Searching for GRB Counterparts to Gravitational Waves with Fermi-GBM

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on behalf of the Fermi-GBM Team and the GBM+LIGO/Virgo Group

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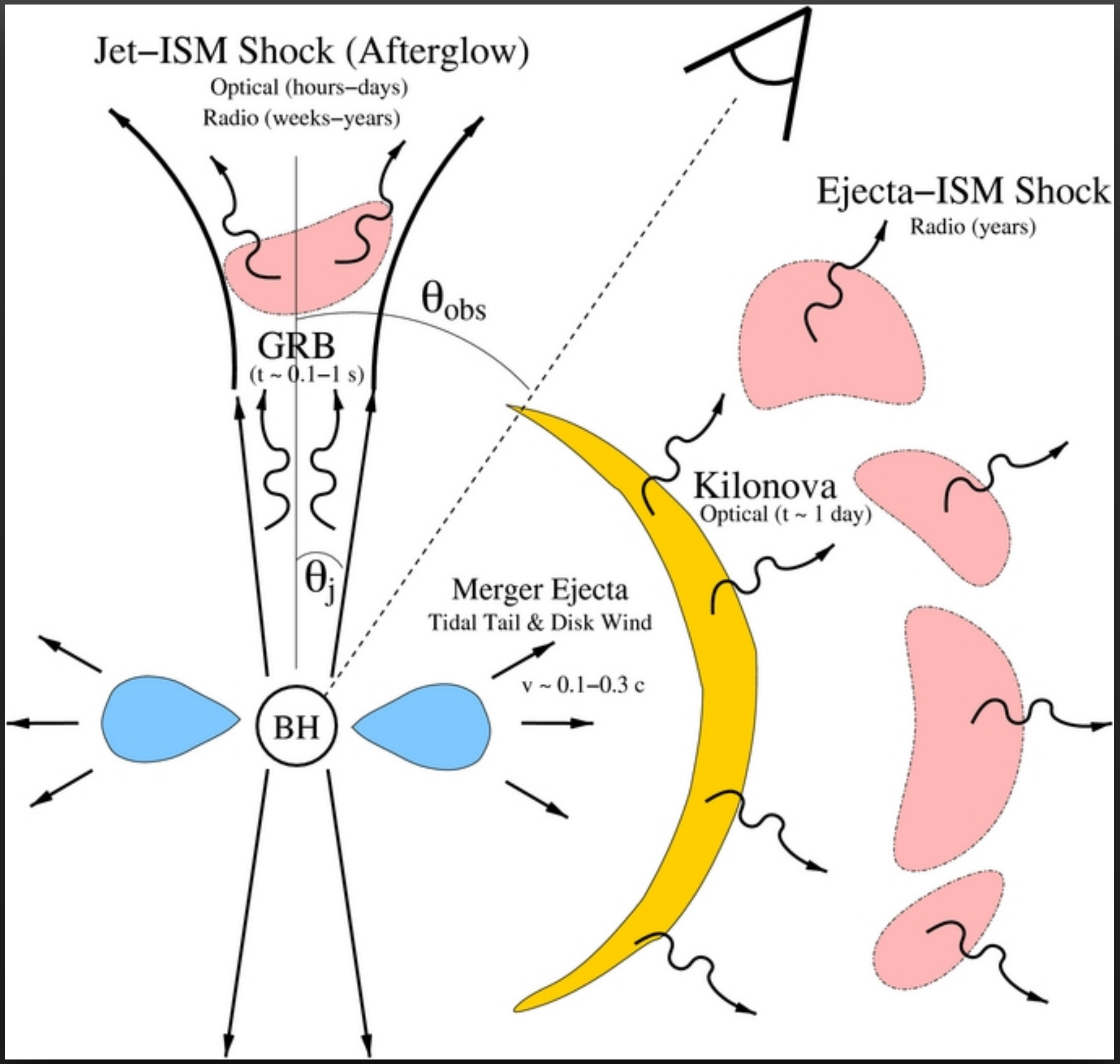
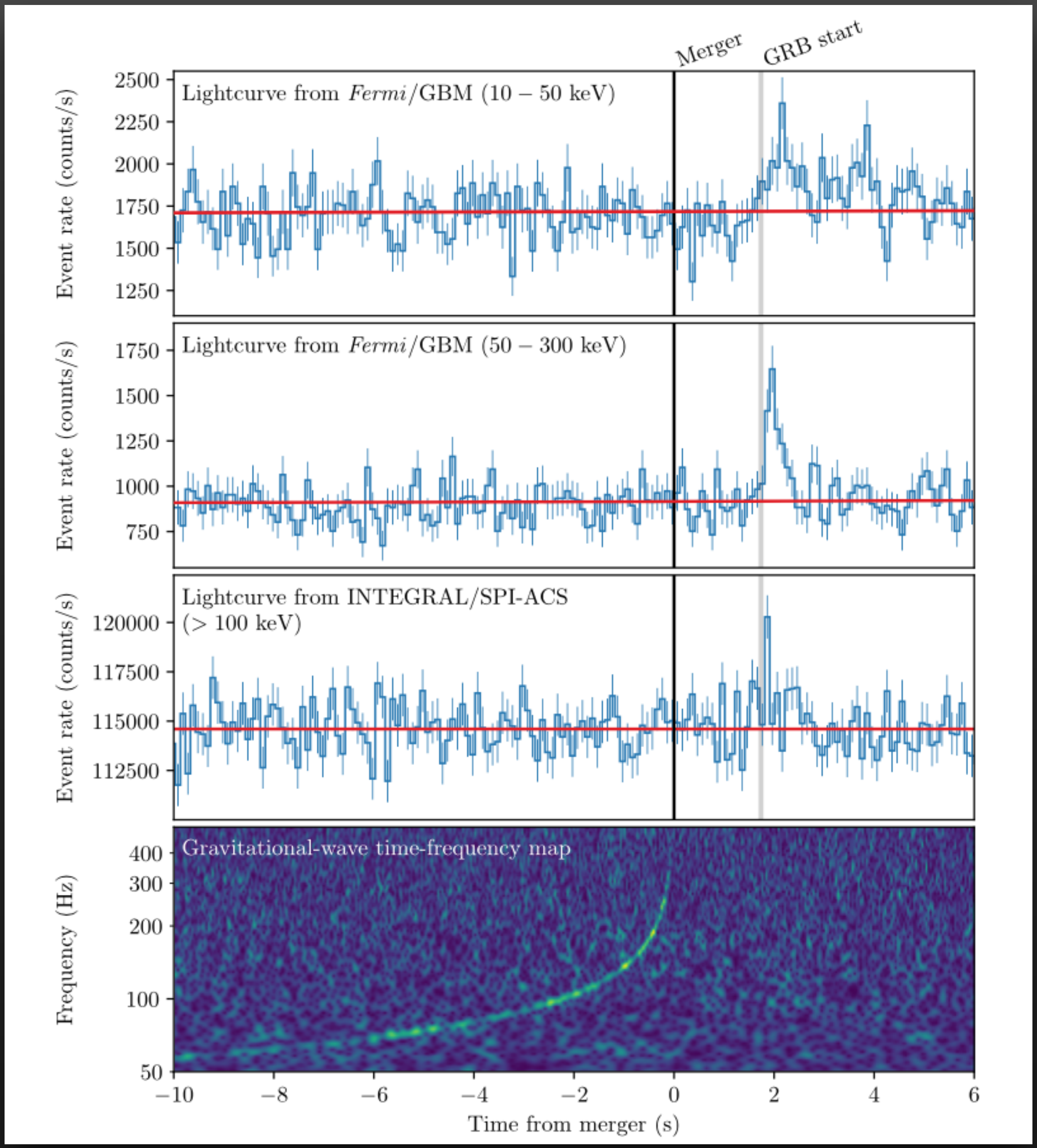
A Theoretical Picture



