# Gravitational Waves and Connections with Fermi


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for the LIGO Scientific Collaboration and Virgo Collaboration


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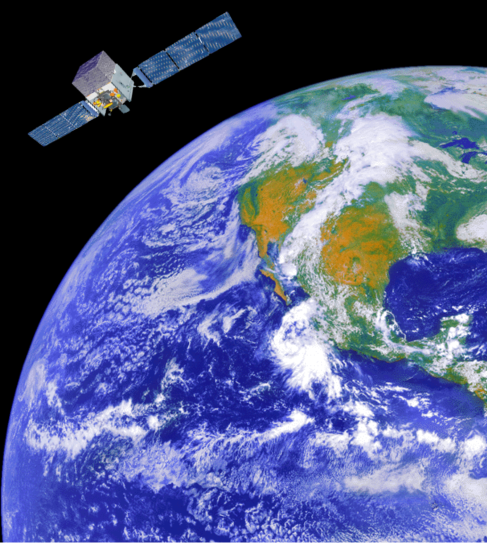
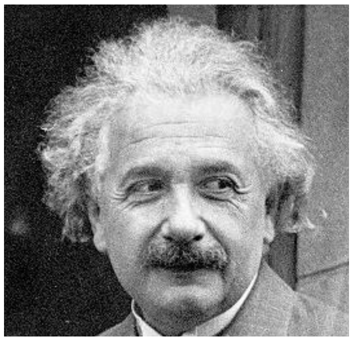


GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

Fermi image: NASA/Sonoma State University/Aurore Simonnet

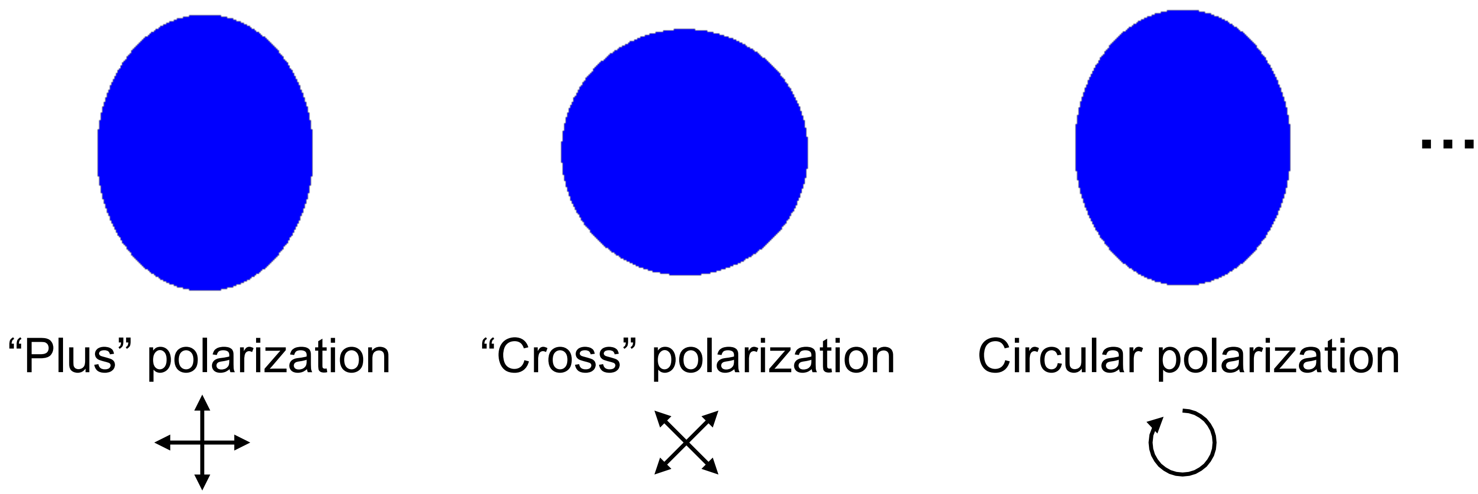
# Gravitational Waves



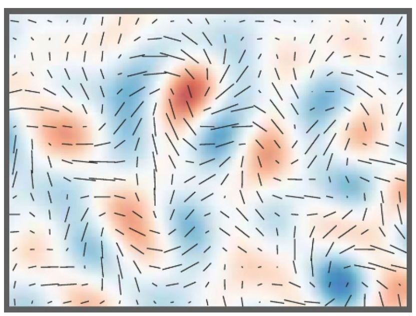
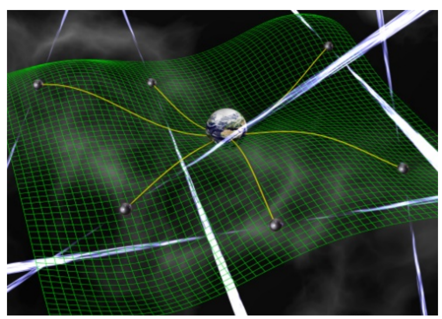
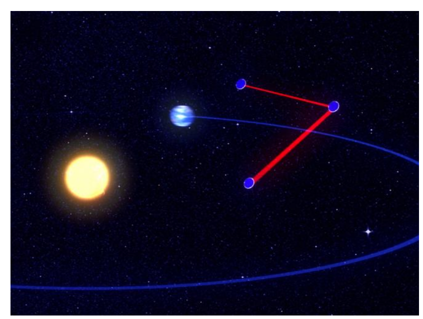
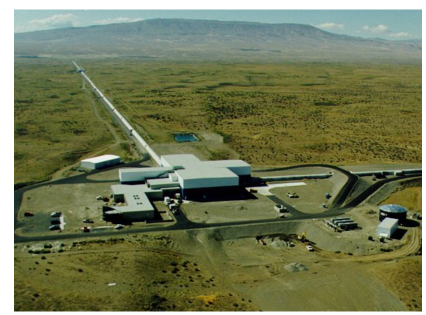
The Einstein field equations have wave solutions !

