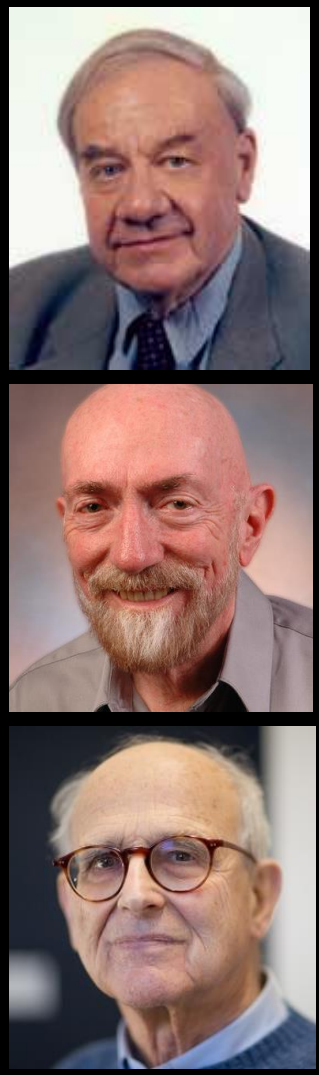
LIGO's First Discovery and Beyond

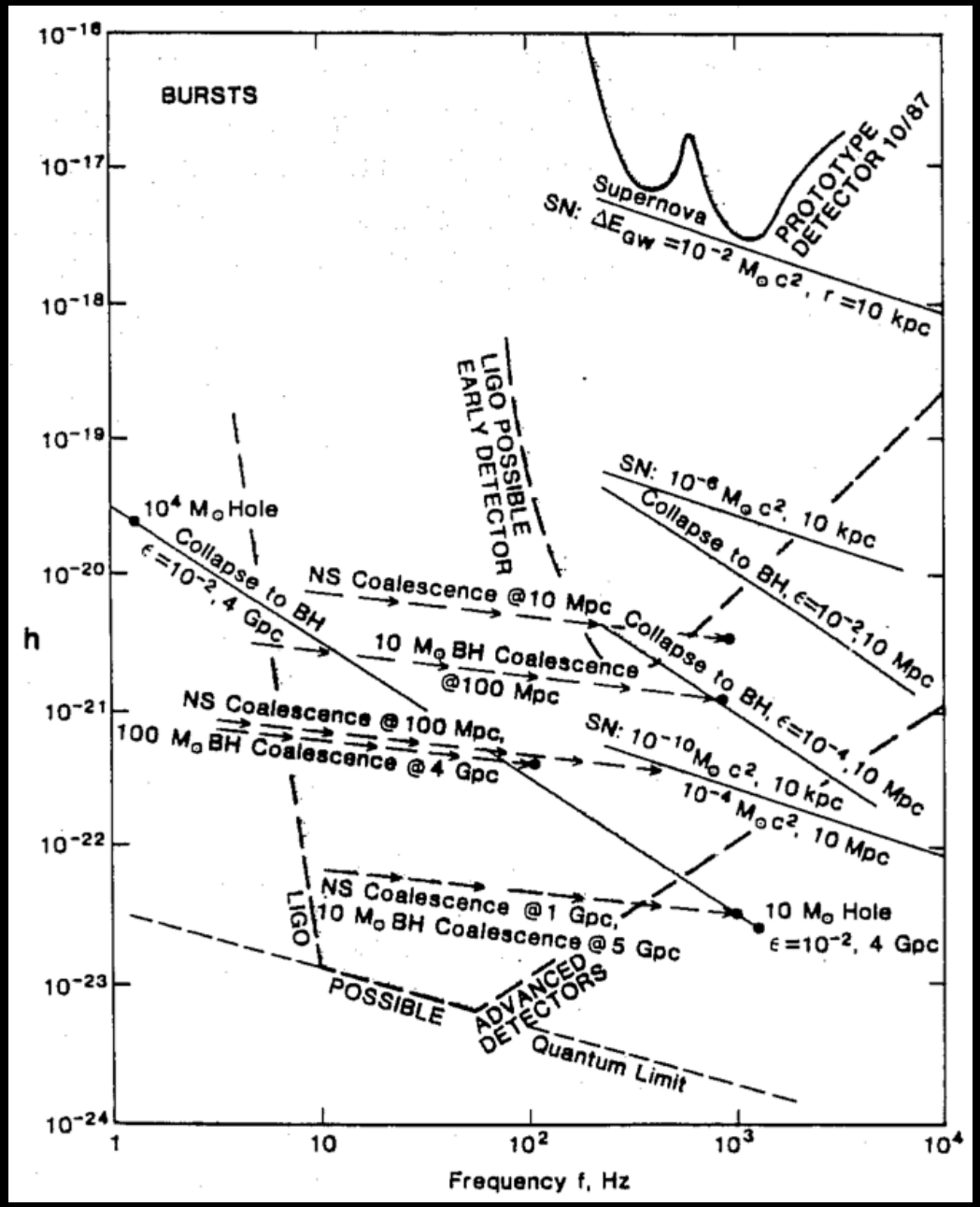
100 years of gravitational waves

100 years of black holes

Imre Bartos, Columbia University

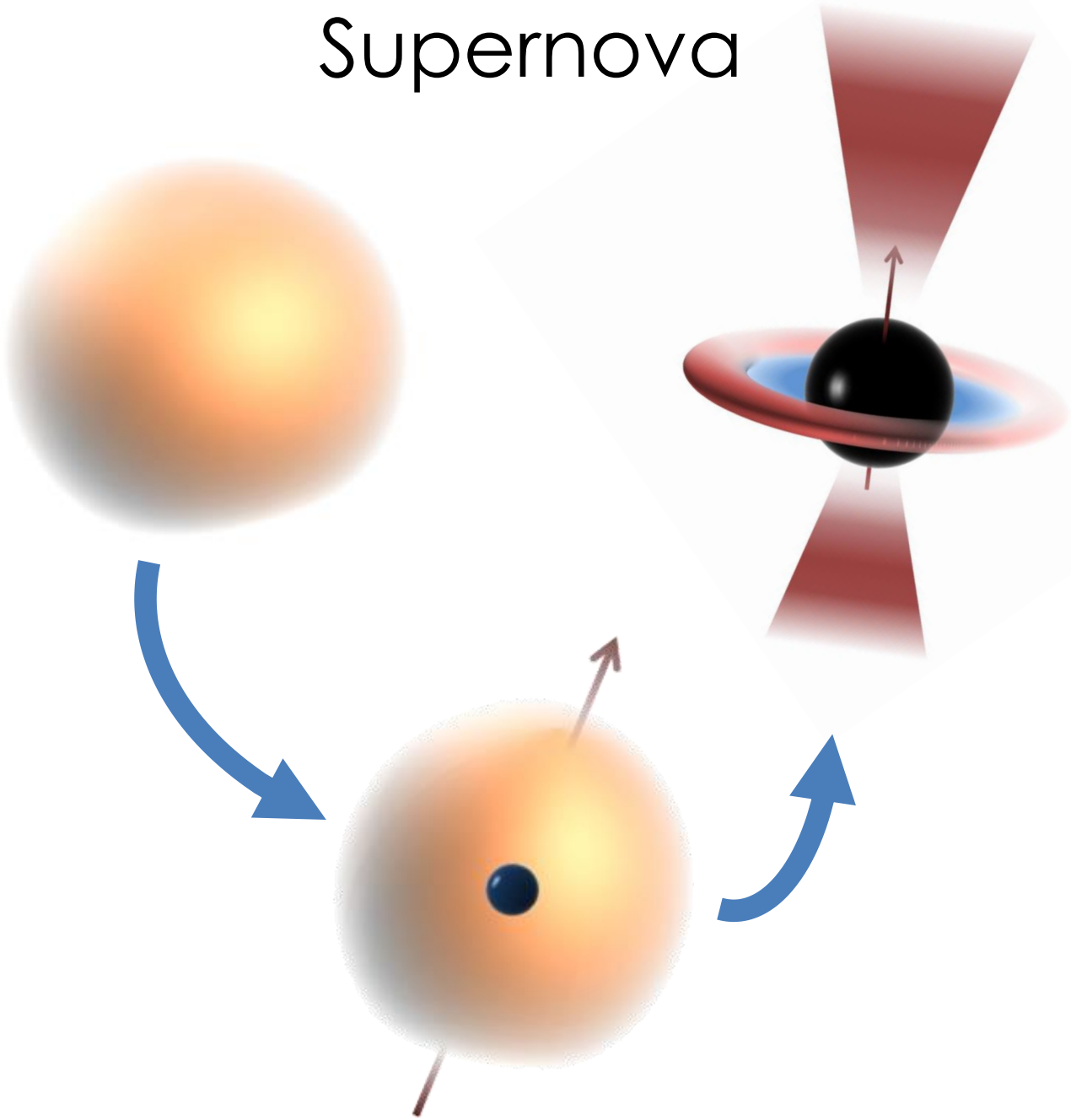
BNL Colloquium, Mar 1 2016

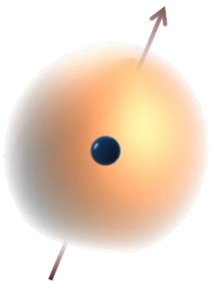


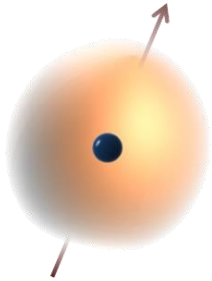


Ron Drever, Kip Thorne, Rai Weiss, 1987

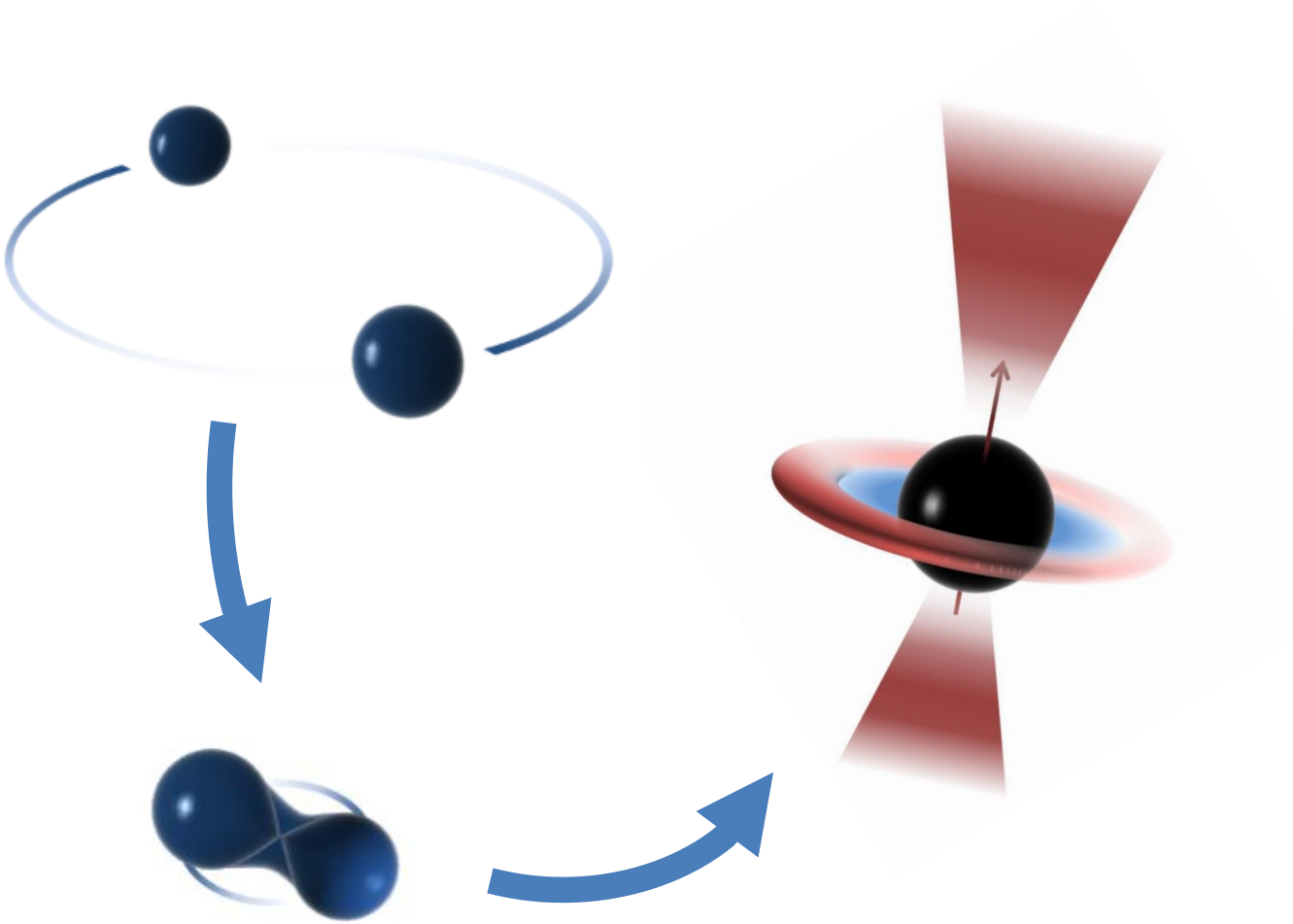
Supernova

