Fermi
Gamma-ray Space Telescope

GRB and GW searches

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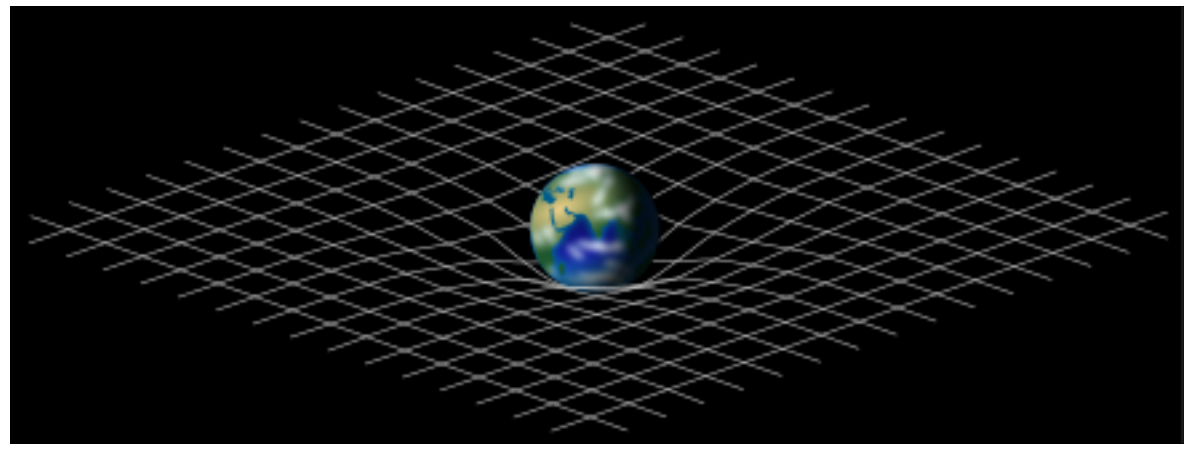
Space Curvature and GW

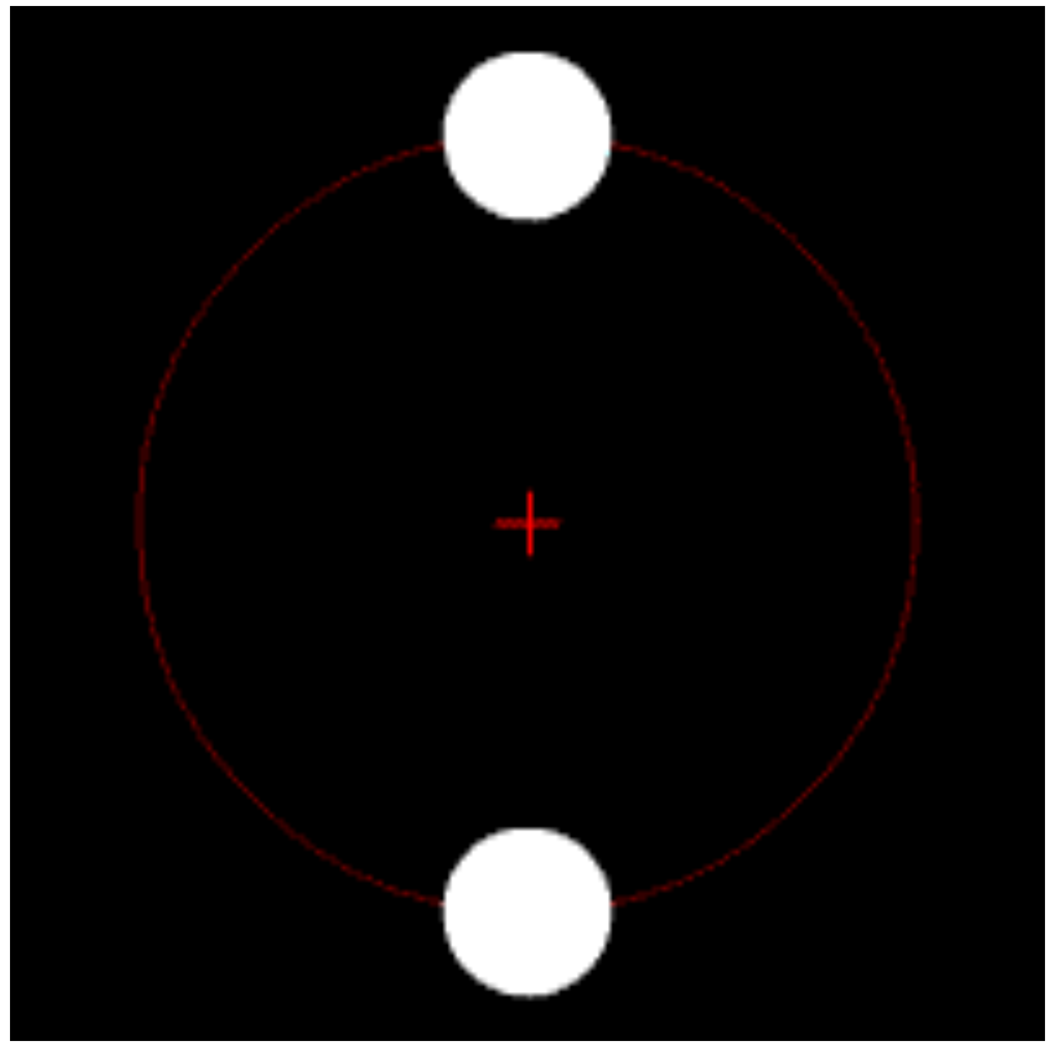
- **General Relativity connects mass (Tmu nu) with curvature R**

Einstein's field equations

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



- **Quadrupole momentum (t) => wave solution => Gravity Wave => The system collapse**



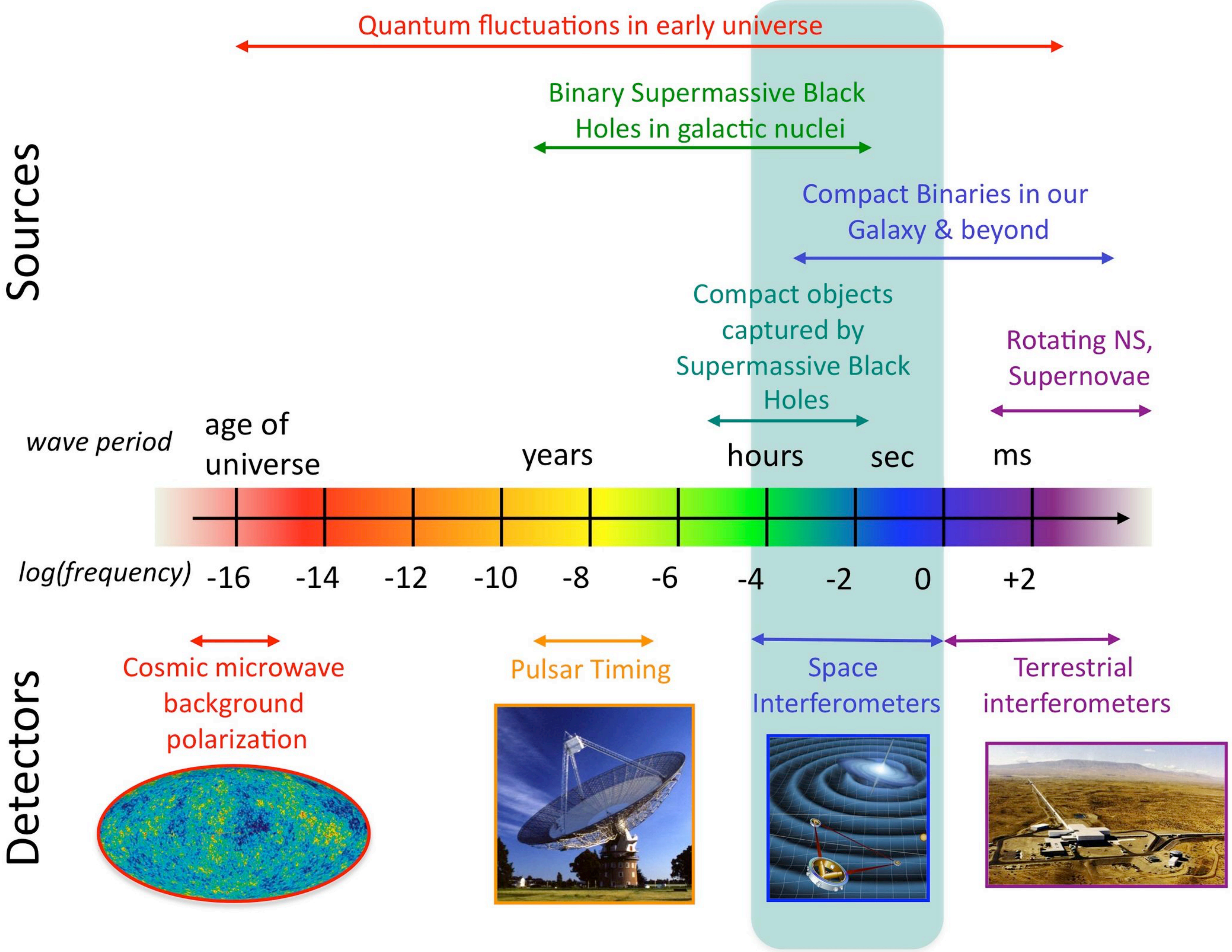
Merging rate:

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -\frac{64}{5} \frac{G^3}{c^5} \frac{(m_1 m_2)(m_1 + m_2)}{r^3}$$

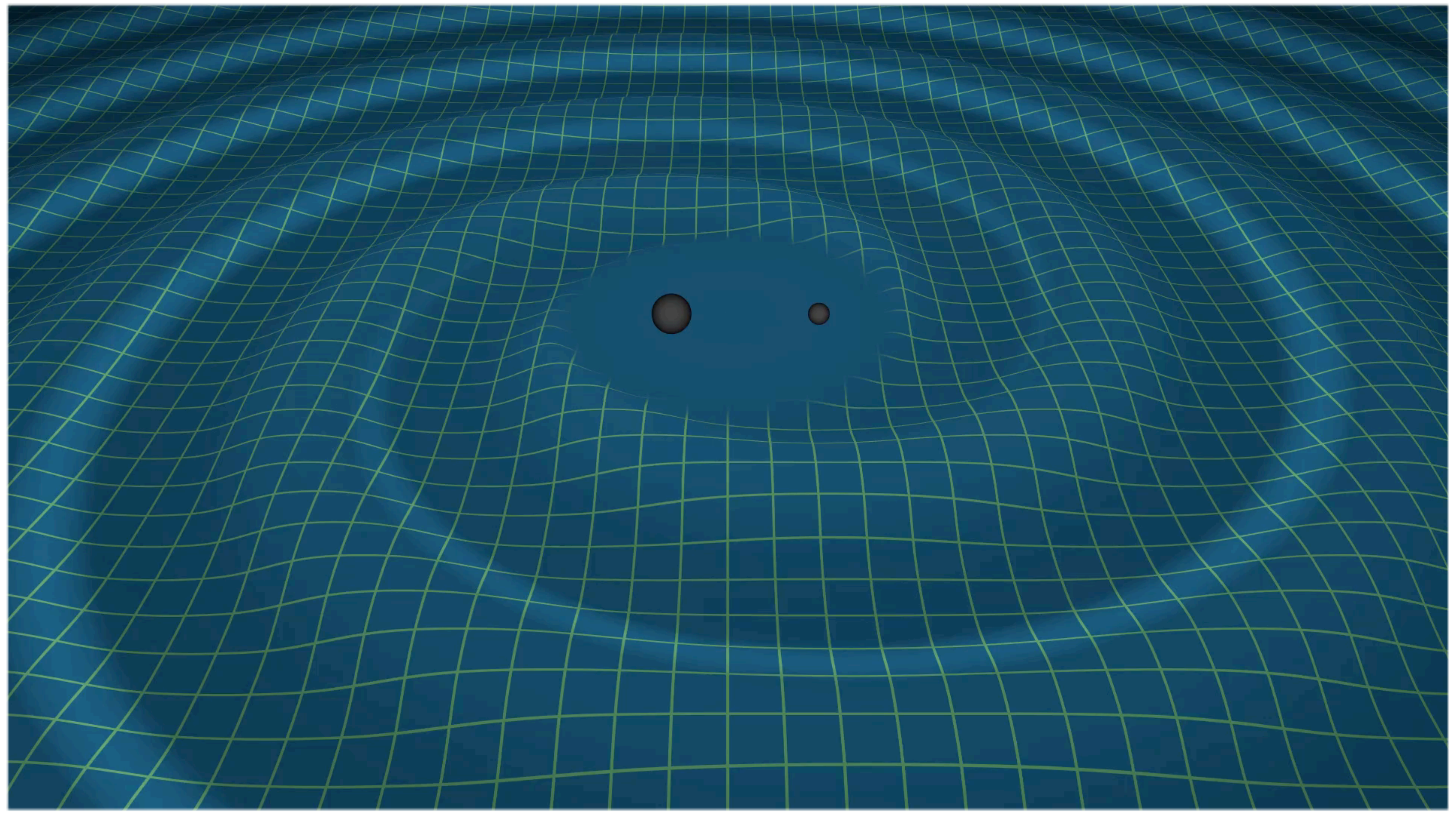
Collapse time:

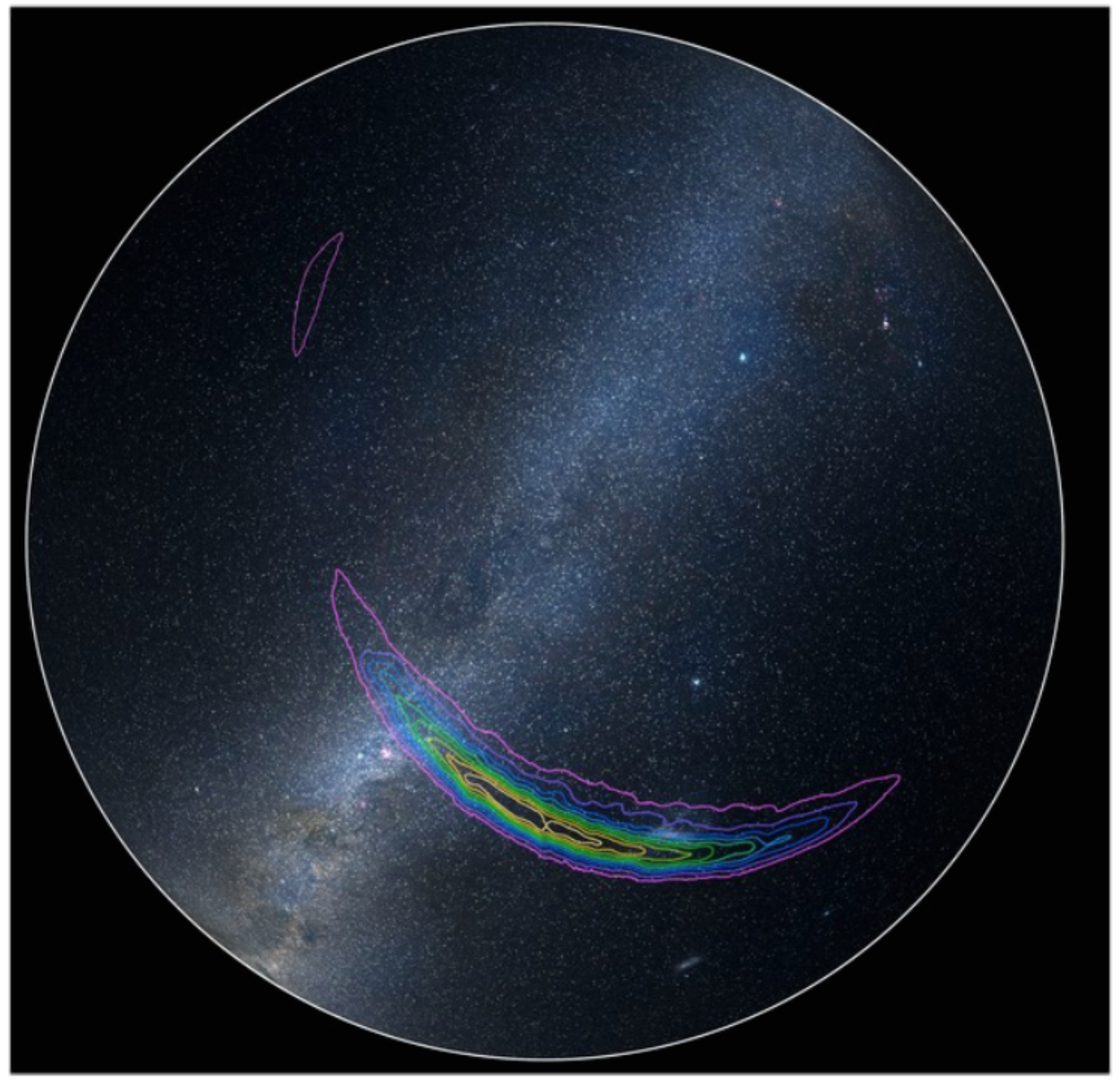
$$t = \frac{5}{256} \frac{c^5}{G^3} \frac{r^4}{(m_1 m_2)(m_1 + m_2)}$$

The Gravitational Wave Spectrum

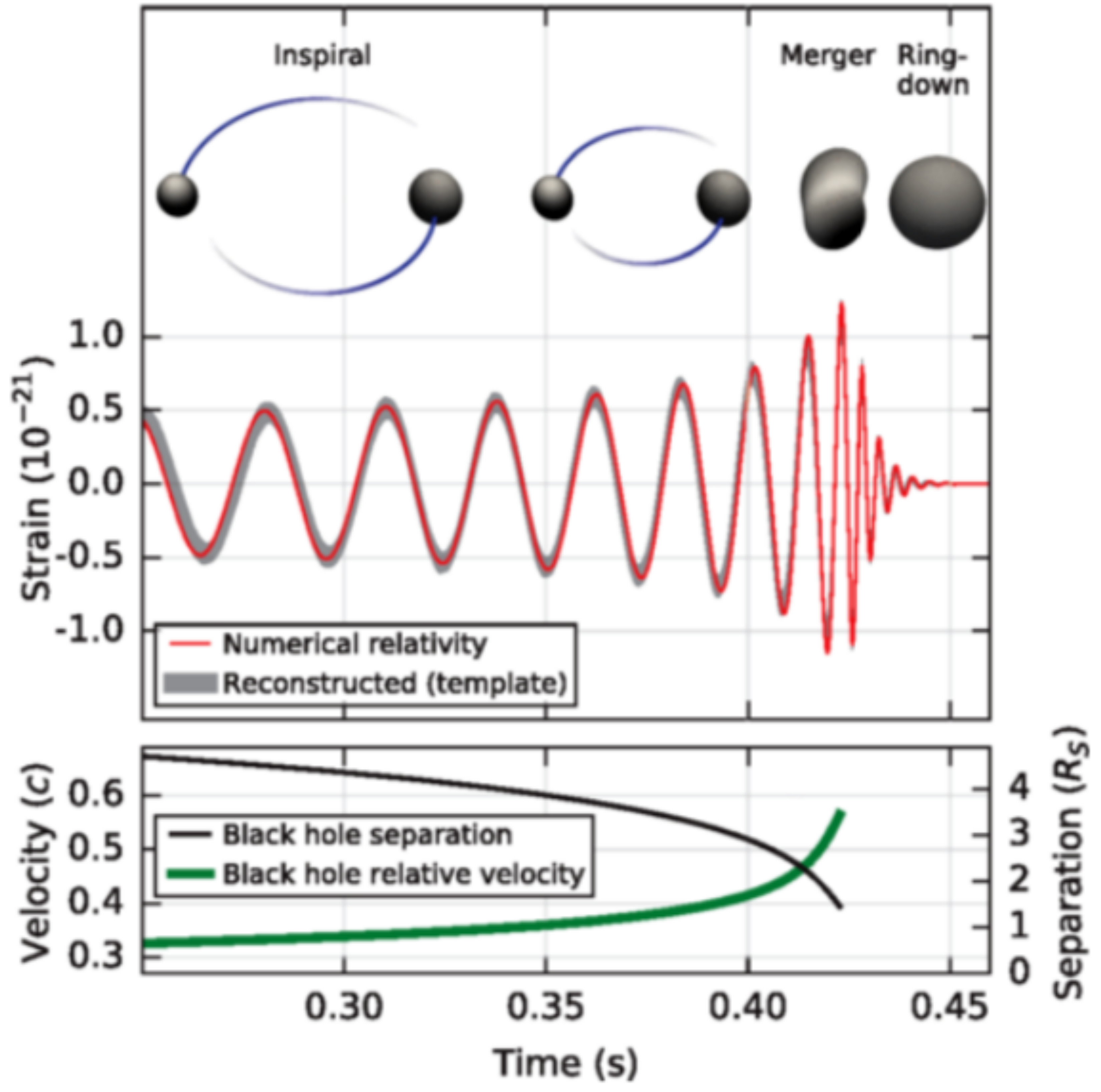


The Discovery



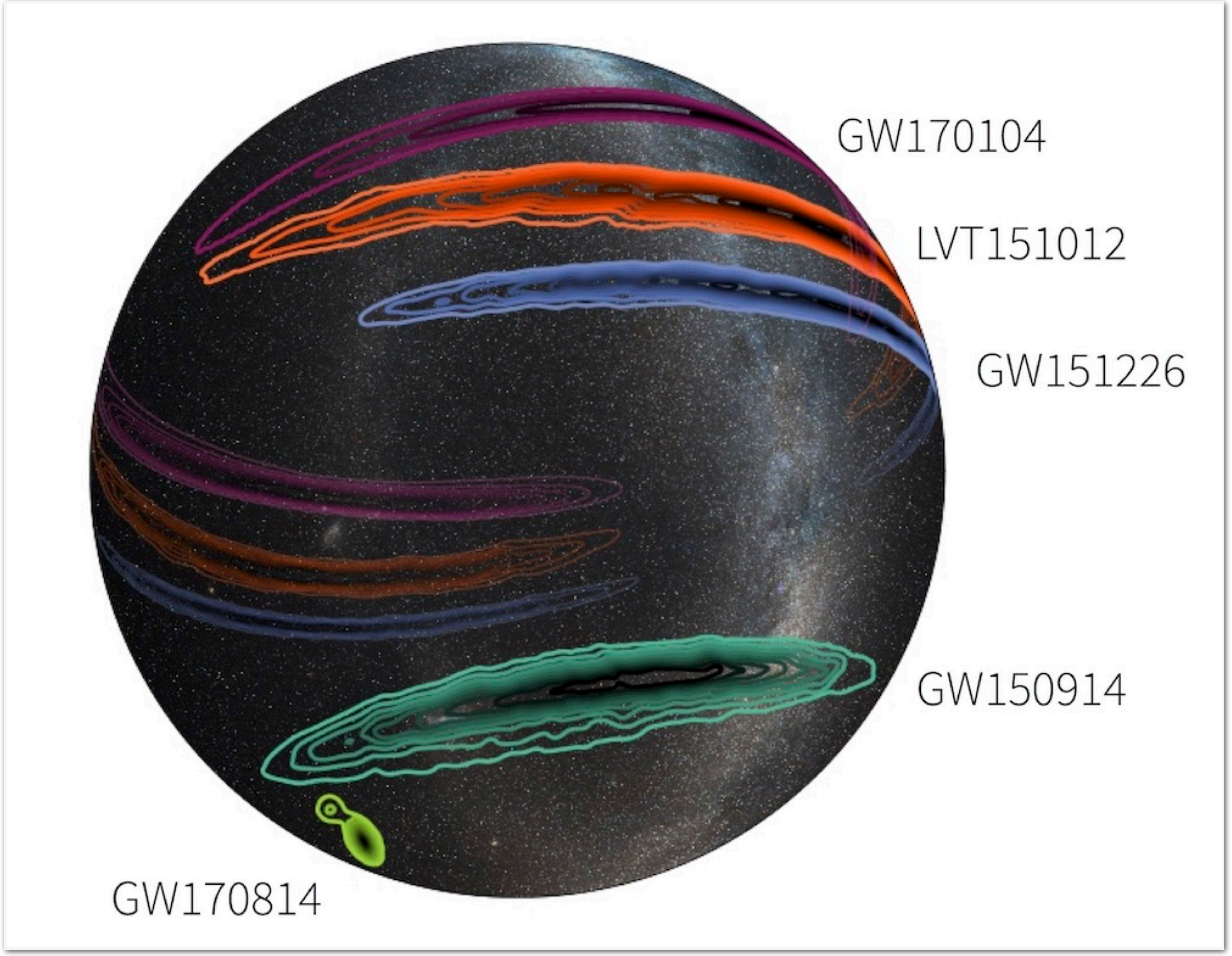


September 14, 2015, the LIGO Scientific Collaboration and Virgo Collaboration made the first observation of gravitational waves, originating from a pair of merging black holes using the Advanced LIGO detectors.

