Title: Advanced LIGO and the first years of gravitational-wave astrophysics

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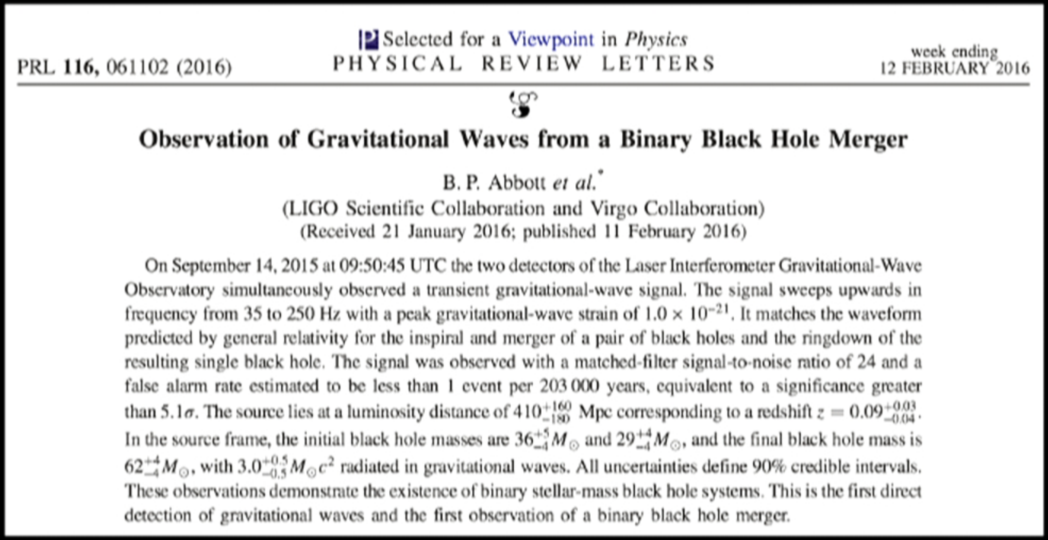
Abstract: <p>Almost fifteen years after LIGO started listening to the cosmos, and 100 years after Einstein discovered general relativity, gravitational waves have been detected by ground-based interferometers, opening a new window on the universe. In this talk I will address some of the most exciting areas of research advanced LIGO will allow us to explore in the coming years. Detection and characterization of gravitational wave transients will be discussed, as well as their impact on astrophysics.</p>

Advanced LIGO and the first years of gravitational wave astrophysics

Salvatore Vitale
MIT- LIGO Laboratory

Perimeter Institute – University of Guelph
March 2016

You might have heard…
GW150914



Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

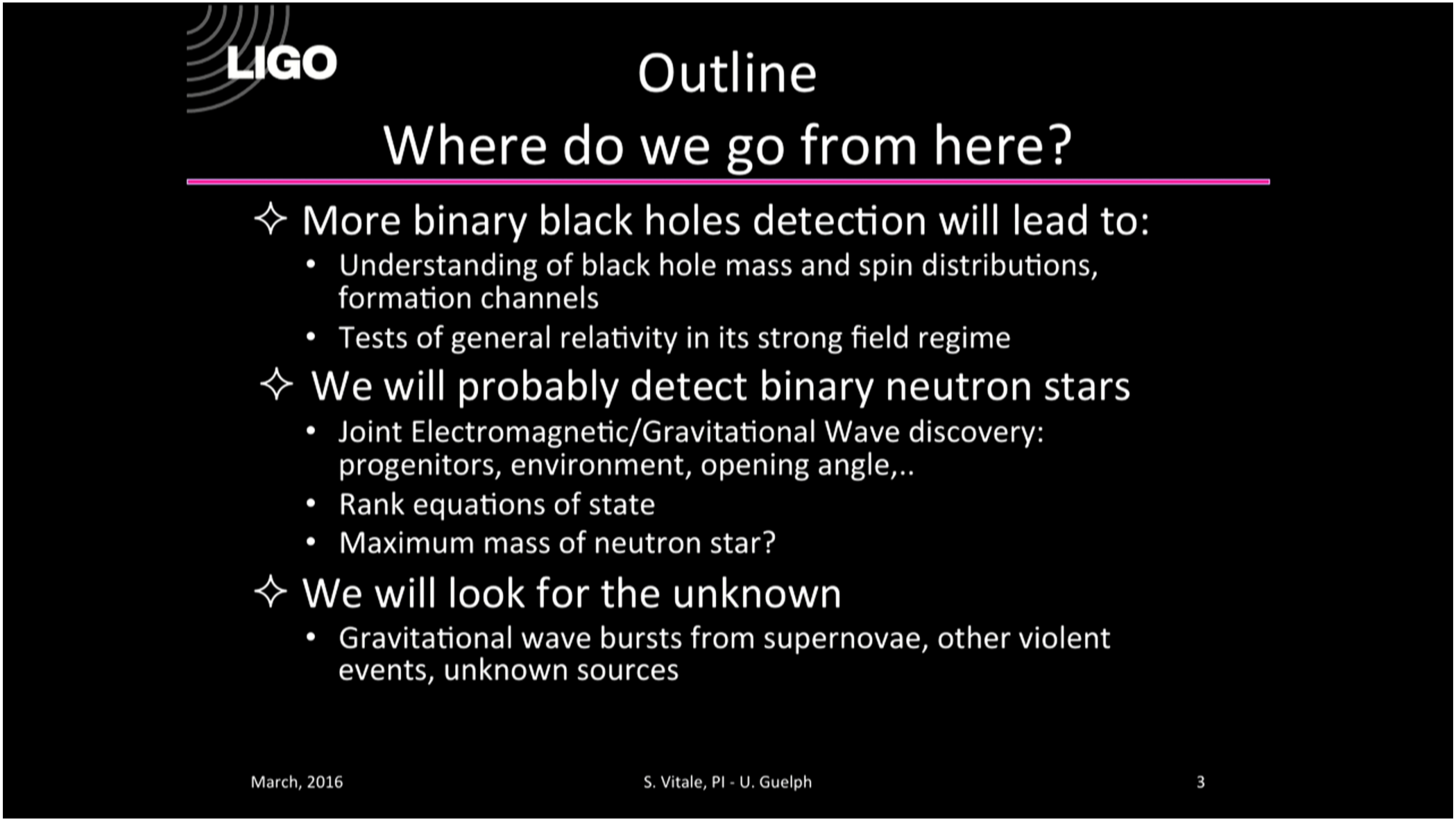
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$, and the final black hole mass is $62^{+4}_{-4} M_{\odot}$, with $3.0^{+0.5}_{-0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

First detection of gravitational waves (GW)
First observation of binary black hole (BBH) merger
First test of general relativity in its strong field dynamical regime
Existence of tens of solar masses black holes (BH)



Outline

Where do we go from here?

✧ More binary black holes detection will lead to:

- Understanding of black hole mass and spin distributions, formation channels
- Tests of general relativity in its strong field regime

✧ We will probably detect binary neutron stars

- Joint Electromagnetic/Gravitational Wave discovery: progenitors, environment, opening angle,..
- Rank equations of state
- Maximum mass of neutron star?

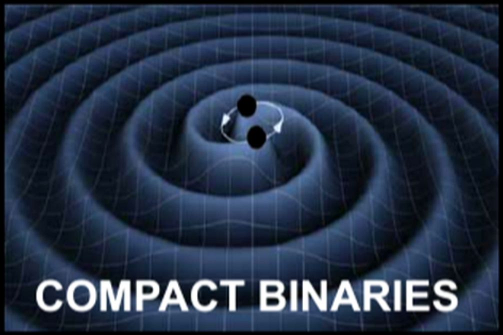
✧ We will look for the unknown

- Gravitational wave bursts from supernovae, other violent events, unknown sources

LIGO

Sources of gravitational waves

TRANSIENT

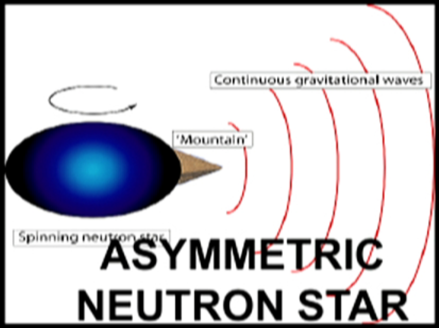


COMPACT BINARIES

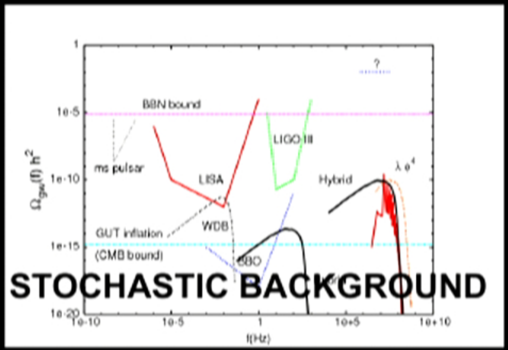
BURSTS

Core collapse Supernovae

PERSISTENT



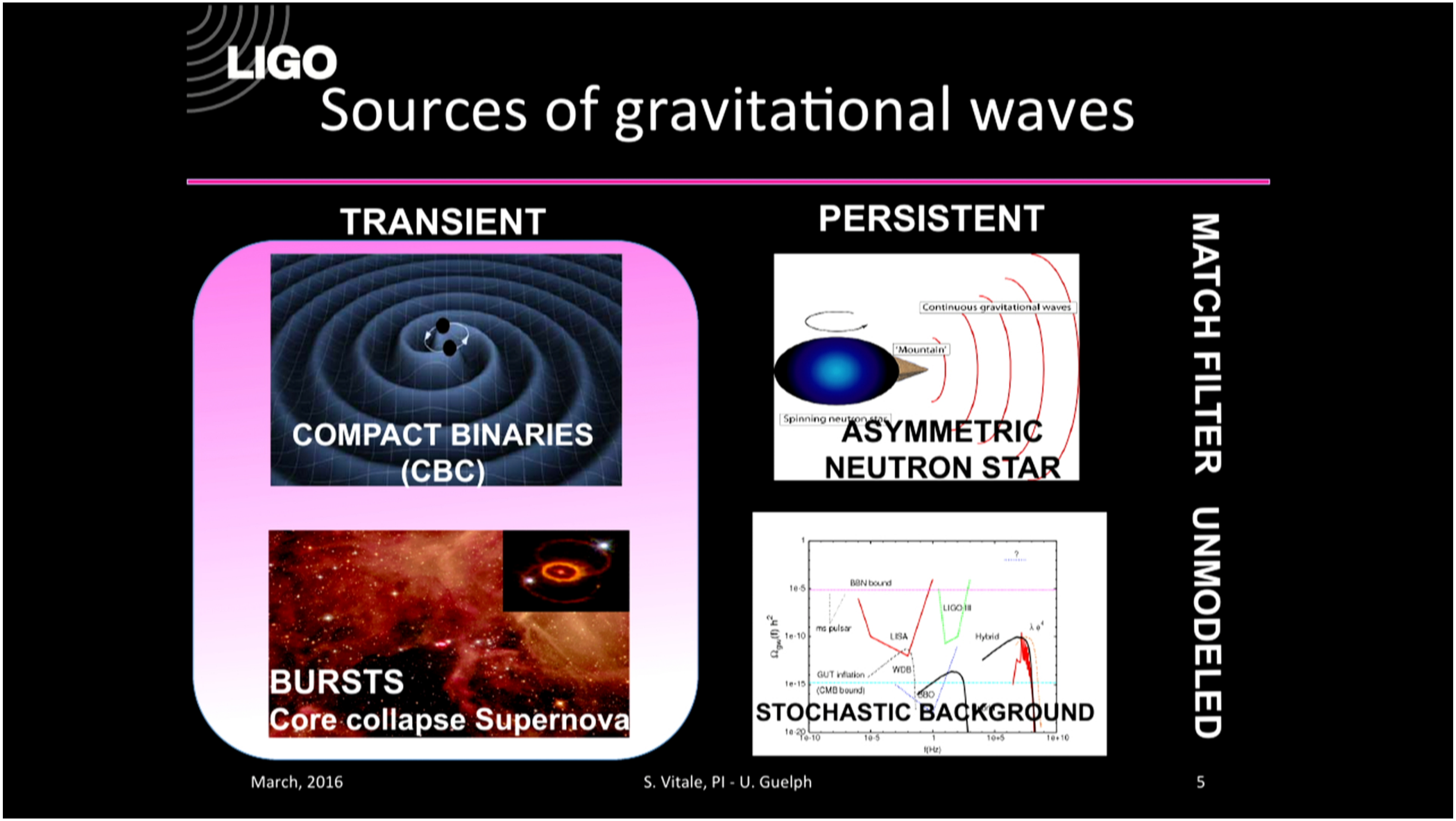
ASYMMETRIC NEUTRON STAR



STOCHASTIC BACKGROUND

MATCH FILTER

UNMODELED



LIGO

Sources of gravitational waves

TRANSIENT

COMPACT BINARIES (CBC)

BURSTS
Core collapse Supernova

PERSISTENT

ASYMMETRIC NEUTRON STAR

STOCHASTIC BACKGROUND

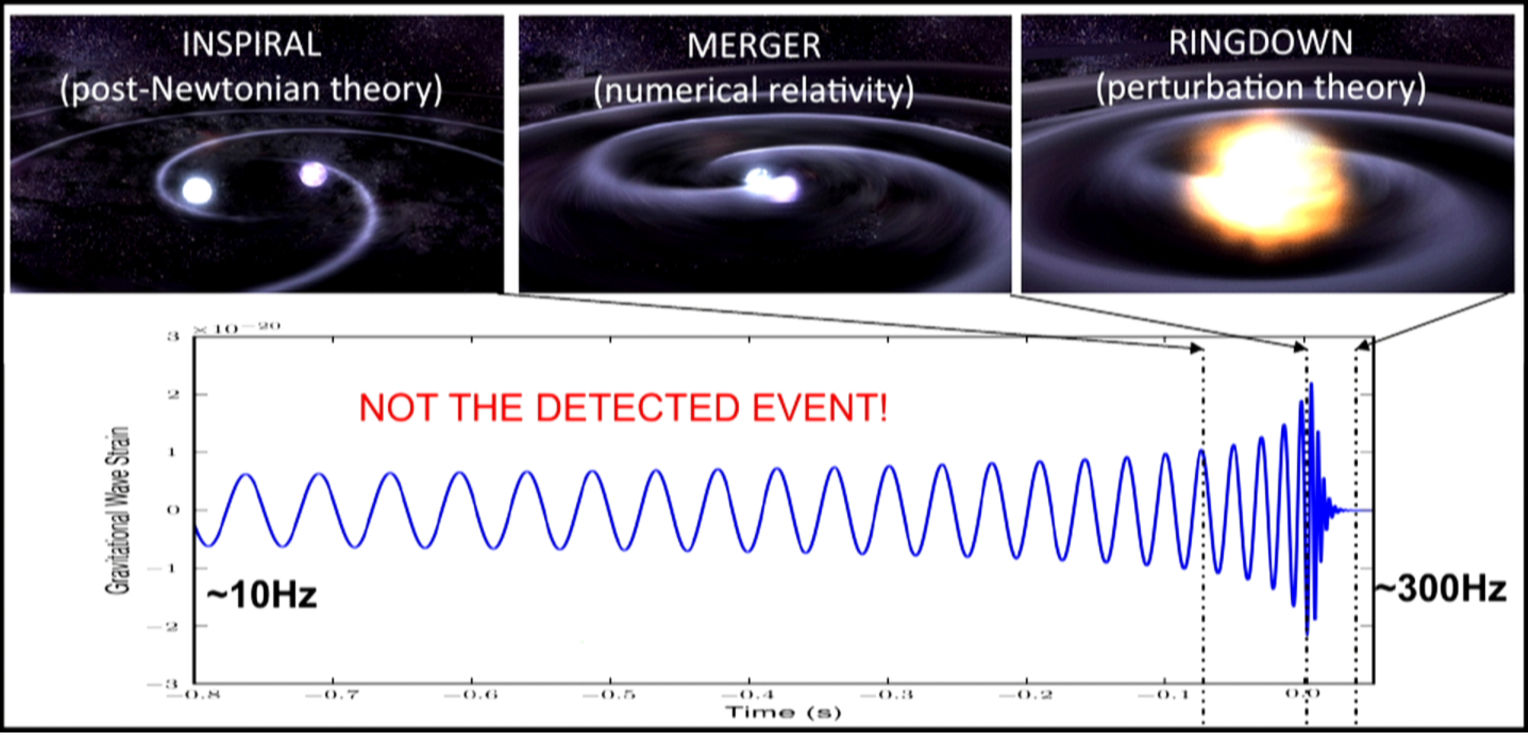
MATCH FILTER **UNMODELED**

March, 2016 S. Vitale, PI - U. Guelph

LIGO

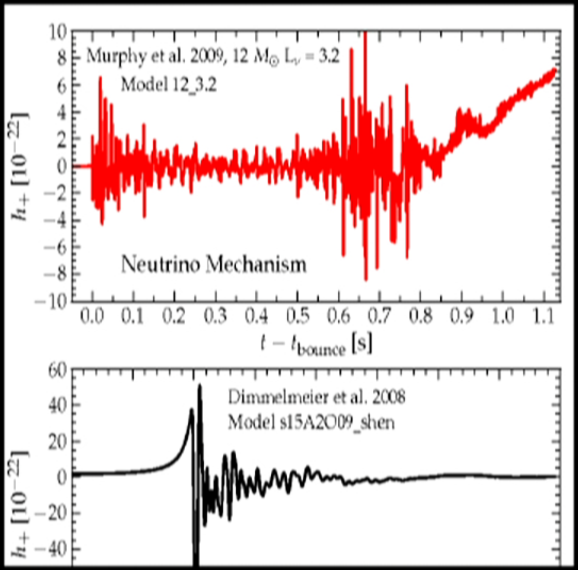
Compact Binaries Coalescences (CBC)

