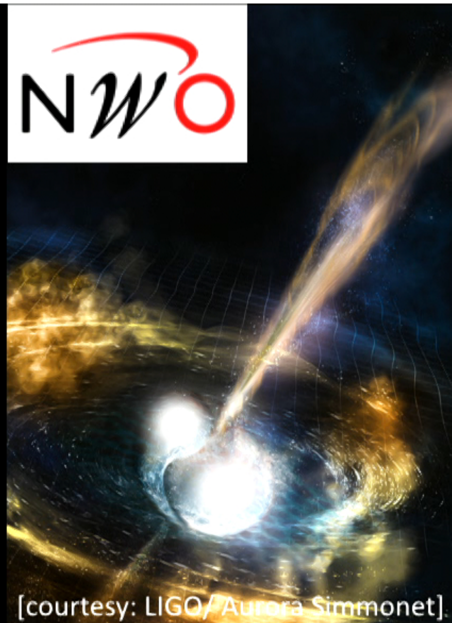
Title: Gravitational wave standard sirens

Speakers: Samaya Nissanke

Collection: Cosmological Frontiers in Fundamental Physics 2019

Date: September 04, 2019 - 9:30 AM

URL: http://pirsa.org/19090012



[courtesy: LIGO/ Aurora Simmonet]

[courtesy: JIVE/ Beabudai Design]

Gravitational Wave Standard Sirens: measuring the Hubble Constant

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

Cosmological Frontiers in Fundamental Physics,
Perimeter Institute, CA,
4th September 2019

Group and collaborations

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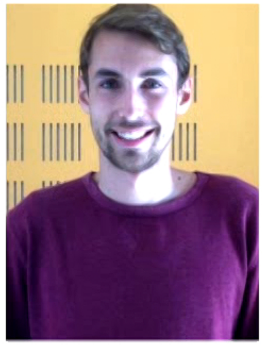
Delta ITP Fellow



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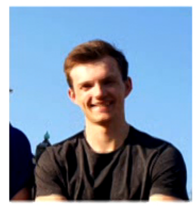

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- LIGO Scientific -Virgo Collaborations
- GROWTH team
- JAGAWR team
- BlackGEM team, NL
- LOFAR, MeerKAT, APERTIF, NL
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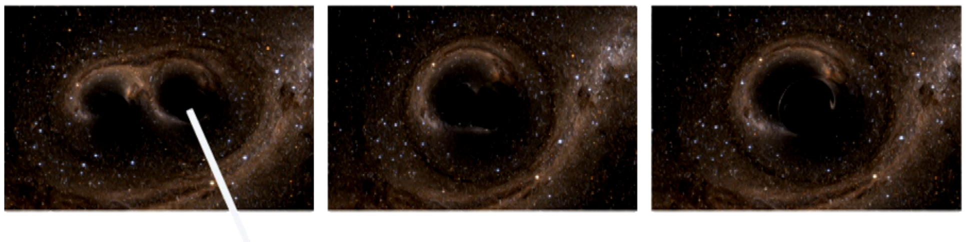
- Kenta Hotokezaka (Princeton)
- Gregg Hallinan (Caltech)
- Mansi Kasliwal (Caltech)
- Kunal Mooley (Caltech)
- Alessandra Corsi (Texas Tech)
- Shri Kulkarni (Caltech)
- Dale Frail (NRAO)
- David Tsang (Southampton)
- Jennifer Barnes (Columbia)
- Hiranya Peiris (UCL, Stockholm)
- Daniel Mortlock (Imperial)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

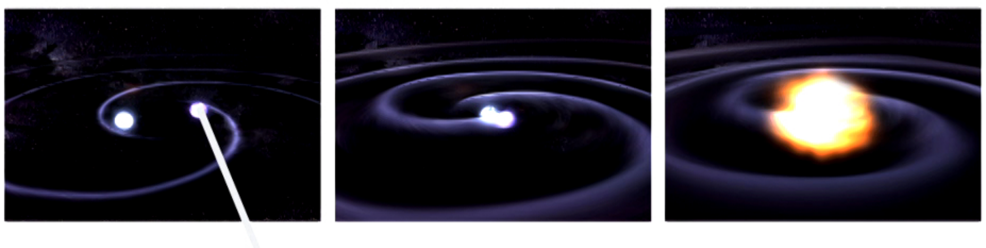
A new revolution in the past four years: gravitational waves (GW), black holes and neutron stars

time



Black Holes (BHs)

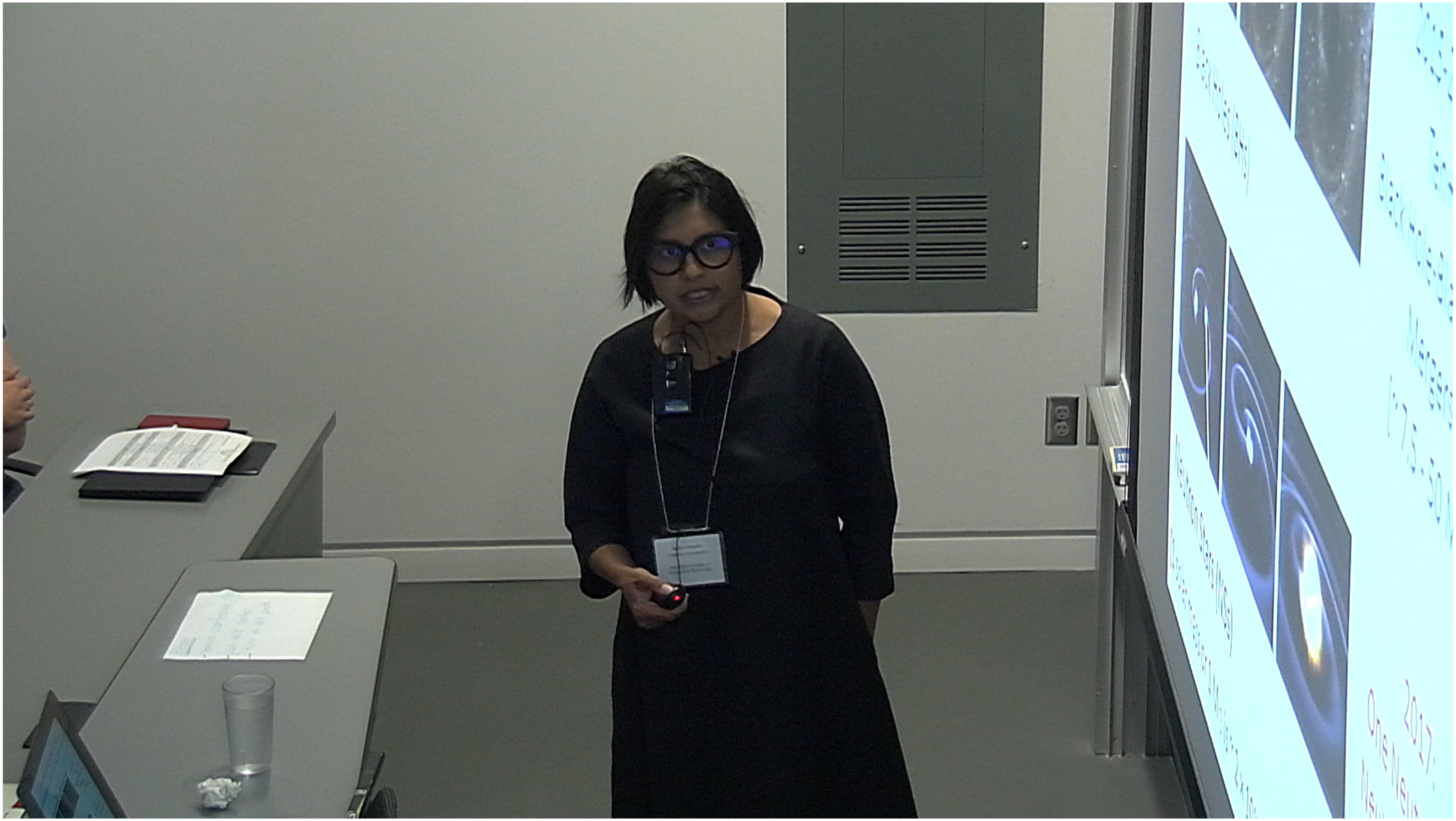
2015-2017:
Ten+
Black Hole-Black Hole
Mergers
[~ 7.5 - 50 M$_\odot$]



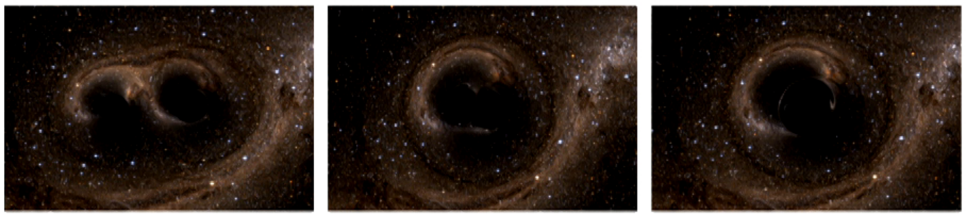
Neutron Stars (NSs)

2017:
One Neutron Star - Neutron Star Merger
“GW170817”
[~ 1.1 - 1.6 M$_\odot$]

[1 solar mass or 1 M$_\odot$ is ~ 2×10^{30} kg]

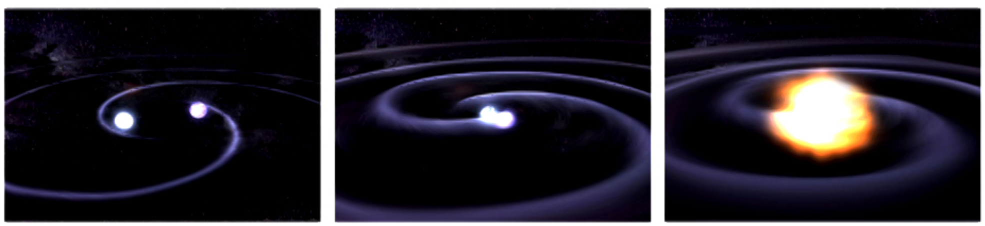


A new revolution in the past four years: gravitational waves (GW), black holes and neutron stars



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

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

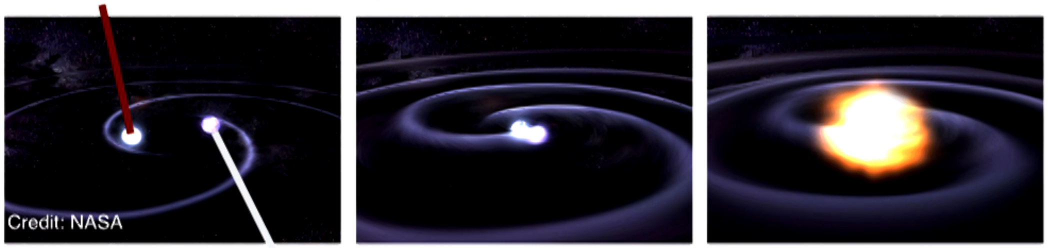


2017:
One Neutron Star -
Neutron Star Merger
"GW170817"

Third science run began 1st April 2019: 20 binary black hole and 4 neutron star binary merger candidates

Game changer today: we can detect and measure Gravitational Waves & Electromagnetic (EM) radiation!

Neutron Star (NS)



???

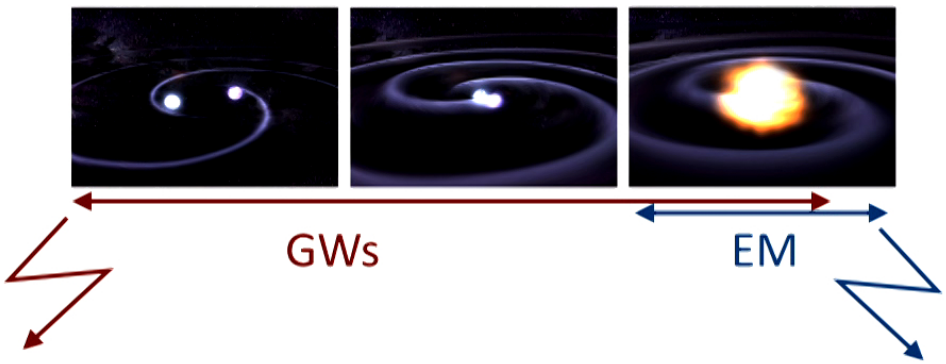
NS/Black Holes (BHs)

Gravitational Waves
~ minute, > 0.025 $M_\odot c^2$

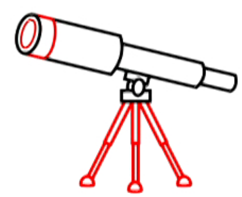
Electromagnetic counterpart:
delayed matter outflows,
post-merger EM is seconds- years,
10^{-6} $M_\odot$ (jet)/ ~ 0.05 $M_\odot$ (isotropic)

[1 $M_\odot$ is ~ 2×10^{30} kg]

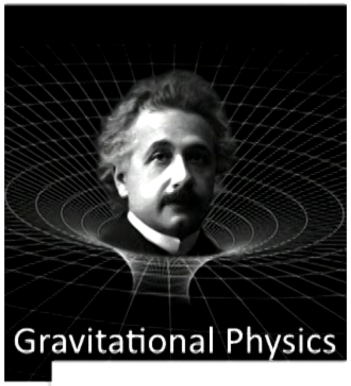
Two complementary probes on extreme-spacetimes: necessary to constrain fundamental (astro)physics



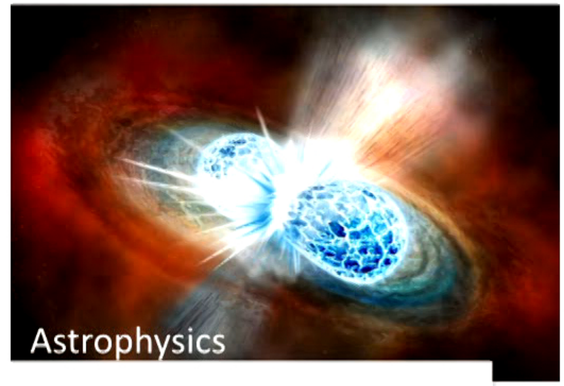
Extract sources' dynamic and fundamental (masses, spins) parameters



Extract sources' environment and energetics



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



First Binary Neutron Star detected in Gravitational Waves

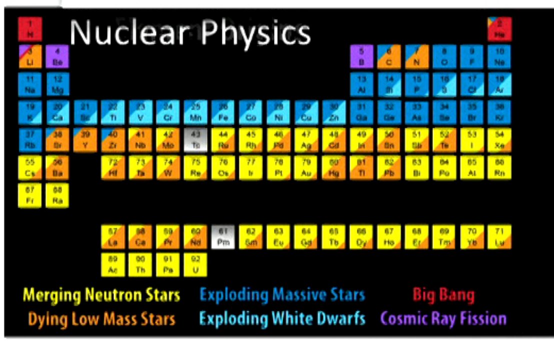
First Electromagnetic Counterpart of a GW merger in every waveband!

First Gravitational Wave Standard Siren Hubble Constant Constraint

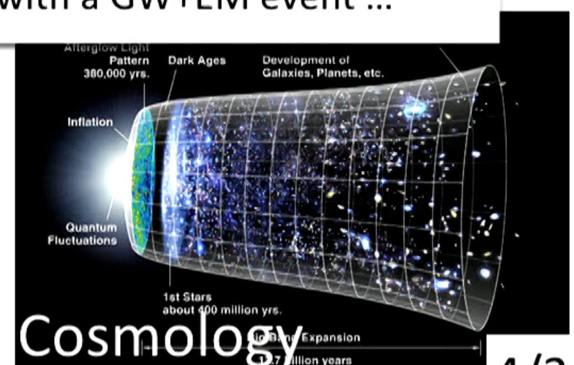
First Short Gamma Ray Burst - Binary Neutron Star Merger Association

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 ...



[Schutz 1986, Dalal + 2006, ...]



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Plan of Talk

Part 1: The physics behind GW measurements
i.e. how to infer luminosity distance?

Part 2: EM follow up and counterparts of GW170817
i.e. how to follow-up GW mergers?

Part 3: How to measure H0 from GW+EM?

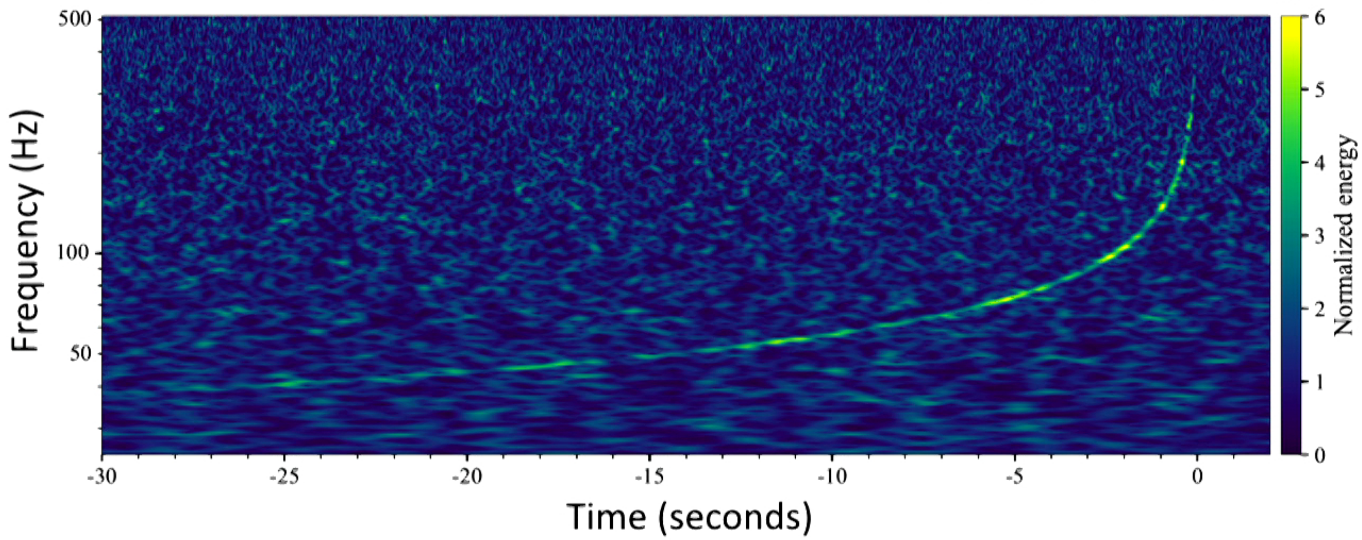
Part 4: Perspectives (my views)

Disclaimer: O (1000) papers — references are bare minimum
See upcoming review article in Living Reviews

First Measurement of GWs from a Binary Neutron Star Merger

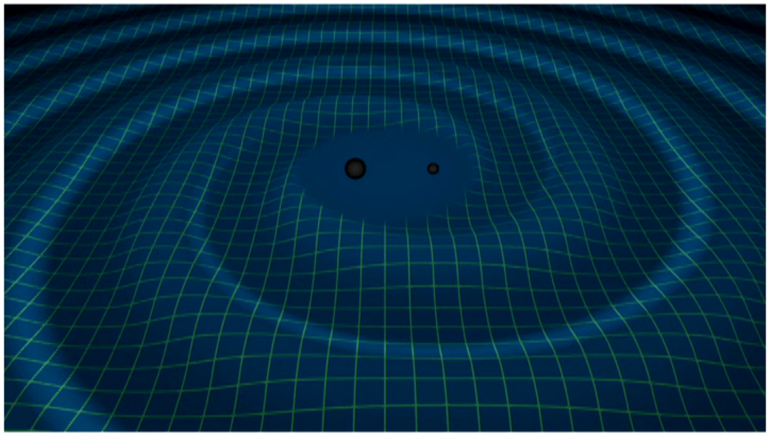
August 17th 2017 at 12:41:04 UTC (14:41, one hour after lunch!)