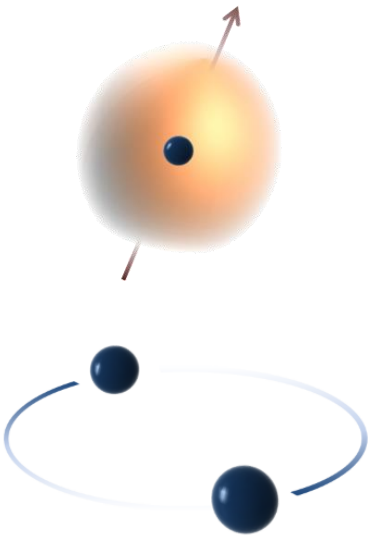


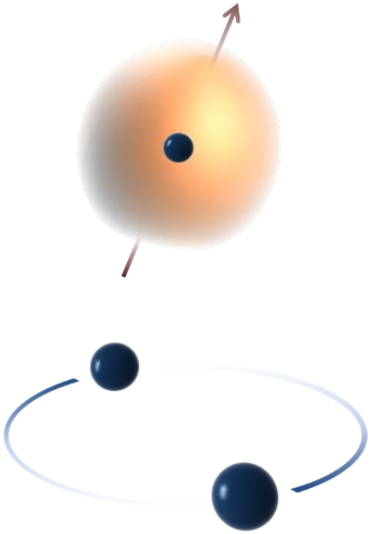




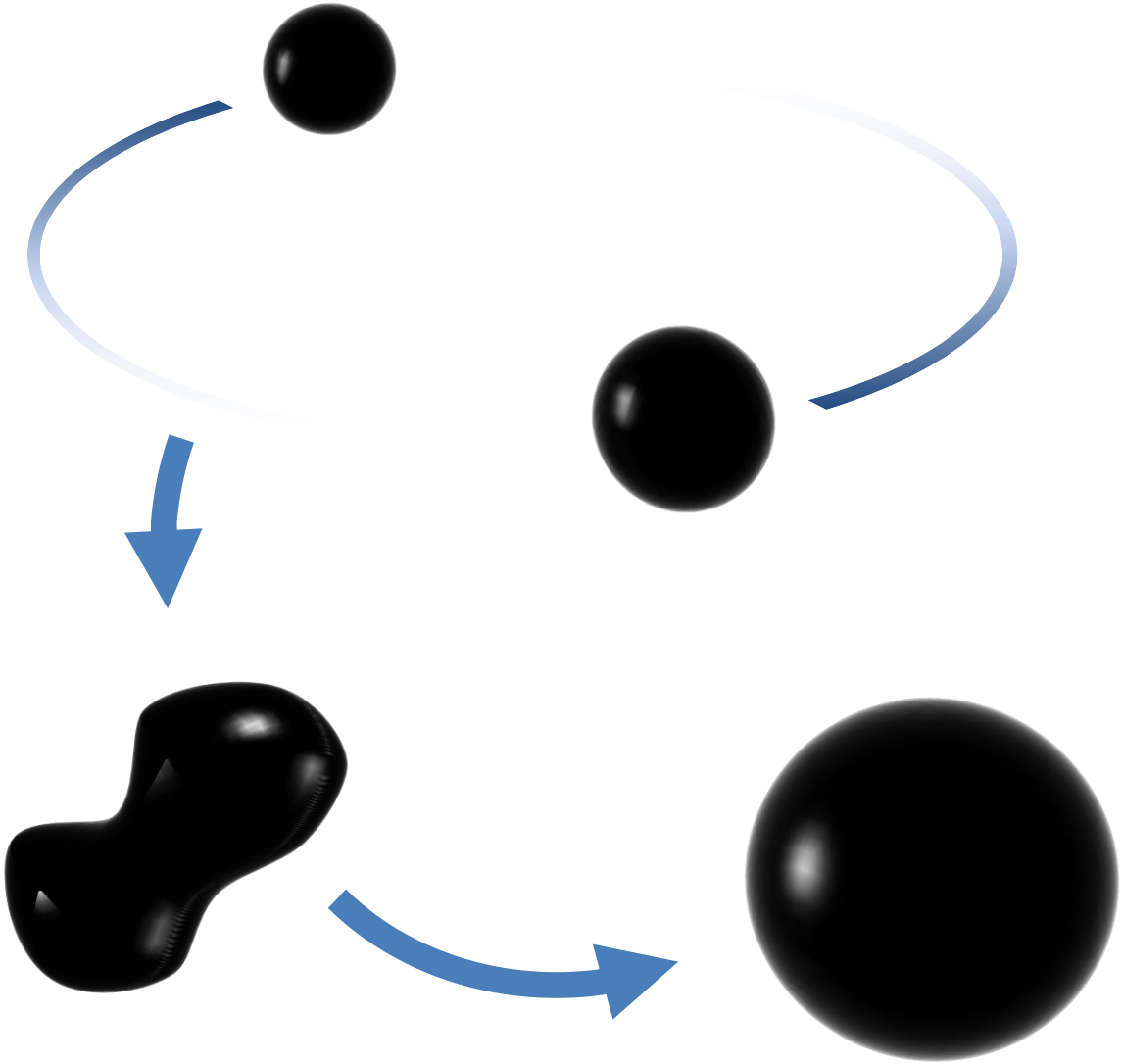
Binary Neutron Star

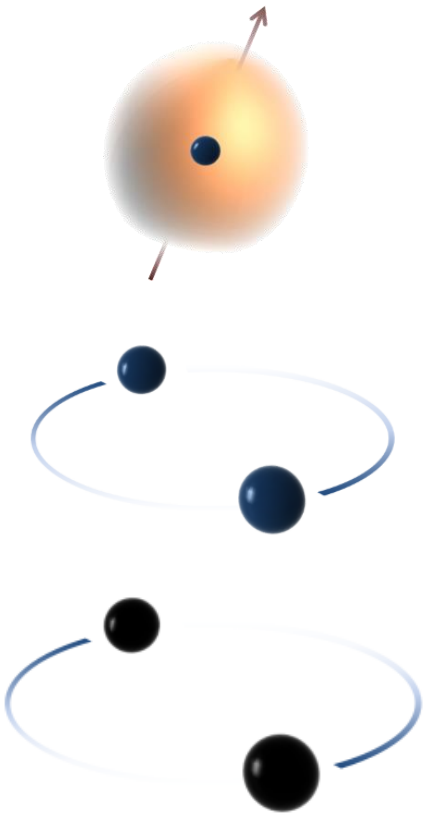


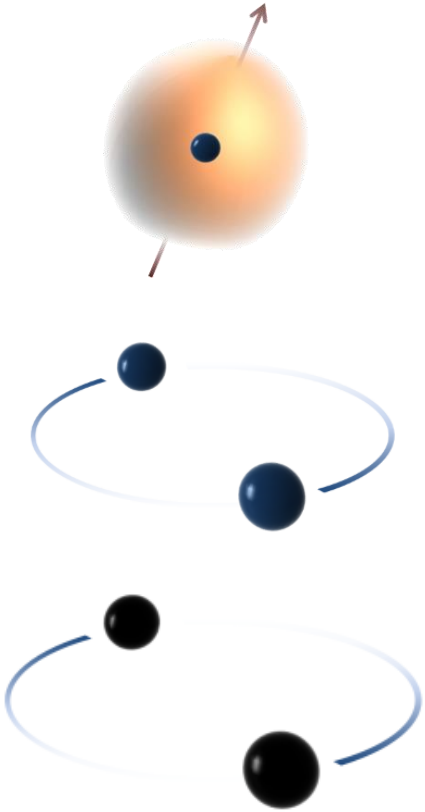




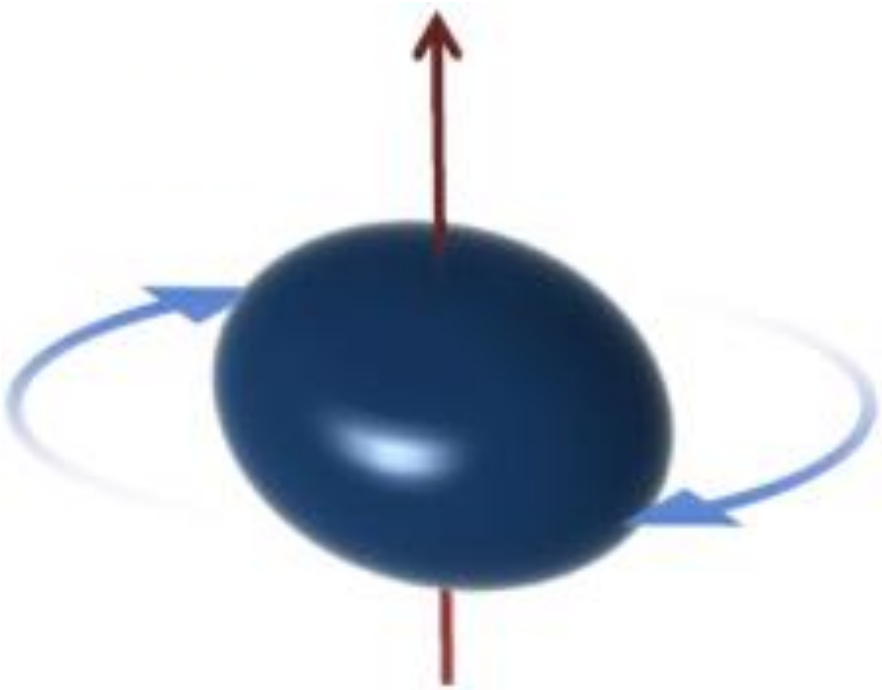
Binary Black Hole

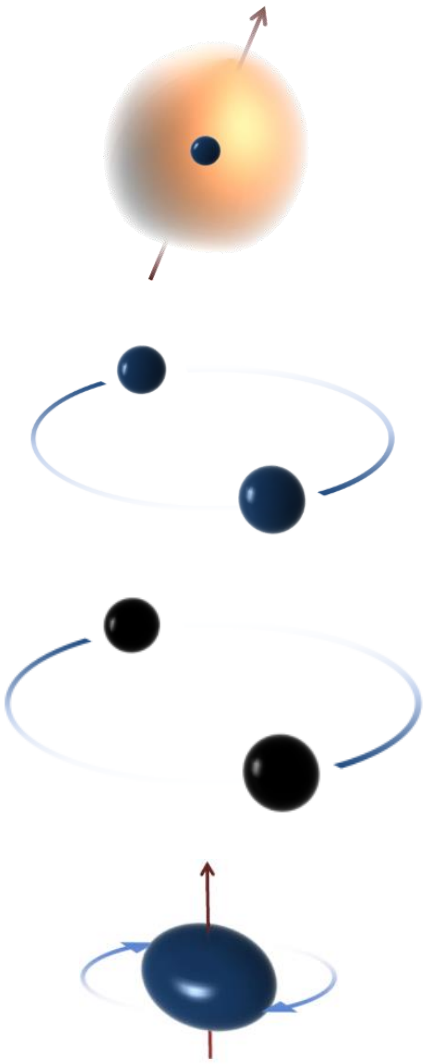


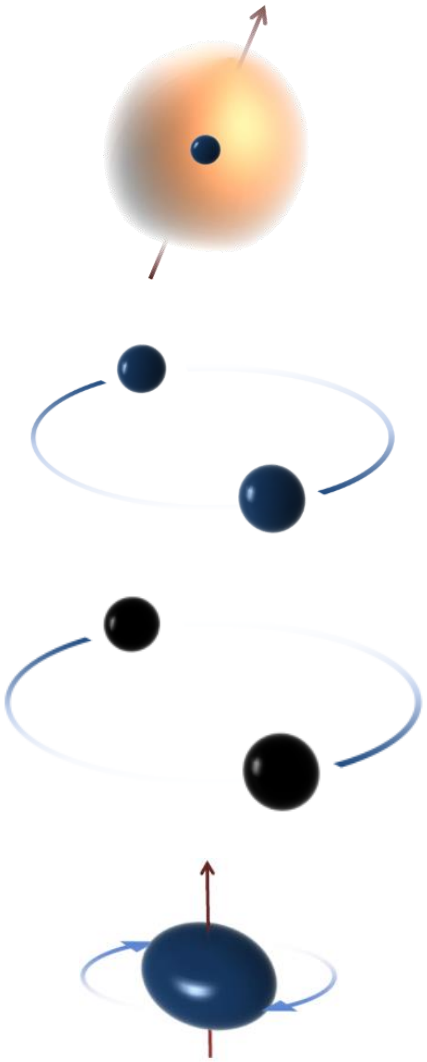




Rapidly Rotating Neutron Star







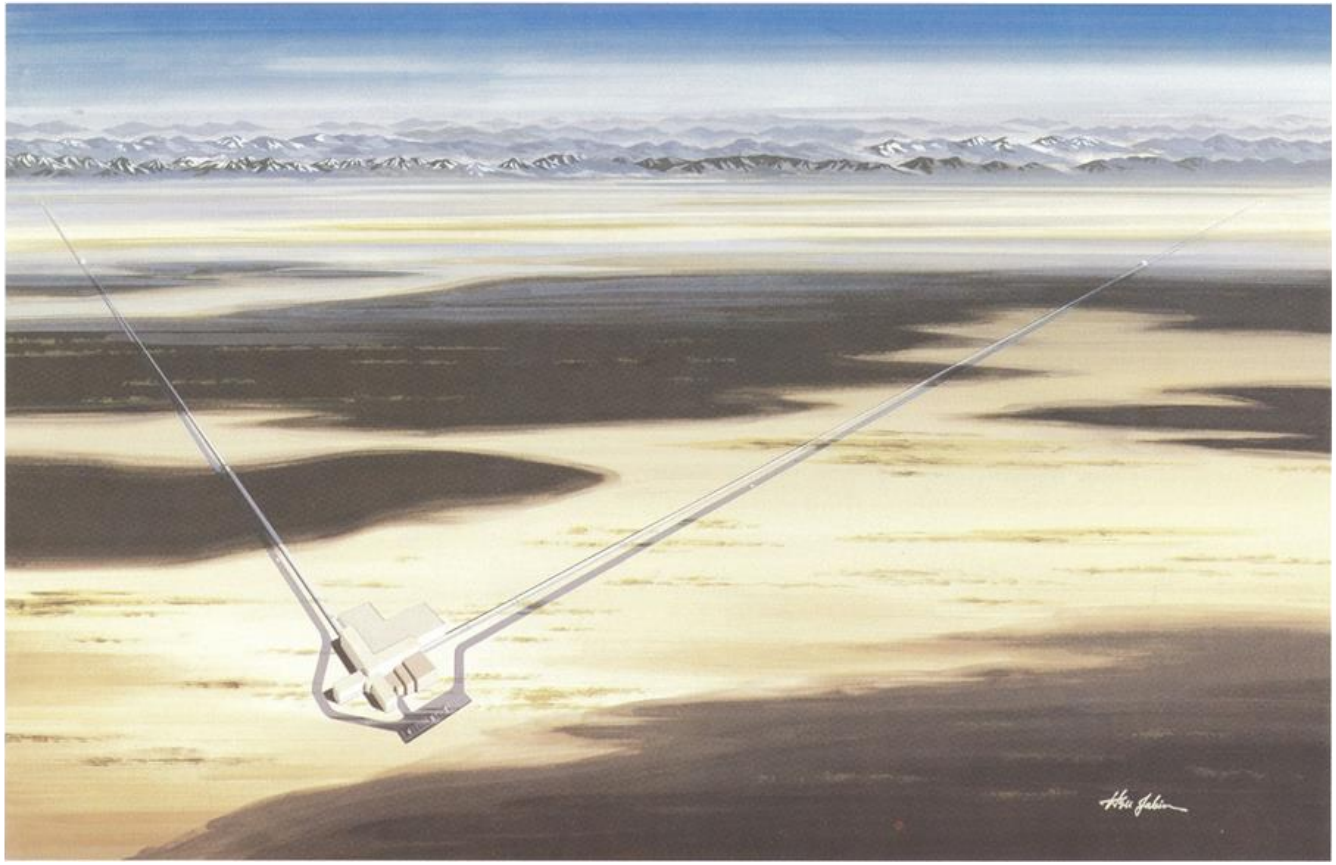
Many Distant Sources