- Sourced by changing mass quadrupole (or higher) moment
- Waves travel away from the source at the speed of light
- Are variations in the spacetime metric —
  *i.e.*, the effective distance between locally inertial points

**Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and *shrink* space and anything in it**



# The Wide Spectrum of Gravitational Waves

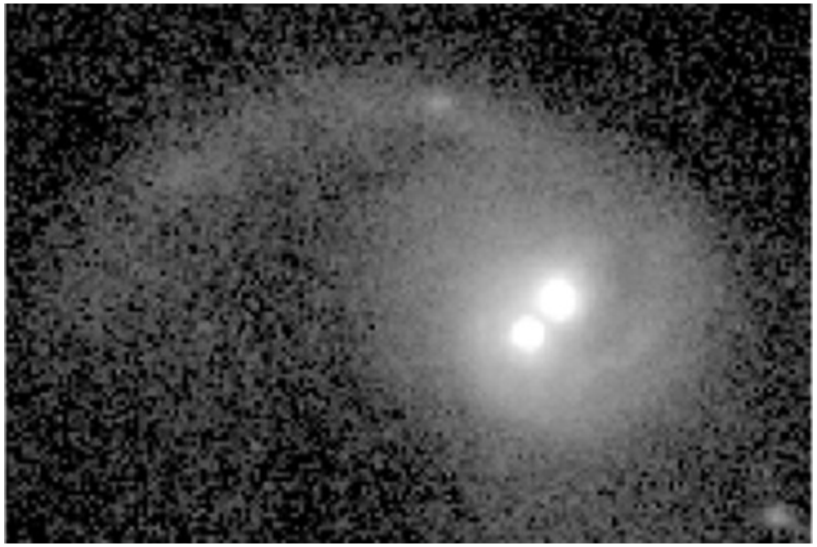
| | $\sim 10^{-17}$ Hz | $\sim 10^{-8}$ Hz | $\sim 10^{-2}$ Hz | $\sim 100$ Hz |
|---|---|---|---|---|
| ***Likely sources*** | **Primordial GWs from inflation** | ***Grav. radiation driven Binary Inspiral + Merger***<br>Supermassive BHs | Massive BHs, extreme mass ratios | Neutron stars, stellar-mass BHs |
| | | | **Ultra-compact Galactic binaries** | **Spinning NSs**<br>**Stellar core collapse** |
| ***Detection method*** | B-mode polarization patterns in cosmic microwave background | Pulsar Timing Array (PTA) campaigns | Interferometry between spacecraft | Ground-based interferometry |
| | <br>BICEP2 | <br>David Champion | <br>AEI/MM/exozet | <br>LIGO Laboratory |
| ***Projects*** | Planck, BICEP/Keck, ABS, POLARBEAR, SPTpol, SPIDER, … | NANOGrav, European PTA, Parkes PTA | eLISA, DECIGO | LIGO, GEO 600, Virgo, KAGRA |

# GW-Fermi Connection: Black Holes

**Fermi AGN studies can shed light on accretion and the environments around supermassive black holes**

Relevant for understanding dynamics which can bring a pair of BHs close enough to inspiral by GW emission – the "final parsec problem" *[e.g. Shannon et al., Science 349, 1522]*

May also impact the population of stellar-mass compact objects available to spiral into the BH *[Merritt et al., PRD 84, 044024]*

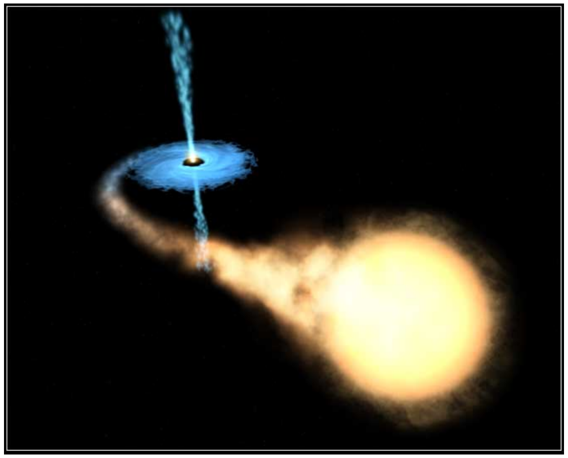

J. Comerford / HST-ACS

**Fermi observations of X-ray binaries contribute to the census of black holes**

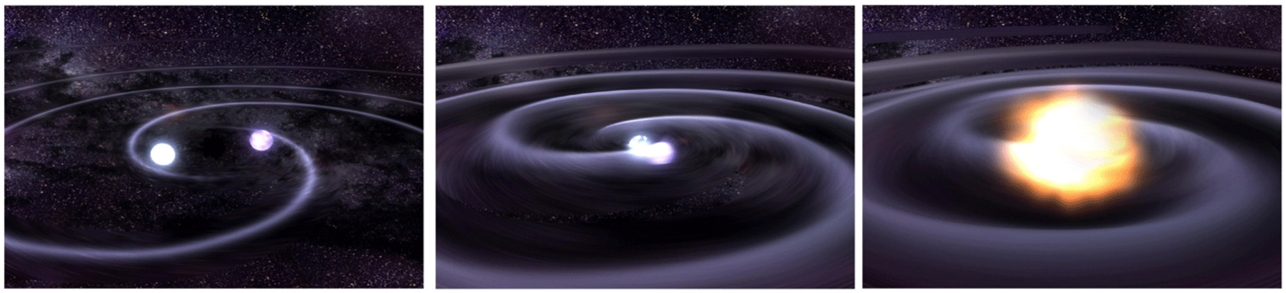
Population, spin history of black holes

HMXB system evolution → future compact binary merger?

