Catching the next wave

Gamma-ray counterparts to O3 gravitational-wave events with Fermi-GBM and Swift-BAT

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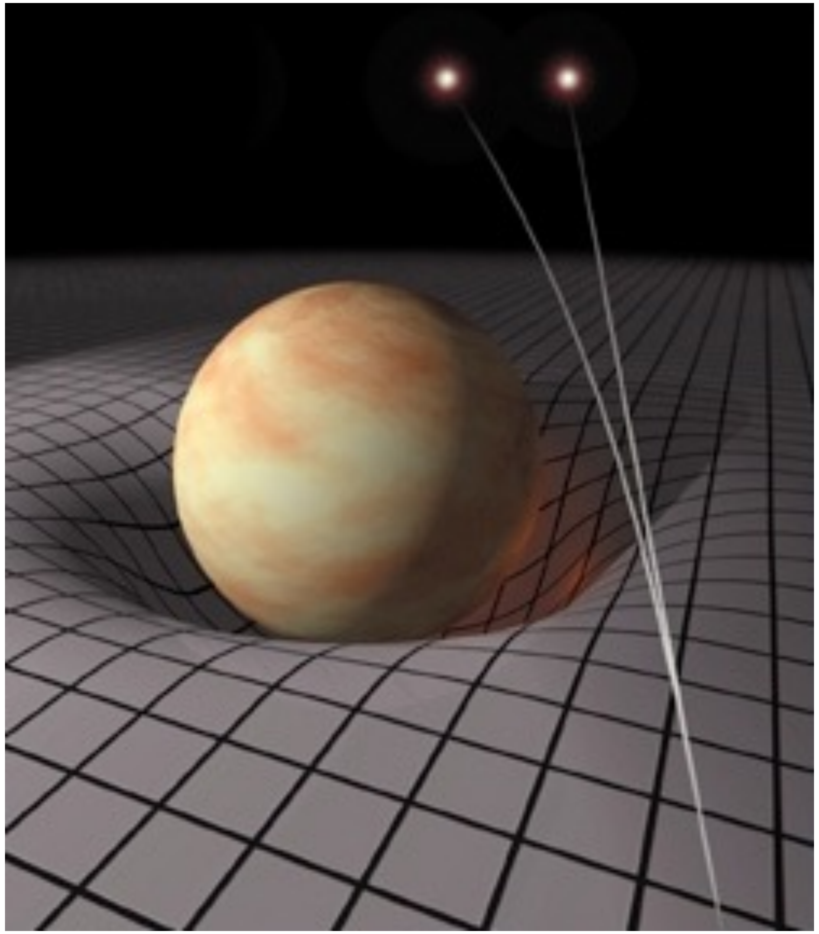
Image: Neutron Star Merger Seen in Gravity and Matter. Credit: Karan Jani/Georgia Tech

Talk outline

- What, why, where, and how: *gravitational waves*
- *Swift* BAT Analysis
- *Fermi* GBM Analysis
- Combining the results
- Binary black-hole systems: what can we learn?
- Conclusions & future projects

GENERAL RELATIVITY 101

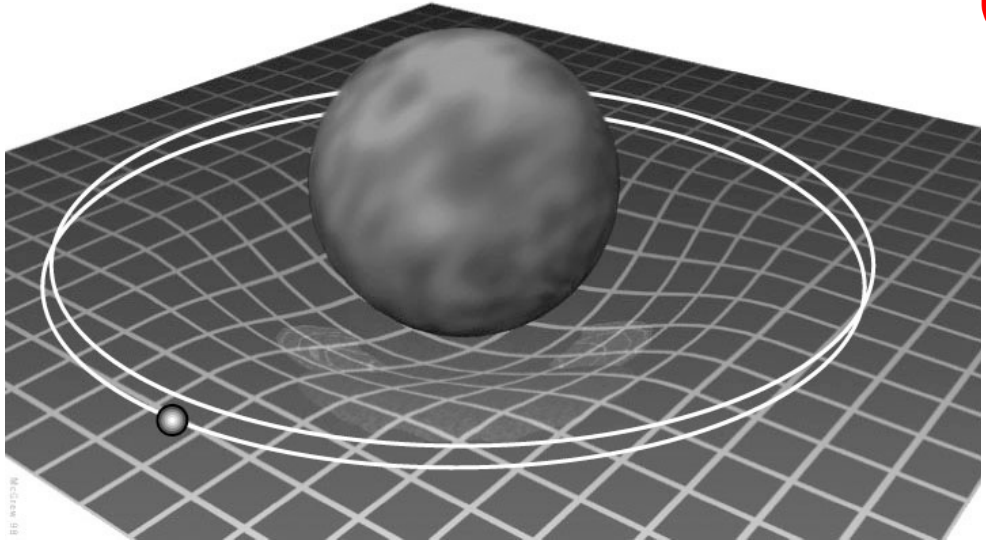


Gravitational lensing

Space tells matter how to move.

Matter tells space how to curve.

– John A. Wheeler



Precession of Mercury

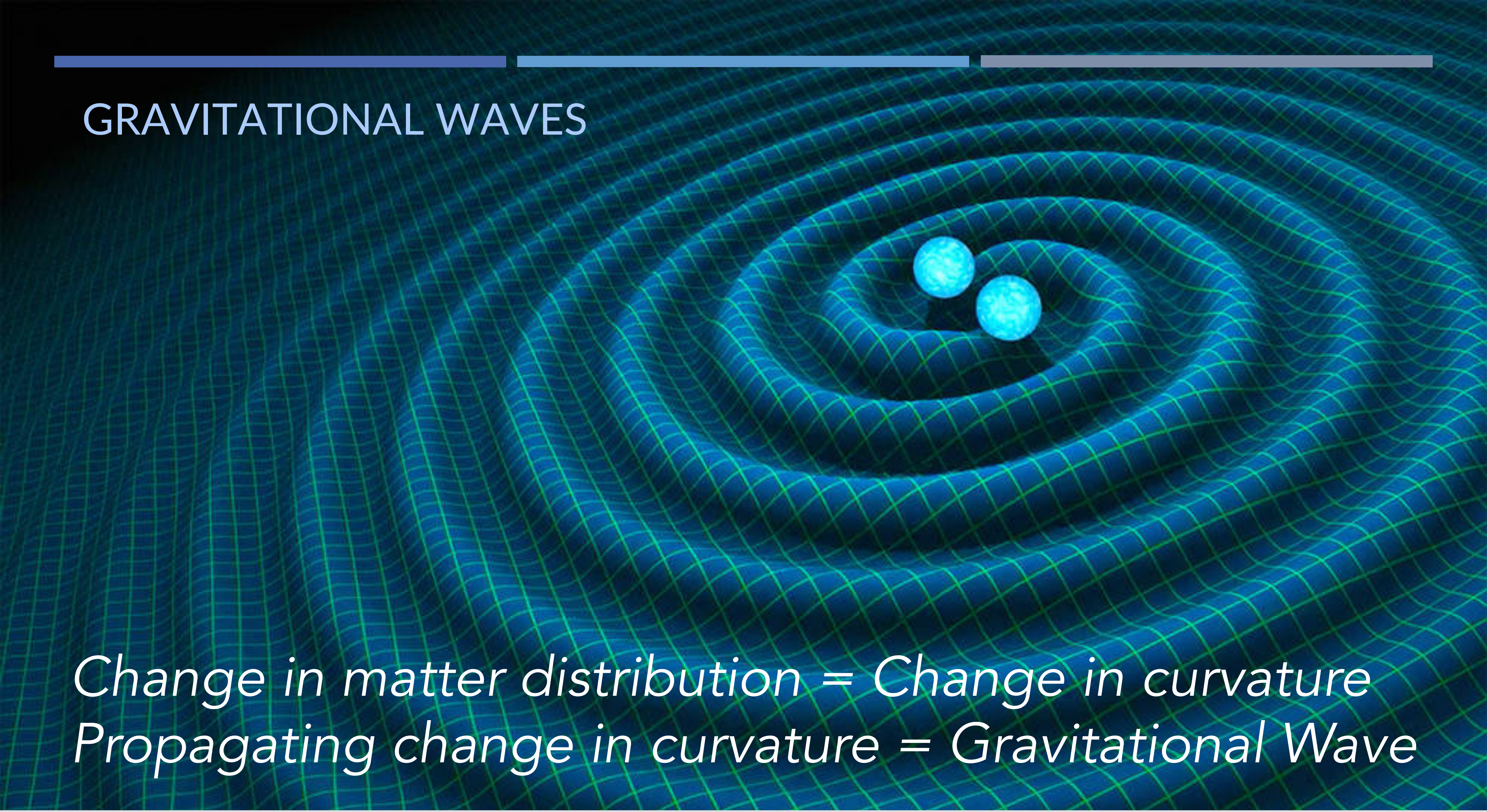
$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

Spacetime curvature

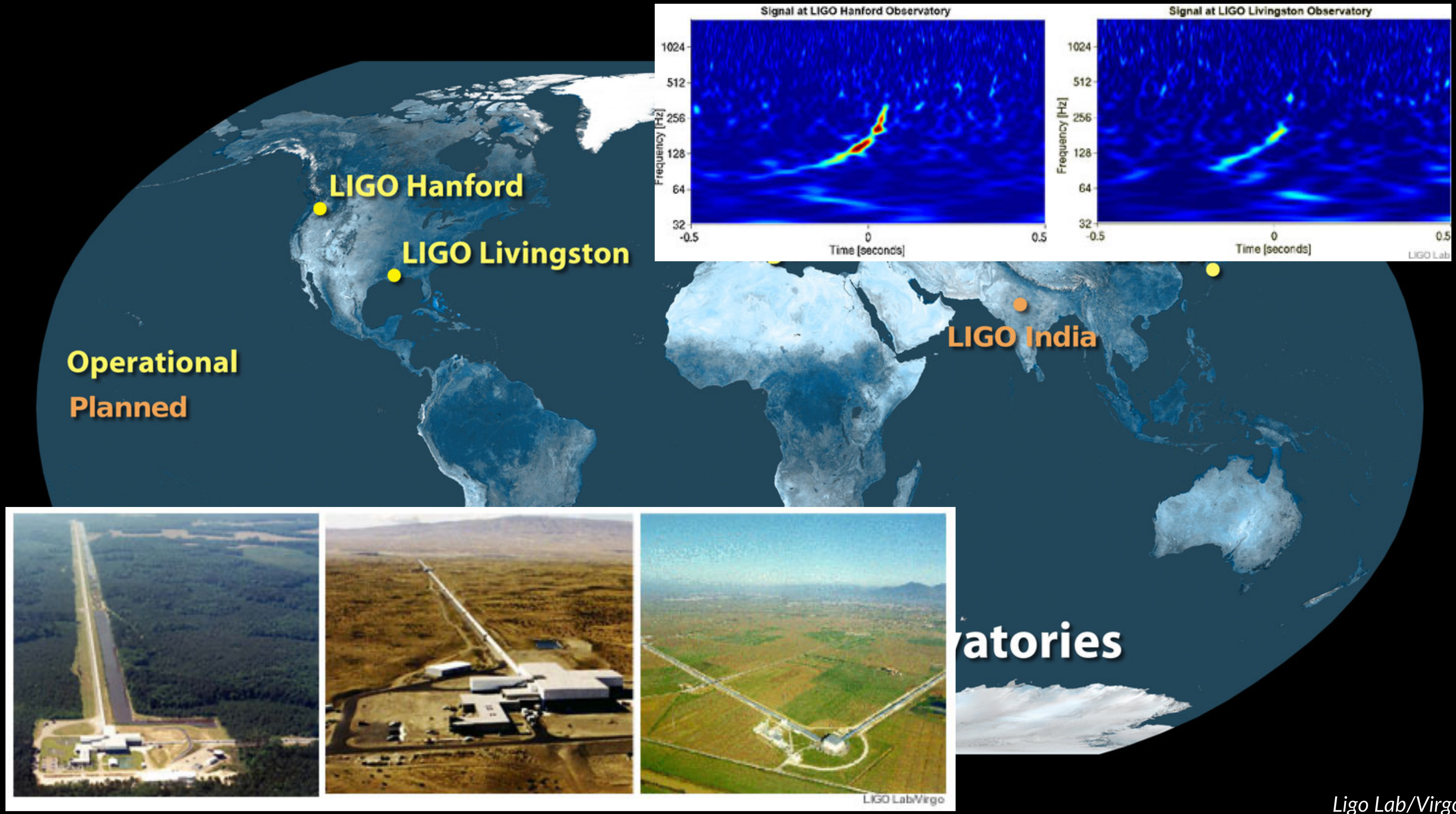
Matter (and energy)

http://preposterousuniverse.com/spacetimeandgeometry/covercrop.jpg
http://zebu.uoregon.edu/ph121/hb/amy/merc.jpg

