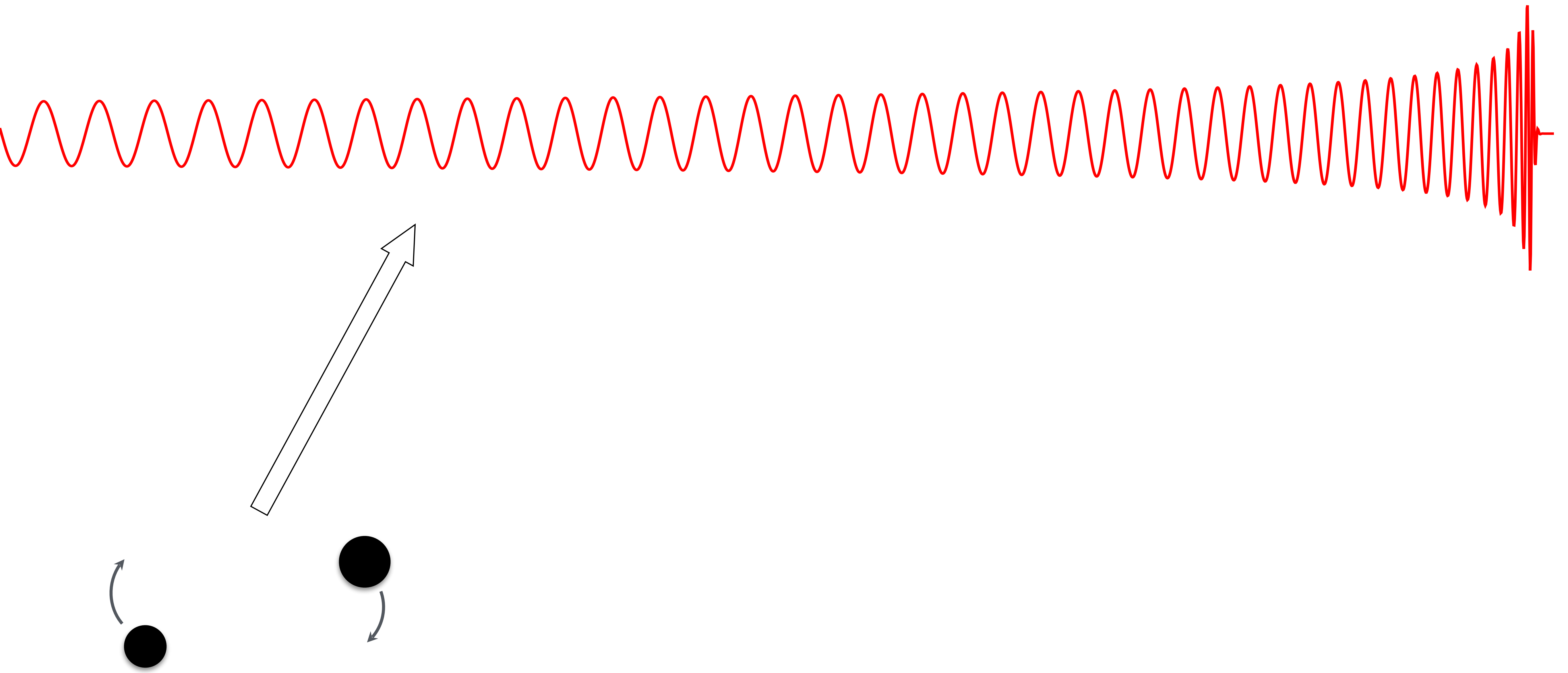
The GW waveform encodes source parameters



~ 10 cycles of merger for ~ 10 $M_\odot$ BHs: seconds

[Numerical Relativity: Pretorius, Sperhake, Campanelli, Baker, Pfeiffer, Scheel …]

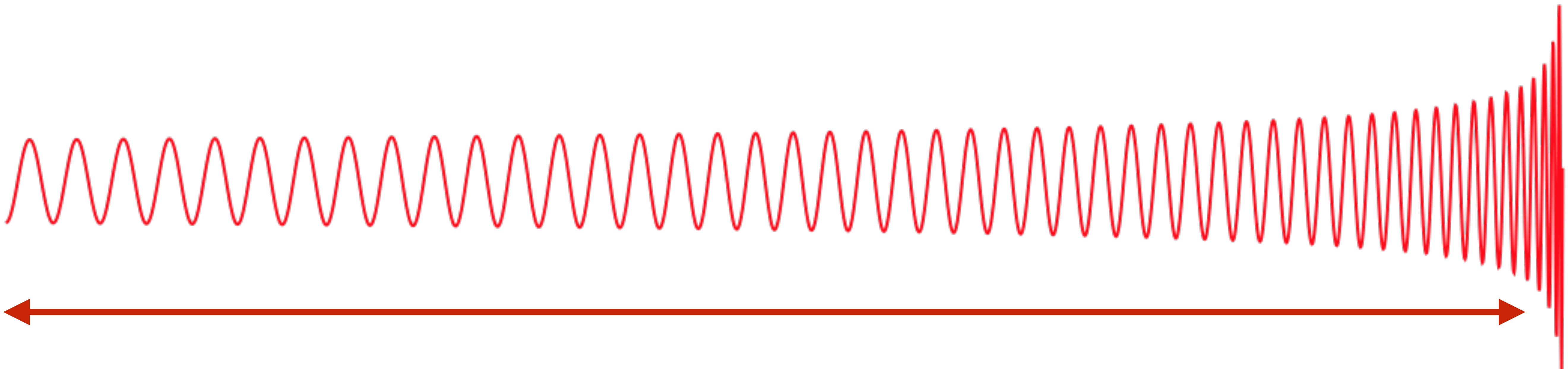
The GW waveform encodes source parameters



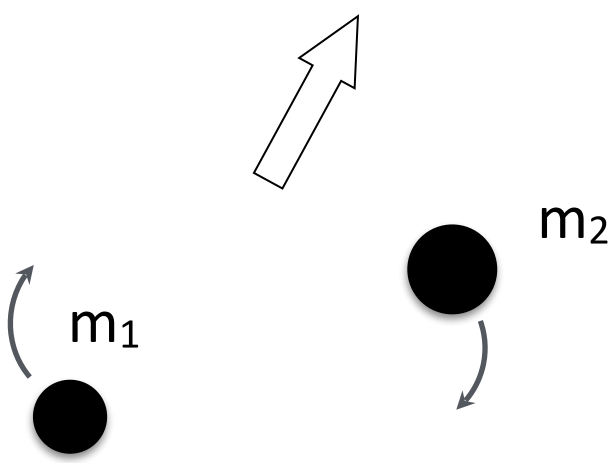
Inspiral

~10^3 cycles of the inspiral for few $M_\odot$ with LIGO/Virgo: minutes

The GW waveform encodes source parameters



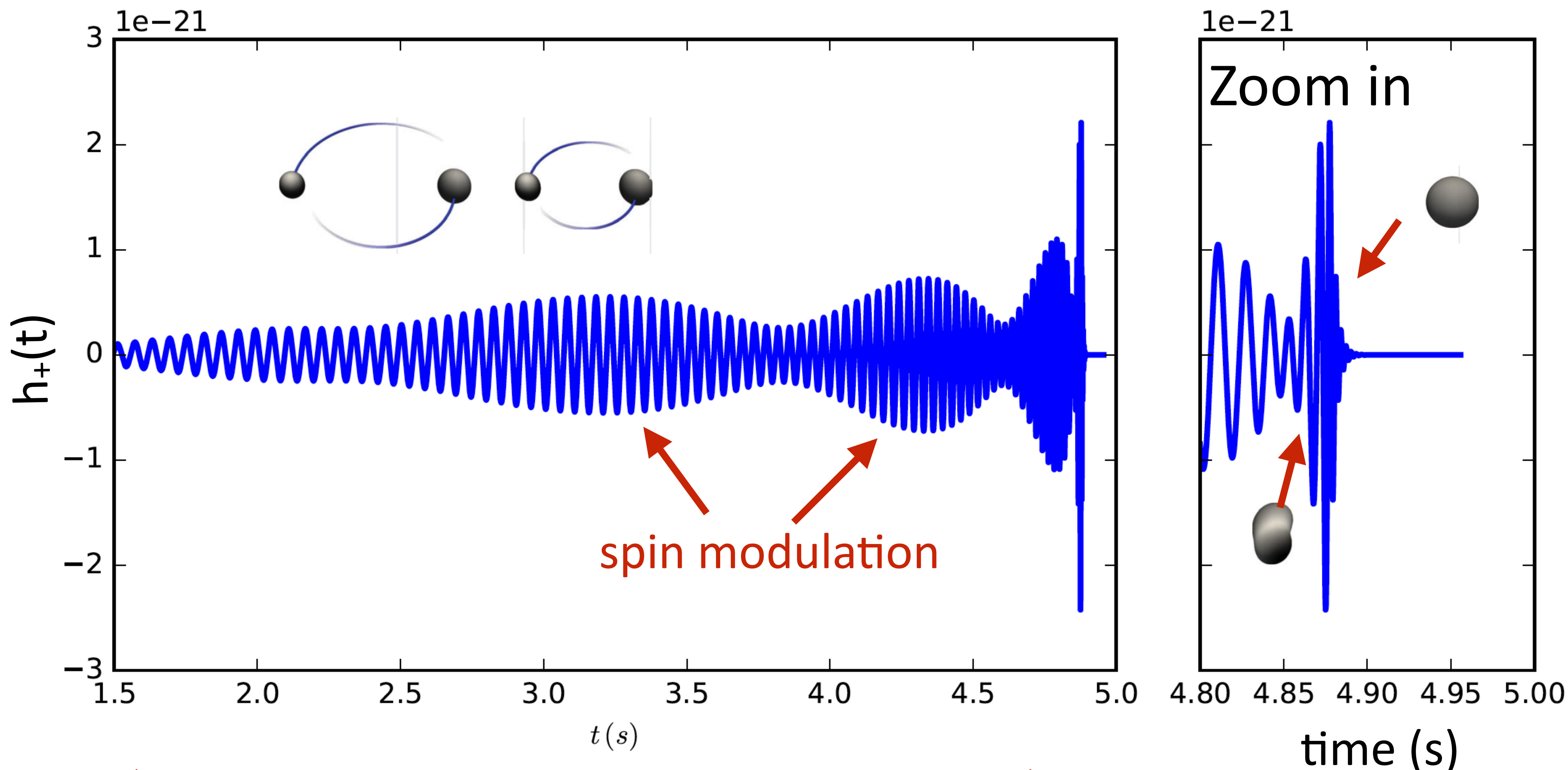
post-Newtonian (PN) Inspiral — driven by the chirp mass



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

The GW waveform encodes source parameters

see talk by Agathos

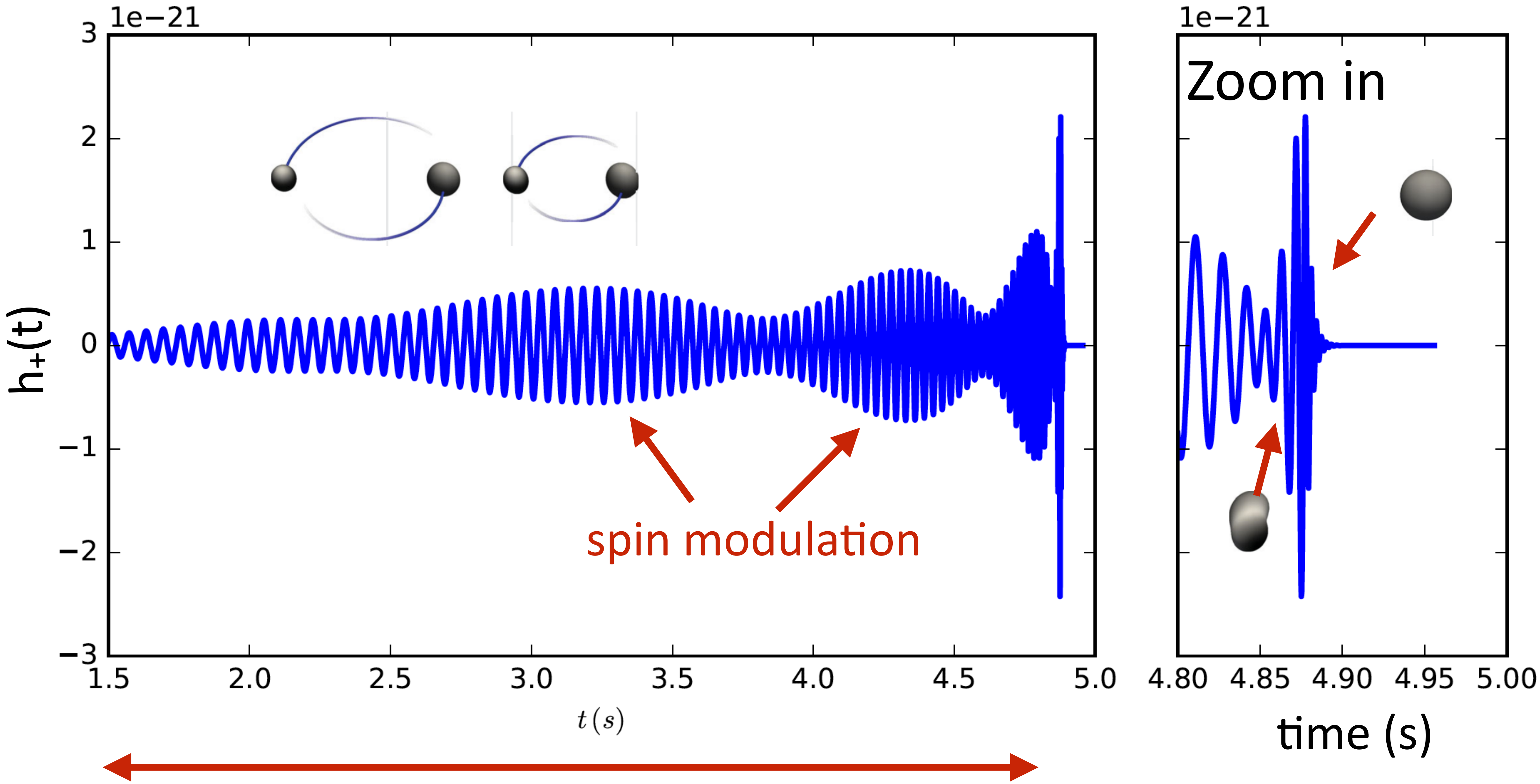


$\Phi_{\mathrm{GW}}(t)$ ⇒ chirp mass, reduced mass (1PN), spin-orbit (1.5PN), …

tidal deformability (5PN)

Task 1: GW waveforms require more physics

see talk by Agathos



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

tidal deformability (5PN)