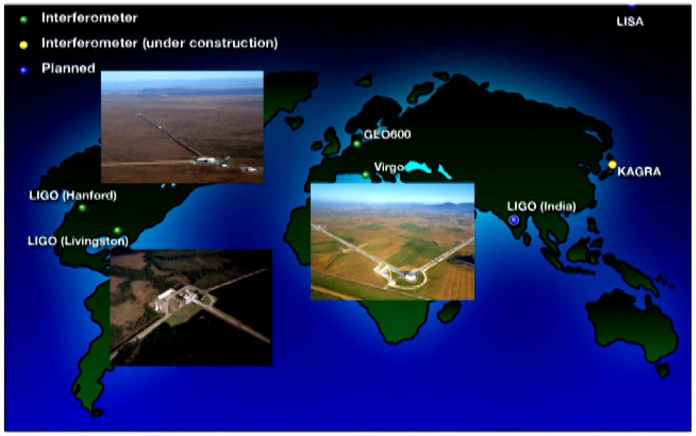
[LVC,PRL, 119, 161101 (2017)]



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



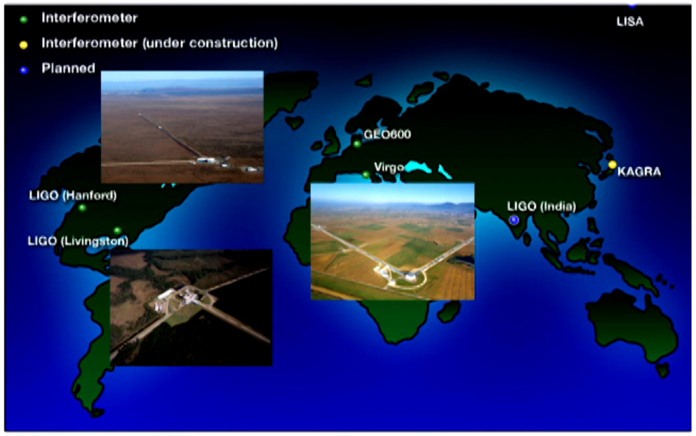


Measurable GW strain h (t) ~ 1/distance
two polarizations h_+ and $h_\times$

24 - 2048 Hz

6/34

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



Measurable GW strain h (t) ~ 1/distance
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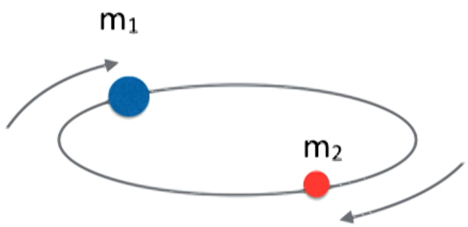
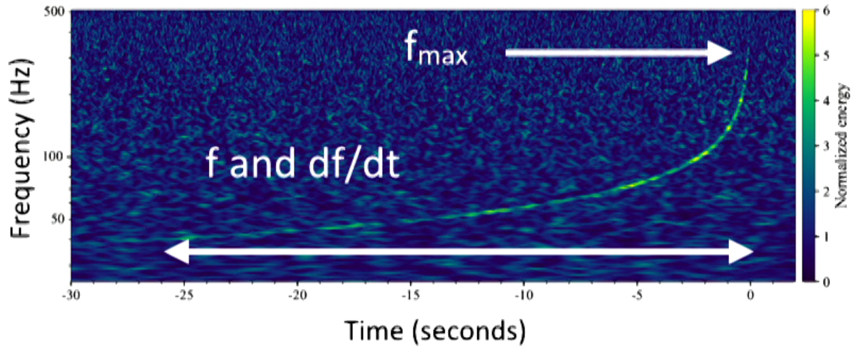
24 - 2048 Hz

6/34

Simplest "Newtonian" model explains frequency chirp



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



[LVC, PRL 119, 161101 (2017)]

⇒ Frequency chirp:

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

Chirp mass:

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

The GW waveform encodes source parameters

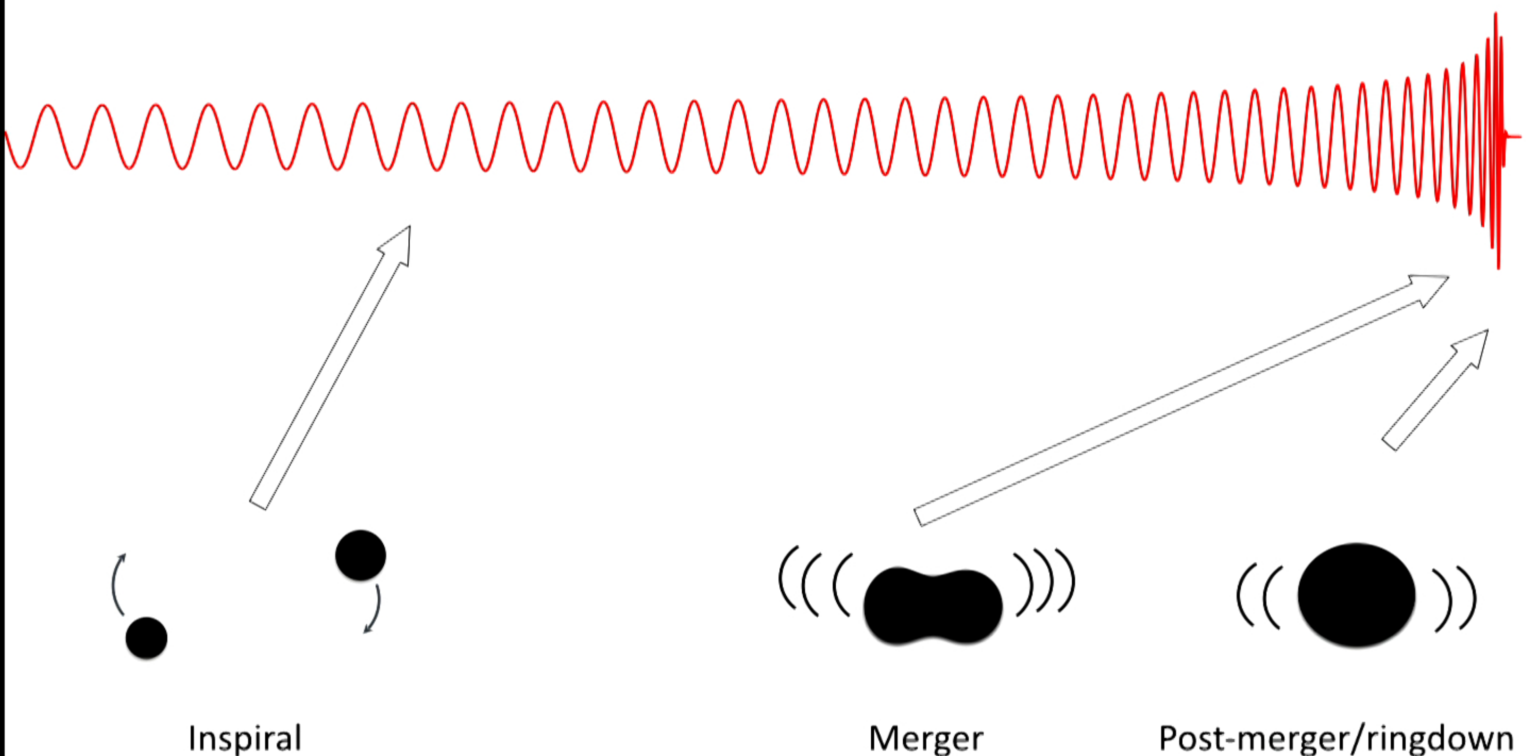
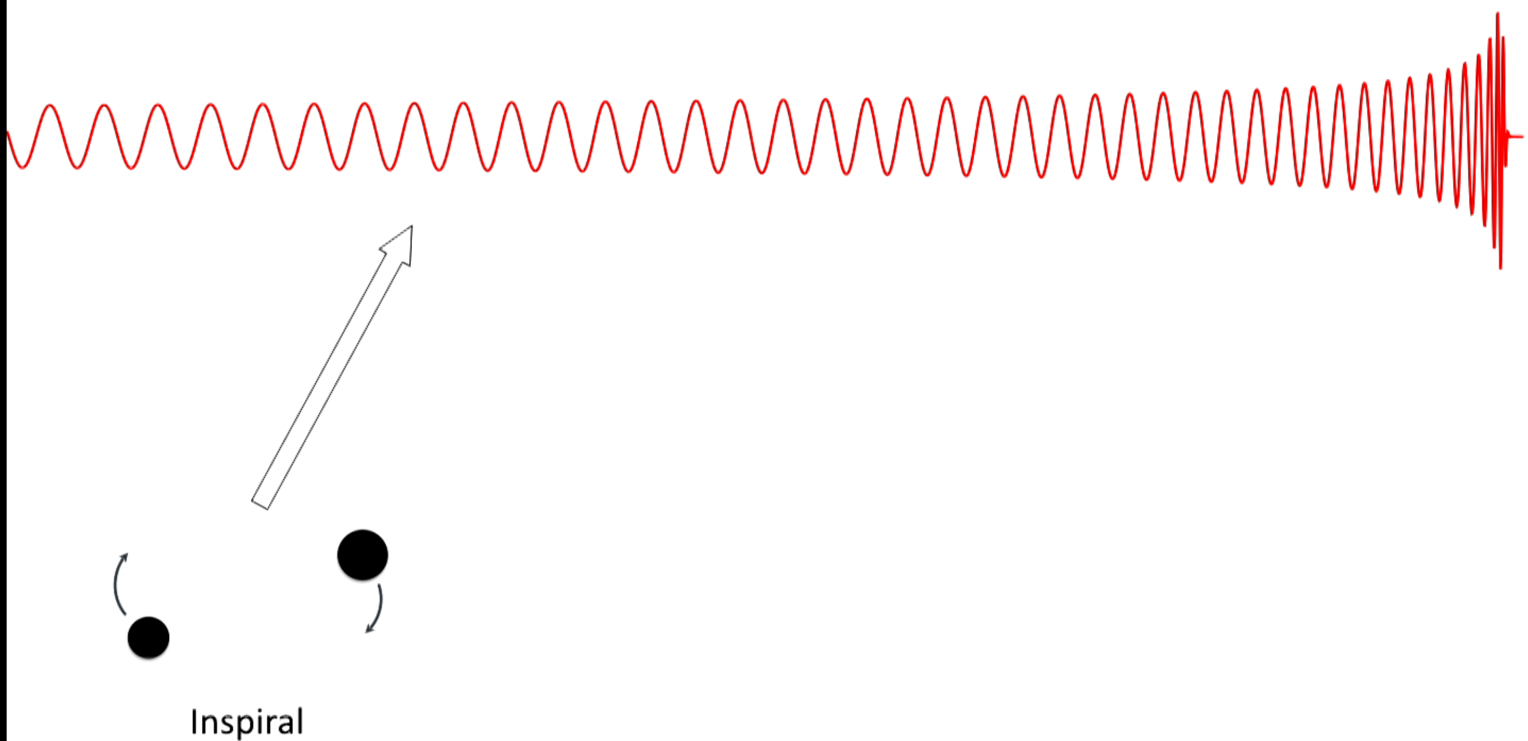


figure courtesy of Tanja Hinderer

The GW waveform encodes source parameters



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

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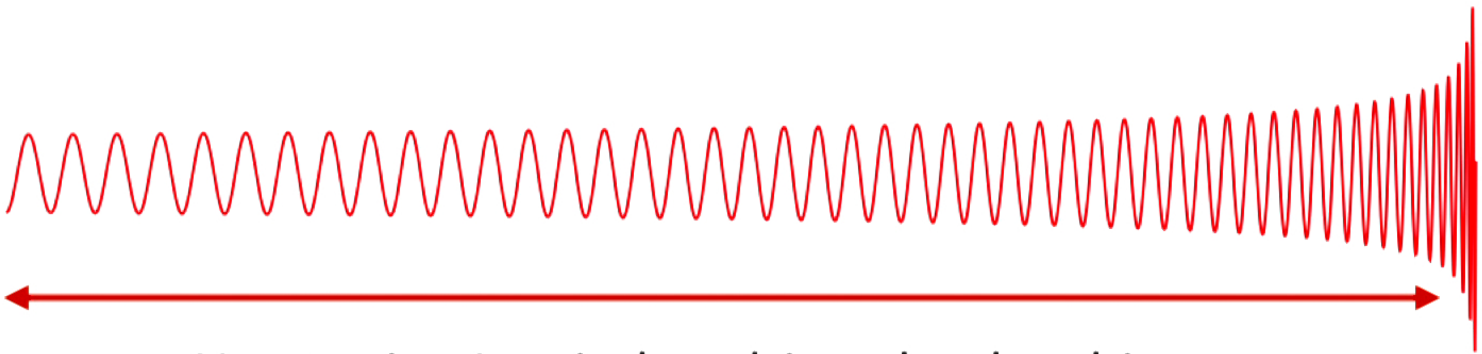
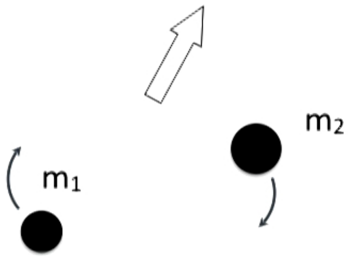
The GW waveform encodes source parameters



post-Newtonian Inspiral — driven by the chirp mass



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

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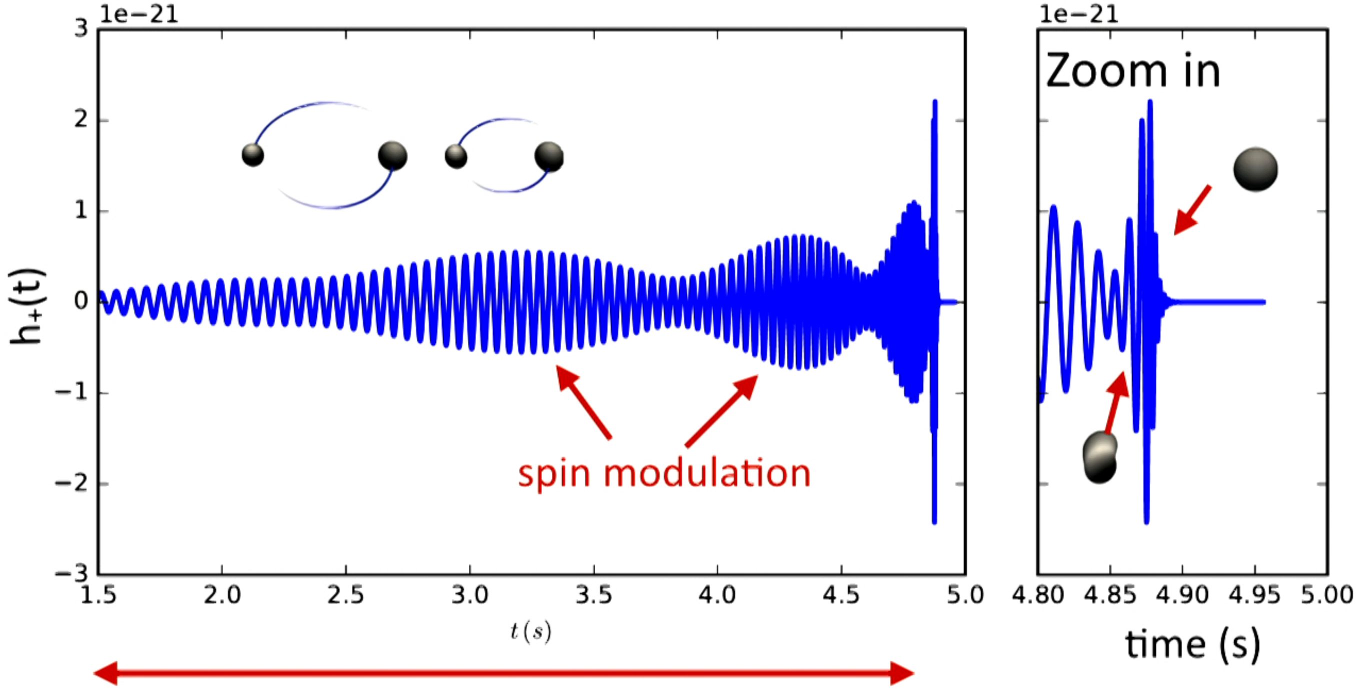
The GW waveform encodes source parameters



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

tidal deformability (5PN)

Extract source information from GWs

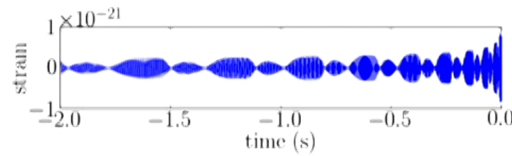
$$h_+(t) = \frac{A[\mathcal{M}\, f(t)]}{D}(1+\cos^2\iota)\cos\Phi_{\rm GW}(t)$$

frequency ($f(t)$); distance (D); inclination angle (ι); GW Phase ($\Phi_{\rm GW}(t)$)

h(t): 9-16 parameters

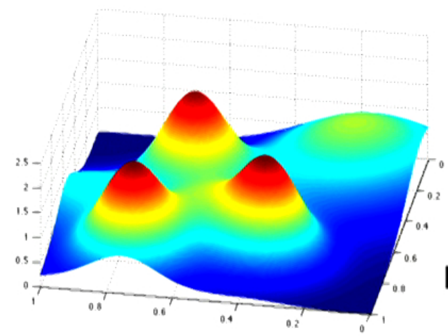
+ Redshifted Masses
+ Spins
+ Tidal deformability
+ Geometric properties:
  - Inclination angle
  - Source Position
  - Luminosity distance

Model h(t)



Detector output

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



Likelihood

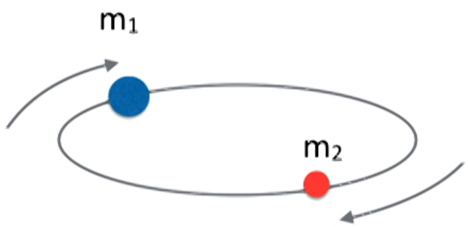
parameter 1

parameter 2

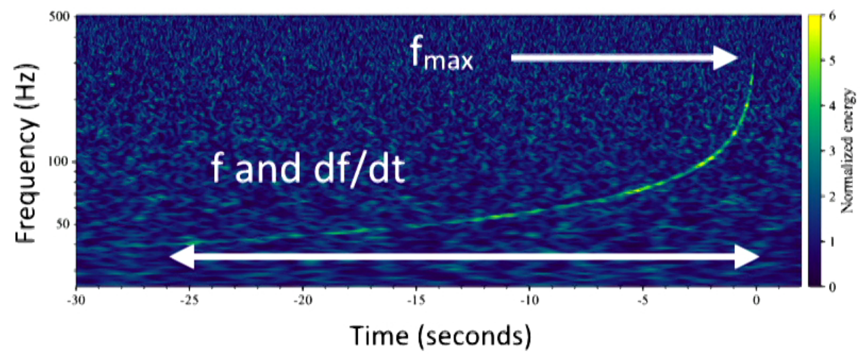
using Bayesian Markov Chain Monte Carlo and Nested Sampling Techniques

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

Simplest "Newtonian" model explains frequency chirp



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



[LVC, PRL 119, 161101 (2017)]

