Catching the next wave

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

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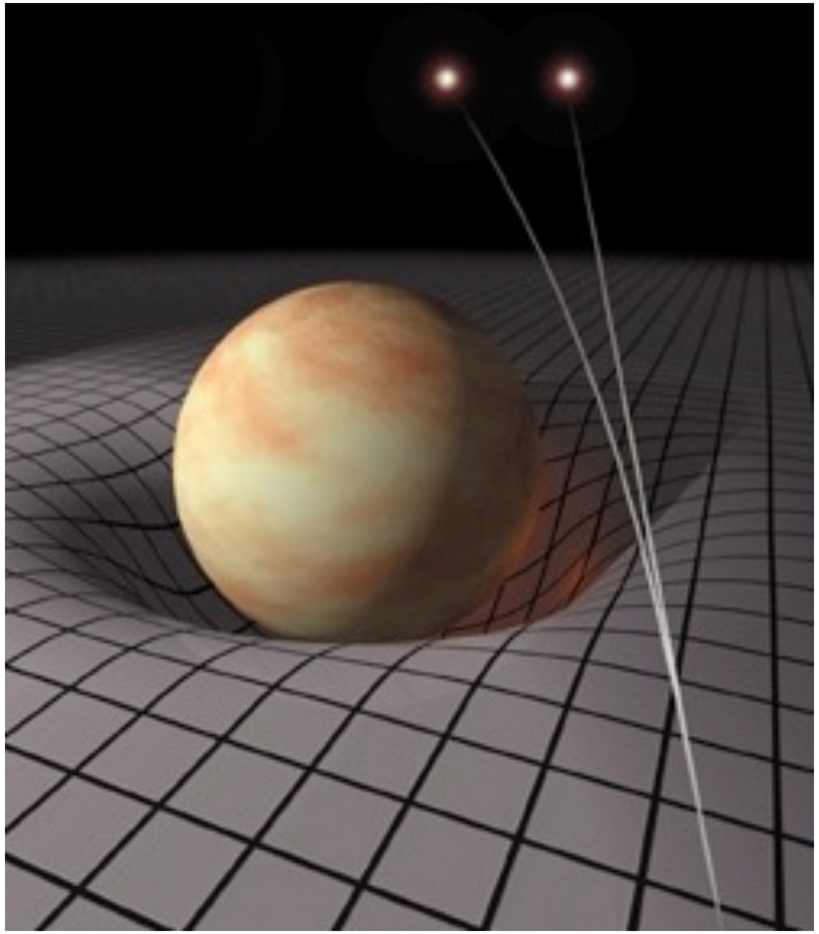
July 12, 2022

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

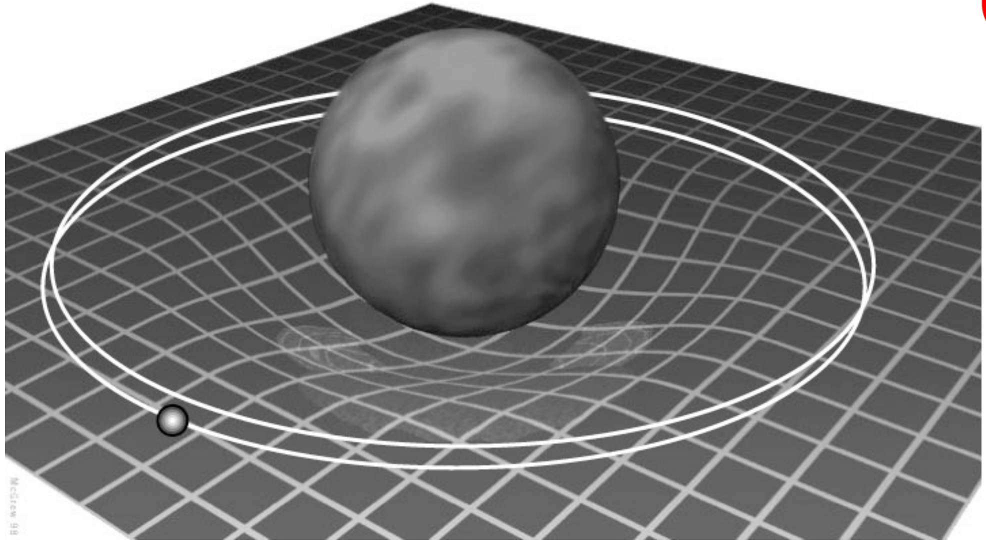


Gravitational lensing

Space tells matter how to move.

Matter tells space how to curve.

– John A. Wheeler



Precession of Mercury

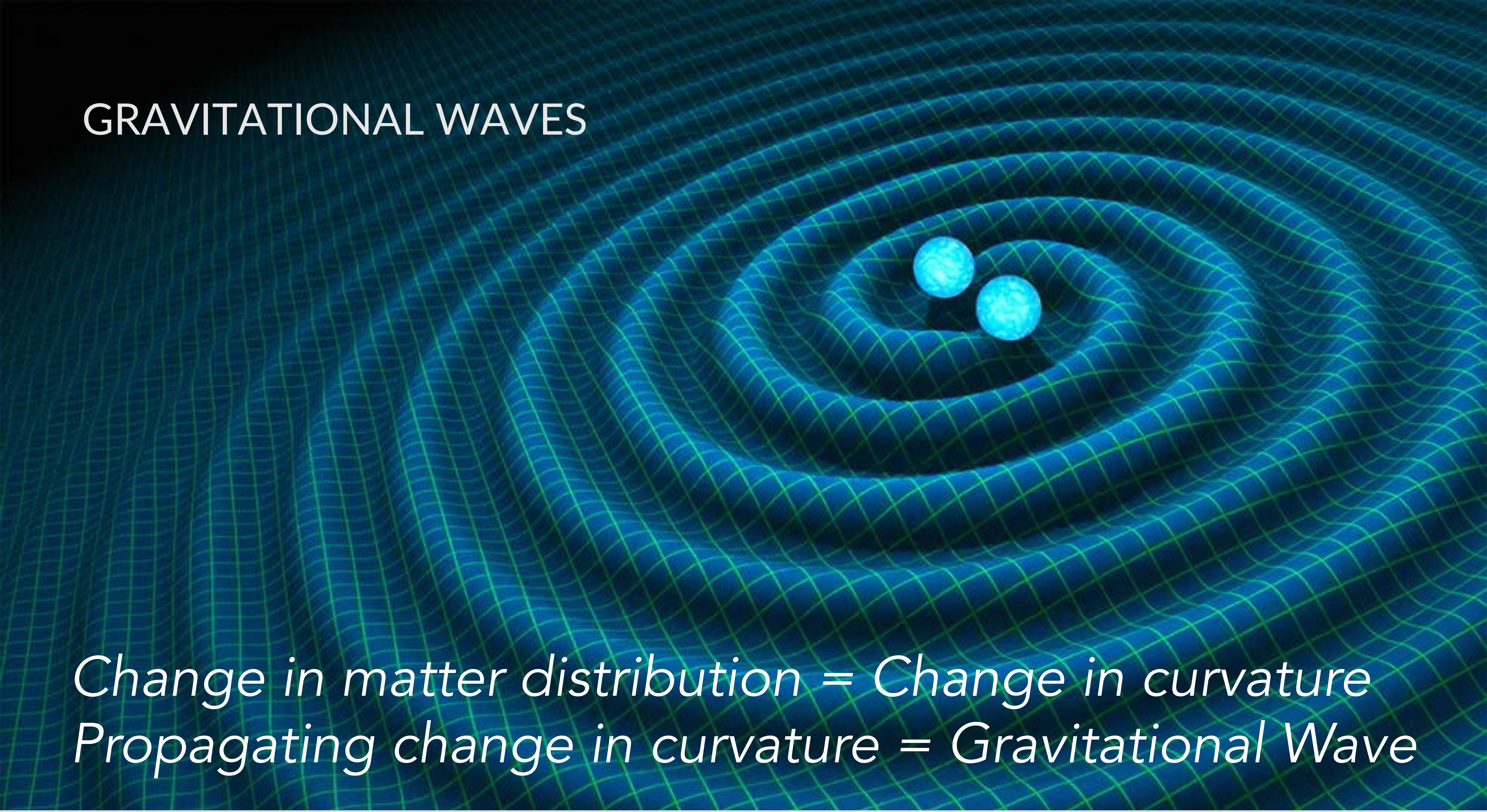
$$\boxed{G_{\mu\nu} = \kappa T_{\mu\nu}}$$

Spacetime curvature

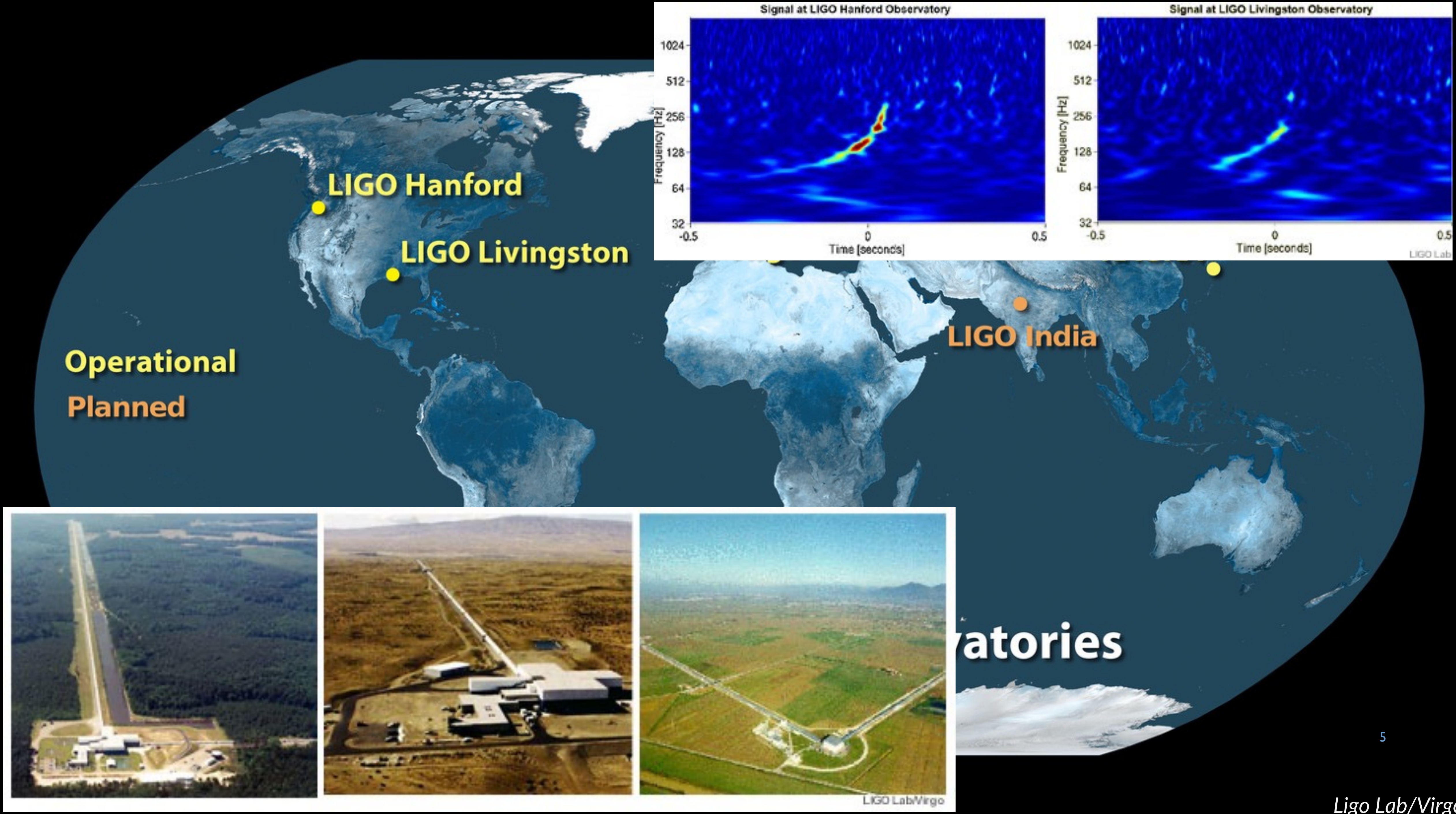
Matter (and energy)