Extract source information from GWs

frequency

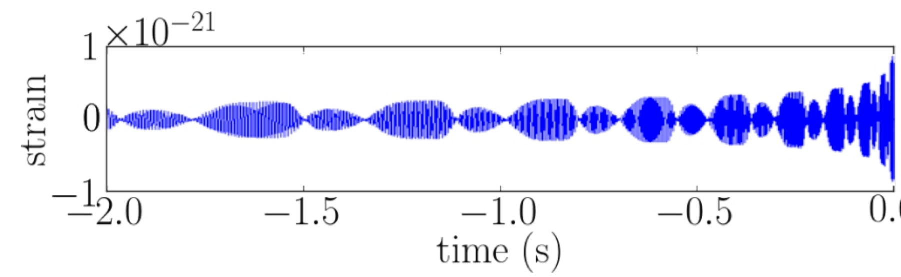
$$h_+(t) = \frac{A[\mathcal{M}\, f(t)]}{D}(1+\cos^2\iota)\cos\Phi_{\rm GW}(t)$$

distance — inclination angle — GW Phase

h(t): 9-16 parameters

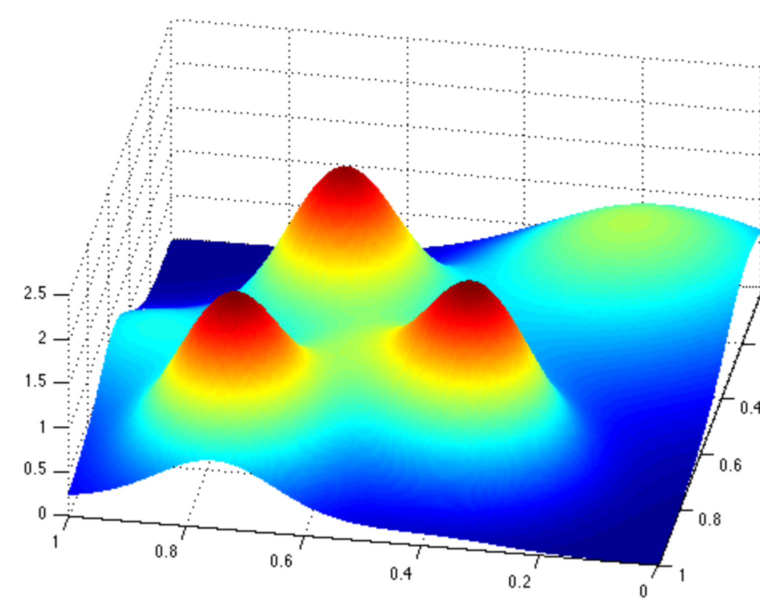
+ Redshifted Masses
+ Spins
+ Tidal deformability
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Model h(t)



Detector output

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



Likelihood

parameter 1

parameter 2

using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

[see LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]
[see Nissanke et al. 2010, 11, 13a, 13b]

Task 2: we require faster analysis

frequency

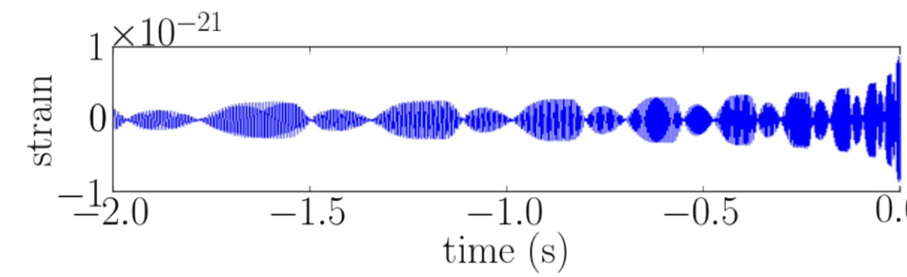
$$h_+(t) = \frac{A[\mathcal{M}\, f(t)]}{D}(1+\cos^2\iota)\cos\Phi_{\rm GW}(t)$$

distance　　inclination angle　　GW Phase

h(t): 9-16 parameters

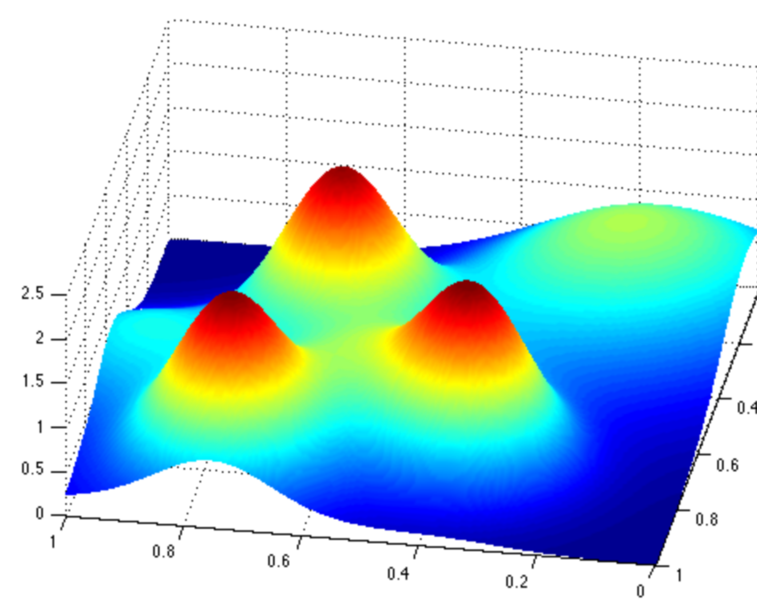
+ Redshifted Masses
+ Spins
+ Tidal deformability
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Model h(t)



Detector output

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



Likelihood

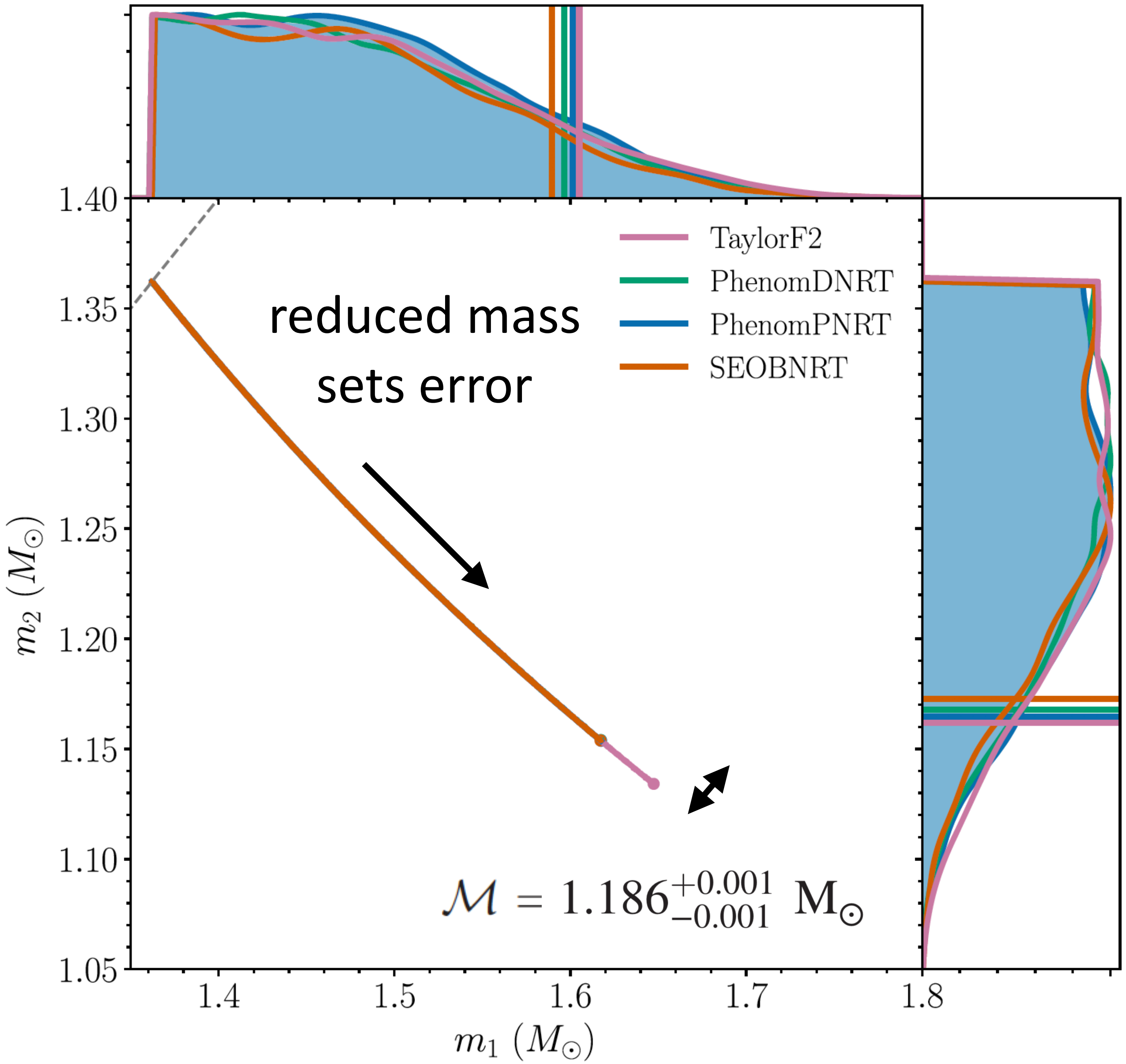
parameter 1

parameter 2

using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

[see LVC, arXiv: 1602.03840, PRL 116, 241102, 2016]
[see Nissanke et al. 2010, 11, 13a, 13b]

Retrieving GW170817 progenitor masses and spins

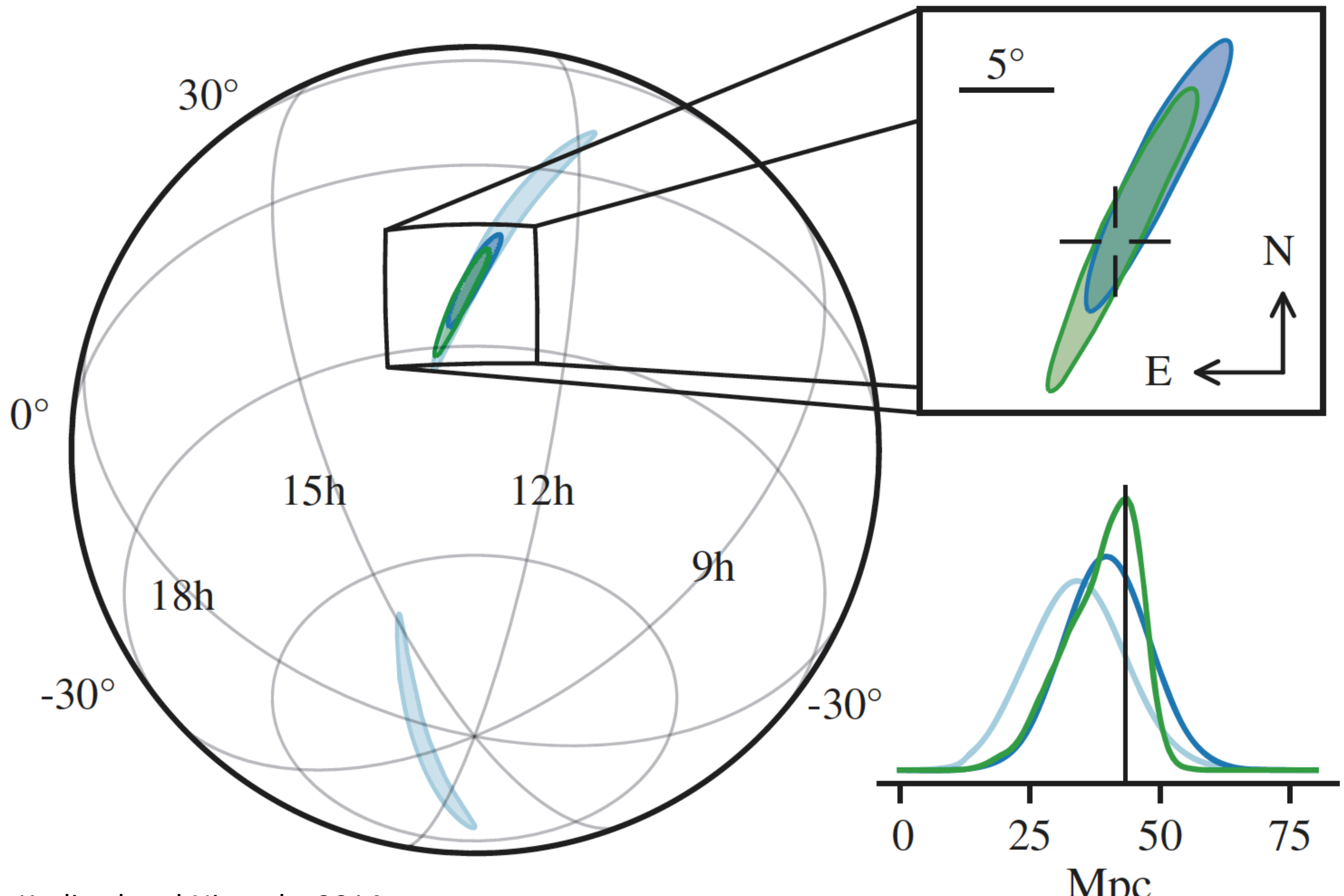


Low spin prior

[LVC, PHYS. REV. X 9, 011001, 2019, and arXiv:1805.11581; see also LVC, PRL, 119, 161101, 2017]

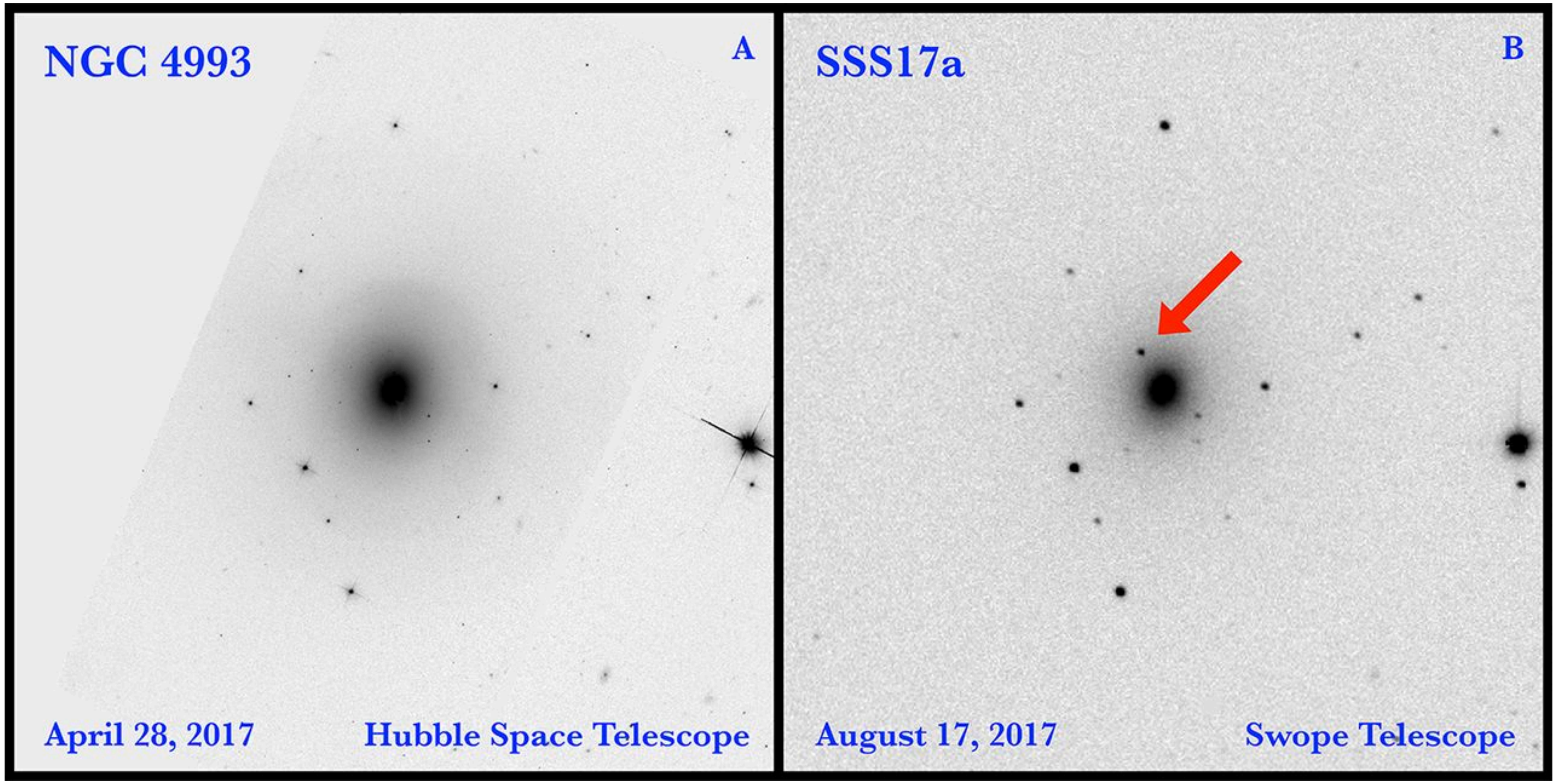
Pinpointing GW170817's location with "GW volumes" and galaxy catalogs

