Gravitational waves

Imre Bartos
University of Florida

Pontecorvo Neutrino Physics School | Sinaia | 09.07.2019

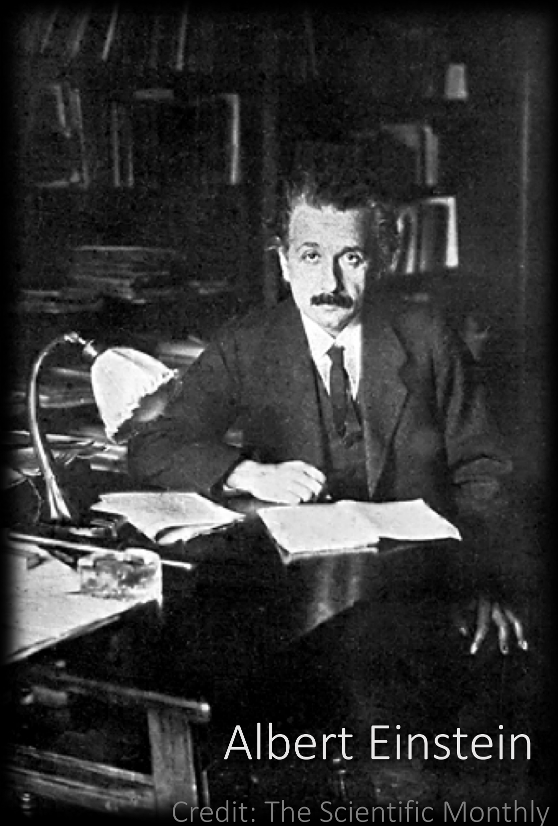
Image credit: MARK GARLICK / SCIENCE PHOTO / GETTY IMAGES

UF UNIVERSITY of FLORIDA

Outline

- What are gravitational waves?
- How are they detected?
- What produces gravitational waves?
- Discoveries, what we learned so far
- Multi-messenger astrophysics

1916

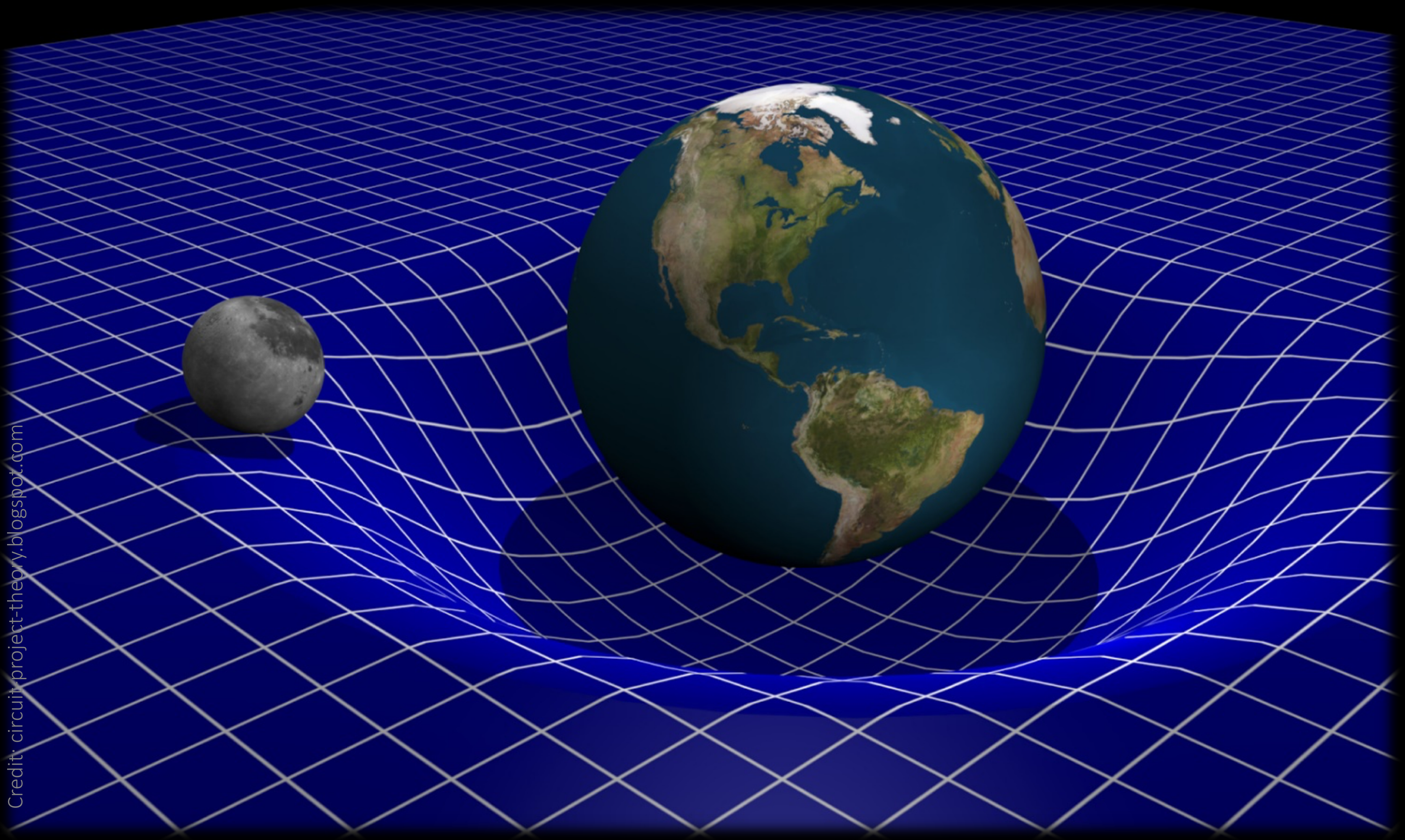


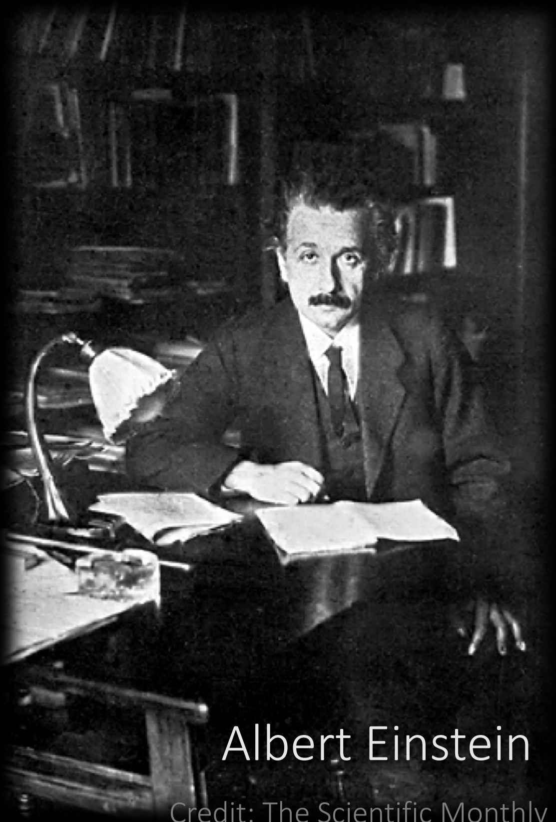
Credit: The Scientific Monthly

Einstein just published his General Theory of Relativity,
and is looking for ways to observationally test it.

1916

gravity = curved spacetime



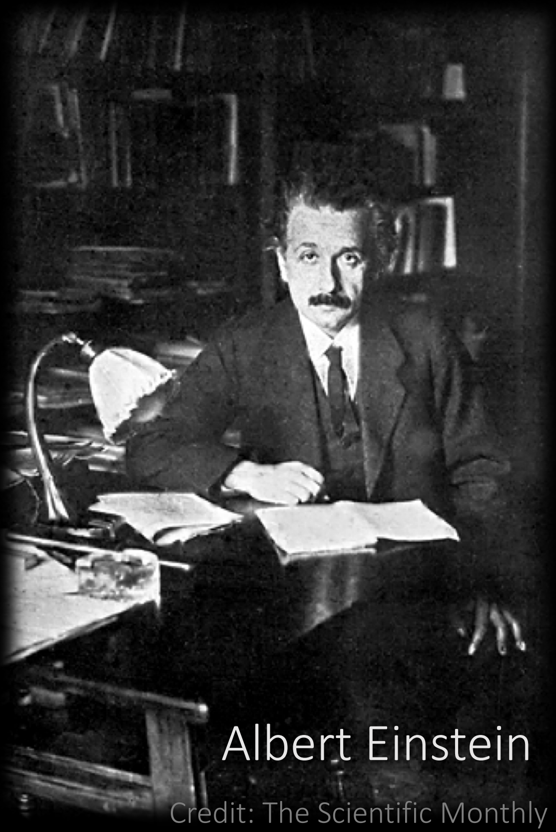


Credit: The Scientific Monthly

1916

<u>gravitational waves</u>: disturbances in the curvature of spacetime, generated by accelerated masses, that propagate as waves.

Credit:Shutterstock.com



Albert Einstein

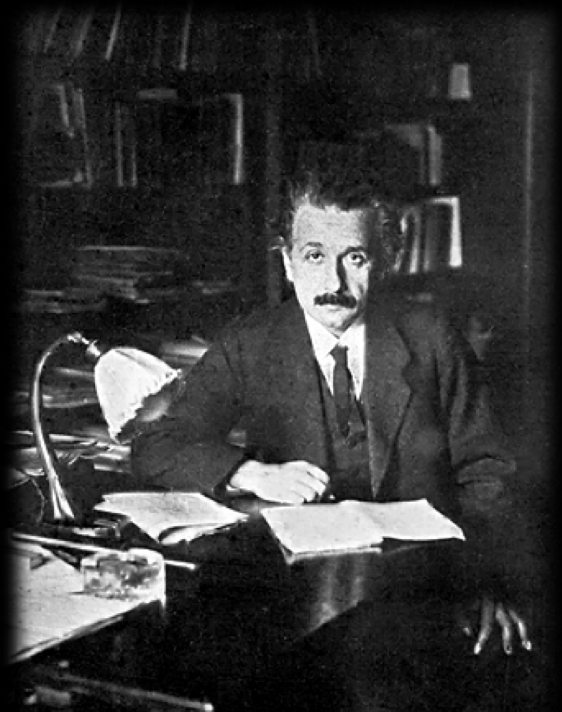
Credit: The Scientific Monthly

1916

To a large extent, gravitational waves are produced like electromagnetic waves.

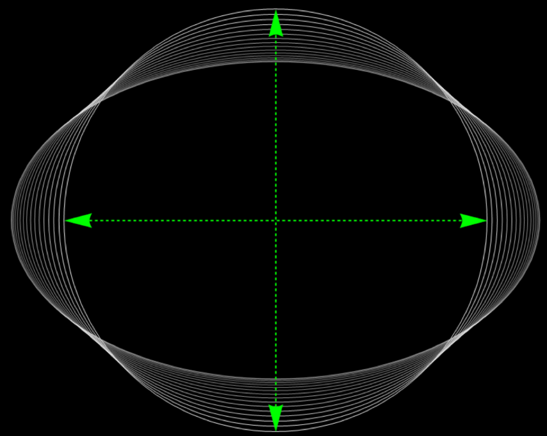
- ✓ *An accelerated charged particle will emit waves.*
- ✓ *Acceleration cannot be spherically symmetric.*
- ✓ *Propagates with the speed of light.*

- ❖ *Gravitational wave emission requires a changing quadrupole moment.*
- ❖ *It is effectively changing distances perpendicular to the propagation (transverse wave).*
- ❖ *Polarizations: + and X (plus and cross).*
- ❖ *Amplitude decreases as 1/r.*



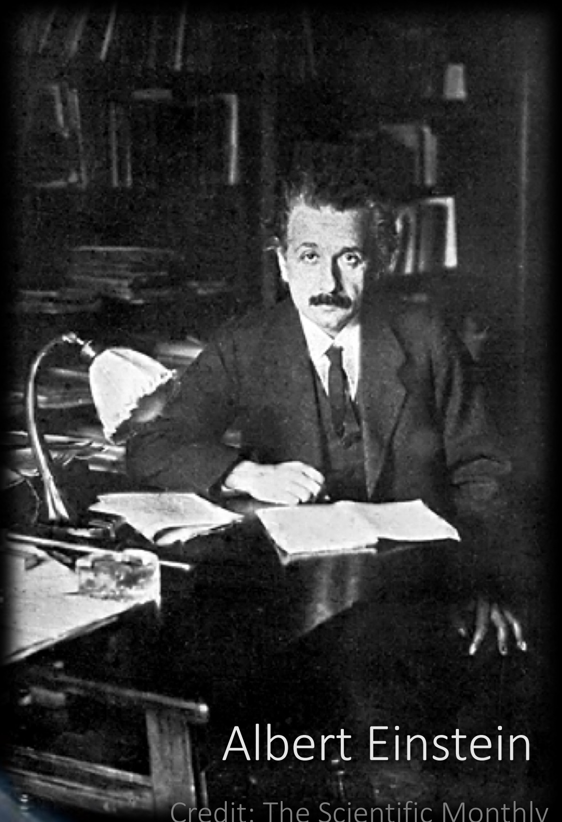
Albert Einstein

Credit: The Scientific Monthly



1916

gravity is weak



Albert Einstein

Credit: The Scientific Monthly

1960's

Richard Feynman convinced the community at the 1957 Chapel Hill conference (under pseudonym Mr. Smith) that gravitational waves are real using the "sticky bead" argument.

Resonance bar detectors (Joseph Weber)

<u>Concept:</u> tidal forces due to gravitational waves distort the bar. It resonates if the distortion changes at the resonance frequency.

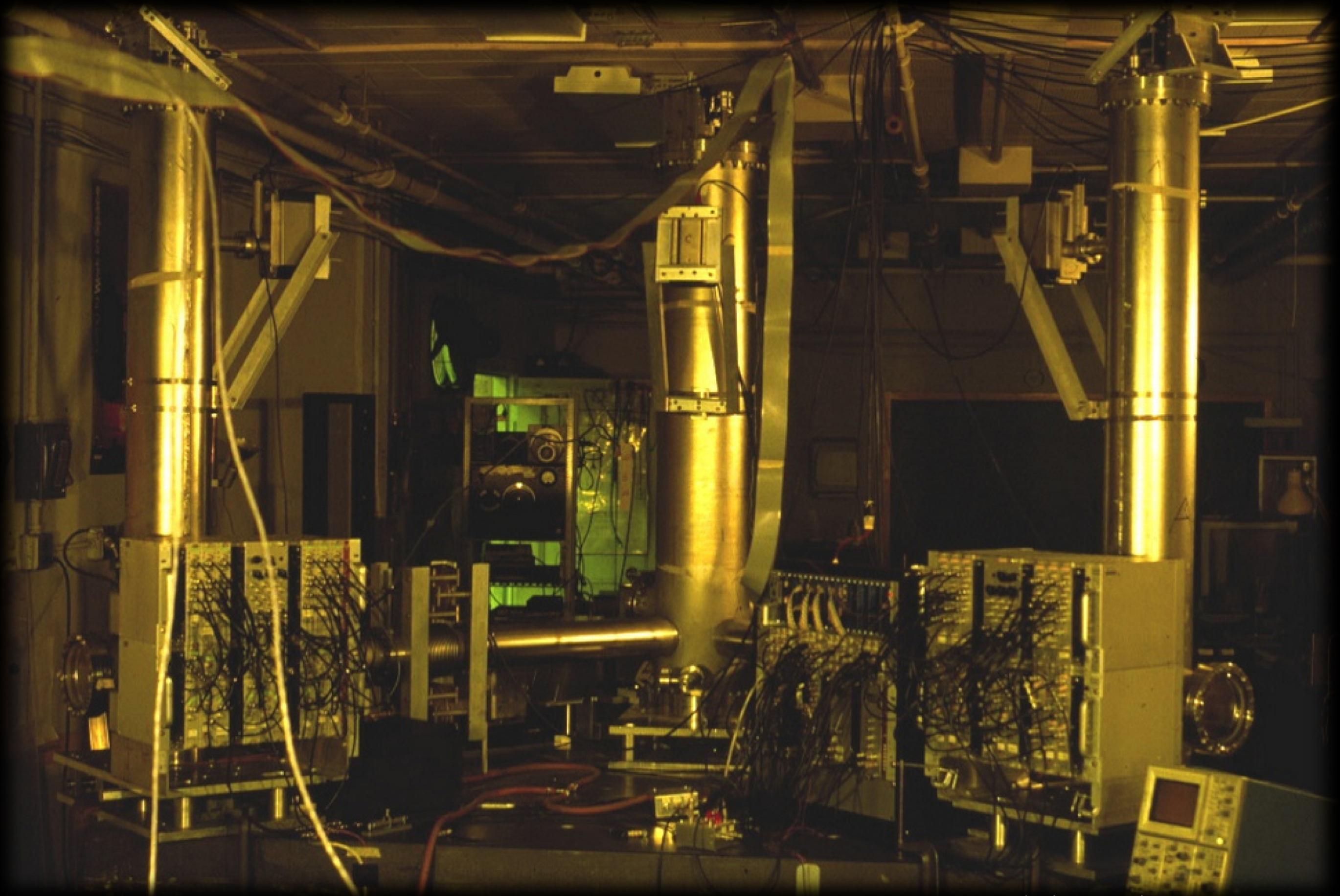
<u>1969:</u> Weber claims discovery of gravitational waves. He starts claiming regular detections. Others try but can't reproduce his results.

1968

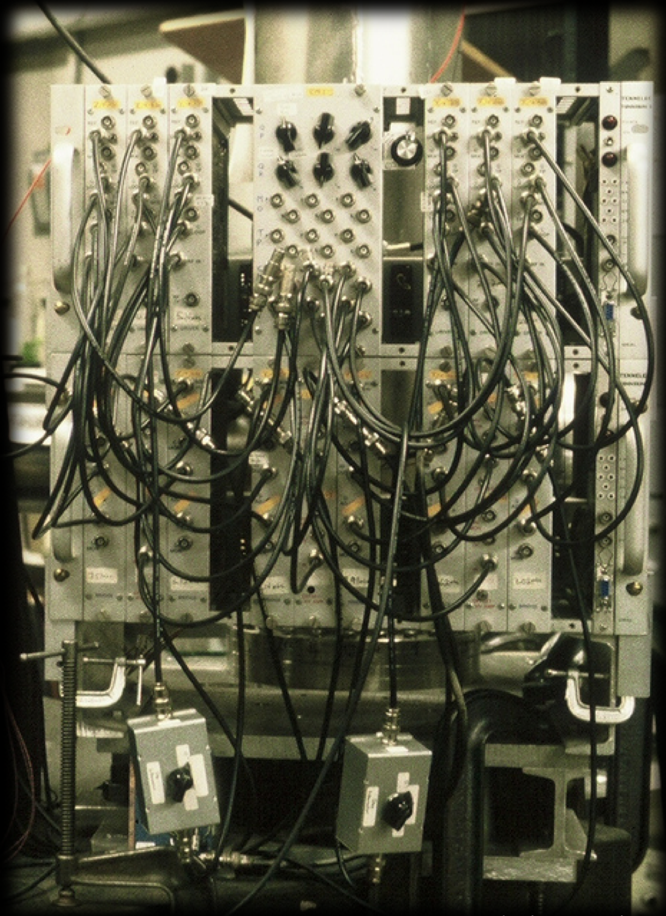
Laser Interferometer
Gravitational-wave Observatory (LIGO)

Courtesy: David Shoemaker

First experiment: laser interferometer with ~1m armlength.

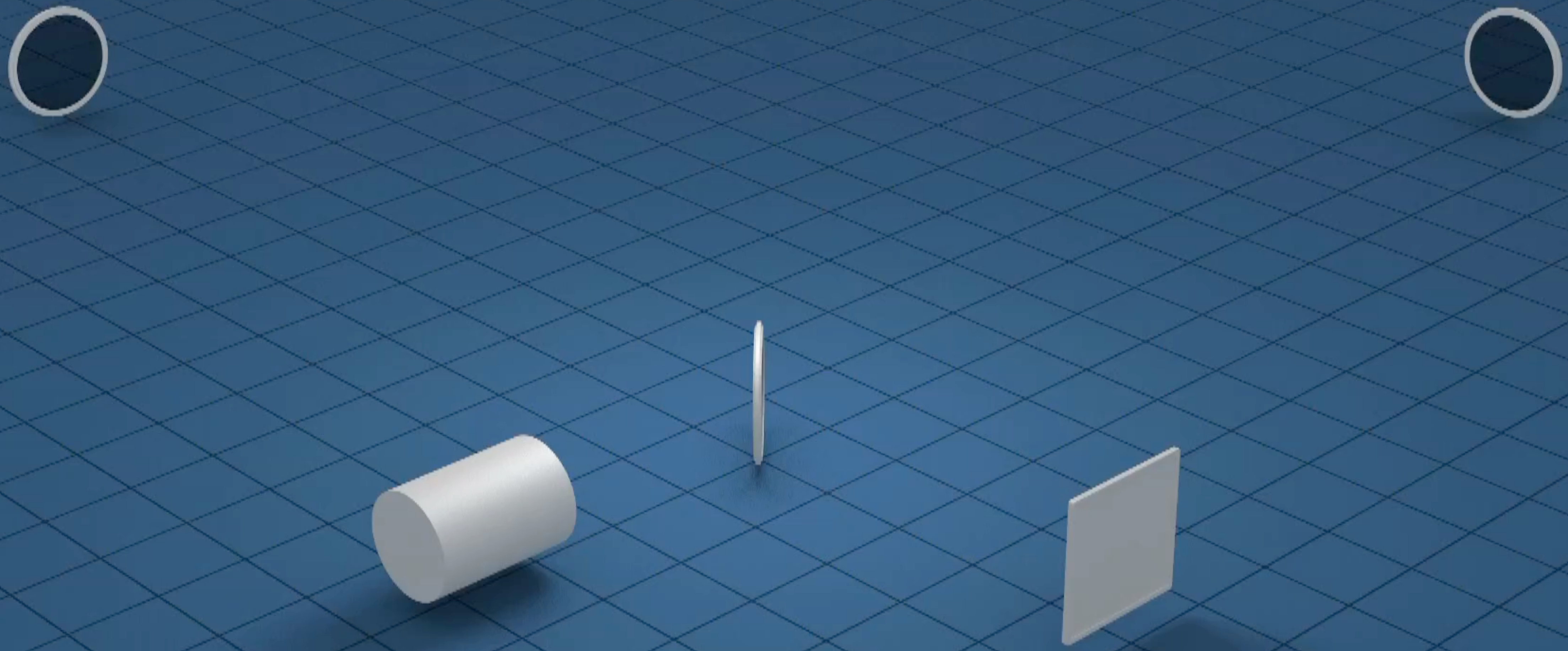


Courtesy: David Shoemaker



Courtesy: David Shoemaker

Laser interferometer

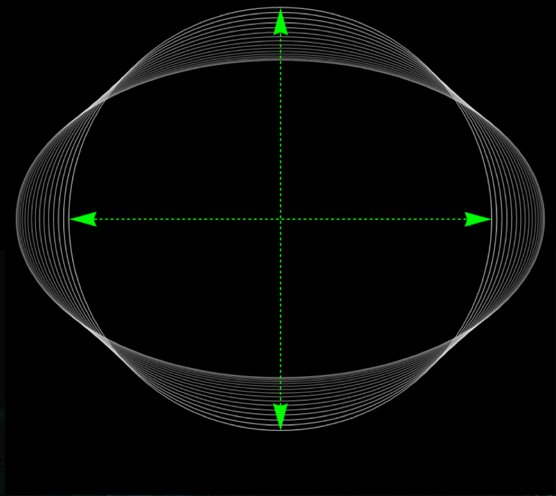


Kipp Thorn started thinking about what could produce detectable gravitational waves.