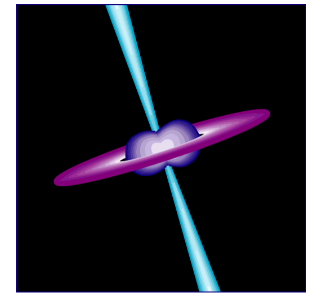
LMXB could be continuous GW source


ESA, NASA, and Felix Mirabel

# GW-Fermi Connection: SGRBs=Mergers?



NASA



P.J.T. Leonard (NASA/GSFC)

**Compact binary mergers are thought to cause most short GRBs**

- Strong evidence from host galaxy types and typical offsets *[Fong & Berger, ApJ 776, 18]*
- Could be NS-NS or NS-BH, with post-merger accretion producing a jet

**Beamed gamma-ray emission → many more mergers than GRBs**

- Some opening angles measured, e.g. $16 \pm 10°$ *[Fong et al., arXiv:1509.02922]*
- Also may get detectable isotropic emission from nearby GRBs, such as infrared "kilonova" peak after several days, *[e.g. Barnes & Kasen, ApJ 775, 18]* seen for GRB 130603B? *[Berger et al., ApJ 765, 121; Tanvir et al., Nature 500, 547]*
- Possible to detect X-ray afterglow from a somewhat off-axis nearby GRB ?

**Exciting possibility to confirm the merger-GRB association!**

# Bonus Features of Mergers+GRBs

**The rate of binary mergers and the beaming angle are uncertain, but the rate of observed SGRBs is known rather well**

Suggests we might detect a handful of joint GW-GRB events per year when LIGO runs at design sensitivity *[Pelassa et al. poster at 4th Fermi Symp]*

**GW emission is stronger along the axis than in the plane of binary**

By a factor of 2 in amplitude

➔ Most favorable for detection when we're in the cone of gamma-ray emission

**If SGRBs are produced by NS-BH mergers, those are detectable out to greater distances than NS-NS**

**Relative arrival time of GW versus gamma rays can test GR**

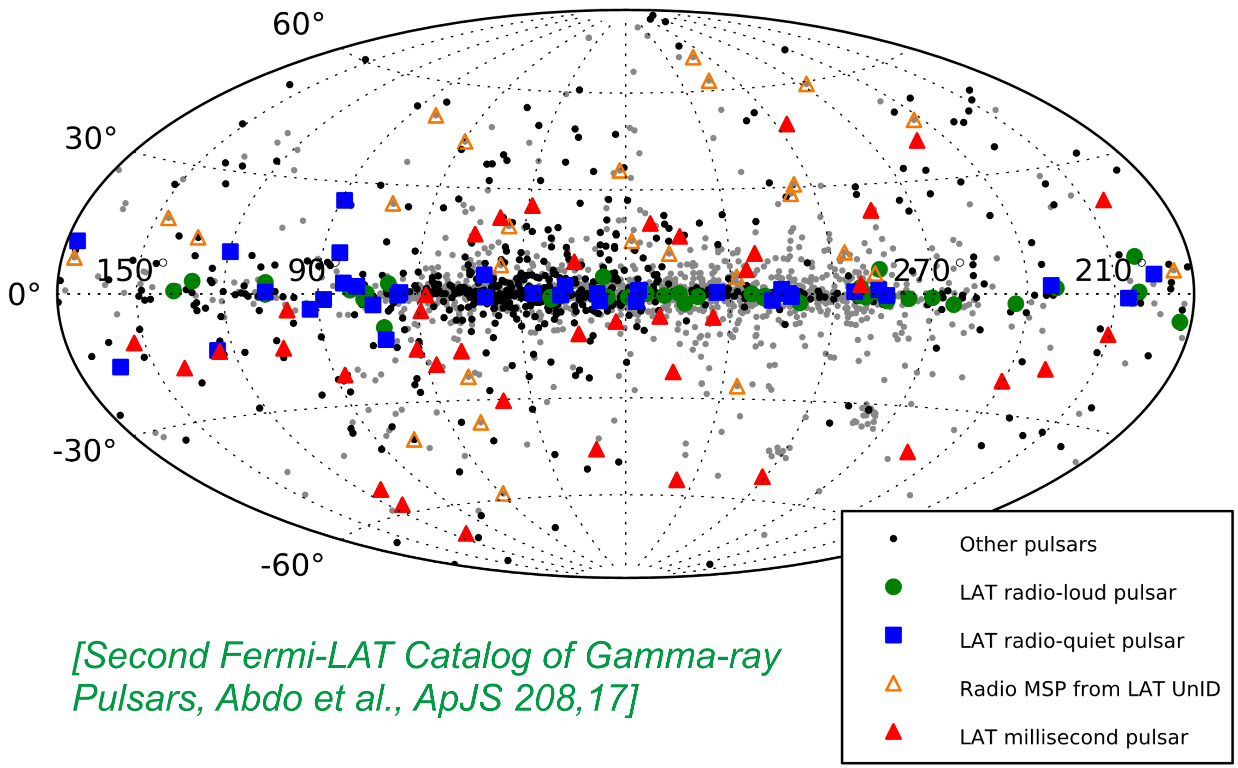
Do GWs travel at exactly the speed of light, or slightly different?