[LVC, PRL, 119, 161101 (2017),
LIGO, Virgo, EM partners +, ApJLetters 848 L12 (2017)]



[Nissanke et al. 2011, 13, Kasliwal and Nissanke 2014,
Gehrels…SN + 2015, Singer….SN + 2016,
Hotokezaka, Nissanke + 2016,]

First optical transient at 11 hours was the real deal: the NS-NS merger

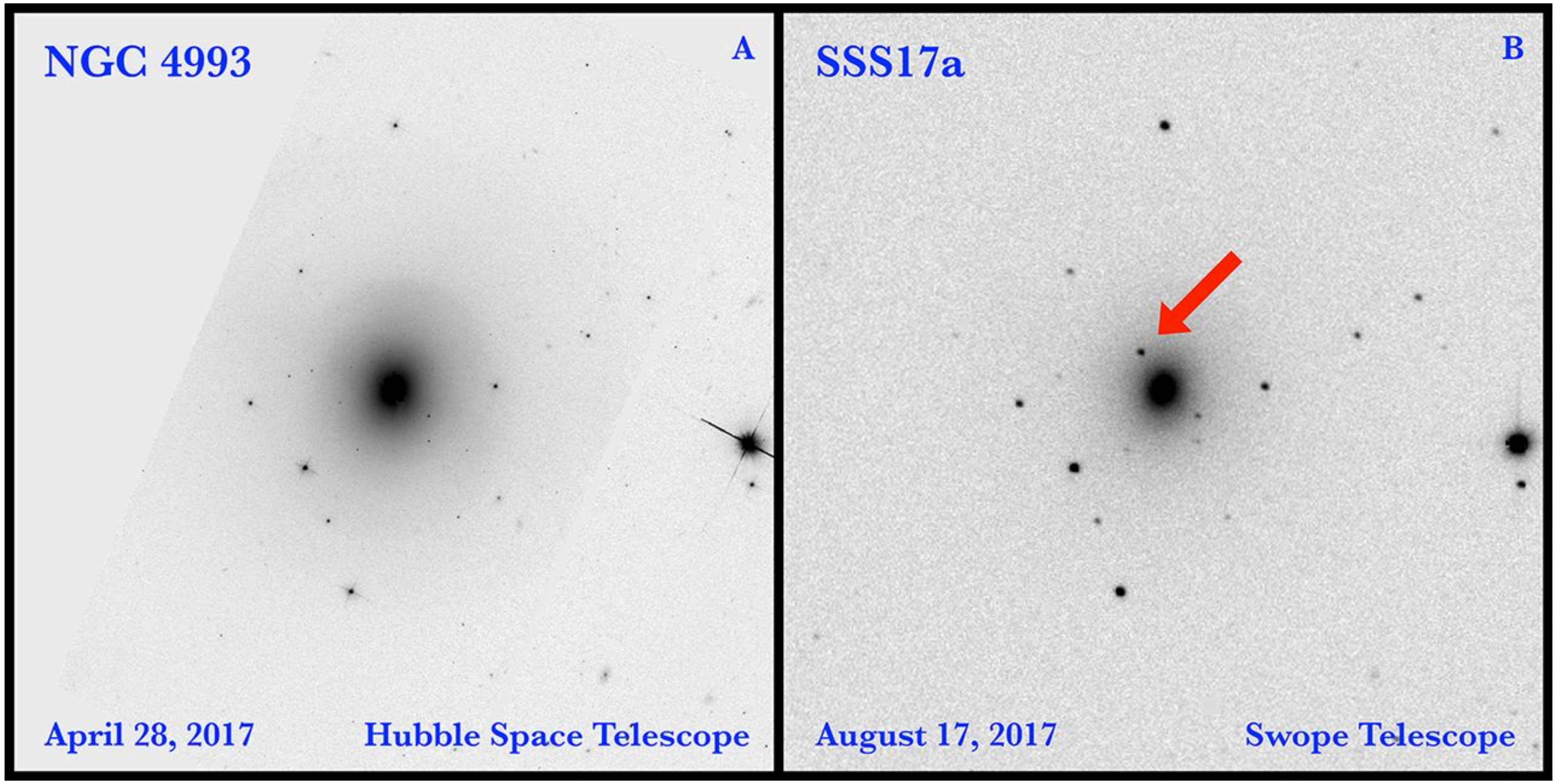


[Coulter et al. 2017, Science]

NGC 4993: 40 Mpc (elliptical galaxy)

Not the case for weaker signal events:
needle in the haystack of other astrophysical transients

Task 3: characterizing other astrophysical transients & variables



[Coulter et al. 2017, Science]

NGC 4993: 40 Mpc (elliptical galaxy)

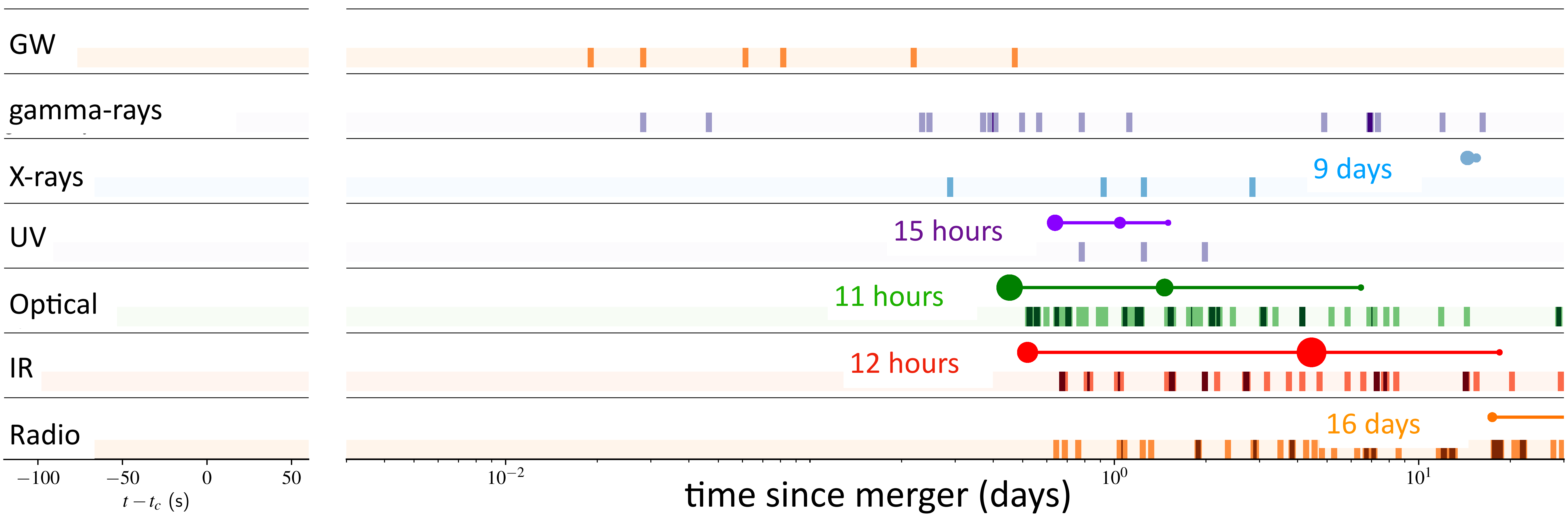
Not the case for weaker signal events:
needle in the haystack of other astrophysical transients

Part II:

The Multi-messenger discovery of GW170817

The first month(s) of multi-messenger observations of GW170817

adapted from LIGO, Virgo, EM partners + ApJ 848 L12 (2017)



Global ground and space-based effort:

70+ teams, 100+ instruments, over 3500 co-authors

Panchromatic View of GW170817

[still going on ... ! see Haleja+ 2018]

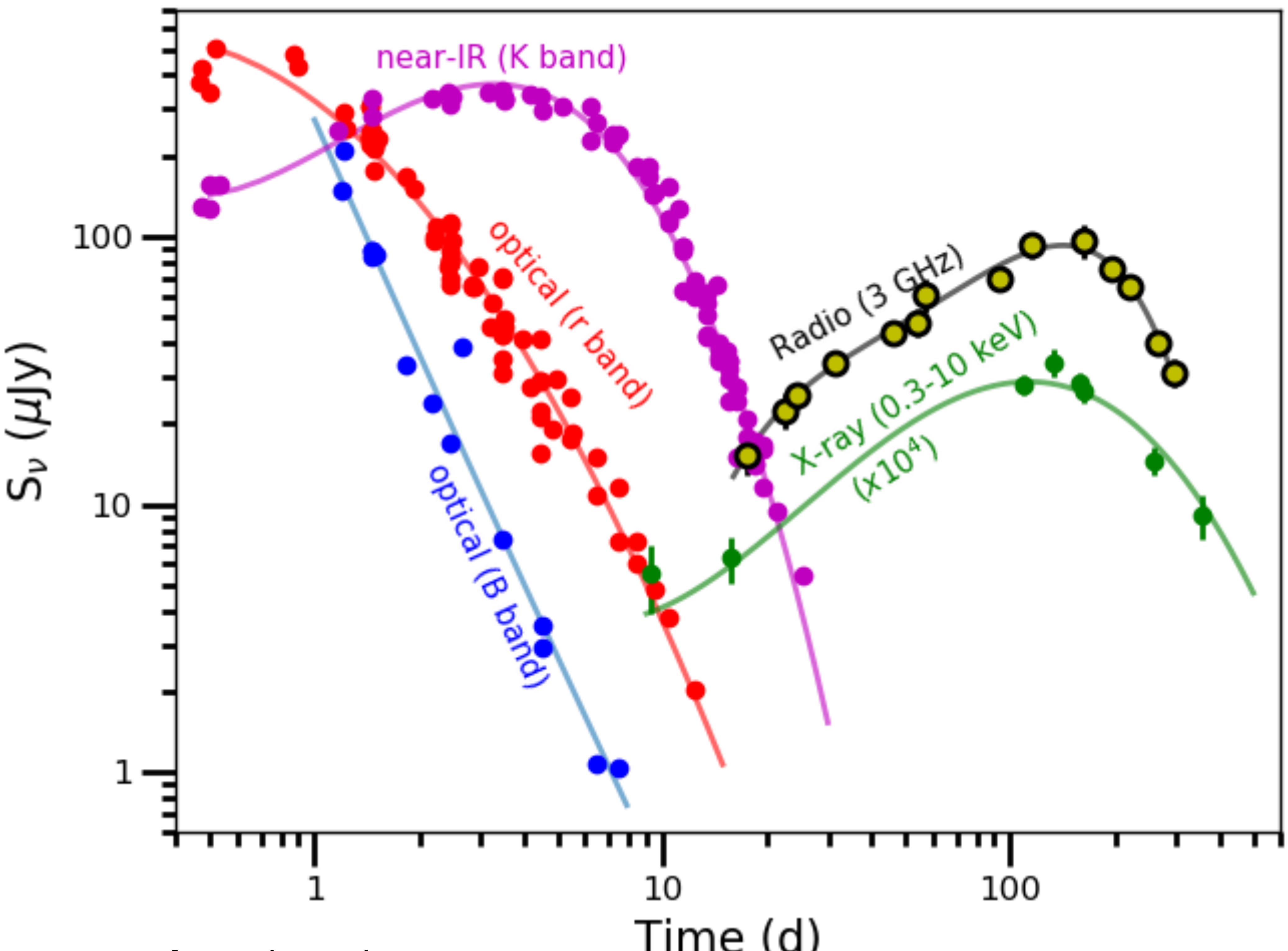
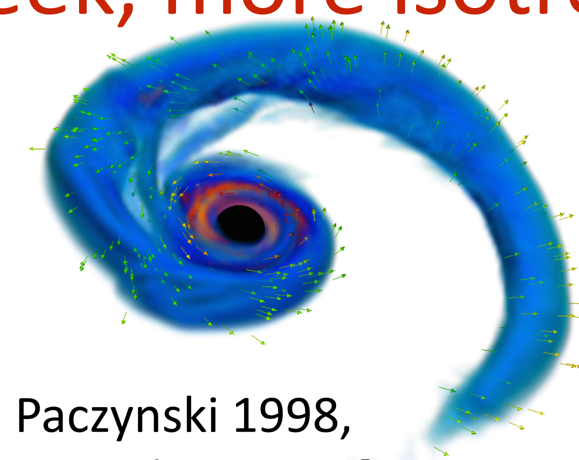


figure courtesy of Kunal Mooley

A Tale of Two Matter Outflows ⇒ EM counterparts

1. Tidal Tails + Disk Winds + Core-bounce Heating ⇒ Kilonova: Ultraviolet Optical IR (days-week, more isotropic)

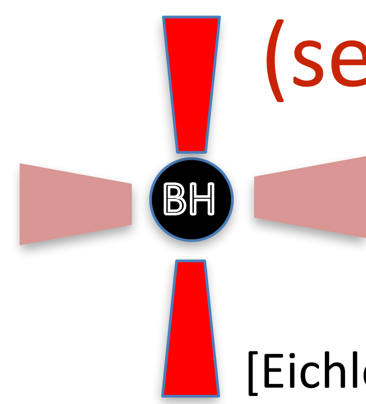


[Foucart et el. 2014]

M_{ej} ≈0.01-0.05 M⊙
E ≈10^{50} ergs
v ≈ 0.1-0.3c

[Lattimer and Schramm 1974, Li and Paczynski 1998, Rosswog 1999, Kulkarni 2005, Metzger et al. 2010, …]

2. Ultra-relativistic Jet ⇒ Short Gamma Ray Burst + afterglow (seconds - months, collimated)



M_{ej} ≈ 10^{-6} M⊙
E ≈ 10^{49} -10^{50} ergs
v ≈ 0.99c - 0.99995c

[Eichler+ 1989, Paczynski 1989,…]

Outflows' kinetic energy is converted into internal energy.
Expands, cools and heated by shocks or radioactivity.