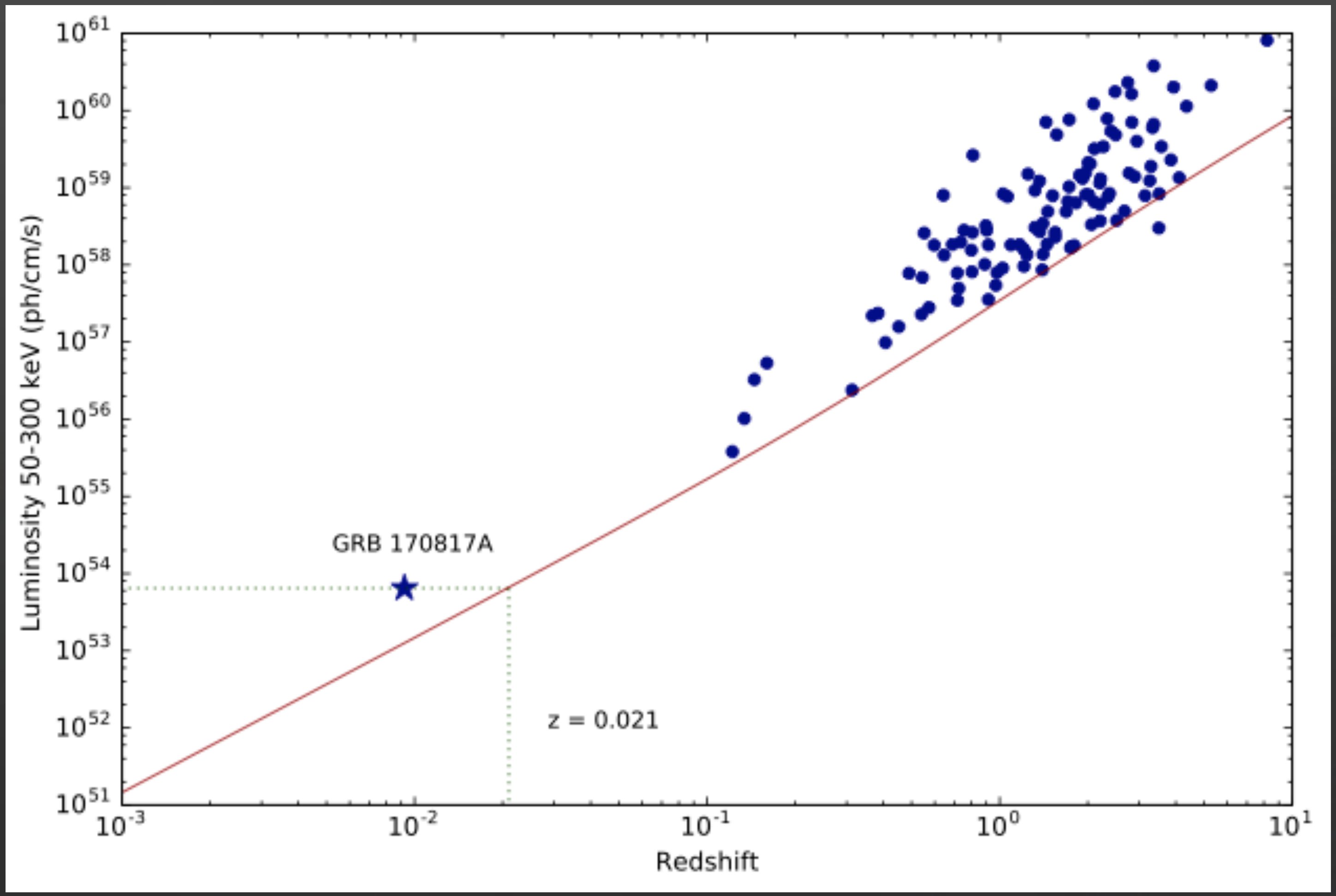
GW170817 / GRB 170817A

- First observation of binary neutron star (BNS) merger in gravitational waves (GWs) and gamma-rays
- Direct confirmation of short gamma-ray burst (SGRB) progenitor
- First unequivocal detection of kilonova and further evidence for r-process production of elements heavier than iron
- Joint science
    - Independent measure of H0
    - Measurement of the speed of gravity
    - Constraints on NS equation of state
    - Test of fundamental physics
    - Much more!



Abbott et al. 2017, ApJL, 848, L13

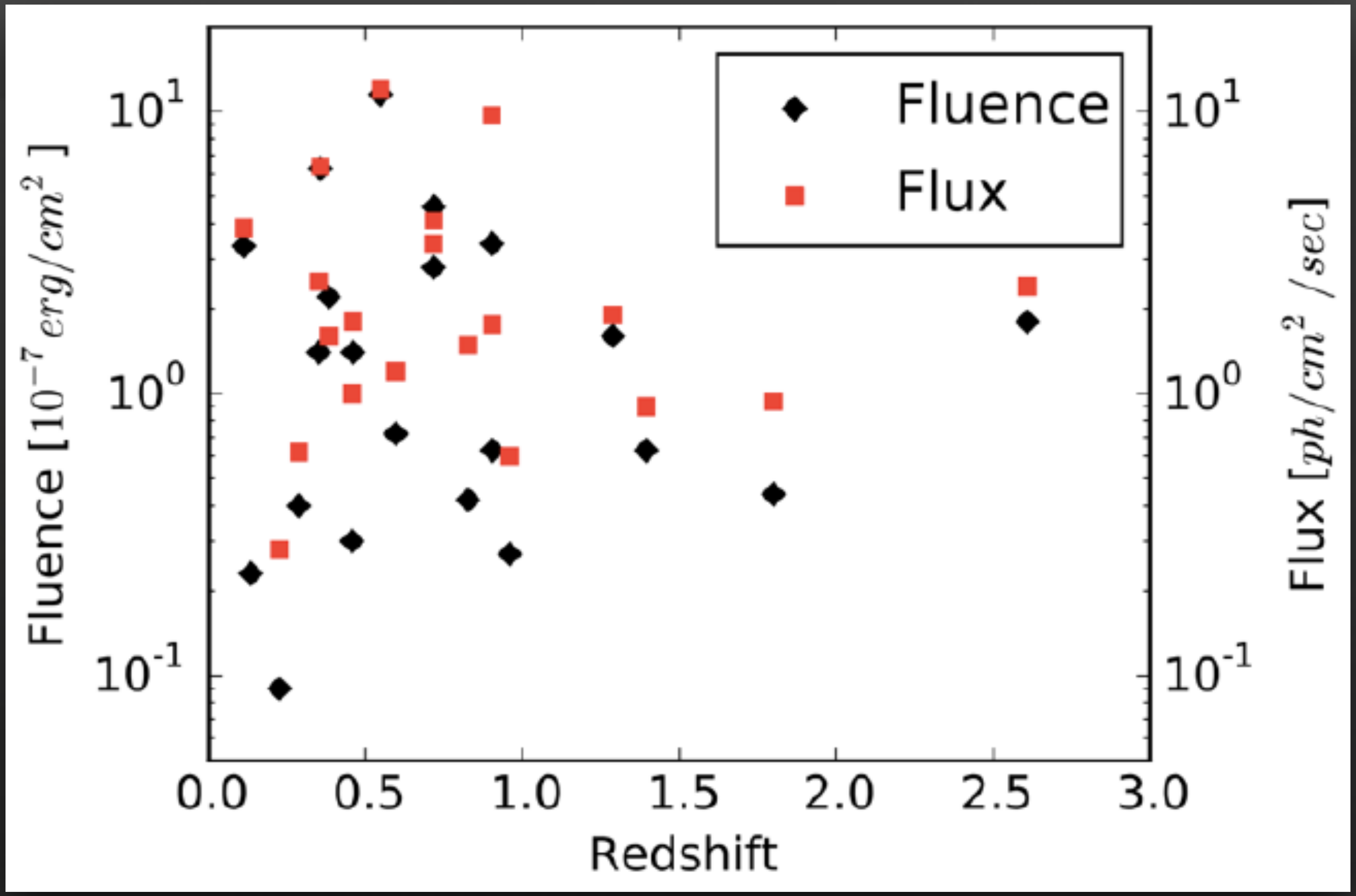
Intriguing Energetics of GRB 170817A



Adapted from Abbott et al. 2017, ApJL, 848, L13

- GRB 170817A was the closest and orders of magnitude less luminous than other GRBs with known redshift
- Late-time x-ray and radio observations support off-axis viewing geometry (Alexander et al. 2018, Mooley et al. 2018)
- Implications for GRB emission mechanisms, jet structure, intrinsic and observed SGRB rate

Nearby, Dim SGRBs



Burns et al. 2016

- Tanvir et al. 2005 - estimated 10-25% of BATSE SGRBs occur $z < 0.025$
- Evans et al. 2016 - predicted SGRB coincident with Advanced LIGO/Virgo BNS would be less luminous than previous bursts
- Burns et al. 2016 - demonstrated nearby SGRBs are not necessarily bright and advocated for subthreshold searches

Detection Horizons

Gamma-ray detection horizon

- GRB 170817A occurred at 43 Mpc
- Max distance GBM would trigger on GRB 170817A: 50 Mpc (Goldstein et al. 2017)
- Bursts as dim as GRB 170817A cannot be detected much farther out by current instruments

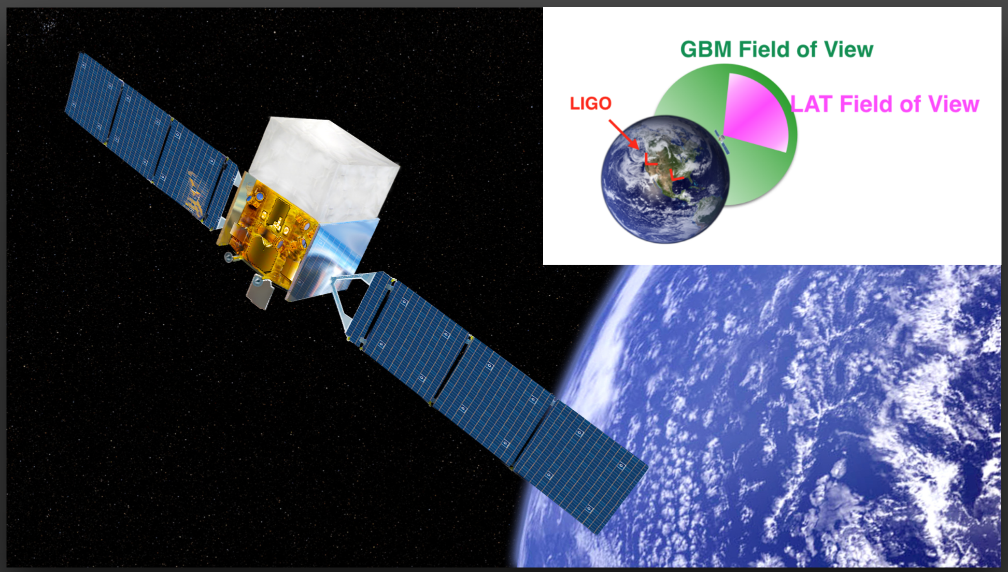
GW detection horizons for BNS during 2018-2019 (Abbot et al. 2018c)

- Advanced LIGO: 120 - 170 Mpc
- Advanced Virgo: 65 - 85 Mpc
- GW interferometers will detect BNS mergers beyond detection limit to weak SGRBs