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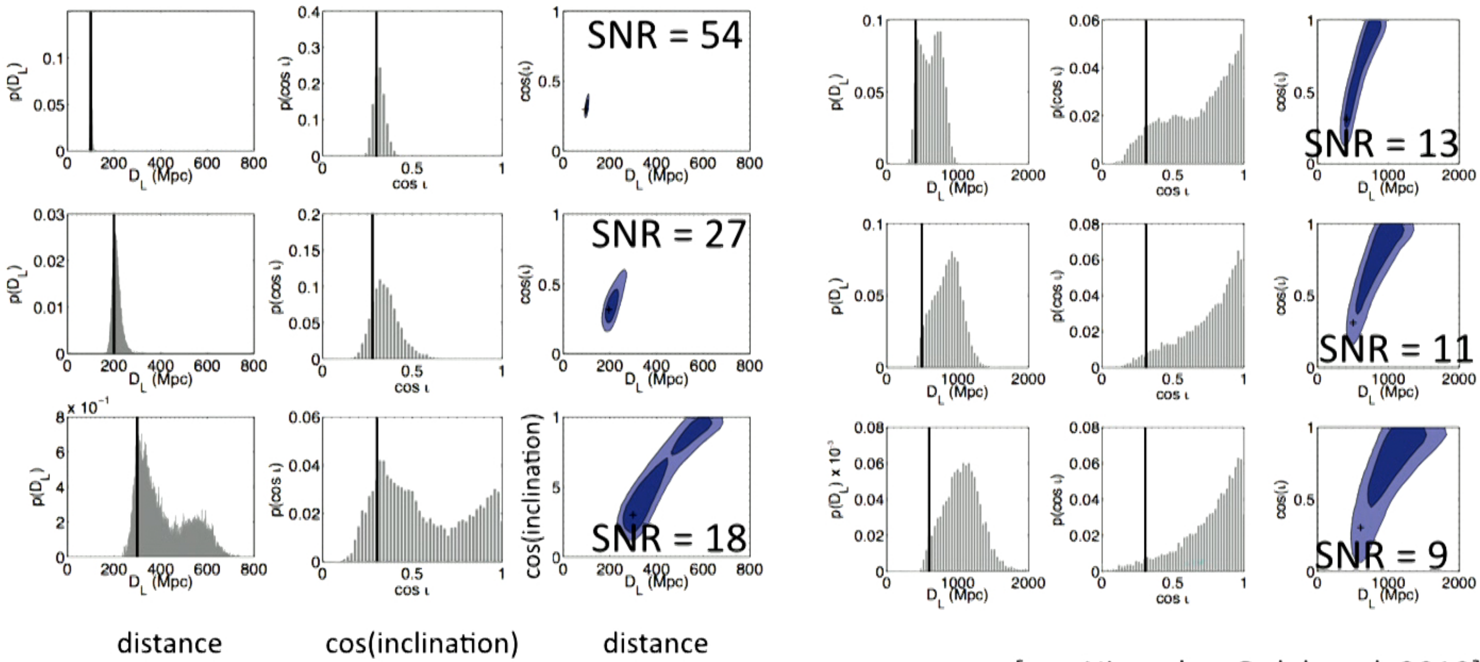
Chirp mass: $$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

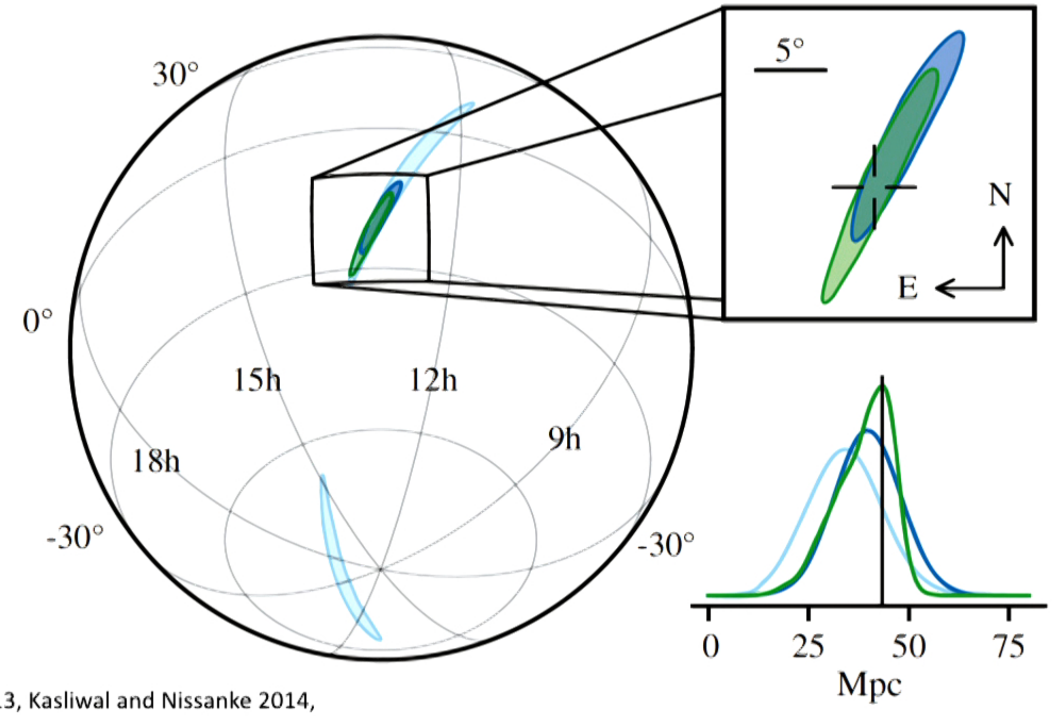
GW distance and inclination degeneracy are critical for standard sirens



[see Nissanke.. Dalal et al. 2010]

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,]

[1 Mpc is 10^{22} m]

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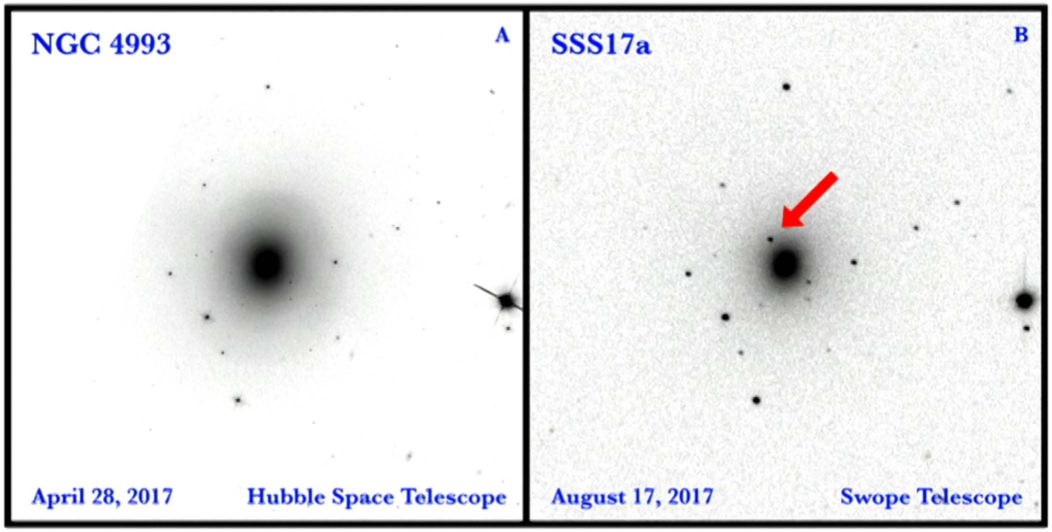
First optical transient at 11 hours was the real deal: the NS-NS merger



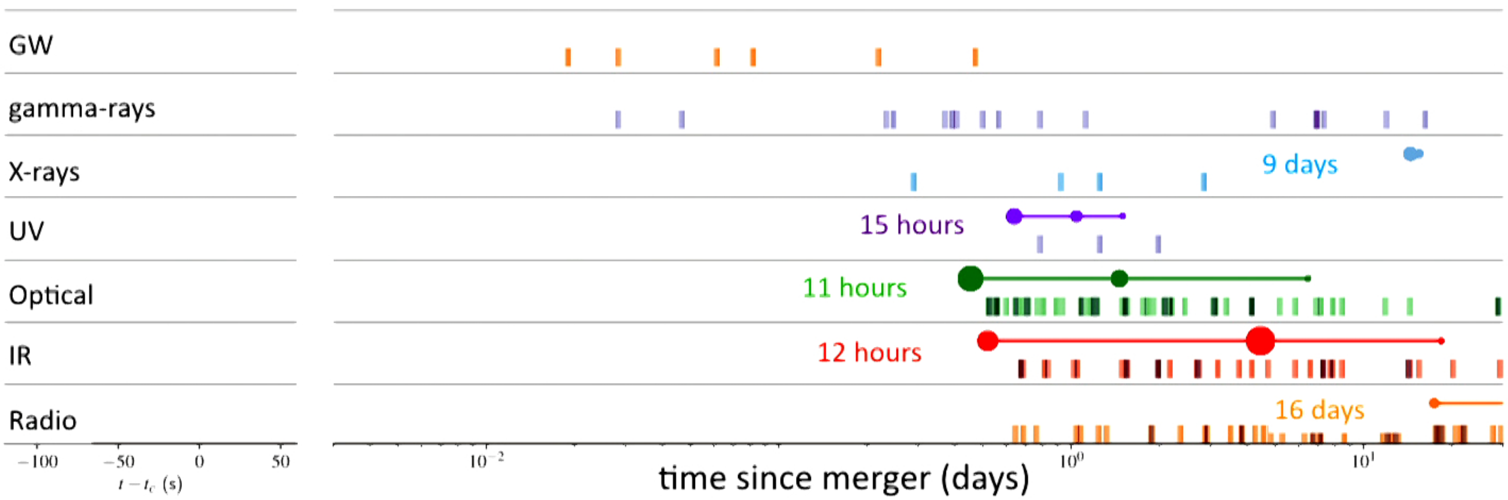
[Coulter et al. 2017, Science]

NGC 4993: 40 Mpc (elliptical galaxy)

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

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:

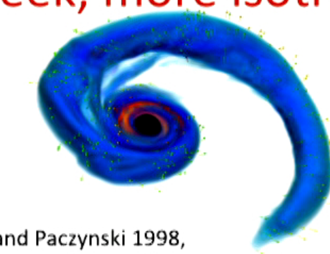
70+ teams, 100+ instruments, over 3500 co-authors

A Tale of Two Matter Outflows ⇒ EM counterparts

[see work by East + 2012, Siegel + 2017 etc]

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

$M_{ej} \approx 0.01\text{-}0.05\ M_\odot$
$E \approx 10^{50}$ ergs
$v \approx 0.1\text{-}0.3c$

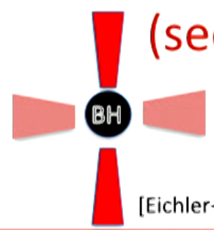


[Lattimer and Schramm 1974, Li and Paczynski 1998, Rosswog 1999, Kulkarni 2005, Metzger et al. 2010, ...]

[Foucart et el. 2014]

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

$M_{ej} \approx 10^{-6}\ M_\odot$
$E \approx 10^{49}\text{-}10^{50}$ ergs
$v \approx 0.99c - 0.99995c$



[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}: 4×10^{26} W or 4×10^{33} erg/s)

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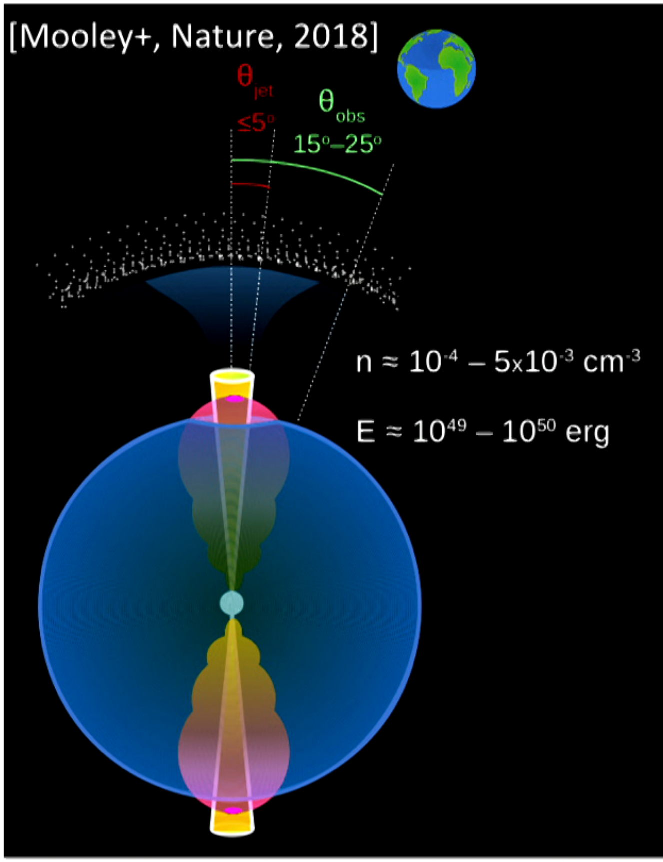
EM: Challenges for EM follow up

1) Source and remnant properties

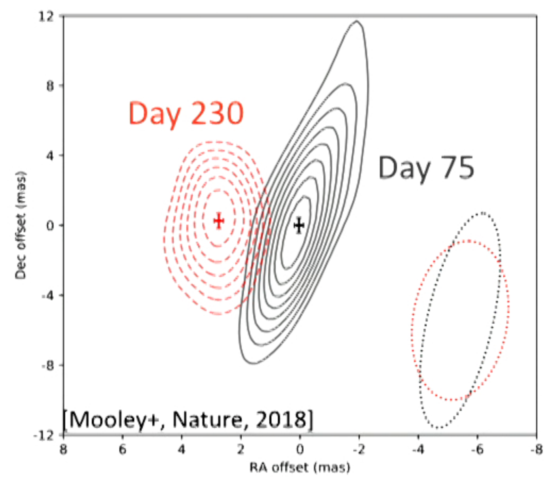
2) Geometry

3) Timescales: physical processes?

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

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

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

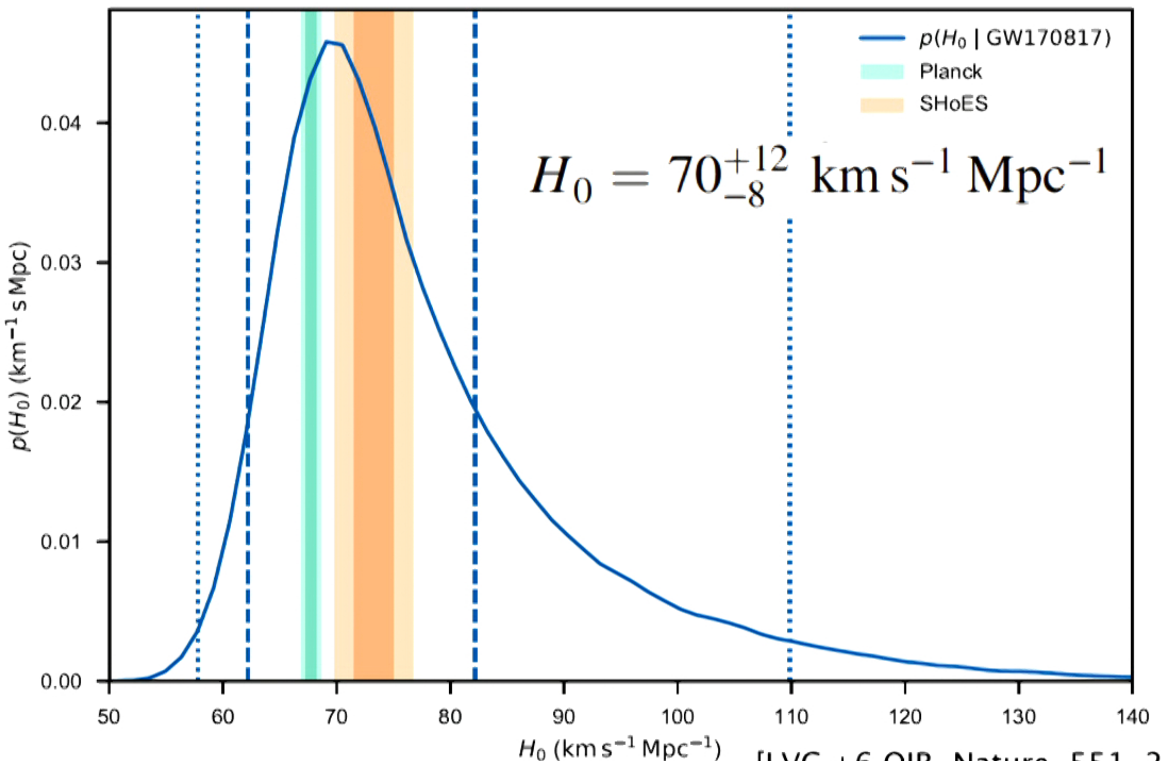
- Energetics and beaming
- R-process nucleosynthesis
- Mass ejecta and velocity
- Environment
- Redshift, Accurate Position (1”)
- Stellar populations
- Magnetic field strength
- Previous binary evolution & mass loss

Strong signal binary: Characterisation

Population: Demographics, ecology and census

GW+EM: Standard siren measurement of Hubble constant

[Schutz 1986, Dalal + 2006, SN + 2010]



[LVC +6 OIR, Nature, 551, 2017]

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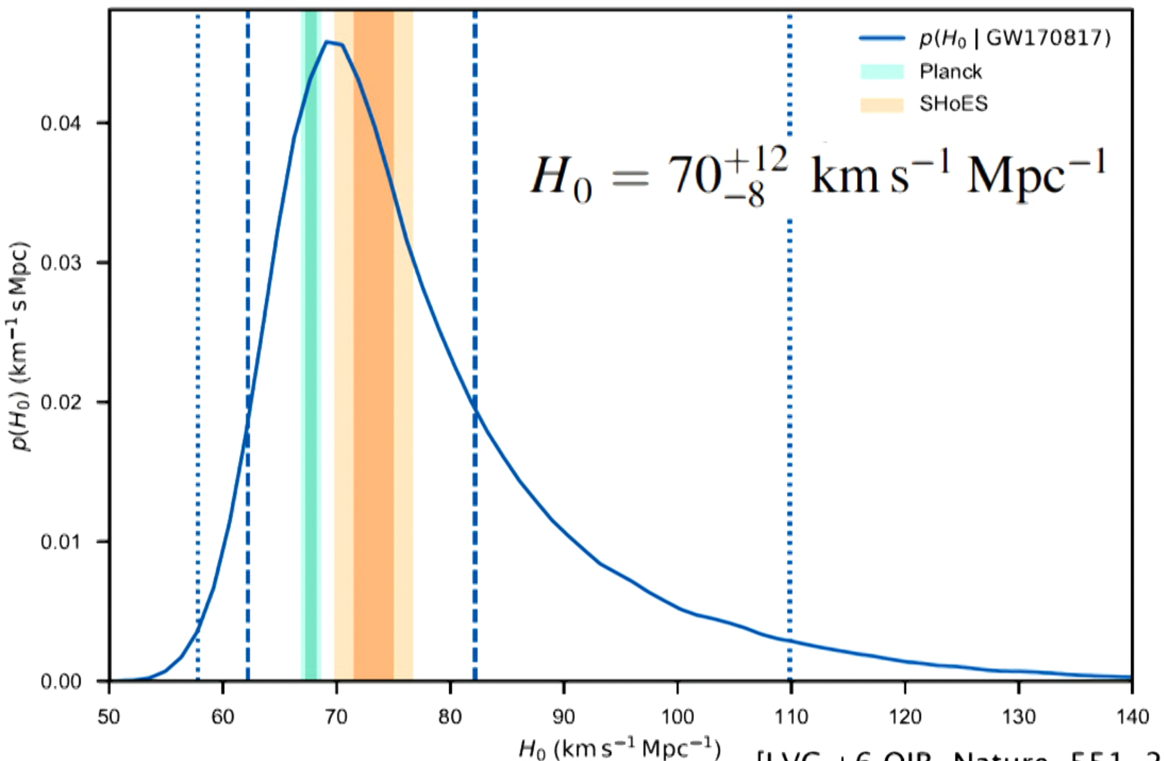
Peculiar velocity error of 150 km/s; Hubble flow velocity of 3017 +/- 166 km s^{-1}

GW+EM: Standard siren measurement of Hubble constant

[Schutz 1986, Dalal + 2006, SN + 2010]