GRAVITATIONAL WAVES

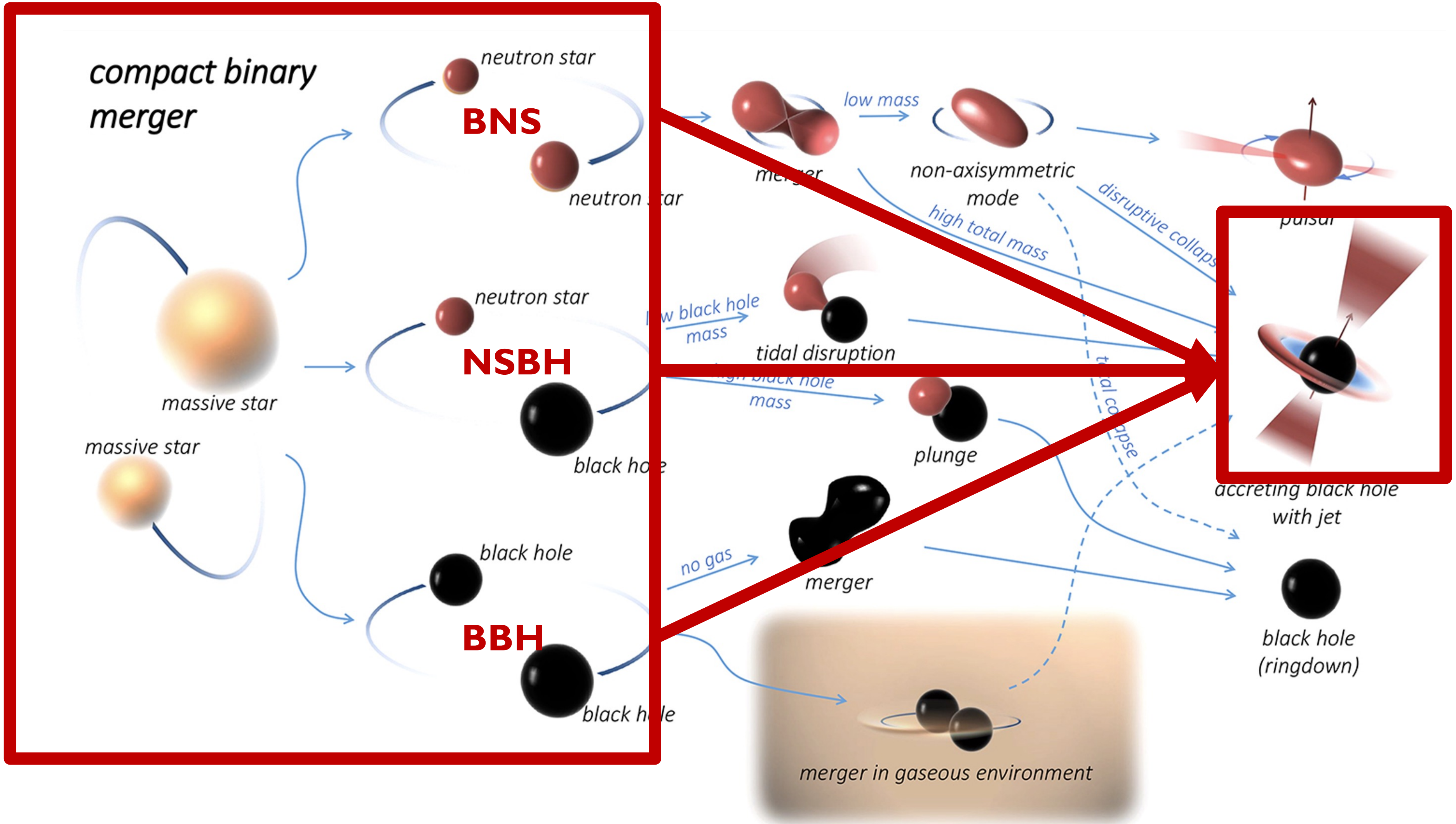


Change in matter distribution = Change in curvature
Propagating change in curvature = Gravitational Wave

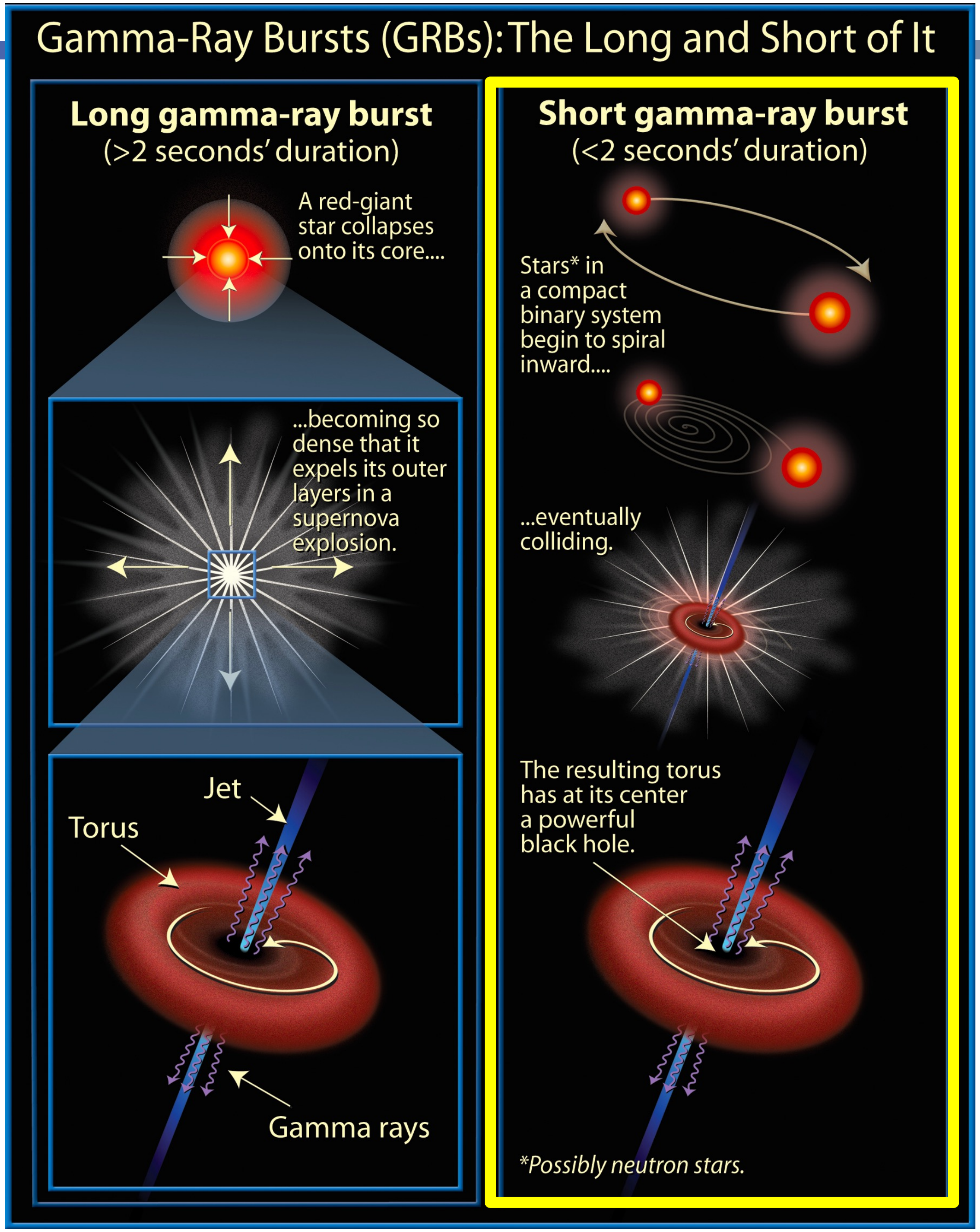


Ligo Lab/Virgo

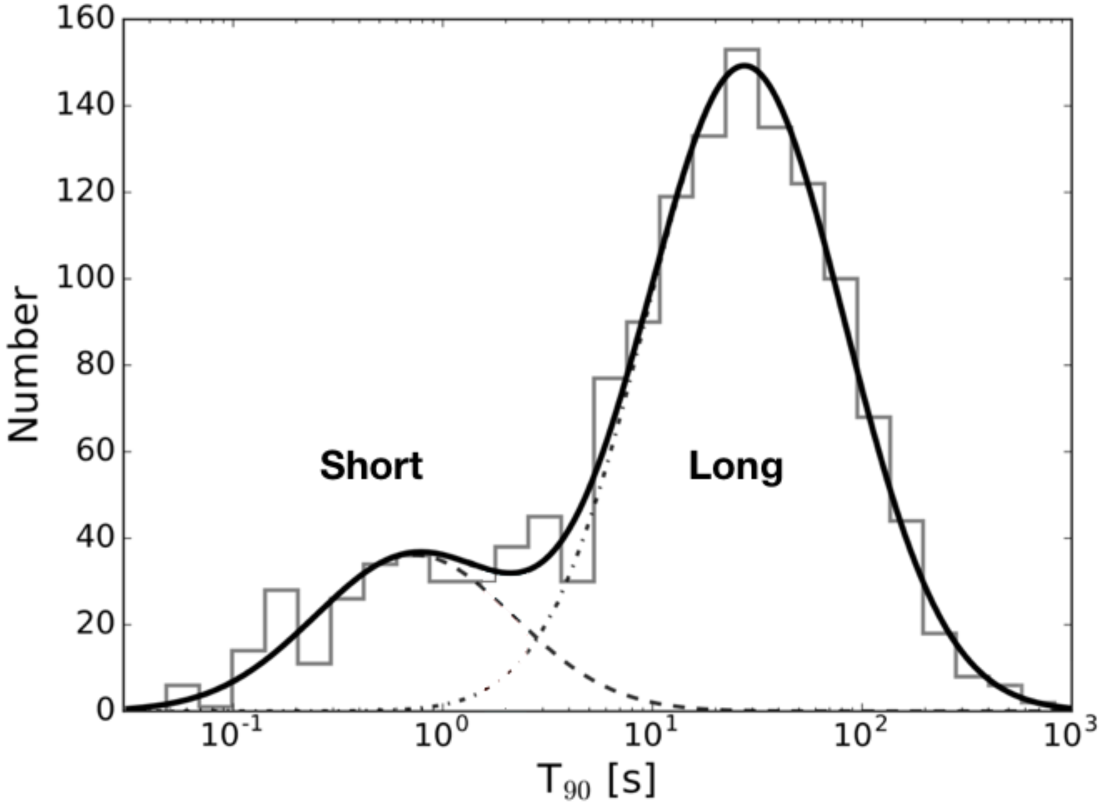
WHERE TO SEARCH FOR GWs: COMPACT BINARY MERGERS

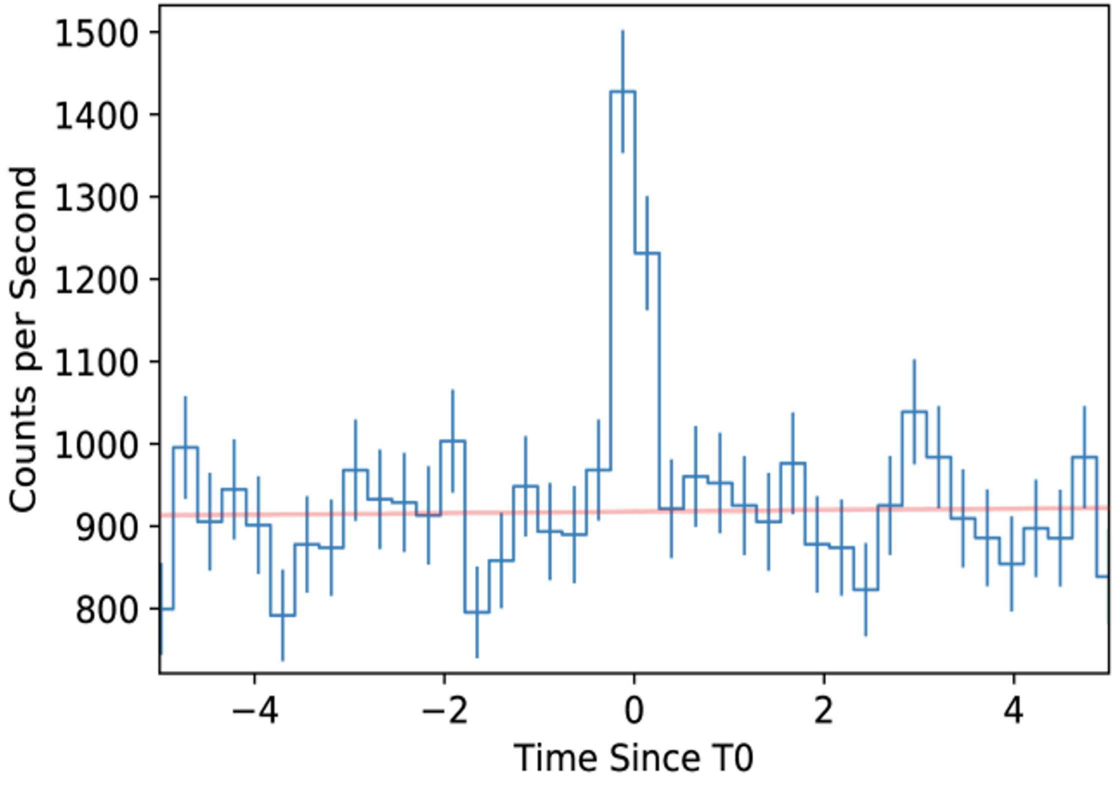


Bartos & Kowalski, 2017


Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

SHORT GAMMA-RAY BURSTS





Goldstein, A., et al., ApJL ***848*** *(2), L14 2017.*

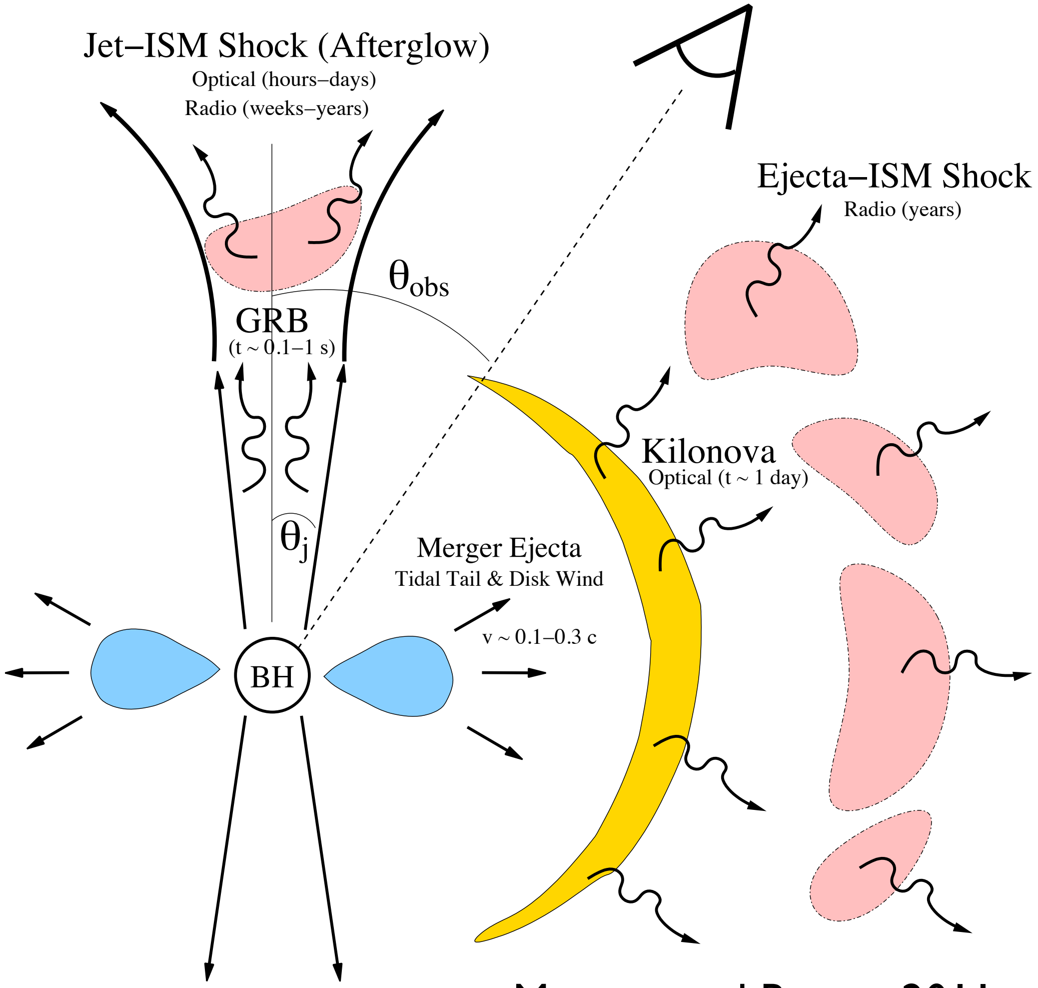
SHORT GRBs AND GWs

GW:

- Confirms the compact-binary-coalescence progenitor model
- Information about binary system parameters
- Merger time
- Luminosity distance

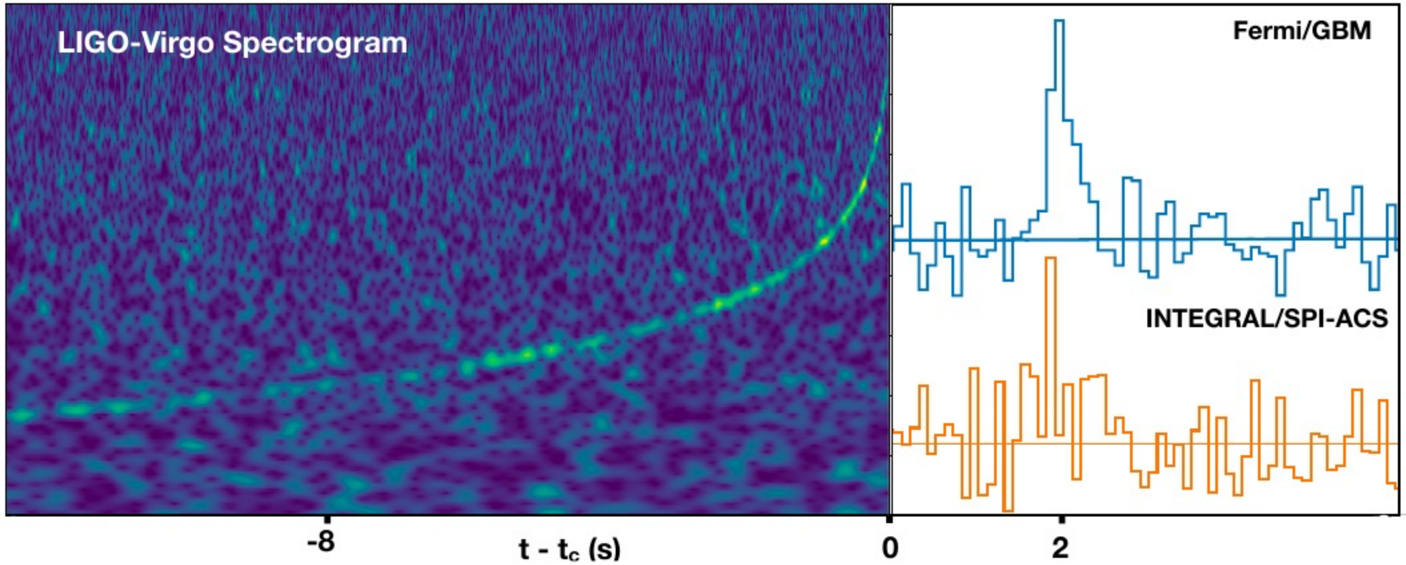
EM

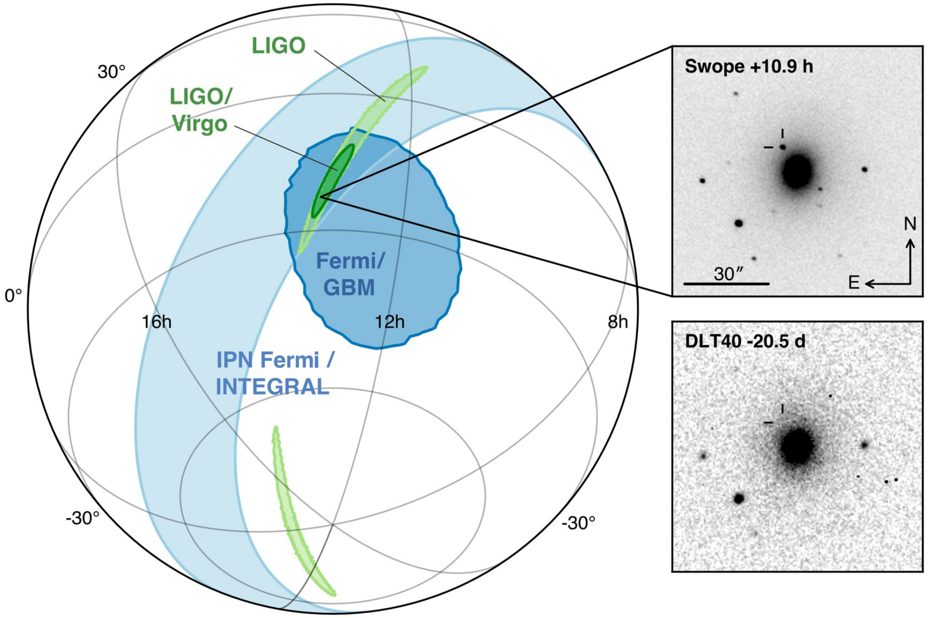
- Detection confidence
- EM emission processes
- X-ray or optical afterglow gives precise location
- Host galaxy/redshift
- Local environment information



Metzger and Berger, 2011

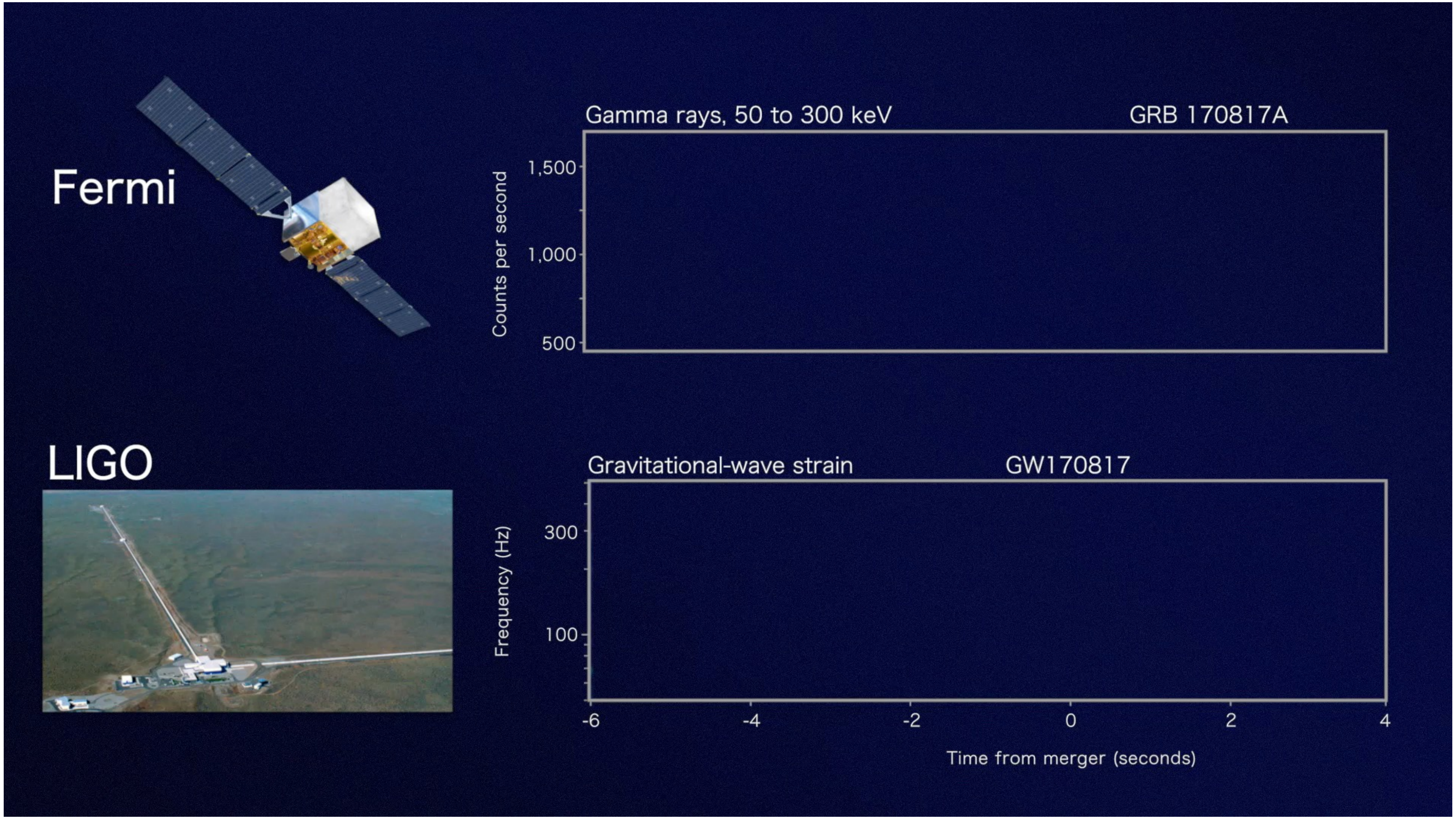
GW 170817 & GRB 170817A





GW170817
[Abbott et al., 2017c]
GRB 170817A
[Goldstein et al., 2017,
Abbott et al., 2017b]

SSS17a
EM170817…
AT 2017gfo
[Abbott et al., 2017d]


Fermi
LIGO
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

LIGO Lab

GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds
A gamma ray burst is detected.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.

+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

+11 hours 36 minutes
Infrared emission observed.

+15 hours
Bright ultraviolet emission

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

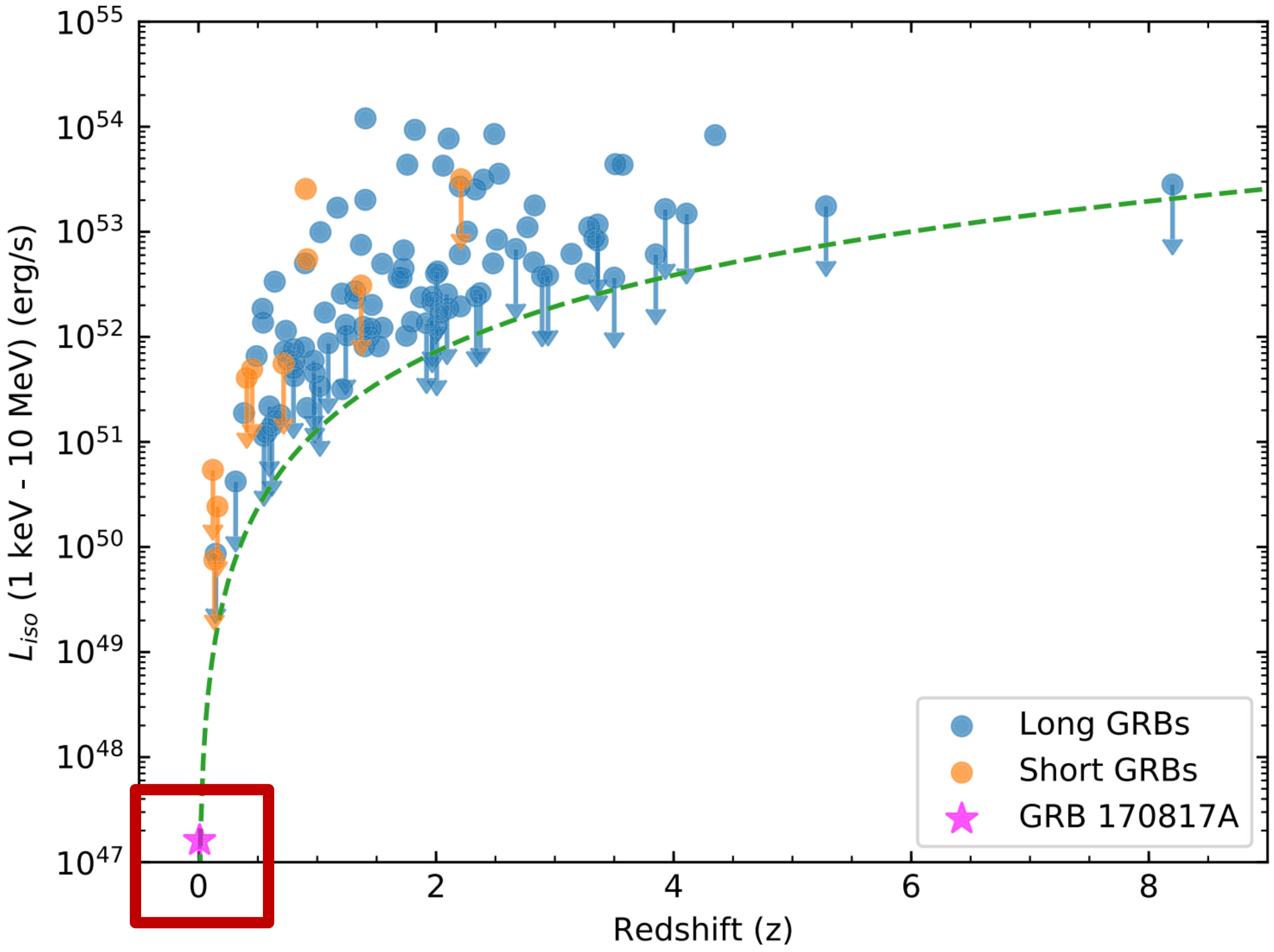
radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

+9 days
X-ray emission detected.