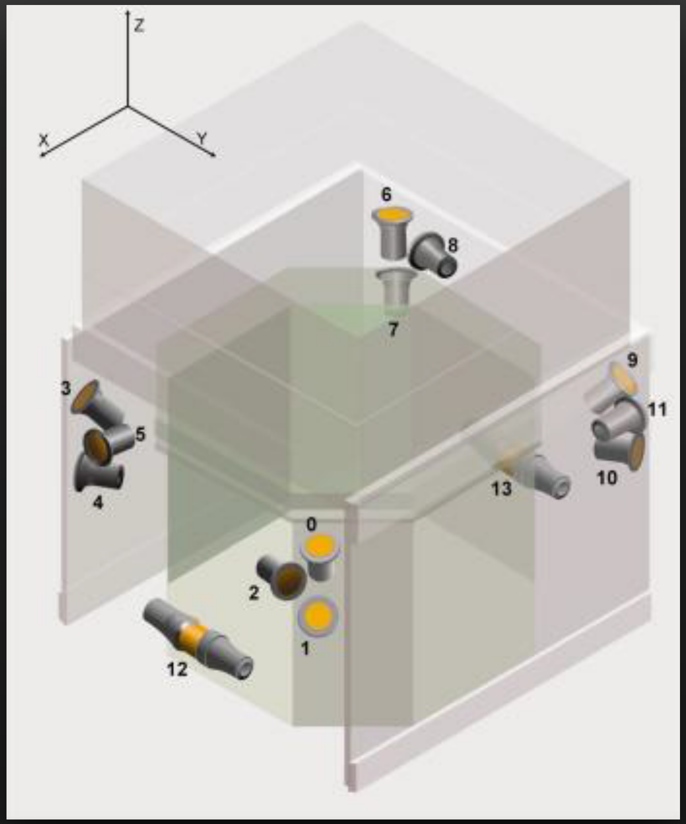
GRB 170817A demonstrates the necessity of the expanding detection horizon to weak SGRBs through subthreshold searches

Fermi-GBM: an ideal instrument

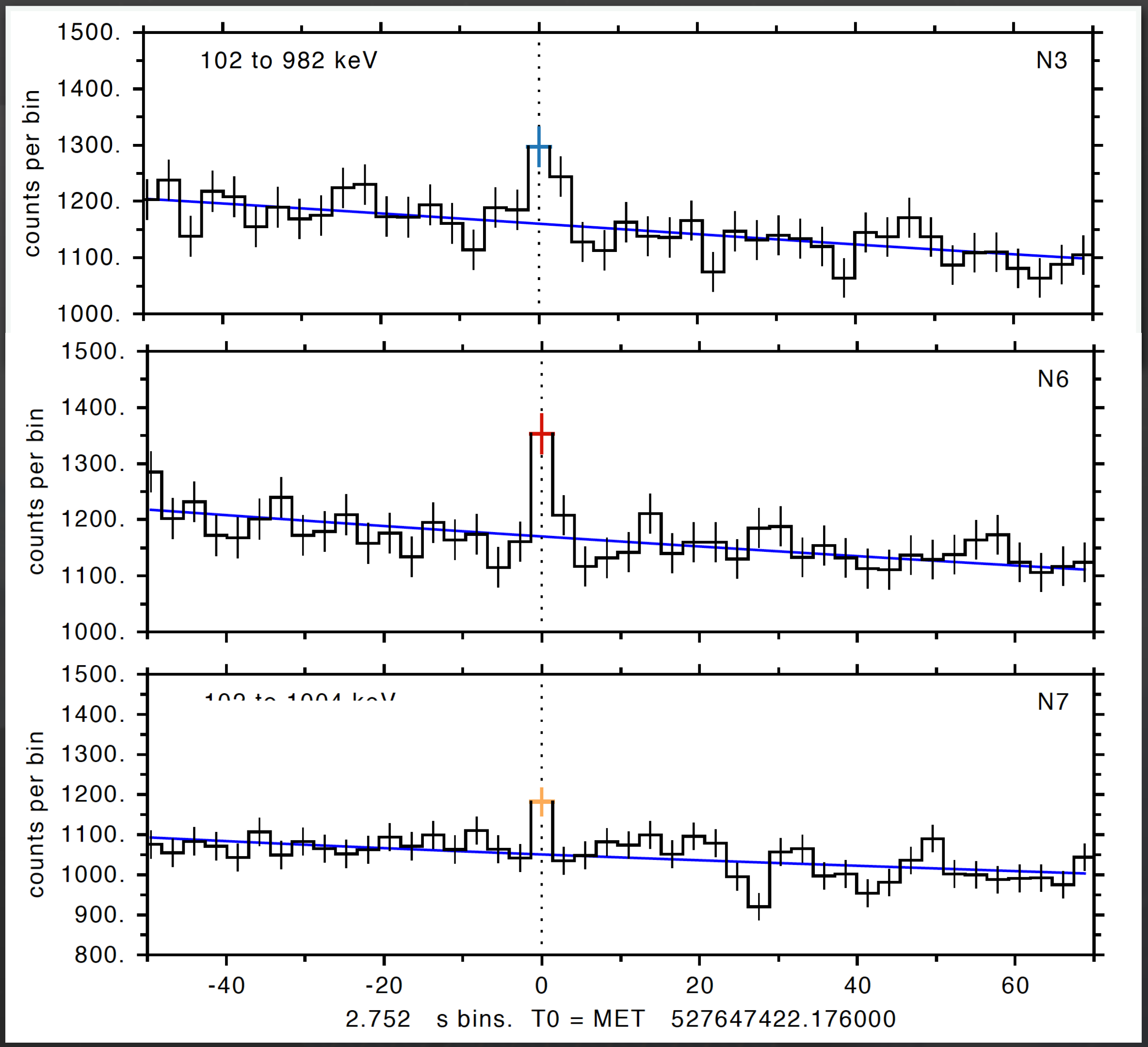
- Survey instrument
- 8 keV - 40 MeV
- 12 NaI(Tl) and 2 BGO detectors
- Large FOV (~70% sky)
- 85% livetime
- Detects ~40 SGRBs per year, more than any other active instrument



- During normal operations GBM gets GW counterparts for free!
- Increased detections of SGRBs through subthreshold searches
- Continuous time-tagged event (CTTE) data for offline analysis
    - 2.6 microsecond timing resolution
    - 128 energy channel resolution