1989 Proposal to the US NSF

PREFACE

This proposal requests support for the design and construction of a novel scientific facility—a gravitational-wave observatory—that will open a new observational window on the universe.

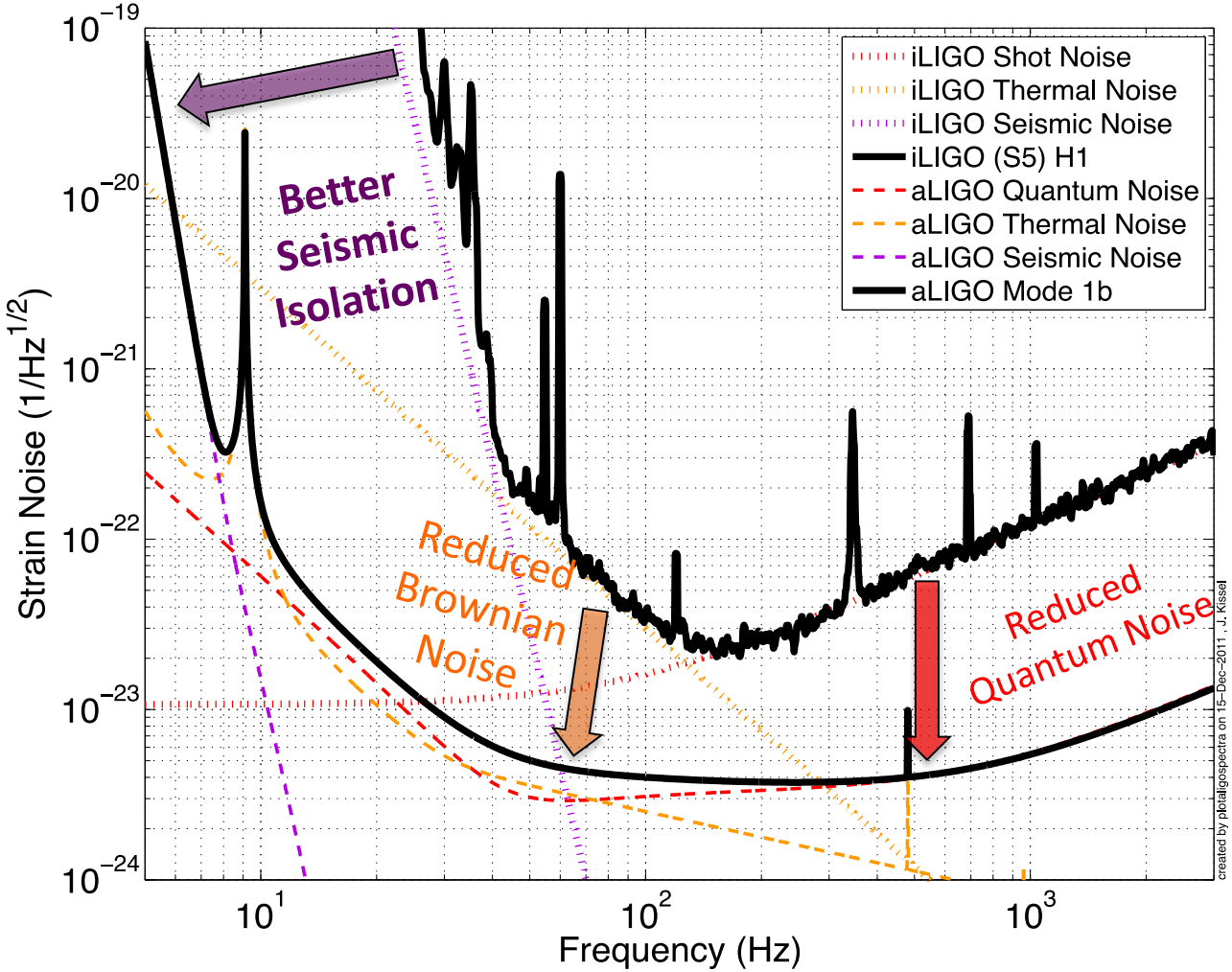
The scale of this endeavor is indicated by the frontispiece illustration, which shows a perspective of one of the two proposed detector installations. Each installation includes two arms, and each arm is 4 km in length.