Colliding black holes and neutron stars

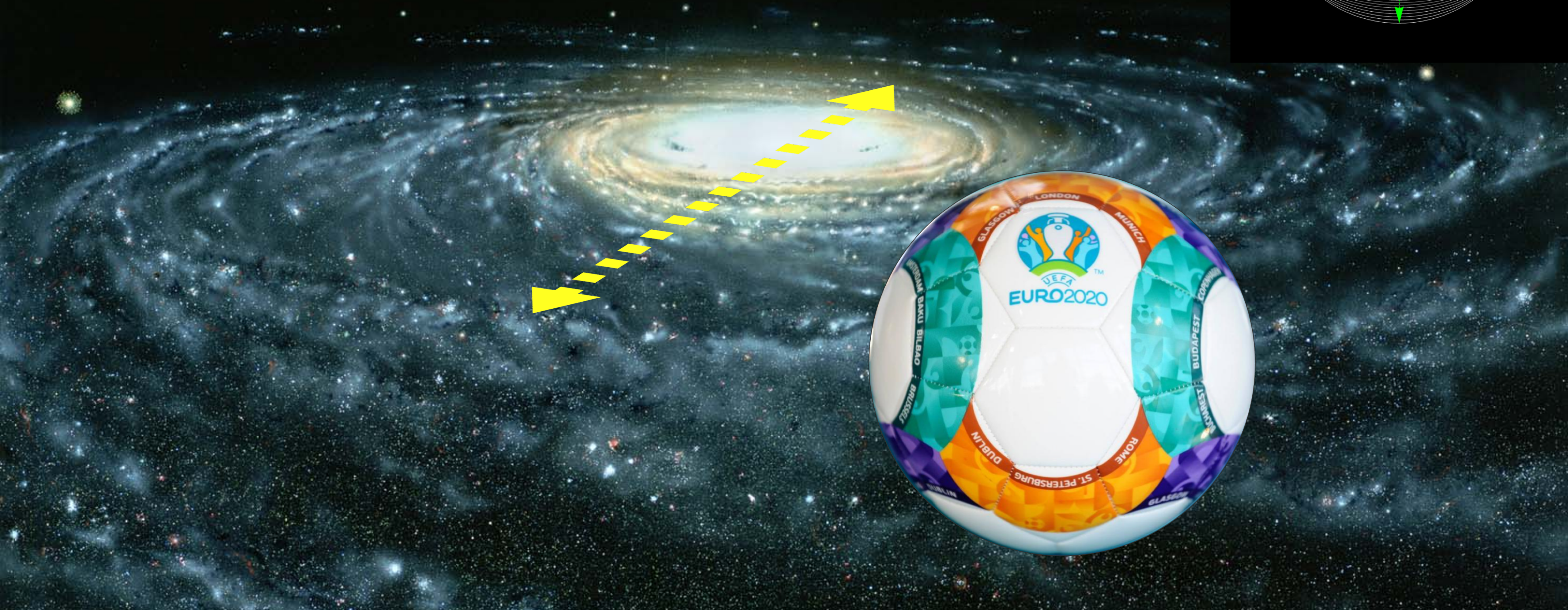
Image credit: Paramount pictures/Warner bros.

Gravitational waves

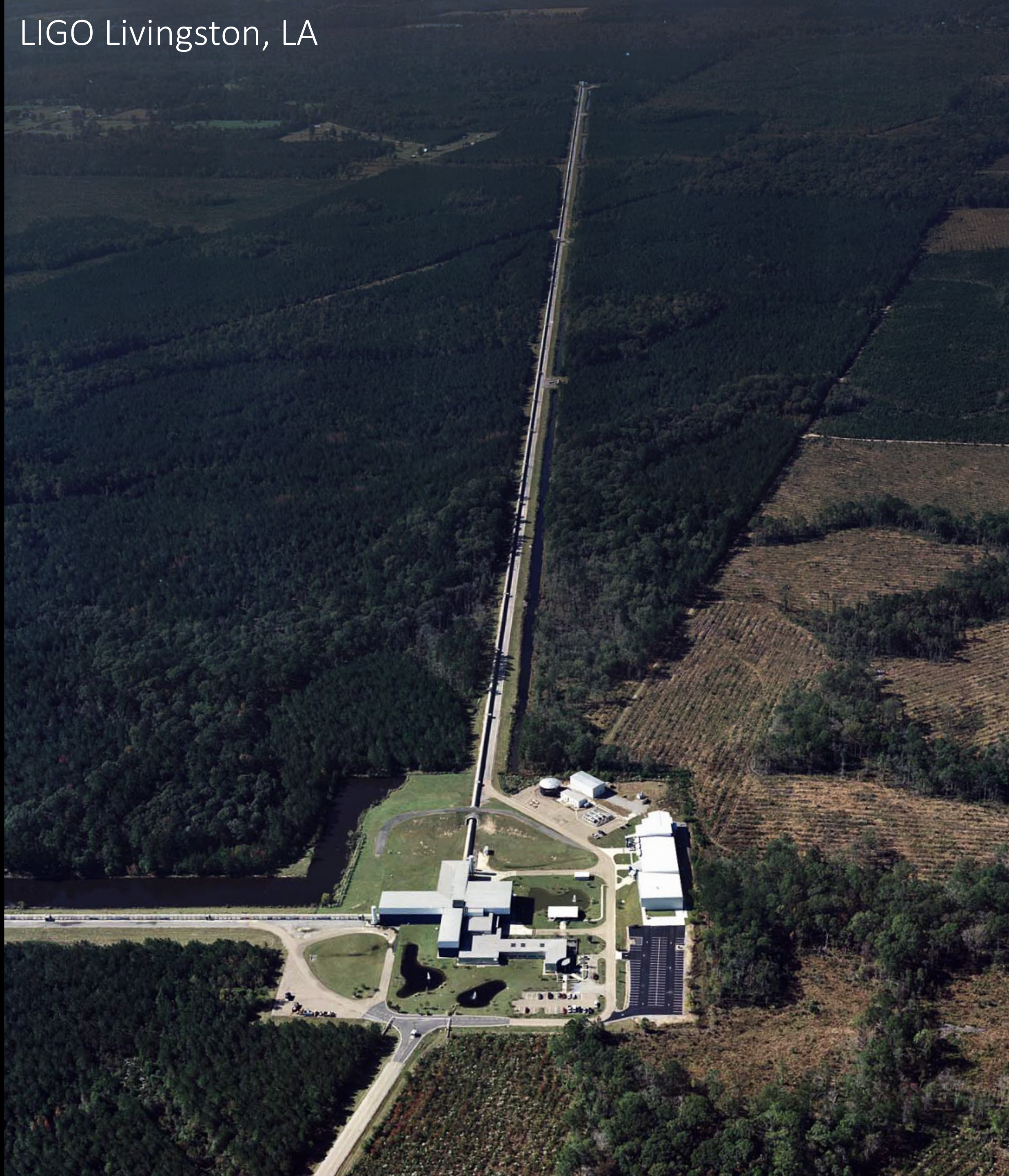


Typical distance variation at Earth ($\sim 10^{-21}$)

0.000000000000000000001

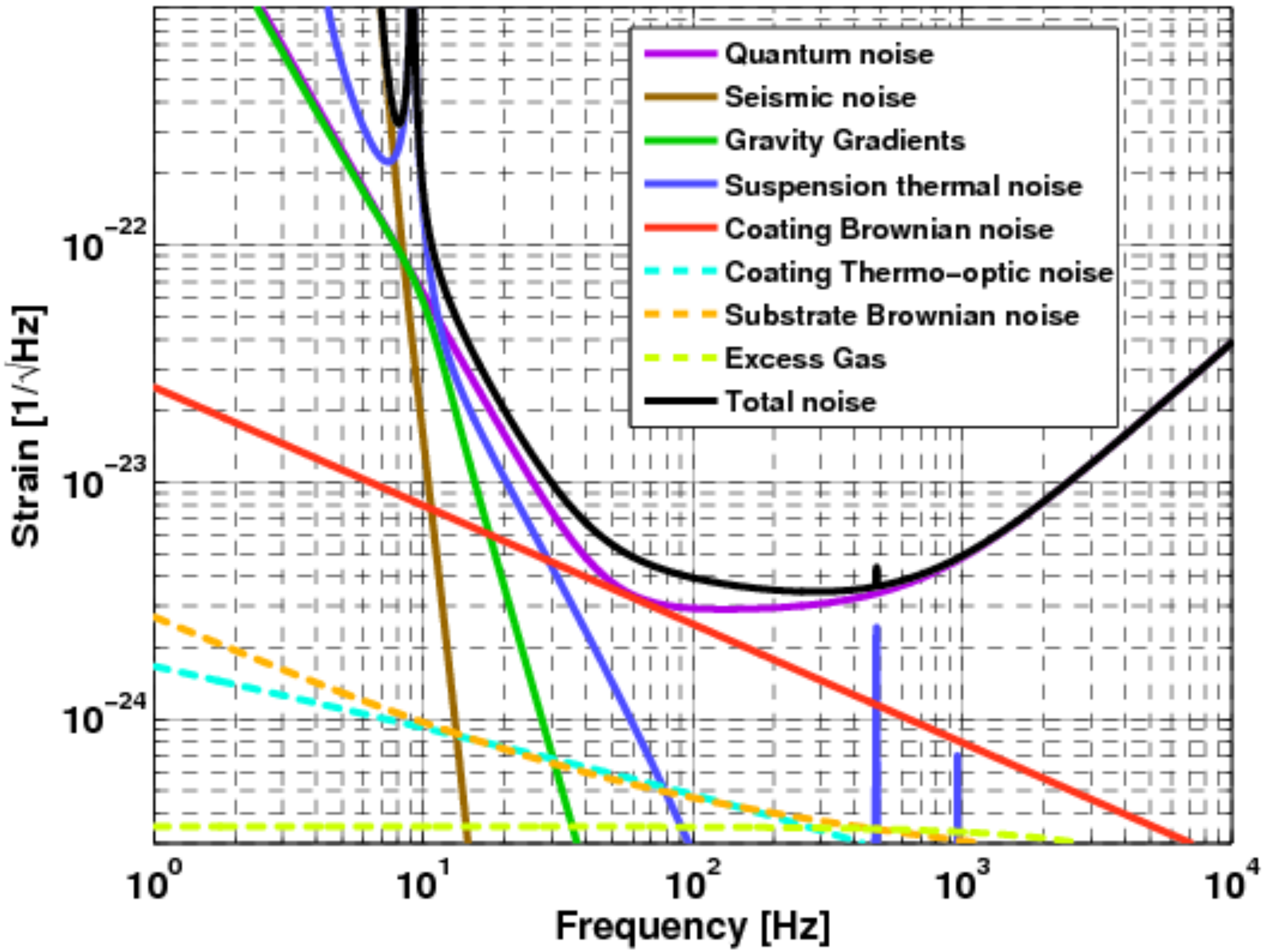



LIGO Hanford, WA


LIGO Livingston, LA

How can we reach such a sensitivity?

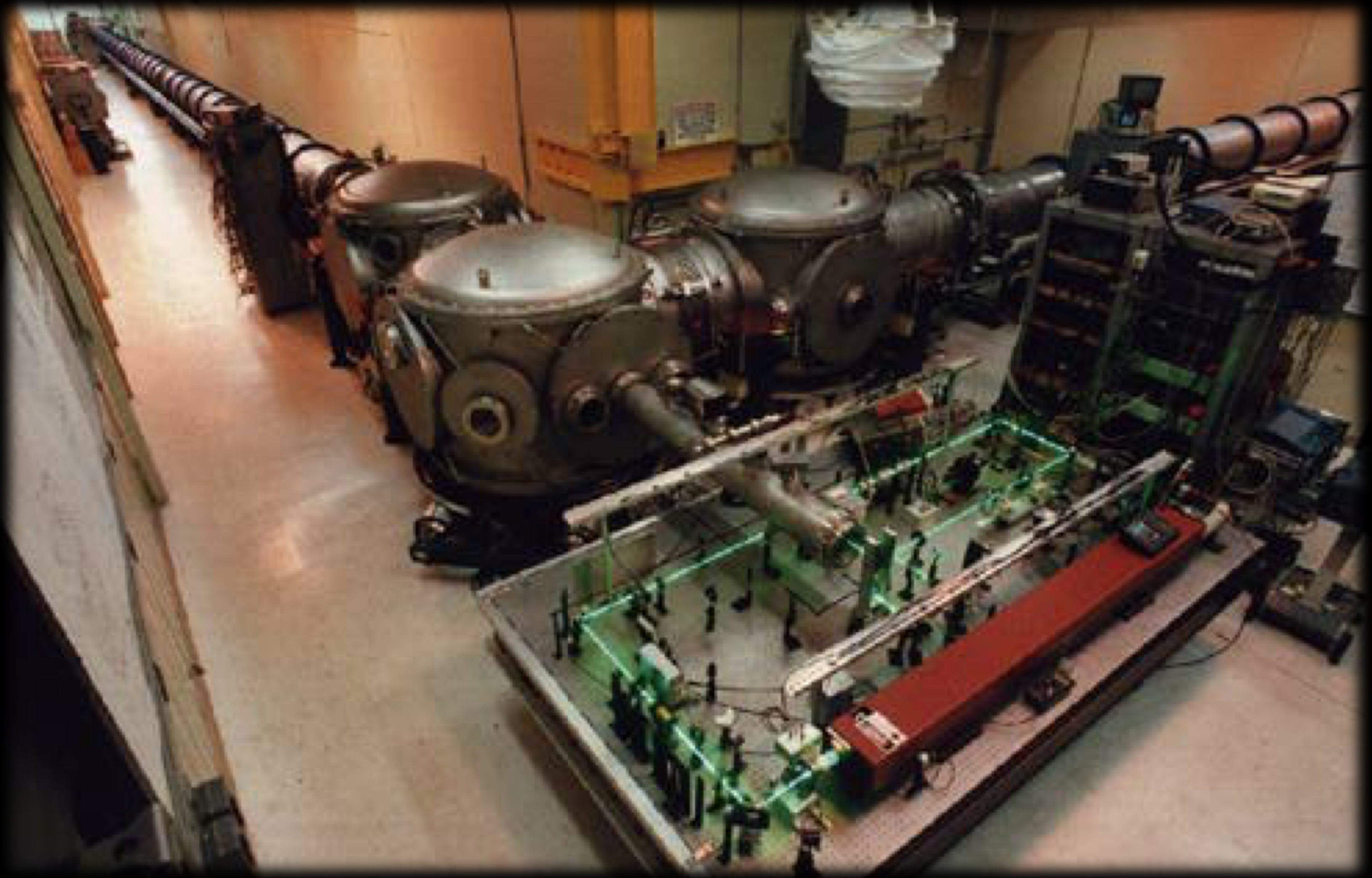
LIGO “noise curve”



Strain = fractional length change of interferometer arm.

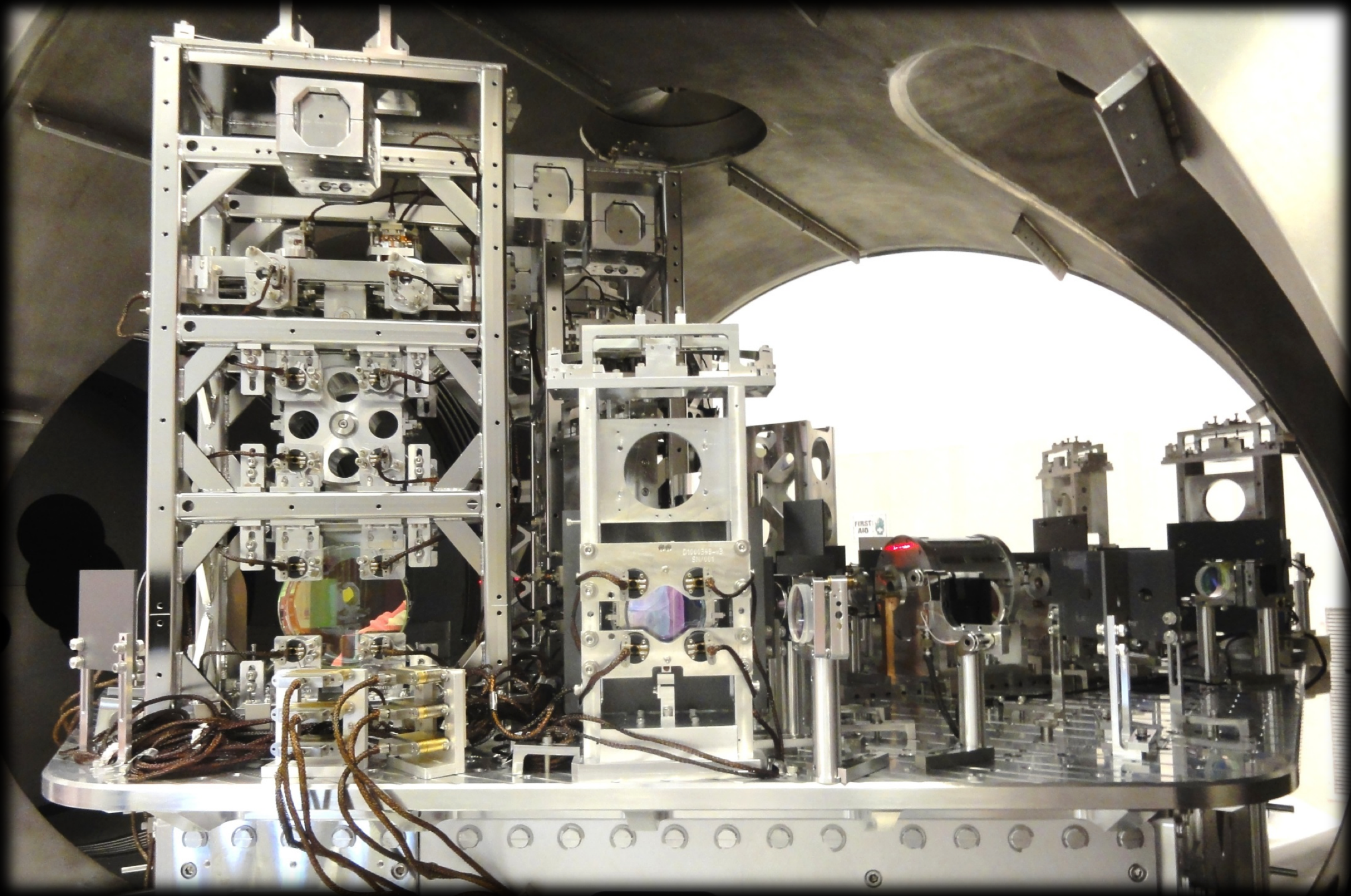
The interferometer arms can have 1MW laser power

This reduces “shot noise” at high frequencies due to the fluctuation of the number of photons “hitting” the mirrors.



Seismic isolation

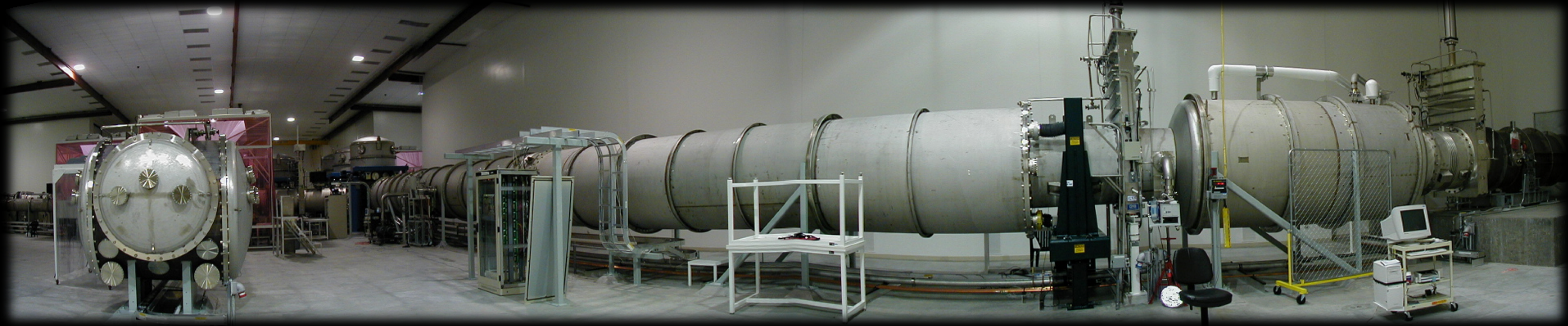
Reduces noise at the lowest frequencies.



Ultrahigh vacuum

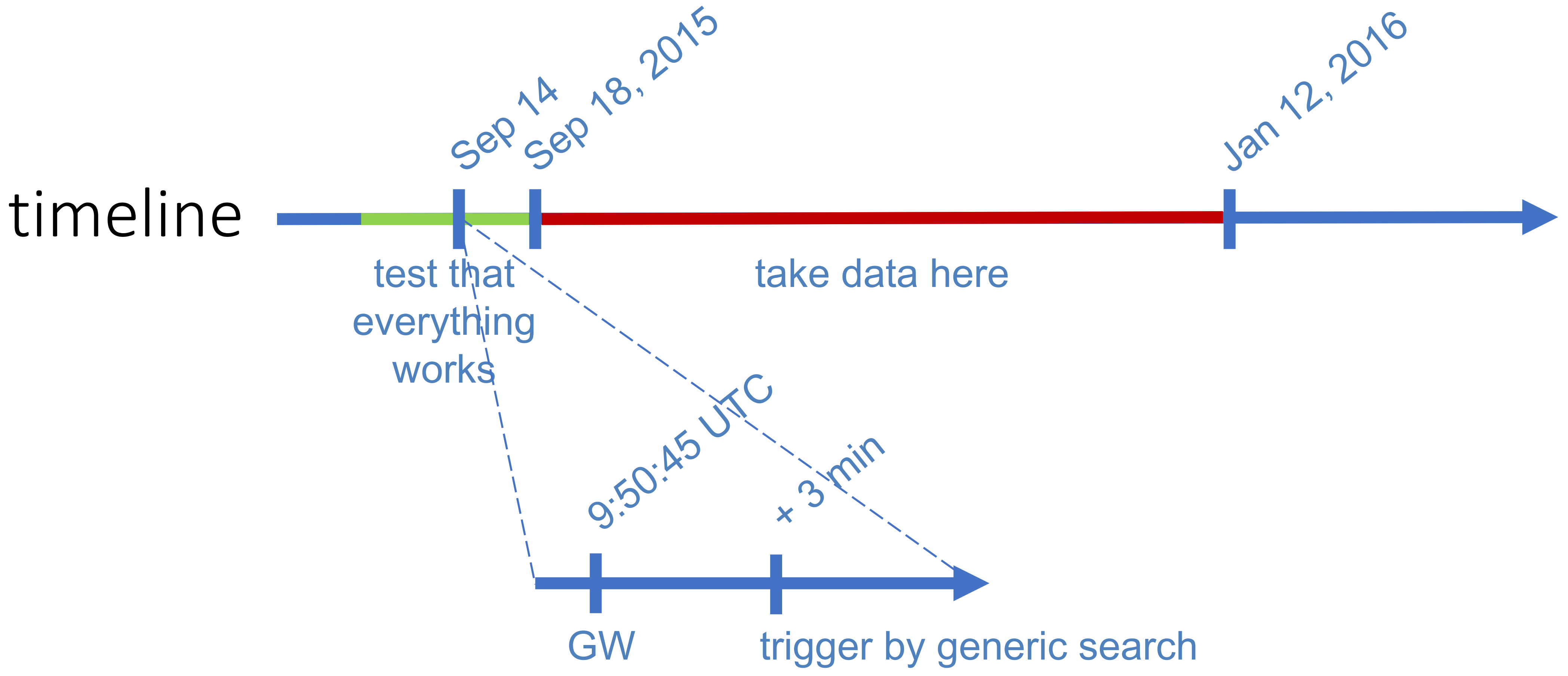
Air would scatter the laser.