CBC gravitational wave signals are very well understood

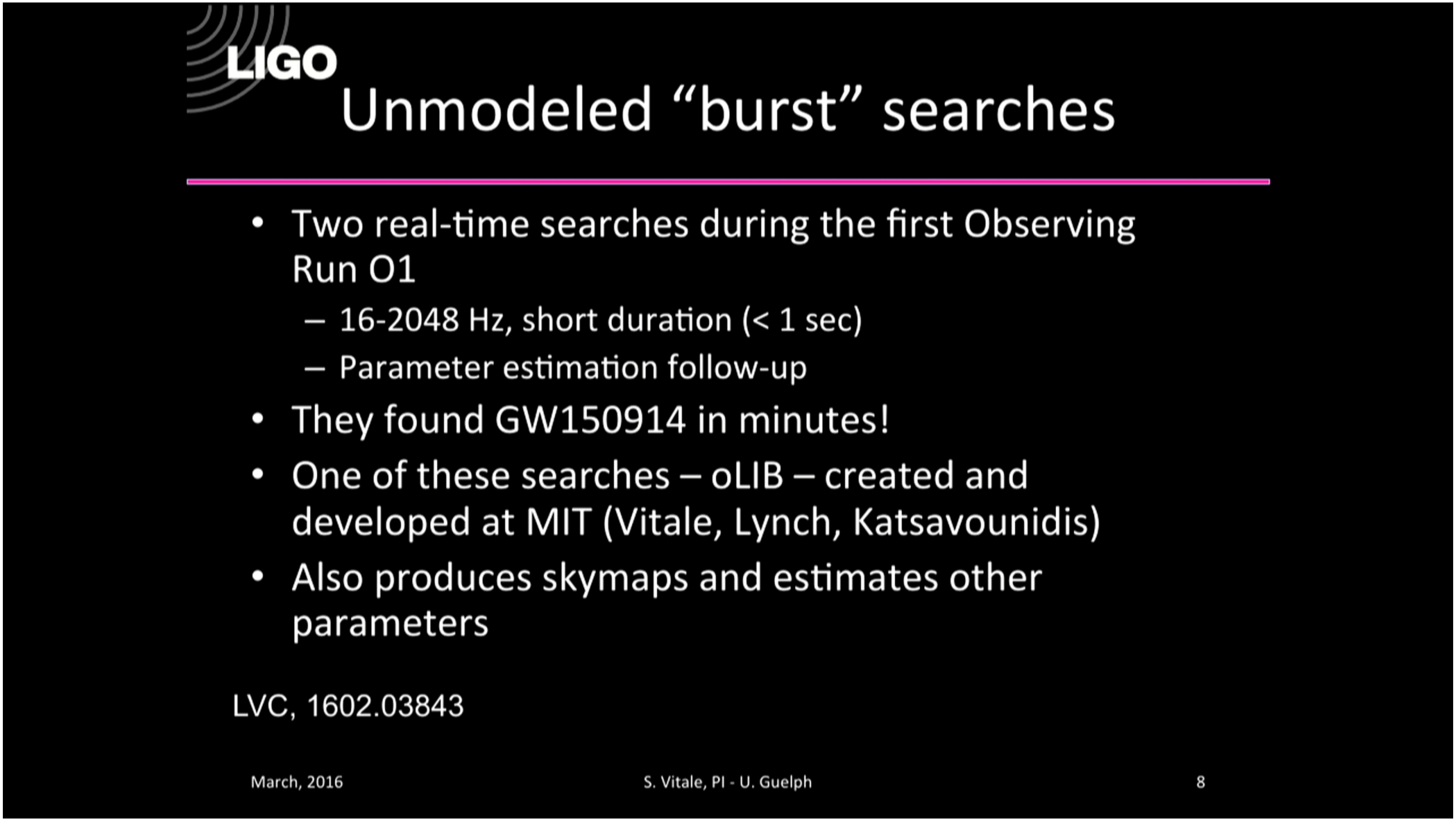


Unmodeled sources

- Any violent astrophysical or cosmological phenomenon
  - Core collapse supernovae
  - Cosmic strings
  - Post-merger signals from hypermassive neutron stars
  - Something unexpected
- Uncertain or no knowledge of gravitational wave signal morphology
- Less advertised, but not less interesting than CBCs
  - High mass binary black holes escaped CBC net



Logue+, PRD 86 044023

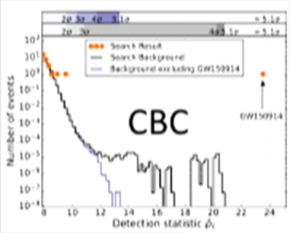


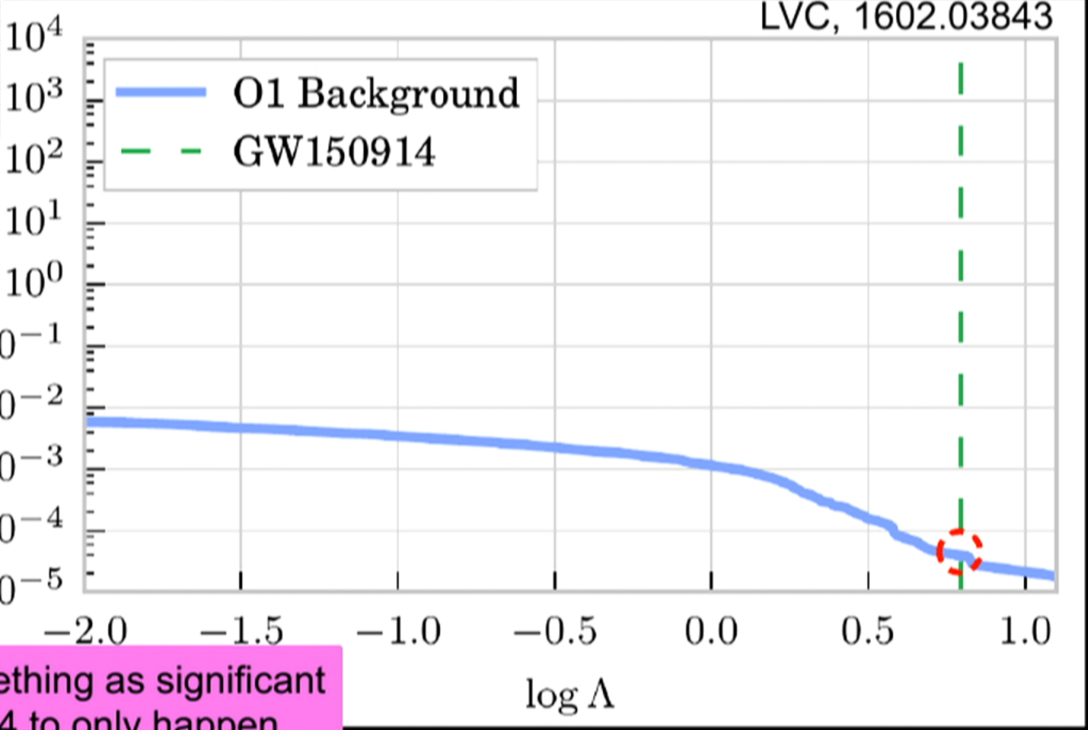
Unmodeled “burst” searches

- Two real-time searches during the first Observing Run O1
  - 16-2048 Hz, short duration (< 1 sec)
  - Parameter estimation follow-up
- They found GW150914 in minutes!
- One of these searches – oLIB – created and developed at MIT (Vitale, Lynch, Katsavounidis)
- Also produces skymaps and estimates other parameters

LVC, 1602.03843

oLIB results for GW150914





More rare

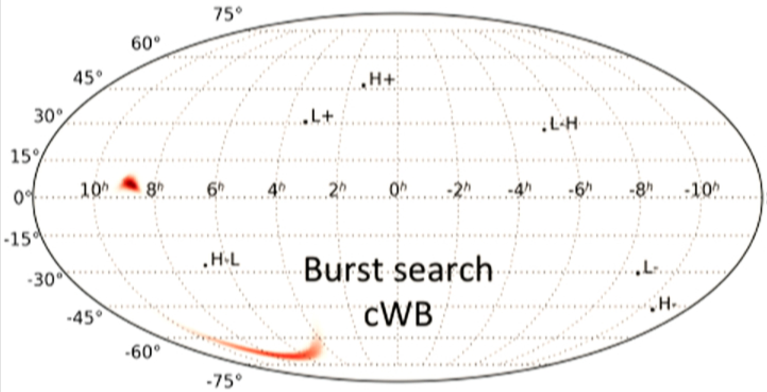
More GW-like

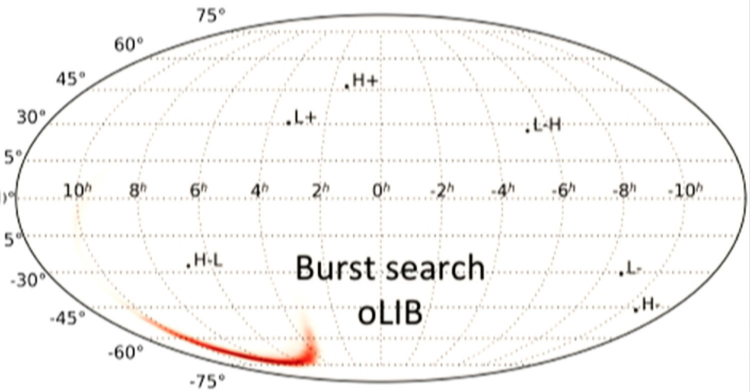
We expect something as significant as GW150914 to only happen once every 27,000 years:
4.6 σ

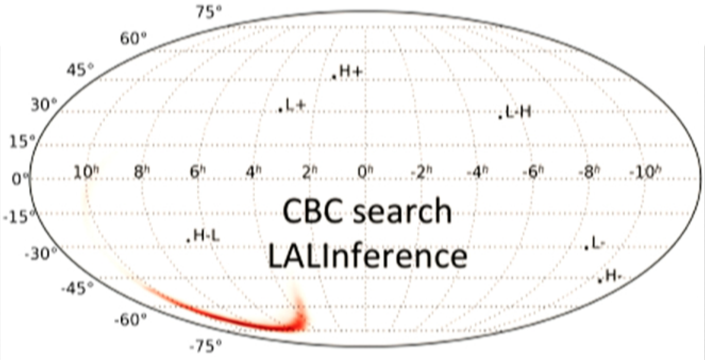
LIGO

GW150914 - Sky localization

Sky maps generated by burst searches and shared with EM partners within 48 hours





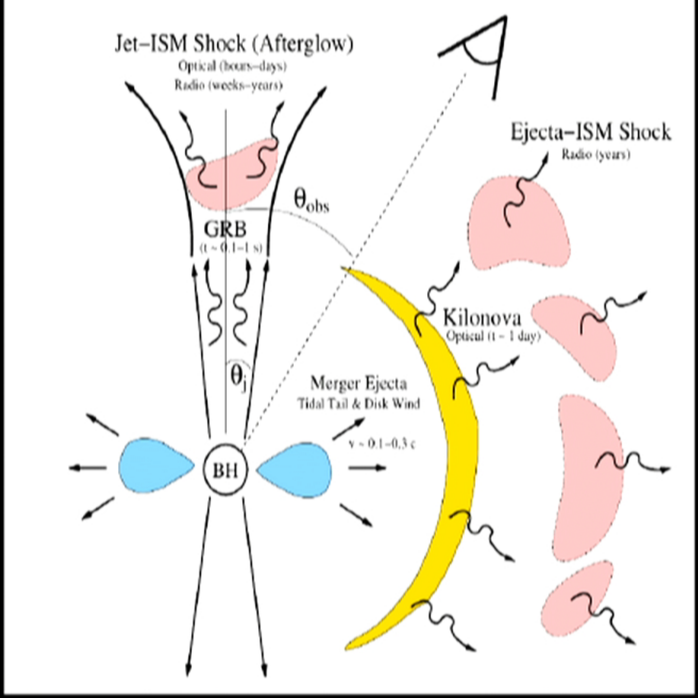


CBC targeted parameter estimation (LALInference, Veitch+ (SV) PRD 91 042003) ran with higher latency

LVC, 1602.03843

GW – Electromagnetic connection

- CBC containing neutron stars are expected to be bright in the EM band
  - Progenitors of short GRBs?
  - Rich variety of frequencies and timescales
- Binary black holes EM luminous too?
- Core collapse supernovae are believed to power long GRBs



Metzger, Berger

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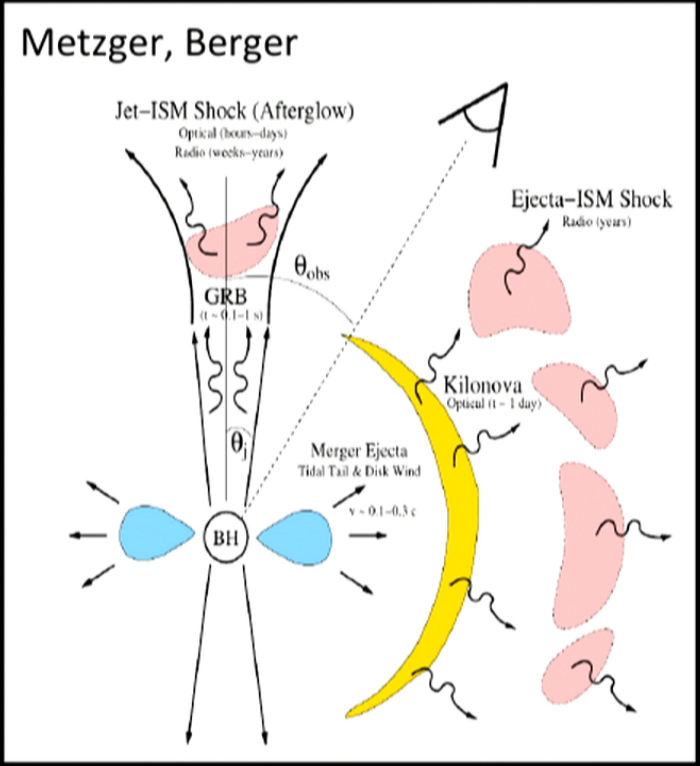
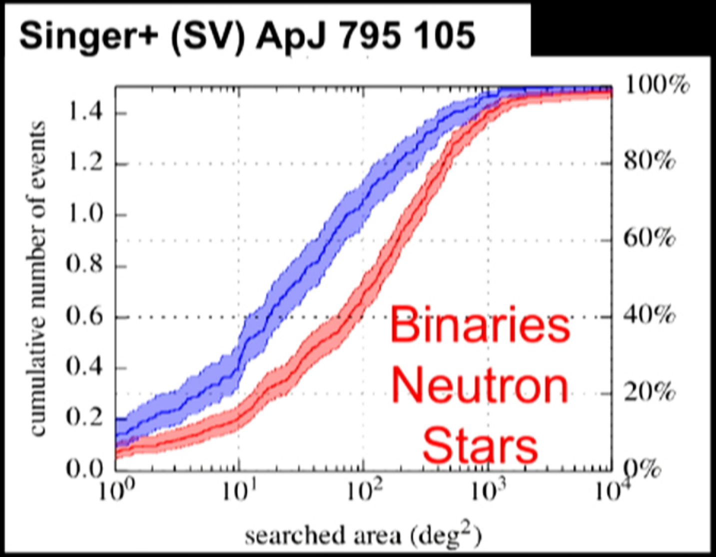
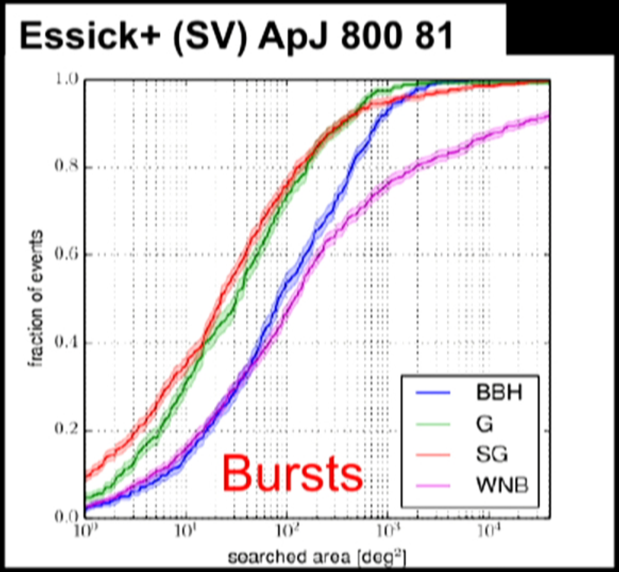