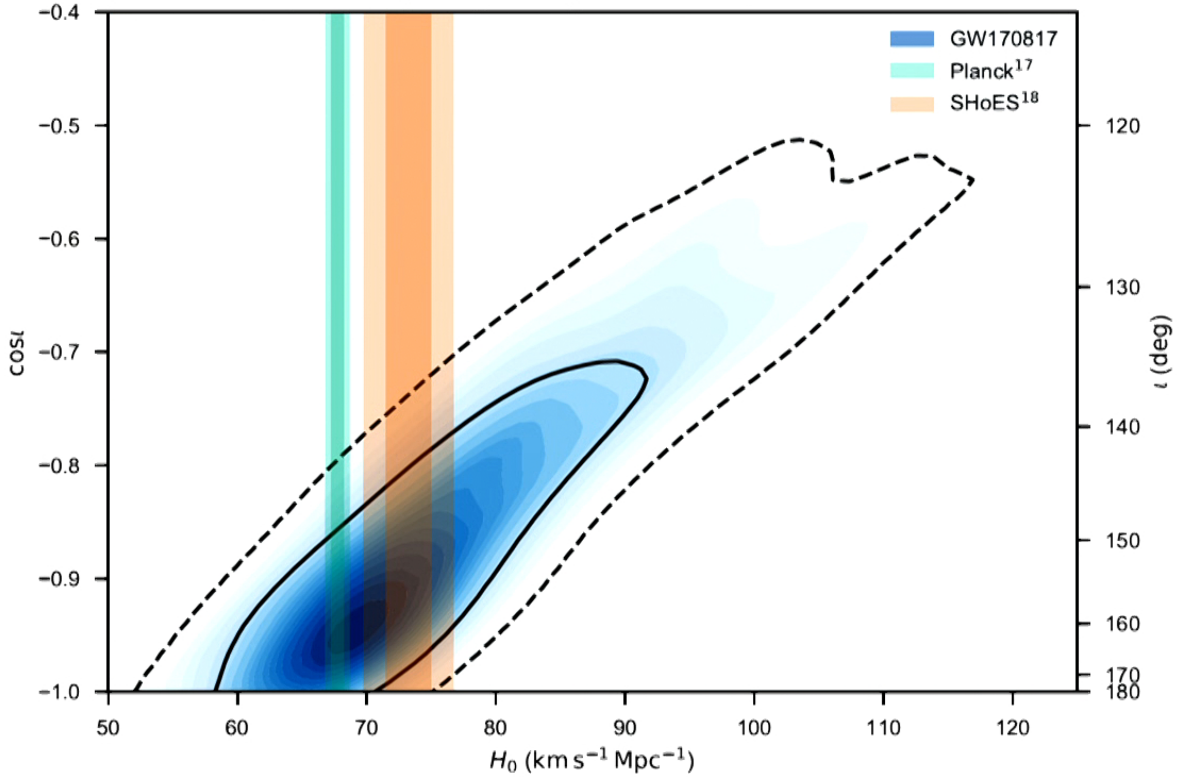
[LVC +6 OIR, Nature, 551, 2017]

18

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

GW+EM challenge: Inclination angle and distance degeneracy

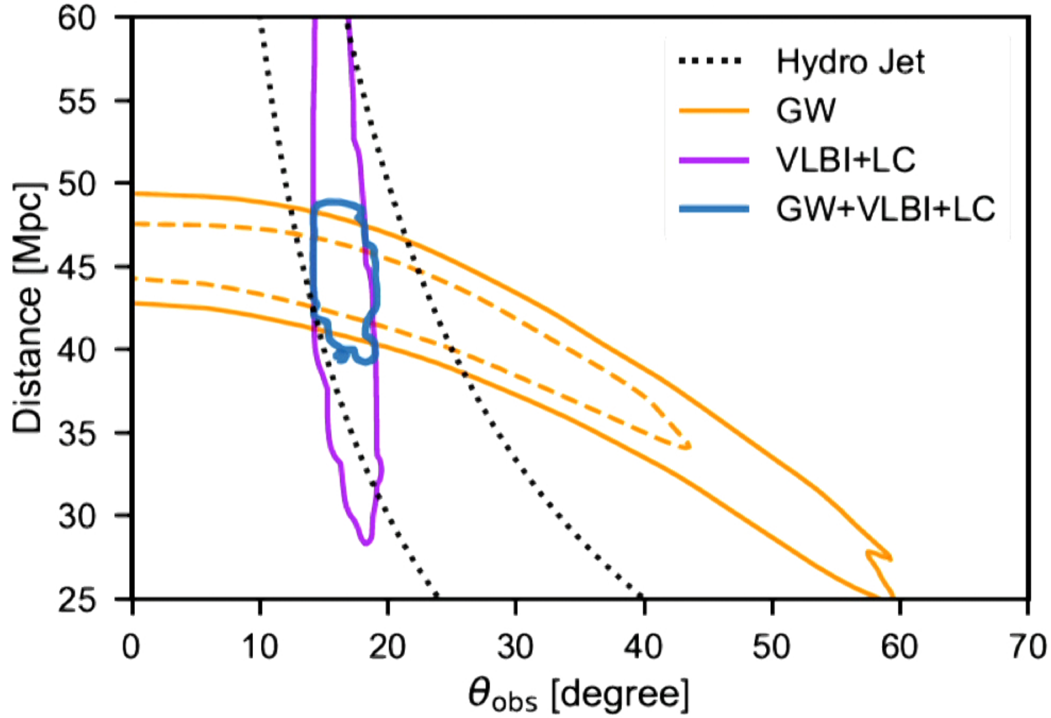
[LVC +6 OIR, Nature, 551, 2017]



[see Guirdozi + 2017, Finstead + 2018, Mandel 2018]

GW+ radio: Hubble measurement improves by a factor of 2-3

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



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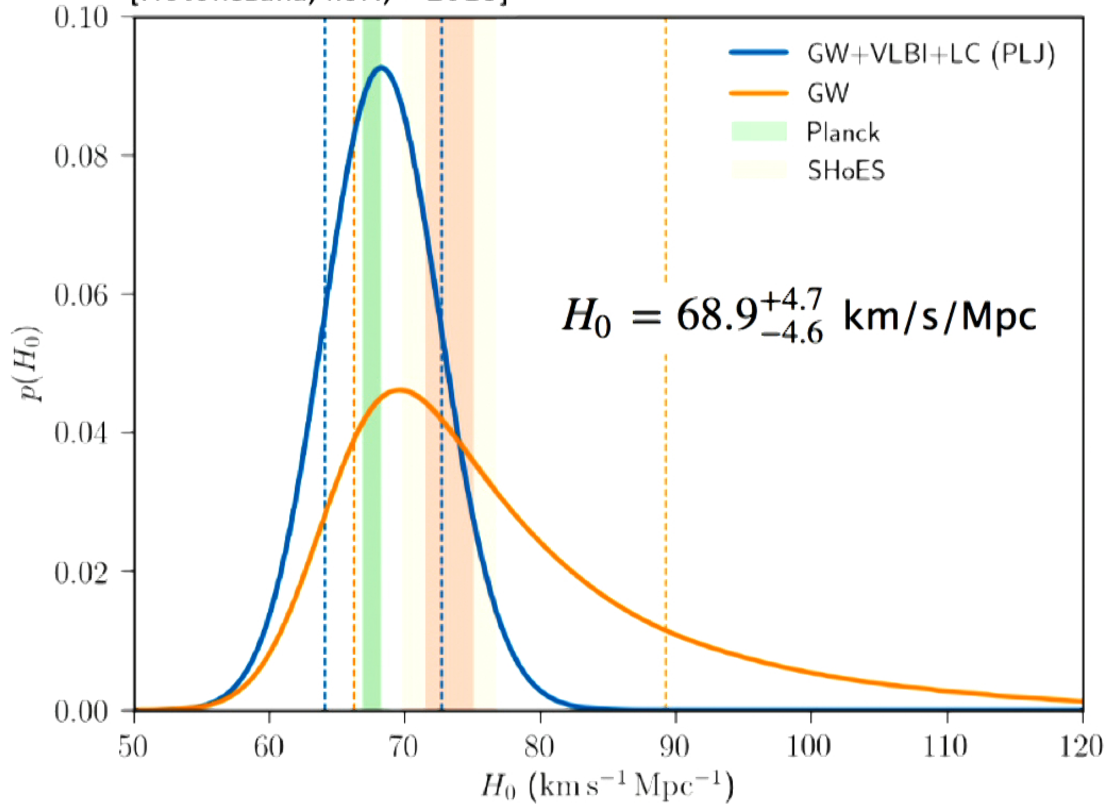
[Hotokezaka, ..SN, + 2018]



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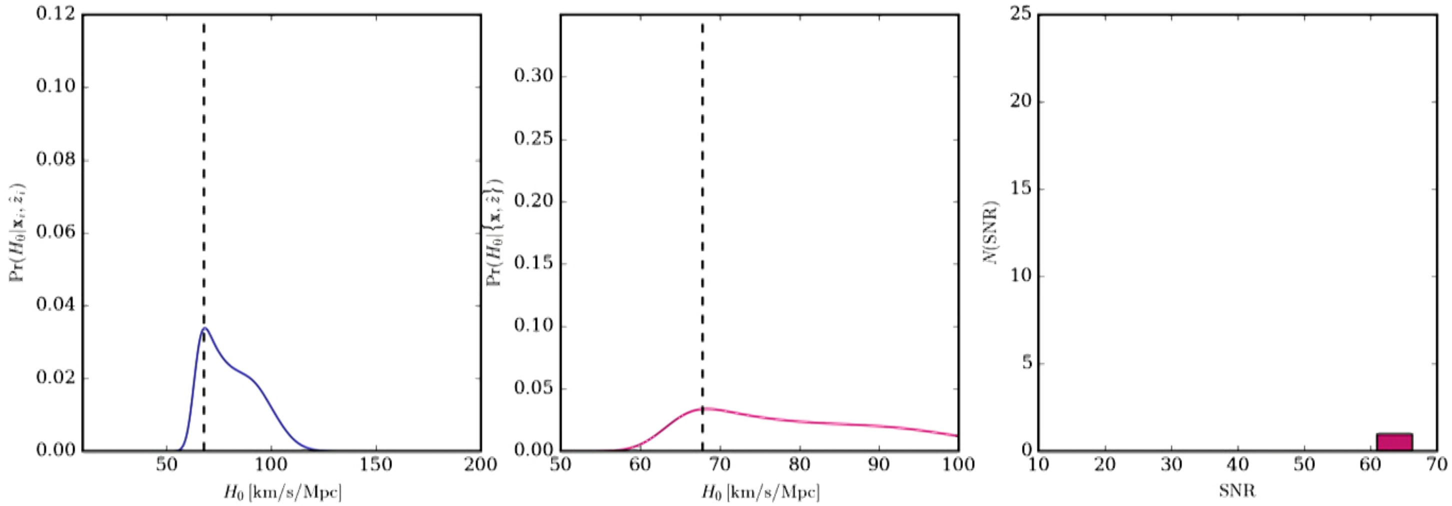
[note new work by Howlett + 2019, Mukherjee + 2019 on improving peculiar velocity measurement]

Part IIIb:

Moving forward with H0 measurements with GW

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

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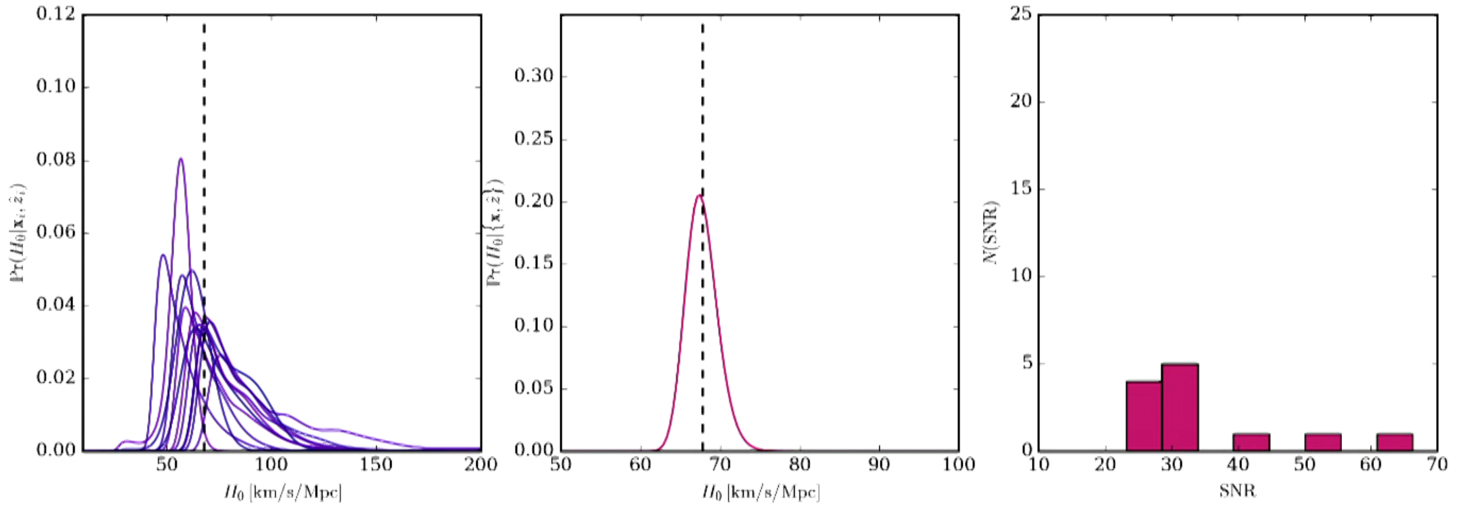
1) GW+EM: importance of populations to potentially resolve "Hubble trouble"

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



[see also Chen+ 2018, ...]

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

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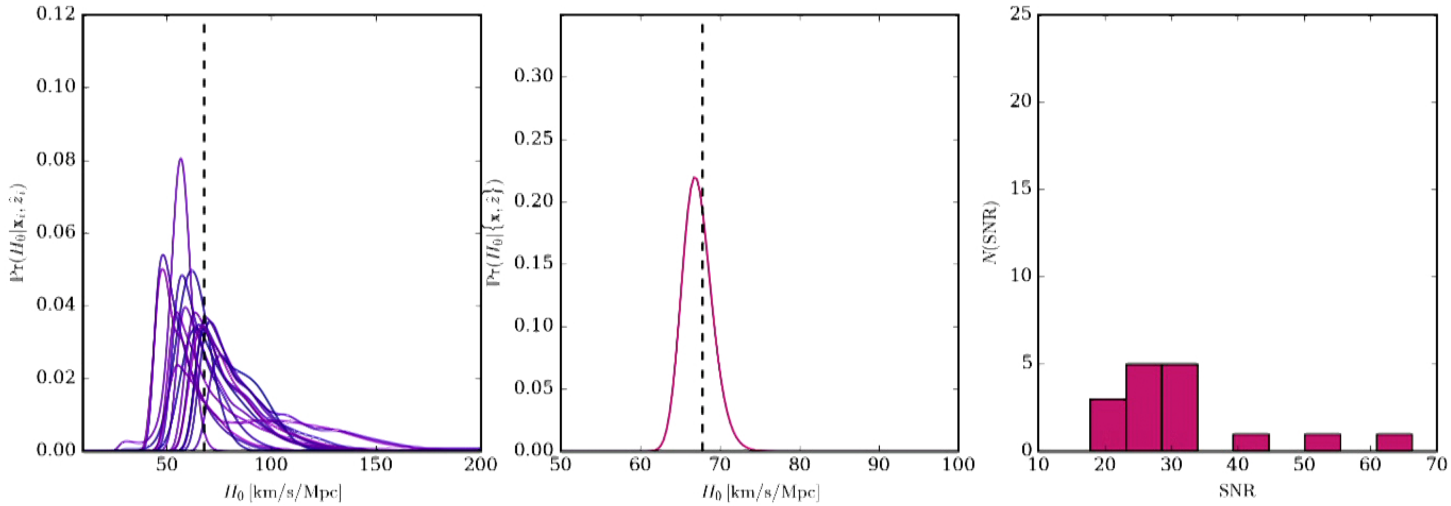

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22/34

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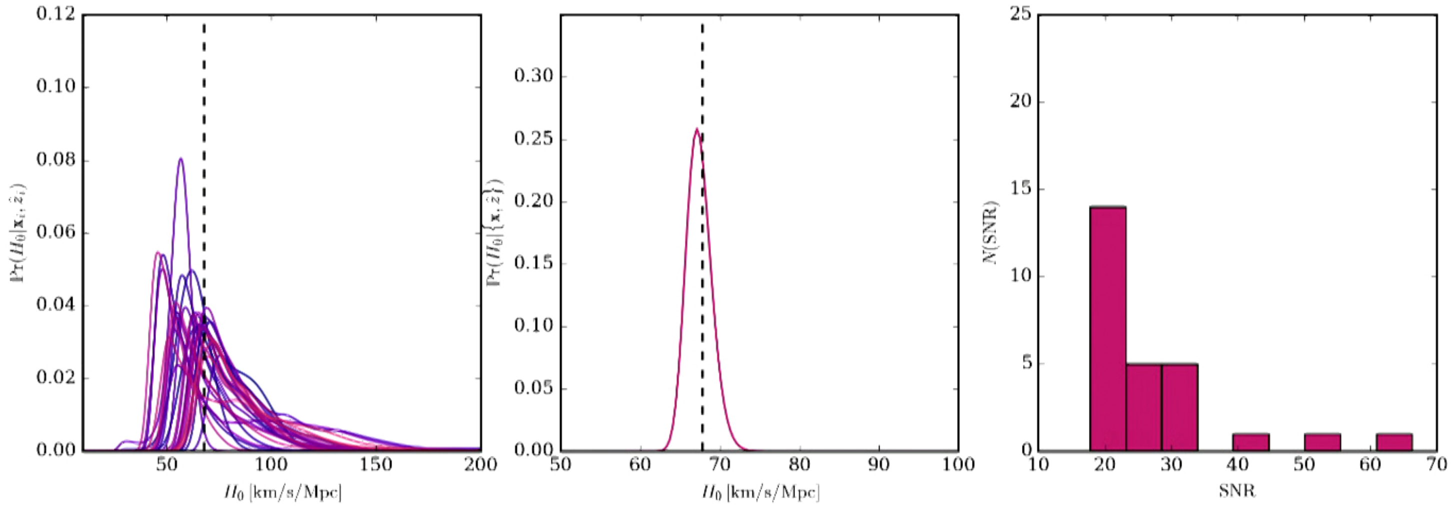

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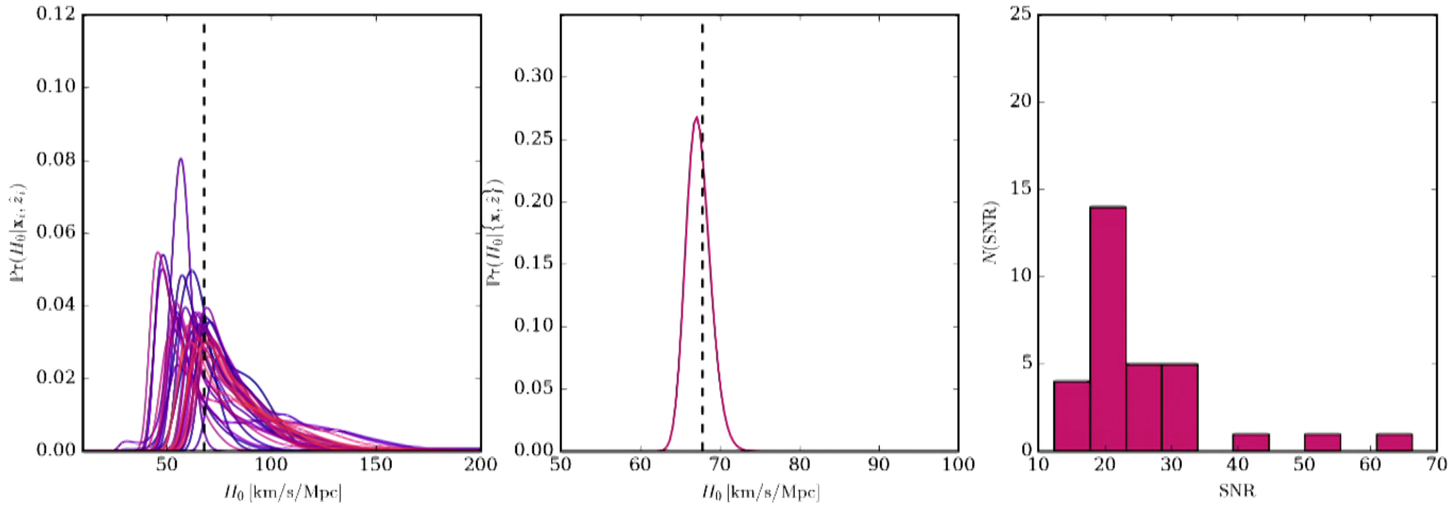