# GW-Fermi Connection: Pulsars

**Additional millisecond pulsars provide more good clocks for Pulsar Timing Array observations**

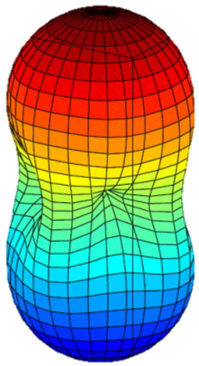
Gain the most from stable pulsars with well-defined pulses

**Short-period binary pulsar systems provide information about the population of compact binaries which merge via GW emission**




*[Second Fermi-LAT Catalog of Gamma-ray Pulsars, Abdo et al., ApJS 208,17]*

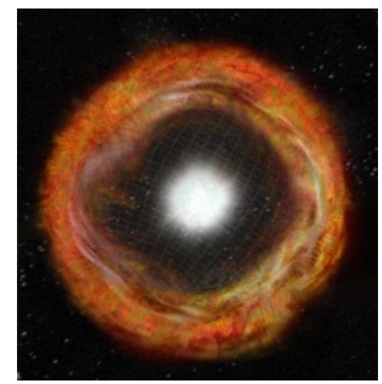
# The Promise and the Challenge



**GW emissions are only weakly beamed, and GW detectors are only weakly directional**

➔ Monitor the whole sky for sources with all inclinations

➔ Not dependent on being within the cone of a jet



Bill Saxton, NRAO/AUI/NSF

**GWs come directly from the central engine**

Not obscured or scattered by material

➔ Complements photon diagnostics of photosphere, outflows, circumburst medium, etc.

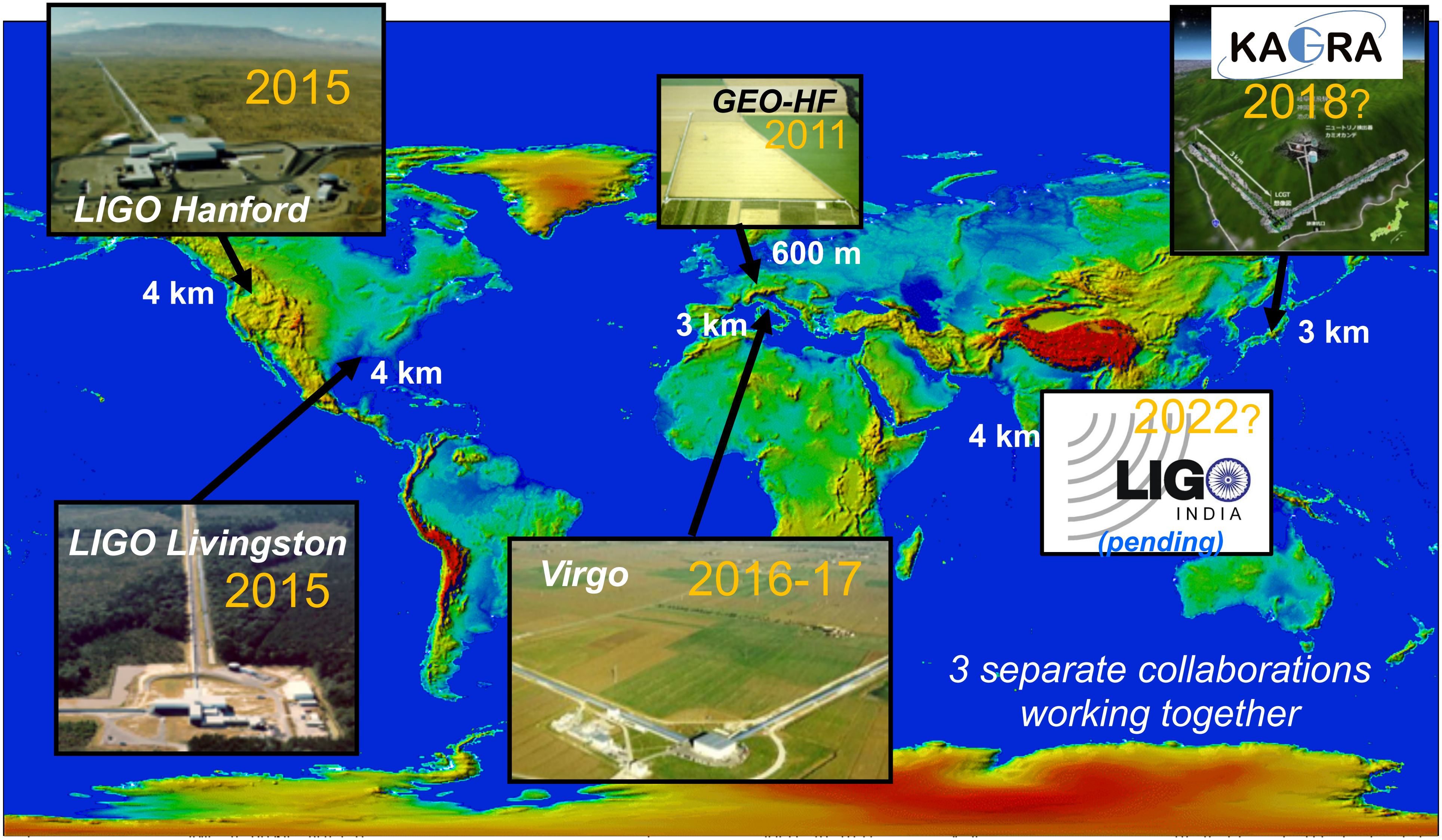
**But, challenging to detect**

Strain amplitude is inversely proportional to distance from source

➔ Have to be able to detect weak signals to search a large volume of space

Typical strain at Earth: $h \sim 10^{-21}$ or even smaller !