Metzger, Berger

GW – Electromagnetic connection

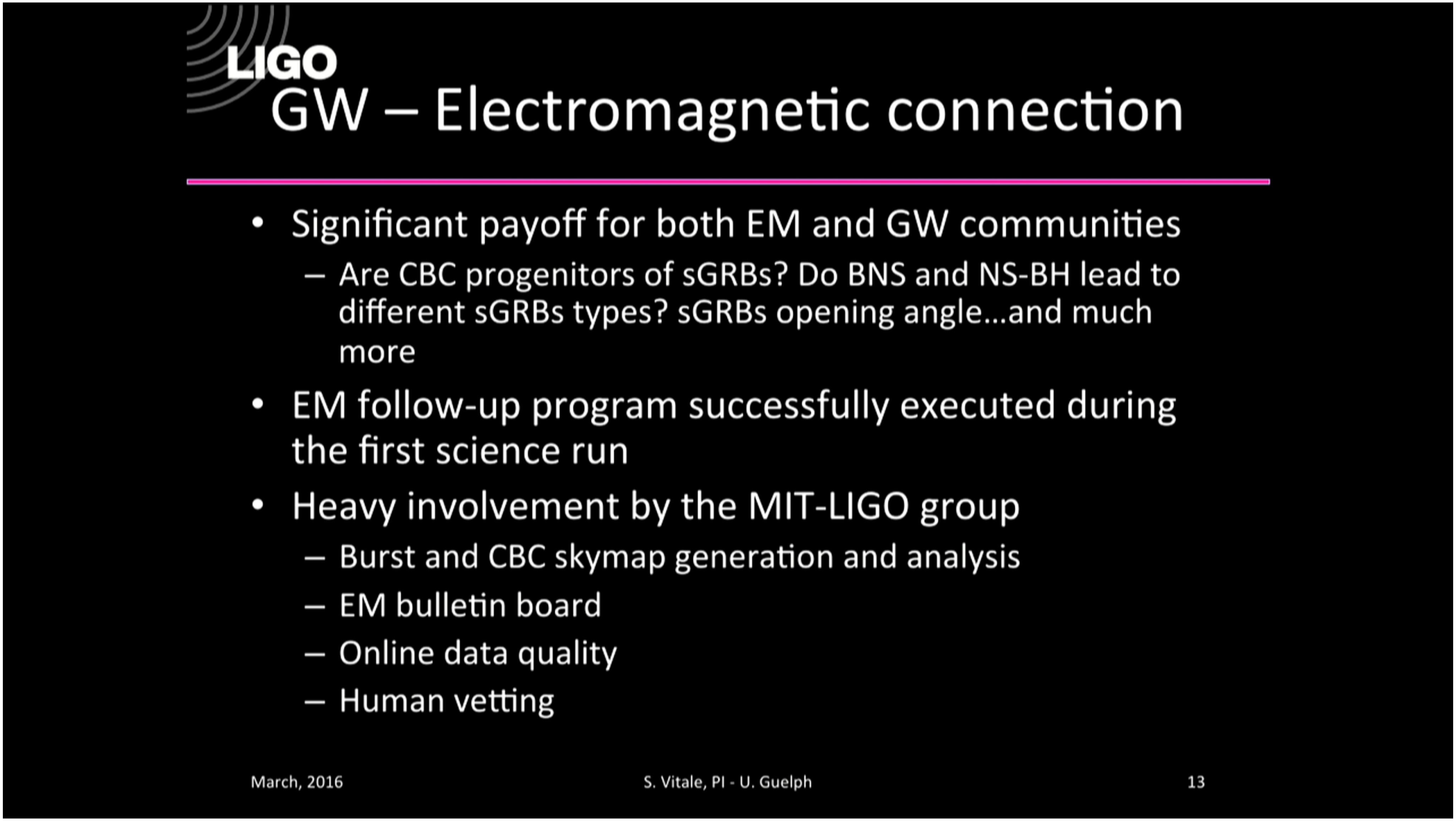
- Challenges: need to be fast and precise; typical latencies few minutes
- Sky error areas from GW data are large, especially with only 2-3 detectors on-line
- Median searched areas ≤ 100 deg^2 in the next science run with Virgo on-line
- Not strongly dependent on model



Singer+ (SV) ApJ 795 105



Essick+ (SV) ApJ 800 81

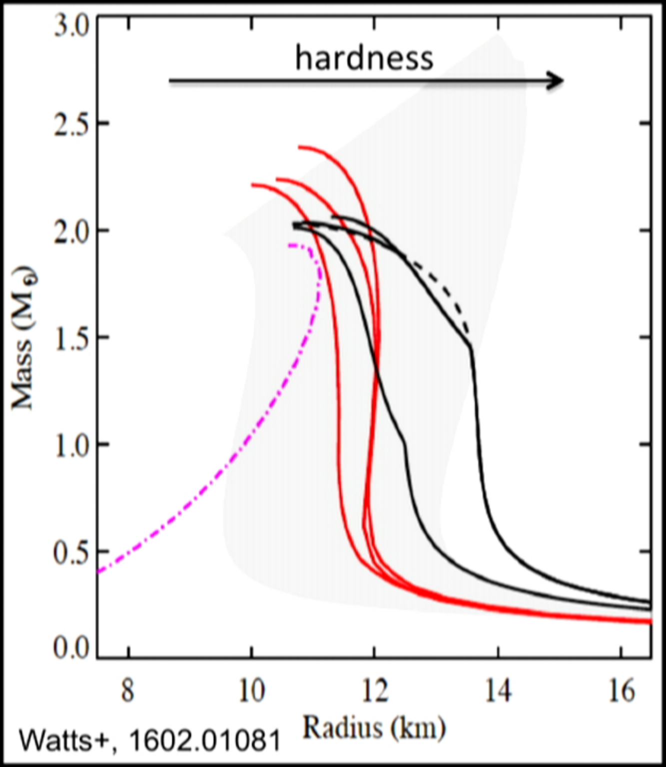


GW – Electromagnetic connection

- Significant payoff for both EM and GW communities
  - Are CBC progenitors of sGRBs? Do BNS and NS-BH lead to different sGRBs types? sGRBs opening angle…and much more
- EM follow-up program successfully executed during the first science run
- Heavy involvement by the MIT-LIGO group
  - Burst and CBC skymap generation and analysis
  - EM bulletin board
  - Online data quality
  - Human vetting

Neutron star equation of state

- Neutron stars host the highest densities in the (visible) universe
- Measuring their equation of state requires joint measurement of radius and mass
- Possible with EM, but challenging
  - Mass estimates not always reliable
  - Radius estimates not often available and not always reliable
  - NICER to launch 2016, few % precision



Watts+, 1602.01081

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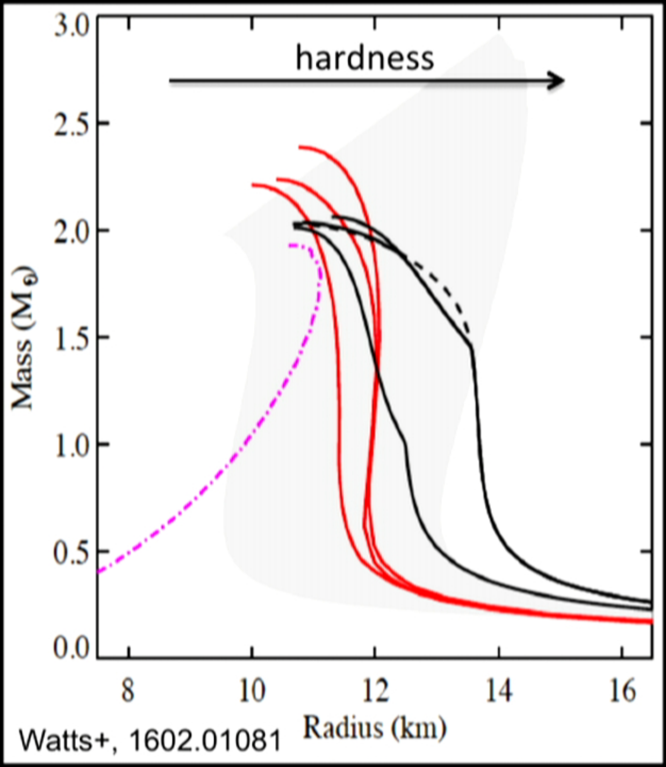
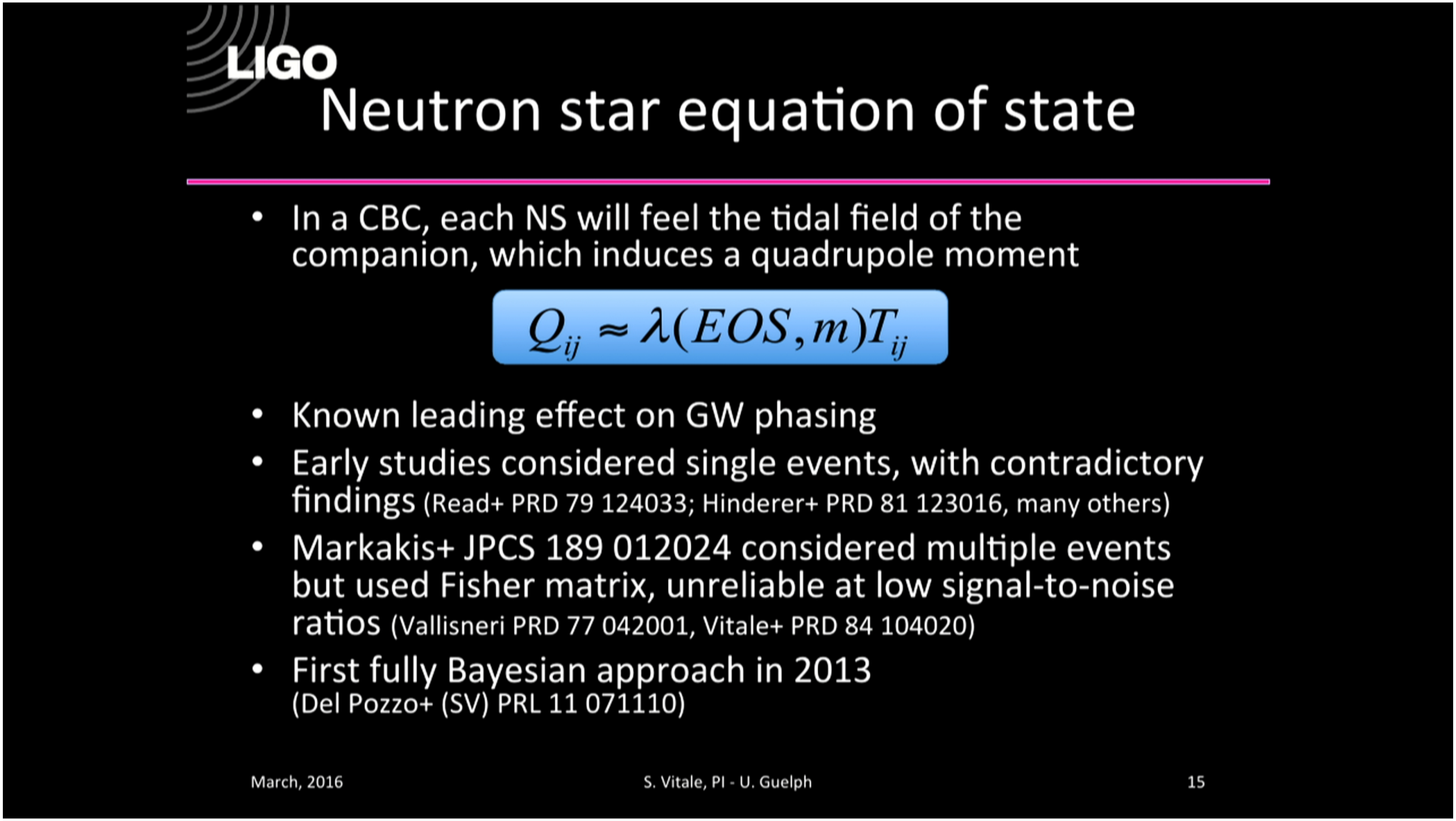


Watts+, 1602.01081



Neutron star equation of state

- In a CBC, each NS will feel the tidal field of the companion, which induces a quadrupole moment

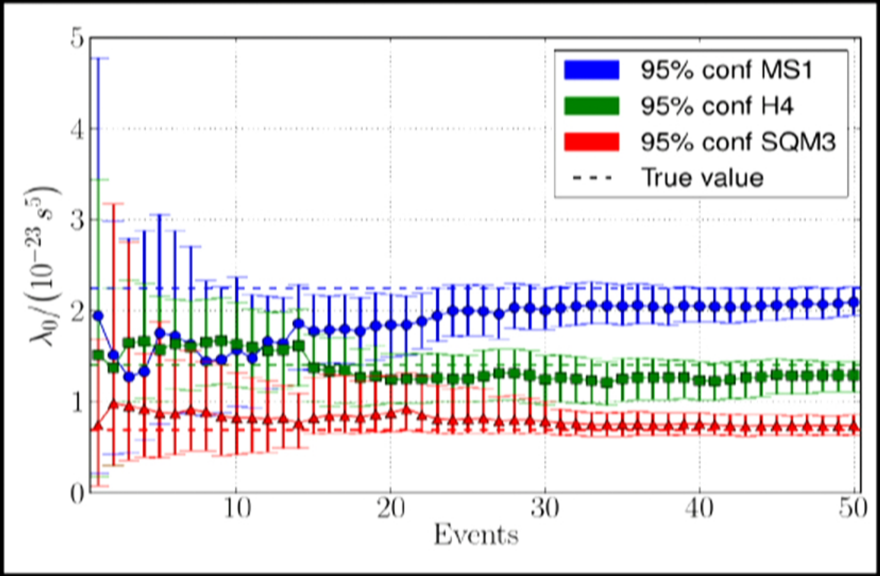
$$Q_{ij} \approx \lambda(EOS, m) T_{ij}$$

- Known leading effect on GW phasing
- Early studies considered single events, with contradictory findings (Read+ PRD 79 124033; Hinderer+ PRD 81 123016, many others)
- Markakis+ JPCS 189 012024 considered multiple events but used Fisher matrix, unreliable at low signal-to-noise ratios (Vallisneri PRD 77 042001, Vitale+ PRD 84 104020)
- First fully Bayesian approach in 2013 (Del Pozzo+ (SV) PRL 11 071110)