(LIGO is the World's biggest vacuum)

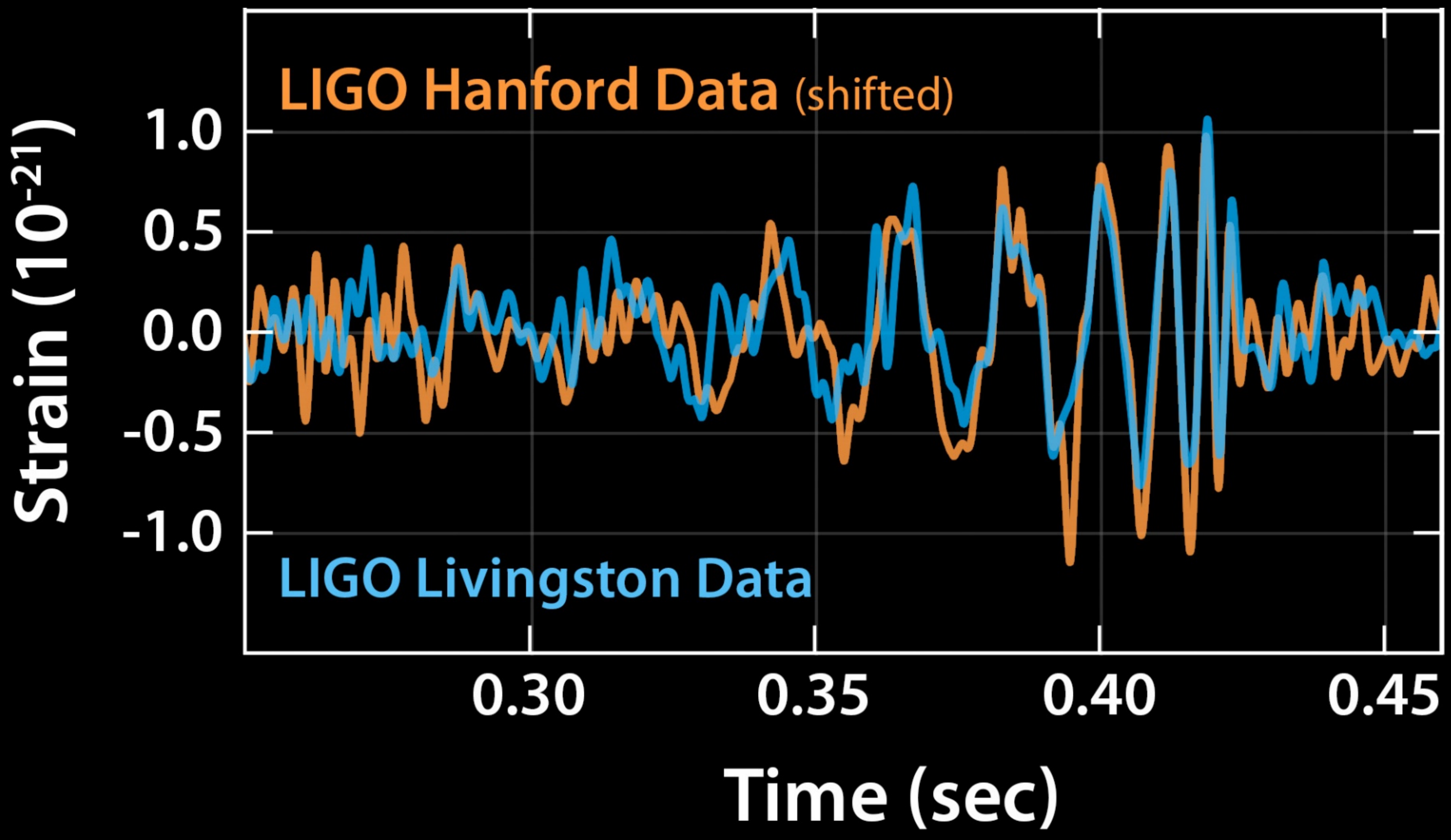


Non-Fundamental Noise

September 14th, 2015

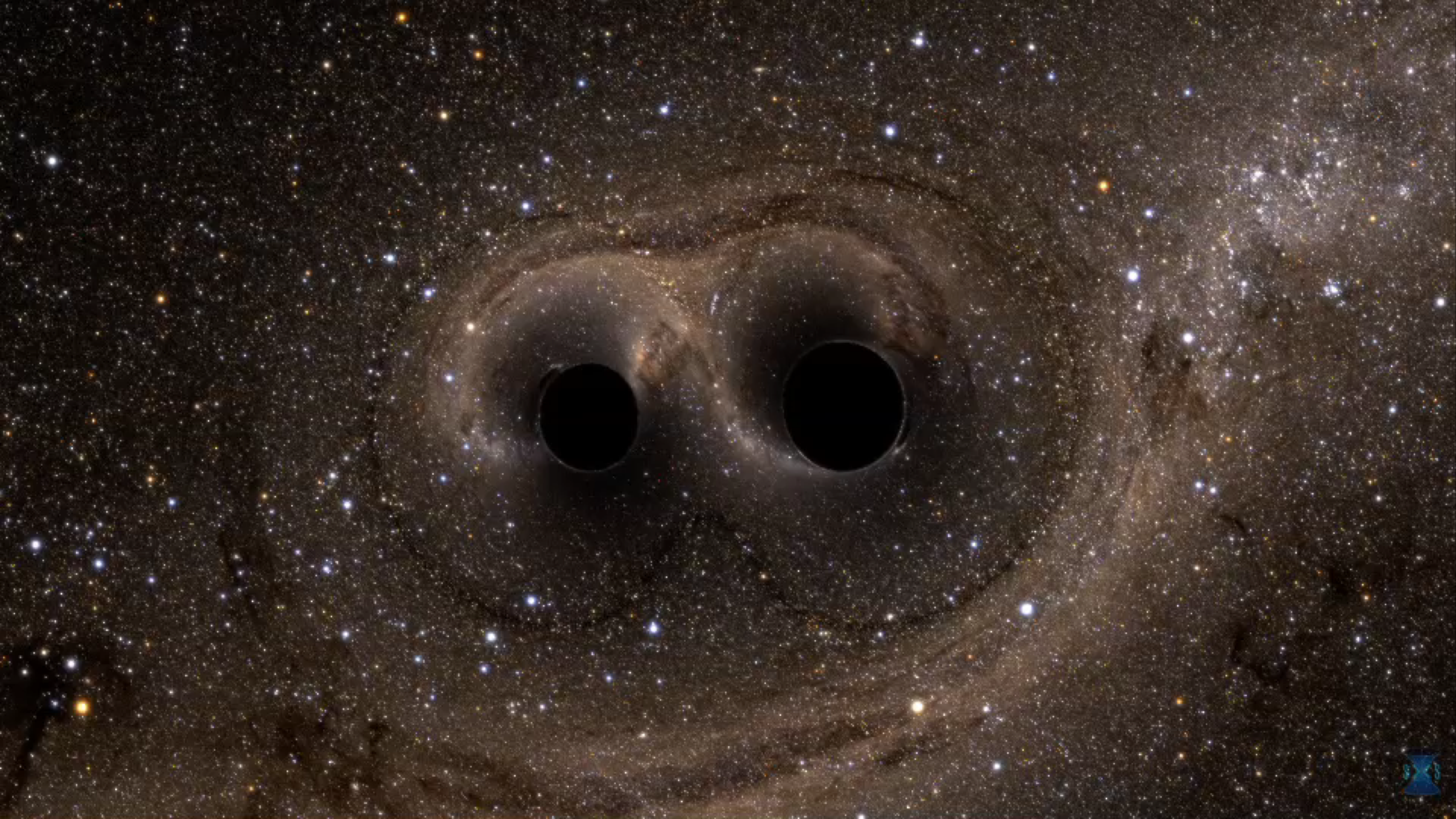


September 14th, 2015



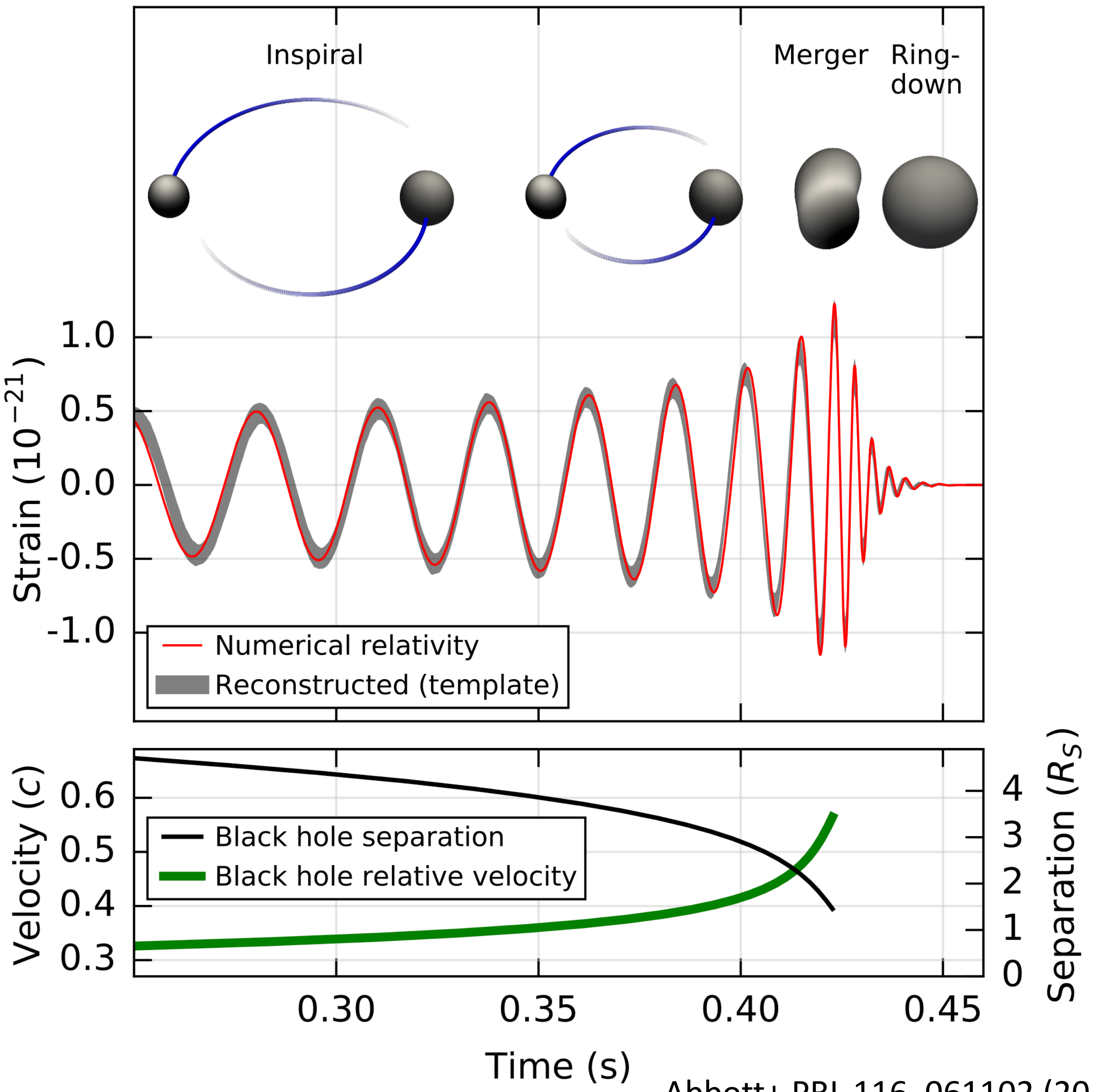
Abbott+ PRL 116, 061102 (2016)

Courtesy of Corey Gray



The properties of the two black holes can be largely reconstructed from the gravitational wave signal:

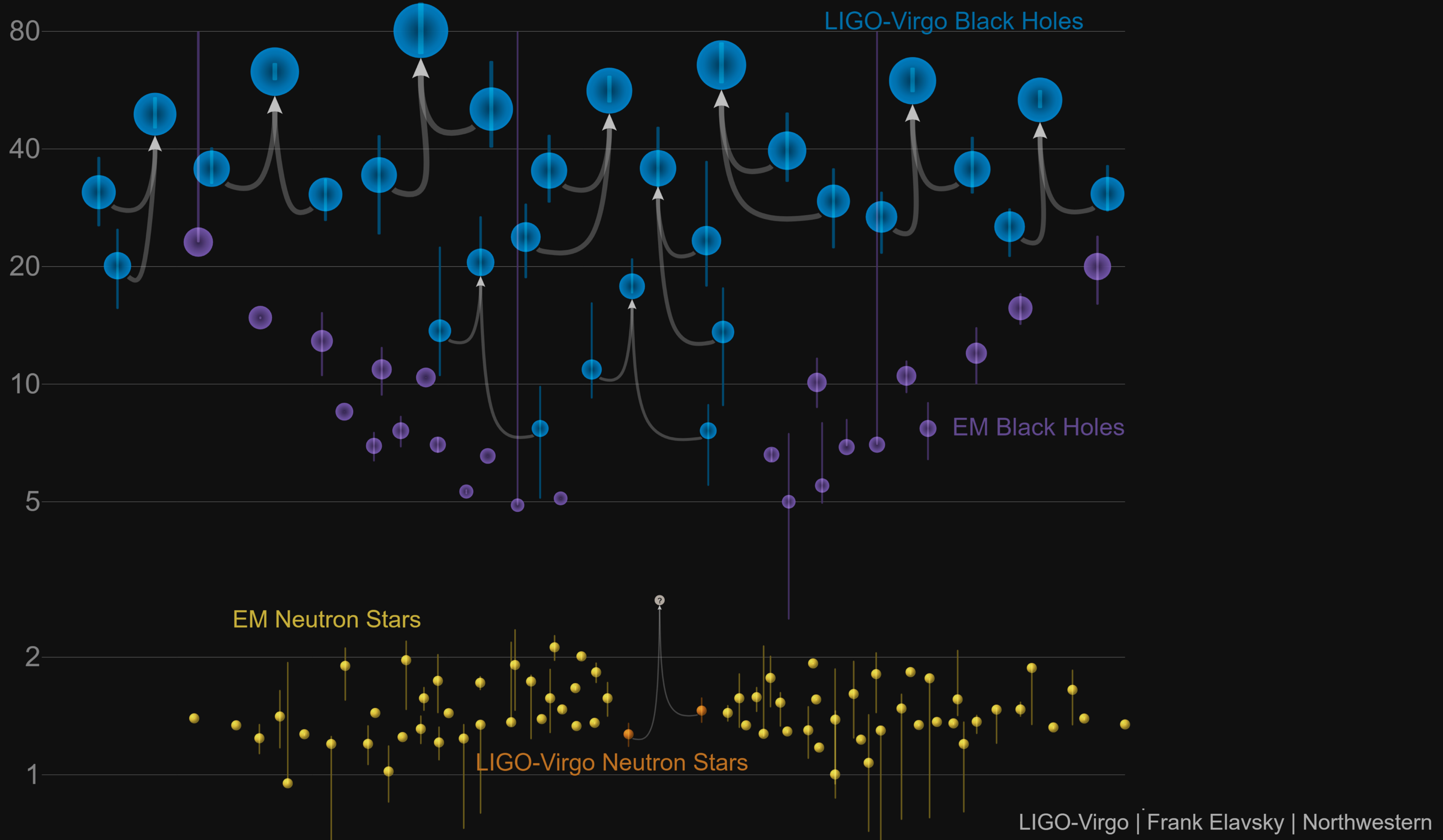
- Masses
- Spins
- Sky location
- Distance
- Inclination
- Orbital eccentricity



Abbott+ PRL 116, 061102 (2016)

Masses in the Stellar Graveyard

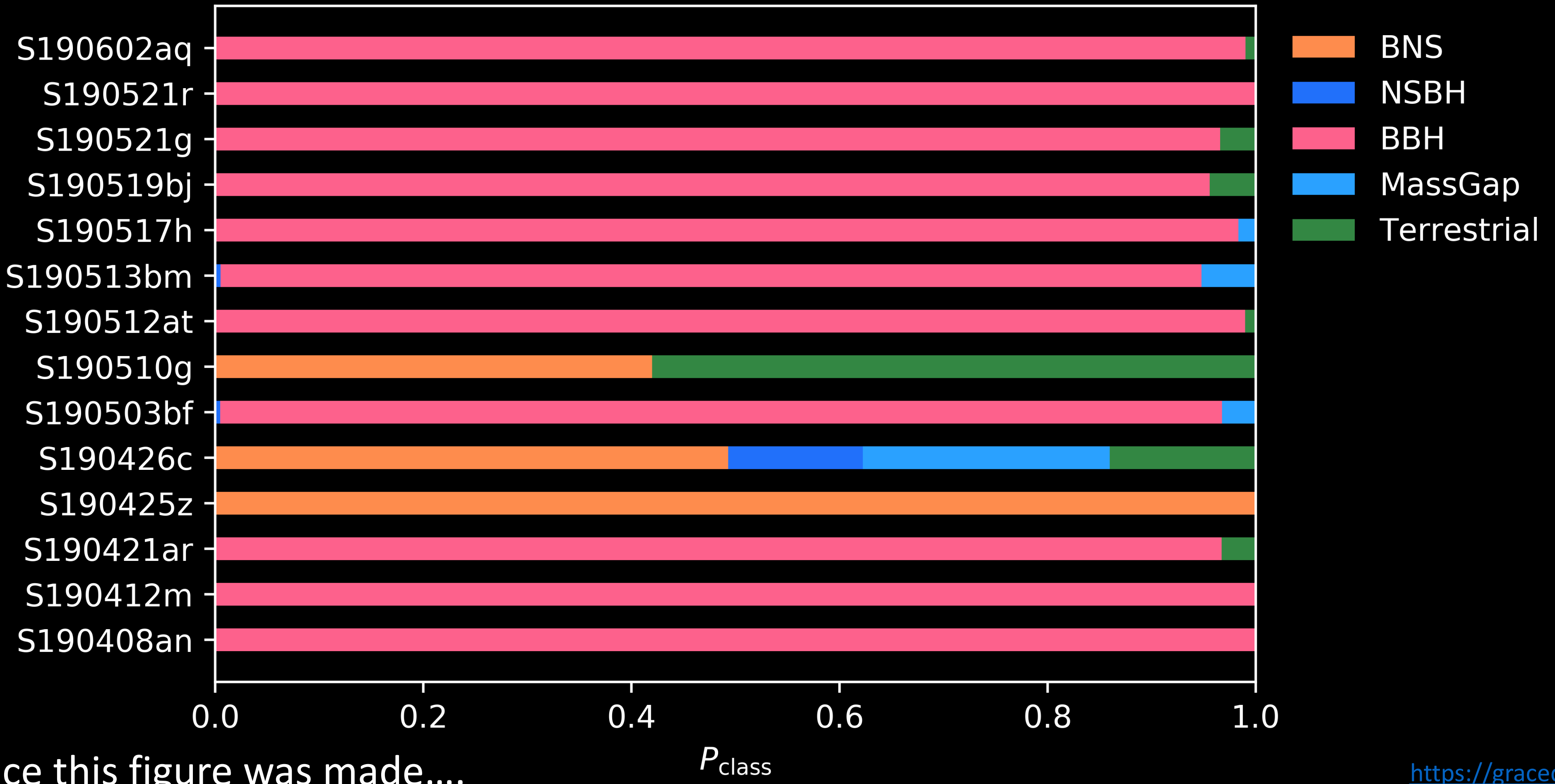
in Solar Masses



Event classification in O3 (so far)

O1:
- 3 BBH

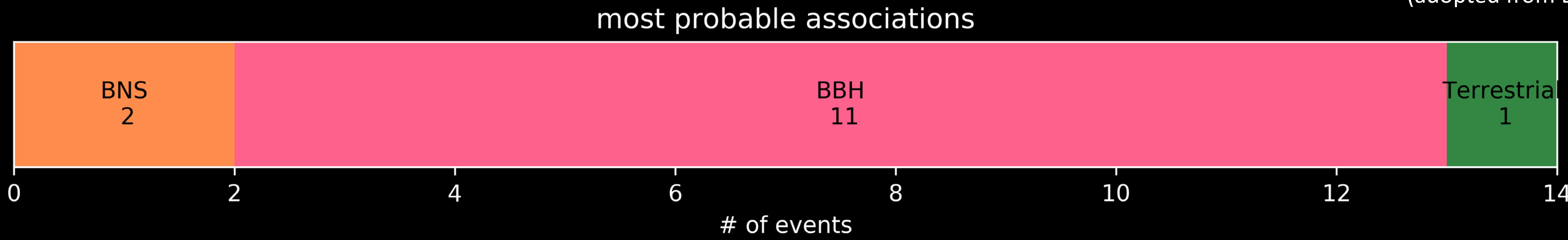
O2:
- 1 BNS
- 7 BBH



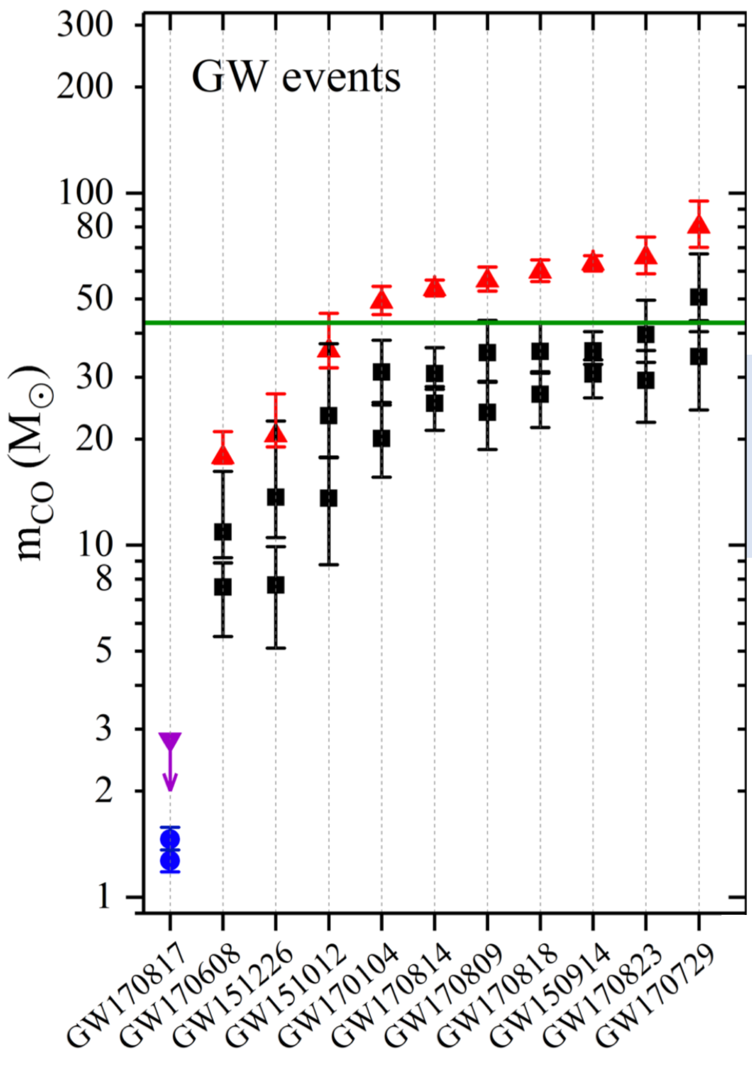
+8 new events since this figure was made….