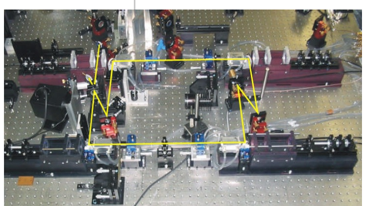
# Advanced GW Detector Network: Under Construction → Operating

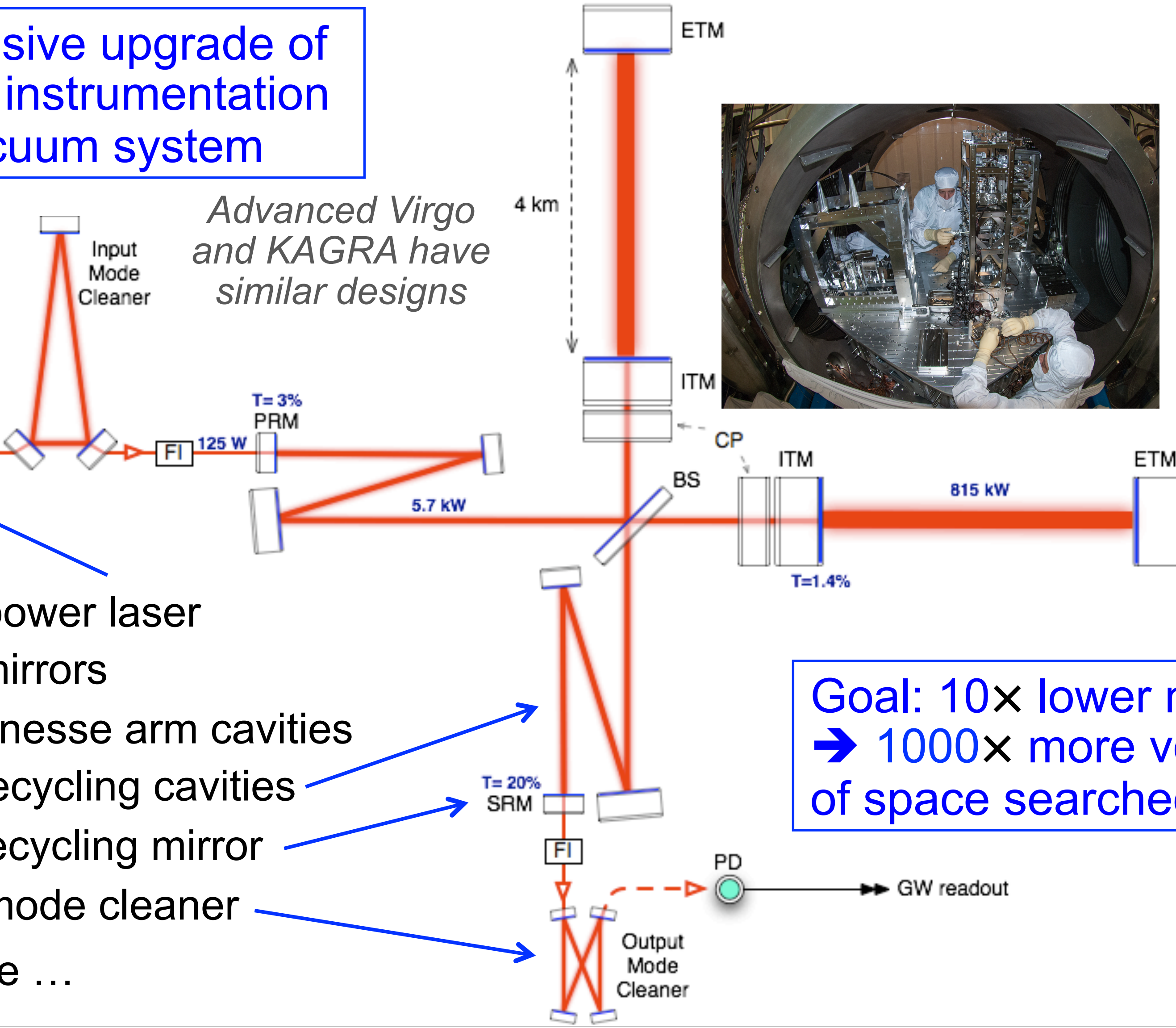


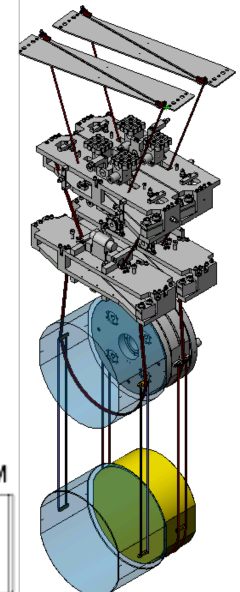
# Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system