Neutron star equation of state

- Two different avenues:
  - Model selection and EOS ranking
  - Parameter estimation on the tidal deformability
- Both allow to use all events
- Will focus on parameter estimation

$$\lambda(m) = \sum_j \frac{1}{j!} \lambda_j \left(\frac{m - m_0}{M_\odot} \right)^j$$



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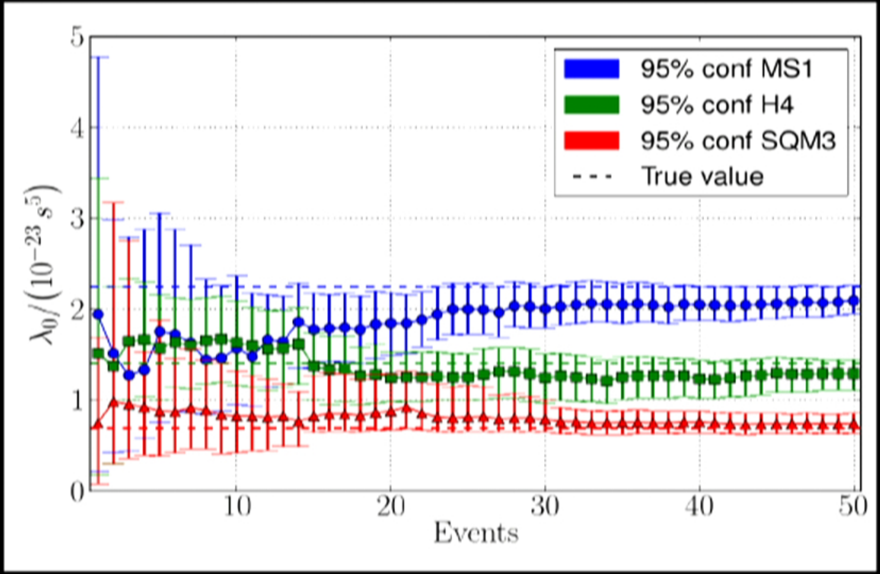
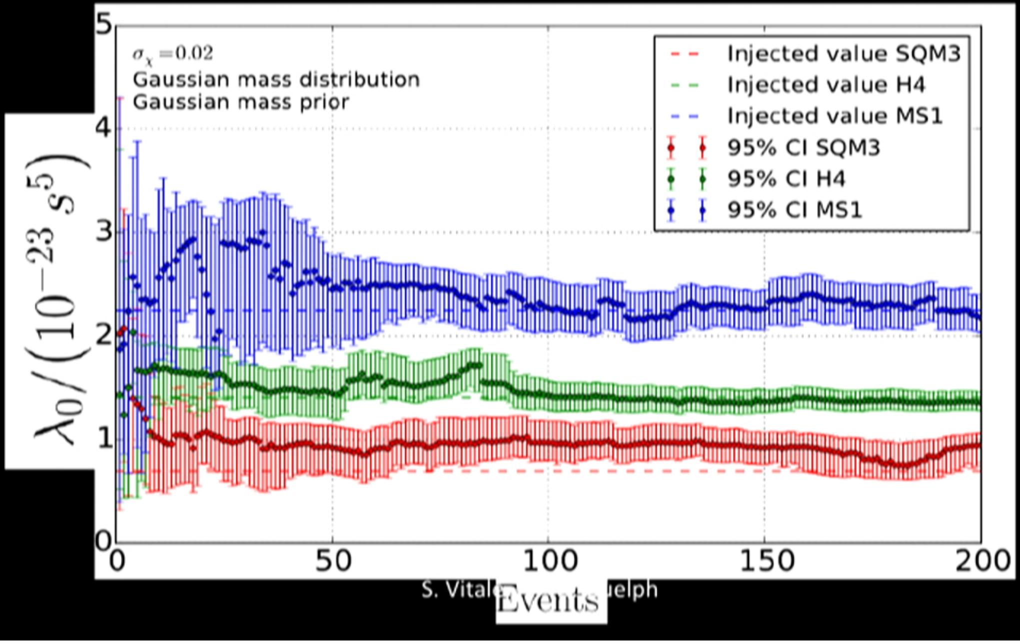
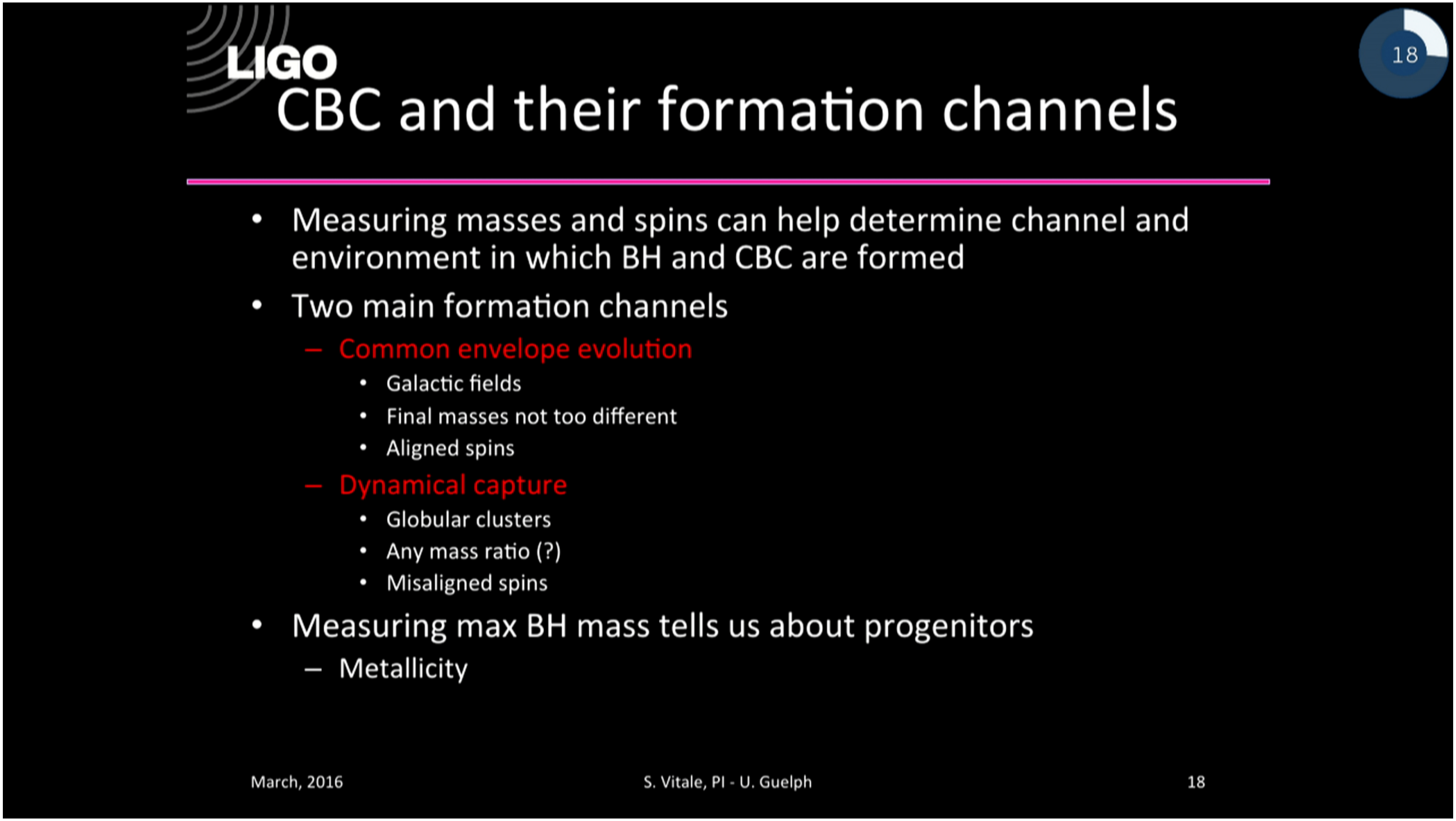


Neutron star equation of state

- In Agathos+ (SV) PRD 89 082001 we extended the initial study
  - Small neutron star spin
  - More physics (quadrupole-monopole term)
  - Better handling of waveform termination



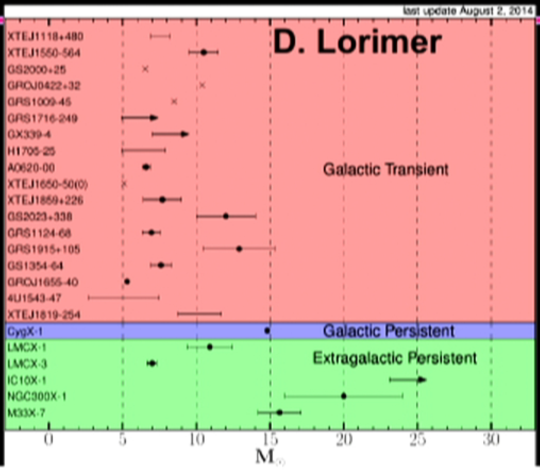


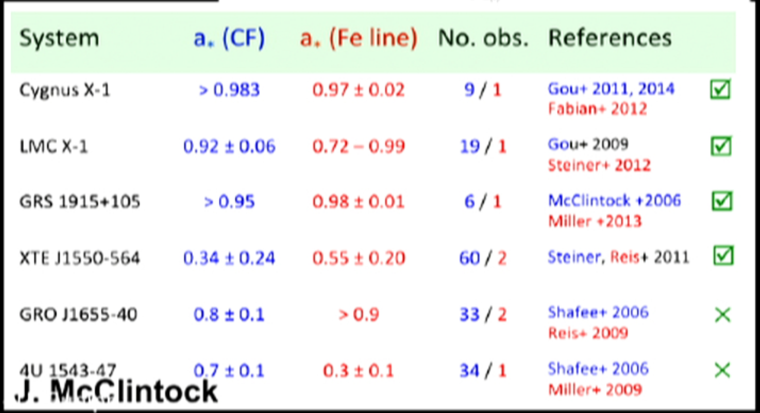
CBC and their formation channels

- Measuring masses and spins can help determine channel and environment in which BH and CBC are formed
- Two main formation channels
  - Common envelope evolution
    - Galactic fields
    - Final masses not too different
    - Aligned spins
  - Dynamical capture
    - Globular clusters
    - Any mass ratio (?)
    - Misaligned spins
- Measuring max BH mass tells us about progenitors
  - Metallicity

Black holes in X-ray binaries

- Known stellar-mass BH masses and spins come from X-ray binaries
- Mass estimate requires period, radial velocity, inclination, companion mass
  - Most massive ~ 15 $M_\odot$
- Spin are estimated with two methods
  - Fe line, continuum fitting
  - Sometimes in tension

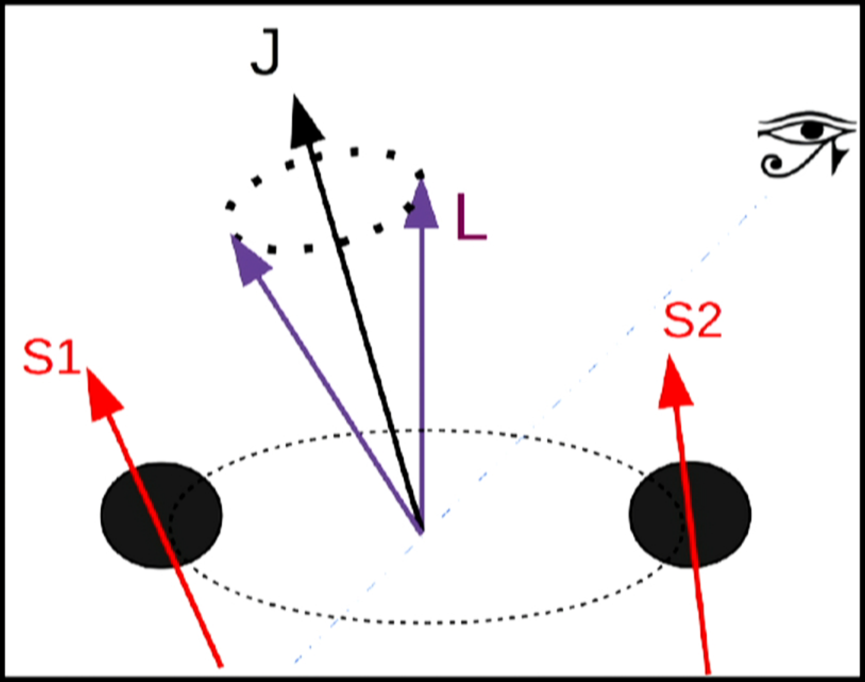




System	a_* (CF)	a_* (Fe line)	No. obs.	References	
Cygnus X-1	> 0.983	0.97 ± 0.02	9 / 1	Gou+ 2011, 2014 Fabian+ 2012	☑
LMC X-1	0.92 ± 0.06	0.72 – 0.99	19 / 1	Gou+ 2009 Steiner+ 2012	☑
GRS 1915+105	> 0.95	0.98 ± 0.01	6 / 1	McClintock +2006 Miller +2013	☑
XTE J1550-564	0.34 ± 0.24	0.55 ± 0.20	60 / 2	Steiner, Reis+ 2011	☑
GRO J1655-40	0.8 ± 0.1	> 0.9	33 / 2	Shafee+ 2006 Reis+ 2009	✗
4U 1543-47	0.7 ± 0.1	0.3 ± 0.1	34 / 1	Shafee+ 2006 Miller+ 2009	✗