Untargeted Search

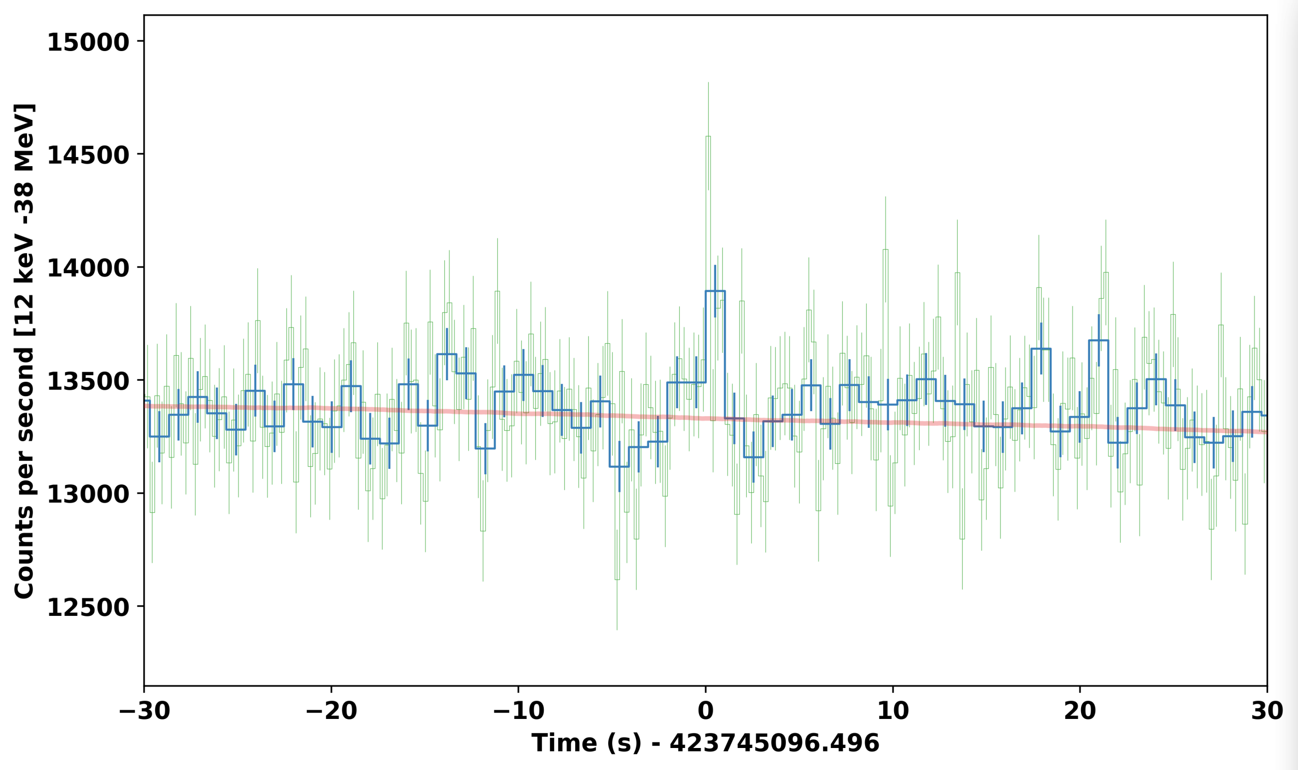


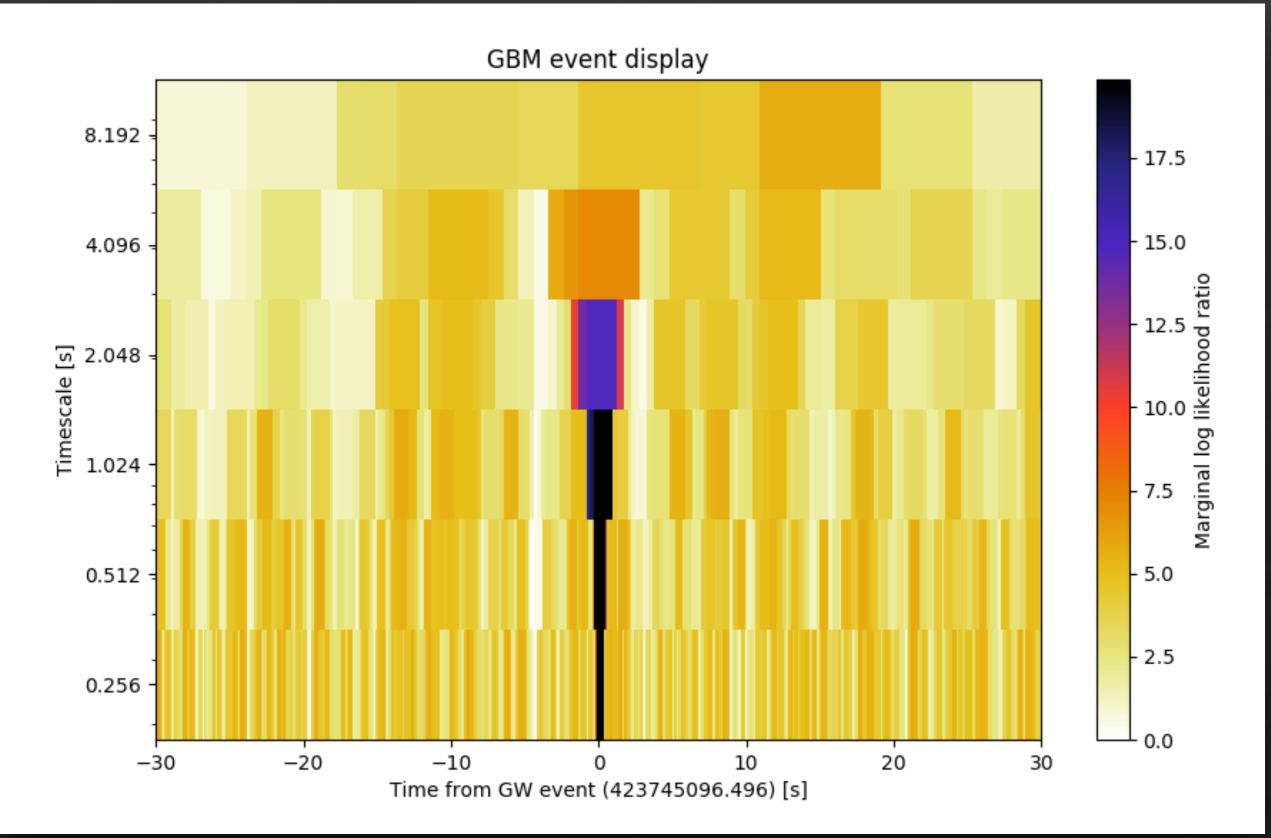
SGRB candidate 527647422 confirmed as GRB 170921C by Insight-HXMT (GCN 21911)

- Offline, agnostic search over all CTTE using extension of flight software trigger algorithms
- Identifies ~80 SGRB candidates / year
- Search results with HEALPIX skymaps distributed via GCN: https://gcn.gsfc.nasa.gov/fermi_gbm_subthreshold.html
- See Briggs et al. poster

Targeted Search

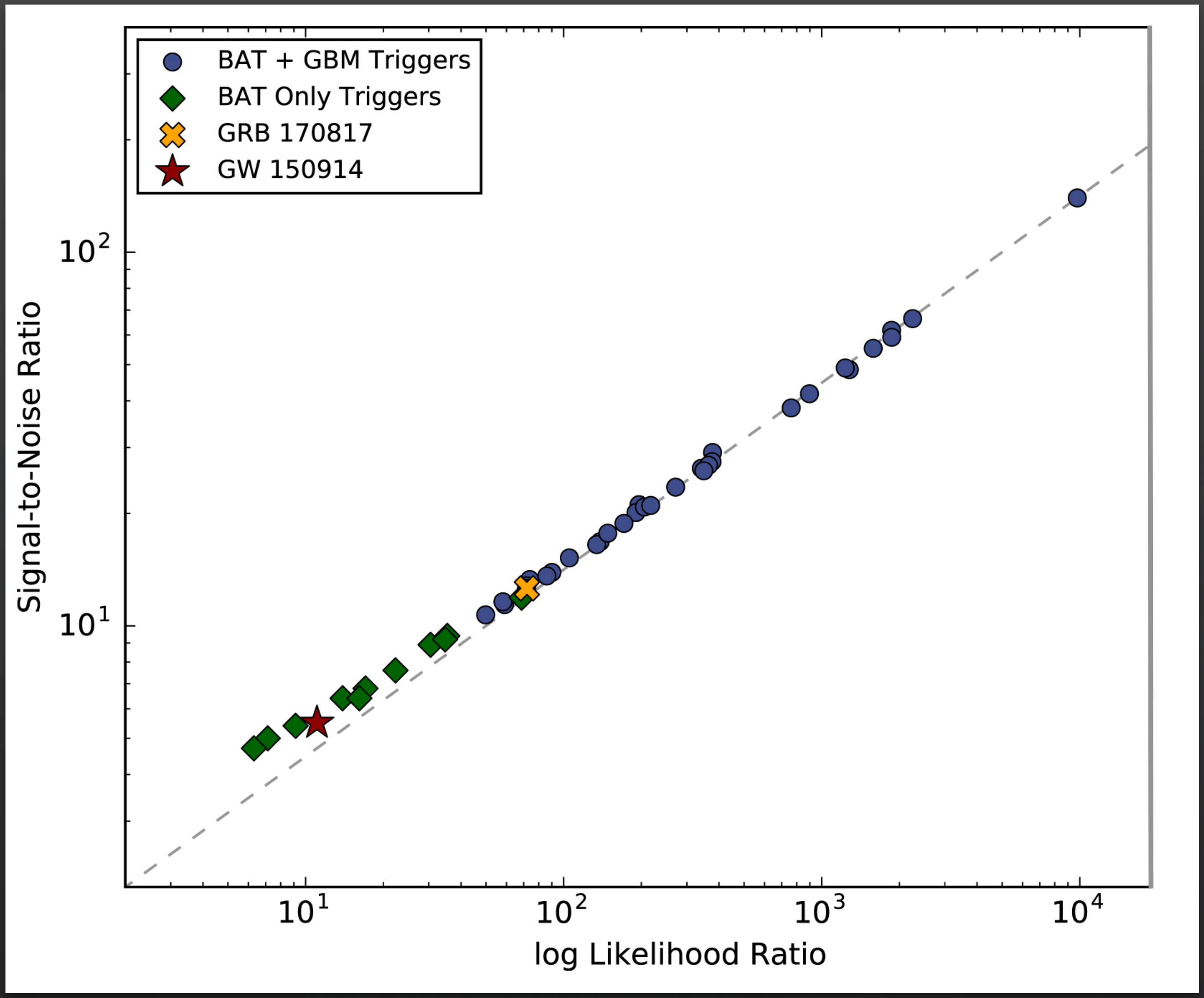
- Input: GW detection time and LIGO/Virgo skymap
- Coherently combines CTTE data from all 14 detectors, using detector responses and assumed photon spectrum
- Test statistic based on log likelihood ratio comparing presence of signal to null hypothesis of pure background





Swift GRB 140606A uncovered in GBM by the Targeted Search

Detecting Subthreshold GRBs



Kocevski et. al 2018

- 9 out of 11 Swift-BAT SGRBs found in GBM data by Targeted Search
- Increases BAT-GBM SGRB detection rate by 20%
- GRB 170817A could have been detected with Targeted Search out to 74 Mpc
- Confirms GBM can successfully recover real signals below trigger threshold