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

GRAVITATIONAL WAVES

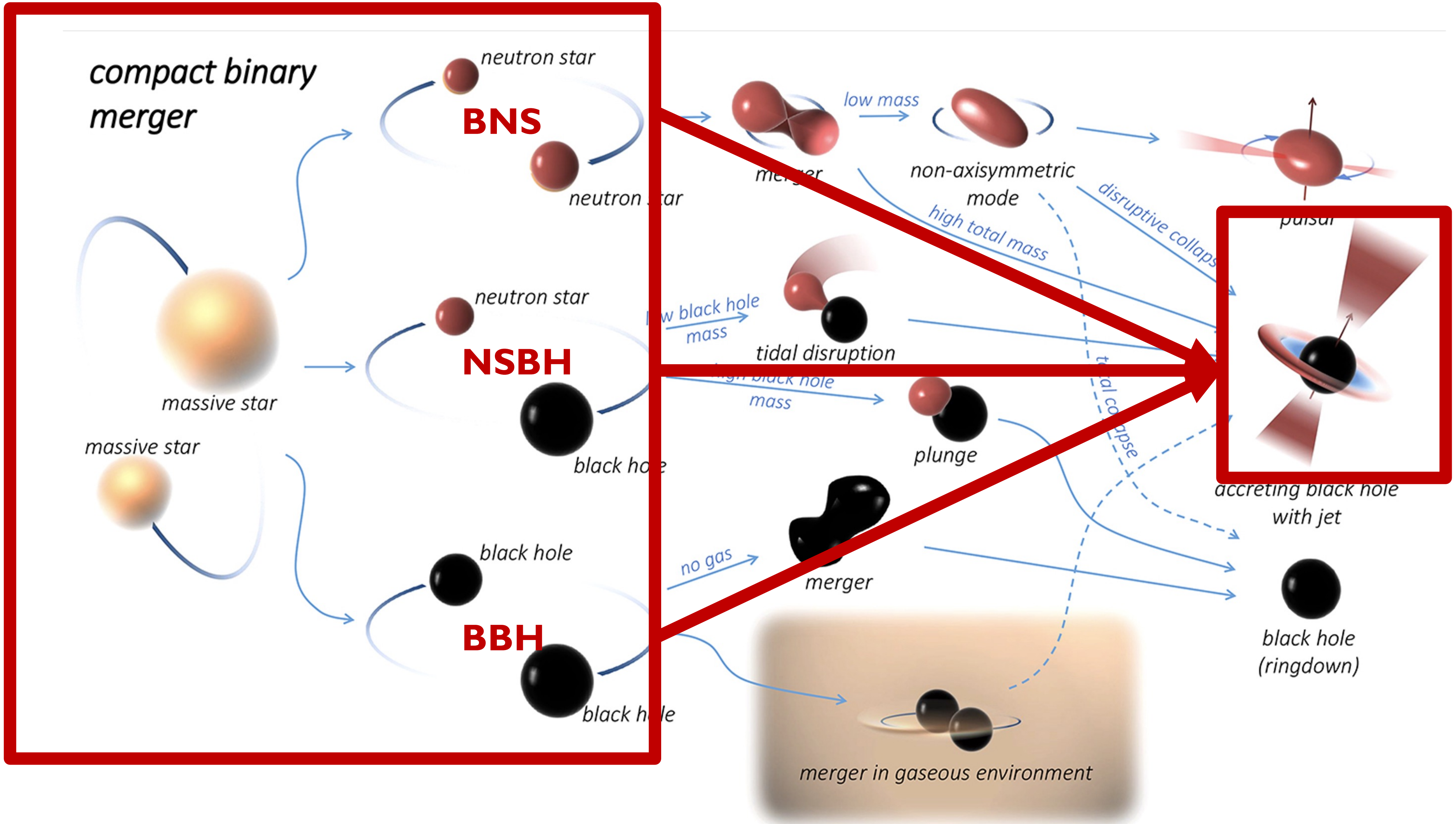


Change in matter distribution = Change in curvature
Propagating change in curvature = Gravitational Wave

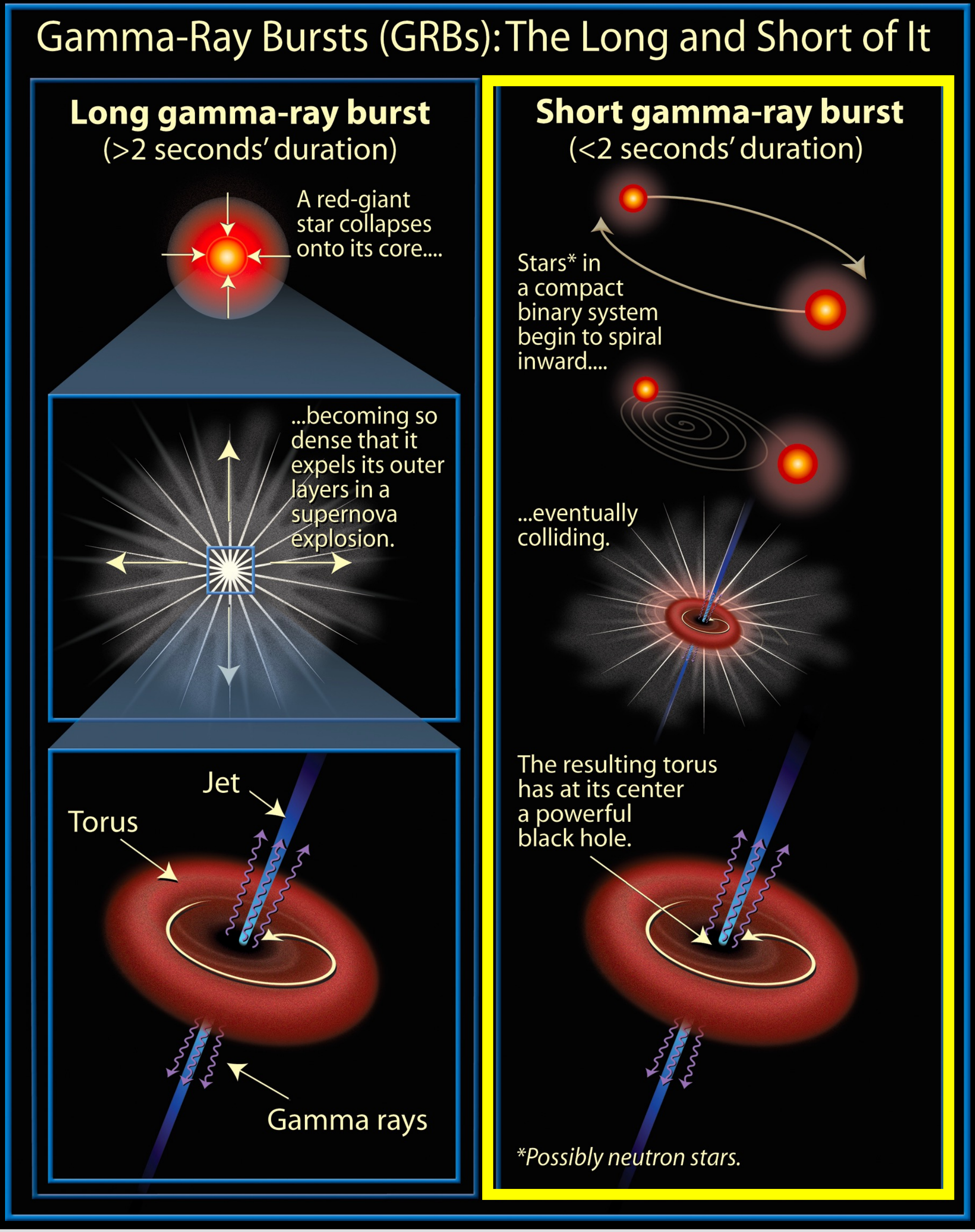


Ligo Lab/Virgo

WHERE TO SEARCH FOR GWs: COMPACT BINARY MERGERS

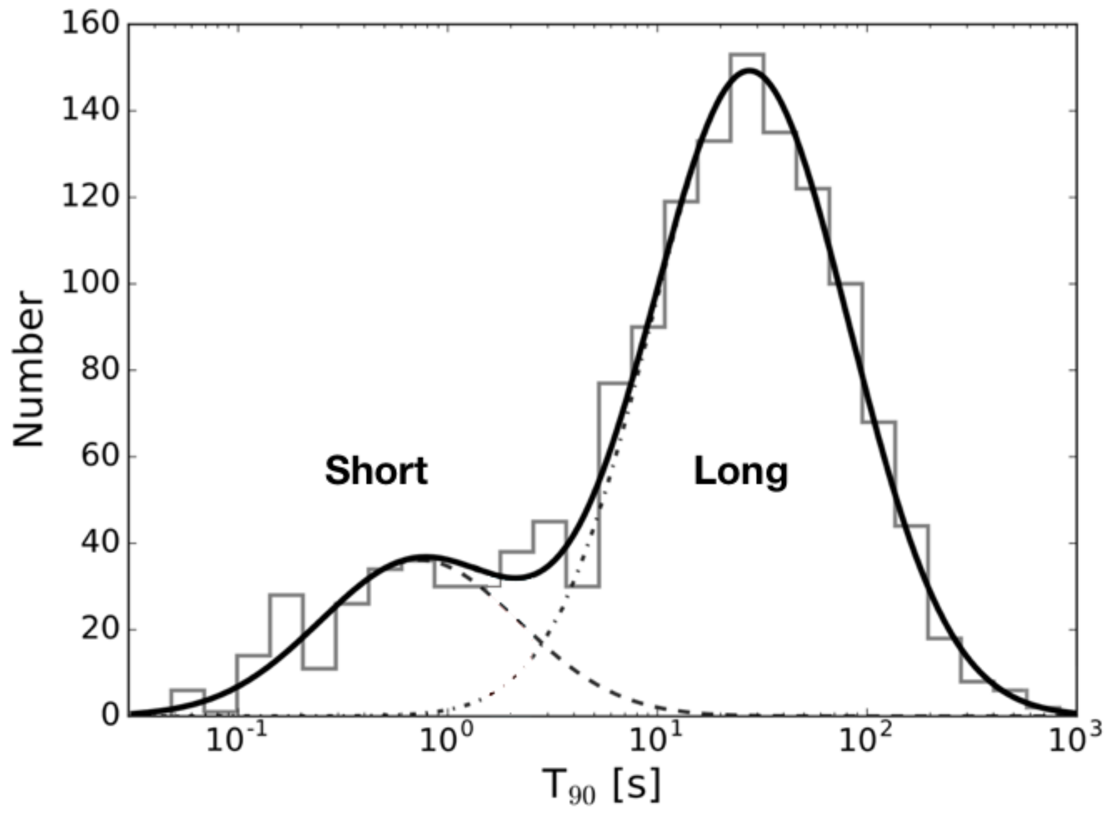


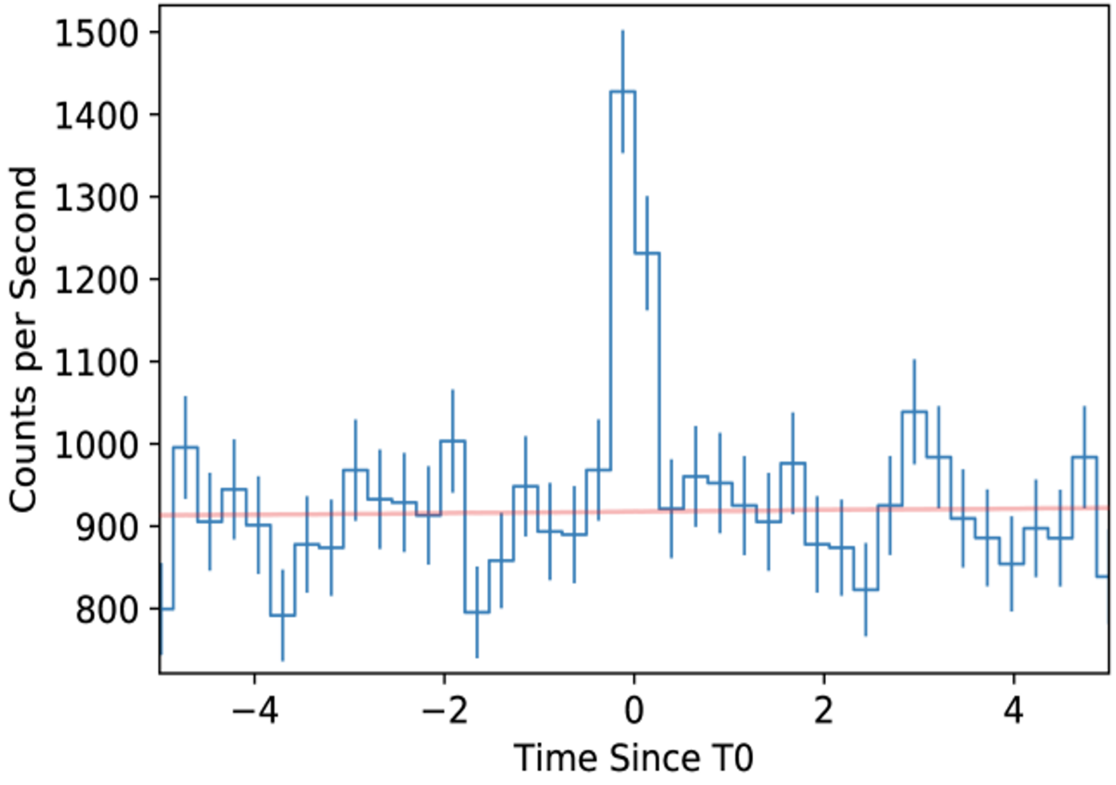
Bartos & Kowalski, 2017



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.*

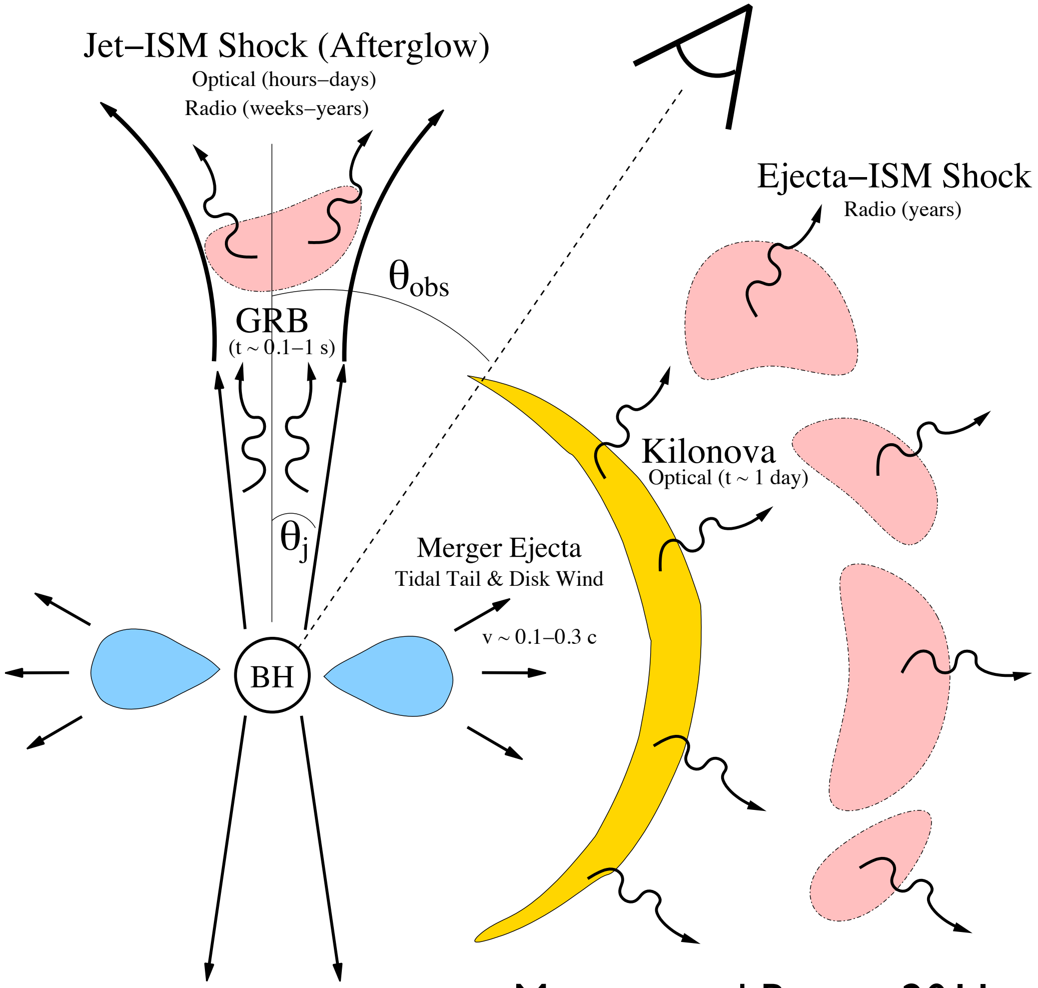
SHORT GRBs AND GWs

GW:

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

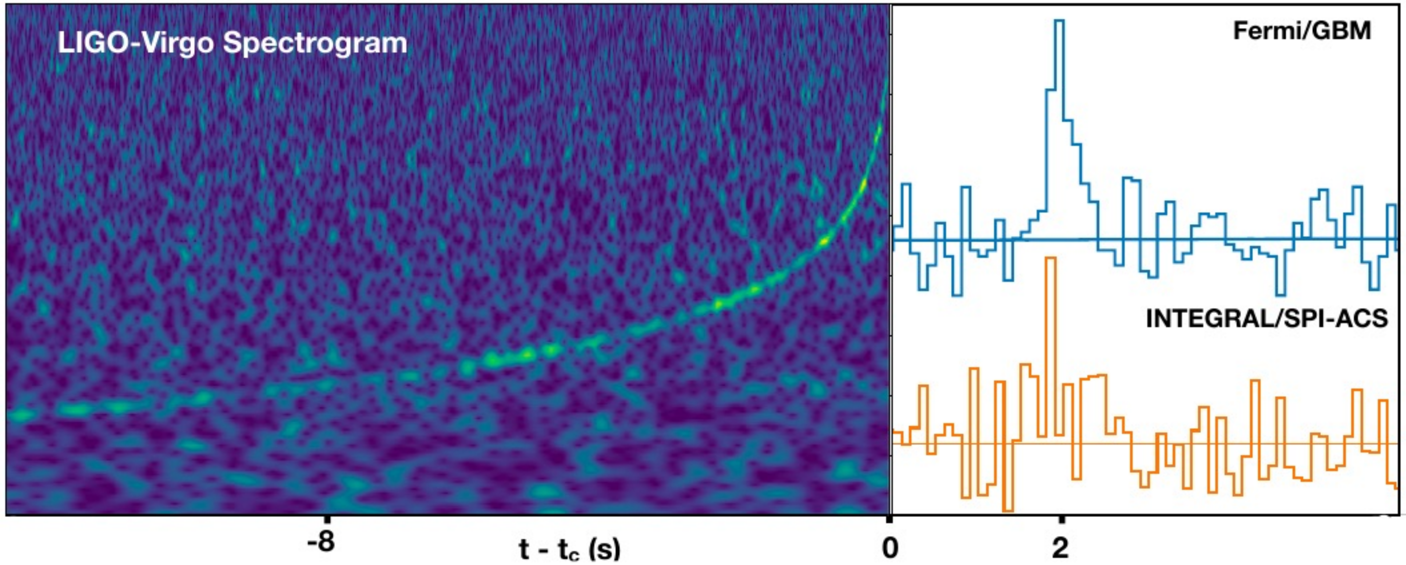
EM

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

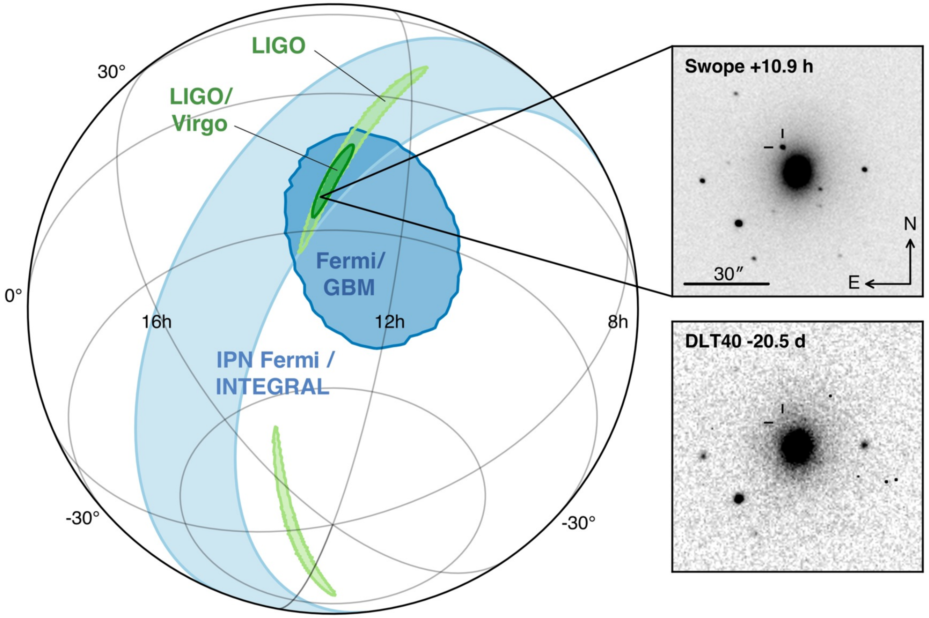


Metzger and Berger, 2011

GW 170817 & GRB 170817A

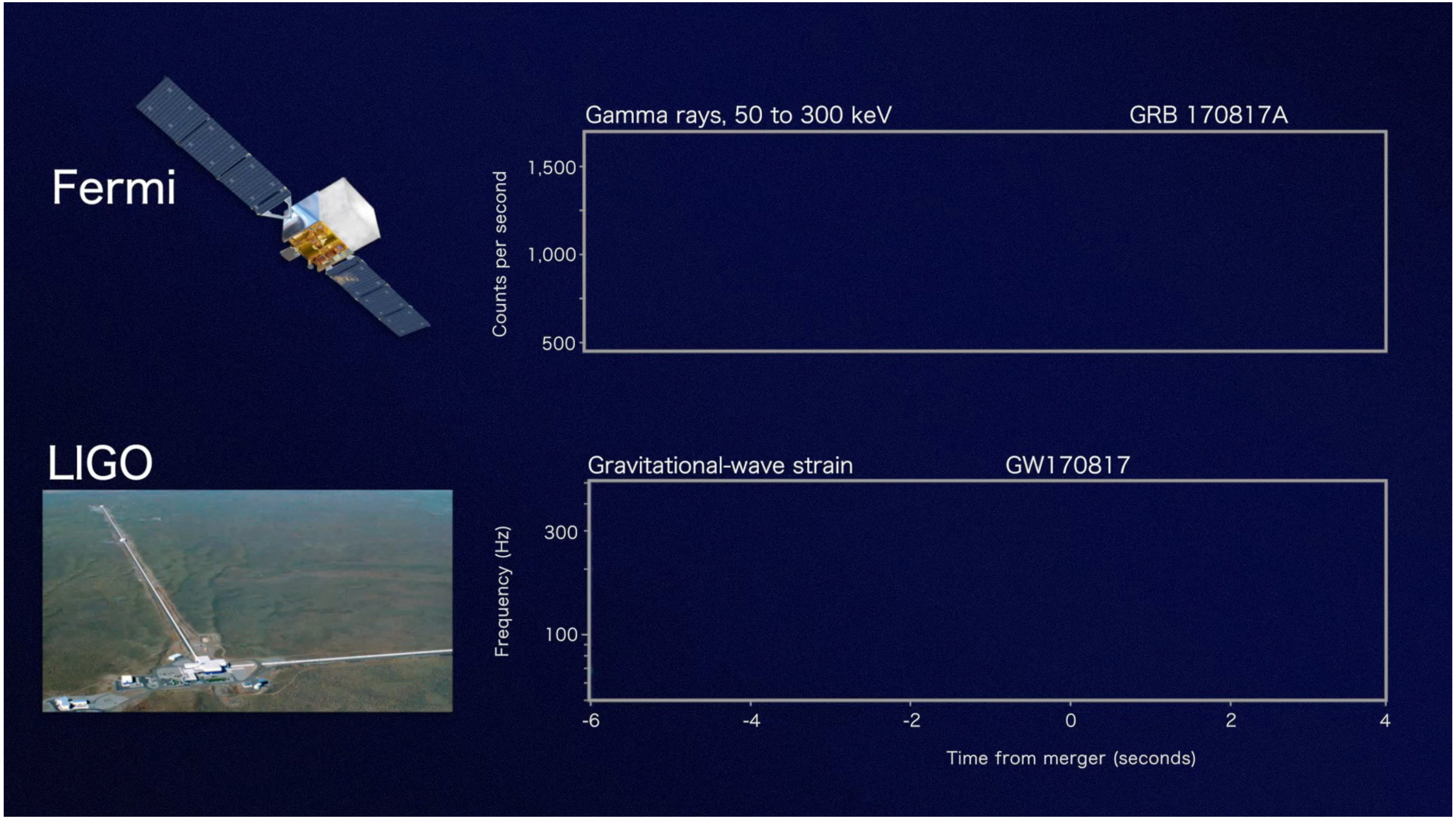


GW170817
[Abbott et al., 2017c]
GRB 170817A
[Goldstein et al., 2017,
Abbott et al., 2017b]

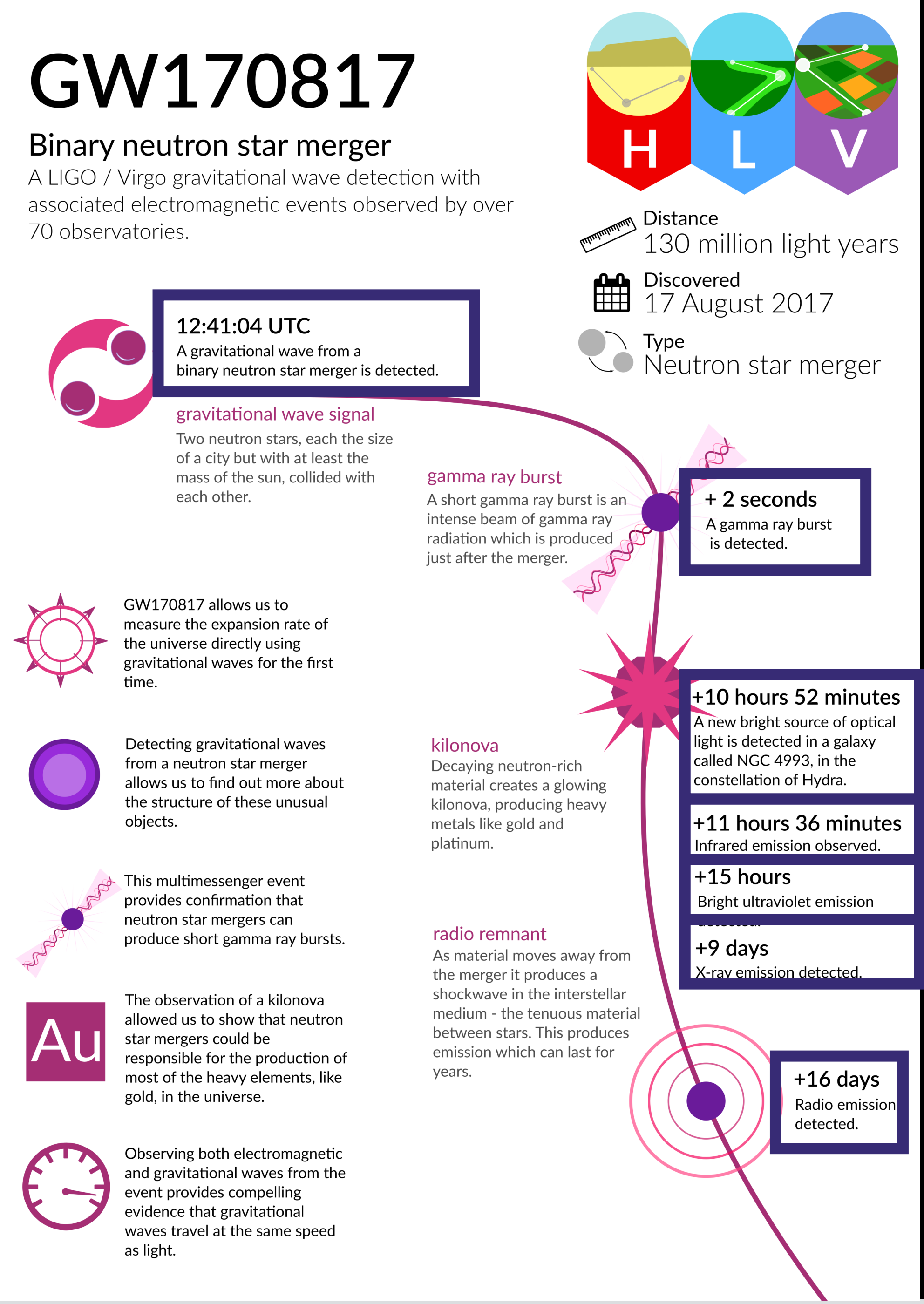


SSS17a
EM170817…
AT 2017gfo
[Abbott et al., 2017d]