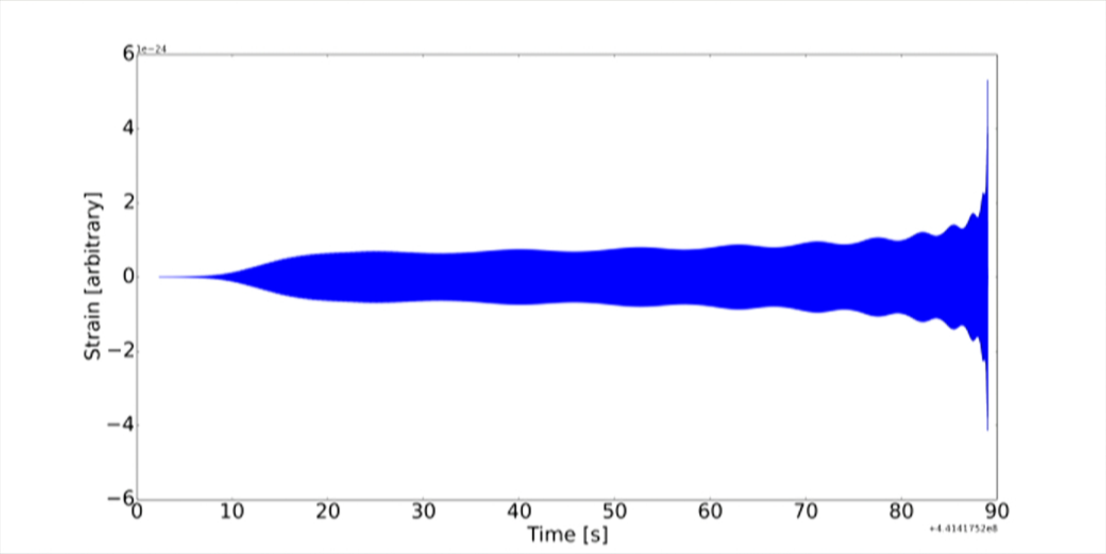
J. McClintock

Precessing spins

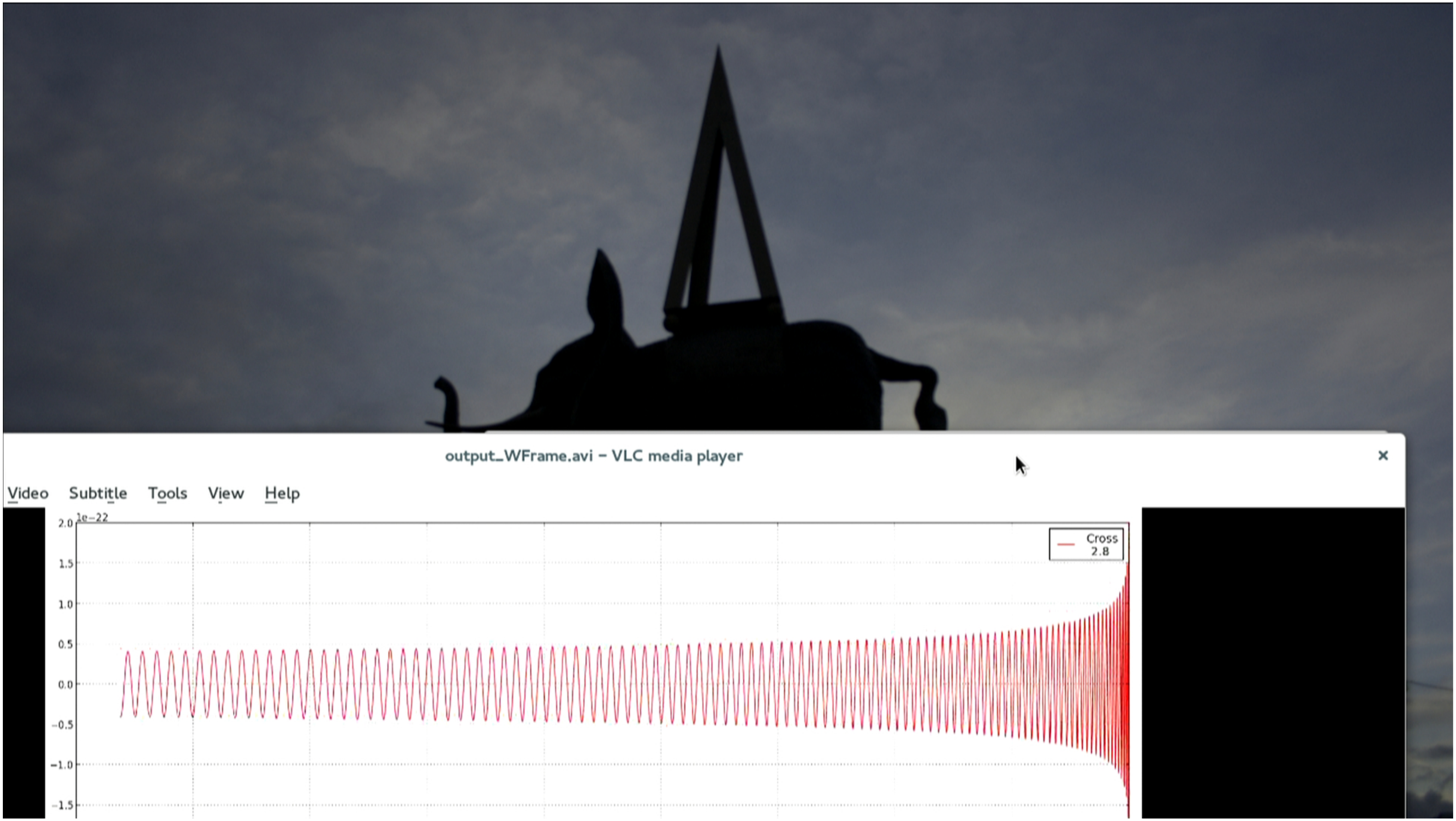


- Spin-Orbit coupling makes the orbit precess
- Spin-Spin coupling
- Waveform gets amplitude and phase modulation
- Rich physics, some degeneracies are reduced

Spinning waveforms w/ precession



- **However**, the amount of modulation visible in the *detector frame* also depends on the orientation
- Face-on CBC → Less modulation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Video
Subtitle
Tools
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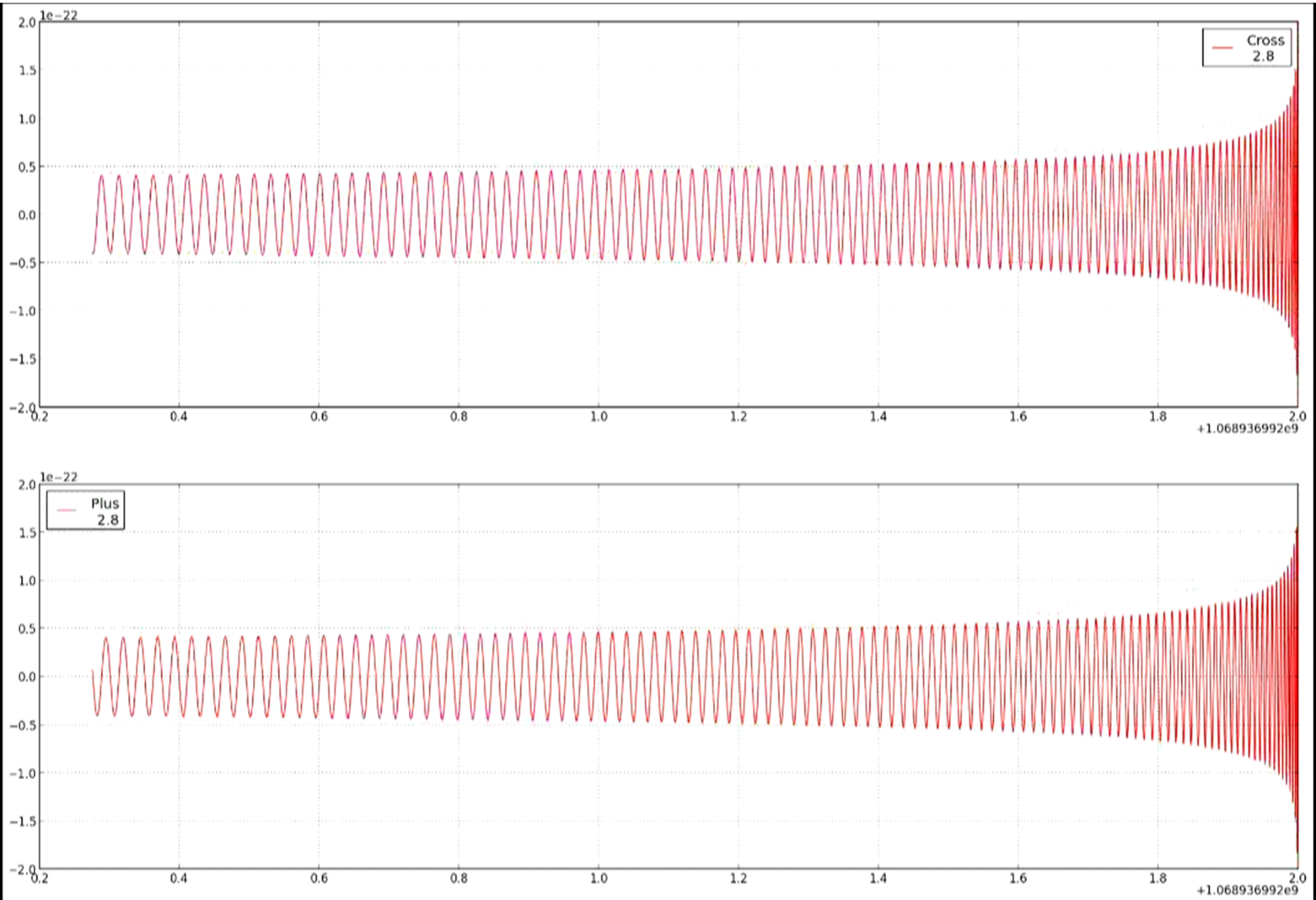

1e−22
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0.8
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1.4
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2.0
+1.068936992e9
Cross
2.8
1e−22
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0.2
0.4
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0.8
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Plus
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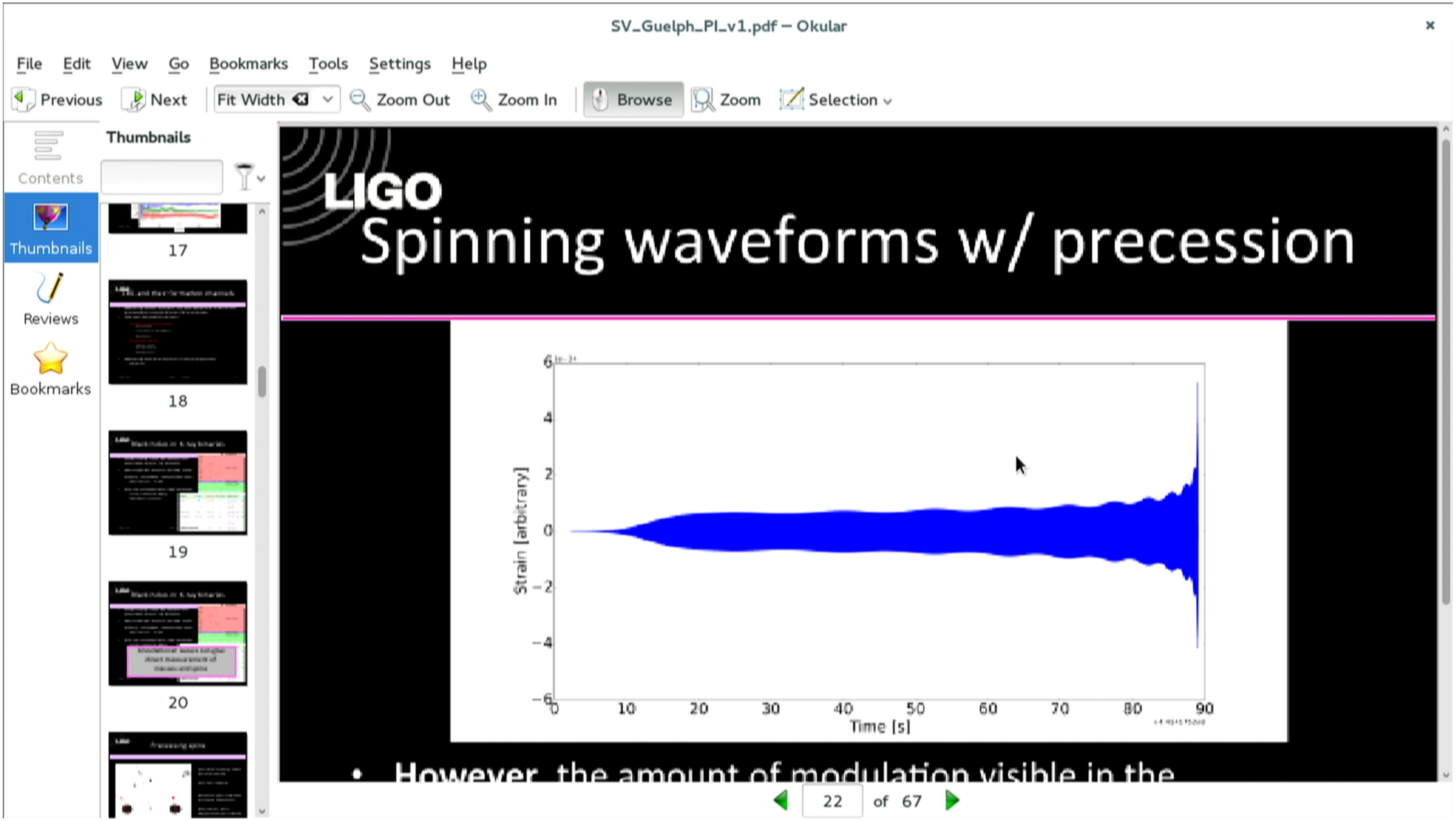
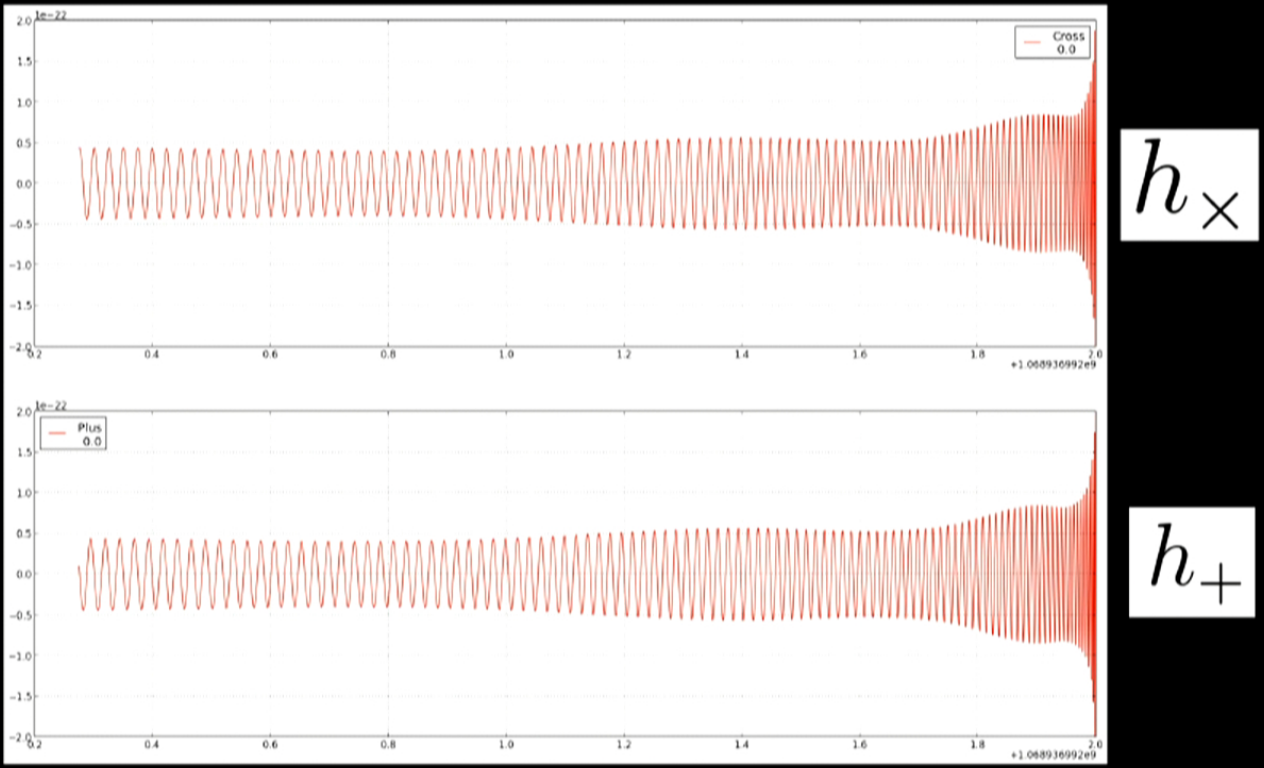


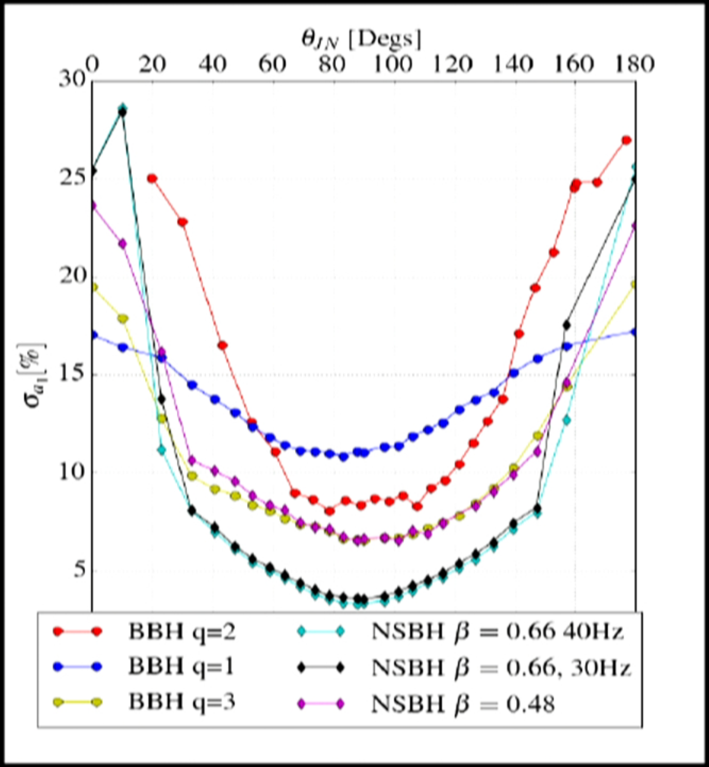
Spinning waveforms w/ precession

- However, the amount of modulation visible in the

Inclination and precession



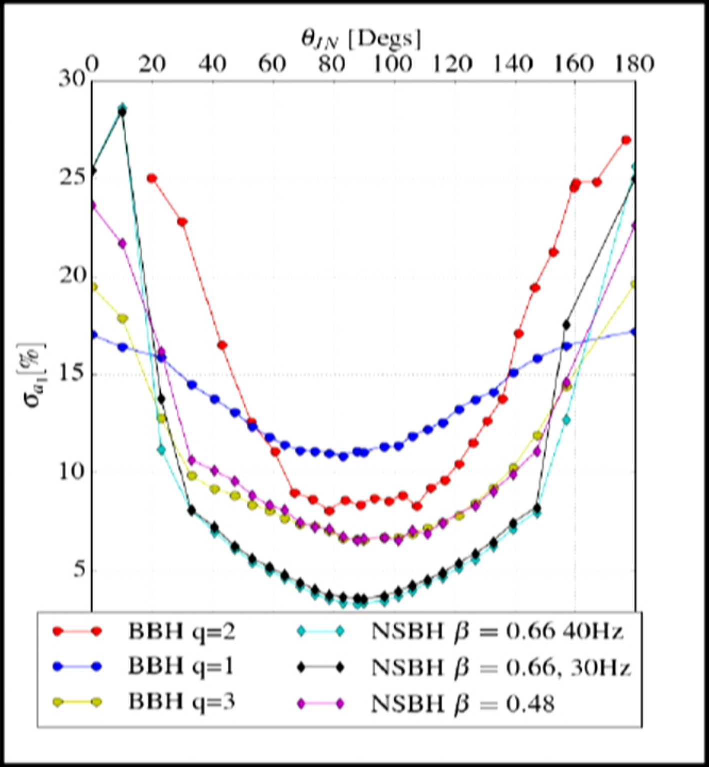
Effects of orbital orientation



Vitale+ in prep., Vitale+ PRL 112 251101

- Spin estimation strongly affected by orientation
- Spin errors minimum if system seen “edge-on”
- Less likely to detect than “face-on”