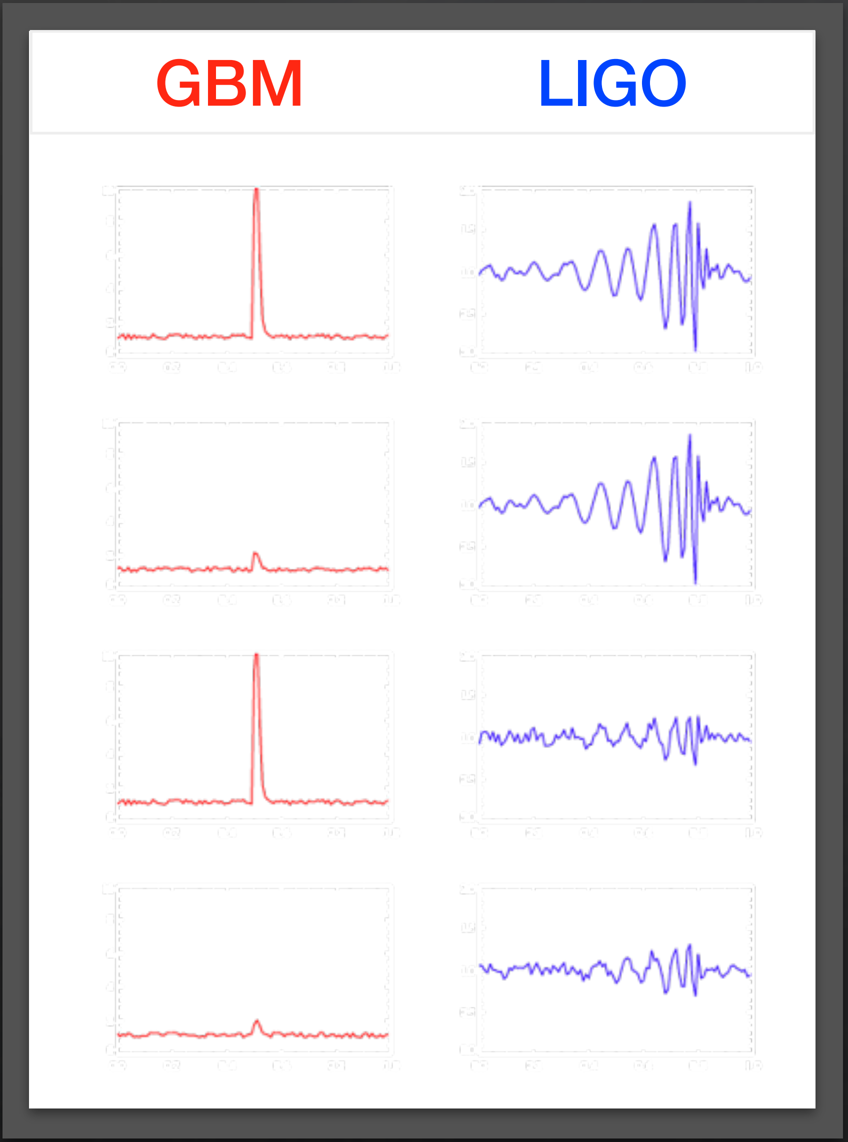
GBM + LIGO/Virgo

- Members from GBM and LIGO/Virgo work together to improve pipelines and participate in joint analysis
- Under special MOU, GBM given access to events below LIGO/Virgo reporting threshold
    - O1 paper submitted to ApJ and currently on arXiv: https://arxiv.org/abs/1810.02764
    - O2 analysis currently underway!
    - Preparing for O3!

Joint Subthreshold Searches

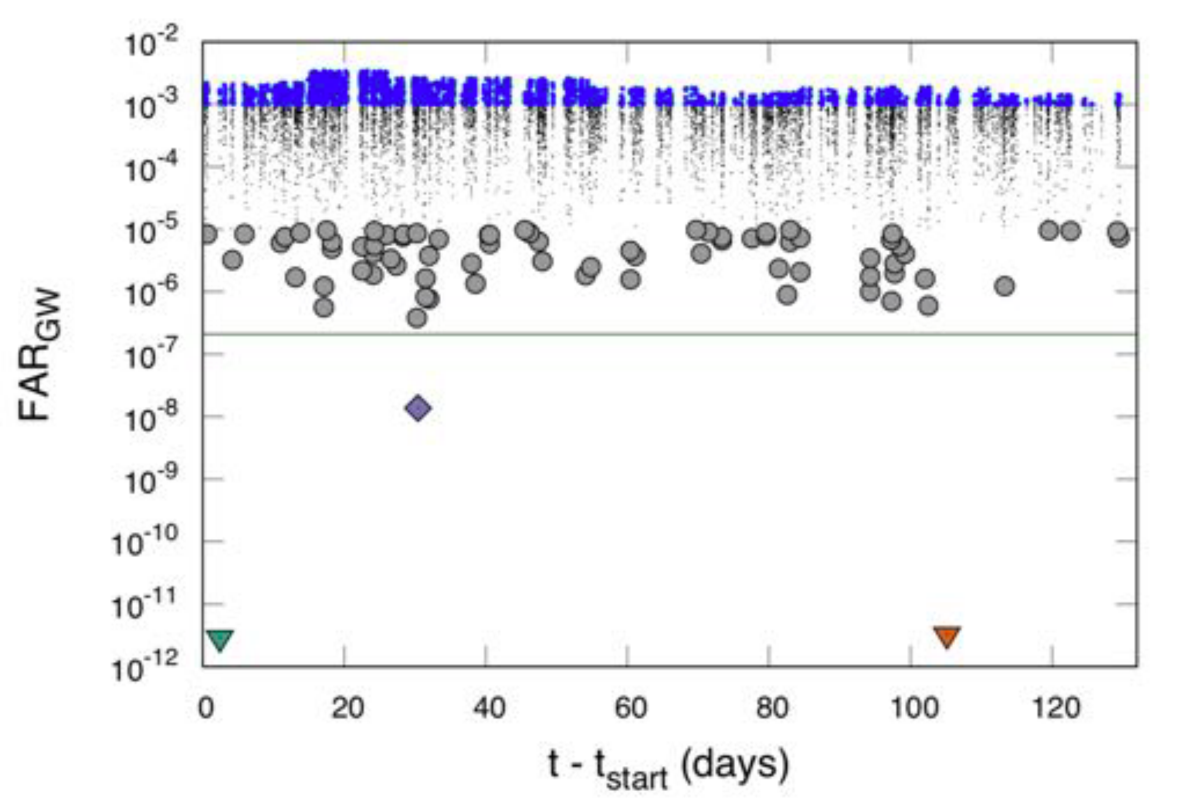
- As GW network improves, GBM will enable additional GW detections of NS mergers through joint searches
- A confident gamma-ray signal can raise confidence in a fainter GW signal, increasing GW detection limit and event rate by a factor of the distance cubed

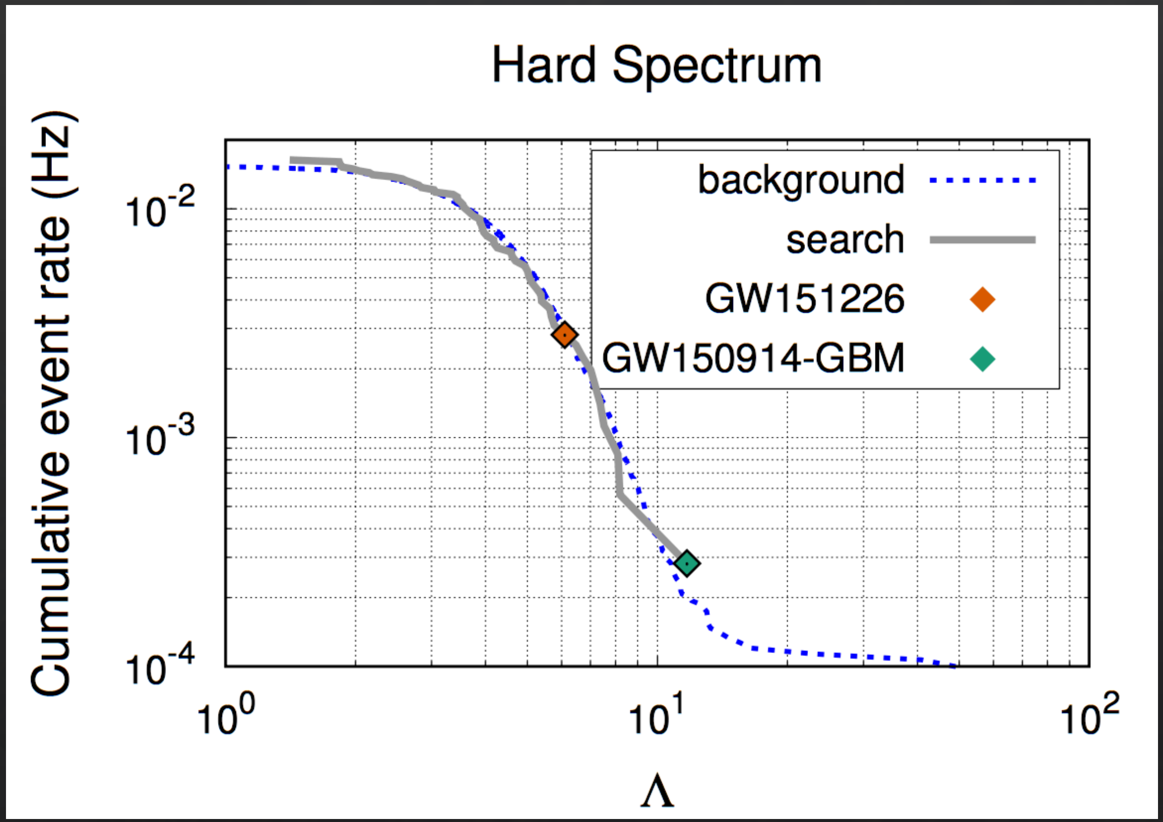
  - Ideal: GRB 170817A scenario
  - Subthreshold GBM
  - Subthreshold LIGO/Virgo
  - Future: both faint sources