Initial LIGO Hanford, WA

Advanced LIGO Hanford, WA

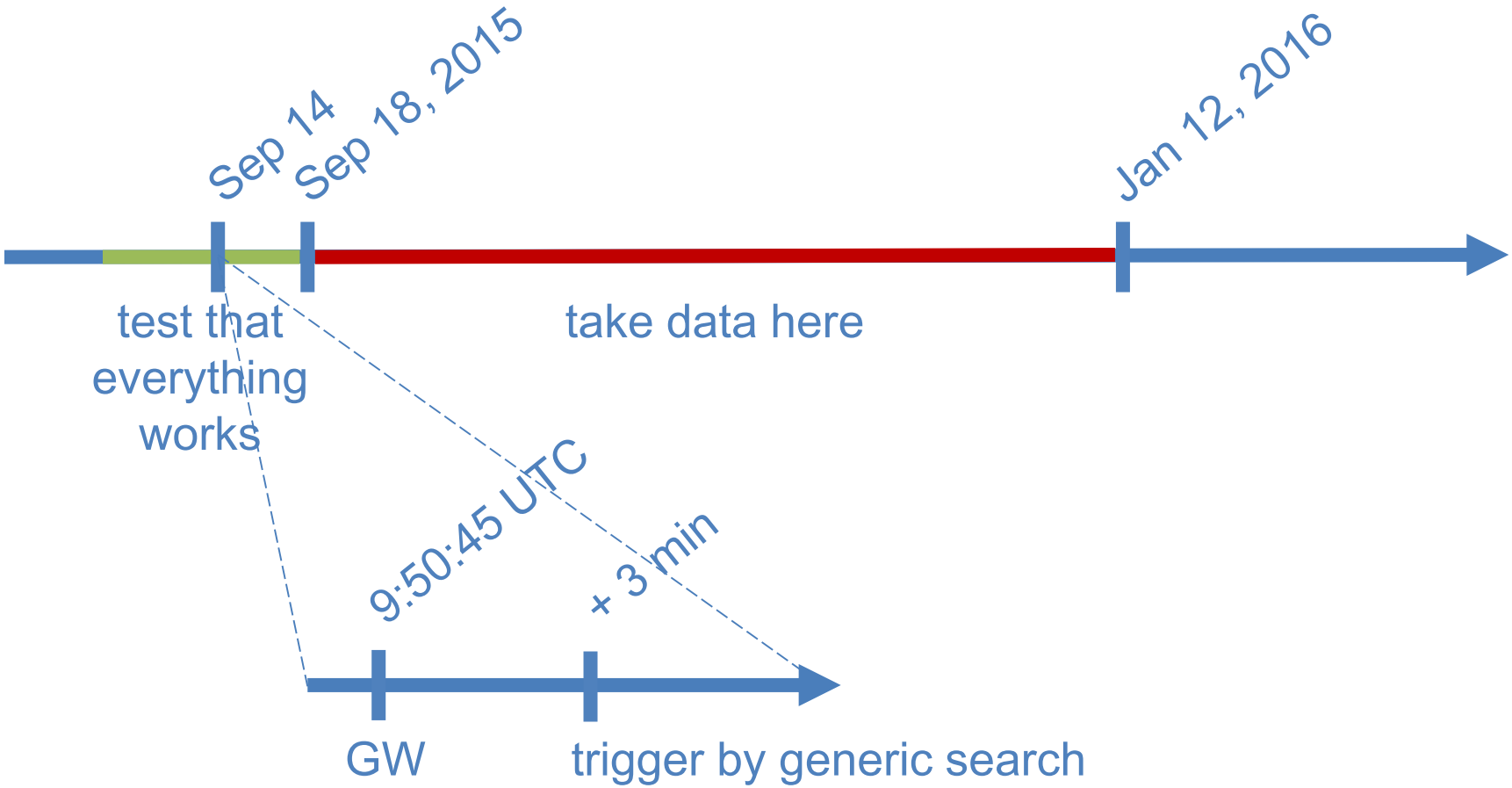
Advanced LIGO vs. Initial LIGO

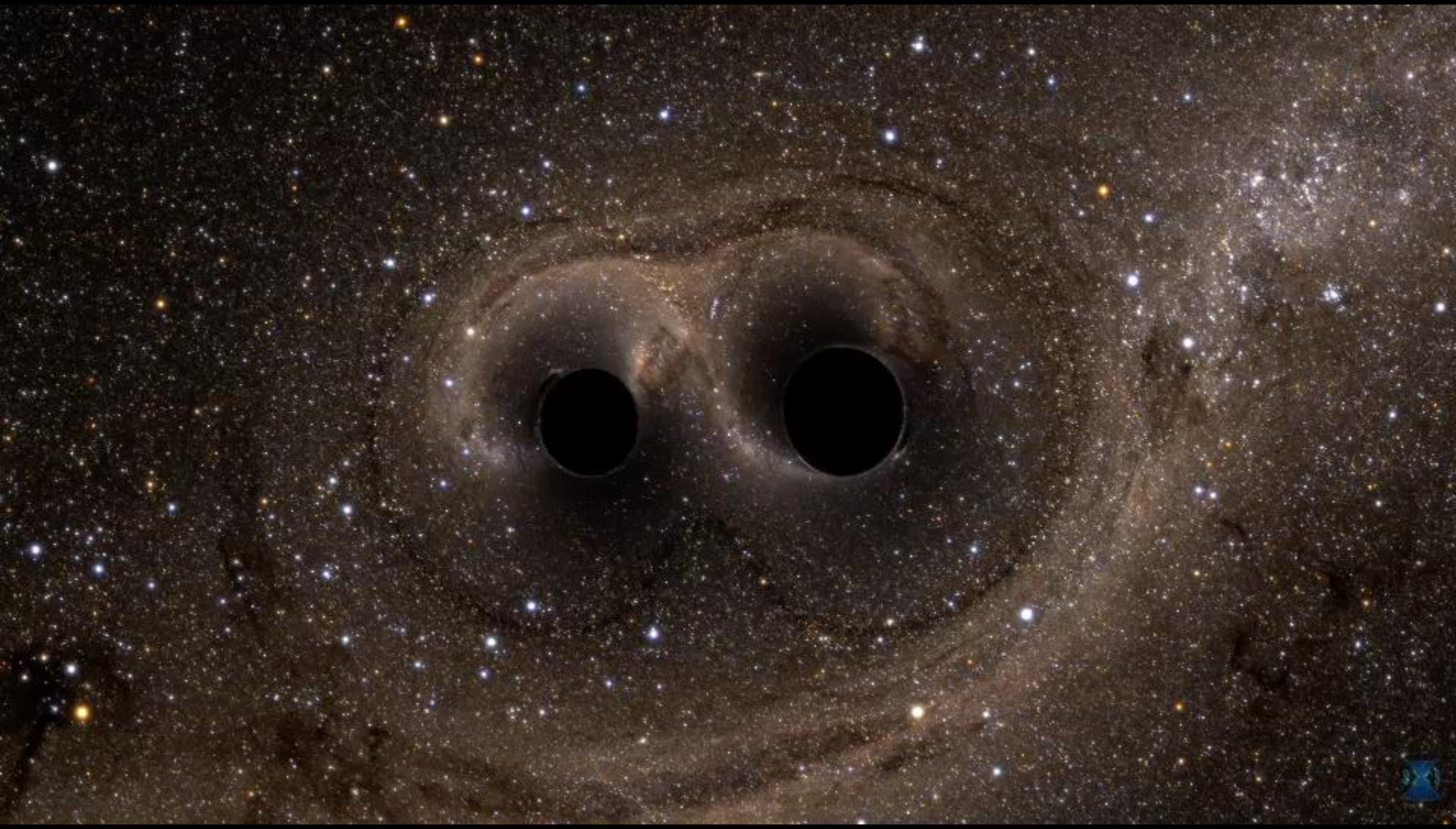


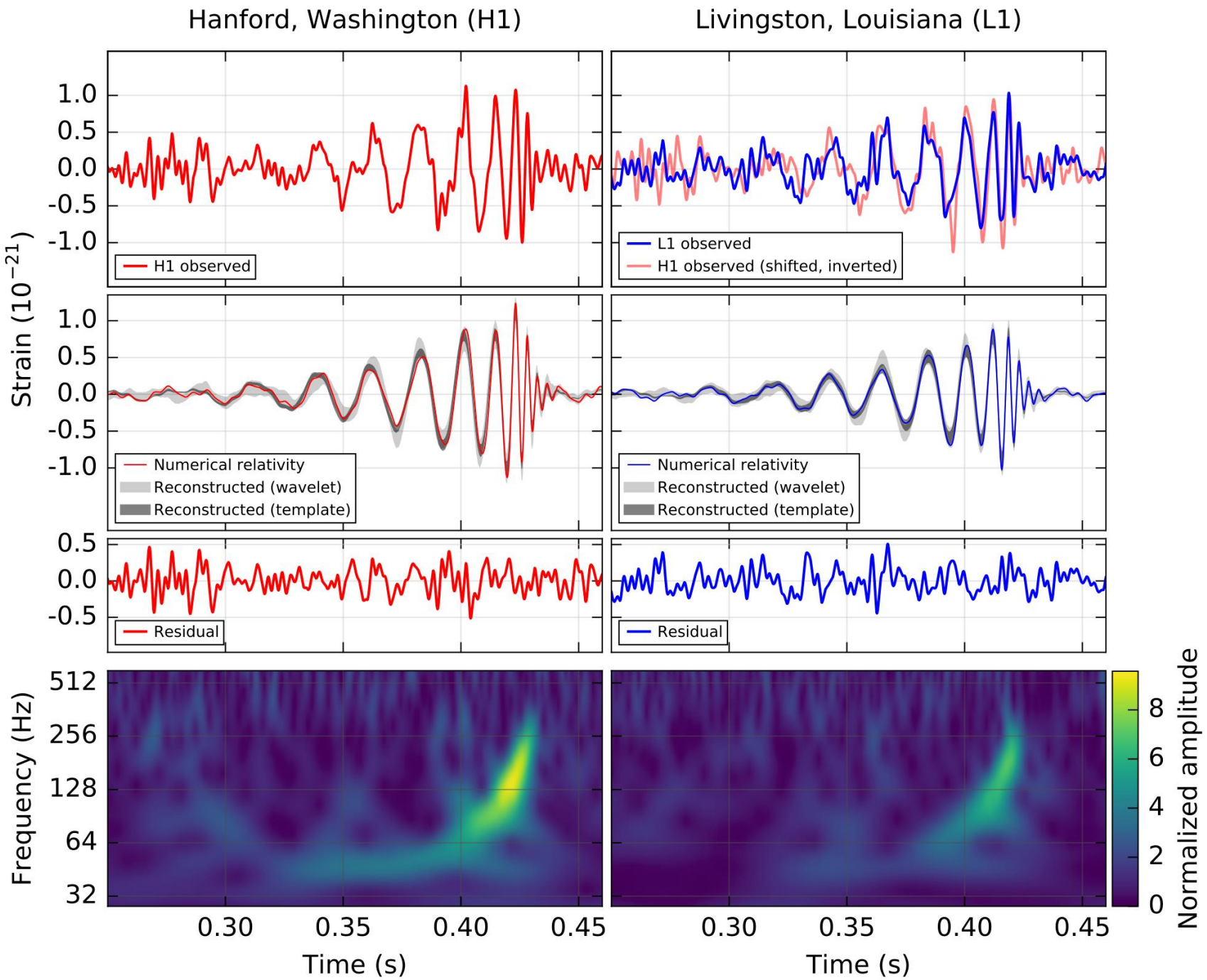
LIGO Hanford
LIGO Livingston
Operational
Under Construction
Planned
Gravitational Wave Observatories

Feb 11, 2015, Hanford, WA

timeline


Sep 14
Sep 18, 2015
Jan 12, 2016
test that everything works
take data here
9:50:45 UTC
+ 3 min
GW
trigger by generic search




Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

What have we discovered?

- Einstein was right
- First signal: “I come from a black hole”
- Binary black holes exist
-
-

“All the News That’s Fit to Print”

The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

VOL. CLXV . . . No. 57,140 © 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016 $2.50

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

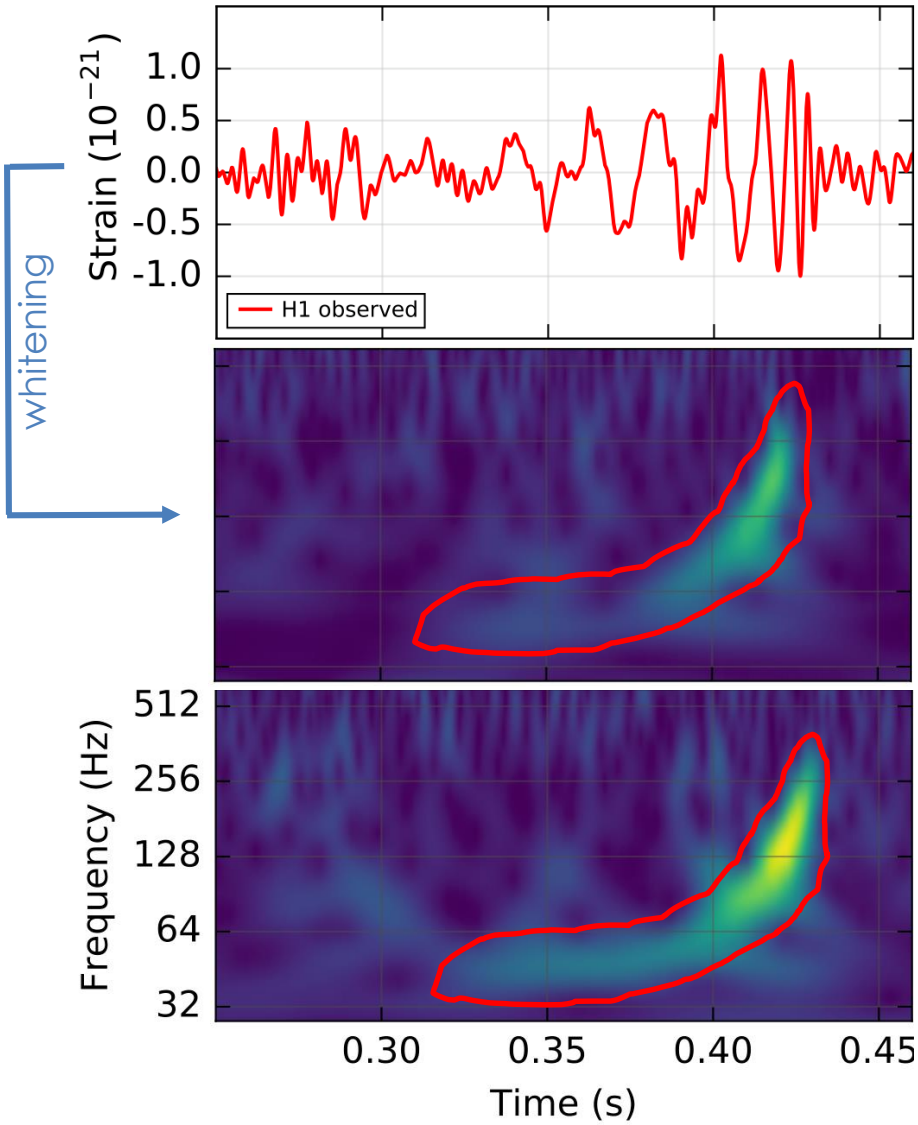
A RIPPLE IN SPACE-TIME

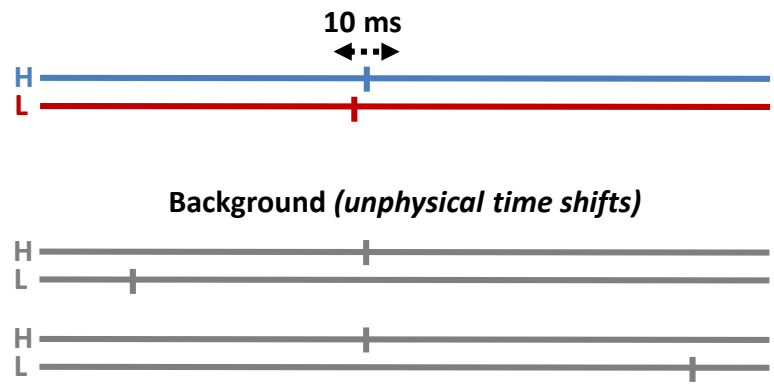
An Echo of Black Holes Colliding a Billion