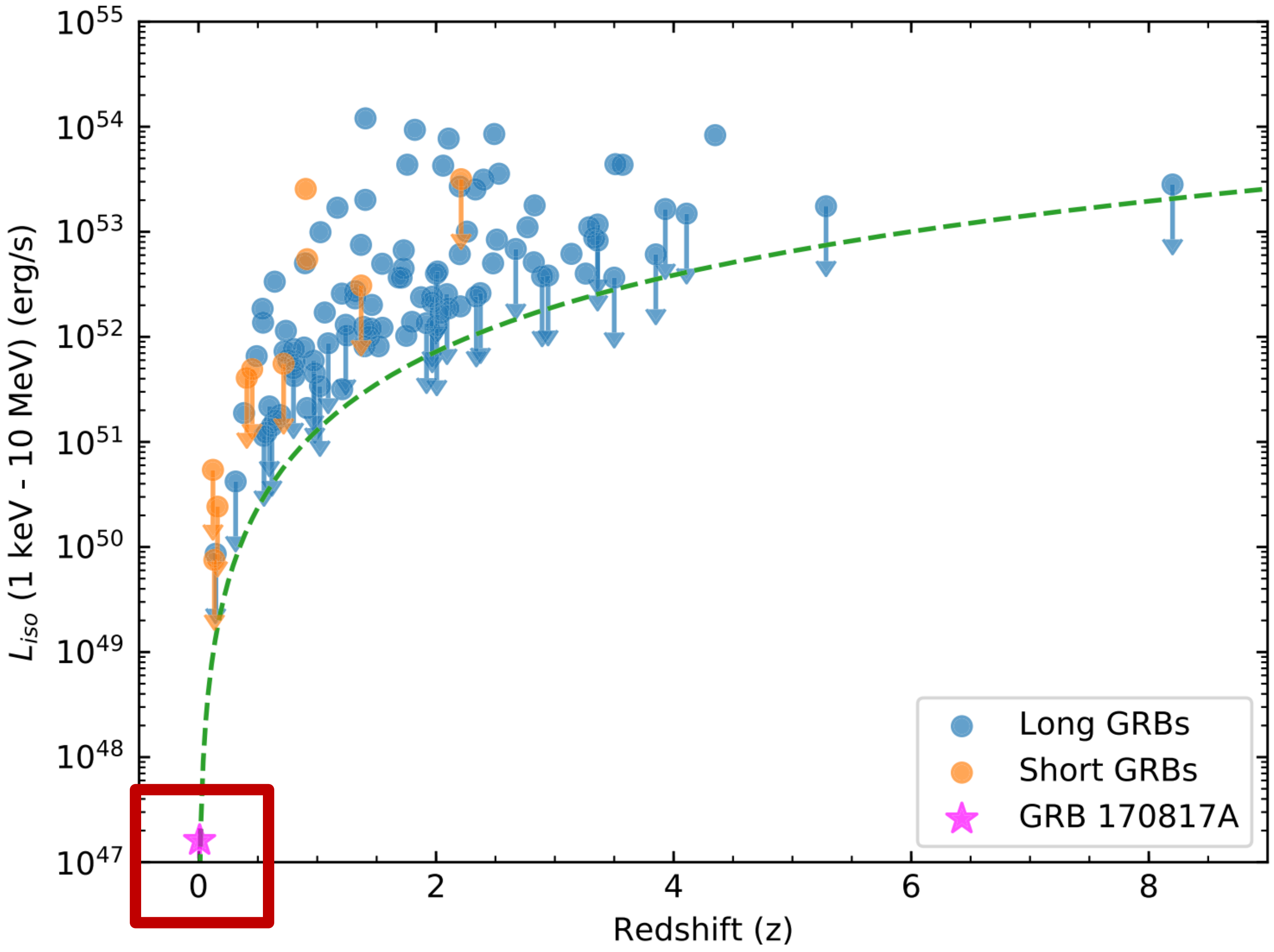
GW 170817 & GRB 170817A



LIGO Lab


GW170817
Binary neutron star merger
A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.
H
L
V
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.
+9 days
X-ray emission detected.
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.
Au
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.

GW 170817 & GRB 170817A



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

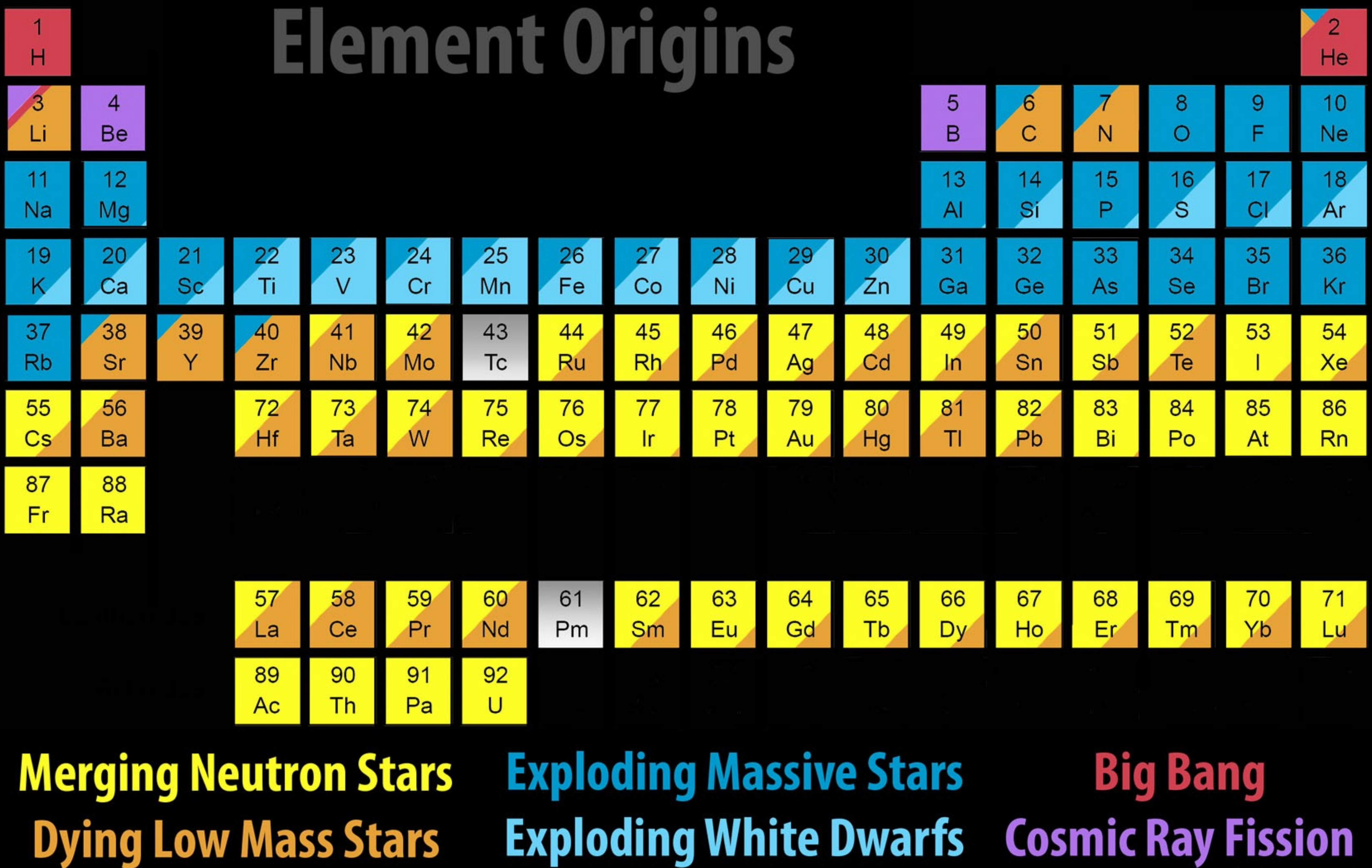
GW170817 & GRB 170817A: WHAT'S LEFT TO UNDERSTAND?

Astrophysics:

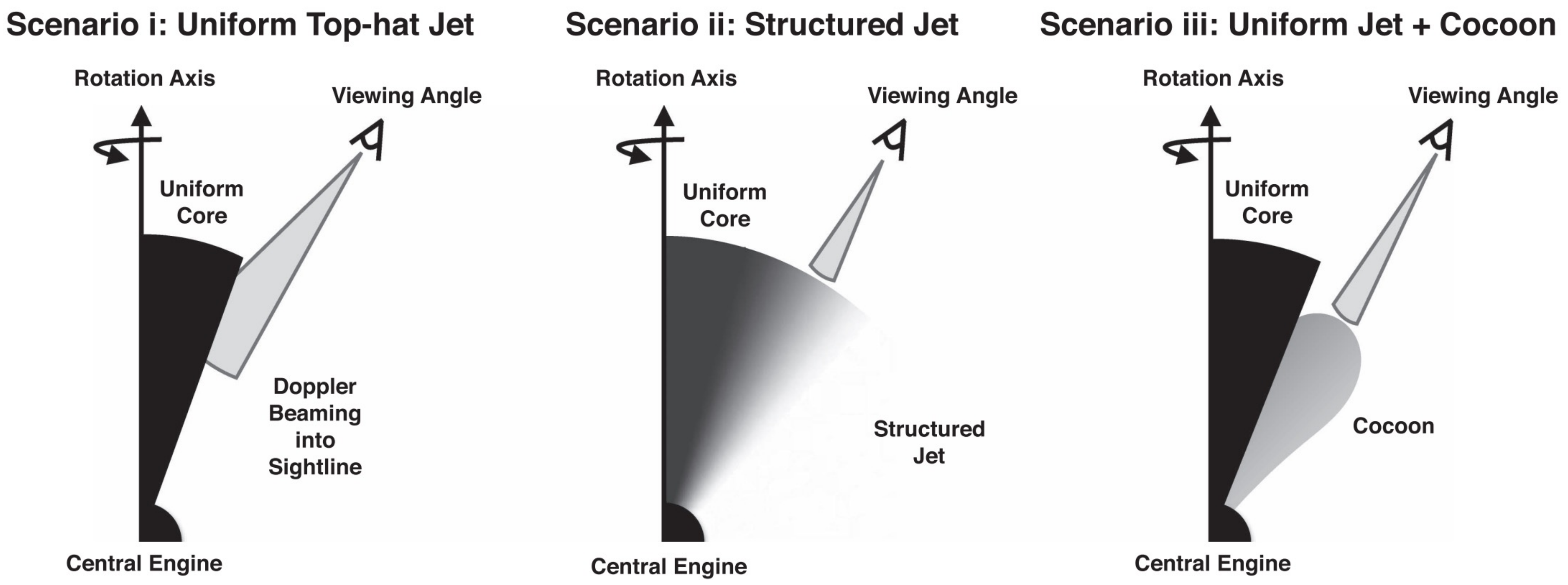
- Origin of heavy nuclei: **are BNS merger rates enough to account for the element abundance?**
- BNS physical system dynamics and the physics of kilanovae: **high-energy particle accelerators?**
- Jets and post-merger remnants: **jet physics?**
- Neutron-star equation of state: **?**
- Cosmology: speed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



Based on graphic created by Jennifer Johnson

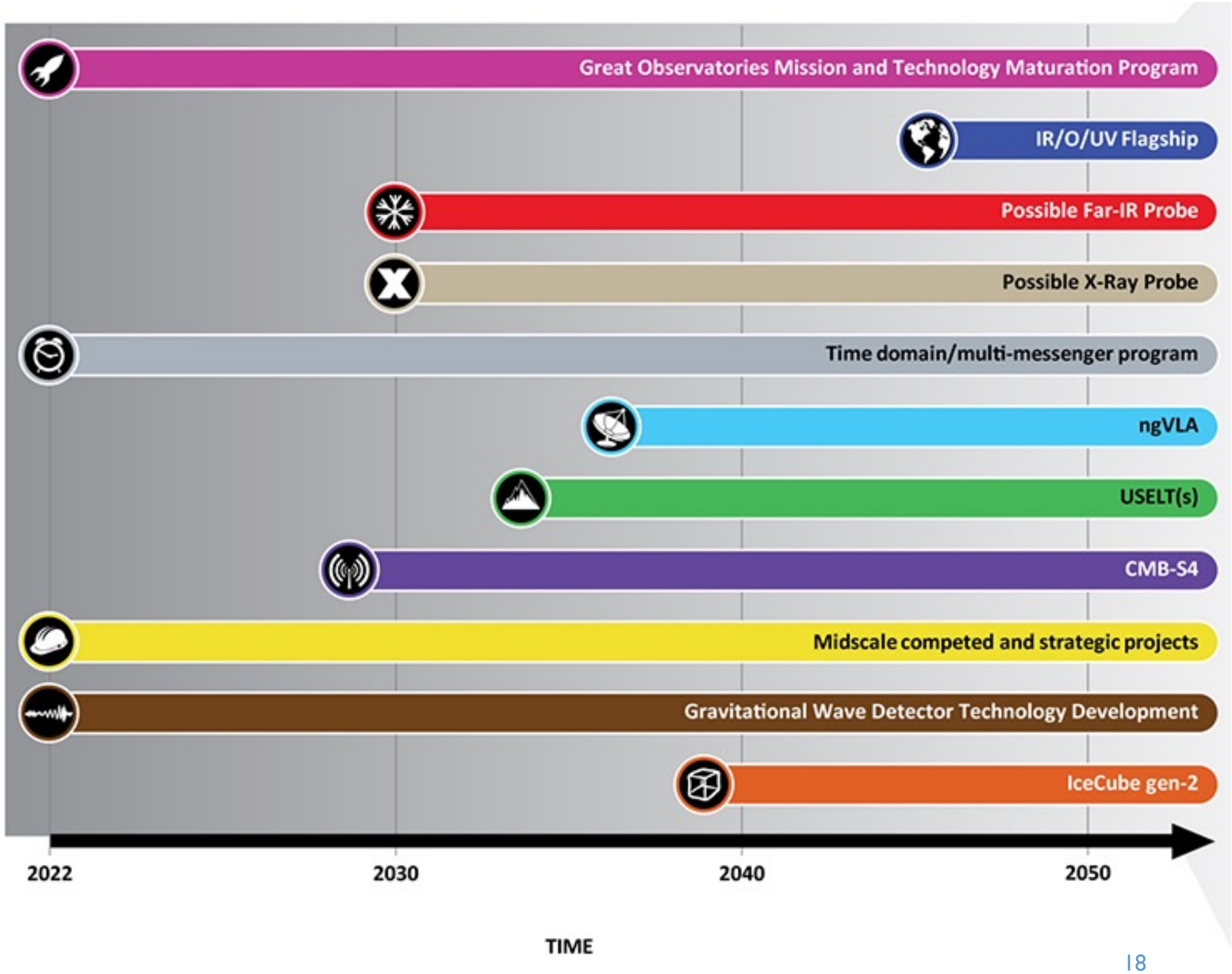

Scenario i: Uniform Top-hat Jet
Rotation Axis
Viewing Angle
Uniform Core
Doppler Beaming into Sightline
Central Engine
Scenario ii: Structured Jet
Rotation Axis
Viewing Angle
Uniform Core
Structured Jet
Central Engine
Scenario iii: Uniform Jet + Cocoon
Rotation Axis
Viewing Angle
Uniform Core
Cocoon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



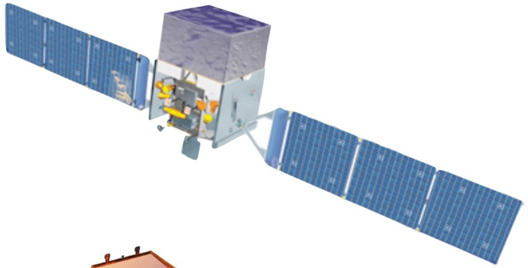
Decadal Survey 2020

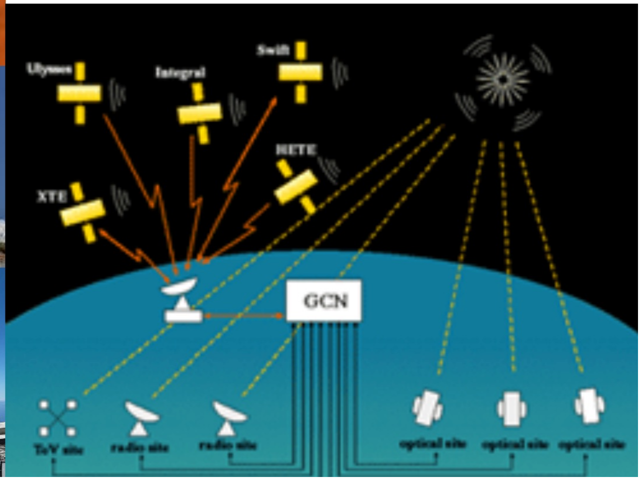
MOTIVATION FOR OUR PROJECT: more measurements!