Joint O1 Analysis

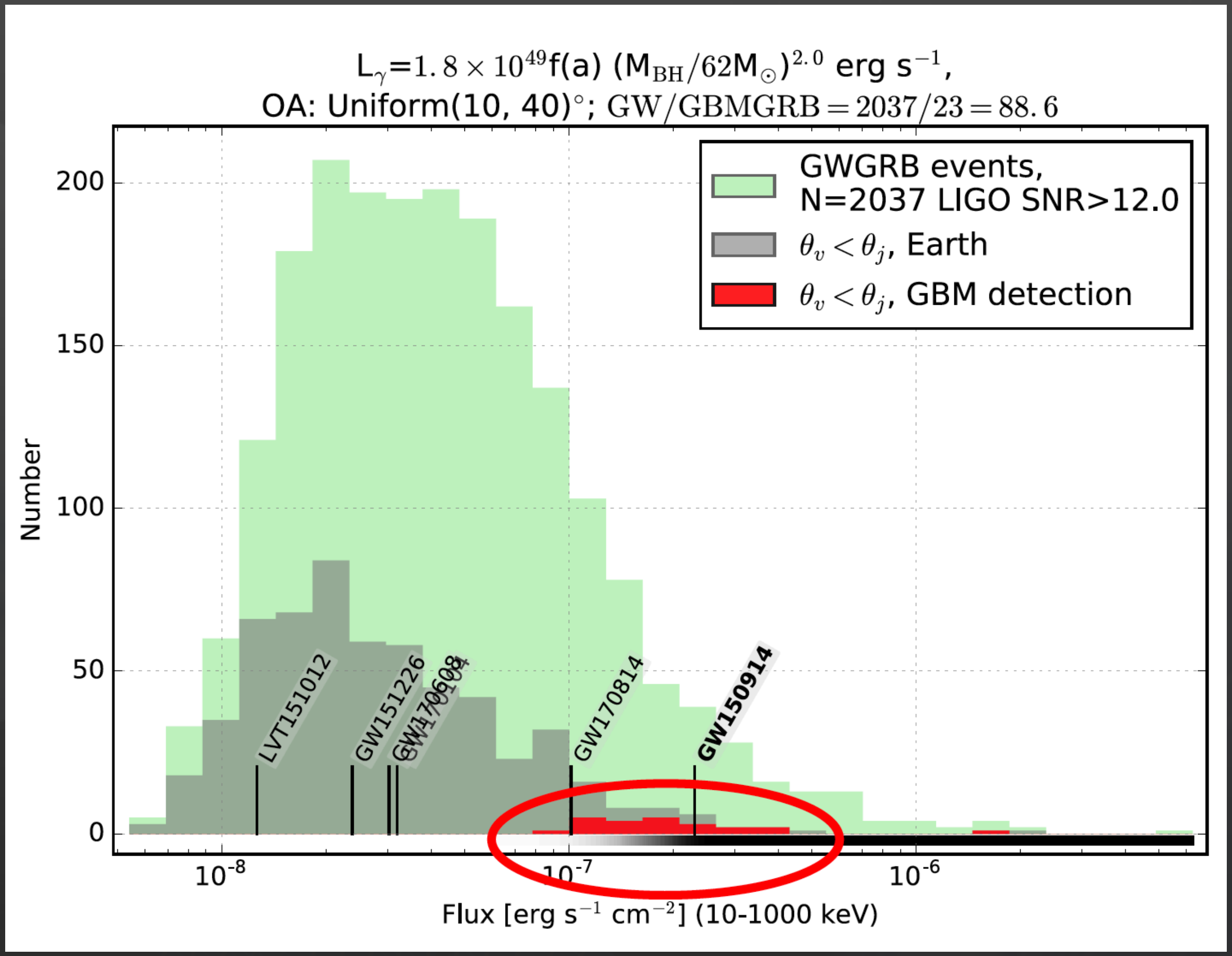
- Search for coincident GBM signals around LIGO CBC events
- The search sample (FAR < ~1/day) is consistent with the background distribution (FAR > 1/(15 min))
- No significant coincidences between CBC events and GBM triggers or untargeted candidates during O1
- GW150914-GBM
    - Candidate with lowest FAR ~2E-4 Hz
    - Lowest post-trials False Alarm Probability ~2E-3
    - Not significant enough to declare EM counterpart





Burns et. al 2018 arXiv:1810.02764

SGRBs From BBH Mergers? (preliminary)

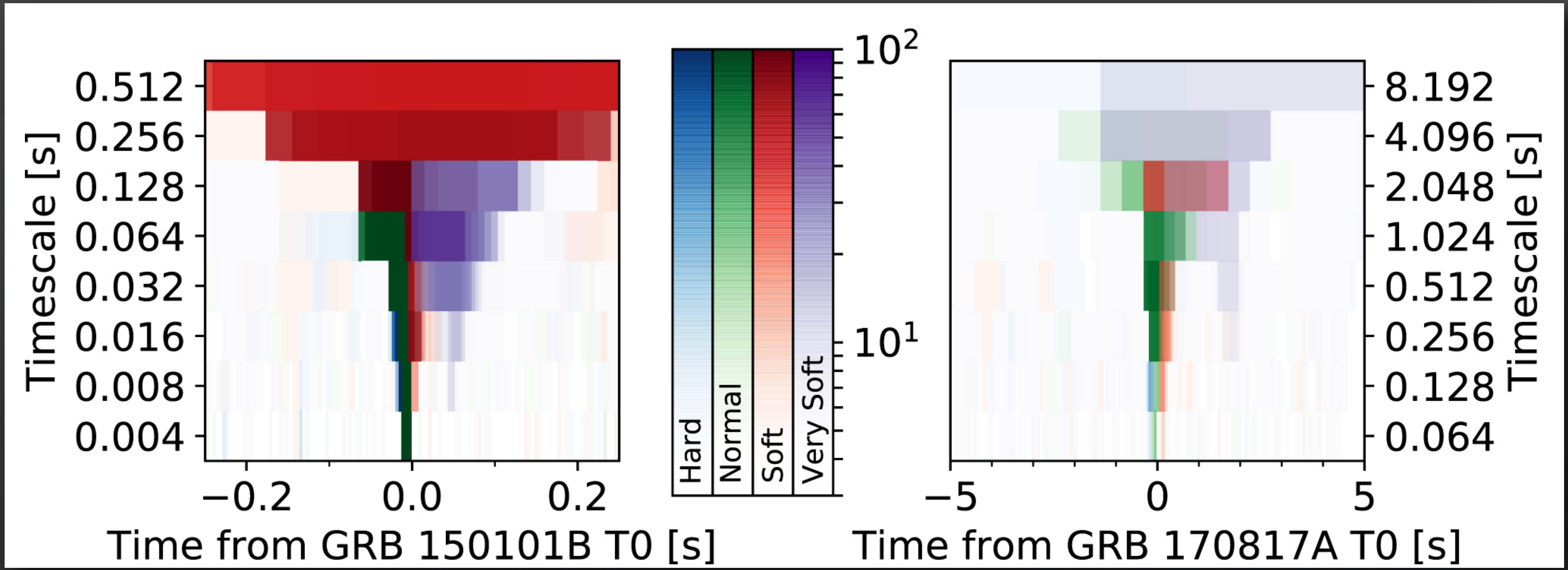


Veres et al. 2018 (in prep.)

1. Generate BBH population (green)
2. Adopt scenario to generate gamma-rays from BBH (Blandford-Znajek, neutrino wind)
3. Normalize flux to GW150914-GBM and assume opening angle
4. Calculate # observed by GBM (red)

Preliminary result: BBH-to-GRB ratio 3 to >100 depending on assumed scenario
Additional observations needed to establish or rule out the nature of GW150914-GBM

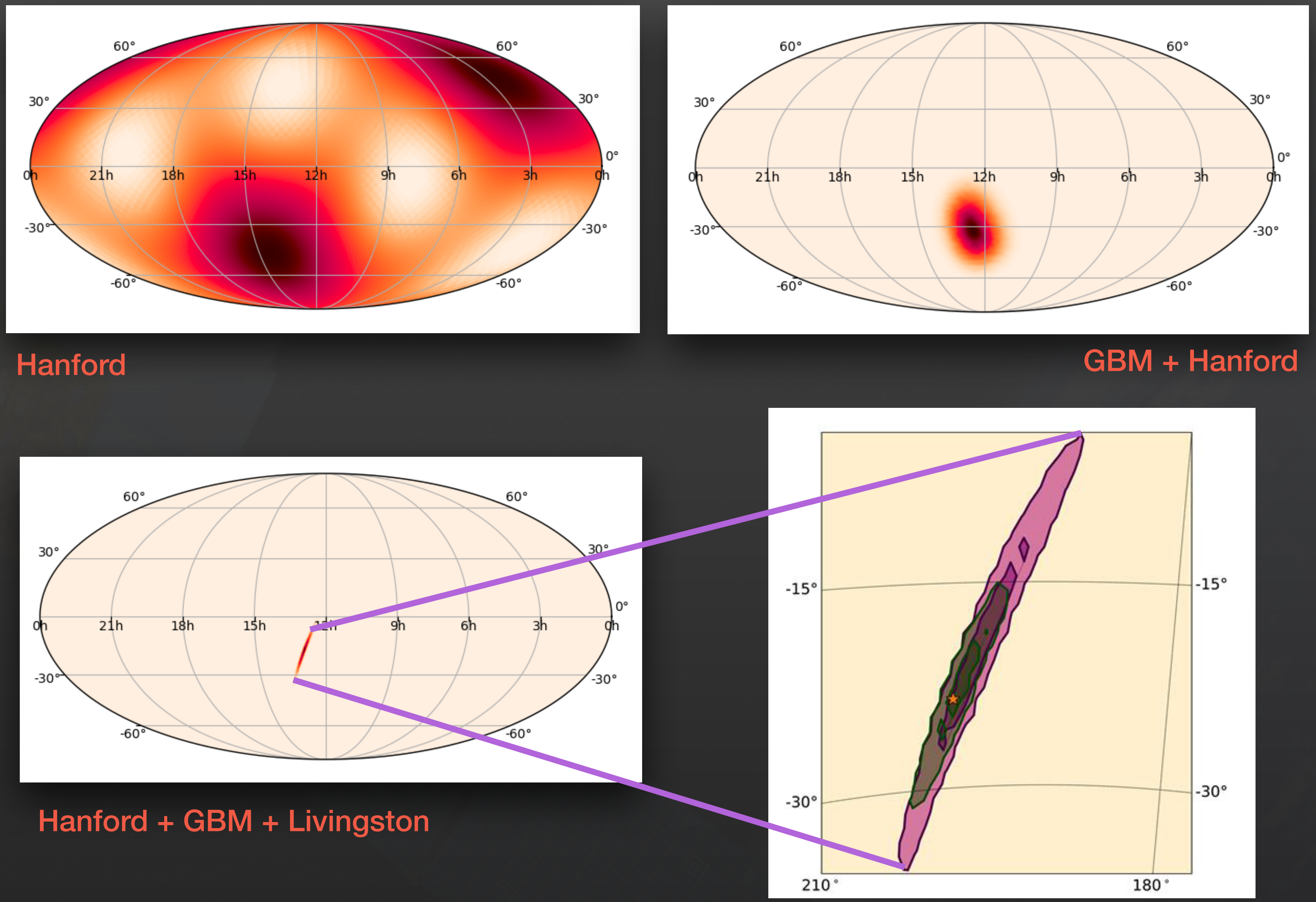
O3 Preparations



Burns et. al 2018

- Pipeline improvements
    - 10x improvement in runtime
    - Improved filters to reduce non-GRB signals in background
    - Additional BB spectral template to identify softer emission