*Advanced Virgo and KAGRA have similar designs*





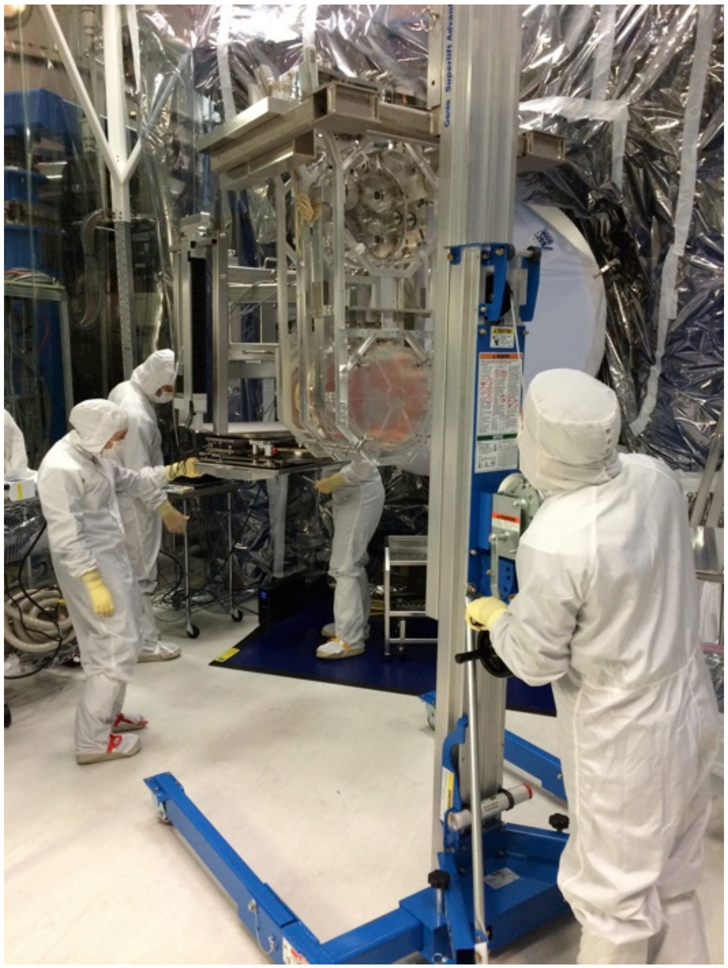
**Improvements**

- Higher-power laser
- Larger mirrors
- Higher finesse arm cavities
- Stable recycling cavities
- Signal recycling mirror
- Output mode cleaner
- and more …

Goal: 10× lower noise ➔ 1000× more volume of space searched

# Advanced LIGO Installation

**Installation went pretty smoothly at both LIGO observatories**



Achieved full interferometer lock in 2014, first at LIGO Livingston, then at LIGO Hanford

Commissioning: lots of work, lots of progress

# Advanced LIGO is Observing Now !

**In August, switched from commissioning work to focus on establishing stable running conditions**

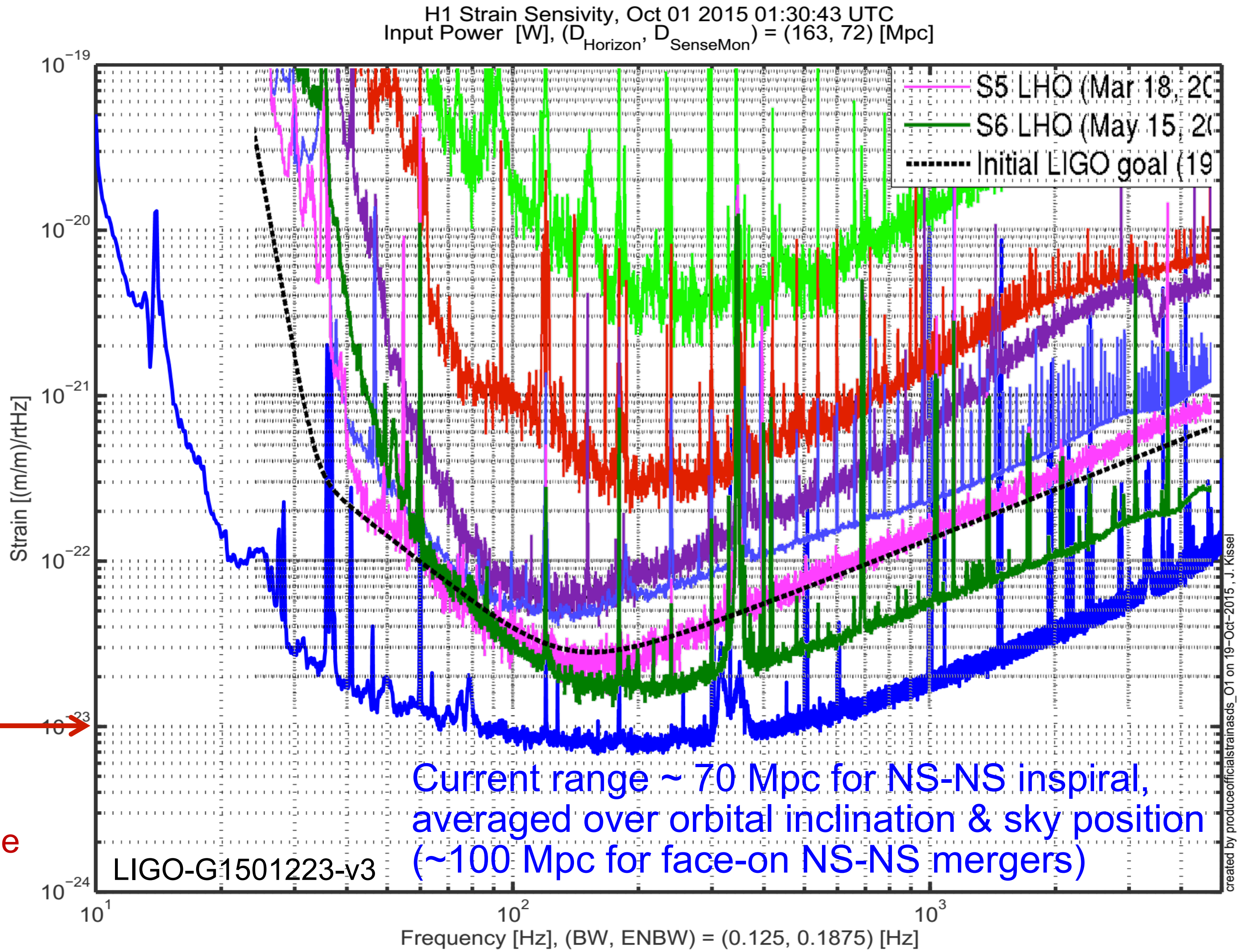
**Calibration studies completed in early September**