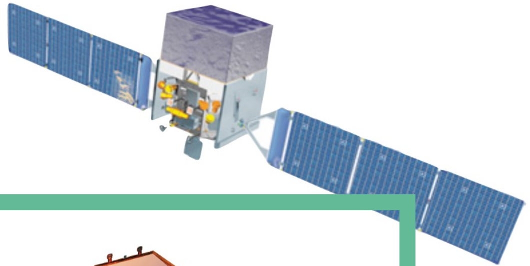
- Since the coincident detection of gravitational waves from a binary neutron-star merger, (GW170817), and the corresponding short gamma-ray burst (GRB170817A), ***detecting an analogous event has been a critical research topic in the multimessenger community***
- The Third Gravitational Wave Transient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

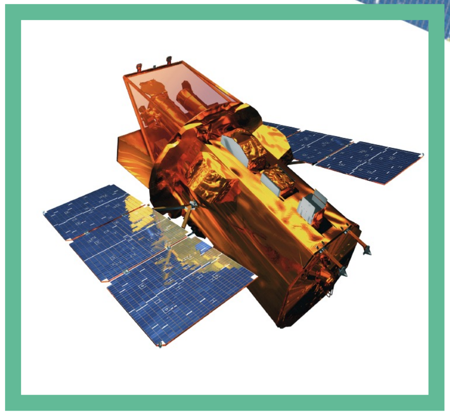
GOALS

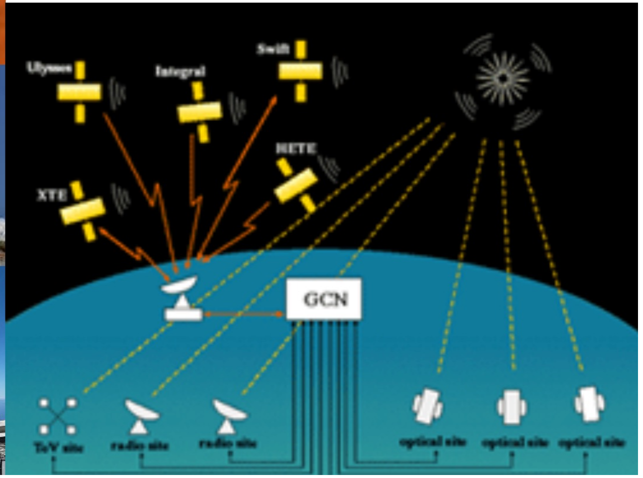
1. **Identify potential electromagnetic (EM) counterparts to GW triggers in GWTC-3 using data from the *Fermi* Gamma-ray Burst Monitor (GBM) and the *Swift* Burst Alert Telescope (BAT)**
2. **Constrain theoretical models for γ-ray emission from GW events**



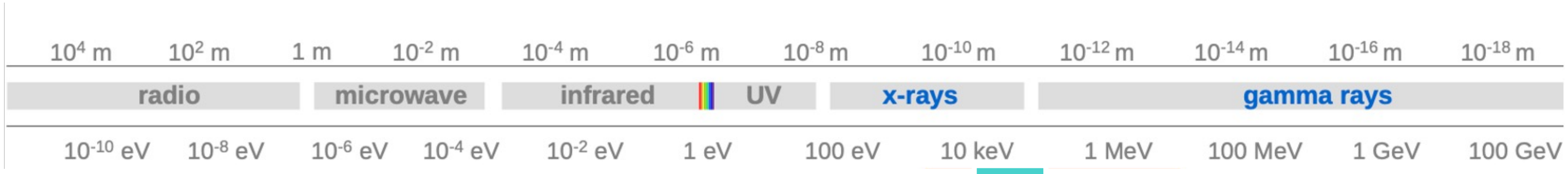

Ulysses
Integral
Swift
HETE
XTE
GCN





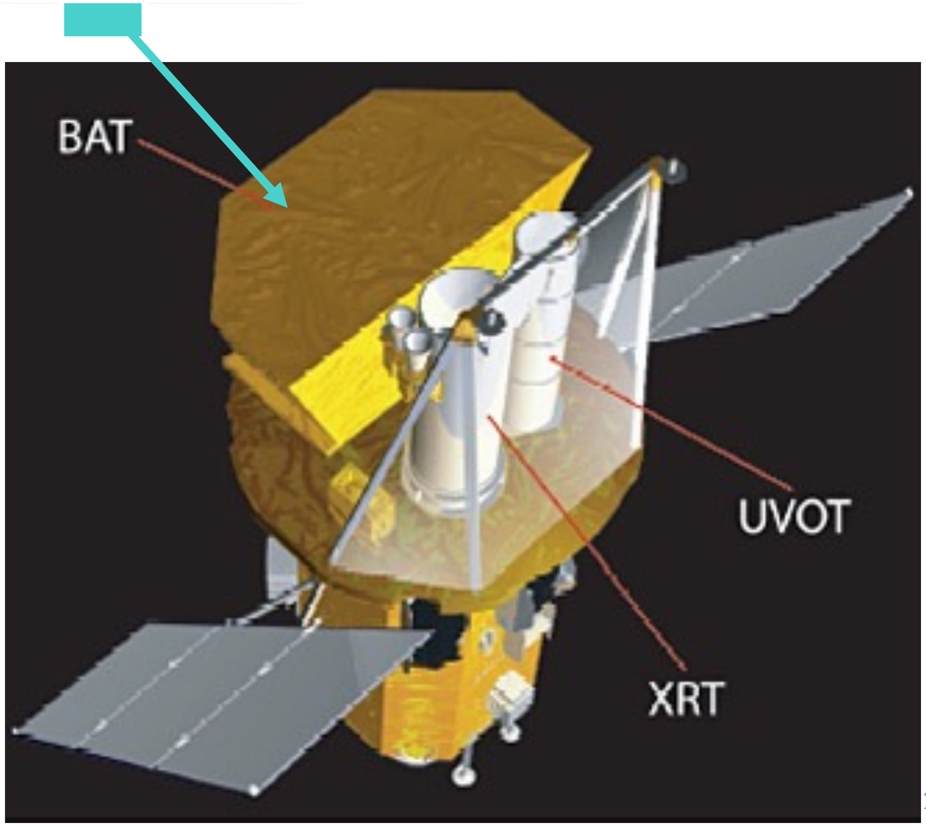

Ulysses
Integral
Swift
HETE
XTE
GCN
TeV site
radio site
radio site
optical site
optical site
optical site

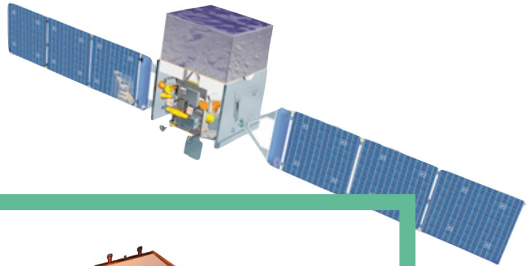
SWIFT BURST ALERT TELESCOPE (BAT)

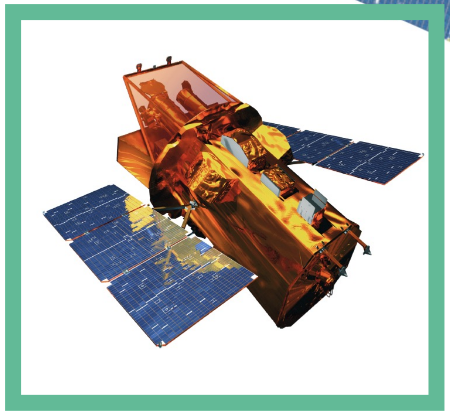


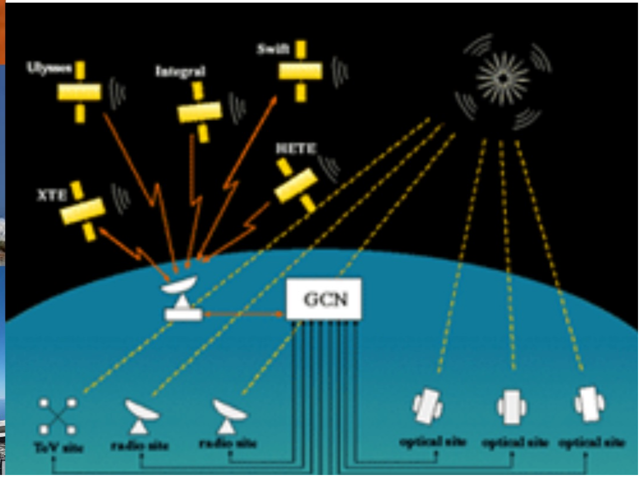
BAT Burst Alert Telescope

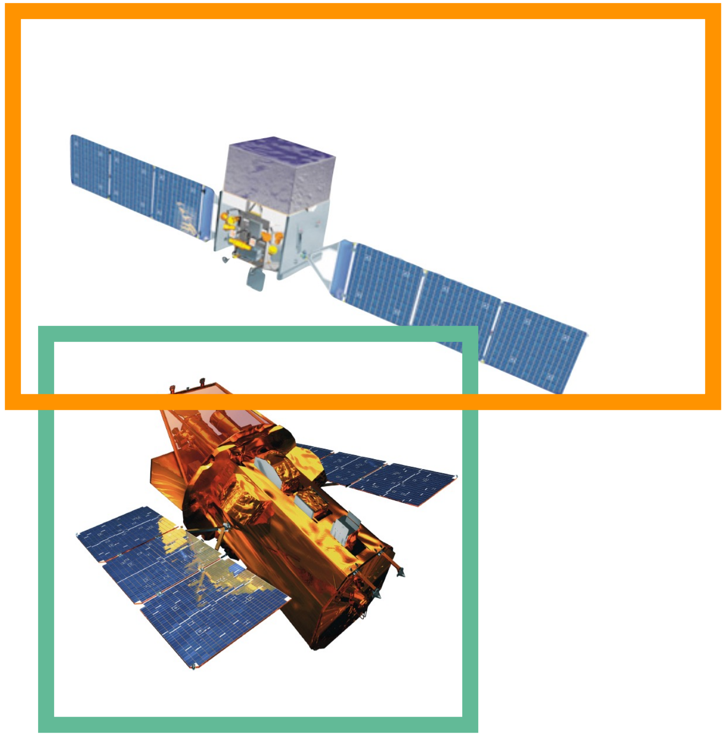
- One of three instruments onboard
- FoV: ~ 2 sr
- Localization ~few arcmin
- 15 keV to 150 keV
- On-board triggers + ground processing