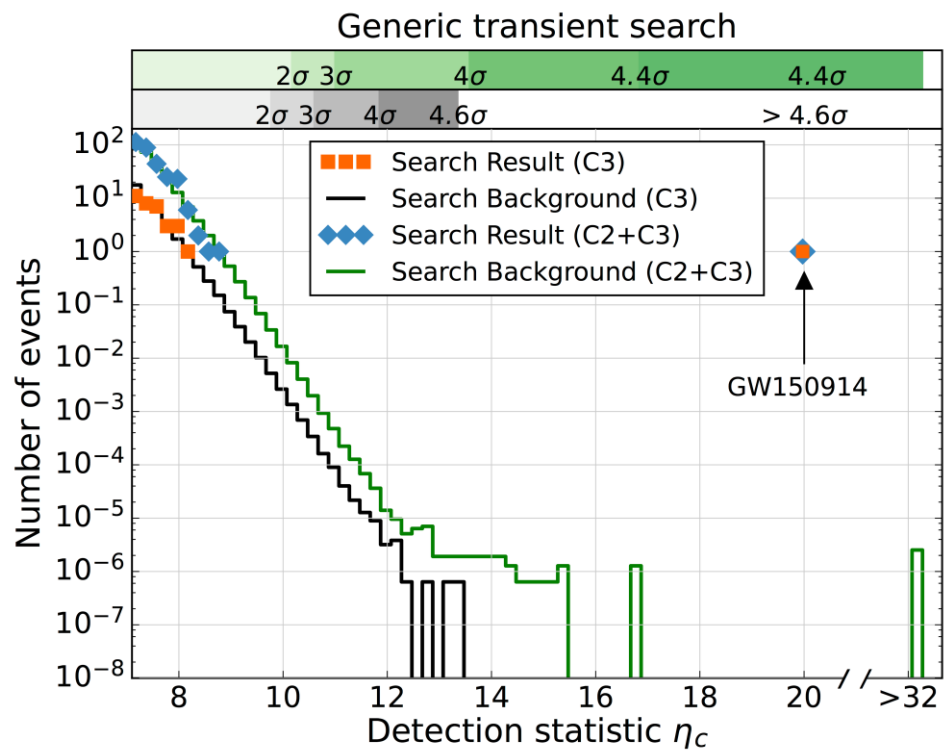
Extraordinary claims require extraordinary evidence

-- Carl Sagan

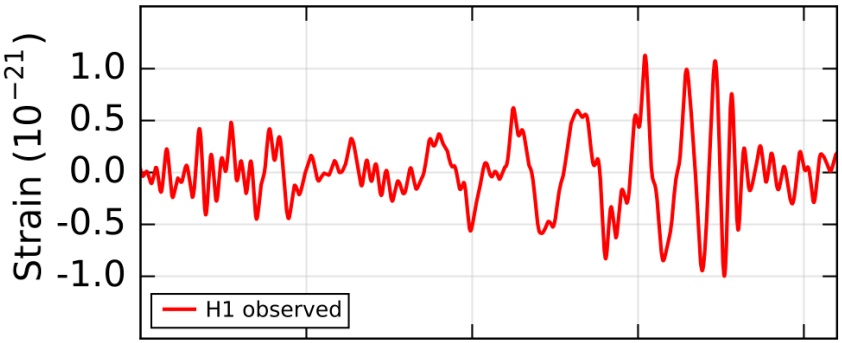
Generic transient search

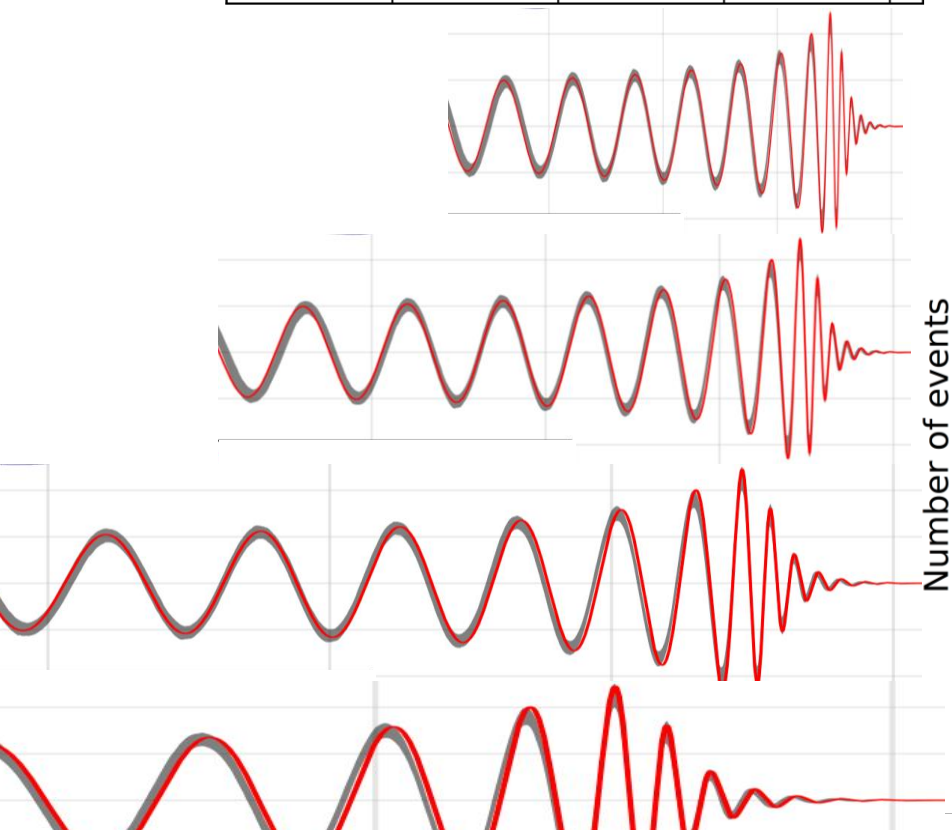






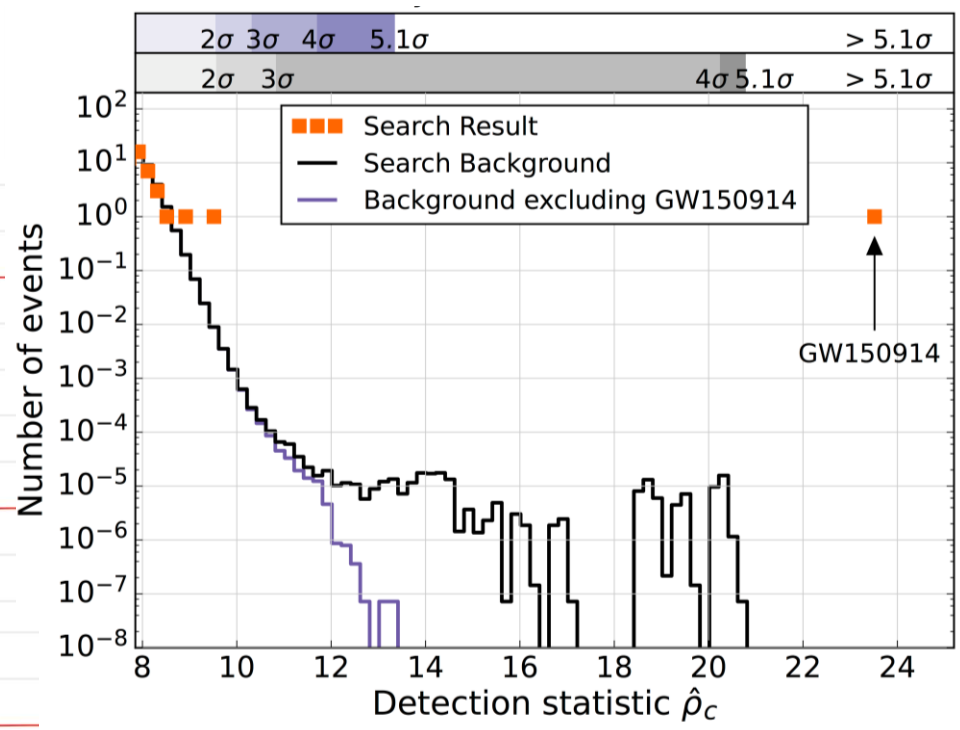
Binary coalescence search



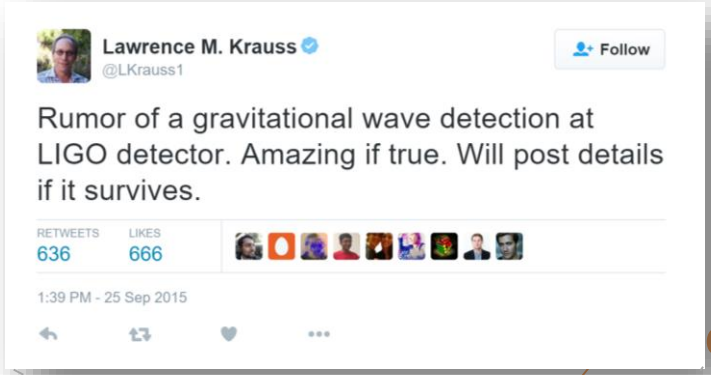


15 (+2) parameters

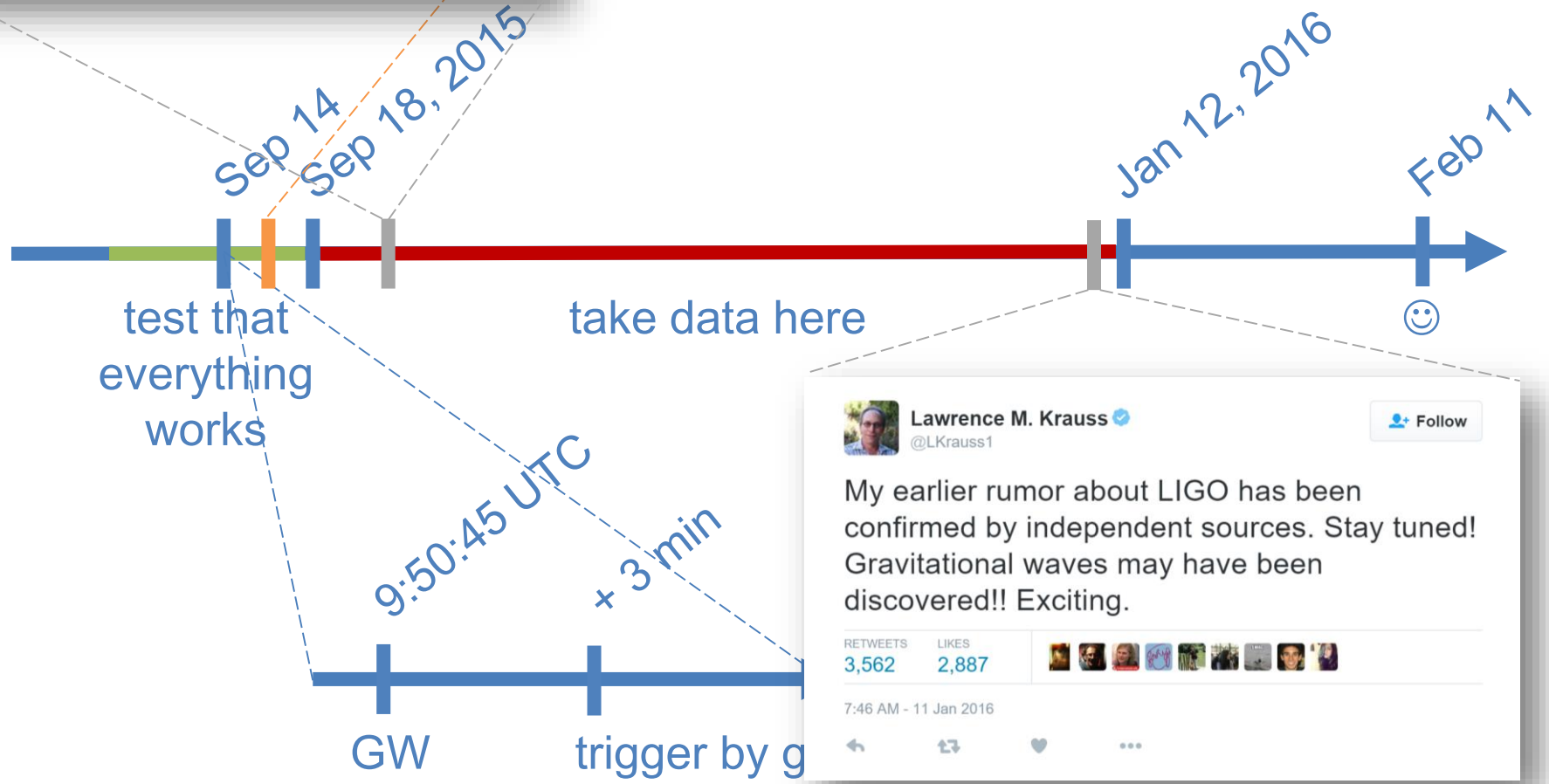
masses (2)
distance (1)
direction (2)
orientation (2)
spin (6)
time (1)
phase (1)
+ eccentricity (2)
+ calibration uncertainty (~10%)