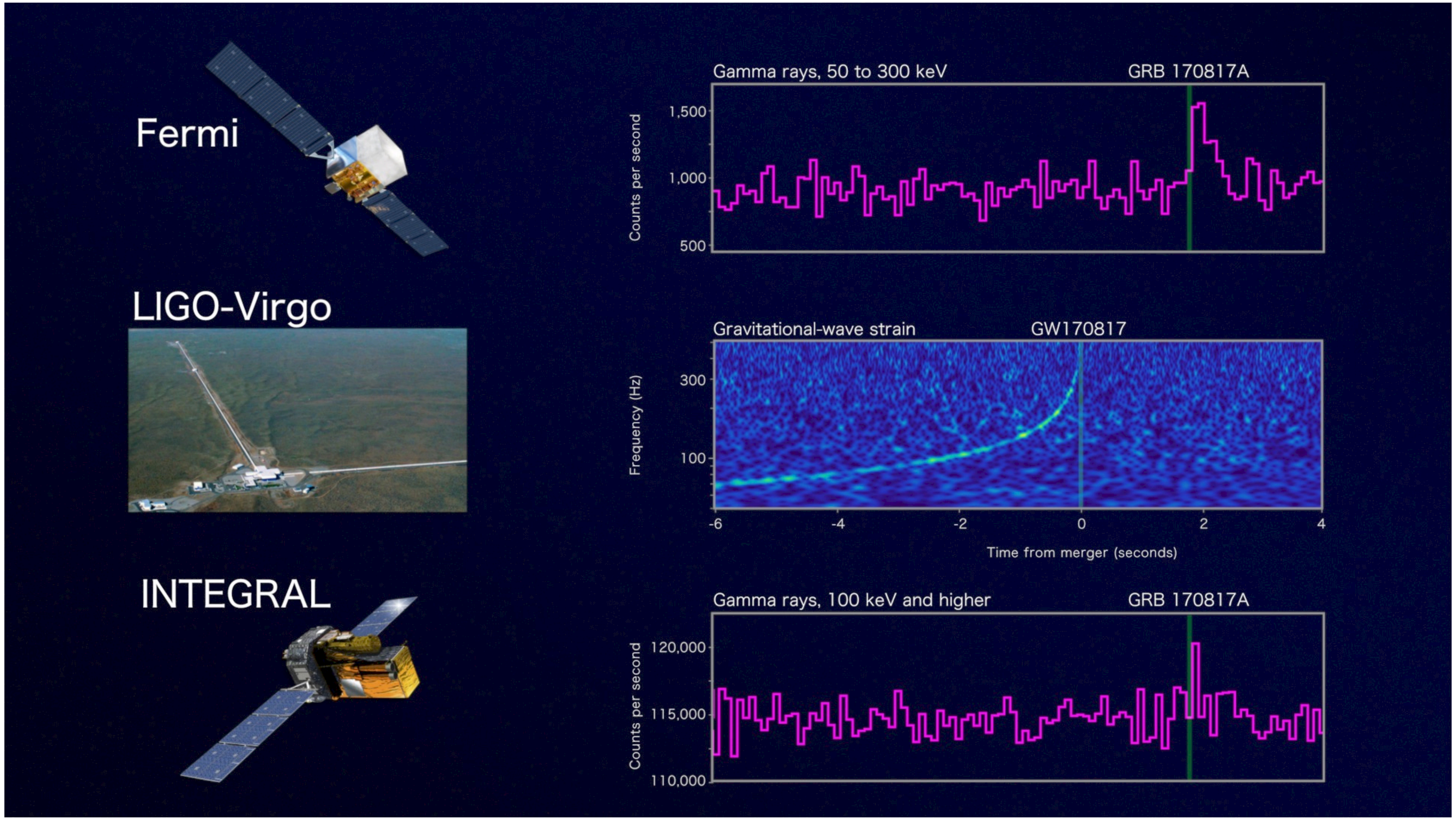


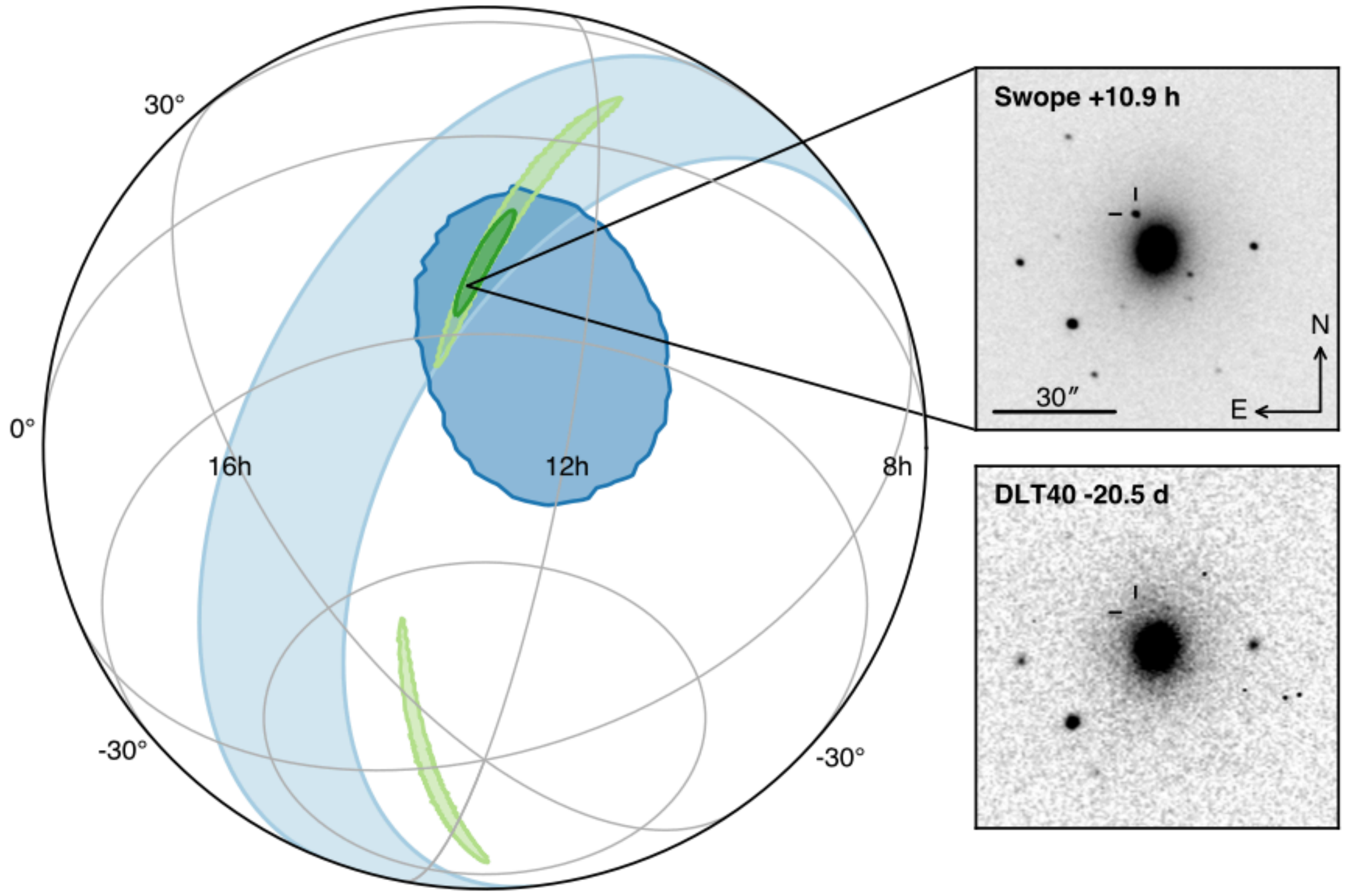
Following up LIGO events

- In O2: 6 GW events announced by the LIGO/ VIRGO Collaboration:
  - 5 BH- BH: GW150914, LVT151012, GW151226,GW170104, GW170814;
  - 1 NS-NS: GW170817;
- BH-BH mergers are not expected to produce EM radiation.
- NS-NS: predicted (and confirmed) to have EM radiation.
- Different strategy to follow
- General strategy for Fermi-LAT searches at high-energy:
  - Automated full sky searches of transients;
  - Specific searches in the LIGO contours;
  - Specific followups of detected counterparts;
  - All done automatically in pipelines to quick alert the community;

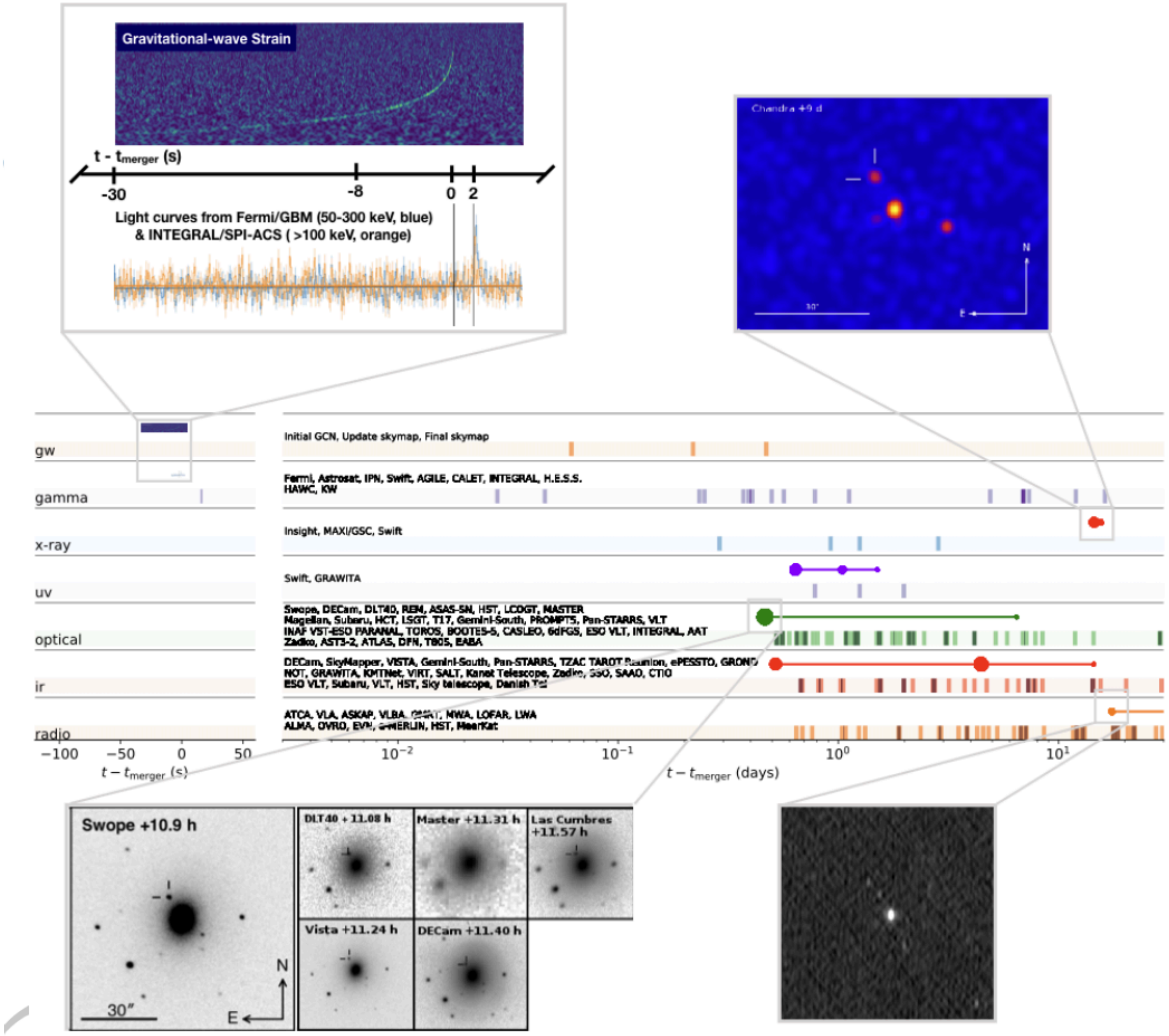


Fermi/Integral detection of GRB170817





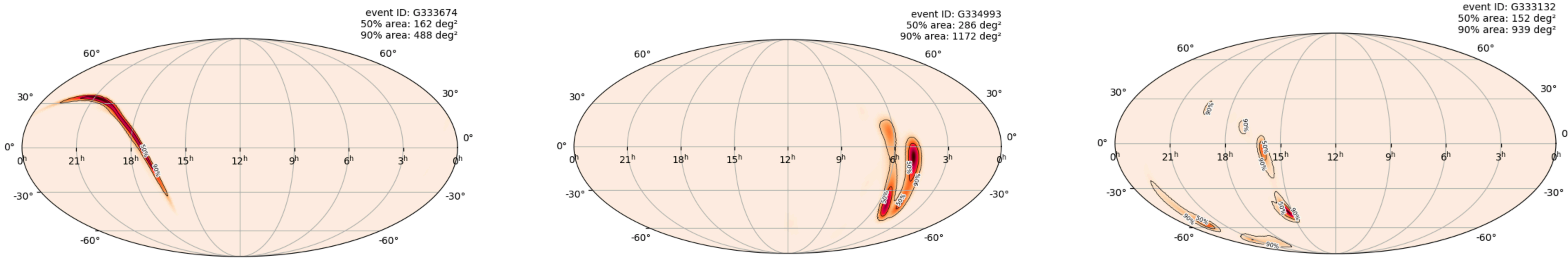
MMA at work!