https://gracedb.ligo.org/latest/

(adopted from B. Farr, LIGO-G1901170)

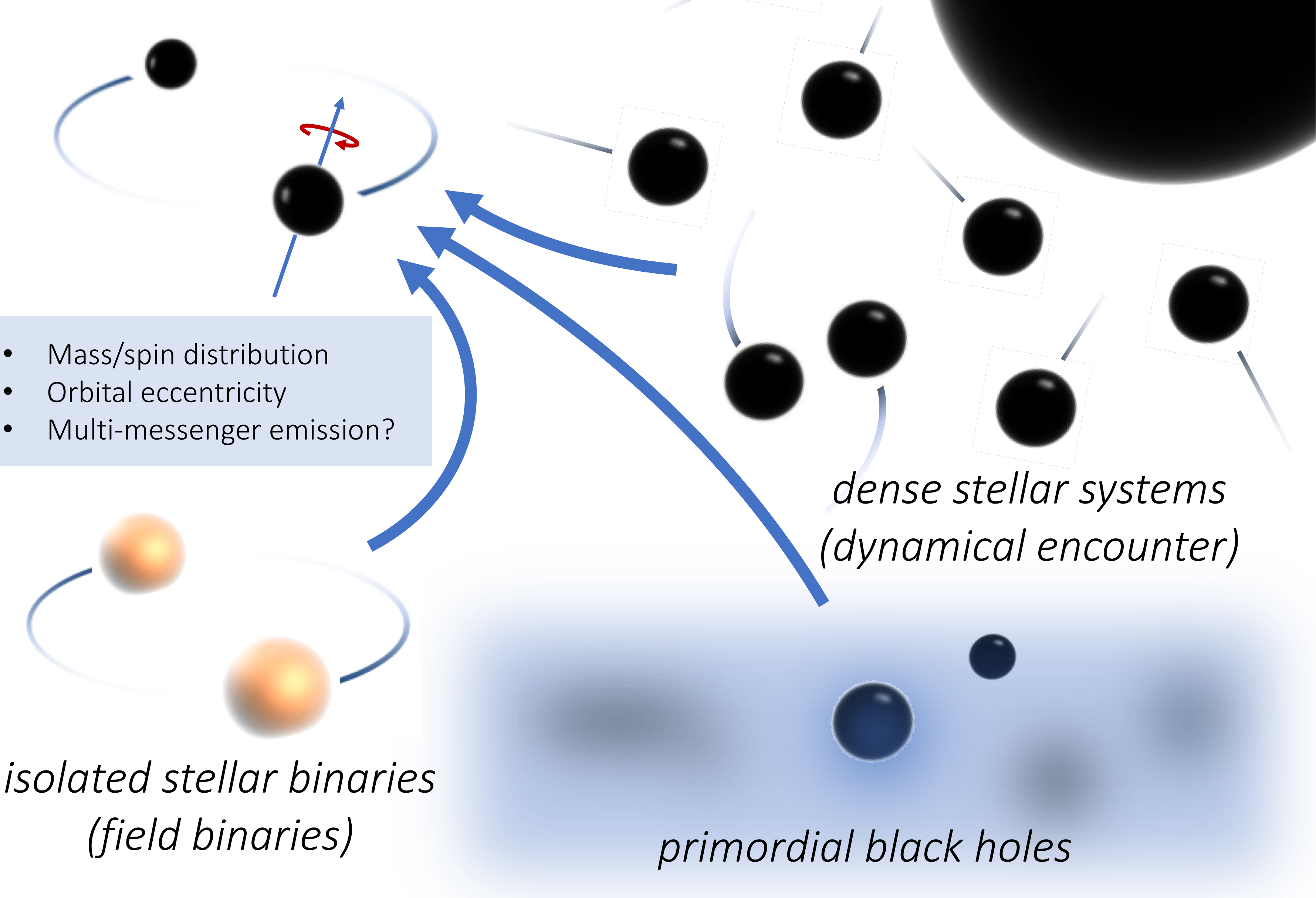


How do binary black holes form?

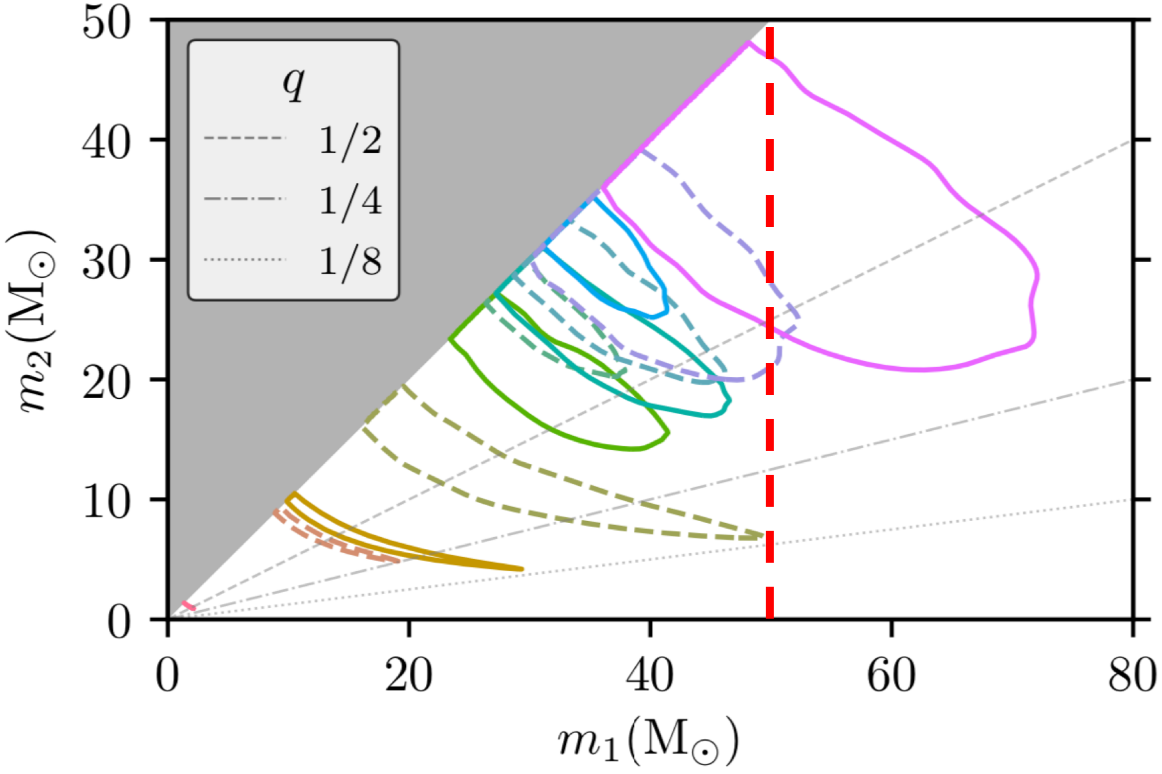


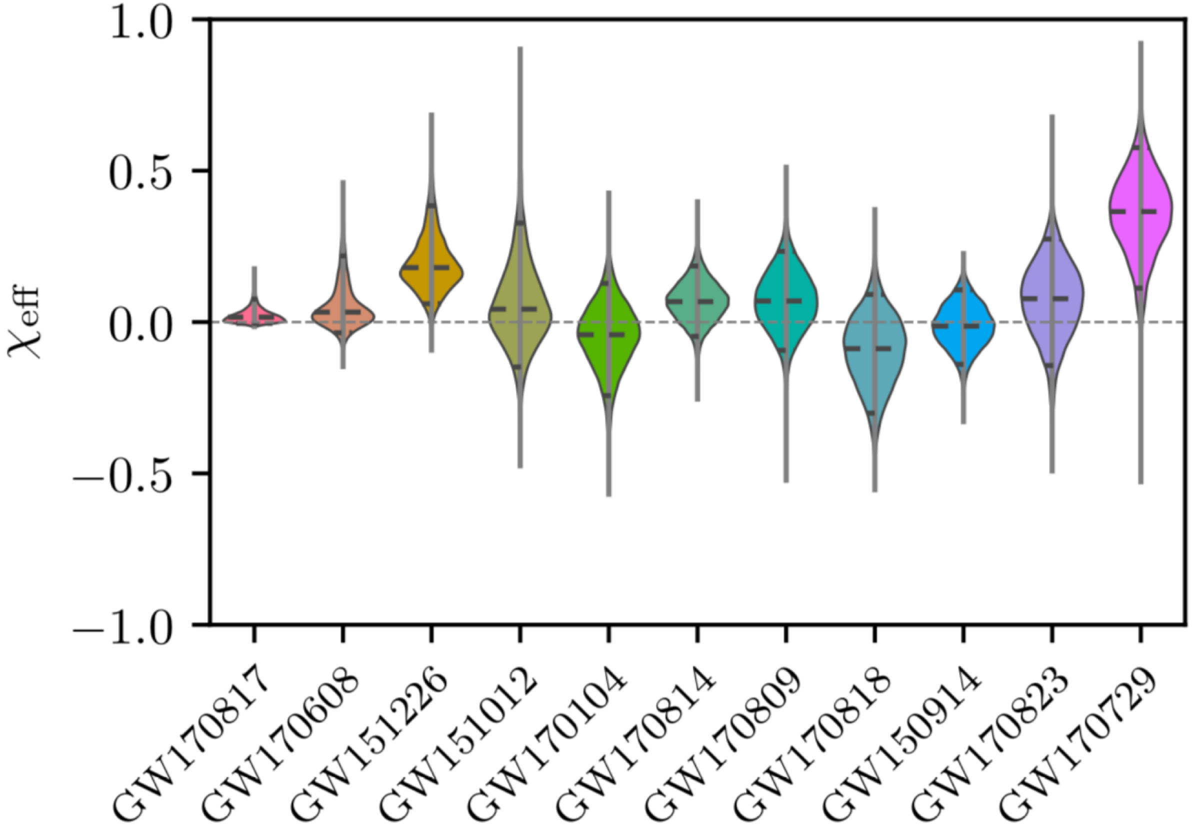
LIGO+Virgo PRX 2019

- Mass/spin distribution
- Orbital eccentricity
- Multi-messenger emission?



GW170729 – different origin?



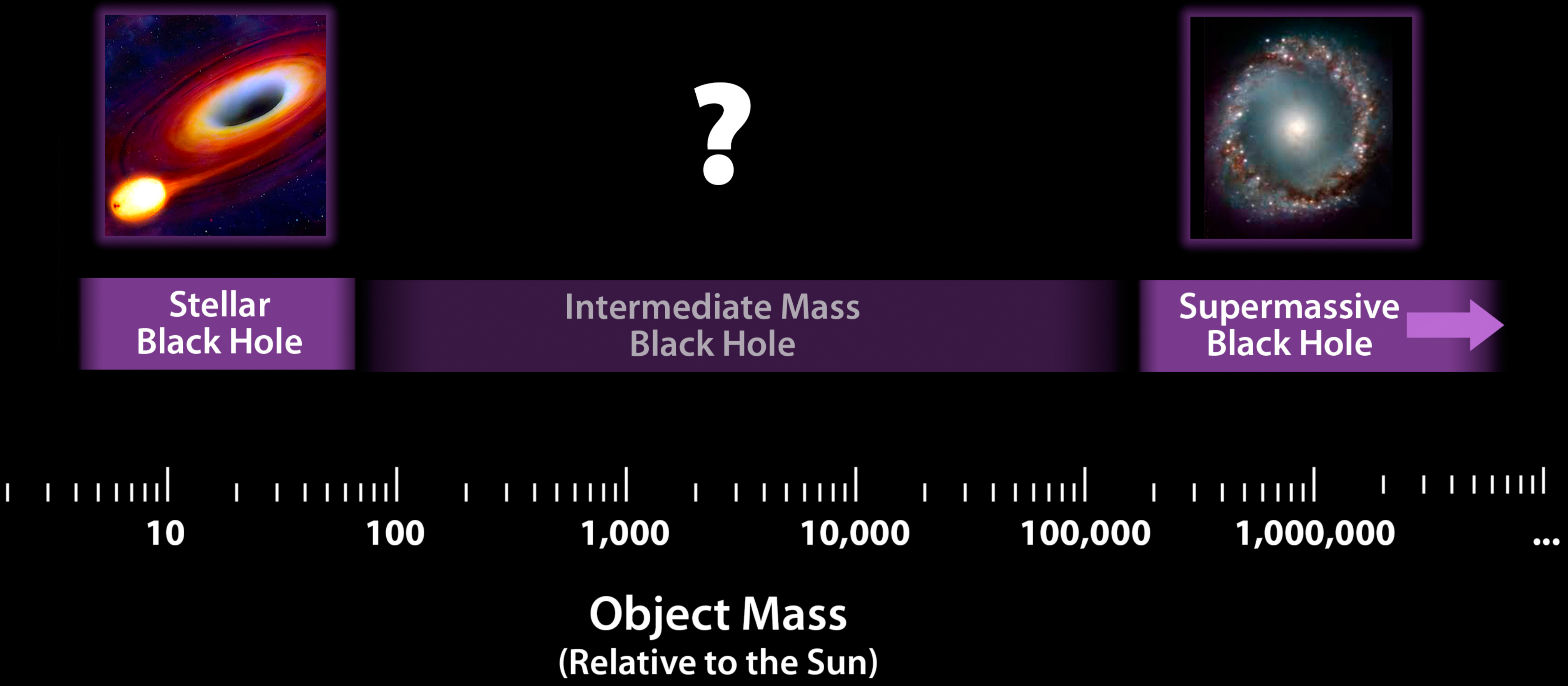


- m_1 possibly beyond mass limit from stellar evolution
- only binary merger with large positive spin

$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M},$$

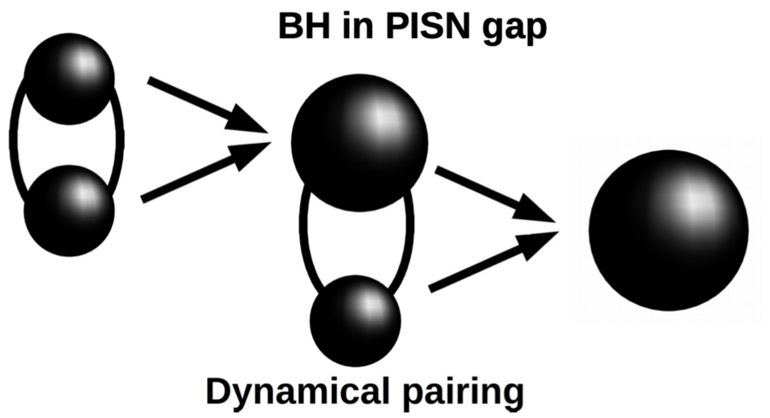
LIGO+Virgo 2018

Observed mass ranges of black holes



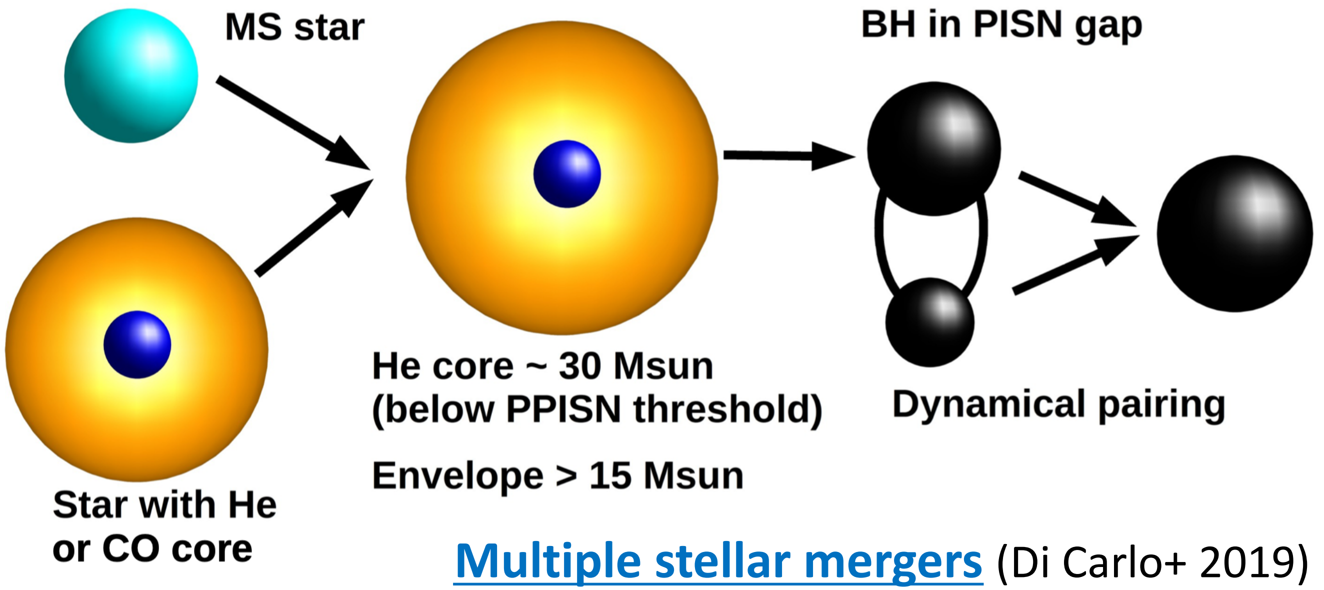
adopted from NASA

Possible formation mechanisms for intermediate mass black holes



Hierarhical mergers

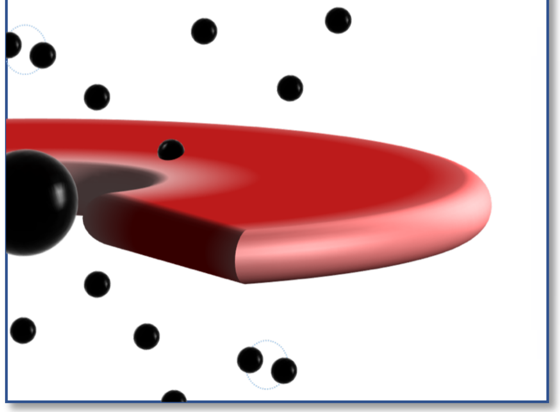
(Gerosa & Berti 2017, Fishbach+ 2017)



Multiple stellar mergers (Di Carlo+ 2019)

adopted from Michela Mapelli

Highly accreting BHs



Primordial black holes


Multi-messenger Astrophysics
SN 1987A
γ
υ
GW170817
γ
GW
IC170922
γ
υ

Multi-messenger astrophysics

<u>Gravitational waves:</u>

- Compact object formation / evolution

<u>EM radiation:</u>

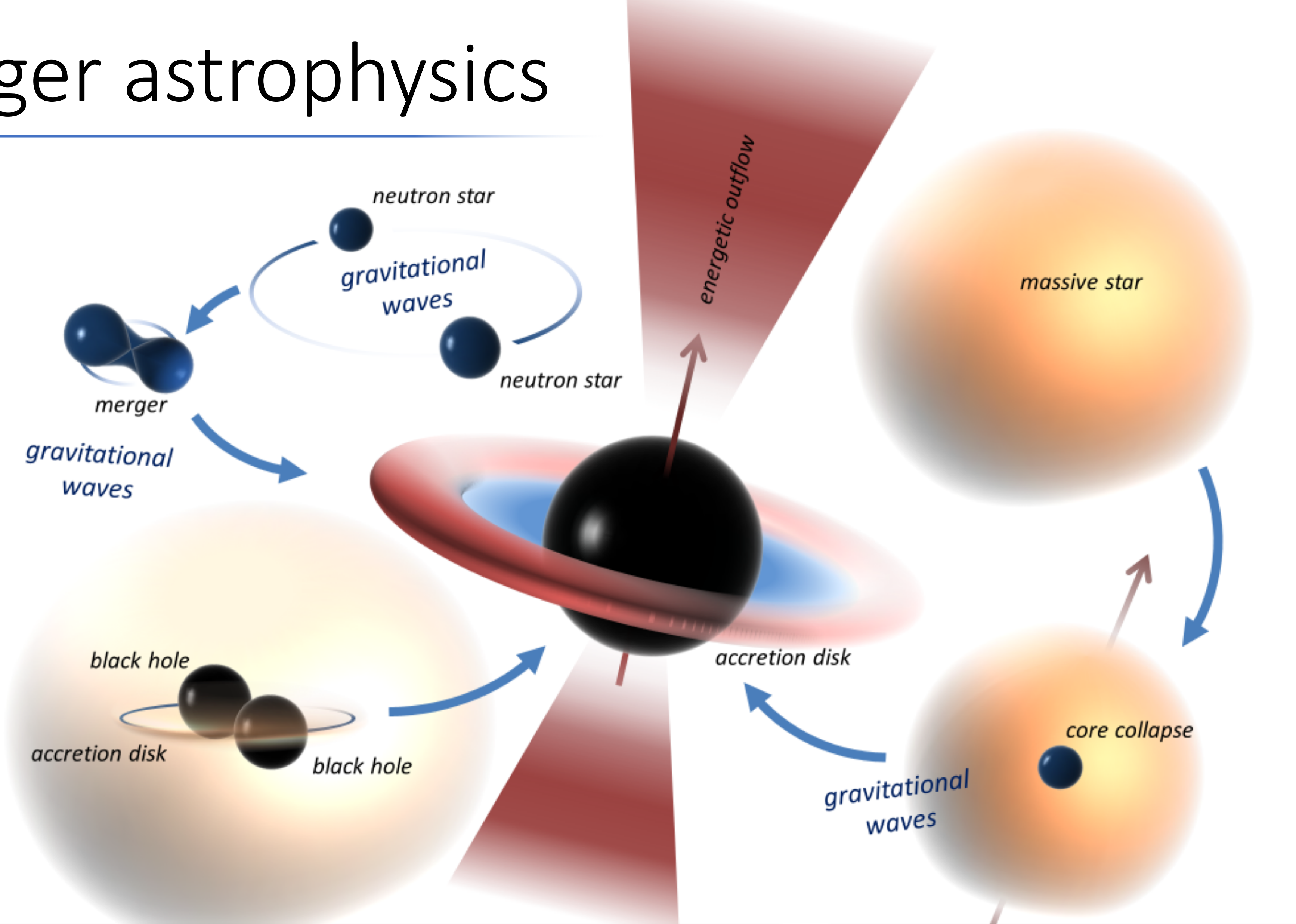
- Particle acceleration
- Environment

<u>Neutrinos:</u>

- Stellar core / structure
  Particle acceleration

<u>Cosmic rays:</u>

- Particle acceleration
- Environment



<u>Powerful transients:</u>

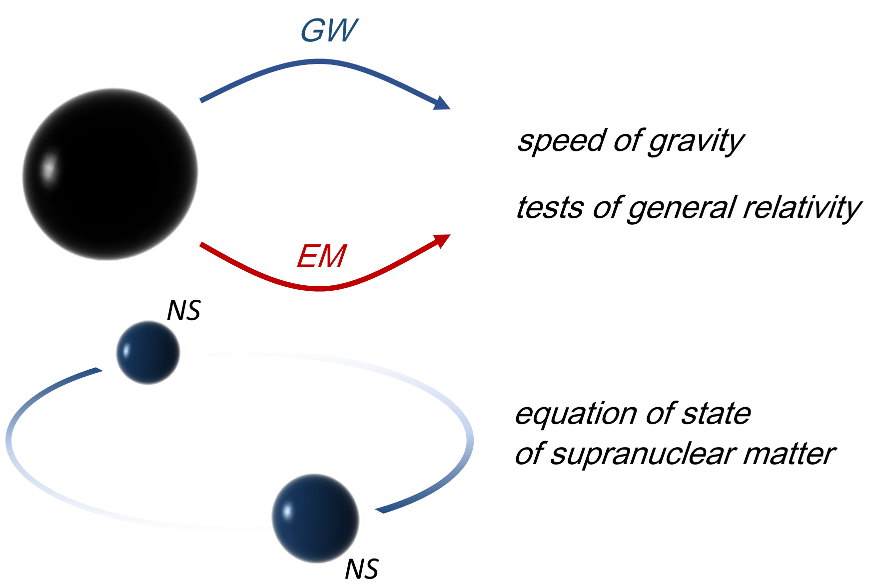
1. compact binary merger
2. stellar core collapse