timeline



e and initial results sent to astronomers



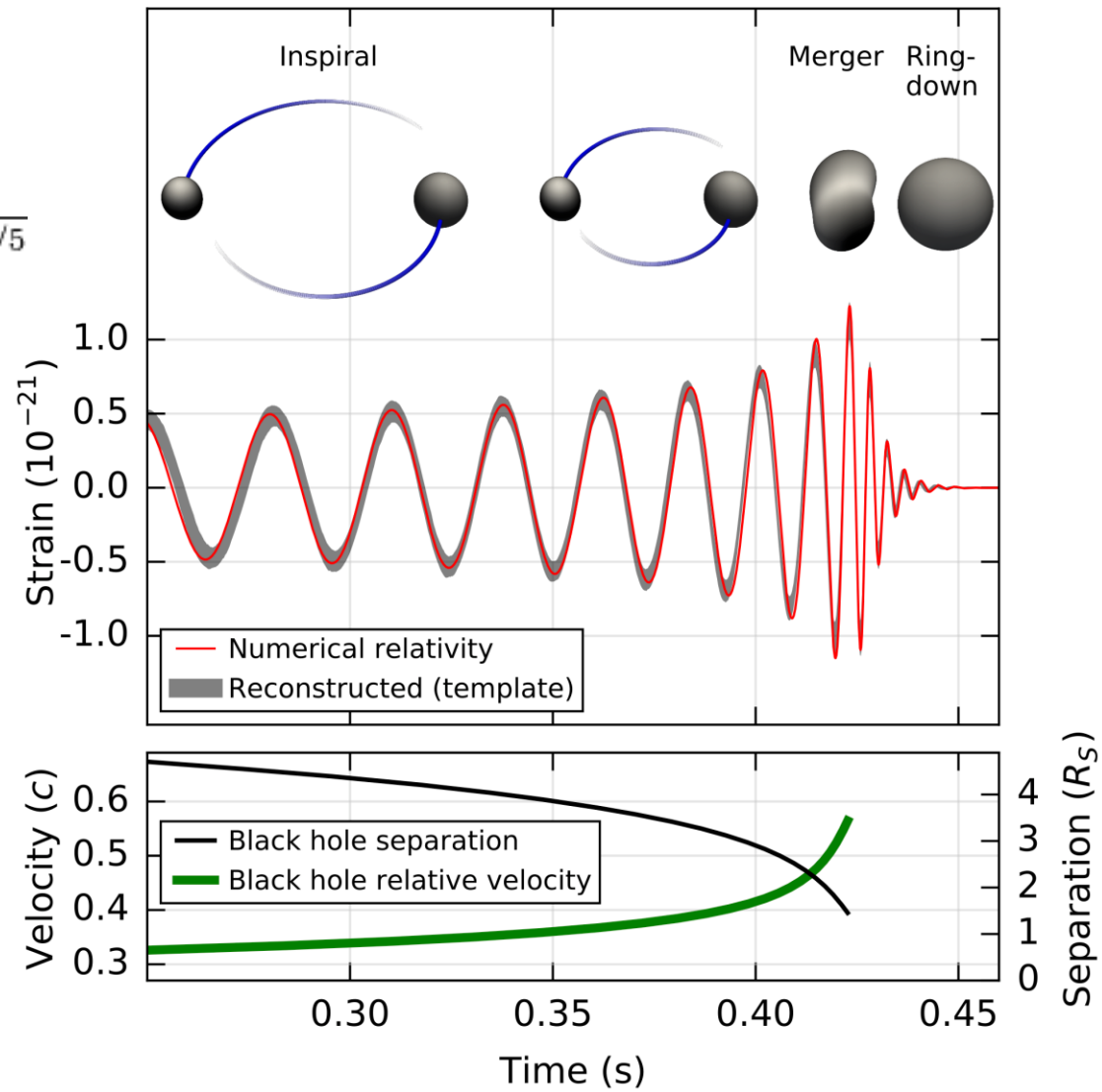
Information content

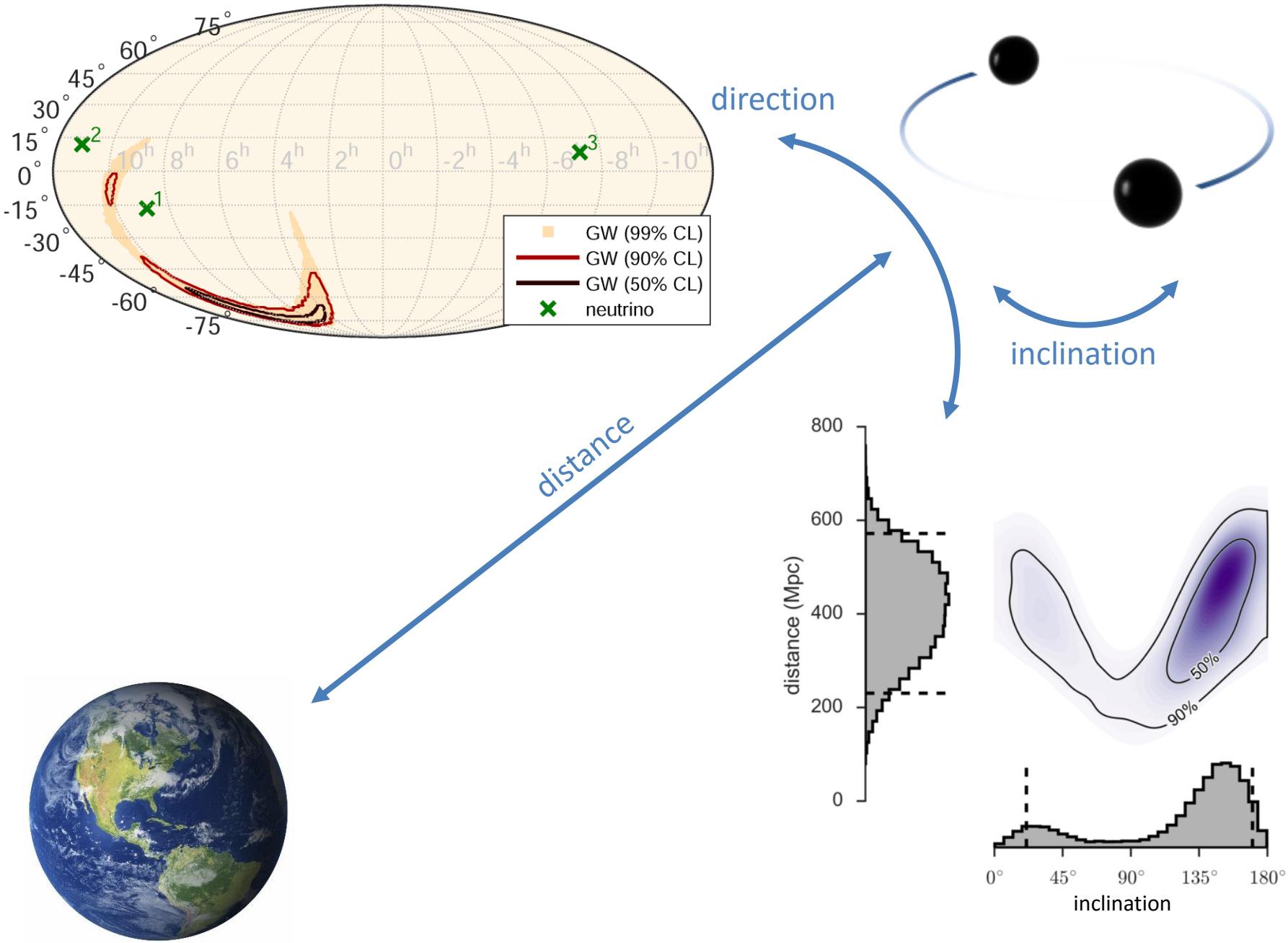
chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$

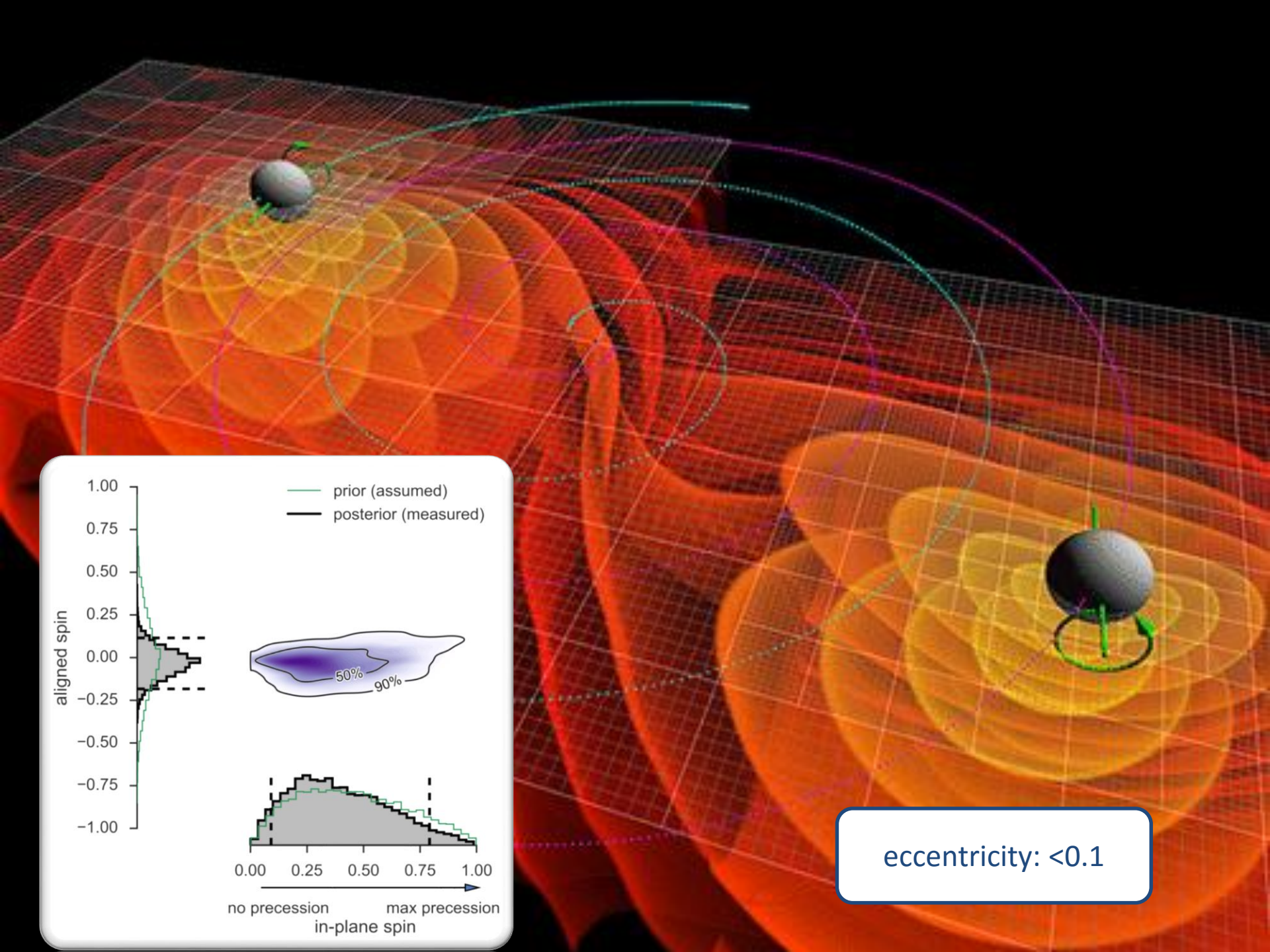
mass ratio $q = m_2/m_1$

spin parallel to the orbital angular momentum

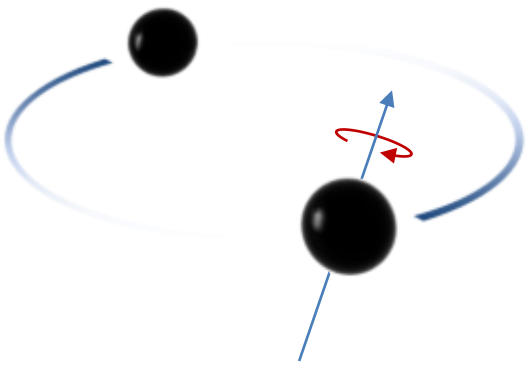
spin perpendicular to the orbital angular momentum