Gravitational-wave Strain
t - t_merger (s)
-30
-8
0
2
Light curves from Fermi/GBM (50-300 keV, blue)
& INTEGRAL/SPI-ACS (>100 keV, orange)
Chandra +9 d
N
E
gw
gamma
x-ray
uv
optical
ir
radio
Initial GCN, Update skymap, Final skymap
Fermi, Astrosat, IPN, Swift, AGILE, CALET, INTEGRAL, H.E.S.S.
HAWC, KW
Insight, MAXI/GSC, Swift
Swift, GRAWITA
Swope, DECam, DLT40, REM, ASAS-SN, HST, LCOGT, MASTER
Magellan, Subaru, HCT, LSGT, T17, Gemini-South, PROMPT5, Pan-STARRS, VLT
INAF VST-ESO PARANAL, TOROS, BOOTES-5, CASLEO, 6dFGS, ESO VLT, INTEGRAL, AAT
Zadko, AST3-2, ATLAS, DFN, T80S, EABA
−100
−50
0
50
$t - t_{merger}$ (s)
10^{-2}
10^{-1}
10^{0}
10^{1}
$t - t_{merger}$ (days)
Swope +10.9 h
30″
N
E
DLT40 +11.08 h
Master +11.31 h
Las Cumbres +11.57 h
Vista +11.24 h
DECam +11.40 h

Strategy to follow up GW events

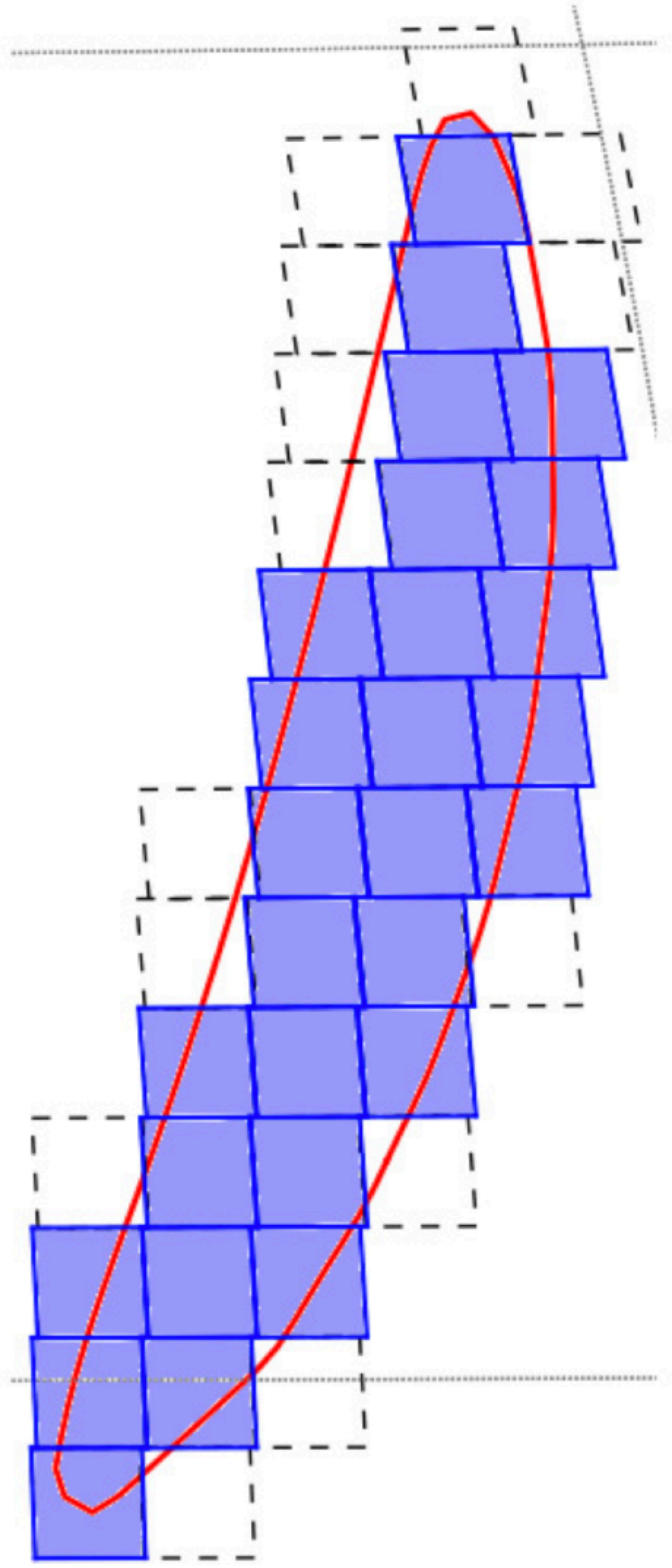
- **Probability maps are quite large (hundreds of square degrees), so the simple strategy to "point" a telescope cannot work…**
- **Example: Hubble Space Telescope: HST : FoV~ 2.4 arc minutes**
- **100 deg^2 ~ 150000 HST FoVs!**



- **Tree strategies discussed here:**
  - **Tiling**
  - **Targeting**
  - **Narrowing**

Tiling

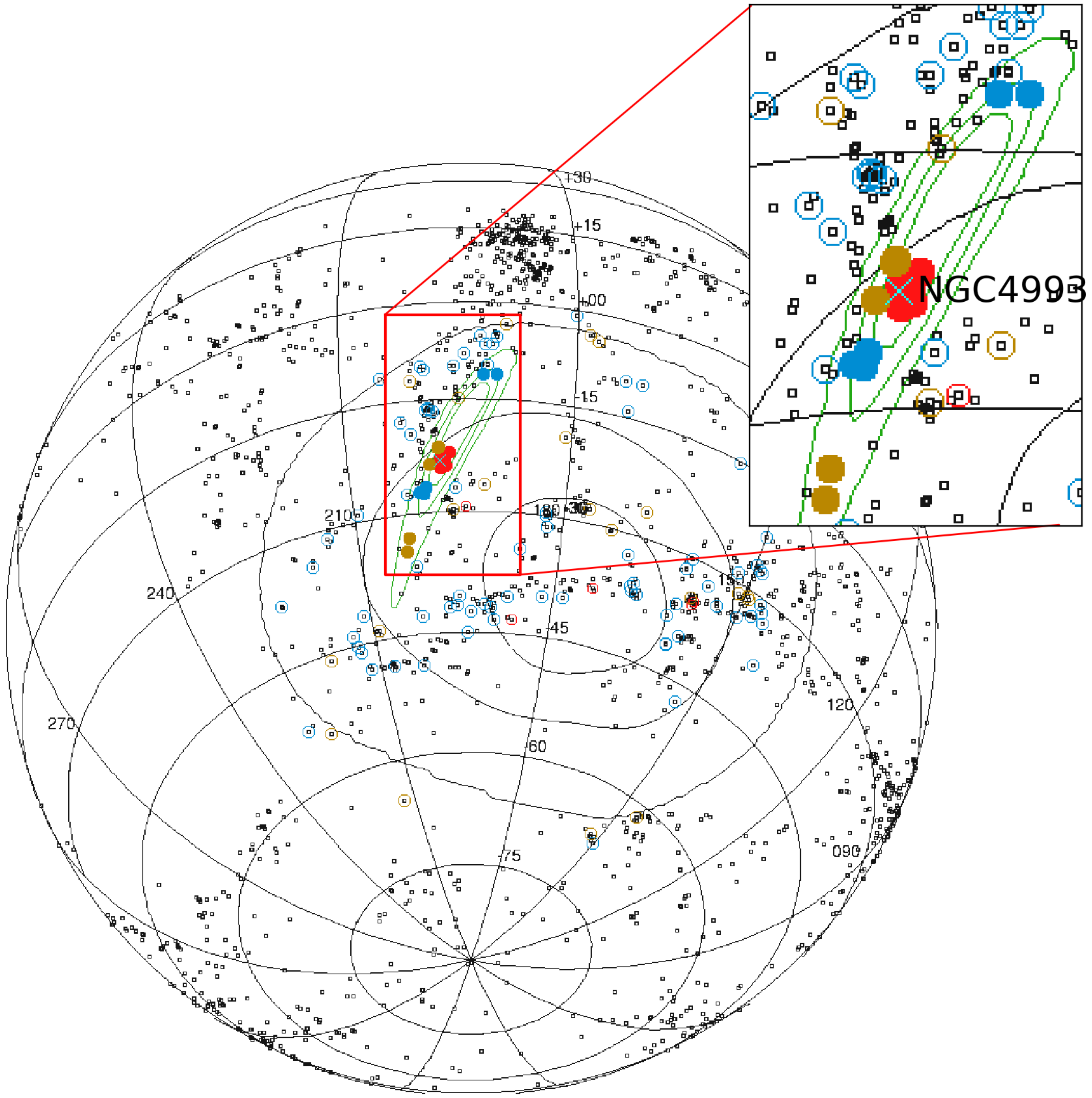
- Tiling is technically impossible for a single telescope as hundreds of pointings would be required!
- A possible solution is to use an array of telescopes in an “organized” way.
  - Prioritization, and ranking of pixels can reduce the number of pointings, see example in the figure.
  - Strategic observations: small slew distances imply faster re-point
  - Coordination: share the load in a clever way between telescope across the globe.

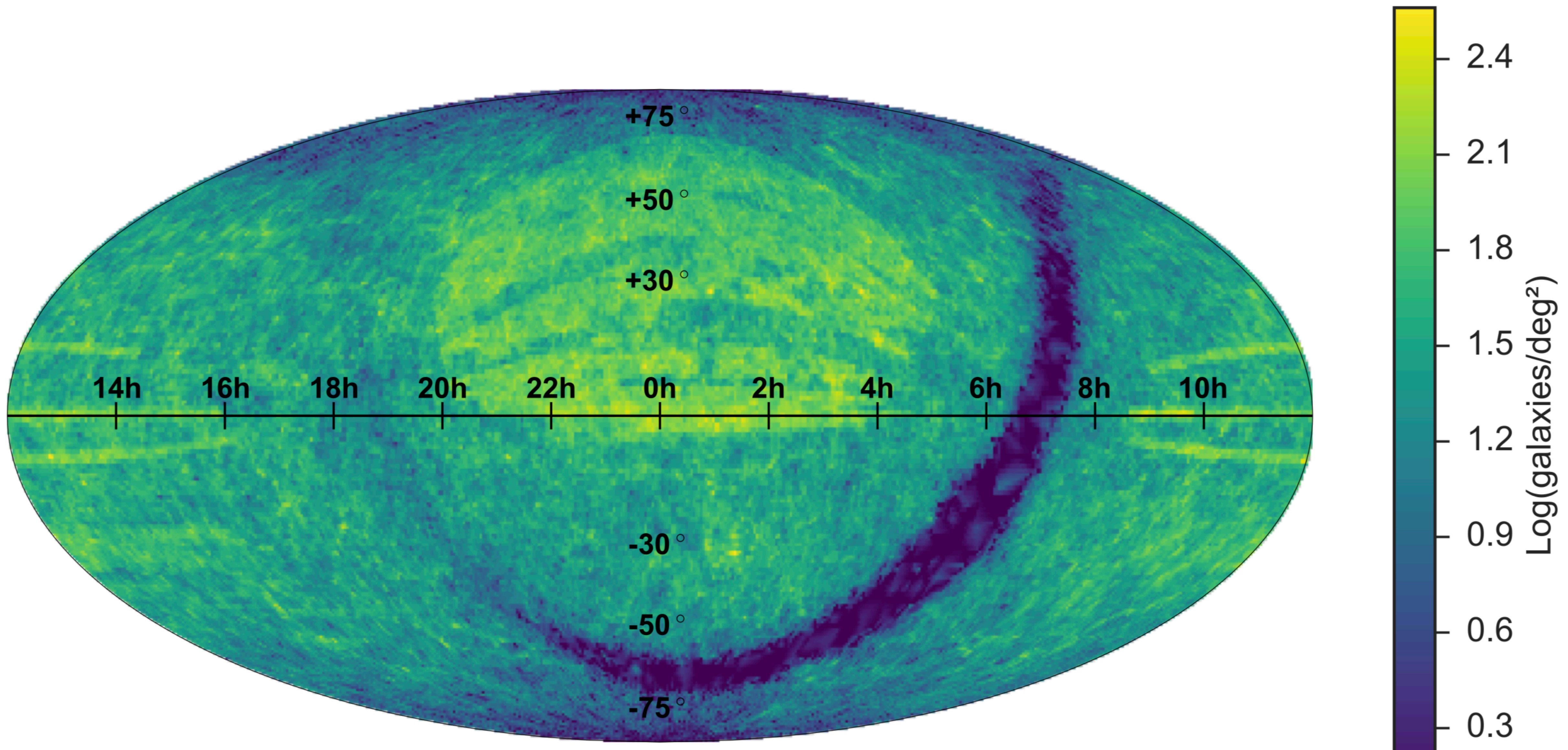


From S. Ghosh et al.: Contour: 95% localization probability.
Dashed squares cover the 96.5% of the localization probability
Fewer shaded tiles covers the 95% probability