The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of most of the heavy elements, like gold, in the universe.

+16 days
Radio emission detected.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.



B. P. Abbott *et al* 2017 *ApJL* **848** L13

Intrinsically dim and but nearby (40 Mpc)

Off-axis viewing angle

GW170817 & GRB 170817A: THE STORY IT TOLD

Astrophysics:

- Origin of heavy nuclei
- BNS physical system dynamics and the physics of kilanovae
- Jets and post-merger remnants
- Neutron-star equation of state
- Cosmology: speed of gravity, Hubble constant

Multimessenger Astronomy:

- Follow-up operations
- Setting up for the following observing run (O3)
- Renewed interest in multimessenger astronomy

GW170817 & GRB 170817A: WHAT'S LEFT TO UNDERSTAND?

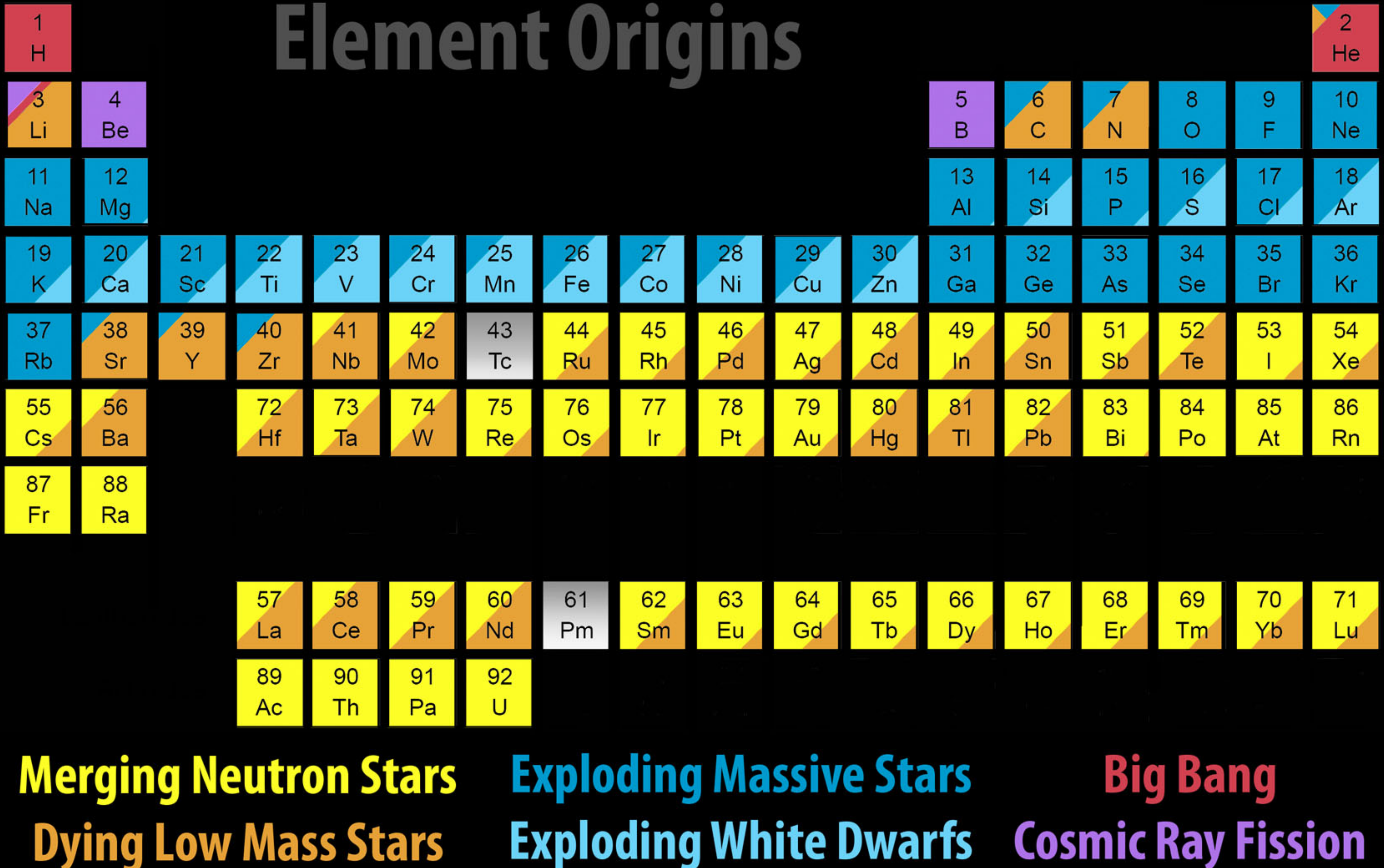
Astrophysics:

- Origin of heavy nuclei: **are BNS merger rates enough to account for the element abundance?**
- BNS physical system dynamics and the physics of kilanovae: **high-energy particle accelerators?**
- Jets and post-merger remnants: **jet physics?**
- Neutron-star equation of state: **?**
- Cosmology: speed of gravity, Hubble constant: **more independent measurements**

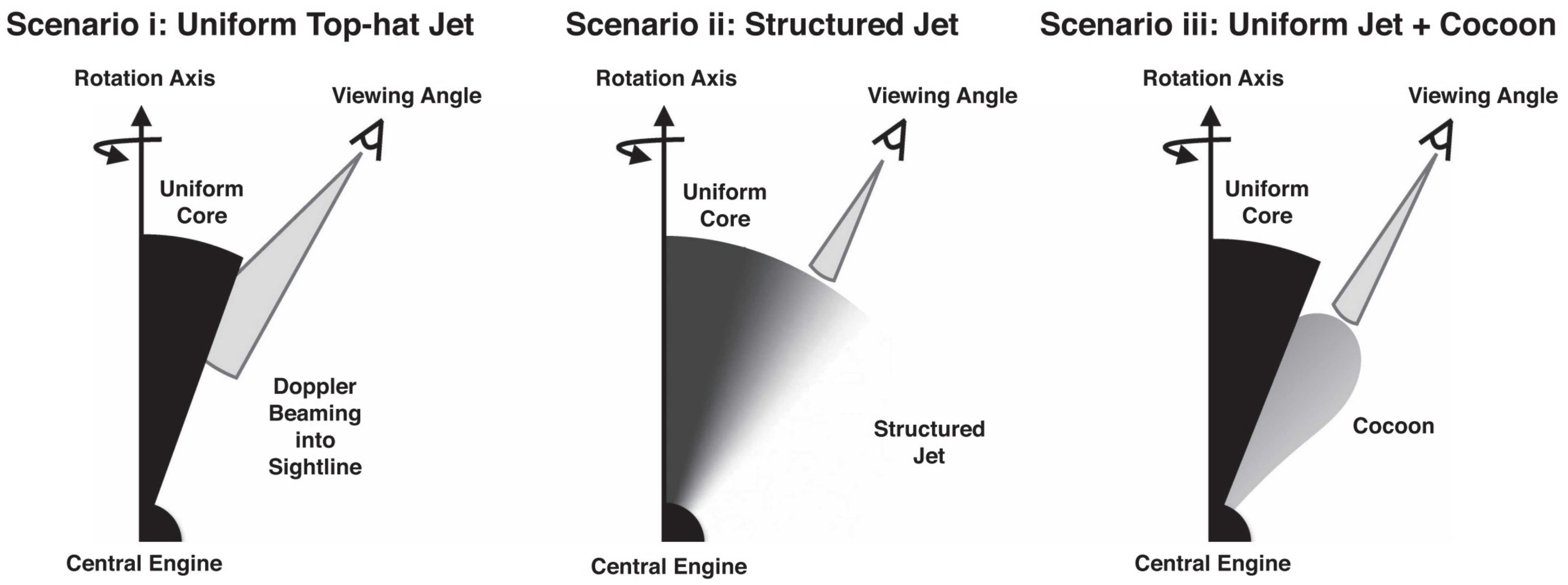
Multimessenger Astronomy:

- Follow-up operations
- Setting up for the next observing runs (O4, O5)
- Renewed interest in multimessenger astronomy

Element Origins



Based on graphic created by Jennifer Johnson

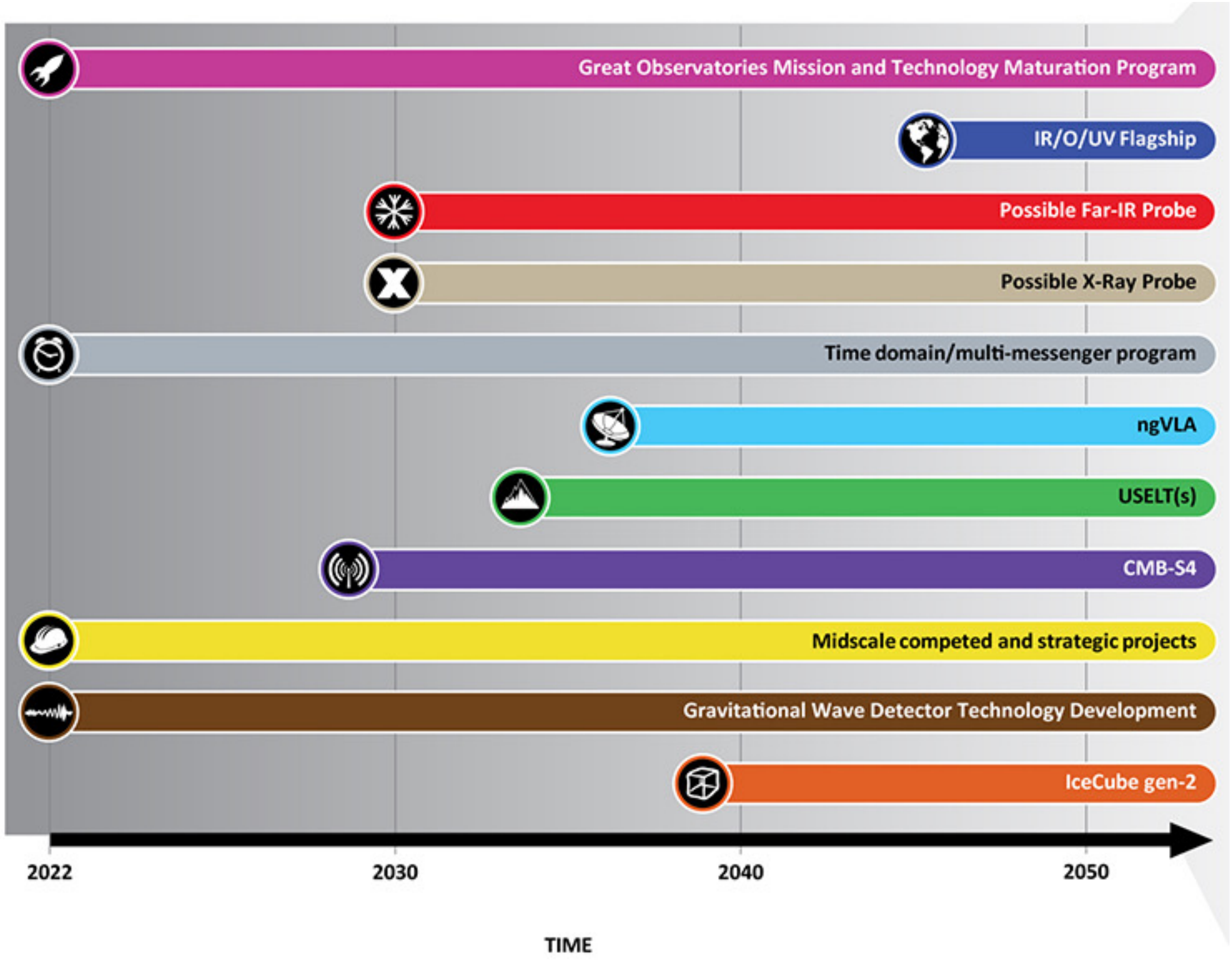

Scenario i: Uniform Top-hat Jet
Rotation Axis
Viewing Angle
Uniform Core
Doppler Beaming into Sightline
Central Engine
Scenario ii: Structured Jet
Rotation Axis
Viewing Angle
Uniform Core
Structured Jet
Central Engine
Scenario iii: Uniform Jet + Cocoon
Rotation Axis
Viewing Angle
Uniform Core
Cocoon
Central Engine

RENEWED INTEREST IN MULTIMESSENGER ASTRONOMY

What have we seen so far?

- TXS 0506+056
- Solar physics
- SN1987A
- BNS 170817

Other maybes: GW150914, GBM-190816, GW190521…



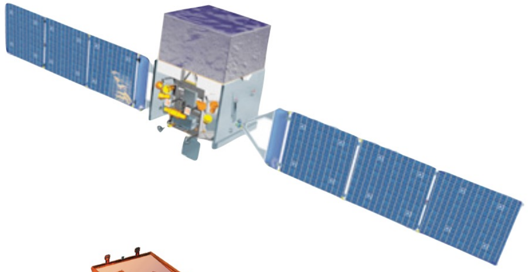
Decadal Survey 2020

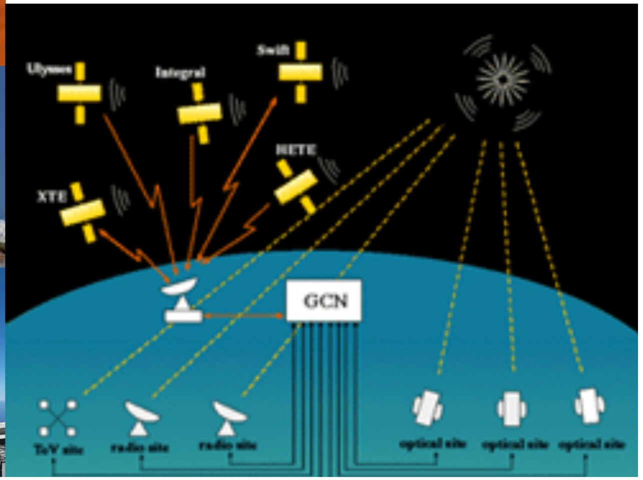
MOTIVATION FOR OUR PROJECT: more measurements!