<u>Goals:</u>

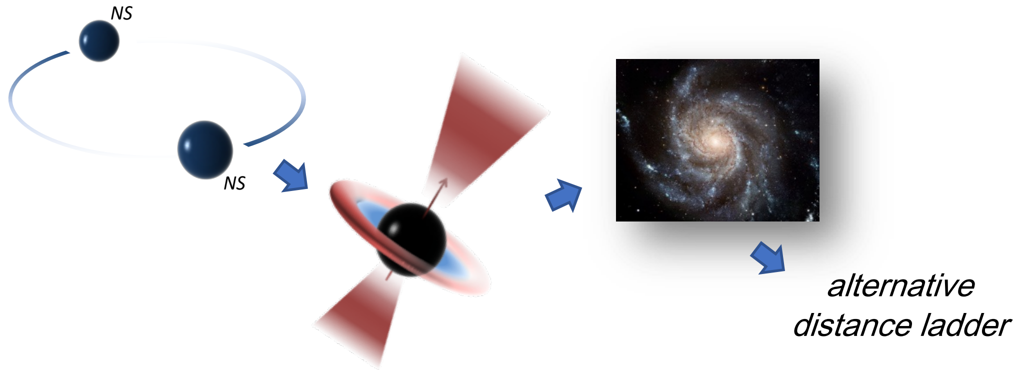
1. Learn more
2. Detect more

Science targets

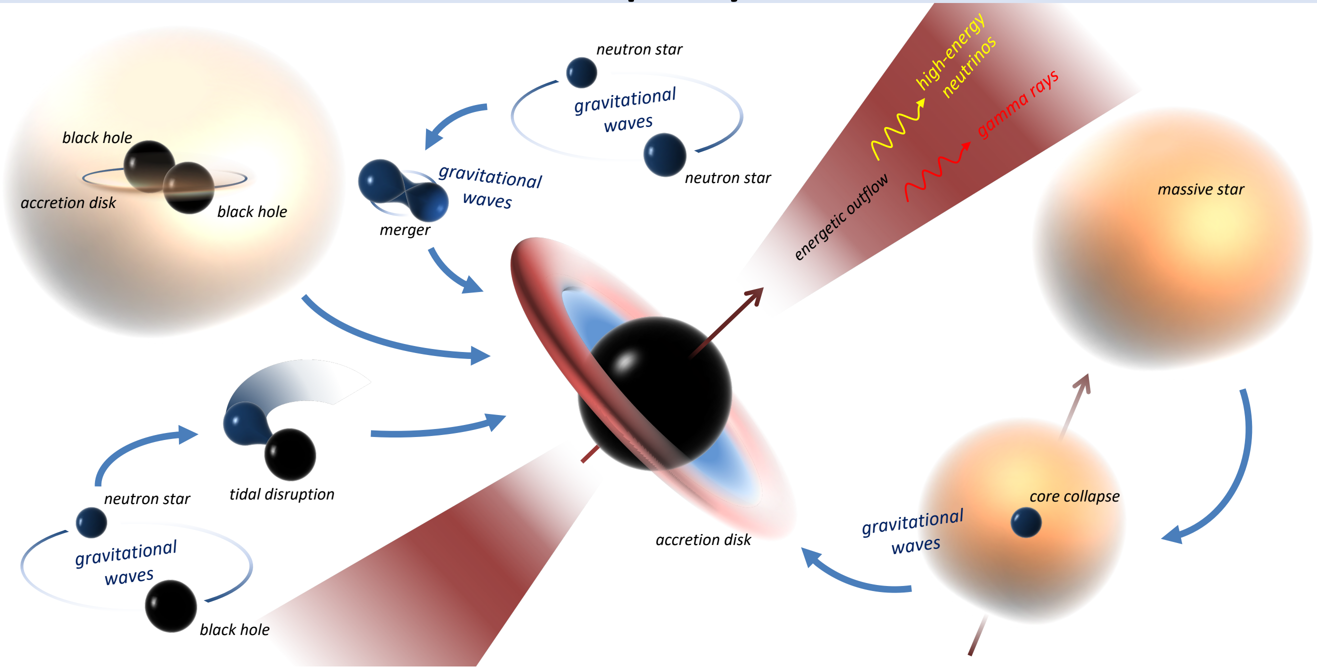
Fundamental physics



Cosmology

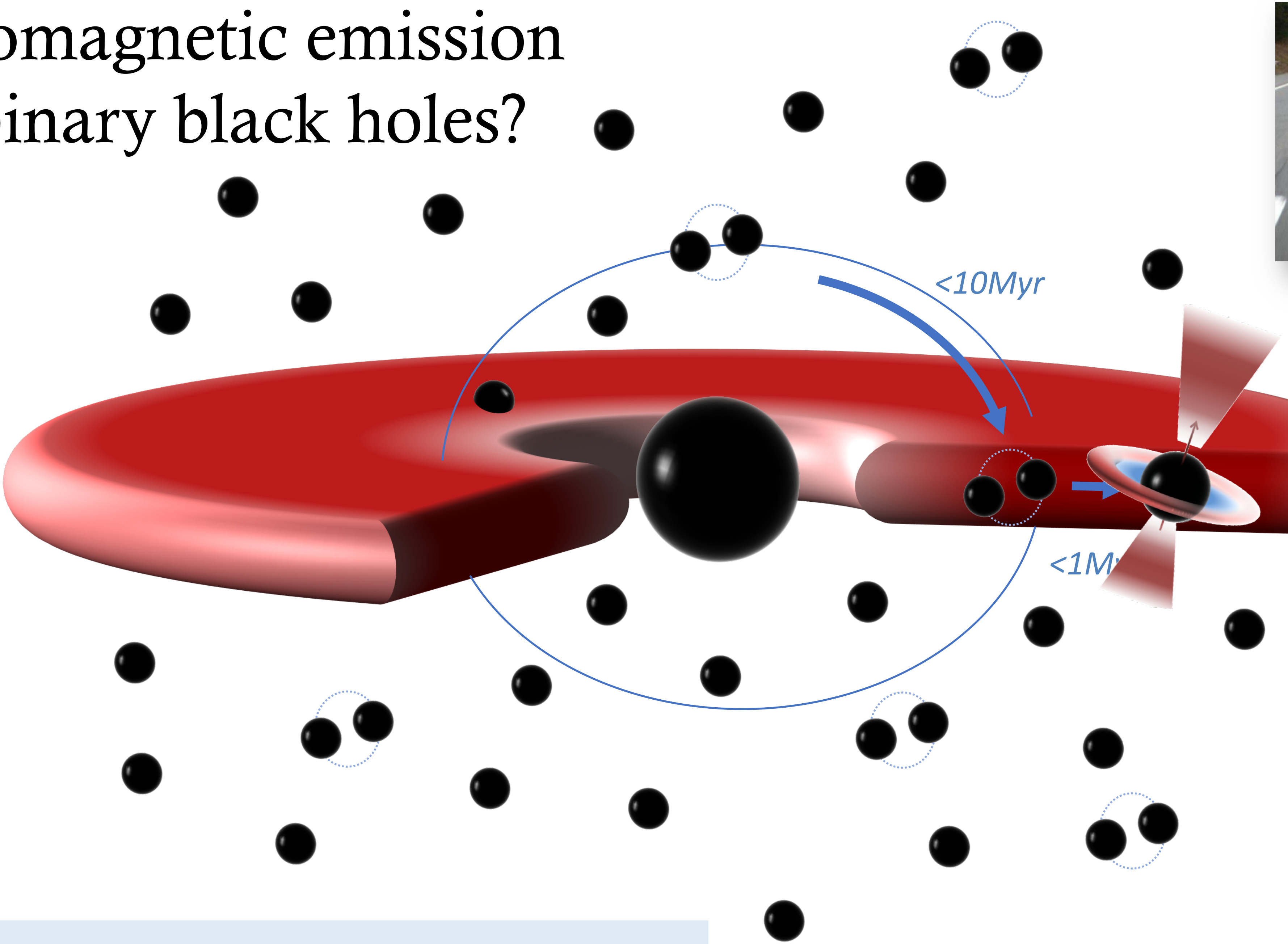


Astrophysics



- *Cosmic particle acceleration*
- *Black hole accretion*
- *Stellar core collapse*
- *Compact binary formation channels*
- *Intermediate mass black holes*
- *Origin of heavy elements*
- *Environment in galactic nuclei*
- *Relativistic outflows*
- *…*

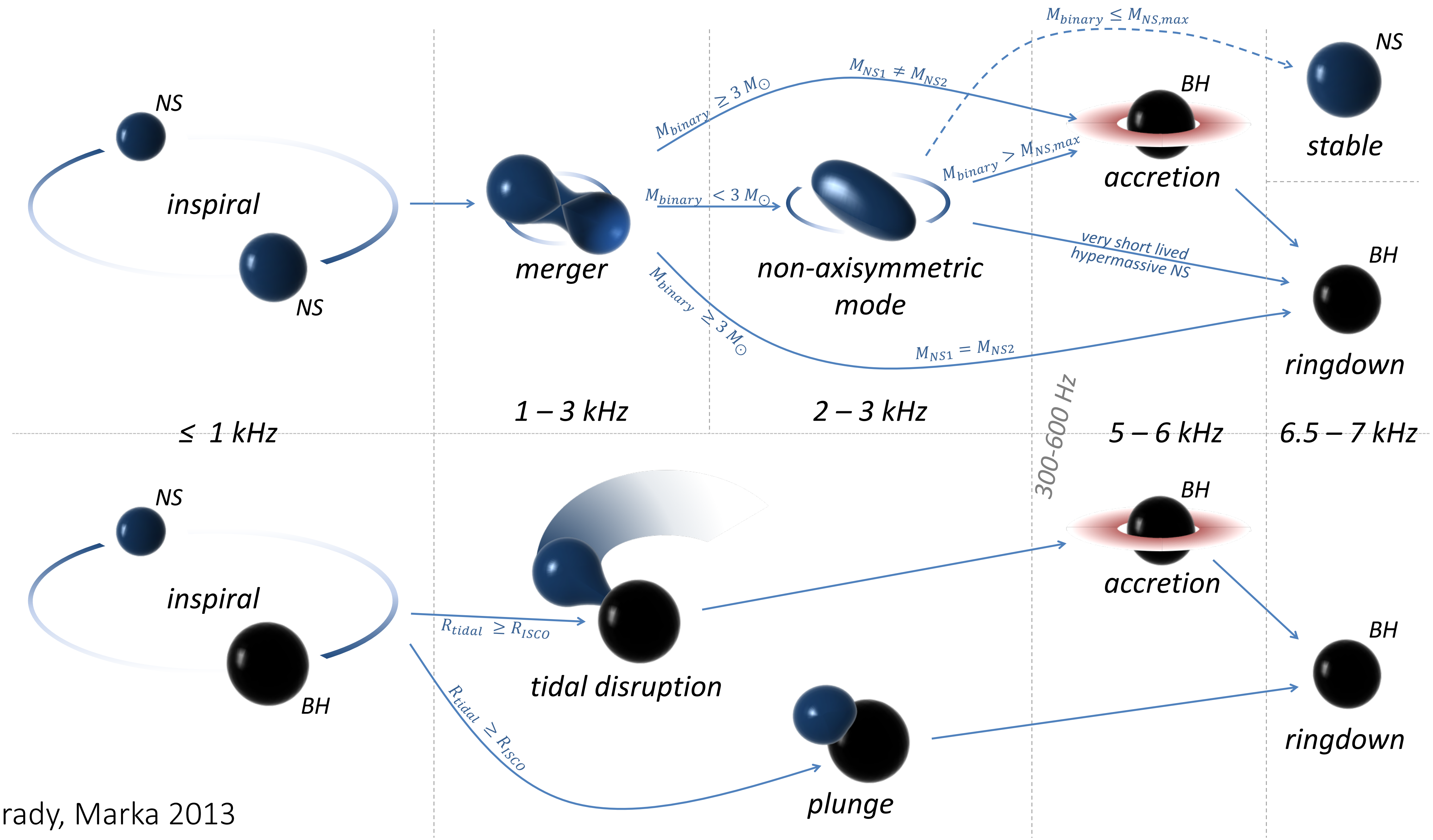
Electromagnetic emission from binary black holes?



They need to reside in a dense, gaseous environment.

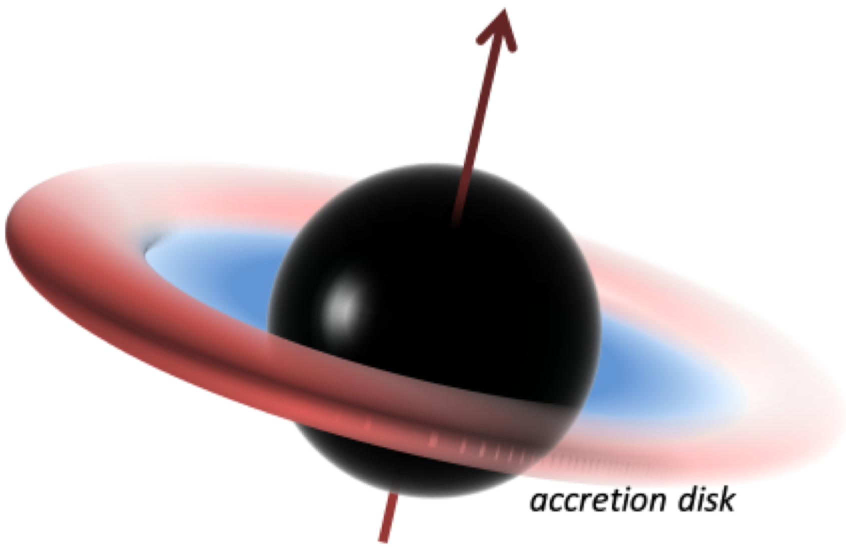
Bartos+ ApJ 2017

Compact binary mergers



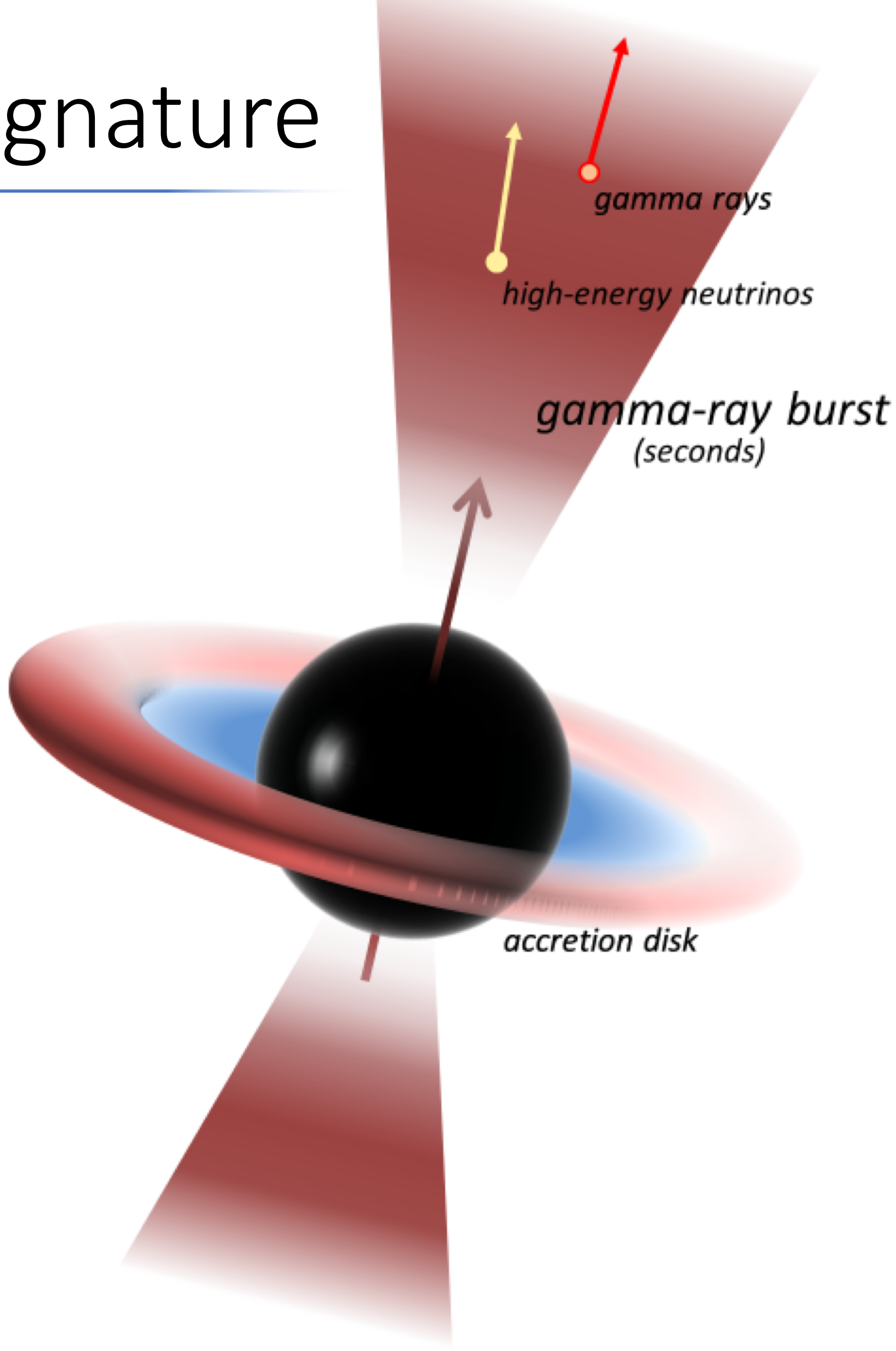
Bartos, Brady, Marka 2013

Electromagnetic signature

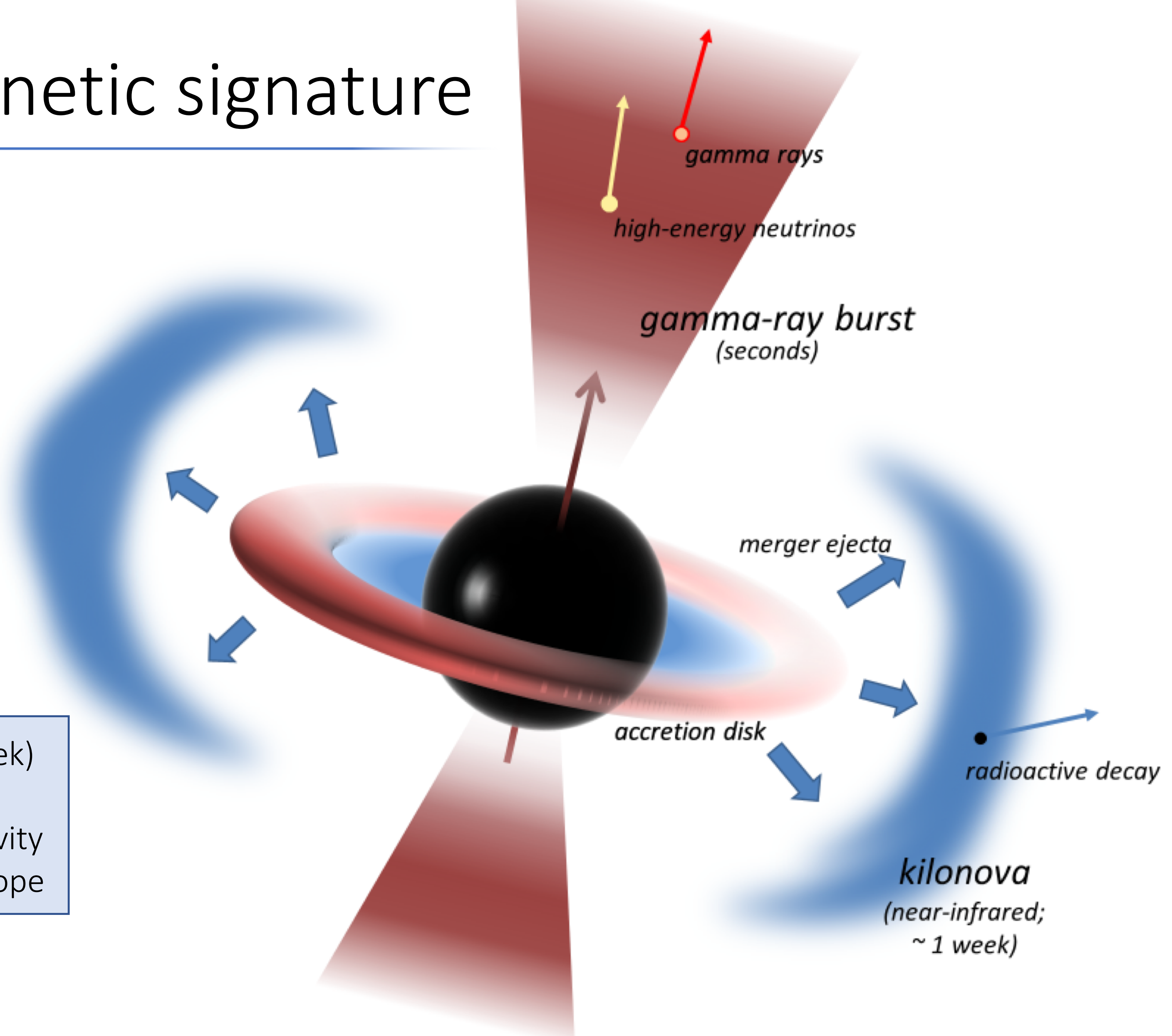


Electromagnetic signature

- Beamed
- Good gamma-ray FoV
- Limited localization (difficult to follow-up)