**Observing run "O1" officially began on September 18, and is scheduled to end on January 12**

- Both LIGO detectors are observing together ~half of the time

Operational snapshot available at
https://ldas-jobs.ligo.caltech.edu/~gwistat/gwsnap.html

# Current GW Strain Sensitivity




$10^{-23}$ amplitude spectral density!

# LIGO / Virgo Observing Run Schedule

**Projection made in 2013 (arXiv:1304.0670) still seems on target**

Was based on guesses at how fast commissioning would progress

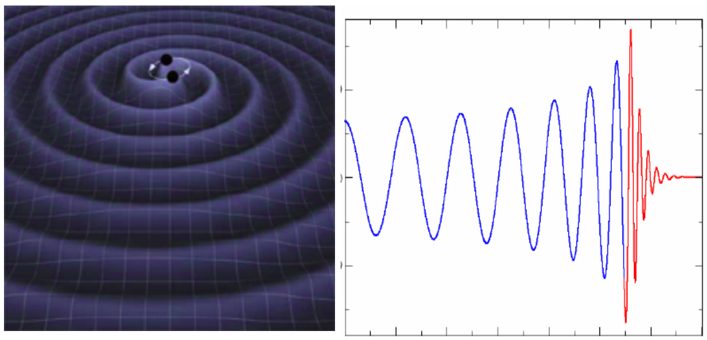
| Epoch | Estimated Run Duration | $E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) | | BNS Range (Mpc) | | Number of BNS Detections |
|---|---|---|---|---|---|---|
| | | LIGO | Virgo | LIGO | Virgo | |
| 2015 | 3 months | 40 – 60 | – | 40 – 80 | – | 0.0004 – 3 |
| 2016–17 | 6 months | 60 – 75 | 20 – 40 | 80 – 120 | 20 – 60 | 0.006 – 20 |
| 2017–18 | 9 months | 75 – 90 | 40 – 50 | 120 – 170 | 60 – 85 | 0.04 – 100 |
| 2019+ | (per year) | 105 | 40 – 70 | 200 | 65 – 130 | 0.2 – 200 |
| 2022+ (India) | (per year) | 105 | 80 | 200 | 130 | 0.4 – 400 |

**Planning for Virgo to join late next year, then KAGRA in a few years**

**Still very uncertain when we'll detect the first GW signal(s)**

Wide range of estimates from observed binary pulsars and population synthesis simulations – begs for observational truth!

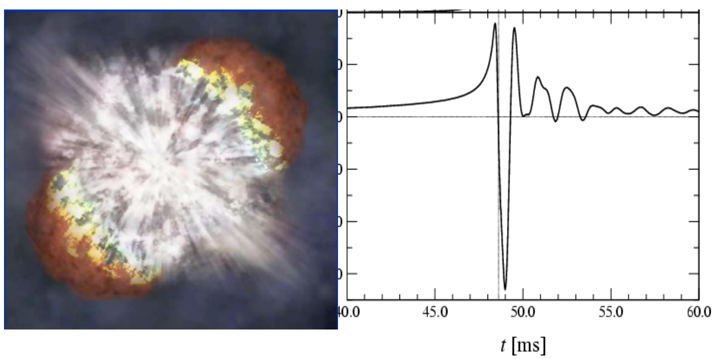
# Searches for GW Transient Sources



## Compact Binary Coalescence (CBC)

Known waveform ➔ Matched filtering

Templates for a range of component masses (spin affects waveforms too, but not so important for initial detection)




## Unmodelled GW Burst (< ~1 sec duration)

e.g. from stellar core collapse

Arbitrary waveform ➔ Excess power

Require coherent signals in detectors, using direction-dependent antenna response

**Low-latency searches run continuously as data is collected**

Whenever two or more detectors are operating normally

With coherent analysis, identify event candidates and generate preliminary sky position probability maps within a few minutes

# Goals for Multi-Messenger Science

**Identify GW event candidates as quickly as possible**

With basic event parameters and an estimate of confidence

**Provide rapid alerts to other observers**

Allow correlation with other transient survey events or candidates *

Trigger follow-up observations (prompt and/or delayed)