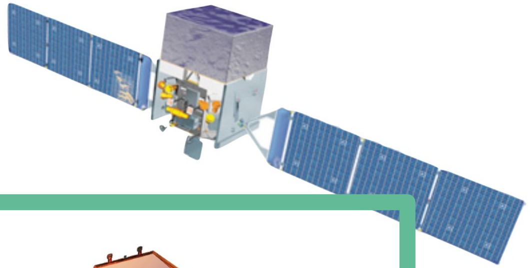
- Since the coincident detection of gravitational waves from a binary neutron-star merger, (GW170817), and the corresponding short gamma-ray burst (GRB170817A), ***detecting an analogous event has been a critical research topic in the multimessenger community***
- The Third Gravitational Wave Transient Catalog (GWTC-3) provided an **8-fold increase** in the number of *likely-astrophysical* GW events

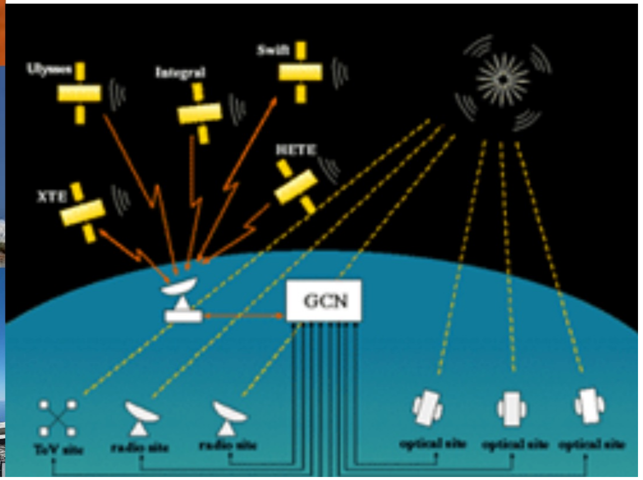
GOALS

1. **Identify potential electromagnetic (EM) counterparts to GW triggers in GWTC-3 using data from the *Fermi* Gamma-ray Burst Monitor (GBM) and the *Swift* Burst Alert Telescope (BAT)**
2. **Constrain theoretical models for γ-ray emission from GW events**




Ulysses
Integral
Swift
HETE
XTE
GCN
TeV site
radio site
radio site
optical site
optical site
optical site




Ulysses
Integral
Swift
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TeV site
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optical site
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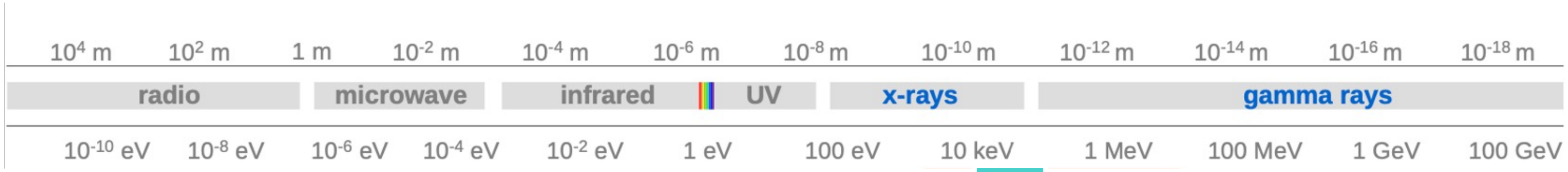
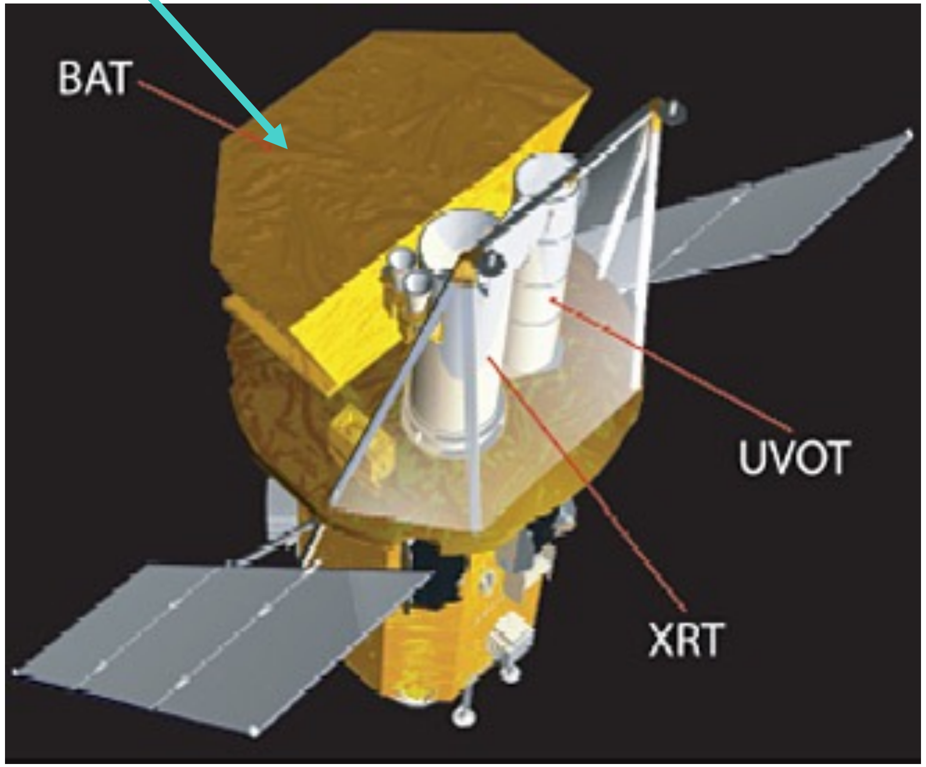
optical site

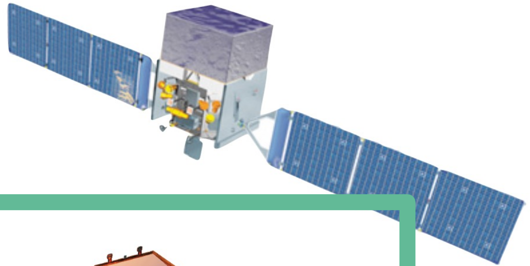
SWIFT BURST ALERT TELESCOPE (BAT)

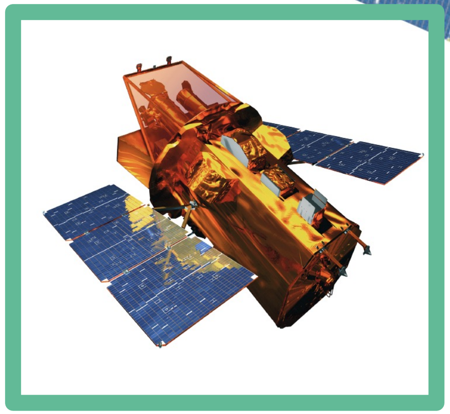


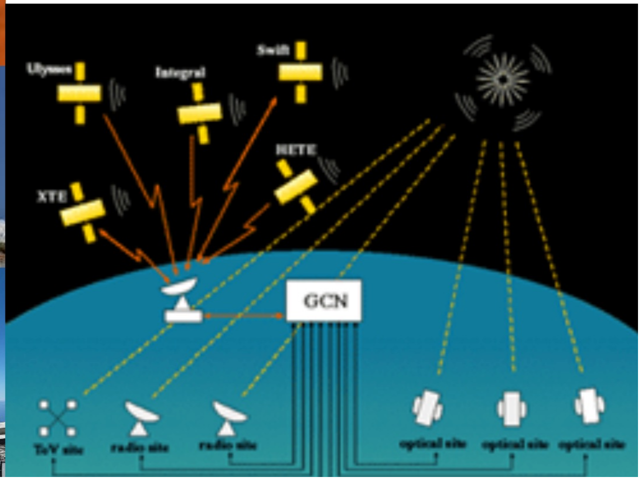


BAT Burst Alert Telescope

- One of three instruments onboard
- FoV: ~ 2 sr
- Localization ~few arcmin
- 15 keV to 150 keV
- On-board triggers + ground processing






Ulysses
Integral
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HETE
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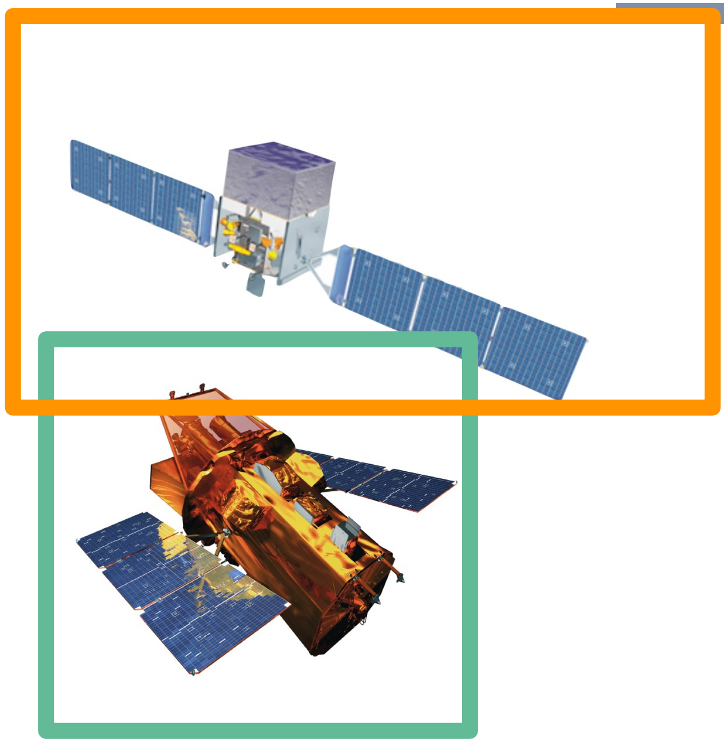
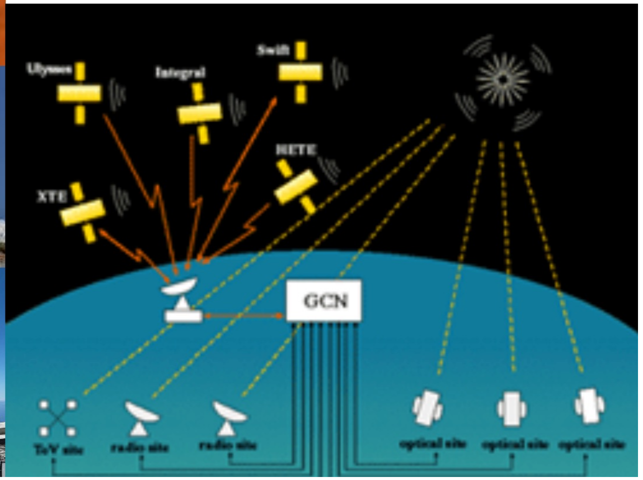
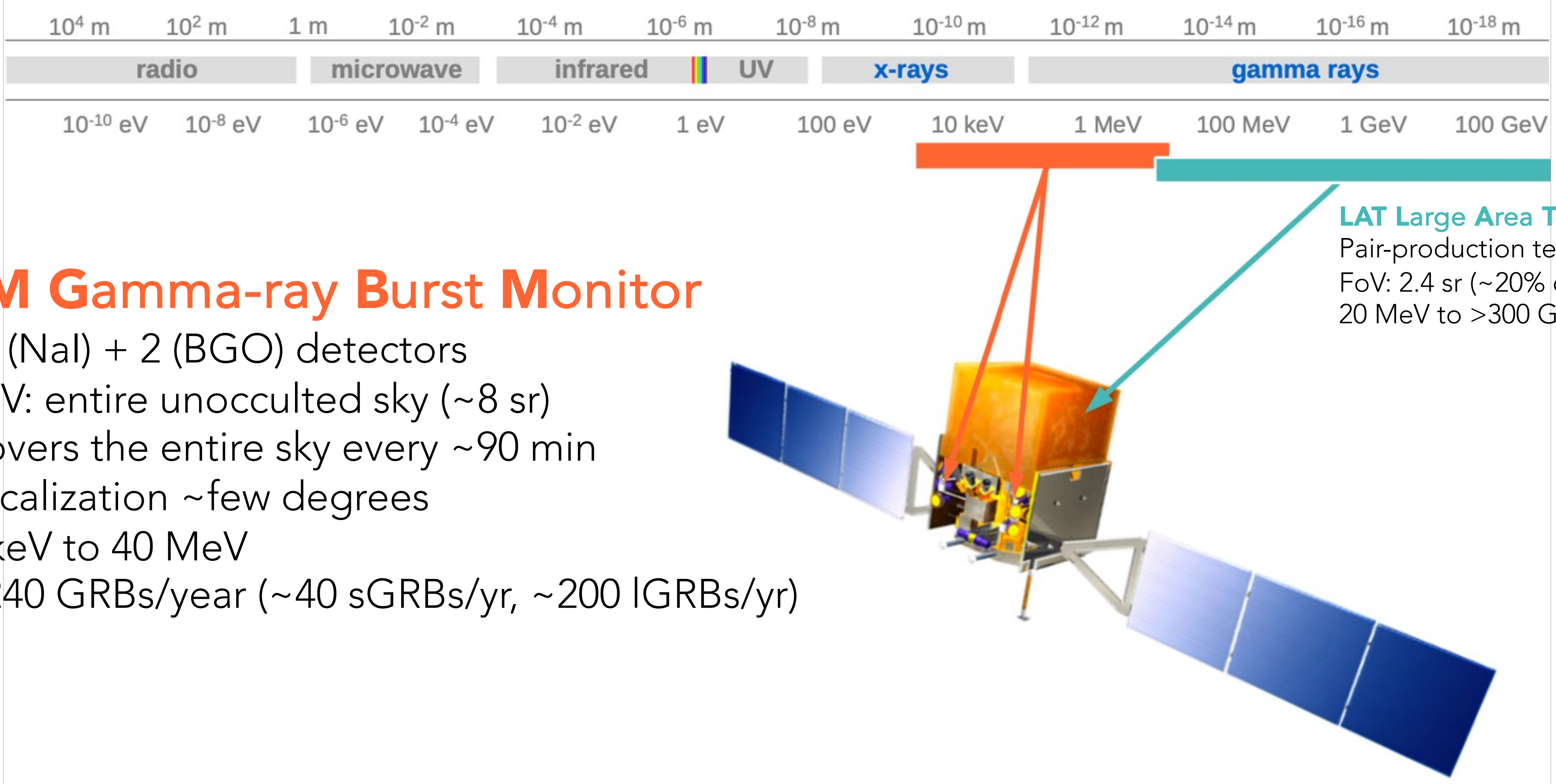
GCN