Joint Localizations



- GW duty cycle ~70-75% (Abbot et al. 2018c)
    - 3 (2) GW detectors operating 34 – 42% (78 – 84%) of the time
    - GBM will often constrain single interferometer localizations
- For GRB 170817A, GBM+HL map (~60 sq. deg) could have been produced ~1 hr after GW trigger

Distribution and Latency in O3

Combined GBM + LIGO/Virgo reporting will be done automatically via GCN and will include joint localization skymaps

GBM

- Triggers ~ seconds
- Untargeted search ~ mins-hours
- Targeted search ~ mins-hours

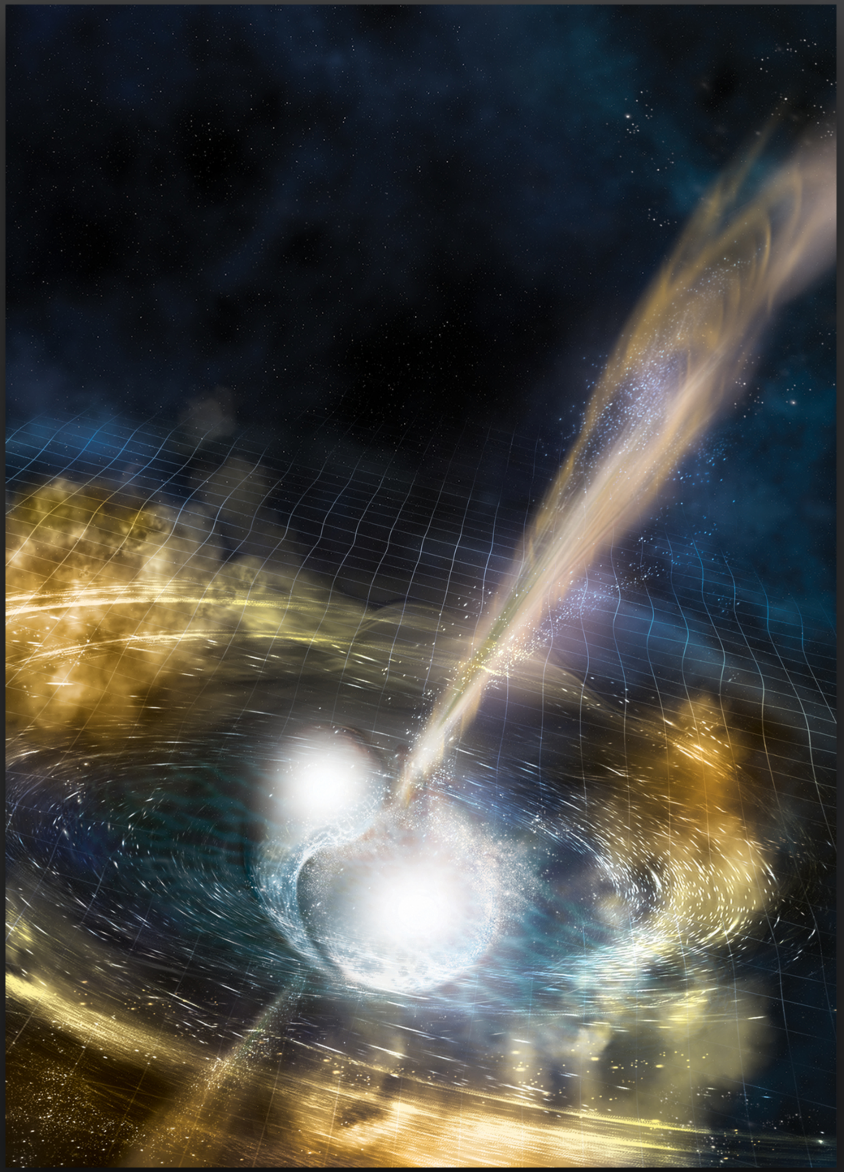
```
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo
Identification of a possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary
identification of a GW candidate associated with the time
 of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47
 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error
radius of 17.45deg.

The candidate is consistent with a neutron star binary coalescence with
False Alarm Rate of ~1/10,000 years.

An offline analysis is ongoing. Any significant updates will be provided
by a new Circular.
```

- Latency for subthreshold searches dominated by data downlink of CTTE from spacecraft
- GRB 170817A was reported via GCN T0+16 s
- First LIGO report on GW trigger coincident with SGRB T0+40 min
- Joint, automatic pipelines between GBM and LIGO/Virgo can reduce reporting latency