75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
10h
8h
6h
4h
2h
0h
-2h
-4h
-6h
-8h
-10h
1
2
3
GW (99% CL)
GW (90% CL)
GW (50% CL)
neutrino
direction
inclination
distance
800
600
400
200
0
distance (Mpc)
50%
90%
0°
45°
90°
135°
180°
inclination


prior (assumed)
posterior (measured)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
aligned spin
50%
90%
0.00
0.25
0.50
0.75
1.00
no precession
max precession
in-plane spin
eccentricity: <0.1

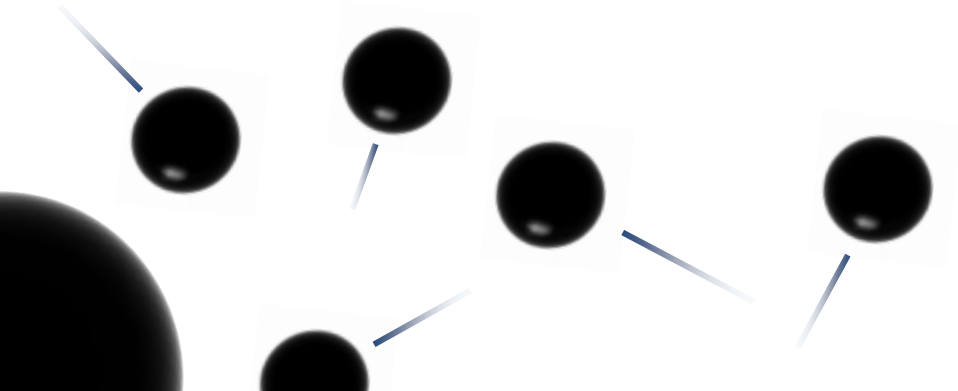
Origin

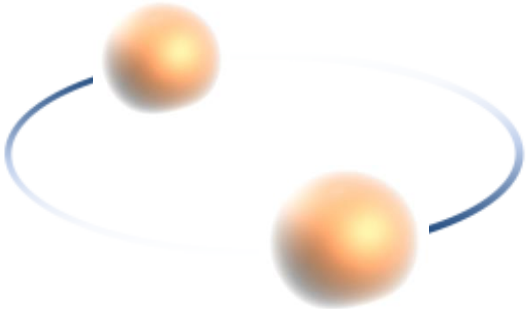


high BH mass → Low metallicity environment (Z<0.5 Solar)

low orbital-aligned BH spin → limit on BH natal kick

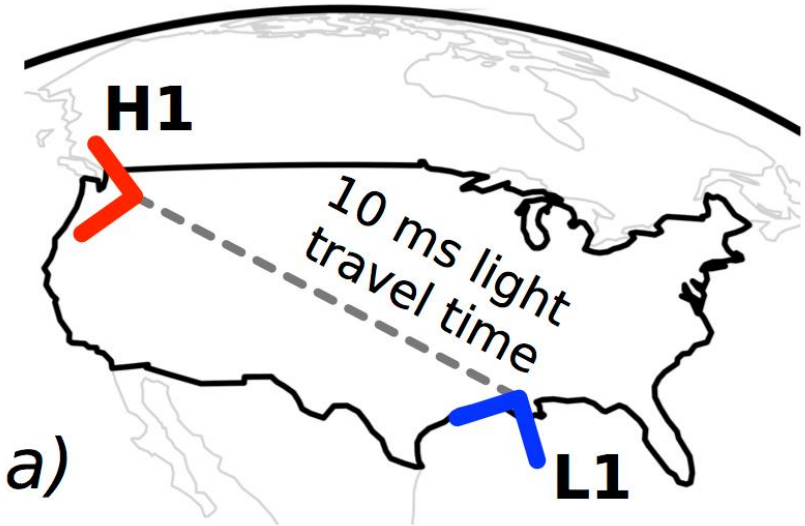
low eccentricity → eccentric encounter in galactic nucleus disfavored



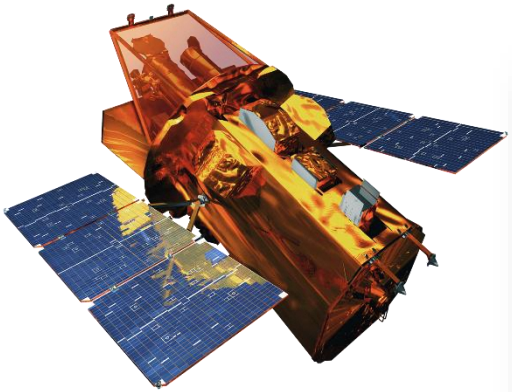


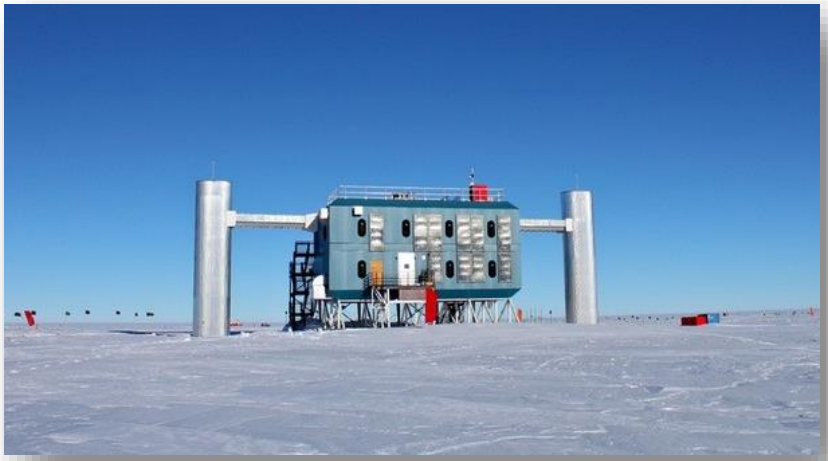
Testing General Relativity

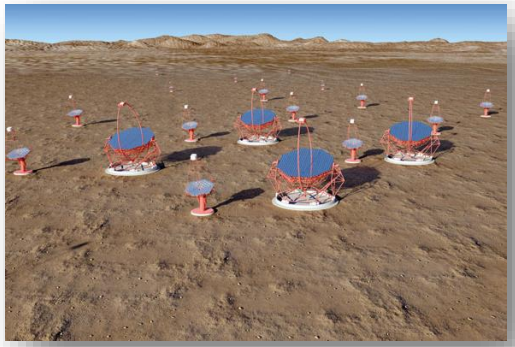
- Difference between expected waveform and observation
- Mass of graviton (dispersion)
- non-GR polarizations