Ulysses
Integral
Swift
HETE
XTE
GCN

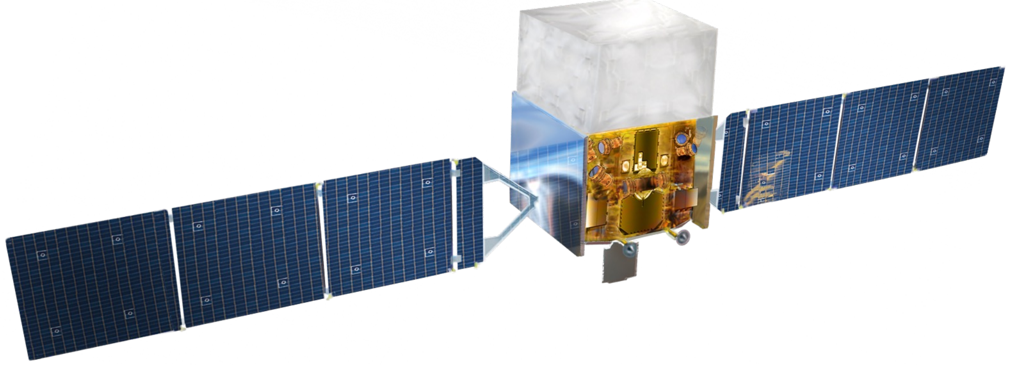
FERMI GAMMA-RAY BURST MONITOR (GBM)



LAT Large Area Telescope
Pair-production telescope
FoV: 2.4 sr (~20% of sky)
20 MeV to >300 GeV

GBM Gamma-ray Burst Monitor

- 12 (NaI) + 2 (BGO) detectors
- FoV: entire unocculted sky (~8 sr)
- Covers the entire sky every ~90 min
- Localization ~few degrees
- 8 keV to 40 MeV
- ~240 GRBs/year (~40 sGRBs/yr, ~200 lGRBs/yr)



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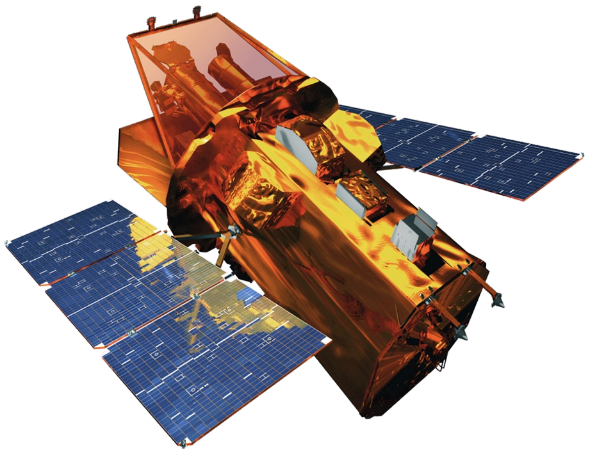


Why *Fermi* GBM?

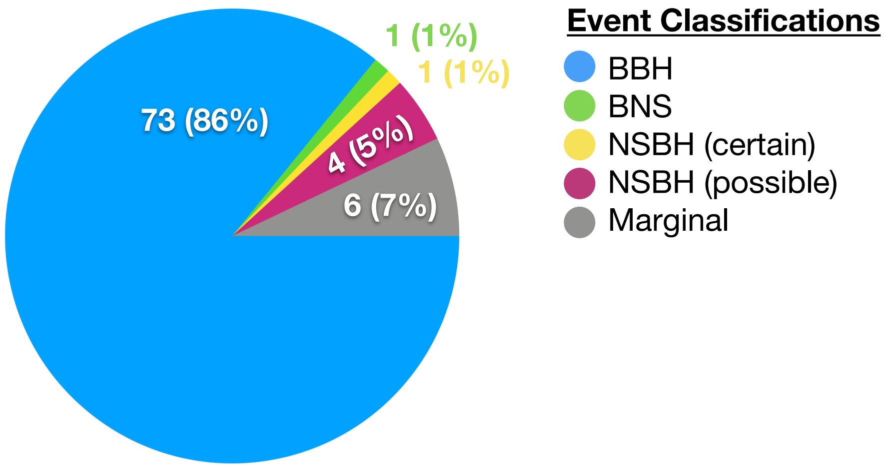
\+ ~full-sky field of view
\+ energy coverage spanning the peak of GRB emission

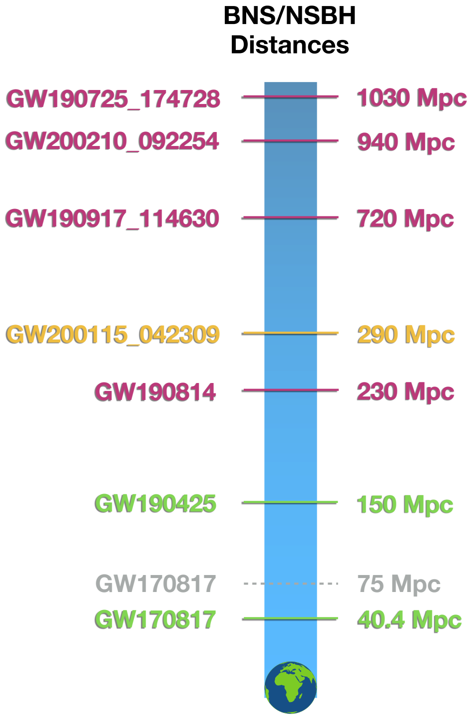
Why *Swift* BAT?

\+ excellent localization sensitivity (~arcminute for detected GRBs)
\+ energy coverage overlaps with the low-energy end of *Fermi* GBM

O3: THE THIRD OBSERVING RUN

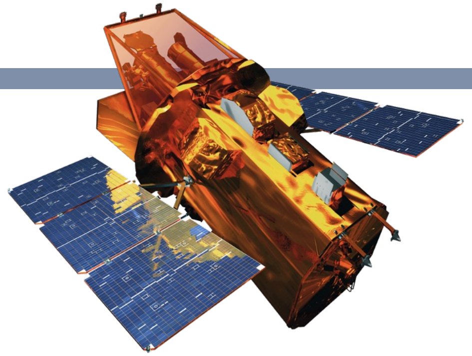
Third LIGO/Virgo observing run (O3): April 2019 -- March 2020 (commissioning break in October 2019)



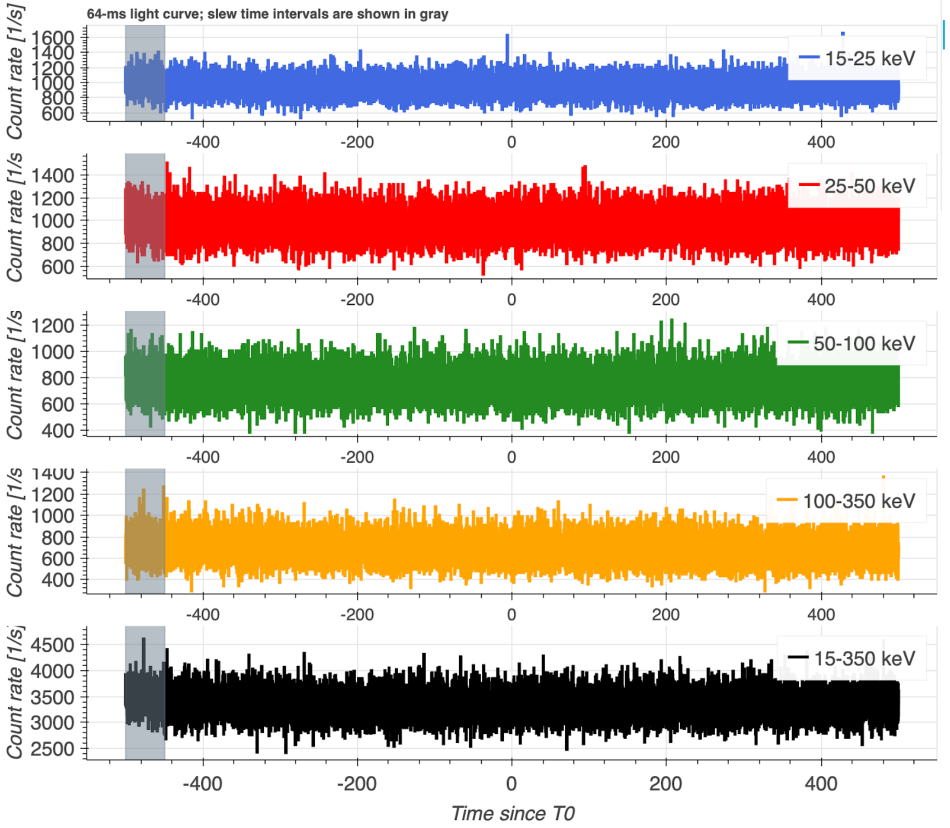


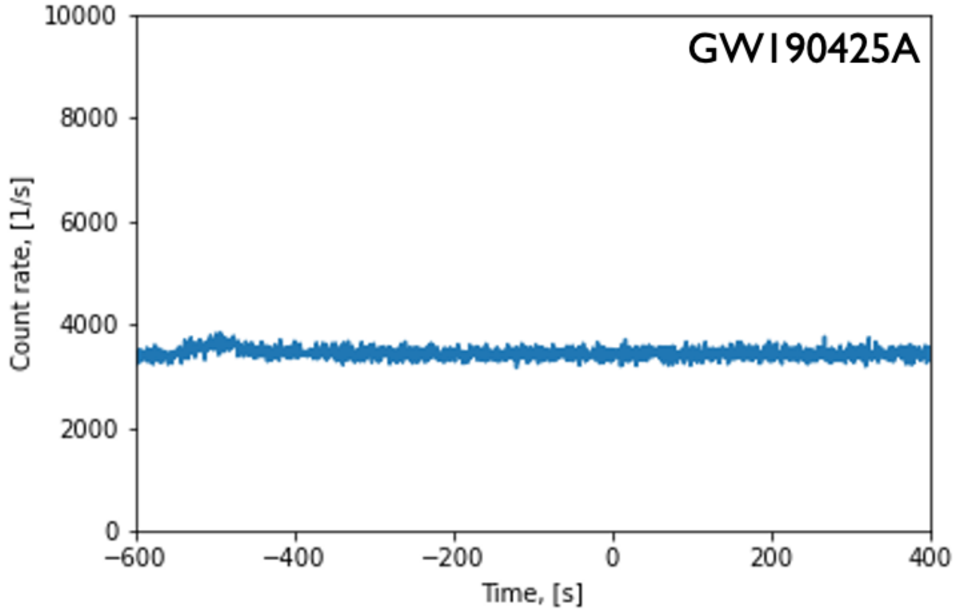
75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

FOLLOW-UP METHODS WITH SWIFT BAT



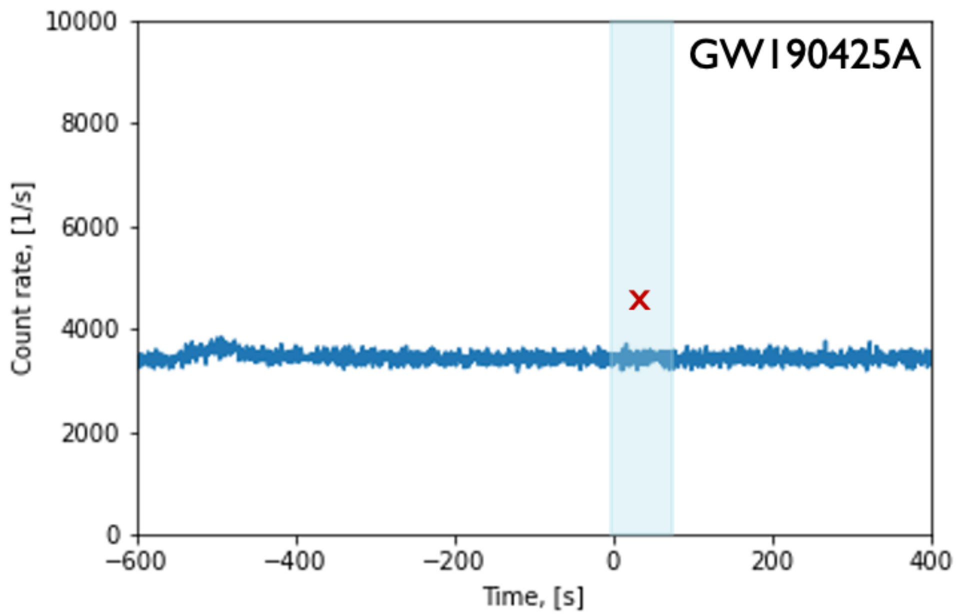
1. Extract BAT raw light curves in 64-ms time bins → rebin to 1 second





FOLLOW-UP METHODS WITH SWIFT BAT

2. Calculate average counts and standard deviation using the data from -1 to +30 seconds around the trigger time



5-sigma detection?