(cf. Supernova: 10^{51} ergs; L_{sun}: 4 x 10^{26} W or 4 x 10^{33} erg/s)

Extract source & environment from EM

$F_\lambda(t)$: 15 parameters

- 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

Task 4: modelling of outflows' microphysics

see talk by Campanelli

$F_\lambda(t)$: 15 parameters

+ Energetics and beaming
+ R-process nucleosynthesis
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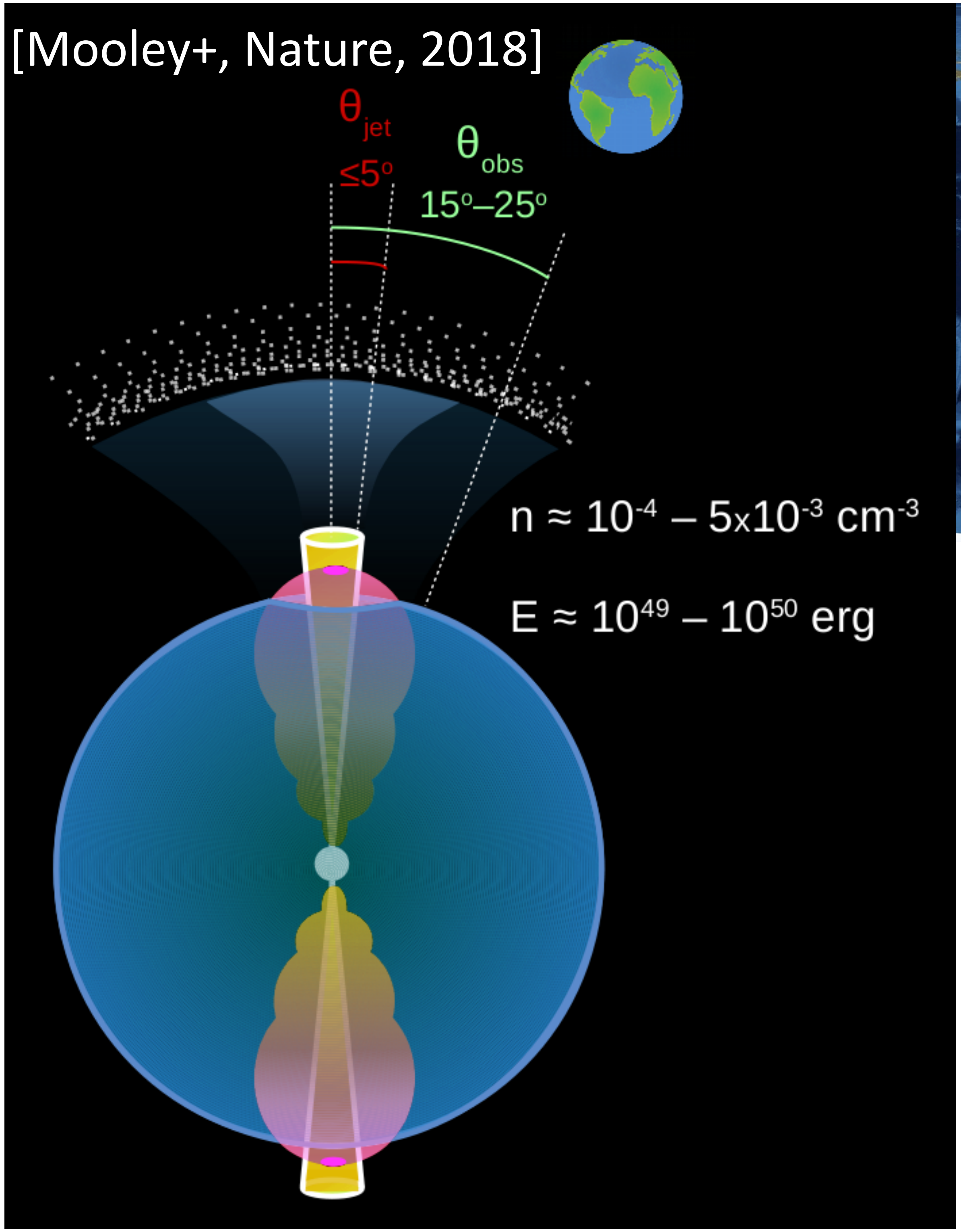
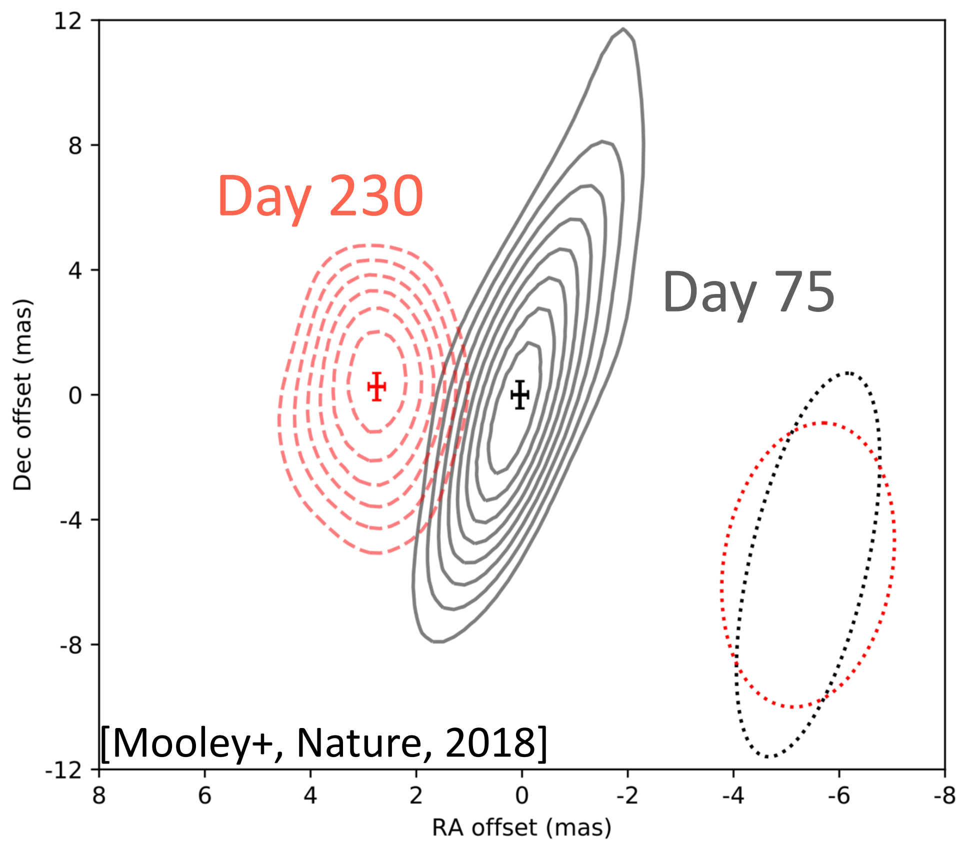
EM SGRB VLBI ⇒ superluminal jet with structure



[see also Lazzati 2017,18, Ghirlanda + 2019, Troja+ 2018]



Proper motion of 2.7 mas, β_{app} ~4.7

Part III:

What have we learnt from GW170817 with GW+EM?

i. Hubble parameter constraint

ii. Equation of State

New field: break degeneracies to measure properties of BHs and NSs

h(t): 9-16 parameters

+ Redshifted Masses (several to tens %)
+ Spins (tens of %)
+ NS radii (tens of %)
+ Geometric properties: (tens of %)
  - Inclination angle
  - Source Position
  - Luminosity distance

$F_X(t)$: 15 parameters

+ 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: Characterisation

Population: Demographics, ecology and census

Task 5: break degeneracies to measure properties of BHs and NSs

h(t): 9-16 parameters

+ Redshifted Masses (several to tens %)
+ Spins (tens of %)
+ NS radii (tens of %)
+ Geometric properties: (tens of %)
  - Inclination angle
  - Source Position
  - Luminosity distance

$F_\chi(t)$: 15 parameters

+ 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

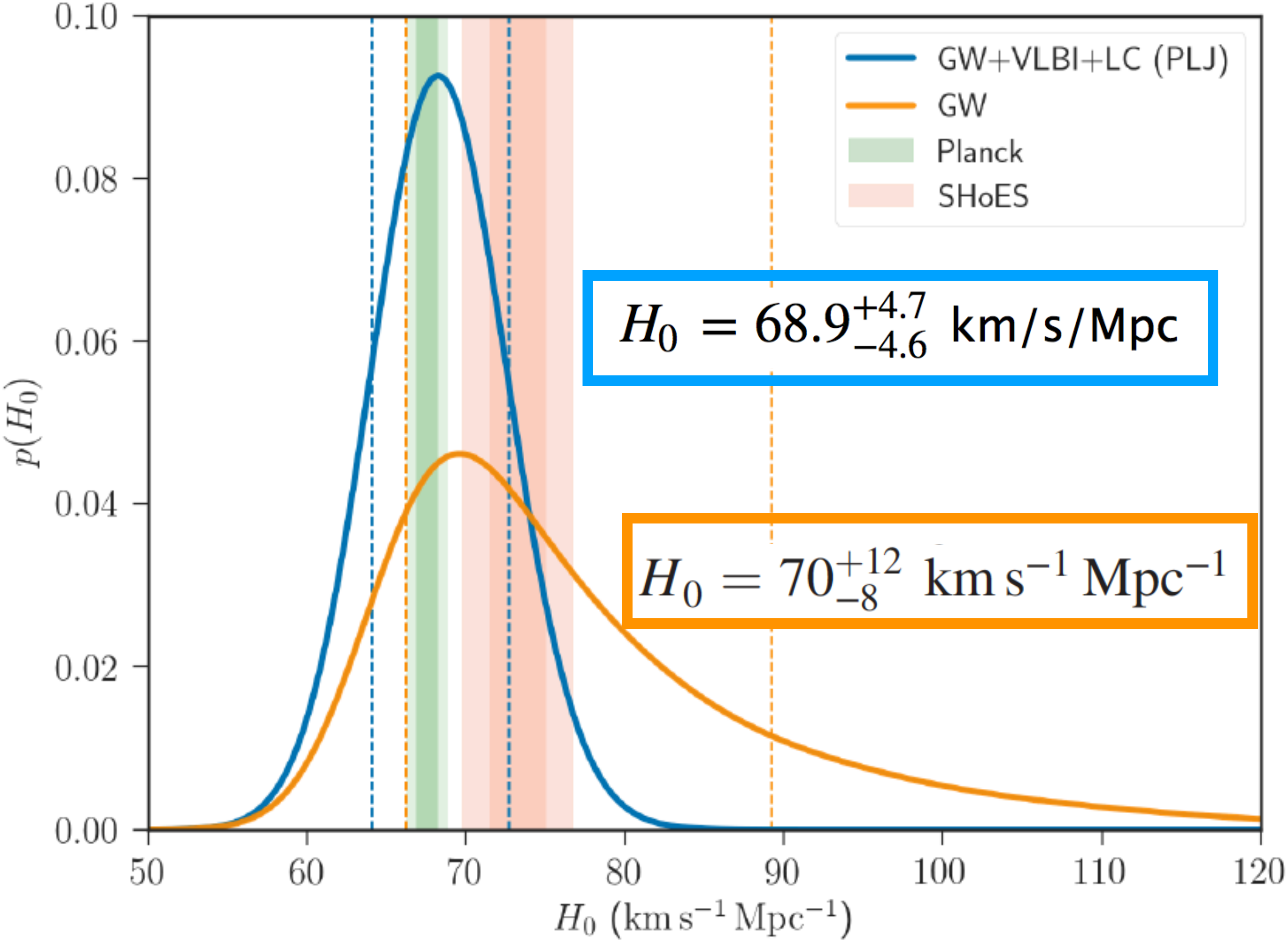
Strong signal binary: Characterisation

Population: Demographics, ecology and census

1) GW+radio: Hubble measurement improves by a factor of 2

[see talks by Holz and Palmese]

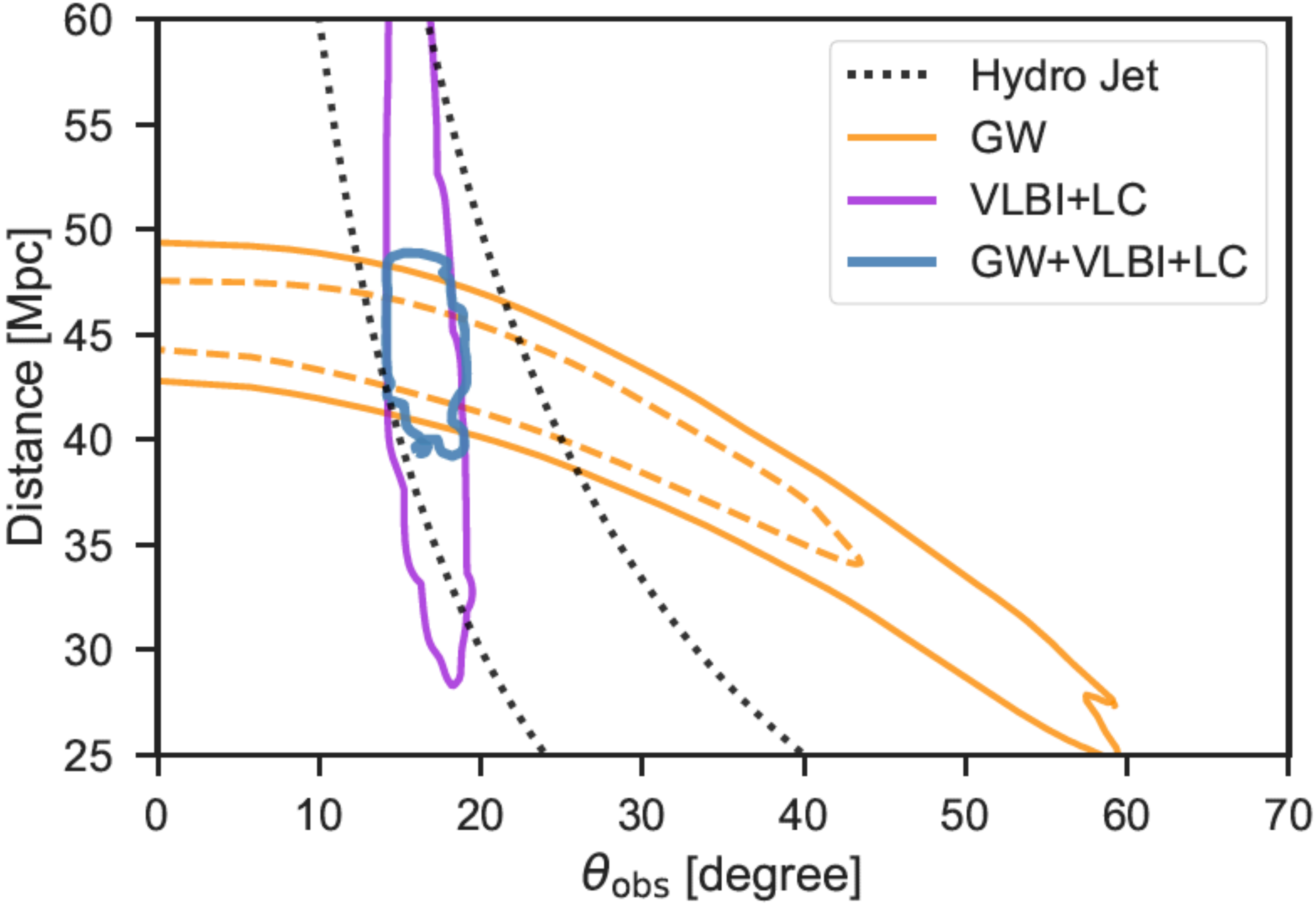
[Hotokezaka, ..SN, + 2019; see Schutz 1986, Dalal + 2006, SN + 2010]



Peculiar velocity error of 150 km/s; Hubble flow velocity of 3017 +/- 166 km s^{-1}

GW+ radio: Hubble measurement improves by a factor of 2

[Hotokezaka, ..SN, + 2019, Nature Astro.]