**What this can enable:**

Pick out interesting (initially marginal) events from GW and other surveys

Prioritize follow-up observing resources

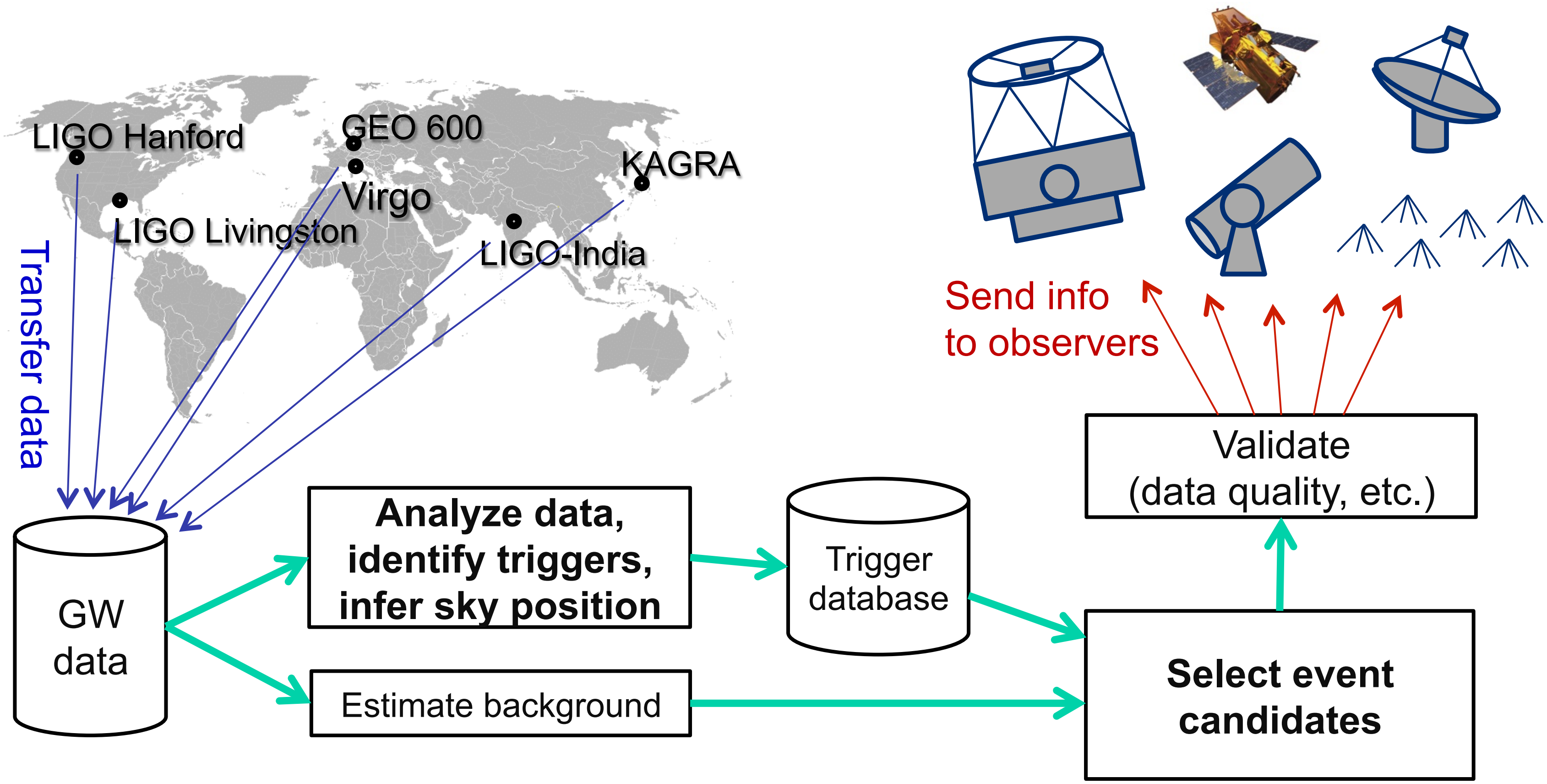
Maybe catch a counterpart that would have been missed, or detected only later

Identify host galaxy ➔ provide astronomical context

Obtain multi-wavelength (and multi-messenger) data for remarkable events

** LIGO/Virgo also monitor GCN and consider other significant transient events, and do deeper GW analysis for notable reported events*

# Generating and Distributing Prompt Alerts




**Challenge: GW reconstructed sky regions are large !**

With just the two LIGO detectors: typically a few hundred square degrees

LIGO+Virgo: typically several tens of square degrees

Will improve with KAGRA and LIGO-India

Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

# Partnerships for Follow-up Observing

**There's a lot to be gained from finding counterparts**

**But confident detection of first few GW signals will require time and care—need to avoid misinformation / rumors / media circus**

➔ **Established a standard MOU framework to share information promptly while maintaining confidentiality for event candidates**

- LIGO/Virgo will need to carefully validate the first few detections, at least
- Once GW detections become routine ($\geq 4$ published), there will be prompt public alerts of *high-confidence* detections

**LIGO & Virgo have signed MOUs with ~70 groups so far!**

- Broad spectrum of transient astronomy researchers and instruments
- Optical, Radio, X-ray, gamma-ray, VHE **– including a team from Fermi**
- Special LVC GCN Notices and Circulars with distribution limited to partners

**Encourage free communication among all "inside the bubble" for multiwavelength follow-up**

# Summary

Gravitational waves are being sought in various frequency bands

- Direct detection will be a major milestone
- Will enable astronomical investigations as well as fundamental physics

There are multiple connections between Fermi and GW science

- Black holes, compact binary mergers → SGRBs (we think), pulsars

Advanced LIGO is observing now!

- With good sensitivity – more than 3 times the distance reach of initial LIGO

Ready for multi-messenger astronomy

- GW signature complements photon diagnostics of outflows, circumburst medium, astronomical context
- Low-latency event candidates are now being identified and shared with partner groups, including Fermi project team