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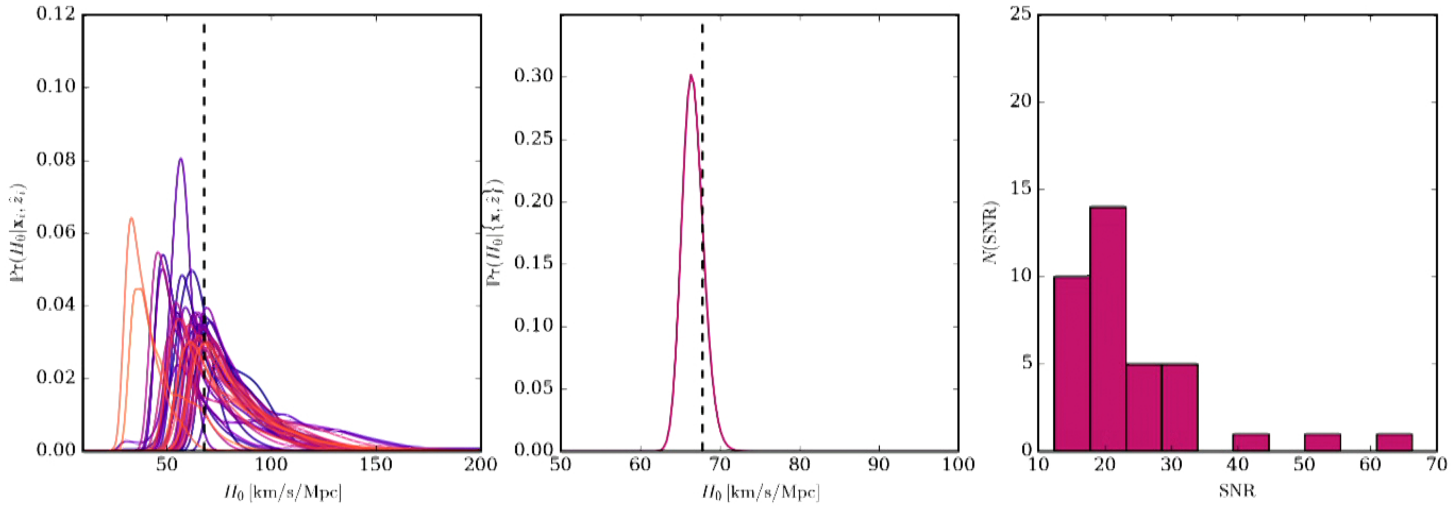

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22/34

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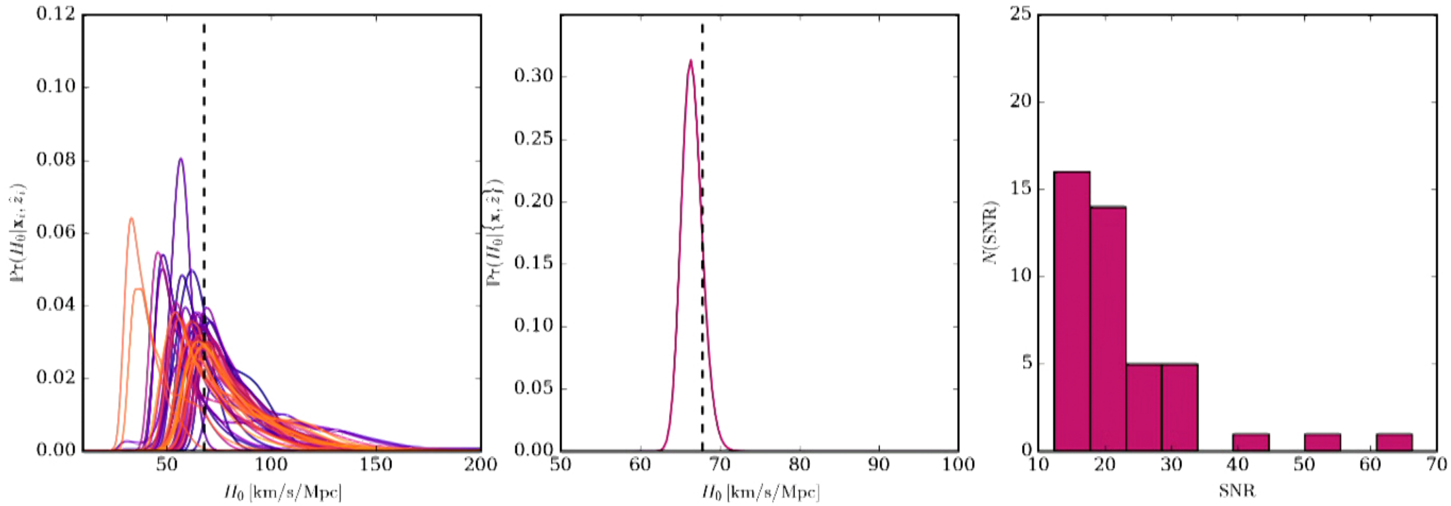

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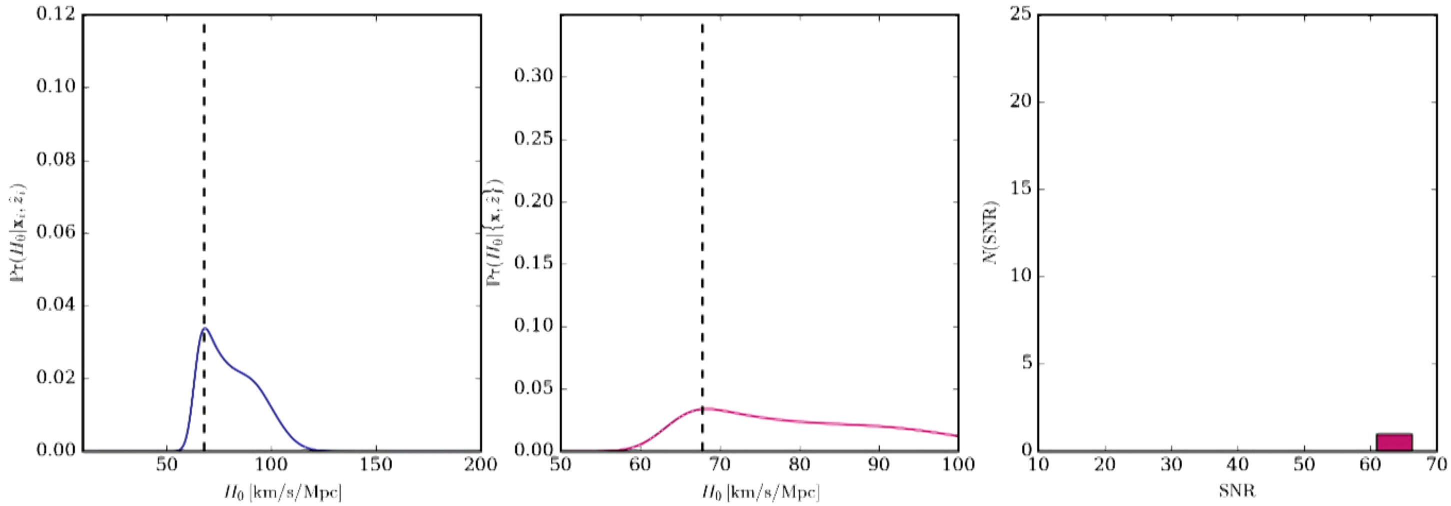


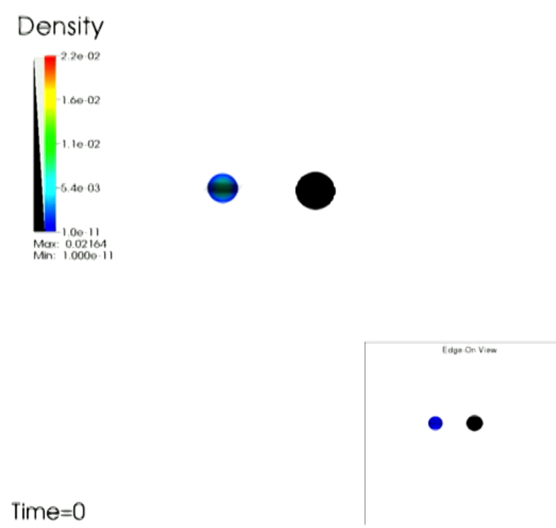
[see also Chen+ 2018, ...]

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

22/34

2) GW+EM: neutron star — black hole mergers for H0 may result in better distance measures

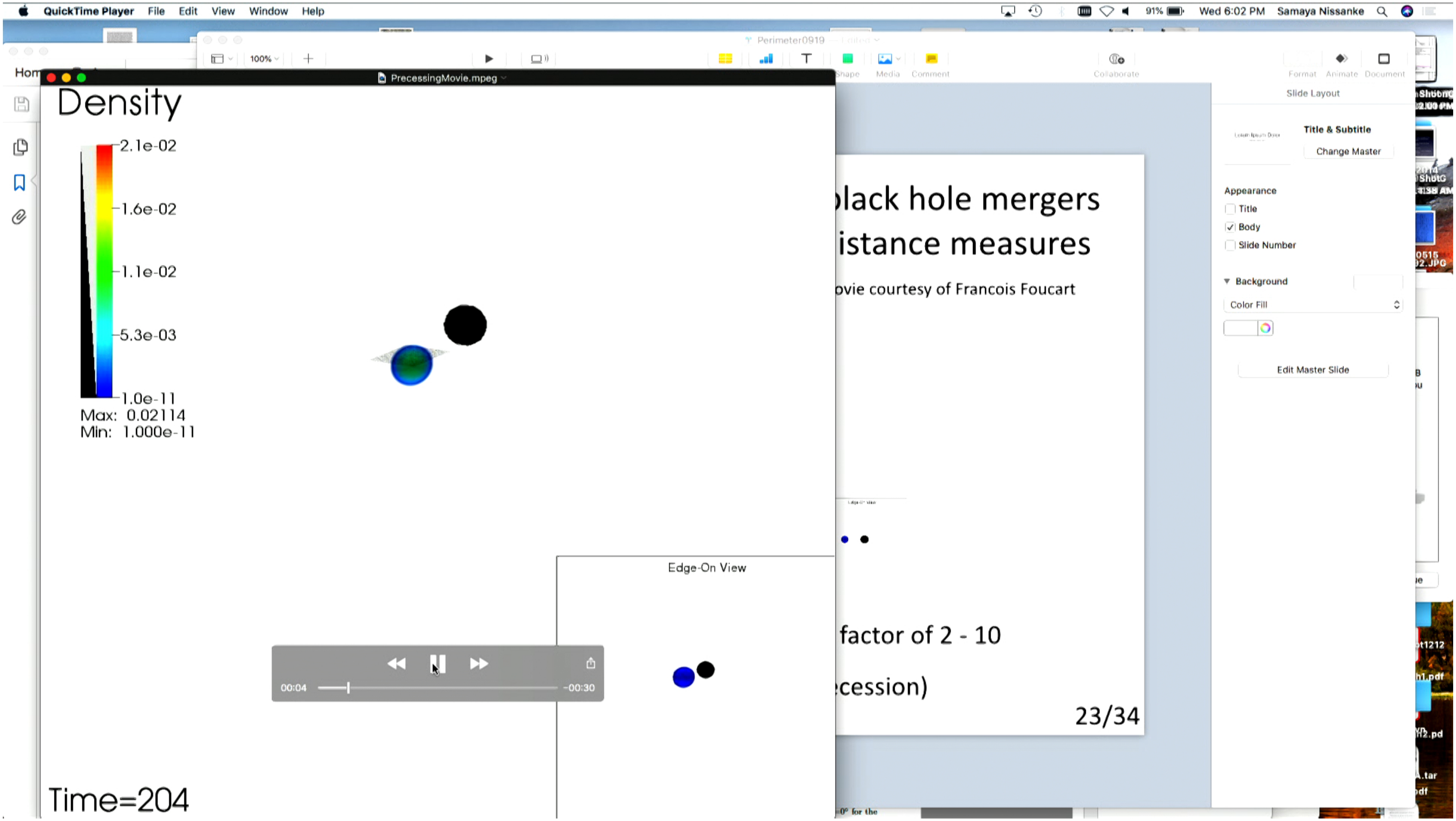
Movie courtesy of Francois Foucart



Distance measures improve by a factor of 2 - 10

(nearer to edge-on for precession)

[SN + 2010, Vitale et al. 2018]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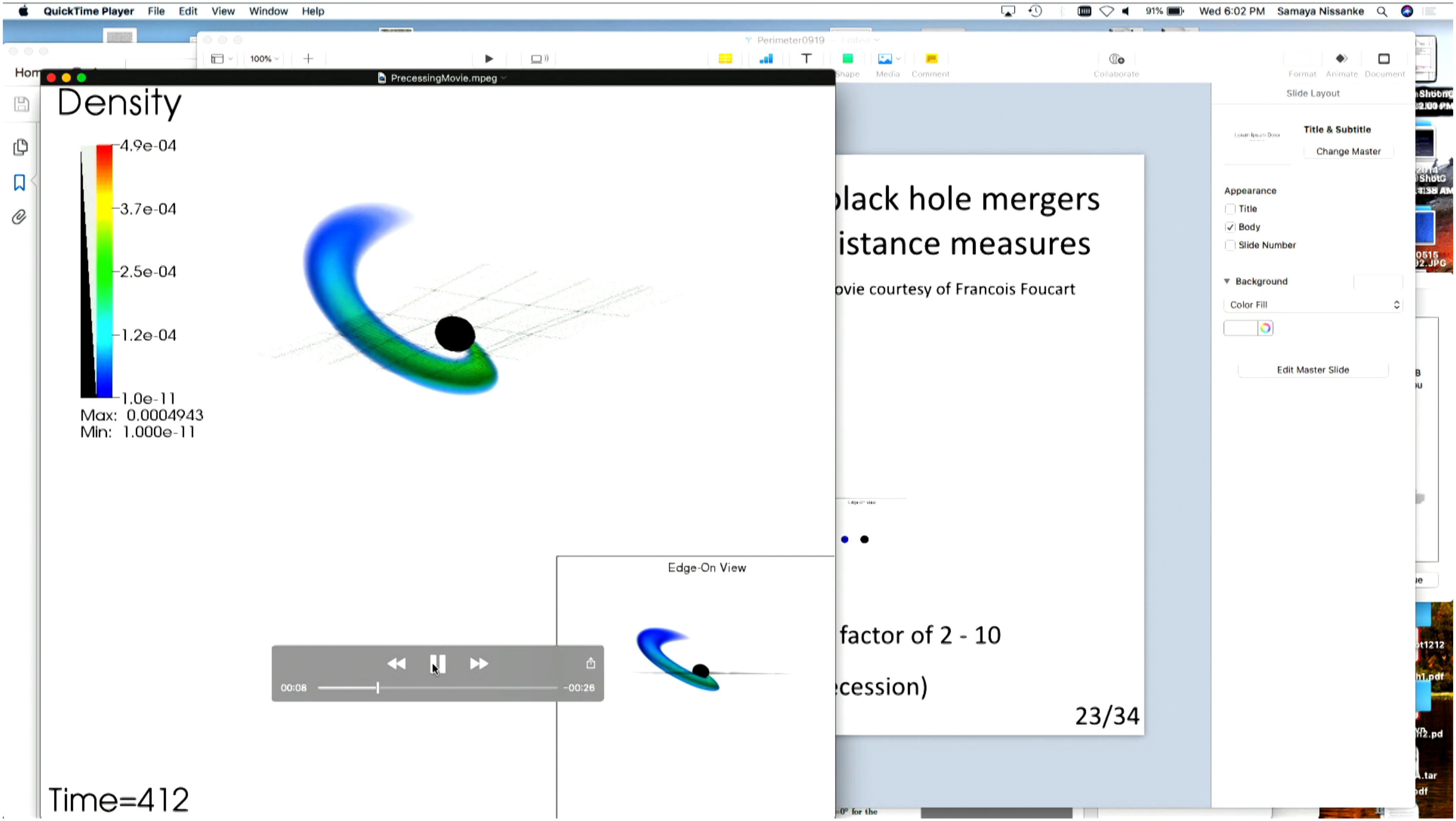
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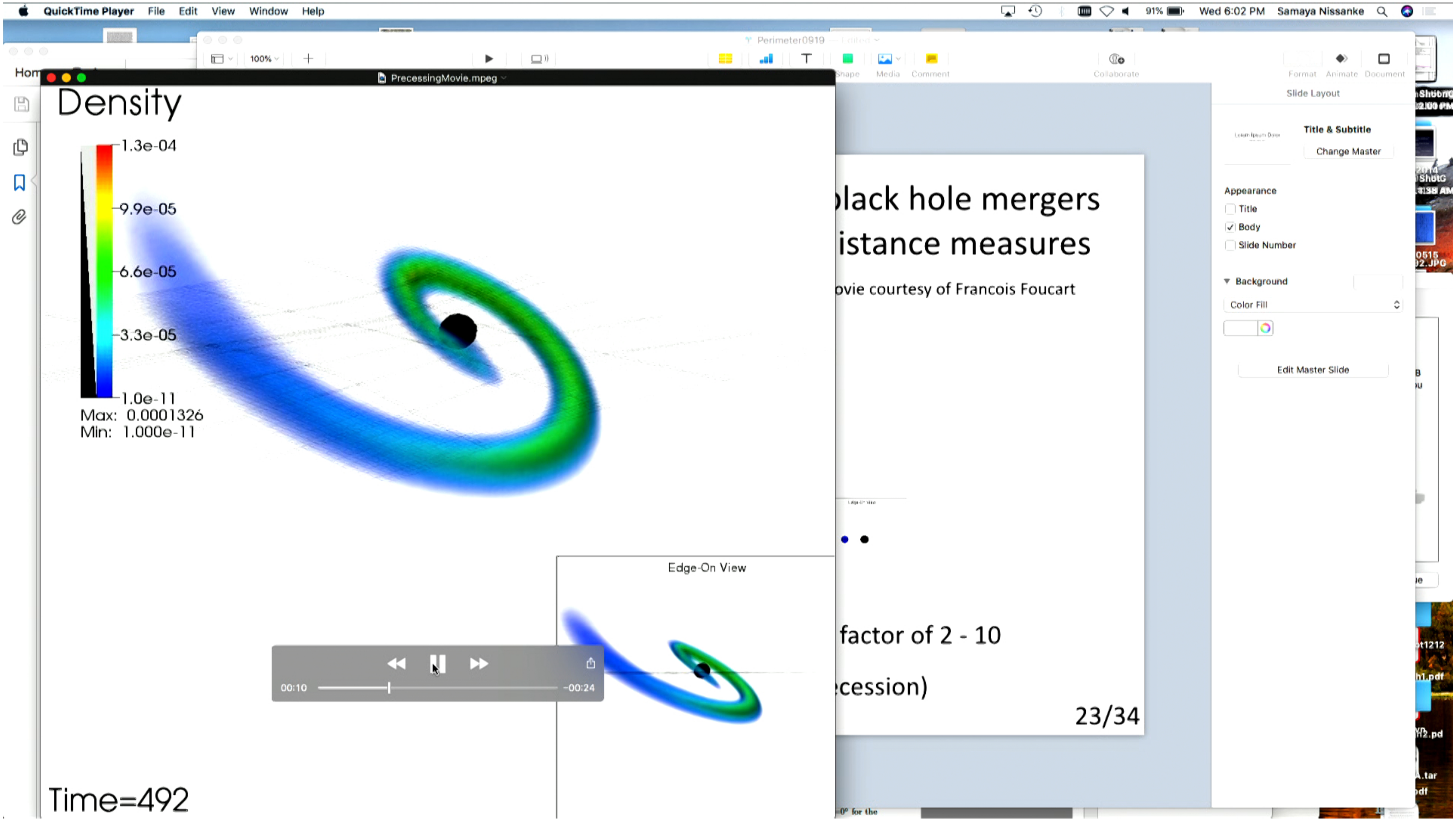
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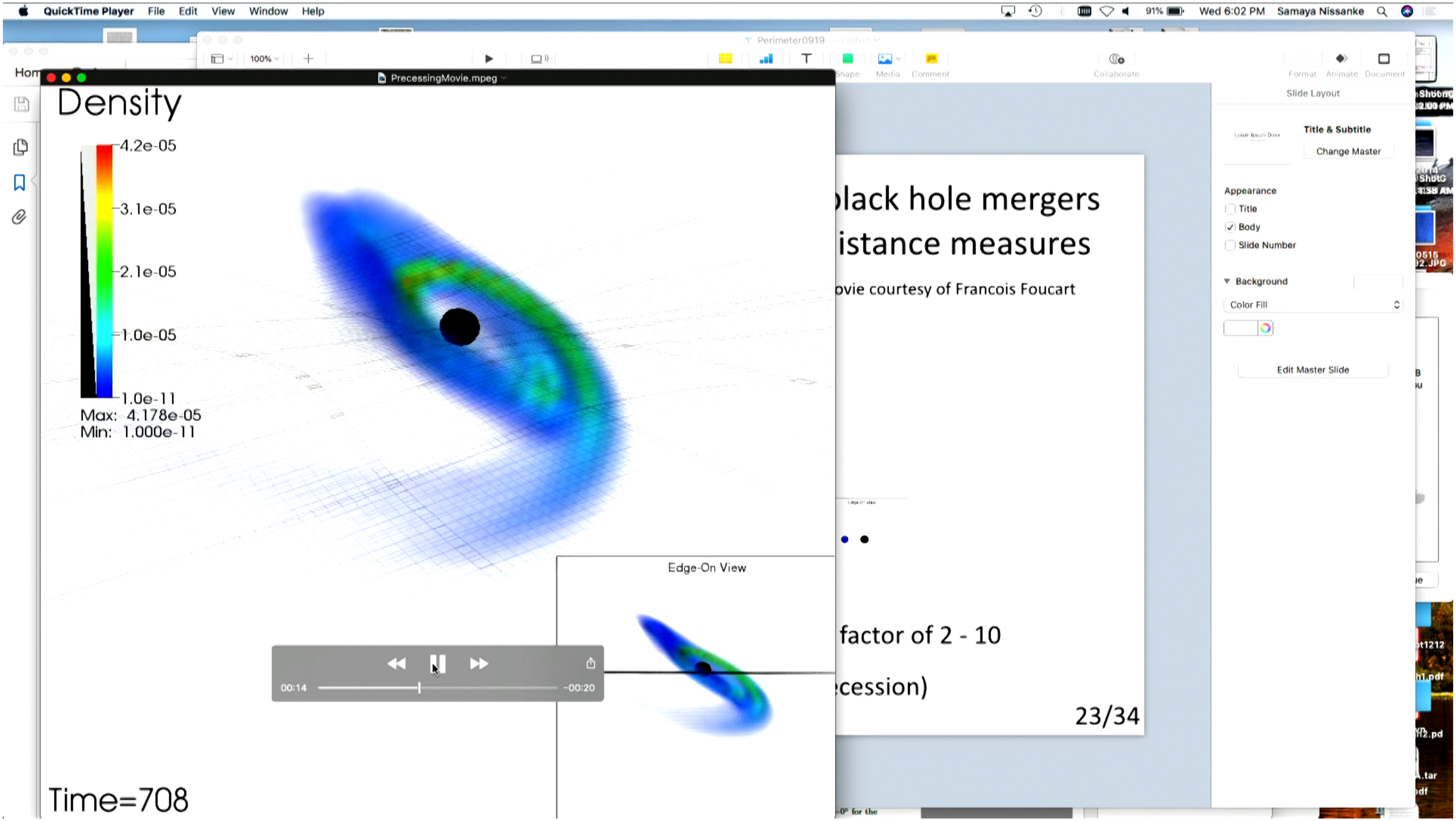