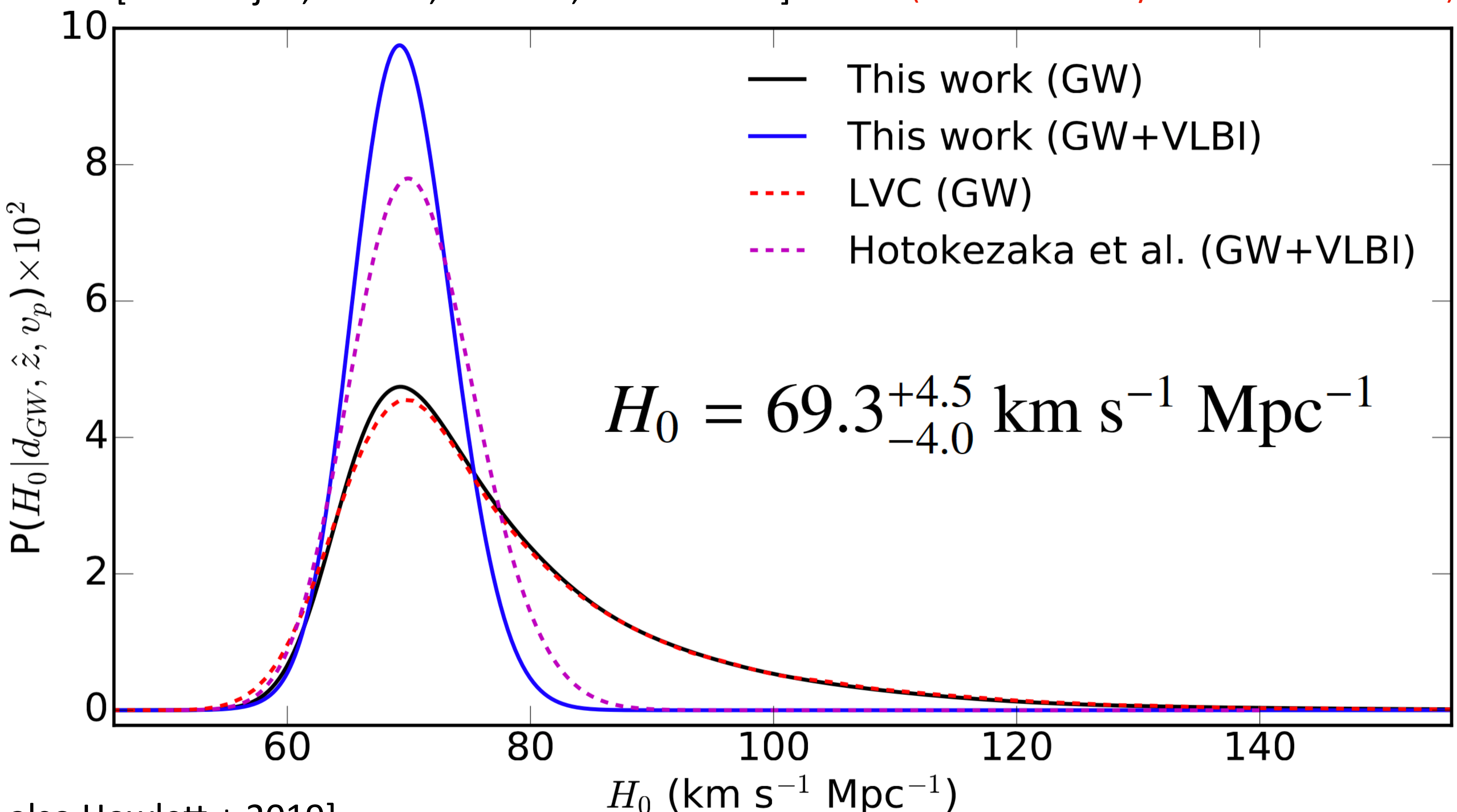


[cos inc- DL; see SN+ 2010; see Guirdozi + 2017, Finstead + 2018, Mandel 2018]

1) GW + EM: peculiar velocity corrections

see talk on BORG by Lavaux

[Mukherjee, Lavaux,..SN+ 19; 1909.08627] PaVES (Peculiar Velocity Estimation for Sirens)

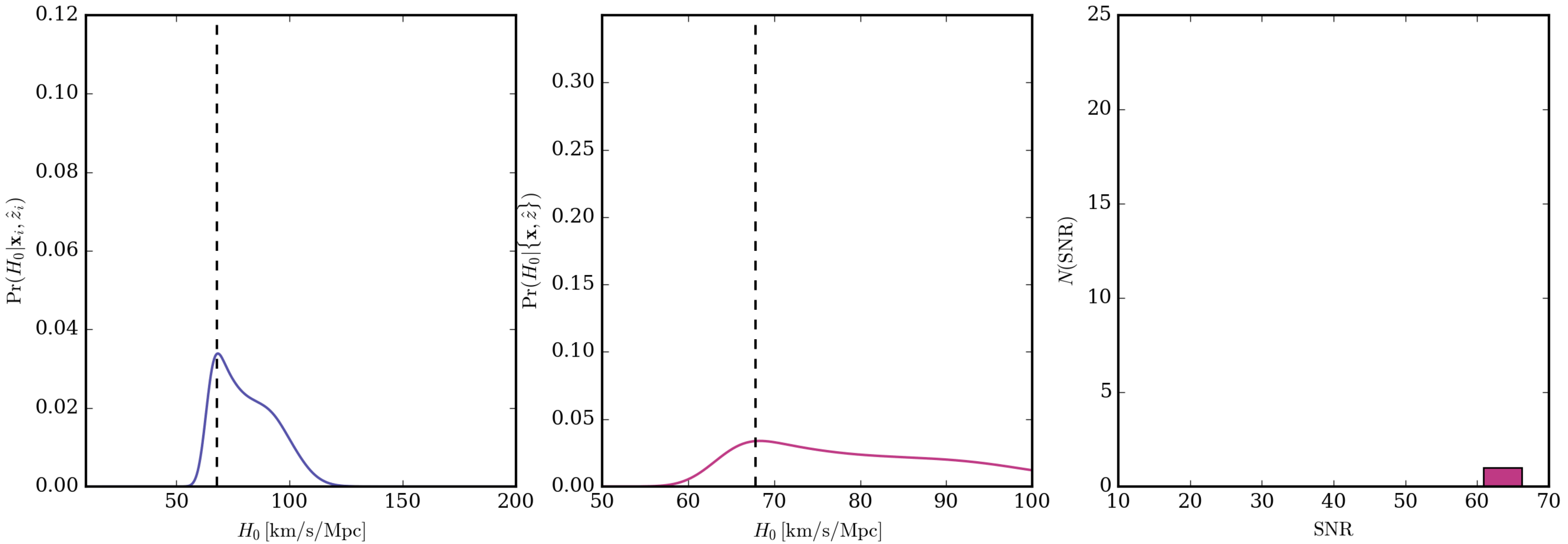


[see also Howlett + 2019]

our method: 16% higher mean value and about 13% less standard deviation

1) GW+EM: importance of populations to potentially resolve “Hubble trouble”

[Feeney, Peiris, Williamson, SN,..+,PRL, 2019; Mortlock, … SN, 2018]

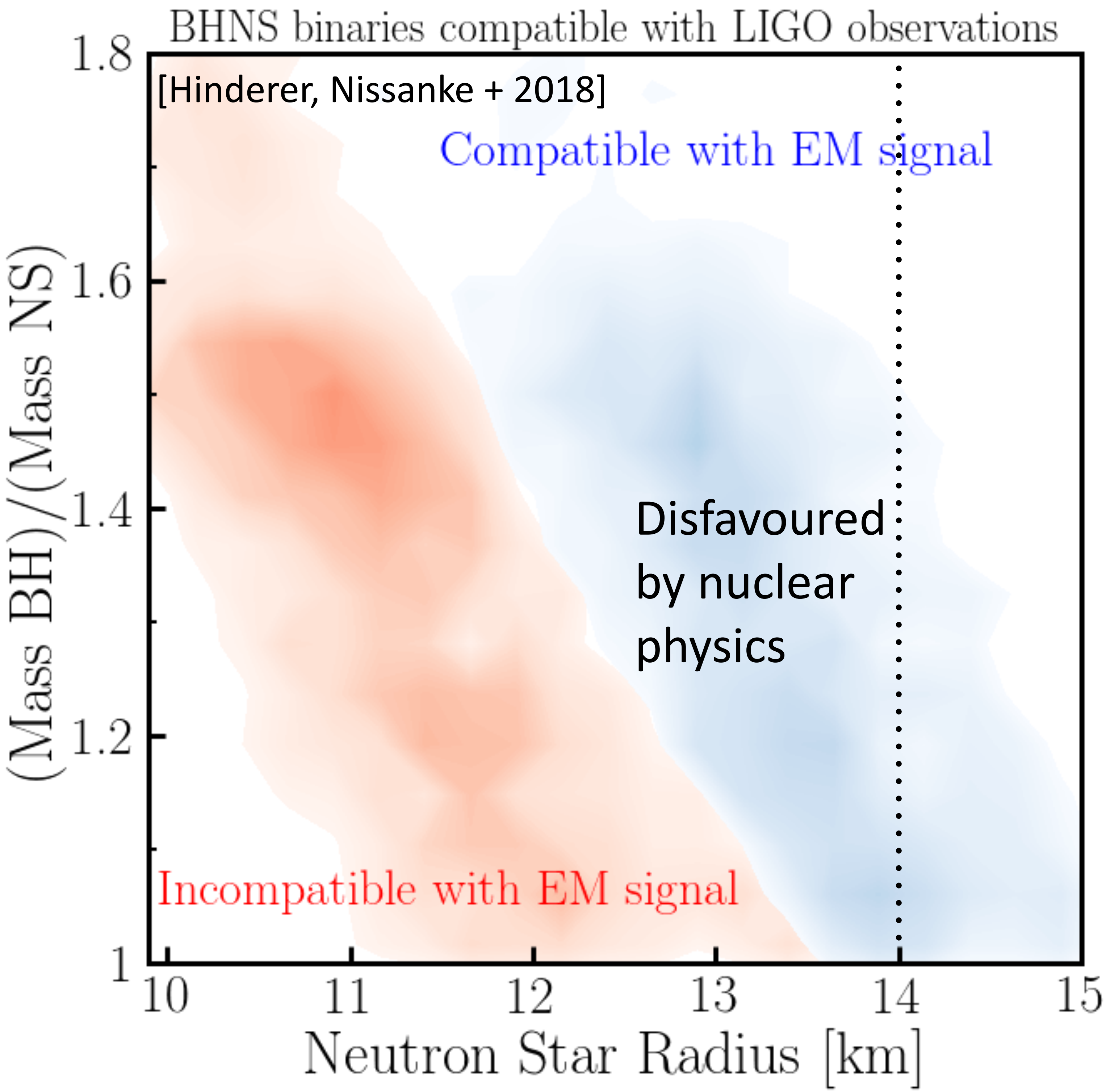


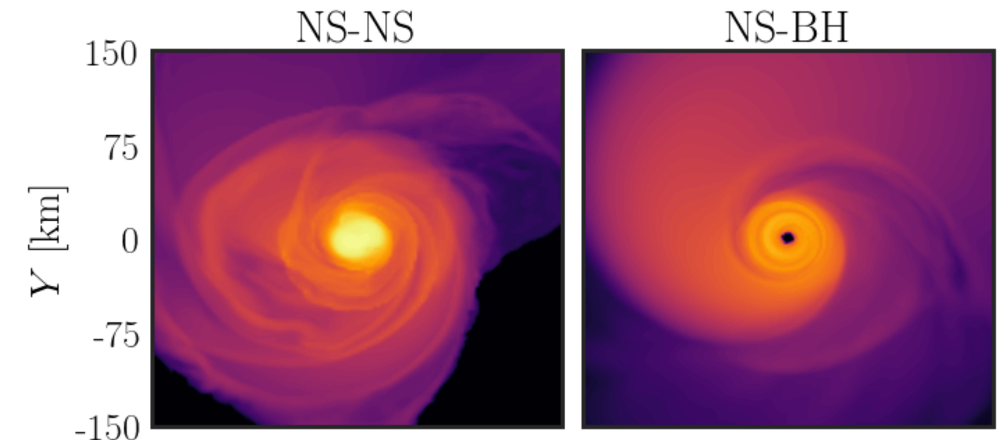
[see also Chen+ 2018, …]

50 binaries (~8-10 years) to reach a precision of 1.8 % (1/√N); high SNR binaries dominate joint PDF; assumes EM

2) GW+EM probes NS Equation of State

see talk by Agathos





Semi-analytical formula for remnant mass for wide range of mass ratio, NS EoS, BH spin

$$M_{\mathrm{rem}}\left(\frac{m_{\mathrm{BH}}}{m_{\mathrm{NS}}}, \frac{G m_{\mathrm{NS}}}{R_{\mathrm{NS}} c^2}, \chi_{\mathrm{BH}}\right)$$

[Foucart, Hinderer, Nissanke 2018;
Foucart, .. SN+ 2019;
Raaijmakers + in prep;
used in LIGO-Virgo alerts]

[Stiffer EoS cf. 11.8 +/-1.4 km assuming NS-NS only (GW+EM); LVC]

Part IV:
Perspectives

GW170817: follow-up was easy — very close by and bright,

small GW volume

BBH merger rate: 9.7-101 $Gpc^{3}\ yr^{-1}$
NS-NS merger rate: 110-3840 $Gpc^{3}\ yr^{-1}$
NS-BH merger rate: < 610 $Gpc^{3}\ yr^{-1}$

[LVC, arXiv: 1811.15007
arXiv: 1901.03310, 2019]

1. GW+EM: Expect a diversity of EM counterparts

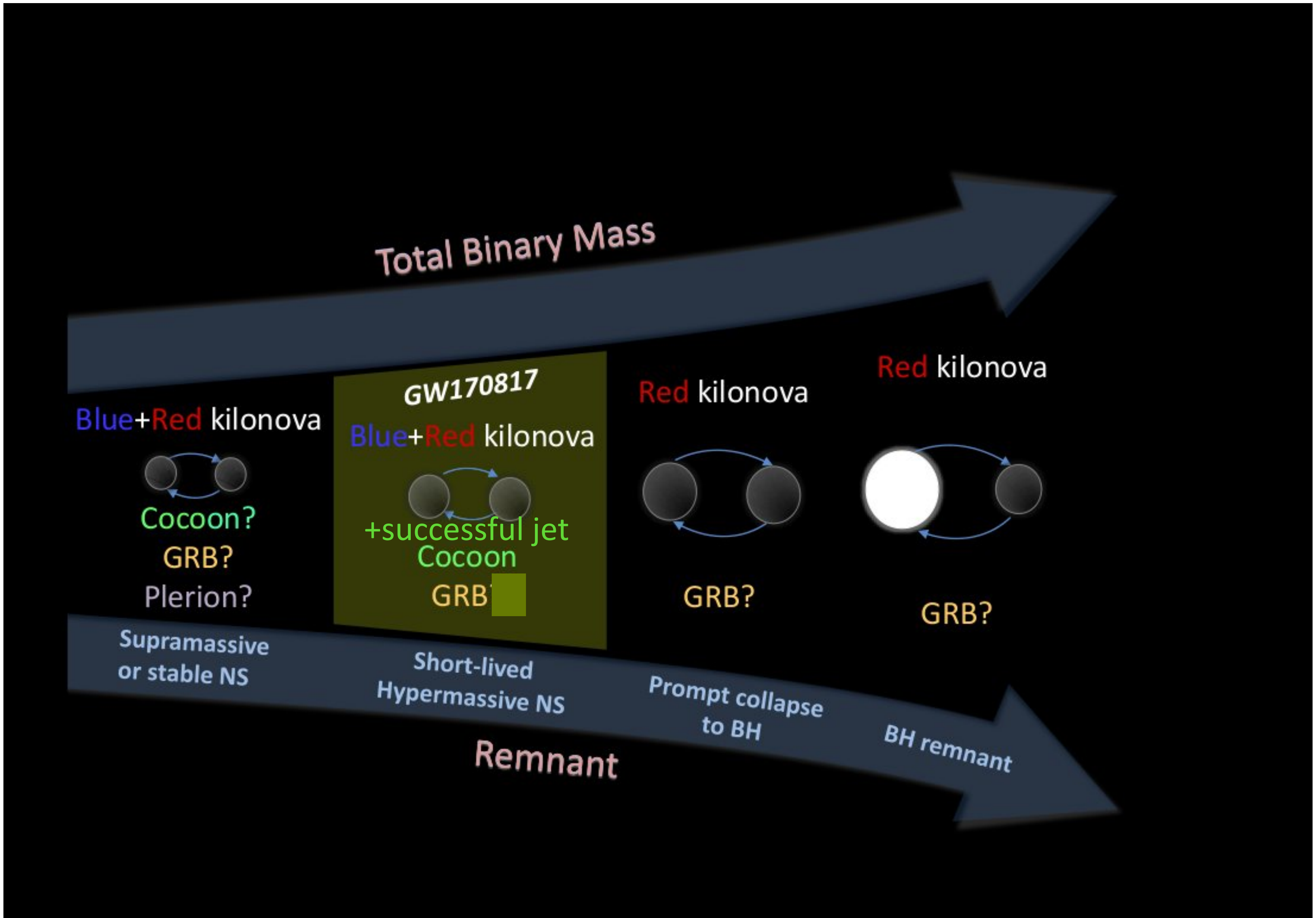
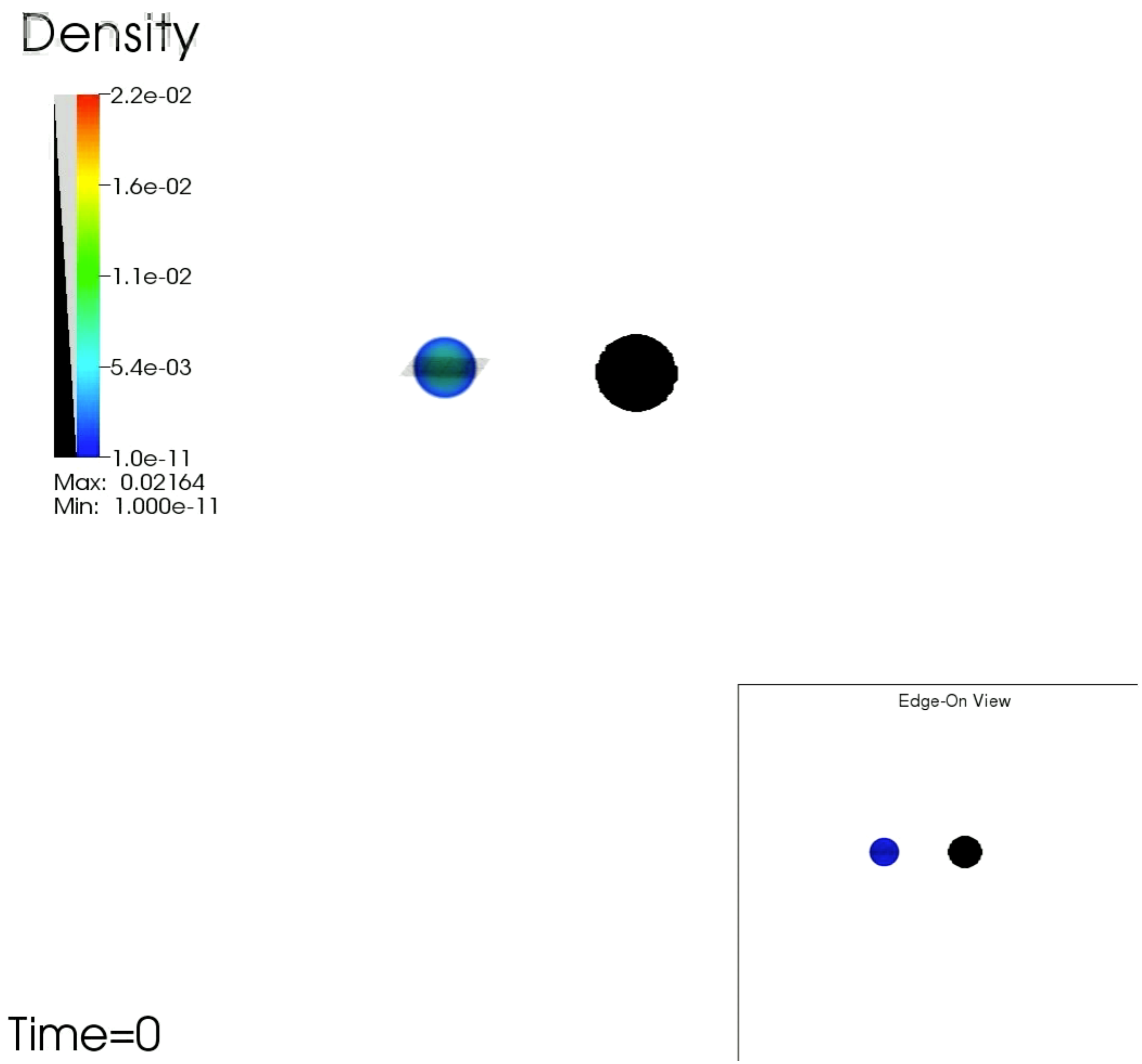