FOLLOW-UP METHODS WITH SWIFT BAT

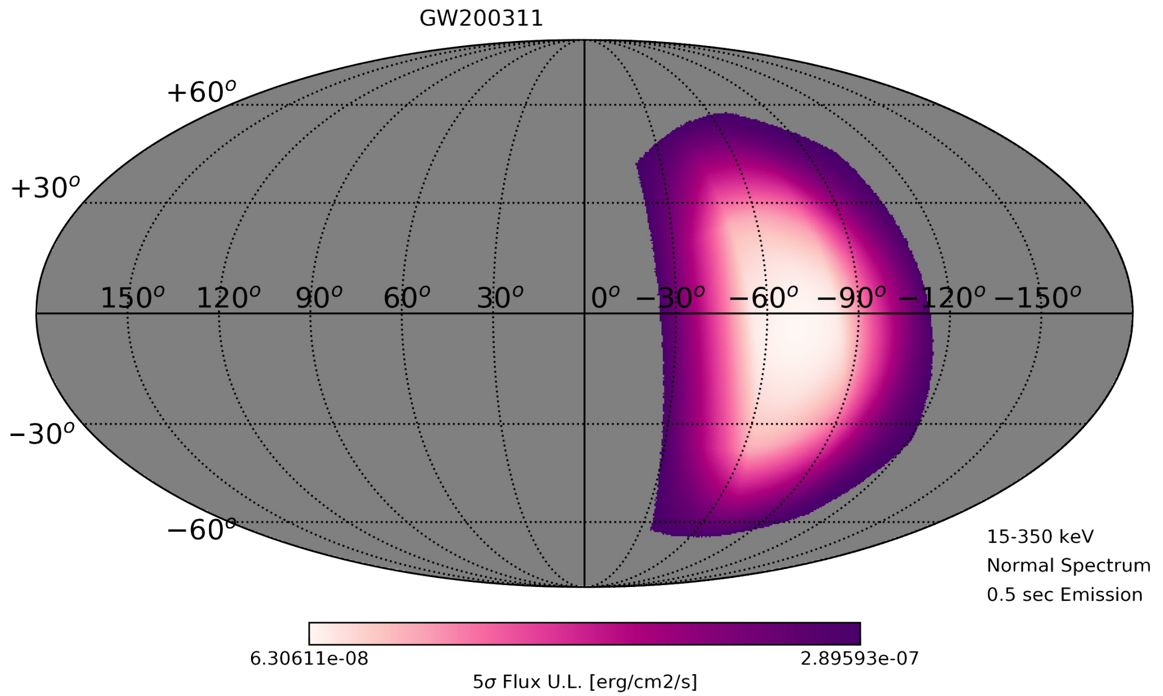
3. Use `NITRATES` to produce response functions for rate data, as a function of the incidence angle onto the BAT detector plane

De Lunay & Tohuvavohu arXiv:2111.01769

FOLLOW-UP METHODS WITH SWIFT BAT

4. Calculate the expected counts using the phenomenological Band function as the expected GRB model

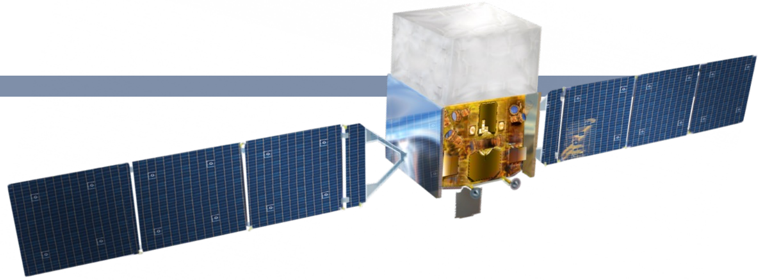
FOLLOW-UP METHODS WITH SWIFT BAT



5. Find the corresponding upper-limit flux

→ Example of the upper-limit map: GW200311

FOLLOW-UP METHODS WITH FERMI GBM



Using *Fermi* GBM triggers and **two** sub-threshold searches:

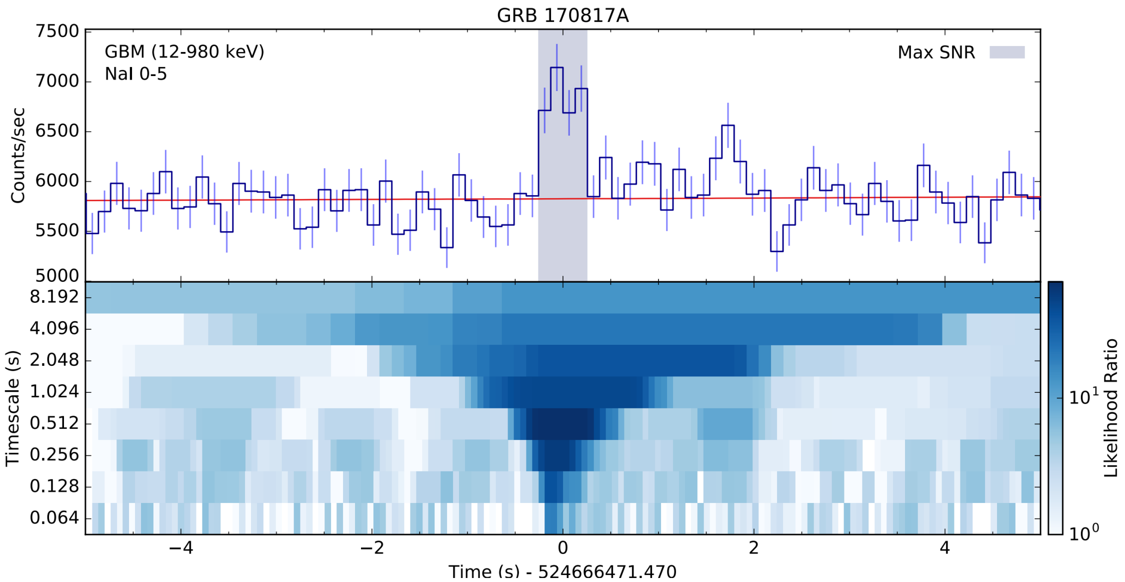
- Targeted: scans -1 to 30 sec around a trigger time
- Untargeted: a blind search of the GBM data

→ Determine if there is any excess γ-ray excess emission coincident with GWTC-3 events

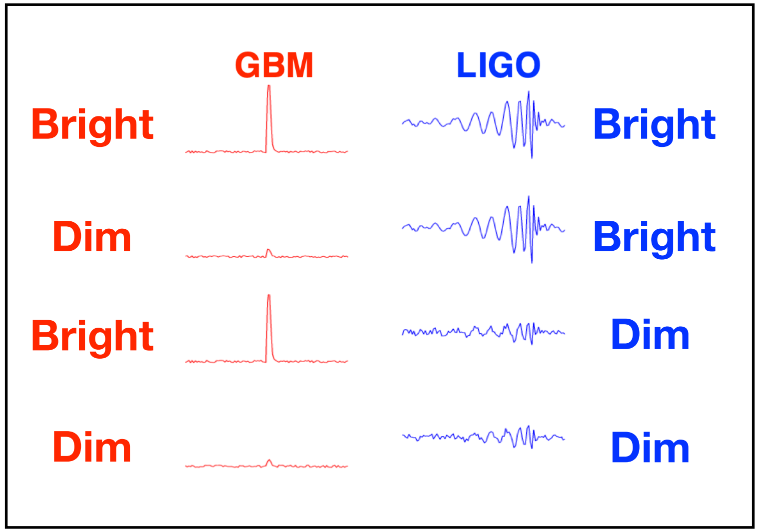
TARGETED SEARCH METHOD FOR COINCIDENT EVENTS

- Examines continuous time-tagged events (CTTE) data in Fermi-GBM for short transients within +/- 30 seconds of an external trigger
- Formulates a likelihood ratio test for the presents of a SGRB on top of the modeled backgrounds in each detector using three pre-defined spectral templates

- Goal: Increase detections through enhanced joint event sensitivity for sub-threshold events



Kocevski et al. *ApJ.* (2018)



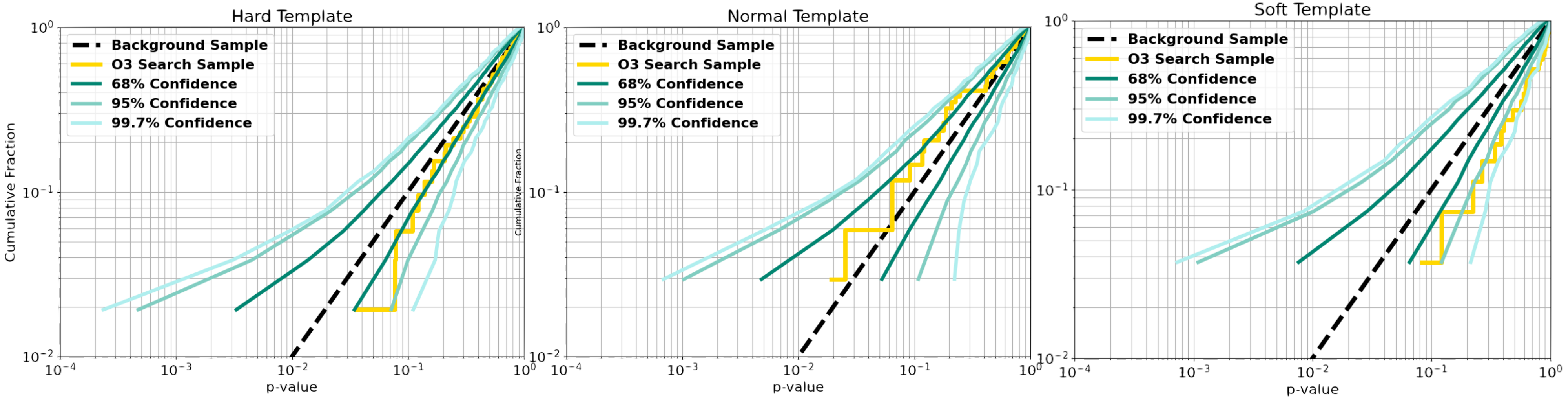
TARGETED SEARCH METHOD FOR COINCIDENT EVENTS

→ comparing the events found with the GBM targeted search around the GW event times with three spectral templates

Ranking statistic (R)

→ R is mapped to a p-value and compared to the cumulative fraction → **no statistically significant counterparts**

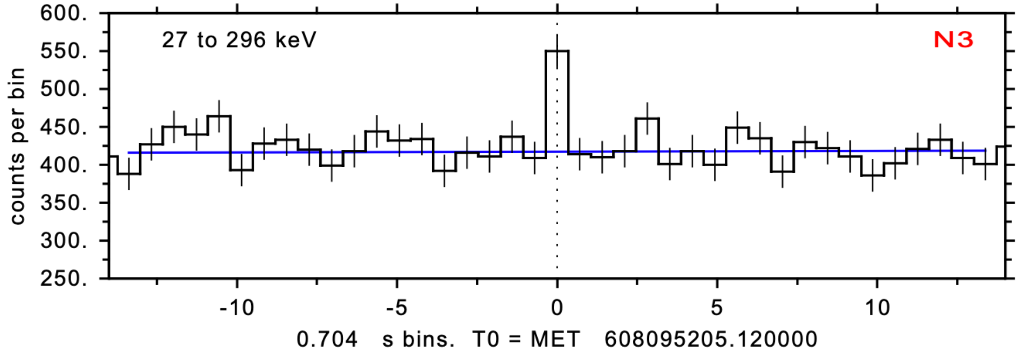
$$R = \frac{p_{\mathrm{astro}} \times p_{\mathrm{vis}} \times p_{\mathrm{assoc}}}{|\Delta t - D| \times FAR_{\mathrm{GBM}}}$$

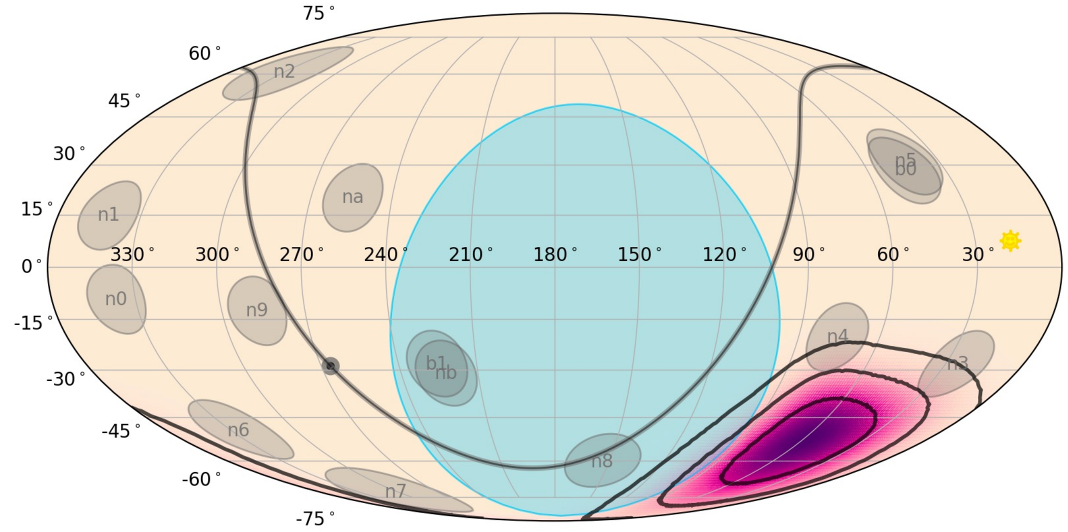


Equation: the probability the GW event is astronomical (p_{astro}), visible to GBM (p_{vis}), and that GW and GBM event are spatially associated (p_{assoc}), the GW-GBM time offset (Δt), GBM event duration (D), and the GBM False Alarm Rate (FAR_{GBM})

UNTARGETED SEARCH METHOD FOR COINCIDENT EVENTS

- Searches CTTE data continuously for GRB-like transients below the on-board trigger threshold with 4-5 hr latency