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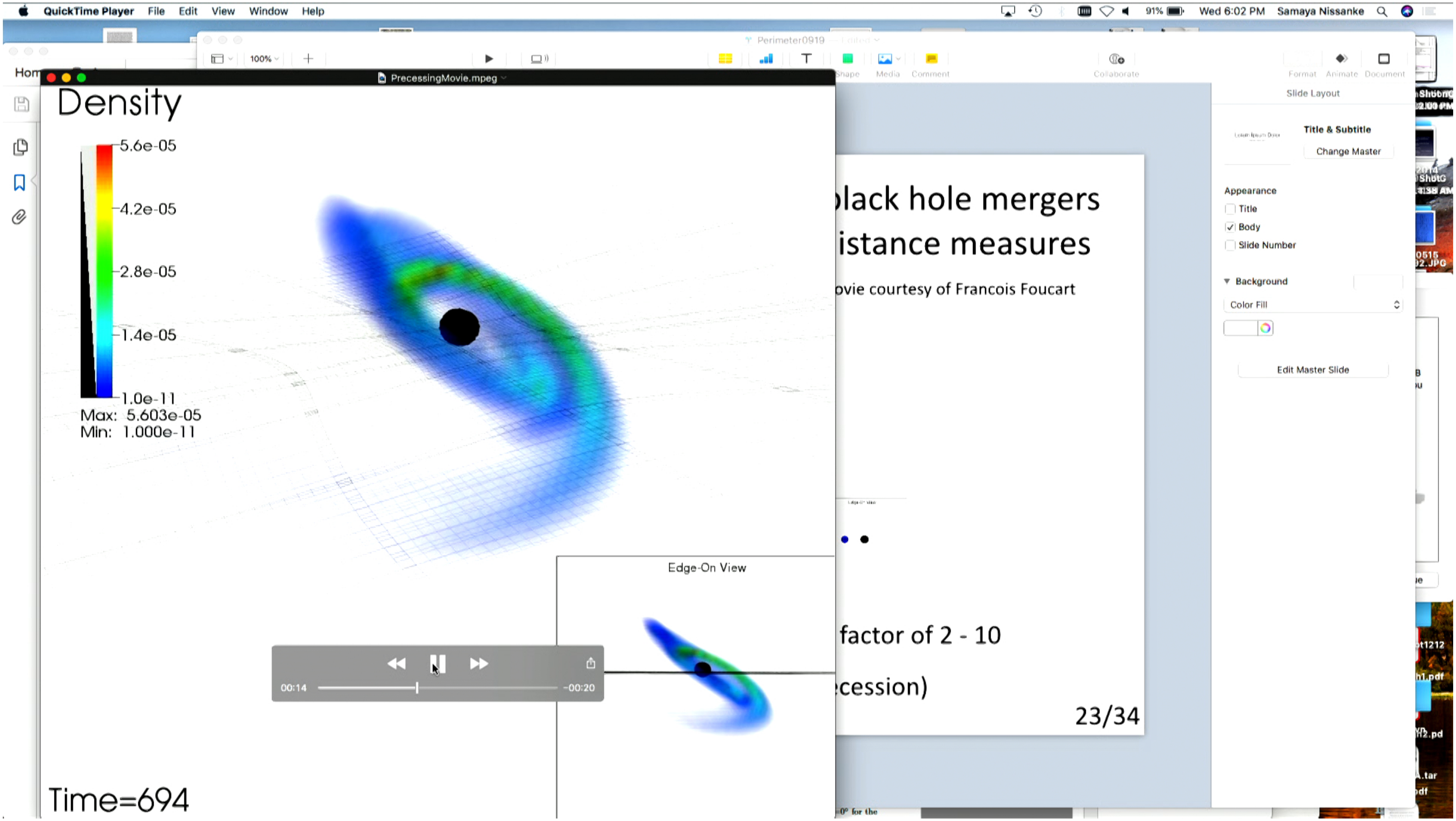
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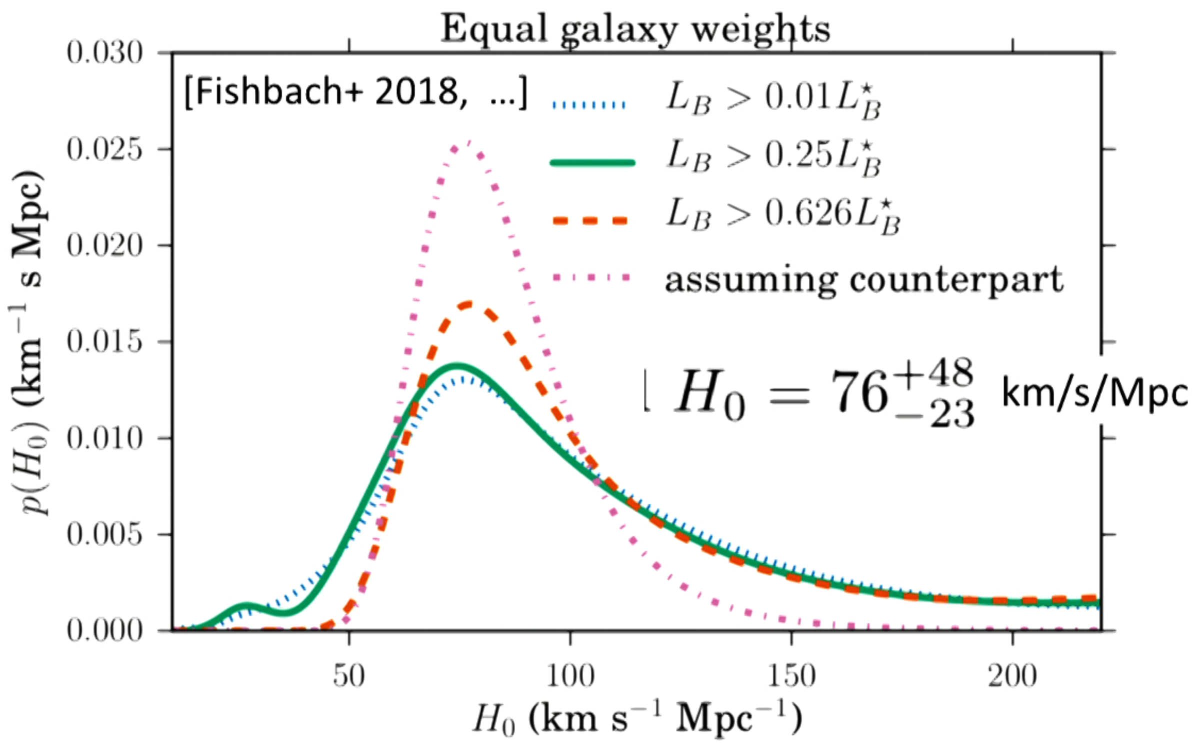
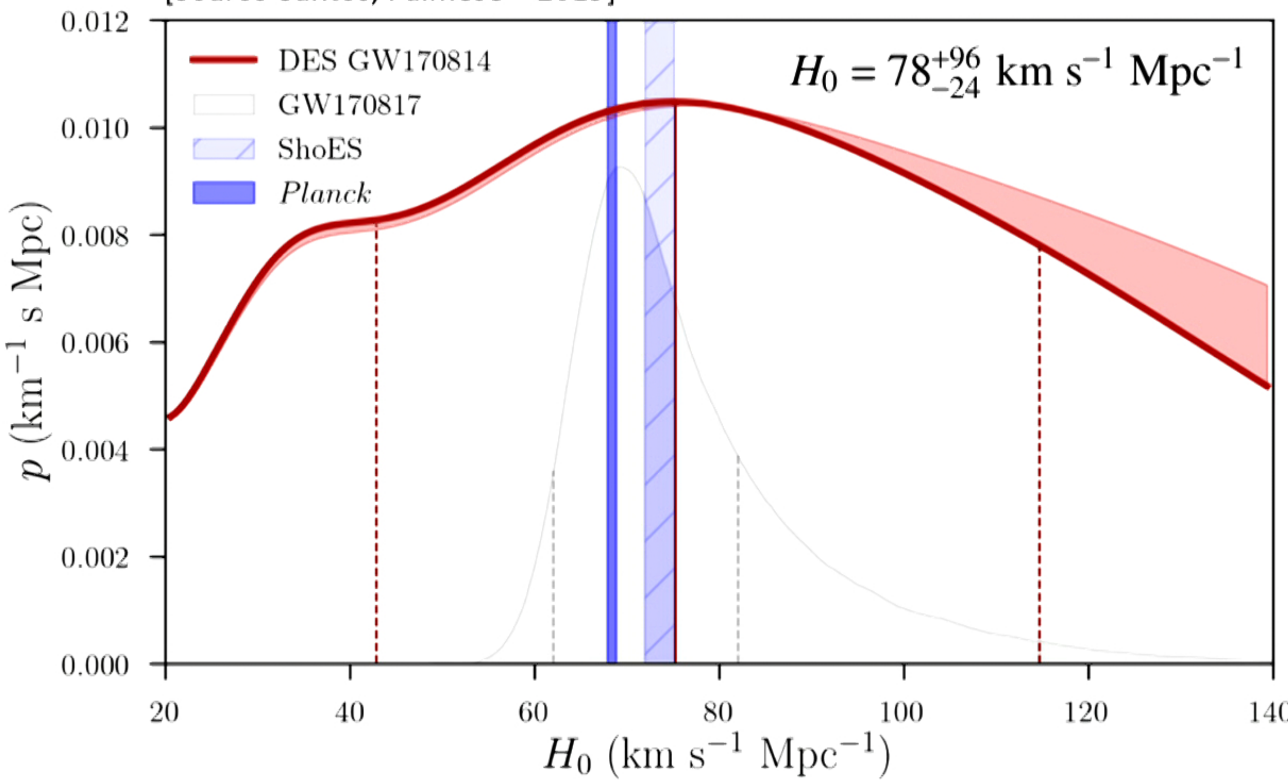
3) GW170817 with galaxy catalog & w/o counterpart:
Hubble measurement worsens by a factor of 2 or more



Completeness (~400 galaxies), Galaxy Weighting 24/34

4) GW without EM counterpart: Hubble for populations of BBH

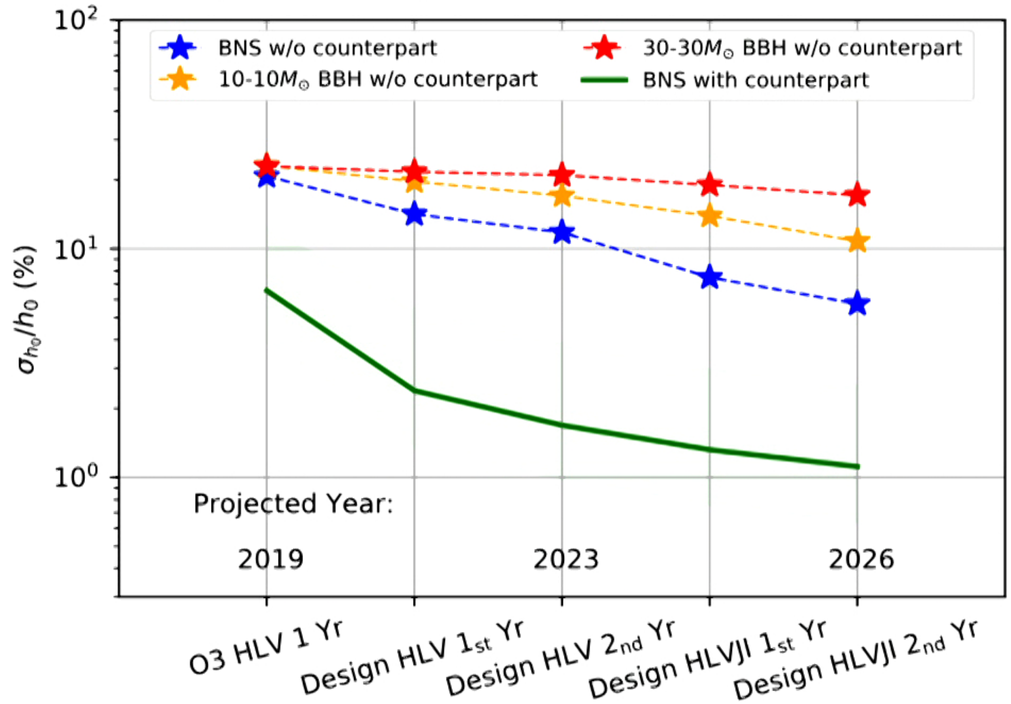
[Soaros-Santos, Palmese + 2019]



25/34

4) GW without EM counterpart: Hubble for populations of BBH

[Chen+, Nature 2018]



Without an EM counterpart: use of galaxy catalogs - O(100) for BBH to 5%

[Schutz, 1986; del Pozzo + 2012]

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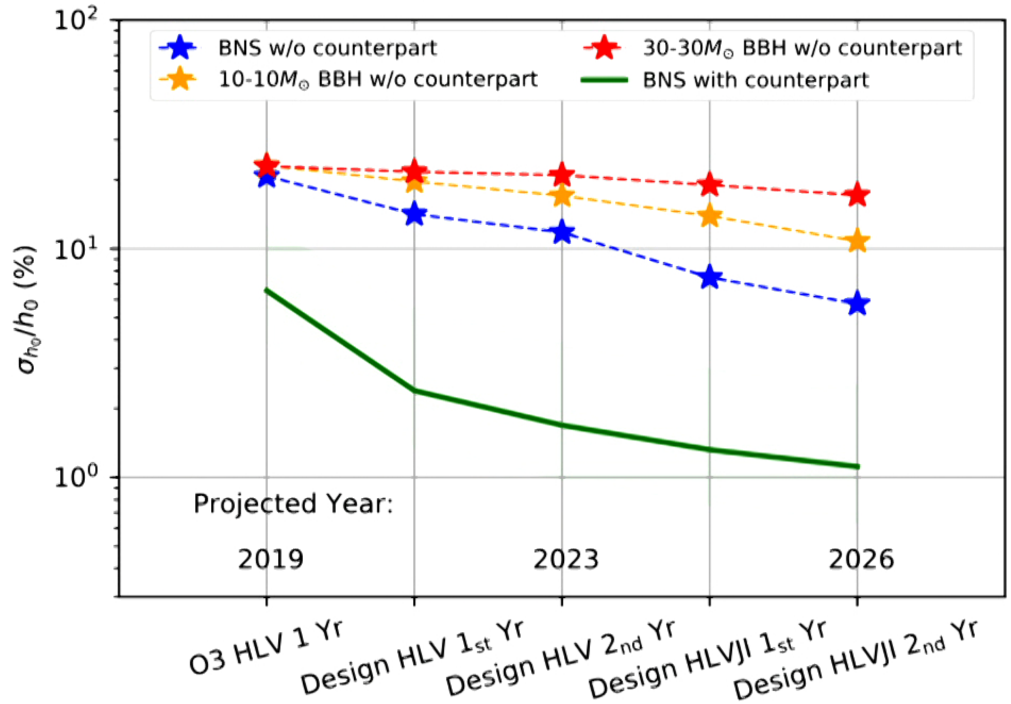


Without an EM counterpart: use of galaxy catalogs - O(100) for BBH to 5%

[Schutz, 1986; del Pozzo + 2012]

26/34

Part IV:

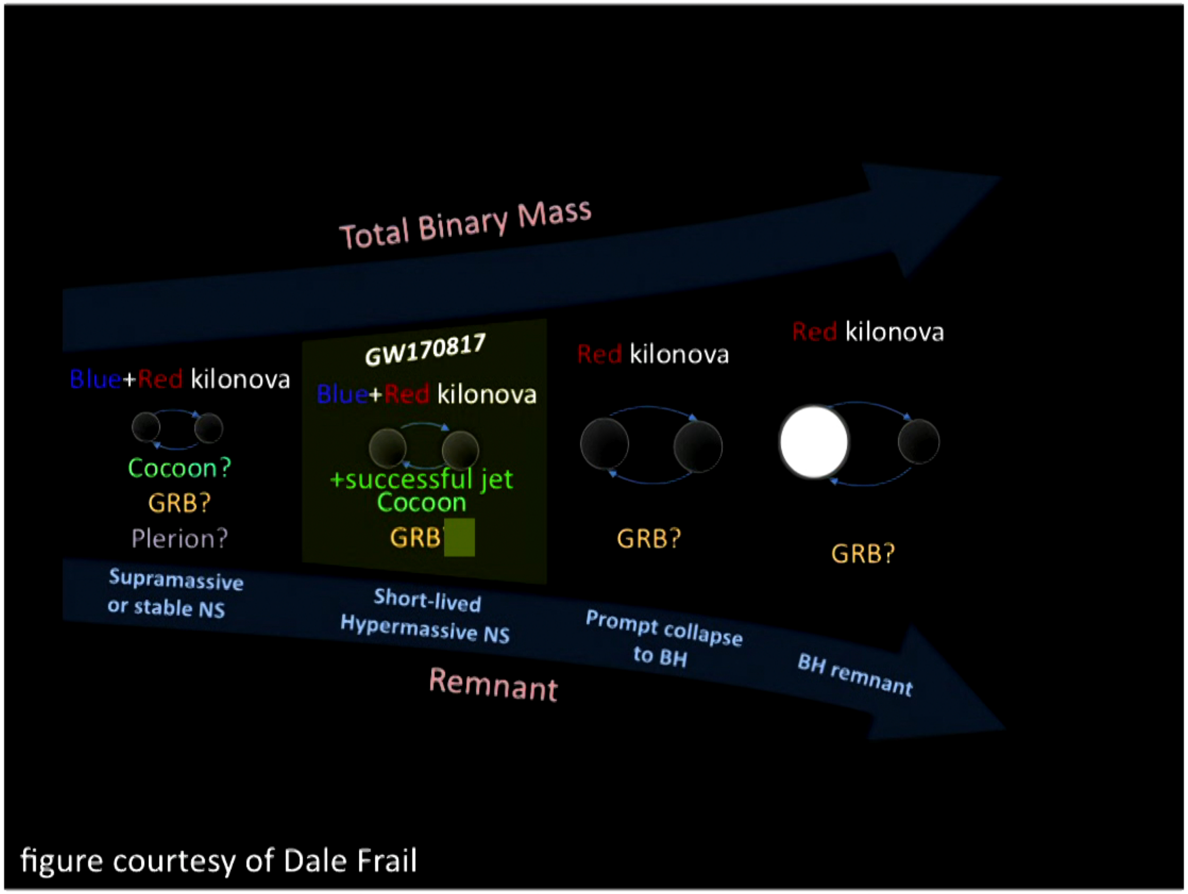
Perspectives

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

small GW volume

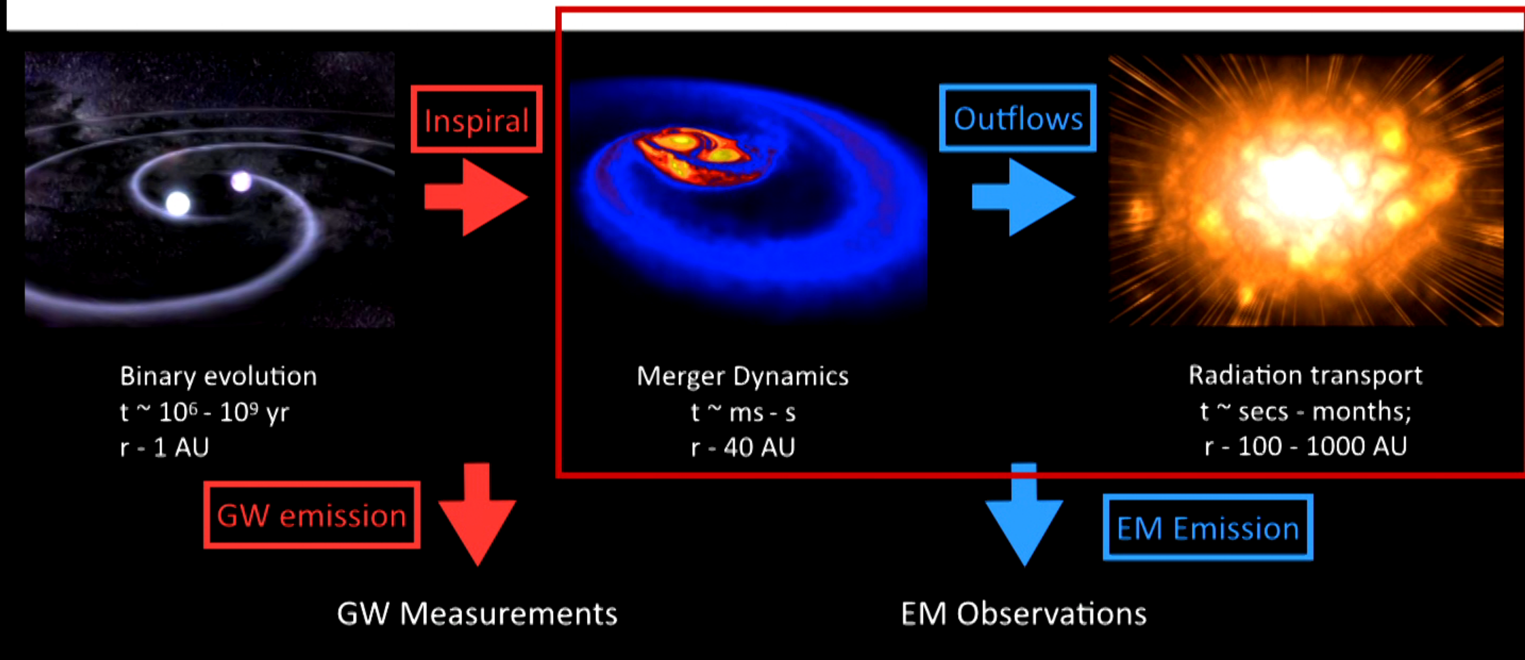
[LVC, arXiv: 1811.15007
arXiv: 1901.03310, 2019]

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



27/34

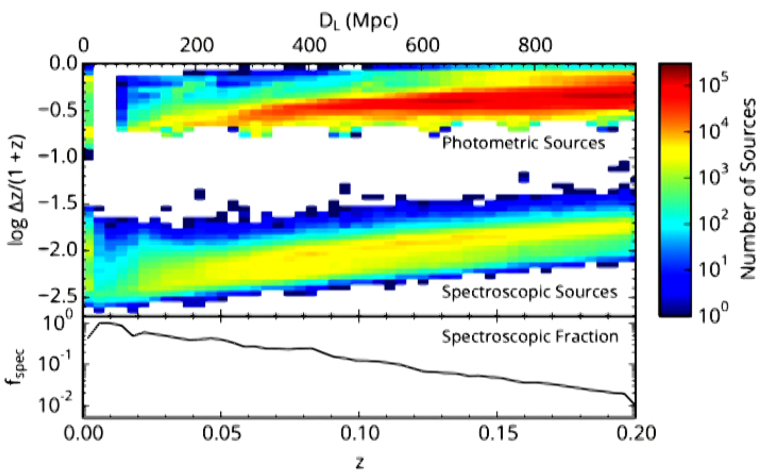
2. GW+EM challenge remains to build a coherent model: a key step to joint characterization



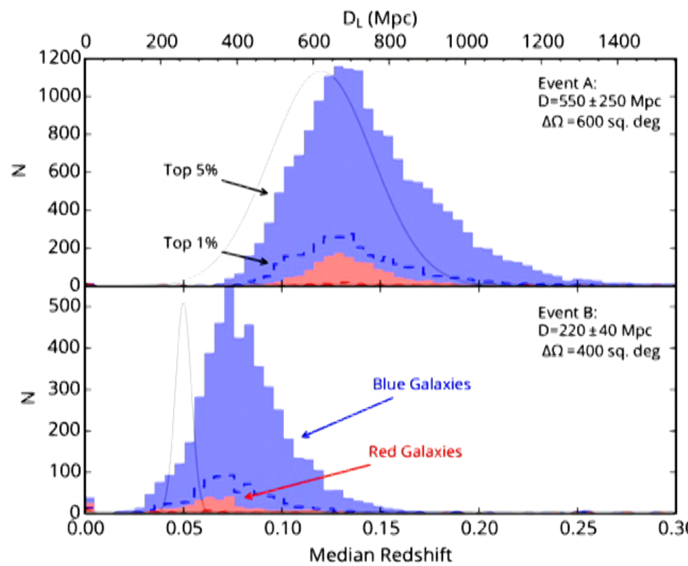
Outflows carry energy from small (10^6 cm) to large distances (10^{14}-10^{16} cm) for radiation to escape.

3. GW with Statistical host galaxy demographics

[Rahman, Nissanke+, in prep; see also DES photo-z]



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



[complementary to direct binary formation channel methods]

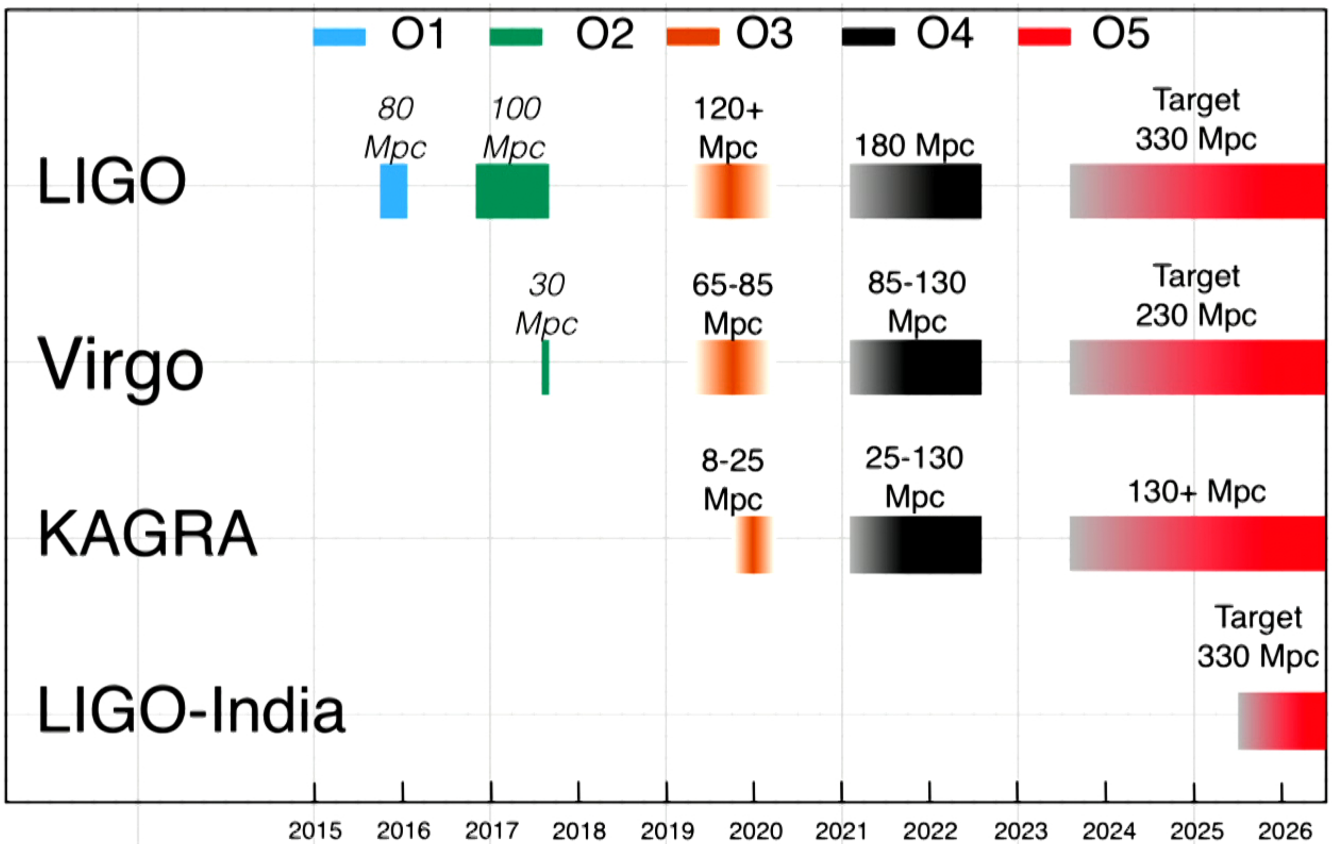
Finding the EM counterpart:

<u>Big data in Astro</u>: Reduce astrophysical transients by factor of 10-100s.

[Nissanke, Kasliwal + 2013; Gehrels,...SN+, 2015; Corley,.., Williamson, SN+ 2019]

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

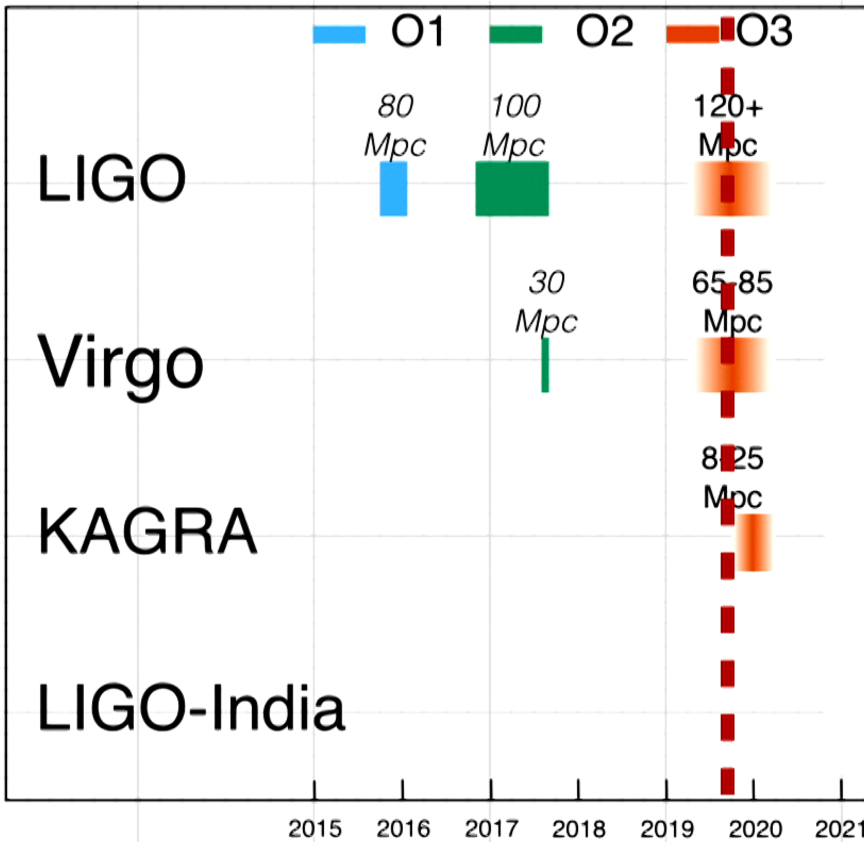
[B. P. Abbott et al., Living Rev Relativ (2018) 21:3]



29

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

[B. P. Abbott et al., Living Rev Relativ (2018) 21:3]



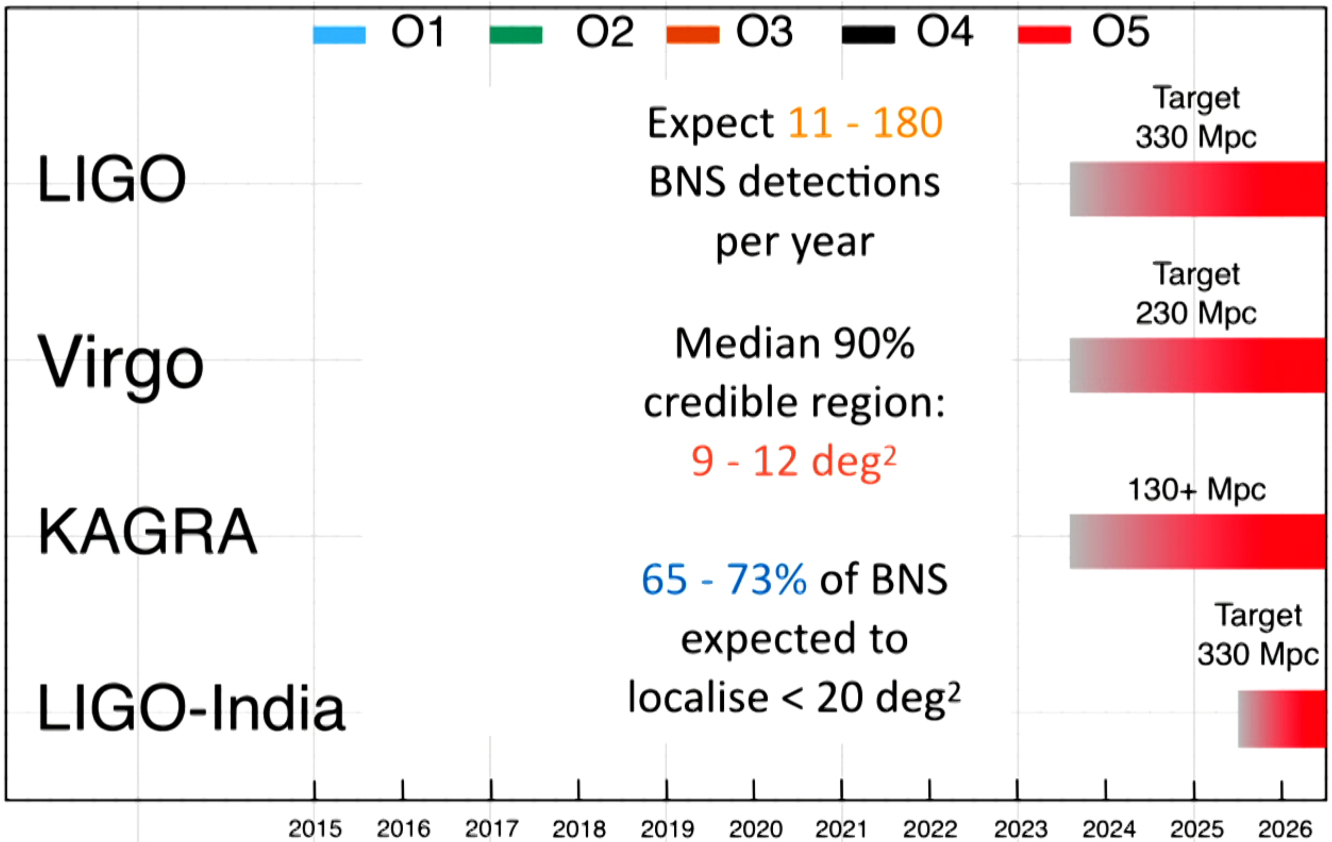
Expect 1 - 50 BNS detections

Median 90% credible region: 120 - 180 deg²

12 - 21% of BNS expected to localise < 20 deg²

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

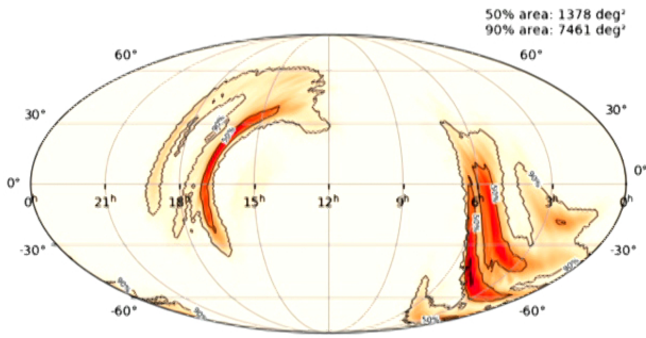
[B. P. Abbott et al., Living Rev Relativ (2018) 21:3]



29

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!
(x340 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 and GROWTH follow up papers arXiv:1907.12634]

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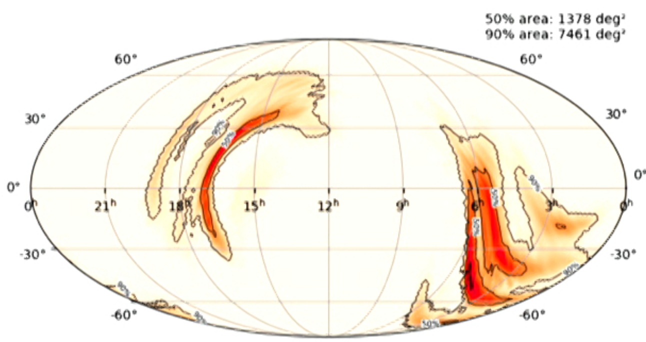