figure courtesy of Dale Frail

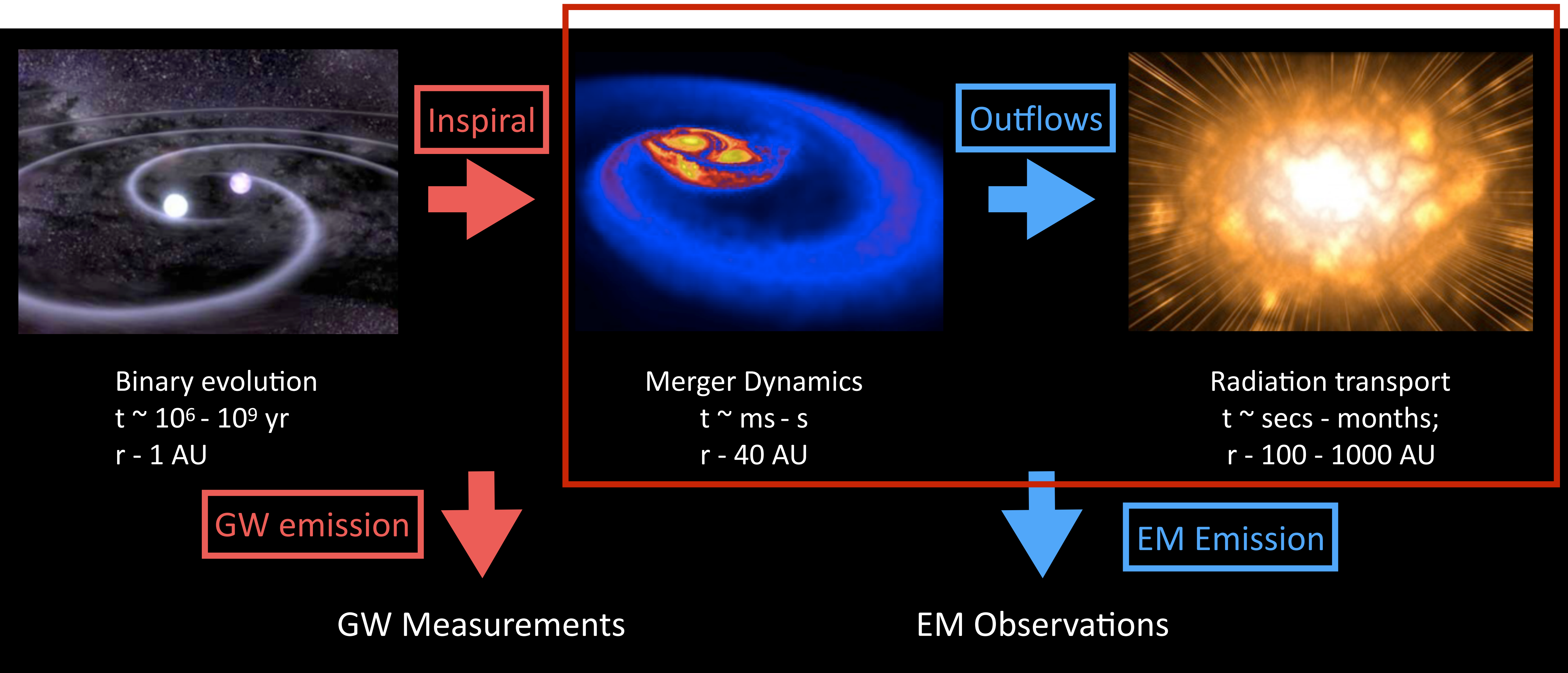
2) GW+EM: New discovery space — NS-BH mergers!

Movie courtesy of Francois Foucart



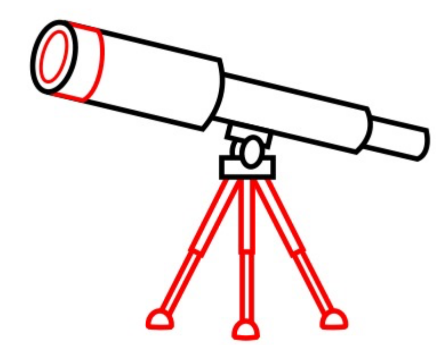
3. GW+EM challenge remains to build a coherent model: a key step to joint characterization

see talk by Campanelli



Outflows carry energy from small (10^6 cm) to large distances (10^{14}-10^{16} cm) for radiation to escape.

4. GW+EM challenge: from individual objects to statistics



2019-2023 (LIGO+Virgo+…):

NS-NS: 0 to 42 year^{-1}

NS-BH: 0 to 96 per year^{-1}

BH-BH: tens to hundred year^{-1}

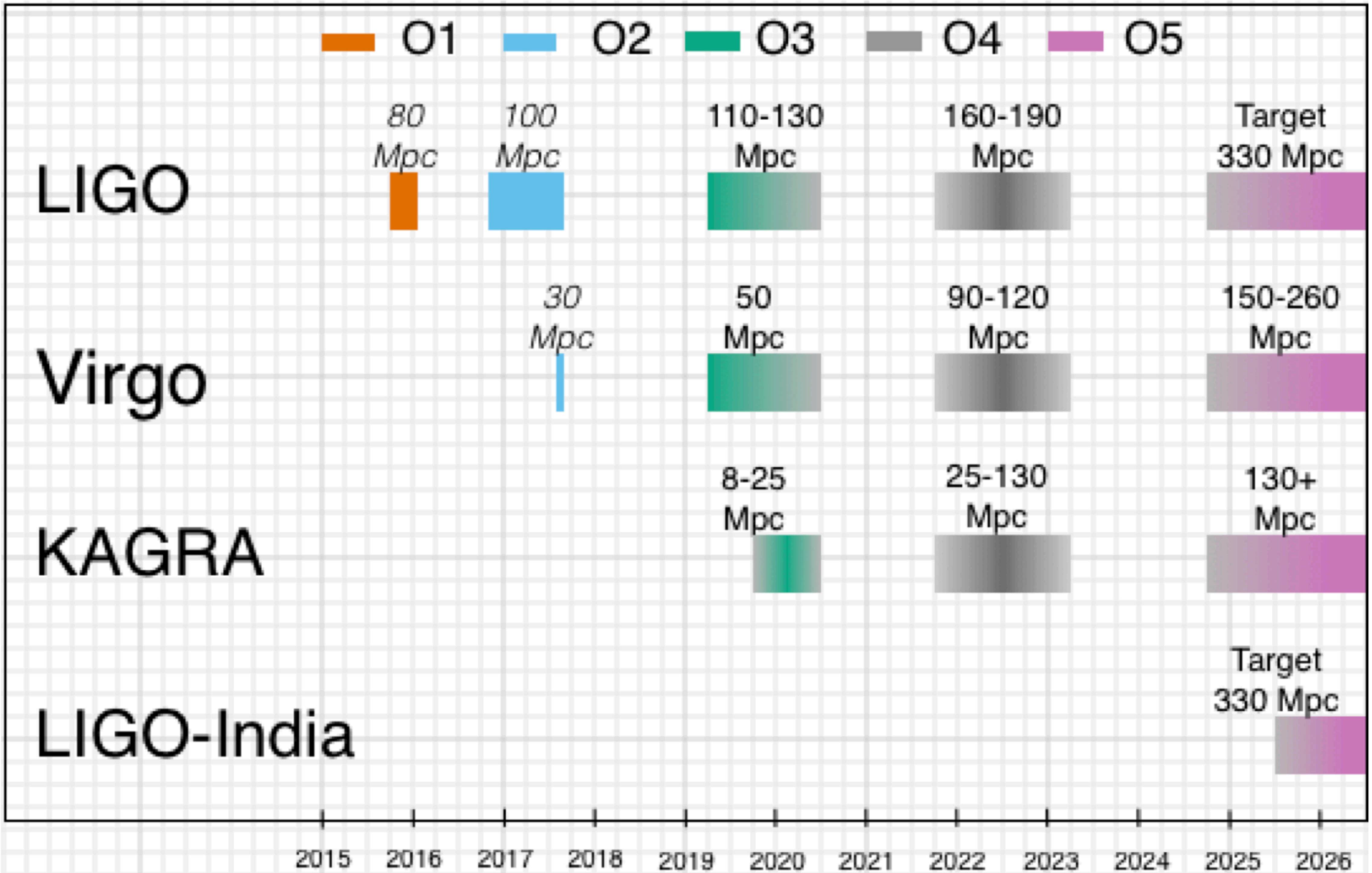
2019-2023:

Wide-field optical and radio telescopes (ZTF, BlackGEM,LOFAR, Apertif, SKA, LSST, ELT ..)

[LVC, Living Reviews in Relativity 19, 1, 2018 and PRX 6, 041015, 2016; LVC+Fermi+Integral, ApJ Lett, 848:L13, 2017]

4. GW+EM challenge: how many this year?

[B. P. Abbott et al., Living Rev Relativ, 2019, 1304.0670]