Targeting

- **GW detections provide also an estimation of the distance of the merger (<100 Mpc). It's possible to cross correlate this with galaxy survey**
- **Galaxy density is not uniform (non-uniformity of the surveys)**

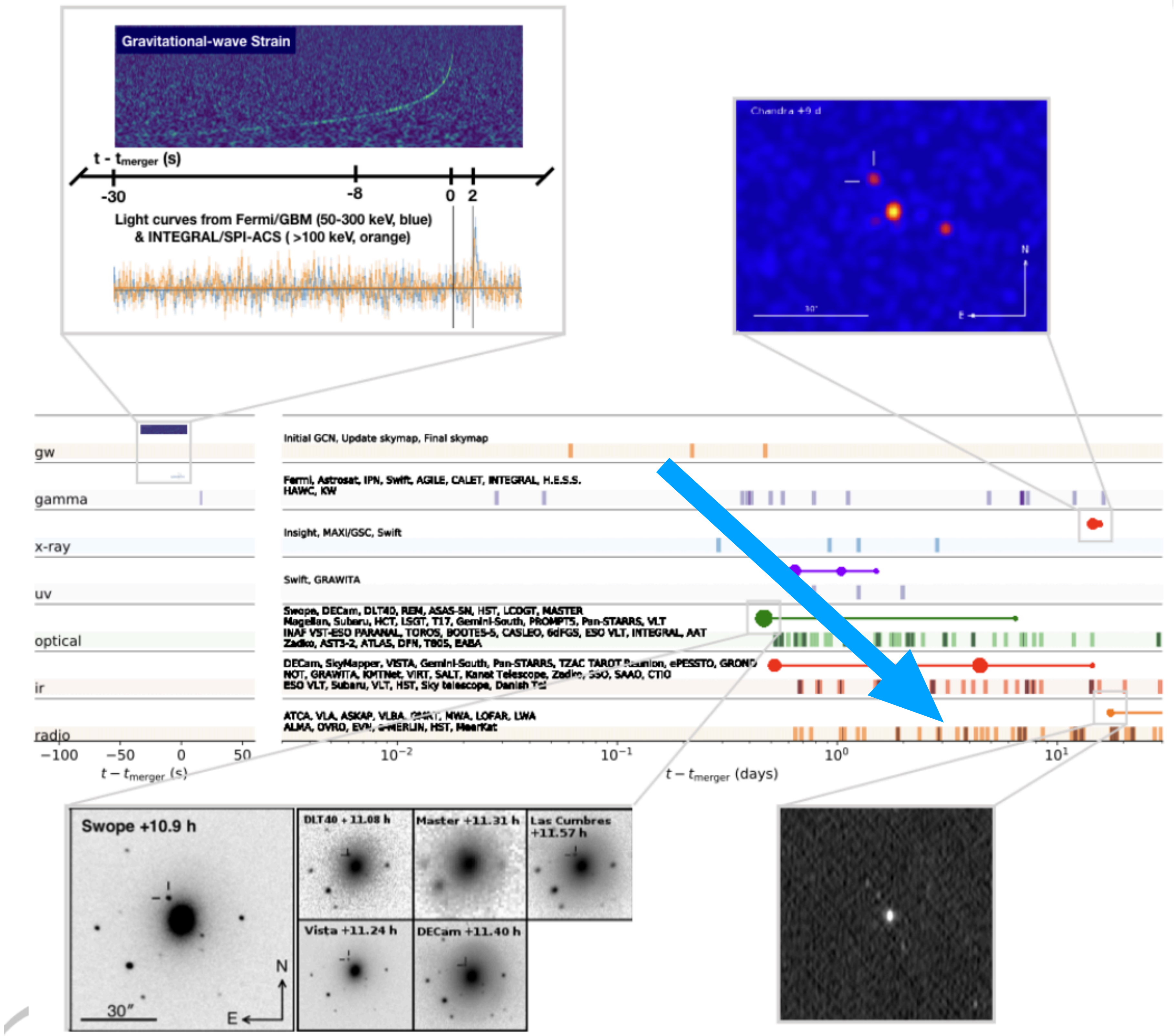




GLADE Galaxy survey

Narrowing

- **High resolution telescopes have very narrow field of view, so they can't observe if the localization is too large.**
- **On the other hand, telescopes with large field of view can provide a localization that matches the field of view of better telescopes.**
  - **Large field of view telescopes can narrow down the localization to be observed with higher resolution telescopes**
  - **Smaller and smaller…**



Fermi Transient Searches

Pipelines

Pipeline
Method
Timescale
Distribution
Status

LAT Transient Factory (LTF)
Likelihood Around GBM/BAT triggers
seconds to orbits
LAT Team - Results in GCNs
Triggered Operating + *Blind Search Coming Soon*

***Fermi* All-sky Variability Analysis (FAVA)**
Counts Map Aperture Photometry
3 day (coming soon), 1 week
ATels
http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/

LAT Burst Advocate Tool
Likelihood Around GBM/BAT triggers
100 s, 1000 s
LAT Team - Results in GCNs
Operating

LAT Catalogs
Likelihood, associations
3 month (0FGL), 1 year (1FGL), 2 years (2FGL), 4 years (3FGL)
http://fermi.gsfc.nasa.gov/ssc/data/access/
4FGL in progress

GBM Untriggered Search
ground search
ms - s
GCN Notices
http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html

GBM Onboard Triggers
rate triggers
16 ms - minutes
GCN Notices
Operating

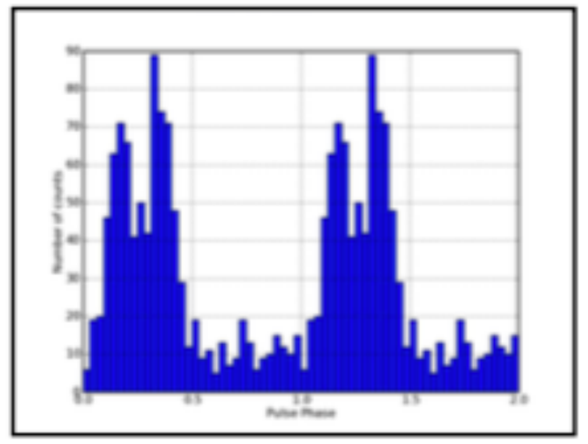
LAT Automated Science Processing (ASP) + Flare Advocates
Likelihood
6 & 24 hour
ATels, GCN notices (on AGN)
Operating

Transients Timescale

μs ***ms*** ***s*** ***minutes*** ***hours*** ***days*** ***months*** ***years***