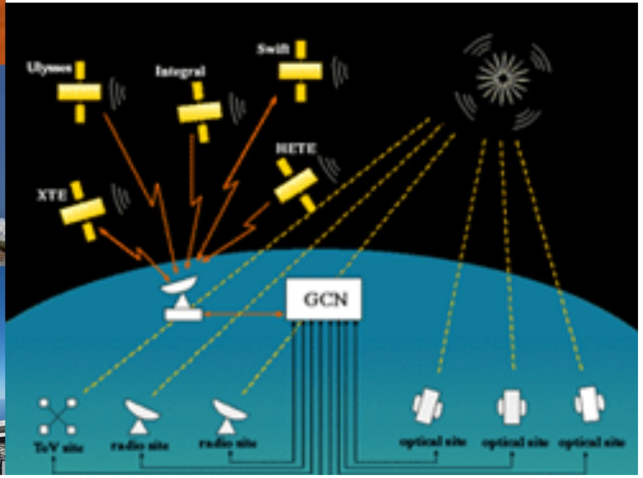




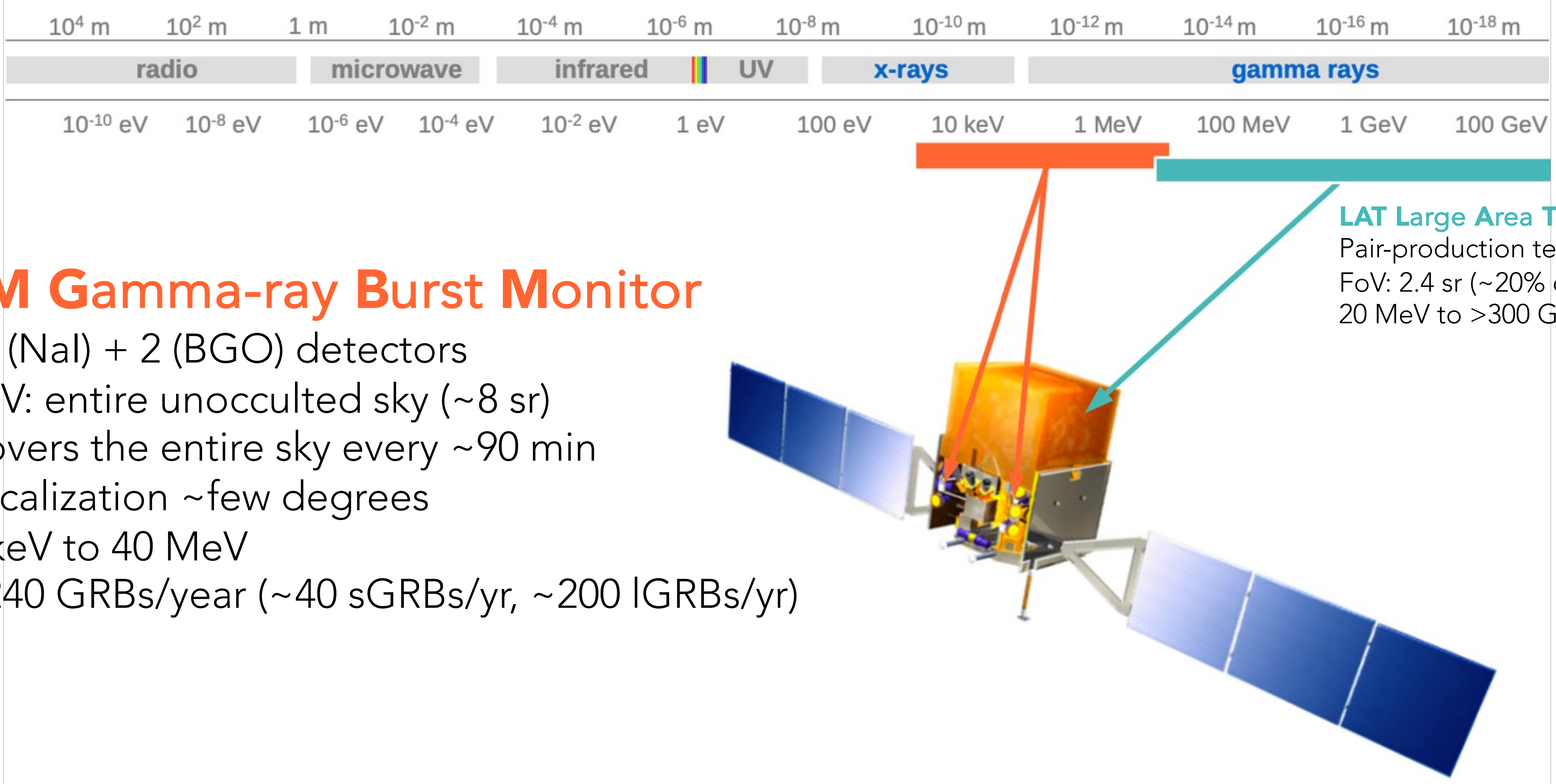



Ulysses
Integral
Swift
HETE
XTE
GCN




Ulysses
Integral
Swift
HETE
XTE
GCN

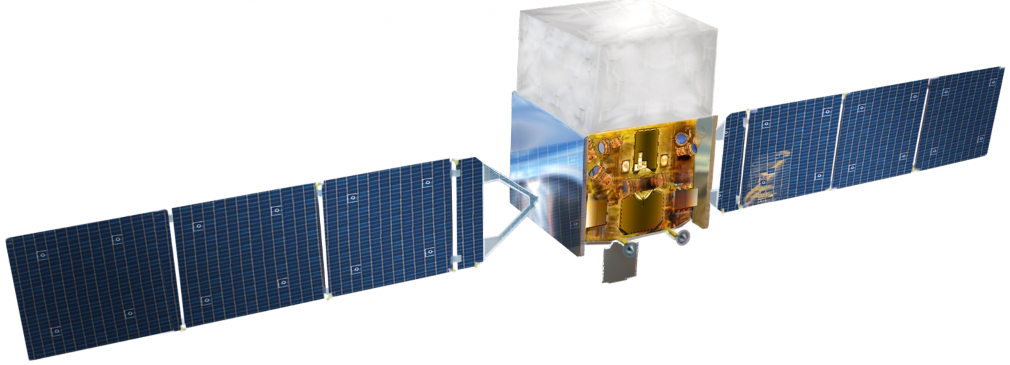
FERMI GAMMA-RAY BURST MONITOR (GBM)

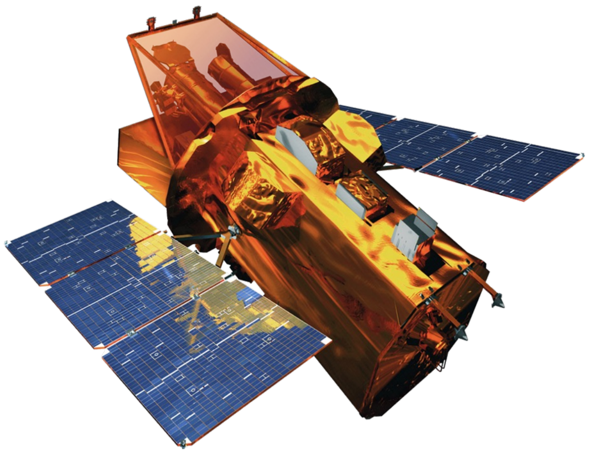


LAT Large Area Telescope
Pair-production telescope
FoV: 2.4 sr (~20% of sky)
20 MeV to >300 GeV

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)





Why *Fermi* GBM?

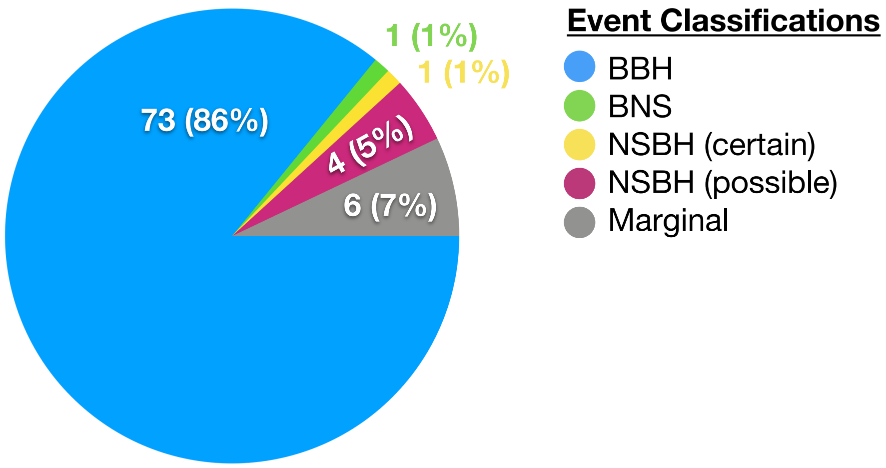
+ ~full-sky field of view
+ energy coverage spanning the peak of GRB emission

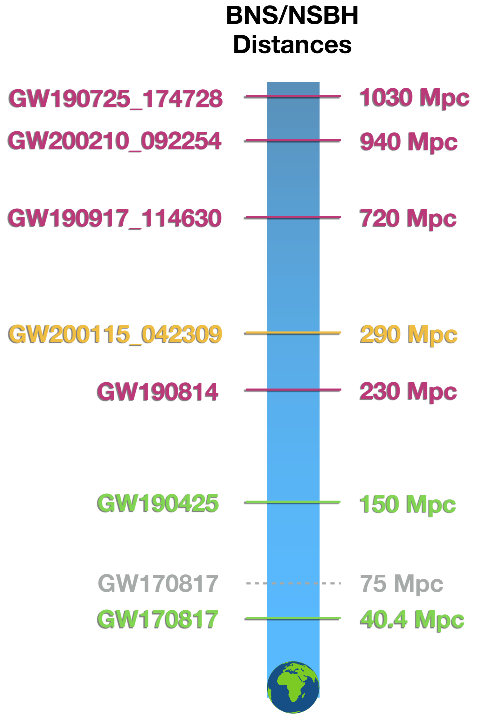
Why *Swift* BAT?

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

O3: THE THIRD OBSERVING RUN

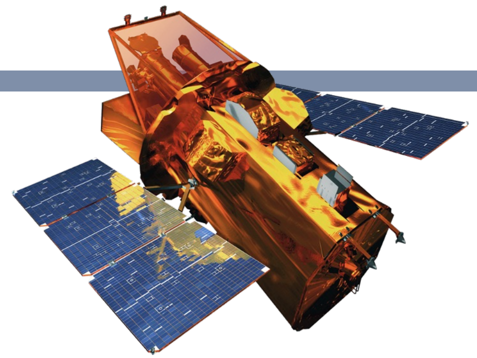
Third LIGO/Virgo observing run (O3): April 2019 -- March 2020 (commissioning break in October 2019)



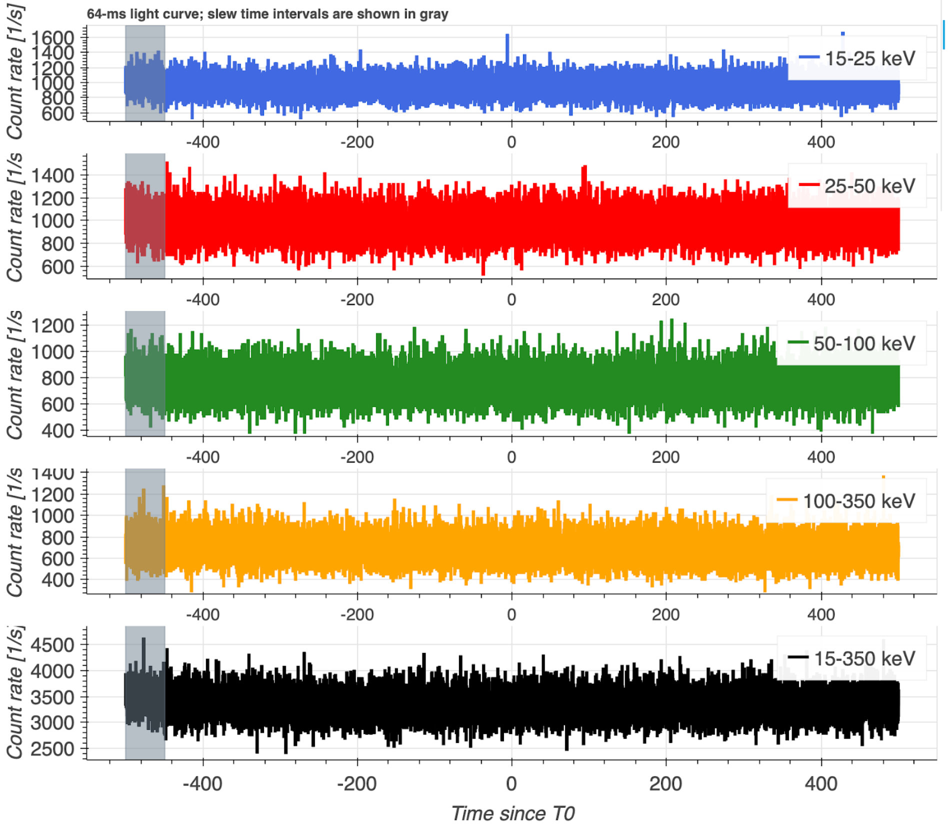


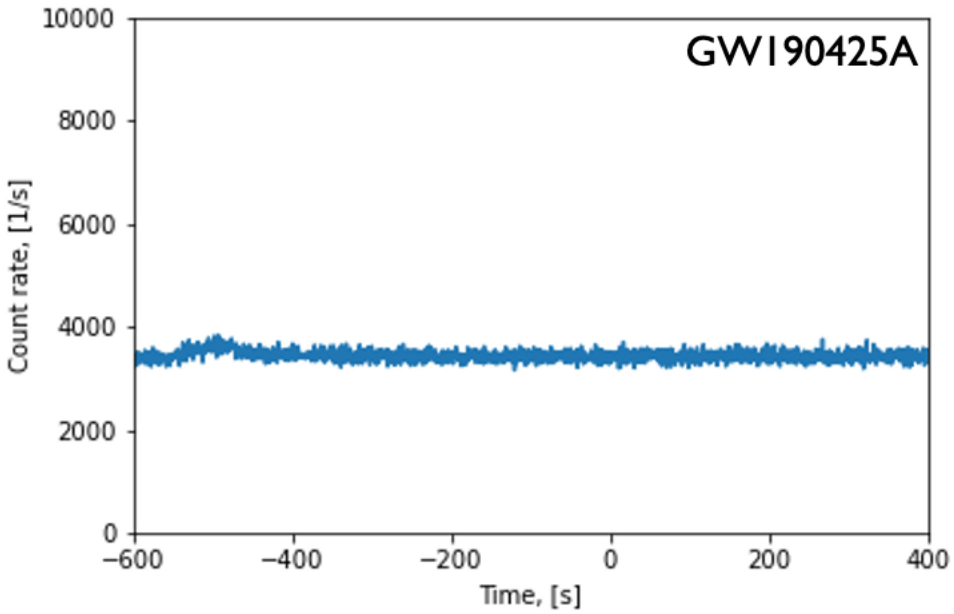
75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