Effects of orbital orientation



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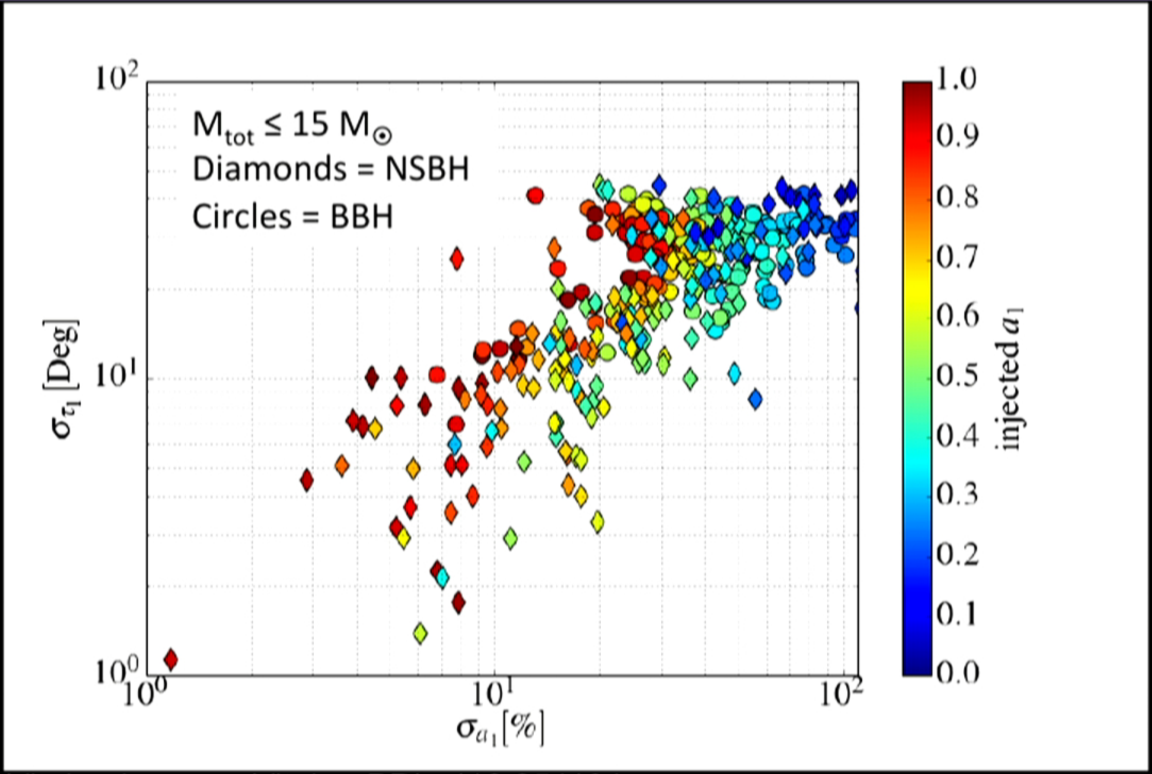
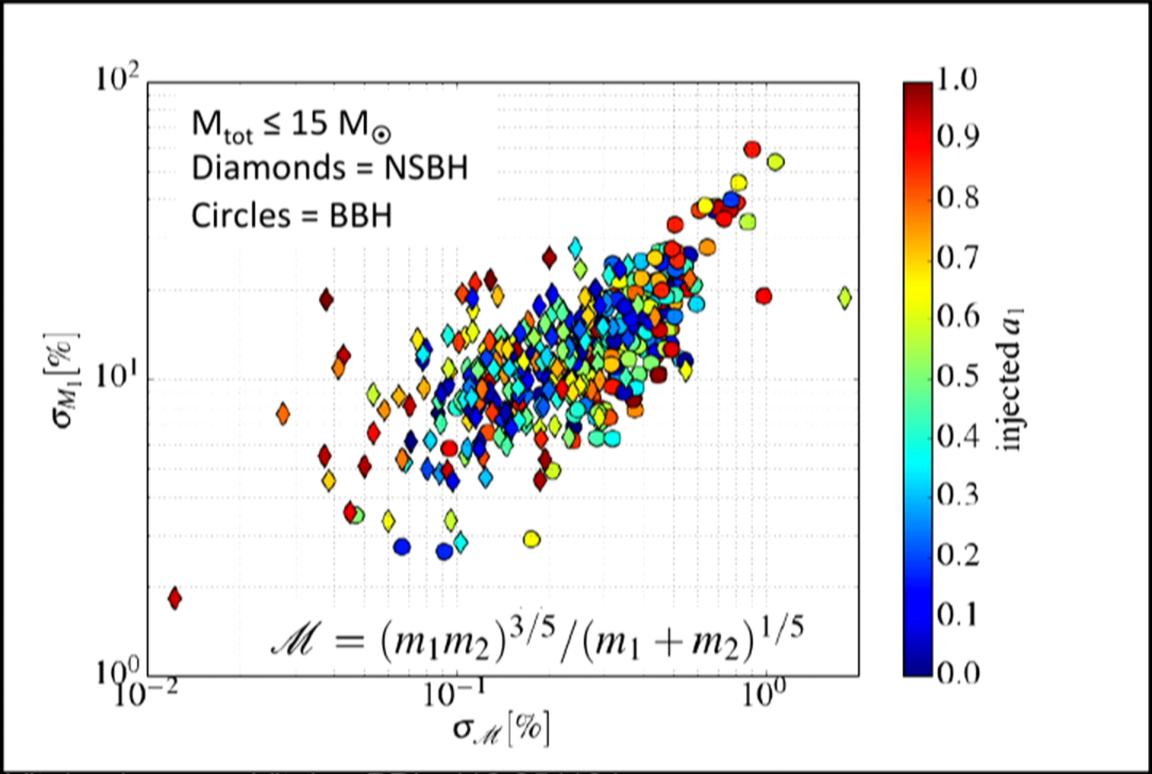
Astrophysical distribution - Spin



Vitale+ in prep., Vitale+ PRL 112 251101

Astrophysical distribution - Masses



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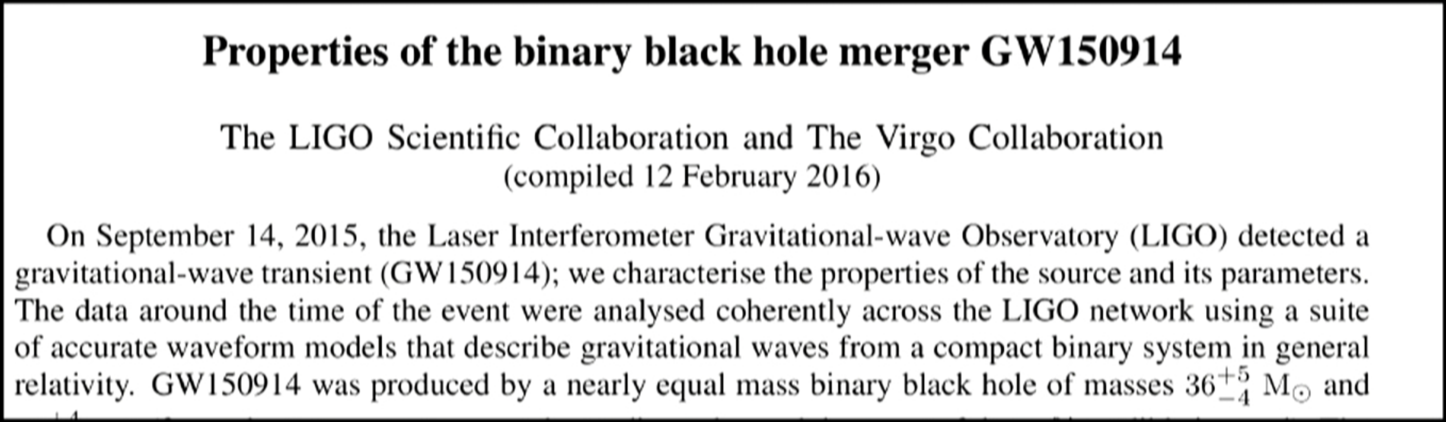
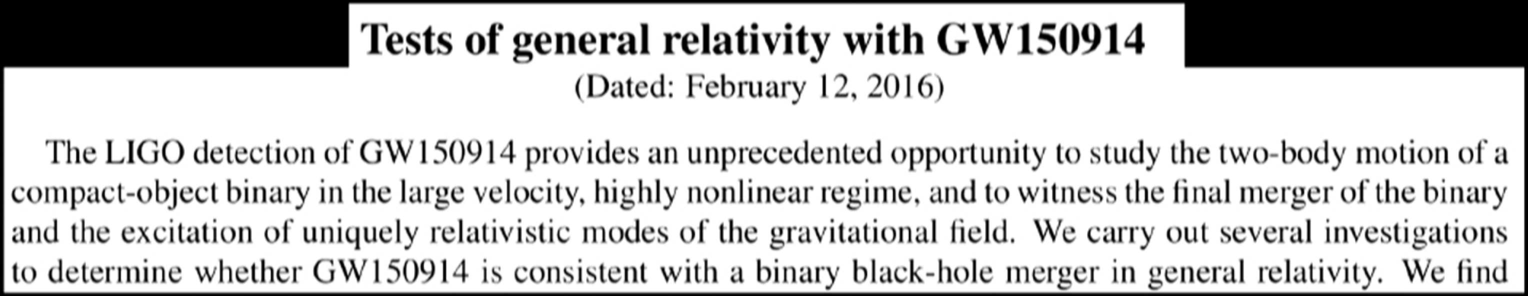


Properties of the binary black hole merger GW150914

The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 12 February 2016)

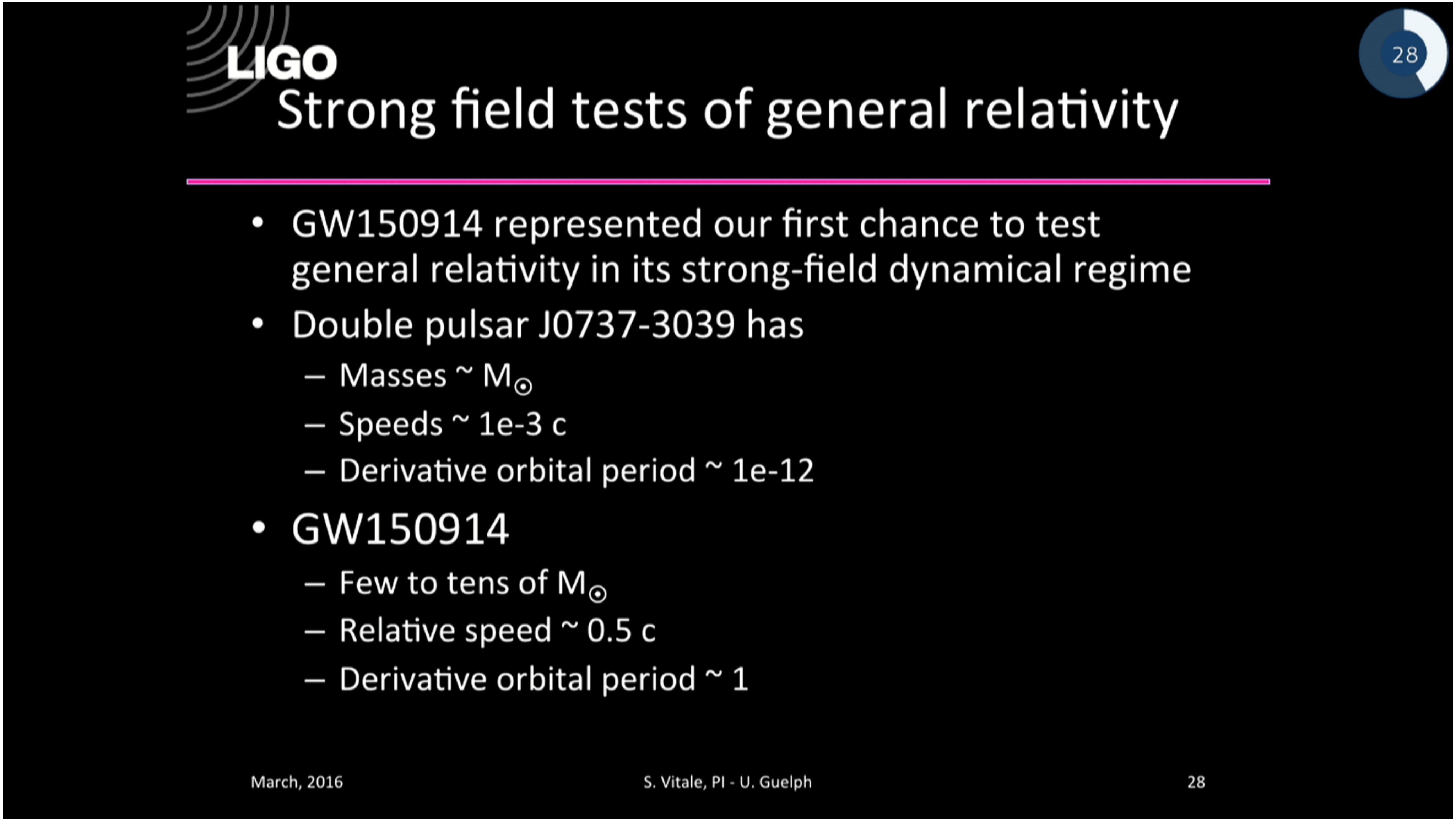
On September 14, 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) detected a gravitational-wave transient (GW150914); we characterise the properties of the source and its parameters. The data around the time of the event were analysed coherently across the LIGO network using a suite of accurate waveform models that describe gravitational waves from a compact binary system in general relativity. GW150914 was produced by a nearly equal mass binary black hole of masses 36^{+5}_{-4} $M_{\odot}$ and



Tests of general relativity with GW150914

(Dated: February 12, 2016)

The LIGO detection of GW150914 provides an unprecedented opportunity to study the two-body motion of a compact-object binary in the large velocity, highly nonlinear regime, and to witness the final merger of the binary and the excitation of uniquely relativistic modes of the gravitational field. We carry out several investigations to determine whether GW150914 is consistent with a binary black-hole merger in general relativity. We find