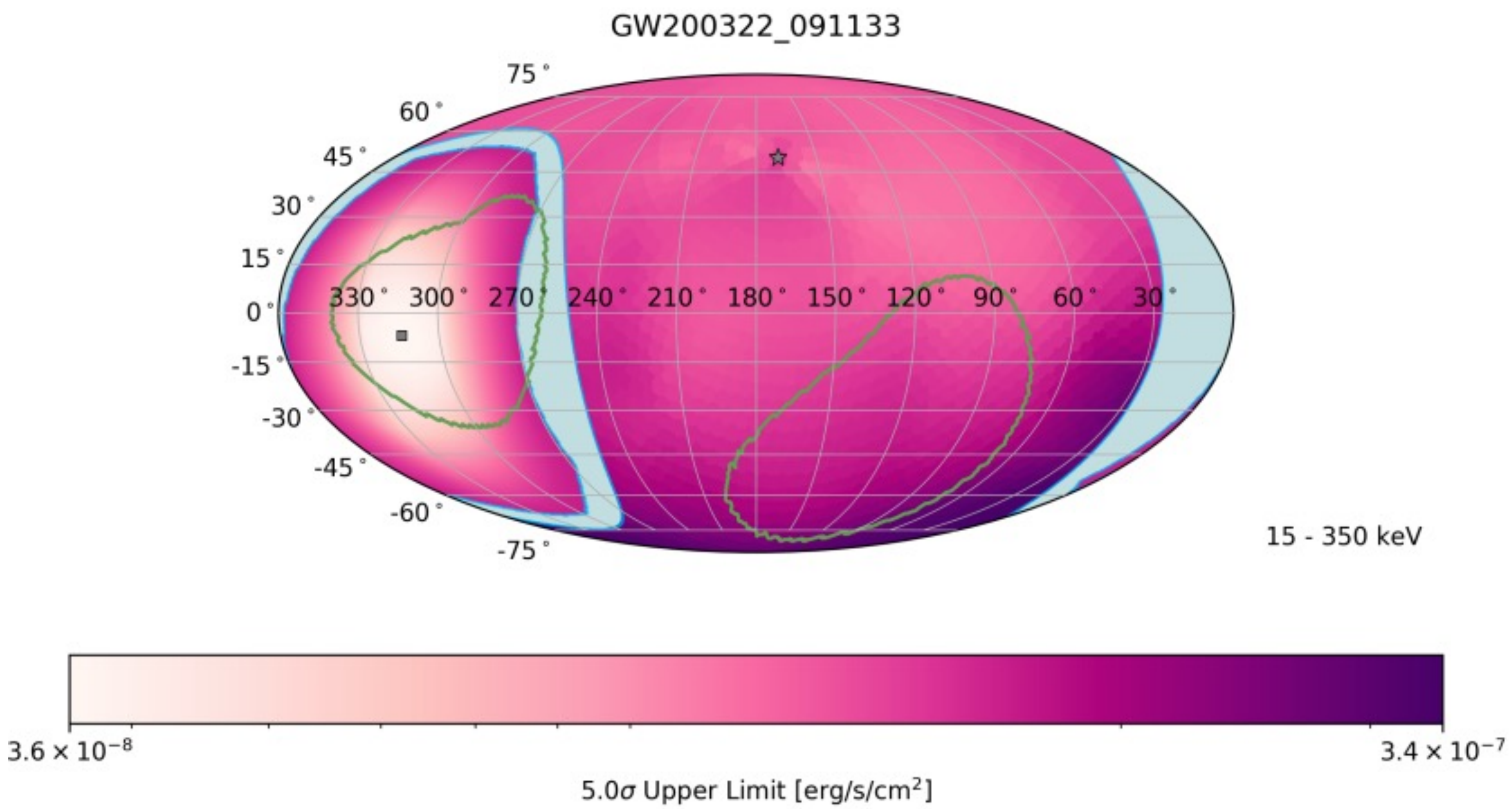


- No statistically significant discoveries.

We report *no* significant discoveries; neither with *Fermi* GBM, nor *Swift* BAT.

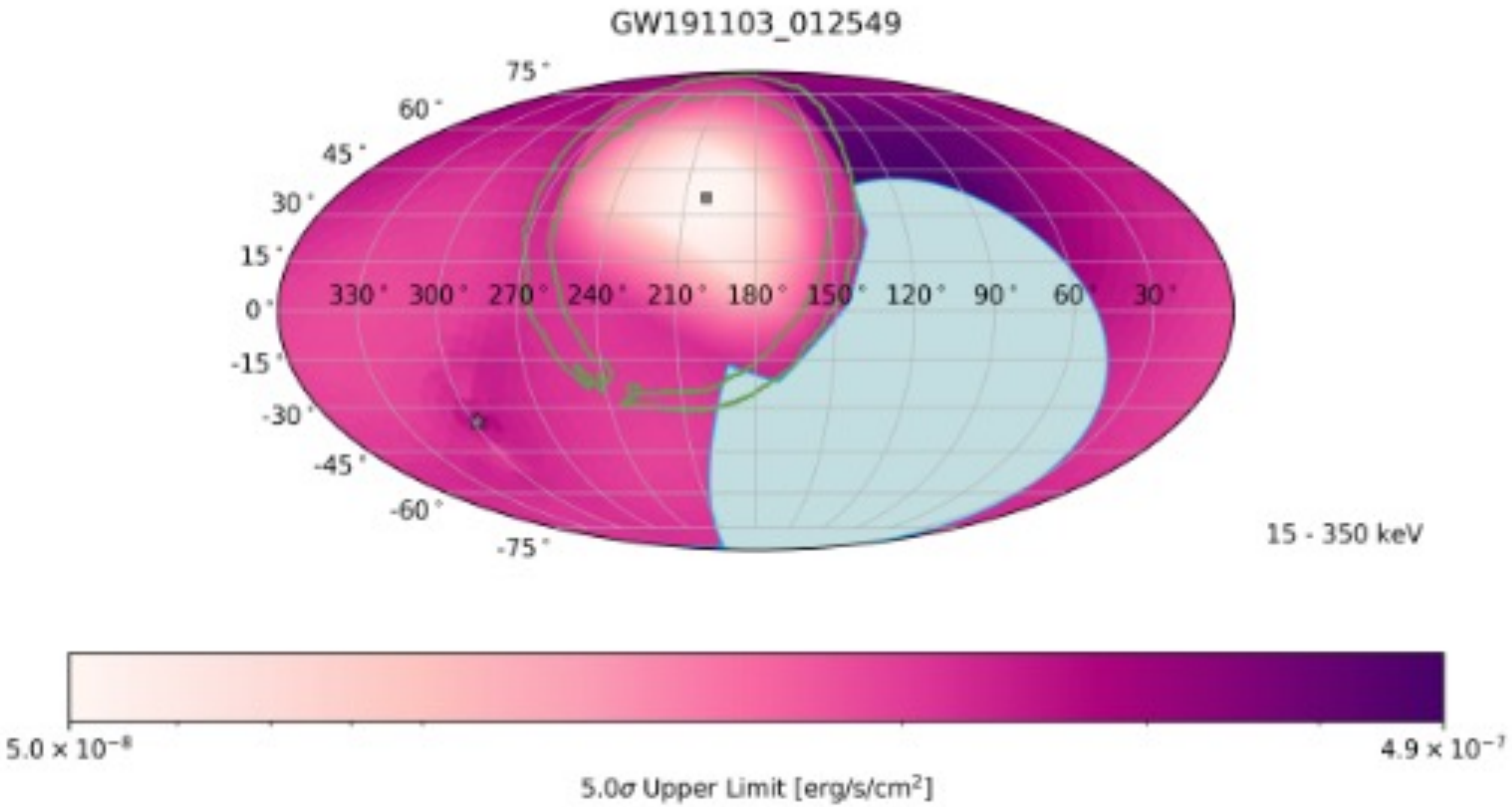
COMBINING THE UPPER LIMITS

- Choosing the most constraining limit for each point in the sky (independent measures)

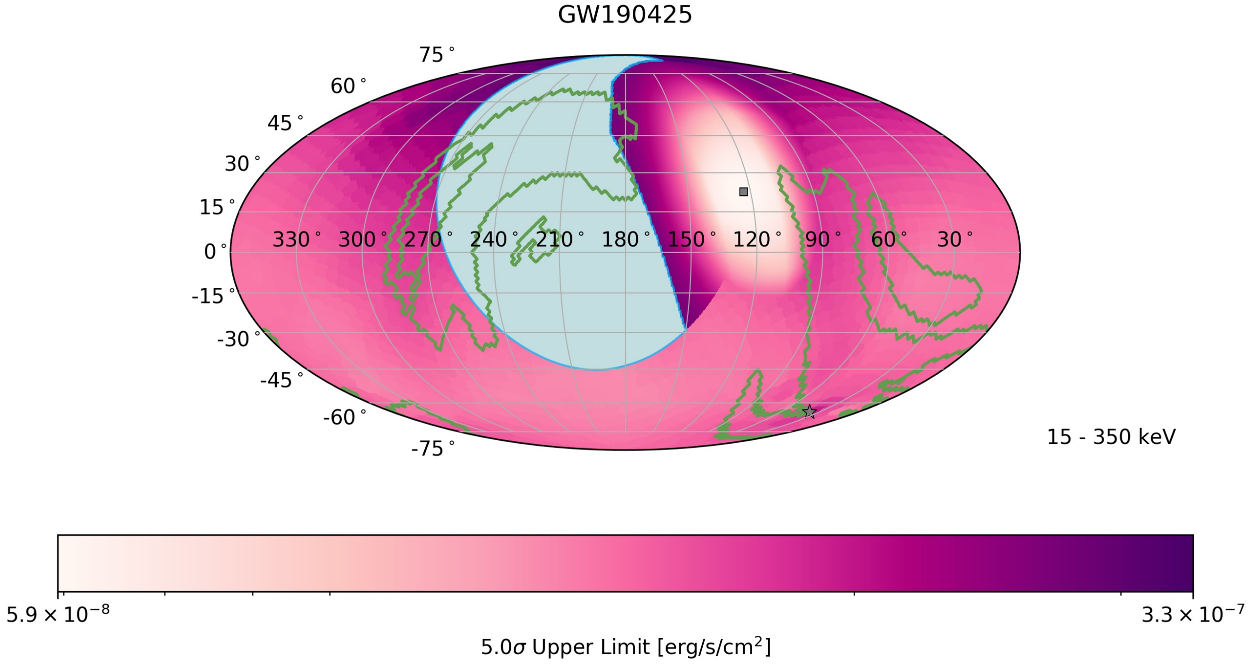


COMBINING THE UPPER LIMITS

- Choosing the most constraining limit for each point in the sky (independent measures)



HONORABLE MENTION: BNS GW190425

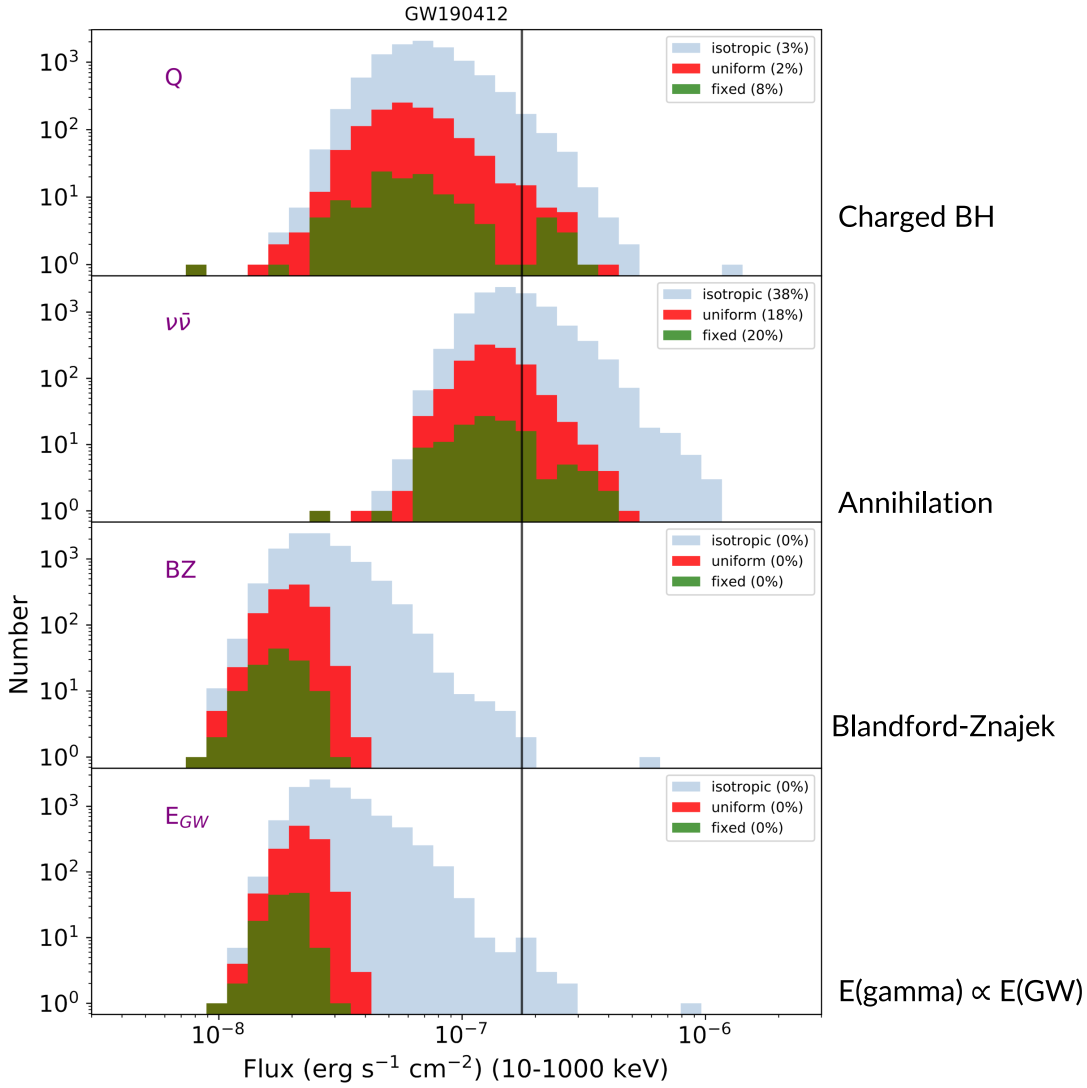


- BNS 190425 is 4 times further away than BNS 170817
- GBM/BAT only see ~60% of the GW localization region
- Inclination angle poorly constrained

EM RADIATION FROM BINARY-BLACK-HOLE MERGERS?

- Assuming association between BBH GW150914 & GW150914-GBM, we can use the BBH parameters to derive a distribution of γ-ray fluxes to compare with the GBM 3-σ flux upper limits (10 – 1000 keV)

- Four different models shown; vertical line represents the 3-σ flux upper limit, with the fraction of cases above that limit shown the legend



CONCLUSIONS

- Using *Fermi* GBM triggers and sub-threshold searches, and *Swift* BAT's data to search for coincident γ-ray emission with the GWTC-3 events, **we found no statistically significant EM counterparts**
- We calculated the **flux upper limits** for both GBM and BAT and **present joint upper-limit skymaps**
- Comparing the upper limits expectations from various BBH merger theoretical models we find that **we can likely rule out the neutrino model** for producing EM emission
- Stay tuned for Fletcher *et al.* 2022, incl. Crnogorčević (currently under the LVK review)
- **Getting ready for O4!**