4. GW+EM challenge: how many this year?

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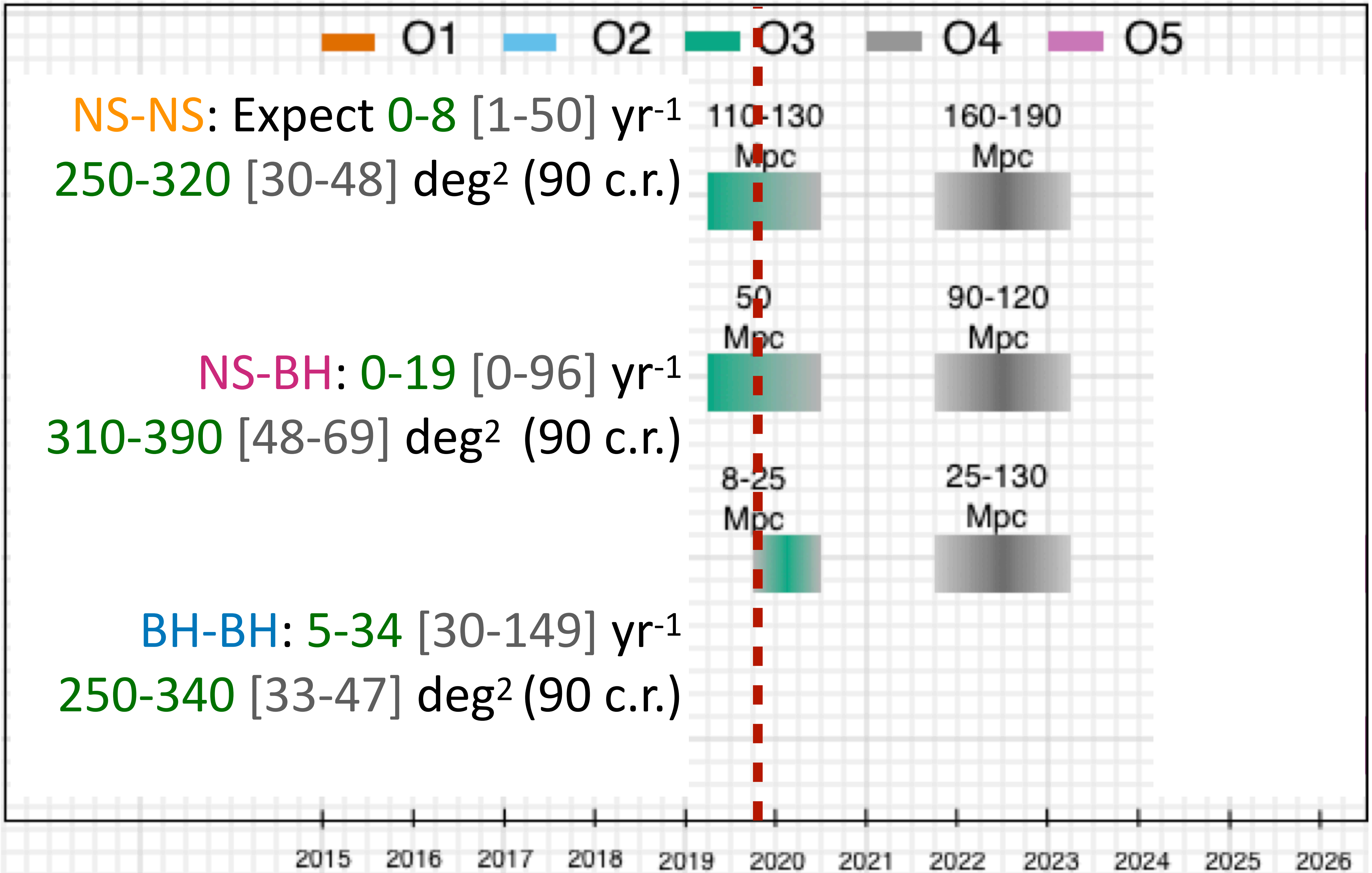
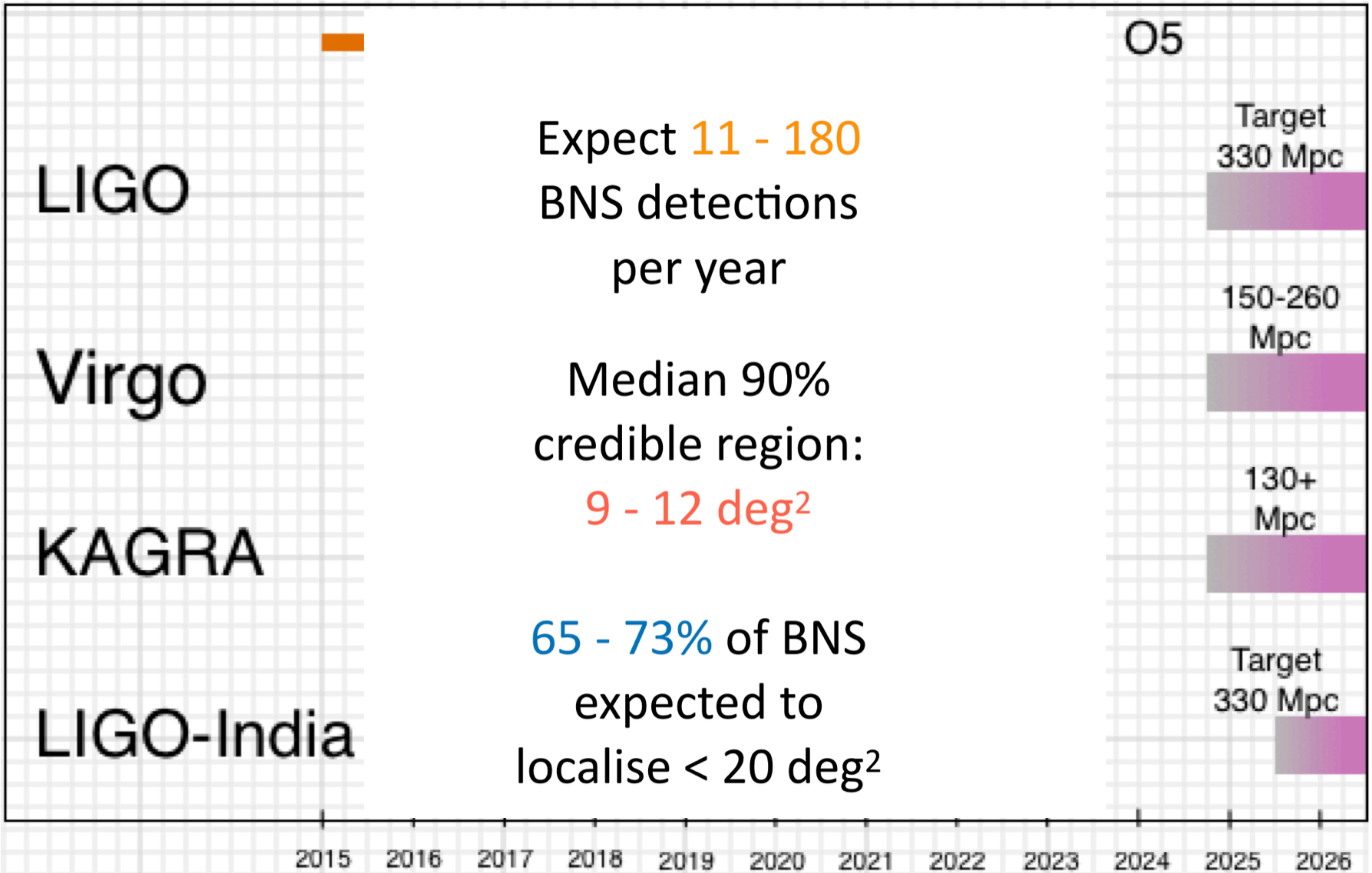


4. Mid 2020s: small GW areas, depth and rate

[B. P. Abbott et al., Living Rev Relativ, 2019, 1304.0670]



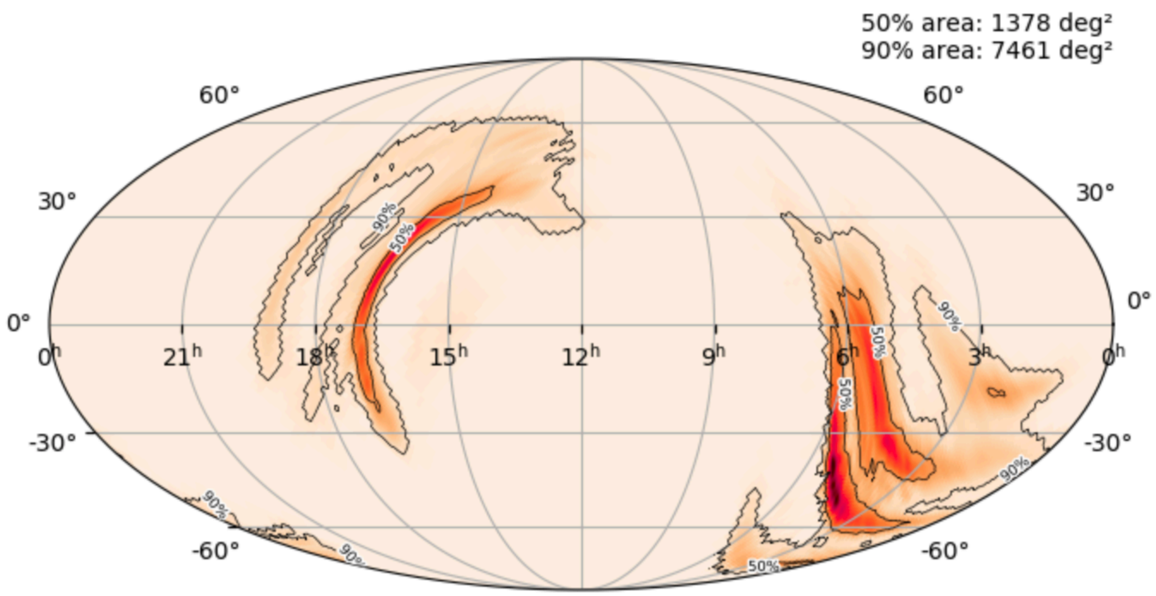
Expect 11 - 180 BNS detections per year

Median 90% credible region: 9 - 12 deg^2

65 - 73% of BNS expected to localise < 20 deg^2

Task 6: First NS-NS binary trigger candidate in 2019: confirmed GW but no EM counterpart

S190425z: Thursday 25th April, 10am CET



p(NS-NS) > 0.99;
p(terrestrial) < 0.01;
p(remnant) > 0.99

FAR: 1 per 70 000 years

Distance: 156 Mpc +/- 40 Mpc
(x4 GW170817)

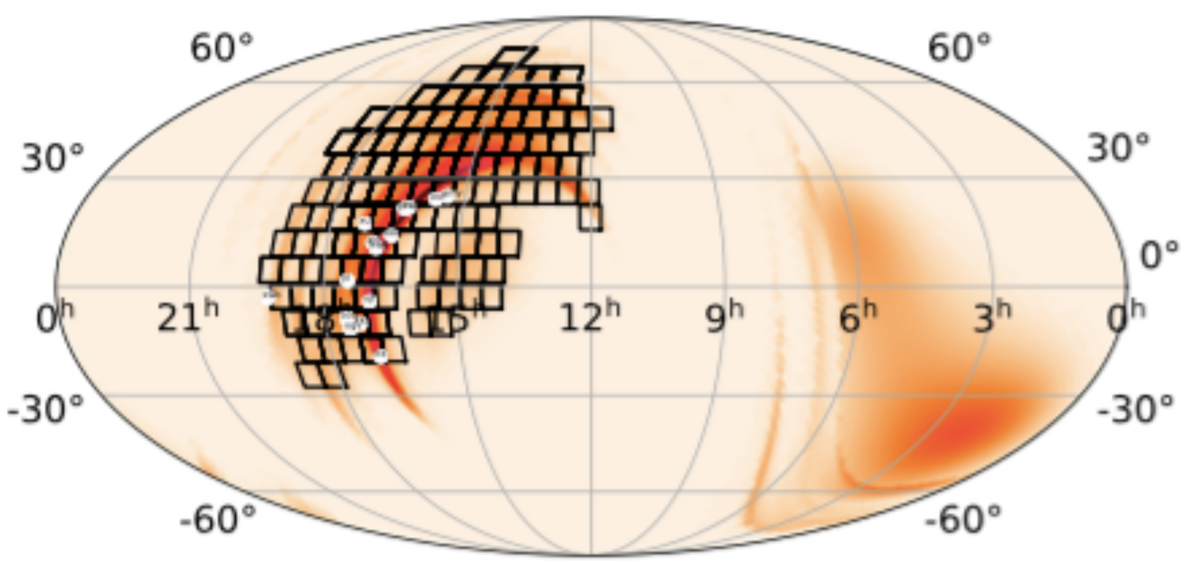
Sky error: 1/4 of the sky!
(x320 GW170817)

O(100) GCNs;
ZTF scanned volume in 3 hours!
10^5 false positives
(supernova and M-dwarf)

[see https://gcn.gsfc.nasa.gov/notices_l/S190426z.lvc
https://gcn.gsfc.nasa.gov/notices_l/S190426c.lvc]

First NS-NS binary trigger candidate in 2019: confirmed GW but no EM counterpart

S190425z: Thursday 25th April, 10am CET



GROWTH: Coughlin + 1907.12645

FAR: 1 per 70 000 years

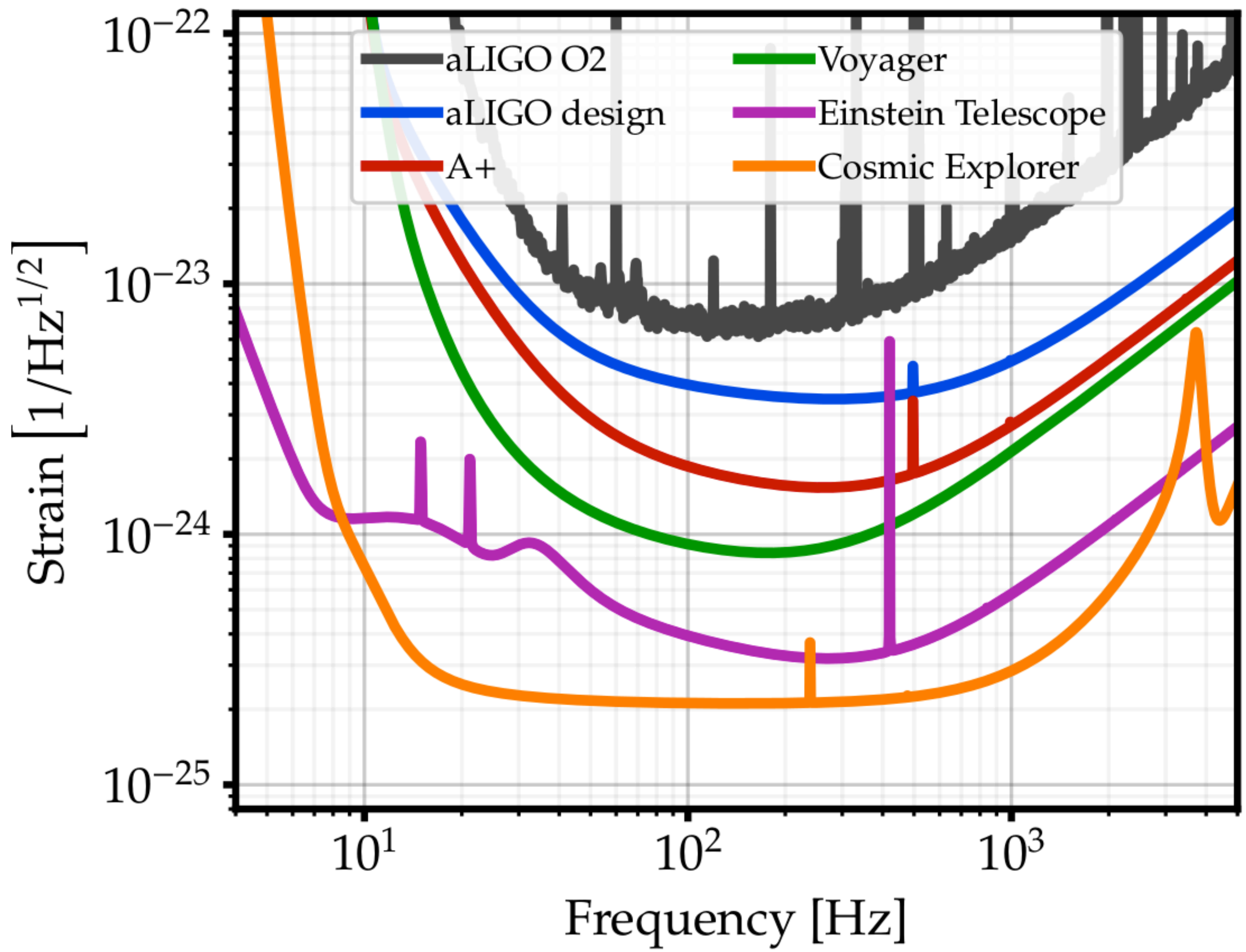
Distance: 156 Mpc +/- 40 Mpc
(x4 GW170817)

Sky error: 1/4 of the sky!
(x320 GW170817)

O(100) GCNs;
ZTF scanned volume in 3 hours!
10^5 false positives
(supernova and M-dwarf)

[see https://gcn.gsfc.nasa.gov/notices_l/S190426z.lvc
https://gcn.gsfc.nasa.gov/notices_l/S190426c.lvc]

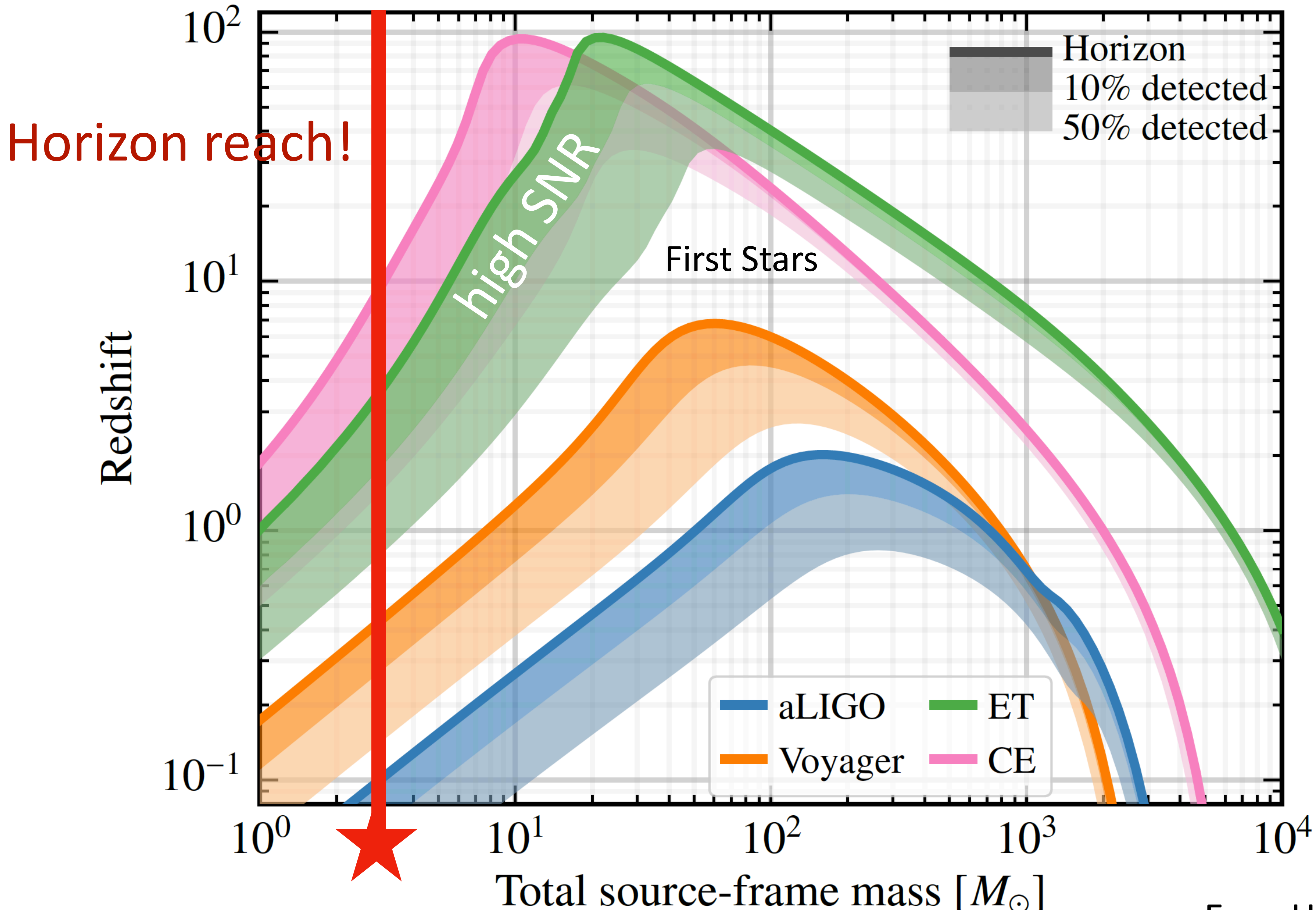
Mid 2020s - 2030a: aLIGO+, Einstein Telescope