Strong field tests of general relativity

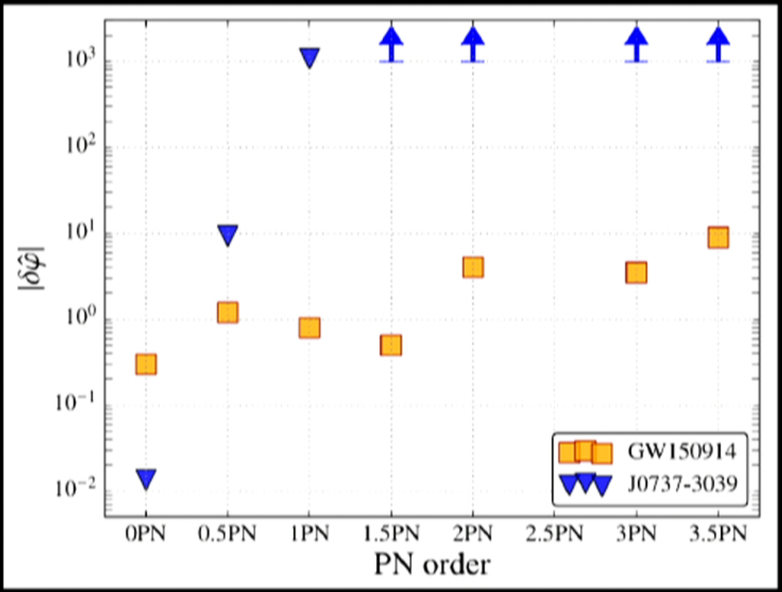
- GW150914 represented our first chance to test general relativity in its strong-field dynamical regime
- Double pulsar J0737-3039 has
  - Masses ~ $M_\odot$
  - Speeds ~ 1e-3 c
  - Derivative orbital period ~ 1e-12
- GW150914
  - Few to tens of $M_\odot$
  - Relative speed ~ 0.5 c
  - Derivative orbital period ~ 1

LIGO

Strong field tests of general relativity

- There is a large number of alternative theories of gravity that we will be able to test using gravitational waves
  - Massive graviton
  - Brans-Dicke
  - Many more!
- But the real theory of gravity might not have been proposed yet. Need unmodeled tests
  - Post Netwonian phasing tests
  - TIGER

GR tests with GW150914: phasing



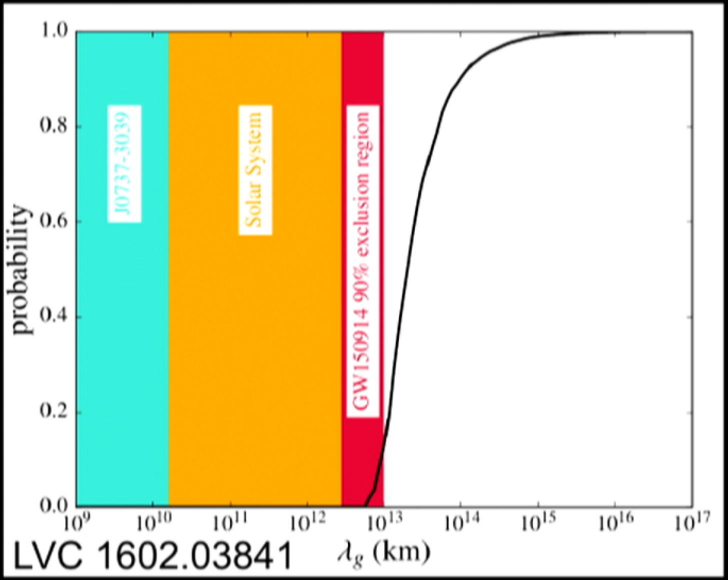
Yunes, Hughes, PRD 82 082002
LVC 1602.03841

- Post Newtonian expansion of GW phase has coefficients known within GR

$$\psi(f) \sim \sum \varphi_k (\pi M f)^{\frac{k-5}{3}}$$

- Can put upper limit on how different from GR they can be
  - Using double pulsar
  - Using GW150914
- Double pulsar already beaten at 0.5PN

GR tests with GW150914: massive graviton

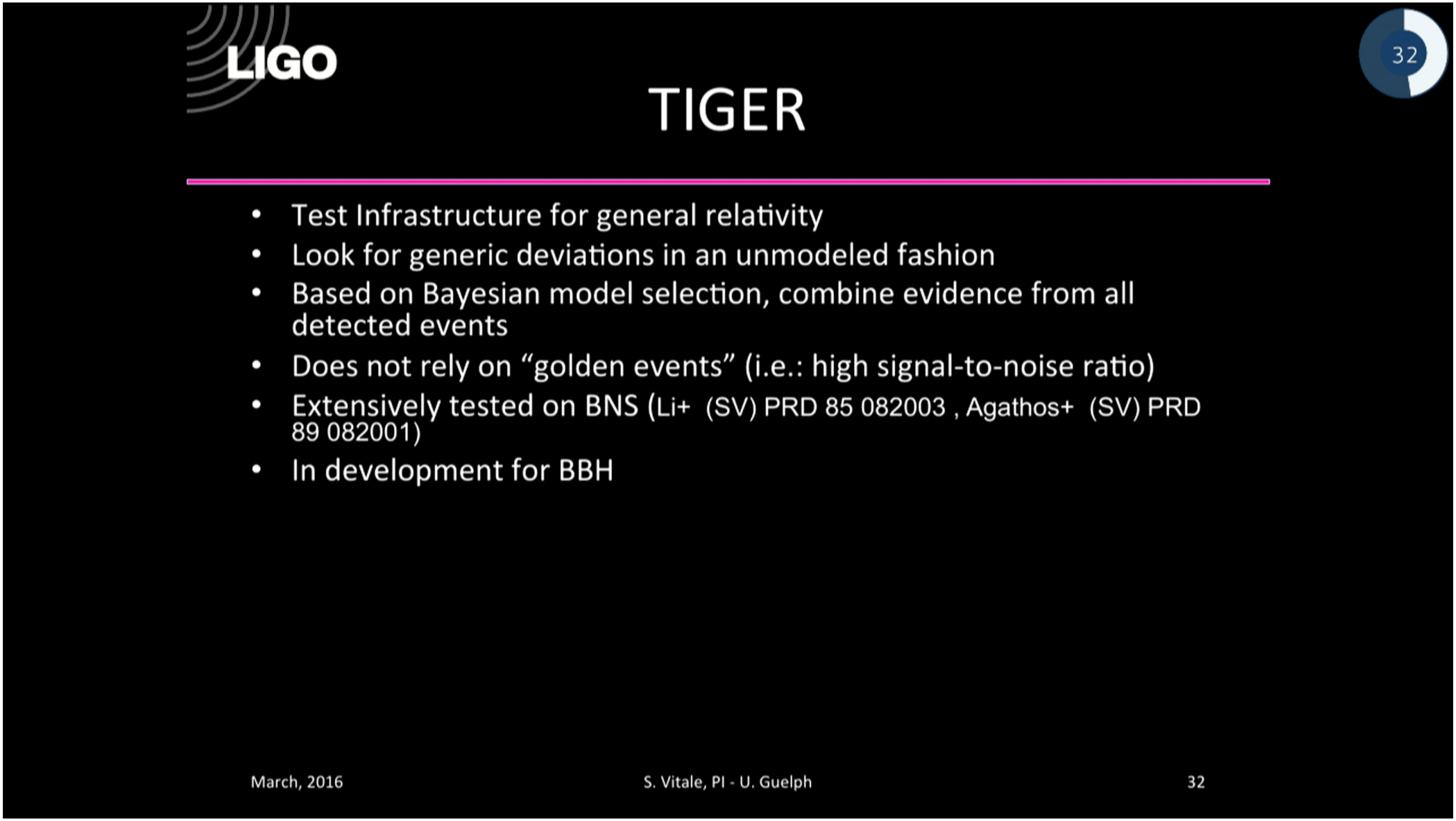


LVC 1602.03841

- A full self-consistent theory of gravitational field mediated by massive particle is not yet available
- However, just modifying the dispersion relation one can calculate extra phasing term for GW phase (Will, PRD 57 2061)

✓ 3 orders of magnitude better than double pulsar
✓ Factor of 3 better than solar system
✓ Some model dependent tests do better

$$m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$



TIGER

- Test Infrastructure for general relativity
- Look for generic deviations in an unmodeled fashion
- Based on Bayesian model selection, combine evidence from all detected events
- Does not rely on “golden events” (i.e.: high signal-to-noise ratio)
- Extensively tested on BNS (Li+ (SV) PRD 85 082003 , Agathos+ (SV) PRD 89 082001)
- In development for BBH

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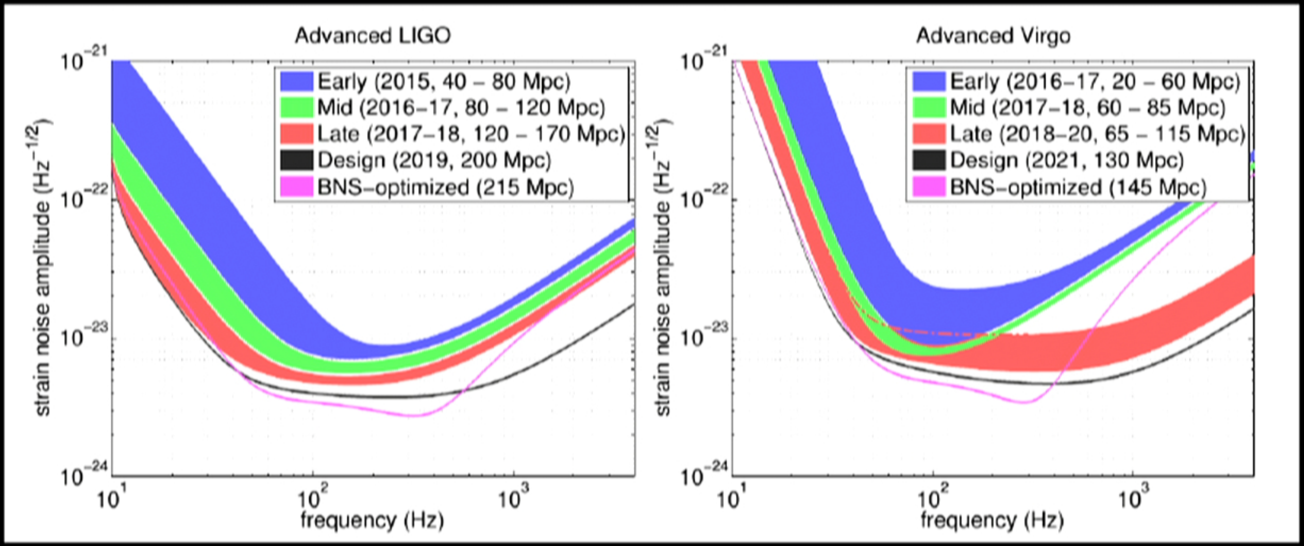
- Define two models “GR is correct” vs “GR is not correct”
  - “GR is not correct” is true if any post Newtonian or phenomenological phase parameters deviates from its GR value
- Calculate Bayesian odds (ratio of probabilities)
- Each detection contributes to odds
- Good efficiency after few tens of BNS

Advanced LIGO not at design sensitivity yet: more detections coming soon!



LVC Liv. Rev. Rel 19, 1

- Next Science Runs:
  - 2015: 1 BBH event
  - 2016 - 2017: 5-10 significant BBH events, ~2 BNS
  - 2017-2018 : 10-30 significant BBH events, ~10 BNS
  - 2019: > 50 significant BBH events, ~20 BNS

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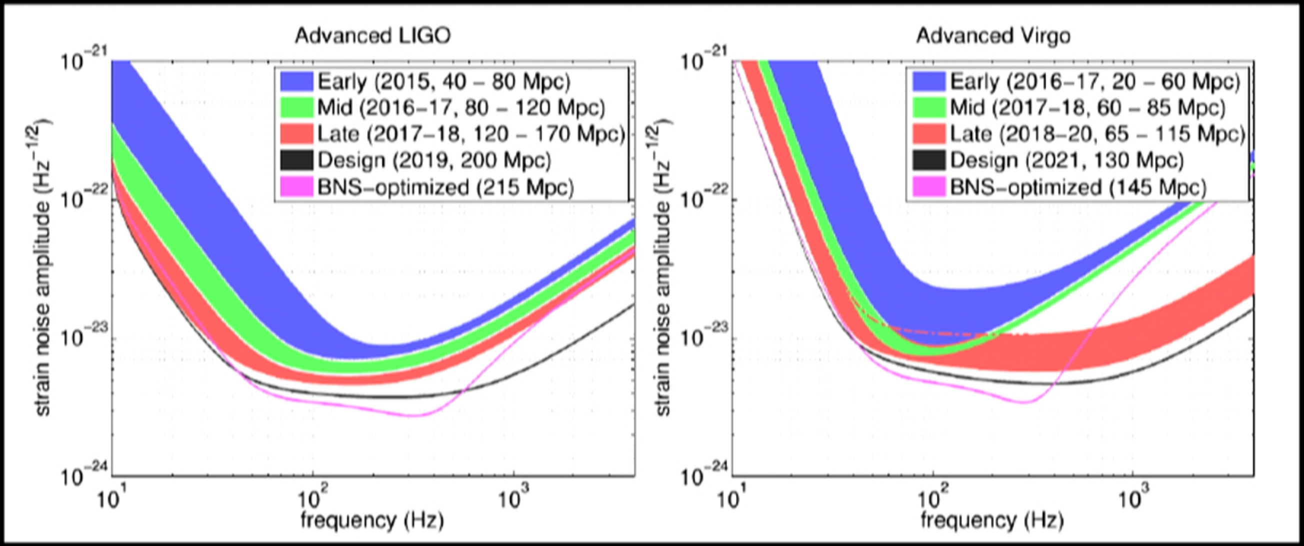

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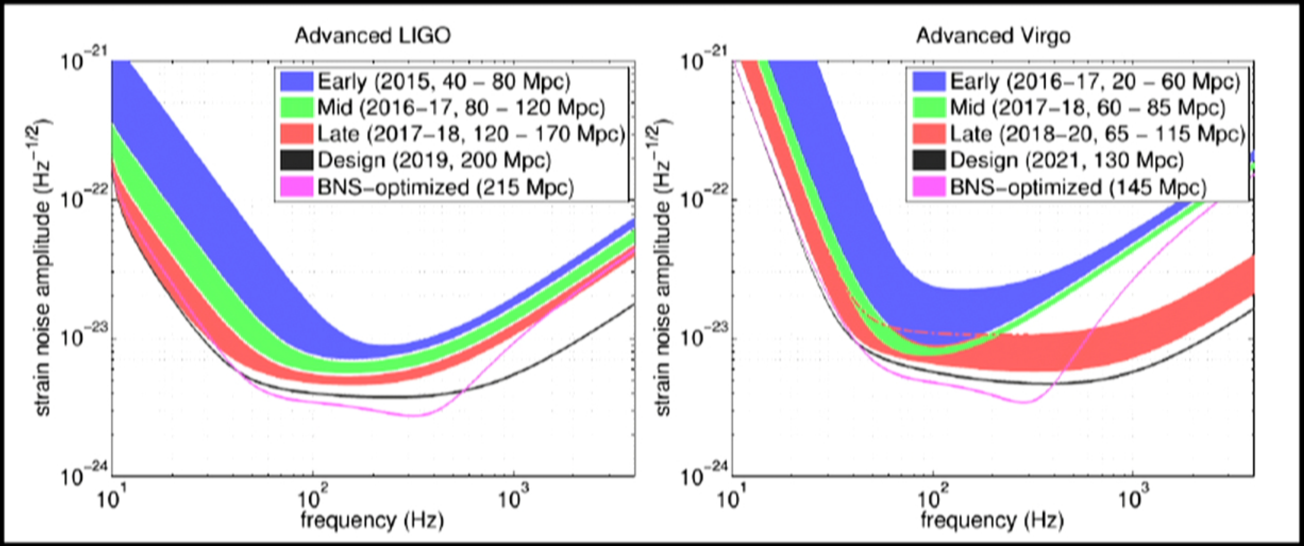