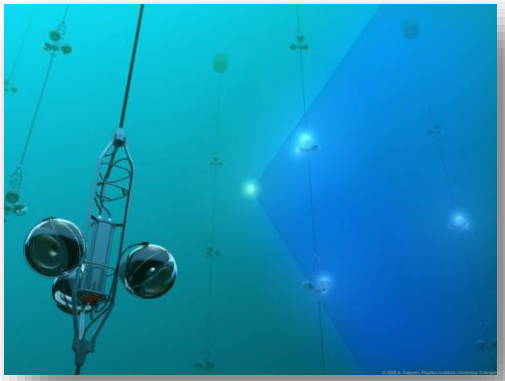


Friends 74 + 2

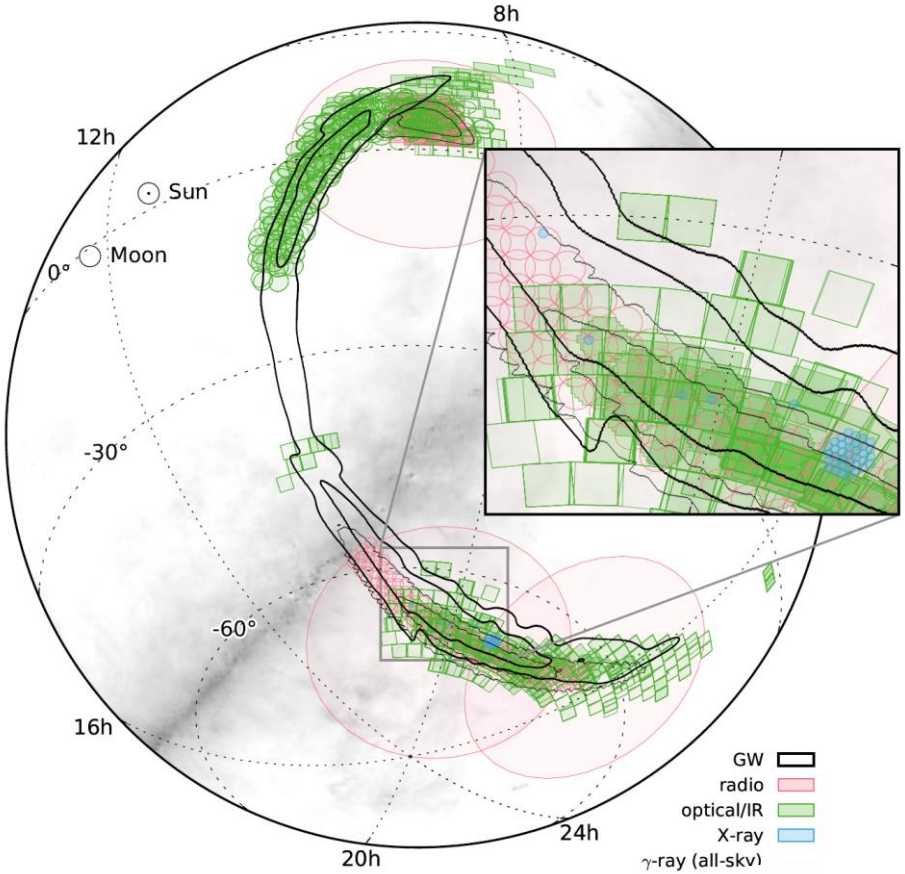


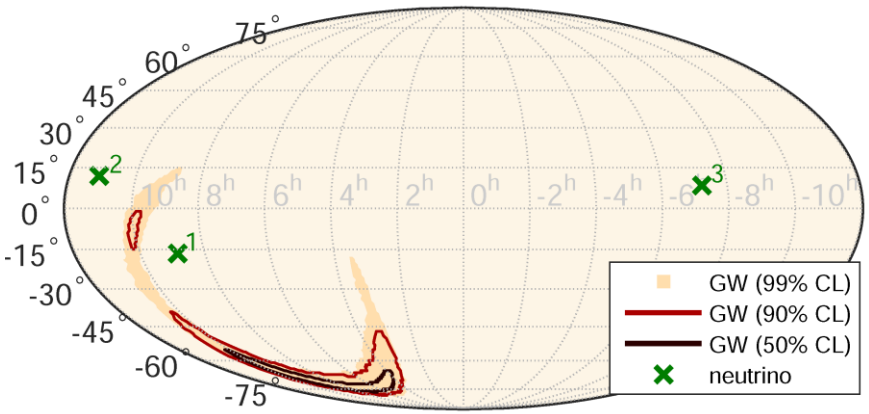


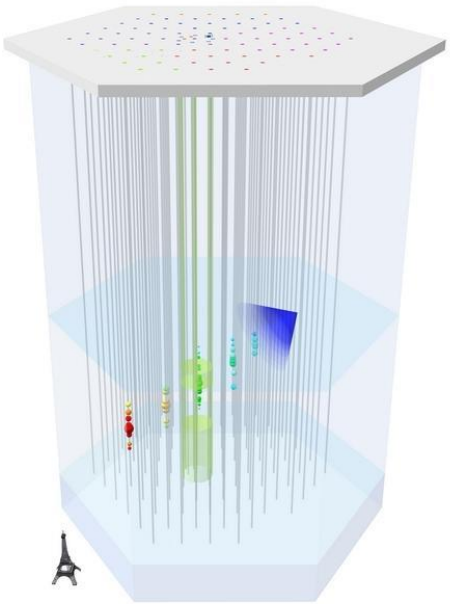




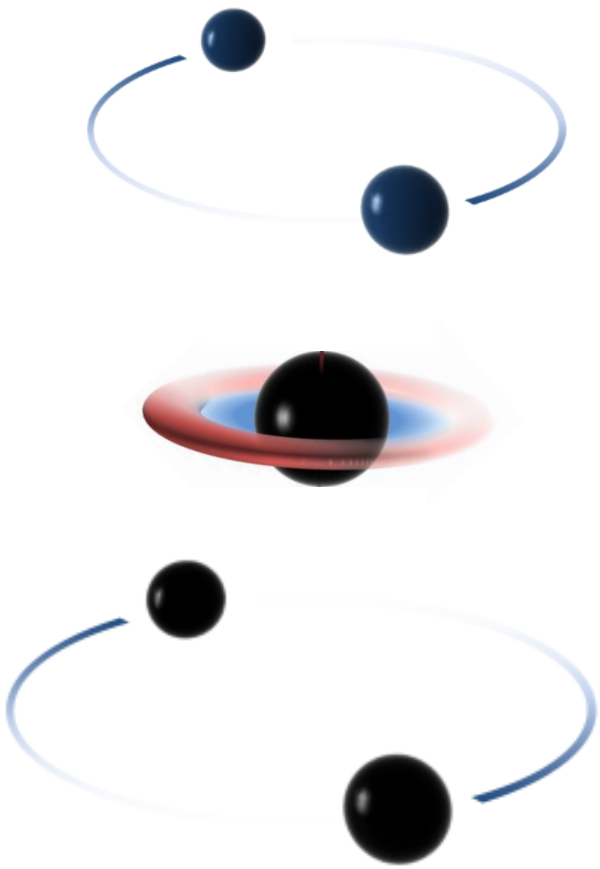
Electromagnetic and neutrino follow-up





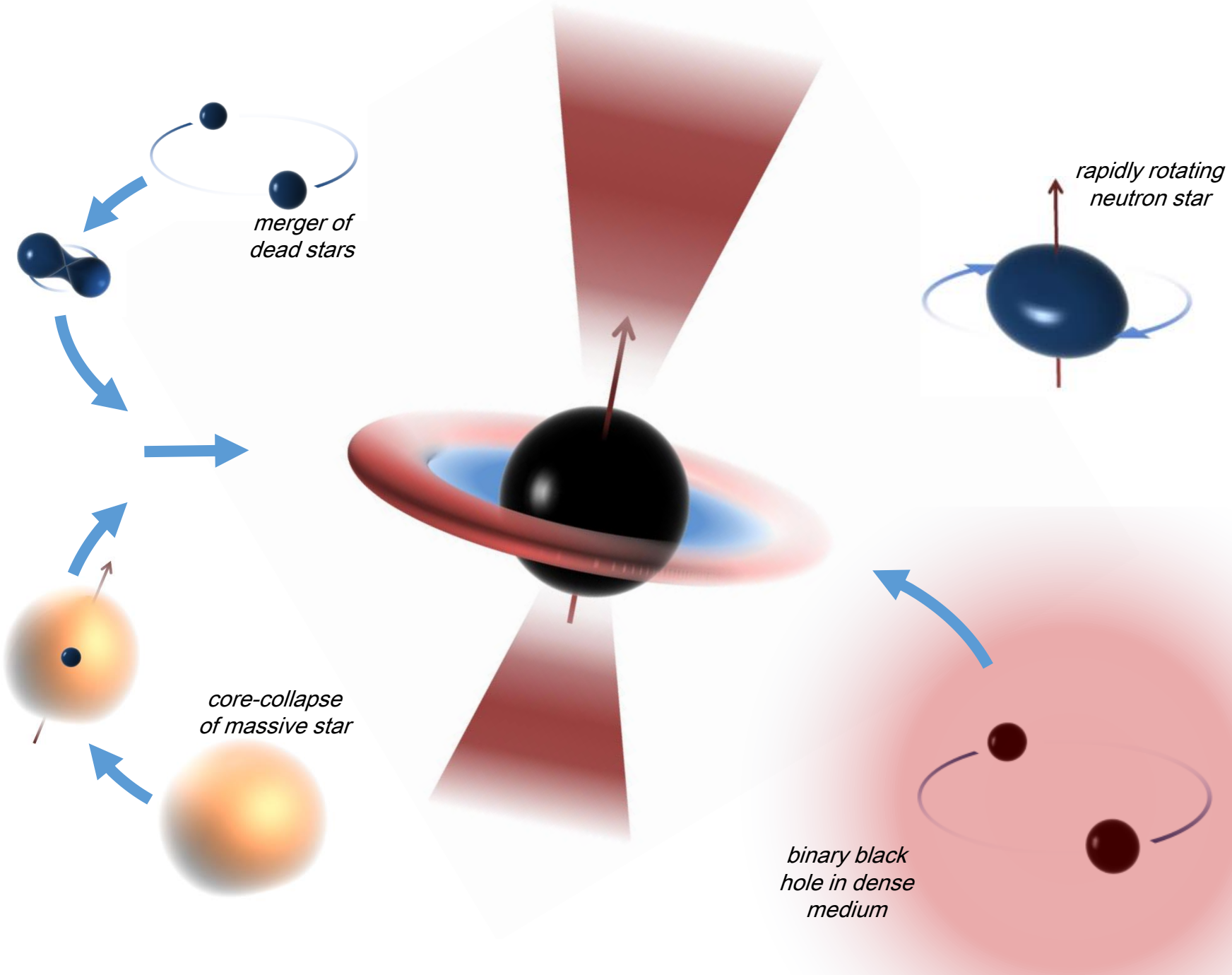


Targets

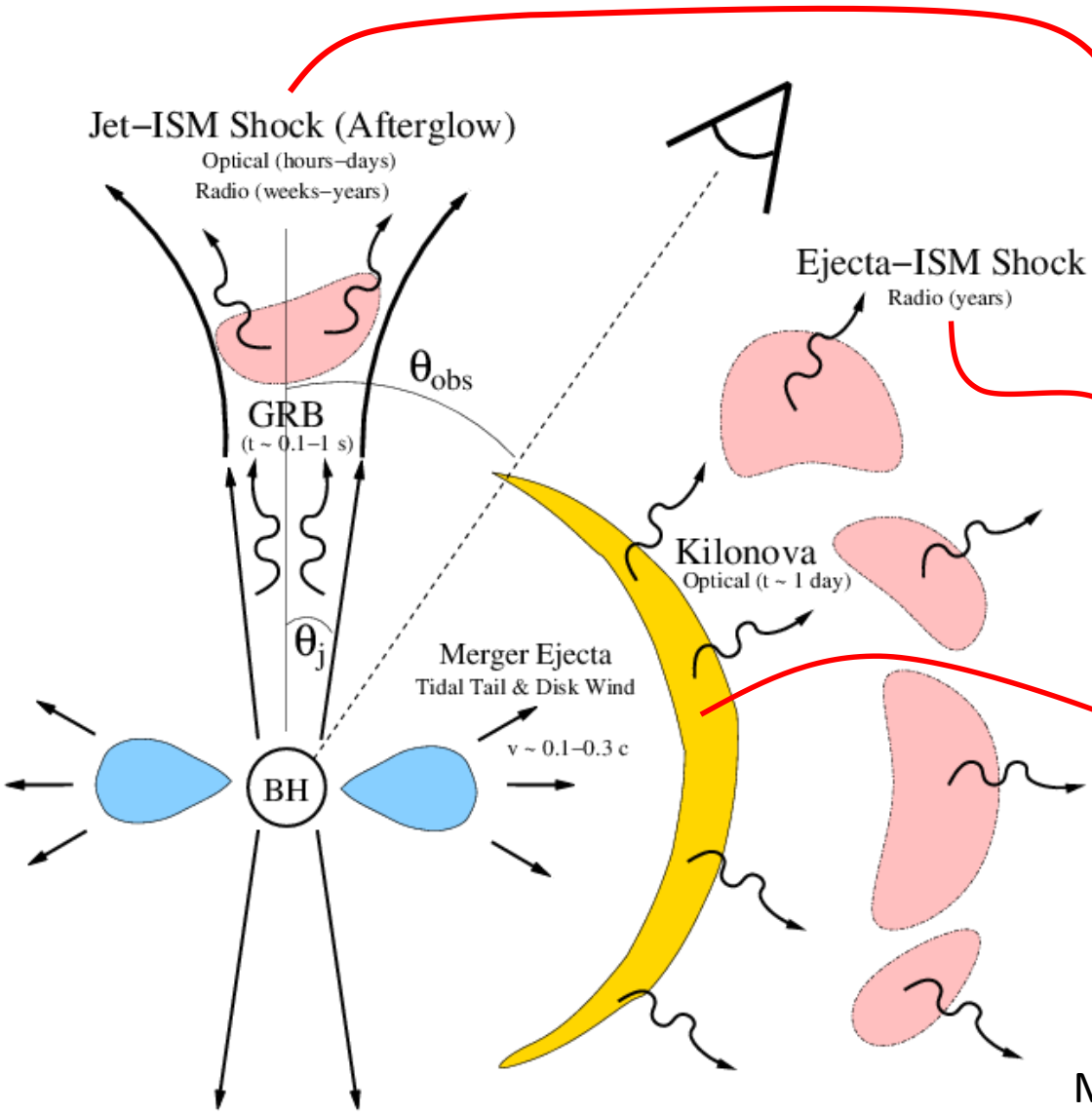


- Cosmic accelerators (cosmic rays, > 10^{20} eV)
- Supranuclear equation of state (NS mass vs radius)
  $\Delta r \sim 1$ km at 100 Mpc
- Alternative cosmological distance ladder
- Many open astrophysics questions

Bartos+ 2013


merger of
dead stars
rapidly rotating
neutron star
core-collapse
of massive star
binary black
hole in dense
medium

Electromagnetic counterparts / follow-up

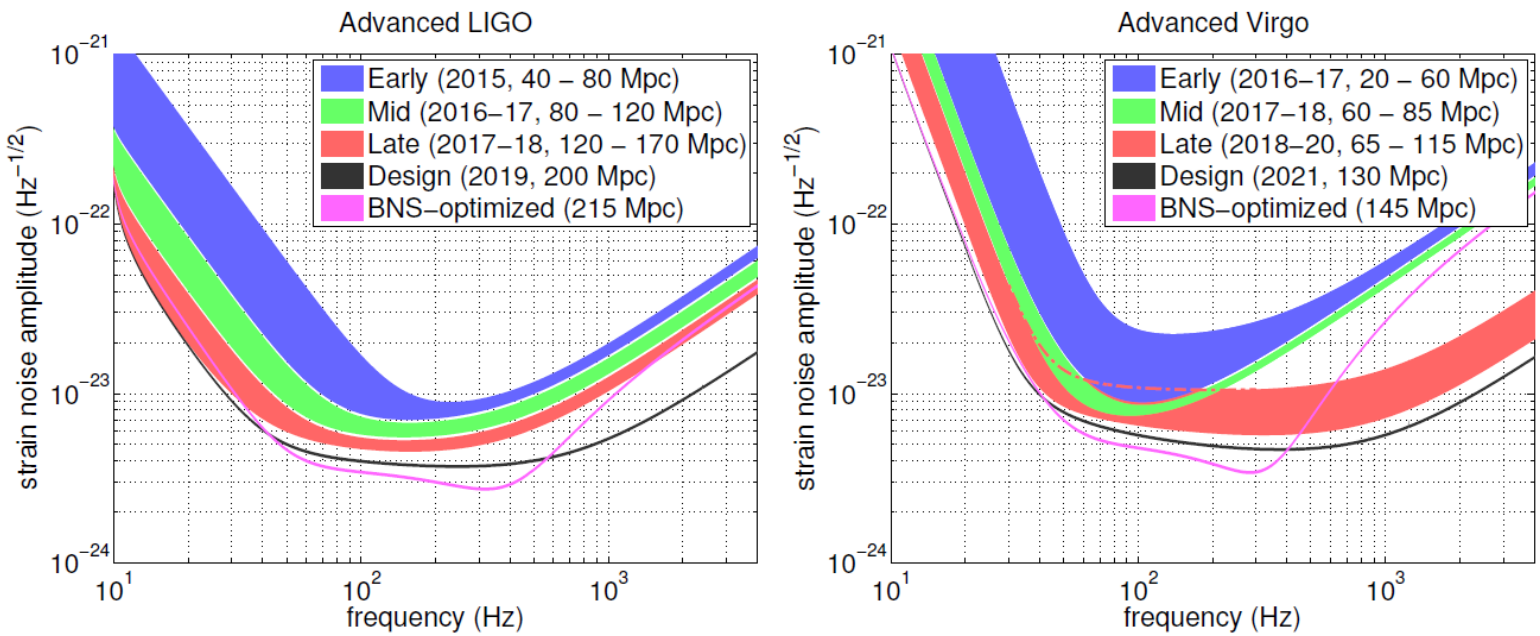


- Beamed
- Good gamma-ray FoV
- Gamma-ray long term?
- Follow-up difficult
- Off-axis light curves

- Isotropic
- Long-term -- easy follow-up
- Flux too small?

- Good time frame (~week)
- Isotropic
- Limited IR FoV / sensitivity
- LSST!

Metzger & Berger 2012



Sensitivity Timeline

Aasi et al. 2013

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

advanced LIGO

New window onto the Universe.

Exciting opportunities for fundamental physics and large scale observatories