Factor of 2/10 in sensitivity; x 8/1000 in rates

2030s: Einstein Telescope and Cosmic Explorer have cosmological reach

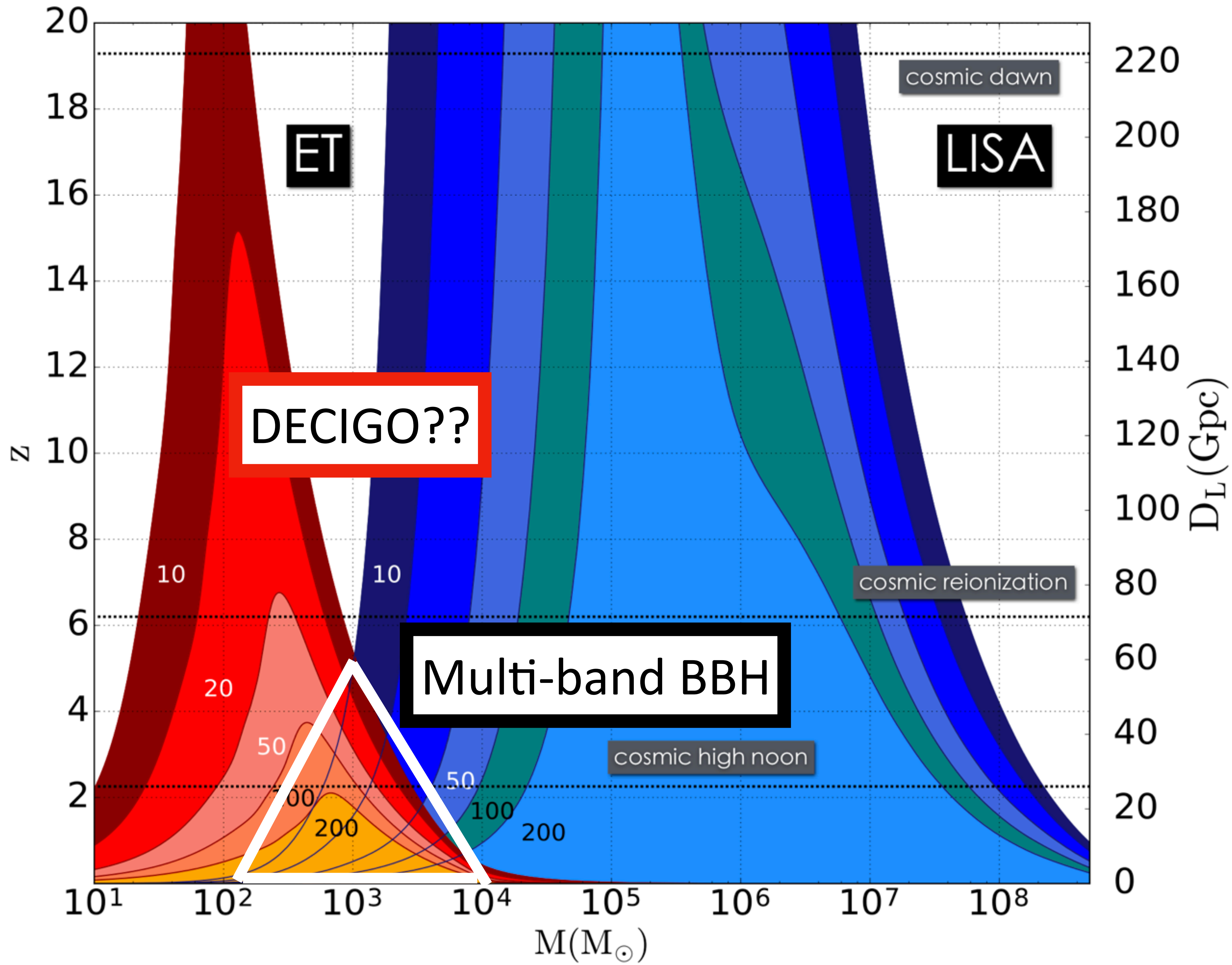
MMA co-chairs: Bailes, Kasliwal, Nissanke



GW170817: $z \sim 10^{-2}$

Evan Hall, MIT

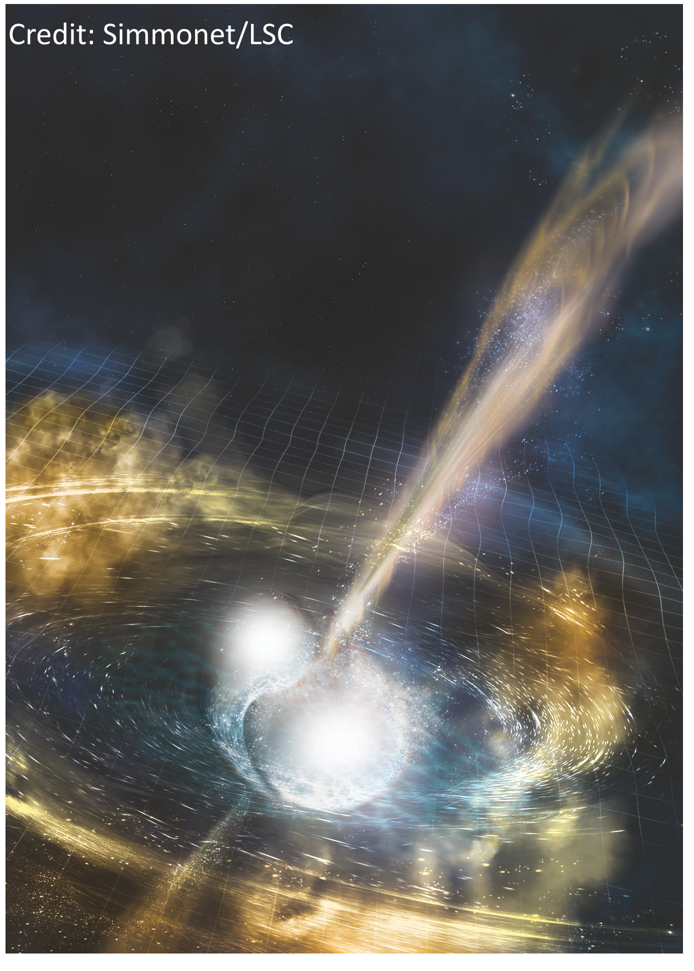
LISA MMA work package leads: Baker, Haiman, Nissanke



Alberto Sesana (Milan); see talk

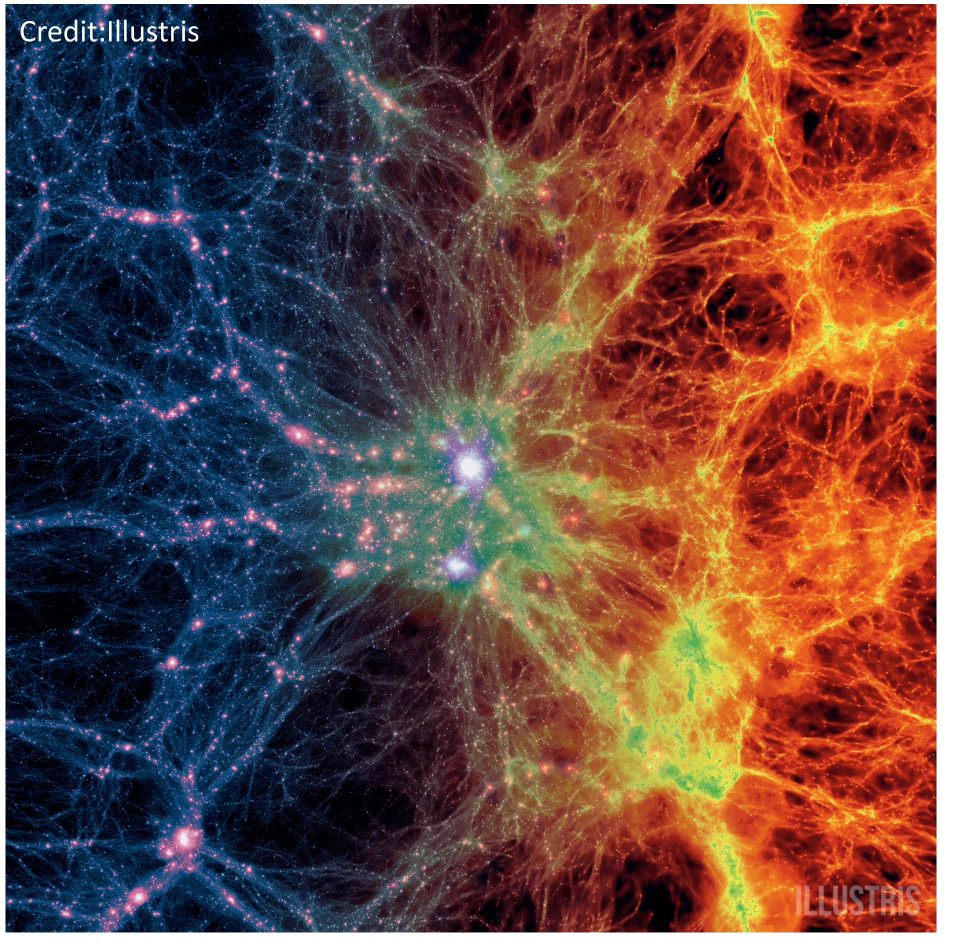
Task 7: MMO in 2030s is not just EM follow up!

EM follow up of single sources

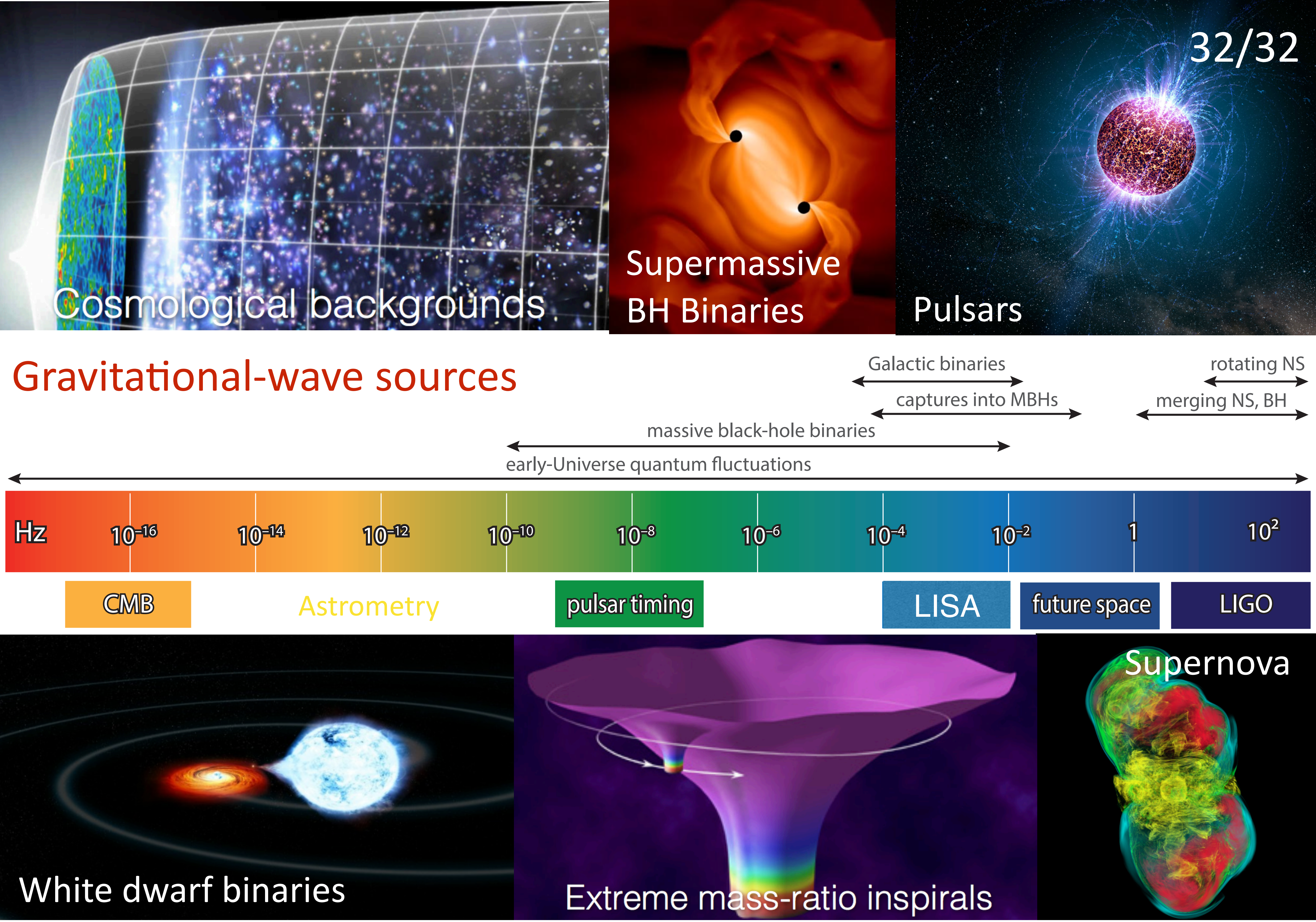


Cherry Pick Loud events - golden for GW+EM

Cross correlating GW and EM source catalogs



Large Scale Structure; Extragalactic Astronomy



First-order phase transitions, superstring kink & cusps, inflationary signature, new sources!

The future is both loud and bright!

Immediately : GW detector sensitivity & network increases => First NS-BH merger! SNe! Tens of BBH mergers yr^{-1} and several of NS-NS yr^{-1}

Key step for GW+EM: joint analysis for masses, spins, sky position and redshifts for populations of compact object mergers are necessary for fundamental physics and astrophysics.

Understanding systematics and finding the EM counterpart are critical for H0 measurement: independent to the cosmological distance level.

Beyond LIGO, Virgo era: Witness the opening of the entire GW spectrum with CMB, PTAs, LISA, new generation ground-based detectors …together with next generation of wide-field synoptic surveys LSST, SKA … and E-ELTs.

The future is both loud and bright!

New Opportunities: GW+EM for astrophysics

- How, when and where do BHs and NSs form? What is the intrinsic nature of compact objects?
- How do compact object mergers impact and drive the evolution of the Universe?
- How do the fundamental laws of physics interact with each other in strong-field gravity?

Challenges: combining GW+EM

- Observations of GW & EM
- Modelling GW + EM simultaneously (microphysics)
- Interpretation (astrophysics and cosmology)