Photon Timing

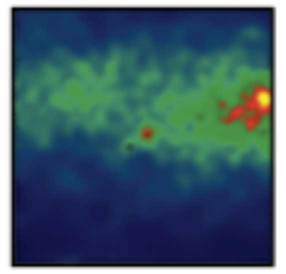
Pulsars



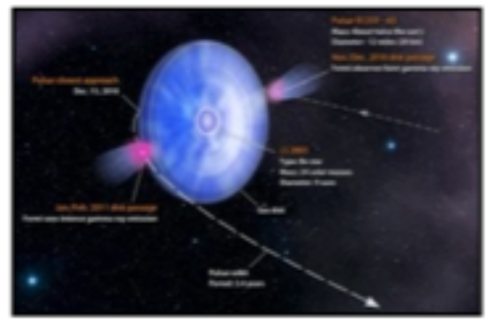
Solar Flares

All Sky Cadence

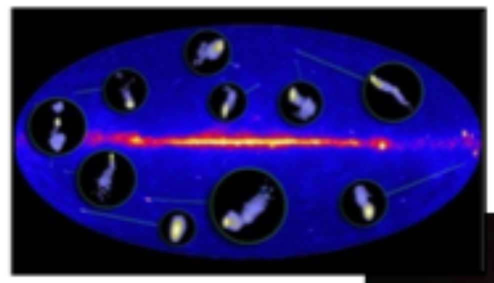
Novae



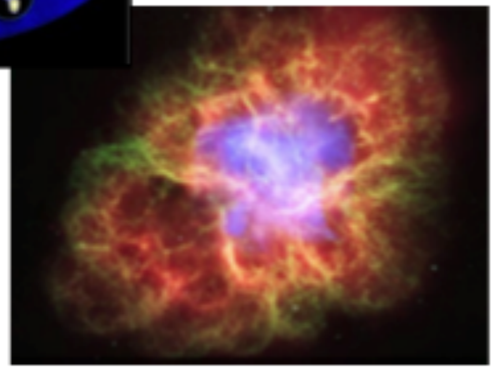
γ-ray Binaries



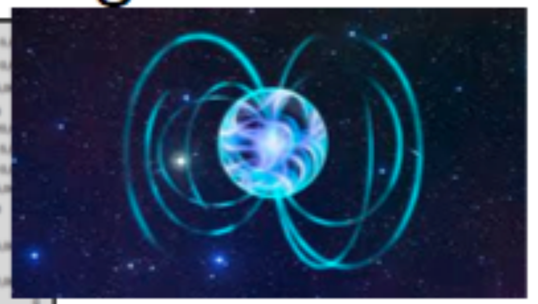
Blazar Flares



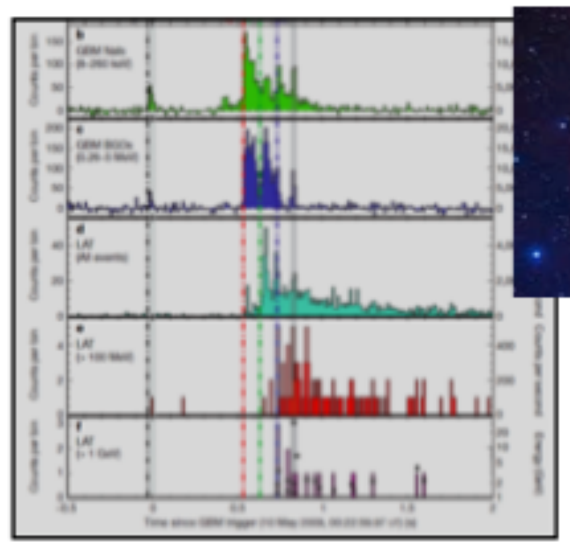
Crab Flares



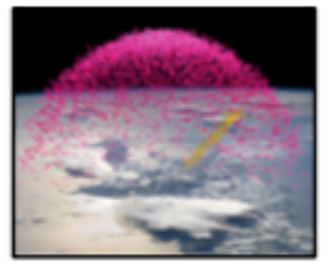
Magnetar Flares



GRBs



Terrestrial γ-ray Flashes

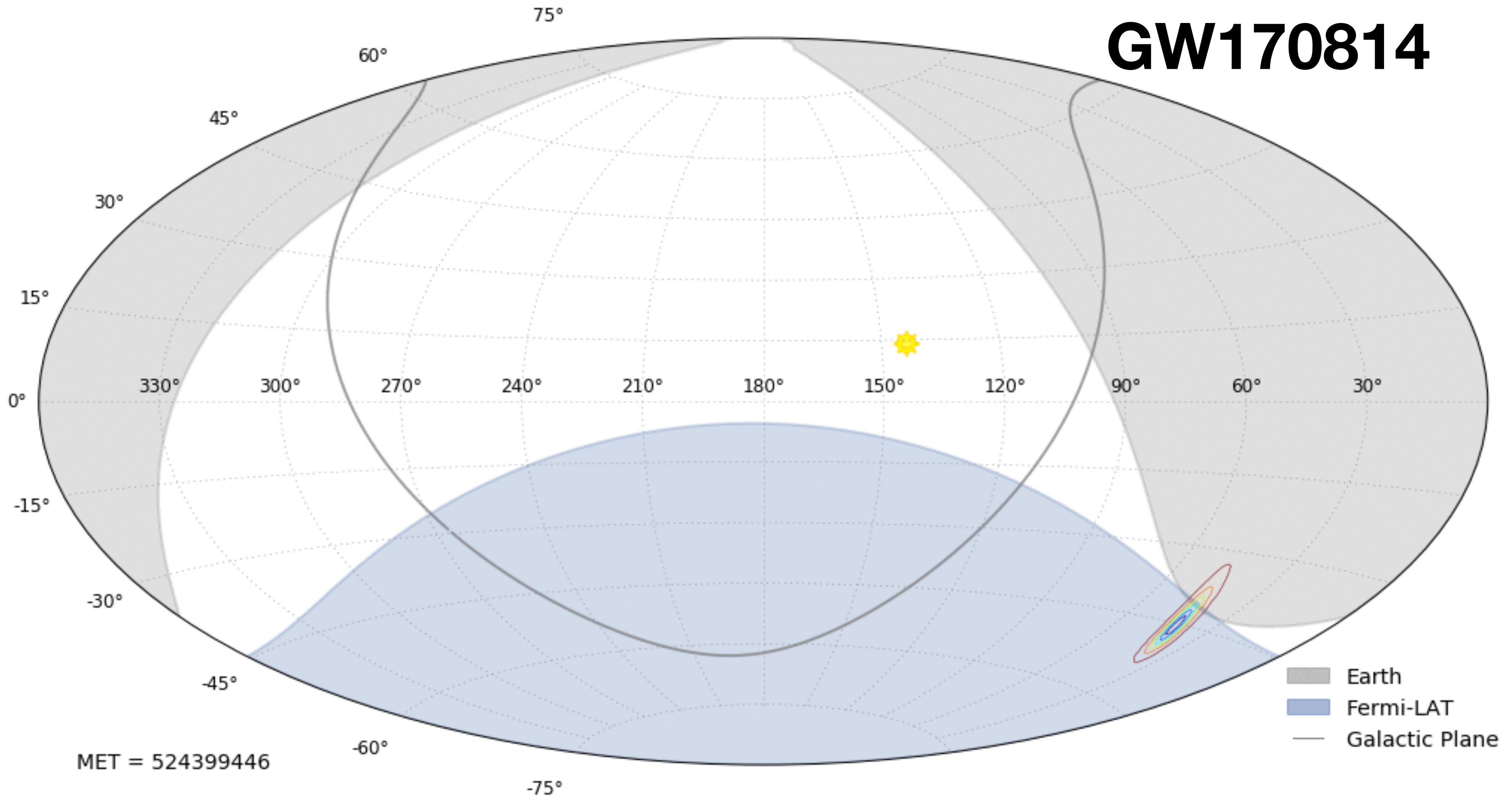


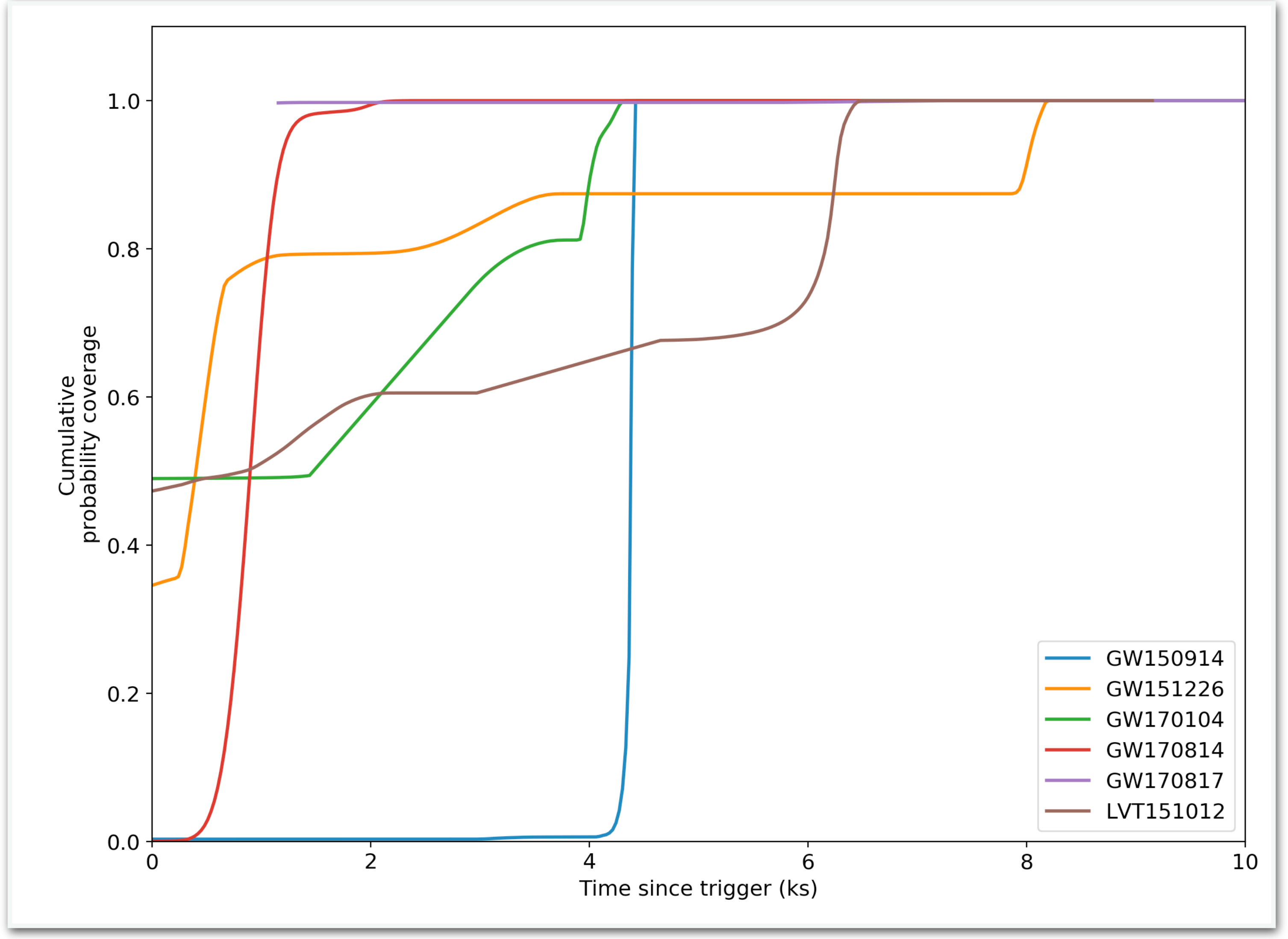
Not to scale

From LVC probability maps to LAT analysis

- We developed a novel technique to search for EM counterpart in LAT data starting from LIGO probability maps:
  - LVC probability maps (in HEALPix) downscaled to match the Fermi LAT PSF (~4 degrees at 100 MeV);
  - We center a ROI in each pixel (p>0.9), and we run standard likelihood analysis (Unbinned);
- Cumulative coverage of the map as a function of time:
  - In some cases we started with ~40-50% of the credibility region in the field of view at the time of the trigger;
  - In all cases we reached 100% of the coverage within 8 ks;
  - Different pixels of the map enter and exit at different time:
    - We set up two different analysis: fixed time window and adaptive time window
    - see: Ackermann et al. 2016 (GW150915), Racusin et al. 2017 (GW151226, LVT151012), Goldstein at al. 2017 (GW170114), Vianello et al. 2017 (Methods)

GW170814





Analysis implemented

- **Fixed Time Interval Analysis (FTI):**
  - **Computes likelihood for each pixel of the LIGO probability map (with P>0.9), providing flux and TS…**
    - **In addition, can automatically calculate the value of the bayesian upper limit for the entire map;**
    - **Added "smart TS" to speed up the calculation;**
- **Adaptive Time Interval (ATI):**
  - **The likelihood is calculated only for the interval of time when the pixel is in the LAT field of view, for each pixel…**
- **LAT Low Energy events (LLE):**
  - **Around the time of the trigger we extract LLE data for each pixel of the map producing Light Curve and estimating the significance. This also produce a map of the significance (the map is downgraded to NSIZE=32)**
- **Automatic followup with LTF**
  - **Significant excesses can be followed up submitting a LTF job**

Searching for High-energy Gamma-ray Counterparts to Gravitational-wave Sources
with Fermi-LAT: A Needle in a Haystack
G. Vianello, N. Omodei, J. Chiang, and S. Digel
The Astrophysical Journal Letters, Volume 841, Number 1

Fixed Time Windows - Adaptive intervals

- **Duration estimated from the full coverage of the event:**
  - **Typically ~10 ks;**
- **Standard unbinned likelihood analysis:**
  - **In each pixel, Test Statistics (TS) evaluates the significant of an excess with respect the background (galactic + isotropic emission + known point source from 3FGL);**
  - **Significance map for every LIGO/Virgo alert;**
  - **When no detection (TS<25): map of upper bounds;**
- **Bayesian upper bounds:**
  - **We developed a fully bayesian method to calculate a "global" upper bound, using the probability map as prior (and using Markov-Chain Monte Carlo to marginalize the posterior probability);**
  - **These UB can be used to constrain models if the location of the GW event is unknown.**