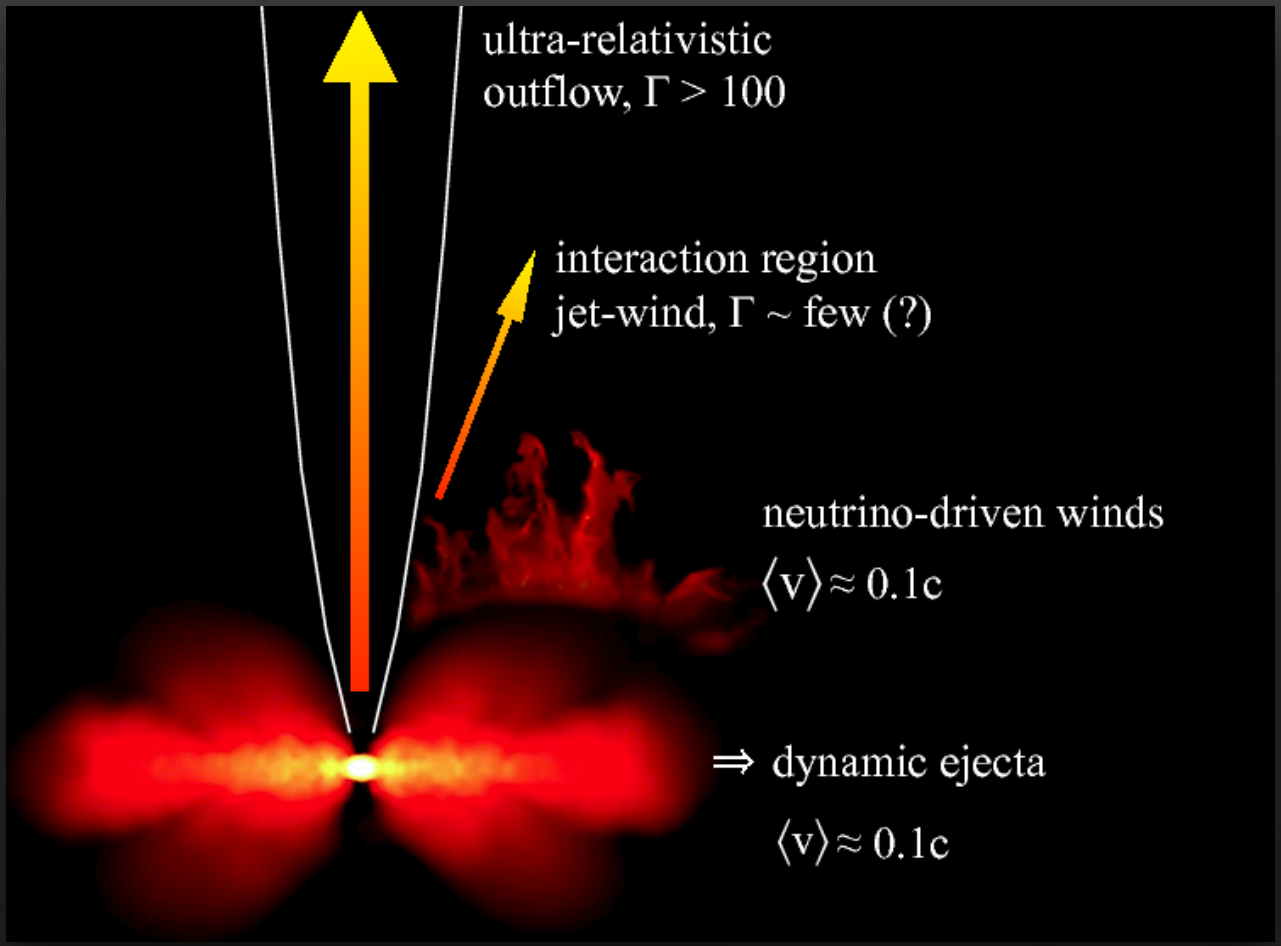
Future GRB Science

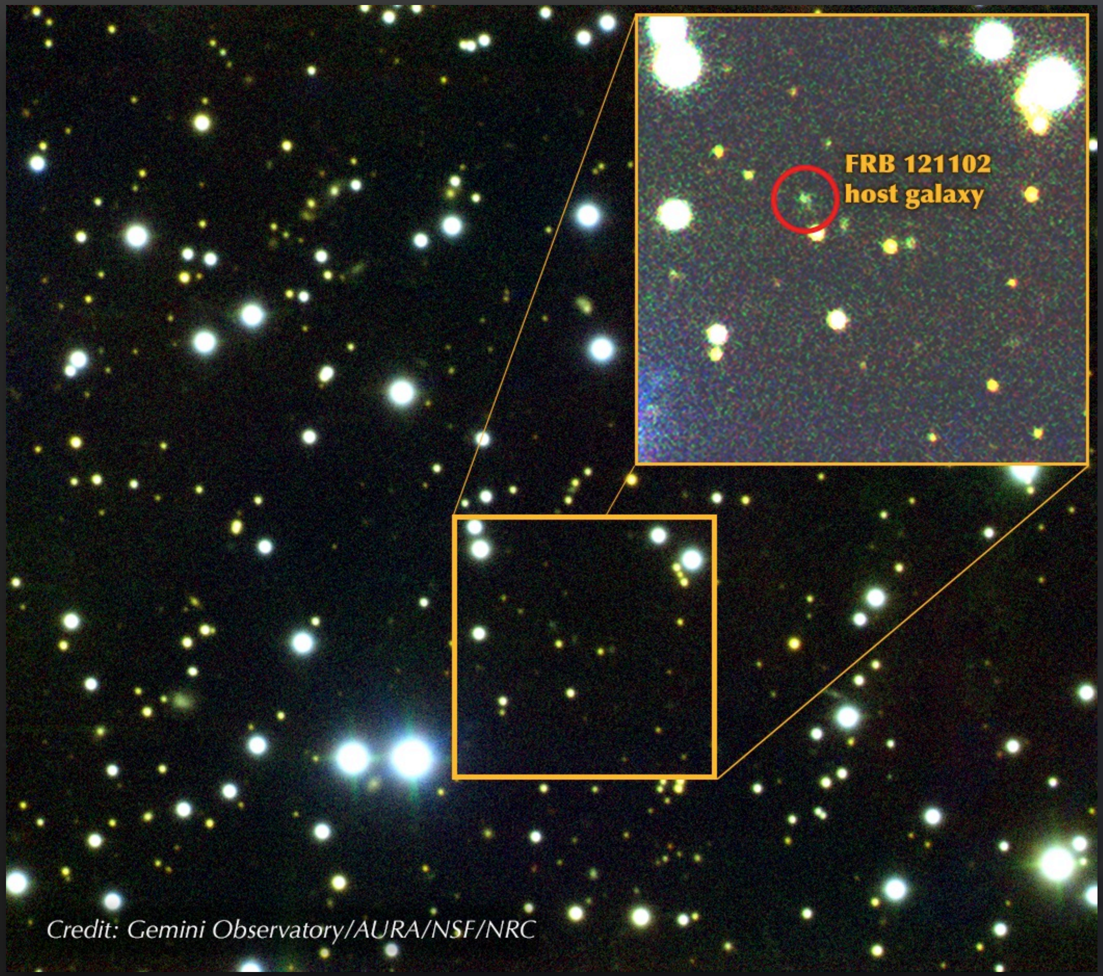
With increased GW interferometer sensitivity, there will be more joint detections with GBM, enabling deeper population studies of SGRBs

- Additional distance measures which yield source energetics
- Constrain jet structure and opening angle distribution
- Cocoon emission from SGRBs
- Causes of precursor and extended emission
- Rates of SGRBs in the universe with implications for source evolution



Future Multimessenger Discoveries





- Detection of coincident NS-BH and SGRB?
- EM emission from BBH mergers?
- GWs, GRB, and neutrinos!
- Gamma-rays associated with FRBs? (Cunningham et al. poster)

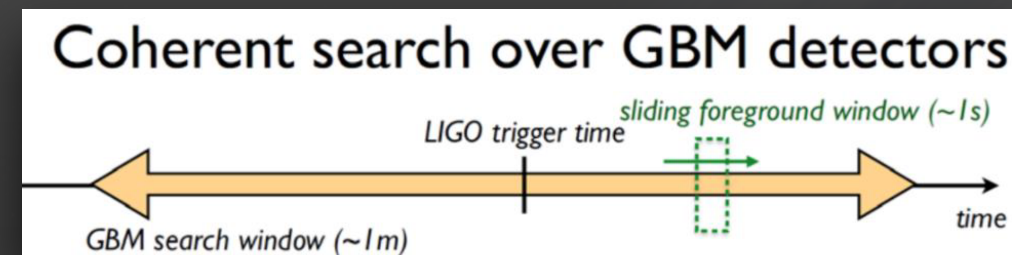
Conclusions

- GW170817 / GRB 170817A highlights the science impact of multimessenger observations
- GBM is ideal for detecting short GRBs in association with GWs
- Subthreshold searches are crucial to increasing GBM sensitivity and the detection horizon to weak events like GRB 170817A
- Joint analysis with LIGO/Virgo will continue into O3
- Fermi will continue to play an important role in future GW counterpart searches during LIGO/Virgo O3 and beyond

Backup Slides

Targeted Search Likelihood Calculation

- Input: GW detection time and (optionally) LIGO/Virgo skymap
- Searches over 60 s window centered at GW time
- Timescales from 0.256 - 8.192 by factors of 2, phased by 64 ms
- Detector responses convolved with photon spectra to estimate expected count rate from a source at each point on the sky grid
- Log likelihood ratio compares probability of expected counts to probability of observed counts
    - 12 energy channel
    - 14 detector
    - 3 spectral templates
    - 41,168 (1,634) sky points
- According to Wilks' theorem, LLR should be distributed approximately as χ2, so we reject the null hypothesis when L > 9 ~ 3σ rejection criteria for a single degree of freedom

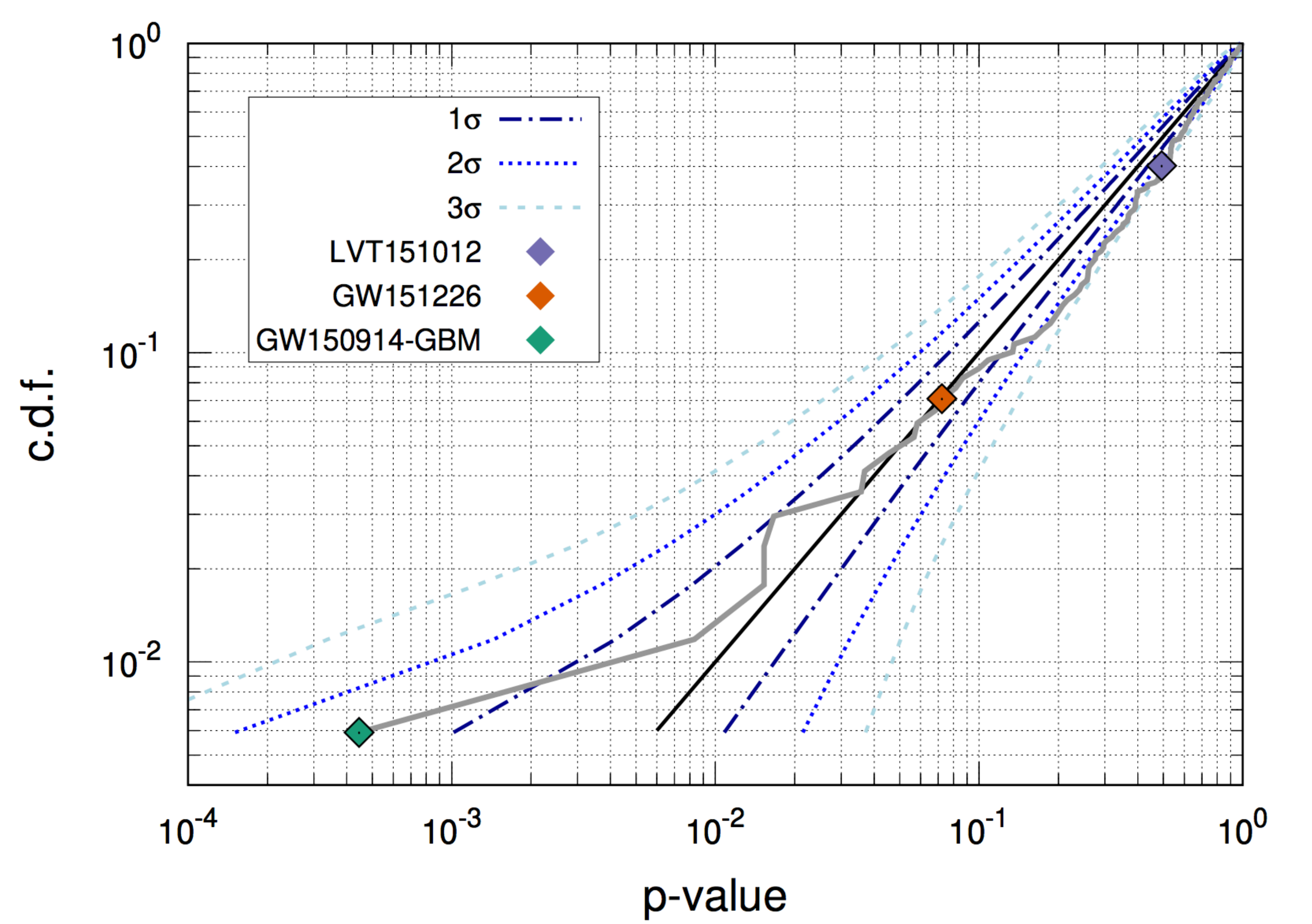


$$P(d_i|H_1) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_{d_i}} \exp\left(-\frac{(\tilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right)$$

$$P(d_i|H_0) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_{n_i}} \exp\left(-\frac{\tilde{d}_i^{\,2}}{2\sigma_{n_i}^2}\right)$$

$$\mathcal{L} = \sum_i \left[\ln\frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\tilde{d}_i^{\,2}}{2\sigma_{n_i}^2} - \frac{(\tilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right]$$

O1 Analysis



Cumulative distribution function of empirically determined of p-values for targeted search. The black solid line corresponds to the null hypothesis that the search sample is consistent with background. The blue dashed lines envelop the 1-, 2-, and 3-σ confidence intervals. The highest ranking (lowest p-value) event is GW150914-GBM (green diamond) which, for this search, has a significance of &1.5σ.