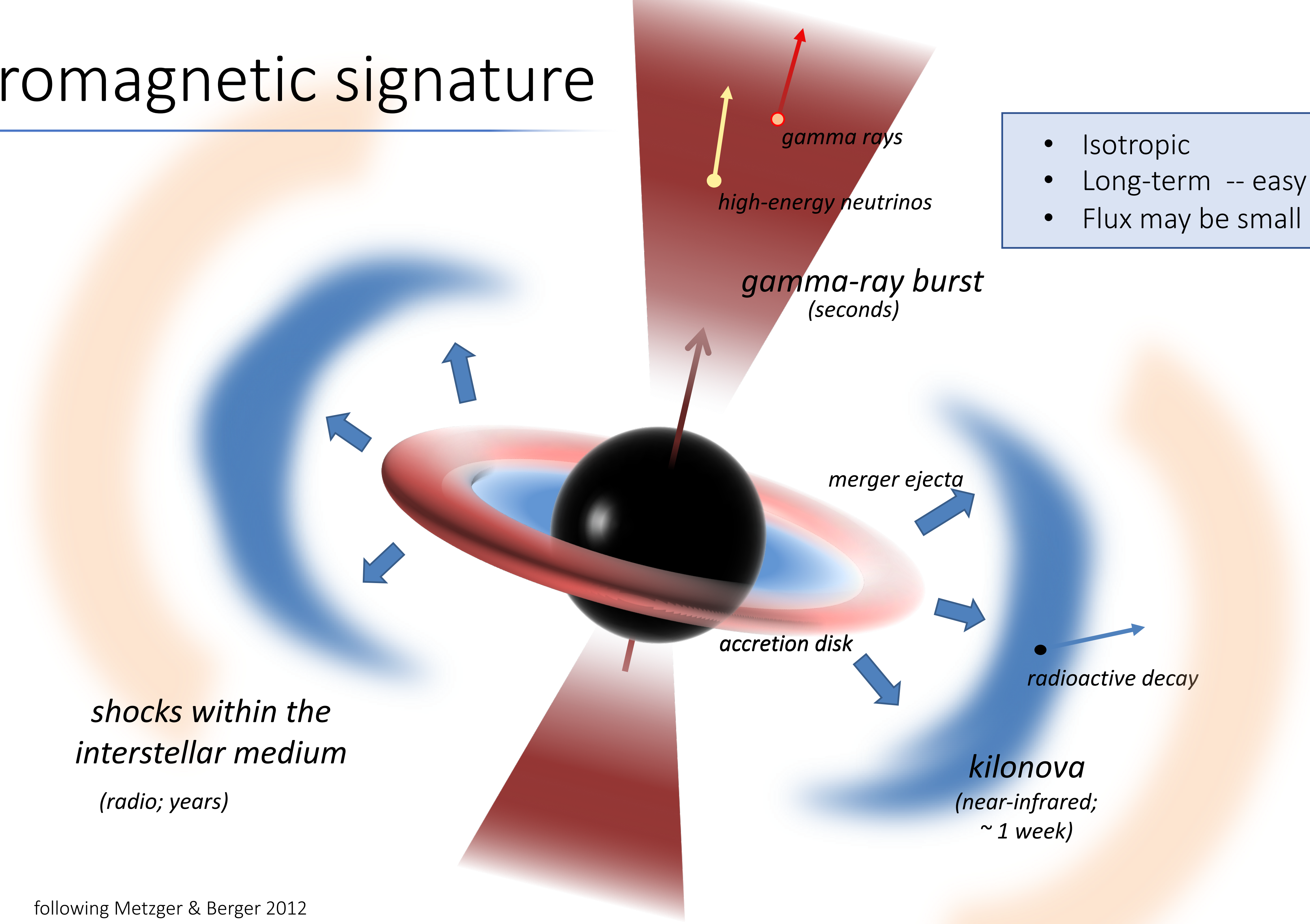
Electromagnetic signature



- Good time frame (~week)
- ~Isotropic
- Limited IR FoV / sensitivity
  → not for every telescope

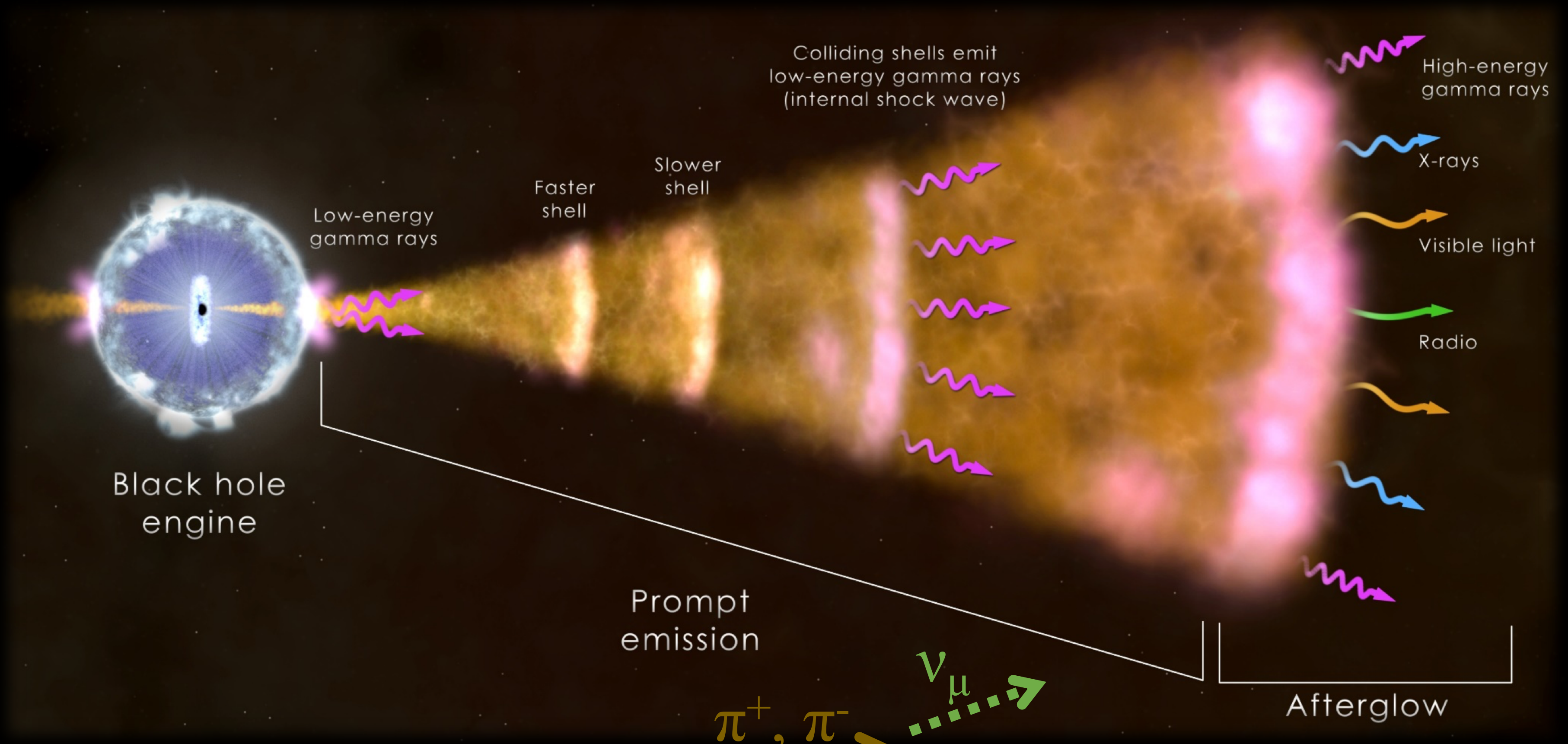
Electromagnetic signature

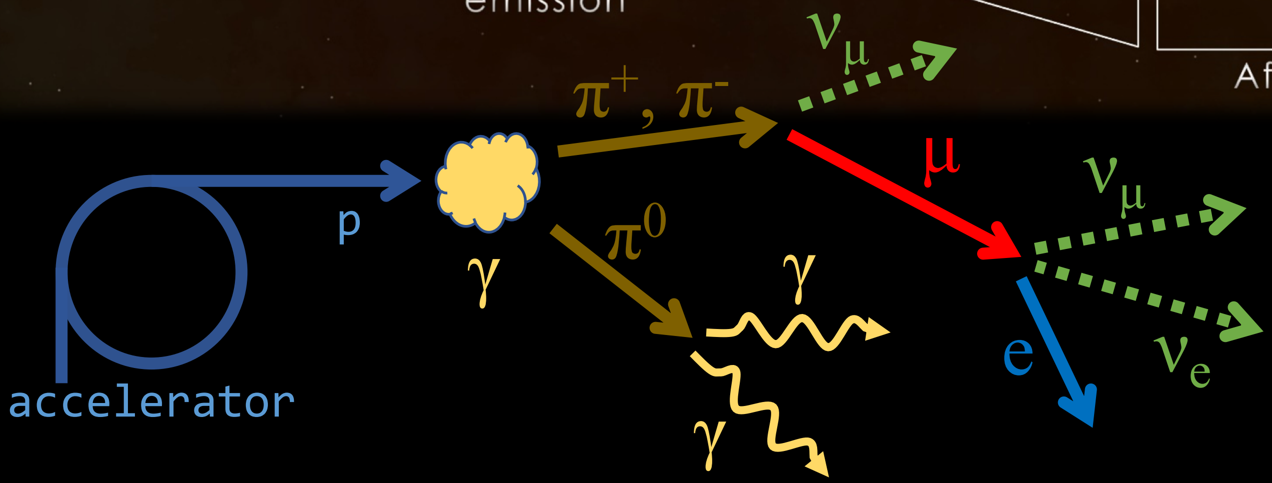
- Isotropic
- Long-term -- easy follow-up
- Flux may be small



following Metzger & Berger 2012

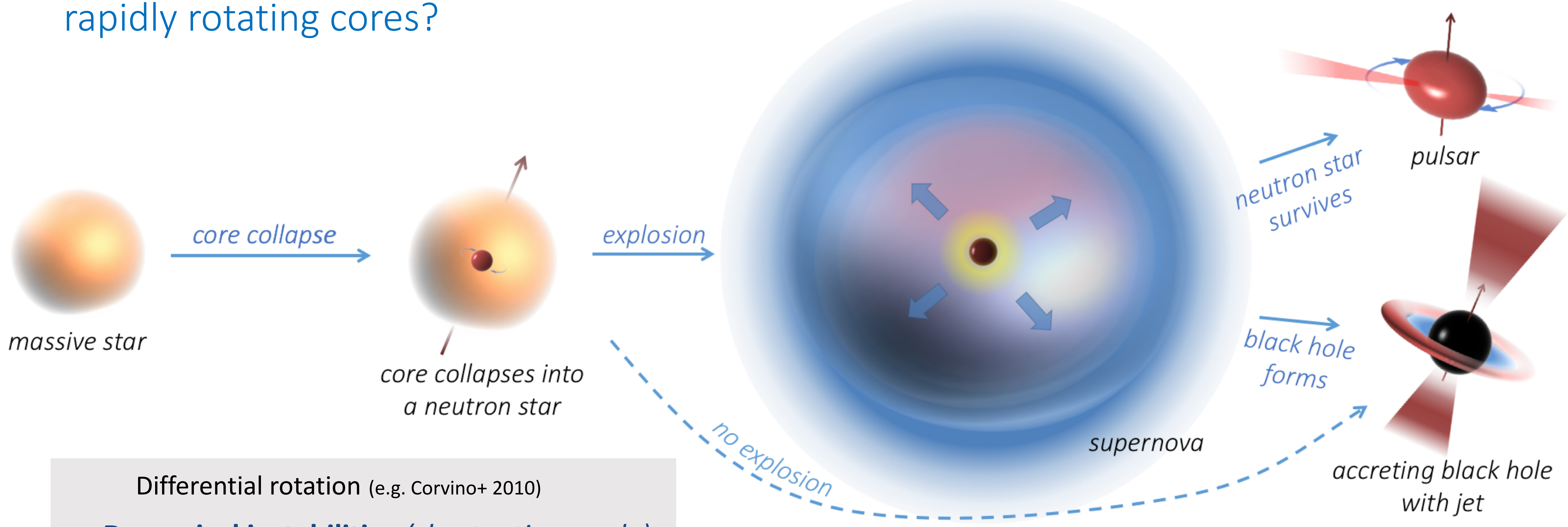
gamma ray bursts





Stellar core collapse

Gravitational waves from rapidly rotating cores?

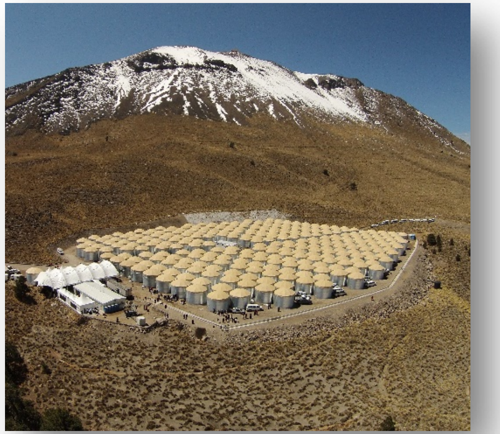


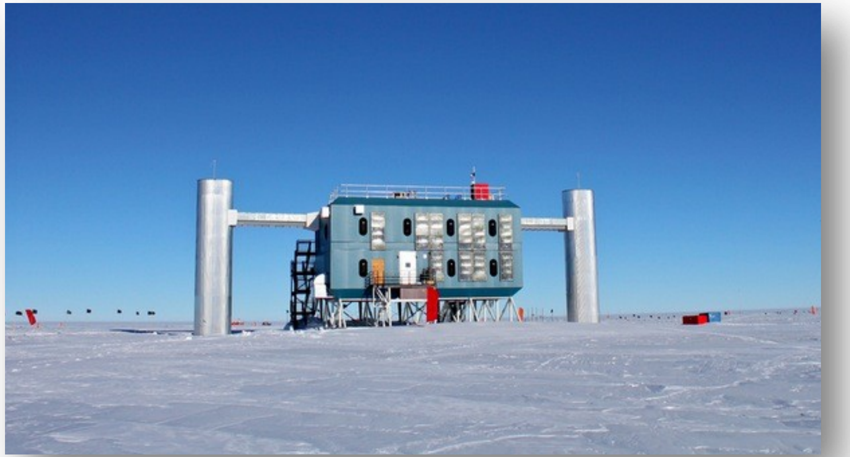
Differential rotation (e.g. Corvino+ 2010)

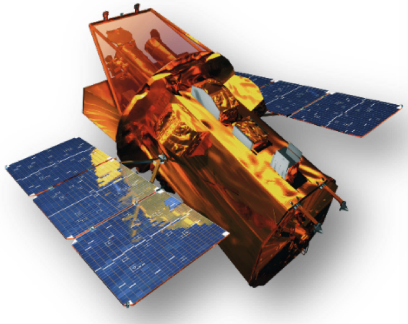
- **Dynamical instabilities** *(shorter time scale)*
- **Secular instabilities** *(longer time scale)*
- **Magnetic distortion**

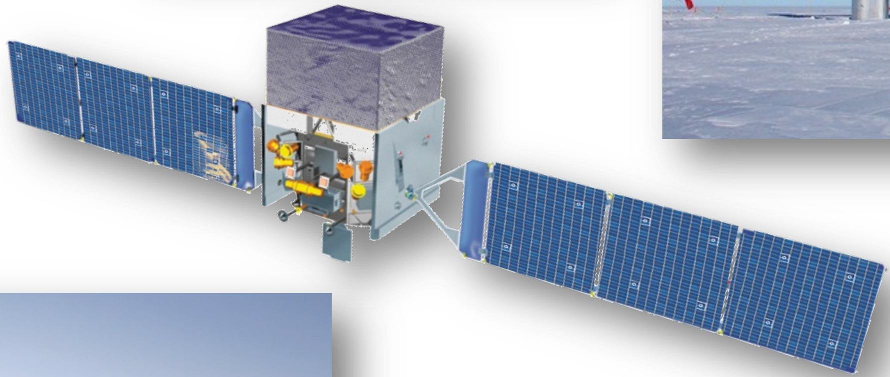
Fallback accretion? *(Piro & Thrane, 2012)*

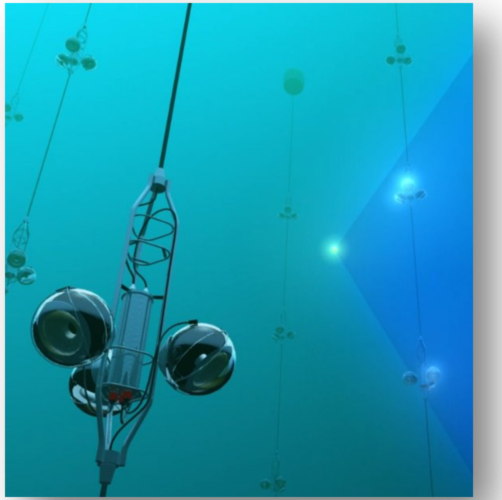
~100 follow-up observatories worldwide
All cosmic messengers, across the spectrum.