FOLLOW-UP METHODS WITH SWIFT BAT



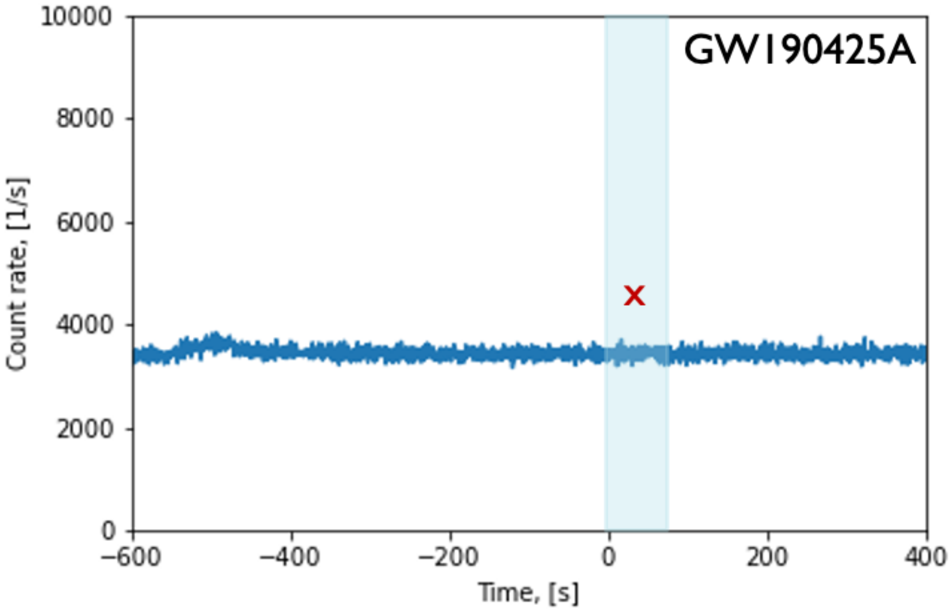
1. Extract BAT raw light curves in 64-ms time bins → rebin to 1 second





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

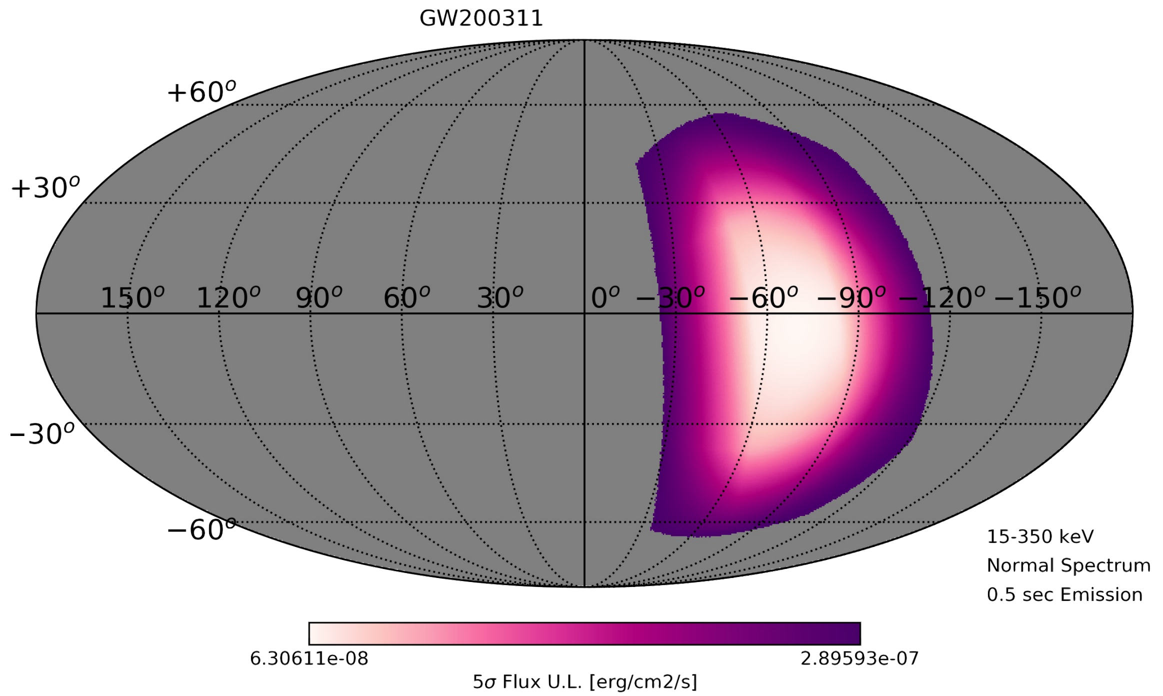
3. Use `NITRATES` to produce response functions for rate data, as a function of the incidence angle onto the BAT detector plane

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

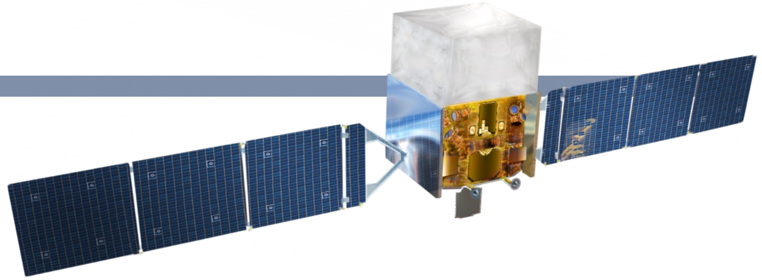
FOLLOW-UP METHODS WITH SWIFT BAT



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:

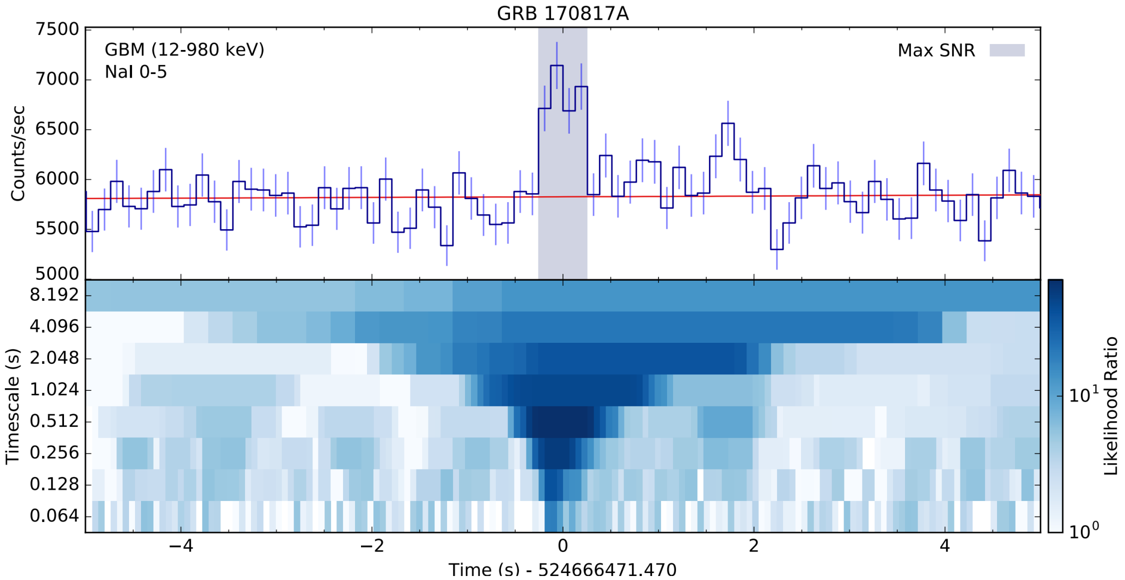
- Targeted: scans -1 to 30 sec around a trigger time
- Untargeted: a blind search of the GBM data

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

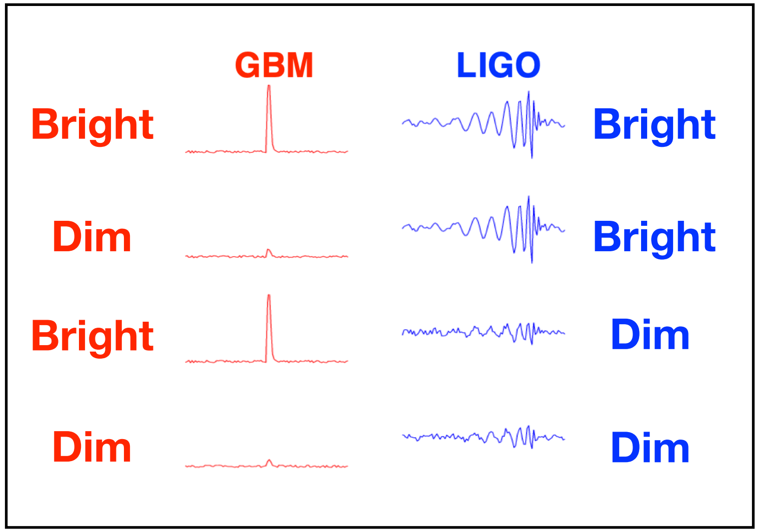
TARGETED SEARCH METHOD FOR COINCIDENT EVENTS

- 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)



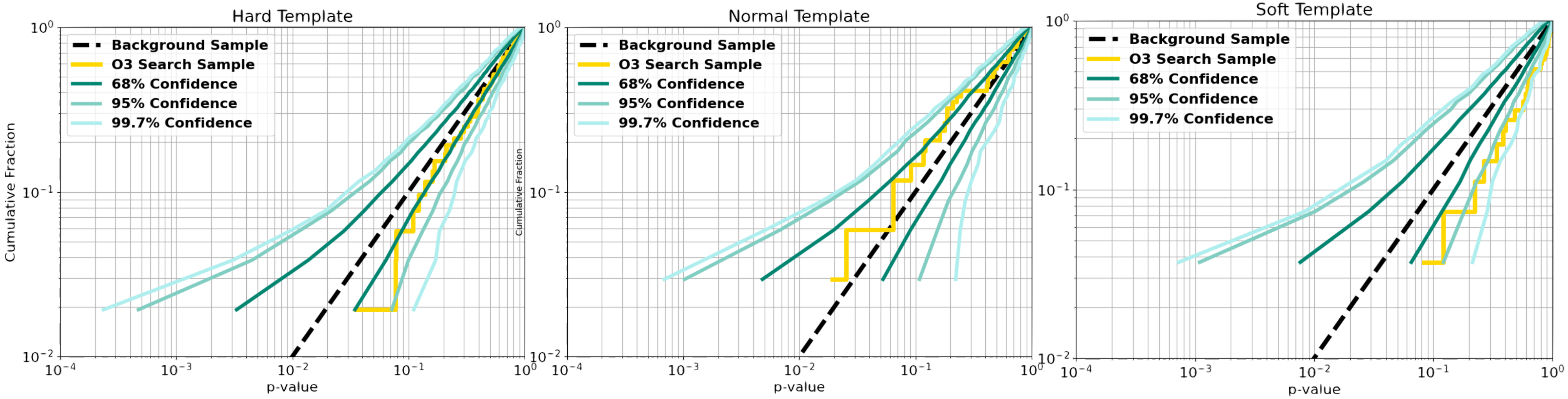
TARGETED SEARCH METHOD FOR COINCIDENT EVENTS

→ 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**

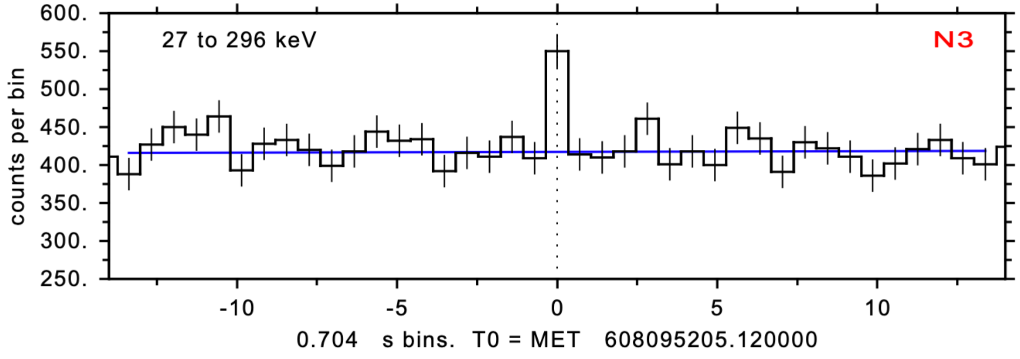
$$R = \frac{p_{\mathrm{astro}} \times p_{\mathrm{vis}} \times p_{\mathrm{assoc}}}{|\Delta t - D| \times FAR_{\mathrm{GBM}}}$$

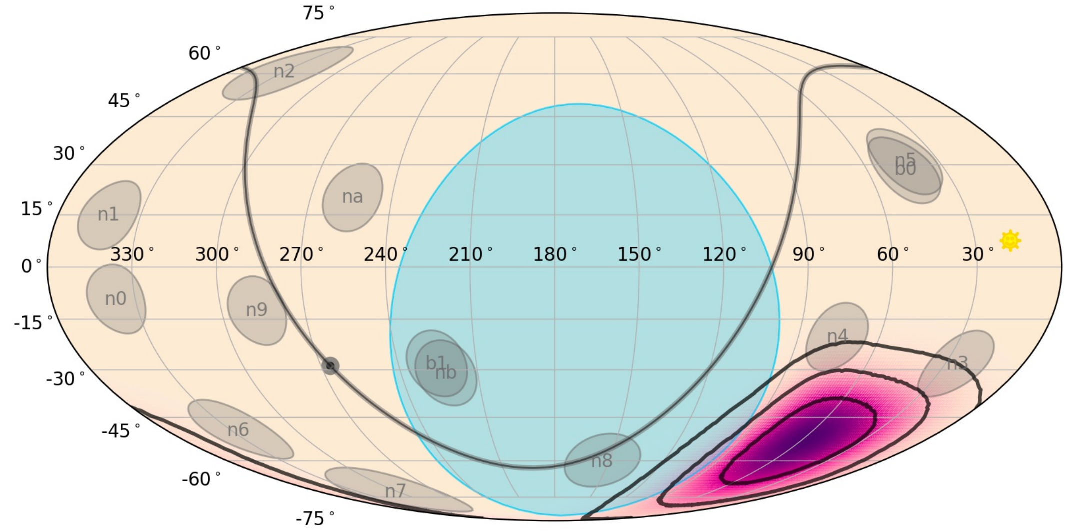


Equation: the probability the GW event is astronomical (p_{astro}), visible to GBM (p_{vis}), and that GW and GBM event are spatially associated (p_{assoc}), the GW-GBM time offset (Δt), GBM event duration (D), and the GBM False Alarm Rate (FAR_{GBM})