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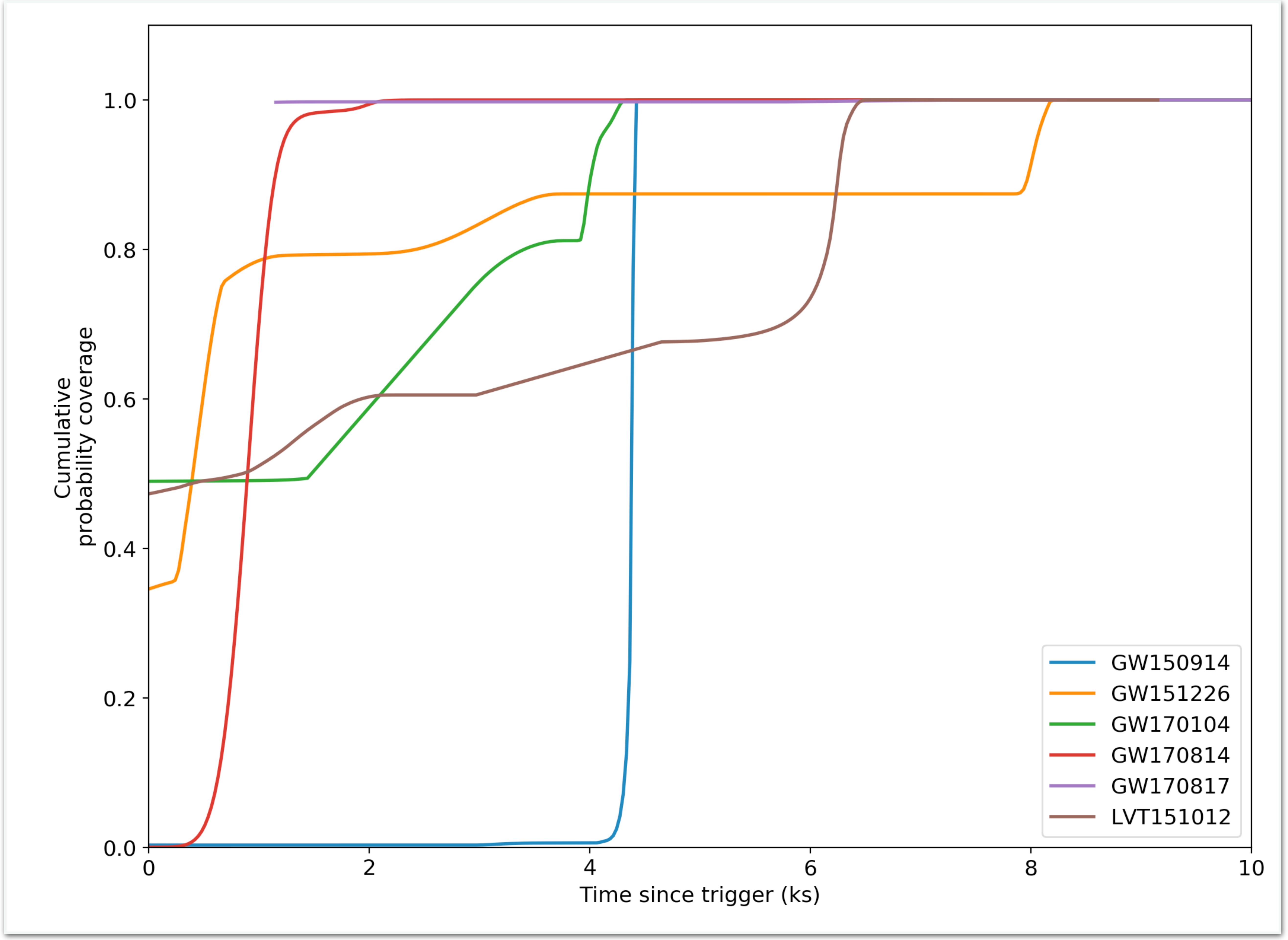
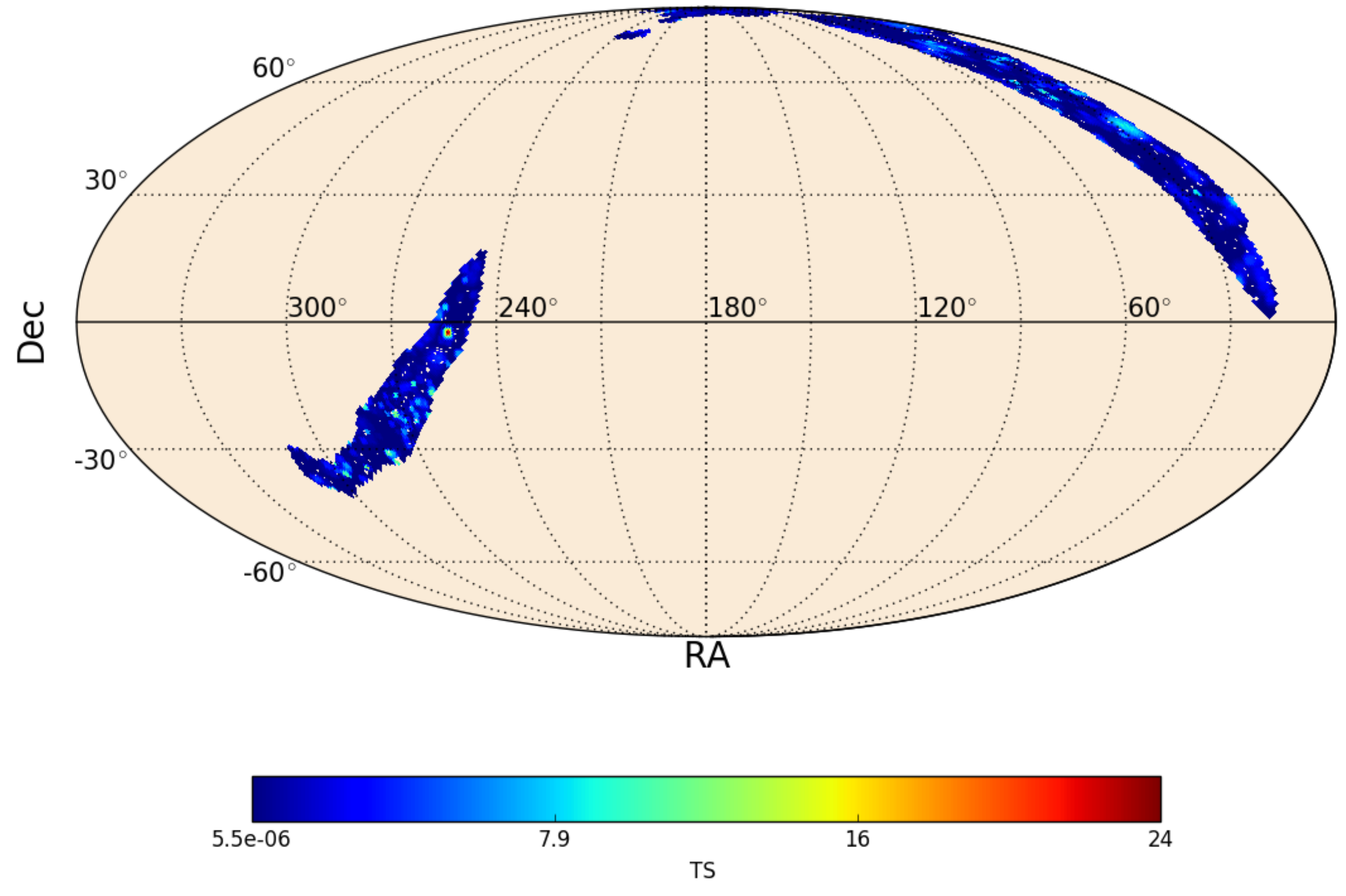
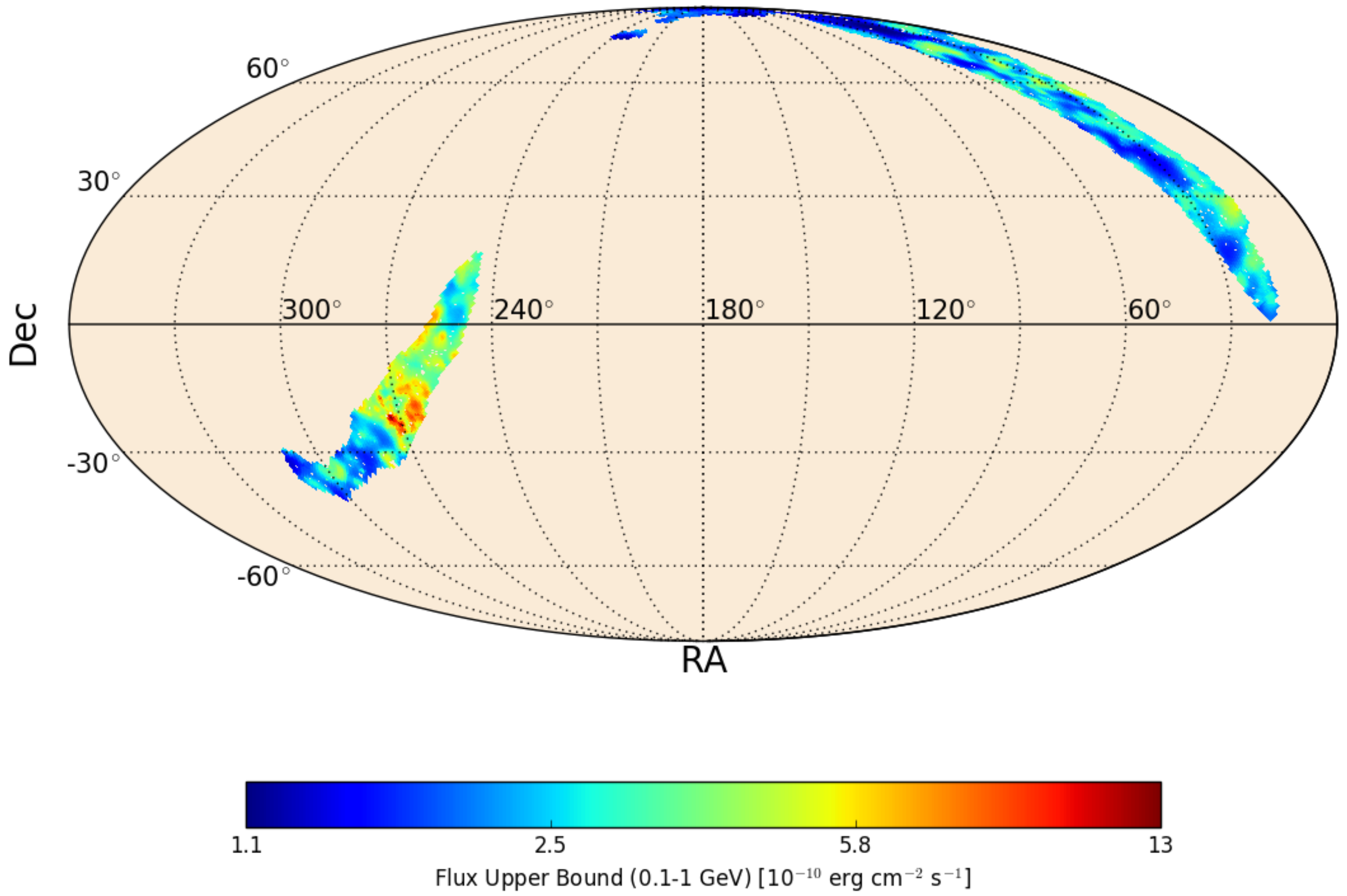






Bayesian approach to compute a Flux upper bound

- By definition, the Flux ub is such that:

$$\int_0^{F_{\mathrm{ub}}} P\,(F|D)\,dF = p_{\mathrm{ub}}\,.$$

- Where p ub is the value of the credibility interval, and P(F|D) is the posterior probability for a flux F given the dataset D. This can ber written as:

$$P\,(F|D) = \int\int P\,(\alpha,\,\boldsymbol{\delta},\,F|D)\,d\alpha\,d\Omega,$$

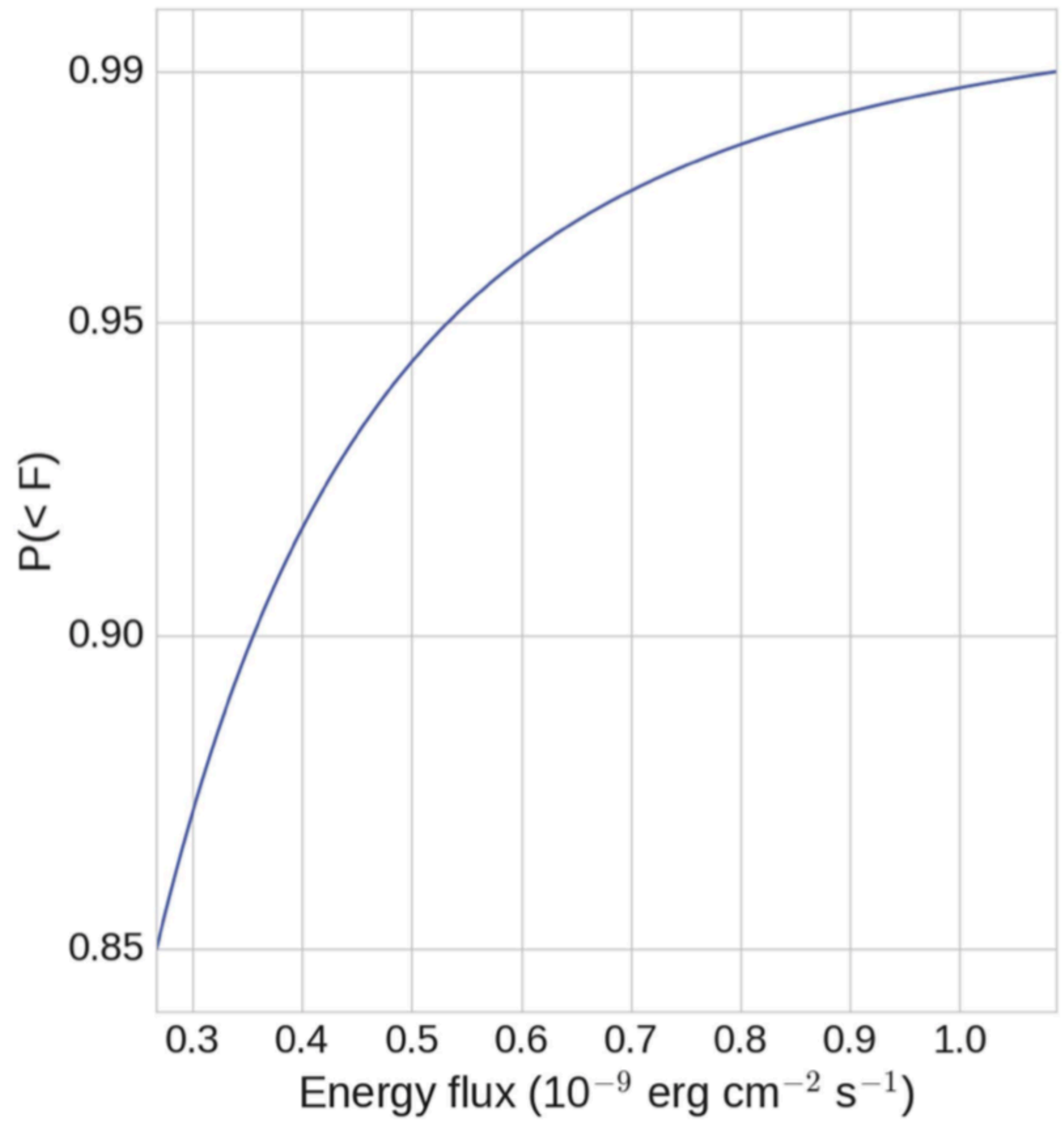
- With alpha: photon index, F, the flux, delta the probability given by the LIGO observation. Using Bayes's theorem, indicating with π all the priors, we can write the posterior probability as:

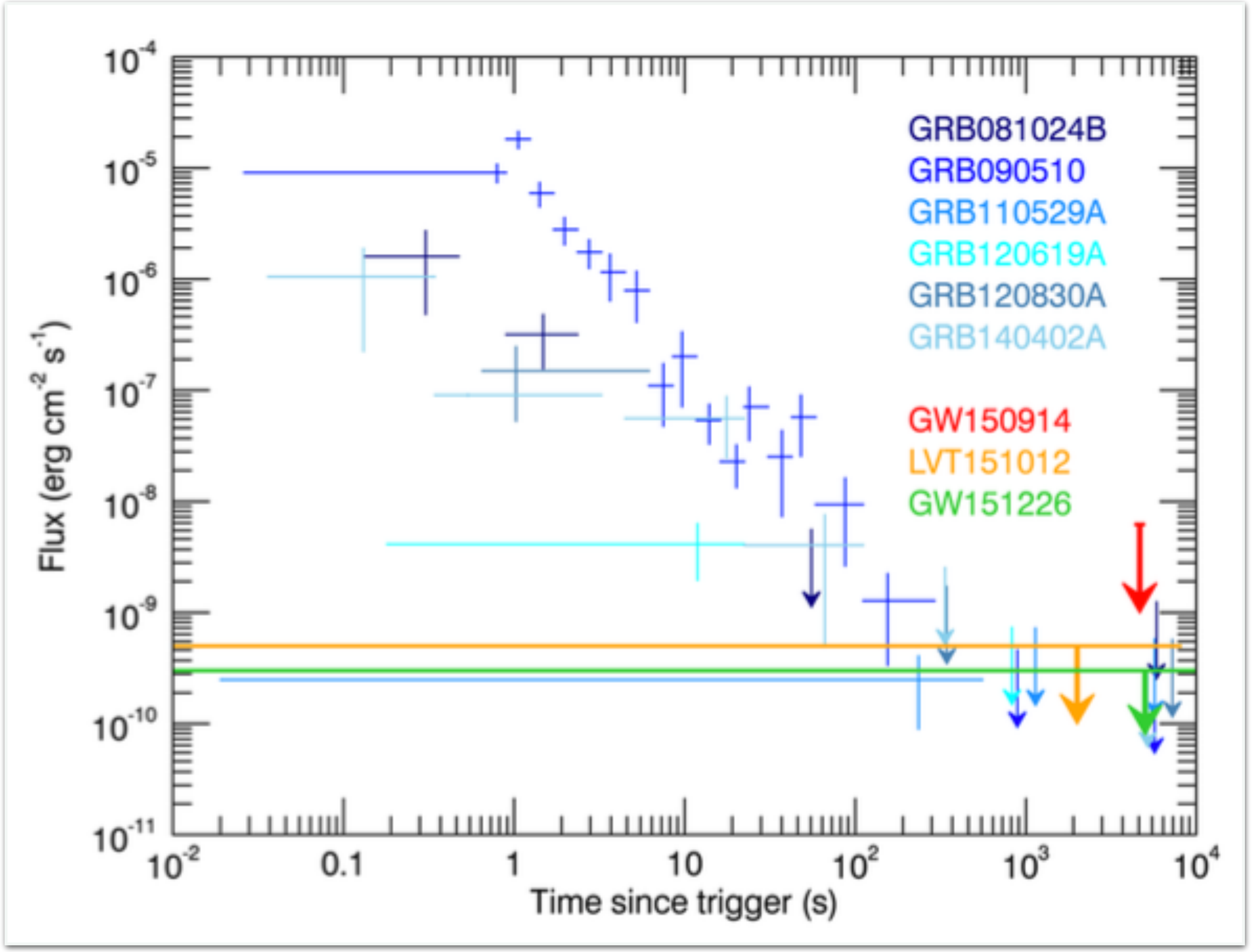
$$P\,(\alpha,\,\boldsymbol{\delta},\,F|D) \propto P\,(D|\alpha,\,\boldsymbol{\delta},\,F)\,\pi\,(\alpha)\,\pi\,(\boldsymbol{\delta})\,\pi\,(F),$$

- $P\,(D|\alpha,\,\boldsymbol{\delta},\,F)$ is the likelihood function for a set of parameters alpha and F at the position delta. Therefore the flux upper bound can be computed using MCMC sampling the values of the likelihood function and multiply them by the various priors, including the probability map for each pixel.

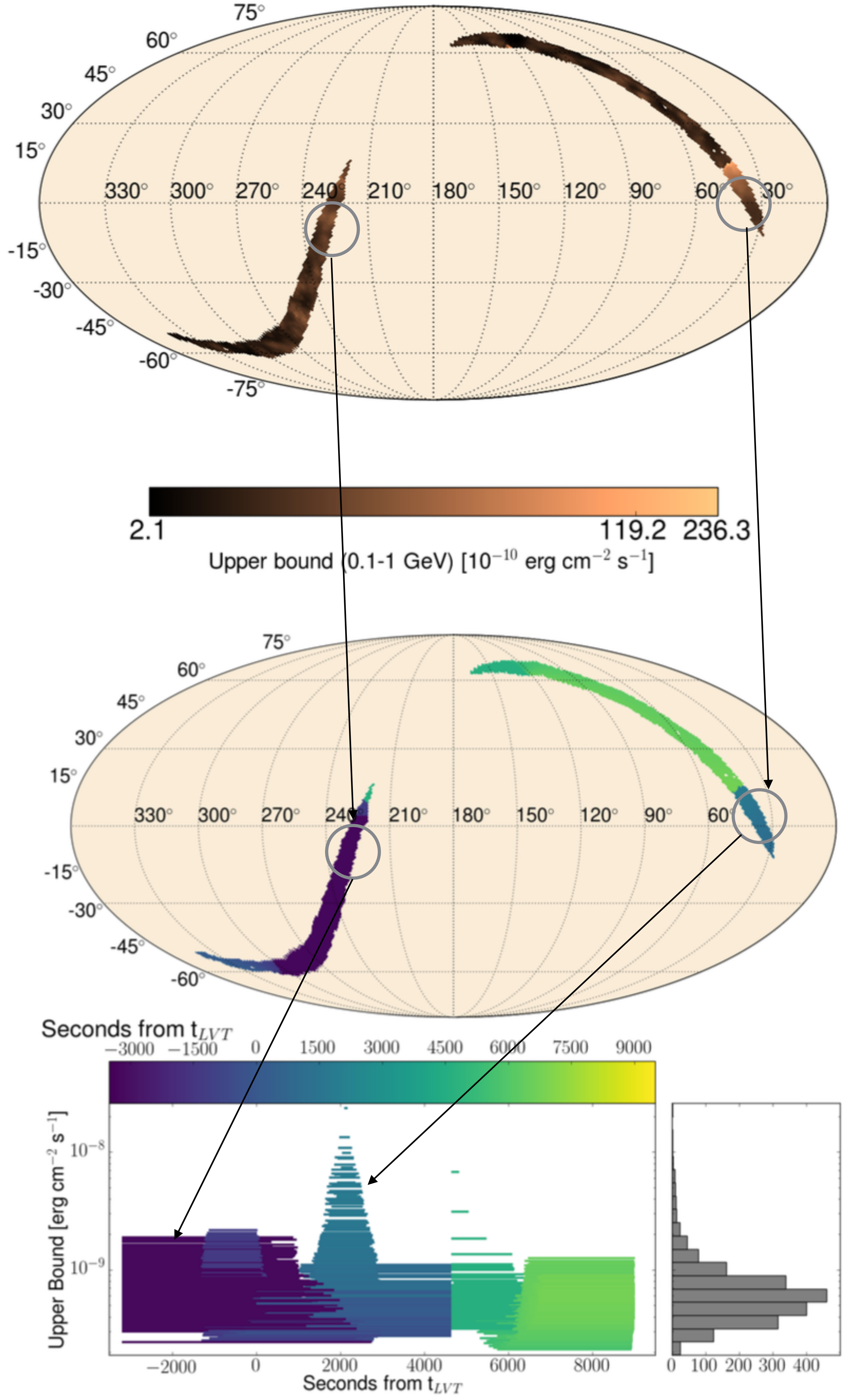
Example, LVT151012

$$\int_0^{F_{\rm ub}} P(F|D)\,dF = p_{\rm ub}.$$





Fixed Time Windows - Adaptive intervals



- Adaptive time window:
  - Entry-exit for each pixel in the sky;
  - During the trigger or the orbit right after;
  - Scan an interval of days (before and after the trigger);
- Standard unbinned likelihood analysis:
  - TS (significance) maps;
  - Maps of upper bounds;

- These upper bounds depend on the location of the pixel in the sky, which also determines the interval of time we used in our analysis:
  - The colors of the horizontal lines in the last panel match the colors of the pixels in the second panel;
  - They can be used to constrain models if the location of the GW event is known (for example from its detection by some other facility);

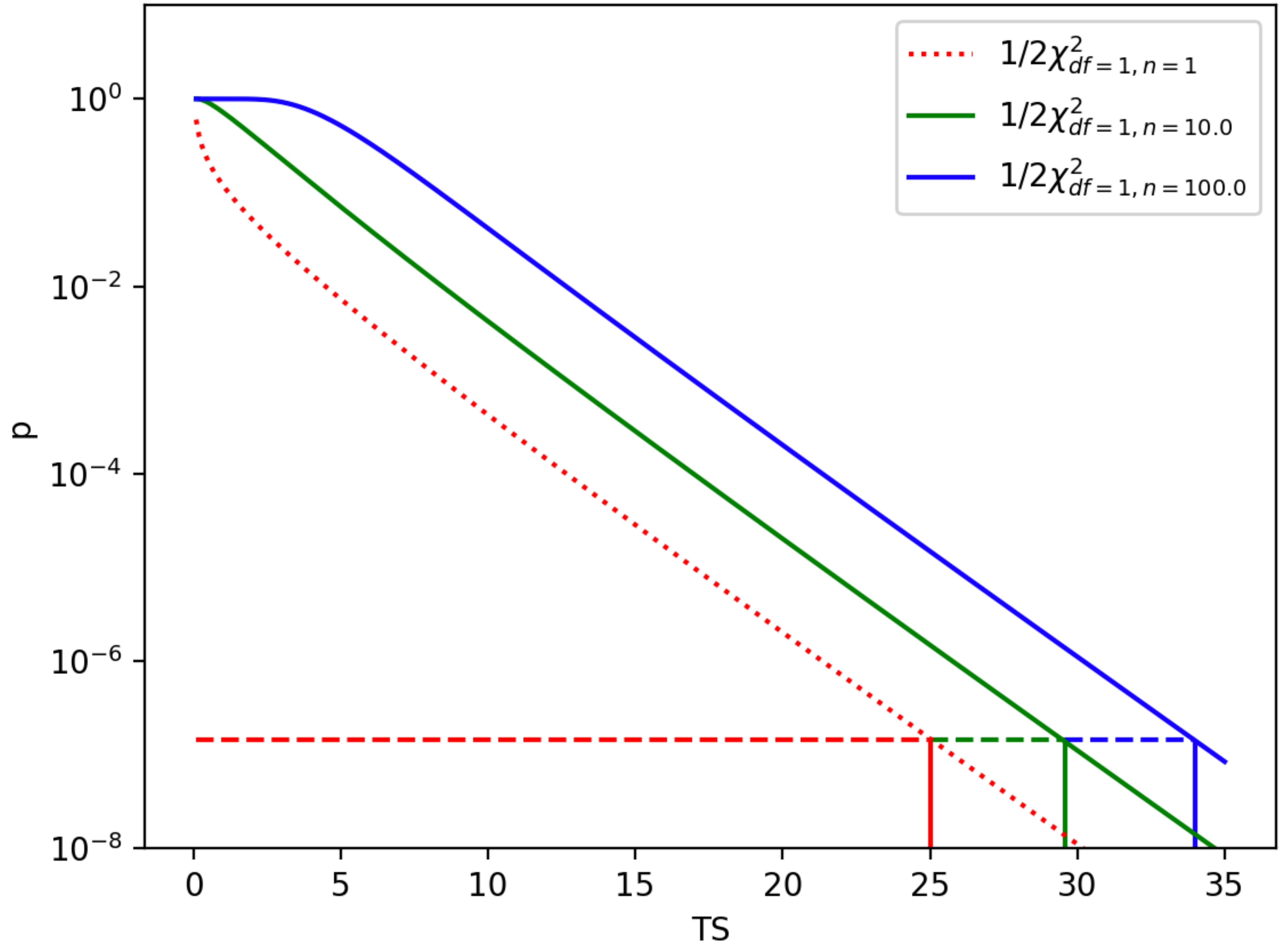
The more you look the less you found

- Simple example: if p is the probability of success (head, p=0.5) and q=(1-p) is the probability of fail, than, the probability of always failing after N trials is:
  - $p_N = (1-p)^N$
  - (0.5 with 1 toss, 0.25 with 2 toss, …)
- The probability of NOT failing is:
  - $1-(1-p)^N$
  - (0.5 with 1 toss, 0.75 with 2 toss, …)

- I can use this simple solution to compute the post trial probability:
  - If p is the probability to obtain a given realization, what is the probability of the same realization if I repeat the experiment N independent times?
  - $p_{post}=1-(1-p_{pre})^N$

For the TS distribution…

- **Test Statistic: TS = -2 (log L0 - log L1) is distributed as a chi^2 with dot = number of parameters to go from model 1 to model 0.**
- **A TS=25 roughly corresponds to a 5 sigma fluctuation, but not if you repeat the experiment N times!**
- **Looking for signal in N pixels will also increase the probability of obtaining a detection, just for statistical fluctuations!**




```
TS_distribution.ipynb
Trials.ipynb
```

Conclusions

- New era of multi messenger astronomy began with the simultaneous detection of a GW signal and a short GRB.
- Neutrino Astronomy joined the party with simultaneous detection of a Ice Cube event with a flaring blazar
  - Fermi was critical in both the discoveries.
  - Excellent prospects for CTA
- Followup of GW events is now “a thing”, new techniques have been developed
  - Tiling
  - Targeting
  - Narrowing
- Look up for number of trials
  - The more you look, the less you found
- Use simulations!
  - Make sure to know what to expect…