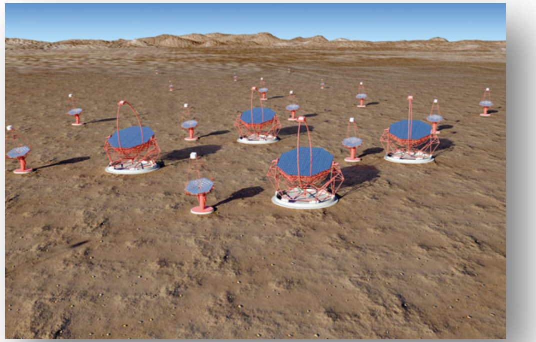






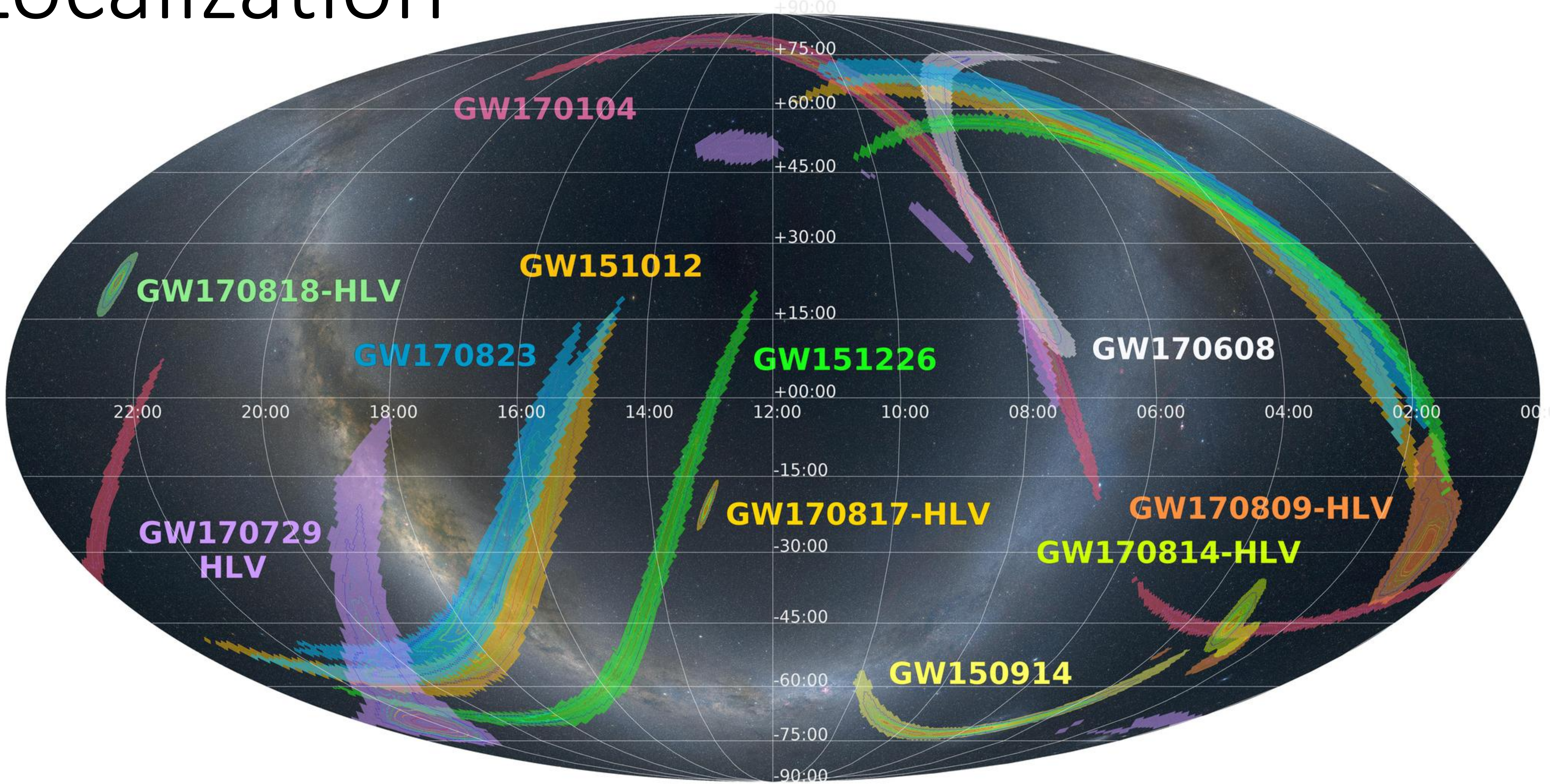







Earth
Space
LIGO Hanford
LIGO Livingston
Virgo

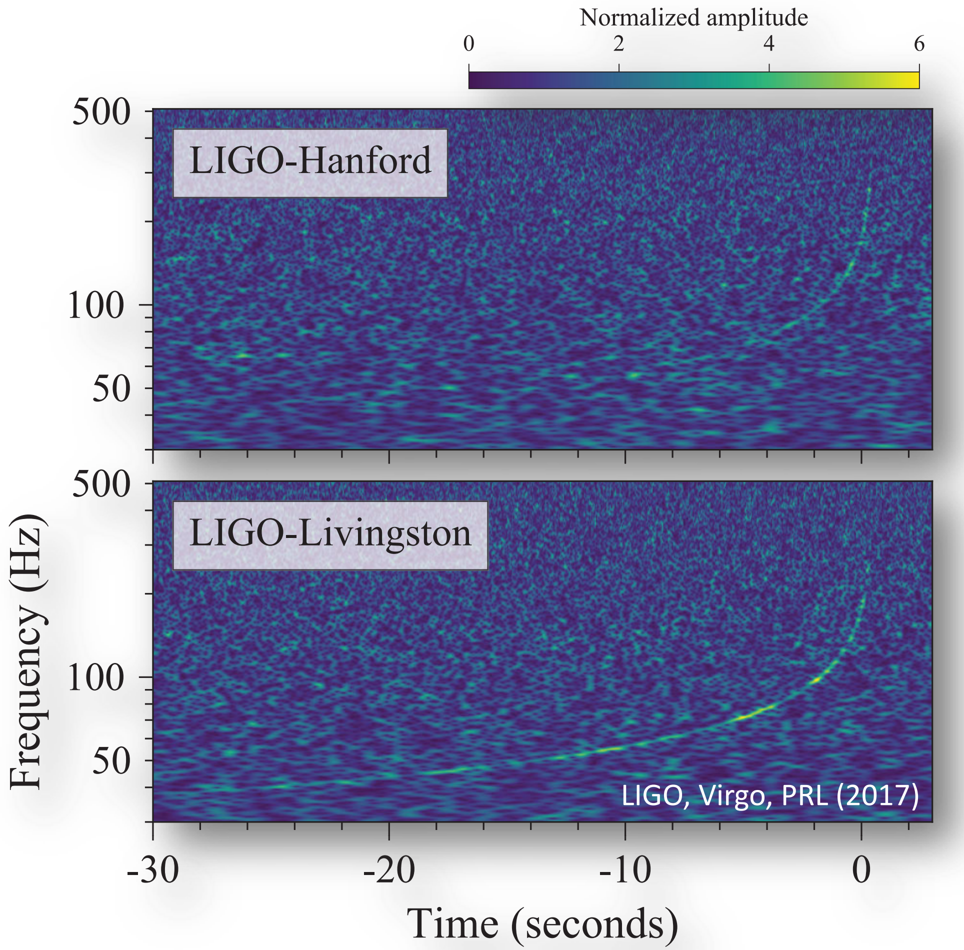
Localization

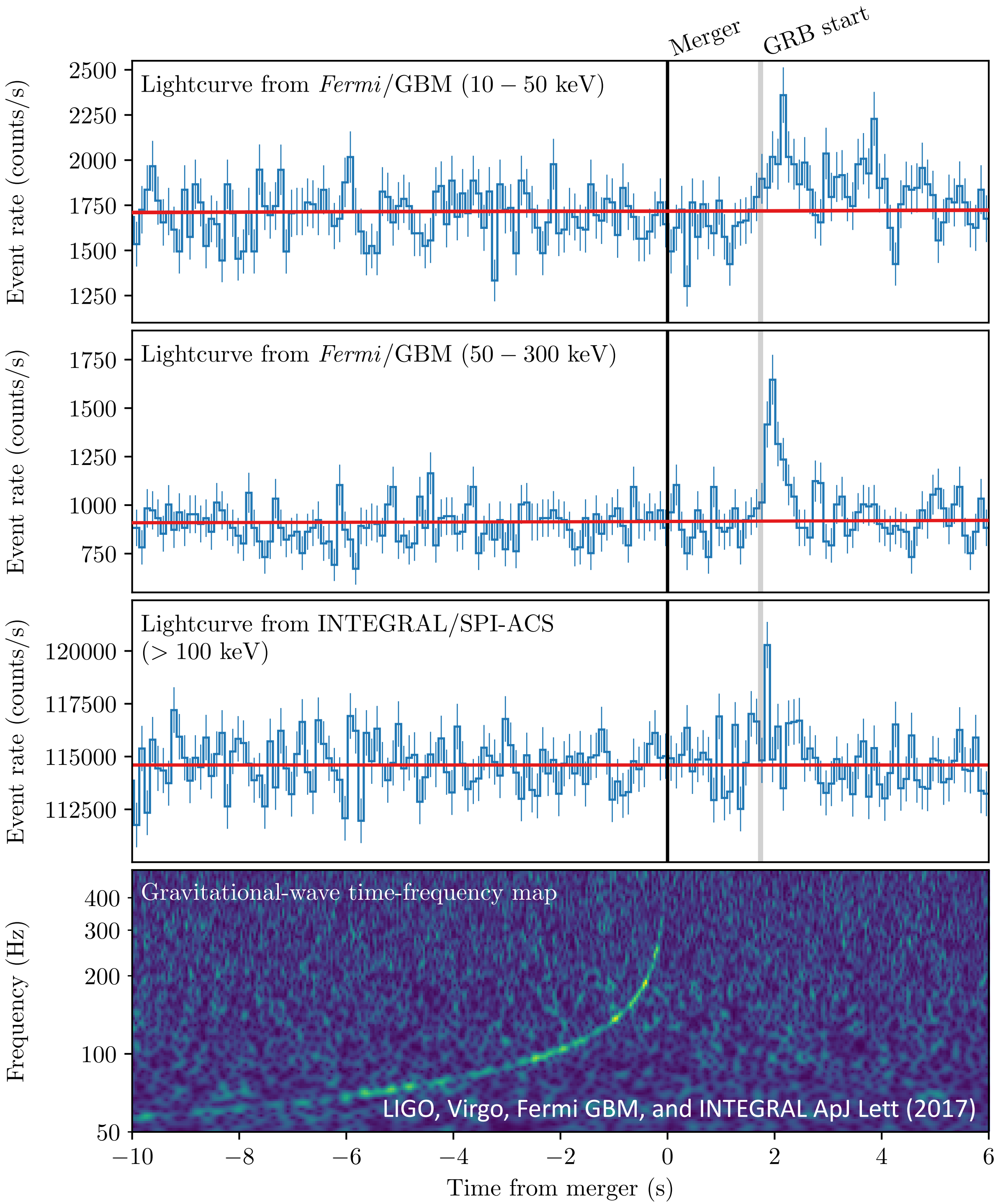


- Not too good, sometimes difficult to scan the whole localization

LIGO-P1200087-v50

August 17, 2017

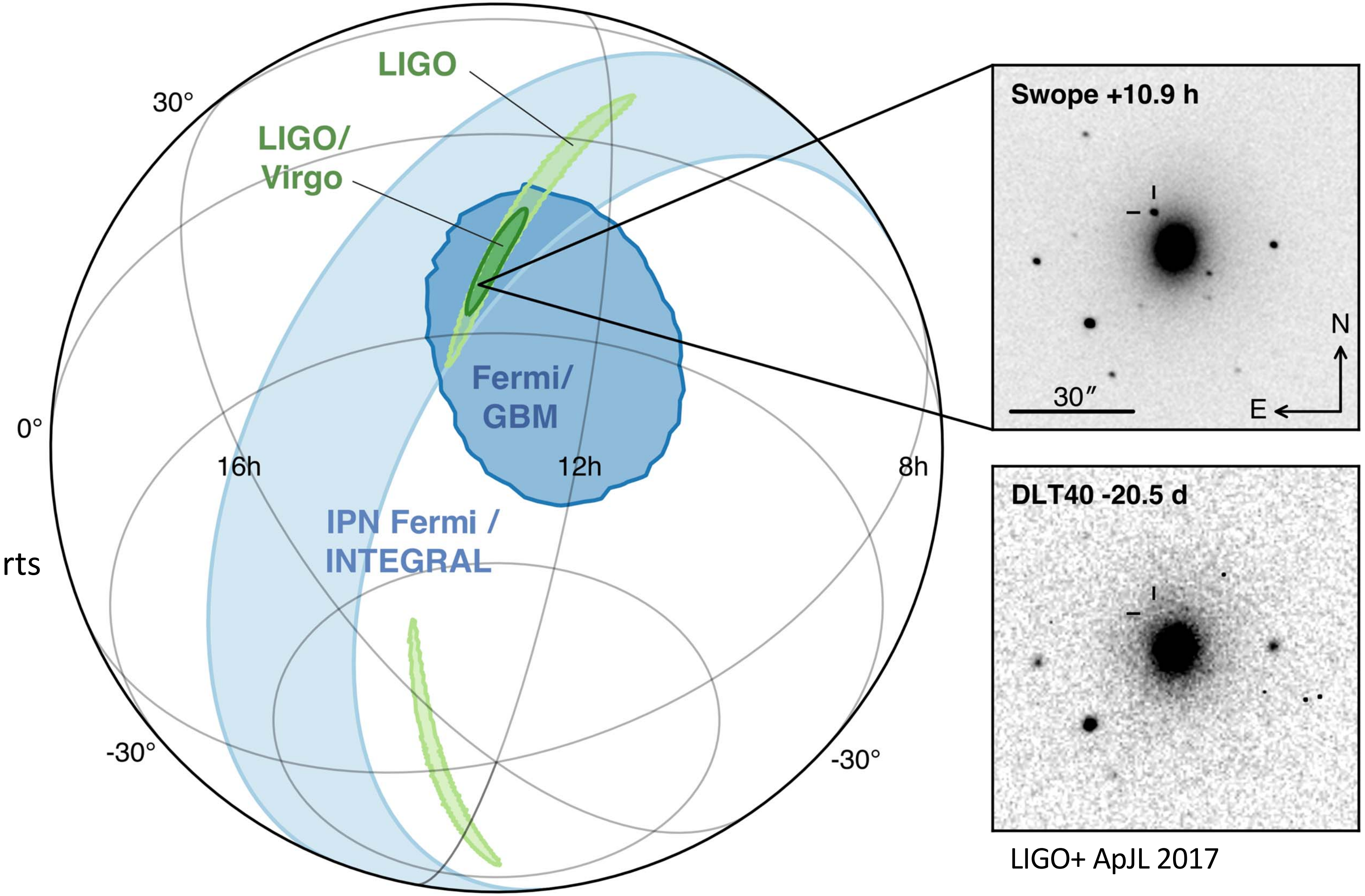




- Gravitational-wave trigger in LIGO-Hanford only
- Livingston – noise transient
- No signal in Virgo
- Consistent with BNS merger
- 1.7s later --- GRB alert from Fermi
- Weak GRB (~10^{-7} erg cm^{-2})

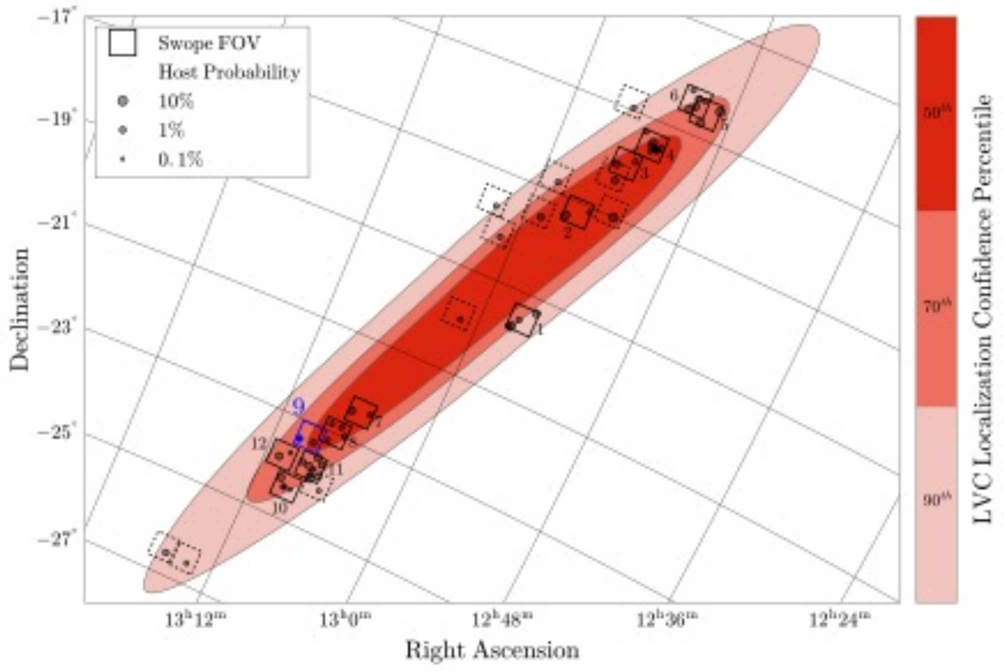
Localization and search for counterpart

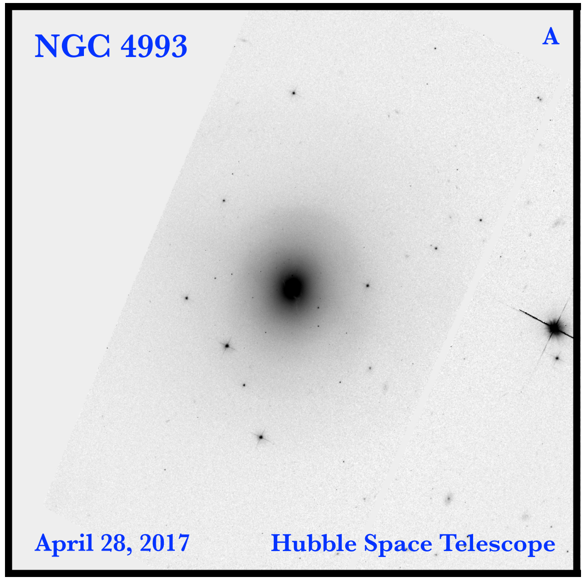
- GW localization: **~30 deg^2**
- Virgo non-detection helped
- Overlap with Fermi **GRB**
- GW: **binary neutron star merger**
- Distance: **~40 Mpc** (+-10)
- GCN notice issued within **30min**
- Over **60 observatories** searched for counterparts (gamma-ray, X-ray, UVOIR, radio, neutrino)
- Optical transient found within **11h**

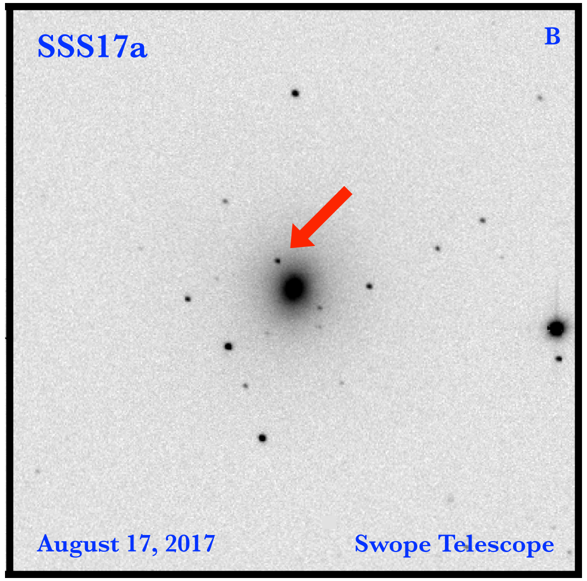


LIGO+ ApJL 2017

Detection of a kilonova

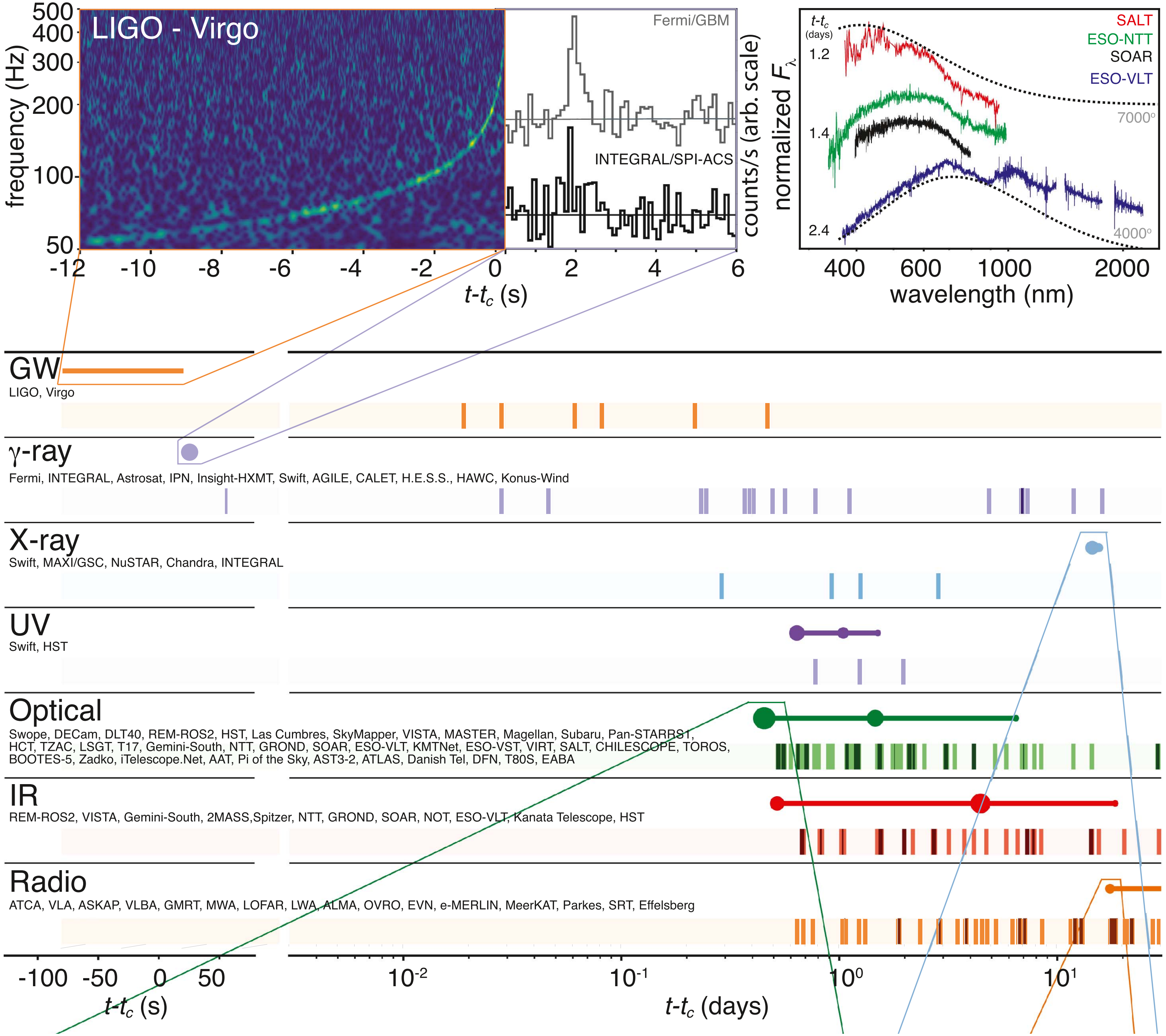






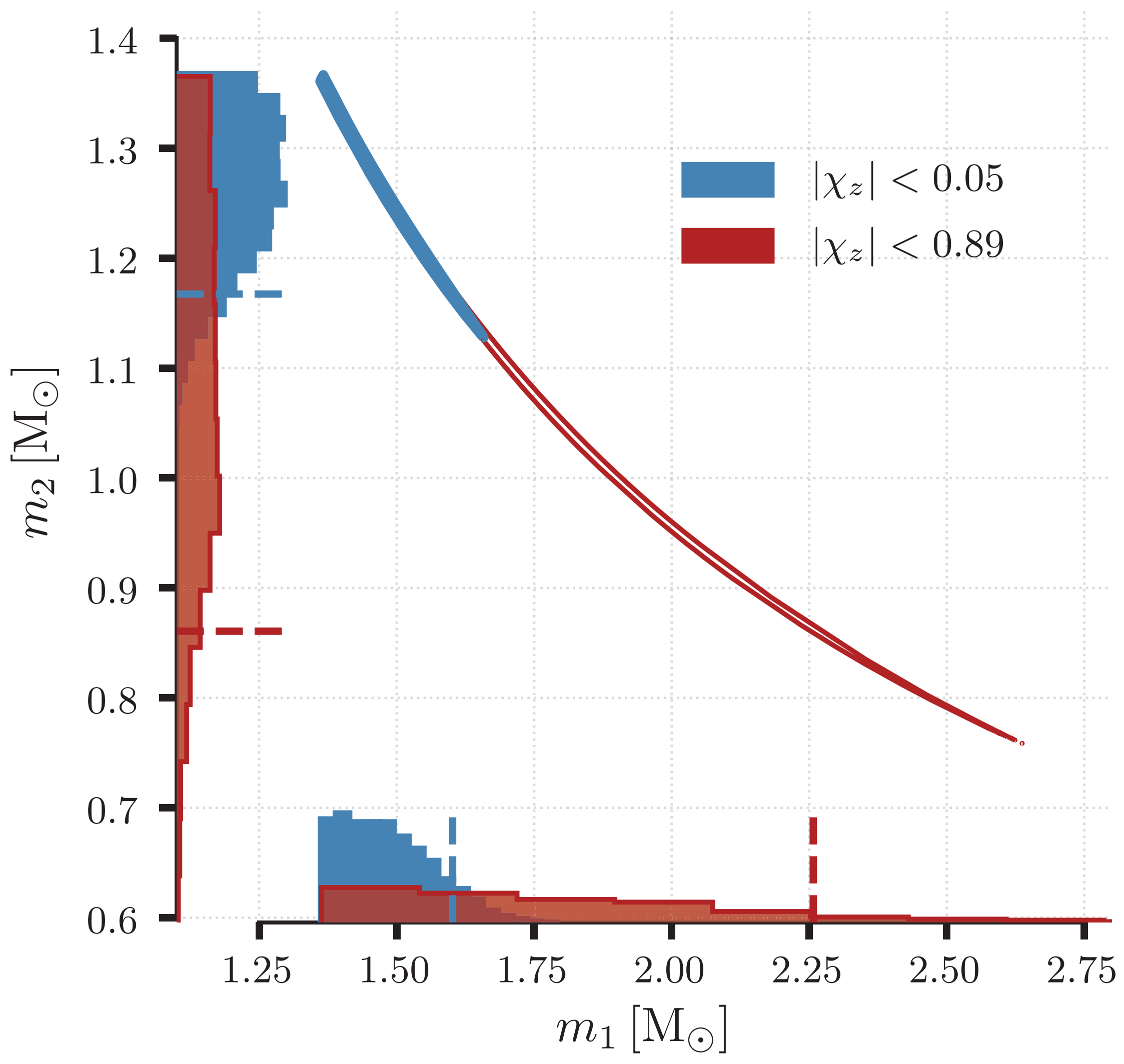
Coulter+ Science 2017

- NGC 4993 --- 40 Mpc
- 2 kpc from center
- i = 17.5 mag
- Very close distance --- 1m telescopes could make significant contribution
- Use of galaxy catalogs



LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-tc (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized Fλ
t-tc (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-tc (s)
10^-2
10^-1
10^0
10^1
t-tc (days)

Information in Gravitational Waves

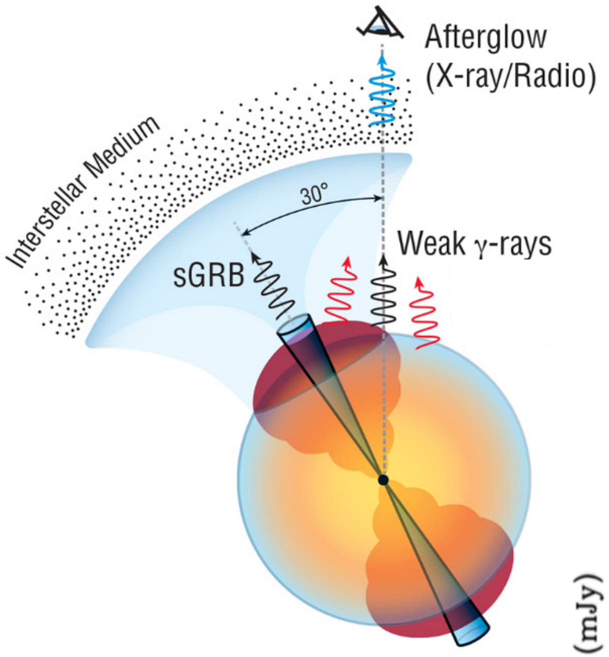


	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$

$$R = 1540^{+3200}_{-1220}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

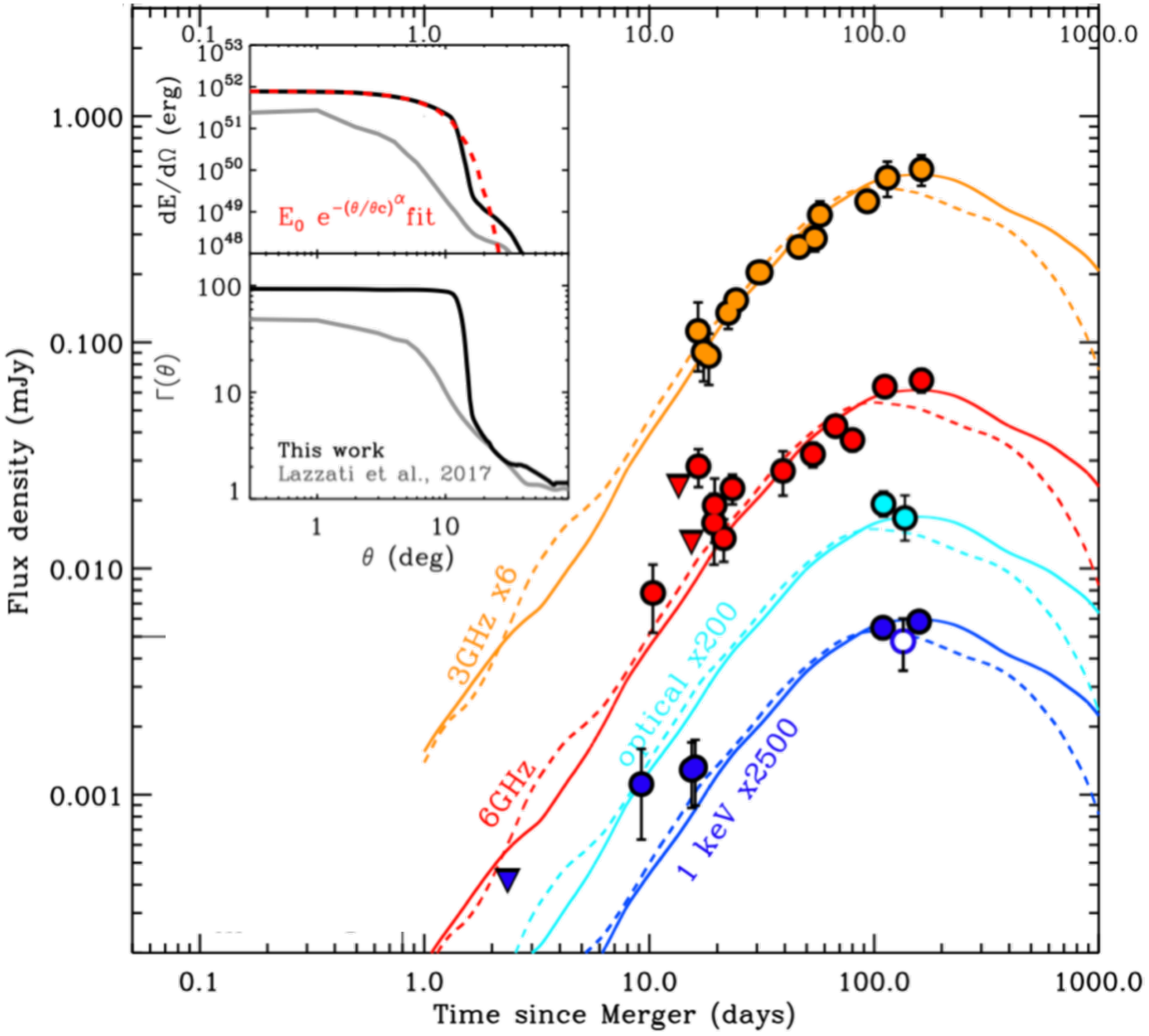
- More common than we expected
- Consistent with galactic BNS observations
- Tidal effects are not taken into account
- Neutron star maximum mass: ~2.2 Msun

GW170817
an off-axis GRB



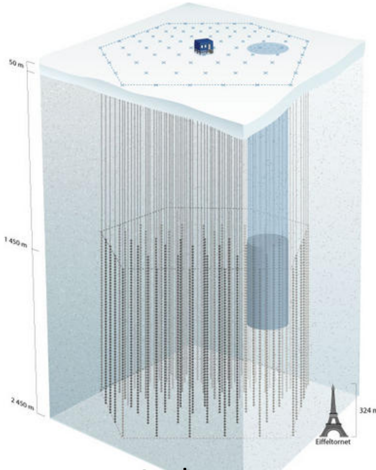
Kasliwal+ 2017

- First GW+high-energy discovery
  - ➢ Already very informative
- Afterglow observations point to <u>structured jet</u>.
  (Margutti, Ghirlanda, Lazzati, Mooley, …)
  - ➢ <u>~30%</u> of GWs from BNS will have GRB counterpart.
  - ➢ Significant fraction (10%) of GRBs should be <u>nearby</u>. (Gupte & Bartos 2018)
- How does TeV emission look like at large viewing angles?
  - ➢ Fermi-LAT did not detect this event.
  - ➢ Can help differentiate between emission mechanisms.
  - ➢ This will be central to whether CTA will see LIGO/Virgo sources.

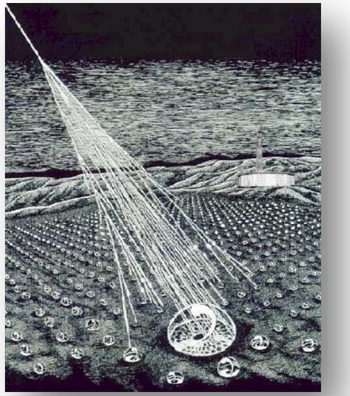


Margutti+ 2018

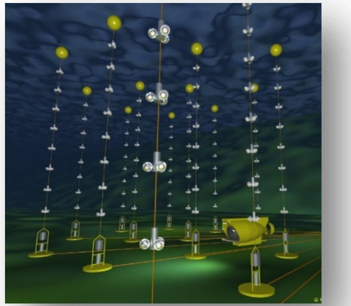
Ultra-high energy emission from neutron star mergers?



IceCube



Pierre Auger

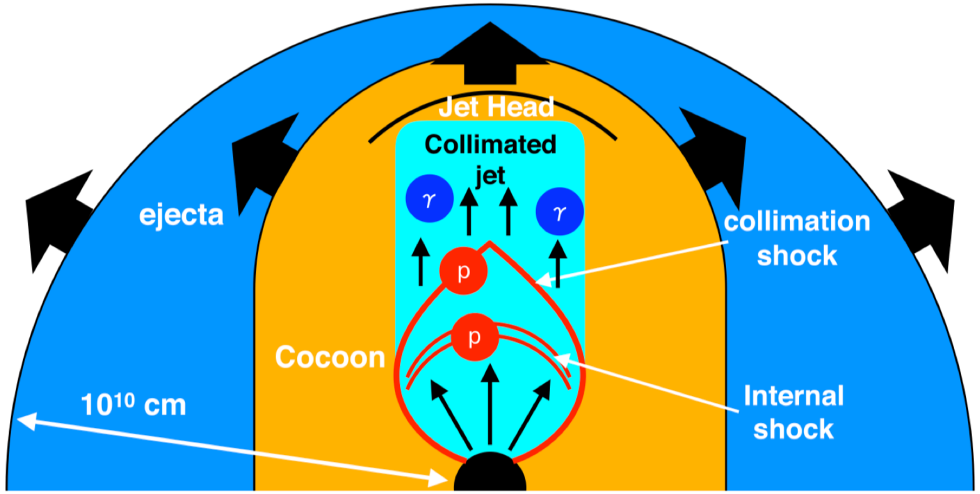


ANTARES

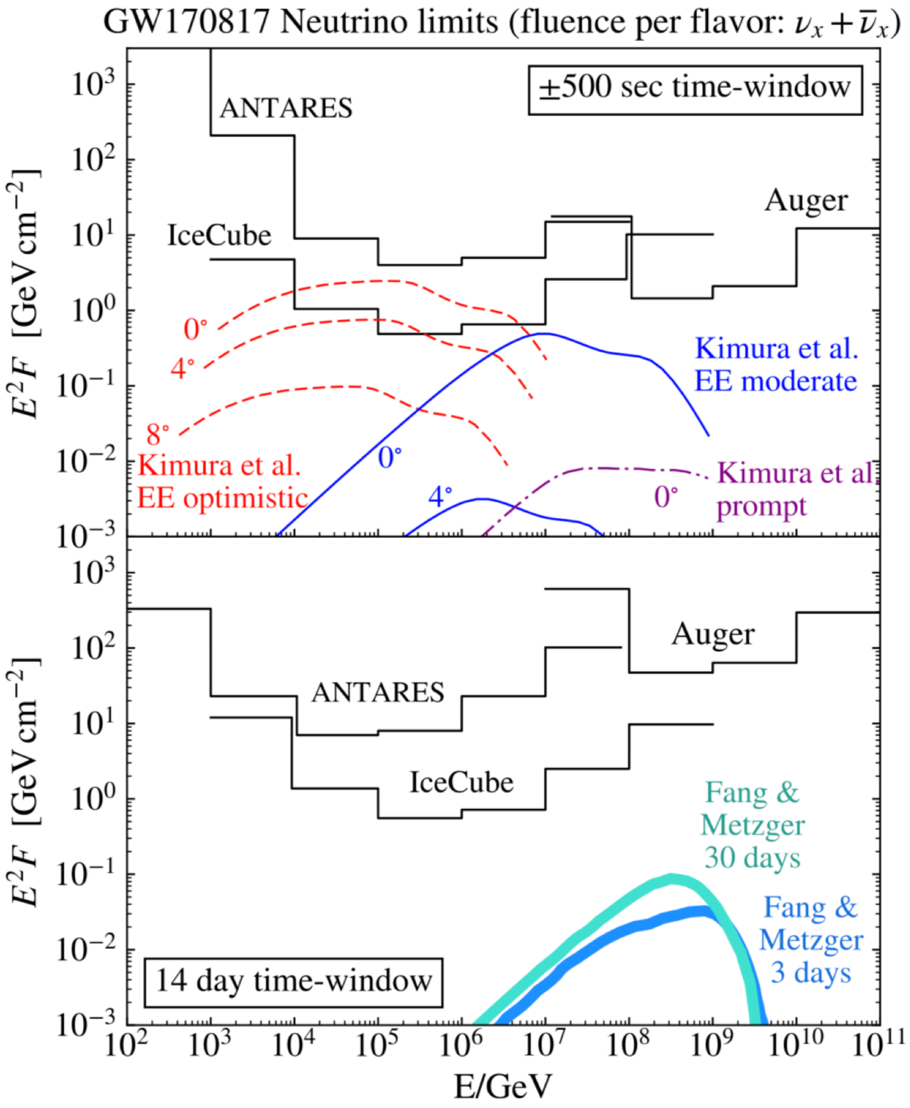
- High-energy neutrinos:
  - Probe PeV+ particle acceleration
  - All-sky detectors --- rapidly provide precise location
  - ν's can escape environments γ-rays cannot

- High-energy (TeV-PeV) neutrinos could have been detected for on-axis GW170817.

- Relativistic outflow will interact with slower ejecta
  → alter neutrino emission
  → can probe jet structure.

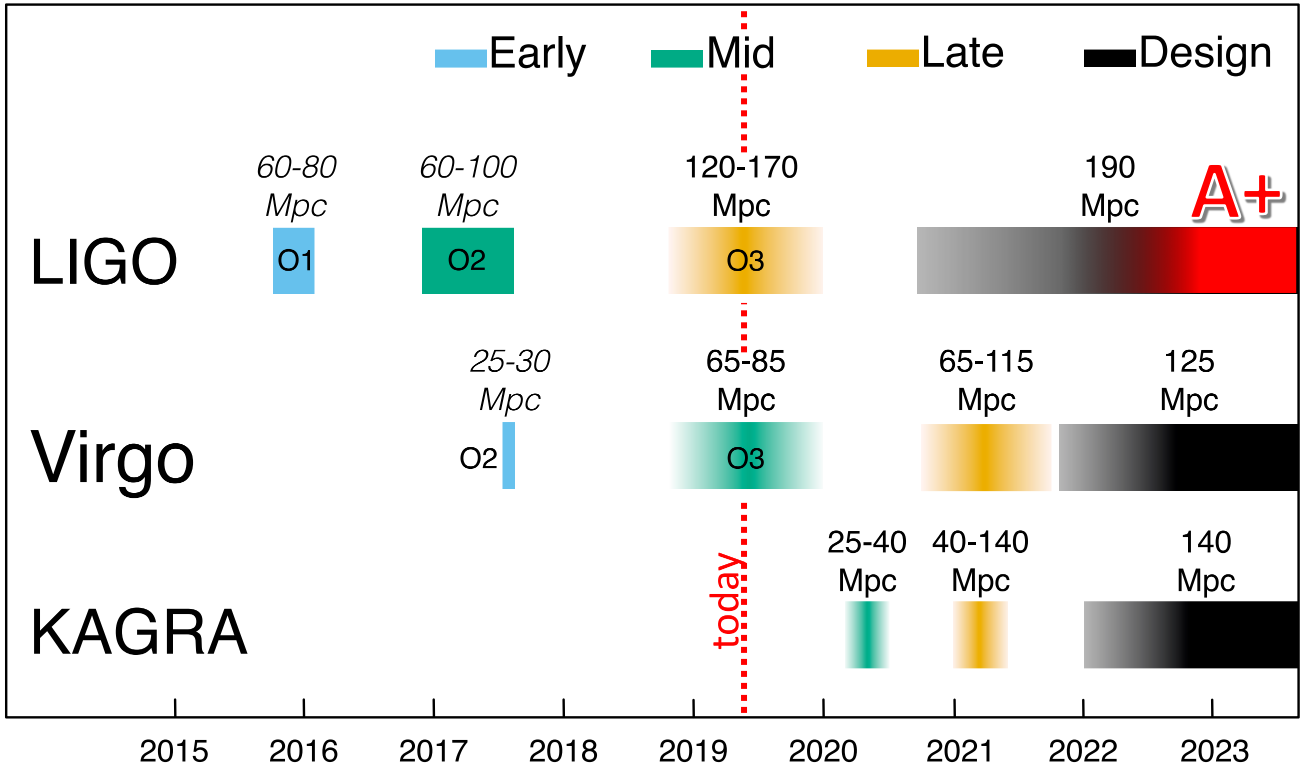


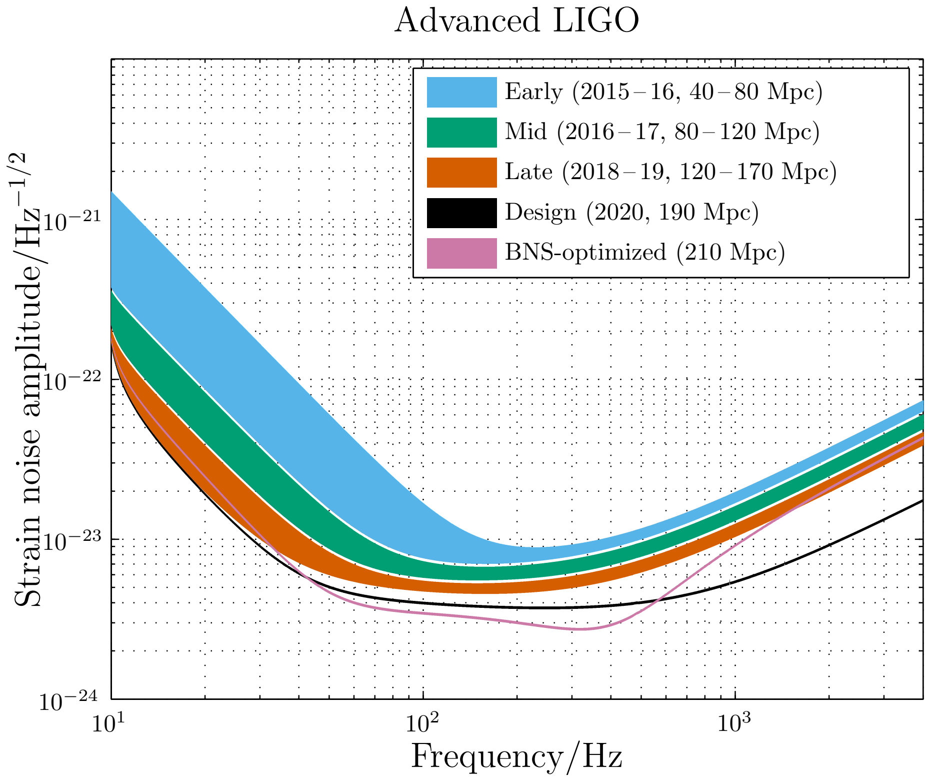
Kimura, Murase, Bartos, Ioka, Heng, Meszaros 2018



ANTARES, IceCube, Pierre Auger, LIGO, Virgo 2017

sensitivity timeline

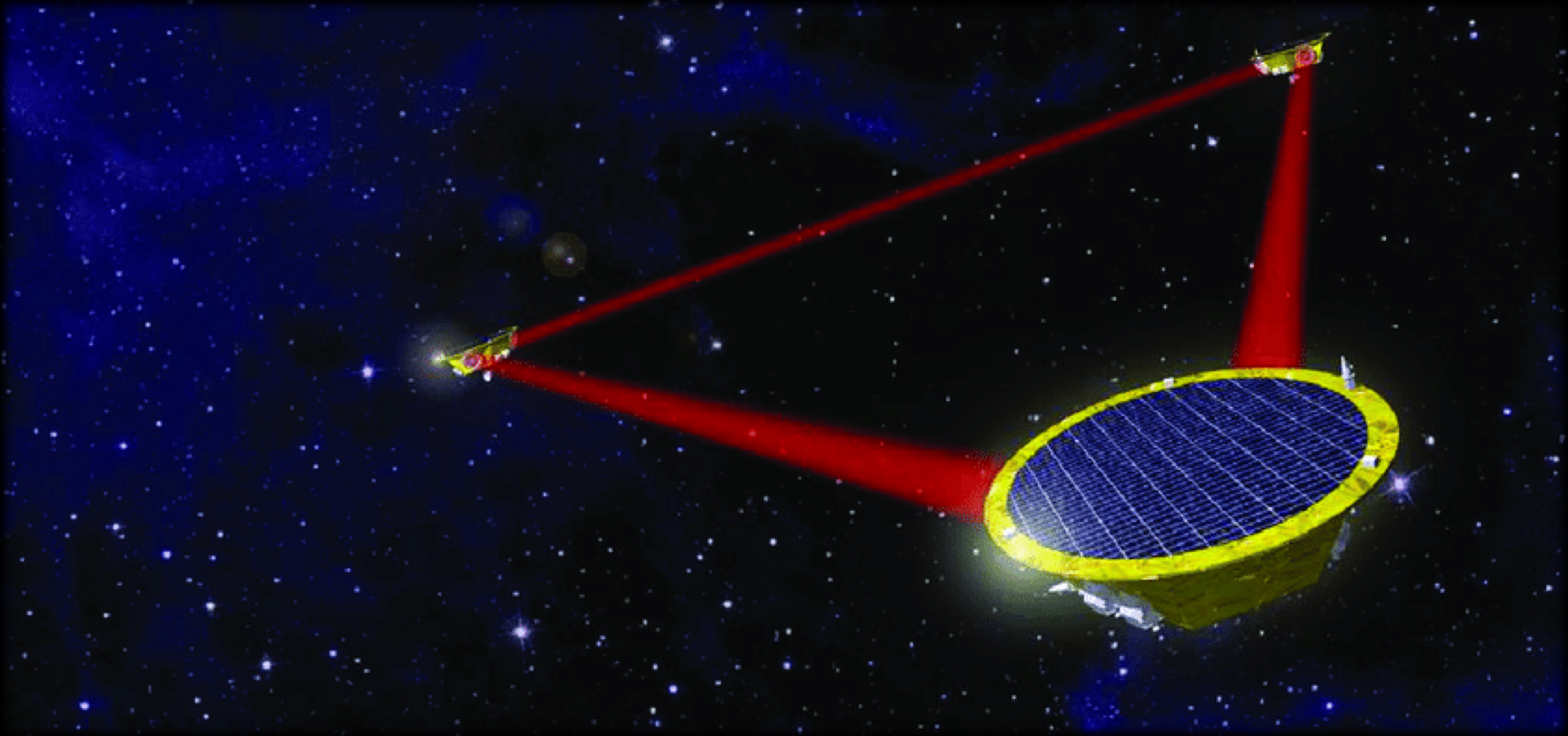




	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40 – 80	415 – 775	20 – 65	220 – 615	8 – 25	80 – 250
Mid	80 – 120	775 – 1110	65 – 85	615 – 790	25 – 40	250 – 405
Late	120 – 170	1110 – 1490	65 – 115	610 – 1030	40 – 140	405 – 1270
Design	190	1640	125	1130	140	1270
A+	325	2600				

KAGRA, LIGO, Virgo 2017, Barsotti+ 2018

- Currently: ~1 BBH / week
  ~1 BNS / month



Summary

- ✓ After many decades of development, gravitational-wave astrophysics finally started in 2016.
- ✓ Gravitational waves opened a new window on the universe---there are many open questions that can now be answered.
- ✓ Growing number of discoveries. The rate of discoveries is rapidly increasing.
- ✓ Multi-messenger astrophysics---we can learn the most about the universe by combining all information available.