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



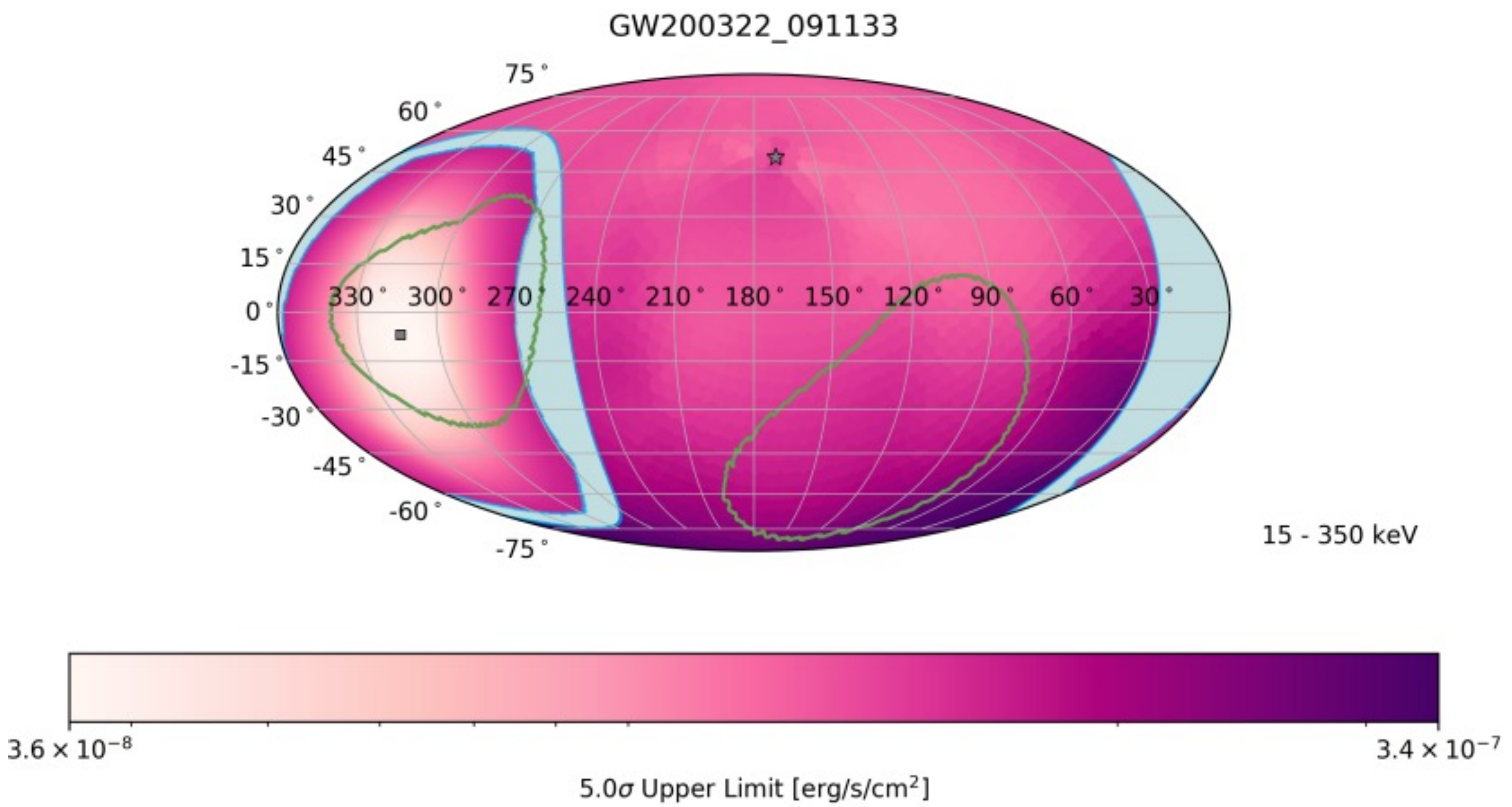


- No statistically significant discoveries.

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

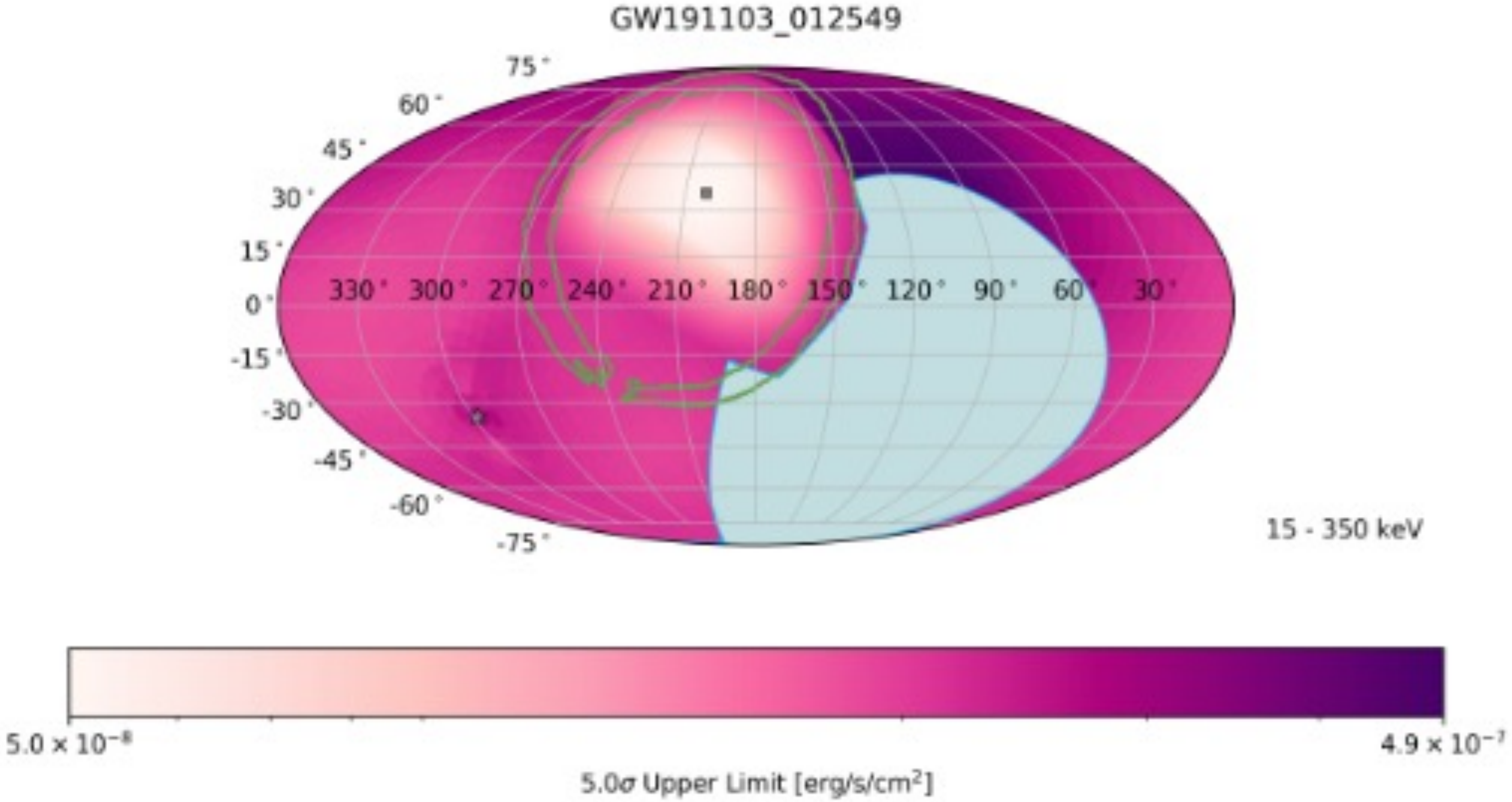
COMBINING THE UPPER LIMITS

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

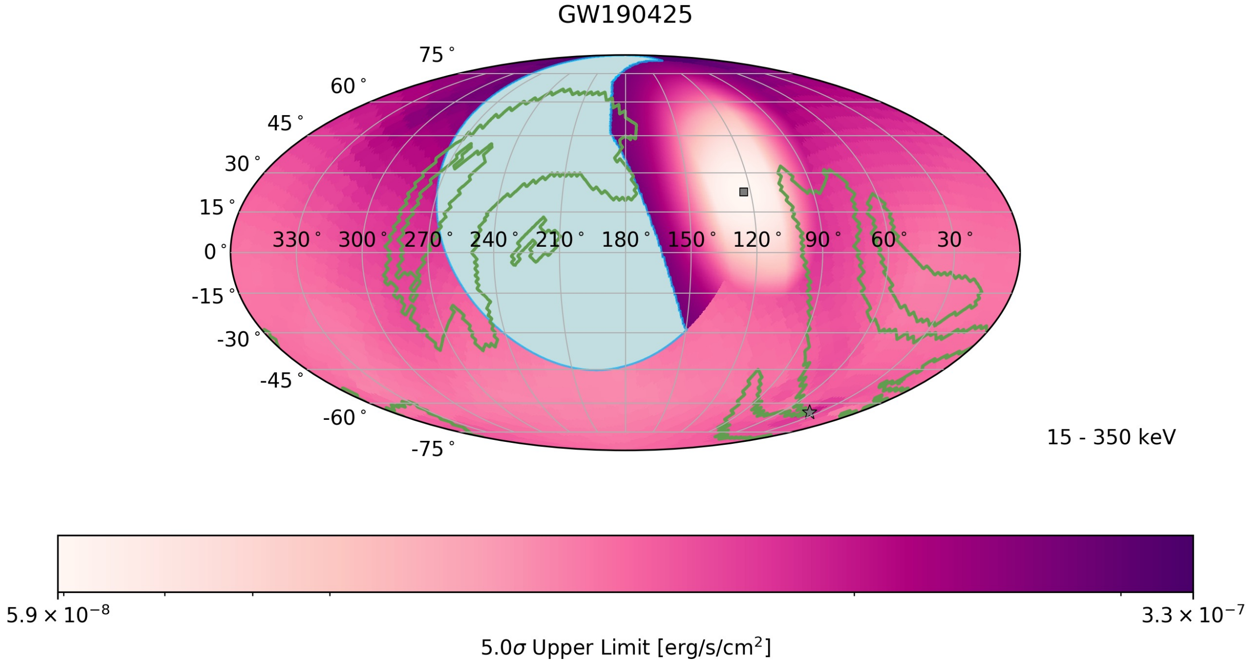


COMBINING THE UPPER LIMITS

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



HONORABLE MENTION: BNS GW190425

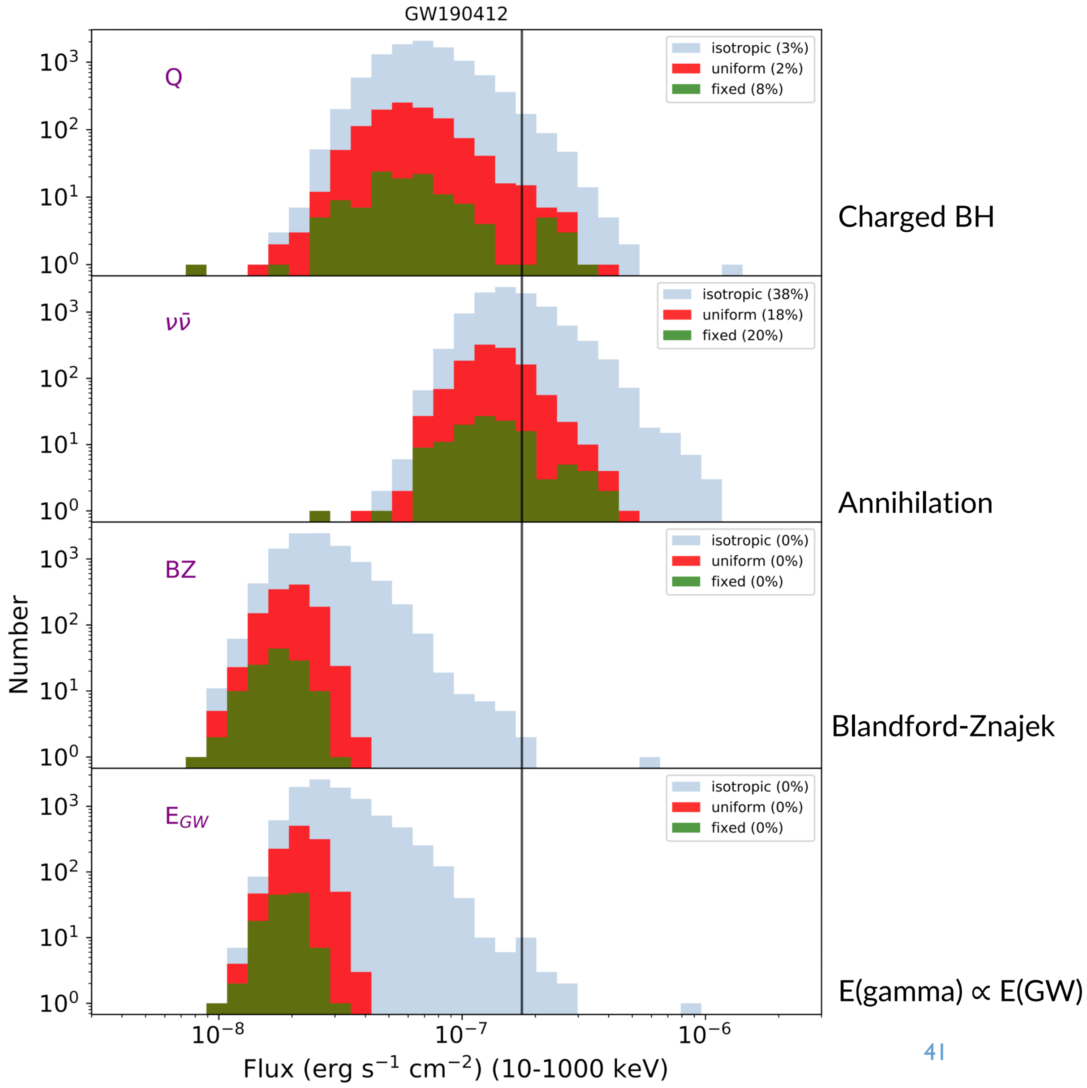


- BNS 190425 is 4 times further away than BNS 170817
- GBM/BAT only see ~60% of the GW localization region
- Inclination angle poorly constrained

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!**