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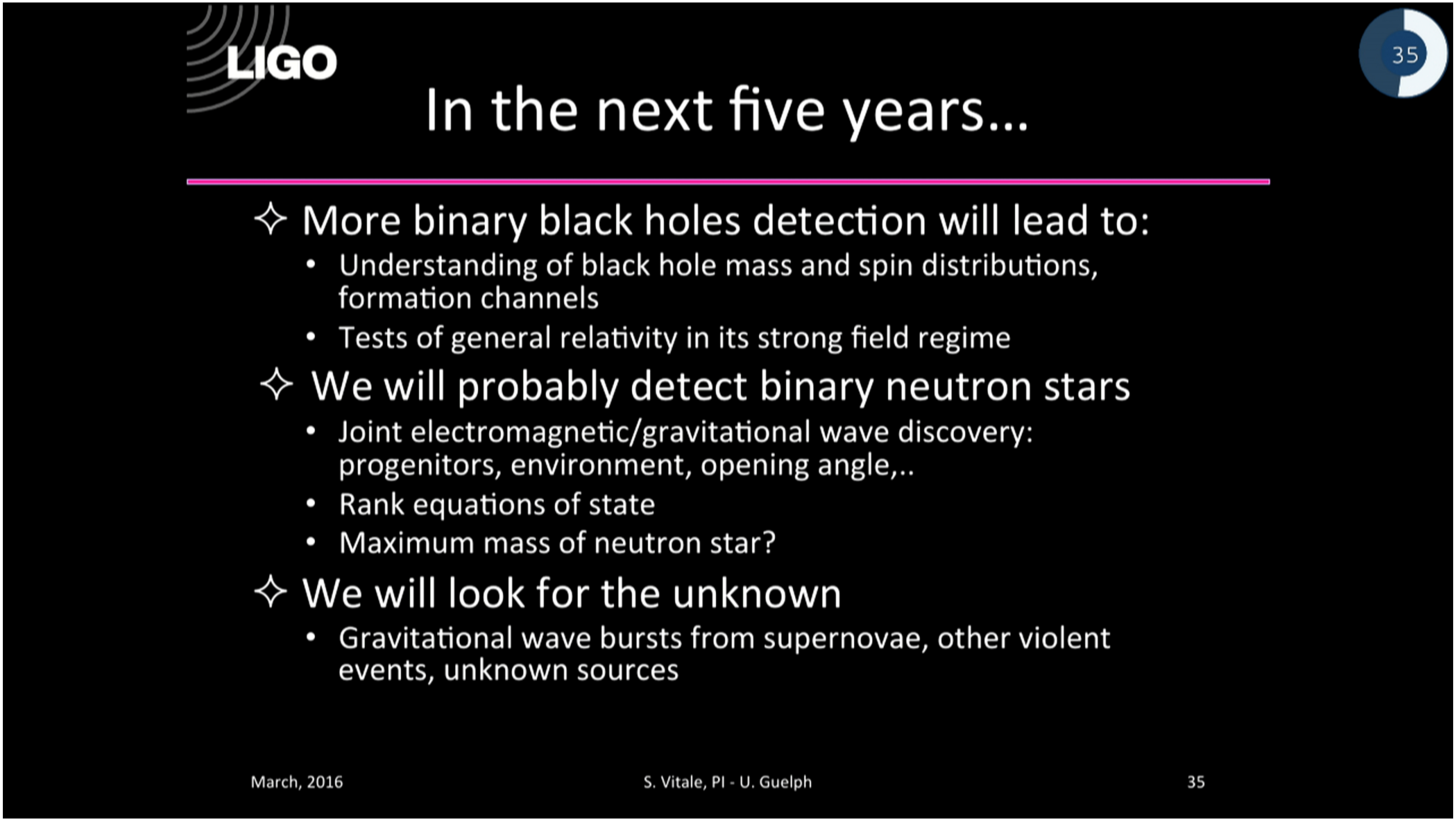


In the next five years...

✧ More binary black holes detection will lead to:

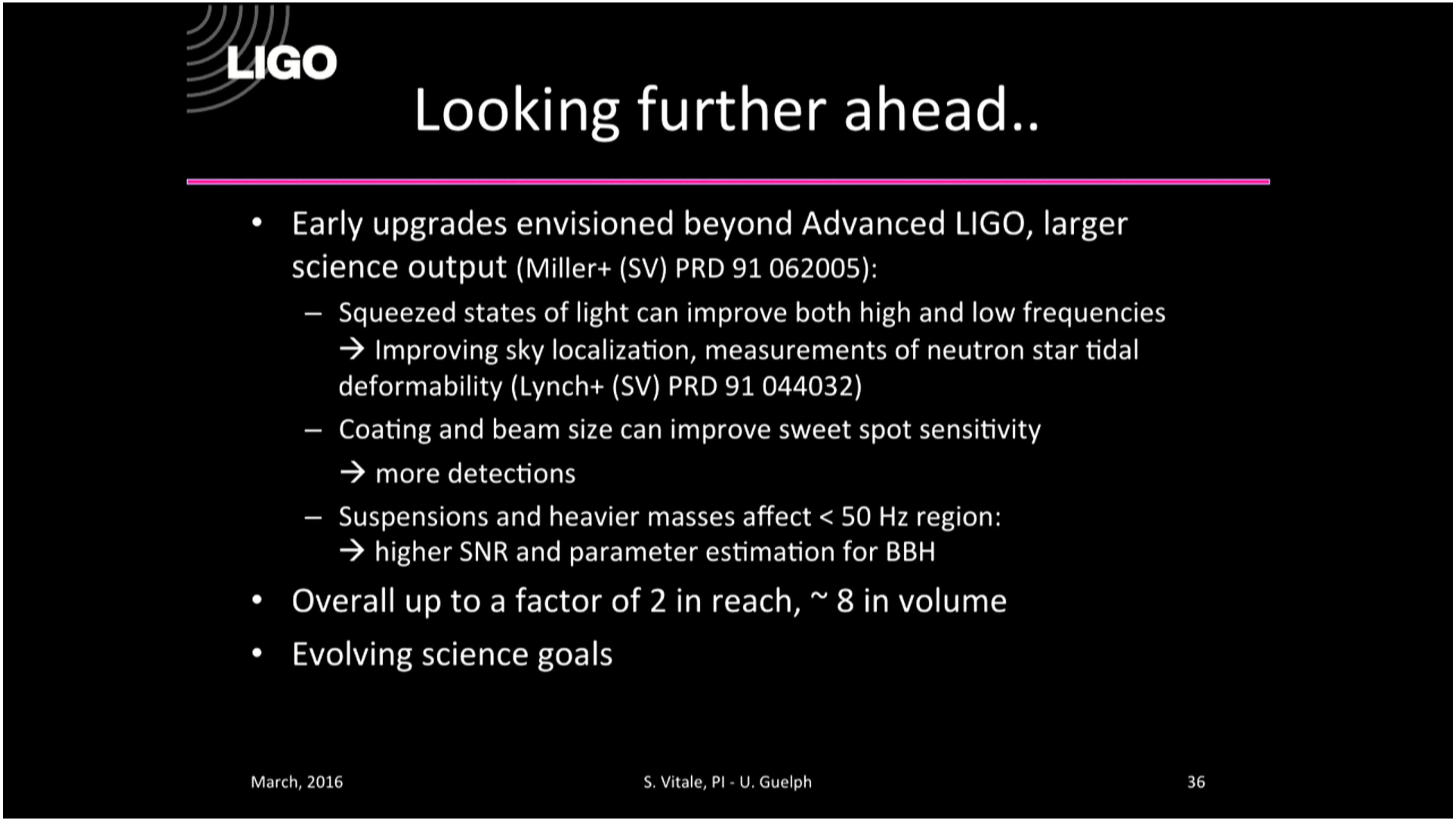
- Understanding of black hole mass and spin distributions, formation channels
- Tests of general relativity in its strong field regime

✧ We will probably detect binary neutron stars

- Joint electromagnetic/gravitational wave discovery: progenitors, environment, opening angle,..
- Rank equations of state
- Maximum mass of neutron star?

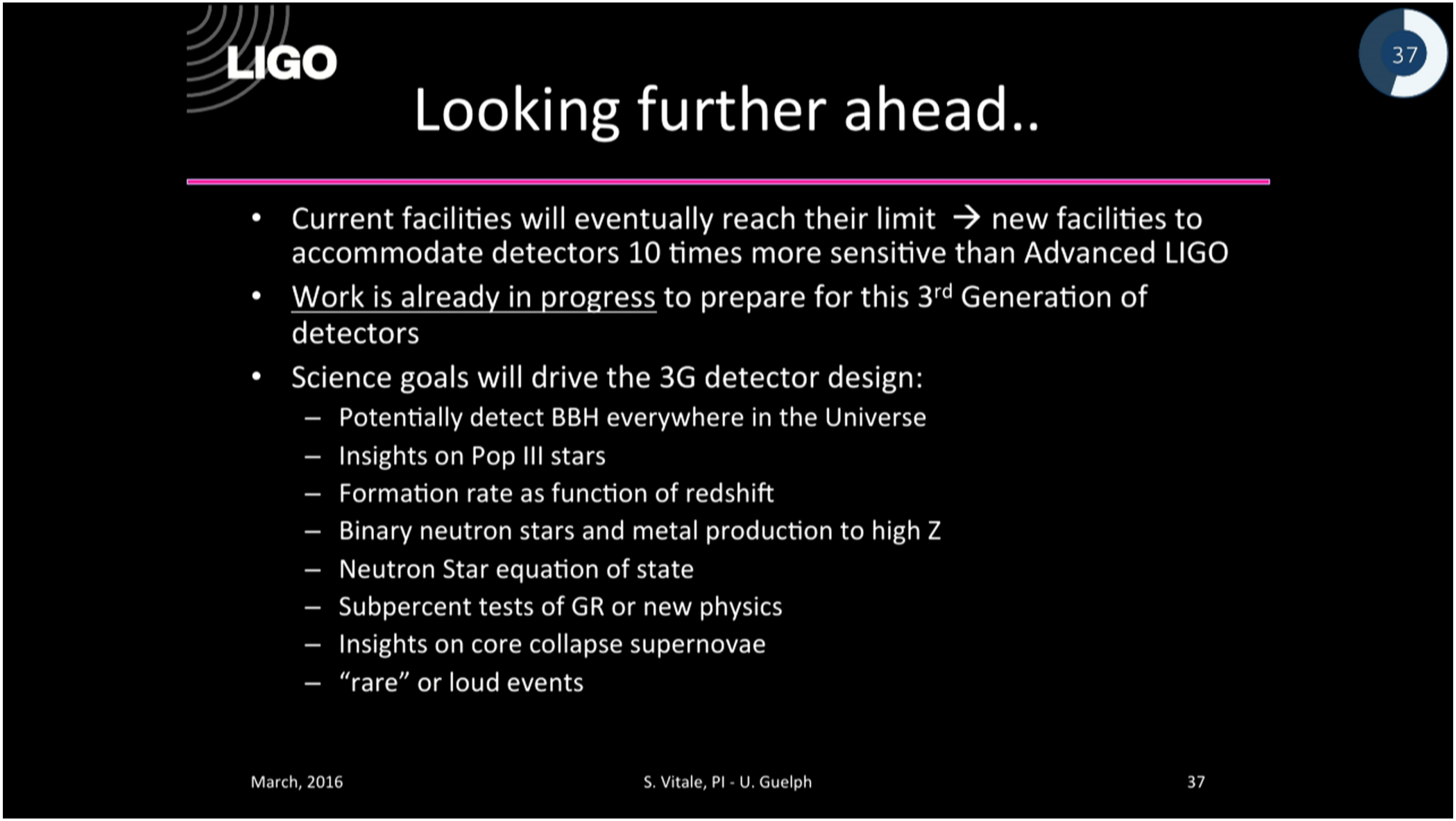
✧ We will look for the unknown

- Gravitational wave bursts from supernovae, other violent events, unknown sources



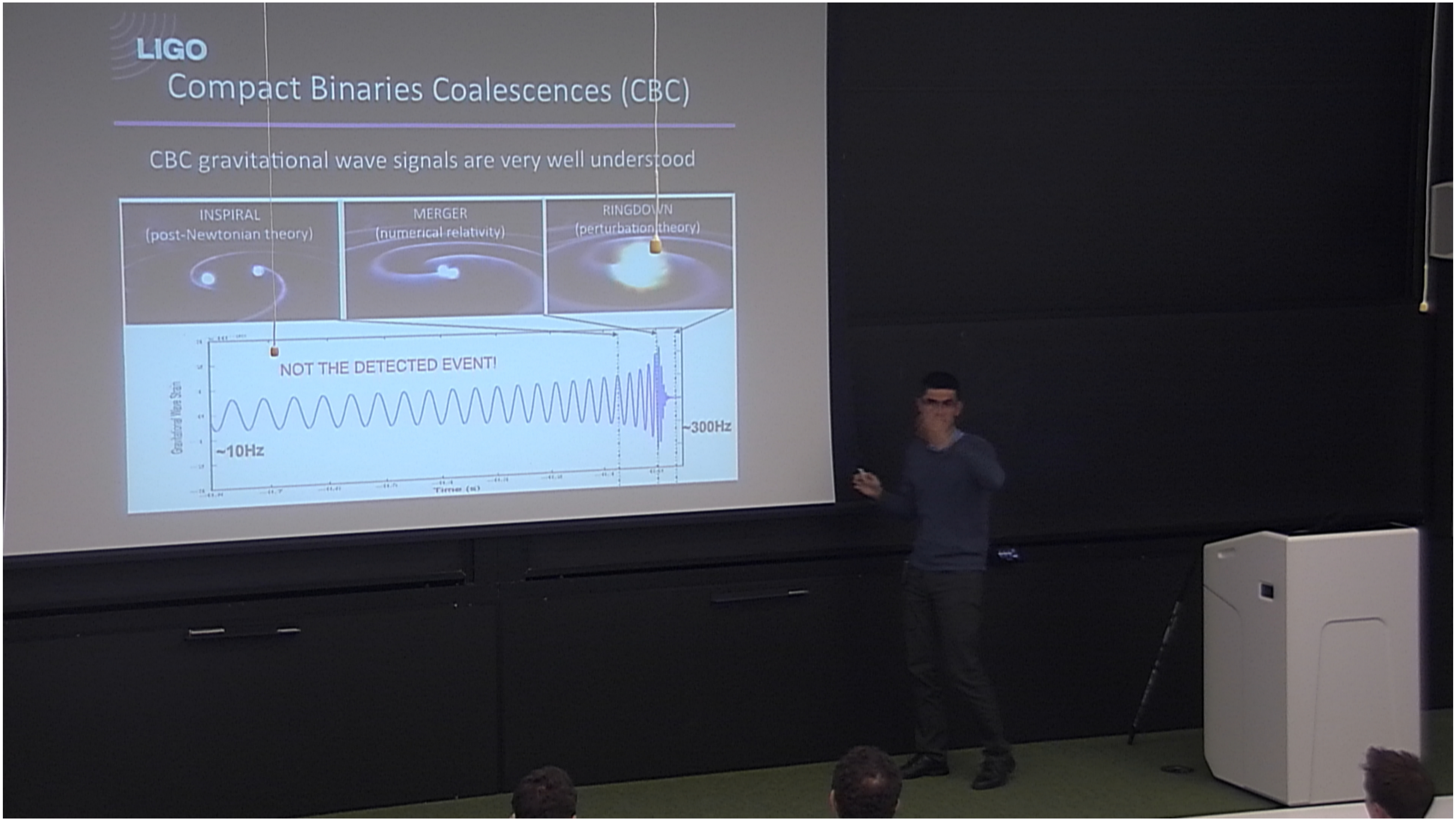
Looking further ahead..

- Early upgrades envisioned beyond Advanced LIGO, larger science output (Miller+ (SV) PRD 91 062005):
  - Squeezed states of light can improve both high and low frequencies → Improving sky localization, measurements of neutron star tidal deformability (Lynch+ (SV) PRD 91 044032)
  - Coating and beam size can improve sweet spot sensitivity → more detections
  - Suspensions and heavier masses affect < 50 Hz region: → higher SNR and parameter estimation for BBH
- Overall up to a factor of 2 in reach, ~ 8 in volume
- Evolving science goals



Looking further ahead..

- Current facilities will eventually reach their limit → new facilities to accommodate detectors 10 times more sensitive than Advanced LIGO
- Work is already in progress to prepare for this 3rd Generation of detectors
- Science goals will drive the 3G detector design:
  - Potentially detect BBH everywhere in the Universe
  - Insights on Pop III stars
  - Formation rate as function of redshift
  - Binary neutron stars and metal production to high Z
  - Neutron Star equation of state
  - Subpercent tests of GR or new physics
  - Insights on core collapse supernovae
  - “rare” or loud events



LIGO

Compact Binaries Coalescences (CBC)

CBC gravitational wave signals are very well understood

INSPIRAL (post-Newtonian theory)

MERGER (numerical relativity)

RINGDOWN (perturbation theory)

NOT THE DETECTED EVENT!