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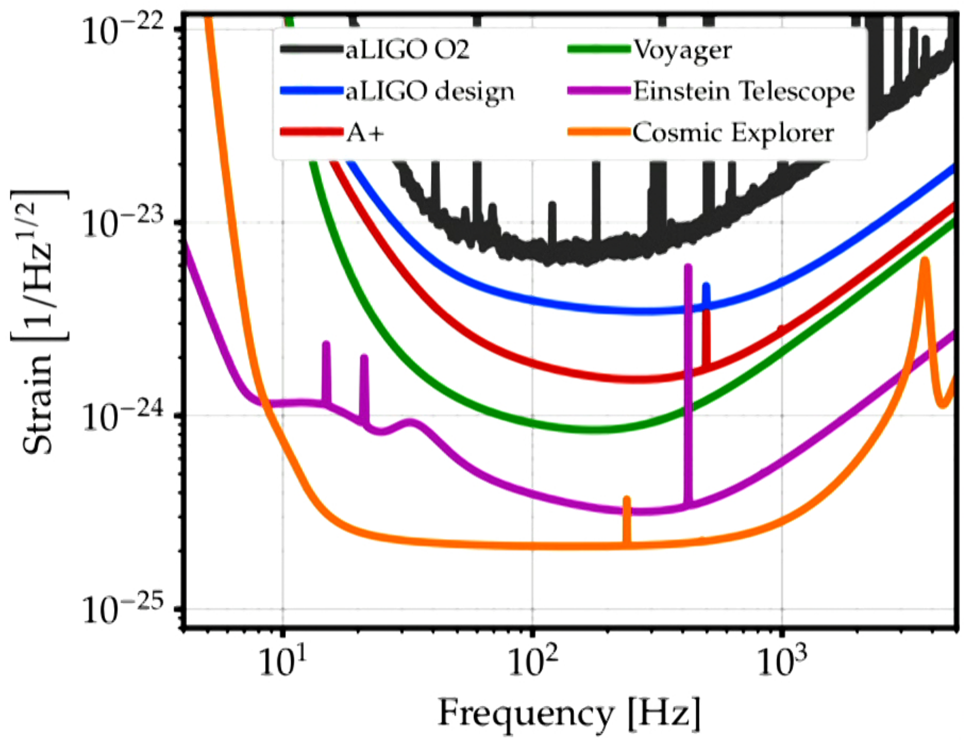
30/34

Mid 2020s - 2030: aLIGO+, Einstein Telescope



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

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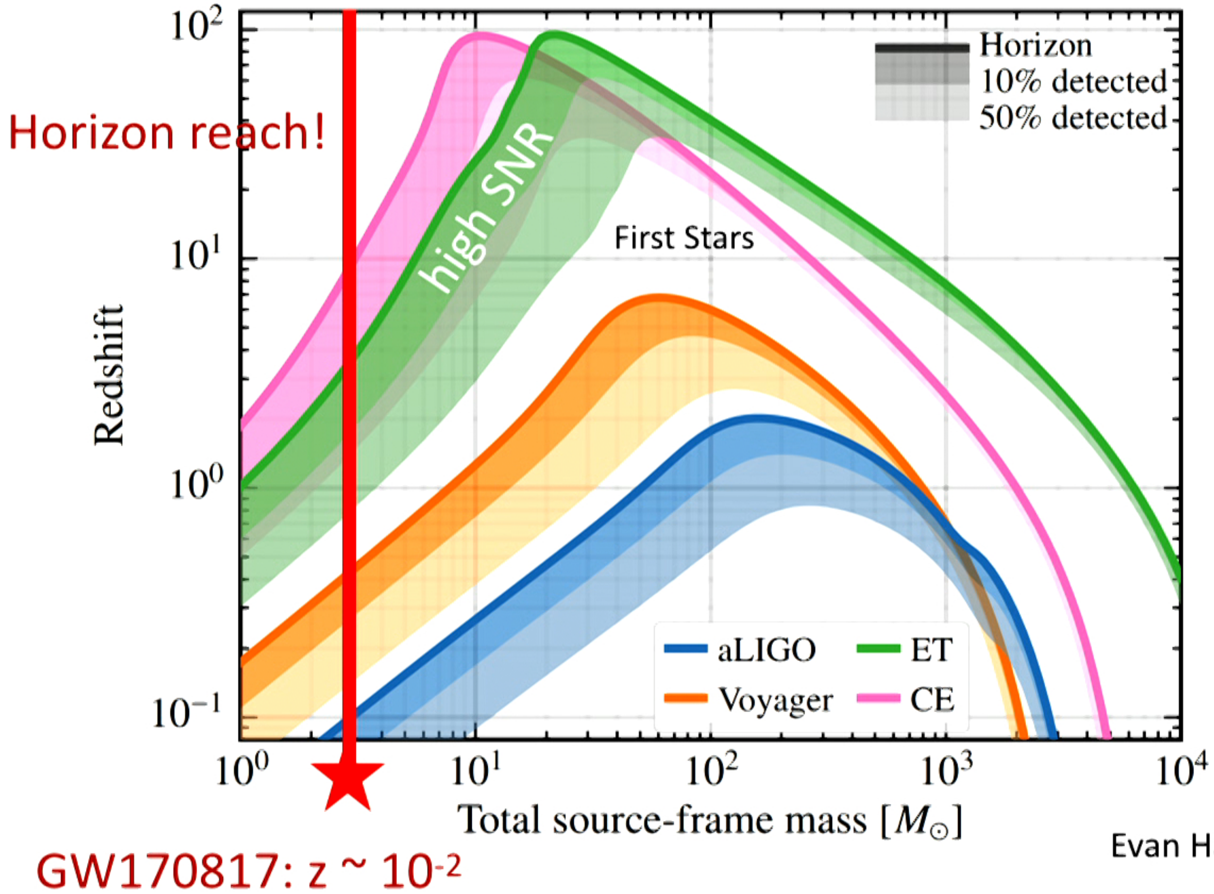
2030s: Einstein Telescope and Cosmic Explorer have cosmological reach

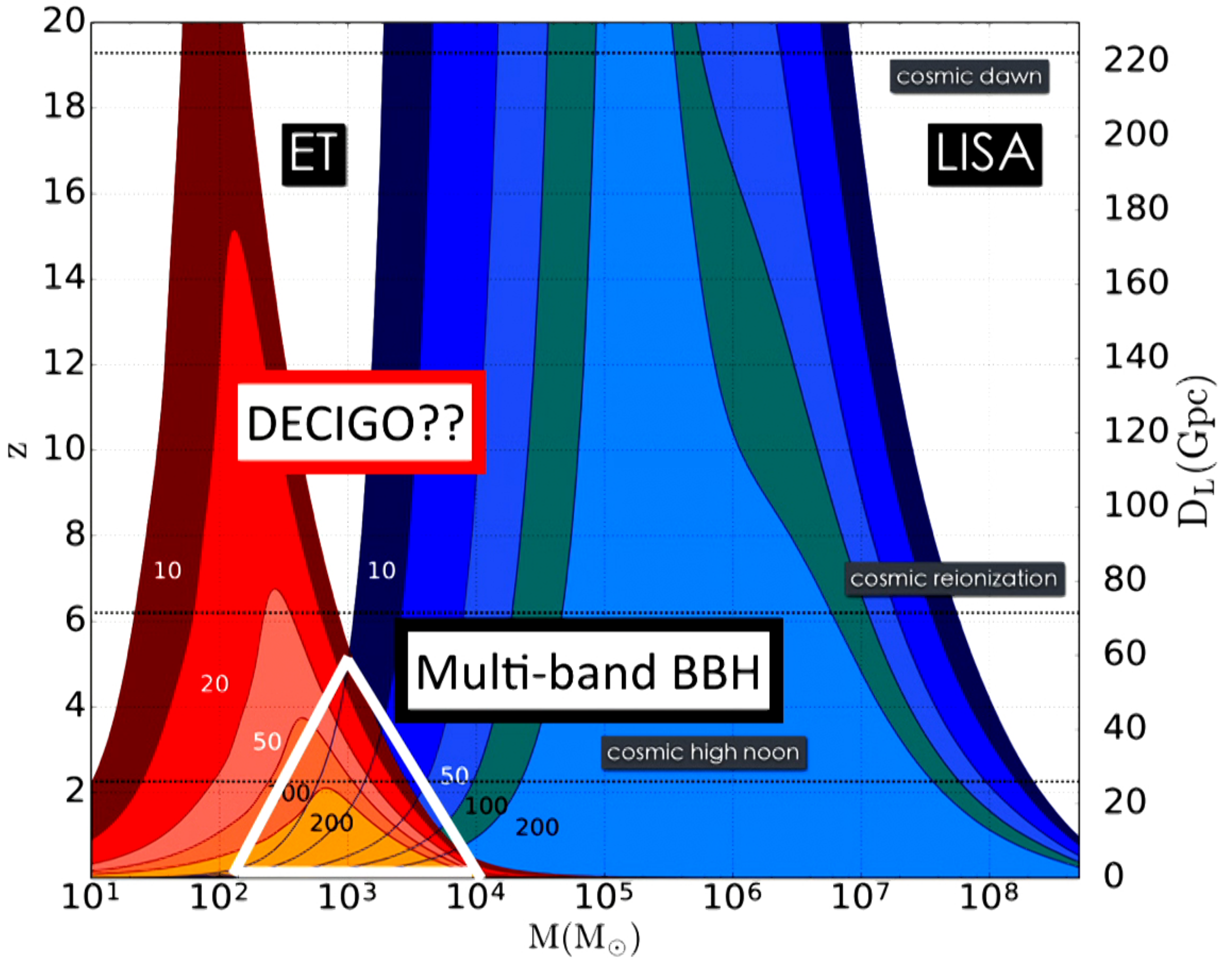
MMA co-chair with Kasliwal and Bailes



Evan Hall, MIT

32

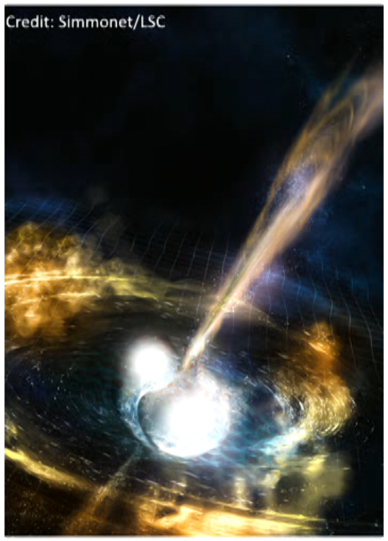
LISA MMA co-chair with Baker and Haiman



Alberto Sesana (Birmingham)

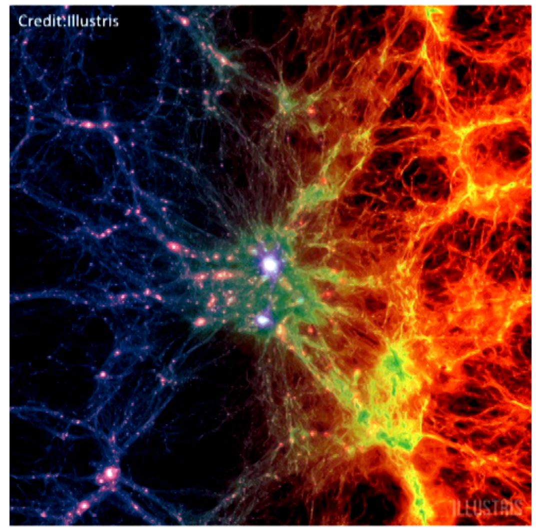
MMO in 2030s is <u>not just</u> EM follow up!

EM follow up of single sources



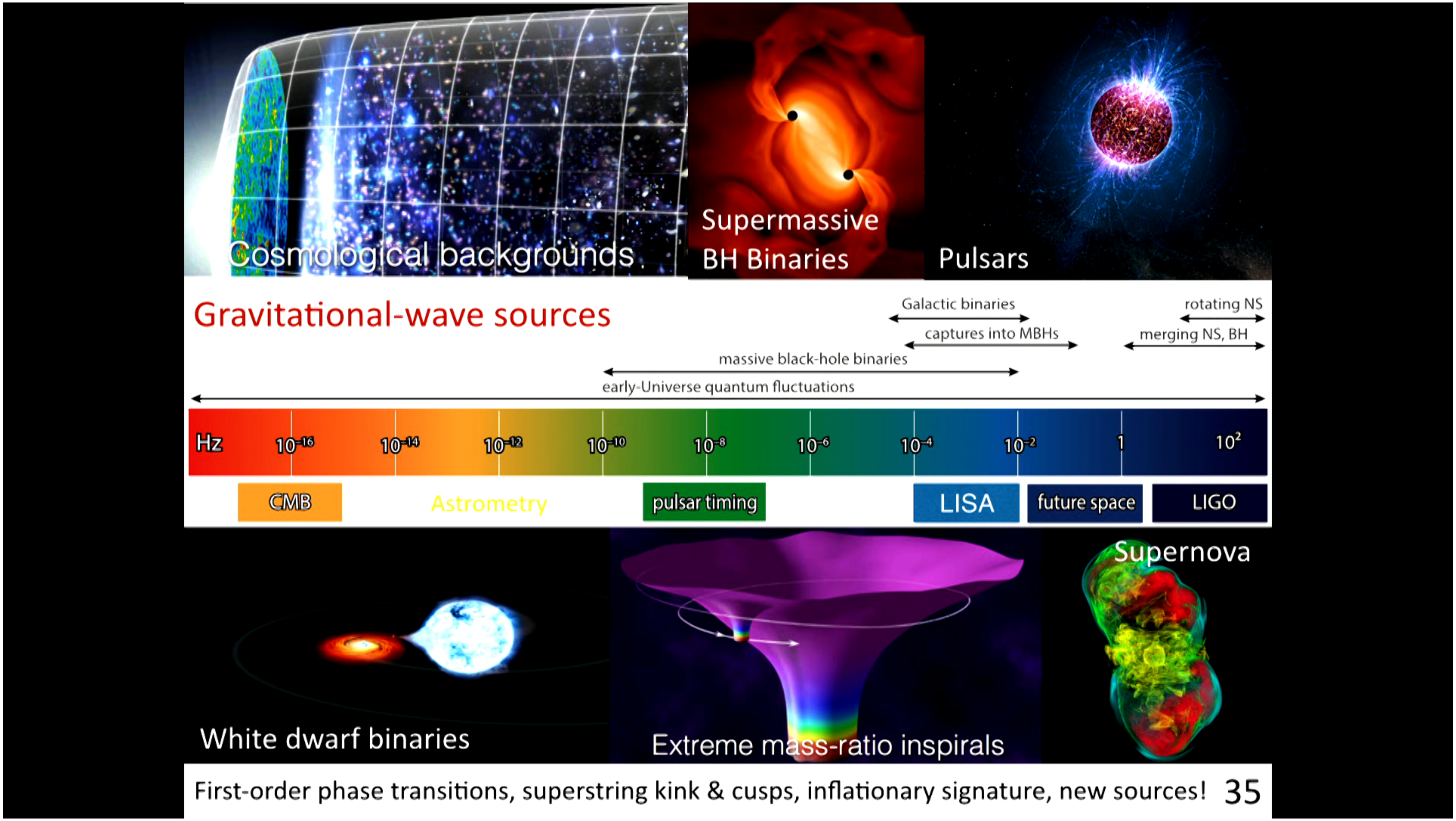
Cherry Pick Loud events - golden for GW+EM

Cross correlating GW and EM source catalogs



Large Scale Structure; Extragalactic Astronomy

34


Cosmological backgrounds
Supermassive
BH Binaries
Pulsars
Gravitational-wave sources
Galactic binaries
rotating NS
captures into MBHs
merging NS, BH
massive black-hole binaries
early-Universe quantum fluctuations
Hz
10^-16
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
CMB
Astrometry
pulsar timing
LISA
future space
LIGO
Supernova
White dwarf binaries
Extreme mass-ratio inspirals
First-order phase transitions, superstring kink & cusps, inflationary signature, new sources!
35

Conclusions

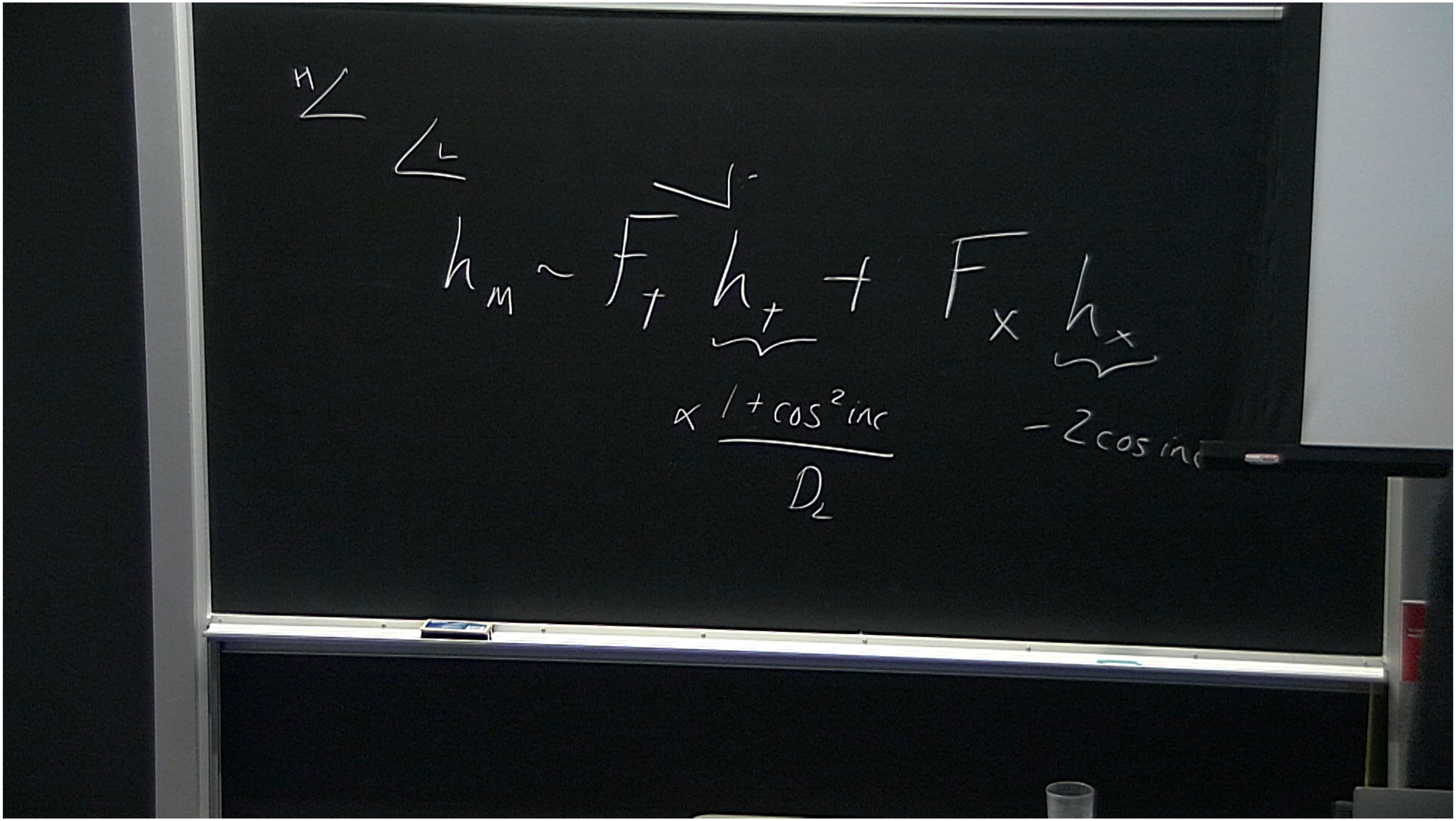
Immediately : GW detector sensitivity & network increases =>
First NS-BH merger! SNe! Tens of BBH mergers yr^{-1} and several of NS-NS yr^{-1}

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.


Supernova
new sources! 35
CAUTION


$h_m \sim F_+ h_+ + F_\times h_\times$
$\propto \frac{1+\cos^2 inc}{D_L}$
$-2\cos inc$